Evidence for a new boson in the search of the SM $H \to ZZ \to 4l$

pp collisions
7 TeV and 8 TeV

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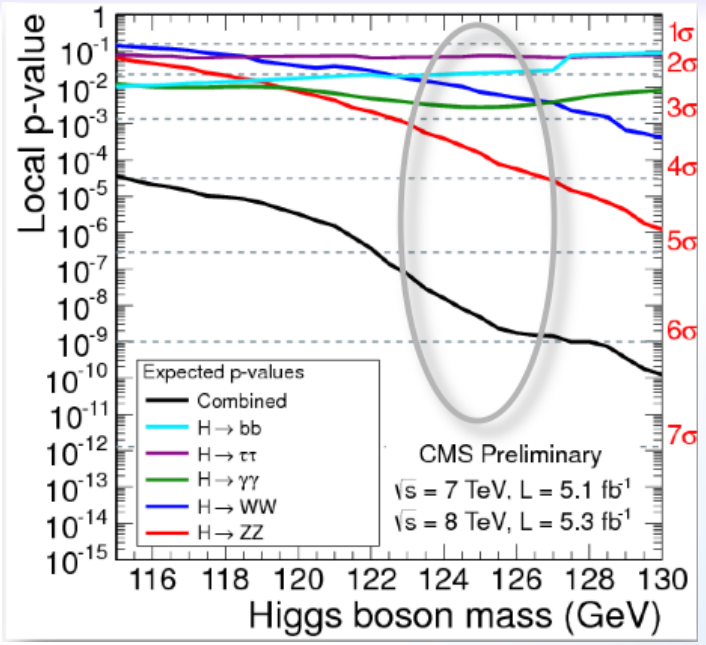
Higgs Hunting, Orsay, 19/07/2012

Introduction

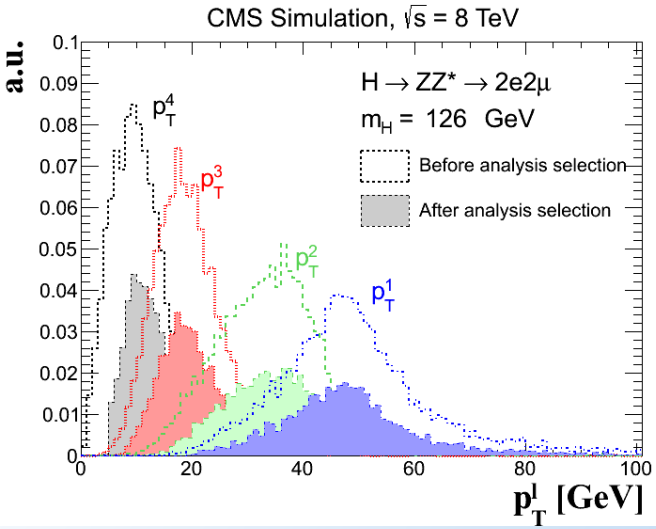
- "Golden channel" H → ZZ → 2l2l'

  (*l*,*l'* = e,μ; *l'* = τ for high mass studies)
  - The **most sensitive** in [120 – not excluded]
  - **Very clean signature**: 4 primary isolated leptons, full 4l mass reco, narrow resonance
  - **Low level of backgrounds**
  - But needs the **highest efficiencies** and performance



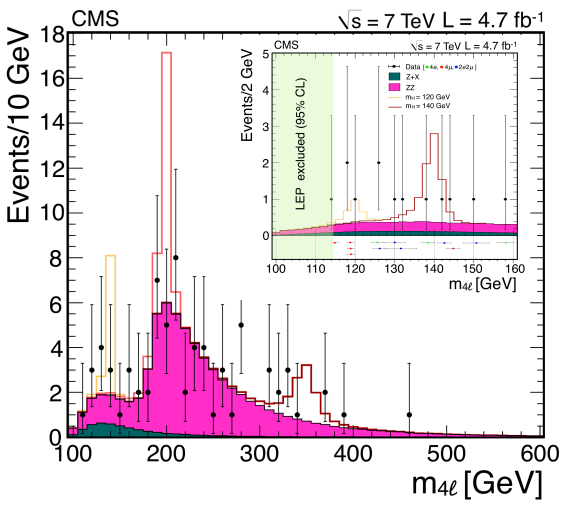
- General strategy in 2012 [110 - 600] GeV
  - Blinding for the 2012 and 2011 data: $110 \le m_{4l} \le 140$ and $m_{4l} \ge 300$
  - Reoptimize analysis: ID, isolation, FSR recovery, use of full kinematics

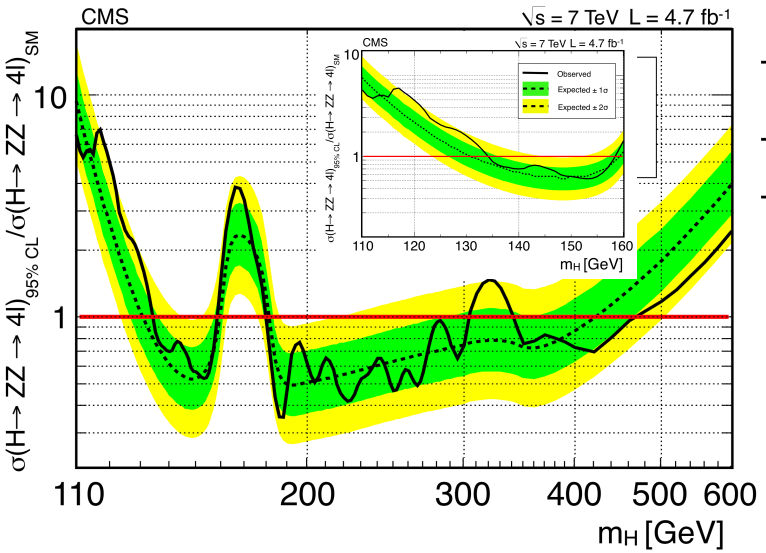
20% gain in significance for $m_H = 126$ GeV

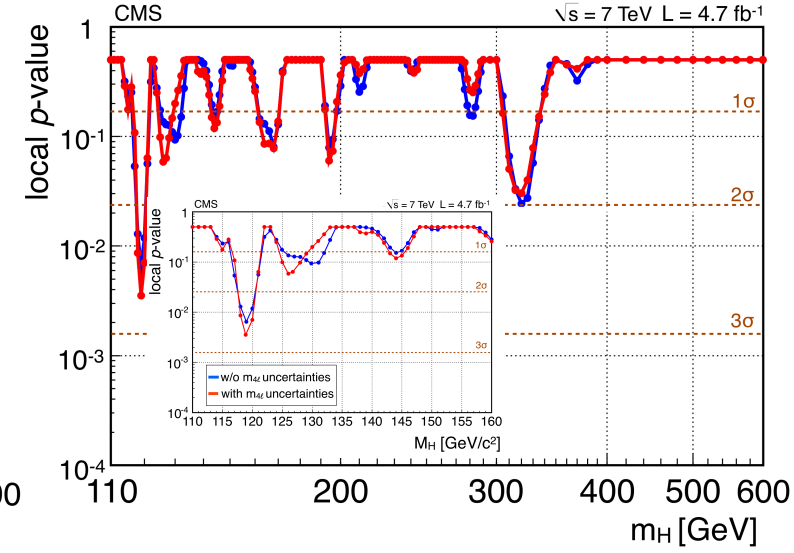


2011 results

Results @ 7 TeV 4.7 fb^{-1}



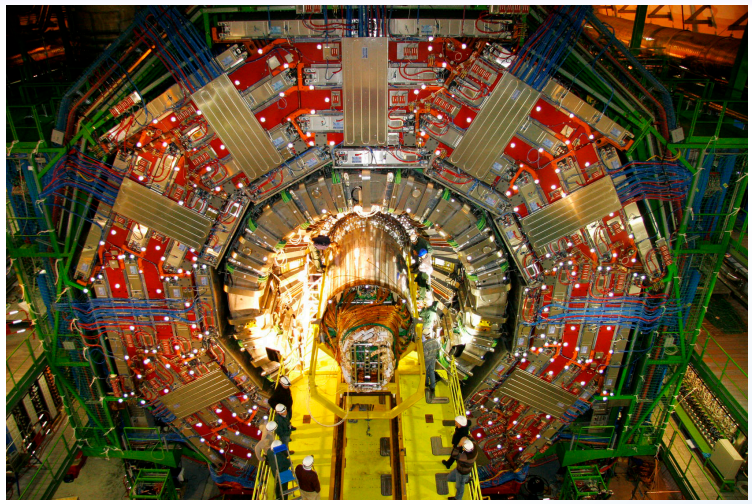


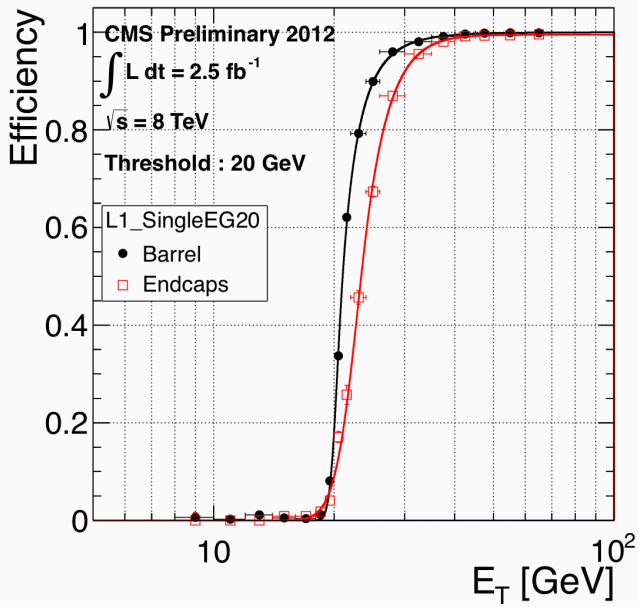


- Exclusion of the SM Higgs boson in the ranges [134 - 158], [180 - 305], and [340 - 465] GeV
- Small excesses of events around masses of 119, 126, and 320 GeV → observed limits weaker than expected in the absence of a signal
- cf. *Phys. Rev. Lett. 108 (2012) 111804.*

Ingredients

- Data
  - 5.05 fb^{-1} @7 TeV and 5.26 fb^{-1} @8 TeV
- CMS detector
- Trigger
  - Excellent performance of the L1 and HLT triggers
  - → Double lepton ee, μμ and eμ with $E(P)_T$ thresholds of 17 and 8 GeV
- Leptons
  - Reconstruction, ID, isolation
- Analysis selection
- Background control and estimation
- Statistical analysis

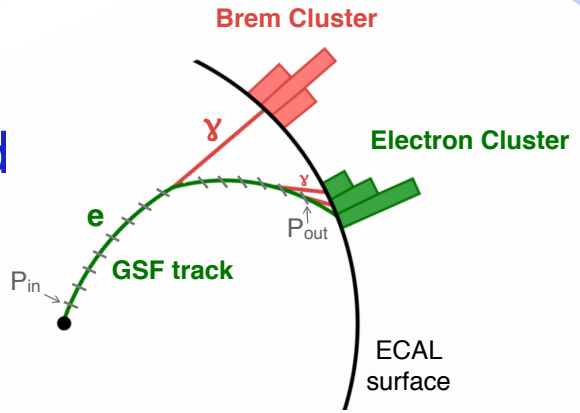




Electrons

Electrons in analysis $|\eta| \leq 2.5$ $p_T \geq 7$ GeV

- Superclusters in ECAL ($E_T > 4$ GeV) + dedicated track finding and GSF fit (before candidate id.)
  - collect energy spread in phi
  - change of curvature and hit collection up to ECAL

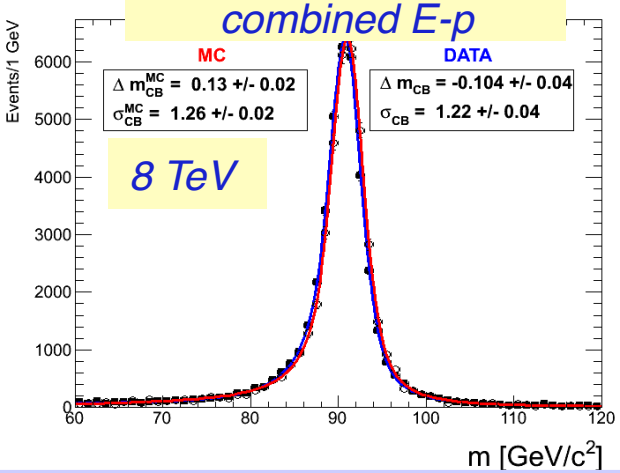


- ECAL-seed complemented by tracker-seed (efficiency gain at low p_T)
- Electron classes brem sensitive
- Momentum from E-p combination

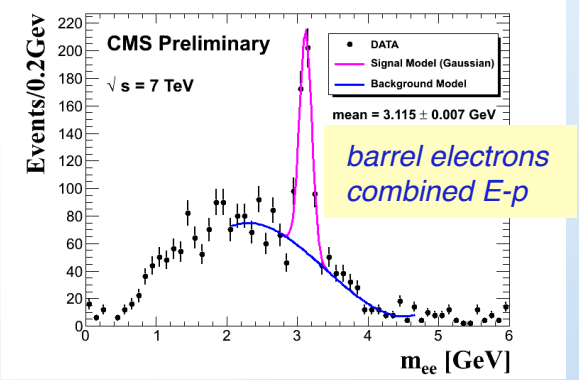
Scale and resolution

- Z peak for different electron categories

Golden barrel electrons combined E-p



- + control low p_T with J/ψ

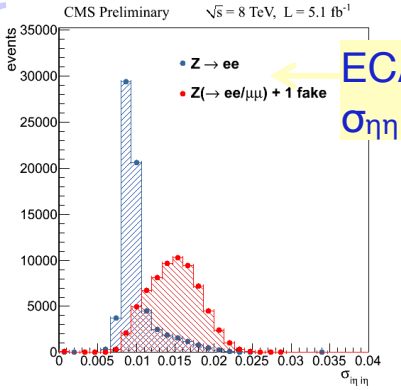


barrel electrons combined E-p

Electrons ID NEW

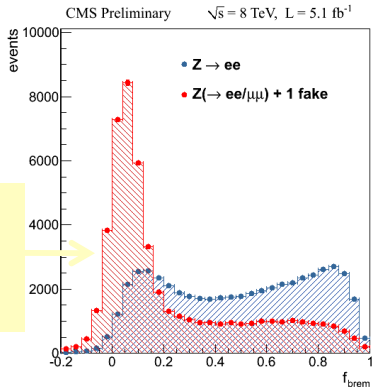
Multivariate in 2012 (BDT)

