# Physics highlights and challenges: particle physics

*Paris Sphicas*
*CERN & NKUA*
*BPU11 (11th International Conference of the Balkan Physical Union)*
*Belgrade, Aug 29, 2022*

- **Introduction: How we got to here: a brief history of the past four decades**
- **Where we stand & the imminent future (next 10-15 years)**
    - **The (fundamental?) scalar sector of the SM**
    - **Direct searches for BSM physics**
- **Dark Matter**
    - **Interplay of Direct and Indirect (collider) searches**
- **Physics of Flavor**
    - **Quark sector: CP violation, rare decays of K and B mesons**
    - **Neutrinos: New source of CP violation(?) Mass ordering?  Nature? New particles/interactions?**
- **Pseudo-summary**

# The Standard Model and colliders
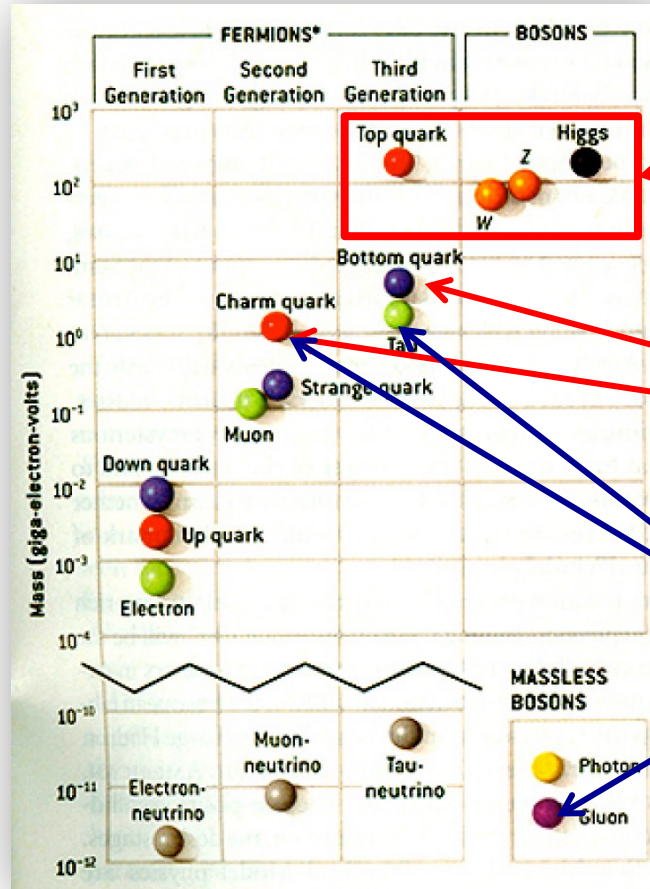


Hadron Colliders
W/Z: UA1/UA2 @ SPS
Top: CDF/D0 @ Tevatron
H: ATLAS/CMS @ LHC

Hadron Collisions
b quark: E288 @ FNAL
c quark: pBe @ AGS

ee Colliders
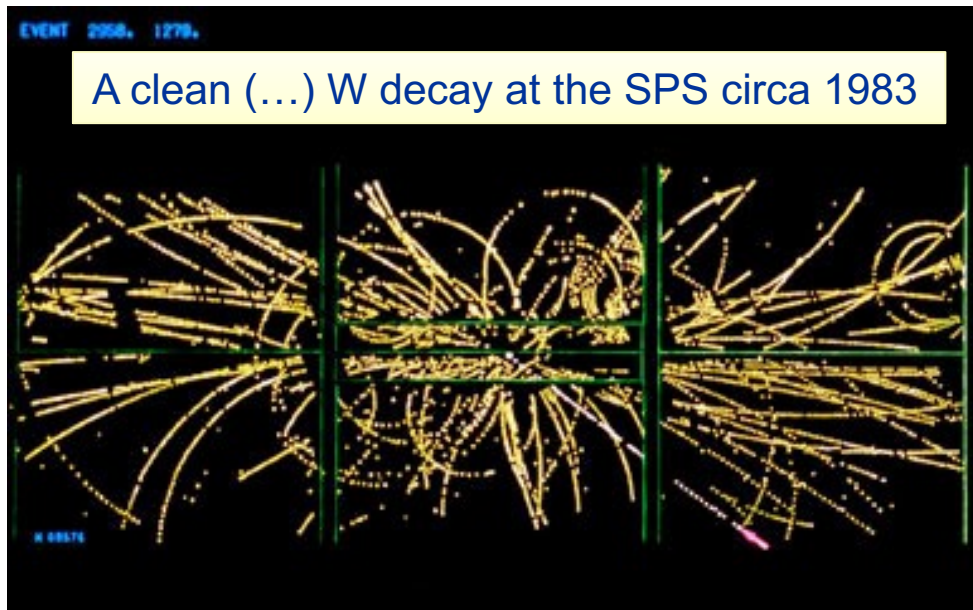c and $\tau$ @ SPEAR (SLAC)
g @ PETRA (DESY)

Not shown: probing/studying the strong, weak and EM interactions

# How we got to here

**A very (very…) brief summary**

# pp collisions :== parton-parton collisions + extra debris

**a** EVENTS WITHOUT JETS   **b** EVENTS WITH JETS

$\left(E_T^{MIS}\right)^2$

WITH JETS

UA1

**It was there, at the right time (number of events → rate → time of rendez-vous!)**
**At the right mass: 81±5 GeV**
**With the right spin: 1**

70 events

Fig. 3. The components of the missing energy parallel and perpendicular to the electron momentum plotted versus the
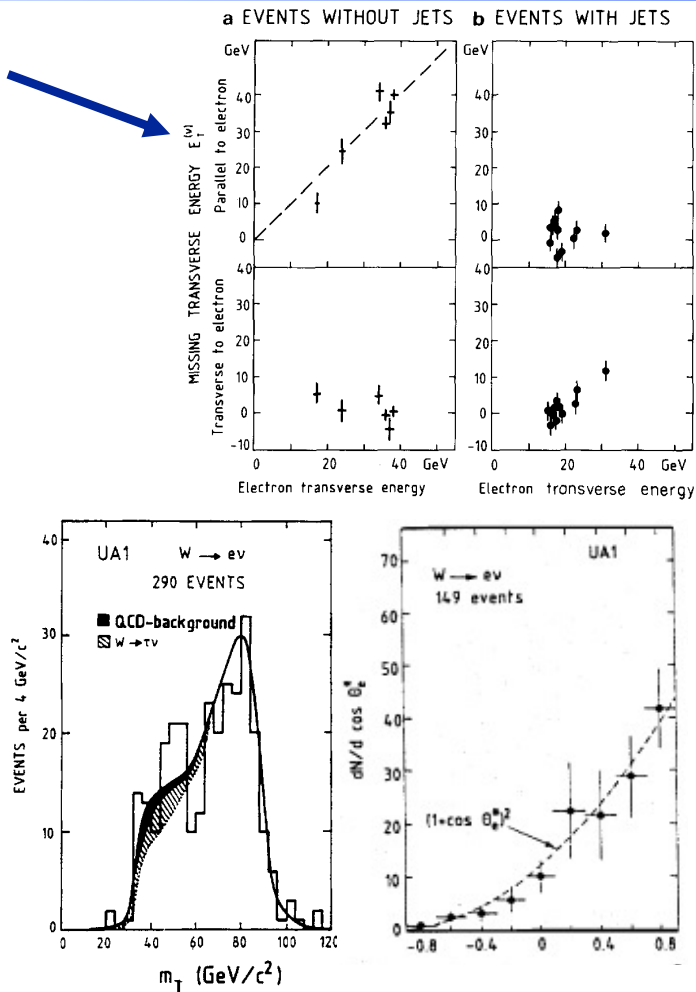
# The similarly punctual cousin: the Z boson

- **The Z boson was there as well**
  - **Also at the right time**
  - **And at the right mass (91 GeV)**
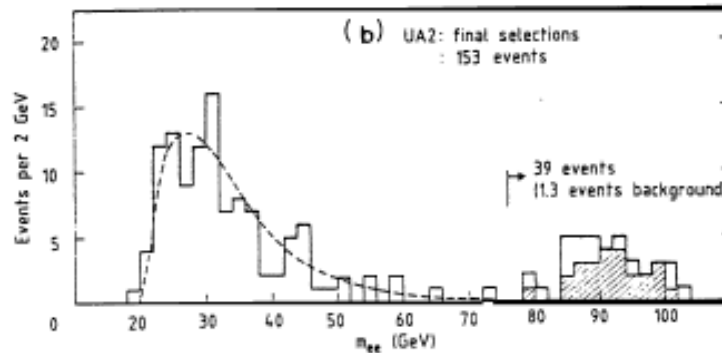


- **Tremendous (other) physics output from the 10 years of the SPS and the UA/UA2 experiments**

# End of the 80s, beginning 90s:

## Passing the baton to
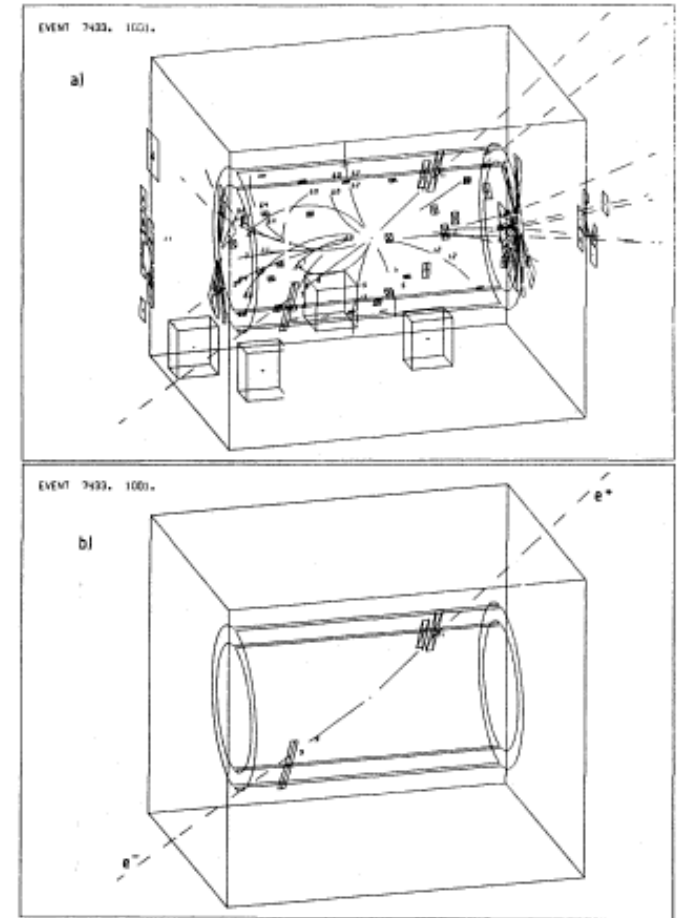## (a) LEP (CERN) & SLC (Stanford) and
## (b) The Tevatron (Fermilab)

# LEP & SLD Overview: Luminosity, Energy, Precision

LEP: Conventional collider e⁺e⁻ ring



PEP @ SLAC: complementary to LEP



Energy upgradeable; measurable;
Four detectors (A,D,L,O); Large luminosity:
        20 Million Z events.
But…. Energy limited by synchrotron radiation loss
($\sim\gamma^4$). At Z: 3 GeV/turn (replenished by the RF system)
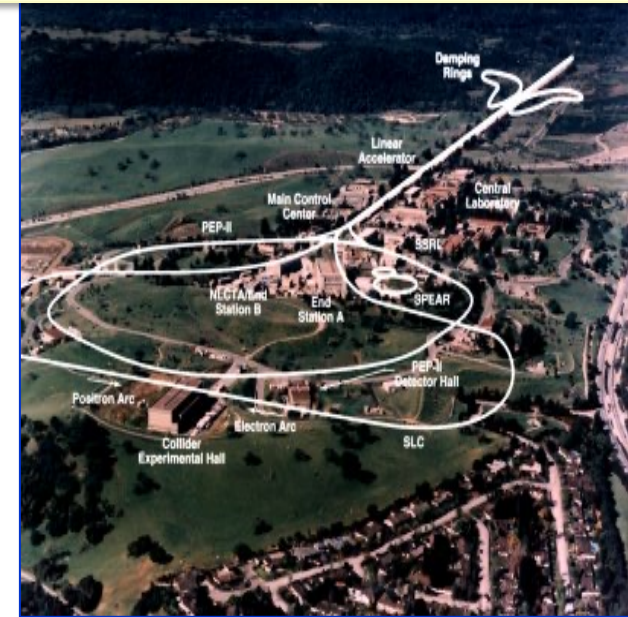
First (high $\sqrt{s}$) e⁺e⁻ "linear" collider (+ arcs);
Small transverse beam sizes (& beam pipe)
Reduced luminosity; Only one expt (SLD):
        0.35 Million Z events
BUT: 73% electron beam polarization;

# e⁺e⁻ collisions: clean, controlled environment

$$e^+e^- \rightarrow Z \rightarrow e^+e^-$$ $$e^+e^- \rightarrow Z \rightarrow \mu^+\mu^-$$ $$e^+e^- \rightarrow Z \rightarrow$$

$$e^+e^- \rightarrow Z \rightarrow q\bar{q} \rightarrow \text{hadrons}$$

$$e^+e^- \rightarrow Z \rightarrow e^+e^-$$

$$e^+e^- \rightarrow Z \rightarrow \mu^+\mu^-$$

$$e^+e^- \rightarrow Z \rightarrow \text{hadrons}$$

**Total Luminosity: 1000 pb⁻¹**
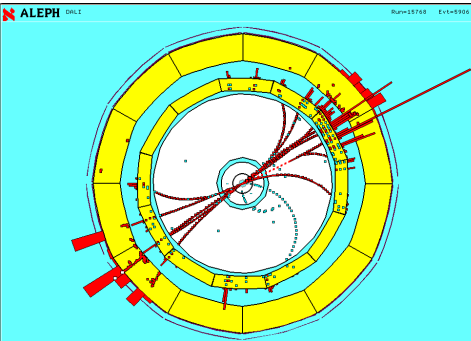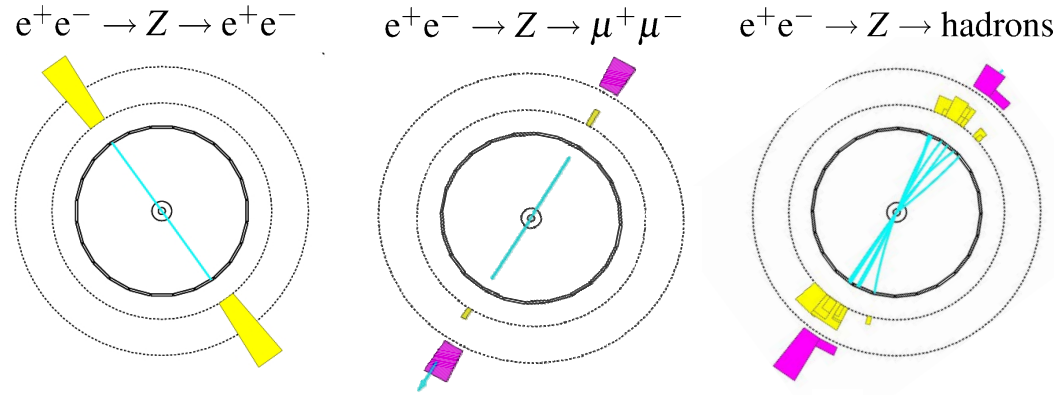
**Precision: 0.1%**

Two-jet event

Three-jet event

**Energy: 88 → 209.2 GeV**
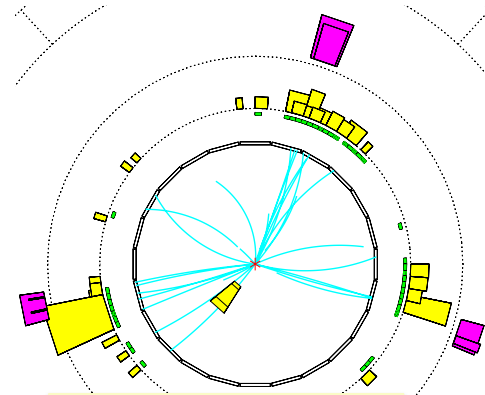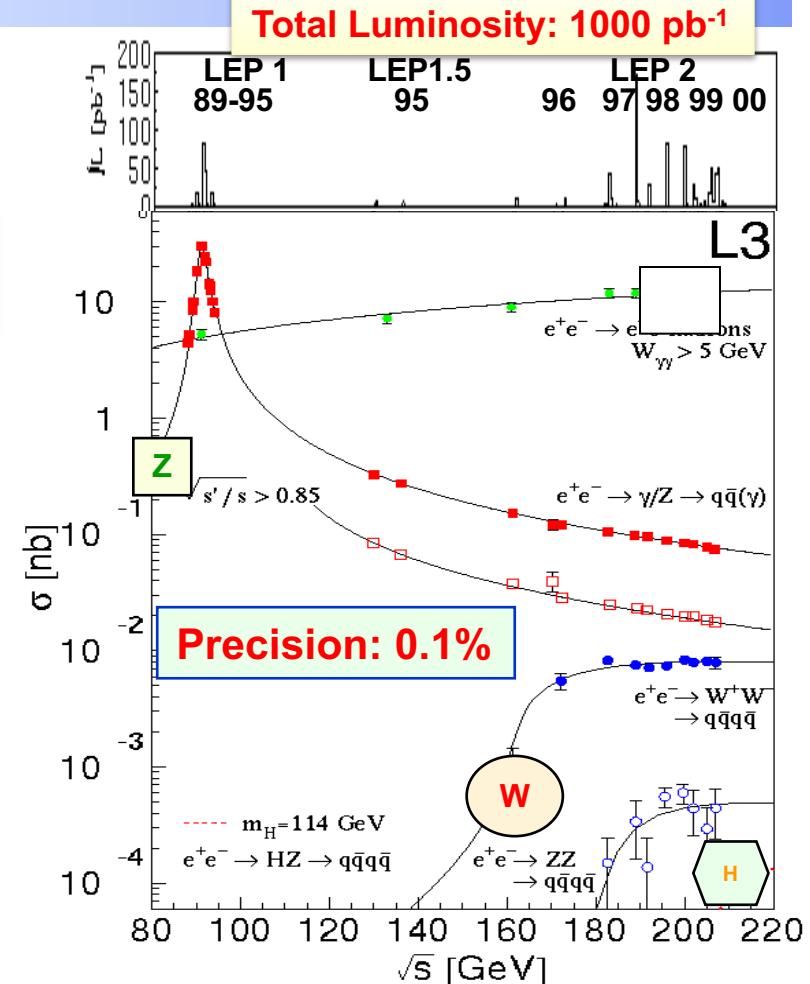
**LEP ran for over a decade
And delivered unprecedented
precision on the Electroweak Theory**
  **On several observables, 0.1%**

We also learned that:
There are at most three neutrino species
lighter than $M_Z$.

$$N_\nu = 2.9919 \pm 0.0081$$

Higgs boson heavier than 114.5 GeV
SUSY not there for masses ≤100 GeV

Precision gives access to loops

*Enter Radiative Corrections...*

*The final LEP blue band plot is created*

Highest √s attained: 209.2 GeV.
K. Hubner Phys. Reports 403-404 (2004)
The maximum energy of LEP2 was determined by the decision
in 1996 to discontinue the production of the SC cavities…

March 2012

$m_{Limit}$ = 152 GeV

Theory uncertainty
$\Delta\alpha_{had}^{(5)}$ =
— 0.02750±0.00033
···· 0.02749±0.00010
···· incl. low Q² data

$\Delta\chi^2$

LEP
excluded

LHC
excluded

40    100    200

# End of 80s, beginning of 90s: Tevatron
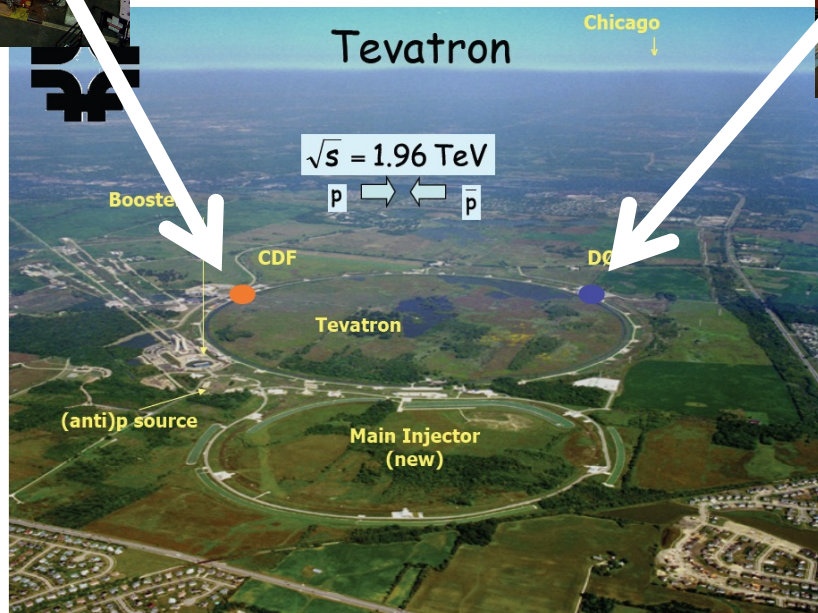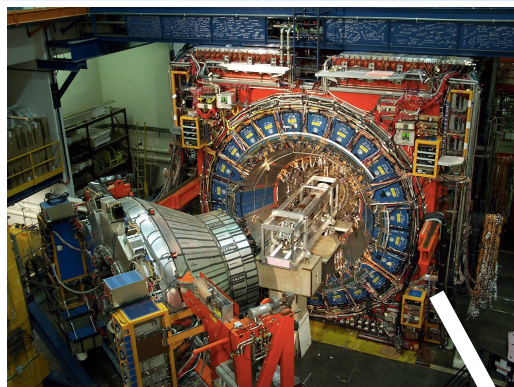
# The Tevatron discovery: the top quark (I)

❑ **The crowning moment for the Tevatron experiments: the observation of the Top quark**

  ❑ **The most complicated signature up to that point in time; leptons, jets, missing transverse energy, and b-tagging!**
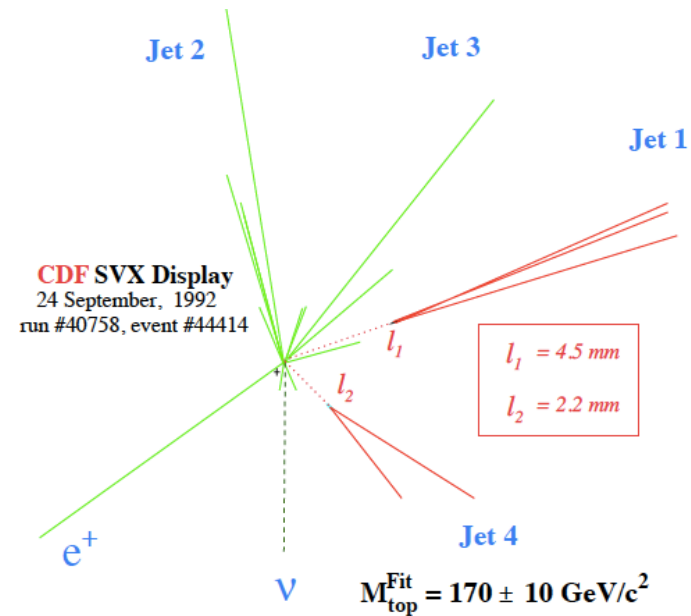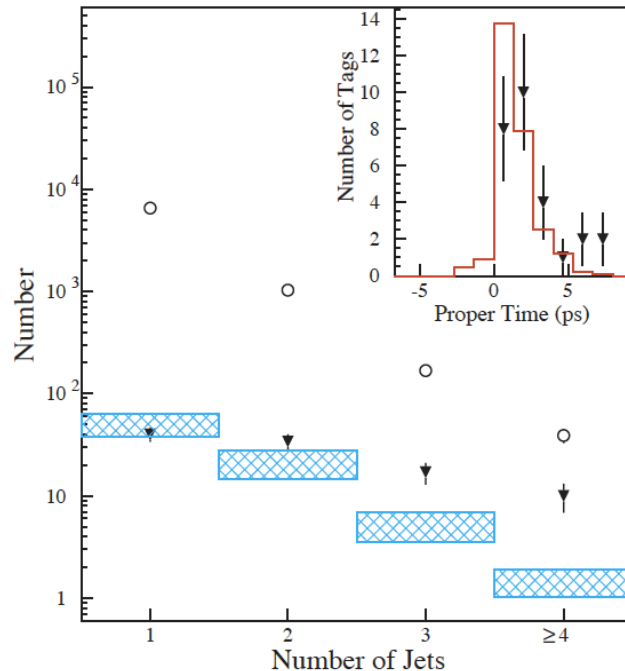
# LEP and the Tevatron were huge successes

**The word "success" does not do justice Yet… the Higgs Boson did not show up**

**And the Higgs… is extremely important:**

**the entire Standard Model of Particle Physics is based on the Brout-Englert-Higgs mechanism to**

*give masses to the W & Z bosons, while leaving the photon massless;*
*bonus: it also gives masses to the fermions!*
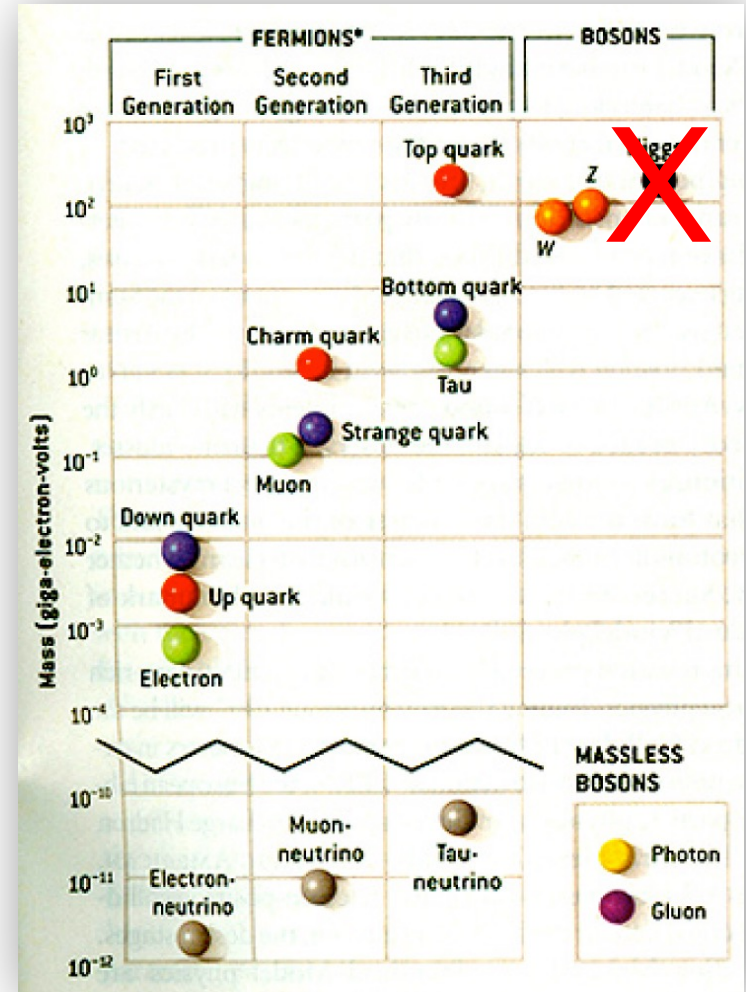
# A machine for EWSB

- **The Large Hadron Collider (LHC)**
  - **Use existing LEP tunnel at CERN**
  - **Replace: e by p; increase bending power (with superconducting magnets)**
  - **At the time (1990s): mass of the Higgs boson was completely unknown. But theoretical arguments said $M_H < 1$ TeV (1000 GeV).**
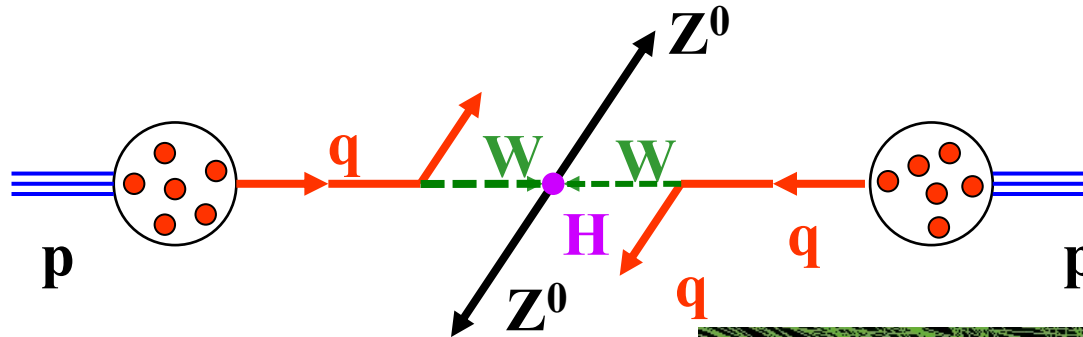


$M_H \sim 1000$ GeV
$E_W \geq 500$ GeV
$E_q \geq 1000$ GeV (1 TeV)
$E_p \geq 6000$ GeV (6 TeV)

But running at close to this energy $\rightarrow$ need high luminosity $\rightarrow$ pileup!
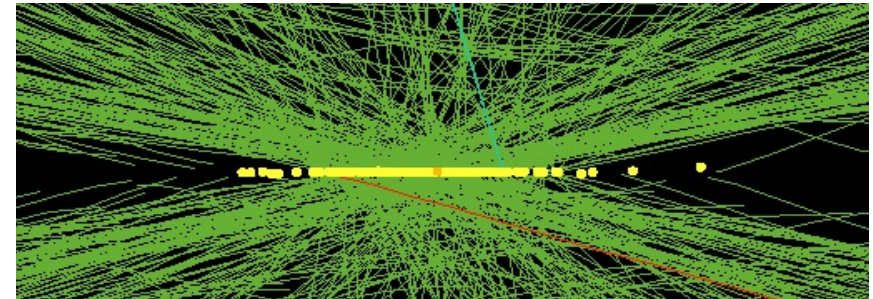
A tremendous, unprecedented challenge

**H→γγ**

CMS Experiment at the LHC, CERN
Data recorded: 2012-May-13 20:08:14.621490 GMT
Run/Event: 194108 / 564224000

**In July 2012: a new particle with mass ≈125 GeV is seen! It decays to γγ, ZZ → it's a boson (spin=0 or 2)**

p$_T$(μ)= 36, 48, 26, 72 GeV; m$_{12}$= 86.3 Ge

μ P$_T$ 32 GeV
e P$_T$ 34 GeV
ME$_T$
47 GeV

**H→Z**
**m$_{4μ}$=**

A New Boson Discovery

Phys. Lett. B 716 (2012) 1

Phys. Lett. B 716 (2012) 30

PHYSICS LETTERS B

☐ **Measurement of Spin-Parity, mass: it IS the vaccuum particle…**

**Production mechanisms, differential distributions**

$\delta M_H/M_H \sim 0.2\%$ (!)

$J^P = 0^+$ (!!!)

hood estimate of the parameters $\theta$ for a fixed value of
es and their correlations are modelled by introducing
normal functions associated with the es

ltaneous profile likelihood fit to the six
the normalisation modifiers in each BDT category
ion 5), and the nuisance parameters associated with
when accounting for the per-event resolu

124.92$^{+0.21}_{-0.20}$ GeV. Figure 4 shows the inclusive $m_{4l}$
fit to the $H \rightarrow ZZ^* \rightarrow$ 4l candidates. The estimate of $m_H$ is extracted by performing a simultaneous profile likelihood fit to the sixteen analysis categories. The free parameters of the fit are $m_H$, the normalisation modifiers in each BDT category for the signal and $ZZ^*$ background (defined in Section 5), and the systematic uncertainties. The measured value of $m_H$ when account to be $m_H^{ZZ^*}$ = 124.92 ± 0.19 (stat)$^{+0.09}_{-0.06}$ (syst) GeV = 124.92$^{+0.21}_{-0.20}$ distribution of the data together with the result of the fit to the $H \rightarrow ZZ^* \rightarrow 4l$ candidates.

where $\hat{m}_H$ and $\hat{\theta}$ denote the unconditional-maximum likelihood estimates of the parameters of the likelihood function $L$, while $\hat{\hat{\theta}}$ is the conditional-maximum-likelihood estimate of the parameters $\theta$ for a fixed value of the parameter of interest $m_H$. Systematic uncertainties and their correlations are modelled by introducing nuisance parameters $\theta$ described by Gaussian or log-normal functions associated with the estimate of the corresponding effect.

$L(m_H, \theta)$

d agreement with the average of the ATLAS and CMS Run 1 measurements. The
ATLAS Run 1 and Run 2 measurements yields
$m_H$ = 124.97 ± 0.24 GeV.

