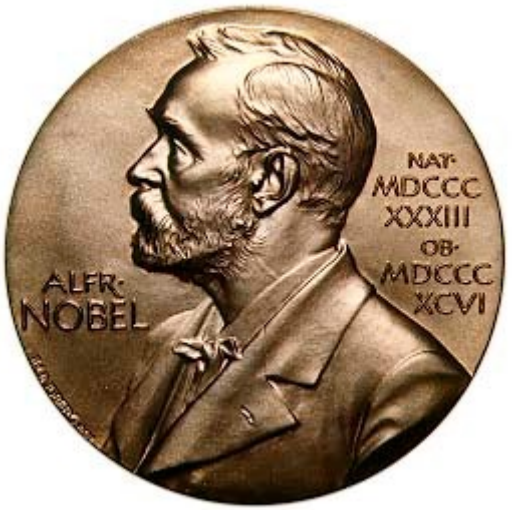
Recent Higgs results from CMS

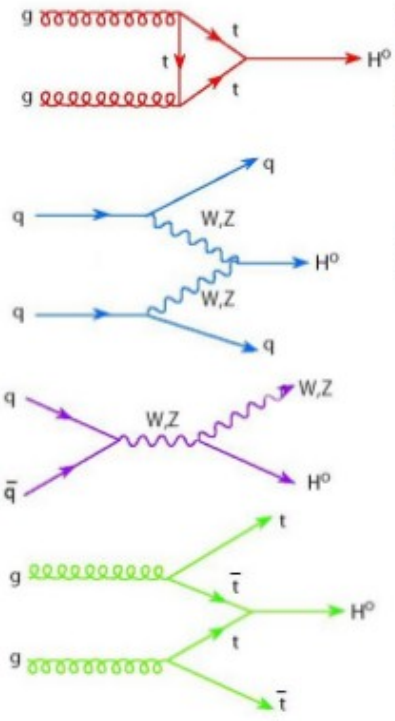
M.Bachtis (CERN-PH)
on behalf of the CMS Collaboration

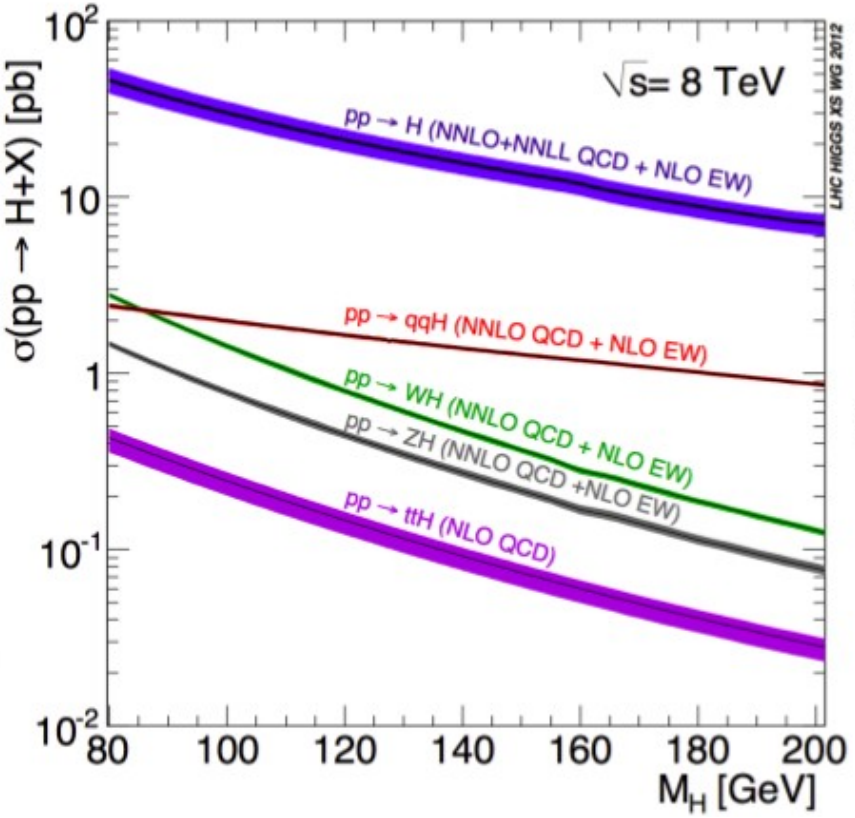
Recent history of Higgs searches

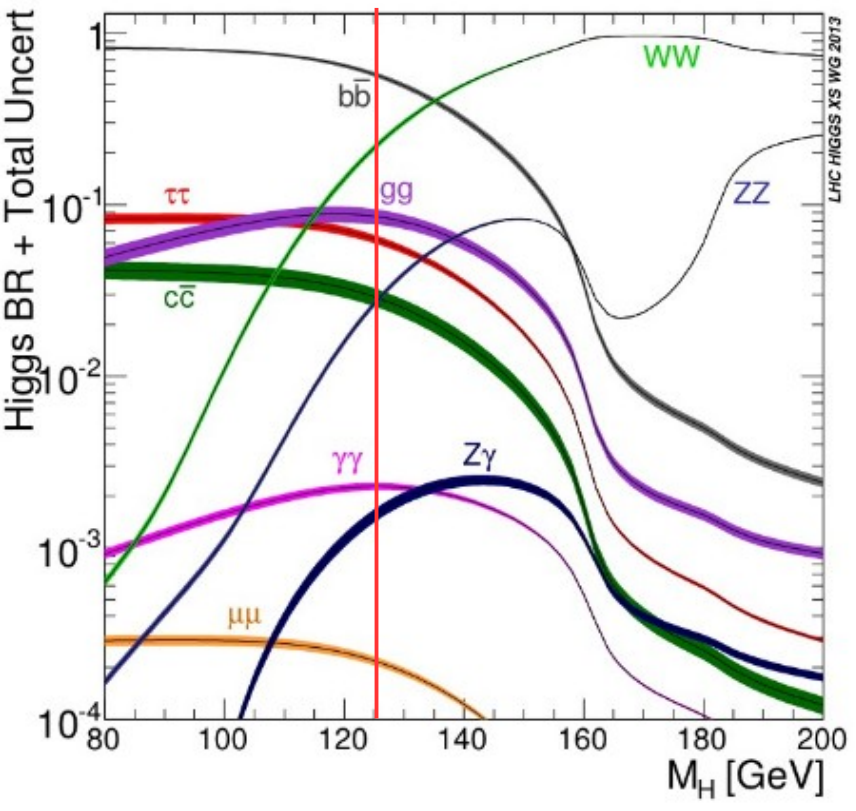
- New boson discovered at LHC in 2012, compatible with the SM scalar
  - Nobel prize in Physics to profs Englert and Higgs in 2013
- Since then experiments finalizing results with Run I data



Production and decay of the Higgs

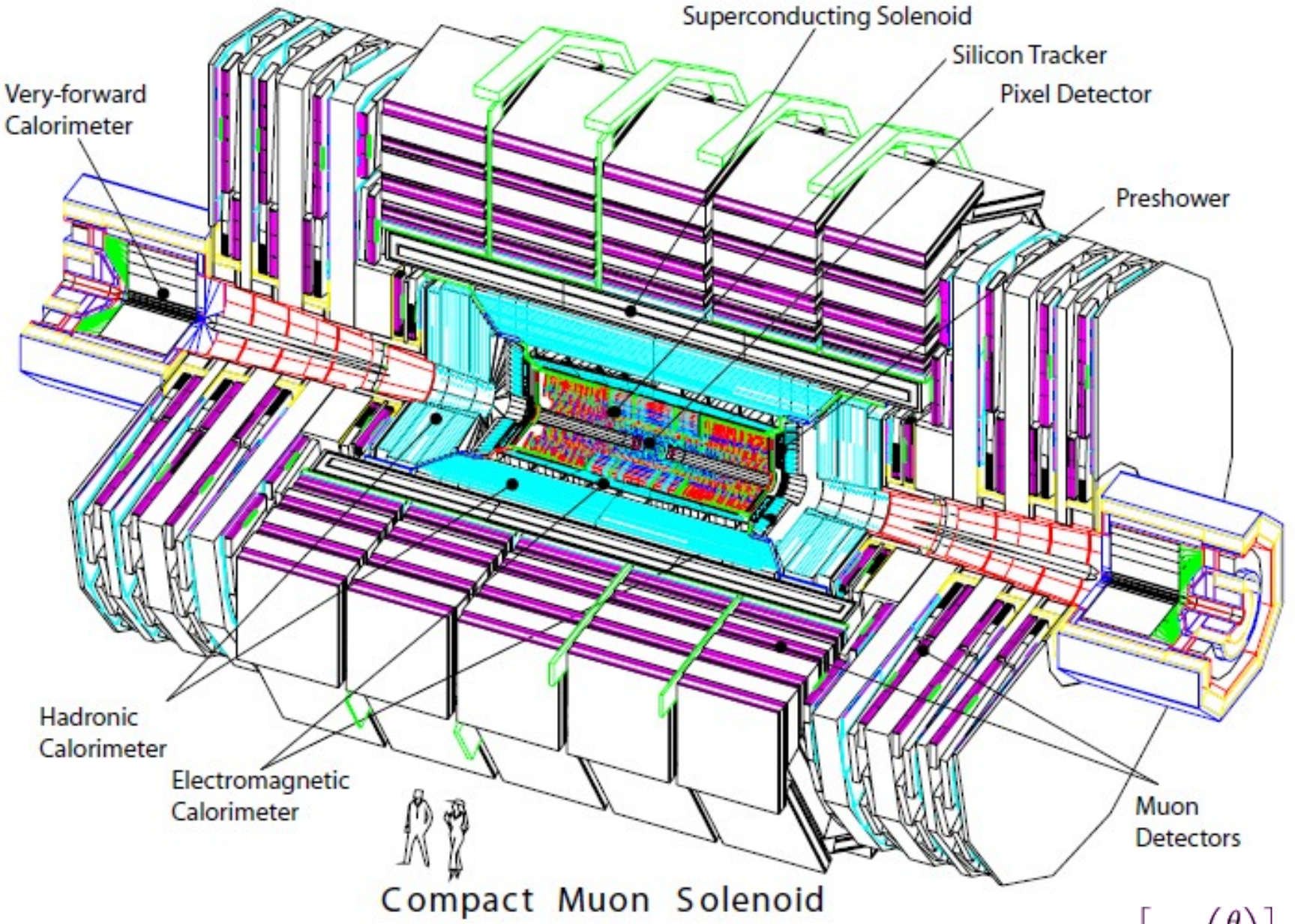






- Dominant production mechanism: gluon fusion
  - Other modes: lower cross section but distinct signatures
- At 125 GeV: a variety of decays can be observed @LHC
  - WW,ZZ,γγ,ττ,bb (maybe Zγ/$\mu\mu$ with very high luminosity)

The CMS detector



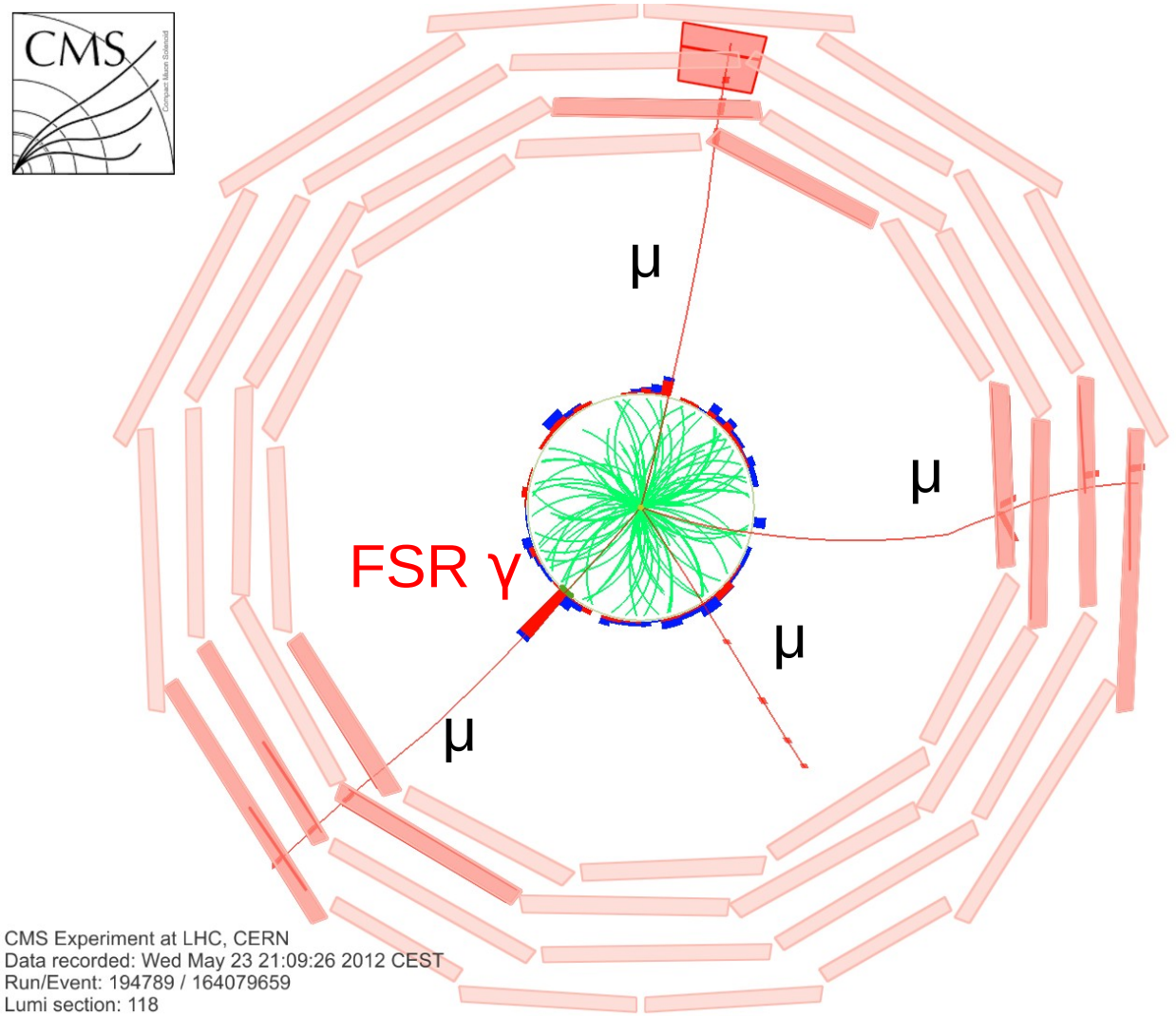
$$\eta = -\ln\left[\tan\left(\frac{\theta}{2}\right)\right]$$

Recent CMS Higgs analyses

Analysis	Integrated lumi 7+8 TeV	documentation
VH / H → bb	5.1 +18.9 fb^{-1}	arXiv:1310.3687
H → WW	4.9 + 19.4 fb^{-1}	arXiv:1312.1129
H → ZZ → 4l	5.1+19.7 fb^{-1}	arXiv:1312.5353
SM H → tautau	4.9+19.7 fb^{-1}	arXiv:1401.5041
Fermion combination	4.9+19.7 fb^{-1}	arXiv: 1401.6527
Combination of invisible searches	4.9+19.7 fb^{-1}	arXiv:1404.1344
Combination of ttH final states	4.9+19.7 fb^{-1}	
Constraints on the Higgs boson width from offshell production	19.7fb^{-1}	CMS PAS HIG-14-002

- Legacy H → γγ and combination coming soon to complete the picture of the Higgs boson with 7/8 TeV data
- Many more public results in MSSM, t → cH, H → γγ → μμγ etc not discussed in this presentation

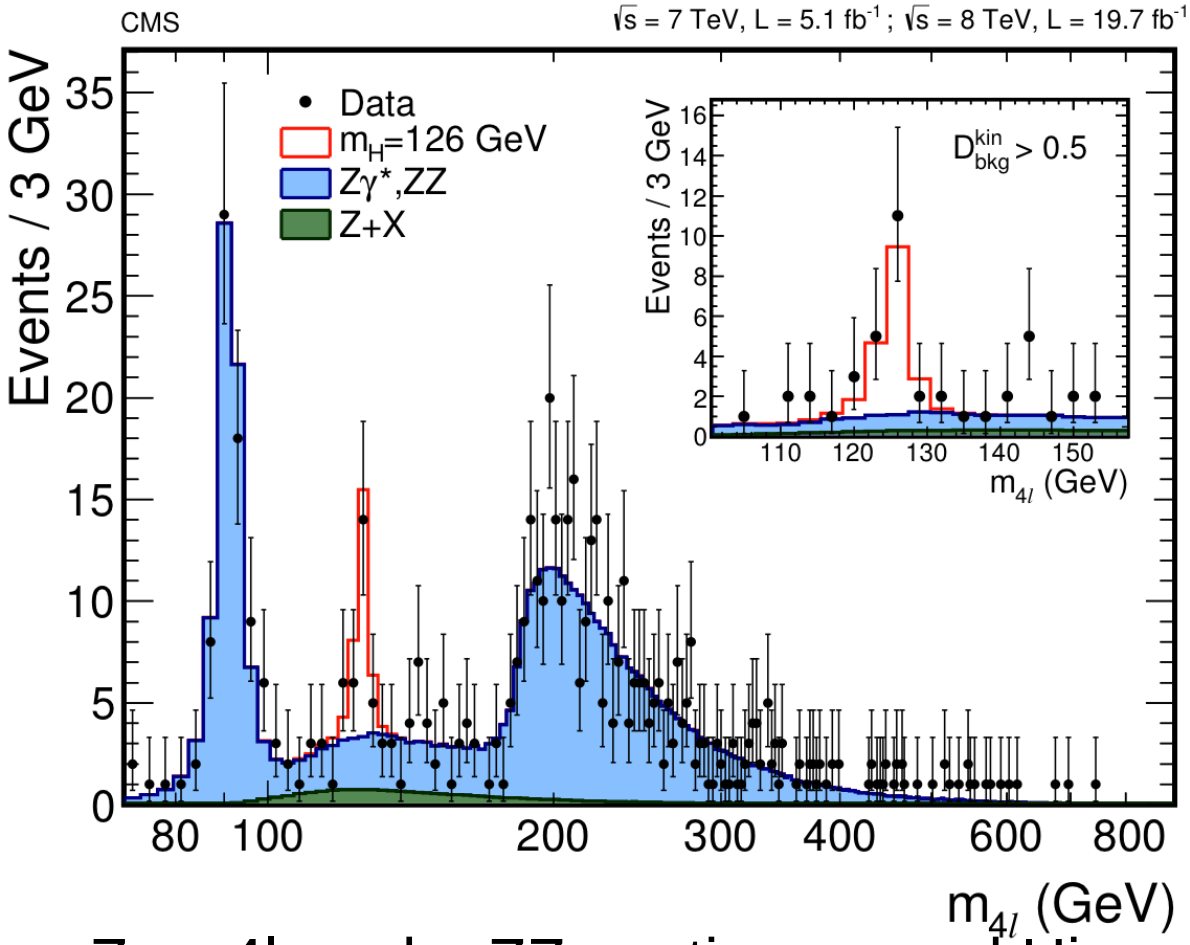
H → ZZ* → 4l

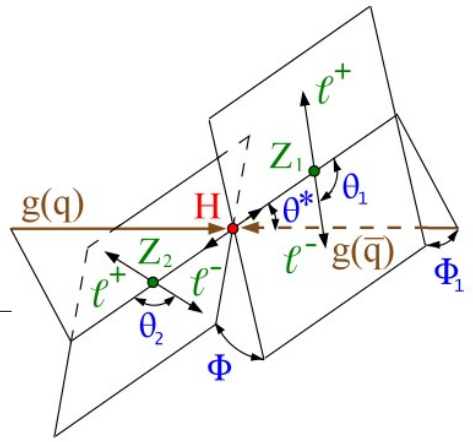


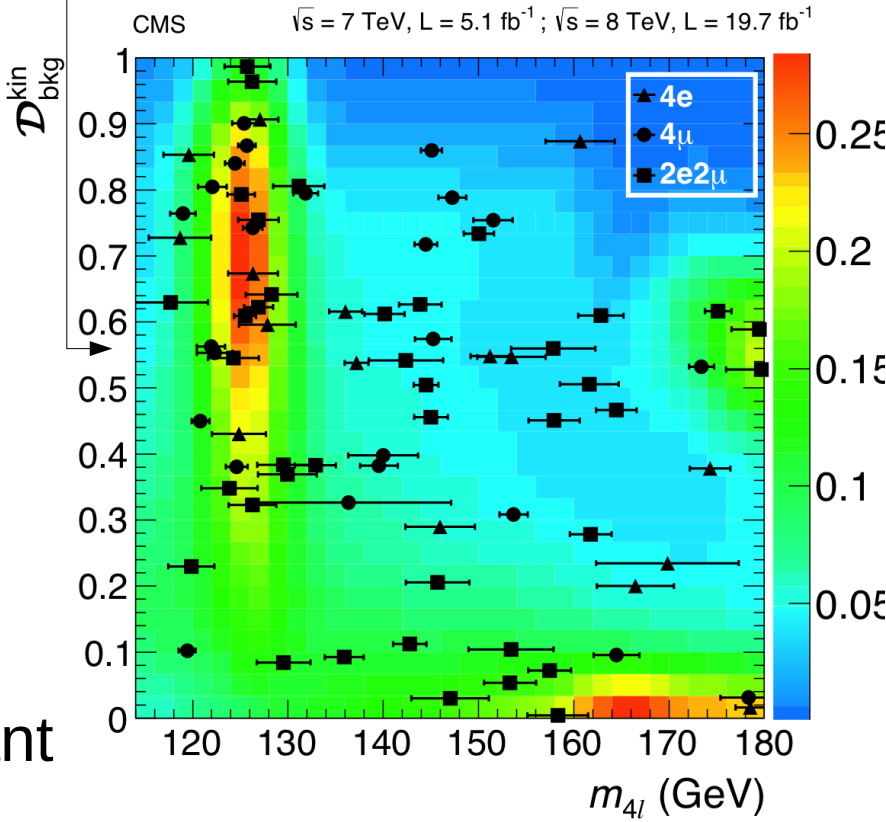
- Signature of 4 high quality leptons
  - Add tagged photons from FSR
- Small and flat backgrounds
  - SM qq/gg → ZZ → 4l
  - Z+ bb/cc , top pairs
- Excellent mass resolution

- Experimental challenge: Excellent lepton reconstruction + coverage
  - CMS designed for both!

