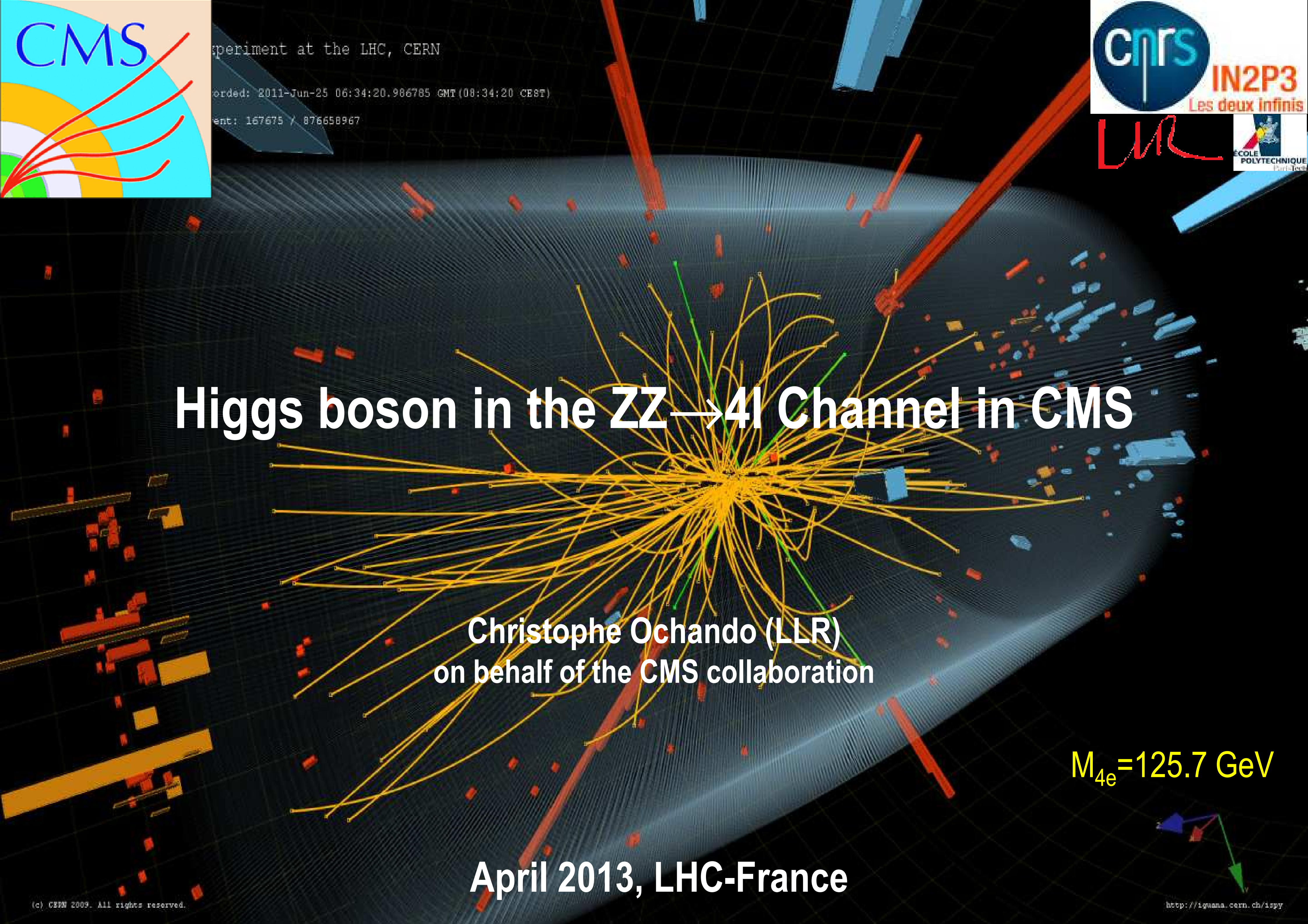
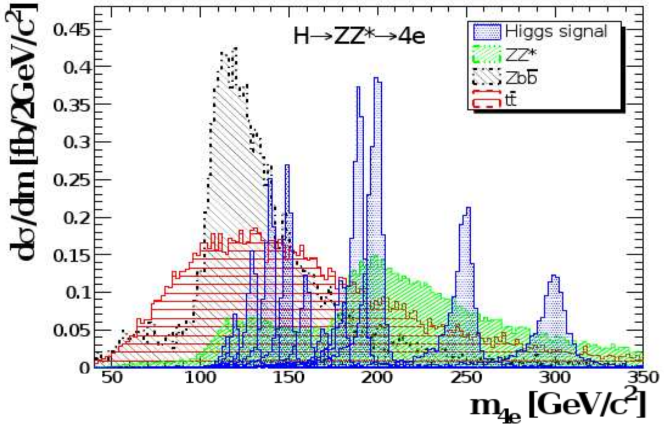


Higgs boson in the ZZ→4l Channel in CMS

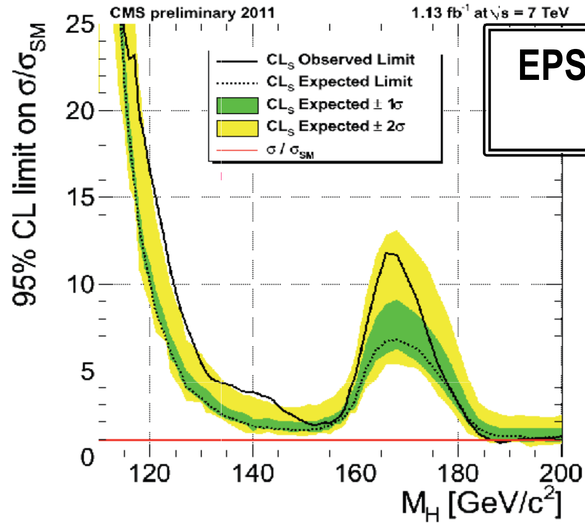
Christophe Ochando (LLR)
on behalf of the CMS collaboration

April 2013, LHC-France

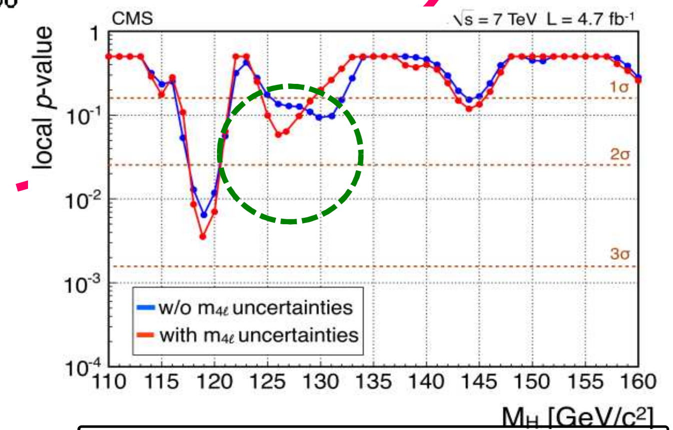
A bit of history…



CMS Physics TDR 2006,
MC Simulation

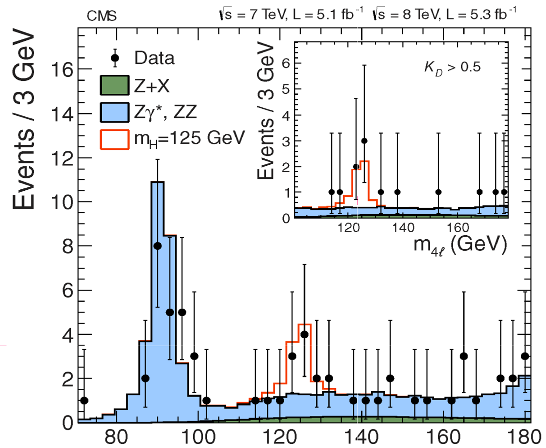


EPS 2011 (7 TeV, 1.1 fb^{-1}),
First exclusion



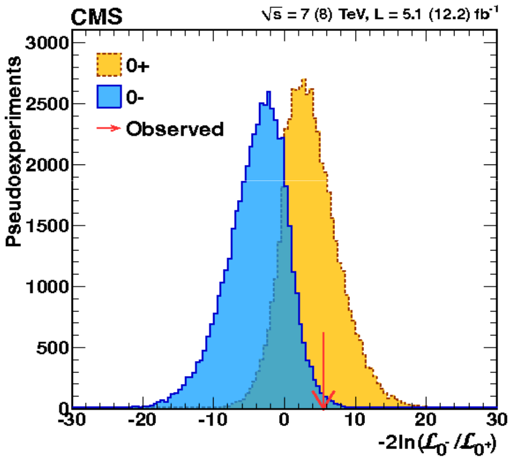
December 2011 (7 TeV, 4.7 fb^{-1}),
First Hint ?

PRL 108 (2012) 111804



July2012 (7+8 TeV, 5.1/5.3 fb^{-1}),
Discovery !

PLB 716 (2012) 30–61



November 2012 (7+8 TeV, 5.1/12.2 fb^{-1}),
First spin-parity results
0- excluded @ > 95% C.L.

PRL 110 (2013) 081803

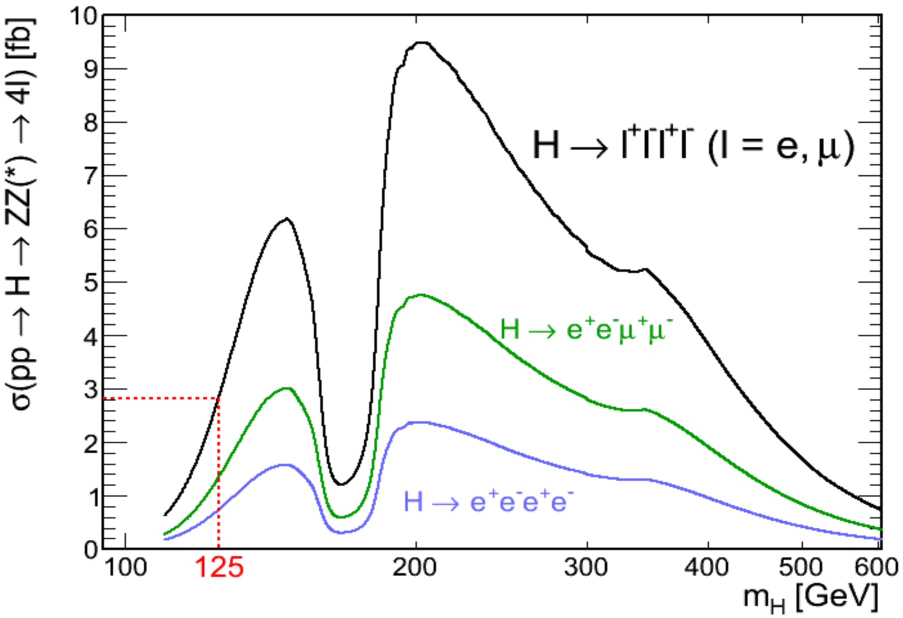
March 2013 (7+8 TeV, 5.1/19.6 fb^{-1}),
Full Run I statistics

This talk

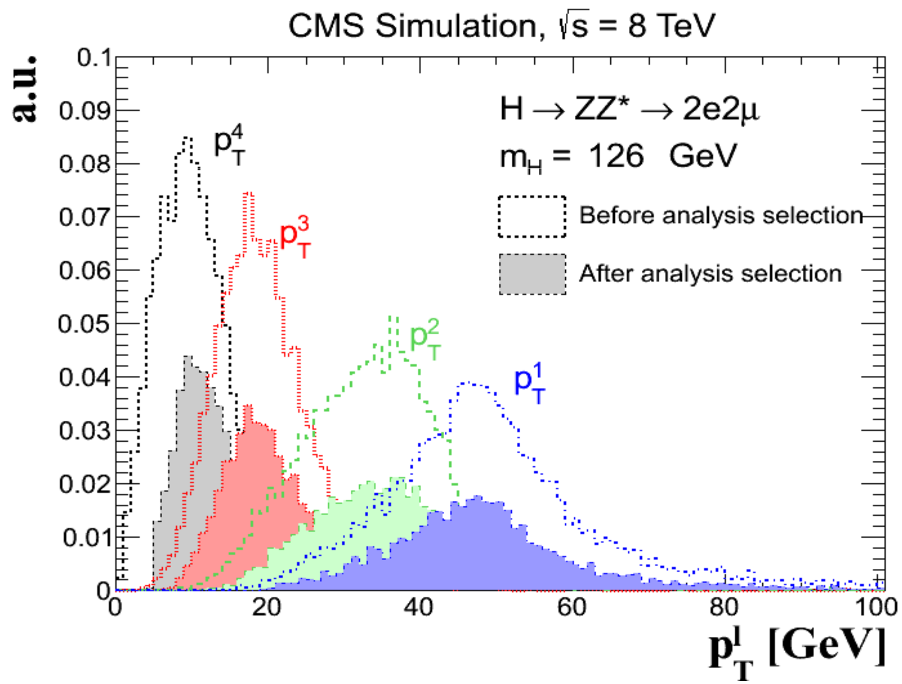
Introduction

"Golden channel": clean experimental signature, high precision on mass, information on J^{PC}

Production cross-section @ 8 TeV

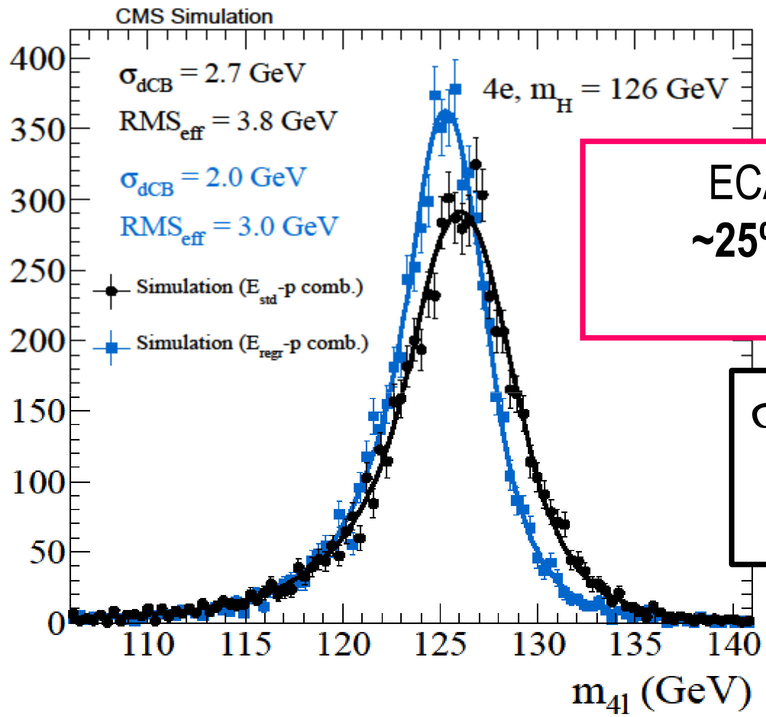


- 4 primary isolated leptons (e, μ)
- Narrow resonance (1-2% resolution) over ~flat background
- **BUT:** low signal yields (<3 events / fb)



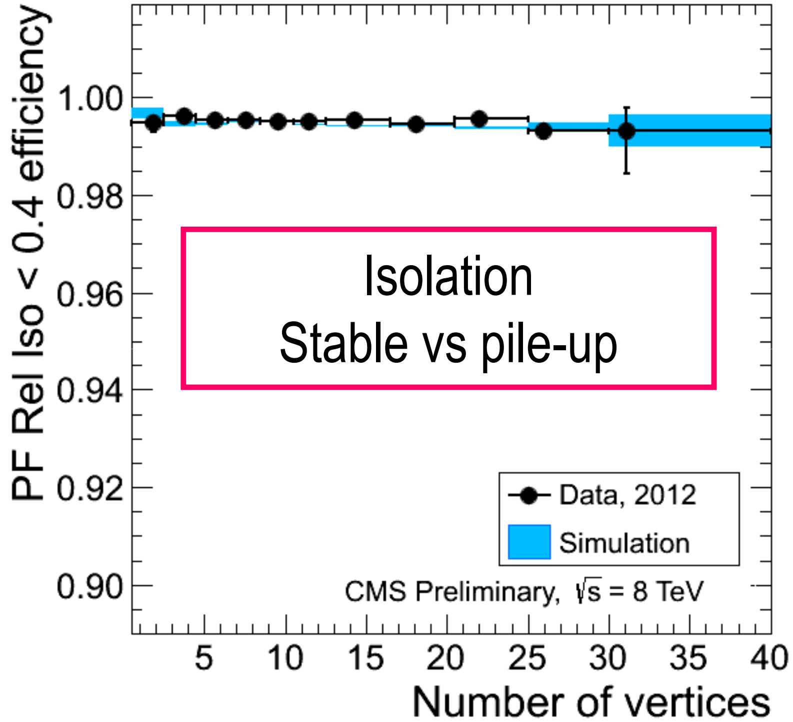
- **Extremely demanding channel for selection (ε^4):**
- Low pT leptons: major experimental challenge
  - Reconstruction/Identification (**see Claude & Nenad's talks on leptons**)
  - Background rejection & control

Objects: some highlights

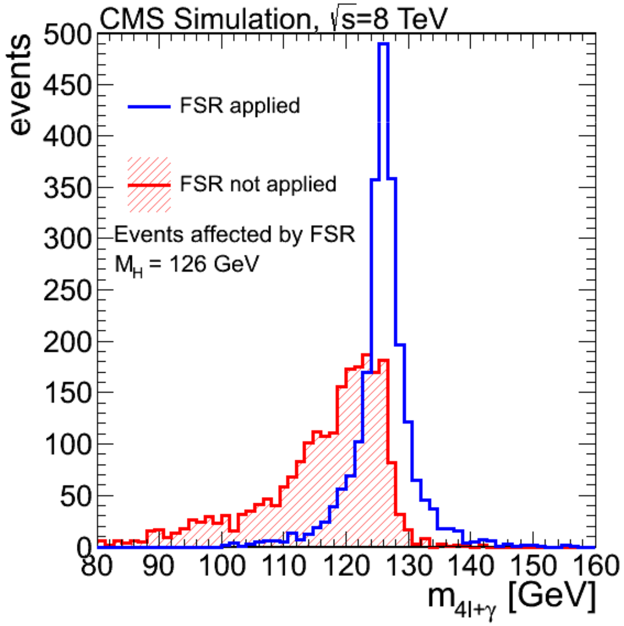


ECAL energy BDT regression:
~25% resolution improvement
for H→ZZ→4e

σ(m4l) = 2.0 GeV (4e)
= 1.2 GeV (4μ)
= 1.7 GeV (2e2μ)



Isolation
Stable vs pile-up

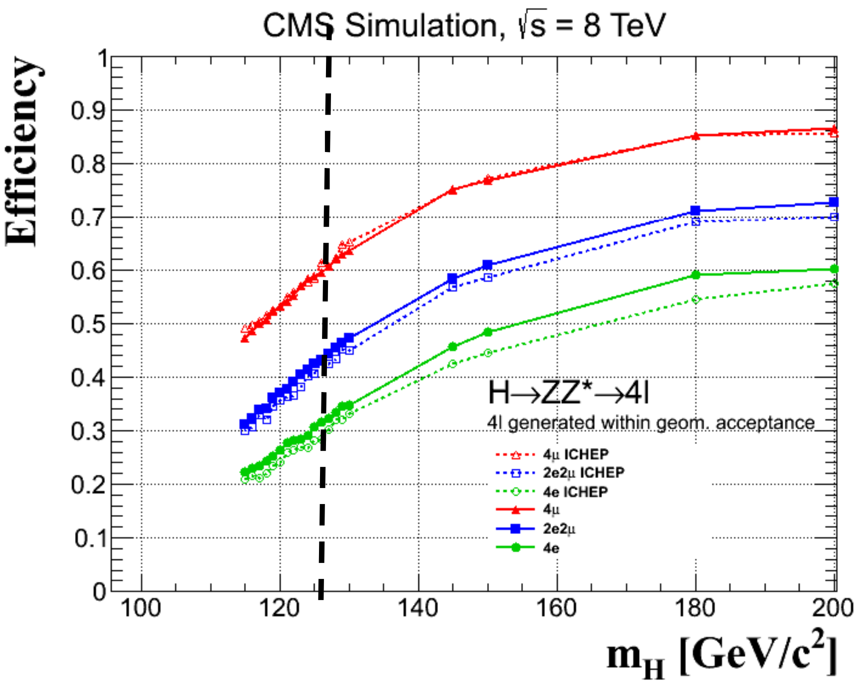


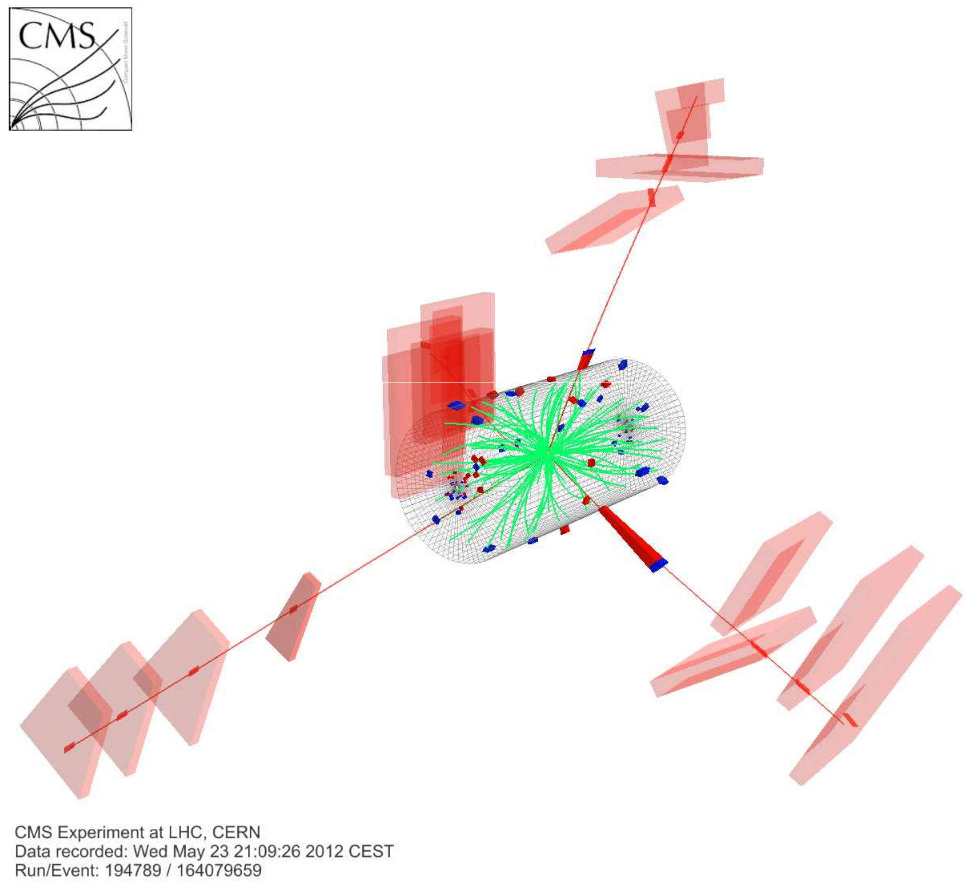
Final State Radiation (FSR) γ Recovery [since ICHEP '12]:

- Recover photons near the leptons from Z's (down to 2 GeV, $\Delta R(l,\gamma)$ up to 0.5)
- 6% of events affected.
- Improve signal efficiency & mass resolution.

