Search for SM Higgs Boson in 4 lepton final state with CMS (4 muon)

Higgs and Beyond the Standard Model Physics at the LHC, ICTP

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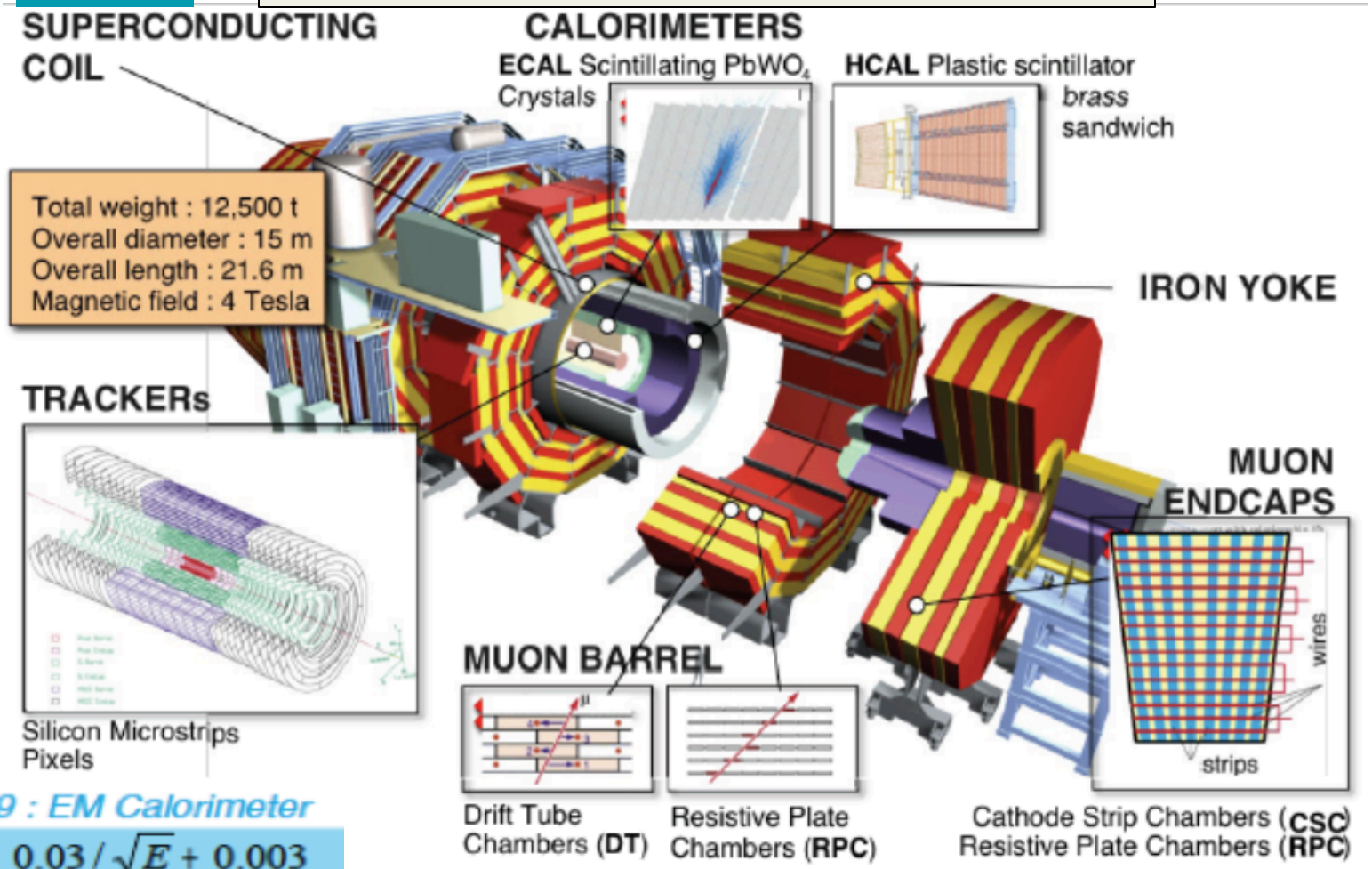
For CMS Collaboration

Outline

- CMS detector
- SM Higgs @ LHC:
  - Production,
  - Decay.
- H→ZZ→ 4*l*
- MC Simulation
- Muon Selection
  - Reco and ID
  - Particle Flow isolation.
- Event Selection.
- FSR Recovery
- Systematic uncertainties
- Results
  - m_{4l} spectrum
  - Event Yields
  - limits, p-value
  - mass mesurement

CMS



|η|<4.9 : EM Calorimeter

$\sigma / E \approx 0.03/\sqrt{E} + 0.003$

|η|<4.9 : HAD Calorimeter

$\sigma / E \approx 1.0/\sqrt{E} + 0.05$

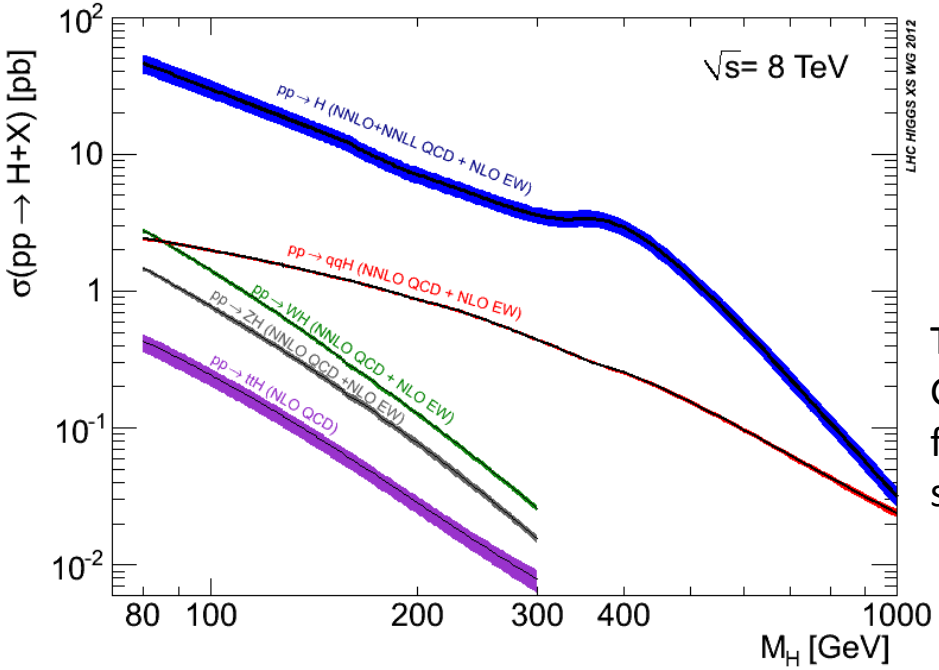
|η|<2.5 : Tracker

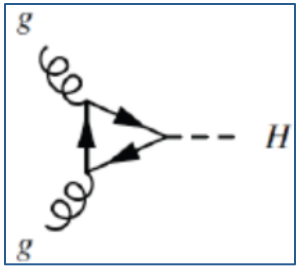
$\sigma / p_T \approx 10^{-4} p_T \oplus 0.005$

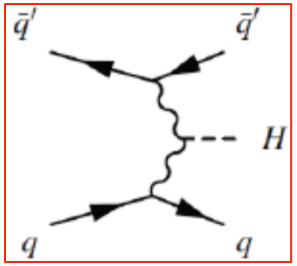
|η|<2.4 : Muon spectrometer

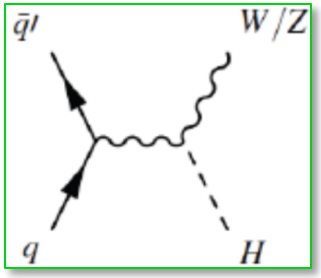
$\sigma / p_T \approx 0.10$ *(1TeV muons)*

SM Higgs @ LHC: Production

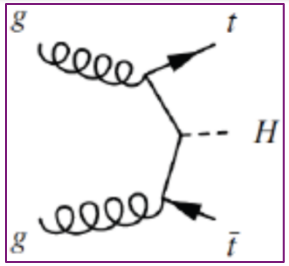








Transition for VBF at M_H=300 GeV at 8 TeV is due to change from ZWA to complex-pole-scheme

