Measurements of Higgs boson production and properties in the WW decay channel using the CMS detector

4th August 2016

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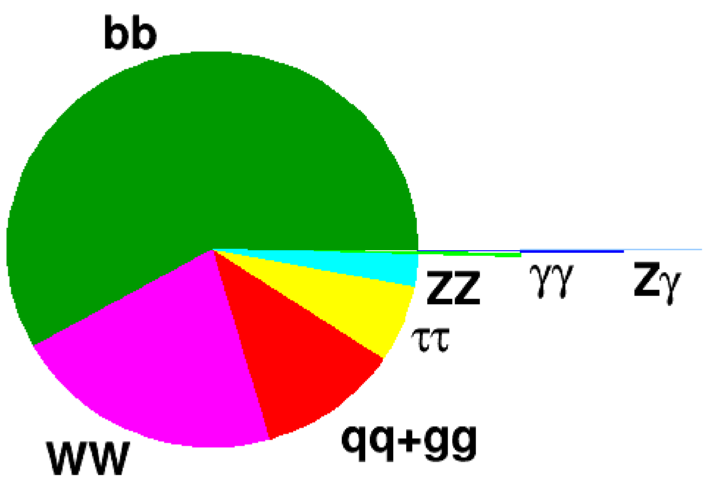
(Northeastern University)
on behalf of the CMS collaboration

ICHEP2016CHICAGO

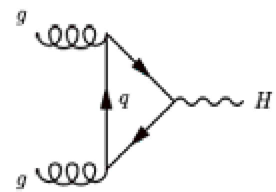
Higgs production and decay

- **Production mechanisms**
  - Gluon fusion is the dominant production mechanism
  - VBF, VH and ttH allow to test H properties
    - ttH, see M. Peruzzi presentation this afternoon

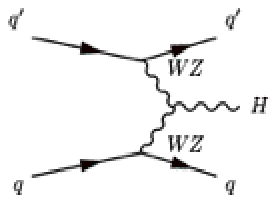
      http://indico.cern.ch/event/432527/contributions/1072545/
- **Higgs decay**
  - WW is one of the Higgs decays with larger BR and a reasonable level of irreducible backgrounds



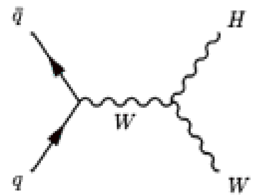
ggH 48.58 pb



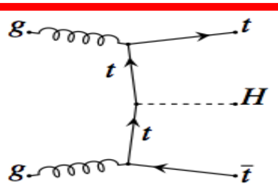
qqH 3.78 pb

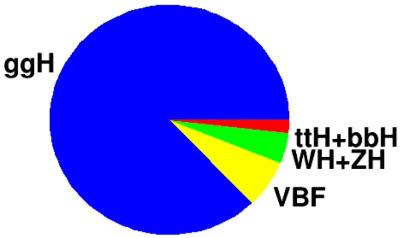


WH+ZH 2.38 pb



ttH+bbH 1.0 pb

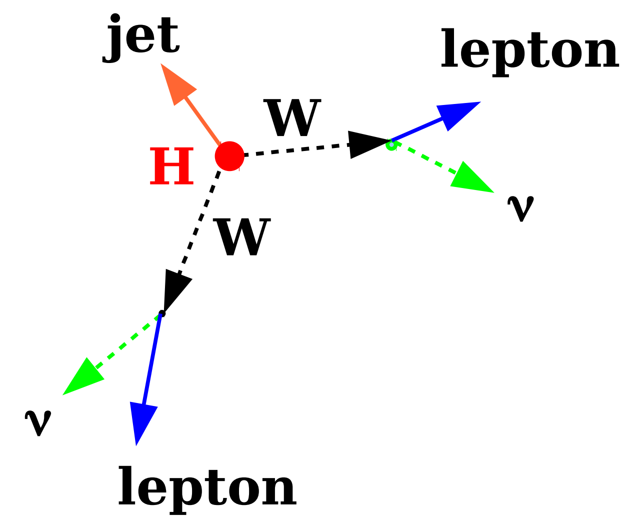


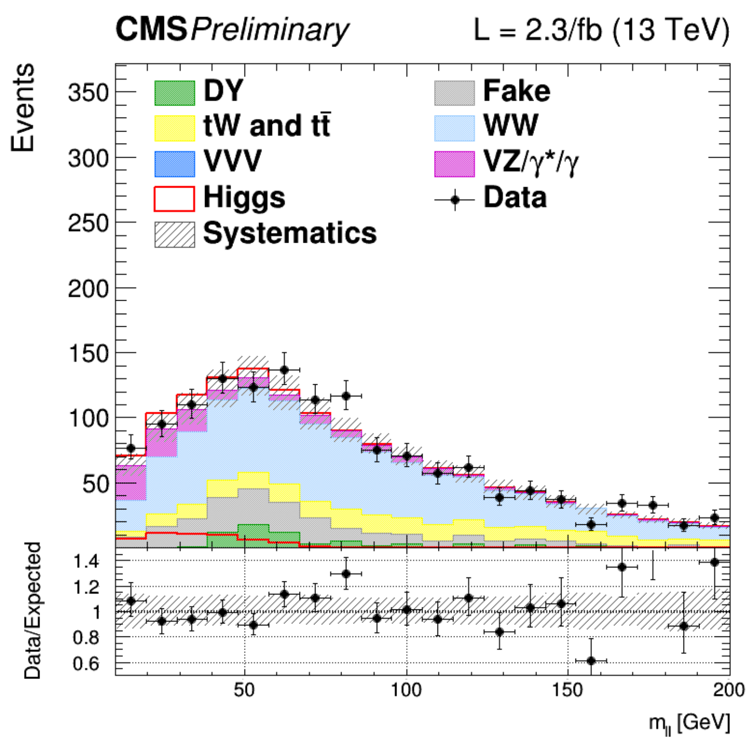


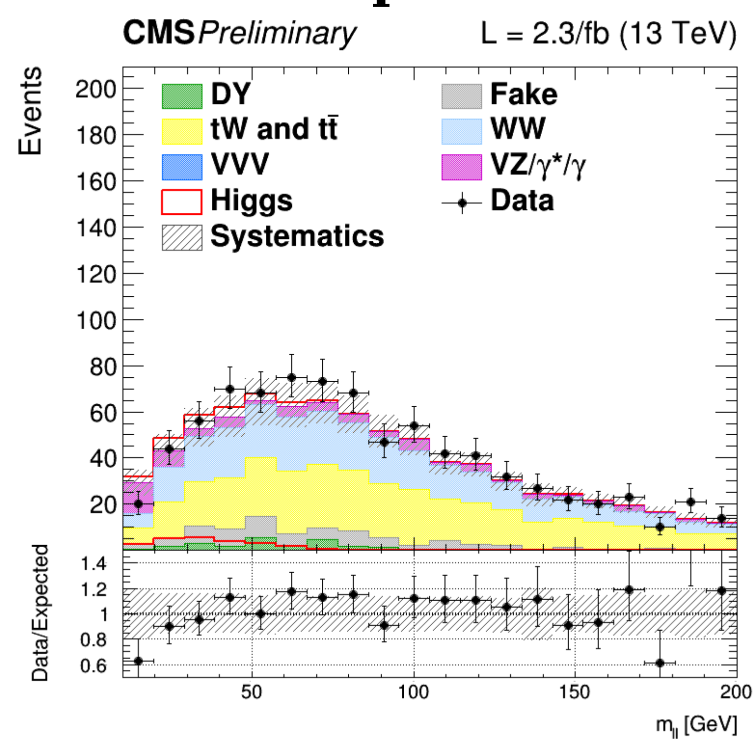
m_H = 125 GeV
13 TeV

Signal and background

- CMS 13 TeV HWW results: HIG-15-003 https://cds.cern.ch/record/2161793
- **2.3/fb** collected in **2015**
- Background composition varies w.r.t. number of jets
  - **0 jets**: WW, W+jets
  - **1 jet**: WW, Top

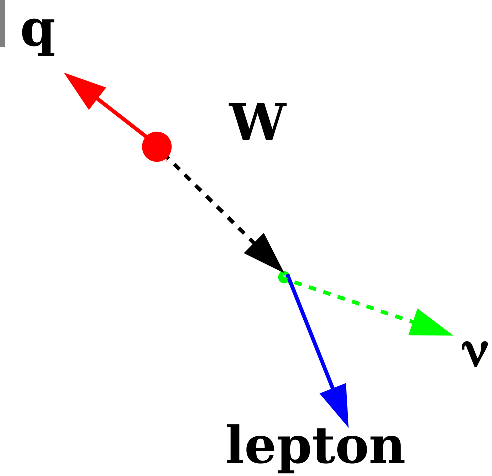




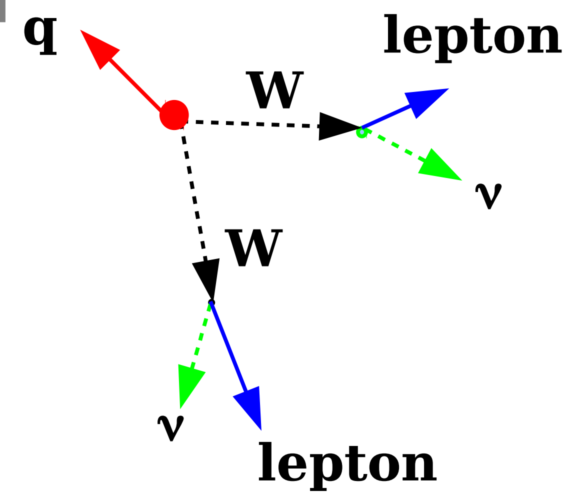


The background menu

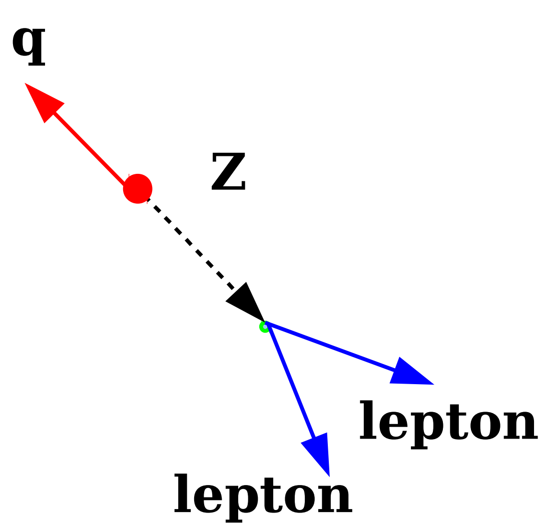
$W \to l\nu$ +jets
~61 nb



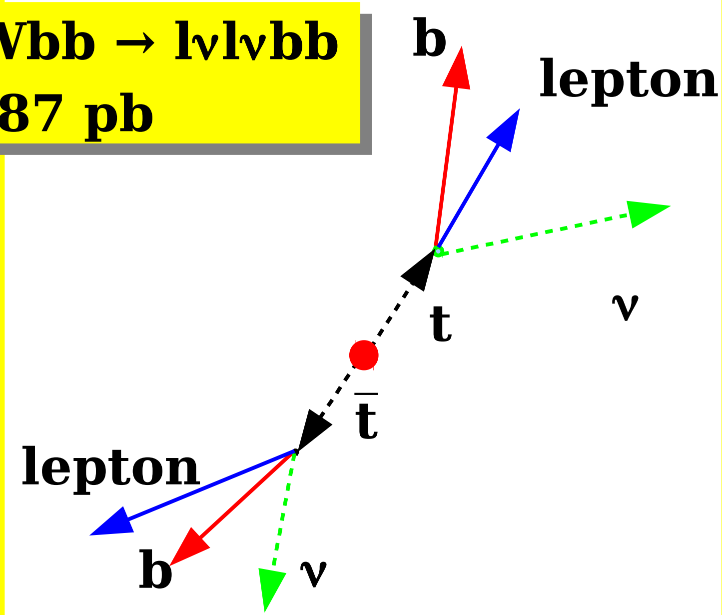
$WW \to l\nu l\nu$
~12 pb



$DY \to ll$
~6 nb



$t\bar{t} \to WWbb \to l\nu l\nu bb$
~87 pb

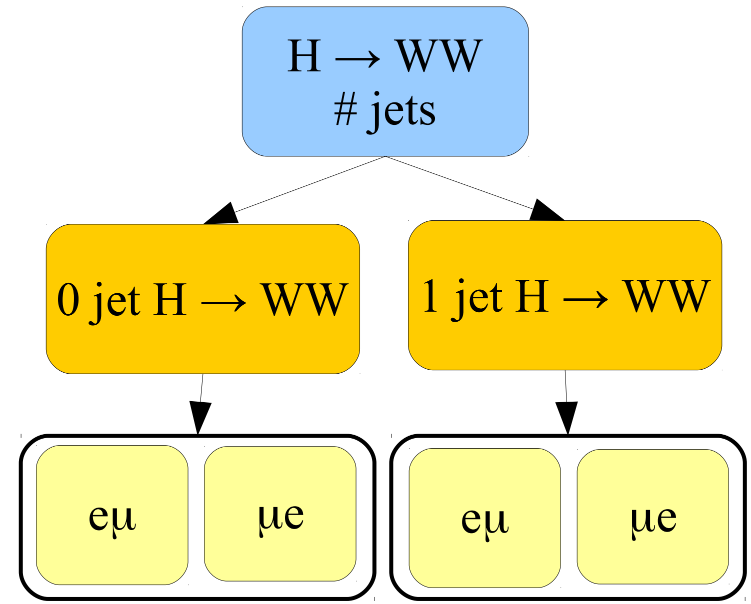


Analysis strategy

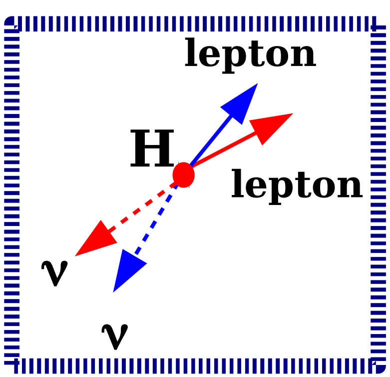
- **Neutrinos** → impossible reconstruct an invariant mass spectrum
- In transverse plane momentum conservation
  - Build a **transverse mass** variable:
    - 2 neutrinos → more complicated than in simple W → lν decay
    - Di-lepton and MET system considered

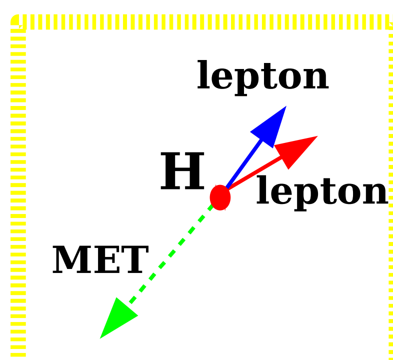
$$m_{\mathrm{T}}^{\ell\ell E_{\mathrm{T}}^{\mathrm{miss}}} = \sqrt{2 \cdot p_T^{\ell\ell} \cdot E_{\mathrm{T}}^{\mathrm{miss}} \left(1 - cos\Delta\phi_{\ell\ell, E_{\mathrm{T}}^{\mathrm{miss}}}\right)}$$

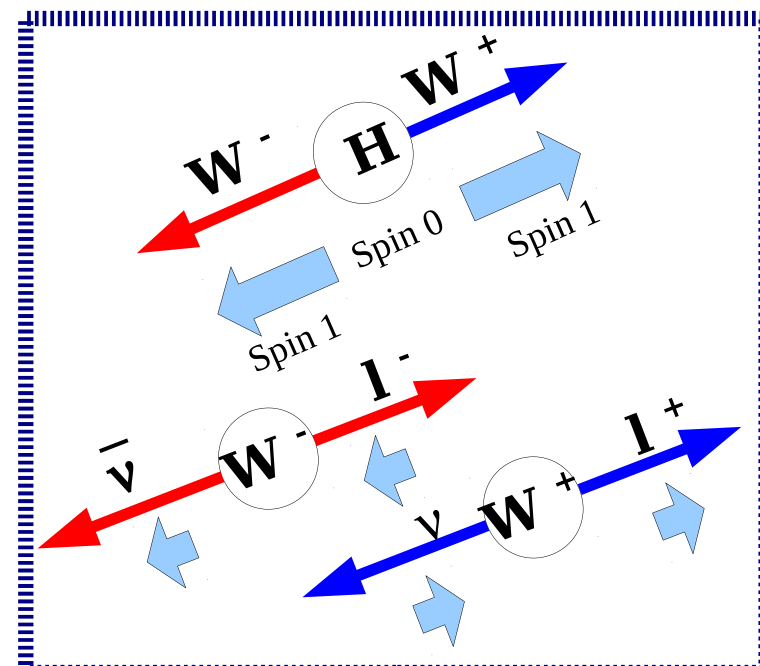
  - Δϕ (ll,MET) = angle between di-lepton system and MET
  - p_T^{ll} = momentum of di-lepton system



- 2D template fit based on $m_{ll}/m_T^{ll\ MET}$ as in Run 1
  - **0 jet** and **1 jet** to have different background contamination
  - eμ and μe p_T ordered leptons, to exploit different fake rate for electrons and muons







Tackling backgrounds

- **Lepton selections:**
  - 2 opposite charge leptons ($|\eta|<2.5$ for e, $|\eta|<2.4$ for μ) with optimized lepton isolation and identification criteria
  - $p_T^{\text{leading lepton}} > 20$ GeV and $p_T^{\text{2nd lepton}} > 10$ (13) GeV for μ(e)
  - WW selections
    - Low mass resonances: $m_{ll} > 12$ GeV
    - Kinematic cut: $p_T^{ll} > 30$ GeV
    - Extra lepton veto: 2 leptons only with $p_T > 10$ GeV

- E_t^{miss} selection:
  - $E_t^{miss} > 20$ GeV

- $m_T^{ll\ MET} > 60$ GeV

- **Jet selections:**
  - B-veto:
    - b jets identified looking at tracks associated to the jet exploiting lifetime of B mesons and soft muons coming from leptonic b decays (combined MVA)