H → ZZ* → 4l distributions

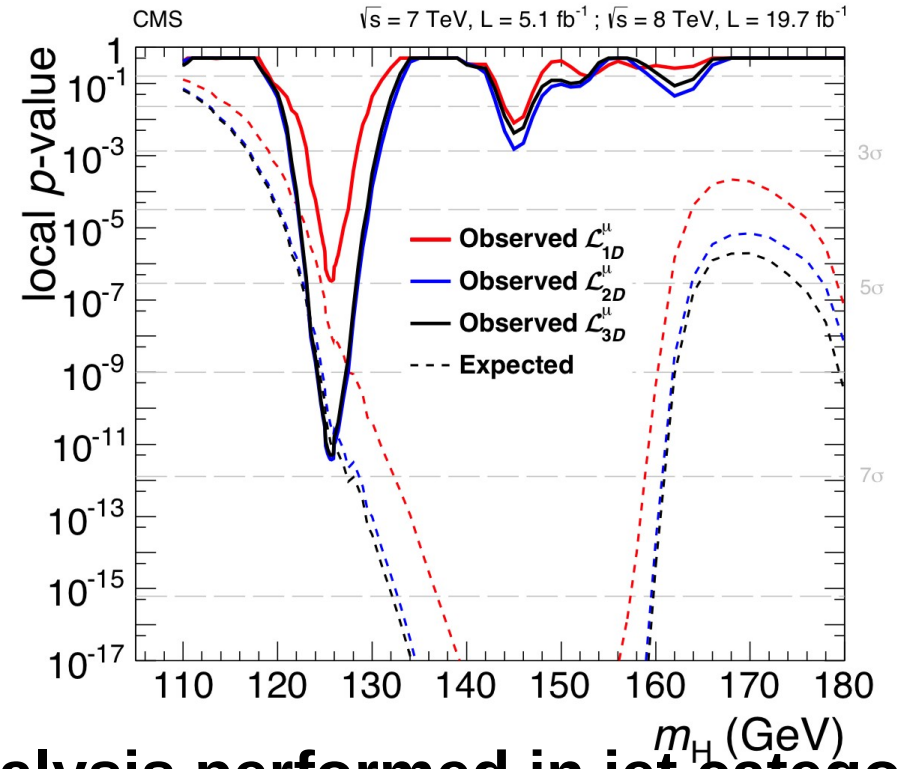


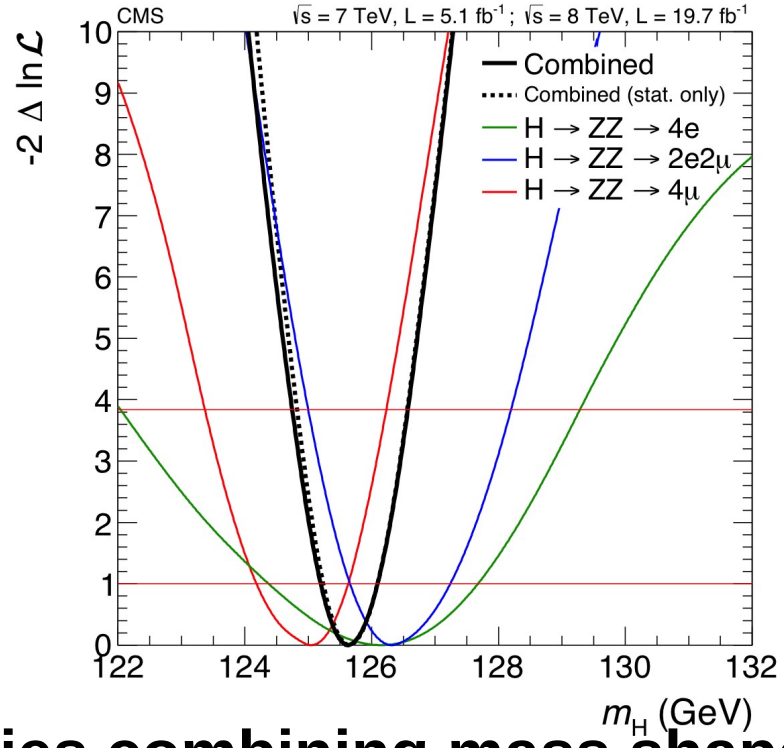




- Z → 4l peak , ZZ continuum and Higgs candidate peak clearly visible
- Kinematic information of production and decay folded into a kinematic discriminant D^{kin}_{bkg}

H → ZZ*→4l: significance and mass





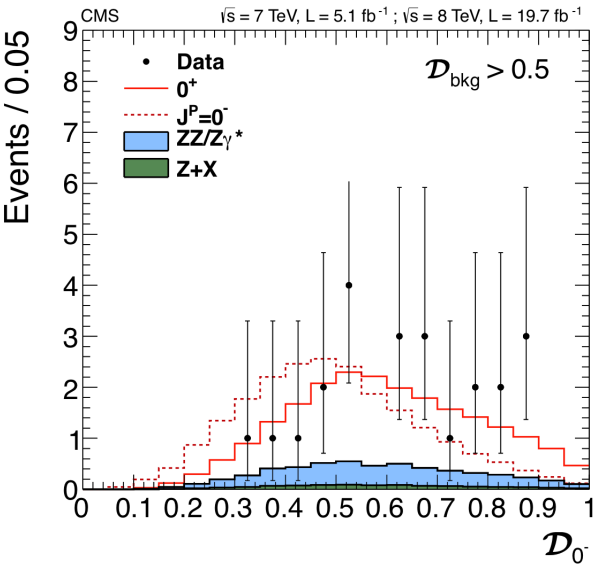
Analysis performed in jet categories combining mass shape, kinematics and jet information

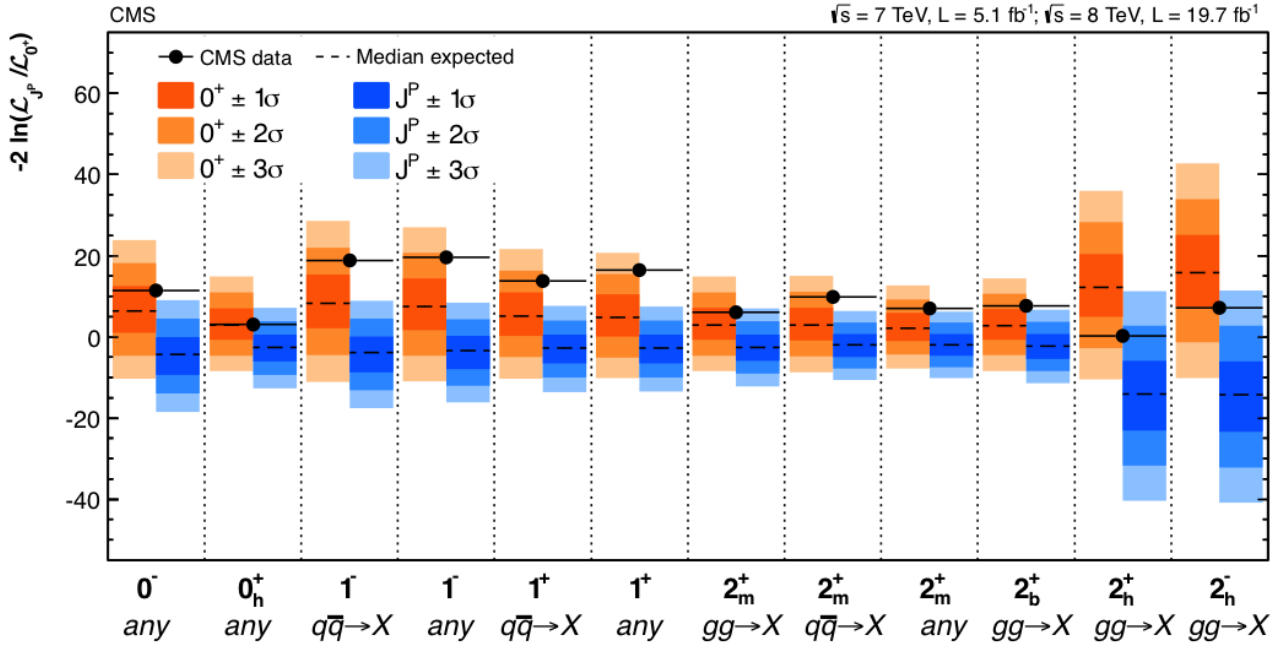
- Expected local significance of 6.7σ (Observed 6.8σ)
- Mass measurement: 125.6 ± 0.4 (stat.) ± 0.2 (syst.) GeV
- Signal strength: $\mu = 0.93\ ^{+0.26}_{-0.23}$ (stat.) $^{+0.13}_{-0.09}$ (syst.)
- **>5σ Observation in a single channel**

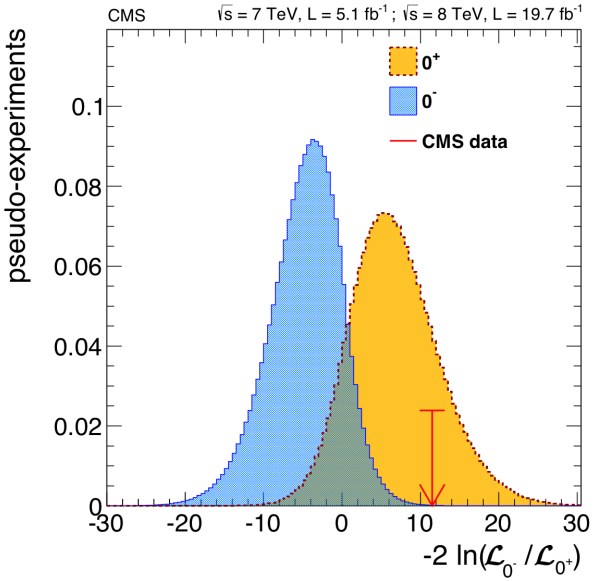
H → ZZ → 4l: spin/parity

Using full angular information

- For each hypothesis create kinematic discriminant for 0^+ vs alternative hypothesis
- Perform 2D fit of hypothesis discriminant vs background discriminant
- Perform hypothesis test

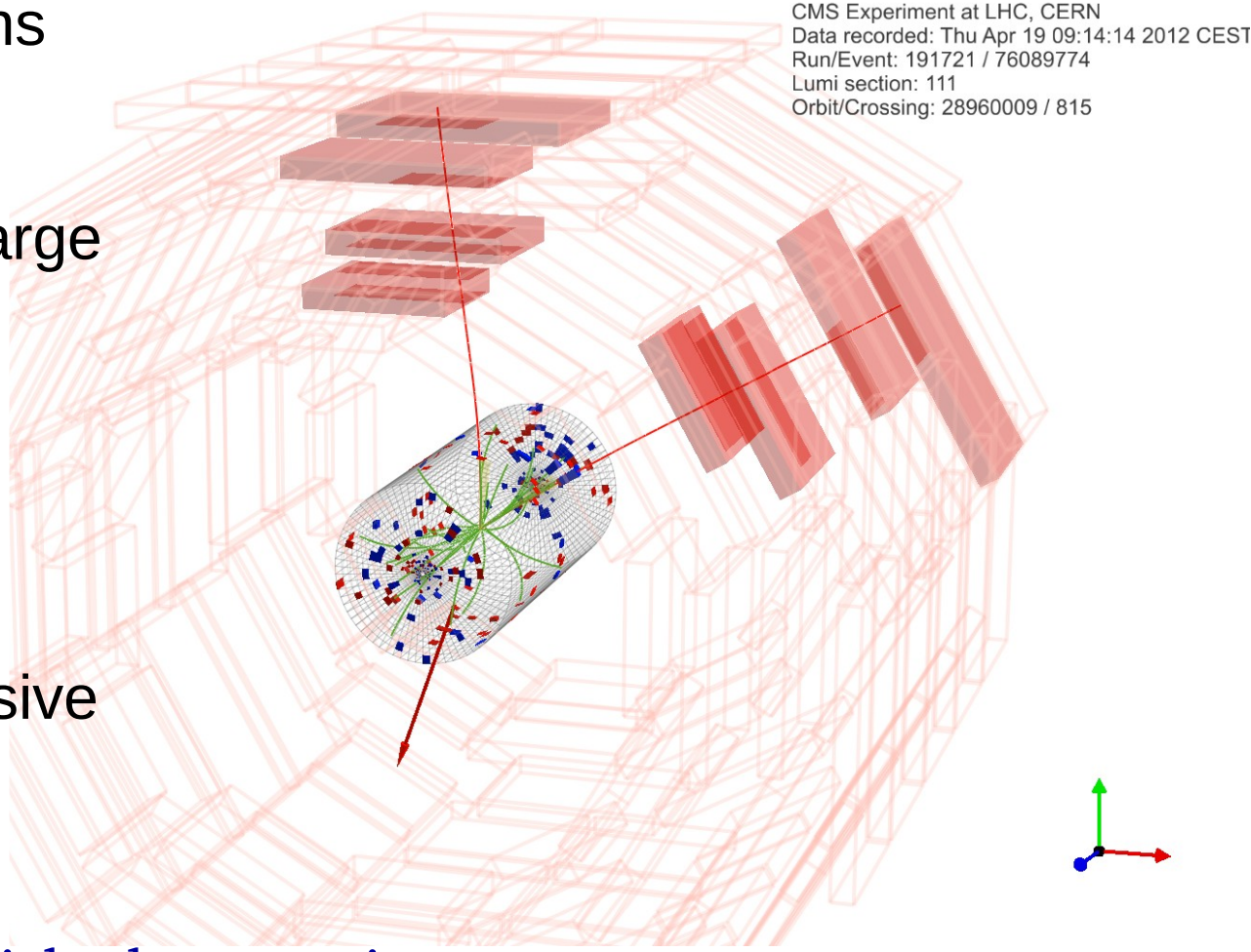




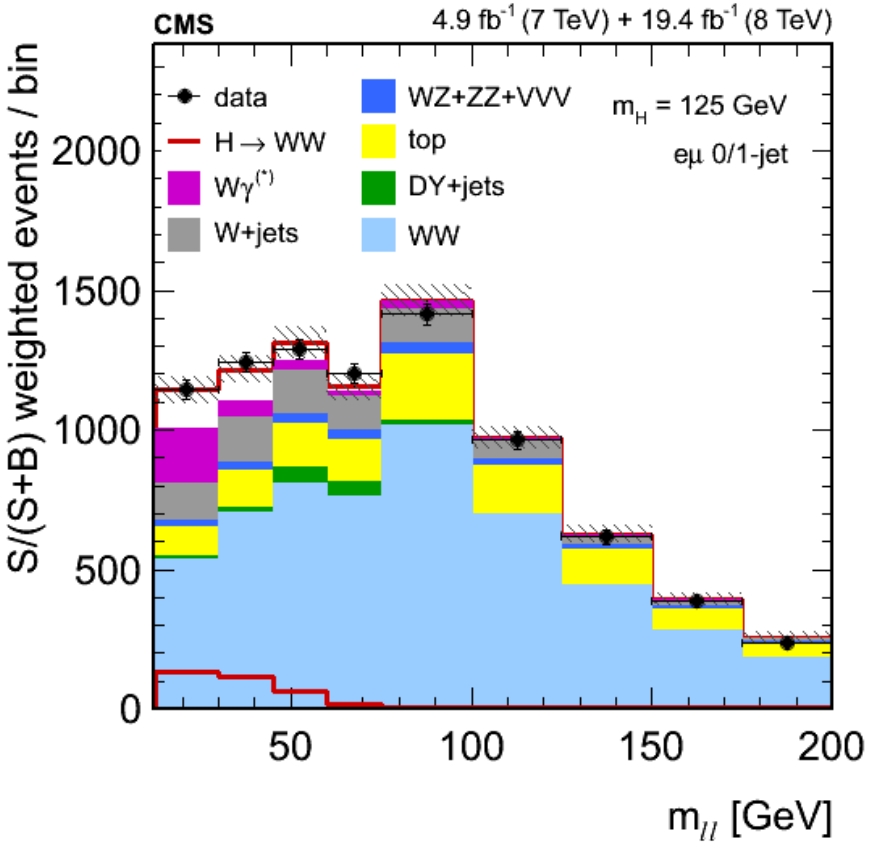


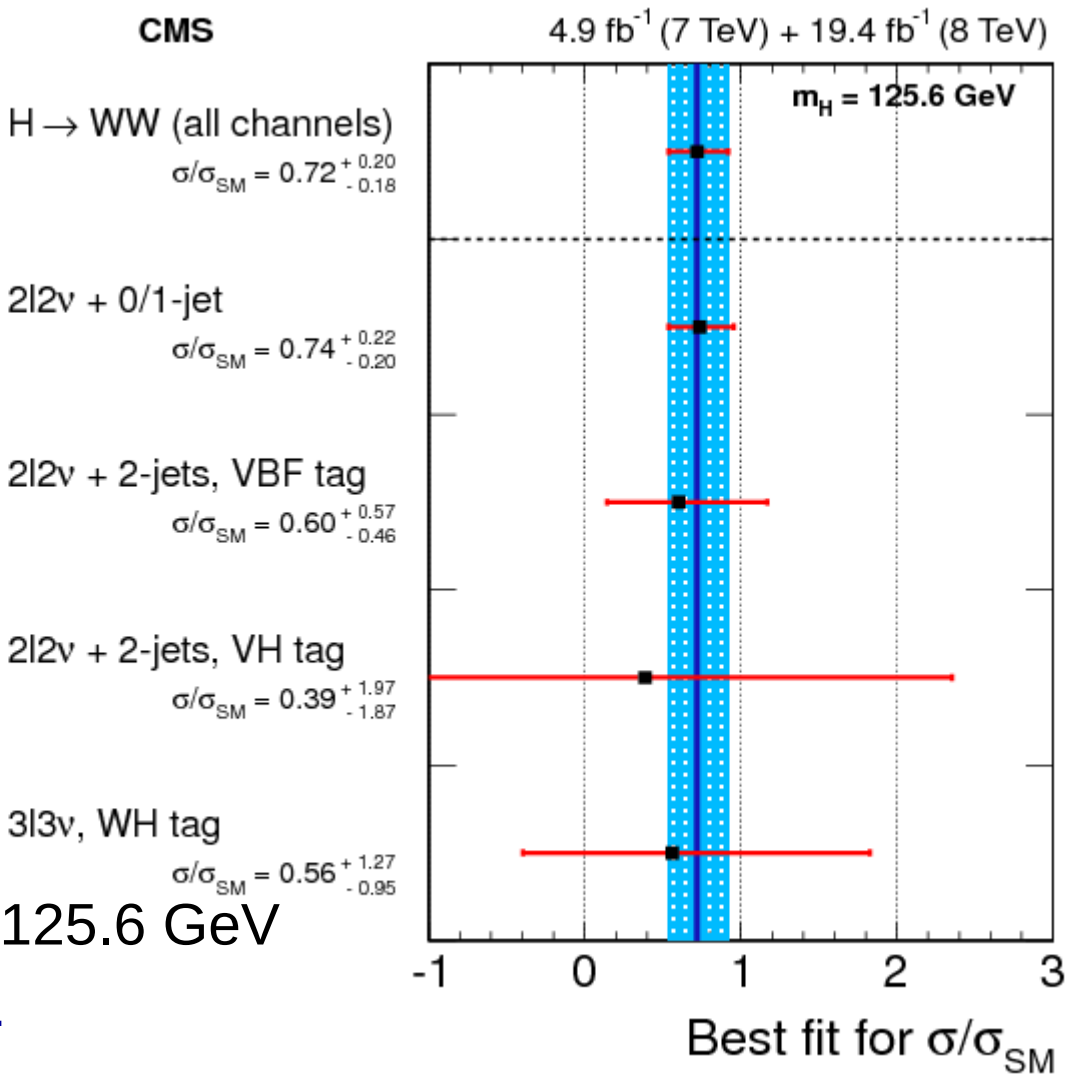
H → WW*

- Two high quality OS leptons
- 2 neutrinos → MET
- Low mass resolution but large yield!
- Main backgrounds
  - WW,top, DY, W+jets
- Categorization per flavour and #jets using also exclusive categories
- Analysis categories
  - 0 jet and 1 jet ggH enriched categories
  - 2 jet VBF and 2 jet VH categories
  - WWW → 3l3ν and ZH → 3lν+2 jets



