Search for the invisible decays of the Higgs boson at 13 TeV (CMS experiment)

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Why the interest for the invisibly decaying Higgs?

- **The "crown jewel" of the experimental particle physics:**
  - Higgs boson was discovered by **ATLAS** and **CMS experiments** at CERN in 2012
  - All of the following measurements of its properties have been **consistent** with the **Standard Model (SM)**
  - Large uncertainties of these measurements can allow for physics beyond the SM

Why the interest in the invisible final state?

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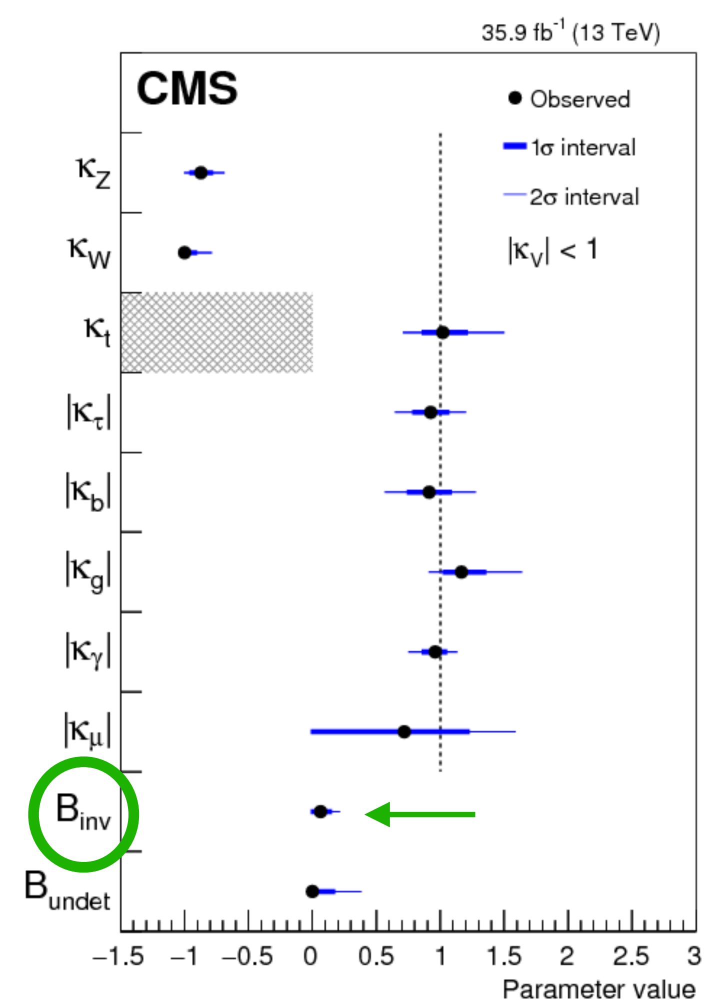
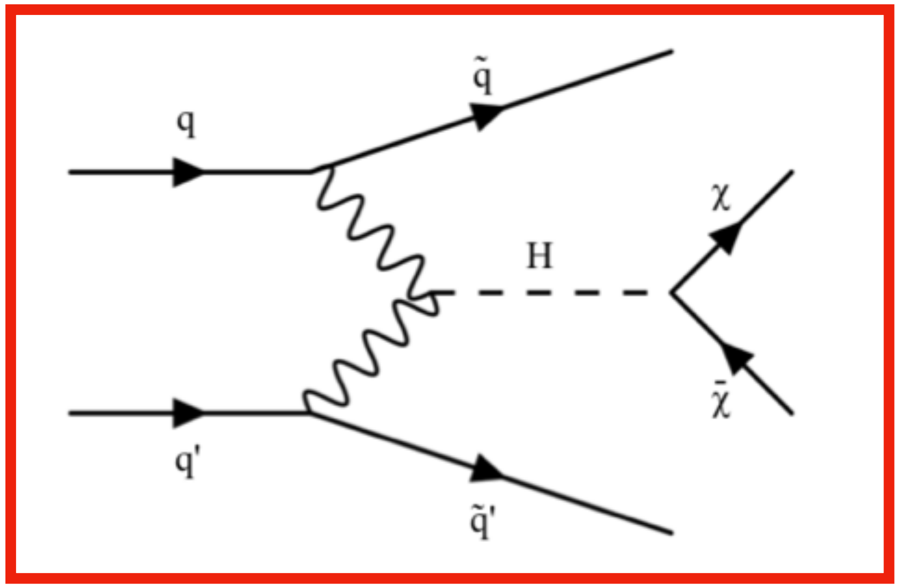


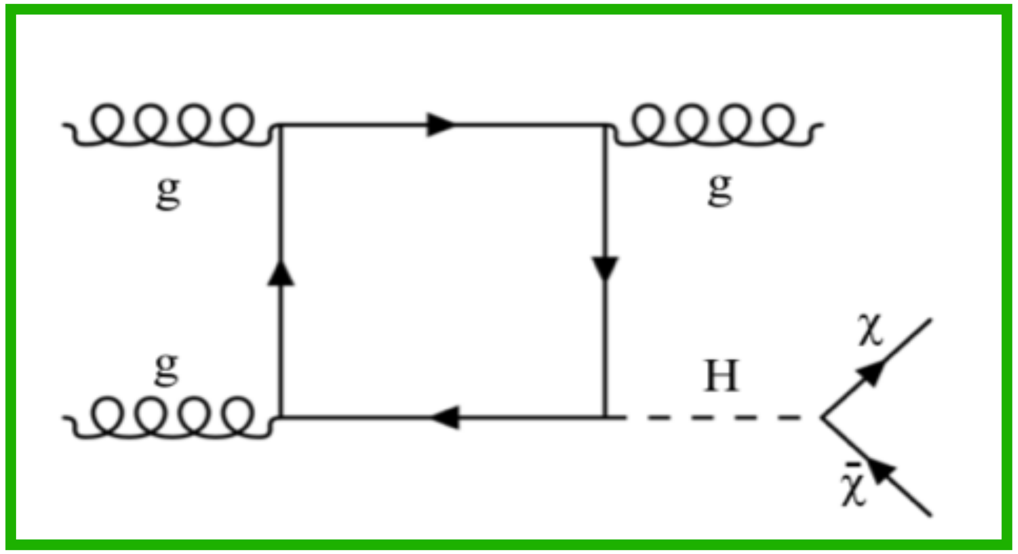
- **According to the SM, the probability of Br(H → 4ν) ~ 0.1 %**
  - **Can represent a good way of testing for BSM physics!**
  - **Higgs boson** could be a **mediator between SM and DM** sector
  - Detection would require it to recoil against a visible system

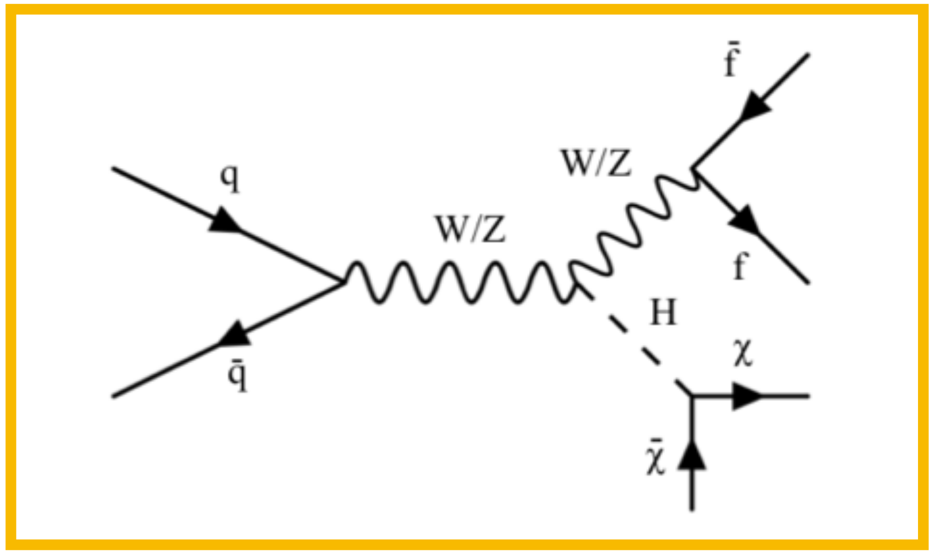
Why the interest for the invisibly decaying Higgs?

