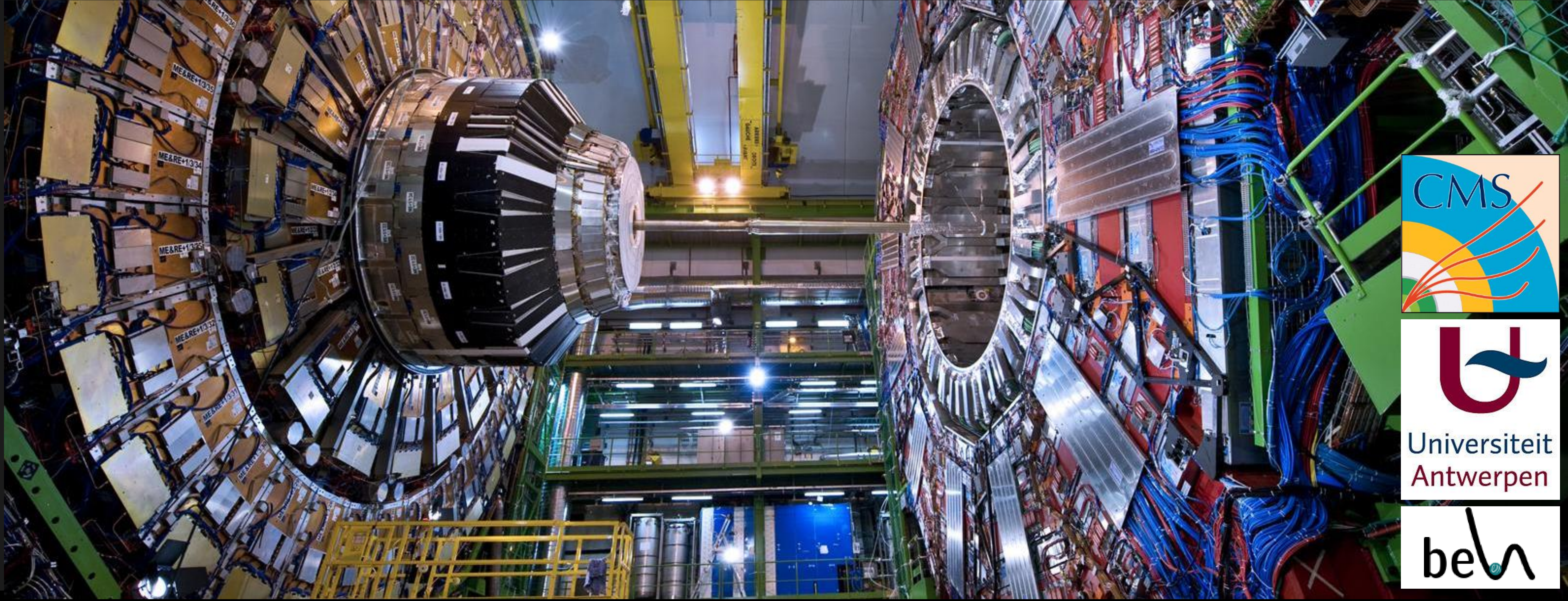
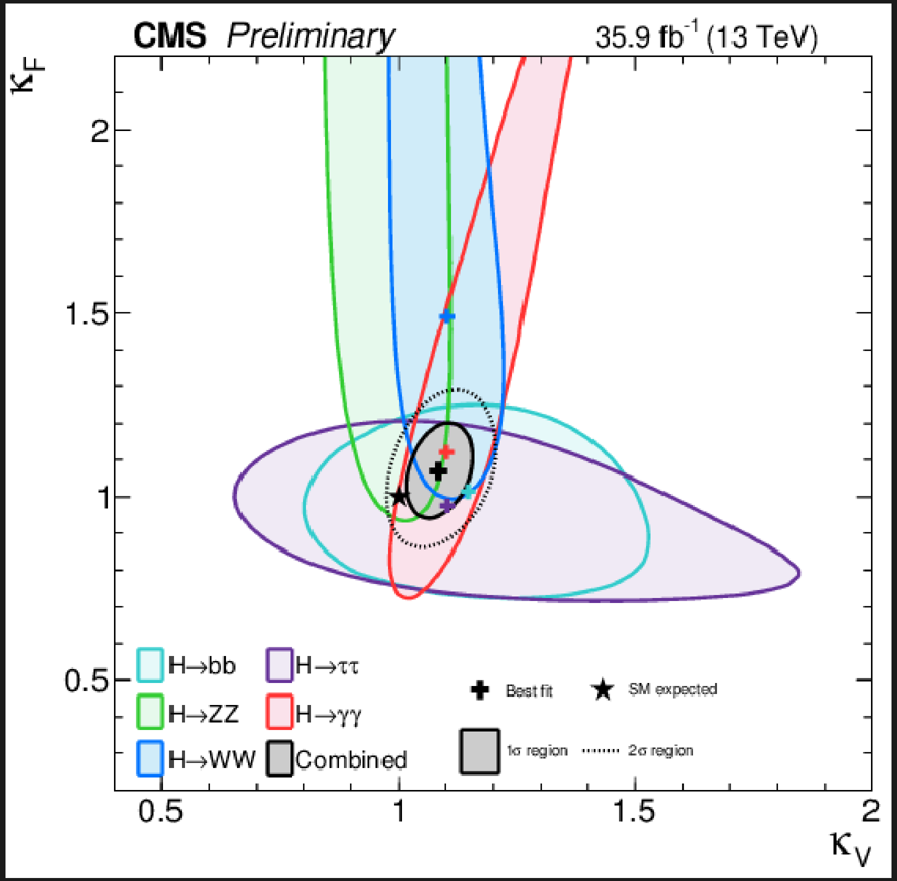


Review of H→WW analysis in CMS and prospect for the full Run2 analysis

EOS Solstice meeting | ULB, December 20th 2018

Davide Di Croce

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

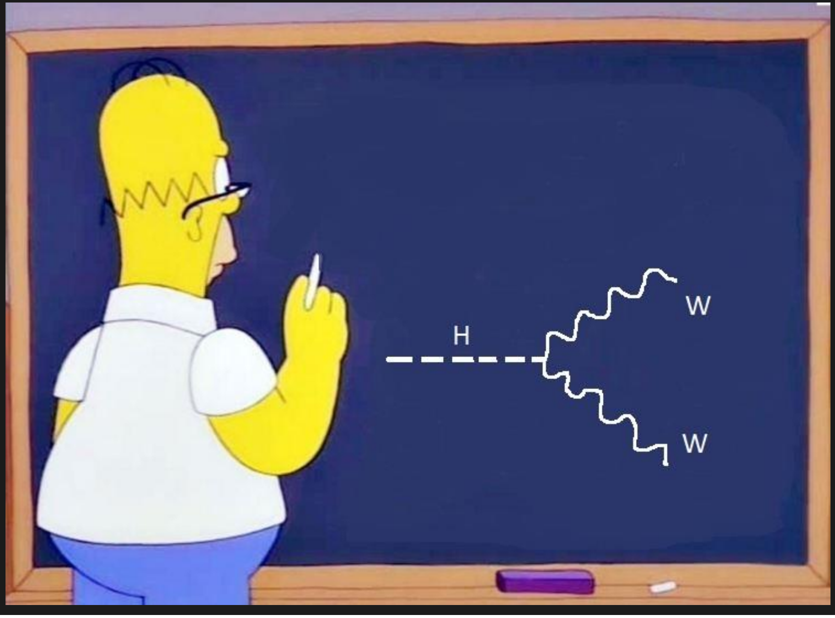


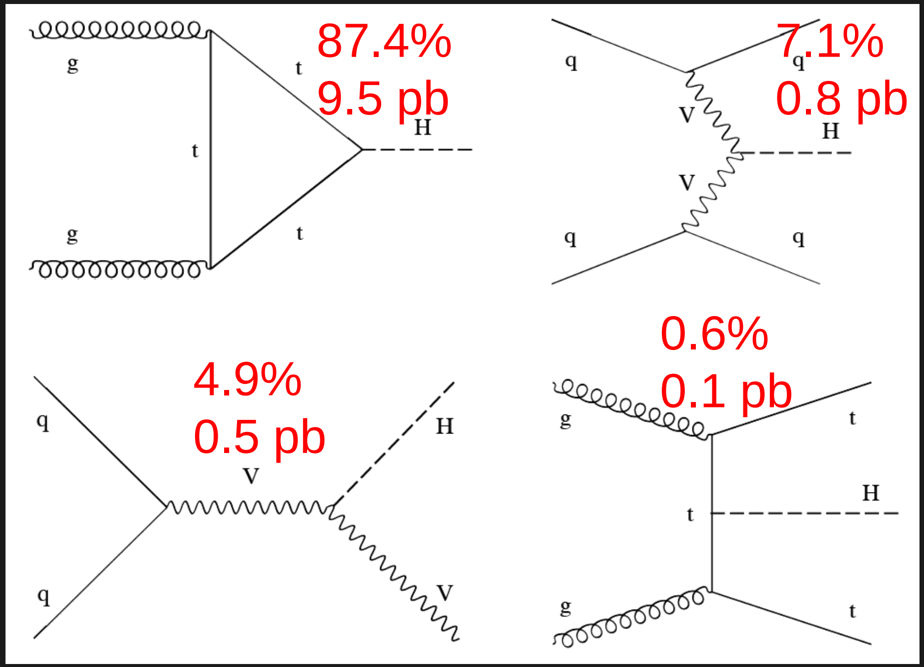
CMS-HIG-17-031, arXiv:1809.10733

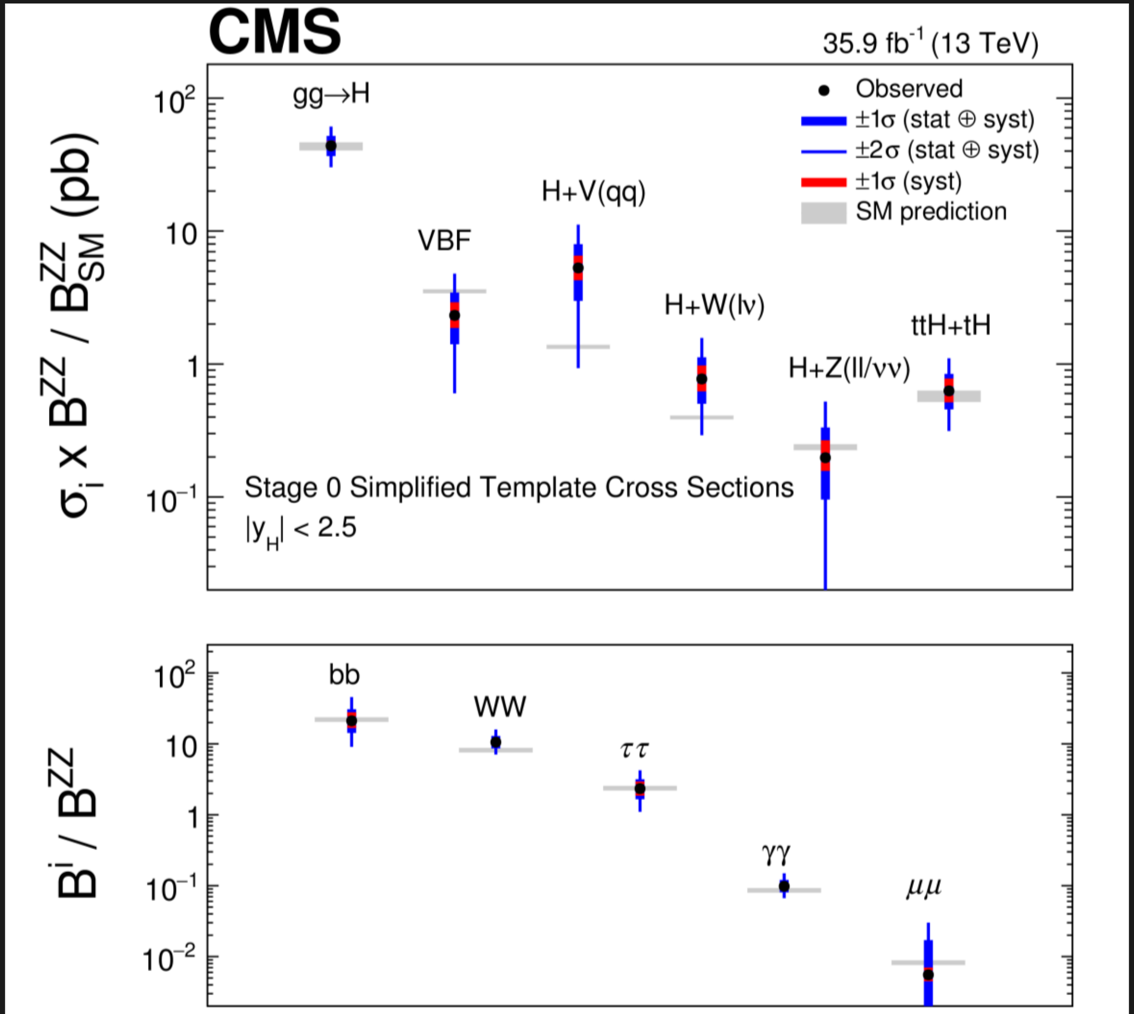
- H → WW is a crucial channel for the measurement of the Higgs boson couplings and properties.

