Higgs $\rightarrow$ ZZ at CMS

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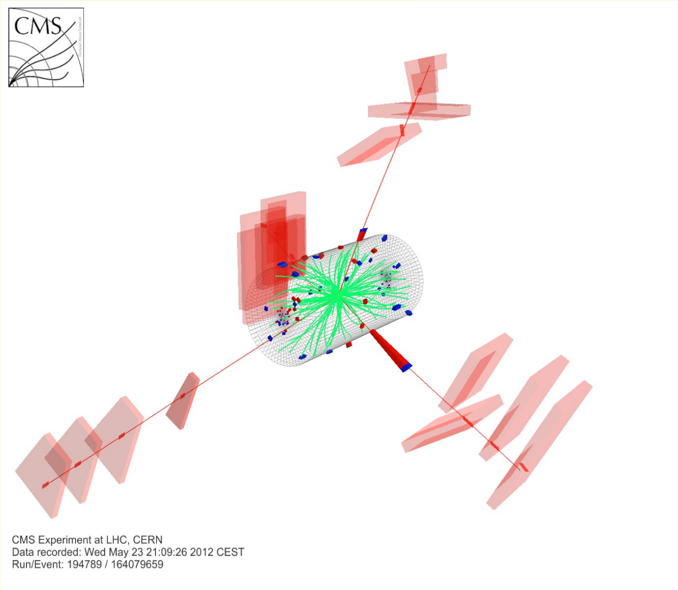
Aspen 2013: Higgs Quo Vadis

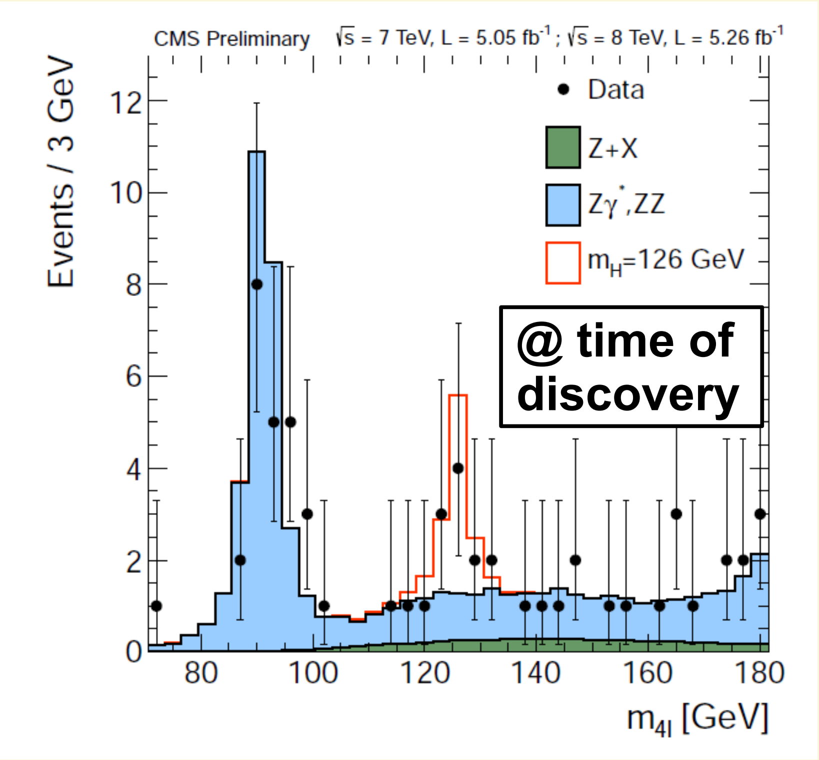
03/12/2013

Caltech

Introduction

- $H \rightarrow ZZ \rightarrow 4l$ becoming the most sensitive channel at the LHC
- Low bkg & High resolution

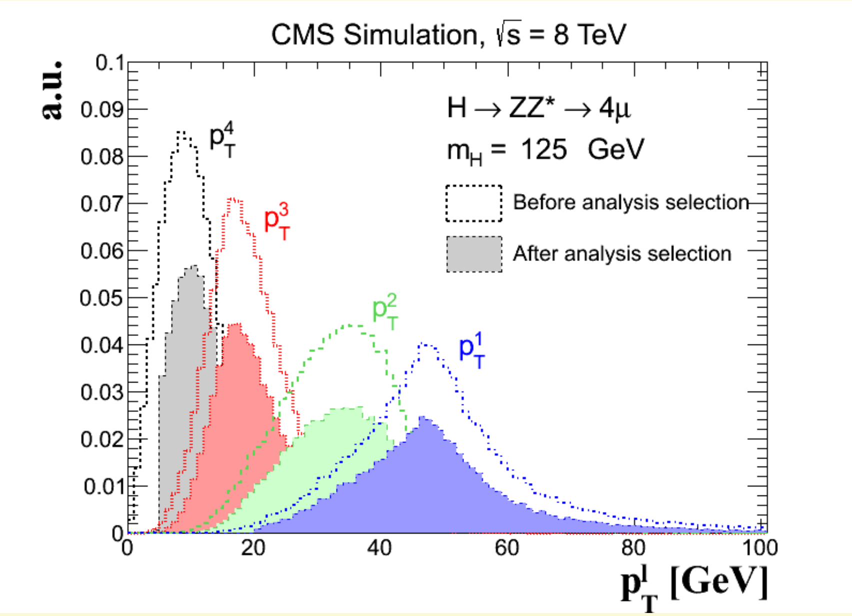




- Fully reconstructed event
- Lots of kinematic information
- Ideal setting for measurement of properties

Selecting Leptons from the Higgs

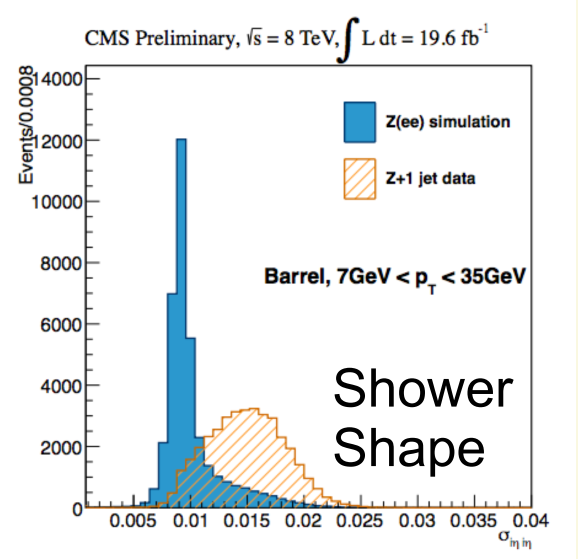
- One pair of leptons mostly yields an on-shell Z
- Other pair is off-shell and typically very low in pT
  - Almost 50% have pT less than 10 GeV



A major challenge for lepton selection

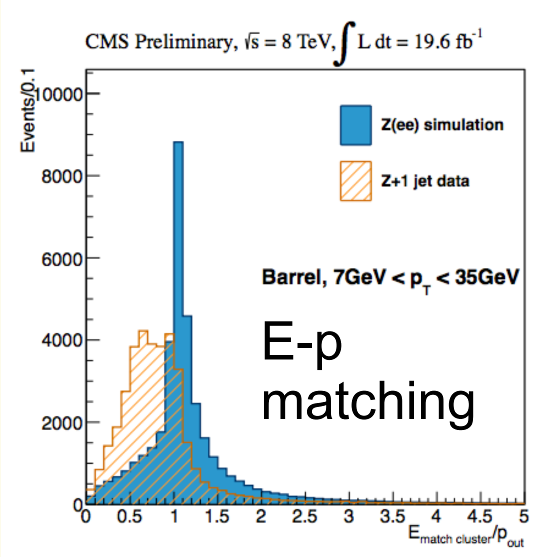
- Control of bkg rate difficult at low pT
- Control of lepton selection efficiency difficult at low pT

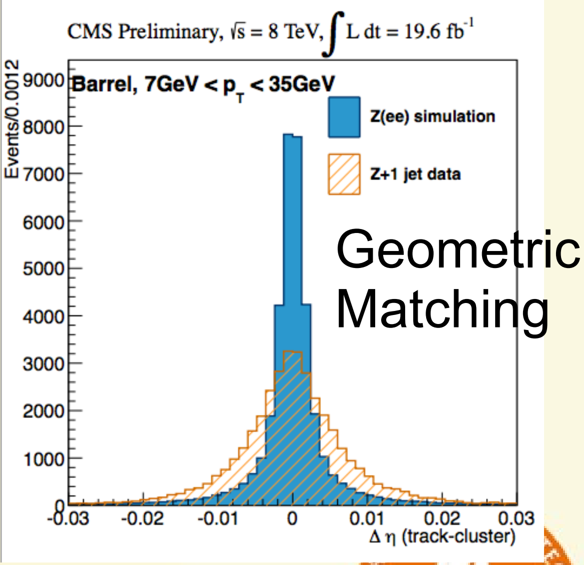
Multivariate Electron selection



• Improve discrimination power by combining multiple observables using a boosted-decision tree

• BDT training is performed using signal simulation & W+Jets data sample

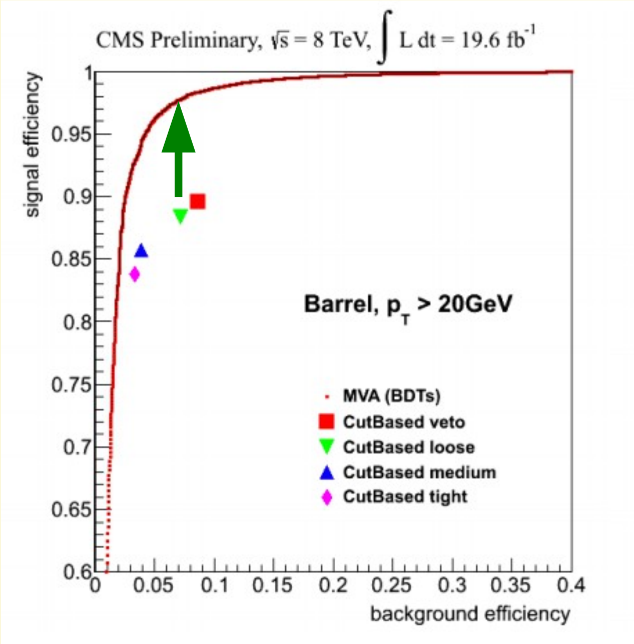


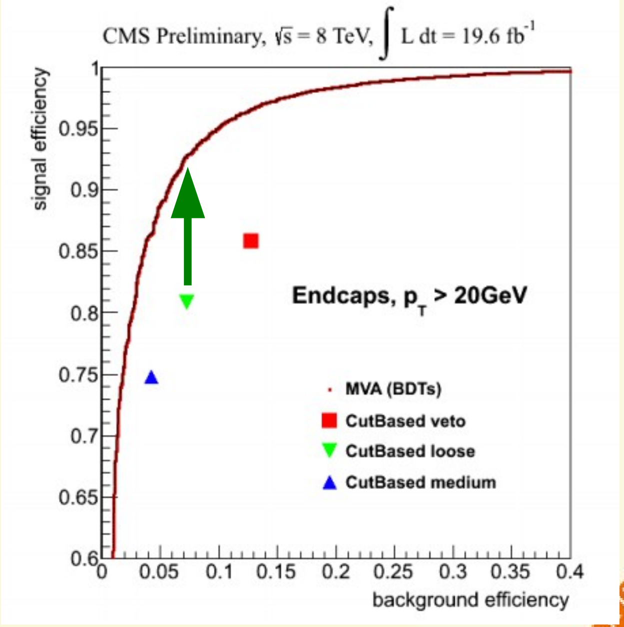


Multivariate Electron selection

- Evaluating with statistically independent signal and bkg samples, we observe significant increase in performance:
  - At same bkg rate, signal efficiency increases wrt cut-based:

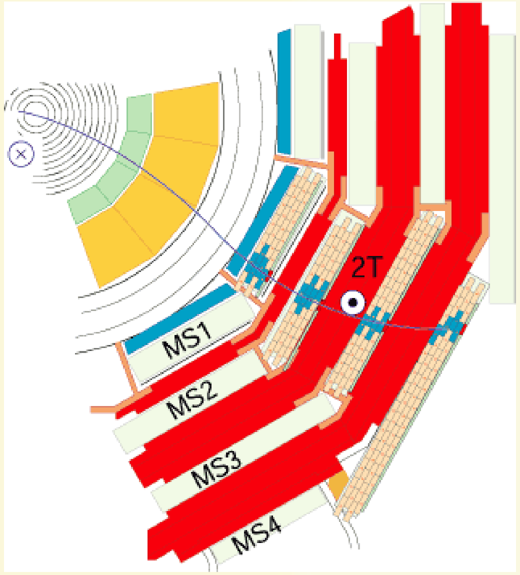
Barrel	Endcap
90% → 98% pT > 20 GeV	85% → 95% pT > 20 GeV
70% → 85% pT < 20 GeV	50% → 70% pT < 20 GeV

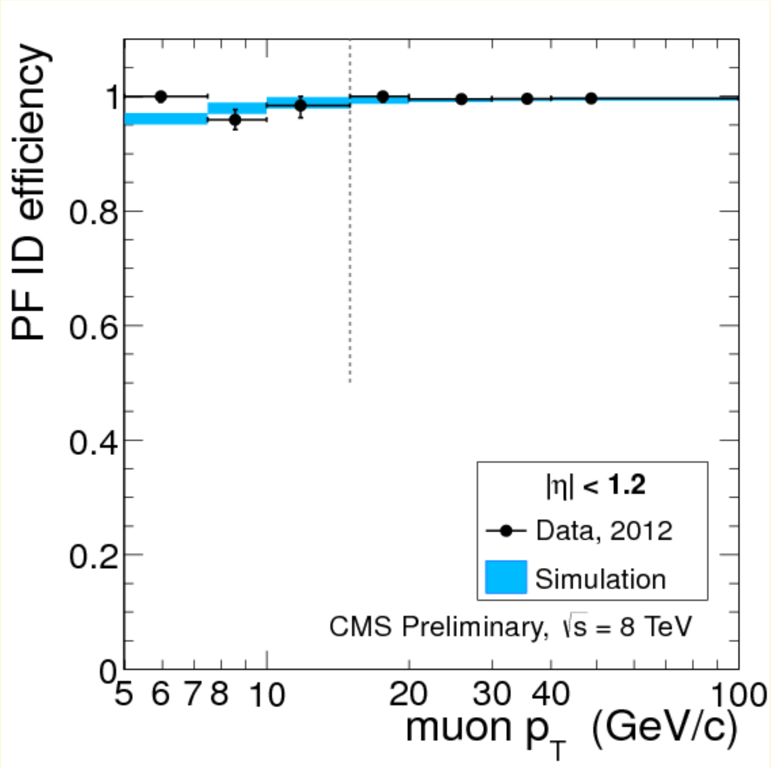




Muon Selection

- Large amount of material and the 3.8T solenoid yields very pure and precisely measured muons at CMS

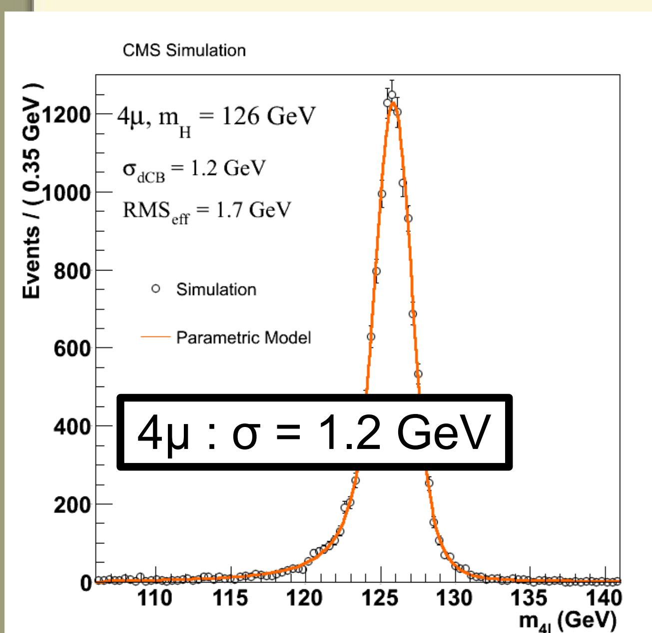


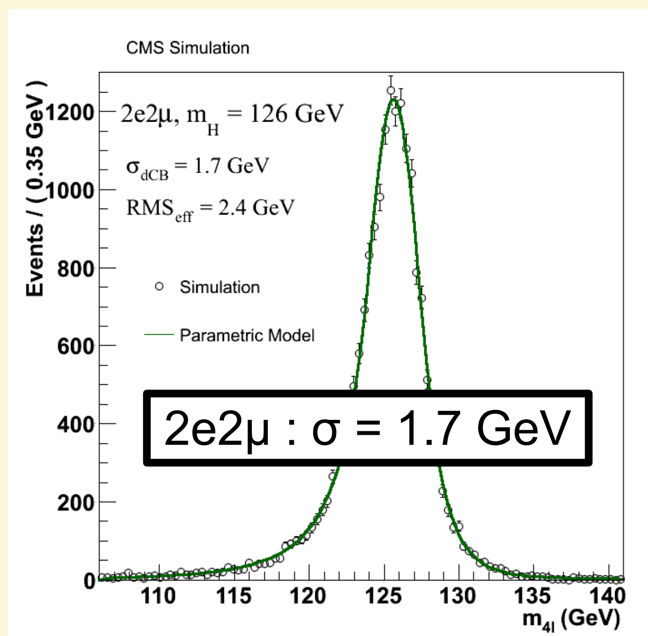


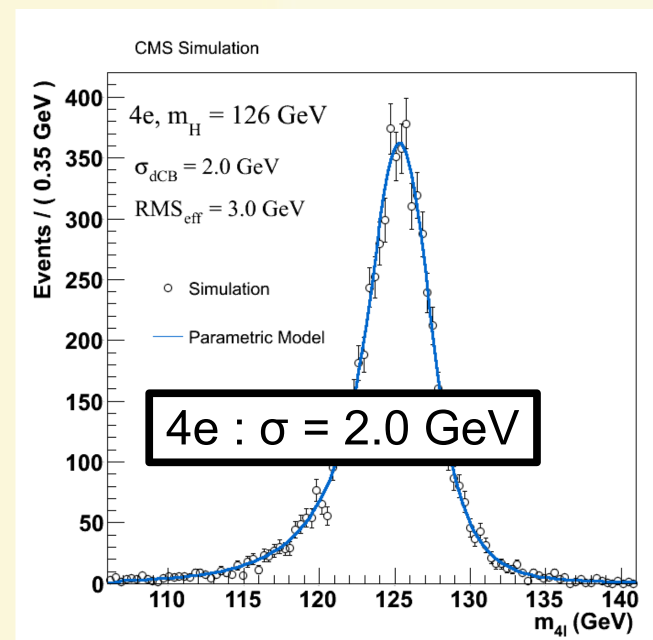
- Very loose cuts on track quality, calorimeter features and isolation yields very low bkg rates for signal efficiencies well above 95% even for muons with p_T down to 5 GeV

Momentum Resolution

- Once four lepton candidate events are selected, we look for a resonance in the 4-lepton mass
- Better lepton momentum resolution will act to suppress the impact of bkg





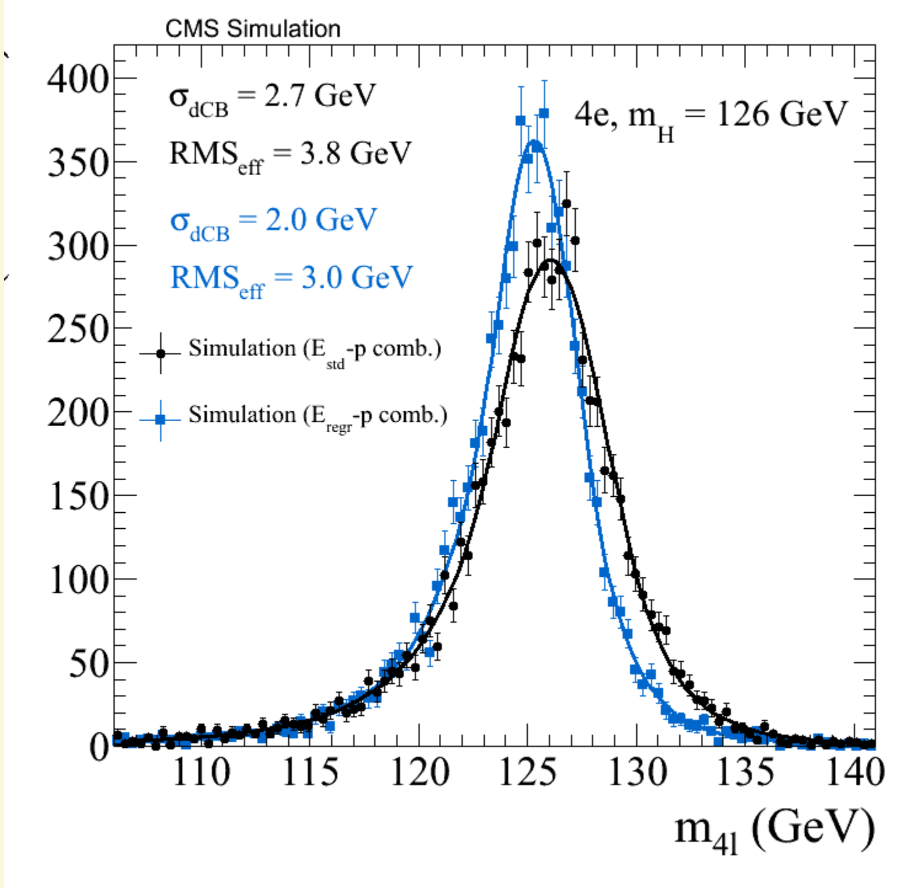


Electron Energy Regression

- Clustering corrections are applied using a multivariate regression trained with simulation

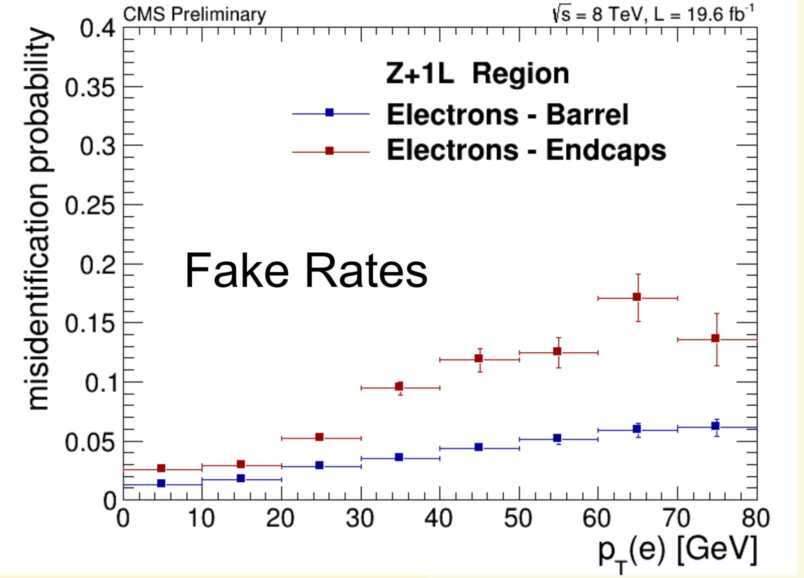
- Incorporates detailed information on shower shape & local geometry (gaps and crystal edges)

