

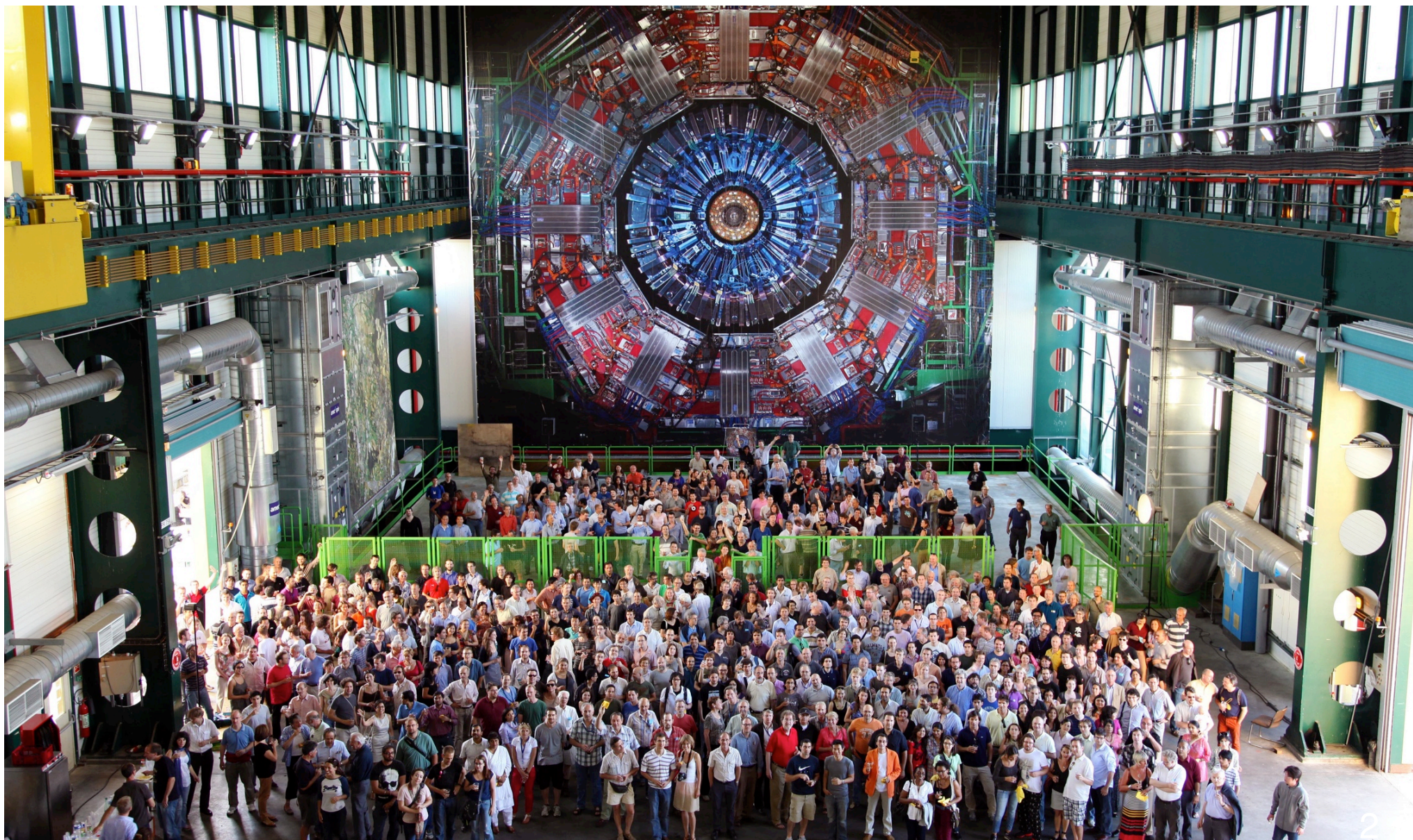
SM Higgs boson searches by CMS



LHC on the march
November 2012 Protvino



On behalf of the CMS Collaboration





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Congratulations to both
Atlas and CMS Collaborations
and to the builders of the LHC
on a magnificent achievement!

Peter Higgs

30 August 2012



Anomalously heavy Higgs @ CMS





Outline

- Short introduction to the SM Higgs boson
- The LHC and CMS
- Strategy of searches for the SM Higgs bosons
- Searches for the SM Higgs bosons in CMS
- Combination of the searches and compatibility with SM Higgs boson
- Conclusion



Short Introduction to the SM Higgs Boson

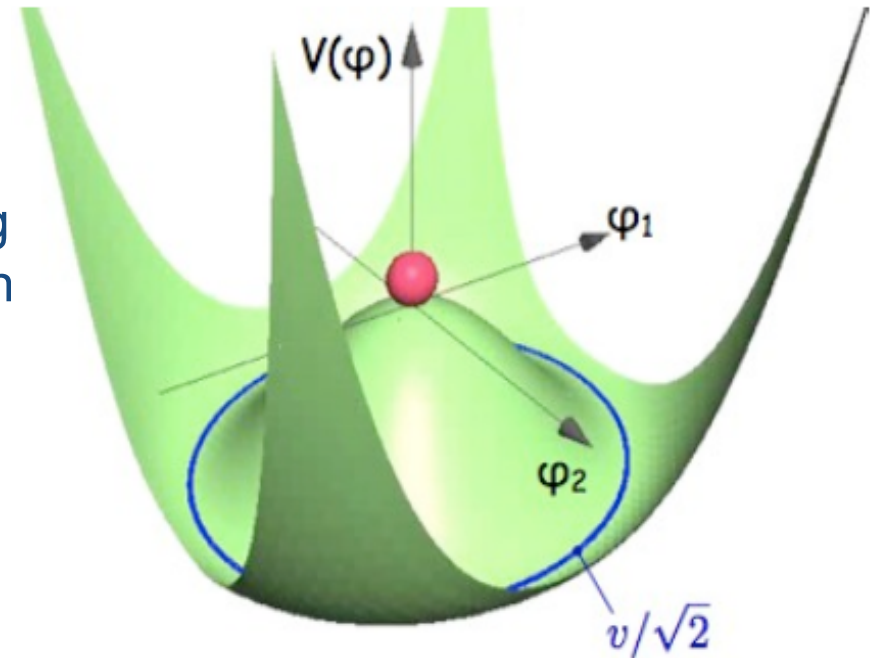
The SM Higgs has been proposed to provide an elegant solution for the ElectroWeak Symmetry Breaking mechanism.

It introduces a scalar field with a non-vanishing value at zero. The scalar boson appears as an excitation of the field above its ground state.

Horizontal excitation \rightarrow massless mode.

Vertical excitation \rightarrow massive mode.

W and Z become massive while the photon remains massless.



The theory does not predict precisely the mass of the boson ;

$$M_Z \cos \theta_W = M_W = \frac{1}{2} v g$$

$$g^2 = 4\sqrt{2} M_W^2 G_F$$

**M_H is a free parameter $M_H^2 = 2 \lambda v^2$
 $g=0.6574$; $v=246\text{GeV}$**



Additional constraints on the Higgs mass

“Unitarity”.

$$M_H < 700 - 800 \text{ GeV}/c^2$$

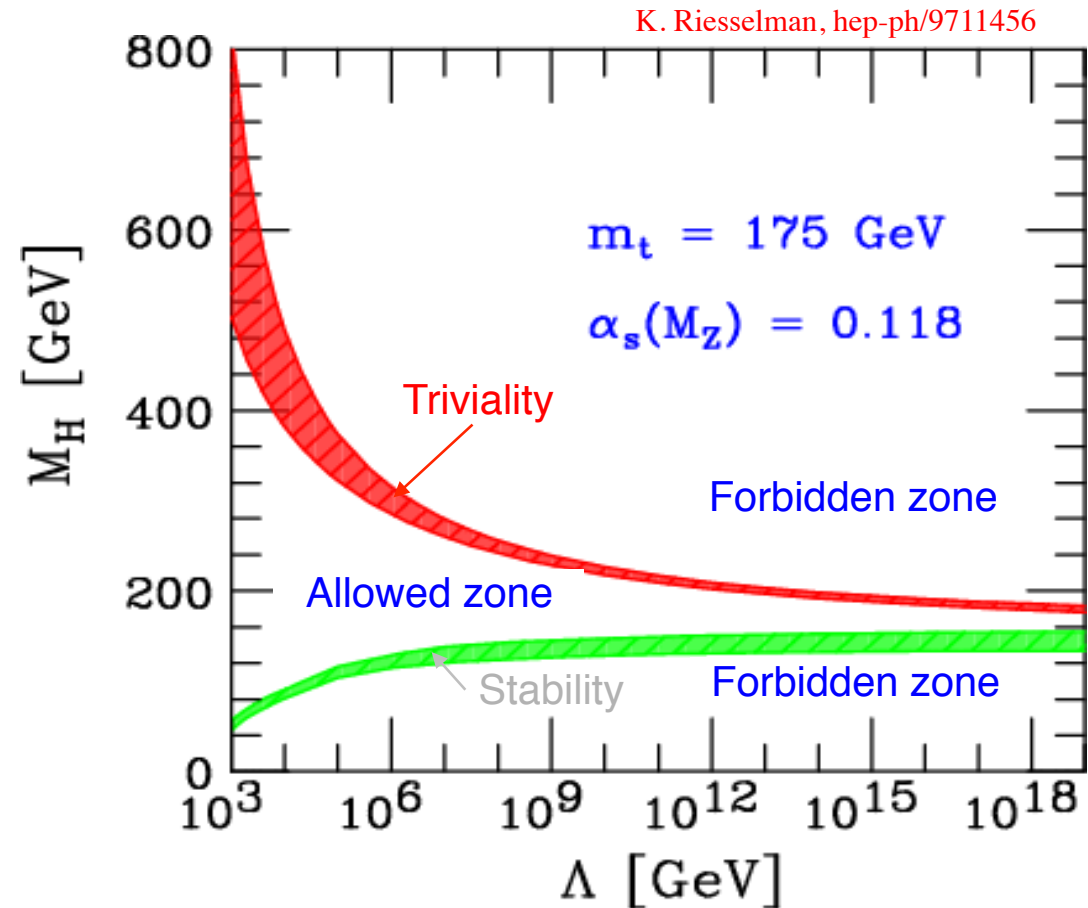
“Triviality”: Higgs self-coupling
Is not too strong

$$M_H^2 < \frac{4\pi^2 v^2}{3\ln(\Lambda/v)}$$

“Stability” of the vacuum.

$$M_H^2 > \frac{4m_t^4}{\pi^2 v^2} \ln(\Lambda/v)$$

Λ = cut-off scale





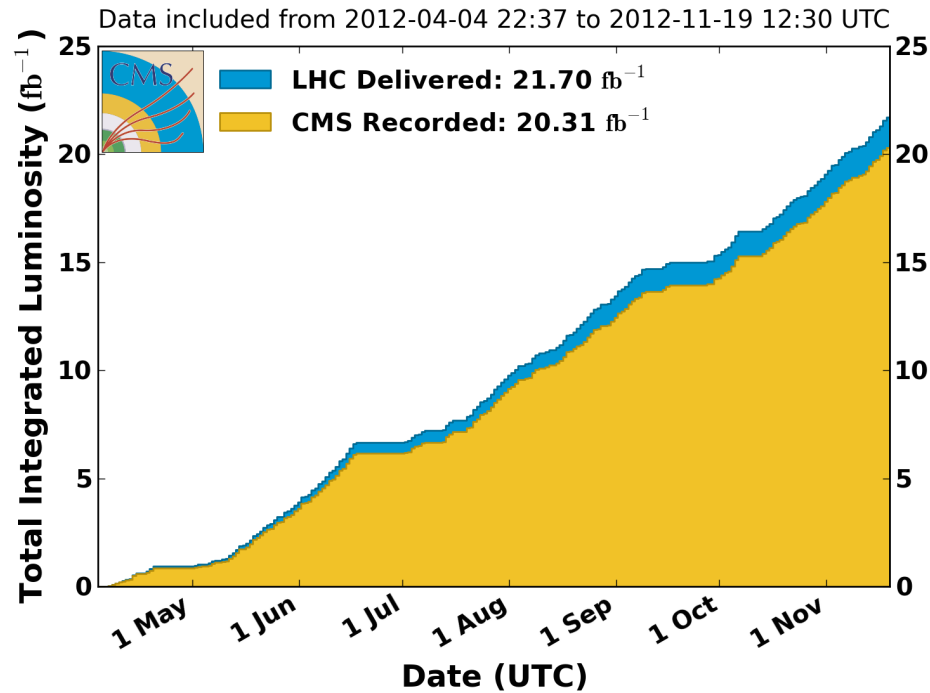
Corrected plan for the LHC

- 2010: first physics run, 7TeV, $L > 2 \times 10^{32} \text{cm}^{-2} \text{s}^{-1}$, (40pb⁻¹ delivered)
- 2011: 7TeV, $L > 3.5 \times 10^{33} \text{cm}^{-2} \text{s}^{-1}$ (>5.5fb⁻¹ delivered)
- 2012: 8TeV, $L \approx 7 \times 10^{33} \text{cm}^{-2} \text{s}^{-1}$ (~21 fb⁻¹ delivered by now)
- **Since 2010 LHC is running smoothly and with excellent performance often exceeding the most optimistic expectations.**
- 2013-14: long shutdown to completely repair all the splices interconnecting the magnets and prepare the machine for 14 TeV.
- 2014-2015-2016: LHC at **13.5-14TeV** and **$L > 10^{34} \text{cm}^{-2} \text{s}^{-1}$**

