

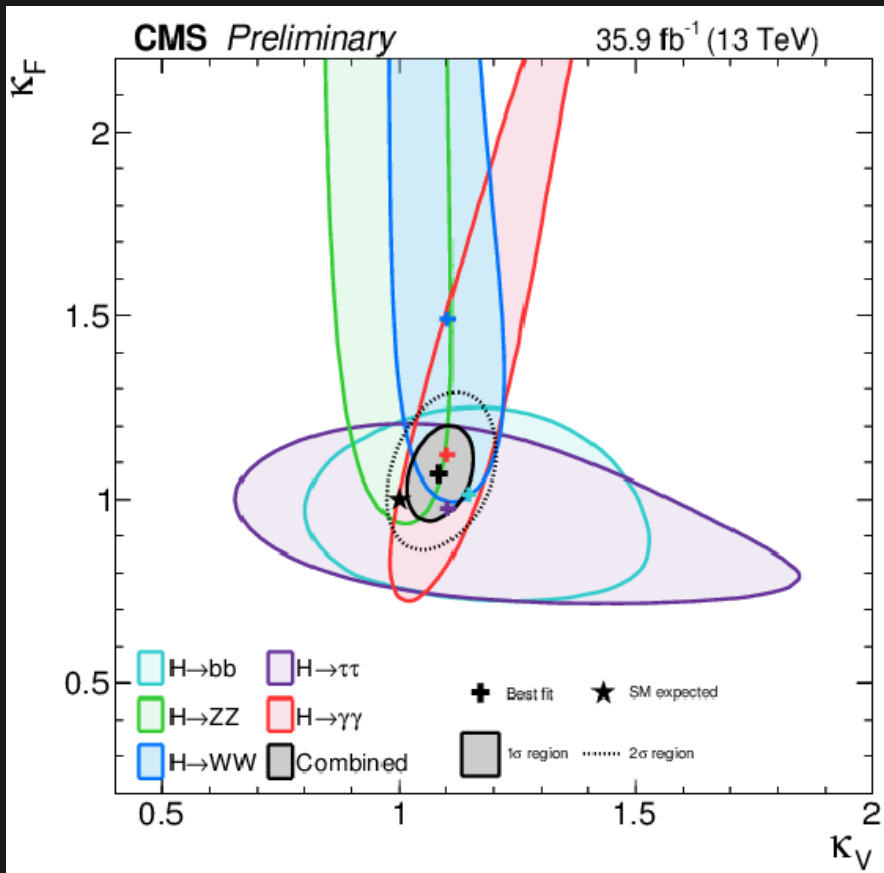


# Higgs to WW measurements with CMS

*Davide Di Croce*  
*On behalf of the CMS Collaboration*



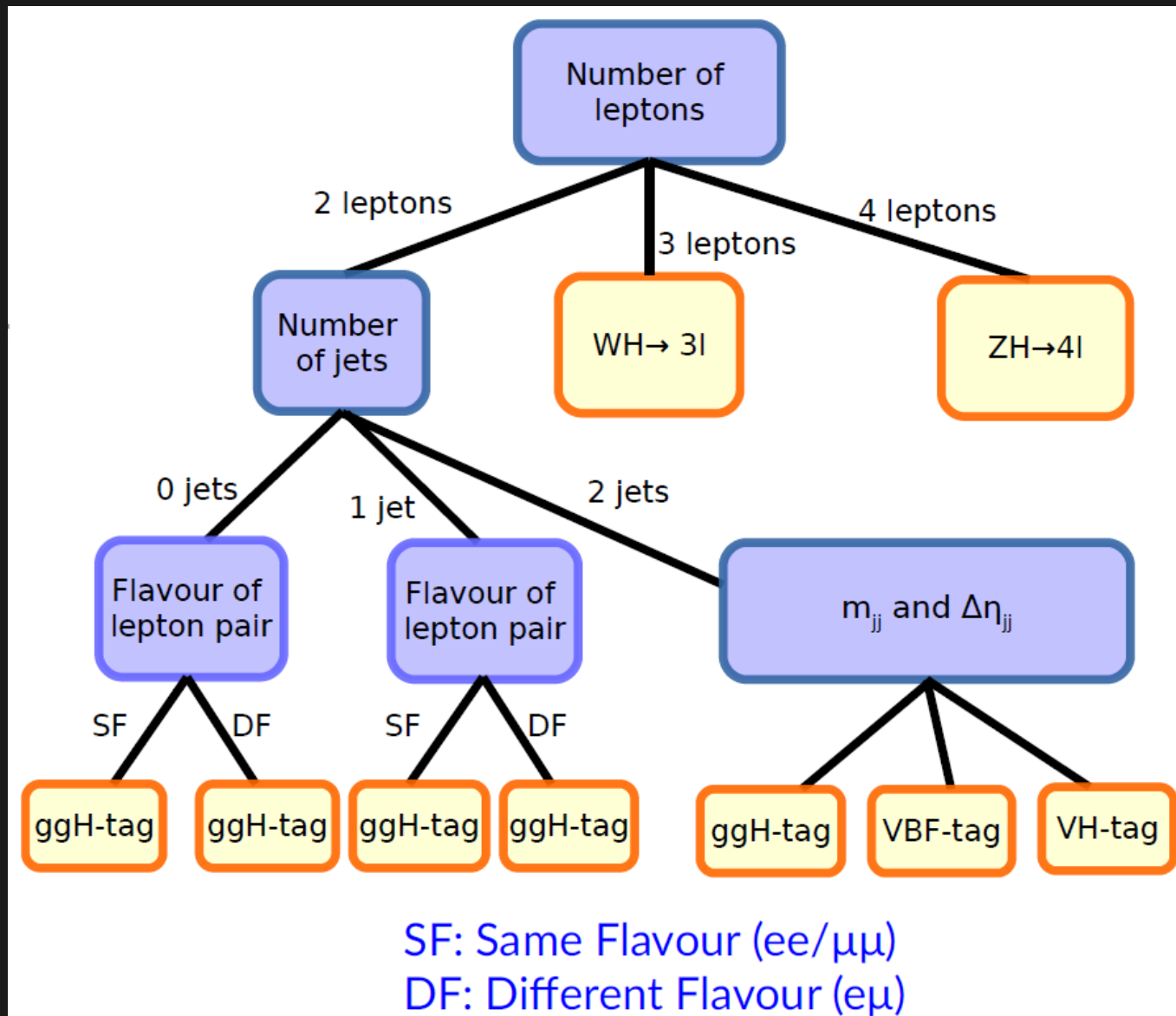
- One of the main goal of the LHC Run2 is the measurement of the Higgs boson properties.



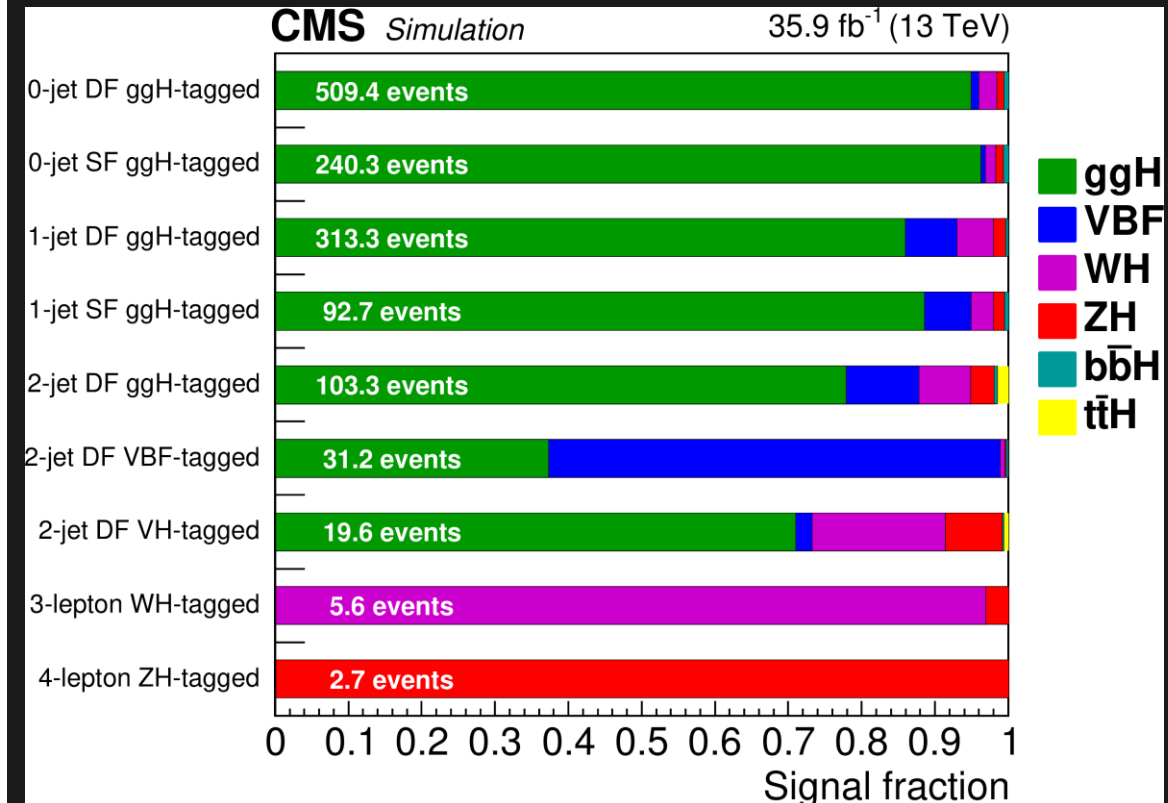
- H → WW is a crucial channel for the measurement of the Higgs boson couplings and properties.
- In this talk:
  - Only fully leptonic state.
  - 13 TeV results based on 2016 dataset of 35.9 fb<sup>-1</sup> by CMS. Phys. Lett. B 791 (2019) 96 ([arXiv:1806.05246](https://arxiv.org/abs/1806.05246)).
  - Prospects for full Run2.

# H→WW categories

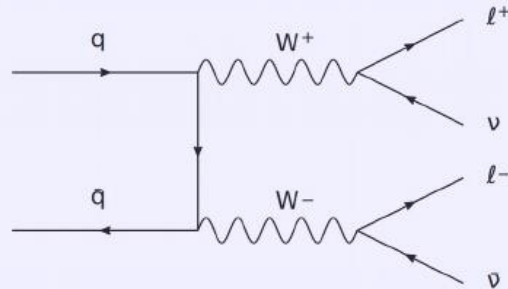
- Events split in 30 categories.



- Opposite charge leptons with  $p_T^{lep1} > 25$  GeV and  $p_T^{lep2} > 10$  (13) for  $\mu(e)$ .
- $p_T^{ll} > 30$  GeV and MET > 20 GeV.
- b-tagged jet veto.

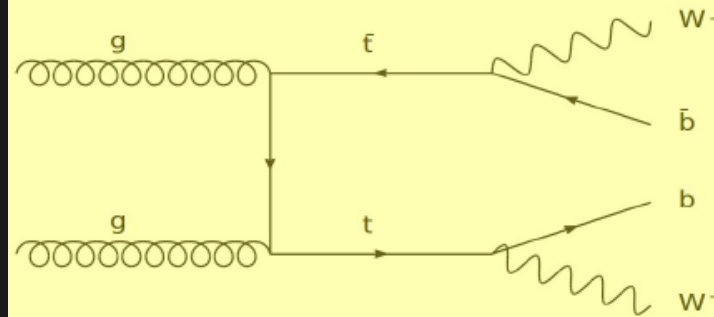


## Non-resonant WW



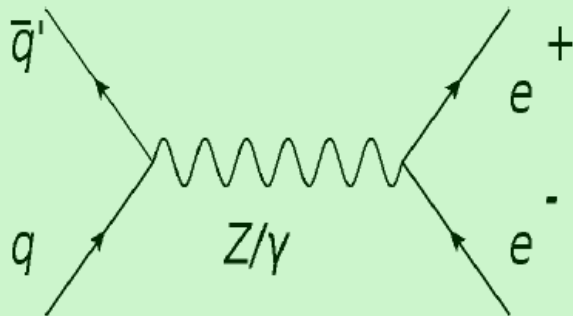
Same final state as the signal process.

## $t\bar{t}$



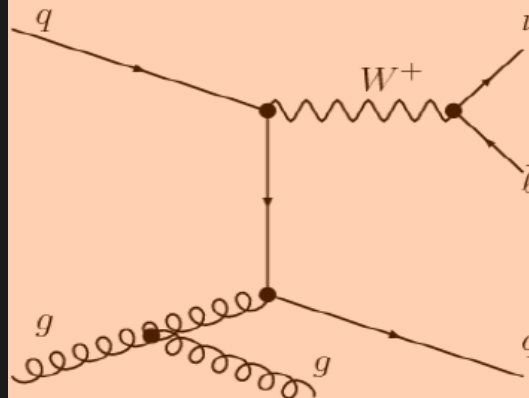
Very large cross section.  
Same final state as the signal process + 2 b-jets.  
Reduced vetoing b-jets

## Drell-Yan



Very large in the same flavour final state.

