DPF 2013 : University of California Santa Cruz

$H \rightarrow ZZ \rightarrow 4l$ Search at CMS

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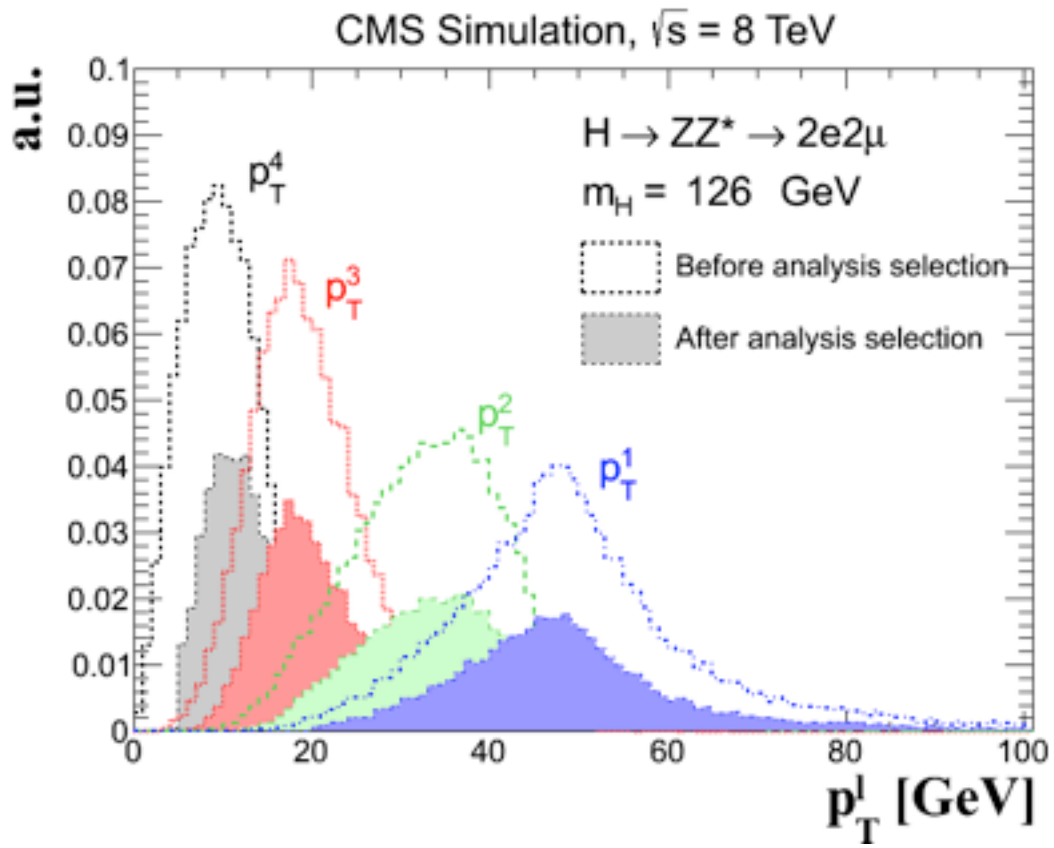
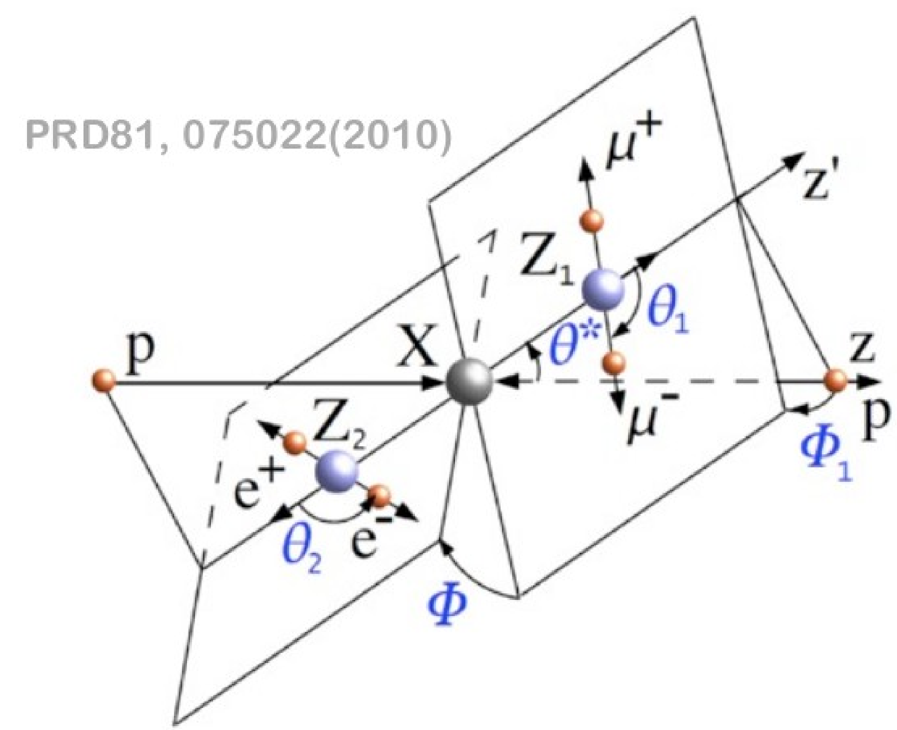
On behalf of the CMS Collaboration

H→ZZ→4l Channel

- The Golden Channel - high resolution, high S/B
- Statistically parched
  - ~20 signal events expected with current data
  - Need very high lepton reconstruction, selection efficiency
  - Crucial to catch the lowest pT leptons
- Squeeze out the most from available events
  - Exploit the rich topology of the 4-lepton final state
  - Use per-event mass uncertainties to have best possible determination of the Higgs boson mass





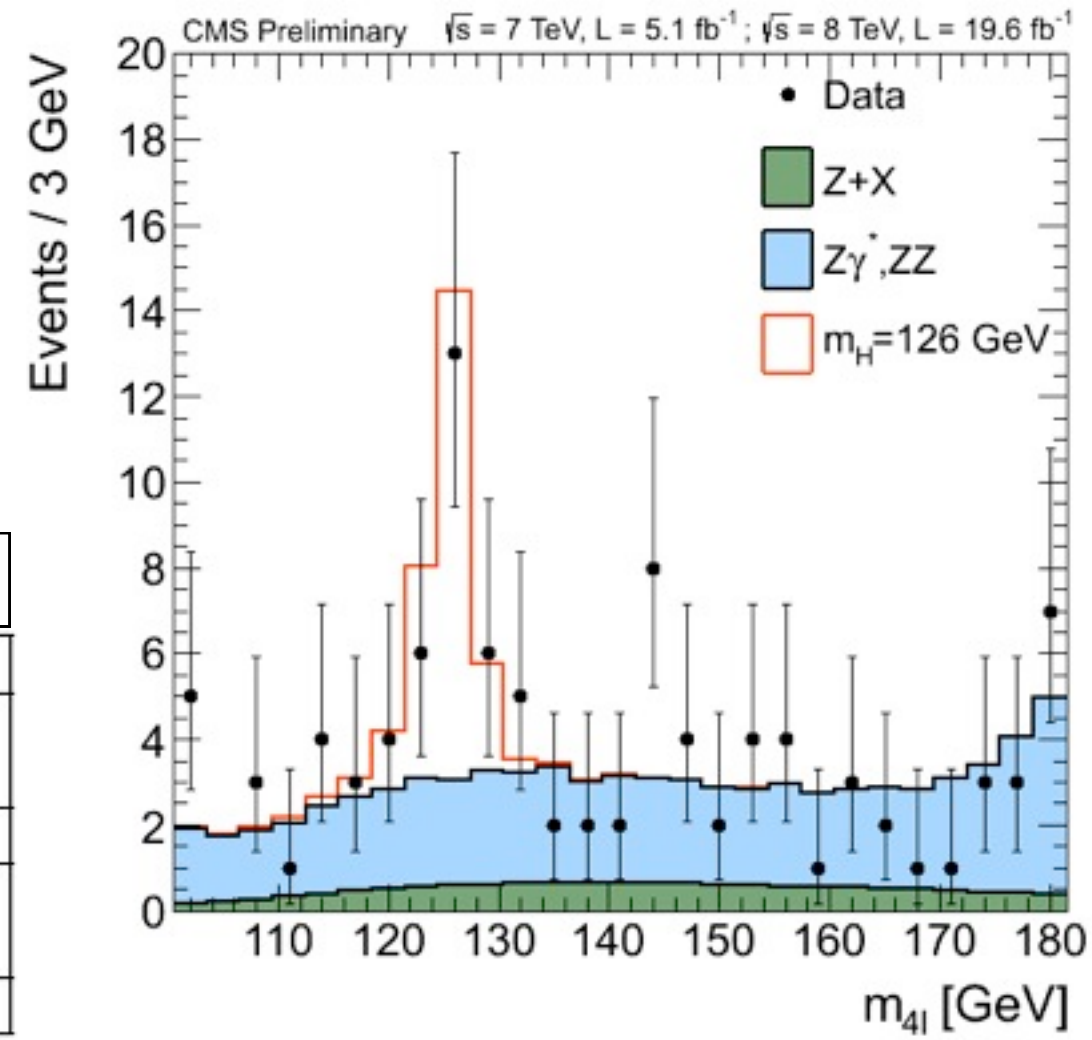
Thursday, August 15, 13

Event Selection

- Require 20/10 GeV leptons in the event (consistency with trigger)
- Lepton selection : p_T > 7(5) GeV for e(μ), $|\eta|$ < 2.4, ID+isolation requirements
- Construct Z candidates and recover FSR close to the leptons (ΔR < 0.5)
- Select "Z1" candidate with mass closest to Z peak (40 < m(Z1) < 120 GeV)
- Select "Z2" candidate from remaining highest pT leptons (12 < m(Z2) < 120 GeV)
- Require all four opposite sign lepton pairs to have mass > 4 GeV to suppress QCD

Analysis Strategy (1D)

- The analysis in its simplest conception is a bump hunt in the m(4l) spectrum
- Narrow peak on top of a relatively flat background

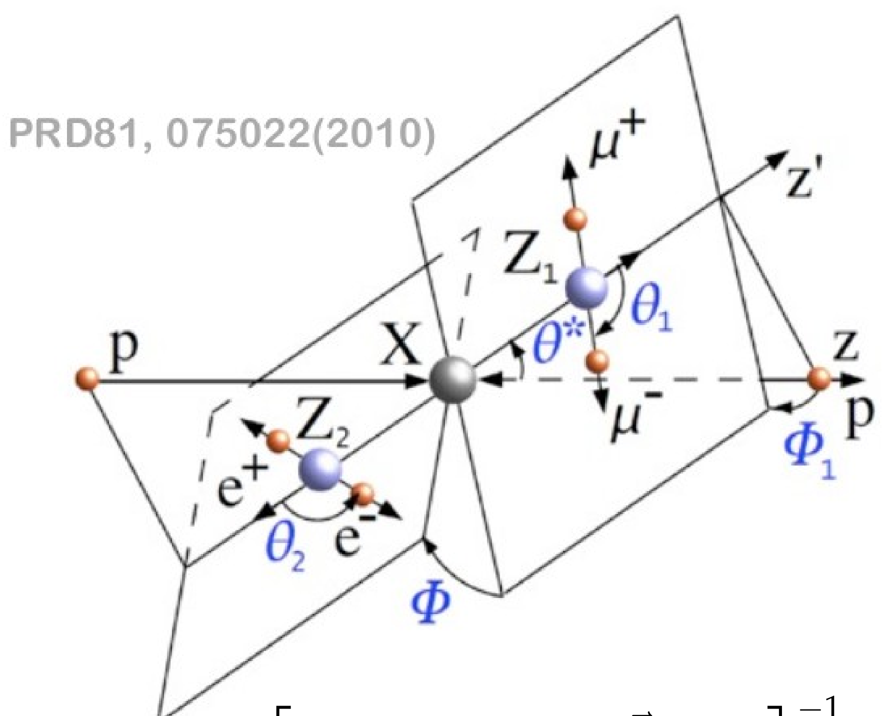


Event yields in the range : 110 GeV < m(4l) < 160 GeV

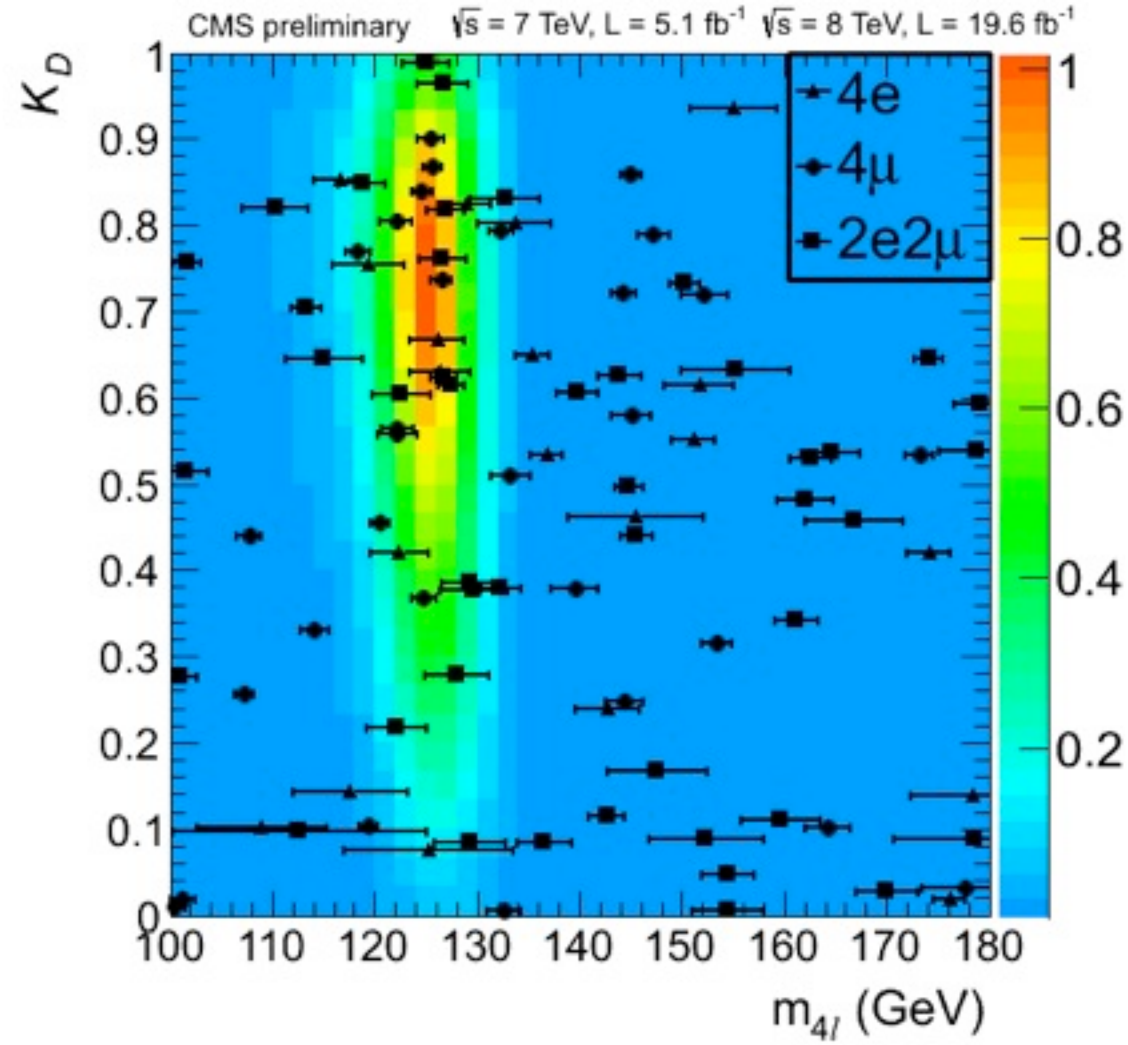
Channel	4e	4μ	$2e2\mu$	4ℓ
ZZ background	6.6 ±0.8	13.8 ±1.0	18.1 ±1.3	38.5 ±1.8
Z+ X	2.5 ± 1.0	1.6 ± 0.6	4.0 ± 1.6	8.1 ±2.0
All background expected	9.1 ± 1.3	15.4 ± 1.2	22.0 ± 2.0	46.5 ±2.7
m_H = 125 GeV	3.5 ±0.5	6.8 ±0.8	8.9 ±1.0	19.2 ±1.4
m_H = 126 GeV	3.9 ±0.6	7.4 ±0.9	9.8 ±1.1	21.1 ±1.5
Observed	16	23	32	71