Selection

- Electrons (muons) down to 7 (5) GeV.
- FSR γ Recovery on all channels
- Open phase space:
  - 40< mZ1 <120 GeV
  - 12< mZ2 <120 GeV





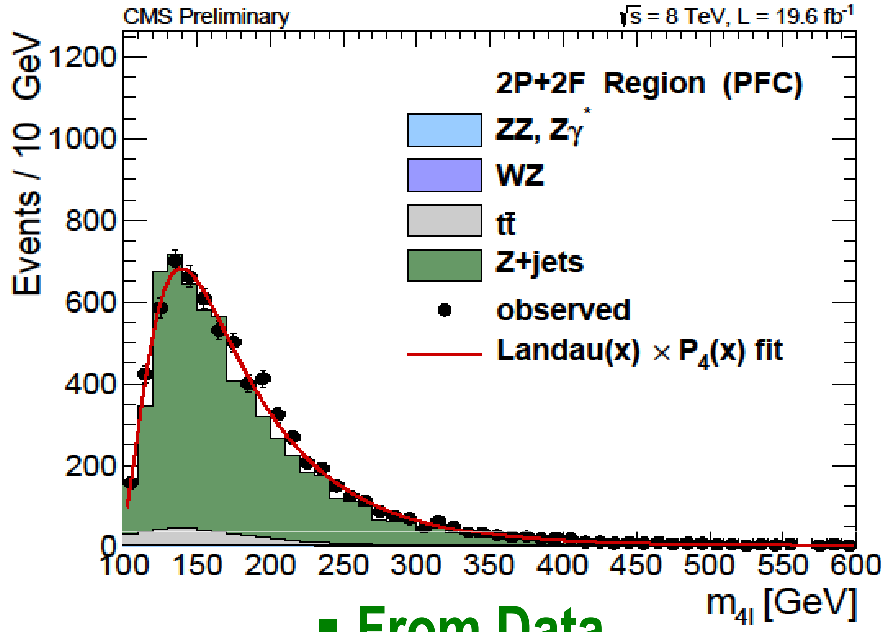
@ mH = 126 GeV, signal efficiencies:
(within the geometrical acceptance for leptons)
31% (4e), 42% (2e2μ), 59%(4μ)

Background Control

Reducible ("Z+X")

(important at low mass)

- Z+jets, WZ+jets, (fake leptons)
- Z+bb, ttbar (non-prompt/isolated leptons)
- Z+γ+jets (conversion)

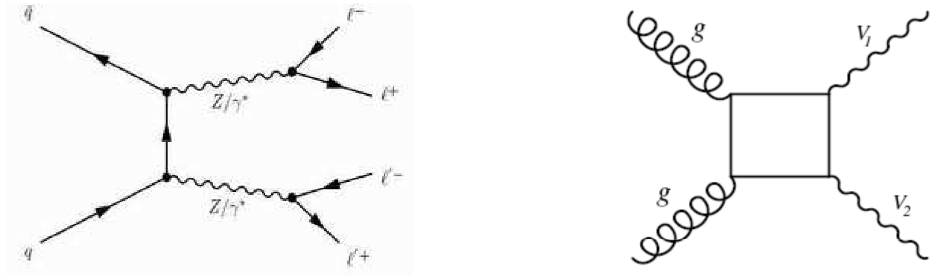


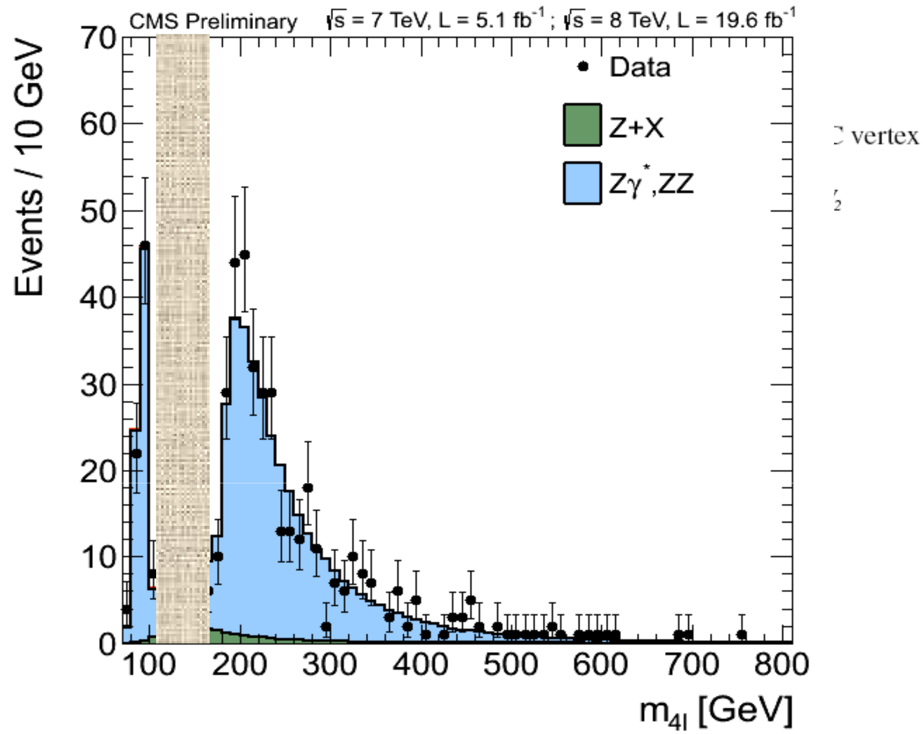
▪ **From Data**

- Build various control regions, with relaxed/inverted criteria
- Extrapolation to signal region with "lepton mis-identification probability"
- Validation in samples with relaxed charge/flavor

Irreducible

(qq/gg→ZZ)





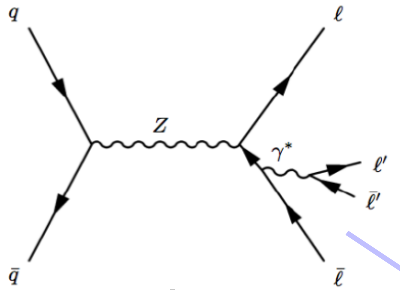
▪ **From Simulation**

(corrected for residual data/MC differences)

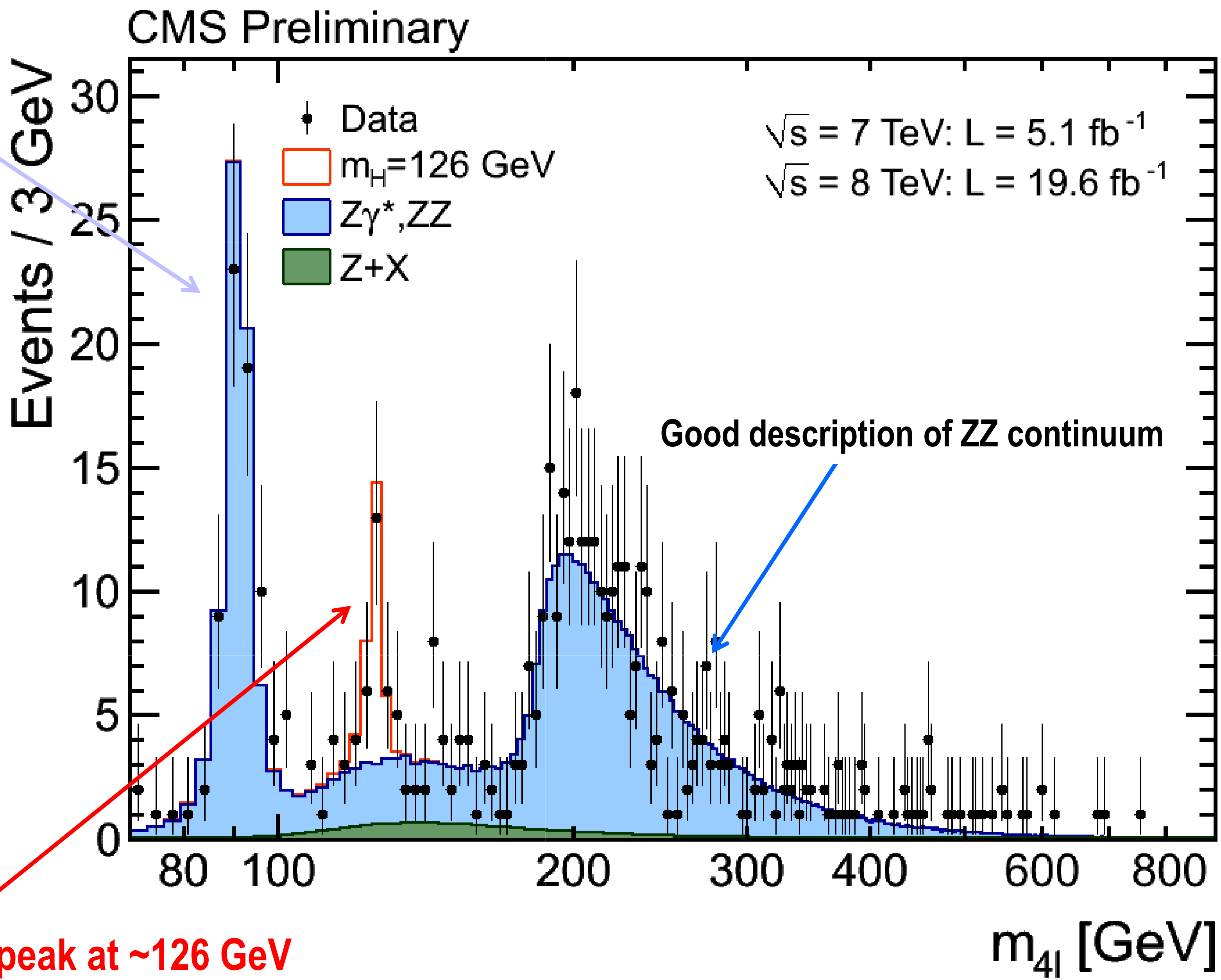
$\sigma(pp \to ZZ, 8TeV) = 8.4 \pm 1.0$ (stat.) $\pm$ 0.7 (syst.) $\pm$ 0.4(lum.) pb

In agreement with NLO prediction

H→ZZ →4l: Mass spectrum



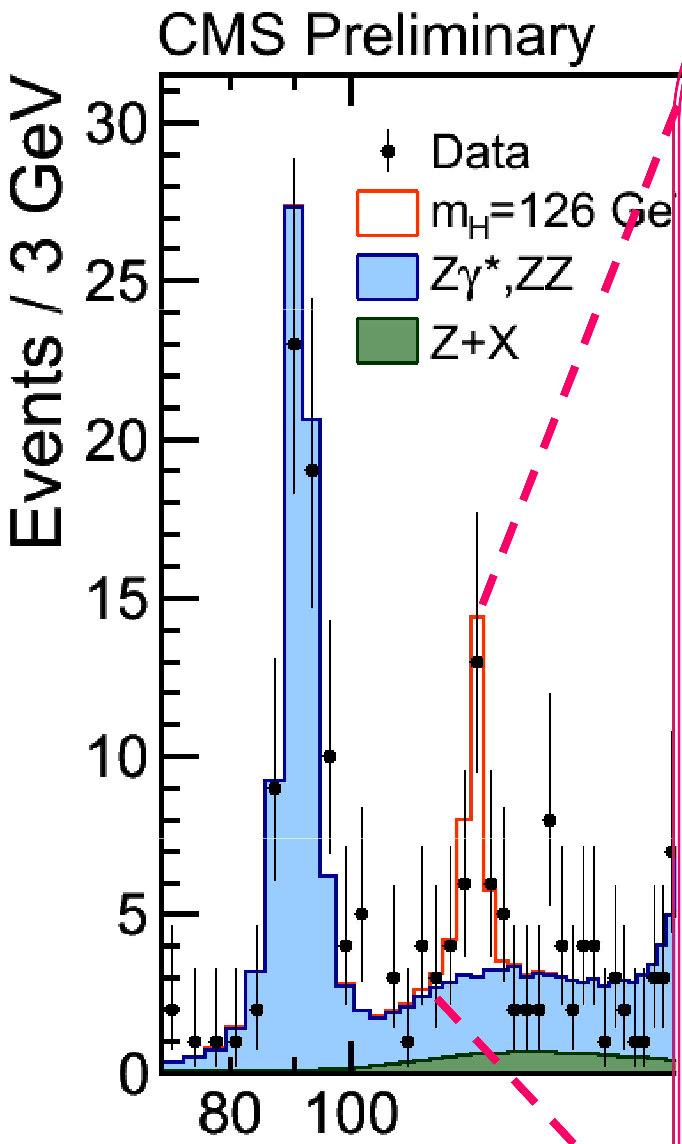
Z→4l peak
well visible

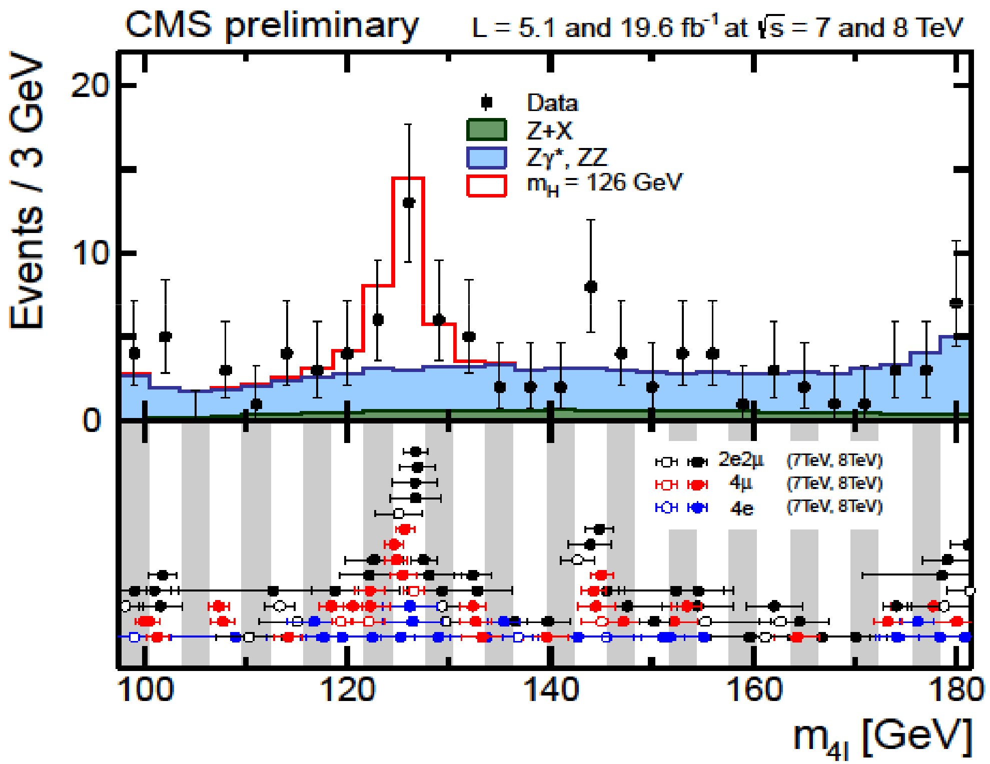


Good description of ZZ continuum

Clean signal peak at ~126 GeV

H→ZZ →4l: Mass spectrum (zoom)





H(126)	18.6
ZZ	7.4
Z+X	2.0
Total Bkg.	9.4

S/B ~ 2

H(126)+Bkg.	28
Data	25

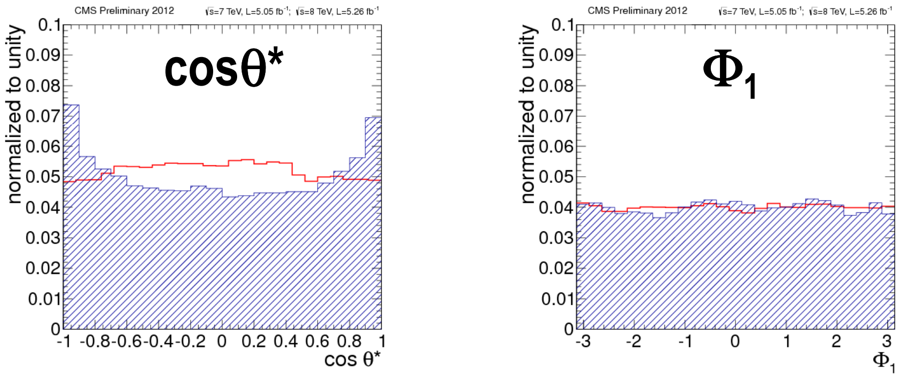
in 121.5<m4l<130.5 GeV range

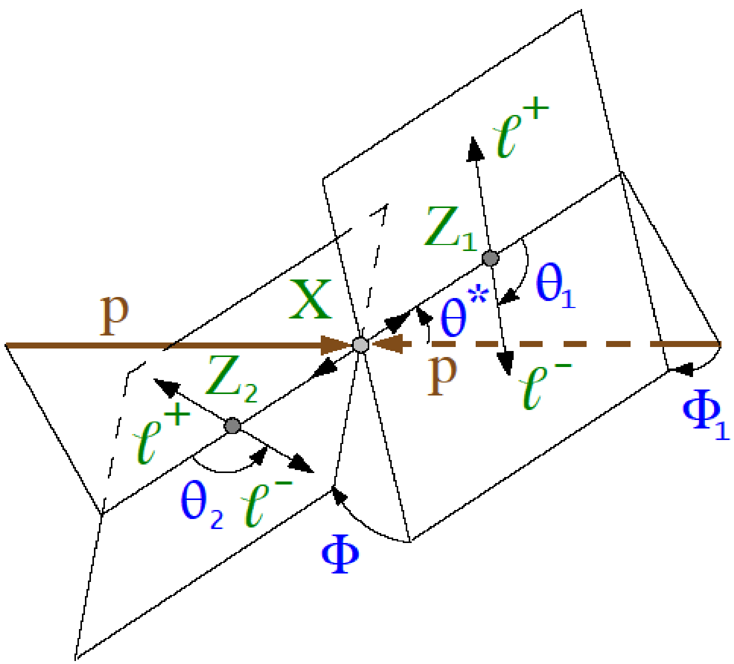
Beyond m4l

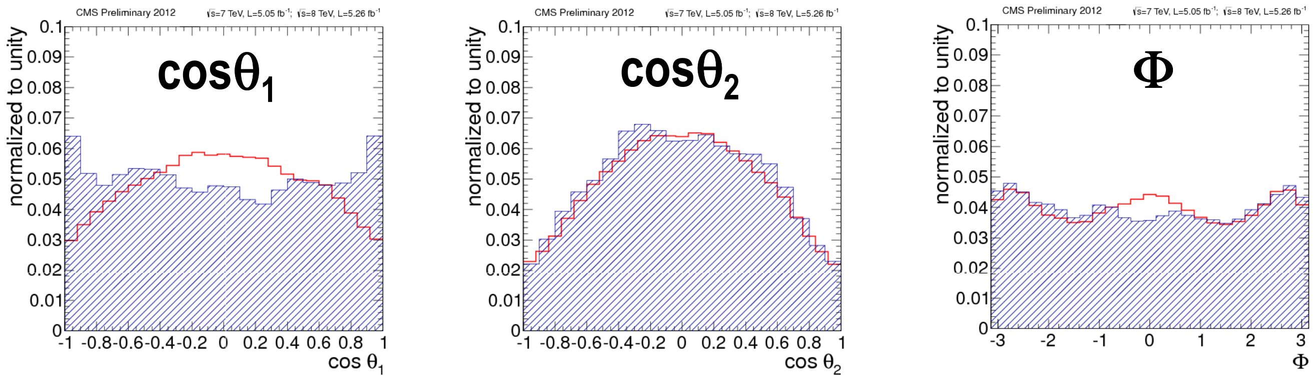
In addition to m4l, use more information in the final fit to:

further separate signal from background…

➢ **Use full Kinematics…**

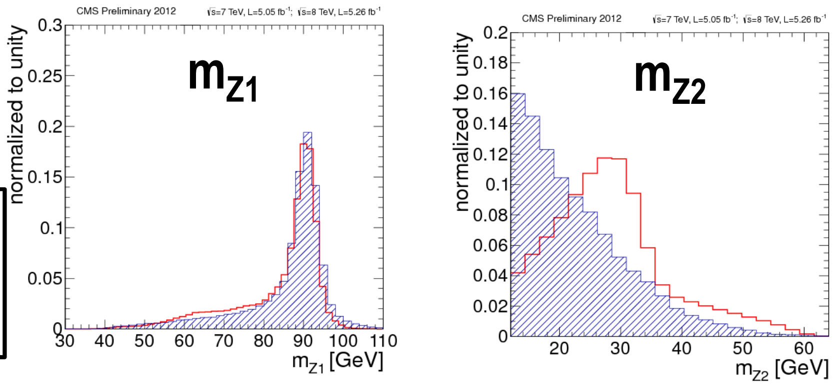






5 production & decay angles
+ mZ1, mZ2

m_H=125 GeV
ZZ



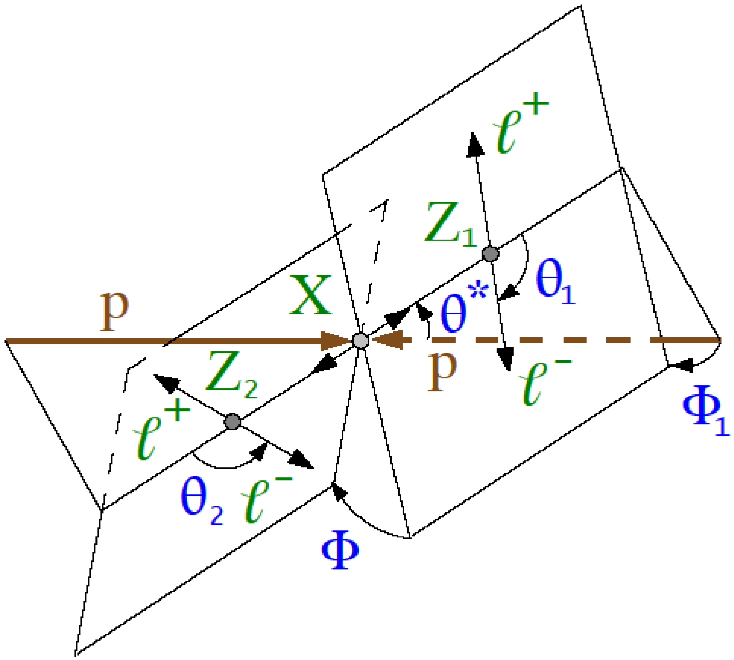
Beyond m4l

In addition to m4l, use more information in the final fit to:

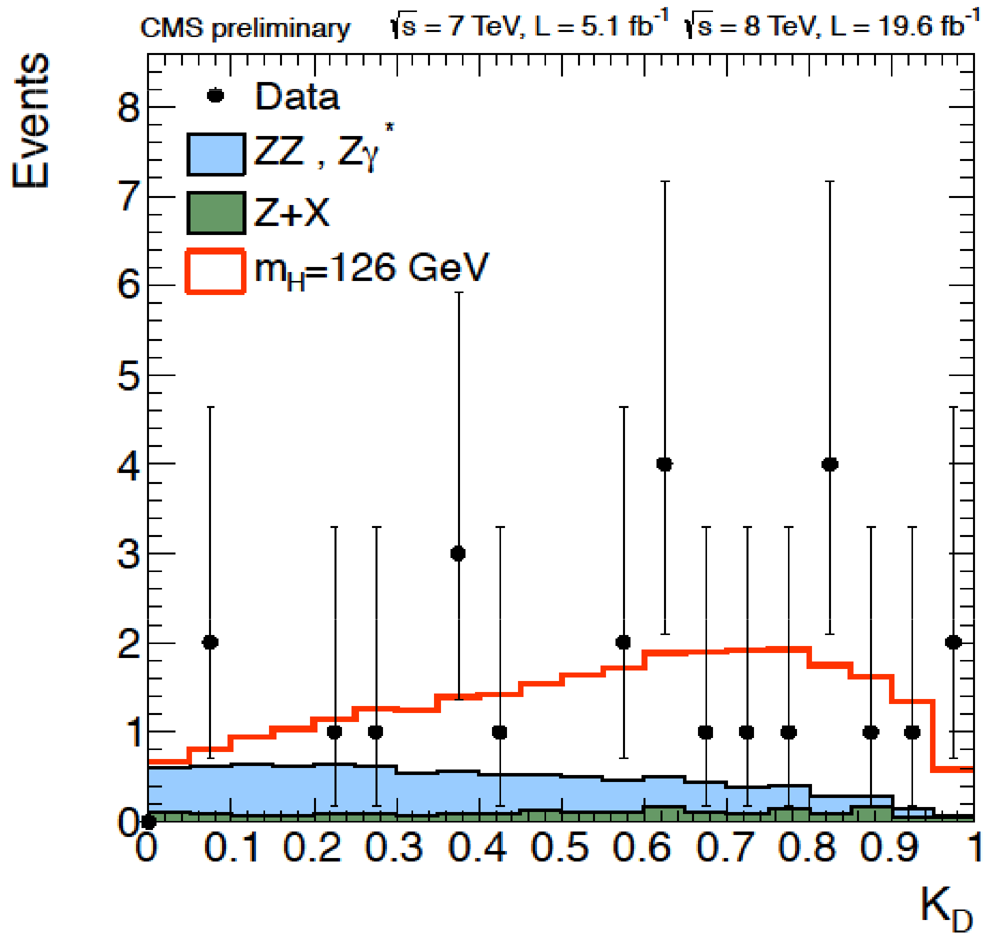
further separate signal from background…

➢ **…Build Kinematic Discriminant from Matrix Element techniques [since ICHEP '12]**

$$K_D(\theta^*, \Phi_1, \theta_1, \theta_2, \Phi, m_{Z_1}, m_{Z_2}) = \mathcal{P}_{sig}/(\mathcal{P}_{sig} + \mathcal{P}_{bkg})$$



5 production & decay angles
+ mZ1, mZ2



Distribution in 121.5<m4l<130.5 GeV range

Beyond m4l

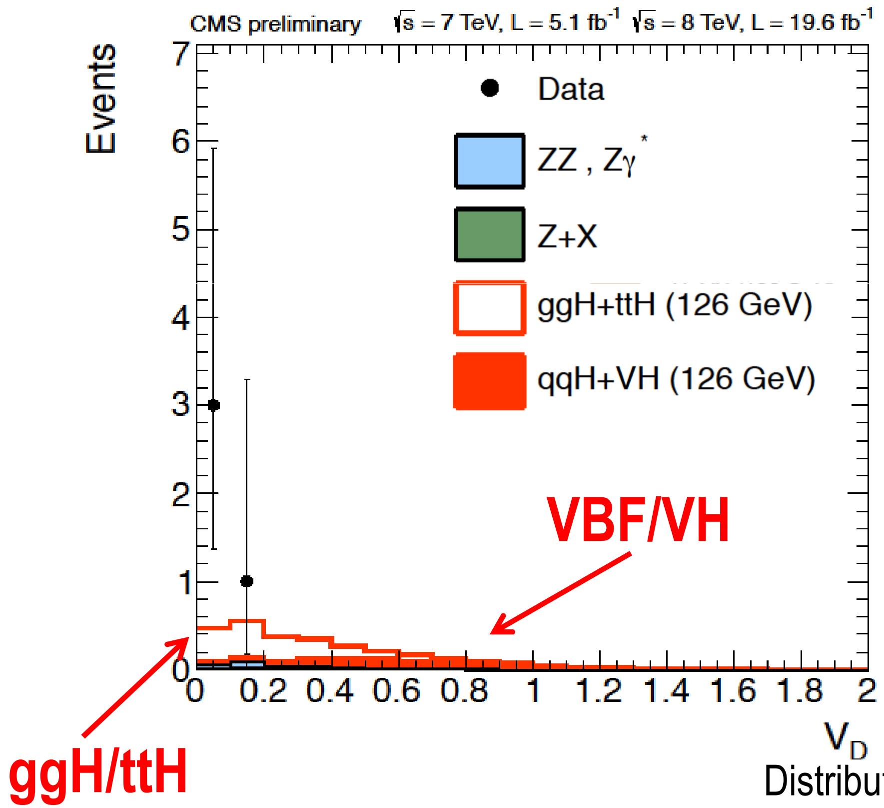
In addition to m4l, use more information in the final fit to:

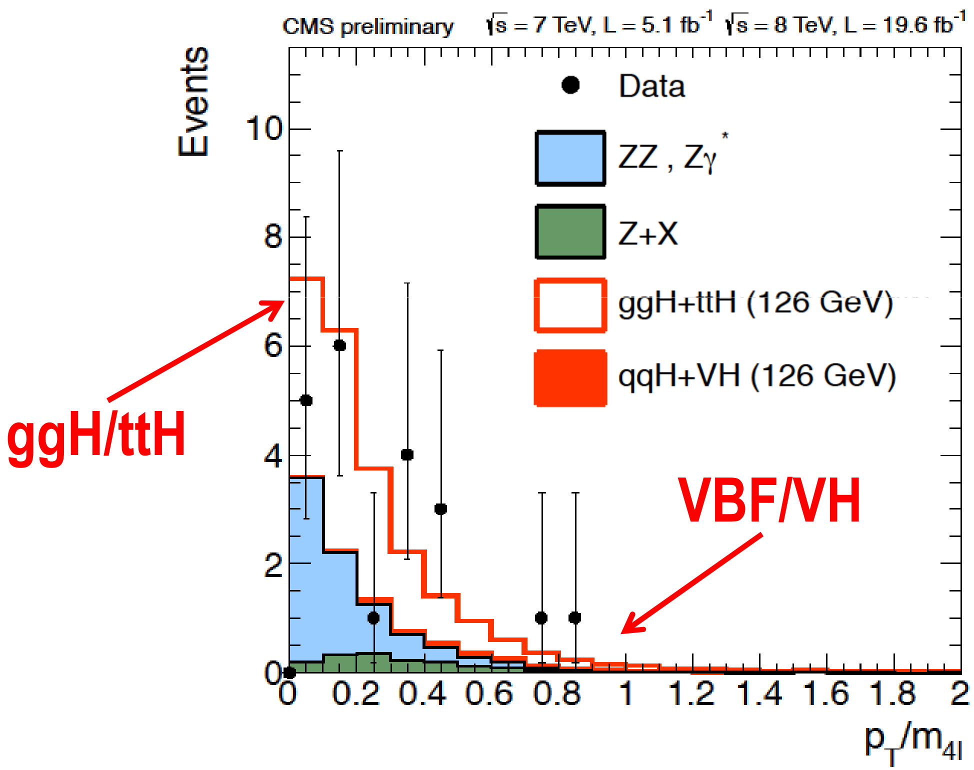
…and increase sensitivity to production mechanisms

➢ **Split events into 2 categories [since Moriond '13] :**

- **Di-jet Tagged (>=2 jets)**
  Use Fisher Discriminant VD (m_{jj}, $\Delta\eta_{jj}$)
  (VBF fraction~20%)

- **Un-tagged (0/1 jet)**
  Use pT_{m4l}/m_{4l}
  (VBF fraction~5%)