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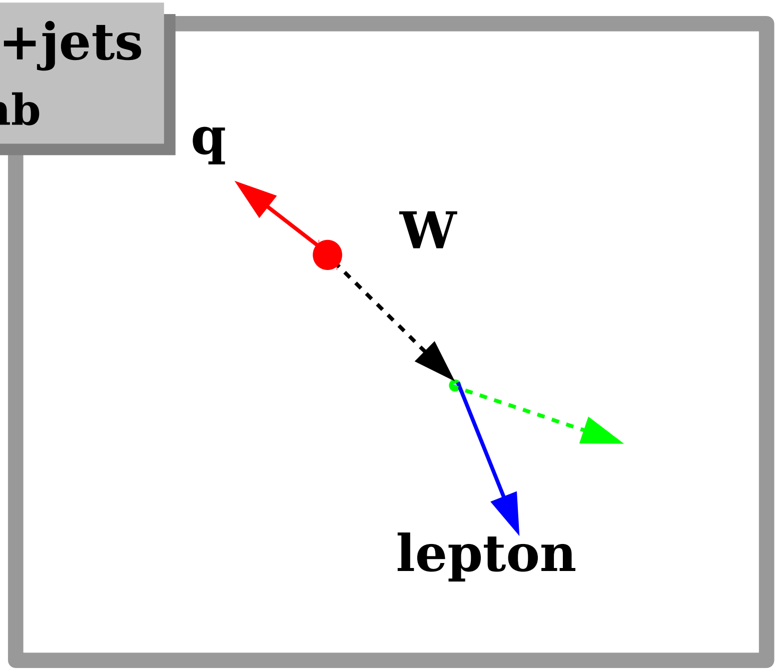
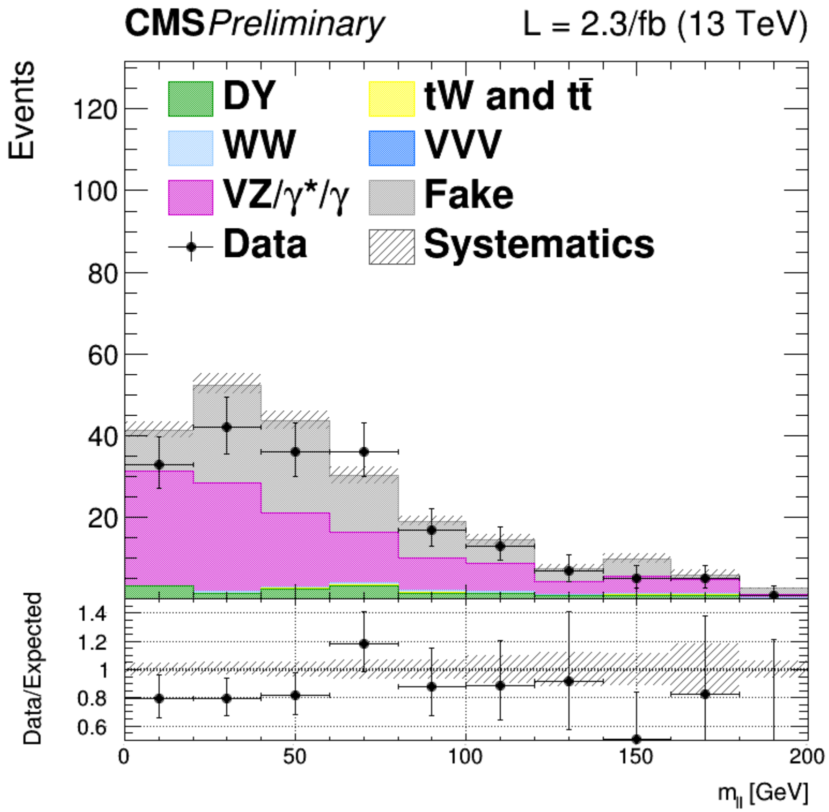
W → lν +jets
~61 nb



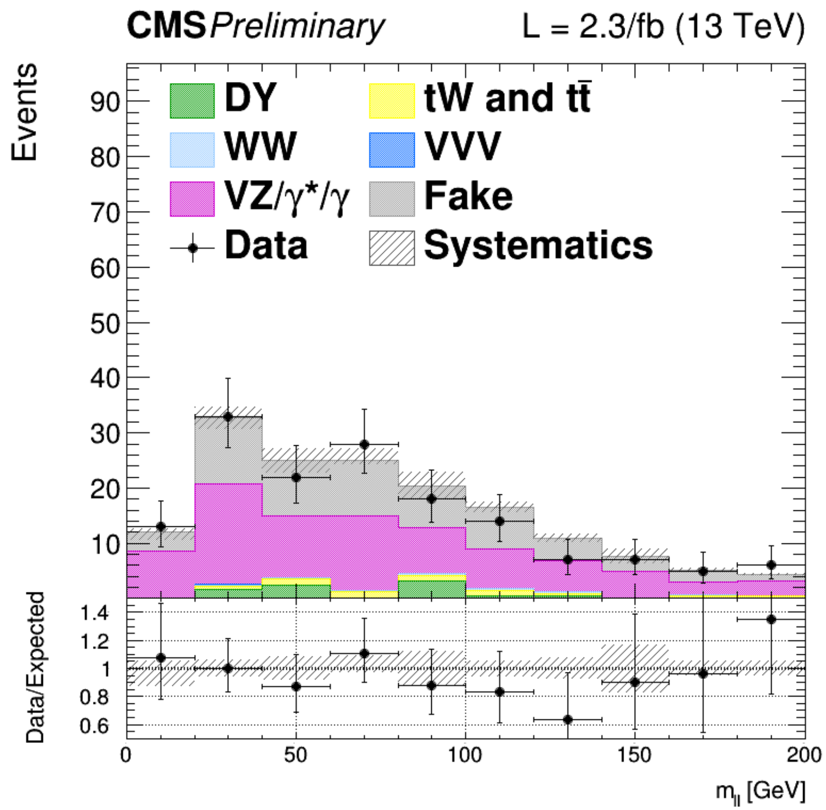
- Data driven estimation based on **fake-rate** method: probability for a jet to be reconstructed as a lepton

- **Control region** in **same-sign** 2-leptons phase space:

0 jet



1 jet



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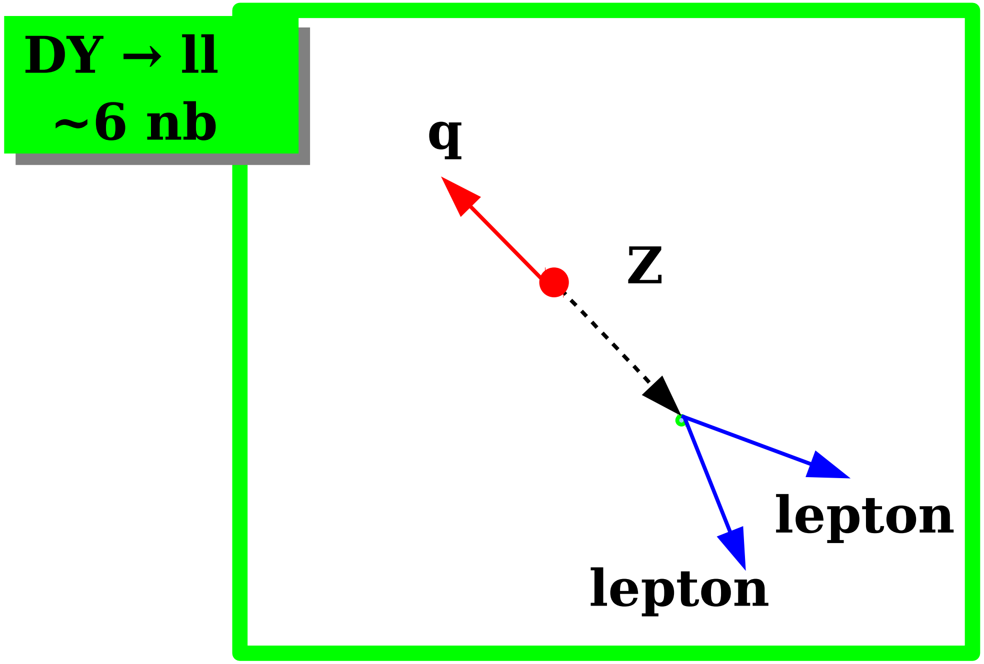
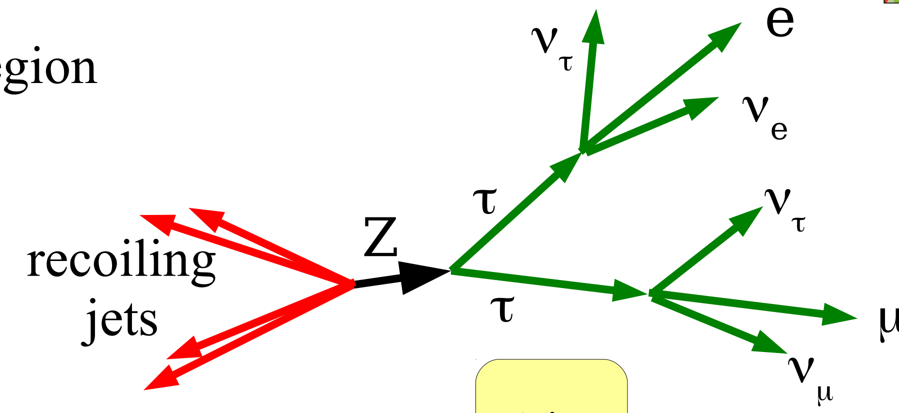
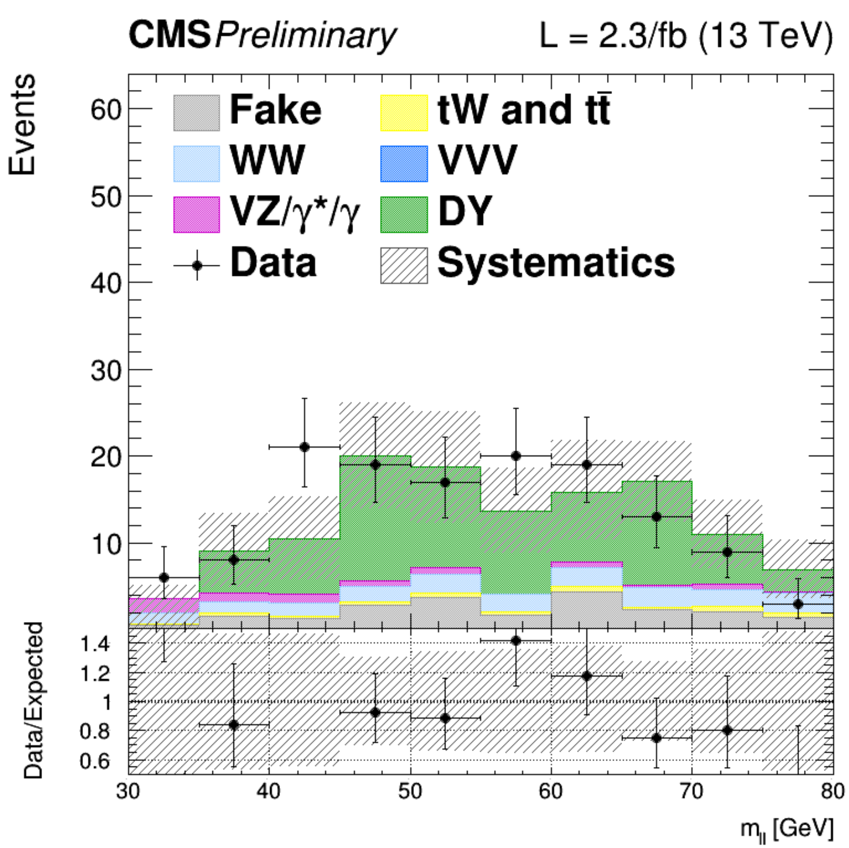


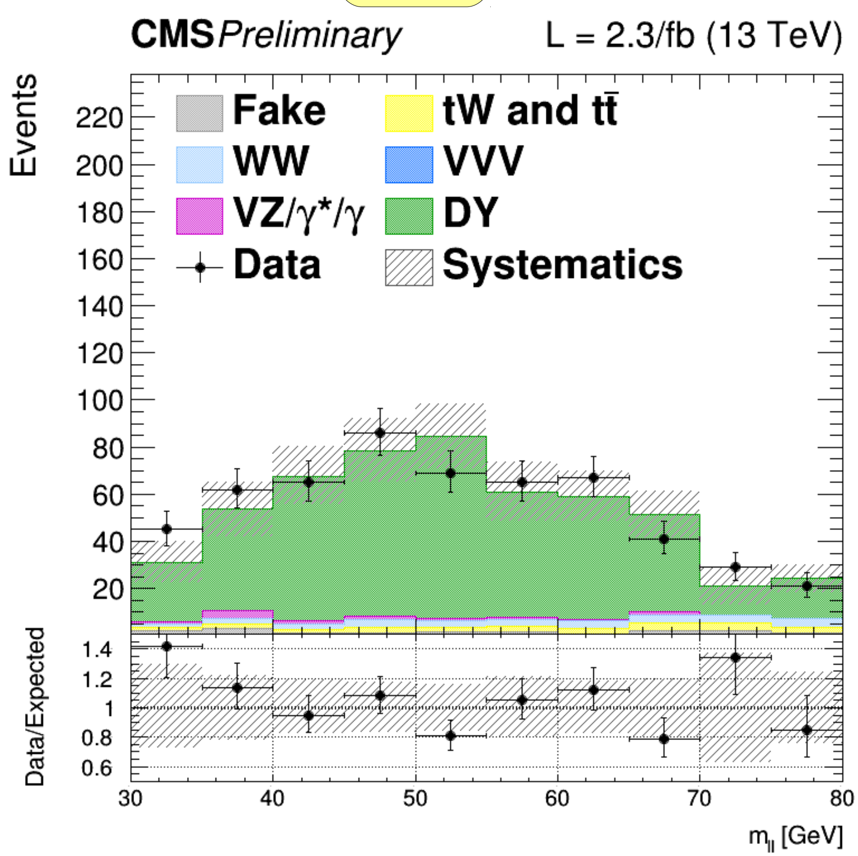
- MC based with **normalization** from control region
- low $m_T^{ll\,MET}$ region
  - $\mathbf{m_T^{ll\,MET} < 60}$ **GeV**



0 jet



1 jet



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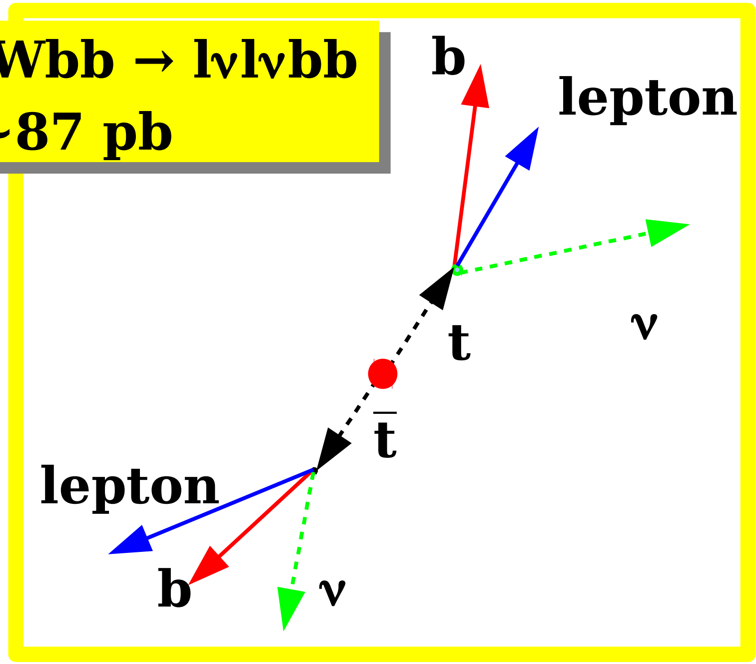
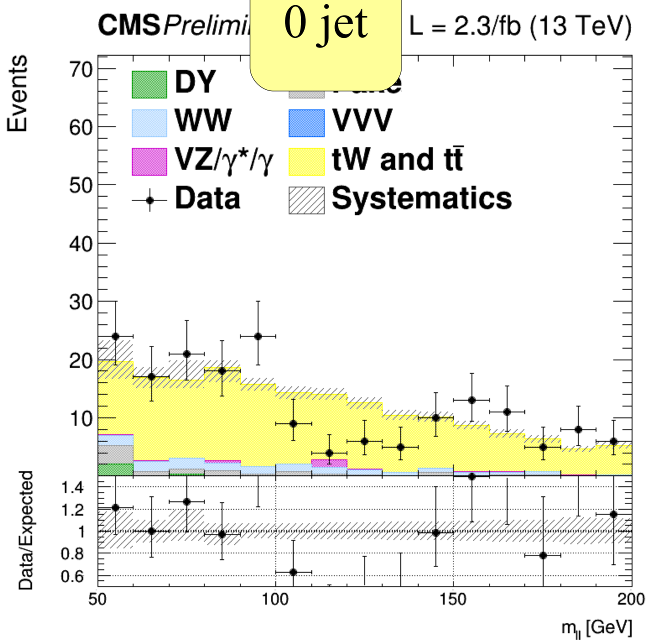
$t\bar{t} \rightarrow WWbb \rightarrow l\nu l\nu bb$
~87 pb



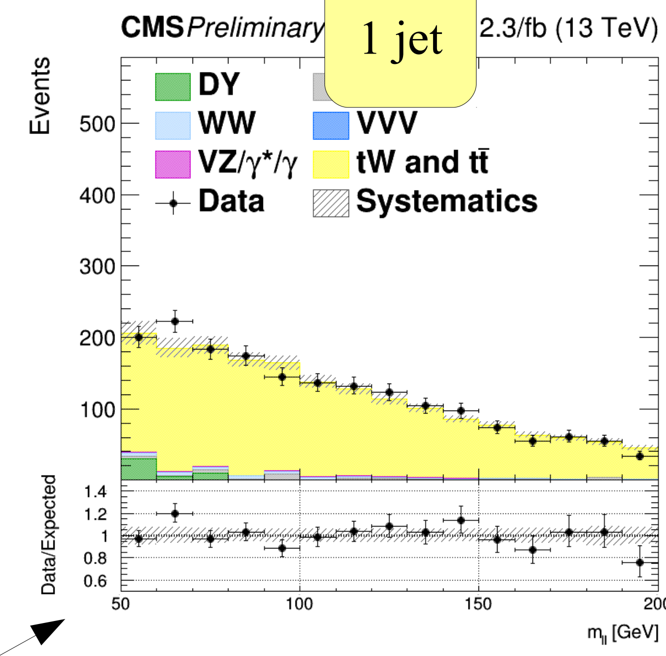
Details on b-tag in M. Verzetti's talk
on Saturday morning
http://indico.cern.ch/event/432527/contributions/1072114/

