Searches for Higgs boson rare and invisible decays at CMS

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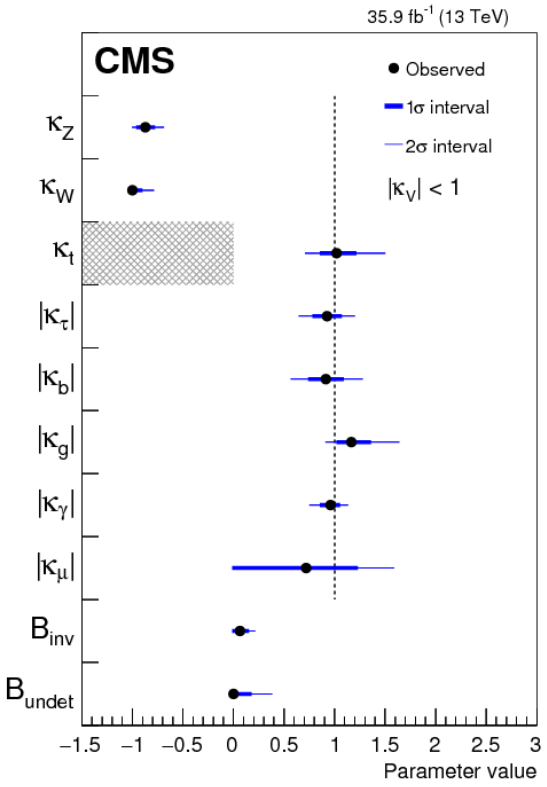
ICHEP2020:
28.07-06.08.2020.

Introduction: A tale of two studies

- 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 shown **a complete agreement** 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**?
- According to the SM: **B(H→4ν) ~ 0.1%**
  - Can represent a good way of testing for new physics at the LHC!
- **Q: What is the current status of these measurement?**

Eur. Phys. J. C 79 (2019) 421



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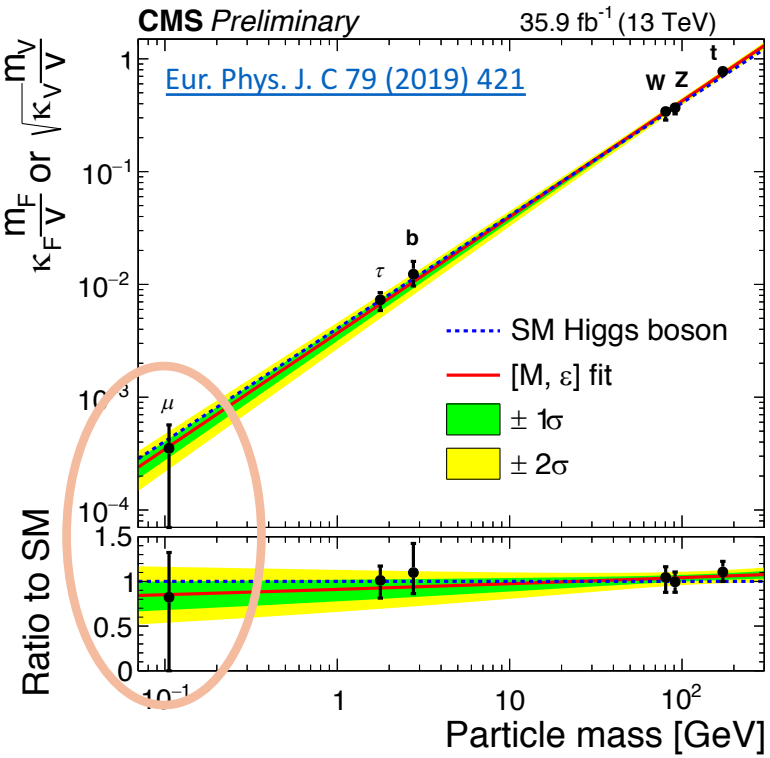
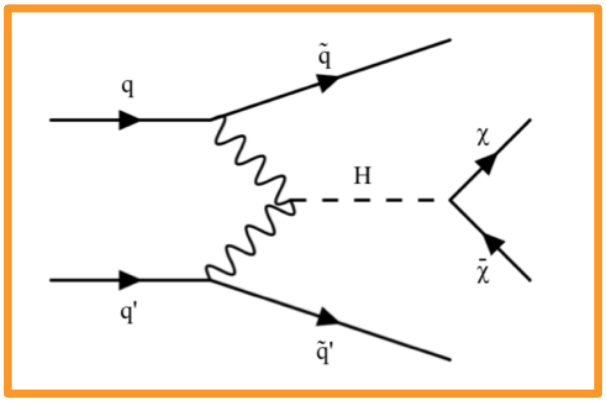


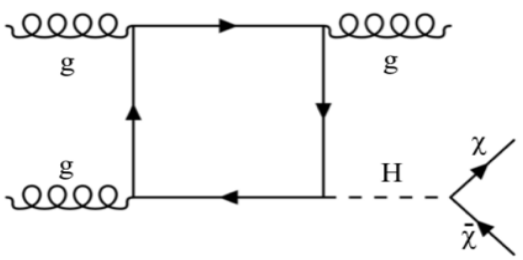
- Why the interest in the **dimuon final state**?
- A golden channel for probing the Higgs boson coupling with the 2nd generation fermions
- Challenging due to:
  - $B(H \to \mu\mu) \sim 2.19 \cdot 10^{-4}$
- **Q: Is there something interesting that we can say today?**

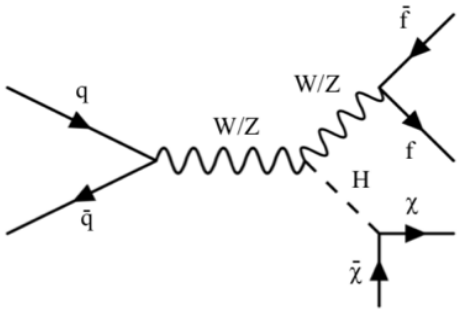
Motivation: The invisible final state

- 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 (MET)



- **qqH:** Vector boson fusion production
  - Largest sensitivity for the invisible final state
  - Main characteristics of this category:
    - **Two jets** separated by **a large η**
    - **Large** dijet invariant mass **(mjj)**
  - Data driven estimation of SM V+jets backgrounds