Phys. Lett. B 784 (2018) 345

**ATLAS**
Run 1: $\sqrt{s}$ = 7-8 TeV, 25 fb$^{-1}$  Run 2: $\sqrt{s}$ = 13 TeV, 36.1 fb$^{-1}$

| | Total (Stat. only) |
|---|---|
| **Run 1** $H \rightarrow 4l$ | 124.51 ± 0.52 (± 0.52) GeV |
| **Run 1** $H \rightarrow \gamma\gamma$ | 126.02 ± 0.51 (± 0.43) GeV |
| **Run 2** $H \rightarrow 4l$ | 124.79 ± 0.37 (± 0.36) GeV |
| **Run 2** $H \rightarrow \gamma\gamma$ | 124.93 ± 0.40 (± 0.21) GeV |
| **Run 1+2** $H \rightarrow 4l$ | 124.71 ± 0.30 (± 0.30) GeV |
| **Run 1+2** $H \rightarrow \gamma\gamma$ | 125.32 ± 0.35 (± 0.19) GeV |
| **Run 1** Combined | 125.38 ± 0.41 (± 0.37) GeV |
| **Run 2** Combined | 124.86 ± 0.27 (± 0.18) GeV |
| **ATLAS + CMS** Run 1 | 124.97 ± 0.24 (± 0.16) GeV |
| | 125.09 ± 0.24 (± 0.21) GeV |

$m_H$ [GeV]

(a) Gluon Fusion
(b) Vector Boson Fusion
(c) Higgsstrahlung
(d) $t\bar{t}$ Production

**ATLAS Preliminary**
$\sqrt{s}$ = 13 TeV, 24.5 - 139 fb$^{-1}$
$m_H$ = 125.09 GeV, $|y_H|$ < 2.5
$p_{SM}$ = 86%

| | Total Stat. Syst. |
|---|---|
| ggF | 1.00 ± 0.07 (± 0.05, ± 0.05) |
| VBF | 1.15 $^{+0.18}_{-0.17}$ (± 0.13, $^{+0.12}_{-0.10}$) |
| WH | 1.20 $^{+0.23}_{-0.21}$ ($^{+0.17}_{-0.16}$, $^{+0.15}_{-0.14}$) |
| ZH | 0.98 $^{+0.22}_{-0.21}$ (± 0.16, $^{+0.15}_{-0.13}$) |
| ttH+tH | 1.10 $^{+0.21}_{-0.20}$ ($^{+0.16}_{-0.15}$, $^{+0.14}_{-0.13}$) |

Cross-section normalized to SM value

$\mu = 1.06 \pm 0.07$

**ATLAS Preliminary**
$\sqrt{s}$ = 13 TeV, 139 fb$^{-1}$
$m_H$ = 125.09 GeV, $|y_H|$ < 2.5
$p_{SM}$ = 95%

Parameter normalized to SM value

**CMS** $\sqrt{s}$ = 7 TeV, ... $\sqrt{s}$ = 13 TeV, ...
137 fb$^{-1}$ (13 TeV)

- Data
- H(125)
- q$\bar{q}$→ZZ, Z$\gamma$*
- gg→ZZ, Z$\gamma$*
- EW
- Z+X

$m_{4l}$ (GeV)

# SM @ the highest E; EWSB ("Higgs" sector) (I)
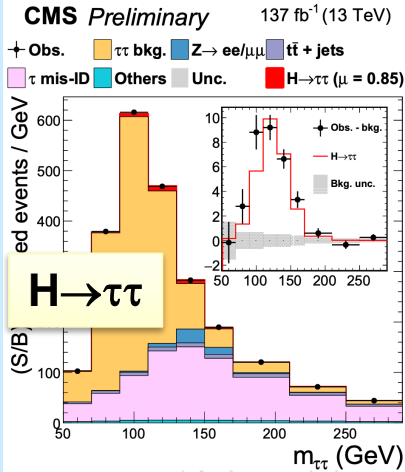


**Clear observation of couplings to 3rd-gen fermions**

**ttH**

**H→ττ**

**H→bb**
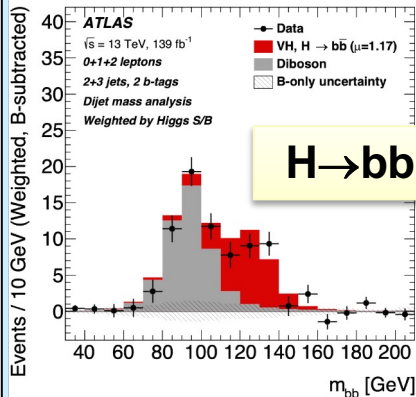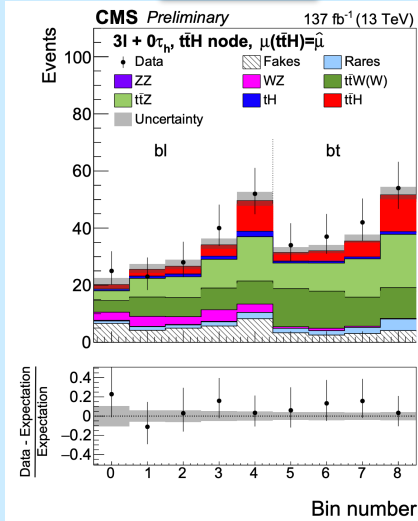
**Evidence of coupling to 2nd-gen fermions**
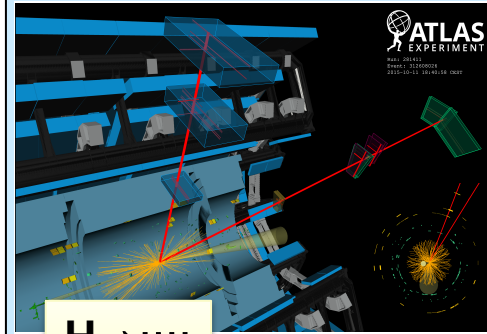


**CMS:**
obs: $3.0\sigma$ (exp: $2.5\sigma$)
**ATLAS:**
obs: $2.0\sigma$ (exp: $1.7\sigma$)

$\mu = 1.2 \pm 0.6$

**H→μμ**
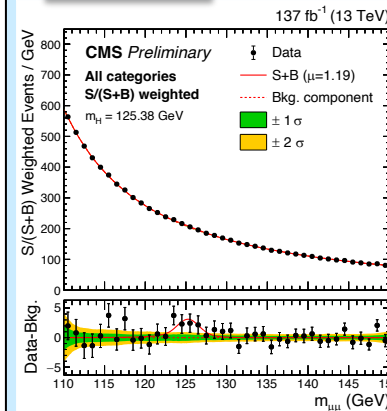
**H→cc**

$\mu_{VZ(Z \to cc)} = 1.01^{+0.23}_{-0.21}$

$\mu_{VH(H \to cc)} < 14$ (7.6 exp.)

$1.1 < |\kappa_c| < 5.5$ ($|\kappa_c| < 3.4$ exp.)

# The overall picture of the measured/seen Higgs couplings

$$\lambda_f = \kappa_f \left( \frac{m_f}{v} \right)$$

$$\left( \frac{g_V}{2v} \right)^{1/2} = \kappa_v^{1/2} \left( \frac{m_V}{v} \right)$$

A new kind of "force", with *non-universal couplings to matter (!)*

*A particle like no other!*
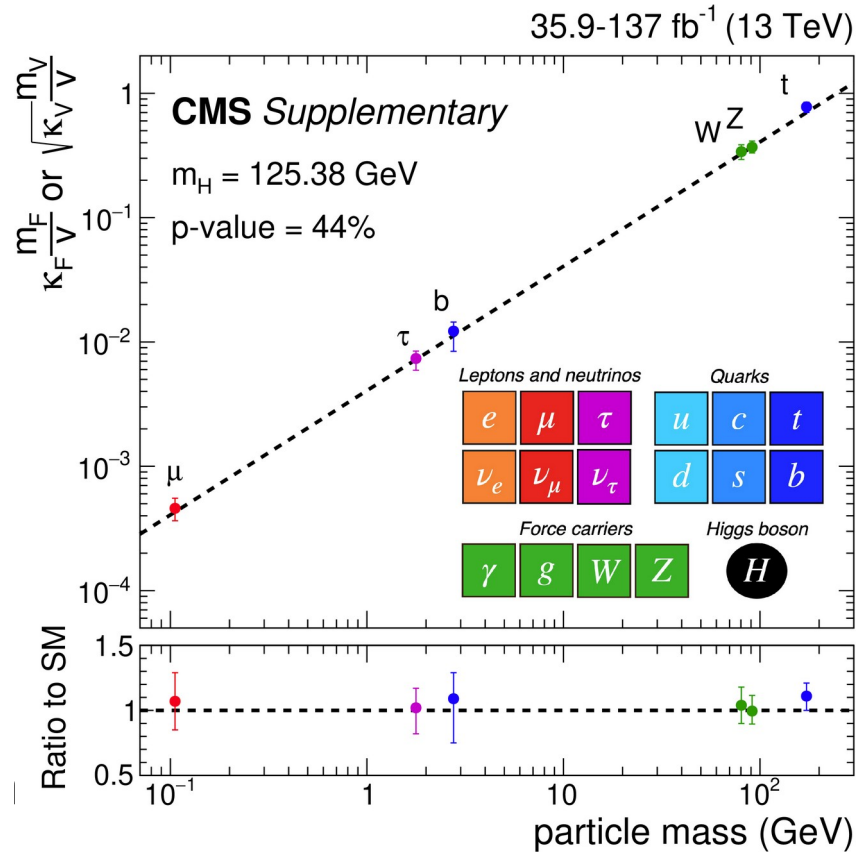
# Where we stand now

**A very brief summary**

# Standard Model of Particle Physics
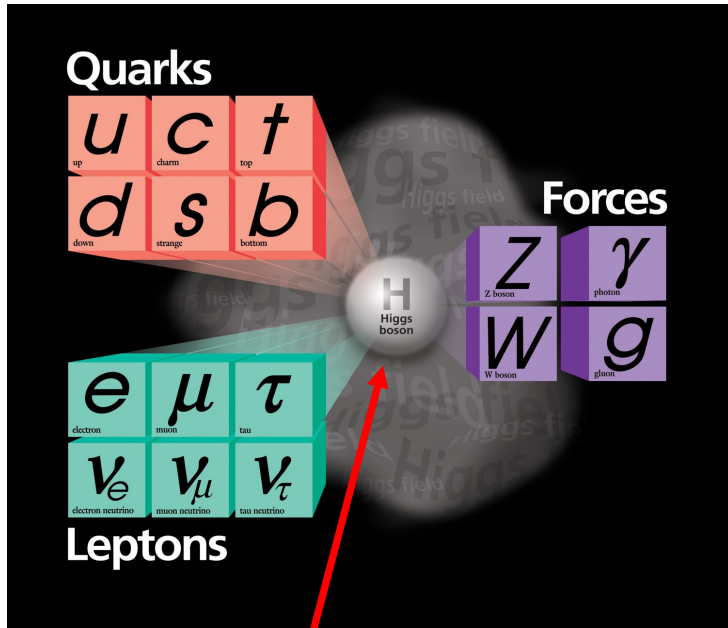


Highest priority: understand this central and most strange element
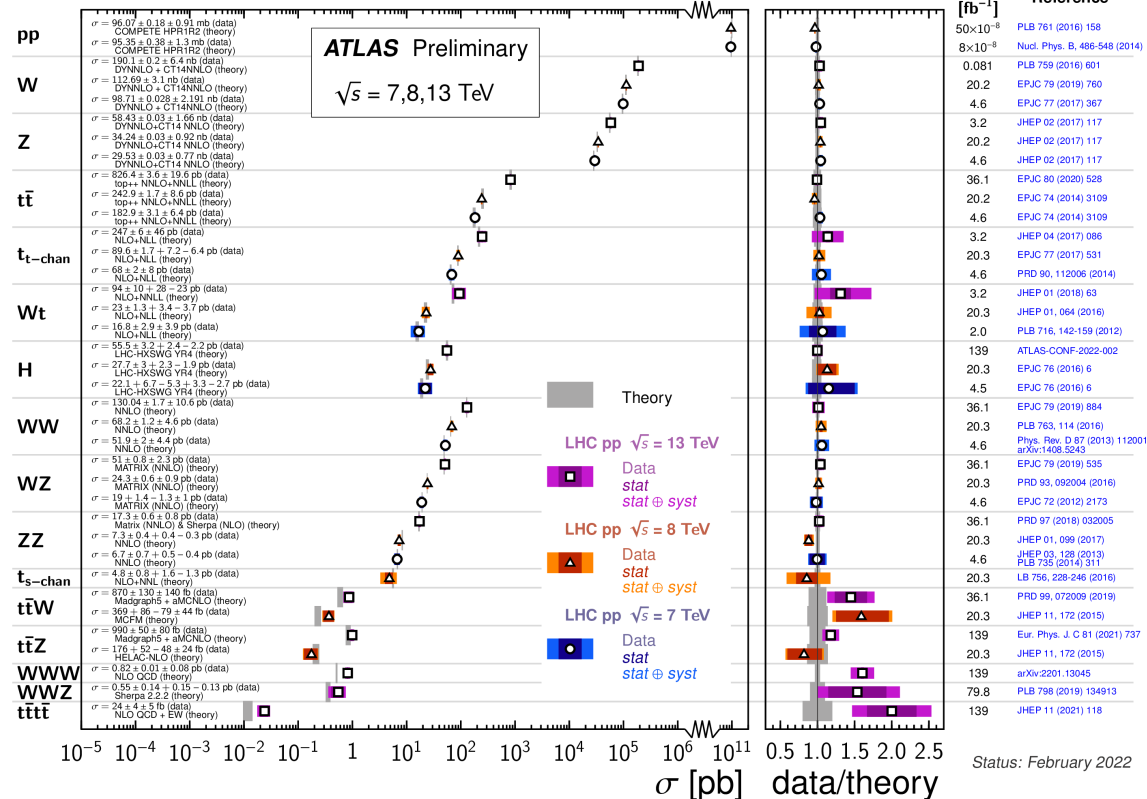
# Putting it all together: SM reigns supreme

- **Goodness of fit**
  - $\chi^2_{min}=18.6 \rightarrow$ **Prob= 23%**
- **Fit result often more accurate than measurement**
  - **Small pulls for $M_H$, $M_Z$, $\Delta\alpha_{had}^{(5)}(M_Z^2)$, $m_c$, $m_b \rightarrow$ input accuracies exceed fit requirements**
- **Knowledge of $m_H \rightarrow$ huge improvement in:**
  - **$m_W$ (28→11 MeV)** arXiv:1407.3792
  - **$m_t$ (6.2→2.5 GeV)**
  - **$\sin^2\theta_W$ (2.3→1.0x10⁻³)**
- **Largest discrepancy**
  - **$A_{FB}(b)$: 2.5 σ**



arXiv:1803.01853

| | $(O_{fit} - O_{meas}) / \sigma_{meas}$ |
|---|---|
| $M_H$ | 0.0 |
| $M_W$ | -1.5 |
| $\Gamma_W$ | 0.1 |
| $M_Z$ | 0.3 |
| $\Gamma_Z$ | -0.2 |
| $\sigma^0_{had}$ | -1.5 |
| $R^0_{lep}$ | -1.0 |
| $A^{0,l}_{FB}$ | -0.9 |
| $A_l(LEP)$ | 0.1 |
| $A_l(SLD)$ | -2.1 |
| $\sin^2\Theta^{lept}_{eff}(Q_{FB})$ | -0.7 |
| $\sin^2\Theta^{lept}_{eff}(Tevt.)$ | 0.1 |
| $A^{0,c}_{FB}$ | 0.8 |
| | 2.4 |
| $A_c$ | 0.0 |
| $A_b$ | 0.6 |
| $R^0_c$ | 0.0 |
| $R^0_b$ | -0.7 |
| $m_t$ | 0.5 |
| $\Delta\alpha_{had}^{(5)}(M_Z^2)$ | -0.2 |
| $\alpha_s(M_Z^2)$ | 1.3 |

**Global EW fit** / **Indirect determination** / **Measurement**

$(O_{indirect} - O) / \sigma_{tot}$

https://project-gfitter.web.cern.ch/

Light blue: fit excluding input from row
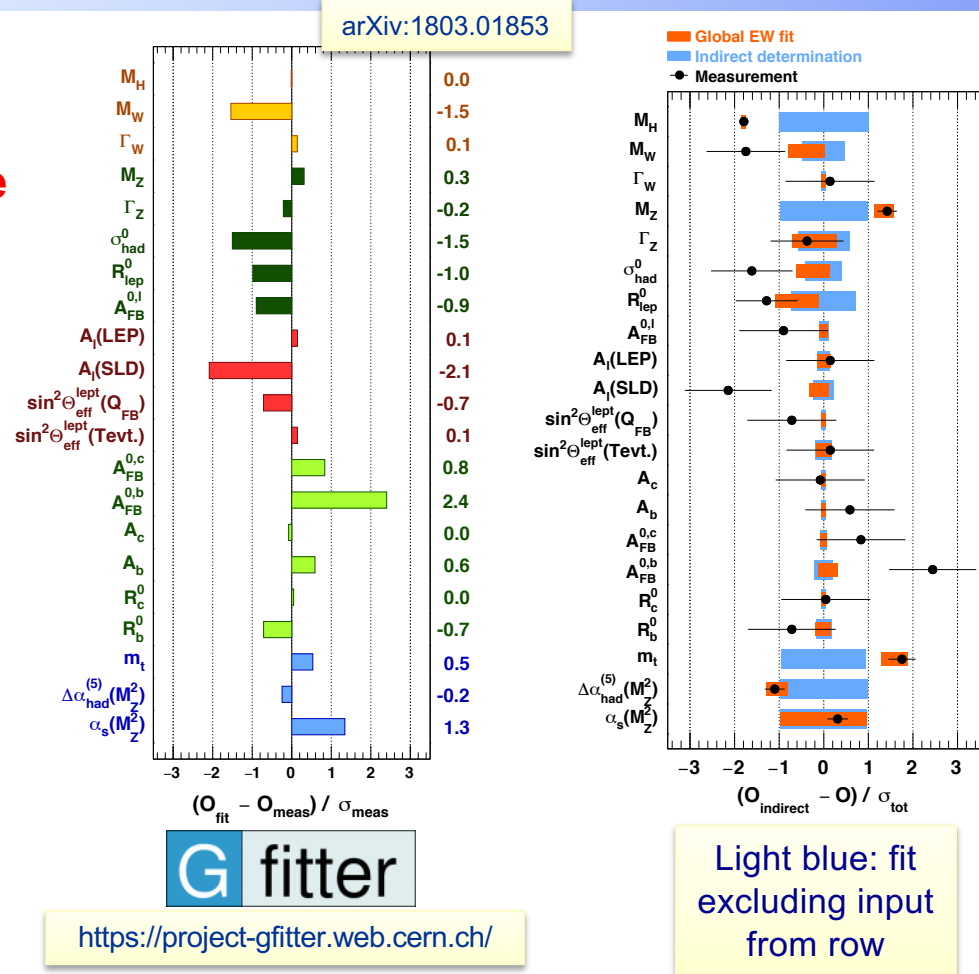
# The discovery of the Higgs boson was the ultimate crown on the Standard Model of Particle Physics

**With the discovery of the Higgs boson, the Standard Model (SM) is now "complete": its full particle content has been observed**

> The SM provides a remarkably accurate description of experiments with and without high-energy accelerators. At the cost of 26 parameters determined by experiment…

**With the physics of the very small [thought to be] understood at energy scales of ≥ 100 GeV, the situation is reminiscent of previous times in history when our knowledge of nature was deemed to be "complete"**
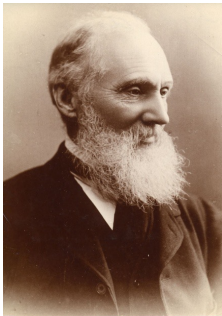


**Lord Kelvin (1900):**
**There is nothing new to be discovered in physics now. All that remains is more and more precise measurement.**

**1905-1920: Relativity, Quantum mechanics…**

# The magic of the Higgs boson mass

**Quantum Mechanics: ultimate destructor of small numbers (in nature) not protected by some symmetry (thus "law")**

**Higgs boson: the ultimate example; spinless → zero cost from mass correction**

$$m^2\left(p^2\right) = m^2\left(\Lambda^2\right) + C g^2 \int_{p^2}^{\Lambda^2} dk^2$$
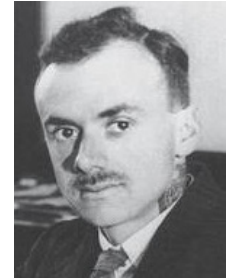
**P.A.M Dirac**

**M(H) with corrections all the way up to the Planck scale: for Λ ~ $10^{19}$ GeV**
**[for illustration only; numbers are random]**
**m² = 123456789012345678901234567 5432189012 –**
    **123456789012345678901234567 5432173387 =**
    **15625 GeV²**

**An immense coincidence of googlic sizes?**
    **Probably, simply some additional (i.e.**
    **New) physics on the way to $10^{19}$ GeV**

**We know there is new physics already**
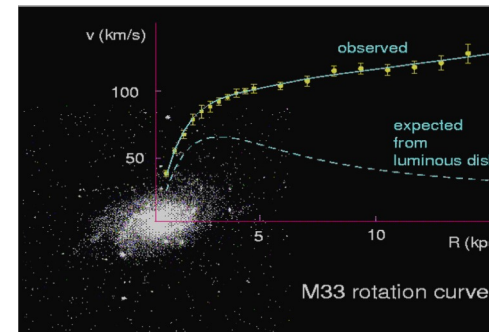
**Dark (invisible) matter!**

**Plus neutrinos and their masses!**

# The hunt for "New Physics"

## Despite finding the last missing piece of the SM, there is plenty of room for NP
### (beyond the magic of the $M_H$-$m_t$ mass)

**Some real and some virtual reasons to believe in new physics**

**Real reasons: dark matter & $\nu$ masses**
**Virtual reasons: naturalness**
**+ matter–antimmater asymmetry in the universe…**

# Solutions to the hierarchy problem

- **Solution #1: a composite Higgs**
  - **H: bound state (e.g. due to some new strong interaction)**
- **Solution #2: supersymmetry**
  - **Partners for ALL SM particles, spin different by ½**
  - **Presumably broken symmetry (since partners unseen)**
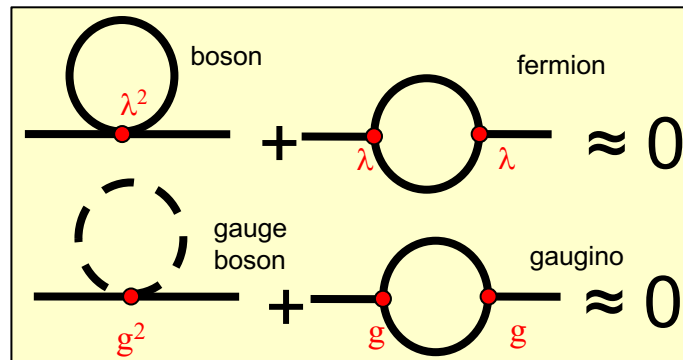


- **Solution #3: little Higgs**
  - **H: pseudo-Goldstone boson of Ultimate Theory; just another effective theory, e.g. valid to ~10 TeV. Loops cancel by particles of same spin (so need to introduce these particles)**
- **Solution #4: extra dimensions**
  - **N-dim space; gravity propagates in all dims, SM only in "our" 3 dims; e.g. warped extra dimension can explain weakness of G**
- **All of these "solutions" introduce either deviations in tails or new particles, with masses whose "natural" values should be O(few TeV)**

# The never-ending search for SUSY…
# (and it's not like we didn't look for them)

**ATLAS SUSY Searches\* - 95% CL Lower Limits**

*June 2021*

*ATLAS* Preliminary

$\sqrt{s}$ = 13 TeV

| Model | Signature | $\int \mathcal{L}\,dt$ [fb$^{-1}$] | Mass limit | | Reference |
|---|---|---|---|---|---|

**Inclusive Searches**

| | | | | | |
|---|---|---|---|---|---|
| $\tilde{q}\tilde{q}, \tilde{q}\to q\tilde{\chi}_1^0$ | $0\ e,\mu$ 2-6 jets $E_T^{miss}$ | 139 | $\tilde{q}$ [1×, 8× Degen.] 1.0 1.85 | m($\tilde{\chi}_1^0$)<400 GeV | 2010.14293 |
| | mono-jet 1-3 jets $E_T^{miss}$ | 36.1 | $\tilde{q}$ [8× Degen.] 0.9 | m($\tilde{q}$)-m($\tilde{\chi}_1^0$)=5 GeV | 2102.10874 |
| $\tilde{g}\tilde{g}, \tilde{g}\to q\bar{q}\tilde{\chi}_1^0$ | $0\ e,\mu$ 2-6 jets $E_T^{miss}$ | 139 | $\tilde{g}$ 2.3 | m($\tilde{\chi}_1^0$)=0 GeV | 2010.14293 |
| | | | $\tilde{g}$ Forbidden 1.15-1.95 | m($\tilde{\chi}_1^0$)=1000 GeV | 2010.14293 |
| $\tilde{g}\tilde{g}, \tilde{g}\to q\bar{q}W\tilde{\chi}_1^0$ | $1\ e,\mu$ 2-6 jets | 139 | $\tilde{g}$ 2.2 | m($\tilde{\chi}_1^0$)<600 GeV | 2101.01629 |
| $\tilde{g}\tilde{g}, \tilde{g}\to q\bar{q}(\ell\ell)\tilde{\chi}_1^0$ | $ee,\mu\mu$ 2 jets $E_T^{miss}$ | 36.1 | $\tilde{g}$ 1.2 | m($\tilde{g}$)-m($\tilde{\chi}_1^0$)=50 GeV | 1805.11381 |
| $\tilde{g}\tilde{g}, \tilde{g}\to qqWZ\tilde{\chi}_1^0$ | $0\ e,\mu$ 7-11 jets $E_T^{miss}$ | 139 | $\tilde{g}$ 1.97 | m($\tilde{\chi}_1^0$)<600 GeV | 2008.06032 |
| | SS $e,\mu$ 6 jets | 139 | $\tilde{g}$ 1.15 | m($\tilde{g}$)-m($\tilde{\chi}_1^0$)=200 GeV | 1909.08457 |
| $\tilde{g}\tilde{g}, \tilde{g}\to t\bar{t}\tilde{\chi}_1^0$ | 0-1 $e,\mu$ 3 $b$ $E_T^{miss}$ | 79.8 | $\tilde{g}$ 2.25 | m($\tilde{\chi}_1^0$)<200 GeV | ATLAS-CONF-2018-041 |
| | SS $e,\mu$ 6 jets | 139 | $\tilde{g}$ 1.25 | m($\tilde{g}$)-m($\tilde{\chi}_1^0$)=300 GeV | 1909.08457 |

**3rd gen. squarks direct production**

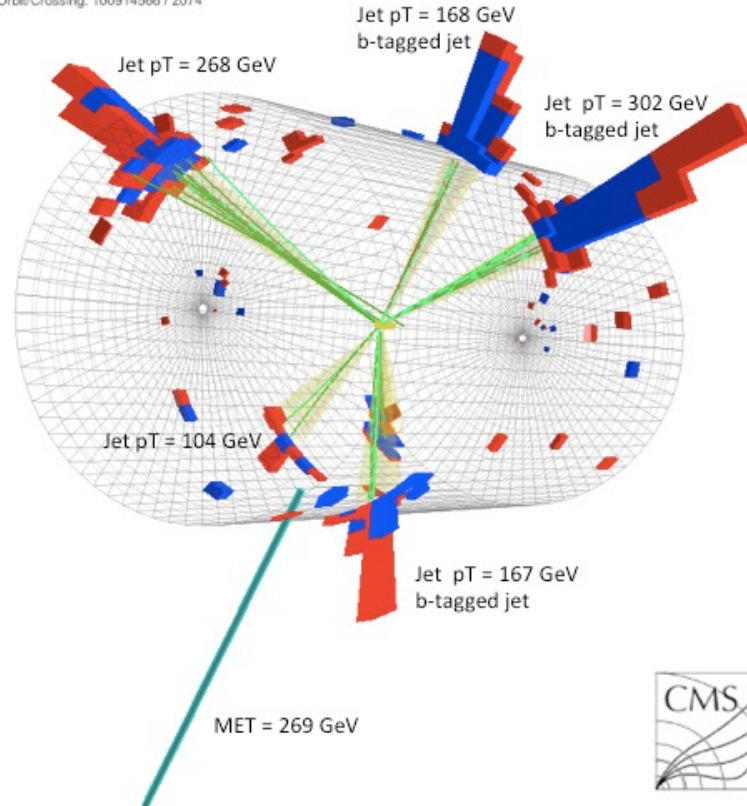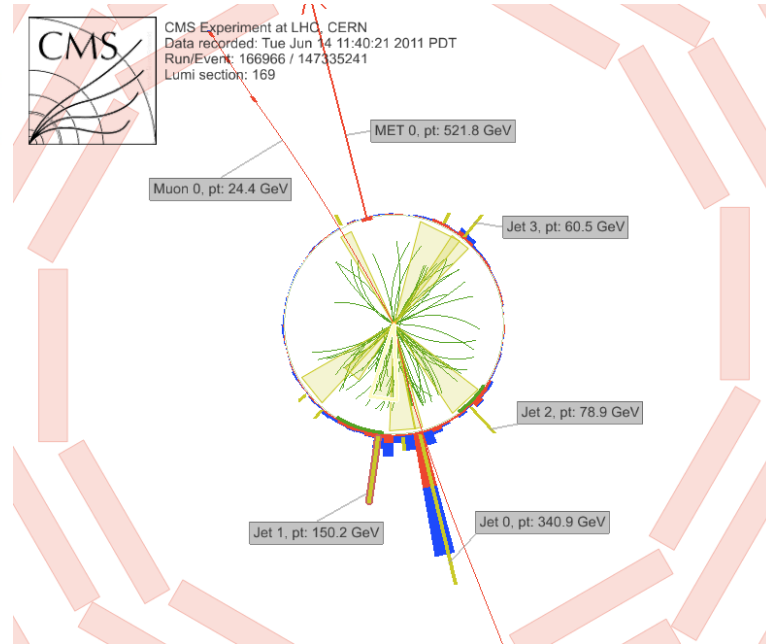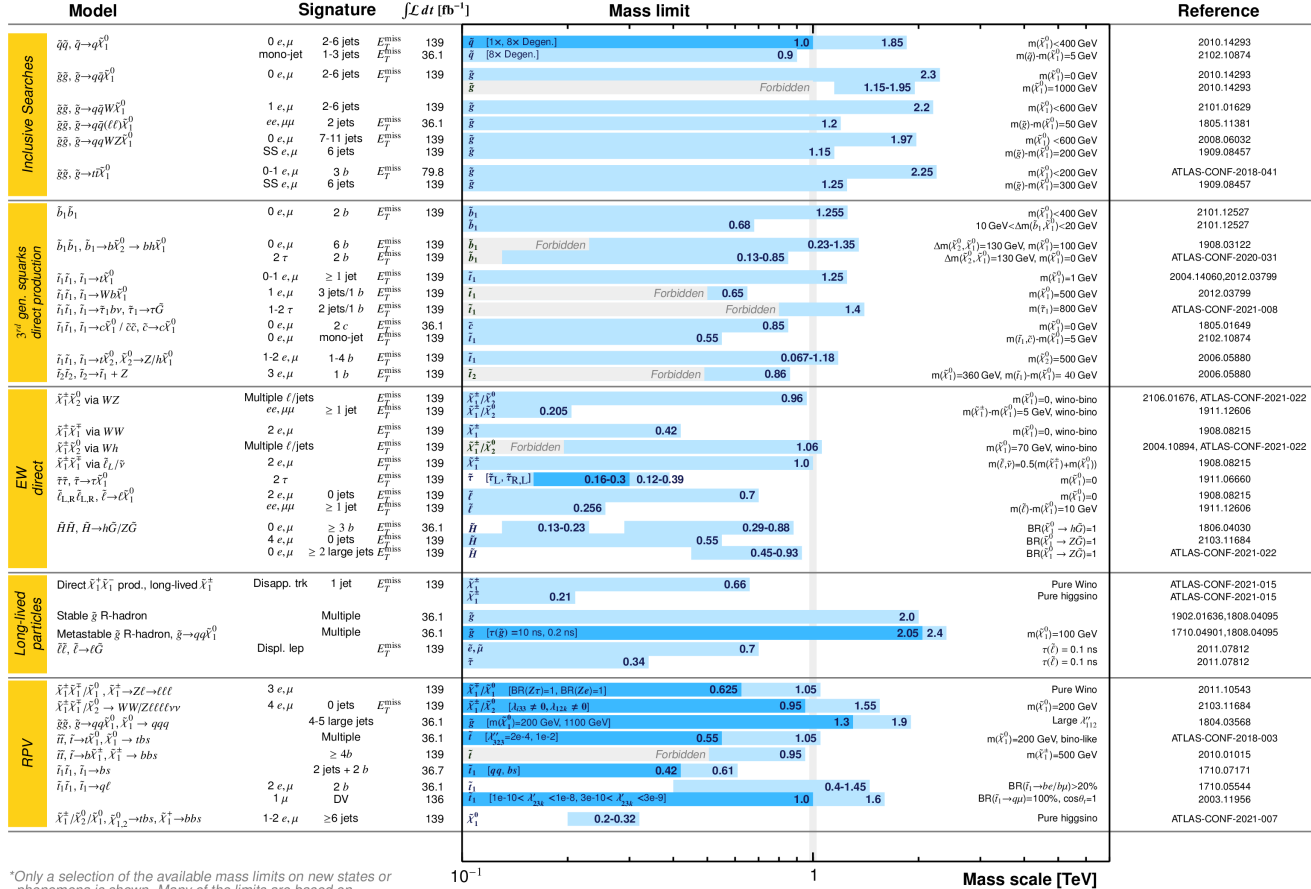| | | | | | |
|---|---|---|---|---|---|
| $\tilde{b}_1\tilde{b}_1$ | $0\ e,\mu$ 2 $b$ $E_T^{miss}$ | 139 | $\tilde{b}_1$ 1.255 | m($\tilde{\chi}_1^0$)<400 GeV | 2101.12527 |
| | | | $\tilde{b}_1$ 0.68 | 10 GeV<Δm($\tilde{b}_1,\tilde{\chi}_1^0$)<20 GeV | 2101.12527 |
| $\tilde{b}_1\tilde{b}_1, \tilde{b}_1\to b\tilde{\chi}_2^0\to bh\tilde{\chi}_1^0$ | $0\ e,\mu$ 6 $b$ $E_T^{miss}$ | 139 | $\tilde{b}_1$ Forbidden 0.23-1.35 | Δm($\tilde{\chi}_2^0,\tilde{\chi}_1^0$)=130 GeV, m($\tilde{\chi}_1^0$)=100 GeV | 1908.03122 |
| | $2\tau$ $E_T^{miss}$ | 139 | $\tilde{b}_1$ 0.13-0.85 | Δm($\tilde{\chi}_2^0,\tilde{\chi}_1^0$)=130 GeV, m($\tilde{\chi}_1^0$)=0 GeV | ATLAS-CONF-2020-031 |
| $\tilde{t}_1\tilde{t}_1, \tilde{t}_1\to t\tilde{\chi}_1^0$ | 0-1 $e,\mu$ ≥ 1 jet $E_T^{miss}$ | 139 | $\tilde{t}_1$ 1.25 | m($\tilde{\chi}_1^0$)=1 GeV | 2004.14060,2012.03799 |
| $\tilde{t}_1\tilde{t}_1, \tilde{t}_1\to Wb\tilde{\chi}_1^0$ | $1\ e,\mu$ 3 jets/1 $b$ $E_T^{miss}$ | 139 | $\tilde{t}_1$ Forbidden 0.65 | m($\tilde{\chi}_1^0$)=500 GeV | 2012.03799 |
| $\tilde{t}_1\tilde{t}_1, \tilde{t}_1\to \tilde{\tau}_1 bv, \tilde{\tau}_1\to\tau\tilde{G}$ | 1-2 $\tau$ 2 jets/1 $b$ $E_T^{miss}$ | 139 | $\tilde{t}_1$ Forbidden 1.4 | m($\tilde{\tau}_1$)=800 GeV | ATLAS-CONF-2021-008 |
| $\tilde{t}_1\tilde{t}_1, \tilde{t}_1\to c\tilde{\chi}_1^0 / \tilde{c}\tilde{c}, \tilde{c}\to c\tilde{\chi}_1^0$ | $0\ e,\mu$ 2 $c$ $E_T^{miss}$ | 36.1 | $\tilde{c}$ 0.85 | m($\tilde{\chi}_1^0$)=0 GeV | 1805.01649 |
| | $0\ e,\mu$ mono-jet $E_T^{miss}$ | 139 | $\tilde{t}_1$ 0.55 | m($\tilde{t}_1,\tilde{c}$)-m($\tilde{\chi}_1^0$)=5 GeV | 2102.10874 |
| $\tilde{t}_1\tilde{t}_1, \tilde{t}_1\to t\tilde{\chi}_2^0, \tilde{\chi}_2^0\to Z/h\tilde{\chi}_1^0$ | 1-2 $e,\mu$ 1-4 $b$ $E_T^{miss}$ | 139 | $\tilde{t}_1$ 0.067-1.18 | m($\tilde{\chi}_2^0$)=500 GeV | 2006.05880 |
| $\tilde{t}_2\tilde{t}_2, \tilde{t}_2\to\tilde{t}_1 + Z$ | 3 $e,\mu$ 1 $b$ $E_T^{miss}$ | 139 | $\tilde{t}_2$ Forbidden 0.86 | m($\tilde{\chi}_1^0$)=360 GeV, m($\tilde{t}_1$)-m($\tilde{\chi}_1^0$)= 40 GeV | 2006.05880 |