Top

0 jet



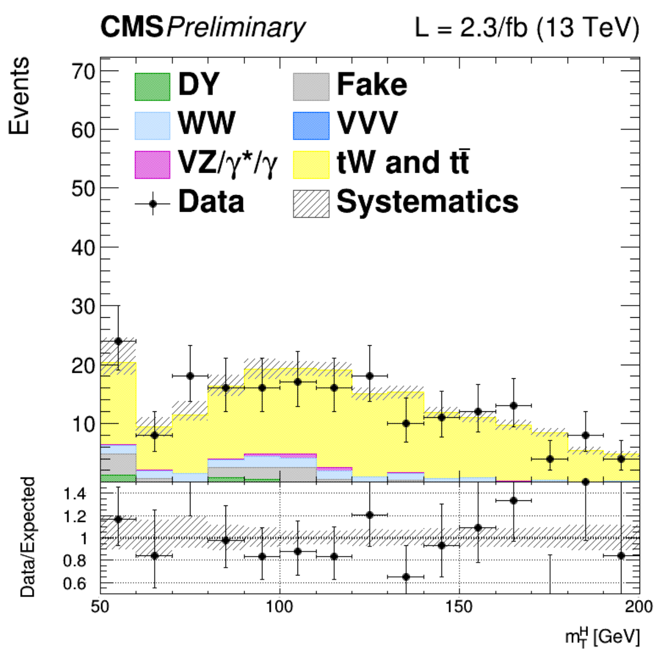
1 jet

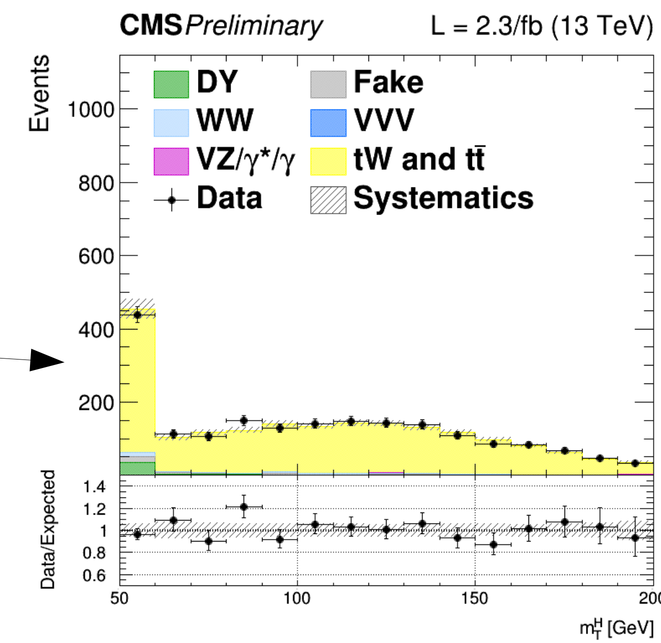


- Requiring at least a jet identified as a **b-induced jet**
  - 0 jet p_T > 30 GeV
  - 1 jet p_T > 30 GeV
- Top shape from MC and **normalization** from data, measured separately in 0/1 jet category

m_{ll}

$m_T^{ll\ MET}$



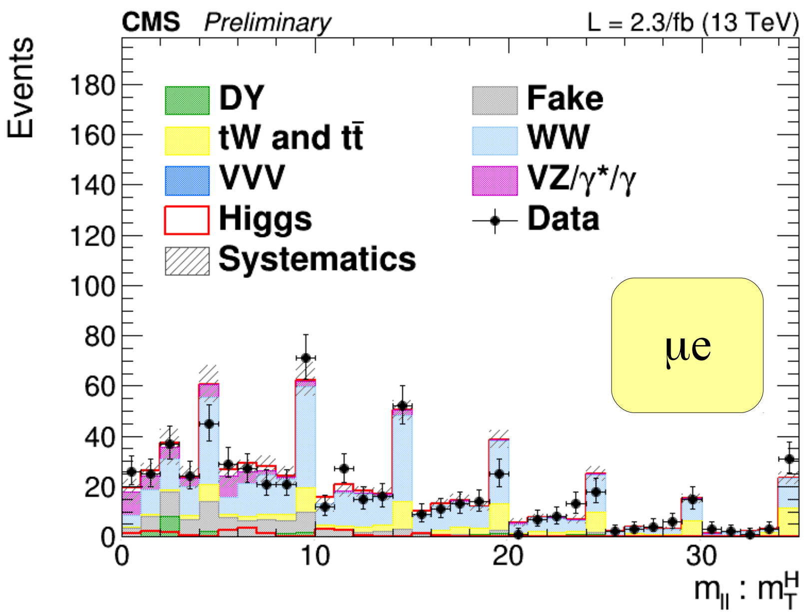


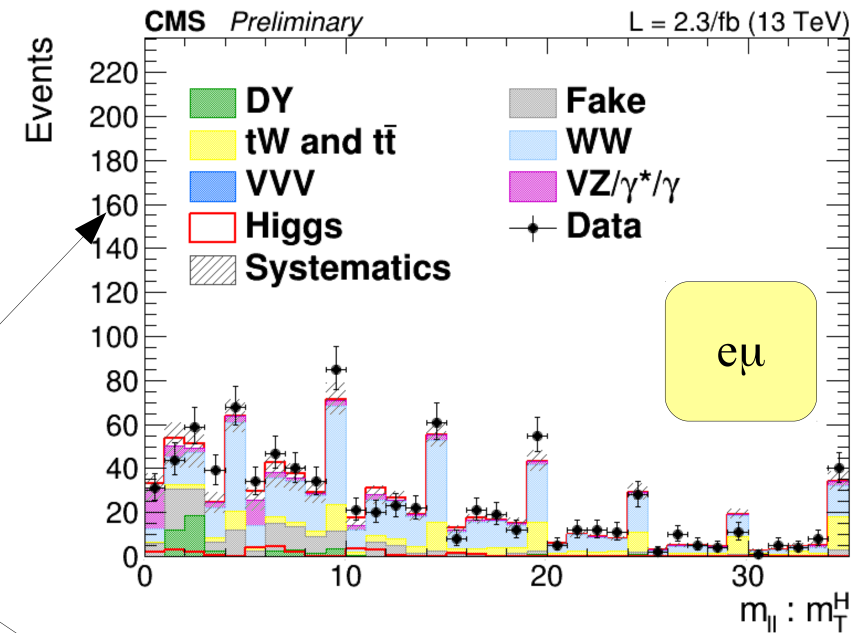
HWW @ 13 TeV results

CMS HIG-15-003

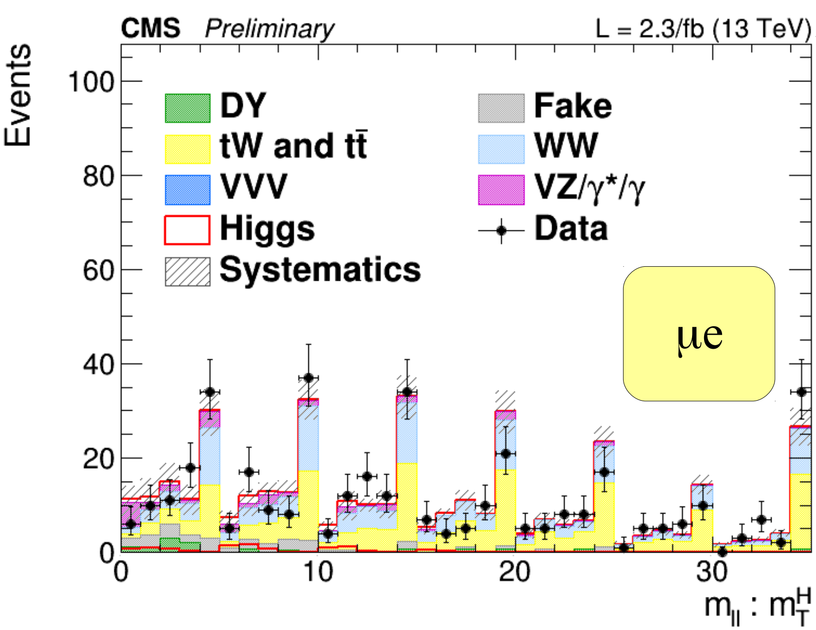
- 2D un-rolled distribution based on $m_{ll}/m_T^{ll\,MET}$: trains of m_{ll} in $m_T^{ll\,MET}$ windows

0 jet

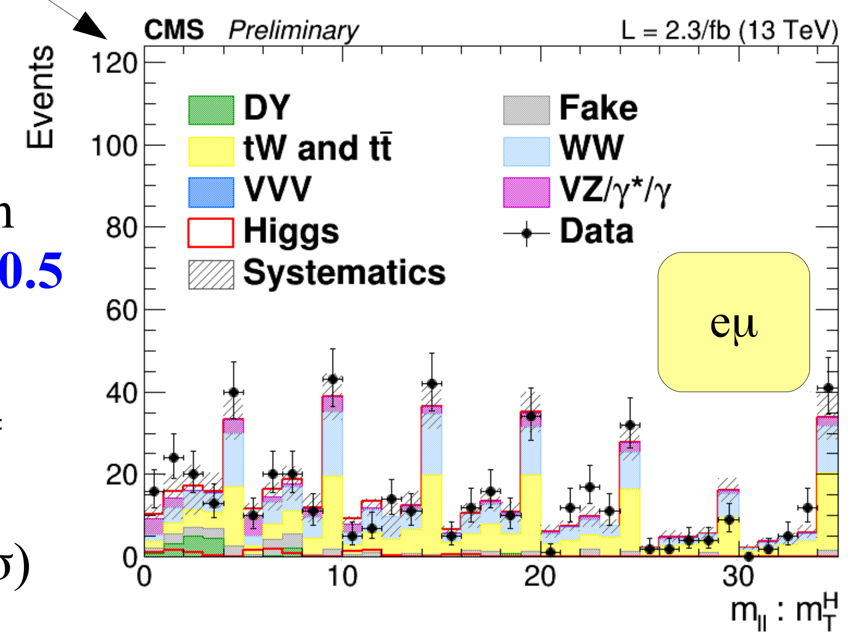




1 jet



- Signal strength σ/σ_{SM} = **0.3 ± 0.5**
- Significance = **0.7σ** (expected 2.0σ)



Recent results @ 7/8 TeV

- Characterization of the new boson
  - Spin tests
  - Anomalous couplings

- Recent results:
  - Higgs width measurement
  - Differential measurement p_T^H

Higgs width

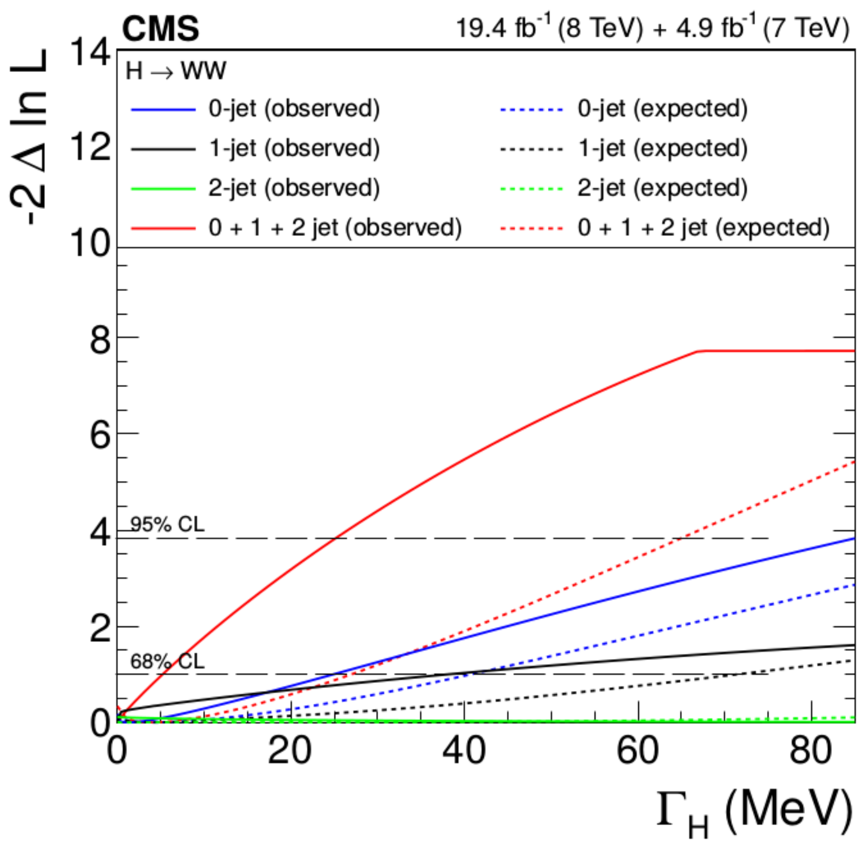
CMS HIG-14-032

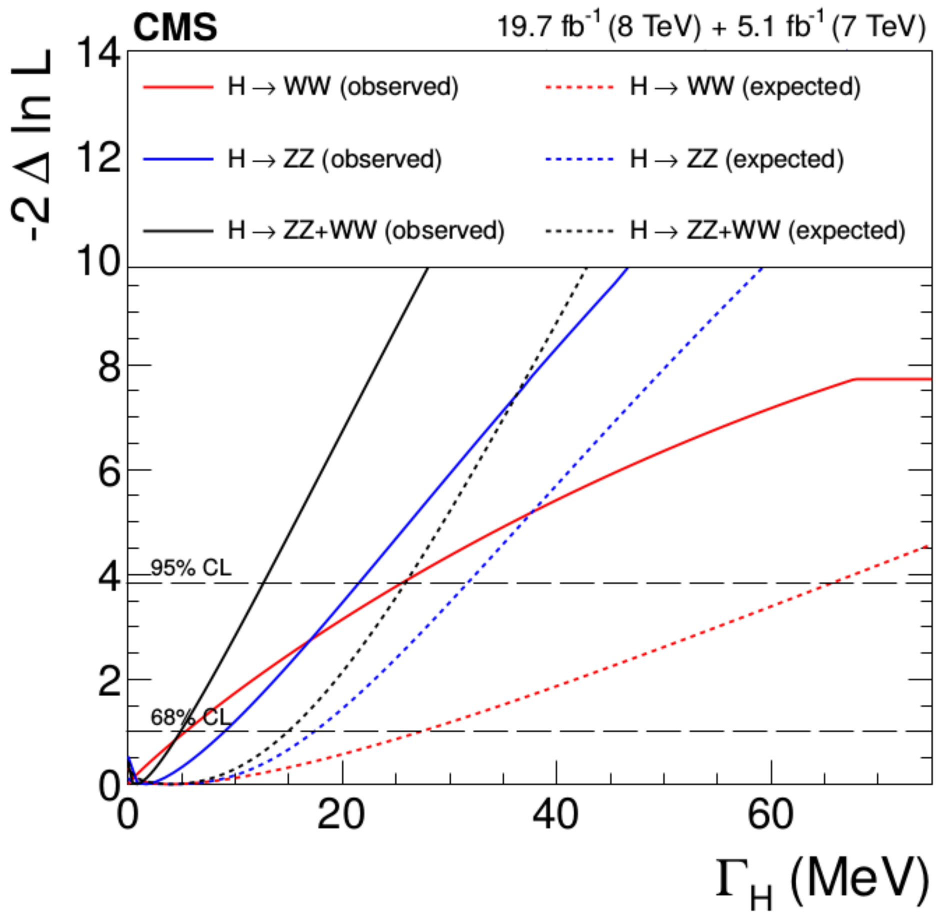
- Measurement of Higgs boson width by looking at the off-shell production
- Simultaneous measurement of on-shell and off-shell Higgs cross section

$$\frac{\sigma^{\mathrm{off-peak}}_{gg\to H\to VV}}{\sigma^{\mathrm{on-peak}}_{gg\to H\to VV}} = \Gamma_H$$

Details on coupling/width in U. Sarica's talk this afternoon
http://indico.cern.ch/event/432527/contributions/1071465/

