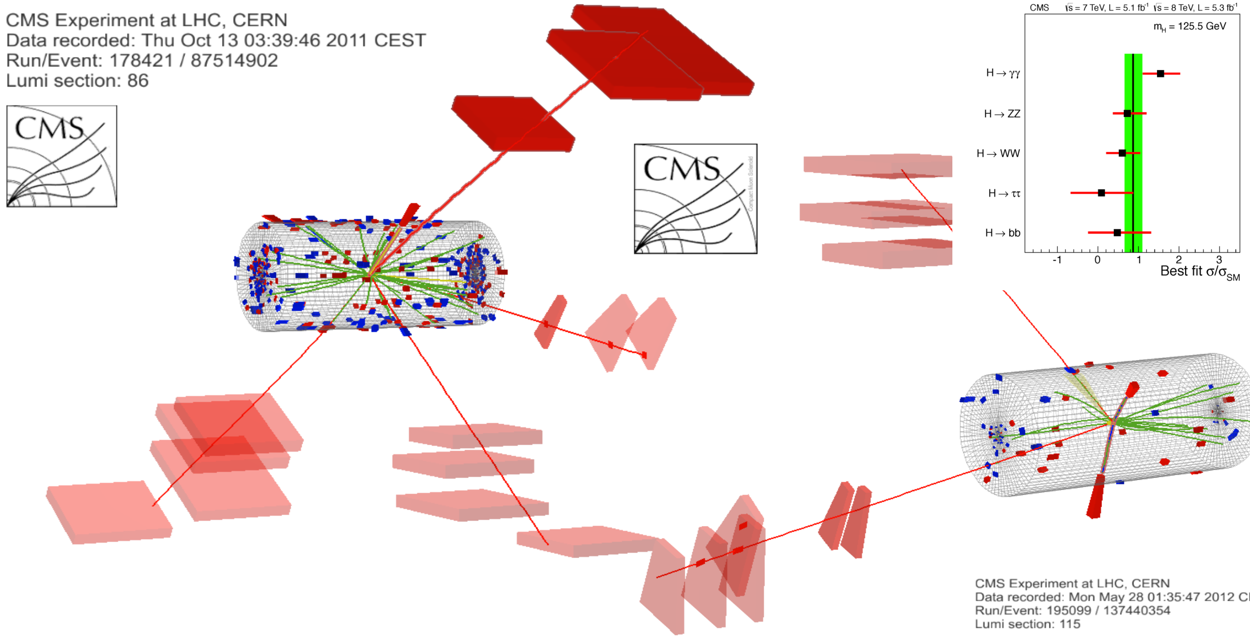
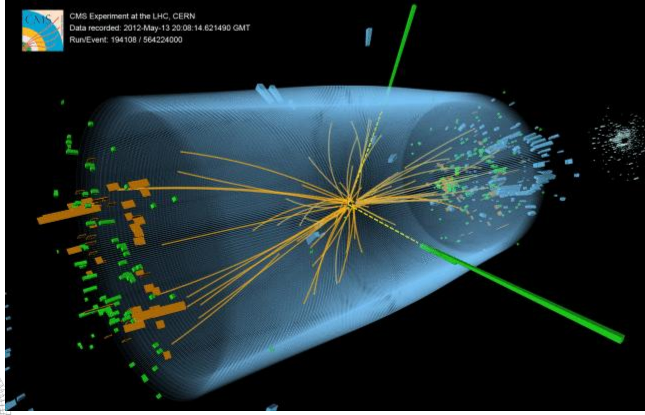
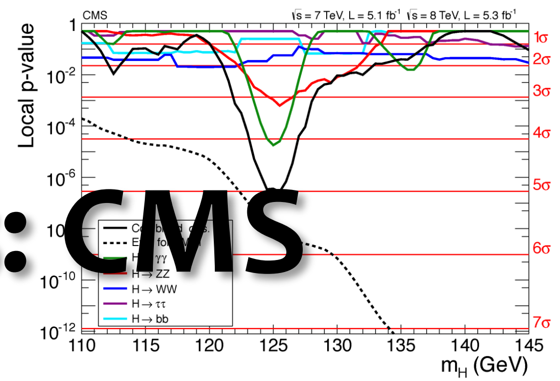


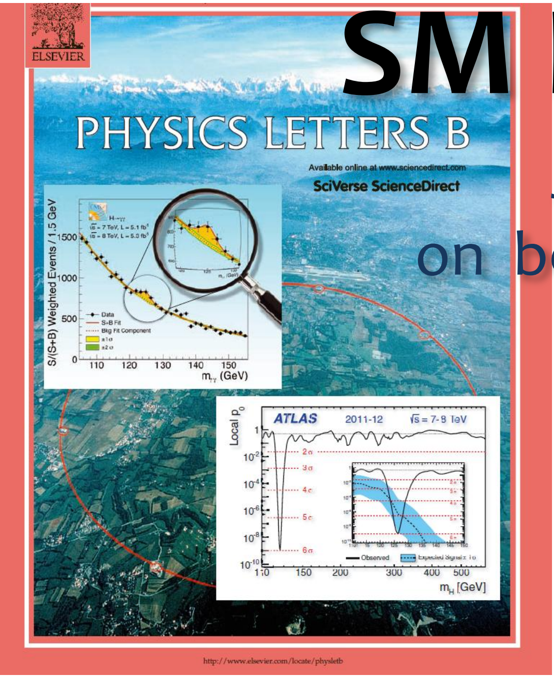


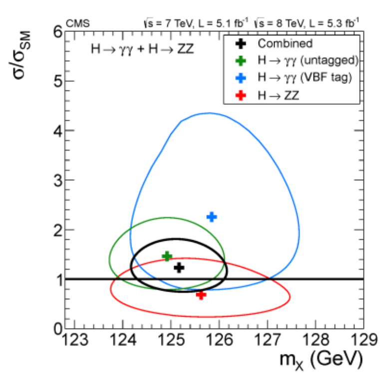


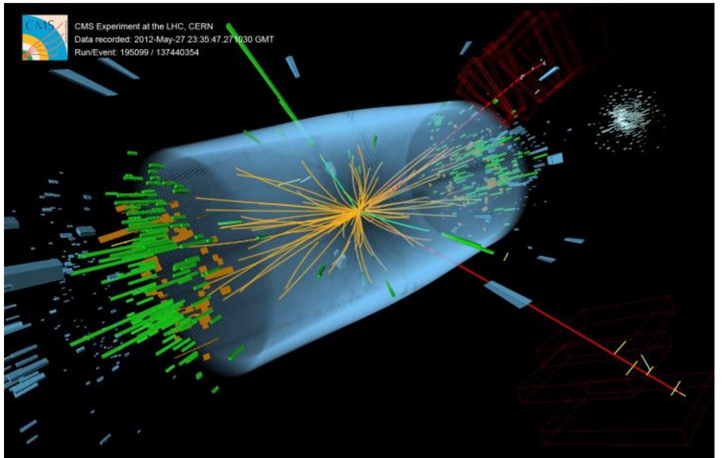
SM Higgs searches: CMS

Javier Cuevas (U. Oviedo)

on behalf of the CMS Collaboration





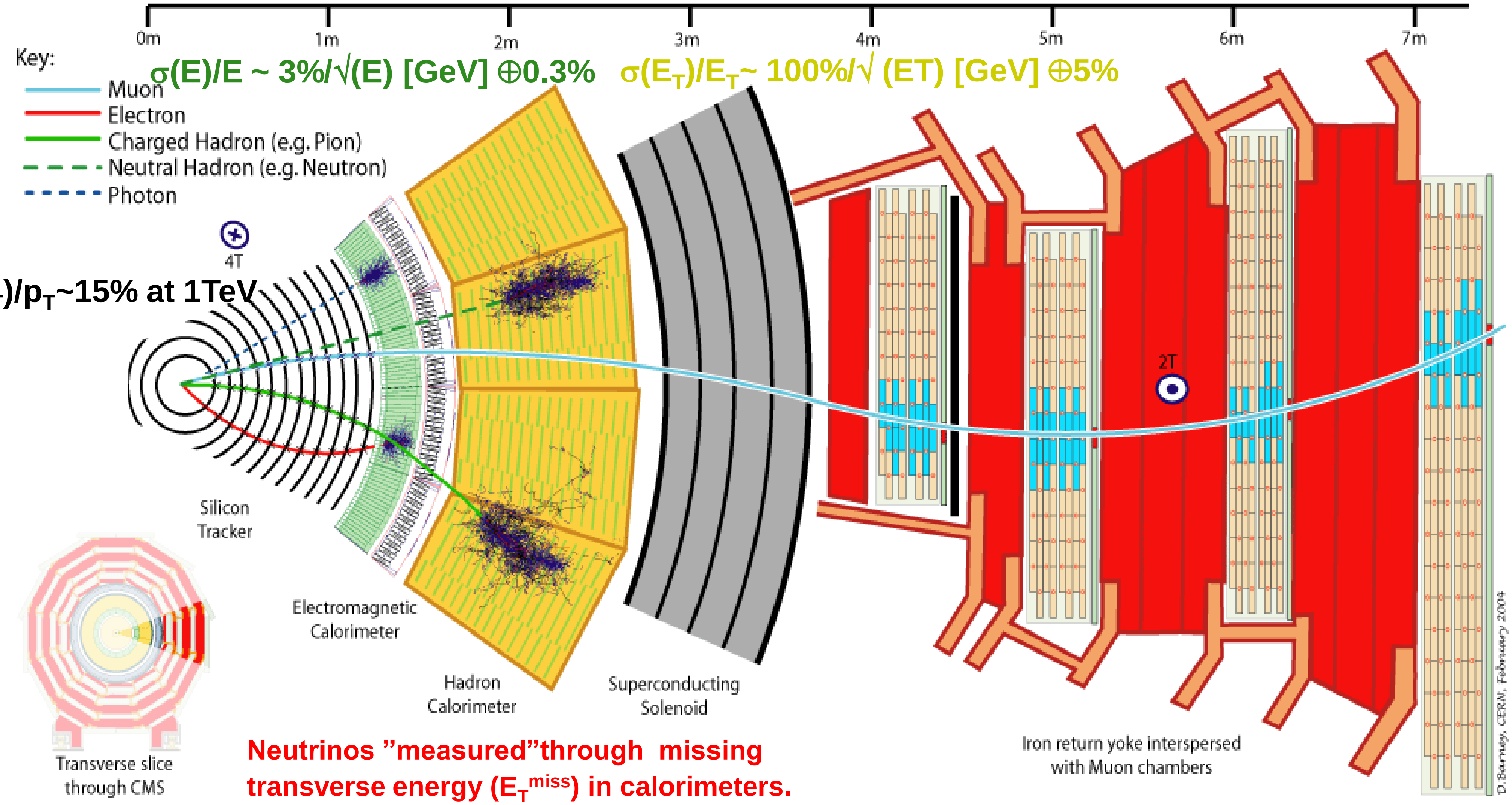


KIAS 2012 – Nov 5th

Outline

- Observation of a new state with mass of **125.3±0.6** GeV
  - 5.0 σ excess observed, 5.8 σ expected.
  - Consistent with SM prediction
    - More data and more studies needed to draw final conclusions
  - HIG-12-028, arXiV:1207.735, Phys. Lett. B 716 (2012) 30-61
- The CMS experiment at LHC and data taking in 2012
- **SM Higgs boson search**
  - **Decay modes with high mass resolution**
  - **Decay modes with low mass resolution**
- Results and combination of the searches
- Conclusions

CMS: a simple and elegant concept



$\sigma(E)/E \sim 3\%/\sqrt{(E)}$ [GeV] $\oplus 0.3\%$

$\sigma(E_T)/E_T \sim 100\%/\sqrt{(ET)}$ [GeV] $\oplus 5\%$

$\sigma(p_T)/p_T \sim 15\%$ at 1TeV

Neutrinos "measured" through missing transverse energy (E_T^{miss}) in calorimeters.

Fast detectors: 25-50ns bunch crossing

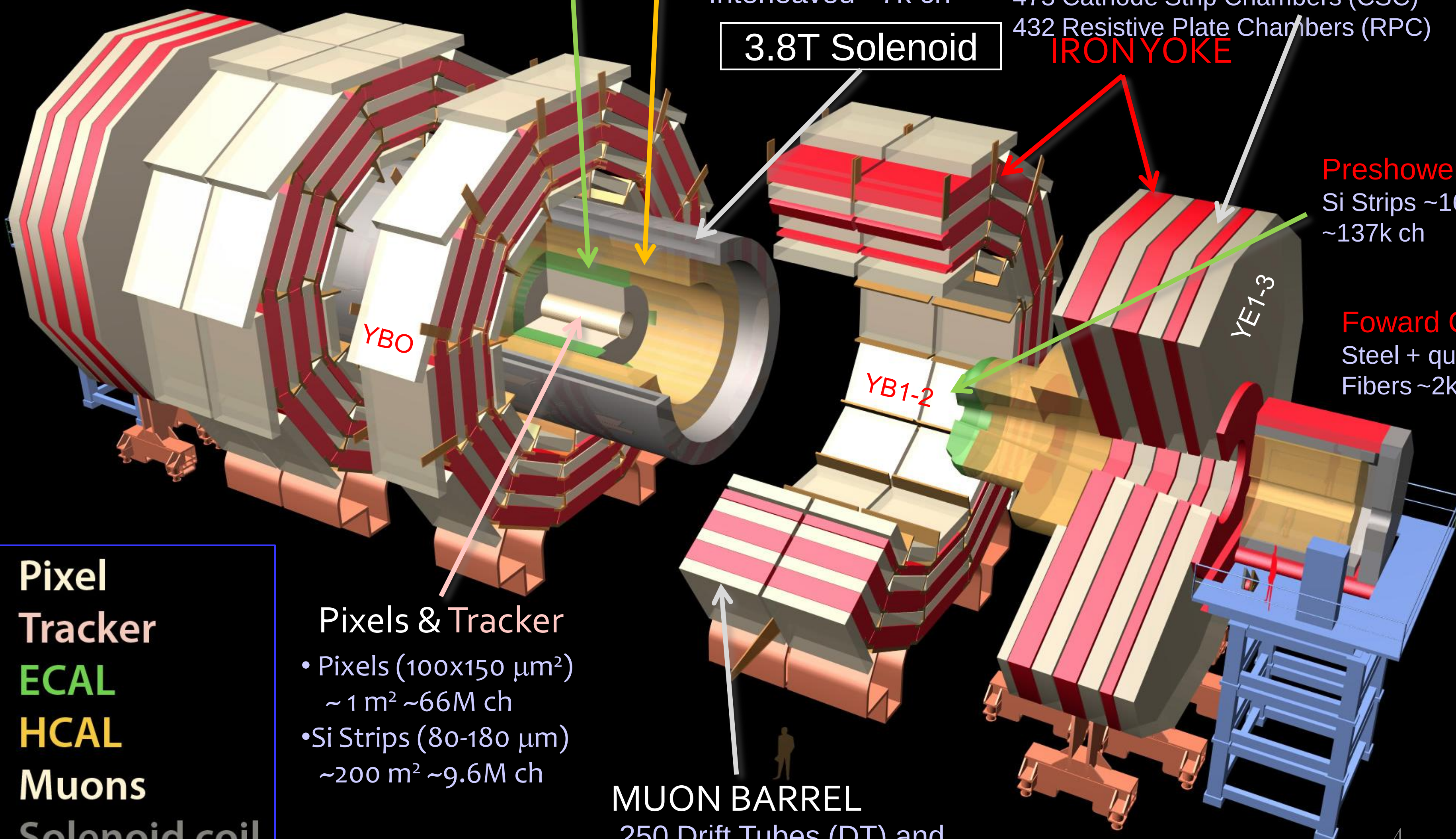
High granularity: 20-40 overlapping complex events

High radiation resistance: >10 years of operation

$\sigma(p_T)/p_T<1\%$ @ 100GeV
$\sigma(p_T)/p_T<10\%$@1 TeV

The CMS Detector

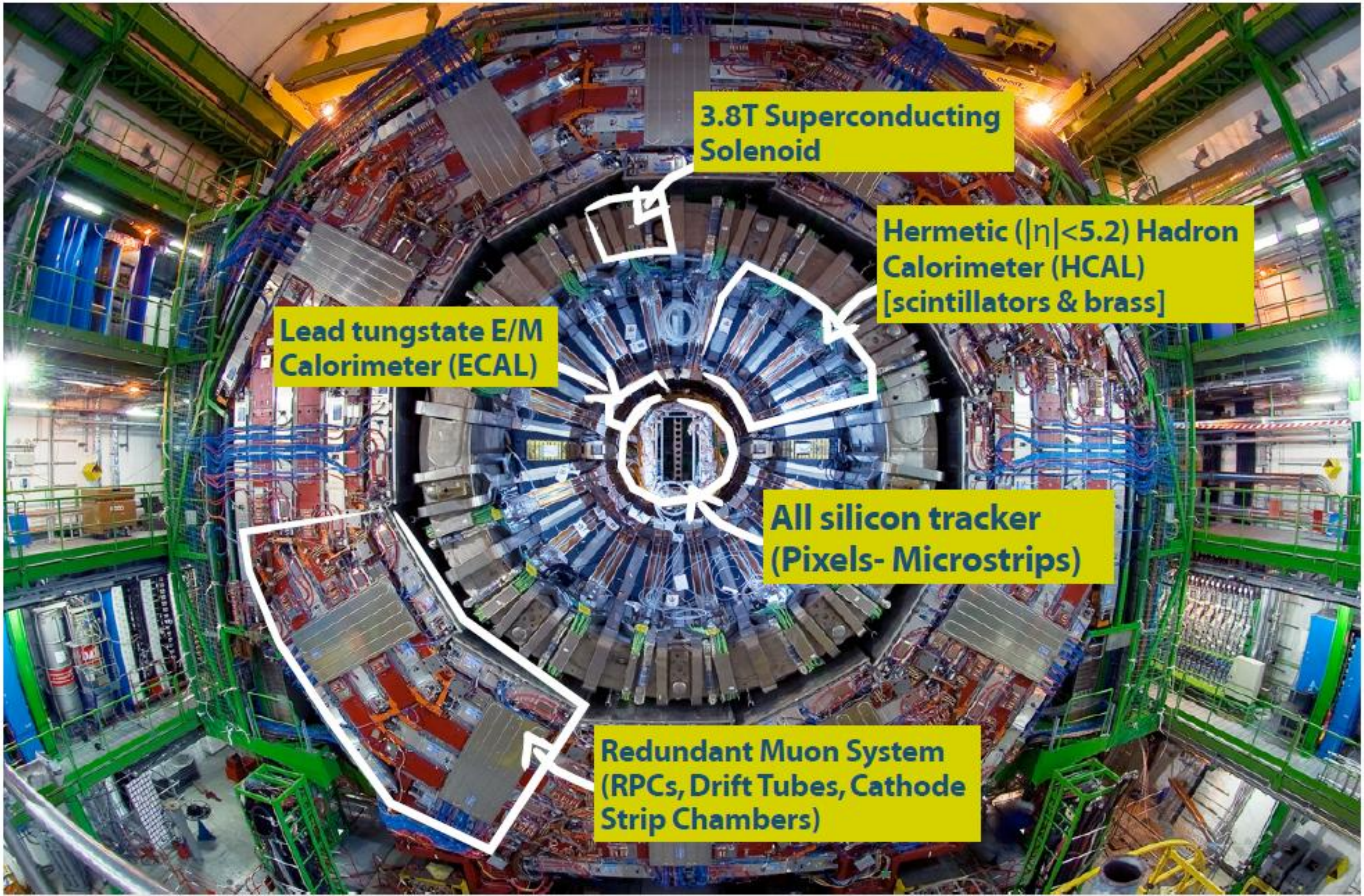
Total weight 14000 t
Overall diameter 15 m
Overall length 28.7 m



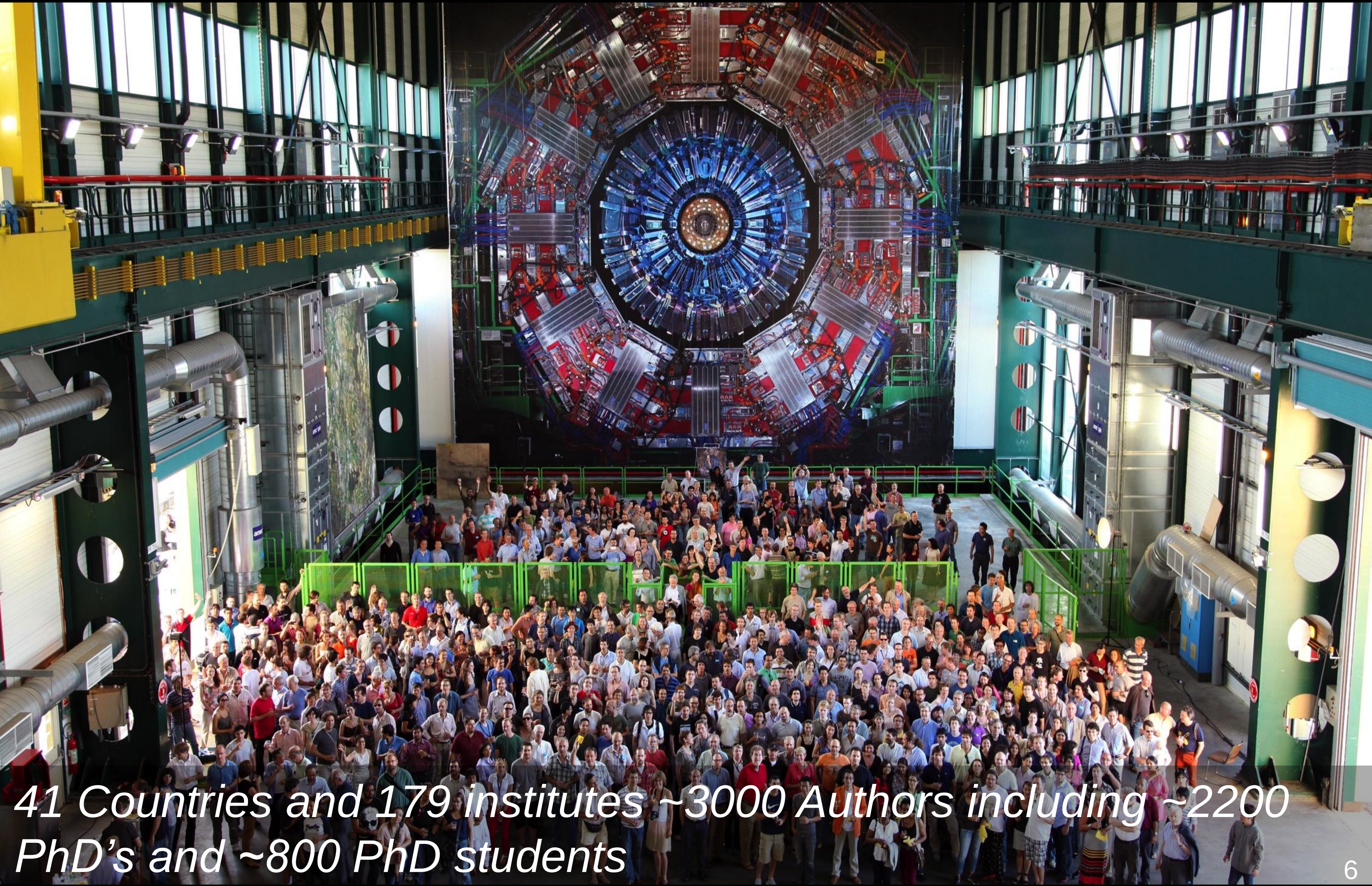
Pixels & Tracker
- Pixels (100x150 μm²)
  ~ 1 m² ~66M ch
- Si Strips (80-180 μm)
  ~200 m² ~9.6M ch

Pixel
Tracker
ECAL
HCAL
Muons
Solenoid coil

The CMS detector



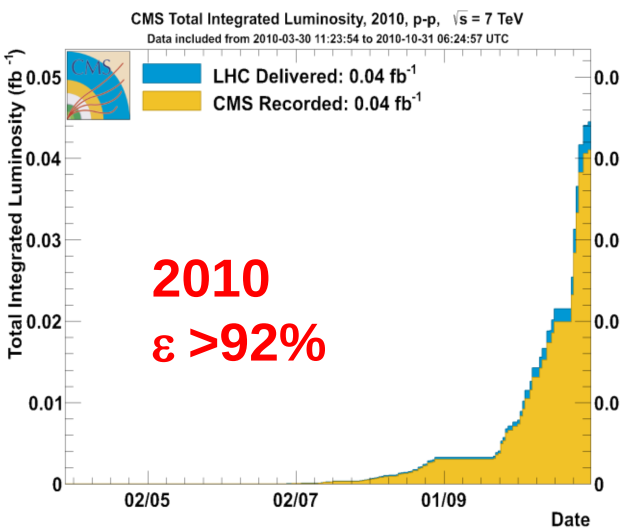
CMS

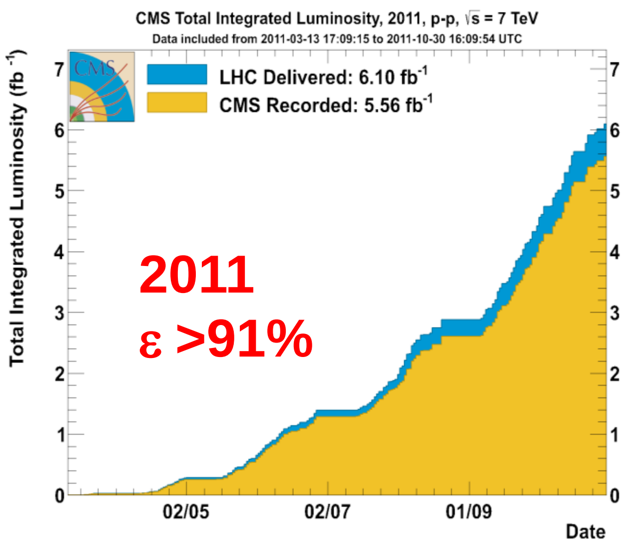


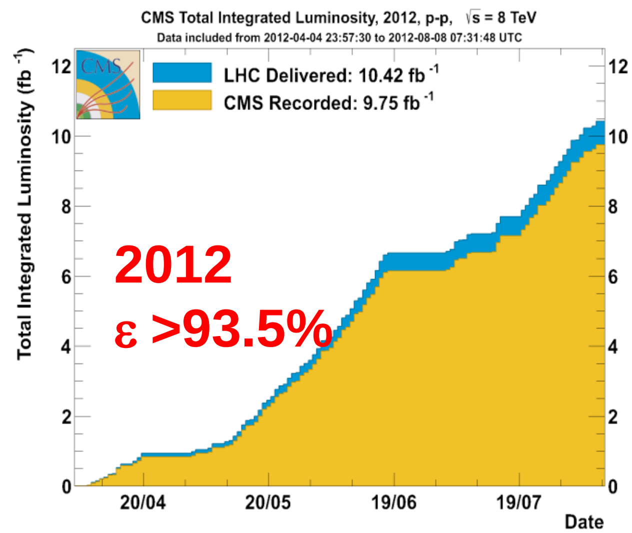
41 Countries and 179 institutes ~3000 Authors including ~2200 PhD's and ~800 PhD students

Detector operations in 2010-11-12

Excellent performance over the three years.
Data taking efficiency always higher than 91%

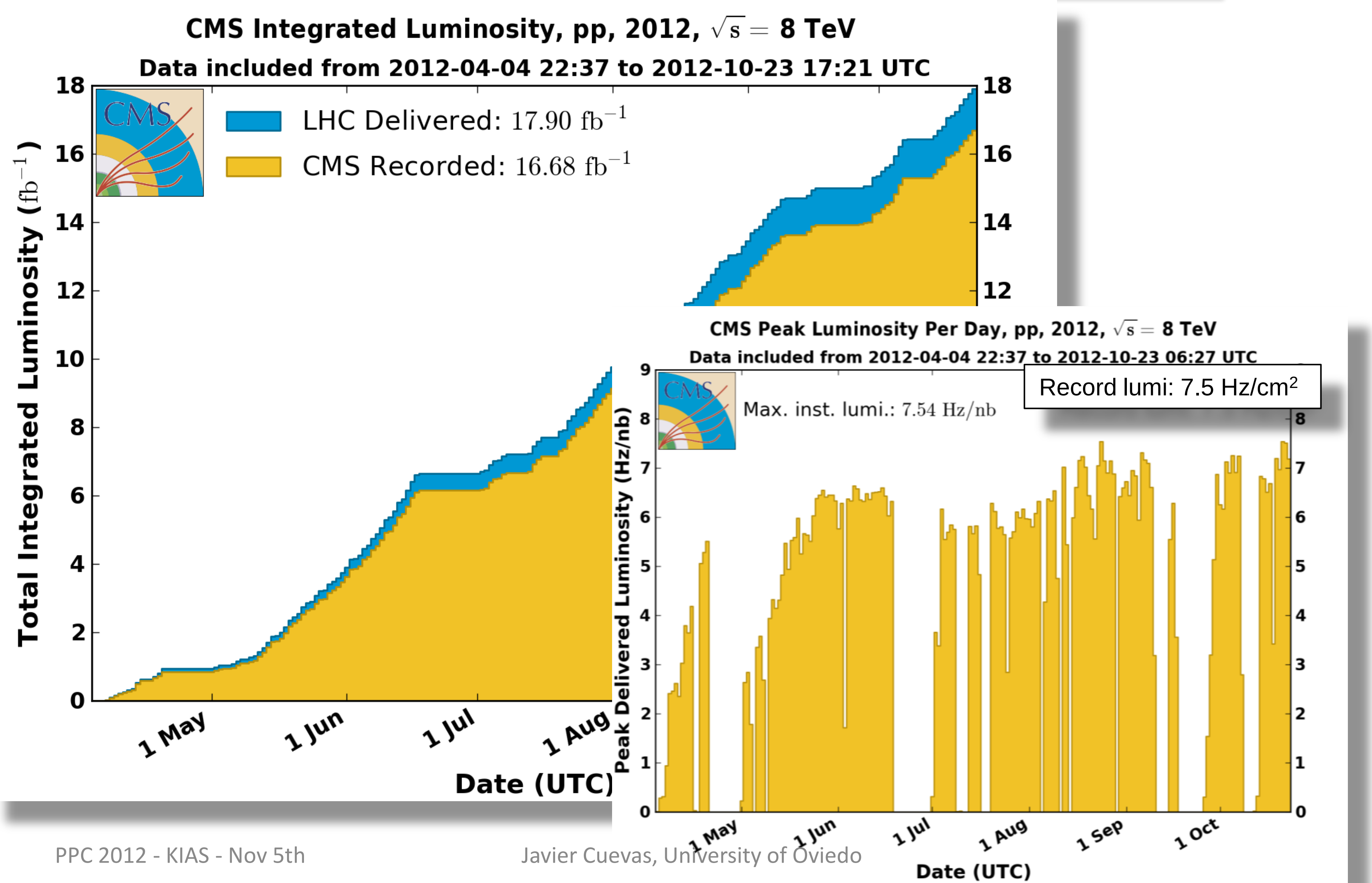




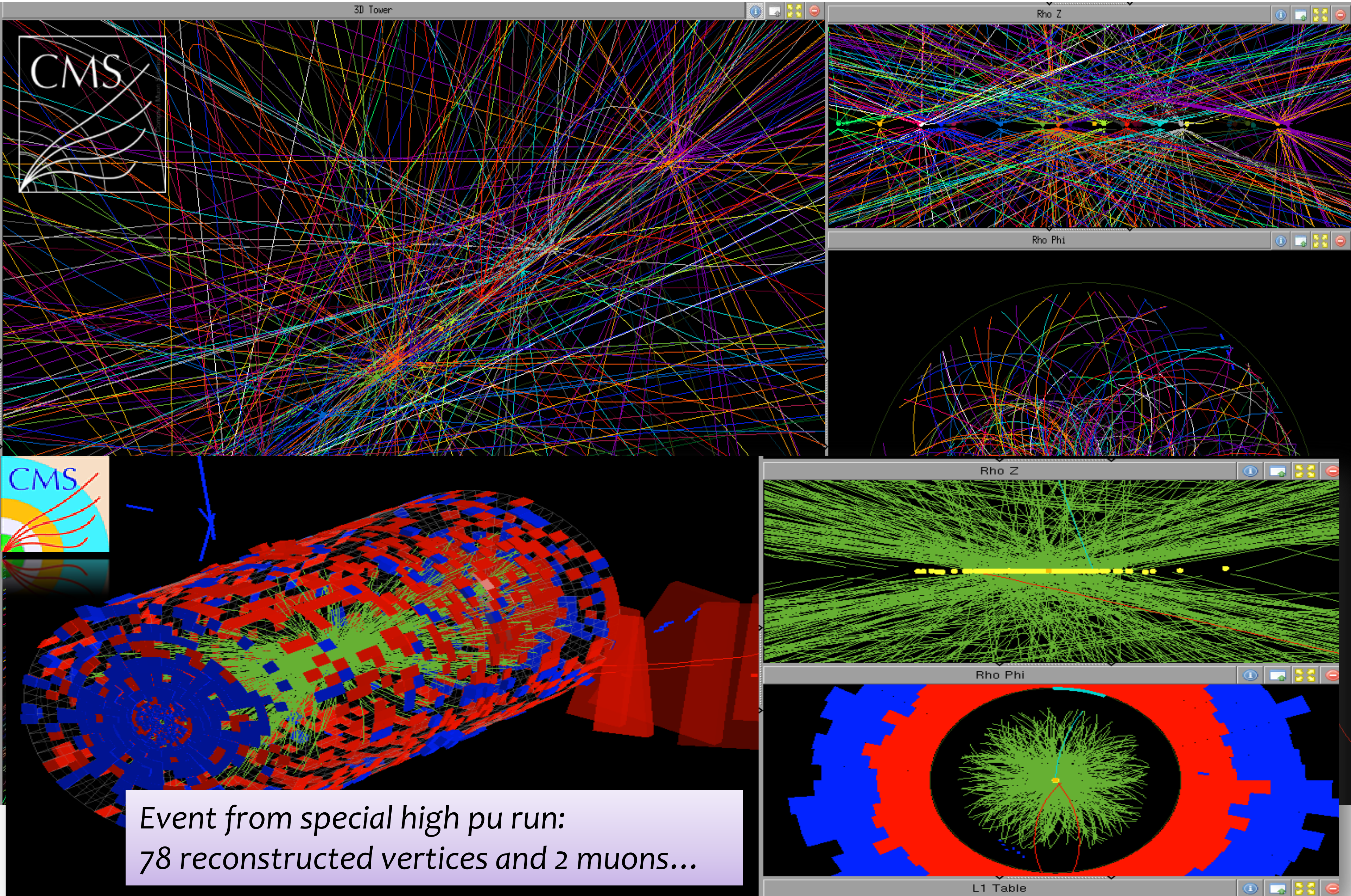


Record efficiency achieved in 2012 despite the most challenging condition:
Instantaneous luminosity higher than **7.5×10^{33} cm^{-2}s^{-1}**
Typical yields of physics quality data: 90-95% of the recorded data.