**EW direct**

| | | | | | |
|---|---|---|---|---|---|
| $\tilde{\chi}_1^\pm\tilde{\chi}_2^0$ via WZ | Multiple $\ell$/jets $E_T^{miss}$ | 139 | $\tilde{\chi}_1^\pm/\tilde{\chi}_2^0$ 0.96 | m($\tilde{\chi}_1^0$)=0, wino-bino | 2106.01676, ATLAS-CONF-2021-022 |
| | $ee,\mu\mu$ ≥ 1 jet $E_T^{miss}$ | 139 | $\tilde{\chi}_1^\pm/\tilde{\chi}_2^0$ 0.205 | m($\tilde{\chi}_1^\pm$)-m($\tilde{\chi}_1^0$)=5 GeV, wino-bino | 1911.12606 |
| $\tilde{\chi}_1^+\tilde{\chi}_1^-$ via WW | 2 $e,\mu$ $E_T^{miss}$ | 139 | $\tilde{\chi}_1^\pm$ 0.42 | m($\tilde{\chi}_1^0$)=0, wino-bino | 1908.08215 |
| $\tilde{\chi}_1^\pm\tilde{\chi}_2^0$ via Wh | Multiple $\ell$/jets $E_T^{miss}$ | 139 | $\tilde{\chi}_1^\pm/\tilde{\chi}_2^0$ Forbidden 1.06 | m($\tilde{\chi}_1^0$)=70 GeV, wino-bino | 2004.10894, ATLAS-CONF-2021-022 |
| $\tilde{\chi}_1^+\tilde{\chi}_1^-$ via $\tilde{\ell}_L/\tilde{\nu}$ | 2 $e,\mu$ $E_T^{miss}$ | 139 | $\tilde{\chi}_1^\pm$ 1.0 | m($\tilde{\ell},\tilde{\nu}$)=0.5(m($\tilde{\chi}_1^\pm$)+m($\tilde{\chi}_1^0$)) | 1908.08215 |
| $\tilde{\tau}\tilde{\tau}, \tilde{\tau}\to\tau\tilde{\chi}_1^0$ | $2\tau$ $E_T^{miss}$ | 139 | $\tilde{\tau}$ [$\tilde{\tau}_L,\tilde{\tau}_{R,L}$] 0.16-0.3 0.12-0.39 | m($\tilde{\chi}_1^0$)=0 | 1911.06660 |
| $\tilde{\ell}_{L,R}\tilde{\ell}_{L,R}, \tilde{\ell}\to\ell\tilde{\chi}_1^0$ | 2 $e,\mu$ 0 jets $E_T^{miss}$ | 139 | $\tilde{\ell}$ 0.7 | m($\tilde{\chi}_1^0$)=0 | 1908.08215 |
| | $ee,\mu\mu$ ≥ 1 jet $E_T^{miss}$ | 139 | $\tilde{\ell}$ 0.256 | m($\tilde{\ell}$)-m($\tilde{\chi}_1^0$)=10 GeV | 1911.12606 |
| $\tilde{H}\tilde{H}, \tilde{H}\to h\tilde{G}/Z\tilde{G}$ | $0\ e,\mu$ ≥ 3 $b$ $E_T^{miss}$ | 36.1 | $\tilde{H}$ 0.13-0.23 0.29-0.88 | BR($\tilde{\chi}_1^0\to h\tilde{G}$)=1 | 1806.04030 |
| | 4 $e,\mu$ 0 jets $E_T^{miss}$ | 139 | $\tilde{H}$ 0.55 | BR($\tilde{\chi}_1^0\to Z\tilde{G}$)=1 | 2103.11684 |
| | $0\ e,\mu$ ≥ 2 large jets $E_T^{miss}$ | 139 | $\tilde{H}$ 0.45-0.93 | BR($\tilde{\chi}_1^0\to Z\tilde{G}$)=1 | ATLAS-CONF-2021-022 |

**Long-lived particles**

| | | | | | |
|---|---|---|---|---|---|
| Direct $\tilde{\chi}_1^+\tilde{\chi}_1^-$ prod., long-lived $\tilde{\chi}_1^\pm$ | Disapp. trk 1 jet $E_T^{miss}$ | 139 | $\tilde{\chi}_1^\pm$ 0.66 | Pure Wino | ATLAS-CONF-2021-015 |
| | | | $\tilde{\chi}_1^\pm$ 0.21 | Pure higgsino | ATLAS-CONF-2021-015 |
| Stable $\tilde{g}$ R-hadron | Multiple | 36.1 | $\tilde{g}$ 2.0 | | 1902.01636,1808.04095 |
| Metastable $\tilde{g}$ R-hadron, $\tilde{g}\to qq\tilde{\chi}_1^0$ | Multiple | 36.1 | $\tilde{g}$ [τ($\tilde{g}$) =10 ns, 0.2 ns] 2.05 2.4 | m($\tilde{\chi}_1^0$)=100 GeV | 1710.04901,1808.04095 |
| $\tilde{\ell}\tilde{\ell}, \tilde{\ell}\to\ell\tilde{G}$ | Displ. lep $E_T^{miss}$ | 139 | $\tilde{e},\tilde{\mu}$ 0.7 | τ($\tilde{\ell}$) = 0.1 ns | 2011.07812 |
| | | | $\tilde{\tau}$ 0.34 | τ($\tilde{\ell}$) = 0.1 ns | 2011.07812 |

**RPV**

| | | | | | |
|---|---|---|---|---|---|
| $\tilde{\chi}_1^+\tilde{\chi}_1^-/\tilde{\chi}_1^0, \tilde{\chi}_1^+\to Z\ell\to\ell\ell\ell$ | 3 $e,\mu$ | 139 | $\tilde{\chi}_1^\pm/\tilde{\chi}_1^0$ [BR($Z\tau$)=1, BR($Ze$)=1] 0.625 1.05 | Pure Wino | 2011.10543 |
| $\tilde{\chi}_1^+\tilde{\chi}_1^-/\tilde{\chi}_2^0 \to WW/Z\ell\ell\ell\ell\nu\nu$ | 4 $e,\mu$ 0 jets $E_T^{miss}$ | 139 | $\tilde{\chi}_1^\pm/\tilde{\chi}_2^0$ [$\lambda_{i33}\neq 0, \lambda_{12k}\neq 0$] 0.95 1.55 | m($\tilde{\chi}_1^0$)=200 GeV | 2103.11684 |
| $\tilde{g}\tilde{g}, \tilde{g}\to qq\tilde{\chi}_1^0, \tilde{\chi}_1^0\to qqq$ | 4-5 large jets | 36.1 | $\tilde{g}$ [m($\tilde{\chi}_1^0$)=200 GeV, 1100 GeV] 1.3 1.9 | Large $\lambda''_{112}$ | 1804.03568 |
| $\tilde{t}\tilde{t}, \tilde{t}\to tb\tilde{\chi}_1^0, \tilde{\chi}_1^+\to tbs$ | Multiple | 36.1 | $\tilde{t}$ 0.55 1.05 | m($\tilde{\chi}_1^0$)=200 GeV, bino-like | ATLAS-CONF-2018-003 |
| $\tilde{t}\tilde{t}, \tilde{t}\to b\tilde{\chi}_1^+, \tilde{\chi}_1^+\to bbs$ | ≥ 4$b$ | 36.1 | $\tilde{t}$ Forbidden 0.95 | m($\tilde{\chi}_1^0$)=500 GeV | 2010.01015 |
| $\tilde{t}_1\tilde{t}_1, \tilde{t}_1\to bs$ | 2 jets + 2 $b$ | 36.7 | $\tilde{t}_1$ [$qq, bs$] 0.42 0.61 | | 1710.07171 |
| $\tilde{t}_1\tilde{t}_1, \tilde{t}_1\to q\ell$ | 2 $e,\mu$ 2 $b$ | 36.1 | $\tilde{t}_1$ 0.4-1.45 | BR($\tilde{t}_1\to be/b\mu$)>20% | 1710.05544 |
| | 1 $\mu$ DV | 136 | $\tilde{t}_1$ [1e-10< $\lambda'_{23k}$ <1e-8, 3e-10< $\lambda'_{23k}$ <3e-9] 1.0 1.6 | BR($\tilde{t}_1\to q\mu$)=100%, cos$\theta_t$=1 | 2003.11956 |
| $\tilde{\chi}_1^\pm/\tilde{\chi}_2^0/\tilde{\chi}_1^0, \tilde{\chi}_{1,2}^0\to tbs, \tilde{\chi}_1^+\to bbs$ | 1-2 $e,\mu$ ≥6 jets | 139 | $\tilde{\chi}_1^0$ 0.2-0.32 | Pure higgsino | ATLAS-CONF-2021-007 |

$10^{-1}$     1     **Mass scale [TeV]**

*\*Only a selection of the available mass limits on new states or phenomena is shown. Many of the limits are based on simplified models, c.f. refs. for the assumptions made.*
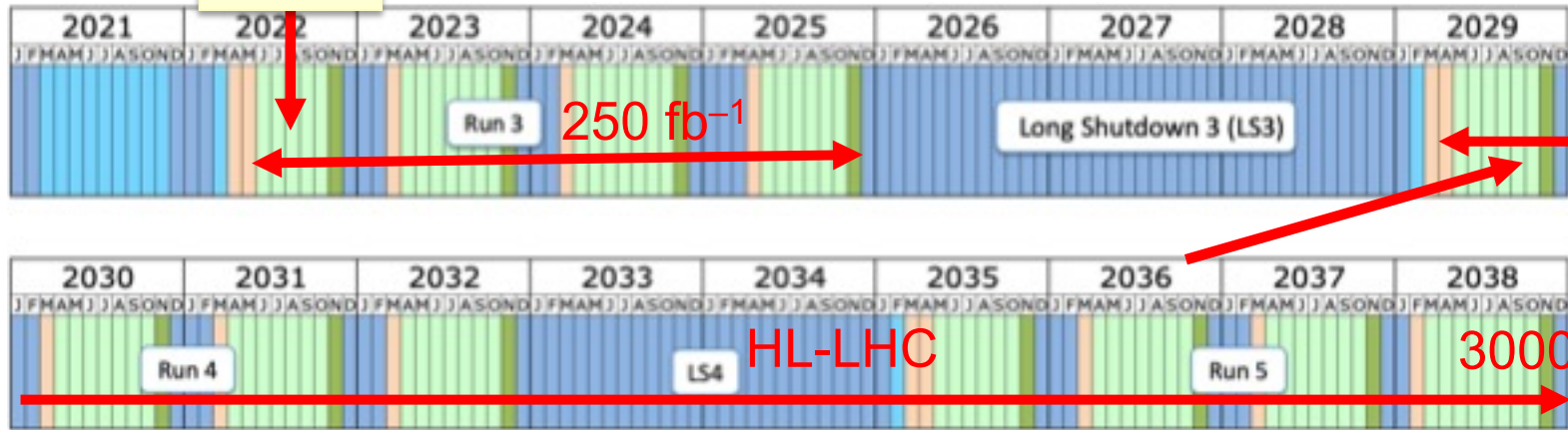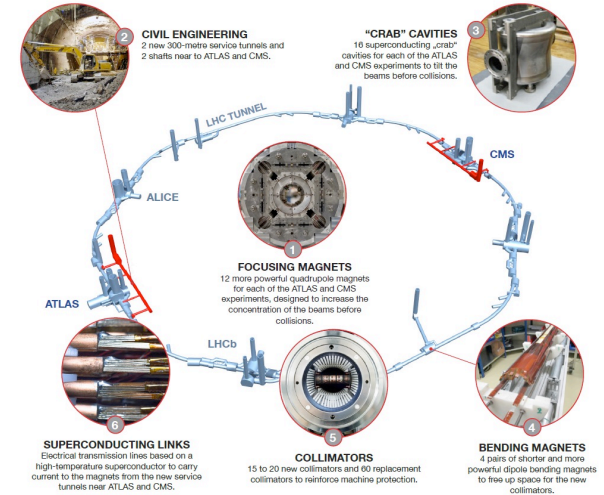
# The High-Luminosity LHC (HL-LHC)

**HL-LHC in a nutshell**

**Some physics projections**

# From the LHC to High-Luminosity LHC (HL-LHC)



L~30 fb$^{-1}$

L~150 fb$^{-1}$
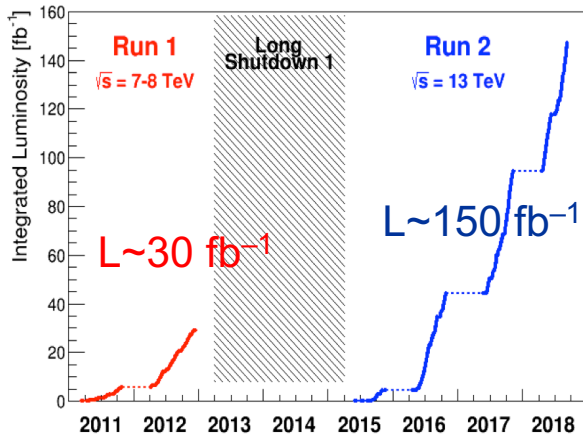
**HL-LHC: major intervention on more than 1.2 km of the LHC with new technologies: Nb$_3$Sn magnets, Crab cavities,...**



**CIVIL ENGINEERING**
2 new 300-metre service tunnels and 2 shafts near to ATLAS and CMS.

**"CRAB" CAVITIES**
16 superconducting „crab" cavities for each of the ATLAS and CMS experiments to tilt the beams before collisions.

**FOCUSING MAGNETS**
12 more powerful quadrupole magnets for each of the ATLAS and CMS experiments, designed to increase the concentration of the collisions before collisions.

**SUPERCONDUCTING LINKS**
Electrical transmission lines based on a high-temperature superconductor to carry current to the magnets from the new service tunnels near ATLAS and CMS.

**COLLIMATORS**
15 to 20 new collimators and 60 replacement collimators to reinforce machine protection.

**BENDING MAGNETS**
4 pairs of shorter and more powerful dipole bending magnets to free up space for the new collimators.

Today



250 fb$^{-1}$

3000 fb$^{-1}$

HL-LHC

Last updated: January 2022

# HL-LHC challenges

Annual dose at HL-LHC: similar to total dose from LHC start to LS3

Dose, 3000 fb$^{-1}$

CMS FLUKA geometry v.3.7.0.0

Key to physics: maintain detector performance in the presence of much higher pileup (140-200!)

tt event with 140 collisions PU
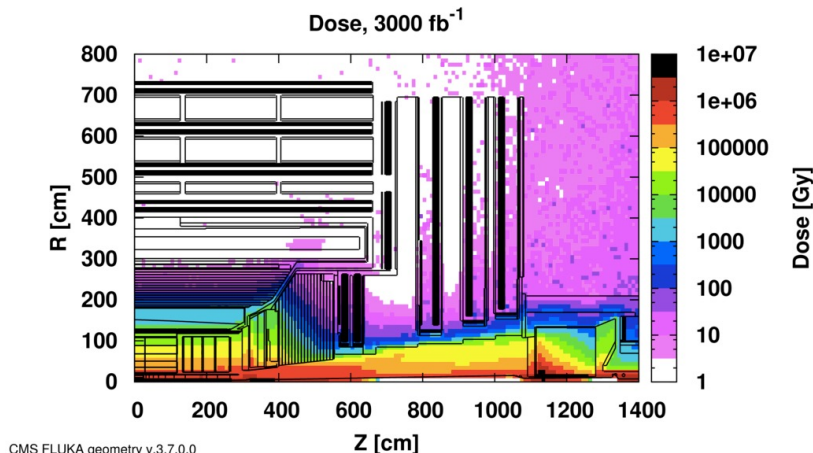
**Upgrade several detector components (trackers, calorimeters, redesign some electronics, new detector technologies, Trigger and DAQ**

## HL-LHC reach: Higgs



$\sqrt{s}$ = 14 TeV, 3000 fb⁻¹ per experiment

**ATLAS** and **CMS**
HL-LHC Projection
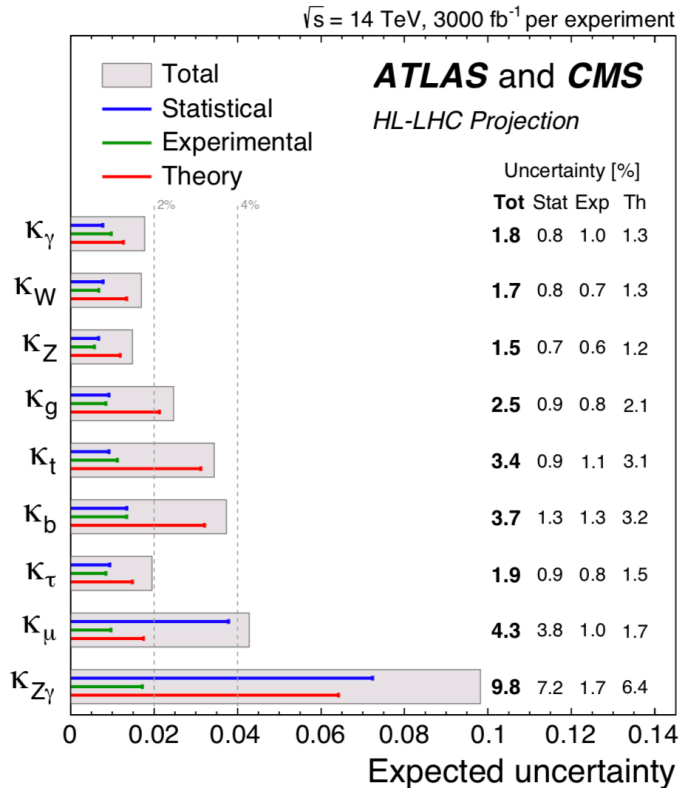
H width to invisible:
h(125)→XX.
Includes BSM decays
and rare SM decays: ≤4%
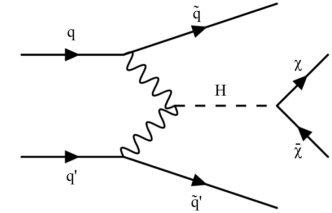
The ultimate frontier: Higgs self-coupling

$$V_h = \frac{m_h^2}{2}h^2 + (1+\kappa_3)\lambda_{hhh}^{SM}vh^3 + \frac{1}{4}(1+\kappa_4)\lambda_{hhhh}^{SM}h^4$$

$$V(H,T) = m^2(T)H^2 - E(T)H^3 + \lambda(T)H^4$$

Negatively Interfere

~ 40 fb @14 TeV × BR

ATLAS and CMS HL-LHC prospects   3 ab⁻¹ (14 TeV)

SM HH significance: 4σ
0.1 < κλ < 2.3 [95% CL]
0.5 < κλ < 1.5 [68% CL]

δλ≤50%
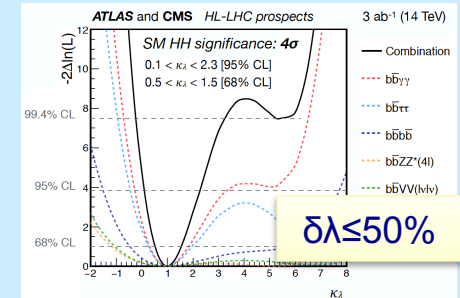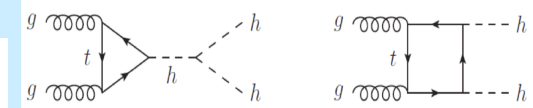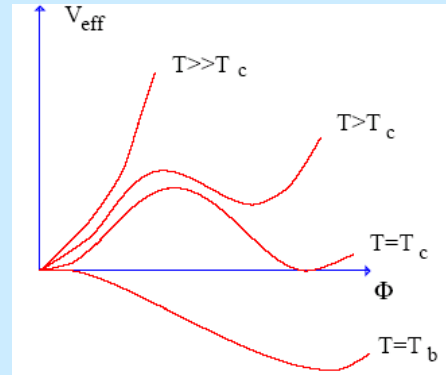
# Long-term future: proposed machines

**A very brief summary**

# EU Strategy: High-priority future initiatives

- **A. An electron-positron Higgs factory is the highest-priority next collider. For the longer term, the European particle physics community has the ambition to operate a proton-proton collider at the highest achievable energy. Accomplishing these compelling goals will require innovation and cutting-edge technology:**

  - *the particle physics community should ramp up its R&D effort focused on advanced accelerator technologies, in particular that for high-field superconducting magnets, including high-temperature superconductors;*

  - *Europe, together with its international partners, should investigate the technical and financial feasibility of a future hadron collider at CERN with a centre-of-mass energy of at least 100 TeV and with an electron-positron Higgs and electroweak factory as a possible first stage. Such a feasibility study of the colliders and related infrastructure should be established as a global endeavour and be completed on the timescale of the next Strategy update.*

  - *The timely realisation of the electron-positron International Linear Collider (ILC) in Japan would be compatible with this strategy and, in that case, the European particle physics community would wish to collaborate.*

# Collider Crib sheet
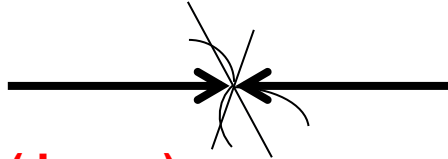
- **ILC (Japan):**
  - **Linear collider with high-gradient superconducting acceleration**
  - **Ultimate: 0.5-1(?) TeV**
  - **To secure (…) funding: reduce cost by starting at 250 GeV (H factory)**

- **CLIC (CERN):**
  - **Linear collider with high gradient normal-conducting acceleration**
  - **Ultimate: multi-TeV (3) e+e− collisions**
  - **Use technology to overcome challenges**
  - **Stages, for physics and funding**

- **FCC-ee/FCC-hh (CERN):**
  - **Protons to extend energy frontier**
  - **100 km ring with 16T magnets**
  - **Use FCC-hh tunnel for e+e− collider**
  - **Technology for ee: "standard"**
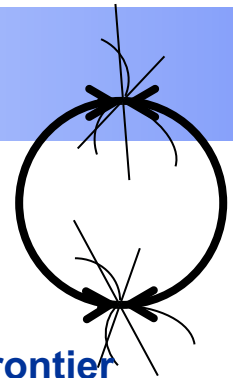
- **CEPC/SppC**
  - **Essentially an FCC-ee, then hh with (a) more conservative luminosity estimates and (b) in China**

- **Outliers:**
  - **"Low-field" (7T) magnets @ FCC (?)**
  - **Muon Collider (???)**
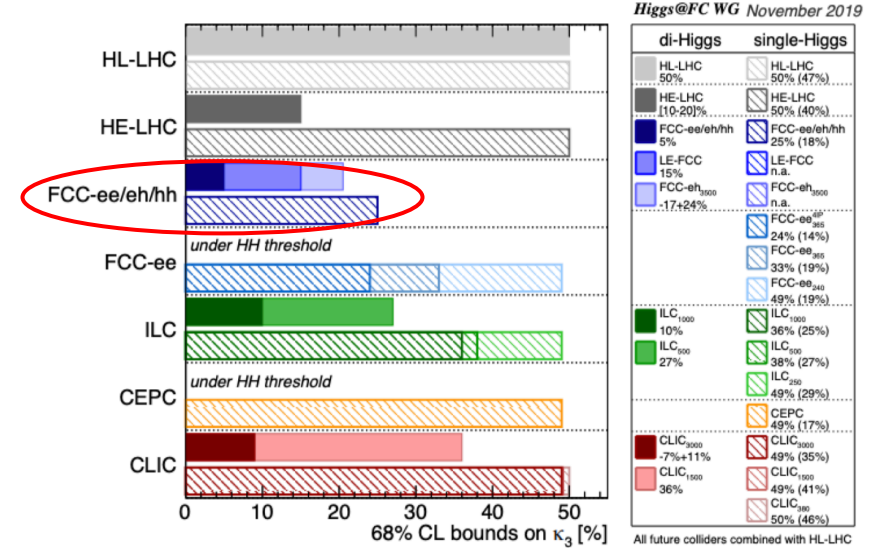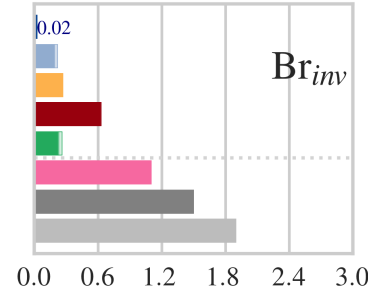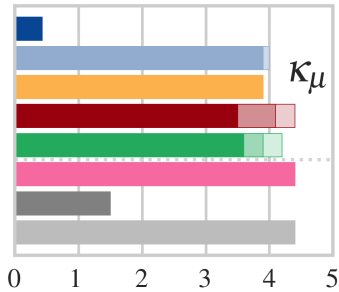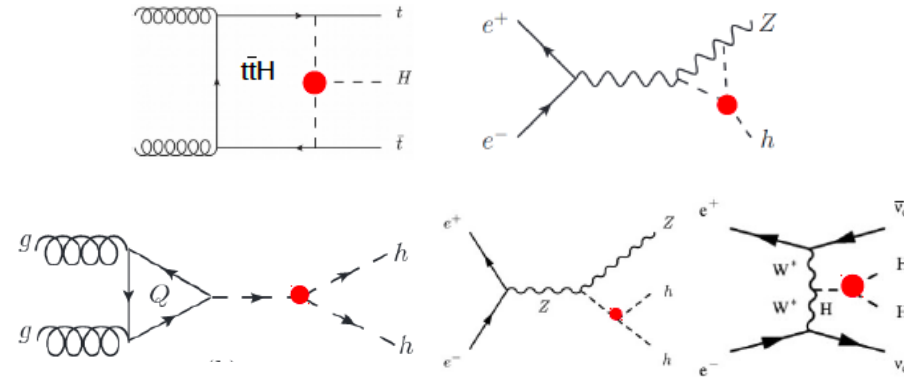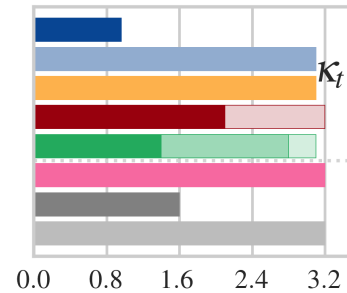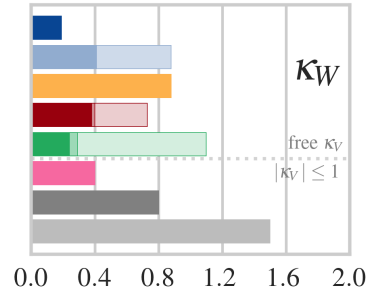
# Precision Observables & Searches: examples

☐ **EWPO:**
**circular ee colliders**

**+ linear colliders for $\sin^2\theta_W$.**

**Note: currently, discussion/plan for a large Z run for the linear colliders…**

Higgs compositeness (?)
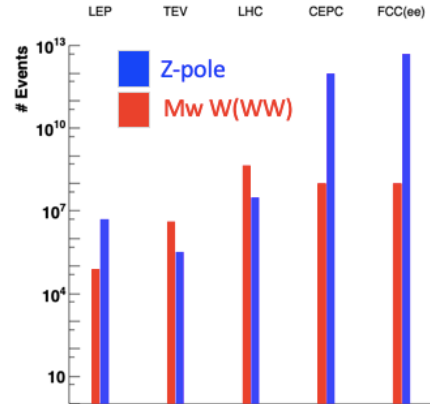
**Precision EWK Observables**
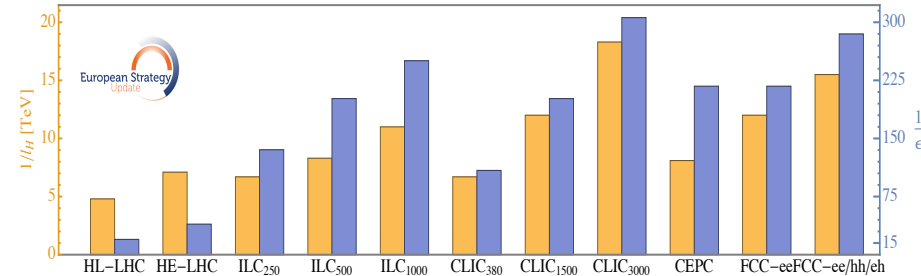
Electroweak SUSY reach
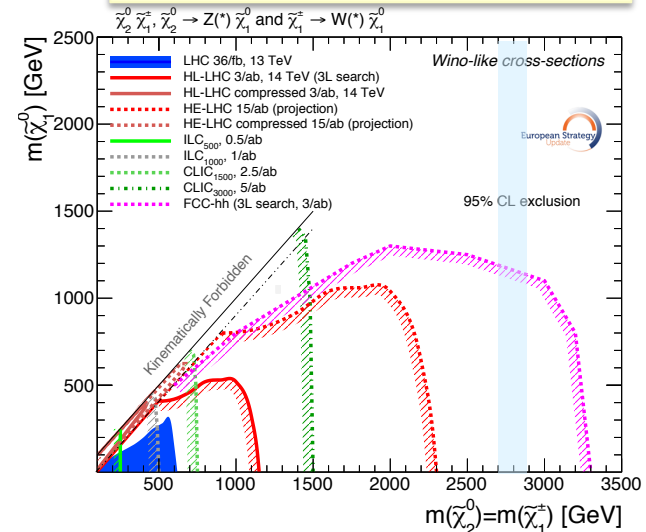
| EWPO | Current | CEPC | FCC (ee) |
|---|---|---|---|
| $M_Z$ [MeV] | 2.1 | 0.5 | 0.1 |
| $\Gamma_Z$ [MeV] | 2.1 | 0.5 | 0.1 |
| $N_\nu$ [%] | 1.7 | 0.05 | 0.03 |
| $M_W$ [MeV] | 12 | 1 | 0.67 |
| $A_{FB}^{0,b}$ [x10$^4$] | 16 | 1 | < 1 |
| $\sin^2\theta_W^{\text{eff}}$ [x10$^5$] | 16 | 1 | 0.6 |
| $R_b^0$ [x10$^5$] | 66 | 4 | 2–6 |
| $R_\mu^0$ [x10$^5$] | 2500 | 200 | 100 |



$\tilde{\chi}_2^0 \tilde{\chi}_1^\pm, \tilde{\chi}_2^0 \to Z^{(*)} \tilde{\chi}_1^0$ and $\tilde{\chi}_1^\pm \to W^{(*)} \tilde{\chi}_1^0$

LHC 36/fb, 13 TeV
HL-LHC 3/ab, 14 TeV (3L search)
HL-LHC compressed 3/ab, 14 TeV
HE-LHC 15/ab (projection)
HE-LHC compressed 15/ab (projection)
ILC$_{500}$, 0.5/ab
ILC$_{1000}$, 1/ab
CLIC$_{1500}$, 2.5/ab
CLIC$_{3000}$, 5/ab
FCC-hh (3L search, 3/ab)

Wino-like cross-sections

95% CL exclusion

Kinematically Forbidden

$m(\tilde{\chi}_2^0)=m(\tilde{\chi}_1^\pm)$ [GeV]

- **An experimental fact & yet, still a total mystery**
  - **And masses span over 80 orders of magnitude**