- **WW** and **ZZ** final state: $\mathbf{\Gamma_H < 13}$ **MeV**

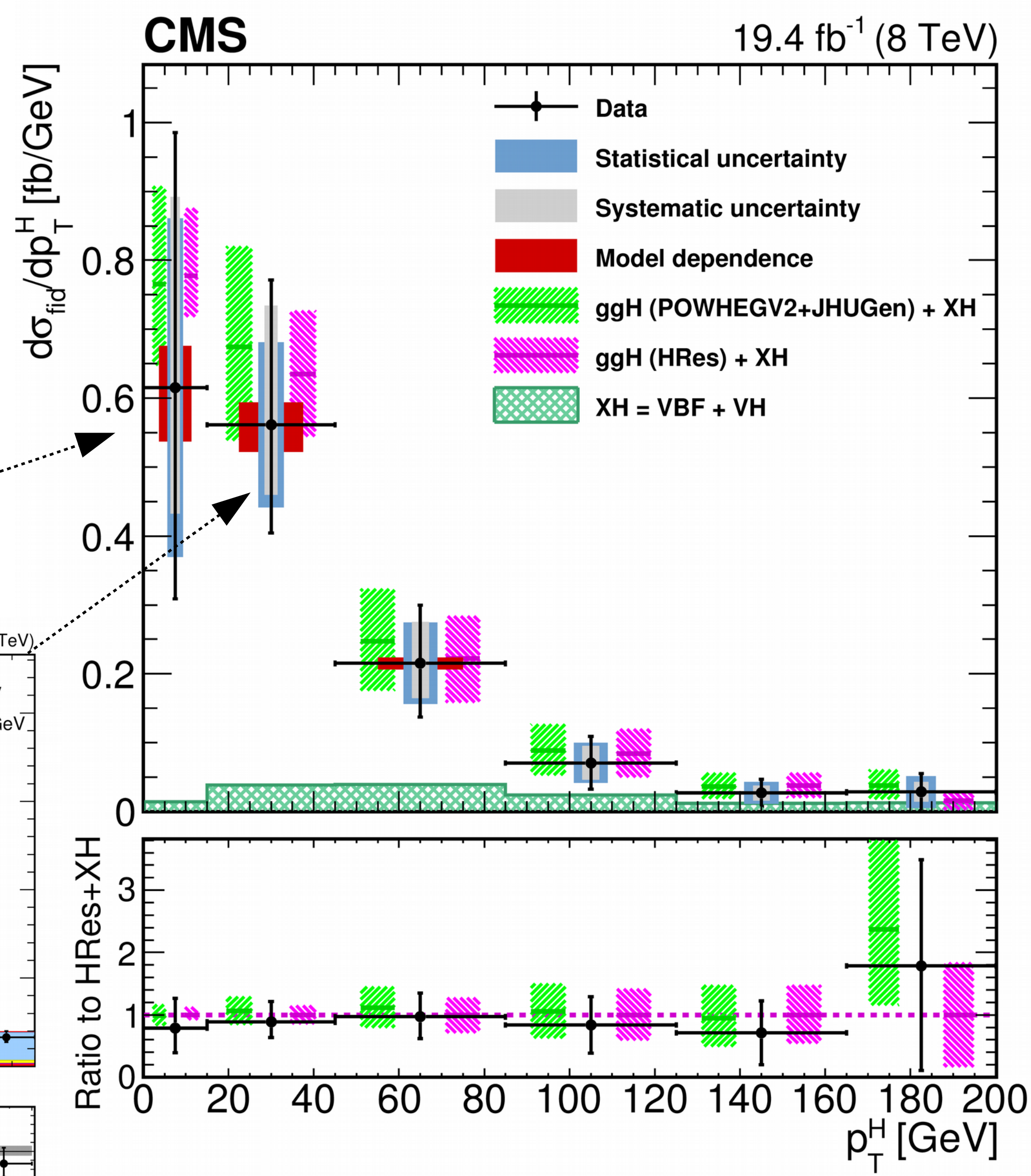


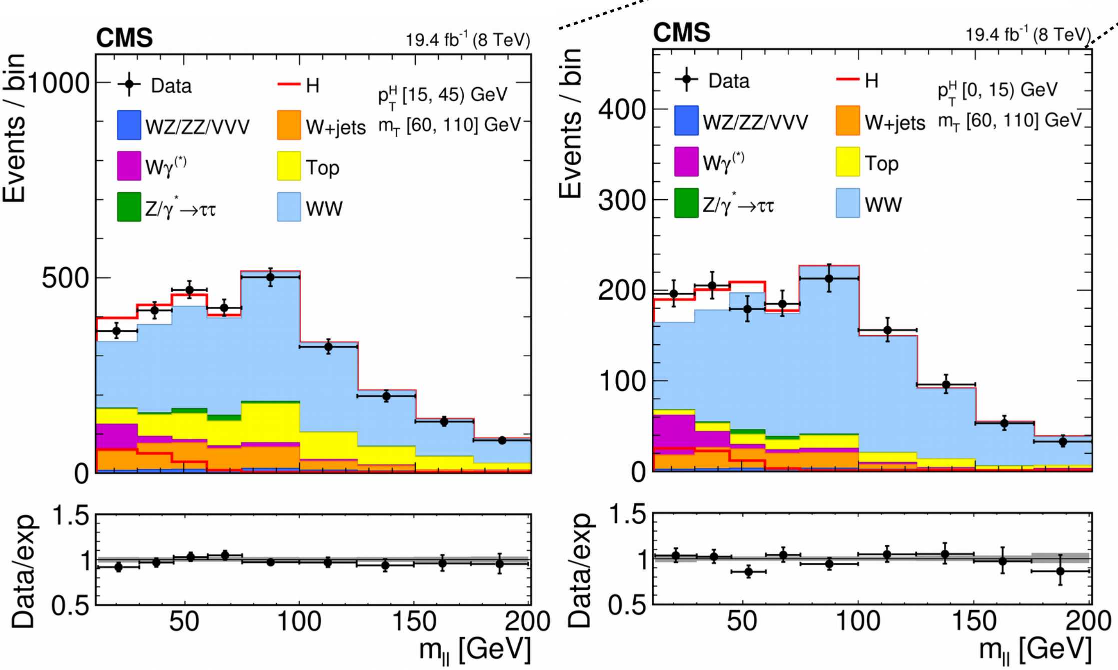


Higgs transverse momentum p_T H

CMS HIG-15-010

- Differential measurement of Higgs transverse momentum
  - With MET resolution, but still p_T^H good observable
- Result unfolded at generation level in fiducial phase space
- Inputs: measure the Higgs cross section in windows of $p_T^{ll\,MET}$





Results

- **7/8 TeV** **H → WW** characterization
  - Cross section
  - Different production modes targeted
  - Anomalous couplings
  - Higgs width indirect measurement
  - Differential measurement of Higgs transverse momentum
  - Some measurement still statistically dominated

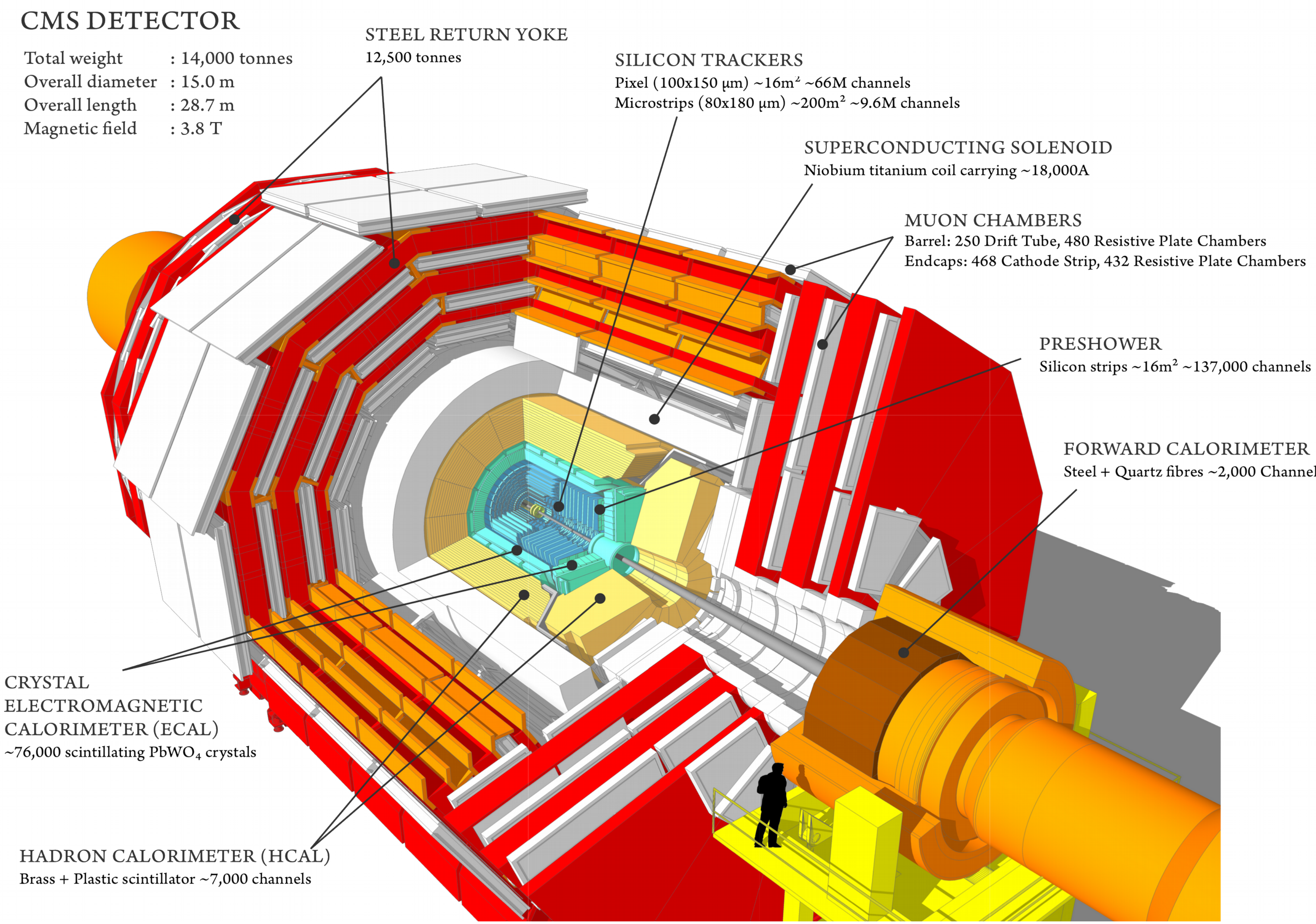
- **13 TeV** search mode
  - Signal strength σ/σ_{SM} = **0.3 ± 0.5**
  - More data → characterization at 13 TeV

- Stay tuned for new results based on more data at 13 TeV backup

References

- http://cms-results.web.cern.ch/cms-results/public-results/publications/HIG/index.html
- http://cms-results.web.cern.ch/cms-results/public-results/publications/

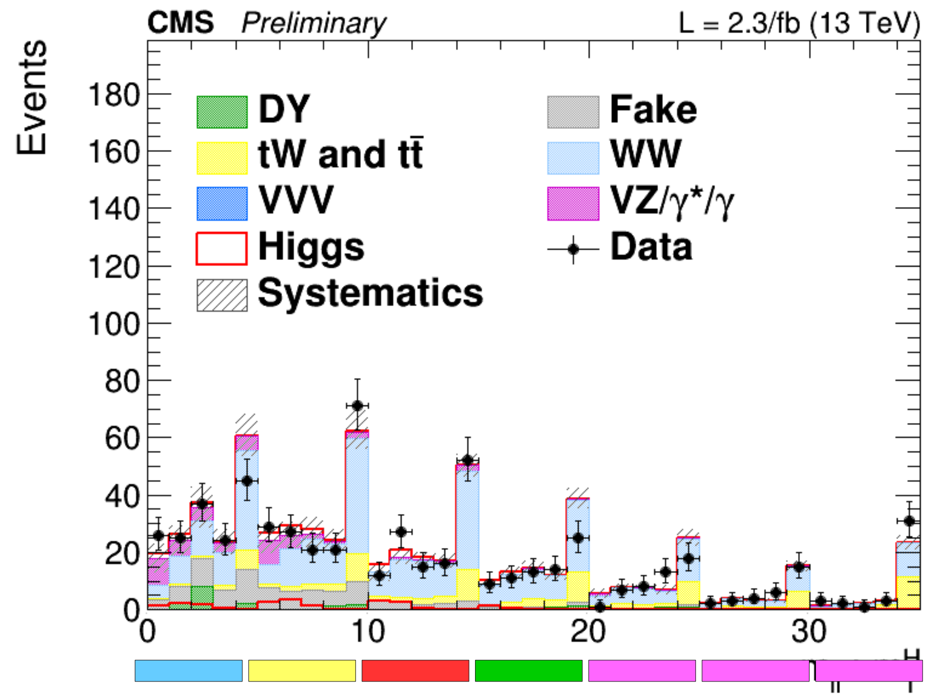
CMS

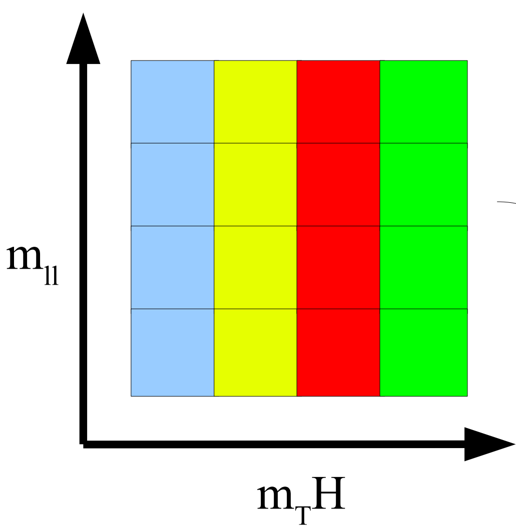


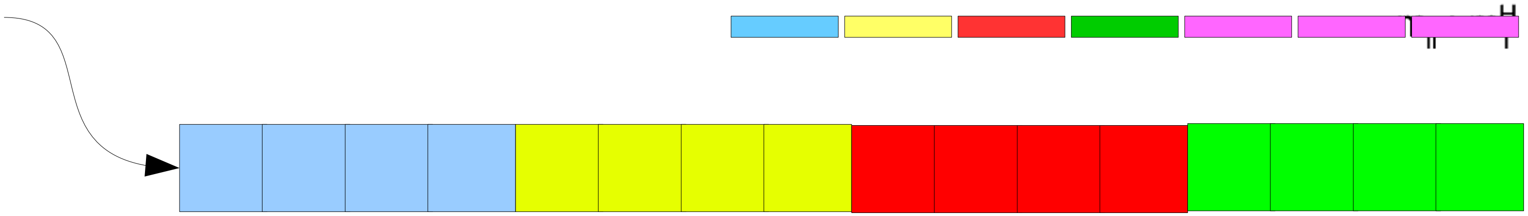
CMS DETECTOR
Total weight : 14,000 tonnes
Overall diameter : 15.0 m
Overall length : 28.7 m
Magnetic field : 3.8 T
STEEL RETURN YOKE
12,500 tonnes
SILICON TRACKERS
Pixel (100x150 μm) ~16m² ~66M channels
Microstrips (80x180 μm) ~200m² ~9.6M channels
SUPERCONDUCTING SOLENOID
Niobium titanium coil carrying ~18,000A
MUON CHAMBERS
Barrel: 250 Drift Tube, 480 Resistive Plate Chambers
Endcaps: 468 Cathode Strip, 432 Resistive Plate Chambers
PRESHOWER
Silicon strips ~16m² ~137,000 channels
FORWARD CALORIMETER
Steel + Quartz fibres ~2,000 Channels
CRYSTAL ELECTROMAGNETIC CALORIMETER (ECAL)
~76,000 scintillating PbWO4 crystals
HADRON CALORIMETER (HCAL)
Brass + Plastic scintillator ~7,000 channels

Final plot

- **2D shape analysis**
  - Di-lepton invariant mass: m_{ll}
  - Lepton + MET transverse mass: $$m_{\mathrm{T}}^{\ell\ell E_{\mathrm{T}}^{\mathrm{miss}}} = \sqrt{2 \cdot p_T^{\ell\ell} \cdot E_{\mathrm{T}}^{\mathrm{miss}} \left(1 - cos\Delta\phi_{\ell\ell, E_{\mathrm{T}}^{\mathrm{miss}}}\right)}$$
    - **7** bins in $m_T H$: 60 – 200 GeV [20 GeV width]
    - **5** bins in m_{ll}: 10-110 GeV [20 GeV width]
- **Unrolled 1D distribution**







The complete H→WW searches at 7/8 TeV

ggH 0 jet

ggH 1 jet

$H \rightarrow WW$ 2 jet

VBF
$H \rightarrow WW$ 2 jet

$VH \rightarrow WW$ 2 jet

WH $H \rightarrow WW$
3 leptons

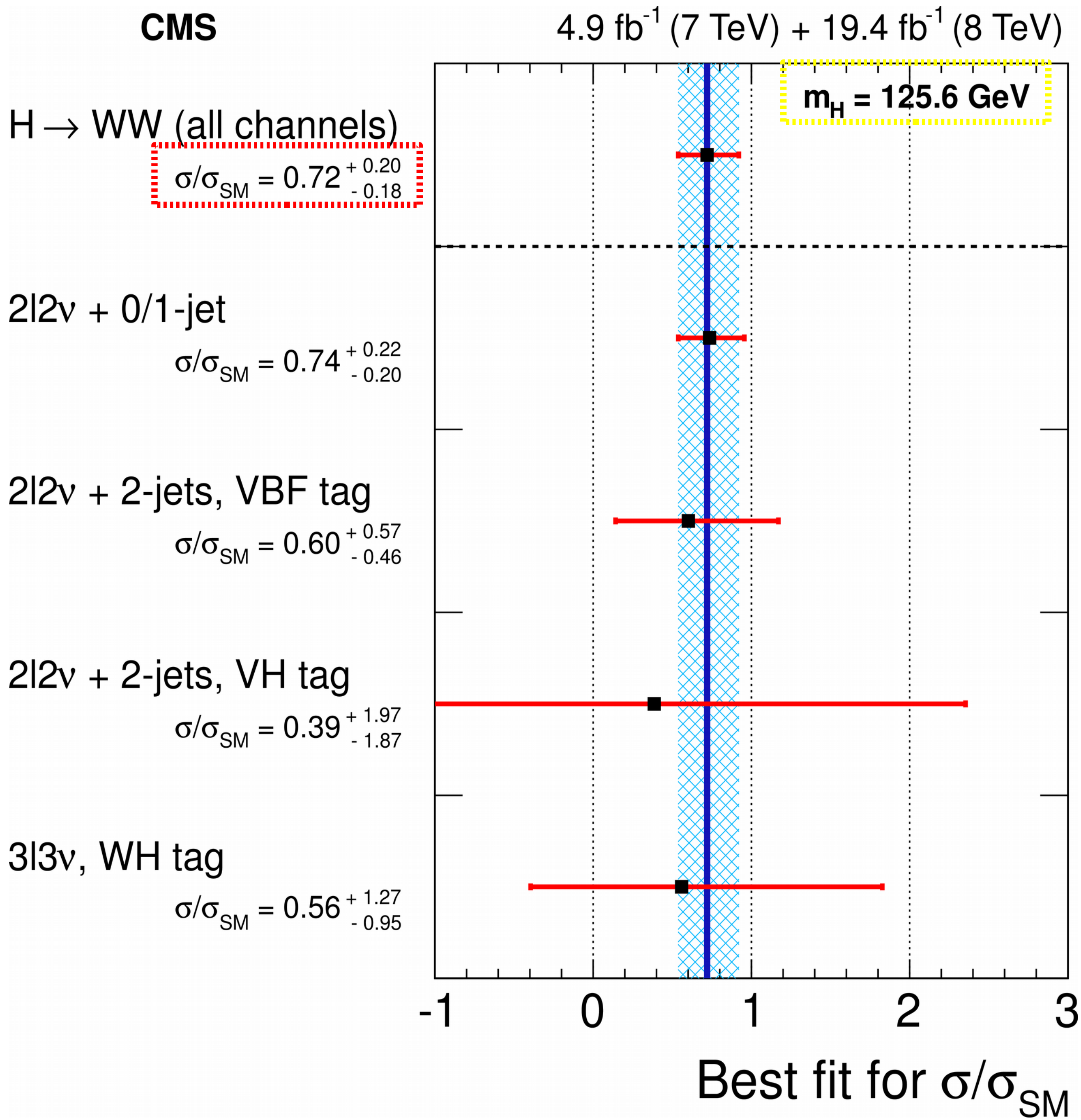
ZH $H \rightarrow WW \rightarrow l\nu jj$
3 leptons

ttH $H \rightarrow WW$
2 same-sign, 3 leptons, 4 leptons

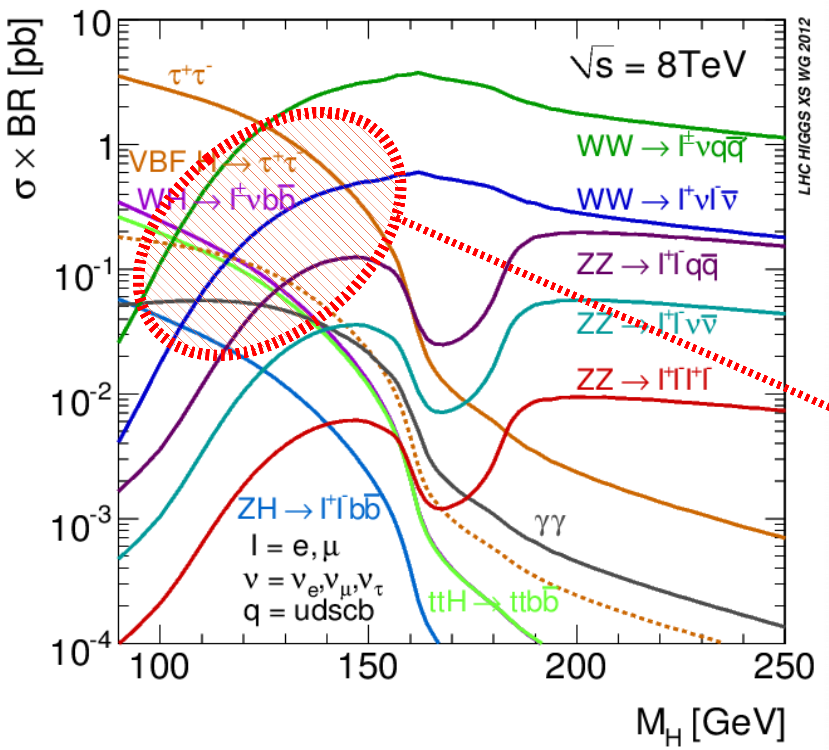
How significant is the excess at 7/8 TeV?

