Higgs boson measurements in ZZ to 4 leptons channel with CMS

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On behalf of **CMS collaboration**

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In next 15 minutes ...

- Go trough the HZZ4l, a.k.a. "Golden channel"
- See several details of the analysis
- Measure the Higgs mass ...
- ... and its Standard-Modelicity

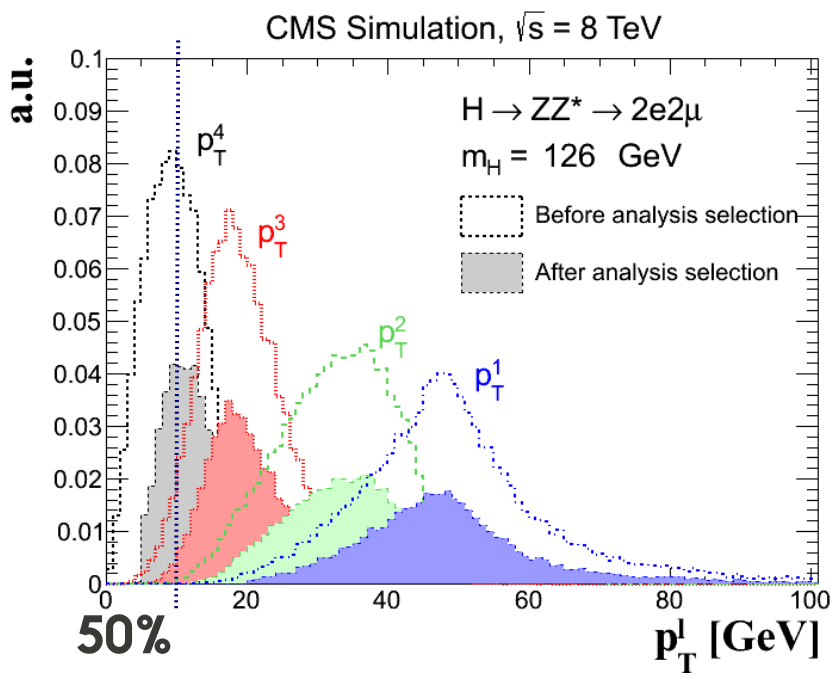
Results briefly presented by **Marco Pieri** on Tuesday

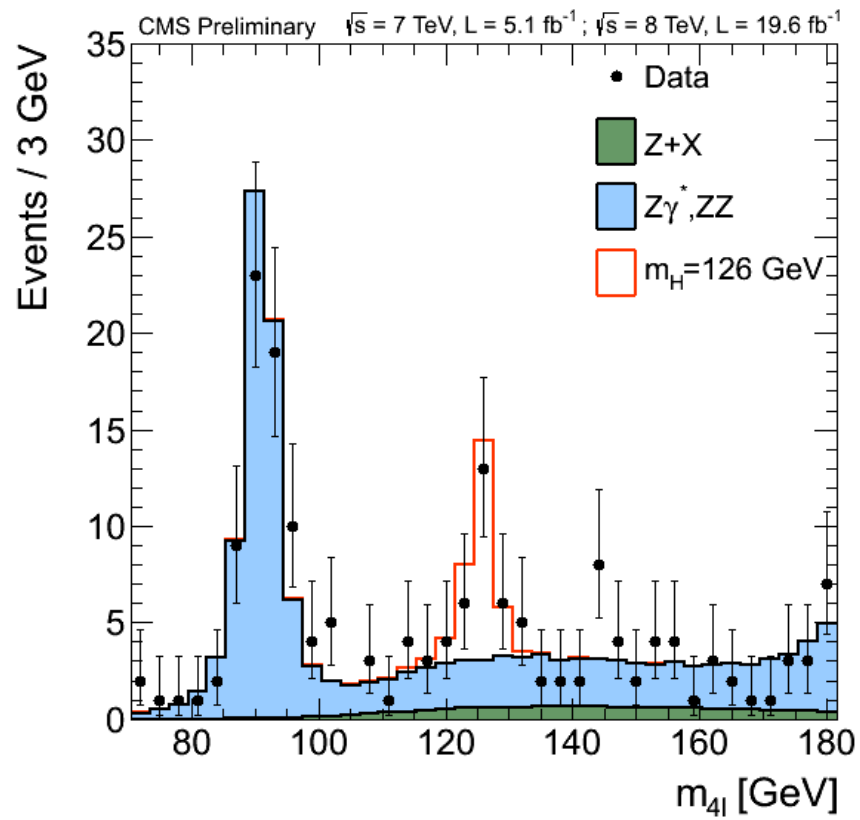
All based Moriond analysis **CMS PAS HIG-13-002**

Setting the scene

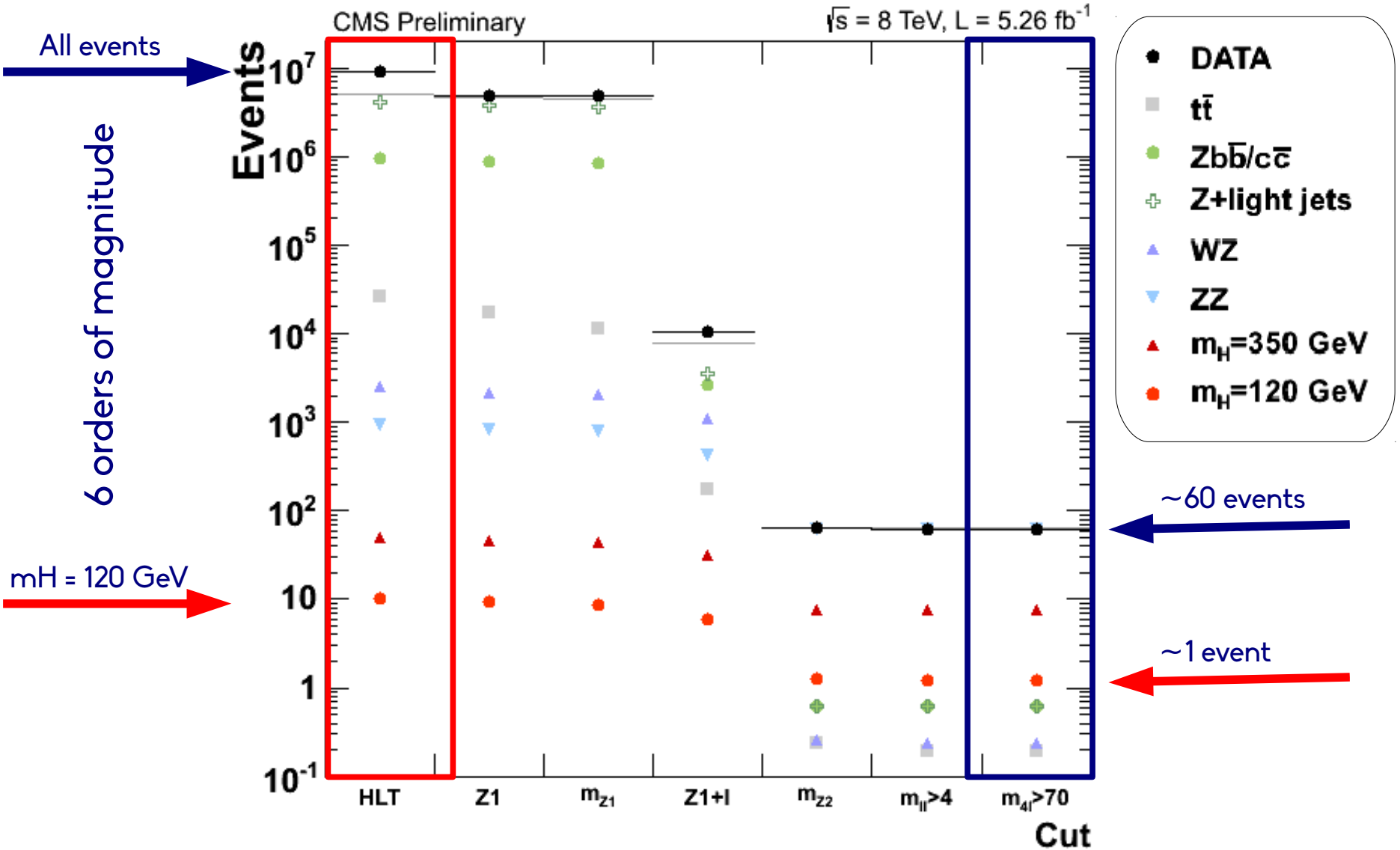
- Search for the narrow peak in 4l mass spectrum on top of a small flat background – excellent energy resolution channel
  - Small number of events expected – large initial background
  - Requires max. signal efficiency (ε^4) and background rejection

Excellent lepton reconstruction, ID and energy-momentum measurement





Setting the scene

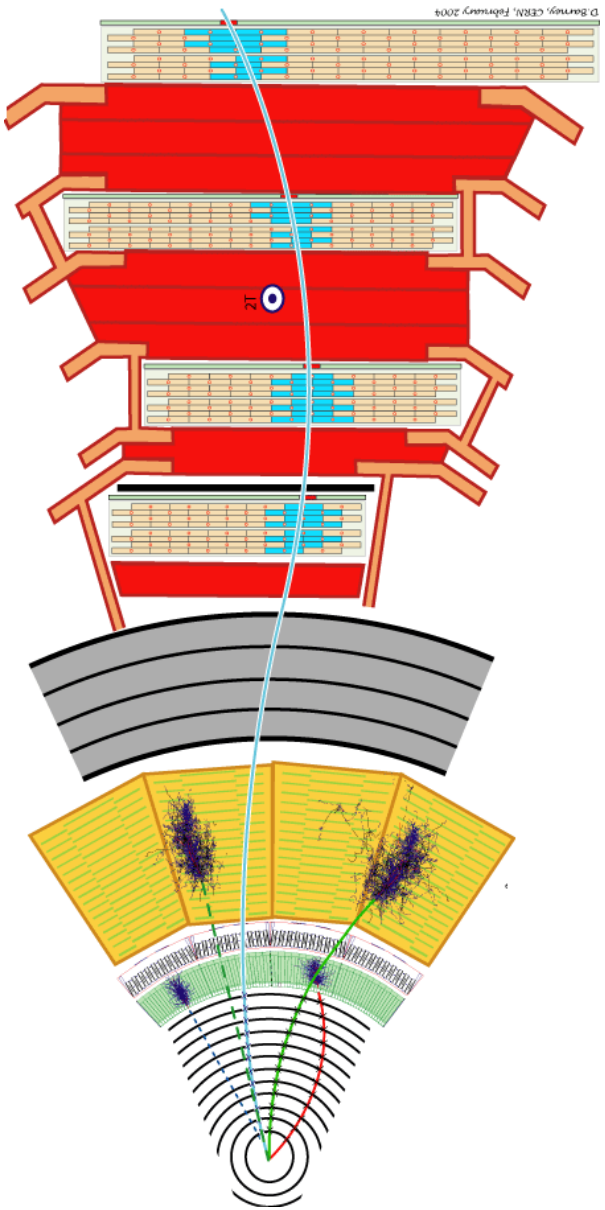


Plot is shown for ~1/4 of 2012 CMS integrated luminosity

Analysis strategy

- Rely critically on excellent measurements of leptons down to very low pT
- Reducible background (Z+jets, tt)
  - Reduce using isolation and impact parameter requirements
  - Estimate from data in carefully selected control regions
- Irreducible background from simulation
- Use jet multiplicity categorization to enhance production mode sensitivity
- Profit from the decay kinematics with kinematic discriminant
- Perform statistical analysis using multi-dim PDFs
  - P-value, mass measurement, spin-parity