LHC: going strong

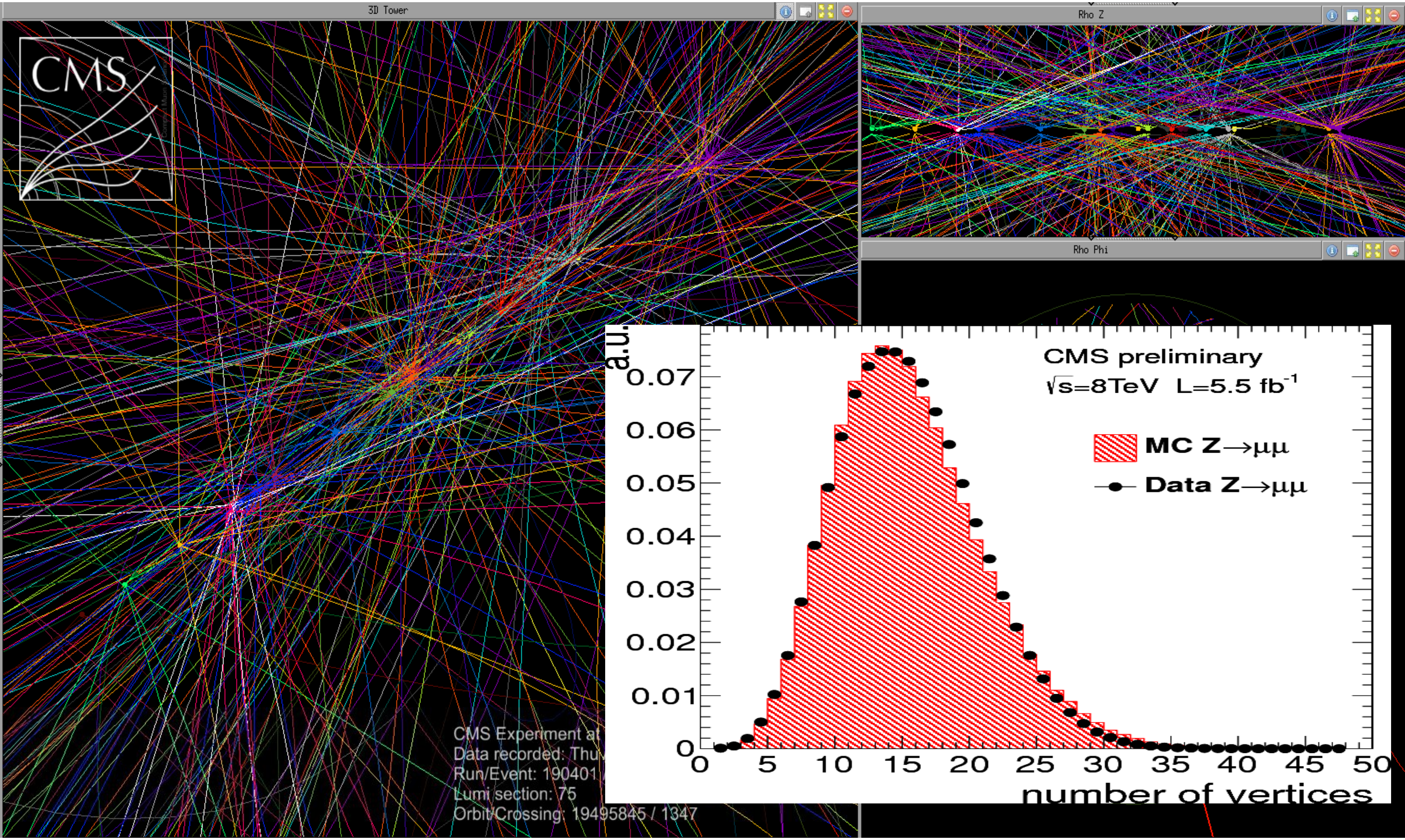


The challenge of 2012: 8 TeV and high pile-up.



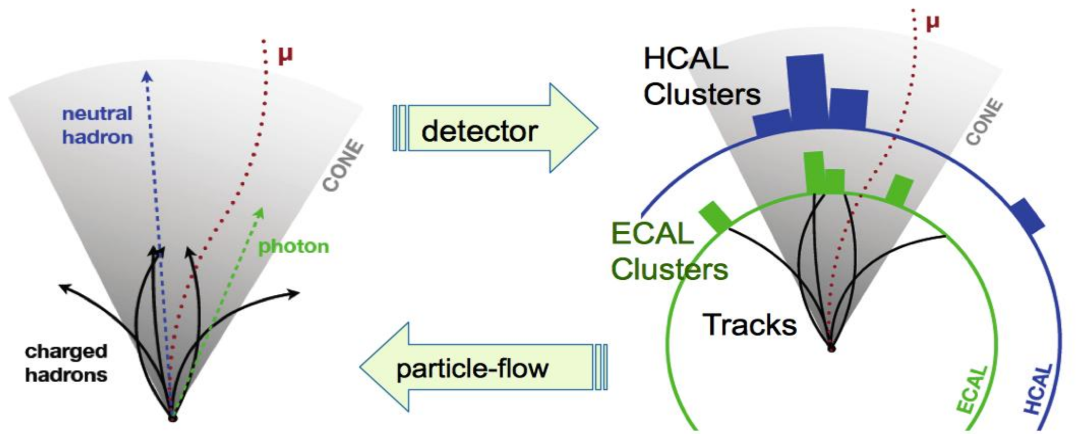
Event from special high pu run:
78 reconstructed vertices and 2 muons…

The challenge of 2012: 8 TeV and high pile-up.



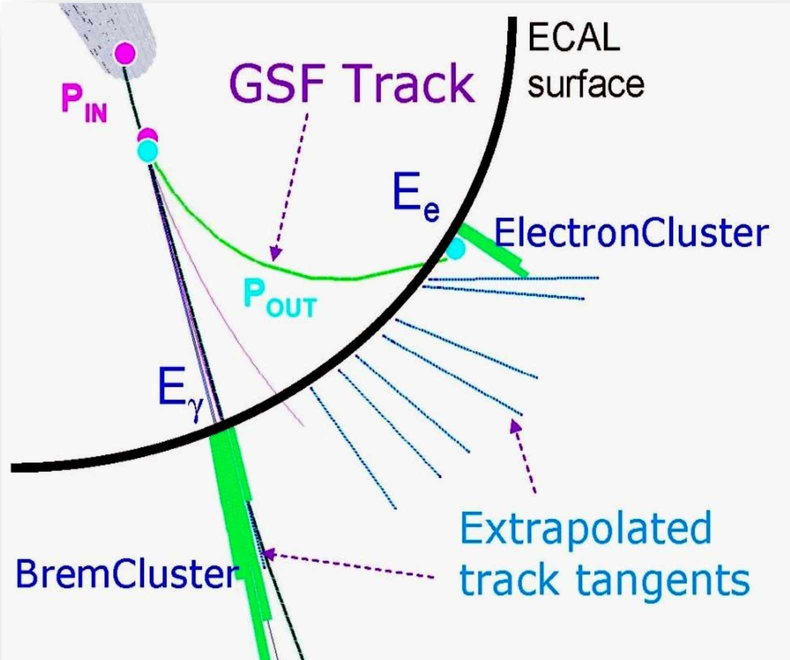
Particle Flow (global event description)

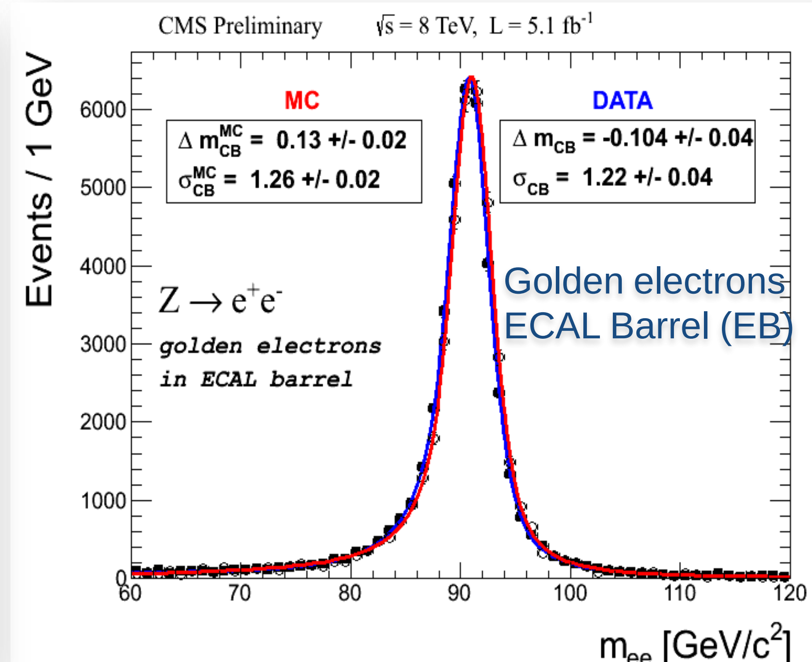
- Rely on high granularity of CMS detector to identify and reconstruct each individual particle in the event in an optimal way.



- Allows tagging of charged particles from pile-up: minimize impact of PU on jet reconstruction, and lepton or photon isolation.
  - Charged particles well separated in large tracker volume and 3.8 T magnetic field
  - Excellent tracking, able to go to down to very low momenta (~100 MeV)
  - Granular electromagnetic calorimeter with excellent energy resolution
  - In multi-jet events, only 10% of the energy goes to neutral (stable) hadrons (~60% charged, ~30% neutral electromagnetic)

Electron/photon reconstruction and identification

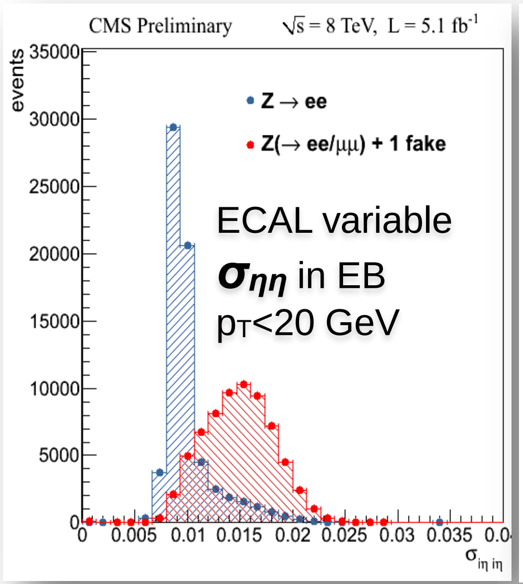


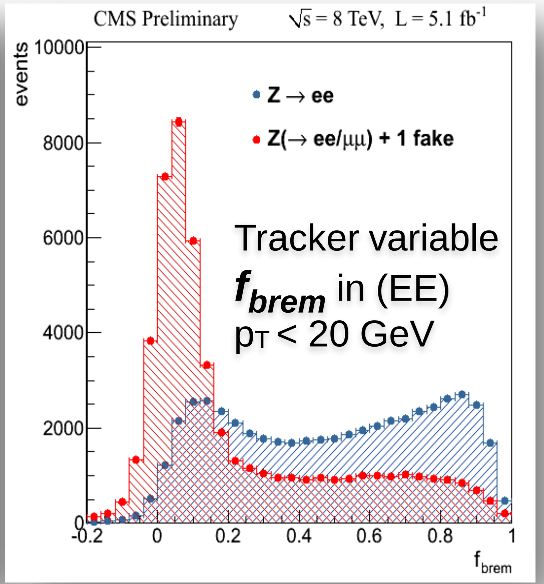


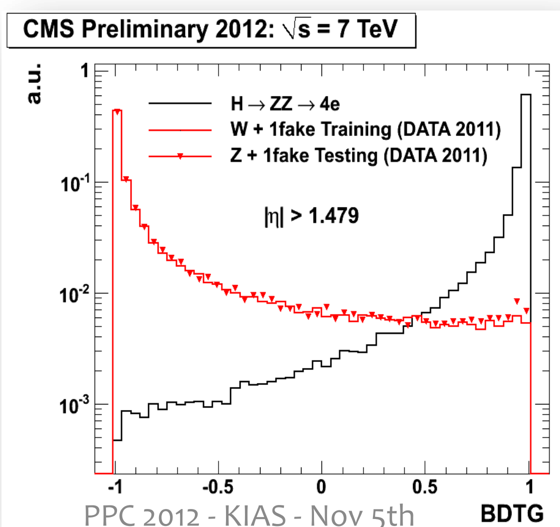
- **Cluster reconstruction in ECAL** **Common for both electrons & photons. Designed to collect bremsstrahlung and conversions in an extended phi region.** Energy spread in ϕ due to brems (E_T>4 GeV)
- **Dedicated track reconstruction for electrons** **Gaussian Sum Filter allows for tracks with large curvature due to brems and** enables hit collection up to ECAL; ECAL-seeded reconstruction complemented by a tracker-seeded reconstruction to gain efficiency at low p_T
- **Energy scale and resolution**
  - **Extensive control at the Z peak (and at the J/ψ➔ee for low p_T electrons)**

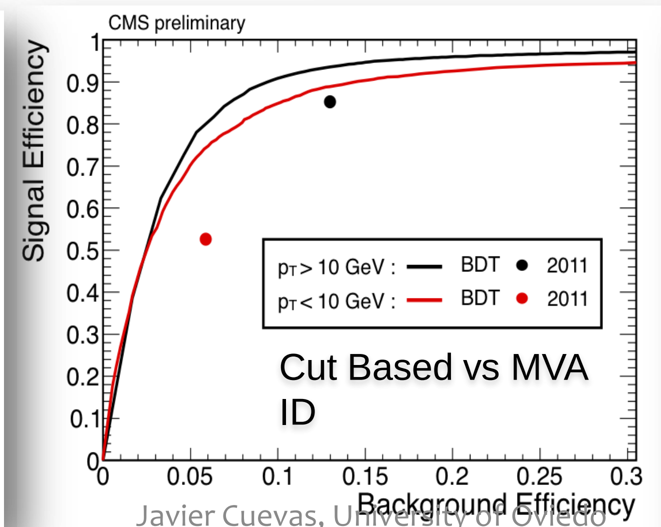
Electron reconstruction and identification

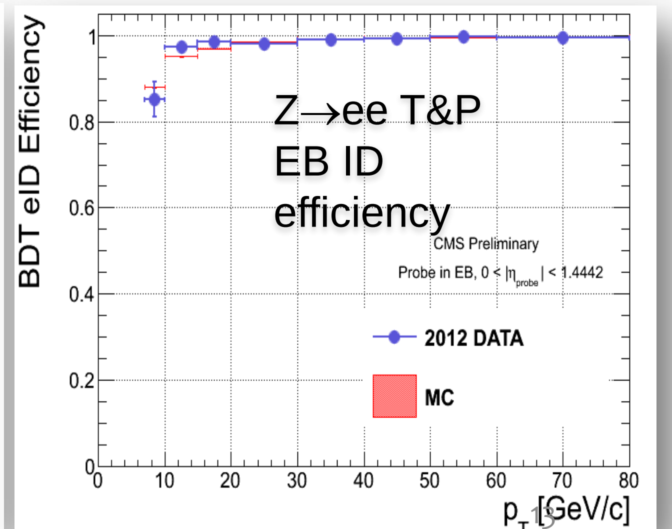
- Multivariate electron identification in 2012
  - ECAL, tracker, ECAL-tracker-HCAL matching and impact parameter (IP) observables
- Background from data samples
  - W+jet for training
  - Z+jet for testing
- Performance
  - 30% efficiency improvement in H->ZZ->4e wrt cut based ID
- Efficiencies
  - Via tag-and-probe at the Z->ee peak





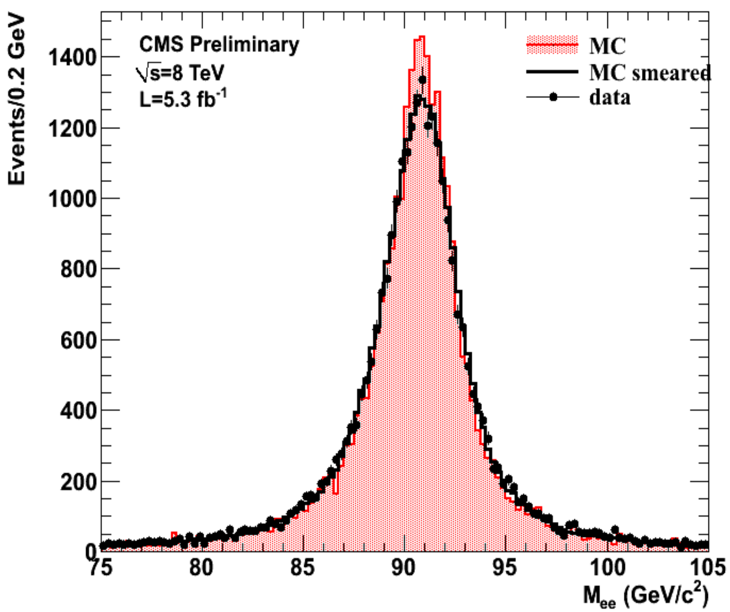




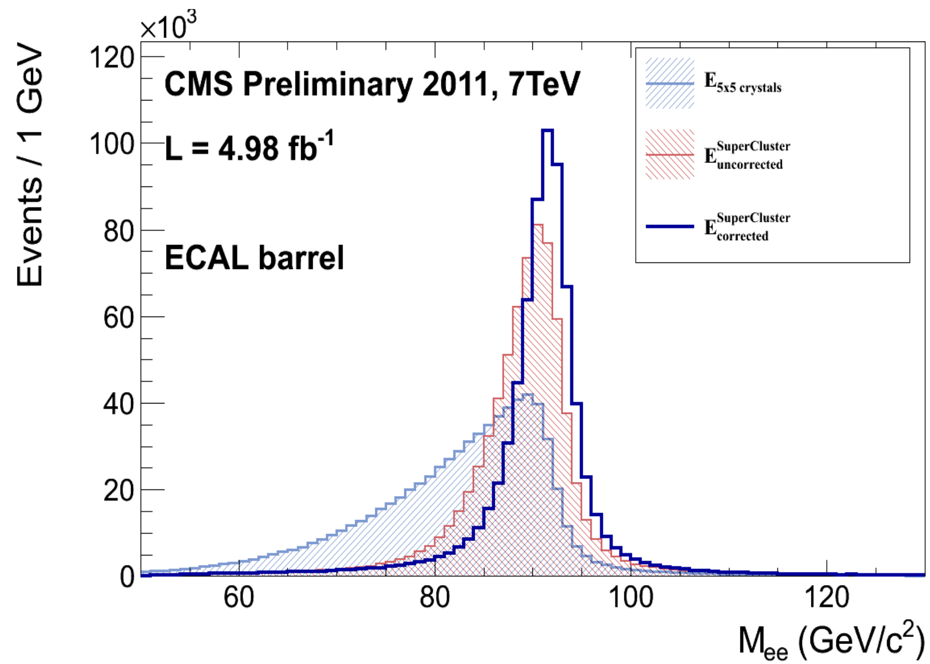


Photon Energy Corrections, Scale and Resolution

- ECAL cluster energies corrected using a MC trained multivariate regression
  - Improves resolution and restores flat response of energy scale versus pileup
  - Inputs: Raw cluster energies and positions, lateral and longitudinal shower shape variables, local shower positions w.r.t. crystal geometry, pileup estimators
- Regression also used to provide a per photon energy resolution estimate
- **Energy Scale and resolution:** use $Z \to e^+e^-$



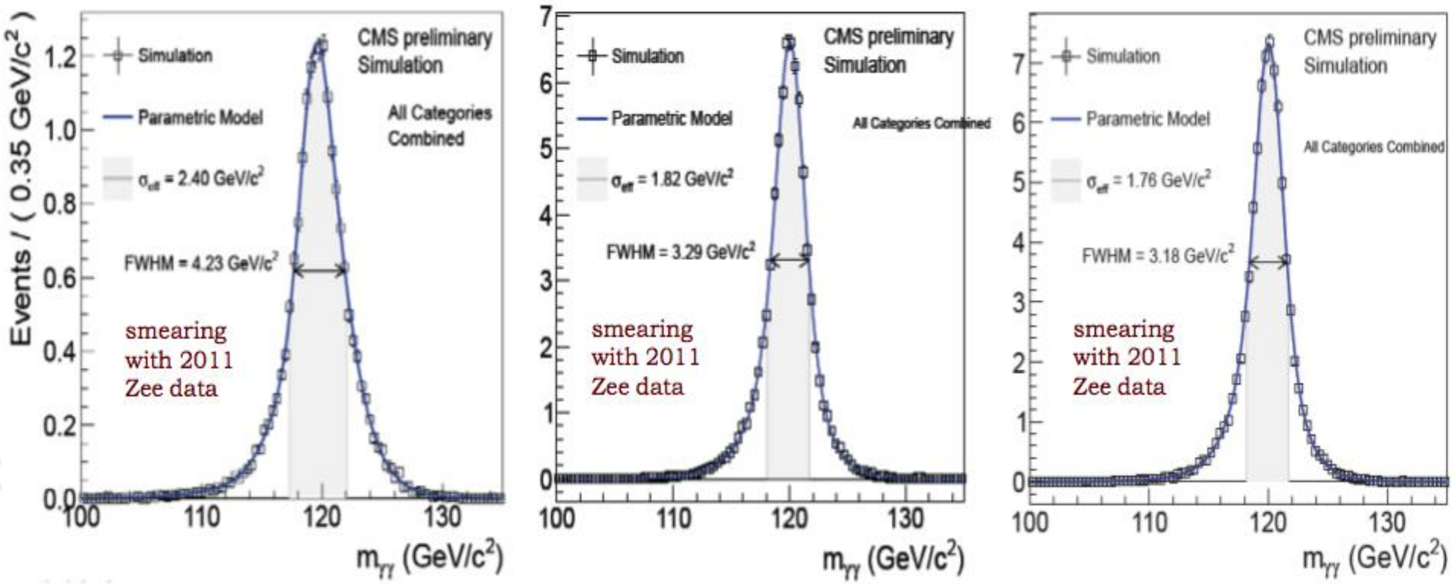
Non converted photons in the barrel $|\eta|<1$



Effect of the regression on the $Z \to e^+e^-$ peak

Progress in ECAL calibration

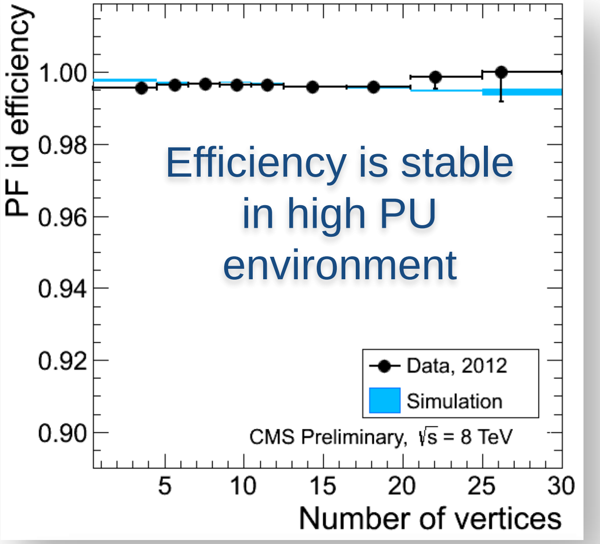
July 2011 EPS	March 2012 Moriond	July 2012 ICHEP
FWHM/2.35 = 1.80 GeV (1.50%)	FWHM/2.35 = 1.40 GeV (1.17%)	FWHM/2.35 = 1.35 GeV (1.13%)



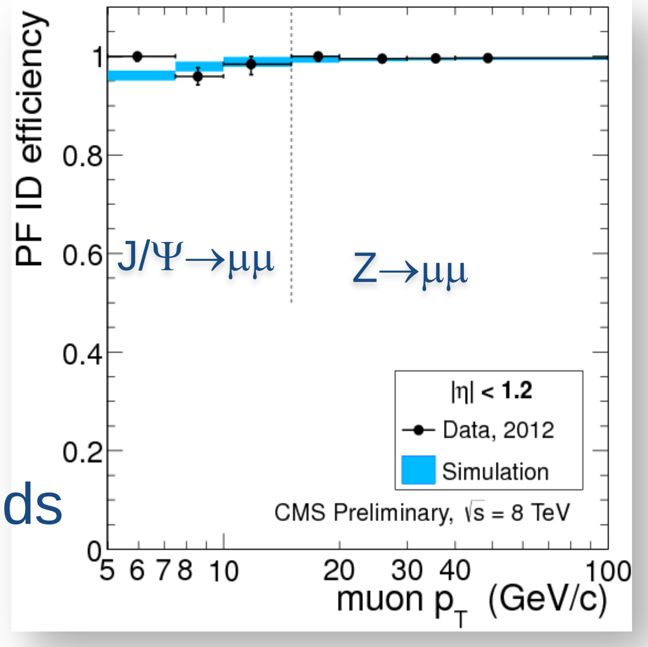
For the golden categories, both photons in the barrel and no conversions: FWHM/2.35=1.04GeV (0.87%) approaching the nominal value. Still room for improvement.

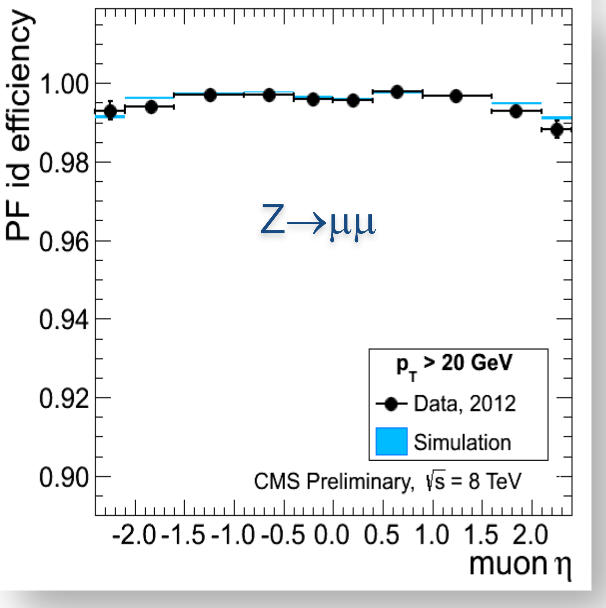
Muon reconstruction and identification

- PF Muon Identification in 2012
  - Exploit information from all subdetectors
- High efficiency **>96% for p_T=5 GeV; >99% for p_T=10 GeV;**
  - Exploit also tracker-based muon ID
  - Important for H->ZZ->4l
  - Efficiency controlled in data with J/Ψ and Z T&P



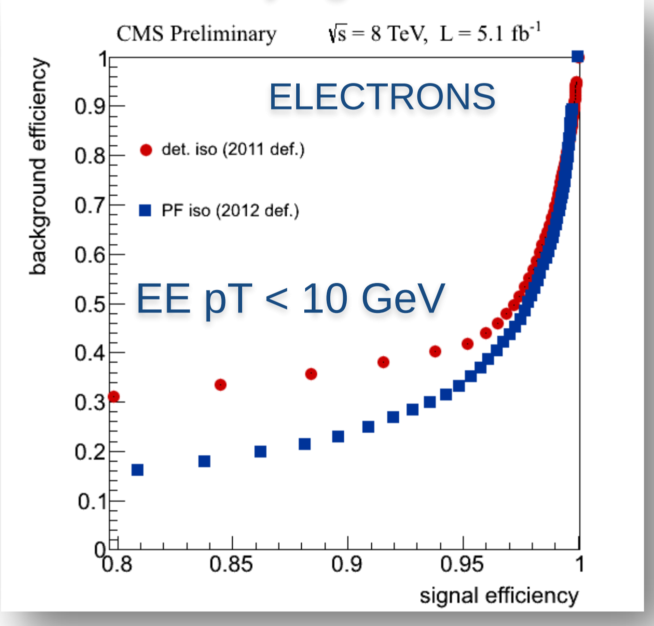
Tighter quality criteria applied in some analyses to further suppress reducible backgrounds





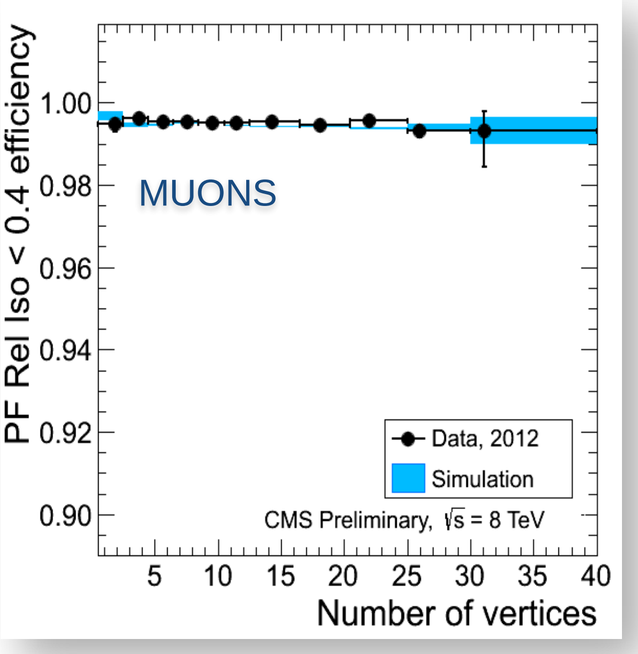
Particle-based isolation

- Created by summing energy deposits from individual particles in DR=0.4 cone around the lepton
  - Avoids double counting of the energy deposit in the calorimeters from charged particles
- Pile-up contribution:
  - Negligible for charged hadrons from vertex
  - Neutral contribution corrected using the average energy density, ρ from the pile-up and underlying event.

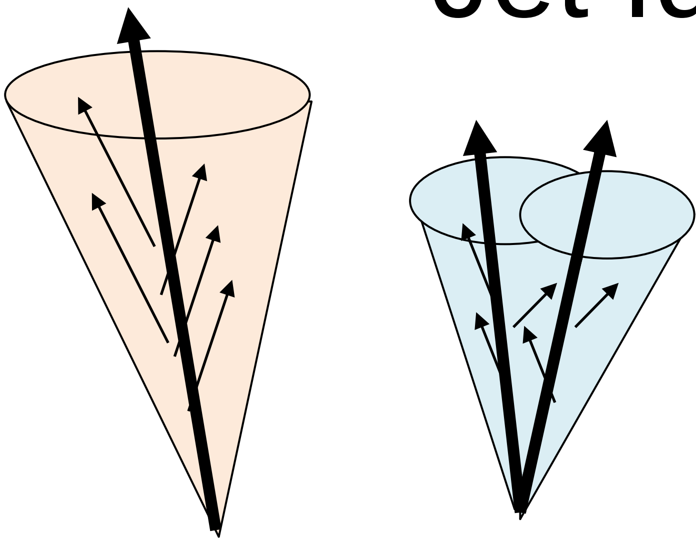


Det Based vs PF Based

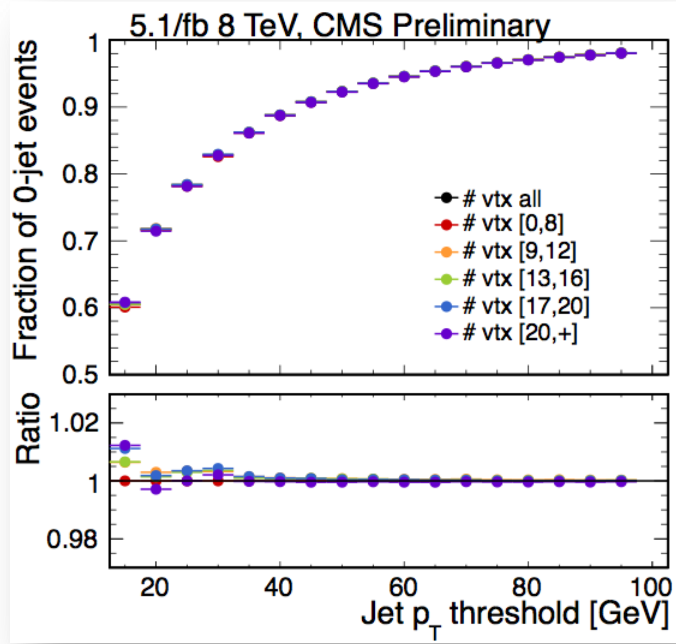
Isolation Efficiency is stable in high PU environment **(important for higher lumi runs in the future!)**



Jet Identification



Typical regular jet Typical Pileup jet

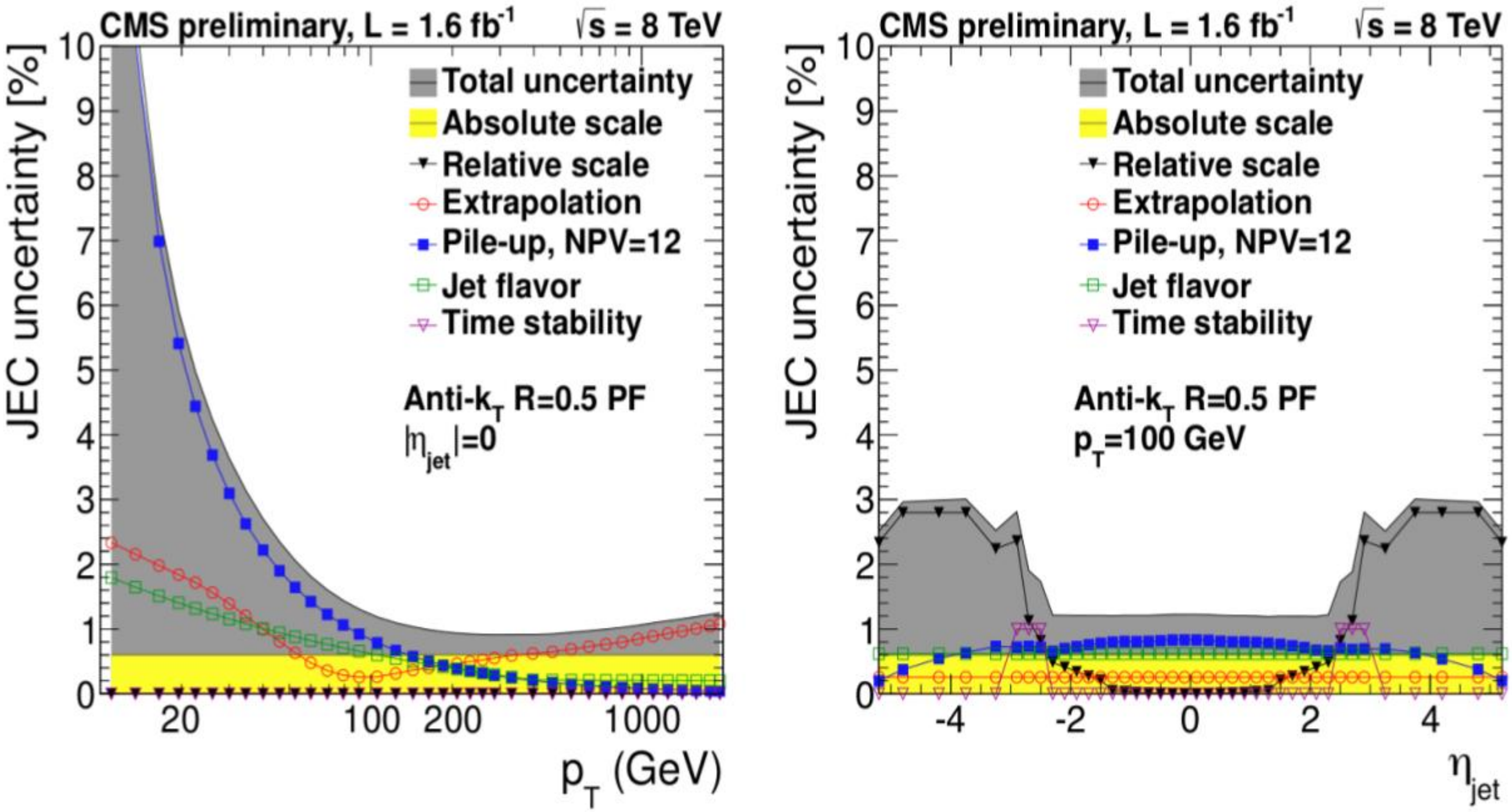


Important in VBF searches.