- **Improvement on mass resolution in 4e of 25%**

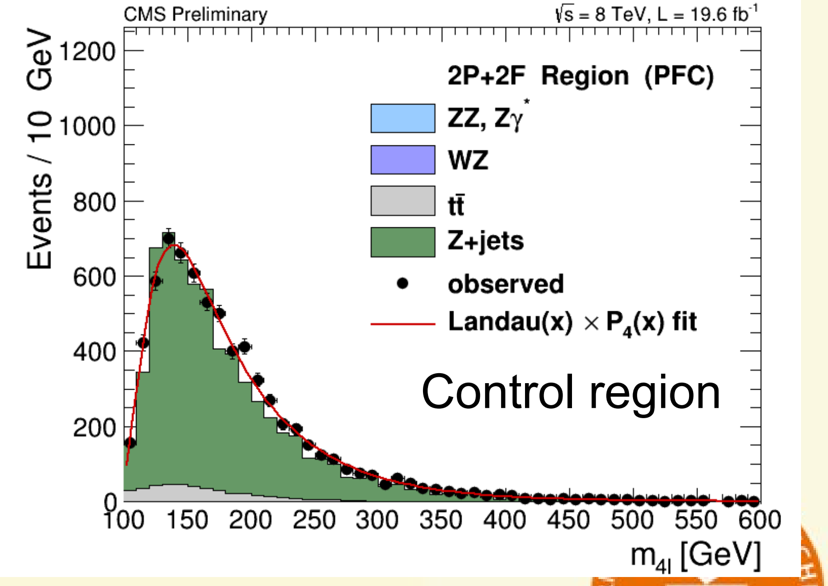


Background estimation

- Main backgrounds include
  - ZZ* production
  - "Fake" lepton bkg
    (mainly Z+jets)



- ZZ* bkg predicted from simulation
- "Fake" lepton bkg estimated by extrapolating in lepton ID & Isolation



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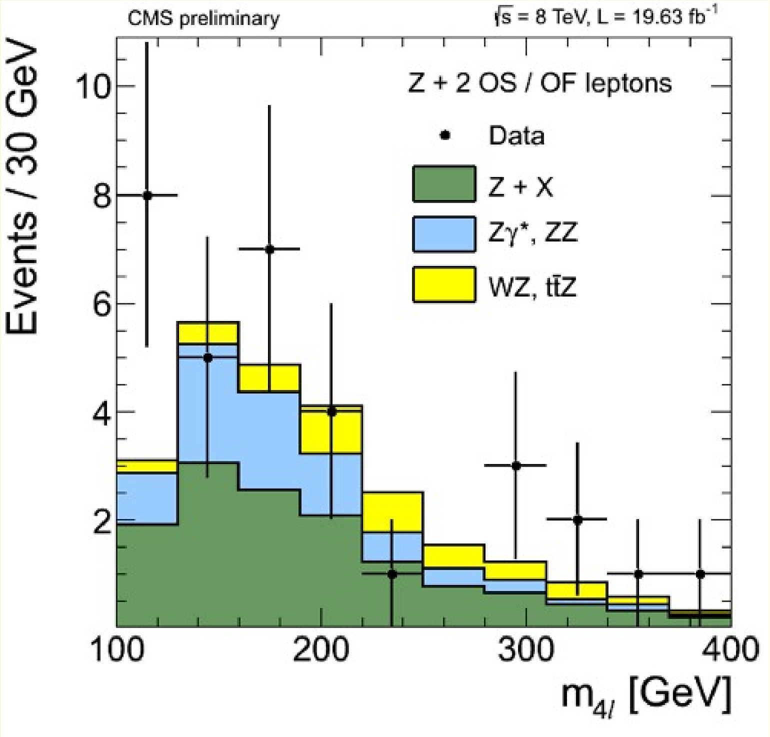
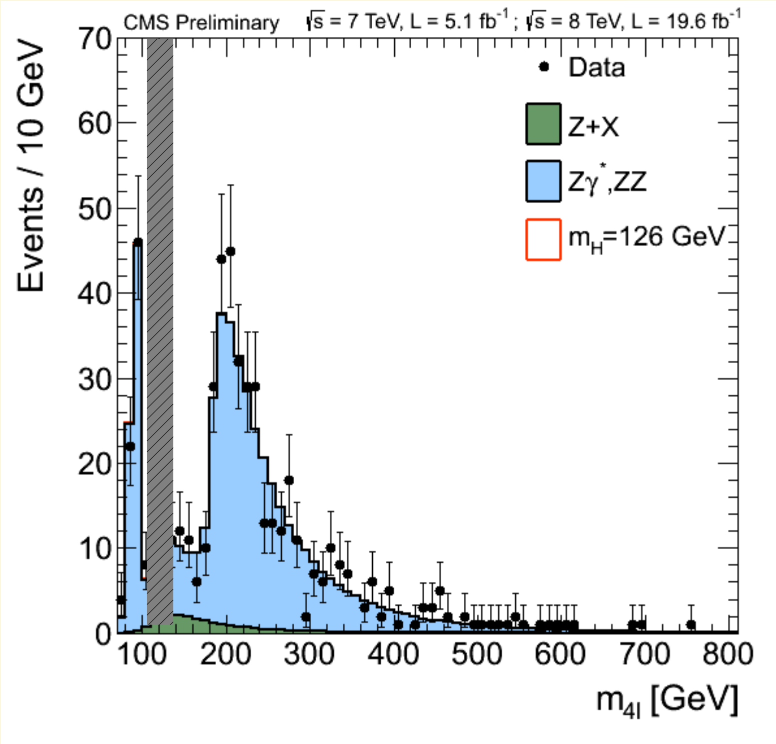
Background Control Regions

- High Mass control region dominated by continuum ZZ bkg well reproduced by Monte Carlo simulation
- Z+eμ control region dominated by fake lepton bkg agrees with data-driven estimates





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Signal & Background

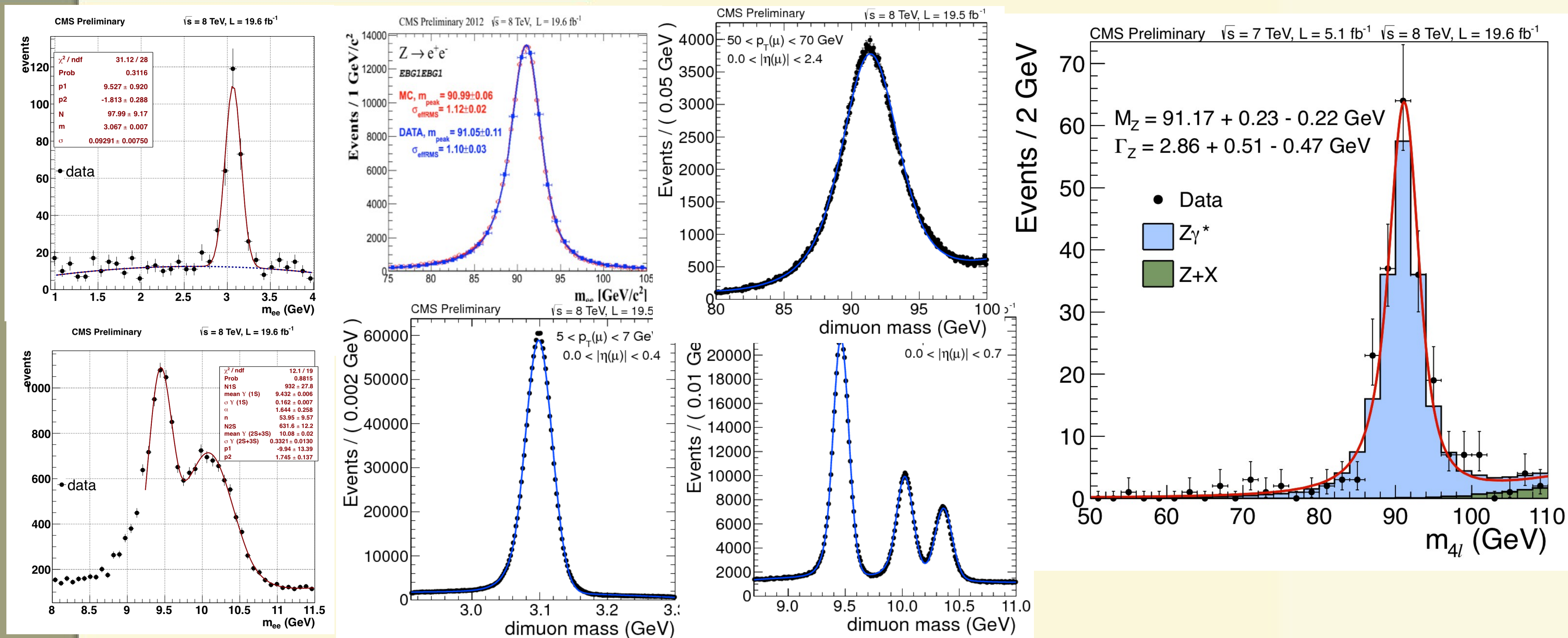
Near the signal resonance:
S/B ~ 2:1

Signal and Bkg Yield
For 121.5 < m4l < 130.5 GeV

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

Signal+Bkg	28.0
Data	25

Controlling the signal model

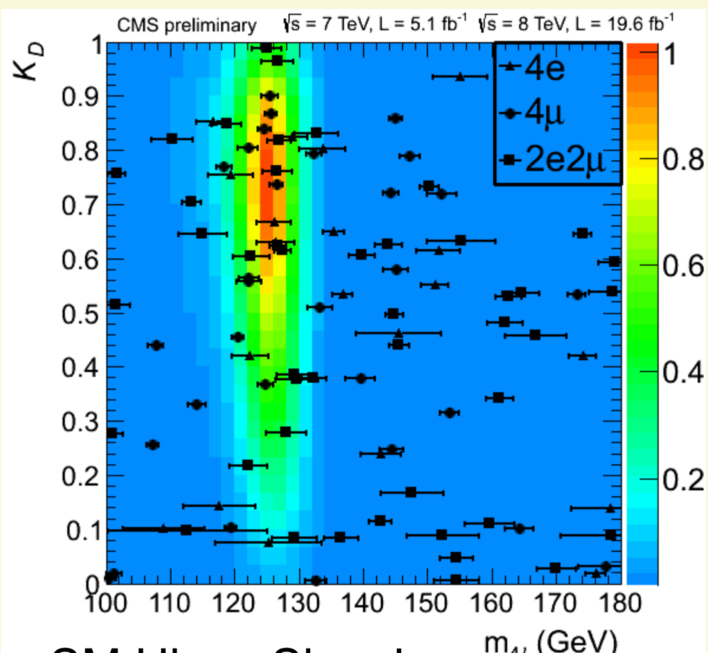


- J/ψ , ϒ & Z decays to ee and μμ used to control momentum scale and resolution across p_T and η spectrum
- Z → 4l resonance used to cross check the signal mass model

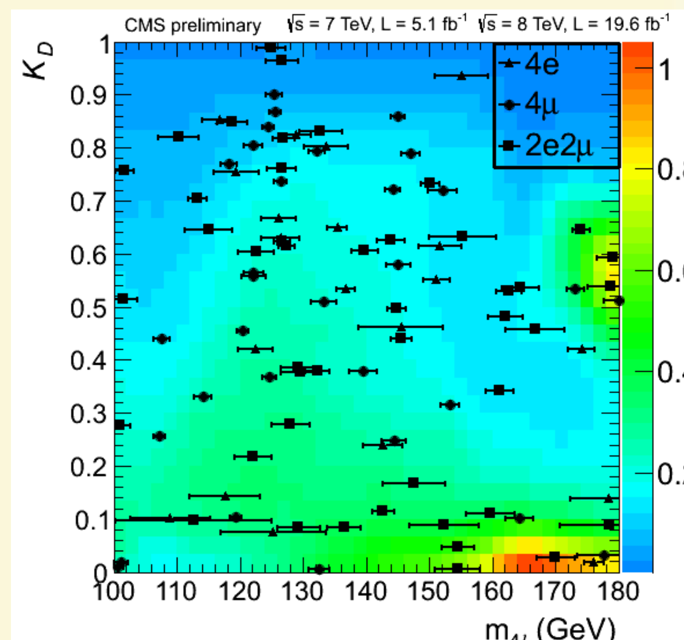
Kinematic Discriminant

- To improve signal to bkg discrimination further, we make use of a discriminant based on kinematic information (angles and masses)

$$KD = \frac{P_{sig}(m_1, m_2, \vec{\Omega} | m_{4l})}{P_{sig}(m_1, m_2, \vec{\Omega} | m_{4l}) + P_{bkg}(m_1, m_2, \vec{\Omega} | m_{4l})}$$