Analysis Strategy (2D)

- Make full use of the kinematic information stored in the 4-lepton final state to enhance sensitivity
- Kinematic discriminant (KD) constructed from LO matrix elements using 5 angles + 2 Z masses which characterize the Higgs decay



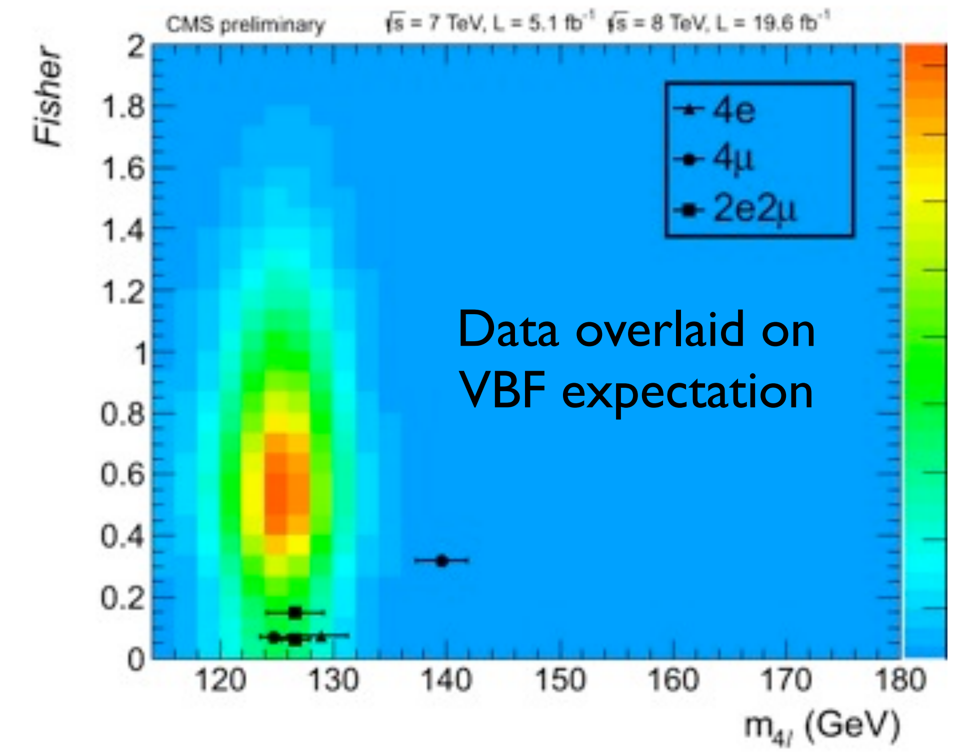
$$\mathrm{KD} = \frac{\mathcal{P}_{\mathrm{sig}}}{\mathcal{P}_{\mathrm{sig}} + \mathcal{P}_{\mathrm{bkg}}} = \left[1 + \frac{\mathcal{P}_{\mathrm{bkg}}(m_1, m_2, \vec{\Omega}|m_{4\ell})}{\mathcal{P}_{\mathrm{sig}}(m_1, m_2, \vec{\Omega}|m_{4\ell})}\right]^{-1}$$

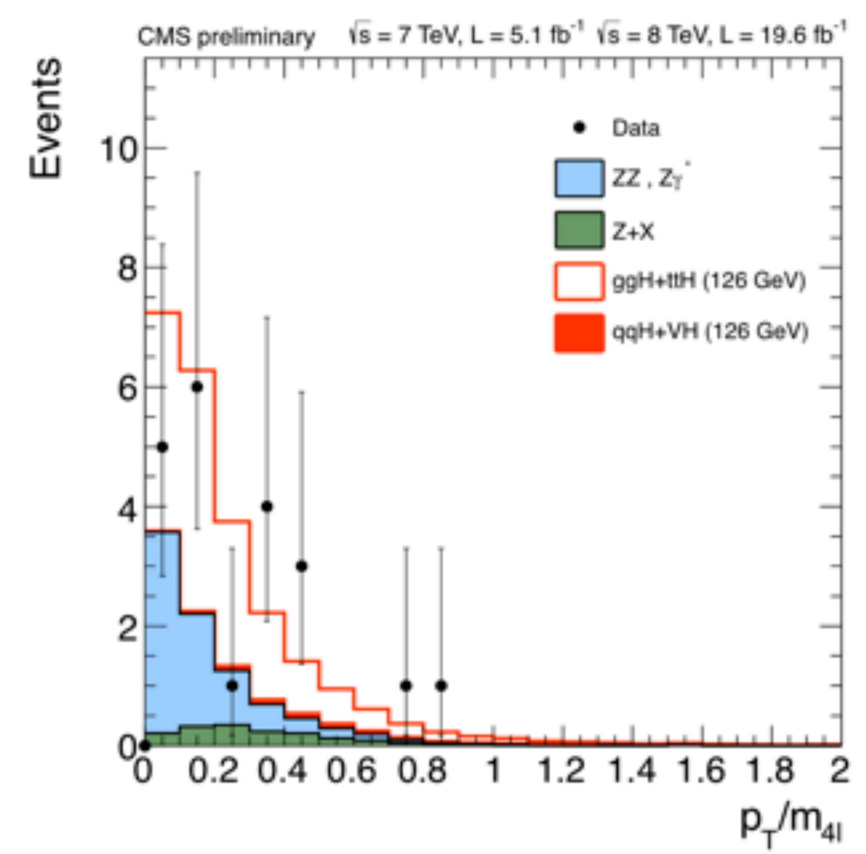


2D likelihood can be constructed from KD and m(4l)

Analysis Strategy (3D)

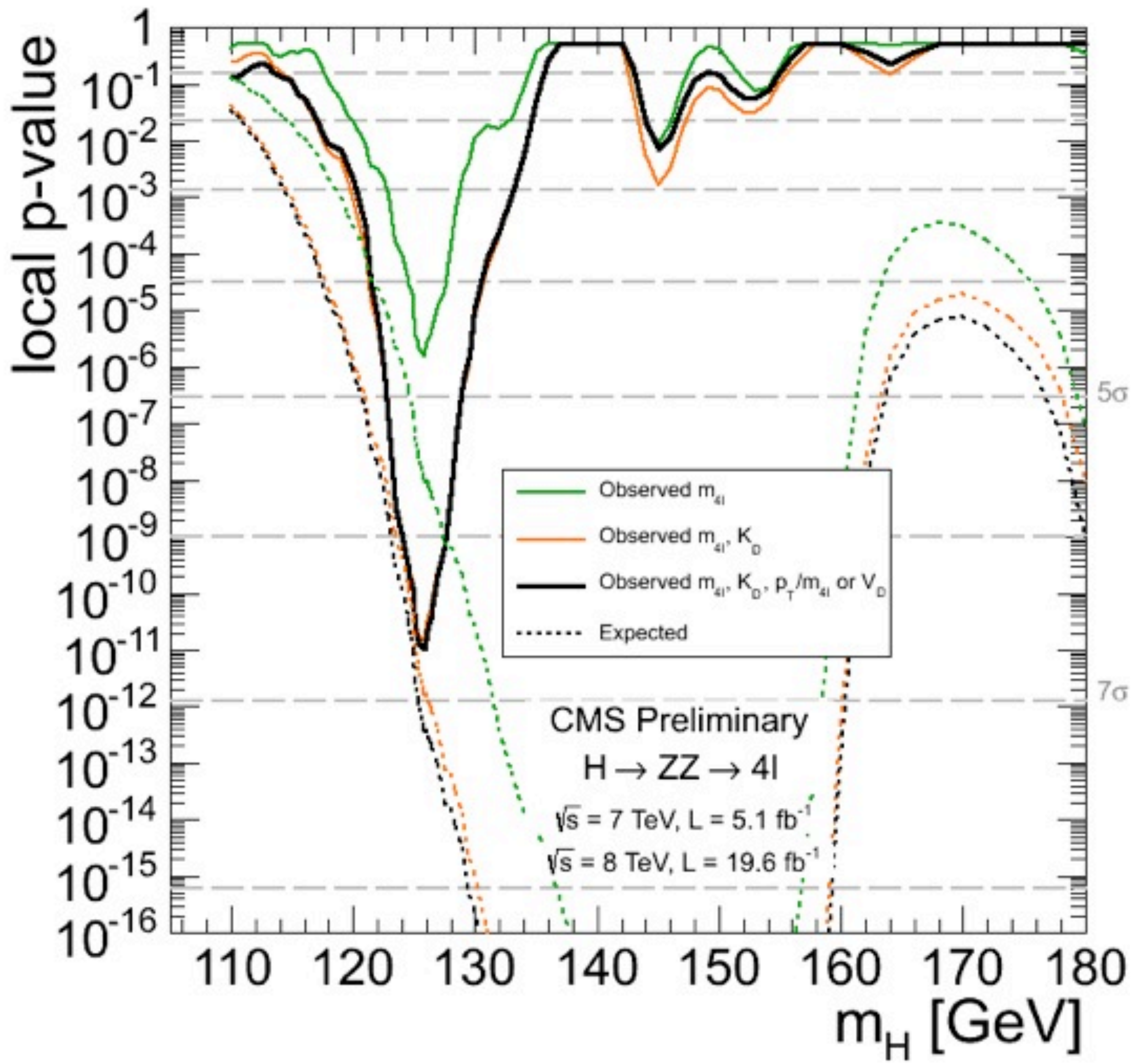
- Probe the Higgs coupling to vector bosons and fermions by separating the production modes
- Events categorized as dijet tagged (2 or more jets with pT > 30 GeV, $|\eta| < 4.7$) and untagged
  - **Dijet tagged events** : Linear discriminant (VD) built from m_{jj} and $\Delta\eta_{jj}$ variables used to discriminate between the VBF and gluon fusion production modes
  - **Untagged events** : $p_T/m(4l)$ of the 4-lepton system used as a discriminant
- Analysis performed using a 3D fit involving m(4l), KD and VD (or p_T/m)
- Nominal strategy for analyzing the full Run 1 dataset





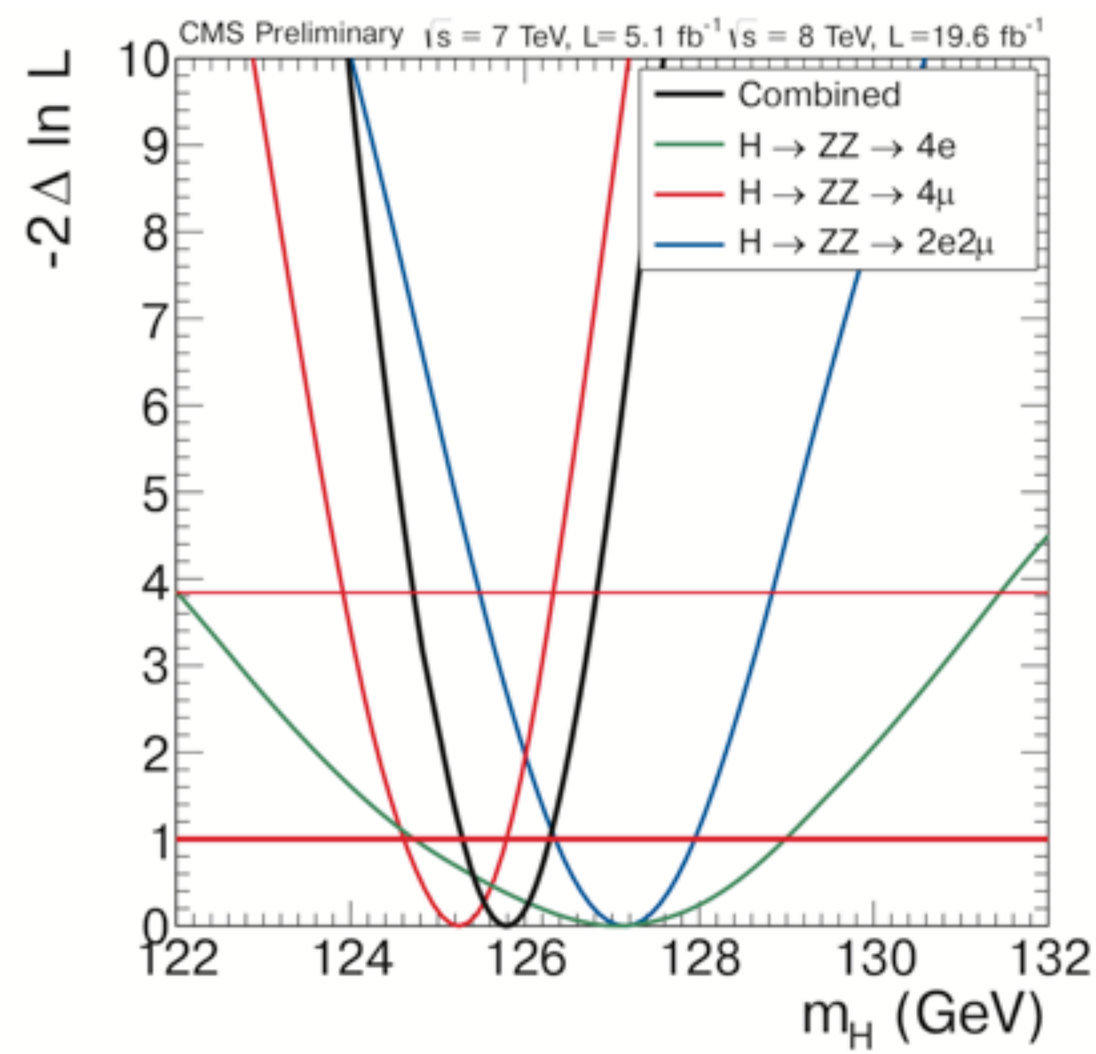
Observed Excess

	1D	2D	**3D**
Expected Significance	5.6σ	6.9σ	**7.2σ**
Observed Significance	4.7σ	6.6σ	**6.7σ**