- In this talk:
  - Only fully leptonic state.
  - 13 TeV results based on 2016 dataset of 35.9 fb^{-1} by CMS. CMS-HIG-16-042, CERN-EP-2018-141: arXiv:1806.05246 (submitted to Phys. Lett. B).
  - Prospective for full Run2.

Higgs Decay Modes and Production



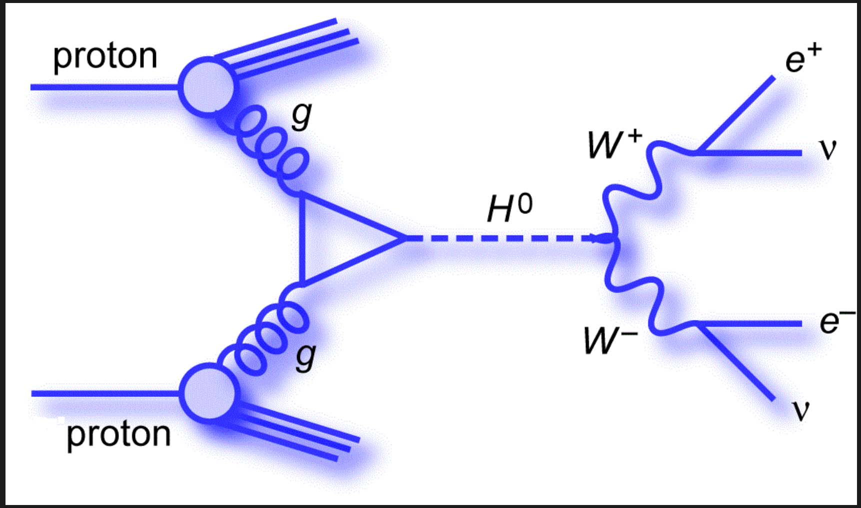




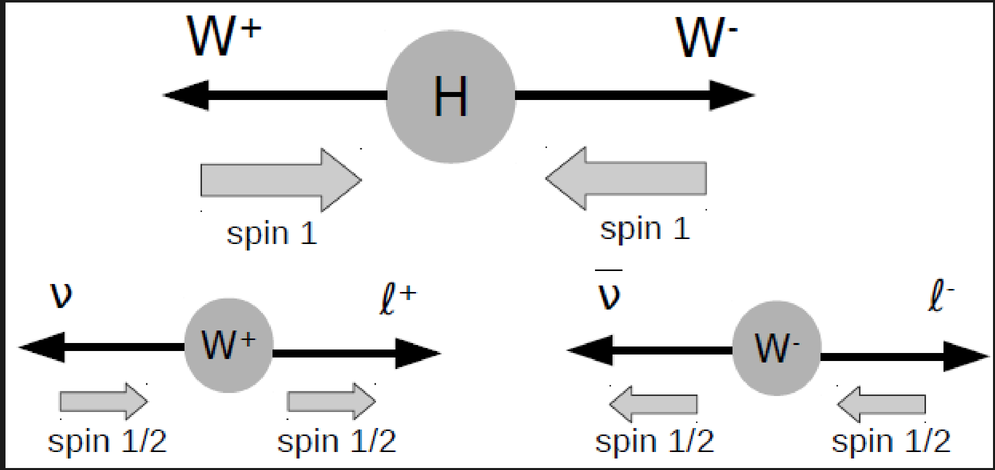
CMS-HIG-17-031, arXiv:1809.10733

- Decay mode with second largest BR!
- Sensitive to Higgs coupling with fermions (ggH), to coupling with W and Z (VBF and VH) and to the direct coupling with top quark (ttH).
- Good agreement of 2016 CMS results with SM predictions within uncertainties.

H→WW channel



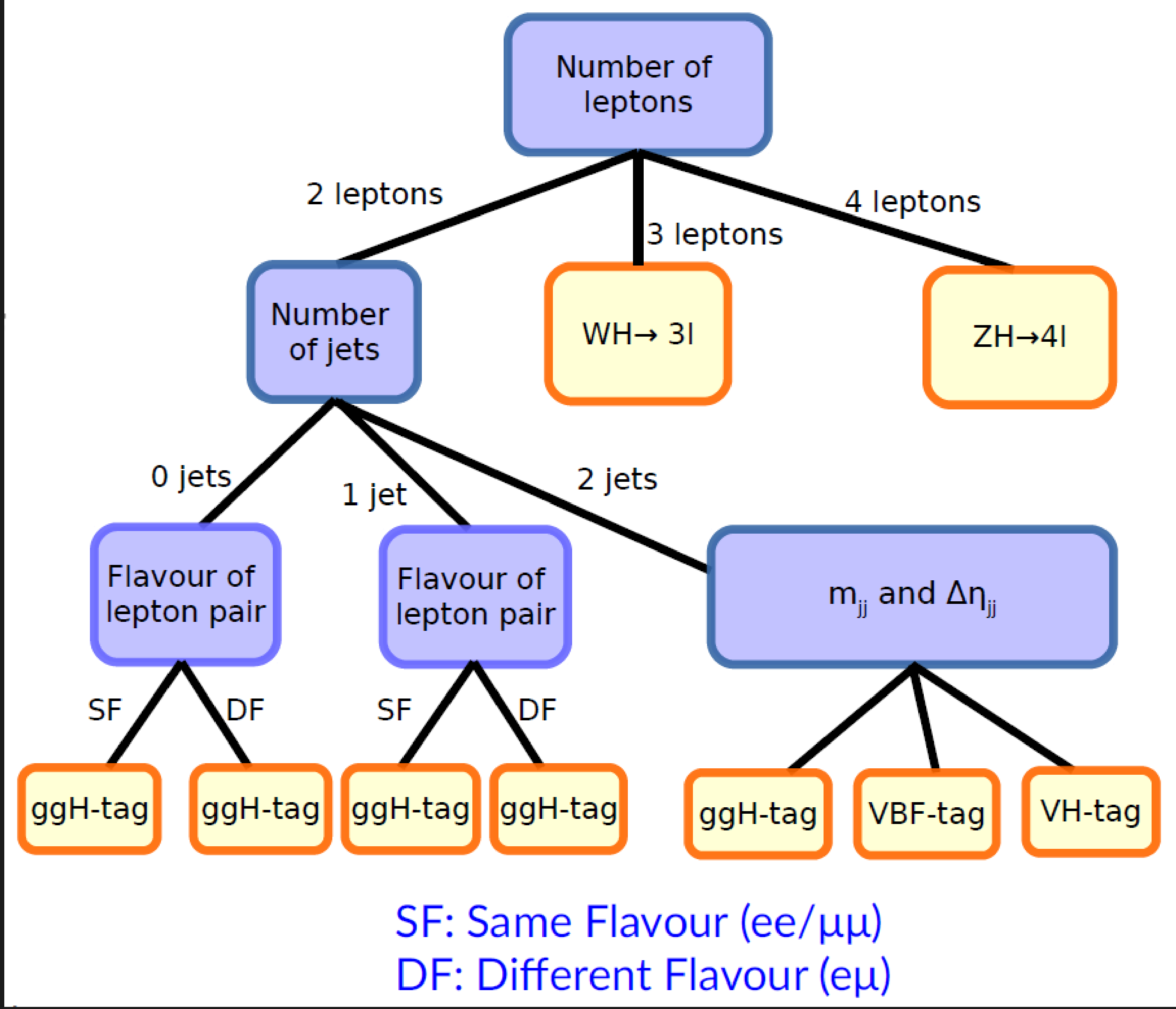
- 2 isolated leptons (electrons or muons) with opposite charge.
- Moderate MET due the presence of 2 neutrinos.
- Number of jet depending on the production mode.
- Large BR and good sensitivity to the Higgs boson couplings.
- Relatively low background final state.
- The neutrinos prevents the reconstruction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



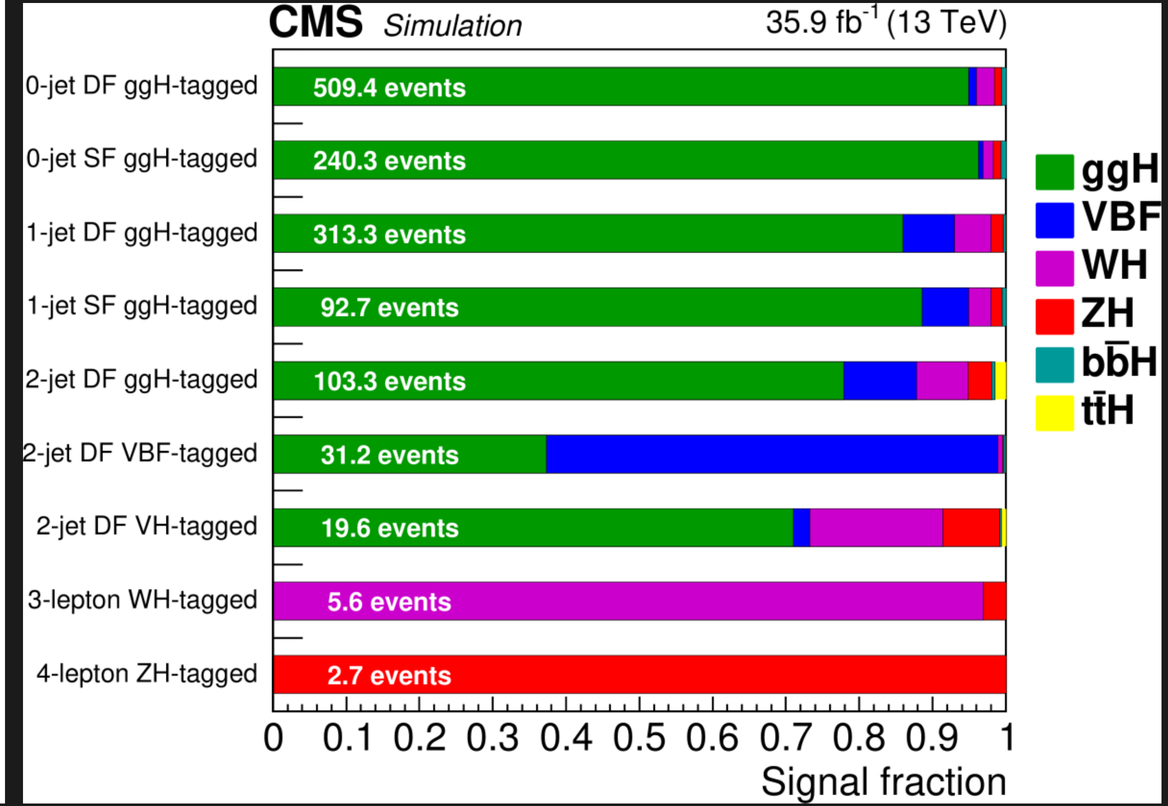
- Higgs boson has spin 0:
  - Leptons are emitted close to each other.
  - Small dilepton mass.

H→WW categories

- Events split in 30 categories.

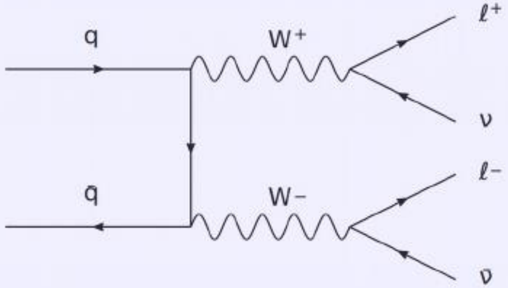


- Opposite charge leptons with $p_T^{lep1} > 25$ GeV and $p_T^{lep2} > 10$ (13) for $\mu(e)$.
- $p_T^{ll} > 30$ GeV and MET > 20 GeV.
- b-tagged jet veto.



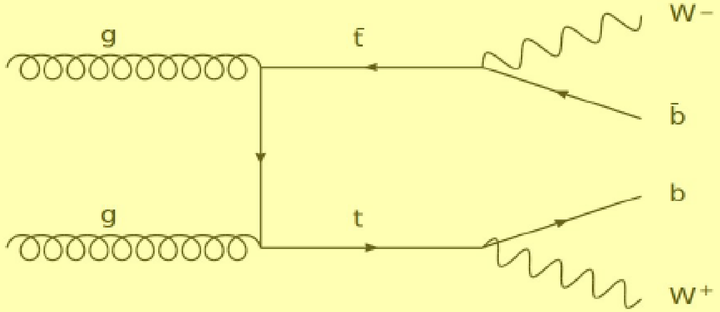
Main backgrounds

Non-resonant WW



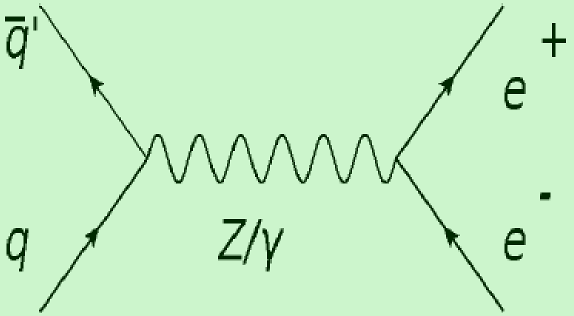
Same final state as the signal process.