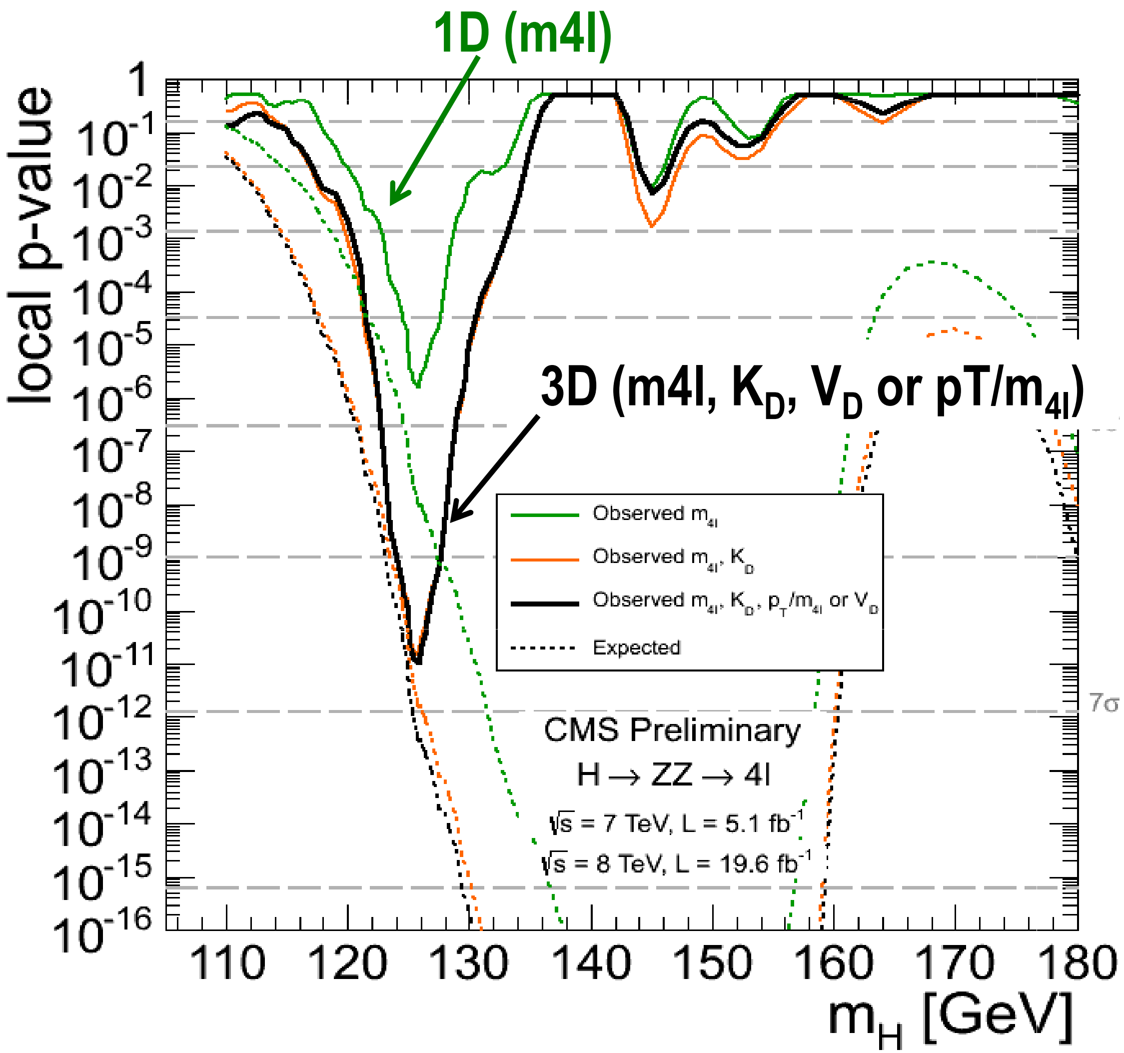


Distributions in 121.5<m4l<130.5 GeV range

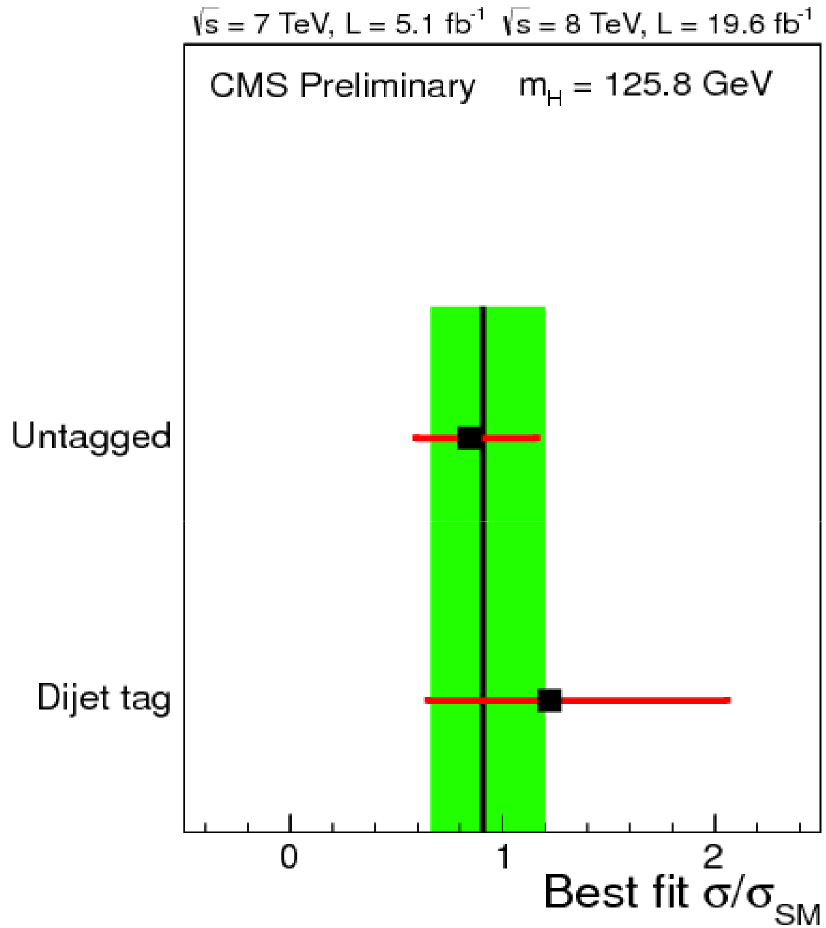
H→ZZ →4l: Results

Significance @ 125.8 GeV: 6.7 σ (7.2 expected)
with 3D (m_{4l}, K_D, V_D or pT/m_{4l}) model

Consistent (but better) wrt 2D (m4l, KD) or 1D (m4l) models.

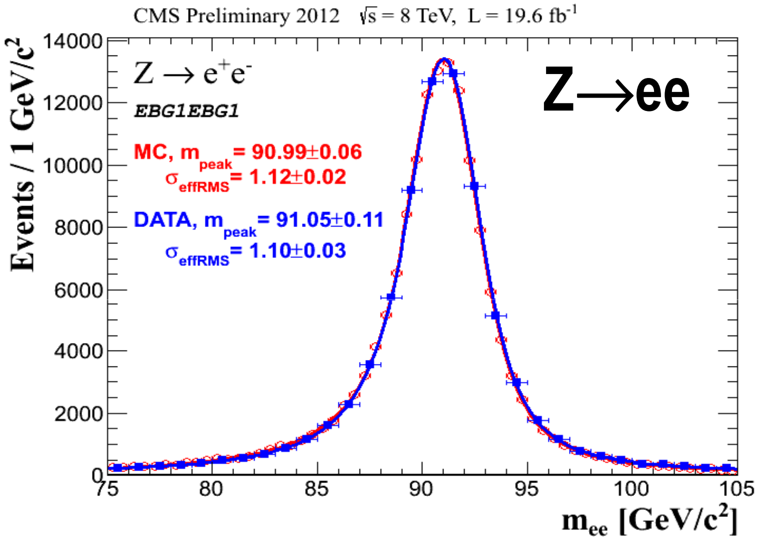


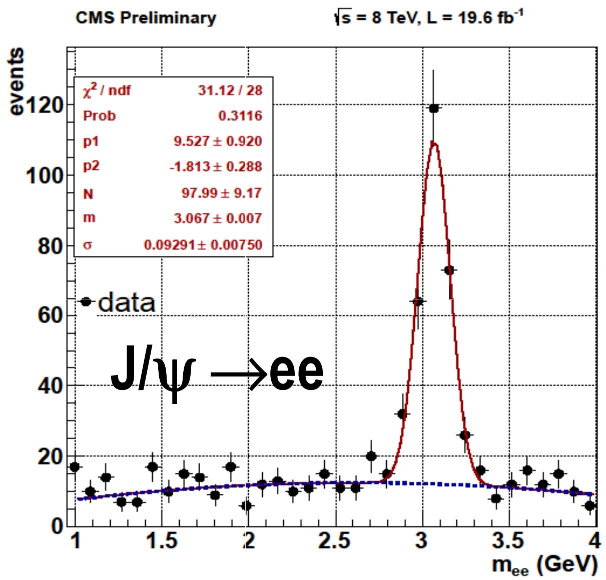
σ/σ_{SM} @ 125.8 GeV = $0.91^{+0.30}_{-0.24}$

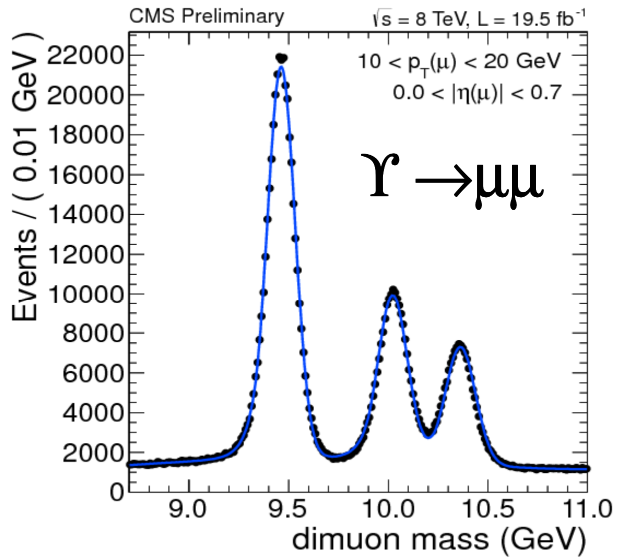


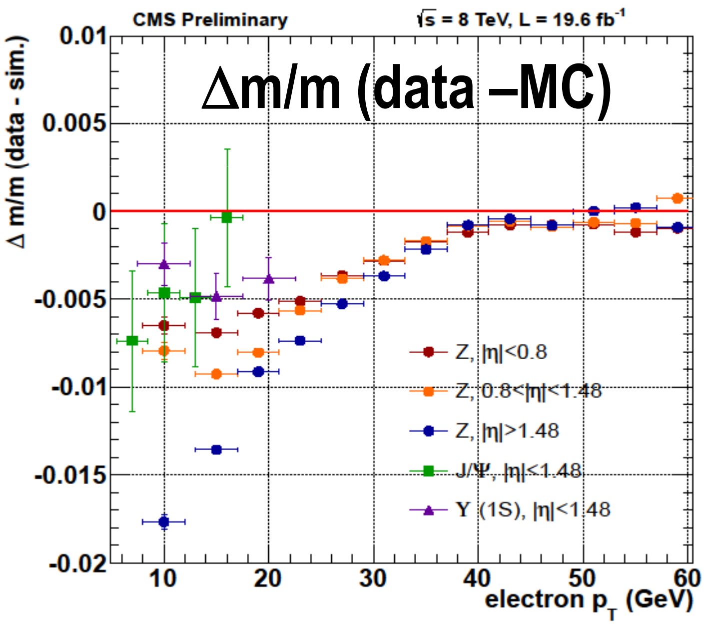
Mass measurement: Lepton Momentum Scale & Resolution

Electron/Muon scale & resolution validated with Z, J/ψ & ϒ→ll

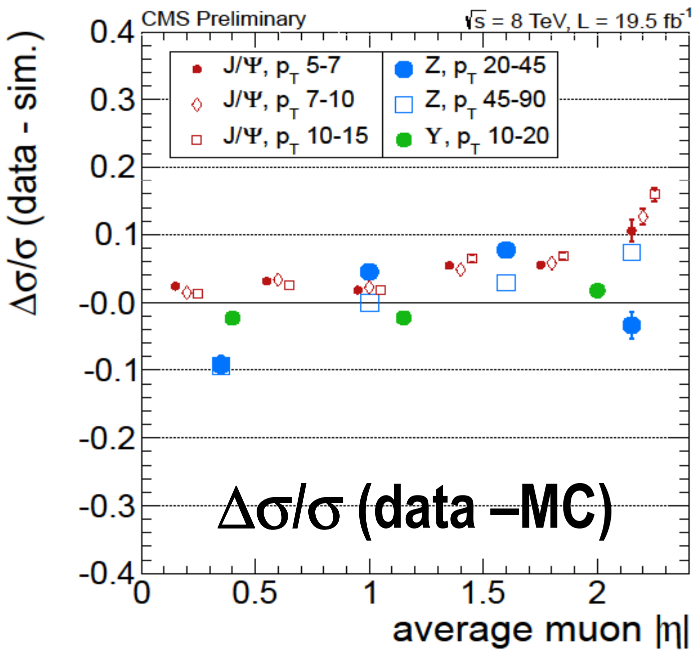








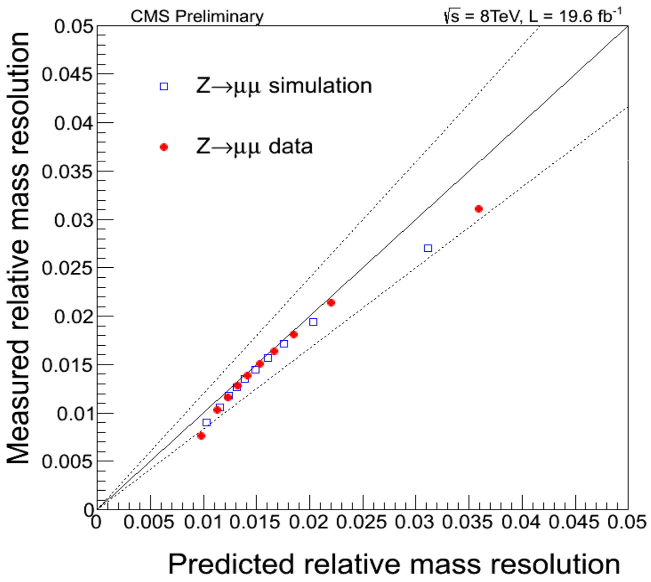
- Data/MC agrees:
  - on the μ-scale within 0.1%
  - on the e-scale within ~0.2% (high pT, barrel) to 1.5 % (low pT, endcaps)
- Data/MC agrees on the resolution within < 10%.

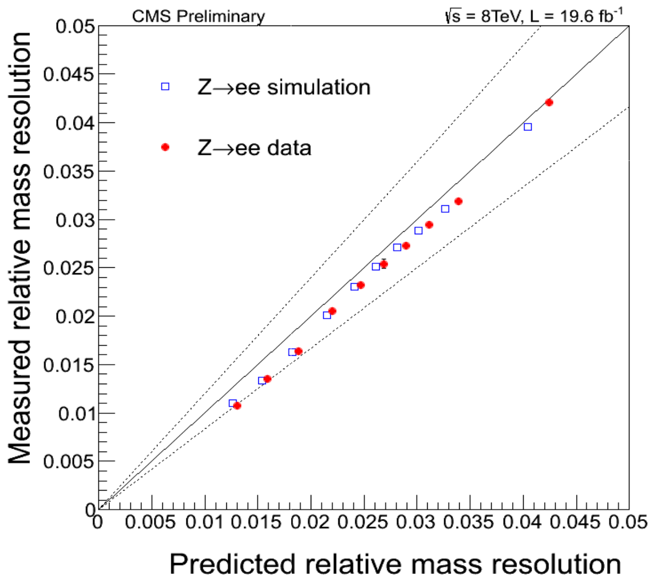


Mass measurement: per-event m4l uncertainty

➢ **m4l uncertainty used on a per-event basis to increase the precision on the mass measurement**

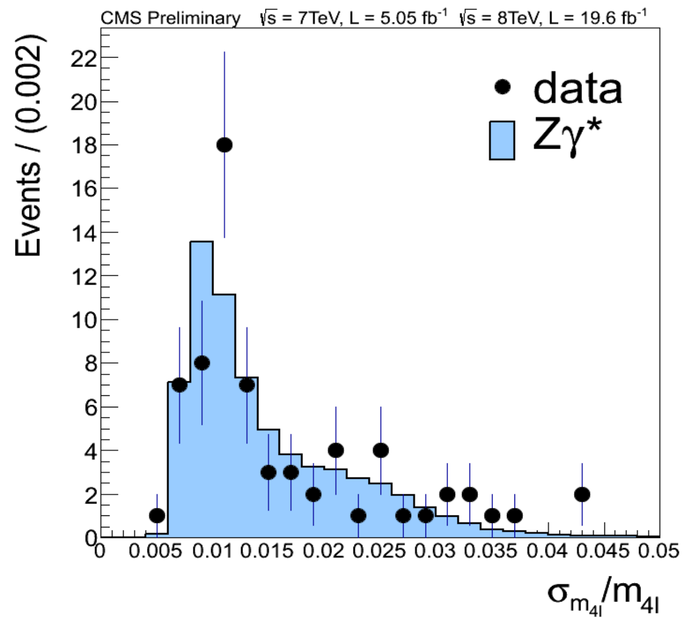
➢ Per-lepton momentum uncertainties are calibrated & validated using $Z\to ee$ & $Z\to\mu\mu$



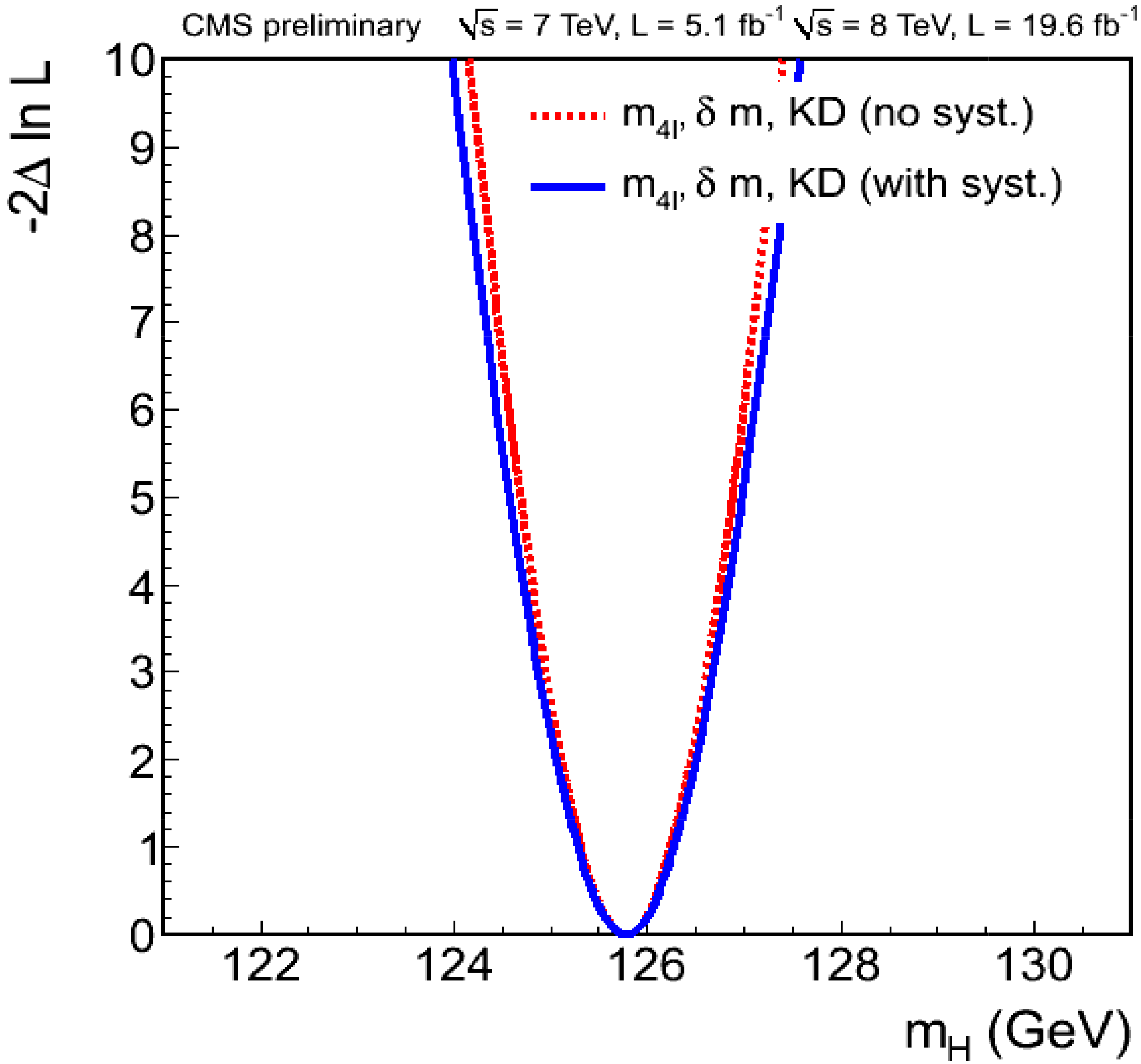


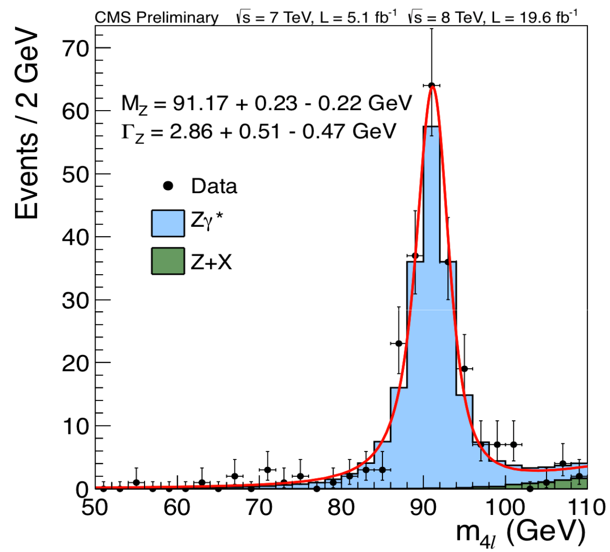
Agreement between predicted & measured mass resolution within 20%

➢ Relative m4l mass uncertainty in good agreement between data & MC for various control regions: $Z\to 4l$, ZZ, Z+X (fakes).



Mass measurement with H→ZZ →4l





- Z→4l used to validate 1D mass measurement
- Good agreement between measured & PDG values

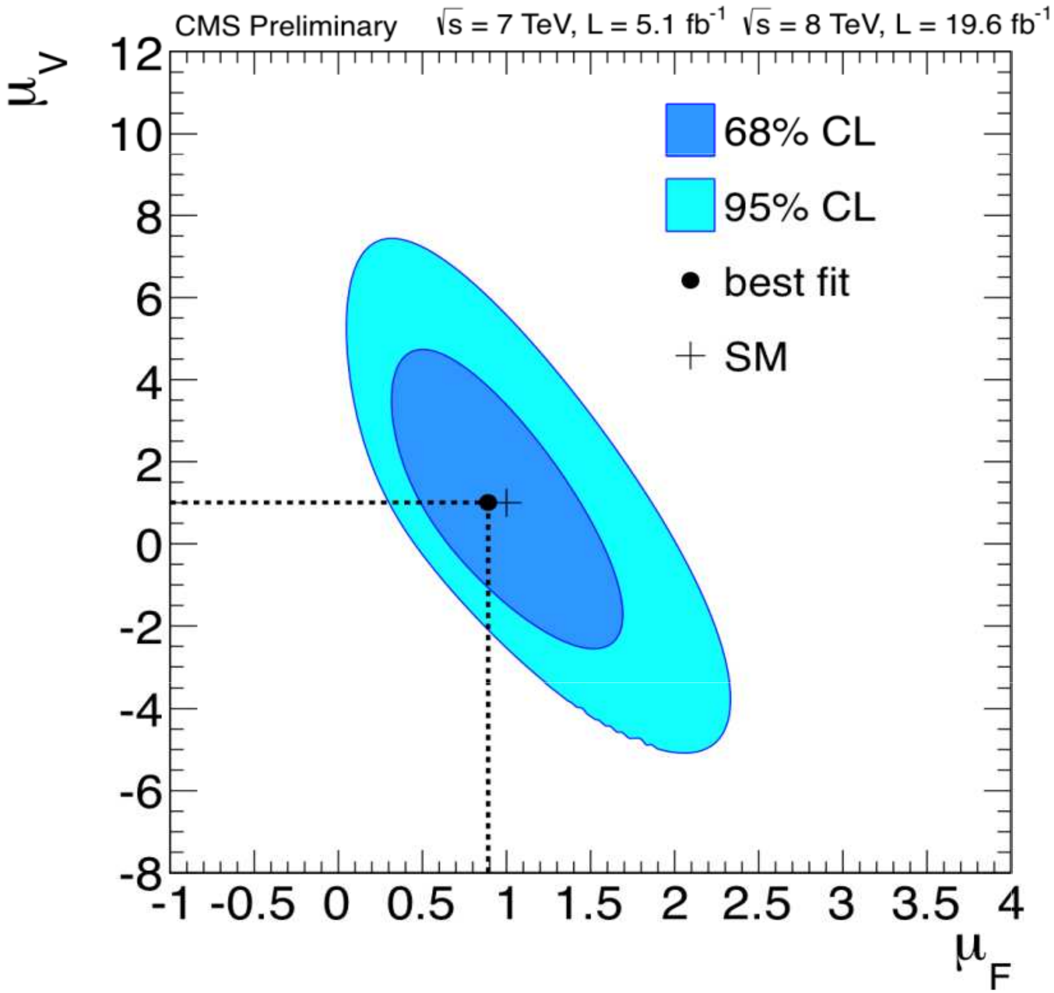
- **m4l uncertainties due to lepton scale: 0.1% (4μ), 0.3% (4e)**

- **3D model (m4l, KD, per-event m4l uncertainty)**

$m_H = 125.8 \pm 0.5$ (stat.) ± 0.2 (syst.)

Production Mechanisms

Measurement of signal strengths for production mechanisms associated with either top (ggF+ttH) or gauge (VBF+VH) couplings



$\mu_{qqH+VH} = 1.0^{+2.4}_{-2.3}$

$\mu_{ggH+ttH} = 0.9^{+0.5}_{-0.4}$

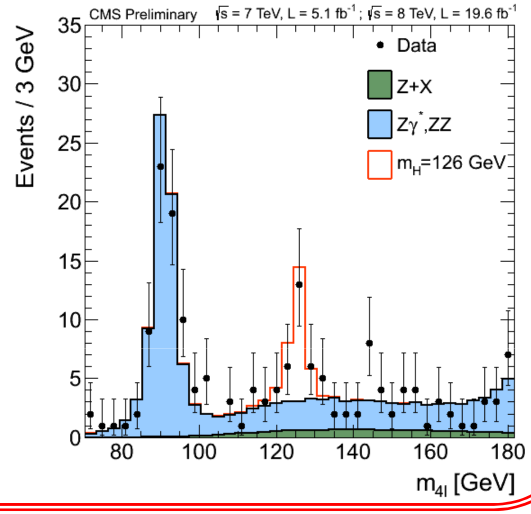
Measurements are compatible with SM expectations

Conclusion

Observation of pp→X→ZZ→4 leptons (e, μ) process at 6.7 σ significance (7.2 expected in case of SM Higgs) with full Run I statistics, with a mass:

mX=125.8 ± 0.5 (stat.) ± 0.2 (syst.)