- **Nightmare scenario: totally dark**
  - **Only Gravity to play with**



zeV aeV feV peV neV μeV meV eV    keV    MeV    GeV    TeV    PeV  30M_⊙

QCD Axion

WIMPs

Ultralight Dark Matter          Hidden Sector Dark Matter          Black Holes

Pre-Inflationary Axion          Hidden Thermal Relics / WIMPless DM

Post-Inflationary Axion          Asymmetric DM

Freeze-In DM

SIMPs / ELDERS
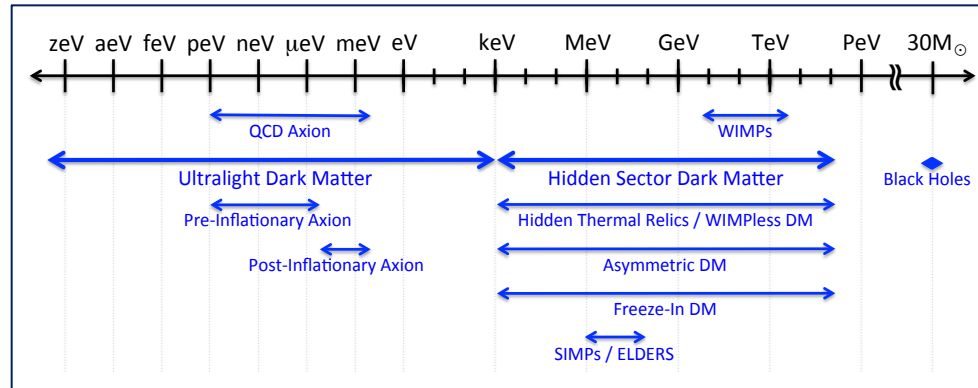
- **More promising: some shade of grey**
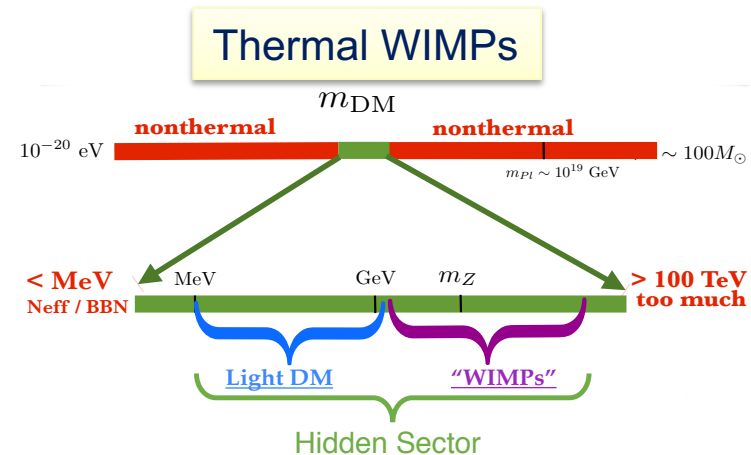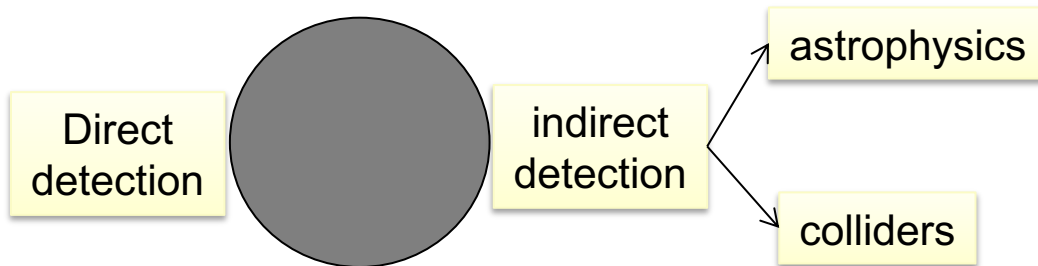


Direct detection — indirect detection → astrophysics / colliders

Thermal WIMPs

$m_{DM}$

nonthermal          nonthermal

$10^{-20}$ eV          $\sim 100 M_\odot$

$m_{Pl} \sim 10^{19}$ GeV

< MeV          MeV          GeV          $m_Z$          > 100 TeV
Neff / BBN                                                          too much

Light DM          "WIMPs"

Hidden Sector

18

expts continuing to increase their sensitivity
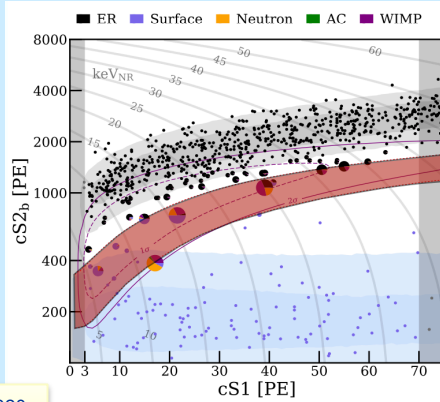
L. Hsu ICHEP2020
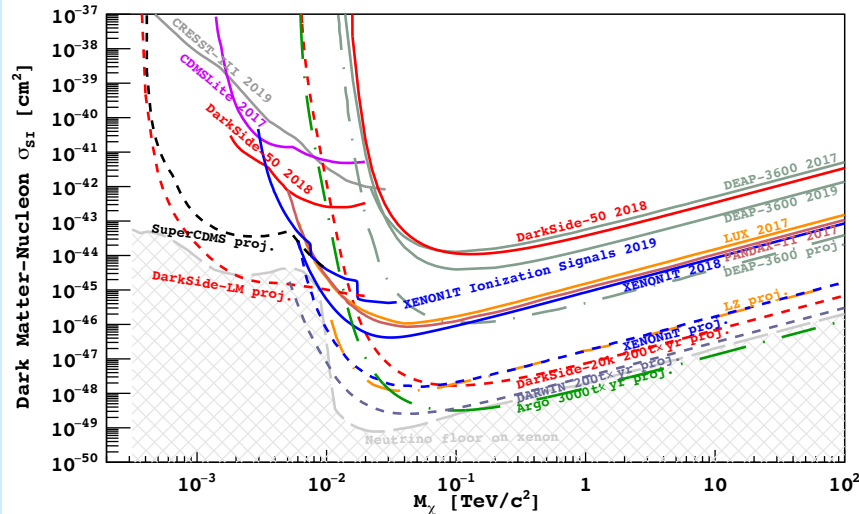
Very large program for subGeV DM

SENSEI: Skipper CCD's

L. Hsu ICHEP2020
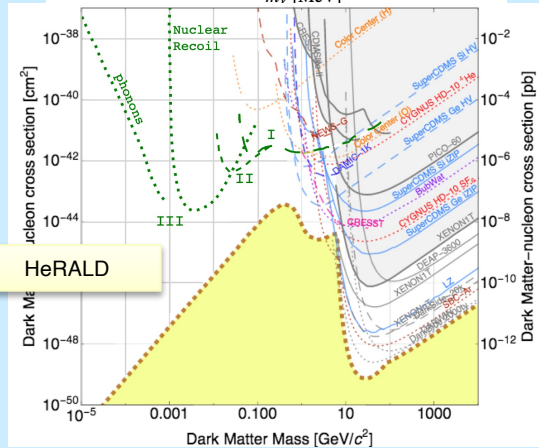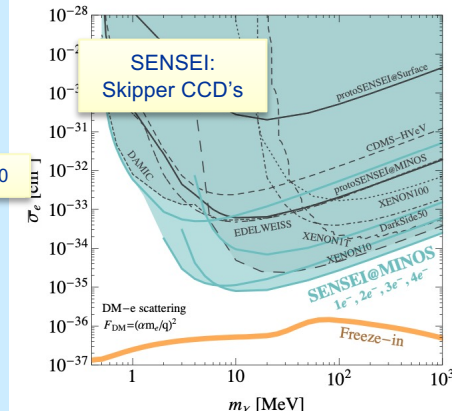
HeRALD

# DM: Classic WIMPs

- **Two (SUSY) "extremes", pure Wino, pure Higgsino**
  - **Main "tools": disappearing track, propagator modifications**

For small Δm, soft $\pi^{\pm}$...
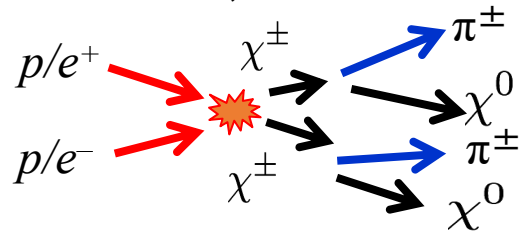
EWKinos in loop change prop
(W, Y parameters)
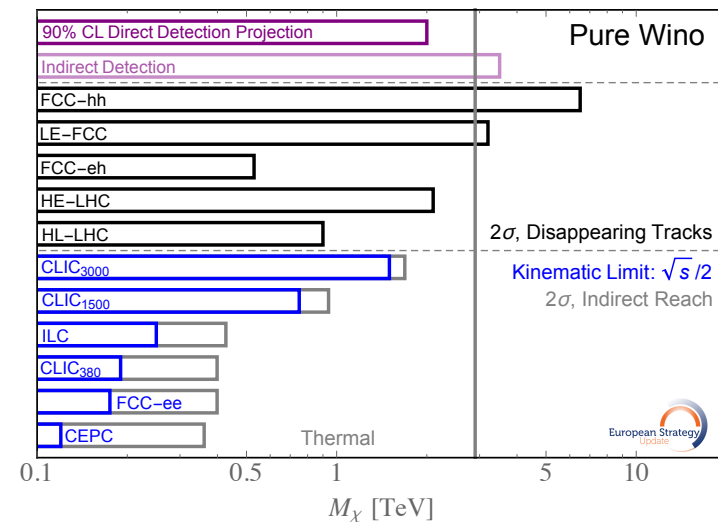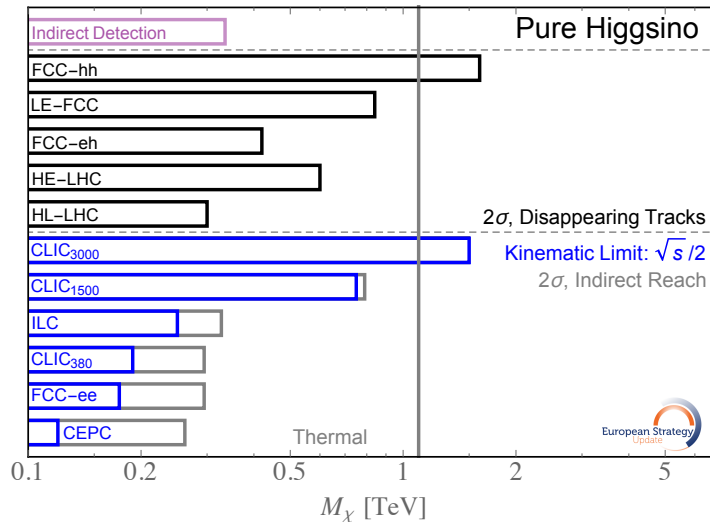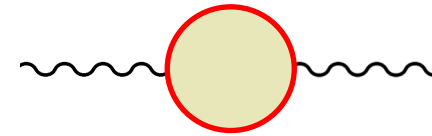
# Scalar mediator: Higgs portal and
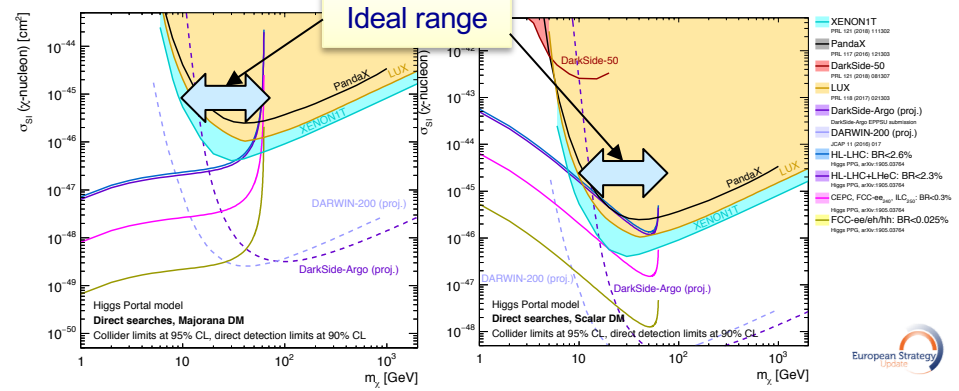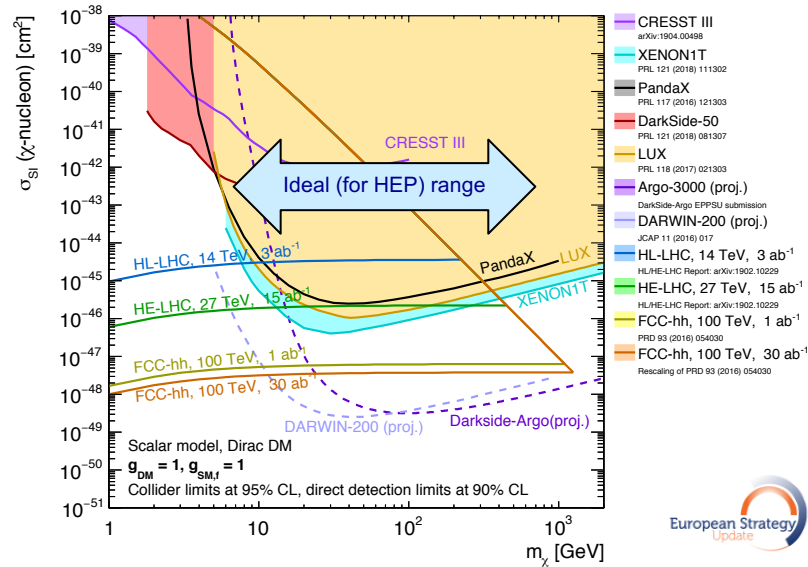


A collider discovery will need confirmation from DD/ID for cosmological origin
A DD/ID discovery will need confirmation from colliders to understand the nature of the interaction
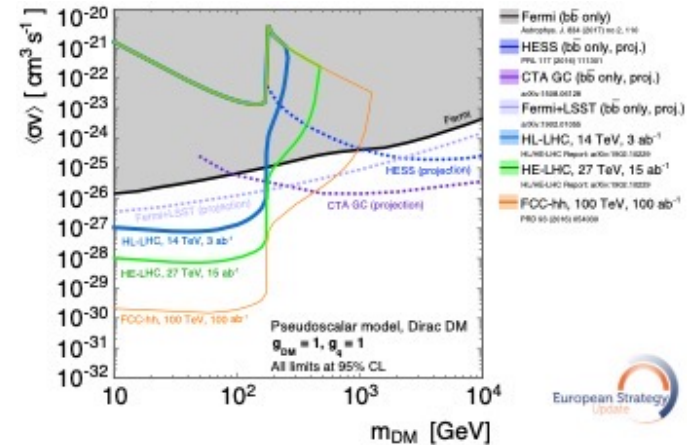
A future collider program that optimizes sensitivity to invisible particles coherently with DD/ID serves us well. Need maximum overlap with DD/ID!

# Physics of Flavor

**Neutrinos**

**Quarks**

**Charged Leptons**

# Super-brief Intro: from hopeless to lucky strike(s)

From invisible particle ($\sigma \sim 10^{-44}$ cm$^2$ @ $E_\nu \sim 2$ MeV) to major source of physics:
From Pontecorvo's few/day/ton with $\sim 10^{11} \nu$/cm$^2$/s to $\rightarrow$ PMNS matrix & CP violation(?!?!)

$$P(\nu_\alpha \rightarrow \nu_\beta) = \sin^2 2\theta \, \sin^2\left(1.27\frac{\Delta m^2(\text{eV}^2)\, L(\text{km})}{E_\nu(\text{GeV})}\right) \quad P(\nu_\alpha \rightarrow \nu_\alpha) = 1 - P(\nu_\alpha \rightarrow \nu_\beta)$$

SuperK, SNO: large mixing; good $\Delta m$
$$\Delta m^2_{\text{sol}} \approx 7 - 8 \times 10^{-5}\text{eV}^2$$

IMB, Kamiokande, Soudan(2)... SuperK:
large mixing; super $\Delta m$: $\Delta m^2_{\text{atm}} \approx 2.5 \times 10^{-3}\text{eV}^2$

$$\Delta m^2_{\text{sol}} \sim E_\nu(\text{MeV})/L(100\,\text{km})$$

$\rightarrow$ Reactors! $\rightarrow$ KamLAND

$$\Delta m^2_{\text{atm}} \sim E_\nu(\text{MeV})/L(100\,\text{m}) = (\text{GeV})/(100\,\text{km})$$

$\rightarrow$ Accelerators! $\rightarrow$ K2K, MINOS(+),..., T2K, NOVA
+ Short baselines: Daya Bay, RENO, ..., xBOONe

$\nu$ physics: PMNS; 3x3 or 4x4? nature (Majorana or Dirac); mass ordering

$$U_{3\times3} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \begin{pmatrix} \cos\theta_{13} & 0 & \sin\theta_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -\sin\theta_{13}e^{i\delta} & 0 & \cos\theta_{13} \end{pmatrix} \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \times (U_{\text{Maj}})$$

atmospheric + accelerator disapp

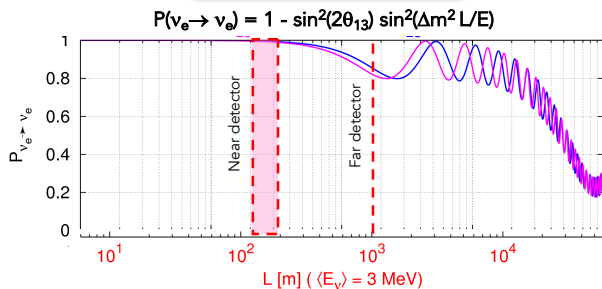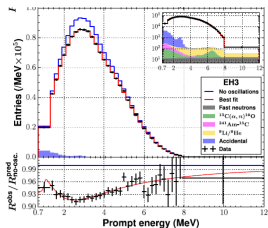SBL reactor + accelerator app

solar + KamLAND
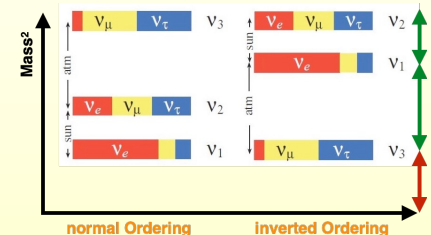
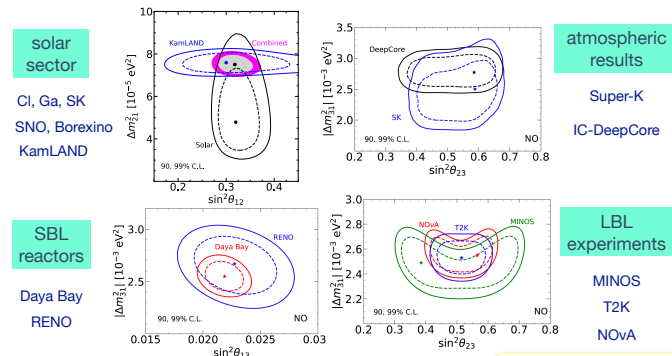# Neutrinos: Reactor experiments; Precision!

**Principle: $\theta_{13}$**

$$P(\nu_e \rightarrow \nu_e) = 1 - \sin^2(2\theta_{13}) \sin^2(\Delta m^2 L/E)$$

Near detector

Far detector

$P_{\nu_e \rightarrow \nu_e}$

$L$ [m] ($\langle E_\nu \rangle = 3$ MeV)

The prized measurement

□ **Long series of measurements have brought us to a "precision era"**

solar sector

Cl, Ga, SK
SNO, Borexino
KamLAND

atmospheric results

Super-K

IC-DeepCore

SBL reactors

Daya Bay
RENO

LBL experiments

MINOS

T2K

NOvA

M. Tortola ICHEP2020

6 × 2.9 GW$_{th}$

EH3

Water Hall

LS Hall

EH2

Ling Ao II NPP

Ling Ao NPP

EH1

Daya Bay NPP

Dayabay Antineutrino Detector

192 8" PMTs

20t Gd-LS target

Reflector

Prompt energy (MeV)

**Third lucky strike (in ν phys)**

de Salas et al, arXiv:2006.11237

$$J_{CP}^{lep} = Im(U_{\mu 3}U_{e3}^*U_{e2}U_{\mu 2}^*) = (1/8) \times$$

$$\times \sin 2\theta_{12} \sin 2\theta_{23} \sin 2\theta_{13} \cos \theta_{13} \sin \delta_{CP}$$

$$\approx 0.033 \sin \delta_{CP} \text{ BUT}: J_{CP}^q \approx 3 \times 10^{-5}$$

| parameter | best fit $\pm 1\sigma$ | $3\sigma$ range | relative $1\sigma$ uncertainty |
|---|---|---|---|
| $\Delta m_{21}^2$ [$10^{-5}$eV$^2$] | $7.50^{+0.22}_{-0.20}$ | $6.94$–$8.14$ | 2.7% |
| $|\Delta m_{31}^2|$ [$10^{-3}$eV$^2$] (NO) | $2.56^{+0.03}_{-0.04}$ | $2.46$–$2.65$ | 1.2% |
| $|\Delta m_{31}^2|$ [$10^{-3}$eV$^2$] (IO) | $2.46 \pm 0.03$ | $2.37$–$2.55$ | |
| $\sin^2\theta_{12}$ /$10^{-1}$ | $3.18 \pm 0.16$ | $2.71$–$3.70$ | 5.2% |
| $\sin^2\theta_{23}$ /$10^{-1}$ (NO) | $5.66^{+0.16}_{-0.22}$ | $4.41$–$6.09$ | 4.9% |
| $\sin^2\theta_{23}$ /$10^{-1}$ (IO) | $5.66^{+0.18}_{-0.23}$ | $4.46$–$6.09$ | 4.8% |
| $\sin^2\theta_{13}$ /$10^{-2}$ (NO) | $2.225^{+0.055}_{-0.078}$ | $2.015$–$2.417$ | 3.0% |
| $\sin^2\theta_{13}$ /$10^{-2}$ (IO) | $2.250^{+0.056}_{-0.076}$ | $2.039$–$2.441$ | |
| $\delta/\pi$ (NO) | $1.20^{+0.23}_{-0.14}$ | $0.80$–$2.00$ | 17% |
| $\delta/\pi$ (IO) | $1.54 \pm 0.13$ | $1.14$–$1.90$ | 8% |

**3-5%**

**Currently (NOvA and T2K) a bit confused**

$$P(\nu_\mu \to \nu_e) = \sin^2\theta_{23} \frac{\sin^2 2\theta_{13}}{(A-1)^2} \sin^2[(A-1)\Delta_{31}]$$

$$+ \quad \alpha^2 \cos^2\theta_{23} \frac{\sin^2 2\theta_{12}}{A^2} \sin^2(A\Delta_{31})$$

$$- \quad \alpha \frac{\sin 2\theta_{12} \sin 2\theta_{13} \sin 2\theta_{23} \cos\theta_{13} \sin\delta_{CP}}{A(1-A)} \sin\Delta_{31} \sin(A\Delta_{31}) \sin[(1-A)\Delta_{31}]$$

$$+ \quad \alpha \frac{\sin 2\theta_{12} \sin 2\theta_{13} \sin 2\theta_{23} \cos\theta_{13} \cos\delta_{CP}}{A(1-A)} \cos\Delta_{31} \sin(A\Delta_{31}) \sin[(1-A)\Delta_{31}]$$

Favored (slightly):
Normal Ordering &
$\delta_{CP} \sim 3\pi/2$

But… fits are complicated

FIG. 16. Oscillation probabilities as a function of the neutrino energy for $\nu_\mu \to \nu_e$ (left) and $\bar\nu_\mu \to \bar\nu_e$ (right) transitions with L=295 km and $\sin^2 2\theta_{13} = 0.1$. Black, red, green, and blue lines correspond to $\delta = 0, \frac{1}{2}\pi, \pi$,

FIG. 17. Oscillation pro...
Left: $\sin^2 2\theta_{13} = 0.1$, ri...
each term of the oscilla...
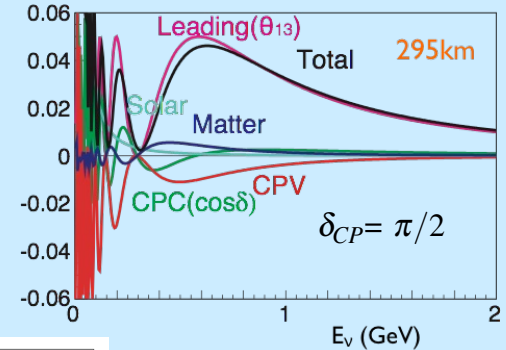
Unknown mass order

Known mass order

T2K-II

NormalO

T2K-II

DUNE Sensitivity
Normal Ordering
$\sin^2 2\theta_{13} = 0.085 \pm 0.003$
$\theta_{23}$: NuFit 2016 (90% C.L. range)
$\sin^2\theta_{23} = 0.441 \pm 0.042$

7 years (staged)
10 years (staged)

DUNE CPV

Hyper-Kamiokande

$\delta_{CP} = -90°$

T2K 2016 systematics
Nominal systematics
Statistics only (no systematics)

TABL

**Hyper-K**

arXiv:2002.03005
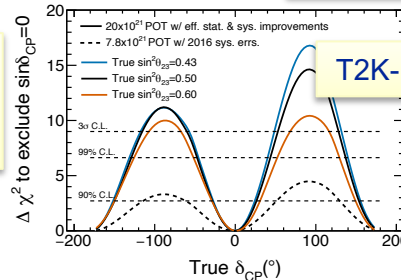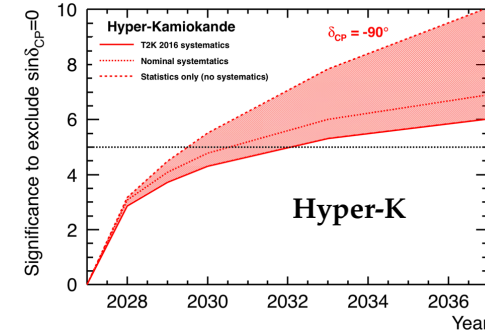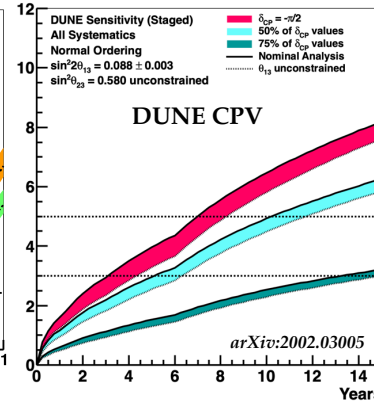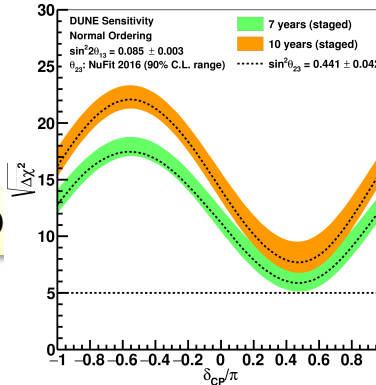
Very useful/nice: complementarity of NOvA/T2K and DUNE/HyperK:
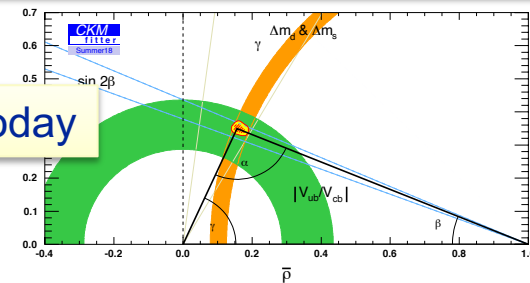baseline (1300 vs 200 km) and detection technique

· Assumes equal running in neutrino and antineutrino mode

# Flavor physics: quark sector

$$V_{ub}V_{ud}^* + V_{tb}V_{td}^* + V_{td}V_{ud}^* + V_{tb}V_{ub}^* = 0$$

$$V_{ud}^*V_{ub} + V_{cd}^*V_{cb} + V_{td}^*V_{tb} = 0$$

$$V_{CKM} = \begin{bmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{bmatrix}$$
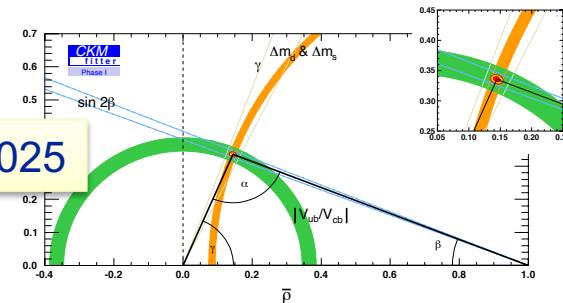
$$V_{ui}V_{uj}^* + V_{ci}V_{cj}^* + V_{ti}V_{tj}^* = 0 \quad (i \neq j)$$

$$\mathbf{V_{ui}\ V_{uj}^* + V_{ci}\ V_{cj}^* + V_{ti}\ V_{tj}^* = 0}$$

Today

2025

2035

$\mathcal{CP}$

**ds** $\quad V_{cd}V_{cs}^* \quad V_{td}V_{ts}^*$

**uc** $\quad V_{ud}V_{cd}^* \quad V_{ub}V_{cb}^*$

**sb** $\quad V_{ts}V_{tb}^* \quad V_s V_{ub}^* \mathbf{f} = \eta_f \mathbf{f}$

$V_{cd}V_{cs}^* \quad V_{td}V_{ts}^* \quad V_{ud}V_{us}^*$

$B^0$

**uc** $\quad V_{ud}V_{cd}^* \quad V_{ub}V_{cb}^*$

$\dfrac{q}{p} \approx \dfrac{V_{tb}^* V_{tq}}{V_{tb} V_{tq}^*} = e^{-2i\phi_M}$

**sb** $\quad V_{ts}V_{tb}^* \quad V_{cs}V_{cb}^* \quad V_{us}V_{ub}^* \approx \begin{cases} \beta \\ -\beta_s \approx -\lambda^2\eta \end{cases}$

$V_{cs}V_{ts}^* \quad V_{cb}V_{cd}^* \quad V_{ts}V_{us}^*$

**bd** $\quad V_{cb}V_{cd}^*$

**tu** $\quad V_{ts}V_{us}^*$

$CP \sim \sin 2\phi$

$V_{cb}V_{tb}^*$

$(\bar{\rho},\bar{\eta})$

$(\bar{\rho},\bar{\eta})$

$\dfrac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*} \dfrac{A_{b\to q\bar{q}q'}}{A_{b\to qq q'}} = e^{2i\phi_D}$

$\dfrac{V_{qb}^* V_{tq}}{V_{qb} V_{qq'}^*} = e^{2i\phi}$

$\gamma \quad (0,0) \quad \beta \quad (1,0)$

$\mathbf{f} = \eta_f \mathbf{f}$

$\mathcal{CP}$

$\mathbf{V} \approx \begin{bmatrix} 1 - \cdots \\ -\lambda \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{bmatrix}$

$B^0$

$\bar{B}^0$

$\dfrac{\Gamma(\bar{B}^0 \to f) - \Gamma(B^0 \to f)}{\Gamma(\bar{B}^0 \to f) + \Gamma(B^0 \to f)} = -\eta_f \ \sin(2\phi)\ \sin(\Delta M\, t)$

$\dfrac{q}{p} \approx \dfrac{V_{tb}^* V_{tq}}{V_{tb} V_{tq}^*} = e^{-2i\phi_M}$ ; $\phi_M \approx \begin{cases} \beta & (B_d^0) \\ -\beta_s \approx -\lambda^2\eta & (B_s^0) \end{cases}$

$\rho_f \equiv \rho_f^* = \eta_f\, e^{2i\phi_D}$

$\eta \equiv \eta\left(1 - \dfrac{1}{2}\lambda^2\right) = 0.343 \pm 0.011$

$\bar{\rho} \equiv \rho\left(1 - \dfrac{1}{2}\lambda^2\right) = 0.153 \pm 0.013$

$\alpha = 91.0 \pm 2.5° \ ; \ \beta = 23.2 \pm 1.2° \ ; \ \gamma = 65.3 \pm 2.0°$
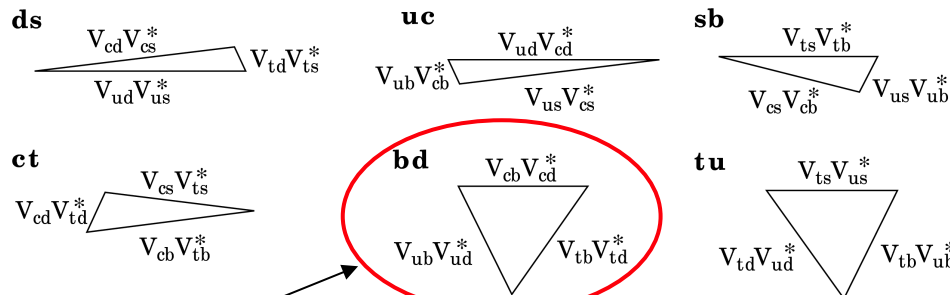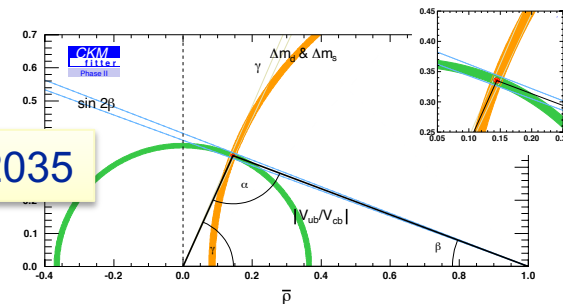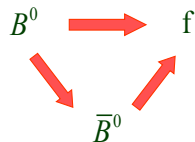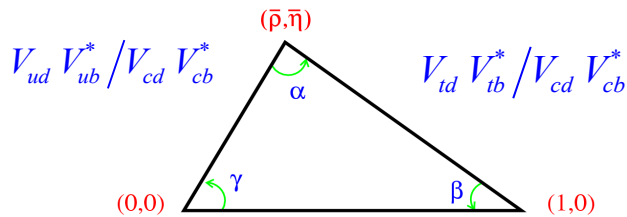
# Pseudo-summary

# Pseudosummary/Outlook

- **Extremely rich physics program ahead to understand the scalar sector**
    - **The LHC and HL-LHC will get us to 3-5% couplings for the Higgs boson;**
    - **All options for a future Higgs "factory" bring in ~O($10^{-2}$–$10^{-3}$) understanding of couplings.**
    - **Important aspects: EWPO (needs next-gen Z factory) and top threshold.**
        - **Actually, the linear and circular options are quite complementary…**
    - **Fundamental scalar?  Can probe it to 15-18 TeV.**
    - **FCC-ee/hh combination has the largest direct reach to new particles/phenomena. From new particles to Higgs self-coupling to Dark Matter searches…**
- **Dark Matter:**
    - **Complementarity with indirect searches at colliders (and astroparticle expts); Next-gen colliders can cover the thermal WIMP scenario.**
- **Flavor Physics: neutrinos have all one could ask for (albeit it with small $\sigma_{int}$). But quark sector may hold the first genuine surprises(?)**
    - **In the next 5-10 years: could get very pleasant news on CP front.  Definitive statement of mass hierarchy and CP from the full program (DUNE and HyperK).**
    - **Quark sector: the current situation will be resolved in the next five years.**

- **Physics at hand, physics of the next decade, physics of the long-term future: remains fully exciting. Stay tuned!**

# Backups

# Higgs boson issues

- **The only (?!) spin-0 fundamental (?) particle**
- **What creates the infamous couplings to the leptons?**
  - **It's a new interaction! The only non-universal one (it's not a gauge interaction…), with a *free* parameter (Yukawa coupling) for each combination (worse for quarks – mass matrix…)**
  - **What about them neutrinos?!?**
- **What protects its mass and sets it to the EWK scale when it should be at $\Lambda_{pl}$?**
  - **There is only one dimensionfull variable in the SM Lagrangian: v=246 GeV (…!?...)**
    - **The rest of the SM is scale-free…**
- **And…. where is all that vaccum energy? Cosmological constant is > $10^{100}$ times off.**