Validation on data: jet counting in $Z \rightarrow \mu\mu$ events vs vertex multeplicity.
Stable to <1% for jet p_T > 20 GeV

- Pileup jets structure differs wrt regular jets:
  - Pileup jets originate from several overlapping jets which merge together
  - Likelihood grows rapidly with high pileup
  - discriminant exploits shape and tracking variables
    - discrimination both inside and outside tracker acceptance

Jet Energy Correction Uncertainties



- the contribution of different uncertainty sources depends on p_T and η
- total uncertainty of the jet energy scale is close to 1% for $|\eta| < 2.4$

Missing Energy Resolution and PU

- MET resolution for different N_{PV} is fitted with:

$$\sigma_{\mathrm{tot}} = \sqrt{c^2 + \frac{N_{\mathrm{PV}}}{0.7} \cdot \sigma_{\mathrm{PU}}}$$

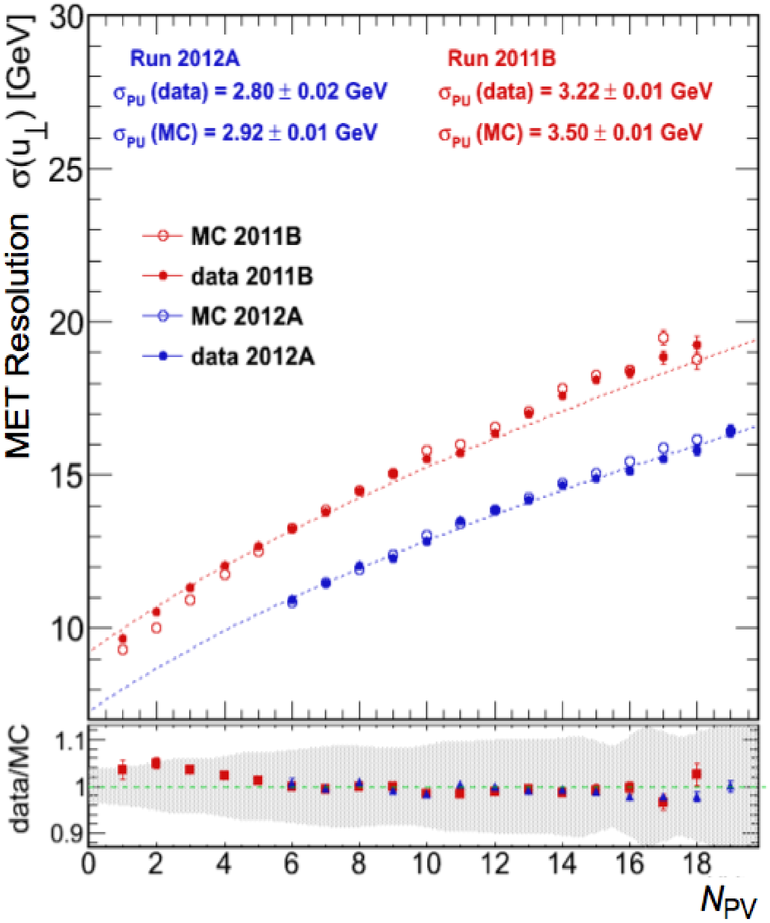
- the fit yields:

  c : average resolution without PU

  σ_{PU} : degradation in resolution caused by PU

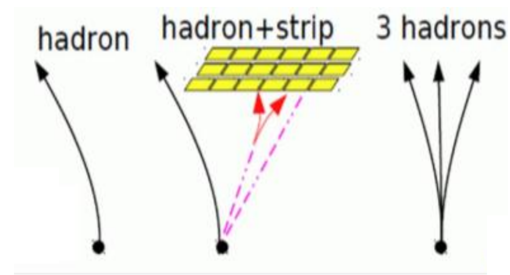
- improved resolution in 2012 for fixed N_{PV}
  - improved ECAL/HCAL energy reconstruction

    ⇒ reduces out-of-time pileup effects
  - MET pile-up corrections applied
- pile-up introduces an additional smearing of ~ 3 GeV on MET resolution σ_{PU} (in quadrature)

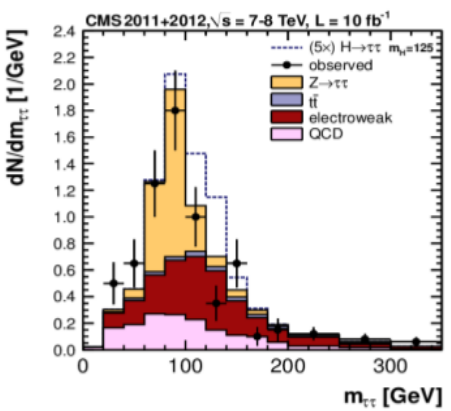


Tau Identification

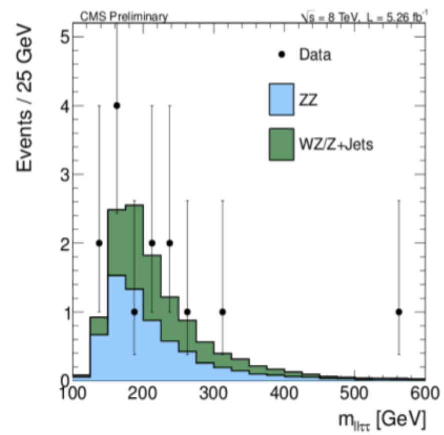
- **Tau identification**:
  - Searches for major τ decay modes within PF jets. Mainly τ decaying to 1 or 3 charged hadrons.
  - Photons/Electrons clustered in strips to reconstruct π^0
  - Discriminating variables computed on reconstructed τ object.
- **Tau isolation**: Multivariate discriminator using sum of energy deposits in dR rings around the τ.



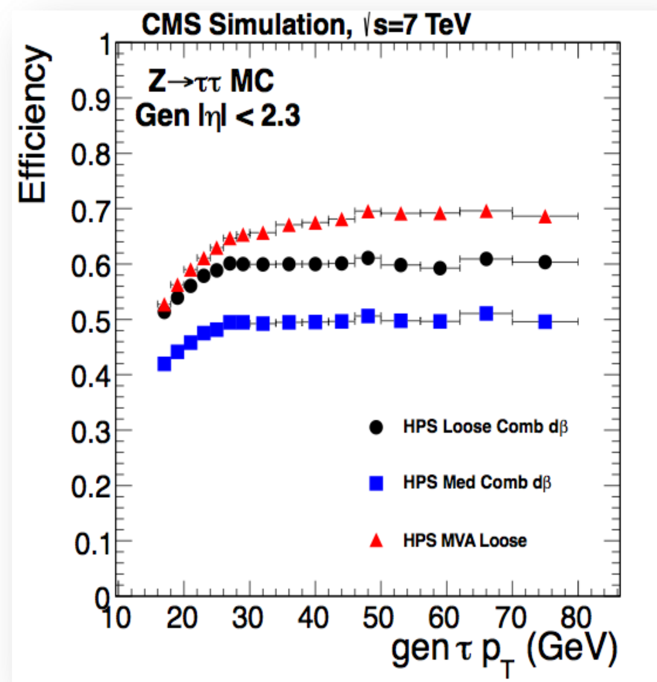
Tau ID + Isolation efficiency



e-τ_h visible Mass



ZZ→ llττ invariant Mass

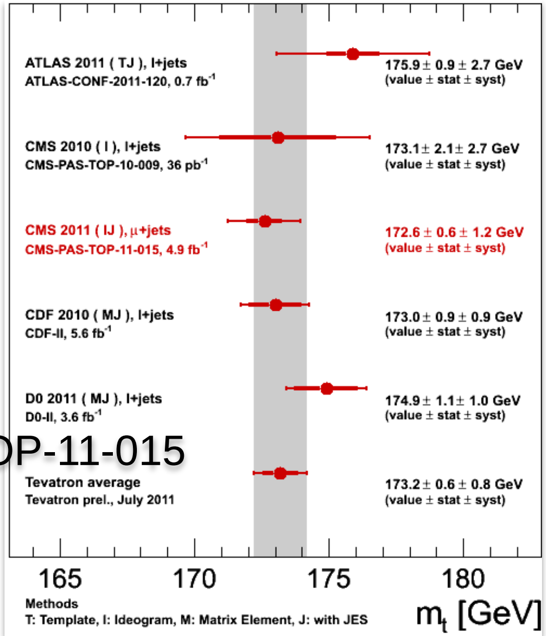


70% efficiency with 5% fake!
τ's in CMS have become "normal" leptons.

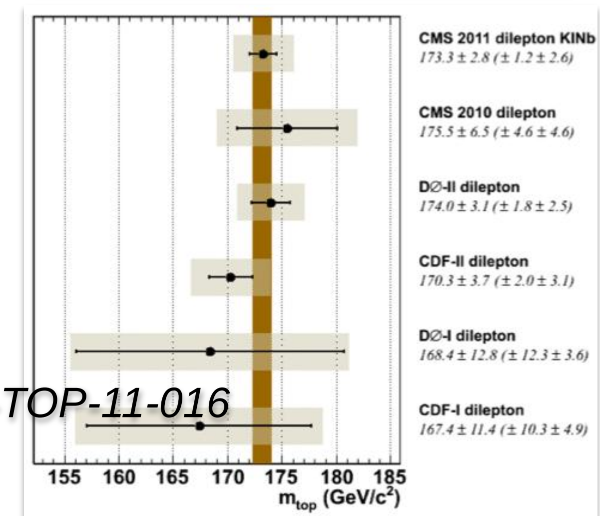
Top mass

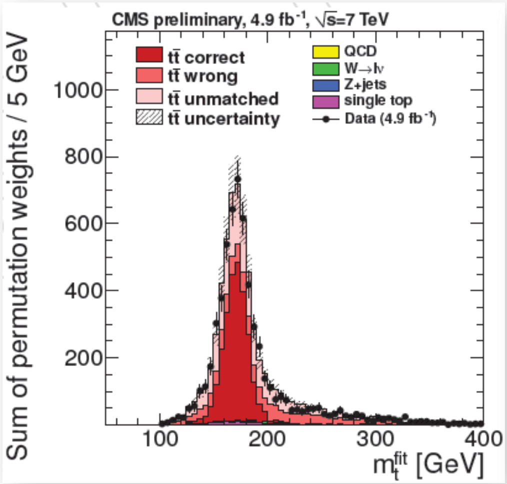
CMS average: 172.6 ± 0.4 ± 1.2 GeV

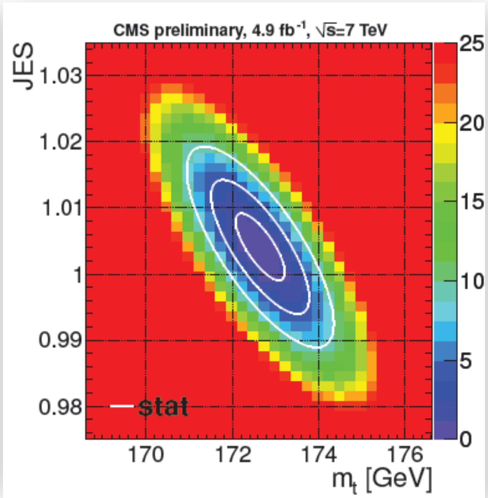
Lepton+jets:
CMS-PAS-TOP-11-015



Dilepton:
CMS-PAS-TOP-11-016





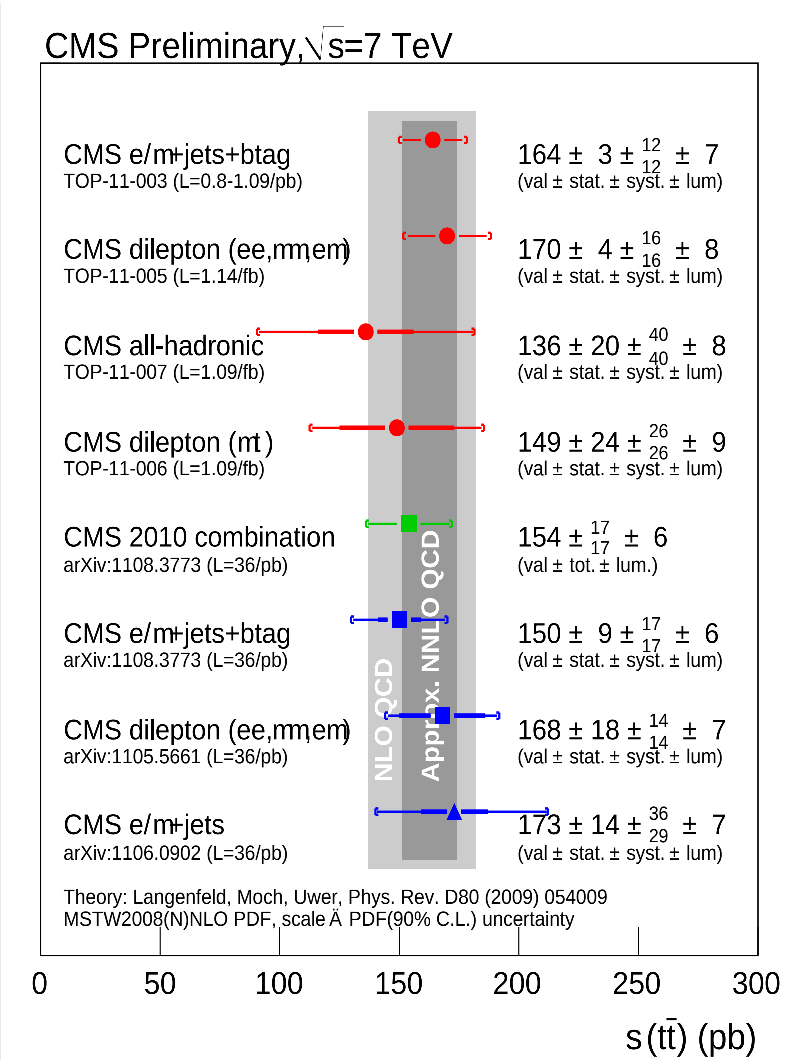


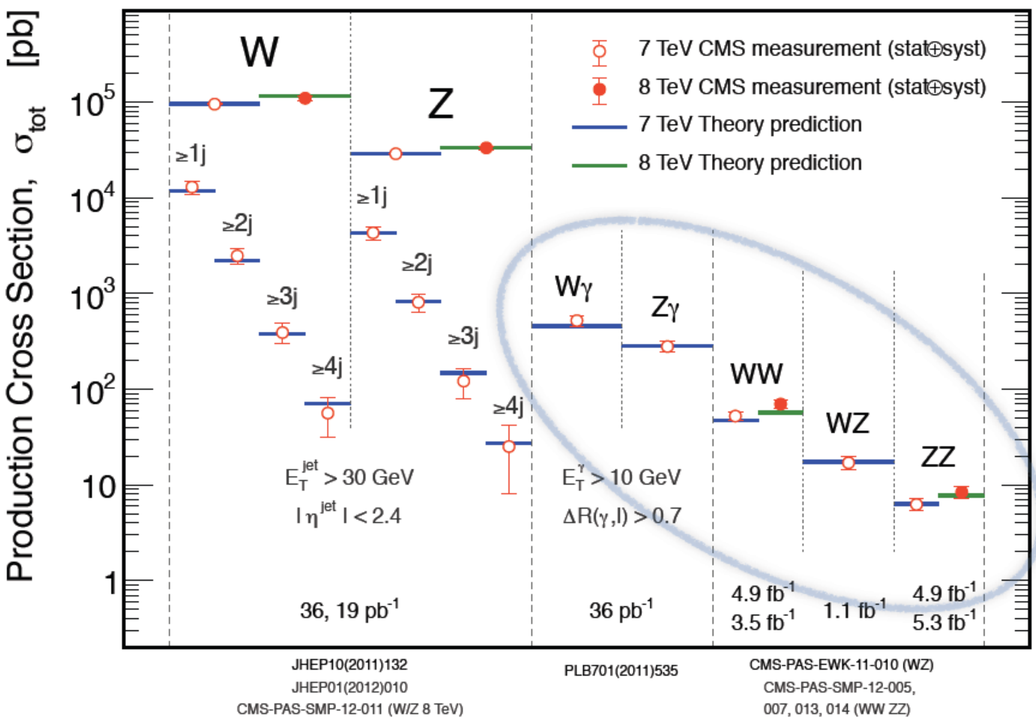
μ+Jets analysis
CMS-PAS-TOP-11-015

$$m_t = 172.64 \pm 0.57\,(\text{stat+JES}) \pm 1.18\,(\text{syst})\ \text{GeV}$$
$$\text{JES} = 1.004 \pm 0.005\,(\text{stat}) \pm 0.012\,(\text{syst})$$

~1.3 (syst) GeV including color reconnection
Effect of the underlying event expected to be small

Standard Model at 7TeV (2010-12)





Excellent agreement with NLO (or approx. NNLO) predictions.

Key ingredients for Higgs hunting:

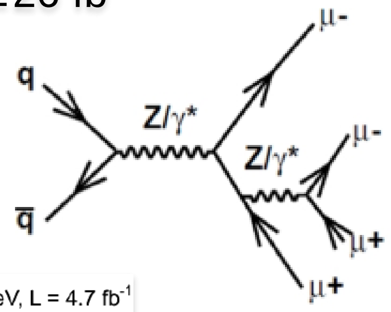
$\sigma(pp) \rightarrow H+X$ (for m_H=125GeV)=17.5pb

same order of magnitude of the diboson (WW, WZ, ZZ production).

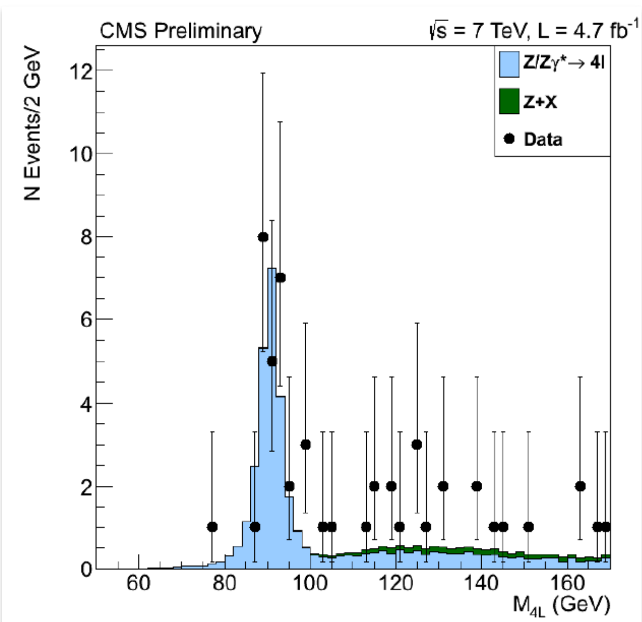
Standard Model rare processes.

4-fermion $Z \rightarrow llll$ decays observed at a hadron collider! (BR = $4.4 \cdot 10^{-6}$), $\sigma \approx 125 \pm 26$ fb

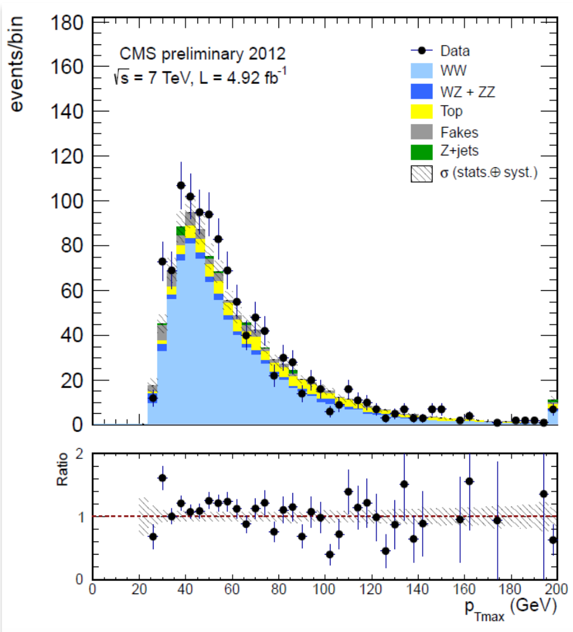
$$Z \rightarrow \mu^+\mu^-\mu^+\mu^-$$



800 $WW \rightarrow l\nu l\nu$ events observed in 2011, $\pm$10% xsec precision. It constrains Higgs backgrounds and anomalous trilinear couplings.



CMS-PAS-SMP-12-009

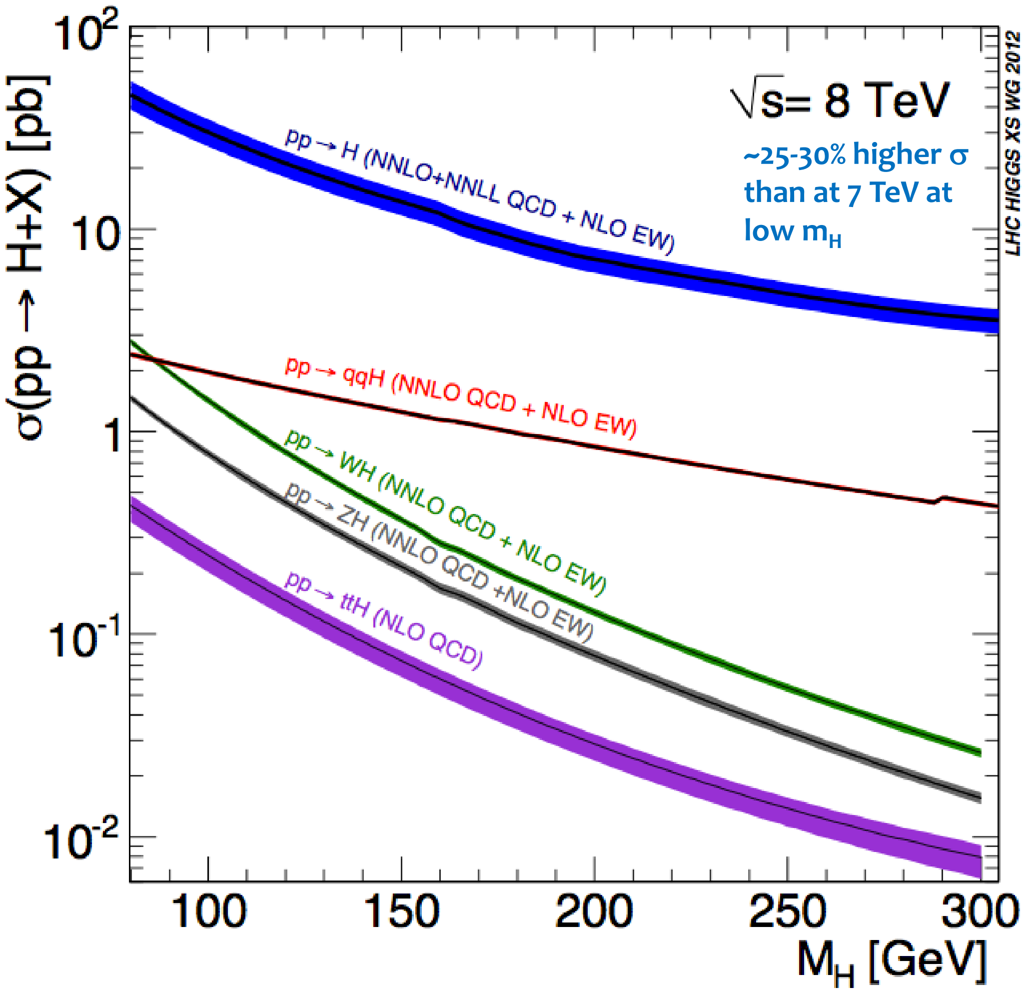


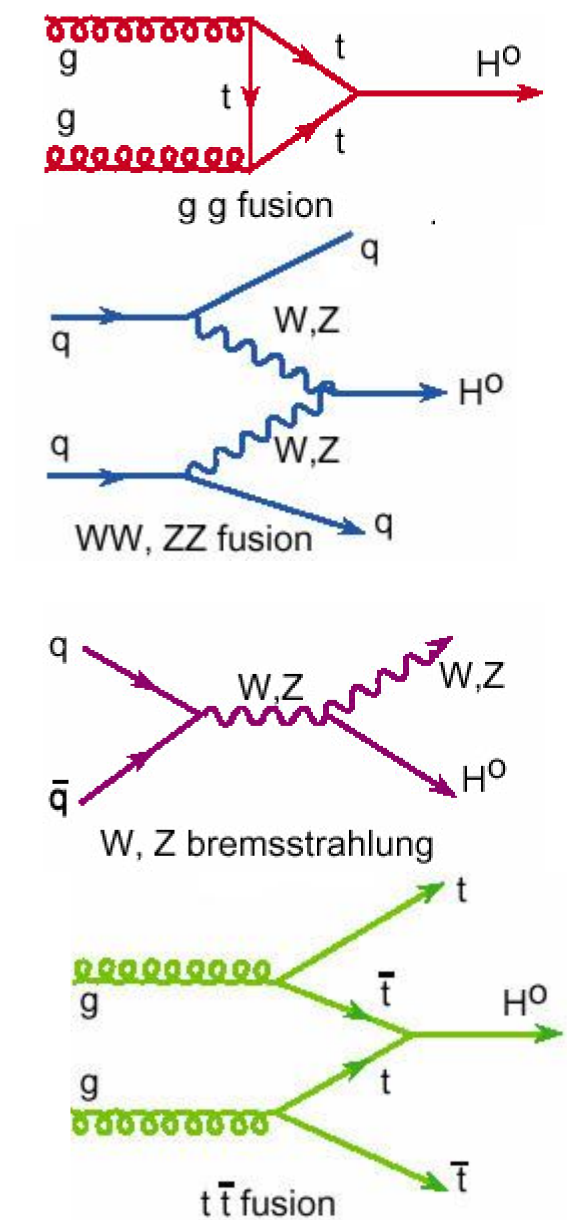
CMS-PAS-SMP-12-005

Search for the SM Higgs Boson

Higgs Boson Production

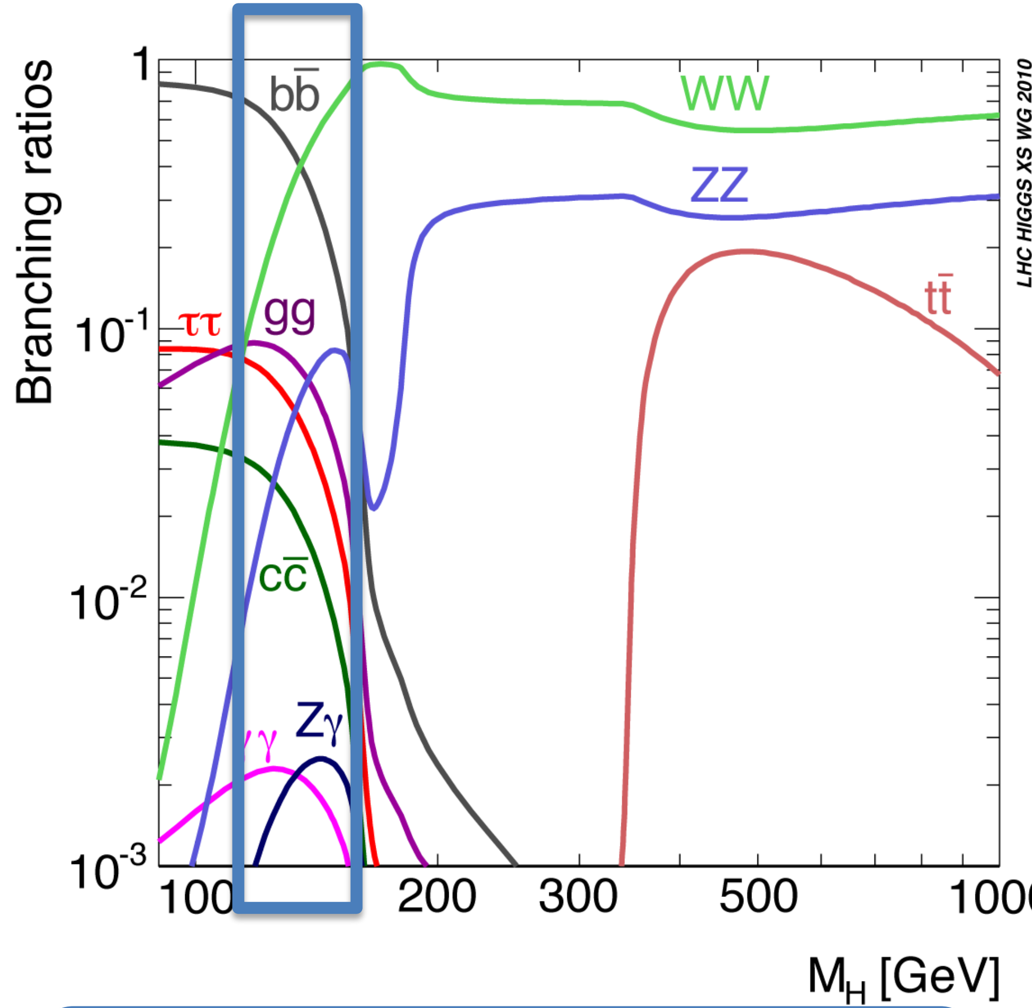
- Dominant production mode: gluon-gluon fusion followed by Vector Boson Fusion (VBF)
- All production modes exploited (gg, VBF, VH, ttH)
  - Latter 3 have smaller σ but better S/B in many cases





Higgs Decays

- Five important decay modes:
  - High mass: **WW**, **ZZ**
  - Low mass **bb**, **ττ**, **WW**, **ZZ**, **γγ**
- Low mass region really reach and challenging:
  - Main identifiable decay modes, **bb** and ττ hard to identify in a huge background
- Two high resolution mass (~ 1%) decay modes: **H → γγ** and **H → ZZ → 4l**
- **H → ZZ → 4l** has in addition very low background



$H \to ZZ \to \ell\ell\nu\nu$ $H \to WW \to \ell\nu qq$ $H \to ZZ \to \ell\ell qq$

