

Search for invisible decays of the Higgs boson with the CMS detector

Laurent Thomas

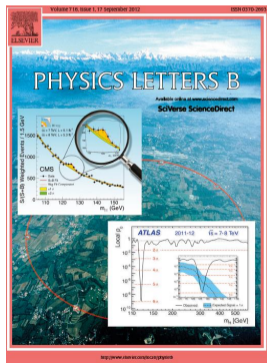
*Institute for Research in Fundamental Sciences (IPM), Tehran
Weekly seminar*



The Higgs boson, the last piece of the Standard Model puzzle

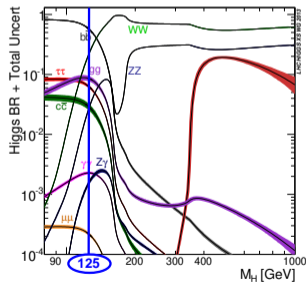
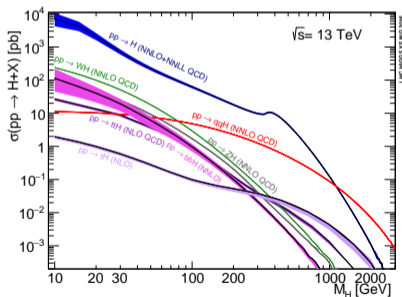
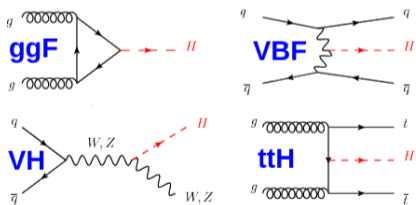
- The Higgs boson discovery in 2012 represents a key confirmation of the Standard Model of particle physics.
- Not just an extra particle, crucial to understand the electroweak symmetry breaking and the mechanism through which particles acquire mass.
- A tremendous effort to achieve this discovery:
 - An almost 50 year journey between its theoretical prediction and experimental observation.
 - A dedicated 27 km circular proton collider and two detectors.
 - Thousands of physicists and engineers involved, from all around the world.

| فرمیون ها امار فرمیونیک | | | بوزون ها امار بوزونیک | |
|------------------------------------|--|---|---|-------------------------------------|
| جرم → محموله اسپین نام | u کوآرک بالا 2.3 2/3 1/2 | c کوآرک اقسوان 1.275 2/3 1/2 | t کوآرک سفل 173.07 2/3 1/2 | g گلوئون 0 1 1 |
| کوآرک ها | d کوآرک پایین 2.3 2/3 1/2 | s کوآرک شگفت 95 1/2 1/2 | b کوآرک ته 4.18 2/3 1/2 | γ فوتون 0 1 0 |
| | e الکترون 0.511 -1 1/2 | μ میون 105.7 -1 1/2 | τ تاو 1.777 -1 1/2 | Z بوزون Z 91.1876 0 1 |
| | ν_e الکترون نوترینو 0 1/2 1/2 | ν_μ میون نوترینو 0 1/2 1/2 | ν_τ تاو نوترینو 0 1/2 1/2 | W بوزون W 80.379 ±1 1 |
| لپتونها | | | | بوزون های عددی |



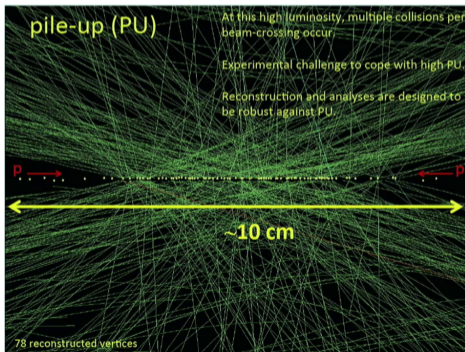
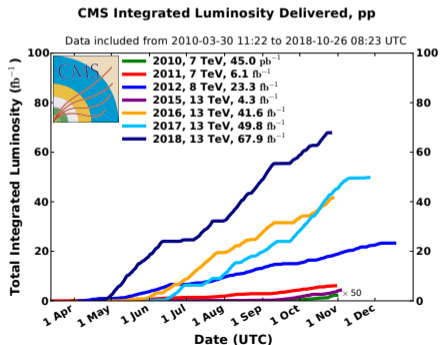
Higgs at the LHC

- Up to 1 Higgs produced every second
- **Producing Higgs is “easy”, recording/isolating them is the tricky part.**
- Various relevant production mechanisms for the LHC energies.
- $M_H = 125$ GeV: the most difficult place to probe experimentally.
- Also the most interesting one: many open decay modes !



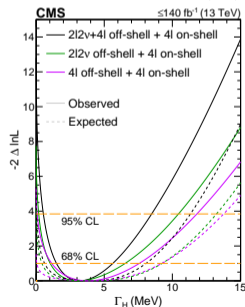
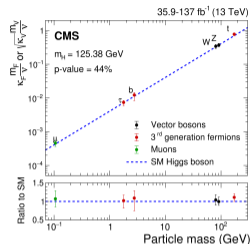
- Excellent performances of the machine since 2010 startup
 - Slightly less energy than initially targeted...
 - ... but instantaneous luminosity reached **twice the designed value** in 2018.
 - **35 pp interactions per bunch crossing** in Run 2.
 - Huge challenges for experiments (trigger, computing, pile up mitigation)

| Run | Year | \sqrt{s} |
|--------|-----------|------------|
| Run 1 | 2010-2012 | 7-8 TeV |
| Run 2 | 2015-2018 | 13 TeV |
| Run 3 | 2022-2025 | 13.6 TeV |
| HL-LHC | 2028-2040 | 14 TeV |



Exhaustive research program to study the H boson properties:

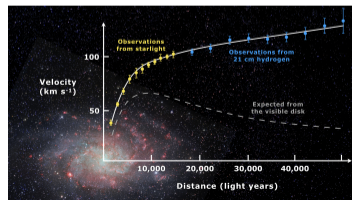
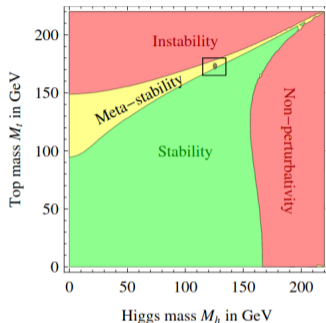
- Coupling to bosons established at the 10% level, $(\delta\sigma)^{stat} \approx (\delta\sigma)^{syst}$
- Coupling to third generation fermions (t, b, τ) observed too.
- 0^+ spin parity confirmed.
- Several production modes observed.
- Mass measured at the 0.1% level (better than m_{top} !)
- Some recent results by CMS using the Run 2 dataset:
 - Indirect measurement of Higgs decay width: arXiv:2202.06923
 - First evidence of Higgs decay to two muons: arXiv:2009.04363
 - Search for Higgs coupling to charmed quarks: CMS-PAS-HIG-21-008
New! March 1st!
 - Search for invisible decays of the Higgs boson: [https://arxiv:2201.11585](https://arxiv.org/abs/2201.11585)
→ **This talk !**



Some shortcomings of the Standard Model

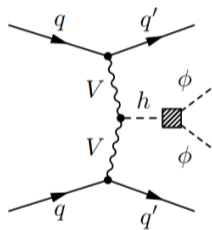
- While subject to quantum corrections of the order of the Planck scale, the Higgs mass remains at the TeV scale, introducing the hierarchy problem.
→ This can be alternatively interpreted as the fact that we seem to live in a metastable universe.
- How do neutrinos acquire mass?
- How to explain the apparent matter-antimatter imbalance?
- Are the forces unified?
- What is dark matter?

