Higgs decaying into bosons

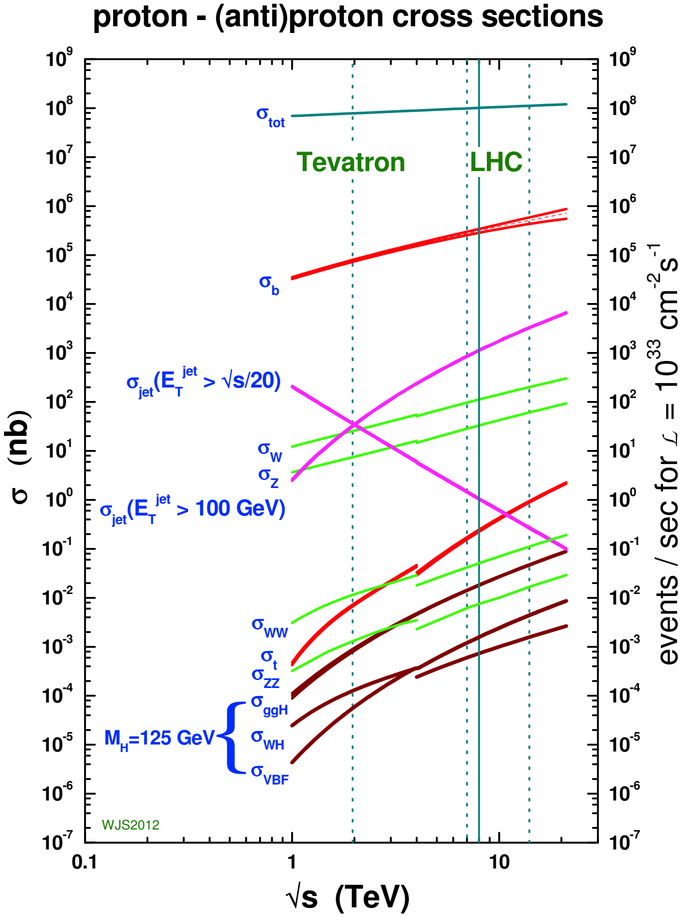
PASCOS 2013 – Nov. 20, 2013

G.Cerati (UCSD)

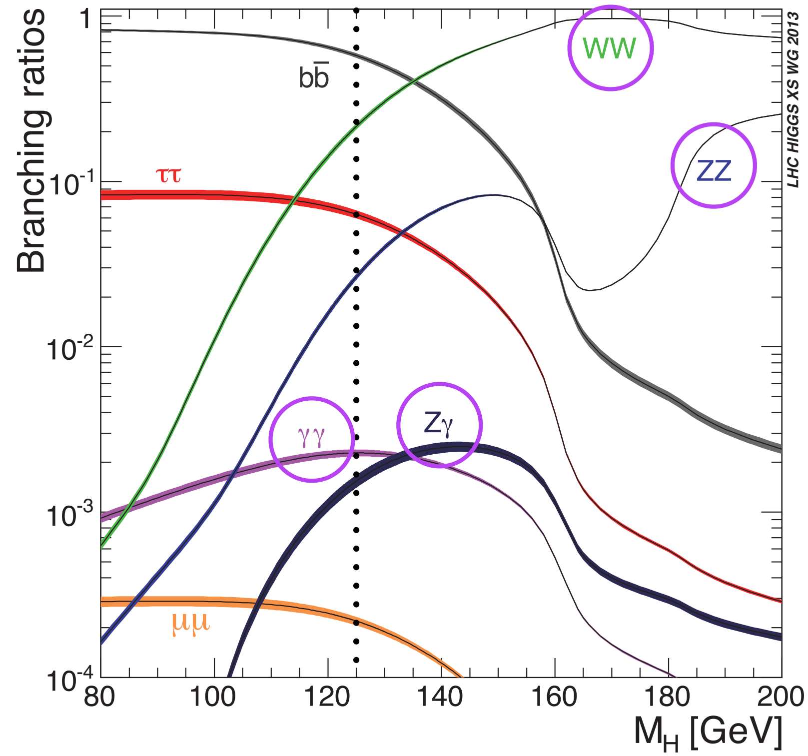
on behalf of the CMS collaboration

Bosonic Higgs Decays

W.J. Stirling, private communication



LHC Higgs Cross Section Working Group



Higgs analyses are huge experimental challenges!

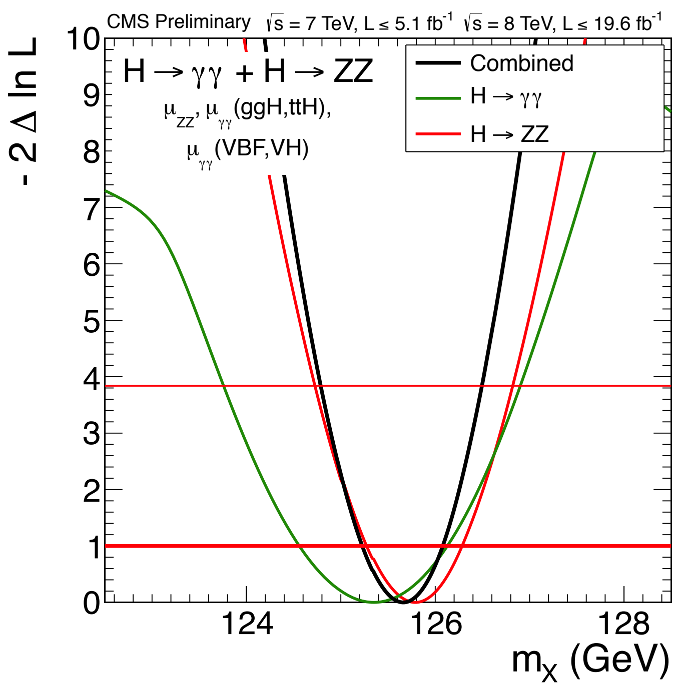
Bosonic decays (WW,ZZ,γγ,Zγ) include the cleanest channels
to search for and study the SM Higgs boson.

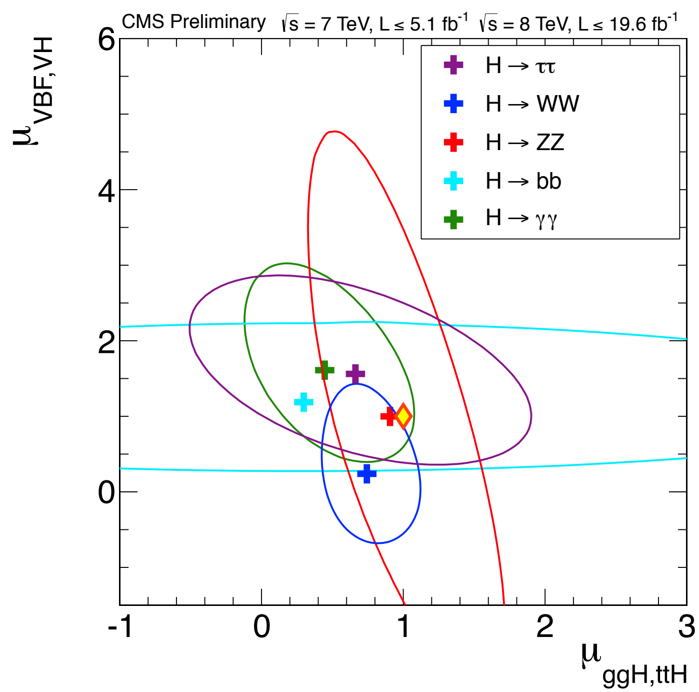
Talk Outline

HIG-13-005

H→ZZ→4l channel drives mass measurement

H→WW→2l2ν most sensitive for signal strength





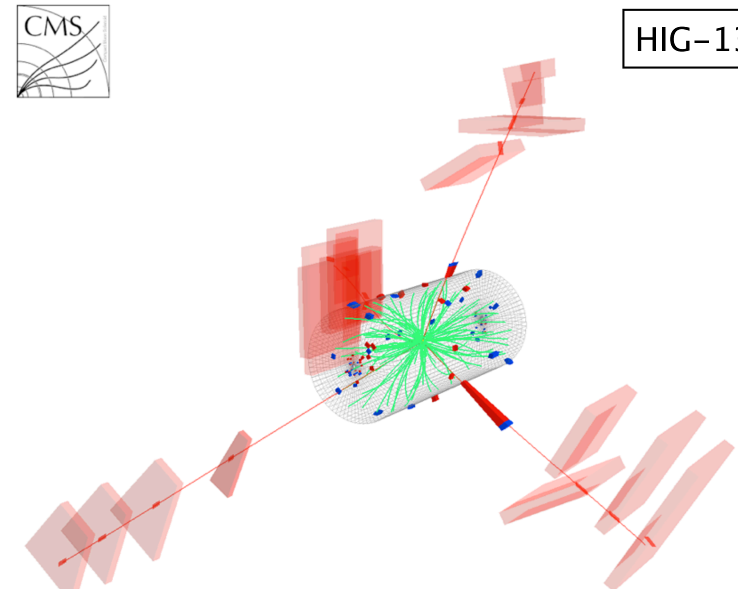
No new results and time is short:
my choice is to focus on H→ZZ→4l and H→WW→2l2ν analyses.

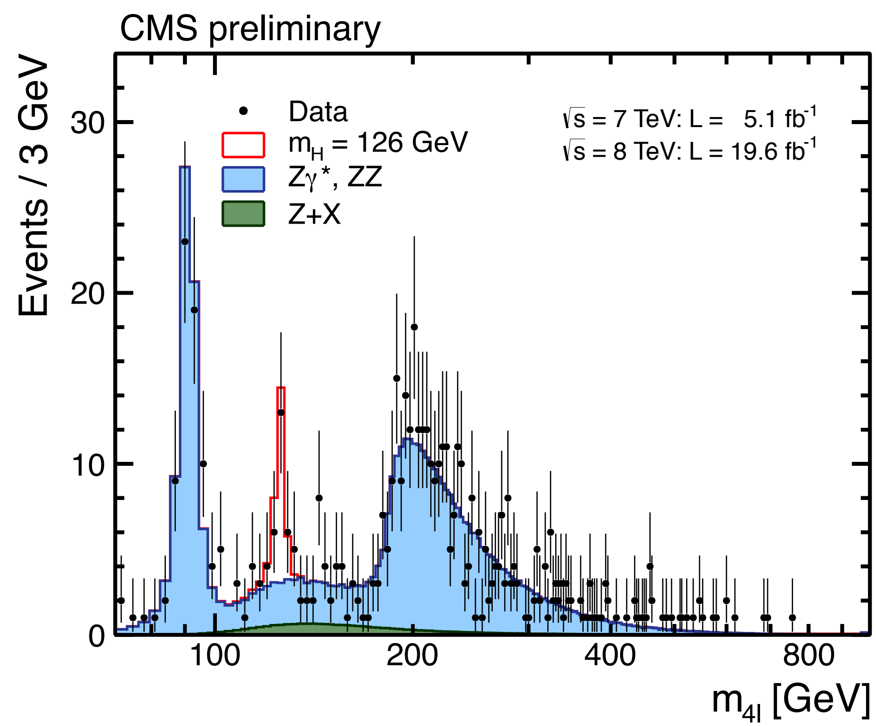
Only highlights from other analyses.

H→ZZ→4l: Analysis Summary

- Golden channel, clean experimental signature
  - Narrow peak in the 4l mass spectrum on top of a flat and small bkg
  - But small signal yield
- Analysis performed in two categories
  - untagged: ≤1 jets
  - tagged: ≥2 jets (p_T>30)
    - ~20% of signal events are VBF ones
    - no evidence for VBF signal events yet
- Signal model:
  - Empirical parametric shape from simulation
  - Corrected for data/simulation scale
- Backgrounds:
  - irreducible from simulation
    - empirical parametric shape
  - instrumental from data
    - two methods: from OS and SS events, ~40% uncert.
- Key features:
  - Lepton reconstruction
  - Zγ*→4l
  - Kinematic discriminants

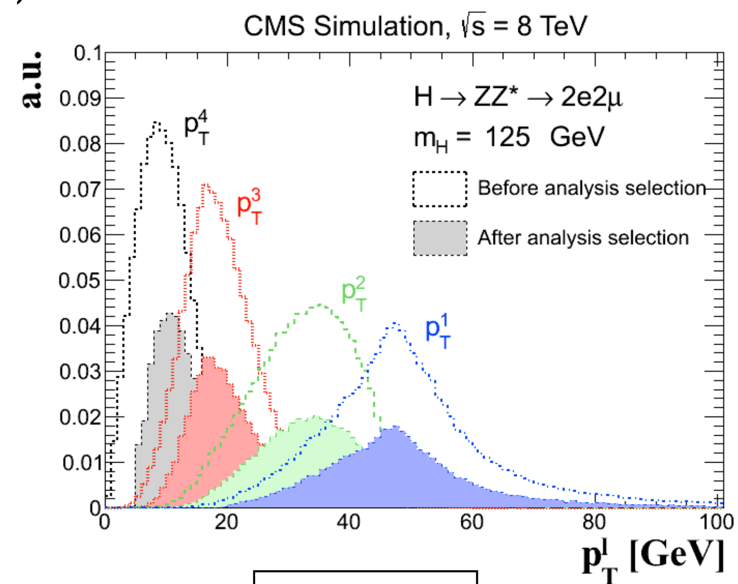
HIG-13-002





H→ZZ→4l: Lepton Reconstruction

- Off-shell Z in Higgs decay ($40<m_{Z1}<120$, $12<m_{Z2}<120$ GeV)
- Need high efficiency down to p_T=5 (7) GeV for μ (el)
  - measured with tag-and-probe on Z, MC corrected accordingly
- Final state radiation recovery using close-by photons
  - 1-3% efficiency gain
- Optimized lepton scale and resolution
  - narrow peak and better mass measurement
  - validation on resonances show data-MC differences of the order of 0.1% for scale and 20% for resolution
- Closure test on Z events, comparing computed resolution from lepton uncertainties and from mass peak fit
  - 10 categories with different expected mass resolution
  - assign 20% systematic error



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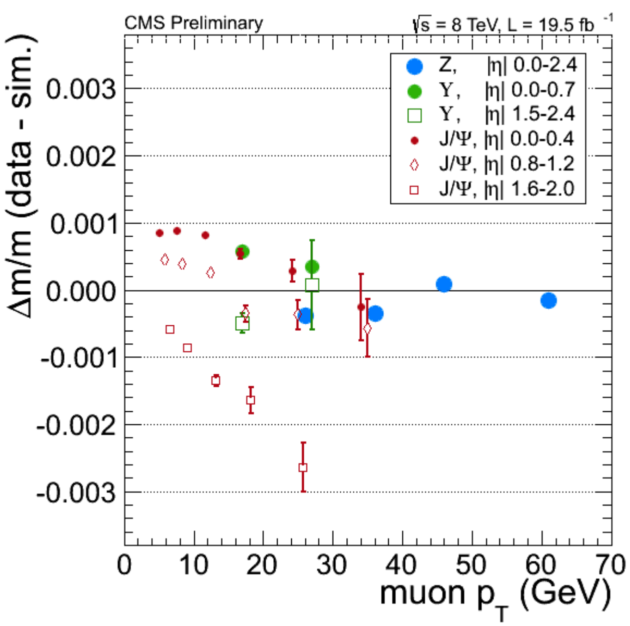
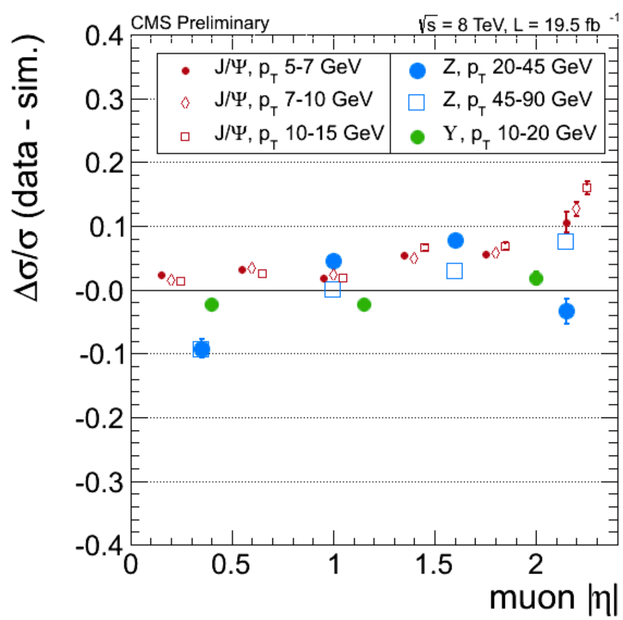
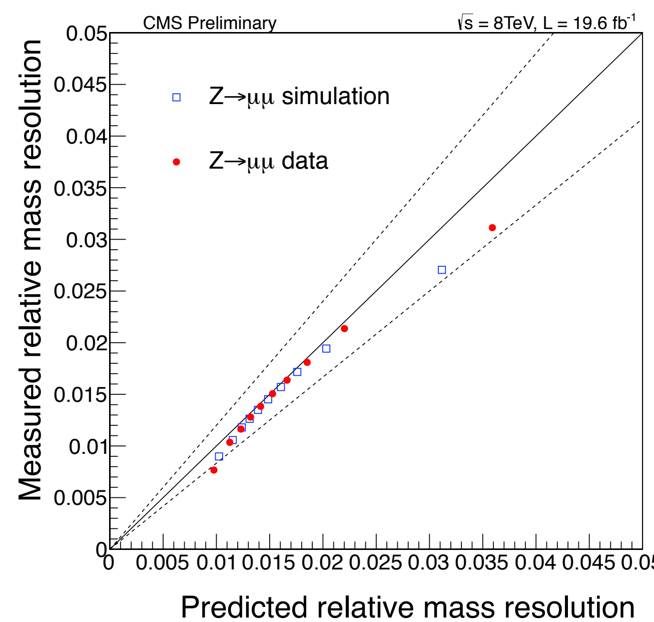
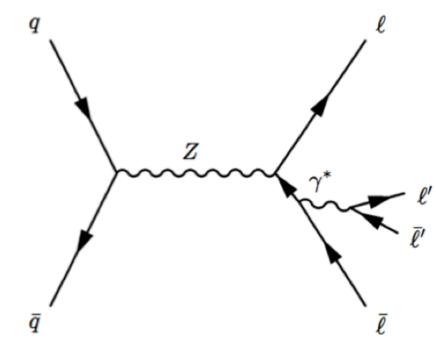