Obtained exploiting3D model using m4l, kinematics and categorization sensitive to production mechanisms.



Measurement of properties (@125.8):

- "Cross-section" (relative to SM Higgs): $\sigma/\sigma_{SM} = 0.91^{+0.30}_{-0.24}$
- Production Mechanisms: $\mu_{qqH+VH} = 1.0^{+2.4}_{-2.3}$ $\mu_{ggH+ttH} = 0.9^{+0.5}_{-0.4}$
- Spin-Parity quantum numbers: **see Roberto's talk.**

So far, all measurements compatible with the production of SM Higgs boson (but still statistically limited)

BACK UP

SLIDES

CMS Results

New $H \to VV$ results for Moriond '13:

- $H \to \gamma\gamma$: **CMS-HIG-13-001**
- $H \to ZZ \to 4l+2l2\tau$: **CMS-HIG-13-002**
- $H \to WW \to 2l2\nu$: **CMS-HIG-13-003**
- $H \to Z\gamma$: **CMS-HIG-13-006**
- $WH \to WWW$: **CMS-HIG-13-009**

All CMS Higgs public results:

https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsHIG

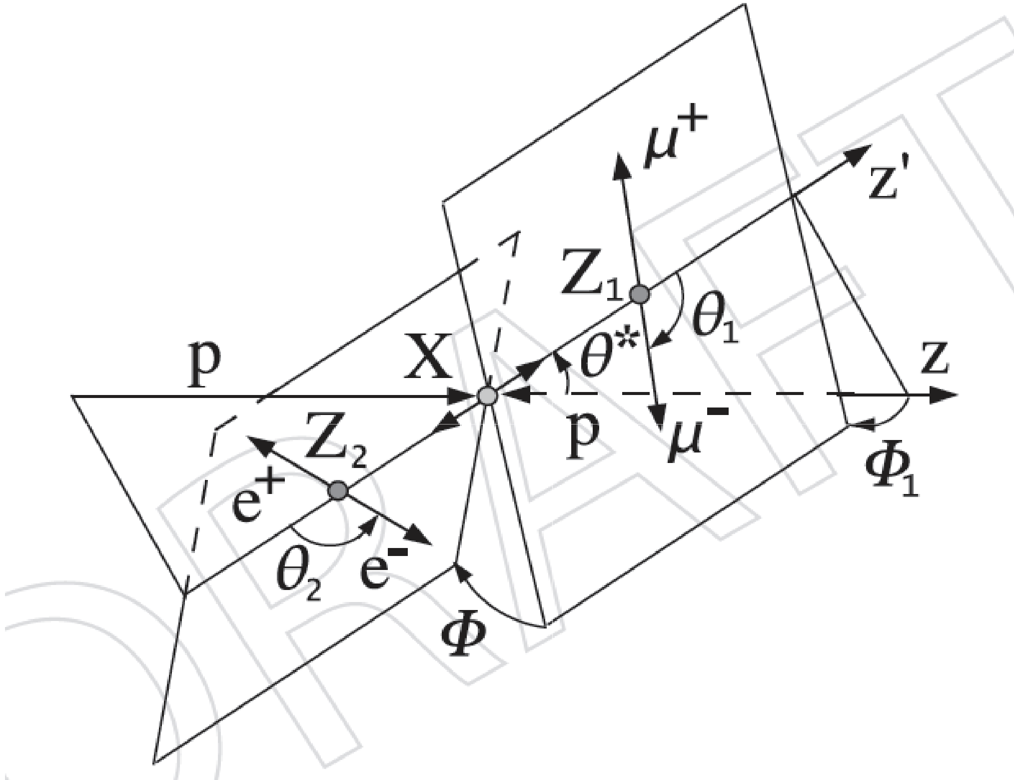
Angles

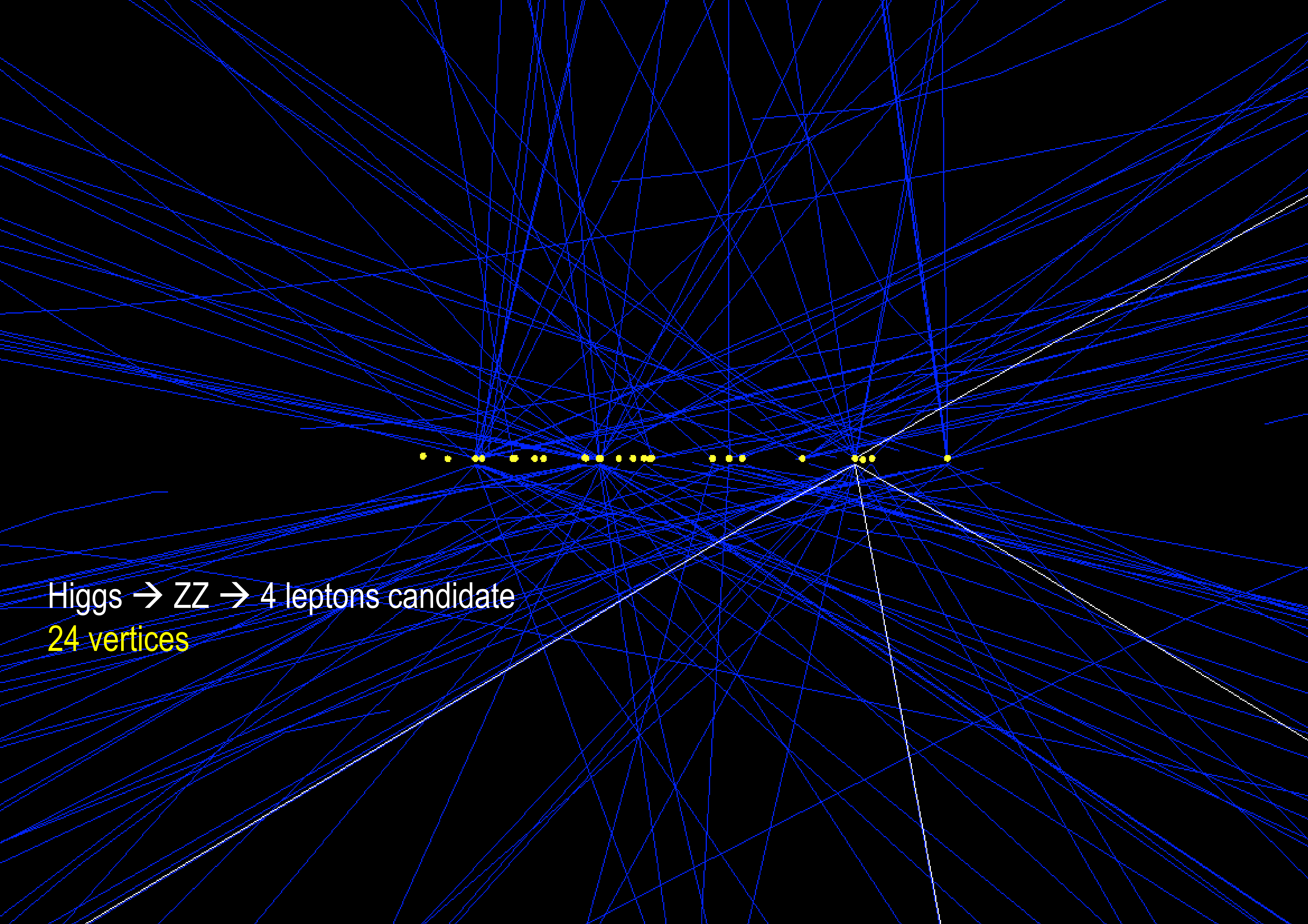
θ^*: angle between the parton collision axis z and X->ZZ decay axis z' (in X rest frame)

Φ_1: angle between zz' plane and plane of Z_1->ff (in X rest frame)

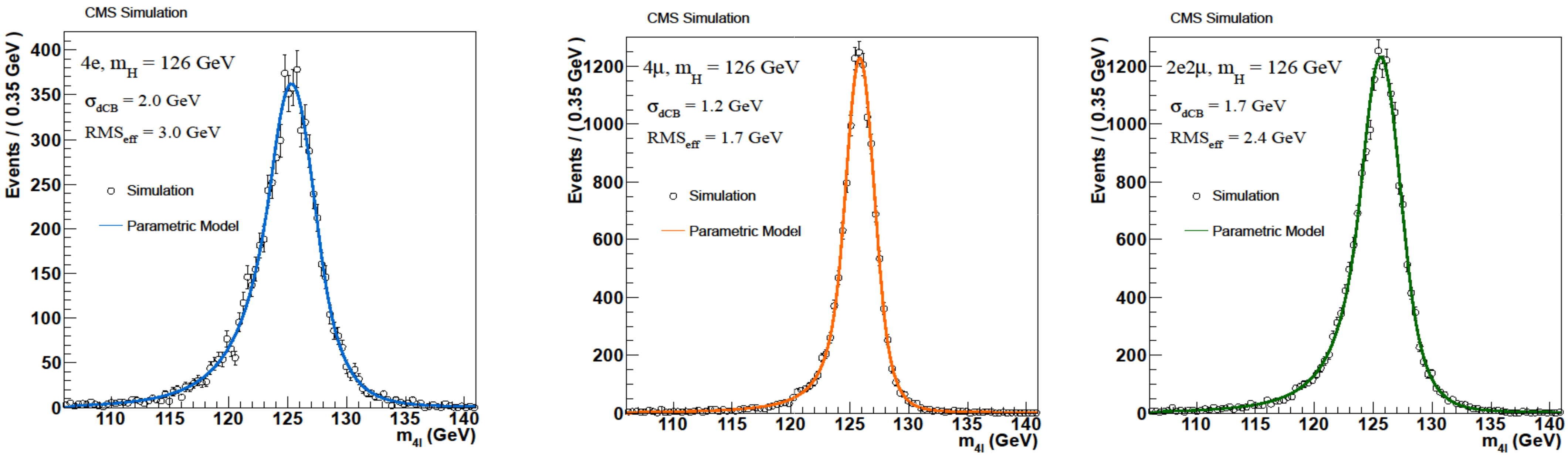
θ_i: angle between direction of fermions fi from Zi->$f_i f_i$ and direction oposite the X in the Z_i rest frame (i=1,2 for the first and second Z)

Φ: angle between the decay planes of the two Z systems (in X rest frame)




Higgs → ZZ → 4 leptons candidate
24 vertices

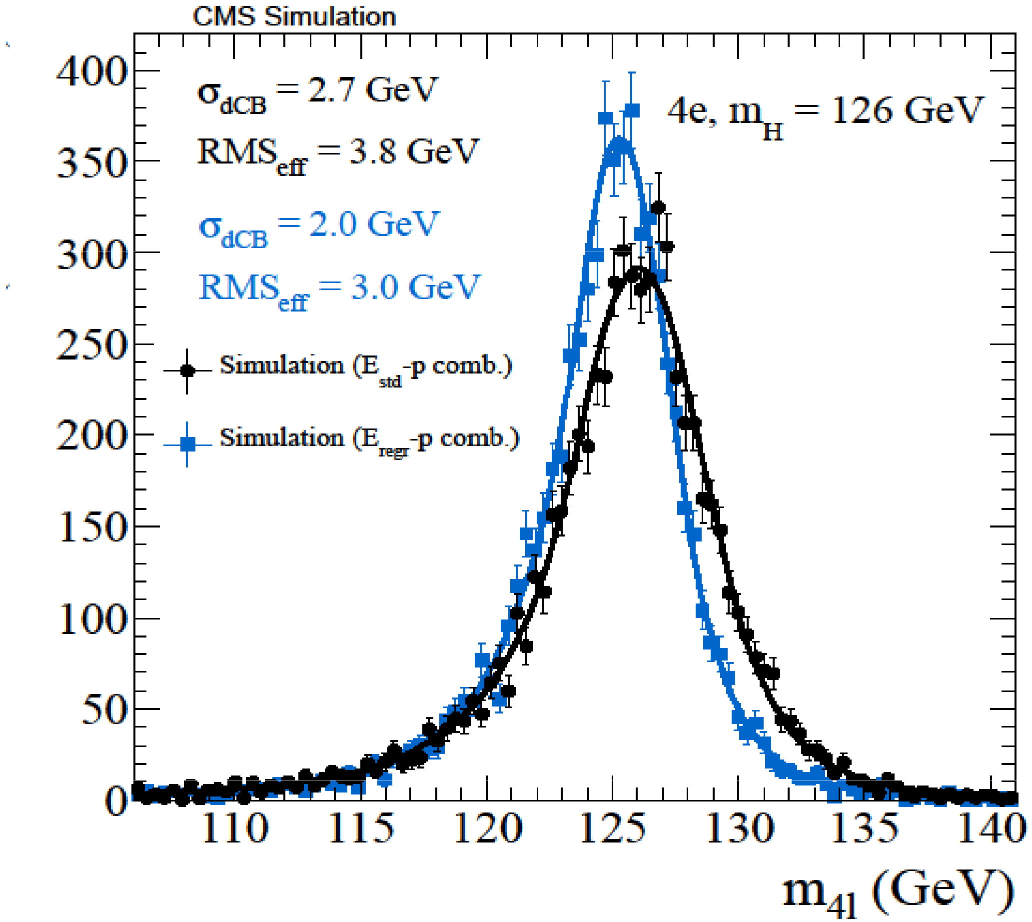
H→ZZ →4l: Signal Model

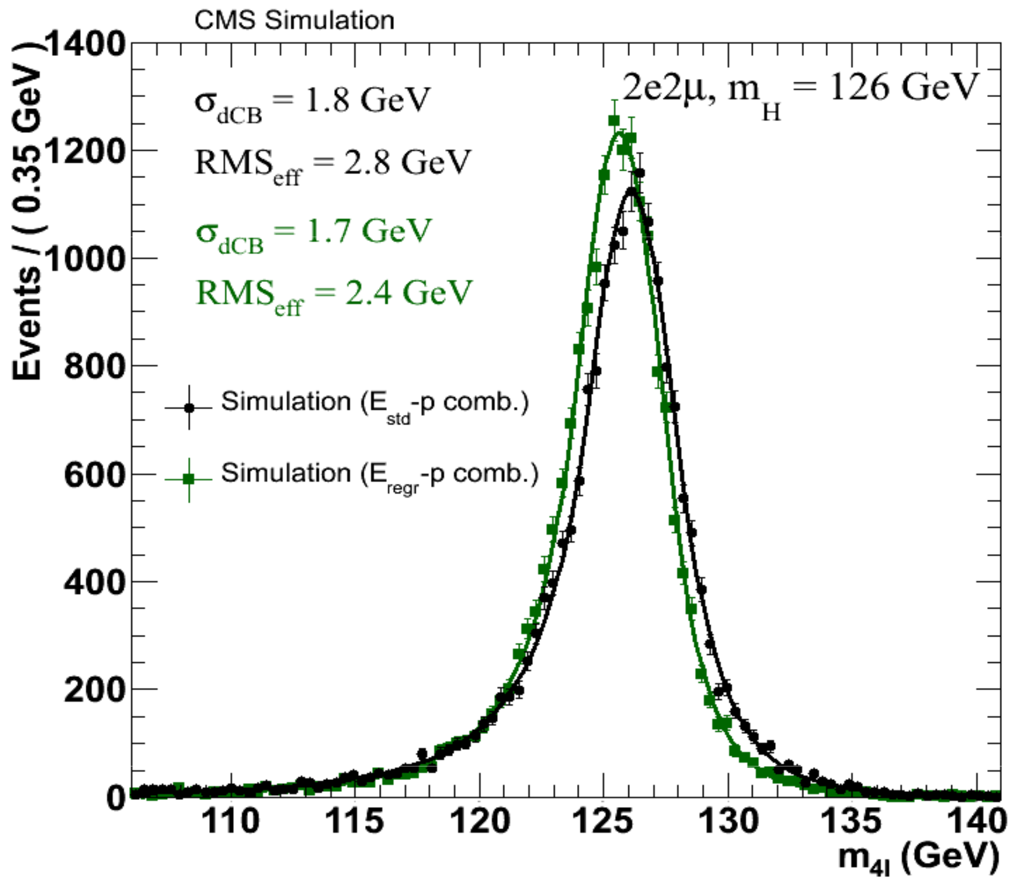


- m4l parametric model for signal: Breit-Wigner convoluted with double-sided Crystal Ball

- MC: POWHEG (ggH, VBF), Pythia (associated production=)
  - low mass: narrow width approximation
  - high mass:
    - line shape corrected to match complex-pole scheme.
    - Interference between ggH and ggZZ are taken into account.

H→ZZ →4l: Resolution improvement





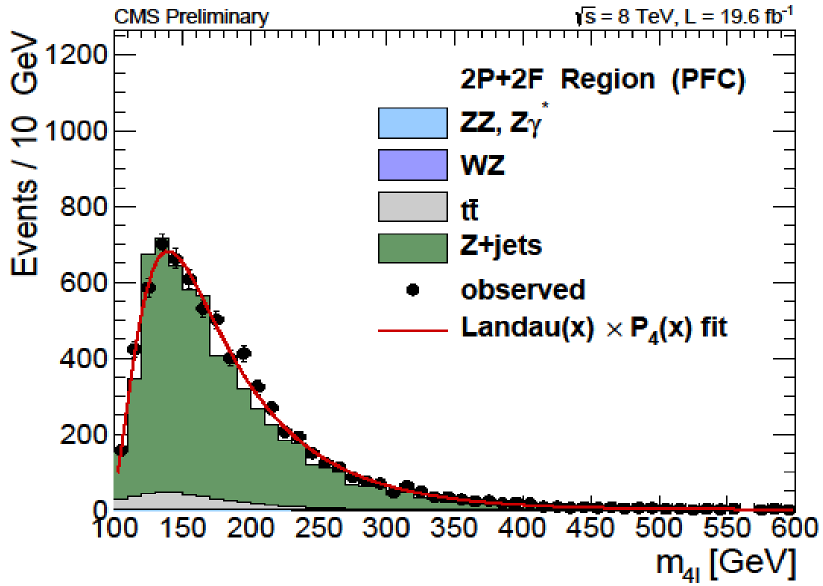
H→ZZ →4l: Background Control

➢ **qq/gg→ZZ**: from MC (POWHEG & gg2zz)

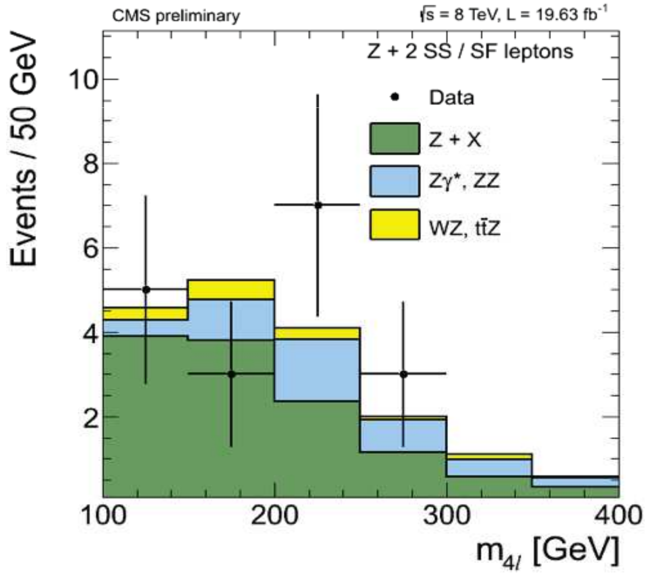
➢ **Reducible (Z+jets, tt, WZ,…):** from DATA.

- 2 "fake rate" methods:

- **Method A:**
  - Control Regions:
    - Z1+2 OS-SF "failing" leptons (2P2F, 2 "prompt" + 2 failed")
    - 3 prompt + 1 failing leptons (3P+1F):
      - target estimation of background WZ, $Z\gamma^*$, …
  - Extrapolation to signal region: lepton mis-identified probability



- **Method AA:**
  - Control Region (CR):
    - Z1+ 2 SS-SF "loose" leptons
  - Extrapolation to signal region:
    - SS/OS factor from MC, cross-checked with data
    - lepton mis-identified probability (corrected for difference in composition of converted photon between CR & sample to extract misID probability)



Validation in Z+2SS/SF

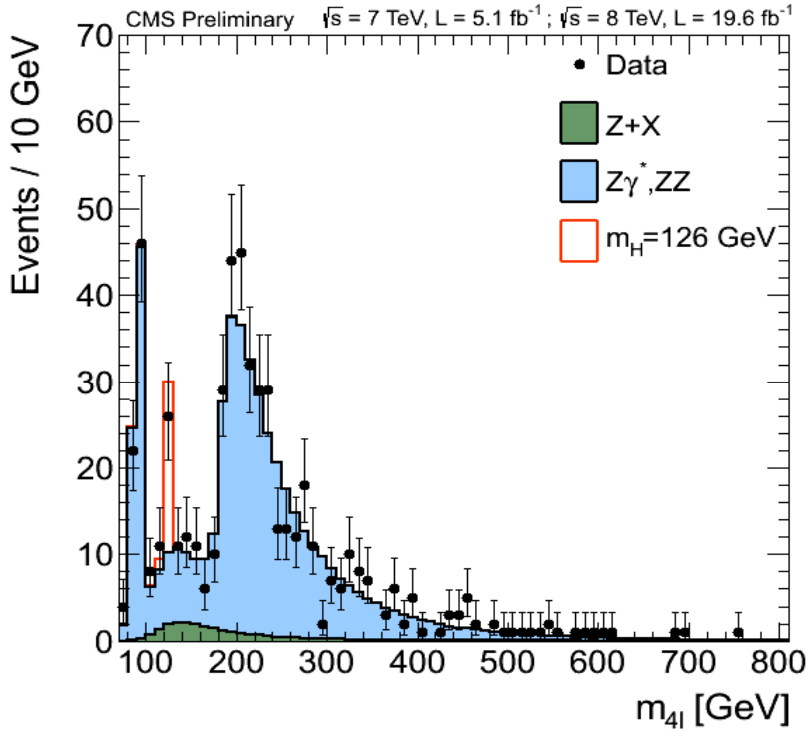
- **Validation:** samples with relaxed charged and/or flavor requirements

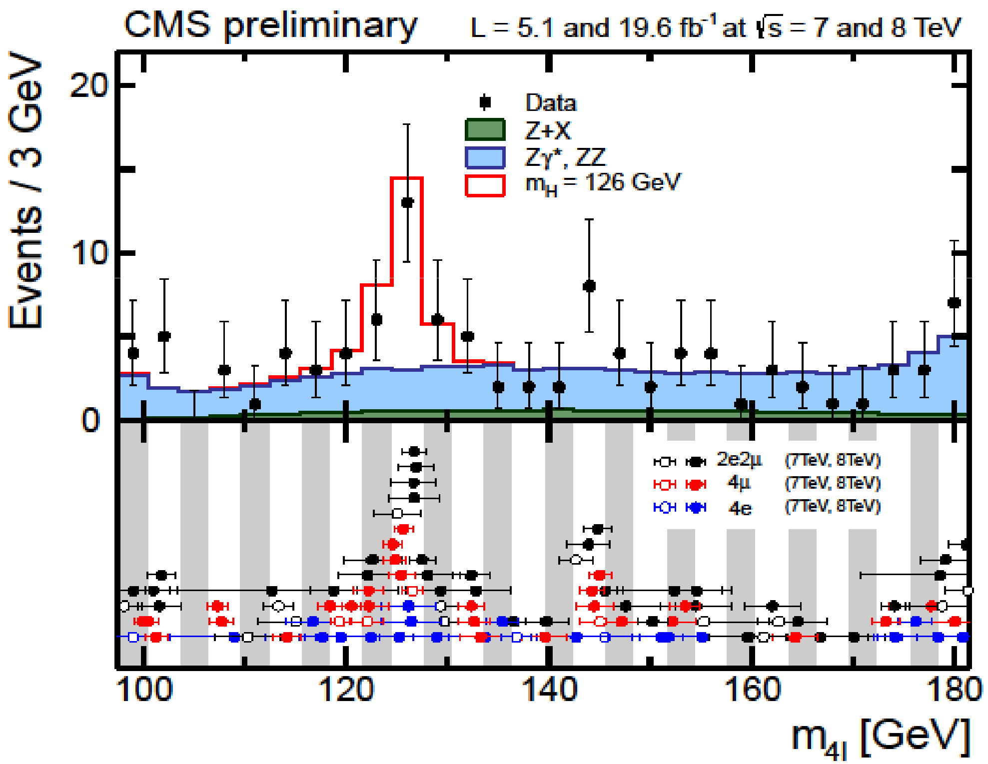
- **Final estimate:** combination of the two methods (yields in control regions & part of the uncertainties un-correlated)

$H \to ZZ \to 4l$: m4l spectrum & tables

110 < m4l < 1000 GeV

Channel	4e	4μ	$2e2\mu$
ZZ background	78.9 ± 10.9	118.9 ± 15.5	192.8 ± 24.8
Z+ X	$6.5^{+2.6}_{-2.6}$	$3.8^{+1.5}_{-1.5}$	$9.9^{+4.0}_{-4.0}$
All background expected	$85.5^{+11.2}_{-11.2}$	$122.6^{+15.5}_{-15.5}$	$202.7^{+25.2}_{-25.2}$
$m_H = 125$ 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
Observed	86	125	240