- **Higgs boson can take a role of a mediator between SM and DM particles:**
  - Detection requires for the **Higgs to recoil against a visible system**
  - **Large** missing transverse energy (**$E_{T,miss}$**)



- **qqH** : Higgs boson is produced in a vector boson fusion topology (VBF)
- **VH**: Higgs boson production with a vector boson
- ggH: Higgs boson produced via gluon fusion.





Where were we up untill now? Early Run 2 combination

- **The first combination measurement using Run 2 data was published using the 2016 dataset**
- **No significant deviation from the SM was reported:**
  - The result of the measurement is expressed as the **95% CL upper limit on the B(H → inv.)**
  - **This publication also included a first combination of Run 1 and 2015+2016 data**
    - Setting the B(H → inv) limit to be at **0.19 (0.15)** for the observed (expected) value

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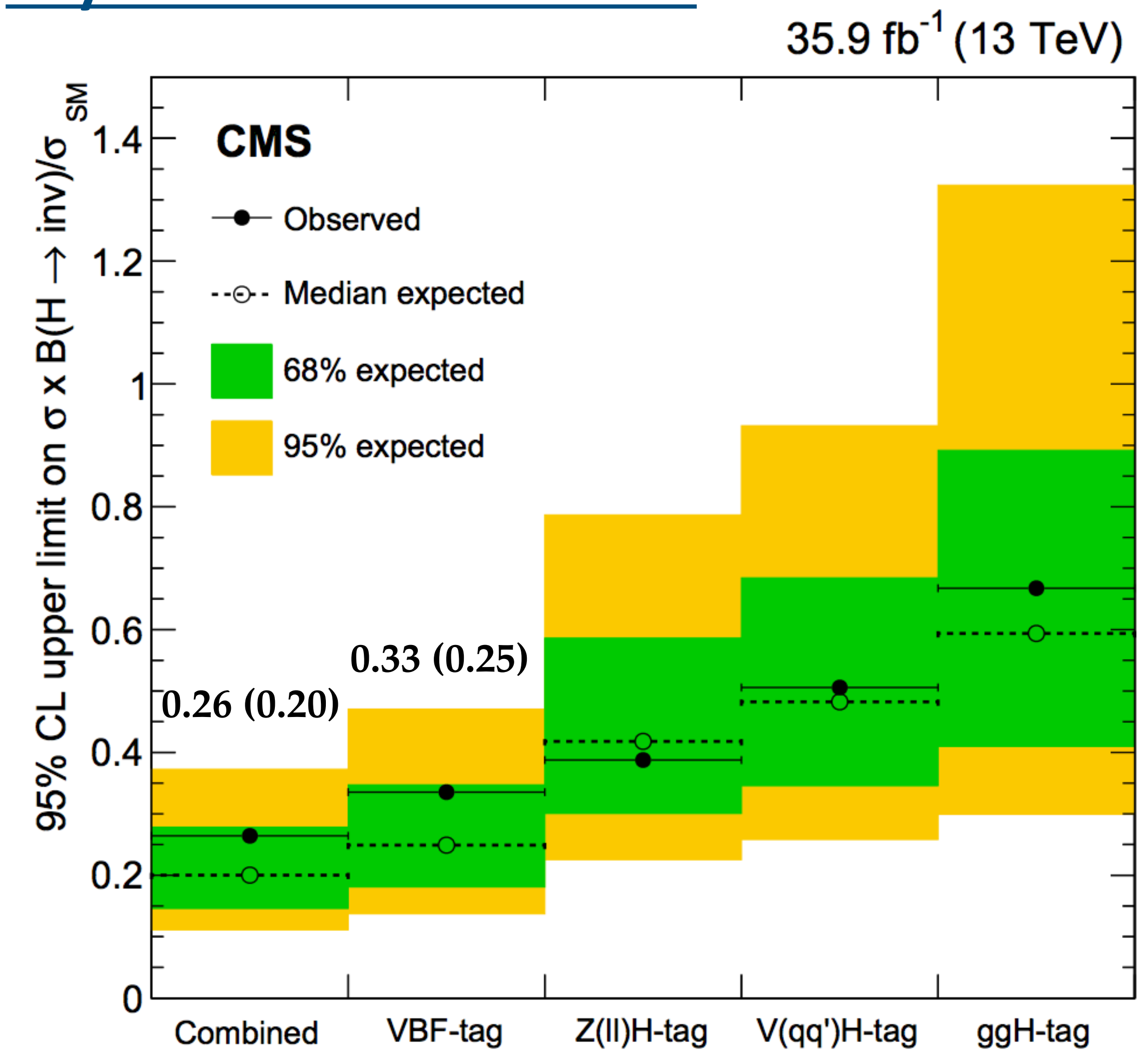
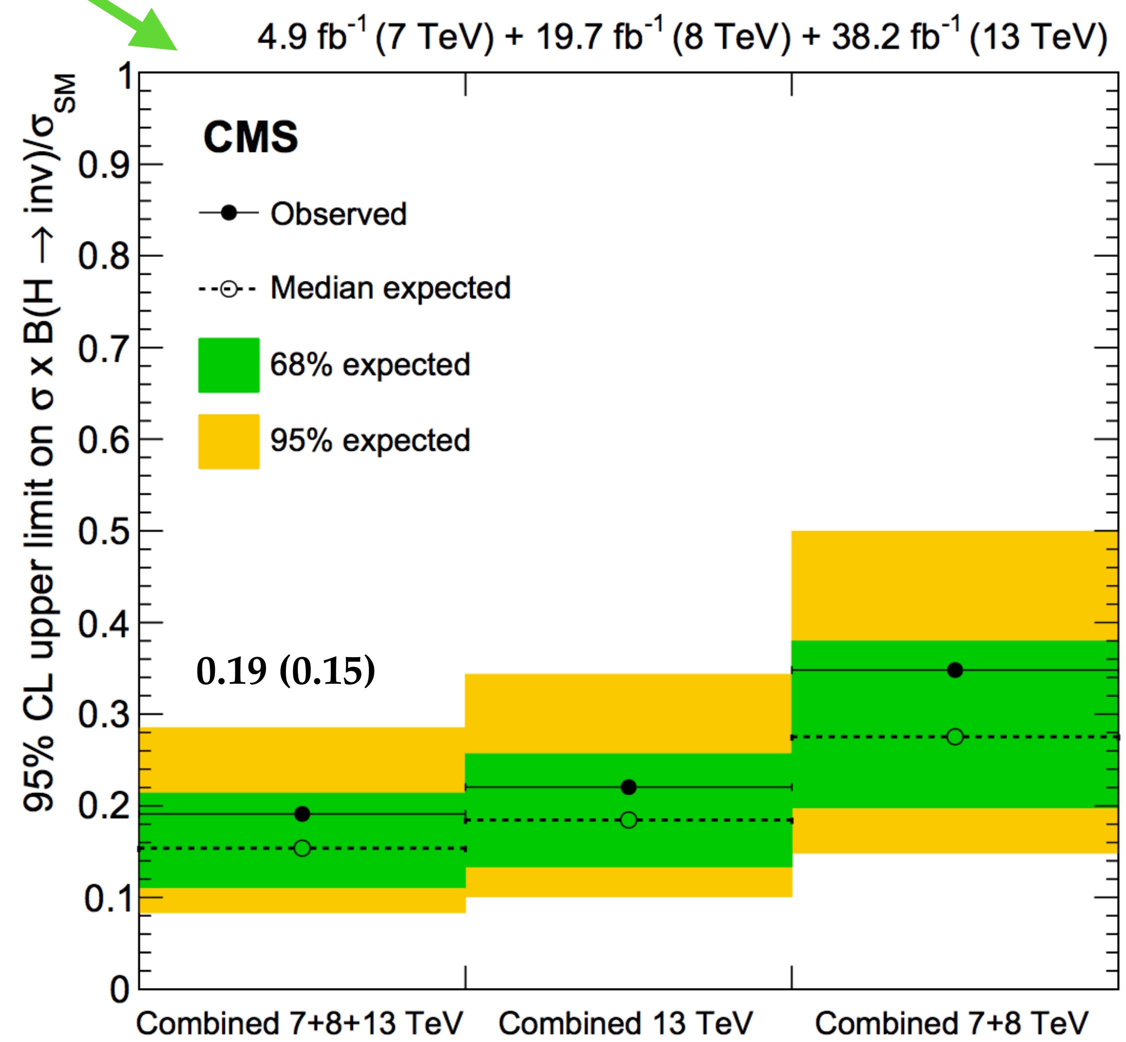
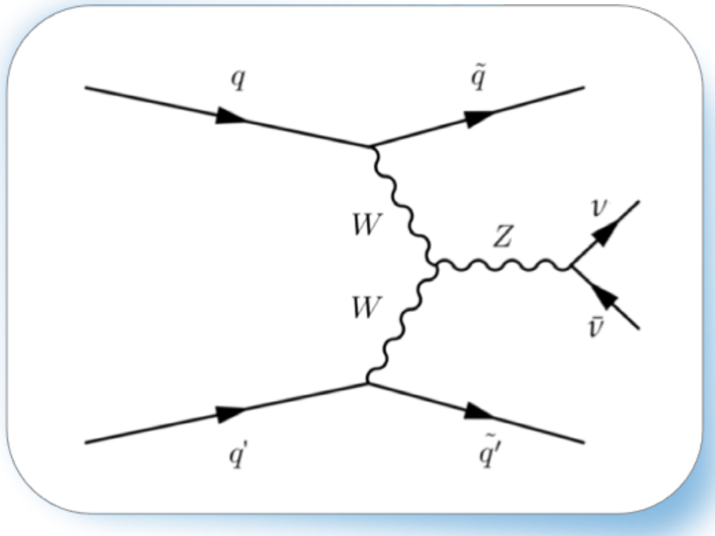