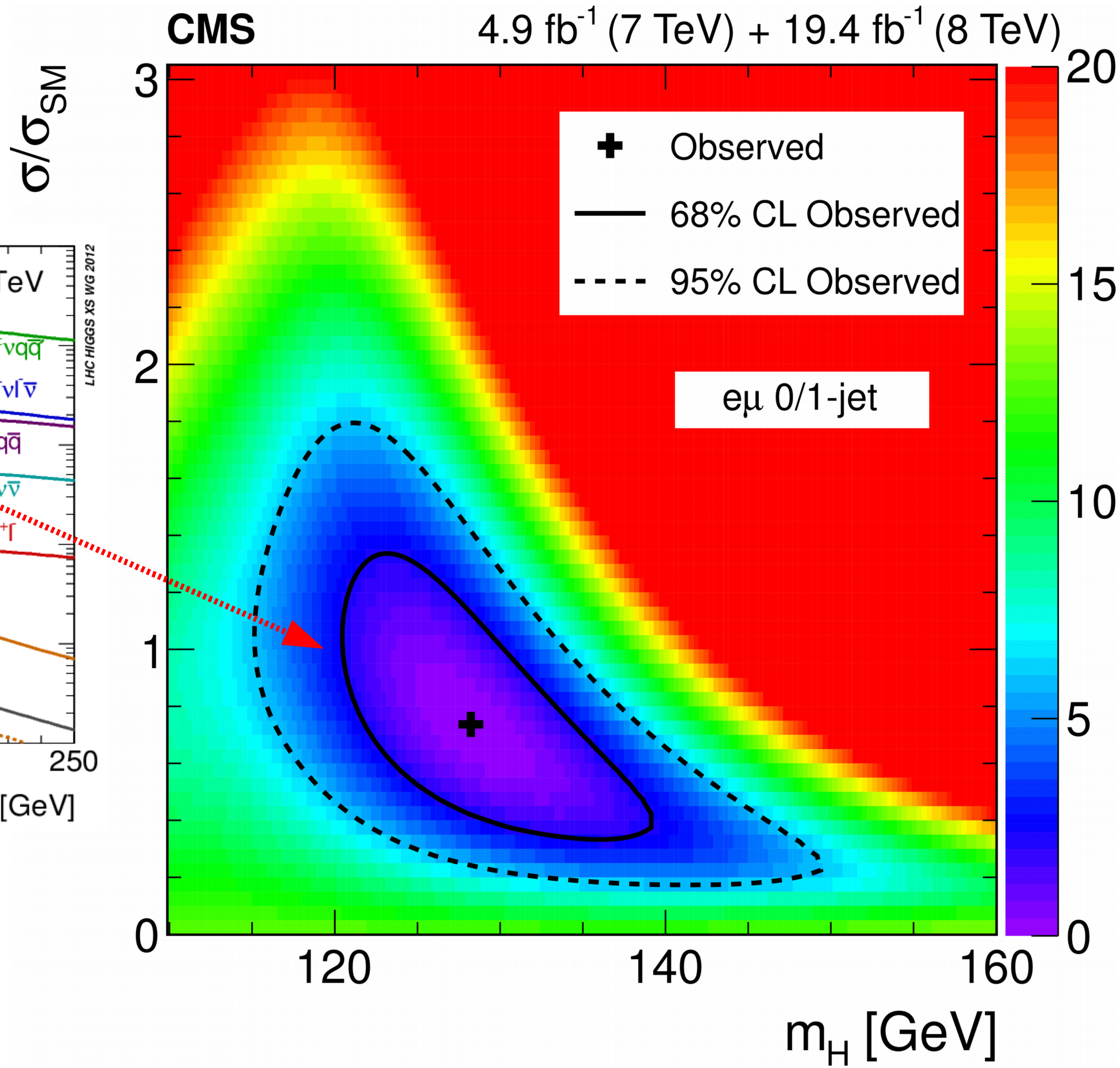
	Significance Obs	Significance Exp	σ/σ_{SM}
combination	4.3σ	5.8σ	$0.72^{+0.20}_{-0.18}$
eμ alone 0/1 jet	4.0σ	5.2σ	0.76 ± 0.21