$t\bar{t}$



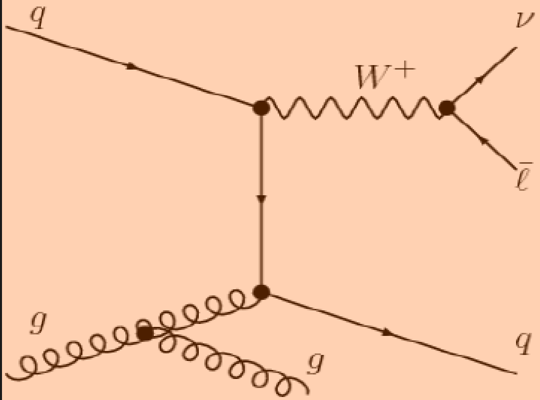
Very large cross section.
Same final state as the signal process + 2 b-jets.
Reduced vetoing b-jets

Drell-Yan



Very large in the same flavour final state.

Nonprompt

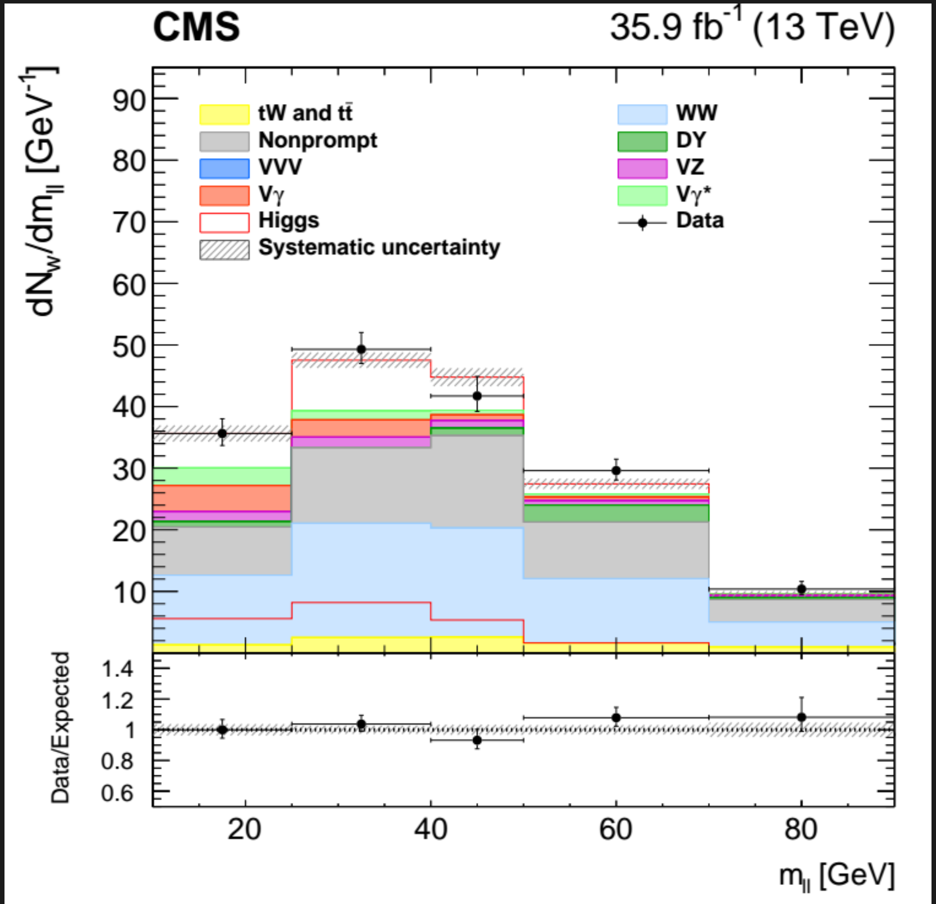


One jet can be misidentified as a lepton. Reduced with lepton ID and isolation.
Contribution also from semi-leptonic $t\bar{t}$.
Totally data-driven with fake rate method.

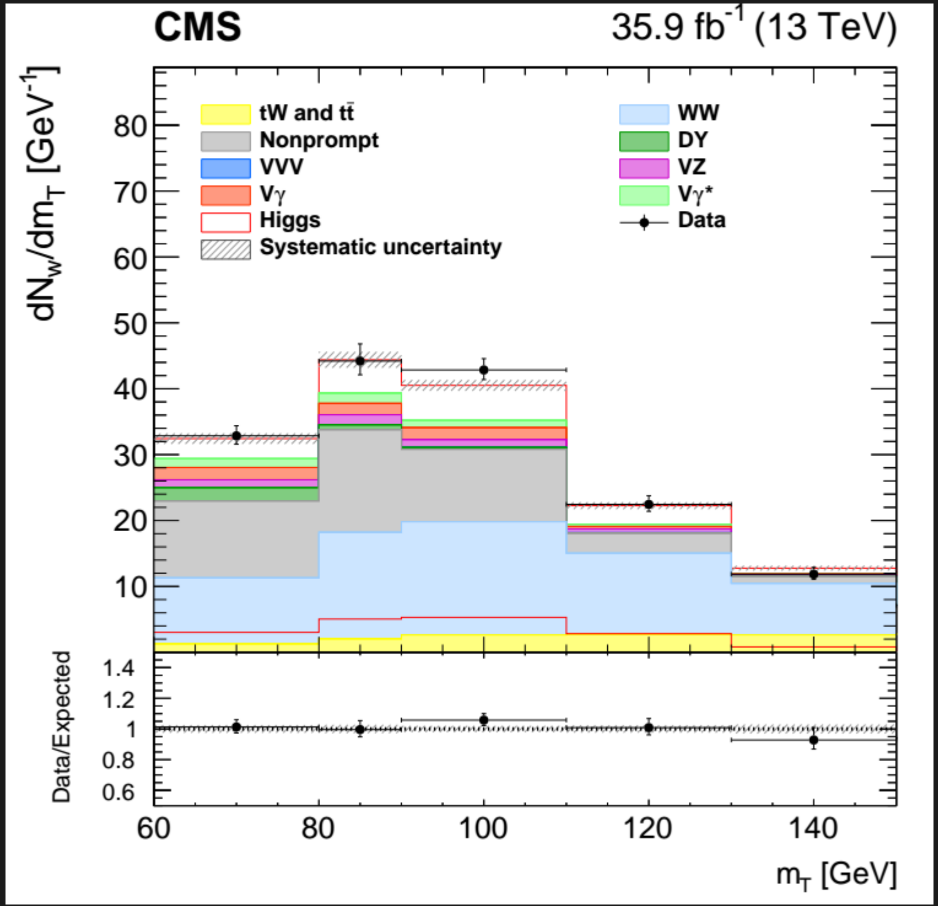
- Top and DY background normalization taken from data using dedicated control regions.
- WW background normalization free-floating in the fit.

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.



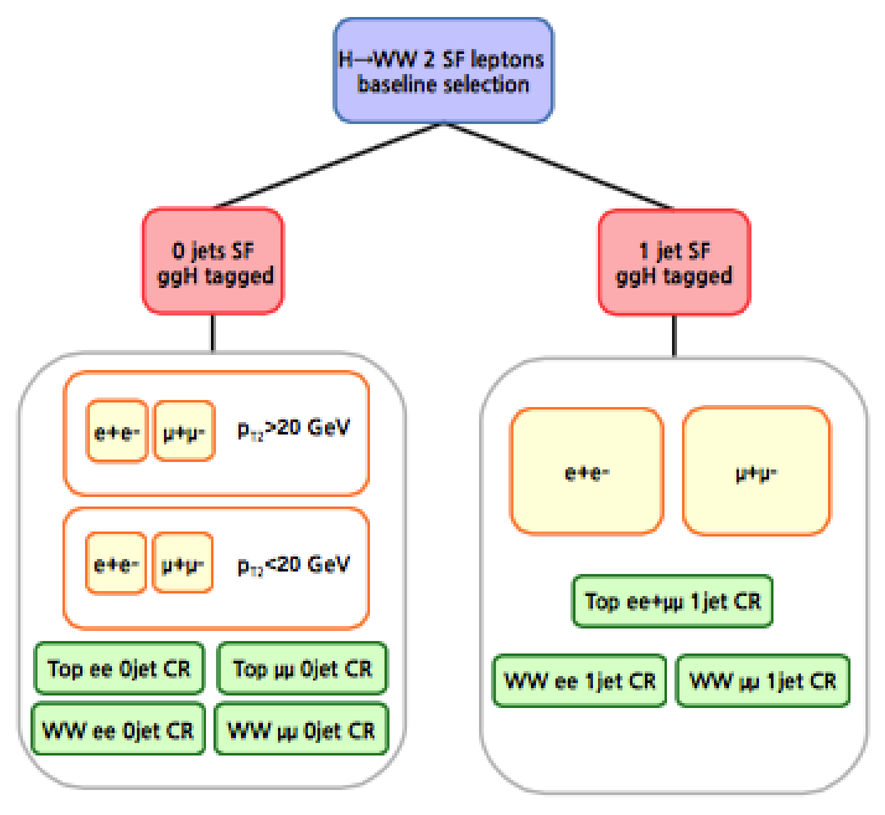
0-jet pT2<20 GeV

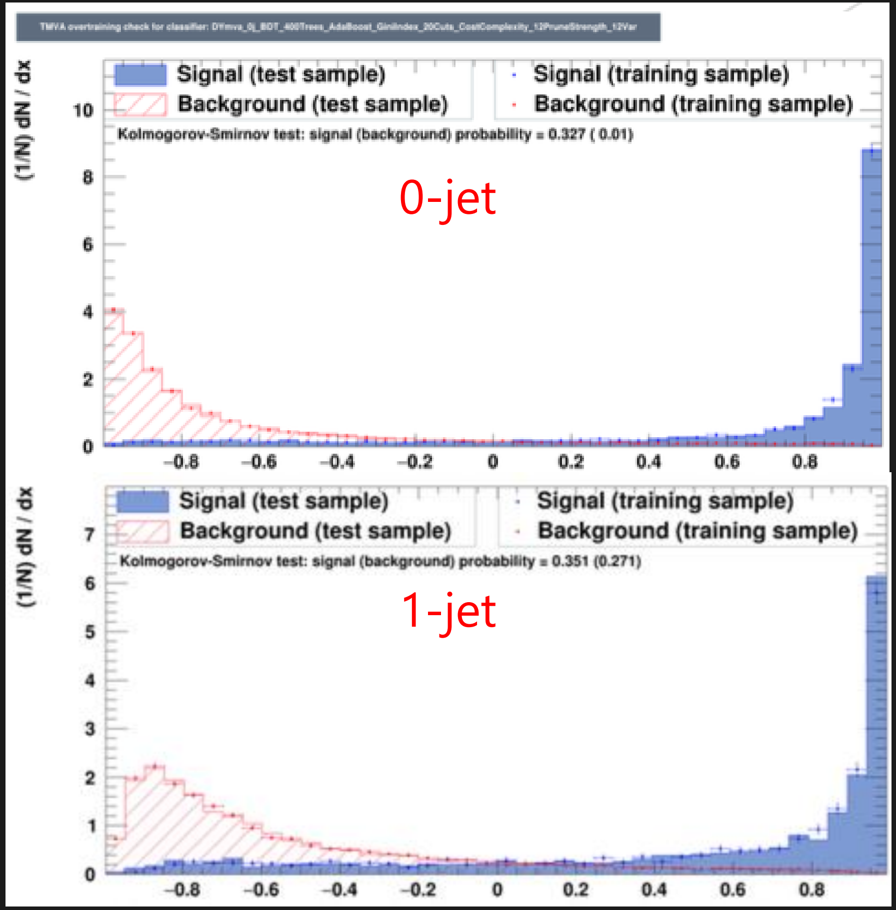


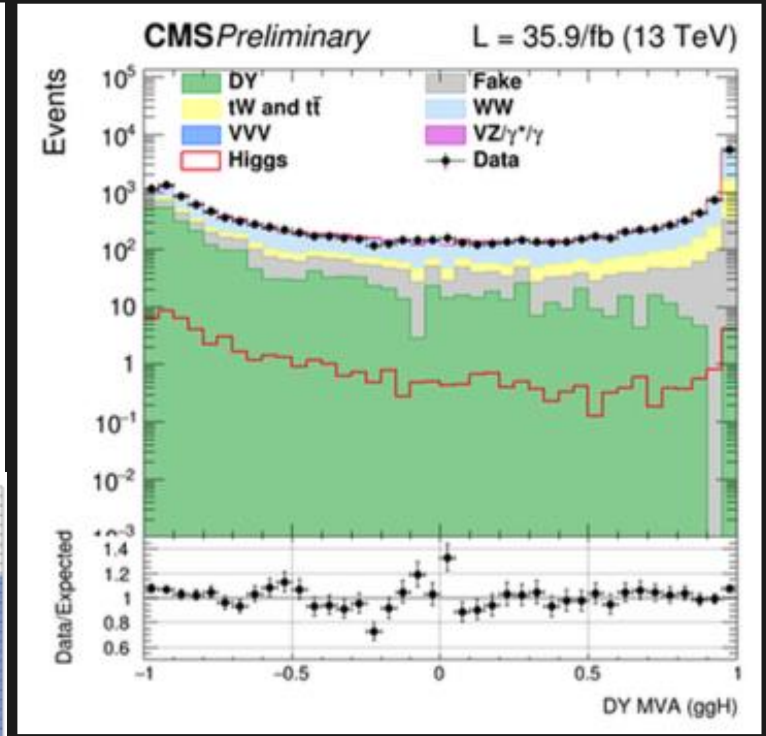
0-jet pT2>20 GeV

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).