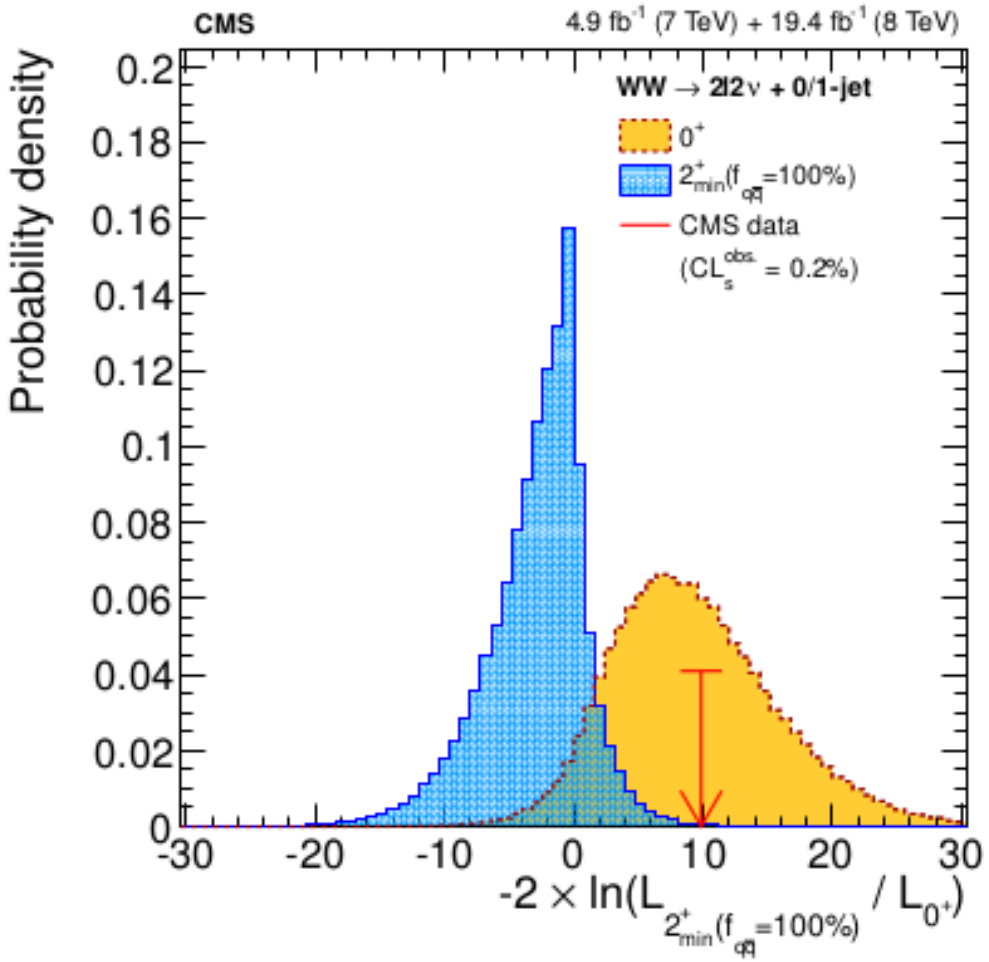
H → WW* results

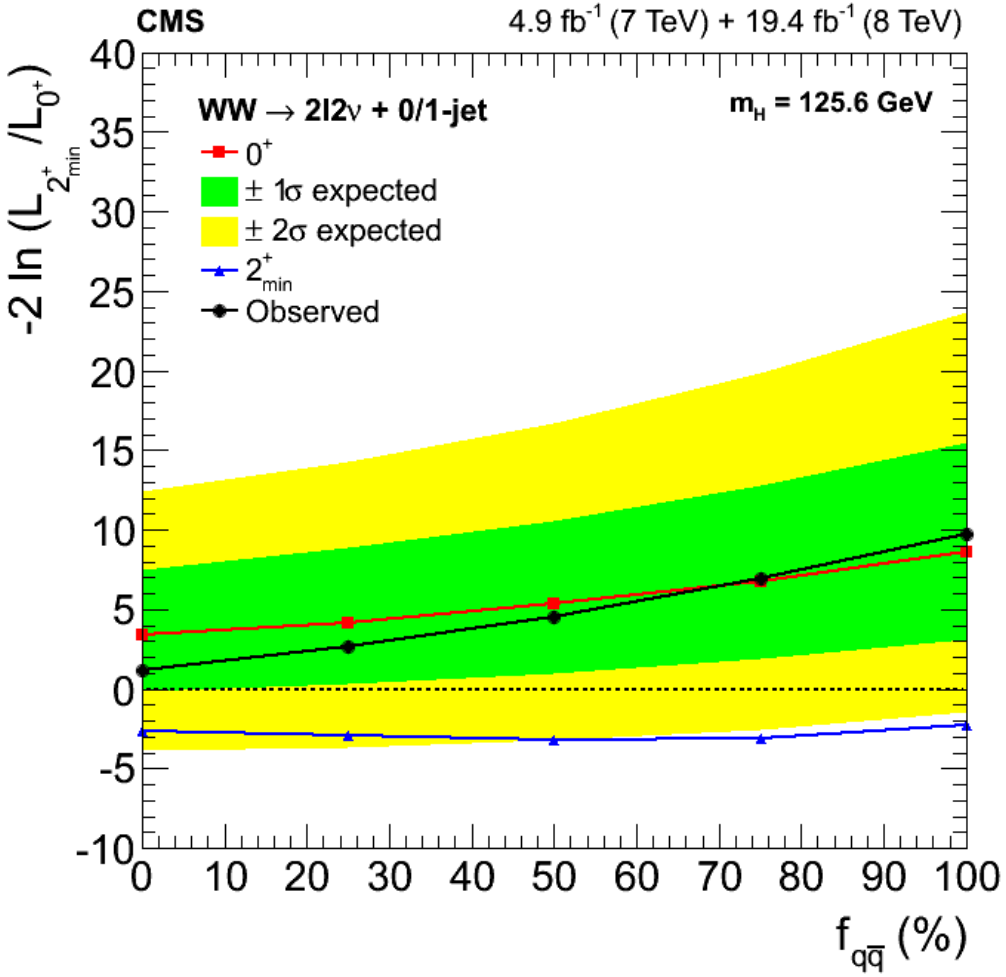




- Expected significance of 5.8σ @125.6 GeV
  - Observed significance of 4.3σ
- Signal strength μ = $0.72^{+0.20}_{-0.18}$
  - Consistent with SM within 2σ

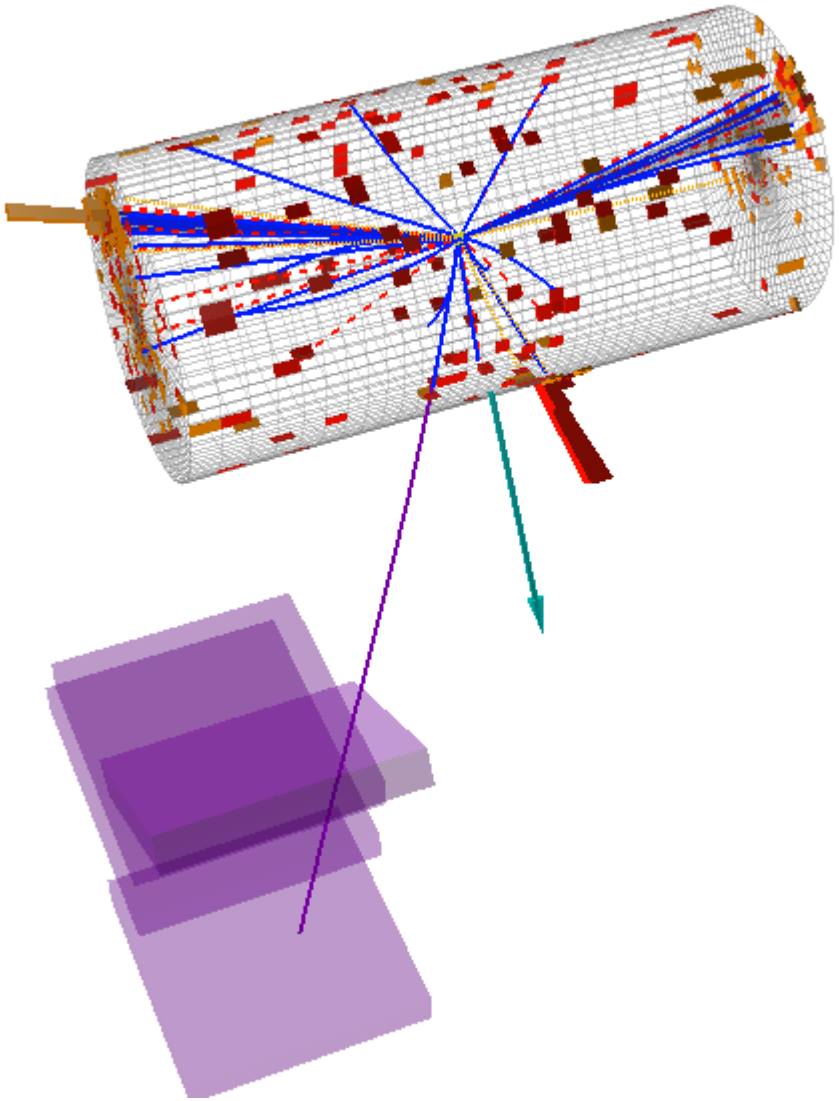
Spin parity in H → WW*





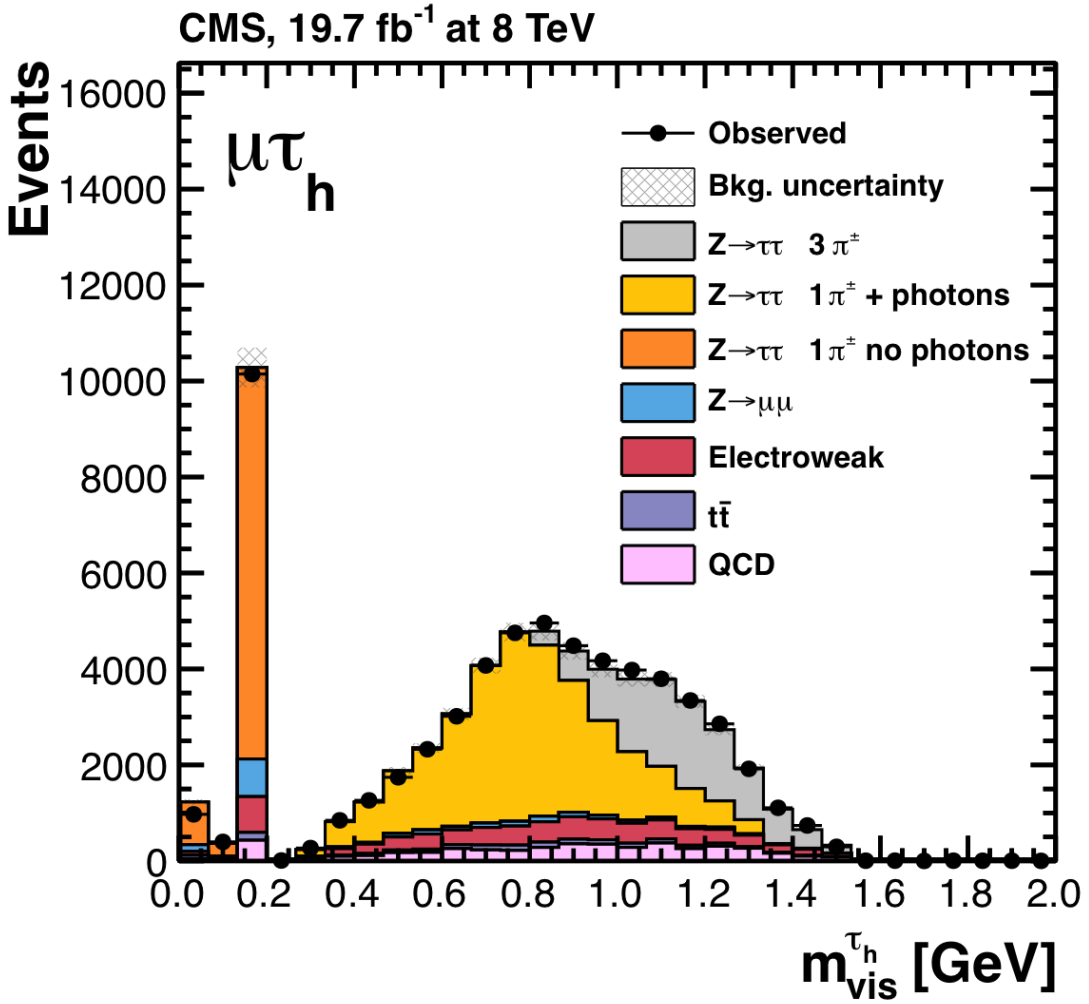
- Hypothesis tests between 0^+ and 2^+_m /0^-
  - Spin 2 tests for different fractions of quark induced production
- Spin 2 hypotheses with $f_{qq} > 50\%$ excluded at 3σ level

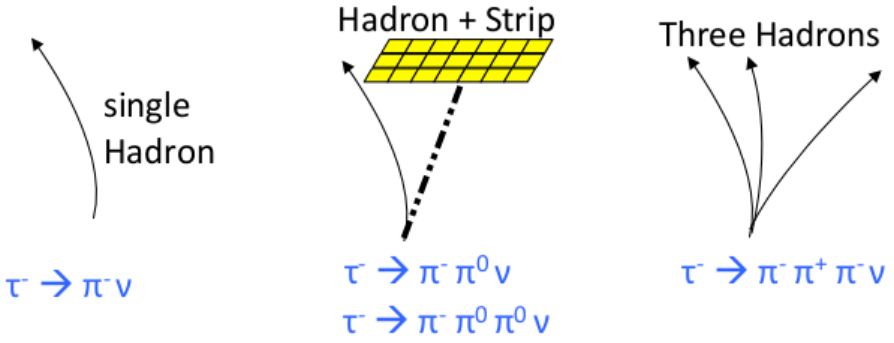
H → ττ



- Excellent probe to fermionic couplings!
- Require a tau pair and split sample in categories
  - Tau leptons can decay hadronically or leptonically
- Experimentally challenging
  - Excellent hadronic tau identification
  - Sophisticated mass reconstruction
  - VBF tagging → important
- Main backgrounds
  - Z → ττ, W+jets, QCD

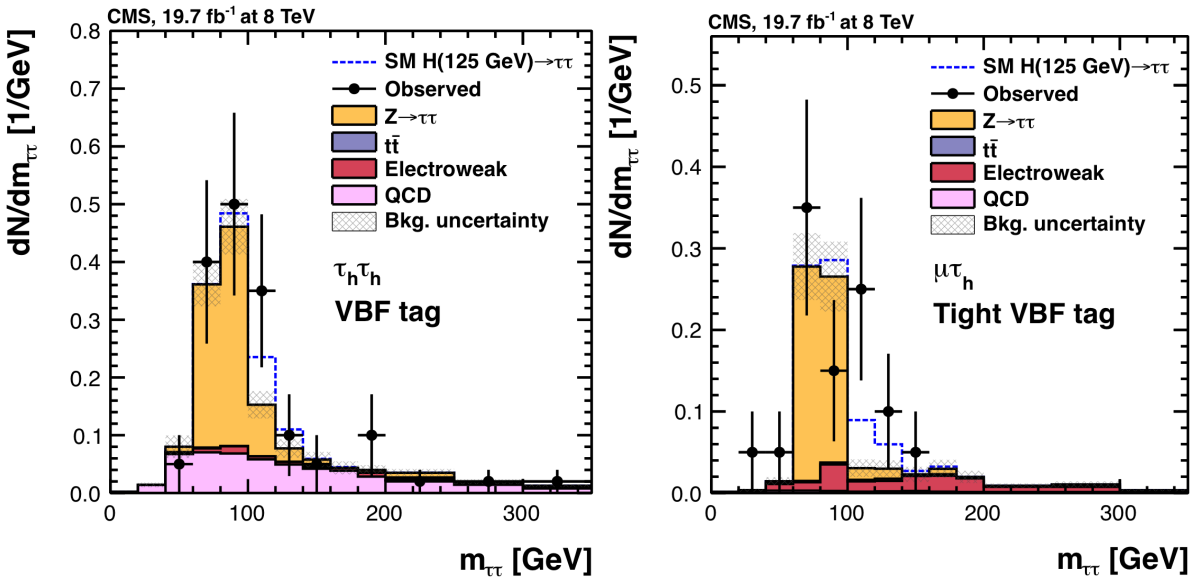
Hadronic Tau Identification

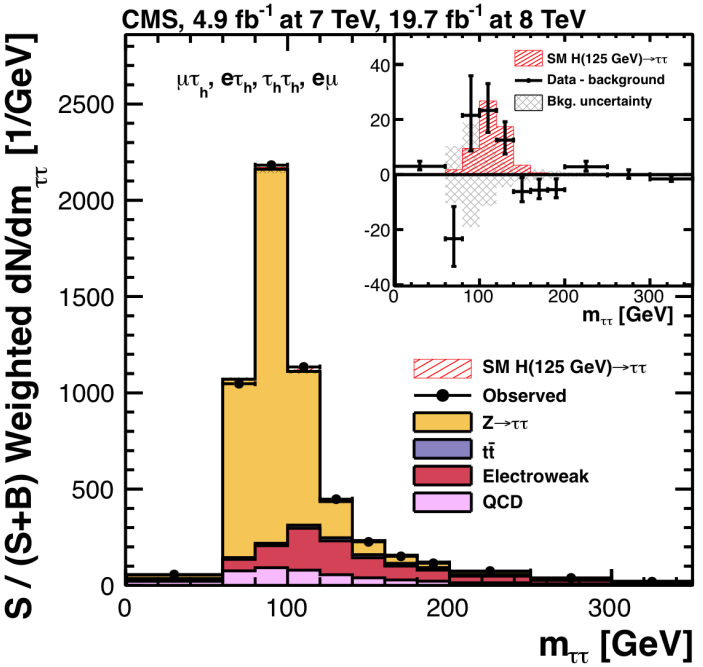




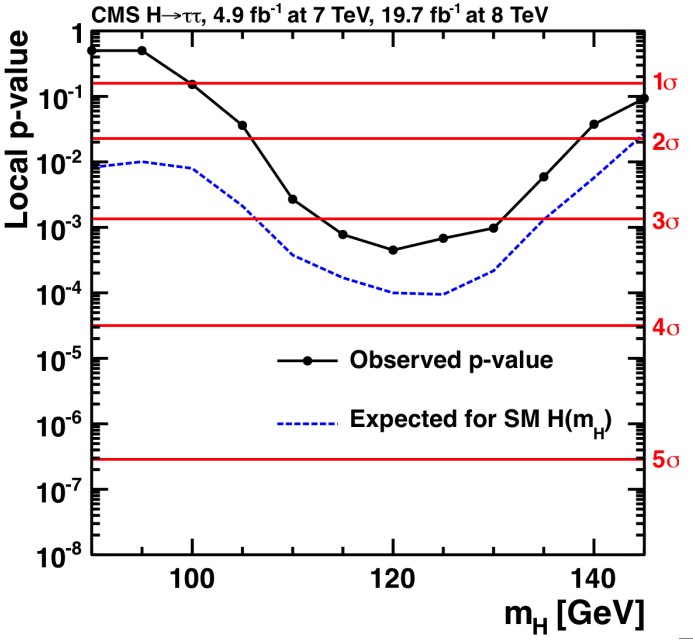
- Full combinatorial algorithm exploiting Particle Flow reconstruction
  - Explicitly reconstructing the mass of the intermediate resonances ($\rho \rightarrow \pi^+\pi^0$, $\alpha 1 \rightarrow \pi^+\pi^-\pi^+$ etc)

H → ττ results

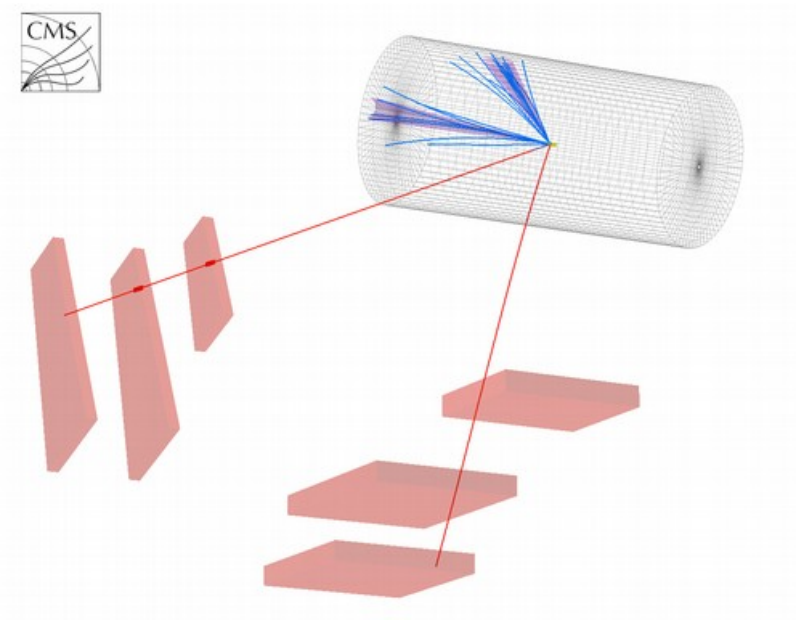


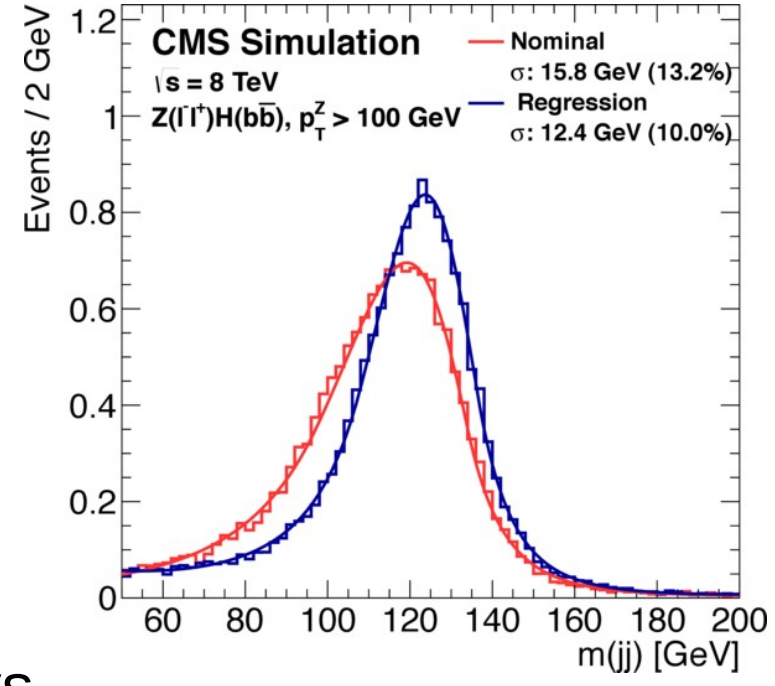


- Analysis is done in categories
  - Higher sensitivity from VBF tag
- Expected significance of 3.8σ
  - Observed significance of 3.2σ
- **Evidence for fermionic decays in a single channel**