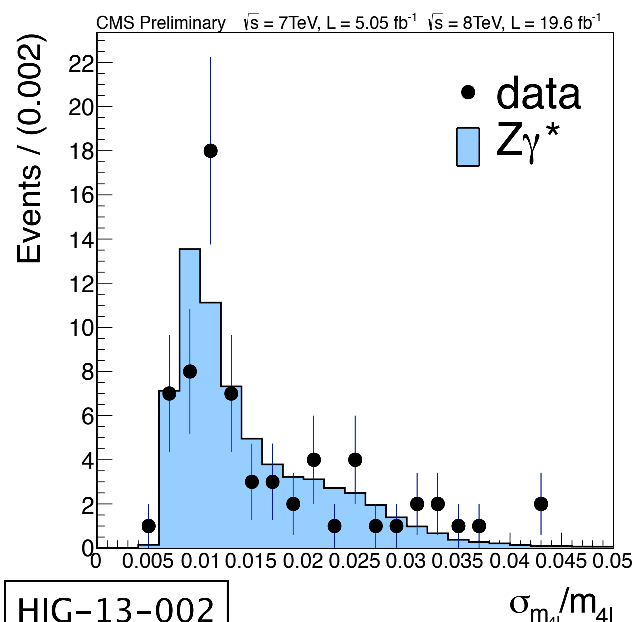


H→ZZ→4l: Zγ*→4l Candle

- How well can we measure the properties of a resonance decaying into 4l?
- Zγ*→4l represents a natural candle for validating H→ZZ analysis features
- Verify that the relative uncertainty on m_{4l} matches expectations
- Perform the mass measurement on Zγ* with identical procedure as for the new boson mass measurement
  - Relaxed phase space due to the limited statistics (m_{Z2} > 4 GeV)
- Measured m_{4l} = 91.17±0.22 GeV
  - PDG value of Z boson mass of 91.188 GeV



80<m_{4l}<100 GeV



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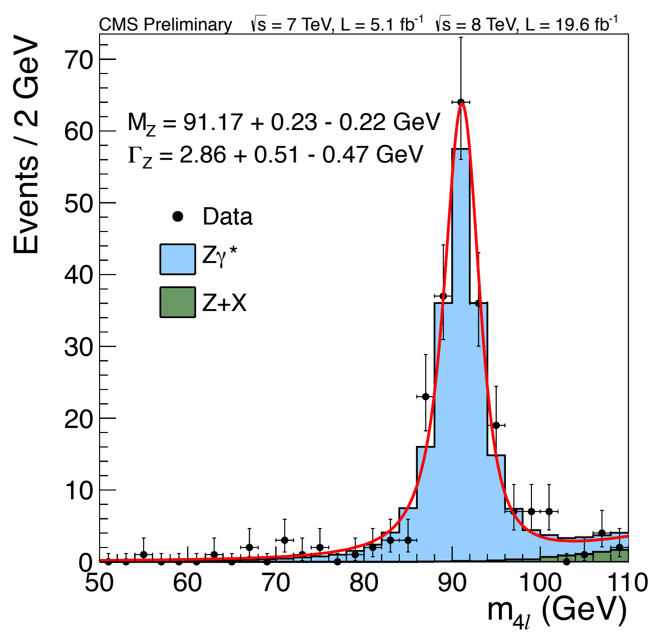
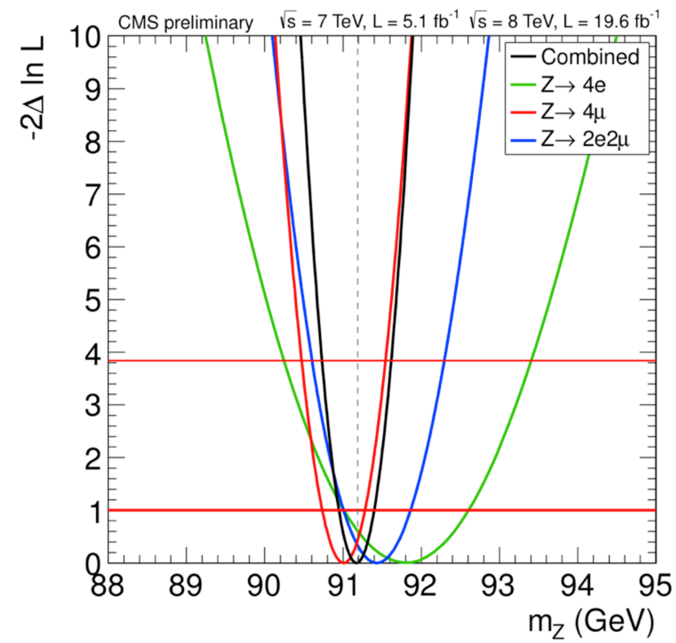




H→ZZ→4l: Kinematic Discriminants

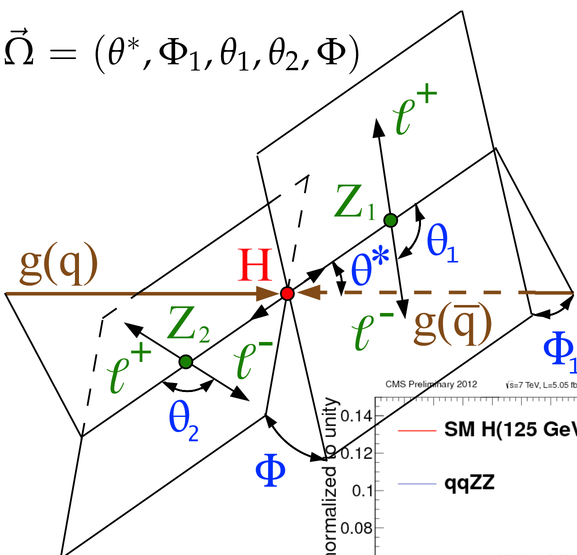
- Multiple kinematic variables can be used as signal/background or SM/BSM kinematic discriminant
  - fully reconstructed final state
- Discriminator K_D to separate SM Higgs from backgrounds:
  - Use the ratio of LO matrix elements
  - Matrix elements computed using JHUGen and MCFM
    - validated with analytical parametrization, Madgraph, also BDT/BNN.

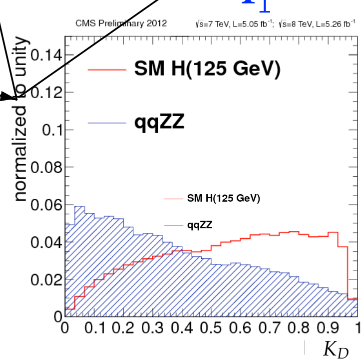
$$K_D = \frac{\mathcal{P}^{\rm kin}_{0^+}}{\mathcal{P}^{\rm kin}_{0^+} + \mathcal{P}^{\rm kin}_{\rm bkg}} = \left[1 + \frac{\mathcal{P}^{\rm kin}_{\rm bkg}(m_{Z_1}, m_{Z_2}, \vec{\Omega}|m_{4\ell})}{\mathcal{P}^{\rm kin}_{0^+}(m_{Z_1}, m_{Z_2}, \vec{\Omega}|m_{4\ell})}\right]^{-1}$$

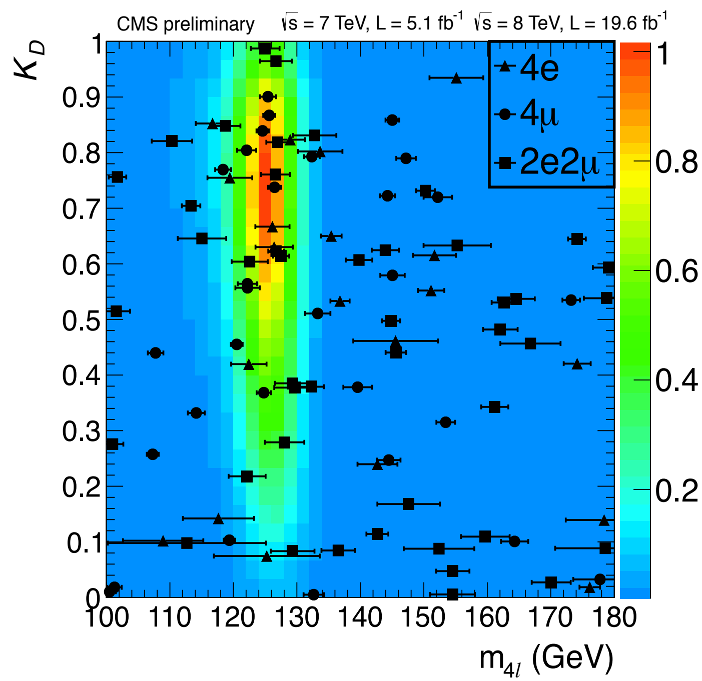
- Discriminator D_{J^P} to separate the SM Higgs hypothesis from an alternative J^P hypothesis:

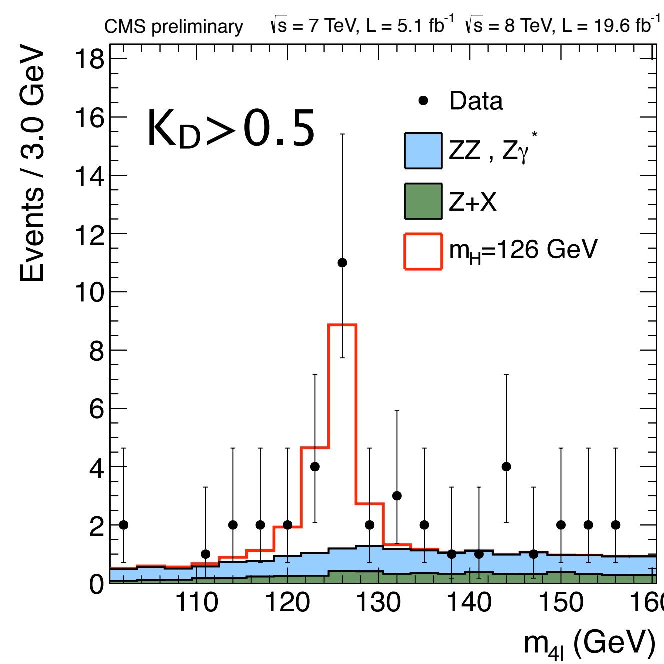
$$\mathcal{D}_{J^P} = \frac{\mathcal{P}_{\rm SM}}{\mathcal{P}_{\rm SM} + \mathcal{P}_{J^P}} = \left[1 + \frac{\mathcal{P}_{J^P}(m_{Z_1}, m_{Z_2}, \vec{\Omega}|m_{4\ell})}{\mathcal{P}_{\rm SM}(m_{Z_1}, m_{Z_2}, \vec{\Omega}|m_{4\ell})}\right]^{-1}$$

$$\vec{\Omega} = (\theta^*, \Phi_1, \theta_1, \theta_2, \Phi)$$







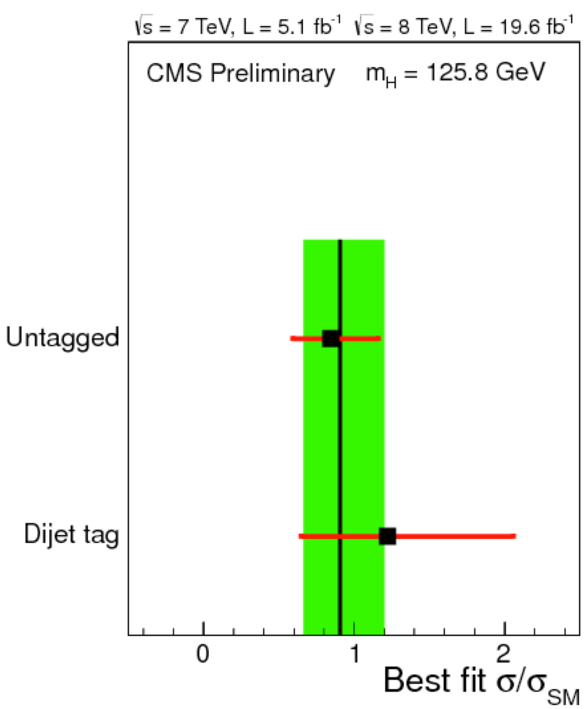


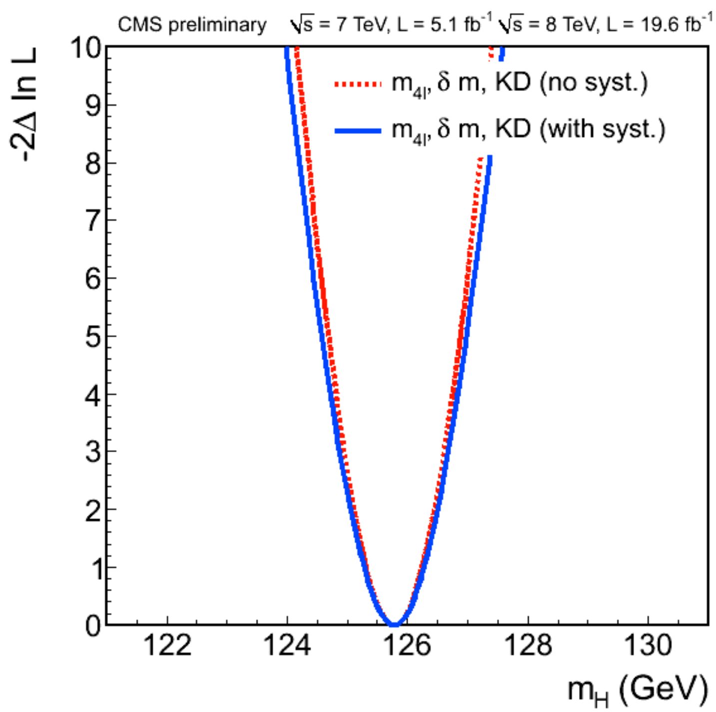
HIG-13-002

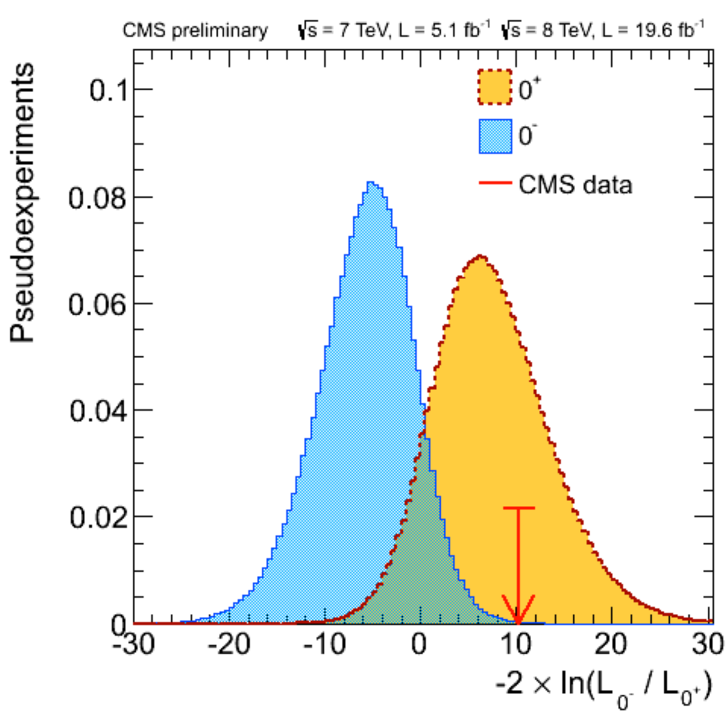
H→ZZ→4l: Results

HIG-13-002

- Limits, significance, signal strength: 3D fit on m_{4l}, K_D, p_T
  - significance = 6.7σ (7.2σ exp)
  - signal strength $\mu=0.91^{+0.30}_{-0.24}$
- Mass measurement: 3D fit on m_{4l}, K_D, $\sigma(m_{4l})$
  - $m_H = 125.8 \pm 0.5$ (stat.) $\pm$ 0.2 (syst.) GeV
- Spin/parity hypothesis: 2D fit on D_{bkg} and D_{JP}
  - where D_{bkg} combines m_{4l} and K_D information
  - tested various models with spin (0,1,2), parity (+,−) and production modes (gg or qq)
  - alternative models disfavored by data with respect to 0^+ (from 1.7σ to >4σ)