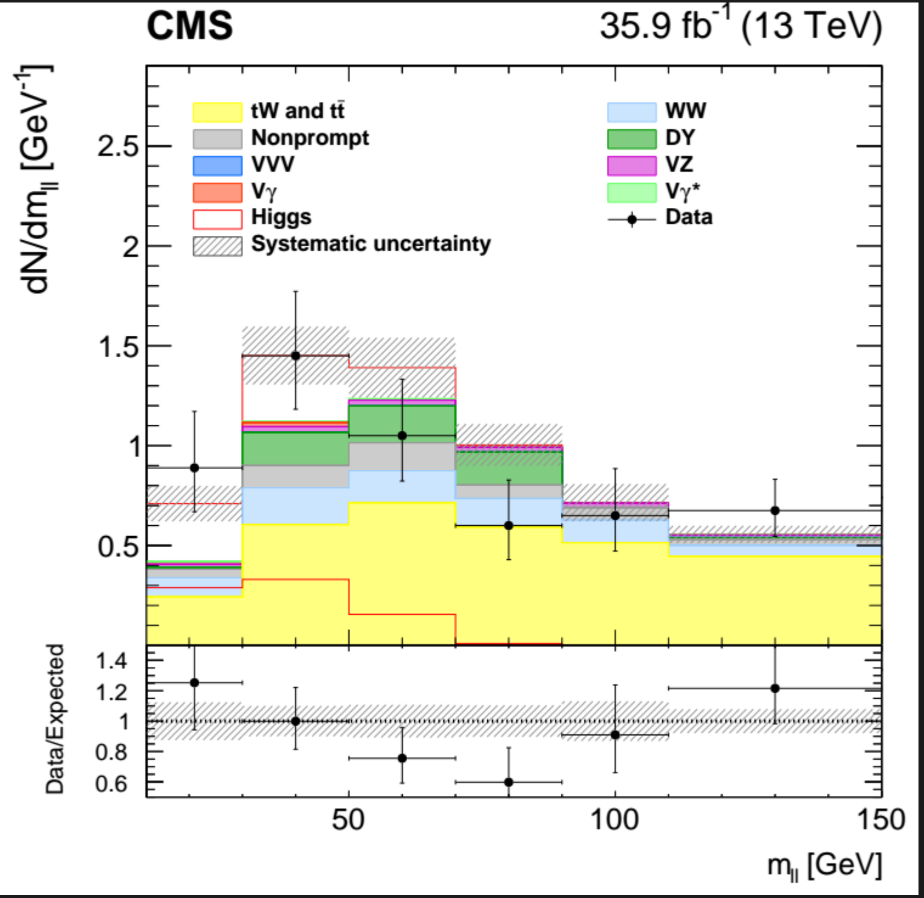




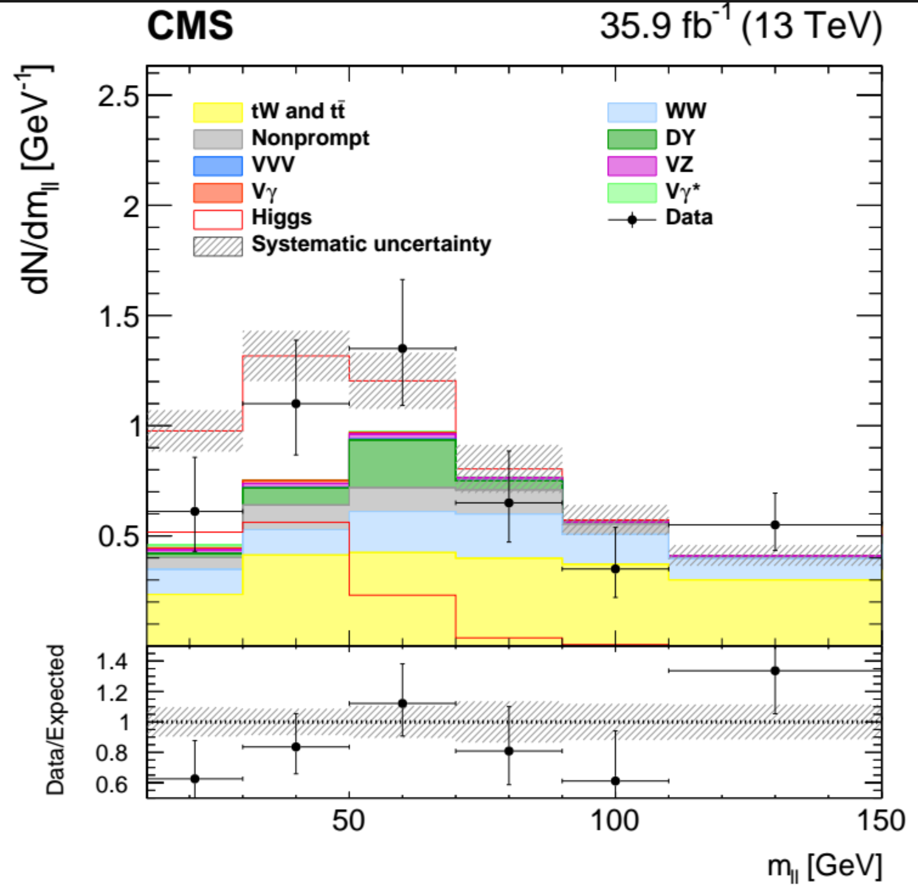
Good agreement in signal like (Top,WW)

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.