- Observables sensitive to brem, geometrical and momentum matching ECAL – tracker – HCAL, shower shape
- Background from data samples
- Performances optimized for H→ZZ→4l
- Efficiency measured via Z Tag&Probe

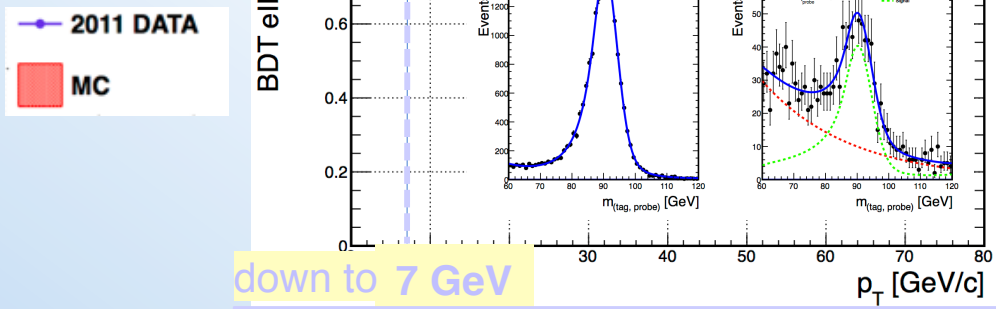


ECAL variable:
$\sigma_{\eta\eta}$ in barrel, $p_T < 20$ GeV

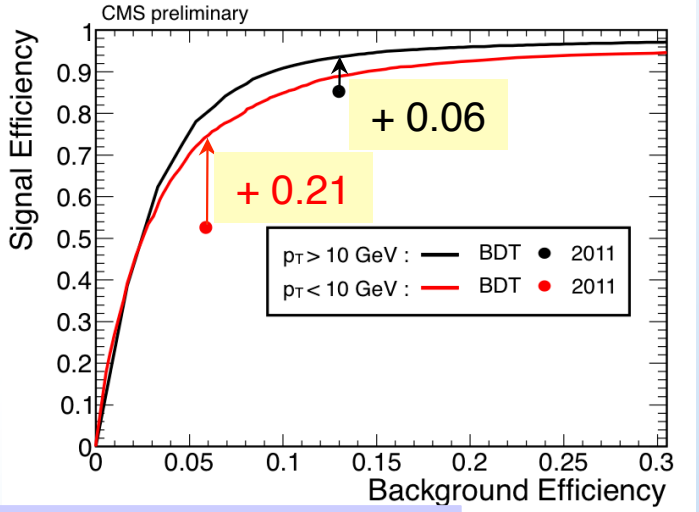
Tracker variable:
fbrem in endcaps,
$p_T < 20$ GeV



e-ID efficiency in barrel



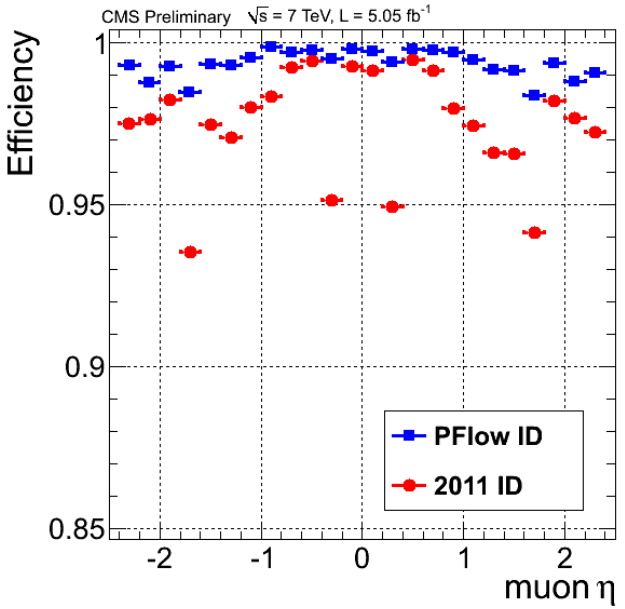
down to 7 GeV

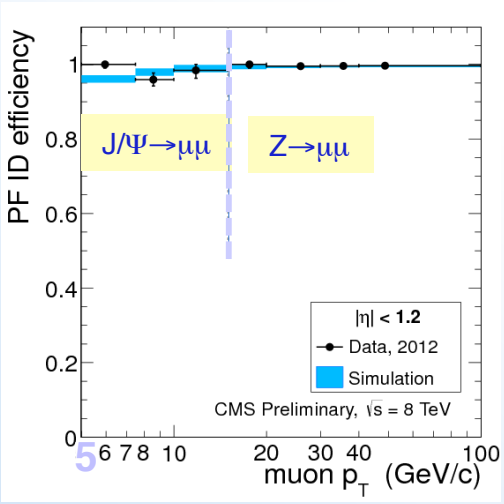


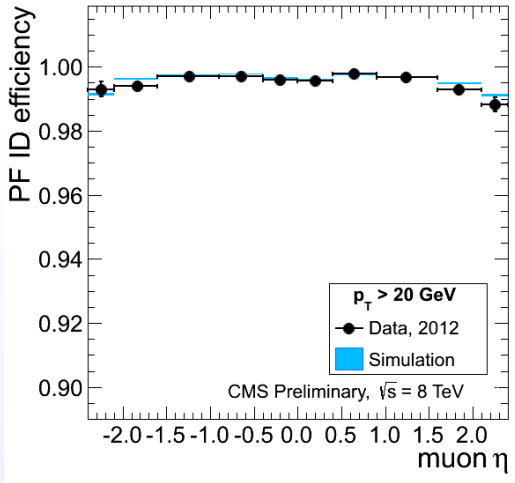
30% efficiency gain in 4e for m_H = 126 GeV (same fake rate) wrt 2011

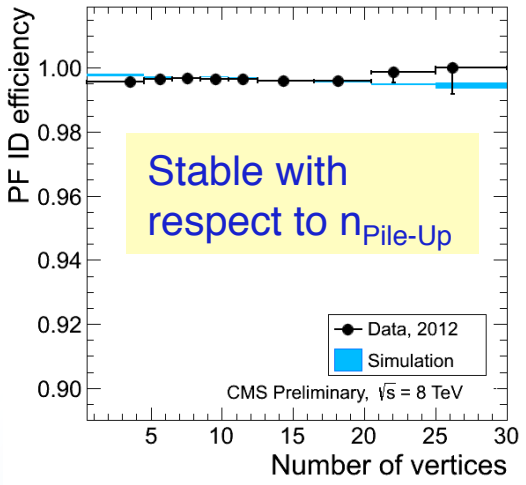
Muons

- Muons in analysis $|\eta| \leq 2.4$ $p_T \geq 5$ GeV
  - Combination of inner tracker tracks and muon system tracks
  - Particle Flow ID: NEW
    - inner and muon tracks quality and matching
    - 99 % efficient for same fake rate as in 2011
  - Efficiency measured via Z and J/ψ Tag&Probe







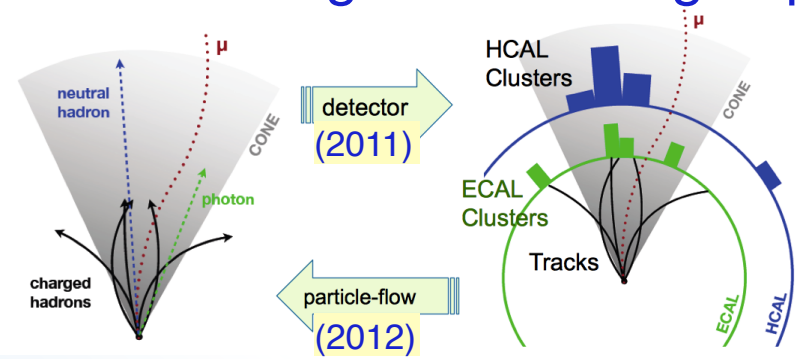


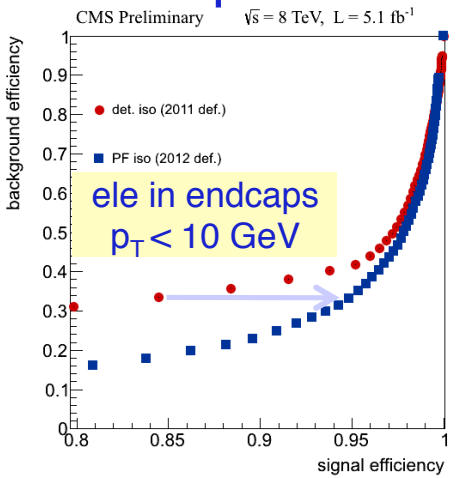
5% efficiency gain in 4μ for m_H = 126 GeV (same fake rate) wrt 2011

Isolation NEW

Particle-based isolation

- In $\Delta R = 0.4$ cone around the lepton
  from the charged and neutral hadrons, photons: $\Sigma iso / p_T < 0.4$
- No double counting for the charged particles, automatic lepton removal

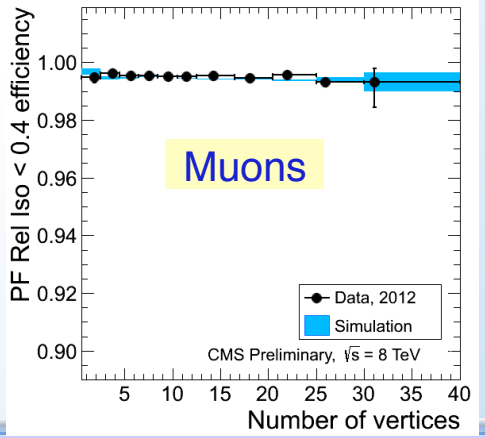




10 to 15% efficiency gain per lepton (same fake rate) wrt 2011

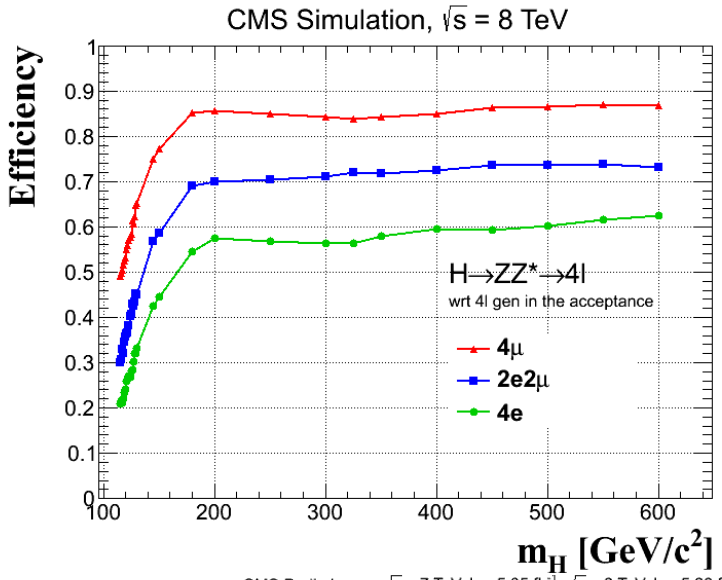
Pile-up (PU) contribution:

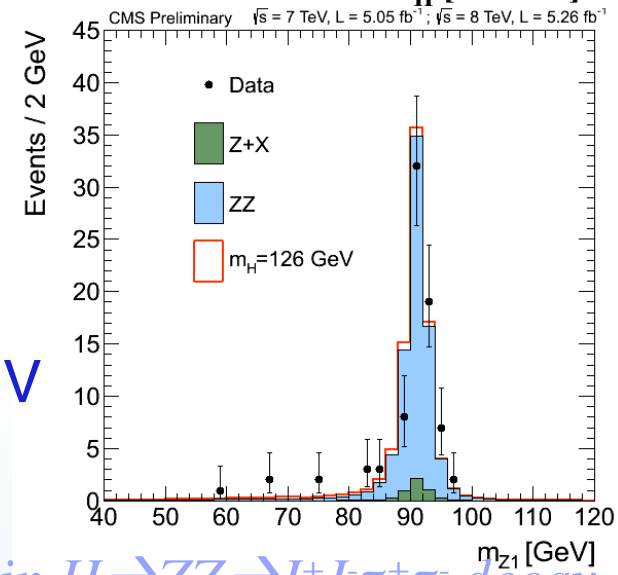
- Charged: negligible (required from the vertex)
- Neutrals: corrected using the average energy density from the PU and underlying event
- → quite stable with respect to n_{PU}



Analysis selection

- Trigger
- Leptons
  - Electrons $|\eta| \leq 2.5$ $p_{Tmin} \geq 7$ GeV
  - Muons $|\eta| \leq 2.4$ $p_{Tmin} \geq 5$ GeV
  - Isolated, ID, compatible with PV
  - $pT \geq 20, 10, p_{Tmin}, p_{Tmin}$
- Final State Radiation (FSR) recovery
- Kinematics
  - Z1 closest to Z_{PDG} $40 \leq m_{Z1} \leq 120$ GeV
  - Z2 with the highest p_T remaining pair
    $12 \leq m_{Z2} \leq 120$ GeV + all l^+l^- pairs $m_{l+l-} \geq 4$ GeV
  - $m_{4l} \geq 100$ GeV