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- Higgs boson can take a role of **a mediator** between SM and DM particles
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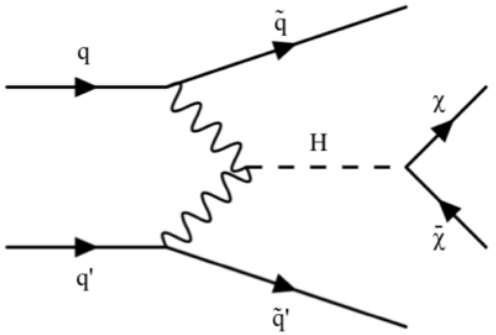
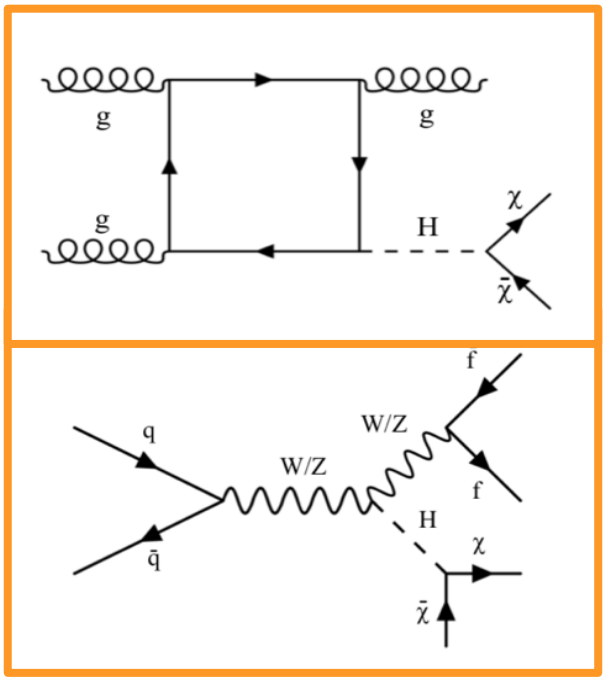
- **ggH:** Gluon fusion production:
  - Category formed around a jet originating from ISR
  - Interpreted as ggH associated with 1 jet

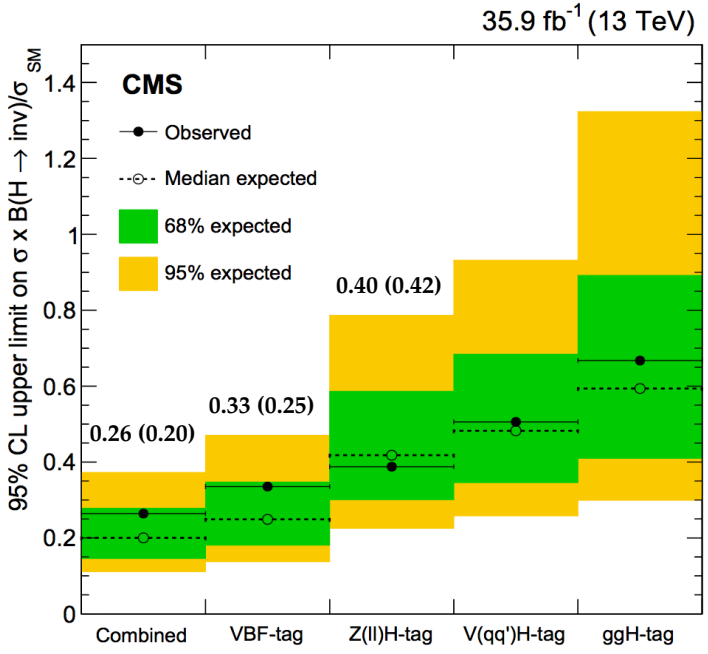


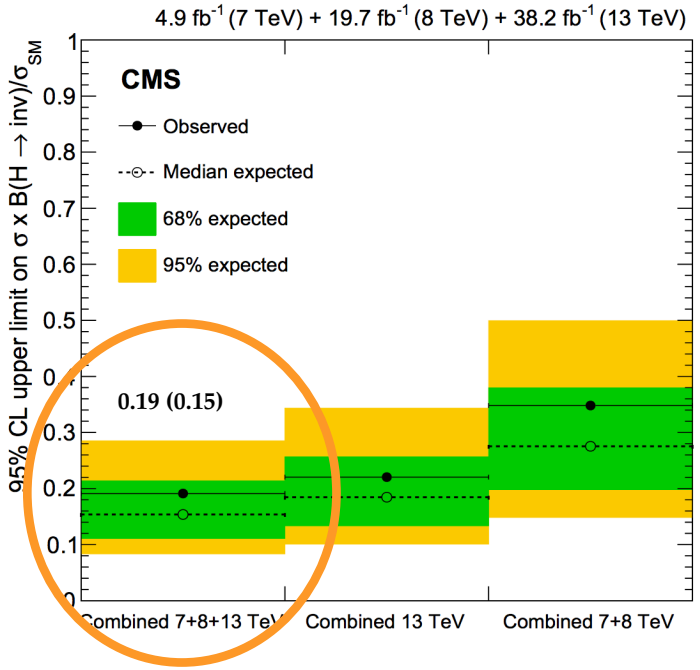
- **VH:** Production in association with a vector boson:
  - **V(qq)H(inv):**
    - Energetic jets + MET
  - **Z(ll)H(inv):**
    - Lepton pair from Z decays + MET
    - **More to come!**



H(inv): Summary of results

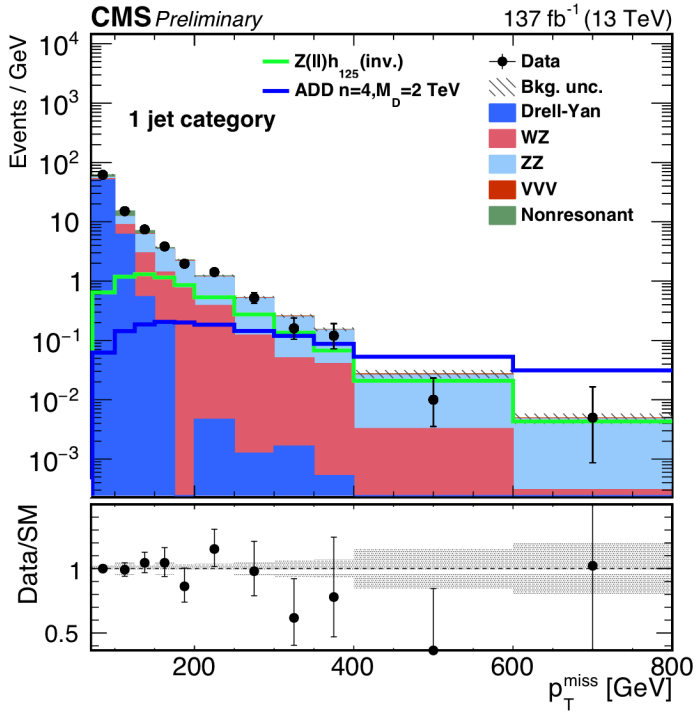
- Latest combination effort was published in: Physics Letters B 793 2019
- Includes combination of early Run 2 (2015+2016) with Run 1 measurements
- Sets a 95% CL upper limit on B(H → inv) = 0.19 (0.15) observed (expected)
  - For a chosen $m_H = 125.09$ GeV