VH → bb

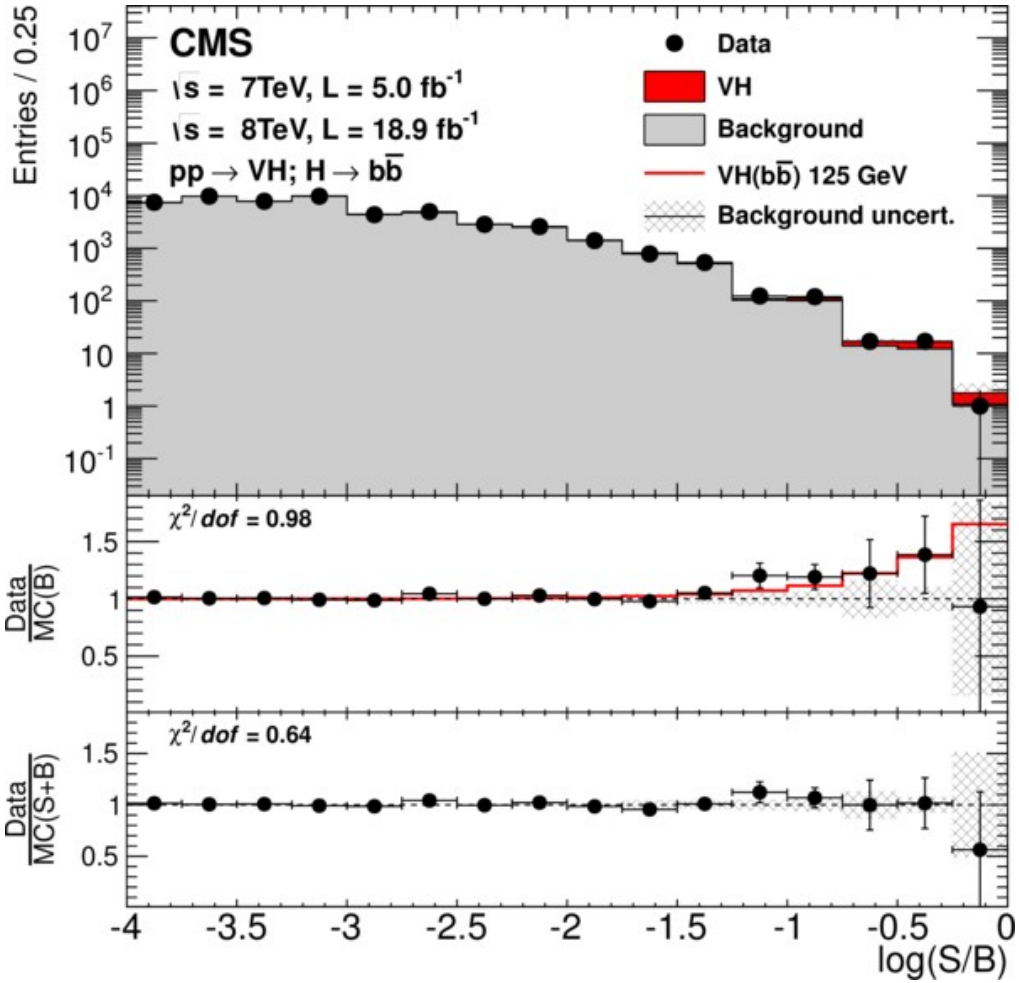


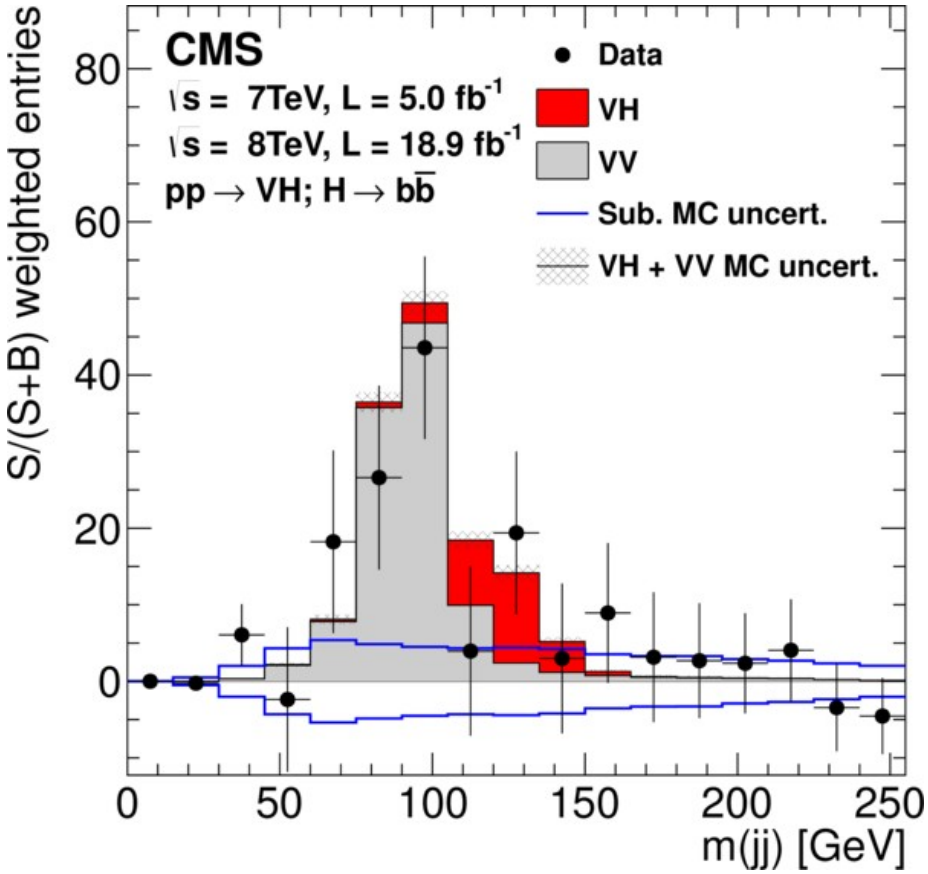


- Second probe to the fermion decays
  - Very challenging experimentally!
- Production of a vector boson plus two b-tagged jets
  - Vector boson decaying to charged leptons/neutrinos
  - Large background from Vbb/ttbar
- Sophisticated techniques used for b-tagging and bb mass reconstruction

VH → bb results

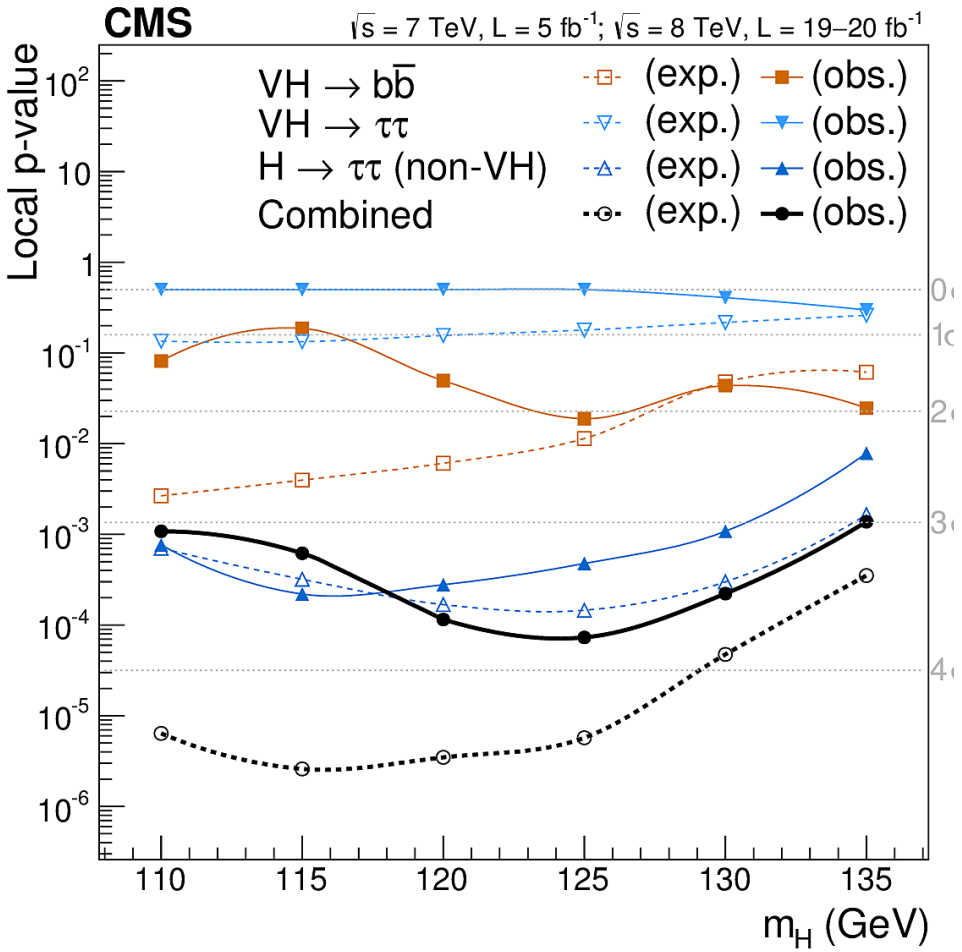
- Analysis performed in categories utilizing a series of BDTs for optimal background discrimination

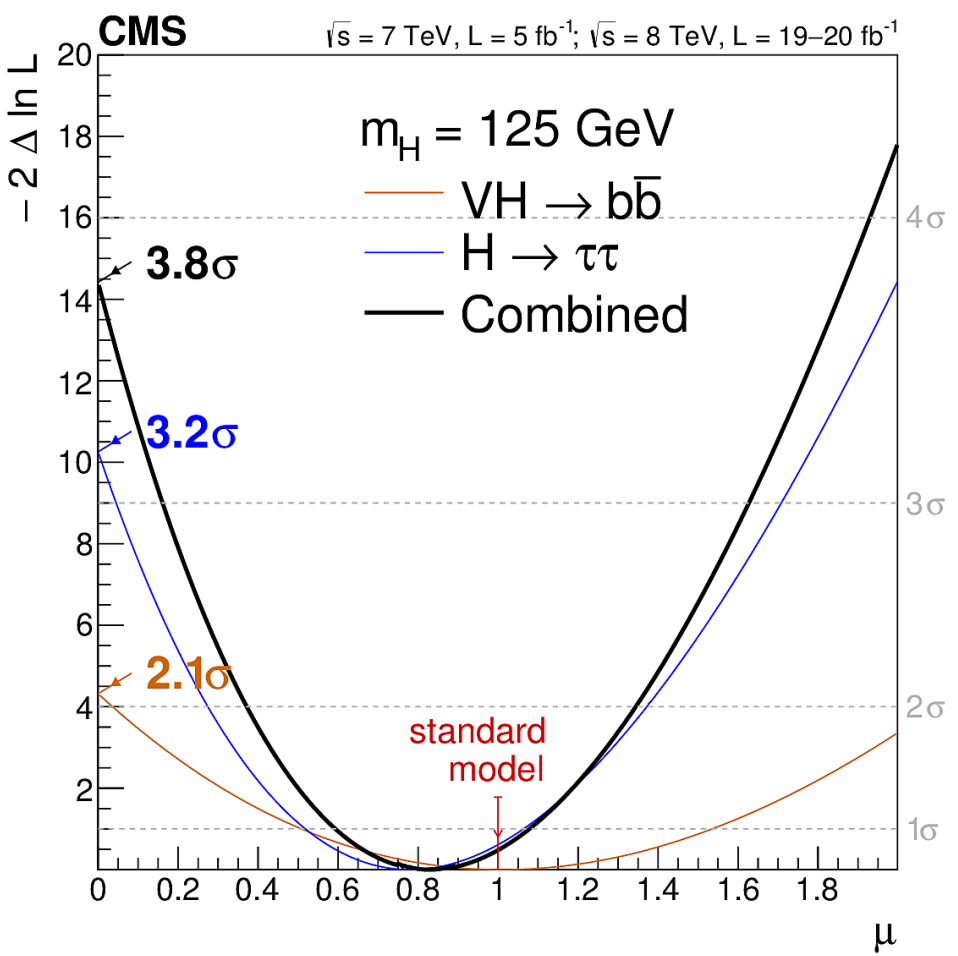




- Obs.(Exp) Significance of ~2σ @ 125 GeV
- Diboson(VZ) peak extracted as cross check >6σ

...and the fermion combination...

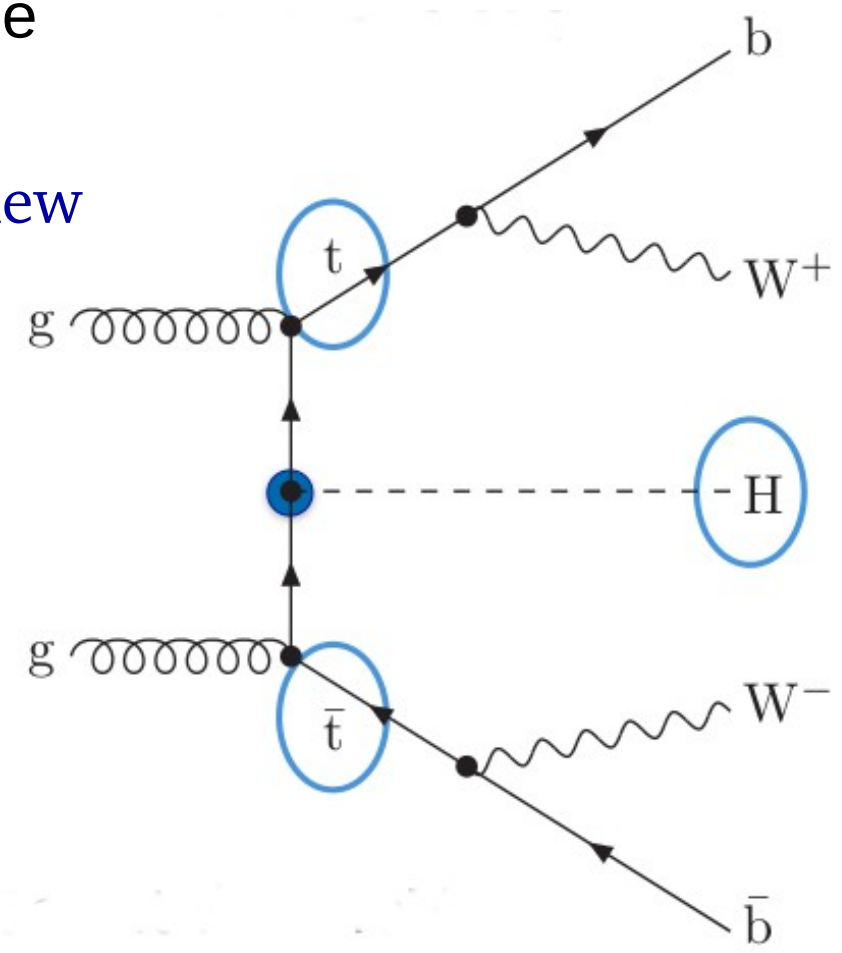




- Combining H → ττ and H → bb yields an expected significance of 4.4σ
- Observed significance of 3.8σ
- **Solid evidence of fermionic decays of the Higgs boson**

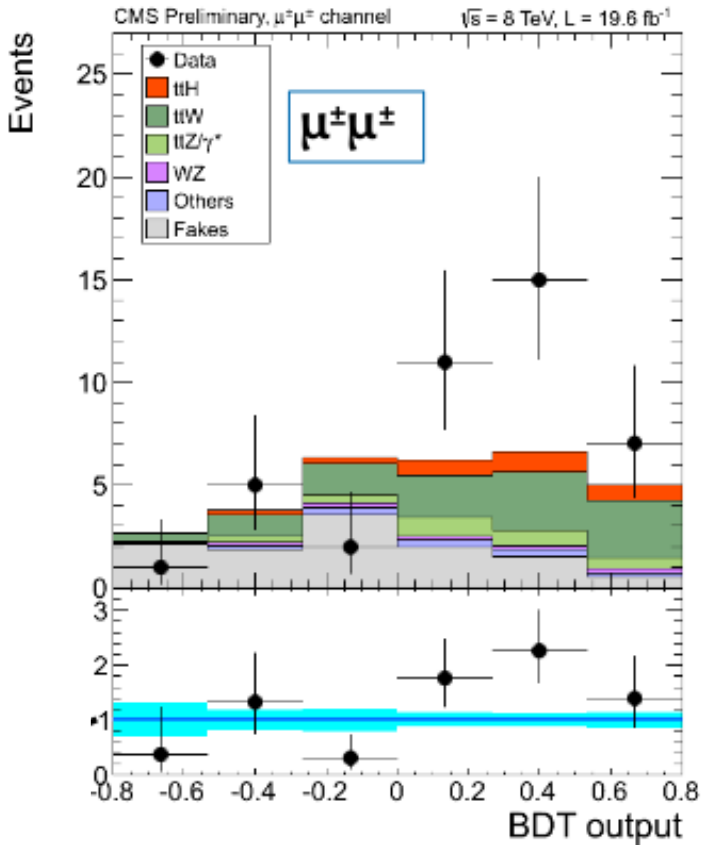
Probing directly the top coupling

- Top coupling is probed by resolving the gluon fusion loop(O(20%)).
  - Not model independent in case of new physics in the loop
- Can be probed at tree level via ttH production
  - Very low cross section but unique experimental signature → bbWWH
- CMS searches so far exploiting both hadronic and leptonic top decays
  - ttH → hadrons (H → bb/ττ)
  - ttH → photons (H → γγ)
  - ttH → leptons (H → WW/ττ/ZZ)
    - 2,3 and 4 lepton categories



ttH results

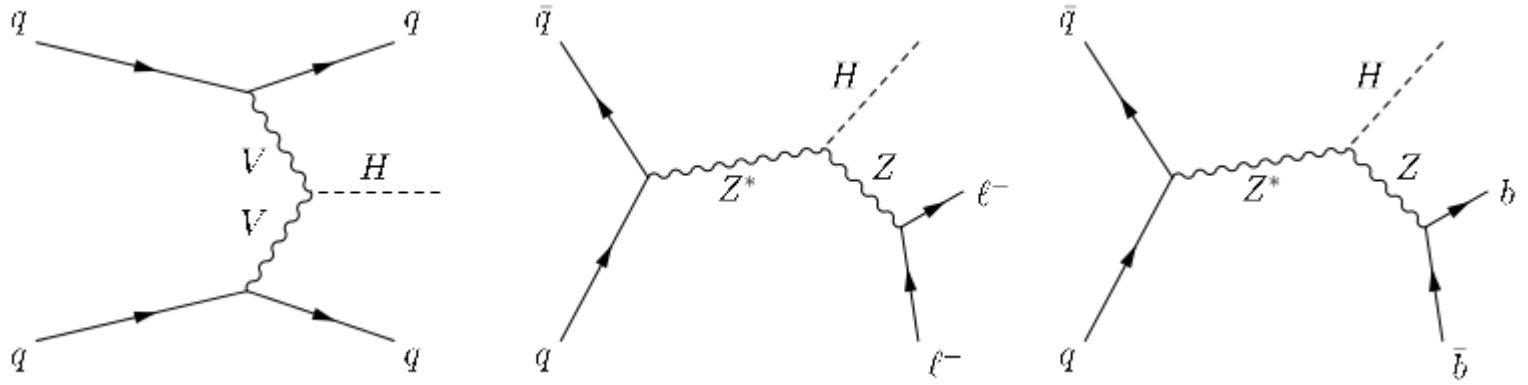
ttH Channel	$\mu = \sigma/\sigma_{SM}$ ($m_H = 125.7$ GeV)
$\gamma\gamma$	$-0.2^{+2.4}_{-1.9}$
$b\bar{b}$	$+1.0^{+1.9}_{-2.0}$
$\tau\tau$	$-1.4^{+6.3}_{-5.5}$
4l	$-4.8^{+5.0}_{-1.2}$
3l	$+2.7^{+2.2}_{-1.8}$
Same-sign 2l	$+5.3^{+2.2}_{-1.8}$
Combined	$+2.5^{+1.1}_{-1.0}$



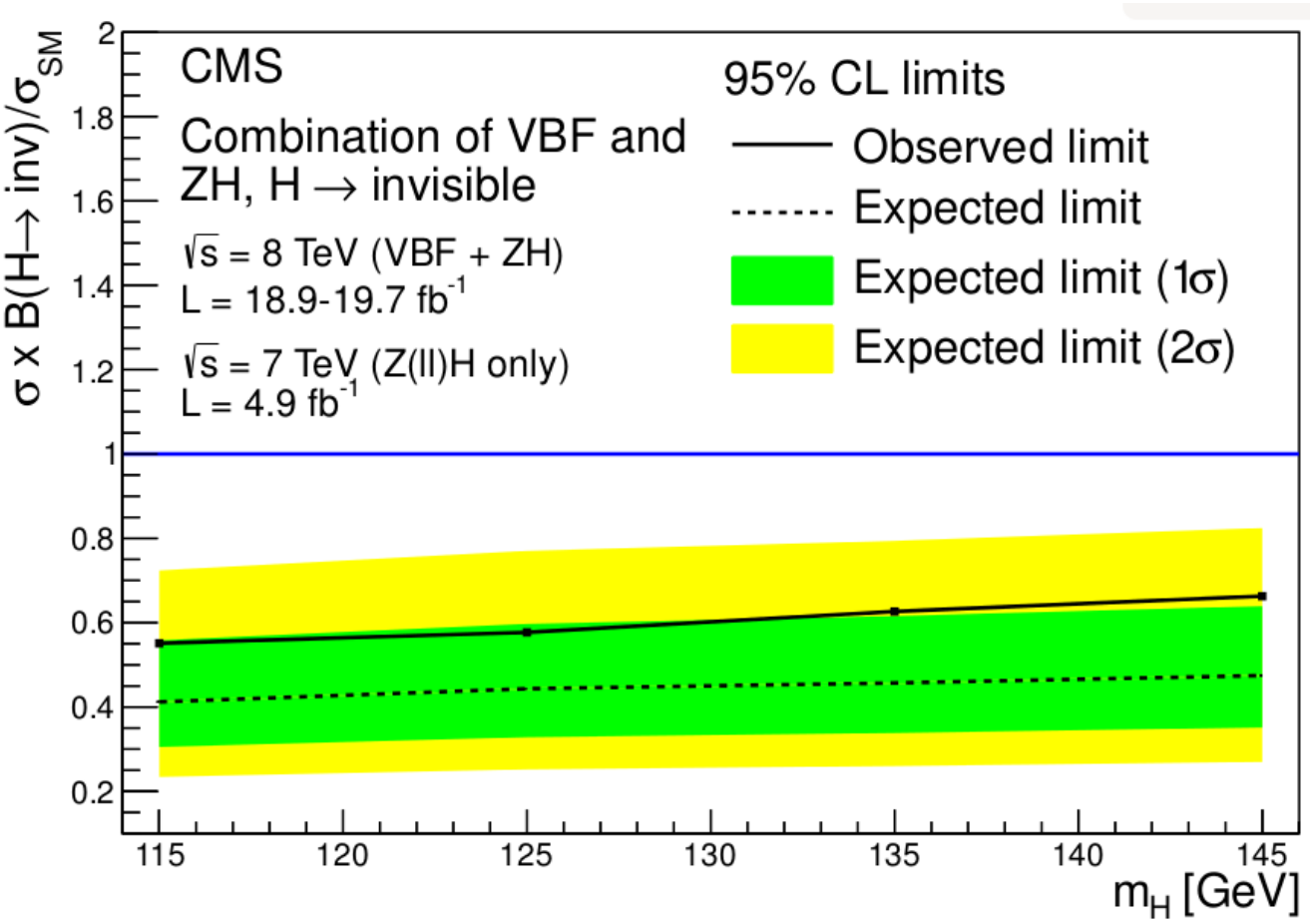
- Expected uncertainty on signal strength ~ 100%
  - Mild excess observed due to overfluctuation in SS di muon category
  - Within two standard deviations wrt SM signal