## Nonprompt

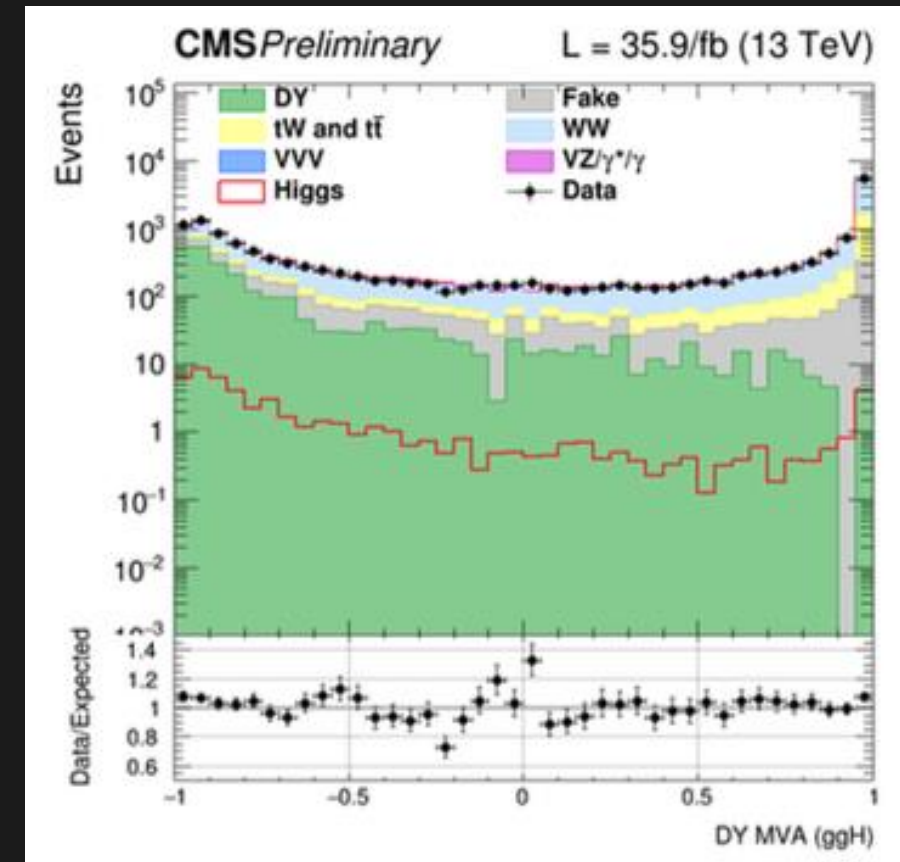
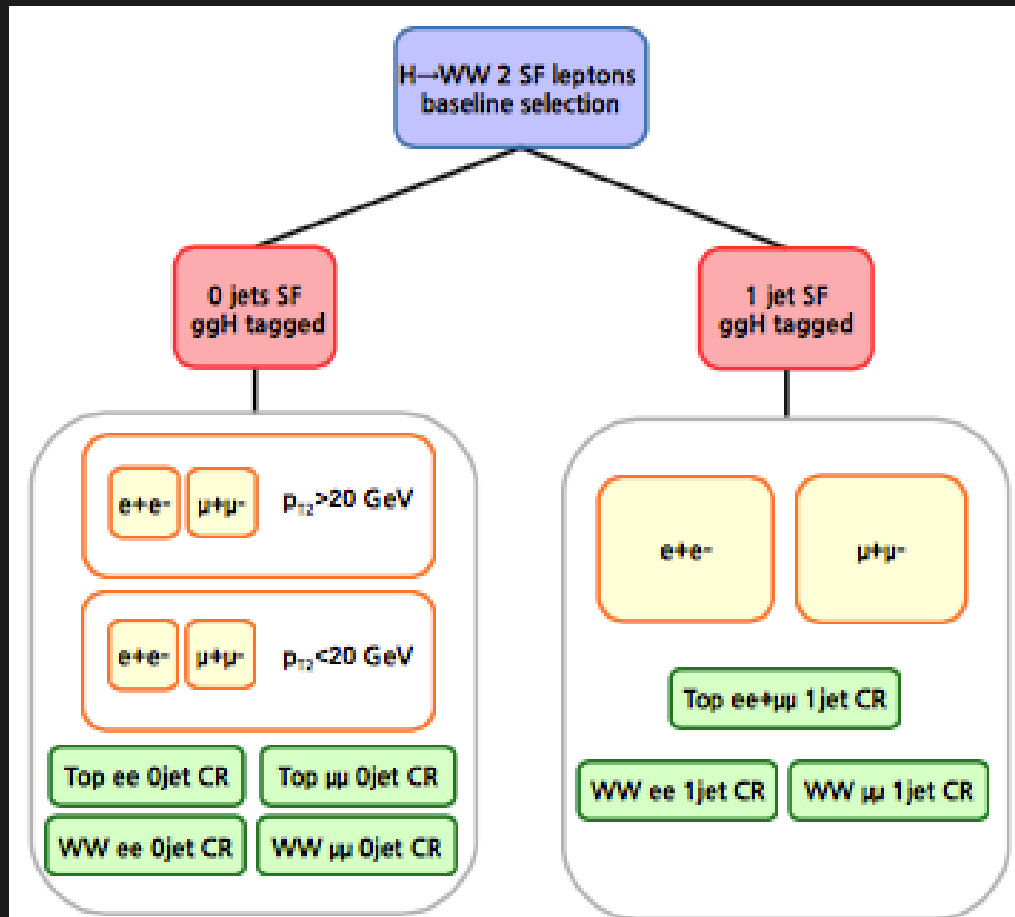


One jet can be misidentified as a lepton. Reduced with lepton ID and isolation.  
Contribution also from semi-leptonic  $t\bar{t}$ .  
Totally data-driven with fake rate method.

- Top and DY background normalization taken from data using dedicated control regions.
- WW background normalization free-floating in the fit.

# SF ggH-tagged categories

- BDT trained for DY against ggH@125 GeV (using alternative MC samples) exploiting: MET variables, kinematics and angular differences between leptons, jets and MET.
- Training and variable list pruned in each jet bin to maximize DY rejection.
- Limited DY MC statistic and poor fake MET/DY MVA description of DY:  
Estimate DY background from data and cut-based analysis only (no shape prediction for DY).

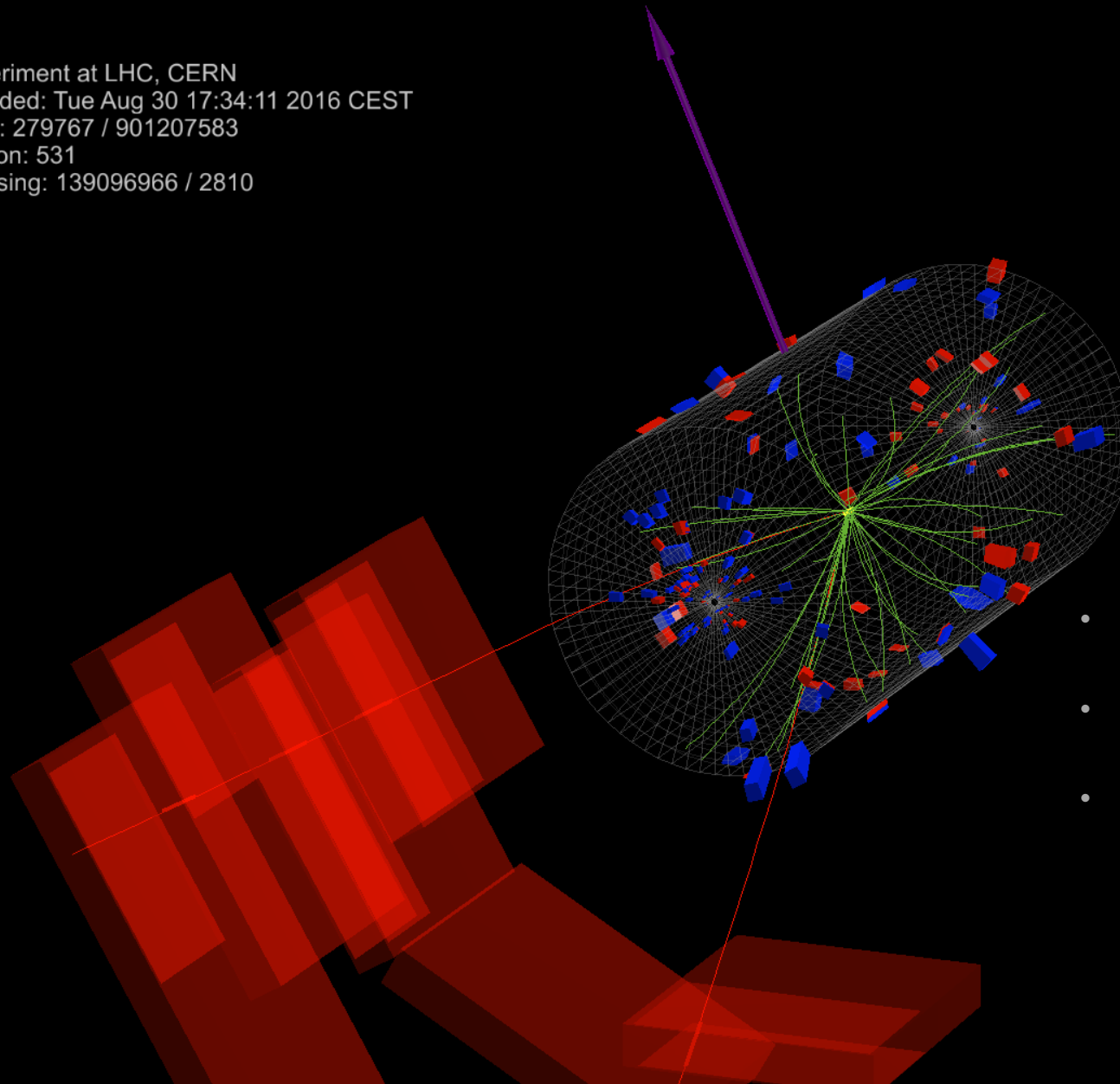


Good agreement in signal like regions

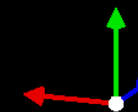
# A good candidate for $H \rightarrow WW$ SF

CMS Experiment at LHC, CERN  
Data recorded: Tue Aug 30 17:34:11 2016 CEST  
Run/Event: 279767 / 901207583  
Lumi section: 531  
Orbit/Crossing: 139096966 / 2810

CMS Experiment at LHC, CERN  
Data recorded: Tue Aug 30 17:34:11 2016 CEST  
Run/Event: 279767 / 901207583



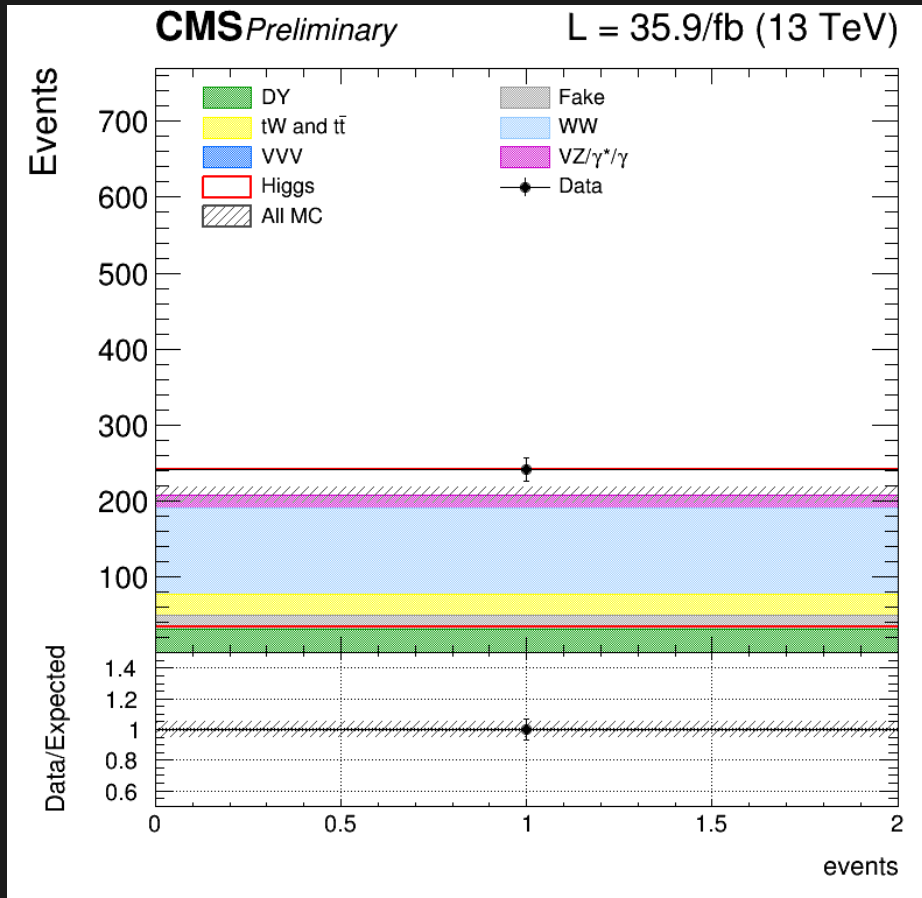
- 2 muons with opposite charge.
- Leptons are emitted close to each other.
- Moderate MET due the presence of 2 neutrinos.



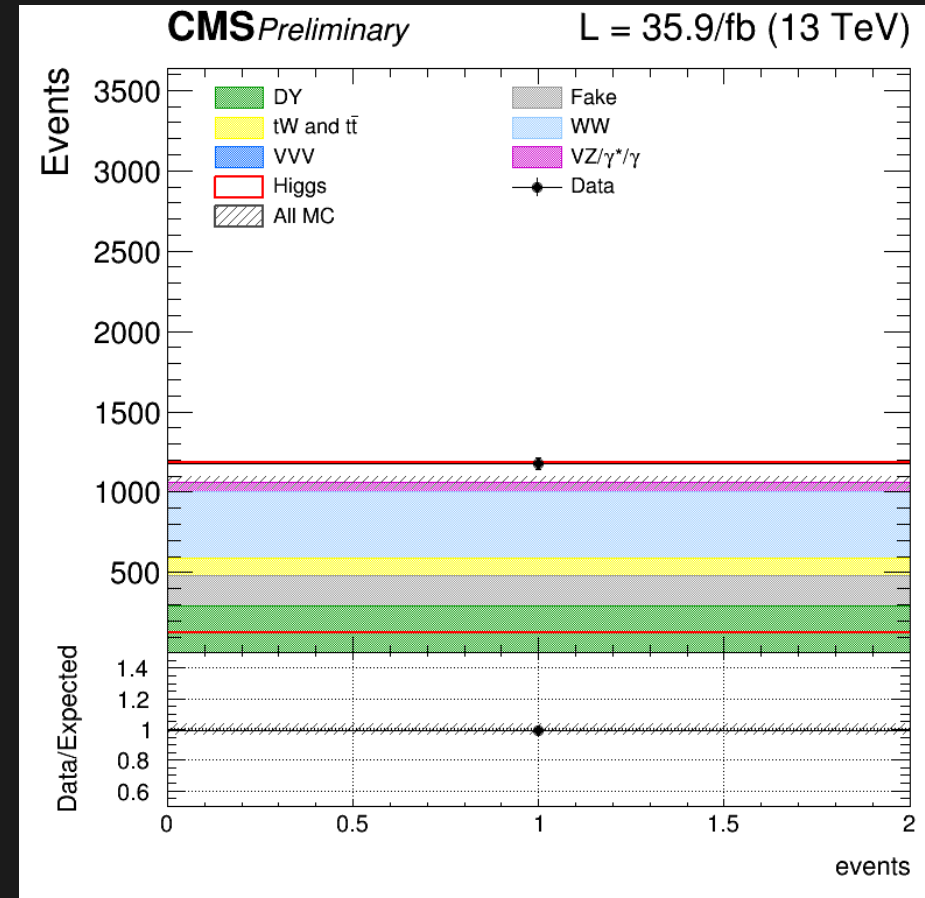


# SF ggH-tagged categories

- Event-counting analysis and the event requirements are chosen to maximize the expected signal significance in each category.
- 0,1 jet categories to handle the Top background.
- Events splits according the lepton pair flavor and trailing lepton  $p_T$ ; to reduce nonprompt background.