Many theories proposed to address these questions, often involving the Higgs

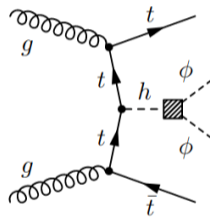


Higgs as a dark matter portal

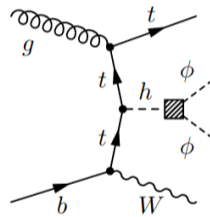
- Many scenarios consider a DM candidate coupling to the Higgs.
- Simplest case: a single DM particle (scalar, Majorana fermion or vector)
- If $m_{DM} < m_H/2$ direct contribution to the H decay.



Vector boson fusion



ttH

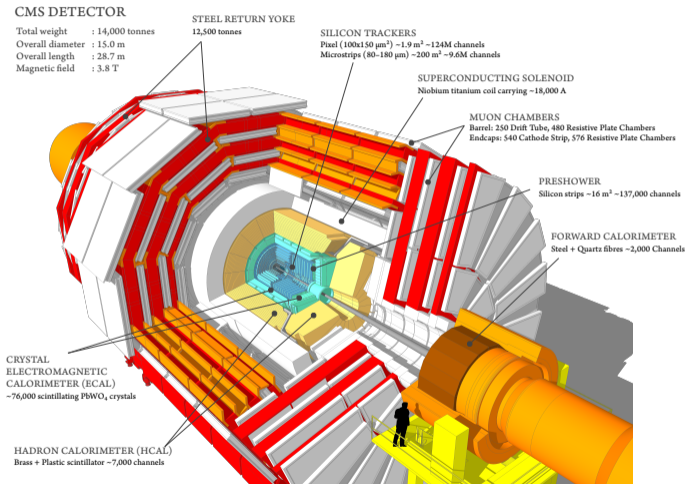


tWH

At colliders, need for visible particles recoiling against the invisible Higgs.

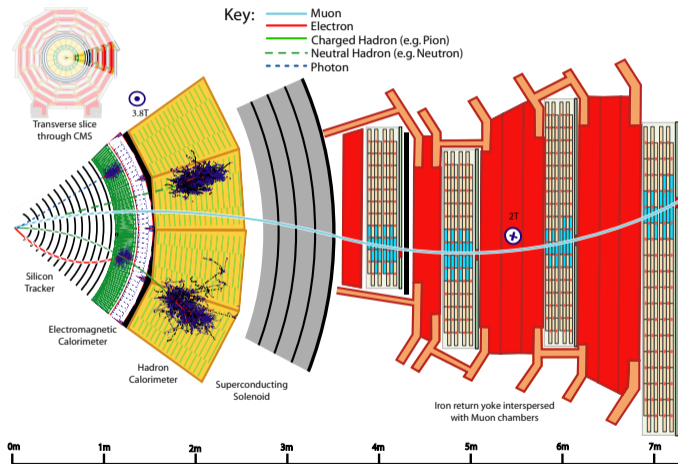
- Vector boson fusion by far the most sensitive channel thanks to large cross section.
- Experimental signature: missing energy and forward jets.

- Multi purpose detector
- Central feature: Solenoid magnet 3.8 T containing tracker (with pixels) and calorimeters (ECAL+HCAL)
- Surrounded by muons chambers.
- Forward calorimeters (HF) to reach good hermeticity
- Almost full geometrical coverage to reconstruct and identify all interacting particles

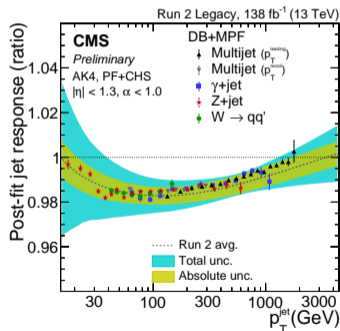
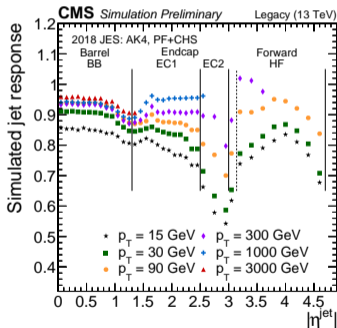
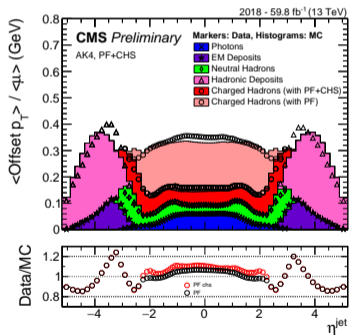


The CMS experiment: particle reconstruction

- Dedicated algorithm (“Particle Flow”-PF) combining detector information to reconstruct/identify particles and measure their 4-momentum
- Non interacting particles (neutrinos) inferred from energy imbalance in the transverse plane (“MET”).

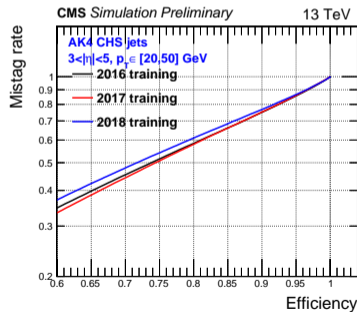
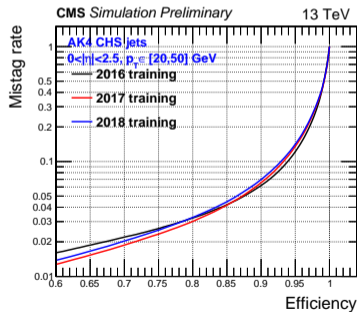
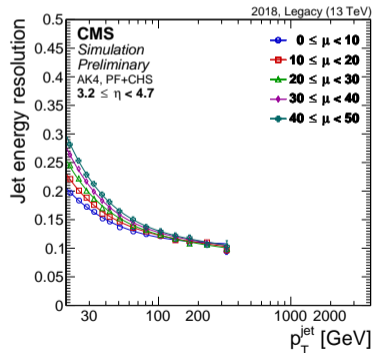


- PF particles clustered into jets using the anti- k_T algorithm (here with $R=0.4$).
- Jet energy corrections applied to account for detector imperfect response.
 - Derived from simulation, as a function of p_T , η , pile up
 - Residual energy scale and resolution corrections for data measured using Z +jets, γ +jets and dijet events.