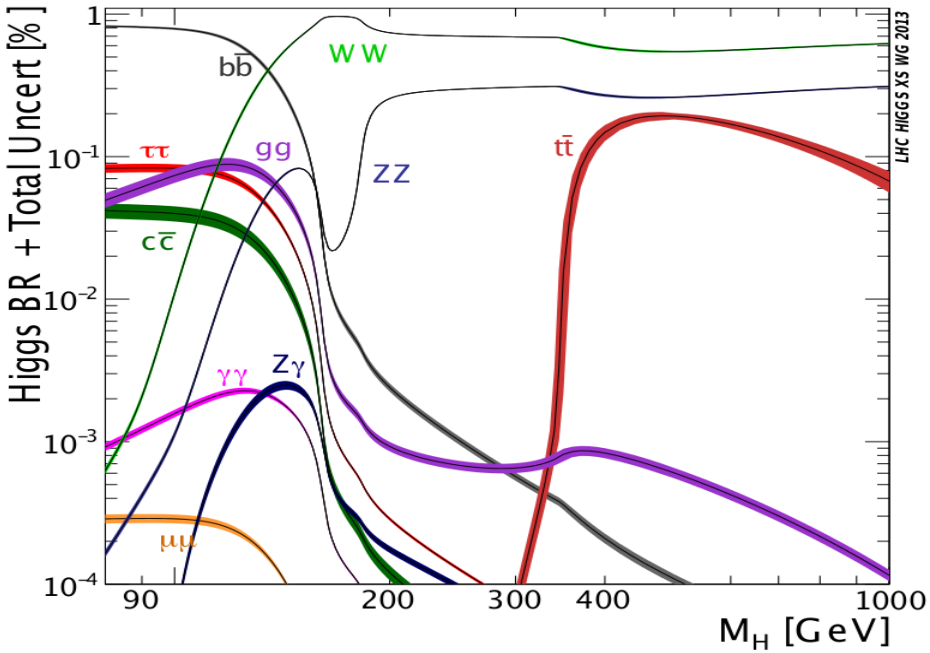


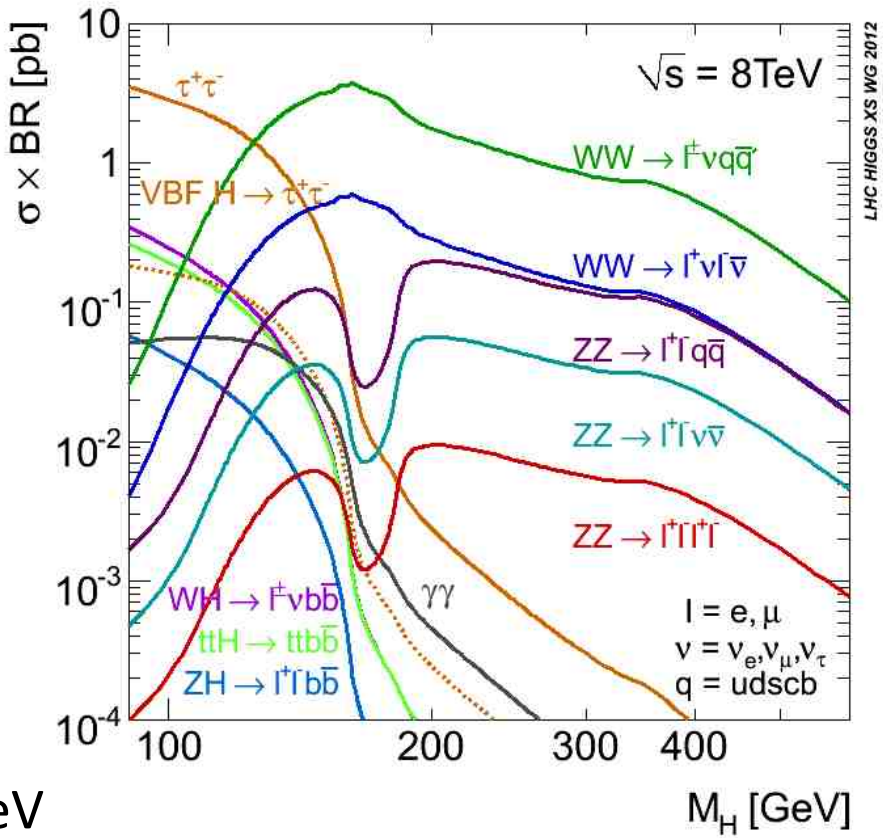
*linear combination of scale and PDF uncertainties

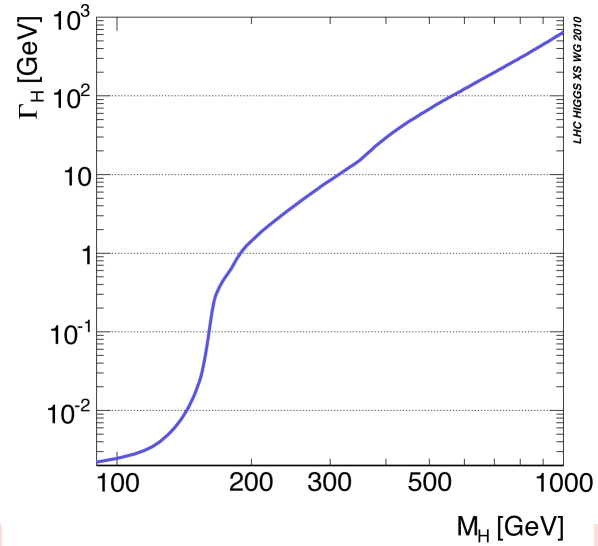
for m_H=125 GeV		ggF	VBF	WH	ZH	ttH
Xsec (pb)	8 TeV	19.52	1.578	0.6966	0.3943	0.1302
	7 TeV	15.32	1.222	0.5729	0.3158	0.0863
Error*	8 TeV	±14.7 %	+2.8%/-3%	+3.7%/-4.1%	+5.1%/-5%	+11.6 % / -17.1%
	7 TeV	±14.7 %	+2.8%/-2.4%	+3.7%/-4.3%	+4.9%/-5.1%	+11.8 % / -17.8%