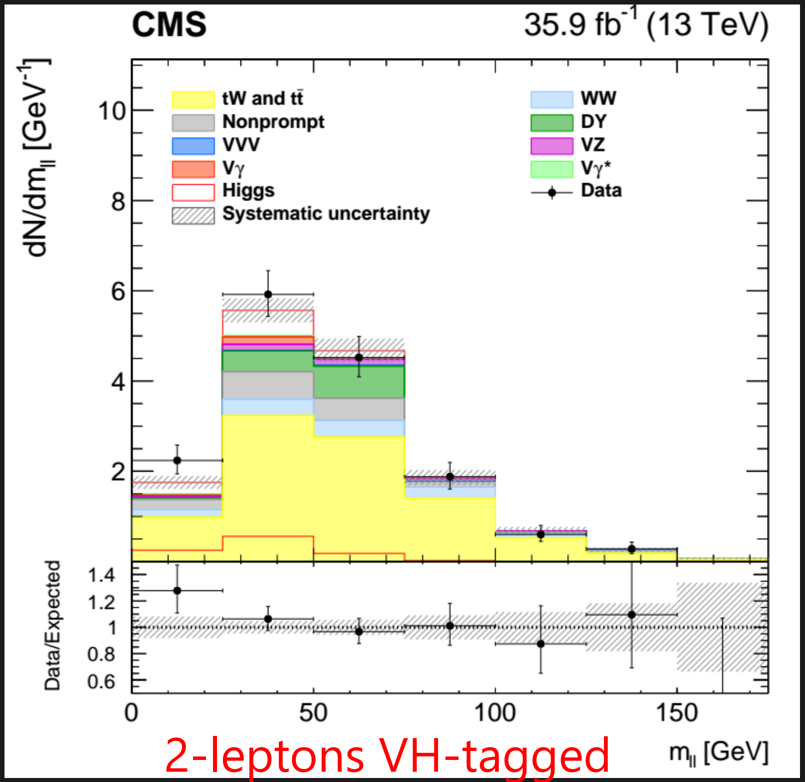
400<m_{jj}<700 GeV

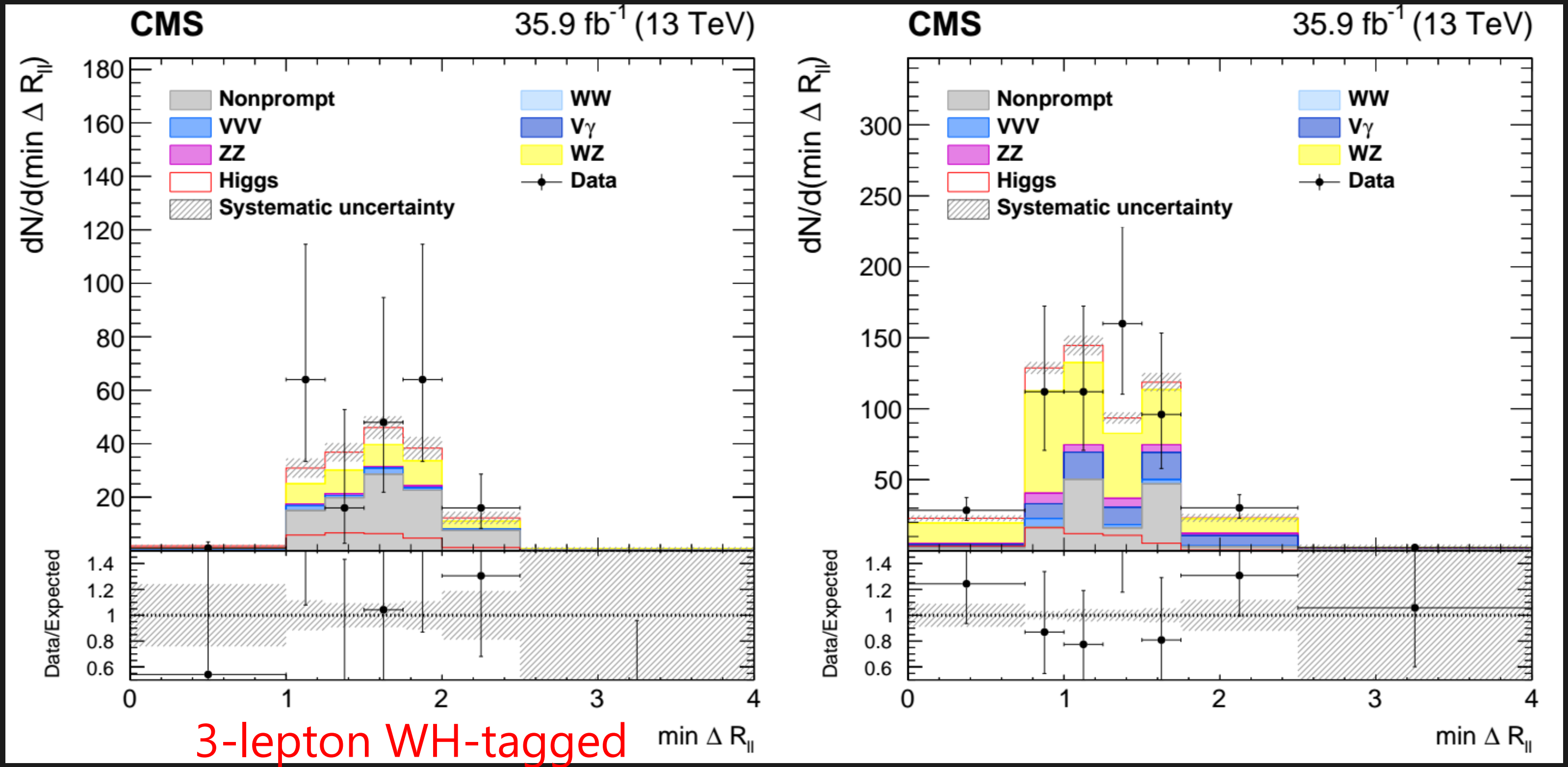


m_{jj} >700 GeV

VH-tagged categories

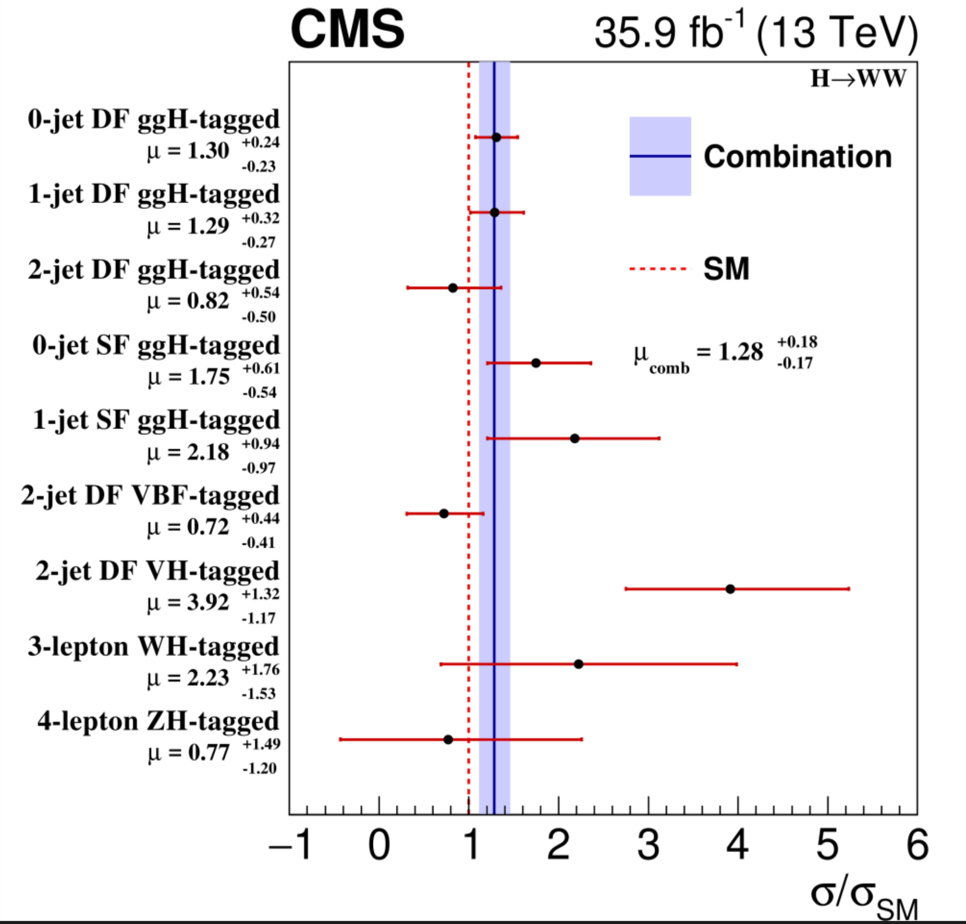
- 3 different categories aiming at 3 different final states:
  - 2 leptons VH-tagged with V→hadrons, H→WW→2l2v. Shape analysis based on m_{ll}.
  - 3 leptons WH-tagged with W→lv, H→WW→2l2v. Shape analysis based on min(ΔR_{ll}).
  - 4 leptons ZH-tagged with Z→2l, H→WW→2l2v. Event counting analysis.
- Only DF in 2016. SF+DF in Full Run2 at least for 2 leptons VH-tagged.

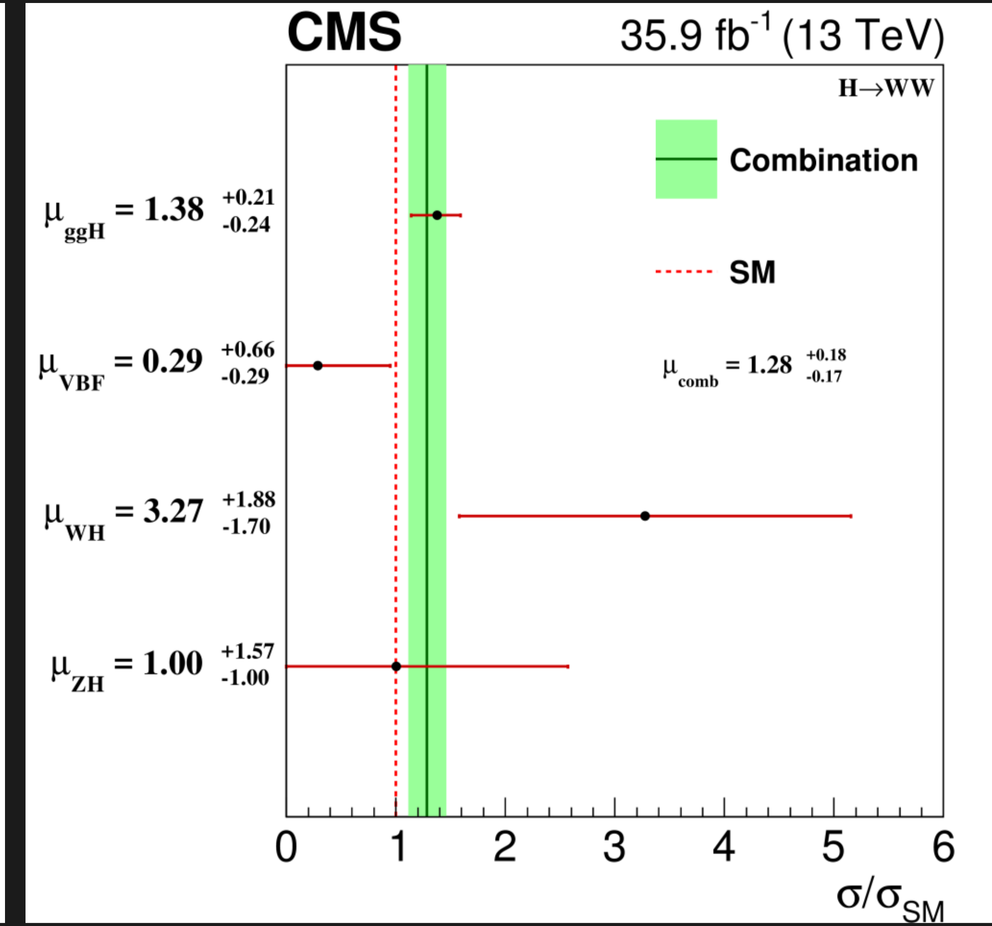




Signal strength measurements

- Signal strengths (σ/σ_{SM}) measured from a simultaneous binned likelihood fit of all signal and control regions.





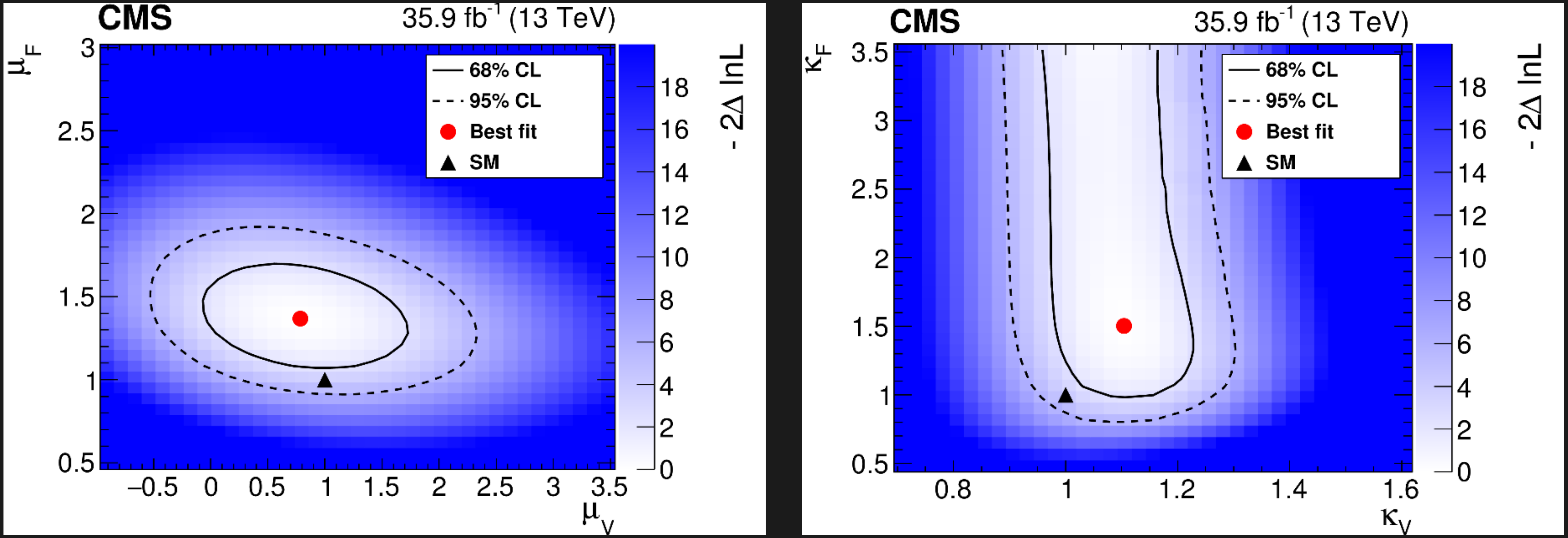
- Limited by lepton reconstruction, background data-driven estimation and ggH theretical uncertainties.

- $\mu = 1.28^{+0.18}_{-0.17}$ at 9.1(7.1) σ observed (expected) significance. First H→WW observation in CMS!!!

Measurement of the Higgs couplings

- μ_F, μ_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.

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

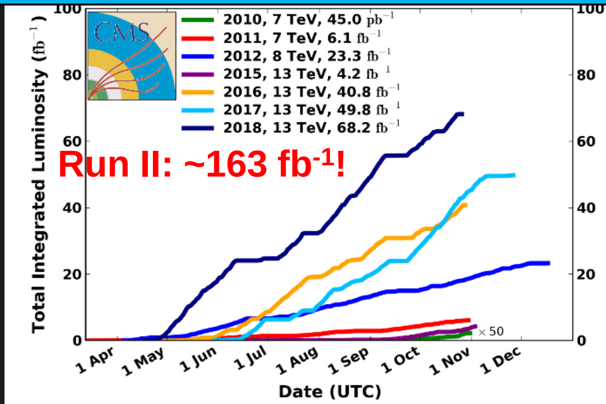


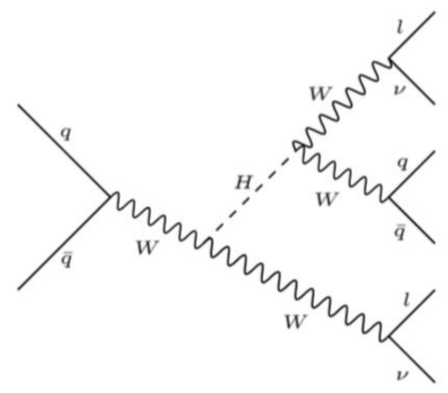
Compatibility with SM within 2σ.

Future prospects

- Spring 2019. 2016+2017 differential cross-section analysis: measurement of number of jets and Higgs p_T.

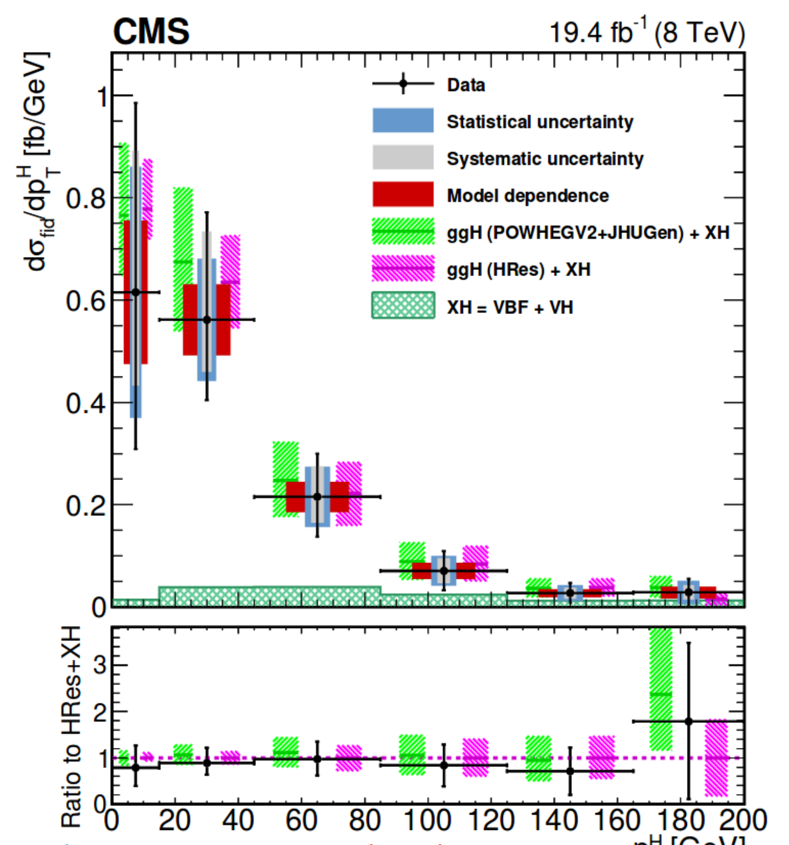
- Summer 2019. Full Run2 categories: improvement of the measurement of signal strength and couplings.
  - Inclusion of SF in 2j categories (ggH / VH / VBF).
  - Improvement in DYMVA algorithm: BDT→DNN.
  - Inclusion of same-sign WH.