$H \to ZZ \to \ell\ell\tau\tau$ $ttH \to ttbb$ ttH

Many other channels also analyzed

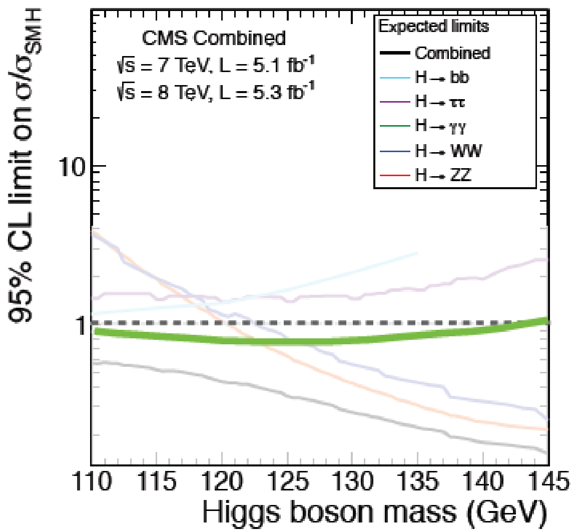
Search for the SM Higgs Boson

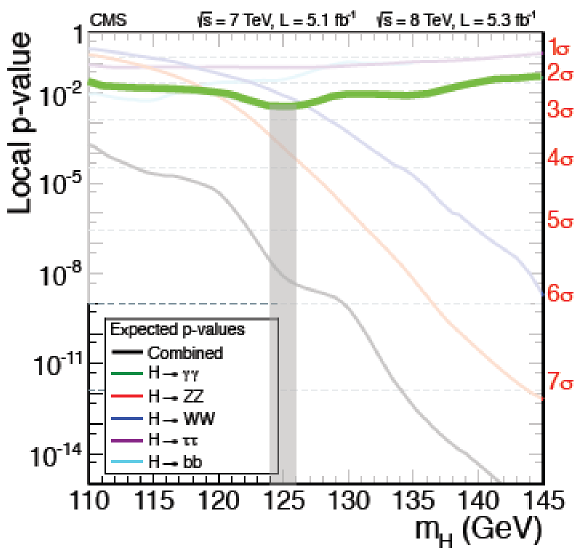
Channel	Mass range [GeV]	Lumi'11 [1/fb]	Lumi'12 [1/fb]	Topologies	gF	VBF	VH	ttH
H → γγ	110-150	5.1	5.3	incl. + VBF	☺	☺	-	-
H → ττ	110-145	4.9	5.0	0/1 jet + VBF + WH + ZH	☺	☺	☺	-
H → bb	110-135	5.0	5.0	WH + ZH + ttH	-	-	☺	☺
H → ZZ → 4l	110-600	5.1	5.3	inclusive	☺	-	-	-
H → WW → 2l2v	110-600	4.9	5.3	0/1 jet + VBF + WH + ZH	☺	☺	☺	-
H → ZZ → 2l2v	200-600	5.0	5.0	0/1 jet + VBF	☺	☺	-	-
H → ZZ → 2l2q	130-600	4.9	-	0/1/2 b-tags	☺	-	-	-
H → WW → lvqq	240-600	4.9	5.1	inclusive	☺	-	-	-

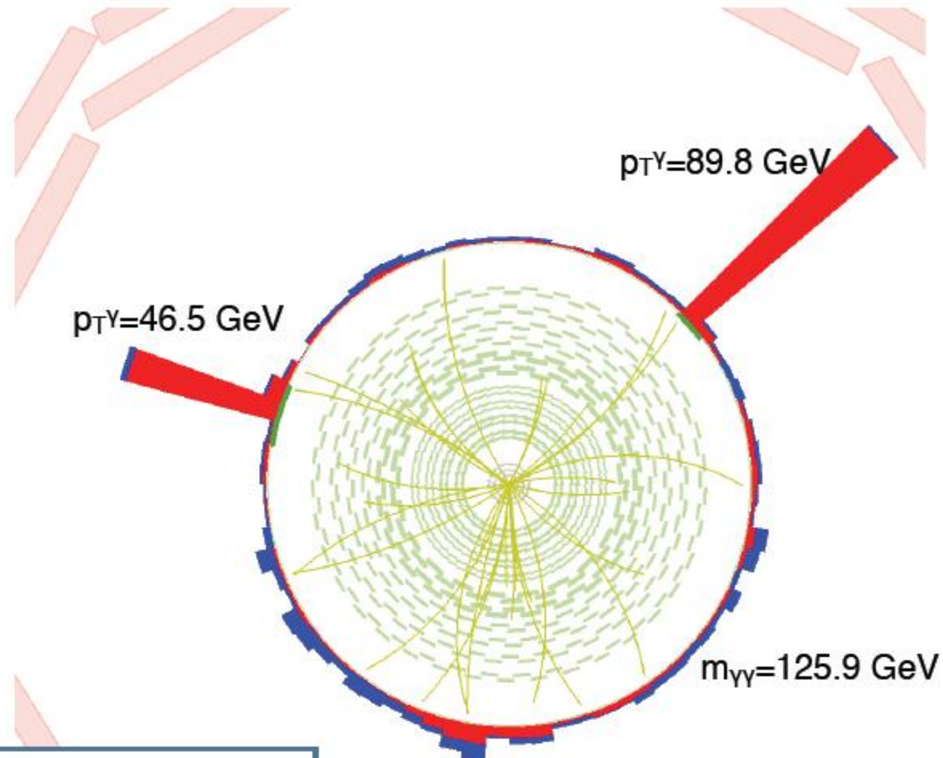
High mass resolution decay mode

$H \rightarrow \gamma\gamma$

5 fb/1 at 7 TeV (2011) + 5 fb/1 at 8 TeV (2012)





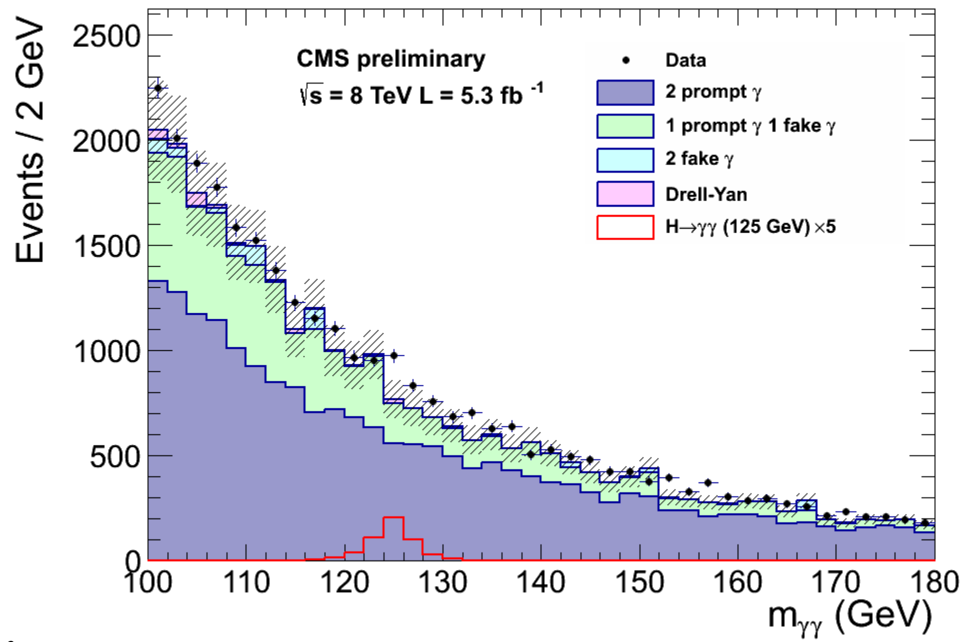


H → γγ candidate

$H \rightarrow \gamma\gamma$

- Search for a narrow peak in the diphoton mass spectrum with two isolated high ET photons on a smoothly falling background
  - In barrel resolution ~ 1%
- Analysis optimized categorizing events according to purity and mass resolution.
  - Specific di-jet tag categories targeting VBF production mode.

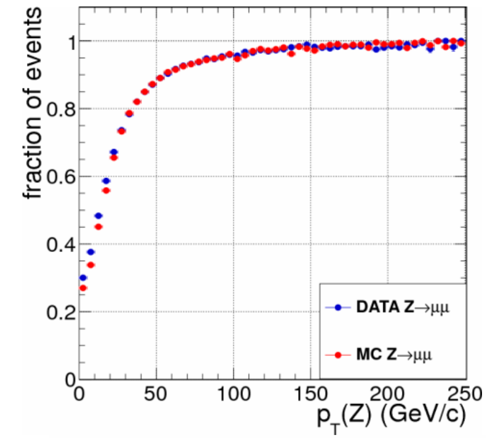
Background model derived from data
Simultaneous polynomial fits of the $m_{\gamma\gamma}$ in all the categories

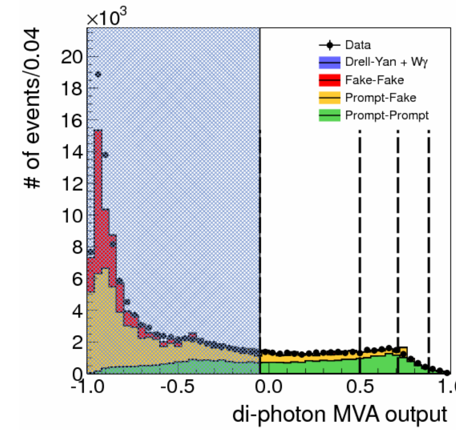


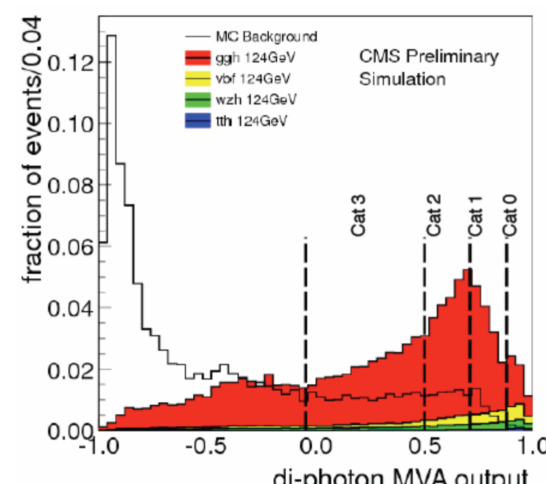
- Several complementary analysis:
  Main analysis optimized using a MultiVariate technique to identify and classify events, cross-checked with (independent) cut based and mass sideband background MVA model

$H \rightarrow \gamma\gamma$

- **Analysis selection (MultiVariate Analysis MVA)**
  - Vertex ID
    - Input variables: $\Sigma p_T^{2\,(\mathrm{tracks})}$, p_T balance wrt $\gamma\gamma$, conversions information
  - ID photons $p_{T1} > m_{\gamma\gamma} / 3$ $p_{T2} > m_{\gamma\gamma} / 4$
- **MVA Diphoton discriminant categories**
  - High score
    - signal-like events
    - good $m_{\gamma\gamma}$ resolution
  - Designed to be $m_{\gamma\gamma}$ independent
  - Trained on signal and background MC
  - Input variables:
    - Kinematic variables: $p_{T\gamma} / m_{\gamma\gamma}$, η_γ, $\cos(\varphi_1 - \varphi_2)$
    - Photon ID MVA output for each photon
    - Per-event mass resolutions for the correct and incorrect choice of vertex

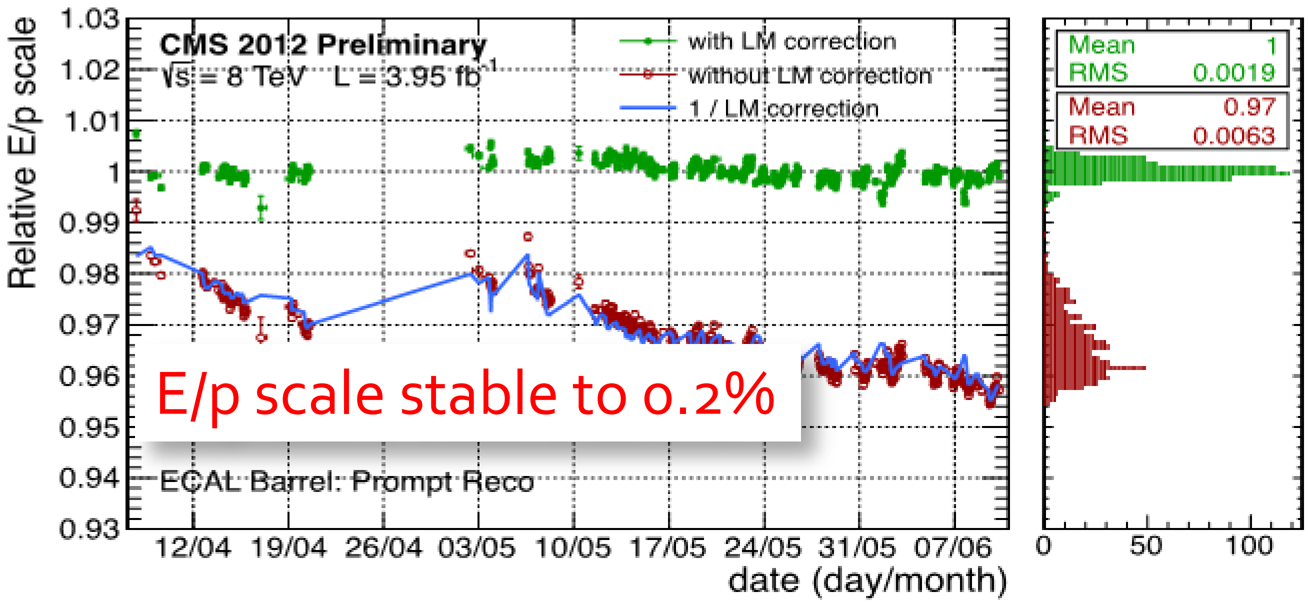






$H \rightarrow \gamma\gamma$: what's new in 2012

- 2011 data reprocessed with new energy calibrations in ECAL to further improve the mass resolution.
- 2012 prompt reco. data: calibration stable vs time thanks to live light monitoring corrections.

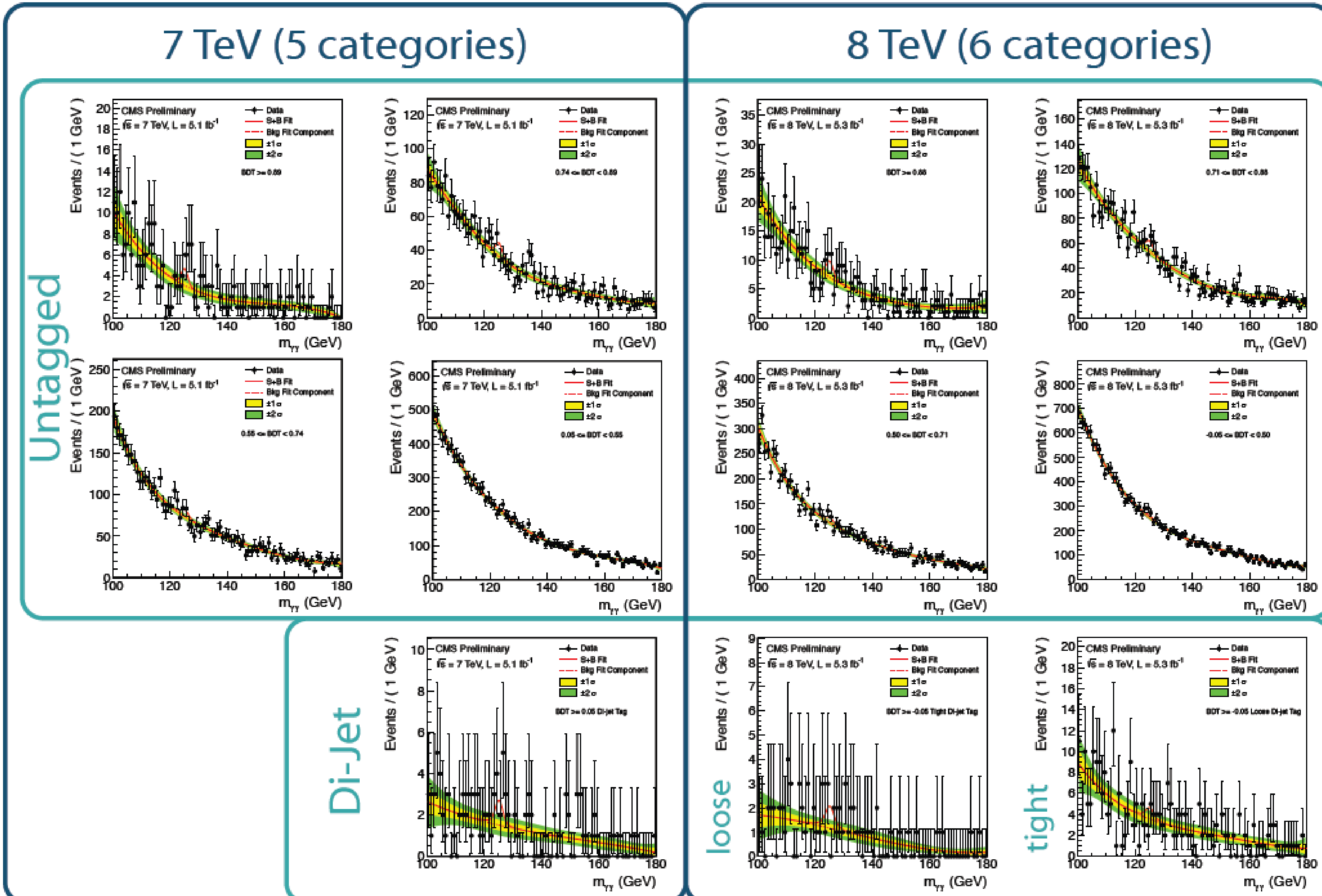


Laser calibration: Automated 48-hour calib. loop.

H $\rightarrow$ γγ: what's new in 2012

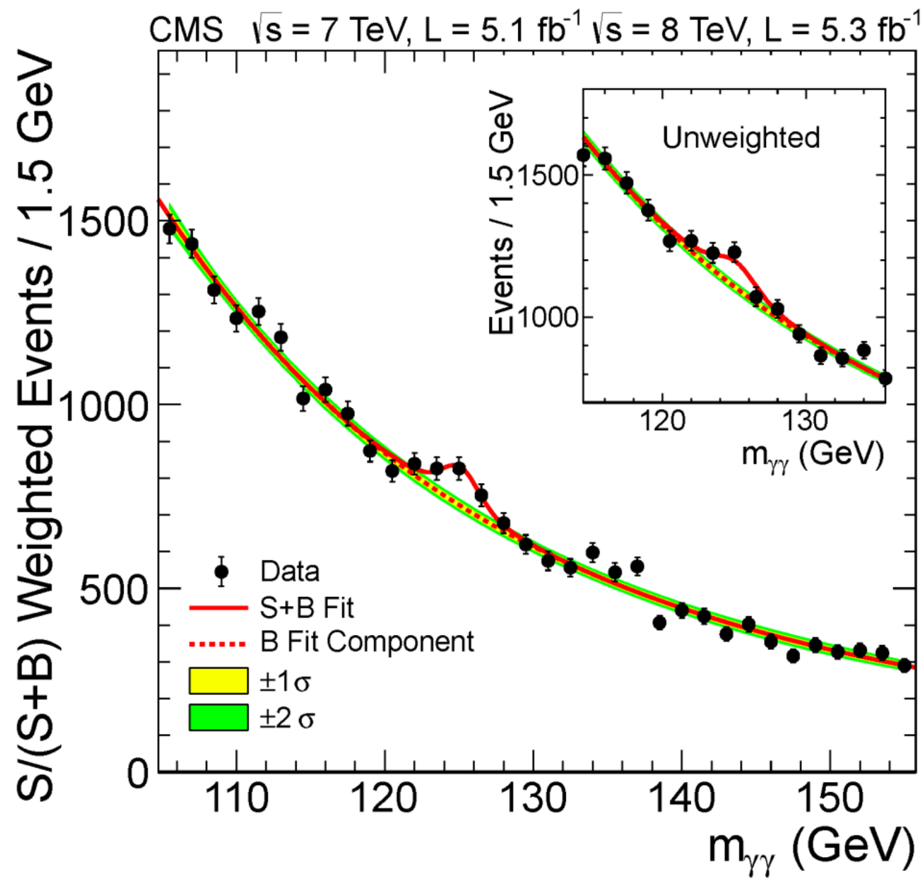
- 2011 data reprocessed with new energy calibrations in ECAL to further improve the mass resolution.
- 2012 prompt reco. data: calibration stable vs time thanks to live light monitoring corrections.
- Re-optimized photon selection using isolation based on Particle Flow reconstruction
- Split di-jet tag events in two categories with different purity (15% better sensitivity)

H → γγ: mass dstributions



S/(S+B) weighted mass distribution

- S and B are the number of signal and background events calculated from the simultaneous fit to all categories
- Summed plot for illustration, results obtained with simultaneous ML fit to all categories



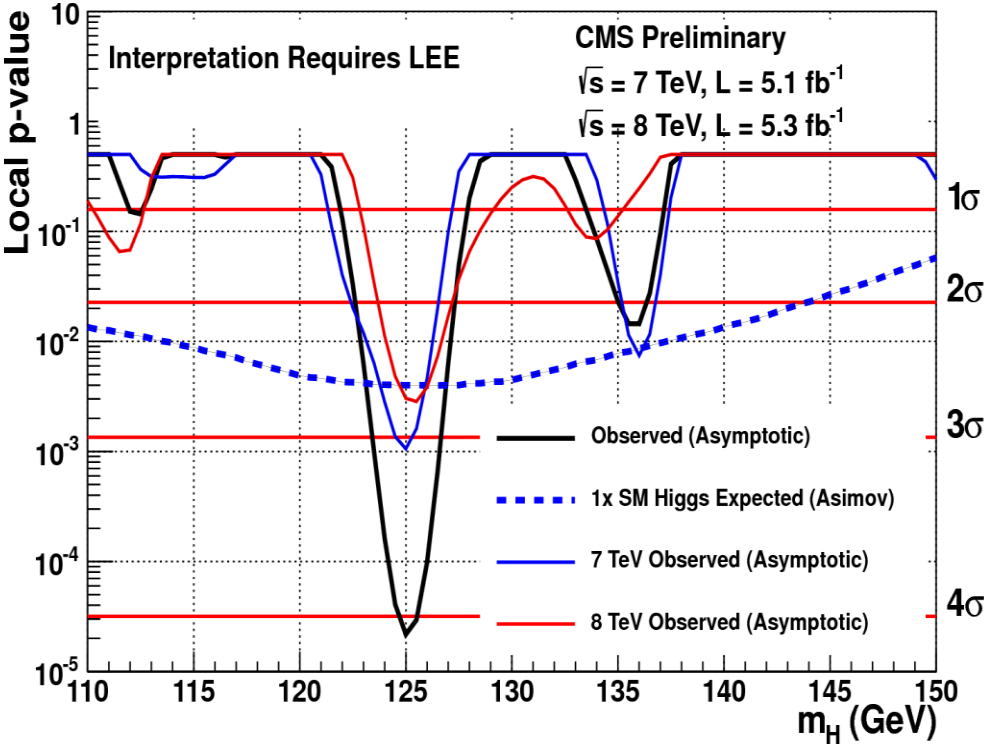
As suggested in R. J. Barlow, "Event classification using Weighting Methods" , J. Comp. Phys. 72 (1982) 202

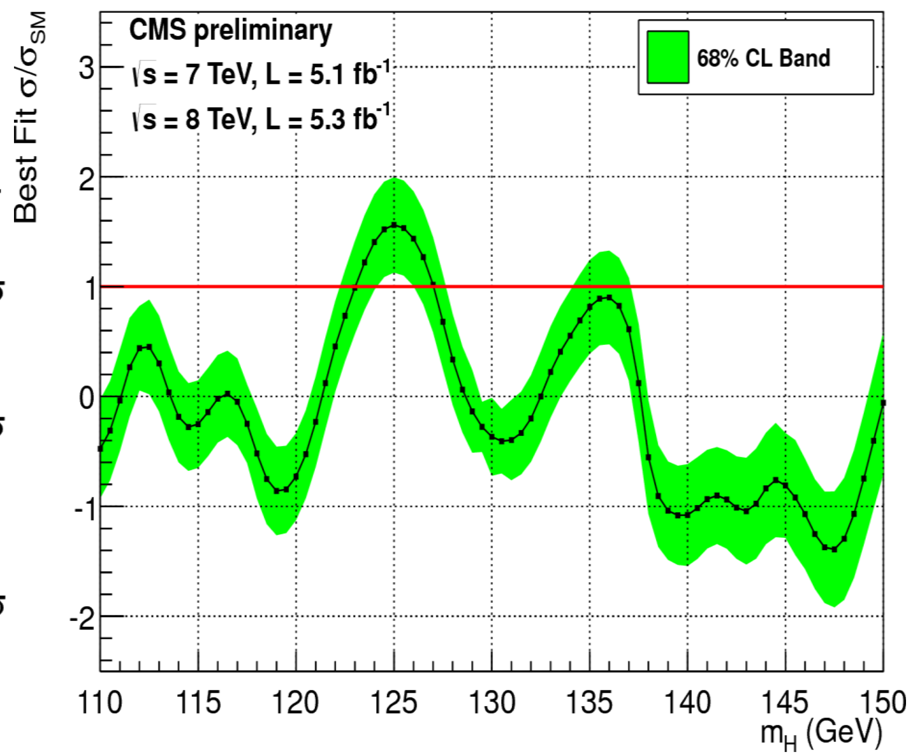
$H \rightarrow \gamma\gamma$ results

Excess of events observed for diphoton masses around 125 GeV, consistently in 7 and 8 TeV data

Local significance 4.1σ. Signal strength $1.6 \pm 0.4 \times \sigma_{SMH}$

Evidence for a new state

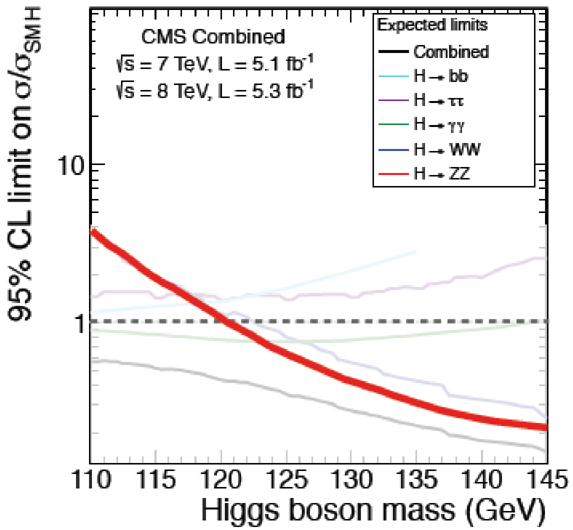


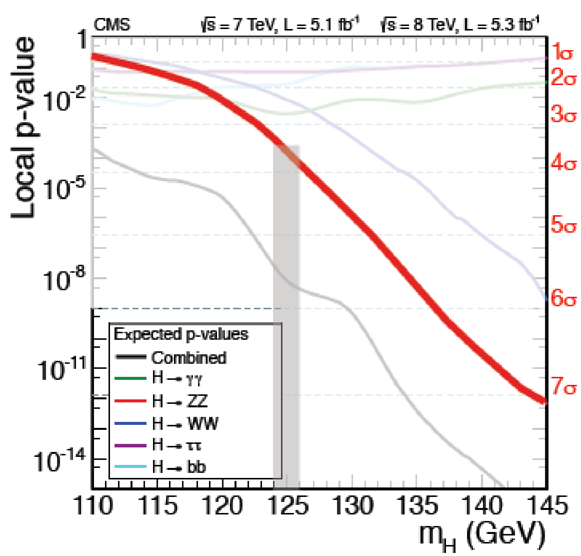


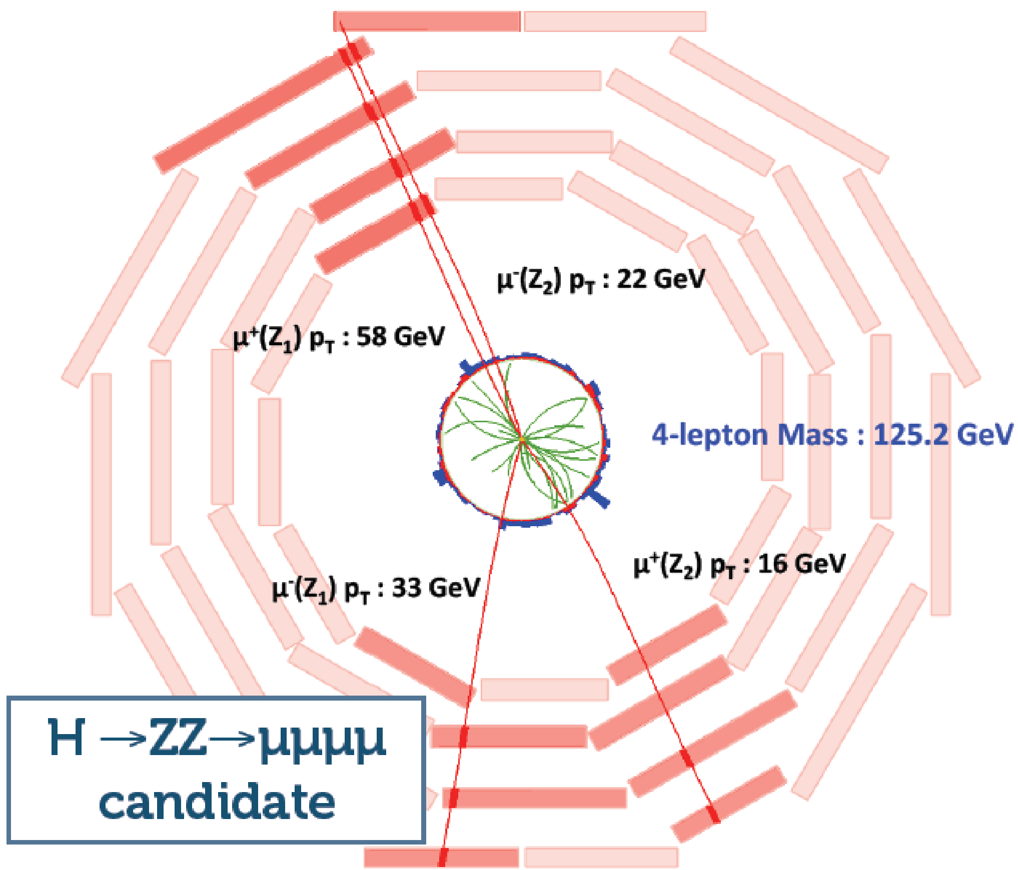
High mass resolution decay mode

$H \rightarrow ZZ \rightarrow 4l$

5 fb/1 at 7 TeV (2011) + 5 fb/1 at 8 TeV (2012)

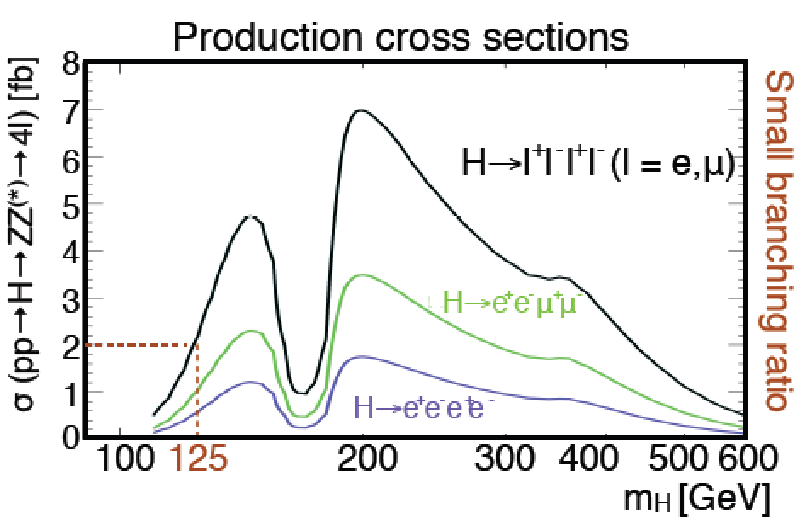


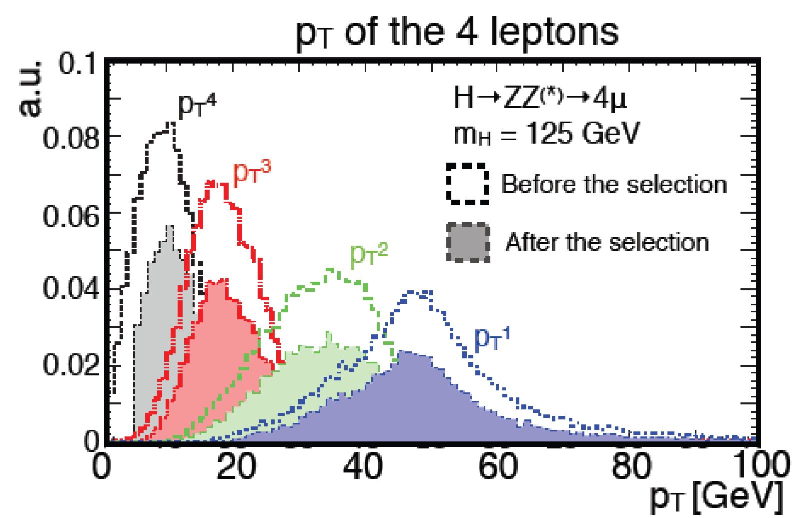




$H \to ZZ \to 4l$

- Golden channel: clean experimental signature
  - Narrow resonance
  - Four (potentially low p_T) tightly identified and isolated leptons
- Low level of background: irreducible ZZ* , reducible Z+jets, t tbar with two leptons from b or light jets, WZ, estimated from data - 50 % uncertainty: fake rate method applied from signal-free control samples, validation (data wrong flavours and charges)
- A great performing channel in the whole mass range, but extremely demanding in terms of selection efficiency down to the lowest p_T ε^4

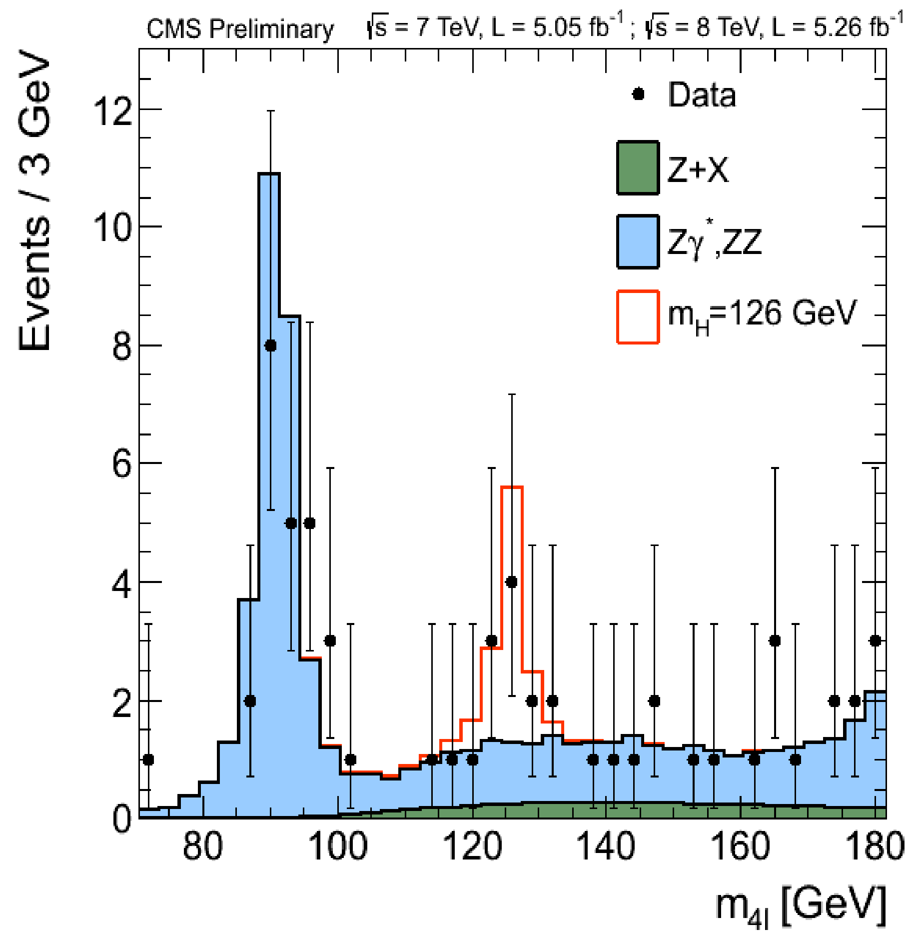




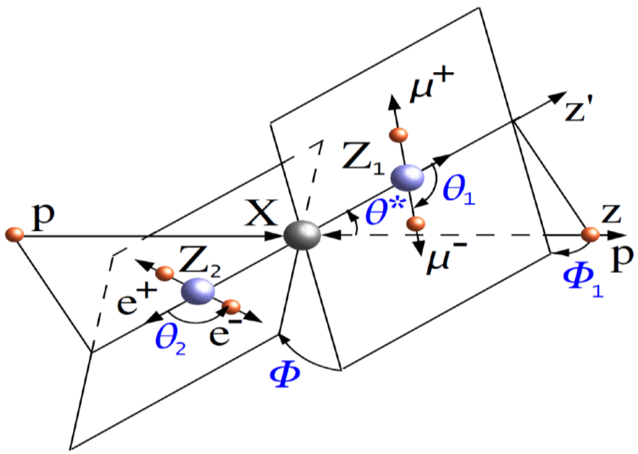
$H \rightarrow ZZ \rightarrow 4l$

Improvements in 2012:

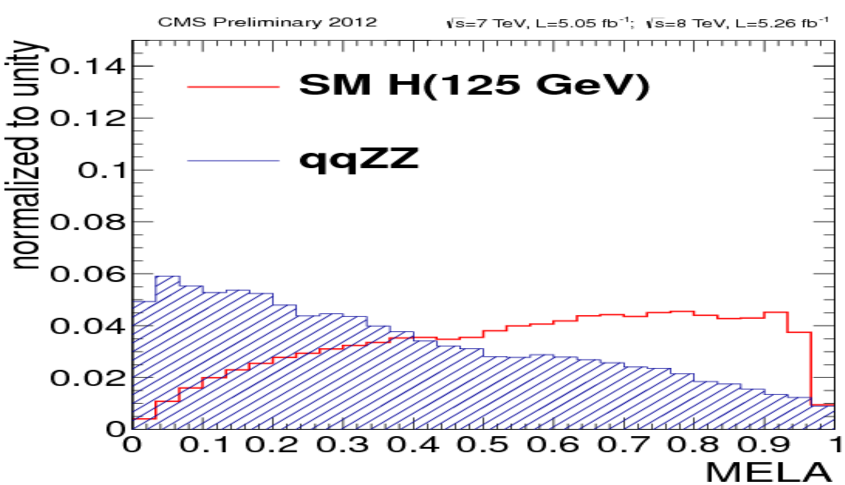
- New lepton selection
- Recovery of photons from final state radiation
- Exploit angular information to discriminate signal from irreducible ZZ background
- ~20% gain in sensitivity with respect to the 2011 analysis
- Optimization done without looking at the data in the signal region.