https://twiki.cern.ch/twiki/bin/view/LHCPhysics/CrossSections

SM Higgs @ LHC: Decay







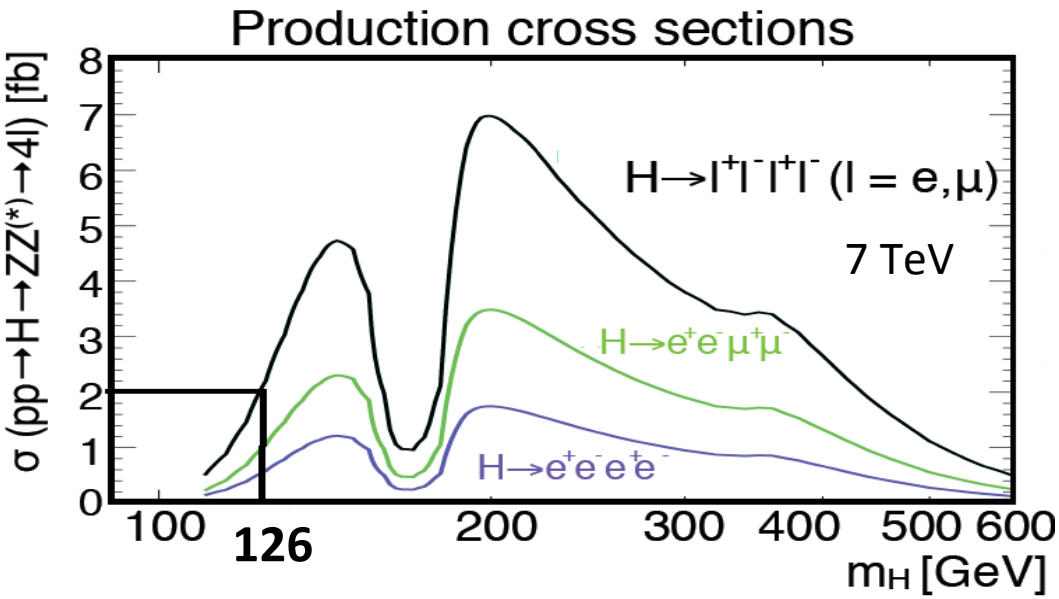
For m_H=125 GeV

	4l (l =e,μ)	4 μ	2e2μ
BR	12.5×10^{-5}	3.3×10^{-5}	5.93×10^{-5}

Total width (Γ_H)= $4.07\times^{-03}$ +4.0% -3.9%

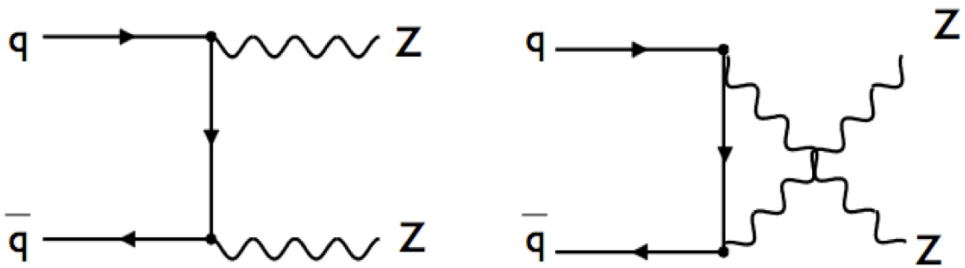
H→ZZ→ 4*l* (*l*=μ|e)

- Very clean channel
- Requiring the highest possible efficiencies (Reco/ID/Isolation).
- Small BR (σ×BR≈few fb)



Background

- Irreducible: ZZ production
- Reducible: Zbb, Z+jets, tt +jets, WZ+jets
- In 4μ channel, the contributions of Z+jets, WZ +jets can be neglected.



Background Estimate (ZZ)

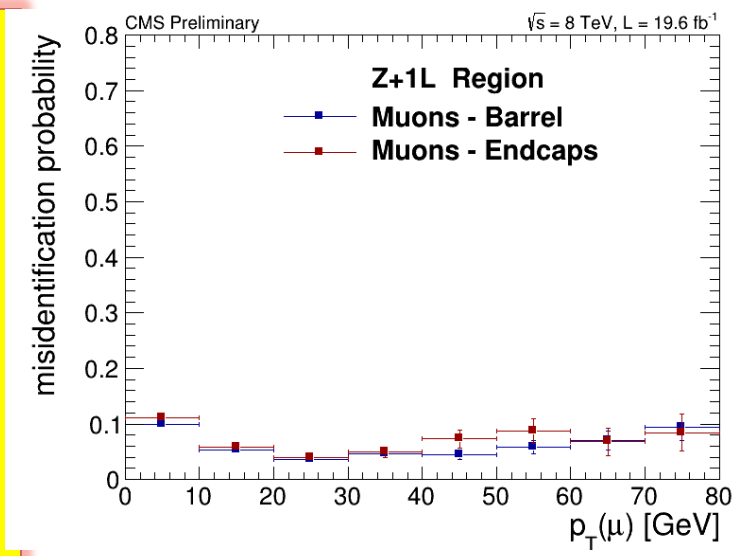
Irreducible background (ZZ) (from simulation)

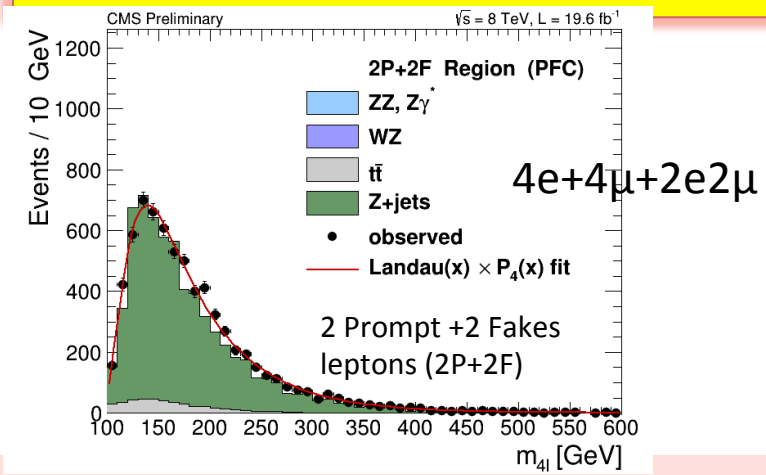
- Phenomenological shape models
- Events yield uncertainty related to PDF+α_s and QCD scale evaluated using MCFM
- Corrected for data/MC differences

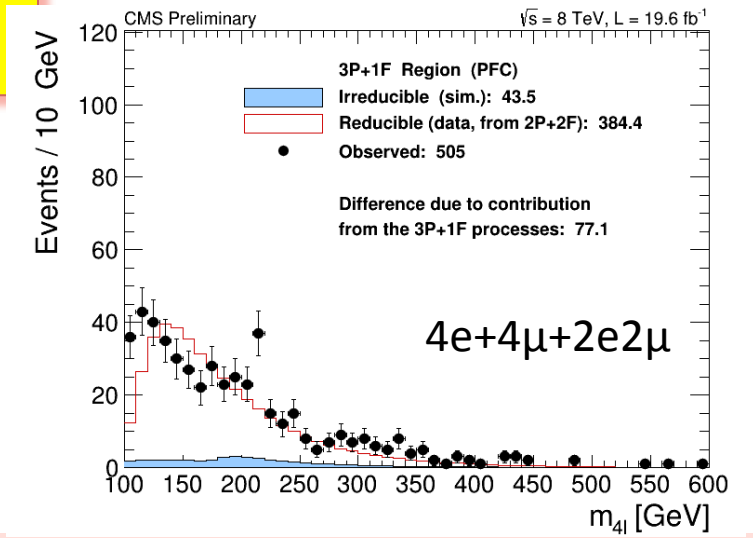
Background Estimate (Z+X)

Reducible background (from data)

- Measure probabilities for lepton mis-id
- **Z➔*ll + leptons* from b-decays or from mis–id of light jets**
- Control samples:
  - Z +1 good lepton+1 loose lepton+ MET<25 GeV (3P+1F)
  - Z +2 loose leptons +MET<25 GeV (2P+2F)
  - Z + 2 loose lepton with same sign and same flavour (SS-SF) + m_{4l}>100 and m_{Z1}, m_{Z2} cut
- Events yield extrapolated in signal region







Muon Selection

Good Muons: for baseline selection

- $|\eta| < 2.4$
- $pT > 5$ GeV
- Rely on information from both the silicon tracker and muon system. Matching can be either "outside-in", "inside-out".
- Passing the Particle Flow Muon ID (see later),
- Relative PFIso < 0.4
- Significance of the Impact Parameter = $IP/\sigma_{IP} < 4$
- FSR photons recovered.

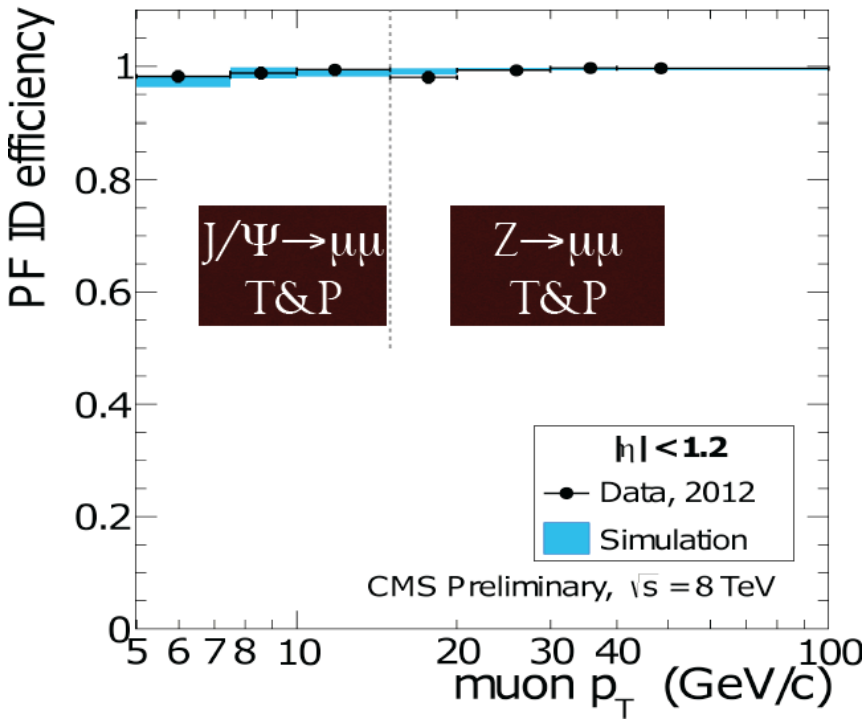
Loose Muons: for reducible background estimation