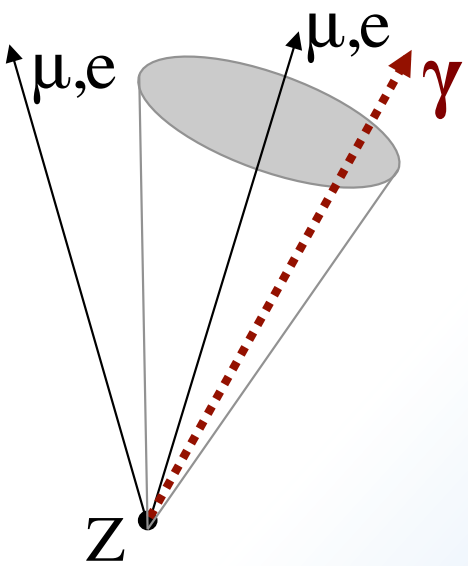


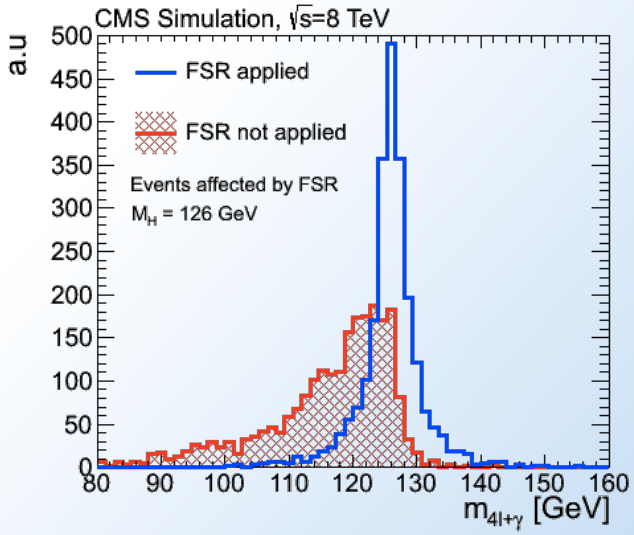
for 2l2τ see: *Search for the Standard Model Higgs boson in $H \rightarrow ZZ \rightarrow l^+l^-\tau^+\tau^-$ decay channel with CMS* (S.CHHIBRA, young scientist forum)

FSR Recovery NEW

- Algorithm
  - ParticleFlow photons near the Z leptons:
    - $|\eta| \leq 2.4$
    - $P_T \geq 2$ GeV if $\Delta R \leq 0.07$
    - $P_T \geq 4$ GeV, isolated, if $0.07 \leq \Delta R \leq 0.5$
  - Associates photon with Z if
    - $m_{ll+\gamma} < 100$ GeV
    - $|m_{ll+\gamma} - m_Z| < |m_{ll} - m_Z|$
  - Removes associated photons from lepton isolation calculation
- Expected Performance for $m_H = 126$ GeV
  - 6% of events affected
  - Efficiency 50 % for purity of 80%

2% efficiency gain for $m_H = 126$ GeV

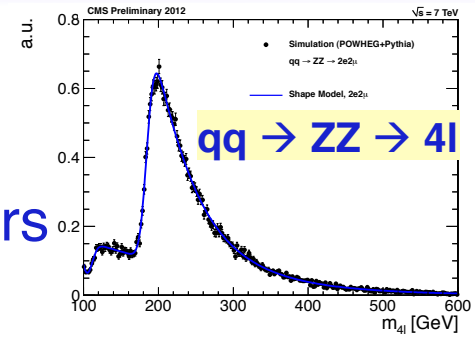


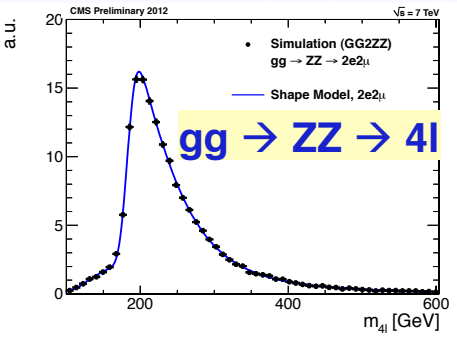


Backgrounds estimation

Irreducible ZZ→4l

- MC and theoretical NLO σ
- Corrected for data/MC scale factors
- Phenomenological shape models

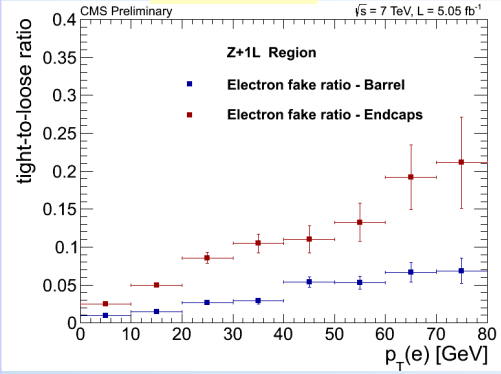




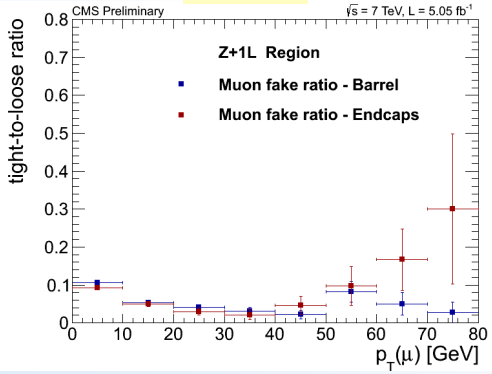
Reducible backgrounds

- Zbb, tt, WZ+jets, Z+jets
- From data - 50 % uncertainty
  - fake rate method

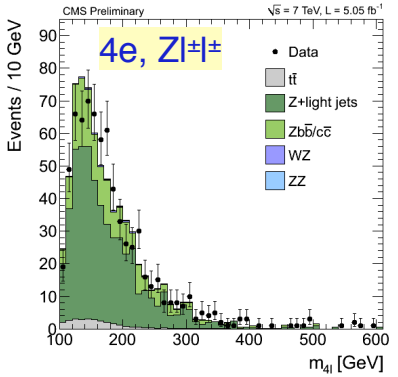
electrons

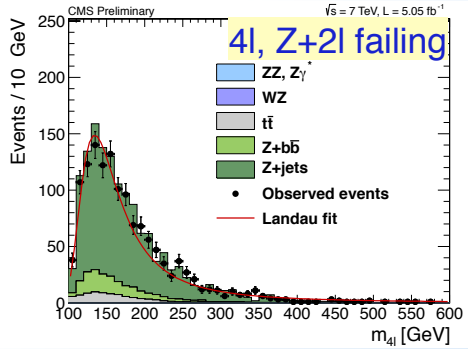


muons

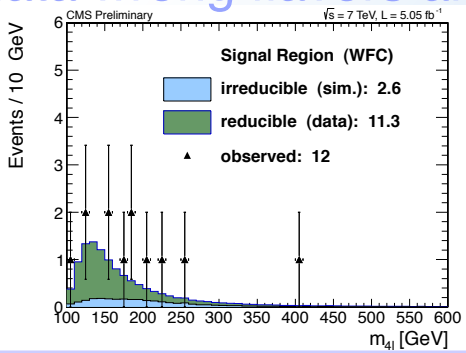


- applied from signal-free control samples



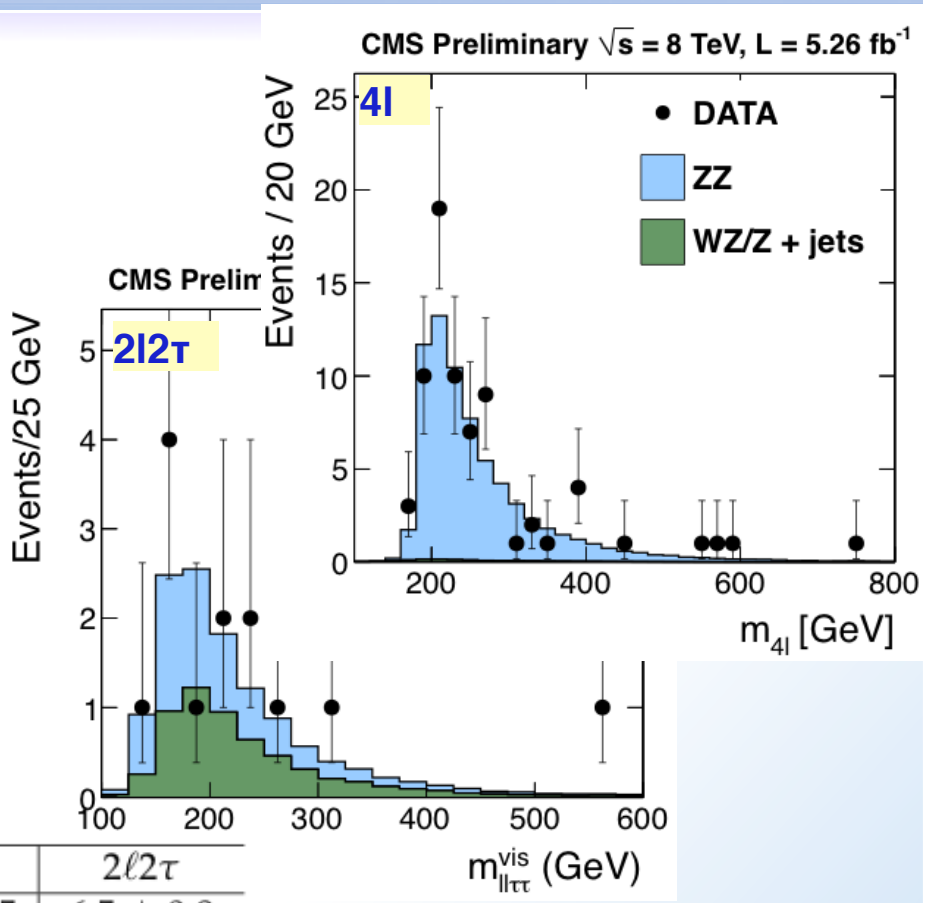


- validation (data wrong flavors and charges)



ZZ cross section

- 4l + 2l2τ $\sqrt{s}$ = 8 TeV 5.26 fb^{-1}
  - 4l: as for the Higgs analysis
    $60 \le m_{Z1} \le 120$ GeV
    $60 \le m_{Z2} \le 120$ GeV
  - 2l2τ:
    - Z1 → e^+e^- or $\mu^+\mu^-$, $p_T > 20, 10$ GeV
      $60 \le m_{Z1} \le 120$
    - Z2 → $\tau^+\tau^-$, $p_T^{\tau l} > 10$, $p_T^{\tau h} > 20$ GeV
      $20\text{-}30 \le m_{\tau\tau} \le 90$ GeV



- Results

Channel	4e	4μ	2e2μ	2ℓ2τ
ZZ	11.6 ± 1.4	20.3 ± 2.2	32.4 ± 3.5	6.5 ± 0.8
Background	0.4 ± 0.2	0.4 ± 0.3	0.5 ± 0.4	5.6 ± 1.4
Total	12.0 ± 1.4	20.7 ± 2.2	32.9 ± 3.5	12.1 ± 1.6
Observed	14	19	38	13

- Measured **σ(pp → ZZ) = 8.4 ± 1.0(stat.) ± 0.7(sys.) ± 0.4(lumi.) pb**
- Good agreement with NLO prediction: σ_{th}(pp → ZZ) = 7.7 ± 0.4 pb

Systematics

Theoretical

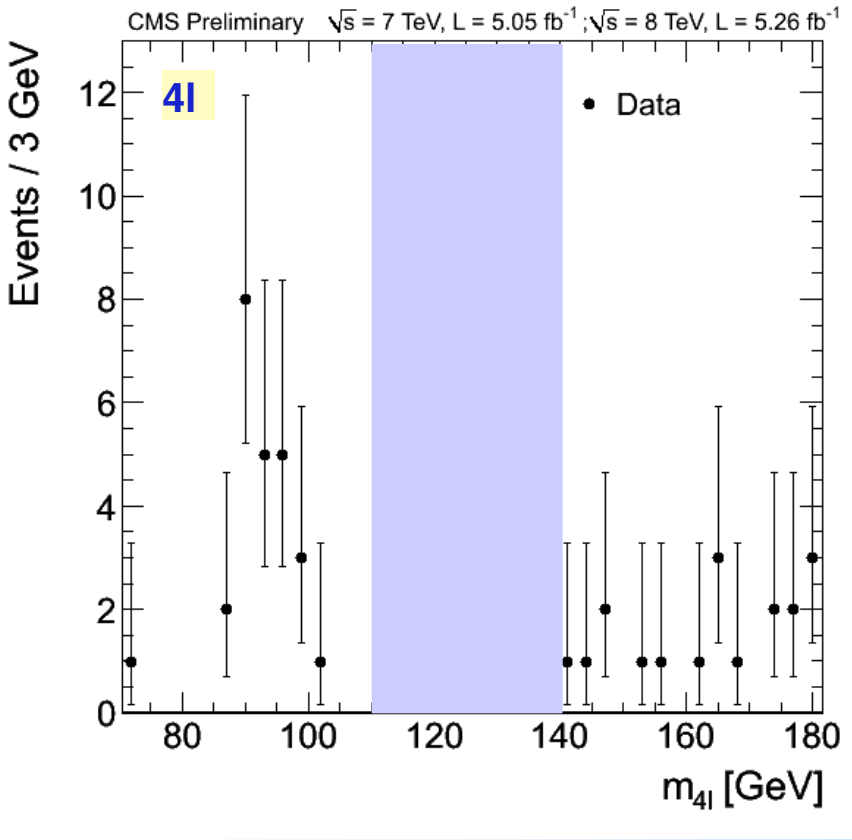
σ_H	17 - 20 %
H Branching fraction	2 %
ZZ cross section	8 %

Experimental

trigger	1.5 %	
lepton reco + ID + iso	1.2 % 4μ high masses to 11% 4e low masses	from T&P studies
lepton momentum scale	≤ 0.4 %	affects signal shape
lepton momentum resolution	20 %	affects signal shape
τ_h *ID and iso*	6 %	
τ_h *energy scale*	3 %	
reducible background	50 %	
luminosity	4.4 % (8TeV) 2.2% (7TeV)	ZZ background + σ measurement + signal yieds