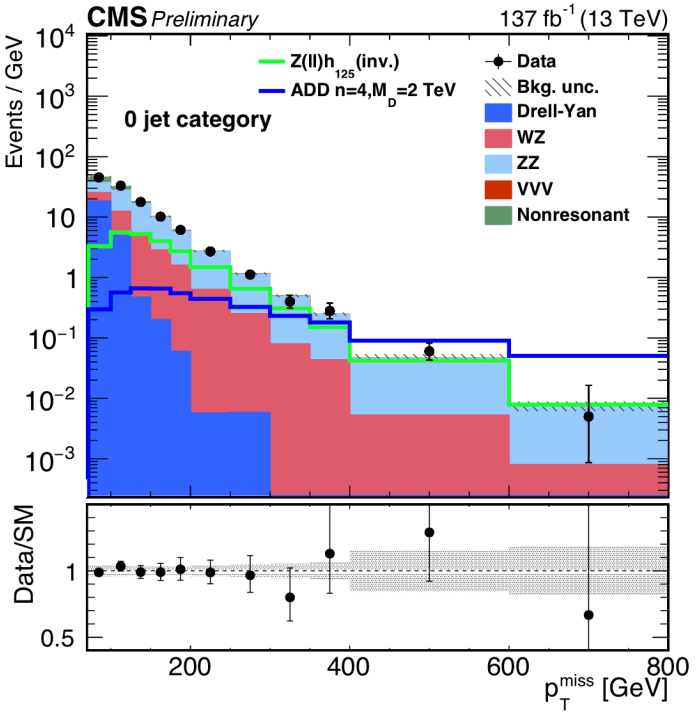




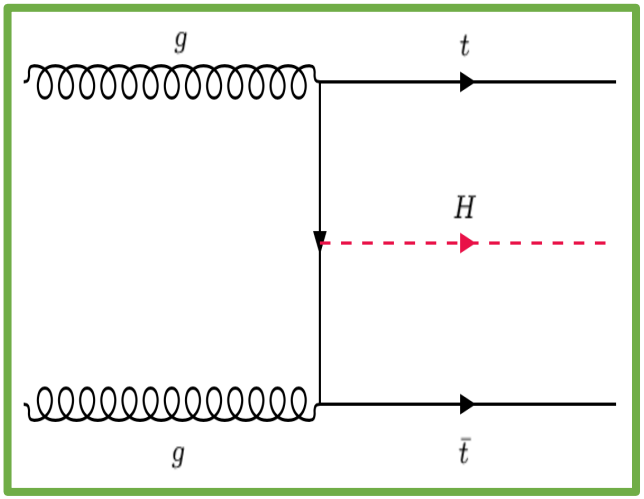
Z(ll)H(inv) full Run 2 measurement

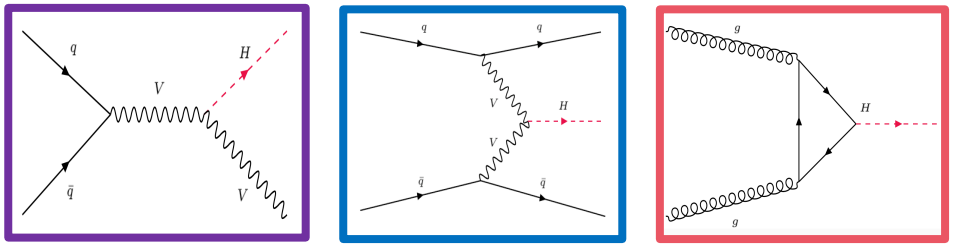
- Recently published result: CMS-PAS-EXO-19-003
- Includes measurements performed using the full Run 2 dataset
- The observed (expected) 95% CL upper limit computed using m_H= 125 GeV:
  - B(H → inv) = 0.29 (0.25)





Motivation: The dimuon final state



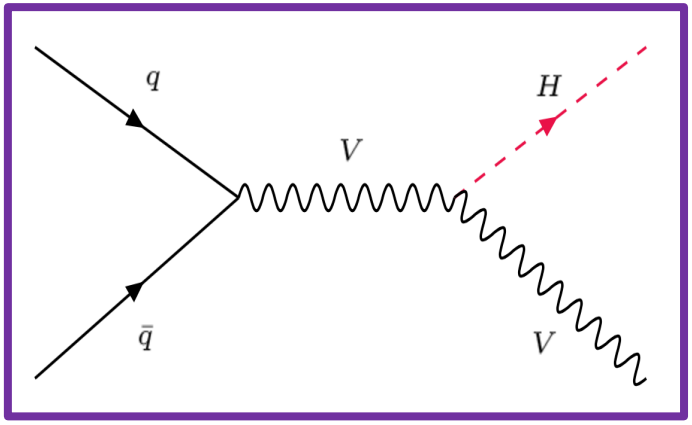


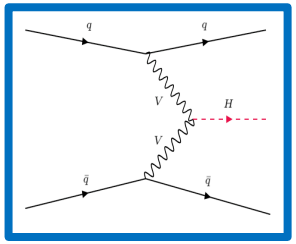
- Events are collected using single muon trigger algorithms
- Common requirements for all channels:
  - Two identified and isolated muons with:
    - $110 < m_{\mu^+\mu^-} < 150$ GeV [1]
- Three **exclusive** channels that are new to the strategy:
  - ttH/VH/VBF

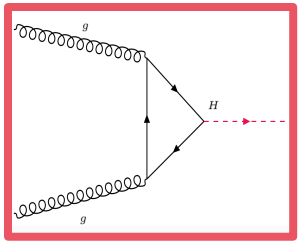
- **ttH channel:**
  - The topology asks for **2 b jets and at least 1 passing medium id criteria**
  - This can further be split into two categories: **hadronic** or **leptonic**

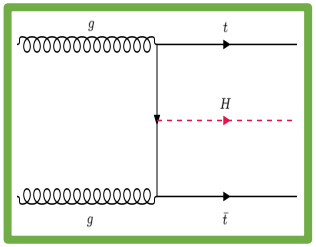
[1] Mass sideband (SB): $110 < m_{\mu^+\mu^-} < 115$ GeV or $135 < m_{\mu^+\mu^-} < 150$GeV
Mass signal region (SR): $115 < m_{\mu^+\mu^-} < 135$ GeV

Motivation: The dimuon final state









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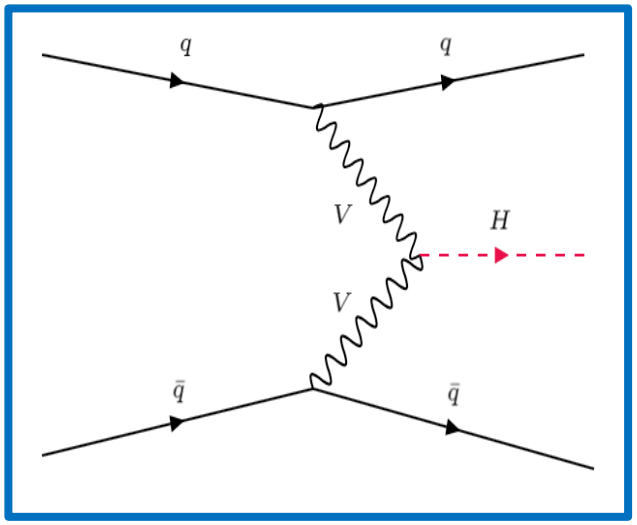
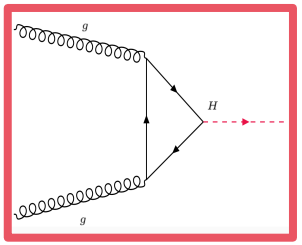
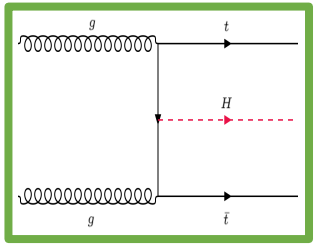
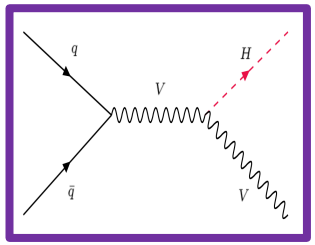
- **VH channel:**
  - Essentially looks at leptonic decays of V (where V = W or Z)
  - Depending on what V is - can be further split into:
    - **ZH**: focusing on 4μ or $2\mu 2e$ final states
    - **WH**: covering 3μ or $2\mu 1e$ final state