Credit: blog.gymlish.com
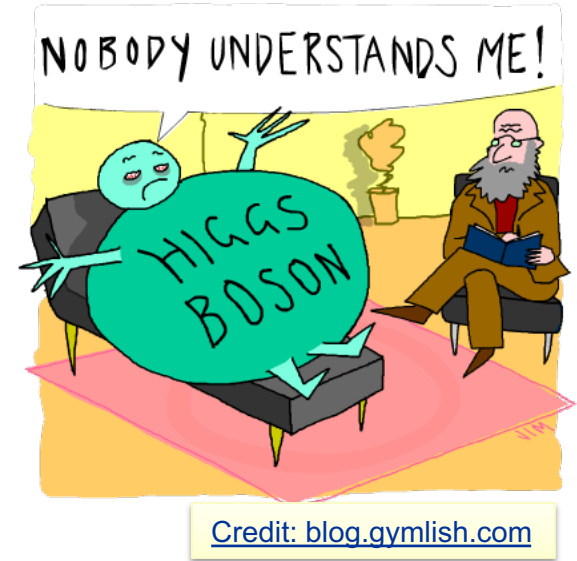
# "Turn on the LHC and... find Higgs & SUSY"

- **ATLAS and CMS were designed to do this; they were "guaranteed" to find the Higgs – period; right away**
  - **In fact: SUSY is strongly produced, so will be observed first**
    - **For the "impatient": join SUSY physics group**



- **Many hard Jets**
- **Large missing energy**
  - **2 LSPs**
  - **Many neutrinos**
- **Many leptons**
- **In a word Spectacular!**
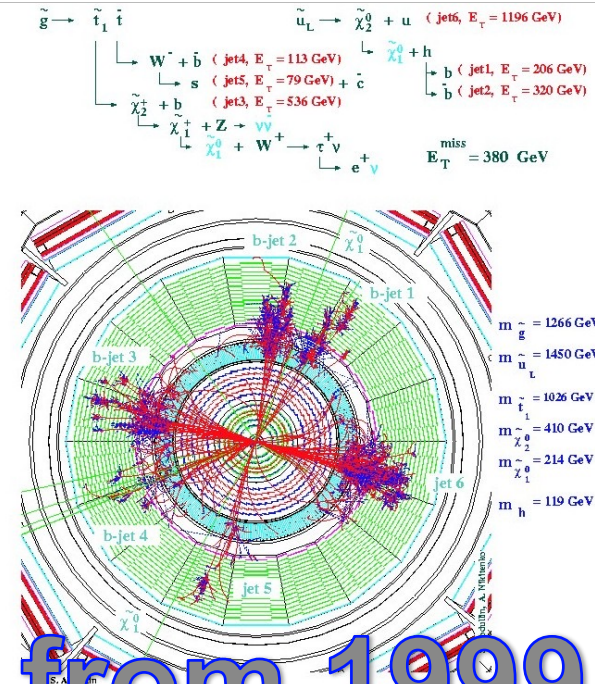
Text & simu from 1999

# The magic of the Higgs boson mass

- **Quantum Mechanics: ultimate destructor of small numbers (in nature) that are not protected by some symmetry (thus "law")**
- **Higgs boson: the ultimate example**
  - **Quadratic divergence in the Higgs mass**
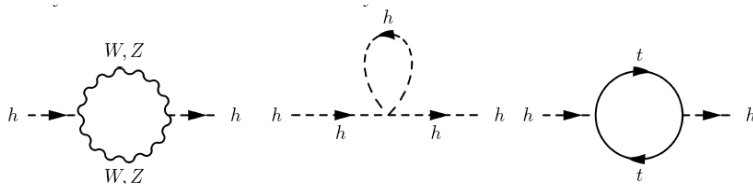


$$m^2\left(p^2\right) = m^2\left(\Lambda^2\right) + C g^2 \int_{p^2}^{\Lambda^2} dk^2$$

- **H mass should be ~ $10^{19}$GeV**
  - **Yet, it lies at 125 GeV…**
- **Put differently: if cut off at $\Lambda_{PL}$, why $m_W \ll M_{Pl}$?**
  - **Or, why is gravity (G~$1/M_{Pl}$) so weak?**

- **Reminder of just two past applications of naturalness argument:**

- **Weisskopf (1939): "the self-energy of charged particles obeying Bose statistics is found to be quadratically divergent...,"**
  → **in theories of elementary bosons, new phenomena must enter at an energy scale of m/e**
  → **+ positron, doubling of particles…**

- **Rare Kaon decays: $K_L \rightarrow \mu^+\mu^-$**



GIM proposal

$$\begin{pmatrix} u \\ d_C \end{pmatrix}_L ; \begin{pmatrix} \nu_e \\ e \end{pmatrix}_L ;$$

$$J_\mu^W (qu$$

**~ G $\Lambda^2$ = G($m_c^2$-$m_u^2$)**
**→ $\Lambda^2$ ~ 3-4 GeV$^2$ !!!**

$$C = \begin{pmatrix} 0 & 0 & \cos\theta & \sin\theta \\ 0 & 0 & -\sin\theta & \cos\theta \\ 0 & 0 & 0 & 0 \end{pmatrix}$$
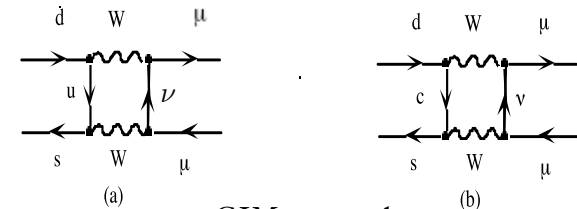
# Other open issues in particle physics

- **Is the Higgs boson at 125 GeV the Higgs boson of the Standard Model? Are there other Higgs-like bosons?**

- **How did (does) the current matter–antimmater asymmetry in the universe arise?**

- **There is now experimental evidence (astrophysics!) that there is a mysterious type of matter: "Dark" matter.  What is it?  What does it interact with?**

- **Neutrinos (which are taken as massless) turned out to have masses.  But tiny-tiny masses.  Natural explanation of this smallness is New Physics**

- **And while we're at it: gravity remains totally intractable (beyond astrophysics that is…)**

# The road to obtaining answers: precise measurements & direct searches…

- **Physics of fundamental scalars and direct searches for New Physics**
  - **LHC, HL-LHC & future collider(s) (FCC-ee, FCC-hh, FCC-eh, CEPC, ILC, CLIC)**
    - **Understand the strangest of all elements of the SM.**
    - **Search for new particles and physics phenomena.**

- **Dark Matter searches**
  - **Very large number of experiments aiming at detecting DM**
    - **Direct detection (lab), indirect detection (astrophy).**
    - **Matter-matter collisions.**

- **Physics of Flavor:**
  - **Quark sector: Kaon and B hadron decays (LHC, HL-LHC, Fixed-Target (CERN, JP), Belle II (JP)**
    - **Measure CP sources as precisely as possible. Probe sacred (but also accidental…) laws (e.g. lepton number conservation). Universality? Probe rarest decay modes.**
  - **Neutrinos: Complementarity of beams [DUNE (US), HyperK (JP)], reactors (JUNO), atmospheric (ORCA)**
    - **Is there CP violation in the lepton sector? PMNS matrix (à la CKM)?**
    - **Mass hierarchy of three $\nu$ generations ("normal" or "inverted")? Dirac or Majorana?**
  - **High-precision measurements; tests of Fundamental Symmetries**

# Future accelerators

| Collider | Type | $\sqrt{s}$ | $\mathscr{P}$ [%] $[e^-/e^+]$ | N(Det.) | $\mathscr{L}_{\text{inst}}$ $[10^{34}]$ cm$^{-2}$s$^{-1}$ | $\mathscr{L}$ $[\text{ab}^{-1}]$ | Time [years] | Refs. | Abbreviation |
|---|---|---|---|---|---|---|---|---|---|
| HL-LHC | $pp$ | 14 TeV | - | 2 | 5 | 6.0 | 12 | [10] | HL-LHC |
| HE-LHC | $pp$ | 27 TeV | - | 2 | 16 | 15.0 | 20 | [10] | HE-LHC |
| FCC-hh | $pp$ | 100 TeV | - | 2 | 30 | 30.0 | 25 | [1] | FCC-hh |
| FCC-ee | $ee$ | $M_Z$ | 0/0 | 2 | 100/200 | 150 | 4 | [1] | |
| | | $2M_W$ | 0/0 | 2 | 25 | 10 | 1-2 | | |
| | | 240 GeV | 0/0 | 2 | 7 | 5 | 3 | | FCC-ee$_{240}$ |
| | | $2m_{top}$ | 0/0 | 2 | 0.8/1.4 | 1.5 | 5 | | FCC-ee$_{365}$ |
| | | | | | | | (+1) | | (1y SD before $2m_{top}$ run) |
| ILC | $ee$ | 250 GeV | $\pm80/\pm30$ | 1 | 1.35/2.7 | 2.0 | 11.5 | [3,11] | ILC$_{250}$ |
| | | 350 GeV | $\pm80/\pm30$ | 1 | 1.6 | 0.2 | 1 | | ILC$_{350}$ |
| | | 500 GeV | $\pm80/\pm30$ | 1 | 1.8/3.6 | 4.0 | 8.5 | | ILC$_{500}$ |
| | | | | | | | (+1) | | (1y SD after 250 GeV run) |
| CEPC | $ee$ | $M_Z$ | 0/0 | 2 | 17/32 | 16 | 2 | [2] | CEPC |
| | | $2M_W$ | 0/0 | 2 | 10 | 2.6 | 1 | | |
| | | 240 GeV | 0/0 | 2 | 3 | 5.6 | 7 | | |
| CLIC | $ee$ | 380 GeV | $\pm80/0$ | 1 | 1.5 | 1.0 | 8 | [12] | CLIC$_{380}$ |
| | | 1.5 TeV | $\pm80/0$ | 1 | 3.7 | 2.5 | 7 | | CLIC$_{1500}$ |
| | | 3.0 TeV | $\pm80/0$ | 1 | 6.0 | 5.0 | 8 | | CLIC$_{3000}$ |
| | | | | | | | (+4) | | (2y SDs between energy stages) |
| LHeC | $ep$ | 1.3 TeV | - | 1 | 0.8 | 1.0 | 15 | [9] | LHeC |
| HE-LHeC | $ep$ | 1.8 TeV | - | 1 | 1.5 | 2.0 | 20 | [1] | HE-LHeC |
| FCC-eh | $ep$ | 3.5 TeV | - | 1 | 1.5 | 2.0 | 25 | [1] | FCC-eh |

# ILC, CLIC, FCC-ee/hh, CEPC



ILC Candidate site in Kitakami, Tohoku

20km

**Qinhuangdao site**

100 km
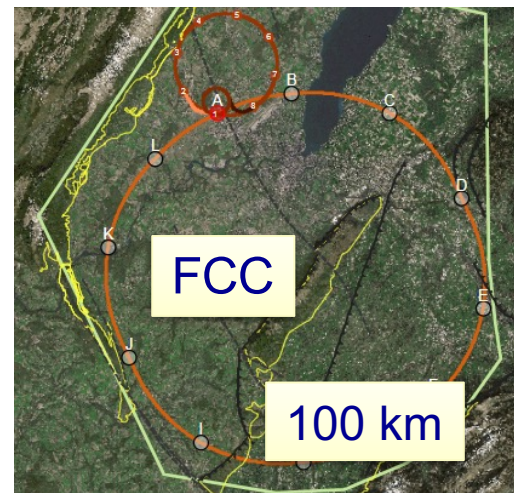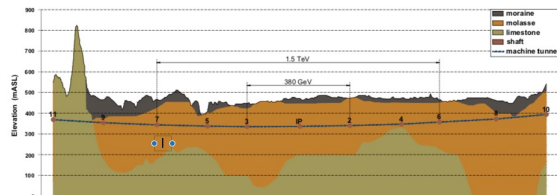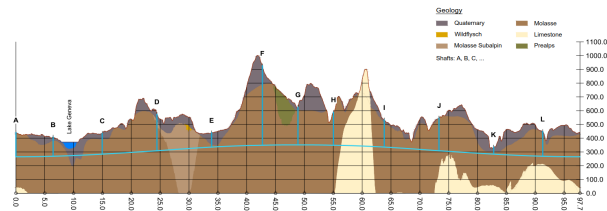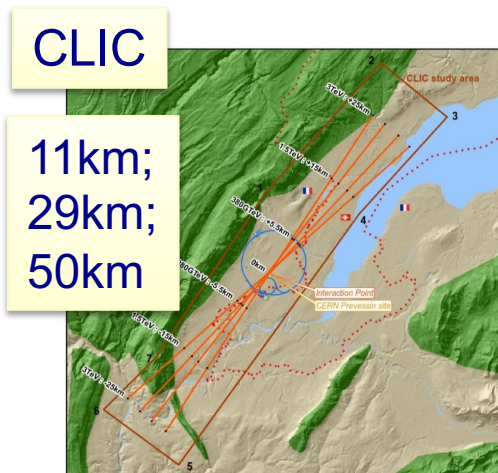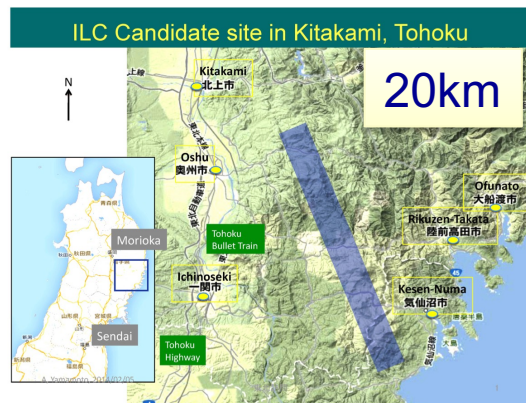
CEPC: multiple candidate sites in China

CLIC

11km;
29km;
50km

FCC

100 km

# The challenges

- **Linear ee colliders:**
    - **Acceleration gradient**
        - **ILC: 30 MV/m; CLIC: 72 MV/m**
    - **Luminosity (to be partially recovered by polarization)**
        - **+ brem loss: e.g. at 3000 GeV, 1/3 at >0.99√s**
    - **Tiny beam spot:**
        - **v: 8 nm for ILC; 3 nm for CLIC3000.**
    - **Power consumption**
        - **ILC: 130-300 MW**
        - **CLIC: 170-590 MW**
- **Circular ee colliders:**
    - **Power consumption: 260-350 MW**
    - **Luminosity drops with E**

- **hh collider:**
    - **Magnets!**
        - **Need 16 TeV (x2 LHC); they do not exist today**
    - **High stored beam energy (8-9 GJ)**
        - **Beam handling, beam dumping**
        - **Collimation**
    - **High synchrotron radiation inside magnets: several MW**
    - **Beam screen design and cryogenic efficiency;**
    - **Power consumption: 580 MW**

**Costs (GUnits):**
ILC: 5.0 (for 250 GeV); 7.8 (500 GeV)
CLIC: 5.9 or 7.3 (for 380 GeV) + 5.1 (1500 GeV) + 7.1 (3000 GeV) (Tot: 19.5)
FCC-ee: 11.6; but 7.1 is the tunnel
FCC-hh: tunnel + 17 (Tot: 24)

# FCC-ee and CEPC

❑ **Double–ring colliders with full-energy top-up booster ring**

  ❑ **CEPC started as 54 km, single-ring design; nowadays ~ FCC-ee 100 km, double-ring**

  ❑ **2 IPs, 2 RF straights, tapering of arc magnet strengths to match local energy**

  ❑ **Common use of RF systems for both beams at highest energy working point**

  ❑ **Synchrotron radiation: 50 MW (30 MW) at FCC-ee (CEPC)**

  ❑ **Beam lifetime >12 min; top-up injection, $e^+$ rate ~$10^{11}$/s.**

❑ **Asymmetric IRs: limit SR of incoming beams towards detectors**

  ❑ **→ large crossing angle**
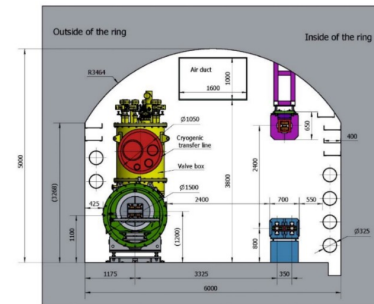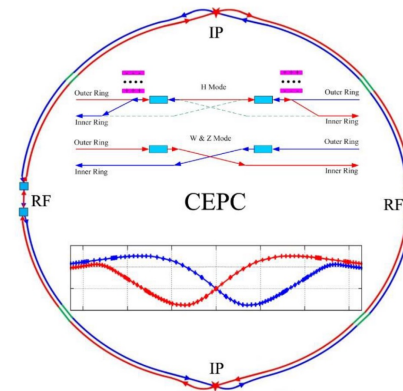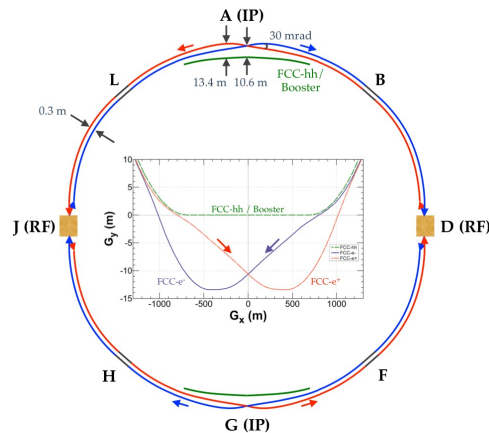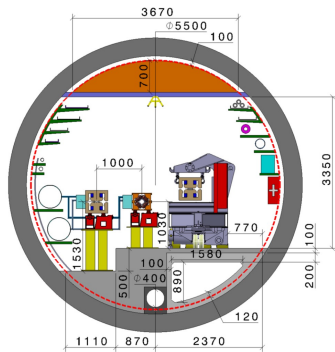
# FCC-hh and SppC

- ❑ **Circumference ~100 km, high luminosity 3(1) $\times$ $10^{35}$cm$^{-2}$s$^{-1}$ (SppC)**
  - ❑ **Two IRs at high lumi potentially two more experiments (possibly combined with injection section, collimation insertions, extraction/dump insertion, RF insertion,**

**FCC-hh**

**SppC**

based on existing CERN injector chain,

Luminosity goal ~20 ab$^{-1}$ per main IP within 25 years
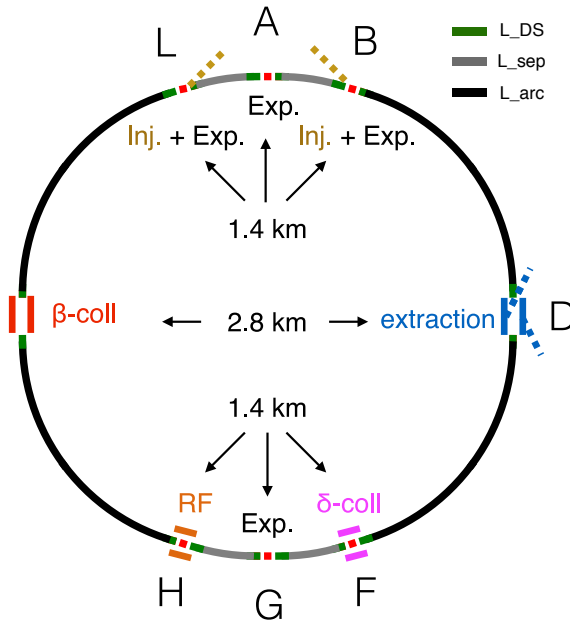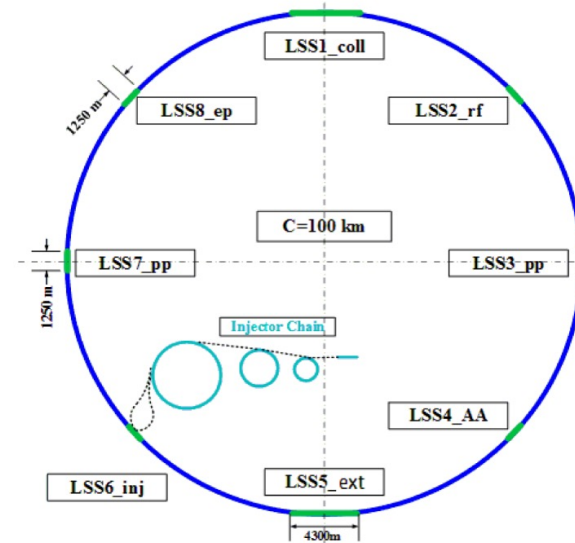
new injector chain,

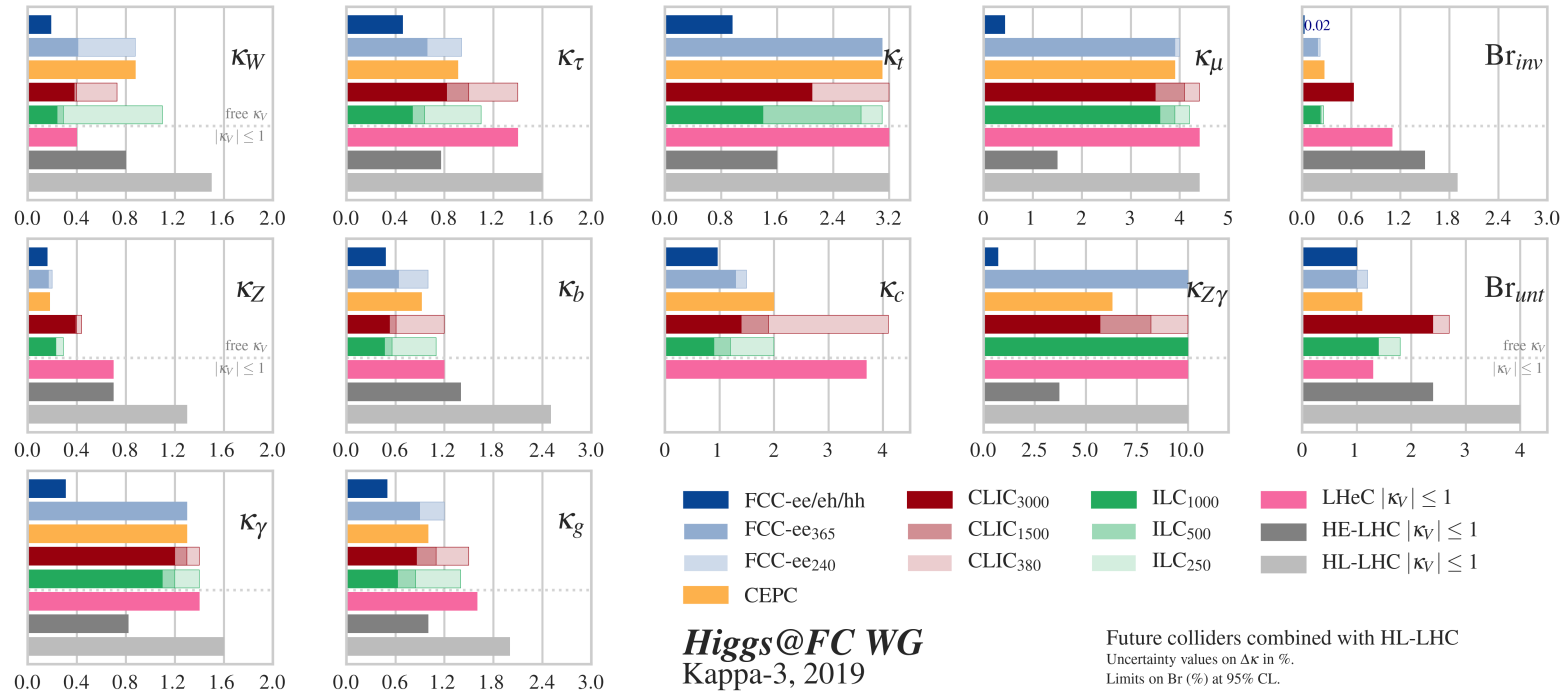simultaneous operation with e$^+$e$^-$ collider

# Grand summary

| kappa-3 scenario | $ILC_{250}$ | $ILC_{500}$ | $CLIC_{380}$ | $CLIC_{1500}$ | HL-LHC+ $CLIC_{3000}$ | CEPC | $FCC\text{-}ee_{240}$ | $FCC\text{-}ee_{365}$ | FCC-ee/eh/hh |
|---|---|---|---|---|---|---|---|---|---|
| $\kappa_W$ (%) | 1.1 | 0.29 | 0.75 | 0.4 | 0.38 | 0.95 | 0.95 | 0.41 | 0.2 |
| $\kappa_Z$ (%) | 0.29 | 0.23 | 0.44 | 0.39 | 0.39 | 0.18 | 0.19 | 0.17 | 0.17 |
| $\kappa_g$ (%) | 1.4 | 0.84 | 1.5 | 1.1 | 0.86 | 1.1 | 1.2 | 0.89 | 0.53 |
| $\kappa_\gamma$ (%) | 1.3 | 1.2 | 1.5* | 1.3 | 1.1 | 1.2 | 1.3 | 1.2 | 0.36 |
| $\kappa_{Z\gamma}$ (%) | 11.* | 11.* | 11.* | 8.4 | 5.7 | 6.3 | 11.* | 10. | 0.7 |
| $\kappa_c$ (%) | 2. | 1.2 | 4.1 | 1.9 | 1.4 | 2. | 1.6 | 1.3 | 0.97 |
| $\kappa_t$ (%) | 2.7 | 2.4 | 2.7 | 1.9 | 1.9 | 2.6 | 2.6 | 2.6 | 0.95 |
| $\kappa_b$ (%) | 1.2 | 0.57 | 1.2 | 0.61 | 0.53 | 0.92 | 1. | 0.64 | 0.48 |
| $\kappa_\mu$ (%) | 4.2 | 3.9 | 4.4* | 4.1 | 3.5 | 3.9 | 4. | 3.9 | 0.44 |
| $\kappa_\tau$ (%) | 1.1 | 0.64 | 1.4 | 0.99 | 0.82 | 0.96 | 0.98 | 0.66 | 0.49 |
| $BR_{inv}$ (<%, 95% CL) | 0.26 | 0.22 | 0.63 | 0.62 | 0.61 | 0.27 | 0.22 | 0.19 | 0.024 |
| $BR_{unt}$ (<%, 95% CL) | 1.8 | 1.4 | 2.7 | 2.4 | 2.4 | 1.1 | 1.2 | 1. | 1. |

All ee colliders achieve major (and comparable) improvements in their first stage already in probing Higgs sector compared to HL-LHC: at least half of the couplings get improved by factor 5 or more
W/Z effective couplings and BR(H → invisible) probed to ~$3\times10^{-3}$
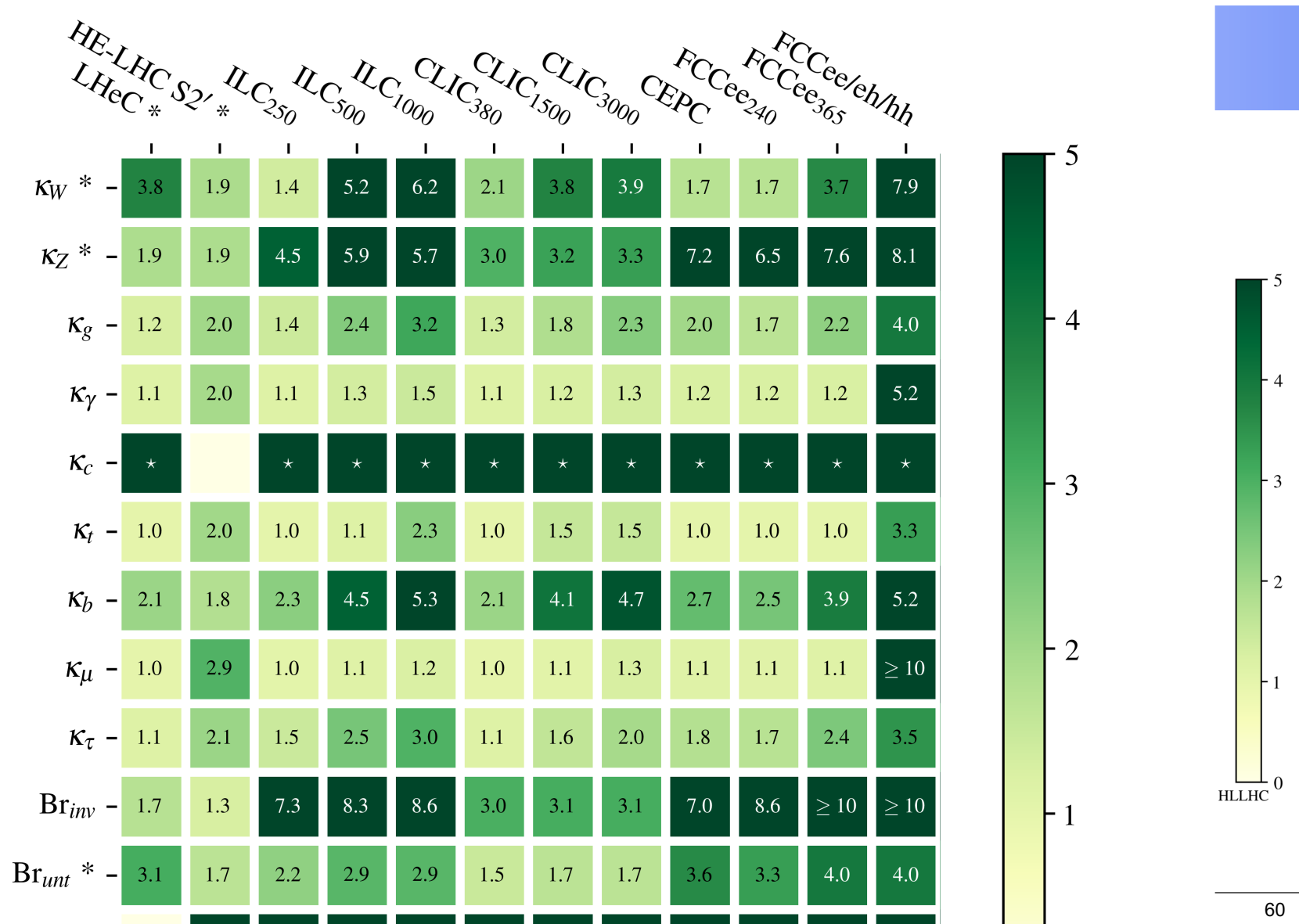Model-independent total cross section measurement → access to width, untagged BR
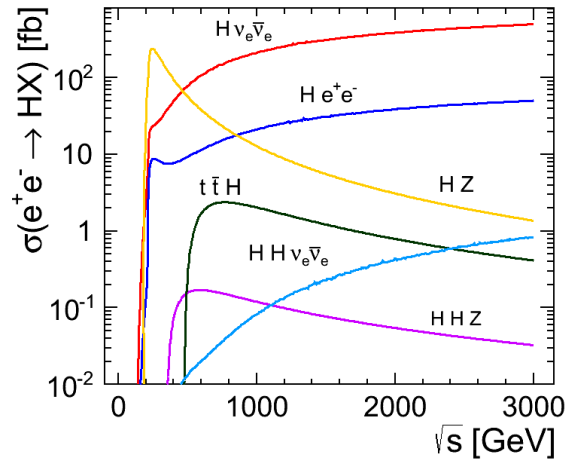Clean environment to study H if/when anomalies are seen to understand underlying physics

**Higgs@FC WG**
Kappa-3, 2019

Future colliders combined with HL-LHC
Uncertainty values on $\Delta\kappa$ in %.
Limits on Br (%) at 95% CL.