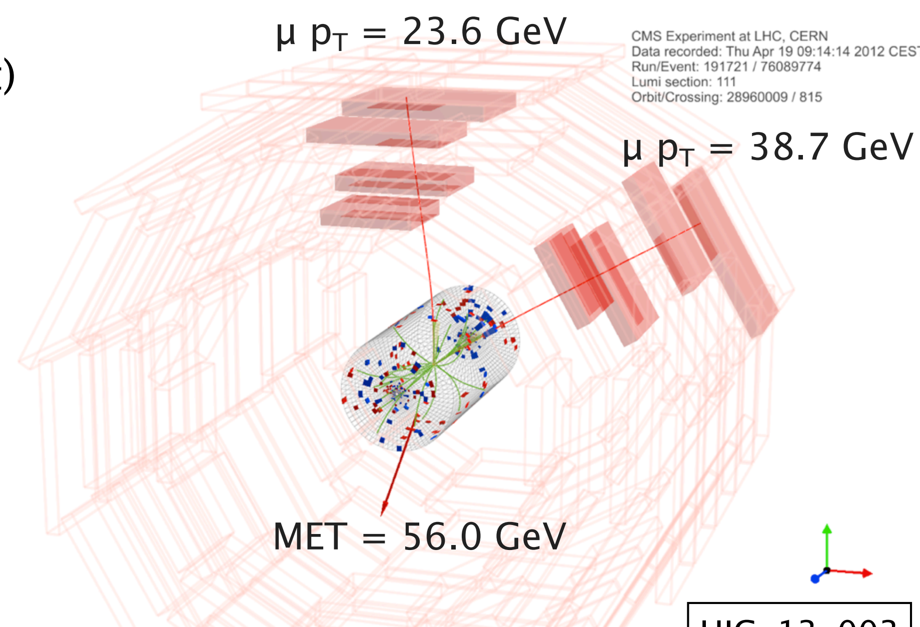




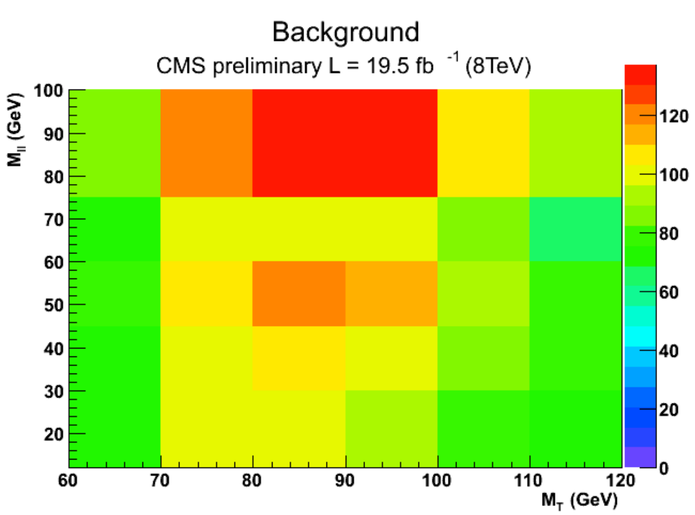
H→WW→2l2v: Analysis Summary

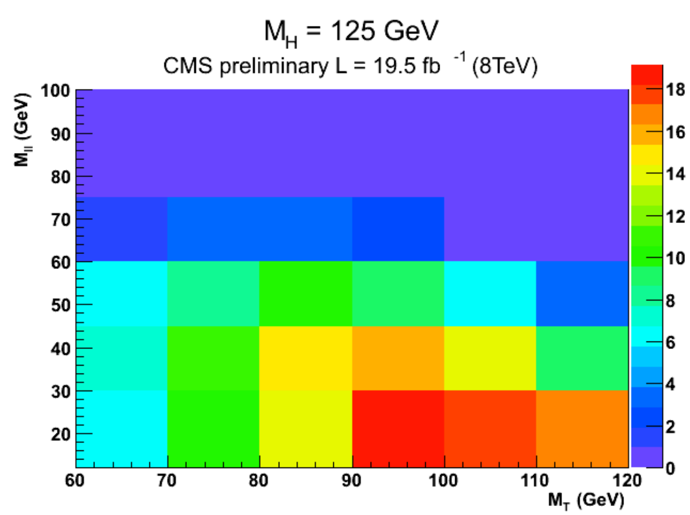
- Large signal yield but also large backgrounds
- No mass peak due to neutrinos
- Default analysis:
  - 2D fit in the m_T–m_{ll} plane for DF final state (0,1 jet)
    - uncorrelated variables
    - range for mH<300 GeV: 60<MT<280 GeV, 12<mll<200 GeV
  - 2D fit used for spin-parity hypothesis testing
  - cut based for SF final state (0,1 jet)
    - m_H-dependent cut values
  - VBF channel for 2-jet bin
- Key features:
  - Background estimation
  - Systematics
  - 2D fit validation

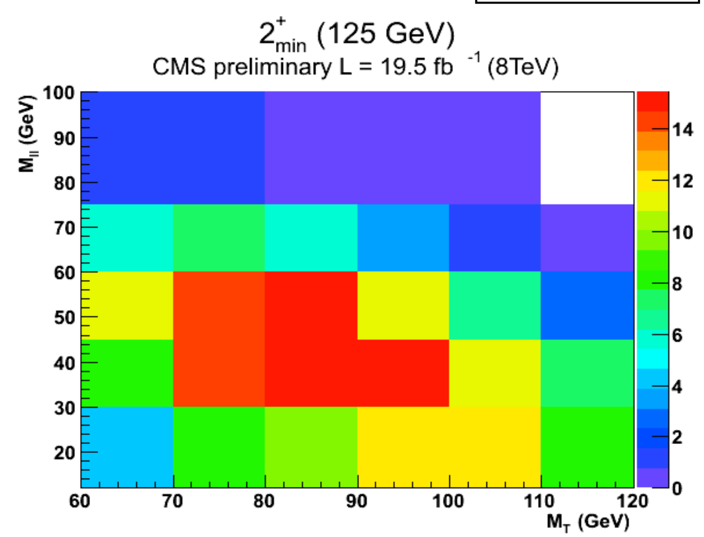
$$M_T = \sqrt{2 p_T^{ll} \cdot \mathrm{MET} \cdot (1 - cos(\Delta\phi_{ll-\mathrm{MET}}))}$$



HIG-13-003



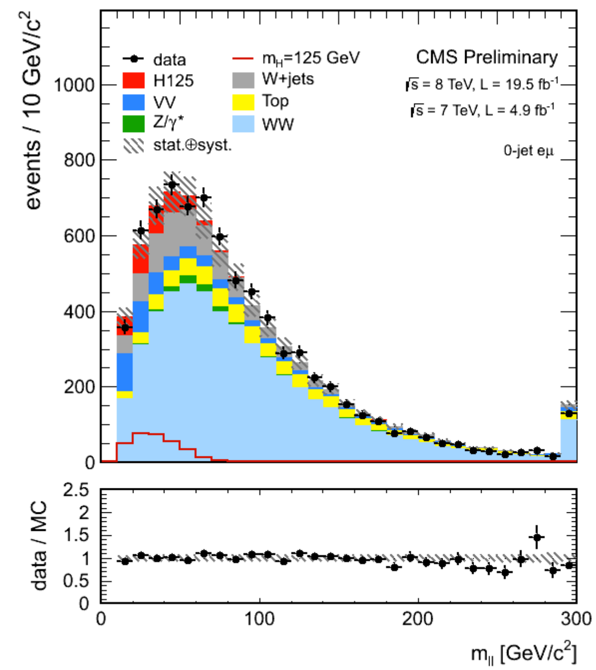


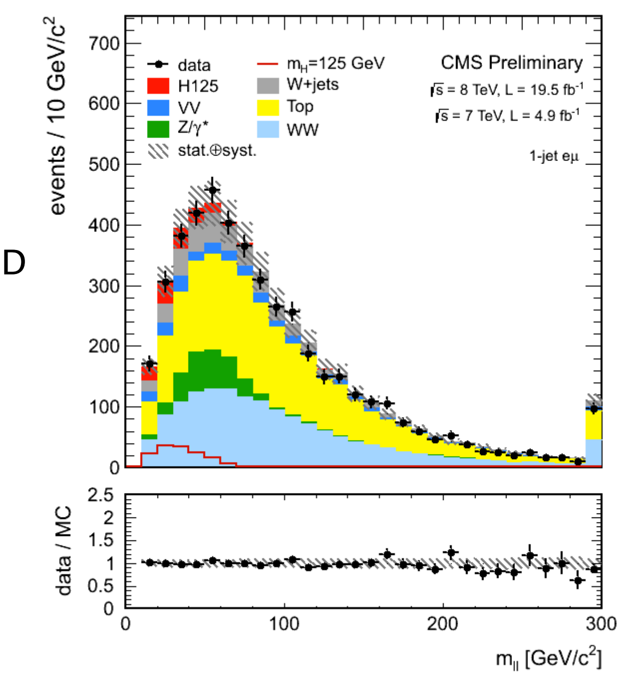


H→WW→2l2ν: Backgrounds

HIG-13-003

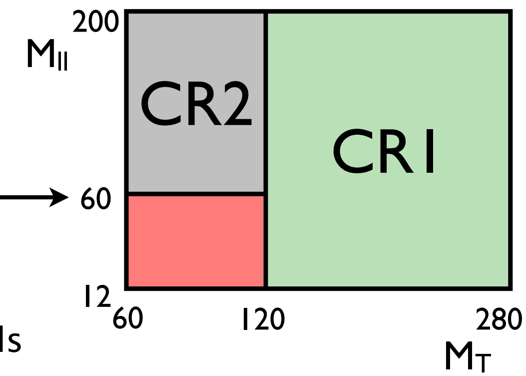
- Background control is crucial for this analysis
  - event count in signal region, no mass peak
  - WW (light blue): dominant background, irreducible, extends to higher mll and mT regions
  - Top (yellow): largest background in 1-jet bin, small in 0-j
  - Wjets (grey): similar size and kinematic region as signal
  - Wγ* (grey): small but similar kinematic as signal
- WW background normalization is a free parameter in the 2D fit
  - fit constrains the dominant background from signal free regions
- Fully data-driven background estimation for most important backgrounds
  - Wjets – Method based on tight-to-loose lepton ID – 36%
    - ratio derived on QCD, applied to dilepton events w/ one lepton failing ID
  - Top – Based on Njets and b-tagging – 20/5% (0/1-jet)
    - measured on top enriched sample, applied on top tagged events
  - Wγ* – Measure k-factor in 3l sample – 30%
  - Backgrounds from MC: WZ/ZZ, Wγ
  - Background estimation for cut based only:
    - Drell-Yan (on-off Z peak, tight-loose MET), WW (low-high m_{ll})

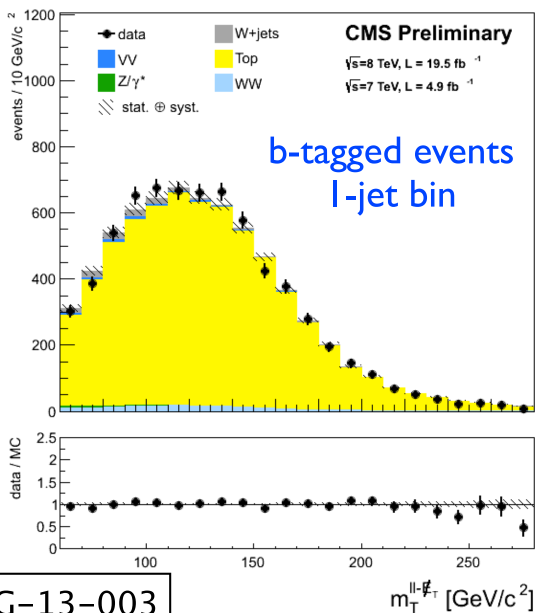


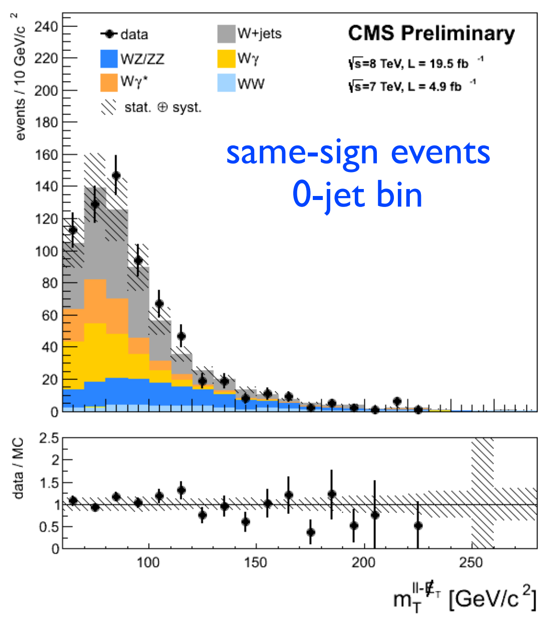


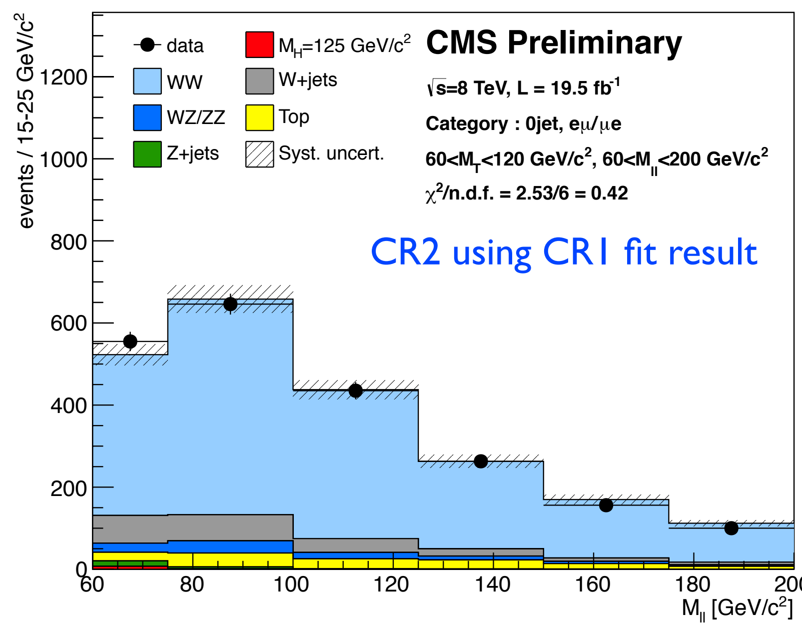
H→WW→2l2v: Systematics and Fit Validation

- Systematics in the 2D fit are both normalization and shape variations
  - Correlated systematics: experimental measurements, theoretical uncertainties
  - Uncorrelated systematics: background normalizations
  - Shape variations done through a morphing parameter between alternative shapes
- Huge effort to validate and understand the fit results
- Full fit performed on data control regions
  - b-tagged events for top, same sign events for Wjets (fakes), Wγ and Wγ*
  - shapes compatible, nuisance parameters are stable, no artificial signal introduced
- Test fit model for WW background
  - two WW control regions, with large m_T or large m_{ll} →
  - predict WW shape in CR2 from fit results in other CR1
- Experiments with pseudo-data
  - no bias on signal, both under nominal conditions and with input bias on backgrounds
  - good compatibility between nuisance parameters pulls from toys and data fit