Motivation: The dimuon final state









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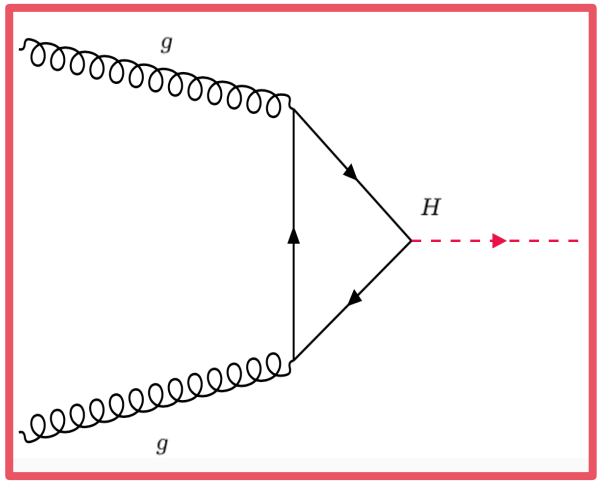
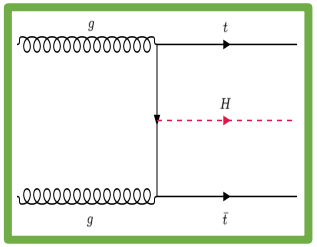
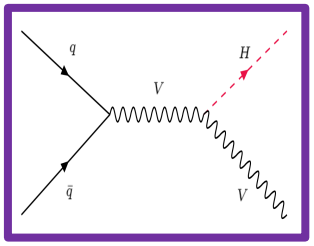
- **VBF channel:**
  - Imposing a selection on VBF jets following the topology:
  - Orthogonality with other channels

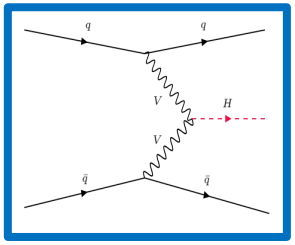
$p_{T,j1}$	$p_{T,j2}$	m_{jj}	$\lvert\Delta\eta_{jj}\rvert$
> 35 GeV	> 25 GeV	> 400 GeV	> 2.5

Motivation: The dimuon final state









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- **ggH channel:**
  - Orthogonality with the previous (**ttH**, **VH** and **VBF**) channels
  - Largest category, collects all events discarded by other categories
    - Dominated by 0/1 jet + 2μ events

$H \rightarrow \mu\mu$: ggH channel

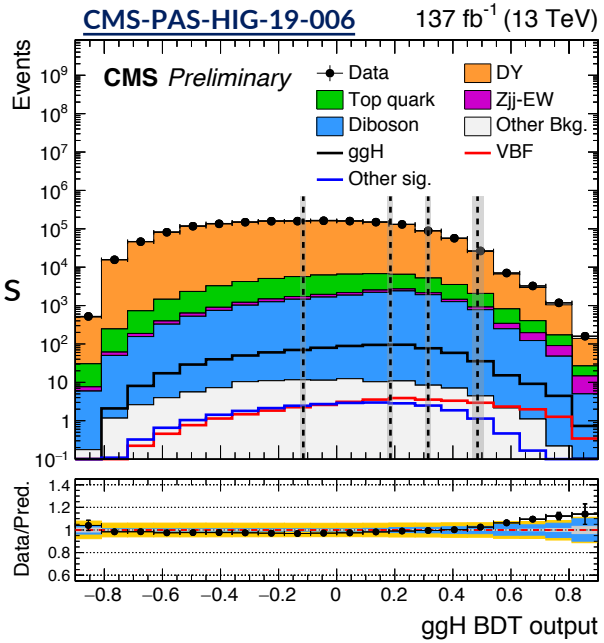
- **ggH channel** - category with the largest % of inclusive event - smallest S/B
  - Dominating background: **Drell-Yan (DY) processes**

- Usage of boosted decision tree (**BDT**) multivariate discriminator:
  - Tailored use of muon variables → $m_{\mu\mu}$-decorrelated training
  - Including jet variables in the training → recovers ggH+X signal
  - Trained separately for each data taking period to incorporate detector effects

- **Further division of selected events based on S/B:**

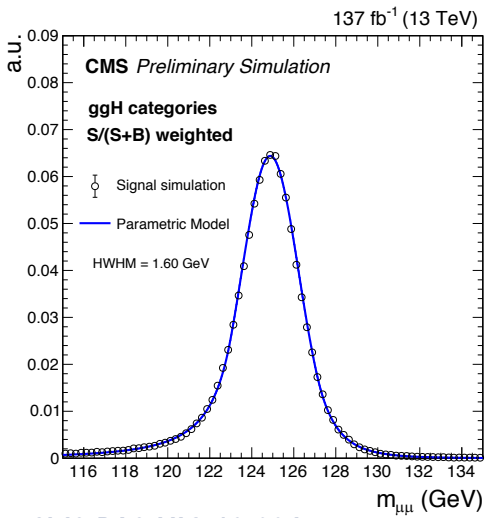
- Iterative strategy along the range of BDT scores
  - Maximizing the expected sensitivity from profile likelihoods

- Significance is extracted by fitting $m_{\mu\mu}$ with analytical shapes inspired from simulation



$H \rightarrow \mu\mu$: ggH channel

- **Signal composition** is **stable** across the categories:
  - **Modelling** each production mode of the signal with **a Double Crystal-ball function**
- **Background** composition follows, being also **stable** along categories:
  - **Largely** dominated by **DY** (larger than ~90%)
  - Modeling via discrete profile likelihood:
    - Functions in the discrete envelope (modified Breit-Wigner, etc.)
      - modulated in each category via polynomials
    - Negligible bias in the final extraction
- Presented for m_H= 125.38GeV
  - Most precise measurement of the Higgs boson mass ★ - [Phys. Lett. B 805 (2020) 135425]



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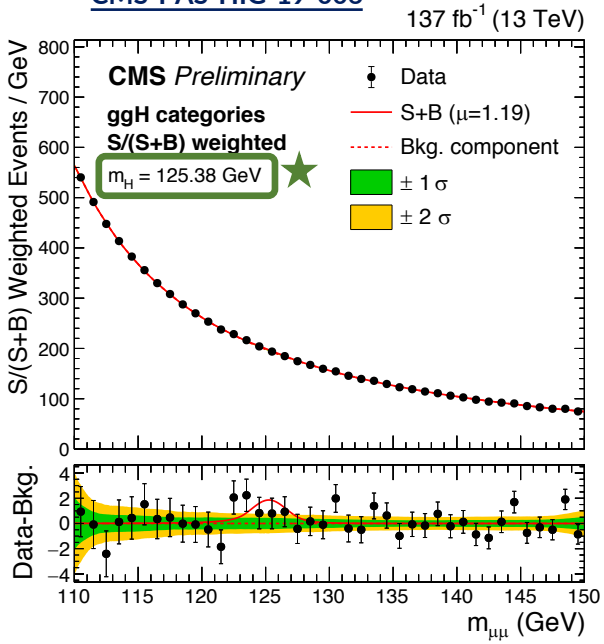