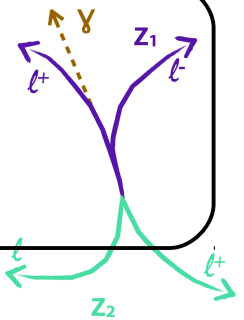
Building blocks



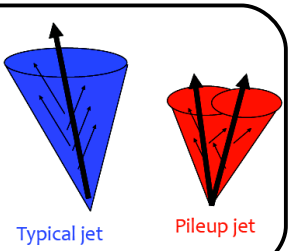
- **Muons**
  - pT > 5 GeV, |η| < 2.4

- **Electrons**
  - pT > 7 GeV, |η| < 2.5

- Photons for FSR
  - pT > 2 GeV, |η| < 2.4
  - ΔR(γ, lepton) < 0.5 and isolated



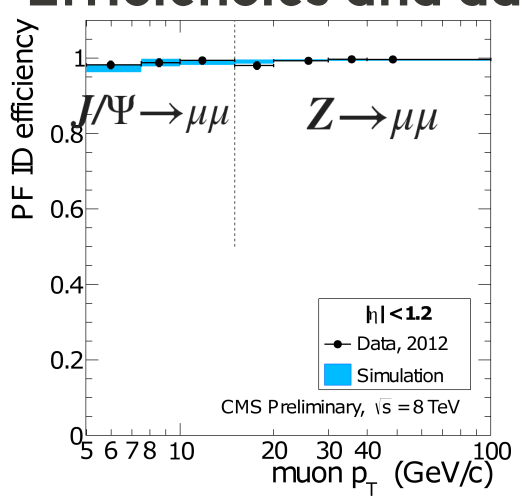
- Jets for categorization
  - pT > 30 GeV, |η| < 4.7
  - Loose jet ID, MVA PU jet ID



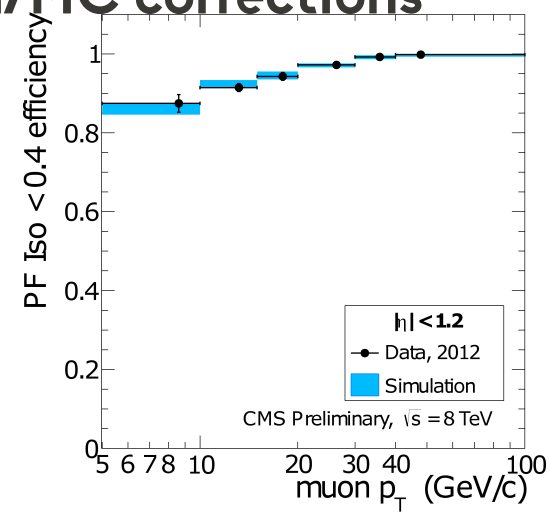
Muons

- Using particle flow muon ID
  - Exploiting full detector information for high efficiency with maximum fake rejection
- Particle flow isolation – powerfull against red. background
  - Using avarage energy density PU corrections
- Impact parameter significance(SIP)

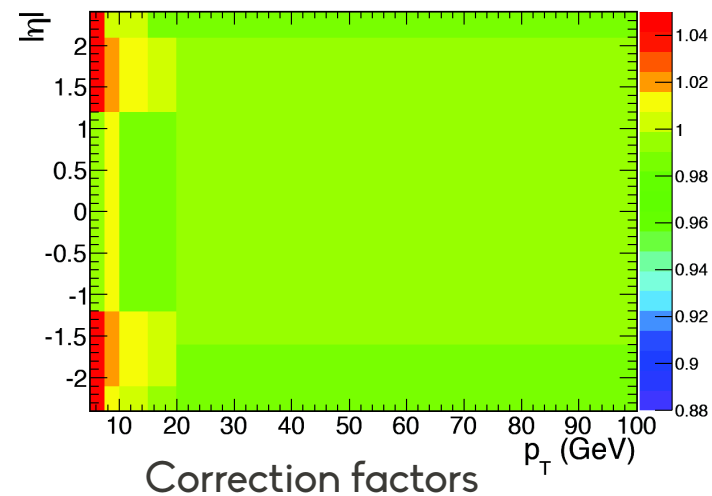
Efficiencies and data/MC corrections



Identification



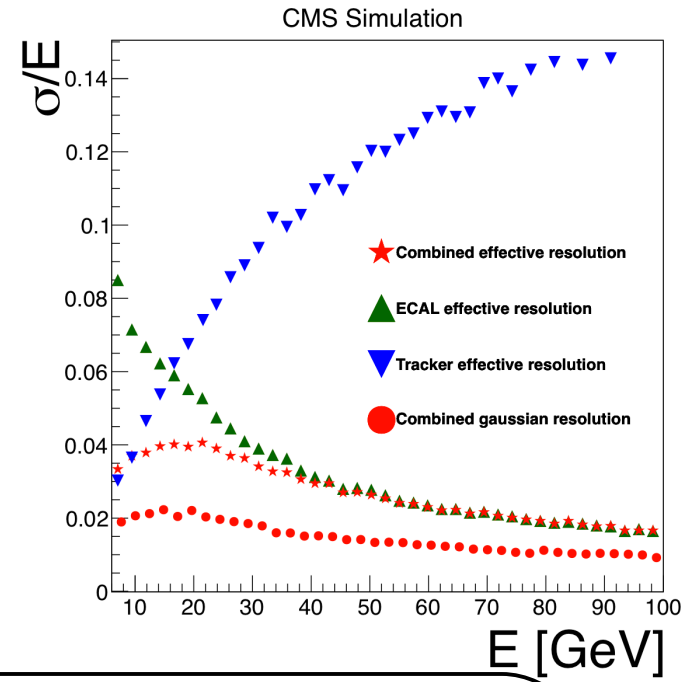
Isolation



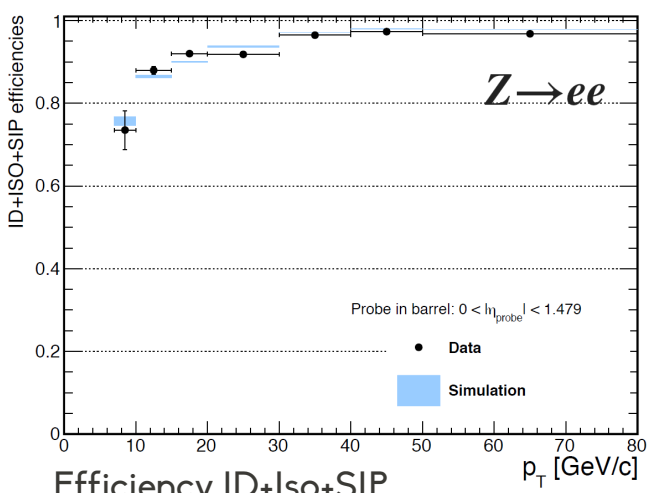
Correction factors from 2012 data close to 1

Electrons

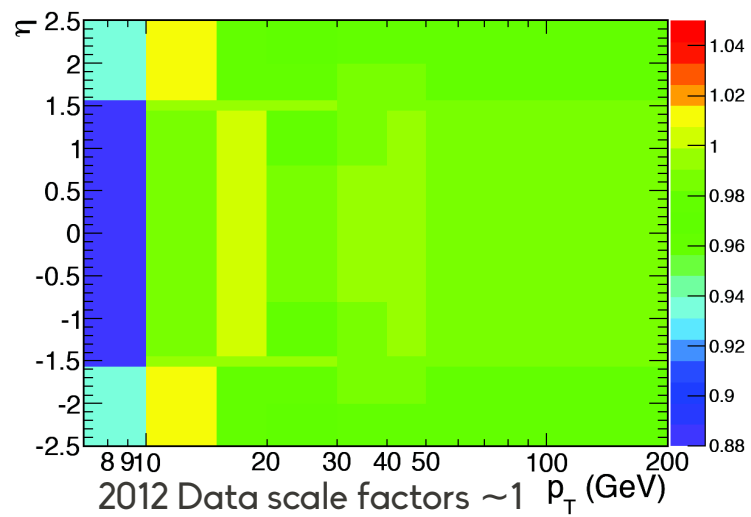
- EM energy derived by MVA regression (BDT)
  - energy scale correction from Zee
- BTD ID trained on Z/γ* electrons
- PF based relative isolation
  - Using ρ PU corrections
- Impact parameter significance(SIP)