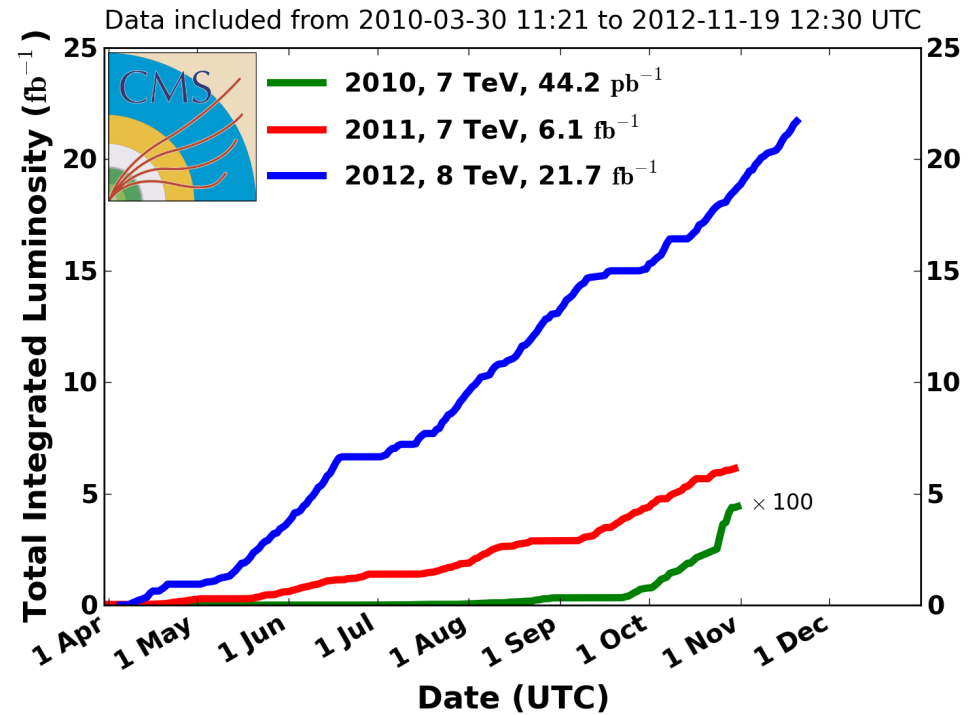


The LHC 2012 run at 8 TeV is ongoing

CMS Integrated Luminosity, pp, 2012, $\sqrt{s} = 8$ TeV

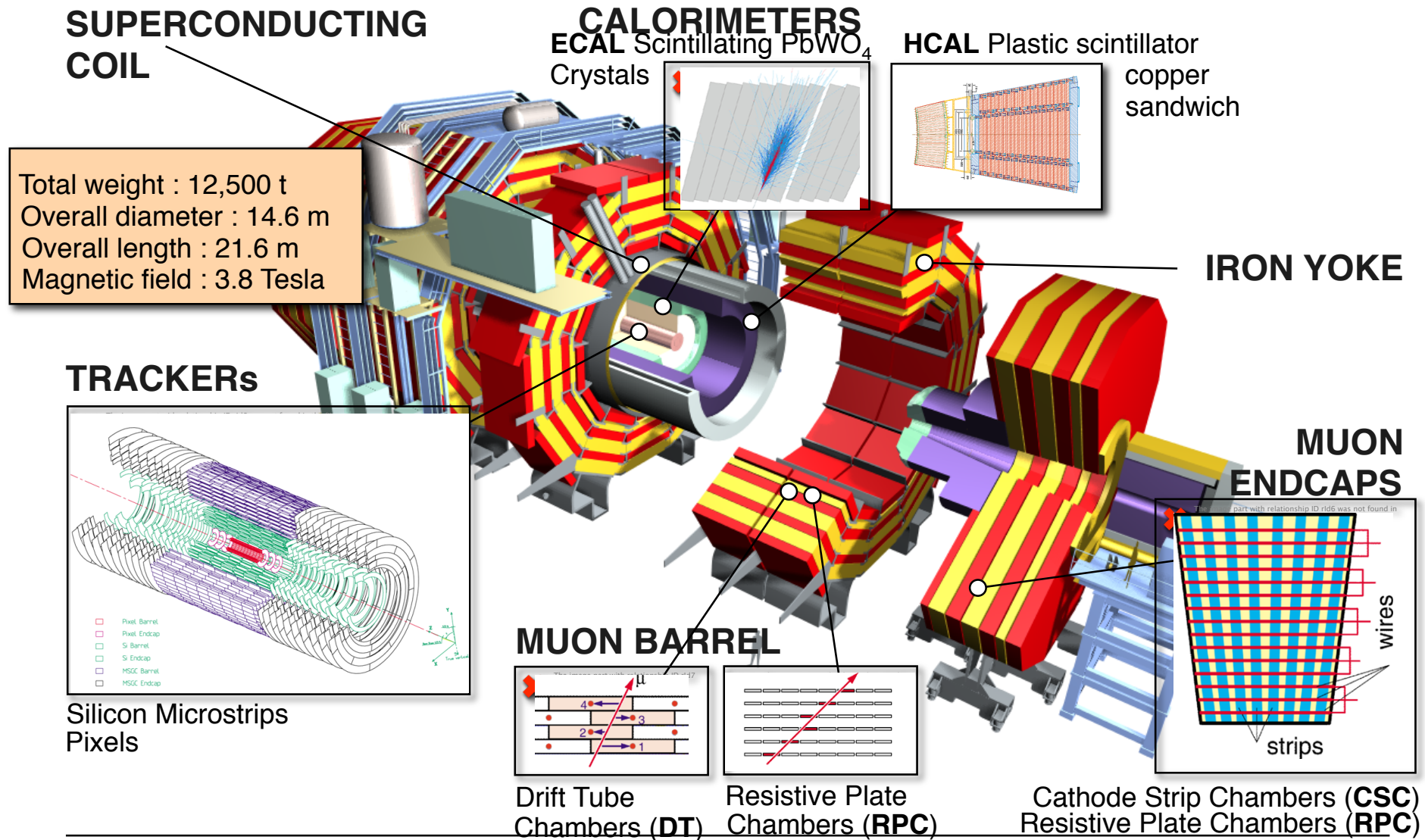


CMS Integrated Luminosity, pp

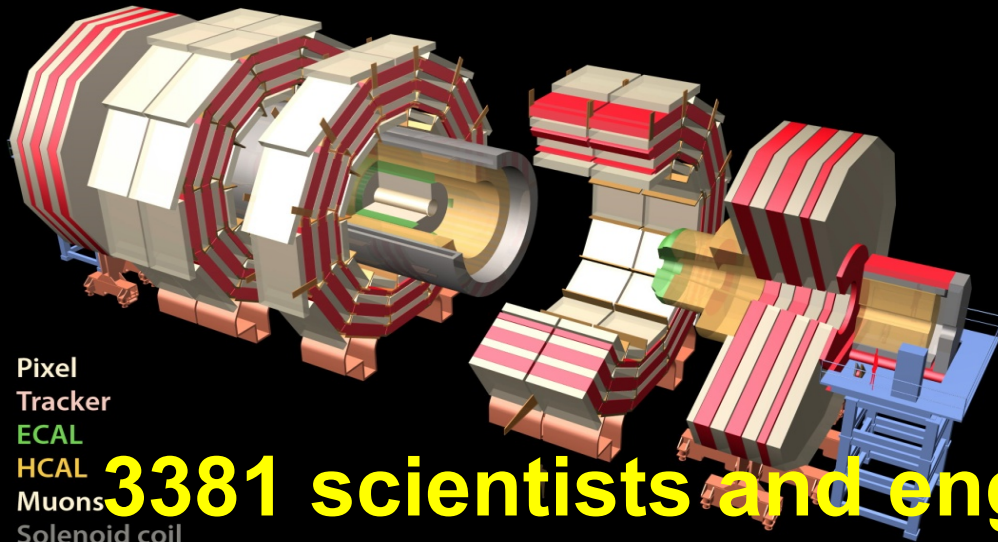




The Compact Muon Solenoid (CMS)



The CMS Collaboration



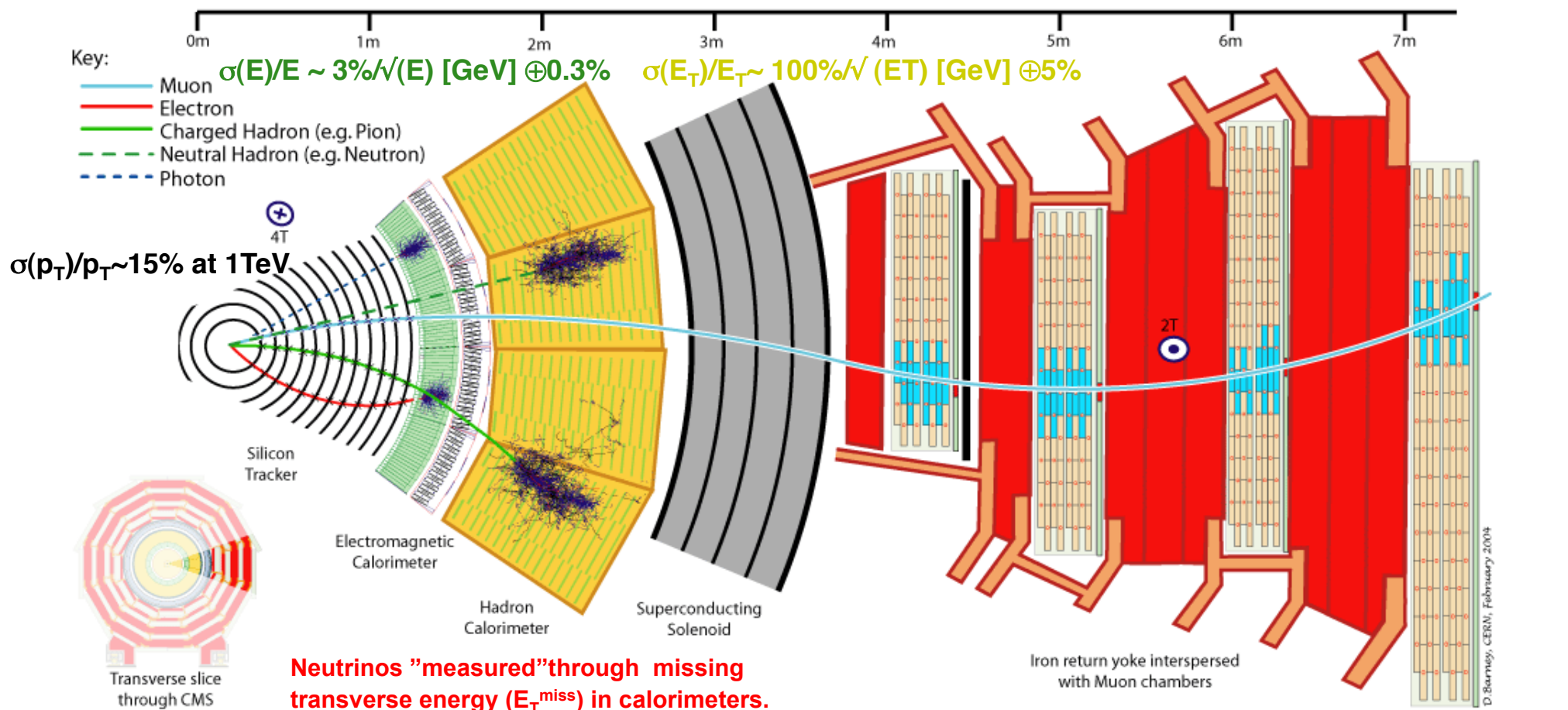
Pixel
Tracker
ECAL
HCAL
Muons
Solenoid coil

3381 scientists and engineers (including ~840 students) from 173 institutes in 40 countries