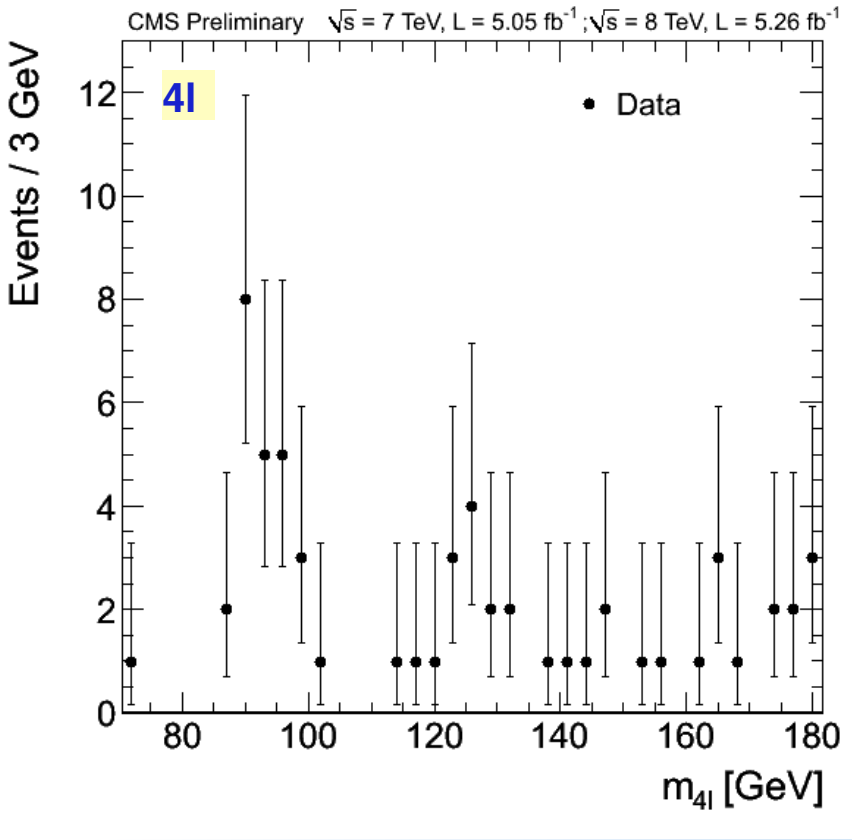
Results

- m_{4l} distribution
  - Low mass range
  - Data only
  - Blinded



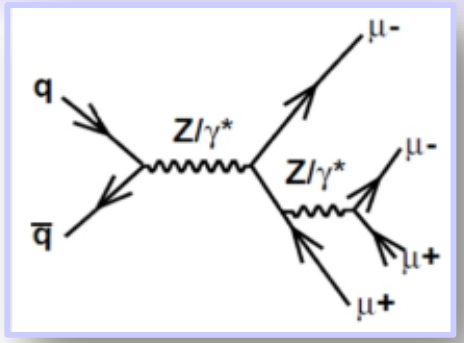
Results

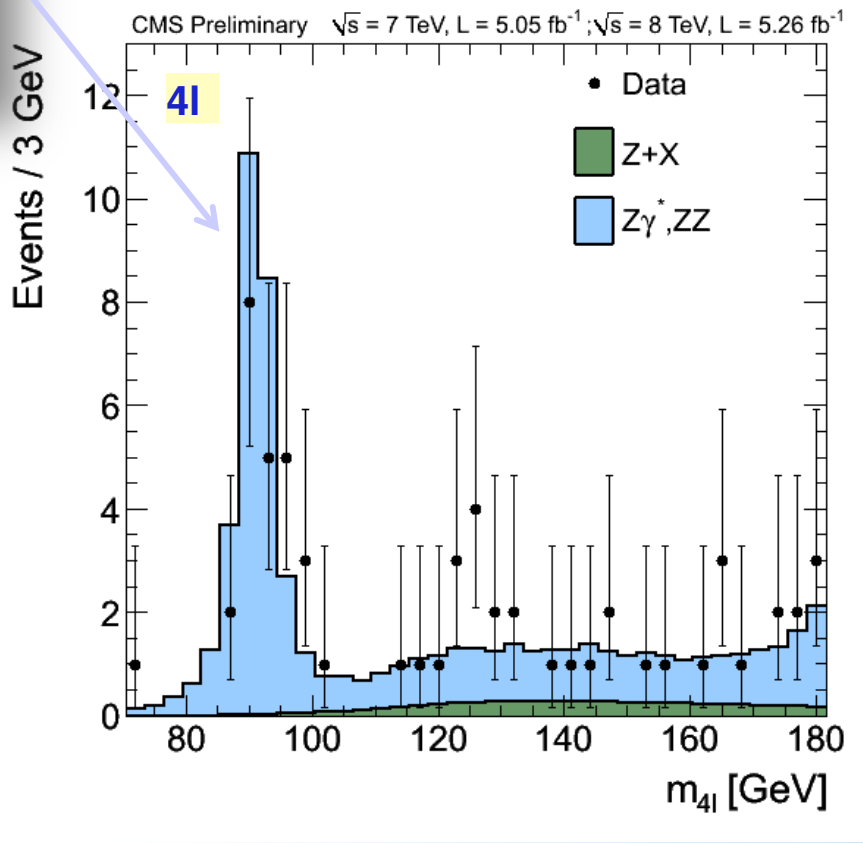
- m_{4l} distribution
  - Low mass range
  - Data only
  - Un-Blinded



Results

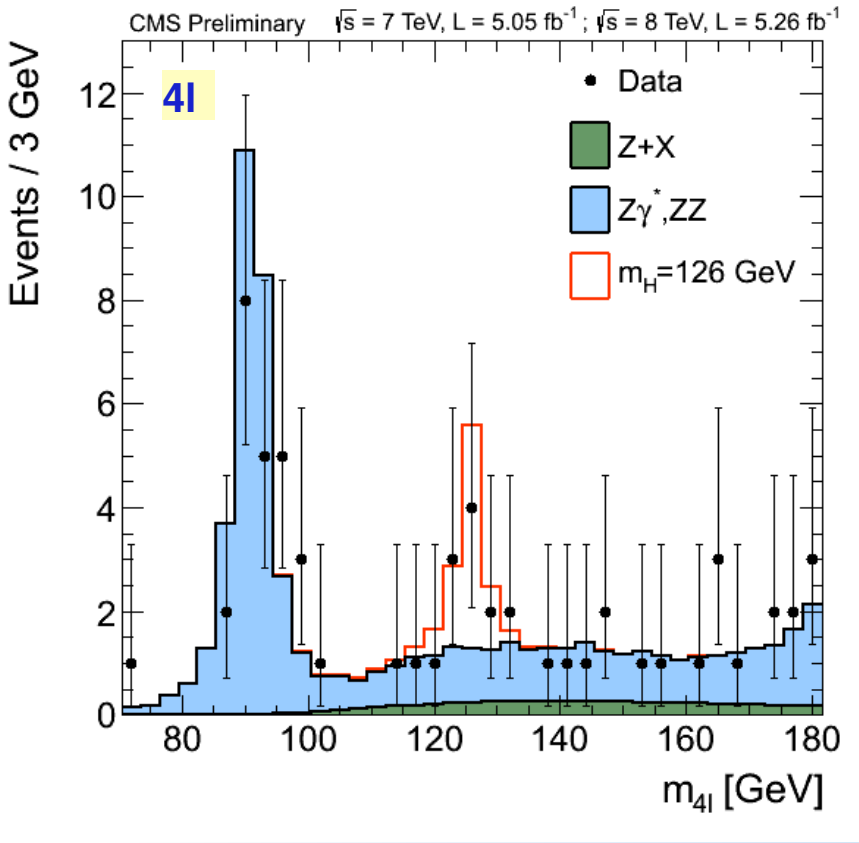
- m_{4l} distribution
  - Low mass range
  - Un-Blinded
  - Background expectation





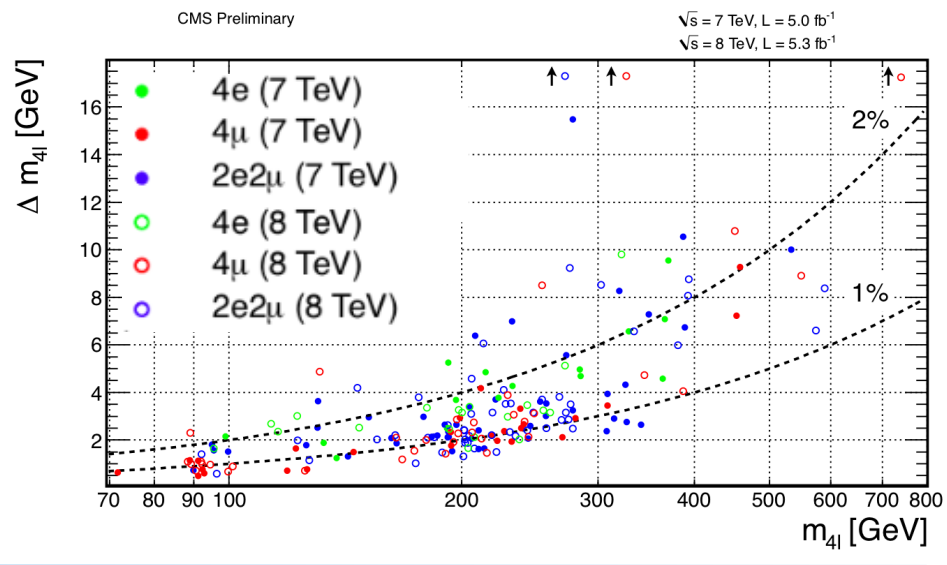
Results

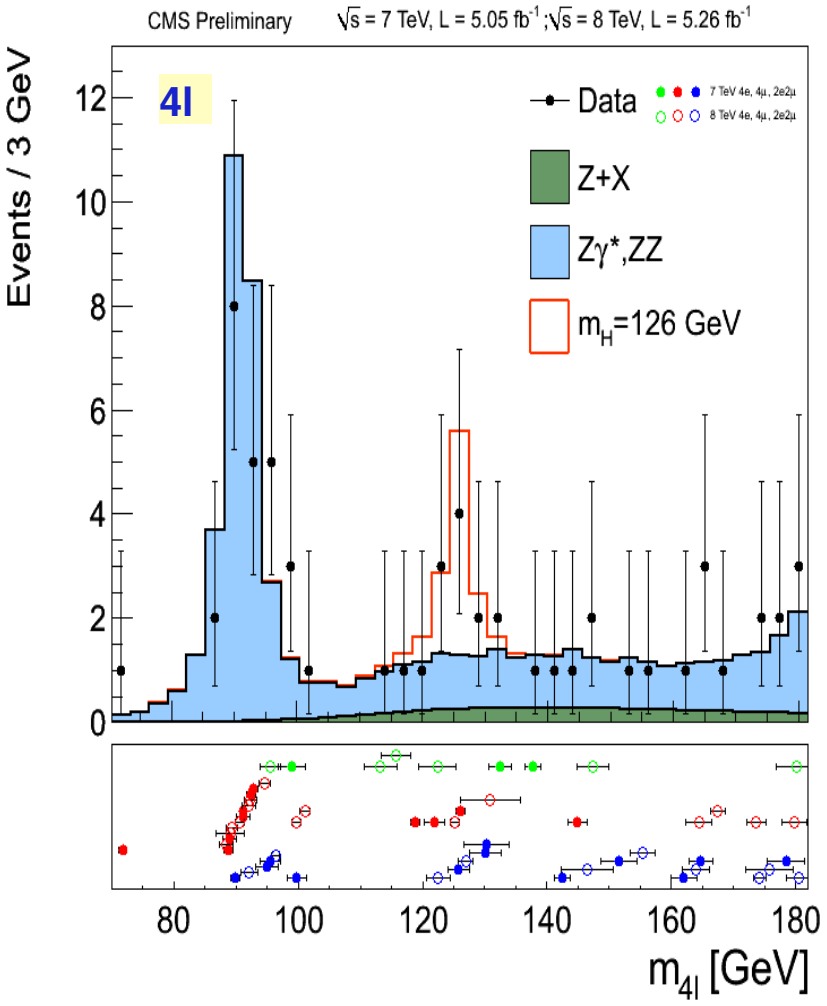
- m_{4l} distribution
  - Low mass range
  - Un-Blinded
  - Background expectation
  - Signal m_H = 126 GeV expectation



Results

- m_{4l} distribution
  - Low mass range
  - Un-Blinded
  - Background expectation
  - Signal m_H = 126 GeV expectation
  - Event by event errors



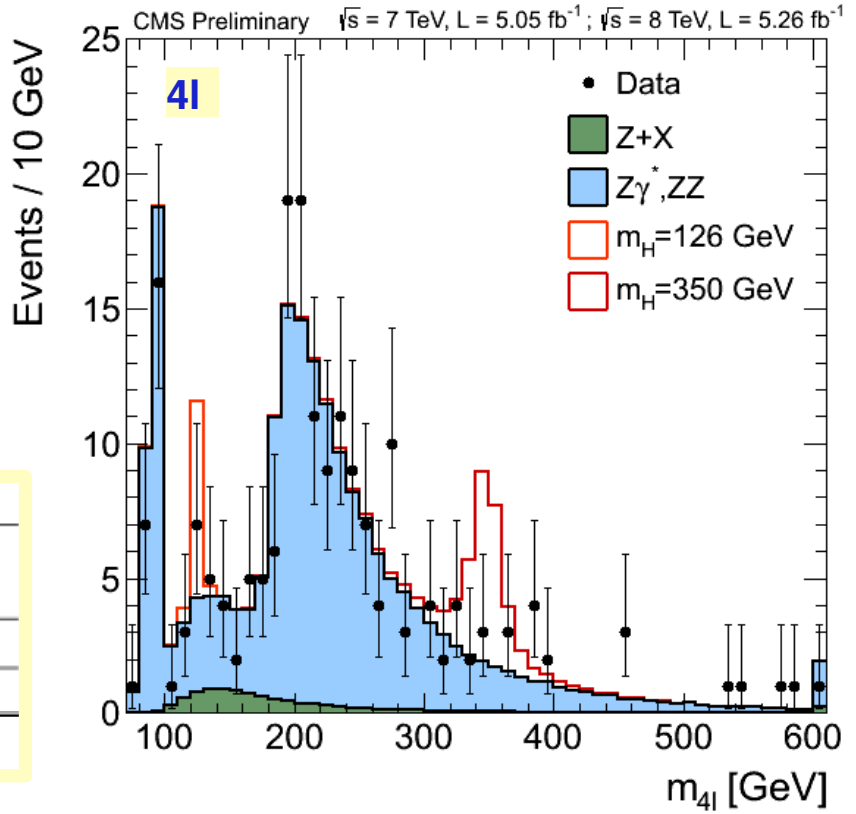


Results

- m_{4l} distribution
  - Full mass range
  - Un-Blinded
  - Background expectation
  - Signal m_H = 126, 350 GeV expecta
  - Event Yields