SM Higgs Signal



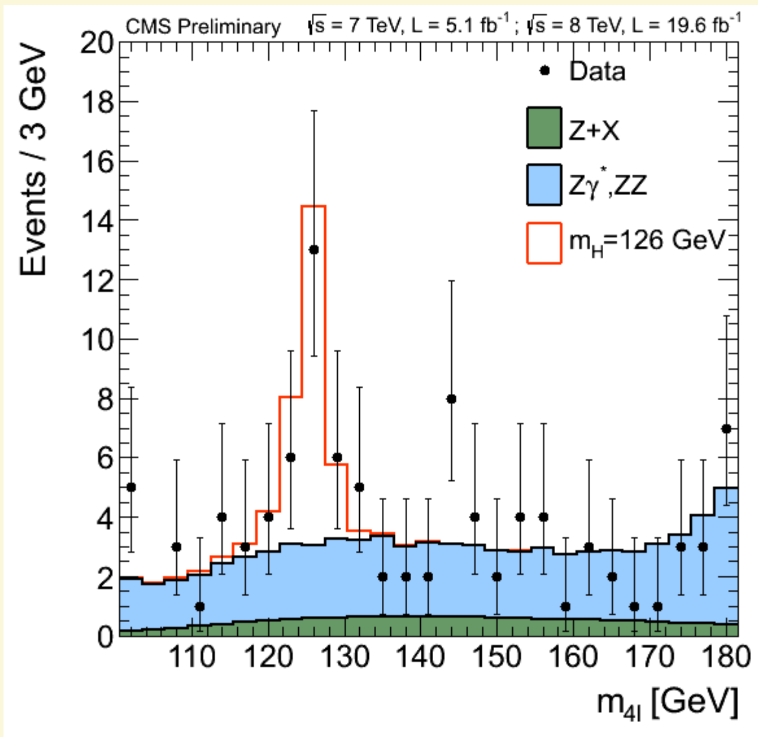
ZZ* Bkg

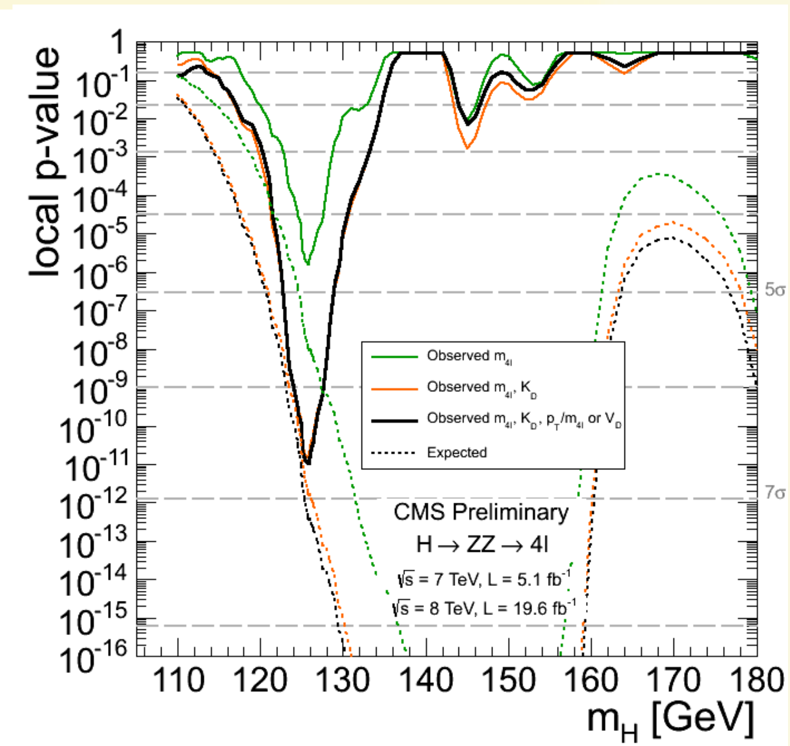
Dijet Category

• To have sensitivity to both VV couplings and fermion couplings, we split events into 2 categories:

Di-jet tag PT > 30 GeV, |n| < 4.7 Jet ID to reject fake jets from pileup **VBF signal fraction ~ 20%**	Then fit for shape of discriminant based on m_{jj} and $\Delta\eta_{jj}$
Un-tagged **VBF signal fraction ~ 5%**	Then fit using p_{T4l} / m_{4l} as discriminant

The Higgs Resonance





	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	5.6 σ

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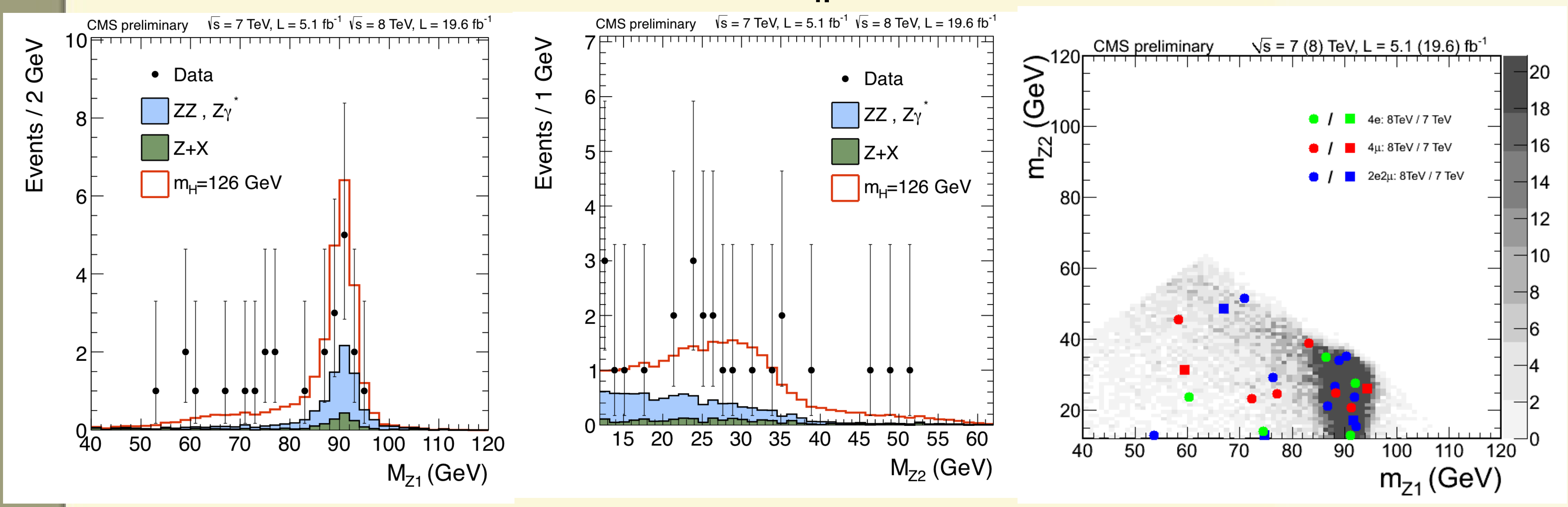
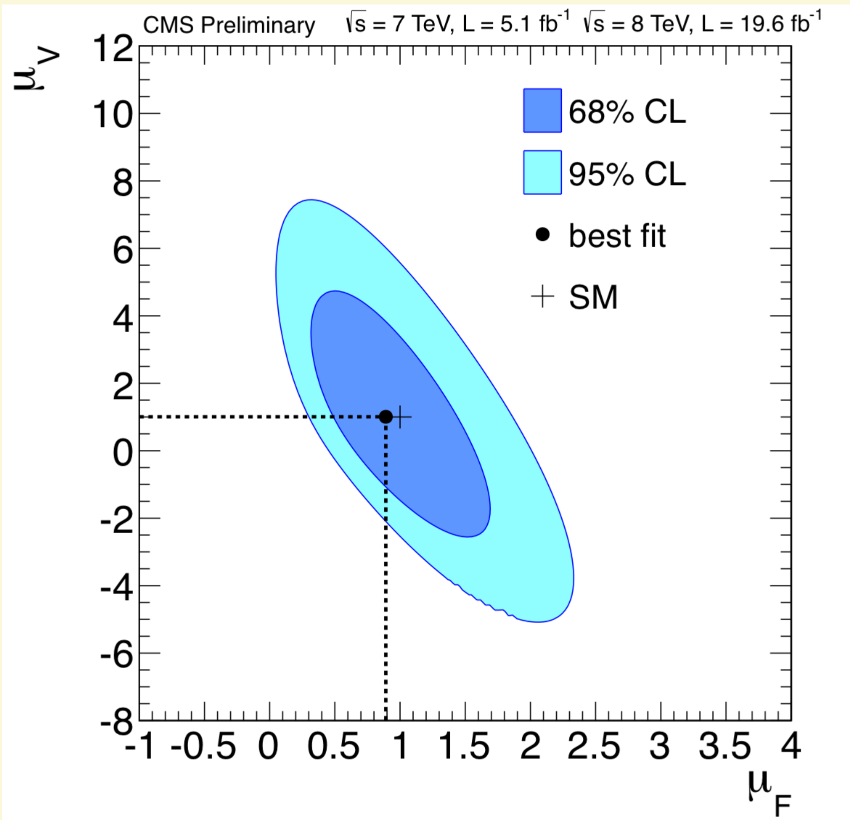
The Higgs Resonance

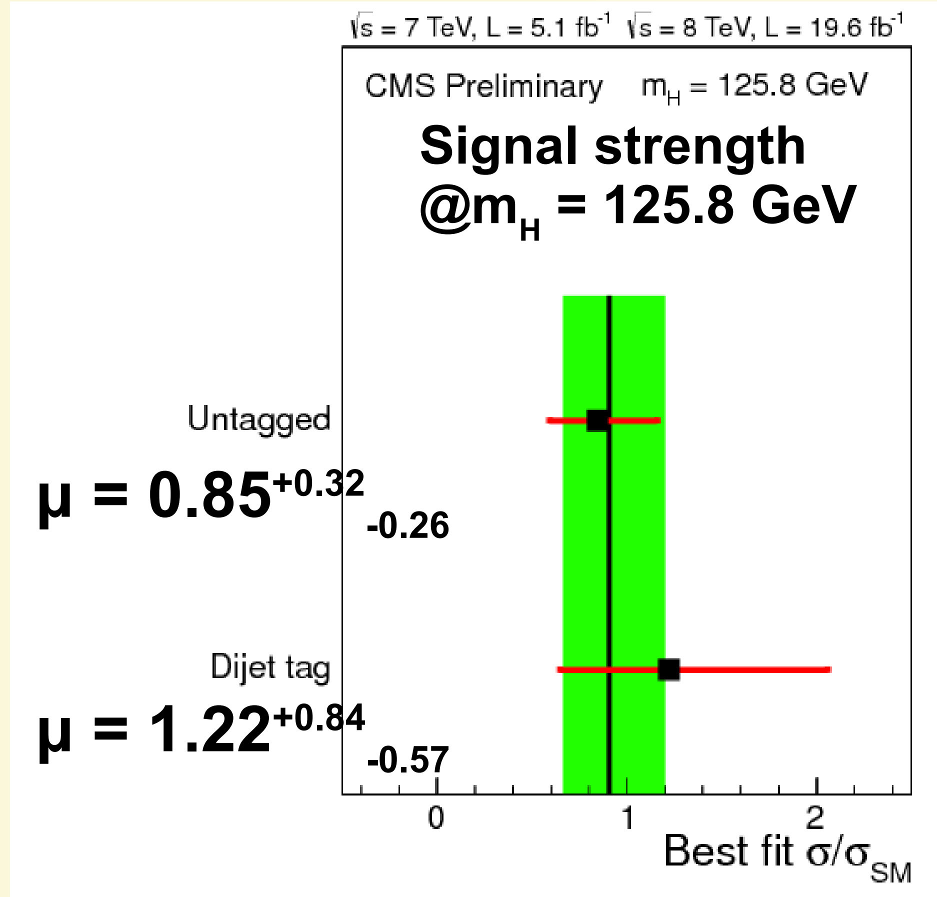
m_{4l} in [121.5, 130.5]