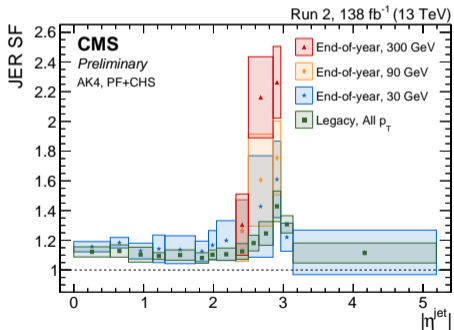
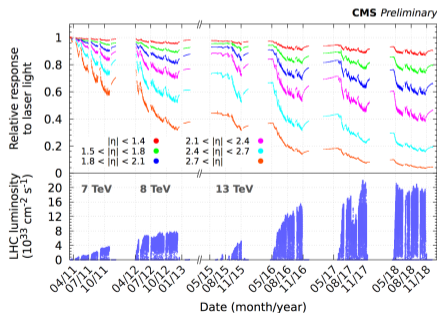
Experimental challenge: pile up

- Charged particles from pileup efficiently discarded based on vertex information
- Neutral particles are more complicated to deal with. Can degrade jet energy resolution or even Can create “fake” jets.
- Dedicated multivariate discriminator developed to reject such jets. Limited performance beyond the tracker coverage though.



Experimental challenge: detector ageing

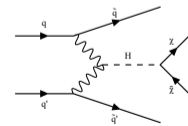
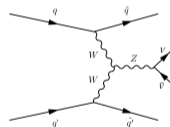
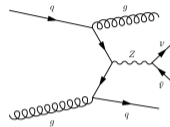
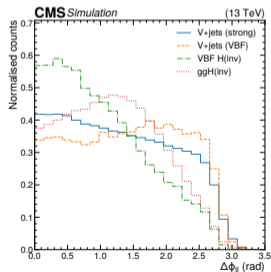
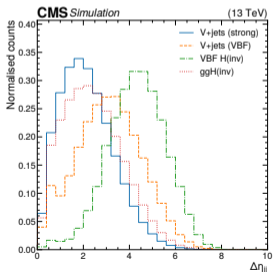
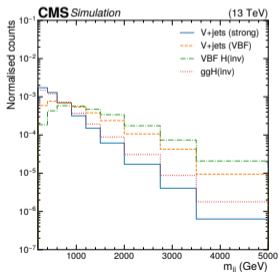
- High radiation level can impact detector operation.
- For example, fast corrections derived to correct for ECAL crystal loss of transparency during data taking.
- **Full reprocessing of the Run 2 dataset in 2019/2020 with refined detector calibration.**
- Allowed to significantly improve jet resolution in data



Search for invisible decays of the Higgs boson produced via vector boson fusion in proton-proton collisions at $\sqrt{s} = 13$ TeV

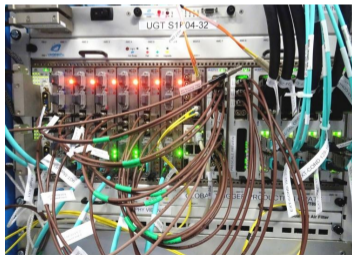
Event selection and analysis strategy in a nutshell

- Selecting events with two jets ($p_T > 80/40$ GeV) and large MET (>175 GeV).
- Main background: $Z(\nu\nu)+$ jets (strong and electroweak productions)
- Large angular separation and invariant mass to reduce background in particular from strong production
- Signal extraction performed from a fit to the dijet invariant mass.
- **“Top up” of the 2016 data analysis, with significant improvements.**

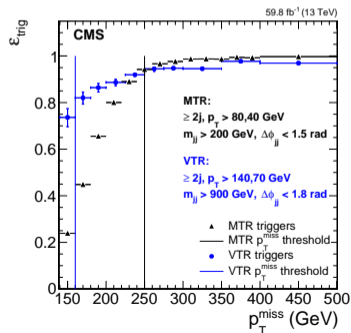


Triggers

- CMS uses a 2 level trigger system (L1: custom electronics, HLT: processor farm) to reduce the amount of data recorded from ≈ 30 MHz (LHC collision rate) to ≈ 1 kHz
- Here using a generic MET trigger complemented with a dedicated VBF dijet+MET trigger
- The latter allows us to probe a lower MET region.
- Defining two signal regions (“MTR” and “VTR”) for $\text{MET} > 250$ GeV and $250 > \text{MET} > 175$ GeV respectively
- Efficiency measured in data and used to correct simulations.



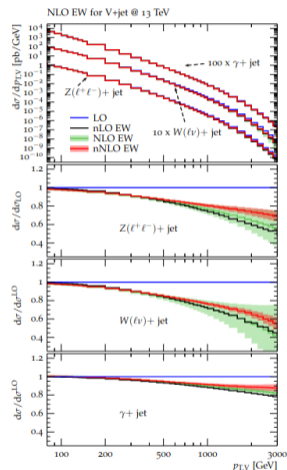
CMS Level 1 trigger



- Loose kinematic cuts on the dijet pair, compatible with VBF signature.
 - Tighter conditions on the jet pair in VTR to meet trigger requirements.
- B-tagged jet veto, lepton veto to remove $t\bar{t}$, EWK processes
- $\min(\Delta\phi(\vec{p}_T^{\text{miss}}, \vec{p}_T^{\text{jet}}))$ condition to reject severely mismeasured jets from QCD
- Quality cuts on jets to reject noise/mismeasured jets.

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

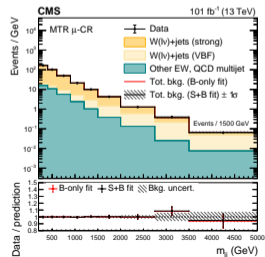
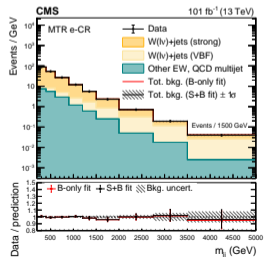
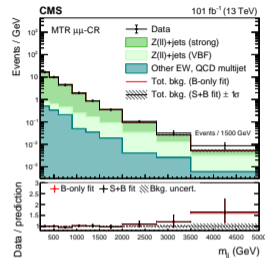
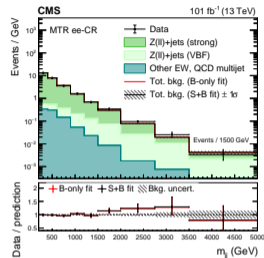
- This analysis is very sensitive to the impact of high order corrections at high boson p_T
- Whenever possible NLO (QCD) generators are used for the generation of the simulated samples
- Missing corrections (e.g. NLO EWK) are parametrized as a function of $p_T(V), m_{jj}$ and used to reweight the simulation.