- 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.

- Begin of 2020. EFT study by UA PhD student (Tomas Kello).



arXiv:1606.01522 JHEP03(2017)03

EFT approach application

- 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:**

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

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

relevant operators are those with
$\mathbf{dim}\boldsymbol{\mathcal{O}} = \mathbf{6}$
couplings dimensions are inverse powers of mass (Λ 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 Λ scale)

$$\mathcal{O}_{WW} = \Phi^\dagger \widehat{W}_{\mu\nu} \widehat{W}^{\mu\nu} \Phi$$

$$\mathcal{O}_{\widetilde{W}W} = \Phi^\dagger \widetilde{\widehat{W}}_{\mu\nu} \widehat{W}^{\mu\nu} \Phi$$

$$\mathcal{O}_{W} = \left(D_\mu \Phi\right)^\dagger \widehat{W}^{\mu\nu} \left(D^\nu \Phi\right)$$

contribute to HWW vertex

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

FIT this value minimizing χ^2 ⇒ if non-zero ⇒ NEW PHYSICS

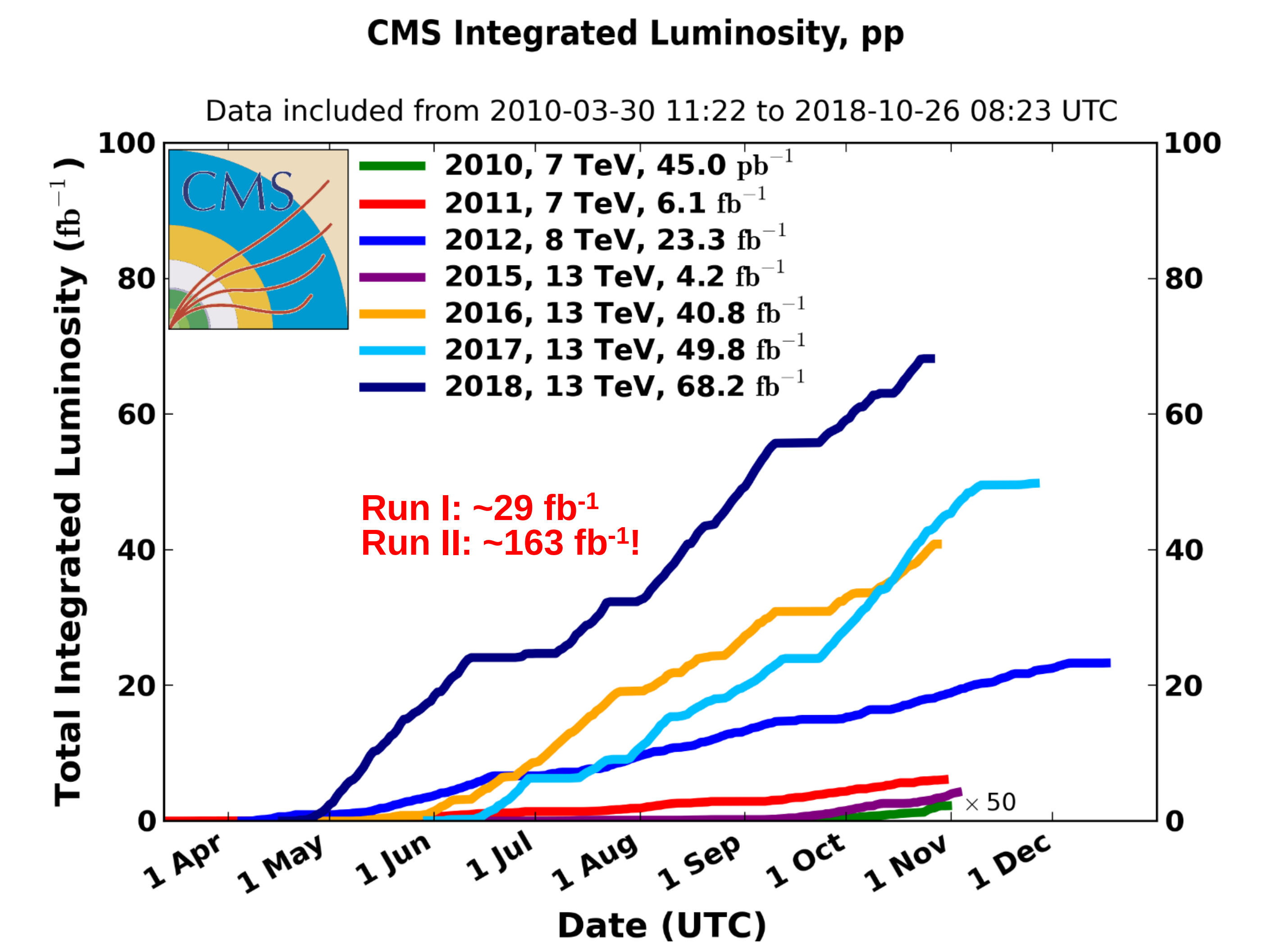
Summary

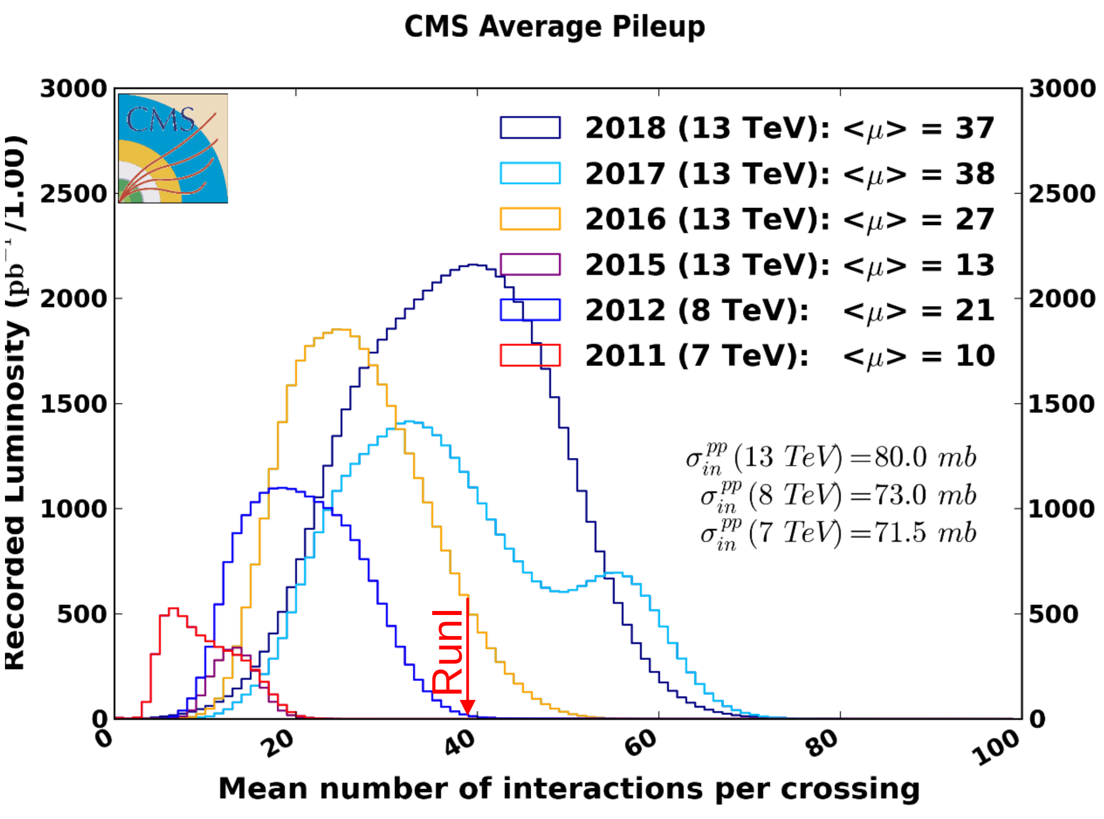
- First observation in CMS of the H→WW channel with 2016 data.
- Crucial contribution to the Higgs combination measurement of production cross-section and couplings.
- Several measurement in confirming SM predictions.
- Some results show tension that have to be monitored with more data. Many categories are limited by statistical uncertainty.
- More data needed for full description of Higgs properties:
  - First measurement of differential cross-section with 2016+2017 data: Higgs p_T.
  - Improvement of cross-section and coupling measurements with full Run2 data.
  - Measurement of differential cross-section with full Run2 data: Higgs spin...
  - EFT approach measurements of HWW.


MERCI - DANK U

SLIDES

LHC Luminosity and PU



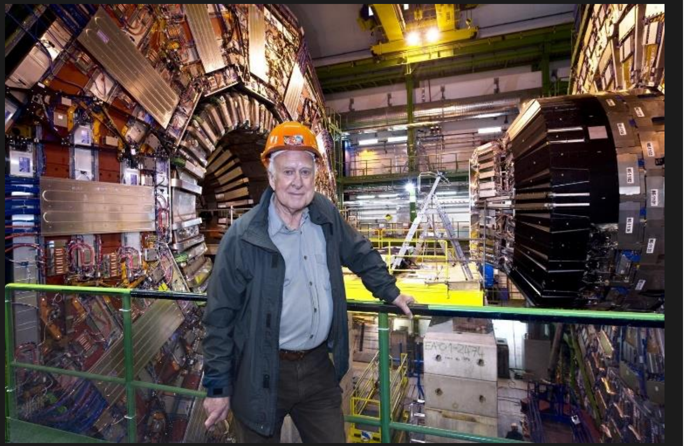


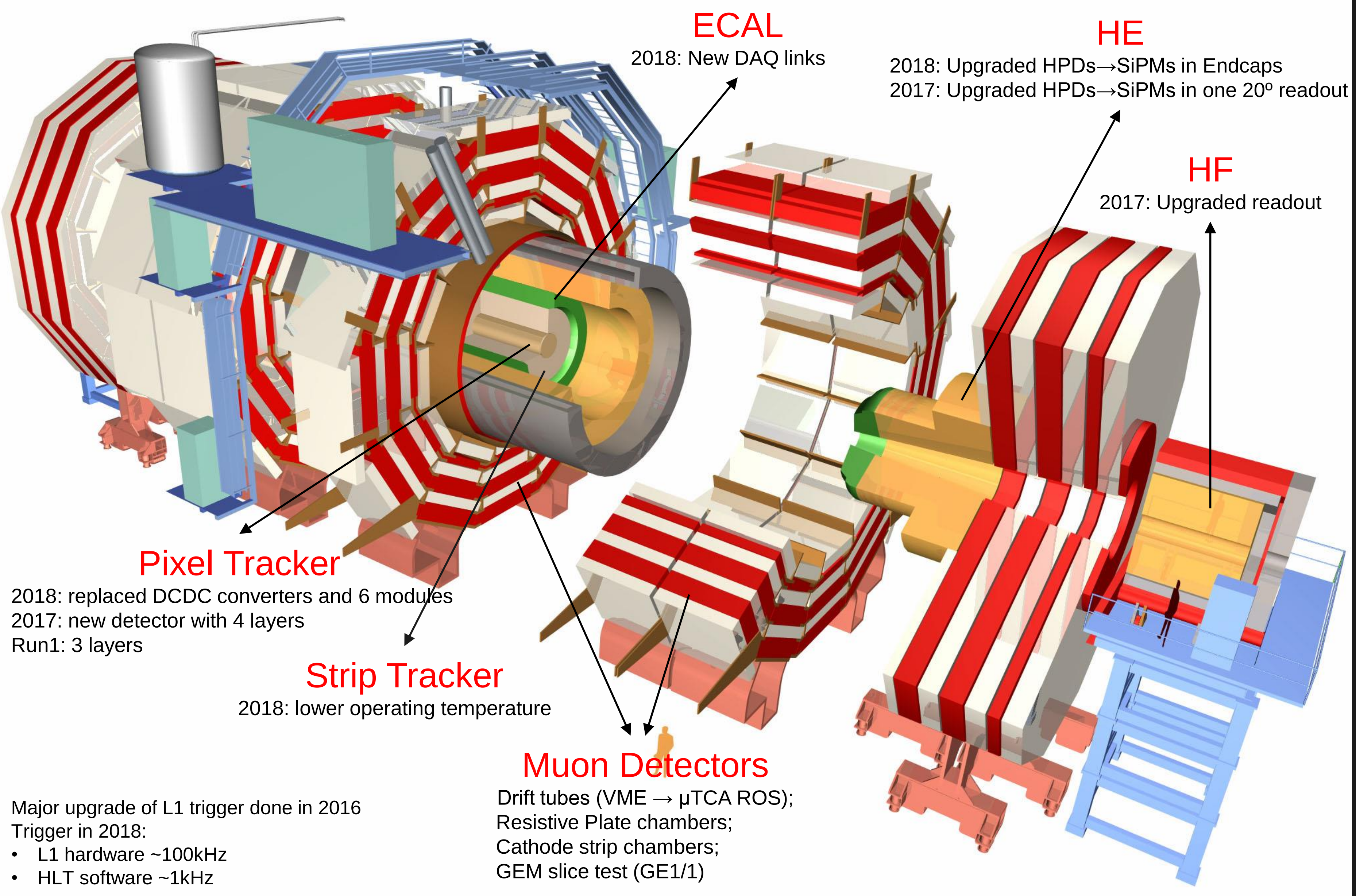
- LHC has delivered ~163 fb^{-1}, CMS has collected data with >94% recording efficiency with a data certification ~90%.