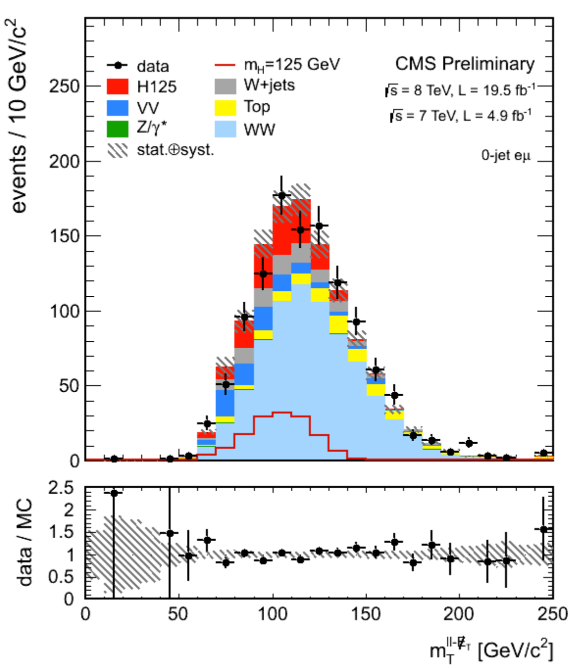


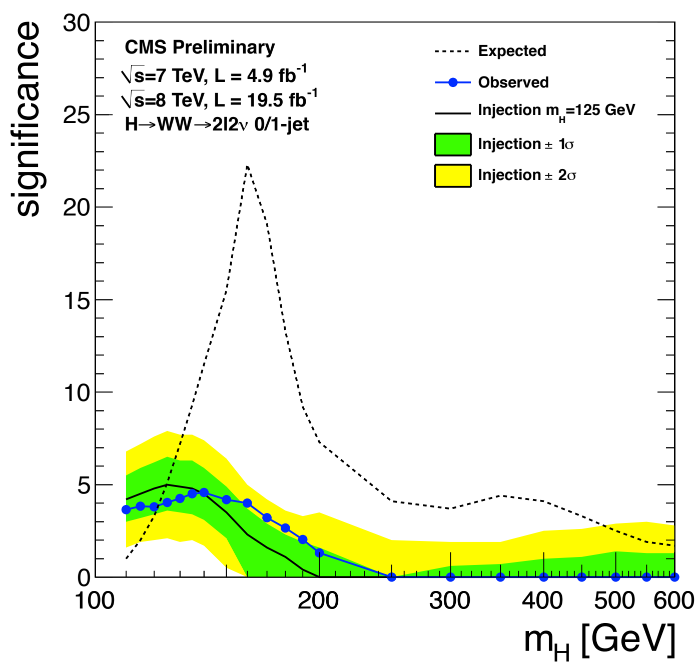
HIG-13-003

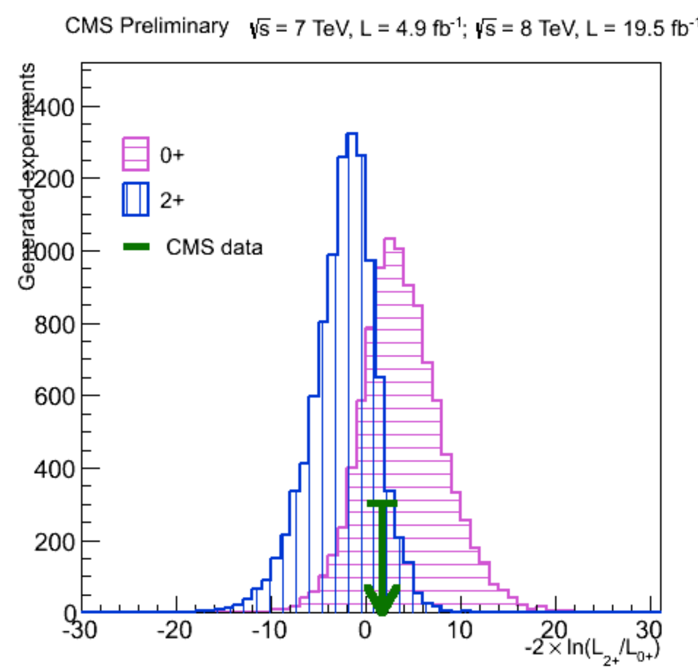
H→WW→2l2ν: Results

HIG-13-003

- Exclusion limits: 128-600 GeV (115-575 GeV exp.)
- Significance: 4.0σ (5.1σ expected)
  - broad excess, compatible with SM m_H=125 GeV
- Signal strength: μ = 0.76 ± 0.13 (stat.) ± 0.16 (syst.)
  - good compatibility across channels and datasets
- Spin-parity hypothesis test performed in 0/1-jet eμ categories
  - Model of spin-2 resonance, with minimal dibosons couplings
  - Compatibility: 0.5σ with 0^+, 1.3σ with 2^+ model
- Using SM Higgs as background no significant excess for m_X=100-600 GeV



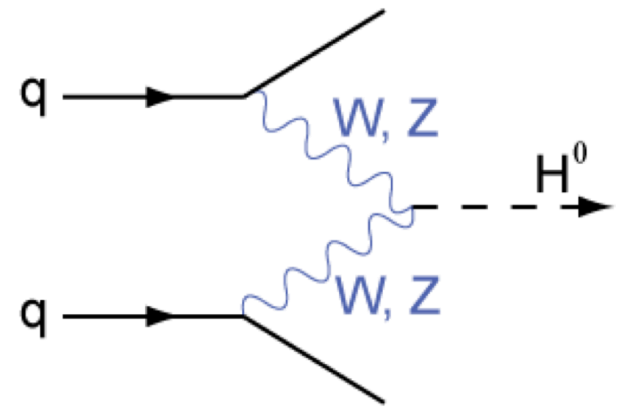


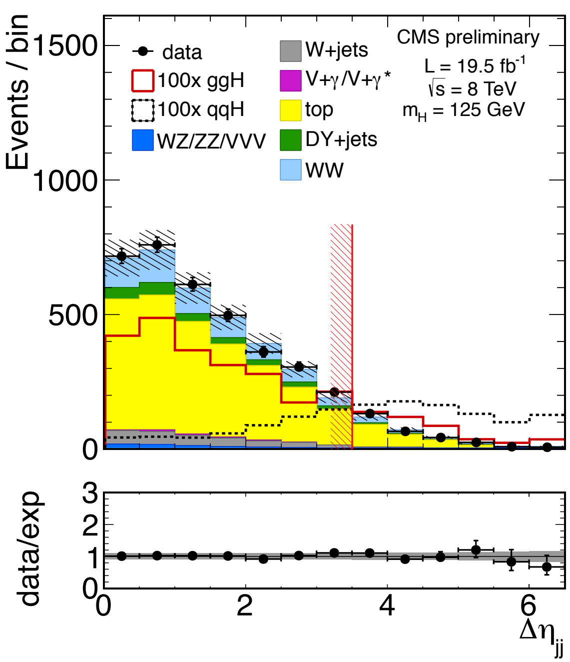


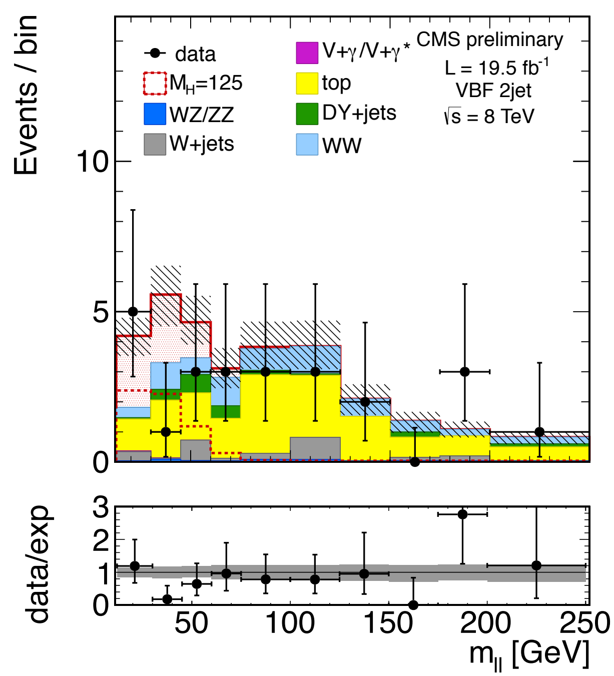
VBF $H \to WW \to 2l2\nu$

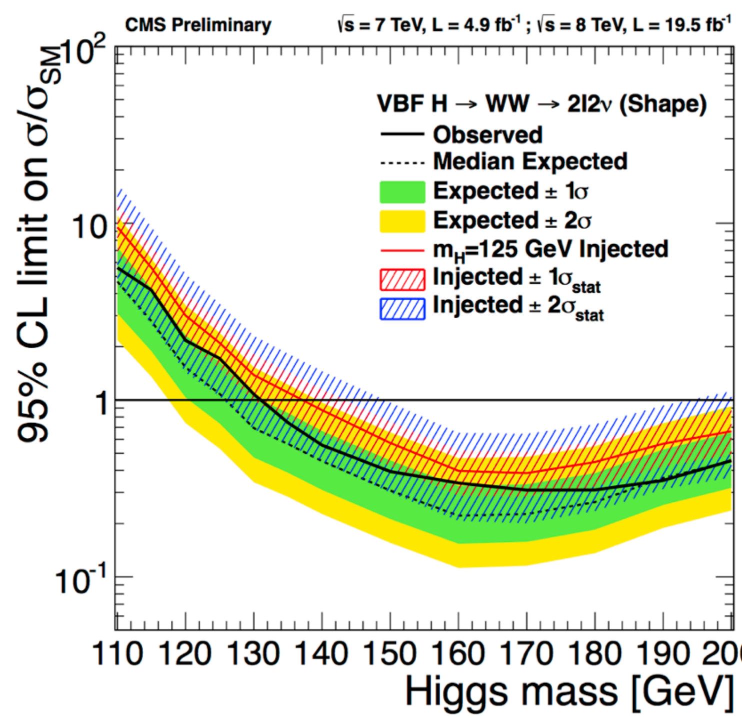
HIG-13-022

- Similar selection and background estimation techniques as in 0/1-jet analysis
- Requires ≥2 jets plus a VBF-topology selection:
  - m_{jj}>500 GeV, $\Delta\eta_{jj}$>3.5, central jet veto
- Analysis strategy:
  - Shape based (1D on m_{ll}) for different-flavor
  - Cut based for same-flavor
- Results (7+8 TeV, SF+DF):
  - Limit at m_H=125 GeV: 1.7 (1.1 exp.)
  - Significance: 1.3 (2.1 exp.)
  - Signal strength: $\mu=0.62^{+0.58}_{-0.47}$



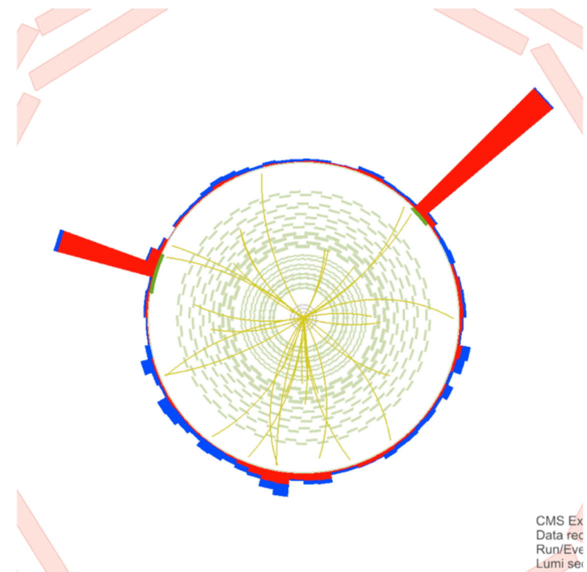


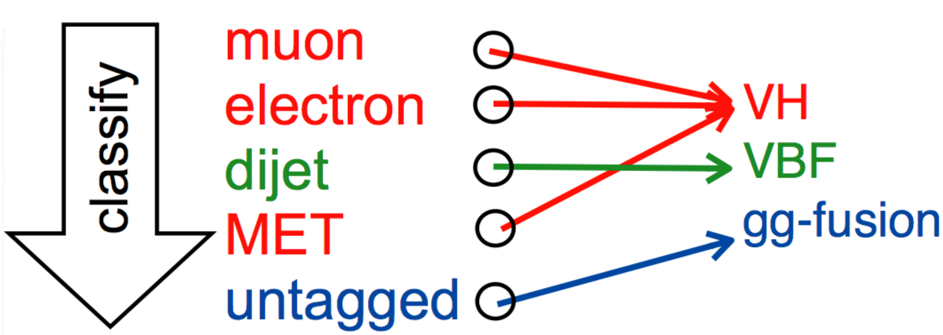


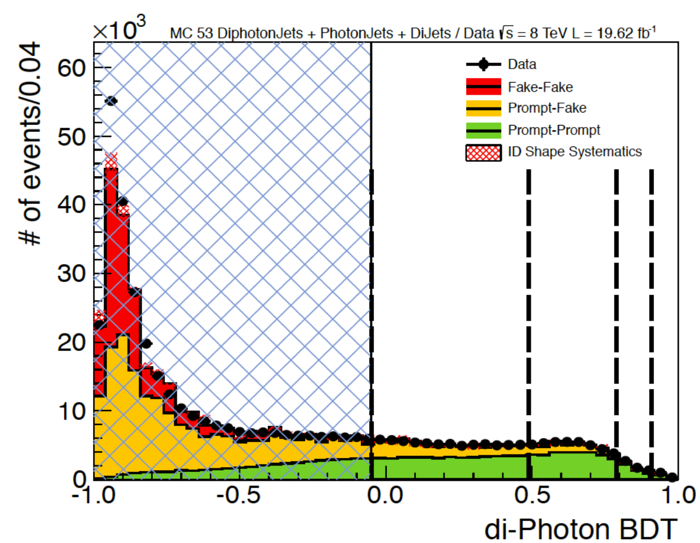


H→γγ: Overview

- High resolution fully reconstructed invariant mass
  - Large QCD backgrounds (γ-γ, γ-jet, jet-jet)
  - Small BR(H→γγ) ~ 0.1%
- 2 analyses: MVA-based and Cuts-in-Categories
- Separate events into classes to improve the analysis sensitivity and coupling measurements
  - 4 tagged categories, 4 untagged categories
- MVA diphoton categories:
  - Mass independent classification (BDT)
    - variables = diphoton kinematics (excluding mγγ), evt diphoton mass resolution, photon ID
  - 4 categories in high-score region of BDT output
  - MVA ~15% better expected sensitivity wrt CiC
- Cut-in-Categories:
  - 4 categories: high/low R_9 (shower shape); EB / EE





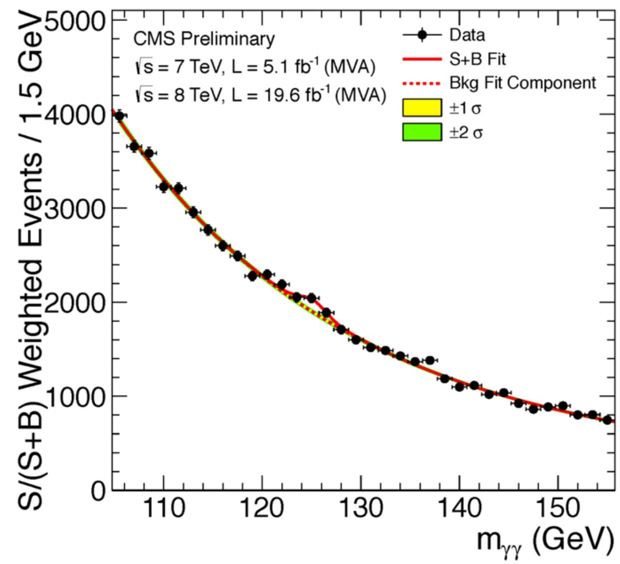


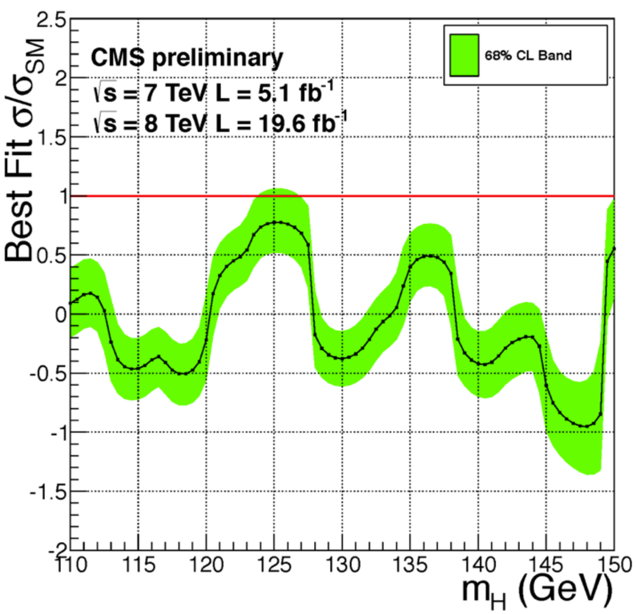
HIG-13-001

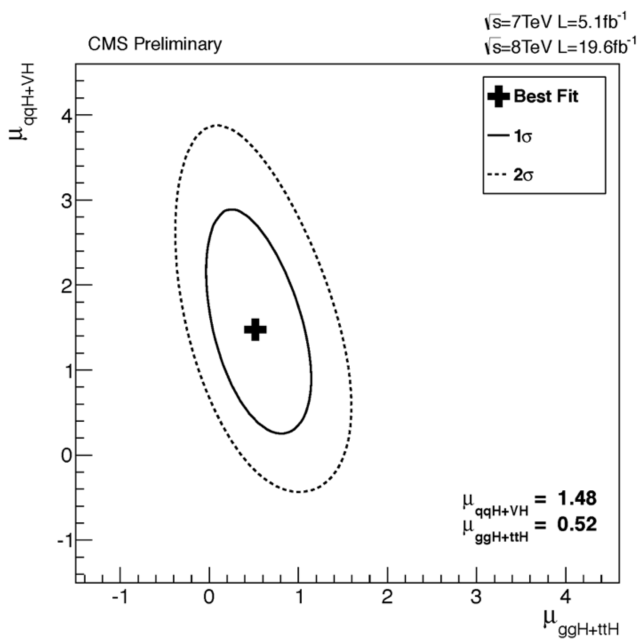
H→γγ: Results

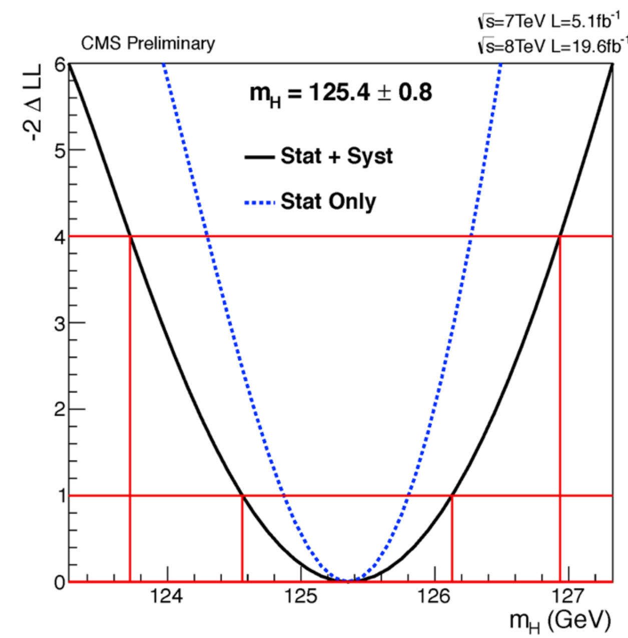
HIG-13-001

- Excess with observed significance of 3.2σ
  - 4.2σ expected
- Best fit strength $\sigma/\sigma_{SM} = 0.78^{+0.28}_{-0.26}$
  - μ(ggH+ttH)=0.52, μ(qqH+VH)=1.48
- Measured m_H=125.4 ± 0.5(stat.) ± 0.6(syst.) GeV
- Cut-based analysis sees a slightly larger excess
  - $\sigma/\sigma_{SM} = 1.1^{+0.32}_{-0.30}$
  - the two results are compatible at 1.5σ level once correlations are properly taken into account