Yields for m_{4l}= [110 - 160] GeV

Channel	4e	4μ	2e2μ	4ℓ
ZZ background	2.65 ± 0.31	5.65 ± 0.59	7.17 ± 0.76	15.48 ± 1.01
Z+X	$1.20^{+1.08}_{-0.78}$	$0.92^{+0.65}_{-0.55}$	$2.29^{+1.81}_{-1.36}$	$4.41^{+2.21}_{-1.66}$
All backgrounds	$3.85^{+1.12}_{-0.84}$	$6.58^{+0.88}_{-0.81}$	$9.46^{+1.96}_{-1.56}$	$19.88^{+2.43}_{-1.95}$
$m_H = 126$ GeV	1.51 ± 0.48	2.99 ± 0.60	3.81 ± 0.89	8.31 ± 1.18
Observed	6	6	9	21

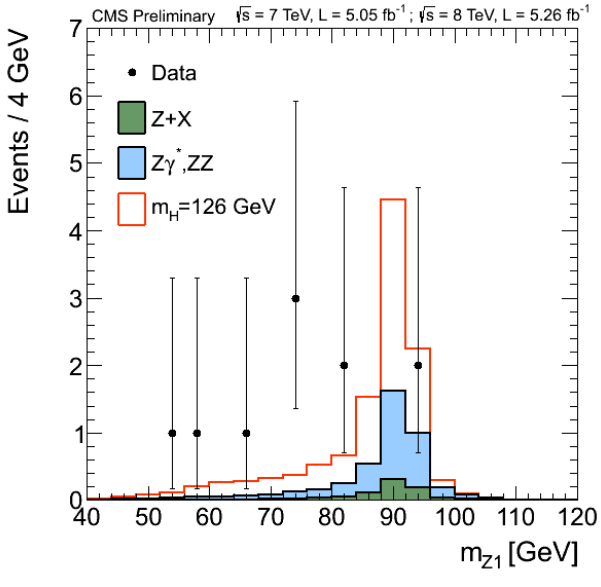


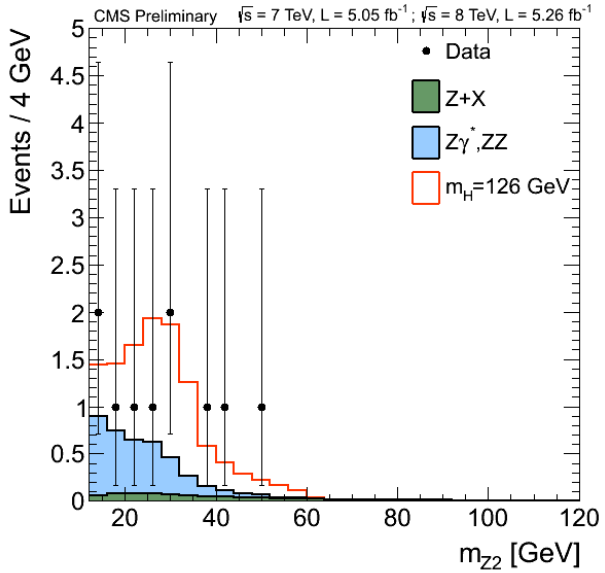
Yields for m_{4l}= [100 - 800] GeV:
expected: 164 ± 11 events
observed: 172

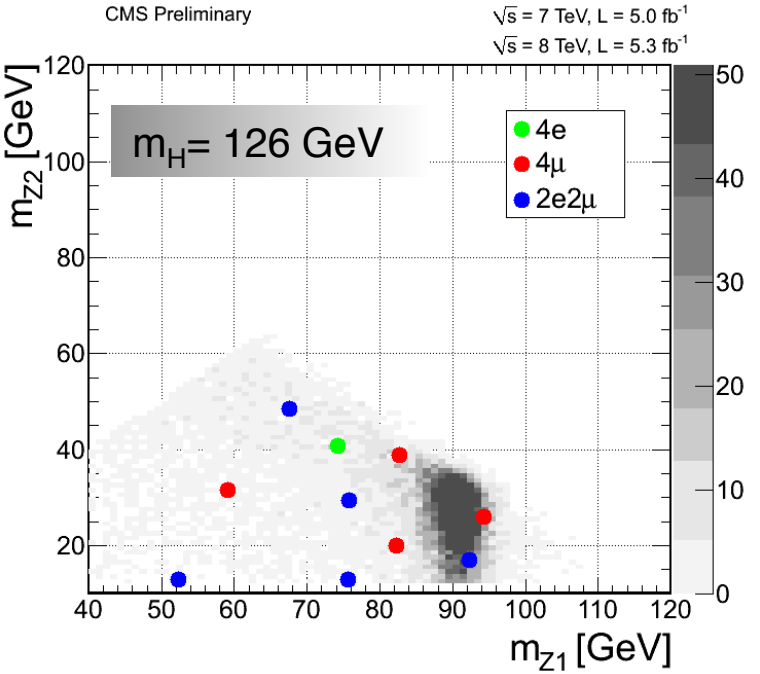
Results

2l invariant masses

- $121 \leq m_{4l} \leq 131$ GeV







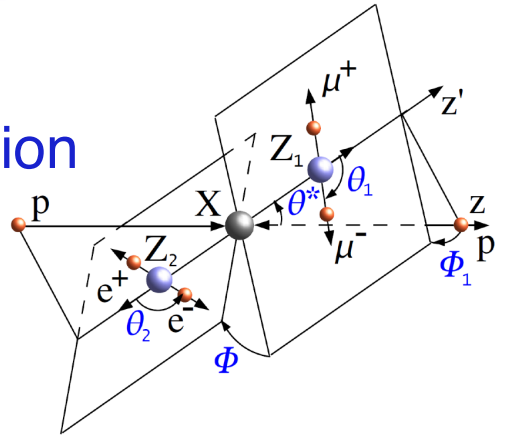
- Z_1 and Z_2 masses seem too low for signal and background

Kinematic Analysis (MELA)

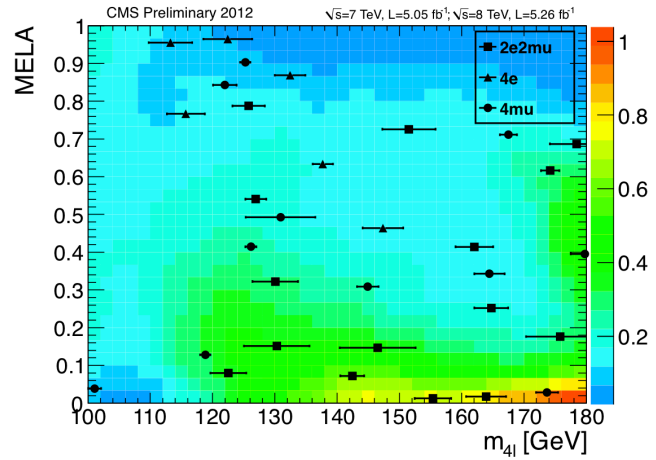
NEW

Matrix Element *L*ikelihood **A**nalysis (MELA)

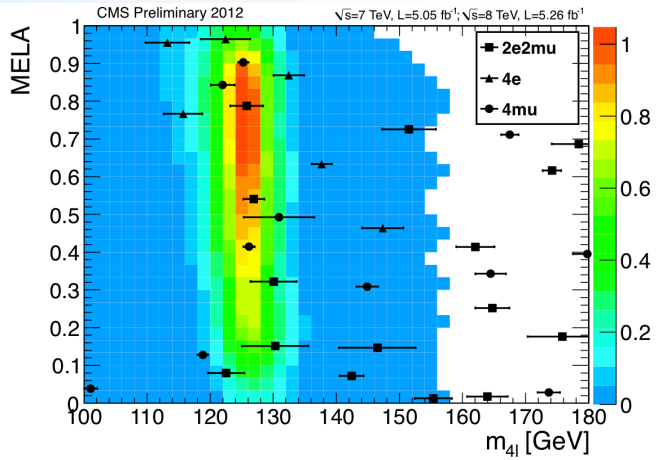
- Kinematic inputs for signal to background discrimination
- 2D analyis {m_{4l}, MELA}

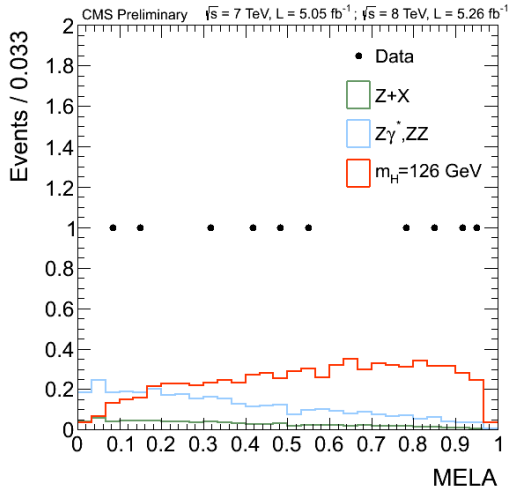


background

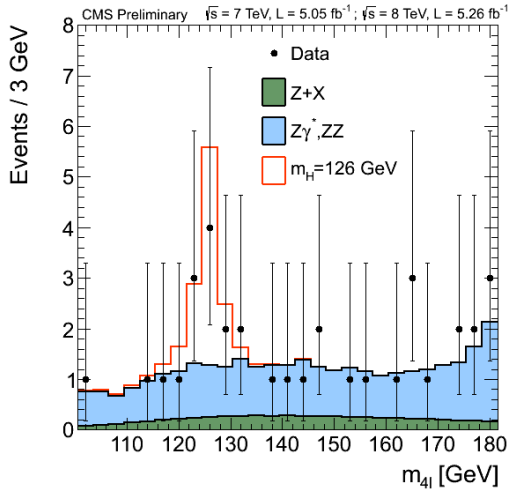


m_H = 126 GeV





$121 \le m_{4l} \le 131$ GeV



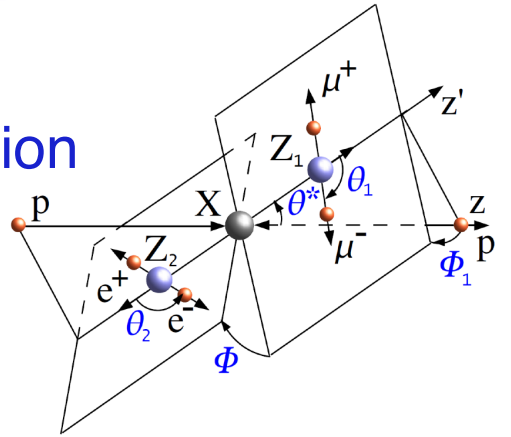
m_{4l}

Kinematic Analysis (MELA)

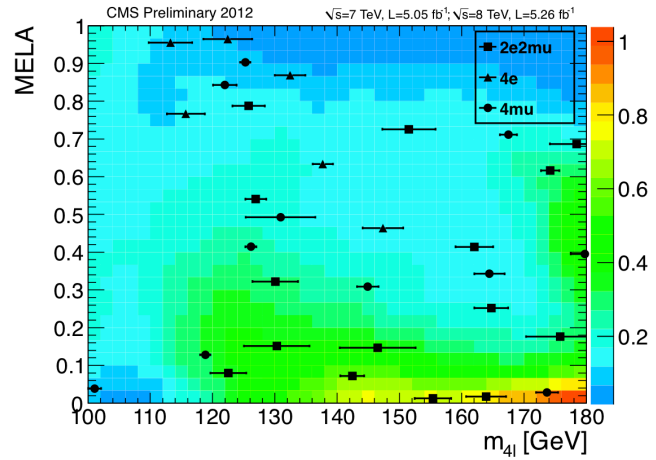
NEW

Matrix Element *L*ikelihood **A**nalysis (MELA)

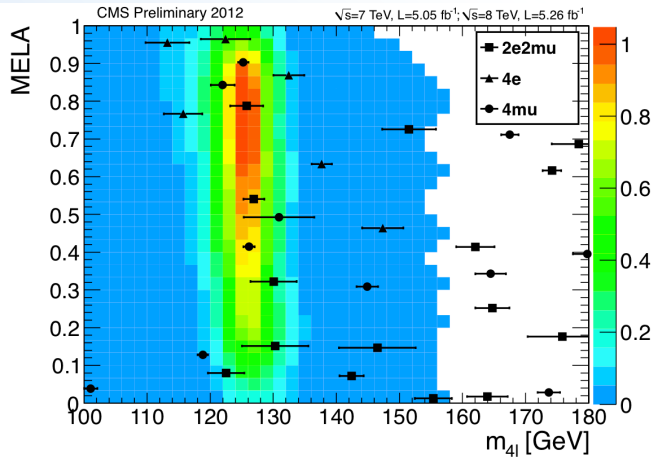
- Kinematic inputs for signal to background discrimination
- 2D analyis {m_{4l}, MELA}