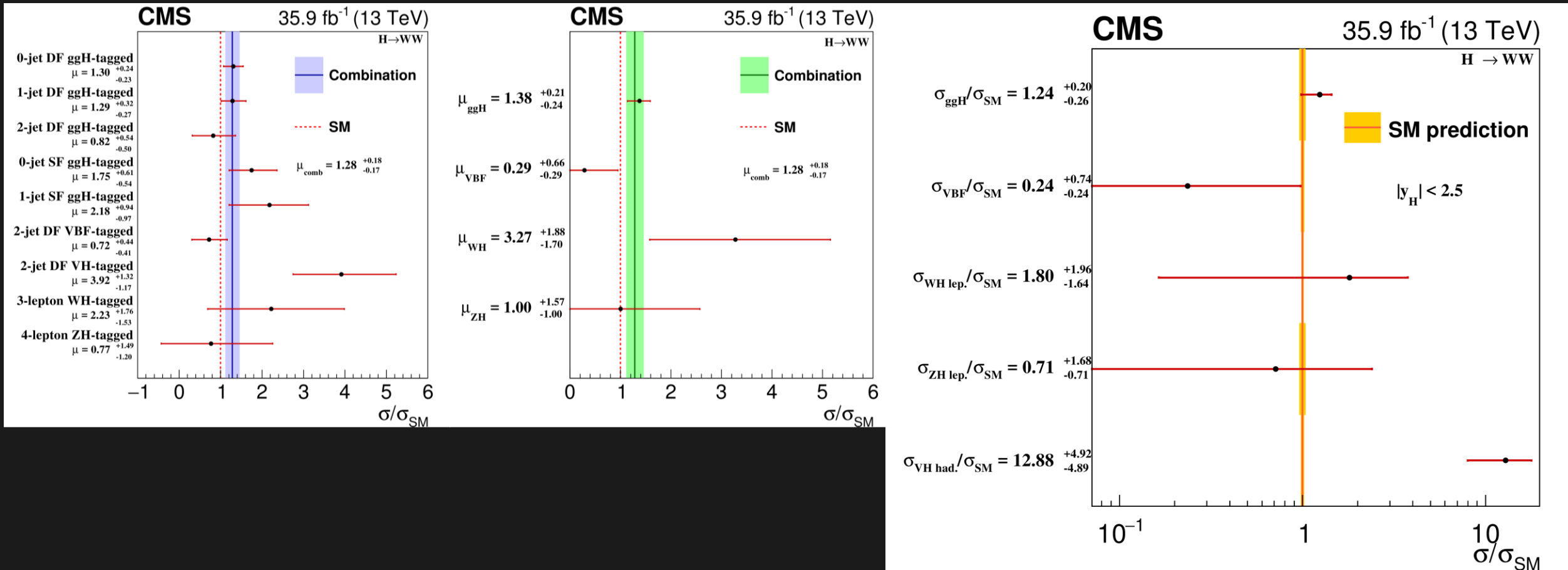
0-jet  $ee$   $p_{T2} < 20$  GeV



0-jet  $\mu\mu$   $p_{T2} < 20$  GeV

# Signal strength measurements

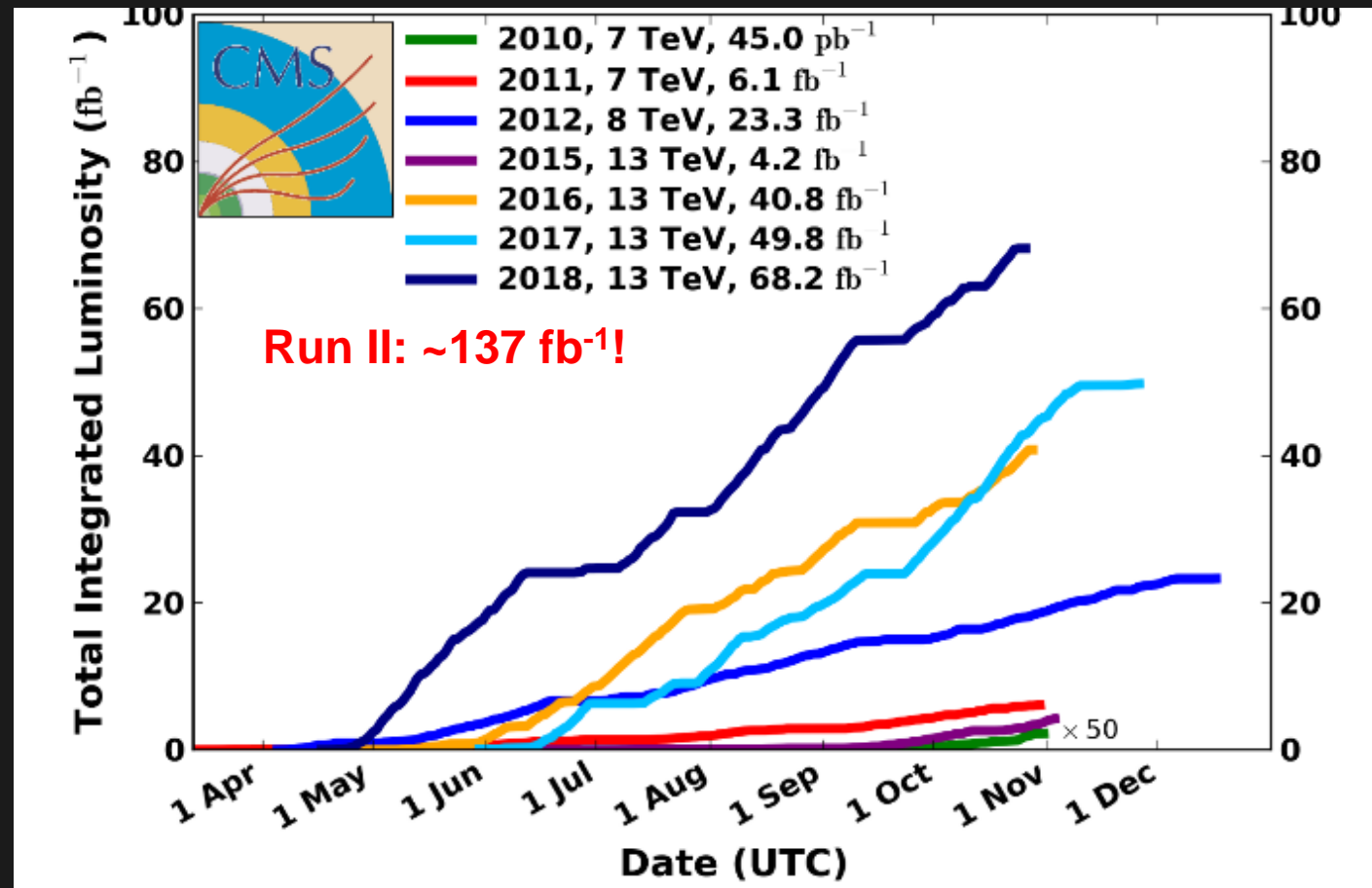
- Signal strengths ( $\sigma/\sigma_{SM}$ ) measured from a simultaneous binned likelihood fit of all signal and control regions.



- Limited by lepton reconstruction, background data-driven estimation and ggH theoretical uncertainties.
- $\mu = 1.28^{+0.18}_{-0.17}$  at 9.1(7.1)  $\sigma$  observed (expected) significance. First H→WW observation in CMS!!!



- Full Run2 categories: improvement of the measurement of signal strength and couplings.
  - Inclusion of SF in 2j categories (ggH / VH / VBF).
  - Improvement in DYMVA algorithm: BDT→DNN.



- First observation in CMS of the  $H \rightarrow WW$  channel.
- Crucial contribution to the Higgs combination measurement of production cross-section and couplings.
- Several measurement in confirming SM predictions.
- Some results show tension that have to be monitored with more data. Many categories are limited by statistical uncertainty.
- More data needed for full description of Higgs properties:
  - Improvement of cross-section and coupling measurements with full Run2 data.
  - Improvement of analysis technique and addition of new final states.





# MERCI





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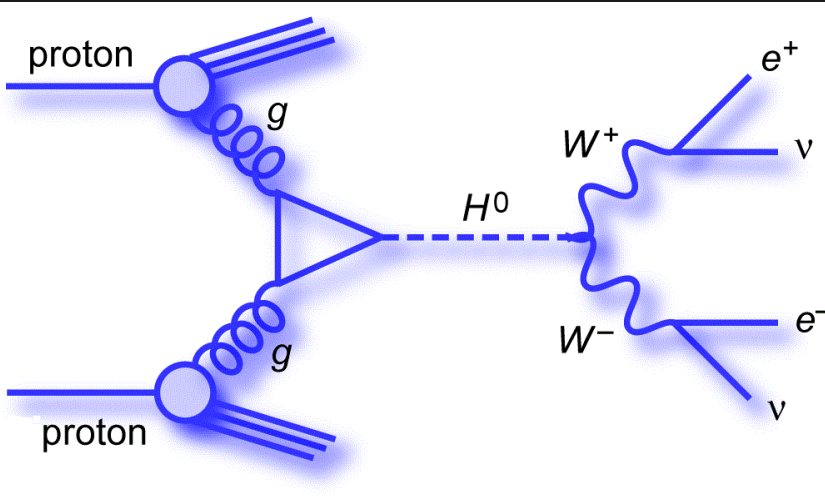
1-1

308

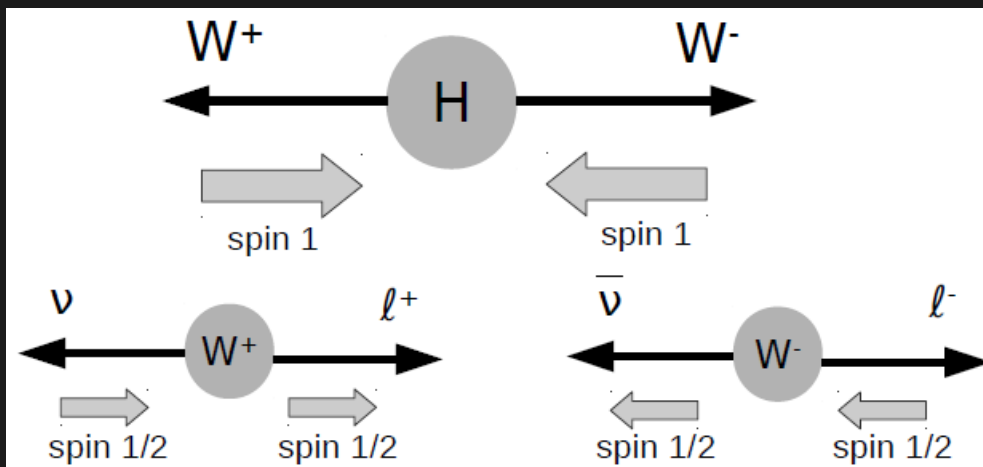
★BONUS★

SLIDES





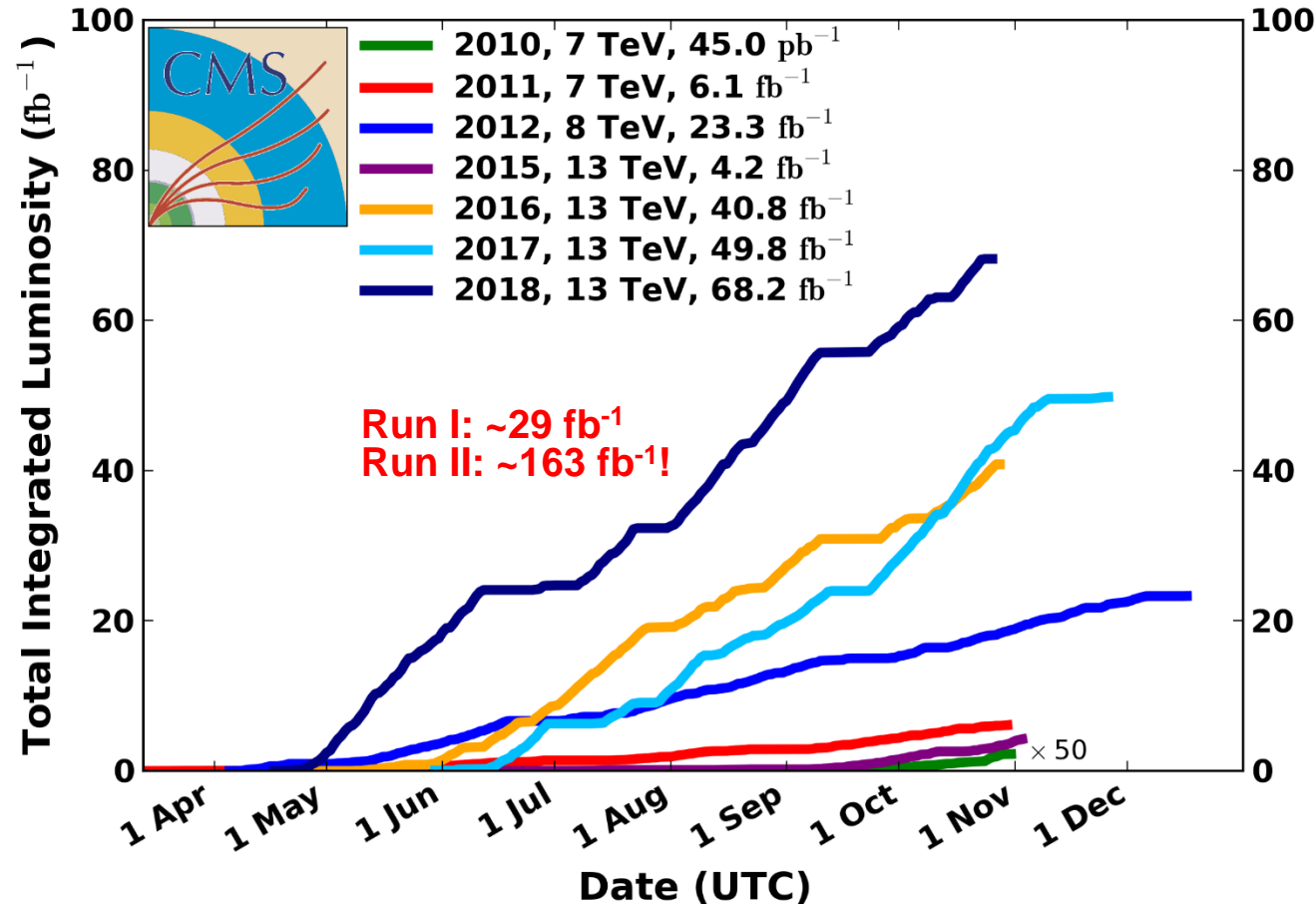
- 2 isolated leptons (electrons or muons) with opposite charge.
- Moderate MET due the presence of 2 neutrinos.
- Number of jet depending on the production mode.
- Large BR and good sensitivity to the Higgs boson couplings.
- Relatively low background final state.
- The neutrinos prevents the reconstruction of Higgs mass.



