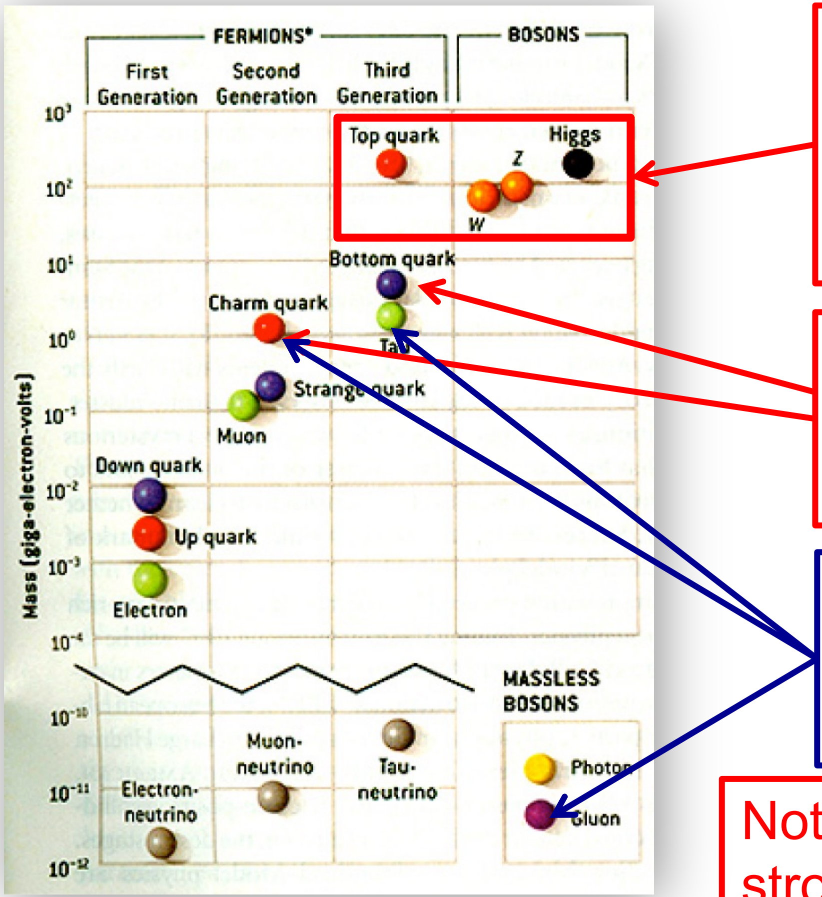
Physics highlights and challenges: particle physics

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/new 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 τ @ SPEAR (SLAC)
g @ PETRA (DESY)

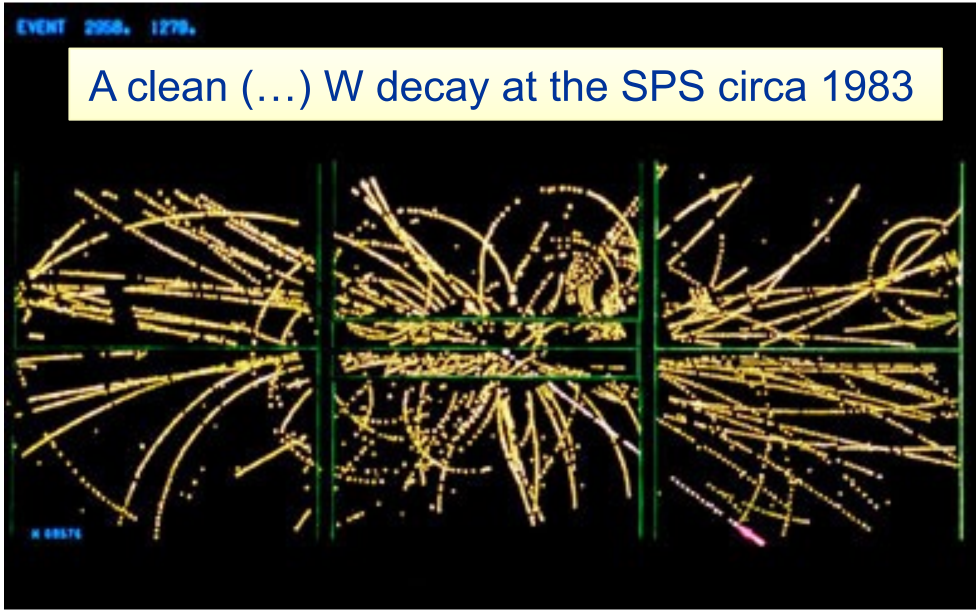
Not shown: probing/studying the strong, weak and EM interactions

How we got to here

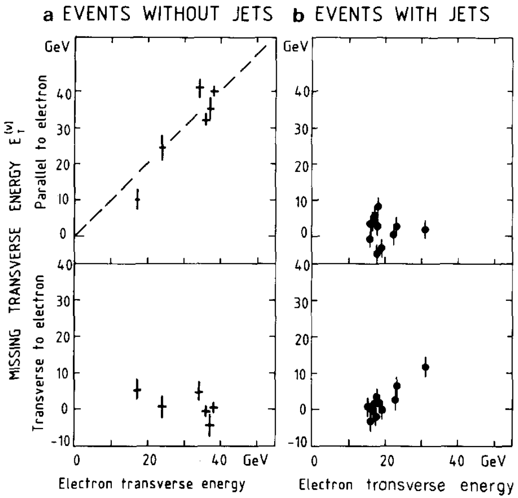
A very (very…) brief summary

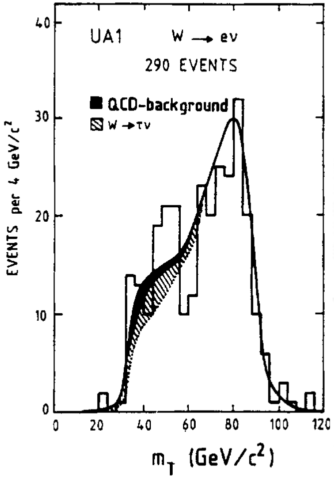
pp collisions :== parton-parton collisions + extra debris

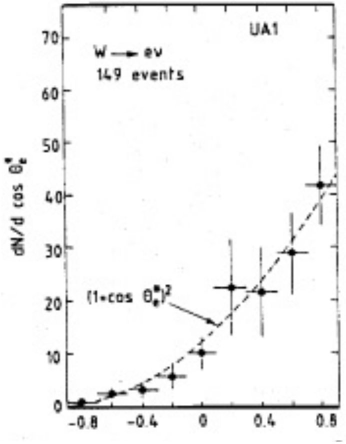
Early 80s: The rendez-vous with the W boson.



A clean (…) W decay at the SPS circa 1983



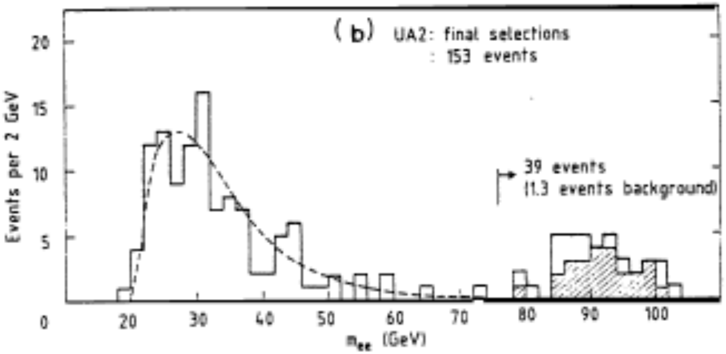




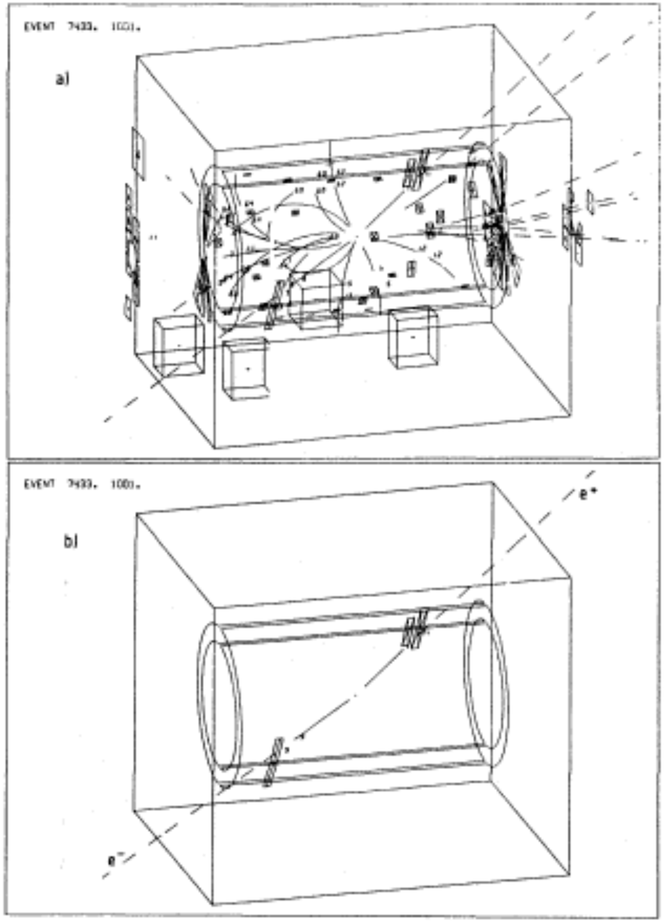
It was there, at the right time (number of events → rate → time of rendez-vous!)
At the right mass: 81±5 GeV
With the right spin: 1

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



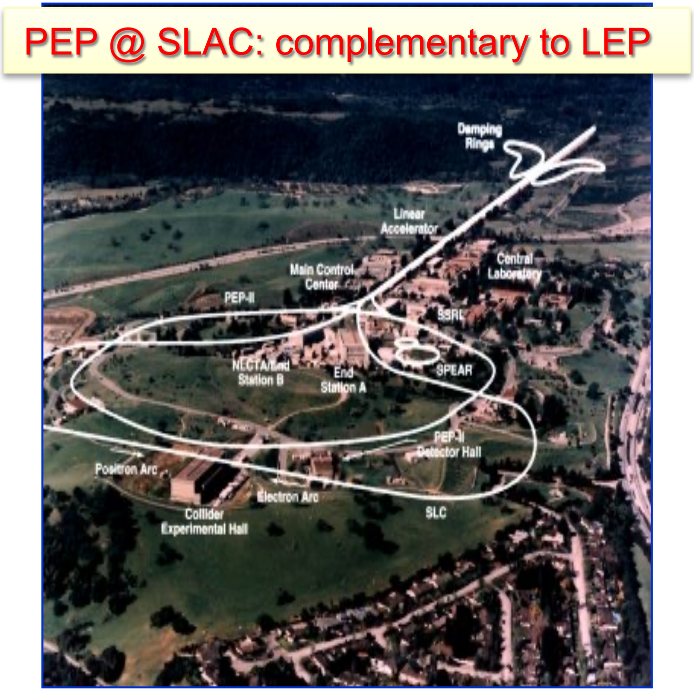
End of the 80s, beginning 90s:

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



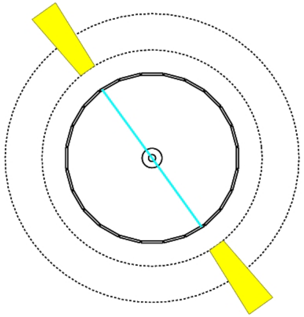
Energy upgradeable; measurable;
Four detectors (A,D,L,O); Large luminosity:
20 Million Z events.
But…. Energy limited by synchrotron radiation loss $(\sim\gamma^4)$. At Z: 3 GeV/turn (replenished by the RF system)

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;

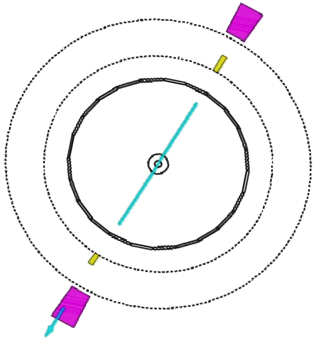
e^+e^- collisions: clean, controlled environment

Total Luminosity: 1000 pb^{-1}

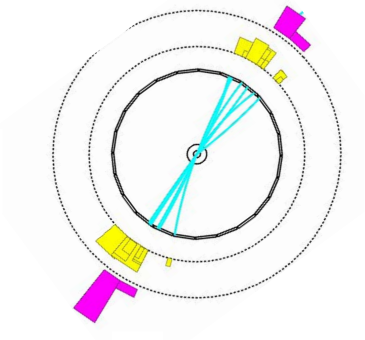
$e^+e^- \to Z \to e^+e^-$

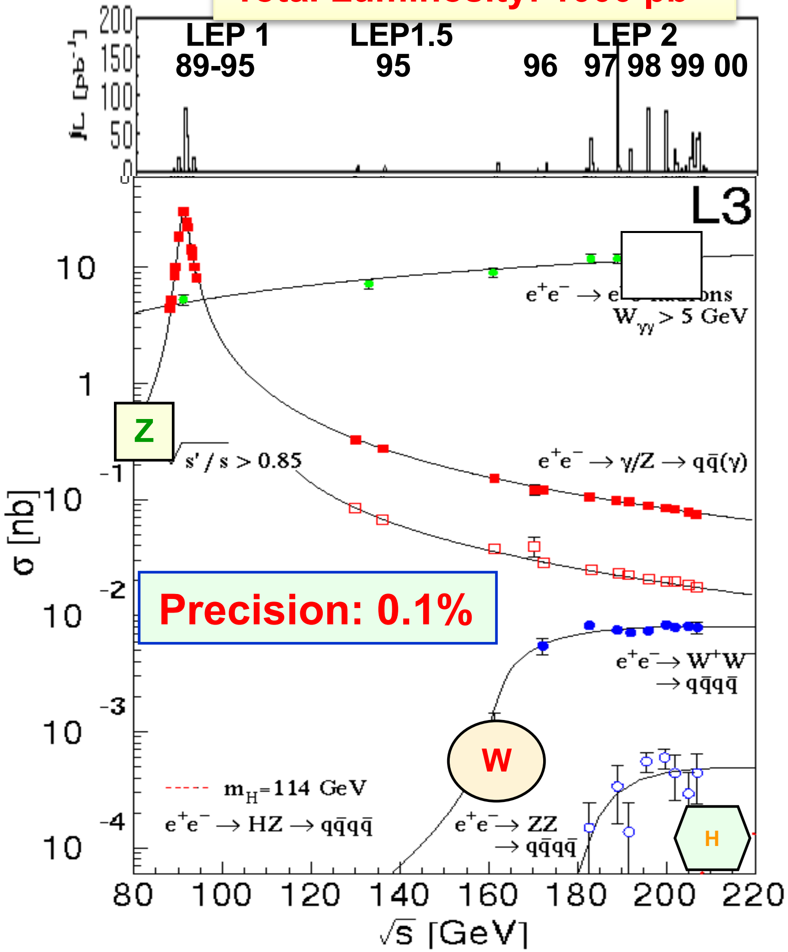


$e^+e^- \to Z \to \mu^+\mu^-$



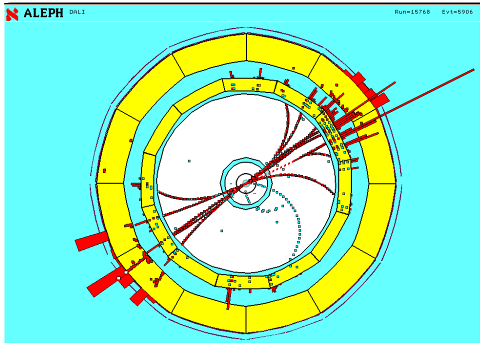
$e^+e^- \to Z \to \text{hadrons}$



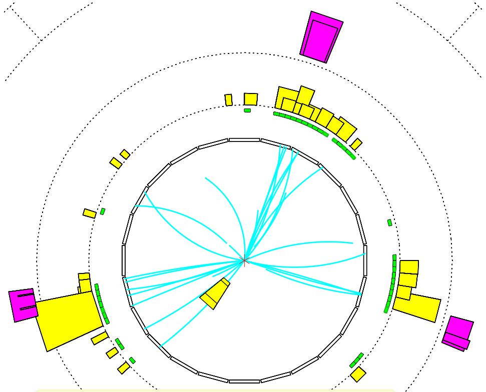


Precision: 0.1%

Energy: 88 → 209.2 GeV



Two-jet event



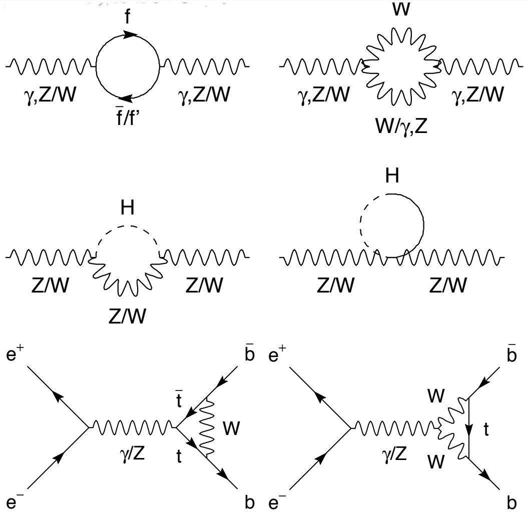
Three-jet event

The LEP legacy

LEP ran for over a decade
And delivered unprecedented precision on the Electroweak Theory

On several observables, 0.1%

Precision gives access to loops



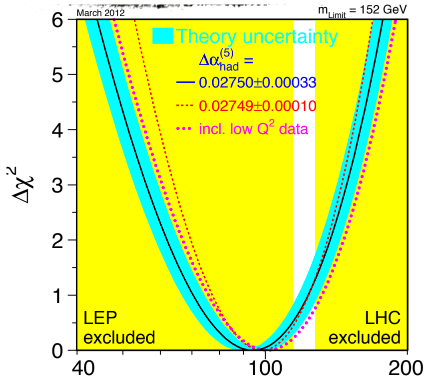
We also learned that:

There are at most three neutrino species lighter than M_Z. $\boxed{N_\nu = 2.9919 \pm 0.0081}$

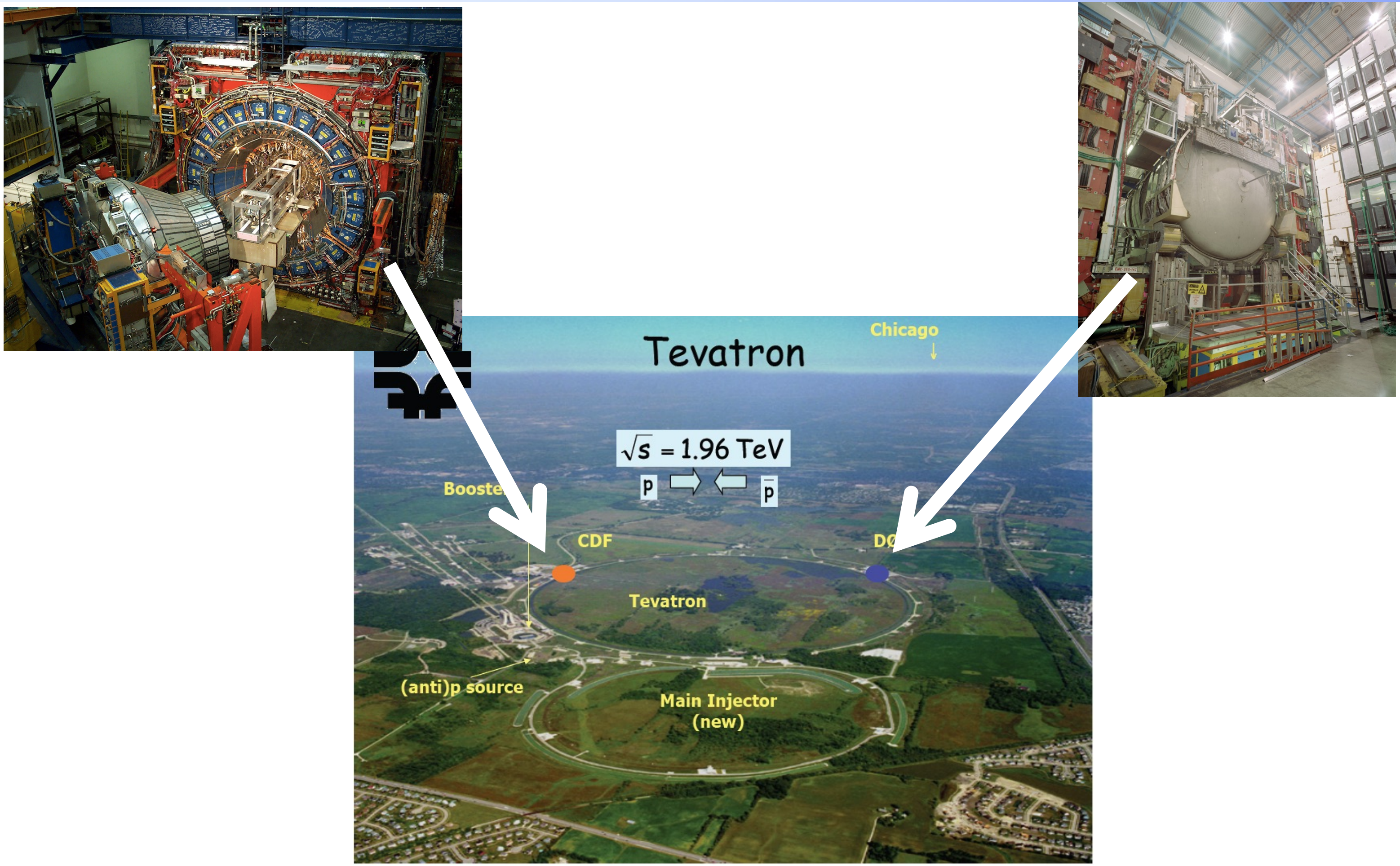
Higgs boson heavier than 114.5 GeV

SUSY not there for masses ≤100 GeV

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…

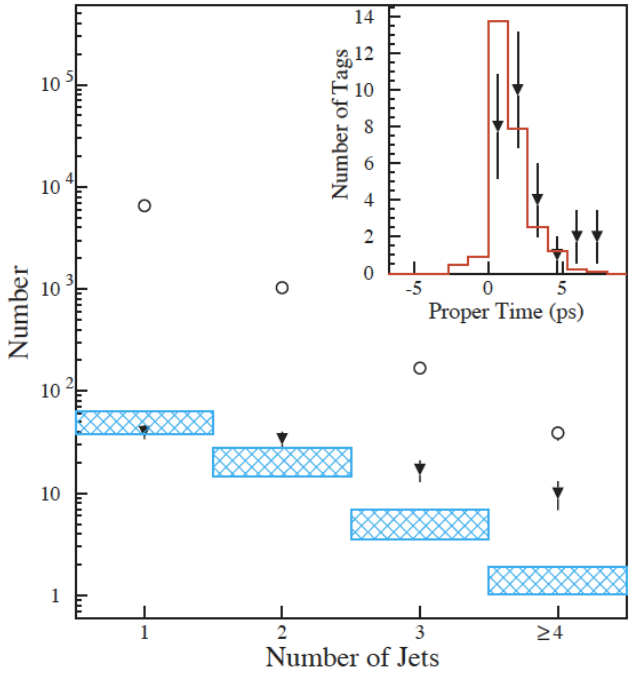


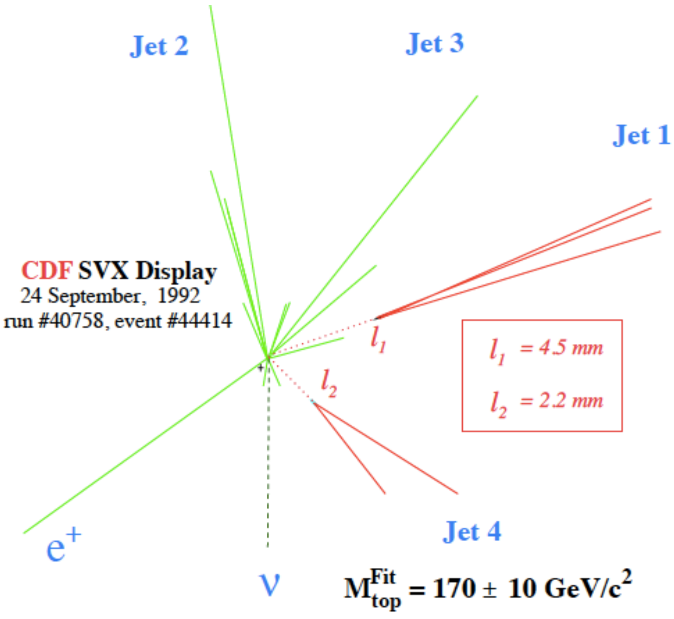
End of 80s, beginning of 90s: Tevatron



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!**





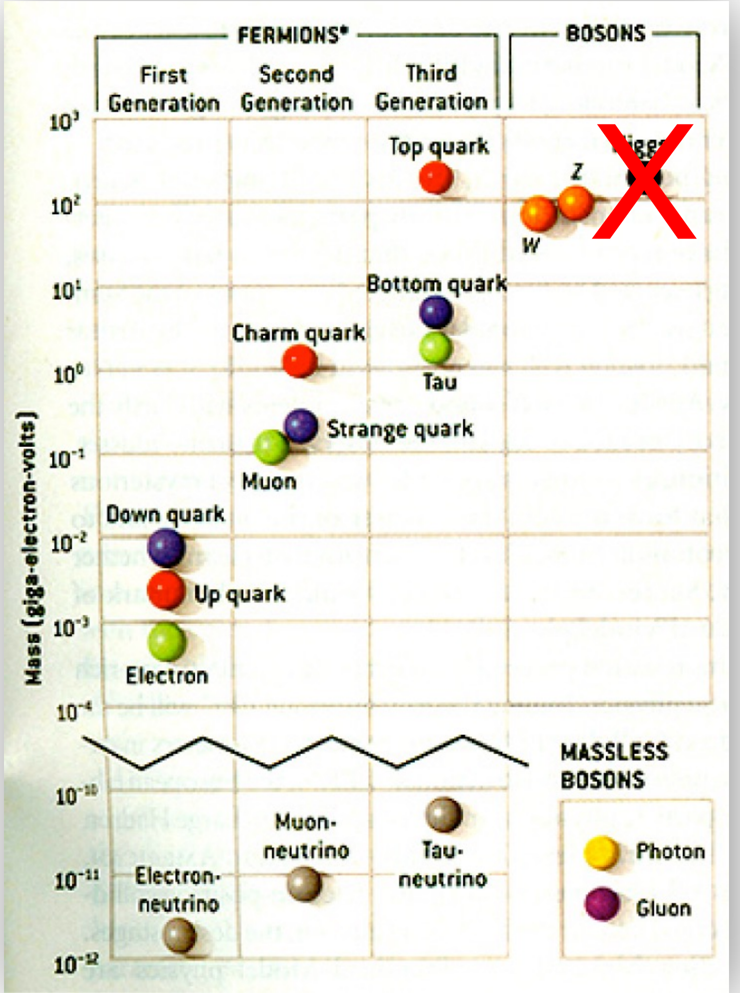
LEP and the Tevatron were huge successes

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

And the Higgs… is extremely important:

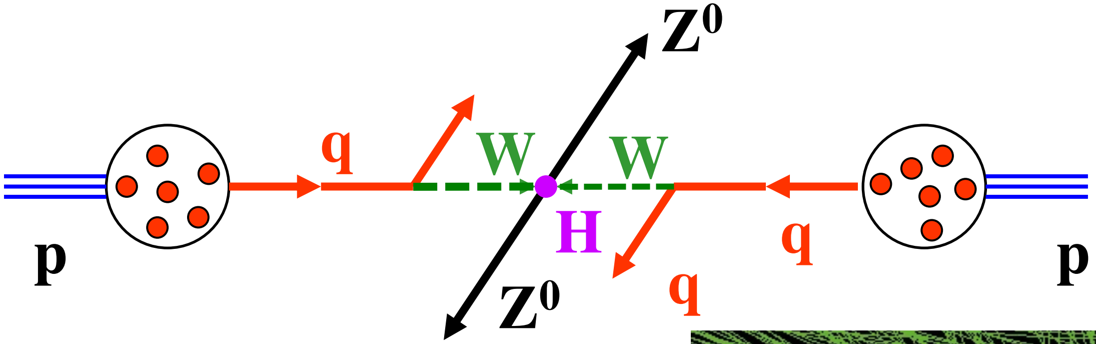
the entire Standard Model of Particle Physics is based on the Brout-Englert-Higgs mechanism to

give masses to the W & Z bosons, while leaving the photon massless;
bonus: it also gives masses to the fermions!



