Higgs Boson Production and Properties in the $H \to ZZ \to 4\ell$ Channel

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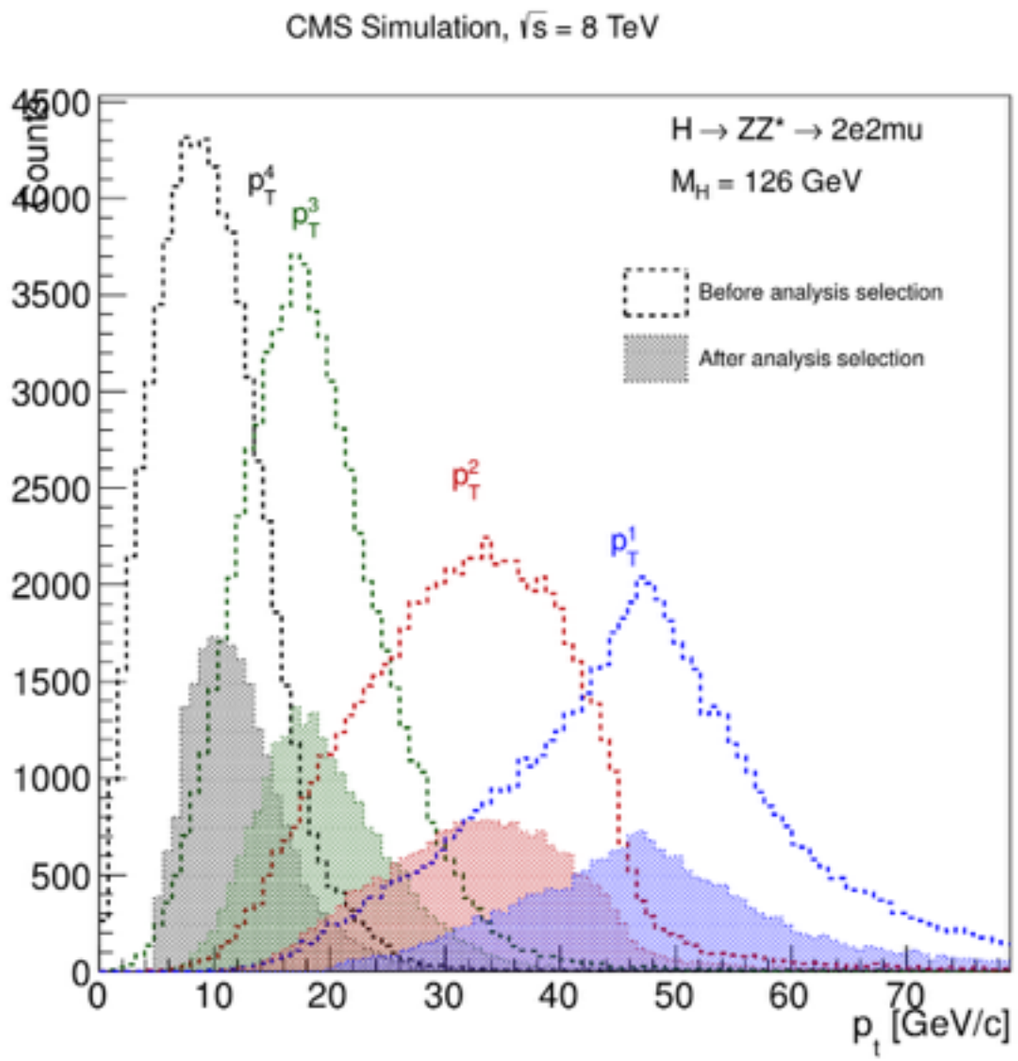
On behalf of the CMS Collaboration
ICHEP 2014

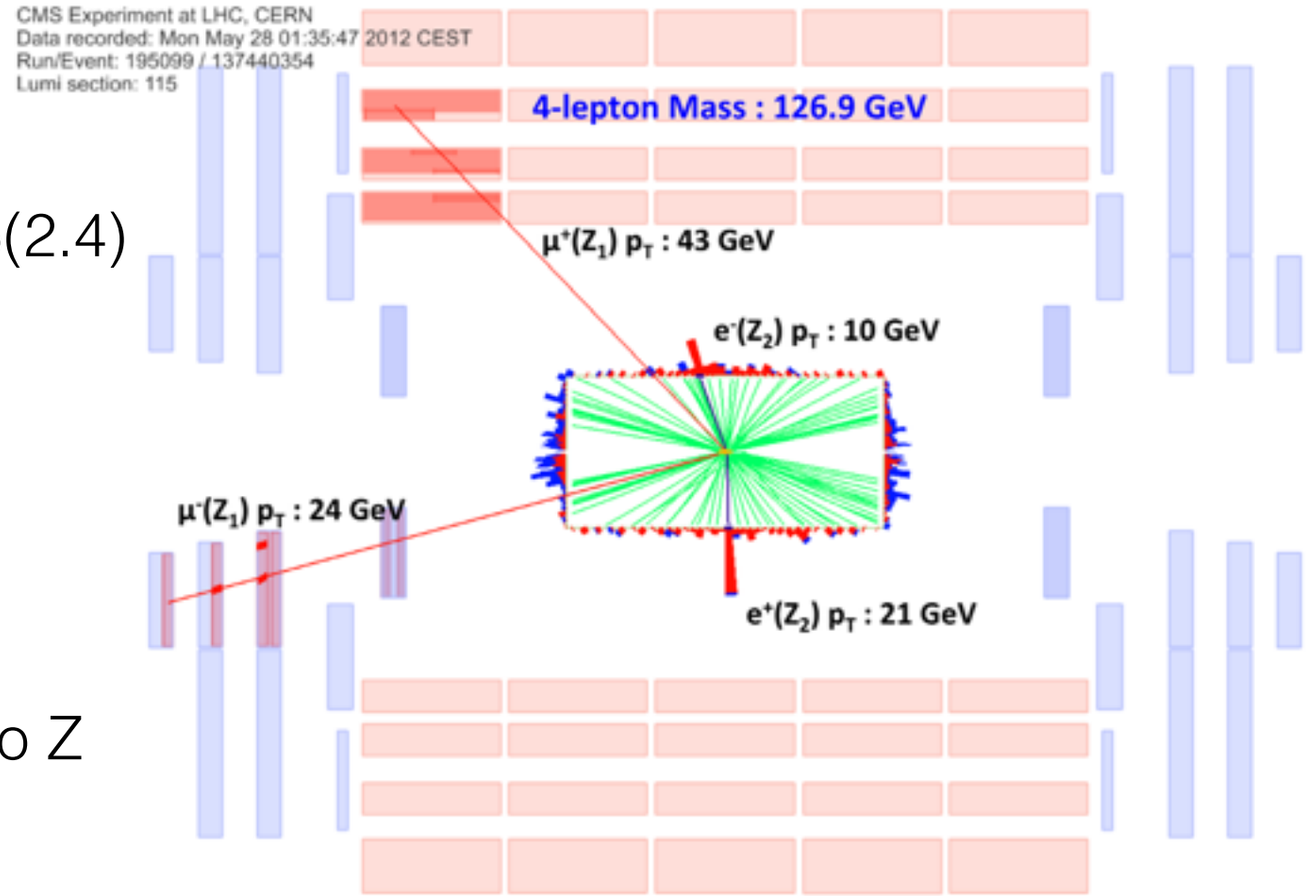
H→ZZ→4ℓ Overview

- "Golden" channel for Higgs discovery and measurements
  - High resolution and high S/B
- Statistically parched
  - ~20 signal events expected with current data
  - Need high lepton reconstruction, selection efficiency to catch lowest p_T leptons
- We attempt to squeeze the most possible information from available events
  - Exploit the rich final state topology to enhance search sensitivity and then to measure Higgs properties
  - Use event-by-event mass uncertainties to measure mass



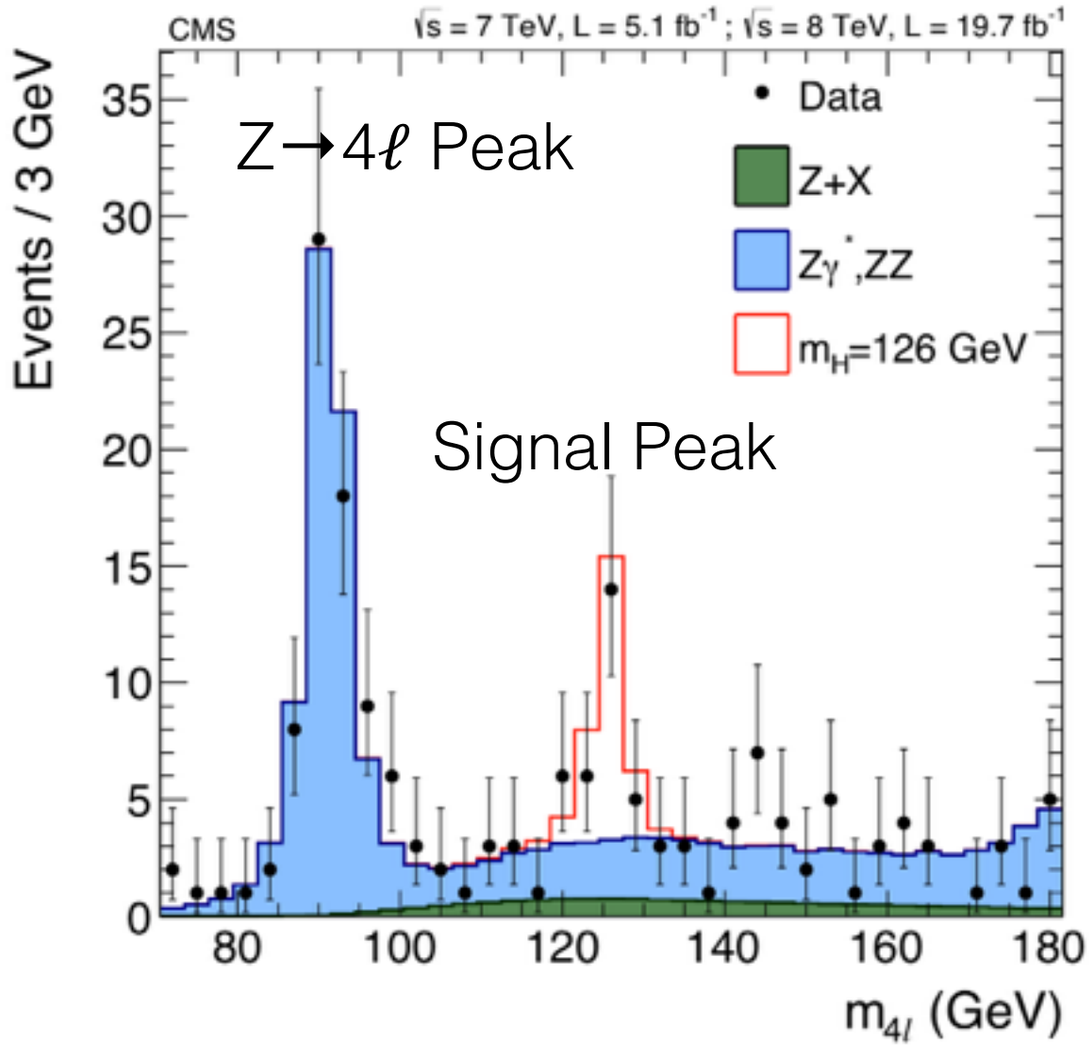
Event Selection

- Require 20/10 GeV leptons in the event (consistency with trigger)
- Lepton selection : p_T > 7(5) GeV, |η| < 2.5(2.4) for e(μ), ID+isolation+IP requirements
- Construct Z candidates and recover FSR photons (ΔR<0.5)
- Select "Z_1" candidate with mass closest to Z peak (40 < m(Z_1) < 120 GeV)
- Select "Z_2" candidate from remaining highest p_T leptons (12 < m(Z_2) < 120 GeV)
- Require m($\ell^+\ell^-$) > 4 GeV to suppress QCD



Search Strategy (I)

- $ZZ \rightarrow 4\ell$ events form the dominant and irreducible background
- Some additional reducible background from sources such as Z+jets, ttbar, etc.
- Higgs signal produces a sharp bump on a smooth background mass distribution
- We can see the signal peak building up around m(4ℓ) ~ 125 GeV