$H \to \mu\mu$: ttH channel

- **ttH channel** - category with the smallest production xs
  - The presence of t helps with background reduction
- Separation into **two categories** based on the **final state of the W** from t decay:

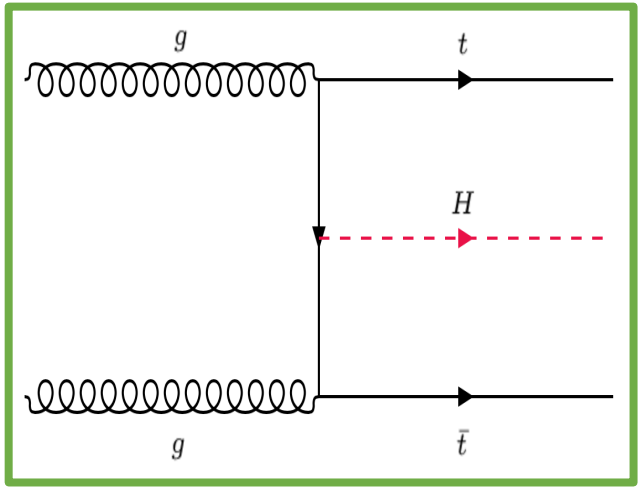
$$t \to bW$$

$W \to l\nu$

$W \to qq'$

- Final states include 1 or 2 additional leptons (besides the muon pair)
- In case of a 3/4 muon scenario:
  - Higgs forming pair chosen as the one with the largest p_T
- Main backgrounds: **tt and ttZ**

- Fully hadronic final state of the W decay
- Main backgrounds: **tt**



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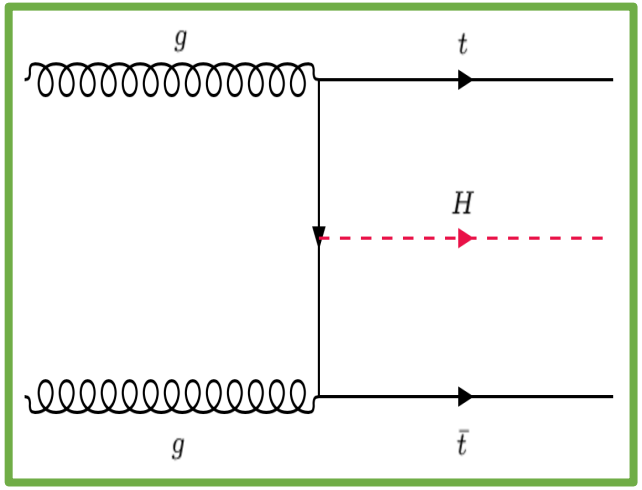
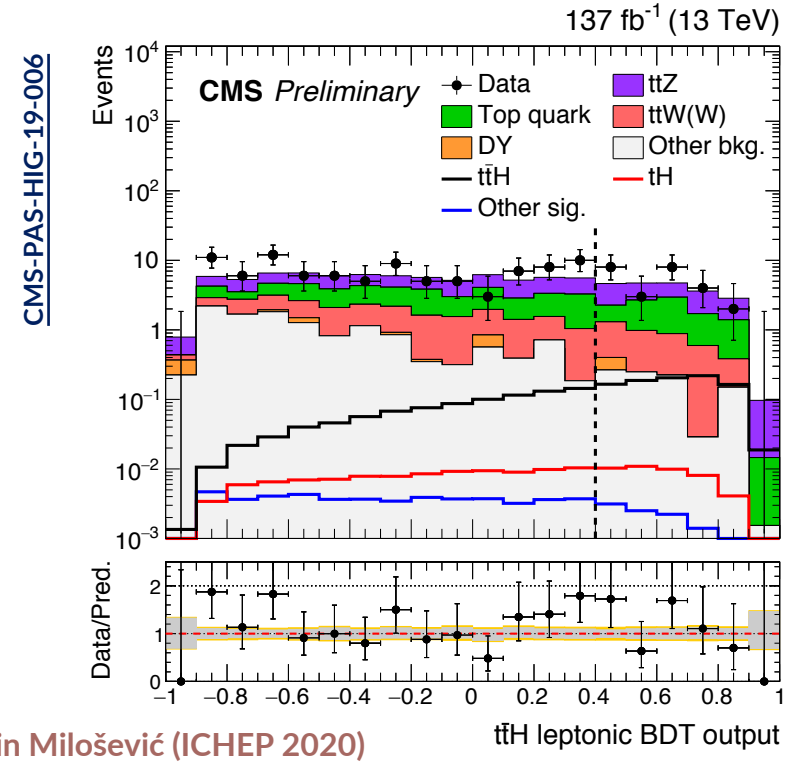
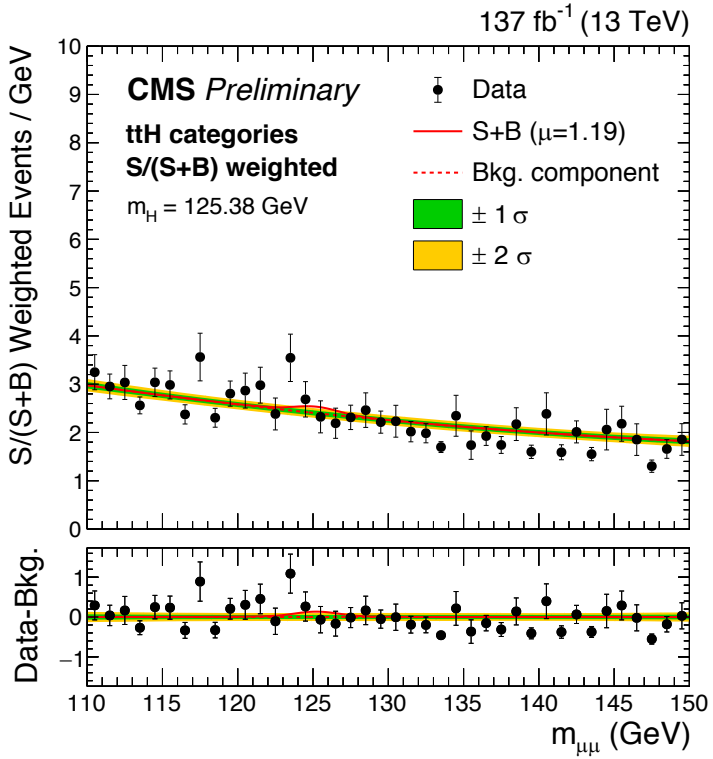


$H \rightarrow \mu\mu$: ttH channel

- Training of BDTs on **both categories**:
  - Both $\mu\mu$ and **tt** oriented variables, but keeping the **BDT output uncorrelated with $m_{\mu\mu}$**
  - BDT learns of mass resolution due to the reweighting of events before the training (same as with ggH and VH categories)