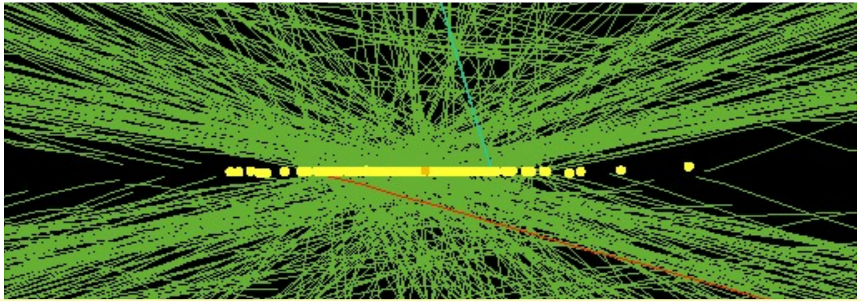
A machine for EWSB

- **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).**



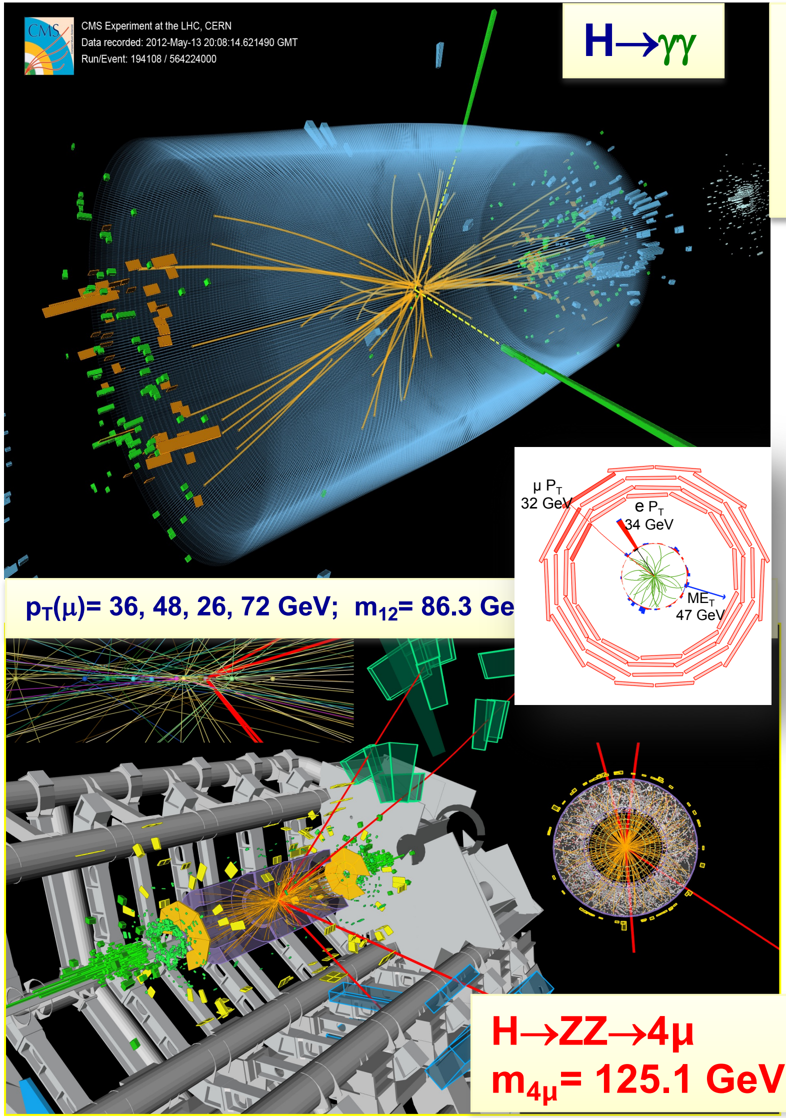
M_H ~ 1000 GeV
$E_W \geq 500$ GeV
$E_q \geq 1000$ GeV (1 TeV)
$E_p \geq 6000$ GeV (6 TeV)

But running at close to this energy → need high luminosity → pileup!



A tremendous, unprecedented challenge

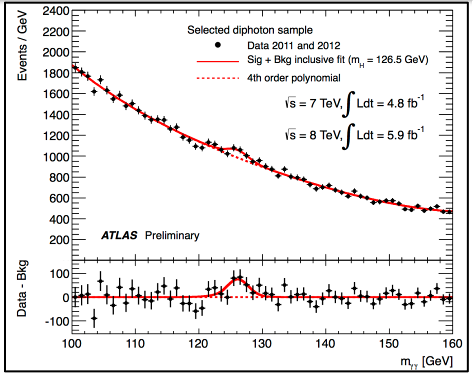
In July 2012: a new particle with mass ≈125 GeV is seen! It decays to γγ, ZZ → it's a boson (spin=0 or 2)

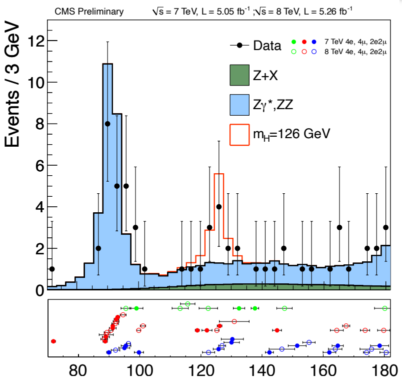


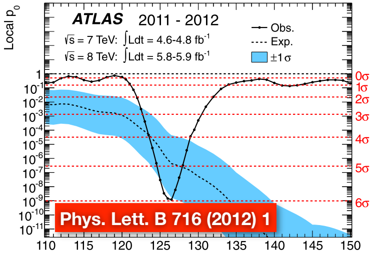
H→γγ

$p_T(\mu)$= 36, 48, 26, 72 GeV; m_{12}= 86.3 Ge

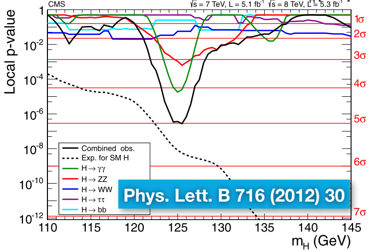
H→ZZ→4μ
$m_{4\mu}$= 125.1 GeV



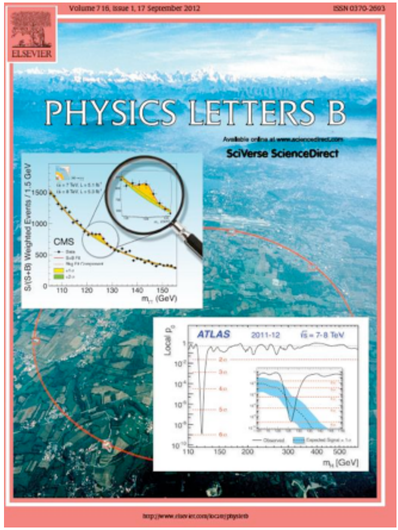




Phys. Lett. B 716 (2012) 1



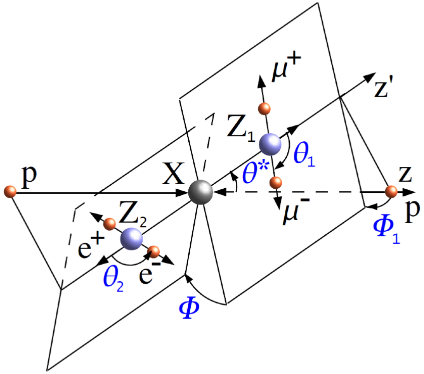
Phys. Lett. B 716 (2012) 30



Higgs Physics: after the discovery

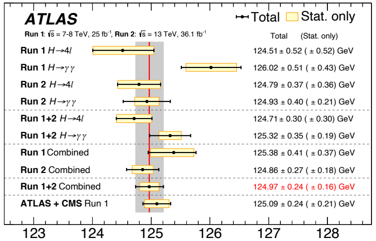
- **Measurement of Spin-Parity, mass: it IS the vaccuum particle…**

Production mechanisms, differential distributions

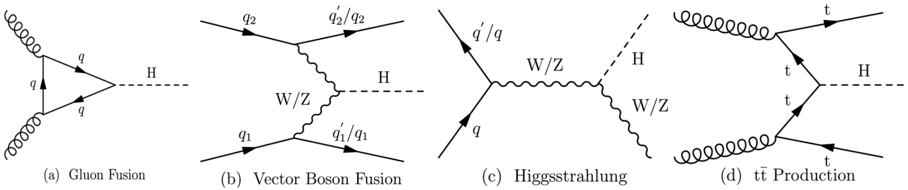


J^P=0$^+$(!!!)

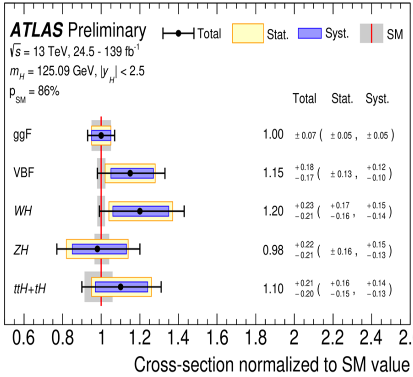
δM$_H$/M$_H$ ~ 0.2% (!)



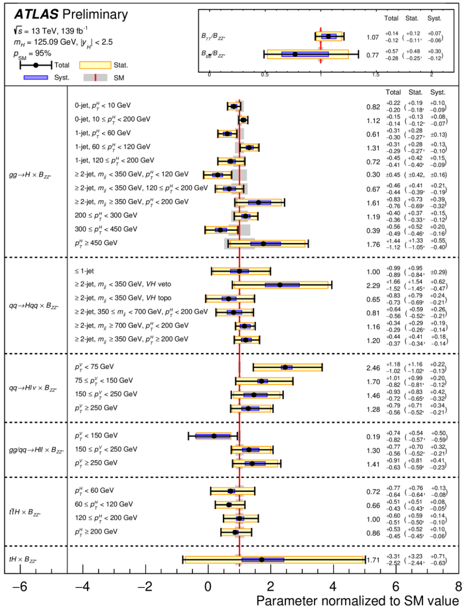
Phys. Lett. B 784 (2018) 345

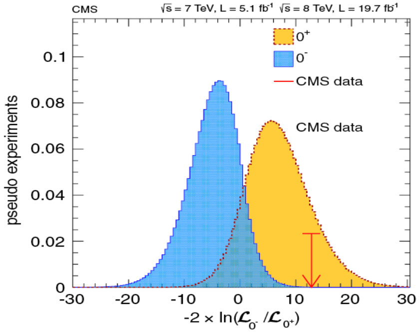


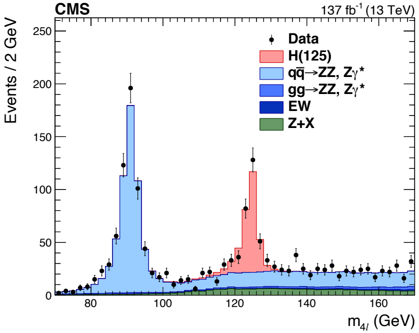
(a) Gluon Fusion (b) Vector Boson Fusion (c) Higgsstrahlung (d) $t\bar{t}$ Production



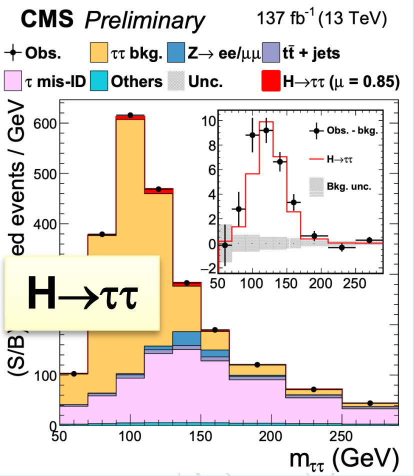
$$\boxed{\mu = 1.06 \pm 0.07}$$







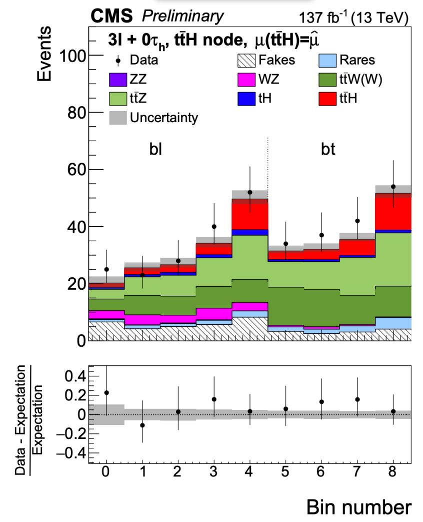
SM @ the highest E; EWSB (“Higgs” sector) (I)

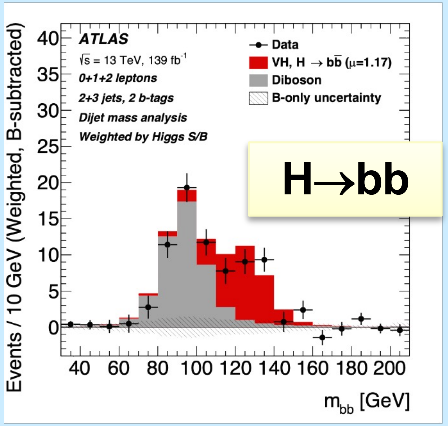


H→ττ

Clear observation of couplings to 3rd-gen fermions

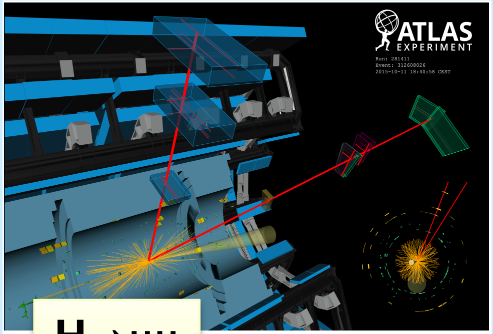
ttH





H→bb

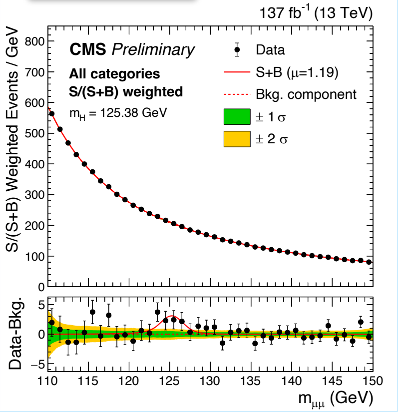
Evidence of coupling to 2nd-gen fermions



H→μμ

CMS:
obs: 3.0σ (exp: 2.5σ)
ATLAS:
obs: 2.0σ (exp: 1.7σ)

$\mu = 1.2 \pm 0.6$



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.)

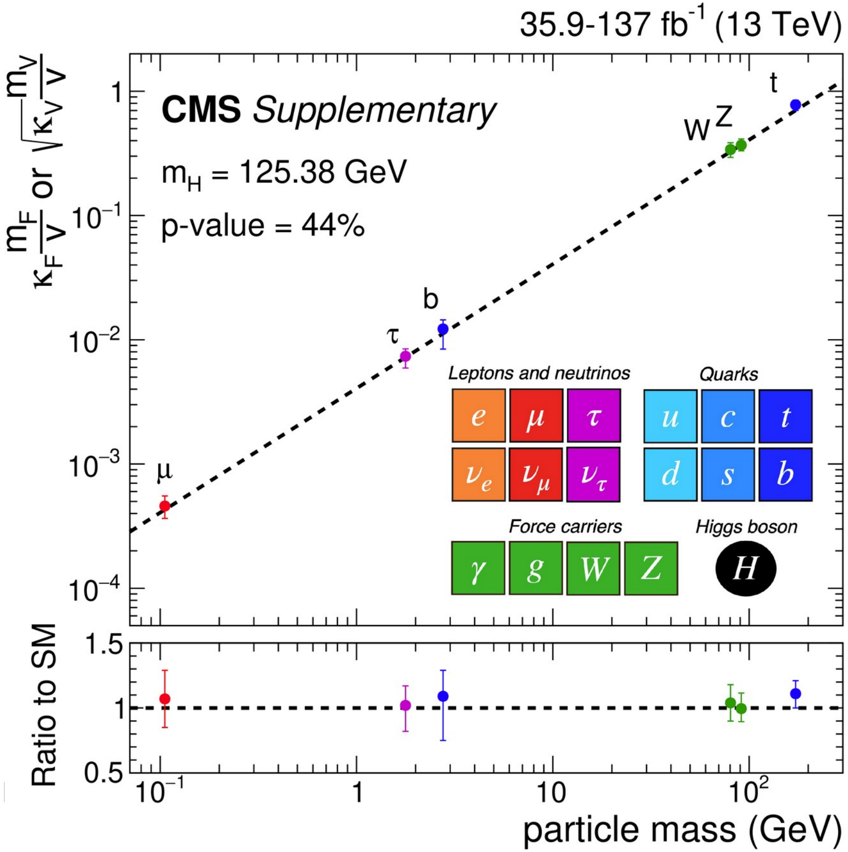
The overall picture of the measured/seen Higgs couplings

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

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

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

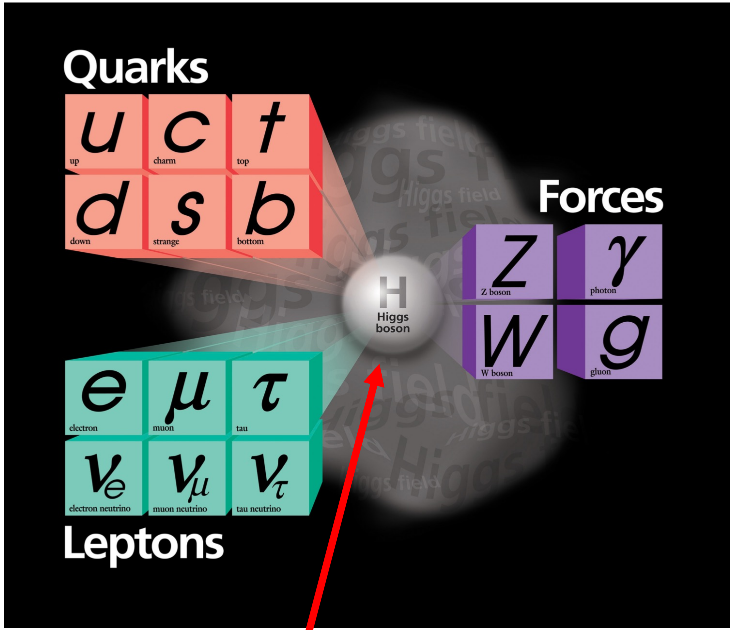
A particle like no other!

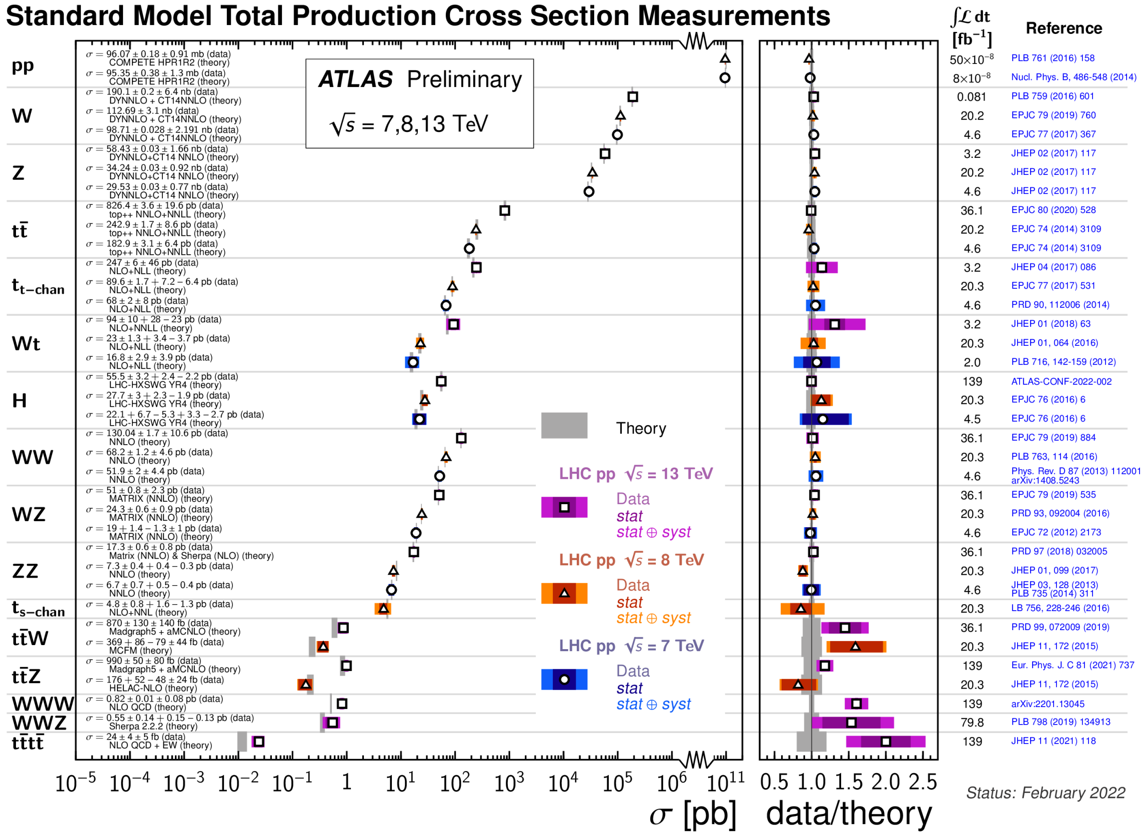


Where we stand now

A very brief summary

Standard Model of Particle Physics





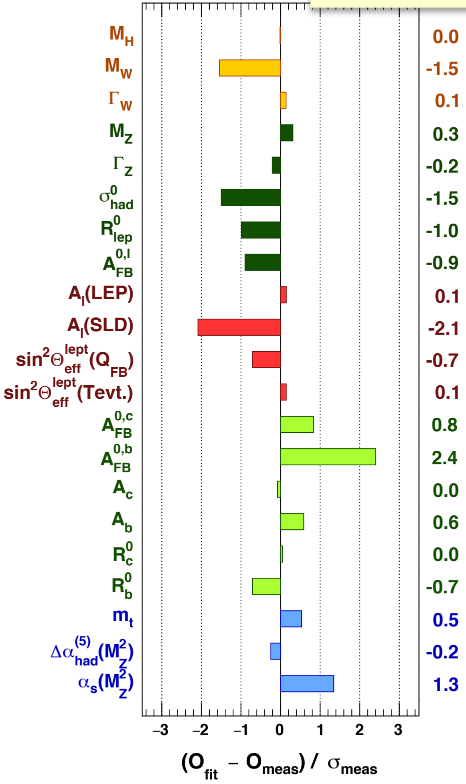
Highest priority:
understand this central
and most strange element

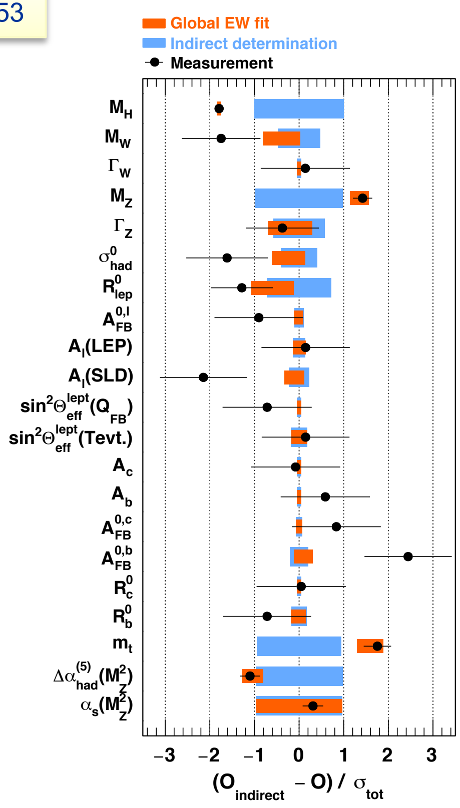
Putting it all together: SM reigns supreme

- **Goodness of fit**
  - χ^2_{min}=18.6 → 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 → input accuracies exceed fit requirements
- **Knowledge of m_H → huge improvement in:**
  - m_W (28→11 MeV)
  - 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:1407.3792

arXiv:1803.01853





G fitter

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

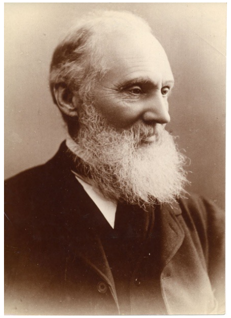
Light blue: fit excluding input from row

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"



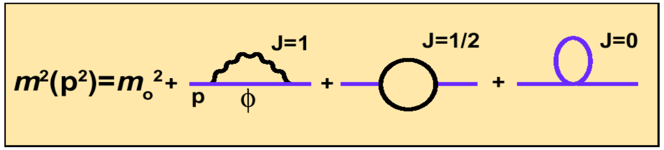
Lord Kelvin (1900):
There is nothing new to be discovered in physics now. All that remains is more and more precise measurement.