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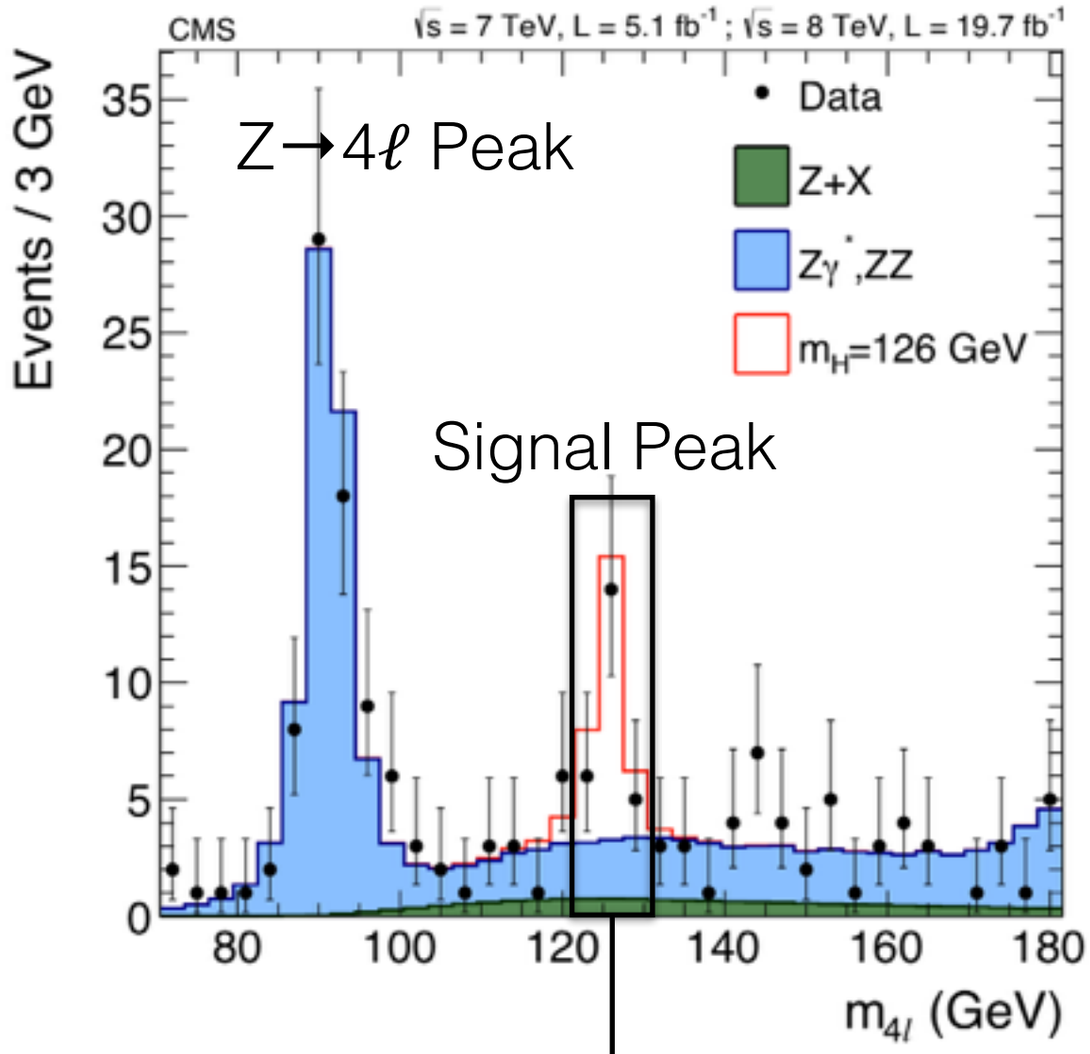
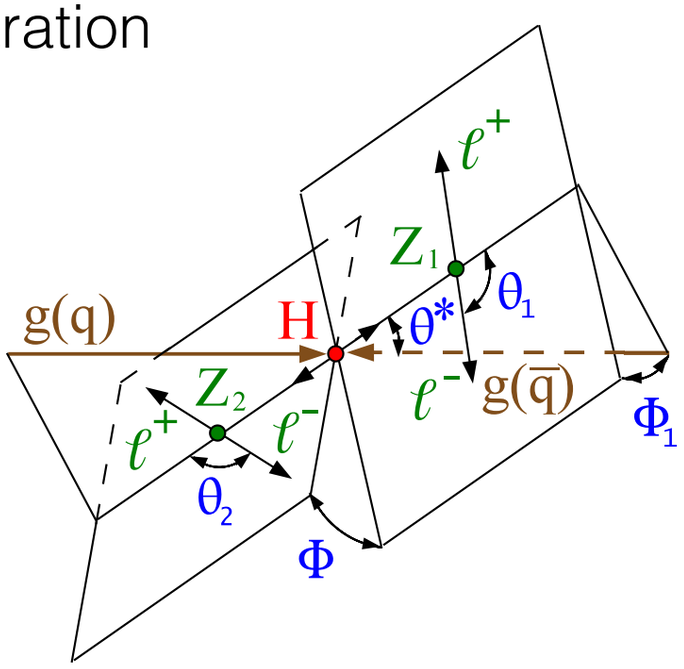


Channel	$4e$	$2e2\mu$	4μ	4ℓ
ZZ background	1.1 ± 0.1	3.2 ± 0.2	2.5 ± 0.2	6.8 ± 0.3
$Z + X$ background	0.8 ± 0.2	1.3 ± 0.3	0.4 ± 0.2	2.6 ± 0.4
All backgrounds	1.9 ± 0.2	4.6 ± 0.4	2.9 ± 0.2	9.4 ± 0.5
$m_H = 125$ GeV	3.0 ± 0.4	7.9 ± 1.0	6.4 ± 0.7	17.3 ± 1.3
$m_H = 126$ GeV	3.4 ± 0.5	9.0 ± 1.1	7.2 ± 0.8	19.6 ± 1.5
Observed	4	13	8	25

Search Strategy (II)

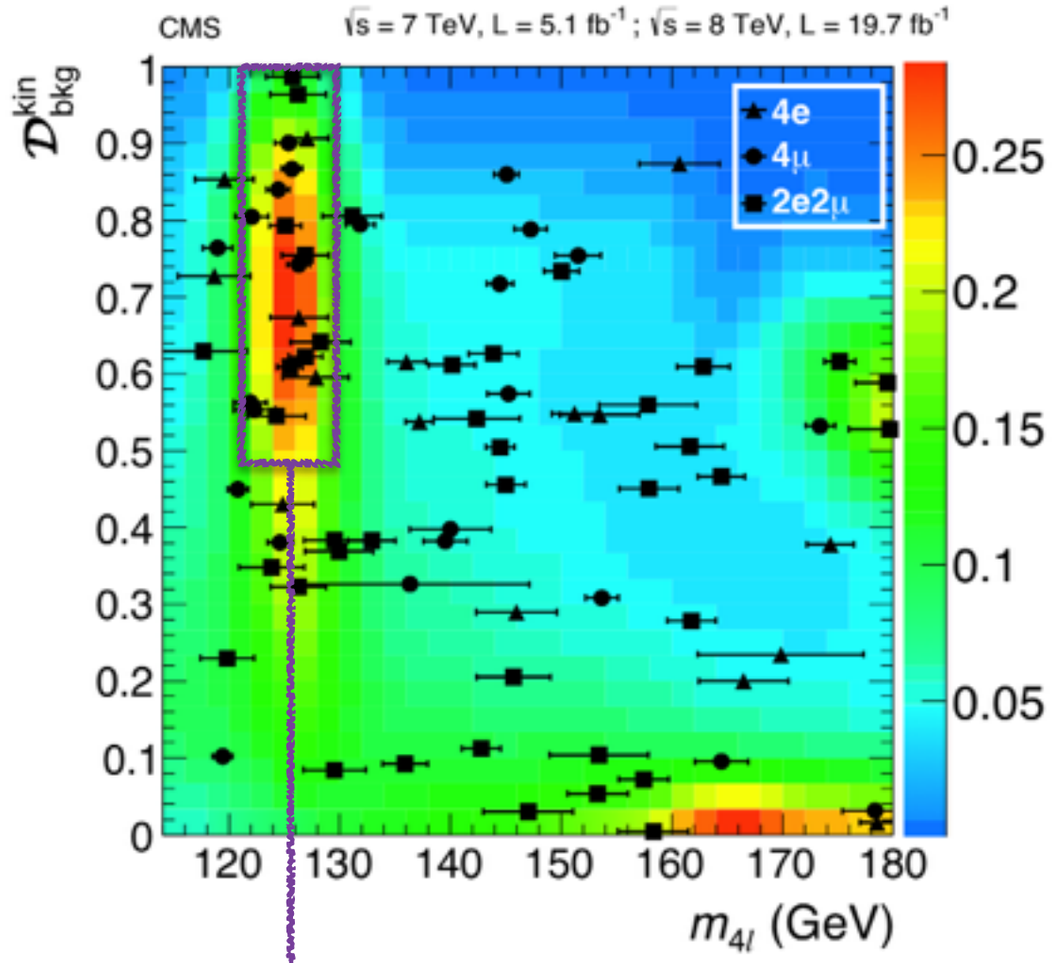
- Use additional information in the event (two Z masses, five production & decay angles) to increase signal-background separation



- Construct a kinematic discriminant with these inputs using LO matrix elements

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

D^{kin} v/s m(4ℓ) distribution
Data overlaid on signal+background prediction

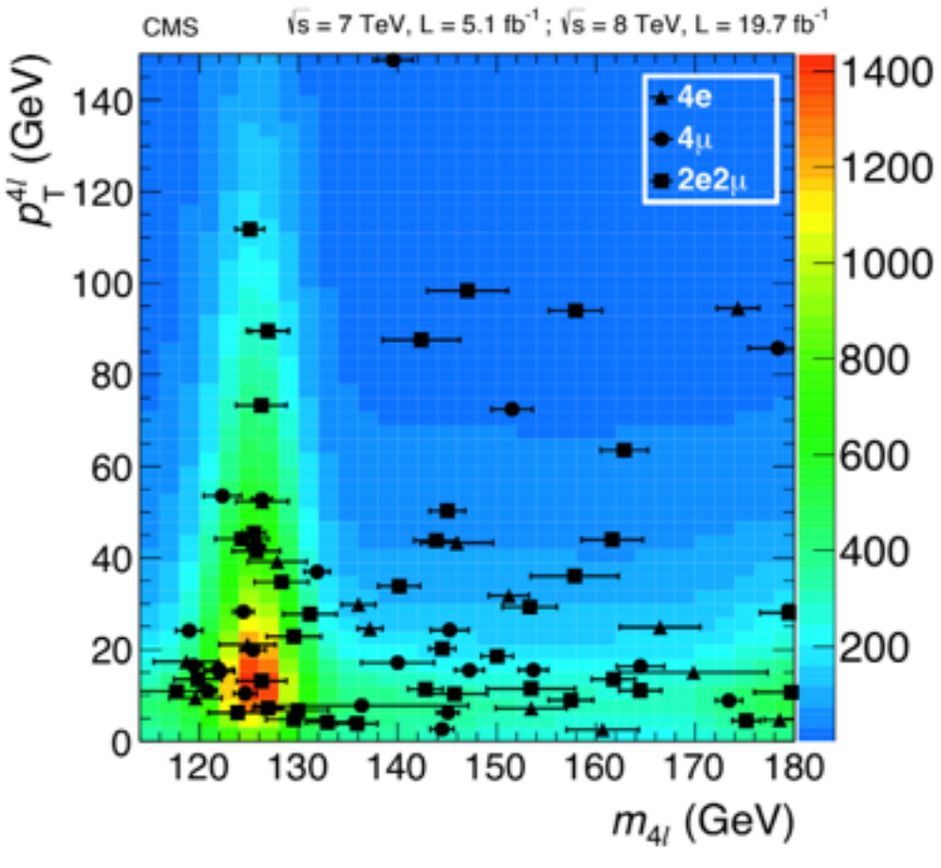


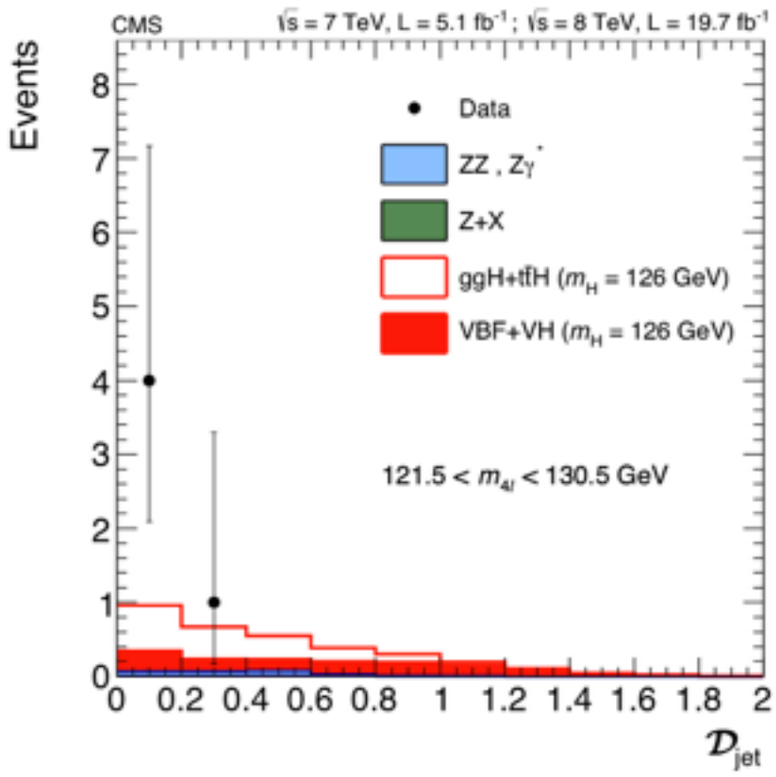
Signal events concentrated in the region D^{kin} > 0.5

Such discriminants also used to measure Higgs properties like spin-parity, Higgs width

Search Strategy (III)

- Probe the different production modes of the Higgs boson
- Categorize events as dijet-tagged and untagged
- *Dijet tagged events* : A linear discriminant constructed using Δη(jj) and m(jj) to separate VBF from gluon fusion
- *Untagged events* : The p_T of the four-lepton system used to discriminate between VBF and gluon fusion
- Search performed using a 3D fit with m(4ℓ), kinematic discriminant, dijet discriminant (or four-lepton p_T)