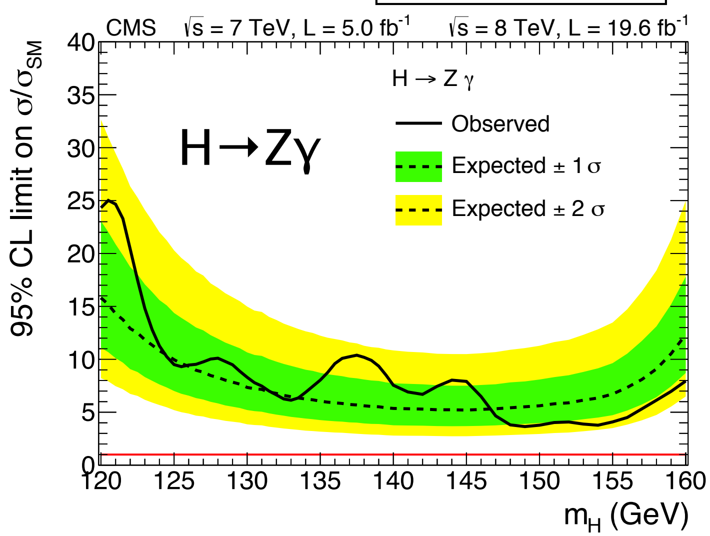




Other Results (Low Mass)

- Other production and decay modes needed to complete the picture for SM Higgs boson
- VH production decaying into VWW
  - 3l3ν and 2j2l2ν final states
- ttH production decaying into γγ
  - All-hadronic and semileptonic tt decays with loose selection and at least one b-tagged jet
- Zγ decay (where Z→2l)
  - similar approach as in H→γγ
- Need more data to probe SM in this channels!

arXiv:1307.5515



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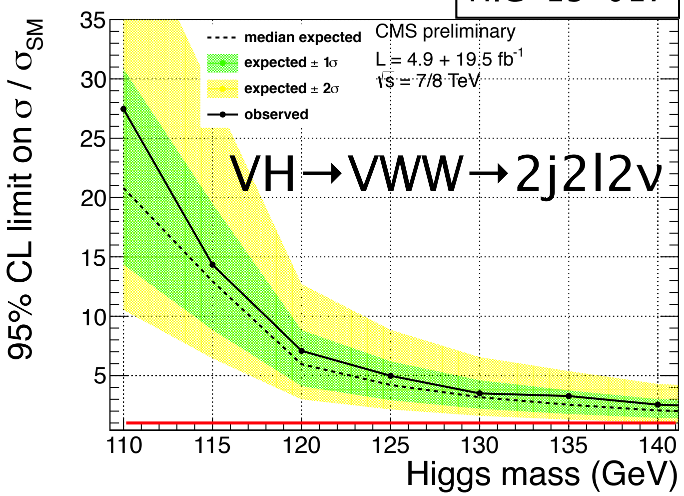

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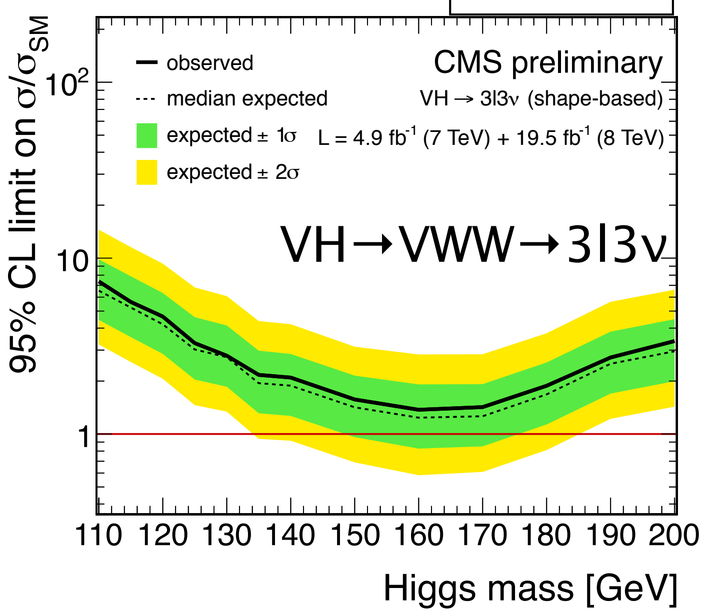

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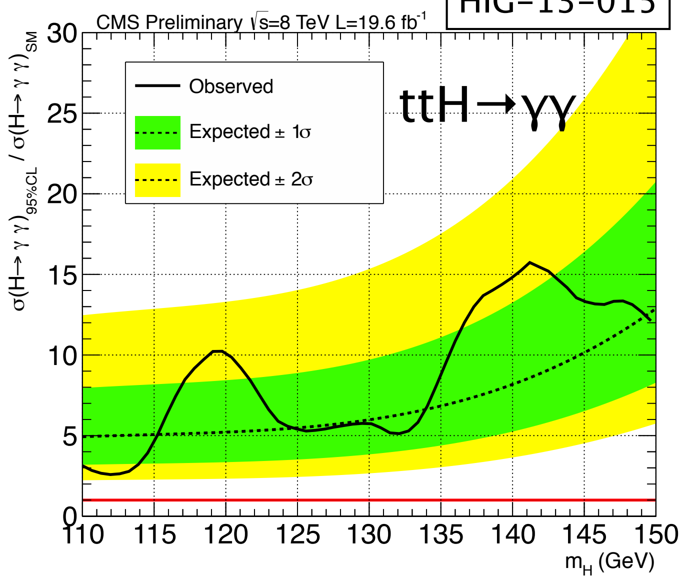
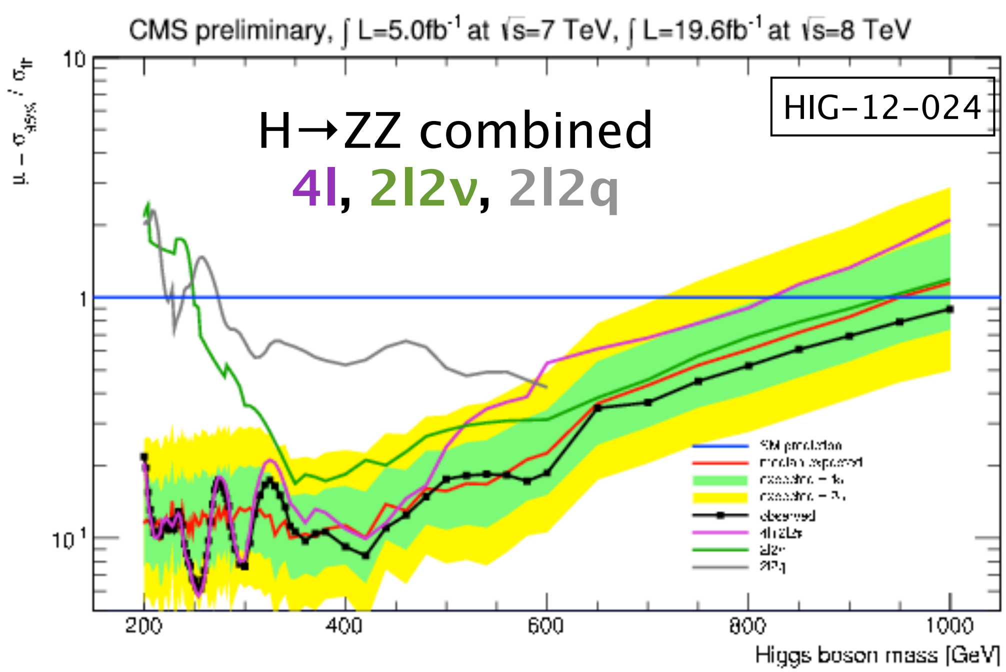
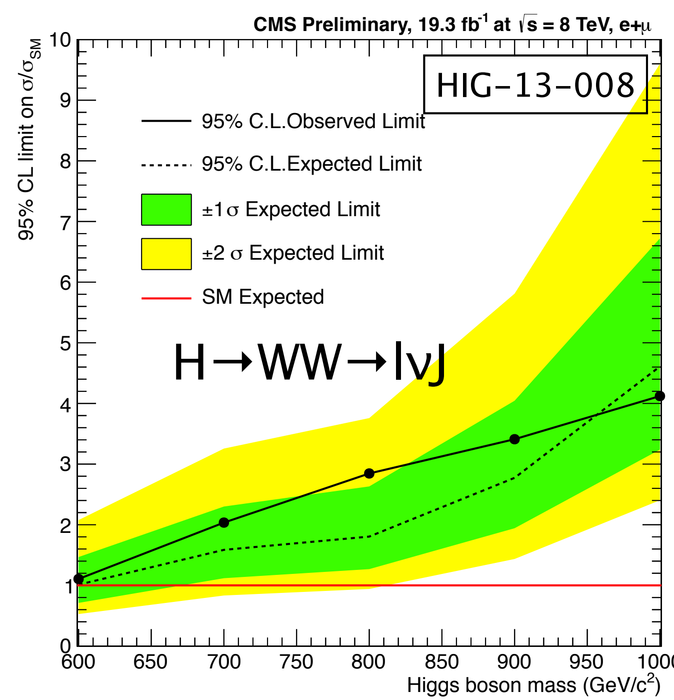


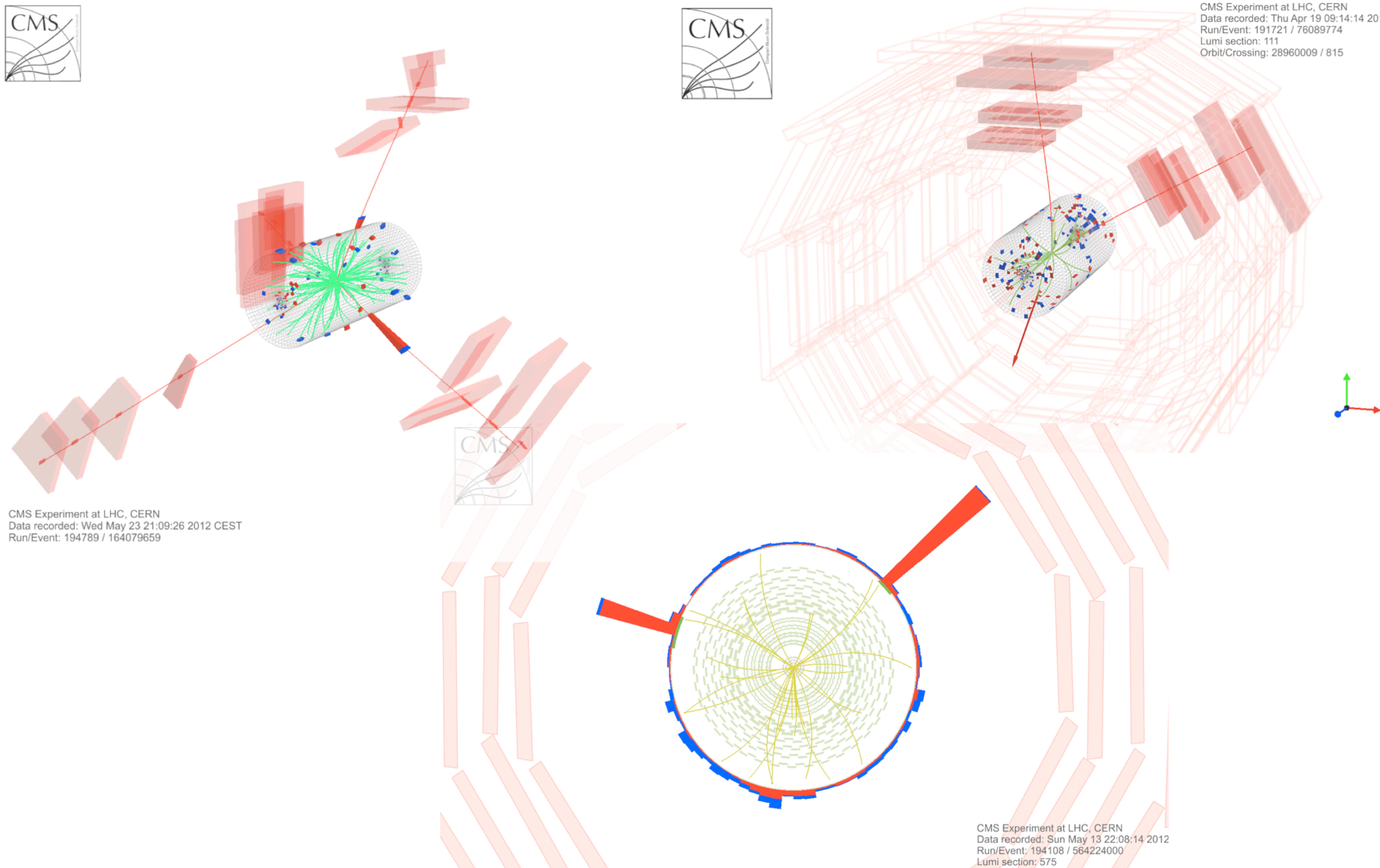
High Mass Results

- Search for high-mass SM-like Higgs boson and explore modified couplings of an additional Higgs boson
- Combined high-mass ZZ search to full statistics
  - Including fully leptonic and semi-leptonic (where the other Z decays hadronically or invisible) final states
  - Probes SM-like heavy Higgs up to ~1 TeV
- Search in the W(lν)W(“J”) channel in a boosted regime
  - Highly boosted W: its decay products are contained in one jet.
  - Jet substructure techniques are used in identifying the hadronically decaying W
  - Sensitive to Higgs masses above ~600 GeV

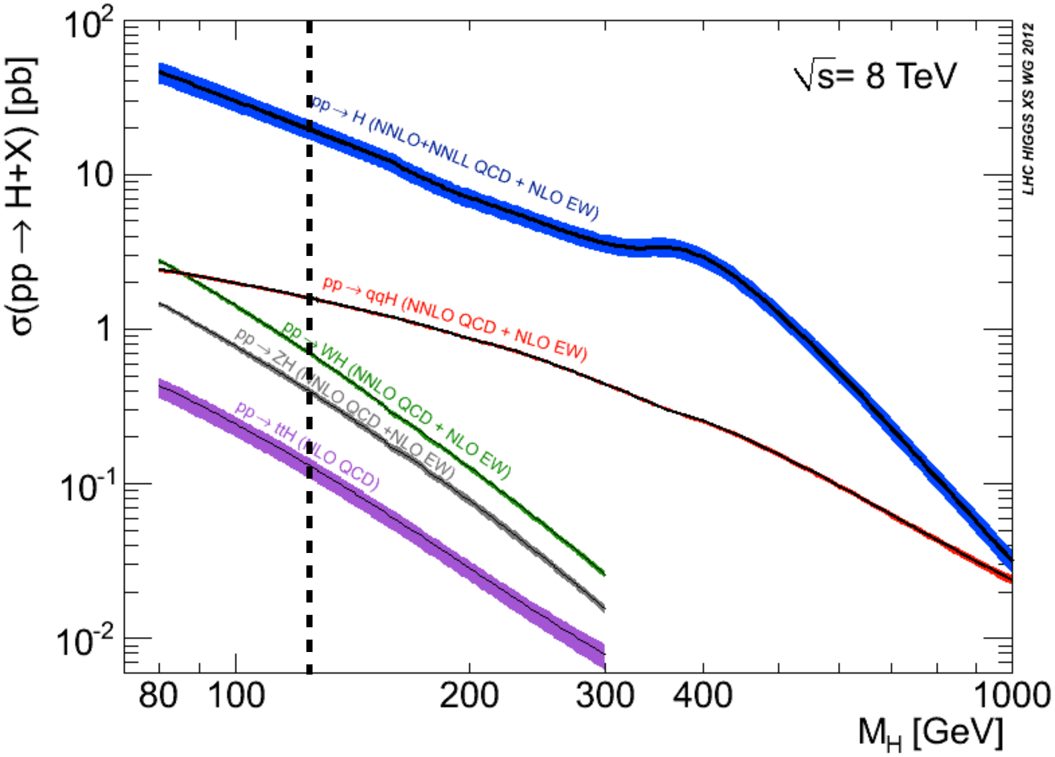




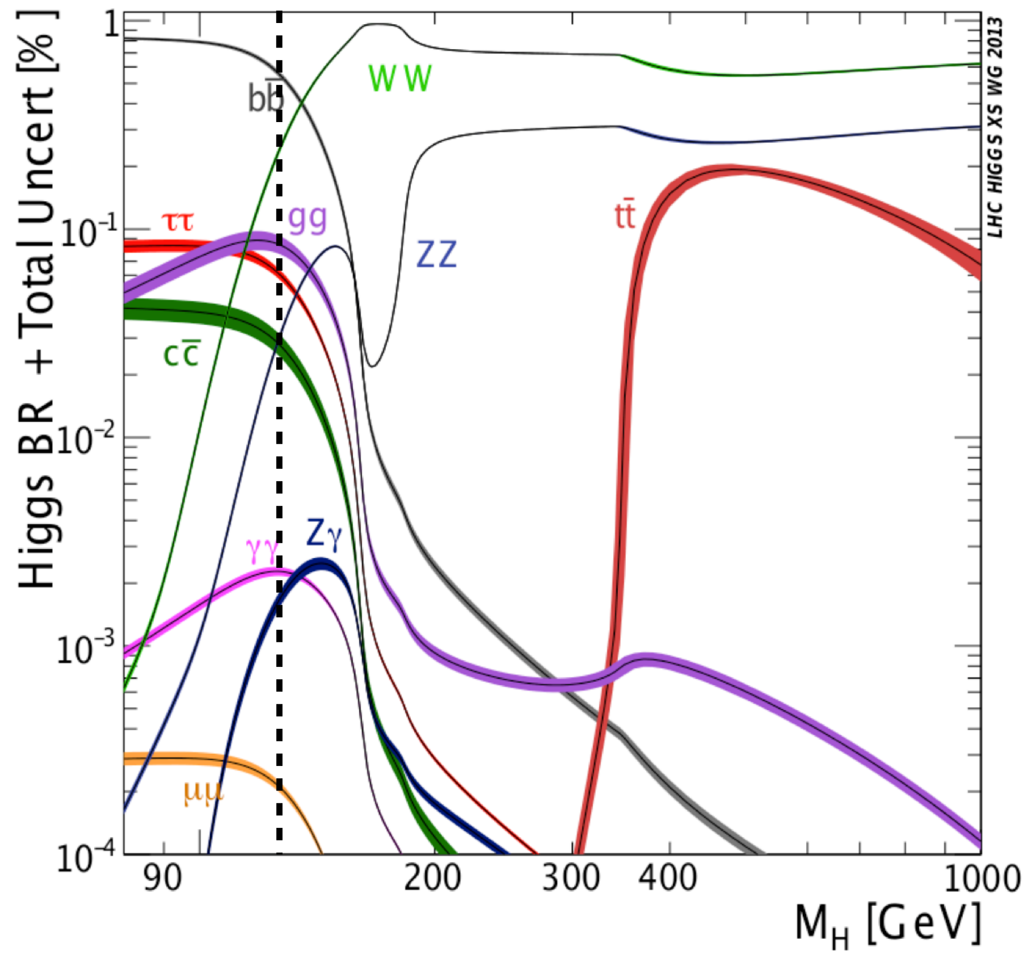
Thank you!