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



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

P.A.M Dirac

M(H) with corrections all the way up to the Planck scale: for Λ ~ 10^{19} GeV

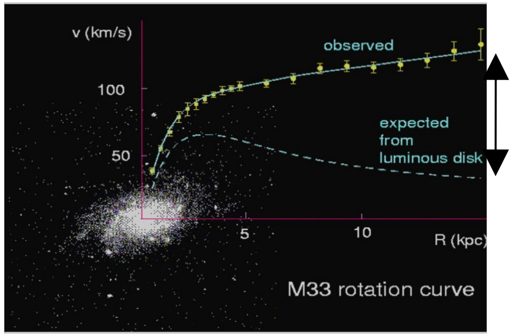
[for illustration only; numbers are random]

m^2 = 1234567890123456789012345675432189012 –
1234567890123456789012345675432173387 =
15625 GeV^2

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

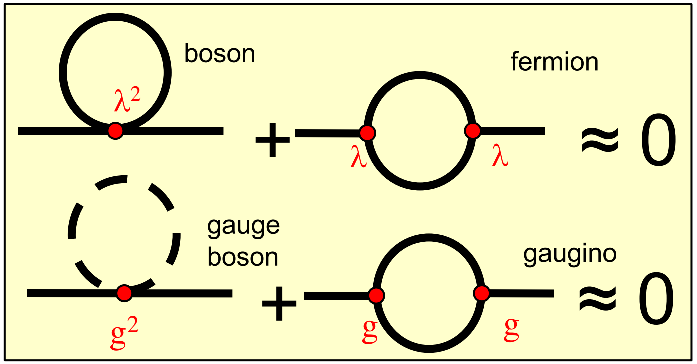
(beyond the magic of the M_H-m_t mass)

Some real and some virtual reasons to believe in new physics

Real reasons: dark matter & ν masses
Virtual reasons: naturalness
+ matter–antimmater asymmetry in the universe…

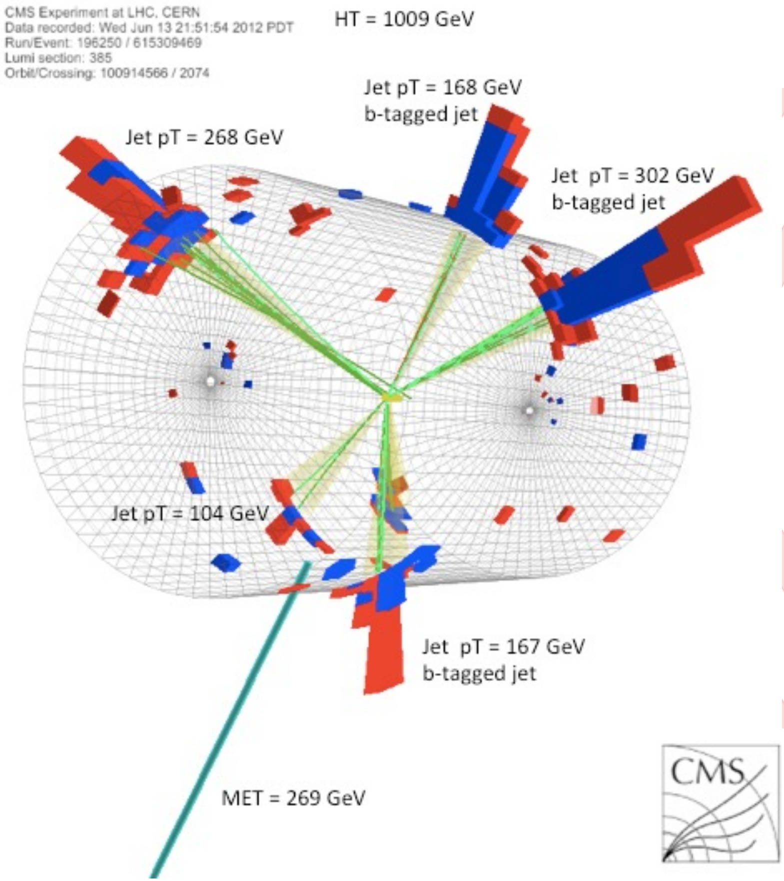
Solutions to the hierarchy problem

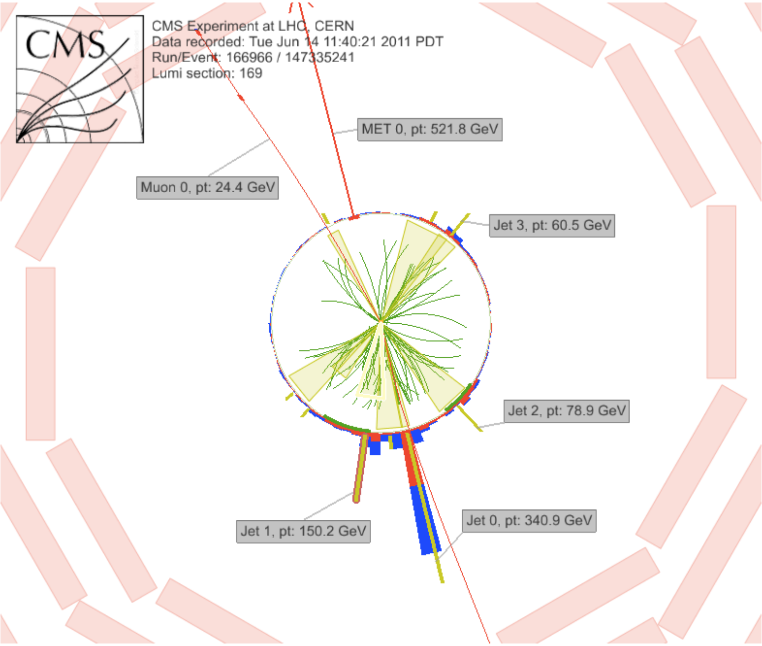
- **Solution #1: a composite Higgs**
  - **H: bound state (e.g. due to some new strong interaction)**
- **Solution #2: supersymmetry**
  - **Partners for ALL SM particles, spin different by ½**
  - **Presumably broken symmetry (since partners unseen)**



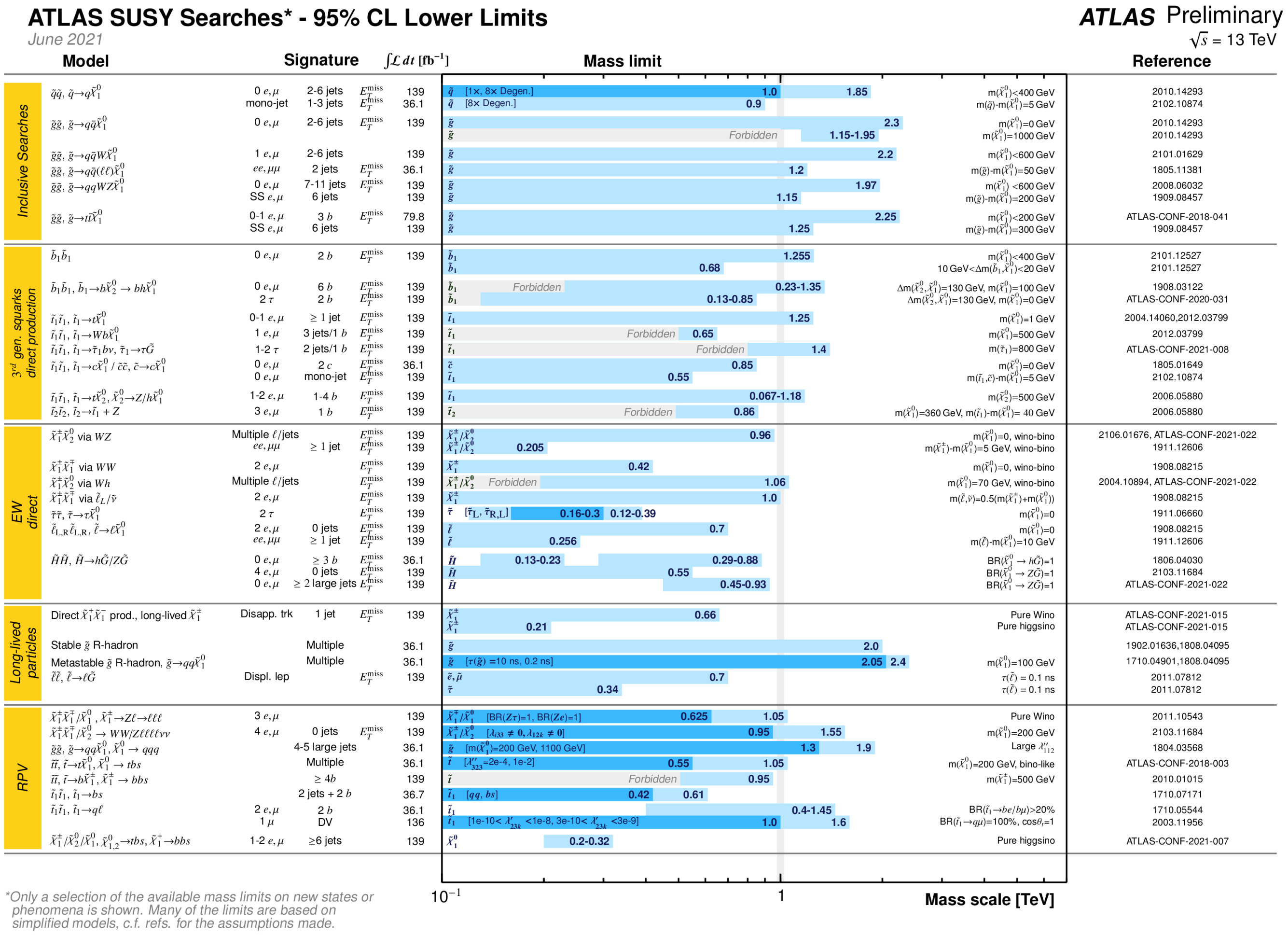
- **Solution #3: little Higgs**
  - **H: pseudo-Goldstone boson of Ultimate Theory; just another effective theory, e.g. valid to ~10 TeV. Loops cancel by particles of same spin (so need to introduce these particles)**
- **Solution #4: extra dimensions**
  - **N-dim space; gravity propagates in all dims, 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)**

What we have been looking for (mainly)





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	$\tilde{q}\tilde{q}, \tilde{q}\to q\tilde{\chi}^0_1$	0 e,μ	2-6 jets	$E_T^{\rm miss}$	139	$\tilde{q}$	[1×, 8× Degen.] 1.0 1.85	m($\tilde{\chi}^0_1$)<400 GeV	2010.14293
		mono-jet	1-3 jets	$E_T^{\rm miss}$	36.1	$\tilde{q}$	[8× Degen.] 0.9	m($\tilde{q}$)-m($\tilde{\chi}^0_1$)=5 GeV	2102.10874
	$\tilde{g}\tilde{g}, \tilde{g}\to q\bar{q}\tilde{\chi}^0_1$	0 e,μ	2-6 jets	$E_T^{\rm miss}$	139	$\tilde{g}$	2.3	m($\tilde{\chi}^0_1$)=0 GeV	2010.14293
						$\tilde{g}$	Forbidden 1.15-1.95	m($\tilde{\chi}^0_1$)=1000 GeV	2010.14293
	$\tilde{g}\tilde{g}, \tilde{g}\to q\bar{q}W\tilde{\chi}^0_1$	1 e,μ	2-6 jets		139	$\tilde{g}$	2.2	m($\tilde{\chi}^0_1$)<600 GeV	2101.01629
	$\tilde{g}\tilde{g}, \tilde{g}\to q\bar{q}(\ell\ell)\tilde{\chi}^0_1$	$ee,\mu\mu$	2 jets	$E_T^{\rm miss}$	36.1	$\tilde{g}$	1.2	m($\tilde{g}$)-m($\tilde{\chi}^0_1$)=50 GeV	1805.11381
	$\tilde{g}\tilde{g}, \tilde{g}\to qqWZ\tilde{\chi}^0_1$	0 e,μ	7-11 jets	$E_T^{\rm miss}$	139	$\tilde{g}$	1.97	m($\tilde{\chi}^0_1$) <600 GeV	2008.06032
		SS e,μ	6 jets		139	$\tilde{g}$	1.15	m($\tilde{g}$)-m($\tilde{\chi}^0_1$)=200 GeV	1909.08457
	$\tilde{g}\tilde{g}, \tilde{g}\to t\bar{t}\tilde{\chi}^0_1$	0-1 e,μ	3 b	$E_T^{\rm miss}$	79.8	$\tilde{g}$	2.25	m($\tilde{\chi}^0_1$)<200 GeV	ATLAS-CONF-2018-041
		SS e,μ	6 jets		139	$\tilde{g}$	1.25	m($\tilde{g}$)-m($\tilde{\chi}^0_1$)=300 GeV	1909.08457
3^{rd} gen. squarks direct production	$\tilde{b}_1\tilde{b}_1$	0 e,μ	2 b	$E_T^{\rm miss}$	139	$\tilde{b}_1$	1.255	m($\tilde{\chi}^0_1$)<400 GeV	2101.12527
						$\tilde{b}_1$	0.68	10 GeV<Δm($\tilde{b}_1$,$\tilde{\chi}^0_1$)<20 GeV	2101.12527
	$\tilde{b}_1\tilde{b}_1, \tilde{b}_1\to b\tilde{\chi}^0_2\to bh\tilde{\chi}^0_1$	0 e,μ	6 b	$E_T^{\rm miss}$	139	$\tilde{b}_1$	Forbidden 0.23-1.35	Δm($\tilde{\chi}^0_2$,$\tilde{\chi}^0_1$)=130 GeV, m($\tilde{\chi}^0_1$)=100 GeV	1908.03122
		2 τ	2 b	$E_T^{\rm miss}$	139	$\tilde{b}_1$	0.13-0.85	Δm($\tilde{\chi}^0_2$,$\tilde{\chi}^0_1$)=130 GeV, m($\tilde{\chi}^0_1$)=0 GeV	ATLAS-CONF-2020-031
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1\to t\tilde{\chi}^0_1$	0-1 e,μ	$\geq$ 1 jet	$E_T^{\rm miss}$	139	$\tilde{t}_1$	1.25	m($\tilde{\chi}^0_1$)=1 GeV	2004.14060,2012.03799
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1\to Wb\tilde{\chi}^0_1$	1 e,μ	3 jets/1 b	$E_T^{\rm miss}$	139	$\tilde{t}_1$	Forbidden 0.65	m($\tilde{\chi}^0_1$)=500 GeV	2012.03799
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1\to\tilde{\tau}_1 b\nu, \tilde{\tau}_1\to\tau\tilde{G}$	1-2 τ	2 jets/1 b	$E_T^{\rm miss}$	139	$\tilde{t}_1$	Forbidden 1.4	m($\tilde{\tau}_1$)=800 GeV	ATLAS-CONF-2021-008
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1\to c\tilde{\chi}^0_1$ / $\tilde{c}\tilde{c}, \tilde{c}\to c\tilde{\chi}^0_1$	0 e,μ	2 c	$E_T^{\rm miss}$	36.1	$\tilde{c}$	0.85	m($\tilde{\chi}^0_1$)=0 GeV	1805.01649
		0 e,μ	mono-jet	$E_T^{\rm miss}$	139	$\tilde{t}_1$	0.55	m($\tilde{t}_1$,$\tilde{c}$)-m($\tilde{\chi}^0_1$)=5 GeV	2102.10874
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1\to t\tilde{\chi}^0_2, \tilde{\chi}^0_2\to Z/h\tilde{\chi}^0_1$	1-2 e,μ	1-4 b	$E_T^{\rm miss}$	139	$\tilde{t}_1$	0.067-1.18	m($\tilde{\chi}^0_2$)=500 GeV	2006.05880
	$\tilde{t}_2\tilde{t}_2, \tilde{t}_2\to\tilde{t}_1 + Z$	3 e,μ	1 b	$E_T^{\rm miss}$	139	$\tilde{t}_2$	Forbidden 0.86	m($\tilde{\chi}^0_1$)=360 GeV, m($\tilde{t}_1$)-m($\tilde{\chi}^0_1$)= 40 GeV	2006.05880
EW direct	$\tilde{\chi}^\pm_1\tilde{\chi}^0_2$ via WZ	Multiple ℓ/jets		$E_T^{\rm miss}$	139	$\tilde{\chi}^\pm_1/\tilde{\chi}^0_2$	0.96	m($\tilde{\chi}^0_1$)=0, wino-bino	2106.01676, ATLAS-CONF-2021-022
		$ee,\mu\mu$	$\geq$ 1 jet	$E_T^{\rm miss}$	139	$\tilde{\chi}^\pm_1/\tilde{\chi}^0_2$	0.205	m($\tilde{\chi}^\pm_1$)-m($\tilde{\chi}^0_1$)=5 GeV, wino-bino	1911.12606
	$\tilde{\chi}^\pm_1\tilde{\chi}^\mp_1$ via WW	2 e,μ		$E_T^{\rm miss}$	139	$\tilde{\chi}^\pm_1$	0.42	m($\tilde{\chi}^0_1$)=0, wino-bino	1908.08215
	$\tilde{\chi}^\pm_1\tilde{\chi}^0_2$ via Wh	Multiple ℓ/jets		$E_T^{\rm miss}$	139	$\tilde{\chi}^\pm_1/\tilde{\chi}^0_2$	Forbidden 1.06	m($\tilde{\chi}^0_1$)=70 GeV, wino-bino	2004.10894, ATLAS-CONF-2021-022
	$\tilde{\chi}^\pm_1\tilde{\chi}^\mp_1$ via $\tilde{\ell}_L/\tilde{\nu}$	2 e,μ		$E_T^{\rm miss}$	139	$\tilde{\chi}^\pm_1$	1.0	m($\tilde{\ell}$,$\tilde{\nu}$)=0.5(m($\tilde{\chi}^\pm_1$)+m($\tilde{\chi}^0_1$))	1908.08215
	$\tilde{\tau}\tilde{\tau}, \tilde{\tau}\to\tau\tilde{\chi}^0_1$	2 τ		$E_T^{\rm miss}$	139	$\tilde{\tau}$	[$\tilde{\tau}_{\rm L}$, $\tilde{\tau}_{\rm R,L}$] 0.16-0.3 0.12-0.39	m($\tilde{\chi}^0_1$)=0	1911.06660
	$\tilde{\ell}_{\rm L,R}\tilde{\ell}_{\rm L,R}, \tilde{\ell}\to\ell\tilde{\chi}^0_1$	2 e,μ	0 jets	$E_T^{\rm miss}$	139	$\tilde{\ell}$	0.7	m($\tilde{\chi}^0_1$)=0	1908.08215
		$ee,\mu\mu$	$\geq$ 1 jet	$E_T^{\rm miss}$	139	$\tilde{\ell}$	0.256	m($\tilde{\ell}$)-m($\tilde{\chi}^0_1$)=10 GeV	1911.12606
	$\tilde{H}\tilde{H}, \tilde{H}\to h\tilde{G}/Z\tilde{G}$	0 e,μ	$\geq$ 3 b	$E_T^{\rm miss}$	36.1	$\tilde{H}$	0.13-0.23 0.29-0.88	BR($\tilde{\chi}^0_1\to h\tilde{G}$)=1	1806.04030
		4 e,μ	0 jets	$E_T^{\rm miss}$	139	$\tilde{H}$	0.55	BR($\tilde{\chi}^0_1\to Z\tilde{G}$)=1	2103.11684
		0 e,μ	$\geq$ 2 large jets	$E_T^{\rm miss}$	139	$\tilde{H}$	0.45-0.93	BR($\tilde{\chi}^0_1\to Z\tilde{G}$)=1	ATLAS-CONF-2021-022
Long-lived particles	Direct $\tilde{\chi}^+_1\tilde{\chi}^-_1$ prod., long-lived $\tilde{\chi}^\pm_1$	Disapp. trk	1 jet	$E_T^{\rm miss}$	139	$\tilde{\chi}^\pm_1$	0.66	Pure Wino	ATLAS-CONF-2021-015
						$\tilde{\chi}^\pm_1$	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, $\tilde{g}\to qq\tilde{\chi}^0_1$		Multiple		36.1	$\tilde{g}$	[$\tau(\tilde{g})$ =10 ns, 0.2 ns] 2.05 2.4	m($\tilde{\chi}^0_1$)=100 GeV	1710.04901,1808.04095
	$\tilde{\ell}\tilde{\ell}, \tilde{\ell}\to\ell\tilde{G}$	Displ. lep		$E_T^{\rm miss}$	139	$\tilde{e},\tilde{\mu}$	0.7	$\tau(\tilde{\ell})$ = 0.1 ns	2011.07812
						$\tilde{\tau}$	0.34	$\tau(\tilde{\ell})$ = 0.1 ns	2011.07812
RPV	$\tilde{\chi}^\pm_1\tilde{\chi}^\mp_1/\tilde{\chi}^0_1$, $\tilde{\chi}^\pm_1\to Z\ell\to\ell\ell\ell$	3 e,μ			139	$\tilde{\chi}^\mp_1/\tilde{\chi}^0_1$	[BR($Z\tau$)=1, BR(Ze)=1] 0.625 1.05	Pure Wino	2011.10543
	$\tilde{\chi}^\pm_1\tilde{\chi}^\mp_1/\tilde{\chi}^0_2\to WW/Z\ell\ell\ell\ell\nu\nu$	4 e,μ	0 jets	$E_T^{\rm miss}$	139	$\tilde{\chi}^\pm_1/\tilde{\chi}^0_2$	[$\lambda_{i33}\neq 0, \lambda_{12k}\neq 0$] 0.95 1.55	m($\tilde{\chi}^0_1$)=200 GeV	2103.11684
	$\tilde{g}\tilde{g}, \tilde{g}\to qq\tilde{\chi}^0_1, \tilde{\chi}^0_1\to qqq$		4-5 large jets		36.1	$\tilde{g}$	[m($\tilde{\chi}^0_1$)=200 GeV, 1100 GeV] 1.3 1.9	Large λ''_{112}	1804.03568
	$\tilde{t}\tilde{t}, \tilde{t}\to t\tilde{\chi}^0_1, \tilde{\chi}^0_1\to tbs$		Multiple		36.1	$\tilde{t}$	[λ''_{323}=2e-4, 1e-2] 0.55 1.05	m($\tilde{\chi}^0_1$)=200 GeV, bino-like	ATLAS-CONF-2018-003
	$\tilde{t}\tilde{t}, \tilde{t}\to b\tilde{\chi}^\pm_1, \tilde{\chi}^\pm_1\to bbs$		$\geq 4b$		139	$\tilde{t}$	Forbidden 0.95	m($\tilde{\chi}^\pm_1$)=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,μ	2 b		36.1	$\tilde{t}_1$	0.4-1.45	BR($\tilde{t}_1\to be/b\mu$)>20%	1710.05544
		1 μ	DV		136	$\tilde{t}_1$	[1e-10< λ'_{23k} <1e-8, 3e-10< λ'_{23k} <3e-9] 1.0 1.6	BR($\tilde{t}_1\to q\mu$)=100%, cosθ_t=1	2003.11956
	$\tilde{\chi}^\pm_1/\tilde{\chi}^0_2/\tilde{\chi}^0_1, \tilde{\chi}^0_{1,2}\to tbs, \tilde{\chi}^+_1\to bbs$	1-2 e,μ	$\geq$6 jets		139	$\tilde{\chi}^0_1$	0.2-0.32	Pure higgsino	ATLAS-CONF-2021-007

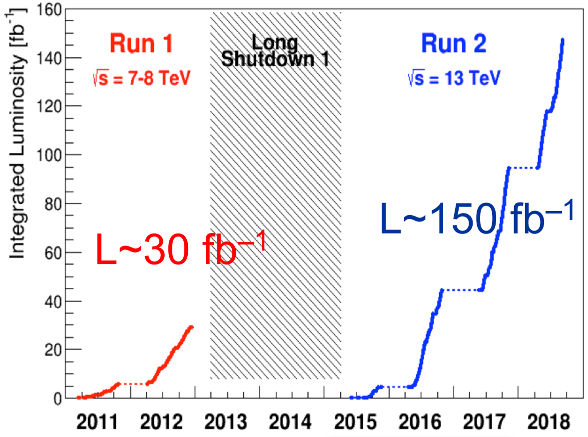
*Only a selection of the available mass limits on new states or phenomena is shown. Many of the limits are based on simplified models, c.f. refs. for the assumptions made.

The High-Luminosity LHC (HL-LHC)

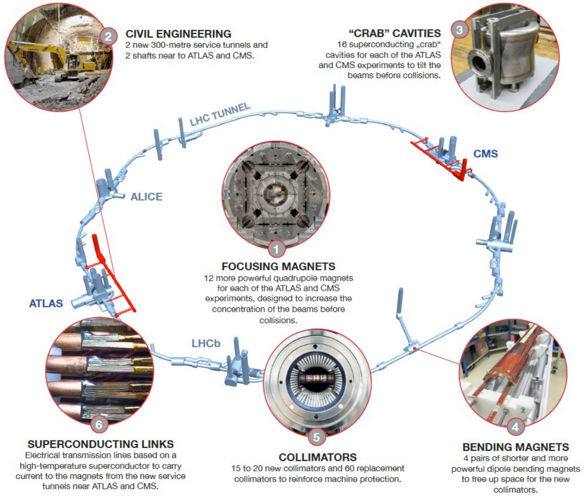
HL-LHC in a nutshell

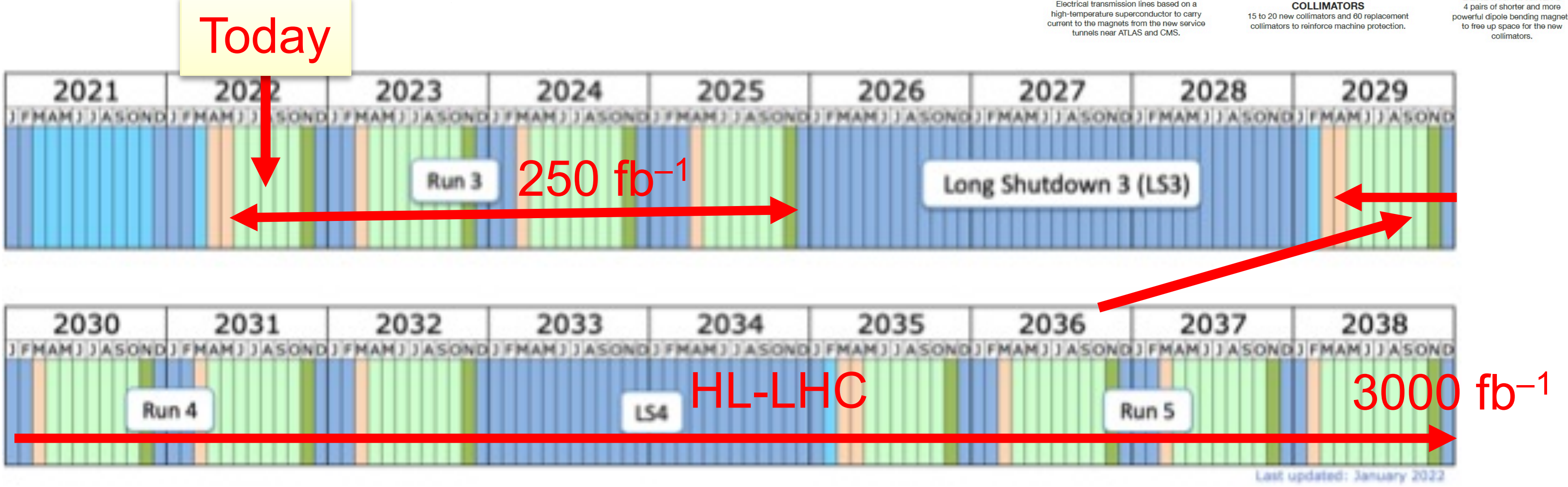
Some physics projections

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



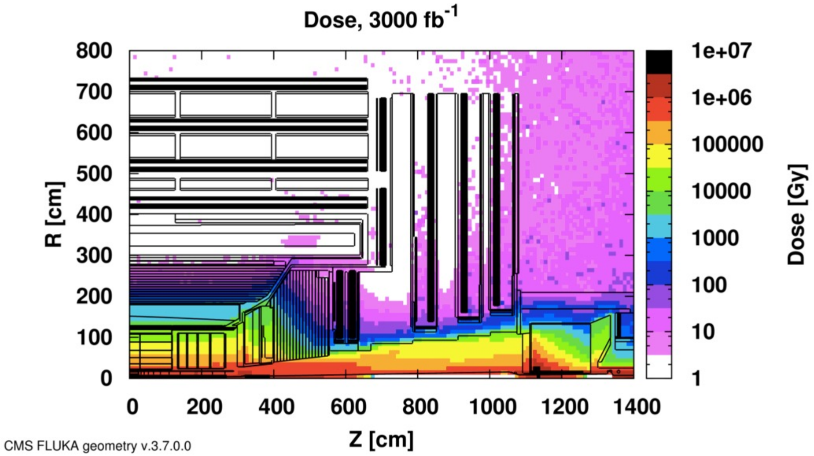
HL-LHC: major intervention on more than 1.2 km of the LHC with new technologies: Nb_3Sn magnets, Crab cavities,...



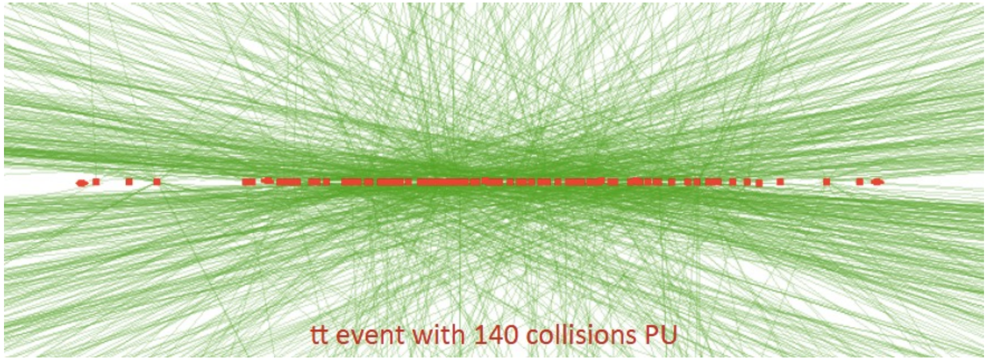


HL-LHC challenges

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



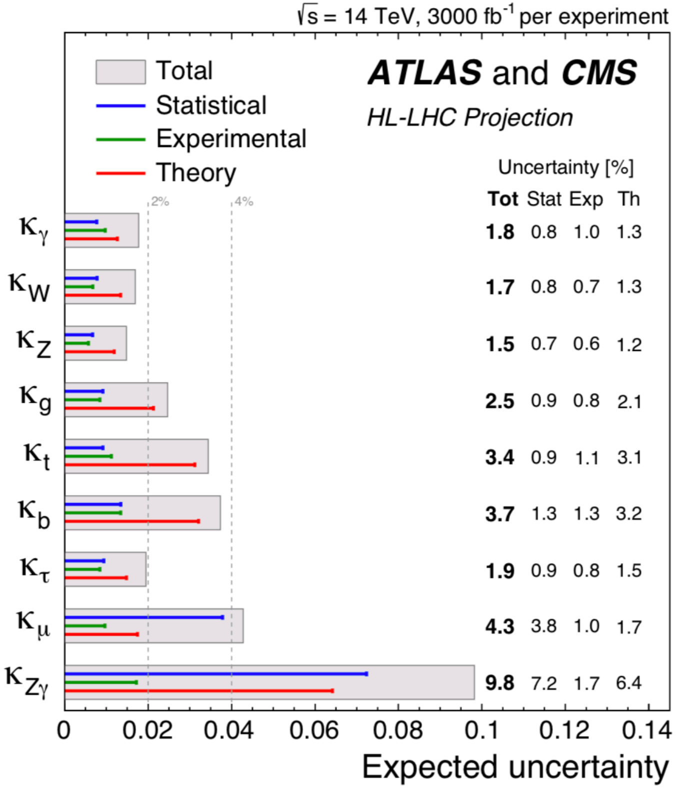
Key to physics: maintain detector performance in the presence of much higher pileup (140-200!)