Particles through a CMS slice



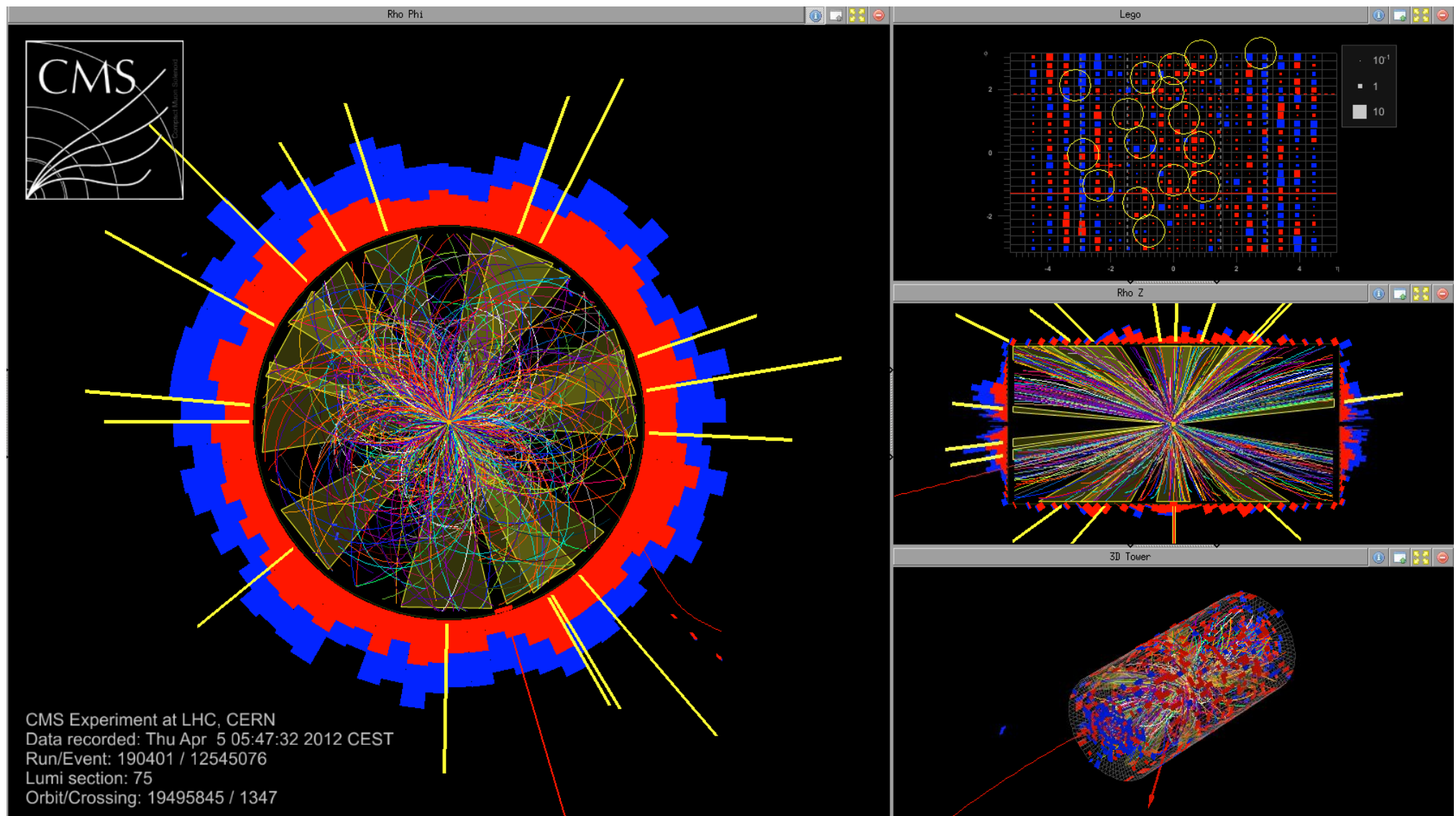
Fast detectors: 25-50ns bunch crossing

High granularity: 20-40 overlapping complex events

High radiation resistance: >10 years of operation

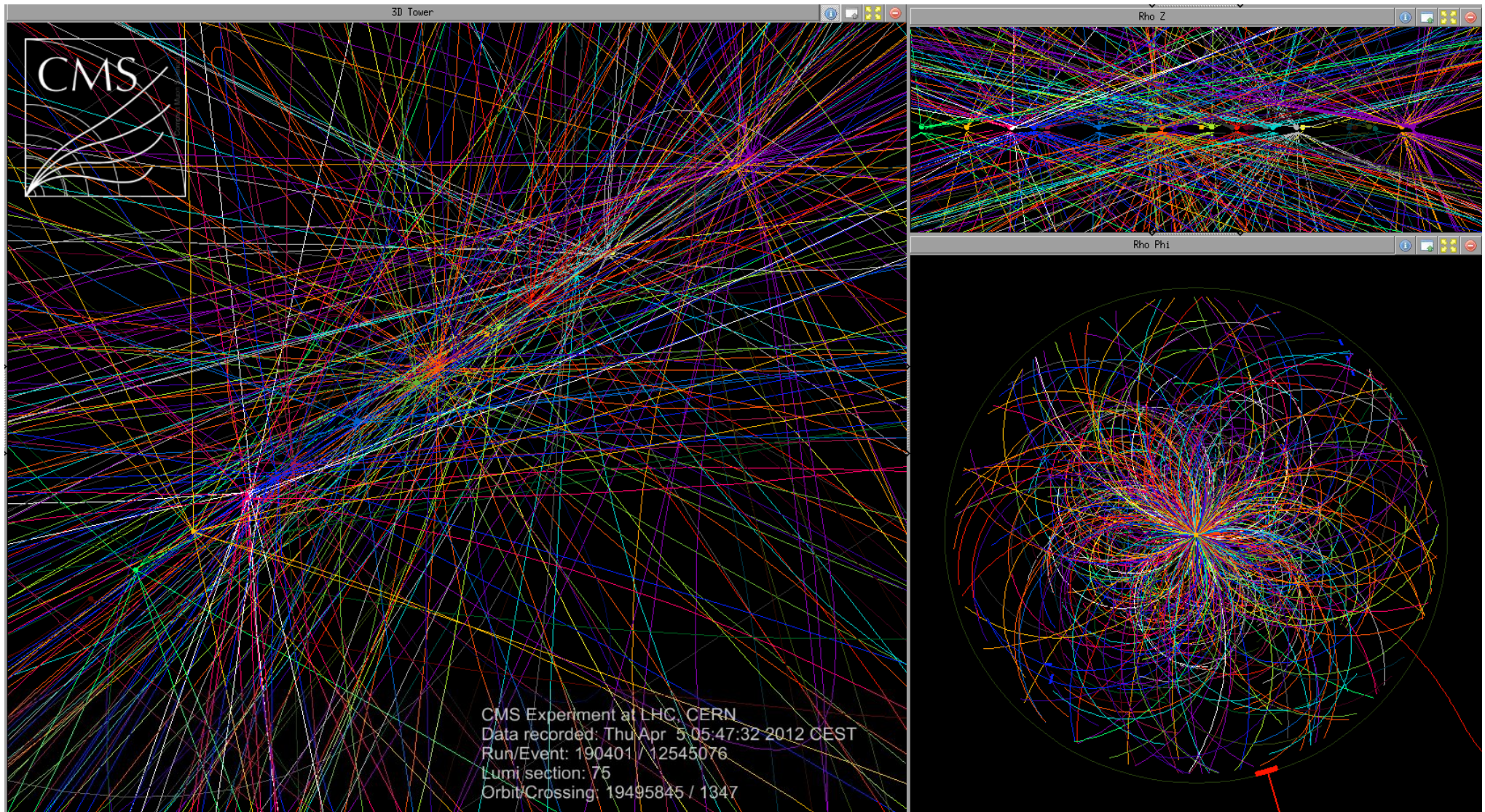


The challenge of the 2012 run





8 TeV and high pile-up conditions

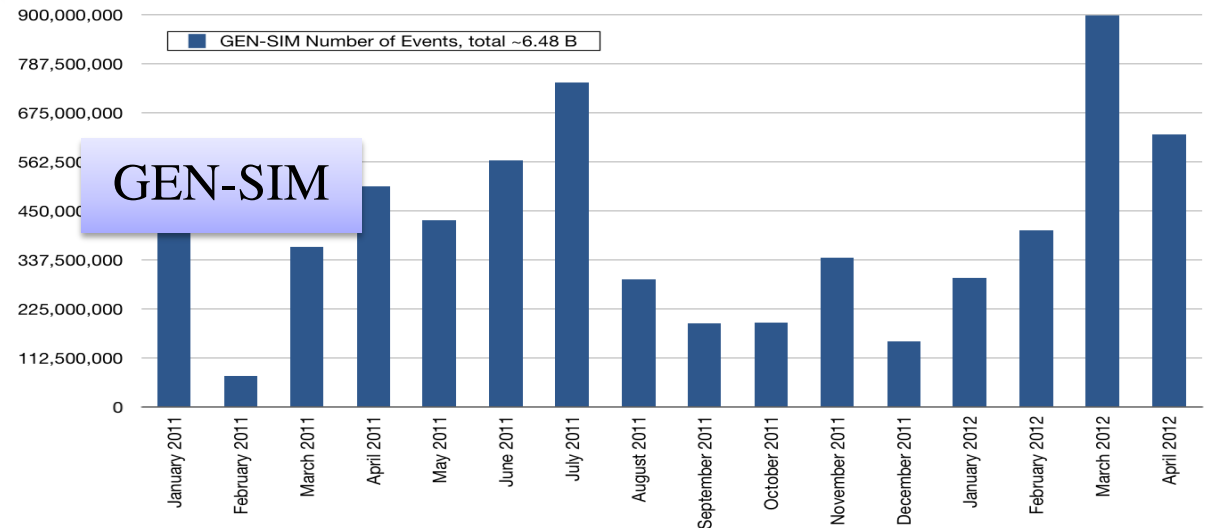




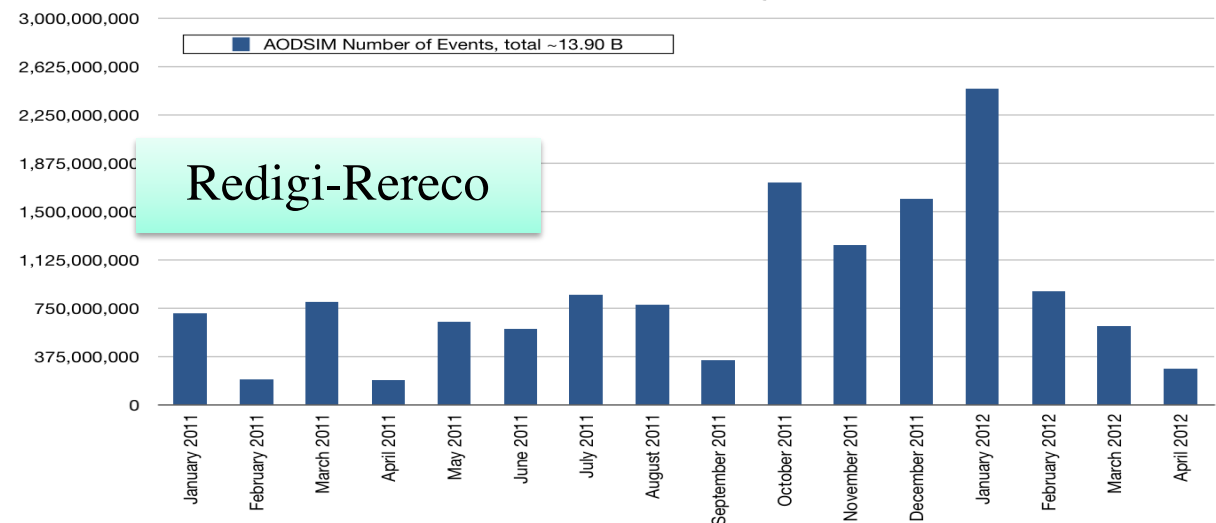
MC Production Capabilities

- GEN-SIM @ Tier-2's
 - Sustain 400M /Month
 - *900M, 600M past 2 months but had help from Tier-1's*
- Redigi-Rereco@ Tier-1's
 - Sustain 1B/month
 - *Peaks high as 2.3B*

MC in 2011/2012: Number of Events per Month - GEN-SIM



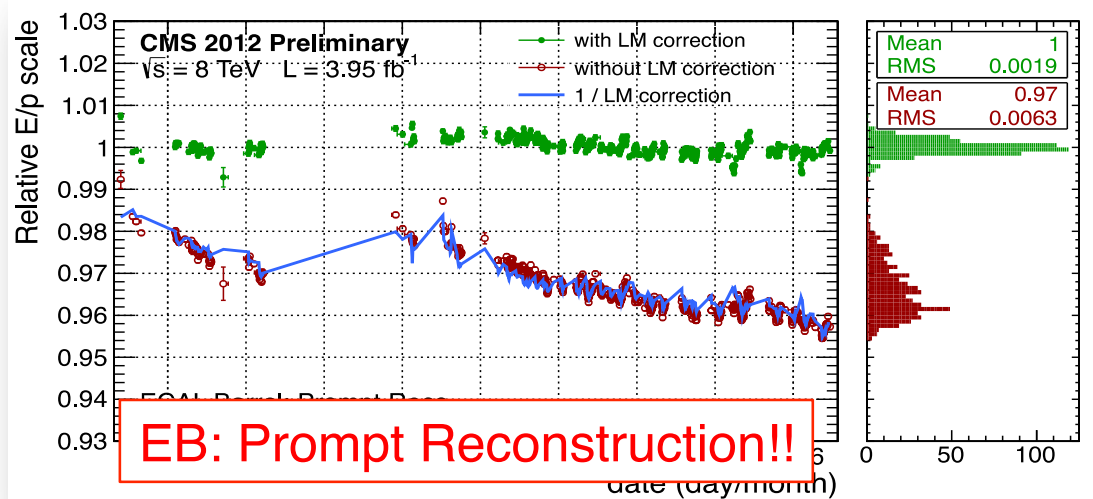
MC in 2011/2012: Number of Events per Month - AODSIM



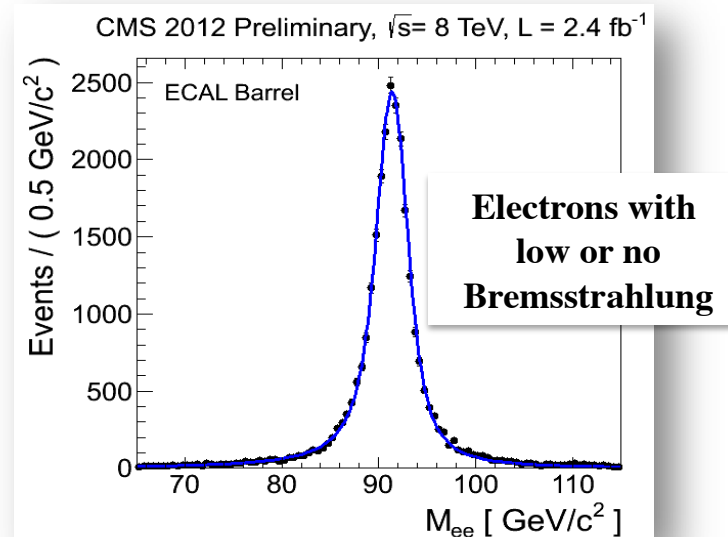


ECAL calibration, 2012 data

Single electron energy scale (E/p) stability
in barrel measured with $W \rightarrow e\nu$ events



$Z \rightarrow ee$ invariant mass distribution for
electrons measured in the barrel



- $W \rightarrow e\nu$ E/p: Stable E scale during 2012 run after light monitoring (LM) corrections:
 - ECAL Barrel (EB): RMS stability after corrections 0.19%
- $Z \rightarrow ee$: Good resolution with preliminary energy calibration for 2012:
 - Instrumental resolution: 1.0 GeV in ECAL Barrel



Reconstruction: key moments

- **Particle flow**: analyse and combine information from subdetectors to create “particles”
- **Multivariate electron identification** in 2012: 30% efficiency improvement wrt cut based ID
- **Particle-based isolation**: important in conditions of high pile-up
- Multivariate discriminator for tau ID
- Jets identification: analyse shape to reject pile-up jets and detector noise effects



Properties of signal and backgrounds



Signal and background@ 10^{33}

Cross sections for various physics processes vary over many orders of magnitude

Higgs ($500 \text{ GeV}/c^2$) $\sigma \sim 1 \text{ pb}$ @ $10^{33} \rightarrow 10^{-3} \text{ Hz}$

Higgs ($150 \text{ GeV}/c^2$) $\sigma \sim 10 \text{ pb}$ @ $10^{33} \rightarrow 10^{-2} \text{ Hz}$

tt production: $\rightarrow 1 \text{ Hz}$

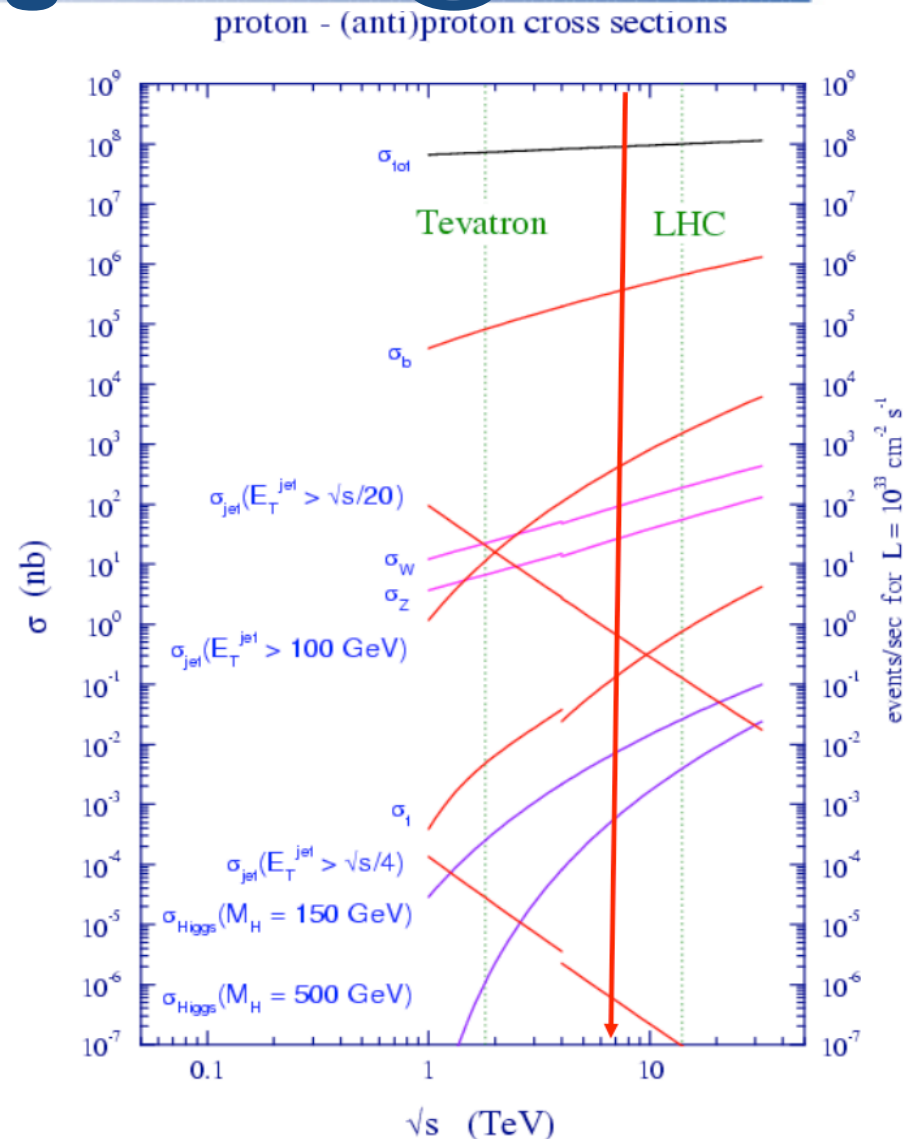
$W \rightarrow \ell \nu$: $\rightarrow 100 \text{ Hz}$

bb inclusive: $\rightarrow 10^{5-6} \text{ Hz}$

Inelastic: $\rightarrow 10^8 \text{ Hz}$

**The needed selection (10^{-11}) is feasible but
a fast and efficient Trigger system is a key**

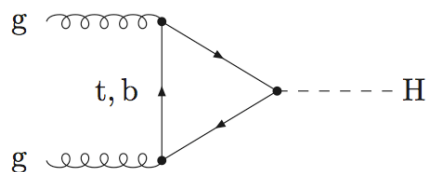
Protons collide at 20MHz but we can record on tape only 300Hz. Trigger selection, based on **electron, muon, tau, jet and missing energy** signatures is crucial for all analyses.