Mass Measurement

- $H \to ZZ \to 4l$ is a very sensitive probe to measure the mass of the Higgs boson
- Precise measurement of lepton momenta critical
- Multivariate regression used to improve the ECAL energy measurement of electrons
- Corrections applied to electrons as well as muons to account for differences in momentum scale between data and simulation
- To make optimal use of available data the analysis is performed as a 3D fit using m(4l), KD and event-by-event mass uncertainty



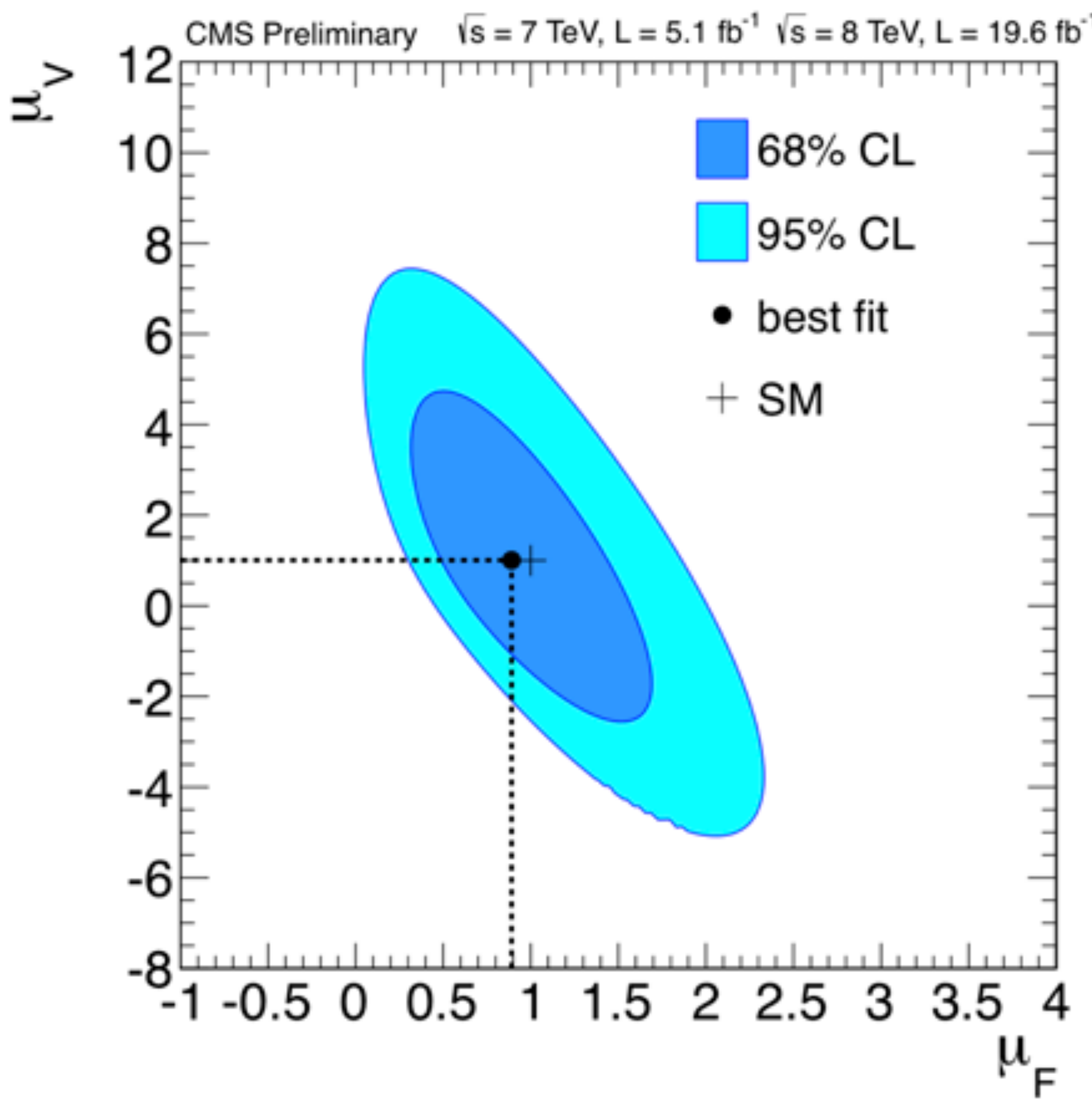
Best fit mass :

125.8 ± 0.5 (stat) ± 0.2 (syst) GeV

Signal Strength

- 3D analysis allows to disentangle the production modes
- Production modes split into two categories
  - Vector boson induced (VBF, WH, ZH)
  - Fermion induced (gluon fusion, ttH)
- Signal strength measured in each category at mH = 125.8 GeV

	μ_V	μ_F	μ Overall
Observed	$1.0^{+2.4}_{-2.3}$	$0.9^{+0.5}_{-0.4}$	$0.9^{+0.3}_{-0.2}$



Spin/Parity Measurement

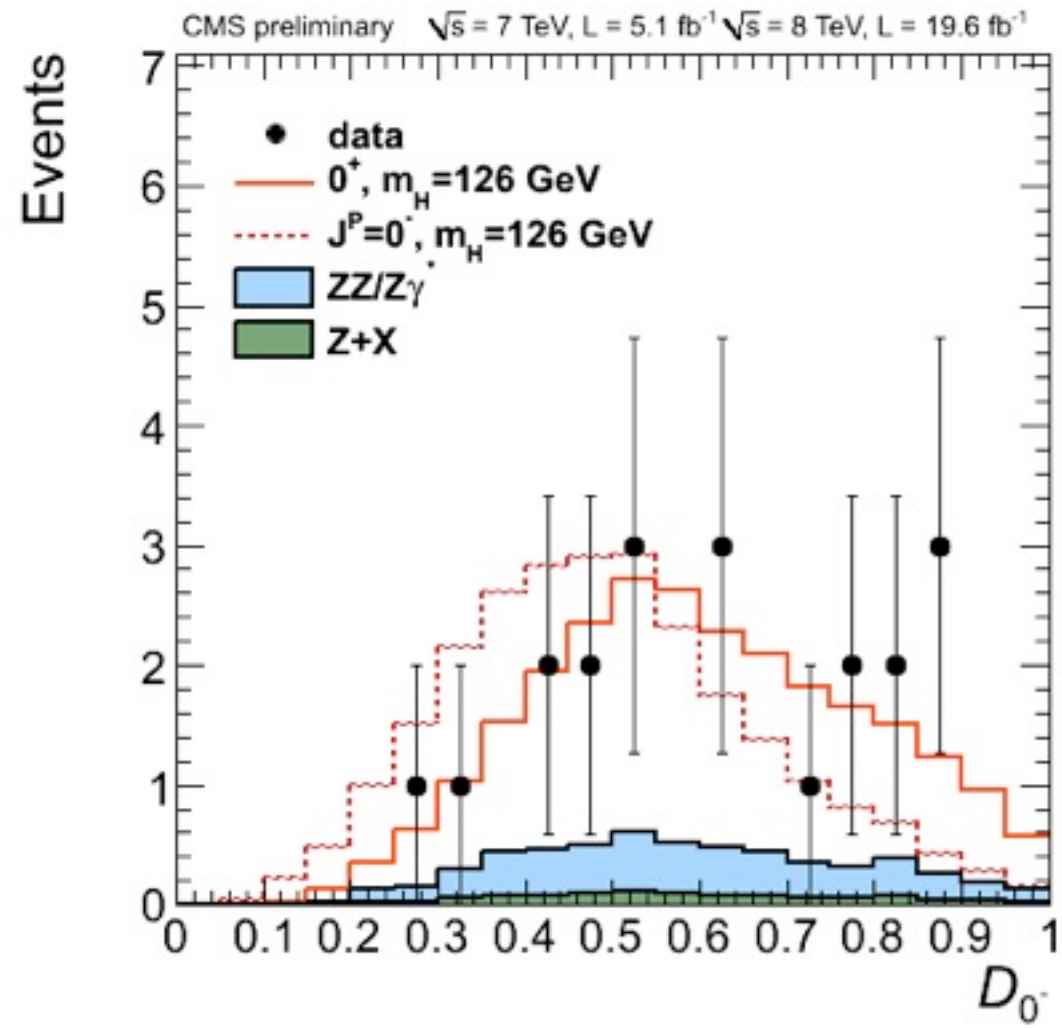
- Angular variables which characterize the Higgs decay can be used to distinguish between the 0^+ state and several other spin/parity hypotheses

- Construct a matrix element based discriminant to distinguish between 0^+ and alternate J^P hypotheses

$$\mathcal{D}_{J^P} = \frac{\mathcal{P}_{\rm SM}}{\mathcal{P}_{\rm SM} + \mathcal{P}_{J^P}} = \left[1 + \frac{\mathcal{P}_{J^P}(m_1, m_2, \vec{\Omega}|m_{4\ell})}{\mathcal{P}_{\rm SM}(m_1, m_2, \vec{\Omega}|m_{4\ell})}\right]^{-1}$$

- Several spin/parity hypotheses are tested w.r.t. 0^+

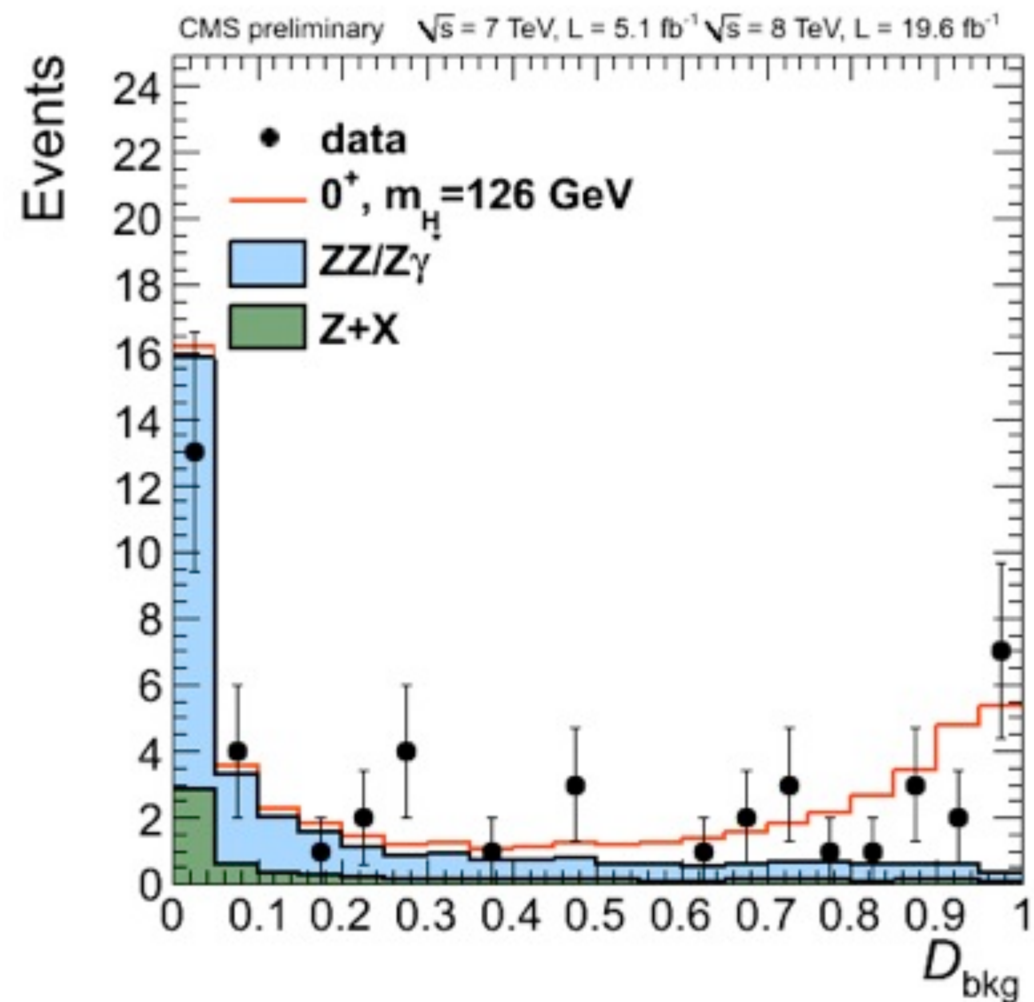
J^P	production	comment
0^-	$gg \to X$	pseudoscalar
0_h^+	$gg \to X$	higher dim operators
2_{mgg}^+	$gg \to X$	minimal couplings
$2_{mq\bar{q}}^+$	$q\bar{q} \to X$	minimal couplings
1^-	$q\bar{q} \to X$	exotic vector
1^+	$q\bar{q} \to X$	exotic pseudovector



D_{0^-} distribution for events with : 106 < m(4l) < 141 GeV; KD > 0.5

Hypothesis Testing Strategy

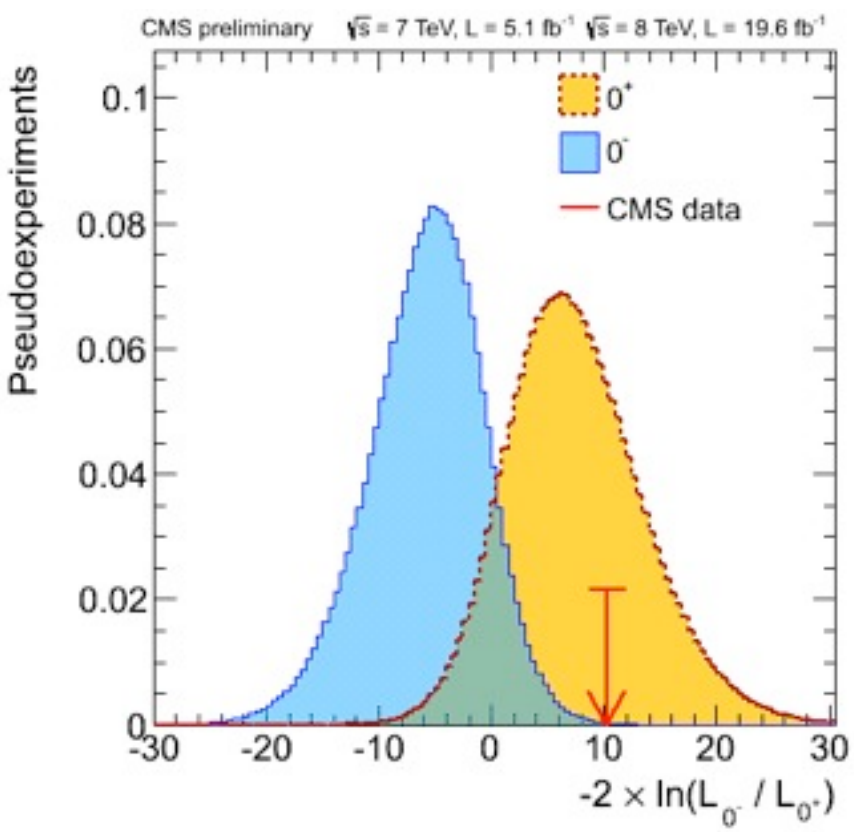
- To test the spin/parity of a Higgs like resonance we need to
  - Isolate signal events from the background
  - Use the discriminant defined on the previous slide to separate the spin/parity hypotheses
- This is achieved by performing a 2D fit using
  - likelihood discriminant (D_{bkg}) constructed by combining m(4l) with the KD - to isolate signal from background
  - D_{JP} used for spin/parity separation