- M_{Z1} exhibits a few more events off-shell compared to SM Higgs expectation
- Statistically not very significant

Cross-Section Measurement





$\mu = 0.85^{+0.32}_{-0.26}$

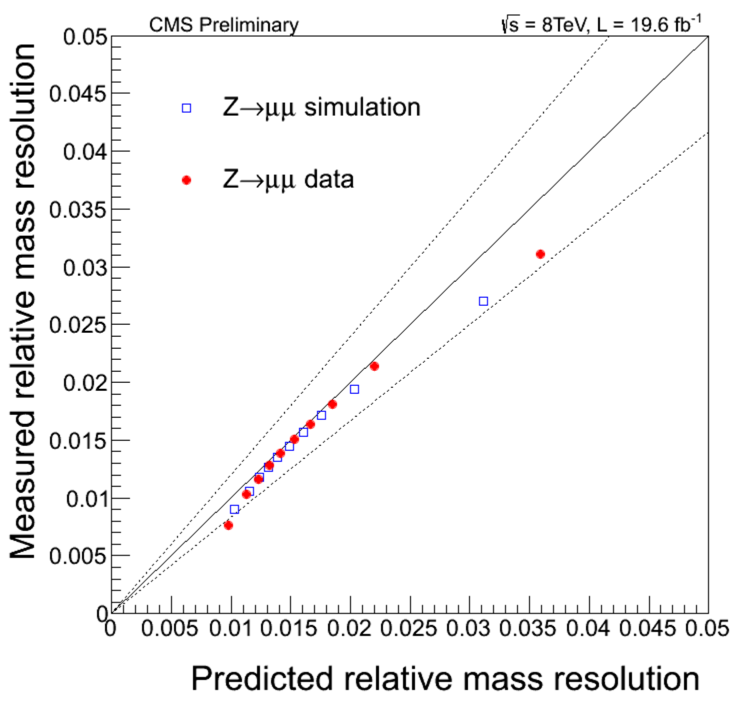
$\mu = 1.22^{+0.84}_{-0.57}$

Combined $\mu = 0.91^{+0.30}_{-0.24}$

- Well compatible with SM expectations

Mass Measurement with Event-by-Event Uncertainties

- To improve the precision of the mass measurement, we perform a fit to the estimated per-event mass uncertainty in addition to m_{4l} and the KD
  - The predicted per-event mass uncertainty is validated and corrected using Z→μμ and Z→ee data
  - Additional cross-check performed by measuring the Z mass and width from Z→4l decays:

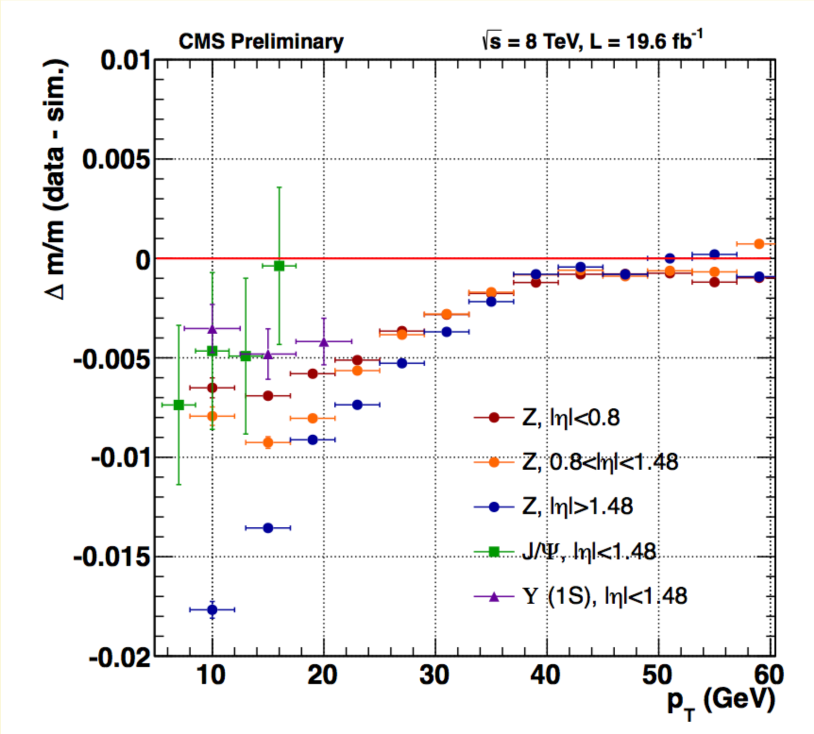


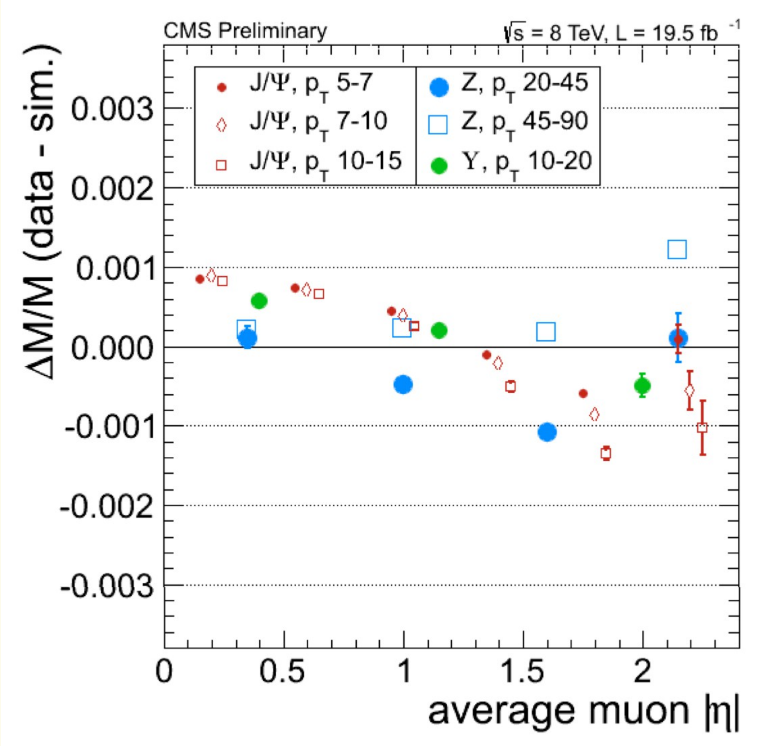
$\Gamma_Z = 2.86^{+0.51}_{-0.47}$ GeV **$M_Z = 91.17^{+0.23}_{-0.22}$ GeV**

Consistent with PDG value of 2.4952 GeV and 91.1876 GeV

Lepton Momentum Scale

- The leading systematic uncertainty for mass measurement



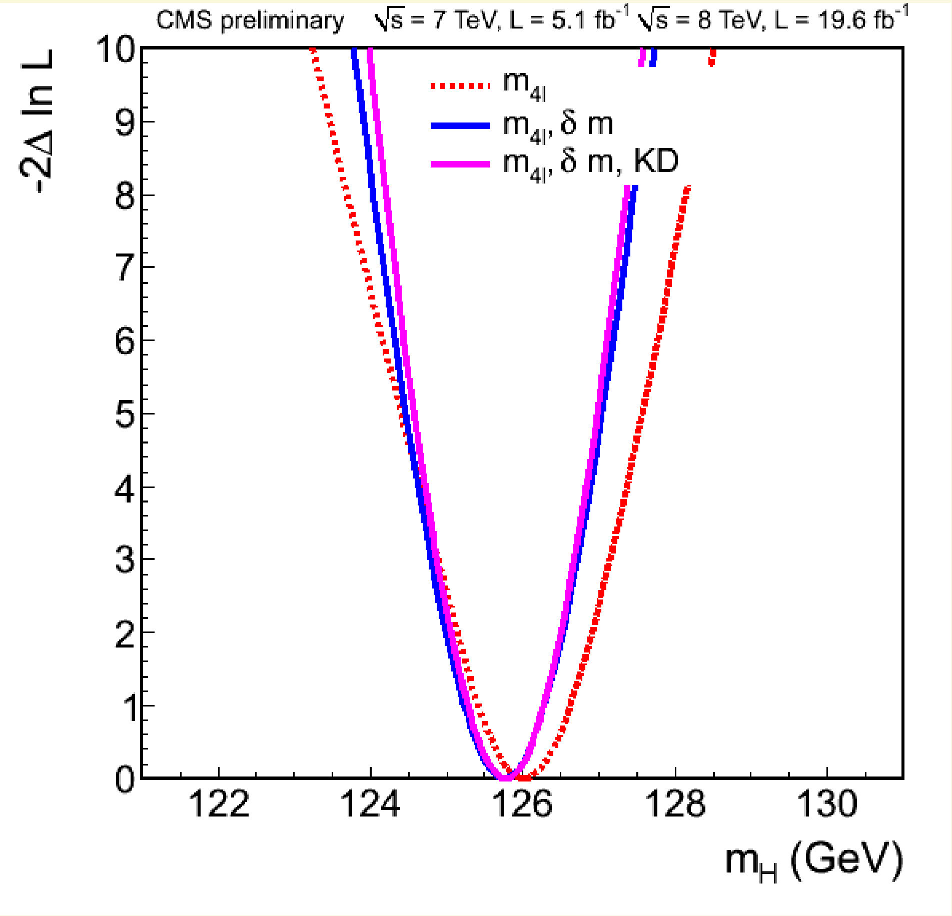


- We control momentum scale to:
  - 0.1% for muons & 0.2% for electrons with $35 < p_T < 50$
  - Up to ~1.5% for the lowest pT electrons

Mass Measurement

Measured mass :
125.8 ± 0.5 (stat) ± 0.2 (syst)

- Well cross-checked by alternative statistical methods
- **Most sensitive mass measurement in a single channel at the LHC**



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Spin and Parity

- Use kinematic discriminator to discriminate against different signal hypotheses:

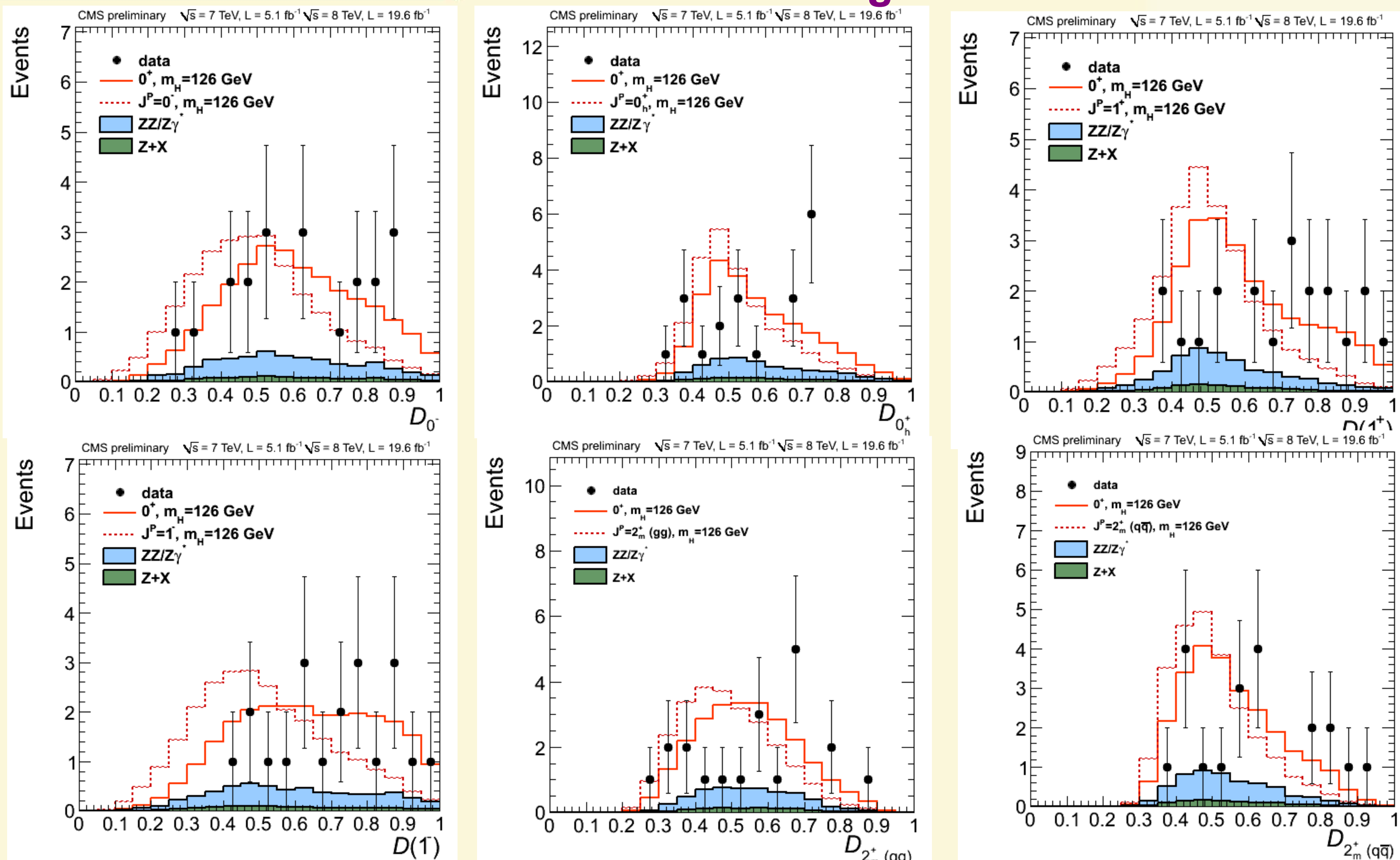
$$\mathcal{D}_{J^P} = \frac{\mathcal{P}_{\rm SM}}{\mathcal{P}_{\rm SM} + \mathcal{P}_{J^P}} = \left[1 + \frac{\mathcal{P}_{J^P}(m_1, m_2, \vec{\Omega}|m_{4\ell})}{\mathcal{P}_{\rm SM}(m_1, m_2, \vec{\Omega}|m_{4\ell})}\right]^{-1}$$

- A two-dimensional template fit in D_{bkg} and D_{JP} is used to perform hypothesis tests against the following alternative models :

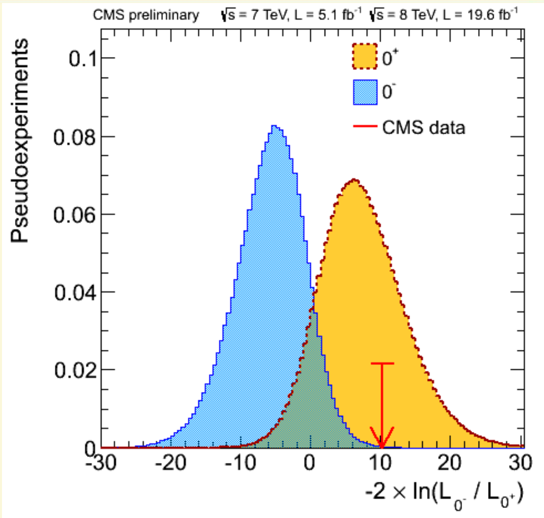
Models		
	0^+	: SM Higgs with minimal coupling
	0^-	: pure pseudoscalar
	0^+_h	: higher dimension operators (in decay amplitude)
	1^-	: vector
	1^+	: axial vector
	2^+_{gg}	: graviton with minimal coupling
	2^+_{qq}	: graviton with minimal coupling

D_{JP} for alternative models

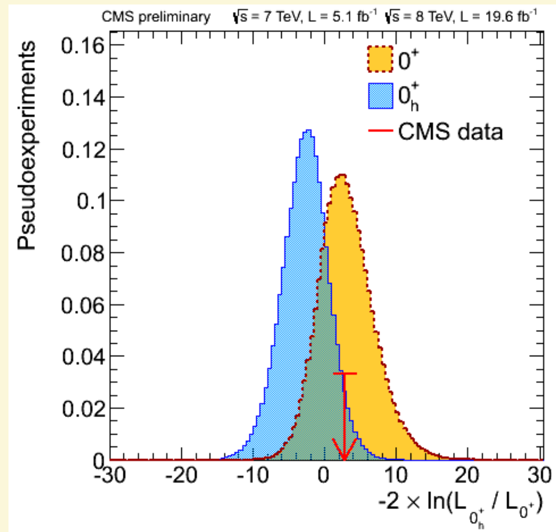
After a cut on background discriminator > 0.5



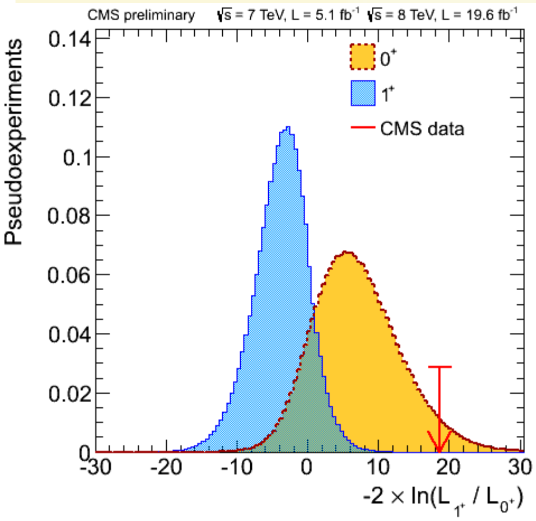
Hypothesis Testing: Alternative Models



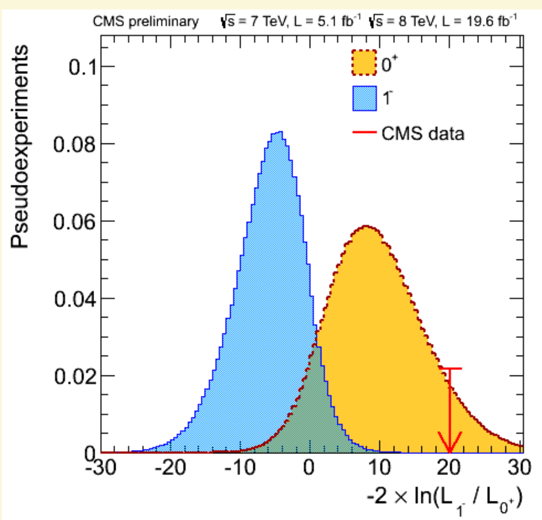
CL_s (0^-) : 0.16%



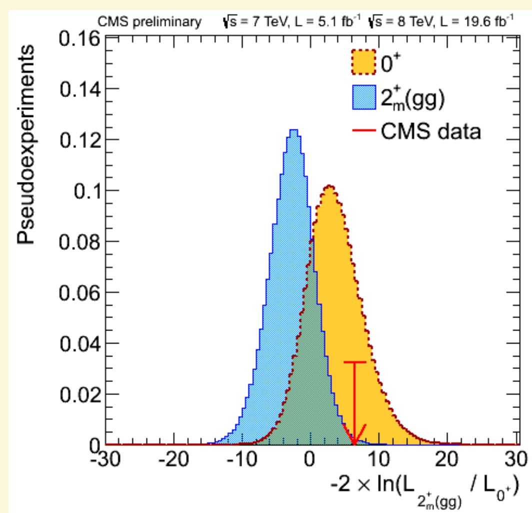
CL_s (0^+_h) : 8.1%



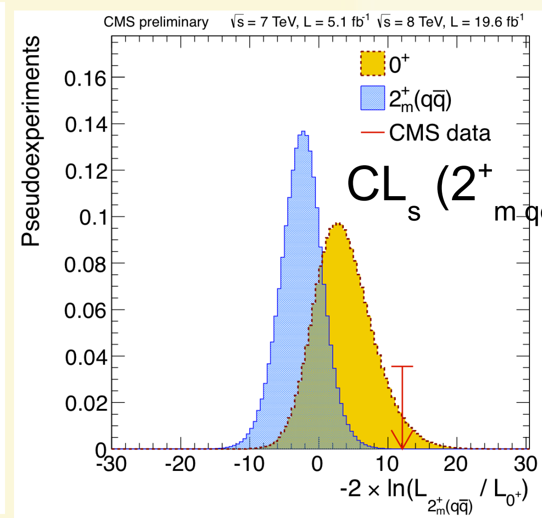
CL_s (1^+) < 0.1%



CL_s (1^-) < 0.1%



CL_s ($2^+_{m\ gg}$) : 1.5%



CL_s ($2^+_{m\ qq}$) < 0.1%

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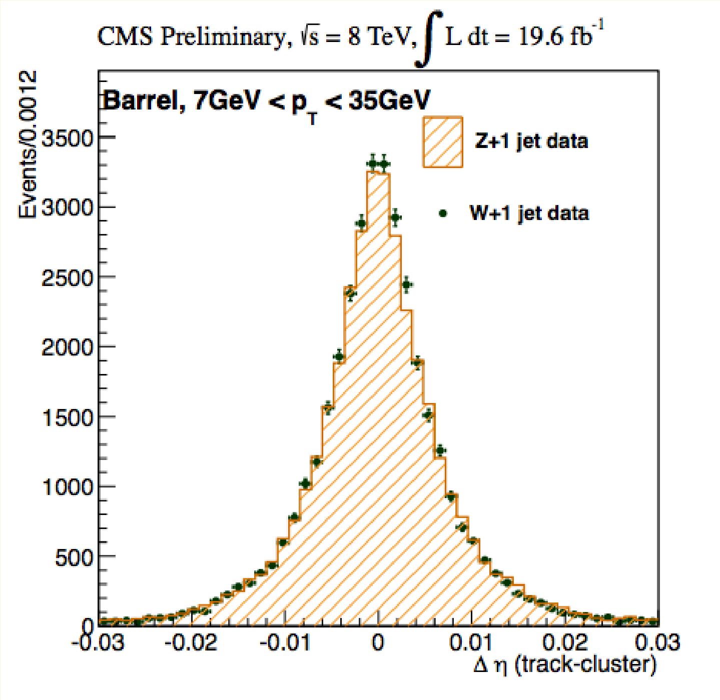
Summary

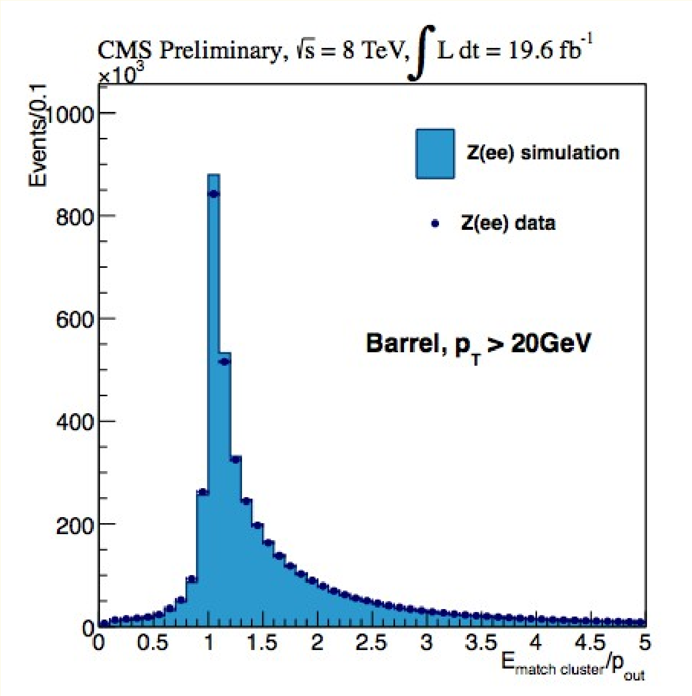
- HZZ making the transition from discovery to measurement:
  - Signal significance now approaching 7σ
  - Cross section: $\mu = 0.91^{+0.30}_{-0.24}$
  - Mass : $m_H = 125.8 \pm 0.50$ GeV
  - Excluding various alternative J^P hypotheses
- So far everything is statistically compatible with SM Higgs, but all measurements still statistically limited