Efficiencies and data/MC corrections



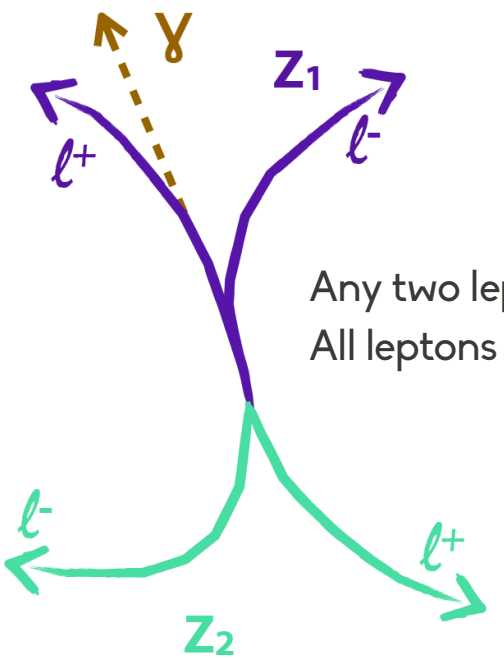
Efficiency ID+Iso+SIP



2012 Data scale factors ~1

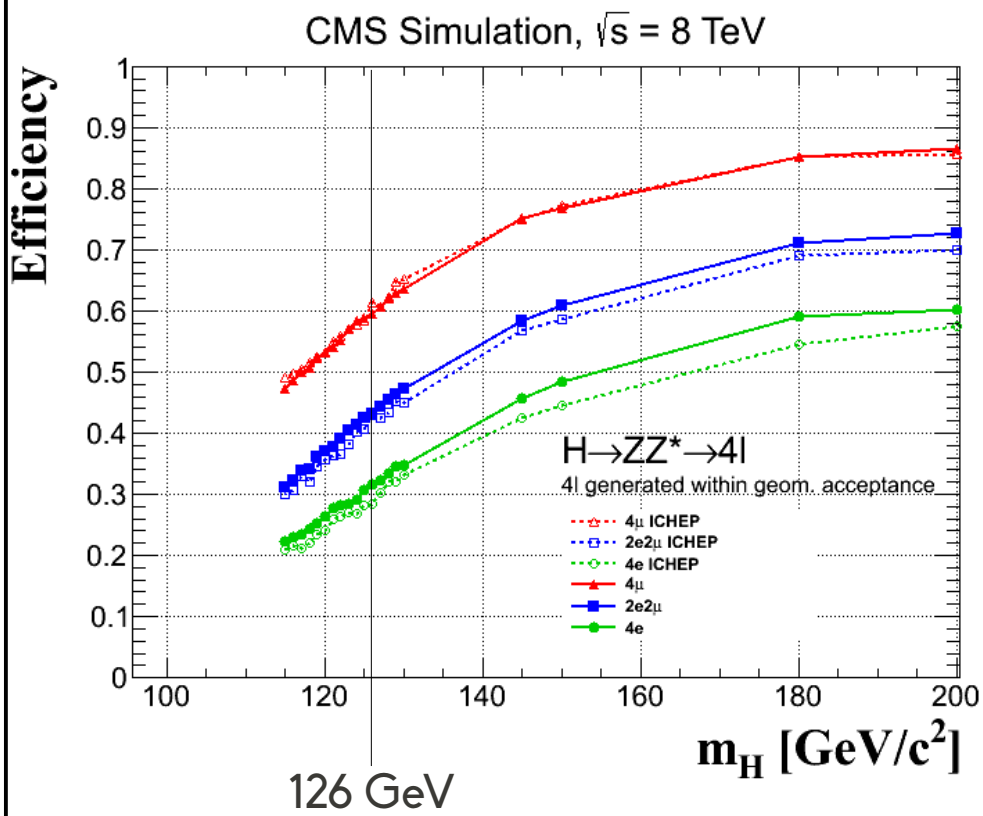
Inclusive selection – 4l candidates

- OS/SF nearest to Z mass: $40 < m_{Z1} < 120$ GeV

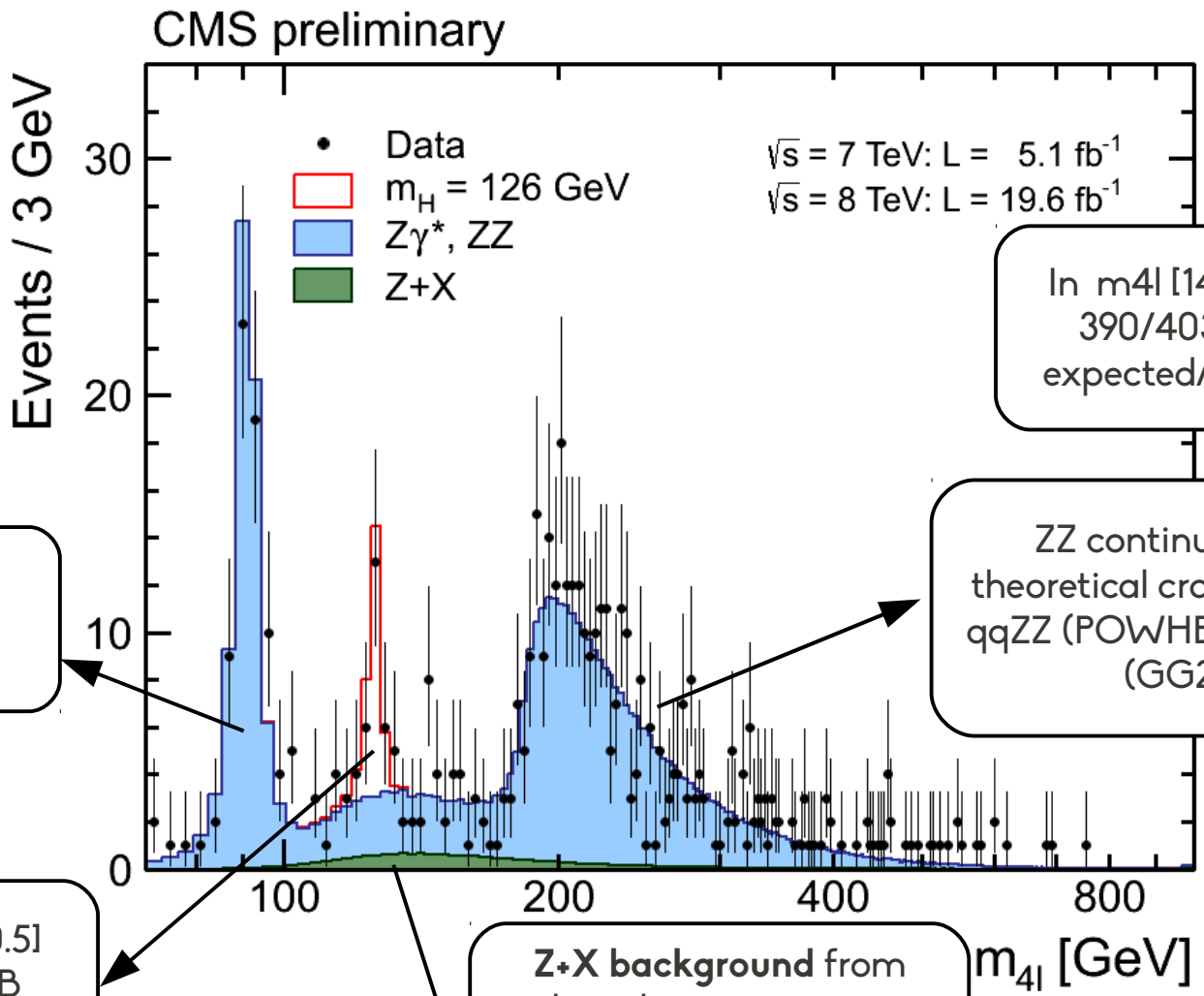


Any two leptons with p_T>20/10 GeV
All leptons after ID/Iso/SIP cuts

- OS/SF higest sum p_T: $12 < m_{Z2} < 120$ GeV
- FSR photon recovery on each Z before cuts
- Supress QCD with $m_{ll} > 4$ GeV on OS pairs



Spectrum of m_{4l} – full mass range



Z->4l peak with good data/MC agreement

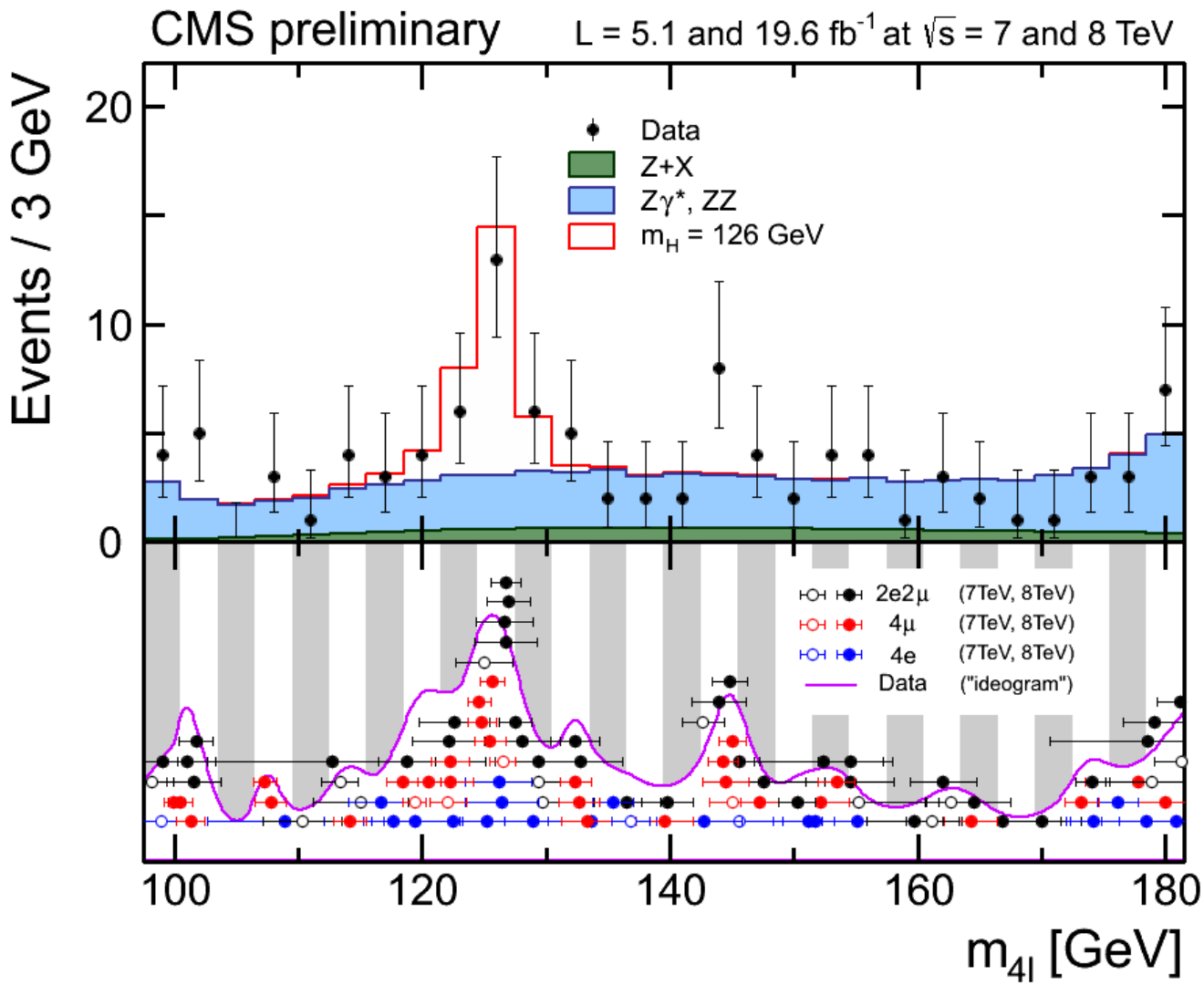
In m4l [121.5-130.5] expected 28 S+B events, observed 25