Hunting different production mechanisms

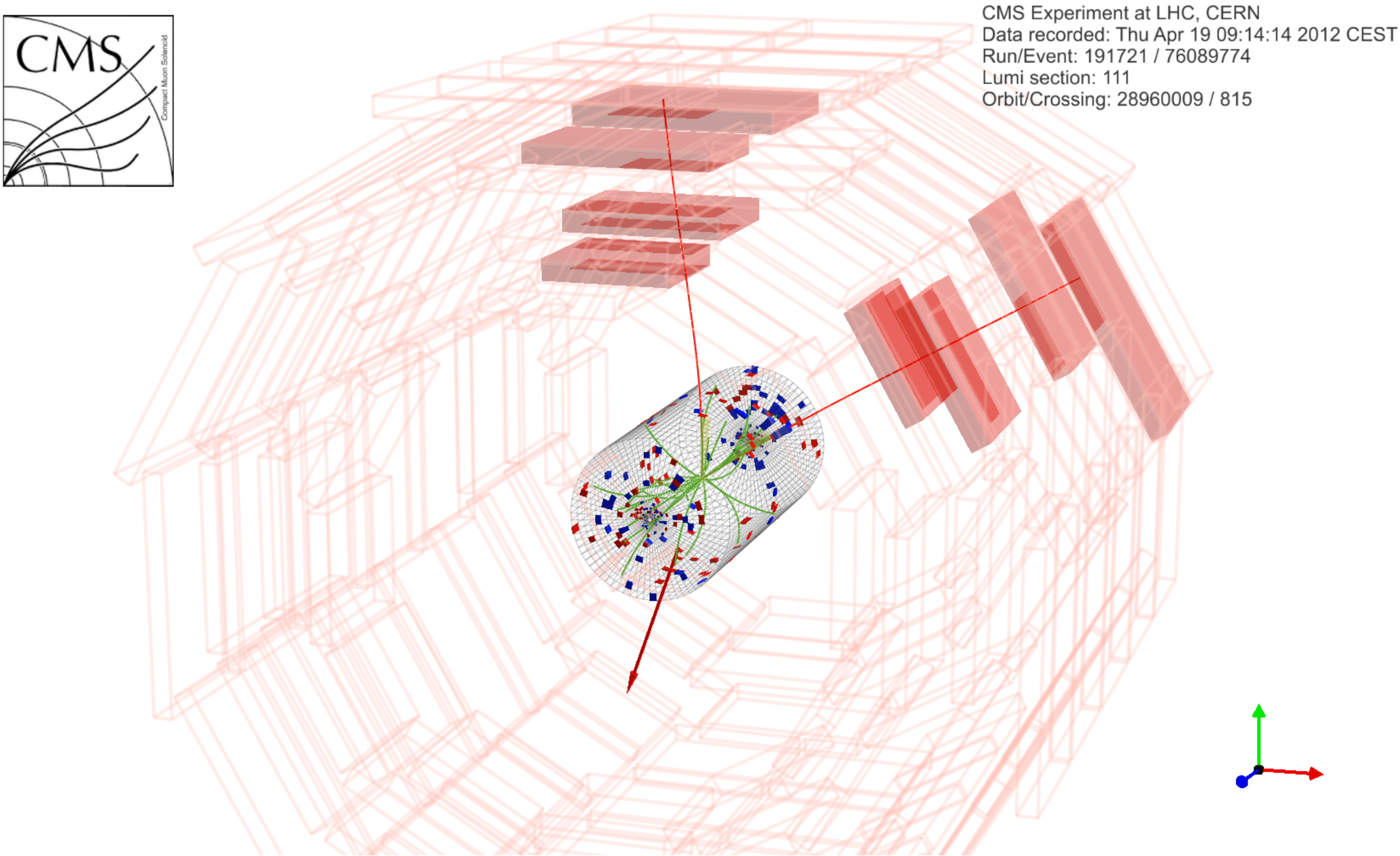


Signal strength vs Higgs mass

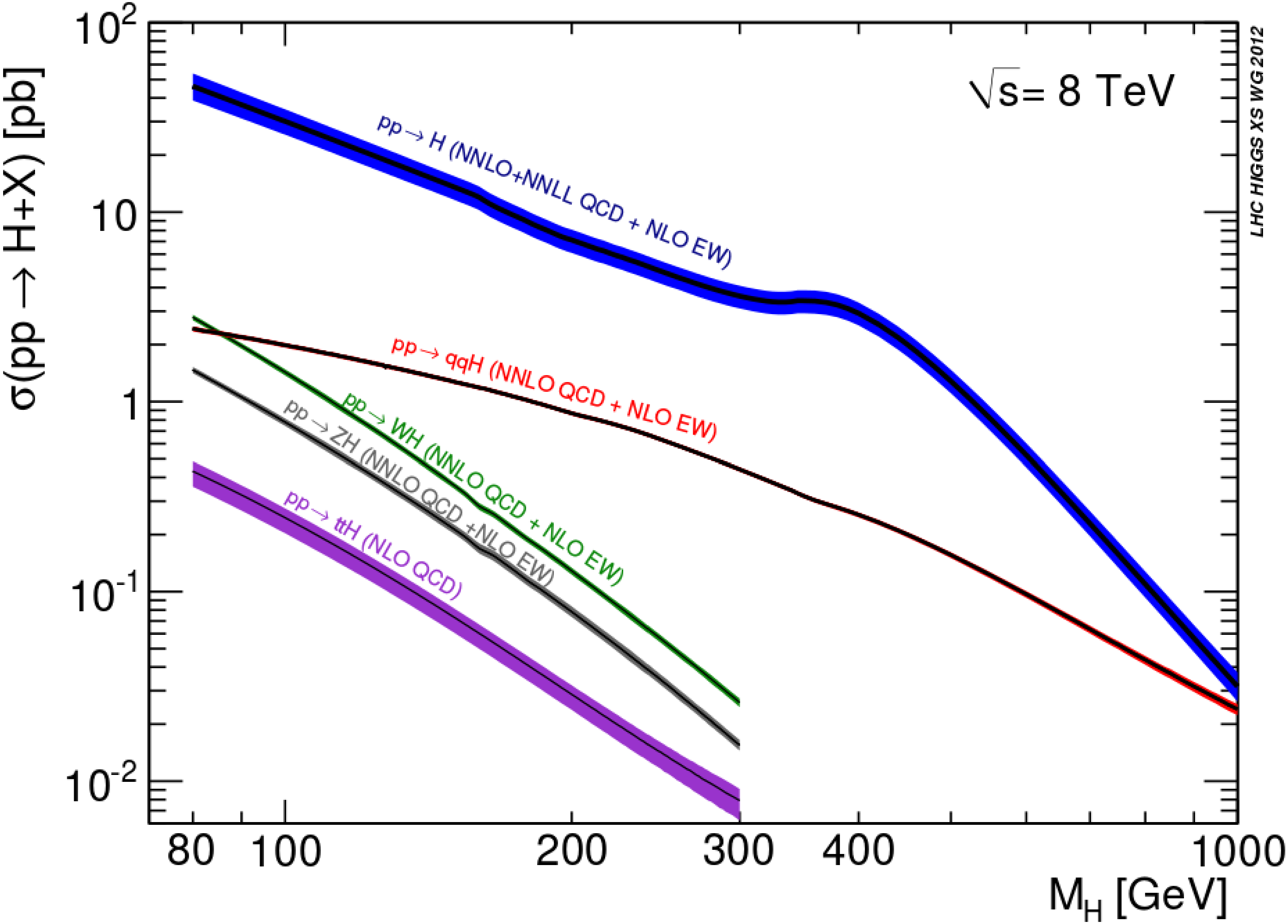




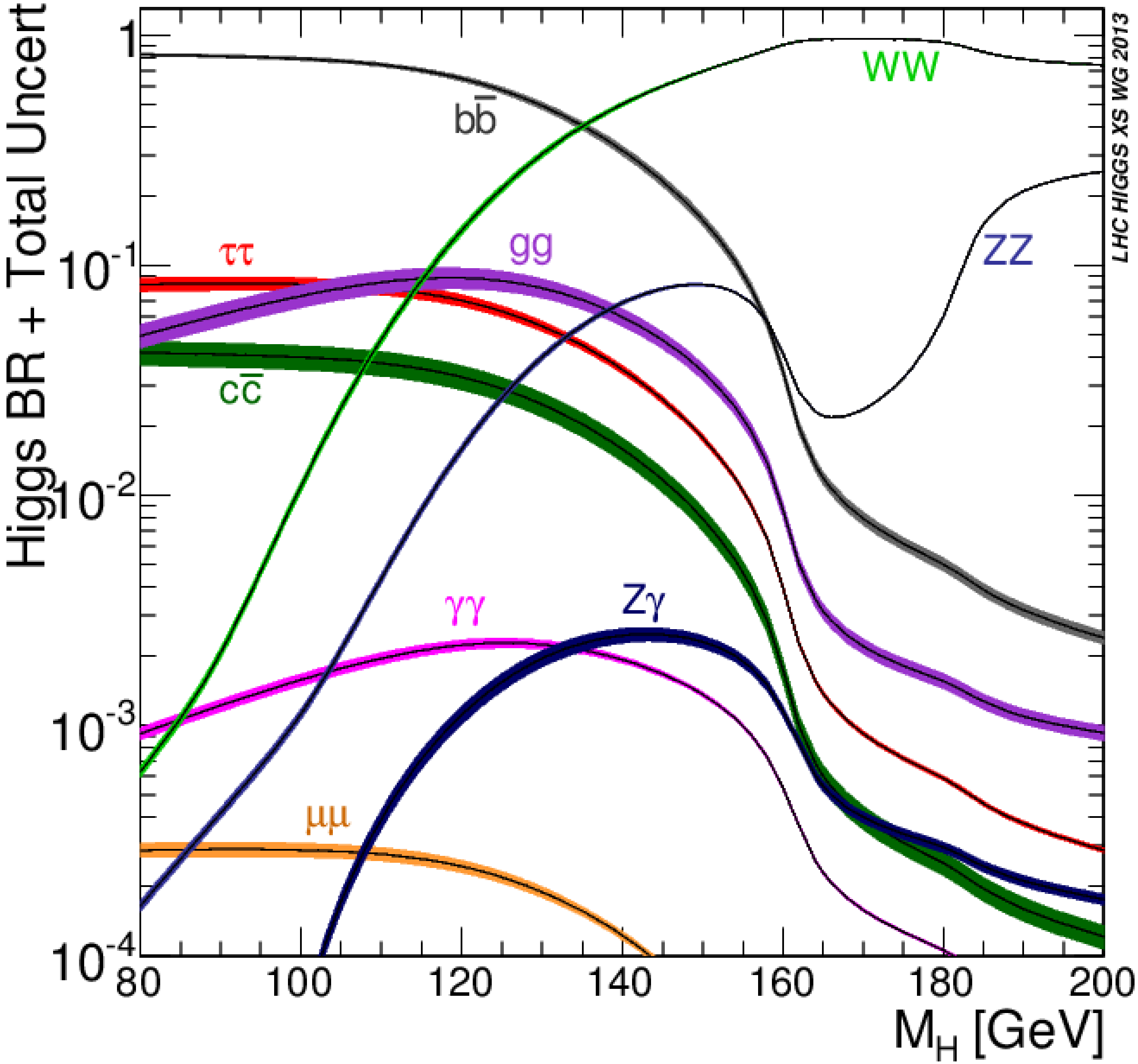
Candidate H → WW → μμνν



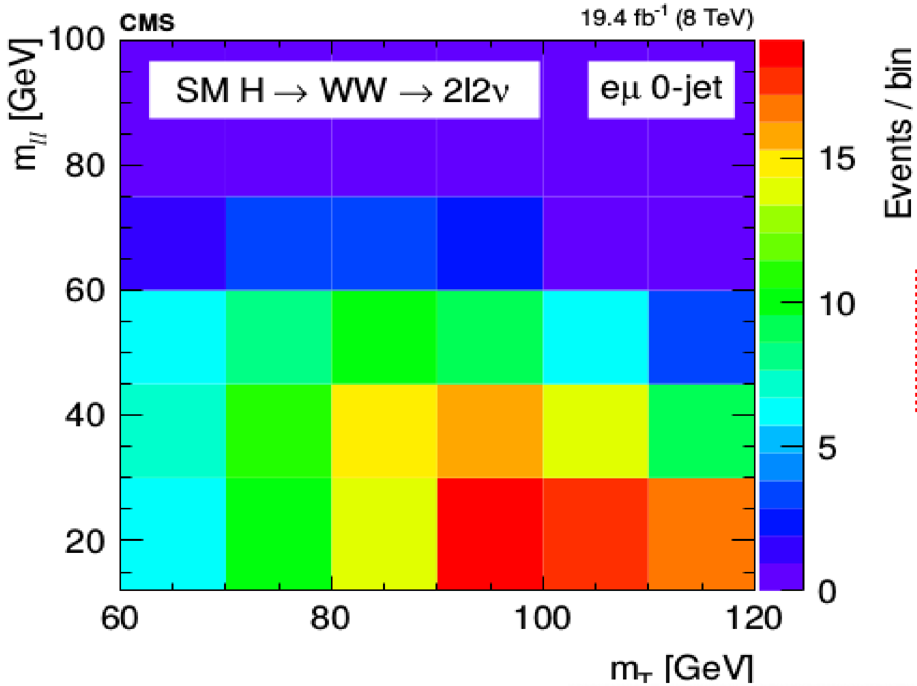
Cross section



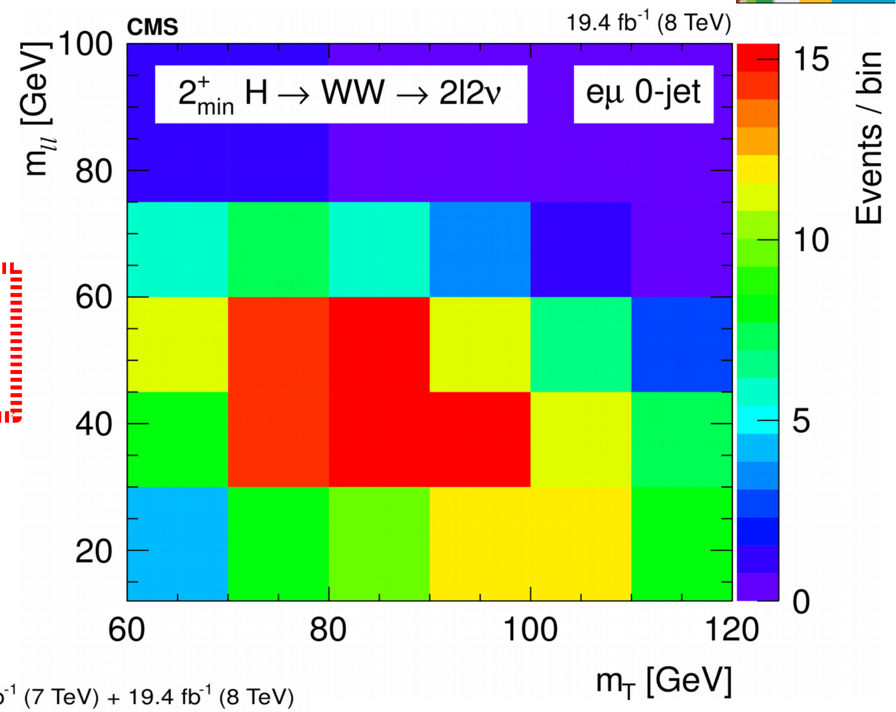
Branching ratio

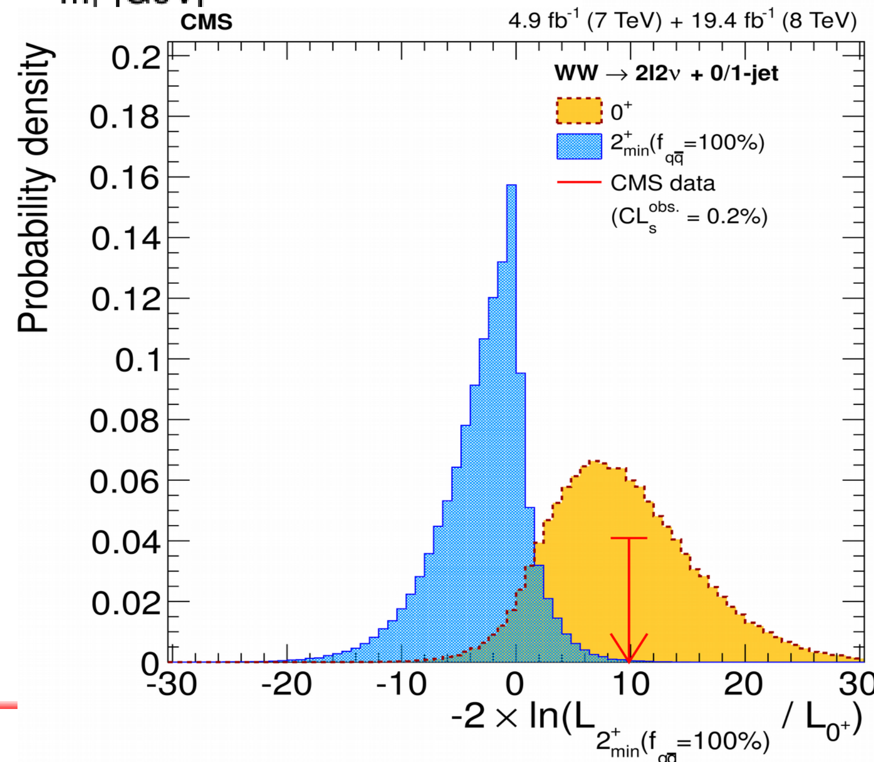


Spin testing

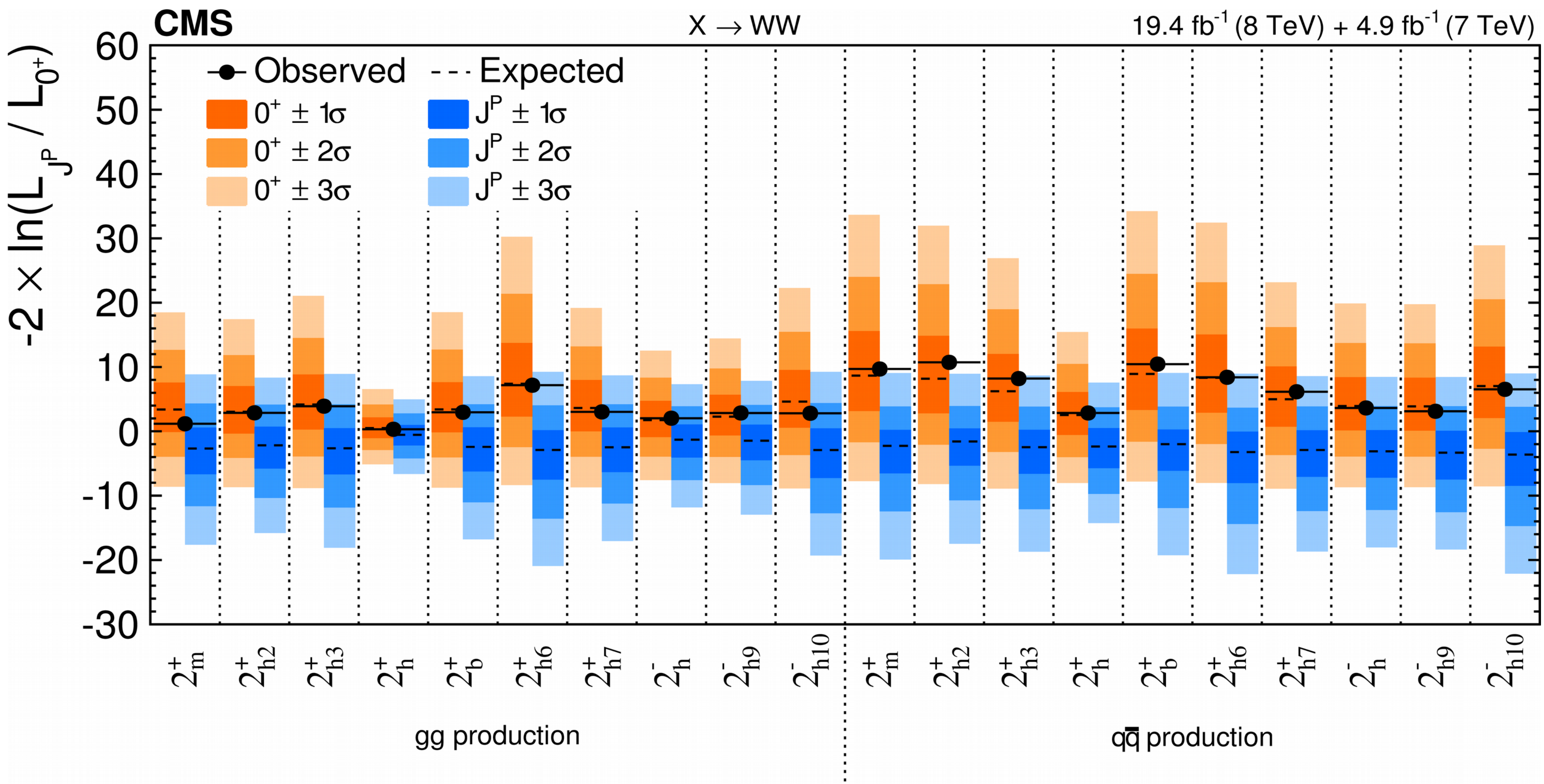


VS





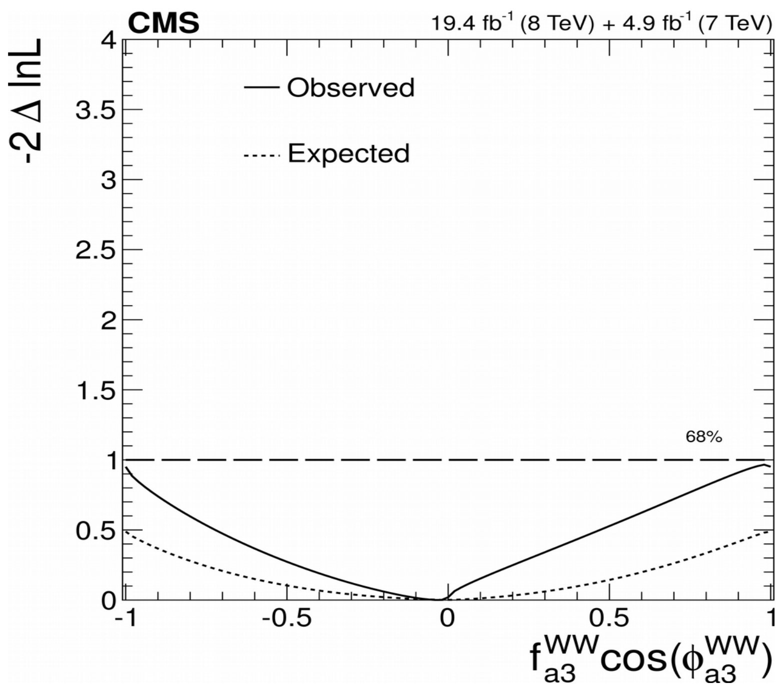
Spin testing

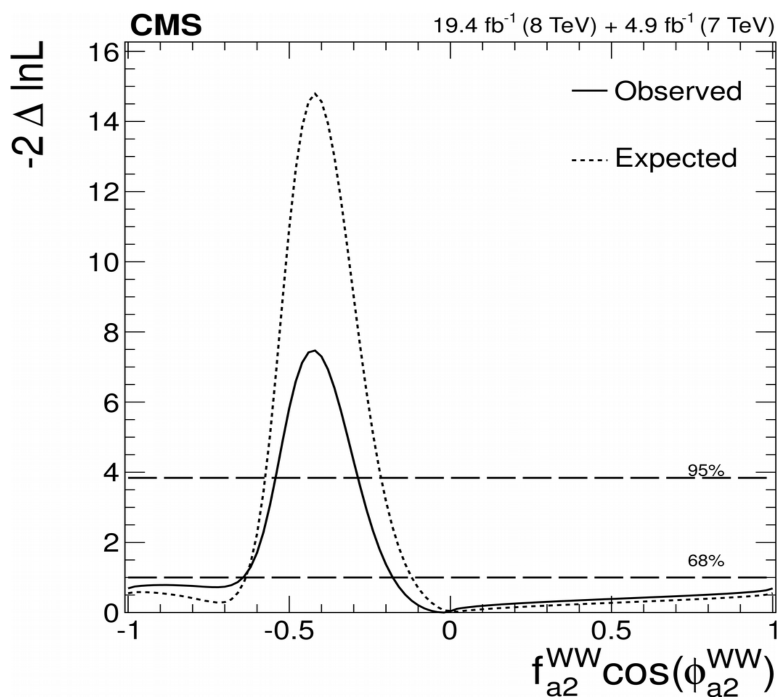


Anomalous couplings

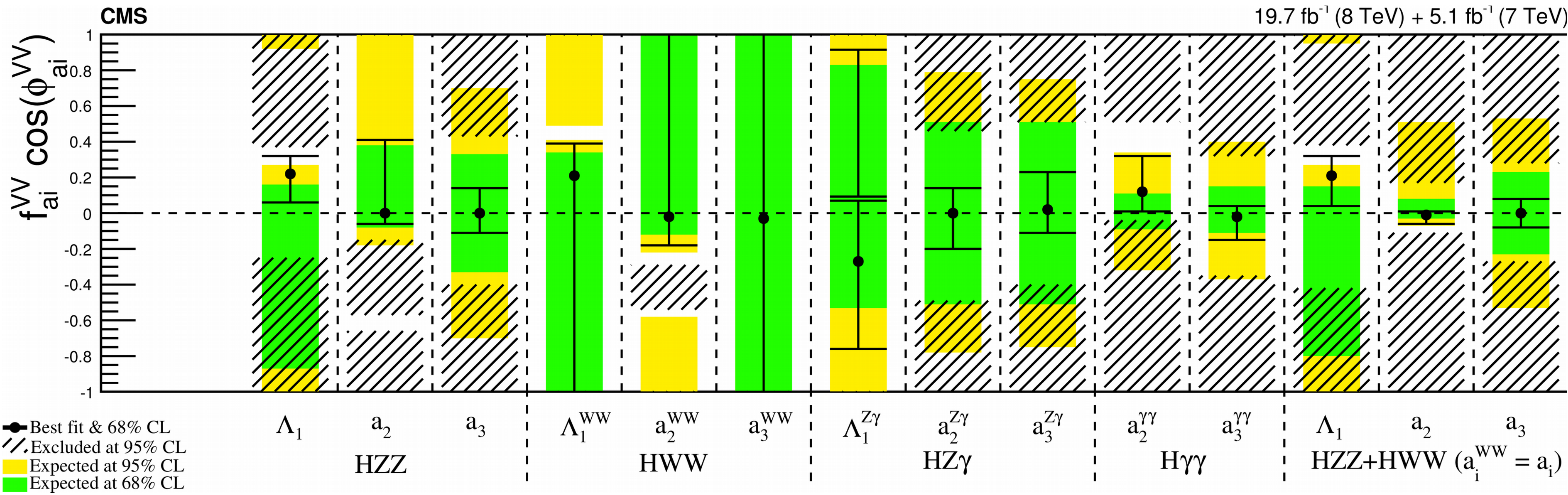
$$A(\mathrm{HV_1V_2}) \sim \left[a_1^{\mathrm{V_1V_2}} + \underbrace{\frac{\kappa_1^{\mathrm{V_1V_2}} q_{\mathrm{V1}}^2 + \kappa_2^{\mathrm{V_1V_2}} q_{\mathrm{V2}}^2}{\left(\Lambda_1^{\mathrm{V_1V_2}}\right)^2}}_{\text{Λ_1 term, leading momentum expansion}} \right] m_{\mathrm{V}}^2 \epsilon_{\mathrm{V1}}^* \epsilon_{\mathrm{V2}}^* + \underbrace{a_2^{\mathrm{V_1V_2}} f_{\mu\nu}^{*(\mathrm{V_1})} f^{*(\mathrm{V_2}),\mu\nu}}_{\text{a_2 term, CP even state}} + \underbrace{a_3^{\mathrm{V_1V_2}} f_{\mu\nu}^{*(\mathrm{V_1})} \tilde{f}^{*(\mathrm{V_2}),\mu\nu}}_{\text{a_3 term, CP odd state}}$$

$$f_{a3} = \frac{|a_3|^2\sigma_3}{|a_1|^2\sigma_1 + |a_2|^2\sigma_2 + |a_3|^2\sigma_3 + \tilde{\sigma}_{\Lambda 1}/\left(\Lambda_1\right)^4 + \ldots}, \qquad \phi_{a3} = \arg\left(\frac{a_3}{a_1}\right)$$





Anomalous couplings



Couplings in k-framework

$$\frac{\sigma_{\mathrm{ggH}}}{\sigma_{\mathrm{ggH}}^{\mathrm{SM}}} = \begin{cases} \kappa_{\mathrm{g}}^2(\kappa_{\mathrm{b}}, \kappa_{\mathrm{t}}, m_{\mathrm{H}}) \\ \kappa_{\mathrm{g}}^2 \end{cases}$$

$$\frac{\sigma_{\mathrm{VBF}}}{\sigma_{\mathrm{VBF}}^{\mathrm{SM}}} = \kappa_{\mathrm{VBF}}^2(\kappa_{\mathrm{W}}, \kappa_{\mathrm{Z}}, m_{\mathrm{H}})$$

$$\frac{\sigma_{\mathrm{WH}}}{\sigma_{\mathrm{WH}}^{\mathrm{SM}}} = \kappa_{\mathrm{W}}^2$$

$$\frac{\sigma_{\mathrm{ZH}}}{\sigma_{\mathrm{ZH}}^{\mathrm{SM}}} = \kappa_{\mathrm{Z}}^2$$

$$\frac{\sigma_{\mathrm{t\bar{t}H}}}{\sigma_{\mathrm{t\bar{t}H}}^{\mathrm{SM}}} = \kappa_{\mathrm{t}}^2$$

$$\frac{\Gamma_{\mathrm{WW}^{(*)}}}{\Gamma_{\mathrm{WW}^{(*)}}^{\mathrm{SM}}} = \kappa_{\mathrm{W}}^2$$

$$\frac{\Gamma_{\mathrm{ZZ}^{(*)}}}{\Gamma_{\mathrm{ZZ}^{(*)}}^{\mathrm{SM}}} = \kappa_{\mathrm{Z}}^2$$

$$\frac{\Gamma_{\mathrm{b\bar{b}}}}{\Gamma_{\mathrm{b\bar{b}}}^{\mathrm{SM}}} = \kappa_{\mathrm{b}}^2$$

$$\frac{\Gamma_{\tau^-\tau^+}}{\Gamma_{\tau^-\tau^+}^{\mathrm{SM}}} = \kappa_{\tau}^2$$

$$\frac{\Gamma_{\gamma\gamma}}{\Gamma_{\gamma\gamma}^{\mathrm{SM}}} = \begin{cases} \kappa_{\gamma}^2(\kappa_{\mathrm{b}}, \kappa_{\mathrm{t}}, \kappa_{\tau}, \kappa_{\mathrm{W}}, m_{\mathrm{H}}) \\ \kappa_{\gamma}^2 \end{cases}$$