from arxiv:1705.04664

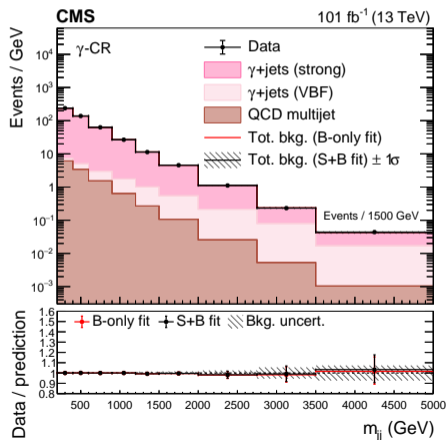
- Single lepton (e/μ), double lepton (e/μ) used to constrain the $Z\nu\nu$ and $W \rightarrow l\nu$ backgrounds in the signal region.
- Selection identical in signal region, except for the presence of lepton(s).
- Leptons 4-momenta removed from the event to mimic the signal region.
- Subleading backgrounds estimated from simulation.

| Control region | Condition |
|----------------|---|
| e/μ | $=1l, MET > 80 \text{ GeV}$ |
| $ee/\mu\mu$ | $=2l, 60 < M(ee)/(\mu\mu) (\text{GeV}) < 120$ |

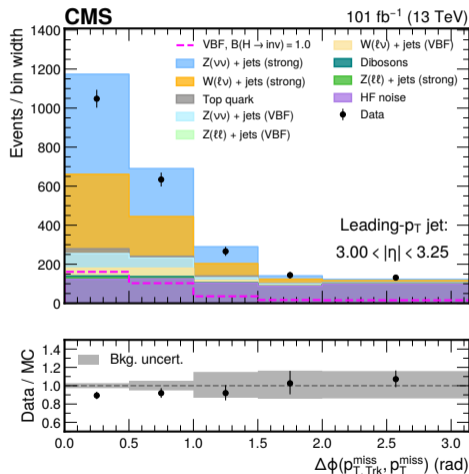


Photon control region (NEW !)

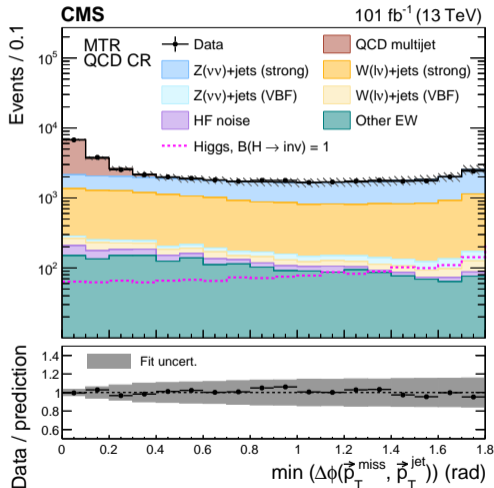
- Similar to lepton control regions, requires exactly one high p_T photon.
- Higher statistics leading to better constrain on the last m_{jj} bins. ($\approx 10\%$ signal sensitivity improvement)
- QCD backgrounds estimated from template fit to a photon shower shape variable.



- Significant rate of “fake jets” observed in the HF region.
- Spurious signal from charged particles from late showering hadron/muons hitting directly the photomultipliers window.
- Dedicated cut based on the distinctive shower shape (narrow in ϕ , spread in η)
- Residual contribution estimated from a sample of events failing the cut reweighted according to the fake rate probability (in data).
- Estimate validated by looking at the correlation between total MET and MET (tracks only)



- Background contribution from severely mismeasured jets from QCD
- m_{jj} template built by reverting the condition on $\min(\Delta\phi(\vec{p}_T^{min}, \vec{p}_T^{jet}))$.
- Normalization extracted from a fit to $\min(\Delta\phi(\vec{p}_T^{min}, \vec{p}_T^{jet}))$
- Small background yet relevant as not constrained by other control regions.



- Simultaneous likelihood fit to the m_{jj} distribution in signal and control regions.
- Nuisance parameters to model systematic uncertainties.

$$\mathcal{L}(\mu, \kappa^{v\bar{v}}, \boldsymbol{\theta}) = \prod_i \text{P} \left(d_i \mid B_i(\boldsymbol{\theta}) + Z_i(\kappa_i^{v\bar{v}}) + W_i(\kappa_i^{v\bar{v}}, \boldsymbol{\theta}) + \mu S_i(\boldsymbol{\theta}) \right) \\ \prod_{\text{CR}} \left(\prod_i \text{P} \left(d_i^{\text{CR}} \mid B_i^{\text{CR}}(\boldsymbol{\theta}) + V_i^{\text{CR, strong}}(\kappa_i^{v\bar{v}}, \boldsymbol{\theta}) + V_i^{\text{CR, VBF}}(\kappa_i^{v\bar{v}}, \boldsymbol{\theta}) \right) \right) \\ \prod_j \text{P}(\theta_j),$$

$$Z_i(\kappa_i^{v\bar{v}}) = \left(1 + Z_i^{\frac{\text{VBF}}{\text{strong}}}\right) \kappa_i^{v\bar{v}},$$

$$W_i(\kappa_i^{v\bar{v}}, \boldsymbol{\theta}) = \left(f_i^{\text{W/Z, strong}}(\boldsymbol{\theta}) + Z_i^{\frac{\text{VBF}}{\text{strong}}} f_i^{\text{W/Z, VBF}}(\boldsymbol{\theta})\right) \kappa_i^{v\bar{v}},$$

$$V_i^{\text{CR, strong}}(\kappa_i^{v\bar{v}}, \boldsymbol{\theta}) = C_i^{\text{CR, strong}}(\boldsymbol{\theta}) R_i^{\text{CR, strong}}(\boldsymbol{\theta}) \kappa_i^{v\bar{v}},$$

$$V_i^{\text{CR, VBF}}(\kappa_i^{v\bar{v}}, \boldsymbol{\theta}) = C_i^{\text{CR, VBF}}(\boldsymbol{\theta}) Z_i^{\frac{\text{VBF}}{\text{strong}}} R_i^{\text{CR, VBF}}(\boldsymbol{\theta}) \kappa_i^{v\bar{v}},$$