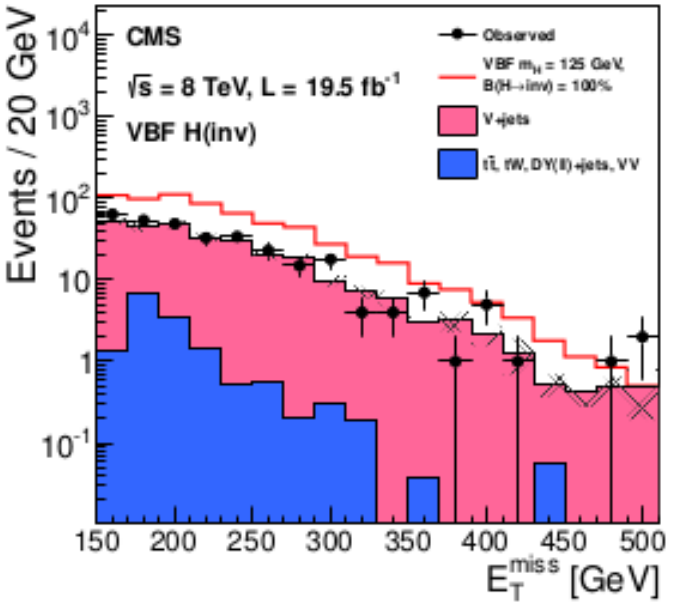
Invisible Decays

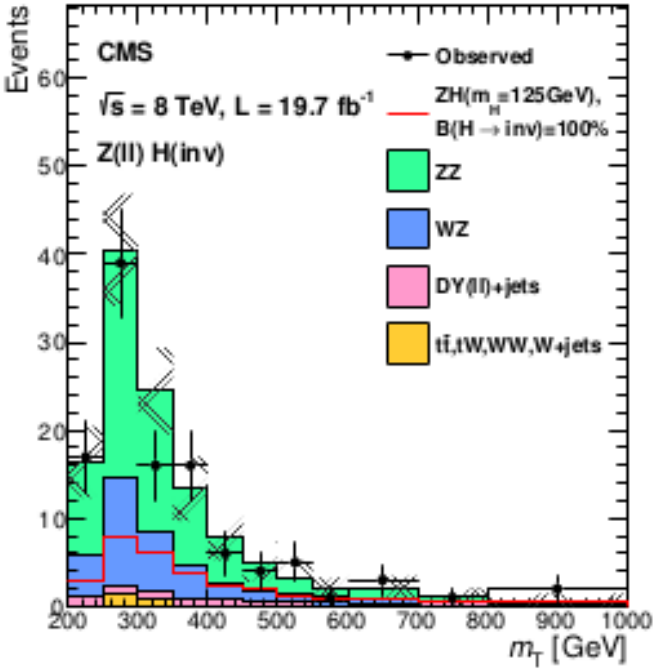
- Invisible decays of Higgs → New physics
  - Higgs → portal to the Dark Matter sector via invisible decays
- BR (H → inv) constrained by global couplings fit
- Direct searches also possible @ LHC
- Current CMS analysis on VBF H → qq+MET, ZH → ll+MET, ZH → bb+MET



Invisible Decays: Results

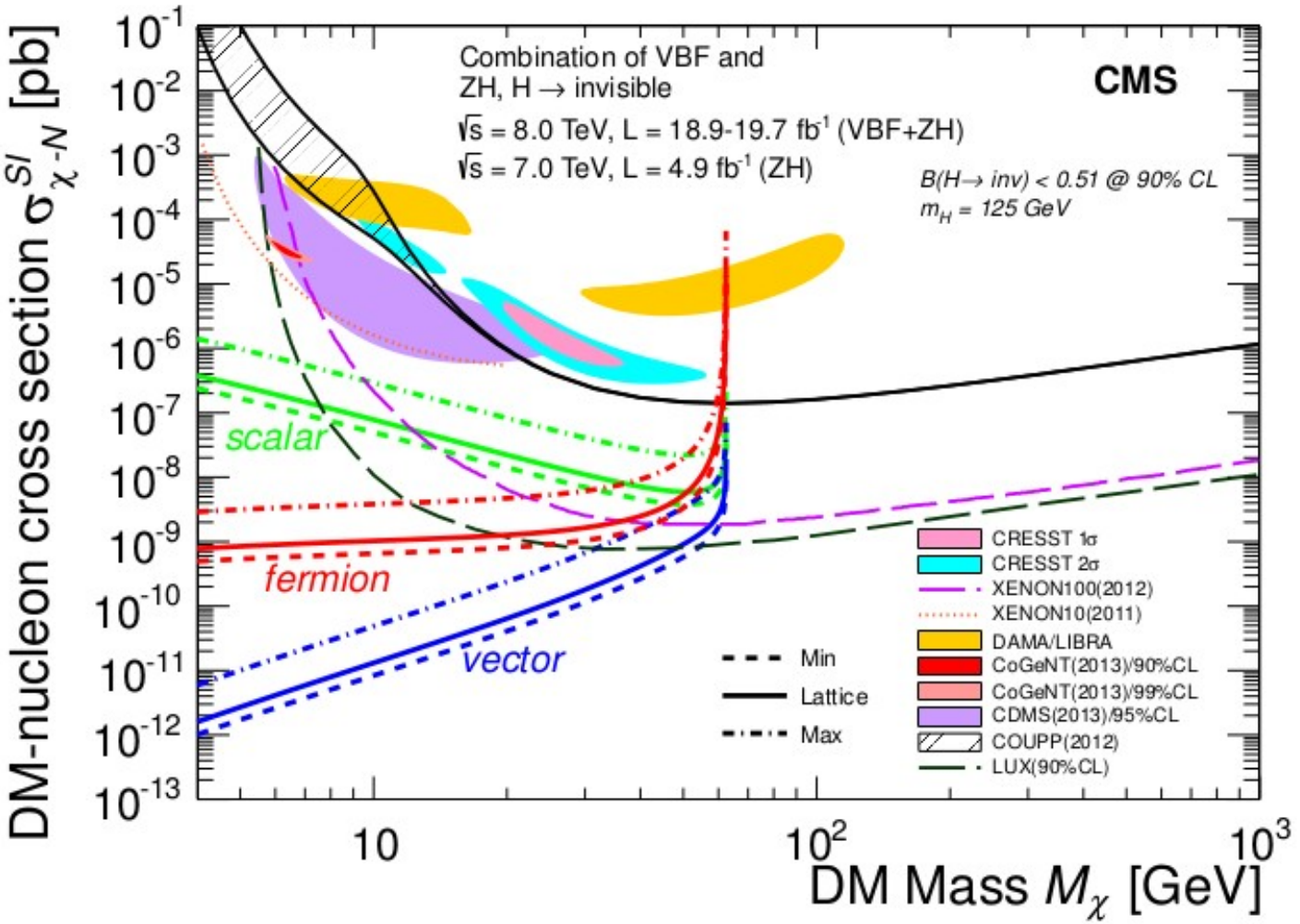






- Expected limit of 44% in the invisible BR @ 95% CL
  - Assuming SM production cross section
- Observed limit of 51%

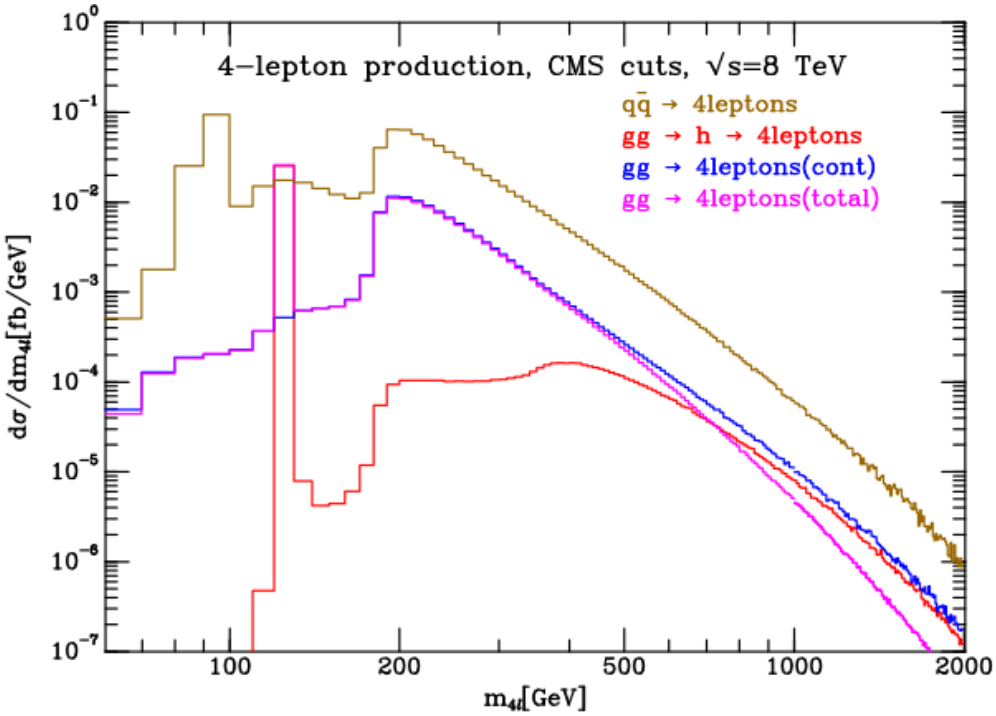
Dark Matter Interactions



- BR results reinterpreted in the context of Higgs portal of DM interactions
- LHC Higgs search extends reach at low DM mass

Bounding the Higgs width in ZZ

- Offshell Higgs production sizeable at high mass
  - ~7.6% of the total cross-section for $m_{ZZ} > 2M_Z$
  - Destructive interference between gg → H → ZZ and gg → ZZ



On shell and off shell production in ZZ:

$$\sigma^{\text{on-peak}}_{gg\to H\to ZZ} \propto \frac{g^2_{ggH} g^2_{HZZ}}{\Gamma_H}, \qquad \sigma^{\text{off-peak}}_{gg\to H\to ZZ} \propto g^2_{ggH} g^2_{HZZ}$$

- Measuring the ratio of on-shell and off-shell production cross section gives a direct handle to constrain the total width!

Proposed by F. Caola, K. Melnikov (Phys. Rev. D88 (2013) 054024), N. Kauer and G. Passarino, JHEP 08 (2012) 116, J. Campbell et al. (arXiv:1311.3589)

Analysis strategy

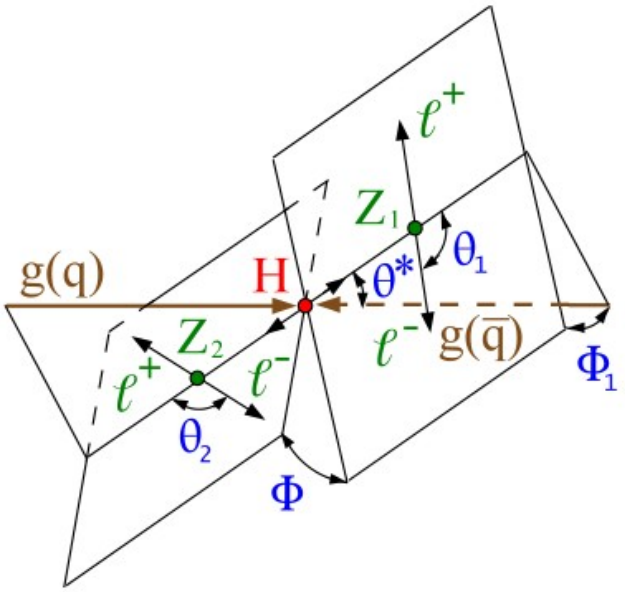
- On shell and off-shell cross-section can be expressed as a function of signal strength by scaling the couplings
  - On-shell cross section constrained by H → ZZ → 4l search
    - $\mu=\sigma/\sigma_{SM} = 0.93\ ^{+0.26}_{-0.23}$ (Expectation of $1\ ^{+0.27}_{-0.24}$)
  - Off-shell cross section is constrained by H → ZZ → 4l and H → ZZ → 2l2ν final states
- Signal background and interference are treated as three correlated distributions as a function of $r = \Gamma/\Gamma_{SM}$.

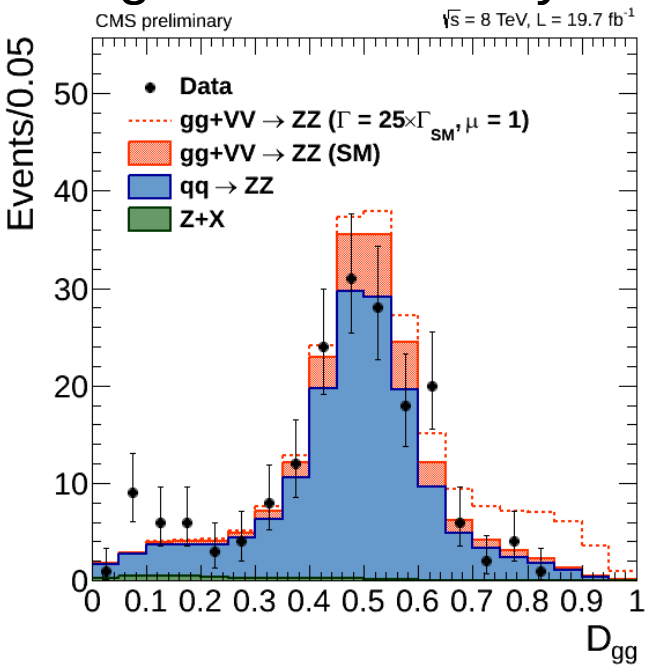
$$\mathcal{L}_i = N_{gg\to ZZ}\left[\mu r \times \mathcal{P}^{gg}_{sig} + \sqrt{\mu r} \times \mathcal{P}^{gg}_{int} + \mathcal{P}^{gg}_{bkg}\right] + N_{VBF}\left[\mu r \times \mathcal{P}^{VBF}_{sig} + \sqrt{\mu r} \times \mathcal{P}^{VBF}_{int} + \mathcal{P}^{VBF}_{bkg}\right] + N_{q\bar{q}\to ZZ}\mathcal{P}^{q\bar{q}}_{bkg} + \ldots$$

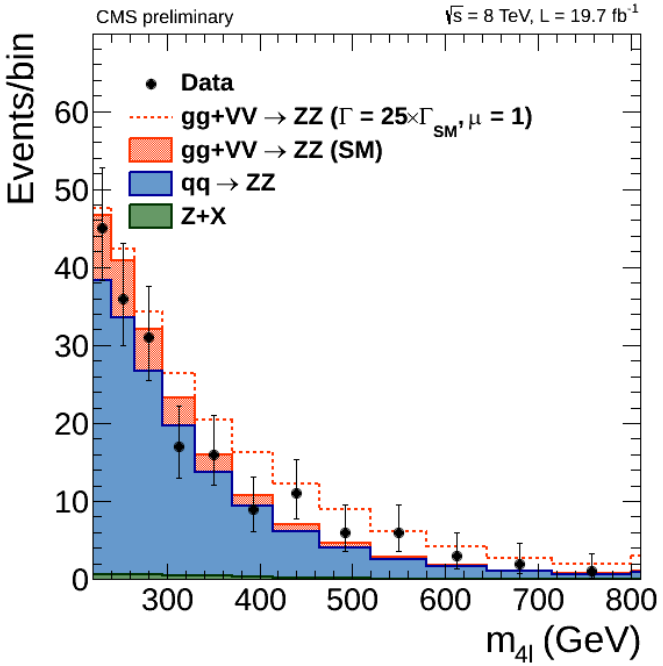
- ggH signal simulated with gg2VV / MCFM, VBF using PHANTOM
- NNLO K factors applied as a function of mZZ; same K factors applied to continuum backgrounds [M. Bonvini et al. (Phys. Rev. D88 (2013) 034032)]

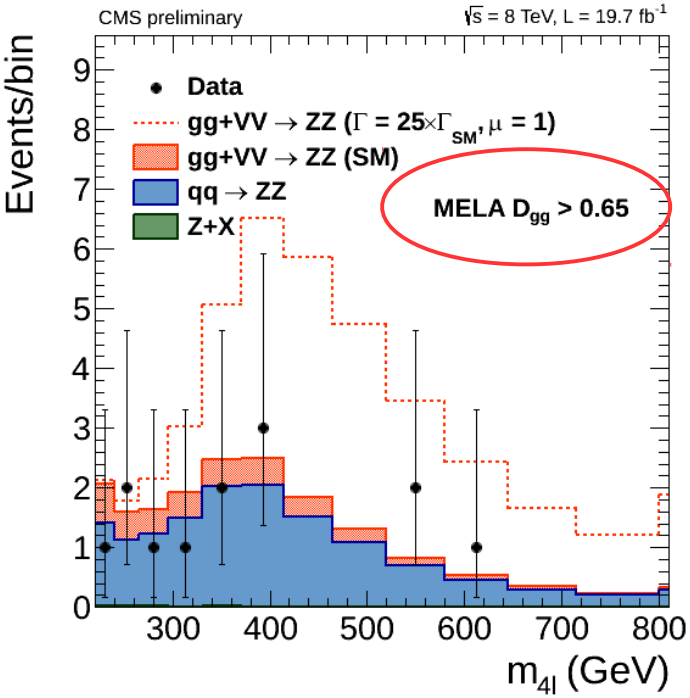
Four lepton final state

- Re-using baseline low mass H → ZZ* → 4l selection
- Exploiting full reconstructed final state to separate gg → ZZ from qq → ZZ at high mass
  - Using angular discriminant as in baseline search
- Signal extracted by 2D fit in mass and

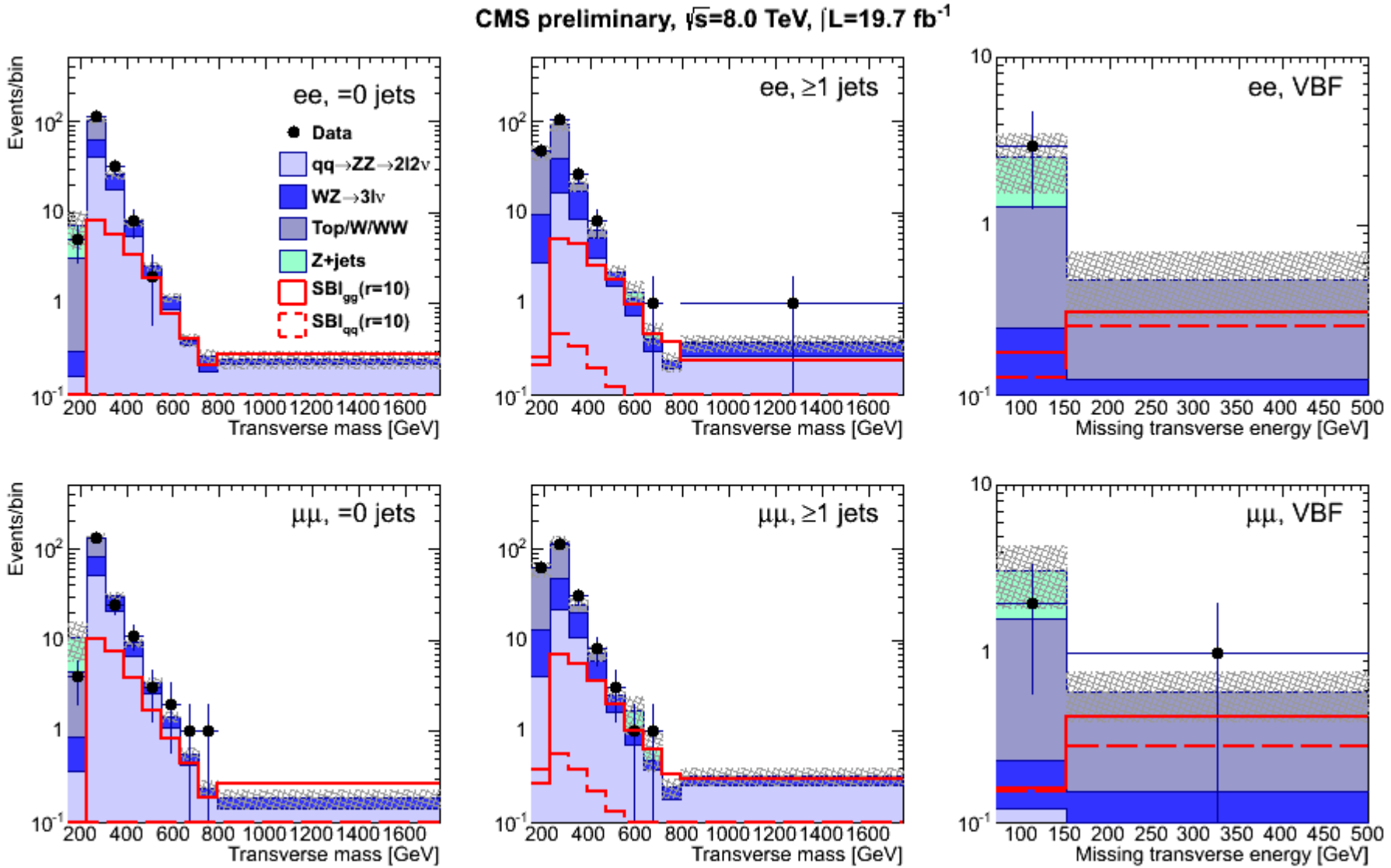








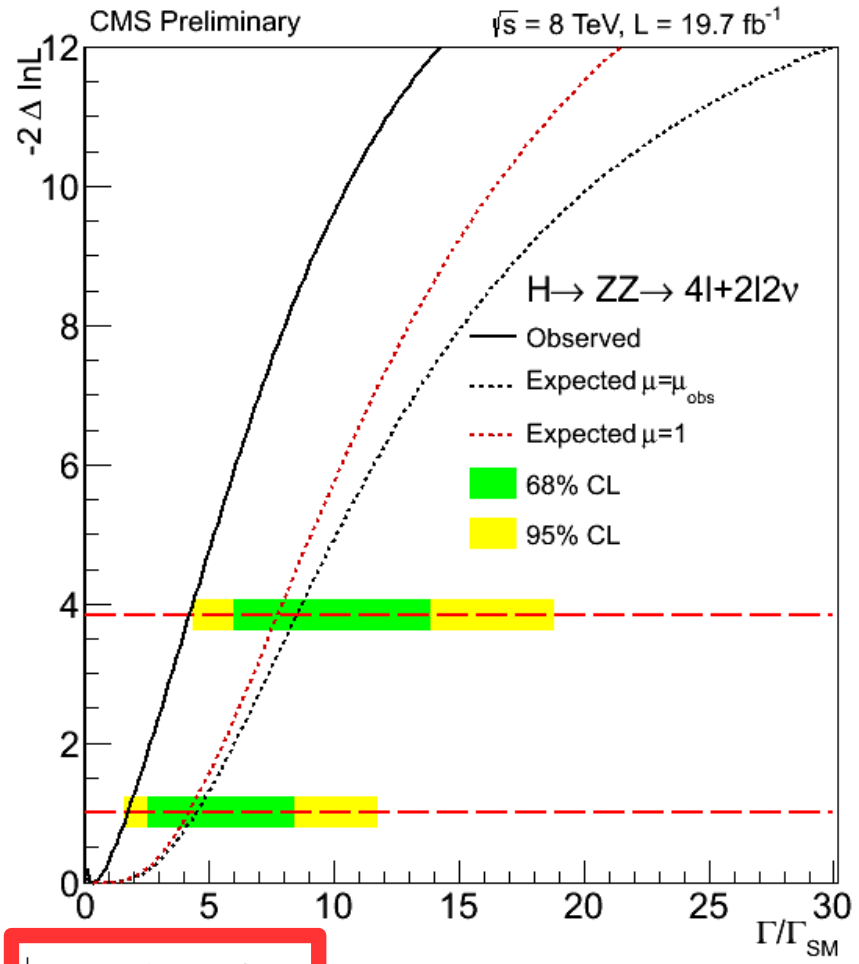
2l2ν final state



- Requiring a di-lepton and high missing ET
  - Signal extracted by transverse mass shape fit in jet categories