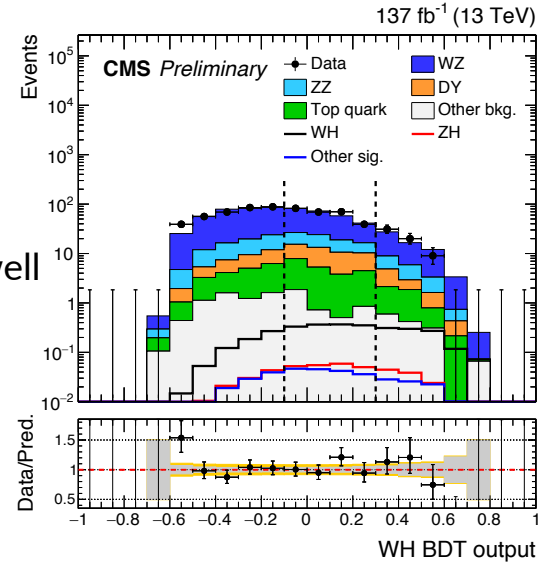
- Further separated into additional **2** (leptonic) and **3** (hadronic) **subcategories** (dashed line)
  - Similar opitimisation of categories as explained for the ggH channel
- **Polynomial (hadronic) and exponential (leptonic) functions** used to fit the background

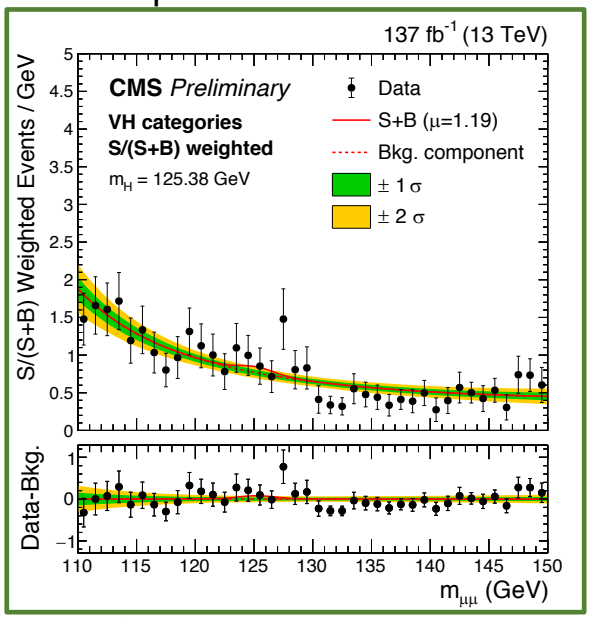




$H \rightarrow \mu\mu$: VH channel

- **VH channel** - category focused on searching for additional leptons (besides the μμ pair)
  - Further separation done into ZH and WH categories
- **BDTs** used for discriminating signal processes in both categories
  - Variables chosen in order to explore the topology of Z/W as well
  - Further split into **2** (ZH) and **3** (WH) **categories** (dashed lines)
- Signal is fitted using a **DCB function**
- Background modelled via modified Breit-Wigner functions
  - More in the backup





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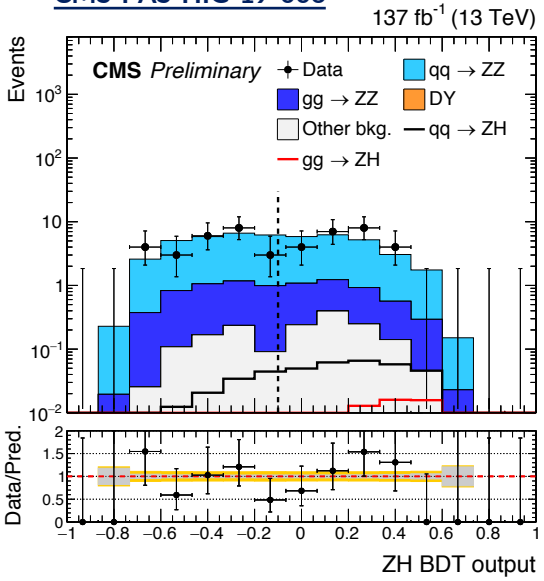