CMS
CMS
CMS Experiment at LHC, CERN
Data recorded: Thu Apr 19 09:14:14 20
Run/Event: 191721 / 76089774
Lumi section: 111
Orbit/Crossing: 28960009 / 815
CMS
CMS Experiment at LHC, CERN
Data recorded: Wed May 23 21:09:26 2012 CEST
Run/Event: 194789 / 164079659
CMS Experiment at LHC, CERN
Data recorded: Sun May 13 22:08:14 2012
Run/Event: 194108 / 564224000
Lumi section: 575

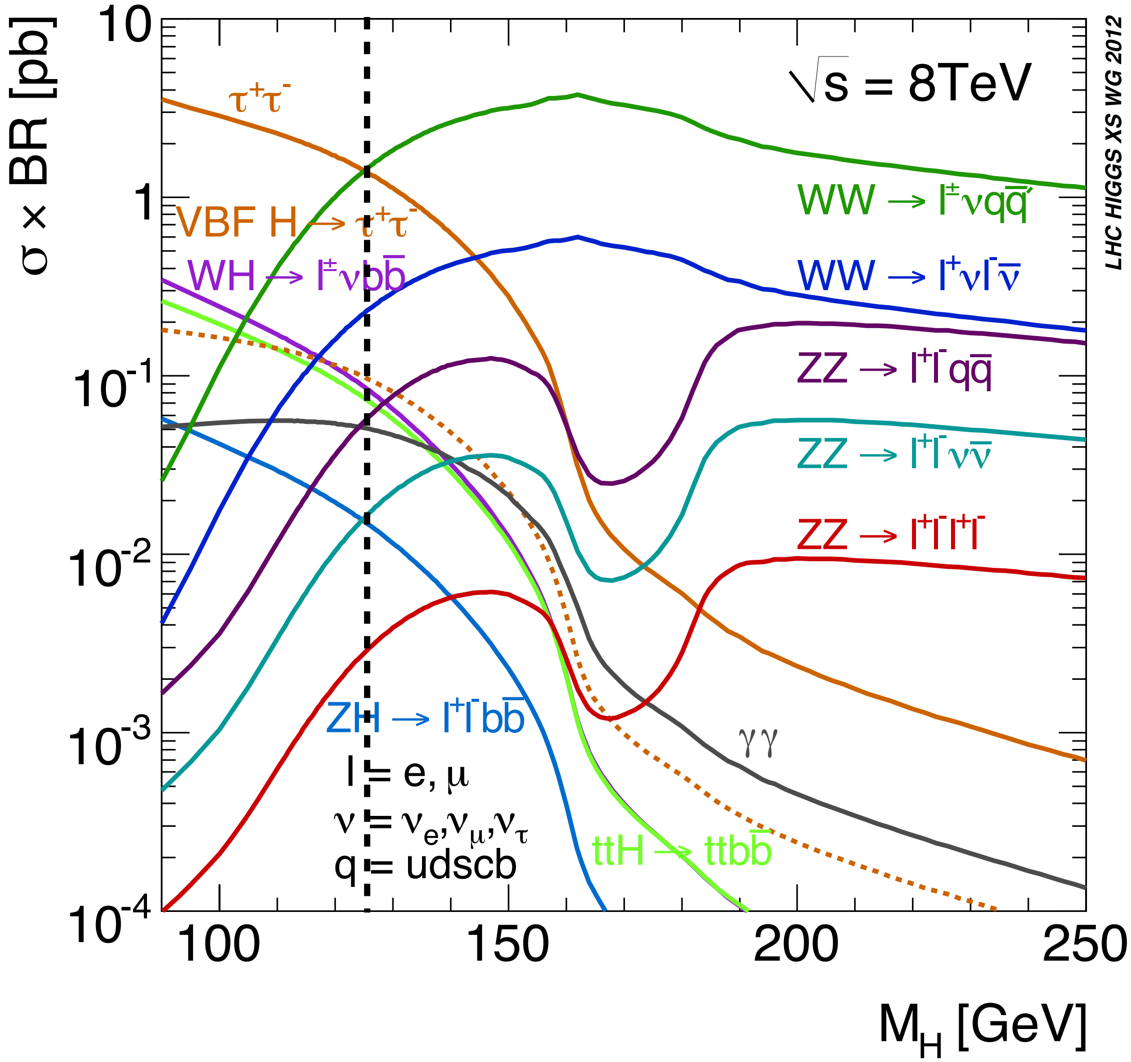
backup



$\sqrt{s}$= 8 TeV
pp → H (NNLO+NNLL QCD + NLO EW)
pp → qqH (NNLO QCD + NLO EW)
pp → WH (NNLO QCD + NLO EW)
pp → ZH (NNLO QCD +NLO EW)
pp → ttH (NLO QCD)
LHC HIGGS XS WG 2012
σ(pp → H+X) [pb]
M_H [GeV]



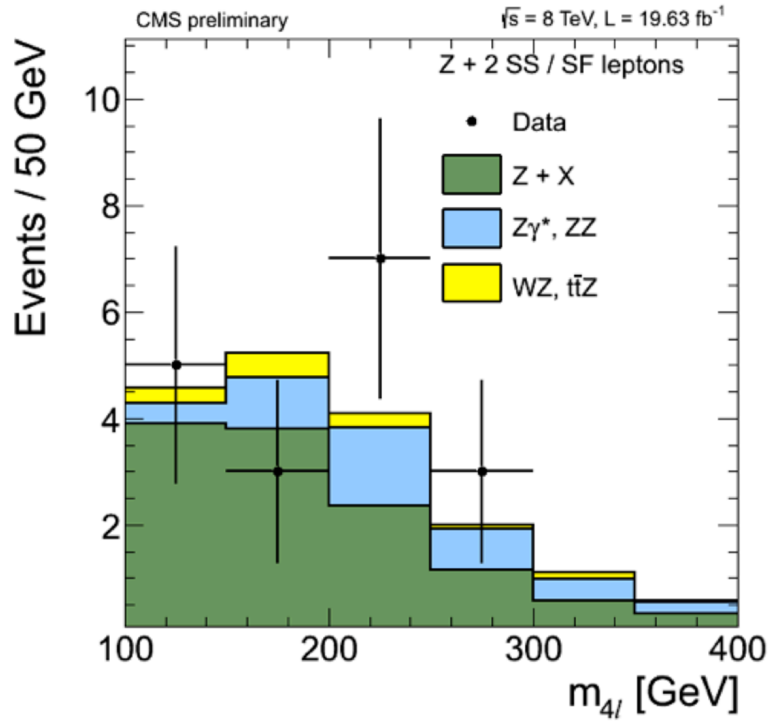
Higgs BR + Total Uncert [%]
$b\bar{b}$
WW
ττ
gg
$c\bar{c}$
ZZ
$t\bar{t}$
γγ
Zγ
μμ
LHC HIGGS XS WG 2013
M_H [GeV]

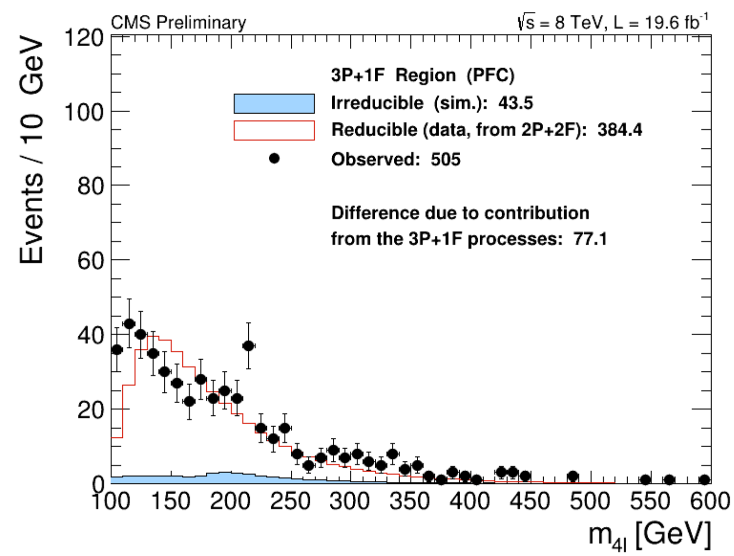


σ × BR [pb]
10
1
10-1
10-2
10-3
10-4
100
150
200
250
M_H [GeV]
√s = 8TeV
LHC HIGGS XS WG 2012
τ+τ-
VBF H → τ+τ-
WH → l±νbb̄
WW → l±νqq̄'
WW → l+νl-ν̄
ZZ → l+l-qq̄
ZZ → l+l-νν̄
ZZ → l+l-l+l-
ZH → l+l-bb̄
γγ
ttH → ttbb̄
l = e, μ
ν = νe,νμ,ντ
q = udscb

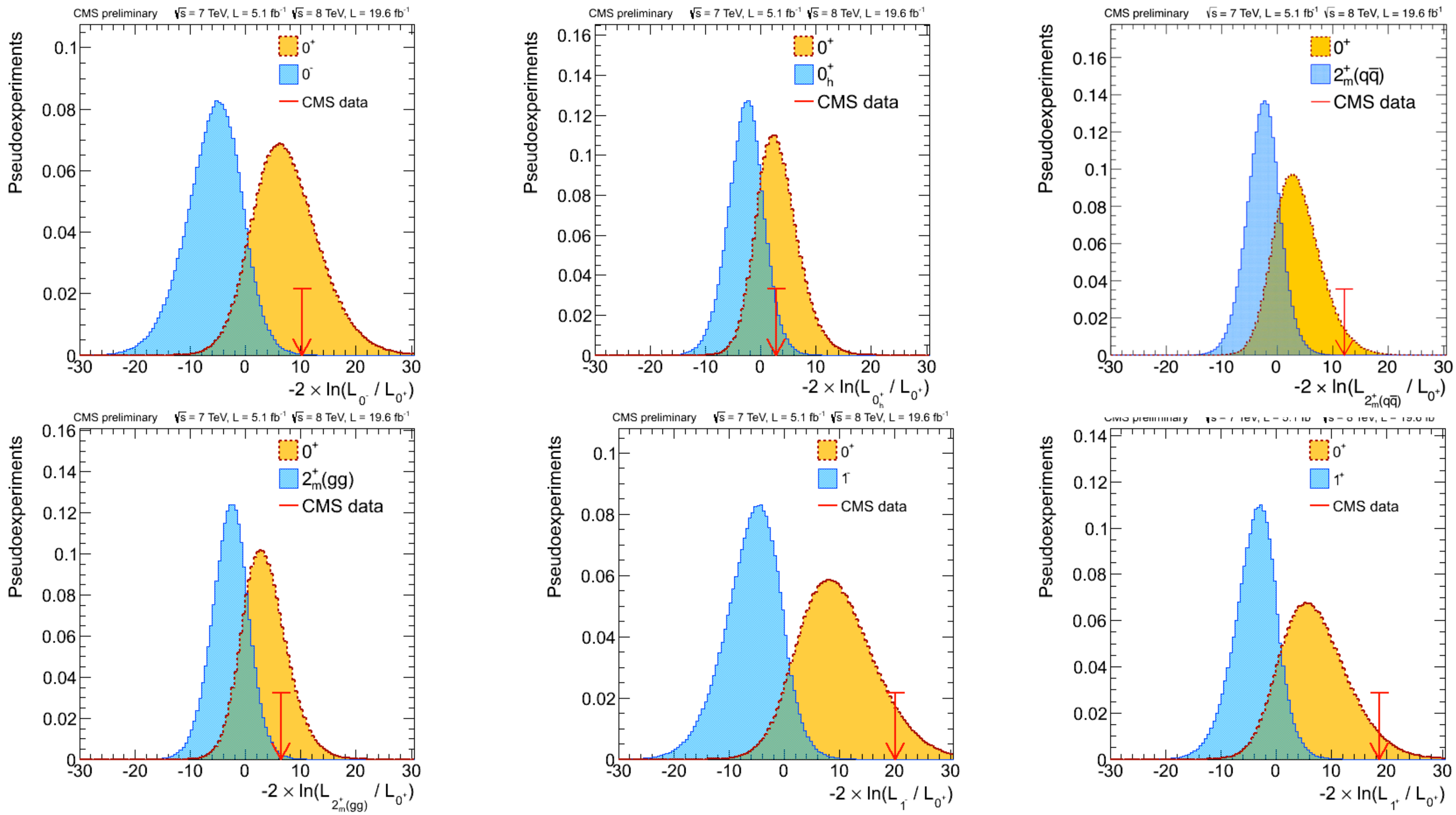
H→ZZ→4l: backgrounds

- Irreducible background
  - Empirical param. shapes from simulation
  - Corrected for data/simulation scale
- Instrumental backgrounds estimated from data
  - Extrapolation from samples enriched with misidentified leptons (iso+ID)
- 2 independent methods
  - 2P+2F (2 pass + 2 fail) sample, dedicated correction for γ conversions in Z+γ+jets
  - 2P+2F & 3P+1F (3 pass + 1 fail) sample, measures contributions from Z+γ+jets & WZ+jets
- Total uncertainty ~40%
  - statistics, systematics of method/shape