Results on the total width

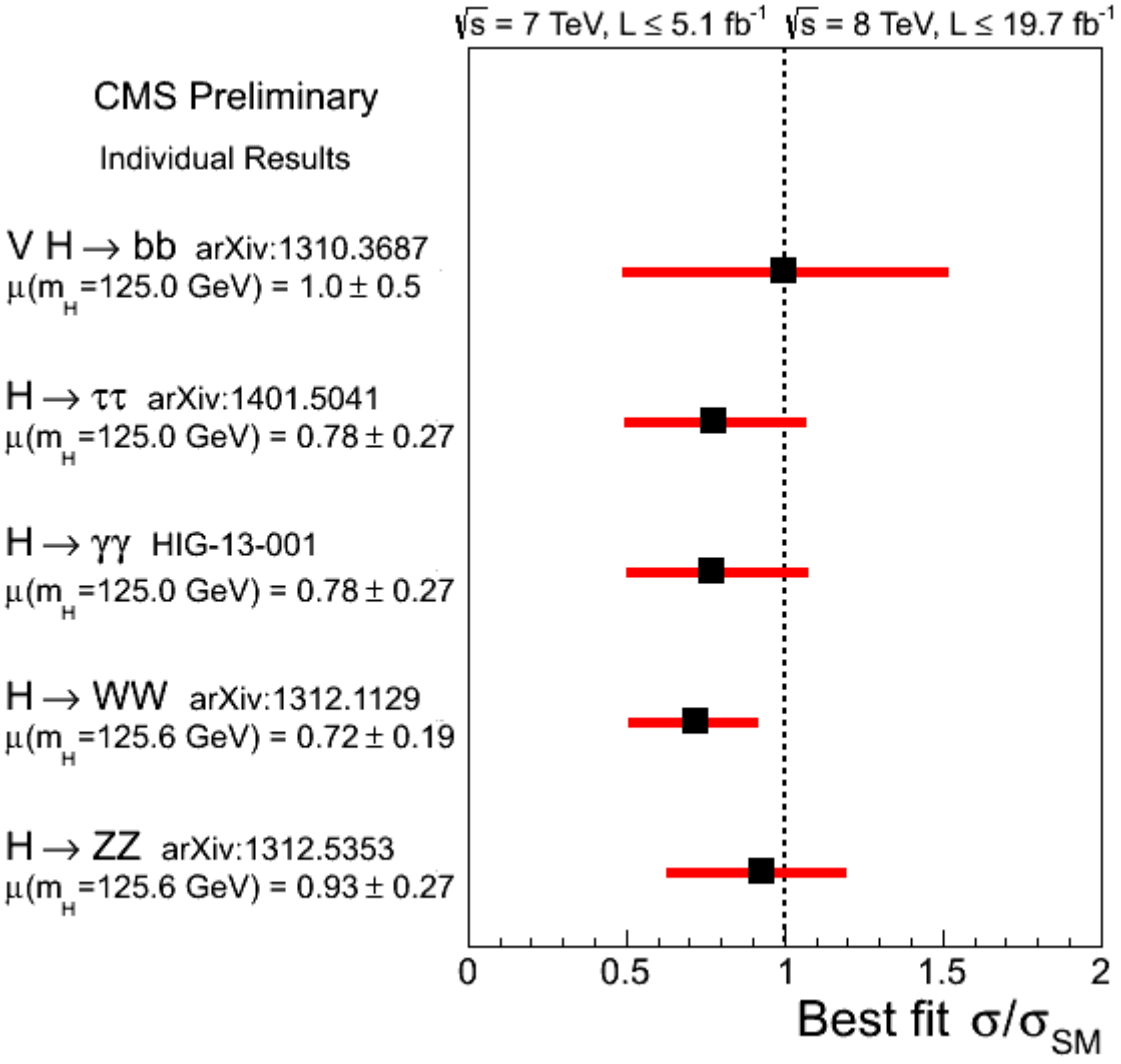
- Expected limit on the total width of 8.5 x SM @95% CL
  - Observed limit of 4.2 x SM corresponding to ~17 MeV @ 95% CL
- Sensitivity exceeds all expectations and enhances the LHC role as a Higgs factory in the next years



	4ℓ	$2\ell 2\nu$	Combined
Expected 95% CL limit, r	11.5	10.7	8.5
Observed 95% CL limit, r	6.6	6.4	4.2
Observed 95% CL limit, Γ_H(MeV)	27.4	26.6	17.4
Observed best fit, r	$0.5^{+2.3}_{-0.5}$	$0.2^{+2.2}_{-0.2}$	$0.3^{+1.5}_{-0.3}$
Observed best fit, Γ_H(MeV)	$2.0^{+9.6}_{-2.0}$	$0.8^{+9.1}_{-0.8}$	$1.4^{+6.1}_{-1.4}$

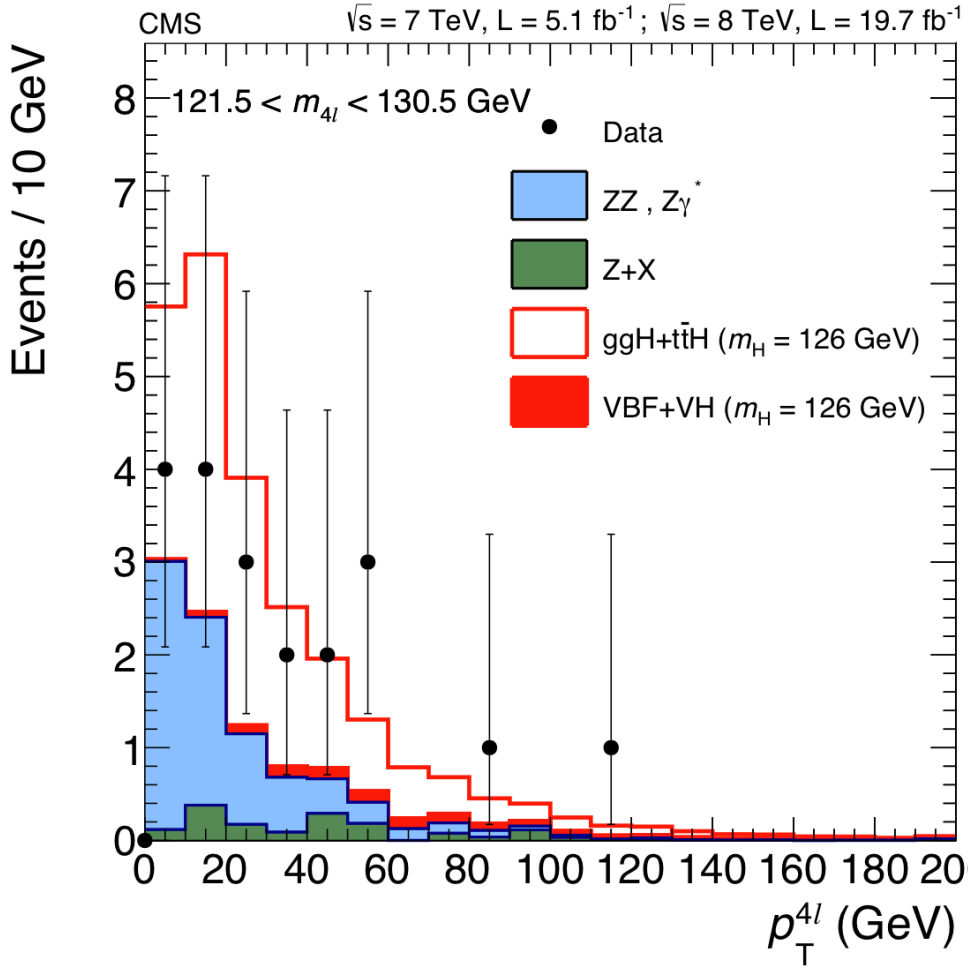
Summary and Conclusions

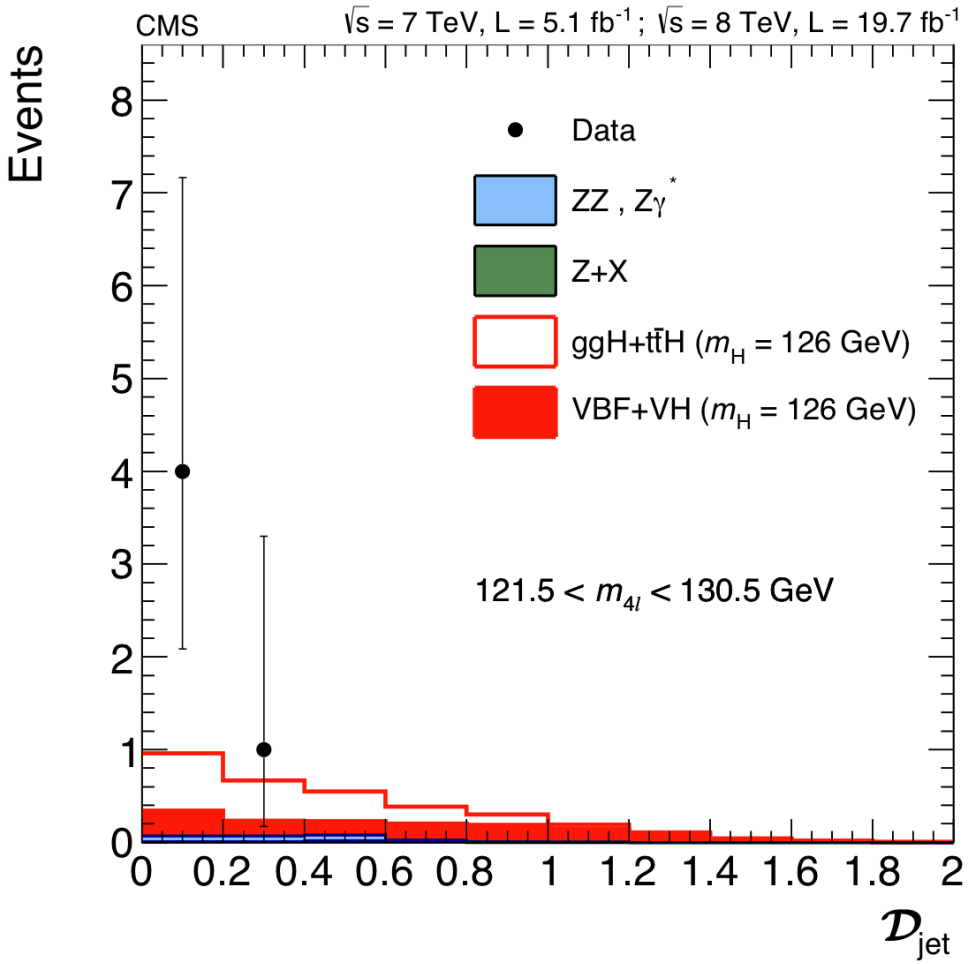
- Final publications on the Higgs from CMS run I data are being produced
  - $H \rightarrow \gamma\gamma$ and combination coming soon
- Run I exceeded every expectation
- The newly discovered boson looks more and more consistent with the SM scalar
- First results on the total width from interferometry very promising
  - LHC was not expected to achieve such precision



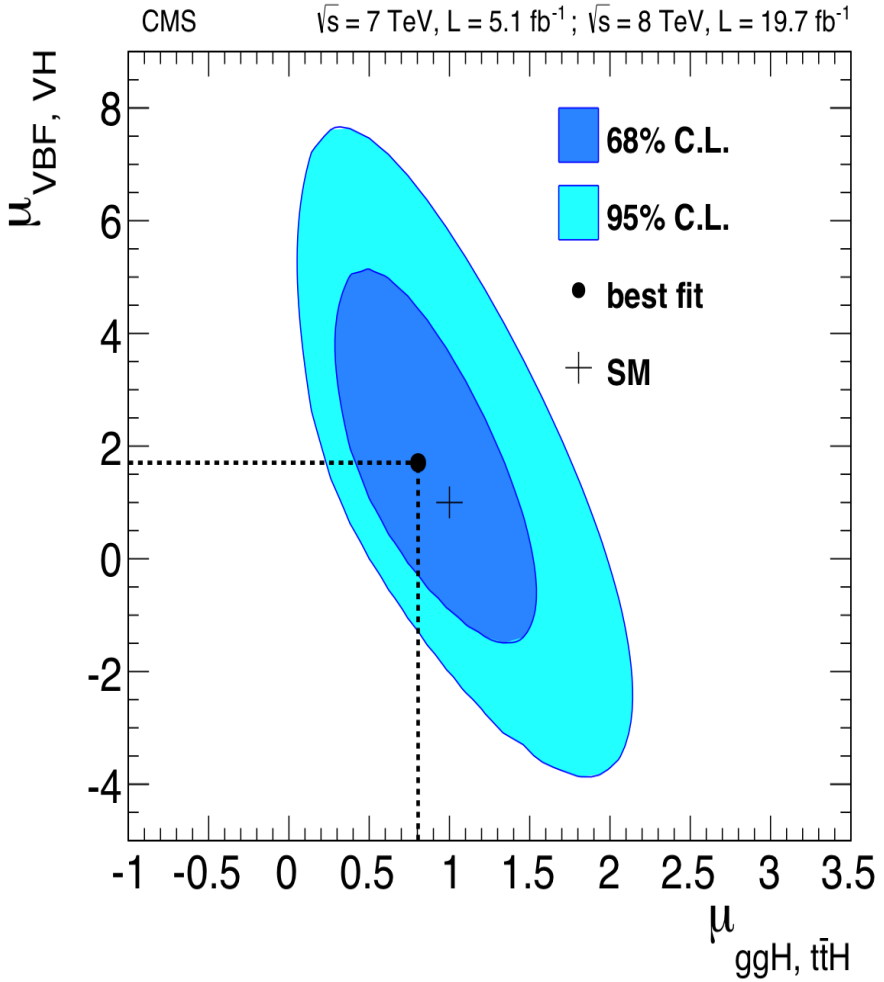
BACKUP

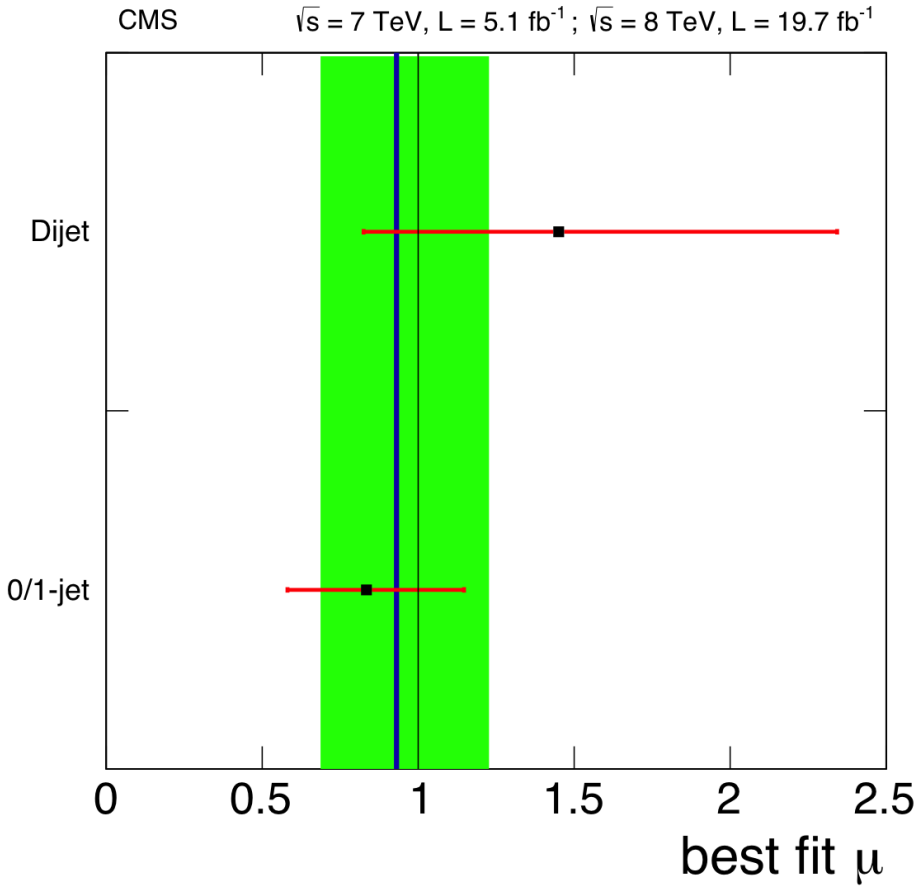
H → ZZ → 4l [jet categories]



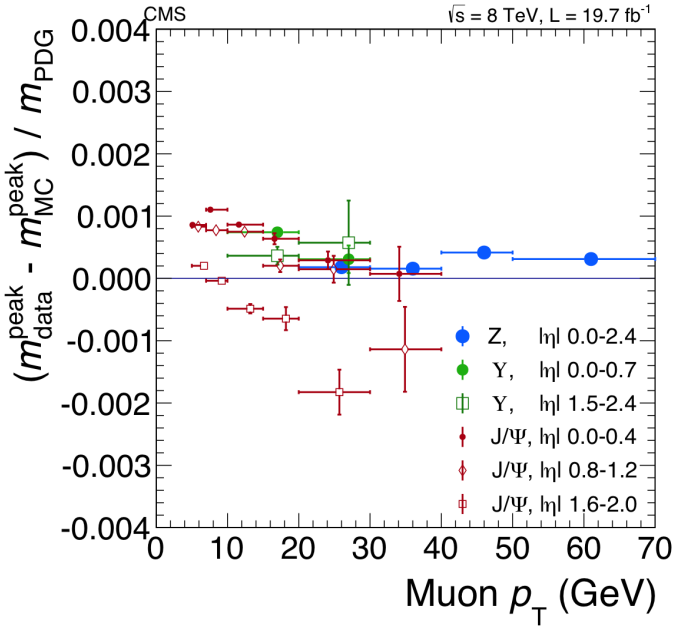


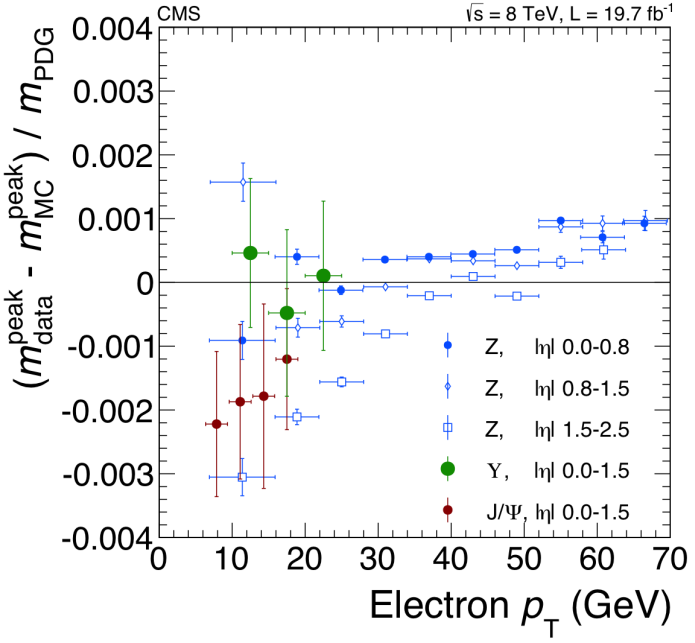
H → ZZ → 4l [production modes]