Upgrade several detector components (trackers, calorimeters, redesign some electronics, new detector technologies, Trigger and DAQ

Medium-term Higgs physics: the LHC/HL-LHC program

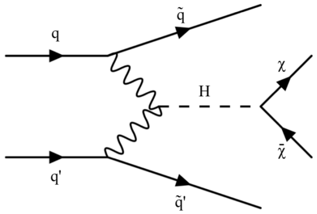
HL-LHC reach: Higgs



Uncertainty [%]

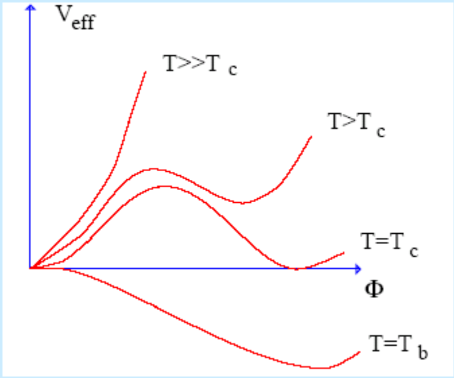
	Tot	Stat	Exp	Th
κ_γ	**1.8**	0.8	1.0	1.3
κ_W	**1.7**	0.8	0.7	1.3
κ_Z	**1.5**	0.7	0.6	1.2
κ_g	**2.5**	0.9	0.8	2.1
κ_t	**3.4**	0.9	1.1	3.1
κ_b	**3.7**	1.3	1.3	3.2
κ_τ	**1.9**	0.9	0.8	1.5
κ_μ	**4.3**	3.8	1.0	1.7
$\kappa_{Z\gamma}$	**9.8**	7.2	1.7	6.4

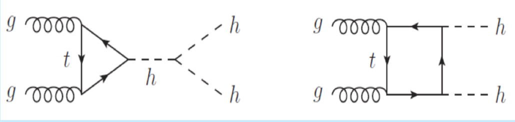
H width to invisible:
h(125)→XX.
Includes BSM decays
and rare SM decays: ≤4%

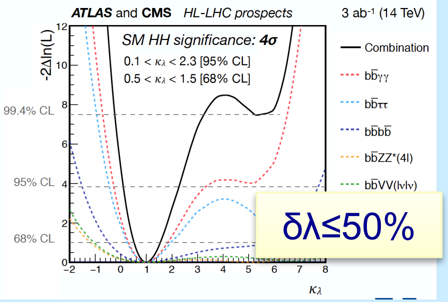


The ultimate frontier: Higgs self-coupling

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







δλ≤50%

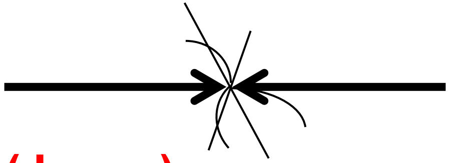
Long-term future: proposed machines

A very brief summary

EU Strategy: High-priority future initiatives

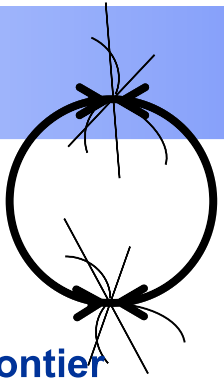
- **A. An electron-positron Higgs factory is the highest-priority next collider. For the longer term, the European particle physics community has the ambition to operate a proton-proton collider at the highest achievable energy. Accomplishing these compelling goals will require innovation and cutting-edge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

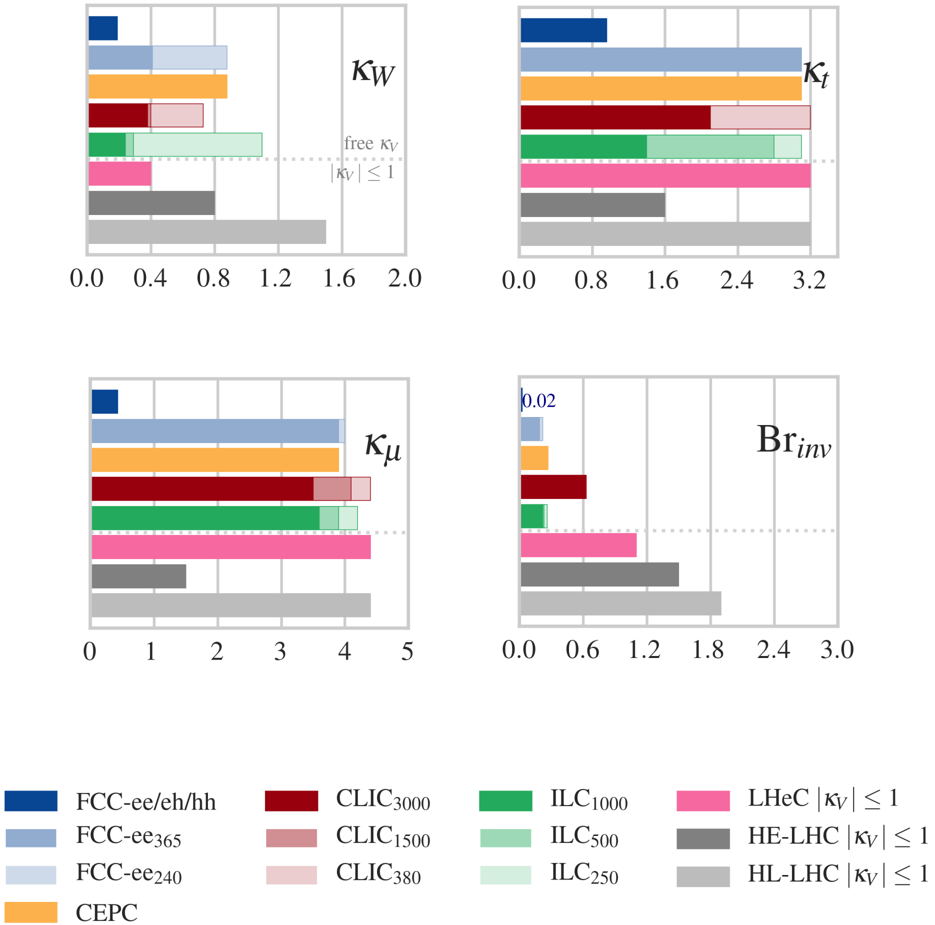


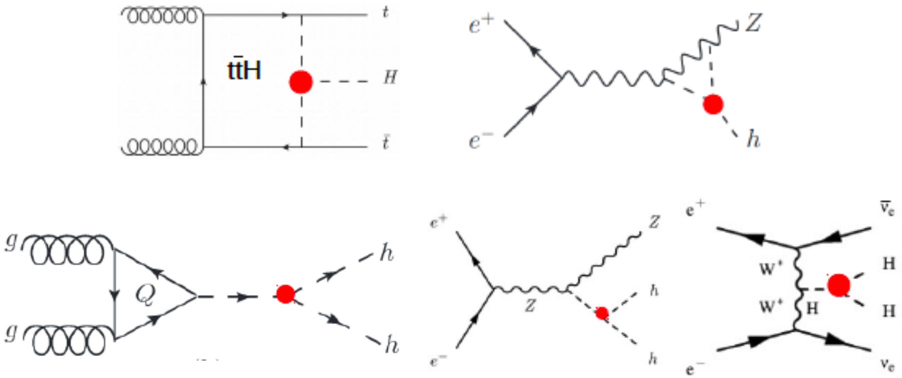
- **FCC-ee/FCC-hh (CERN):**
  - Protons to extend energy frontier
  - 100 km ring with 16T magnets
  - Use FCC-hh tunnel for e+e– collider
  - Technology for ee: “standard”

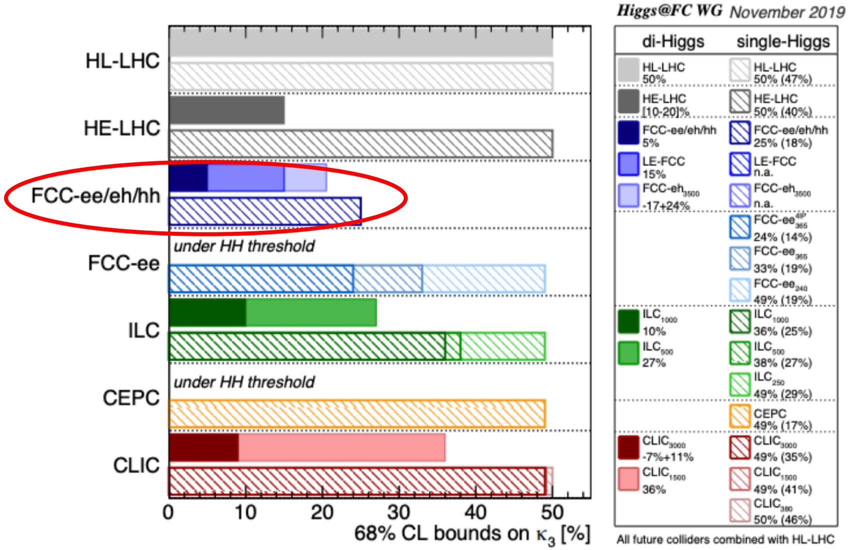
- **CEPC/SppC**
  - Essentially an FCC-ee, then hh with (a) more conservative luminosity estimates and (b) in China

- **Outliers:**
  - “Low-field” (7T) magnets @ FCC (?)
  - Muon Collider (???)

The Higgs sector: from the HL-LHC to the "future"





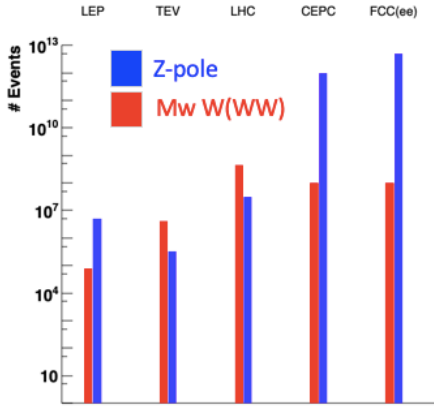


Precision Observables & Searches: examples

- **EWPO: circular ee colliders**

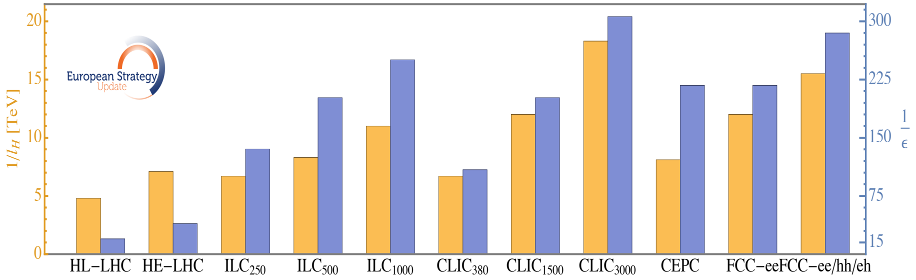
  + linear colliders for sin$^2\theta_W$.

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

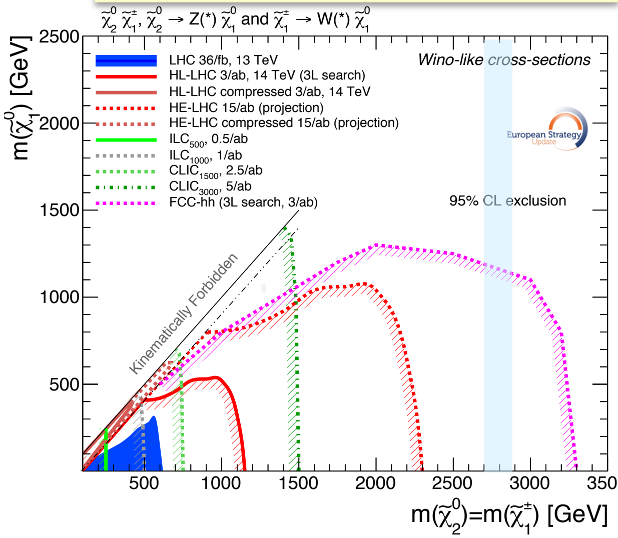


EWPO	Current	CEPC	FCC (ee)
M_Z [MeV]	2.1	0.5	0.1
Γ_Z [MeV]	2.1	0.5	0.1
N_ν [%]	1.7	0.05	0.03
M_W [MeV]	12	1	0.67
$A_{FB}^{0,b}$ [x10^4]	16	1	< 1
$\sin^2\theta_W^{\rm eff}$ [x10^5]	16	1	0.6
R_b^0 [x10^5]	66	4	2–6
R_μ^0 [x10^5]	2500	200	100

Higgs compositeness (?)

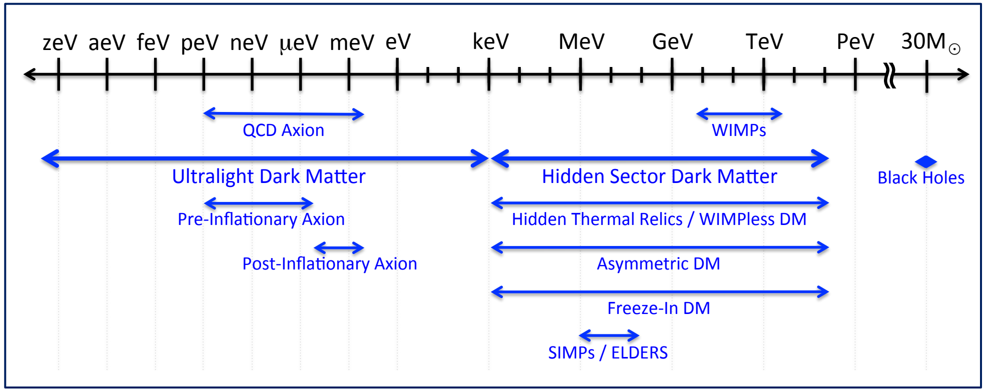


Electroweak SUSY reach

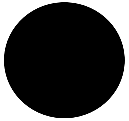


The Dark Sector

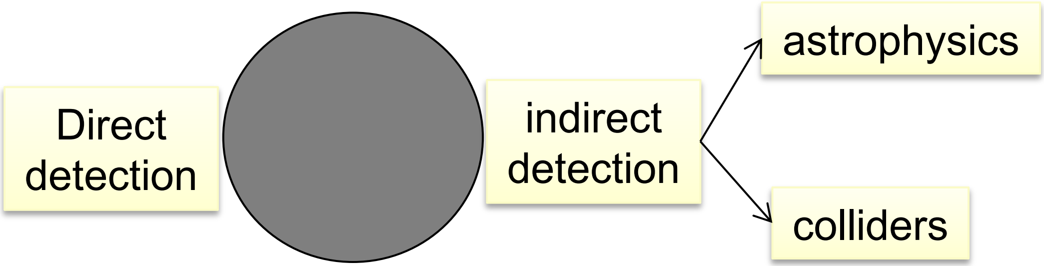
- **An experimental fact & yet, still a total mystery**
  - **And masses span over 80 orders of magnitude**



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



- **More promising: some shade of grey**



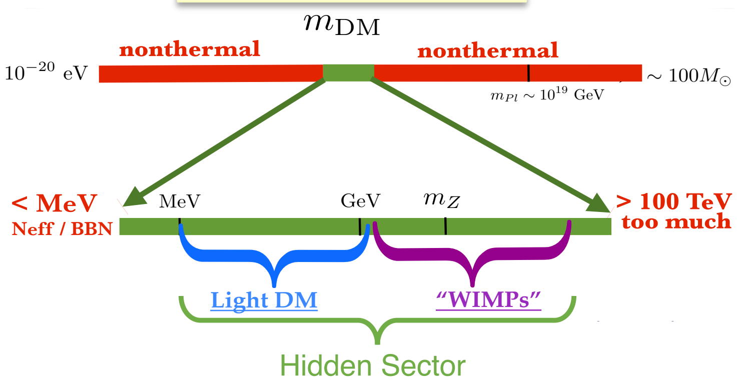
Direct detection

indirect detection

astrophysics

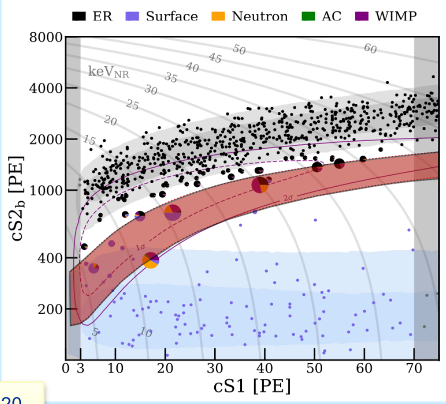
colliders

Thermal WIMPs

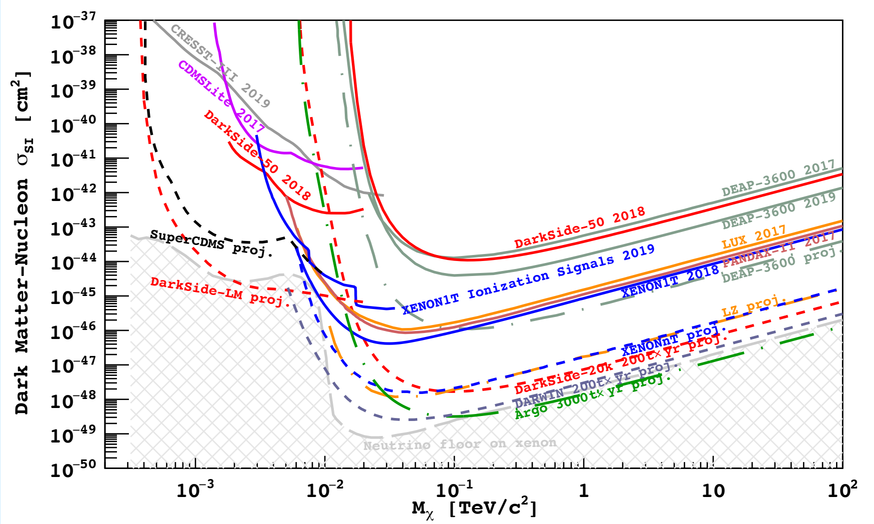


DM: direct detection experiments

Two-phase liquid-Xe expts continuing to increase their sensitivity

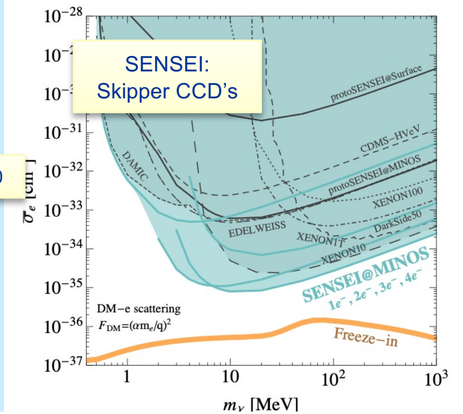


L. Hsu ICHEP2020

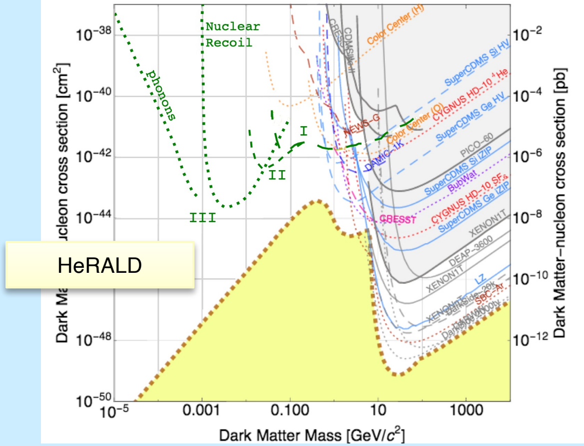


Very large program for subGeV DM

L. Hsu ICHEP2020



SENSEI: Skipper CCD's

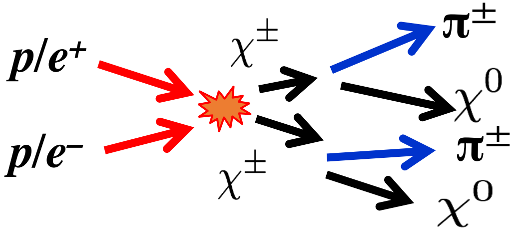


HeRALD

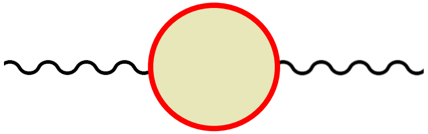
DM: Classic WIMPs

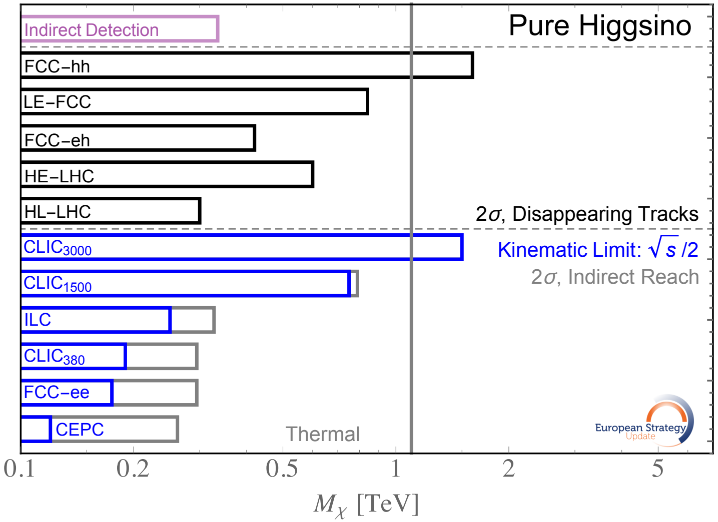
- **Two (SUSY) “extremes”, pure Wino, pure Higgsino**
  - **Main “tools”: disappearing track, propagator modifications**

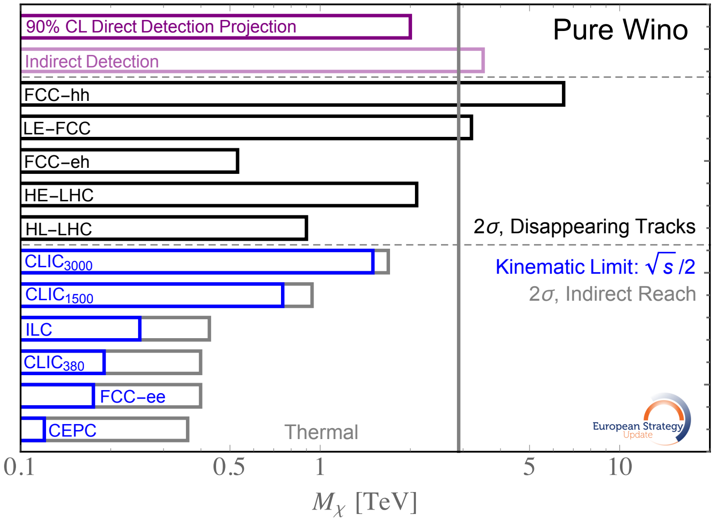
For small Δm, soft $\pi^\pm$...



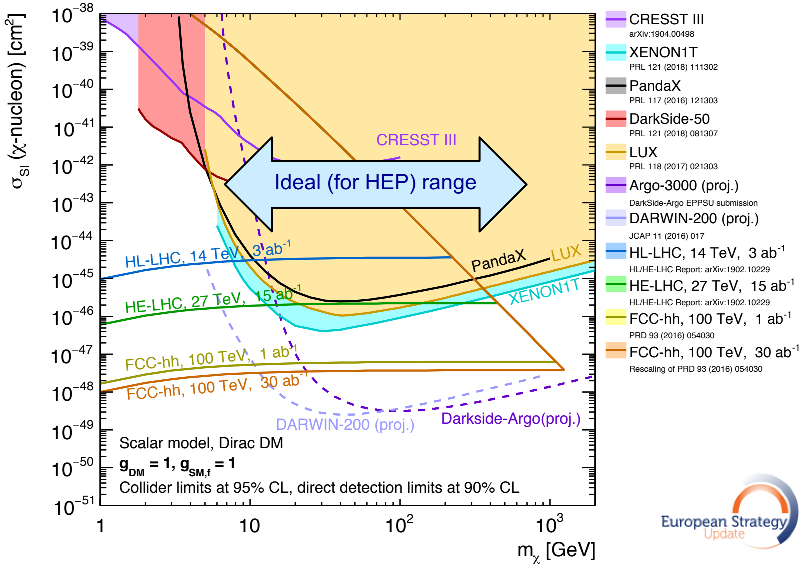
EWKinos in loop change prop
(W, Y parameters)

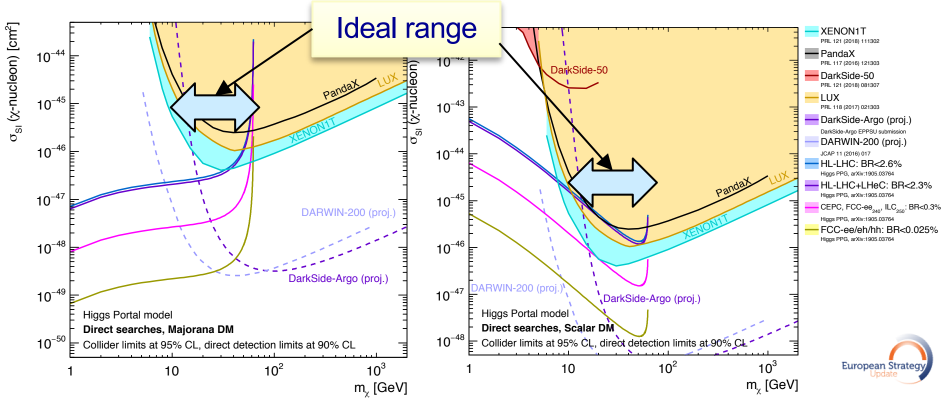


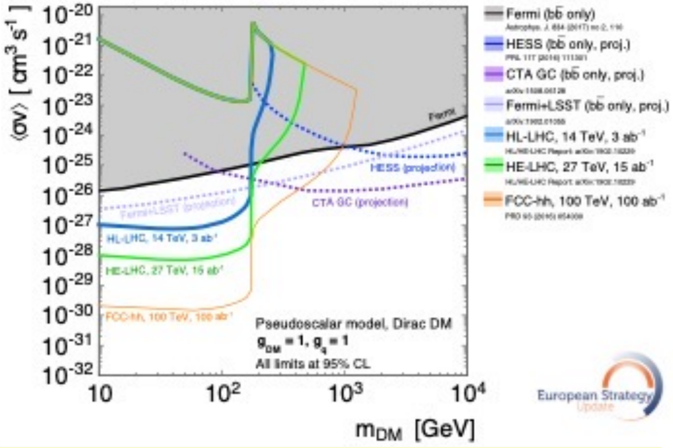




Scalar mediator: Higgs portal and BSM scalar







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!

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 → PMNS matrix & CP violation(?!?!)

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

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

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

$\Delta m^2_{\mathrm{sol}} \sim E_\nu(\mathrm{MeV})/\mathrm{L}(100\,\mathrm{km})$
→ Reactors! → KamLAND

$\Delta m^2_{\mathrm{atm}} \sim E_\nu(\mathrm{MeV})/\mathrm{L}(100\,\mathrm{m}) = (\mathrm{GeV})/(100\,\mathrm{km})$
→ Accelerators! → K2K, MINOS(+),…, T2K, NOVA
+ Short baselines: Daya Bay, RENO, …, xBOONe

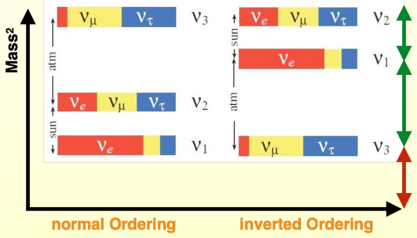
ν physics: PMNS; 3x3 or 4x4? nature (Majorana or Dirac); mass ordering

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

atmospheric +
accelerator disapp

SBL reactor +
accelerator app

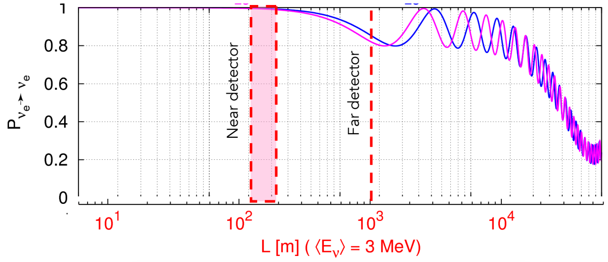
solar +
KamLAND



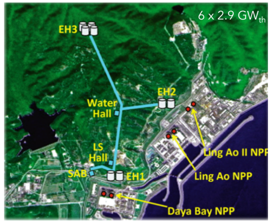
Neutrinos: Reactor experiments; Precision!