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$$\prod_{\text{CR}} \left(\prod_i \text{P} \left(d_i^{\text{CR}} \mid B_i^{\text{CR}}(\boldsymbol{\theta}) + V_i^{\text{CR, strong}}(\kappa_i^{v\bar{v}}, \boldsymbol{\theta}) + V_i^{\text{CR, VBF}}(\kappa_i^{v\bar{v}}, \boldsymbol{\theta}) \right) \right) \quad \text{Control regions}$$

$$\prod_j \text{P}(\theta_j), \quad \text{Nuisance params (gaussian or logN)}$$

$$Z_i(\kappa_i^{v\bar{v}}) = (1 + Z_i^{\frac{\text{VBF}}{\text{strong}}}) \kappa_i^{v\bar{v}},$$

$$W_i(\kappa_i^{v\bar{v}}, \boldsymbol{\theta}) = (f_i^{\text{W/Z, strong}}(\boldsymbol{\theta}) + Z_i^{\frac{\text{VBF}}{\text{strong}}} f_i^{\text{W/Z, VBF}}(\boldsymbol{\theta})) \kappa_i^{v\bar{v}},$$

$$V_i^{\text{CR, strong}}(\kappa_i^{v\bar{v}}, \boldsymbol{\theta}) = C_i^{\text{CR, strong}}(\boldsymbol{\theta}) R_i^{\text{CR, strong}}(\boldsymbol{\theta}) \kappa_i^{v\bar{v}},$$

$$V_i^{\text{CR, VBF}}(\kappa_i^{v\bar{v}}, \boldsymbol{\theta}) = C_i^{\text{CR, VBF}}(\boldsymbol{\theta}) Z_i^{\frac{\text{VBF}}{\text{strong}}} R_i^{\text{CR, VBF}}(\boldsymbol{\theta}) \kappa_i^{v\bar{v}},$$

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Signal strength x signal yield

$$Z_i(\kappa_i^{v\bar{v}}) = \left(1 + Z_i^{\frac{\text{VBF}}{\text{strong}}}\right) \kappa_i^{v\bar{v}}, \\ W_i(\kappa_i^{v\bar{v}}, \boldsymbol{\theta}) = \left(f_i^{\text{W/Z, strong}}(\boldsymbol{\theta}) + Z_i^{\frac{\text{VBF}}{\text{strong}}} f_i^{\text{W/Z, VBF}}(\boldsymbol{\theta})\right) \kappa_i^{v\bar{v}}, \\ V_i^{\text{CR, strong}}(\kappa_i^{v\bar{v}}, \boldsymbol{\theta}) = C_i^{\text{CR, strong}}(\boldsymbol{\theta}) R_i^{\text{CR, strong}}(\boldsymbol{\theta}) \kappa_i^{v\bar{v}}, \\ V_i^{\text{CR, VBF}}(\kappa_i^{v\bar{v}}, \boldsymbol{\theta}) = C_i^{\text{CR, VBF}}(\boldsymbol{\theta}) Z_i^{\frac{\text{VBF}}{\text{strong}}} R_i^{\text{CR, VBF}}(\boldsymbol{\theta}) \kappa_i^{v\bar{v}},$$

- Simultaneous likelihood fit to the m_{jj} distribution in signal and control regions.
- Nuisance parameters to model systematic uncertainties.

$$\mathcal{L}(\mu, \kappa^{v\bar{v}}, \boldsymbol{\theta}) = \prod_i \text{P} \left(d_i \mid B_i(\boldsymbol{\theta}) + Z_i(\kappa_i^{v\bar{v}}) + W_i(\kappa_i^{v\bar{v}}, \boldsymbol{\theta}) + \mu S_i(\boldsymbol{\theta}) \right) \\ \prod_{\text{CR}} \left(\prod_i \text{P} \left(d_i^{\text{CR}} \mid B_i^{\text{CR}}(\boldsymbol{\theta}) + V_i^{\text{CR, strong}}(\kappa_i^{v\bar{v}}, \boldsymbol{\theta}) + V_i^{\text{CR, VBF}}(\kappa_i^{v\bar{v}}, \boldsymbol{\theta}) \right) \right) \\ \prod_j \text{P}(\theta_j),$$

Z→vv (strong) yields
(floating parameter)

$$Z_i(\kappa_i^{v\bar{v}}) = \left(1 + Z_i^{\frac{\text{VBF}}{\text{strong}}}\right) \kappa_i^{v\bar{v}}, \\ W_i(\kappa_i^{v\bar{v}}, \boldsymbol{\theta}) = \left(f_i^{\text{W/Z, strong}}(\boldsymbol{\theta}) + Z_i^{\frac{\text{VBF}}{\text{strong}}} f_i^{\text{W/Z, VBF}}(\boldsymbol{\theta})\right) \kappa_i^{v\bar{v}}, \\ V_i^{\text{CR, strong}}(\kappa_i^{v\bar{v}}, \boldsymbol{\theta}) = C_i^{\text{CR, strong}}(\boldsymbol{\theta}) R_i^{\text{CR, strong}}(\boldsymbol{\theta}) \kappa_i^{v\bar{v}}, \\ V_i^{\text{CR, VBF}}(\kappa_i^{v\bar{v}}, \boldsymbol{\theta}) = C_i^{\text{CR, VBF}}(\boldsymbol{\theta}) Z_i^{\frac{\text{VBF}}{\text{strong}}} R_i^{\text{CR, VBF}}(\boldsymbol{\theta}) \kappa_i^{v\bar{v}},$$

- Simultaneous likelihood fit to the m_{jj} distribution in signal and control regions.
- Nuisance parameters to model systematic uncertainties.

$$\mathcal{L}(\mu, \kappa^{v\bar{v}}, \boldsymbol{\theta}) = \prod_i \text{P} \left(d_i \left| \mathcal{B}_i(\boldsymbol{\theta}) + Z_i(\kappa_i^{v\bar{v}}) + W_i(\kappa_i^{v\bar{v}}, \boldsymbol{\theta}) + \mu S_i(\boldsymbol{\theta}) \right. \right) \\ \prod_{\text{CR}} \left(\prod_i \text{P} \left(d_i^{\text{CR}} \left| \mathcal{B}_i^{\text{CR}}(\boldsymbol{\theta}) + V_i^{\text{CR, strong}}(\kappa_i^{v\bar{v}}, \boldsymbol{\theta}) + V_i^{\text{CR, VBF}}(\kappa_i^{v\bar{v}}, \boldsymbol{\theta}) \right. \right) \right) \\ \prod_j \text{P}(\theta_j),$$

Rare background estimate
(from simulation except HF
noise/QCD)

$$Z_i(\kappa_i^{v\bar{v}}) = \left(1 + Z_i^{\frac{\text{VBF}}{\text{strong}}}\right) \kappa_i^{v\bar{v}},$$

$$W_i(\kappa_i^{v\bar{v}}, \boldsymbol{\theta}) = \left(f_i^{\text{W/Z, strong}}(\boldsymbol{\theta}) + Z_i^{\frac{\text{VBF}}{\text{strong}}} f_i^{\text{W/Z, VBF}}(\boldsymbol{\theta})\right) \kappa_i^{v\bar{v}},$$

$$V_i^{\text{CR, strong}}(\kappa_i^{v\bar{v}}, \boldsymbol{\theta}) = C_i^{\text{CR, strong}}(\boldsymbol{\theta}) R_i^{\text{CR, strong}}(\boldsymbol{\theta}) \kappa_i^{v\bar{v}},$$

$$V_i^{\text{CR, VBF}}(\kappa_i^{v\bar{v}}, \boldsymbol{\theta}) = C_i^{\text{CR, VBF}}(\boldsymbol{\theta}) Z_i^{\frac{\text{VBF}}{\text{strong}}} R_i^{\text{CR, VBF}}(\boldsymbol{\theta}) \kappa_i^{v\bar{v}},$$