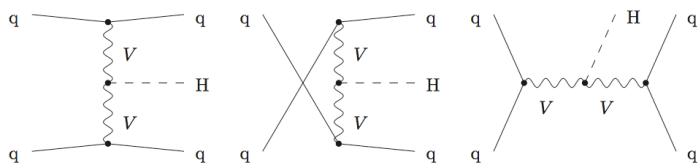


SM Higgs production at LHC

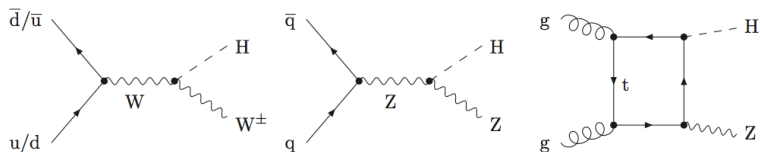
Gluon-gluon fusion (gg-fusion)



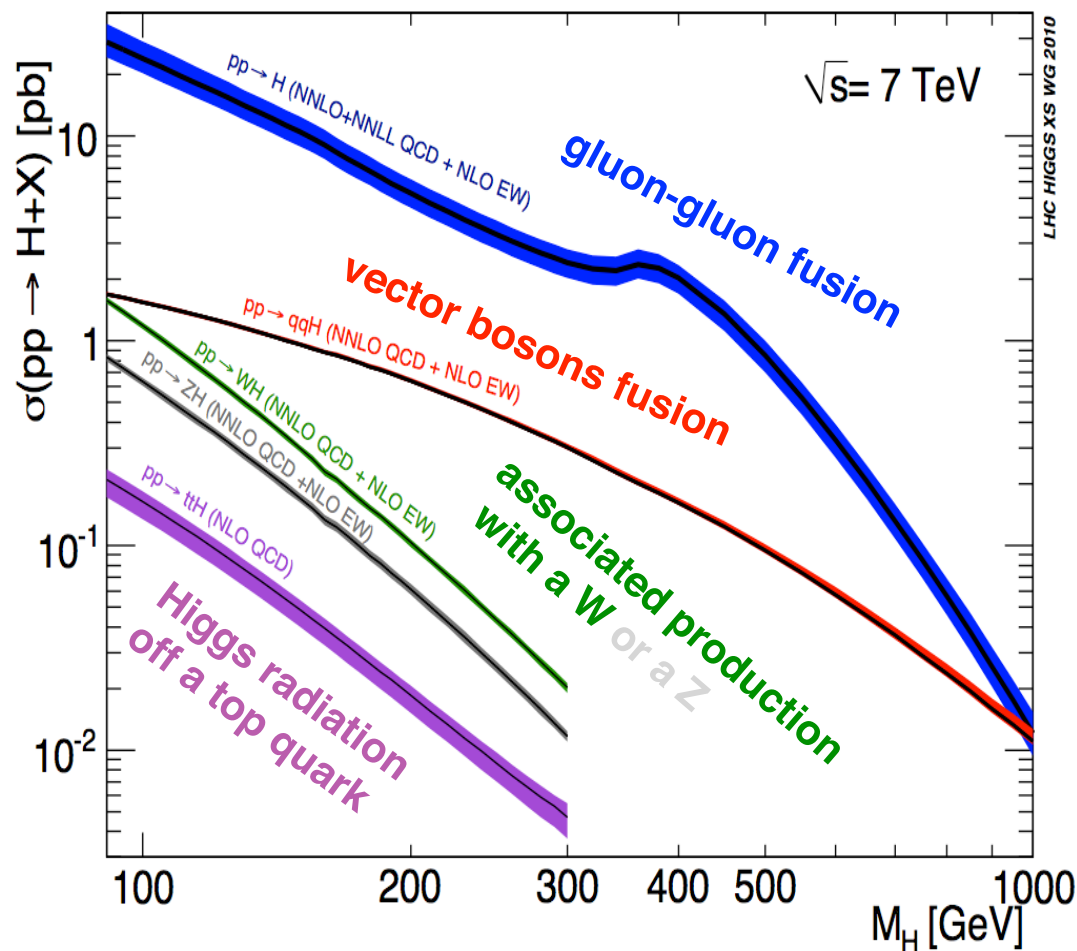
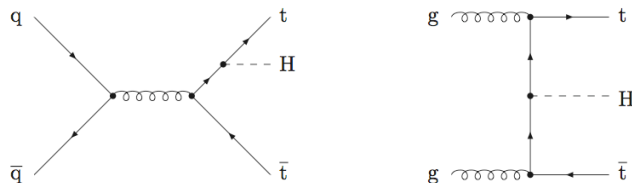
Vector bosons fusion (VBF)



Associated production with W, Z (VH)



Higgs radiation off a top quark



Typical size of the uncertainty
(there is also a dependence
on the mass)

	ggF	VBF	WH/ZH	$t\bar{t}H$
QCD scale:	+12% -8%	$\pm 1\%$	$\pm 1\%$	+3% -9%
PDF + α_s :	$\pm 8\%$	$\pm 4\%$	$\pm 4\%$	$\pm 8\%$
Mass line shape:	$(150\%) \times \left(\frac{M_H}{\text{TeV}}\right)^3$			

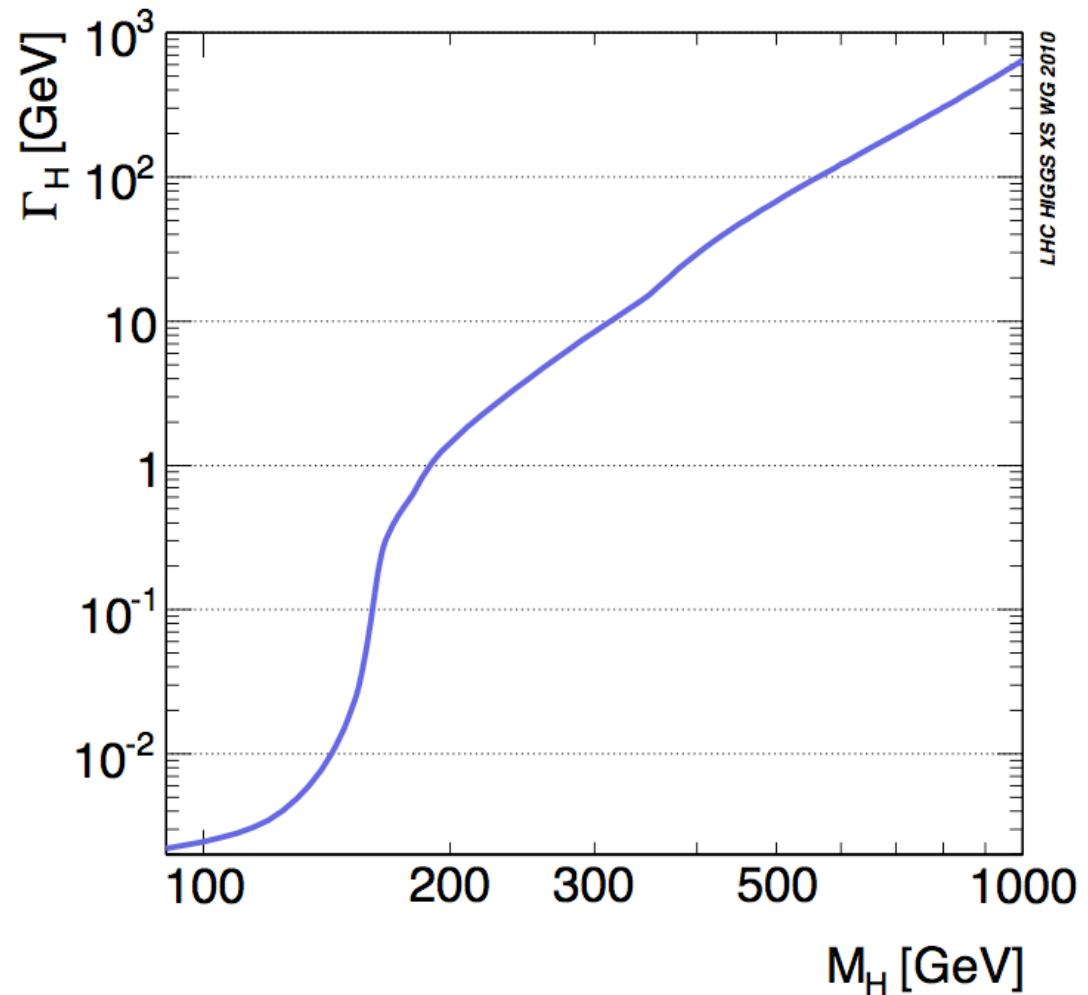


SM Higgs boson width

Very narrow resonance at low mass: $\sim 4\text{MeV}$ at $125\text{GeV}/c^2$

The width grows rapidly with the mass.

Around 1TeV the width of the boson becomes comparable to its mass i.e the concept of particle fades away.



SM Higgs boson width vs mass under the relativistic Breit-Wigner assumption



SM Higgs decay modes vs mass

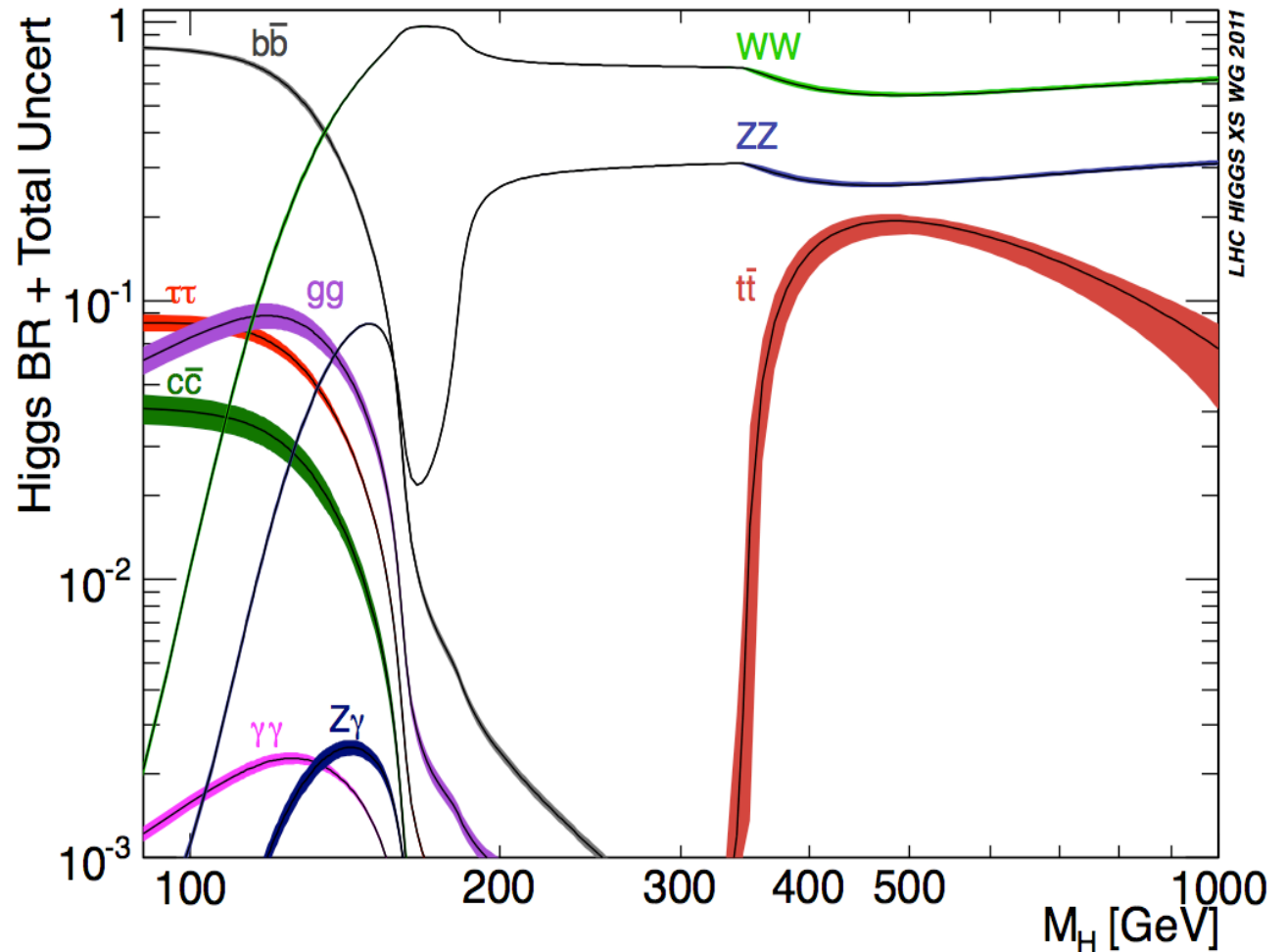
Higgs couples to mass

$$\Gamma_{Hff} \sim m_f^2$$

$$\Gamma_{HVV} \sim m_V^4$$

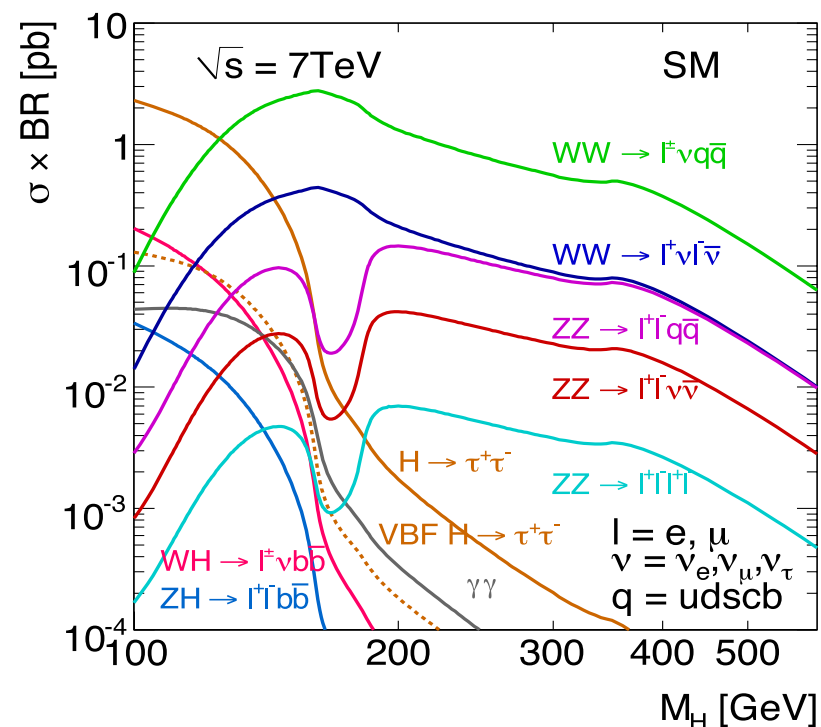
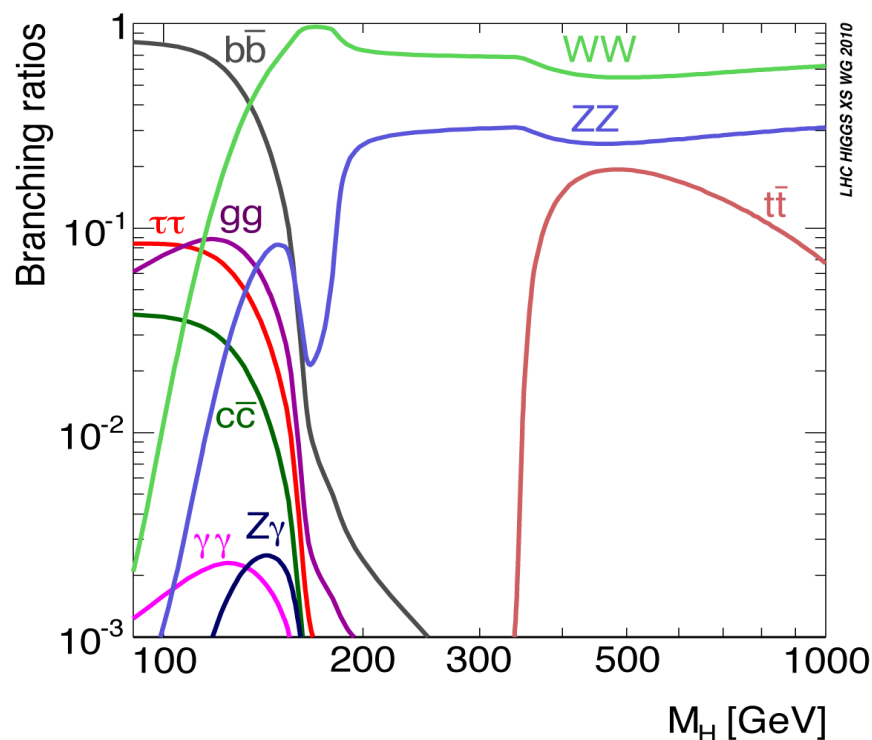
Different decay channels are used to explore the low and the high mass region.

All available channels are combined to increase the sensitivity.





SM Higgs Decay Modes Vs Mass



High mass searches: based on $H \rightarrow WW$ and $H \rightarrow ZZ$ decay modes reconstructed in several channels; i.e $H \rightarrow WW \rightarrow l \nu jj$ + $H \rightarrow WW \rightarrow l \nu l \nu$

Low mass searches: $H \rightarrow \gamma\gamma$; $H \rightarrow bb$; $H \rightarrow \tau\tau$, $H \rightarrow ZZ \rightarrow 4\text{leptons}$, $H \rightarrow WW \rightarrow l \nu l \nu$.