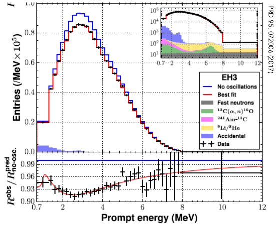
Principle: θ_{13}

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



The prized measurement





Third lucky strike (in ν phys)

$$J_{CP}^{lep} = \mathrm{Im}(U_{\mu 3}U_{e3}^{*}U_{e2}U_{\mu 2}^{*}) = (1/8) \times$$
$$\times \sin 2\theta_{12} \sin 2\theta_{23} \sin 2\theta_{13} \cos \theta_{13} \sin \delta_{CP}$$
$$\approx 0.033 \sin \delta_{CP} \quad \mathrm{BUT}: J_{CP}^{q} \approx 3 \times 10^{-5}$$

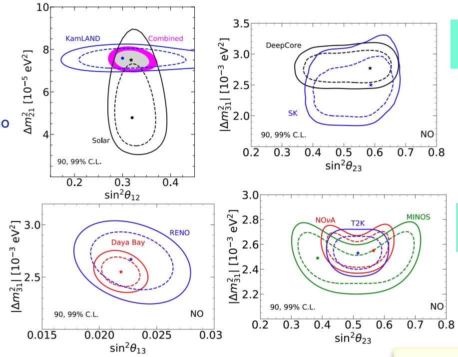
- **Long series of measurements have brought us to a "precision era"**

solar sector

Cl, Ga, SK
SNO, Borexino
KamLAND

SBL reactors

Daya Bay
RENO



atmospheric results

Super-K
IC-DeepCore

LBL experiments

MINOS
T2K
NOvA

M. Tortola ICHEP2020

de Salas et al, arXiv:2006.11237

parameter	best fit ± 1σ	3σ range	relative 1σ uncertainty
Δm^2_{21} [10^{-5}eV^2]	$7.50^{+0.22}_{-0.20}$	6.94–8.14	2.7%
$\lvert\Delta m^2_{31}\rvert$ [10^{-3}eV^2] (NO)	$2.56^{+0.03}_{-0.04}$	2.46–2.65	1.2%
$\lvert\Delta m^2_{31}\rvert$ [10^{-3}eV^2] (IO)	2.46 ± 0.03	2.37–2.55	
$\sin^2\theta_{12}$ /10^{-1}	3.18 ± 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	
δ/π (NO)	$1.20^{+0.23}_{-0.14}$	0.80–2.00	17%
δ/π (IO)	1.54 ± 0.13	1.14–1.90	8%

3-5%

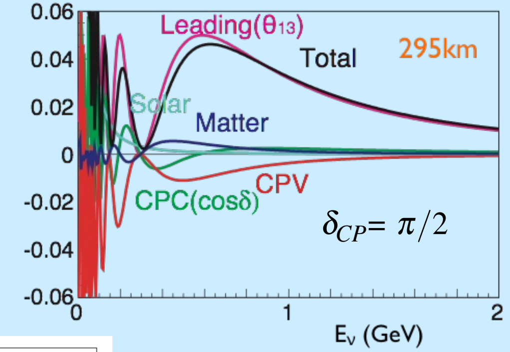
Neutrinos: oscillations & CPV

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

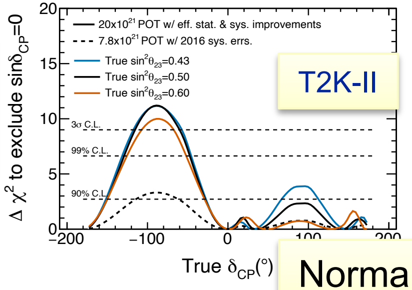
$$\begin{aligned} P(\nu_\mu \to \nu_e) &= \sin^2\theta_{23}\frac{\sin^2 2\theta_{13}}{(A-1)^2}\sin^2[(A-1)\Delta_{31}] \\ &+ \alpha^2\cos^2\theta_{23}\frac{\sin^2 2\theta_{12}}{A^2}\sin^2(A\Delta_{31}) \\ &- \alpha\frac{\sin 2\theta_{12}\sin 2\theta_{13}\sin 2\theta_{23}\cos\theta_{13}\sin\delta_{CP}}{A(1-A)}\sin\Delta_{31}\sin(A\Delta_{31})\sin[(1-A)\Delta_{31}] \\ &+ \alpha\frac{\sin 2\theta_{12}\sin 2\theta_{13}\sin 2\theta_{23}\cos\theta_{13}\cos\delta_{CP}}{A(1-A)}\cos\Delta_{31}\sin(A\Delta_{31})\sin[(1-A)\Delta_{31}] \end{aligned}$$

Favored (slightly): Normal Ordering & δ_{CP}~3π/2

But… fits are complicated



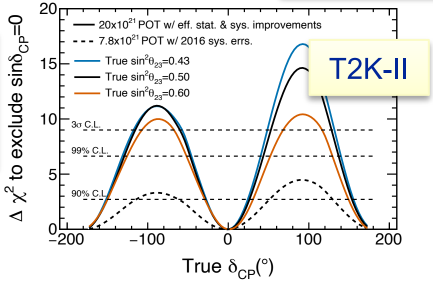
Unknown mass order



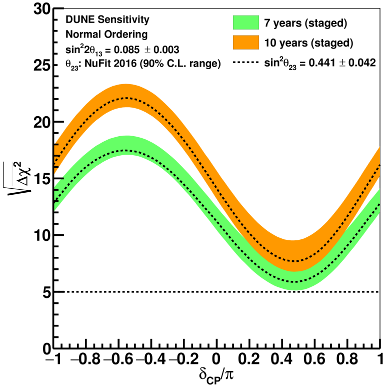
T2K-II

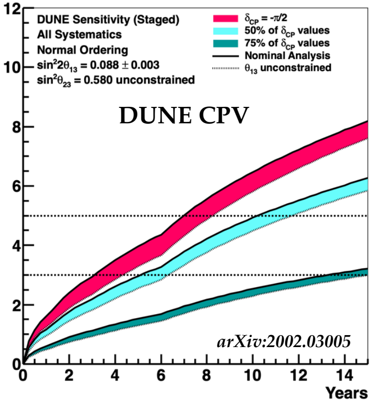
NormalO

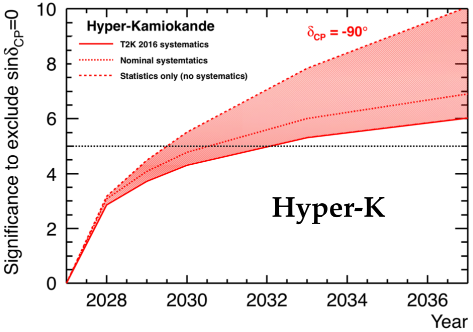
Known mass order



T2K-II





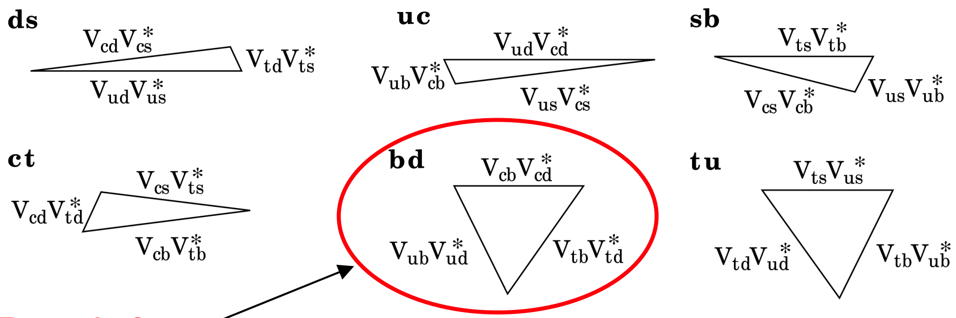


Very useful/nice: complementarity of NOvA/T2K and DUNE/HyperK: baseline (1300 vs 200 km) and detection technique

Flavor physics: quark sector

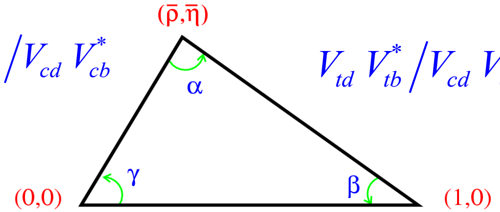
$$V_{CKM} = \begin{bmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{bmatrix}$$

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

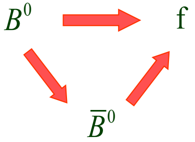


CP ~ sin2ϕ

$$V_{ud}\,V^*_{ub} / V_{cd}\,V^*_{cb}$$

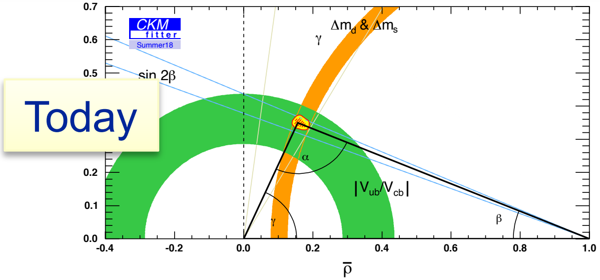


$$V_{td}\,V^*_{tb} / V_{cd}\,V^*_{cb}$$

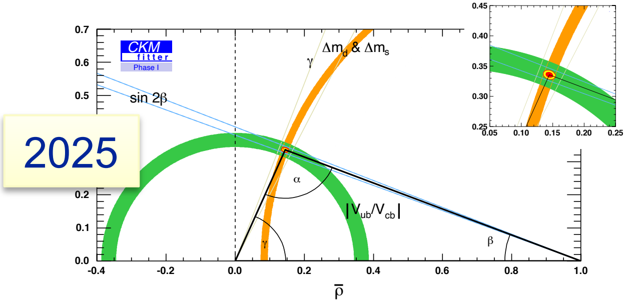


$$\frac{\Gamma(\bar B^0 \to \bar f) - \Gamma(B^0 \to f)}{\Gamma(\bar B^0 \to \bar f) + \Gamma(B^0 \to f)} = -\eta_f\ \sin(2\phi)\ \sin(\Delta M\, t)$$

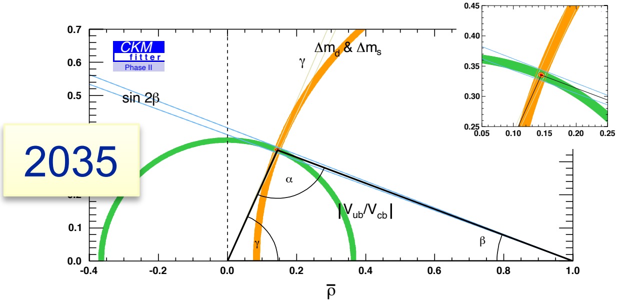
CKM triangle: extensive precision program en route



Today



2025



2035

Pseudo-summary

Pseudosummary/Outlook

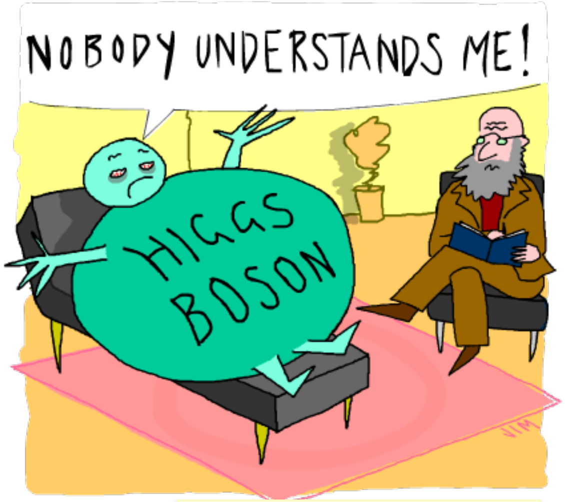
- Extremely rich physics program ahead to understand the scalar sector
  - The LHC and HL-LHC will get us to 3-5% couplings for the Higgs boson;
  - All options for a future Higgs "factory" bring in ~O(10^{-2}–10^{-3}) understanding of couplings.
  - Important aspects: EWPO (needs next-gen Z factory) 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 σ_{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 Λ_{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.

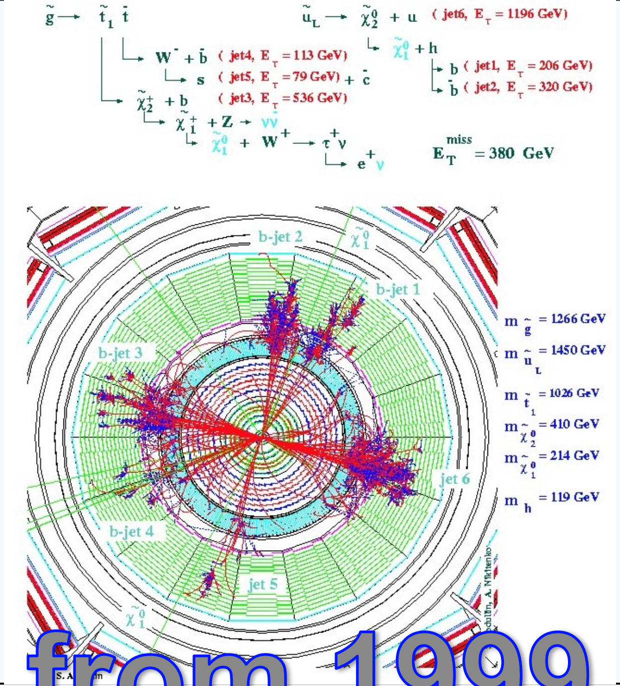


Credit: blog.gymlish.com

“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

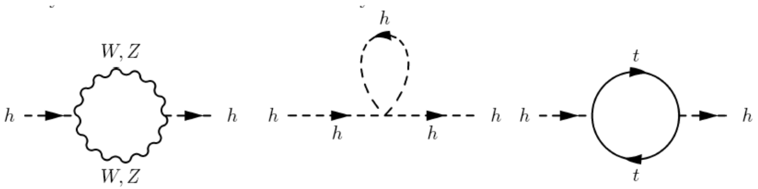
- Many hard Jets
- Large missing energy
  - 2 LSPs
  - Many neutrinos
- Many leptons
- In a word Spectacular!



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



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

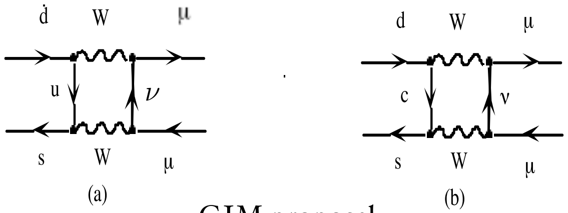
- **H mass should be ~ 10^{19}GeV**
  - Yet, it lies at 125 GeV…
- **Put differently: if cut off at Λ_{PL}, why $m_W \ll M_{Pl}$?**
  - Or, why is gravity ($G\sim1/M_{Pl}$) so weak?

- **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: $K_L \to \mu^+\mu^-$**



GIM proposal

$\sim G\,\Lambda^2 = G(m_c^2 - m_u^2)$

$\to \Lambda^2 \sim$ 3-4 GeV^2 !!!

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…)

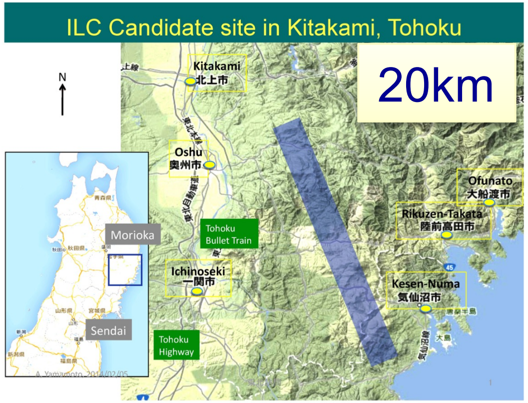
The road to obtaining answers: precise measurements & direct searches…

- 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 ν 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.)	$\mathscr{L}_{\text{inst}}$ $[10^{34}]\ \text{cm}^{-2}\text{s}^{-1}$	$\mathscr{L}$ $[\text{ab}^{-1}]$	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	±80/±30	1	1.35/2.7	2.0	11.5	[3, 11]	ILC$_{250}$
		350 GeV	±80/±30	1	1.6	0.2	1		ILC$_{350}$
		500 GeV	±80/±30	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	±80/0	1	1.5	1.0	8	[12]	CLIC$_{380}$
		1.5 TeV	±80/0	1	3.7	2.5	7		CLIC$_{1500}$
		3.0 TeV	±80/0	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



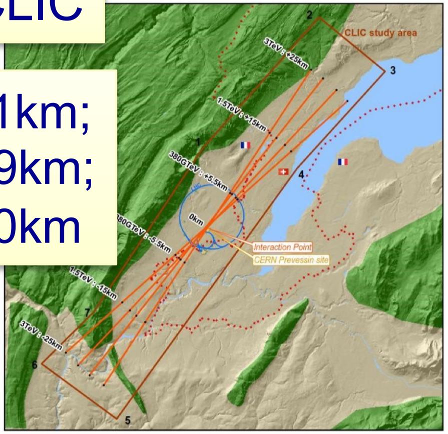
20km

Qinhuangdao site

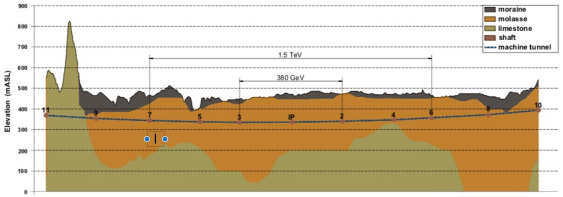
100 km

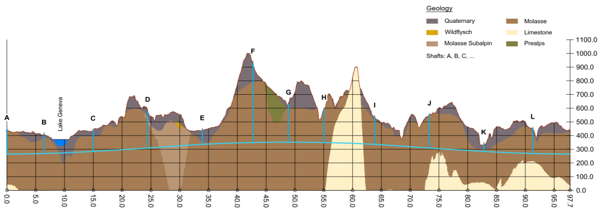
CEPC: multiple candidate sites in China

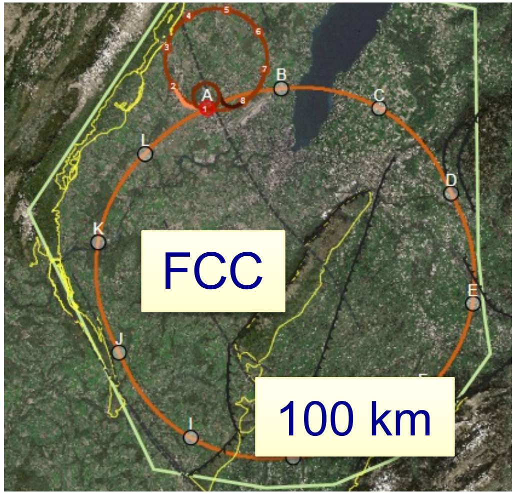
CLIC



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

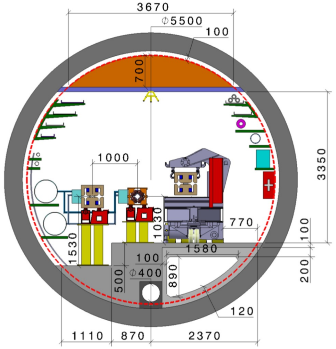
- **hh collider:**
  - Magnets!
    - Need 16 TeV (x2 LHC); they do not exist today
  - High stored beam energy (8-9 GJ)
    - Beam handling, beam dumping
    - Collimation
  - High synchrotron radiation inside magnets: several MW
  - Beam screen design and cryogenic efficiency;
  - Power consumption: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

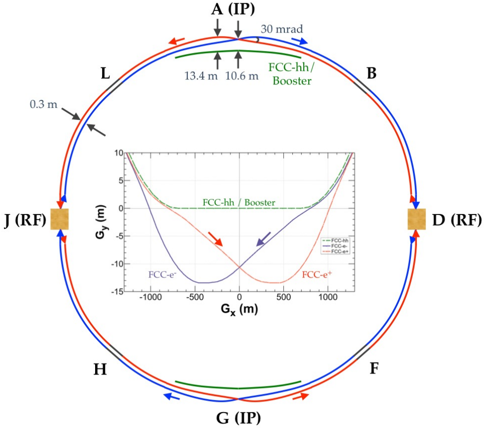
Costs (GUnits):

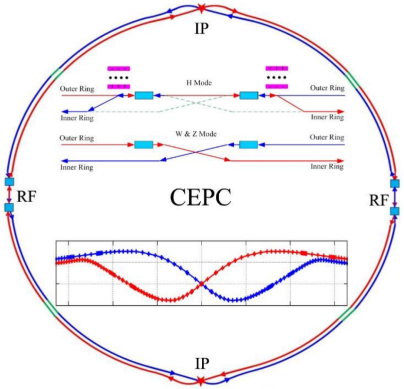
ILC: 5.0 (for 250 GeV); 7.8 (500 GeV)
CLIC: 5.9 or 7.3 (for 380 GeV) + 5.1 (1500 GeV) + 7.1 (3000 GeV) (Tot: 19.5)
FCC-ee: 11.6; but 7.1 is the tunnel
FCC-hh: tunnel + 17 (Tot: 24)

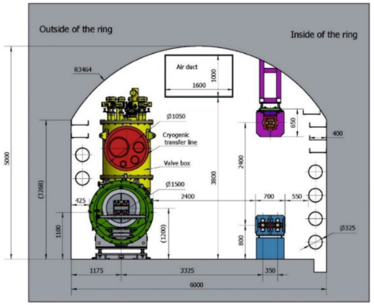
FCC-ee and CEPC

- **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









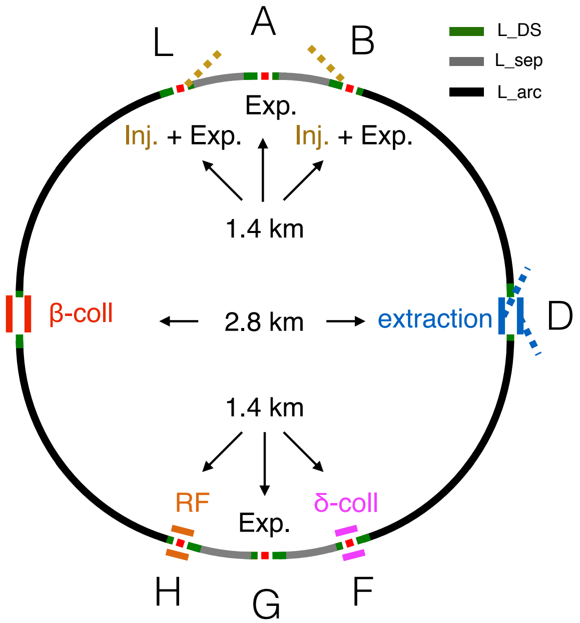
FCC-hh and SppC

- **Circumference ~100 km, high luminosity 3(1) x 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,**

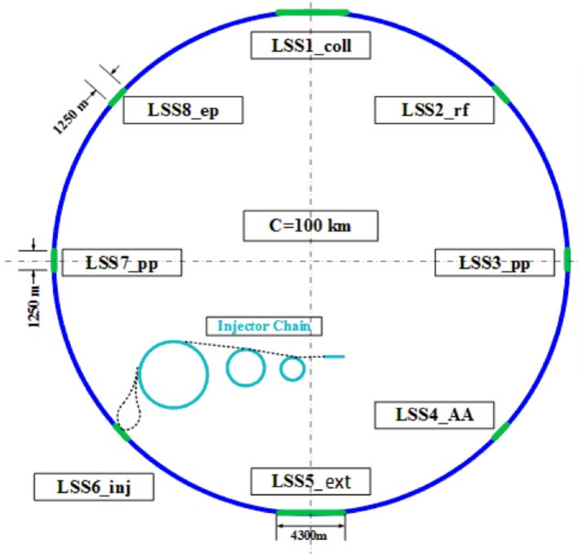
FCC-hh

based on existing CERN injector chain,

Luminosity goal ~20 ab^{-1} per main IP within 25 years



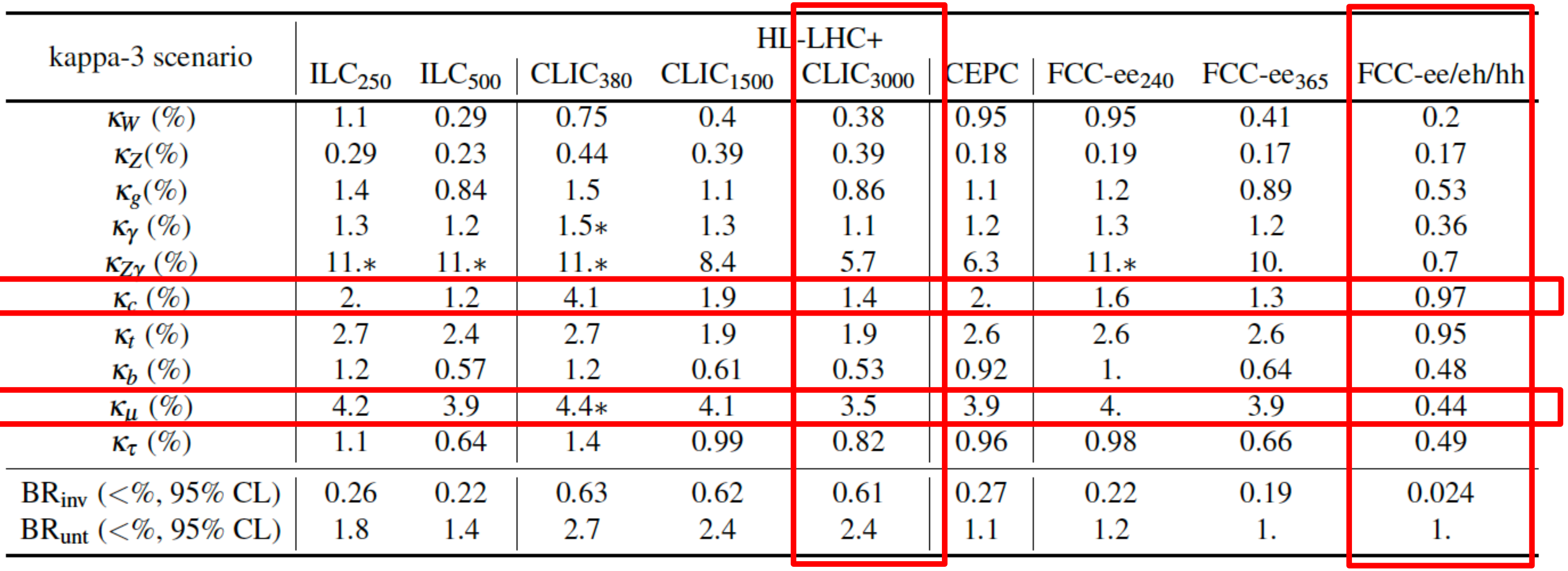
SppC



new injector chain,

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

Grand summary



kappa-3 scenario	HL-LHC+								
	ILC$_{250}$	ILC$_{500}$	CLIC$_{380}$	CLIC$_{1500}$	CLIC$_{3000}$	CEPC	FCC-ee$_{240}$	FCC-ee$_{365}$	FCC-ee/eh/hh
κ_W (%)	1.1	0.29	0.75	0.4	0.38	0.95	0.95	0.41	0.2
κ_Z(%)	0.29	0.23	0.44	0.39	0.39	0.18	0.19	0.17	0.17
κ_g(%)	1.4	0.84	1.5	1.1	0.86	1.1	1.2	0.89	0.53
κ_γ (%)	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
κ_c (%)	2.	1.2	4.1	1.9	1.4	2.	1.6	1.3	0.97
κ_t (%)	2.7	2.4	2.7	1.9	1.9	2.6	2.6	2.6	0.95
κ_b (%)	1.2	0.57	1.2	0.61	0.53	0.92	1.	0.64	0.48
κ_μ (%)	4.2	3.9	4.4∗	4.1	3.5	3.9	4.	3.9	0.44
κ_τ (%)	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.