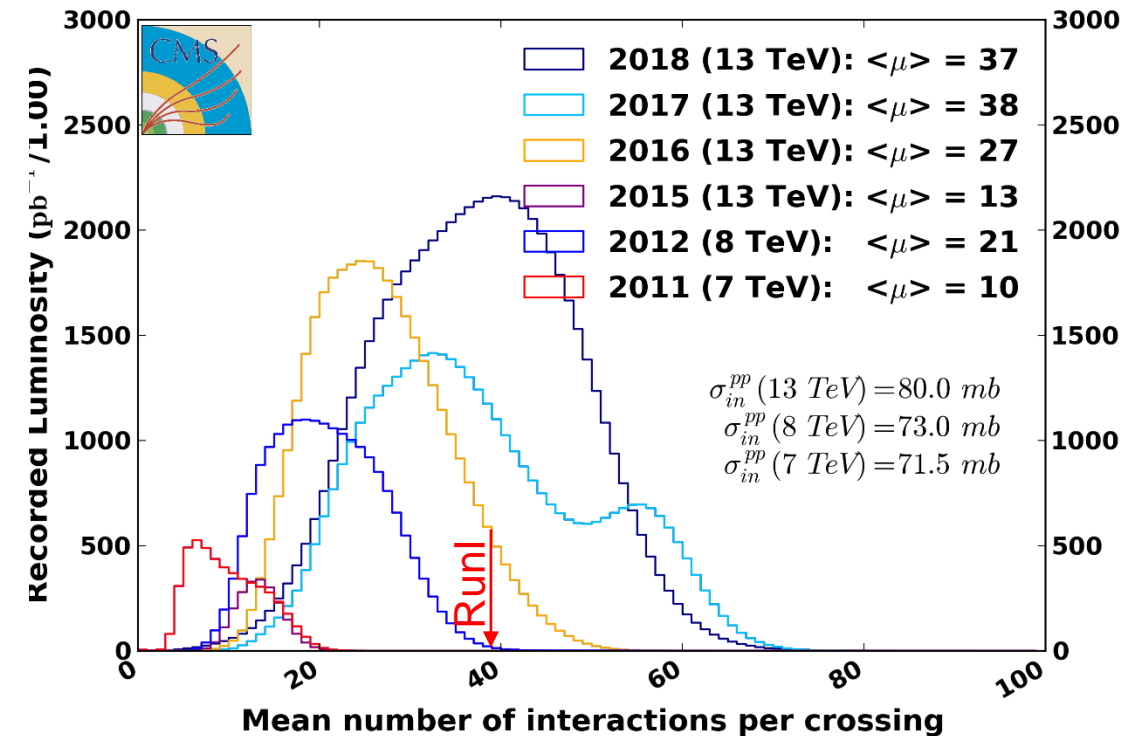
- Higgs boson has spin 0:
  - Leptons are emitted close to each other.
  - Small dilepton mass.

## CMS Integrated Luminosity, pp

Data included from 2010-03-30 11:22 to 2018-10-26 08:23 UTC



## CMS Average Pileup

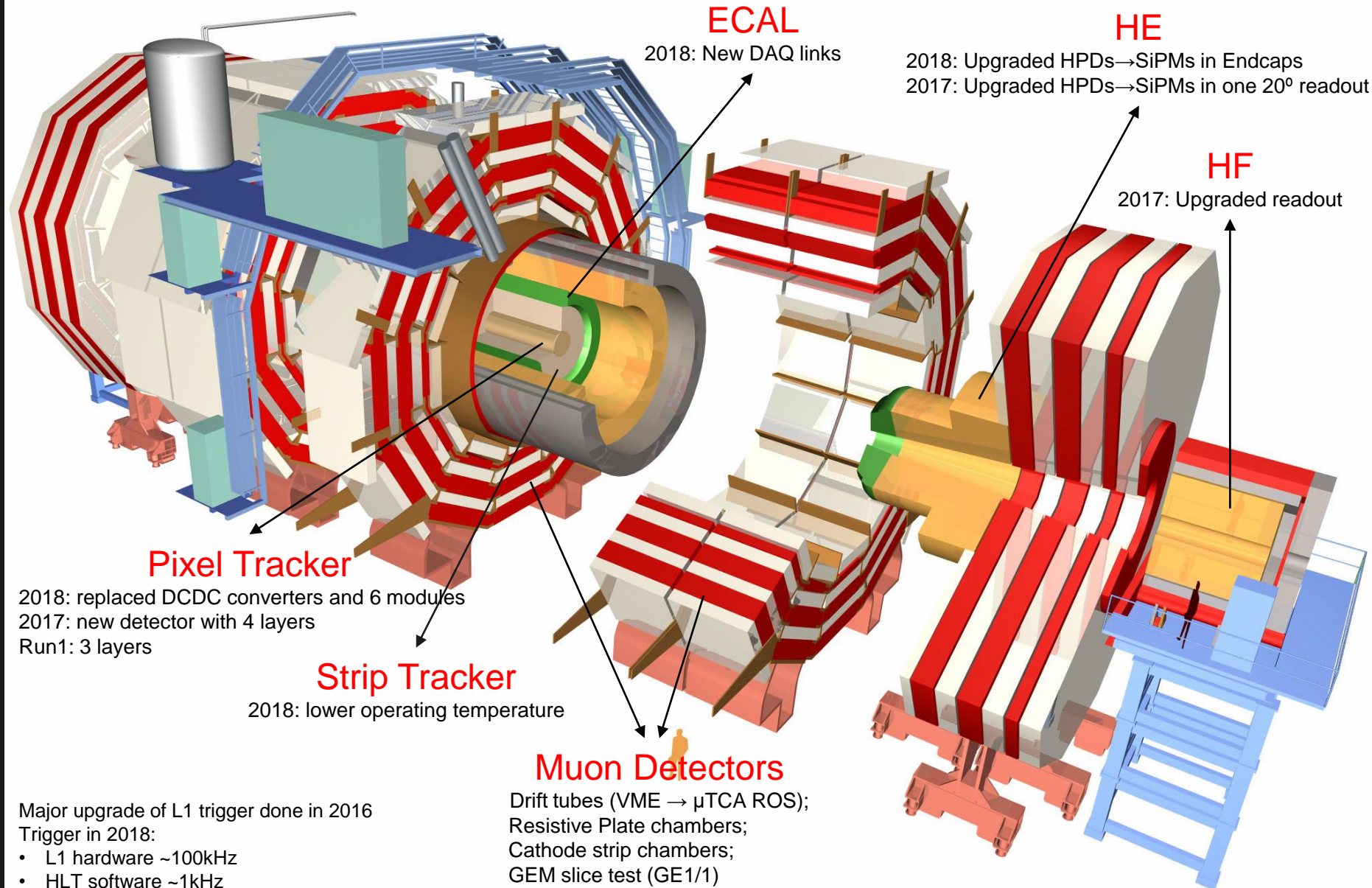
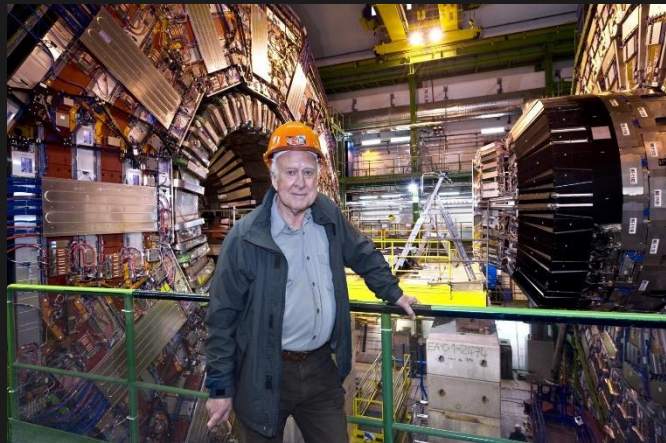


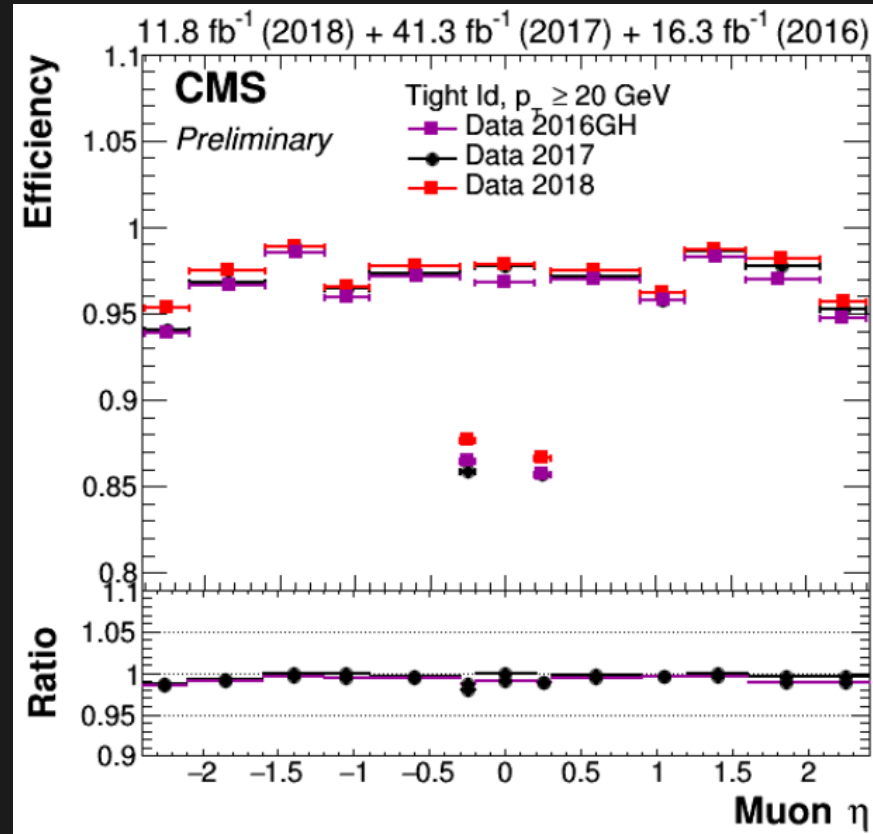
- LHC has delivered ~163 fb<sup>-1</sup>, CMS has collected data with >94% recording efficiency with a data certification ~90%.

+ data = + challenges! Improved analysis techniques and operations for a successful program!!