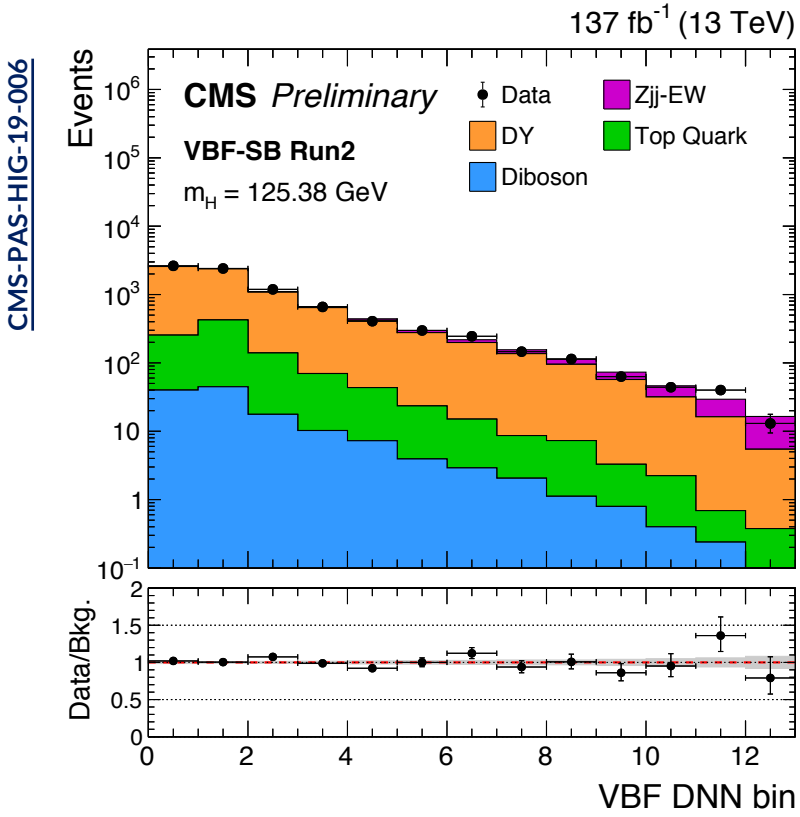
$H \rightarrow \mu\mu$: VBF channel

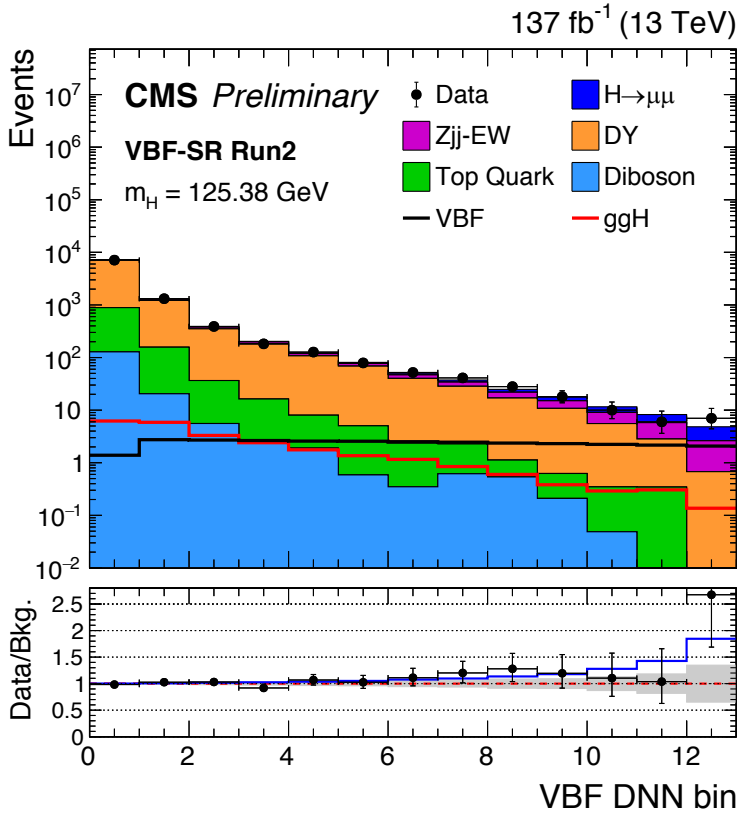
- **VBF channel** - specific jet topology allows for a tailored selection
- Main backgrounds: **QCD/EWK** production of **Z+jets**
- Estimation through data-driven methods:
  - Strongly limited by statistics in the mass sideband
- Instead opting for an **estimation** through the **usage of simulated events**
  - Trading limited data statistics for simulation prediction with associated uncertainty
- **Signal extraction:** Deep neural network (DNN) multivariate discriminant:
  - Usage of a DNN in order to distinguish signal over background
    - Training performed on SR and SB events

$H \to \mu\mu$: VBF channel

- Maximum likelihood fit to the DNN output score simultaneously in SR and SB
- Constraints on background normalization improved through the inclusion of mass sideband (VBF-SB) in the fit

- Fit is performed simultaneously across regions - independently per data taking period

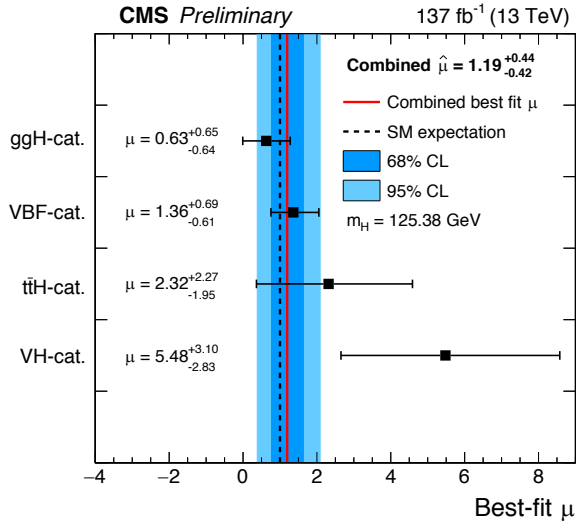




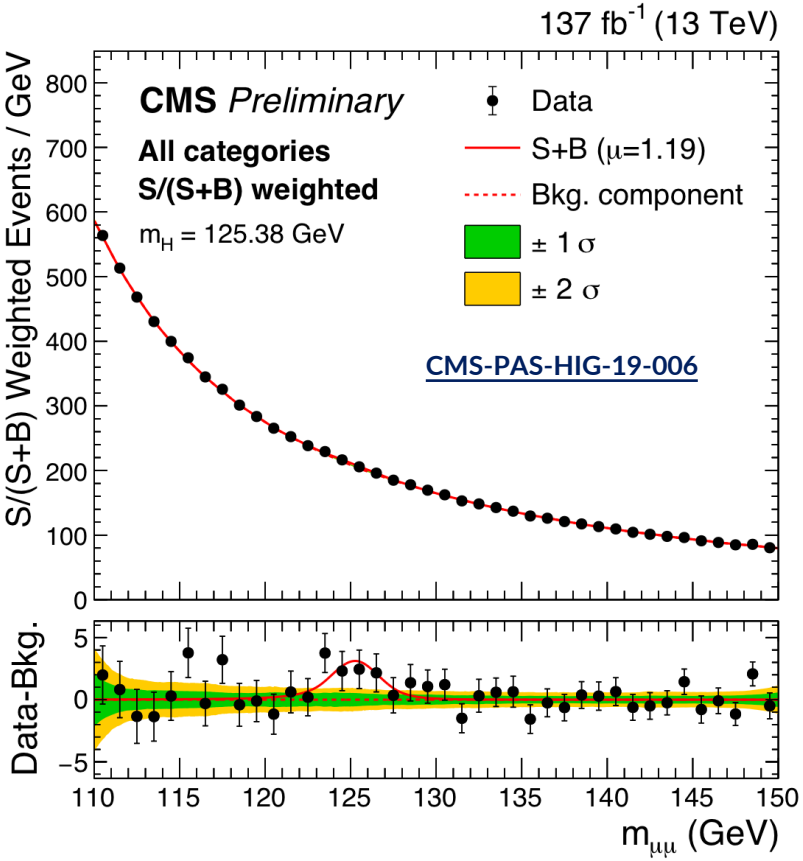
H->μμ: Results

- Simultaneous fit performed across all channels with $\mu = \frac{[\sigma B(H\to\mu\mu)]_{observed}}{[\sigma B(H\to\mu\mu)]_{SM}}$
  - $\mu = 1.19^{+0.41}_{-0.39}(stat)^{+0.17}_{-0.16}(sys)$, for the m_H= 125.38 GeV
  - An excess has been observed in data with a significance of 3.0 σ!

CMS-PAS-HIG-19-006



Uncertainty source	$\Delta\mu$	
Total uncertainty	+0.44	−0.42
Statistical uncertainty	+0.41	−0.39
Total systematic uncertainty	+0.17	−0.16
Size of simulated samples	+0.07	−0.06
Total experimental uncertainty	+0.12	−0.10
Total theoretical uncertainty	+0.10	−0.11

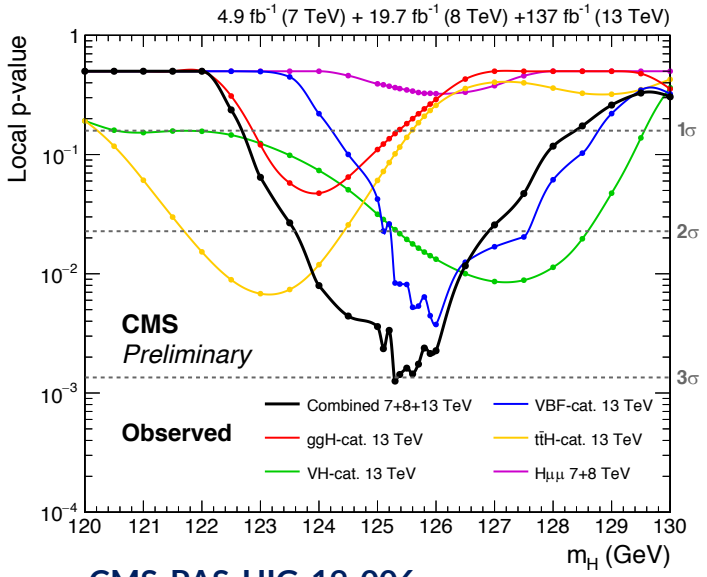


N.B. For illustration purposes – does not represent fit results

H->μμ: Results

- A combination with Run 1 measurement has been performed:
  - *Run 1: Phys. Lett. B* **744** (2015) 184
- An **excess** has been observed in data with **a significance of 3.0 σ**!