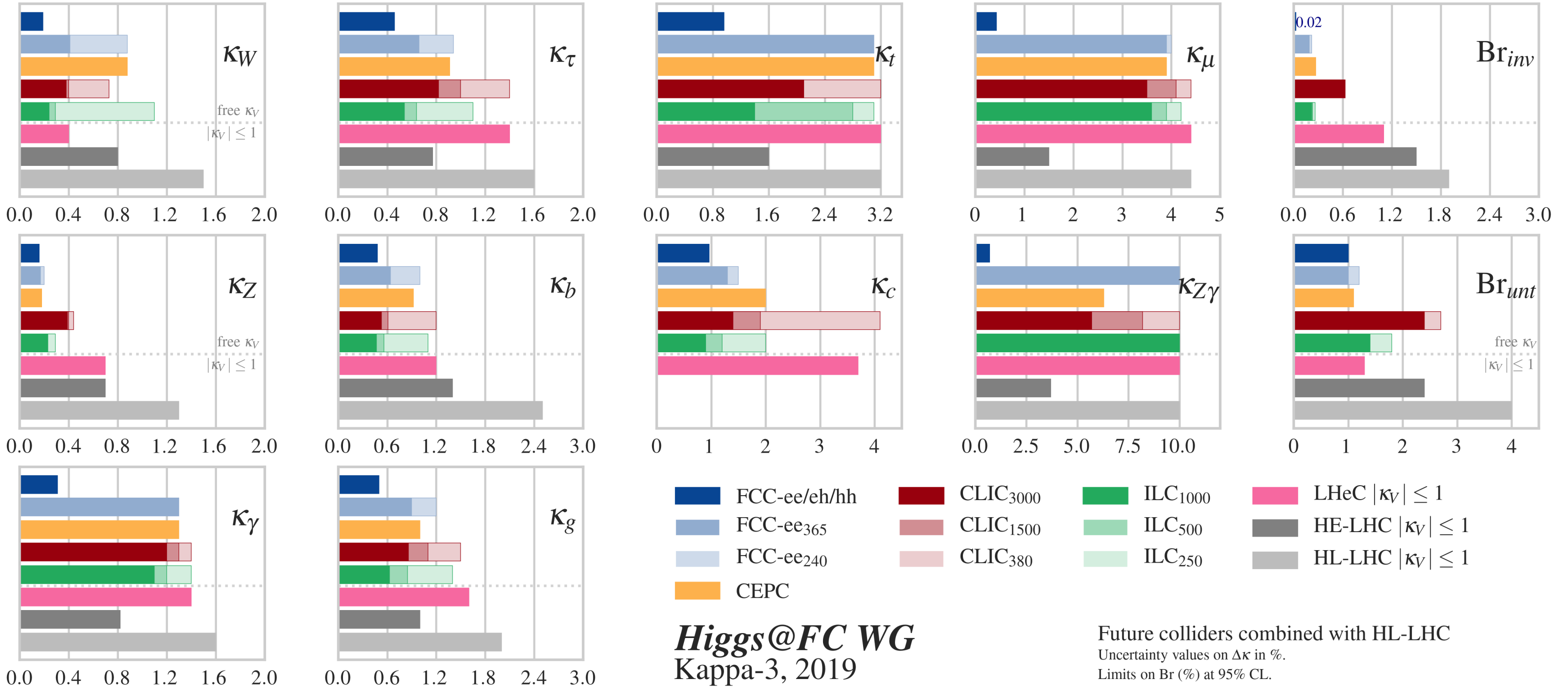
All ee colliders achieve major (and comparable) improvements in their first stage already in probing Higgs sector compared to HL-LHC: at least half of the couplings get improved by factor 5 or more

W/Z effective couplings and BR(H → invisible) probed to ~3×10^{-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

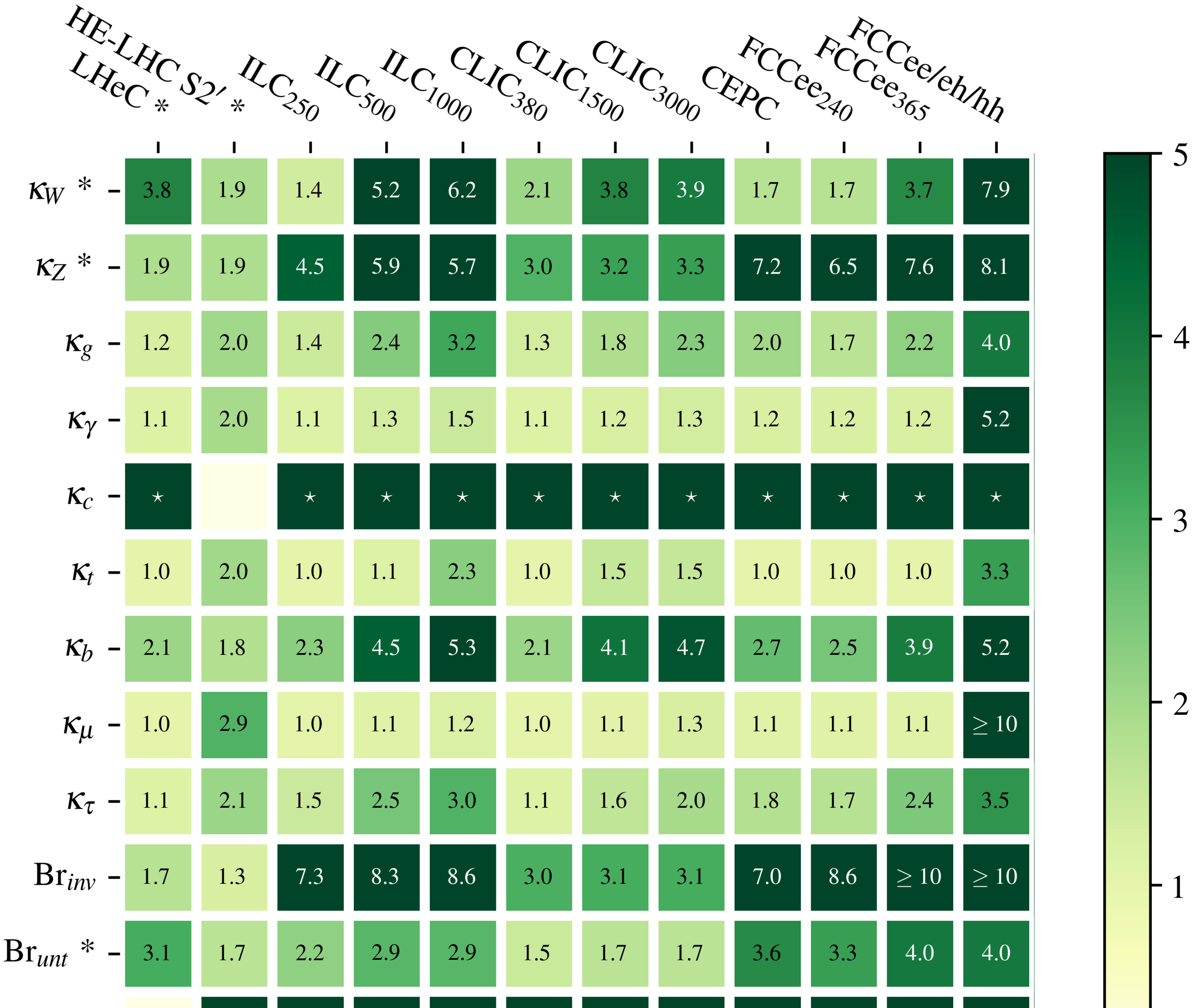
Grand summary: Higgs couplings (κ framework) (Future Collider+HL-LHC)



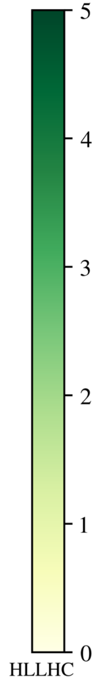
Plus of κ framework: it is simple; Minus: underestimates effects of polarization

Can show deviation from SM, but no real further information on nature of source of deviation;

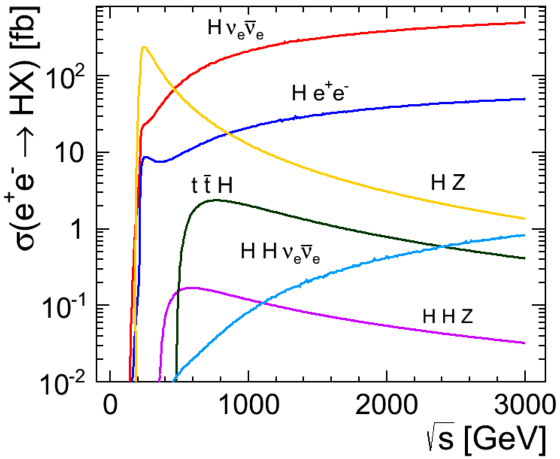
Untagged and invisible BRs constrained by measurements.

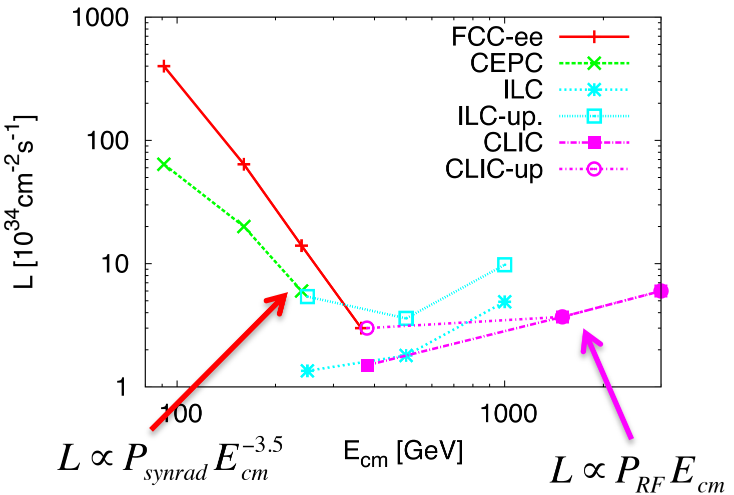


	LHeC *	HE-LHC S2′ *	ILC$_{250}$	ILC$_{500}$	ILC$_{1000}$	CLIC$_{380}$	CLIC$_{1500}$	CLIC$_{3000}$	CEPC	FCCee$_{240}$	FCCee$_{365}$	FCCee/eh/hh
κ_W *	3.8	1.9	1.4	5.2	6.2	2.1	3.8	3.9	1.7	1.7	3.7	7.9
κ_Z *	1.9	1.9	4.5	5.9	5.7	3.0	3.2	3.3	7.2	6.5	7.6	8.1
κ_g	1.2	2.0	1.4	2.4	3.2	1.3	1.8	2.3	2.0	1.7	2.2	4.0
κ_γ	1.1	2.0	1.1	1.3	1.5	1.1	1.2	1.3	1.2	1.2	1.2	5.2
κ_c	⋆		⋆	⋆	⋆	⋆	⋆	⋆	⋆	⋆	⋆	⋆
κ_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
κ_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
κ_μ	1.0	2.9	1.0	1.1	1.2	1.0	1.1	1.3	1.1	1.1	1.1	≥ 10
κ_τ	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	≥ 10	≥ 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”





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

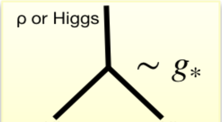
$L \propto P_{RF} E_{cm}$

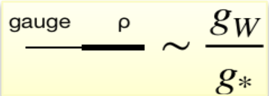
Schemes for increasing luminosity:
- FCC-ee: consider more IRs/running longer
- ILC: more bunches per pulse, doubling repetition rate?
  - Each: x 2 in lumi; higher power consumption and somewhat higher cost
- CLIC: doubling repetition rate at 380 GeV?
  - Factor 2 in lumi; power increases from 170 MW 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}

Higgs Compositeness?



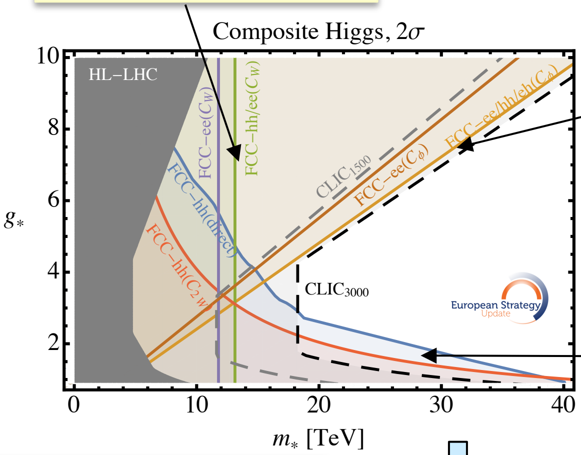


H $\quad \dfrac{c_\phi}{\Lambda^2} = \dfrac{g_*^2}{m_*^2}$

2f-2b $\quad \dfrac{c_W}{\Lambda^2} = \dfrac{1}{m_*^2}$

4f, W'/Z' $\quad \dfrac{c_{2W}}{\Lambda^2} = \dfrac{1}{g_*^2 m_*^2}$

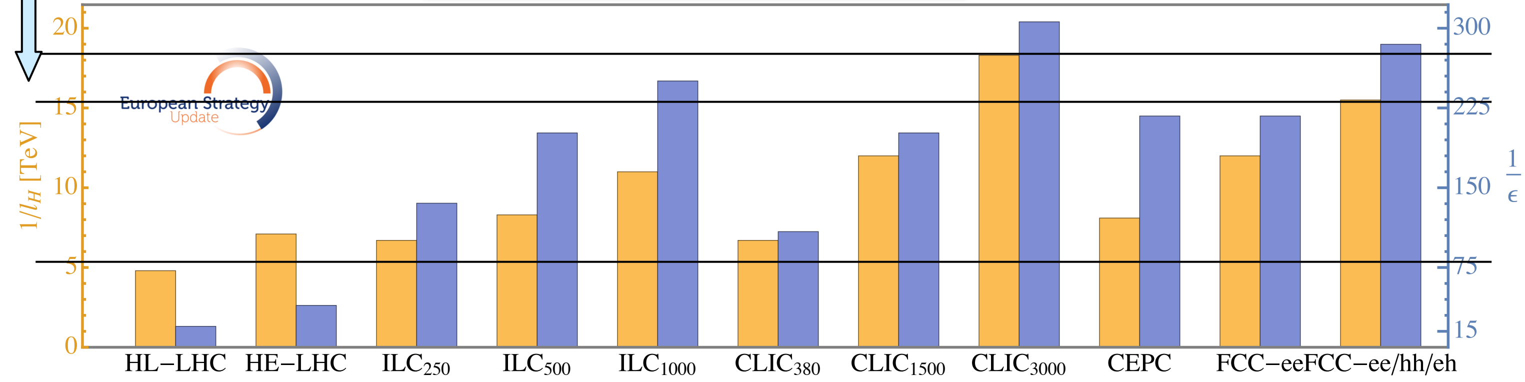
O_W (independent of g_*)



O_φ (Higgs measurements, primarily FCC-ee & CLIC)

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

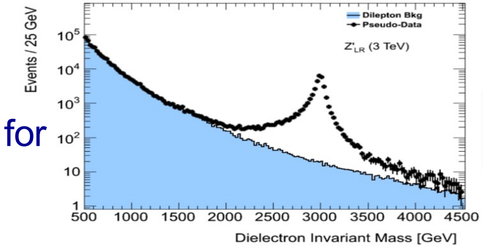
Obtain limit on m*, i.e. on 1/length(H)



New resonances/particles/forces?

Seeing the peak. Reach:

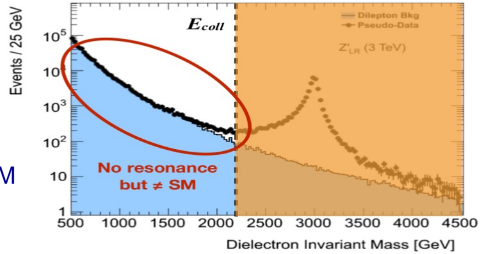
- M < √s for lepton colliders
- M ≲ 0.3-0.5 √s in hadron colliders for couplings ~ weak couplings



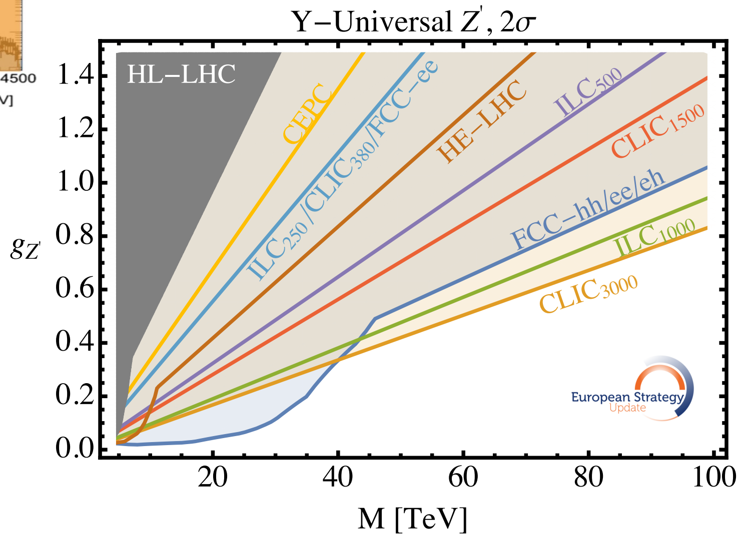
Courtesy:
J. De Blas

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

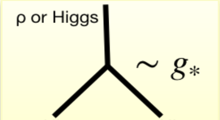


Use very simple model as example. Universal Z'. Clearly, many models with flavor dependence etc.



Higgs Compositeness?

- **Using fits from EWK/Higgs group (arXiv:1905.03764)**
  - **Connection between notations:**



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

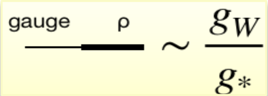
H

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

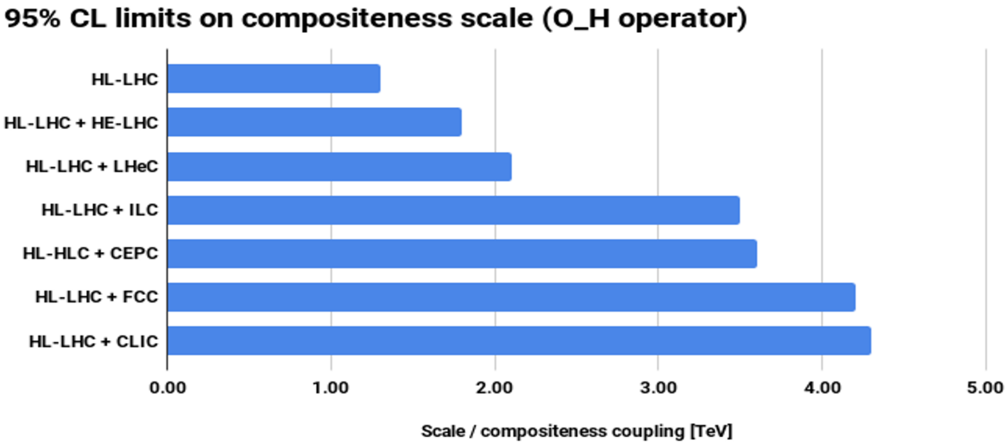
2f-2b

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

4f, W'/Z'



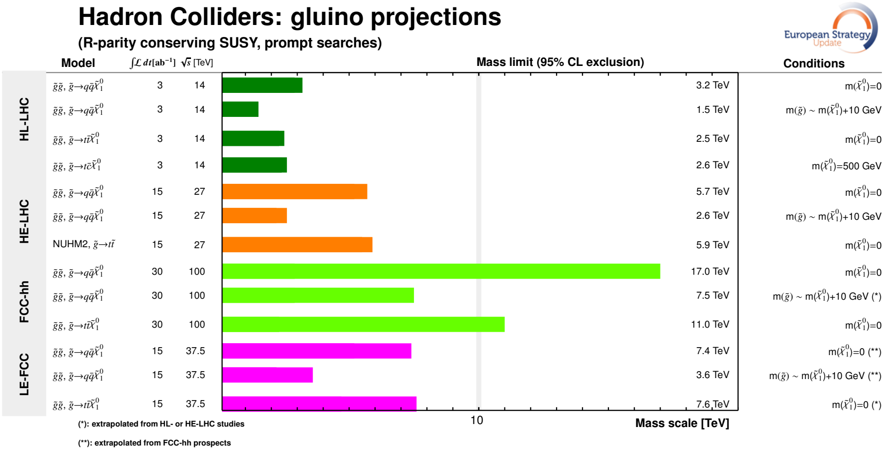
  - **For mass/coupling ~2 TeV → deviations ~1% in Higgs couplings**



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**



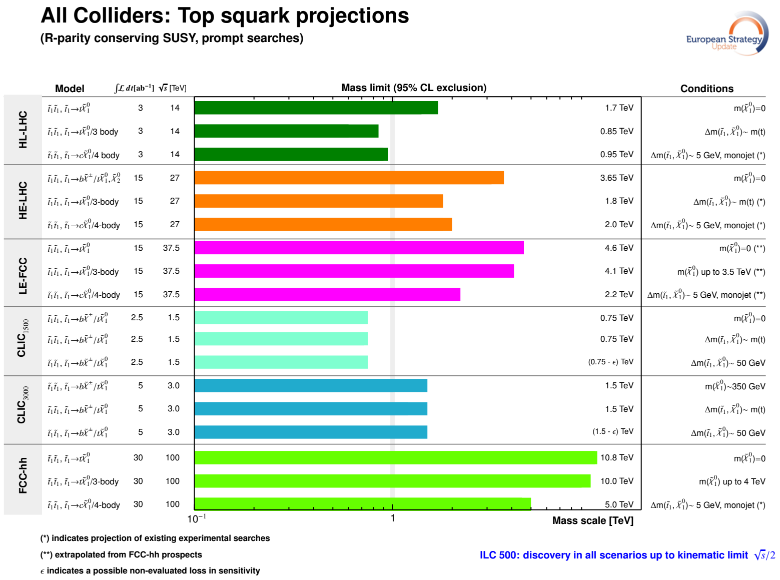
Hadron Colliders: gluino projections

(R-parity conserving SUSY, prompt searches)

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

(**): extrapolated from FCC-hh prospects

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



All Colliders: Top squark projections

(R-parity conserving SUSY, prompt searches)

(*) indicates projection of existing experimental searches

(**) extrapolated from FCC-hh prospects

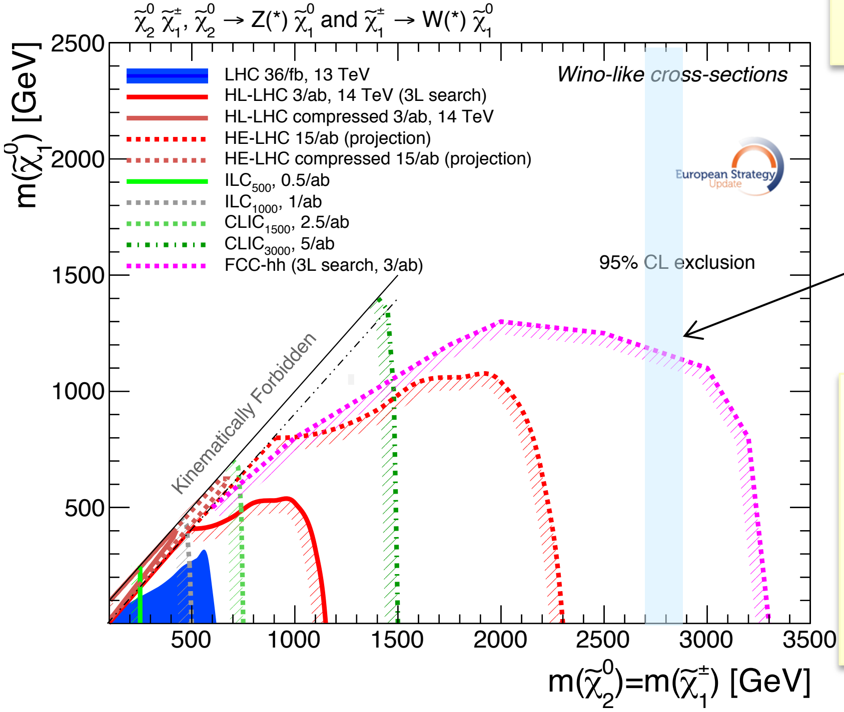
ϵ indicates a possible non-evaluated loss in sensitivity

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

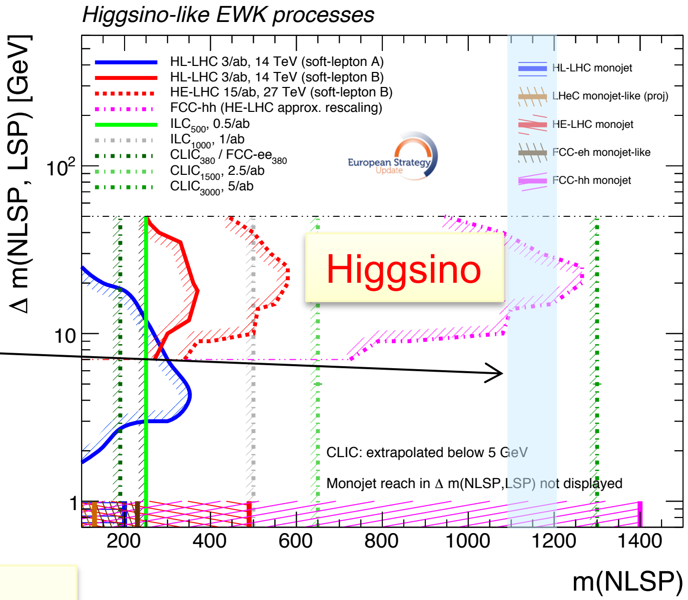
Long-term future: SUSY EWK sector

ee: mainly $\chi^0_2\chi^0_1$ and $\chi^+_1\chi^-_1$ (Δm>1GeV)
pp: mainly $\chi^0_2\chi^\pm_1$ (gaps at low Δm)

ee sensitivity
~independent
of nature of
LSP
(but up to √s/2)

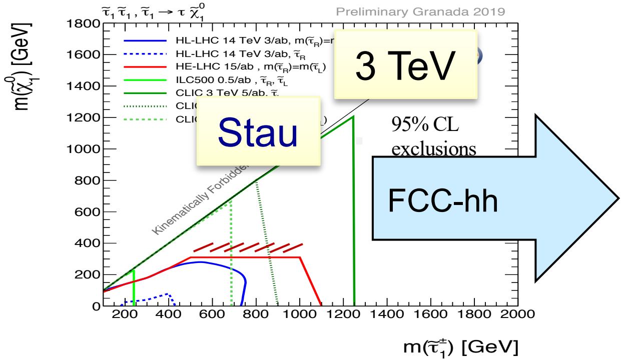


Thermal
WIMP



Higgsino

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

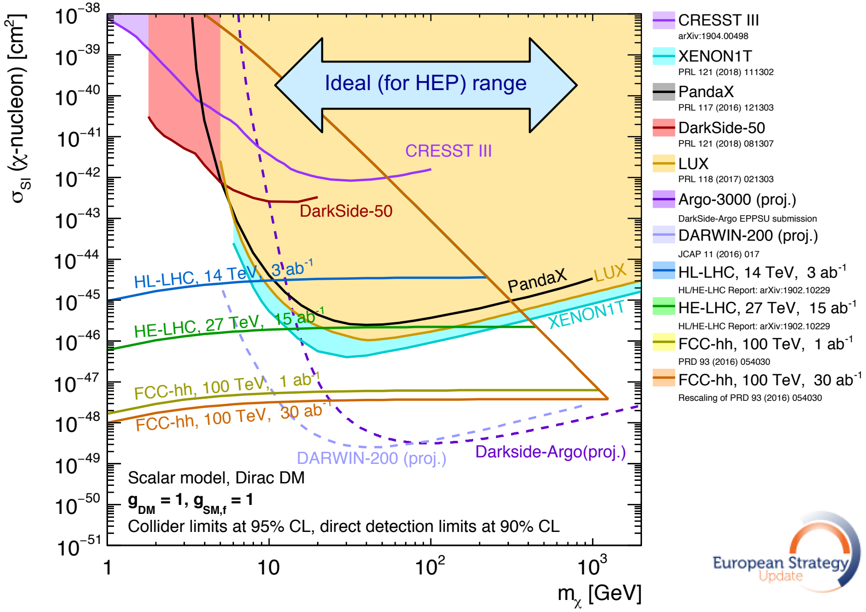


3 TeV

Stau

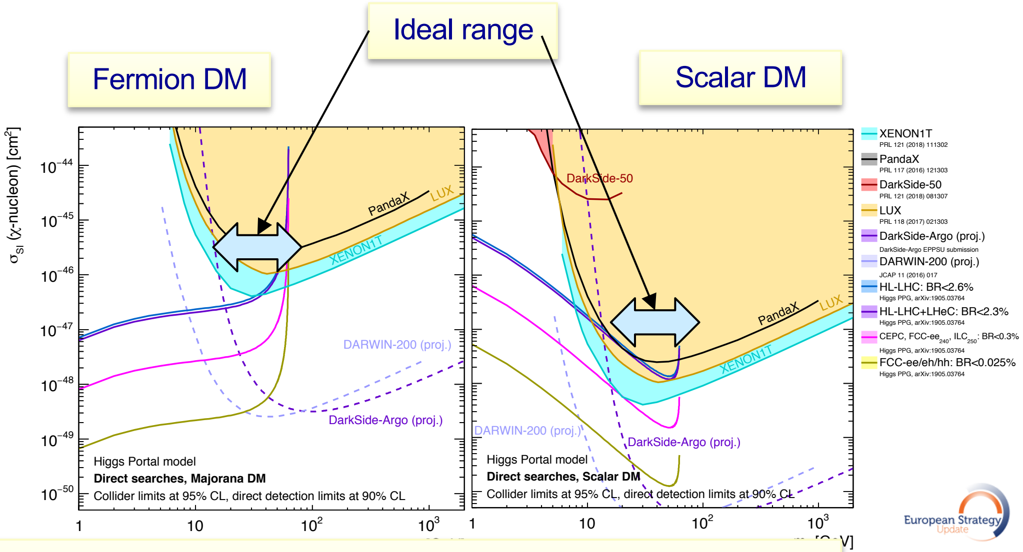
FCC-hh

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

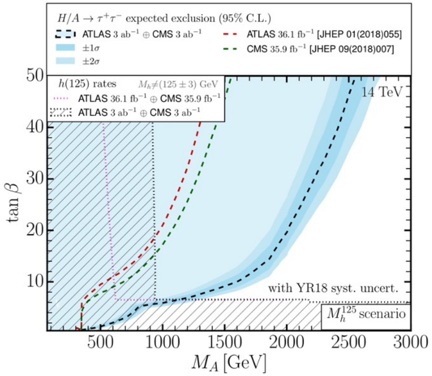


A future collider program that optimizes sensitivity to invisible particles coherently with DD/ID serves us well. Need maximum overlap with DD/ID!