46 countries, 198 institutes.  
2885 physicist + 995 engineers.  
Weight: 14 tonnes  
Diameter: 15m  
Length: 29 m  
Magnetic Field: 3.8 T

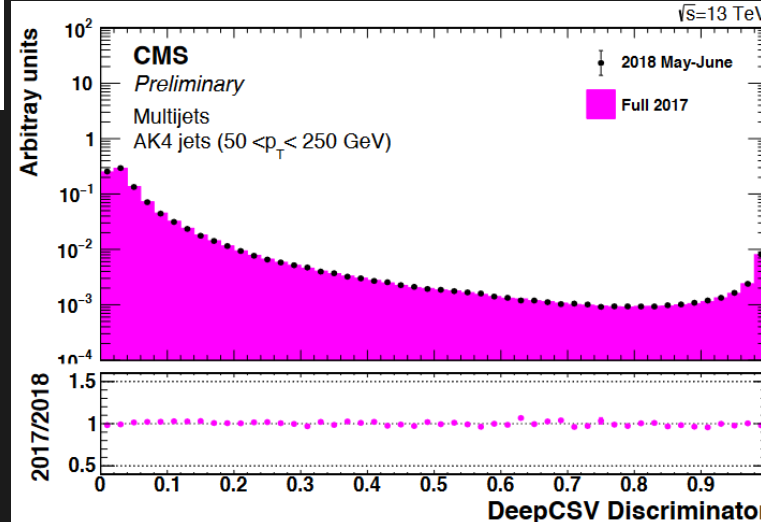
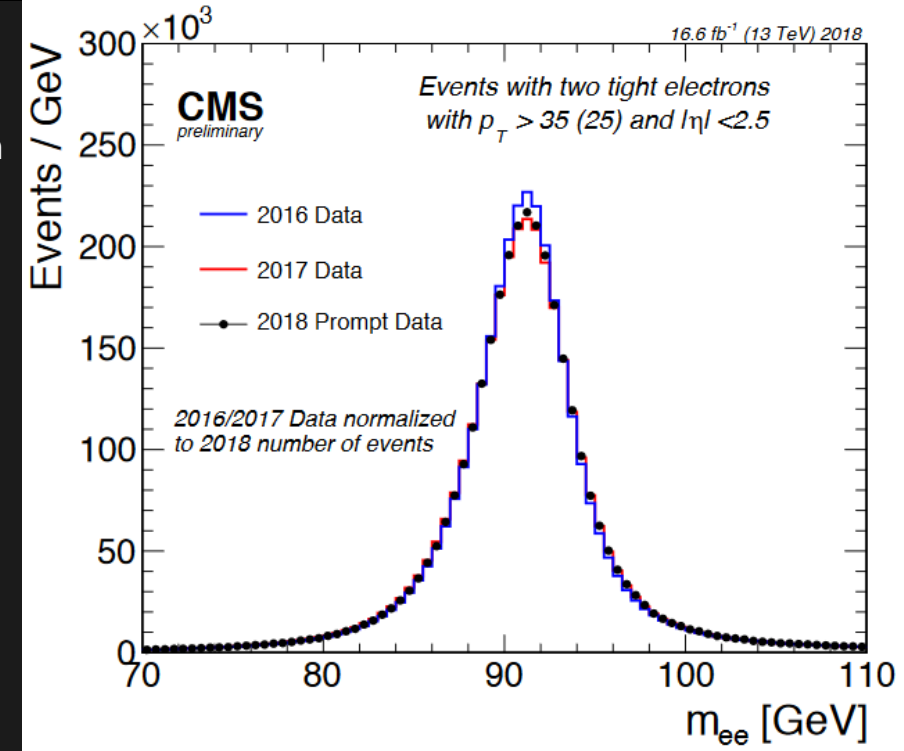




2017 improvement due new pixel detectors  
2018 improvement due recovery of some CSC

Excellent 2017 performance for e/gamma due improvement of HLT, reconstruction, identification efficiency, despite harsh experimental conditions of 2017

First look at 2018 data shows very good quality!



Good agreement of btagging algorithms between 2018 data and 2017 Multijets MC or 2017 data.



Category	Subcategory	Requirements
Preselection	—	$m_{\ell\ell} > 12 \text{ GeV}$ , $p_{T1} > 25 \text{ (20) GeV}$ for e ( $\mu$ ), $p_{T2} > 13 \text{ (10) GeV}$ for e ( $\mu$ ), track $p_T^{\text{miss}} > 20 \text{ GeV}$ , $p_T^{\ell\ell} > 30 \text{ GeV}$ no additional leptons with $p_T > 10 \text{ GeV}$ two electrons or two muons with opposite charges
0-jet ggH-tagged	$e^+e^- \ p_{T2} < 20 \text{ GeV}$ $\mu^+\mu^- \ p_{T2} < 20 \text{ GeV}$	DYMVA $> 0.991$ , $m_{\ell\ell} < 55 \text{ GeV}$ , $m_T > 50 \text{ GeV}$ , $p_{T2} < 20 \text{ GeV}$ , $\Delta\phi_{\ell\ell} < 1.7$ no jets with $p_T > 30 \text{ GeV}$ no b-tagged jets with $p_T > 20 \text{ GeV}$
	$e^+e^- \ p_{T2} > 20 \text{ GeV}$ $\mu^+\mu^- \ p_{T2} > 20 \text{ GeV}$	DYMVA $> 0.991$ , $m_{\ell\ell} < 55 \text{ GeV}$ , $m_T > 50 \text{ GeV}$ , $20 \text{ GeV} < p_{T2} < 50 \text{ GeV}$ , $\Delta\phi_{\ell\ell} < 1.7$ no jets with $p_T > 30 \text{ GeV}$ no b-tagged jets with $p_T > 20 \text{ GeV}$
1-jet ggH-tagged	$e^+e^-$ $\mu^+\mu^-$	DYMVA $> 0.95$ , $m_{\ell\ell} < 57 \text{ GeV}$ , $50 < m_T < 155 \text{ GeV}$ , $p_{T1} < 50 \text{ GeV}$ , $\Delta\phi_{\ell\ell} < 1.75$ exactly one jet with $p_T > 30 \text{ GeV}$ no b-tagged jets with $p_T > 20 \text{ GeV}$



# DY estimation for SF ggH-tagged categories

$$N_{Z \rightarrow ee}^{OUT} = R_{OUT}/R_{IN} \left( N_{ll}^{IN} - \frac{1}{2} k_{ee} \left( N_{e\mu}^{IN} - N_{e\mu}^{IN}(VV) \right) - N_{ee}^{IN}(VV) \right)$$

$$N_{Z \rightarrow \mu\mu}^{OUT} = R_{OUT}/R_{IN} \left( N_{ll}^{IN} - \frac{1}{2} k_{\mu\mu} \left( N_{e\mu}^{IN} - N_{e\mu}^{IN}(VV) \right) - N_{\mu\mu}^{IN}(VV) \right)$$

MC  
DATA

$$k_{ee} = \sqrt{\frac{N_{ee}^{IN,loose}}{N_{\mu\mu}^{IN,loose}}}$$

$$k_{\mu\mu} = \sqrt{\frac{N_{\mu\mu}^{IN,loose}}{N_{ee}^{IN,loose}}}$$

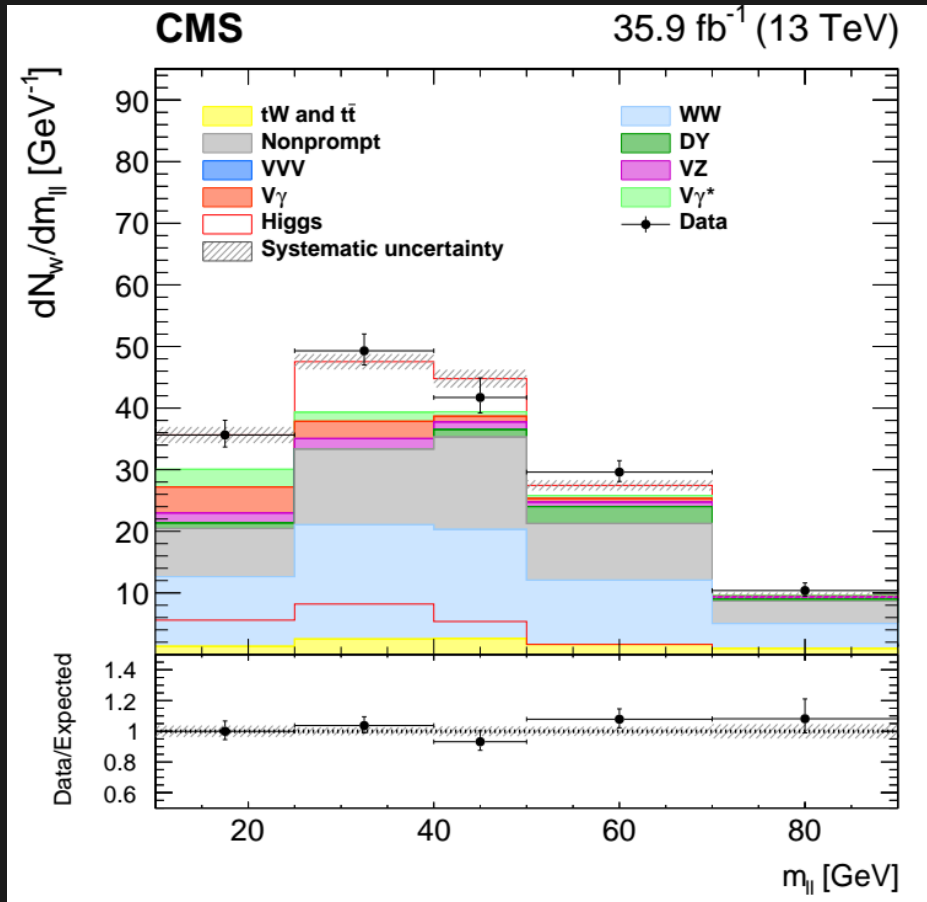
- IN =  $|m_{ll} - m_Z| < 7.5$  GeV. OUT =  $|m_{ll} - m_Z| > 15$  GeV. No H or WW selection.
- $R_{OUT}/R_{IN}$  and  $k_{ll}$  taken from MC in relaxed DY MVA regions but systematics from difference to DATA and MVA cut dependence.
- Extrapolate OUT region to final H and WW selections based on acceptance ( $A_H$  and  $A_{WW}$ ) from MC in relaxed DY MVA regions (+systematics on MVA dependence):  $N_{DY \rightarrow ll}^H = A_H N_{DY \rightarrow ll}^{OUT}$   $N_{DY \rightarrow ll}^{WW} = A_{WW} N_{DY \rightarrow ll}^{OUT}$

State	$n_{in}^{data}$	$R_{out/in}$	$A_H$	$n_{DY}^{data}$	$n_{DY}^{MC}$	$n_{DY}^{data} \cdot A_H$
0-jet $p_T^{lep2} < 20$ bin						
ee	1404	$0.21 \pm 0.00 \pm 0.04$	$0.22 \pm 0.01 \pm 0.06$	$172.07 \pm 54.32$	9.93	$38.27 + 26.94 - 19.81$
$\mu\mu$	3450	$0.31 \pm 0.00 \pm 0.03$	$0.43 \pm 0.00 \pm 0.02$	$610.56 \pm 175.58$	241.45	$264.88 + 95.38 - 86.80$
0-jet $p_T^{lep2} \geq 20$ bin						
ee	1404	$0.21 \pm 0.00 \pm 0.04$	$0.21 \pm 0.01 \pm 0.06$	$172.07 \pm 54.32$	79.42	$36.64 + 26.32 - 19.24$
$\mu\mu$	3450	$0.31 \pm 0.00 \pm 0.03$	$0.15 \pm 0.00 \pm 0.02$	$610.56 \pm 175.58$	73.93	$92.85 + 45.08 - 36.87$
1-jet bin						
ee	868	$0.19 \pm 0.01 \pm 0.02$	$0.33 \pm 0.01 \pm 0.10$	$100.07 \pm 32.09$	19.79	$32.79 + 24.45 - 17.68$
$\mu\mu$	2136	$0.31 \pm 0.00 \pm 0.08$	$0.36 \pm 0.00 \pm 0.06$	$395.80 \pm 152.86$	122.86	$144.04 + 90.39 - 71.02$

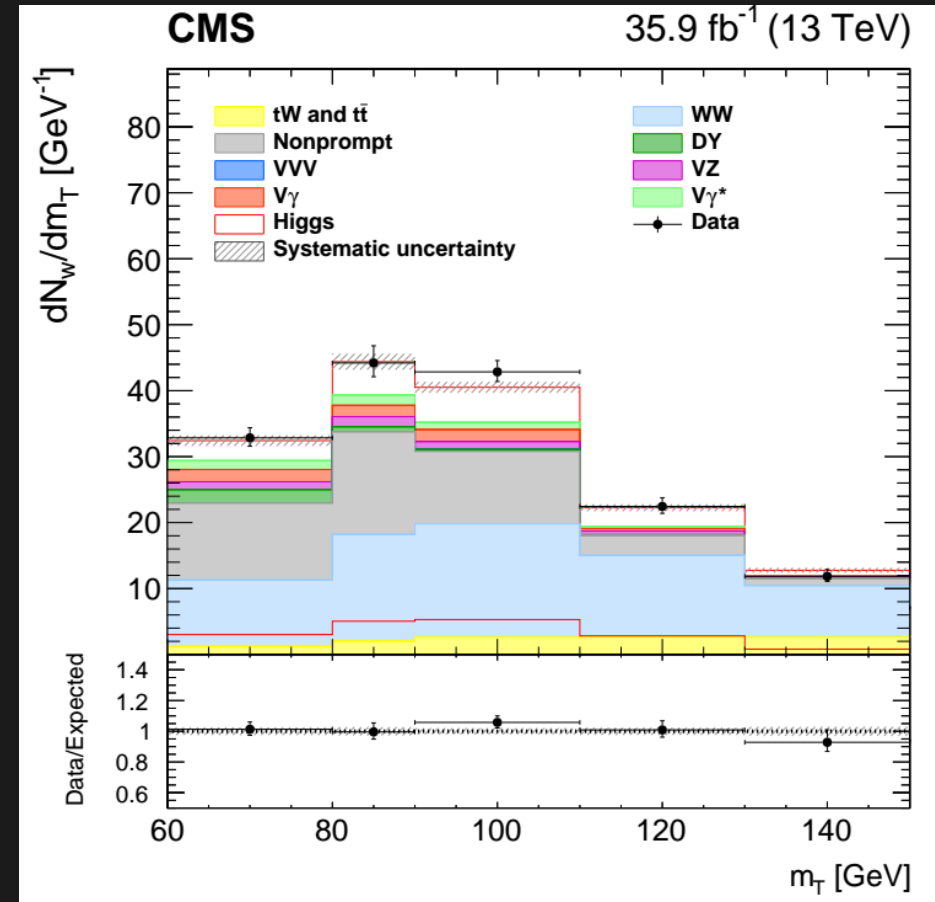
40 to 70% normalization uncertainties on DY background

# DF ggH-tagged categories

- Discriminant variables:  $m_{ll}$  and  $m_T^H$ .
- 0,1 and 2 jets categories to handle the Top background.
- Events splits according the lepton pair flavor, charge and trailing lepton pT; to reduce nonprompt background.