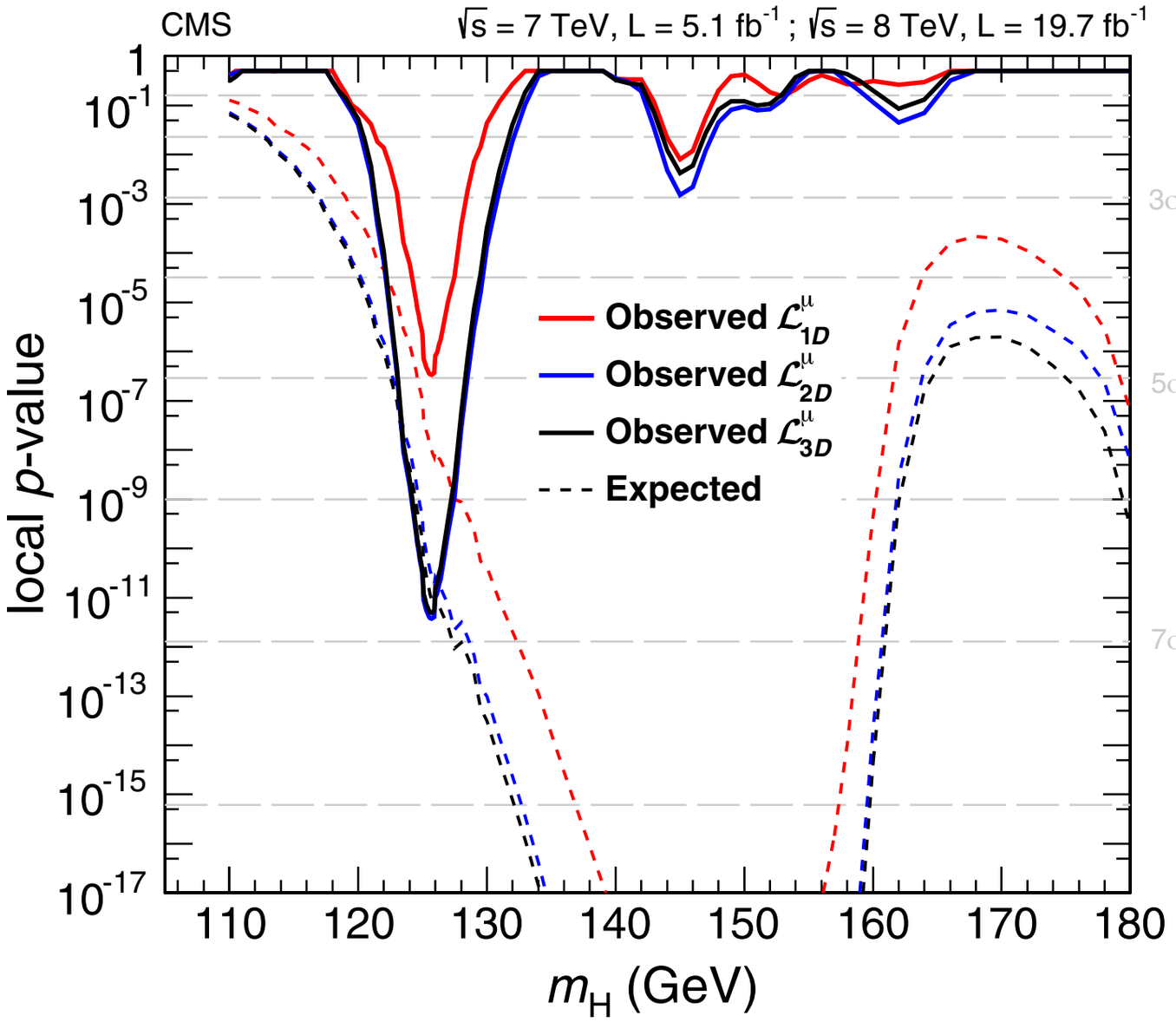




Search Results

	1D	2D	**3D**
Expected Significance	5.6σ	6.6σ	**6.7σ**
Observed Significance	5.0σ	6.9σ	**6.8σ**

1D : m(4ℓ) only
2D : m(4ℓ), kinematic discriminant
3D : m(4ℓ), kinematic discriminant, dijet discriminant (or four-lepton p_T)

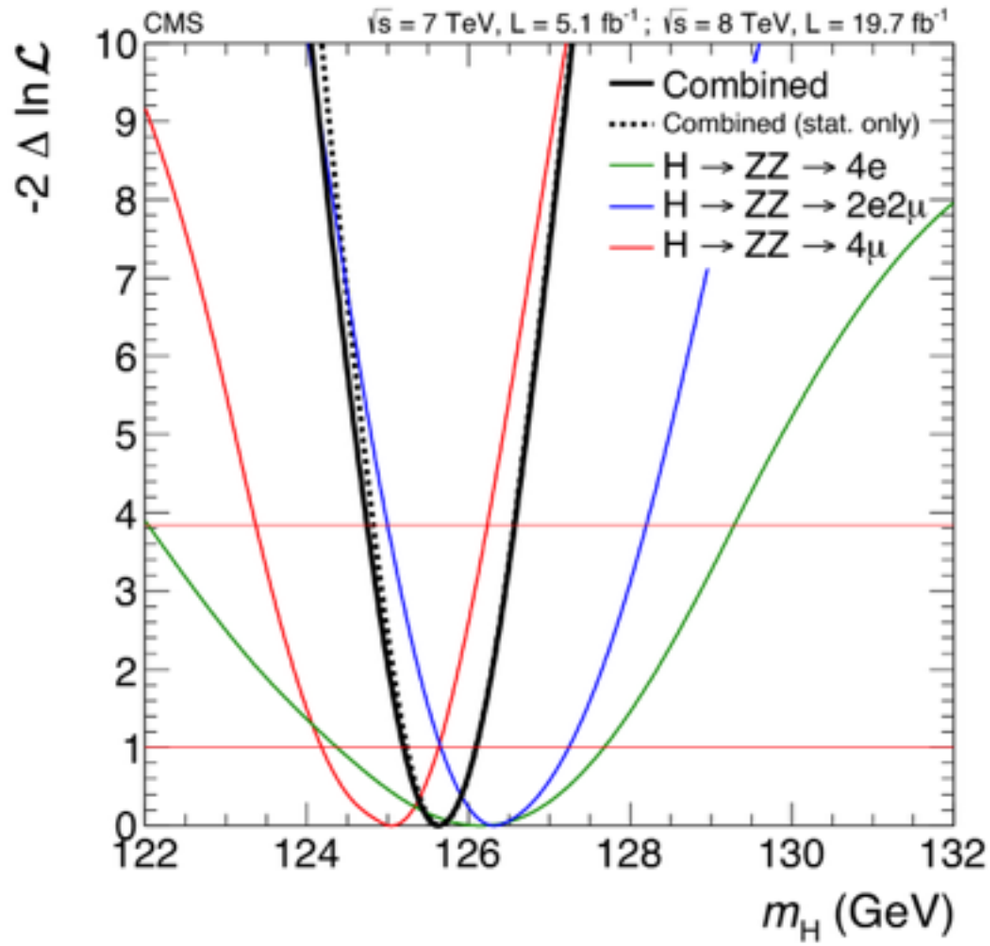


6.8σ signal observed for m_H = 125.7 GeV

Phys. Rev. D **89**, 092007 (2014)

Mass Measurement

- $H \to ZZ \to 4\ell$ channel is highly sensitive to the Higgs mass
- Precise measurement of lepton momenta is critical
- Multivariate regression used to improve the measurement of electron momentum
- Corrections applied to account for differences in momentum scale/resolution between data and simulation
- Event-by-event mass uncertainties used to optimally exploit the available data
- Mass measurement performed as a 3D fit using m(4ℓ), kinematic discriminant, and event-by-event mass uncertainties



Channel	Measured mass (GeV)
$4e$	$126.2^{+1.5}_{-1.8}$
$2e2\mu$	$126.3^{+0.9}_{-0.7}$
4μ	$125.1^{+0.6}_{-0.9}$
4ℓ	$125.6 \pm 0.4(\text{stat}) \pm 0.2(\text{syst})$

Dedicated talk on the mass measurement by M. Sani

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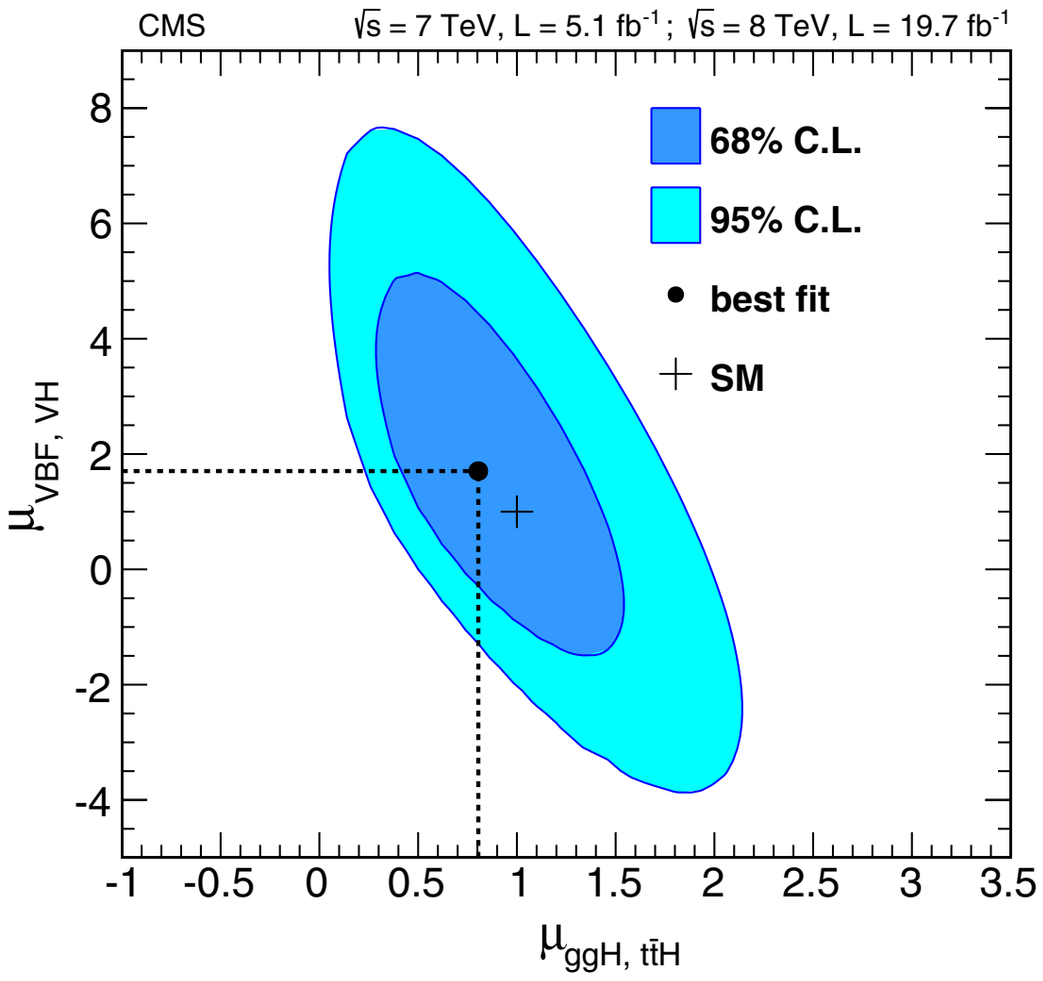
Signal Strength

- 3D search analysis allows to disentangle the production modes
- Production modes grouped in two categories:
  - ➡ Vector boson induced (VBF, WH, ZH)
  - ➡ Fermion induced (gluon fusion, ttH)



	VBF,VH	ggH,ttH	Overall
μ	$1.45^{+0.89}_{-0.62}$	$0.83^{+0.31}_{-0.25}$	$0.93^{+0.26}_{-0.23}(\text{stat})^{+0.13}_{-0.09}(\text{syst})$

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Width Measurement

- Measurement of the Higgs width from the observed peak is limited by detector resolution (~1 GeV)

  ➡ Width of a 125.6 GeV SM Higgs boson : 4.15 MeV

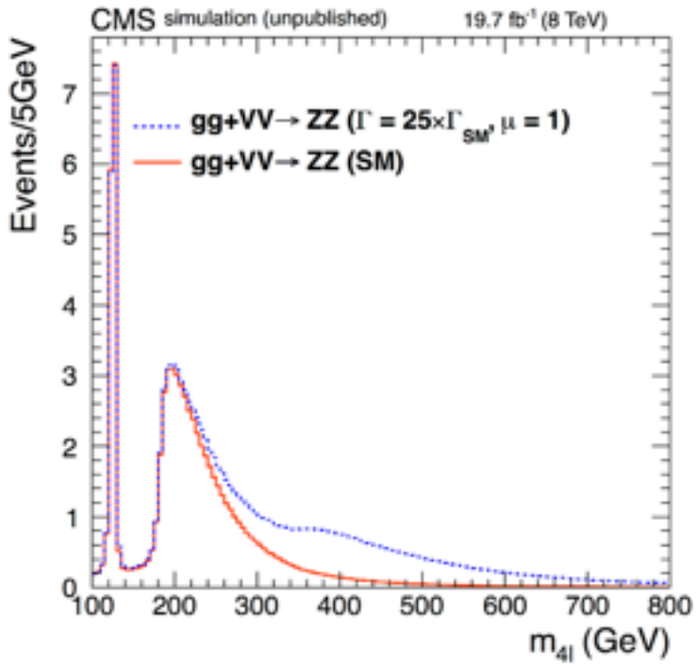
  ➡ Direct fit to the signal resonance gives Γ_H < 3.4 GeV at 95% CL