Events expected to be produced with $L=1 \text{ fb}^{-1}$

m_H, GeV	$WW \rightarrow l \nu l \nu$	$ZZ \rightarrow 4l$	$\gamma\gamma$
120	127	1.5	43
150	390	4.6	16
300	89	3.8	0.04



Summary of the channels

Channel	Masses [GeV]	Branch. ratio	N_{ev} , 10 fb^{-1}	Prod. modes	S/B	Mass res.	Remark
$H \rightarrow \gamma\gamma$	110 - 150	2×10^{-3}	200/400	inclusive, VBF	low O(0.1)	2%	max. sens. at low mass
$H \rightarrow bb$	110 - 135	0.7	30/10 ⁵	VH	low O(0.1)	10%	
$H \rightarrow \tau\tau$	110 - 150	0.08	20/10 ⁴	inclusive, VBF, VH	low O(0.1)	15%	
$H \rightarrow WW^{(*)} \rightarrow l\nu l\nu$	110 - 700	0.03	60/10 ³	gg fusion, VBF, VH	medium O(1)	-	max. sens. at interm.
$H \rightarrow ZZ^{(*)} \rightarrow 4l$	110 - 700	$(3-8) \times 10^{-4}$	6/20	inclusive	high >1	2%	
$H \rightarrow ZZ \rightarrow \text{other}$	200 - 700	0.2	-	inclusive		10%	max. sens. at high mass
$H \rightarrow WW \rightarrow l\nu qq$	170 - 700	0.15	-	inclusive			

N_{ev} estimated for SM Higgs with a mass of 125 GeV at the collision energy 8 TeV



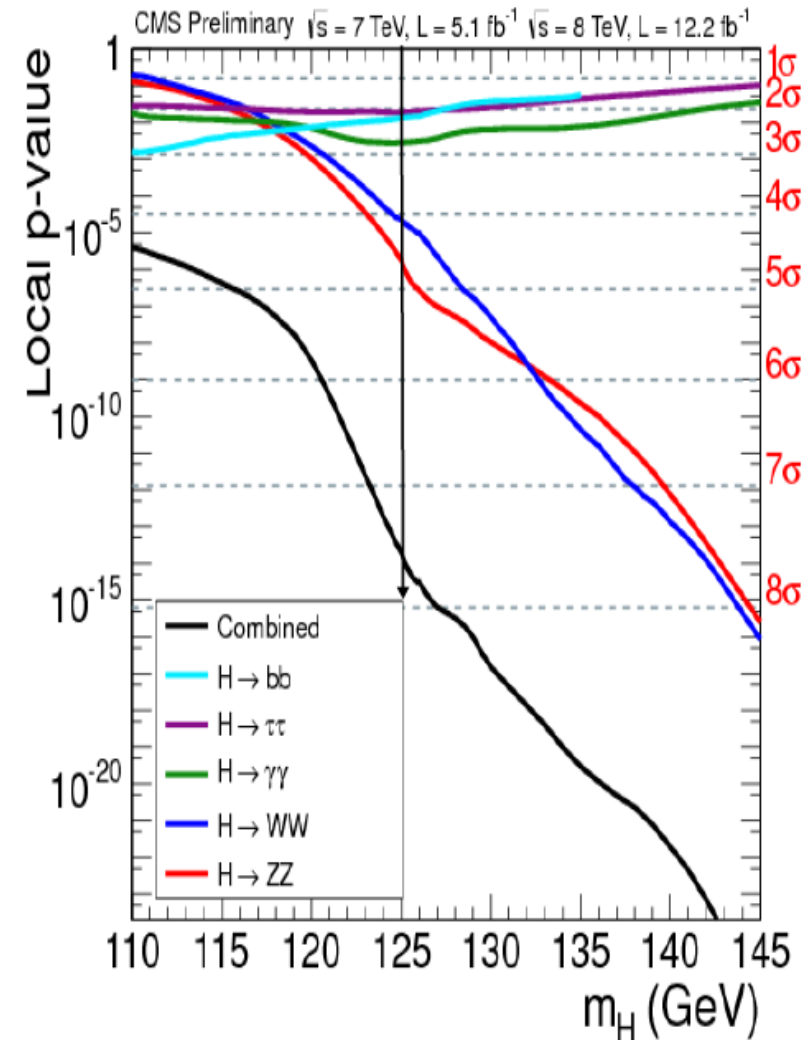
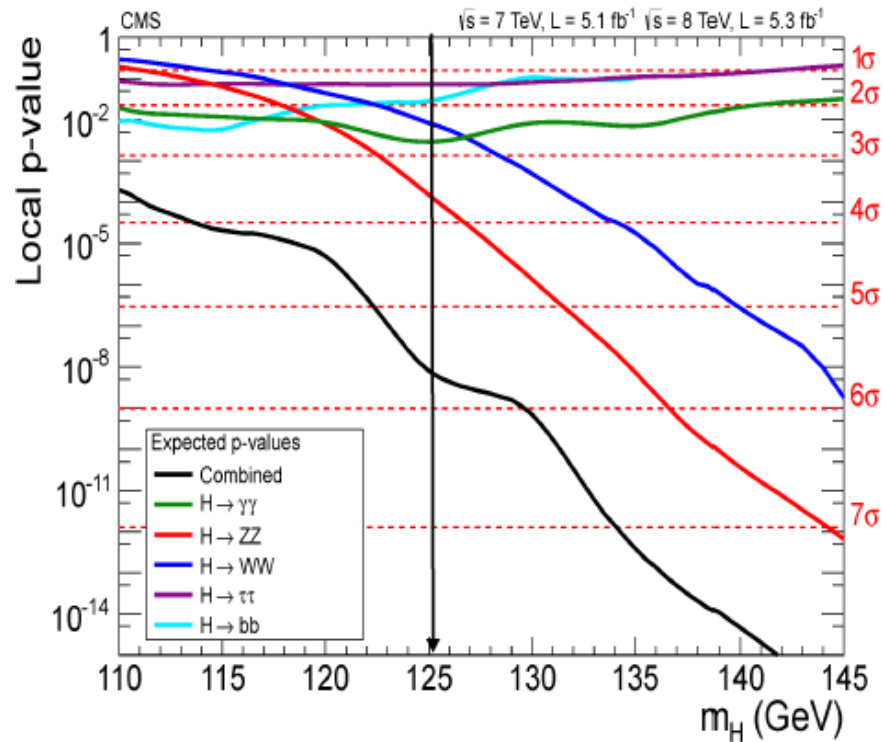
Searches for the SM Higgs boson



Expected performance

ICHEP (old)

New



- **Statistics increased**
- Some analyses made more sensitive
- Move towards studies of the discovered boson



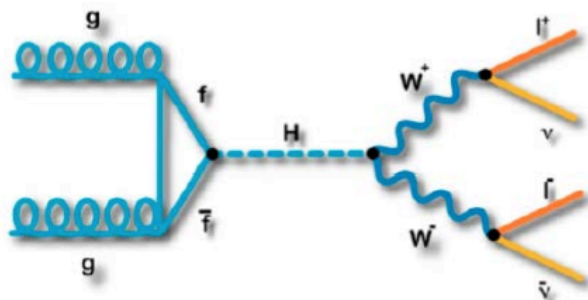
Public results

<http://cdsweb.cern.ch>

Channel	Masses [GeV]	Data used, fb^{-1} (7 + 8 TeV)	References 10 fb^{-1}
$H \rightarrow \gamma\gamma$	110 - 150	5.1 + 5.3	HIG-12-15
$H \rightarrow b\bar{b}$	110 - 135	5 + 12.1	HIG-12-44
$H \rightarrow \tau\tau$	110 - 145	4.9 + 12.1	HIG-12-43
$H \rightarrow WW(*) \rightarrow l\nu l\nu$	110 - 700	4.9 + 12.1	HIG-12-42
$H \rightarrow ZZ(*) \rightarrow 4l$	110 - 700	5.1 + 12.2	HIG-12-41
Higgs combination	110 - 700	4.9–5.1 + 5.3–12.2	HIG-12-45
$H \rightarrow ZZ \rightarrow 2l2\nu$	200 - 700	5 + 12.2	HIG-12-47
$H \rightarrow WW \rightarrow l\nu qq$	170 - 700	5 + 12	HIG-12-46

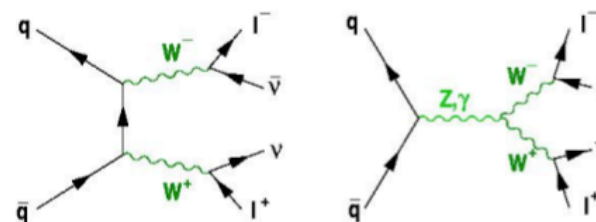


H → WW → 2l2ν: the “work horse”

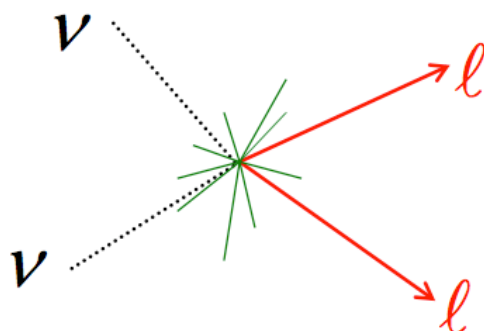


$$\sigma(H \rightarrow WW^* \rightarrow l\nu l\nu) \approx 0.18 \text{ pb} \quad (m_H = 125 \text{ GeV})$$

The SM WW is said to be “irreducible”



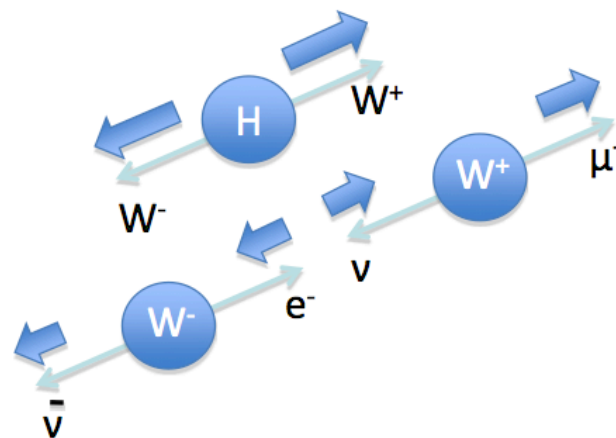
However, WW from the scalar Higgs is expected to have different kinematics



Main background:

WW, W/Z+jets, t \bar{t} , ...

$$M_T = \sqrt{2p_T^{\ell\ell} E_T^{\text{miss}} (1 - \cos \Delta\phi_{E_T^{\text{miss}} \ell\ell})}$$

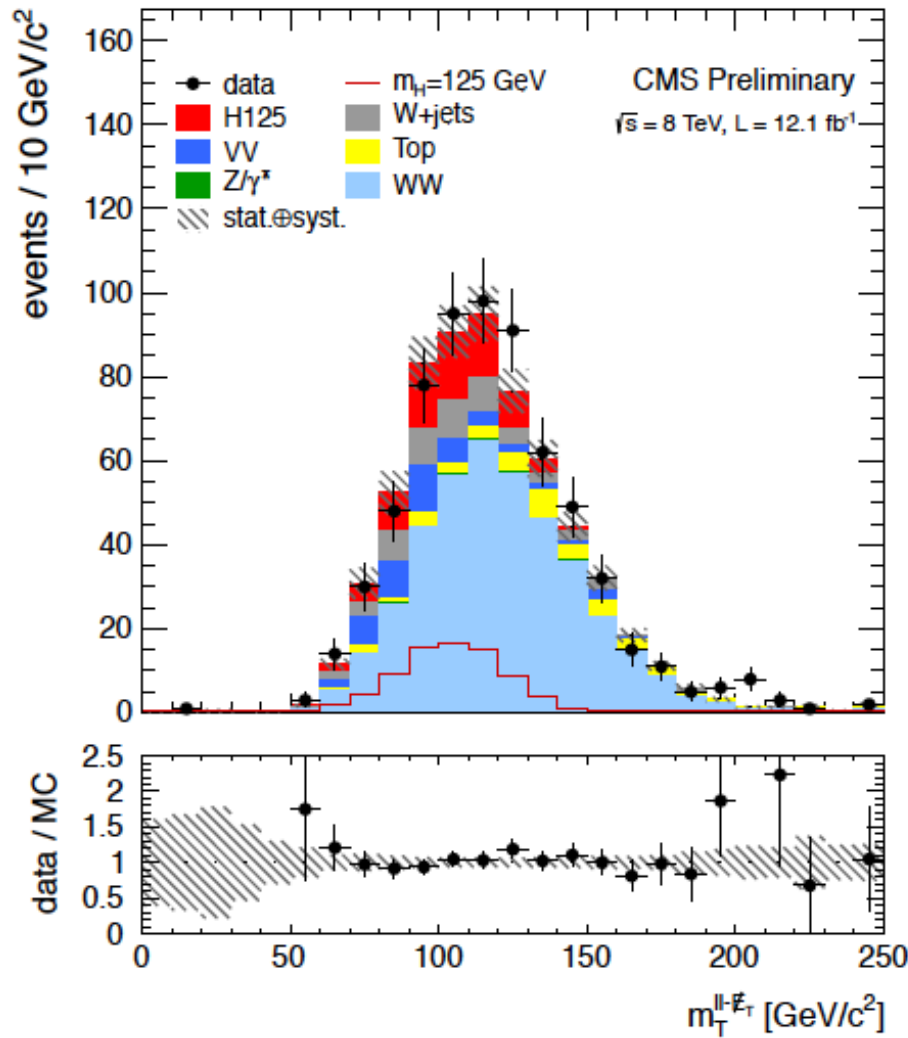


The spin correlation leads to a smaller average opening angle between the two leptons