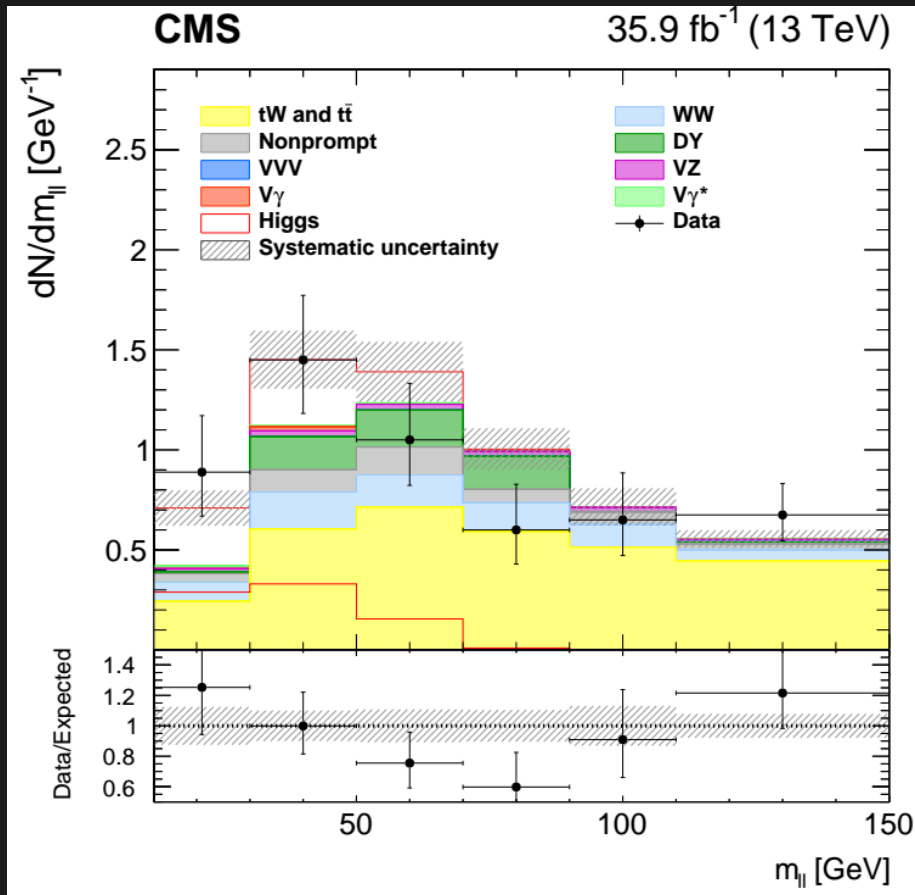
0-jet  $p_{T2} < 20$  GeV



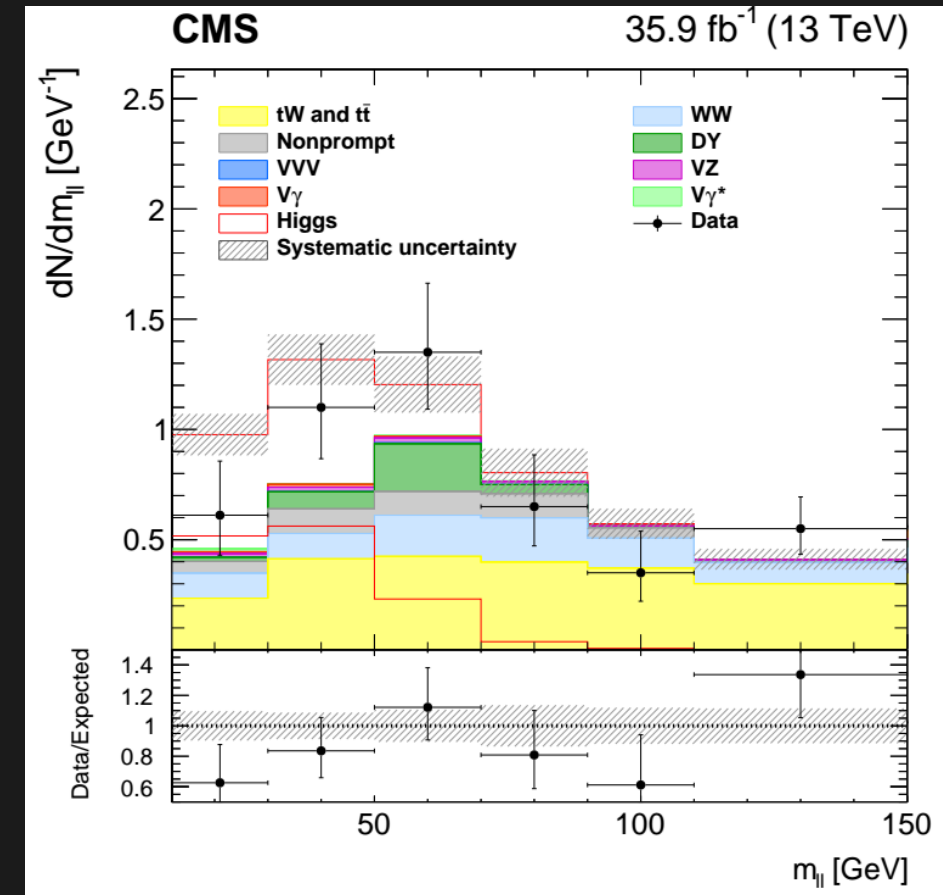
0-jet  $p_{T2} > 20$  GeV

# VBF-tagged categories

- Only DF in 2016. SF+DF for full Run2.
- S/B enhanced by selecting events with VBF topology ( $m_{jj} > 400$  GeV and  $|\Delta\eta_{jj}| > 3.5$ ).
- MC template fit of the  $m_{ll}$  distribution in 2  $m_{jj}$  categories.



$400 < m_{jj} < 700$  GeV

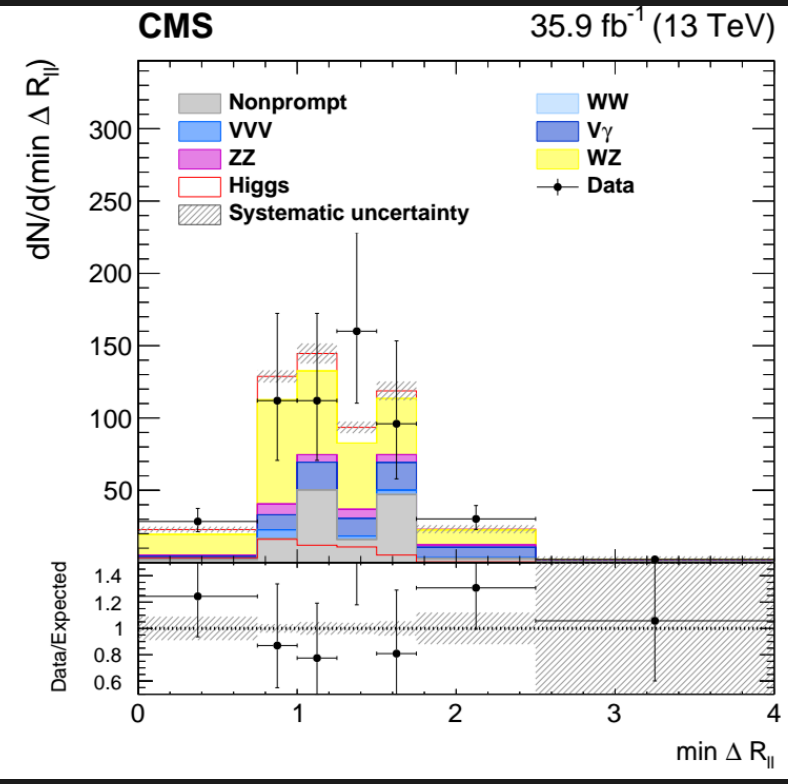
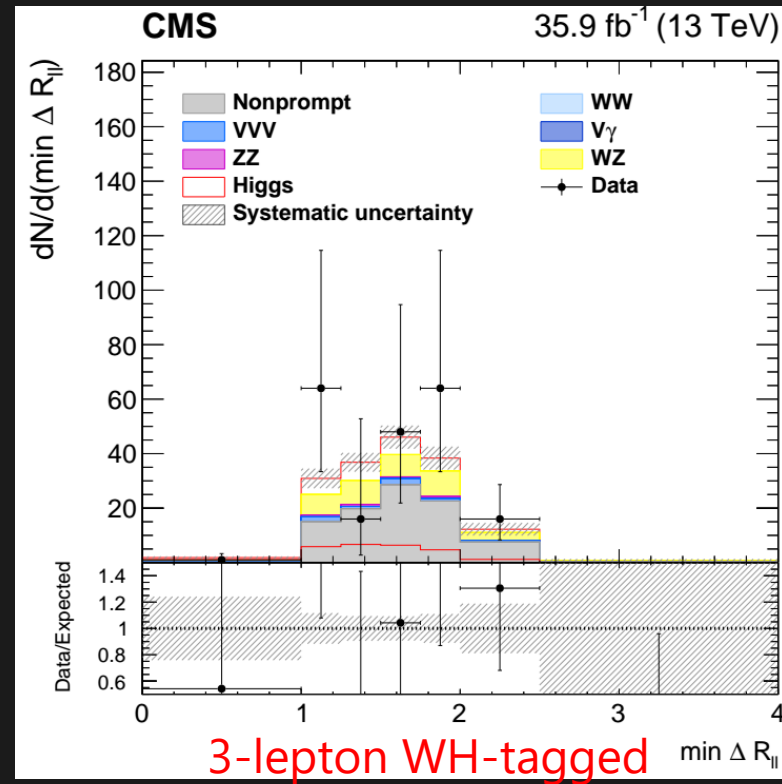
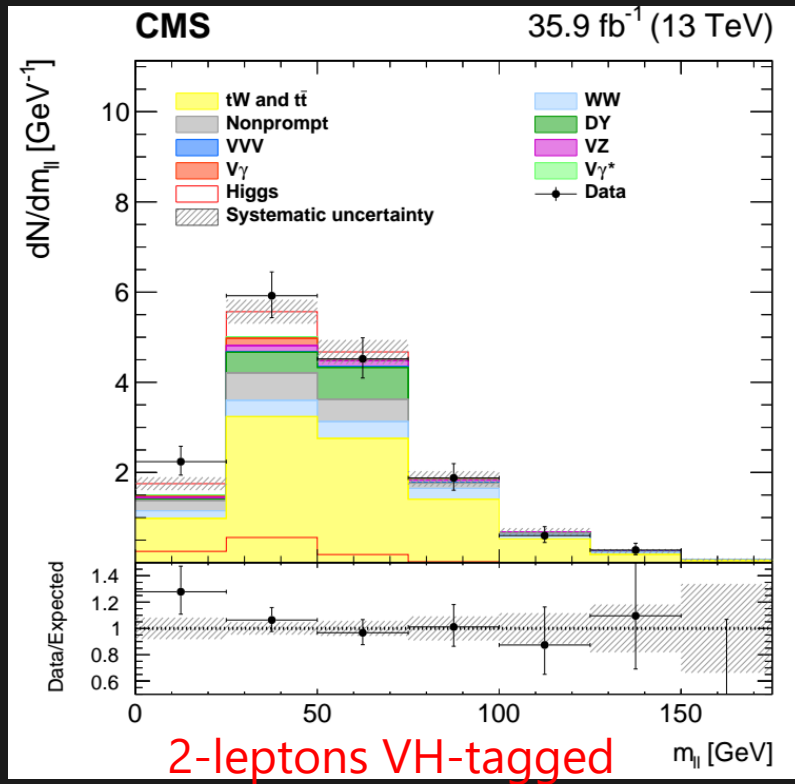


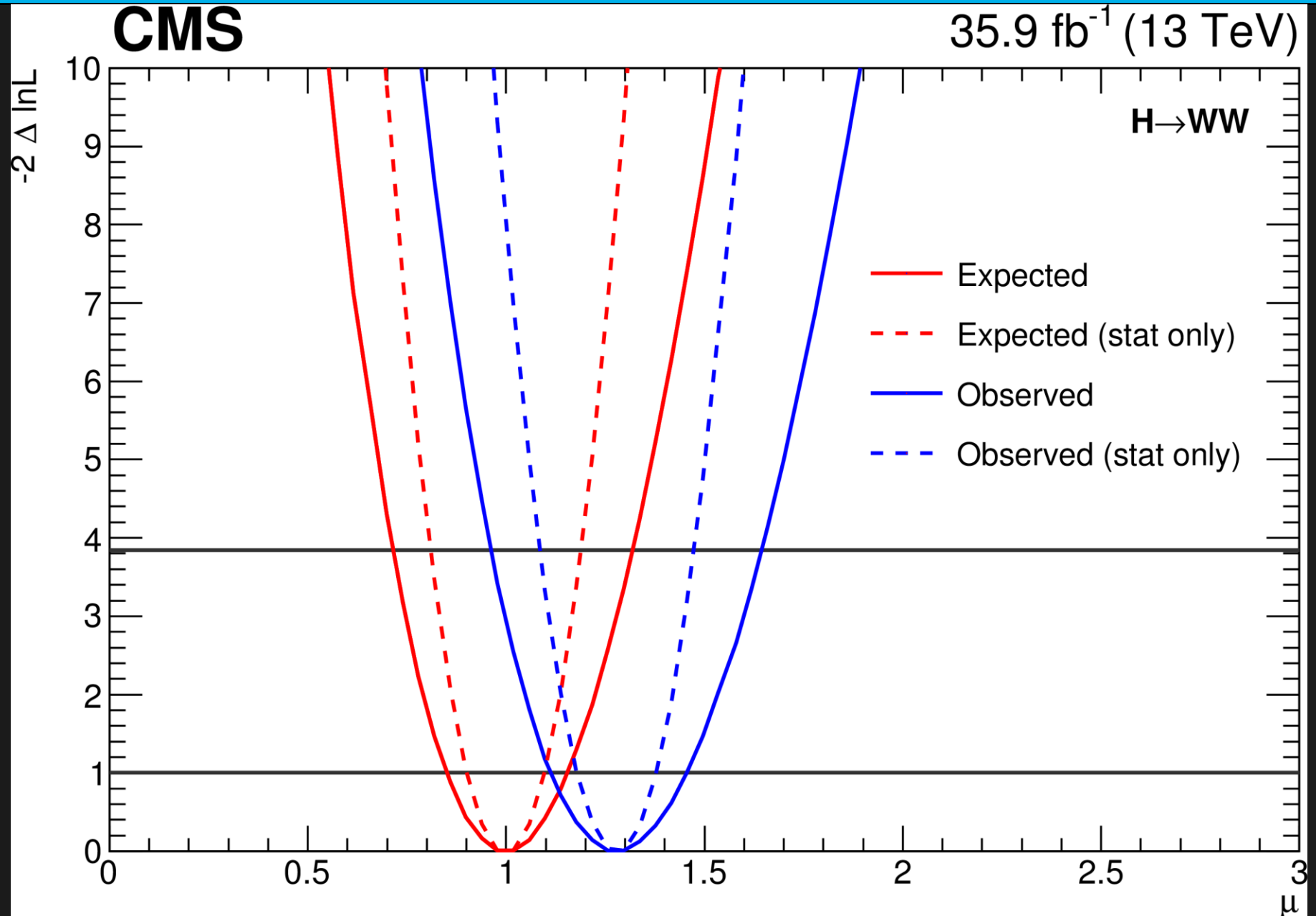
$m_{jj} > 700$  GeV



# VH-tagged categories

- 3 different categories aiming at 3 different final states:
  - 2 leptons VH-tagged with  $V \rightarrow \text{hadrons}$ ,  $H \rightarrow WW \rightarrow 2l2\nu$ . Shape analysis based on  $m_{ll}$ .
  - 3 leptons WH-tagged with  $W \rightarrow l\nu$ ,  $H \rightarrow WW \rightarrow 2l2\nu$ . Shape analysis based on  $\min(\Delta R_{ll})$ .
  - 4 leptons ZH-tagged with  $Z \rightarrow 2l$ ,  $H \rightarrow WW \rightarrow 2l2\nu$ . Event counting analysis.
- Only DF in 2016. SF+DF in Full Run2 at least for 2 leptons VH-tagged.