Z+X background from data driven estimates based on fake-rate measurements

ZZ continuum from theoretical cross-section of qqZZ (POWHEG) and ggZZ (GG2ZZ)

In m4l [140 – 1000] 390/403 events expected/observed

Spectrum of m_{4l} – low mass range

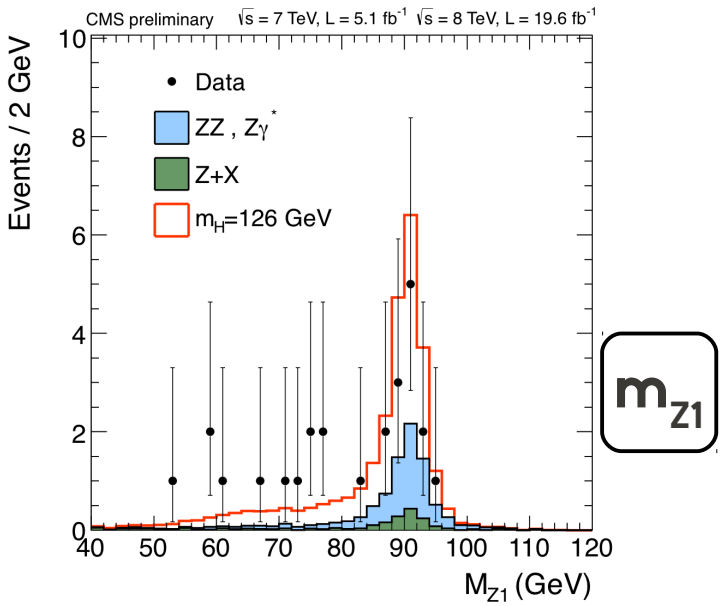


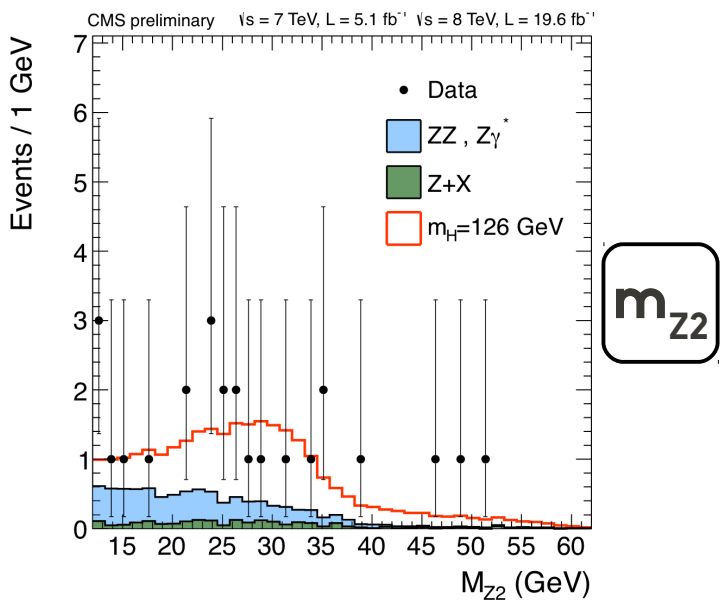
Yields for 7 and 8 TeV in range $121.5 < m_{4l} < 130.5$

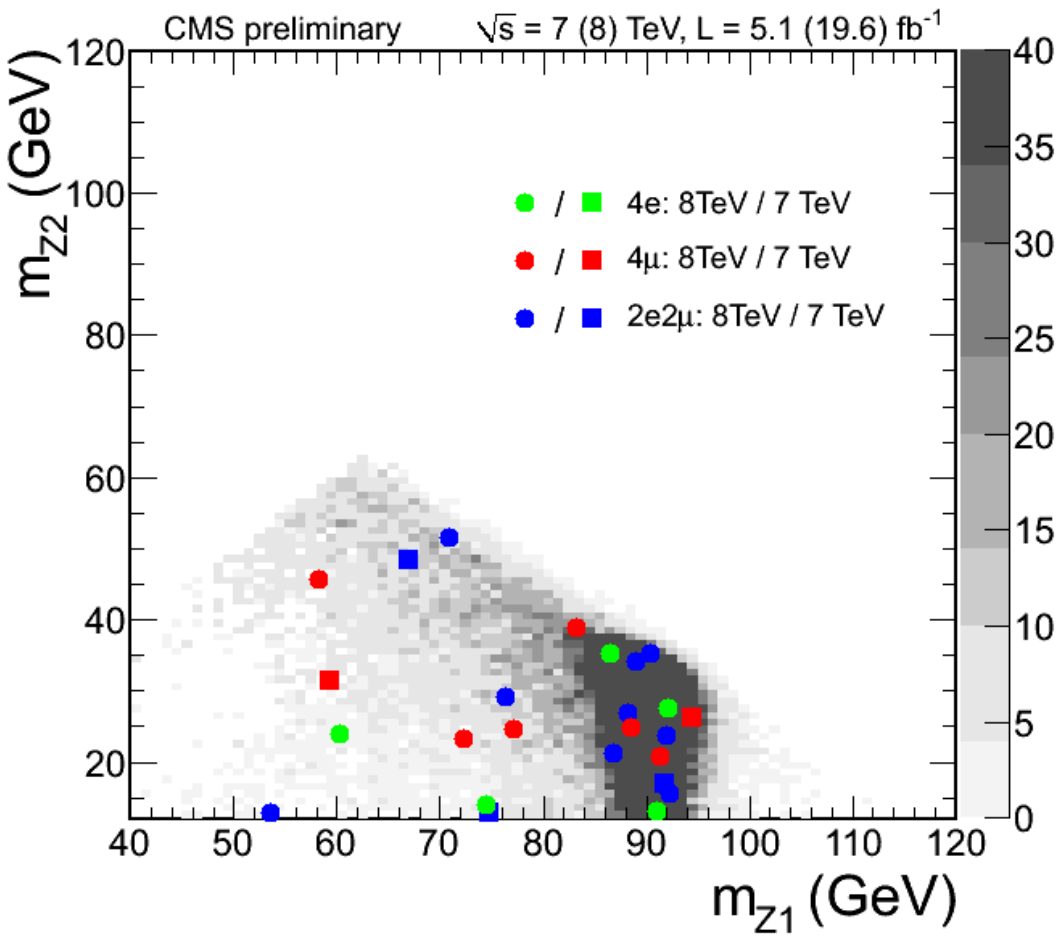
	4e	4μ	2e2μ
H(126)	3.0	6.7	8.9
ZZ	1.2	2.7	3.5
Z+X	0.6	0.5	0.9
Total Bkg.	1.8	3.2	4.4
Data	5	8	12

A double Crystall ball ideogram drawn for each event including the event error.

Anatomy of the excess







M_{Z1} and M_{Z2} in **121.5 < m_{4l} < 130.5 GeV** is consistent with SM Higgs

Jet categories – couplings

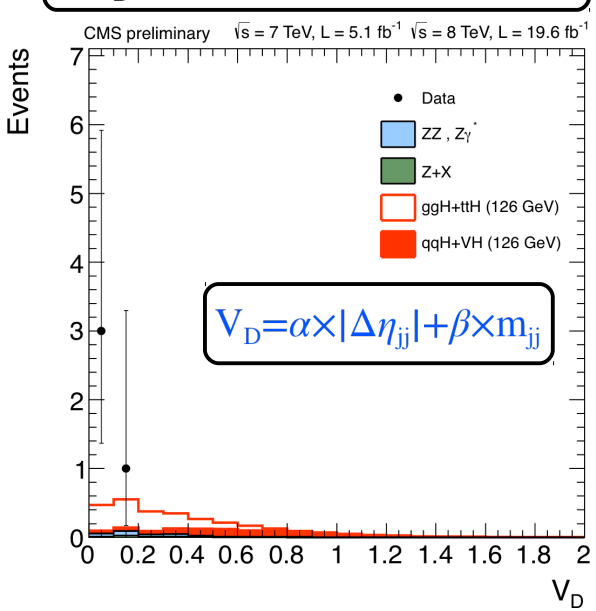
- To **gain sensitivity to VVH and ffH couplings** (μ_V and μ_F) we split events into two mutually exclusive categories:

Category I – "di-jets"
- More than 2 jets (p_T > 30)
- ~20% of signal is VBF

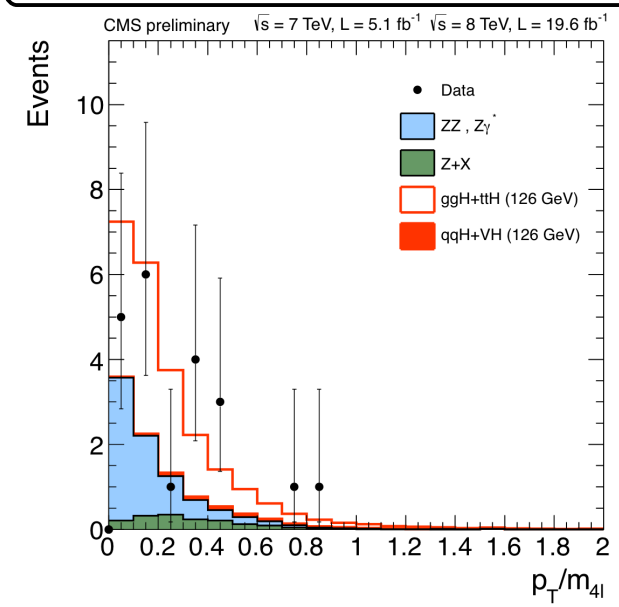
Category II - "untagged"
- Remaining events
- <5% of signal is VBF