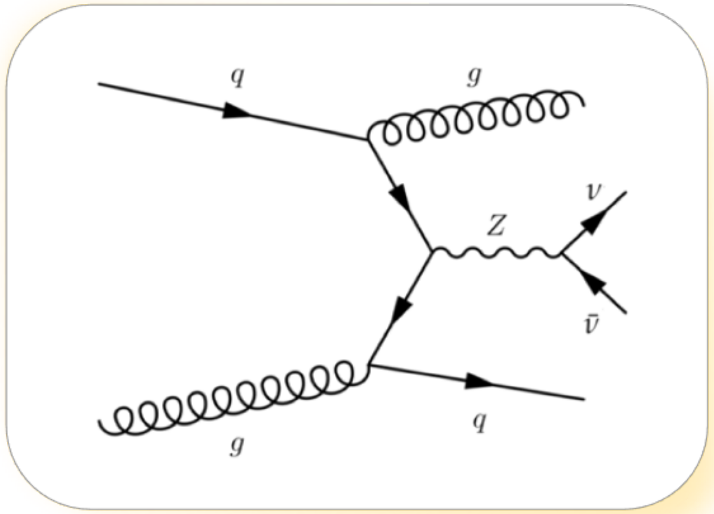


The Run 2 analysis strategy: Introduction

- **VBF production mode of the Higgs boson has a characteristic signature:**
  - **Two jets** with a **large geometrical separation**
  - **High dijet invariant mass** (a good way to control S/B)
  - Represents a channel with the largest sensitivity

- **Main backgrounds:**
  - **QCD and EWK produced V+jets (where V= W/Z)**
    - Irreducible when Z->νν and W->lν
      - With the charged lepton being missed in the detection
  - **Estimated through dedicated control regions in data (CR):**
    - Z or W boson associated with the same dijet topology
    - Resulting in four CRs separated by lepton flavour (e/μ)
  - **QCD multi jet processes - data driven estimation**
  - **Contributions expected from diboson and top processes are estimated using simulation**