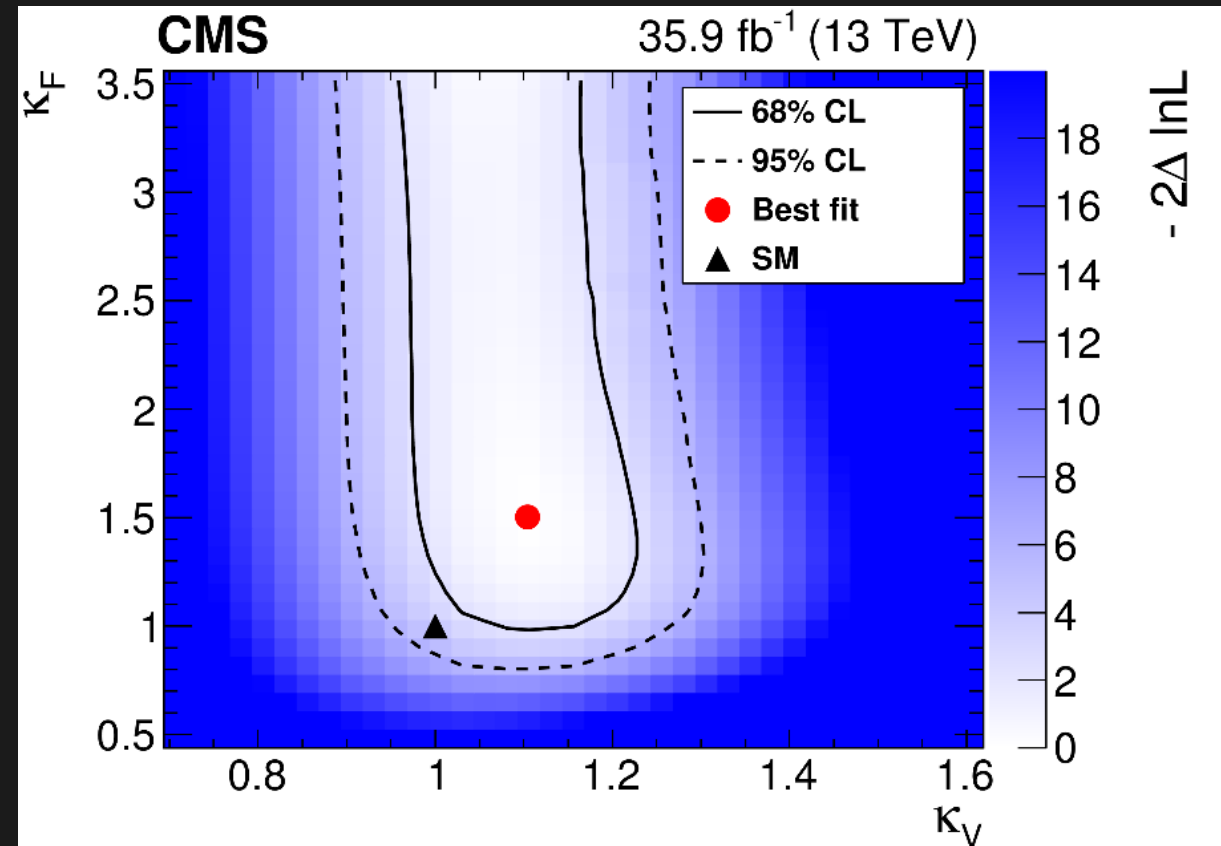
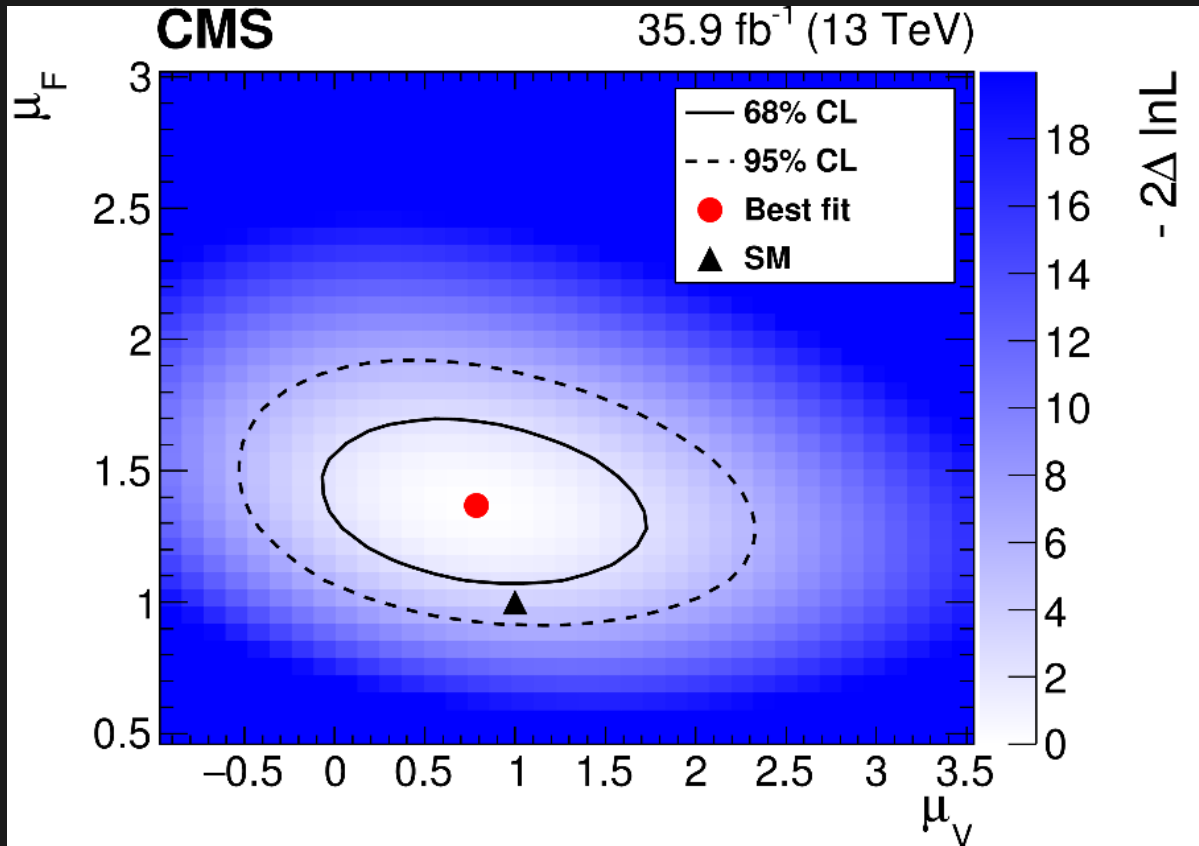




# Measurement of the Higgs couplings

- $\mu_F, \mu_V$ : signal strengths associated to ggH and VBF/VH.
- $k_F, k_V$ : coupling constants associated to fermionic and bosonic processes, as defined in the k framework.

$$\sigma \times \mathcal{B}(X \rightarrow H \rightarrow WW) = k_i^2 \frac{k_V^2}{k_H^2} \sigma_{SM} \times \mathcal{B}_{SM}(X \rightarrow H \rightarrow WW)$$



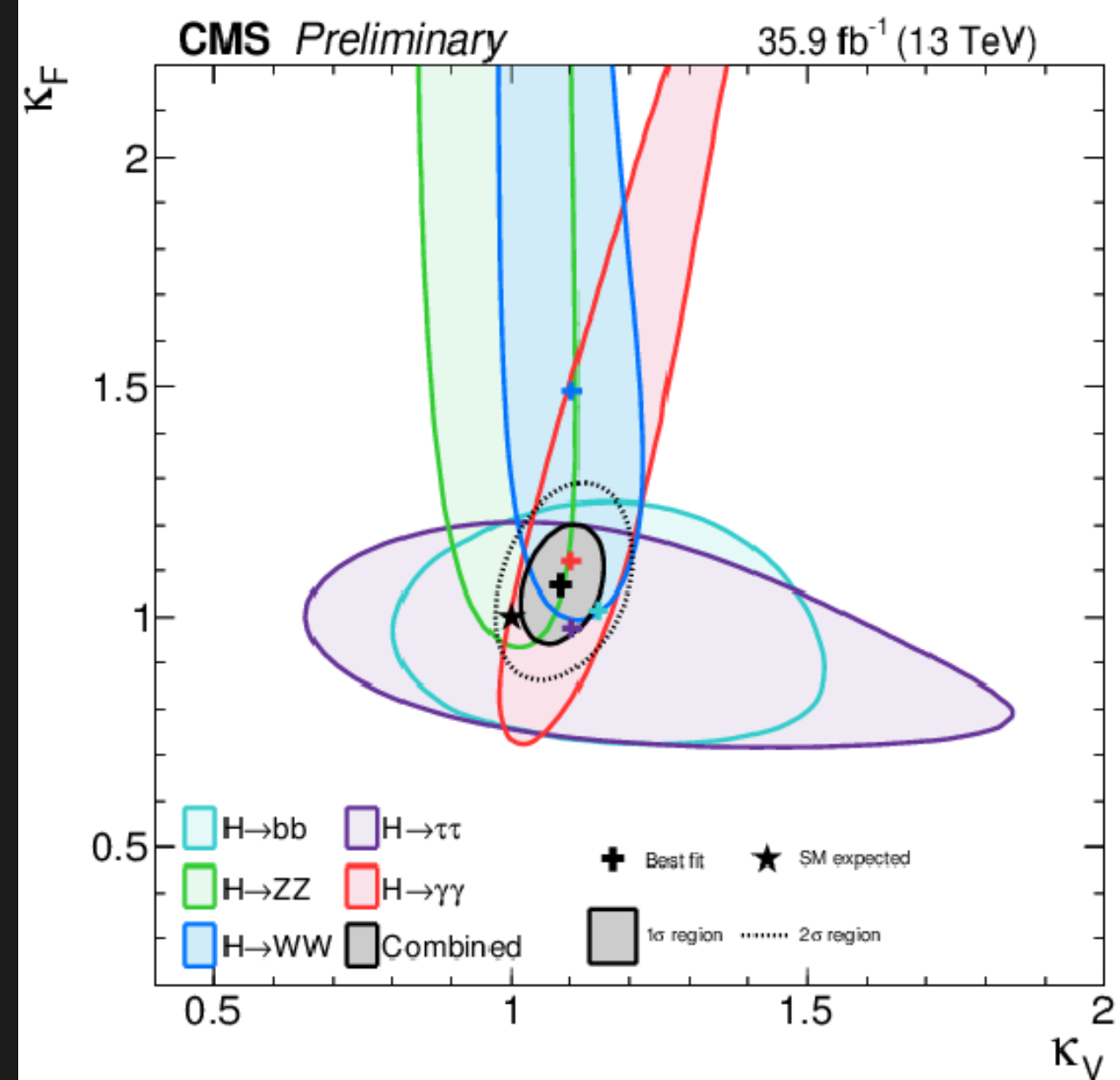
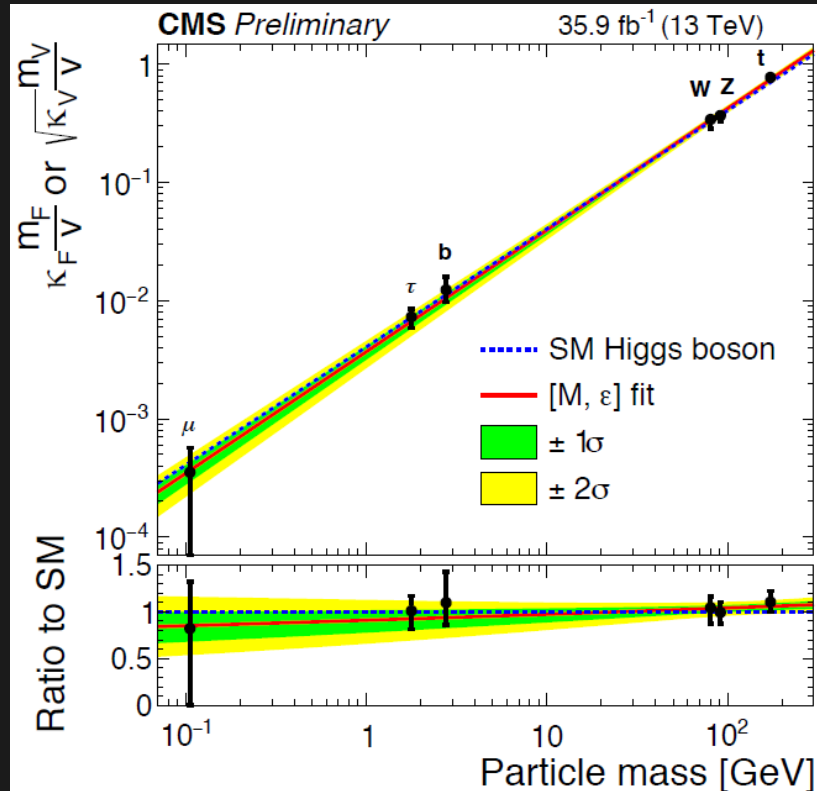
Compatibility with SM within  $2\sigma$ .