- Adding another dimension to the analysis to separate the production mechanisms

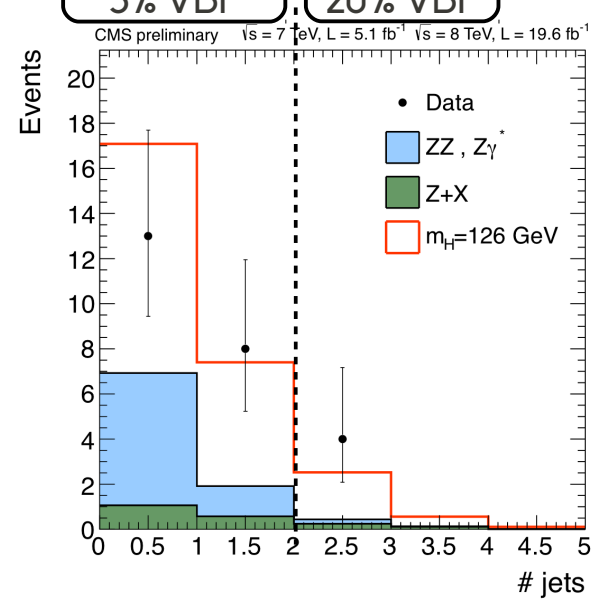
V_D (VBF discriminant)



pT_{4l}/m_{4l} in range m_H<180 GeV



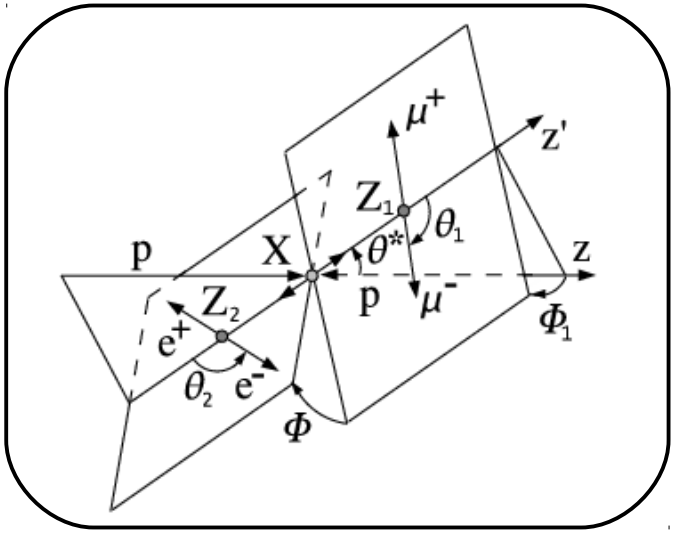
Untagged 5% VBF | **Di-jet 20% VBF**

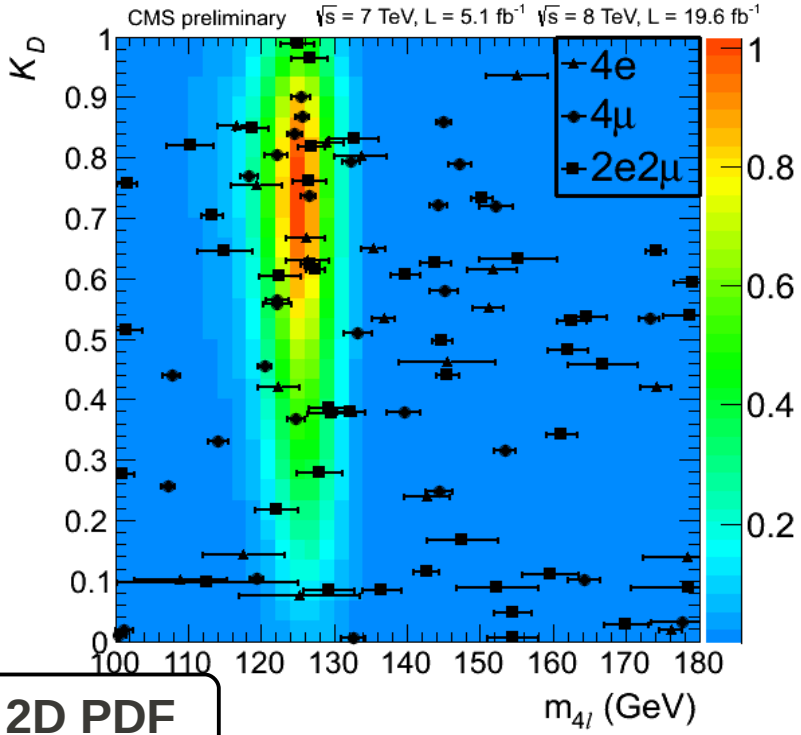


Kinematic discriminant K_D

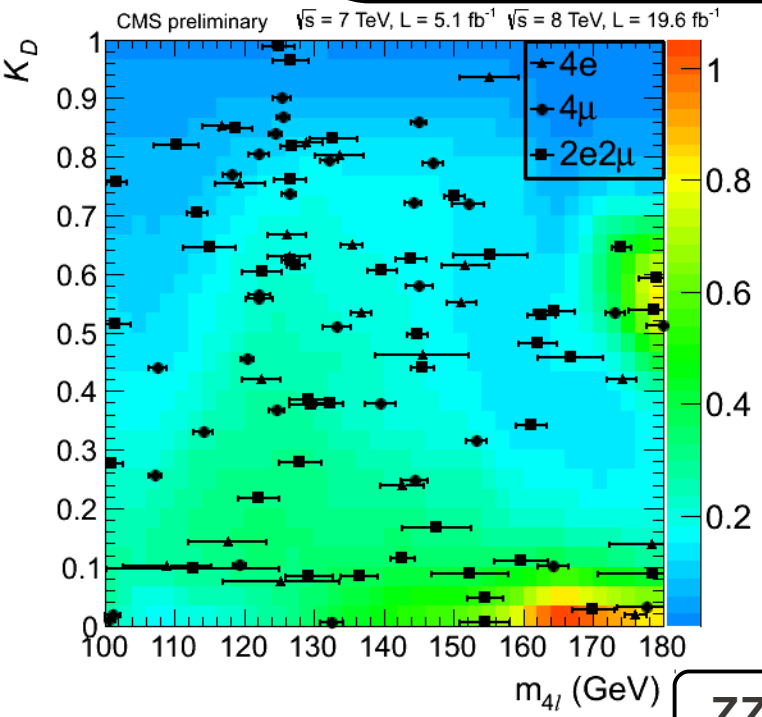
- An additional dimension to profit from the **kinematical differences** between Higgs boson decay and ZZ backgound - K_D
- Builded using Matrix element methods

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





H(126) 2D PDF



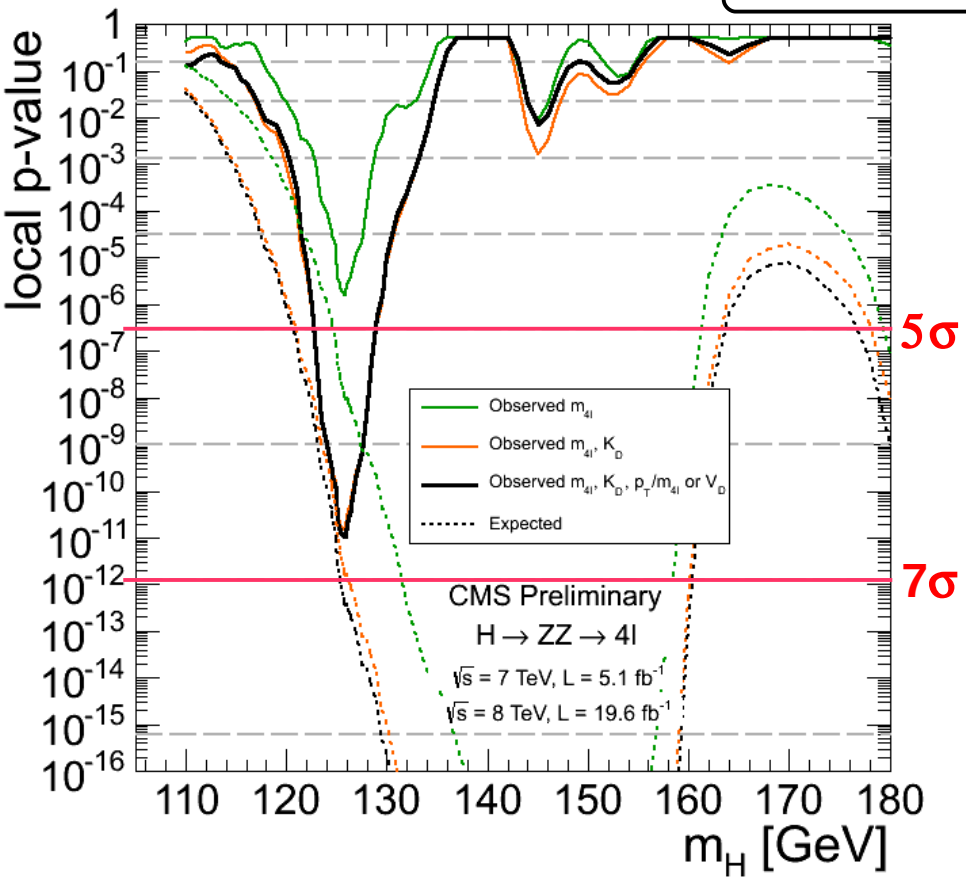
ZZ 2D PDF

Significance of the excess

- Build a factorized 3D model:
  - Category I: $P(m_{4l}, K_D, V_D) = P(V_D|m_{4ll}) \times P(K_D|m_{4l}) \times P(m_{4l})$
  - Category II: $P(m_{4l}, K_D, p_T/m_{4l}) = P(p_T/m_{4l}|m_{4ll}) \times P(K_D|m_{4l}) \times P(m_{4l})$

Binned 2D MC templates

Unbinned m_{4l} model



	Expected	Observed
3D (m_{4l}, K_D, V_D or p_T/m_{4l})	**7.2 σ**	**6.7 σ**
2D (m_{4l}, K_D)	**6.9 σ**	**6.6 σ**
1D(m_{4l})	**5.6 σ**	**4.7 σ**