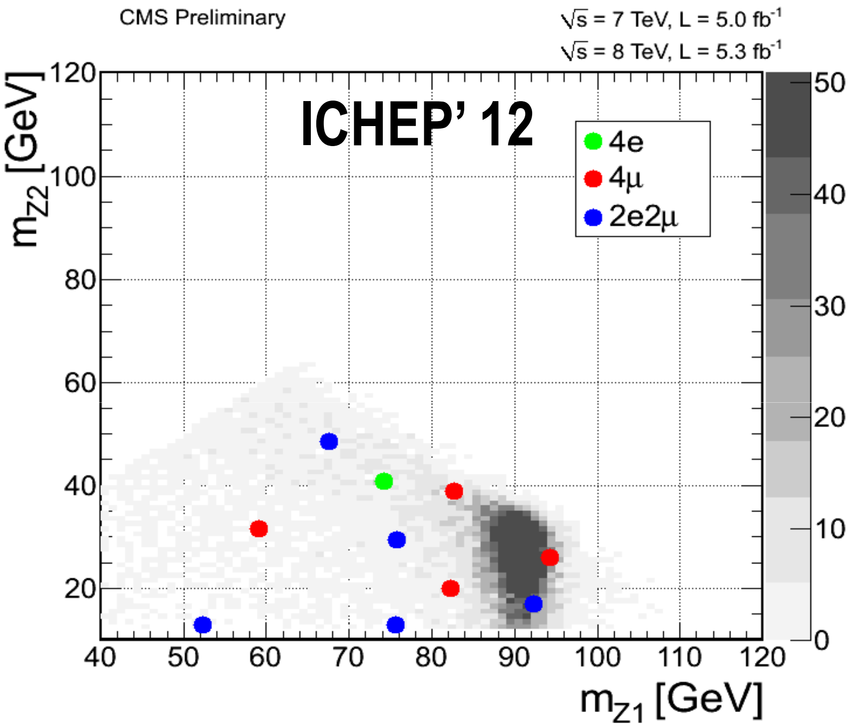


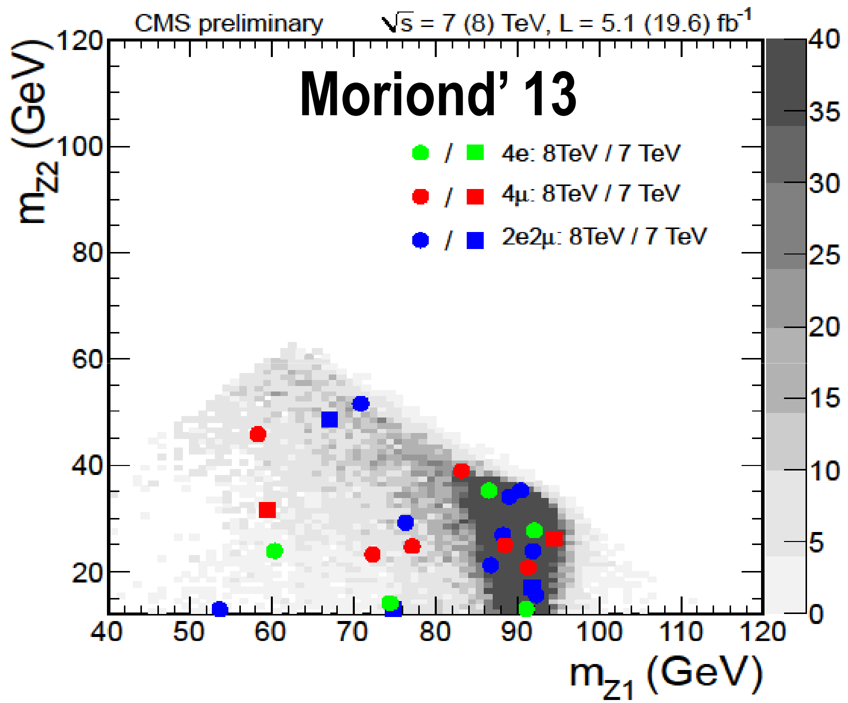


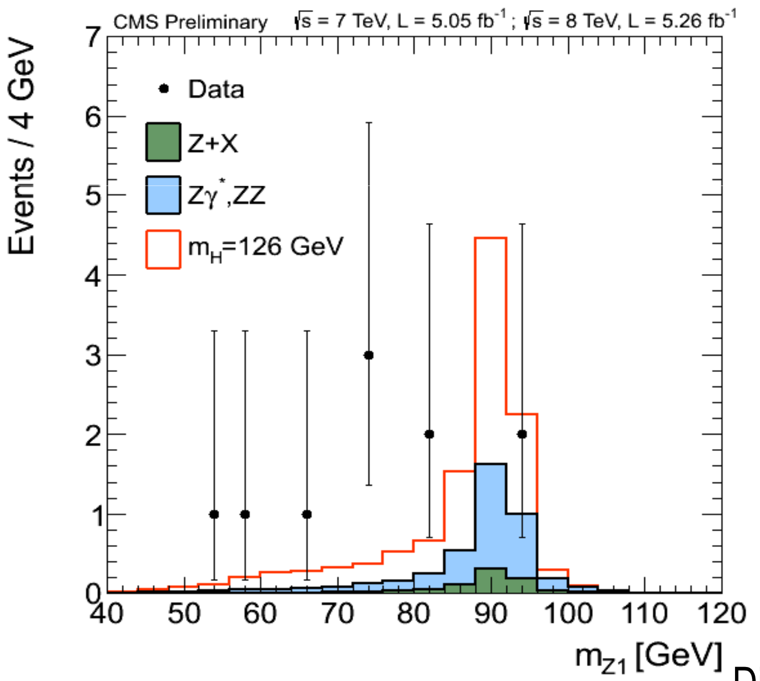
110 < m4l < 160 GeV

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

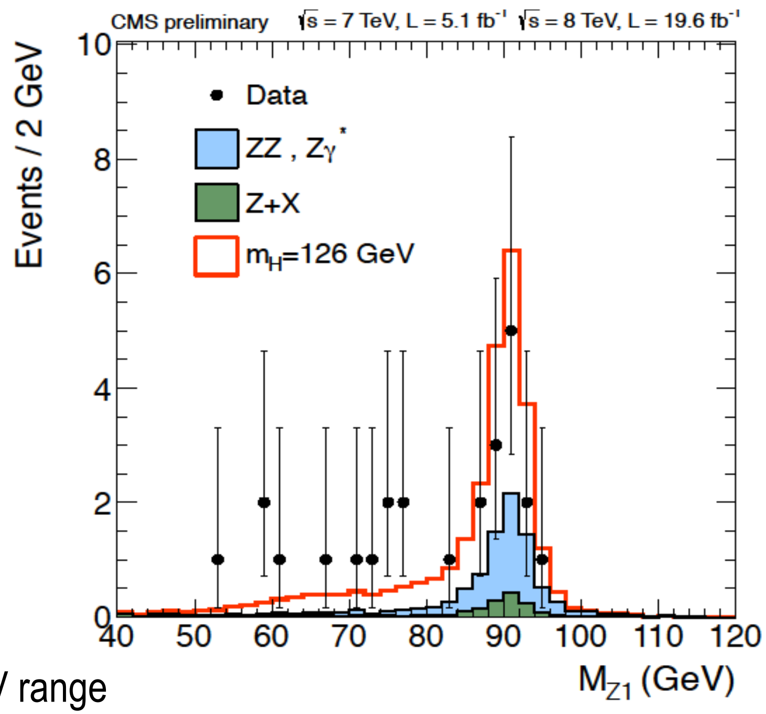
H→ZZ →4l: MZ1 vs MZ2







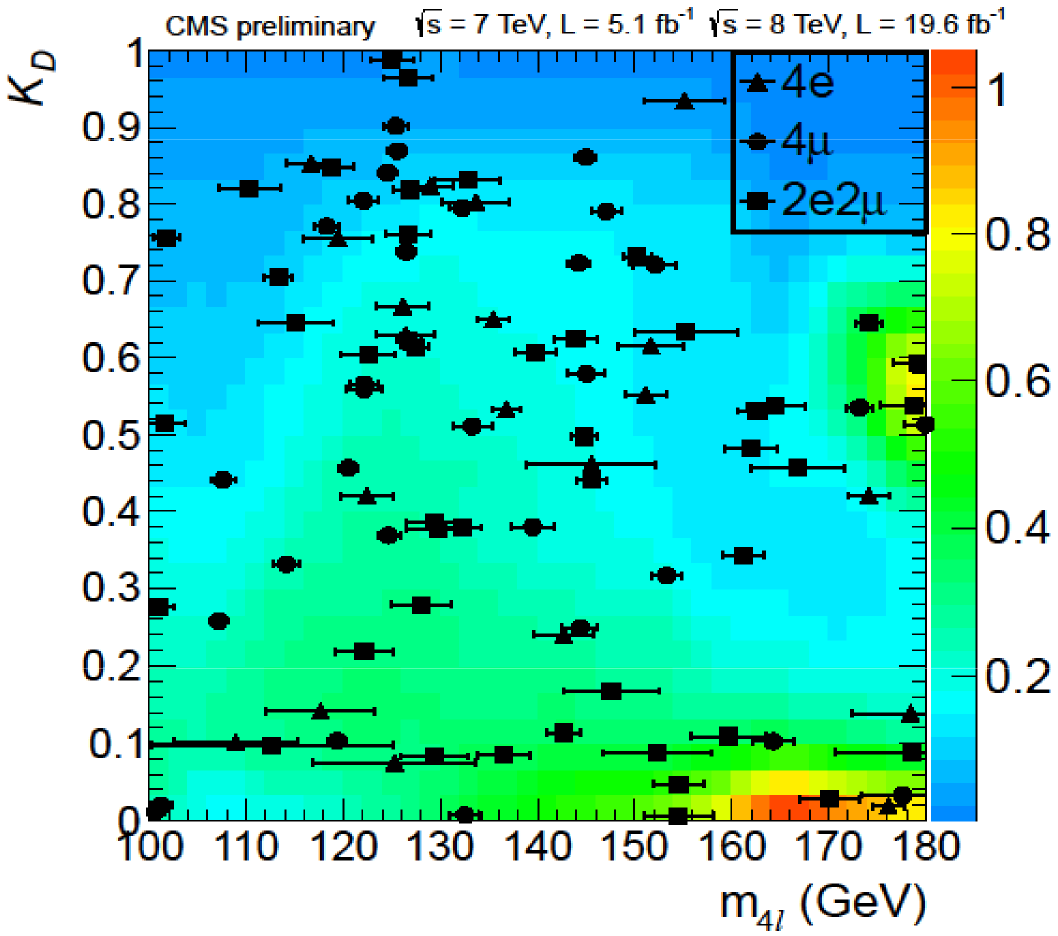
Statistical fluctuation at ICHEP that is filling in…



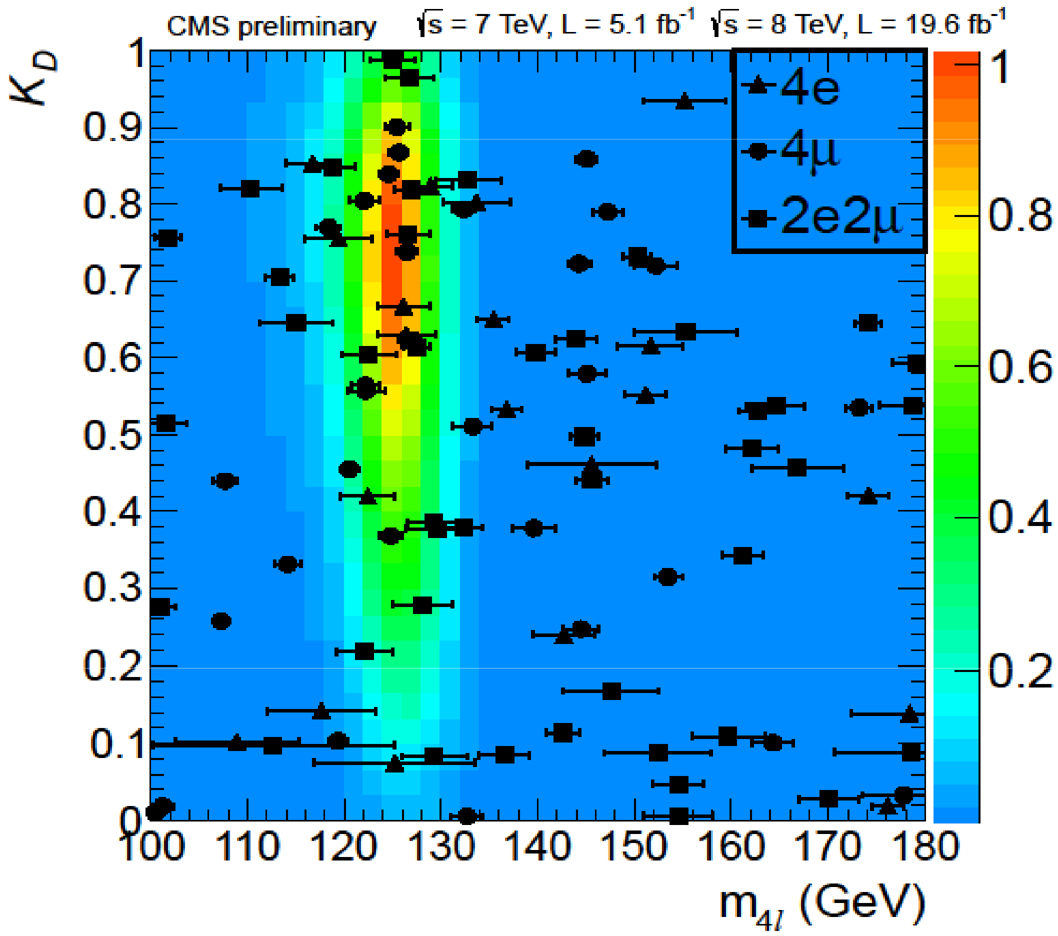
Distributions in 121.5<m4l<130.5 GeV range

$H \rightarrow ZZ \rightarrow 4l$: K_D vs m_{4l}

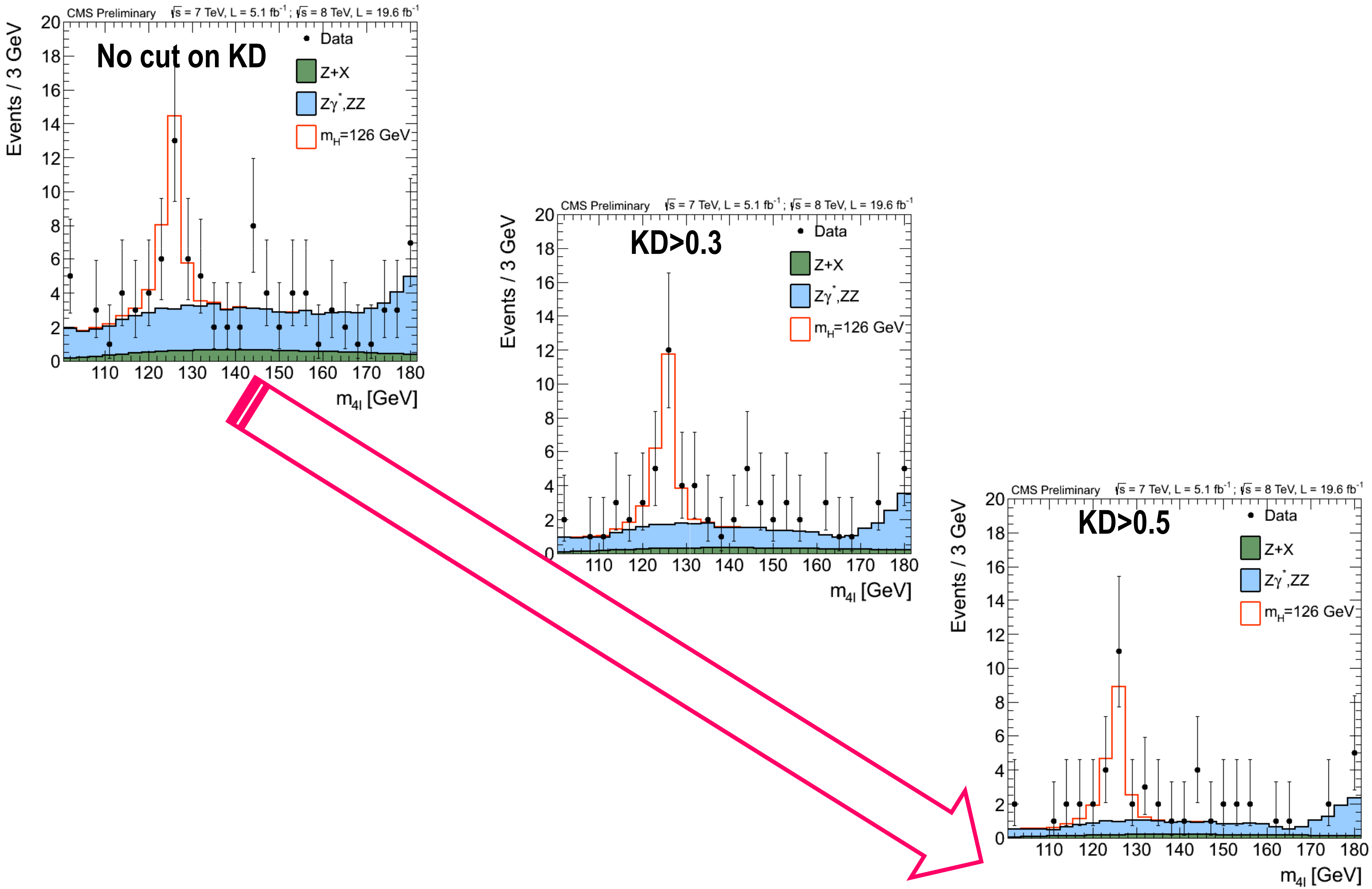
background



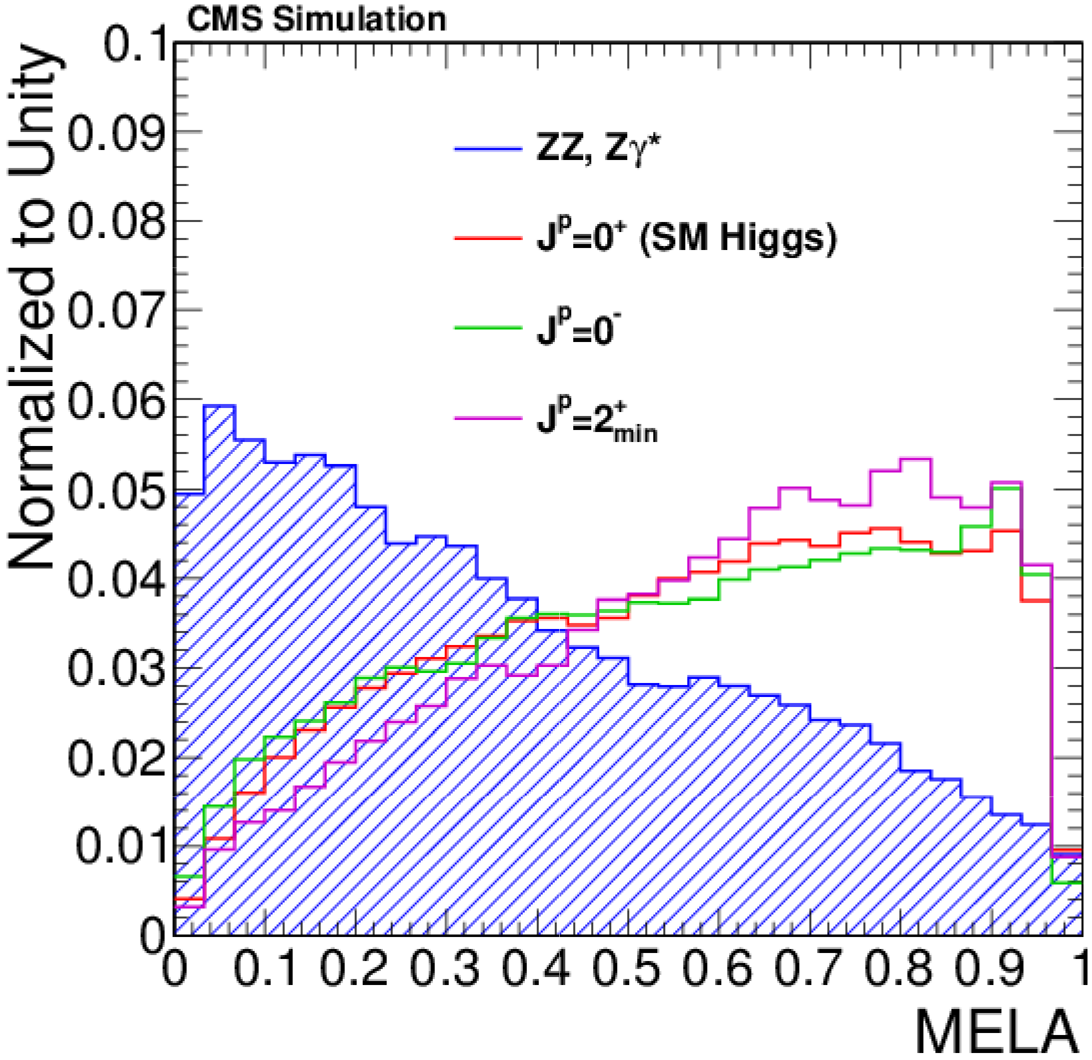
$m_H = 126$ GeV



M4l vs KD cut (for illustration)