Plus of $\kappa$ framework: it is simple; Minus: underestimates effects of polarization
Can show deviation from SM, but no real further information on nature of source of deviation;
Untagged and invisible BRs constrained by measurements.

| | LHeC * | HE-LHC S2' * | ILC$_{250}$ | ILC$_{500}$ | ILC$_{1000}$ | CLIC$_{380}$ | CLIC$_{1500}$ | CLIC$_{3000}$ | CEPC | FCCee$_{240}$ | FCCee$_{365}$ | FCCee/eh/hh |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| $\kappa_W$ * | 3.8 | 1.9 | 1.4 | 5.2 | 6.2 | 2.1 | 3.8 | 3.9 | 1.7 | 1.7 | 3.7 | 7.9 |
| $\kappa_Z$ * | 1.9 | 1.9 | 4.5 | 5.9 | 5.7 | 3.0 | 3.2 | 3.3 | 7.2 | 6.5 | 7.6 | 8.1 |
| $\kappa_g$ | 1.2 | 2.0 | 1.4 | 2.4 | 3.2 | 1.3 | 1.8 | 2.3 | 2.0 | 1.7 | 2.2 | 4.0 |
| $\kappa_\gamma$ | 1.1 | 2.0 | 1.1 | 1.3 | 1.5 | 1.1 | 1.2 | 1.3 | 1.2 | 1.2 | 1.2 | 5.2 |
| $\kappa_c$ | * | | * | * | * | * | * | * | * | * | * | * |
| $\kappa_t$ | 1.0 | 2.0 | 1.0 | 1.1 | 2.3 | 1.0 | 1.5 | 1.5 | 1.0 | 1.0 | 1.0 | 3.3 |
| $\kappa_b$ | 2.1 | 1.8 | 2.3 | 4.5 | 5.3 | 2.1 | 4.1 | 4.7 | 2.7 | 2.5 | 3.9 | 5.2 |
| $\kappa_\mu$ | 1.0 | 2.9 | 1.0 | 1.1 | 1.2 | 1.0 | 1.1 | 1.3 | 1.1 | 1.1 | 1.1 | $\geq 10$ |
| $\kappa_\tau$ | 1.1 | 2.1 | 1.5 | 2.5 | 3.0 | 1.1 | 1.6 | 2.0 | 1.8 | 1.7 | 2.4 | 3.5 |
| Br$_{inv}$ | 1.7 | 1.3 | 7.3 | 8.3 | 8.6 | 3.0 | 3.1 | 3.1 | 7.0 | 8.6 | $\geq 10$ | $\geq 10$ |
| Br$_{unt}$ * | 3.1 | 1.7 | 2.2 | 2.9 | 2.9 | 1.5 | 1.7 | 1.7 | 3.6 | 3.3 | 4.0 | 4.0 |

# Higgs "factories"



$$L \propto P_{synrad} E_{cm}^{-3.5}$$

$$L \propto P_{RF} E_{cm}$$

Schemes for increasing luminosity:
- FCC-ee: consider more IRs/running longer
- ILC: more bunches per pulse, doubling repetition rate?
  - Each: x 2 in lumi; higher power consumption and somewhat higher cost
- CLIC: doubling repetition rate at 380 GeV?
  - Factor 2 in lumi; power increases from 170 MW to 220 MW (+slight cost increase)
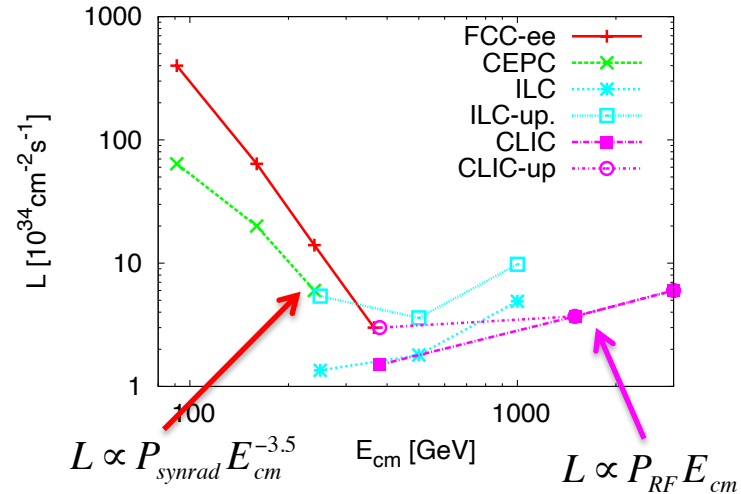
Low energies: circular colliders superior performance Higher energies: CC lumi reduction due to synchrotron radiation; linear colliders better: luminosity per beam power roughly constant

**Longit. polarisation:** only at Linear Colliders
$e^-$: 80%; $e^+$: 30% @ ILC; 0 @ CLIC (not needed)
FCC-ee: transverse polarization for precise $E_{beam}$

$$\frac{c_\phi}{\Lambda^2} = \frac{g_*^2}{m_*^2}$$

H
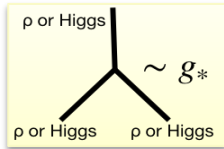
2f-2b

$$\frac{c_W}{\Lambda^2} = \frac{1}{m_*^2}$$

4f, W'/Z'

$$\frac{c_{2W}}{\Lambda^2} = \frac{1}{g_*^2 m_*^2}$$

gauge   $\rho$   $\sim \dfrac{g_W}{g_*}$

$O_W$ (independent of g*)
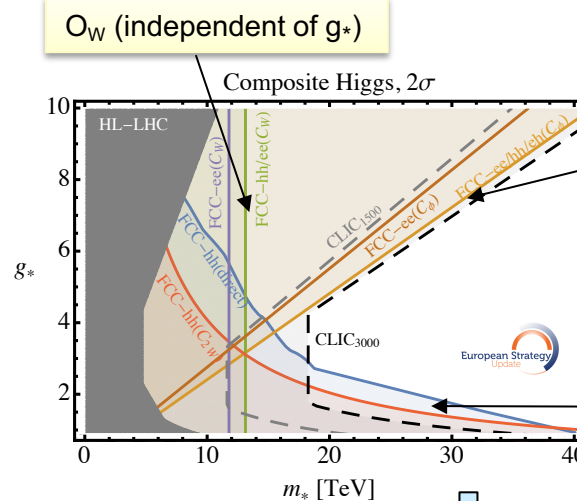
$O_\phi$ (Higgs measurements, primarily FCC-ee & CLIC)

Direct resonance searches (generic "ρ" EWK triplet); dileptons & dibosons)

Obtain limit on m*, i.e. on 1/length(H)
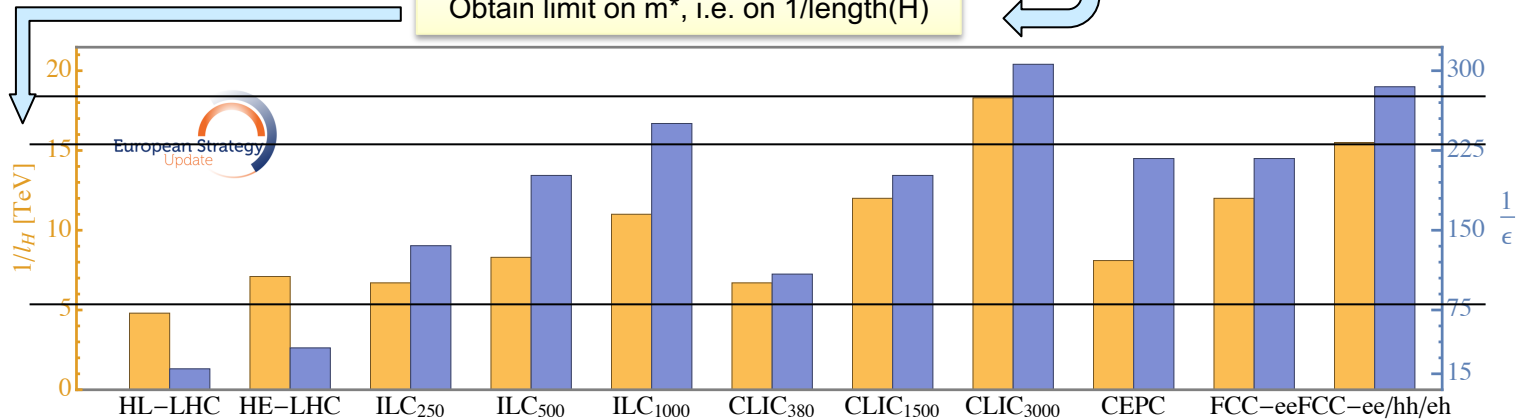
# New resonances/particles/forces?

**Seeing the peak. Reach:**
- M < √s for lepton colliders
- M ≲ 0.3-0.5 √s in hadron colliders for couplings ~ weak couplings
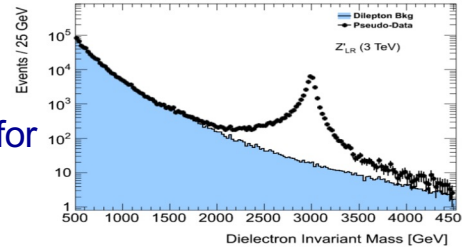
Courtesy: J. De Blas



**Deviations in high-M tails:**
- Better suited for lepton colliders; sensitive to [mass/coupling] ≫ √s
- Hadron colliders relevant for $g_{Z'} > g_{SM}$ couplings: [mass/coupling] ≫ 0.5√s
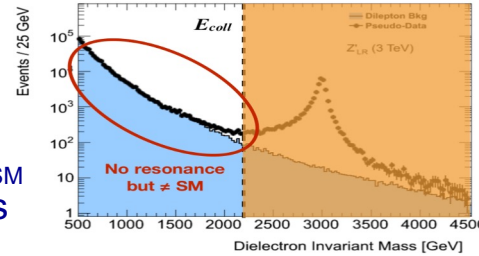


Use very simple model as example. Universal Z'. Clearly, many models with flavor dependence etc.



Y−Universal Z', 2σ
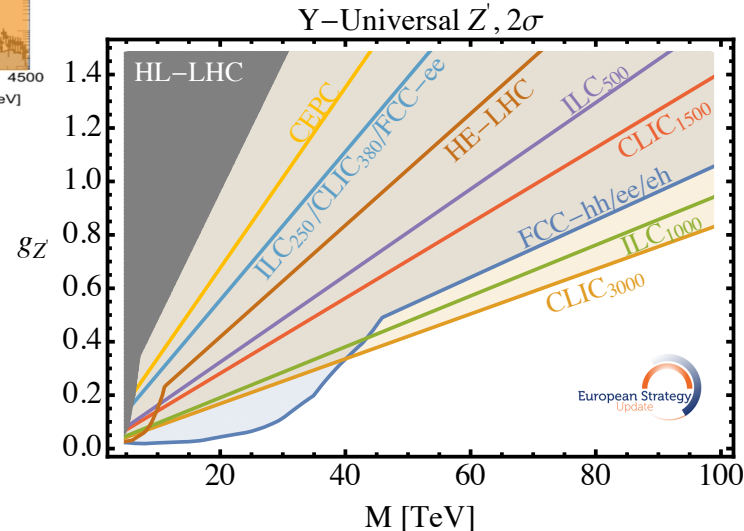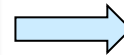
# Higgs Compositeness?

❑ **Using fits from EWK/Higgs group (arXiv:1905.03764)**

❑ **Connection between notations:**

$$\frac{c_\phi}{\Lambda^2} = \frac{g_*^2}{m_*^2} \qquad \frac{c_W}{\Lambda^2} = \frac{1}{m_*^2} \qquad \frac{c_{2W}}{\Lambda^2} = \frac{1}{g_*^2 m_*^2}$$

H        2f-2b        4f, W'/Z'
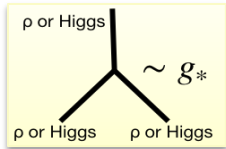
gauge   ρ   $\sim \dfrac{g_W}{g_*}$

❑ **For mass/coupling ~2 TeV → deviations ~1% in Higgs couplings**



95% CL limits on compositeness scale (O_H operator)
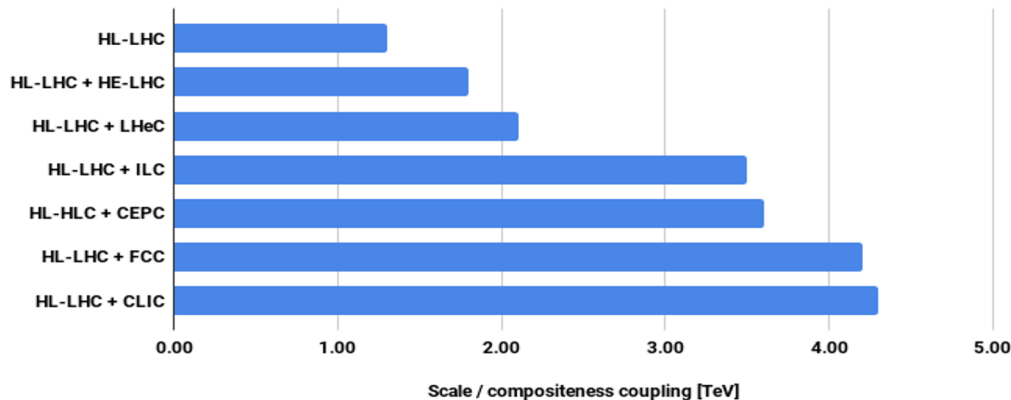
**Maximum sensitivities: @CLIC and FCC(ee+eh+hh)**

# Long-term future: SUSY at >1TeV…. <10 TeV?
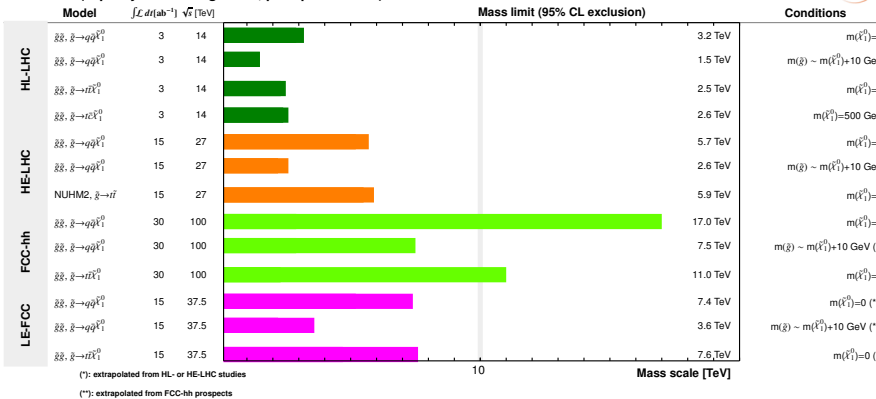
- **The questions:**
  - **If {SUSY} which masses (and mass differences) of strongly- or weakly-coupled super-partners can we reach?**
  - **Is nature fundamentally fine-tuned? If the solution is SUSY, how well can we test this?**
  - **Is dark matter a thermal SUSY WIMP?**

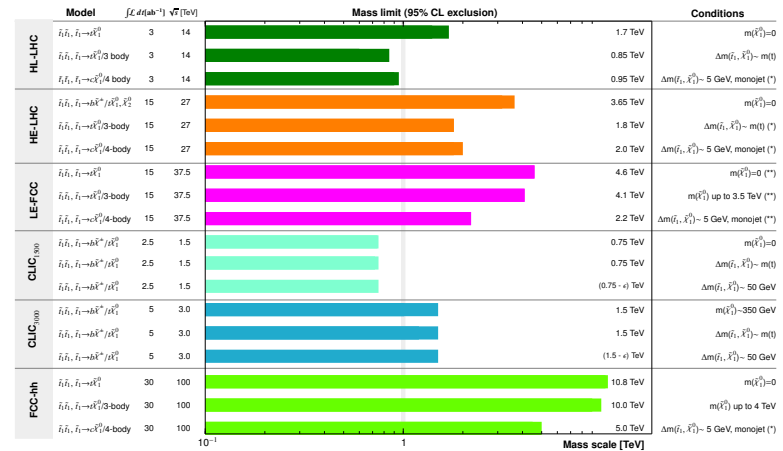- **Strongly-interacting SUSY (gluinos and squarks): simply, the purview of hadron colliders**

**Hadron Colliders: gluino projections**
(R-parity conserving SUSY, prompt searches)

| | Model | $\int \mathcal{L}\,dt$[ab$^{-1}$] | $\sqrt{s}$ [TeV] | Mass limit (95% CL exclusion) | | Conditions |
|---|---|---|---|---|---|---|
| HL-LHC | $\tilde{g}\tilde{g}, \tilde{g}\to q\bar{q}\tilde{\chi}_1^0$ | 3 | 14 | | 3.2 TeV | $m(\tilde{\chi}_1^0)=0$ |
| | $\tilde{g}\tilde{g}, \tilde{g}\to q\bar{q}\tilde{\chi}_1^0$ | 3 | 14 | | 1.5 TeV | $m(\tilde{g}) \sim m(\tilde{\chi}_1^0)+10$ GeV |
| | $\tilde{g}\tilde{g}, \tilde{g}\to t\bar{t}\tilde{\chi}_1^0$ | 3 | 14 | | 2.5 TeV | $m(\tilde{\chi}_1^0)=0$ |
| | $\tilde{g}\tilde{g}, \tilde{g}\to t\bar{c}\tilde{\chi}_1^0$ | 3 | 14 | | 2.6 TeV | $m(\tilde{\chi}_1^0)=500$ GeV |
| HE-LHC | $\tilde{g}\tilde{g}, \tilde{g}\to q\bar{q}\tilde{\chi}_1^0$ | 15 | 27 | | 5.7 TeV | $m(\tilde{\chi}_1^0)=0$ |
| | $\tilde{g}\tilde{g}, \tilde{g}\to q\bar{q}\tilde{\chi}_1^0$ | 15 | 27 | | 2.6 TeV | $m(\tilde{g}) \sim m(\tilde{\chi}_1^0)+10$ GeV |
| | NUHM2, $\tilde{g}\to t\tilde{t}$ | 15 | 27 | | 5.9 TeV | $m(\tilde{\chi}_1^0)=0$ |
| FCC-hh | $\tilde{g}\tilde{g}, \tilde{g}\to q\bar{q}\tilde{\chi}_1^0$ | 30 | 100 | | 17.0 TeV | $m(\tilde{\chi}_1^0)=0$ |
| | $\tilde{g}\tilde{g}, \tilde{g}\to q\bar{q}\tilde{\chi}_1^0$ | 30 | 100 | | 7.5 TeV | $m(\tilde{g}) \sim m(\tilde{\chi}_1^0)+10$ GeV (*) |
| | $\tilde{g}\tilde{g}, \tilde{g}\to t\bar{t}\tilde{\chi}_1^0$ | 30 | 100 | | 11.0 TeV | $m(\tilde{\chi}_1^0)=0$ |
| LE-FCC | $\tilde{g}\tilde{g}, \tilde{g}\to q\bar{q}\tilde{\chi}_1^0$ | 15 | 37.5 | | 7.4 TeV | $m(\tilde{\chi}_1^0)=0$ (**) |
| | $\tilde{g}\tilde{g}, \tilde{g}\to q\bar{q}\tilde{\chi}_1^0$ | 15 | 37.5 | | 3.6 TeV | $m(\tilde{g}) \sim m(\tilde{\chi}_1^0)+10$ GeV (**) |
| | $\tilde{g}\tilde{g}, \tilde{g}\to t\bar{t}\tilde{\chi}_1^0$ | 15 | 37.5 | | 7.6 TeV | $m(\tilde{\chi}_1^0)=0$ (*) |

Mass scale [TeV]

(*): extrapolated from HL- or HE-LHC studies
(**): extrapolated from FCC-hh prospects

**All Colliders: Top squark projections**
(R-parity conserving SUSY, prompt searches)

| | Model | $\int \mathcal{L}\,dt$[ab$^{-1}$] | $\sqrt{s}$ [TeV] | Mass limit (95% CL exclusion) | | Conditions |
|---|---|---|---|---|---|---|
| HL-LHC | $\tilde{t}_1\tilde{t}_1, \tilde{t}_1\to t\tilde{\chi}_1^0$ | 3 | 14 | | 1.7 TeV | $m(\tilde{\chi}_1^0)=0$ |
| | $\tilde{t}_1\tilde{t}_1, \tilde{t}_1\to t\tilde{\chi}_1^0$/3-body | 3 | 14 | | 0.85 TeV | $\Delta m(\tilde{t}_1, \tilde{\chi}_1^0)-m(t)$ |
| | $\tilde{t}_1\tilde{t}_1, \tilde{t}_1\to c\tilde{\chi}_1^0$/4 body | 3 | 14 | | 0.95 TeV | $\Delta m(\tilde{t}_1, \tilde{\chi}_1^0)\sim 5$ GeV, monojet (*) |
| HE-LHC | $\tilde{t}_1\tilde{t}_1, \tilde{t}_1\to b\tilde{\chi}^+/t\tilde{\chi}_1^0, \tilde{\chi}_2^0$ | 15 | 27 | | 3.65 TeV | $m(\tilde{\chi}_1^0)=0$ |
| | $\tilde{t}_1\tilde{t}_1, \tilde{t}_1\to t\tilde{\chi}_1^0$/3-body | 15 | 27 | | 1.8 TeV | $\Delta m(\tilde{t}_1, \tilde{\chi}_1^0)-m(t)$ (*) |
| | $\tilde{t}_1\tilde{t}_1, \tilde{t}_1\to c\tilde{\chi}_1^0$/4-body | 15 | 27 | | 2.0 TeV | $\Delta m(\tilde{t}_1, \tilde{\chi}_1^0)\sim 5$ GeV, monojet (*) |
| LE-FCC | $\tilde{t}_1\tilde{t}_1, \tilde{t}_1\to t\tilde{\chi}_1^0$ | 15 | 37.5 | | 4.6 TeV | $m(\tilde{\chi}_1^0)=0$ (**) |
| | $\tilde{t}_1\tilde{t}_1, \tilde{t}_1\to t\tilde{\chi}_1^0$/3-body | 15 | 37.5 | | 4.1 TeV | $m(\tilde{\chi}_1^0)$ up to 3.5 TeV (**) |
| | $\tilde{t}_1\tilde{t}_1, \tilde{t}_1\to c\tilde{\chi}_1^0$/4-body | 15 | 37.5 | | 2.2 TeV | $\Delta m(\tilde{t}_1, \tilde{\chi}_1^0)\sim 5$ GeV, monojet (**) |
| CLIC(1500) | $\tilde{t}_1\tilde{t}_1, \tilde{t}_1\to b\tilde{\chi}^+/t\tilde{\chi}_1^0$ | 2.5 | 1.5 | | 0.75 TeV | $m(\tilde{\chi}_1^0)=0$ |
| | $\tilde{t}_1\tilde{t}_1, \tilde{t}_1\to b\tilde{\chi}^+/t\tilde{\chi}_1^0$ | 2.5 | 1.5 | | 0.75 TeV | $\Delta m(\tilde{t}_1, \tilde{\chi}_1^0)-m(t)$ |
| | $\tilde{t}_1\tilde{t}_1, \tilde{t}_1\to b\tilde{\chi}^+/t\tilde{\chi}_1^0$ | 2.5 | 1.5 | | (0.75 - $\epsilon$) TeV | $\Delta m(\tilde{t}_1, \tilde{\chi}_1^0)\sim 50$ GeV |
| CLIC(3000) | $\tilde{t}_1\tilde{t}_1, \tilde{t}_1\to b\tilde{\chi}^+/t\tilde{\chi}_1^0$ | 5 | 3.0 | | 1.5 TeV | $m(\tilde{\chi}_1^0)<350$ GeV |
| | $\tilde{t}_1\tilde{t}_1, \tilde{t}_1\to b\tilde{\chi}^+/t\tilde{\chi}_1^0$ | 5 | 3.0 | | 1.5 TeV | $\Delta m(\tilde{t}_1, \tilde{\chi}_1^0)-m(t)$ |
| | $\tilde{t}_1\tilde{t}_1, \tilde{t}_1\to b\tilde{\chi}^+/t\tilde{\chi}_1^0$ | 5 | 3.0 | | (1.5 - $\epsilon$) TeV | $\Delta m(\tilde{t}_1, \tilde{\chi}_1^0)\sim 50$ GeV |
| FCC-hh | $\tilde{t}_1\tilde{t}_1, \tilde{t}_1\to t\tilde{\chi}_1^0$ | 30 | 100 | | 10.8 TeV | $m(\tilde{\chi}_1^0)=0$ |
| | $\tilde{t}_1\tilde{t}_1, \tilde{t}_1\to t\tilde{\chi}_1^0$/3-body | 30 | 100 | | 10.0 TeV | $m(\tilde{\chi}_1^0)$ up to 4 TeV |
| | $\tilde{t}_1\tilde{t}_1, \tilde{t}_1\to c\tilde{\chi}_1^0$/4-body | 30 | 100 | | 5.0 TeV | $\Delta m(\tilde{t}_1, \tilde{\chi}_1^0)\sim 5$ GeV, monojet (*) |

Mass scale [TeV]

(*) indicates projection of existing experimental searches
(**) extrapolated from FCC-hh prospects
$\epsilon$ indicates a possible non-evaluated loss in sensitivity

ILC 500: discovery in all scenarios up to kinematic limit $\sqrt{s}/2$

HE-LHC: ~ 2 x $M_{HL-LHC}$
FCChh:   ~ 5 x $M_{HL-LHC}$

# Long-term future: SUSY EWK sector

ee: mainly $\tilde{\chi}^0_2\tilde{\chi}^0_1$ and $\tilde{\chi}^+_1\tilde{\chi}^-_1$ ($\Delta m > 1\,\text{GeV}$)
pp: mainly $\tilde{\chi}^0_2\tilde{\chi}^\pm_1$ (gaps at low $\Delta m$)
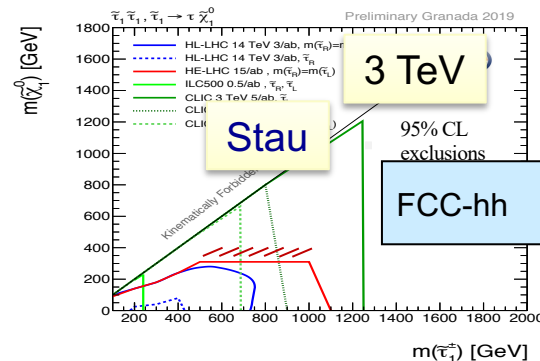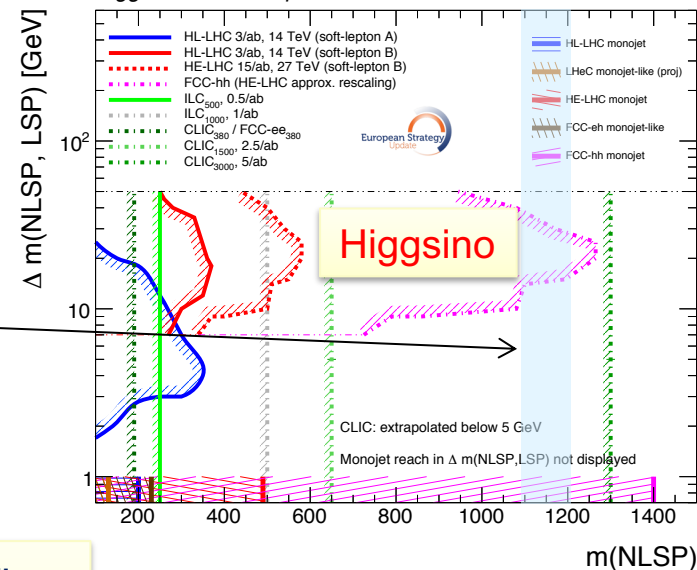
ee sensitivity ~independent of nature of LSP (but up to $\sqrt{s}/2$)

Thermal WIMP

pp sensitivity: depends on LSP; ISR jet for very low $\Delta m$ (up to ~5 GeV); Pure Higgsino: stopped track



$\tilde{\chi}^0_2\,\tilde{\chi}^\pm_1,\ \tilde{\chi}^0_2 \to Z^{(*)}\,\tilde{\chi}^0_1$ and $\tilde{\chi}^\pm_1 \to W^{(*)}\,\tilde{\chi}^0_1$

Wino-like cross-sections

- LHC 36/fb, 13 TeV
- HL-LHC 3/ab, 14 TeV (3L search)
- HL-LHC compressed 3/ab, 14 TeV
- HE-LHC 15/ab (projection)
- HE-LHC compressed 15/ab (projection)
- ILC$_{500}$, 0.5/ab
- ILC$_{1000}$, 1/ab
- CLIC$_{1500}$, 2.5/ab
- CLIC$_{3000}$, 5/ab
- FCC-hh (3L search, 3/ab)

Kinematically Forbidden

95% CL exclusion

$m(\tilde{\chi}^0_1)$ [GeV] vs $m(\tilde{\chi}^0_2)=m(\tilde{\chi}^\pm_1)$ [GeV]
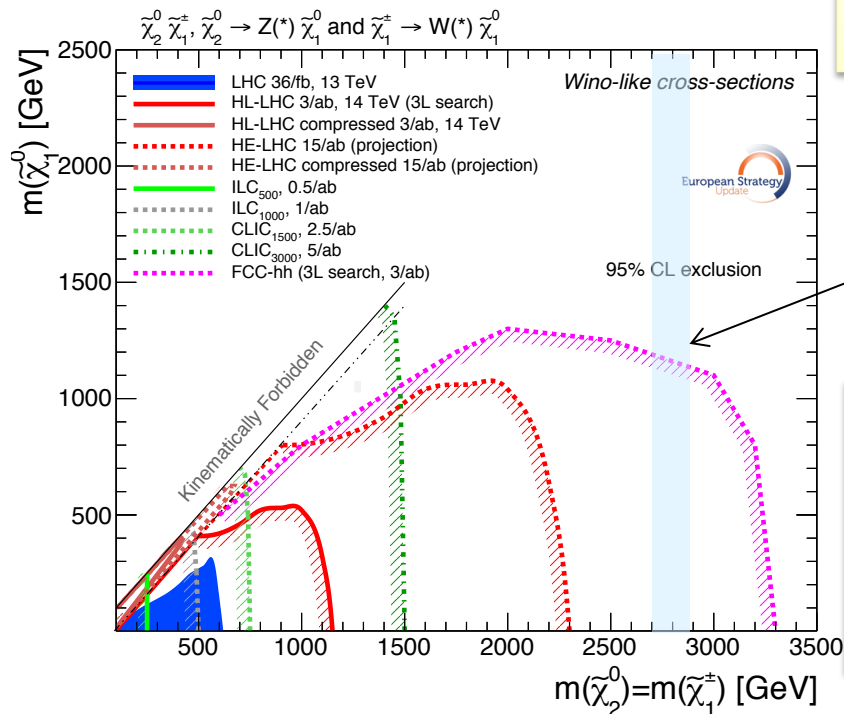


Higgsino-like EWK processes

- HL-LHC 3/ab, 14 TeV (soft-lepton A)
- HL-LHC 3/ab, 14 TeV (soft-lepton B)
- HE-LHC 15/ab, 27 TeV (soft-lepton B)
- FCC-hh (HE-LHC approx. rescaling)
- ILC$_{500}$, 0.5/ab
- ILC$_{1000}$, 1/ab
- CLIC$_{380}$ / FCC-ee$_{380}$
- CLIC$_{1500}$, 2.5/ab
- CLIC$_{3000}$, 5/ab

- HL-LHC monojet
- LHeC monojet-like (proj)
- HE-LHC monojet
- FCC-eh monojet-like
- FCC-hh monojet

Higgsino

CLIC: extrapolated below 5 GeV

Monojet reach in $\Delta m$(NLSP,LSP) not displayed

$\Delta m$(NLSP, LSP) [GeV] vs m(NLSP)



$\tilde{\tau}_1\,\tilde{\tau}_1,\ \tilde{\tau}_1 \to \tau\,\tilde{\chi}^0_1$

Preliminary Granada 2019

- HL-LHC 14 TeV 3/ab, $m(\tilde{\tau}_R)$=...
- HL-LHC 14 TeV 3/ab, $\tilde{\tau}_R$
- HE-LHC 15/ab, $m(\tilde{\tau}_R)$=$m(\tilde{\tau}_L)$
- ILC500 0.5/ab, $\tilde{\tau}_R$, $\tilde{\tau}_L$
- CLIC 3 TeV 5/ab, $\tilde{\tau}_R$

Stau

3 TeV

Kinematically Forbidden

95% CL exclusions

FCC-hh

$m(\tilde{\chi}^0_1)$ [GeV] vs $m(\tilde{\tau}^\pm_1)$ [GeV]

# Scalar mediator: Higgs portal and BSM scalar



A collider discovery will need confirmation from DD/ID for cosmological origin
A DD/ID discovery will need confirmation from colliders to understand the nature of the interaction
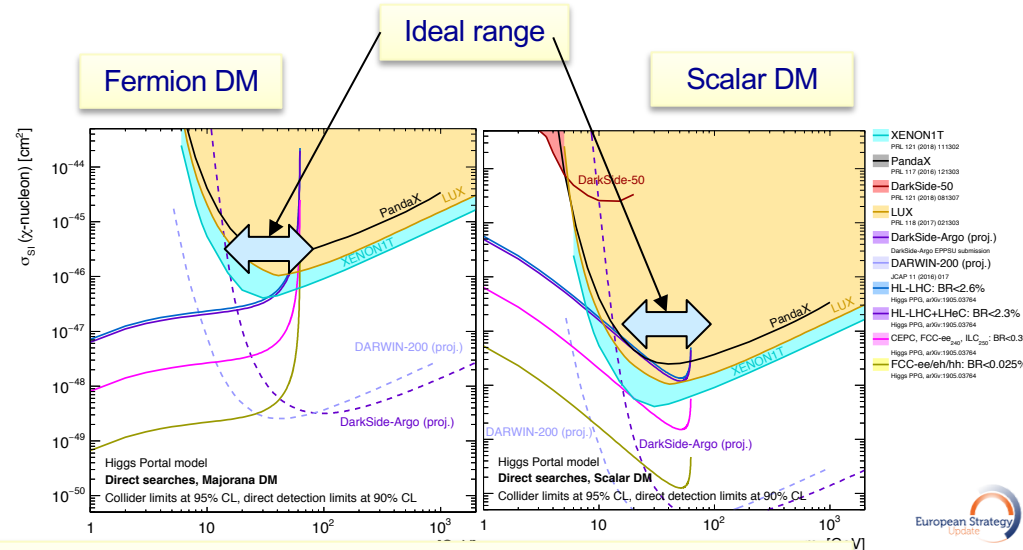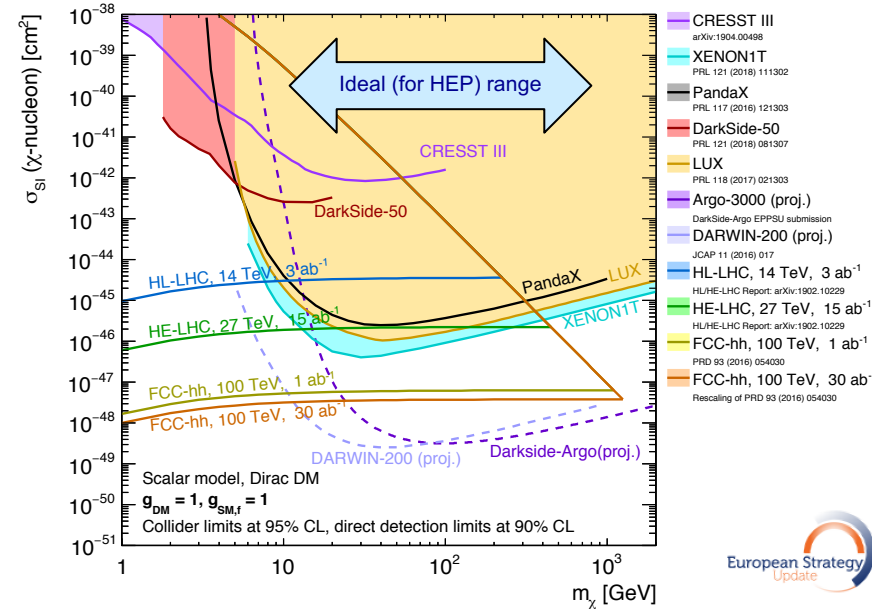
A future collider program that optimizes sensitivity to invisible particles coherently with DD/ID serves us well. Need maximum overlap with DD/ID!