Prod. Category	Obs. (exp.) significance (m_H = 125.38 GeV)	Obs. (exp.) 95% CL upper limit (m_H = 125.38 GeV)
VBF	2.40 (1.77)	2.57 (1.22)
ggH	0.99 (1.56)	1.77 (1.28)
ttH	1.20 (0.54)	6.48 (4.20)
VH	2.02 (0.42)	10.80 (5.13)
Comb. 13 TeV	2.95 (2.46)	1.94 (0.82)
Comb Run 1+2	2.98 (2.48)	1.93 (0.81)



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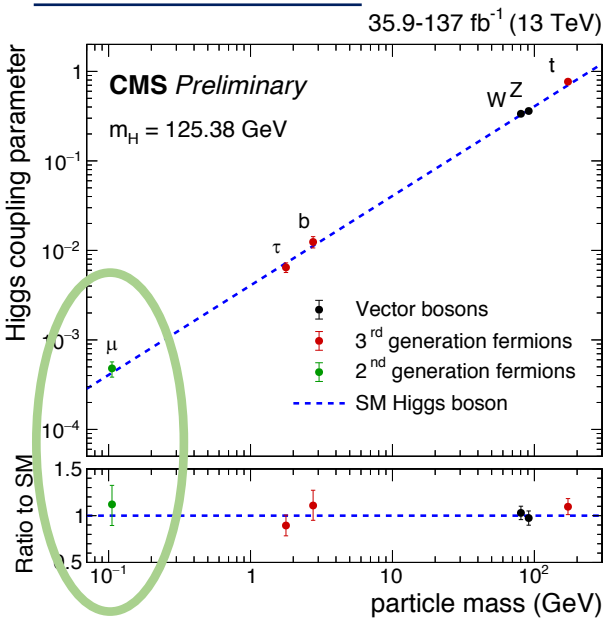
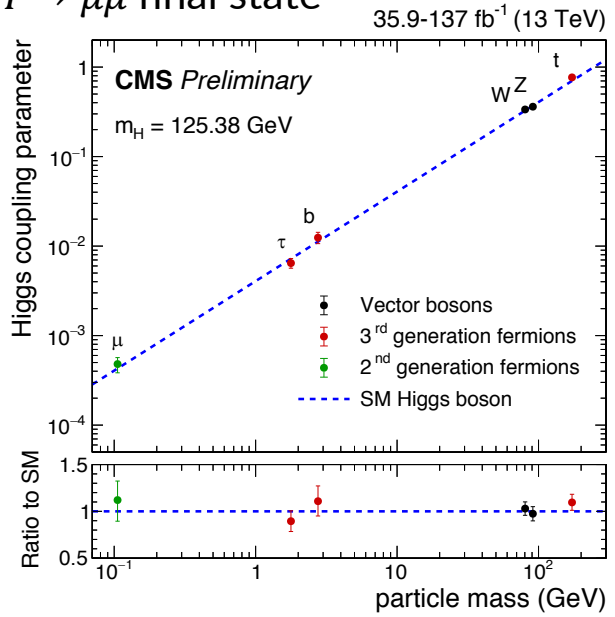
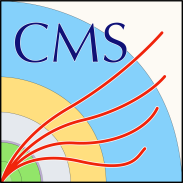


Summary

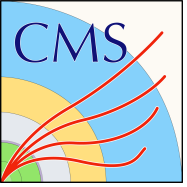
- Combination effort yields B(H→inv) = 0.19 (0.15) observed (expected)
  - Full Run 2 result in preparation !
  - Details about future prospects can be found in talk by Sandhya
- Presented the full Run 2 measurement looking for Z(ll)H(inv)
  - Sets a 95% CL upper limit on Br(Hinv) = 0.29 (0.25) observed (expected)

- Presented the full Run 2 measurement targeting the $H \to \mu\mu$ final state
  - Combination of 4 exclusive channels:
    - VBF, ggH, VH and ttH
- Observed (expected) significance: 3.0 (2.5) σ
  - First evidence for $H \to \mu\mu$!
- Signal strength: $\mu = 1.19^{+0.41}_{-0.39}(stat)^{+0.17}_{-0.16}(sys)$
- Combination performed with Run 1





Thank you for your time!



Backup

$H \to \mu\mu$: Background models

- Signal is fitted using a **DCB function**

$$\mathrm{DCB}(m_{\mu\mu}) = \begin{cases} e^{-(m_{\mu\mu}-\hat{m})^2/2\sigma^2} & -\alpha_{\mathrm{L}} < \frac{m_{\mu\mu}-\hat{m}}{\sigma} < \alpha_{\mathrm{R}} \\ \left(\frac{n_{\mathrm{L}}}{|\alpha_{\mathrm{L}}|}\right)^{n_{\mathrm{L}}} e^{-\alpha_{\mathrm{L}}^2/2}\left(\frac{n_{\mathrm{L}}}{|\alpha_{\mathrm{L}}|} - |\alpha_{\mathrm{L}}| - \frac{m_{\mu\mu}-\hat{m}}{\sigma}\right)^{-n_{\mathrm{L}}} & \frac{m_{\mu\mu}-\hat{m}}{\sigma} \leq -\alpha_{\mathrm{L}} \\ \left(\frac{n_{\mathrm{R}}}{|\alpha_{\mathrm{R}}|}\right)^{n_{\mathrm{R}}} e^{-\alpha_{\mathrm{R}}^2/2}\left(\frac{n_{\mathrm{R}}}{|\alpha_{\mathrm{R}}|} - |\alpha_{\mathrm{R}}| - \frac{m_{\mu\mu}-\hat{m}}{\sigma}\right)^{-n_{\mathrm{R}}} & \frac{m_{\mu\mu}-\hat{m}}{\sigma} \geq \alpha_{\mathrm{R}} \end{cases}.$$

- Background either with **mBW** (ggH), **BWZGamma** (WH-cat1) or **BWZ functions** (rest of W/ZH)

$$\mathrm{BWZGamma}(m_{\mu\mu}; a, f, m_{\mathrm{Z}}, \Gamma_{\mathrm{Z}}) = f \times \mathrm{BWZ}(m_{\mu\mu}; a, m_{\mathrm{Z}}, \Gamma_{\mathrm{Z}}) + (1-f) \times \frac{e^{a m_{\mu\mu}}}{m_{\mu\mu}^2}.$$

$$\mathrm{BWZ}(m_{\mu\mu}; a, m_{\mathrm{Z}}, \Gamma_{\mathrm{Z}}) = \frac{\Gamma_{\mathrm{Z}} e^{a m_{\mu\mu}}}{(m_{\mu\mu} - m_{\mathrm{Z}})^2 + (\Gamma_{\mathrm{Z}}/2)^2},$$

$$\mathrm{mBW}(m_{\mu\mu}; m_{\mathrm{Z}}, \Gamma_{\mathrm{Z}}, a_1, a_2, a_3) = \frac{e^{a_2 m_{\mu\mu} + a_3 m_{\mu\mu}^2}}{(m_{\mu\mu} - m_{\mathrm{Z}})^{a_1} + (\Gamma_{\mathrm{Z}}/2)^{a_1}}.$$

$H \to \mu\mu$: Categorisation summary