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

CMS Experiment

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

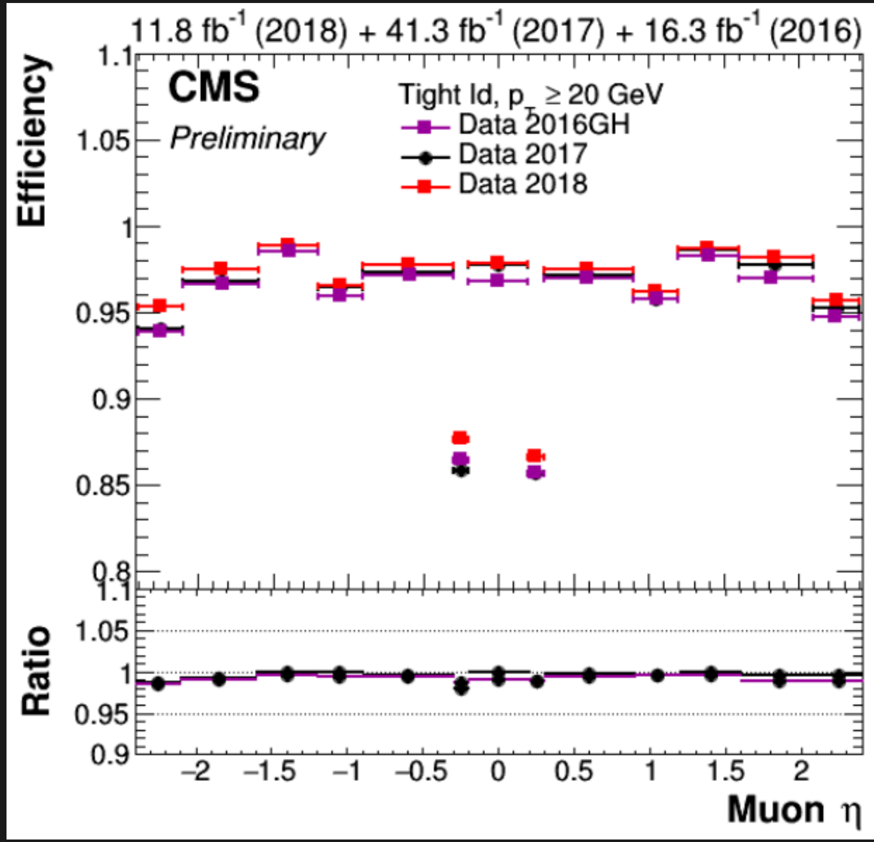




Major upgrade of L1 trigger done in 2016
Trigger in 2018:

- L1 hardware ~100kHz
- HLT software ~1kHz

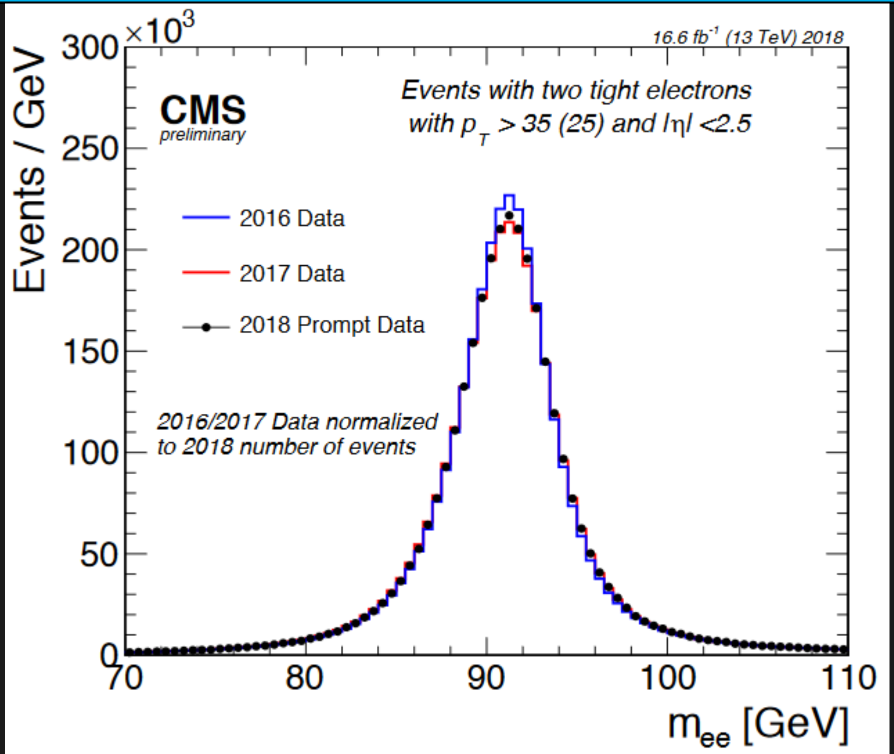
CMS Performance

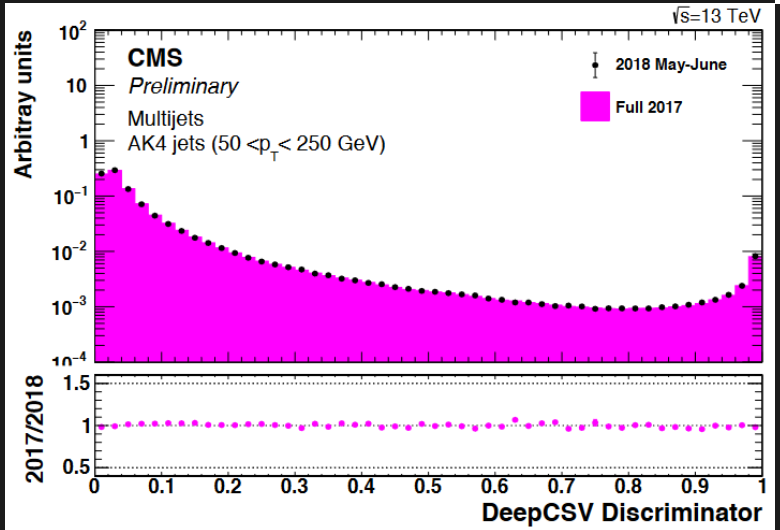


2017 improvement due new pixel detectors
2018 improvement due recovery of some CSC

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

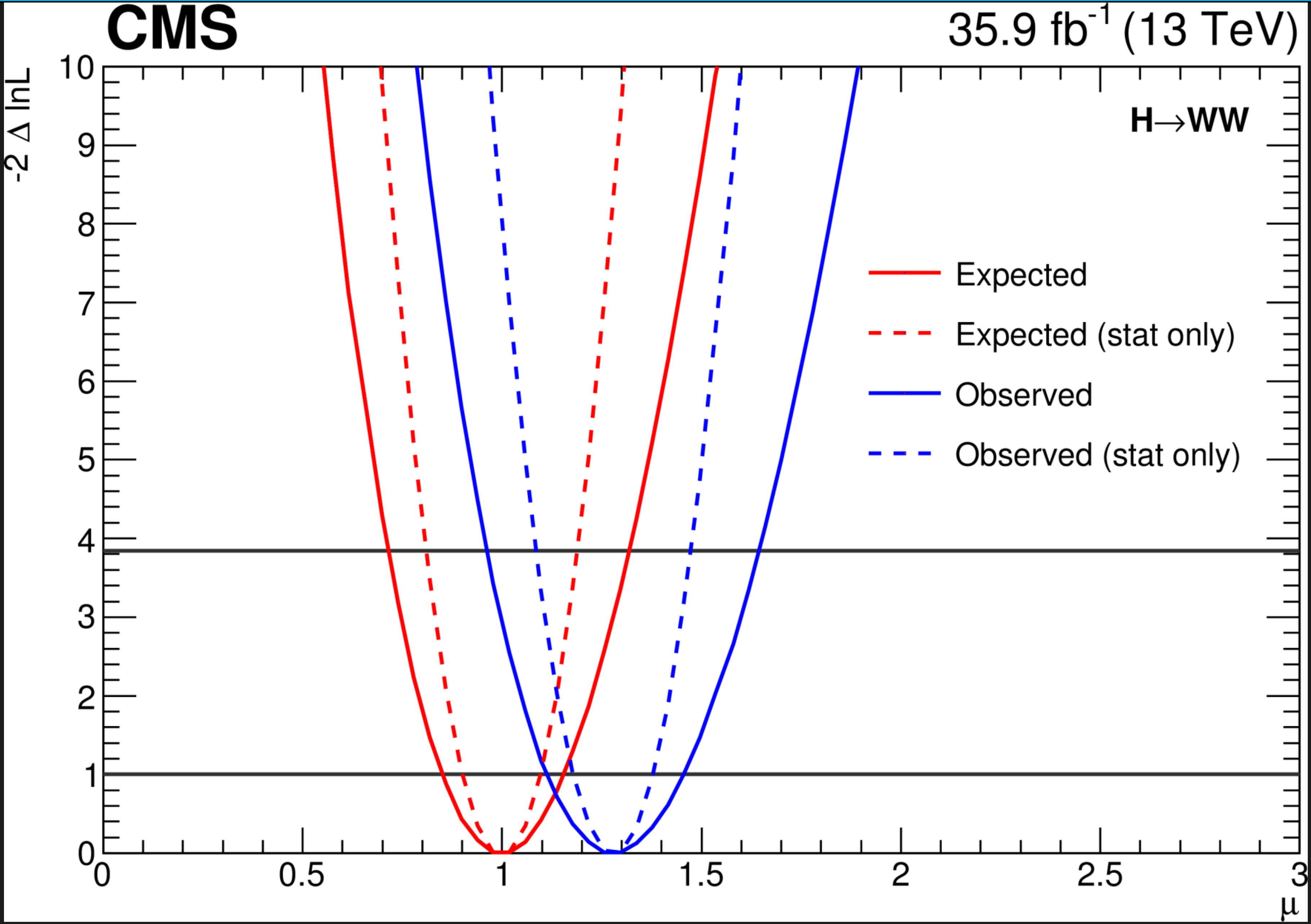
First look at 2018 data shows very good quality!