Have relaxed criteria on PF ID and isolation

Muon Reco. and ID

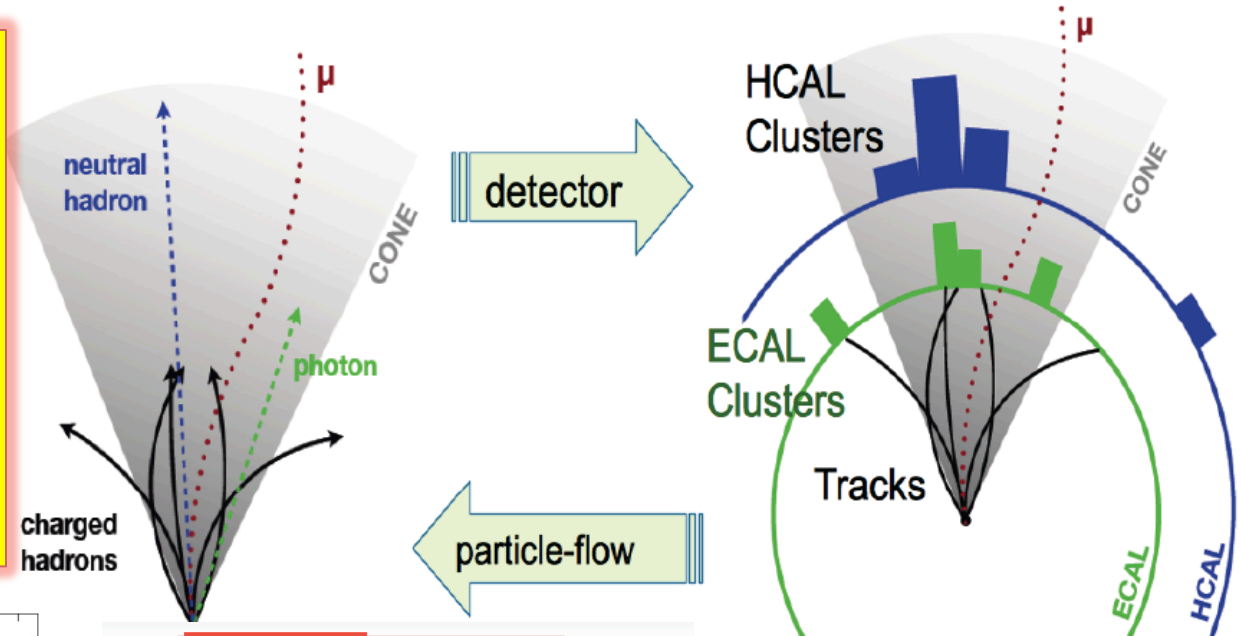
Muon ID:

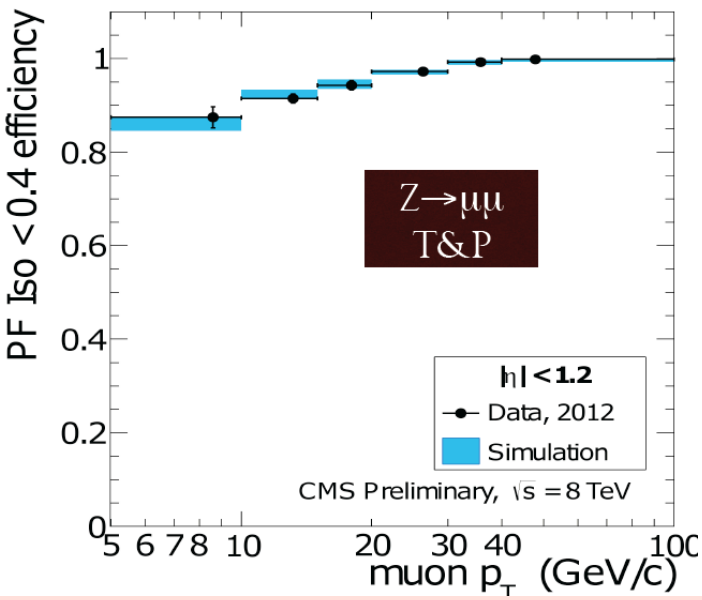
- Particle Flow: rely on information from all sub-detectors
- Exploit also tracker-based muon ID
- Efficiency is high down to pT=5 GeV
- Controlled in data with J/ψ and Z T&P

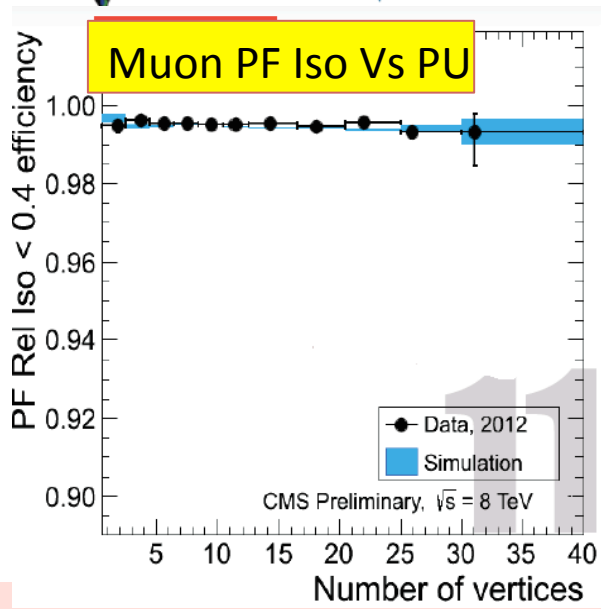


Particle Flow Isolation

- Summing energy deposits from photons, neutral and charged hadrons in ΔR=0.4 cone. Avoid double counting of calorimetric energy deposits from charged hadrons.



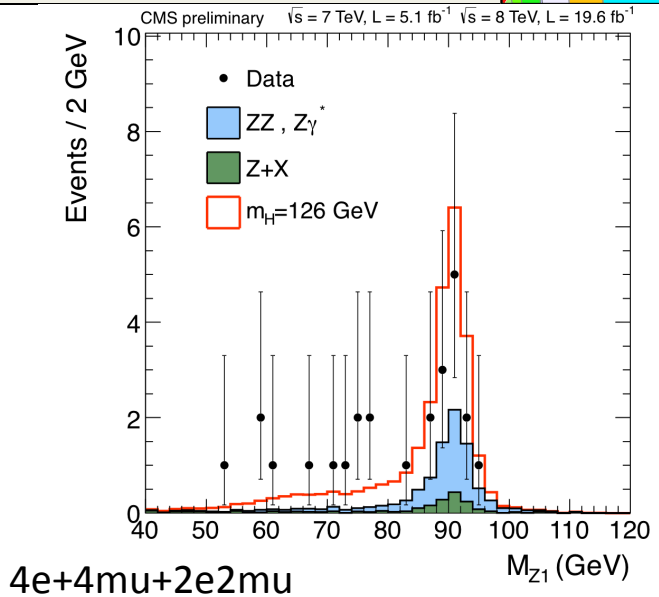




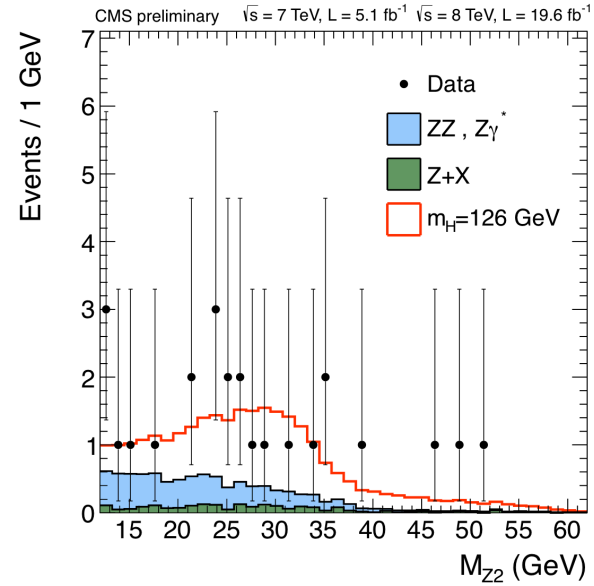
Efficiency is stable in high PU environment.