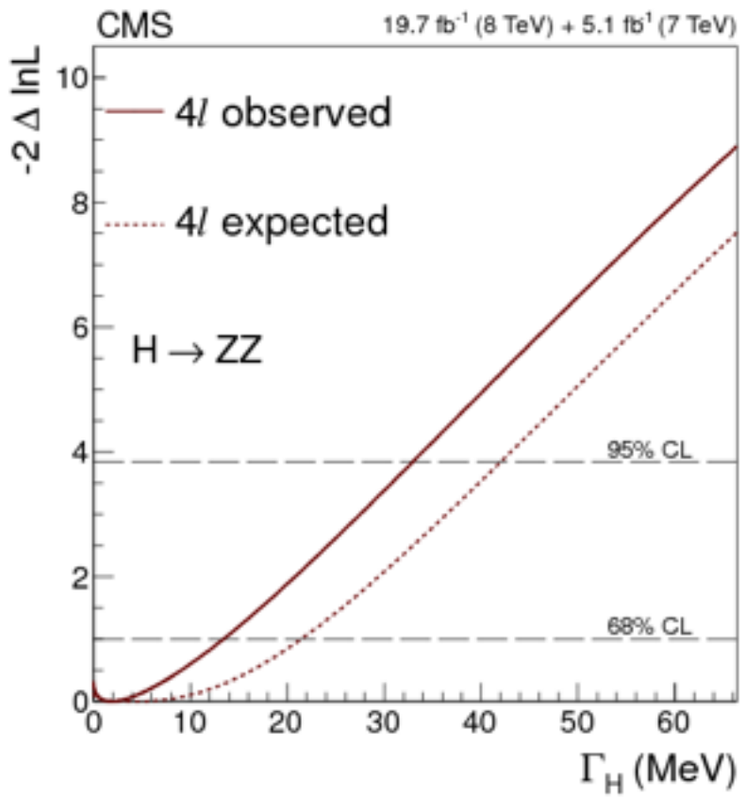
- It has been recently shown* that Γ_H can be constrained (with mild model dependence) at few 10s of MeV with current data using off-shell signal events

$$\sigma^{\text{on-shell}}_{gg\to H\to ZZ} \sim \frac{g^2_{ggH} g^2_{HZZ}}{m_H \Gamma_H} \qquad \sigma^{\text{off-shell}}_{gg\to H\to ZZ} \sim \frac{g^2_{ggH} g^2_{HZZ}}{(2m_Z)^2}$$

* *JHEP* **08** 116 (2012); *Phys. Rev. D* **88** 054024 (2013);
* arxiv:1311.3589

Dedicated talk on the width measurement by L. Quertenmont



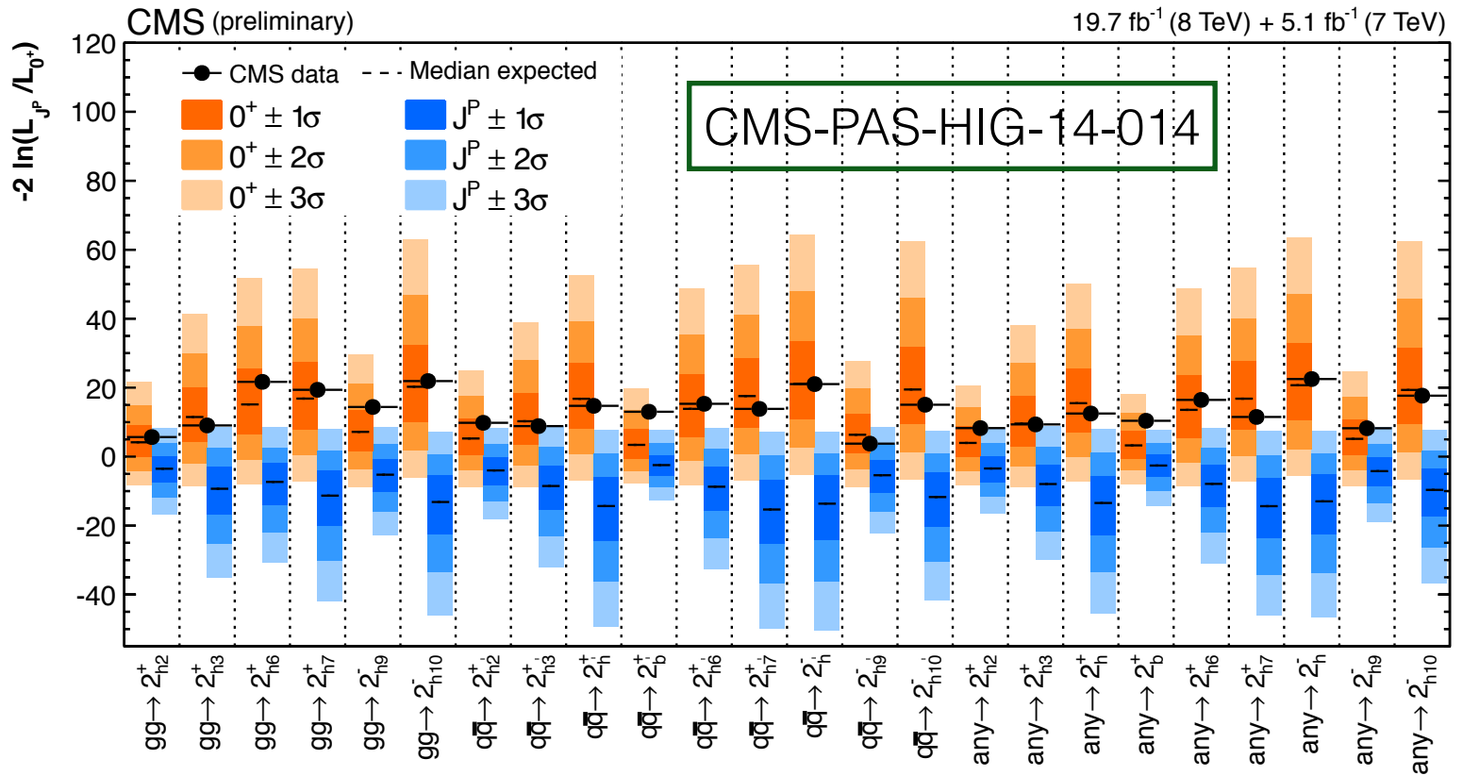


Γ_H < 33 MeV at 95% CL

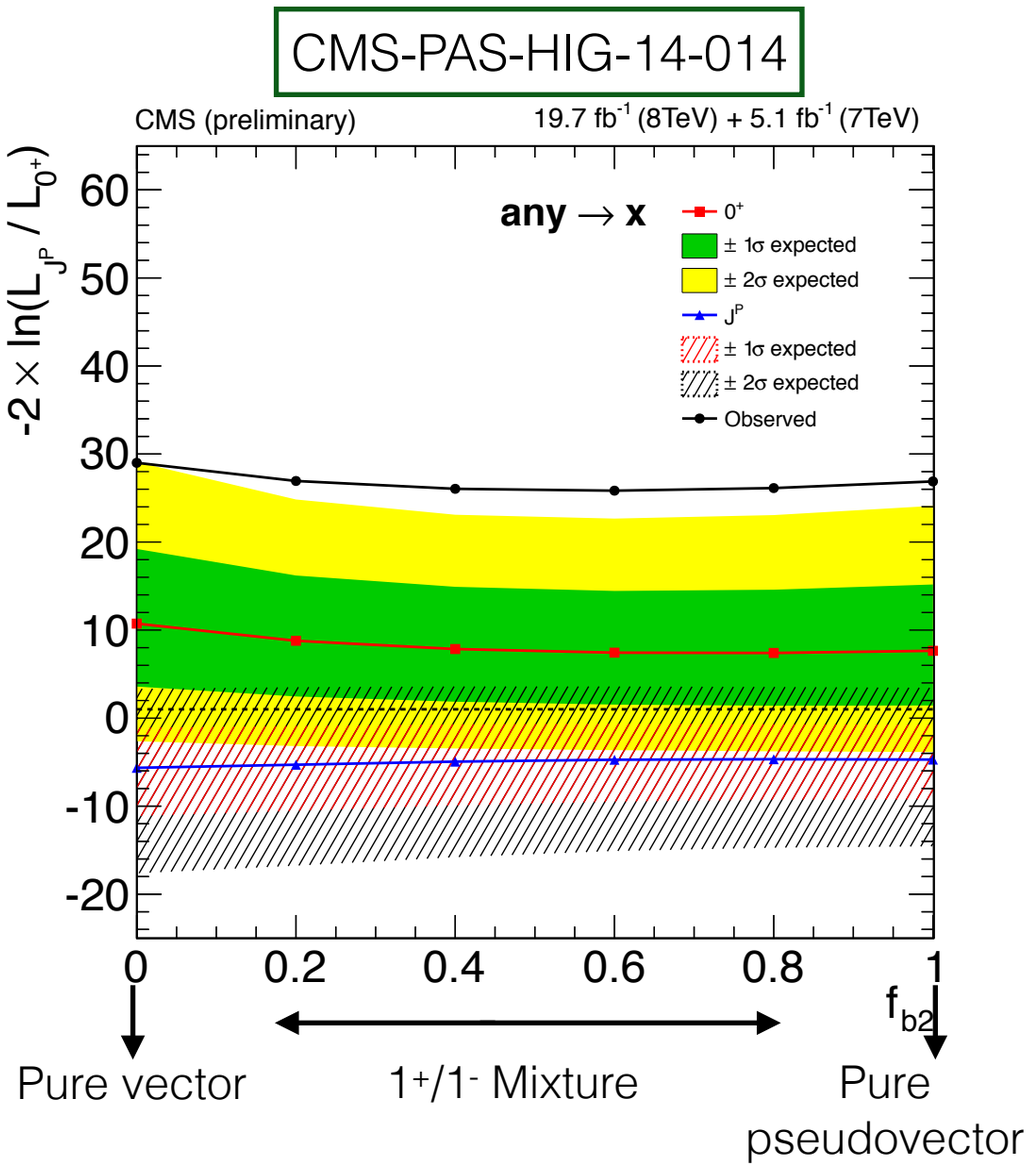
arxiv:1405.3455 (Accepted by PLB)

Spin-Parity Tests

- SM Higgs boson expected to be a scalar particle
- This needs to be established in data
- Perform hypothesis tests w.r.t. spin-1 or spin-2 models using dedicated kinematic discriminants



All spin-2 models considered are excluded at 95% CL or higher



Any mixture of 1^+ and 1^- states excluded at 99% CL or higher

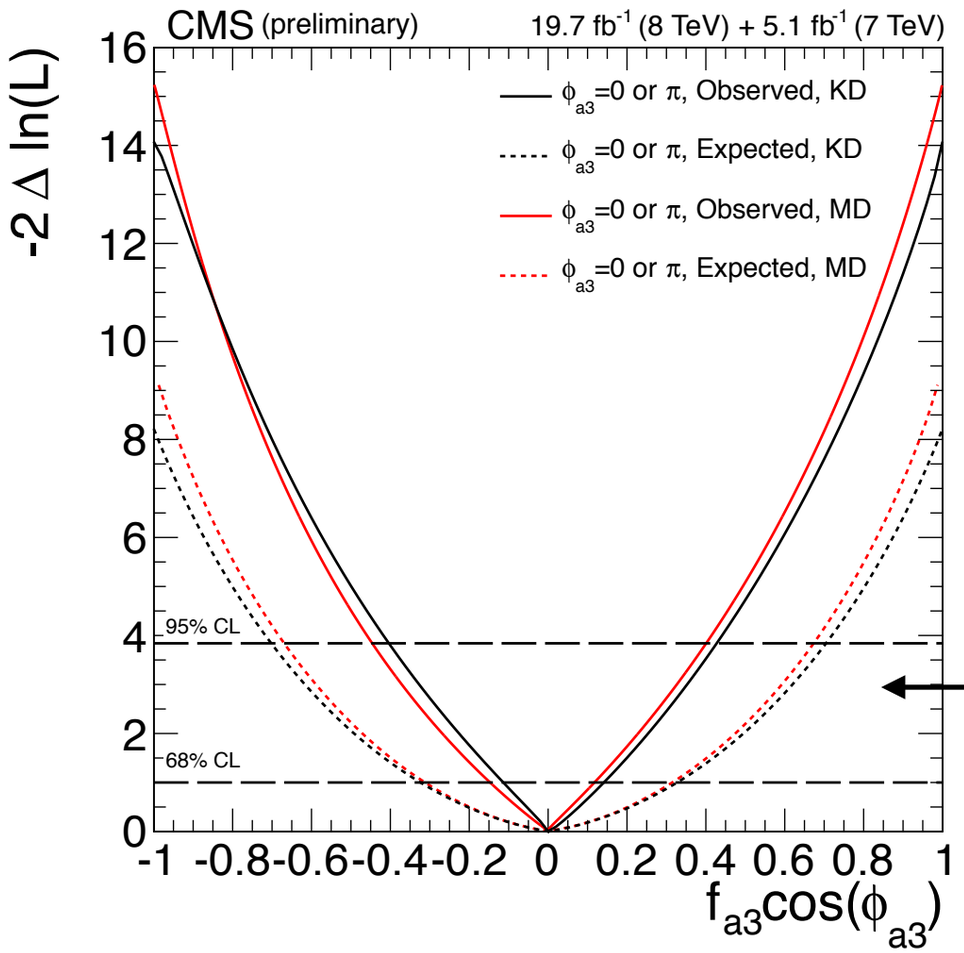
Dedicated talk on spin-parity studies by E. Di Marco

Probing Spin-0 Couplings

- **We have excluded the pure pseudoscalar hypothesis at greater than 99% CL**

- Extensive set of studies of the tensor structure of the spin-0 amplitude have been performed