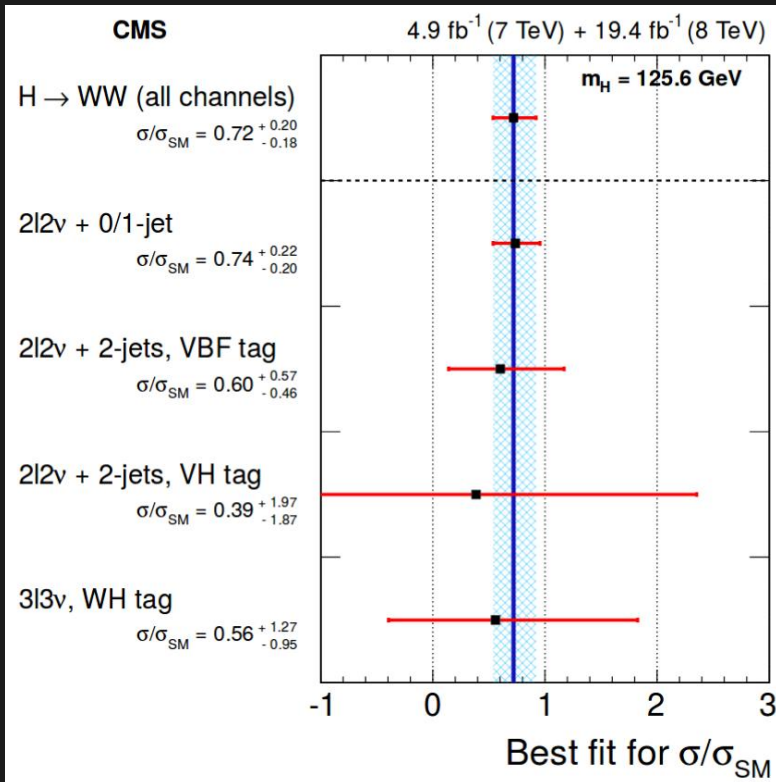
Leading order coupling modifier framework used to correlate prod/decay rates.

$$k_i^2 = \sigma_i / \sigma_i^{SM}$$

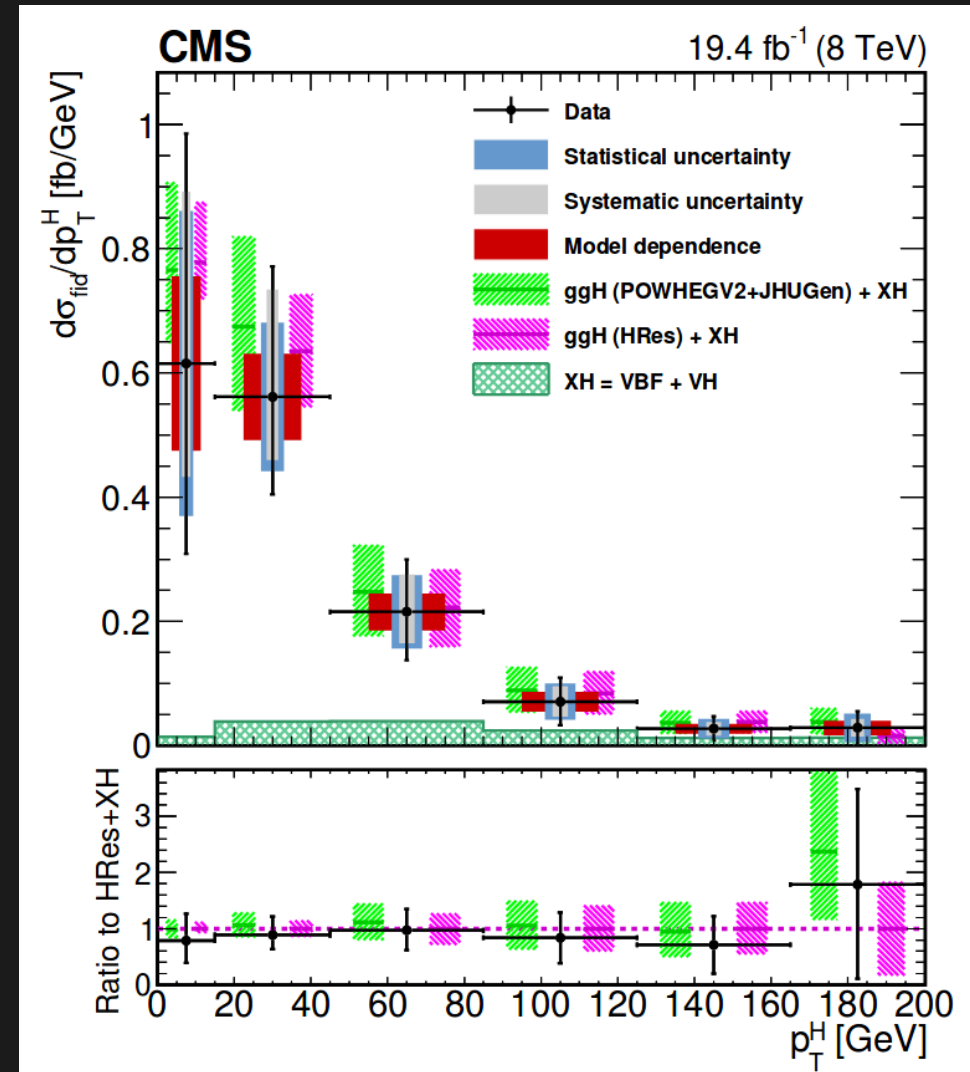
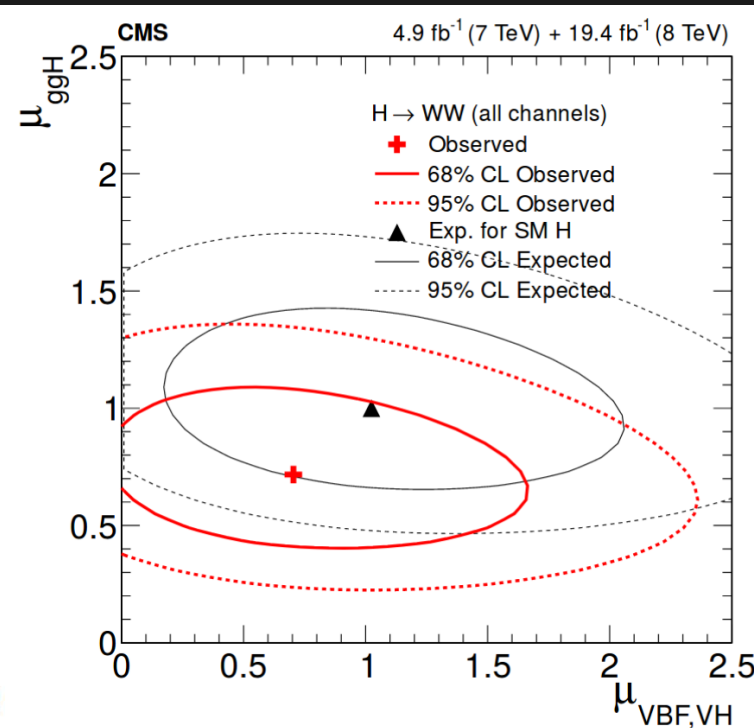
$$k_i^2 = \Gamma_i / \Gamma_i^{SM}$$



# Highlights from Run1



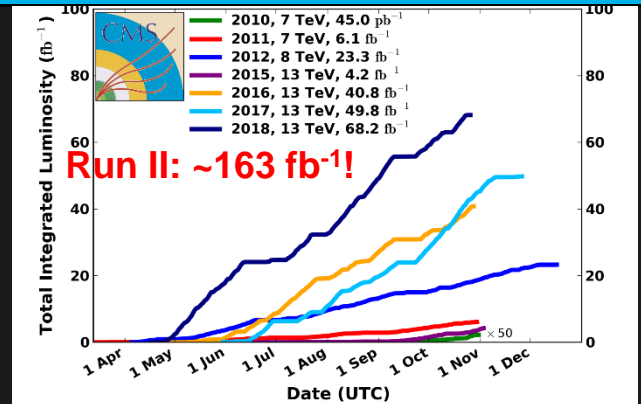
[arXiv:1312.1129](https://arxiv.org/abs/1312.1129)  
JHEP01(2014)096



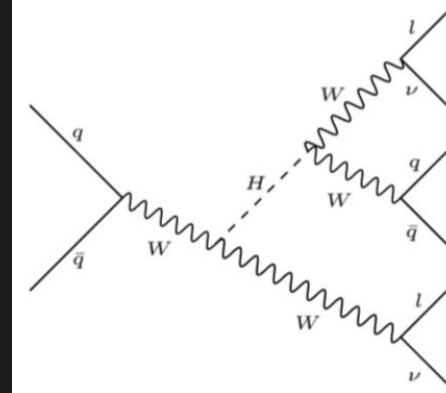
[arXiv:1606.01522](https://arxiv.org/abs/1606.01522)  
JHEP03(2017)032

# Future prospects (II)

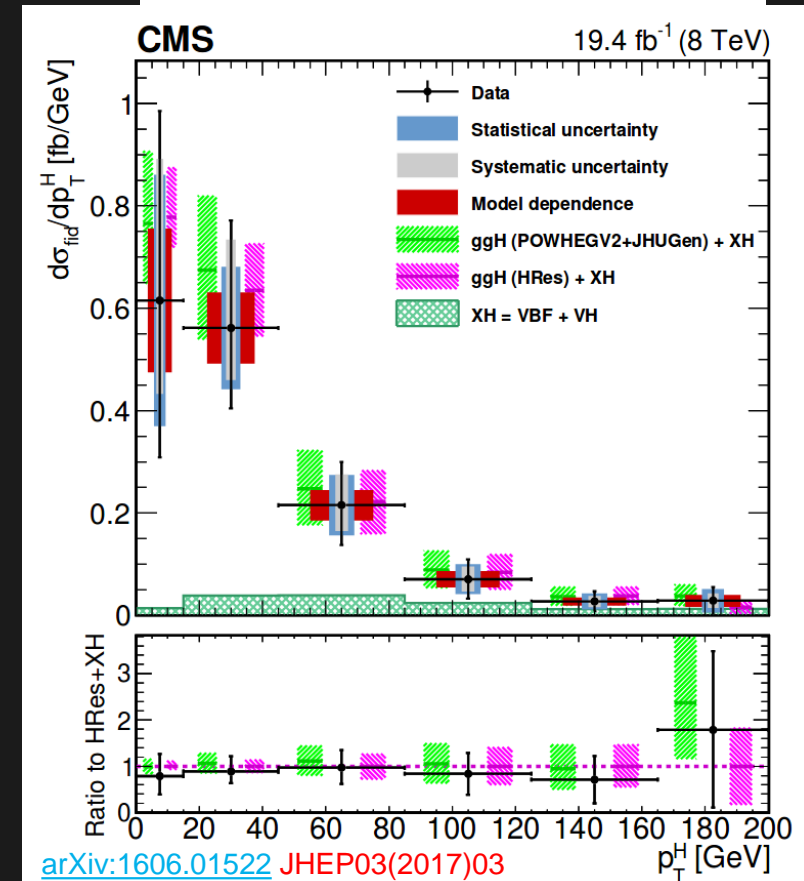
- Summer 2019. 2016+2017 differential cross-section analysis: measurement of number of jets and Higgs  $p_T$ .
- Summer 2019. Full Run2 categories: improvement of the measurement of signal strength and couplings.



- Inclusion of SF in 2j categories (ggH / VH / VBF).
- Improvement in DYMVA algorithm: BDT→DNN.
- Inclusion of same-sign WH.



- Autumn 2019. Full Run2 differential cross-section analysis:
  - Measurement of Higgs  $p_T$ .
  - Measurement of number of jets and jet  $p_T$ .
  - Measurement of  $\Delta\phi_{ll}$ , study of Higgs spin.
- 2020. EFT study.





- Targeting **VBF Higgs production**, Higgs decaying into the **WW ( $e\mu$  channel)**
- Measuring the SM **Higgs to WW coupling** as precise as possible → then every misbehaviour from SM might be the sign of new physics
- **EFT approach:**

$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} + \sum_{n=1}^{\infty} \sum_i \frac{c_i^{(n)}}{\Lambda^n} \mathcal{O}_i^{(n+4)}$$

$\swarrow$   
 $\dim \mathcal{O} = 4$   
 couplings are dimensionless

$\searrow$   
 relevant operators are those with  **$\dim \mathcal{O} = 6$**   
**couplings dimensions are inverse powers of mass** ( $\Lambda$  is a mass scale)

➡ Dim 6 operators give amplitudes  $\sim \frac{s}{\Lambda^2}$  what **eventually leads to unitarity violation**

➡ **EFT valid within unitarity bounds**  
 (low energy EFT is valid below  $\Lambda$  scale)

➡  $m_{ll}^{\text{theory}} = m_{ll}^{\text{SM}} + \sum_i \frac{c_i^{(2)}}{\Lambda^2} m_{ll;i}^{(6)}$

**FIT this value minimizing  $\chi^2 \Rightarrow$  if non-zero  $\Rightarrow$  NEW PHYSICS**

$$\left. \begin{aligned} \mathcal{O}_{WW} &= \Phi^\dagger \hat{W}_{\mu\nu} \hat{W}^{\mu\nu} \Phi \\ \mathcal{O}_{\tilde{W}W} &= \Phi^\dagger \tilde{\hat{W}}_{\mu\nu} \hat{W}^{\mu\nu} \Phi \\ \mathcal{O}_W &= (D_\mu \Phi)^\dagger \hat{W}^{\mu\nu} (D_\nu \Phi) \end{aligned} \right\} \text{contribute to HWW vertex}$$