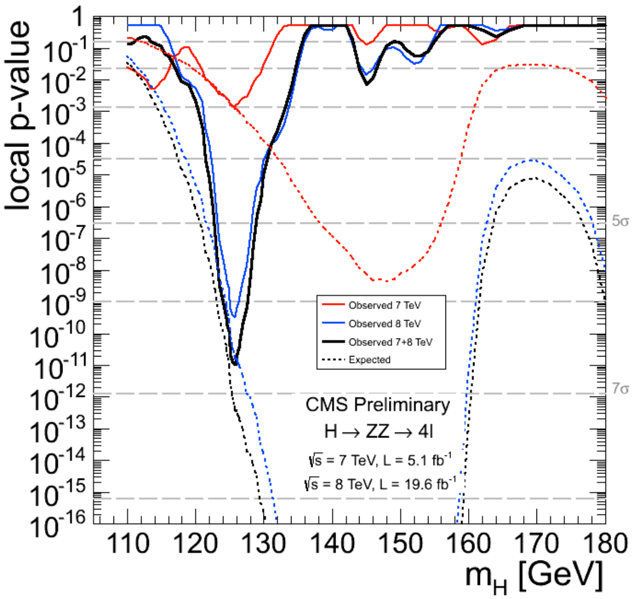


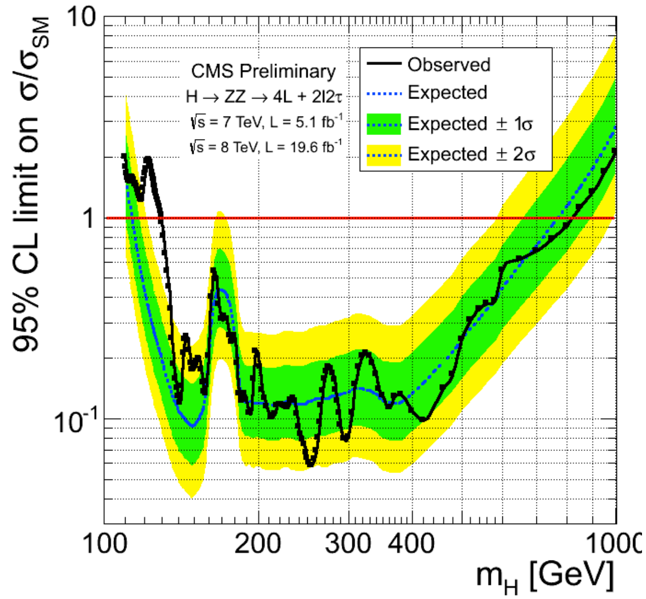
H→ZZ→4l: spin parity results

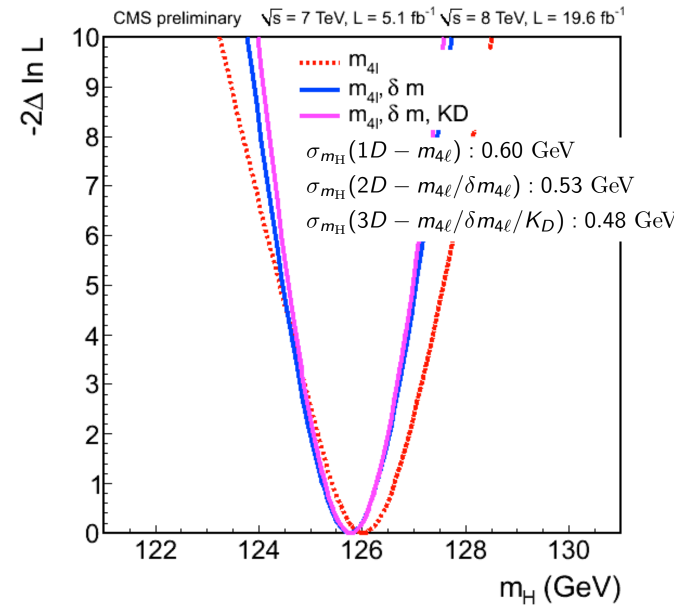


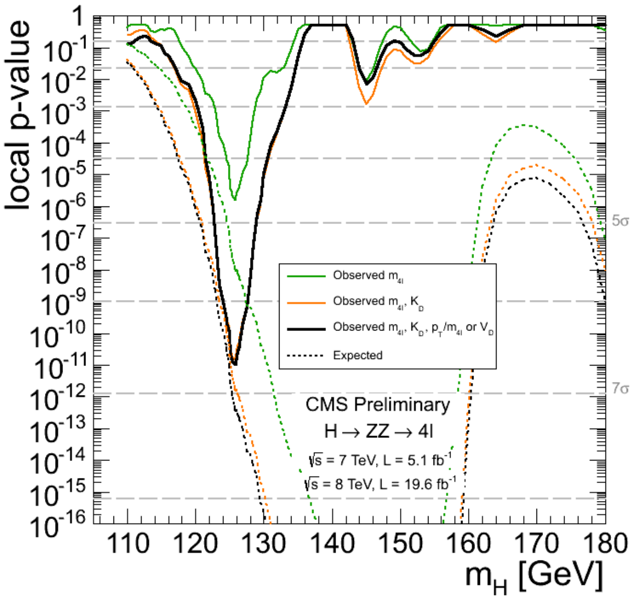
J^P	production	comment	expect (μ=1)	obs. 0^+	obs. J^P	CL_s
0^-	$gg \to X$	pseudoscalar	2.6σ (2.8σ)	0.5σ	3.3σ	0.16%
0_h^+	$gg \to X$	higher dim operators	1.7σ (1.8σ)	0.0σ	1.7σ	8.1%
2^+_{mgg}	$gg \to X$	minimal couplings	1.8σ (1.9σ)	0.8σ	2.7σ	1.5%
$2^+_{mq\bar{q}}$	$q\bar{q} \to X$	minimal couplings	1.7σ (1.9σ)	1.8σ	4.0σ	$<$0.1%
1^-	$q\bar{q} \to X$	exotic vector	2.8σ (3.1σ)	1.4σ	$>4.0\sigma$	$<$0.1%
1^+	$q\bar{q} \to X$	exotic pseudovector	2.3σ (2.6σ)	1.7σ	$>4.0\sigma$	$<$0.1%

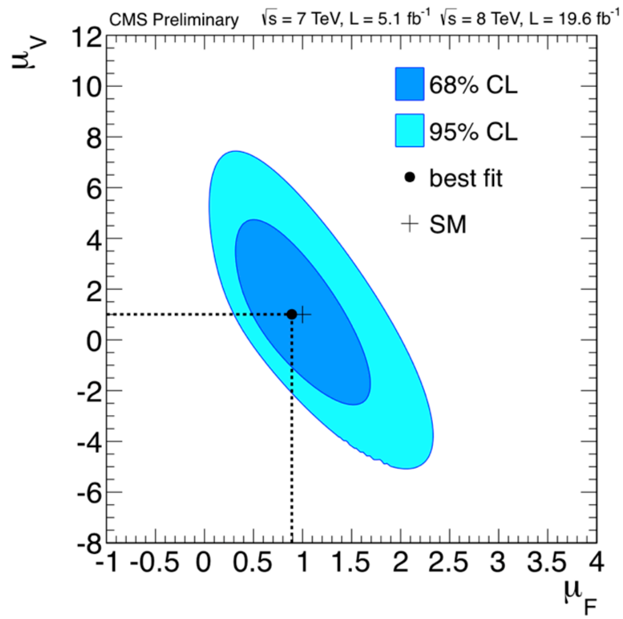
H→ZZ→4l: more results

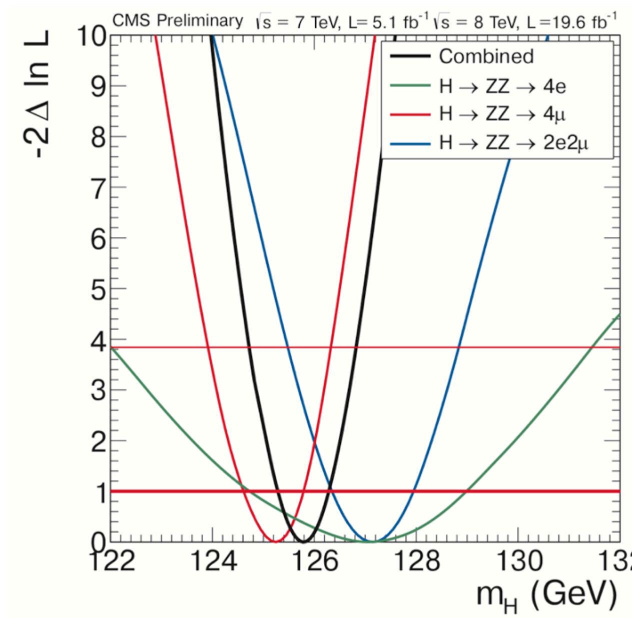








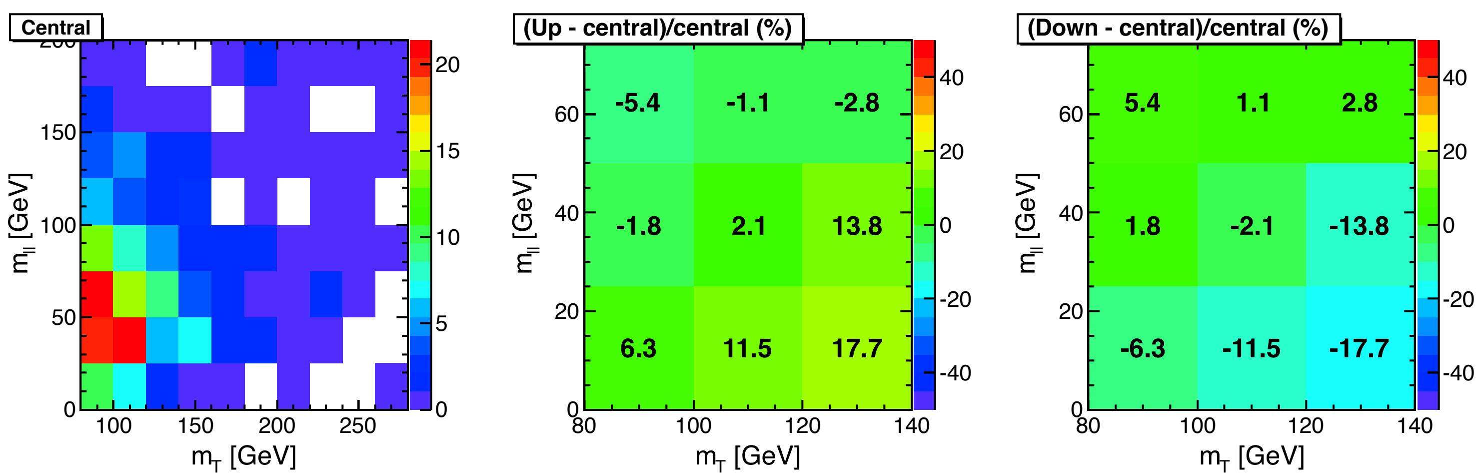




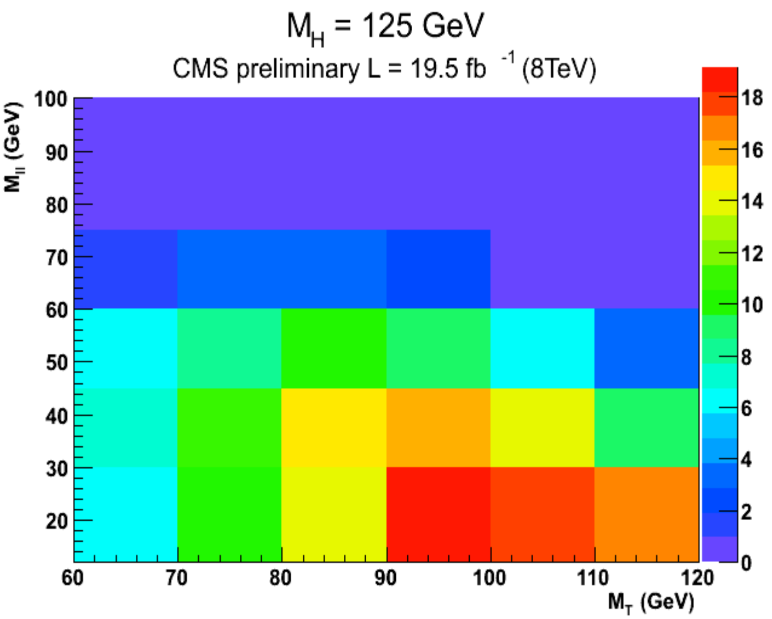
H→WW→2l2ν: Systematics

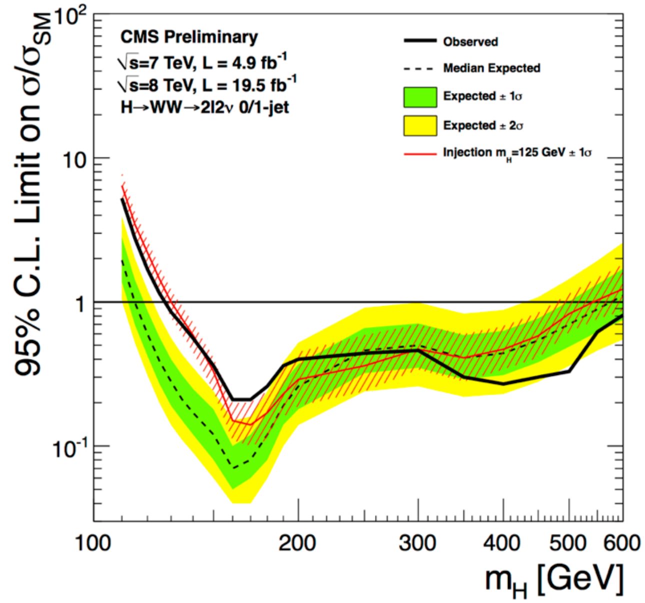
- Systematics in the 2D fit are both normalization and shape variations
  - Correlated systematics: experimental measurements, theoretical uncertainties
  - Uncorrelated systematics: background normalizations or background model parameters from control regions
  - Shape variations done through a morphing parameter between alternative shapes (up and down variation)
- Theoretical uncertainties on signal following LHC cross section recommendation
  - PDF + higher order effects + UEPS: 20-30%
- Instrumental
  - Luminosity: 4.4% (8TeV), 2.2% (7 TeV)
  - Lepton identification and trigger efficiency : 3(4) % for muon (electron)
  - Lepton Energy/Momentum scale : 1.5% for muon, 2% (5%) for electron in barrel (endcap)
  - MET resolution: 2%, Jet energy scale: 2-10%
- Shape variations
  - Instrumental variation: list same as above
  - WW : QCD scale variation and different generators (Madgraph vs MC@NLO)
  - Top : different generators (Madgraph vs Powheg)
  - W+jets : different thresholds used in background estimation method