CMS-PAS-HIG-14-014



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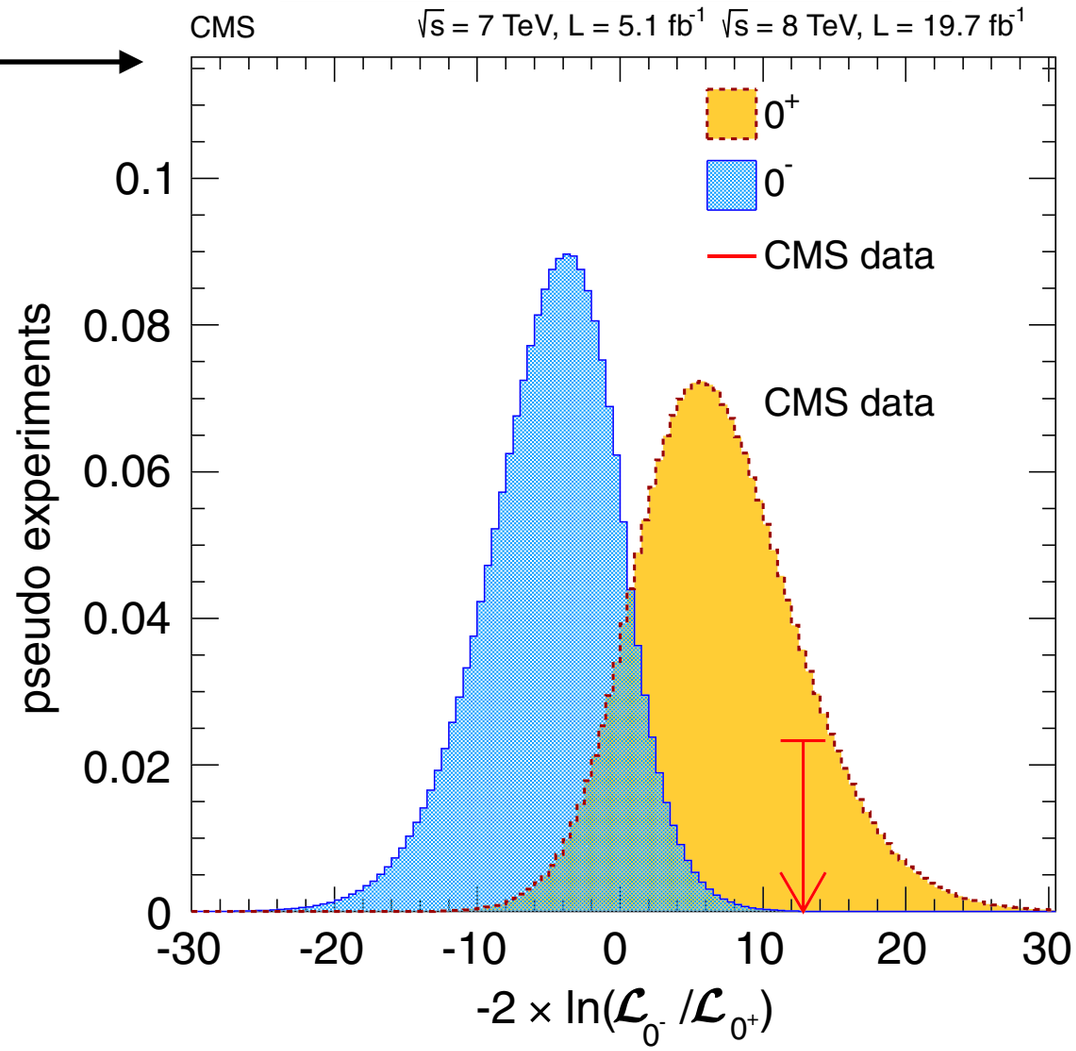


fit for the effective fraction of the 0^- component

More results in the talk by E. Di Marco

Summary

- A Higgs boson candidate observed in the H→ZZ→4l search with a local significance of 6.8σ

- Several properties of the particle have been measured with this channel

  - ✓ Mass : 125.6±0.4(stat)±0.2(syst) GeV

  - ✓ Signal strength consistent with SM prediction

  - ✓ Width constrained to $\Gamma_H < 33$ MeV at 95% CL

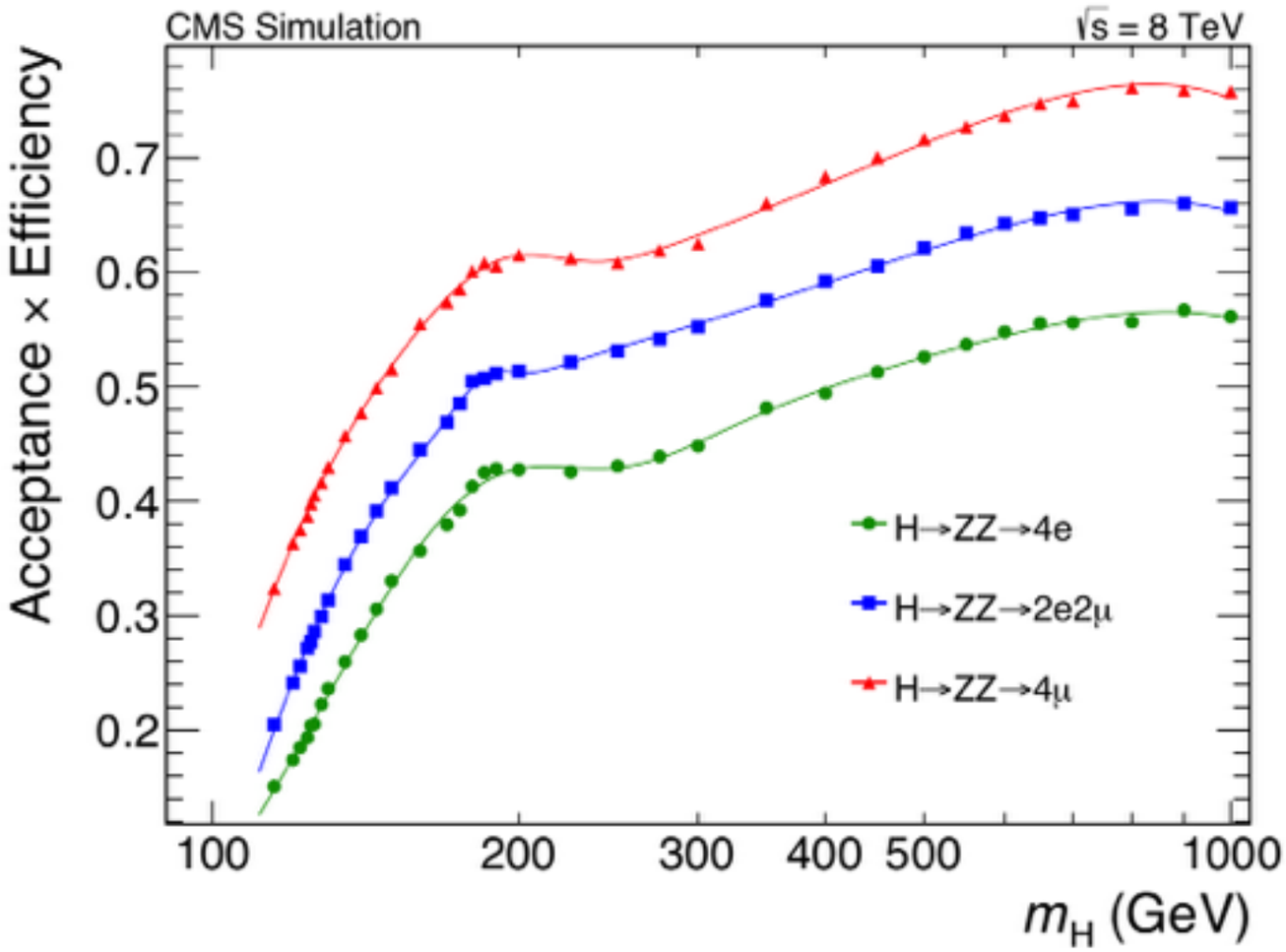
  - ✓ Spin-parity of the particle consistent with a scalar

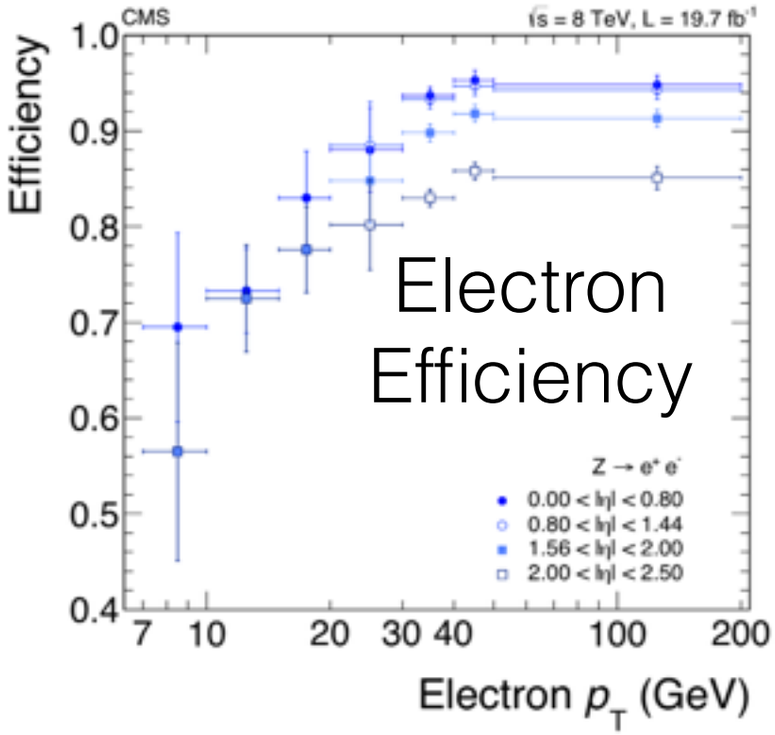
- *The Higgs boson candidate is consistent with the SM Higgs boson*