# Extended Scalar sectors: MSSM

Simply: hadron colliders…

LHC+HL-LHC



Indirect info also probes additional h bosons (e.g. $\kappa_b \sim m_Z^2/m_A^2$)

$pp \rightarrow bbH^0/A \rightarrow bb\tau\tau$ (large $\tan\beta$)
$pp \rightarrow bbH^0/A \rightarrow ttbb$ (int. $\tan\beta$)
$pp \rightarrow ttH^0/A \rightarrow tttt$ (low $\tan\beta$)

$pp \rightarrow btH^\pm \rightarrow bb\tau\nu$
$pp \rightarrow btH^\pm \rightarrow tbtb$

FCC-hh

FCC-hh

$H^0/A$: exclusion limits > 5 TeV
(20 TeV at low $\tan\beta$)
$H^\pm$: exclusion limits ~10 - 15 TeV

# EU Strategy: other essential scientific activities for particle physics

- **A. The quest for dark matter and the exploration of flavour and fundamental symmetries are crucial components of the search for new physics.**
    - **This search can be done in many ways, for example through precision measurements of flavour physics and electric or magnetic dipole moments, and searches for axions, dark sector candidates and feebly interacting particles. There are many options to address such physics topics including energy-frontier colliders, accelerator and non-accelerator experiments. A diverse programme that is complementary to the energy frontier is an essential part of the European particle physics Strategy. *Experiments in such diverse areas that offer potential high-impact particle physics programmes at laboratories in Europe should be supported, as well as participation in such experiments in other regions of the world.***

- **B. Theoretical physics is an essential driver of particle physics that opens new, daring lines of research, motivates experimental searches and provides the tools needed to fully exploit experimental results. It also plays an important role in capturing the imagination of the public and inspiring young researchers.**

- **C. The success of particle physics experiments relies on innovative instrumentation and state-of-the-art infrastructures. To prepare and realise future experimental research programmes, the community must maintain a strong focus on instrumentation.**

# Where we stand

- **Most successful Theory ever: Standard Model of Particle Physics**
  - **Highest priority:** *extend understanding of SM and its newly discovered scalar sector*.
- **Evidence that SM is either incomplete or an Effective Theory of some Ultimate Theory (or another step in a series of Effective Theories…)**
  - **Experimental evidence**
    - **Dark Matter (DM): The "thing" we know the least about: Unknown nature, unknown number(s) of DM particles, unknown mass range(s) – $10^{80}$.**
    - **Neutrino masses: SM gauge group allows for Majorana masses, "explaining" their tiny values; unknown (putative) Majorana scale.**
    - **Matter-antimatter asymmetry of the Universe: nowhere near what we measure in CP violation experiments. What about CP violation in the lepton sector?**
  - **Theory issues**
    - **Electroweak (EW) hierarchy problem. Why is the Higgs so light?**
    - **The flavour puzzle. Why three generations of quarks and leptons? With *very* different masses and mixings? Size of CP violation? (explain matter universe???)**
    - **And lots more… e.g. Strong CP problem. Another vacuum issue (this time QCD). Why is its θ parameter experimentally constrained to be extremely small? For a priori no good reason…. → Axions?**

# SM Outliers

**Current issues to watch…**

# A very sensitive SM test: the $m_W$–$m_t$ plane
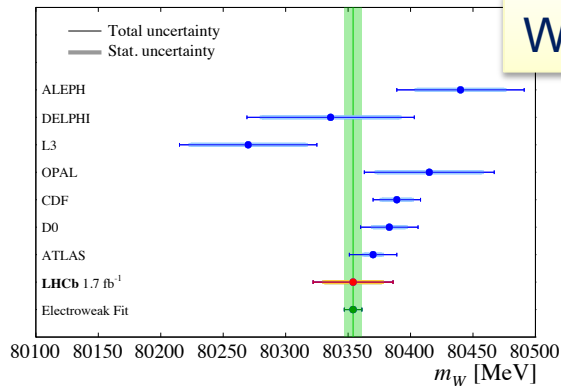


W mass

$$m_W^2\left(1 - \frac{m_W^2}{m_Z^2}\right) = \frac{\pi\alpha}{\sqrt{2}G_\mu}(1 + \Delta r)$$

t mass

# A very sensitive SM test: the $m_W$–$m_t$ plane

**W mass**



| | | |
|---|---|---|
| D0 I | 80478 ± 83 | |
| CDF I | 80432 ± 79 | |
| DELPHI | 80336 ± 67 | |
| L3 | 80270 ± 55 | |
| OPAL | 80415 ± 52 | |
| ALEPH | 80440 ± 51 | |
| D0 II | 80376 ± 23 | |
| ATLAS | 80370 ± 19 | |
| CDF II | 80433 ± 9 | |

W boson mass (MeV/c²)

$$m_W^2 \left( 1 - \frac{m_W^2}{m_Z^2} \right) = \frac{\pi \alpha}{\sqrt{2} G_\mu} (1 + \Delta r)$$
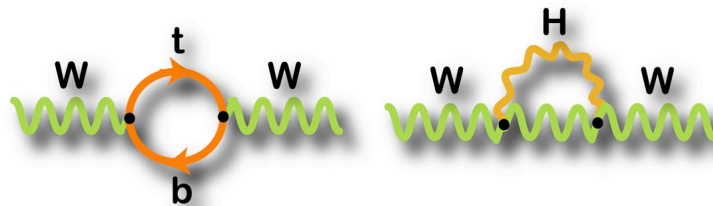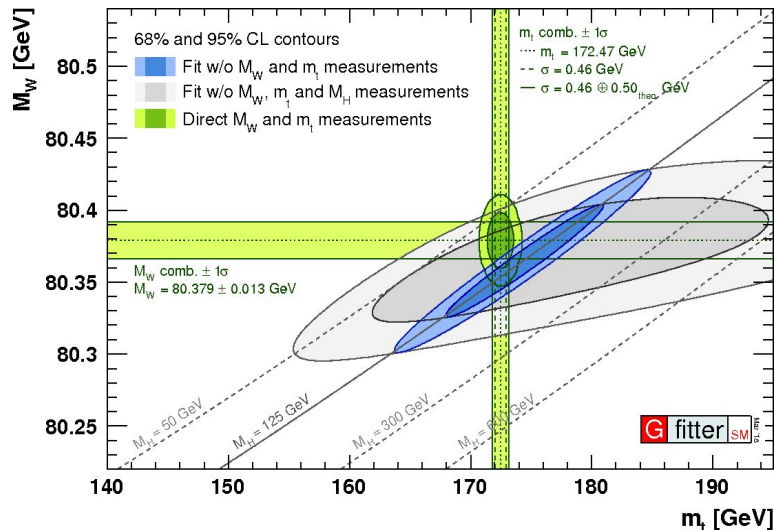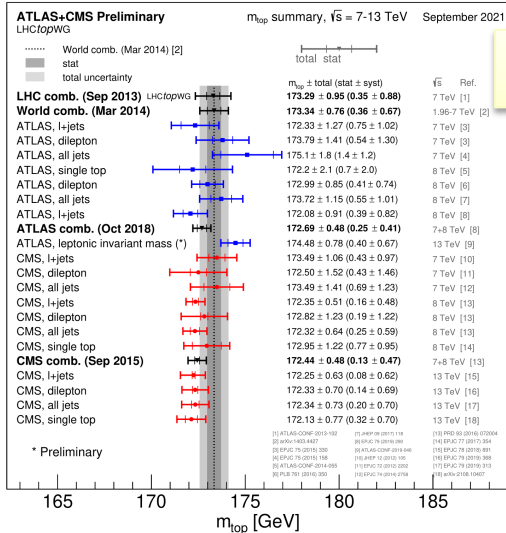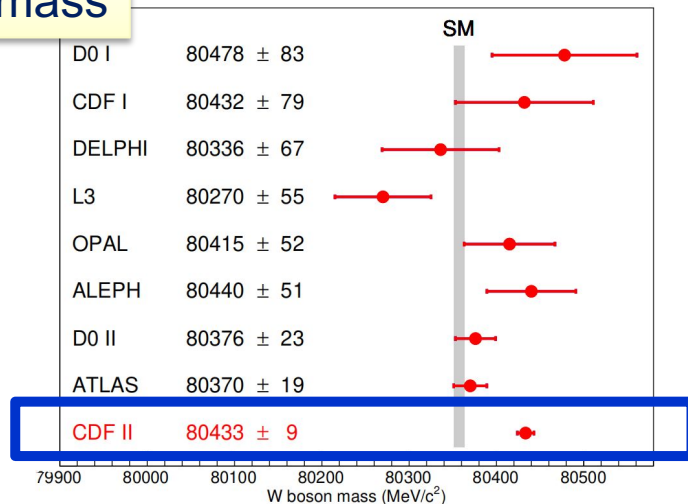
$m_W$(SM)   = 80375±4(inp)±4(th) MeV
$m_W$(CDF) = 80433±9.4 MeV
$\Delta m_W$(SM-CDF)= 7σ…

More precise than all previous $m_W$ measurements combined
~ 3σ higher than most precise other measurements
~ 3σ higher than previous CDF result (1/4 of data, correlations taken into account)
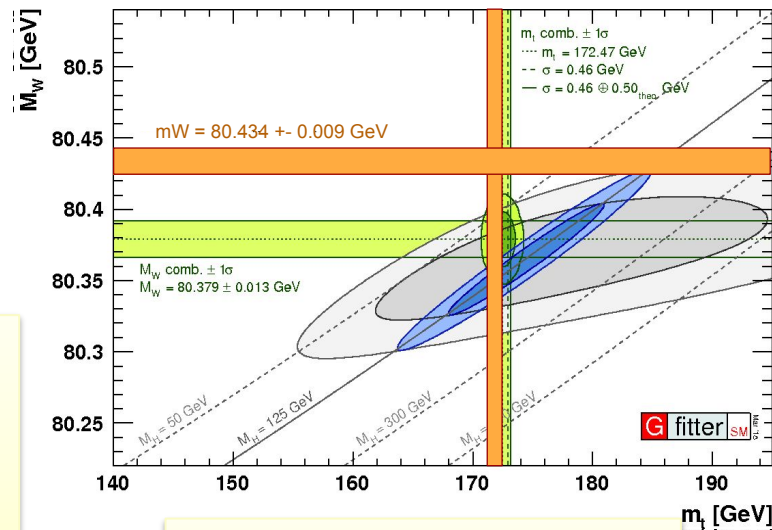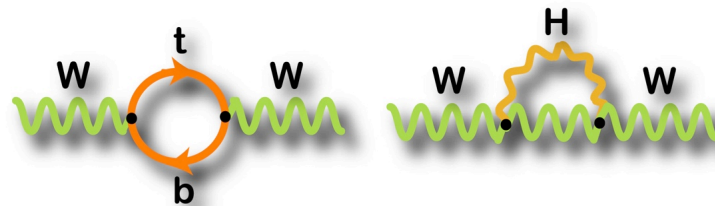
"in tension" with SM pred

# Muon $a_\mu = g_\mu - 2$
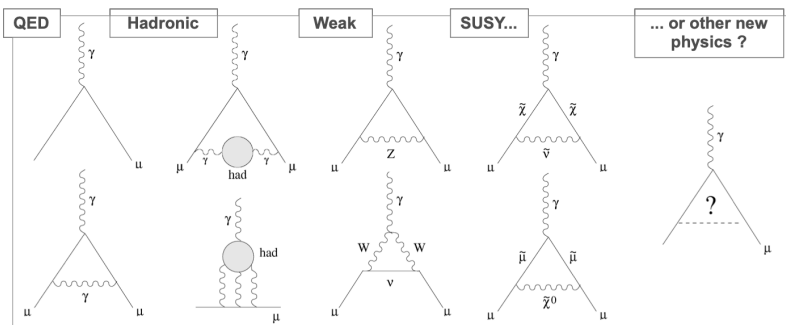
$$a_\mu^{\text{QED}} = \frac{\alpha}{2\pi} + A_2 \left(\frac{\alpha}{\pi}\right)^2 + A_3 \left(\frac{\alpha}{\pi}\right)^3 + A_4 \left(\frac{\alpha}{\pi}\right)^4 + A_5 \left(\frac{\alpha}{\pi}\right)^5$$

$a_\mu^{\text{EW}} = 153.6\,(1.0) \times 10^{-11}$

$a_\mu^{\text{HLbL}} = 94\,(19) \times 10^{-11}$

Main uncertainty: Hadronic Vaccum Polarization
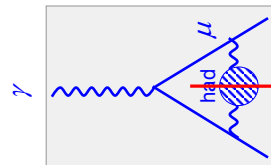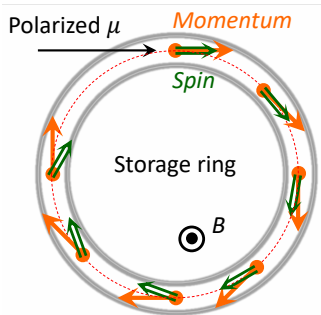
Low-energy $e^+e^-$
or Lattice QCD

4.2σ; but:

BNL+FNAL
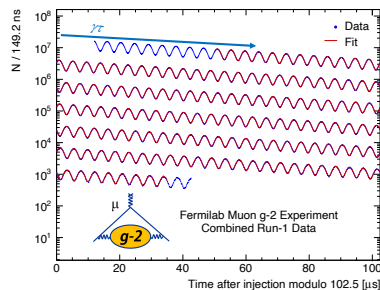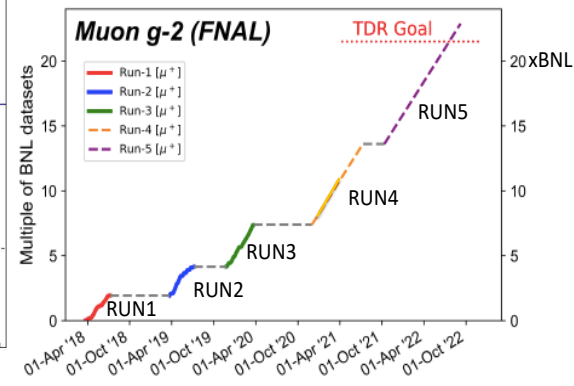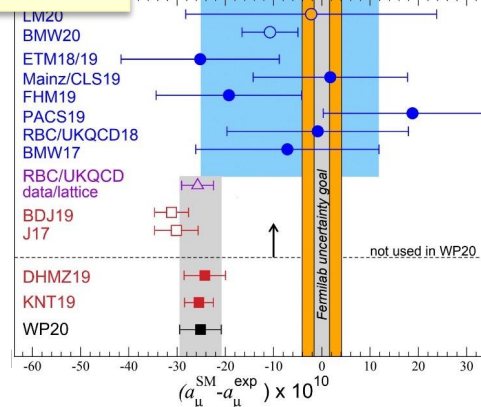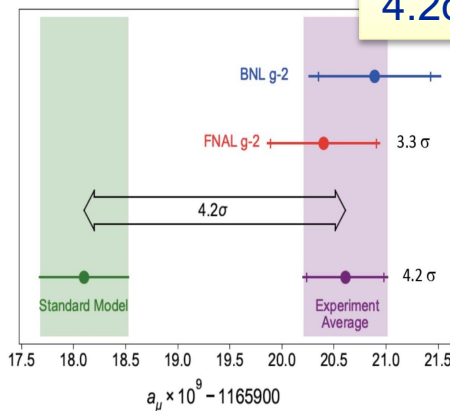
# Flavor physics: charged lepton sector & summary

Final MEG upper limit $B(\mu \to e\gamma) < 4.2 \ 10^{-13}$ @90% CL: there since 2016…
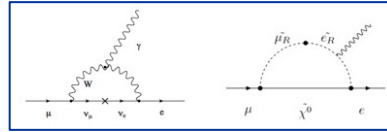
Muon LFV quiet since 2016… Exciting times ahead with MEGII, Mu2e, COMET, Mu3e…

$\mu \to e\gamma$
$\mu \to eee$
$\mu N \to eN$

$\tau \to \mu\mu\mu$

Expect $5 \times 10^{10}$ $\tau\tau$ evts…

Belle II
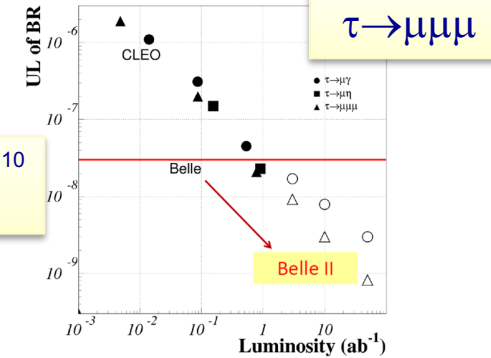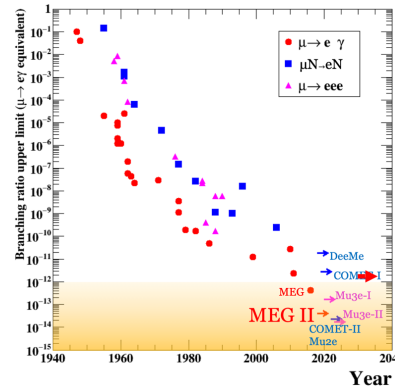
Qualitative summary
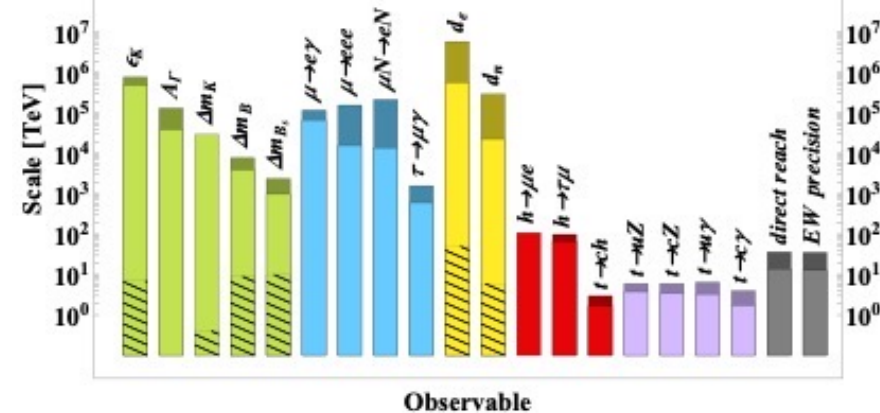


Searches for Charged-Lepton Flavor Violation in Experiments using Intense Muon Beams
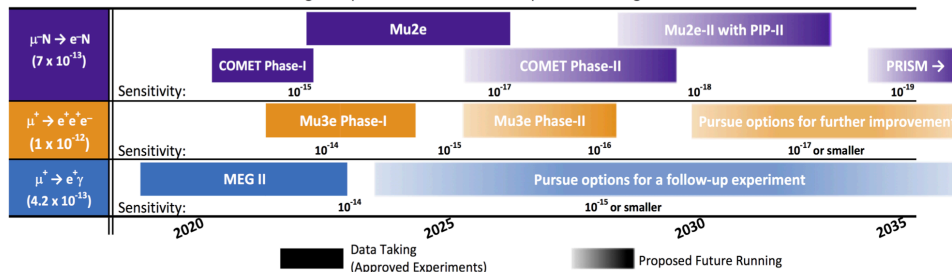
## Confirmation of Brookhaven result. Question is now more on Theory…



Fermilab Muon g-2 Experiment
Combined Run-1 Data
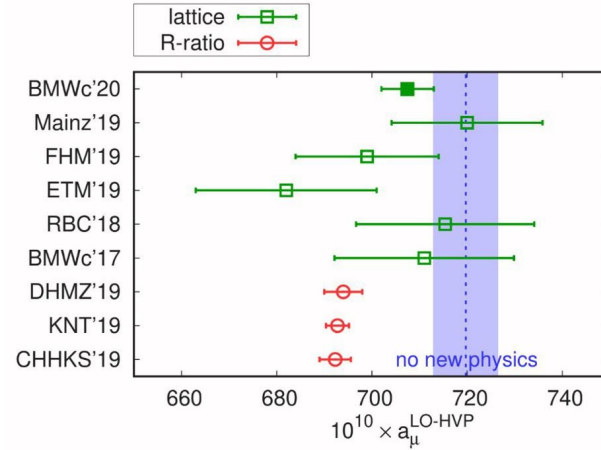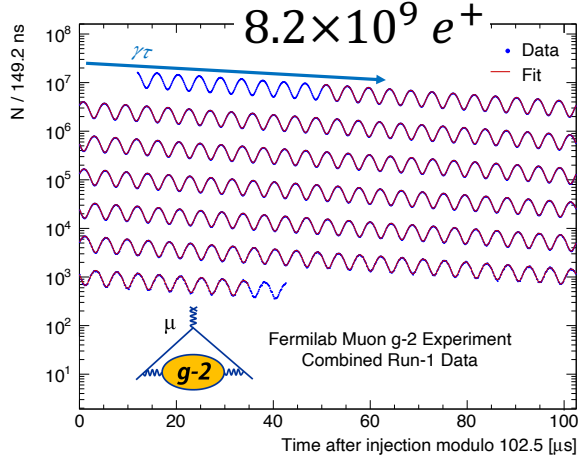
$$a_\mu(\text{FNAL}) = 116\,592\,040(54) \times 10^{-11} \quad (0.46\,\text{ppm})$$
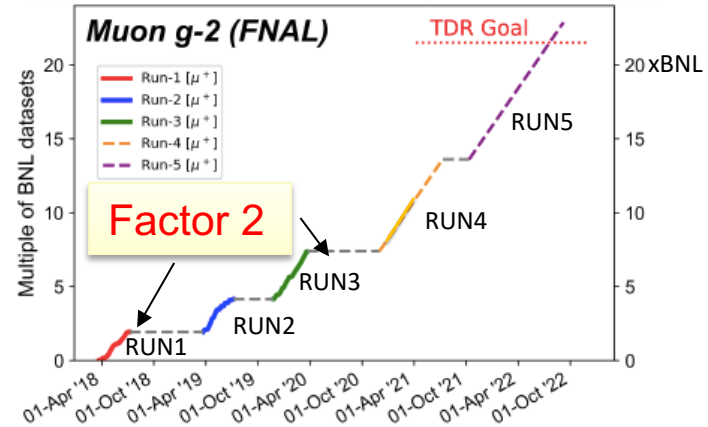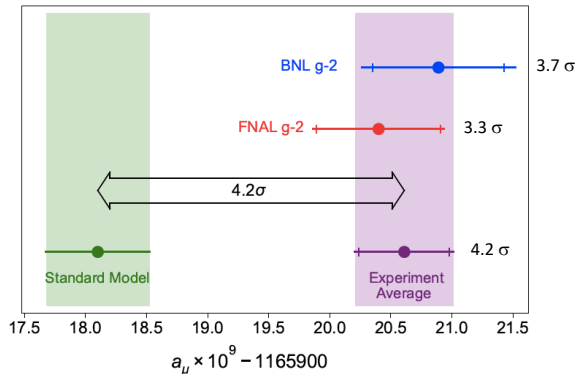
# Flavor physics: quark sector (II)

### k penguin (EWP) decays $b \Rightarrow s\ell^+\ell^-$

hanging neutral currents (FCNC) decays are forbidden at tree level (in SM)

C are possible via quark loops:
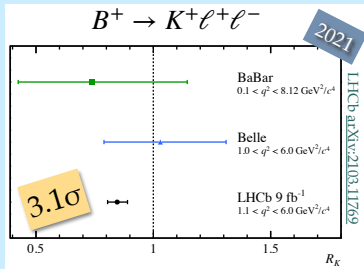


+semileptonic + ang. distrib.

e loop suppressed → rare ... SM of ... $10^{-6}$ ... $10^{-8}$

A. Greljo @ FAW21*



**Class I** $g_\tau \lesssim g_\mu$
- Scalar LQ
- Vector LQ
- $Z'$
- $M_X$ [GeV]

**Class II** $g_\tau \gg g_\mu$
- Scalar LQ
- Vector LQ
- $Z'$
- $M_X$ [GeV]

B. Capdevila et al @ FAW21*



global fit

fit to LFU observables + $\bar{B}_s \to \mu\mu$



Fit (1903.11517):
- 1-σ region
- 2-σ region

Projections:
- CLIC$_{3000}$
- HL-LHC, pp → UU*
- HL-LHC, pp → $\tau^+\tau^-$
- HE-LHC, pp → UU*

European Strategy Update
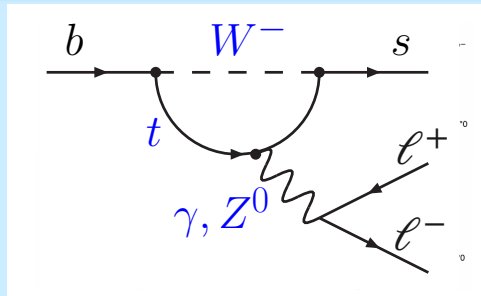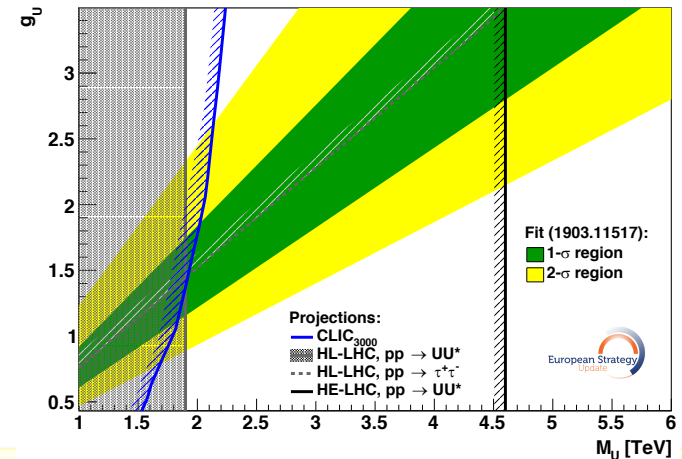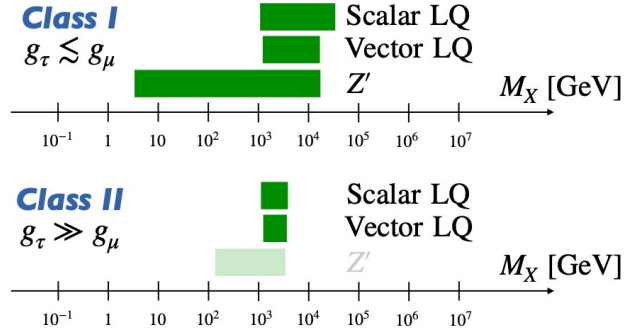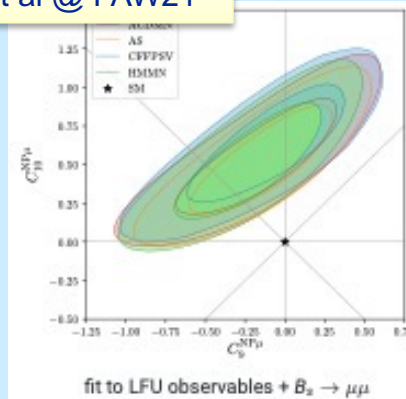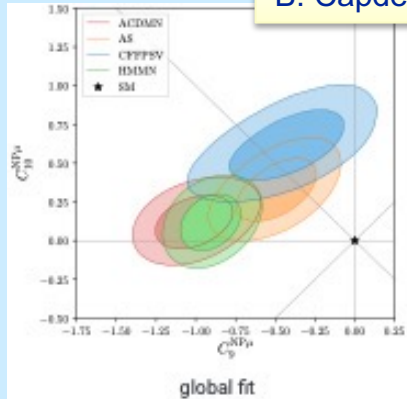
*Unpaid ad for FAW21: Flavour Anomaly Workshop 2021

# Flavor physics: quark sector (III)

$(K^+ \to \pi^+ \nu\bar{\nu}) = (11.0^{+4.0}_{-3.5}) \times 10^{-11}$



## FCNC in top decays
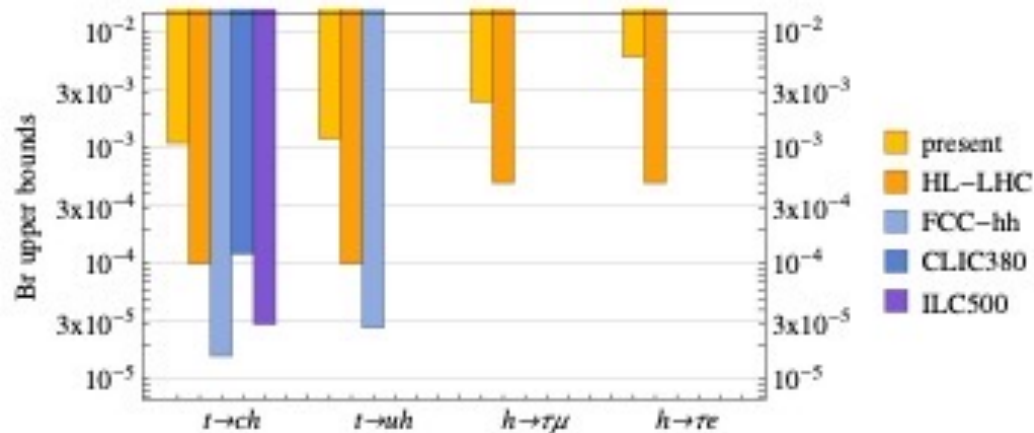
| $BR \times 10^5$ | HL-LHC | HE-LHC | ILC$_{500}$ | CLIC$_{380}$ | LHeC | FCC-ee | FCC-hh | FCC-eh |
|---|---|---|---|---|---|---|---|---|
| $t \to Zq$ | 2.4 - 5.8 | | | | 4 | 2.4 | $\approx 0.1$ | 0.6 |
| $t \to \gamma c$ | 7.4 | | $\approx 1$ | 2.6 | | | 0.024 | |
| $t \to \gamma u$ | 0.86 | | | | | | 0.018 | |
| $t \to \gamma q$ | | | | | 1 | 1.7 | | 0.085 |
| $t \to gc$ | 3.2 | 0.19 | | | | | | |
| $t \to gu$ | 0.38 | 0.056 | | | | | | |

## FCNC with higgs decays
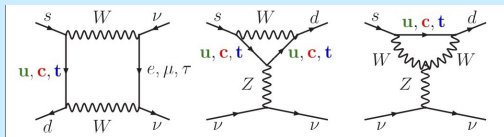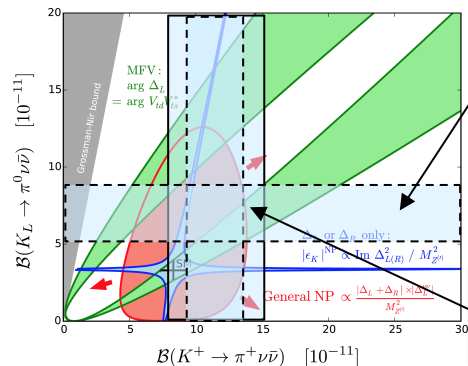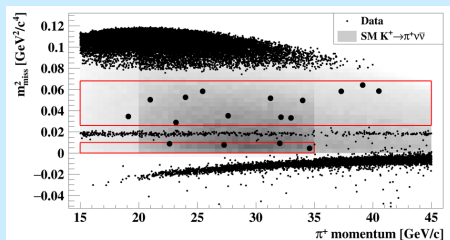


KOTO 2
KLEVER

NA62
(today+guess)

# Physics of flavor: Lepton & Quark sectors

- **Neutrinos:**
    - **The very nature of them: Majorana or Dirac?**
    - **Oscillations, (additional) mass generation (beyond EWSB?)**
    - **Richness of the lepton sector (PMNS, CP violation)**
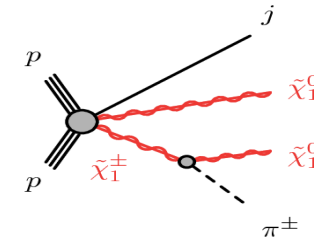- **Quark sector:**
    - **CP violation, CKM triangle**
    - **Rare decays of K and B mesons; SM elements: motivated (universality) and accidental (lepton number conservation)**
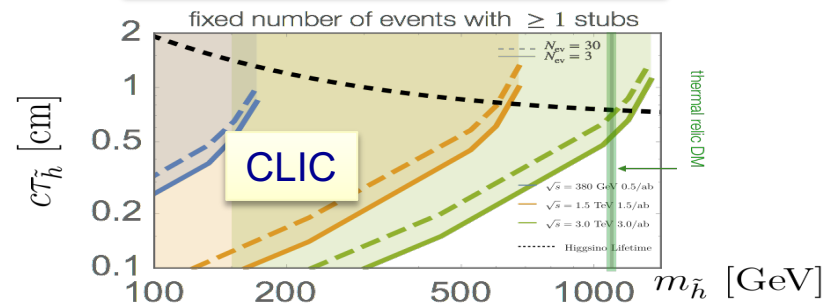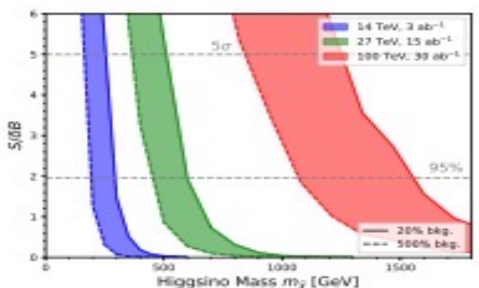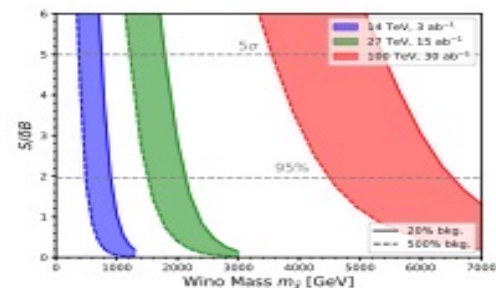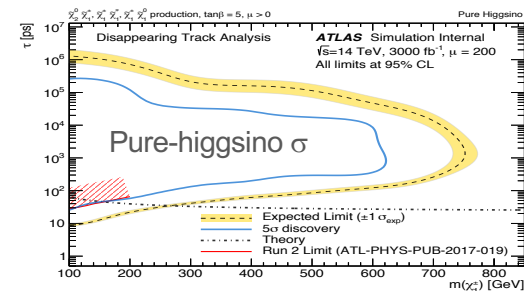    - **Forbidden (?) decays (e.g. $\mu \rightarrow e\gamma$)**

# Long-lived S...
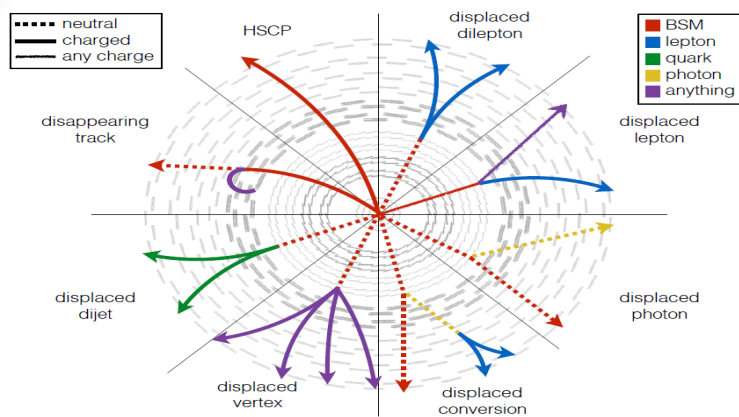


HL-LHC

Charged stub + photon

CLIC

Pure-wino σ

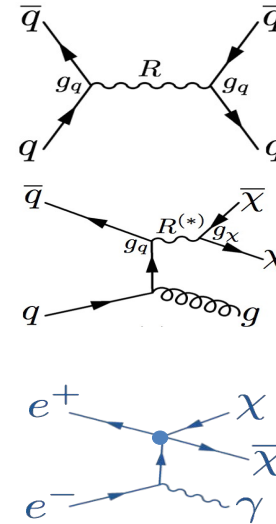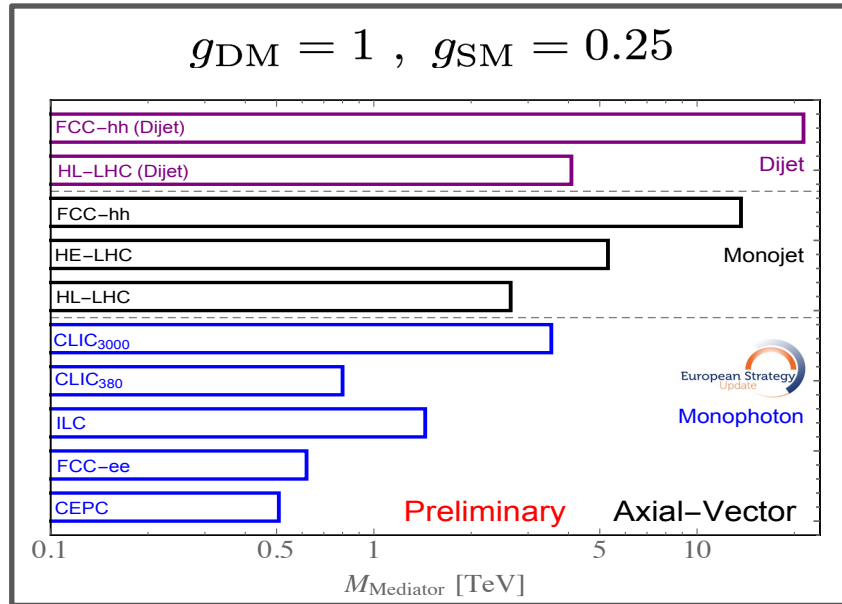Pure-higgsino σ
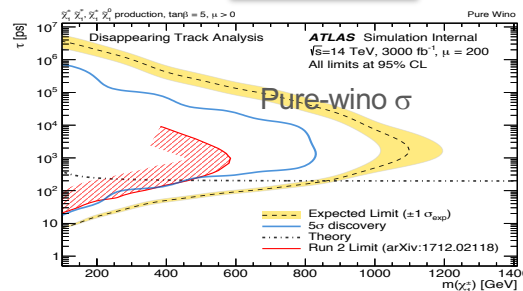
# DM: summary

- **Strengths in WIMP searches both in future lepton and hadron options:**
  - **Combined FCC program shows best sensitivity to benchmarks**
  - **Still, needs complementary experiments: DM ≠ WIMP (only)**
- **We can probe the thermal WIMP parameter region**
- **Large (& yet unknown) parts of phase space can be probed by precision environment/lower bkg in ee**

Synergies with DD/ID communities welcome (and necessary)

cosmological origin
DD/ID/astrophysics

nature of DM-SM interaction
colliders(/beam dumps)

# Simplified Models: axial vector

❑ **Light DM, m$_\chi$=1GeV**

$$g_{\mathrm{DM}} = 1 \ , \ g_{\mathrm{SM}} = 0.25$$

FCC–hh (Dijet)
HL–LHC (Dijet)
Dijet
FCC–hh
HE–LHC
Monojet
HL–LHC
CLIC$_{3000}$
CLIC$_{380}$
ILC
Monophoton
FCC–ee
CEPC

Preliminary    Axial–Vector

$$g_{\mathrm{DM}} = 1 \ , \ g_{\mathrm{SM}} = 0.25$$

FCC–hh (Dijet)
HL –LHC (Dijet)
Dijet
FCC–hh
HE–LHC
Monojet
HL–LHC
CLIC$_{3000}$
CLIC$_{380}$
ILC
FCC–ee
Monophoton
CEPC

Preliminary    Axial–Vector

0.1       0.5    1        5    10
$M_{\mathrm{Mediator}}$ [TeV]

pp: assumes mediator couplings to quarks only.
  750 GeV, HL-LHC
  1.5 TeV, HE-LHC
  3.9 TeV for FCC-hh
Dependence on couplings!

ee: assumes mediator couplings to leptons only. Also in EFT limit, so can be easily rescaled for modified couplings.