Values at the minimum of p-value m_H=125.8 GeV

This is the only significant excess in the range up to 1 TeV

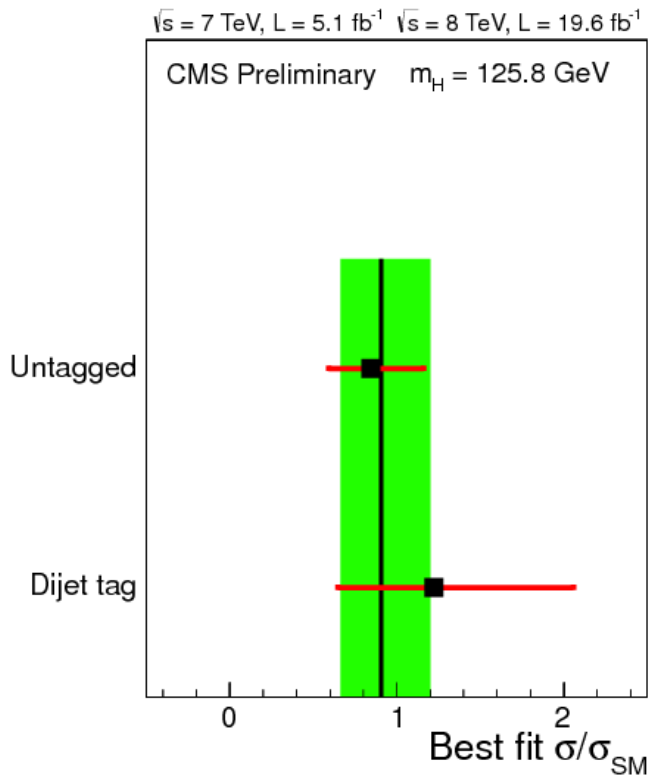
Signal strength σ/σ_{SM}

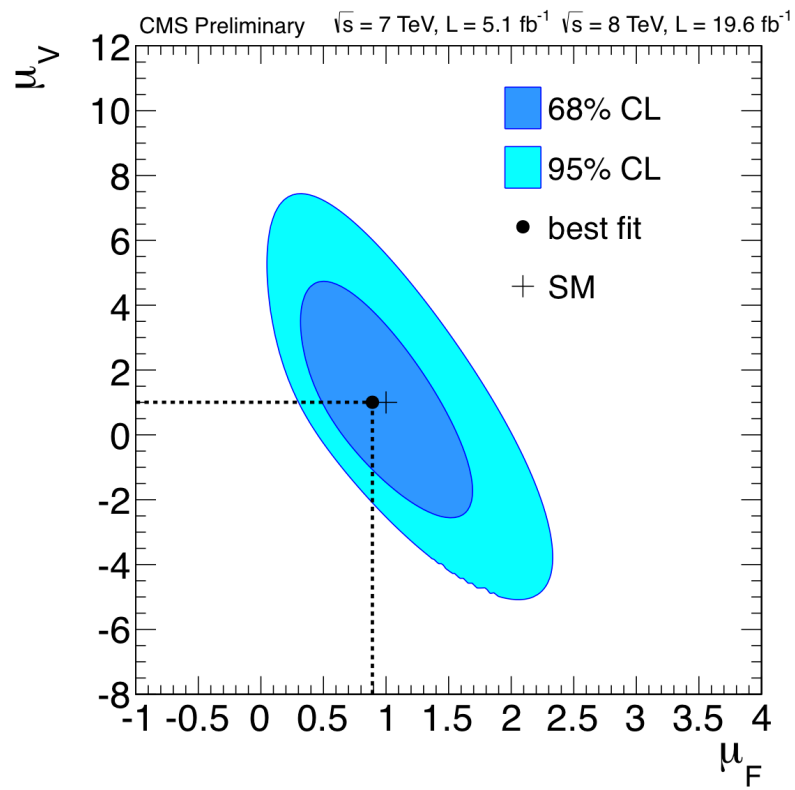
- Results around the best fit mass m_H = 125.8 GeV

$$\sigma/\sigma_{SM} = 0.9^{+0.3}_{-0.2}$$

Reminder:
ICHEP: $\mu = 0.7^{+0.4}_{-0.3}$ @ m_H = 125.6 GeV
HCP: $\mu = 0.80^{+0.35}_{-0.28}$ @ m_H = 125.8 GeV

$$\mu_V(qqH,ZH,WH) = 1.0^{+2.4}_{-2.3}$$
$$\mu_F(ggH, ttH) = 0.9^{+0.5}_{-0.4}$$



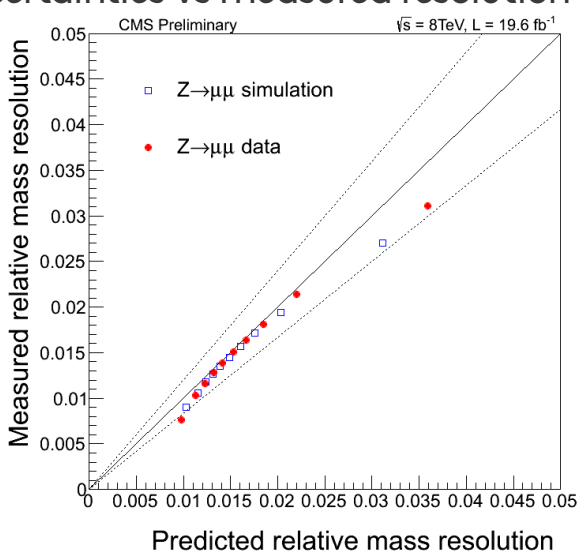


Event-by-event errors on 4l mass

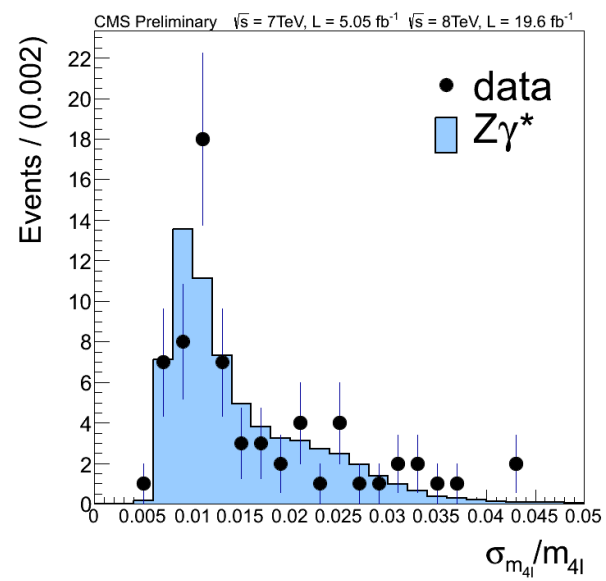
- Added as another dimension to 3D fit when measuring mass
- Per lepton uncertainties:
  - **Electron:** weights from comb. momentum and the track fit for the angles
  - **Muons:** full covariance matrix from the track fit
- Scaled in pT/eta bins to match Z (J/ψ) measured widths
- Propagated to the δm_{4l} using full covariance matrix

Validation

Resolution predicted from the per-lepton uncertainties vs measured resolution



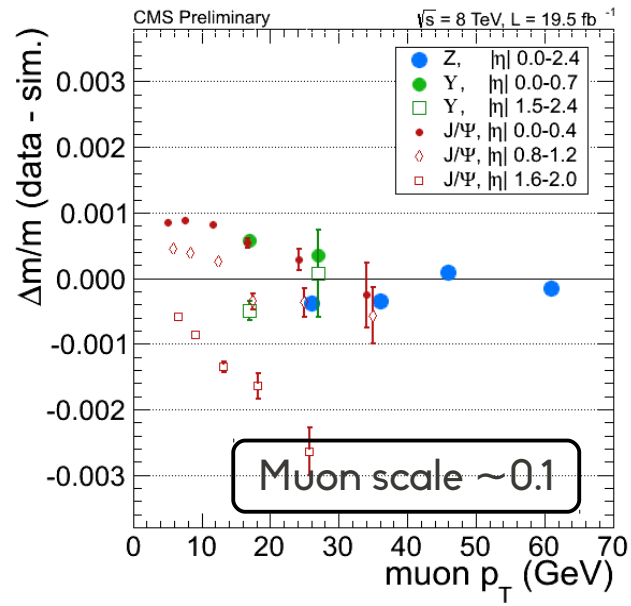
Z-> 4l control region, m4l in [80-100] GeV