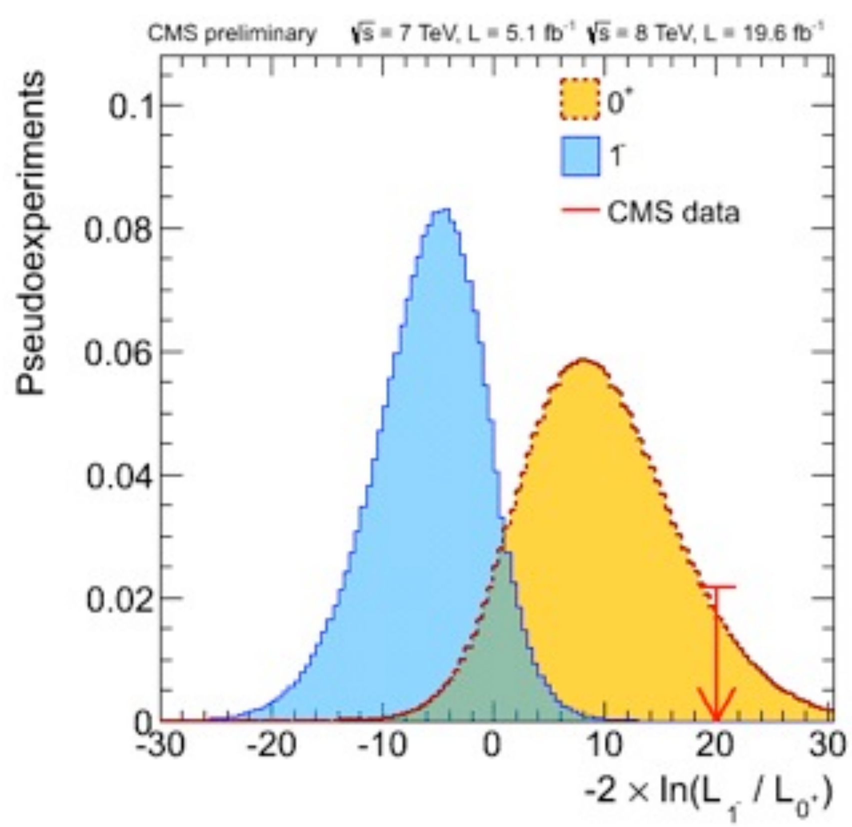
$$\frac{\mathcal{P}_{\rm sig}}{\mathcal{P}_{\rm sig}+\mathcal{P}_{\rm bkg}} = \left[1+\frac{\mathcal{P}_{\rm bkg}(m_1,m_2,\vec{\Omega}|m_{4\ell})\times\mathcal{P}_{\rm bkg}(m_{4\ell})}{\mathcal{P}_{\rm sig}(m_1,m_2,\vec{\Omega}|m_{4\ell})\times\mathcal{P}_{sig}(m_{4\ell})}\right]^{-1}.$$

J^P Results

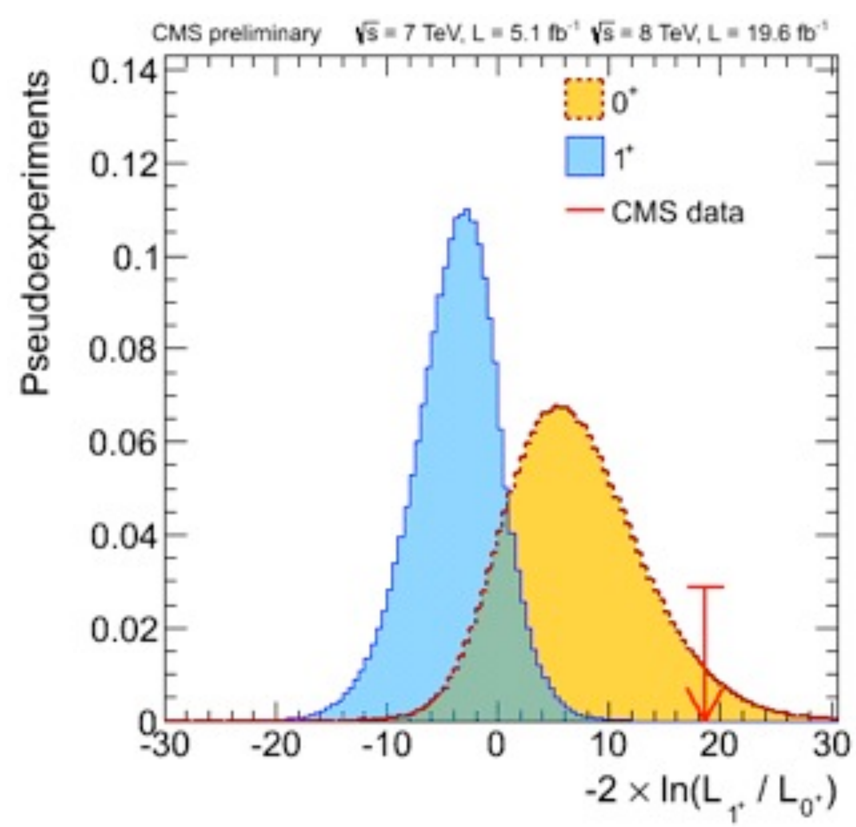
J^P	production	comment	expect (μ=1)	obs. 0^+	obs. J^P	CL_s
0^-	$gg \to X$	pseudoscalar	2.6σ (2.8σ)	0.5σ	3.3σ	0.16%
0_h^+	$gg \to X$	higher dim operators	1.7σ (1.8σ)	0.0σ	1.7σ	8.1%
2_{mgg}^+	$gg \to X$	minimal couplings	1.8σ (1.9σ)	0.8σ	2.7σ	1.5%
$2_{mq\bar{q}}^+$	$q\bar{q} \to X$	minimal couplings	1.7σ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



0^- v/s 0^+



1^- v/s 0^+



1^+ v/s 0^+

J^P Results

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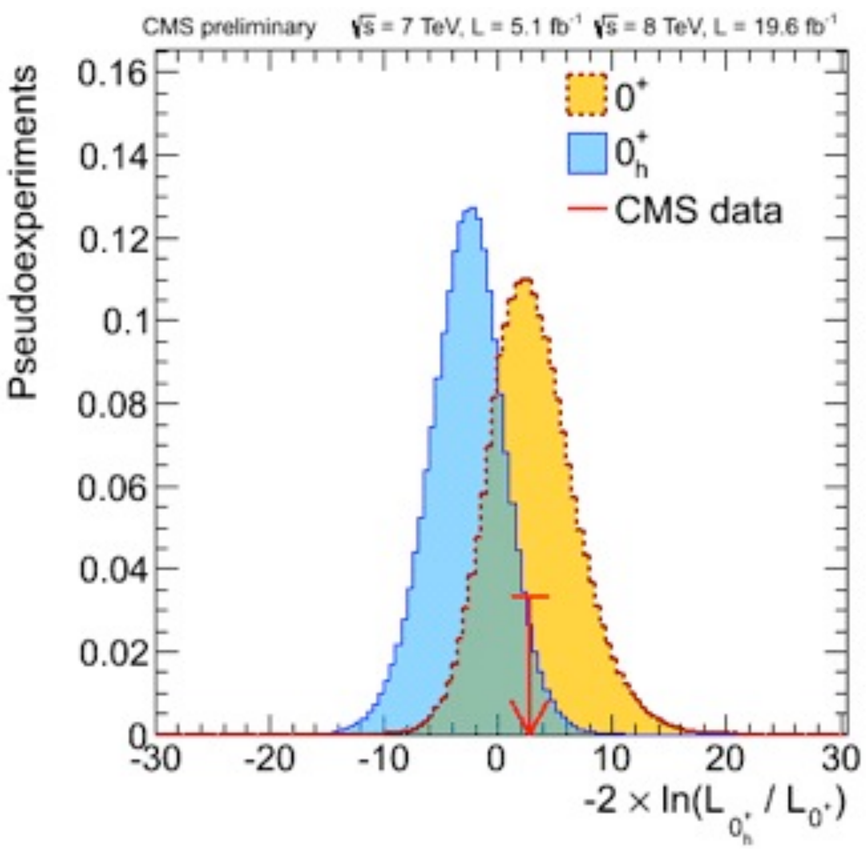
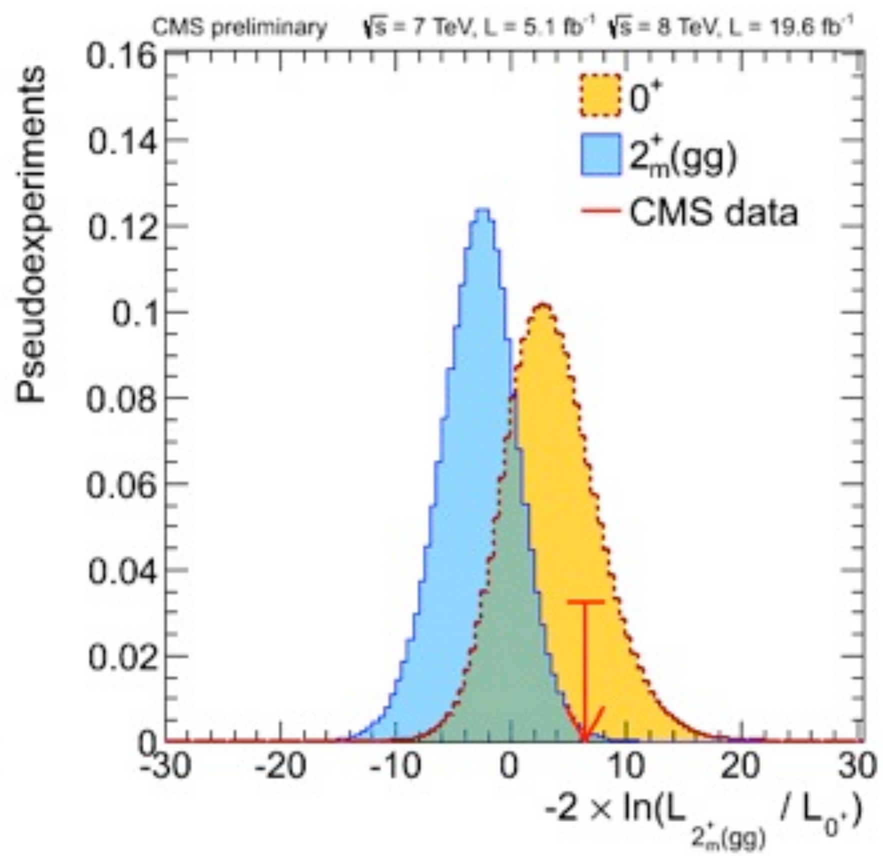
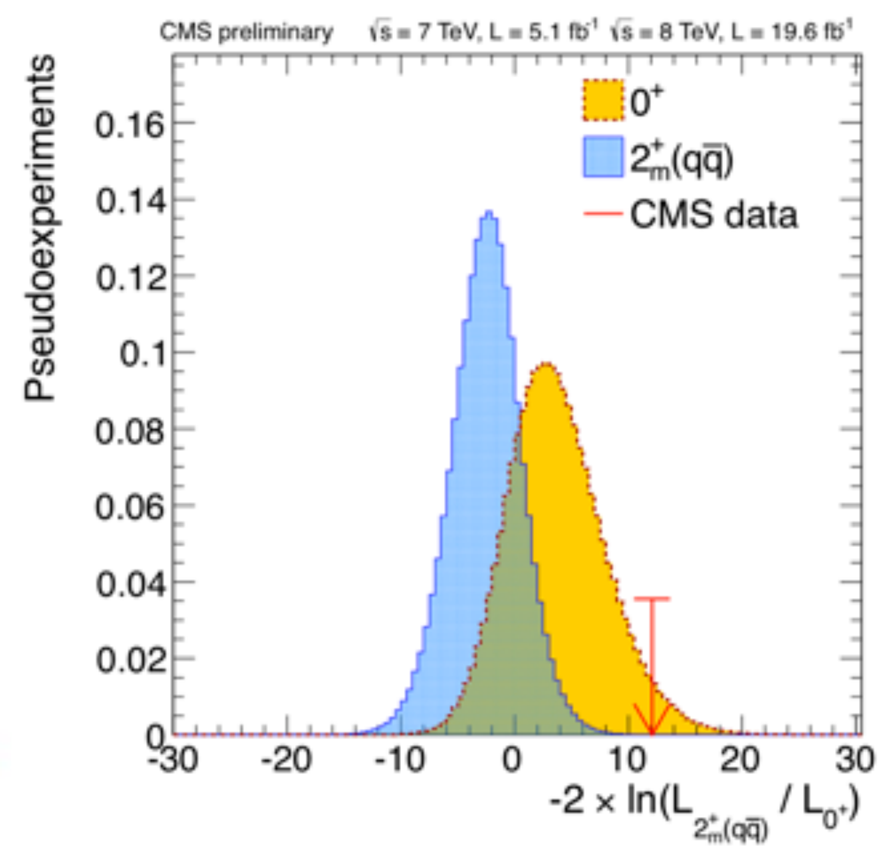
0_h^+	$gg \to X$	higher dim operators	1.7σ (1.8σ)	0.0σ	1.7σ	8.1%
2^+_{mgg}	$gg \to X$	minimal couplings	1.8σ (1.9σ)	0.8σ	2.7σ	1.5%
$2^+_{mq\bar{q}}$	$q\bar{q} \to X$	minimal couplings	1.7σ (1.9σ)	1.8σ	4.0σ	<0.1%
1^-	$q\bar{q} \to X$	exotic vector	2.8σ (3.1σ)	1.4σ	>4.0σ	<0.1%
1^+	$q\bar{q} \to X$	exotic pseudovector	2.3σ (2.6σ)	1.7σ	>4.0σ	<0.1%