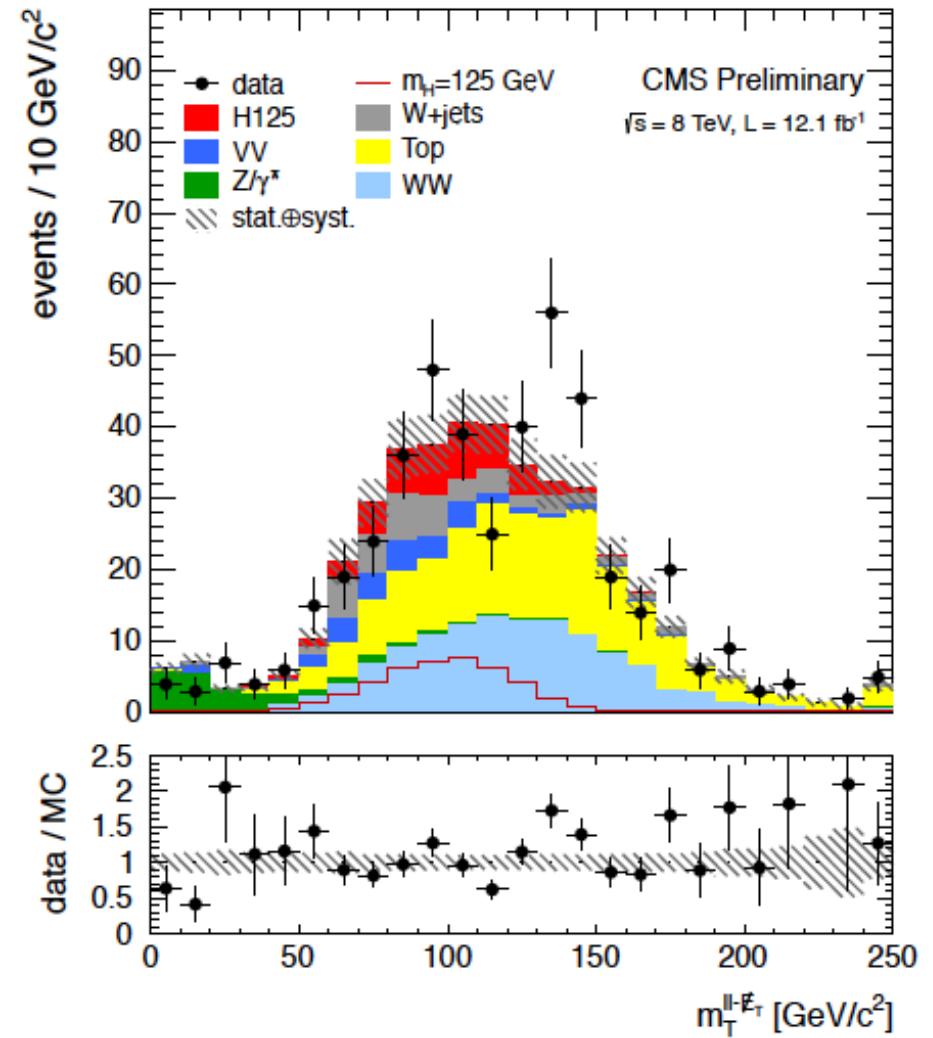


MT distributions

0-jet



1-jet



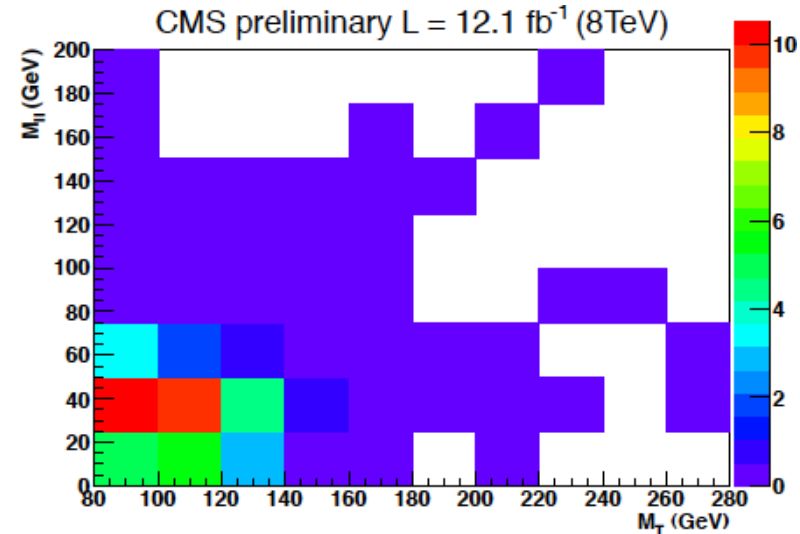
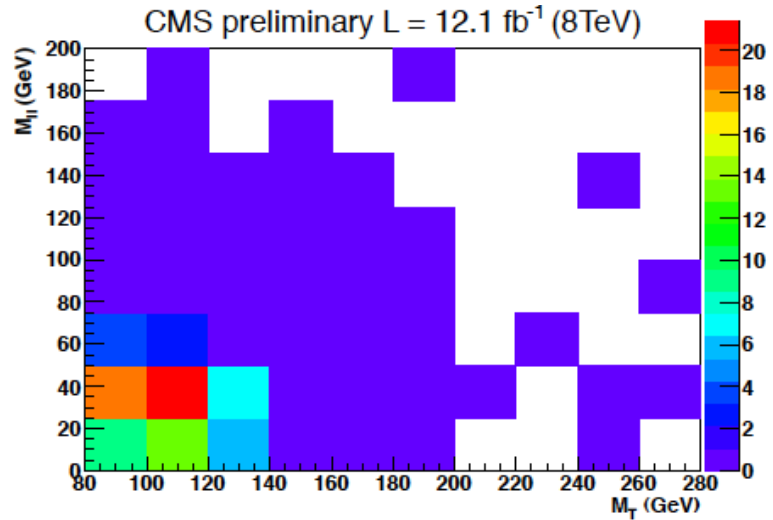


Shape analysis for 8 TeV data

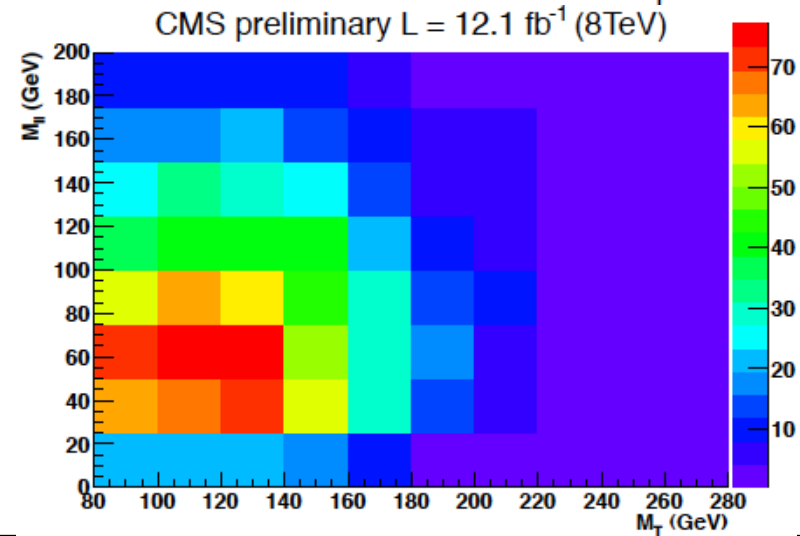
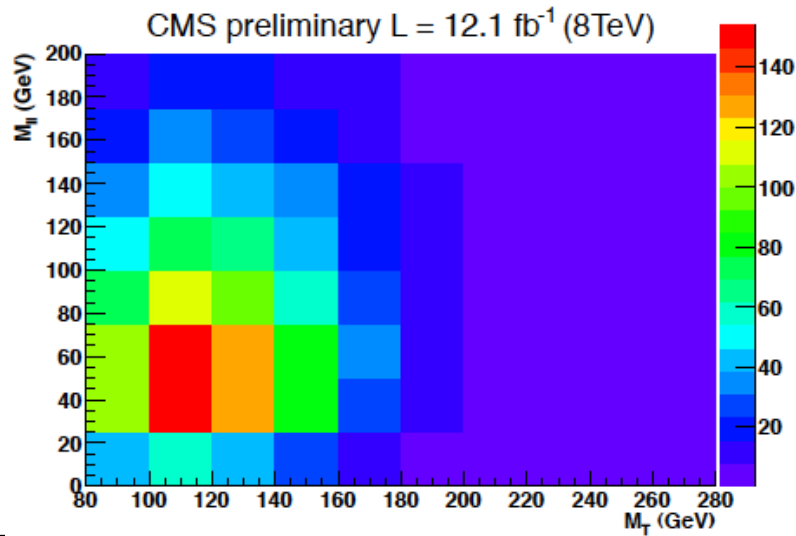
Higgs boson 125 GeV

Background

0-jet

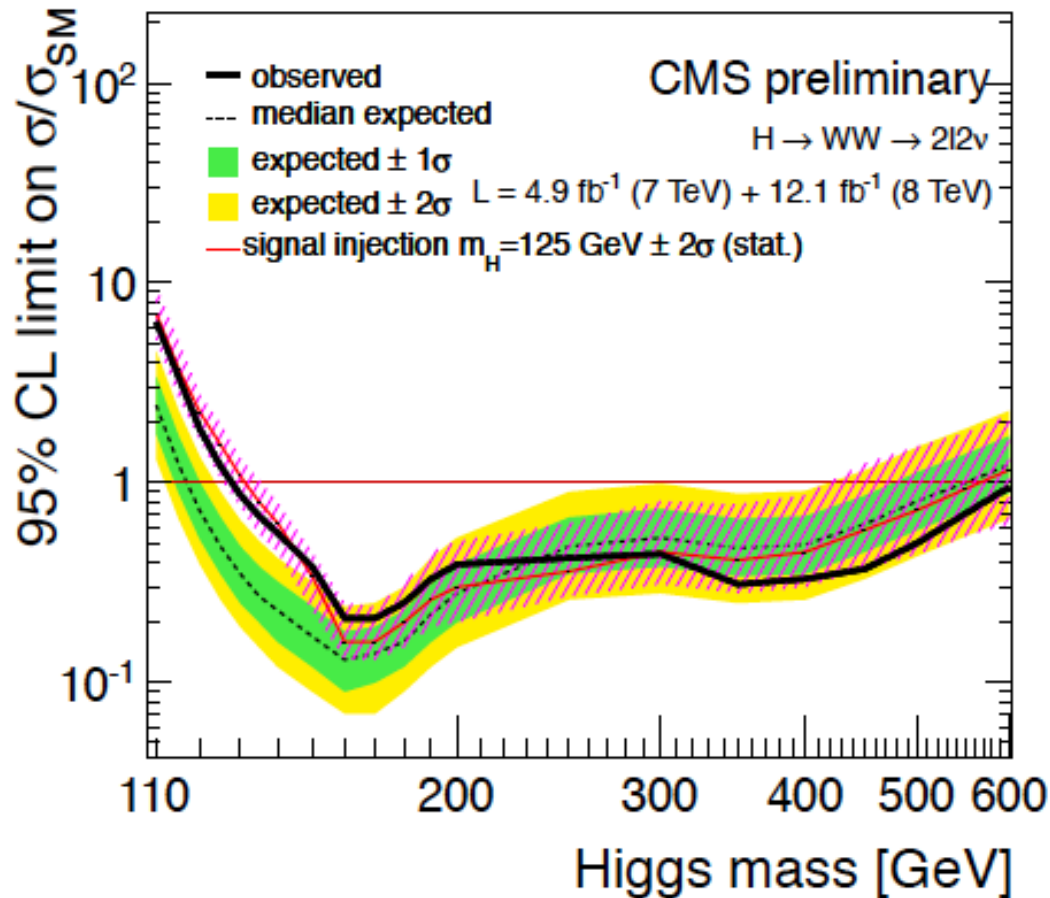


1-jet

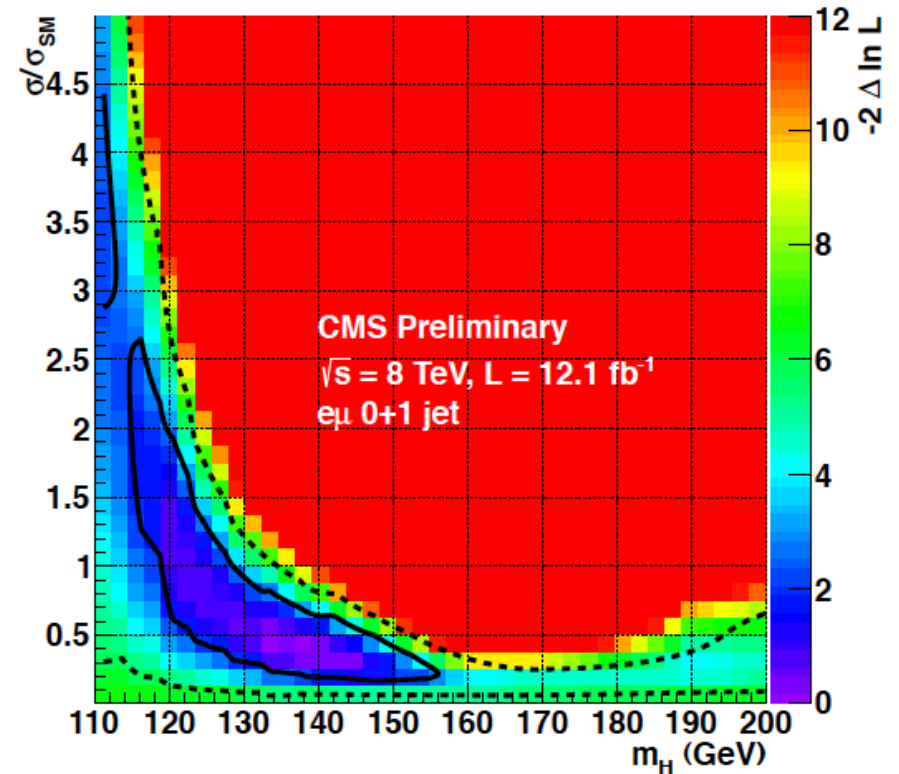




Combination of 7 TeV + 8 TeV



Exclusion range
expected: 120-550 GeV
observed: 128-600 GeV

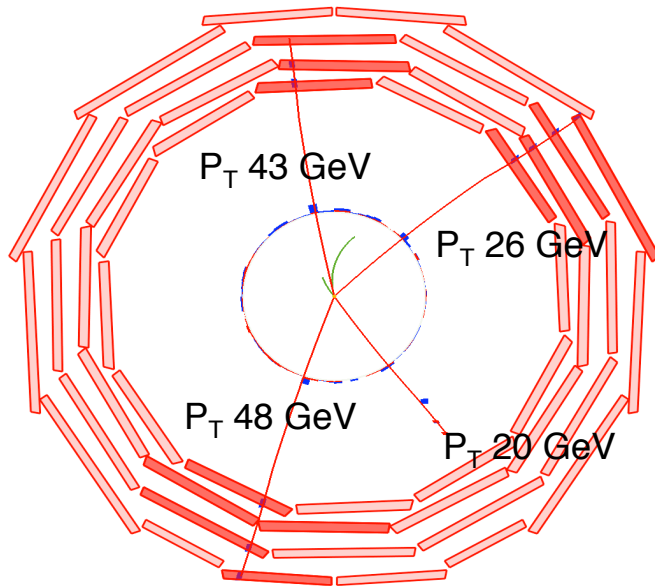
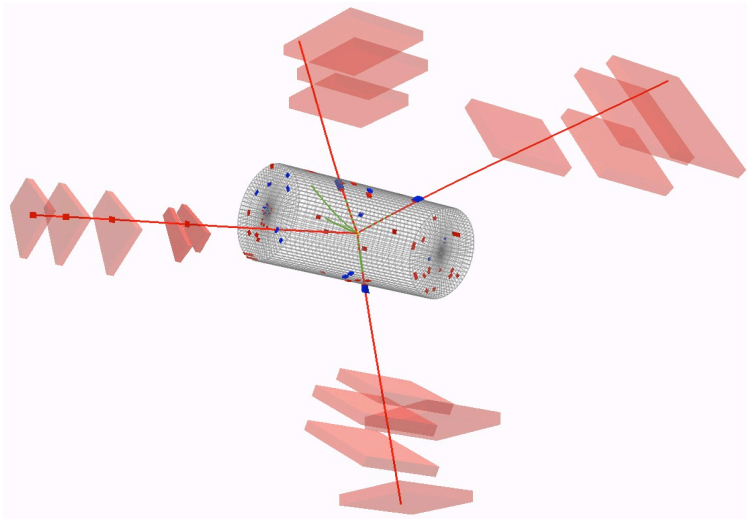


$$\sigma/\sigma_{\text{SM}} = 0.74 \pm 0.25$$

Significance of excess at $\sim 125 \text{ GeV}$
Expected: 4.1 sigma
Observed: 3.1 sigma



$H \rightarrow ZZ \rightarrow 4e, 4\mu, 2e2\mu$: The Golden Channel



Signature: Two pairs of same flavor high p_T oppositely charged isolated leptons. One or both pairs with invariant mass compatible with the Z .

Extremely clean, high resolution channel (1-2%) but very low rate ($\sigma \sim 2\text{-}5\text{fb}$).

Kinematics fully available: reconstruction of the invariant mass of the system.

Main backgrounds: ZZ^* (irreducible) for $m_H < 2m_Z$, Zbb , $Z+\text{jets}$, $t\bar{t}$

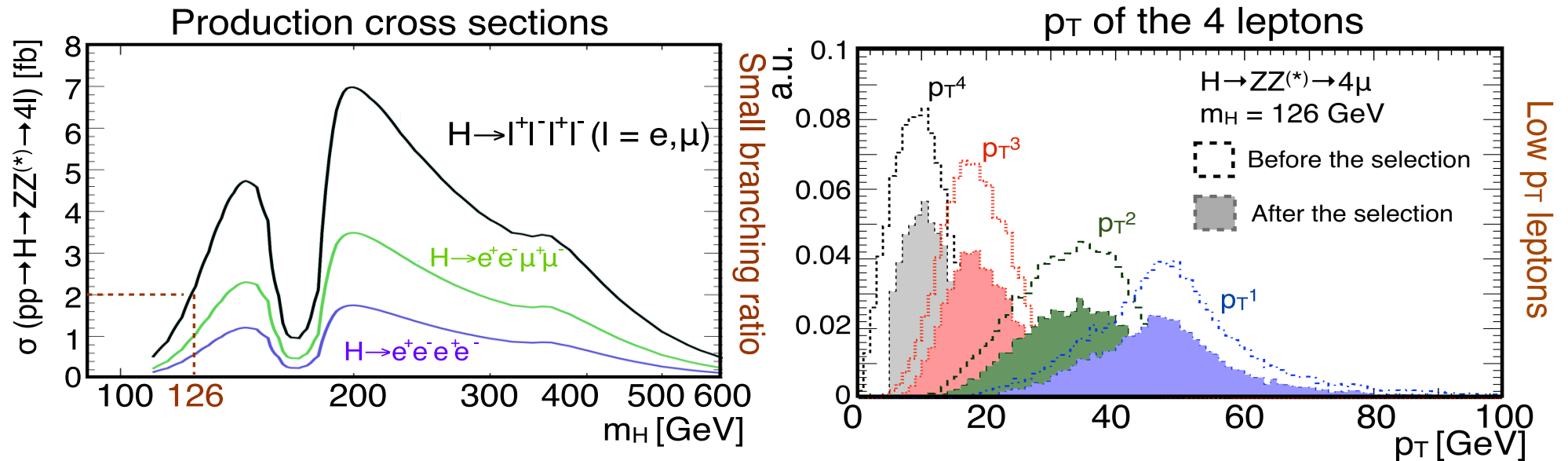
Suppress backgrounds with isolation and impact parameters cuts on two softest leptons.