Backup

Multivariate Electron selection

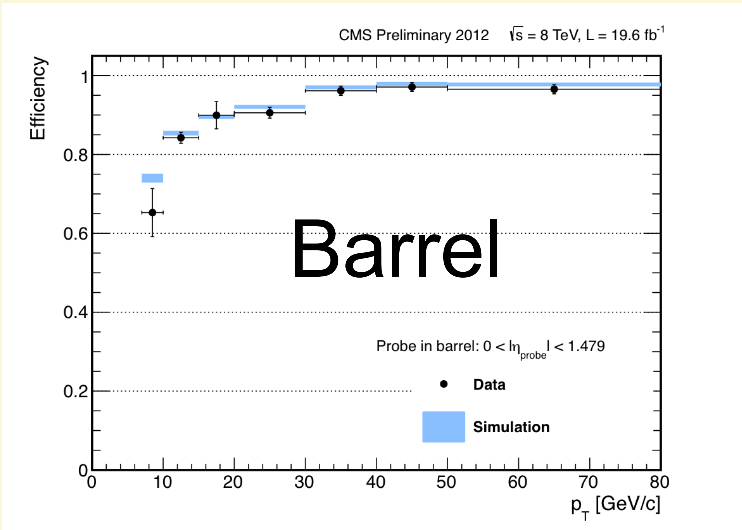
- Many checks and validations were made to ensure that...
  - Bkg training sample was appropriate

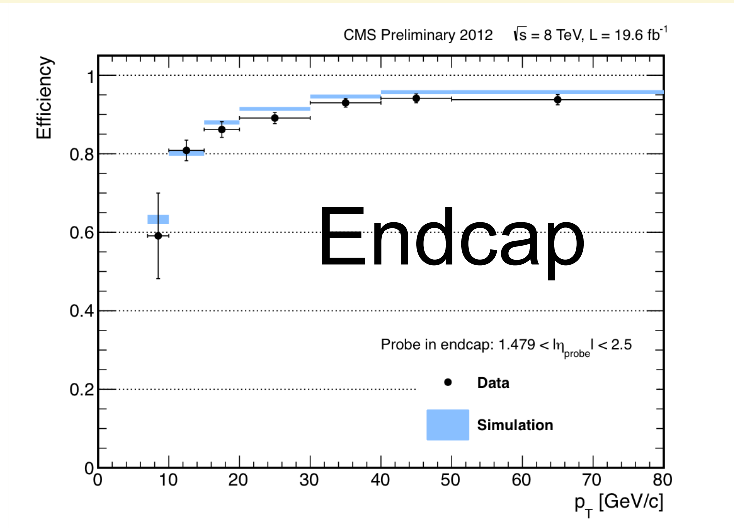




  - Signal training sample from simulation reasonably agrees with data

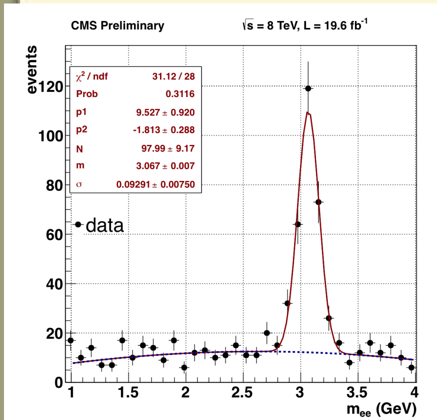
Lepton Selection Efficiency

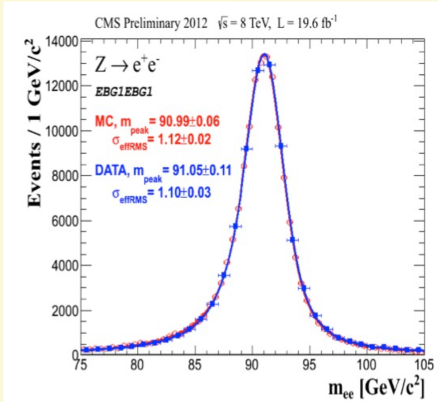




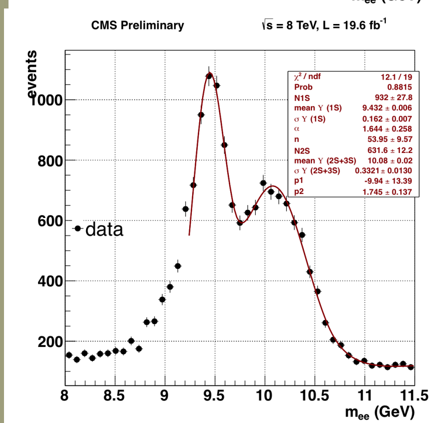
Electrons

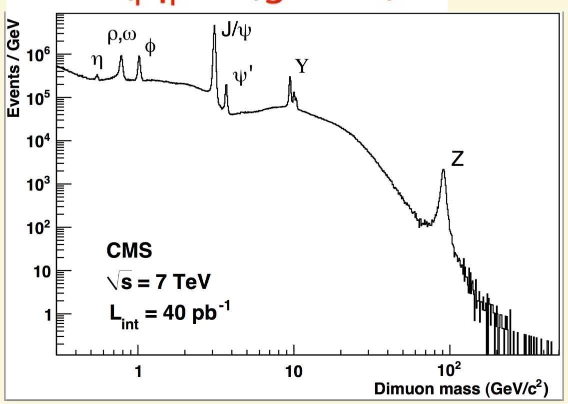
Controlling the signal model

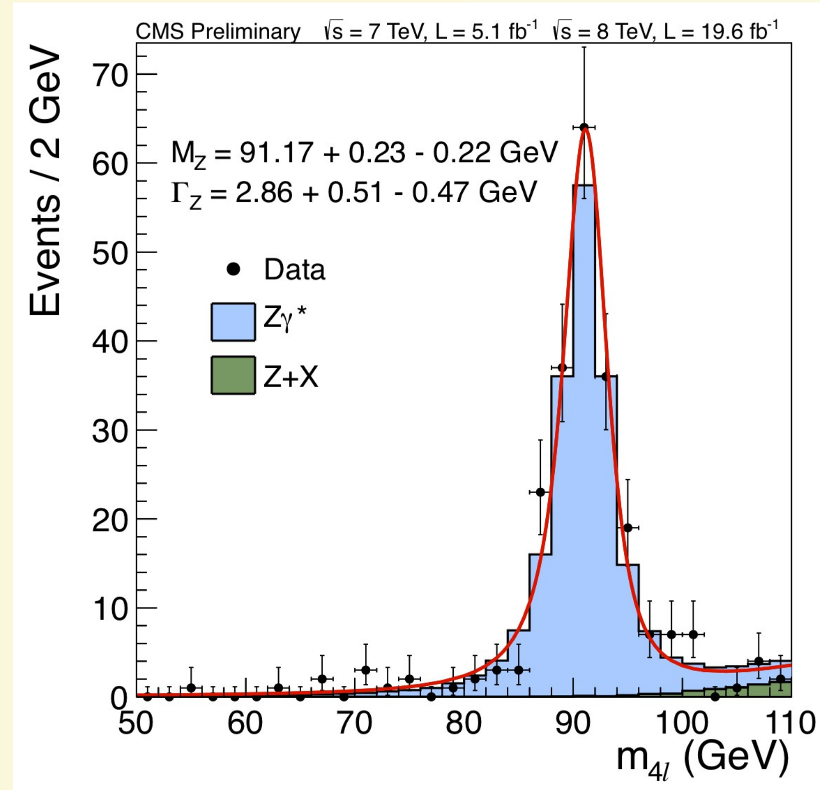




Z (|η|<1.5,golden)







- J/ψ , ϒ & Z decays to ee and μμ used to control momentum scale and resolution across p_T and η spectrum
- Z → 4l resonance used to cross check the signal model

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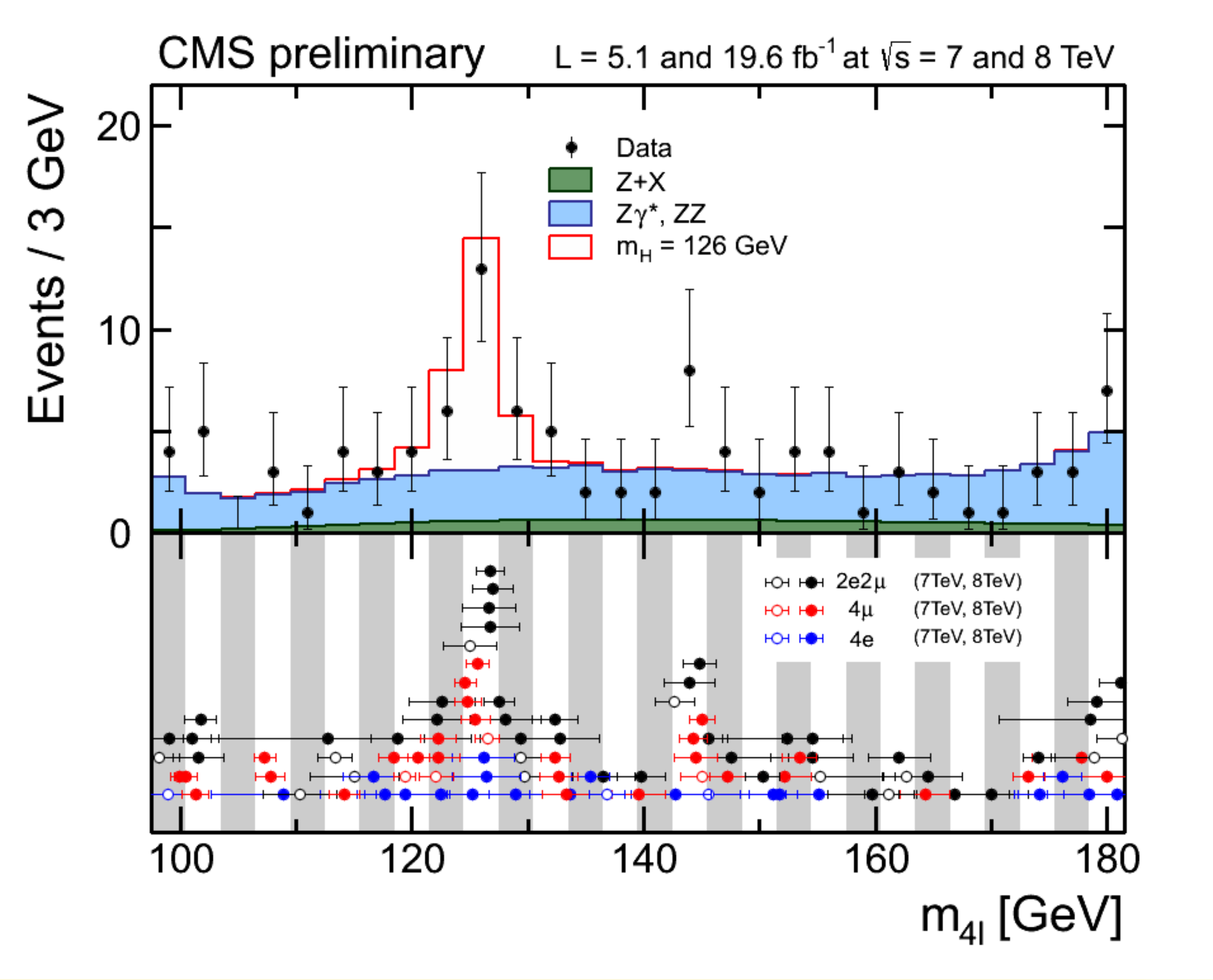
Signal Region with Per-Event Error