Note: taking EFT scale as free parameter, M$_{DM}$ reach ~kinematic reach of collider.

Significant model dependence. UV models may have comparable quark and lepton couplings. If both present, can also use dilepton resonances.

# SUSY: any "holes"?
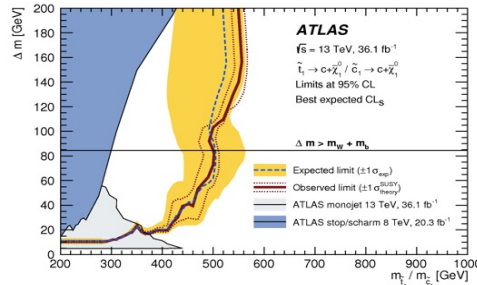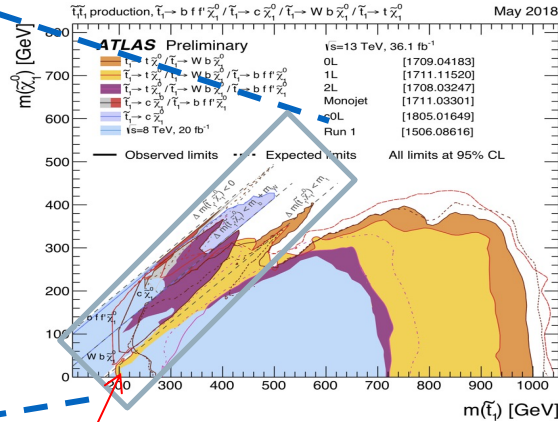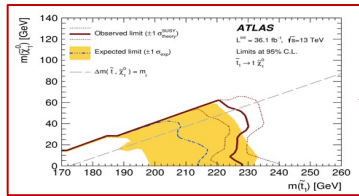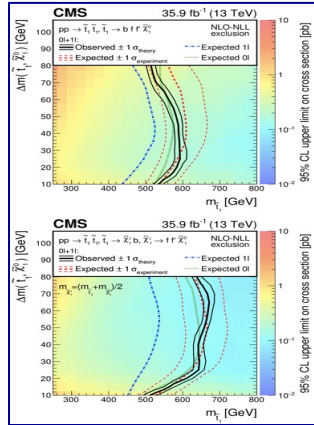


−:
Info only from LHC (& only for stop).
+:
based on data!
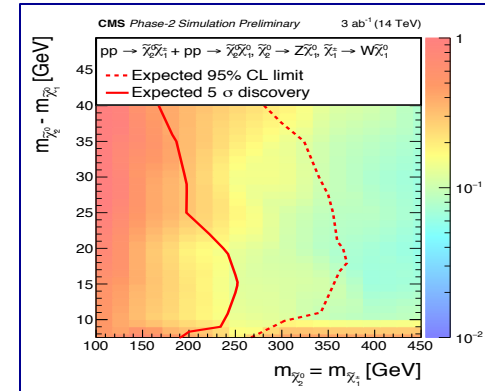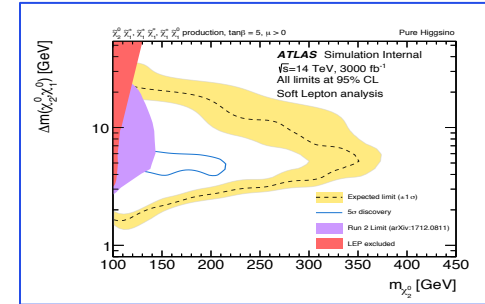
Indeed, after LHC, there will be holes [in low mass regions]; closing or looking at how to close them at HL-LHC; for EWKinos, some regions will remain difficult @ pp.

# DM: direct detection experiments (I)

time

S2

drift time
(depth)

S1

Two-phase (liquid) Xe expts continuing to increase their sensitivity
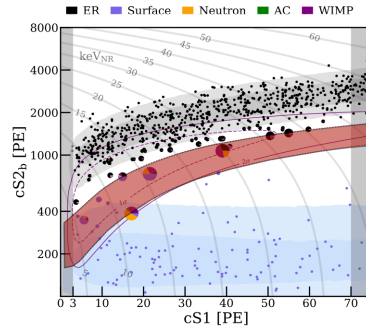
Extending to electron recoils: bkg level: 76x10$^{-3}$ evt/t/yr/keV (1-30 keV)
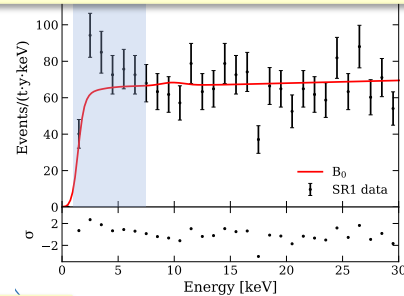
Tritium contam or Solar Axions ?

Axion explanation? but minuses:
1. very significant model dependence
2. "tension" with astrophysics

Cannot tell, but… sensitivity to 10$^{-24}$ contamination is impressive
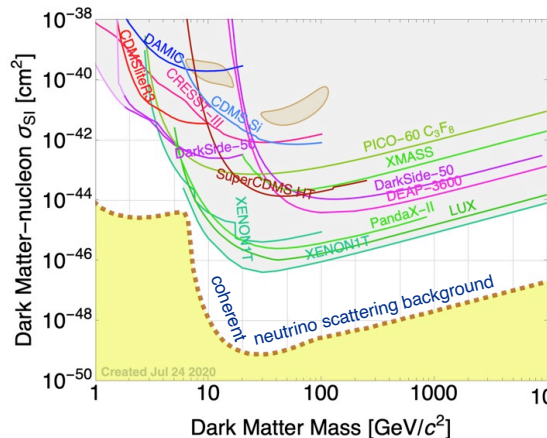
A. Elykov ICHEP2020

Dark Matter - electron scattering
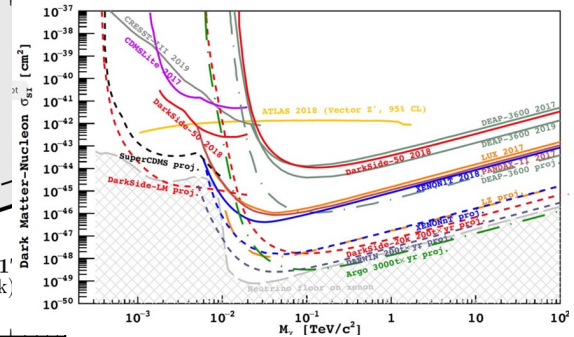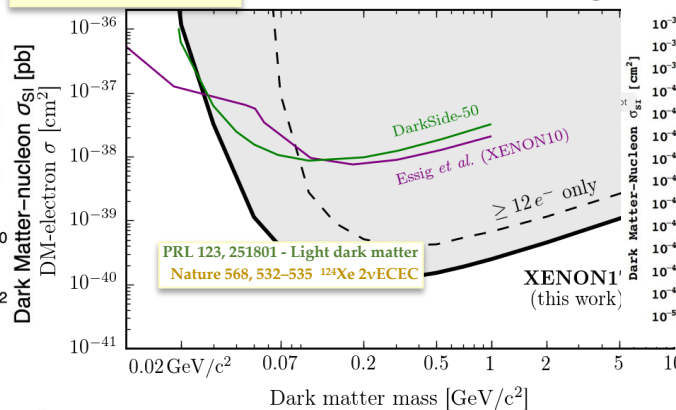
L. Hsu ICHEP2020

The dream scenario
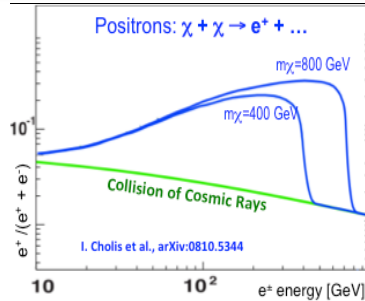
Reality: tantalizing fall (?!).  But pulsars? Moreover: antiprotons!
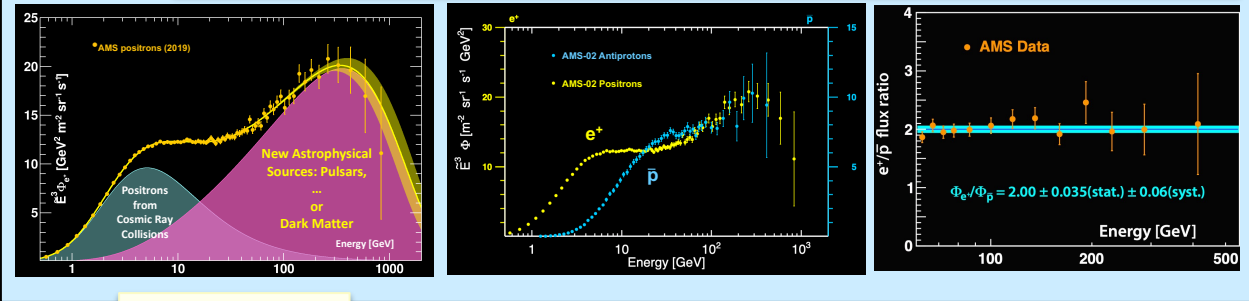
Z. Weng ICHEP2020

The future (~2028)
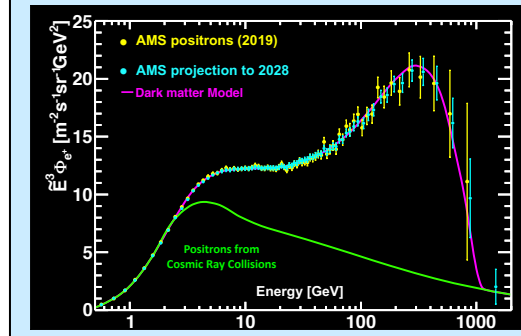
A parting thought: these are (very) difficult measurements; aka: precision makes a difference
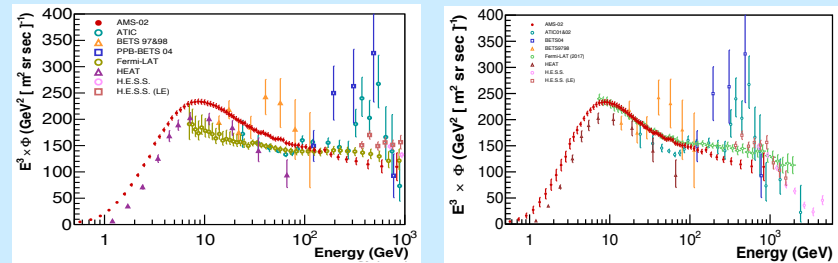
# Neutrinos

**Extras**

al as a question can get &...

$$\left(T_{1/2}\right)^{-1} = G^{0\nu} \cdot |M^{0\nu}...$$

**GERDA**
$T_{0\nu} > 1.8 \times 10^{26}$ yr

Prior to analysis cuts
After analysis cuts
$2\nu\beta\beta$ decay ($T_{1/2} = 1.93 \times 10^{21}$)

ackground best fit and 68% C.L. interval
0% C.L. $T_{1/2}$ lower limit ($1.8 \times 10^{26}$ yr)

Energy (keV)

Counts / 15 keV

Energy (keV)
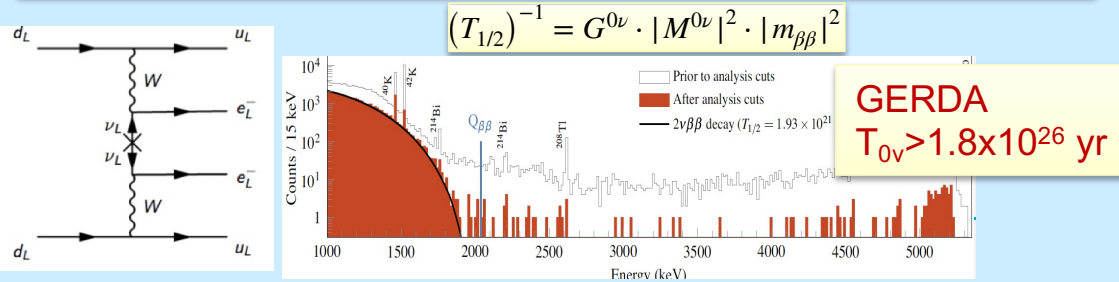
**Mass limits (measurements…)**

Today (BAO +struct. form):
$\Sigma m_\nu < 0.12$ (95% CL)
Ultimate (DESI+BAO): $\Sigma m_\nu < 0.02$

Direct $m_\nu$ measurement(s)
KATRIN: $m_\beta < 1.1$ eV (90% CL)
Asymptotic: $m_\beta < 0.2$ eV
Ultimate (Project-8): 40 meV

(J. Detwiler @ Neutrino2020)

## Extremely active field

- Bolometers (CUPID, AMoRE, CANDLES IV)
  - Measure $E$ ($\sigma \sim 0.1\text{-}0.3\%$) from phonons; granularity gives position info
  - Instrumenting with photon detectors for background rejection

- External trackers (SuperNEMO)
  - Trackers + calorimeters, measure $E$ ($\sigma \sim 3\text{-}10\%$) + tracks / positions + PID

- Scintillators (KamLAND2-Zen, SNO+, Theia, ZICOS)
  - Measure $E$ ($\sigma \sim 3\text{-}10\%$) + position from scintillation light; some PID

- Semiconductors (LEGEND, SELENA)
  - Measure $E$ ($\sigma \sim 0.05\text{-}0.3\%$) from ionization; some tracking / position sensitivity

- TPCs (nEXO, NEXT, PandaX, AXEL, NvDEx, DARWIN, LZ)
  - Collect scintillation + ionization: measure $E$ ($\sigma \sim 0.4\text{-}3\%$) + tracks / position + PID

(But) one example: EXO-200 (0.2 t) $\rightarrow$ nEXO (5 t)
Xe; $T_{1/2} < 3.5 \times 10^{25}$ yr $\rightarrow$ $T_{1/2} < 10^{28}$ yr

KATRIN data with 1 $\sigma$ errorbars $\times$ 50
Fit result

*arXiv: 1909.06048*

Count rate (cps)

Residuals ($\sigma$)

Stat.    Stat. and syst.

NSM
IBM
EDF
QRPA

IO

$m_{\beta\beta}$ 99.7% CL discovery sensitivity [eV]

GERDA-II
MJD
LEND-200
ND-1000
EXO-200
nEXO
NEXT-100
PandaX-III
SNO+II
CUORE
CUPID
Amore-II

# Neutrinos: Mass & nature (Majorana/Dirac – 0νββ)



Direct $m_\nu$ measurement(s)
KATRIN
$m_\beta < 1.1$ eV (90% CL)
Asymptotic: $m_\beta < 0.2$ eV

Ultimate (Project-8): 40 meV

Sound Horizon : $r_s \propto 1/H$
Photon diffusion : $r_d \propto 1/\sqrt{H}$
$H^2 = 8\pi G\rho/3$

$\theta_s = r_s/D_A$

$\theta_d = r_d/D_A$

$\Delta\ell_d = \pi/\theta_d \approx 1950$

$\Delta\ell_s = \pi/\theta_s \approx 300$

L. Knox Neutrino2020

Today (BAO
+struct.
form):
$\Sigma m_\nu < 0.12$
(95% CL)

Future
(DESI+BAO)
:
$\sigma(\Sigma m_\nu)$
<0.02!
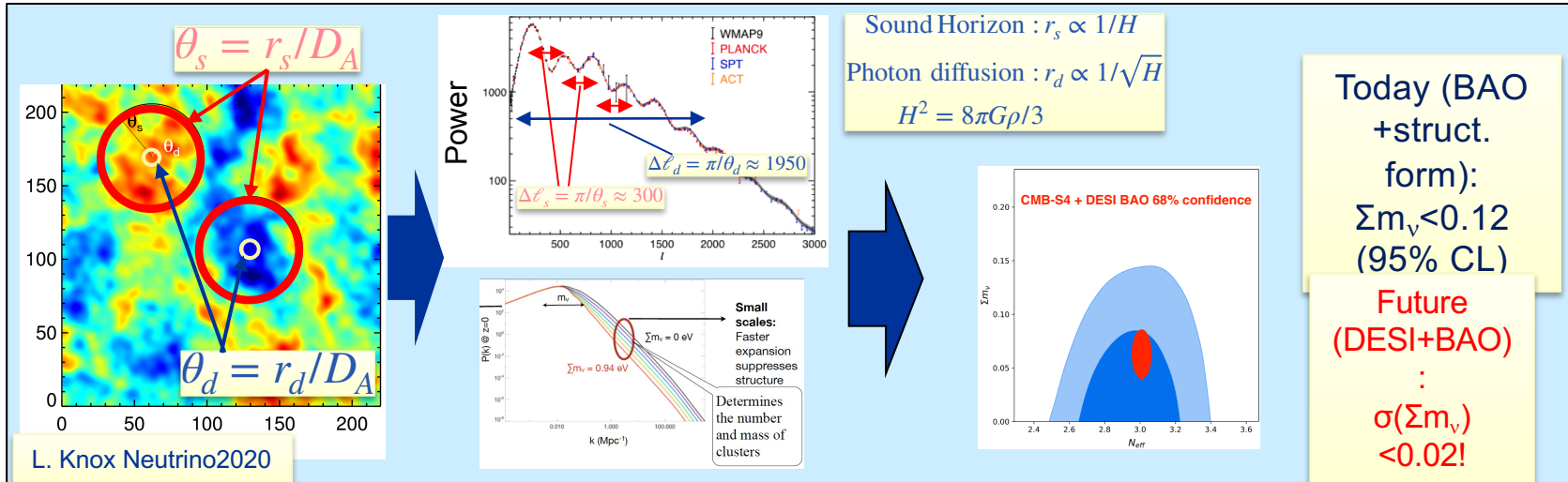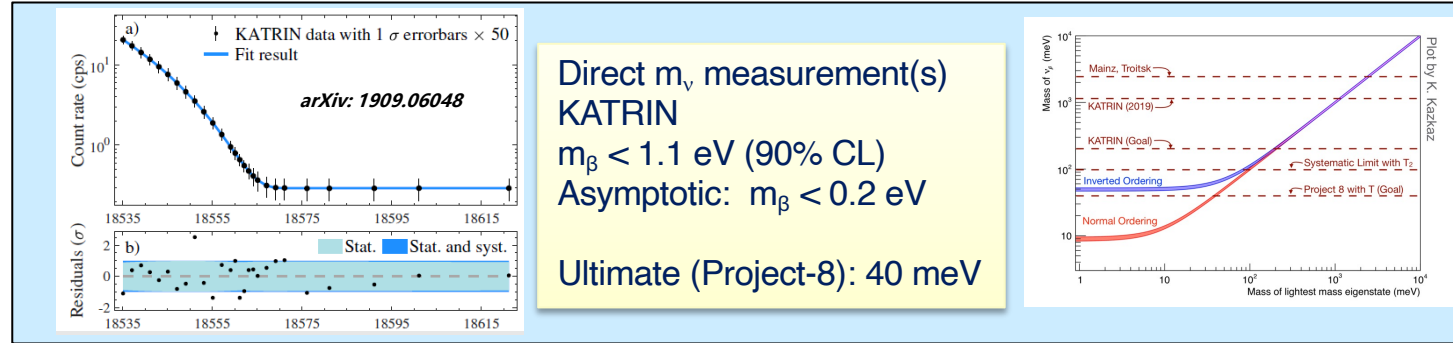
# Neutrinos: sterile sector (?)

Add 4th neutrino with mixing

by electroweak interactions (flavor states) are non-trivial linear combinations of mass eigen-states, that is, eigenstates of the free Hamiltonian with well defined masses. A $3+1$ mixing matrix:

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \\ \nu_s \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} & U_{\mu 4} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} & U_{\tau 4} \\ U_{s1} & U_{s2} & U_{s3} & U_{s4} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \\ \nu_4 \end{pmatrix}$$

$\ell = \ell_{...}$ ... with the 3 neutrino phase typically denoted by $\delta_{CP}$ (case, $\delta_{12}$ becomes unphysical).

... along ... $\gg \Delta m_{21}^2$, $\Delta m_{21}^2$, oscillations at short-baseline experiments well described by a two-flavor vacuum oscillation formula

$$P_{\nu_\alpha \to \nu_\beta} = 4|U_{\alpha\beta}|^2(\delta_{\alpha\beta} - |U_{\alpha\beta}|^2)\sin^2\left(\frac{\Delta m_{41}^2 L}{4E}\right),$$

can be parameterized as (see, e.g., Ref. (33))

$U = R_{34}(\theta_{34})R_{24}(\theta_{24},\delta_{24})R_{14}(\theta_{14},\delta_{14})R_{23}(\theta_{23})R_{13}(\theta_{13},\delta_{13})R_{12}(\theta_{12})$

$L$ is the baseline and $E$ is the neutrino energy.

In a nutshell, each oscillation channel $\nu_\alpha \to \nu_\beta$ is driven by a different effective $\sin^2 2\theta_{\alpha\beta} \equiv 4|U_{\alpha\beta}|^2 |\delta_{\alpha\beta} - |U_{\alpha\beta}|^2|$, $\sin^2\left(\frac{\Delta m_{41}^2 L}{4E}\right)$

... a rotation in the $ij$-plane by an angle $\theta_{ij}$ and a possible phase $\delta_{ij}$ (if present). The standard three neutrino framework can be recovered by setting $\theta_{i4} = 0$ for

$\nu_\mu \to \nu_e$ : $\sin^2 2\theta_{\mu e} \equiv 4|U_{\mu 4}|^2|U_{e4}|^2$ — (LSND, MiniBooNE, OPERA anomalies);

$\nu_e \to \nu_e$ : $\sin^2 2\theta_{ee} \equiv 4|U_{e4}|^2(1 - |U_{e4}|^2)$ — (Reactors, solar, Gallium anomalies);

$\nu_\mu \to \nu_\mu$ : $\sin^2 2\theta_{\mu\mu} \equiv 4|U_{\mu 4}|^2(1 - |U_{\mu 4}|^2)$ — MiniBooNE, MINOS, IceCube.

$\sin^2 2\vartheta_{e\mu} = 4|U_{e4}|^2|U_{\mu 4}|^2 \simeq \frac{1}{4}\sin^2 2\vartheta_{ee}\sin^2 2\vartheta_{\mu\mu}$

There are two important features that should be noticed regarding sterile neutrino oscillations. First, the characteristic $\sin^2(\Delta m^2 L/4E)$ dependence of neutrino oscillations allow to distinguish ... anomalies. Second, baseline transition ... necessarily inducing ... to over-constrain parameter space ... $\nu_\mu$ disappearance short baselines ... crucial to test the ... neutrino hypothesis.

## Very active field

e vs $\gamma$ ? → $\mu$BOONe: LArTPC

Several expts: proposed running

+ICHEP2020 : + DayaBay, RENO…

$\nu_\mu \to \nu_e$ : LSND, MiniBOONe, OPERA

$\nu_\mu \to \nu_\mu$ : MiniBOONe, MINOS et al

$\nu_e \to \nu_e$ : Gallium, Reactors, Solar Exp

Phys. Rev. Lett. 121, 221801 (2018)

LSND
L~30m
E~30MeV

MiniBooNe
4.6σ $\nu_e$ excess!
L~500m
E~500MeV

$\nu_\mu \to \nu_e$
NEOS
$\nu_e$

$\nu_e$ shortage in reactor expts (But TH shaky)

Taking 5 MeV bump as due to sterile $\nu$

M. Danilov ICHEP 2020

DANSS: excludes RAA by >8σ (5σ since 2018)

| Experiment | Reactor Power/Fuel |
|---|---|
| DANSS (Russia) | 3000 MW LEU fuel |
| NEOS (South Korea) | 2800 MW LEU fuel |
| nuLat (USA) | 40 MW |
| Neutrino4 (Russia) | 100 MW 235U fuel |
| PROSPECT (USA) | 235U fuel |
| SoLid (UK Fr Bel US) | 72 MW 235U fuel |
| Chandler (USA) | |
| Stereo (France) | 57 MW 235U fuel |

99.73% CL
2 dof

**HL-LHC**

- 36 fb⁻¹ Run-2 ...
3 ab⁻¹ and co...

√s = 14 TeV, 3000 fb⁻¹ per experiment

**ATLAS** and **CMS**
*HL-LHC Projection*

| | Uncertainty [%] |
|---|---|
| | **Tot** Stat Exp Th |
| $\kappa_\gamma$ | **1.8** 0.8 1.0 1.3 |
| $\kappa_W$ | **1.7** 0.8 0.7 1.3 |
| $\kappa_Z$ | **1.5** 0.7 0.6 1.2 |
| $\kappa_g$ | **2.5** 0.9 0.8 2.1 |
| $\kappa_t$ | **3.4** 0.9 1.1 3.1 |
| $\kappa_b$ | **3.7** 1.3 1.3 3.2 |
| $\kappa_\tau$ | **1.9** 0.9 0.8 1.5 |
| $\kappa_\mu$ | **4.3** 3.8 1.0 1.7 |
| $\kappa_{Z\gamma}$ | **9.8** 7.2 1.7 6.4 |

Total — Statistical — Experimental — Theory

0  0.02  0.04  0.06  0.08  0.1  0.12  0.14
Expected uncertainty

**ATLAS** and **CMS** — Stat. + Exp. / + Theory
*HL-LHC Projection* — ATLAS / CMS

$\sigma(m_H) \sim$

Expect ≲
channels a...

Coupling s...
on multipli...

$\mathscr{B}(H \to$ i...
e.g. attrac...

$\kappa_\gamma$, $\kappa_W$, $\kappa_Z$, $\kappa_g$, $\kappa_t$, $\kappa_b$, $\kappa_\tau$, $\kappa_\mu$, $\kappa_{Z\gamma}$

0.06  0.08  0.1  0.12
ed relative uncertainty

**CMS Phase-2**
*Simulation Preliminary*

95% CL upper limit on $\sigma \times B(H \to \text{inv})/\sigma_{SM}$ (%)

- ■ Median exp. vs $E_T^{miss}$
- 68% exp.
- 95% exp.
- ▲ Median exp. smeared $E_T^{mi...}$

150  200  250  300
Minimum threshold on ...

H self-coupling

- $\lambda_{HHH}$ accessible via *di-Higgs production*
  → *flagship measurement at HL-LHC*

- $\lambda_{HHH}$ and $\sigma(HH)$ affected by BSM
  physics, sensitivity studied as function
  of ...

λ very challenging;
need multiple channels

**ATLAS** and **CMS**    3000 fb⁻¹ (14 TeV)
*HL-LHC prospects*
−2Δln(L)
- ATLAS
- CMS
- Combination

95%
68%

−2  −1  0  1  2  3  4  5  6  7  8

**ATLAS** Simulation
Br(H→J/ψγ)~15SM

showing the total expected ... uncertain ... 95% CL limits on ...
modifier parameters for ATLAS ... CMS (red). The fi...
cal and experimental systematic uncertainties, while the hatch...
ibution to the total uncertainty due to theoretical systematic u...
g the total expected ±1σ uncertainties in S2 (with YR18 syste...
lifier parameters for the combination of ATLAS and CMS ex...
can vary by a factor of 4 when no ex...
tal uncertainty is indicated by a grey box while the statistical, e...
is used to remove all pileup jets. T...
and theory uncertainties are indicated by a blue, green and red line respectively.
an important development to empo...
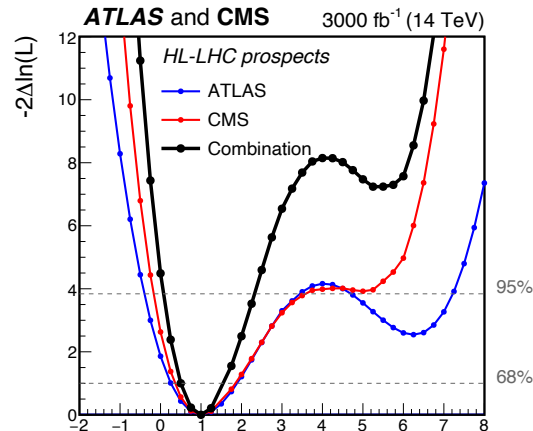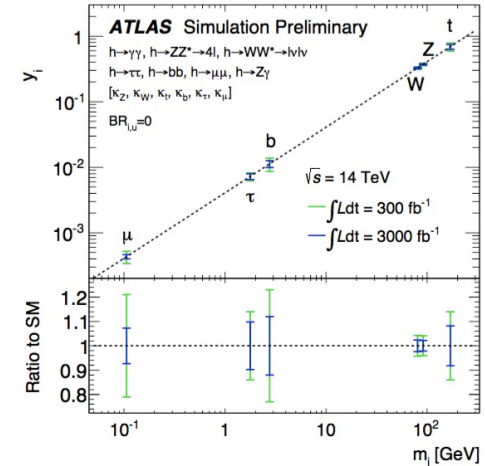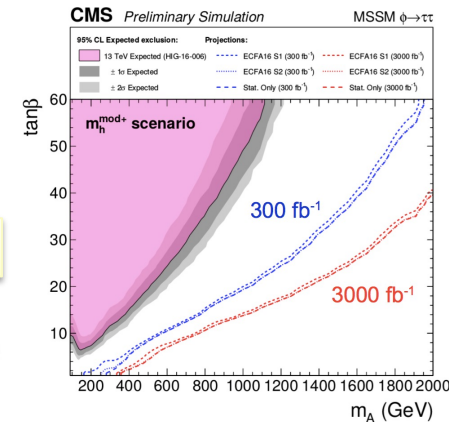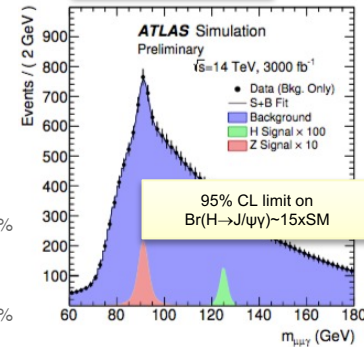
# Colliders: the high energy frontier