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

HWW likelihood



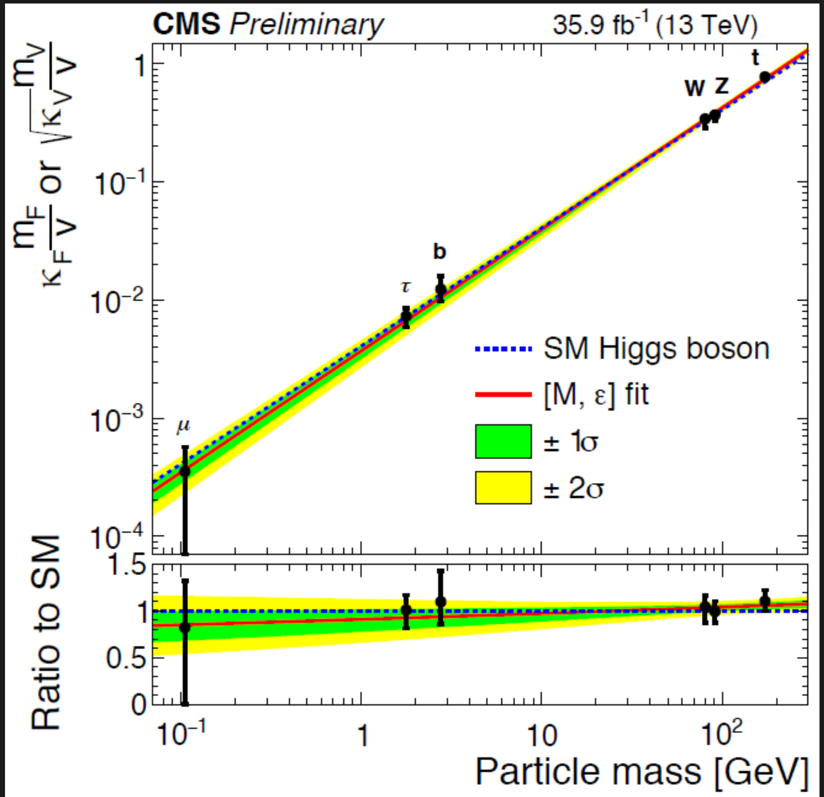
SM coupling constrains

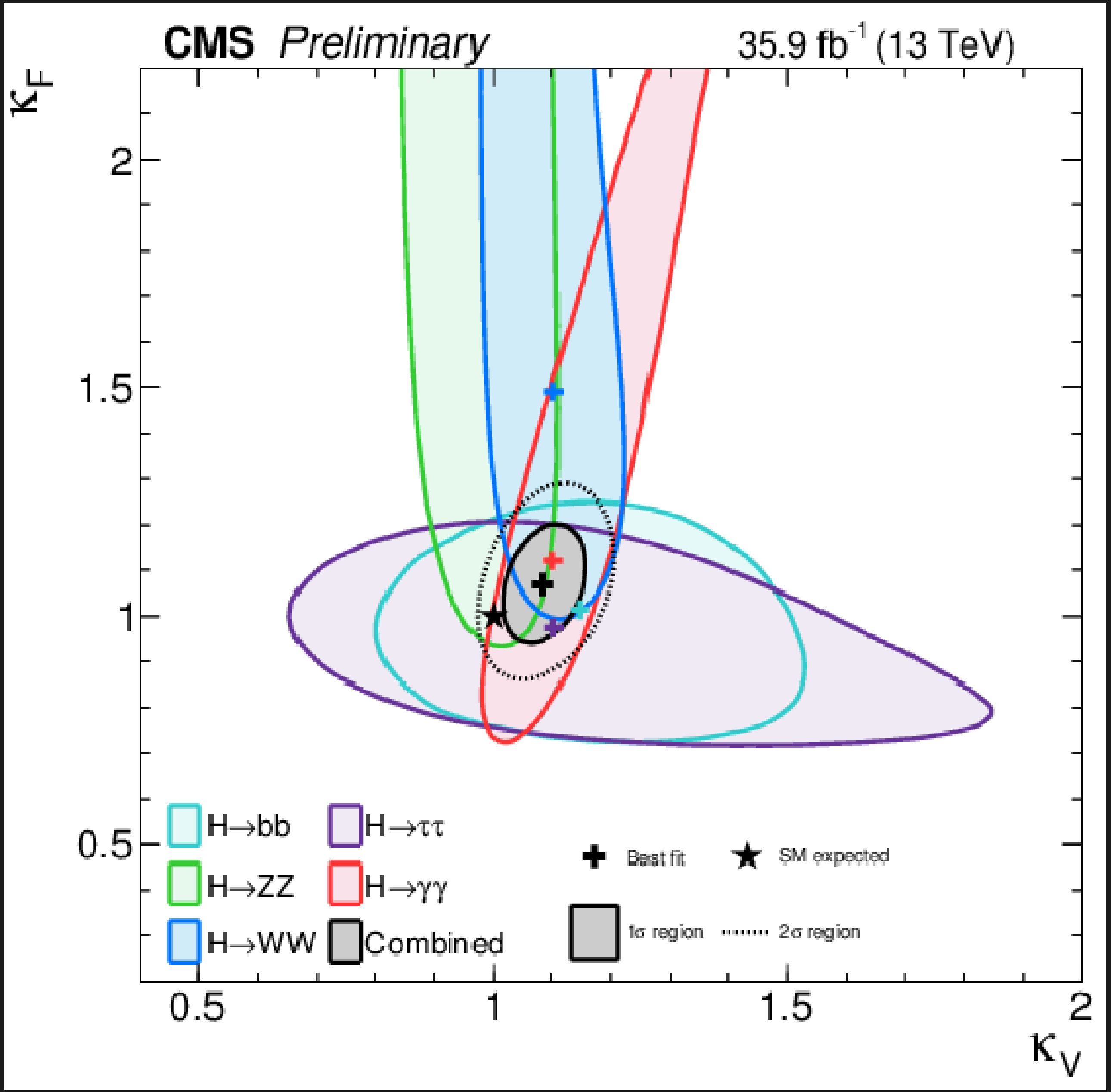
arXiv:1809.10733
Submitted to EPJC

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

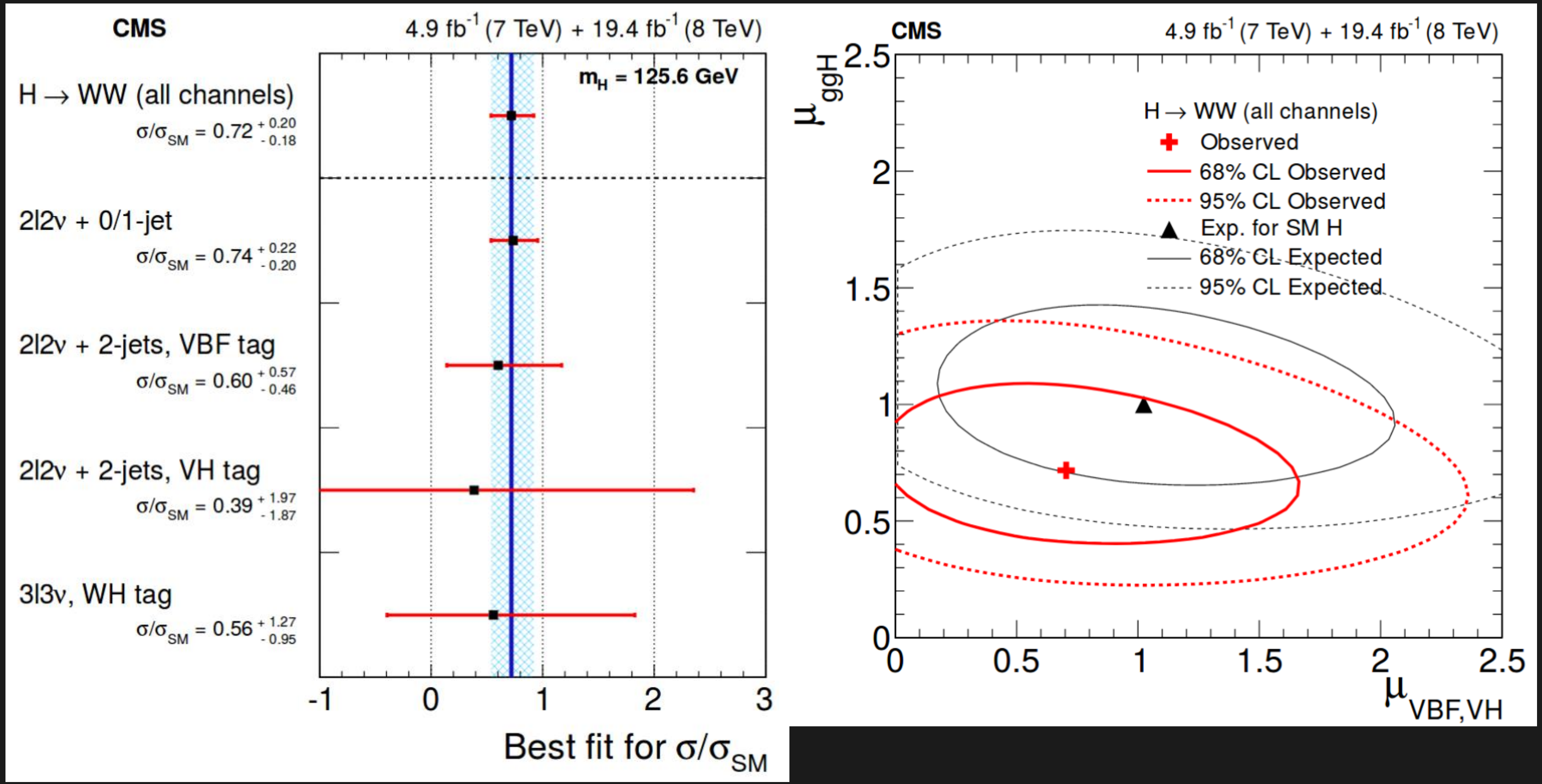
$$k_i^2 = \sigma_i/\sigma_i^{SM}$$

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

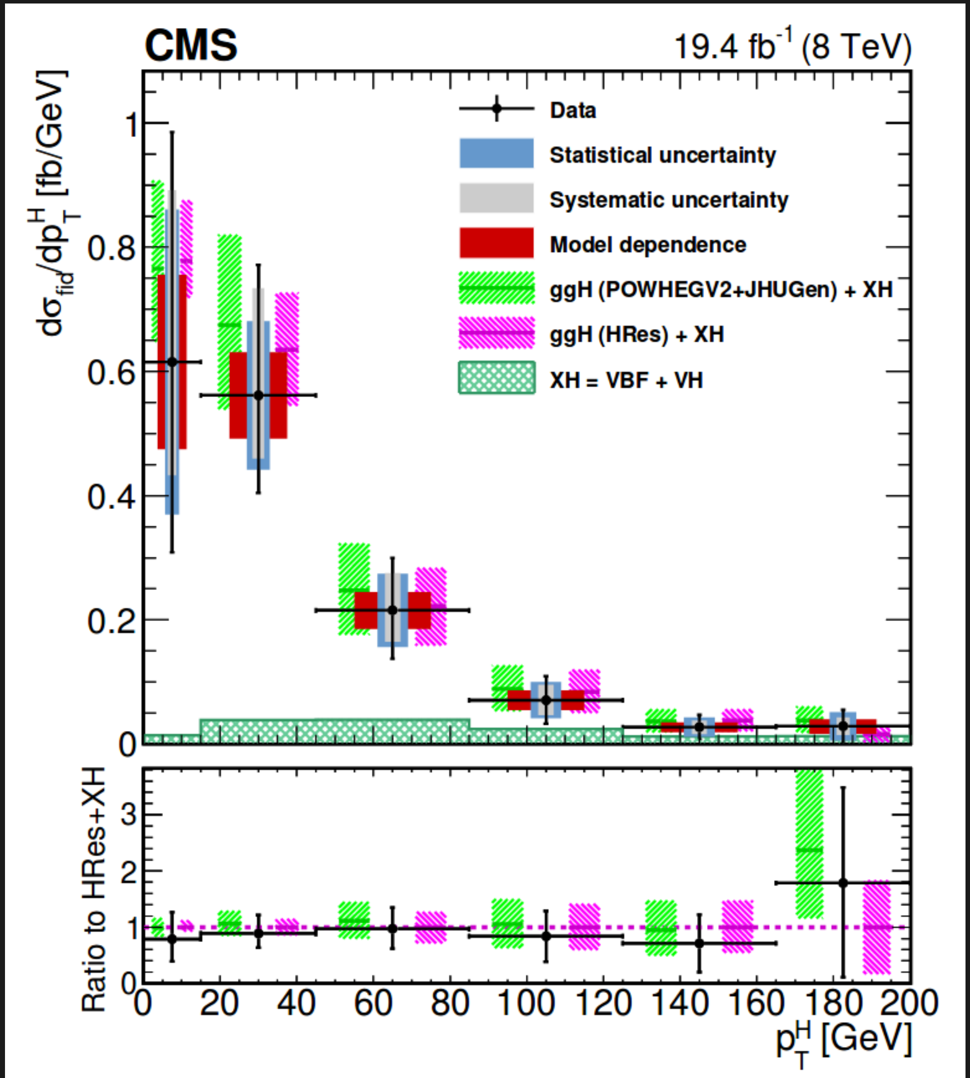




Highlights from Run1



arXiv:1312.1129
JHEP01(2014)096



arXiv:1606.01522
JHEP03(2017)032

SF ggH-tagged categories: DY estimate

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

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

MC

DATA

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

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

- 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): $N^{H}_{DY\to ll} = A_H N^{OUT}_{DY\to ll}$ $N^{WW}_{DY\to ll} = A_{WW} N^{OUT}_{DY\to ll}$

State	n^{data}_{in}	$R_{out/in}$	A_H	n^{data}_{DY}	n^{MC}_{DY}	$n^{data}_{DY}\cdot A_H$
0-jet $p_T^{lep_2} < 20$ bin						
ee	1404	0.21±0.00±0.04	0.22±0.01±0.06	172.07±54.32	9.93	38.27 + 26.94 - 19.81
$\mu\mu$	3450	0.31±0.00±0.03	0.43±0.00±0.02	610.56±175.58	241.45	264.88 + 95.38 - 86.80
0-jet $p_T^{lep_2} \geq 20$ bin						
ee	1404	0.21±0.00±0.04	0.21±0.01±0.06	172.07±54.32	79.42	36.64 + 26.32 - 19.24
$\mu\mu$	3450	0.31±0.00±0.03	0.15±0.00±0.02	610.56±175.58	73.93	92.85 + 45.08 - 36.87
1-jet bin						
ee	868	0.19±0.01±0.02	0.33±0.01±0.10	100.07±32.09	19.79	32.79 + 24.45 - 17.68
$\mu\mu$	2136	0.31±0.00±0.08	0.36±0.00±0.06	395.80±152.86	122.86	144.04 + 90.39 - 71.02

40 to 70% normalization uncertainties on DY background