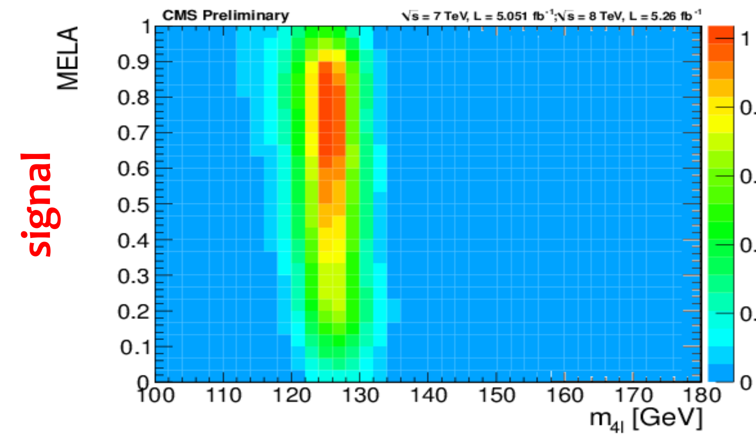
Matrix Element Likelihood Analysis

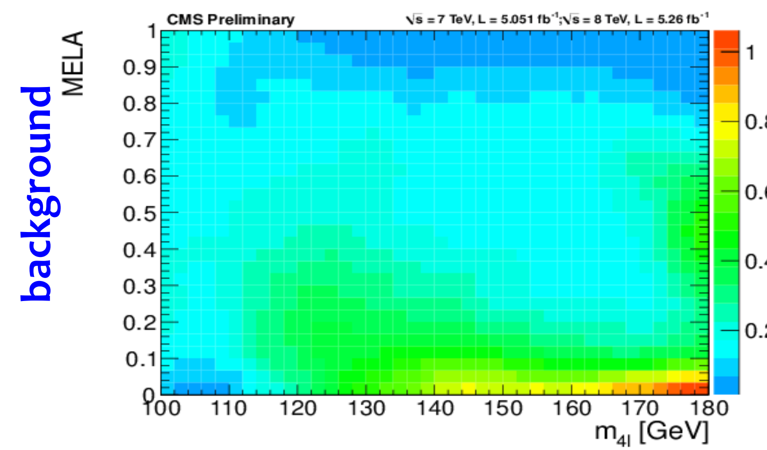


$$\text{MELA} = \left[1 + \frac{\mathcal{P}_{\text{bkg}}(m_1, m_2, \theta_1, \theta_2, \Phi, \theta^*, \Phi_1 | m_{4\ell})}{\mathcal{P}_{\text{sig}}(m_1, m_2, \theta_1, \theta_2, \Phi, \theta^*, \Phi_1 | m_{4\ell})}\right]^{-1}$$



2D analysis using m_{4l} and MELA

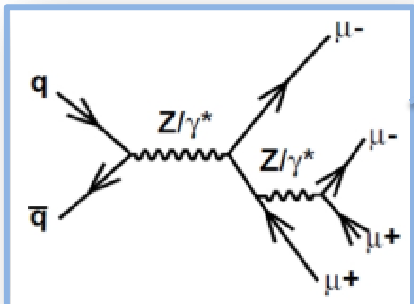


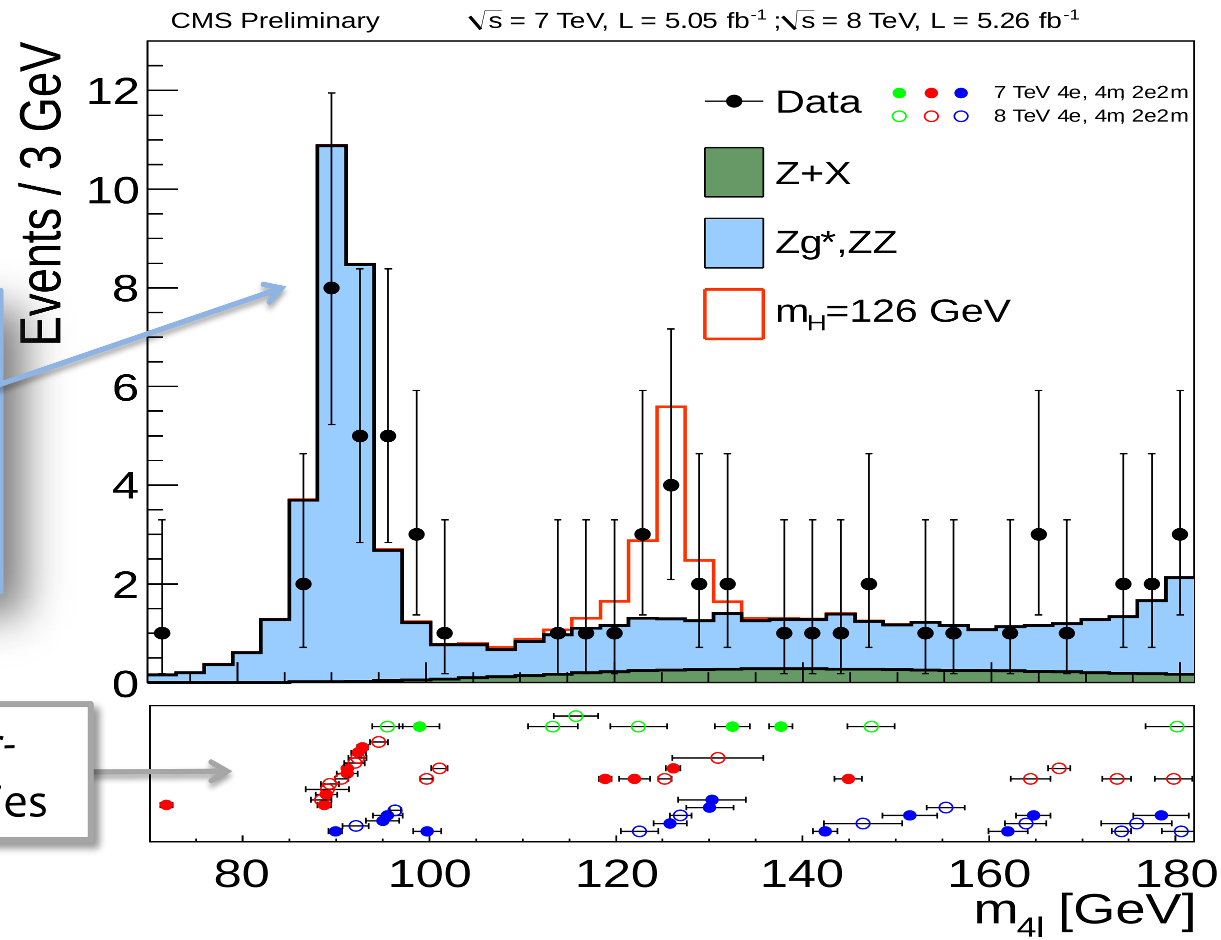


PRD81,075022(2010),[arXiv:1001.5300]

H → ZZ → 4l results

- Localized excess of events observed around 126 GeV

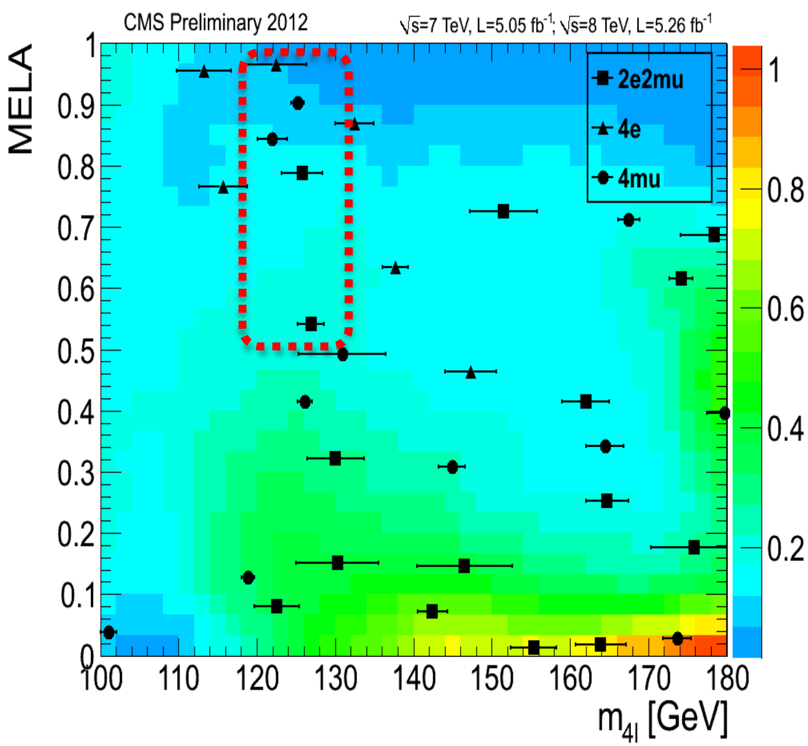


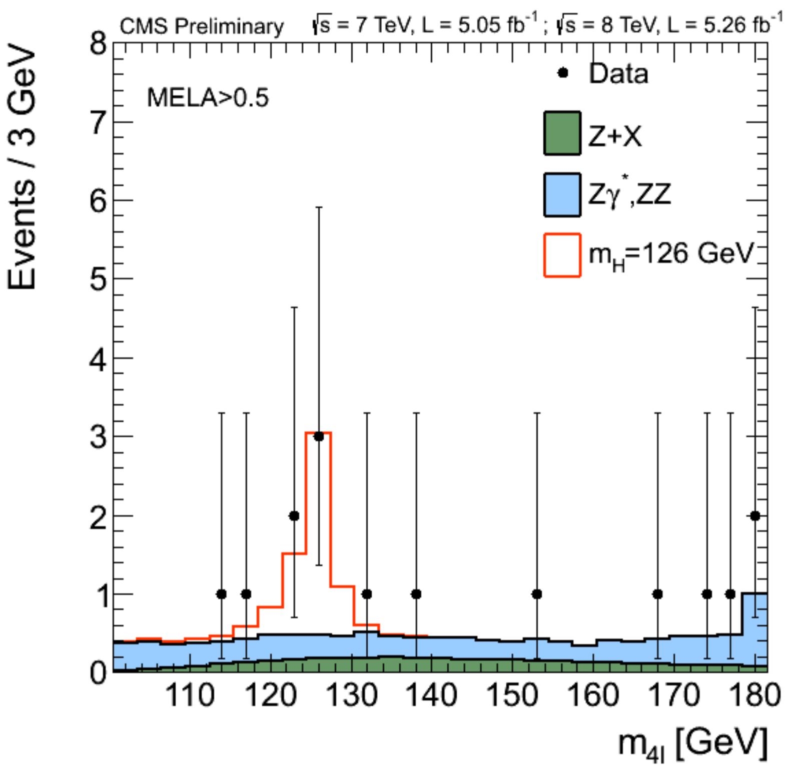


ZZ candidates with per-event mass uncertainties

H → ZZ → 4l results

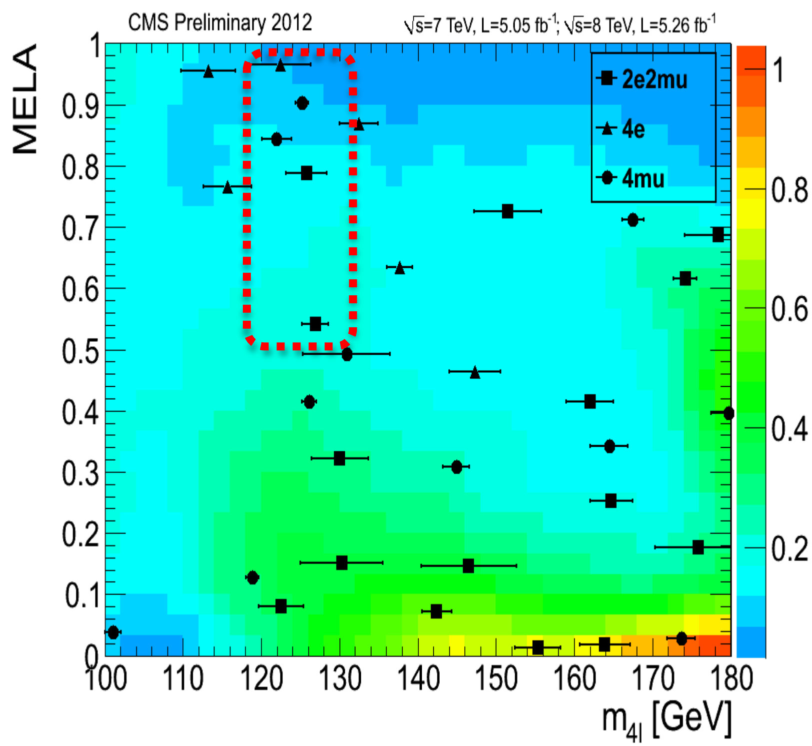
- Localized excess of events observed around 126 GeV and at signal-like values of the angular discriminator

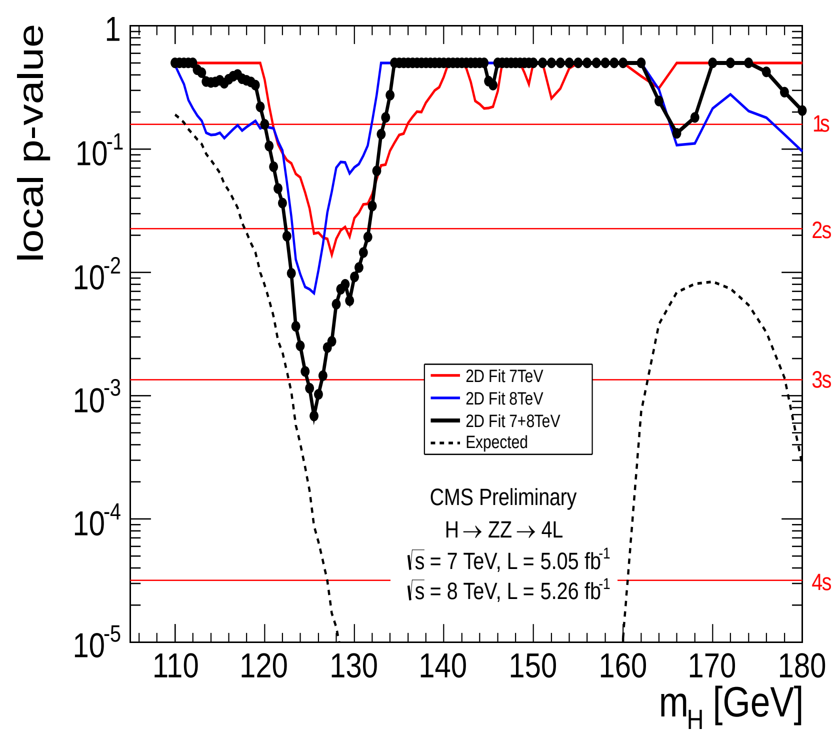




$H \to ZZ \to 4l$ results

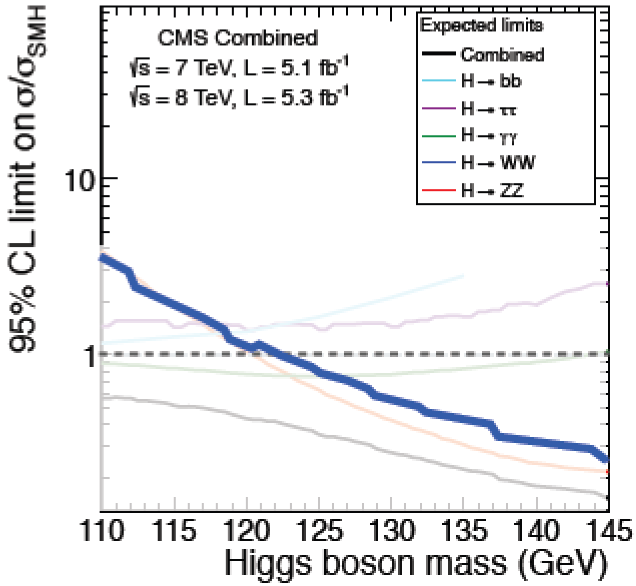
- **Localized excess of events observed around 126 GeV and at signal-like values of the angular discriminator**
- Local significance **3.2σ** (expected from SM H: **3.8σ**)

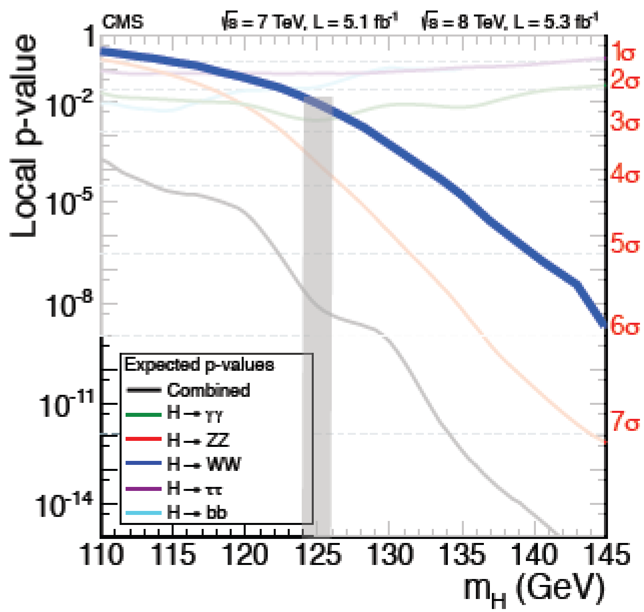


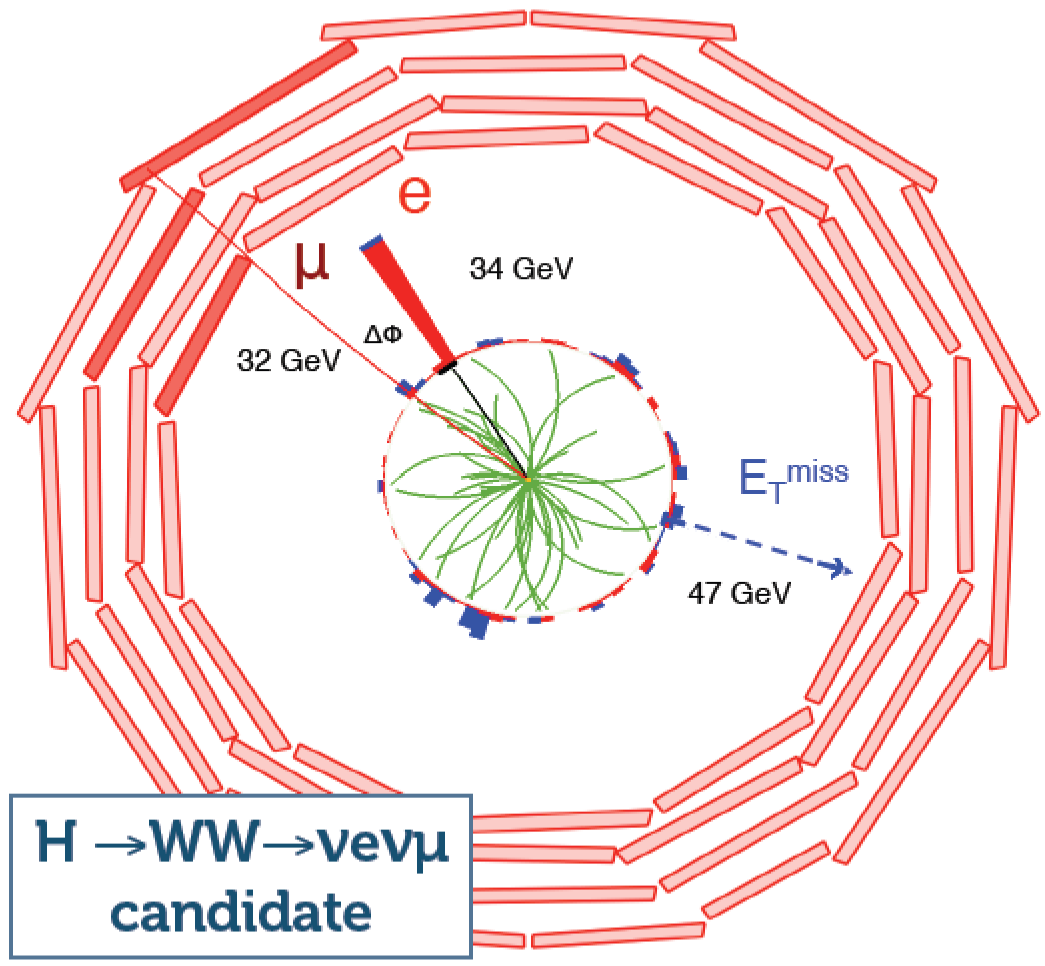


$H \rightarrow WW$ (2l 2ν, lν jj)

5 fb/1 at 7 TeV (2011) + 5 fb/1 at 8 TeV (2012)

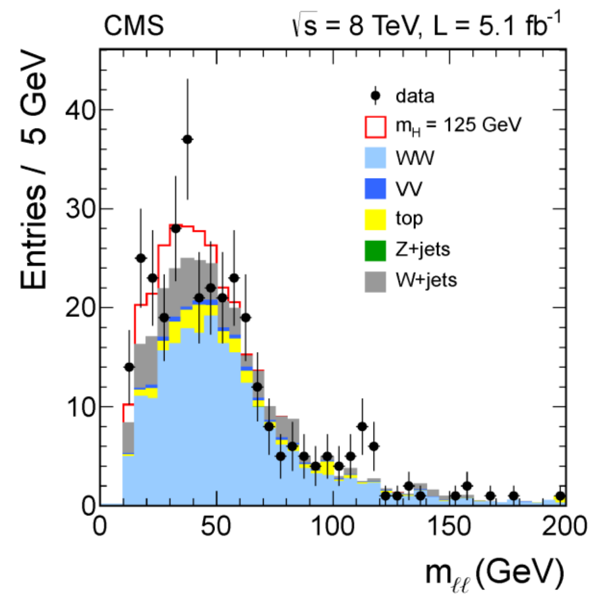


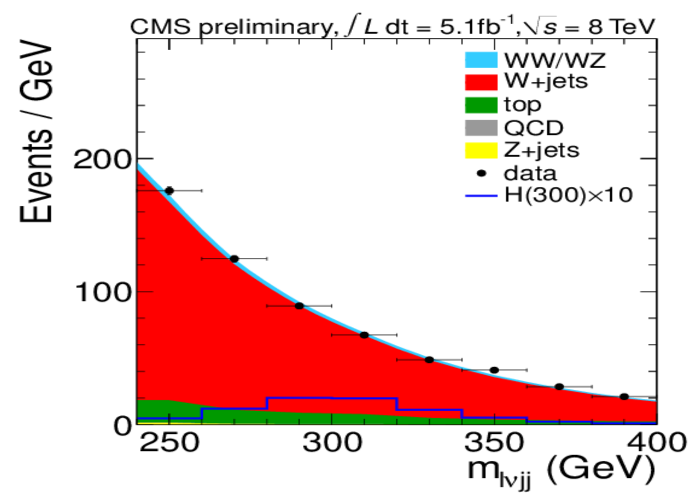




$H \to WW$

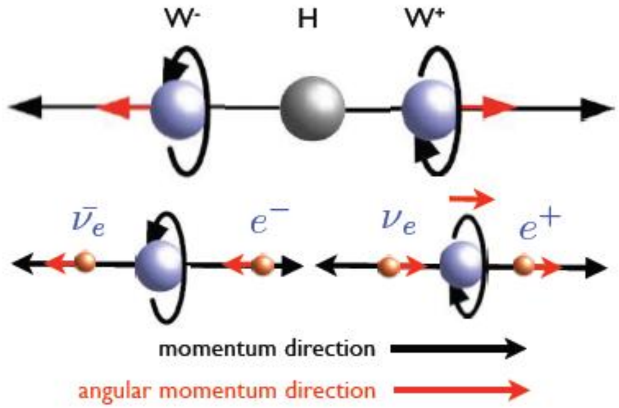
- Dileptonic channel:
  - 2011 analysis unchanged.
  - 2012 analysis with improvements in objects and methods to deal with the increase in pile-up.
    Cut-based analysis for ICHEP.
  - Shape analysis in eμ
- Semi-leptonic channel, new after Moriond'12, for Higgs boson masses above 170 GeV.





$H \rightarrow WW \rightarrow 2l\ 2\nu$

- Excess of events with two leptons of opposite sign, and missing transverse energy.
  - Irreducible background:
    - $qq \rightarrow WW + gg \rightarrow WW$
  - Data driven estimates
    - W+jets: Fake rate measured in QCD enriched data sample
    - Z/γ^*: Normalized in Z mass
    - Top: b-tagging efficiency from top control region in data
- Split in categories with different S/B and B composition:
  - 0/1 jet and VBF
  - Final state lepton flavors (ee, μμ, eμ)



Spin correlation, scalar boson decay to Vector bosons, and V-A structure of the W interaction

Expect small di-lepton $\Delta\phi$ and mass if SM Higgs

H → WW → 2l 2ν : kinematics at final selection

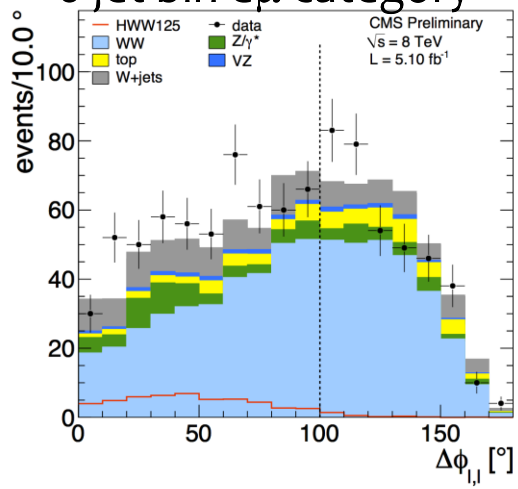
Trigger 1 or 2 leptons > 97 %

p_T^l > 20,10 GeV, iso, ID, from PV

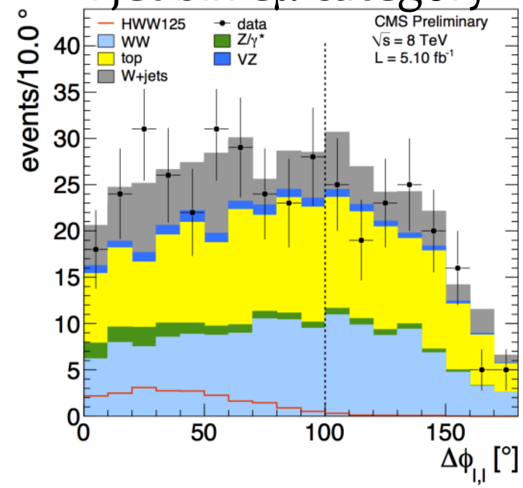
Projected mET > 20 GeV

- Anti-top + p_T^{ll} > 45 GeV
- 3rd lepton veto
- Z veto and mE_T cuts
- Mass dependant: p_T^l, m_{ll}, $\Delta\varphi_{ll}$, m_T

0 jet bin eμ category

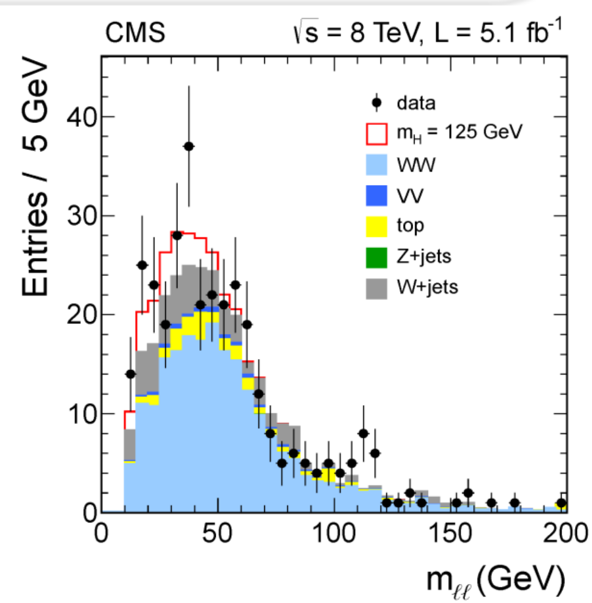


1 jet bin eμ category



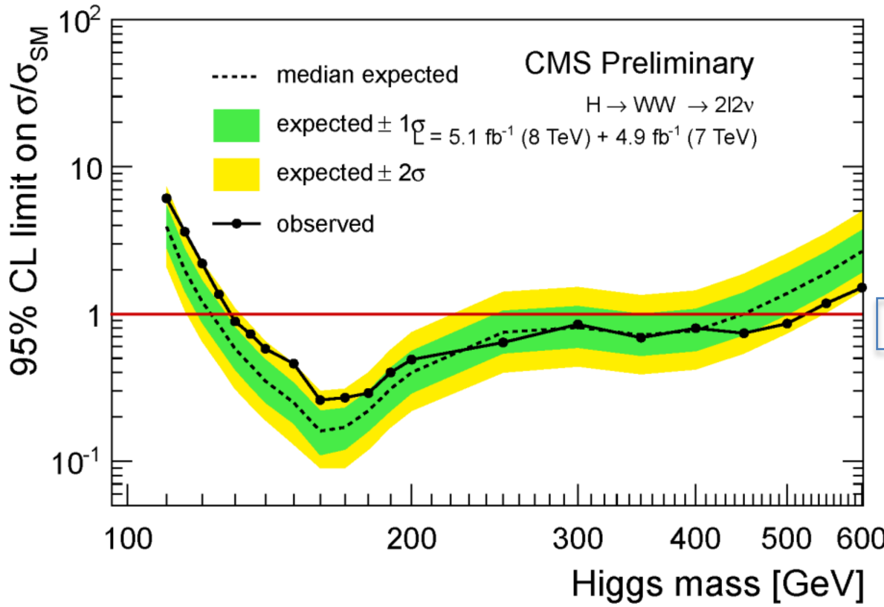
Final selection (8 TeV dataset): Observed number of events in data, estimates of the background and signal predictions for mH=125 GeV

Category:	0-jet $e\mu$	0-jet $\ell\ell$	1-jet $e\mu$	1-jet $\ell\ell$	2-jet $e\mu$	2-jet $\ell\ell$
WW	87.6 ± 9.5	60.4 ± 6.7	19.5 ± 3.7	9.7 ± 1.9	0.4 ± 0.1	0.3 ± 0.1
$WZ + ZZ + Z\gamma$	2.2 ± 0.2	37.7 ± 12.5	2.4 ± 0.3	8.7 ± 4.9	0.1 ± 0.0	3.1 ± 1.8
Top	9.3 ± 2.7	1.9 ± 0.5	22.3 ± 2.0	9.5 ± 1.1	3.4 ± 1.9	2.0 ± 1.2
$W +$ jets	19.1 ± 7.2	10.8 ± 4.3	11.7 ± 4.6	3.9 ± 1.7	0.3 ± 0.3	0.0 ± 0.0
$W\gamma^{(*)}$	6.0 ± 2.3	4.6 ± 2.5	5.9 ± 3.2	1.3 ± 1.2	0.0 ± 0.0	0.0 ± 0.0
All backgrounds	124.2 ± 12.4	115.5 ± 15.0	61.7 ± 7.0	33.1 ± 5.7	4.1 ± 1.9	5.4 ± 2.2
Signal ($m_H = 125$ GeV)	23.9 ± 5.2	14.9 ± 3.3	10.3 ± 3.0	4.4 ± 1.3	1.5 ± 0.2	0.8 ± 0.1
Data	158	123	54	43	6	7

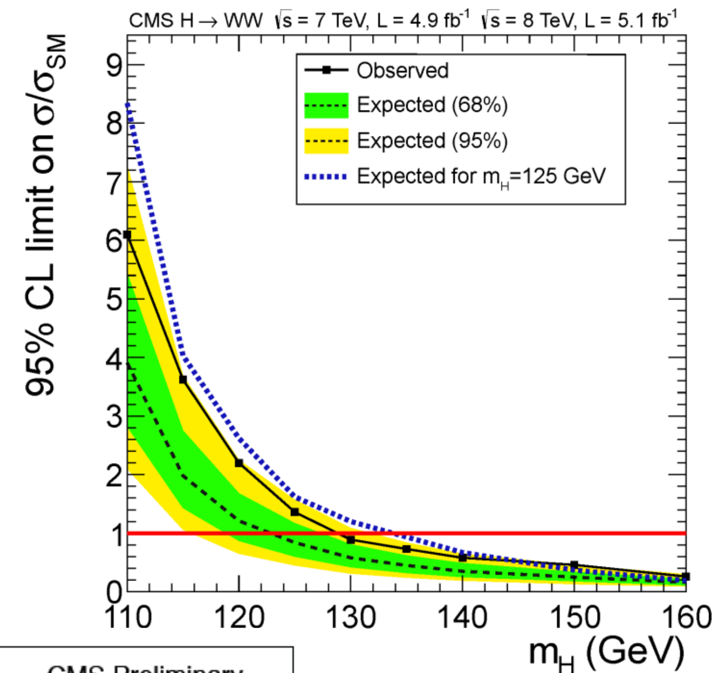


$H \rightarrow WW \rightarrow 2l\,2\nu$: ICHEP results

- Broad excess of about 1.6 σ observed (2.4 σ expected) in the low mass range. Compatible with the expectations from a SM Higgs signal at 125 GeV, given the low mass resolution.