Event Selection

- Trigger: di-muon stream
- Muons:
  - $|\eta| < 2.4$, pT > 5 GeV, isolated.
  - At least two muons with pT > 10 GeV. At least 1 muon pT>20 GeV.
- First Z candidate (Z1):
  - Muon pair with closest m_{ll} to m_Z.
  - 40 GeV < $m_{\mu\mu}$ < 120 GeV.
- Second Z candidate (Z2):
  - Built using the remaining highest pT muons.
  - 4 GeV < $m_{\mu\mu}$ < 120 GeV.
- $m_{\mu\mu\mu\mu}$ > 100 GeV && m_{Z2} > 12 GeV.



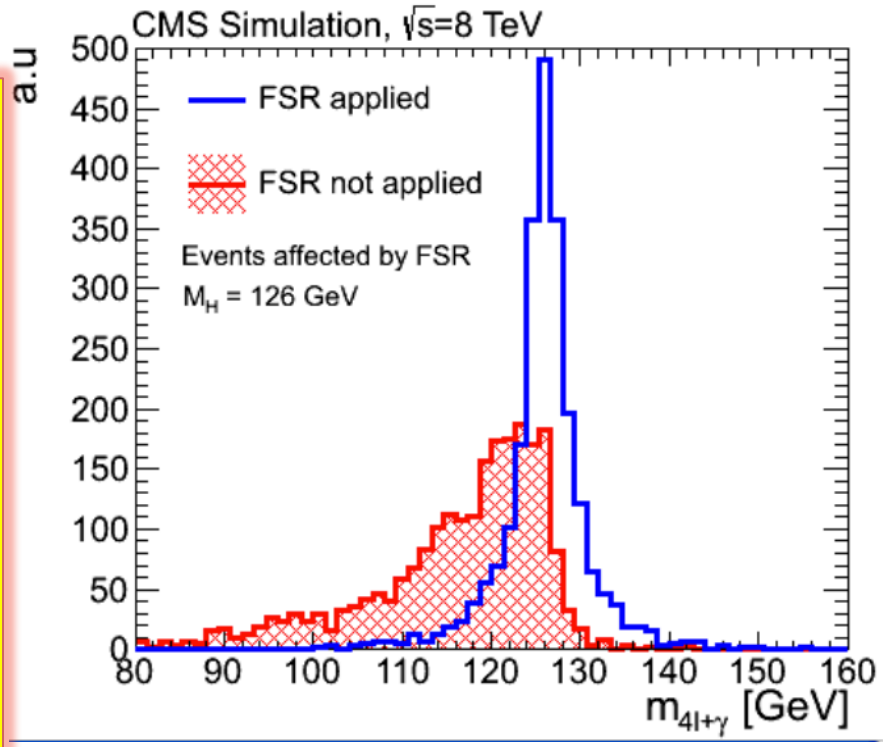
4e+4mu+2e2mu



FSR Recovery

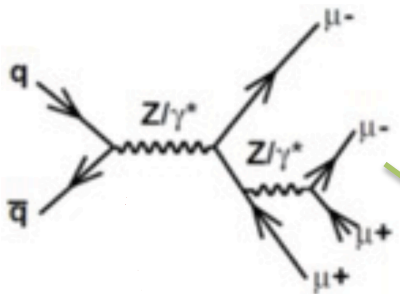
FSR photons selection:

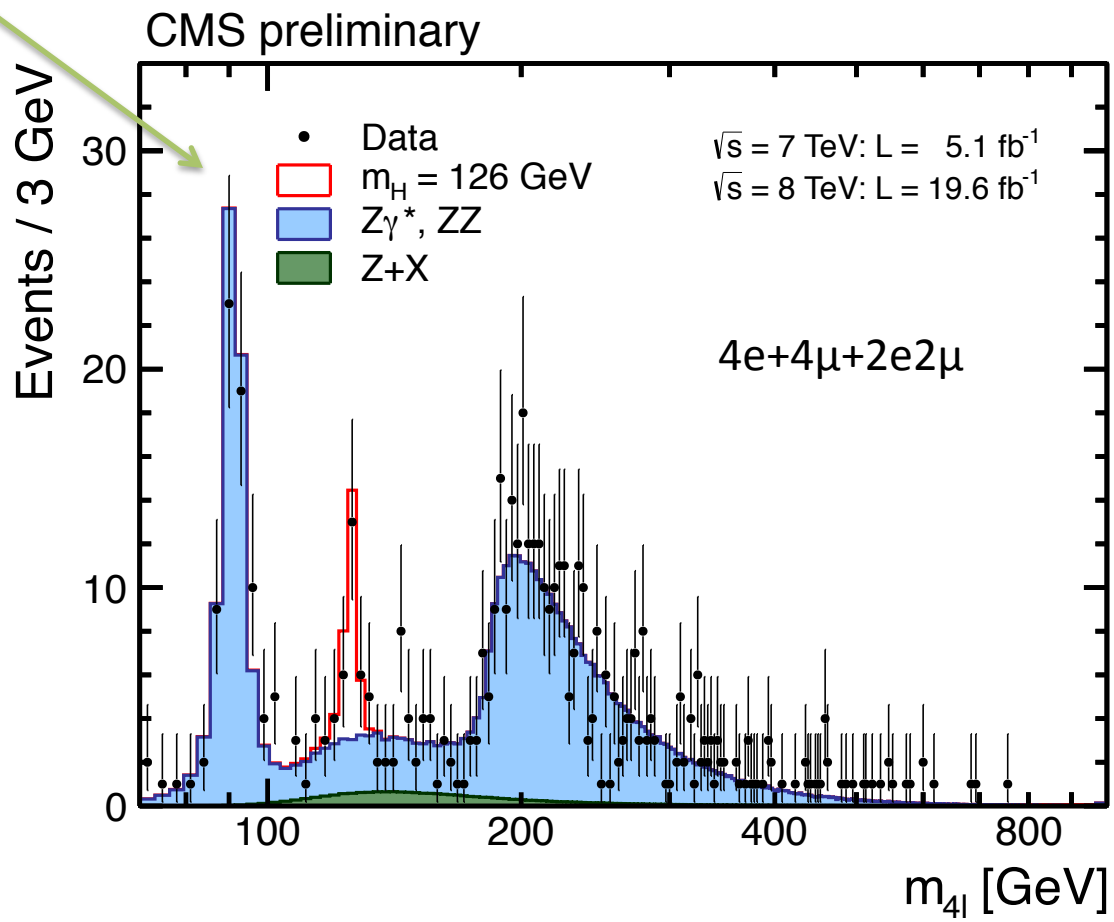
- Particle Flow ID
- $|\eta|<2.4$
- (p_T> 2 GeV && ΔR(photon,lepton) < 0.7) ||
  (p_T> 2 GeV && PF Iso < 1 GeV && 0.07< ΔR(photon,lepton) < 0.7)
- Associated to with Z if:
  - $m_{\mu\mu\gamma} < 100$ GeV
  - $|m_{\mu\mu\gamma} - m_Z| < |m_{\mu\mu} - m_Z|$
- photons removed from muon isolation calculation



For m_H =126 GeV, about 3% events added in analysis in the 4 mu channel.