$H \rightarrow ZZ \rightarrow 4e, 4\mu, 2e2\mu$

One of the best performing channels
in the whole mass range ...

... but extremely demanding channel for
selection, requiring the highest possible
efficiencies (lepton Reco/ID/Isolation).

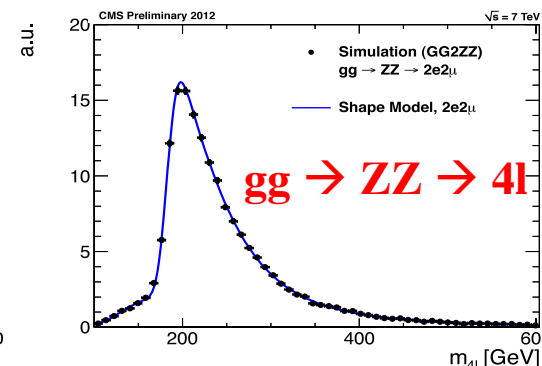
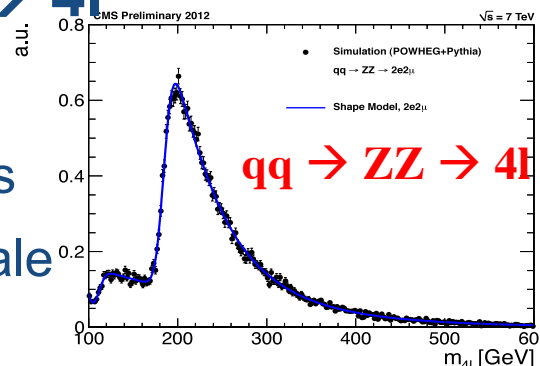




Background models

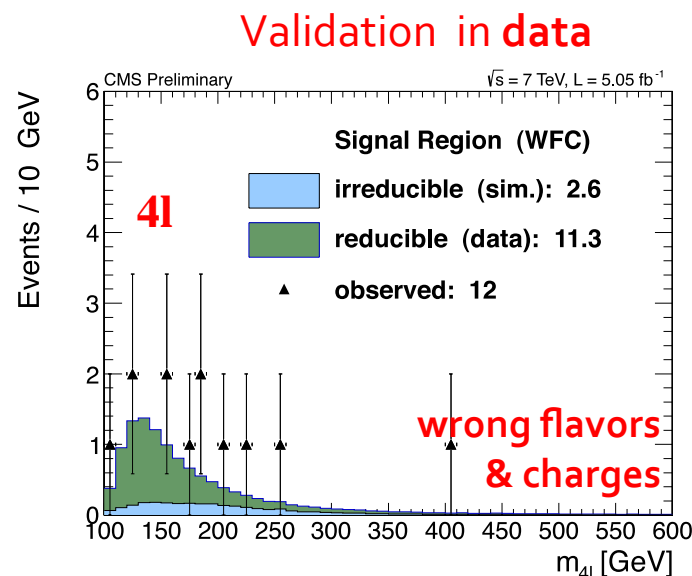
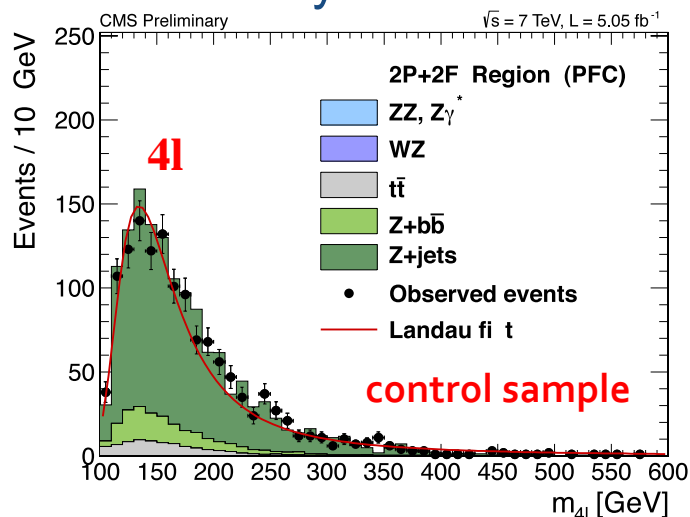
- Irreducible background $ZZ \rightarrow 4l$

- Estimated using simulation
- Phenomenological shape models
- Corrected for data/simulation scale



- Reducible backgrounds estimated from data

- Extrapolation from control samples enriched with misidentified leptons
- Total uncertainty $\sim 50\%$

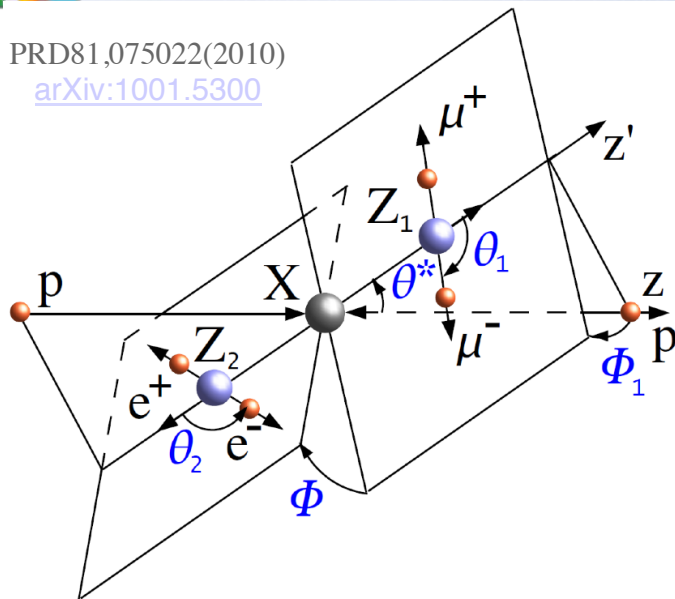




MELA

PRD81,075022(2010)

[arXiv:1001.5300](https://arxiv.org/abs/1001.5300)



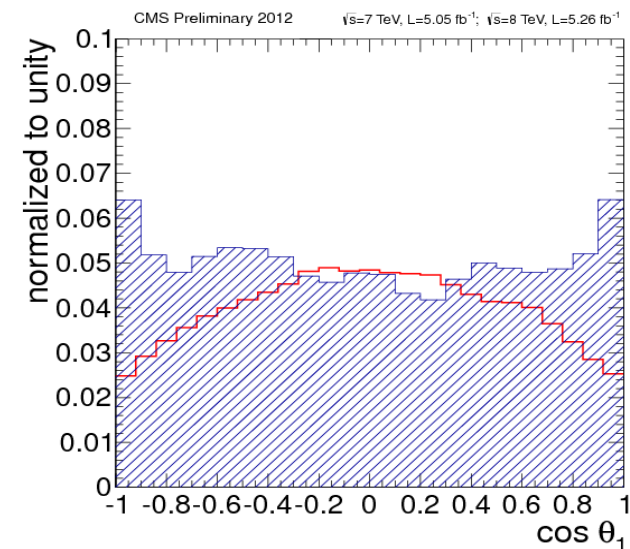
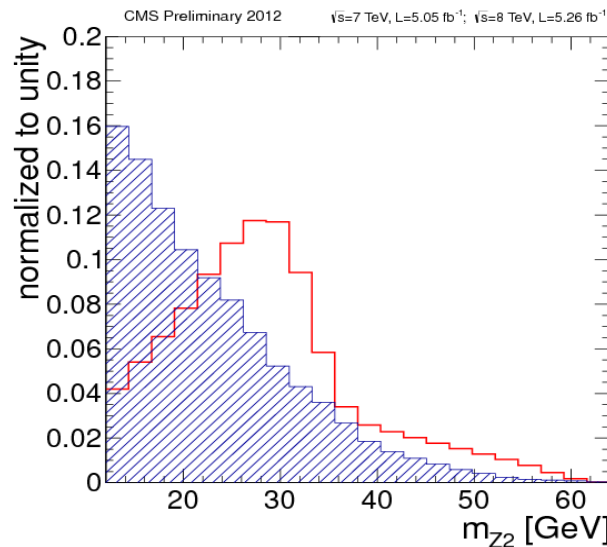
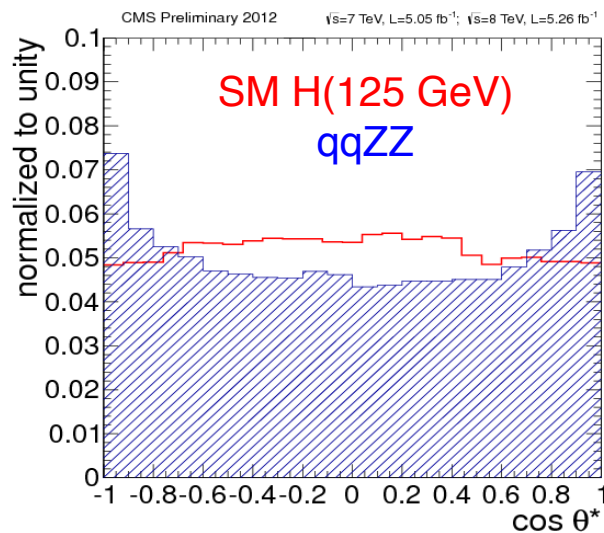
Matrix **E**lement **L**ikelihood **A**nalysis:

uses kinematic inputs for

signal to background discrimination

$$\{m_1, m_2, \theta_1, \theta_2, \theta^*, \Phi, \Phi_1\}$$

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

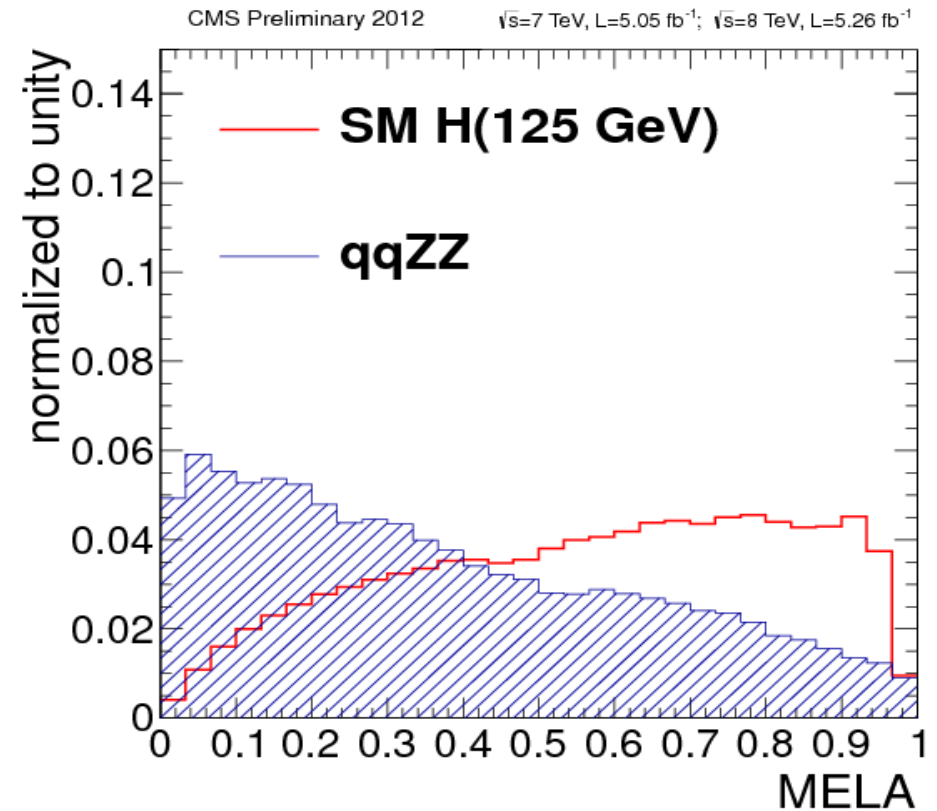
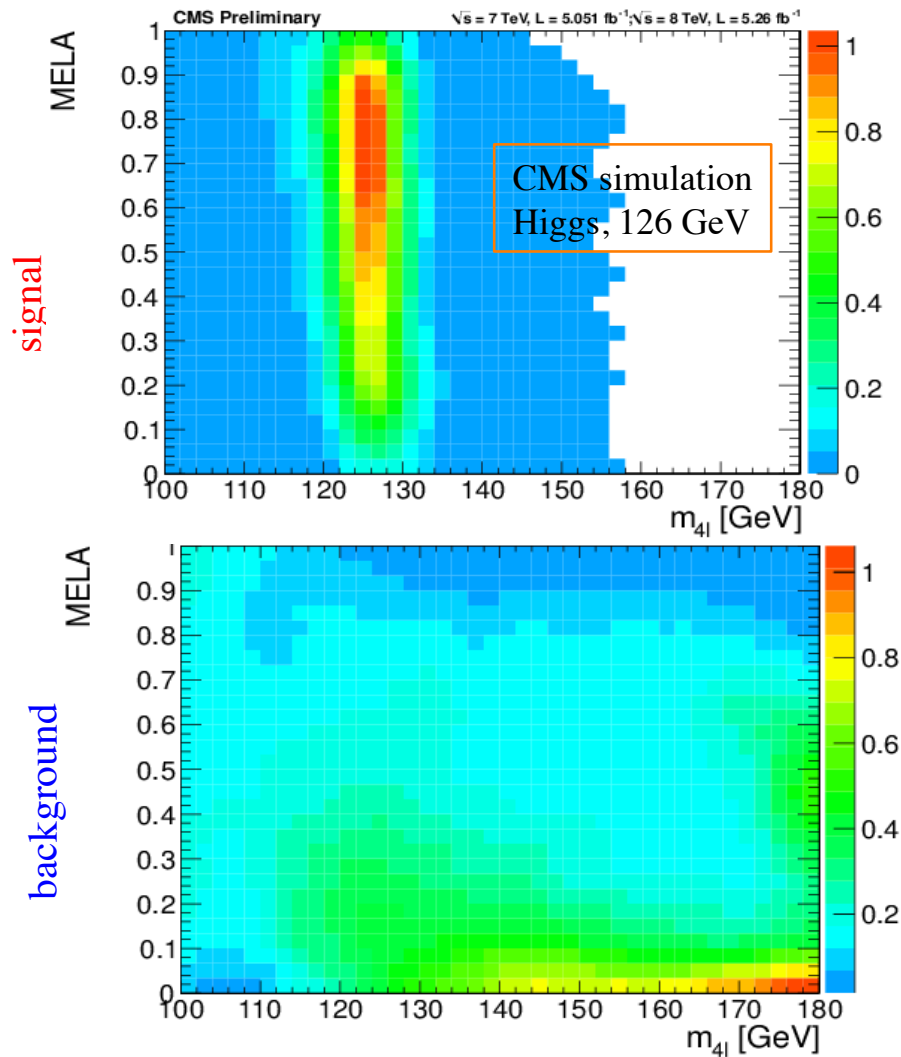