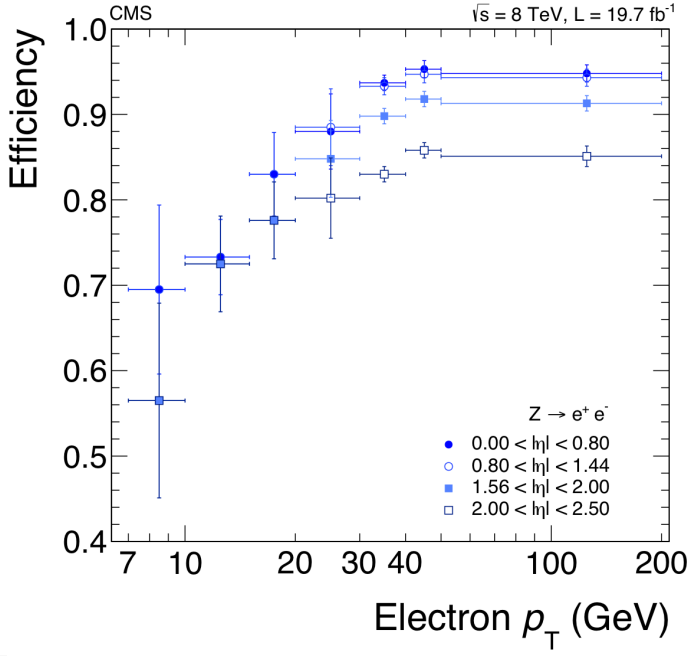


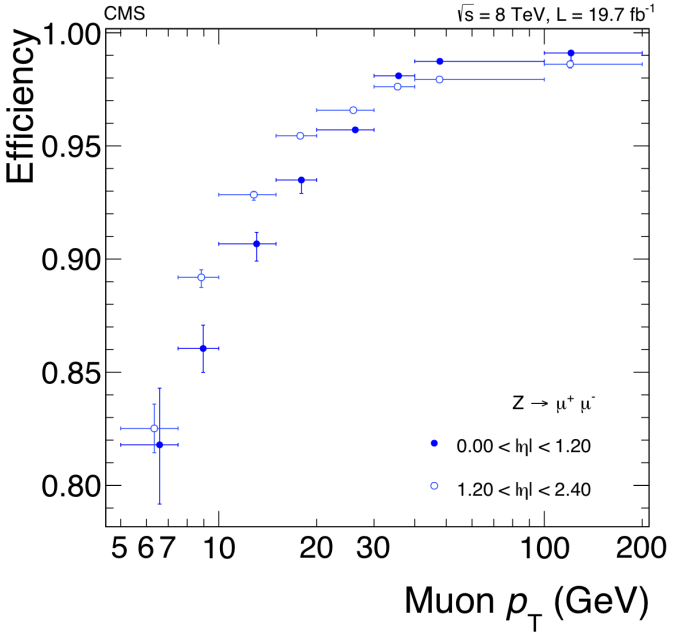


Lepton performance

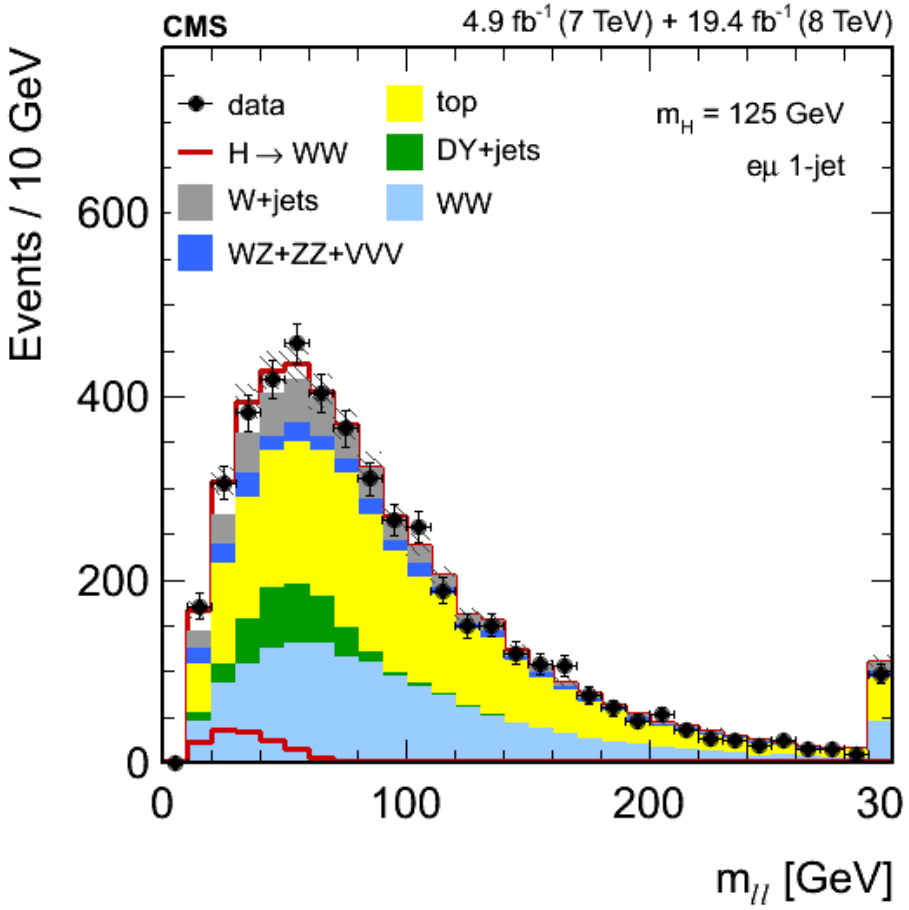


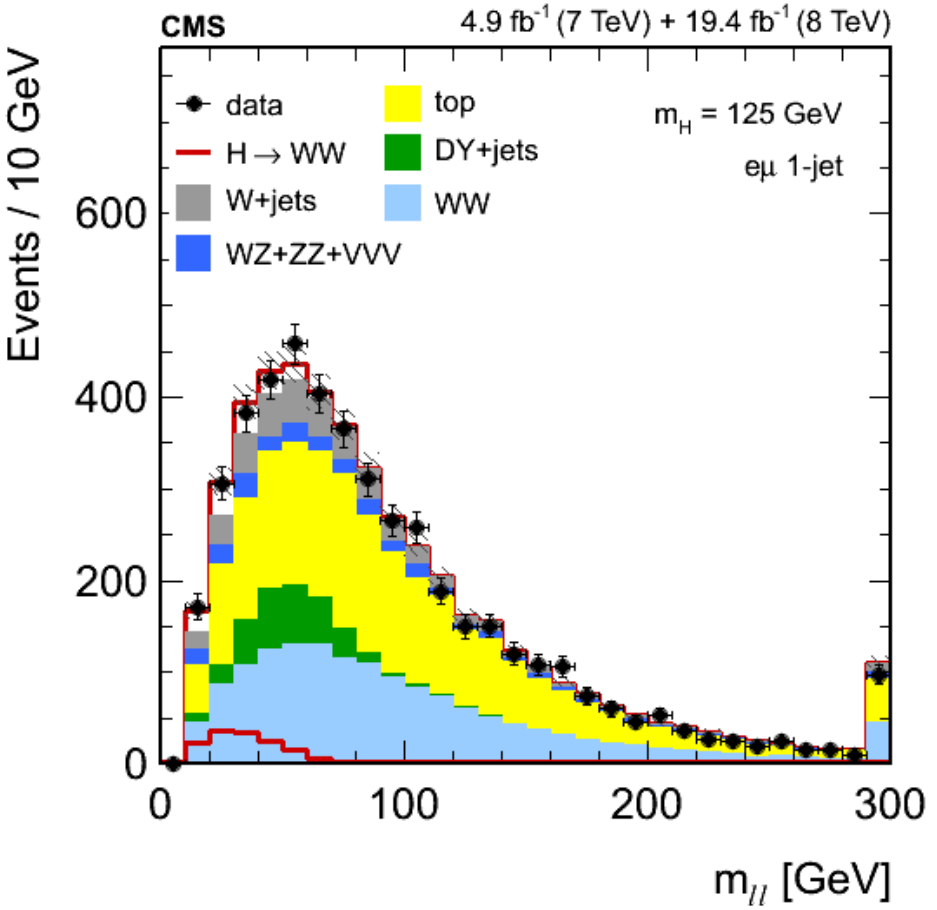




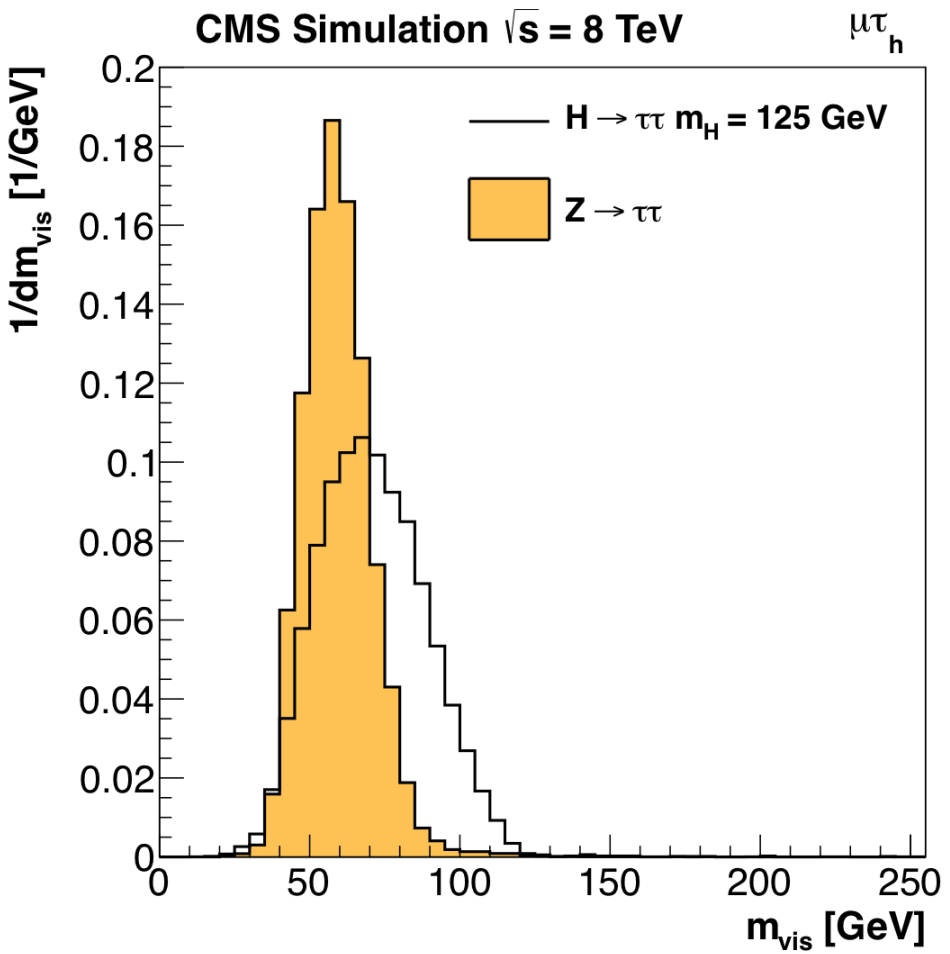


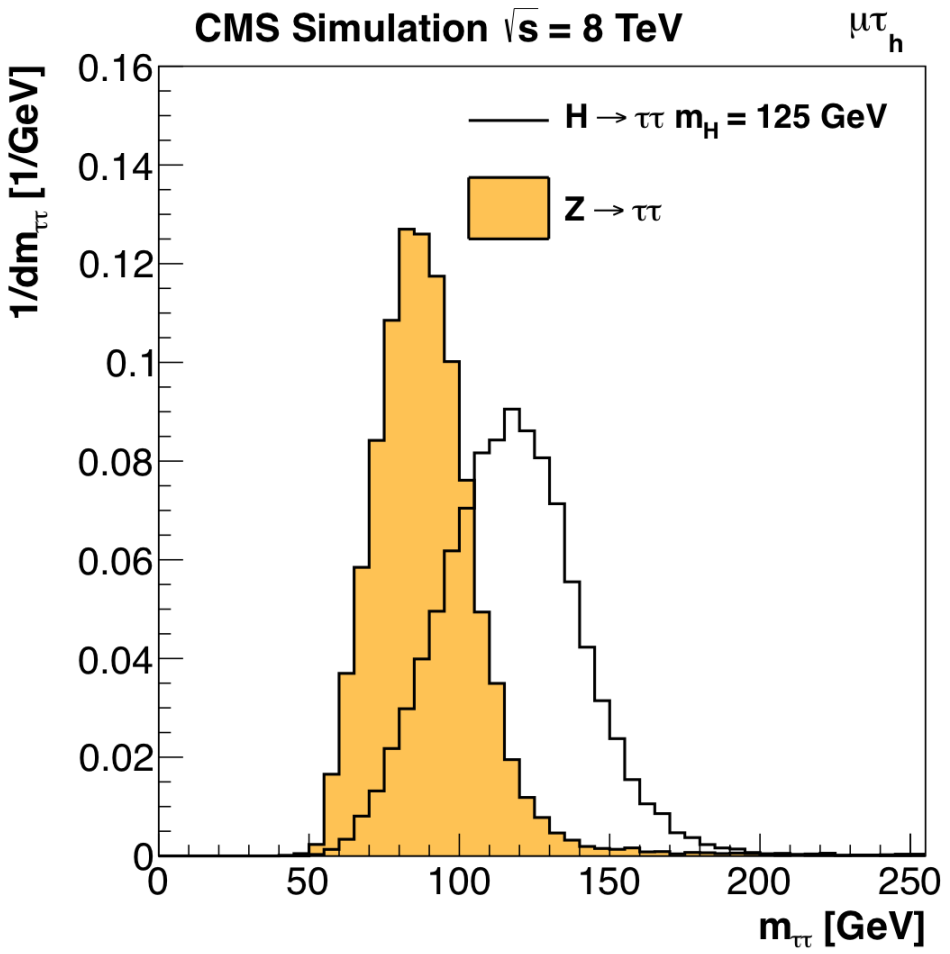
H → WW mass plots (unweighted)





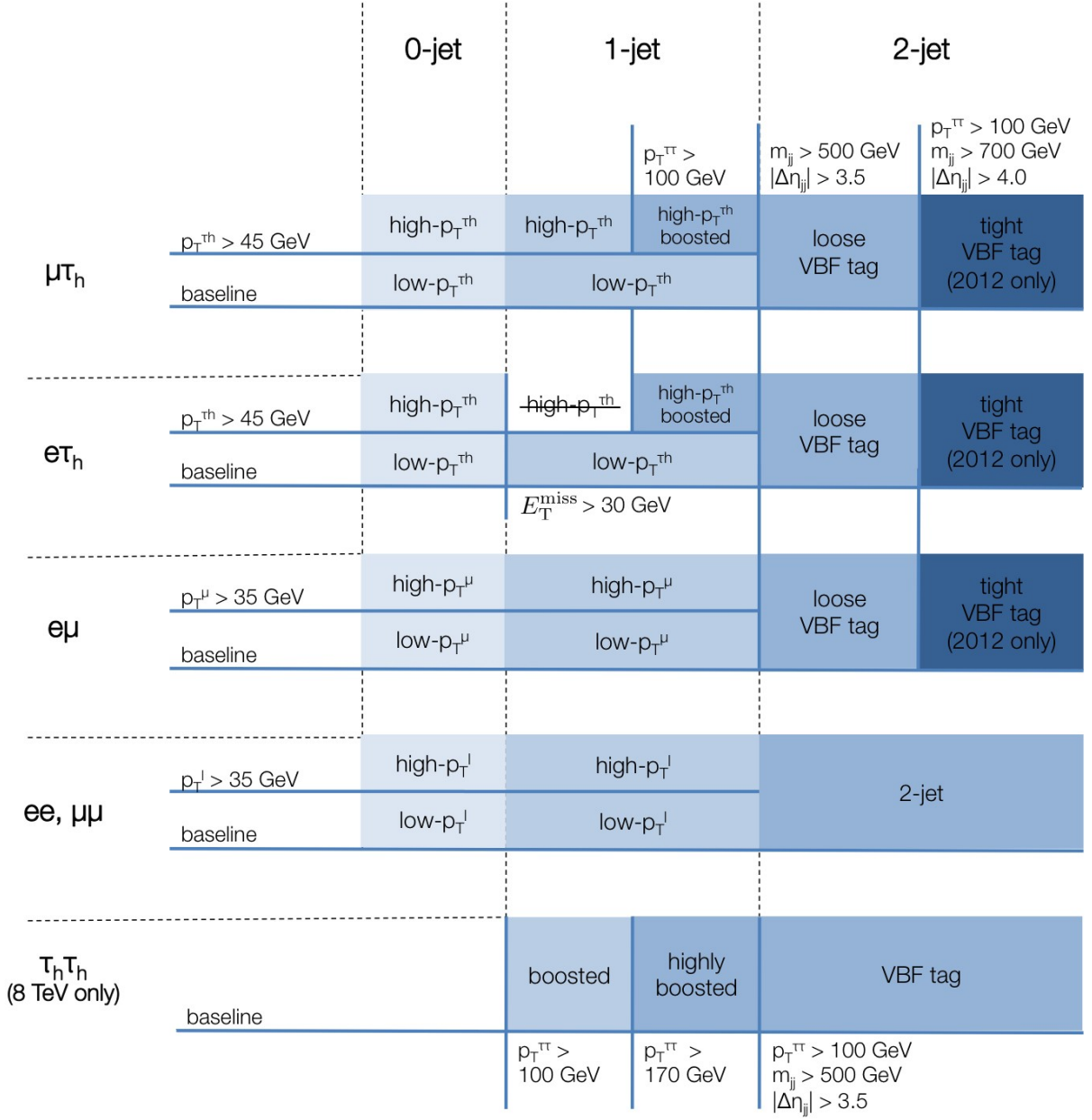
Di-tau mass reconstruction



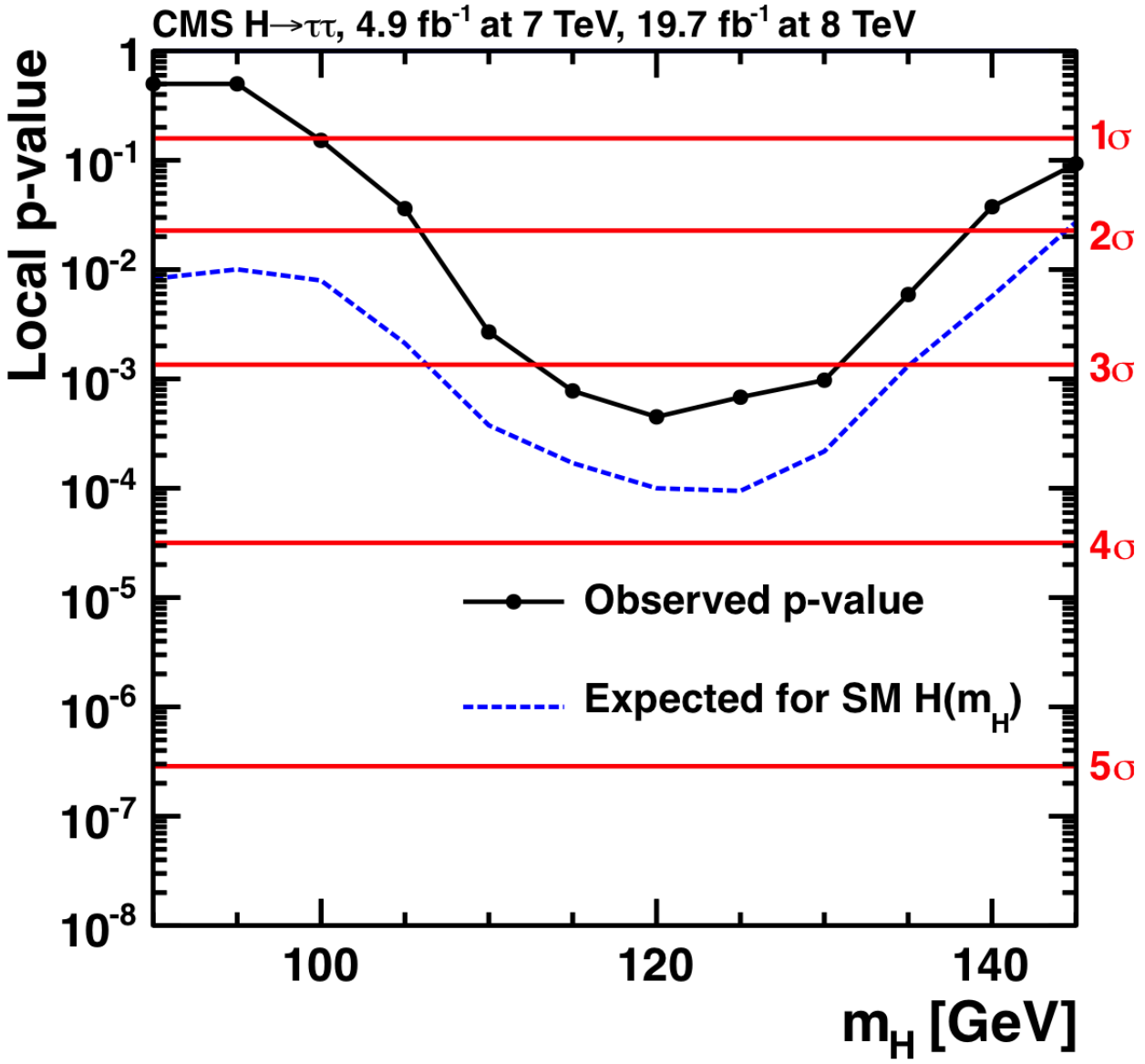


- Two to four neutrinos in the final state
  - Four constrains from tau mass and MET
  - Use probability to estimate the mass