m_{4l} spectrum

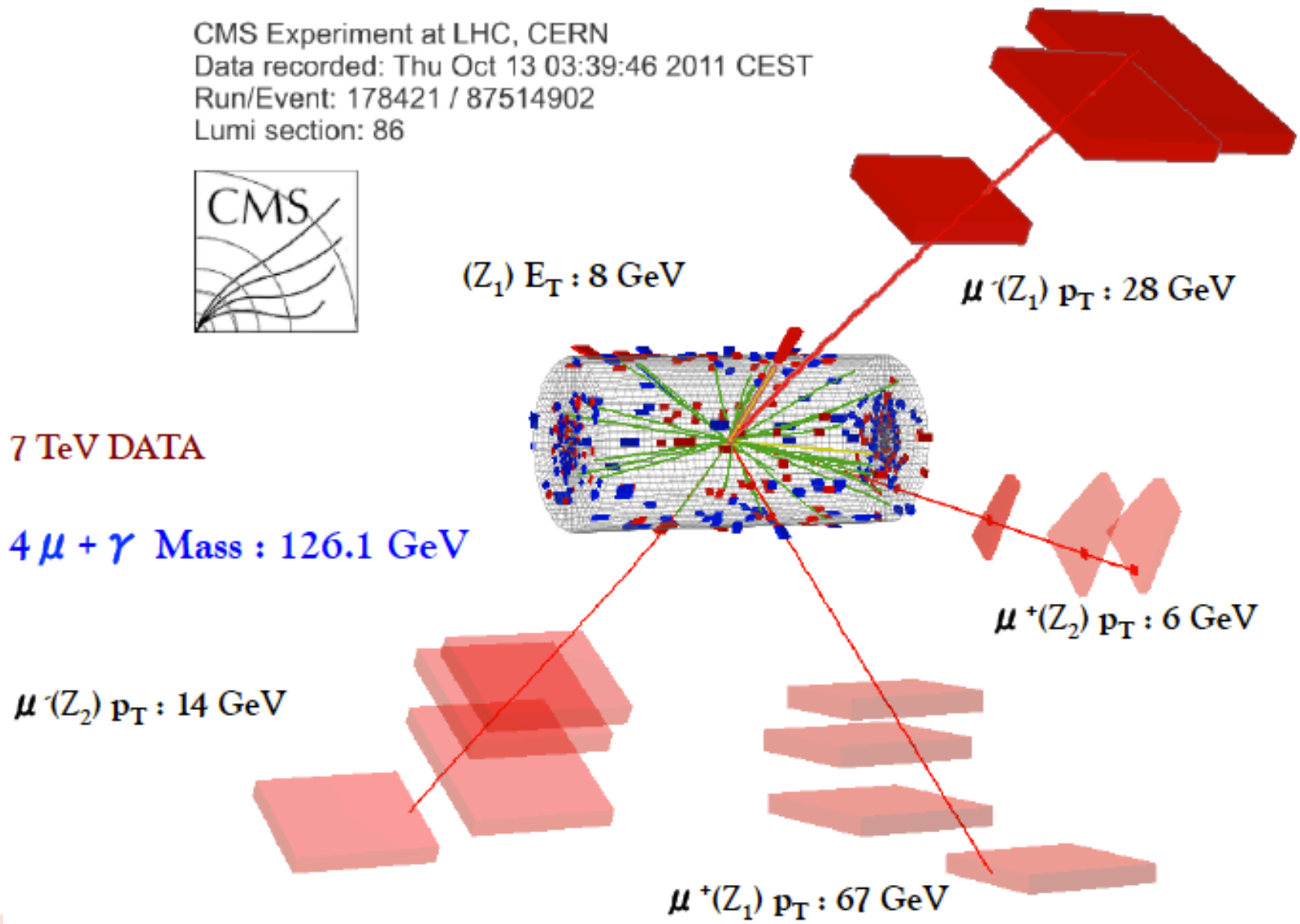




Event Yields (4μ)

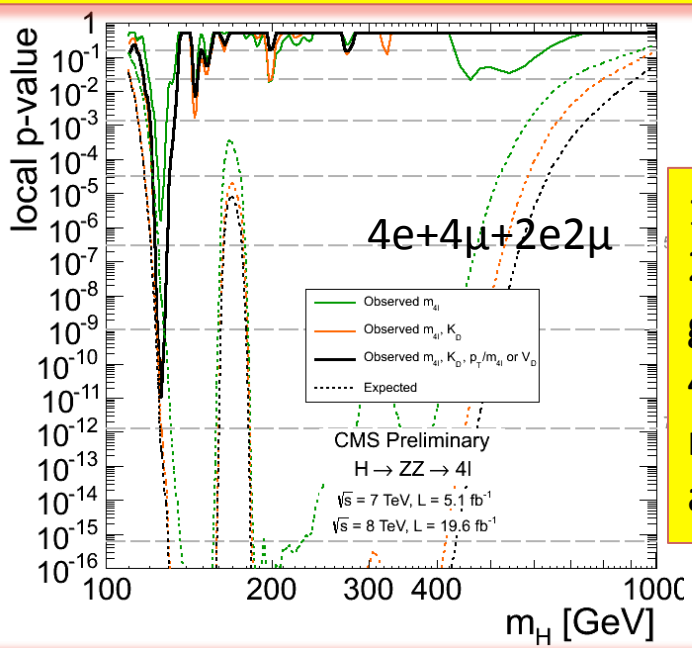
	$100 < m_{4\mu} < 1000$ GeV	$110 < m_{4\mu} < 160$ GeV
ZZ background	118.9 ±15.5	13.8 ±1.0
Z+X	3.8 ± 1.5	1.6 ± 0.6
All backgrounds expected	122.6 ± 15.5	15.4 ± 1.2
m_H=125 GeV m_H=126 GeV m_H=500 GeV m_H=800 GeV	6.8 ±0.8 7.4 ±0.9 6.8 ±0.8 0.9 ±0.1	6.8 ±0.8 7.4 ±0.9
Observed	125	23

Event Display

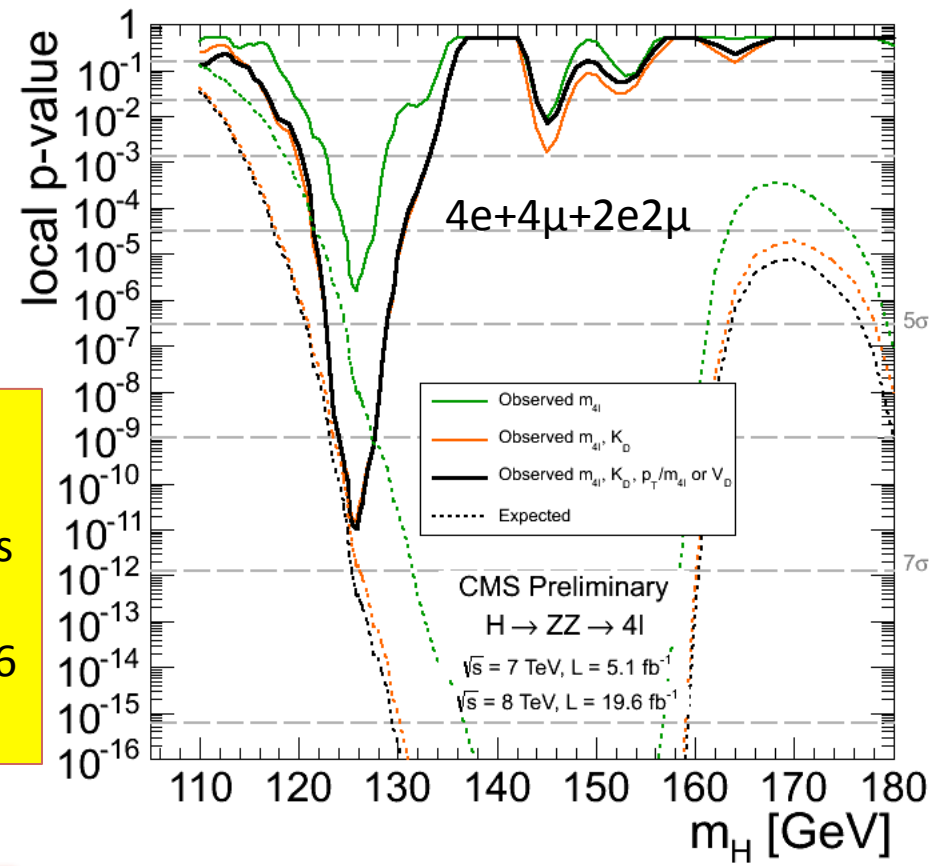


Local Significance

p-value: probability that the background can fluctuate to give an excess of events equal or larger than what observed



1D(m_{4l}) and 2D(m_{4l} , KD) gives p-values 4.7 and 6.6 σ resp. (exp. 5.6 and 6.9σ)



3D pdf built (m_{4l} , KD,X), where X=V_D in category I* and X=p_T/ m_{4l} in category II**

*Events with < 2 jets, **at least two jets
*** p_T/m_{4l} is not used for m_{4l} >180 GeV.