0^+_h v/s 0^+



2^+_m(gg) v/s 0^+



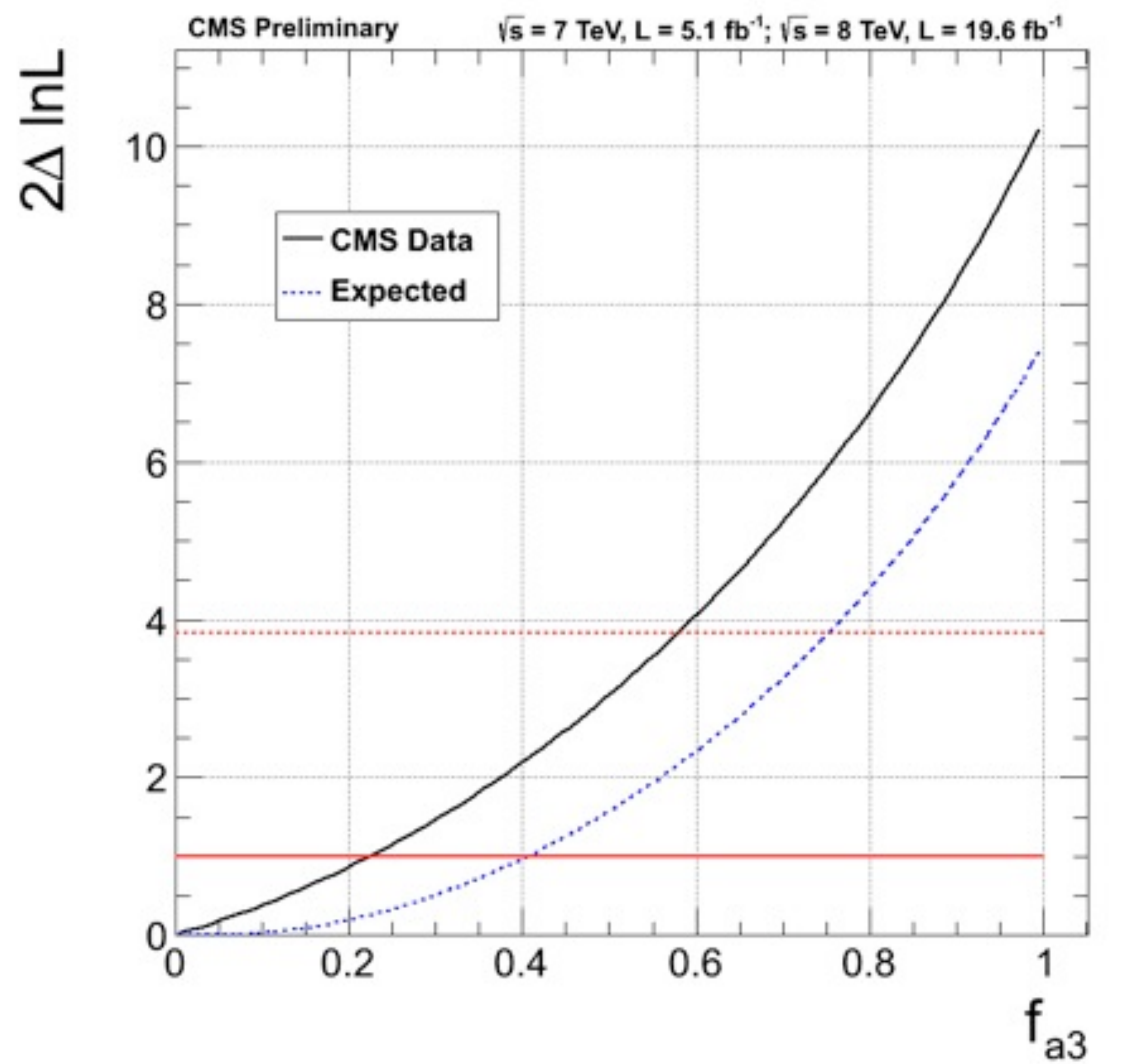
2^+_m(qq) v/s 0^+

f_{a3} Measurement

Most general amplitude for a spin-0 boson is :

$$A = v^{-1}\epsilon_1^{*\mu}\epsilon_2^{*\nu}\left(\underbrace{\boxed{a_1 g_{\mu\nu} m_H^2}}_{A_1} + a_2\, q_\mu q_\nu + \underbrace{\boxed{a_3 \epsilon_{\mu\nu\alpha\beta}\, q_1^\alpha q_2^\beta}}_{A_3}\right)$$

- A_1 dominates the 0^+ decay
- A_3 dominates the 0^- decay
- Define $f_{a3} = |A_3|^2 / (|A_1|^2 + |A_3|^2)$
- Presence of both A_1 and A_3 ($f_{a3} \neq 0$ and $f_{a3} \neq 1$) indicates CP violation
- f_{a3} can be measured by performing a 2D(D_{bkg}, D_{0-}) fit on data



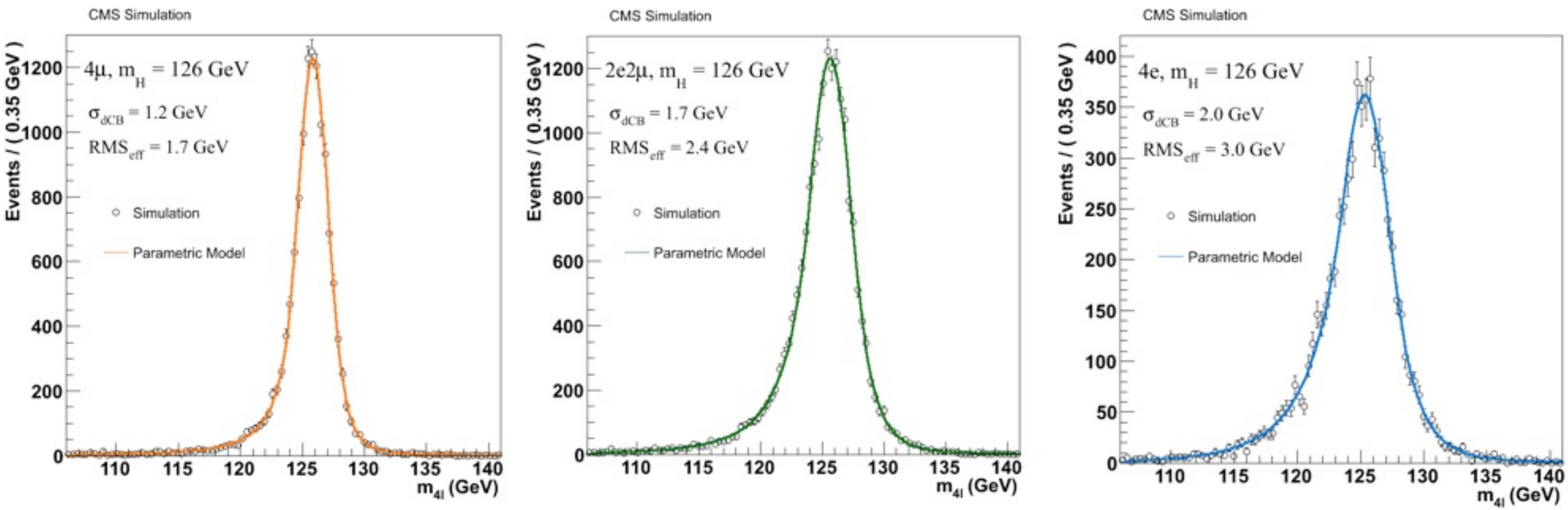
Best fit value of $f_{a3} = 0.00^{+0.23}_{-0.00}$

Summary

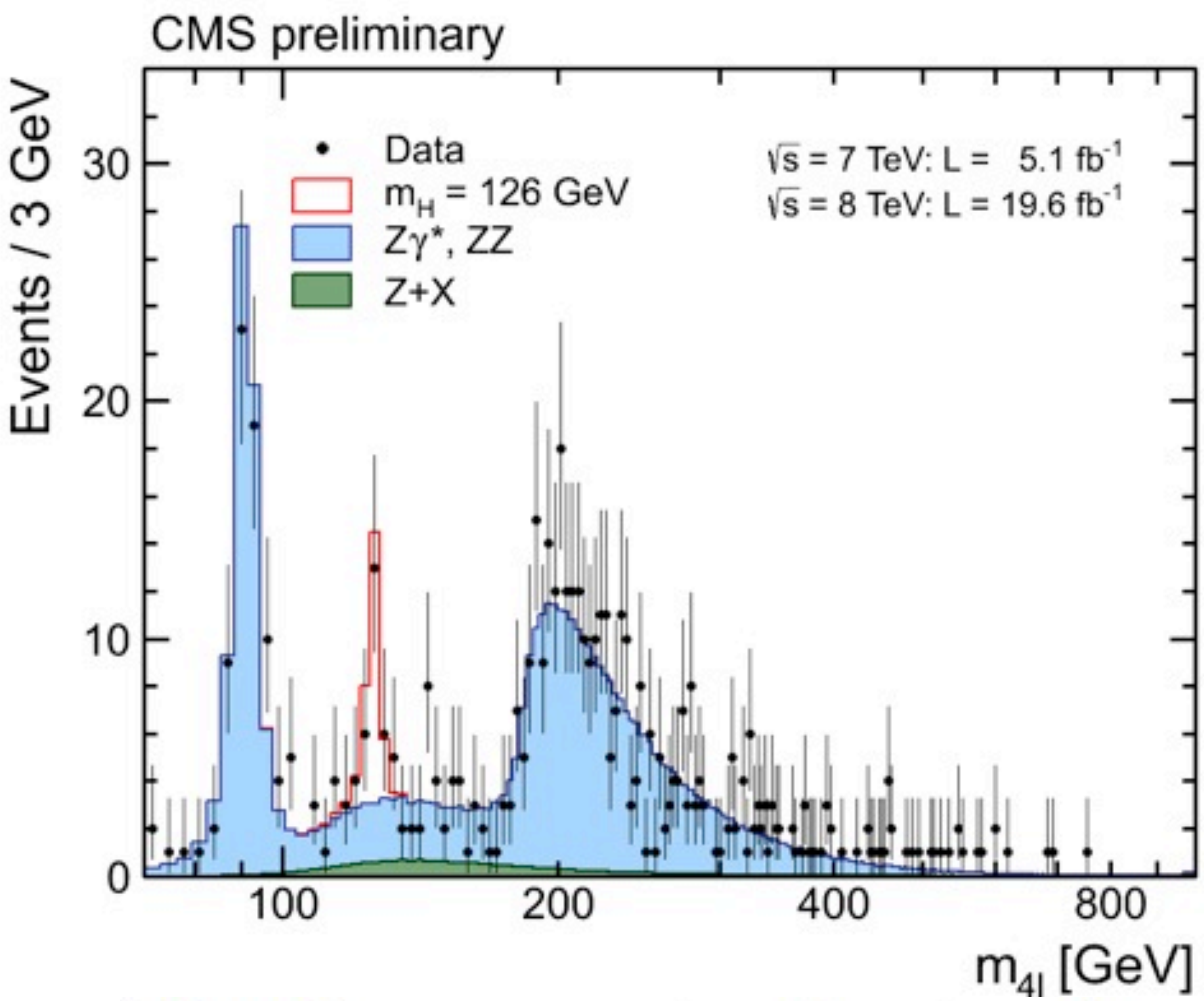
- 6.7σ excess observed in the search for the Higgs boson in the $H \rightarrow ZZ \rightarrow 4l$ channel
- The best fit mass of the particle is : 125.8 ± 0.5 (stat) ± 0.2 (syst) GeV
- Spin parity tests indicate that the particle is consistent with a pure 0^+ boson
- Pseudoscalar hypothesis disfavored with CLs = 0.16%, spin-2 hypothesis of a narrow resonance with minimal couplings disfavored with CLs = 1.5% while spin-1 hypotheses are disfavored with CLs < 0.1%