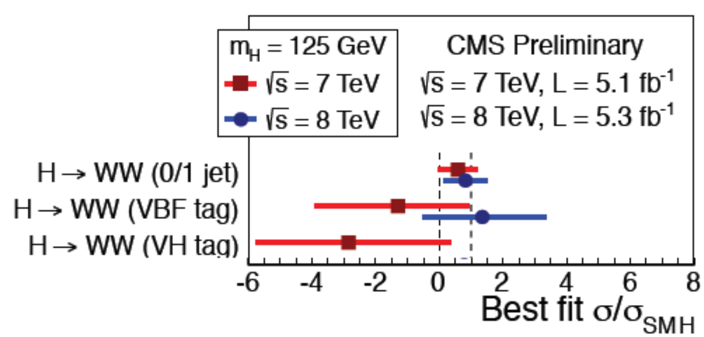
Zoom



Exclusion Range

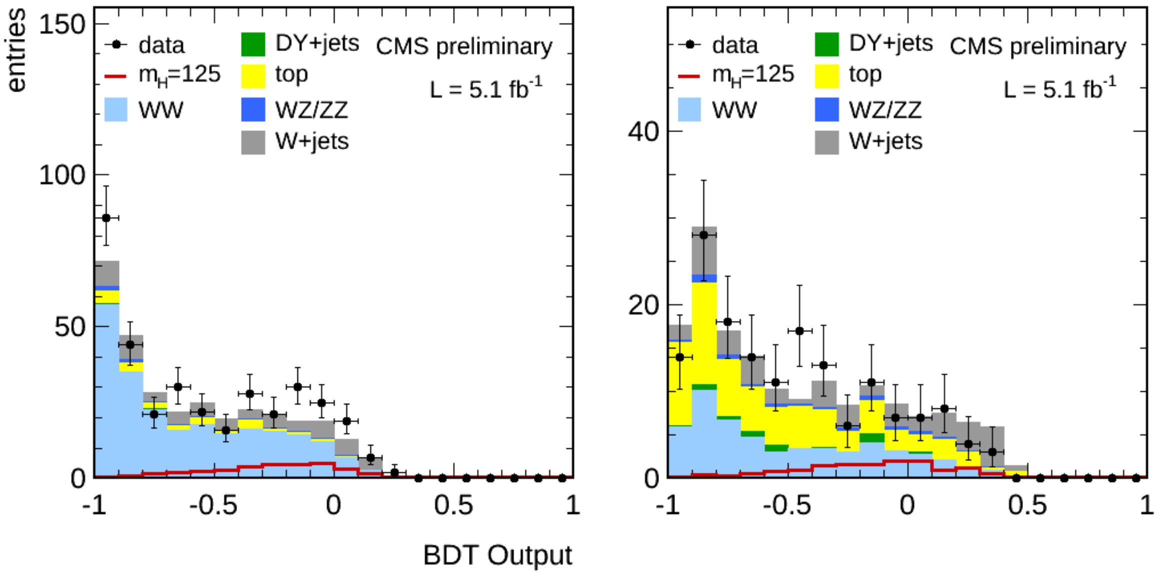
Observed: 129 - 520 GeV

Expected: 123 - 450 GeV



Results in WW topologies are compatible within uncertainties

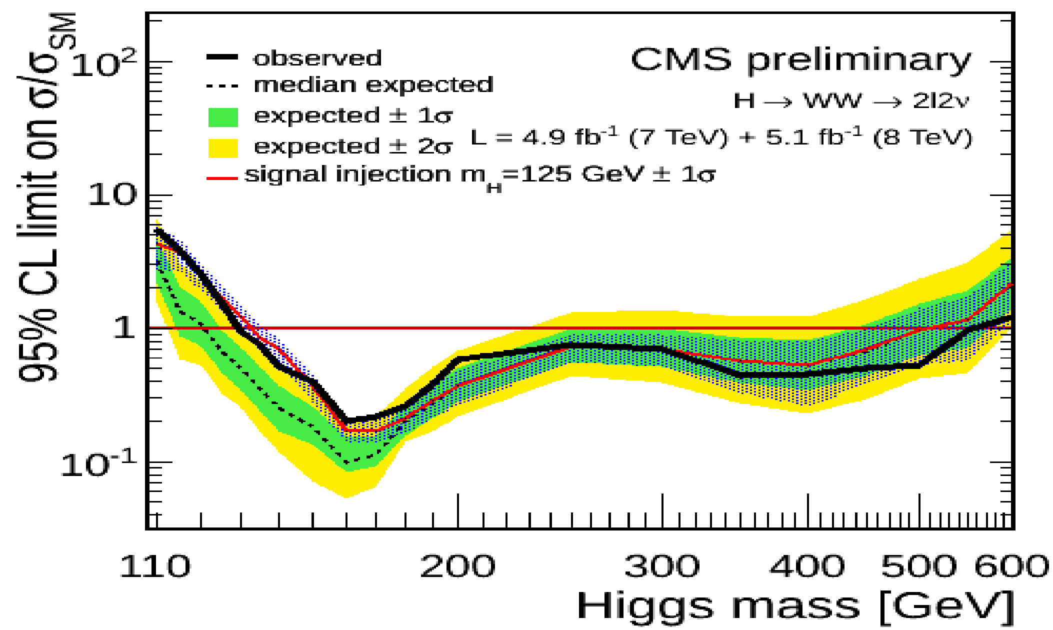
H → WW → 2l 2ν : post-ICHEP results



MultiVariate shape analysis in the eμ final state in the 0 and 1 jet categories: Cut-based variables + ΔR_{ll}, $m_T^{(1,2)}$, $\Delta\phi$(ll, MET), $\Delta\phi$(ll, jet1)

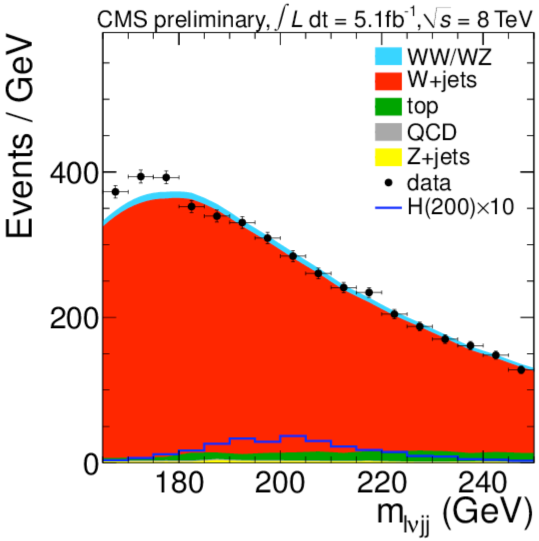
@ mH = 125 GeV
Exp. significance 2.5 σ
Obs. significance 2.2 σ

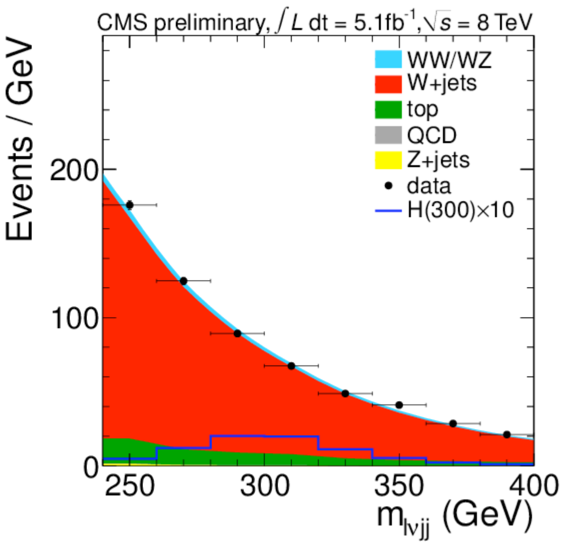
Signal strength: 0.82 ± 0.38



H→WW→lνqq, Analysis

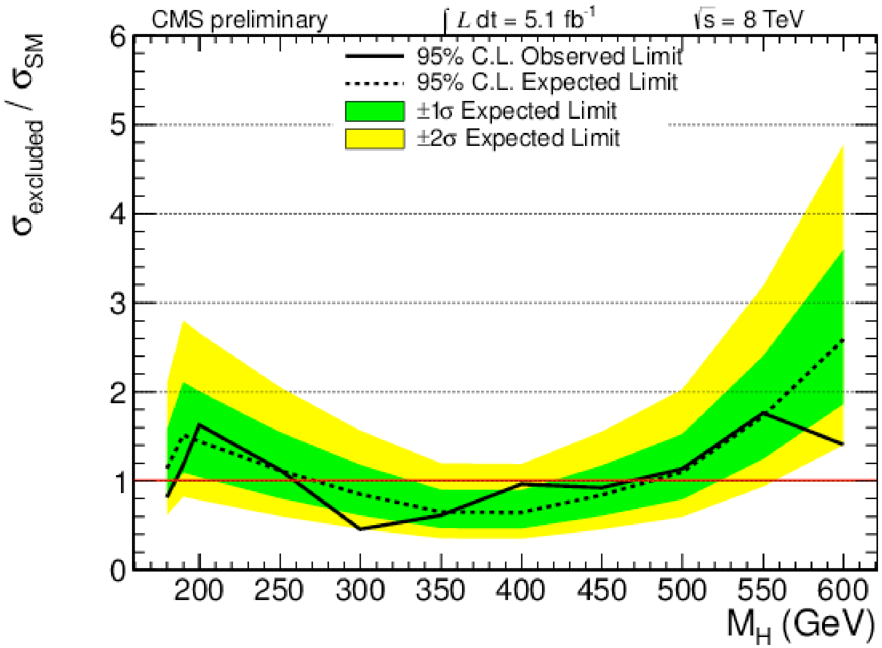
- Most sensitive for Higgs boson mass around 350 GeV
- Selection differences to lνlν channel
  - One electron (muon) with pT > 35 (25) GeV and MET > 25 (30) GeV (leptonic W decay)
  - Two jets with 65 < Mjj < 95 (hadronic W decay)
- Main background: W+jets
  - Suppressed using angular likelihood discriminant for each mass hypothesis
- Signal extraction
  - Kinematic fit allows full reconstruction of Higgs boson mass
  - Search for mass peak against continuum background from W+jets events



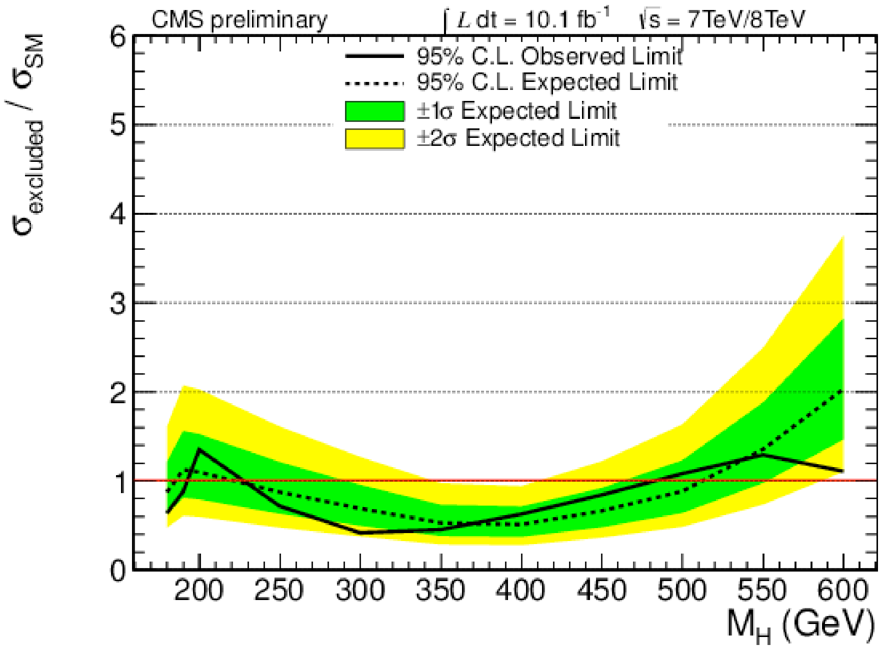


H→WW→lνqq, Results

8 TeV Analysis



Combined 7 + 8 TeV



- The 8 TeV data analysis excludes [260, 390] GeV at 95% CL
- In combination with the 7 TeV data [240, 450] GeV is excluded at 95% CL

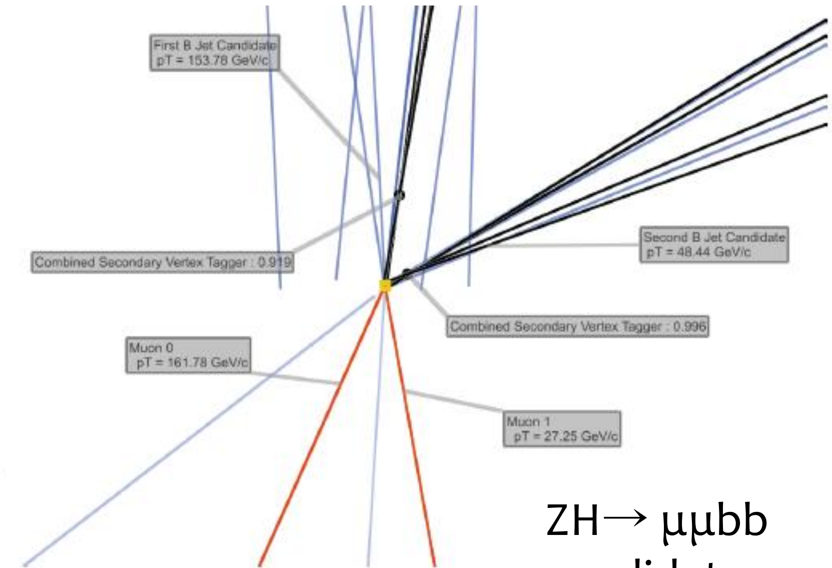
W/Z + H, H → bb

The largest BR for m_H<130 GeV, but $\sigma_{bb}(QCD) \sim 10^7 \times \sigma_H \times BR(H \to bb)$

Search in assiciated production with W or Z, leading to final states with leptons, MET and b-jets.

- General strategy:
  - High boosted vector boson and dijet
  - 2 b-tagged jets
  - Back to back V and H
  - Reconstruct mbb
- Main backgrounds, V+jets and top anti top, estimated from data in control regions.

M_{bb} = 128 GeV, $p_T(bb)$= 181 GeV



ZH→ μμbb candidate

5 channels: Z(ll)H(bb), Z(νν)H(bb), W(lν)H(bb)

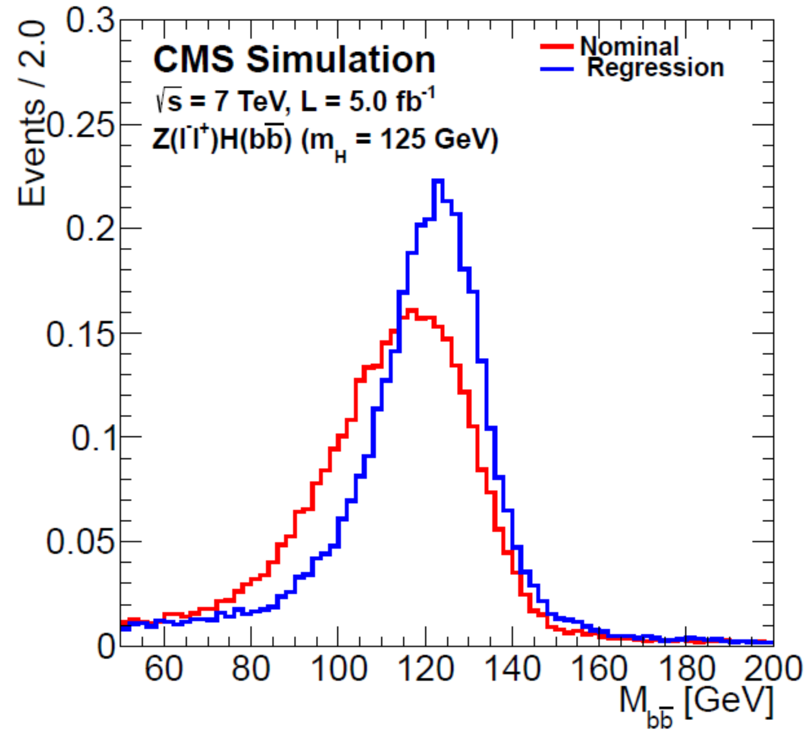
Reducible Backgrounds: QCD, top, W/Z+ light jets
Less reducible: V+bb, ZZ(bb), WZ(bb)

Key piece of the observation puzzle
Tests specific production & decay couplings

W/Z + H, H → bb

Many improvements:

- Jet energy reconstruction using BDT regression (15-20% improvement)

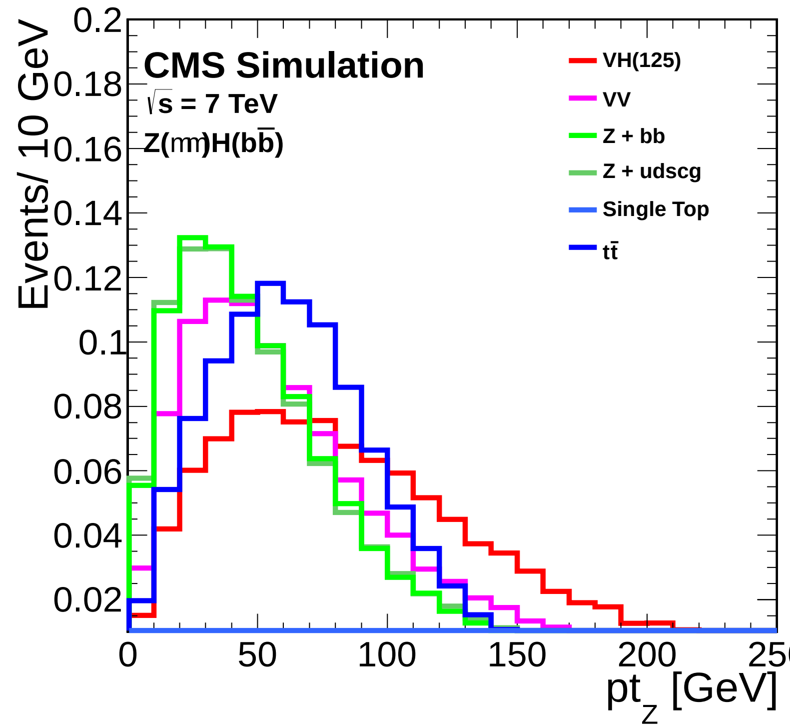


Extensively validated in data using Z(ll) + bb, ttbar and single top events

W/Z + H, H → bb

Many improvements:

- Jet energy reconstruction using BDT regression (15-20% improvement)
- Categorize events in medium and high boost



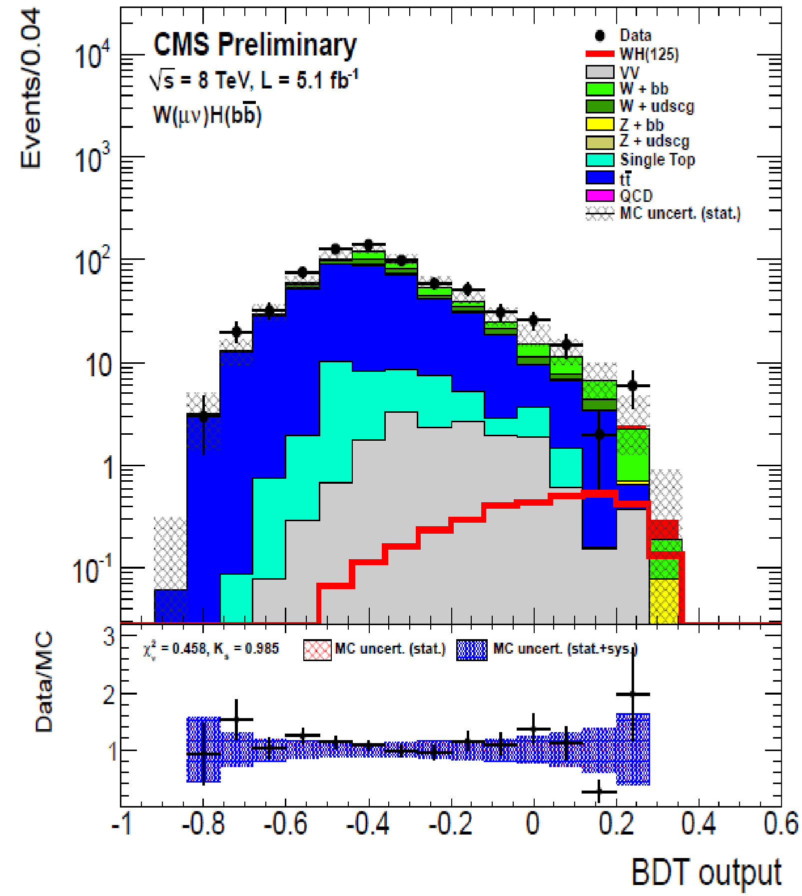
Channel	Medium boost	High boost
ZllH	50<Zpt<100	Zpt>100
WlnH	120< Wpt<170	Wpt>170
ZnnH	120<Zpt<160	Zpt>160

W/Z + H, H → bb

Many improvements:

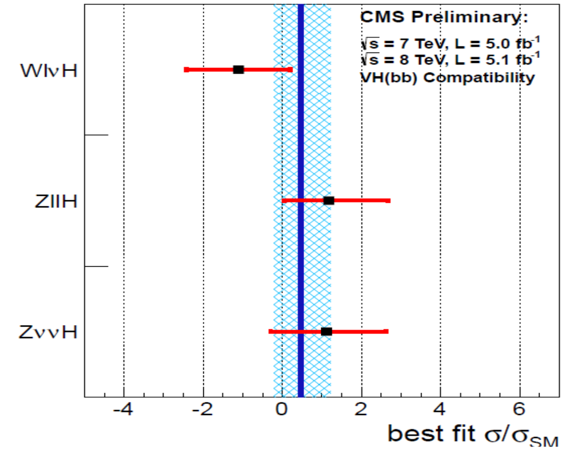
- Jet energy reconstruction using BDT regression (15-20% improvement)
- Categorize events in medium and high boost
- Use full shape of final MVA discriminator

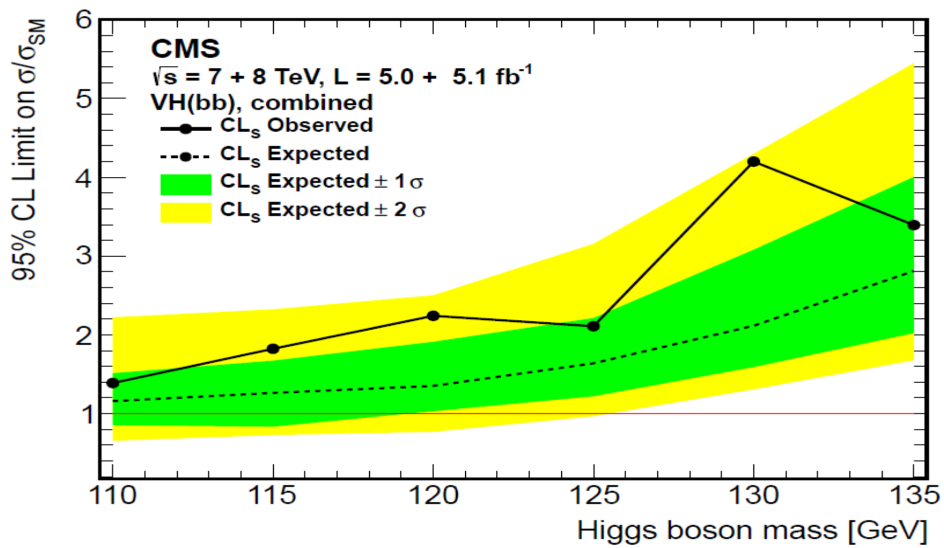
Gain in sensitivity ~50% already on 2011 dataset!

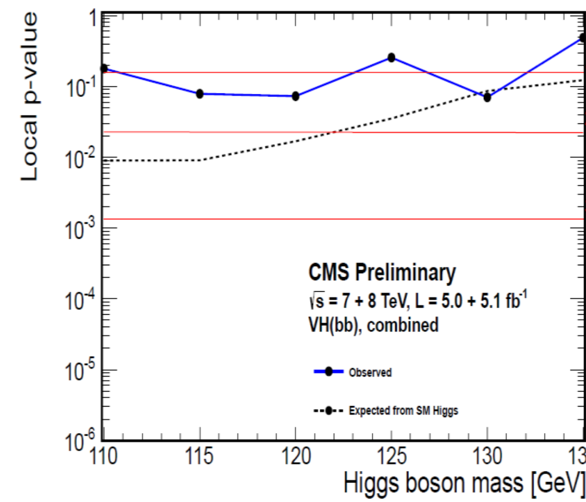


W/Z + H, H → bb: results

- Some excess compared to background predictions (significance ~1σ)
- Compatible both with a 1×σ_{SMH} signal and with just background.



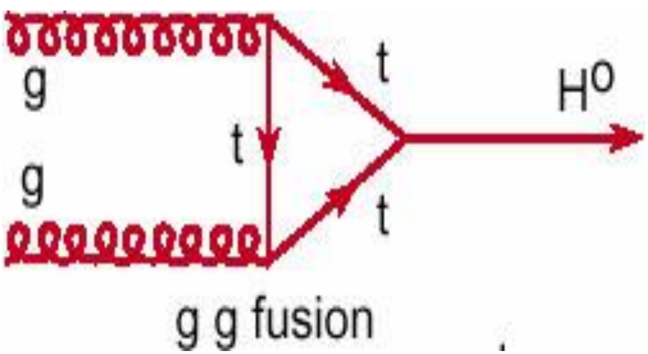


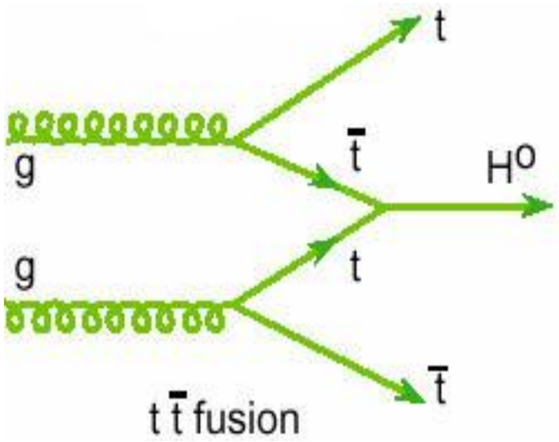


$t\bar{t}H$, $H \to b\bar{b}$

Important to probe the coupling:

same couplings as the dominant part of $\sigma(gg \to H)$ production cross section but at tree level (no loopholes for BSM particles to contribute...)



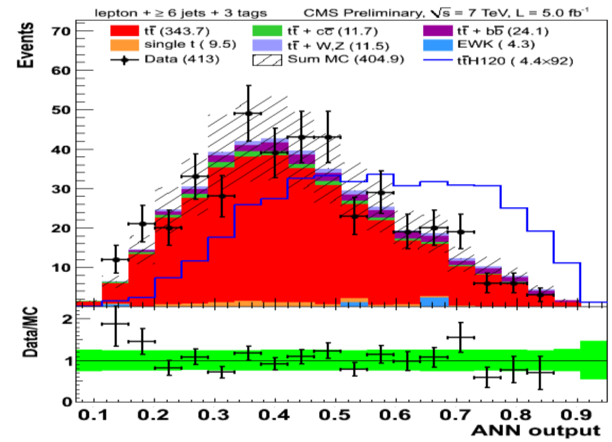


ttH, H → bb

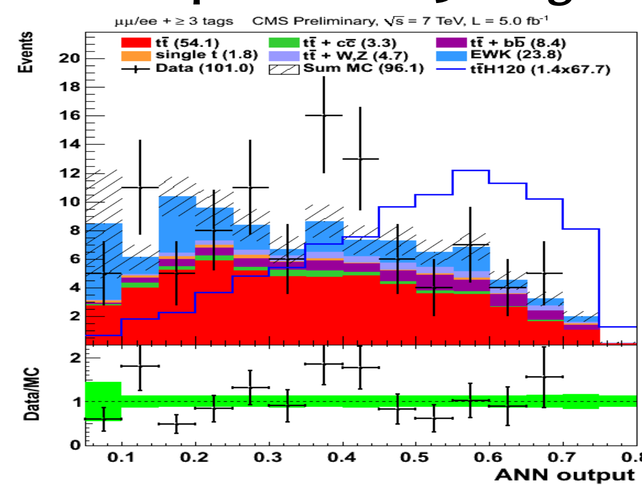
Strategy:

- Separate events by top decay mode (di-lep., lep+jets), and by number of jets and b-tags
- MVA shape analysis in each event category
- Categories with low S/B used to constrain the background in higher S/B ones.

lep+jets with 6 jets, 3 b-tags

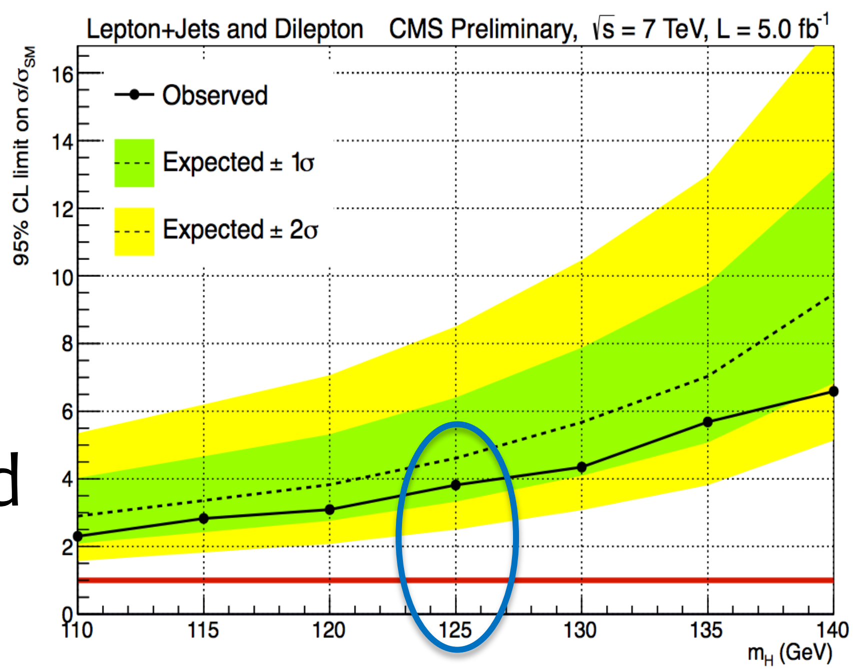


di-leptonic with 3 b-tags



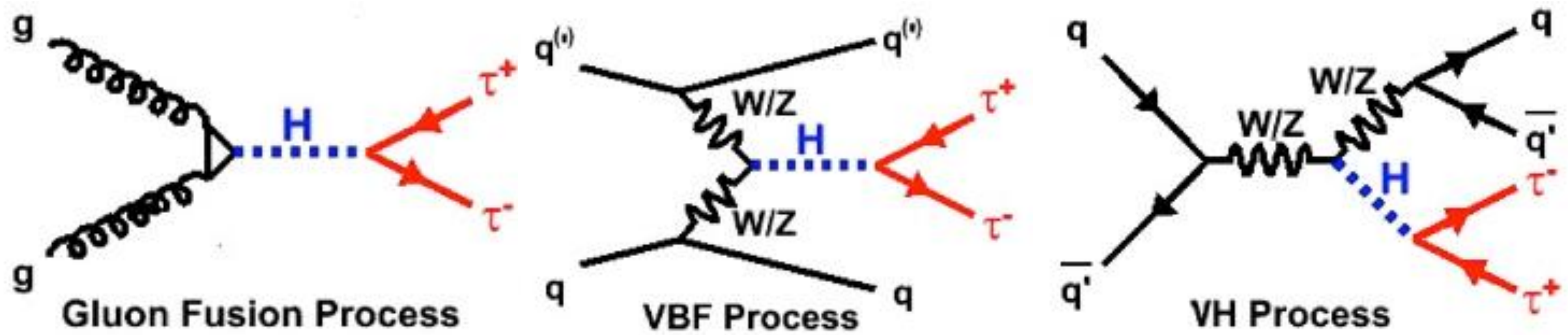
ttH, H → bb: results

- Only 2011 data analyzed at the moment. No evidence of excess, but not yet sensitive to a $1\times\sigma_{SMH}$ signal anyway.
- ttH cross section grows very quickly with $\sqrt{s}$. (x1.5 from 7 to 8 TeV, x5 from 8 to 14 TeV!)
- If scaling as $\sqrt{(\sigma\times L)}$ could have $\Delta\sigma/\sigma_{SMH}$ ~1 already with L ~20 fb^{-1} at 8 TeV.