Minimum obs. p-value ≈ 6.7σ (7.2 σ exp) at m_{4l} = 125.8 GeV .
As a cross-check, 1D (m4l) and 2D (m4l, KD) models gives 4.7 and 6.6 σ, for an exp. of 5.6 and 6.9 σ, resp.

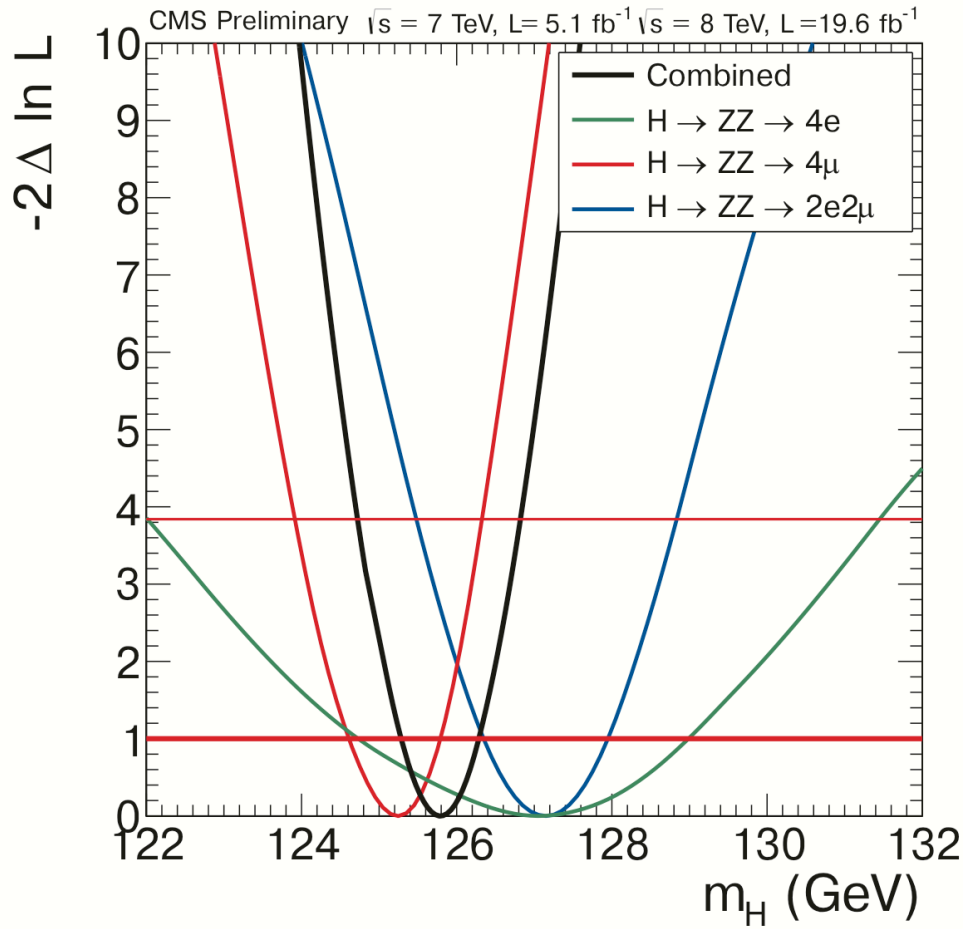
Mass Measurement

3D pdf built (KD,m4l, EBE):

$$\mathcal{P}_{\rm sig}(m_{4\ell}, EBE, KD) = \mathcal{P}^{\rm 1D}_{\rm sig}(m_{4\ell}) \times \mathcal{P}_{\rm sig}(EBE|m_{4\ell}) \times \mathcal{P}_{\rm sig}(KD|m_{4\ell})$$

Event by Event mass error (EBE) included

- from muon track fit error matrix
- from electron momentum error

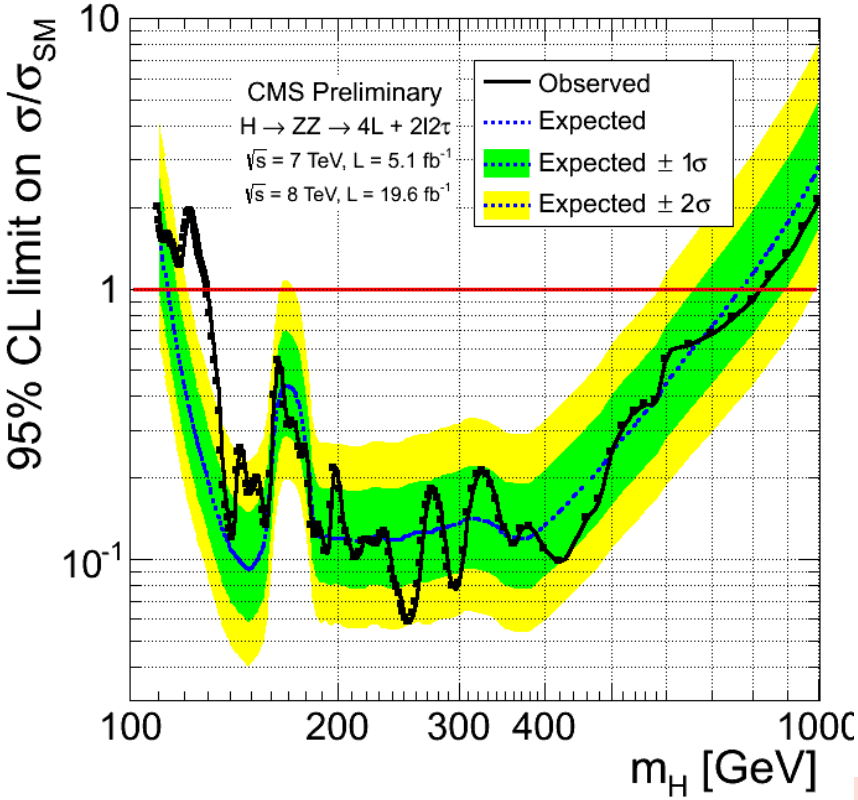


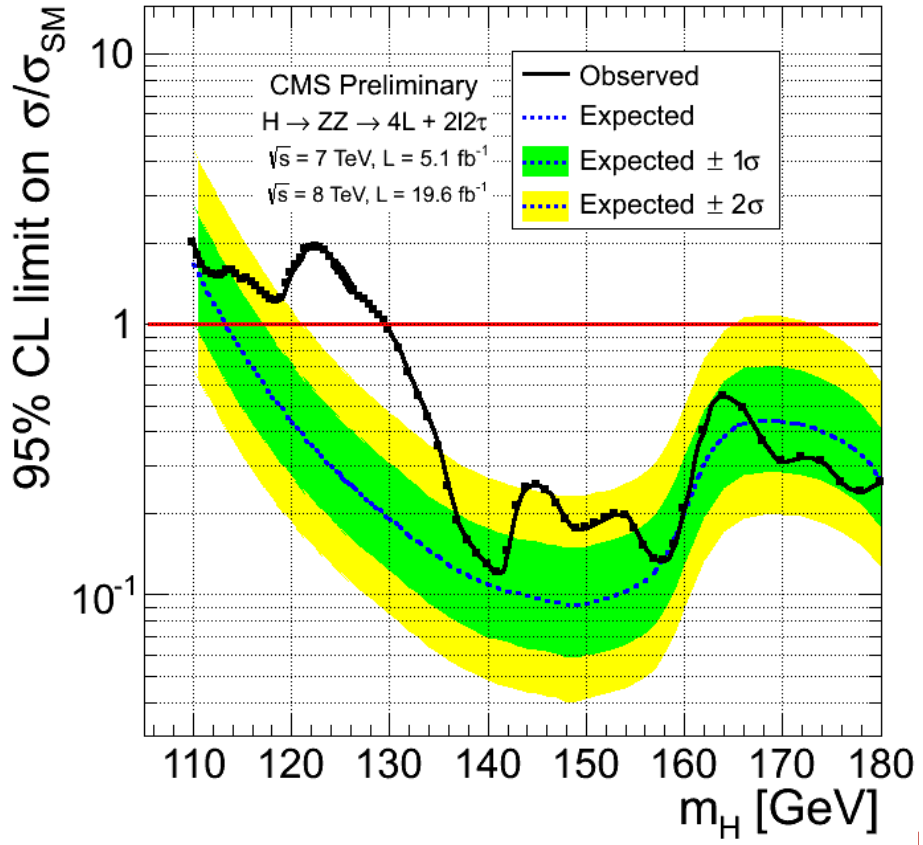
m_X = 125.8 ± 0.5 ± 0.2 GeV

$m_{4\mu}$ =125.2 -0.6/+0.5 GeV

Exclusion Limits

- Profile likelihood ratio
- Nuisance parameters included
- CL_s method for exclusion limit