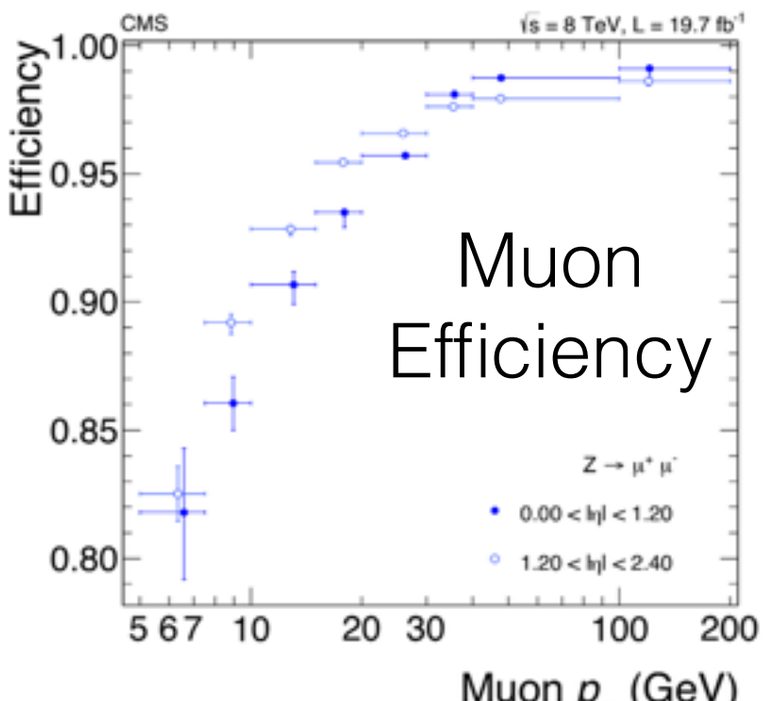
Backup

Signal Efficiency

Fraction of signal events selected

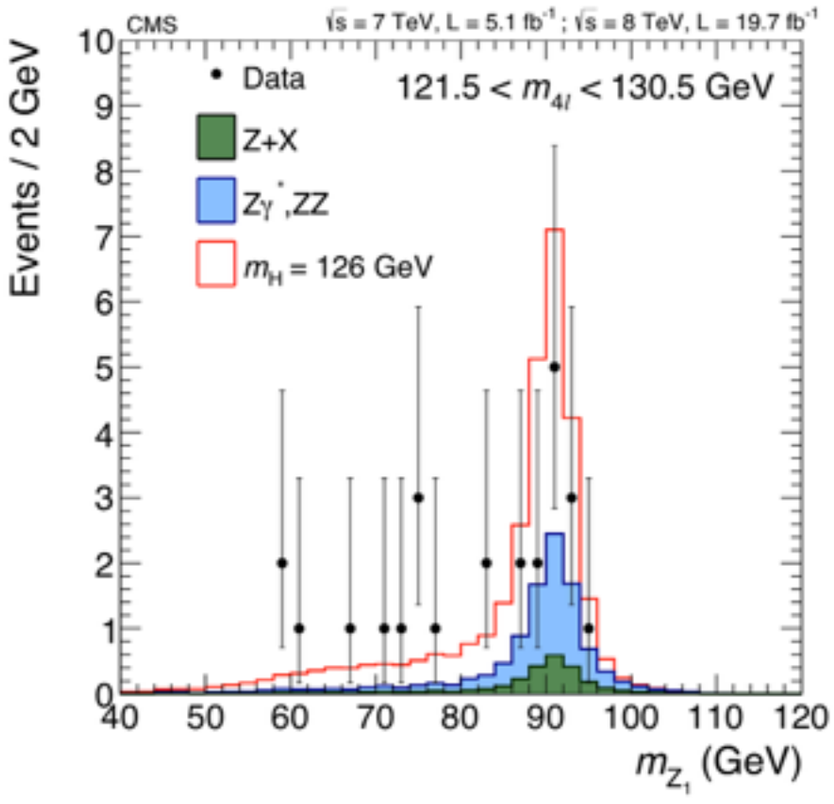




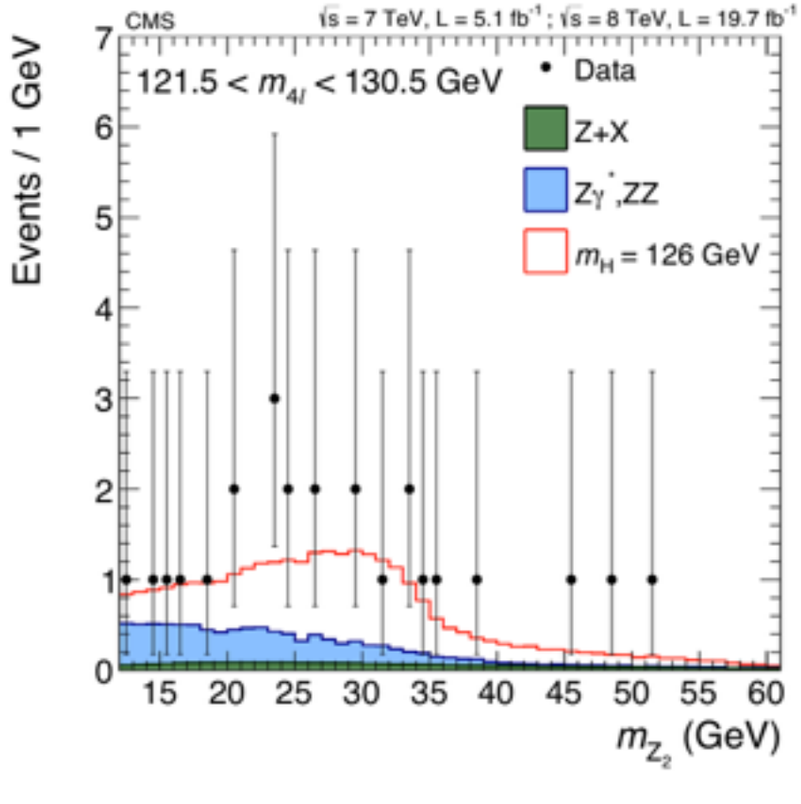


Kinematic Distributions

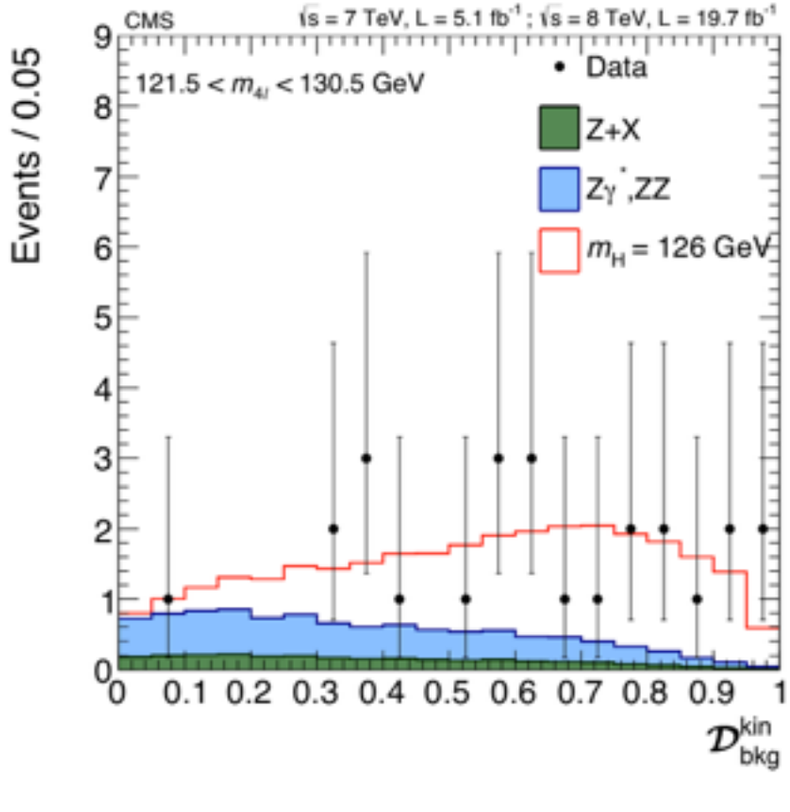
Z_1 Mass



Z_2 Mass

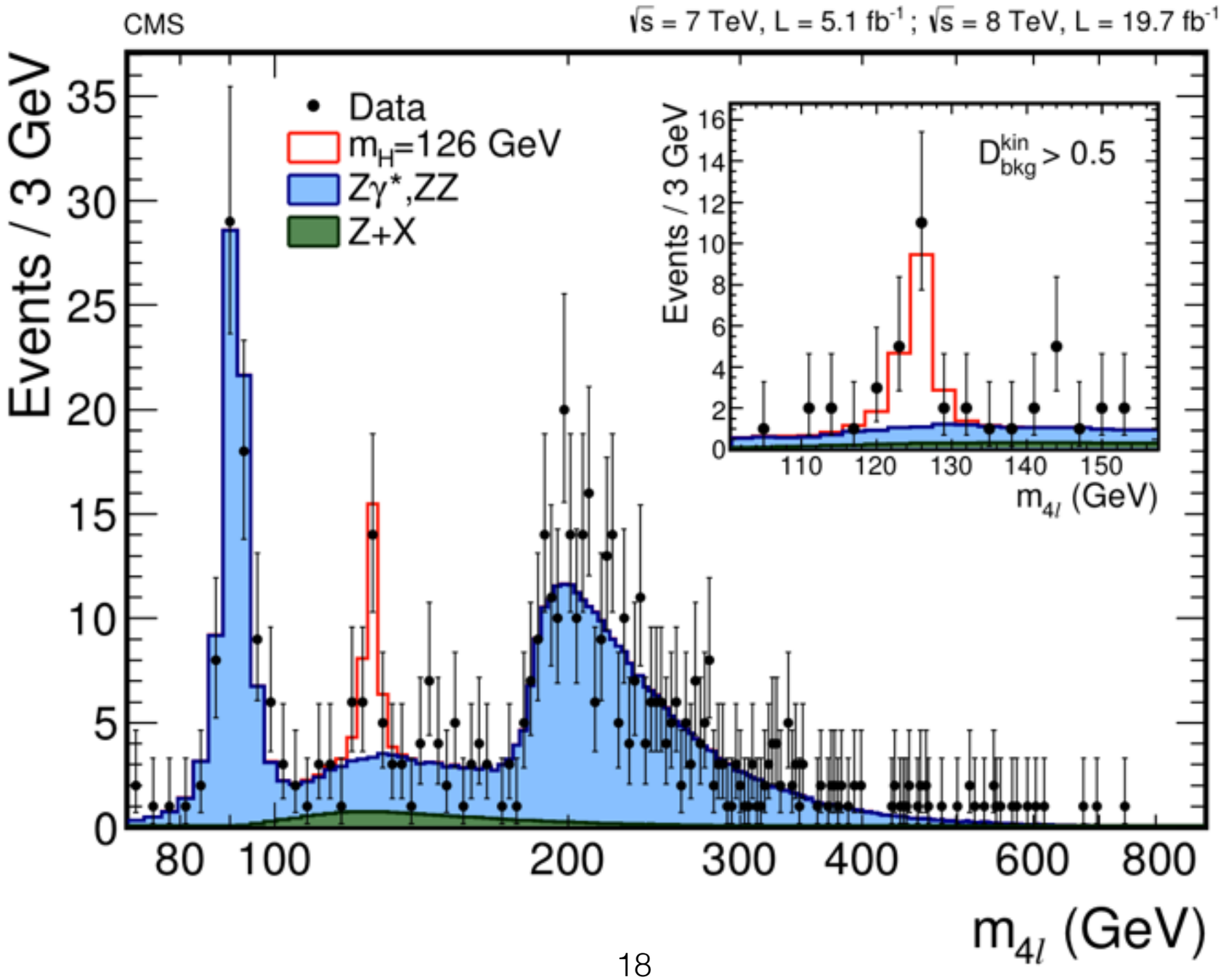


Kinematic Discriminant



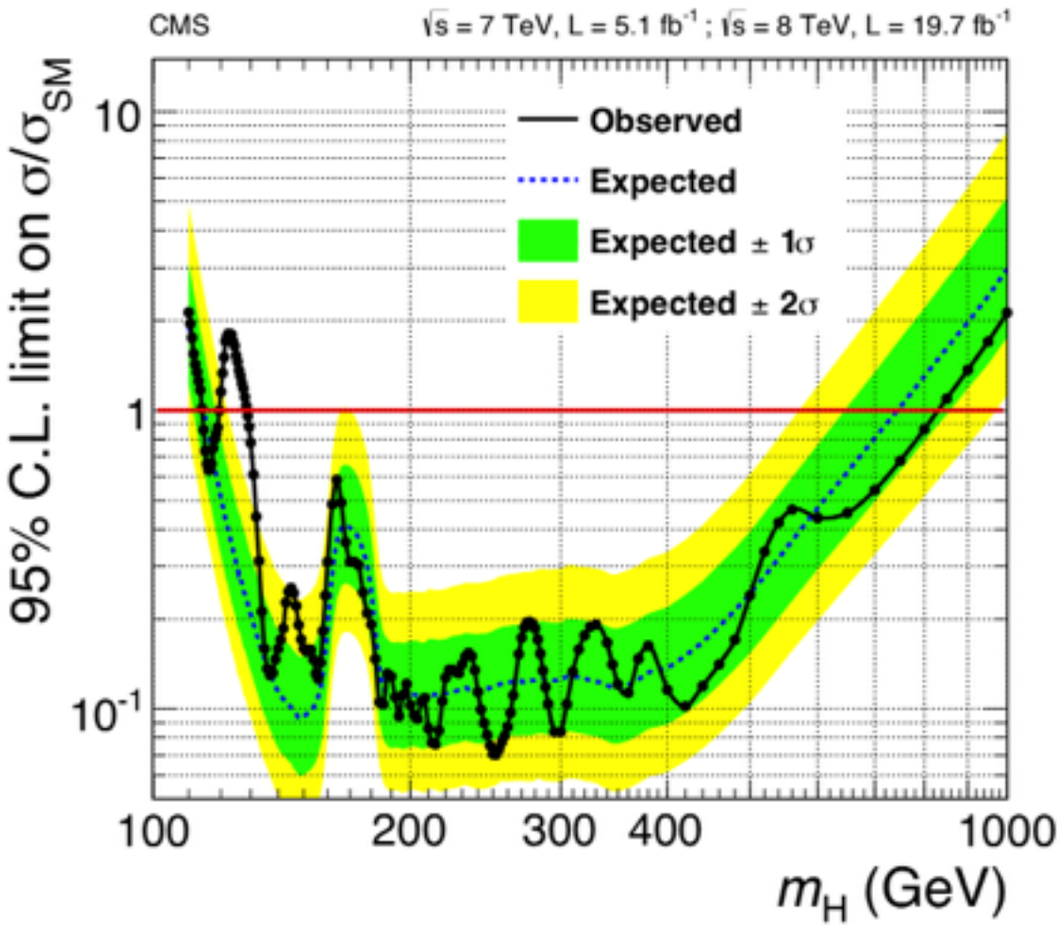
Events in the mass range 121.5-130.5 GeV

Four-lepton Mass Distribution



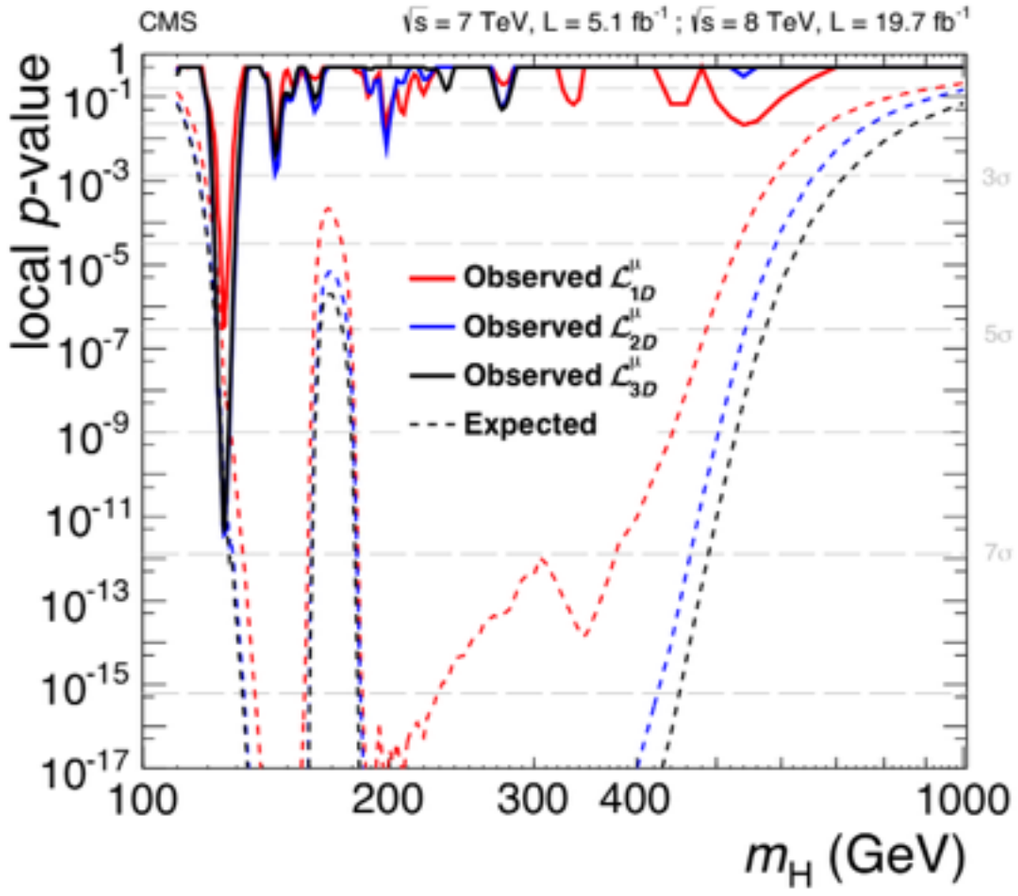
Search Results Upto 1 TeV

Limits



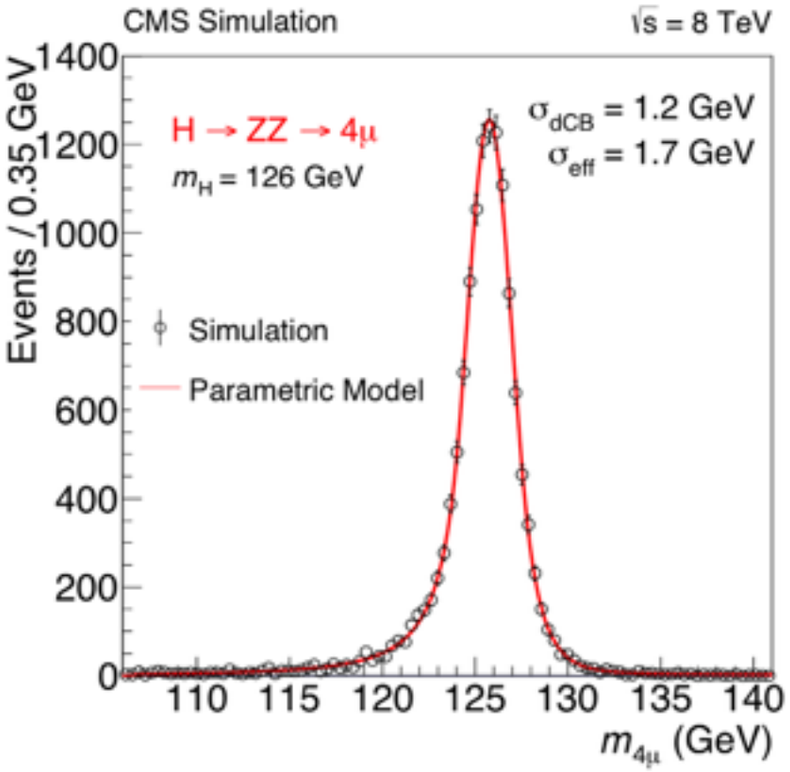
SM Higgs boson excluded at 95% in the range 114.5-119 GeV and 129.5-832 GeV