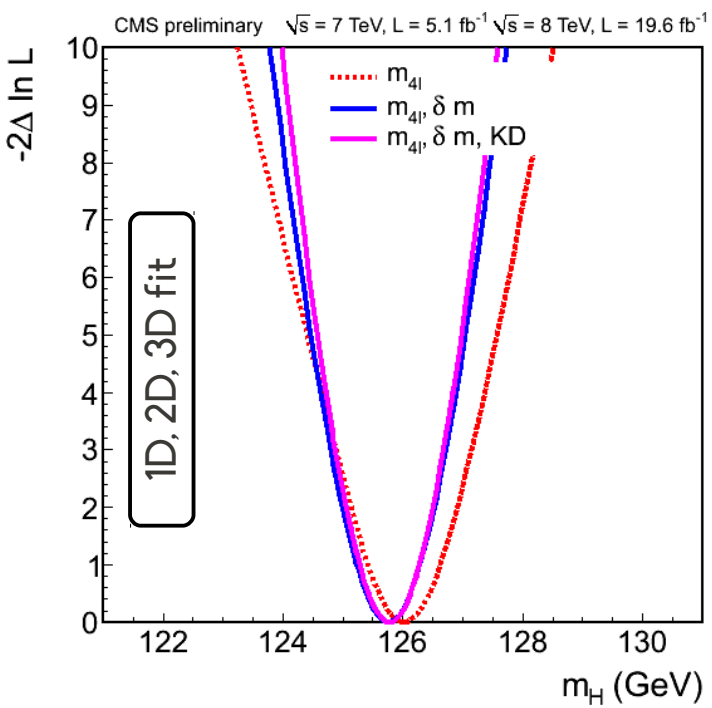


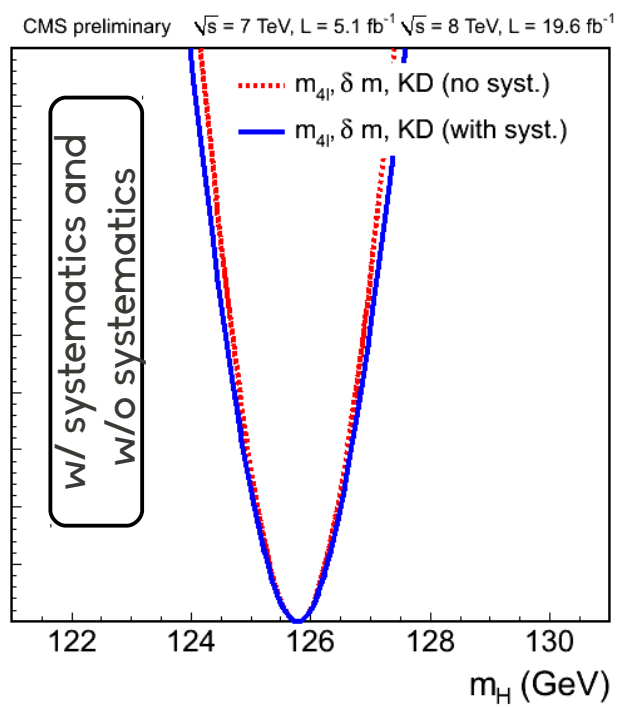
Mass measurement

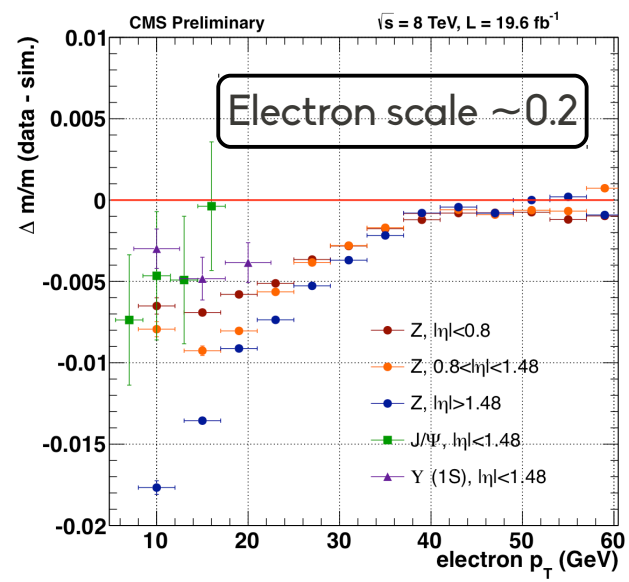
- Measure using 3D fit with **(m_{4l}, δm_{4l}, K_D)**
- Per-event mass errors brings ~8% improvement
- Scale and resolution are main sys. uncertainties
  - calibrated with Z(J/ψ)->ll and Z->4l

$$m_H = 125.8 \pm 0.5(\text{stat.}) \pm 0.2(\text{syst.})\ \text{GeV}$$







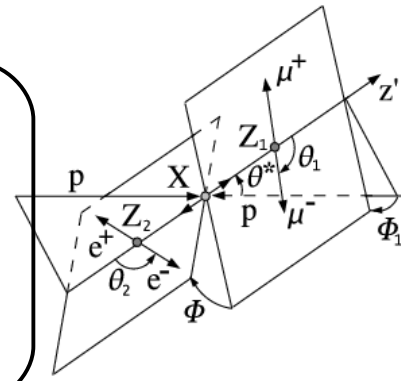


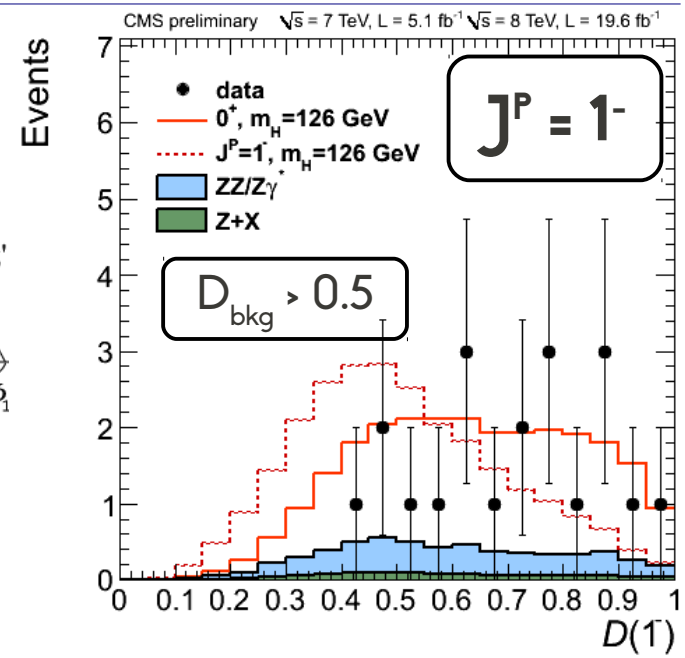
Spin-parity measurements

- Analysis in 2D (D_{J^P}, D_{bkg}) plane:

Discriminator D_{J^P} to separate alternative J^P hypothesis from SM Higgs hypothesis

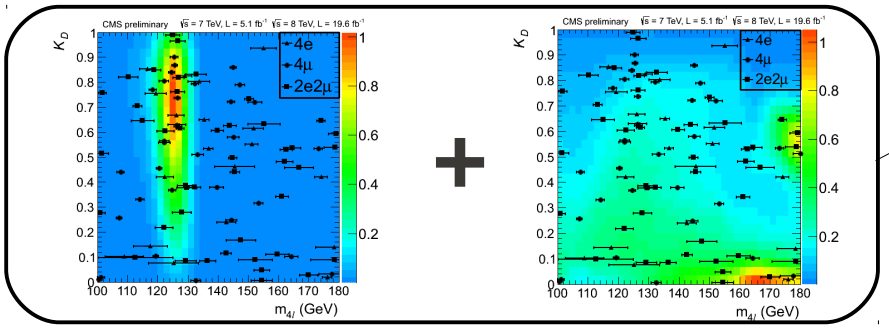
$$D_{J^P} = \left[1 + c_{J^P} \cdot \frac{|\mathcal{M}_{J^P}(\vec{p}_i)|^2}{|\mathcal{M}_{\mathrm{Higgs}}(\vec{p}_i)|^2}\right]^{-1}$$

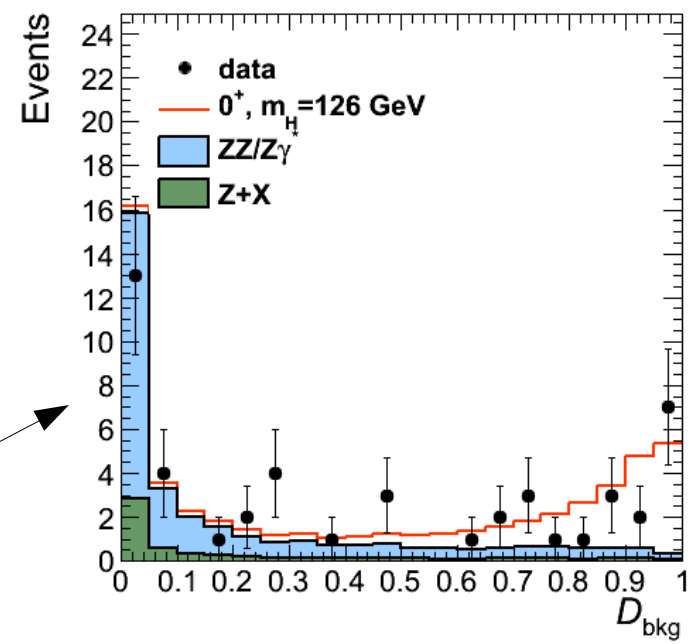




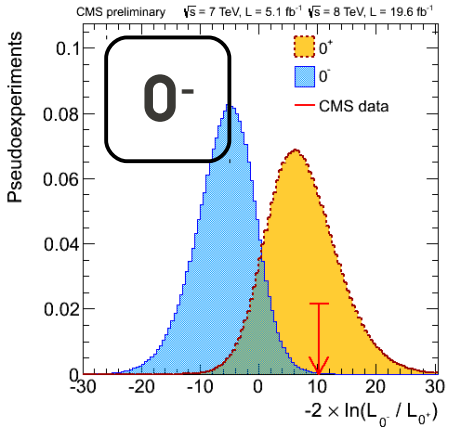
Discriminator D_{bkg} to separate SM Higgs at m_H = 126 GeV from backgrounds

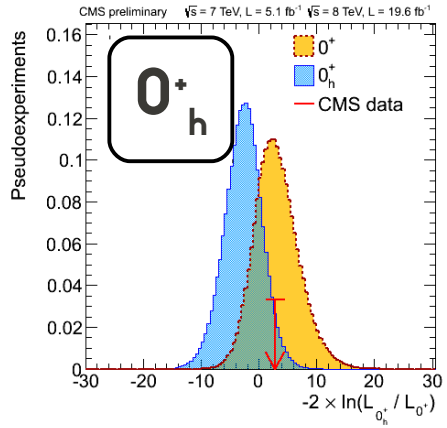
$$D_{\mathrm{BKG}} = \left[1 + c_{\mathrm{bkg}} \cdot \frac{|\mathcal{M}_{\mathrm{BKG}}(\vec{p}_i)|^2 \cdot pdf(m_{4\ell}|\mathrm{BKG})}{|\mathcal{M}_{\mathrm{Higgs}}(\vec{p}_i)|^2 \cdot pdf(m_{4\ell}|\mathrm{Higgs})}\right]^{-1}$$