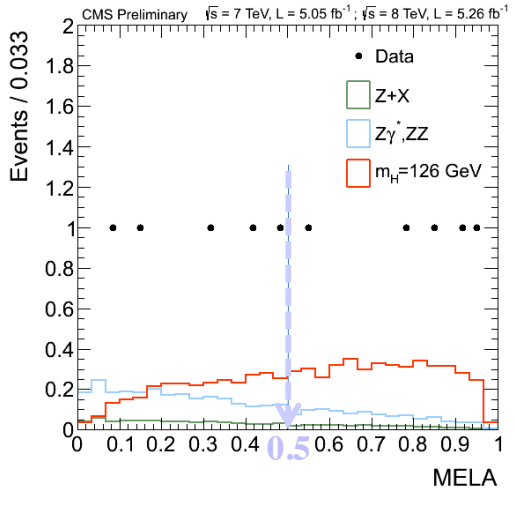


background

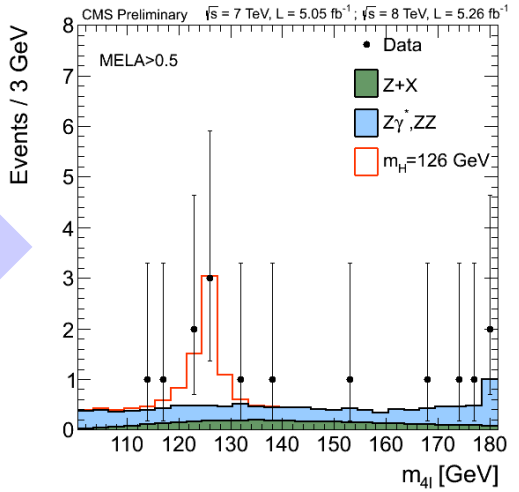


m_H = 126 GeV





$121 \le m_{4l} \le 131$ GeV

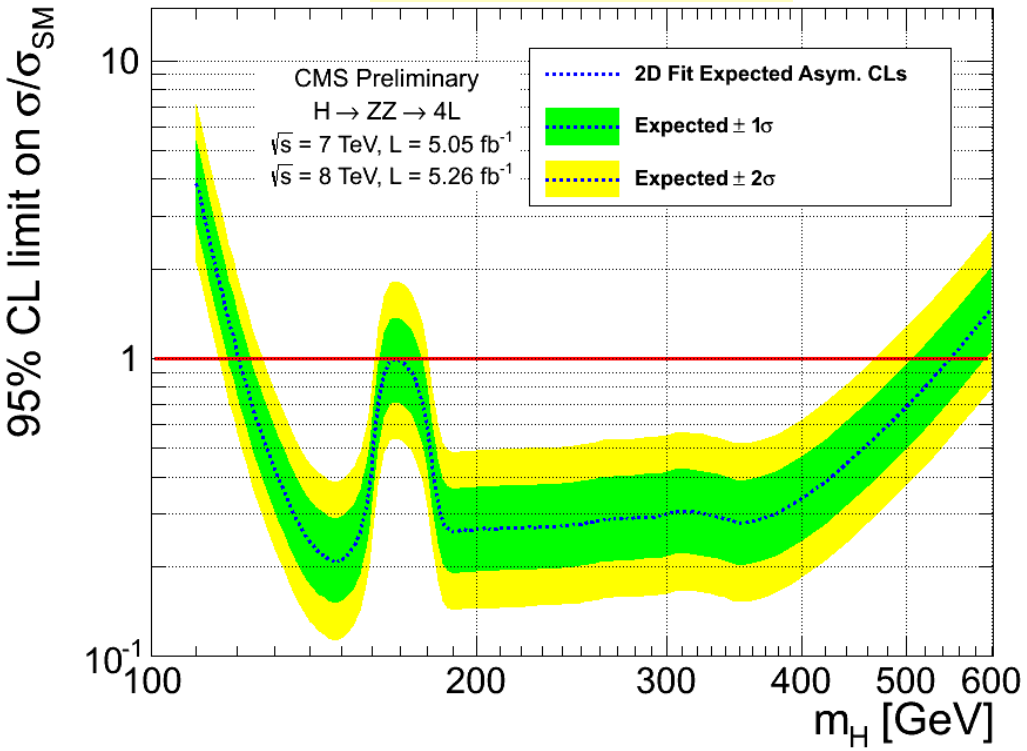


m_{4l} MELA>0.5 (illustration)

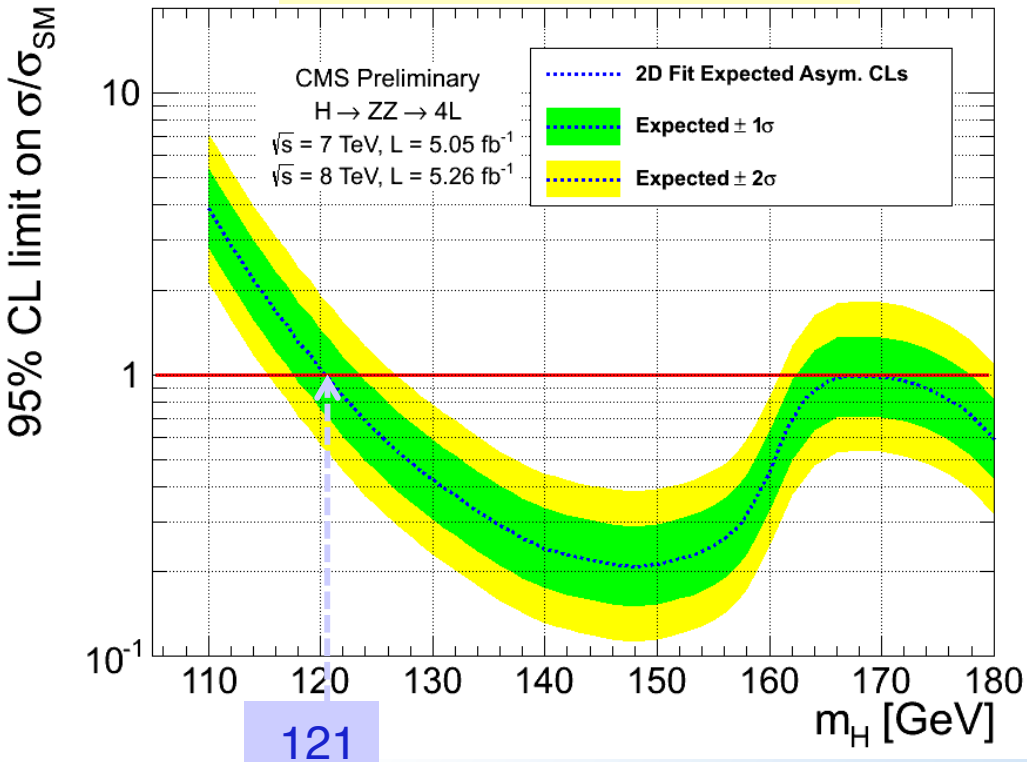
Results (95% CL limits)

Expected limits

full mass range



zoomed mass range

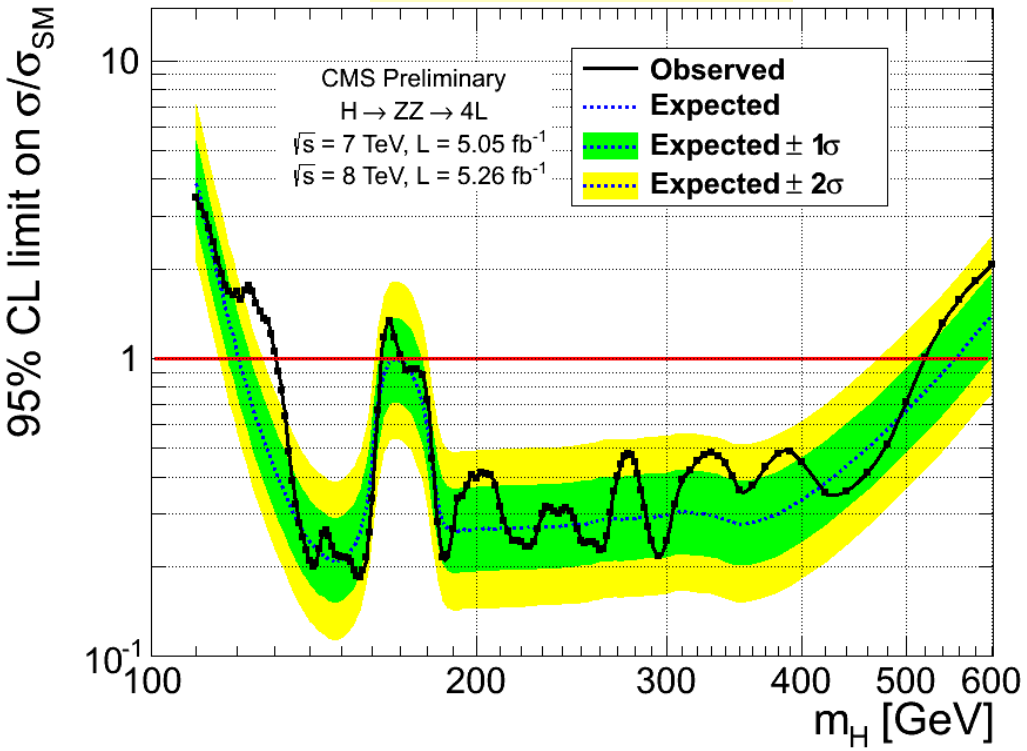


→ expected exclusion of the SM Higgs **[121 - 570]**

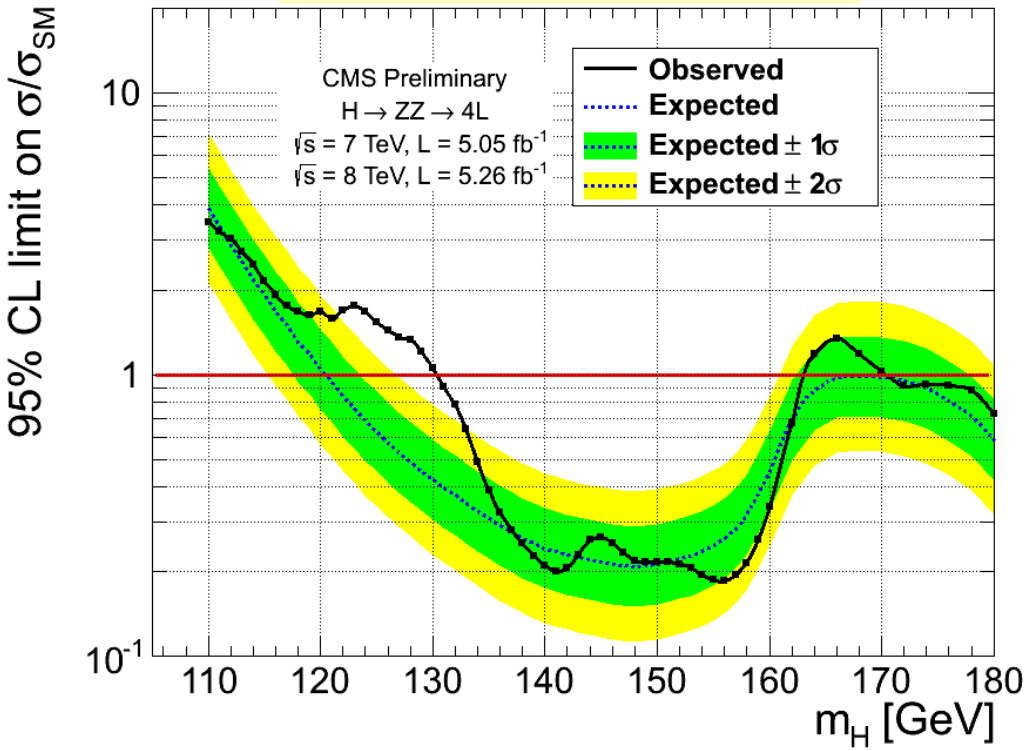
Results (95% CL limits)

- Observed limits

full mass range



zoomed mass range

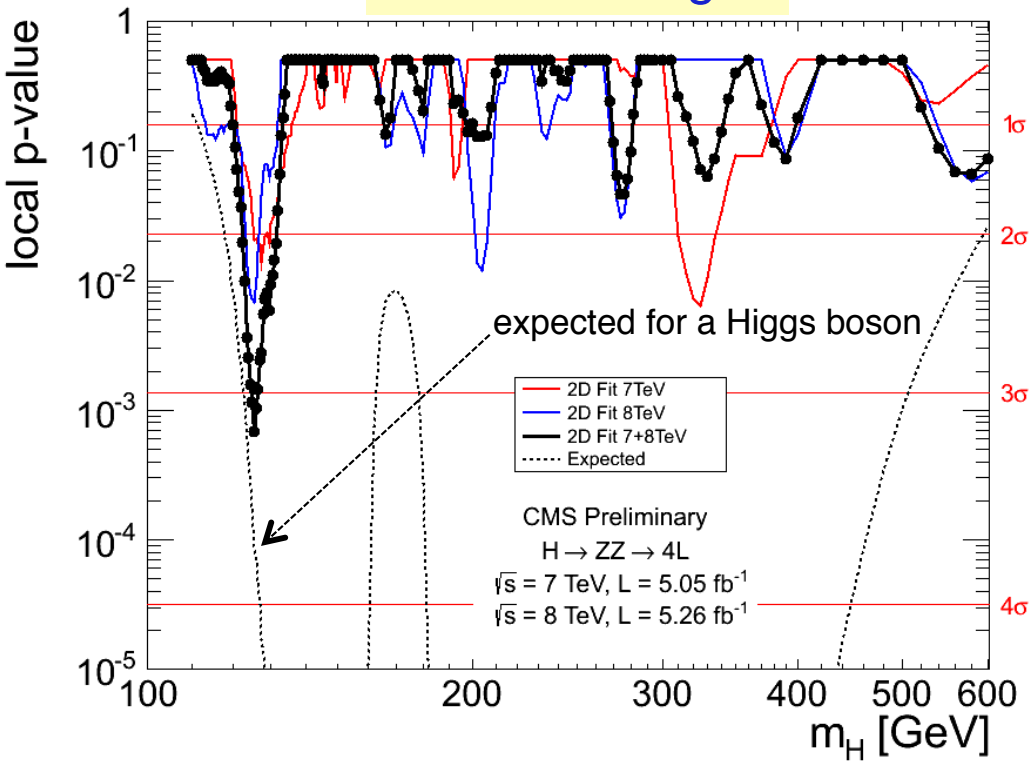


- → expected exclusion of the SM Higgs **[121 - 570]**
- → observed exclusion of the SM Higgs **[131 - 162] [172 - 525]**
- → observed **excess of events** in the region $m_H \sim 125$ GeV