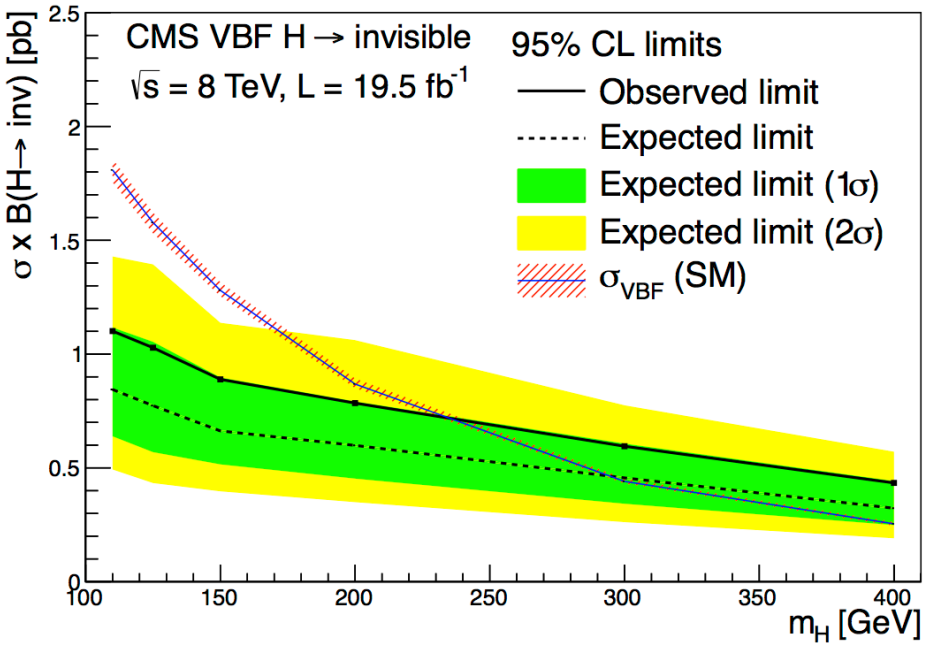
H → tautau categories

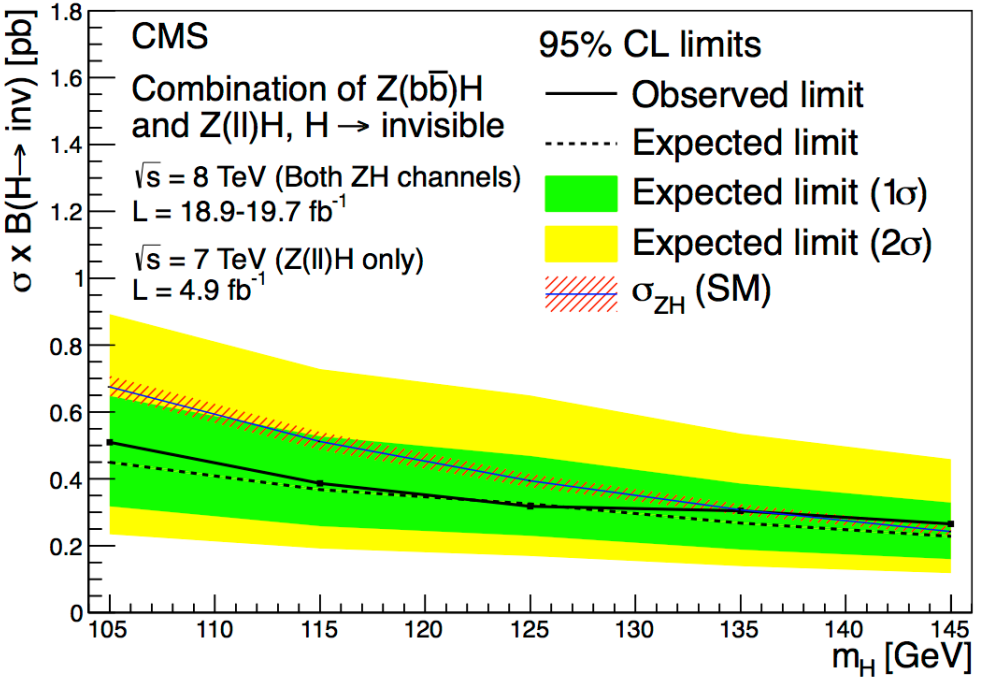


H → tau tau [non VH]

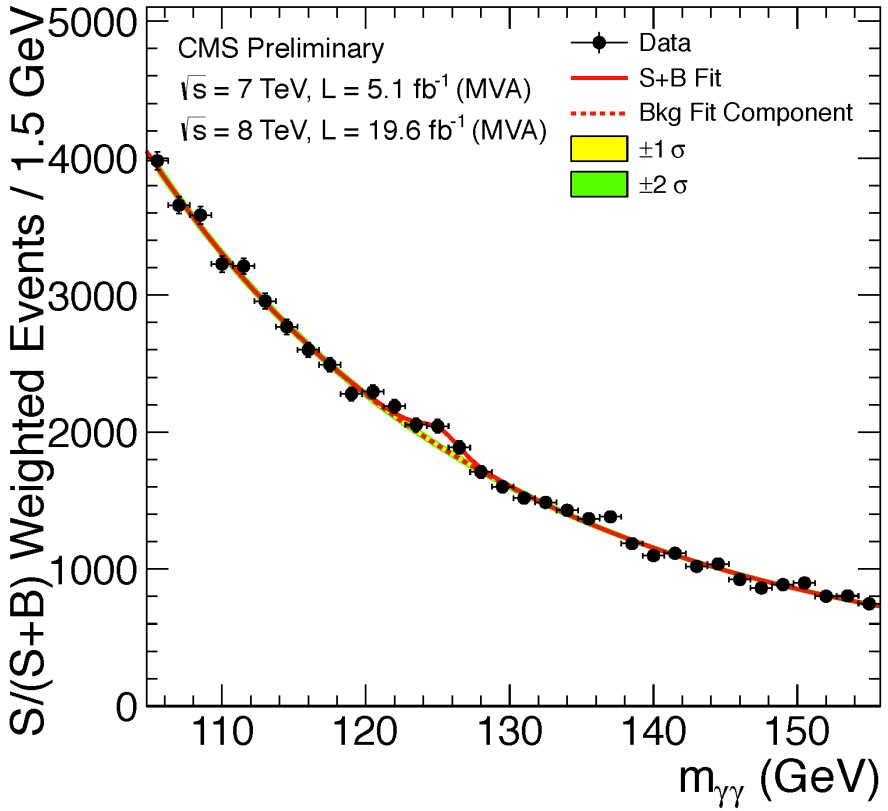


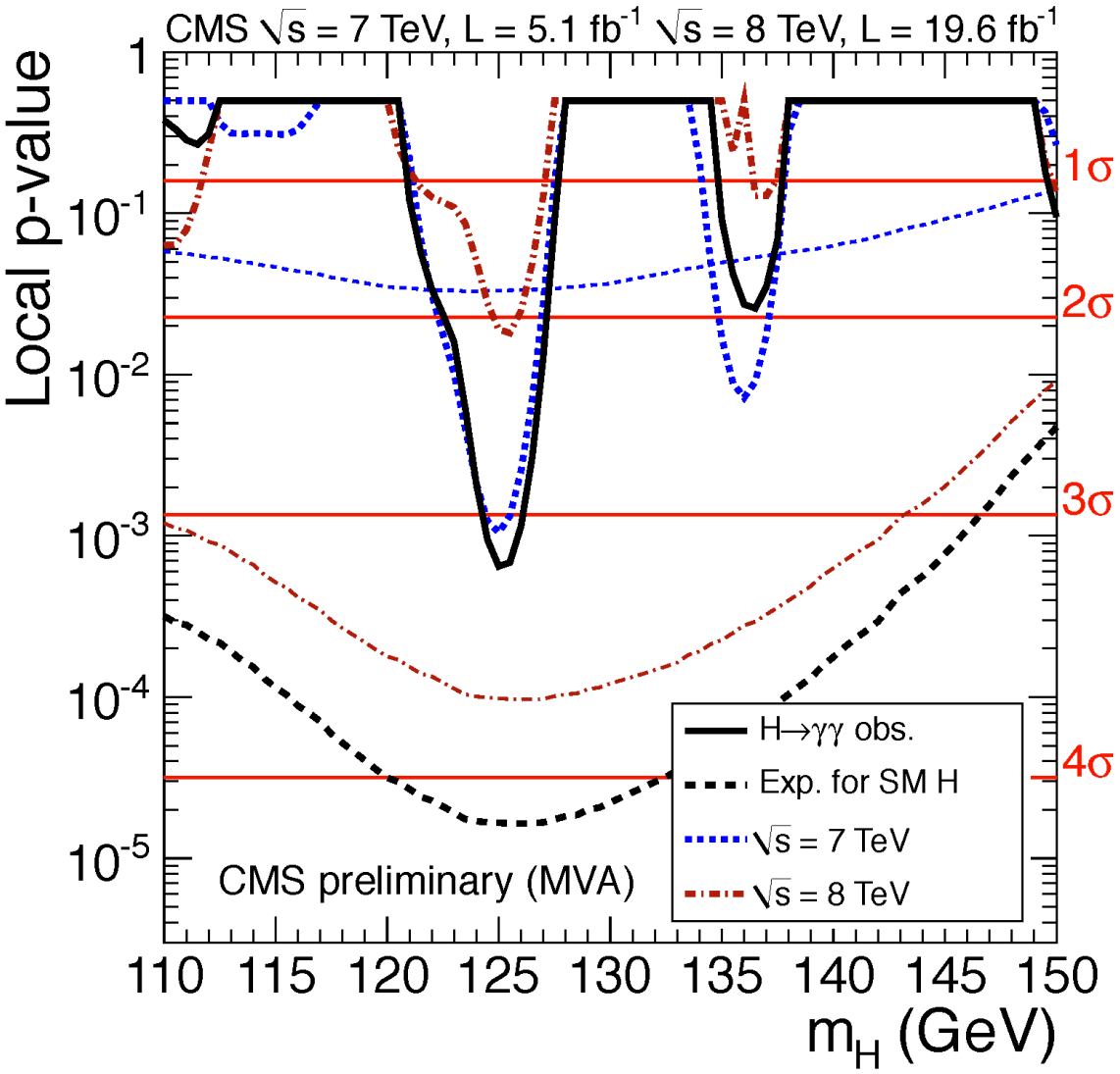
H → Invisible results per channel





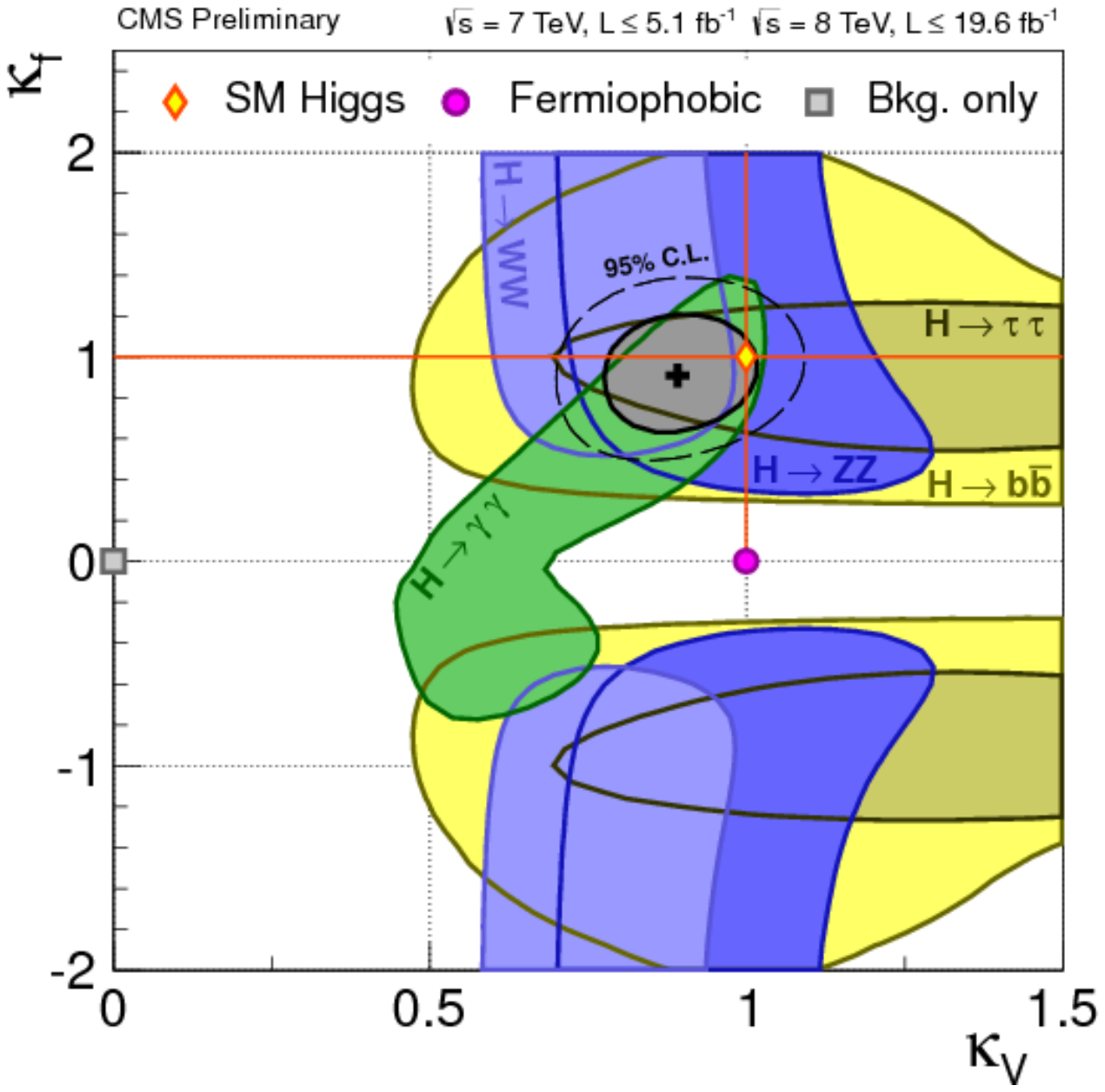
Moriond 2013 H → gamma gamma



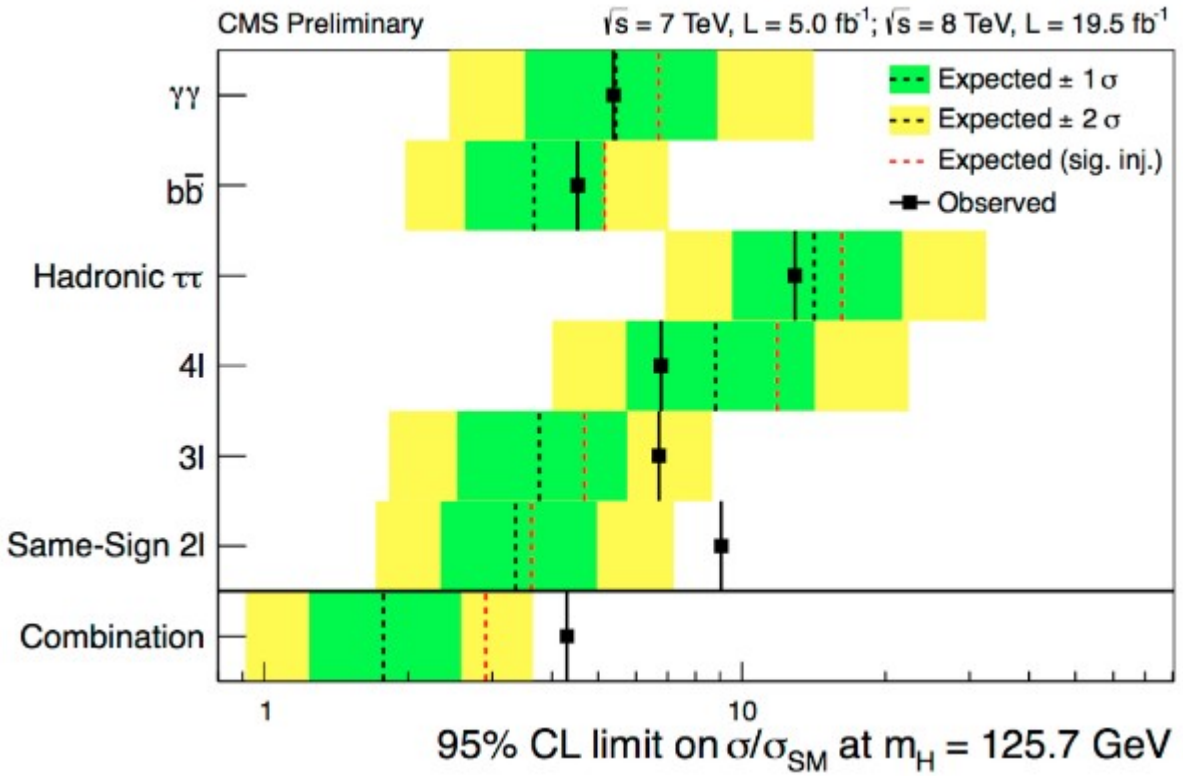


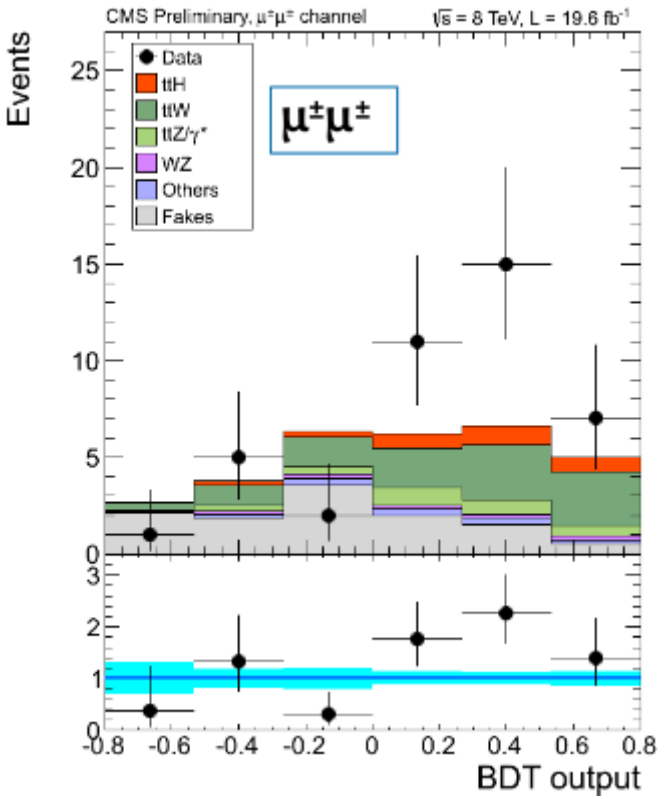
- Signal strength of 0.78±0.27 at mH=125 GeV
- Mass of 125.4 ± 0.5(stat.) ± 0.6(syst.)

Spring 2013 combo:couplings



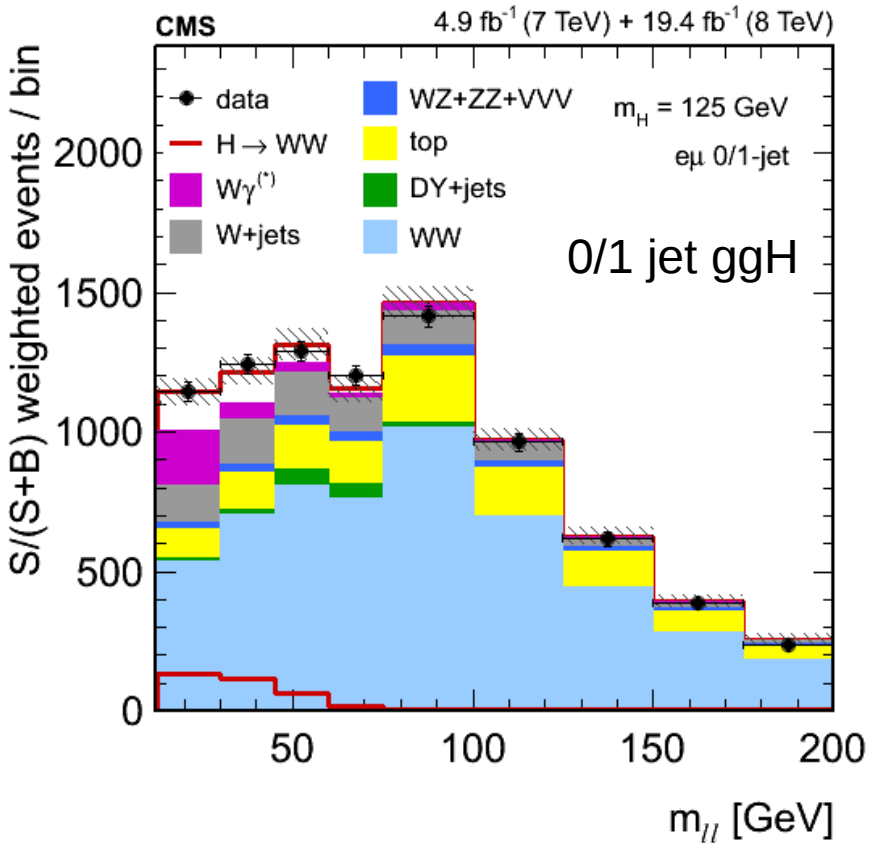
ttH: Upper limits

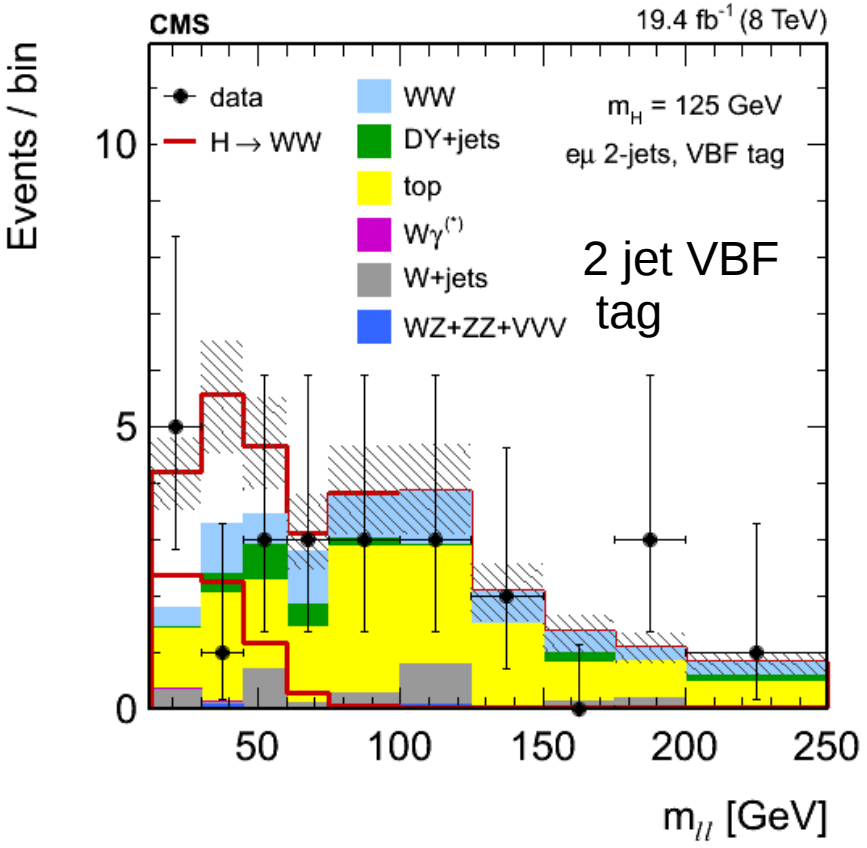




- Expected Combined Limit of 1.8 xSM @95 % CL in the absence of ttH signal (for m =125.7 GeV)
  - 2.9xSM in presence of SM Higgs
  - Observed limit of 4.3xSM (driven by same sign di-muon +4 jets final state)

H → WW* distributions





- Clean SM Higgs signal observed on top of the large background
- Deficit in VBF tagged category but low statistics