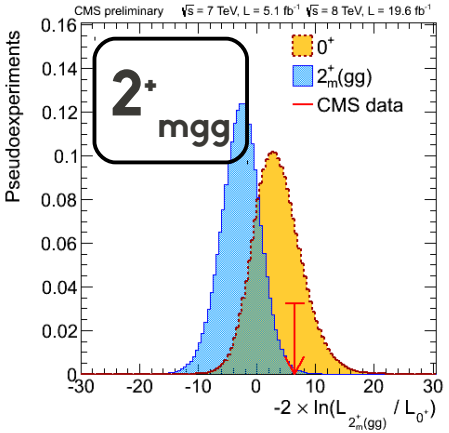




Spin-parity measurements



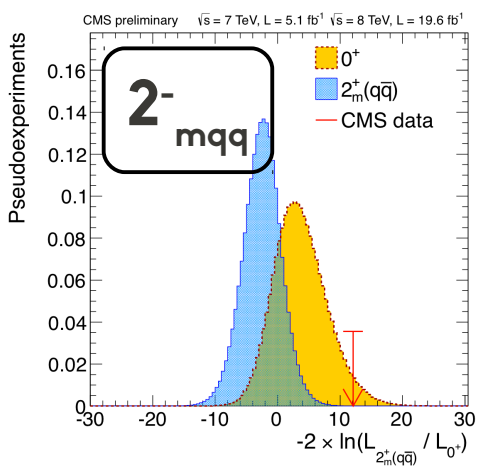


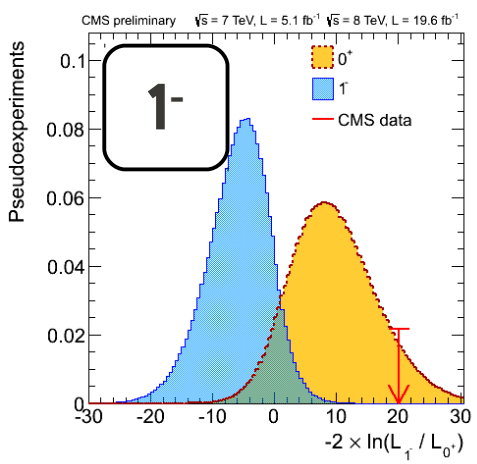


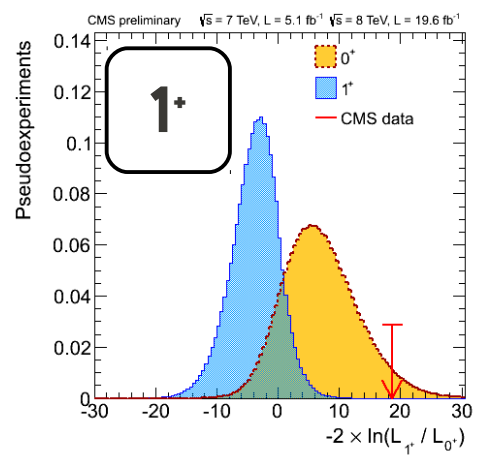
J^P	production	comment	expect (μ=1)	obs. 0^+	obs. J^P	CL_s
0^-	$gg \to X$	pseudoscalar	2.6σ (2.8σ)	0.5σ	3.3σ	0.16%
0^+_h	$gg \to X$	higher dim operators	1.7σ (1.8σ)	0.0σ	1.7σ	8.1%
2^+_{mgg}	$gg \to X$	minimal couplings	1.8σ (1.9σ)	0.8σ	2.7σ	1.5%
$2^+_{mq\bar{q}}$	$q\bar{q} \to X$	minimal couplings	1.7σ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

All but 0^+_h hypothesis excluded at 95% CL

NB:Signal strength free in fits







JP fit - CP violation test

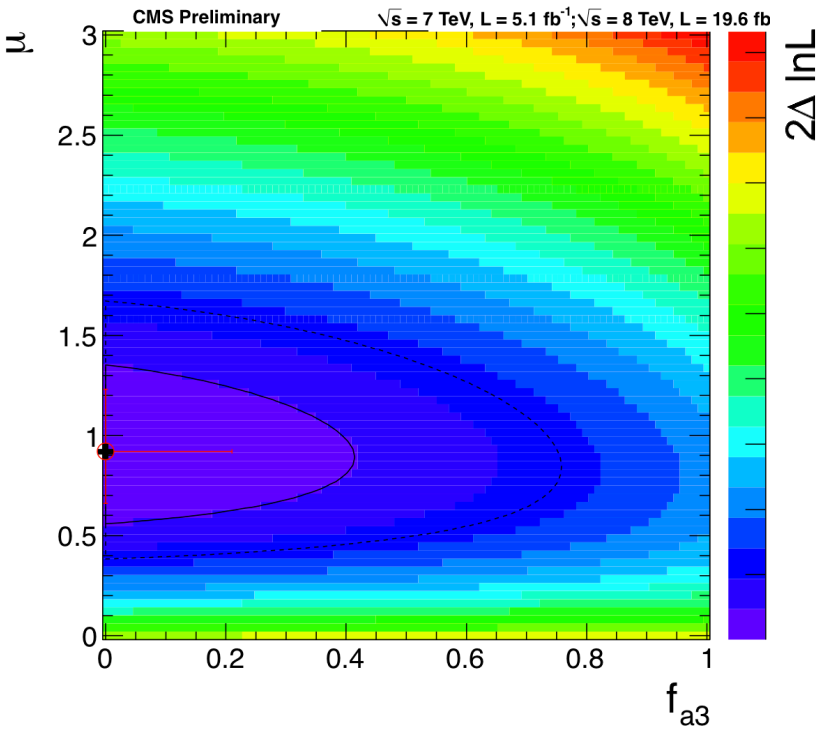
- Spin-0 boson general decay amplitude:

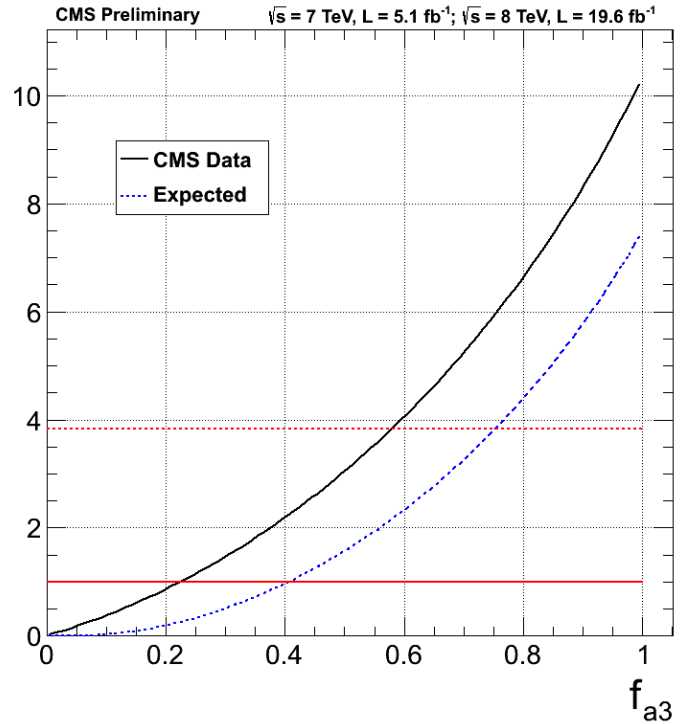
$$A = v^{-1}\epsilon_1^{*\mu}\epsilon_2^{*\nu}(a_1 g_{\mu\nu} m_H^2 + a_2 q_\mu q_\nu + a_3 \epsilon_{\mu\nu\alpha\beta} q_1^\alpha q_2^\beta) = A_1 + A_2 + A_3$$

- A_1 dominates for SM Higgs (0^+) and A_3 for 0^-
- Presence of both amplitudes indicates CP violation

Fraction of CP violating contribution:

$$f_{a3} = \frac{|A_3|^2}{|A_1|^2 + |A_3|^2}$$



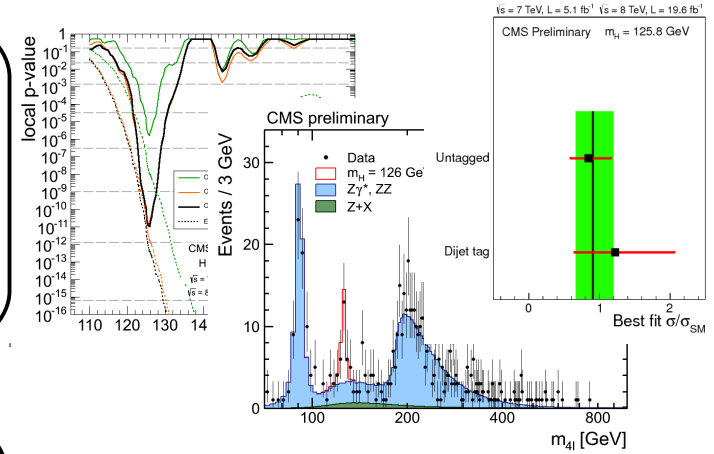


$$f_{a3} = 0.0^{+0.23}_{-0.00}$$

Summary

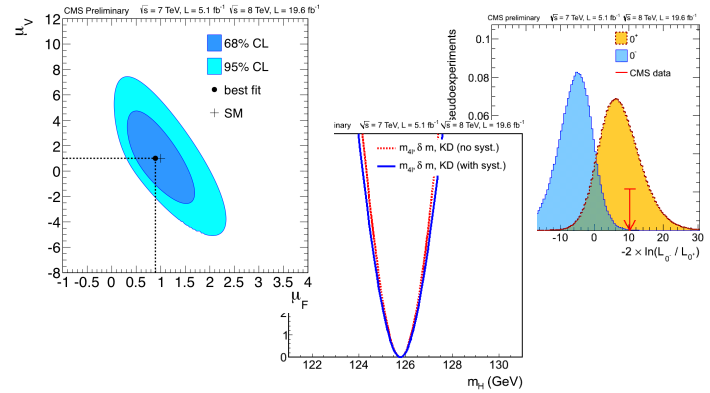
Results from the H→ZZ→4l analysis with full dataset 5.1 fb^{-1} (7 TeV), 19.6 (8TeV):

- 6.7 (7.2) s.d. observed(expected) significance
- $\sigma/\sigma_{SM} = 0.9^{+0.3}_{-0.2}$



H→ZZ→4l properties measurements:

- μ_V(qqH,ZH,WH) = $1.0^{+2.4}_{-2.3}$
- μ_F(ggH, ttH) = $0.9^{+0.5}_{-0.4}$
- m_H = 125.8 ± 0.5(stat.) ± 0.2(syst.) GeV
- 6 spin-parity hypothesis tested
- no CP violating contribution



All the measurements in H→ZZ→4l indicate the

high Standard-Modelicity

of the observed boson

Back-up: Systematics

	ggH	qqH	WH	ZH	ttH	qqZZ	ggZZ
gg partonic luminosity	7.5-10				0-10		10
qq partonic luminosity		2.2-4.7	0-4.5	0-5		5	
QCD scale (ggH)	8.7-10						
QCD scale (qqH)		0-1.5					
QCD scale (VH)			0-0.75				
QCD scale (ttH)				0-8.3			
Uncertainty on BR(H)	2						
QCD scale for ZZ (NLO)						2.6-6.7	
QCD scale for gg							24-44
Electron Scale	0.1-0.2						
Muon Scale	0.1						
Electron/Muon resolution	20%						
Electron Efficiency	2.5-5(4e) ,1.7-2 (2e2μ)						
Muon Efficiency	0.5-5(4μ), 0.2-2.2(2e2μ)						