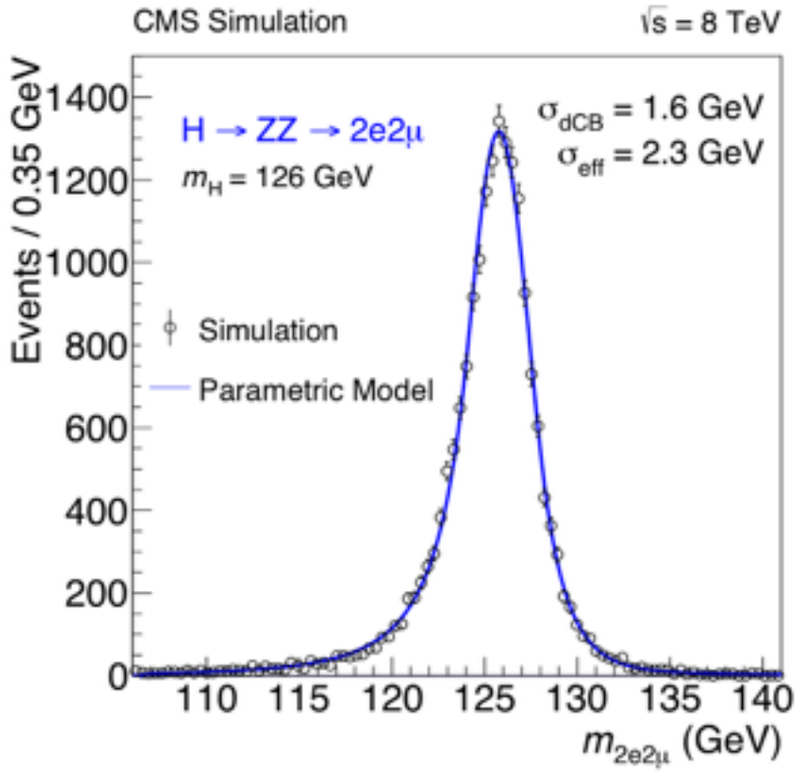
p-values

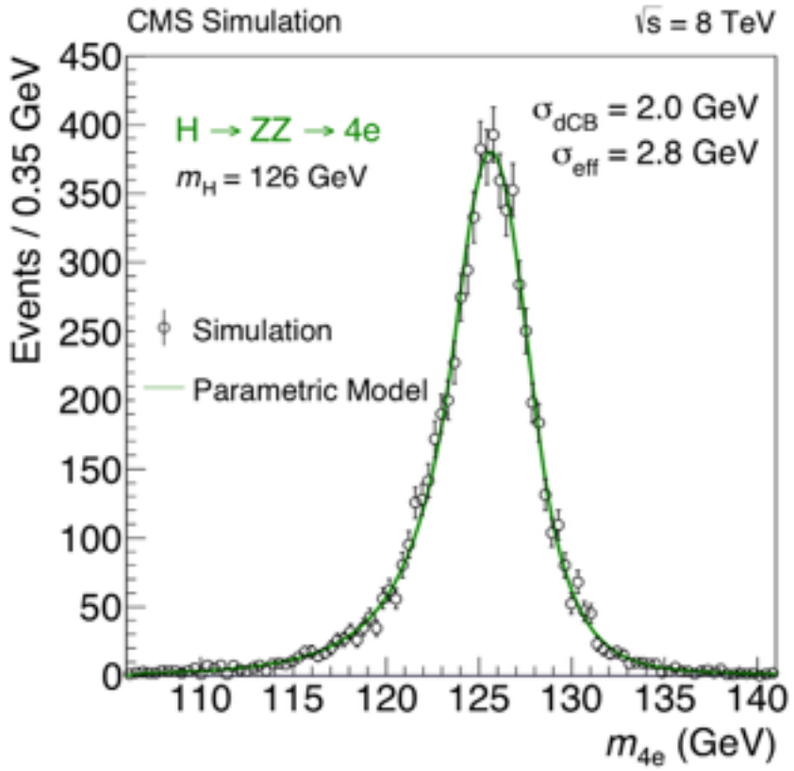


No significant excess except for m_H = 125.7 GeV

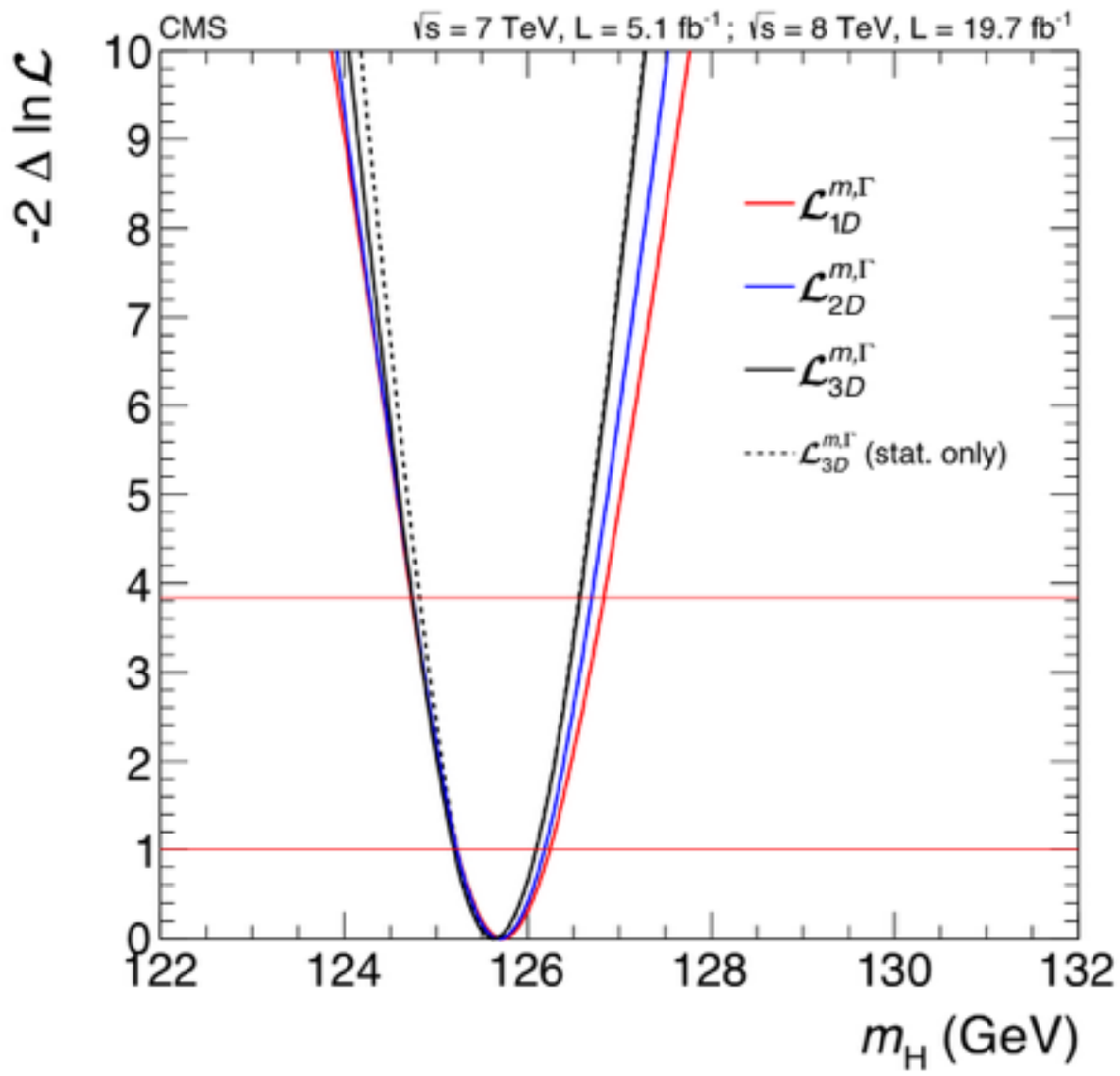
Signal Resolution By Channel

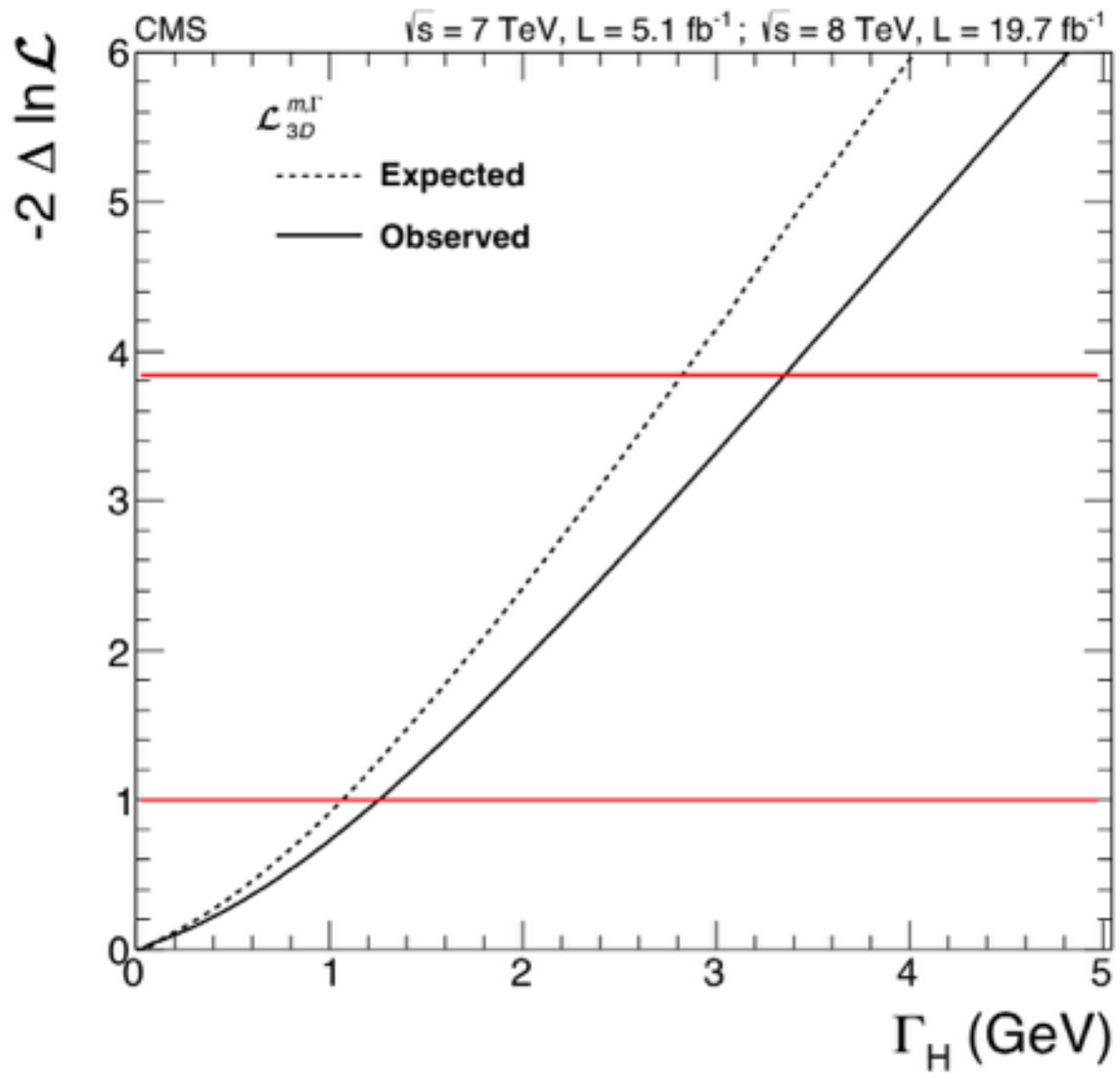






Mass and On-shell Width Measurement

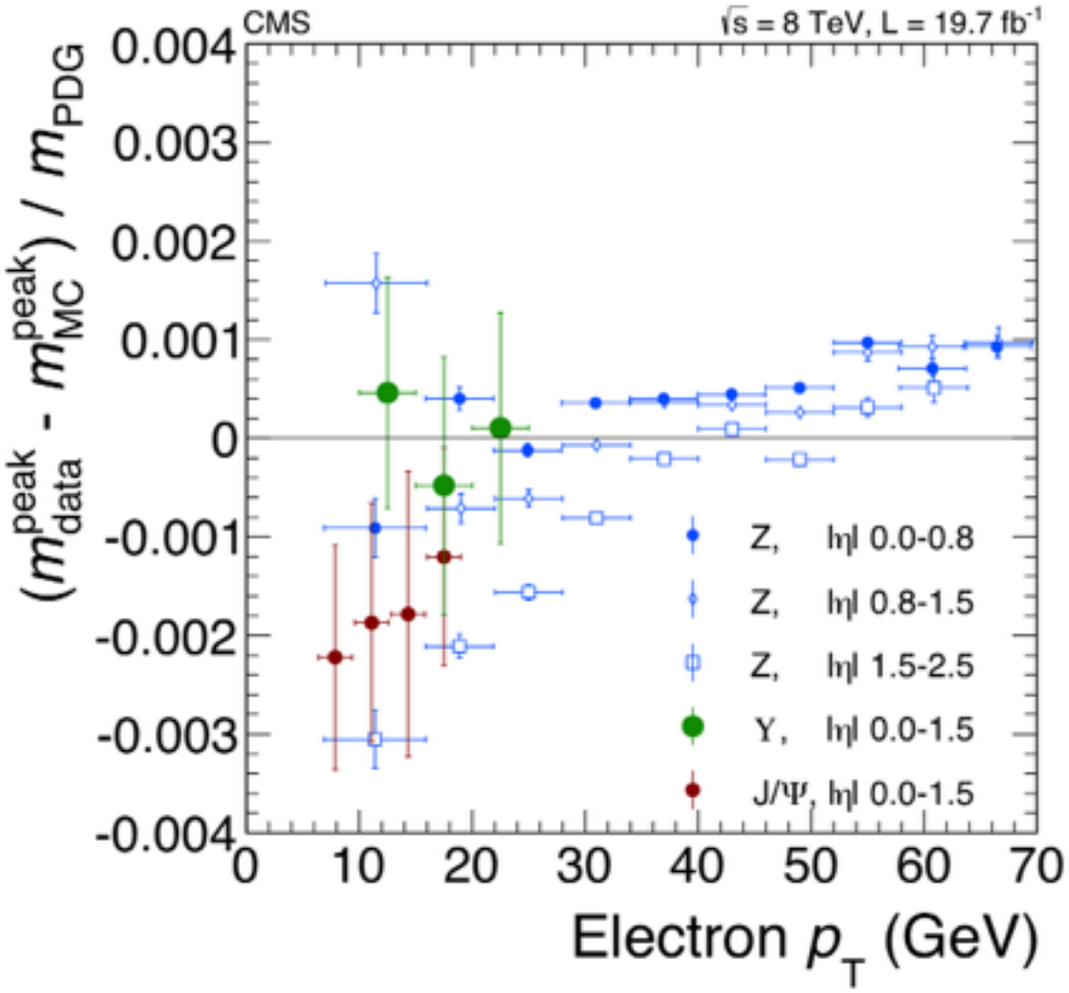




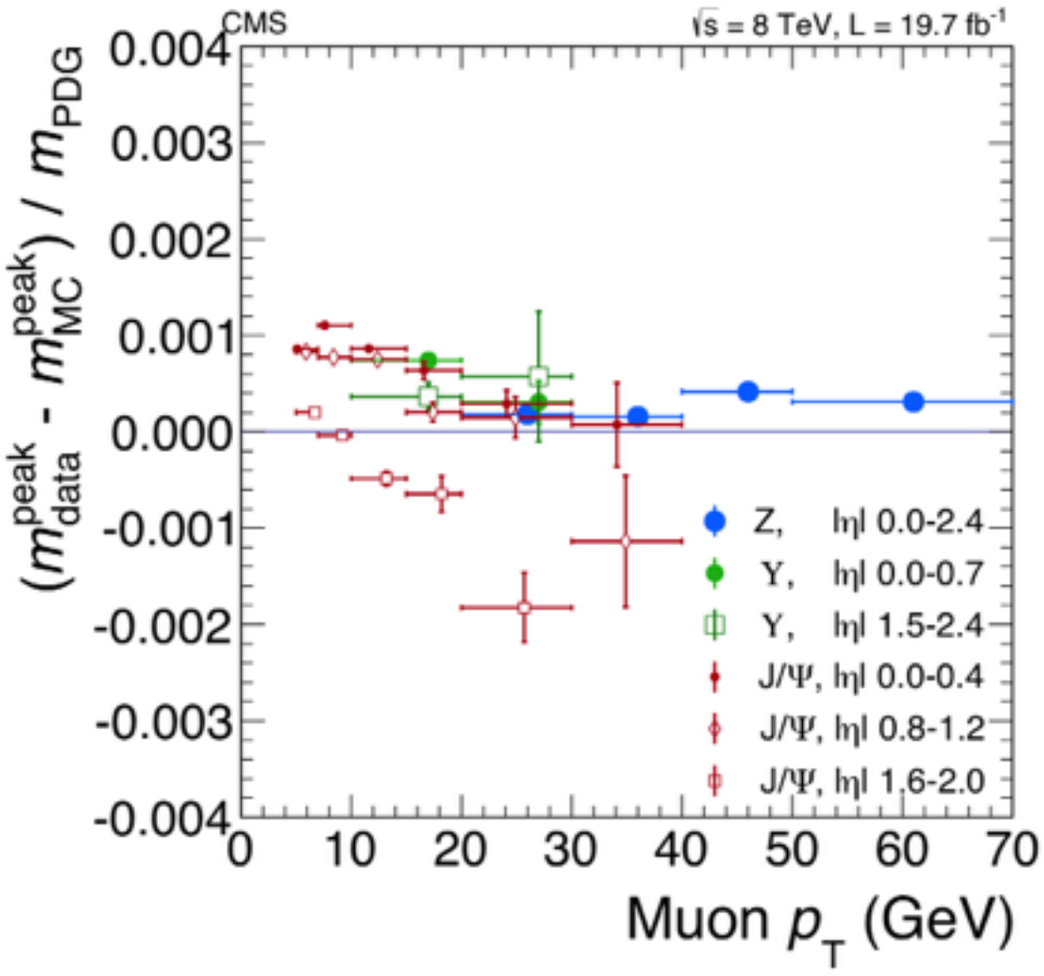