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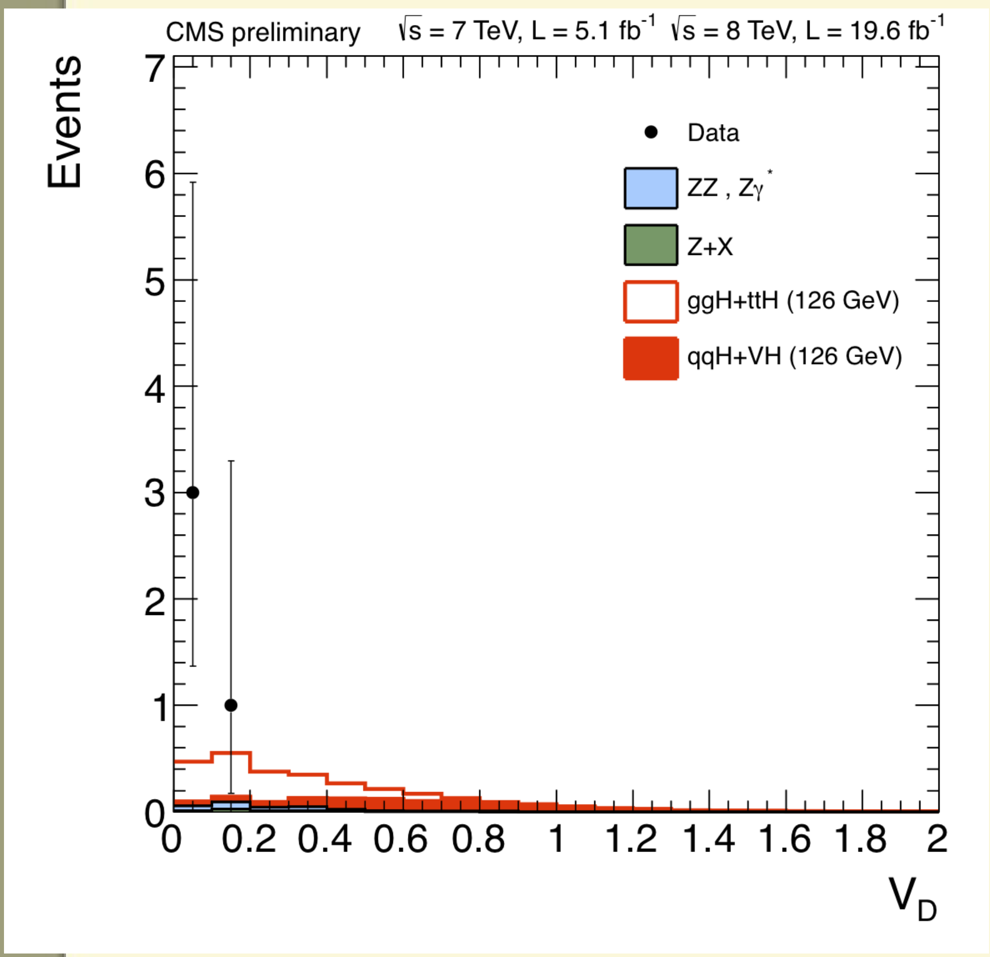
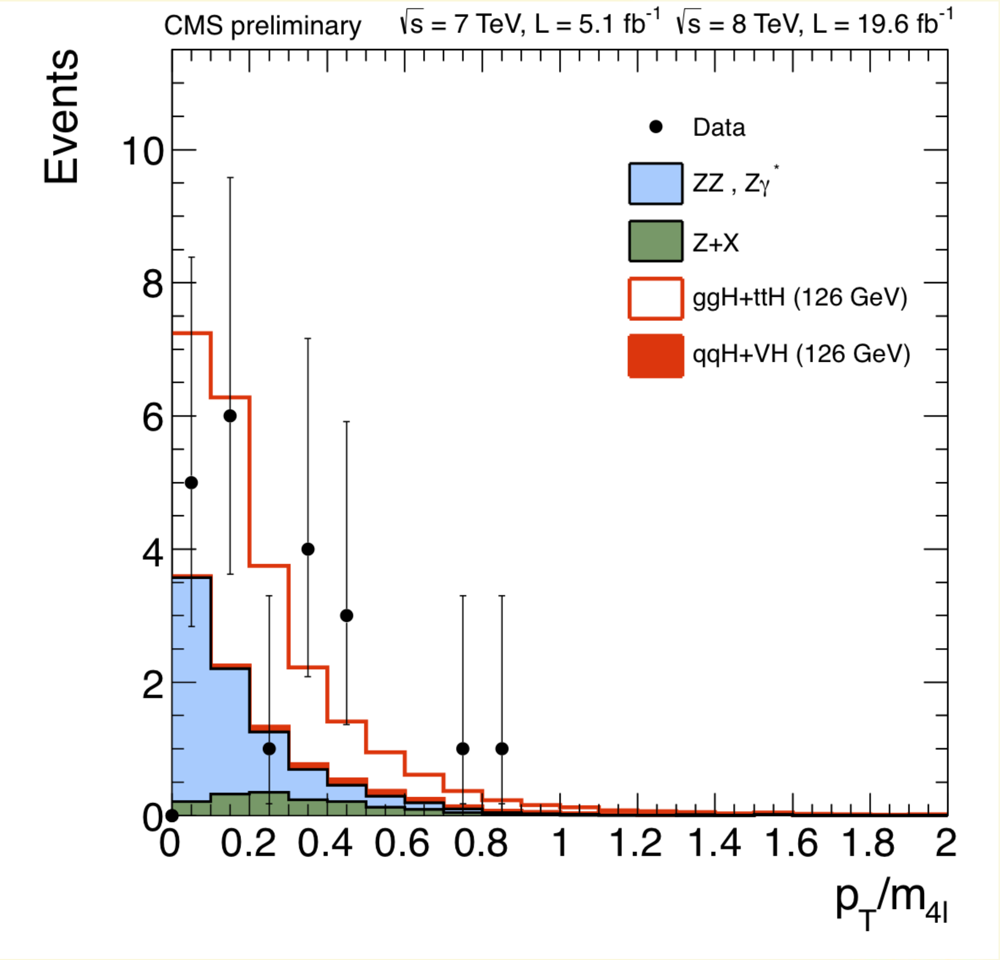
Di-jet Category & Higgs p_T



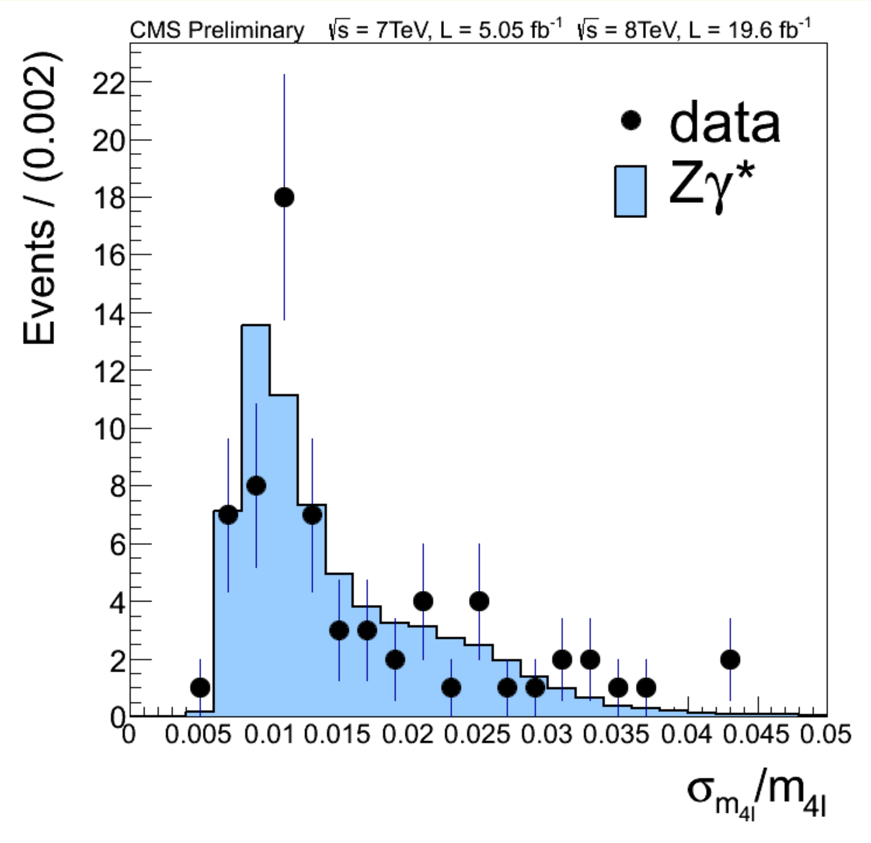


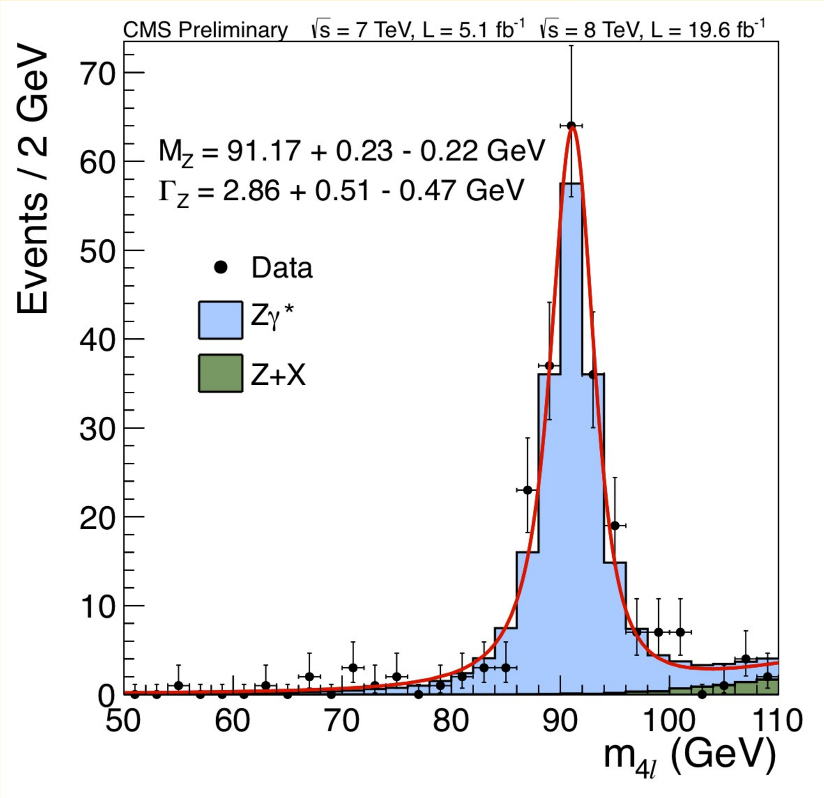
Di-jet Category Systematics

- gg->H+2jets XS from higher order corrections: 30% normalization
- VBF cross section * Acceptance : 10% normalization
- Parton shower (generator & tunes) : shape
  - Generator: Powheg MINLO, Powheg NLO, aMC@NLO, madgraph
- Jet energy scale : shape

- For Higgs pT spectrum:
  - Variation of resummation scale
  - Effect of finite top mass

Mass Measurement with Event-by-Event Uncertainties





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Hypothesis Testing: Alternative Models

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	>4.0σ	<0.1%
1^+	$q\bar{q} \to X$	exotic pseudovector	2.3σ (2.6σ)	1.7σ	>4.0σ	<0.1%

Searches for an additional Higgs