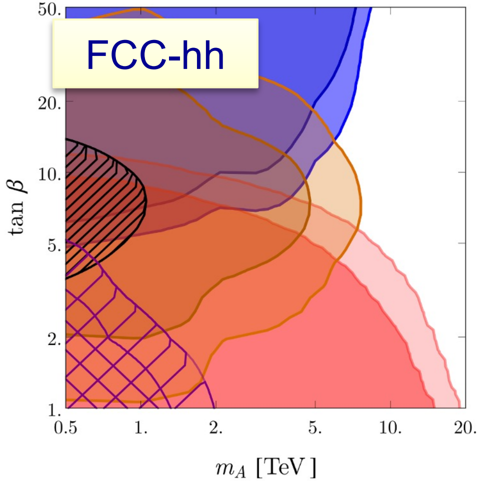
Extended Scalar sectors: MSSM

Simply: hadron colliders…

LHC+HL-LHC

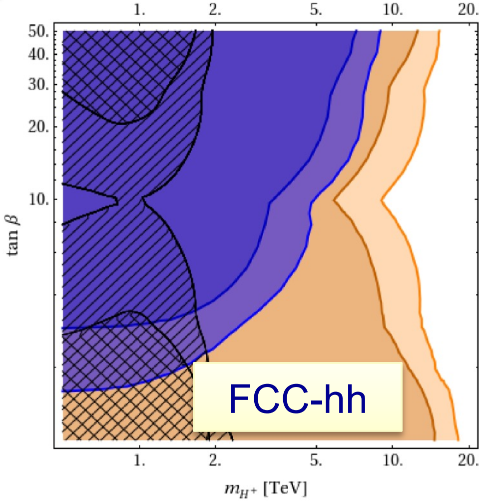


pp → bbH^0/A → bbττ (large tanβ)
pp → bbH^0/A → ttbb (int. tanβ)
pp → ttH^0/A → tttt (low tanβ)



FCC-hh

pp → btH$^\pm$ → bbτν
pp → btH$^\pm$ → tbtb



FCC-hh

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

H^0/A: exclusion limits > 5 TeV
(20 TeV at low tan β)
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.**

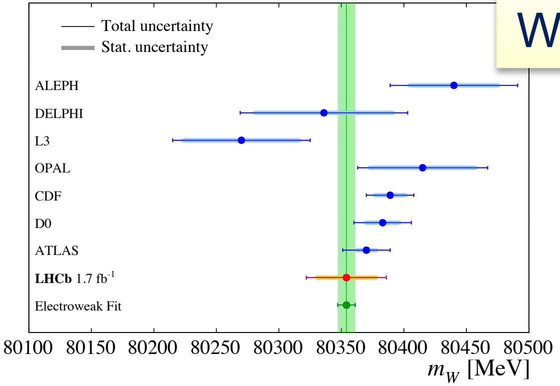
Where we stand

- **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

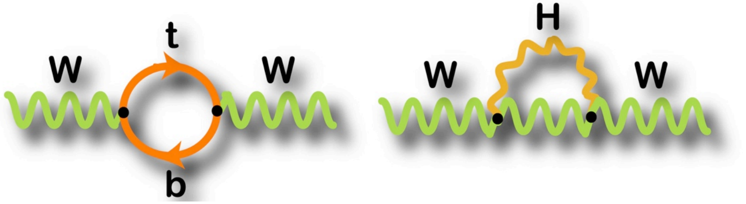
Current issues to watch…

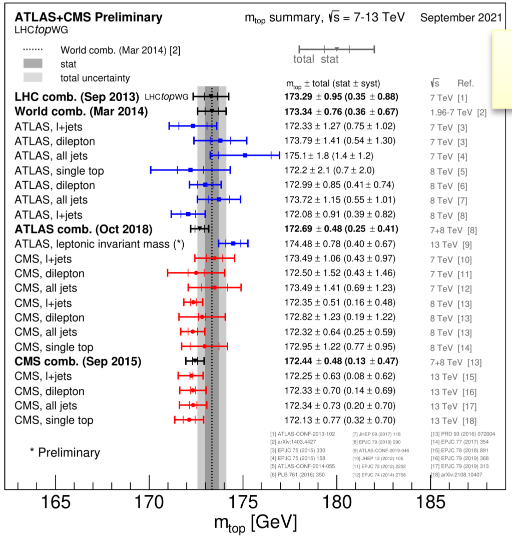
A very sensitive SM test: the m_W–m_t plane



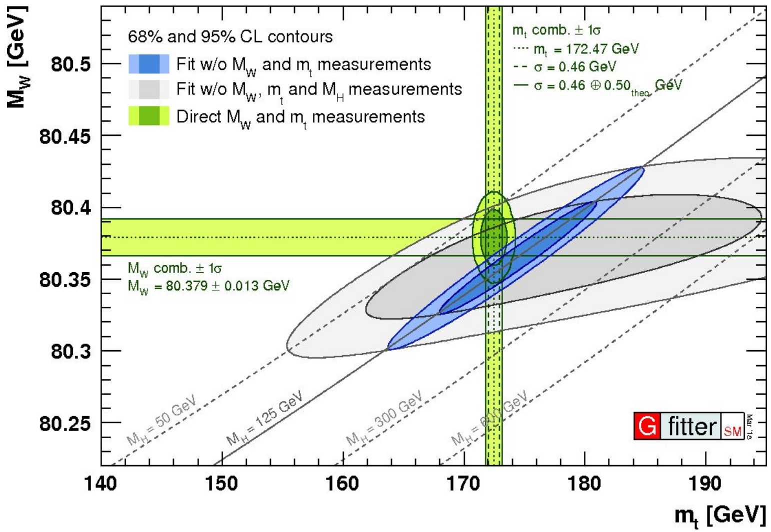
W mass

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



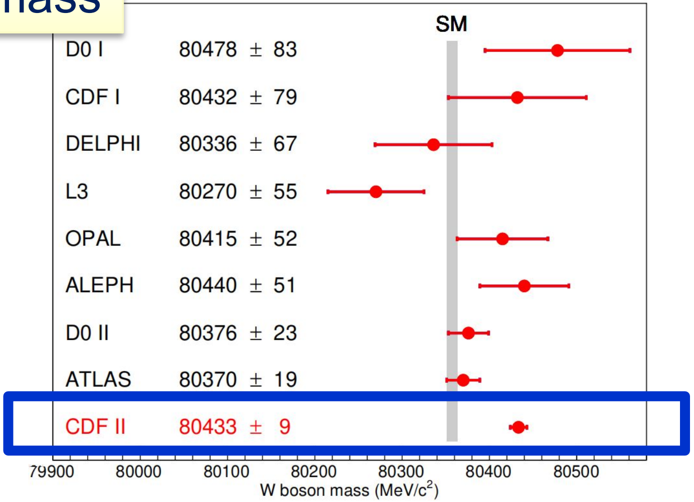


t mass

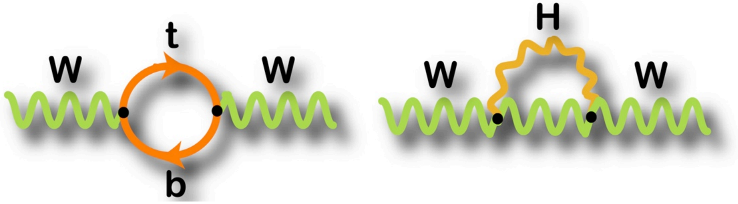


A very sensitive SM test: the m_W–m_t plane

W mass

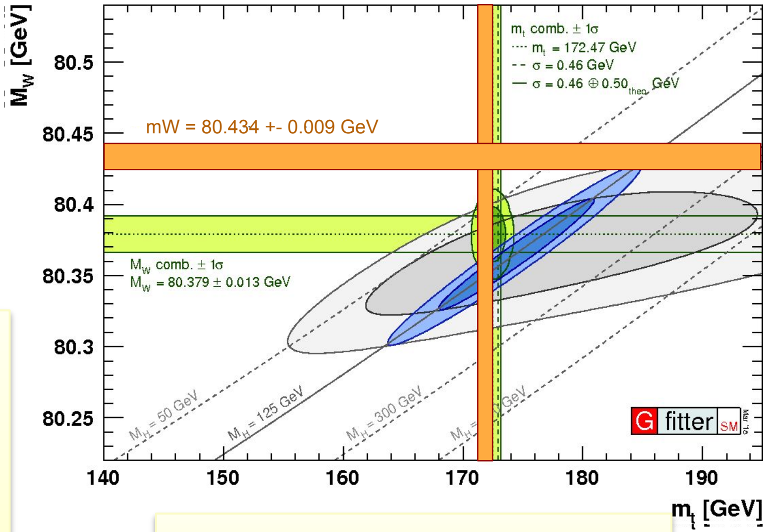


$$m_W^2\left(1-\frac{m_W^2}{m_Z^2}\right)=\frac{\pi\alpha}{\sqrt{2}G_\mu}(1+\Delta r)$$



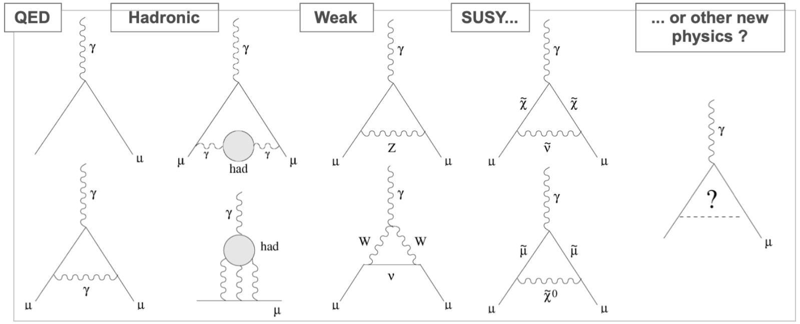
$m_W(SM) = 80375\pm4(inp)\pm4(th)$ MeV
$m_W(CDF) = 80433\pm9.4$ MeV
$\Delta m_W(SM\text{-}CDF) = 7\sigma$…

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_μ=g_μ–2

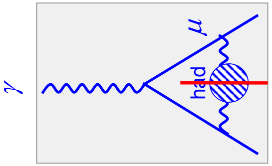


$$a_\mu^{\mathrm{QED}} = \frac{\alpha}{2\pi} + A_2\left(\frac{\alpha}{\pi}\right)^2 + A_3\left(\frac{\alpha}{\pi}\right)^3 + A_4\left(\frac{\alpha}{\pi}\right)^4 + A_5\left(\frac{\alpha}{\pi}\right)^5$$

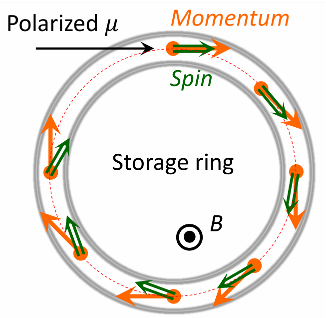
$$a_\mu^{\mathrm{EW}} = 153.6\ (1.0) \times 10^{-11}$$

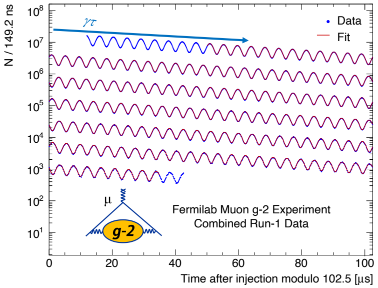
$$a_\mu^{\mathrm{HLbL}} = 94\ (19) \times 10^{-11}$$

Main uncertainty: Hadronic Vaccum Polarization

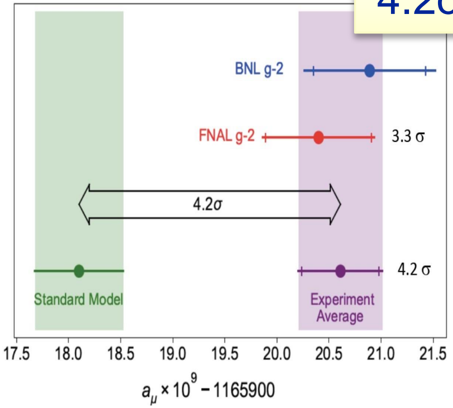


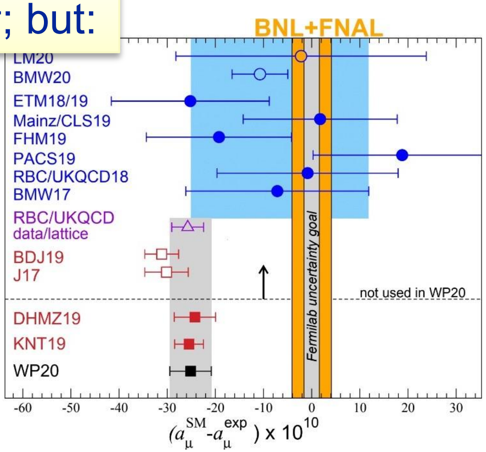
Low-energy e^+e^-
or Lattice QCD

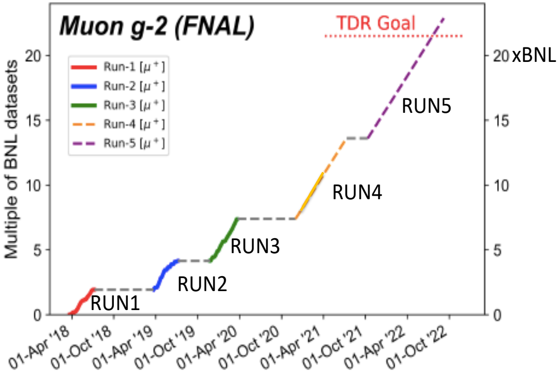




4.2σ; but:

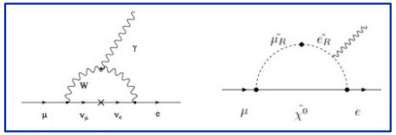






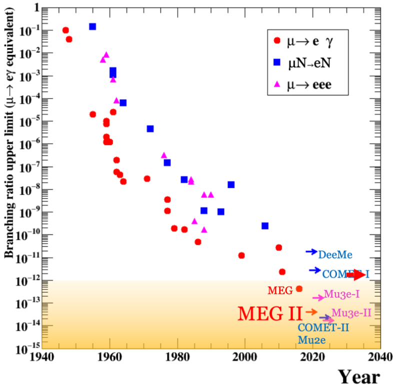
Flavor physics: charged lepton sector & summary

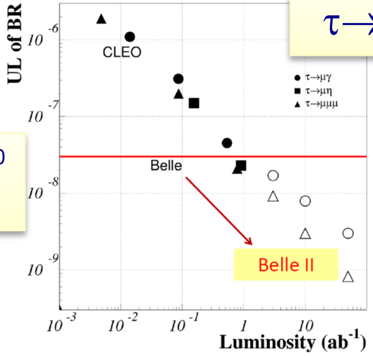
Final MEG upper limit
B(μ→eγ)<4.2 10^{-13}
@90% CL: there
since 2016…



Muon LFV quiet since 2016…
Exciting times ahead with
MEGII, Mu2e, COMET, Mu3e…

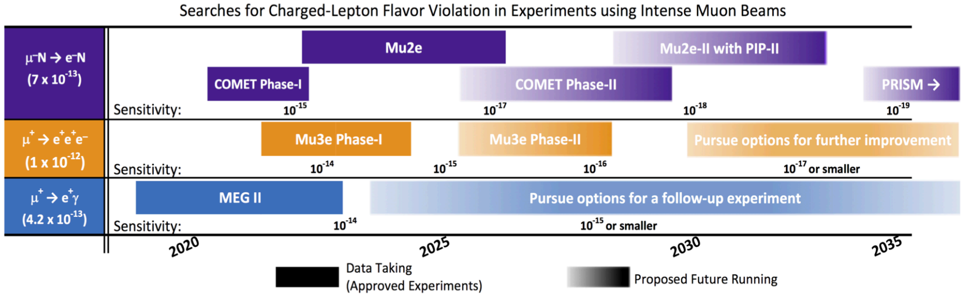
μ→eγ
μ→eee
μN→eN





τ→μμμ

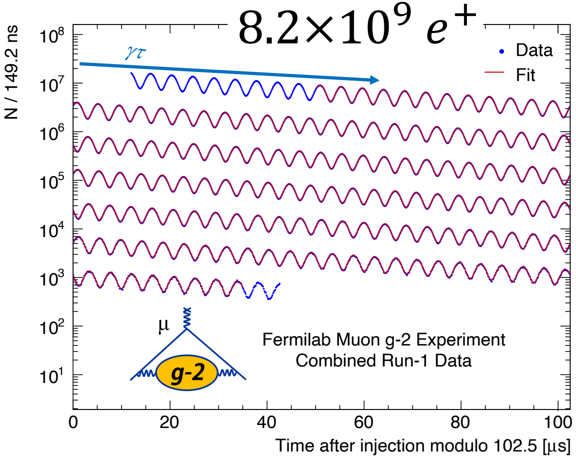
Expect 5x10^{10}
ττ evts…

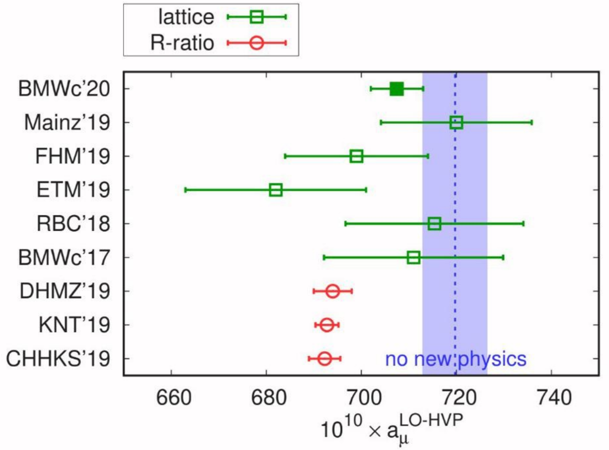


Qualitative summary

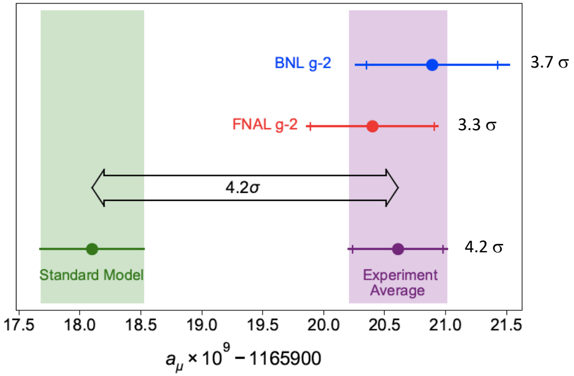
Muon g–2

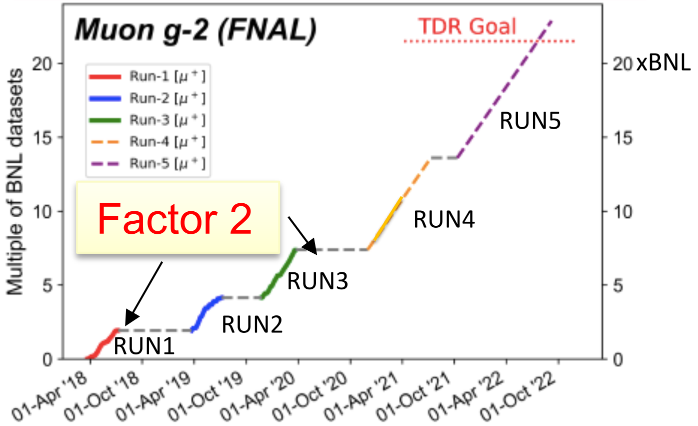
- **Confirmation of Brookhaven result. Question is now more on Theory…**





$$a_\mu(\text{FNAL}) = 116\,592\,040(54)\times10^{-11} \quad (0.46\ \text{ppm})$$



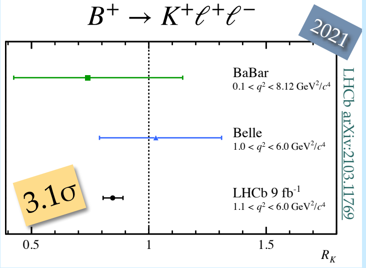


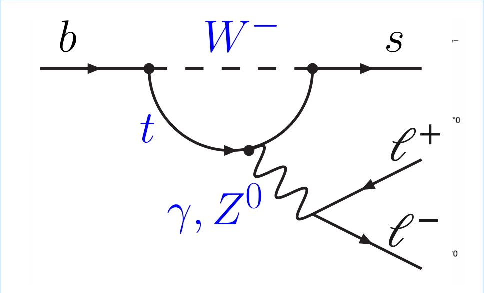
Flavor physics: quark sector (II)

Lots of attention on Lepton Universality.

$b \to s\ell^+\ell^-$

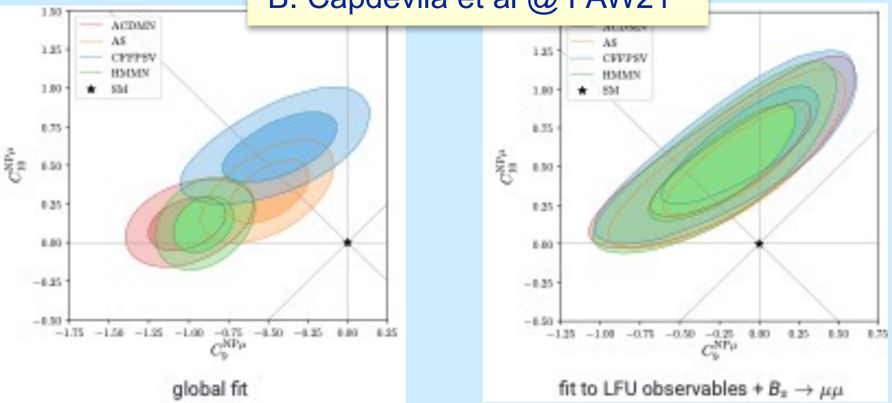
$R_K = \mu\mu K/eeK$ $R_{K^*} = \mu\mu K^*/eeK^*$





+semileptonic + ang. distrib.

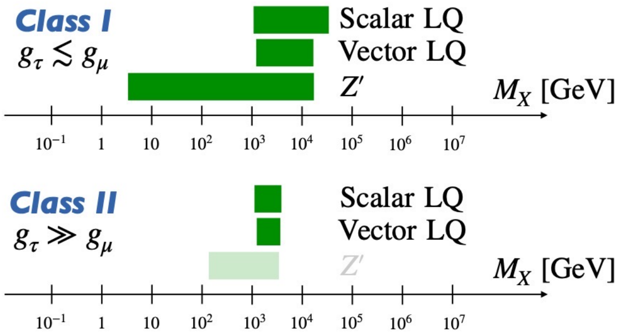
B. Capdevila et al @ FAW21*

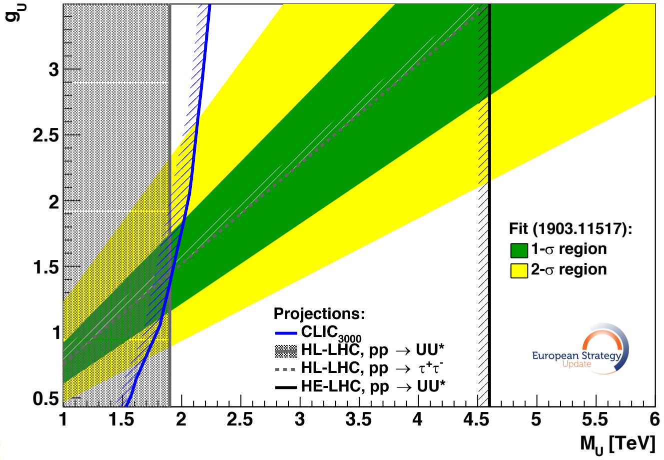


global fit

fit to LFU observables + $B_s \to \mu\mu$

A. Greljo @ FAW21*

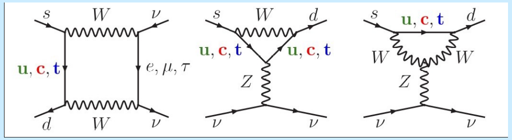




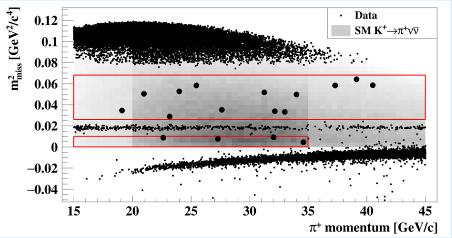
*Unpaid ad for FAW21: Flavour Anomaly Workshop 2021

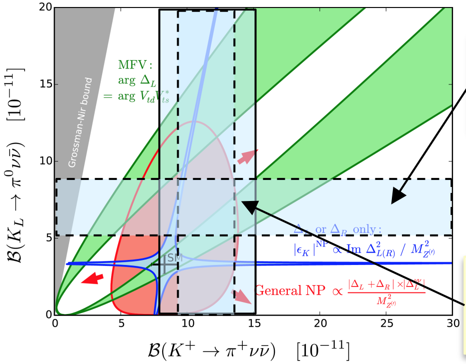
Flavor physics: quark sector (III)

Today: NA62



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





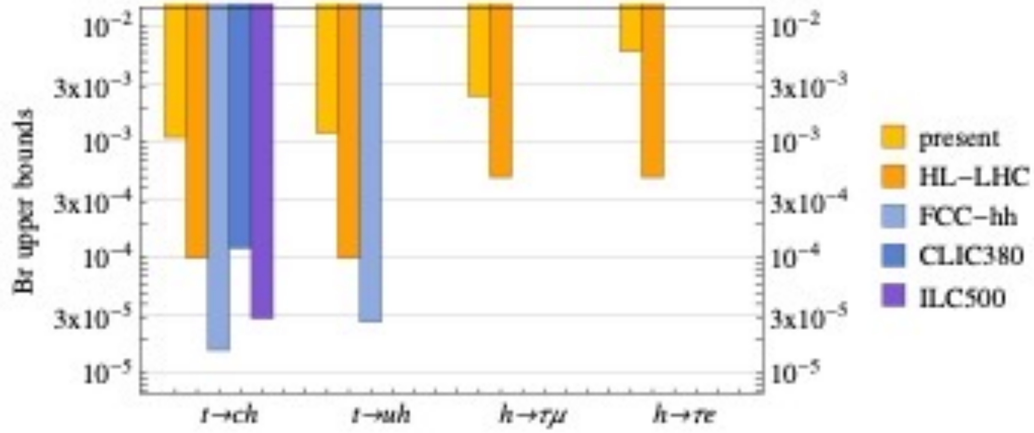
KOTO 2
KLEVER

NA62
(today+guess)

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		[illegible]	[illegible]	4	2.4	≈ 0.1	0.6
$t \to \gamma c$	7.4		≈ 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						

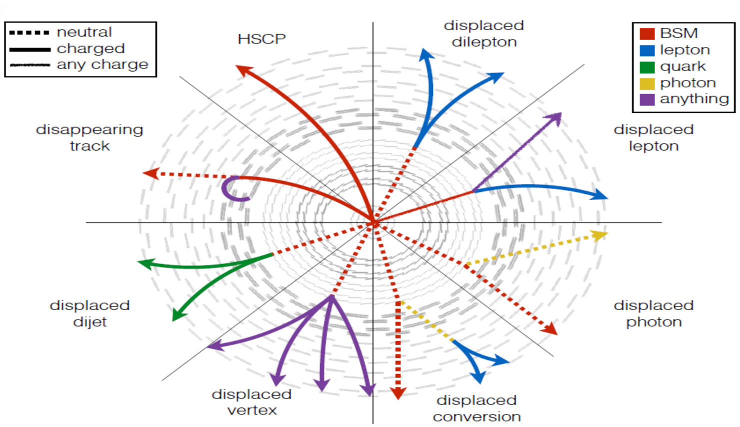
FCNC with higgs decays



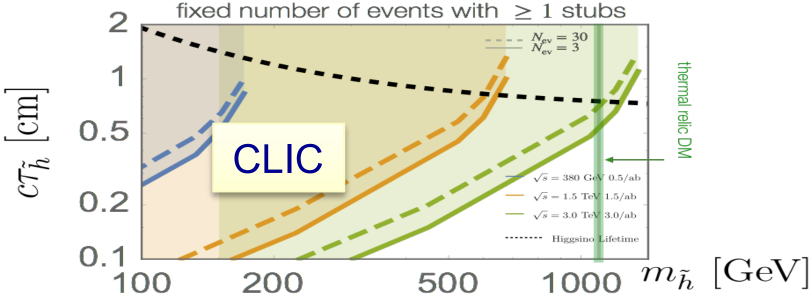
Physics of flavor: Lepton & Quark sectors

- **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. $\mu \to e\gamma$)

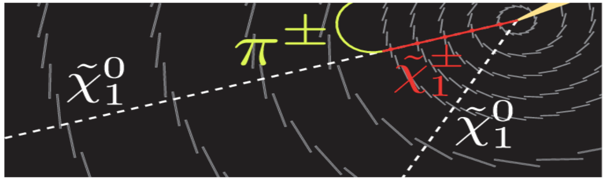
Long-lived SUSY?