- Simultaneous likelihood fit to the m_{jj} distribution in signal and control regions.
- Nuisance parameters to model systematic uncertainties.

$$\mathcal{L}(\mu, \kappa^{v\bar{v}}, \boldsymbol{\theta}) = \prod_i \text{P} \left(d_i \mid B_i(\boldsymbol{\theta}) + \boxed{Z_i}(\kappa_i^{v\bar{v}}) + \boxed{W_i}(\kappa_i^{v\bar{v}}, \boldsymbol{\theta}) + \mu S_i(\boldsymbol{\theta}) \right) \\ \prod_{\text{CR}} \left(\prod_i \text{P} \left(d_i^{\text{CR}} \mid B_i^{\text{CR}}(\boldsymbol{\theta}) + \boxed{V_i^{\text{CR, strong}}}(\kappa_i^{v\bar{v}}, \boldsymbol{\theta}) + \boxed{V_i^{\text{CR, VBF}}}(\kappa_i^{v\bar{v}}, \boldsymbol{\theta}) \right) \right) \\ \prod_j \text{P}(\theta_j),$$

EWK and/or VBF $W/\gamma/Z$ contributions, expressed as $Z \rightarrow v\bar{v}$ (strong) yields times transfer factors taken from simulations

$$Z_i(\kappa_i^{v\bar{v}}) = \left(1 + \boxed{Z_i^{\text{VBF}}(\boldsymbol{\theta})} \right) \kappa_i^{v\bar{v}}, \quad \text{Z} \rightarrow v\bar{v} \text{ (VBF) / Z} \rightarrow v\bar{v} \text{ (strong) contribution}$$

$$W_i(\kappa_i^{v\bar{v}}, \boldsymbol{\theta}) = \left(\boxed{f_i^{W/Z, \text{strong}}(\boldsymbol{\theta})} + \boxed{Z_i^{\text{VBF}}(\boldsymbol{\theta})} \boxed{f_i^{W/Z, \text{VBF}}(\boldsymbol{\theta})} \right) \kappa_i^{v\bar{v}}, \quad \text{Z} \rightarrow W \text{ transfer factor}$$

$$V_i^{\text{CR, strong}}(\kappa_i^{v\bar{v}}, \boldsymbol{\theta}) = \boxed{C_i^{\text{CR, strong}}(\boldsymbol{\theta})} \boxed{R_i^{\text{CR, strong}}(\boldsymbol{\theta})} \kappa_i^{v\bar{v}}, \quad \text{CR} \rightarrow \text{SR transfer factor}$$

$$V_i^{\text{CR, VBF}}(\kappa_i^{v\bar{v}}, \boldsymbol{\theta}) = \boxed{C_i^{\text{CR, VBF}}(\boldsymbol{\theta})} \boxed{Z_i^{\text{VBF}}(\boldsymbol{\theta})} \boxed{R_i^{\text{CR, VBF}}(\boldsymbol{\theta})} \kappa_i^{v\bar{v}}, \quad \text{Channel dependent factors (1 for ee}/\mu\mu)$$

Main experimental uncertainties:

- Jet energy scale and resolution (up to 25% for VBF H at high m_{jj})
- Data/simulation scale factors related to object reconstruction/identification/triggers (b-tagging, leptons)
- Integrated luminosity and pile up profile

Main theoretical uncertainties:

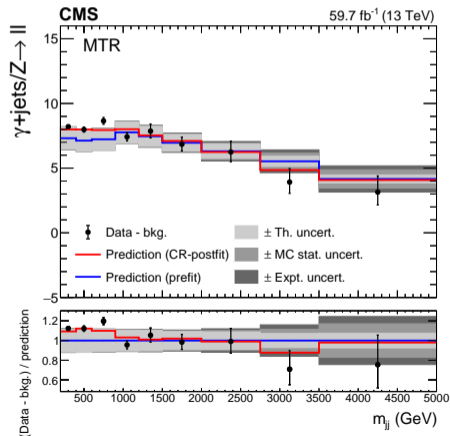
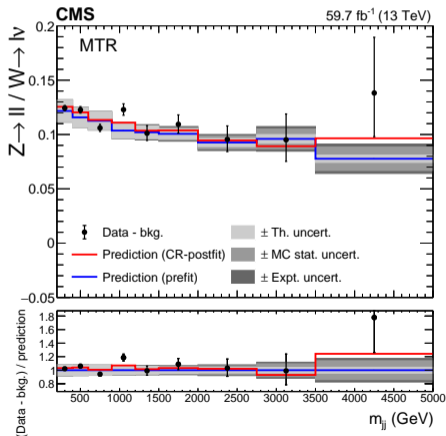
- Factorization/renormalization scales
- Parton density functions