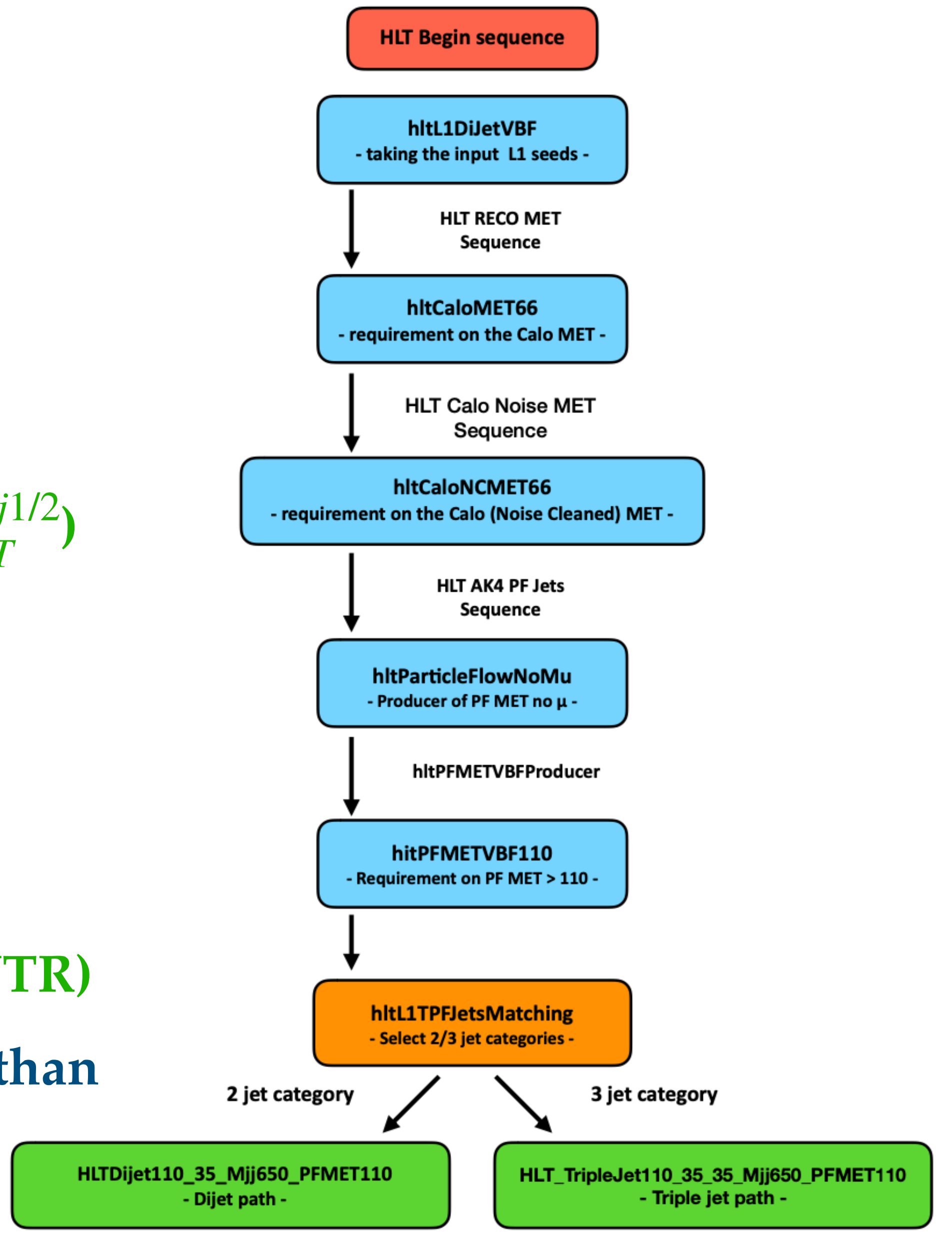


The Run 2 analysis strategy: Two trigger approach

- **Previous analysis strategy relied on purely $E_{T,miss}$ trigger algorithms**
  - **VBF topology targeting cuts were applied at the offline stage**
  - Imposed a high $E_{T,miss}$ **requirement: $E_{T,miss}$ > 250 GeV**
    - **Froming the high-$E_{T,miss}$ (MTR) analysis category**

- **The recent upgrades of the Level-1 trigger enabled complex variable manipulation at the first triggering stage:**
  - **Brought in the possibility to target VBF topology**
  - **New VBF H L1 algorithm explored selection requirements (m_{jj}, $p_T^{j1/2}$)**
  - **A follow up path at the second (HLT) stage:**
    - Matched the selection logic of the L1 seed
    - Imposed $E_{T,miss}$ **cuts in order to reduce rate/timing**

- **These additions led to a formation of a low-$E_{T,miss}$ analysis category (VTR)**
  - **For 160 <$E_{T,miss}$< 250 GeV, where the VBF trigger performs better than the generic $E_{T,miss}$ ones**



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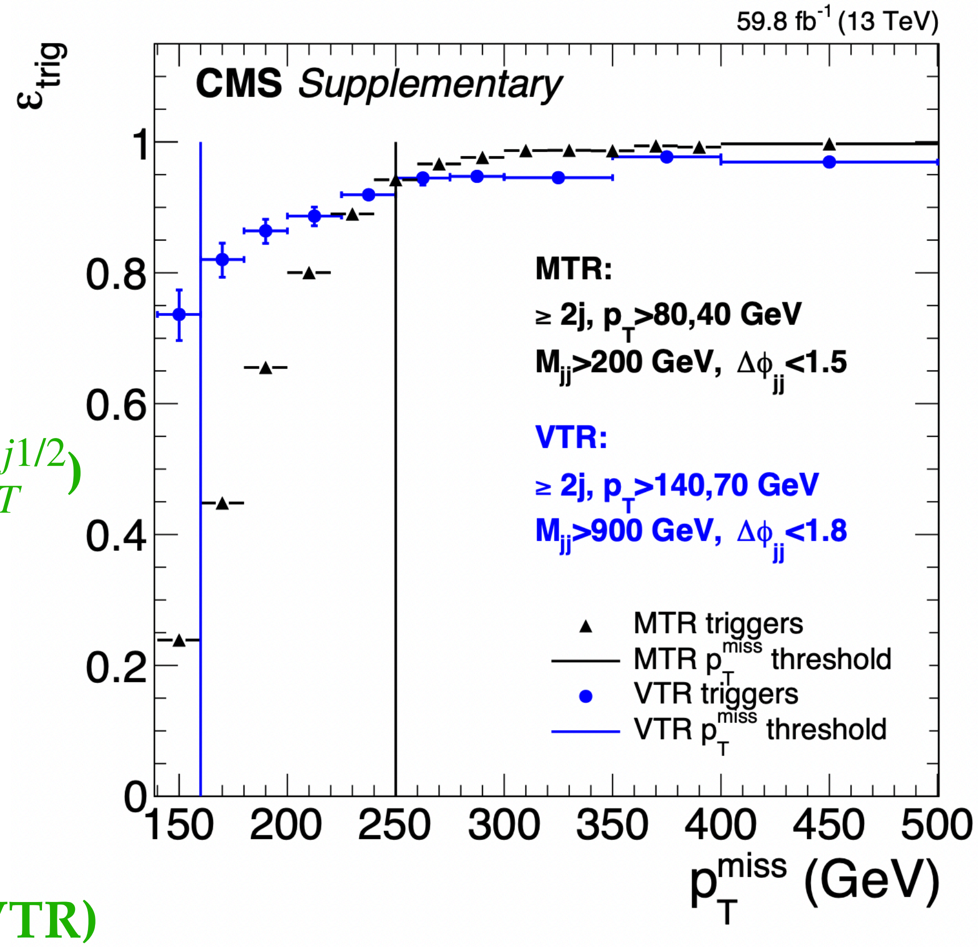