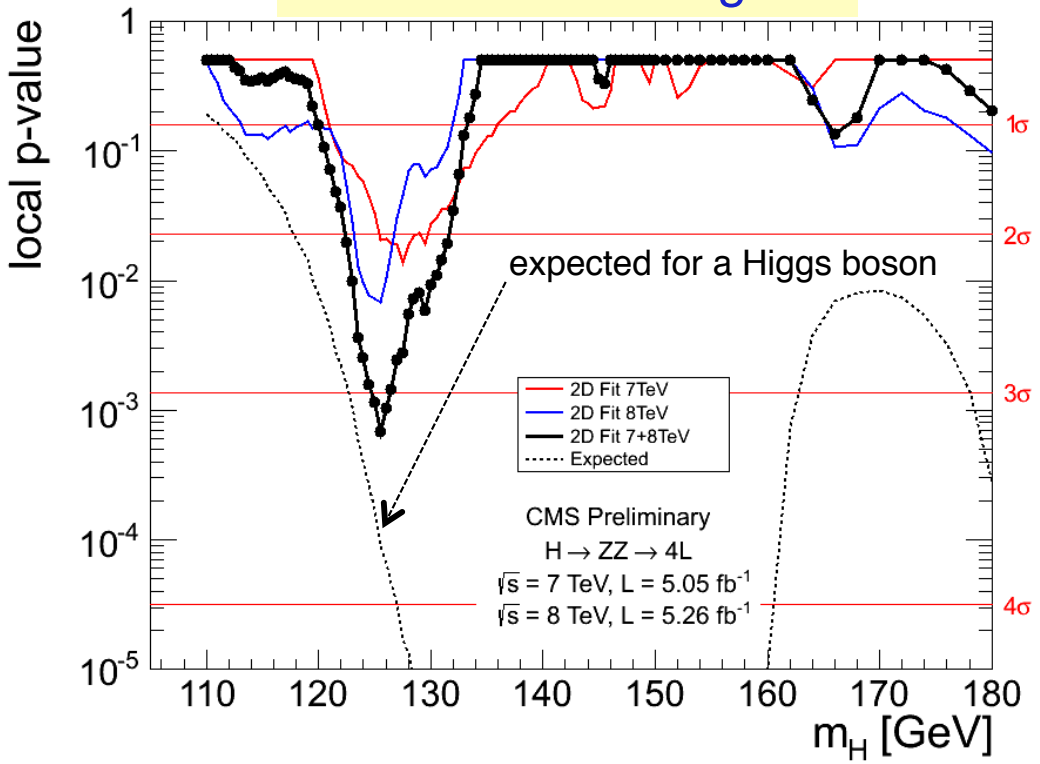
Results (p-values)

- p-values

full mass range



zoomed mass range



→ expected local significance m_H = 125.5 GeV : **3.8 σ**

→ observed local significance m_H = 125.5 GeV : **3.2 σ**

Conclusion

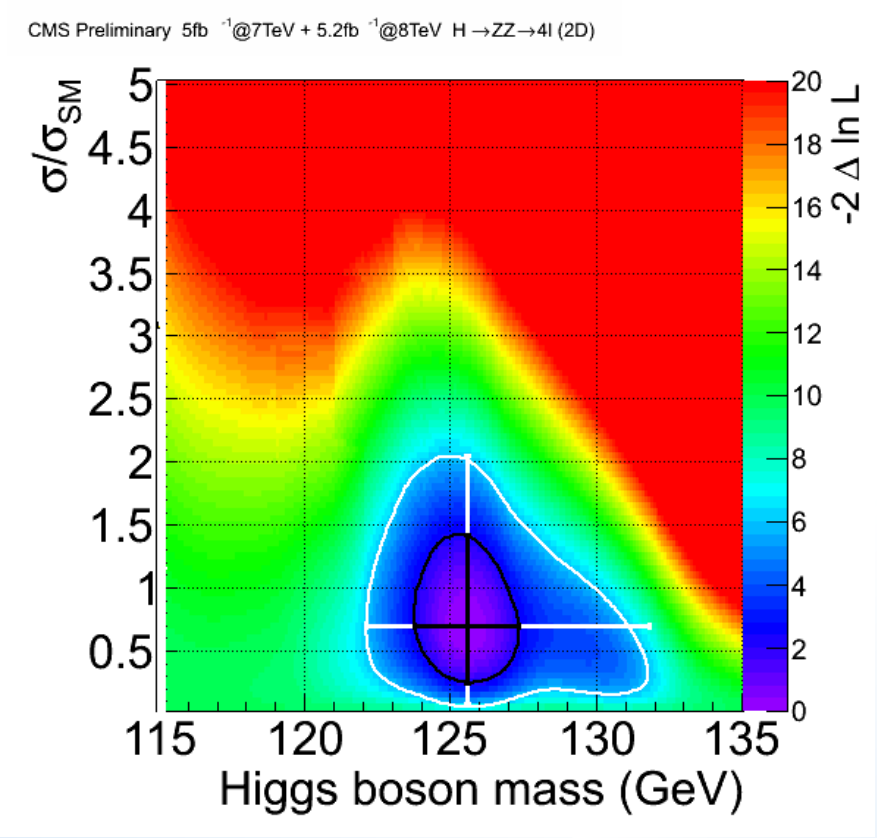
- Search for **H→ZZ→4l** in the range [110 - 600] GeV
  - **@7 TeV 5.1 fb^{-1}** and **@8 TeV 5.3 fb^{-1}** analysed with **significant improvement** with respect to 2011 analysis
  - Including **2l2τ** analysis

- ZZ cross section:
  - Predicted**:** $\sigma_{th}(pp \rightarrow ZZ) = 7.7 \pm 0.4$ pb (NLO)
  - Observed: **$\sigma(pp \rightarrow ZZ) = 8.4 \pm 1.0(stat.) \pm 0.7(sys.) \pm 0.4(lumi.)$ pb**

- SM Higgs exclusion
  - Expected: exclusion of the SM Higgs [121 - 570]
  - Observed: exclusion of the SM Higgs **[131 - 162] [172 - 525]**

Conclusion

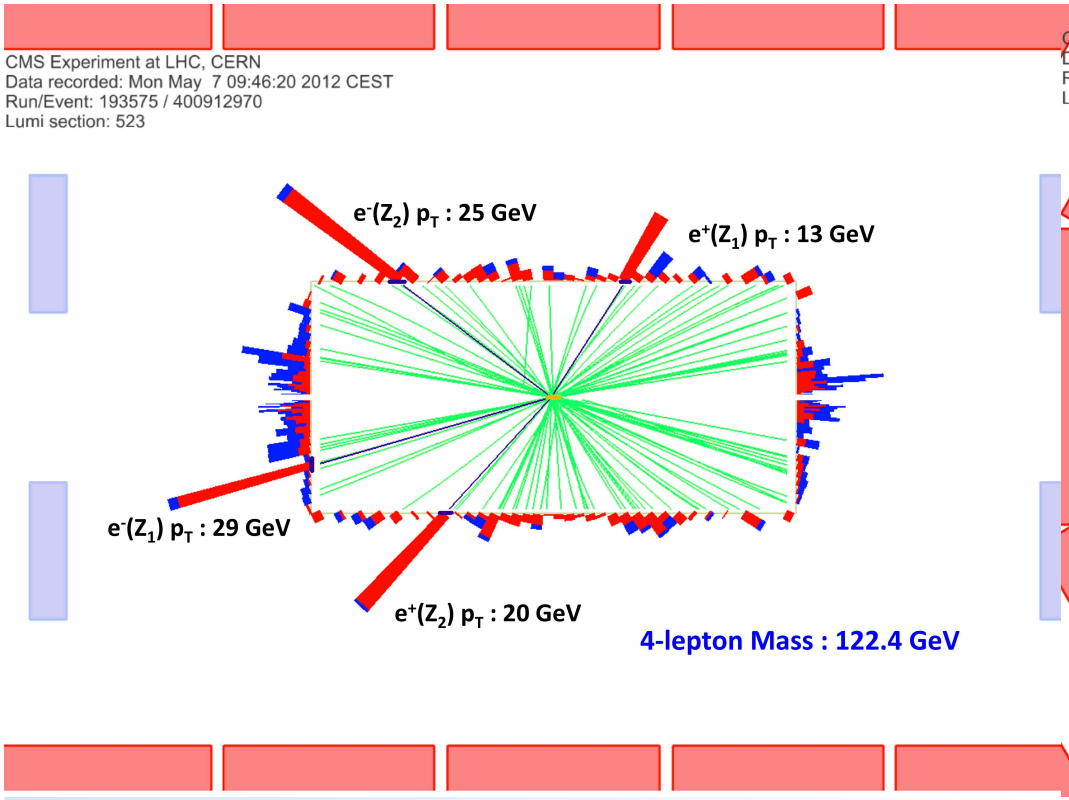
- **Evidence for a new massive boson: 3.2 σ at 125.5 GeV**
  - Best mass = **125.6 ± 1.2 GeV**
  - Best signal strength: **μ = 0.7 ± 0.4**

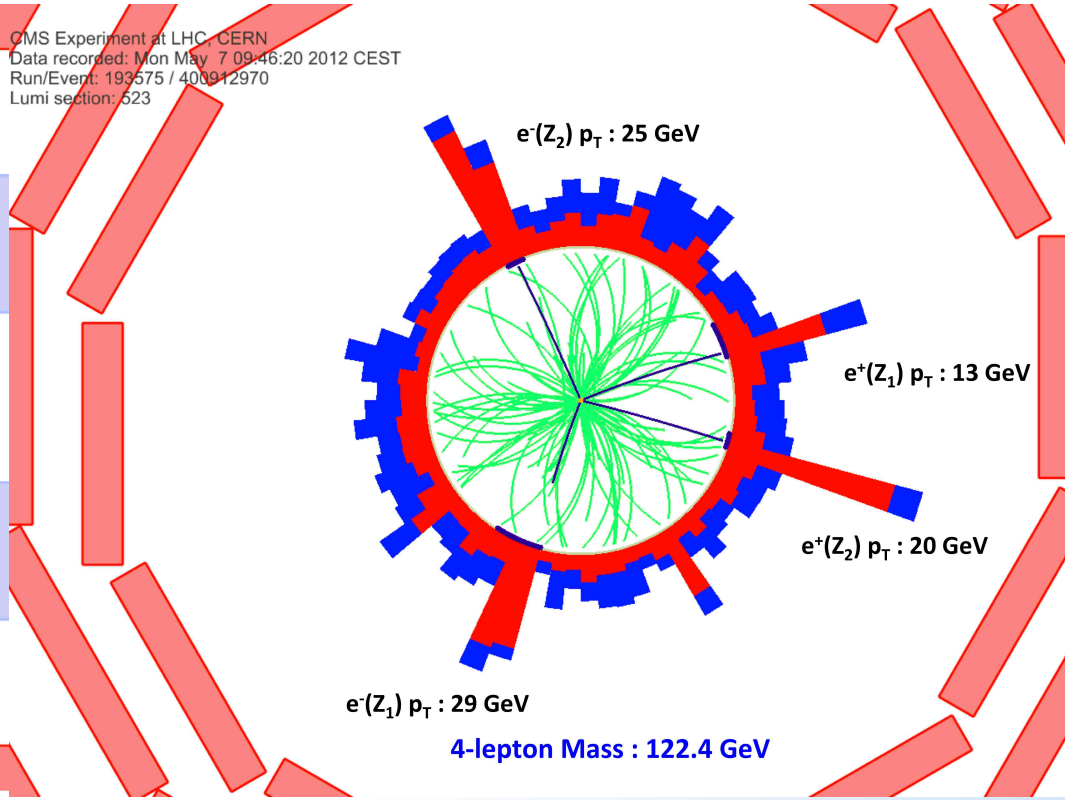


References

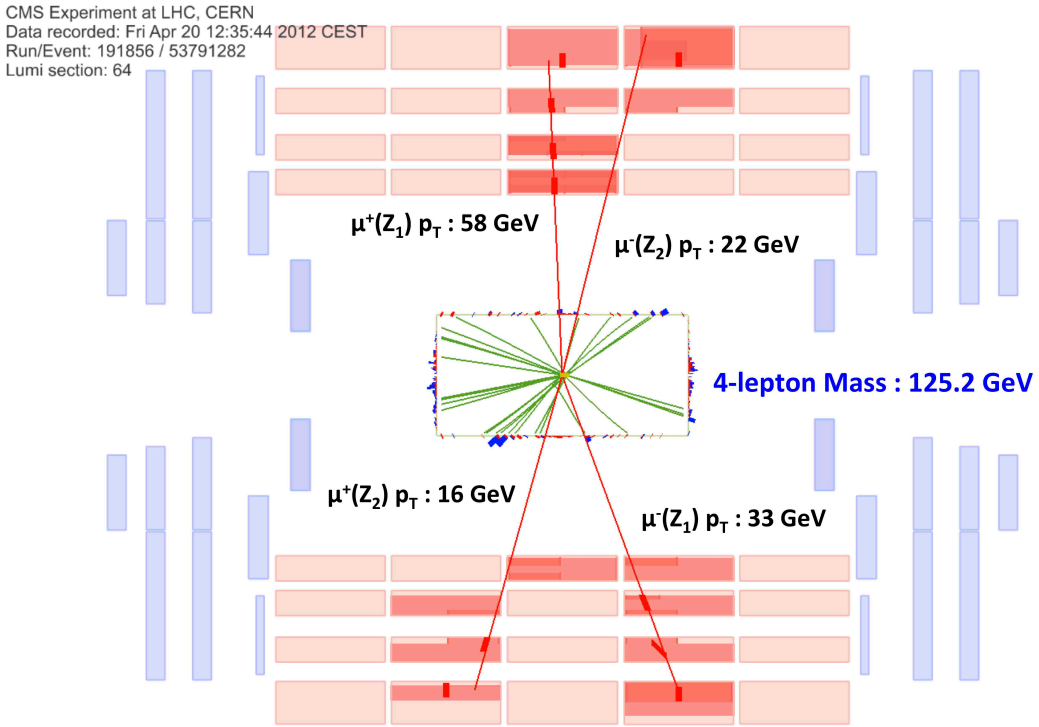
- *CMS-PAS-HIG-016*: Evidence for a new state in the search for the standard model Higgs boson in the H→ZZ→4l channel in pp collisions at √s = 7 and 8 TeV
- *CMS-PAS-HIG-014*: Measurement of ZZ production cross section in ZZ → 2l2l′ decay channel in pp collisions at √s = 8 TeV
- *Phys. Rev. Lett. 108 (2012) 111804, doi:10.1103/PhysRevLett.108.111804, arXiv:1202.1997*: Search for the standard model Higgs boson in the decay channel H to ZZ to 4 leptons in pp collisions at sqrt(s) = 7 TeV