Backup

Signal Shapes



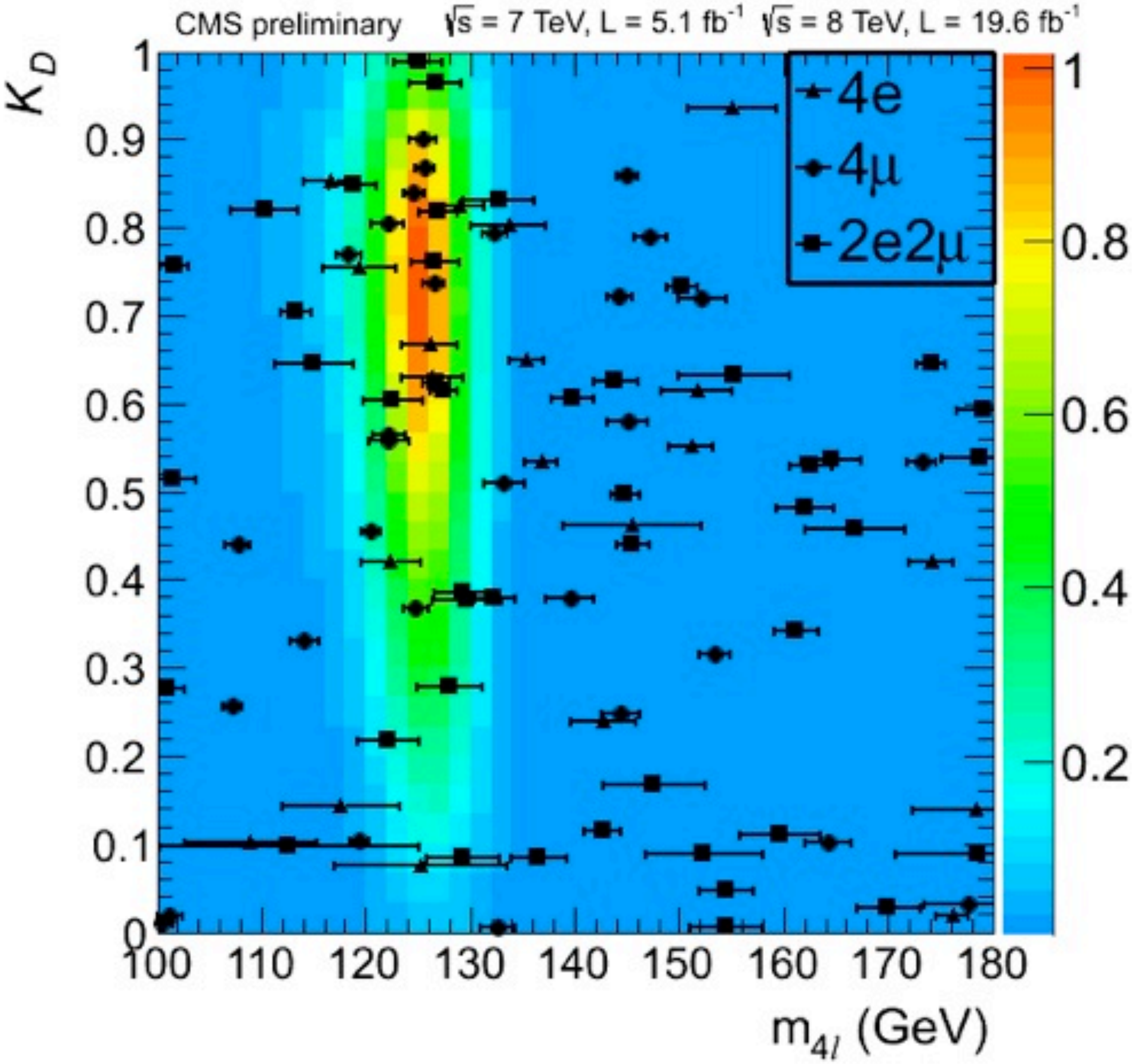
Mass Spectrum



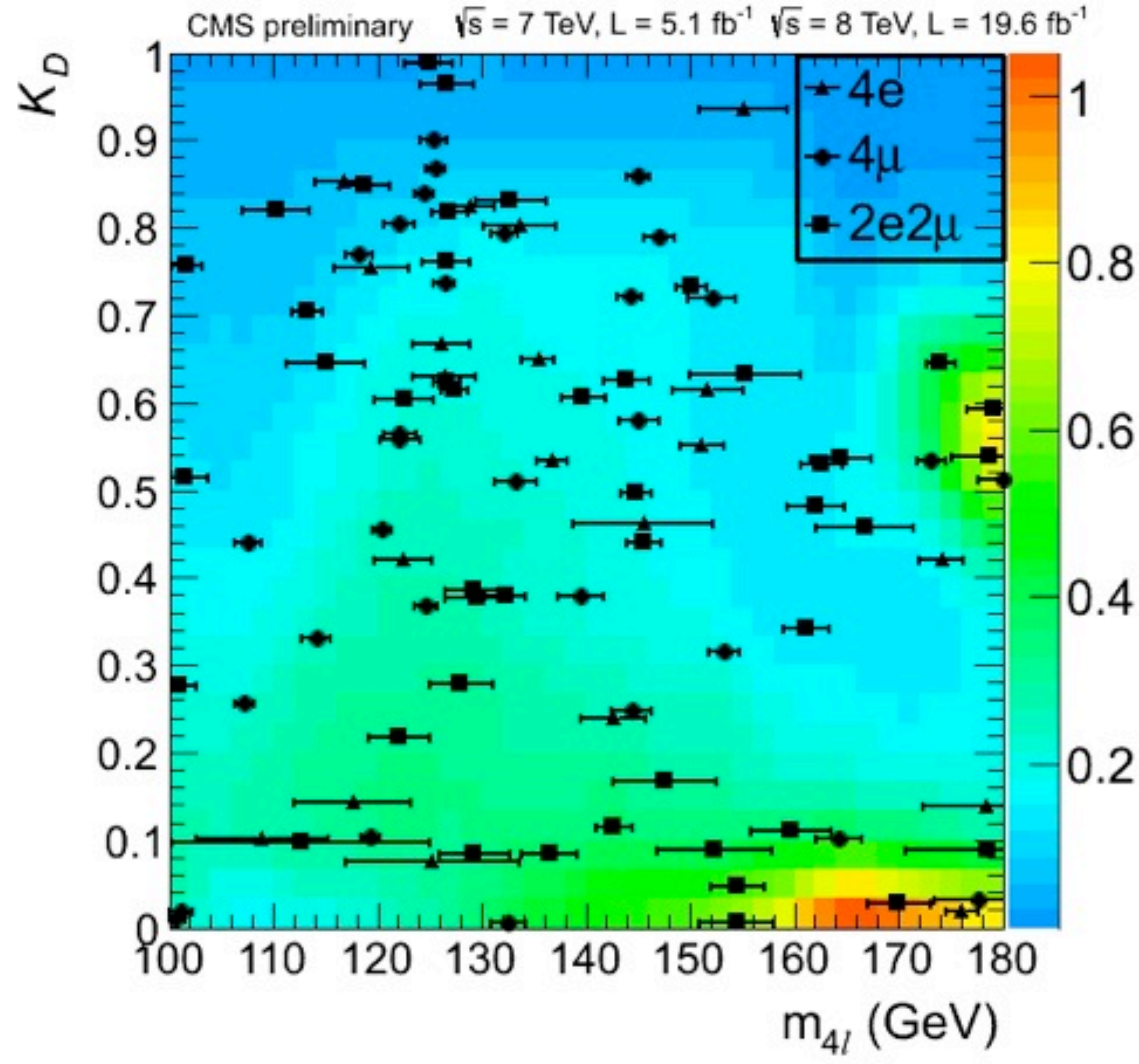
100 GeV < m(4l) < 1000 GeV Yields

Channel	4e	4μ	$2e2\mu$	$2\ell2\tau$
ZZ background	78.9 ±10.9	118.9 ±15.5	192.8 ±24.8	27.4 ±3.6
Z+ X	6.5 ± 2.6	3.8 ± 1.5	9.9 ± 4.0	22.9 ±7.8
All background expected	85.5 ± 11.2	122.6 ± 15.5	202.7 ± 25.2	50.3 ±8.6
m_H = 125 GeV	3.5 ±0.5	6.8 ±0.8	8.9 ±1.0	–
m_H = 126 GeV	3.9 ±0.6	7.4 ±0.9	9.8 ±1.1	–
m_H = 500 GeV	5.1 ±0.6	6.8 ±0.8	12.0 ±1.3	3.7 ±0.4
m_H = 800 GeV	0.7 ±0.1	0.9 ±0.1	1.6 ±0.2	0.4 ±0.1
Observed	86	125	240	57

KD v/s m(4l)

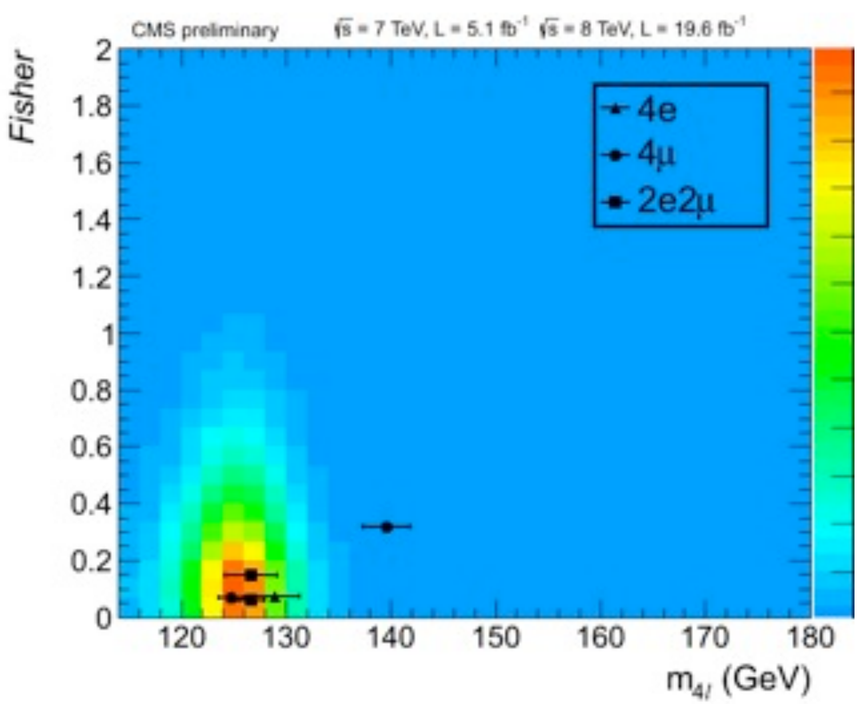


Data overlaid on signal expectation

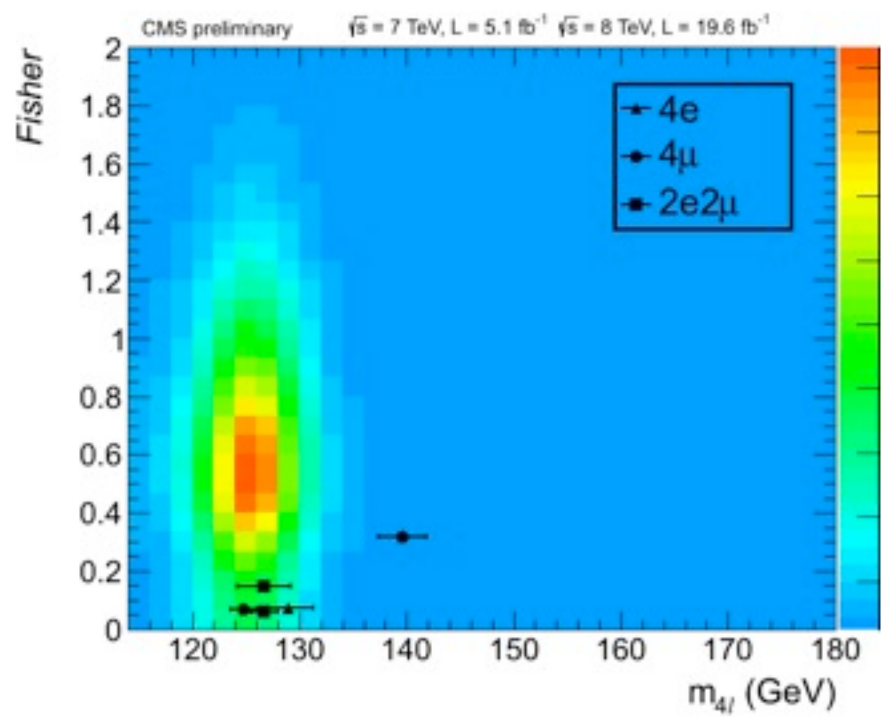


Data overlaid on background expectation

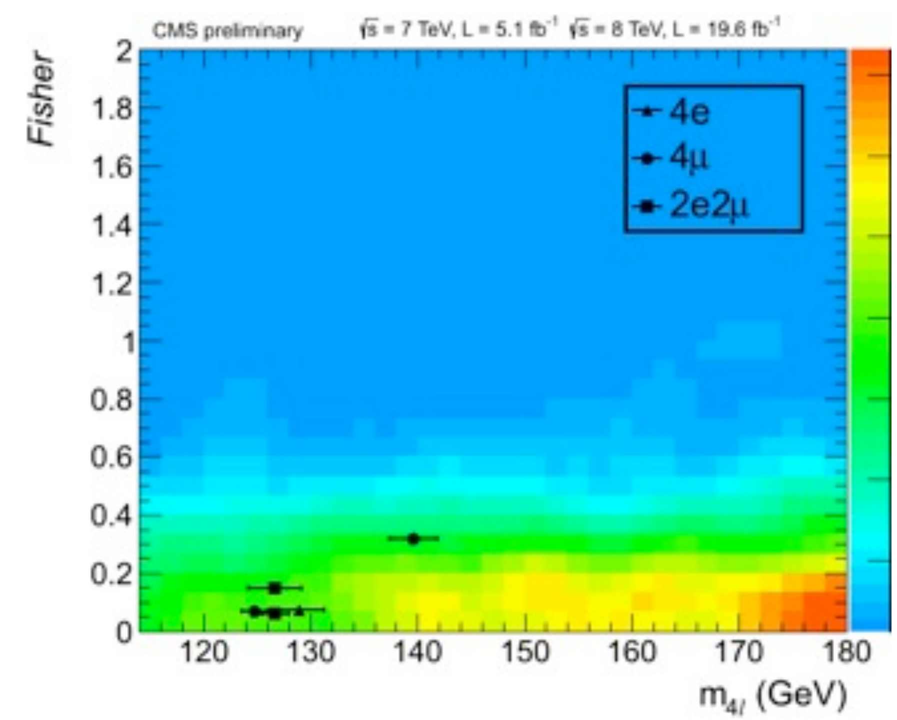
VD v/s m(4l)