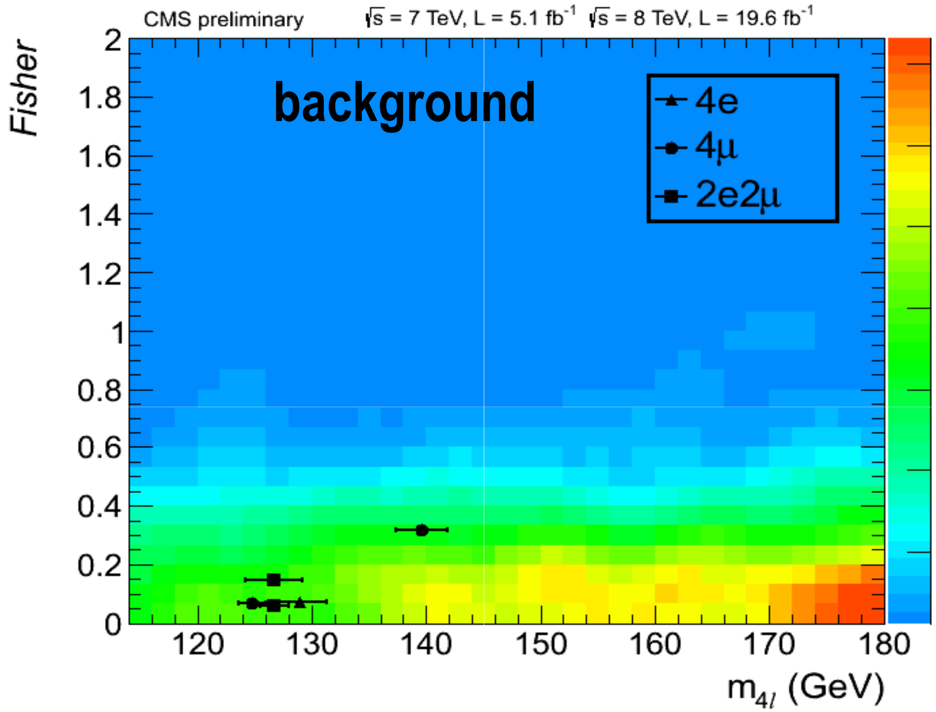


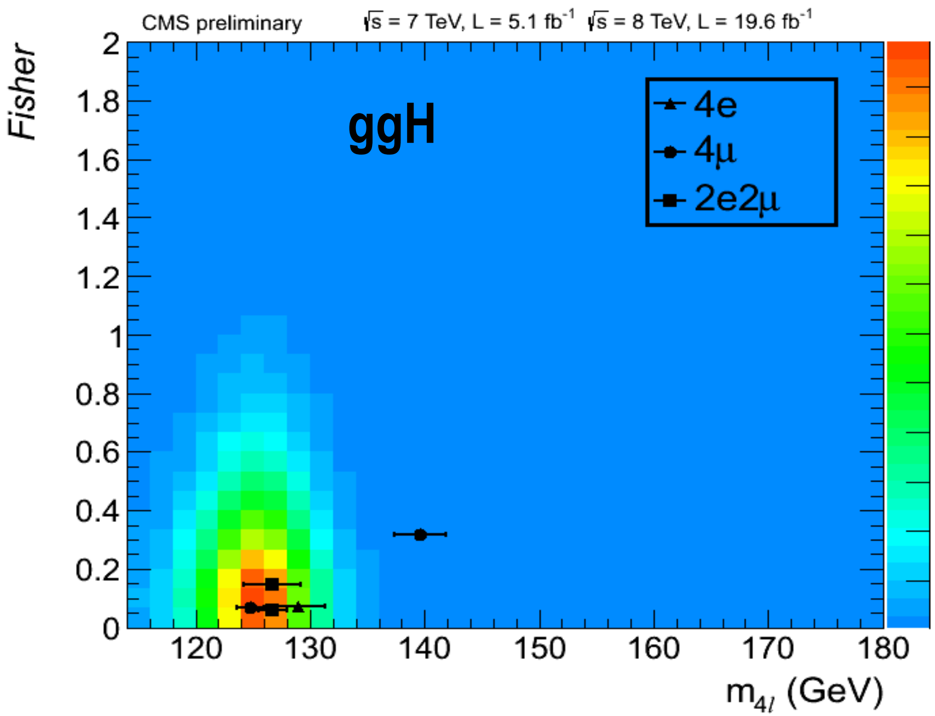
Model (in)dependence

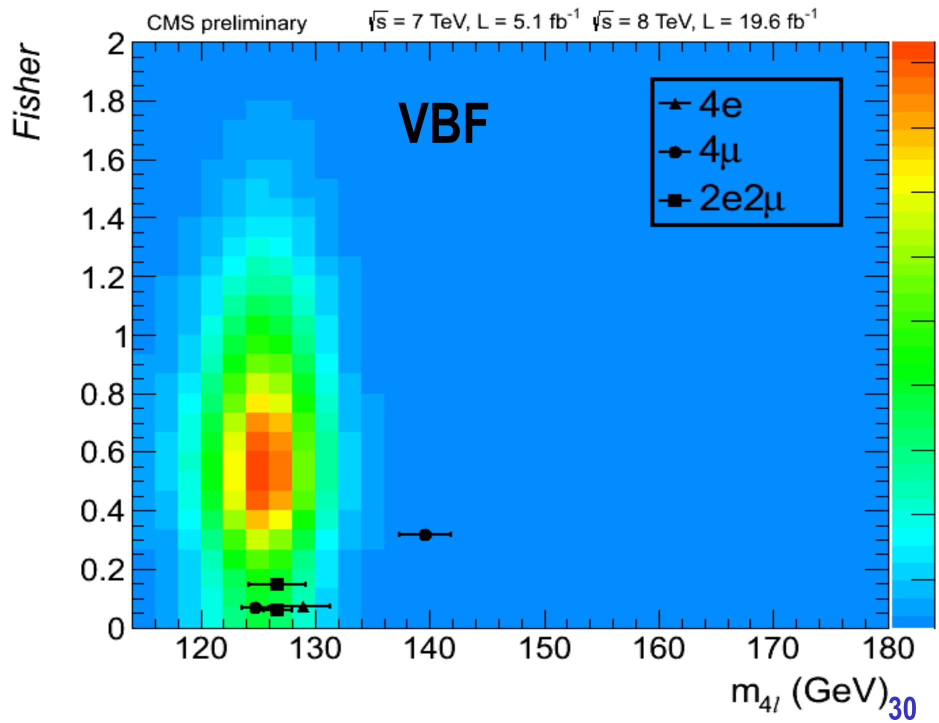


MELA: KD from ICHEP'12

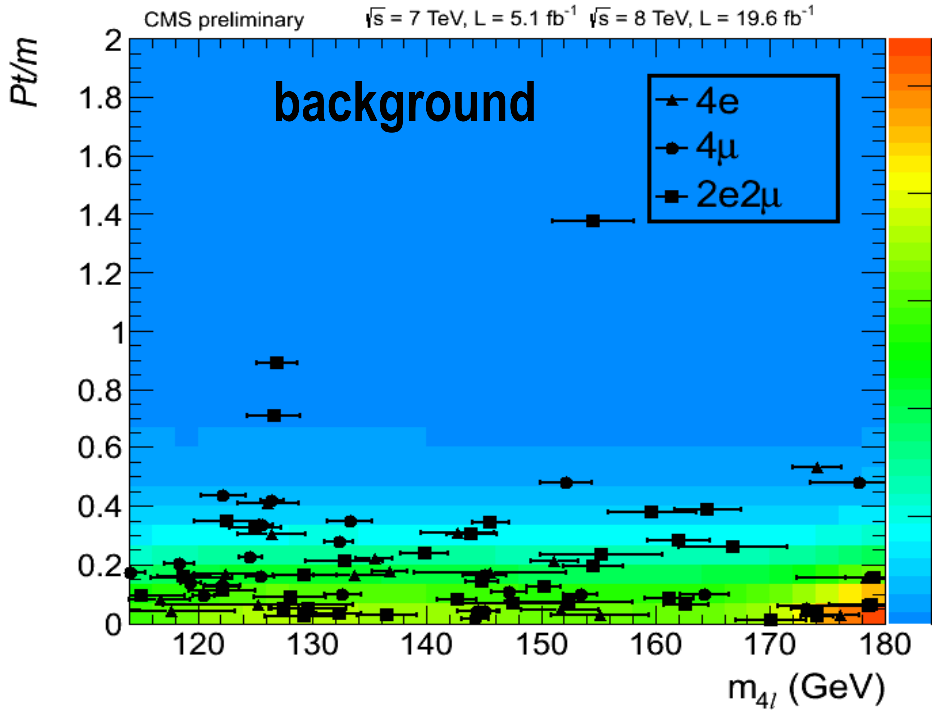
$H \to ZZ \to 4l$: V_D vs m_{4l}

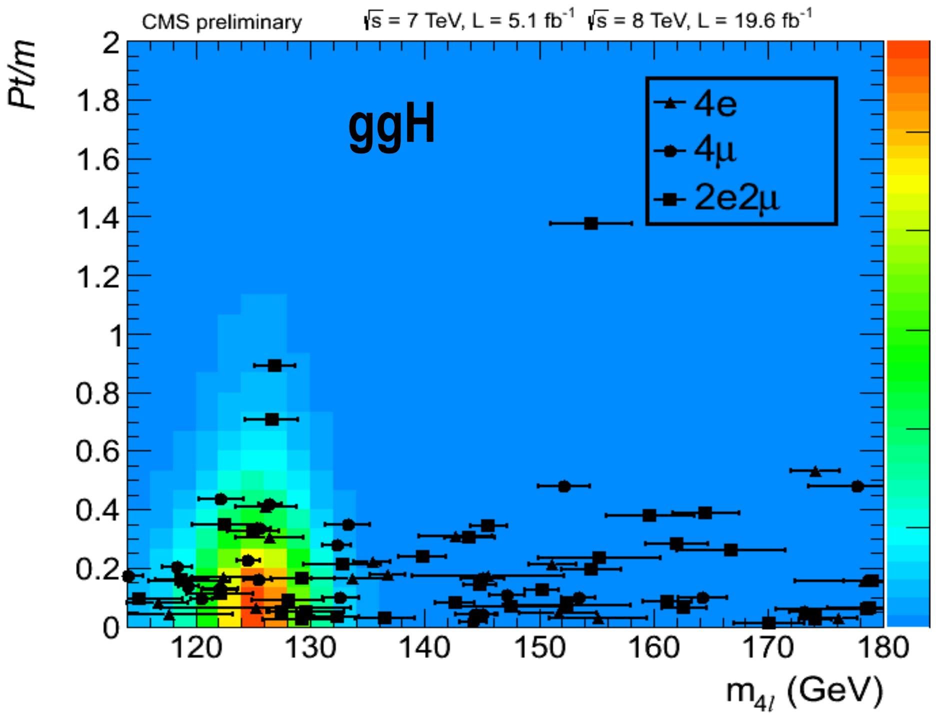


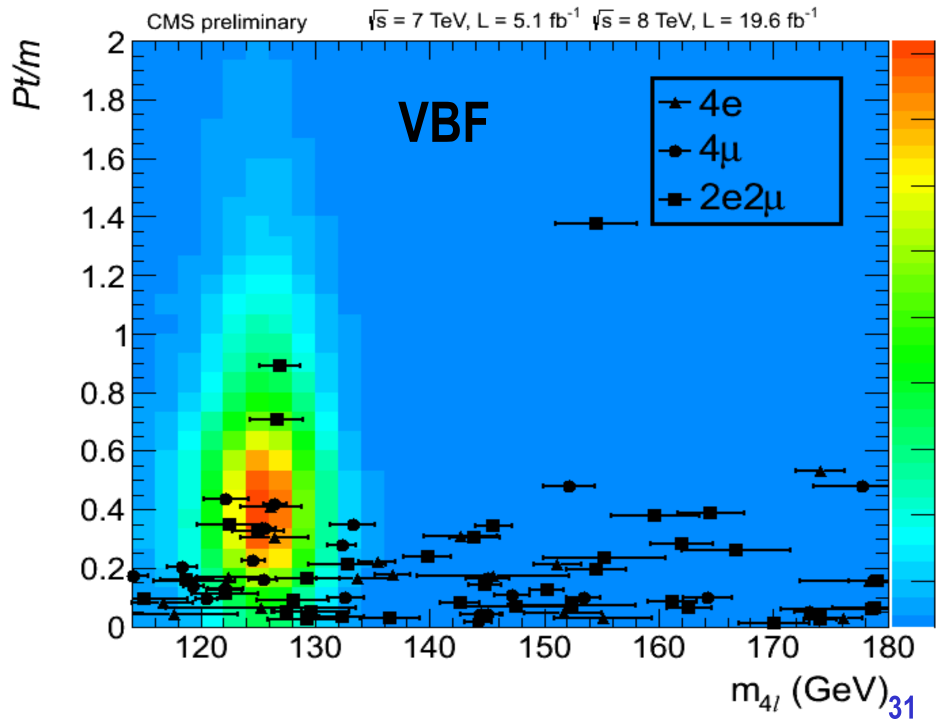




$H \rightarrow ZZ \rightarrow 4l$: p_{Tm4l} vs m_{4l}

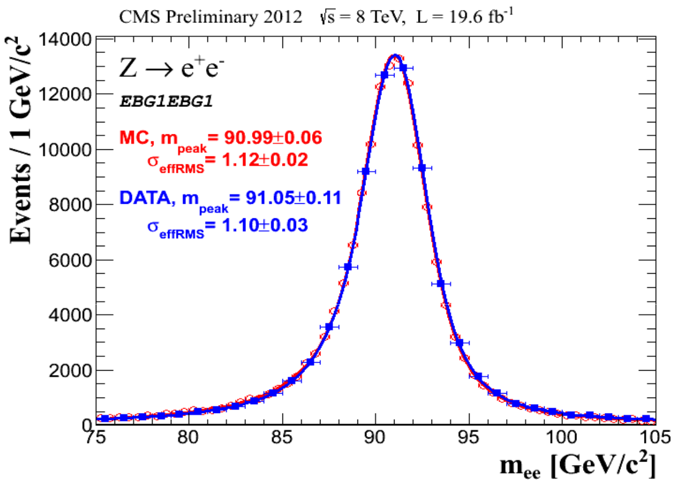


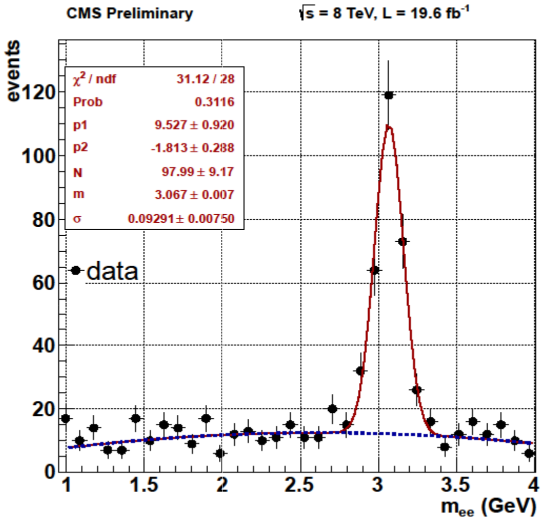


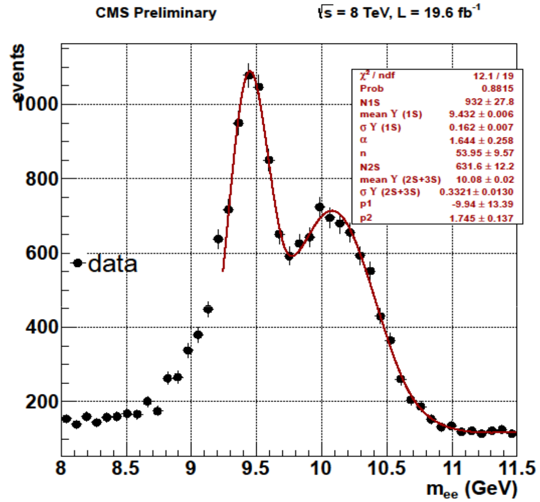


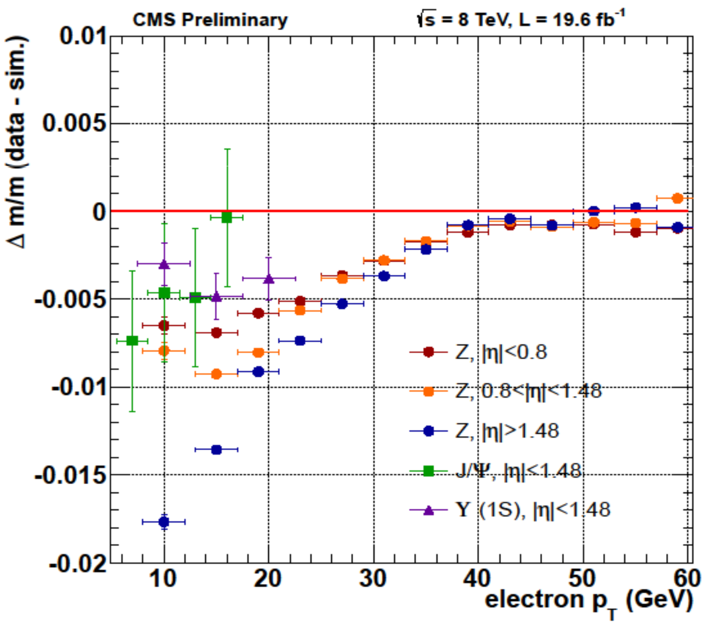
Mass measurement: Electron Momentum Scale & Resolution

Electron scale & resolution validated with Z, J/ψ & ϒ→ee



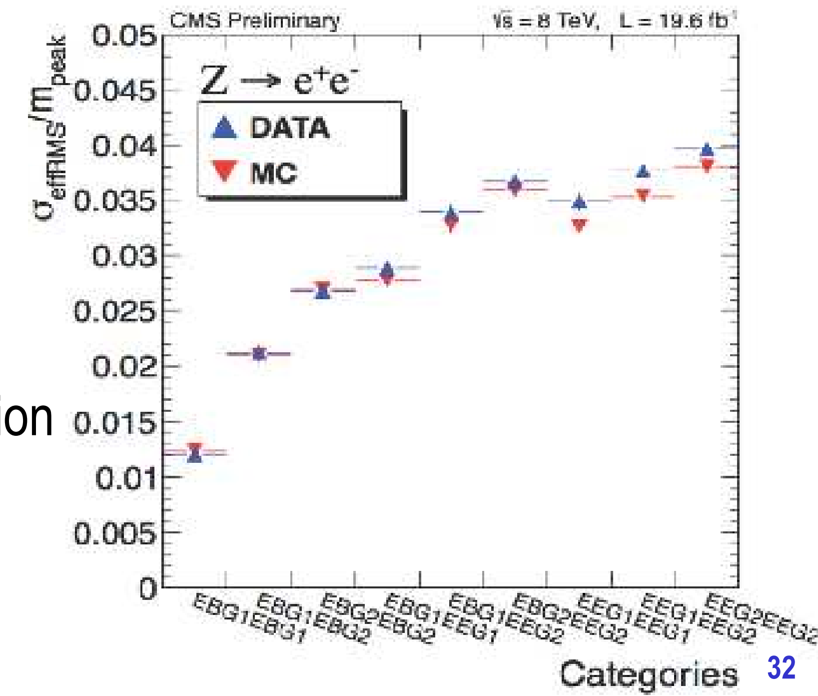




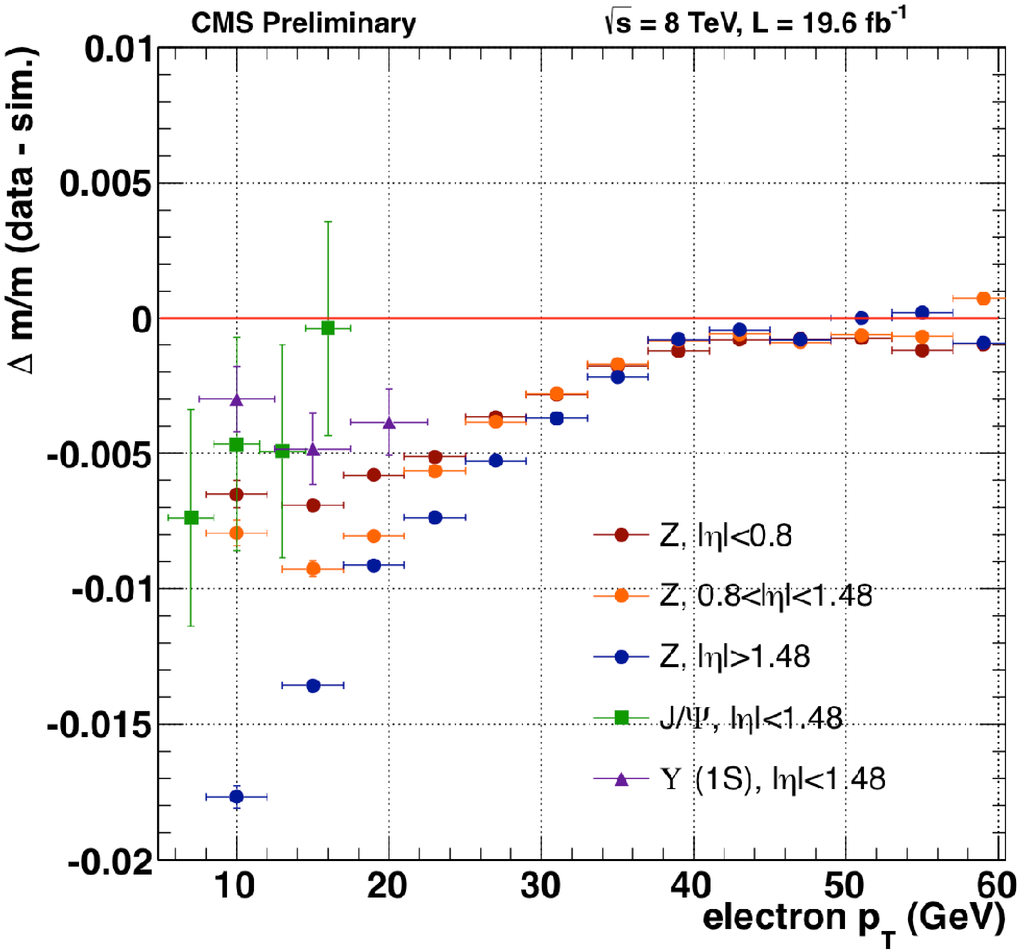


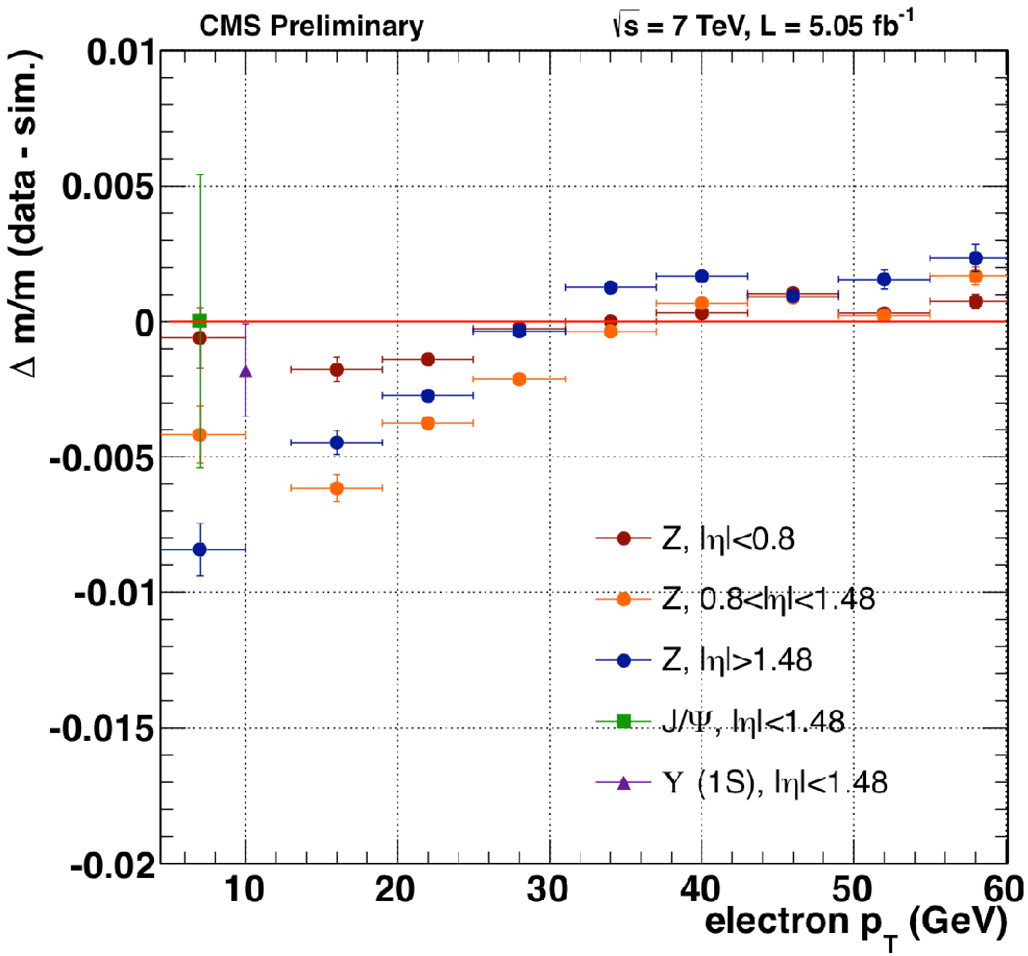
- Data/MC agrees on the e-scale within ~0.2% (high pT, barrel) to 1.5 % (low pT, endcaps)

- Data/MC agrees on the resolution within < 10%.



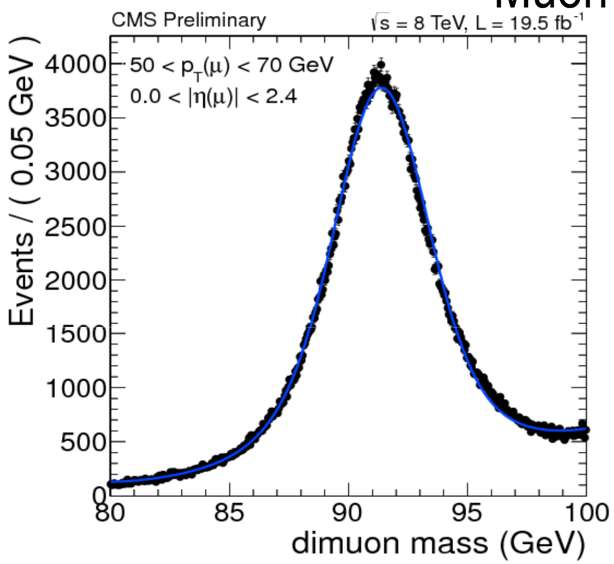
Mass measurement: Electron Momentum Scale

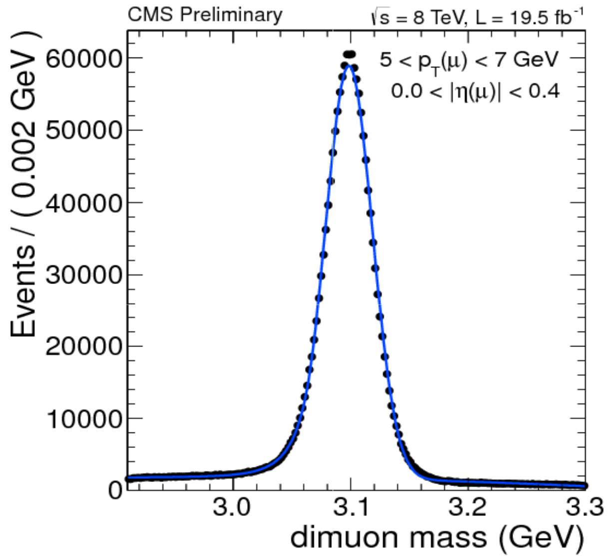


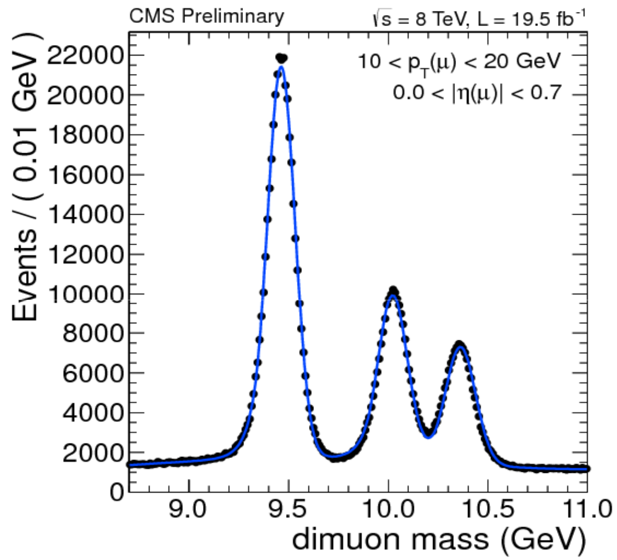


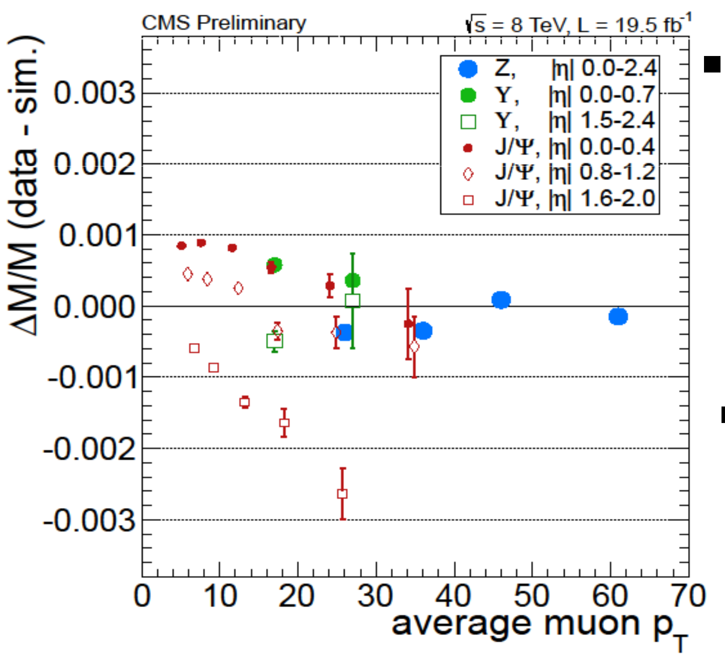
Mass measurement: Muon Momentum Scale & Resolution

Muon scale & resolution validated with Z, J/ψ & $\Upsilon \rightarrow \mu\mu$



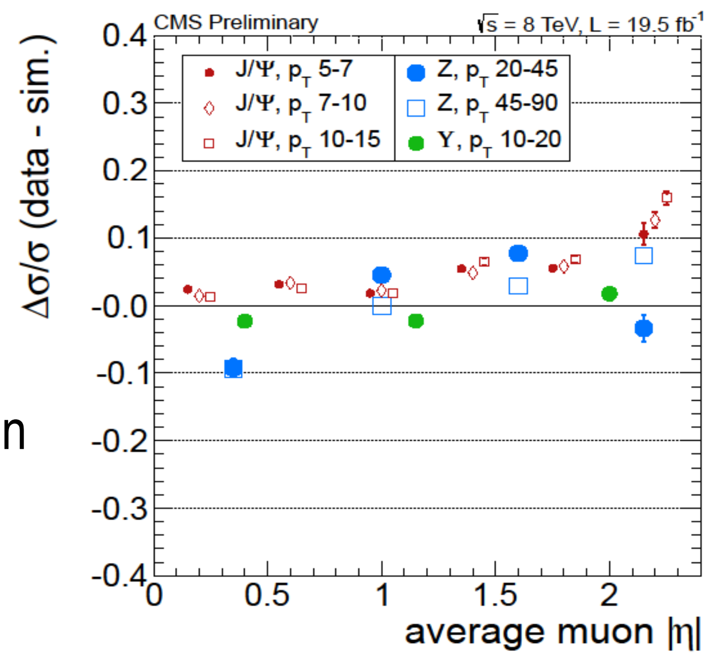




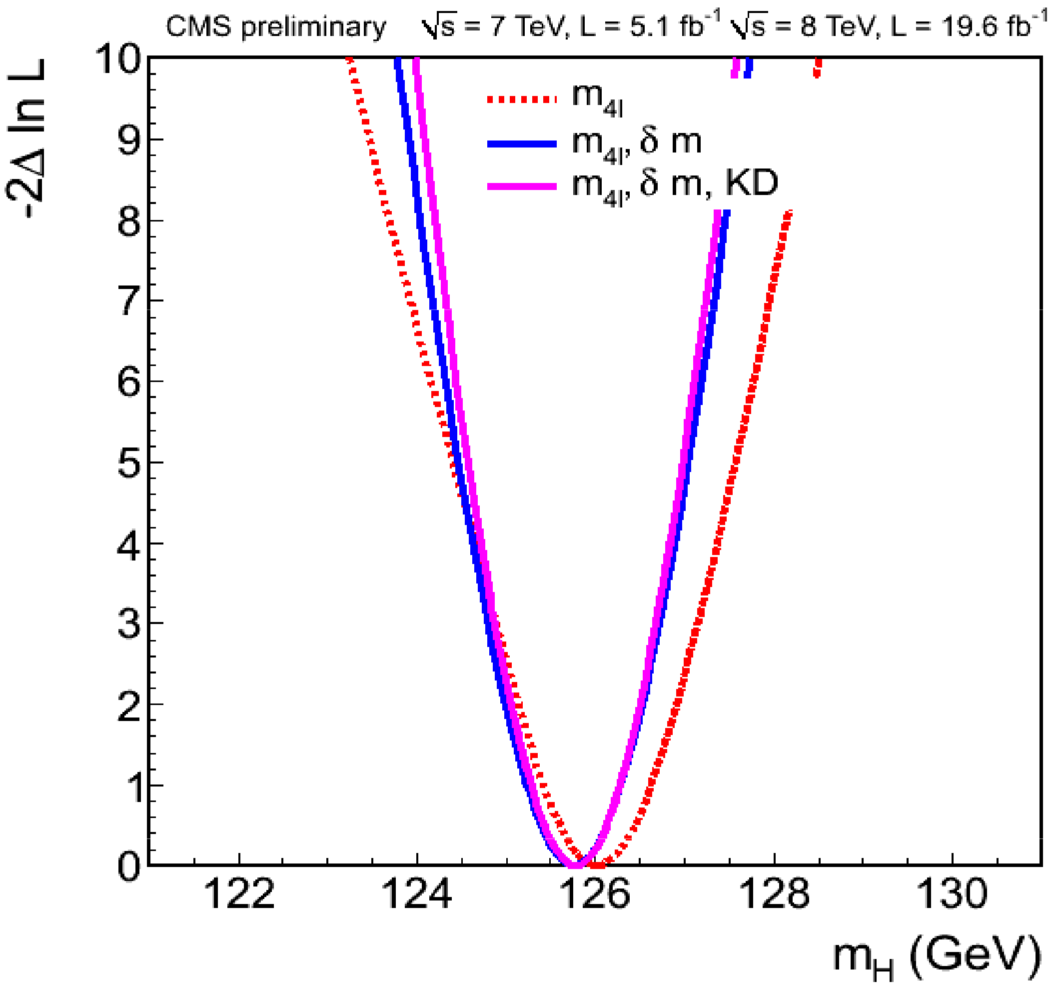


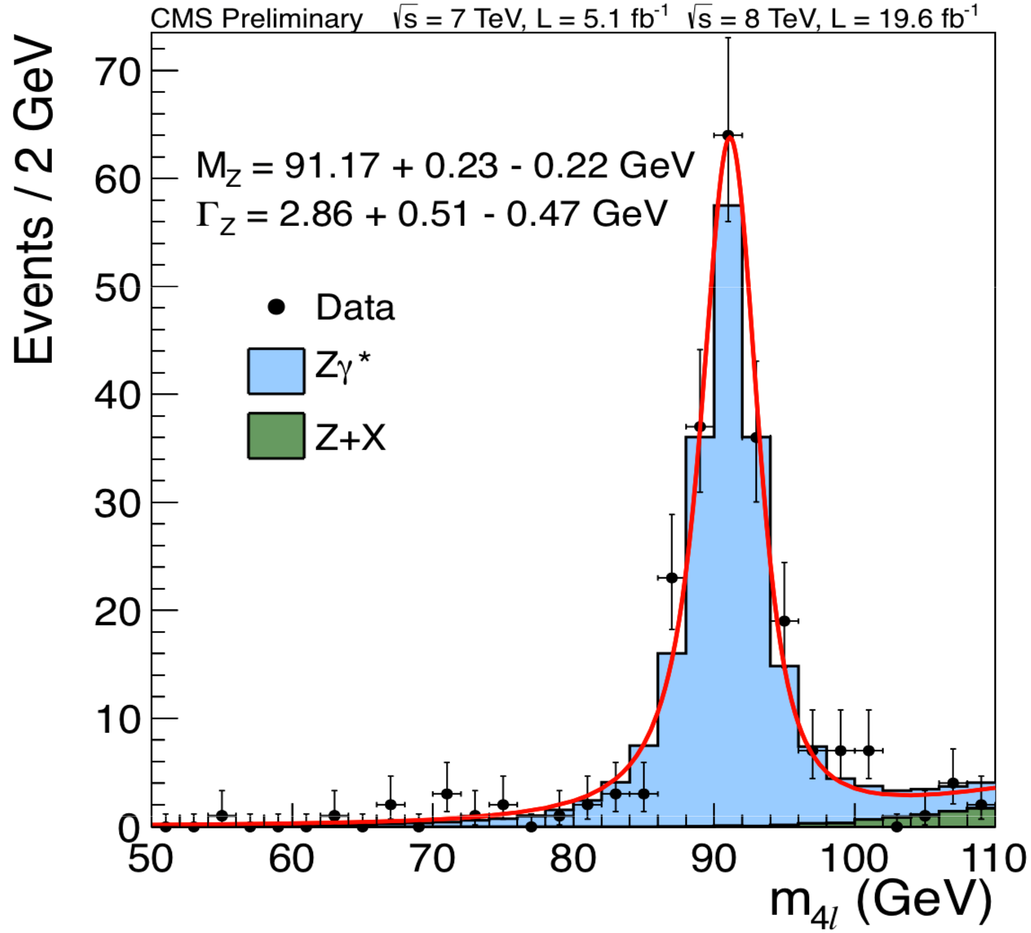
- Data/MC agrees on the μ-scale within 0.1%

- Data/MC agrees on the resolution within < 10%.