Uncertainties apply to signal yields and transfer factors mostly

| Source of uncertainty | Ratios | Uncertainty vs. m_{jj} |
|------------------------------------|---|---------------------------------------|
| <i>Theoretical uncertainties</i> | | |
| Ren. scale V+jets (VBF) | $f_1^{W/Z,VBF}$ | 7.5% |
| Ren. scale V+jets (strong) | $f_1^{W/Z,strong}$ | 8.2% |
| Fac. scale V+jets (VBF) | $f_1^{W/Z,VBF}$ | 1.5% |
| Fac. scale V+jets (strong) | $f_1^{W/Z,strong}$ | 1.3% |
| PDF V+jets (VBF) | $f_1^{W/Z,VBF}$ | 0% |
| PDF V+jets (strong) | $f_1^{W/Z,strong}$ | 0% |
| NLO EW corr. V+jets (strong) | $f_1^{W/Z,strong}$ | 0.5% |
| Ren. scale γ +jets (VBF) | $f_1^{\gamma}/Z,VBF$ | 6–10% |
| Ren. scale γ +jets (strong) | $f_1^{\gamma}/Z,strong$ | 6–10% |
| Fac. scale γ +jets (VBF) | $f_1^{\gamma}/Z,VBF$ | 2.5% |
| Fac. scale γ +jets (strong) | $f_1^{\gamma}/Z,strong$ | 2.5% |
| PDF γ +jets (VBF) | $f_1^{\gamma}/Z,VBF$ | 2.5% |
| PDF γ +jets (strong) | $f_1^{\gamma}/Z,strong$ | 2.5% |
| NLO EW corr. γ +jets | $f_1^{\gamma}/Z,strong$ | 3% |
| <i>Experimental uncertainties</i> | | |
| Electron reco. eff. | $R_1^{CR,proc}, CR=Z(ee) \text{ or } W(ev)$ | $\approx 0.5\%$ (per lepton) |
| Electron id. eff. | $R_1^{CR,proc}, CR=Z(ee) \text{ or } W(ev)$ | $\approx 1\%$ (per lepton) |
| Muon id. eff. | $R_1^{CR,proc}, CR=Z(\mu\mu) \text{ or } W(\mu\nu)$ | $\approx 0.5\%$ (per lepton) |
| Muon iso. eff. | $R_1^{CR,proc}, CR=Z(\mu\mu) \text{ or } W(\mu\nu)$ | $\approx 0.1\%$ (per lepton) |
| Photon id. eff. | $f_1^{\gamma}/Z,proc$ | 5% |
| Electron veto (reco) | $f_1^{W/Z,proc}, R_1^{CR,proc}, CR=W(\ell\nu)$ | $\approx 1.5\%$ (1%) for VBF (strong) |
| Electron veto (id) | $f_1^{W/Z,proc}, R_1^{CR,proc}, CR=W(\ell\nu)$ | $\approx 2.5\%$ (2%) for VBF (strong) |
| Muon veto | $f_1^{W/Z,proc}, R_1^{CR,proc}, CR=W(\ell\nu)$ | $\approx 0.5\%$ |
| τ_b veto | $f_1^{W/Z,proc}, R_1^{CR,proc}, CR=W(\ell\nu)$ | $\approx 1\%$ |
| Electron trigger | $R_1^{CR,proc}, CR=Z(ee) \text{ or } W(ev)$ | $\approx 1\%$ |
| p_{min}^{miss} trigger | $R_1^{CR,proc}, CR=Z(\mu\mu) \text{ or } W(\mu\nu)$ | $\approx 2\%$ |
| Photon trigger | $f_1^{\gamma}/Z,proc$ | 1% |
| | $f_1^{W/Z,proc}$ | 1–2% |
| JES | $R_1^{CR,proc}, CR=W(ev) \text{ or } W(\mu\nu)$ | 1.0–1.5% |
| | $R_1^{CR,proc}, CR=Z(ee) \text{ or } Z(\mu\mu)$ | 1% |
| | $f_1^{\gamma}/Z,proc$ | 3% |
| | $f_1^{W/Z,proc}$ | 1.0–2.5% |
| JER | $R_1^{CR,proc}, CR=W(ev) \text{ or } W(\mu\nu)$ | 1.0–1.5% |
| | $R_1^{CR,proc}, CR=Z(ee) \text{ or } Z(\mu\mu)$ | 1% |
| | $f_1^{\gamma}/Z,proc$ | 1–4% |

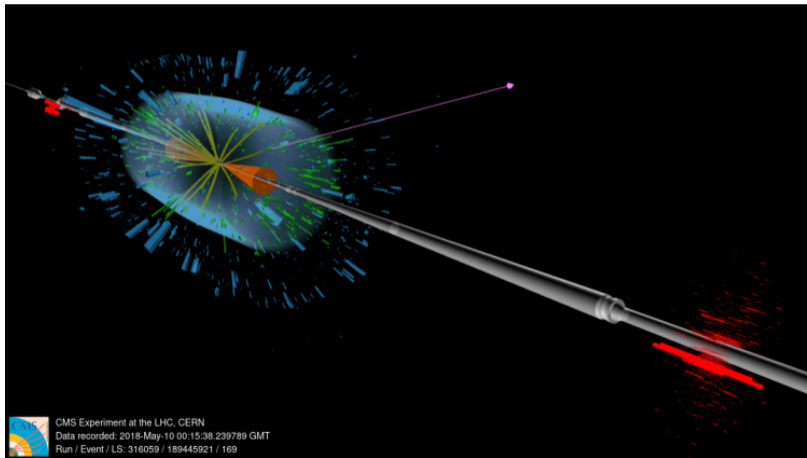
Control region ratios

- All transfer factors taken from simulations
- Comparison of control region ratios in data builds confidence that simulation is reliable
 - No significant with respect to m_{jj} across signal regions/years?



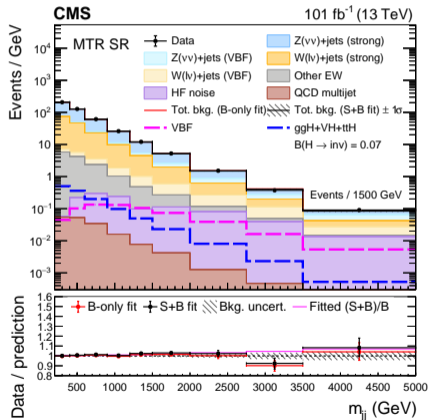
High mass dijet event

- Two jets in opposite **HF**
- $m_{jj} = 4.8$ TeV

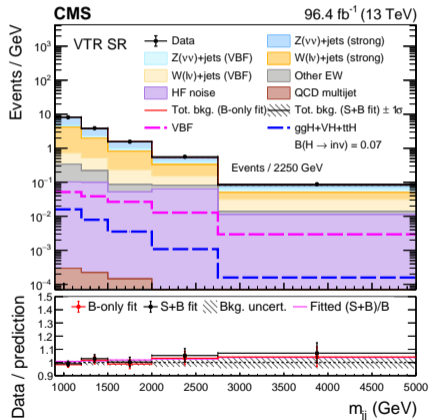


Signal region dijet mass spectrum

- No significant deviation with respect to Standard Model expectation.
- Background only fit able to describe the data in both categories



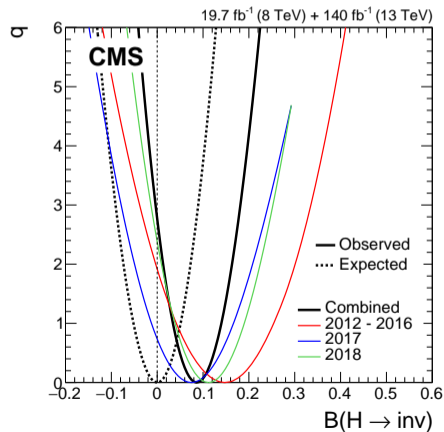
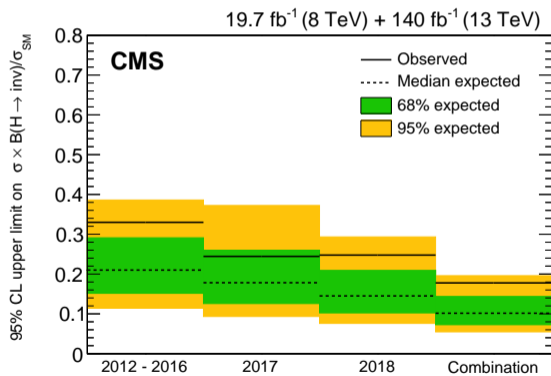
MTR