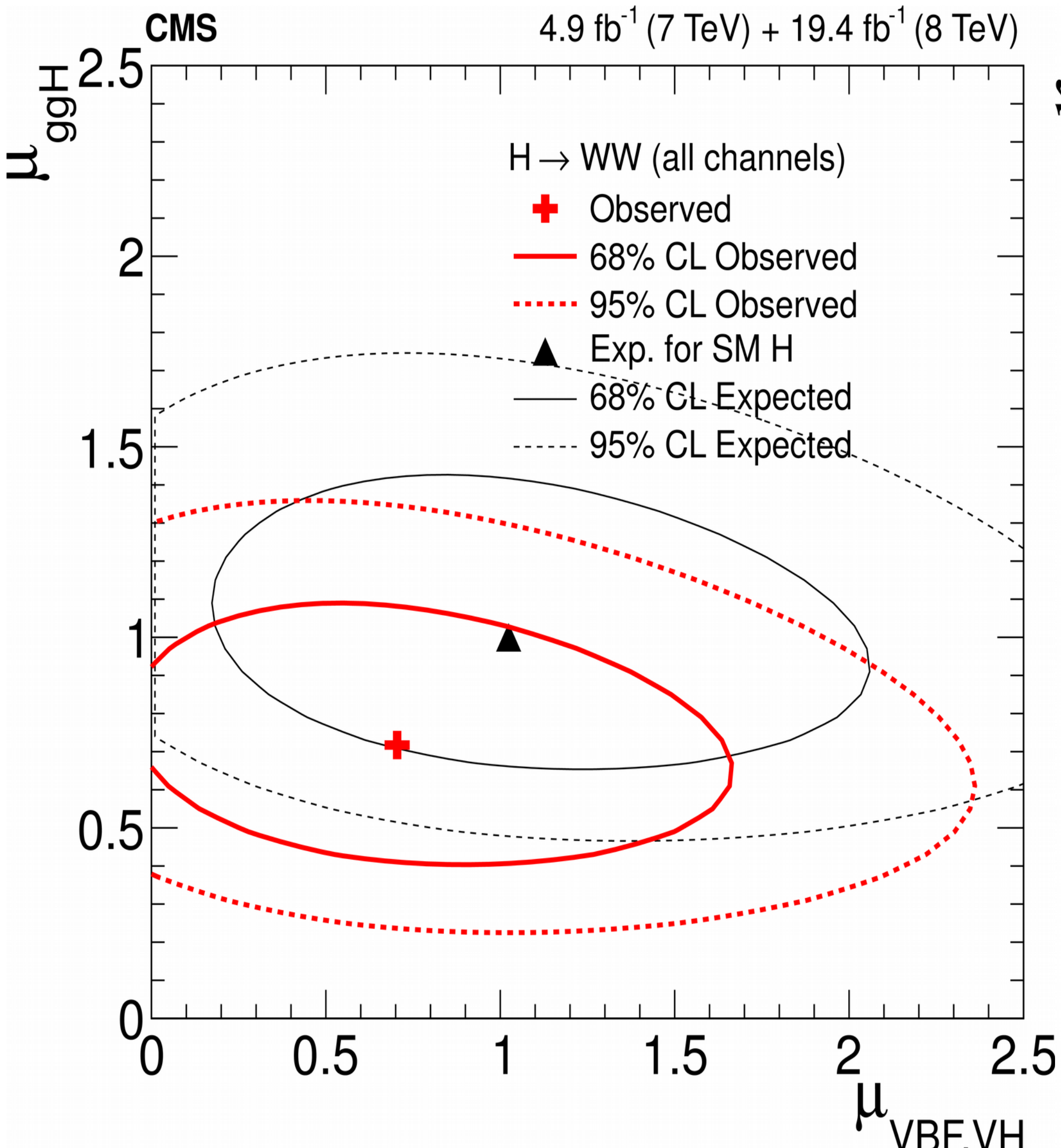
$$\kappa_{\mathrm{H}}^2(\kappa_i, m_{\mathrm{H}}) = \sum_{\substack{j = \mathrm{WW}^{(*)}, \mathrm{ZZ}^{(*)}, \mathrm{b\bar{b}}, \tau^-\tau^+, \\ \gamma\gamma, \mathrm{Z}\gamma, \mathrm{gg}, \mathrm{t\bar{t}}, \mathrm{c\bar{c}}, \mathrm{s\bar{s}}, \mu^-\mu^+}} \frac{\Gamma_j(\kappa_i, m_{\mathrm{H}})}{\Gamma_{\mathrm{H}}^{\mathrm{SM}}(m_{\mathrm{H}})}$$

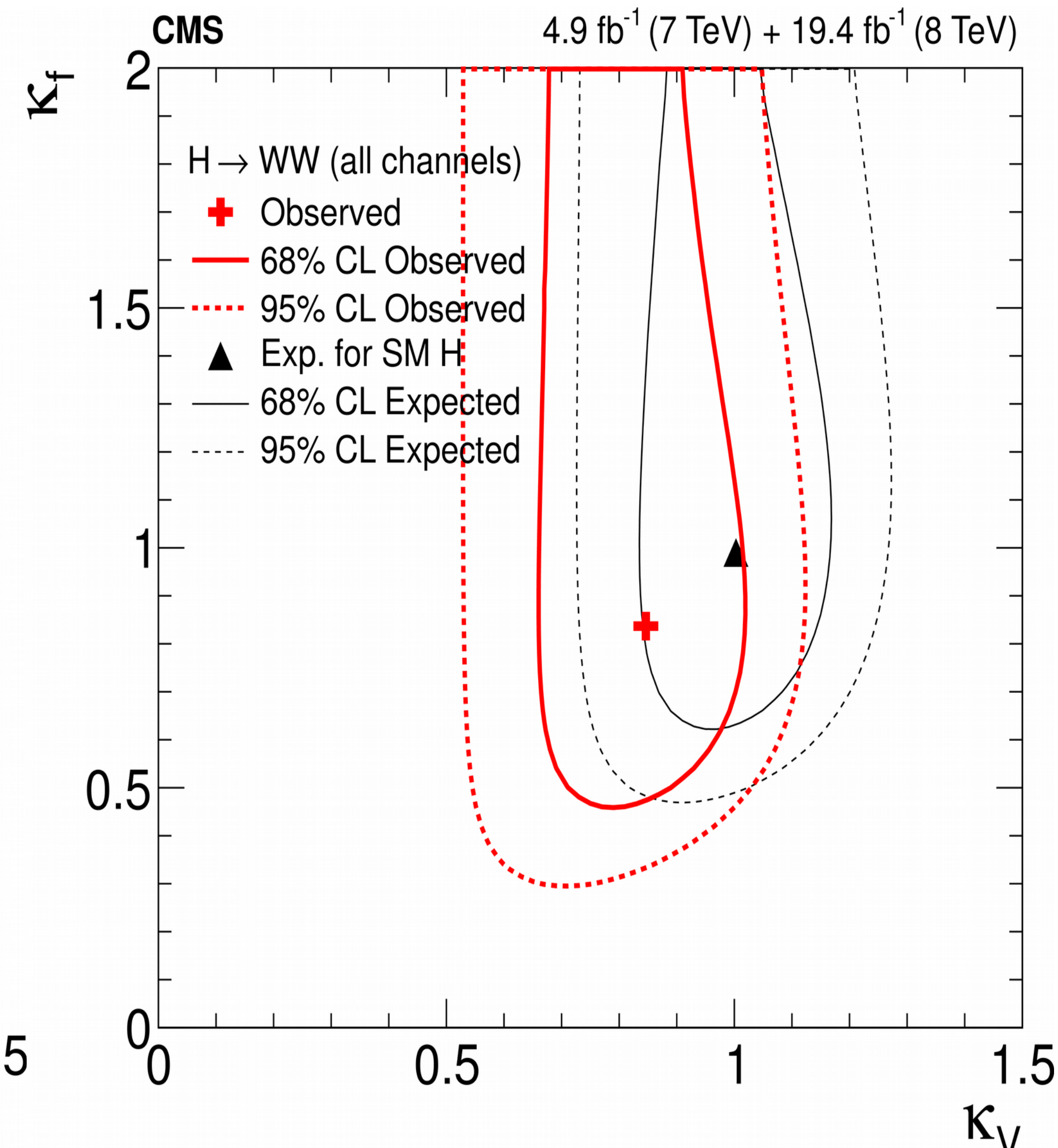
Couplings results from HWW

$\mu_{ggH} * \sigma_{ggH} + \mu_{VBF,VH} * (\sigma_{VBF}+\sigma_{VH})$

$\kappa_V^2\ \kappa_f^2 / \kappa_H^2 * \sigma_{ggH} + \kappa_V^2\ \kappa_V^2 / \kappa_H^2\ (\sigma_{VBF}+\sigma_{VH})$

$\kappa^2_H \sim \kappa^{\square}_f$

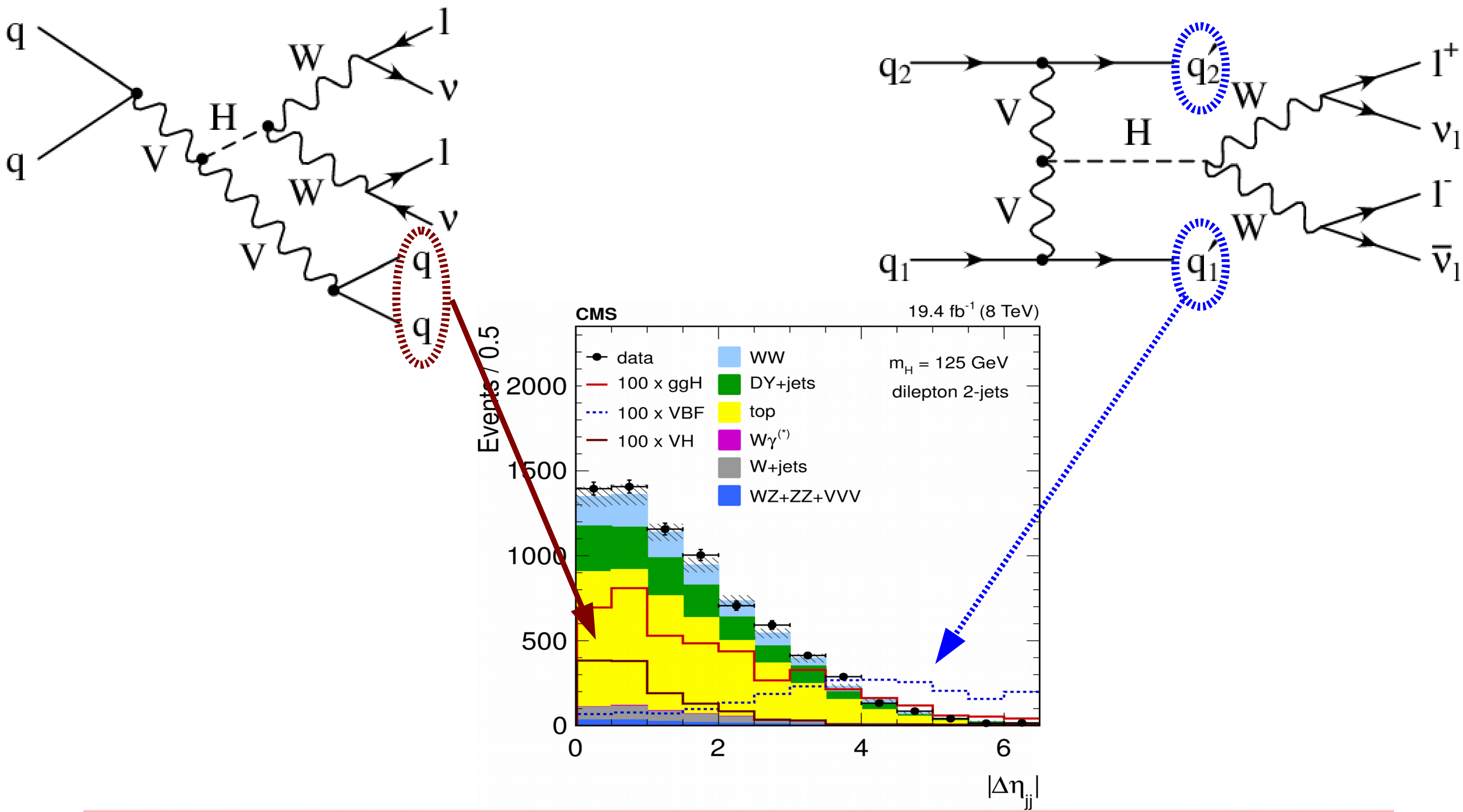




Rare channels: 2l + 2 jets

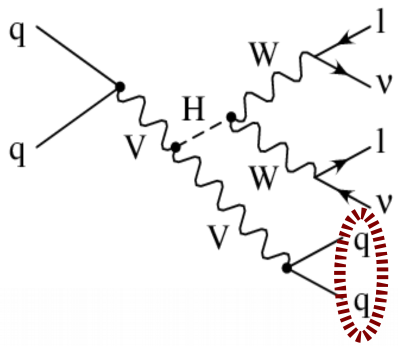
VH

VBF

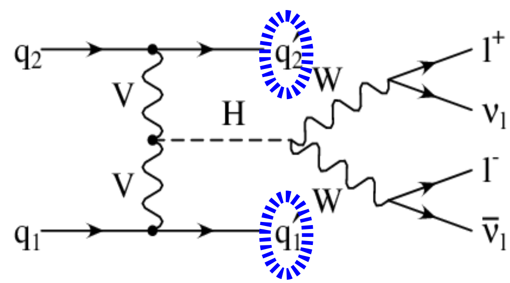


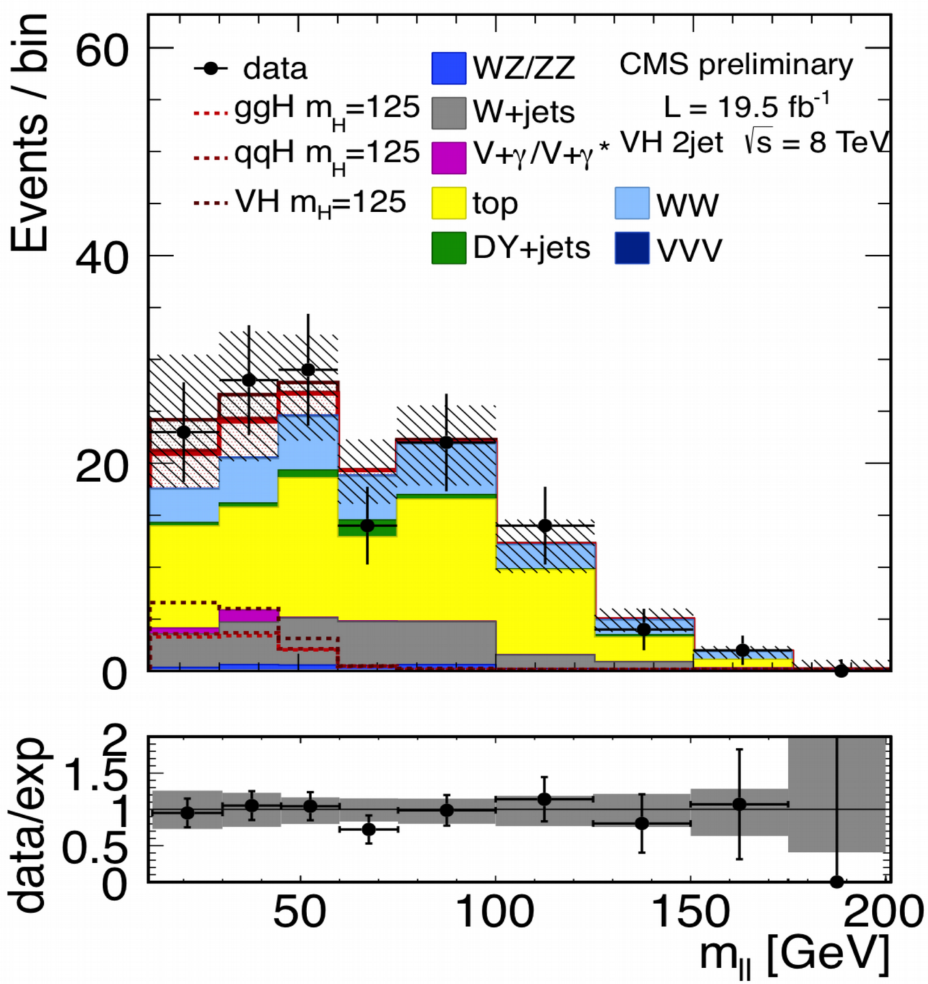
Rare channels: VH and VBF

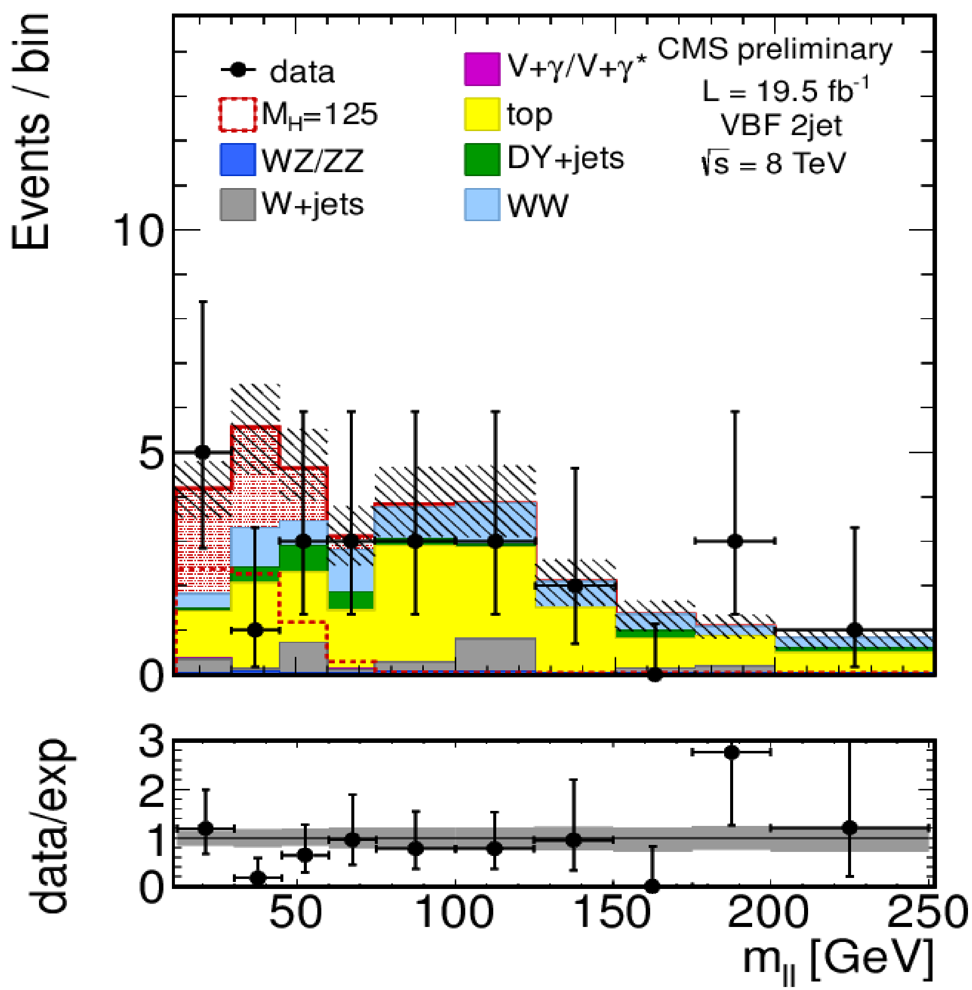
VH



VBF

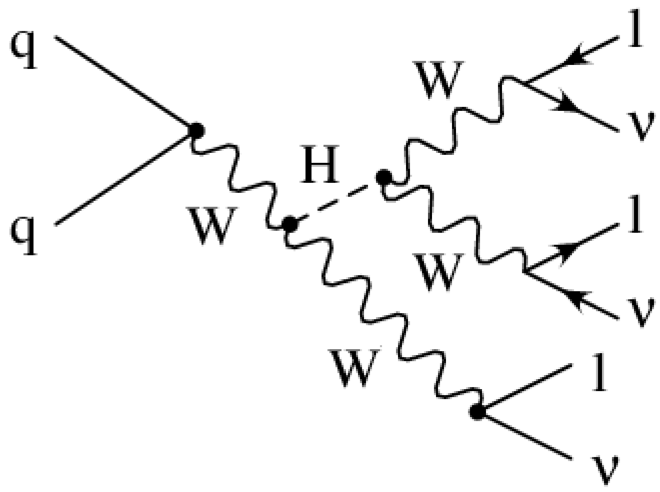




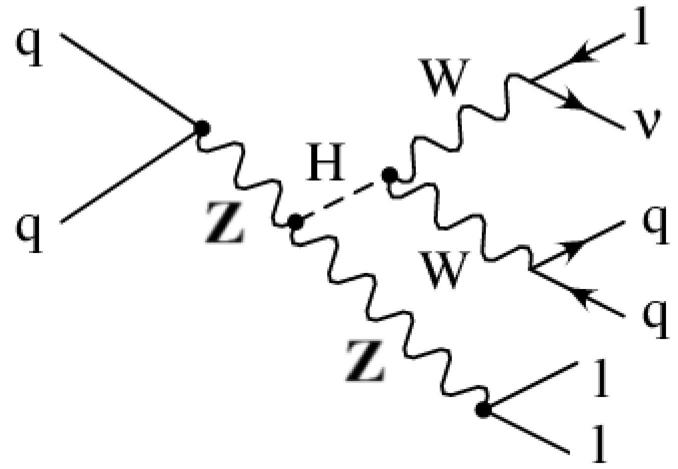


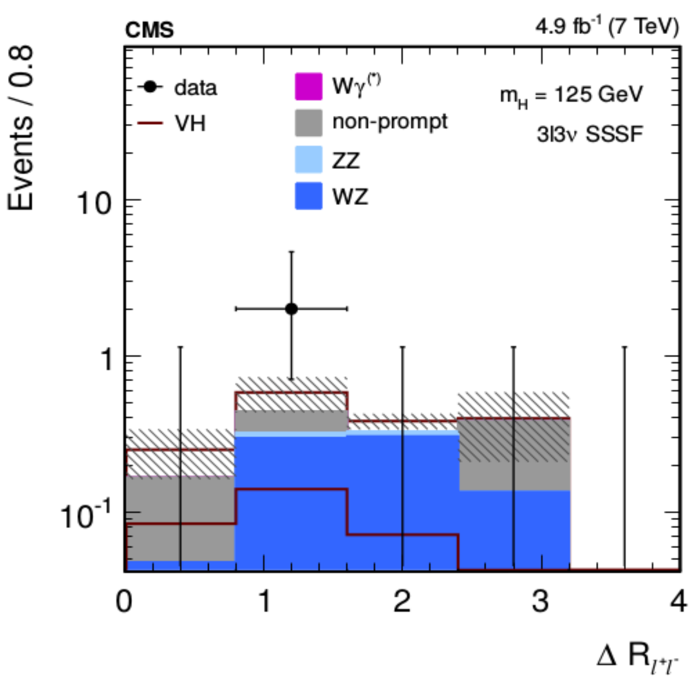
Rare channels: 3l (+2jet)