H→ZZ →4l: Mass Measurement

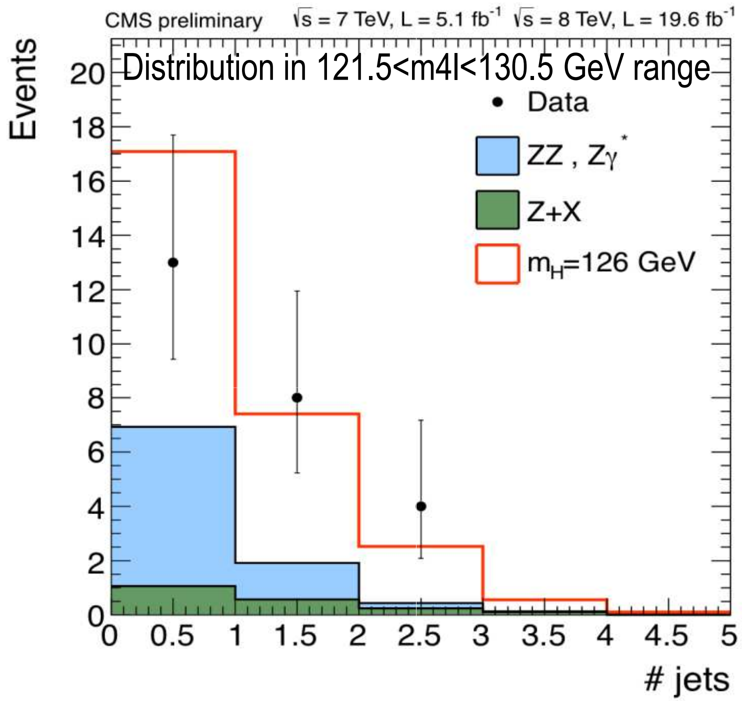




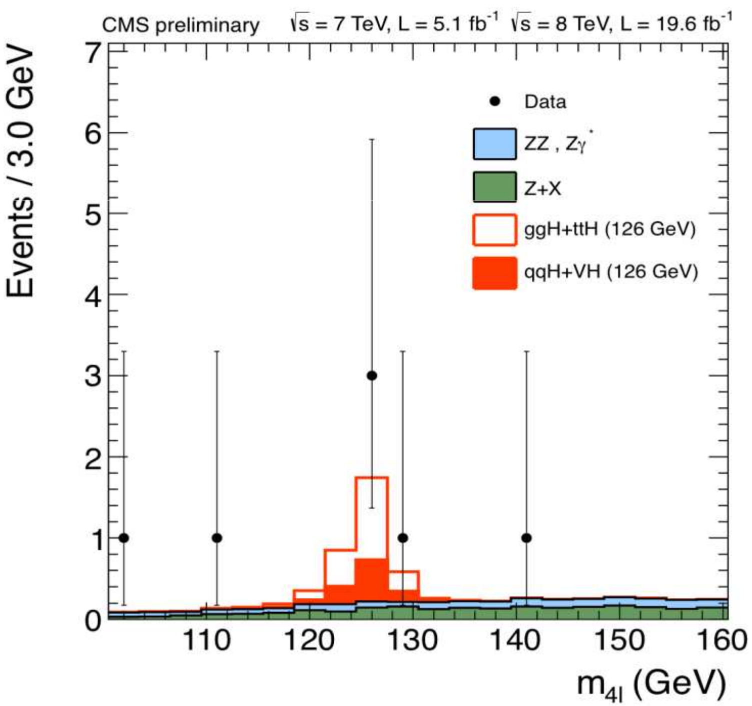
Mass Measurements with different techniques: 1D (m4l), 2D (m4l, δ_{m4l}) & 3D (m4l, K_D) gives consistent results

- Z→4l used to validate 1D mass measurement
- Good agreement between measured & PDG values

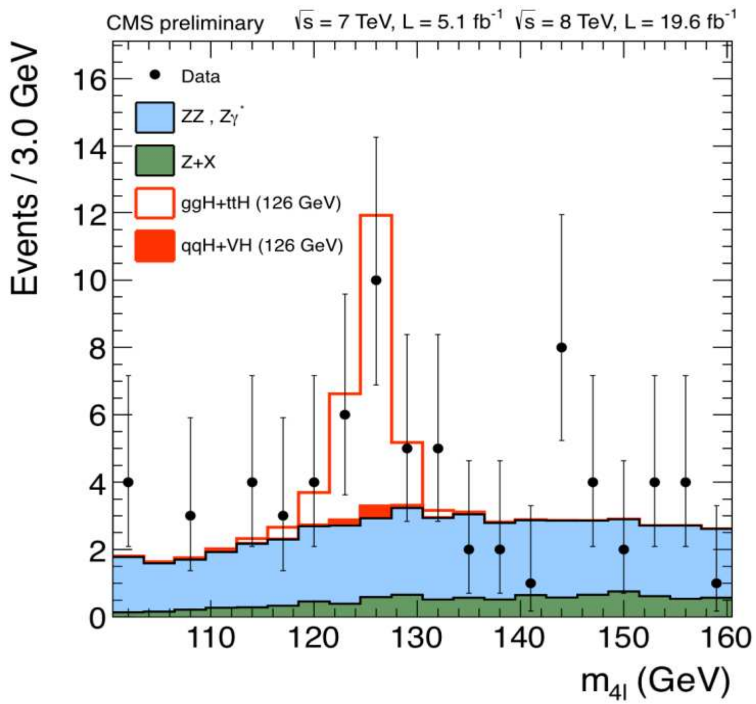
H→ZZ →4l: some more distributions



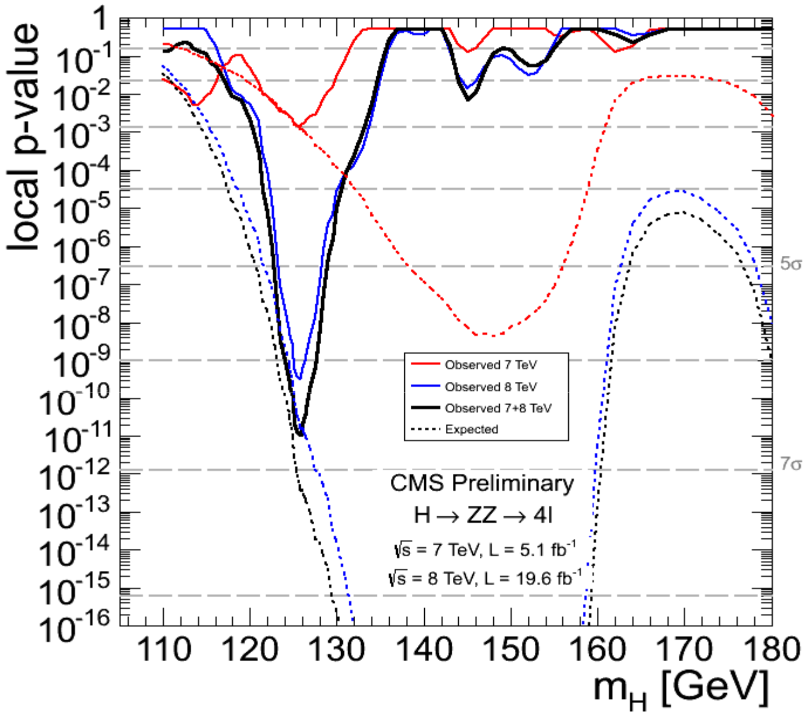
Di-jet tagged category



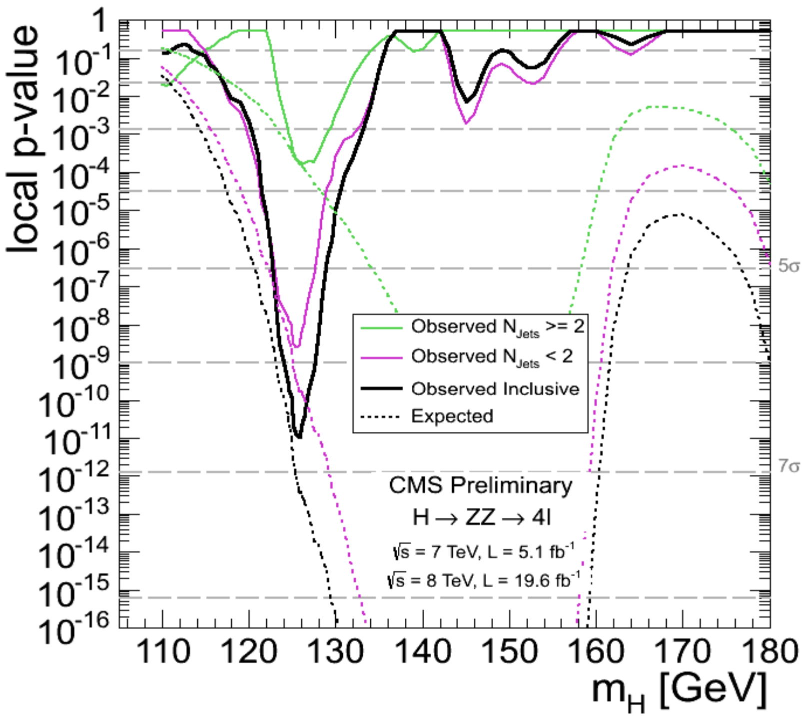
Un-tagged category

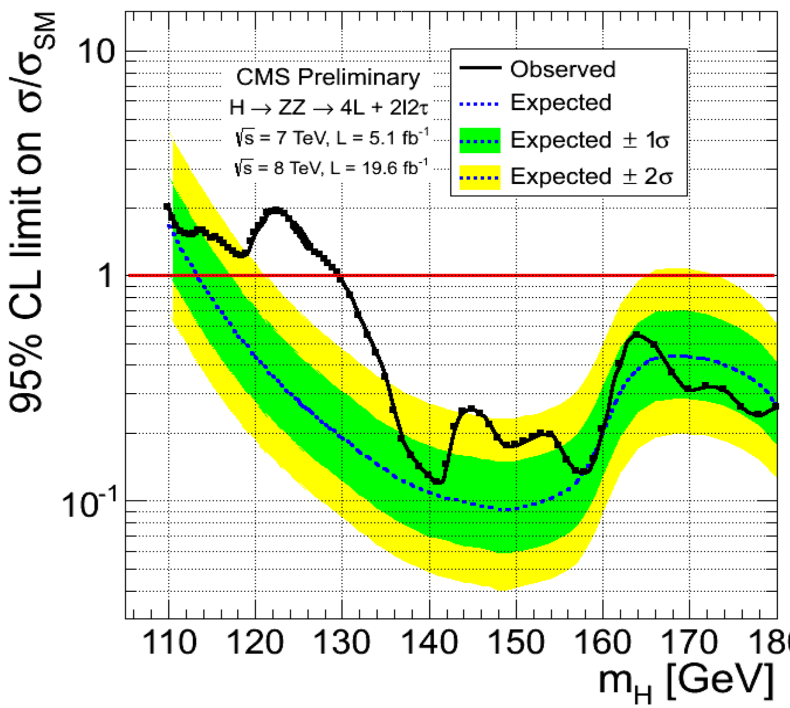


H→ZZ →4l: p-values & limits (low mass)



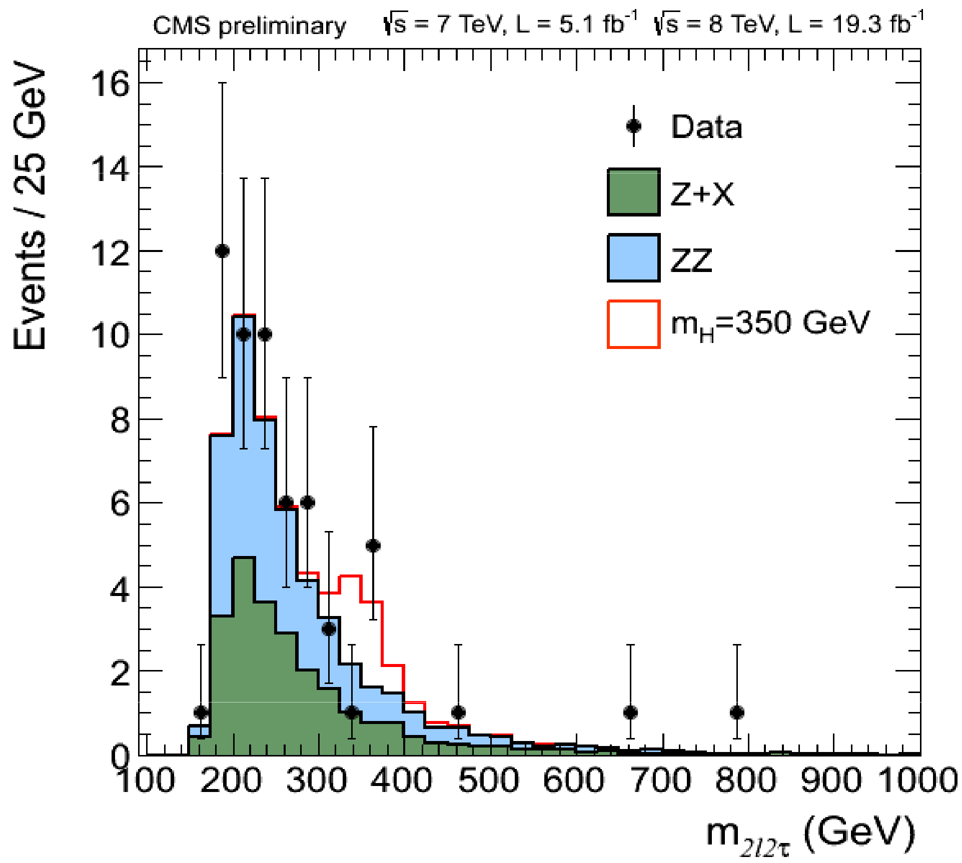
Excess at ~126 GeV consistent per category & data taking periods

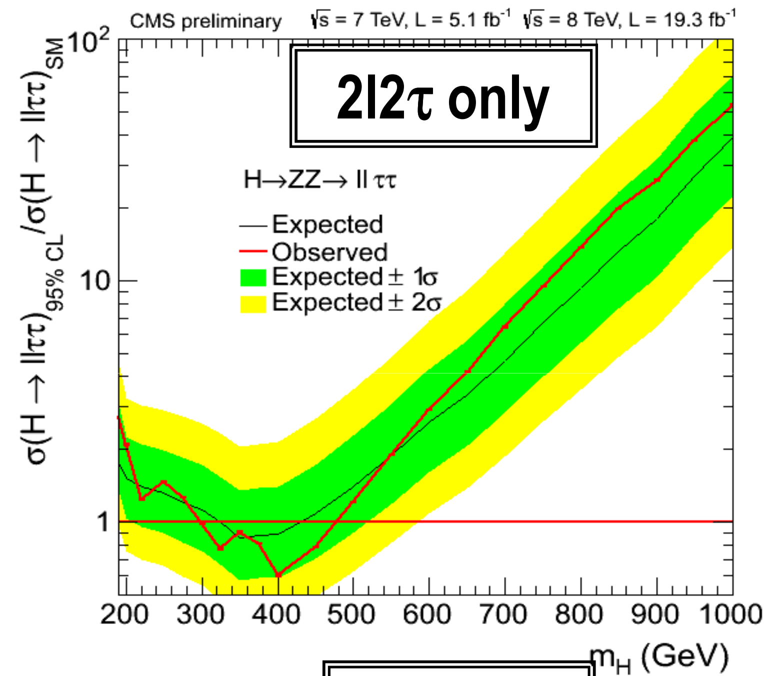


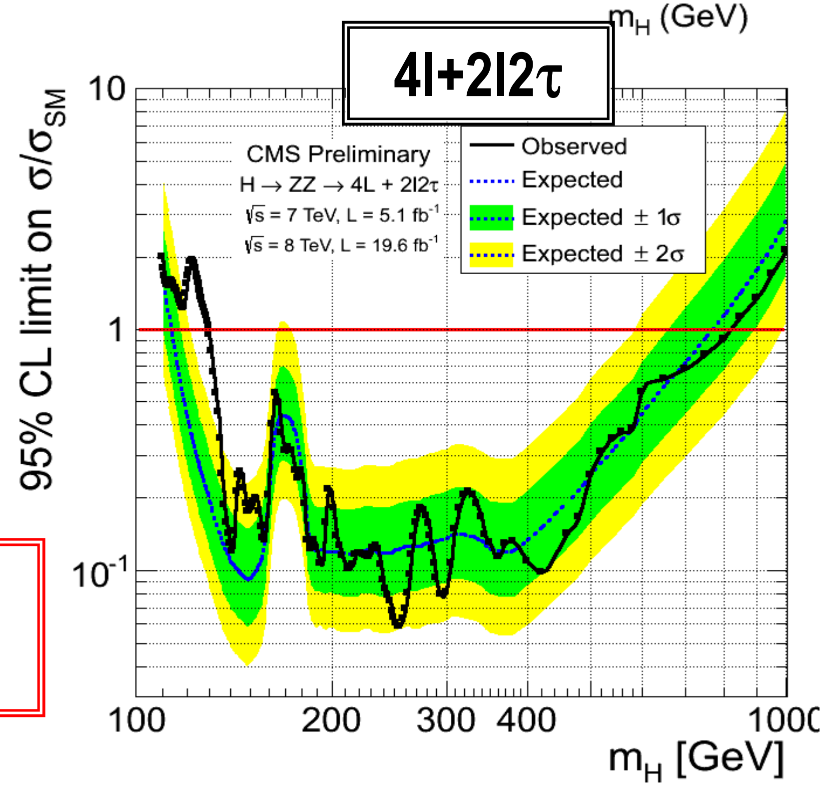


Exclude mH > 130 @ 95%CL

High Mass: $H \to ZZ \to 4l$ & $2l2\tau$: limits



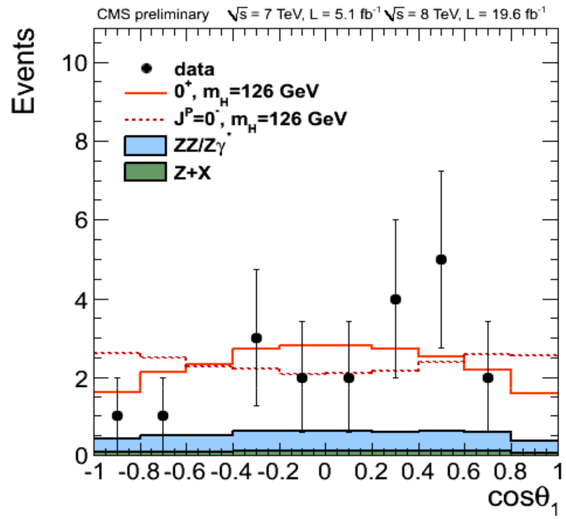




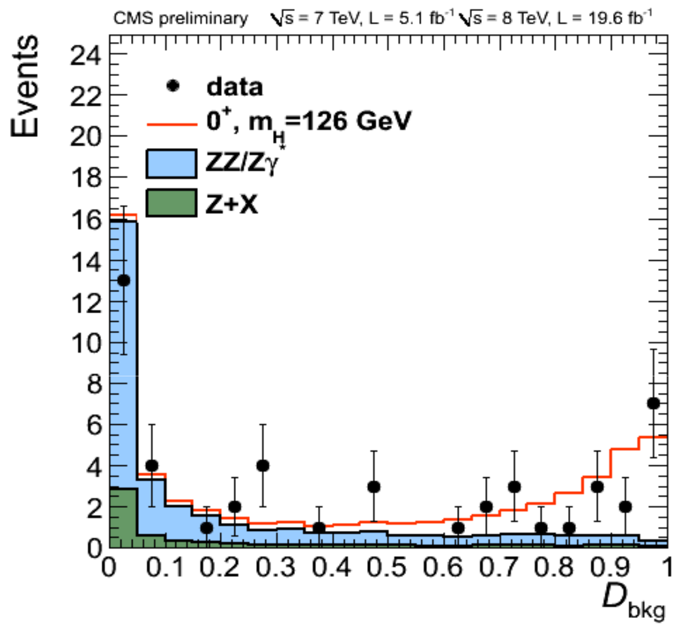
Exclude SM-like Higgs boson in the range 130-827 GeV @ 95% CL

H→ZZ →4l: J^{PC} Analysis

- The kinematics of the production and decay of the new boson are sensitive to its spin-parity state



- Build Discriminator (D) based of ratio of LO Matrix Elements
  - Don't use the system pT (NLO effect)
  - Don't use the rapidity (mostly PDF's)

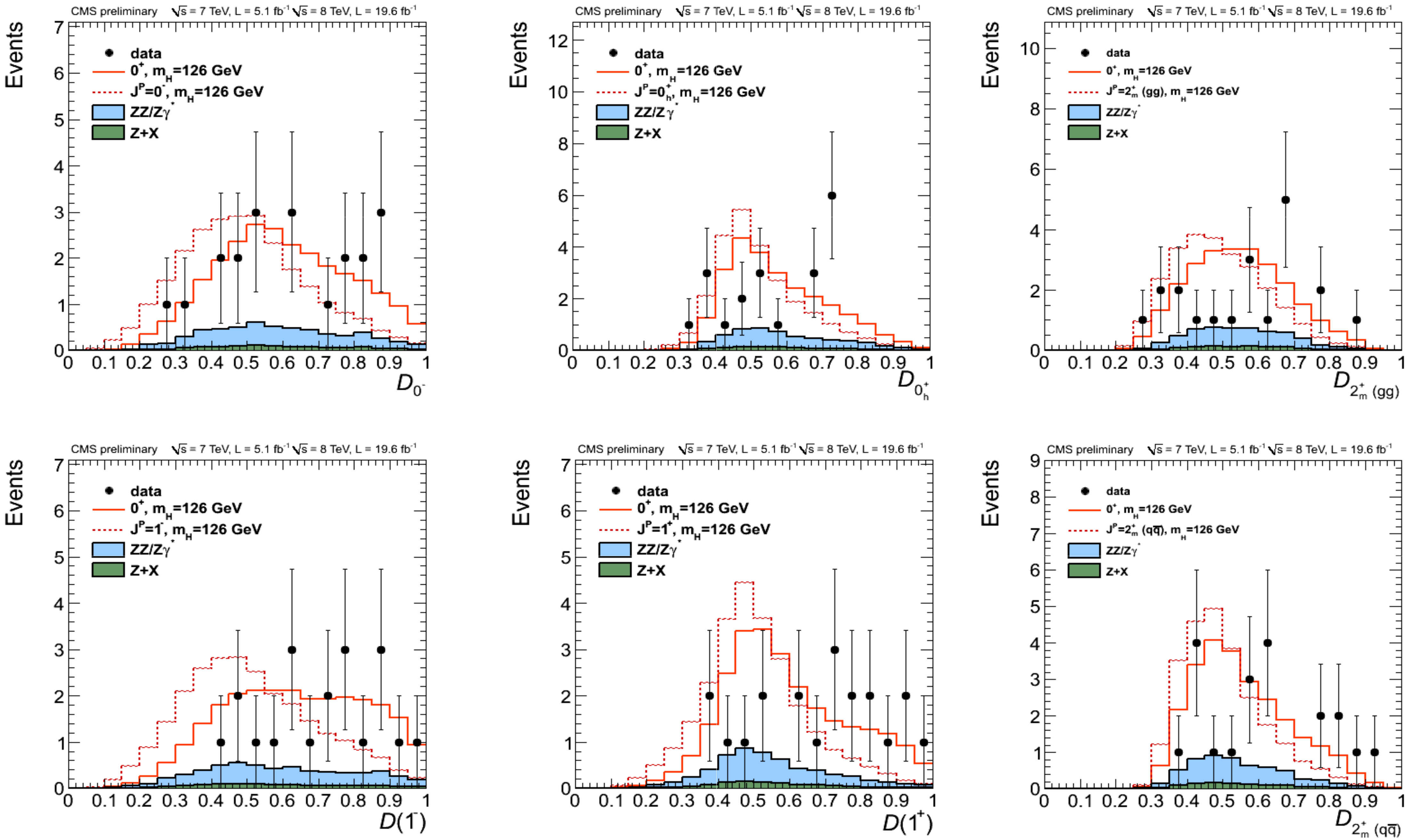


- **D_{bkg}**: separate signal from background
  - 5 angles, mZ1, mZ2 and m4l
- **D_{J^P}**: separate SM Higgs from alternative J^P hypothesis
  - 5 angles, mZ1, mZ2