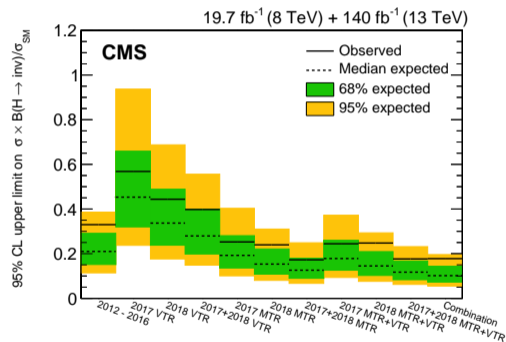
VTR

Constraints on the SM Higgs boson invisible decay mode

- Combination with previous data sets (Run 1 + 2015/2016)
- Set observed exclusion on $\mathcal{B}(H \rightarrow \text{inv}) < 0.18$ (0.10 expected)
- Signal strength best fit: $0.086^{+0.054}_{-0.052}$ ($0.00^{+0.051}_{-0.052}$ expected)



- General 1σ excess across years/signal regions



| Group of systematic uncertainties | Impact on $\mathcal{B}(H \rightarrow \text{inv})$ | |
|-----------------------------------|---|------------------|
| | Observed | 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 |

Interpretation in Higgs portal models

- Limits set on DM-nucleon interaction cross section.
- Competing with direct detection experiments for masses below 12 (6) GeV for a fermion (scalar) DM candidate.

$$\sigma_{S-N}^{SI} = \frac{\lambda_{hSS}^2}{16\pi m_h^4} \frac{m_N^4 f_N^2}{(M_S + m_N)^2},$$

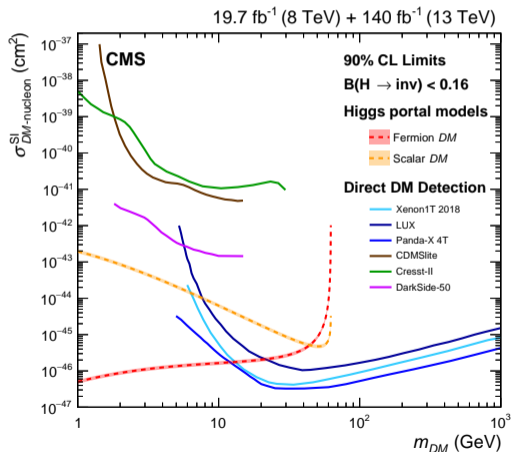
$$\sigma_{V-N}^{SI} = \frac{\lambda_{hVV}^2}{16\pi m_h^4} \frac{m_N^4 f_N^2}{(M_V + m_N)^2},$$

$$\sigma_{f-N}^{SI} = \frac{\lambda_{hff}^2}{4\pi\Lambda^2 m_h^4} \frac{m_N^4 M_f^2 f_N^2}{(M_f + m_N)^2},$$

$$\Gamma_{h \rightarrow SS}^{\text{inv}} = \frac{\lambda_{hSS}^2 v^2 \beta_S}{64\pi m_h},$$

$$\Gamma_{h \rightarrow VV}^{\text{inv}} = \frac{\lambda_{hVV}^2 v^2 m_h^3 \beta_V}{256\pi M_V^4} \left(1 - 4 \frac{M_V^2}{m_h^2} + 12 \frac{M_V^4}{m_h^4} \right),$$

$$\Gamma_{h \rightarrow \chi\chi}^{\text{inv}} = \frac{\lambda_{hff}^2 v^2 m_h \beta_f^3}{32\pi\Lambda^2},$$



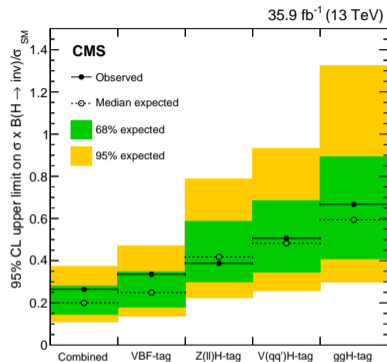
What is next? (short term)

Combination with other production modes?

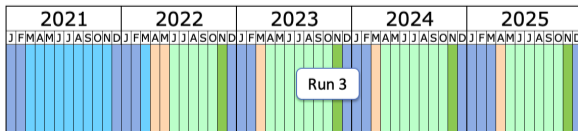
- Analyses in the pipeline.
- Could improve sensitivity by 10-20%?

Run 3:

- Starting this summer !
- Will triple the available dataset.
- Better triggers for better sensitivity?



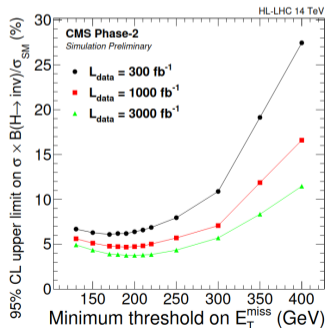
In January 2022, the schedule was updated with long shutdown 3 (LS3) to start in 2026 and to last for 3 years.



What is next? (long term)

Phase 2 upgrade.

- Major upgrade of the experiment planned after Run 3 to sustain the high luminosity LHC run until 2040
- Expect $\mathcal{O}(10)$ times more data with respect to Run 3.
- New tracker extended up to $|\eta| = 3.8$
- New high granularity endcap calorimeter
- **Significant improvement in performances for forward jets.**



L1-Trigger/HLT/DAQ

- <https://cds.cern.ch/record/2283192>
- <https://cds.cern.ch/record/2283193>
- Tracks in L1-Trigger at 40 MHz
- PFlow-like selection 750 kHz output
- HLT output 7.5 kHz

Calorimeter Endcap

- <https://cds.cern.ch/record/2293646>
- 3D showers and precise timing
- Si, Scint+SIPM in Pb/W-SS

Tracker <https://cds.cern.ch/record/2272264>

- Si-Strip and Pixels increased granularity
- Design for tracking in L1-Trigger
- Extended coverage to $|\eta| = 3.8$

Barrel Calorimeters

- <https://cds.cern.ch/record/2283187>
- ECAL crystal granularity readout at 40 MHz with precise timing for e/γ at 30 GeV
- ECAL and HCAL new Back-End boards

Muon systems

- <https://cds.cern.ch/record/2283189>
- DT & CSC new FE/BE readout
- RPC back-end electronics
- New GEM/RPC $1.6 < \eta < 2.4$
- Extended coverage to $|\eta| = 3$

Beam Radiation Instr. and Luminosity, and Common Systems and Infrastructure

- <https://cds.cern.ch/record/2020886>

MIP Timing Detector

- <https://cds.cern.ch/record/2296612>

Precision timing with:

- Barrel layer: Crystals + SIPMs
- Endcap layer: Low Gain Avalanche Diodes

New paradigms (design/technology) for an HEP experiment to fully exploit HL-LHC luminosity

- Strong research program conducted by CMS to study the Higgs properties in details
- Among those, its invisible decays is of particular interest as it could be sensitive to new physics (e.g. dark matter)
- I have presented the latest results from CMS in the vector boson fusion channel, using the full Run 2 dataset.
- No deviation with respect to the SM model but stringent limits set on the Higgs invisible branching ratio and on Higgs portal models for low DM masses.
- The story is not over, stay tuned !

Thanks for your attention !