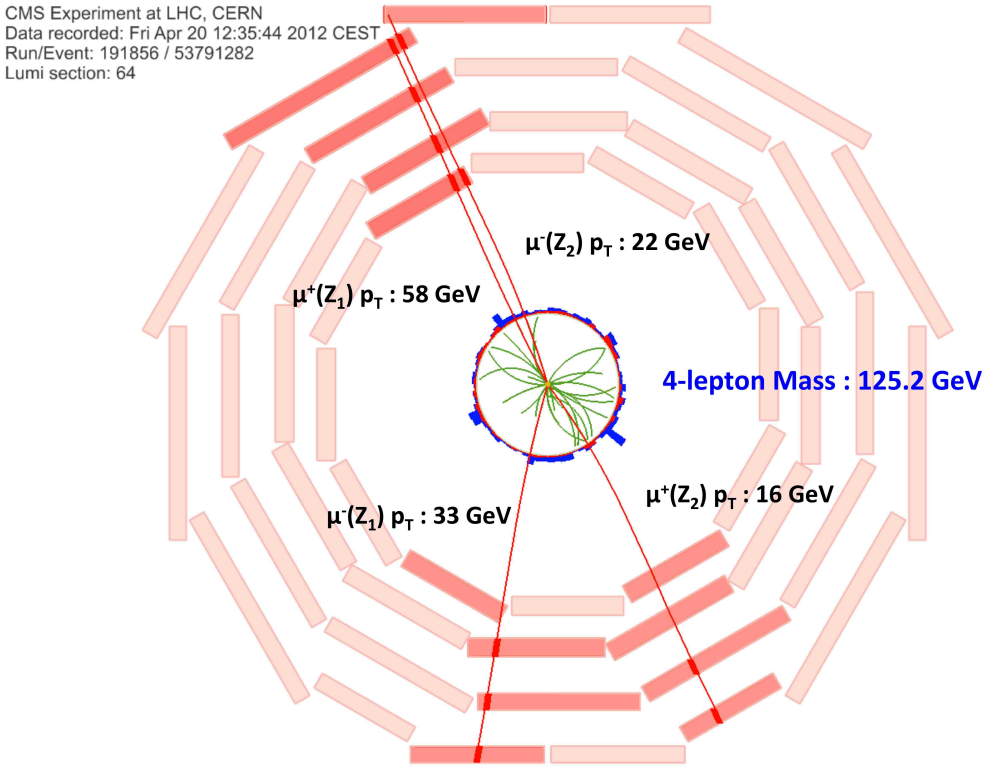
Event Display 4e event



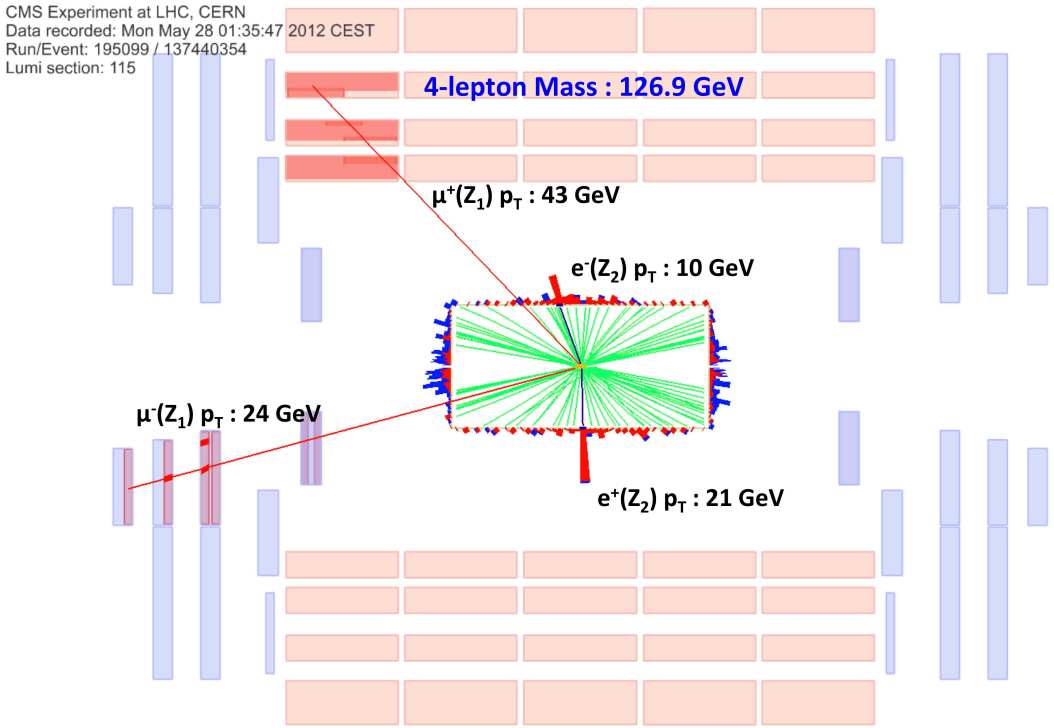


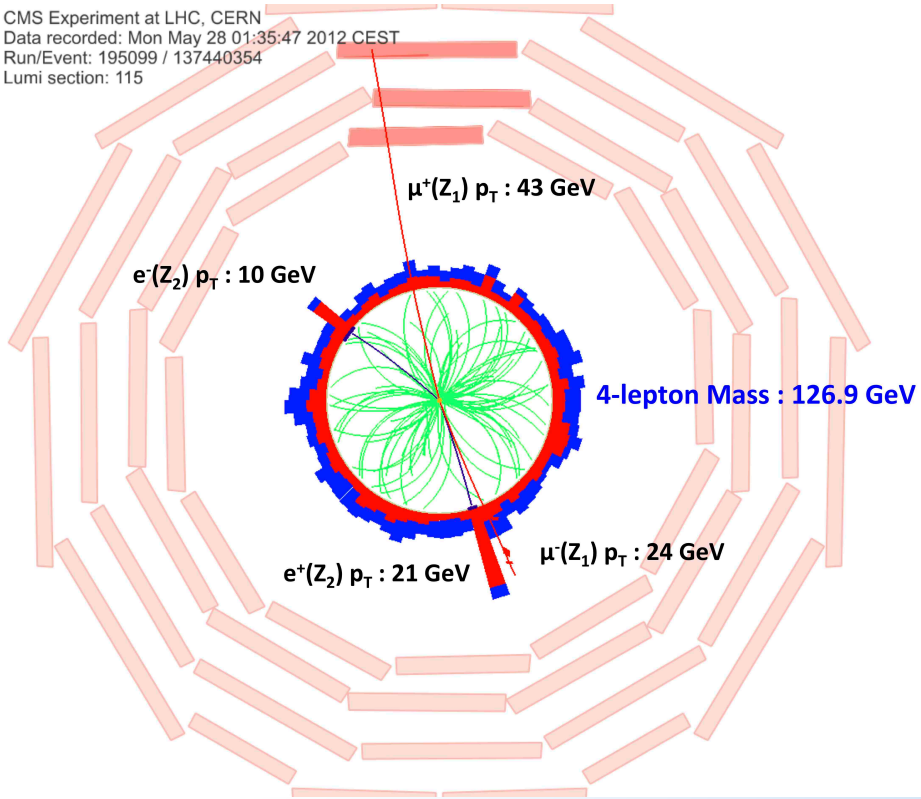
Event Display 4μ event





Event Display 2e2μ event

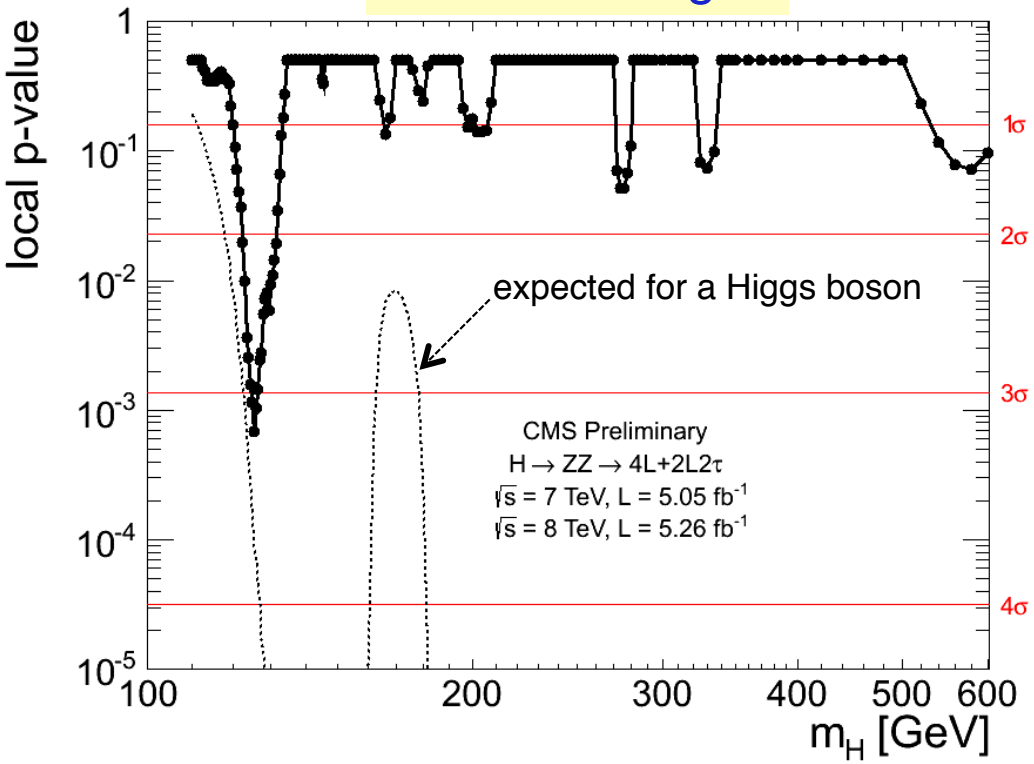




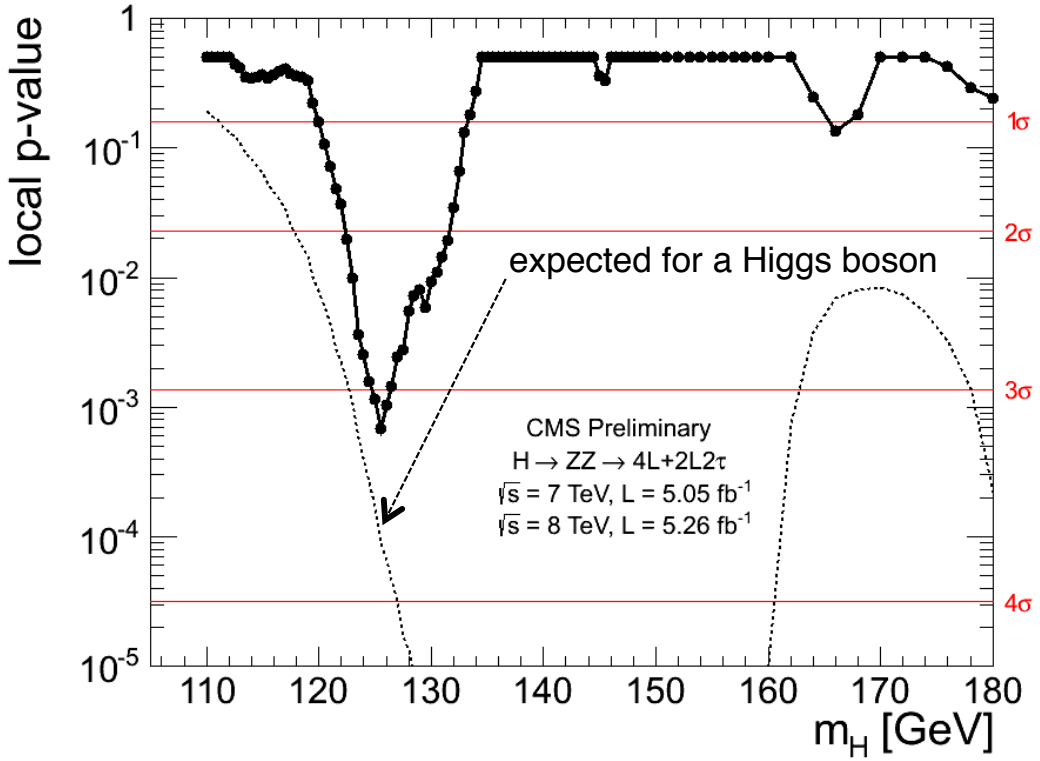
Results (p-values with τ)

- p-values

full mass range



zomed mass range



→ expected local significance m_H = 125.5 GeV : 3.8 σ

→ observed local significance m_H = 125.5 GeV : **3.2 σ**