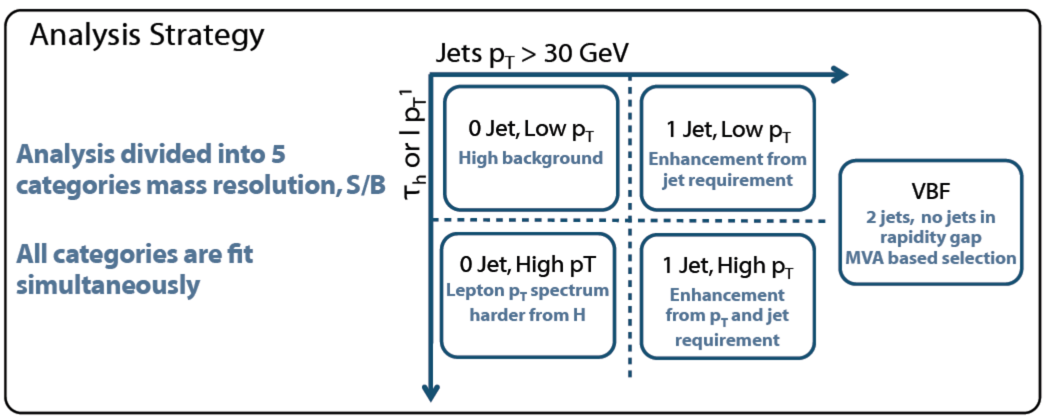
$H \rightarrow \tau\tau$

- Combination of three production mechanisms
- Search is performed in $e\tau_h$, $\mu\tau_h$, $e\mu$, $\mu\mu$ decay modes



Characteristics:

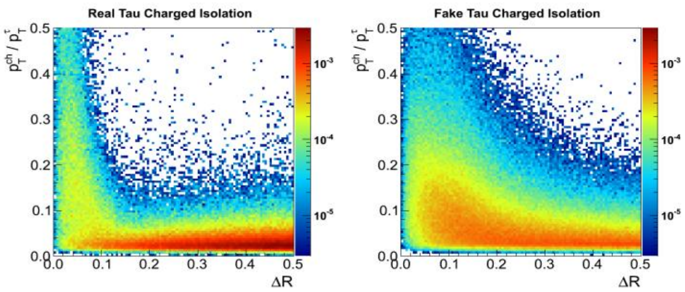
- High σ x BR at low mass
- Sensitive to all production modes
- Probes coupling to leptons
- Enhanced σx BR in MSSM
- Challenging large backgrounds:
  - DY→ττ, W+Jets, QCD



$H \rightarrow \tau\tau$

Analysis re-optimized:

- Improved lepton and τ_{had} identification criteria

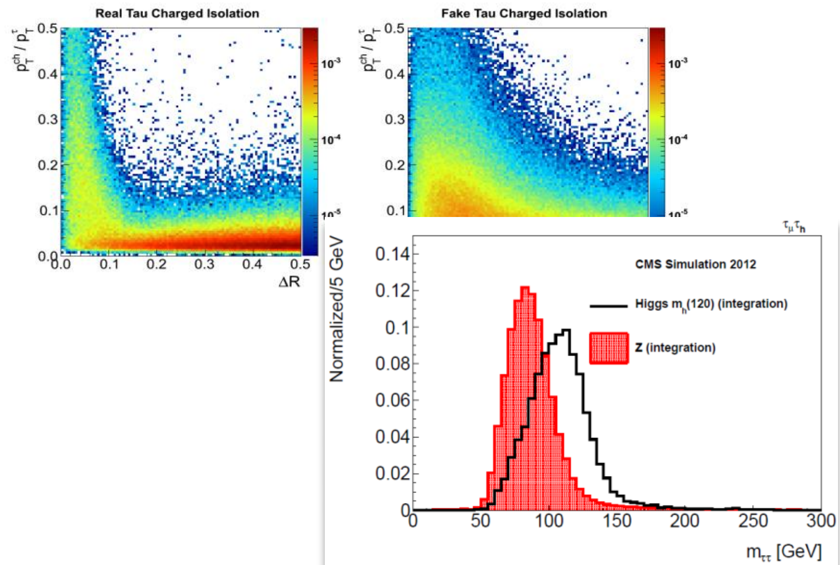


MVA-based tau isolation algorithm

$H \to \tau\tau$

Analysis re-optimized:

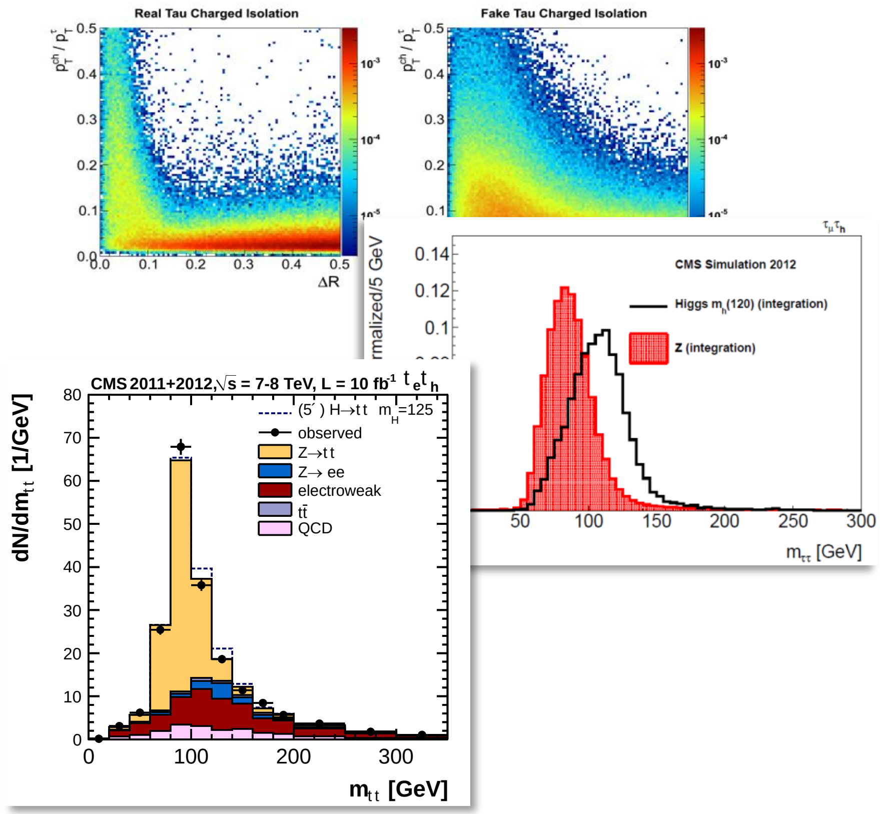
- Improved lepton and τ_{had} identification criteria
- New mass reconstruction (20% better resolution)



$H \to \tau\tau$

Analysis re-optimized:

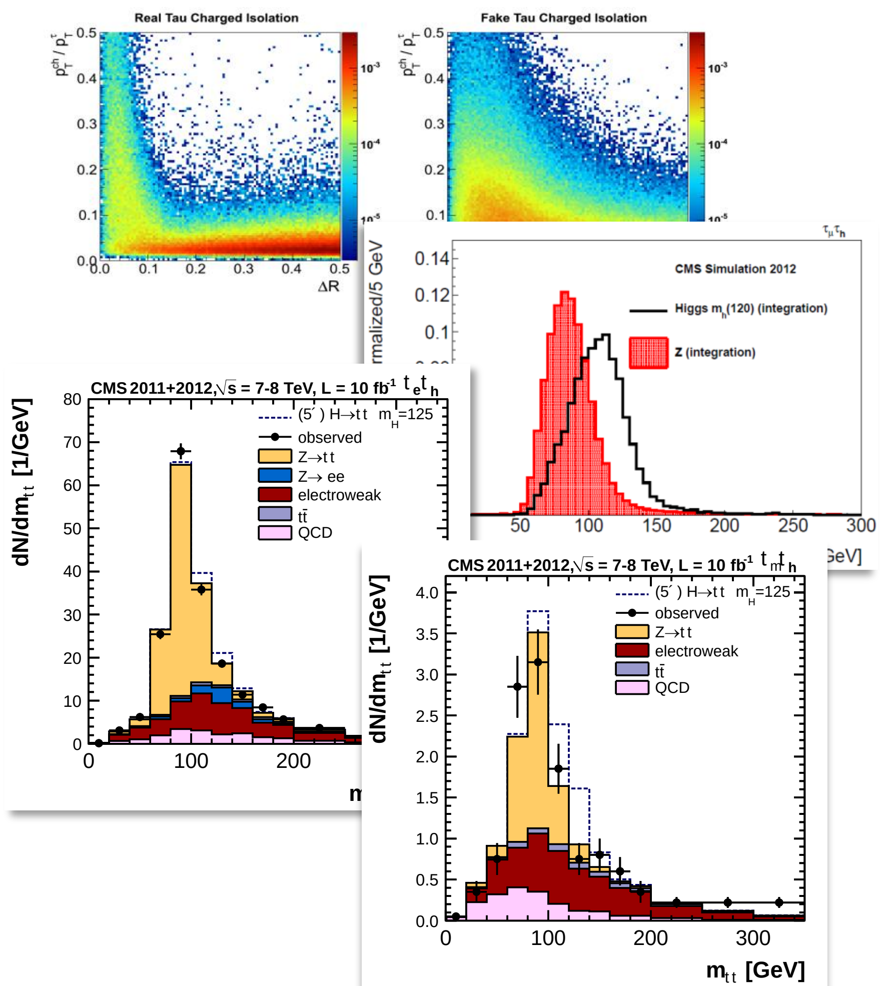
- Improved lepton and τ_{had} identification criteria
- New mass reconstruction (20% better resolution)
- New event categorization: lower jet p_T thresholds, rely also on p_T of the tau.



$H \to \tau\tau$

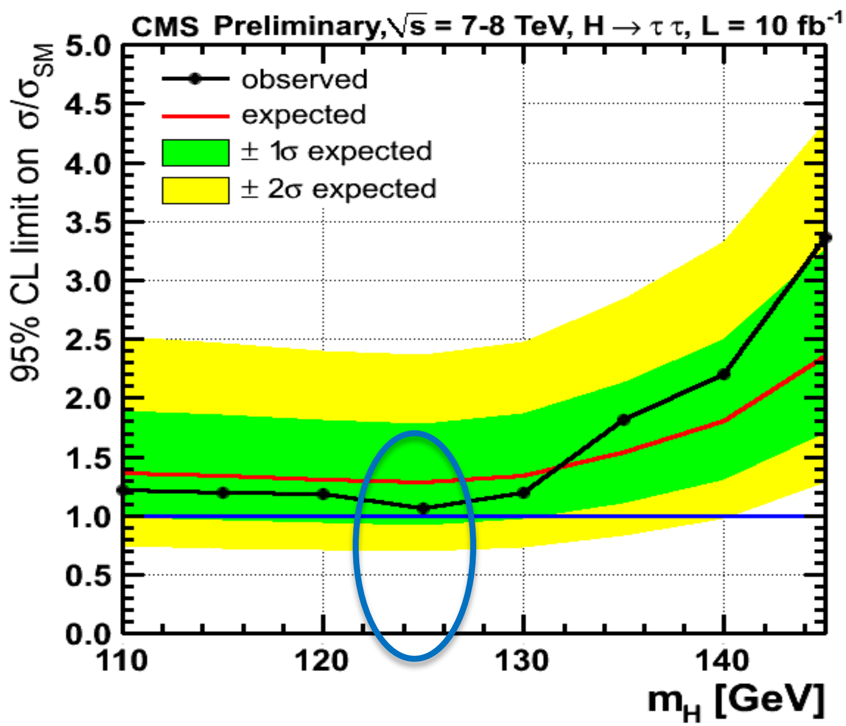
Analysis re-optimized:

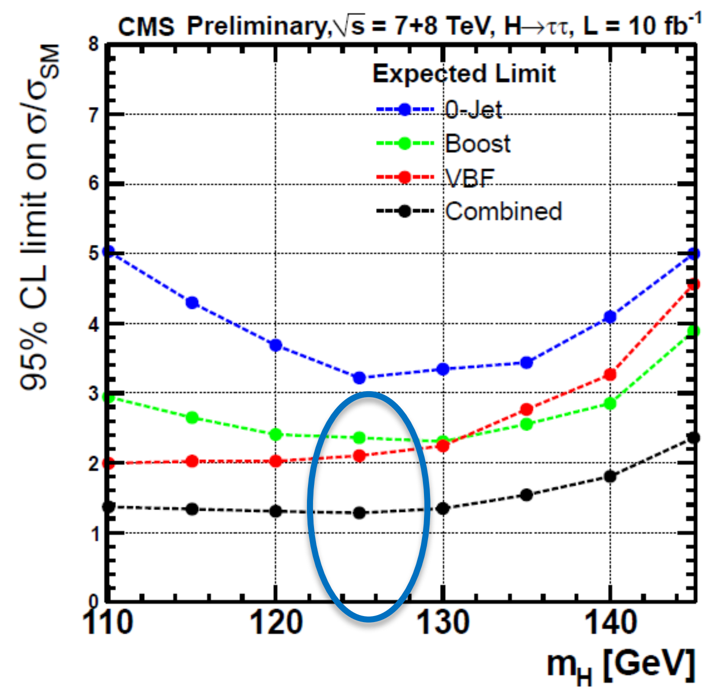
- Improved lepton and τ_{had} identification criteria
- New mass reconstruction (20% better resolution)
- New event categorization: lower jet p_T thresholds, rely also on p_T of the tau.
- MVA selection for VBF tag



$H \to \tau\tau$: results

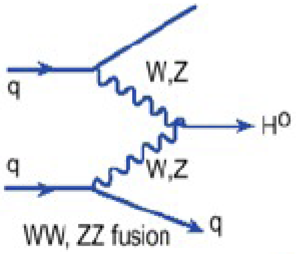
- Sensitivity of new analysis very close to $1\times\sigma_{SMH}$
- No excess seen. Just bad luck or non-SM Higgs?

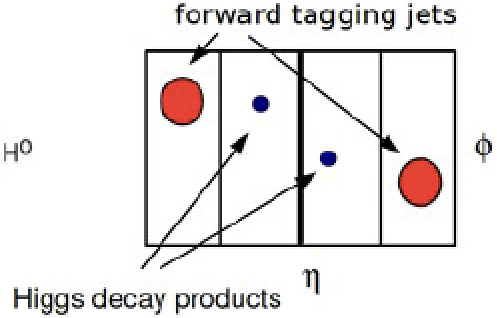




Vector boson fusion

- VBF signature
  - $\gamma\gamma$, $\tau\tau$, WW channels deploy VBF signature
  - ZZ(4l) has very low signal yield
  - bb is challenging and work in progress





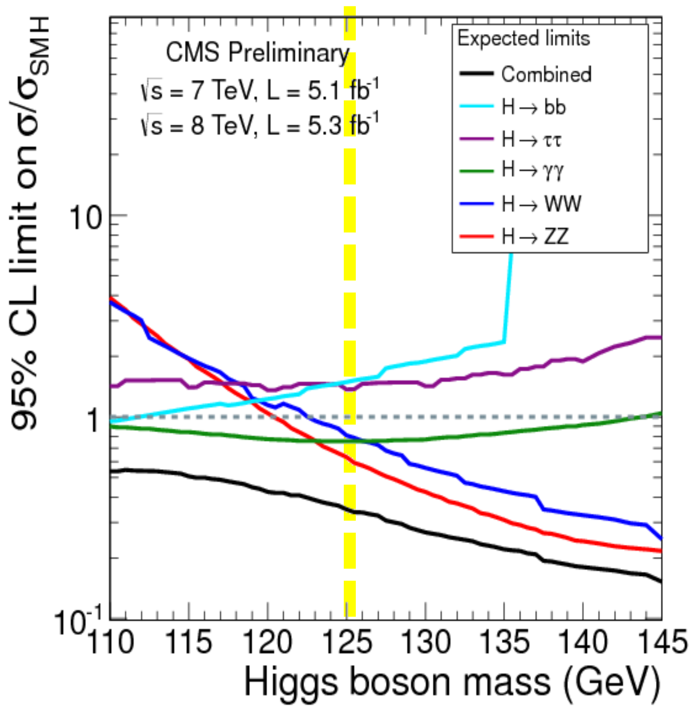
- increases sensitivity and allows coupling measurement
- three analysis deploy quite different strategies

Channel	Technique	Variable	Jet kinematic	Pile-up	gluon fusion cont. at 125 GeV
$H \rightarrow \gamma\gamma$	cuts, 2 categories	m(jj), $\Delta\eta$(jj), $\Delta\phi$(H,jj), Zep.	pT > 20 (30) GeV, $\lvert\eta\rvert$ < 4.7	cut jet ID	53%, 23%
$H \rightarrow \tau\tau$	MVA	m(jj), $\Delta\eta$(jj), $\Delta\eta$(H,j), $\Delta\phi$(jj), pT($\tau\tau$), pT(jj)	pT > 30 GeV, $\lvert\eta\rvert$ < 5.0	MVA jet ID	20%
$H \rightarrow$ WW	cuts	m(jj), $\Delta\eta$(jj)	pT > 30 GeV, $\lvert\eta\rvert$ < 4.7	MVA jet ID	15%

- diversity result of independent development and optimization, but needs investigation!

Combined Results

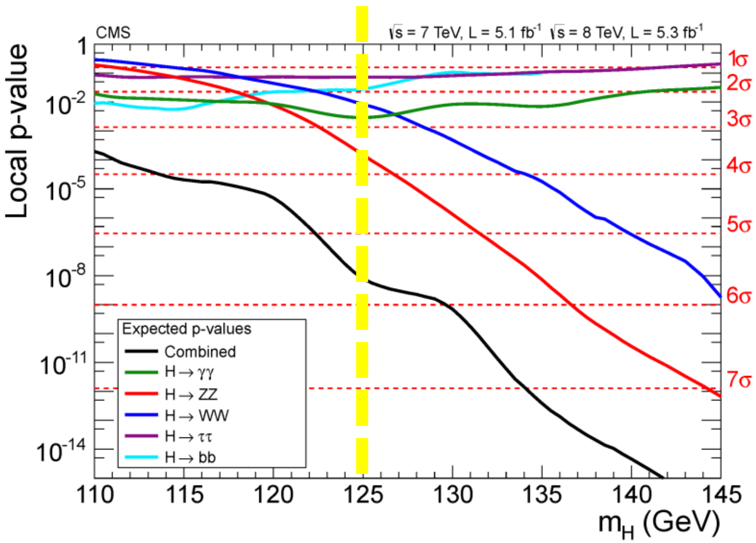
Combined results



Decay	Prod. Topology	Luminosity
$H\rightarrow bb$	WH, ZH	5+5 fb^{-1} at 7+8 TeV
$H\rightarrow bb$	ttH	5 at fb^{-1} at 7 TeV
$H\rightarrow \tau\tau$	Inclusive + VBF	5+5 fb^{-1} at 7+8 TeV
$H\rightarrow \tau\tau$	WH, ZH	5 at fb^{-1} at 7 TeV
$H\rightarrow \gamma\gamma$	Inclusive + VBF	5+5 fb^{-1} at 7+8 TeV
$H\rightarrow WW$	0/1 jet + VBF	5+5 fb^{-1} at 7+8 TeV
$H\rightarrow WW$	WH, ZH	5 at fb^{-1} at 7 TeV
$H\rightarrow ZZ$	Inclusive	5+5 fb^{-1} at 7+8 TeV

- Most analyses using 5+5 fb^{-1}, many improved w.r.t. 2011
- Biggest combination done so far at CMS: 95 individual final states contributing at 125 GeV mass hypothesis!

Combined results



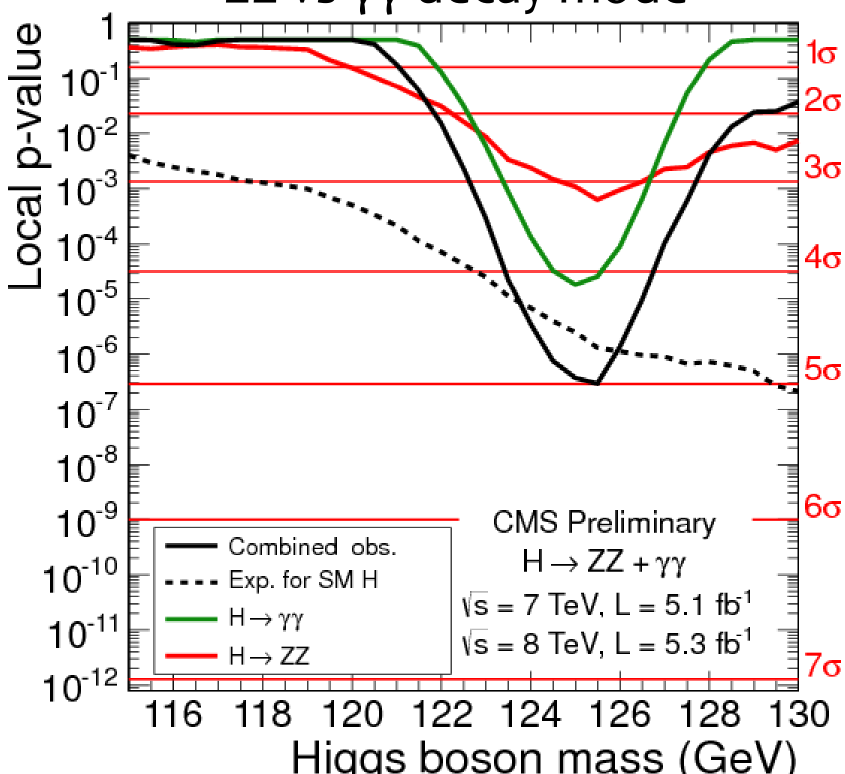
Decay	Prod. Topology	Luminosity
$H \to bb$	WH, ZH	5+5 fb^{-1} at 7+8 TeV
$H \to bb$	ttH	5 at fb^{-1} at 7 TeV
$H \to \tau\tau$	Inclusive + VBF	5+5 fb^{-1} at 7+8 TeV
$H \to \tau\tau$	WH, ZH	5 at fb^{-1} at 7 TeV
$H \to \gamma\gamma$	Inclusive + VBF	5+5 fb^{-1} at 7+8 TeV
$H \to WW$	0/1 jet + VBF	5+5 fb^{-1} at 7+8 TeV
$H \to WW$	WH, ZH	5 at fb^{-1} at 7 TeV
$H \to ZZ$	Inclusive	5+5 fb^{-1} at 7+8 TeV

- Most analyses using 5+5 fb^{-1}, many improved w.r.t. 2011
- Biggest combination done so far at CMS: 95 individual final states contributing at 125 GeV mass hypothesis!

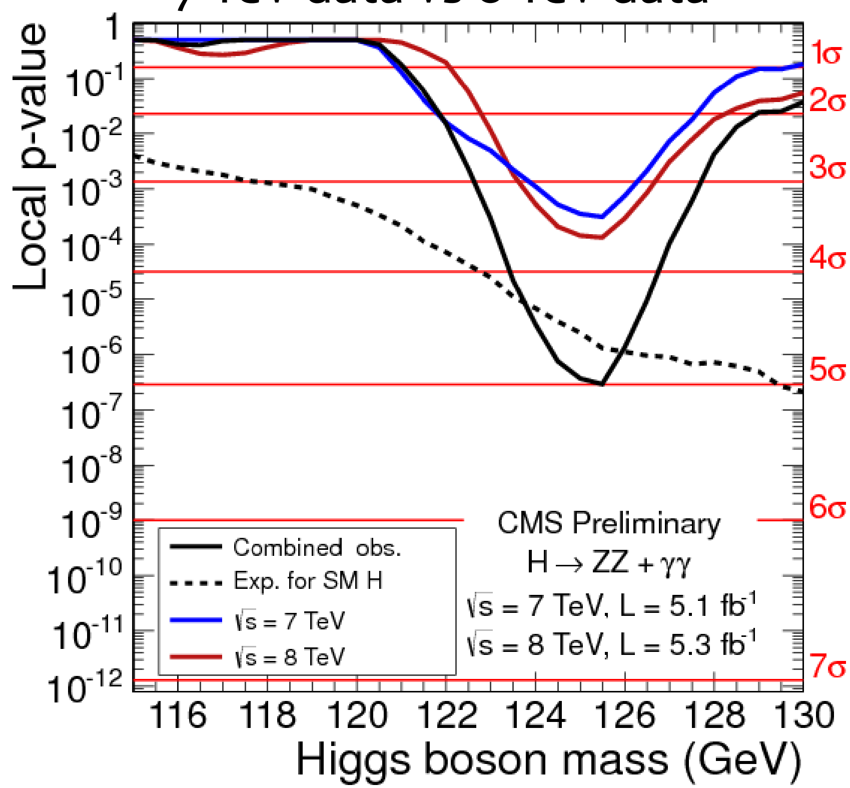
Combined results: ZZ+ γγ

In high mass resolution channels, observe an excess with local significance of 5.0σ (expected from SM H: 4.7σ)

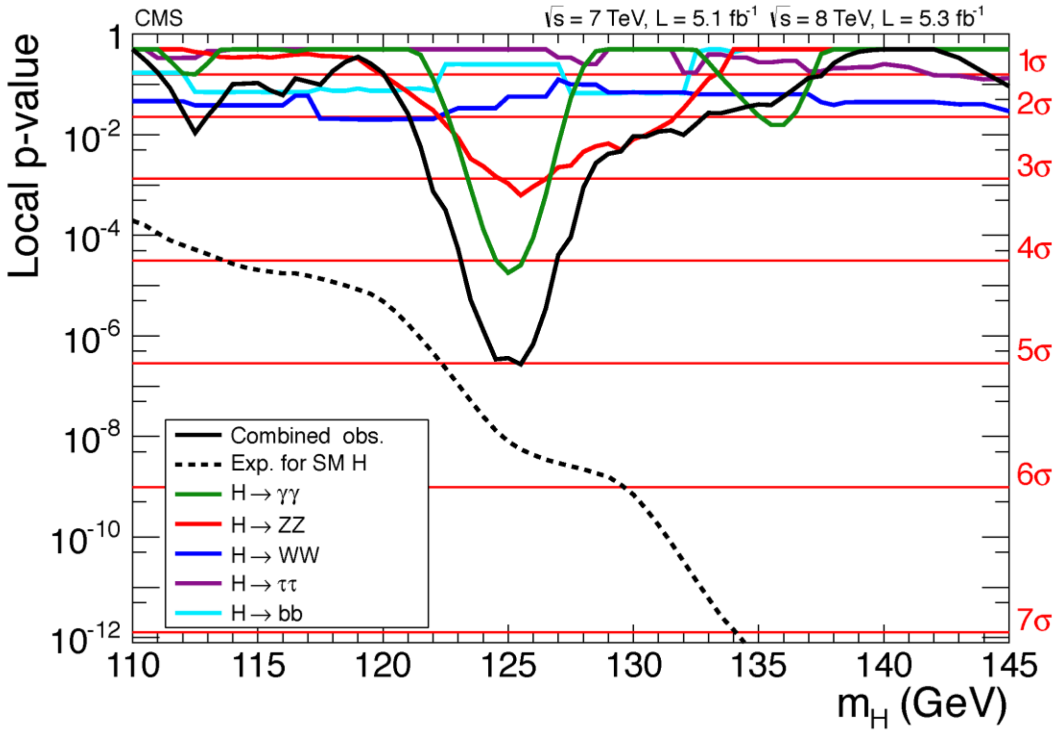
ZZ vs γγ decay mode



7 TeV data vs 8 TeV data



Combined results: all channels



Decay mode/combination	Expected (σ)	Observed (σ)
$\gamma\gamma$	2.8	4.1
ZZ	3.6	3.1
$\tau\tau$ + bb	2.4	0.4
$\gamma\gamma$ + ZZ	4.7	5.0
$\gamma\gamma$ + ZZ + WW	5.2	5.1
$\gamma\gamma$ + ZZ + WW + $\tau\tau$ + bb	5.8	5.0

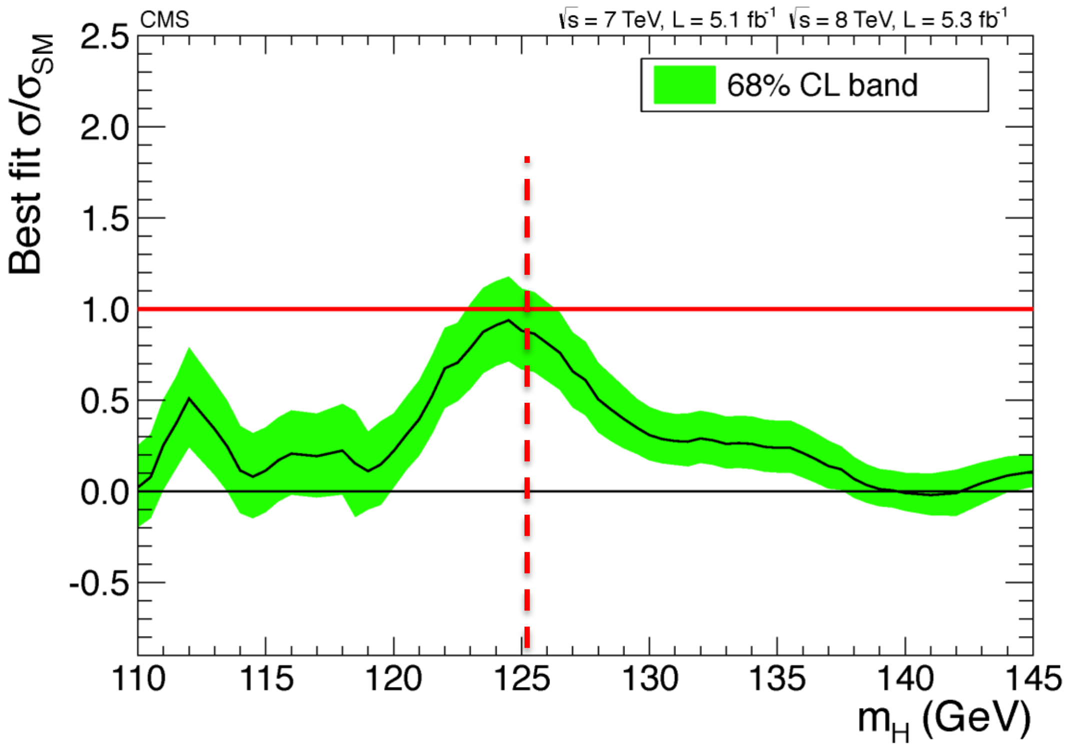
Local significance of excess: **4.9 σ**

Expected for SM Higgs signal: **5.8 σ**

Global significance > 4σ

We interpret this excess as the observation of a new boson with mass around 125 GeV.