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

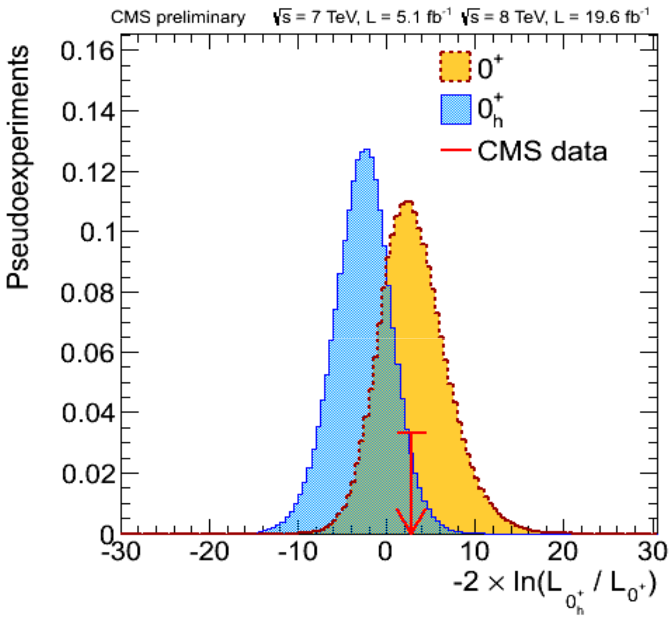
- **Perform statistical analysis in the 2D (D_{bkg}, D_{J^P}) plane.**

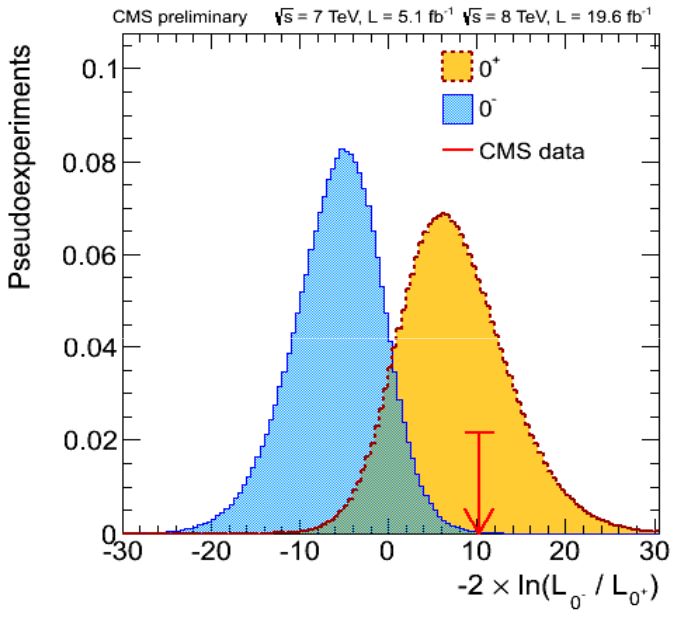
H→ZZ →4l: D_{J^P} distributions

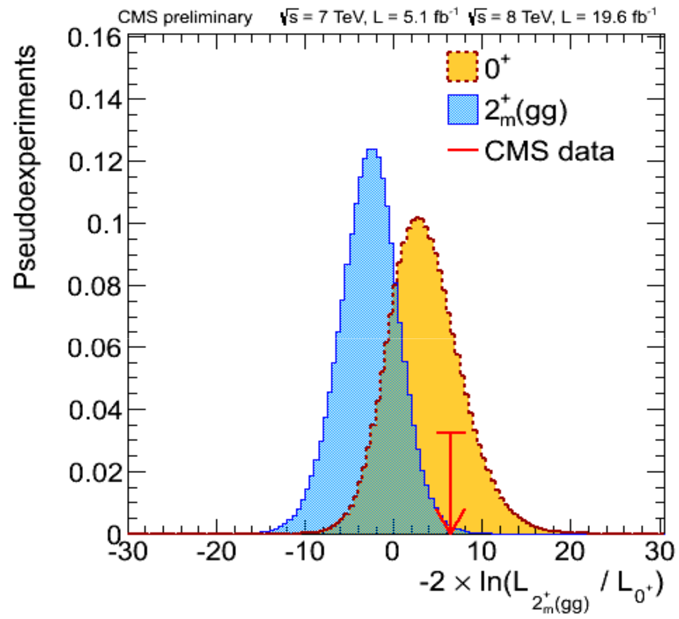


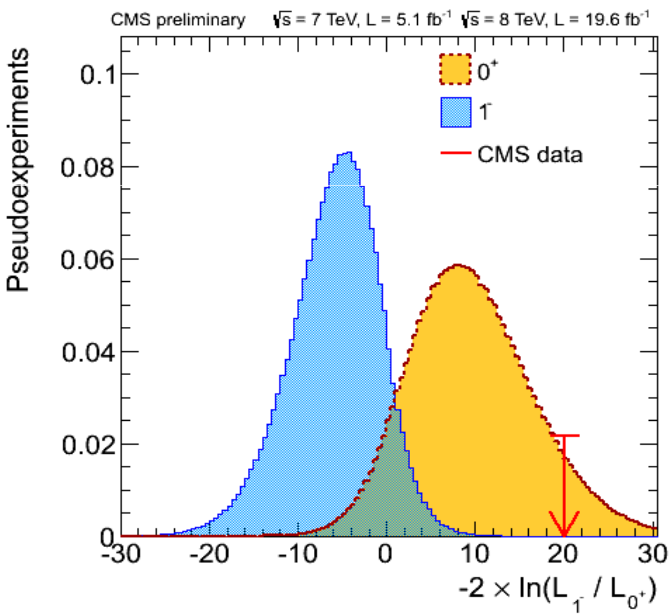
Distributions after $D_{bkg} > 0.5$ (for illustration)

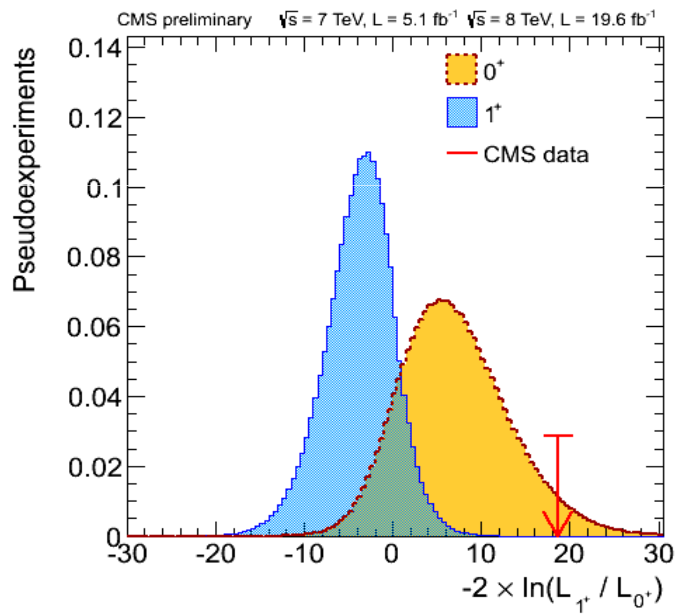
H→ZZ →4l: test statistic

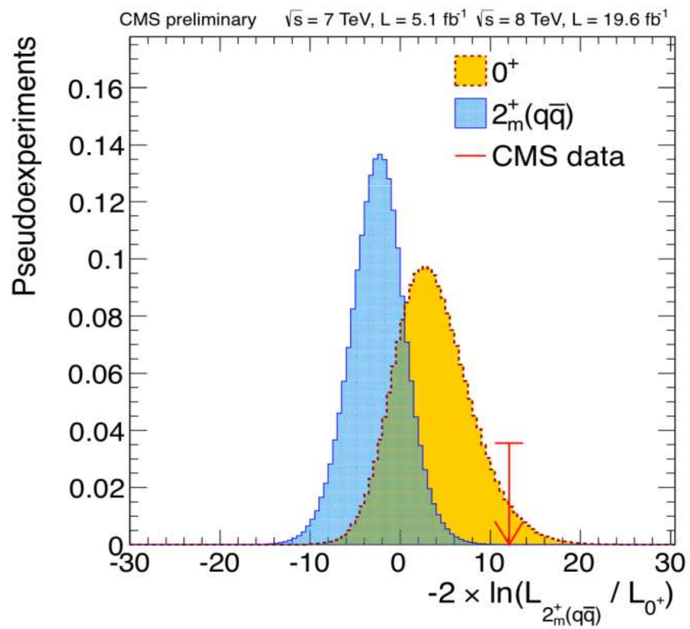












$H \rightarrow ZZ \rightarrow 4l$: J^{PC} Analysis Results

Table 3: List of models used in analysis of spin-parity hypotheses corresponding to the pure states of the type noted. The expected separation is quoted for two scenarios, when the signal strength for each hypothesis is pre-determined from the fit to data and when events are generated with SM expectation for the signal yield (μ=1). The observed separation quotes consistency of the observation with the 0^+ model or J^P model, and corresponds to the scenario when the signal strength is pre-determined from the fit to data. The last column quotes CL_s criterion for the J^P model.

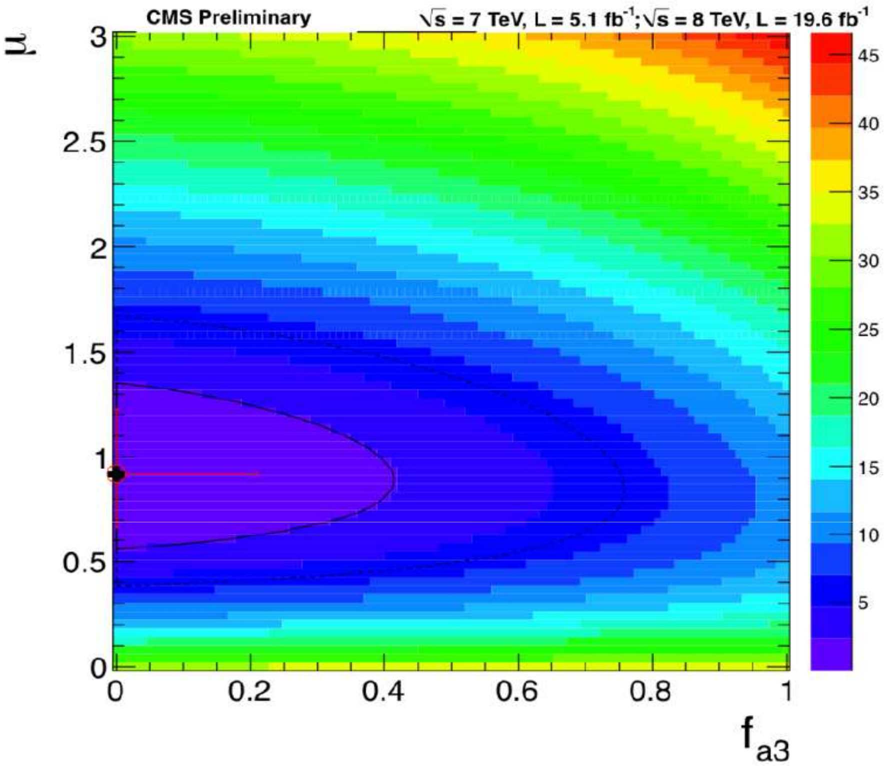
J^P	production	comment	expect (μ=1)	obs. 0^+	obs. J^P	CL_s
0^-	$gg \rightarrow X$	pseudoscalar	2.6σ (2.8σ)	0.5σ	3.3σ	0.16%
0_h^+	$gg \rightarrow X$	higher dim operators	1.7σ (1.8σ)	0.0σ	1.7σ	8.1%
2_{mgg}^+	$gg \rightarrow X$	minimal couplings	1.8σ (1.9σ)	0.8σ	2.7σ	1.5%
$2_{mq\bar{q}}^+$	$q\bar{q} \rightarrow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

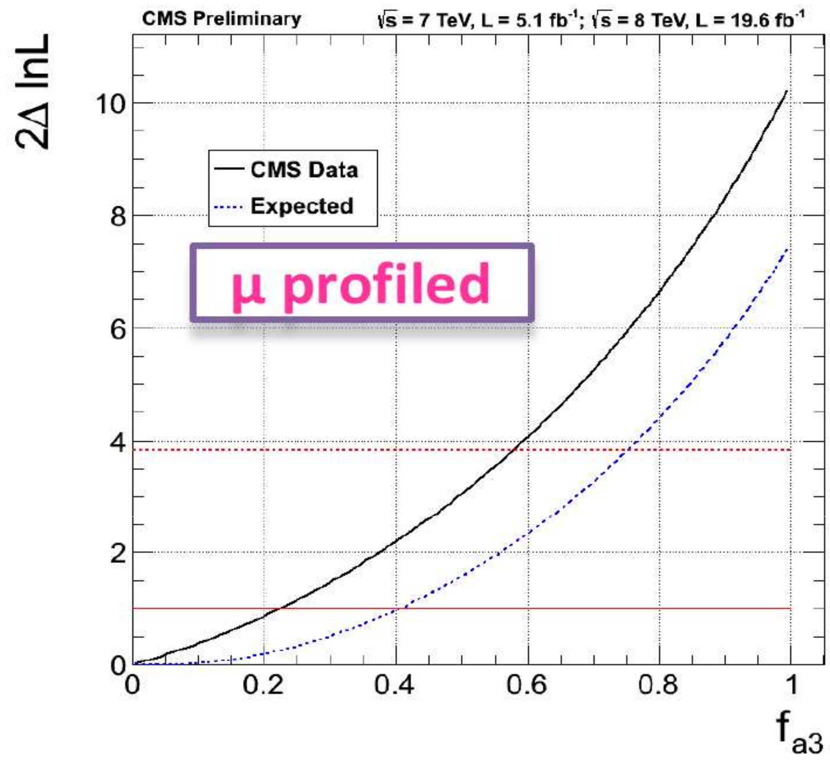
The studied pseudo-scalar, spin-1 and spin-2 models are excluded at 95% CL or higher

H→ZZ →4l: Mixed parity

$$A(X \to V_1 V_2) = v^{-1} \epsilon_1^{*\mu} \epsilon_2^{*\nu} \left(a_1 g_{\mu\nu} m_X^2 + a_2\, q_\mu q_\nu + a_3 \epsilon_{\mu\nu\alpha\beta}\, q_1^\alpha q_2^\beta \right)$$

$$f_{a3} = |A_3|^2 / (|A_1|^2 + |A_3|^2)$$



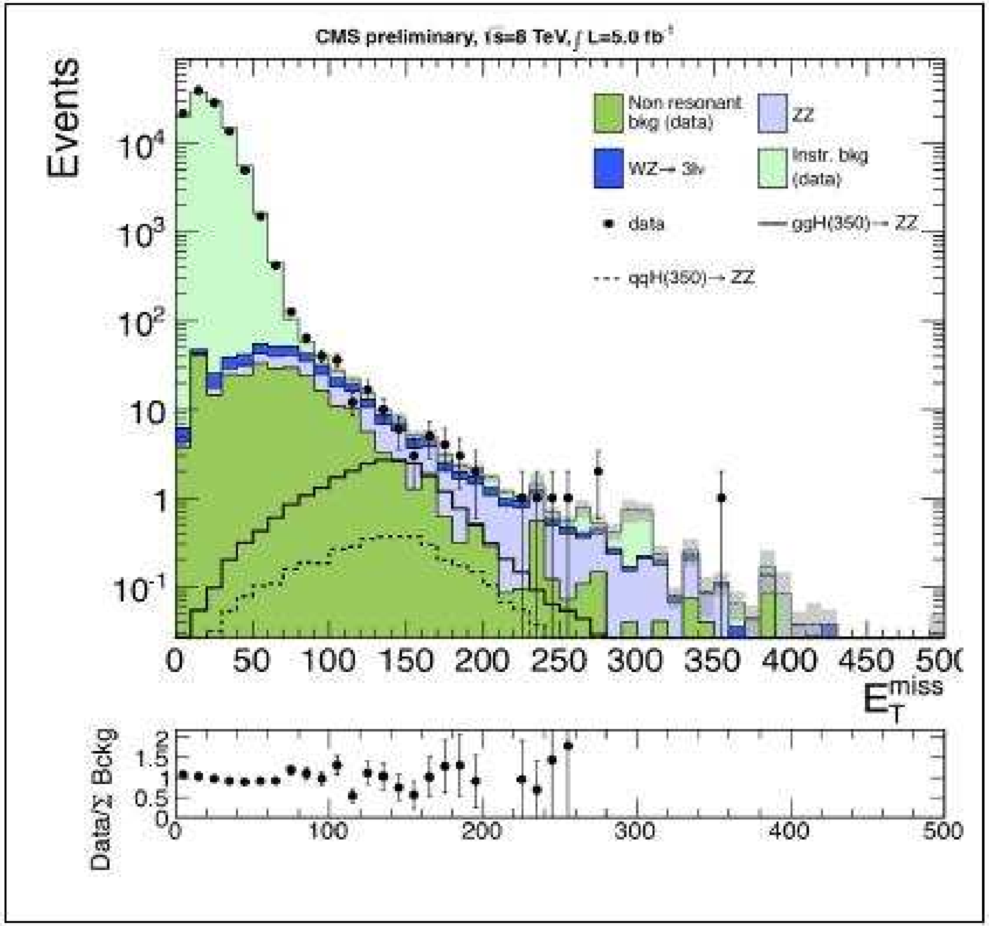


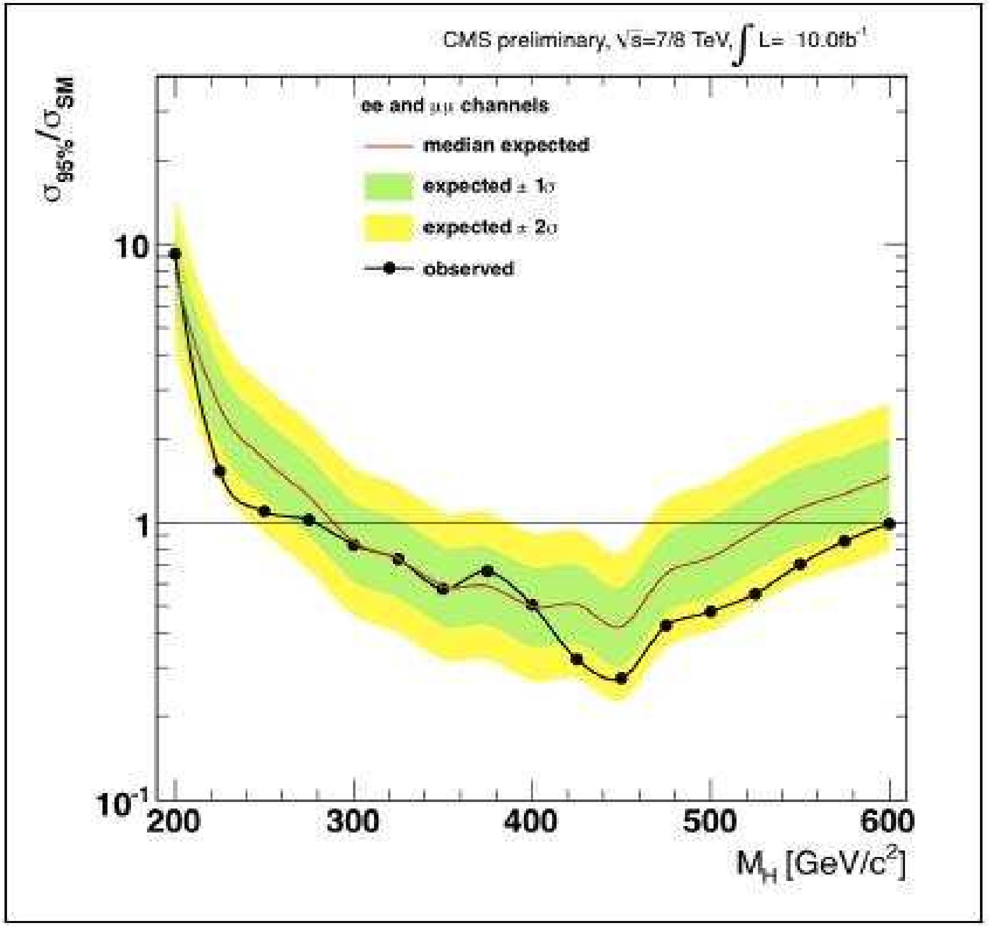
$f_{a3} = 0.00^{+0.23}_{-0.00}$

$f_{a3} < 0.58$ @ 95% C.L.

- SM 0+ decay dominated by A1
- 0- decay dominated by A3

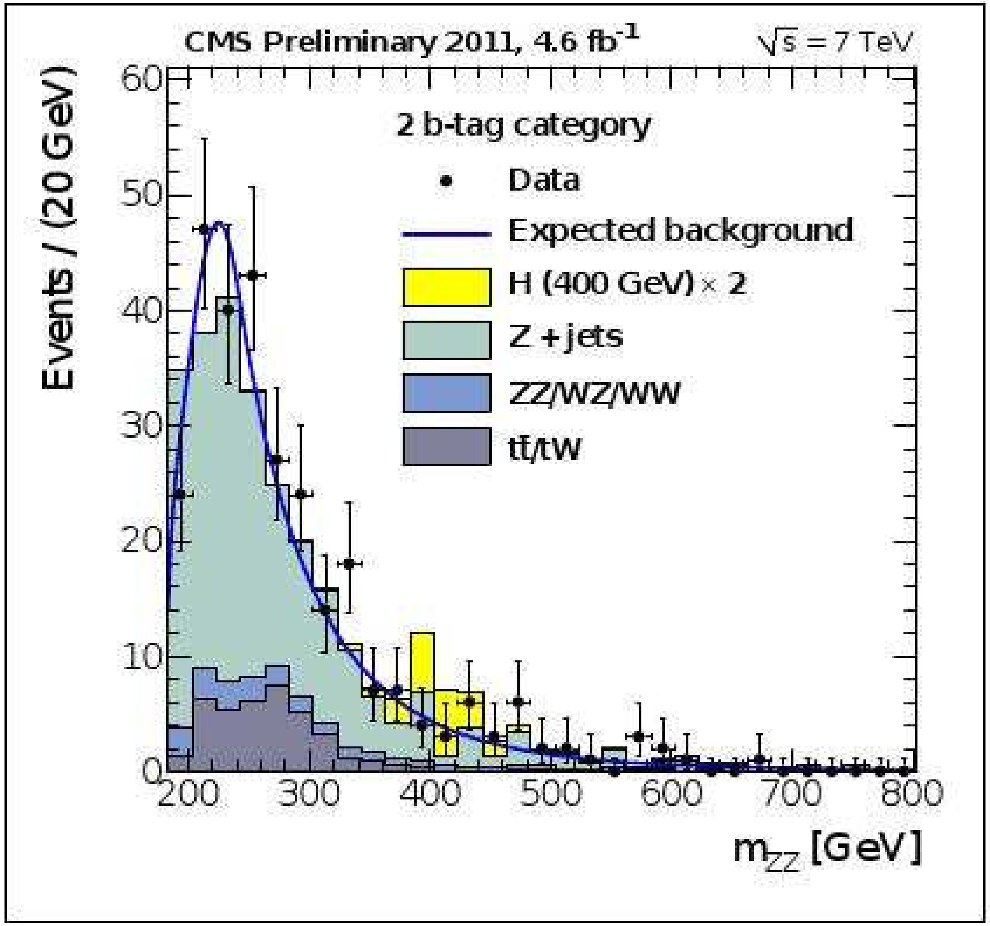
H→ZZ →2lν

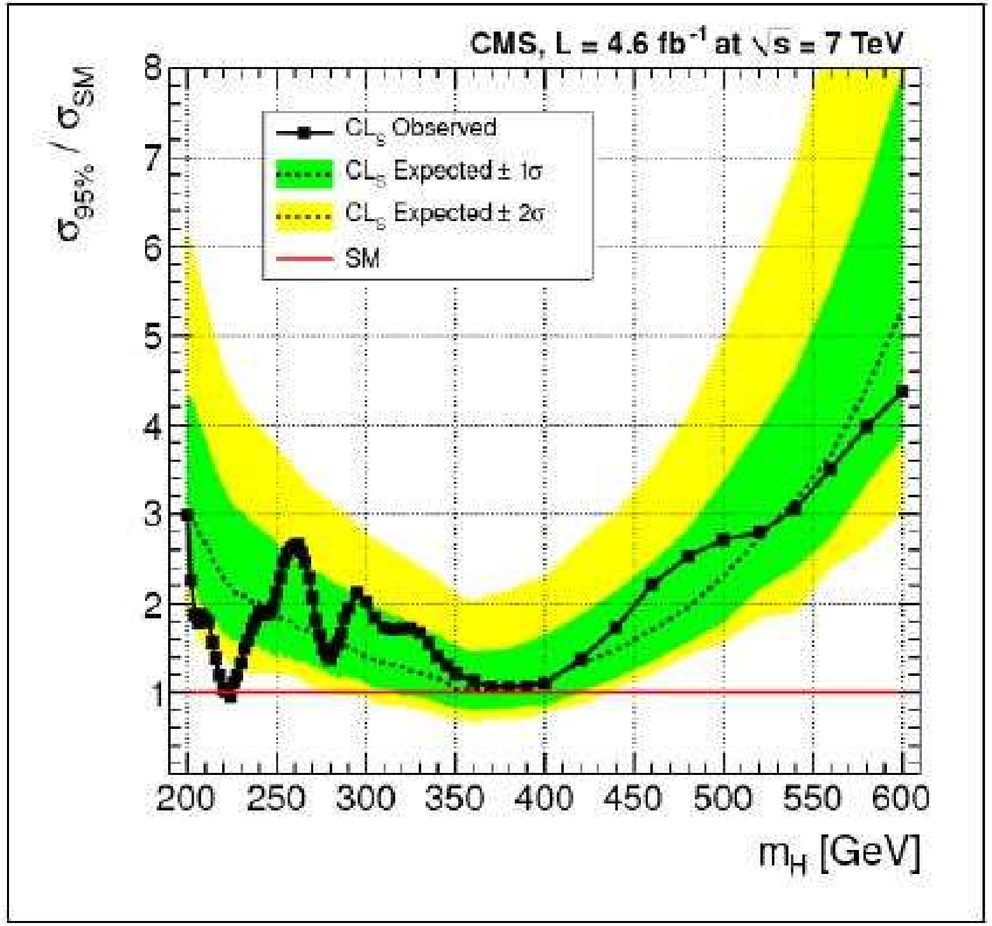




- Two leptons from a Z boson, large $E_{\mathrm{T}}^{\mathrm{miss}}$
- Using m_T as final variable
- Split in several categories: electrons/muons, 0/1/2-jets

H→ZZ →2l2q





- Two leptons from a Z boson, two jets from another Z boson
- Using $m_{2q2\ell}$ as final variable
- Split in several categories: electrons/muons, 0/1/2 *b*-jets