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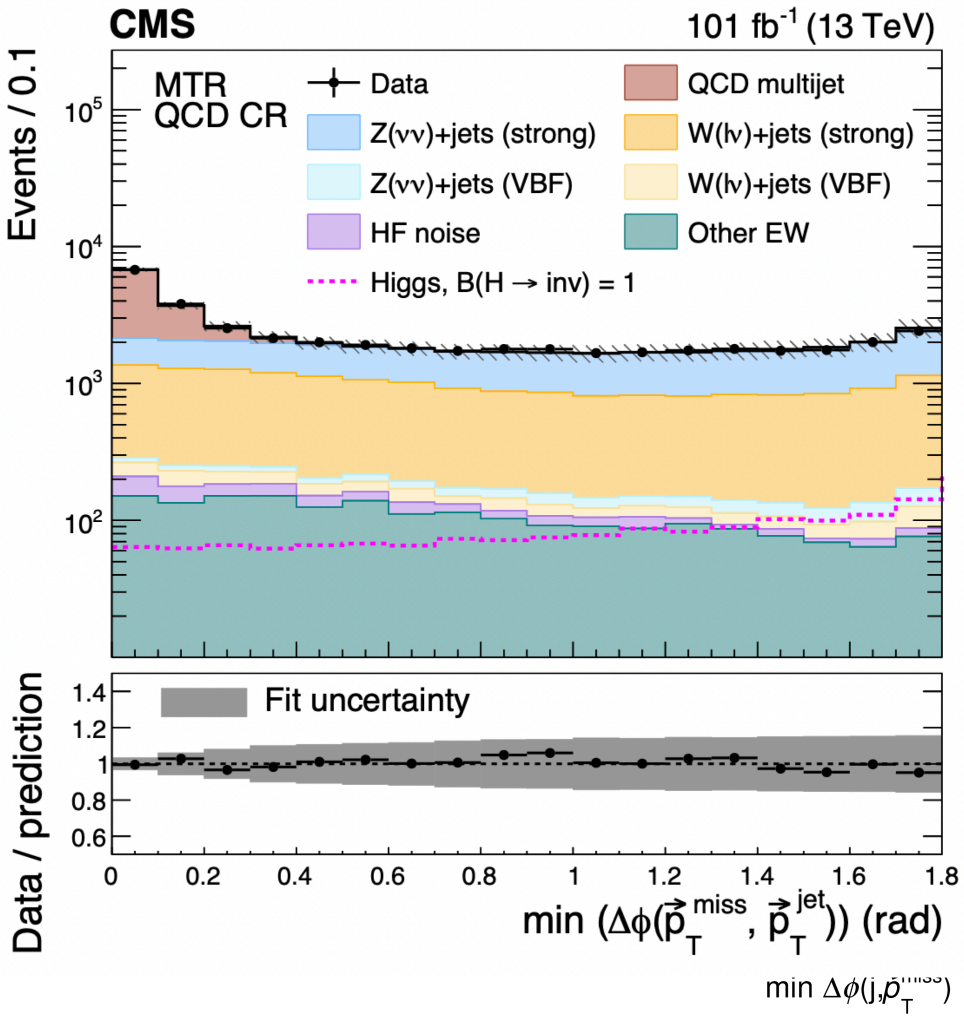
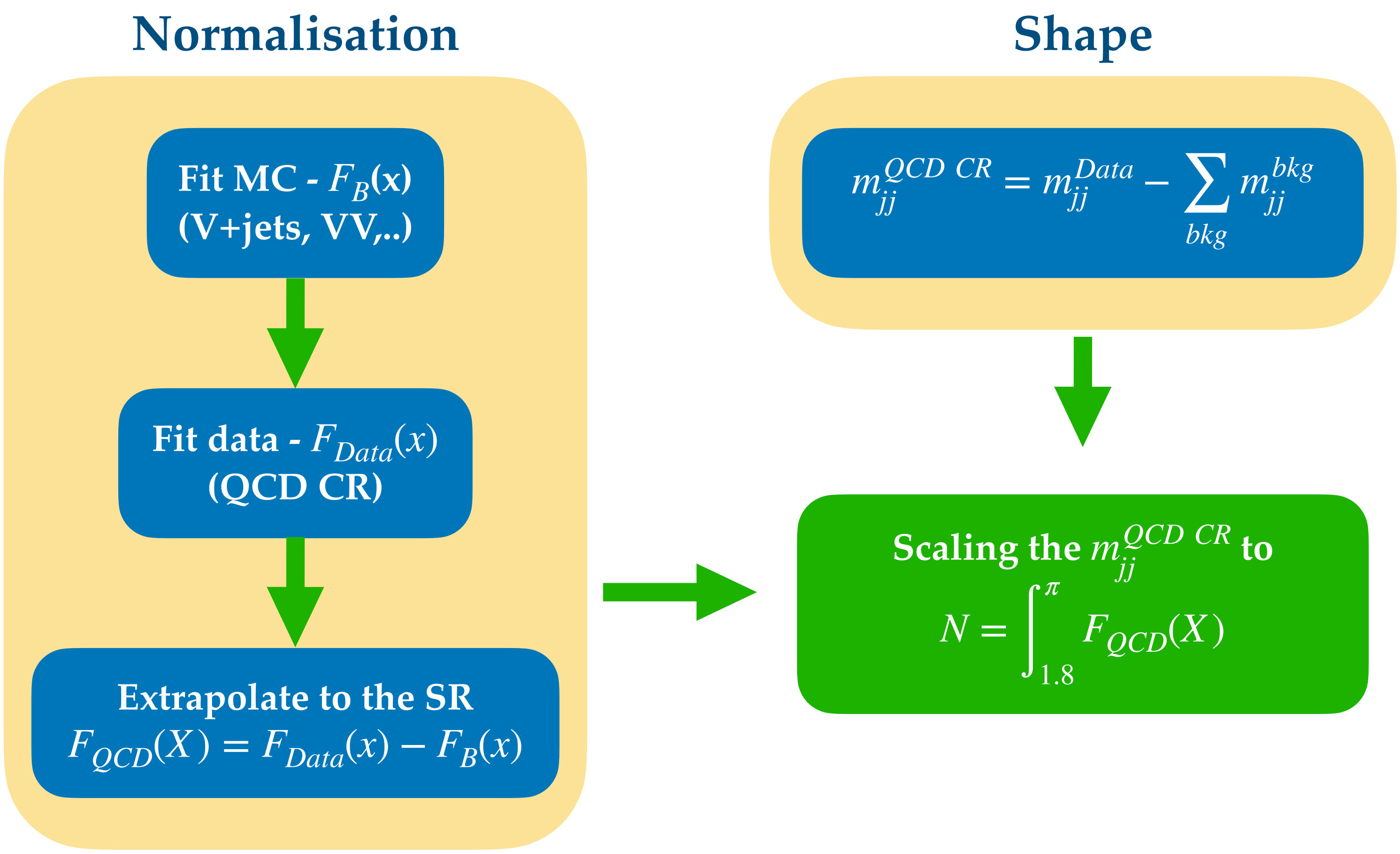
The Run 2 analysis strategy: QCD multijet estimtion

- **A data-driven estimate is performed using events in which the $E_{T,miss}$ arises from mismeasured jets:**
  - A QCD multijet enriched region (CR) is formed by inverting one of the selection requirements
  - The low $X = min\Delta\phi(j, E_{T,miss})$ is used to define QCD CR
- **Two steps are taken in order to obtain the QCD multijet contribution in the SR:**
  - Shape of the dijet mass and its SR normalisation