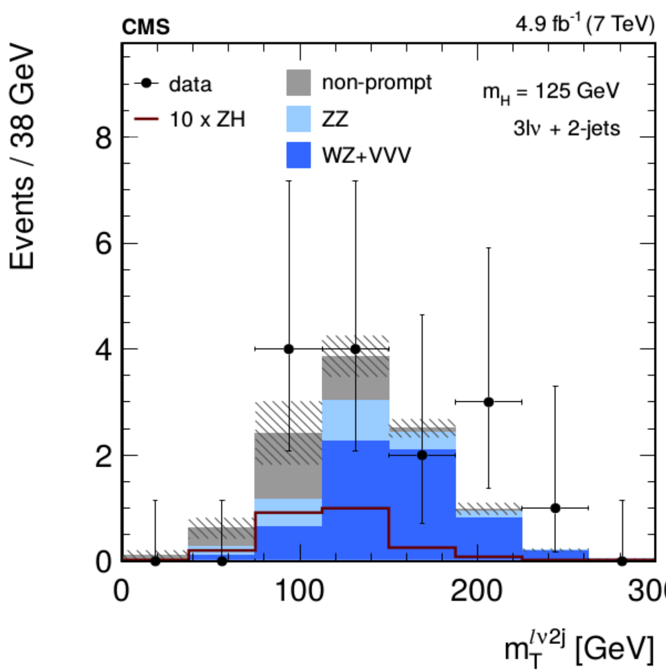
WH



ZH

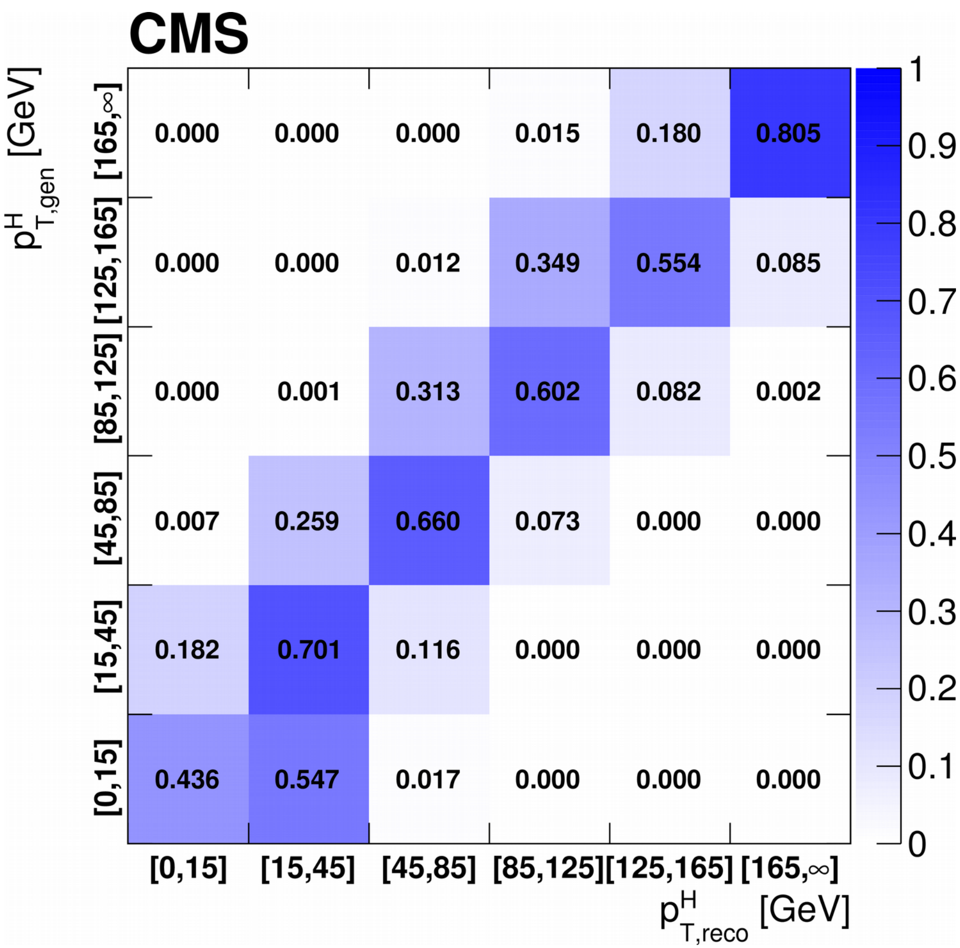




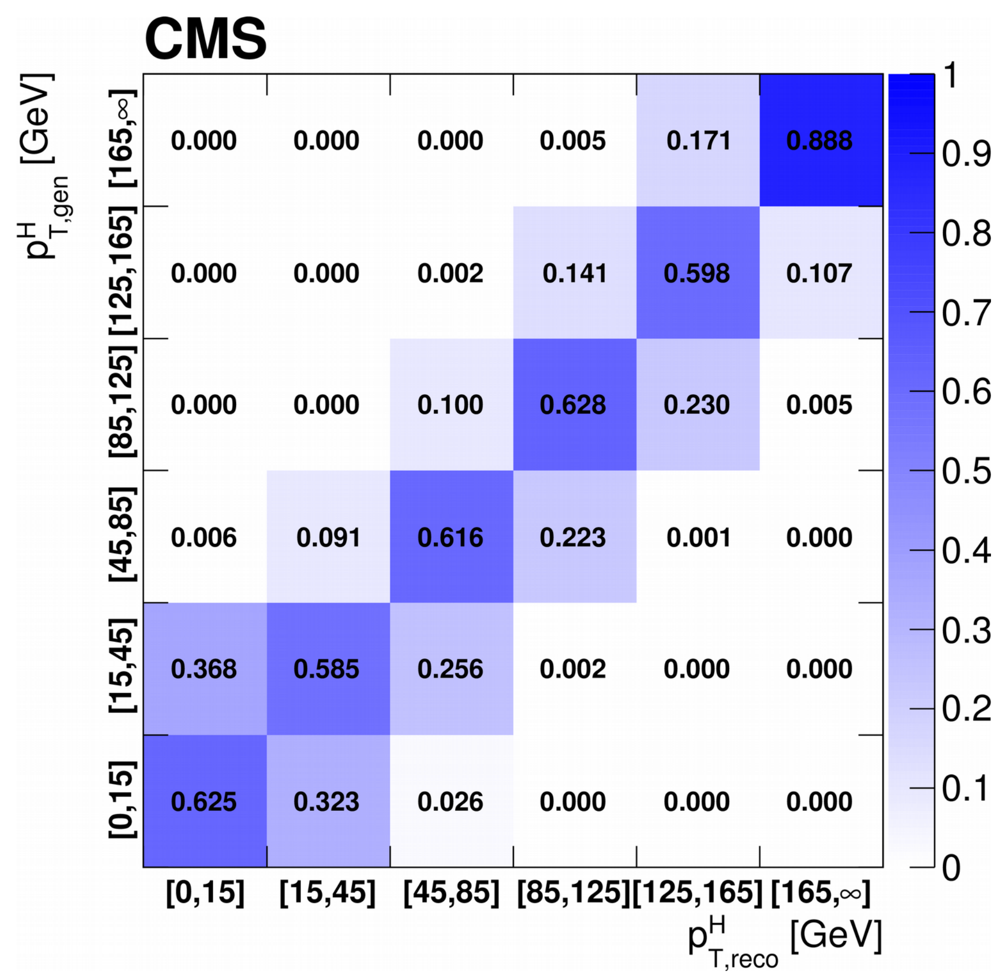


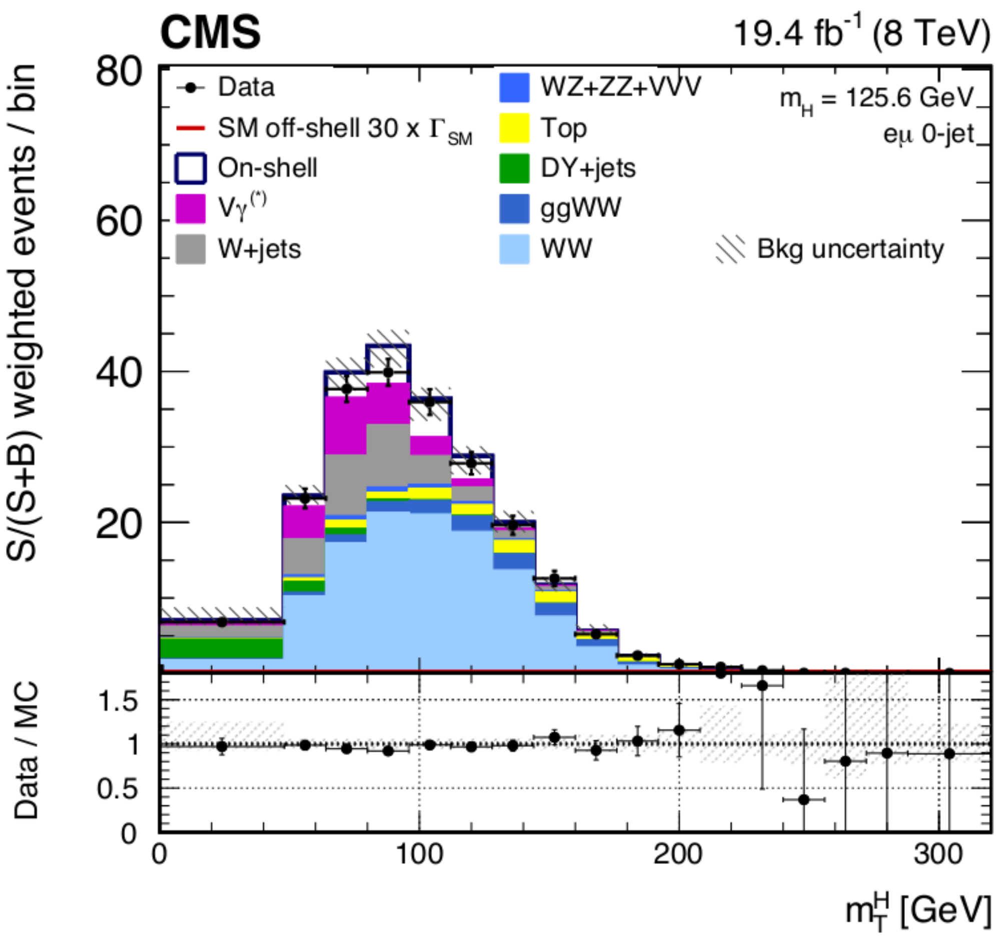
p_T^H response matrix

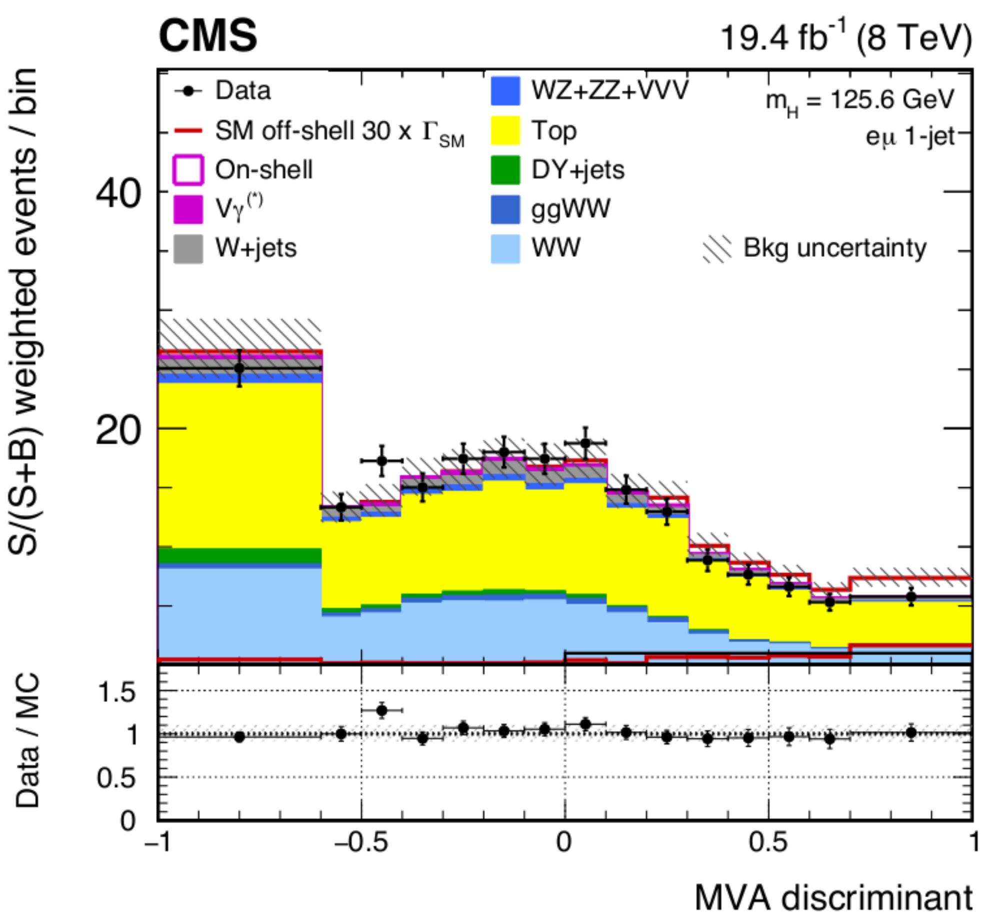
folding



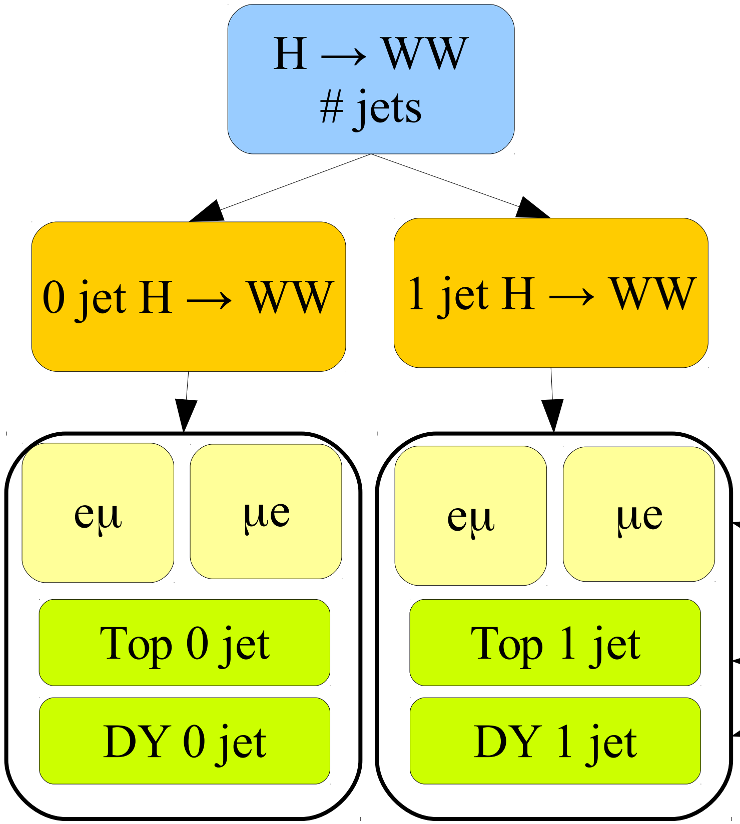
unfolding




CMS
19.4 fb^{-1} (8 TeV)
Data
SM off-shell 30 x Γ_{SM}
On-shell
$V\gamma^{(*)}$
W+jets
WZ+ZZ+VVV
Top
DY+jets
ggWW
WW
Bkg uncertainty
m_H = 125.6 GeV
eμ 0-jet
S/(S+B) weighted events / bin
Data / MC
m_T^H [GeV]


CMS
19.4 fb^{-1} (8 TeV)
Data
SM off-shell 30 x Γ_{SM}
On-shell
$V\gamma^{(*)}$
W+jets
WZ+ZZ+VVV
Top
DY+jets
ggWW
WW
Bkg uncertainty
m_H = 125.6 GeV
eμ 1-jet
S/(S+B) weighted events / bin
Data / MC
MVA discriminant

2015 analysis strategy



- Signal phase space
- Phase space to normalize the backgrounds