Data overlaid on ggH expectation

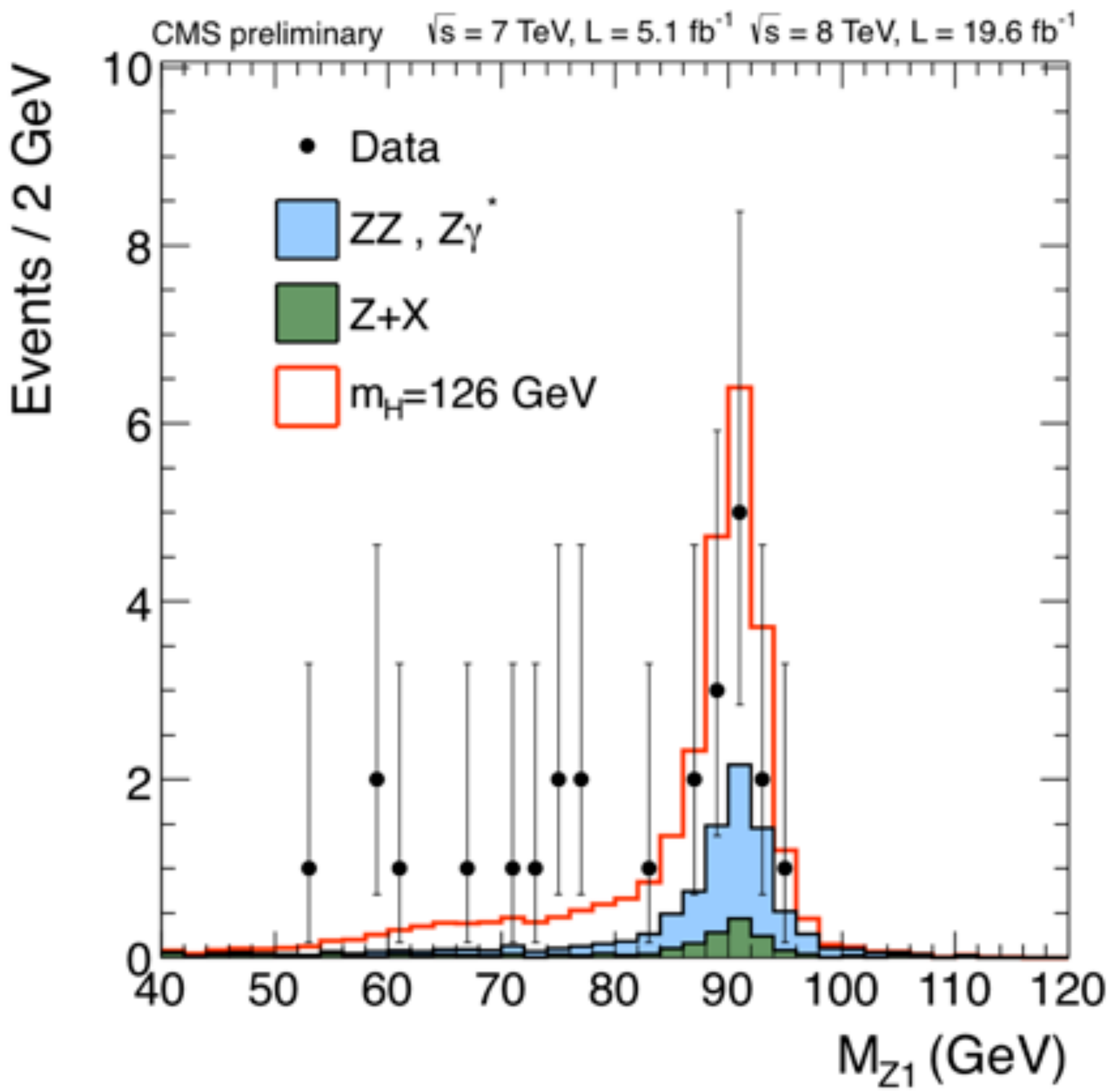


Data overlaid on VBF expectation

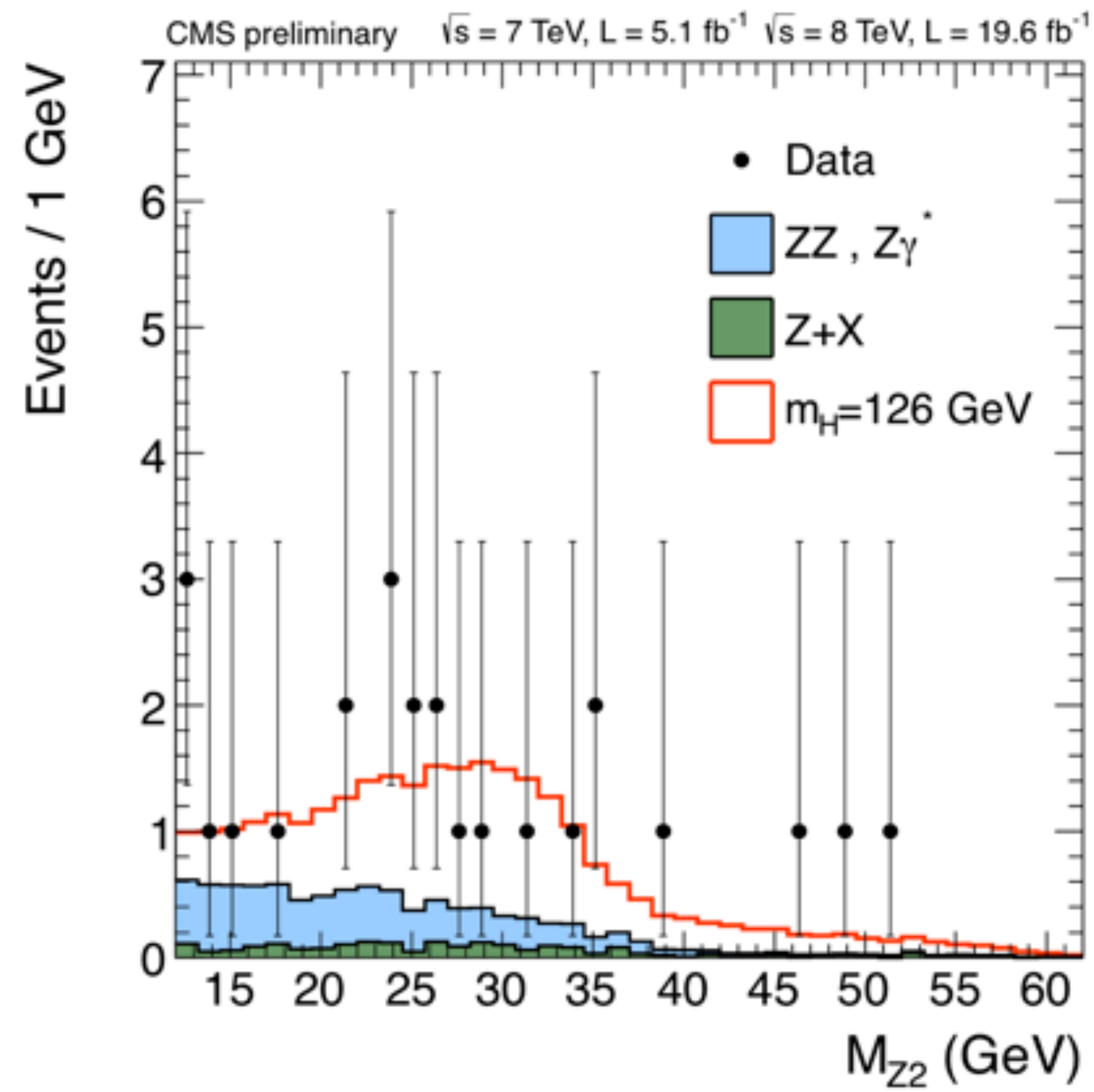


Data overlaid on bkg expectation

m(Z1) and m(Z2)