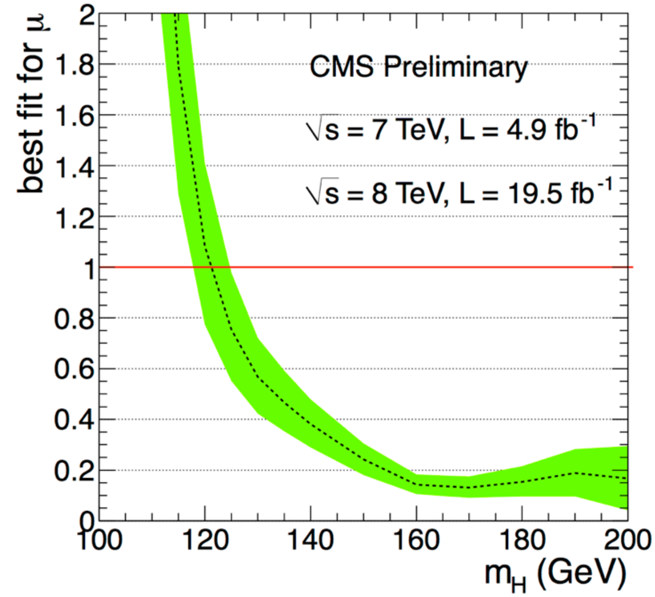
Wjets shape variations

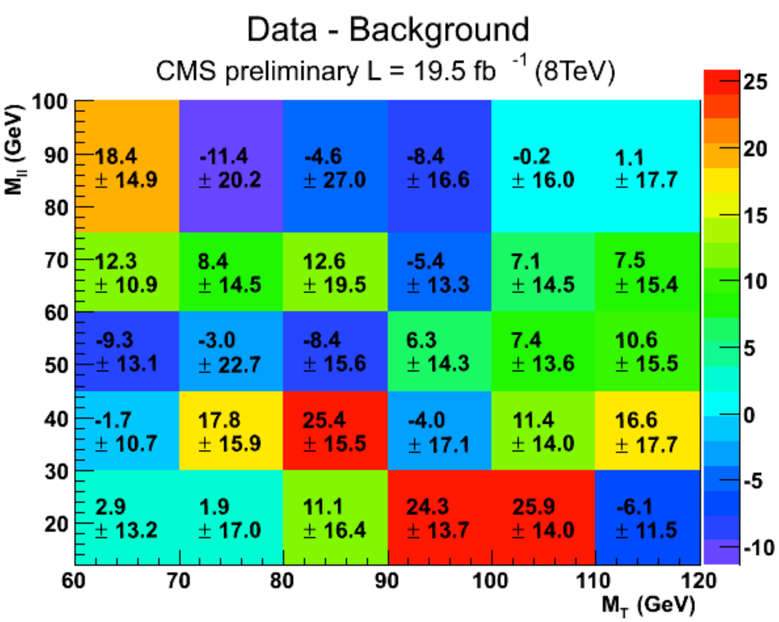


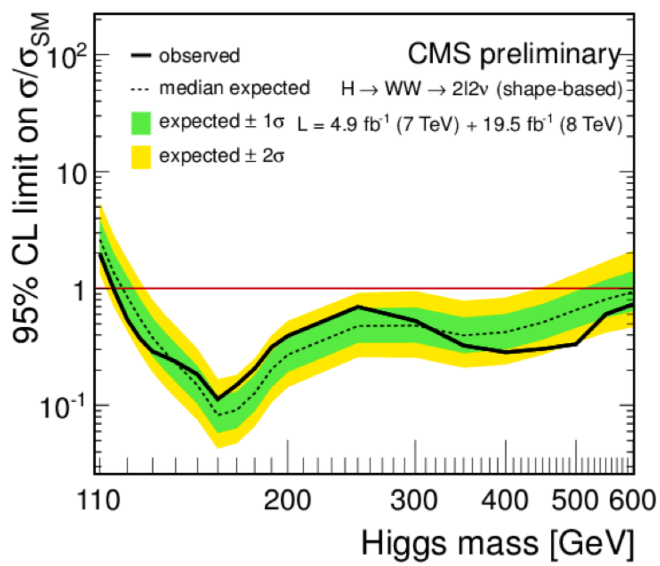
H→WW→2l2ν: More results

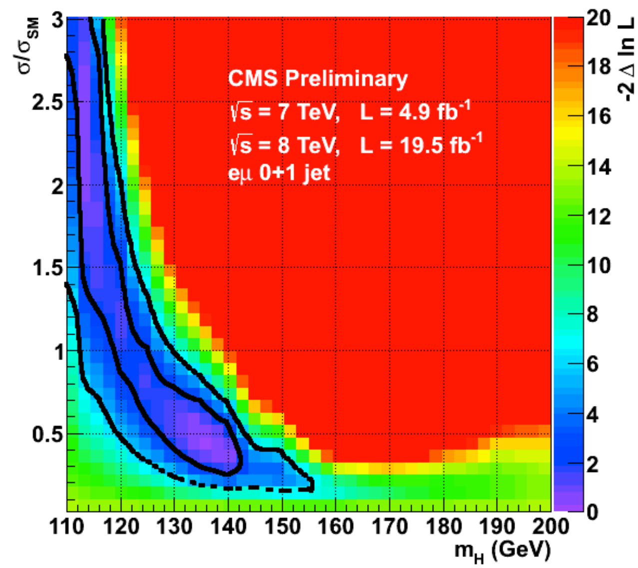






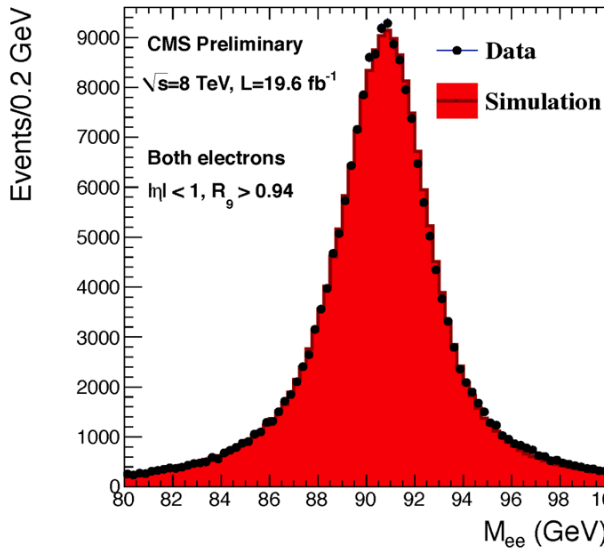


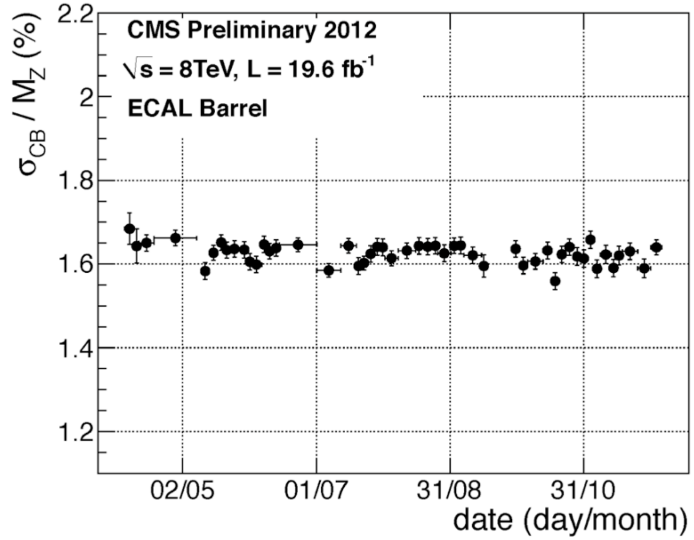




H→γγ: Photon reconstruction

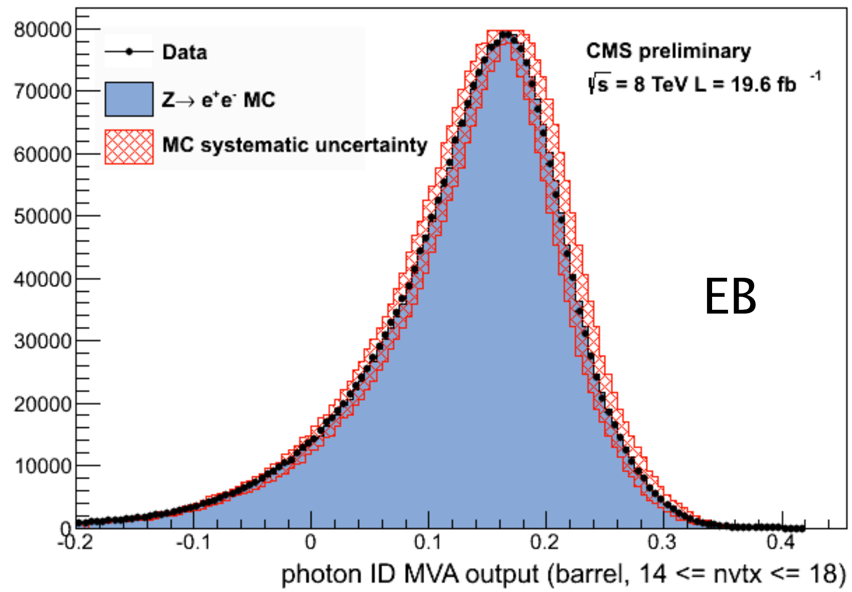
- Single Crystal:
  - Crystal energy calibration: (CMS-PAS-EGM-11-001)
    - transparency loss (laser)
    - inter-calibration (Φ-symmetry, π0/η mass, E/p)
- SuperClustering
- Energy corrections:
  - regression (BDT target = E_{raw}/E_{true});
  - Input variables
    - supercluster η/Φ
    - shower shapes variables
      - $R_9 = E_{3x3}/E_{SC}$; high R9 = γ unconverted, low R9 = γ converted
    - number of vertices
    - median energy density (ρ) per event
- Corrected SuperCluster
- Resolution stability within 0.1%
  - absolute energy scale + long term drifts
  - monitored with Z→e+e-
- Energy uncertainty (evt/evt):
  - regression (BDT target = correction regr - correction true)
  - Used in the MVA analysis

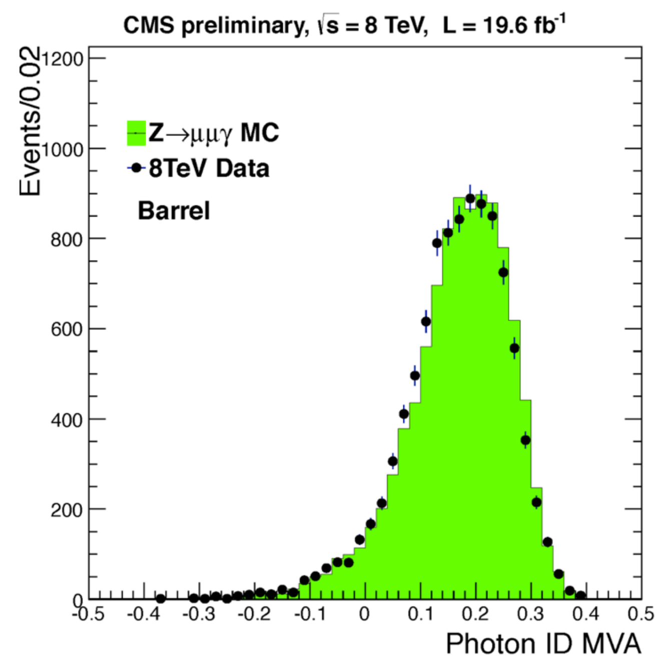




H→γγ: Photon identification

- Preselection:
  - electron-veto, H/E, loose Isolation, loose shower-shapes
  - ε~92%-99%, SF=1
- MVA based photon ID:
  - classification (BDT), variables:
  - η, shower-shapes
  - Particle flow isolation,
  - median energy density (ρ) per event
  - input to diphoton classification
- Cut-based photon ID:
  - optimized separately in 4 categories
  - high/low R9, EB/EE
  - variables: H/E, σiηiη, PF isolation



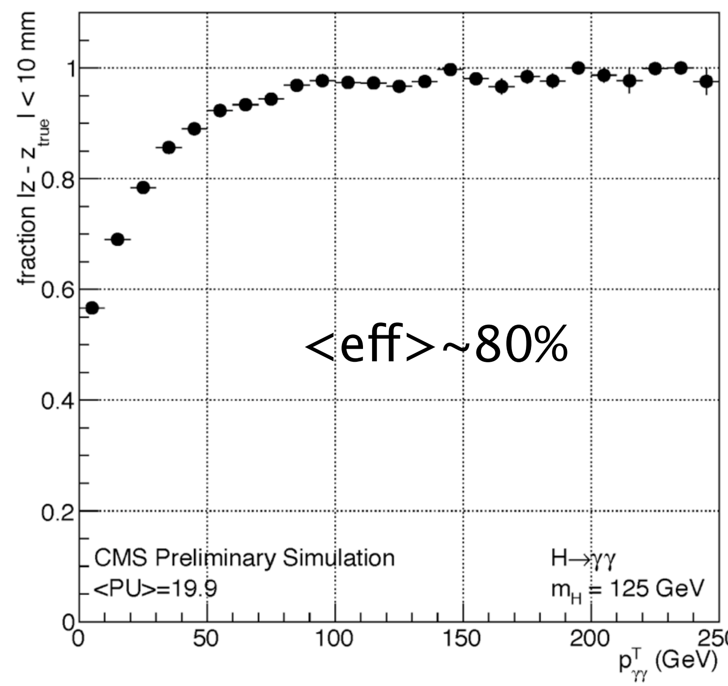


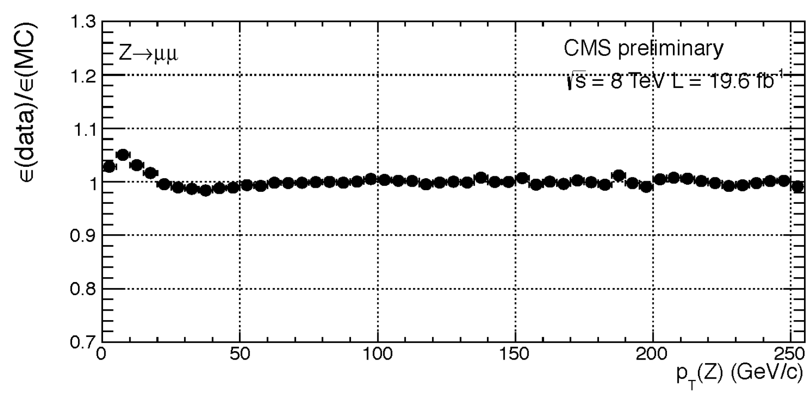
$H \rightarrow \gamma\gamma$: Vertex assignment

- Running conditions:
  - $\langle N_{vtx} \rangle = 9.5$ @ 7 TeV ($\sigma_z = 6$cm)
  - $\langle N_{vtx} \rangle = 19.9$ @ 8 TeV ($\sigma_z = 5$cm)
- No tracking information for photons
  - use kinematics correlations + conversion direction
- MVA-based vertex ID:
  - classification (BDT), variables:
  - sum p_T^2
  - tracks/diphoton balance,
  - sum pT(tracks)-diphoton asymmetry
- if d($vtx_{true} - vtx_{chosen}$ <1 cm) vtx, contribution to σ_{mass} negligible

$$m_{\gamma\gamma} = \sqrt{2E_1E_2(1 - cos\theta)}$$

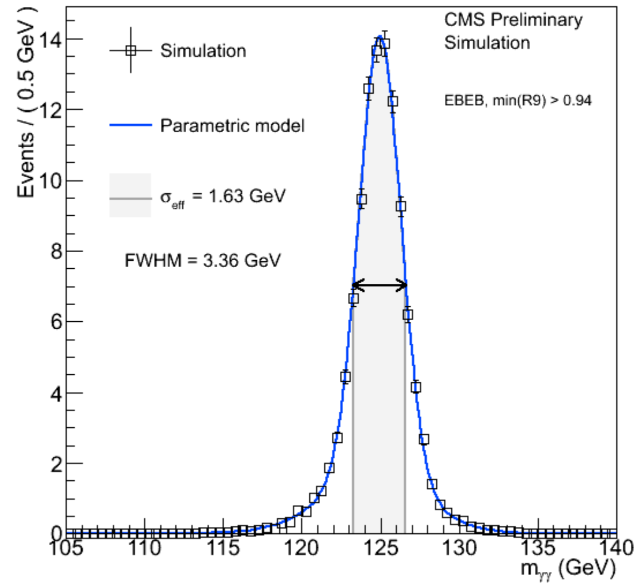
- MVA-based vertex probability:
  - classification (BDT)
  - BDT classifier to select events within 1cm
    - score proportional to the right-vertex probability
    - input to diphoton classification

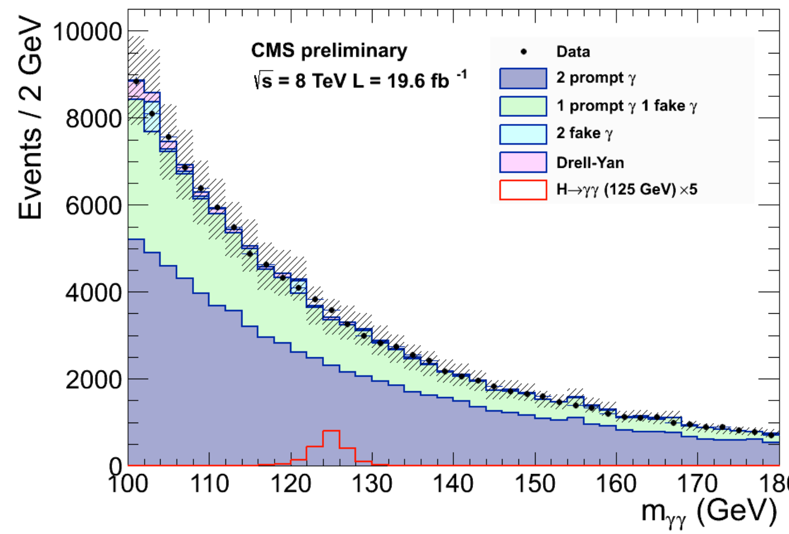




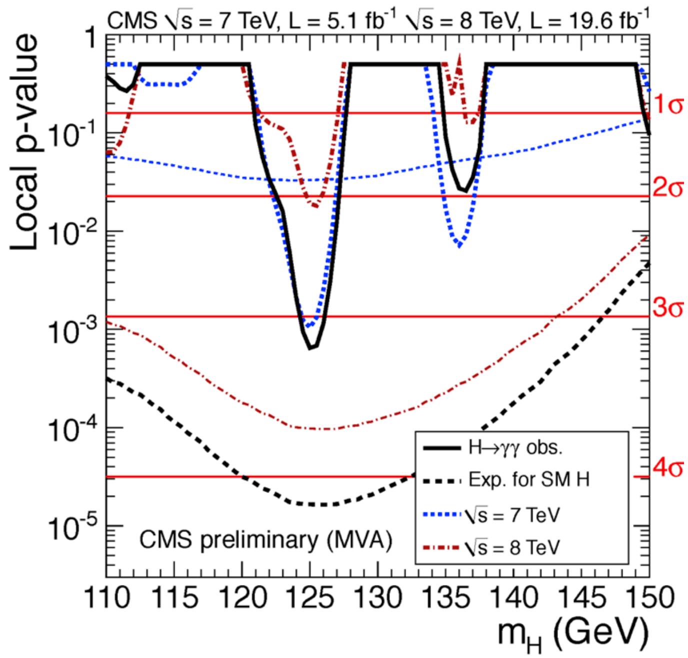
H→γγ: Signal and Bkg Model

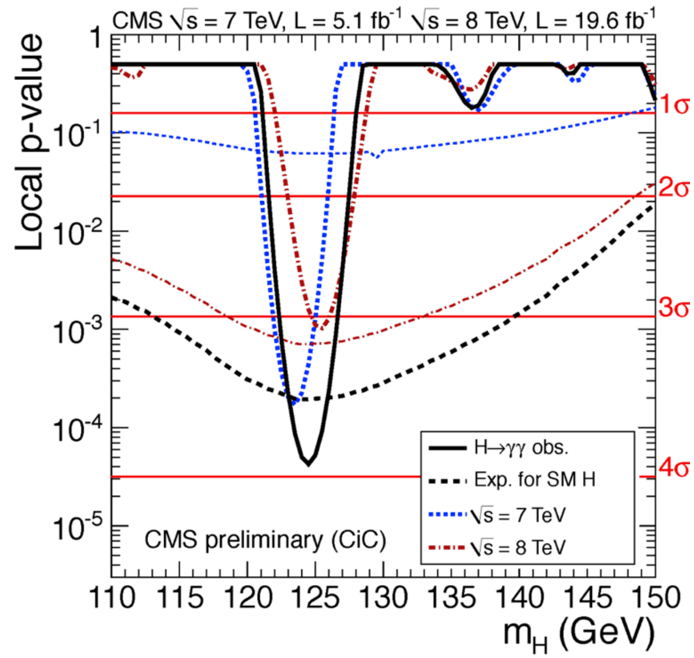
- Parametric signal model:
  - sum of gaussians
  - up to 3 gaussians depending on the category
- Background model
  - fit the data with different functional forms (sums of exponentials, sums of power law terms, Laurent series and polynomials)
  - choose the lowest order of the functional form fitting the data
    - p-value < 0.05 → "truth functions"
  - use the truth functions to throw toy-MC
  - choose the lowest order functional form such that bias on the signal strength <20% of the uncertainty on the background
    - systematics on the background shape can be neglected
  - Polynomials from 2-5 full fill the requirements





H→γγ: More Results





MVA

CIC