The SM-like Higgs boson is excluded by the four-lepton channels at 95% CL in the range 130–827 GeV (exp. 113.5-778 GeV)

Summary (1)

Based on 5.1 fb-1 and 19.6 fb-1 data at 7 TeV and 8 TeV resp.:

- **6.7 σ** of local significance for the m(X) =125.8 GeV
- measured mass: **125.8 ± 0.5(stat.) ± 0.2(syst.) GeV**
- The SM-like Higgs boson is excluded by the four-lepton channels at 95% CL in the range 130–827 GeV (4e+4μ+2e2μ+2l2τ)
- **Agreement with the SM prediction**
- Beside the mass measurement, the CMS Higgs Working Group is now focusing on the properties measurement, in H->ZZ*->4l:
  - Signal strength relative to SM expectation for SM Higgs: $\mu=0.91^{+0.3}_{-0.24}$ at 125.8 GeV.
  - Production mechanism signal modifiers $\mu_V=1.0^{+2.4}_{-2.3}$, $\mu_F=0.9^{+0.5}_{-0.4}$ at 125.8 GeV (consistent with SM expections).
  - Spin-parity: pure scalar hypothesis is found to be consistent with the observation when compared to six other spin-parity hypotheses. (see next slide).

Summary (2)

- Fraction of a CP-violating contribution to the decay amplitude, expressed by the fraction f_{a3} of the corresponding decay rate $f_{a3}=0^{+0.23}_{-0.0}$ → consistent with the SM expectations.

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%

References:

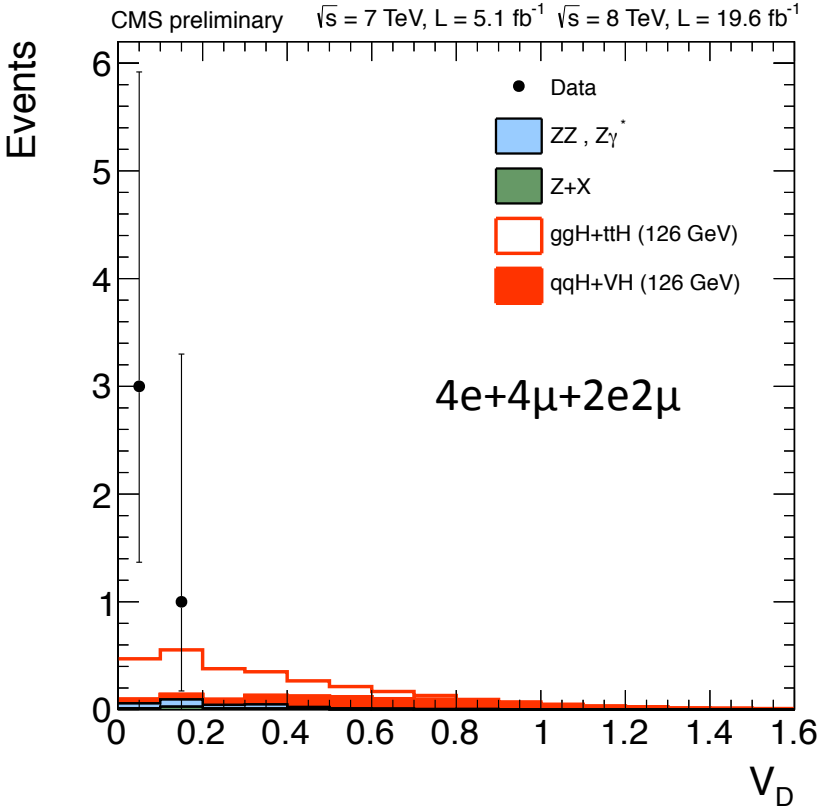
- CMS-PAS-HIG-13-002
- https://twiki.cern.ch/twiki/bin/view/CMSPublic/Hig13002TWiki

More Slides…

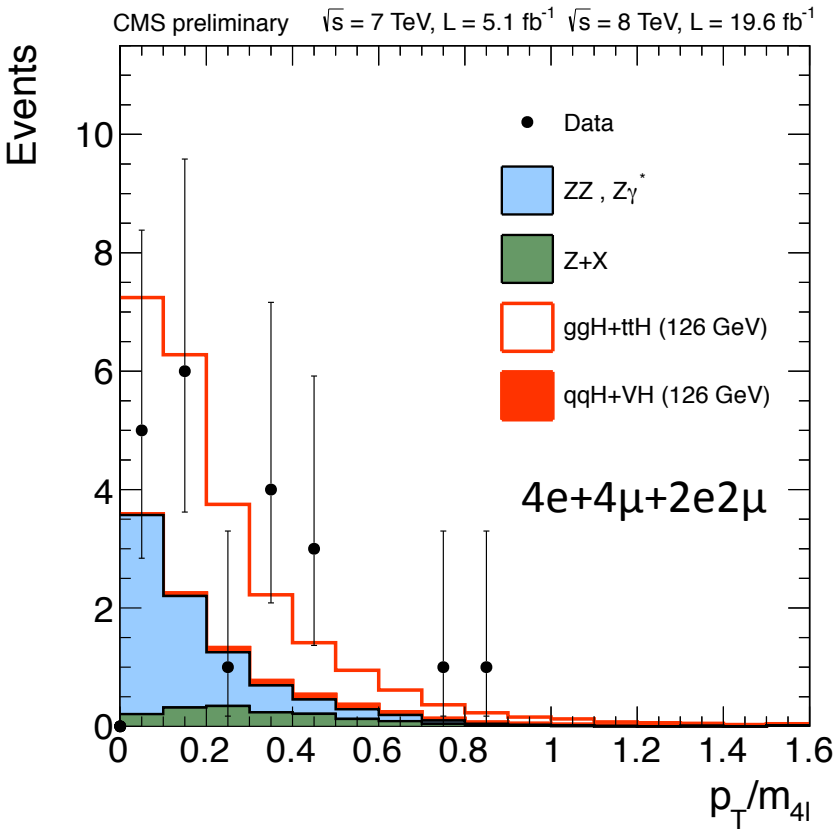
History

- **ATLAS and CMS, used 5 fb^{-1} of 2011 data, in H->ZZ->4*l* channel, set 95% CL exclusion limits on SM Higgs:**
  - **CMS excluded the mass range 127-600 GeV**
  - **ATLAS excluded 111.4-116.6 GeV, 119.4-122.1 GeV, and 129.2-541 GeV**

p_T/m_{4l} and V_D



VBF discriminant in Category II events



p_T/m_{4l} in Category I events.

Only events with $121.5 < m_{4l} < 130.5$ GeV are considered

Kinematical Discriminant (KD)

Matrix Element Likelihood Analysis:
kinematic inputs for signal and background $\{m_1, m_2, \theta_1, \theta_2, \theta^*, \Phi, \Phi_1\}$

$$\mathrm{MELA} = \left[1 + \frac{\mathcal{P}_{\mathrm{bkg}}(m_1, m_2, \theta_1, \theta_2, \Phi, \theta^*, \Phi_1 | m_{4\ell})}{\mathcal{P}_{\mathrm{sig}}(m_1, m_2, \theta_1, \theta_2, \Phi, \theta^*, \Phi_1 | m_{4\ell})}\right]^{-1}$$

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