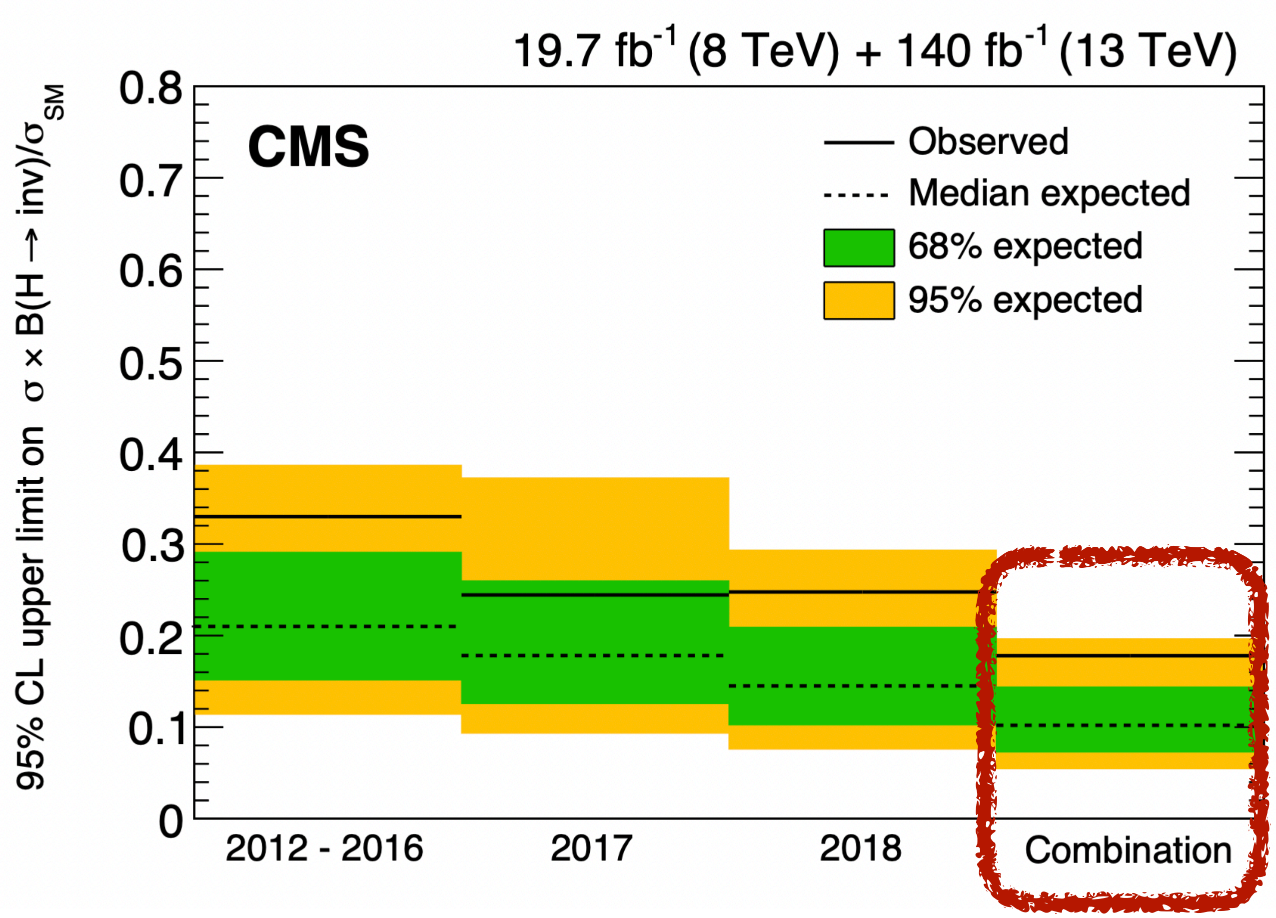




VBF analysis: Full Run 2 measurement - Results

- **The VBF H(invisible) measurement using full Run 2 data - latest result (Phys. Rev. D 105 (2022) 092007)**
  - Improvements to he analysis strategy:
    - **Addition of new VBF H(invisible) topology targeting triggers**
      - **Creating of a new, low E_T^{miss}, analysis category**
    - Addition of another (γ) control region
      - Helping with statistical precision of Z(ll) CRs
    - Brought ~20% gain in terms of signal sensitivity (when compared to 2016 strategy)

- **No significant deviation from the SM was reported and the observed (expected) 95% CL upper limit was placed at:**
  - **B(H → inv) = 0.18 (0.10) for the 2012-2018 data taking periods**



Phys. Rev. D 105 (2022) 092007

Category	Observed	Median expected	65% expected	95% expected
2012–2016	0.33	0.21	[0.15, 0.29]	[0.11, 0.39]
VTR 2017	0.57	0.45	[0.32, 0.66]	[0.24, 0.94]
VTR 2018	0.44	0.34	[0.24, 0.49]	[0.18, 0.69]
VTR 2017+2018	0.40	0.28	[0.20, 0.40]	[0.15, 0.56]
MTR 2017	0.25	0.19	[0.14, 0.28]	[0.10, 0.40]
MTR 2018	0.24	0.15	[0.11, 0.22]	[0.08, 0.31]
MTR 2017+2018	0.17	0.13	[0.09, 0.18]	[0.07, 0.25]
all 2017	0.24	0.18	[0.13, 0.26]	[0.09, 0.37]
all 2018	0.25	0.15	[0.10, 0.21]	[0.08, 0.29]
all 2017+2018	0.18	0.12	[0.08, 0.17]	[0.06, 0.23]
2012–2018	0.18	0.10	[0.07, 0.14]	[0.05, 0.20]

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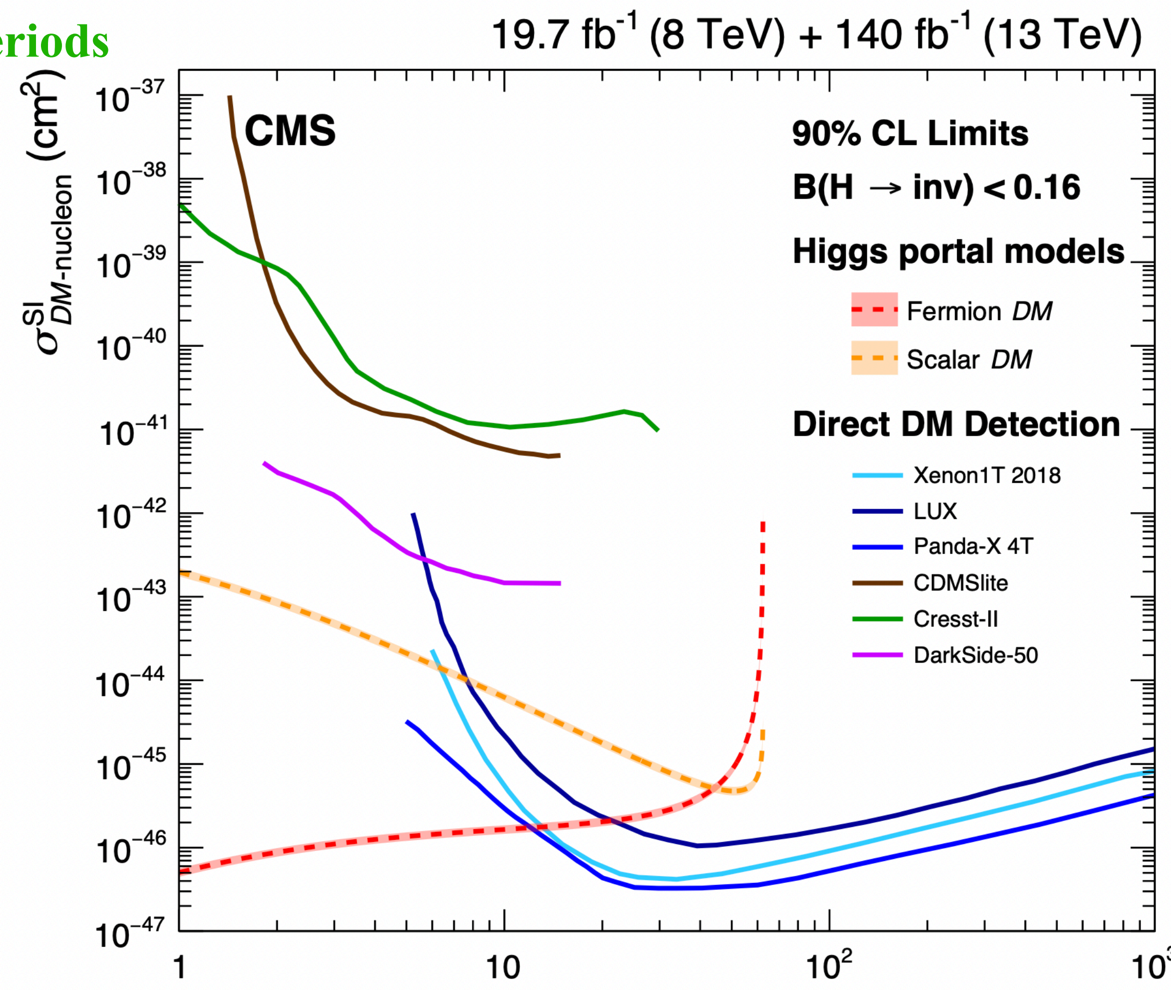
- **Reinterpretation of the results in terms of Higgs portal models:**
  - 90% CL upper limits on the spin-independent DM-nucleon scattering cross section
  - Assuming a scalar or fermion DM candidate