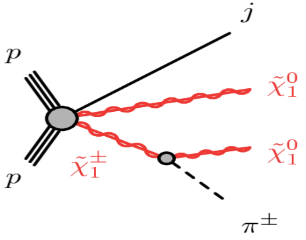


Charged stub + photon

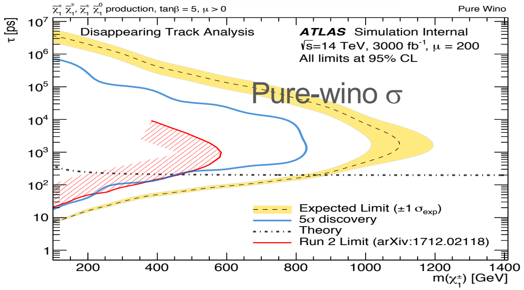


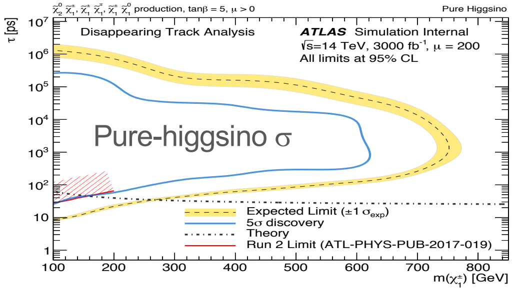
CLIC

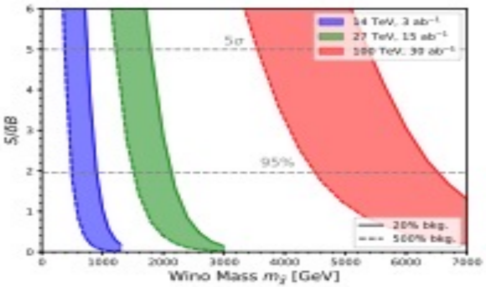


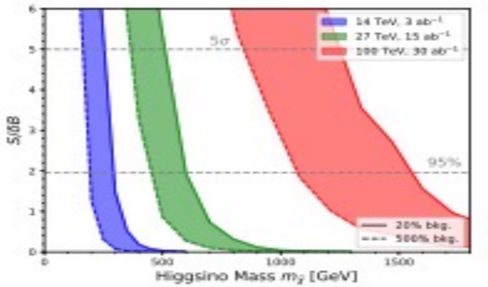


HL-LHC



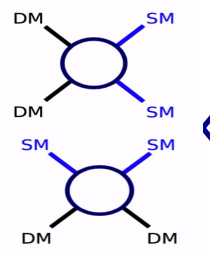




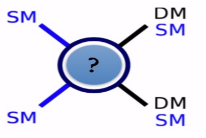


DM: summary

- **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)

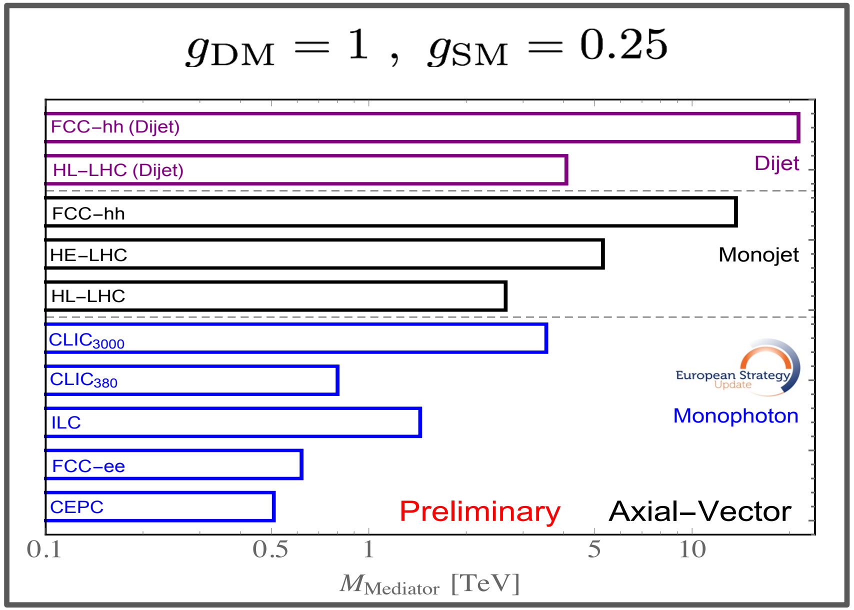


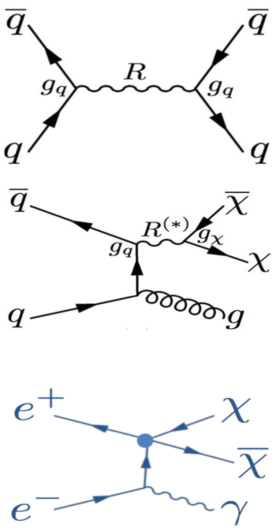
cosmological origin
DD/ID/astrophysics

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

Simplified Models: axial vector

- **Light DM, m_χ=1GeV**





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

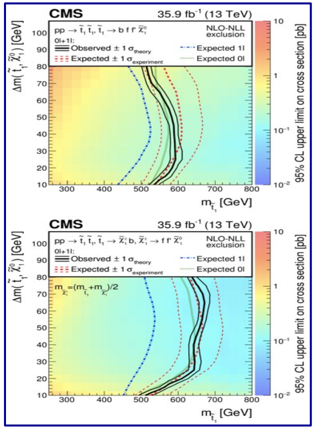
Dependence on couplings!

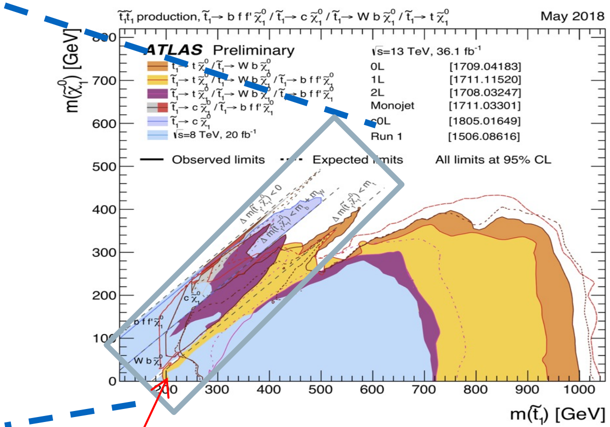
ee: assumes mediator couplings to leptons only. Also in EFT limit, so can be easily rescaled for modified couplings.

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”?



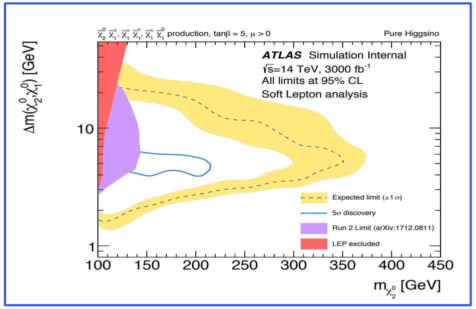


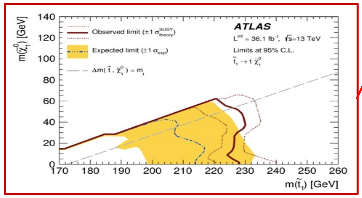
–:

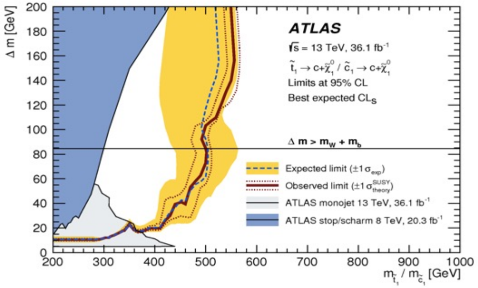
Info only from LHC (& only for stop).

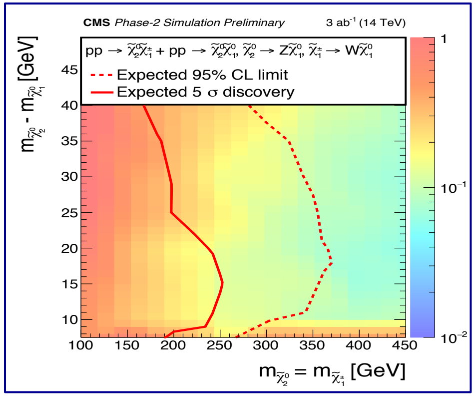
+:

based on data!





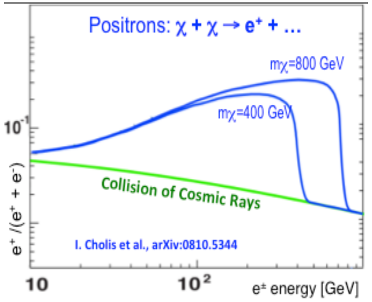




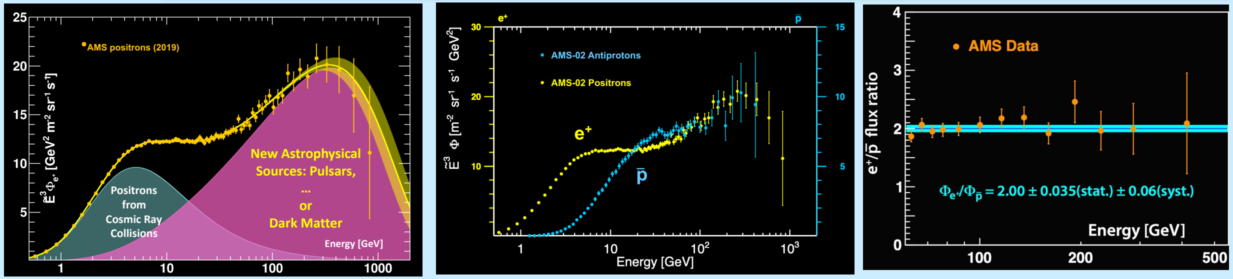
Indeed, after LHC, there will be holes [in low mass regions]; closing or looking at how to close them at HL-LHC; for EWKinos, some regions will remain difficult @ pp.

DM indirect searches: AMS update

The dream scenario

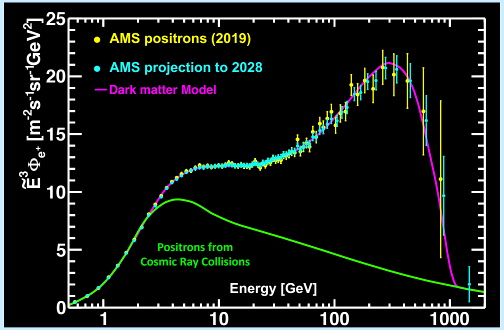


Reality: tantalizing fall (?!). But pulsars? Moreover: antiprotons!

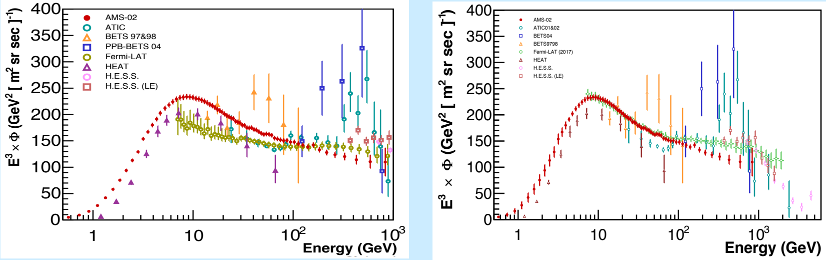


Z. Weng ICHEP2020

The future (~2028)



A parting thought: these are (very) difficult measurements; aka: precision makes a difference



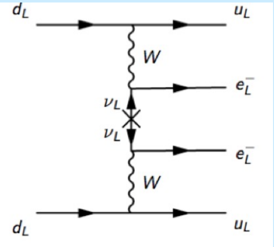
Neutrinos

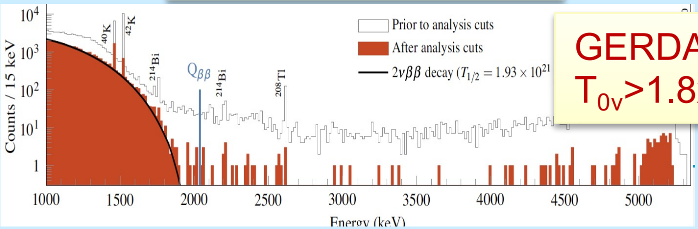
Extras

Neutrinos: Majorana/Dirac (0νββ) & mass measurement

As fundamental as a question can get & very hard to answer

$$(T_{1/2})^{-1} = G^{0\nu} \cdot |M^{0\nu}|^2 \cdot |m_{\beta\beta}|^2$$



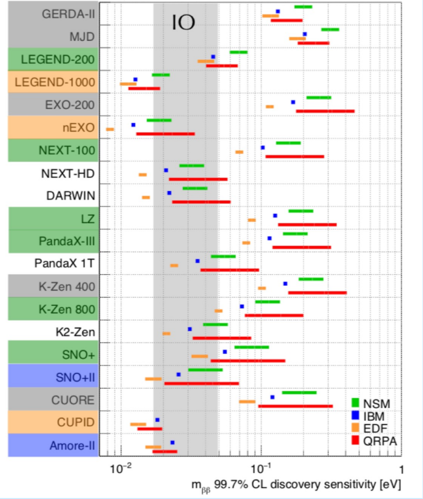


GERDA
$T_{0\nu} > 1.8\text{x}10^{26}$ yr

Extremely active field

- Bolometers (CUPID, AMoRE, CANDLES IV)
  - Measure *E* (σ ~ 0.1-0.3%) from phonons; granularity gives position info
  - Instrumenting with photon detectors for background rejection
- External trackers (SuperNEMO)
  - Trackers + calorimeters, measure *E* (σ ~ 3-10%) + tracks / positions + PID
- Scintillators (KamLAND2-Zen, SNO+, Theia, ZICOS)
  - Measure *E* (σ ~ 3-10%) + position from scintillation light; some PID
- Semiconductors (LEGEND, SELENA)
  - Measure *E* (σ ~ 0.05-0.3%) from ionization; some tracking / position sensitivity
- TPCs (nEXO, NEXT, PandaX, AXEL, NvDEx, DARWIN, LZ)
  - Collect scintillation + ionization: measure *E* (σ ~0.4-3%) + tracks / position + PID

(J. Detwiler @ Neutrino2020)

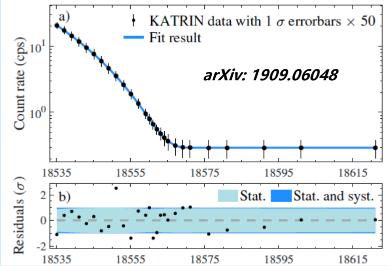


(But) one example: EXO-200 (0.2 t) → nEXO (5 t)
Xe; $T_{1/2} < 3.5\text{x}10^{25}$ yr → $T_{1/2} < 10^{28}$ yr

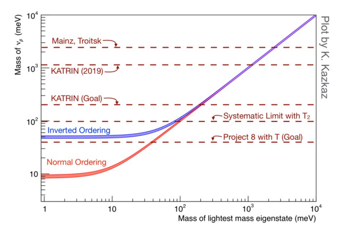
Mass limits (measurements…)

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

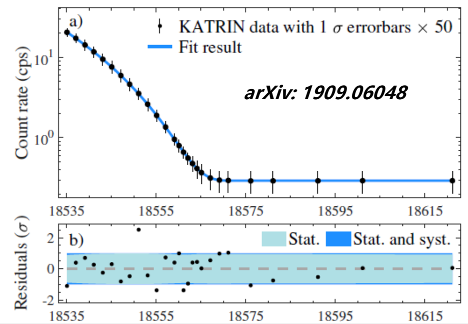
Direct m_ν measurement(s)
KATRIN: $m_\beta < 1.1$ eV (90% CL)
Asymptotic: $m_\beta < 0.2$ eV
Ultimate (Project-8): 40 meV



arXiv: 1909.06048

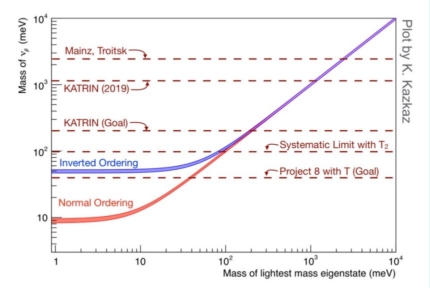


Neutrinos: Mass & nature (Majorana/Dirac – 0νββ)

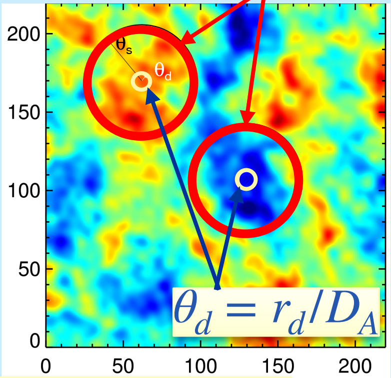


Direct m_ν measurement(s)
KATRIN
$m_\beta < 1.1$ eV (90% CL)
Asymptotic: $m_\beta < 0.2$ eV

Ultimate (Project-8): 40 meV

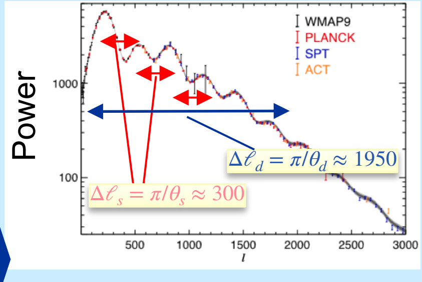


$\theta_s = r_s / D_A$



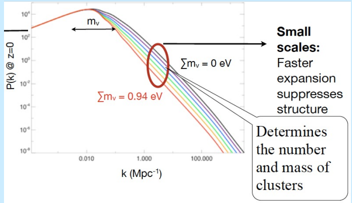
$\theta_d = r_d / D_A$

L. Knox Neutrino2020



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

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



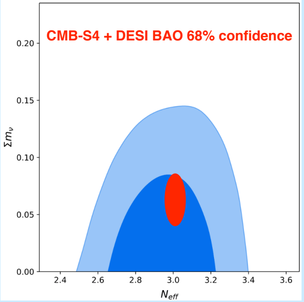
Small scales: Faster expansion suppresses structure

Determines the number and mass of clusters

Sound Horizon : $r_s \propto 1/H$

Photon diffusion : $r_d \propto 1/\sqrt{H}$

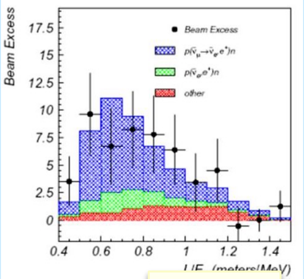
$H^2 = 8\pi G\rho/3$



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

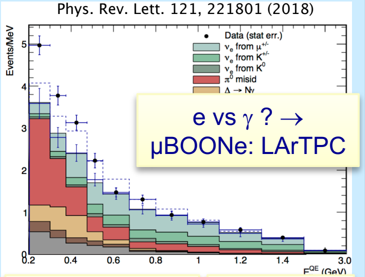
Future (DESI+BAO) : $\sigma(\Sigma m_\nu) < 0.02$!

Neutrinos: sterile sector (?)



LSND

L~30m
E~30MeV

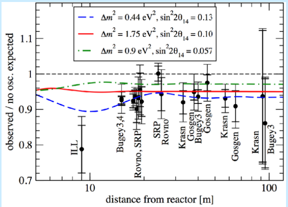

Phys. Rev. Lett. 121, 221801 (2018)

e vs γ ? → μBOONe: LArTPC

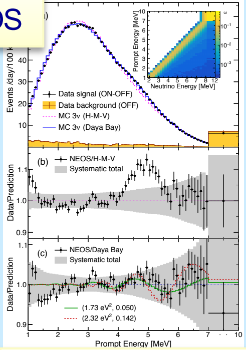
MiniBooNe
4.6σ ν_e excess!

L~500m
E~500MeV

NEOS



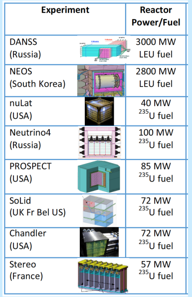
ν_e shortage in reactor expts
(But TH shaky)



Taking 5 MeV bump as due to sterile ν

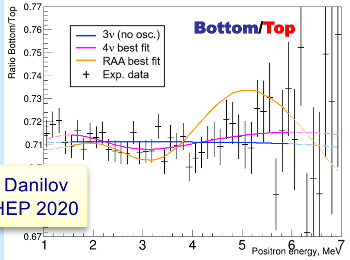
Very active field

Several expts: proposed running



Experiment		Reactor Power/Fuel
DANSS (Russia)		3000 MW LEU fuel
NEOS (South Korea)		2800 MW LEU fuel
nuLat (USA)		40 MW ^{235}U fuel
Neutrino4 (Russia)		100 MW ^{235}U fuel
PROSPECT (USA)		85 MW ^{235}U fuel
SoLid (UK Fr Bel US)		72 MW ^{235}U fuel
Chandler (USA)		72 MW ^{235}U fuel
Stereo (France)		57 MW ^{235}U fuel

+ICHEP2020 : + DayaBay, RENO…



M. Danilov
ICHEP 2020

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

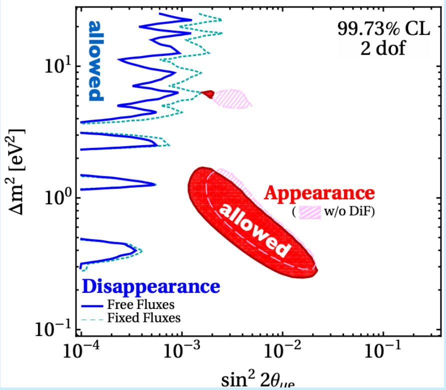
$$P_{\alpha\beta} \simeq \delta_{\alpha\beta} - 4|U_{\alpha\beta}|^2(\delta_{\alpha\beta} - |U_{\alpha\beta}|^2)\sin^2\left(\frac{\Delta m^2_{41} L}{4E}\right)$$

ν_e DIS
$\sin^2 2\vartheta_{ee} \simeq 4|U_{e4}|^2$

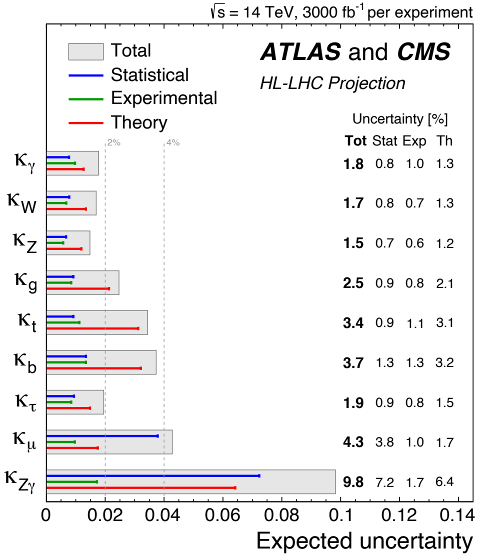
ν_μ DIS
$\sin^2 2\vartheta_{\mu\mu} \simeq 4|U_{\mu4}|^2$

$\nu_\mu \to \nu_e$ APP
$\sin^2 2\vartheta_{e\mu} = 4|U_{e4}|^2|U_{\mu4}|^2 \simeq \frac{1}{4}\sin^2 2\vartheta_{ee}\sin^2 2\vartheta_{\mu\mu}$
[Okada, Yasuda, IJMPA 12 (1997) 3669; Bilenky, CG, Grimus, EPJC 1 (1998) 247]

$\nu_\mu \to \nu_e$: LSND, MiniBOONe, OPERA
$\nu_\mu \to \nu_\mu$: MiniBOONe, MINOSetal
$\nu_e \to \nu_e$: Gallium, Reactors, Solar Exp



HL-LHC: Higgs physics



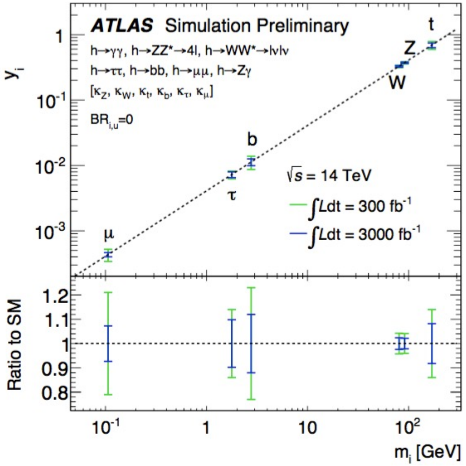
	Uncertainty [%] Tot	Stat	Exp	Th
κ_γ	**1.8**	0.8	1.0	1.3
κ_W	**1.7**	0.8	0.7	1.3
κ_Z	**1.5**	0.7	0.6	1.2
κ_g	**2.5**	0.9	0.8	2.1
κ_t	**3.4**	0.9	1.1	3.1
κ_b	**3.7**	1.3	1.3	3.2
κ_τ	**1.9**	0.9	0.8	1.5
κ_μ	**4.3**	3.8	1.0	1.7
$\kappa_{Z\gamma}$	**9.8**	7.2	1.7	6.4

$\sigma(m_H) \sim$ 10-20 MeV

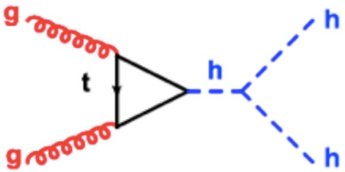
Expect $\lesssim$ 5% uncertainty on main production channels and BRs

Coupling sensitivity expressed as uncertainty on multiplicative modifiers κ_i

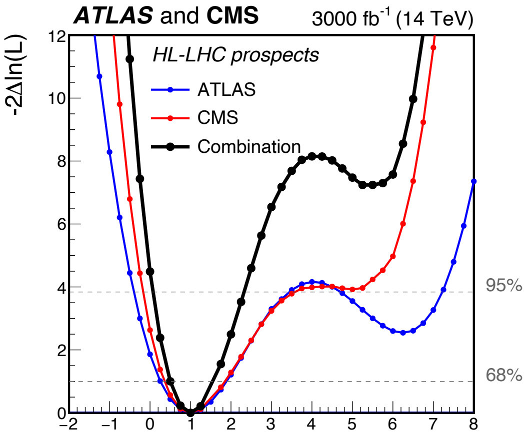
$\mathscr{B}(H \to \mathrm{inv})$ = 0.1% in SM, sensitive to BSM, e.g. attractive Dark Matter models



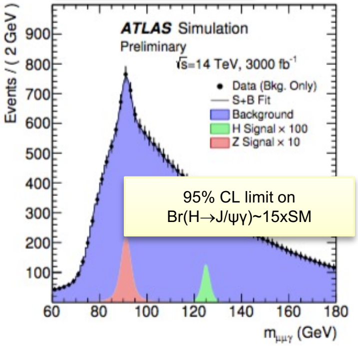
H self-coupling



λ very challenging; need multiple channels



Y$_c$?
Not quite



95% CL limit on Br(H→J/ψγ)~15xSM