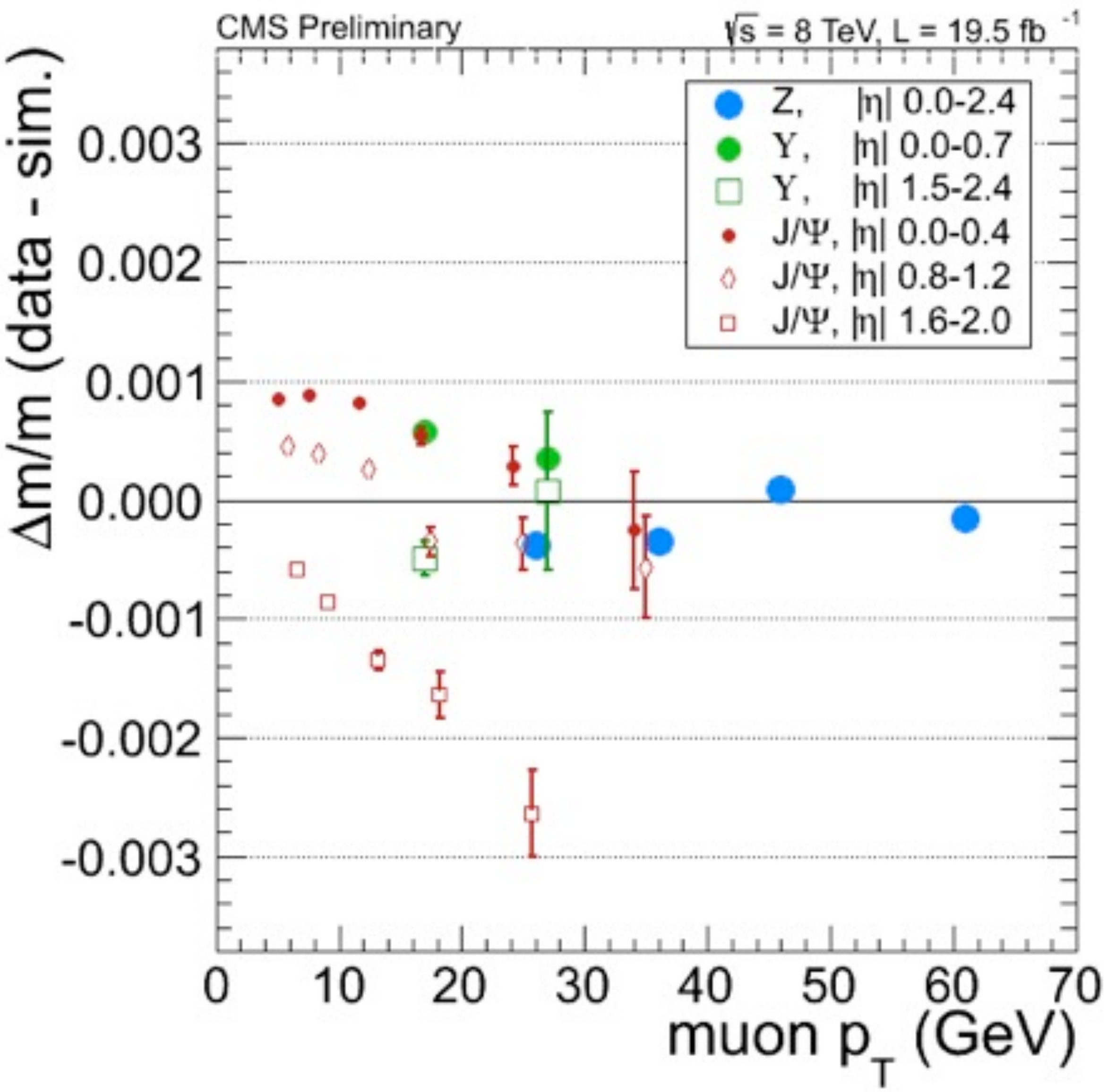


Z1 Mass Spectrum
121.5 GeV < m(4l) < 130.5 GeV

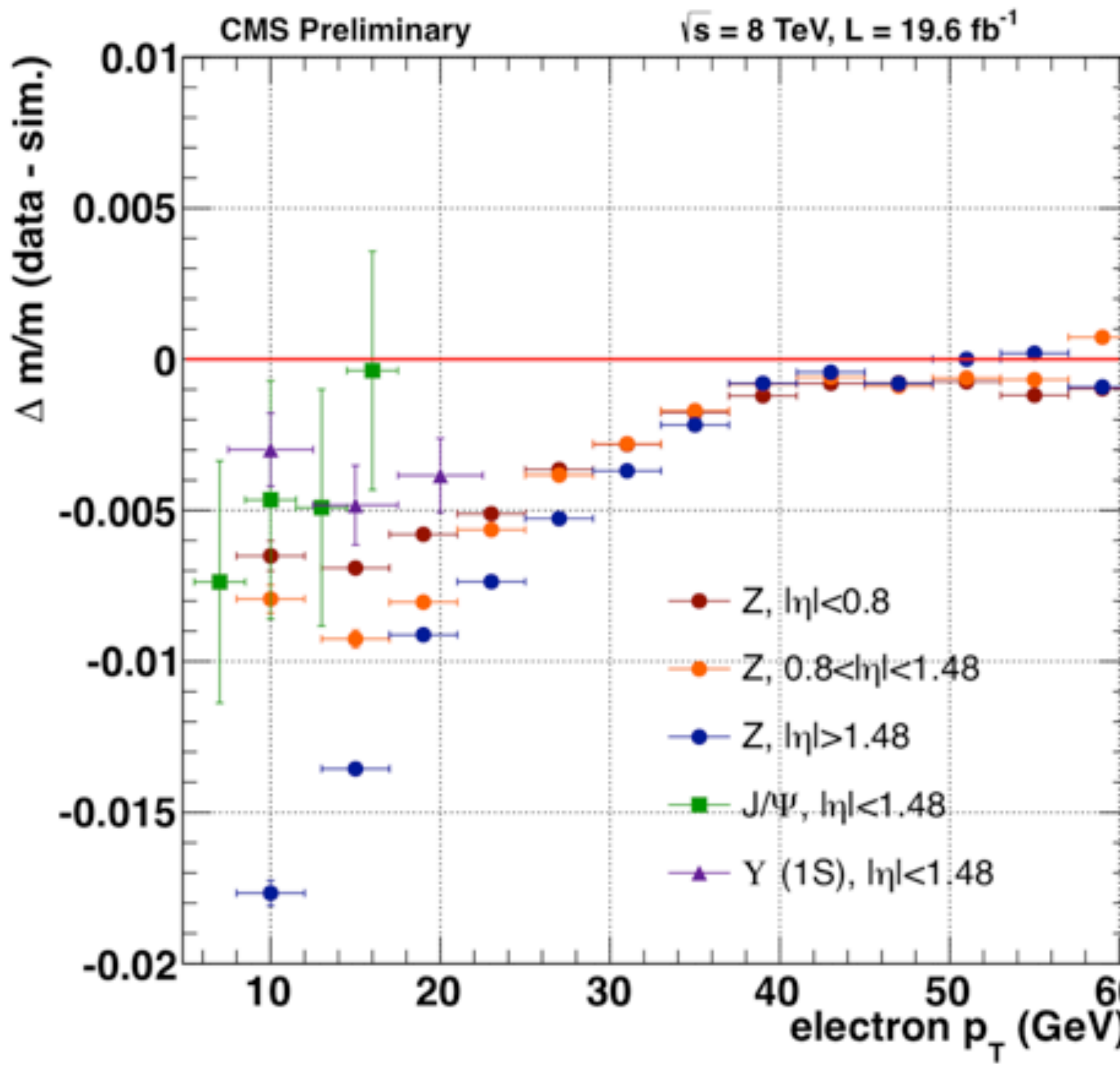


Z2 Mass Spectrum
121.5 GeV < m(4l) < 130.5 GeV

Mass Scale

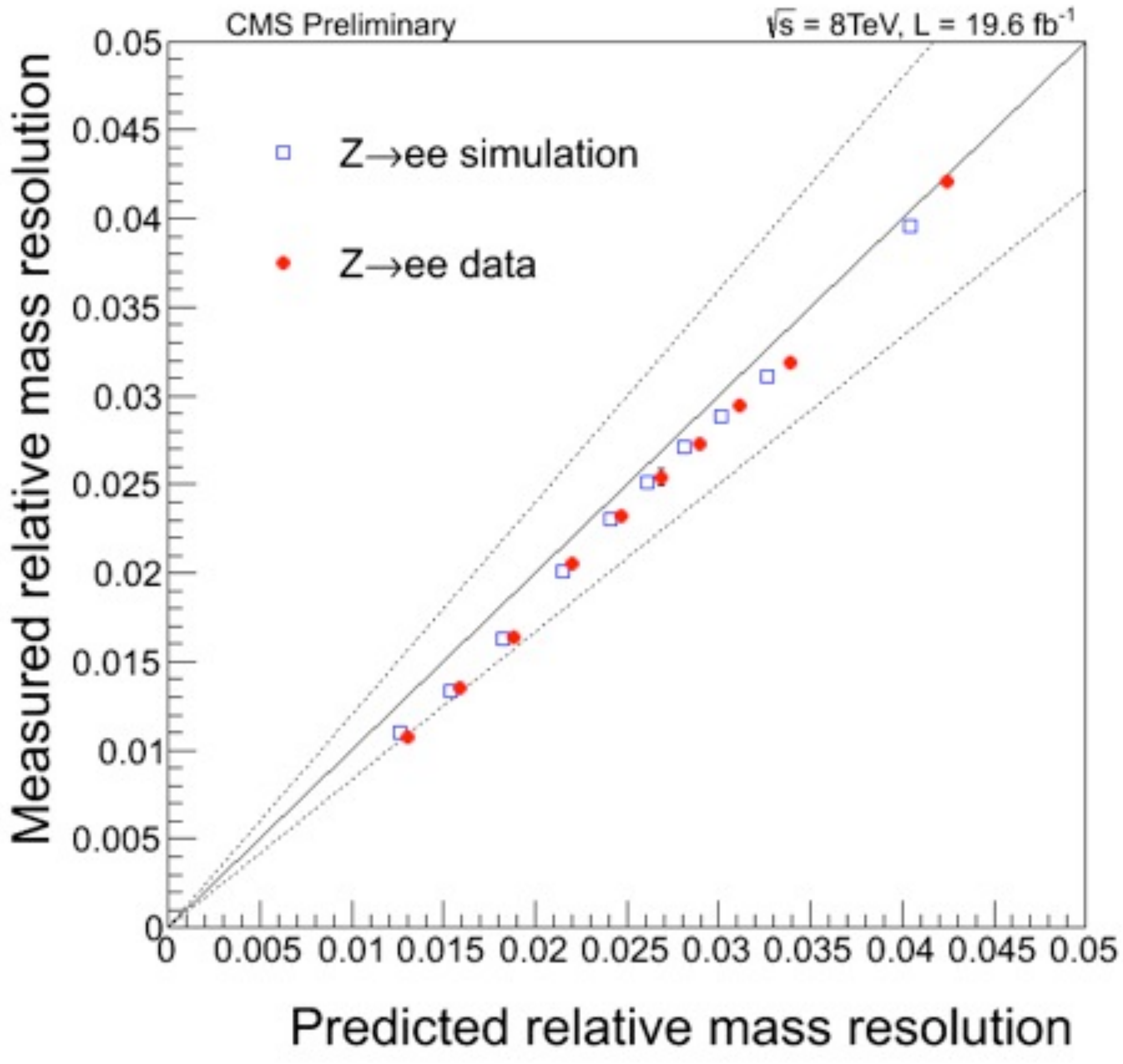


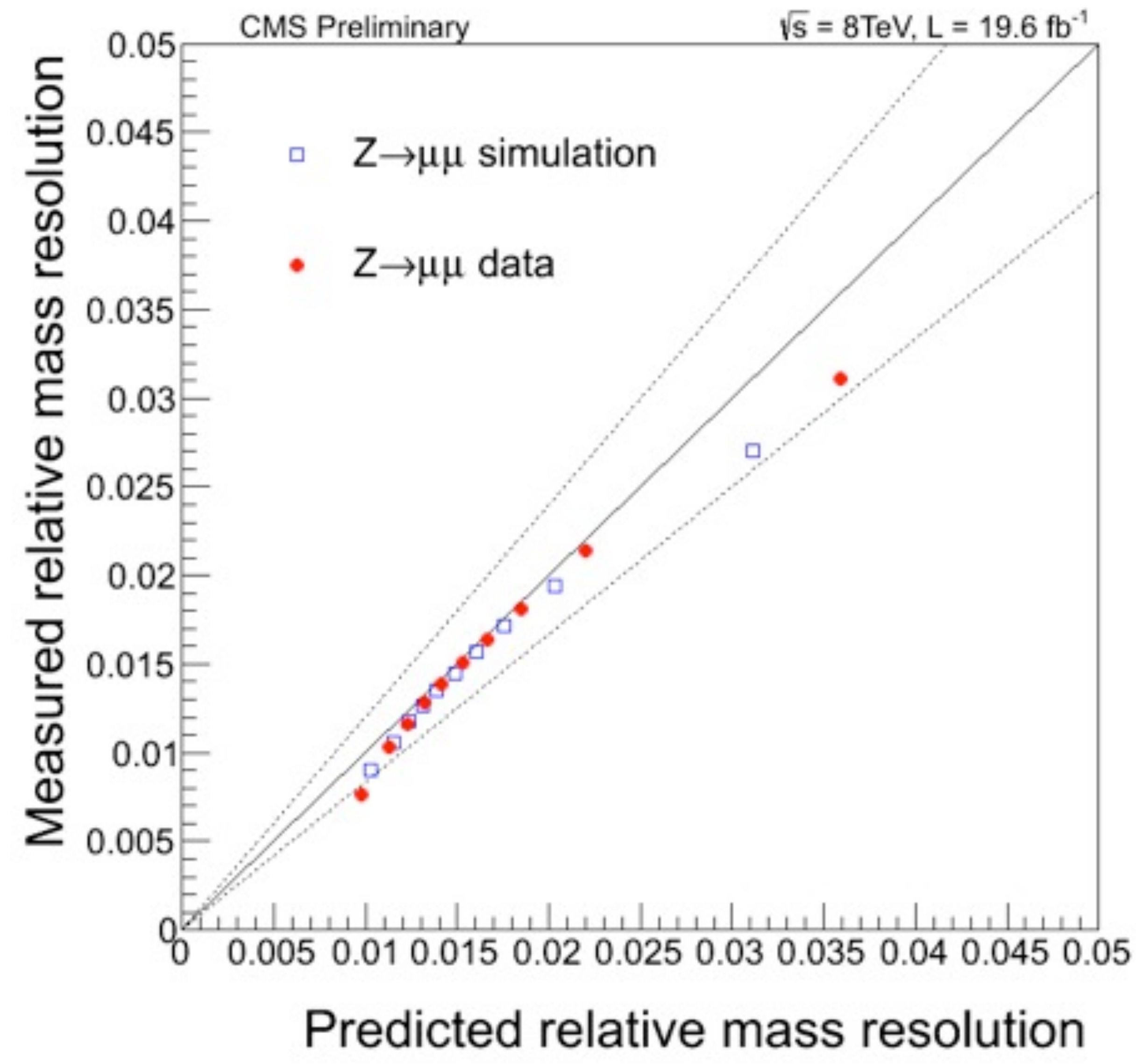
Muons



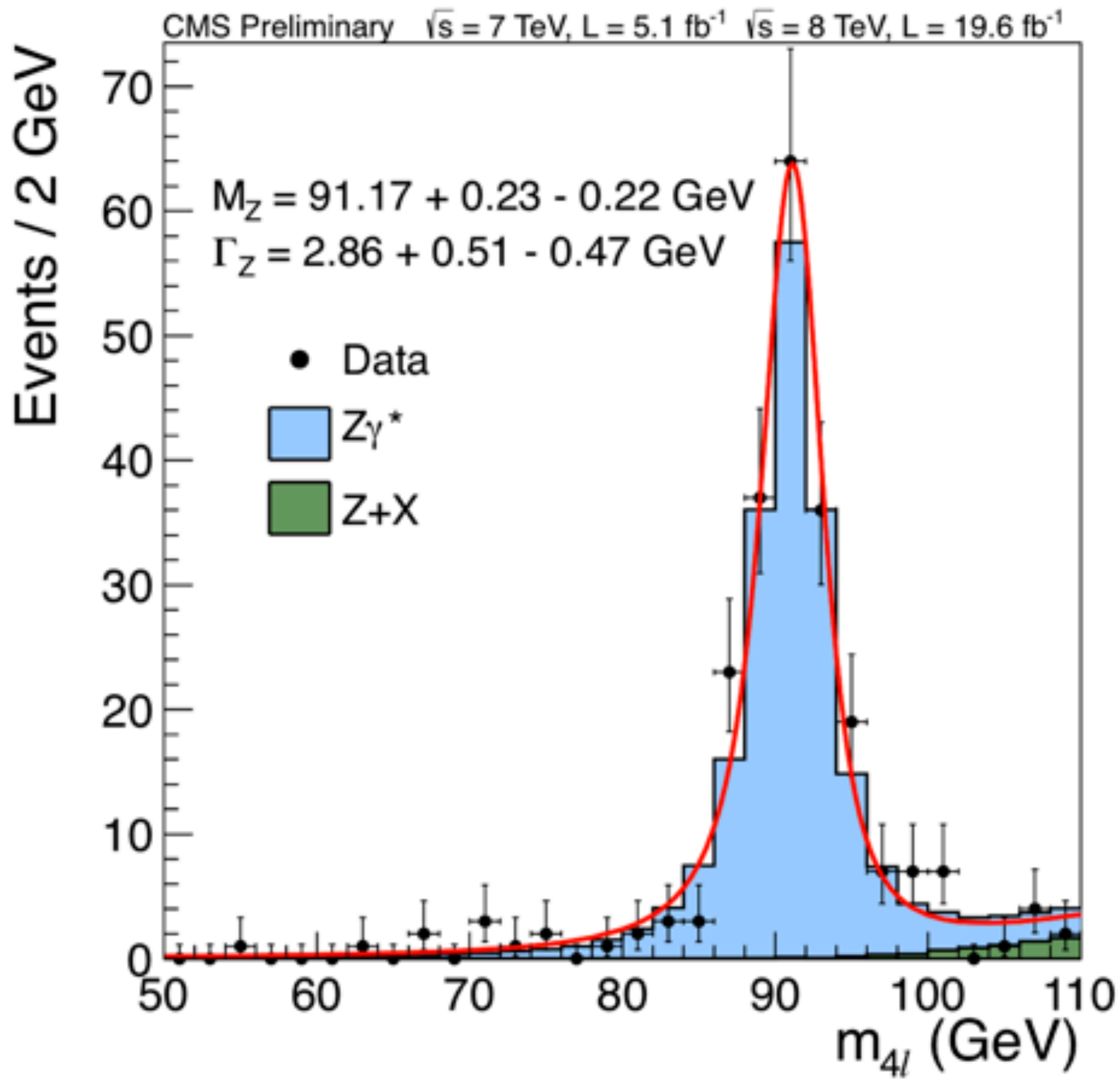
Electrons

Event-by-event Mass Uncertainties

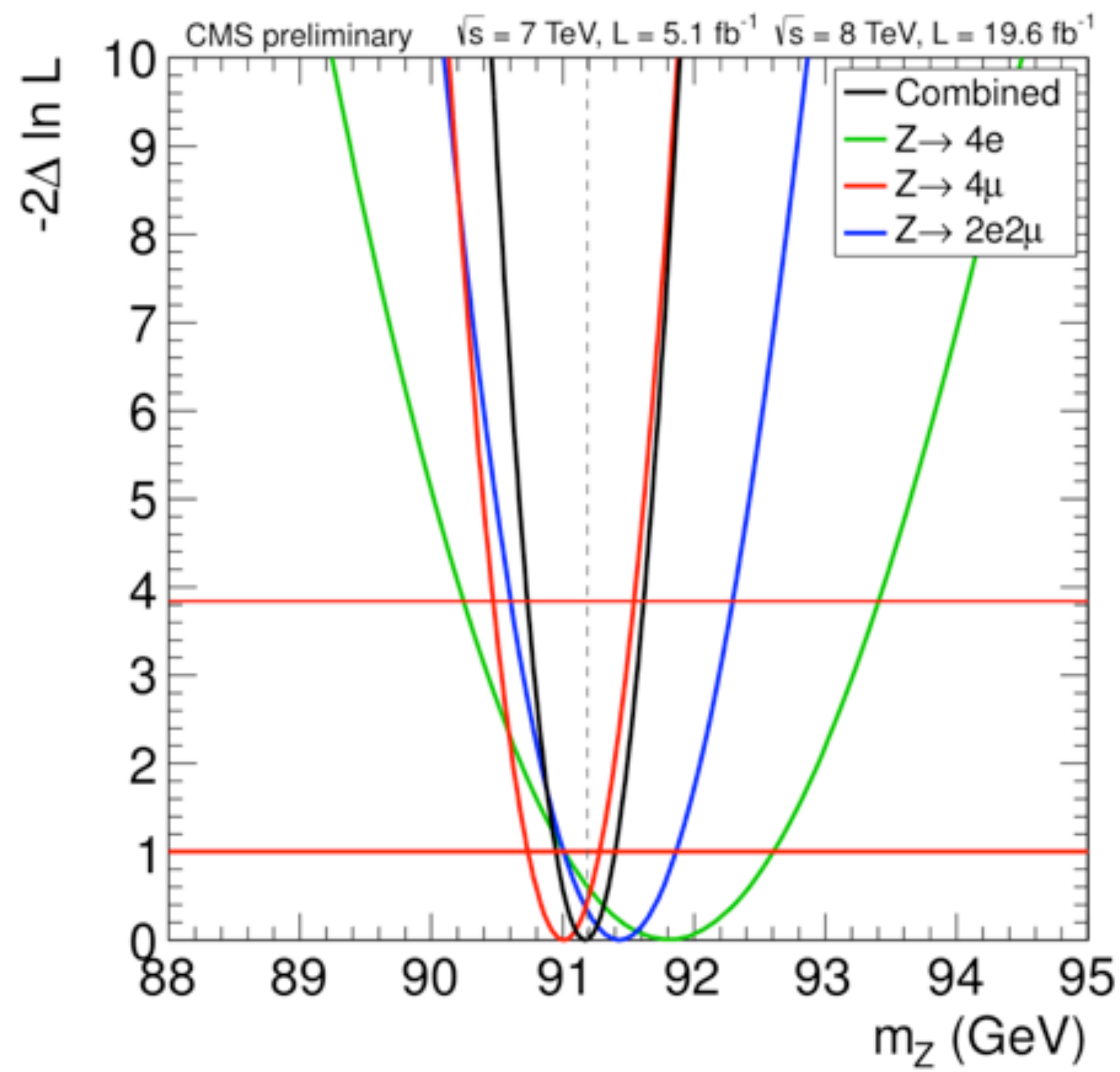




Z→4l Candle

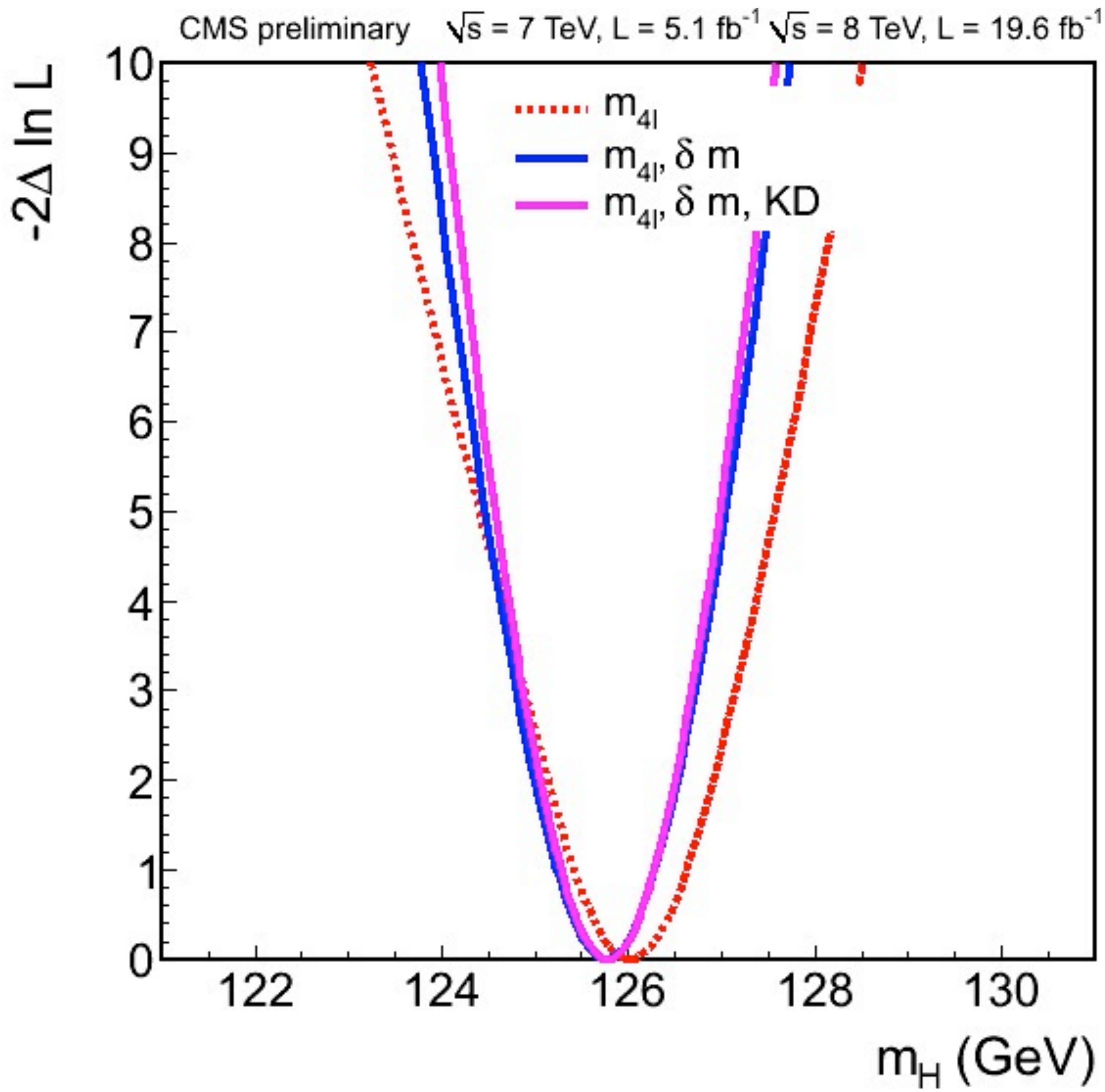


CMS Preliminary √s = 7 TeV, L = 5.1 fb⁻¹ √s = 8 TeV, L = 19.6 fb⁻¹
M_Z = 91.17 + 0.23 - 0.22 GeV
Γ_Z = 2.86 + 0.51 - 0.47 GeV
Data
$Z\gamma^*$
Z+X
Events / 2 GeV
m_{4l} (GeV)



CMS preliminary √s = 7 TeV, L = 5.1 fb⁻¹ √s = 8 TeV, L = 19.6 fb⁻¹
Combined
Z→ 4e
Z→ 4μ
Z→ 2e2μ
-2Δ ln L
m_Z (GeV)

Mass Fits



CMS preliminary $\sqrt{s}$ = 7 TeV, L = 5.1 fb^{-1} $\sqrt{s}$ = 8 TeV, L = 19.6 fb^{-1}
$-2\Delta \ln L$
m_{4l}
m_{4l}, δ m
m_{4l}, δ m, KD
m_H (GeV)