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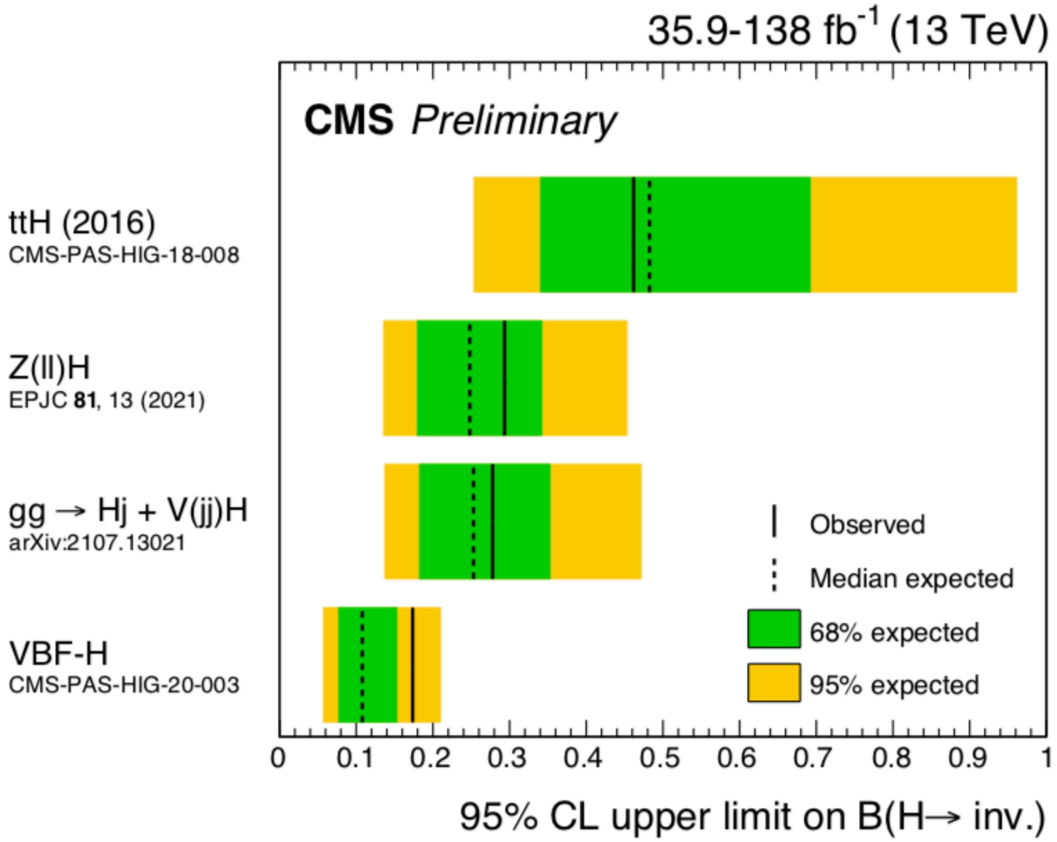
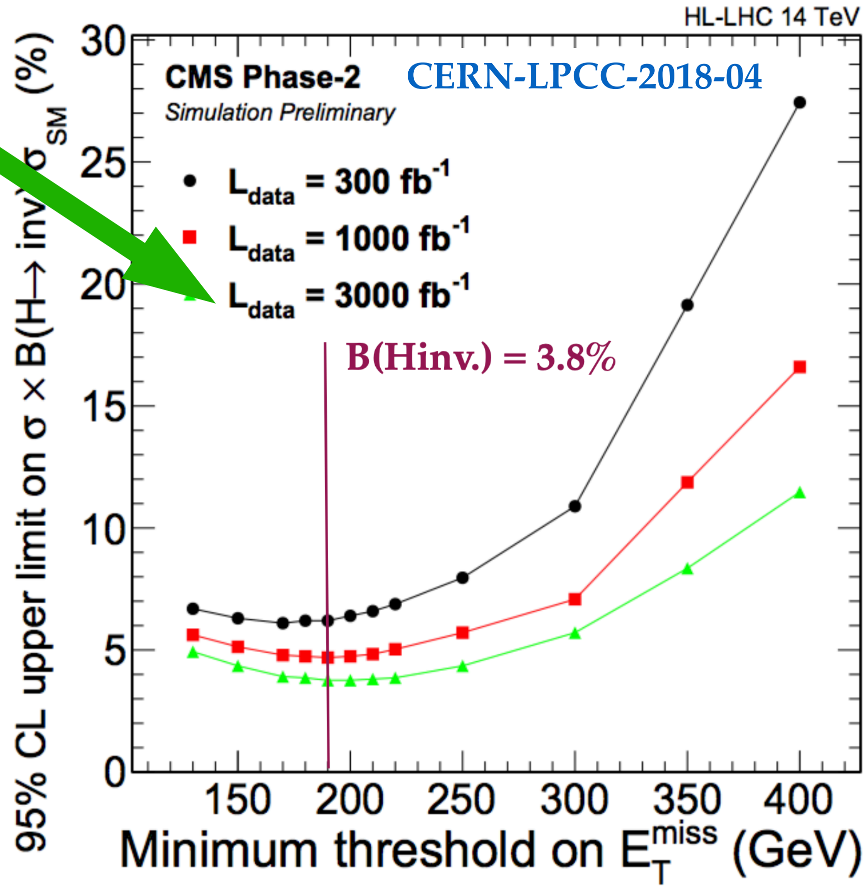
Summary & Conclusion

- **These slides have summarised the recent studies of the invisible decays of the Higgs boson produced in a VBF topology from the CMS Collaboration:**
  - **First combination:**
    - Focused on the **Run 1 + early Run 2 measurements**
    - Sets a limit on B(H → inv) at 0.19 (0.15) for the observed (expected) value
- **Measurements using the full Run 2 dataset:**
  - **Z(ll)H(invisible):** B(H → inv) = 0.29 (0.25)
  - **Mono V/mono Jet:** B(H → inv) = 0.28 (0.25)
  - **VBF H(invisible): B(H → inv) = 0.17 (0.11)**
- **The last missing piece is the ttH full Run 2 search**
  - Currently being prepared - coming really soon!



Summary & Conclusion

- **VBF production mode presents the best sensitivity:**
  - Chosen to investigate the sensitivity of the search with the HL-LHC
  - A **high-mjj** category was used for this study
    - Cut-and-count approach
  - The threshold on E_T^{miss} is varied from **130 to 400 GeV**
    - Likewise, the lower threshold on **mjj** is varied from **1000 to 4000 GeV**
    - Upper limits on the B(H->Invisible) are place at the 95% using the CLs criterion



- Similar study by **ATLAS** for the **VH**:
  - B(H->Invisible) ~ **8%** (ATL-PHYS-PUB-2013-014)
- Preparations for the upcoming phases are well underway!
- **Exciting new possibilities for the analysis specific trigger algorithms!**

Thank you for your time!

BACKUP

Selection requirements

Observable	MTR	VTR
Choice of pair	leading-p_T	leading-M_{jj}
Leading (subleading) jet	$p_T > 80\ (40)$ GeV, $\lvert\eta\rvert < 4.7$	$p_T > 140\ (70)$ GeV, $\lvert\eta\rvert < 4.7$
p_T^{miss}	> 250 GeV	$160 < p_T^{miss} \leq 250$
$\min\Delta\phi(\vec{p}_T^{miss}, \vec{p}_T^{jet})$	> 0.5 rad	> 1.8 rad
$\lvert\Delta\phi_{jj}\rvert$	< 1.5 rad	< 1.8 rad
M_{jj}	> 200 GeV	> 900 GeV
$\lvert p_T^{miss} - \text{calo}p_T^{miss}\rvert / p_T^{miss}$	< 0.5	
Leading/subleading jets $\lvert\eta\rvert < 2.5$	NHEF < 0.8, CHEF > 0.1	
HF-noise jet candidates	0 (see Table **??**)	
τ_h candidates	$N_{\tau_h} = 0$ with $p_T > 20$ GeV, $\lvert\eta\rvert < 2.3$	
b quark jet	$N_{jet} = 0$ with $p_T > 20$ GeV, DeepCSV Medium	
$\eta_{j1} \times \eta_{j2}$	< 0	
$\lvert\Delta\eta_{jj}\rvert$	> 1	
Muons (electrons)	$N_{\mu,e} = 0$ with $p_T > 10$ GeV, $\lvert\eta\rvert < 2.4\ (2.5)$	
Photons	$N_{\gamma} = 0$ with $p_T > 15$ GeV, $\lvert\eta\rvert < 2.5$	