Combined results: all channels

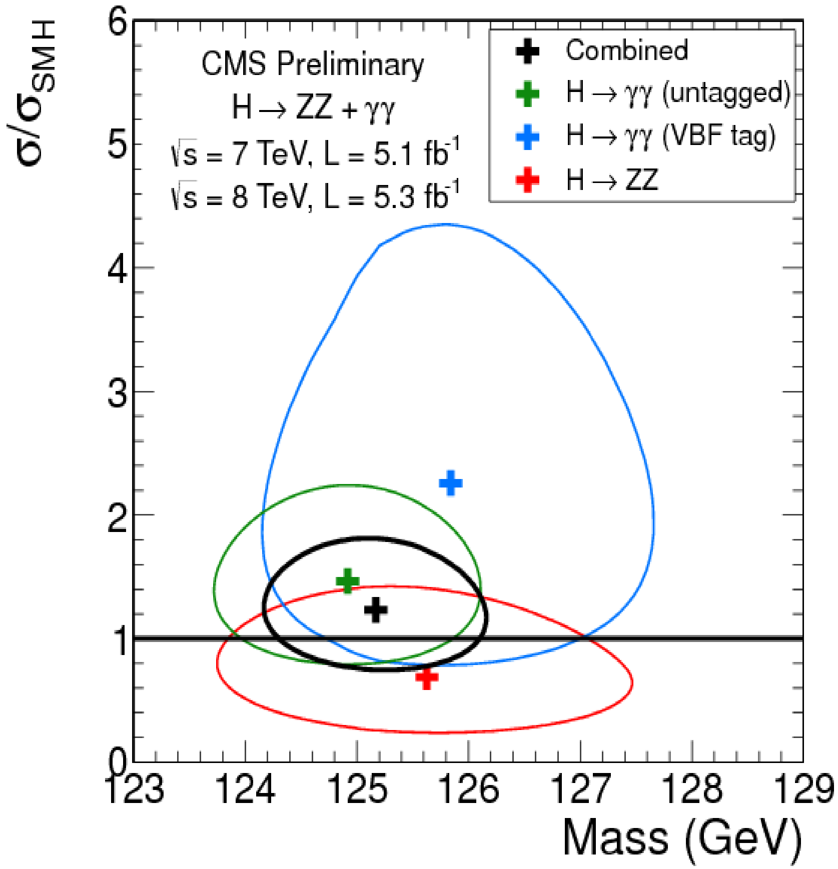


Best fit signal strength at mass 125 GeV:

$$(0.87 \pm 0.23) \times \sigma_{SMH}$$

Compatible with the expectations from a SM Higgs boson signal!

Mass of the observed particle



- Likelihood scan for mass and signal strength in three high mass resolution channels:
  - ZZ 4l
  - γγ untagged
  - γγ with di-jet tag
- Results are compatible within the uncertainties

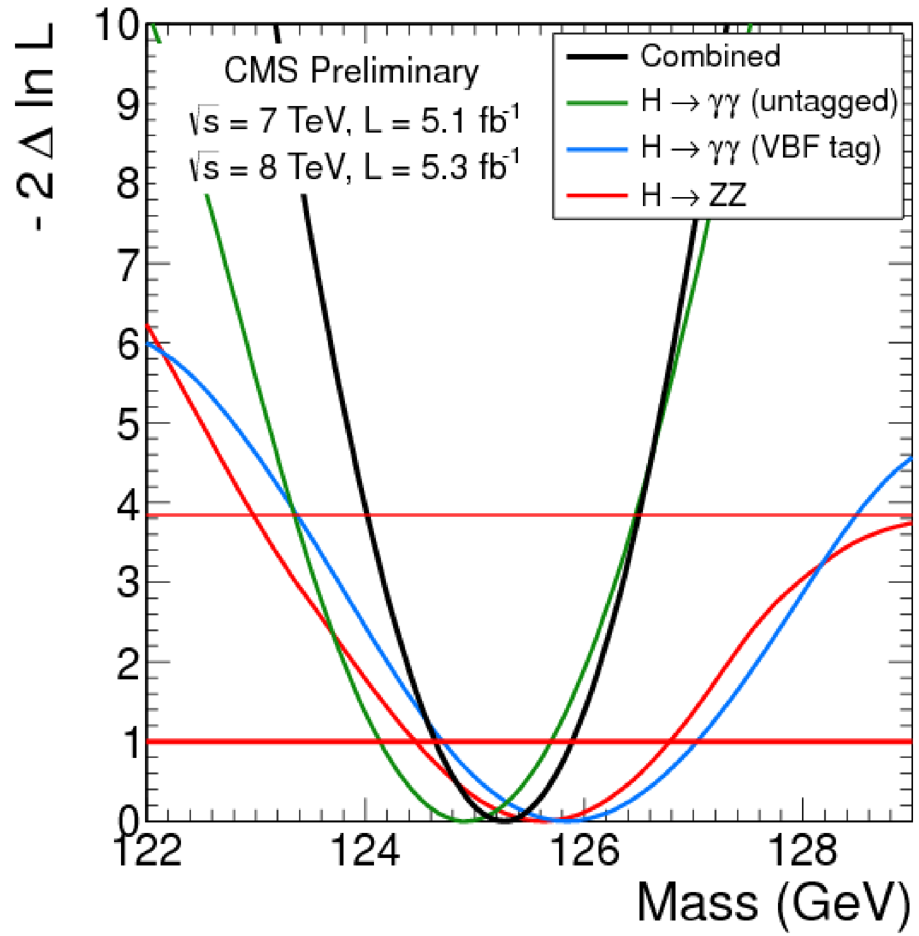
Mass measurement

- Perform a fit of the mass with freely floating signal strength for the three final states, to minimize model dependence.

M = 125.3 ± 0.6

- Ultimate precision:

$\sigma_m < 100$ MeV

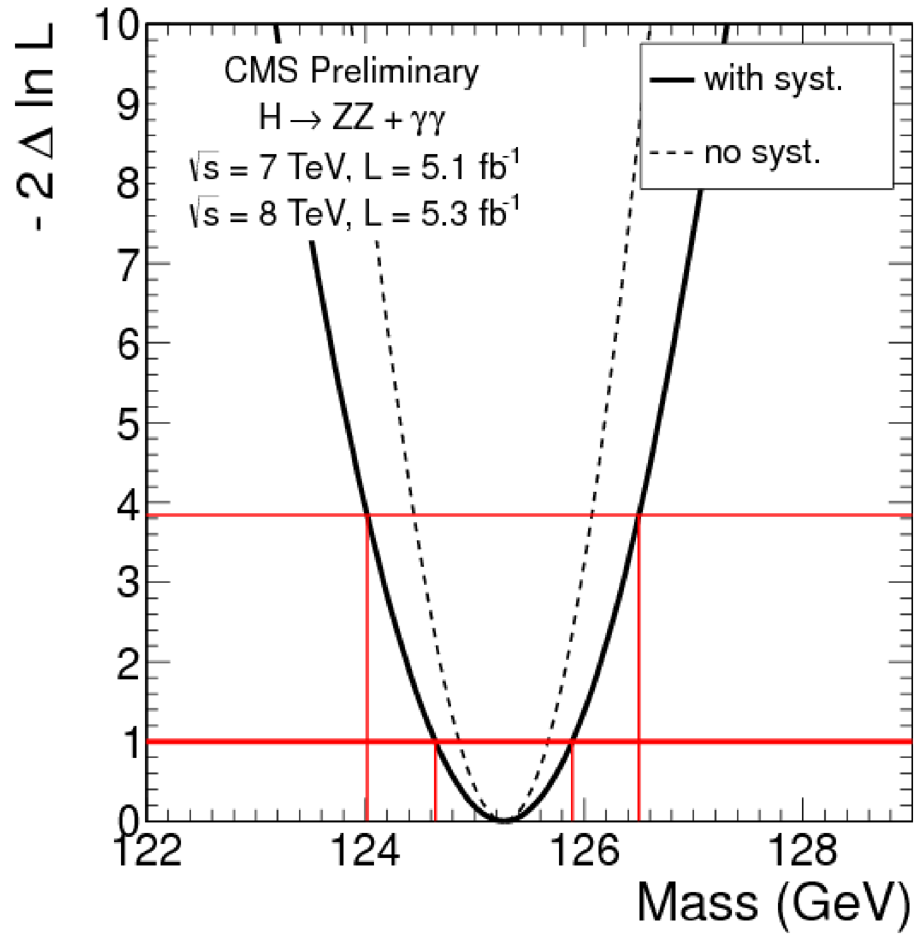


Mass measurement

- Systematical uncertainty on the mass driven by energy scale uncertainty in γγ: now conservative estimate ~0.5%, will improve in the future.

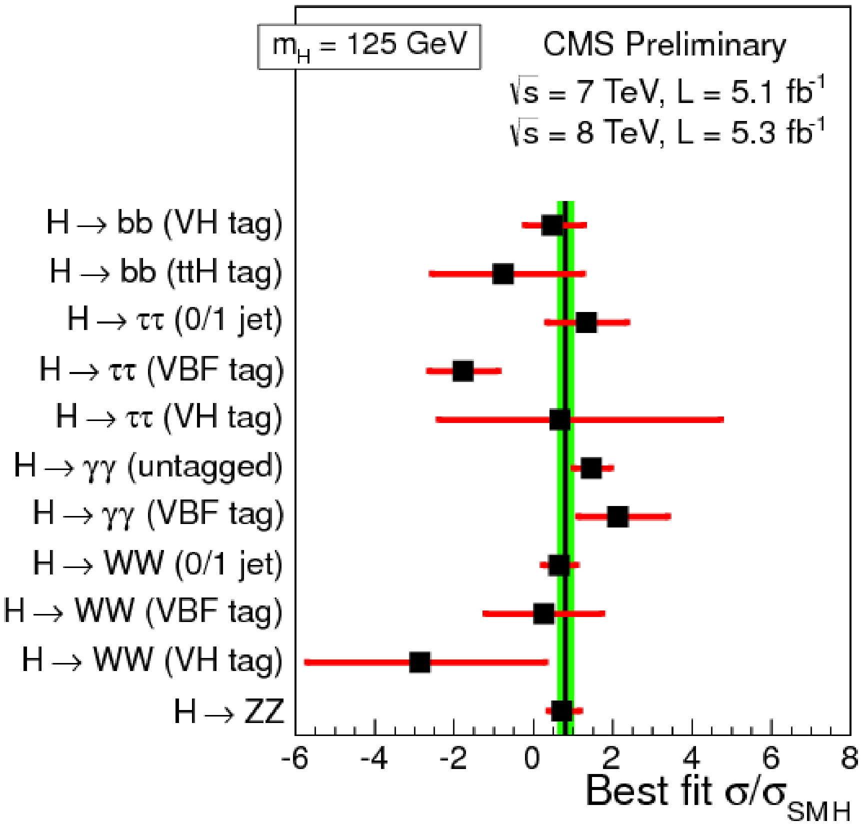
M = 125.3 ± 0.4 (stat.) ± 0.5 (syst.)

= 125.3 ± 0.6 GeV



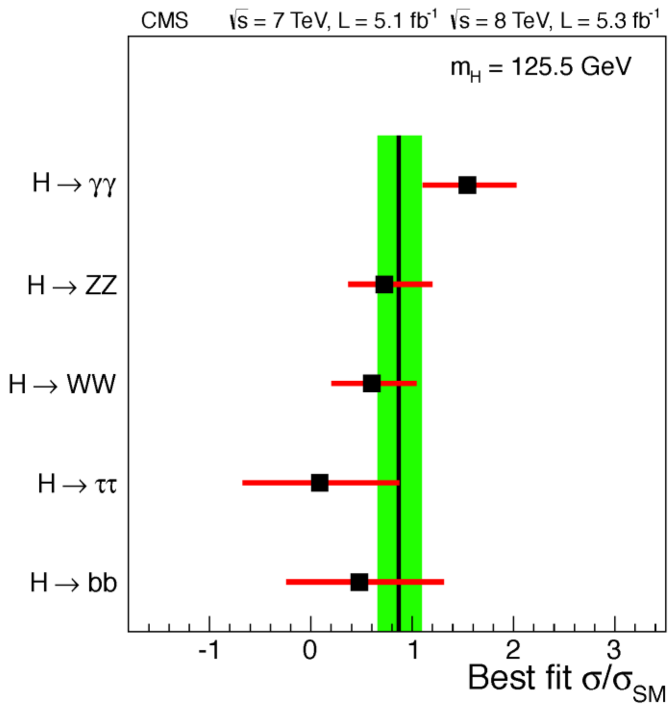
Is it a SM Higgs boson?

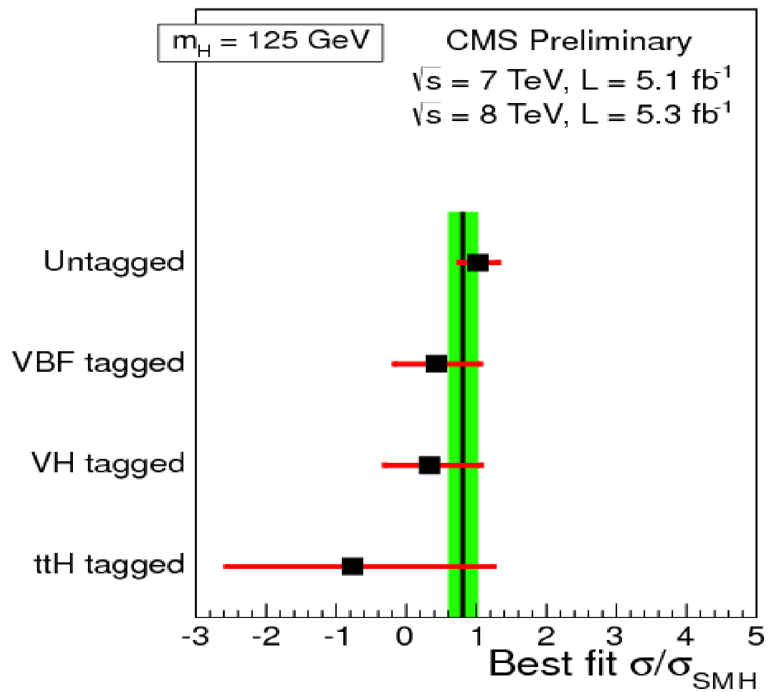
- Observed signal stength in the analzyed decay modes and production topologies compatible with a SM Higgs
- However, with the present data sample only few modes have sensitivity to a signal of SM strength.



Is it a SM Higgs boson?

- Slightly better sensitivity when combining channels by decay mode or production topology.
- Compatible with SM Higgs within uncertainties





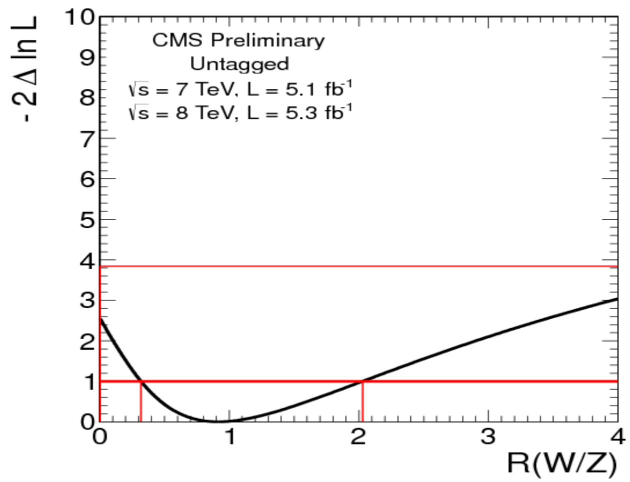
Is it a SM Higgs boson?

- **Test of custodial symmetry: compare the signal strength observed in WW and ZZ modes.**
- Fit the the ZZ and WW (0/1 jet) data assuming:

$$\sigma \times BR_{H\to ZZ} = \boldsymbol{\mu_{ZZ}} \times [\,\sigma \times BR_{H\to ZZ}\,]_{\text{SM Higgs}}$$
$$\sigma \times BR_{H\to WW} = \mathbf{R_{W/Z}} \times \boldsymbol{\mu_{ZZ}} \times [\,\sigma \times BR_{H\to WW}\,]_{\text{SM Higgs}}$$

- Result compatible with SM within the large uncertainties

$$R_{W/Z} = 0.9^{+1.1}_{-0.6}$$



Is it a SM Higgs boson?

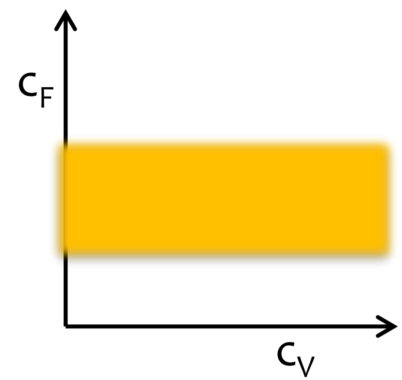
- Test compatibility w.r.t SM predictions by introducing two parameters (**c_V, c_F**) modifying the expected signal yields in each mode through simple LO expressions

Production	Decay	LO SM	
VH	$H \to bb$	$\sim \frac{C_V^2 \times C_F^2}{C_F^2}$	$\sim C_V^2$
ttH	$H \to bb$	$\sim \frac{C_F^2 \times C_F^2}{C_F^2}$	$\sim C_F^2$
VBF	$H \to \tau\tau$	$\sim \frac{C_V^2 \times C_F^2}{C_F^2}$	$\sim C_V^2$
ggH	$H \to \tau\tau$	$\sim \frac{C_F^2 \times C_F^2}{C_F^2}$	$\sim C_F^2$
ggH	$H \to ZZ$	$\sim \frac{C_F^2 \times C_V^2}{C_F^2}$	$\sim C_V^2$
ggH	$H \to WW$	$\sim \frac{C_F^2 \times C_V^2}{C_F^2}$	$\sim C_V^2$
VBF	$H \to WW$	$\sim \frac{C_V^2 \times C_V^2}{C_F^2}$	$\sim C_V^4 / C_F^2$
ggH	$H \to \gamma\gamma$	$\sim \frac{C_F^2 \times (8.6 C_V - 1.8 C_F)^2}{C_F^2}$	$\sim C_V^2$
VBF	$H \to \gamma\gamma$	$\sim \frac{C_V^2 \times (8.6 C_V - 1.8 C_F)^2}{C_F^2}$	$\sim C_V^4 / C_F^2$

Is it a SM Higgs boson?

- Test compatibility w.r.t SM predictions by introducing two parameters (**c_V, c_F**) modifying the expected signal yields in each mode through simple LO expressions, modifying only coupling strength, not the tensor structure.

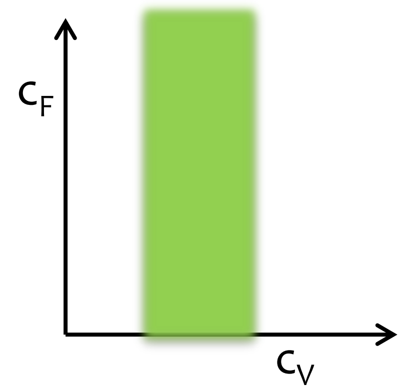
Production	Decay	LO SM	
VH	$H \to bb$	$\sim \frac{C_V^2 \times C_F^2}{C_F^2}$	$\sim C_V^2$
ttH	$H \to bb$	$\sim \frac{C_F^2 \times C_F^2}{C_F^2}$	$\sim C_F^2$
VBF	$H \to \tau\tau$	$\sim \frac{C_V^2 \times C_F^2}{C_F^2}$	$\sim C_V^2$
ggH	$H \to \tau\tau$	$\sim \frac{C_F^2 \times C_F^2}{C_F^2}$	$\sim C_F^2$
ggH	$H \to ZZ$	$\sim \frac{C_F^2 \times C_V^2}{C_F^2}$	$\sim C_V^2$
ggH	$H \to WW$	$\sim \frac{C_F^2 \times C_V^2}{C_F^2}$	$\sim C_V^2$
VBF	$H \to WW$	$\sim \frac{C_V^2 \times C_V^2}{C_F^2}$	$\sim C_V^4/C_F^2$
ggH	$H \to \gamma\gamma$	$\sim \frac{C_F^2 \times (8.6C_V - 1.8C_F)^2}{C_F^2}$	$\sim C_V^2$
VBF	$H \to \gamma\gamma$	$\sim \frac{C_V^2 \times (8.6C_V - 1.8C_F)^2}{C_F^2}$	$\sim C_V^4/C_F^2$



Is it a SM Higgs boson?

- Test compatibility w.r.t SM predictions by introducing two parameters **(c_V, c_F)** modifying the expected signal yields in each mode through simple LO expressions

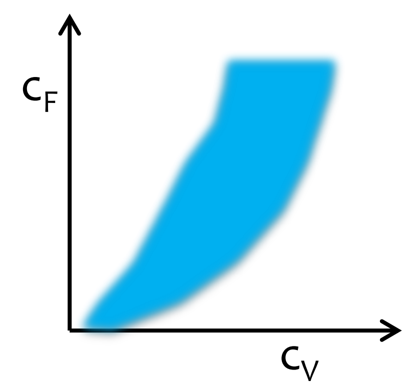
Production	Decay	LO SM	
VH	$H \to bb$	$\sim \frac{C_V^2 \times C_F^2}{C_F^2}$	$\sim C_V^2$
ttH	$H \to bb$	$\sim \frac{C_F^2 \times C_F^2}{C_F^2}$	$\sim C_F^2$
VBF	$H \to \tau\tau$	$\sim \frac{C_V^2 \times C_F^2}{C_F^2}$	$\sim C_V^2$
ggH	$H \to \tau\tau$	$\sim \frac{C_F^2 \times C_F^2}{C_F^2}$	$\sim C_F^2$
ggH	$H \to ZZ$	$\sim \frac{C_F^2 \times C_V^2}{C_F^2}$	$\sim C_V^2$
ggH	$H \to WW$	$\sim \frac{C_F^2 \times C_V^2}{C_F^2}$	$\sim C_V^2$
VBF	$H \to WW$	$\sim \frac{C_V^2 \times C_V^2}{C_F^2}$	$\sim C_V^4 / C_F^2$
ggH	$H \to \gamma\gamma$	$\sim \frac{C_F^2 \times (8.6C_V - 1.8C_F)^2}{C_F^2}$	$\sim C_V^2$
VBF	$H \to \gamma\gamma$	$\sim \frac{C_V^2 \times (8.6C_V - 1.8C_F)^2}{C_F^2}$	$\sim C_V^4 / C_F^2$



Is it a SM Higgs boson?

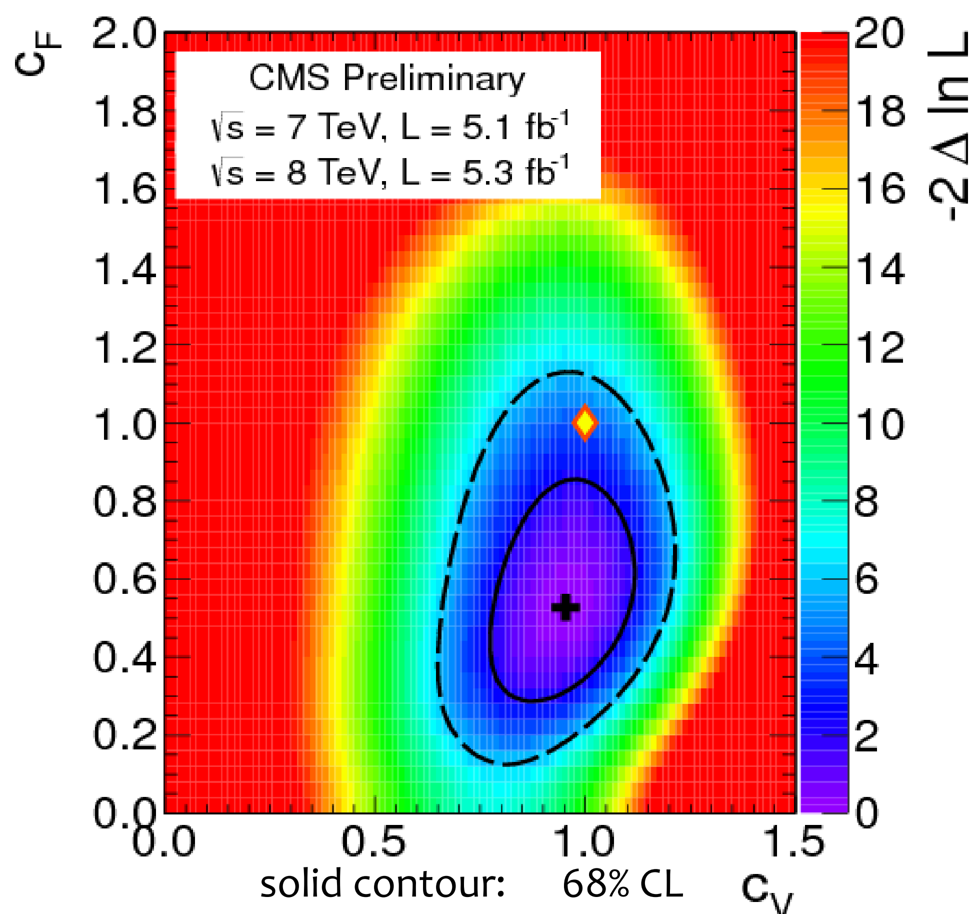
- Test compatibility w.r.t SM predictions by introducing two parameters **(c_V, c_F)** modifying the expected signal yields in each mode through

Production	Decay	LO SM	
VH	$H \to bb$	$\sim \frac{C_V^2 \times C_F^2}{C_F^2}$	$\sim C_V^2$
ttH	$H \to bb$	$\sim \frac{C_F^2 \times C_F^2}{C_F^2}$	$\sim C_F^2$
VBF	$H \to \tau\tau$	$\sim \frac{C_V^2 \times C_F^2}{C_F^2}$	$\sim C_V^2$
ggH	$H \to \tau\tau$	$\sim \frac{C_F^2 \times C_F^2}{C_F^2}$	$\sim C_F^2$
ggH	$H \to ZZ$	$\sim \frac{C_F^2 \times C_V^2}{C_F^2}$	$\sim C_V^2$
ggH	$H \to WW$	$\sim \frac{C_F^2 \times C_V^2}{C_F^2}$	$\sim C_V^2$
VBF	$H \to WW$	$\sim \frac{C_V^2 \times C_V^2}{C_F^2}$	$\sim C_V^4 / C_F^2$
ggH	$H \to \gamma\gamma$	$\sim \frac{C_F^2 \times (8.6 C_V - 1.8 C_F)^2}{C_F^2}$	$\sim C_V^2$
VBF	$H \to \gamma\gamma$	$\sim \frac{C_V^2 \times (8.6 C_V - 1.8 C_F)^2}{C_F^2}$	$\sim C_V^4 / C_F^2$



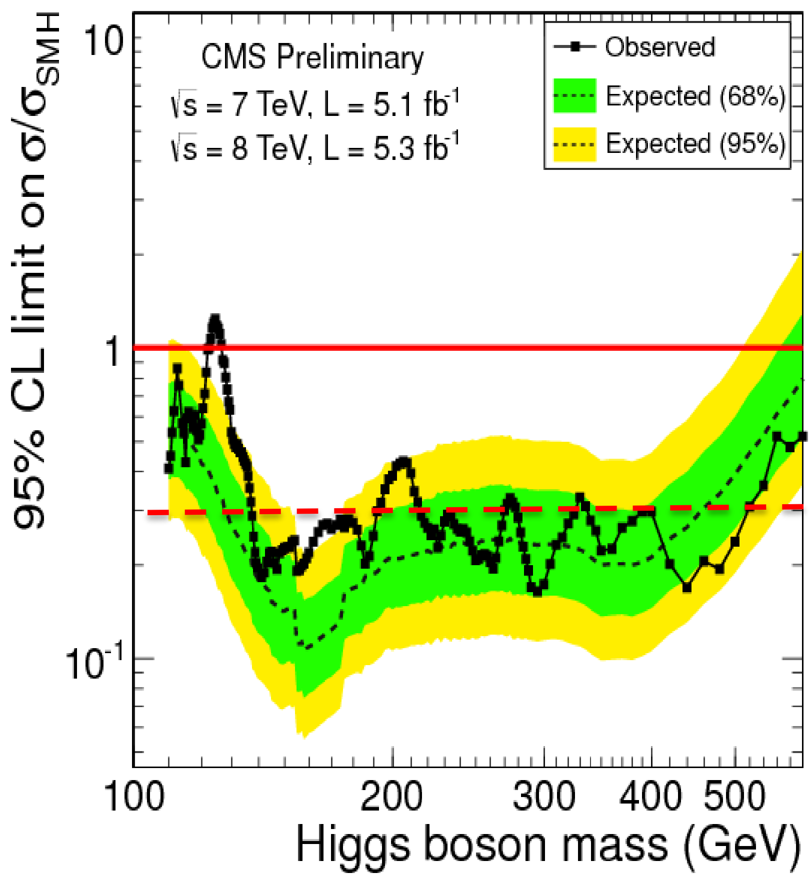
Is it a SM Higgs boson?

- **CMS data compatible with SM prediction at 95% C.L.**
- Best fit c_F driven to low values by VBF γγ excess and ττ deficit.
- **More data needed to draw any definite conclusion.**
- LHC Cross Section WG also converging on an improved models for these kinds of fits.



solid contour: 68% CL
dashed contour: 95% CL

Anything elsewhere?



- Stringent exclusion limits for any heavy Higgs-like boson decaying into WW and ZZ bosons:
- e.g. **$\sigma \sim 0.3 \times \sigma_{SMH}$** is excluded in most of the 140-500 GeV range.

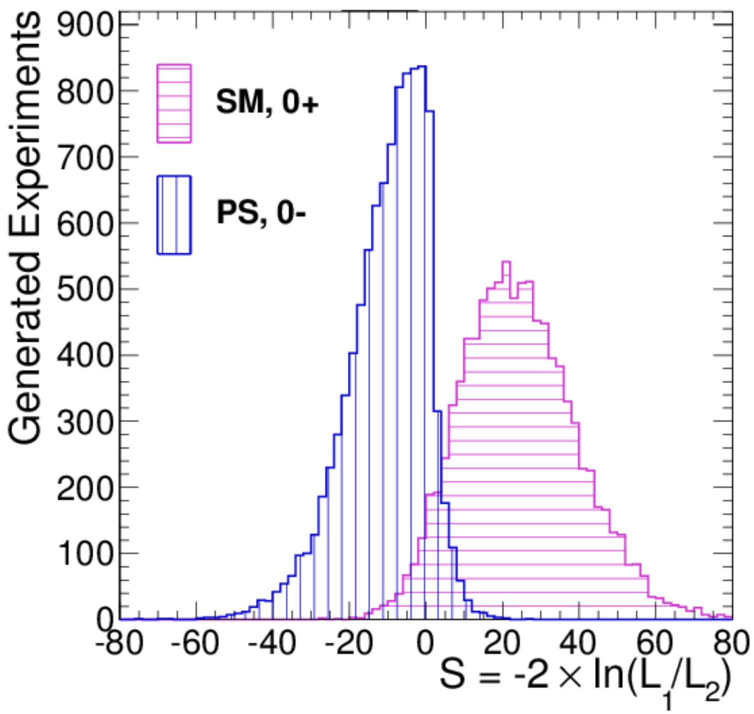
What next?

- *Reassert* the observation with the full 2011+2012 dataset, using 12 fb^{-1} already collected, and then the final Run 1 dataset, **5 fb-1 at 7 TeV and O(20 fb-1) at 8 TeV.**
- **Measurement of spin and parity** using angular distributions in ZZ, WW, γγ.
- **Search for deviations from the SM in the couplings** by progressively introducing new degrees of freedom in the fit to the data, in collaboration with LHC Higgs XS WG.
- **Improve the mass measurement.**

Projections for J^{PC} measurements

$H \to ZZ \to 4l$

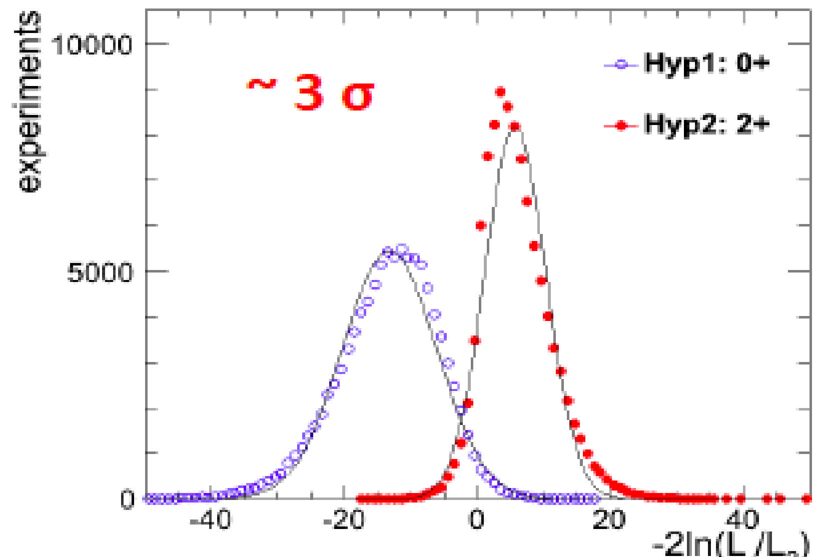
CMS Simulation $L = 30\ fb^{-1}$, $\sqrt{s} = 8$ TeV



Expect ~3σ separation between scalar and pseudoscalar in 2012

$H \to WW \to 2l2\nu$

JHU Generator level $L = 10\ fb^{-1}$, $\sqrt{s} = 8$ TeV



Expect ~3σ separation between spin 0, 2 with 10 fb^{-1} but assuming no systematics and WW as only background

http://indico.cern.ch/contributionDisplay.py?contribId=473&sessionId=53&confId=181298

Conclusion

- LHC, ATLAS, CMS performing extremely well in their 3rd year of first run, with a major battle with pile-up.
- In the searches for a SM Higgs boson at CMS, **a new state with mass 125.3±0.6 GeV has been observed**, dominantly in the $\gamma\gamma$ and 4l modes.
- Within the limited precision of the current data, the observation is compatible with the predictions for a SM Higgs boson signal, despite the larger excess in $\gamma\gamma$ and the deficit in $\tau\tau$, bb modes.
- More data is needed to draw any firm conclusions on this second point.
  - Moriond will have almost 3x the statistics of July 4th

For further information:

- CMS Higgs results twikipage https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsHIG
- 4th July seminar at CERN: https://cms-docdb.cern.ch/cgi-bin/PublicDocDB/ShowDocument?docid=6125
- CMS talks on Higgs searches at ICHEP 2012: https://indico.cern.ch/conferenceProgram.py?confId=181298 (too many to list them all individually)
- CMS long paper in preparation, and new results using 12 fb^{-1} at 8 TeV.