Lepton Scale Uncertainties

Difference in mass scale between data and simulation

Electrons



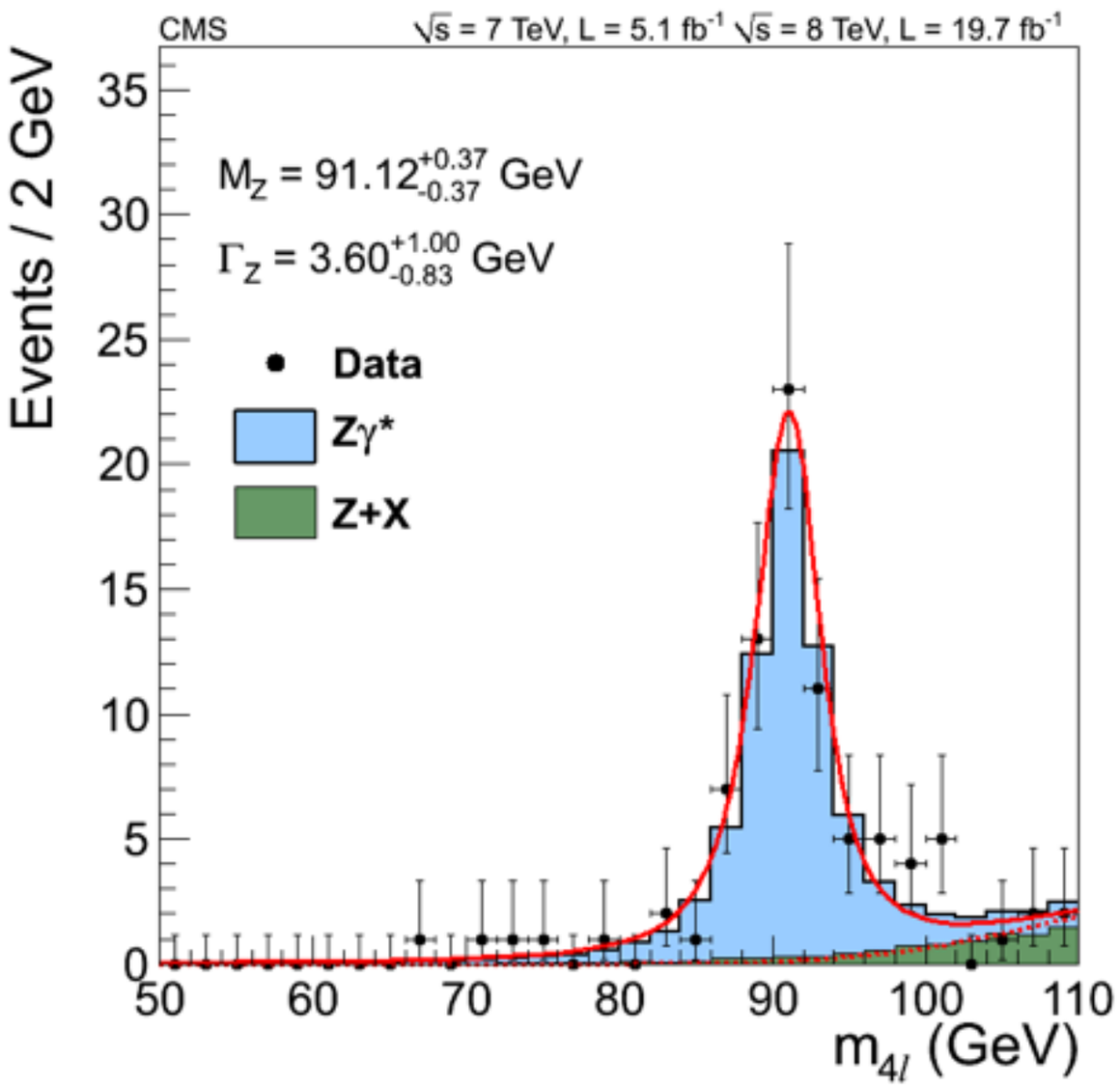
Muons

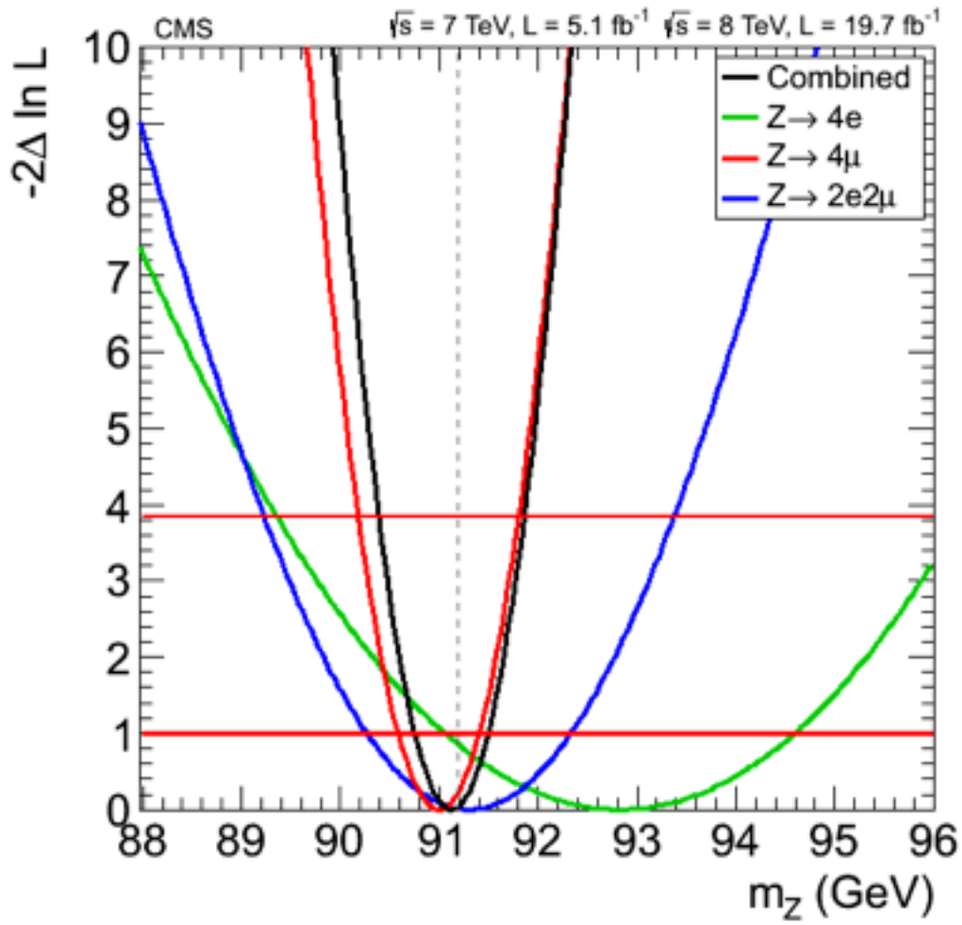


Estimates of scale uncertainty by channel:

0.1% (4μ), 0.1% (2e2μ), 0.3% (4e)

Measurement of $Z \rightarrow 4\ell$ Mass Peak





Best fit mass : 91.1 ± 0.4 GeV