Likelihood function

$$\begin{aligned}
\mathcal{L}(\mu, \kappa^{\nu\bar{\nu}}, \boldsymbol{\theta}) =& \prod_i \mathrm{P}\left(d_i \middle| B_i(\boldsymbol{\theta}) + \mathrm{Z}_i(\kappa_i^{\nu\bar{\nu}}) + \mathrm{W}_i(\kappa_i^{\nu\bar{\nu}}, \boldsymbol{\theta}) + \mu S_i(\boldsymbol{\theta})\right) \\
& \prod_{\mathrm{CR}} \left(\prod_i \mathrm{P}\left(d_i^{\mathrm{CR}} \middle| B_i^{\mathrm{CR}}(\boldsymbol{\theta}) + \mathrm{V}_i^{\mathrm{CR,strong}}(\kappa_i^{\nu\bar{\nu}}, \boldsymbol{\theta}) + \mathrm{V}_i^{\mathrm{CR,VBF}}(\kappa_i^{\nu\bar{\nu}}, \boldsymbol{\theta})\right)\right) \\
& \prod_j \mathrm{P}(\theta_j), \\
\mathrm{Z}_i(\kappa_i^{\nu\bar{\nu}}) =& (1 + Z_i^{\frac{\mathrm{VBF}}{\mathrm{strong}}})\kappa_i^{\nu\bar{\nu}}, \\
\mathrm{W}_i(\kappa_i^{\nu\bar{\nu}}, \boldsymbol{\theta}) =& (f_i^{\mathrm{W/Z,strong}}(\boldsymbol{\theta}) + Z_i^{\frac{\mathrm{VBF}}{\mathrm{strong}}} f_i^{\mathrm{W/Z,VBF}}(\boldsymbol{\theta}))\kappa_i^{\nu\bar{\nu}}, \\
\mathrm{V}_i^{\mathrm{CR,strong}}(\kappa_i^{\nu\bar{\nu}}, \boldsymbol{\theta}) =& \mathrm{C}_i^{\mathrm{CR,strong}}(\boldsymbol{\theta}) R_i^{\mathrm{CR,strong}}(\boldsymbol{\theta})\kappa_i^{\nu\bar{\nu}}, \\
\mathrm{V}_i^{\mathrm{CR,VBF}}(\kappa_i^{\nu\bar{\nu}}, \boldsymbol{\theta}) =& \mathrm{C}_i^{\mathrm{CR,VBF}}(\boldsymbol{\theta}) Z_i^{\frac{\mathrm{VBF}}{\mathrm{strong}}} R_i^{\mathrm{CR,VBF}}(\boldsymbol{\theta})\kappa_i^{\nu\bar{\nu}},
\end{aligned} \tag{4}$$

Uncertainties

Source of uncertainty	Ratios	Uncertainty vs. M_{jj}
	Theoretical uncertainties	
Ren. scale V+jets (VBF)	Z_{SR}/W_{SR}	7.5%
Ren. scale V+jets (strong)	Z_{SR}/W_{SR}	8.2%
Fac. scale V+jets (VBF)	Z_{SR}/W_{SR}	1.5%
Fac. scale V+jets (strong)	Z_{SR}/W_{SR}	1.3%
PDF V+jets (strong)	Z_{SR}/W_{SR}	0%
PDF V+jets (VBF)	Z_{SR}/W_{SR}	0%
NLO EWK corr. V+jets (strong)	Z_{SR}/W_{SR}	0.5%
Ren. scale γ+jets (VBF)	Z_{SR}/γ_{CR}	6–10%
Ren. scale γ+jets (strong)	Z_{SR}/γ_{CR}	6–10%
Fac. scale γ+jets (VBF)	Z_{SR}/γ_{CR}	2.5%
Fac. scale γ+jets (strong)	Z_{SR}/γ_{CR}	2.5%
PDF γ+jets (strong)	Z_{SR}/γ_{CR}	2.5%
PDF γ+jets (VBF)	Z_{SR}/γ_{CR}	2.5%
NLO EWK corr. γ+jets	Z_{SR}/γ_{CR}	3%
	Experimental uncertainties	
Muon id. eff.	Z_{CR}/Z_{SR}, W_{CR}/W_{SR}	$\approx$ 0.5% (per lepton)
Muon iso. eff.	Z_{CR}/Z_{SR}, W_{CR}/W_{SR}	$\approx$ 0.1% (per lepton)
Electron reco. eff.	Z_{CR}/Z_{SR}, W_{CR}/W_{SR}	$\approx$ 0.5% (per lepton)
Electron id. eff.	Z_{CR}/Z_{SR}, W_{CR}/W_{SR}	$\approx$ 1% (per lepton)
Photon id. eff.	Z_{SR}/γ	5%
Muon veto	Z_{SR}/W_{SR}, W_{CR}/W_{SR}	$\approx$ 0.5%
Electron veto (reco)	Z_{SR}/W_{SR}, W_{CR}/W_{SR}	$\approx$ 1.5 (1)% for VBF (strong)
Electron veto (id)	Z_{SR}/W_{SR}, W_{CR}/W_{SR}	$\approx$ 2.5 (2)% for VBF (strong)
τ veto	Z_{SR}/W_{SR}, W_{CR}/W_{SR}	$\approx$ 1%
Electron trigger	Z_{CR}/Z_{SR}, W_{CR}/W_{SR}	$\approx$ 1%
p_T^{miss} trigger	Z_{CR}/Z_{SR}, W_{CR}/W_{SR}	$\approx$ 2%
Photon trigger	Z_{SR}/γ	1%
Jet energy scale	Z_{SR}/W_{SR}	1–2%
	W_{CR}/W_{SR}	1.0–1.5%
	$Z_{CR}/Z_{\nu\nu}$	1%
	Z_{SR}/γ	3%
Jet energy resolution	Z_{SR}/W_{SR}	1.0–2.5%
	W_{CR}/W_{SR}	1.0–1.5%
	Z_{CR}/Z_{SR}	1%
	Z_{SR}/γ	1–4%

Uncertainty breakdown

Group of systematic uncertainties	Impact on $\mathcal{B}(\mathrm{H} \to \mathrm{inv})$ Observed	Impact on $\mathcal{B}(\mathrm{H} \to \mathrm{inv})$ Expected
Theory	$^{+0.026}_{-0.025}$	± 0.024
Simulated event count	± 0.022	$^{+0.021}_{-0.022}$
Triggers	$^{+0.018}_{-0.019}$	± 0.018
Jet calibration	$^{+0.014}_{-0.012}$	± 0.011
QCD multijet mismodelling	± 0.012	± 0.013
Leptons/photons/b-tagged jets	$^{+0.011}_{-0.010}$	$^{+0.009}_{-0.010}$
Integrated luminosity/pileup	± 0.004	± 0.004
Other systematic uncertainties	$^{+0.013}_{-0.009}$	± 0.009
Statistical uncertainty	± 0.028	± 0.028

Data Quality issues in Run 2 data

- **During the 2017/18 data taking period, there were several detector related issues affecting this analysis:**

  - **The HEM problem:**
    - A section of the HCAL endcap calorimeter was not functional during part of the 2018 era
    - Inability to properly identify electrons/photons in the region $\eta < -1.39$ and $-1.6 < \phi < -0.9$
      - Mitigated by including specific selection criteria on electrons
    - A high source of E_T^{miss} in SR in affected phi slice due to the lost tracks
      - Mitigated by placing a removal selection requirement the affected E_T^{miss} phi region

  - **HF noise:**
    - Appearance of jet "horns" (large data to MC discrepancy) for $|\eta| \sim 3.0$
    - HF jet shape variable selection introduced in order to battle it
    - Required a data driven estimation of the multijet HF noise by inverting one selection requirement
      - Creating a noise enriched region, while estimating it through the use of a transfer factor