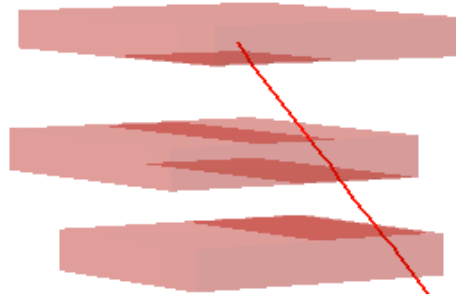


MELA

2D analysis using $\{m_{4l}, \text{MELA}\}$

MELA offers powerful discrimination of background



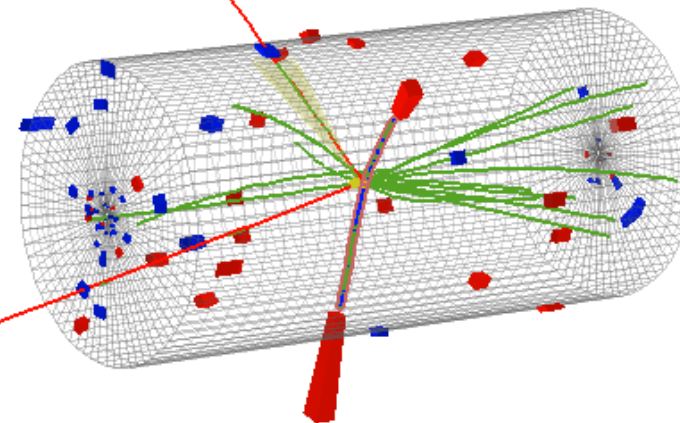


$\mu^+(Z_1) p_T : 43 \text{ GeV}$

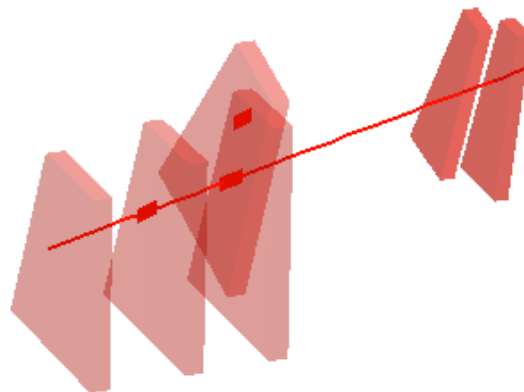
8 TeV DATA

4-lepton Mass : 126.9 GeV

$e^-(Z_2) p_T : 10 \text{ GeV}$



$\mu^-(Z_1) p_T : 24 \text{ GeV}$



$e^+(Z_2) p_T : 21 \text{ GeV}$

CMS Experiment at LHC, CERN
Data recorded: Mon May 28 01:35:47 2012 CEST
Run/Event: 195099 / 137440354
Lumi section: 115



CMS Experiment at LHC, CERN
Data recorded: Thu Oct 13 03:39:46 2011 CEST
Run/Event: 178421 / 87514902
Lumi section: 86



7 TeV DATA

$4\mu+\gamma$ Mass : 126.1 GeV

$\mu^-(Z_2) p_T : 14 \text{ GeV}$

$\gamma(Z_1) E_T : 8 \text{ GeV}$

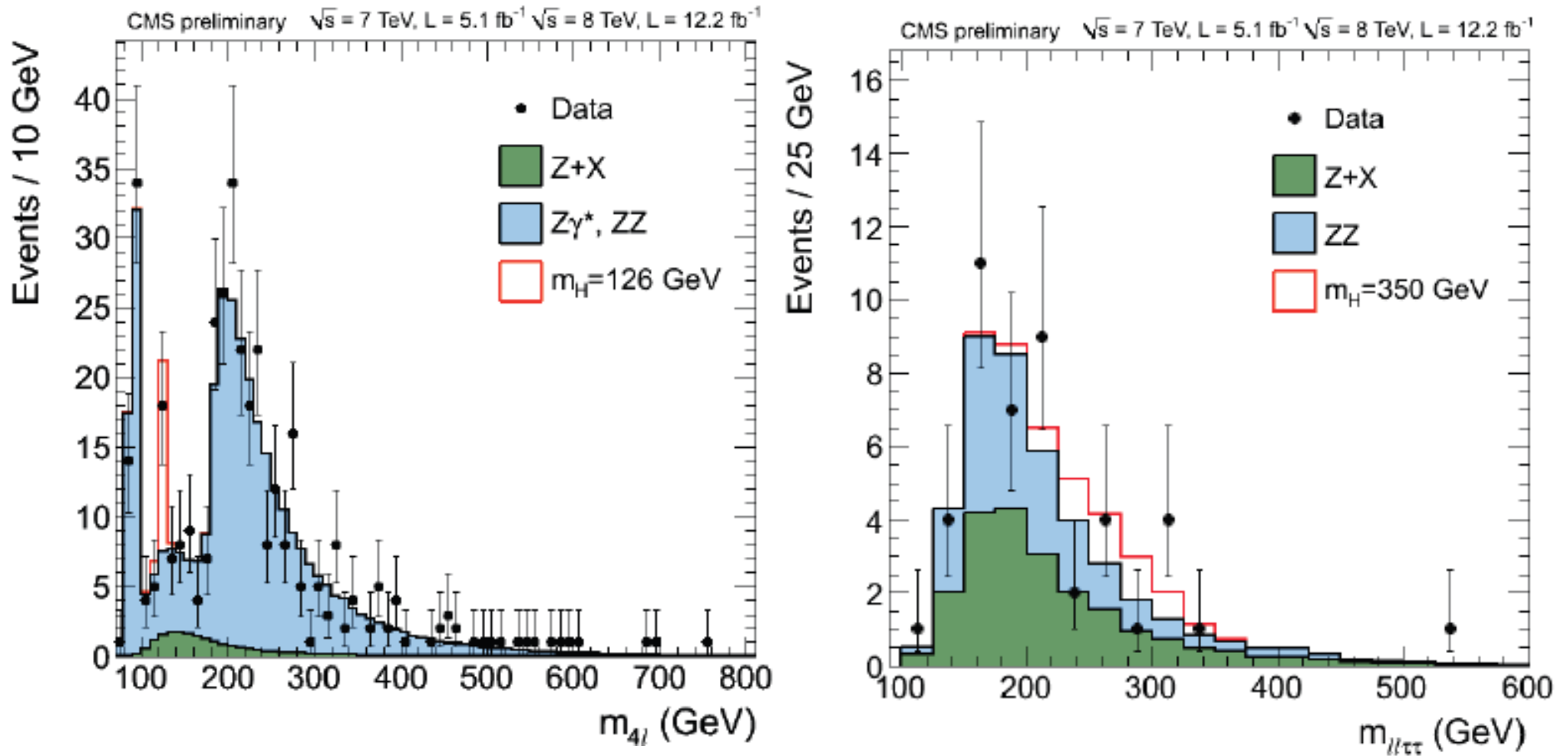
$\mu^-(Z_1) p_T : 28 \text{ GeV}$

$\mu^+(Z_2) p_T : 6 \text{ GeV}$

$\mu^+(Z_1) p_T : 67 \text{ GeV}$

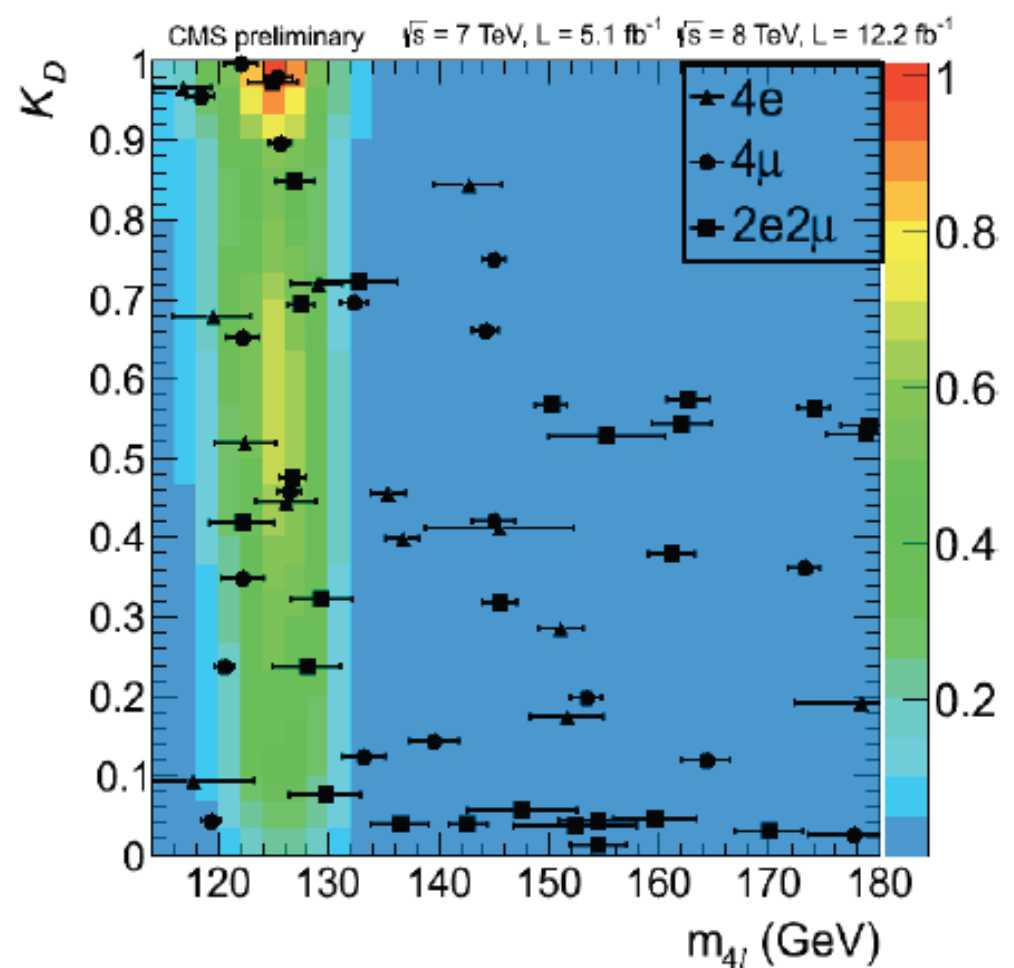
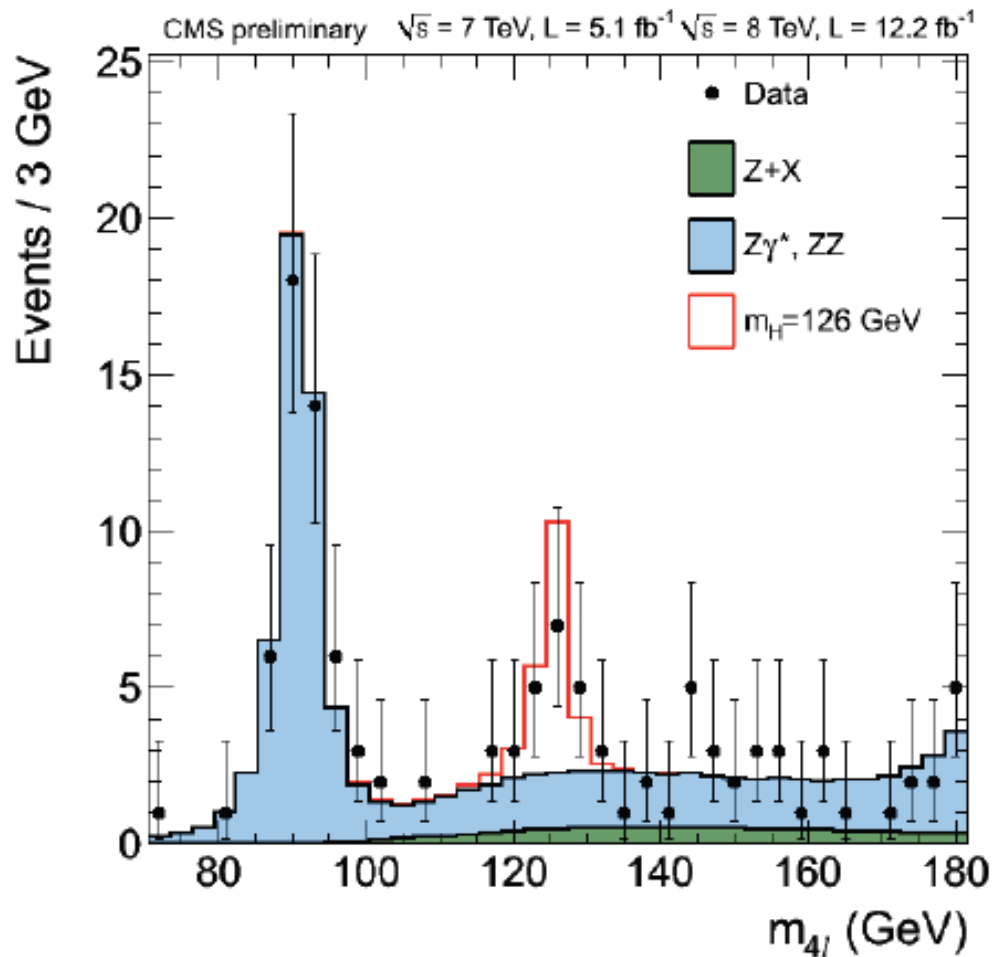


Results: M(4l) spectrum





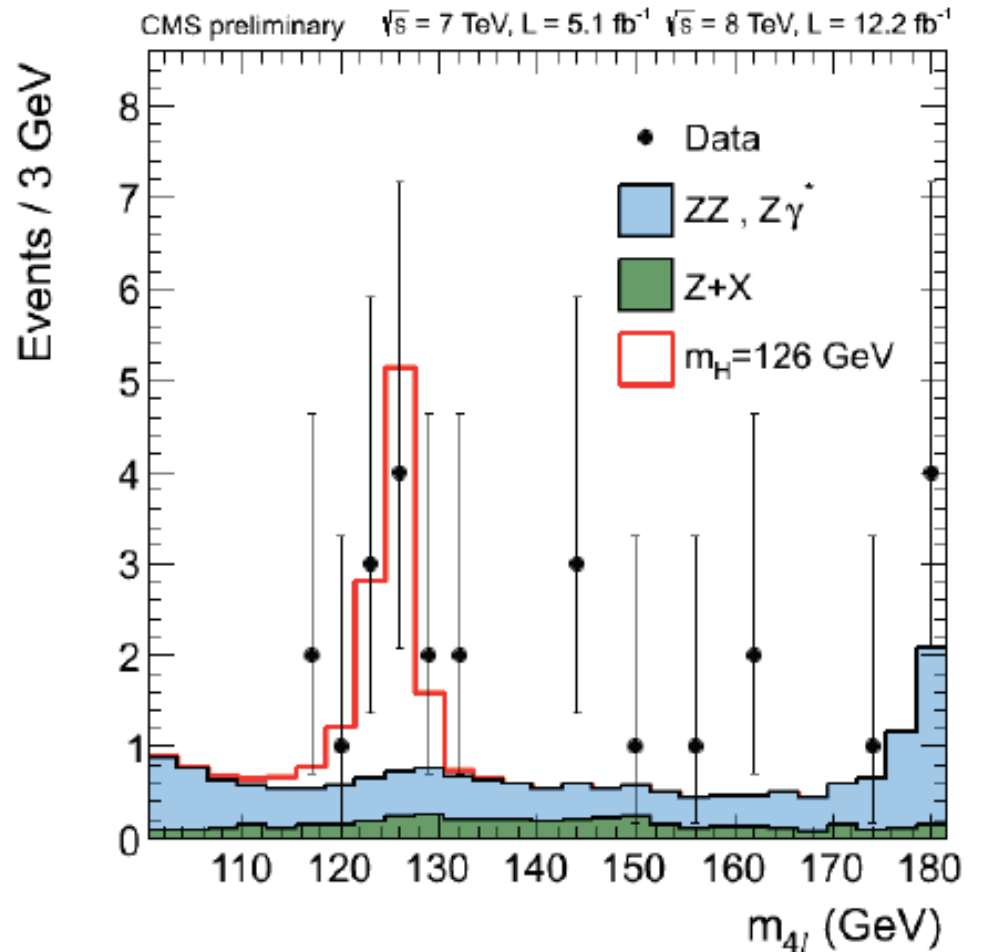
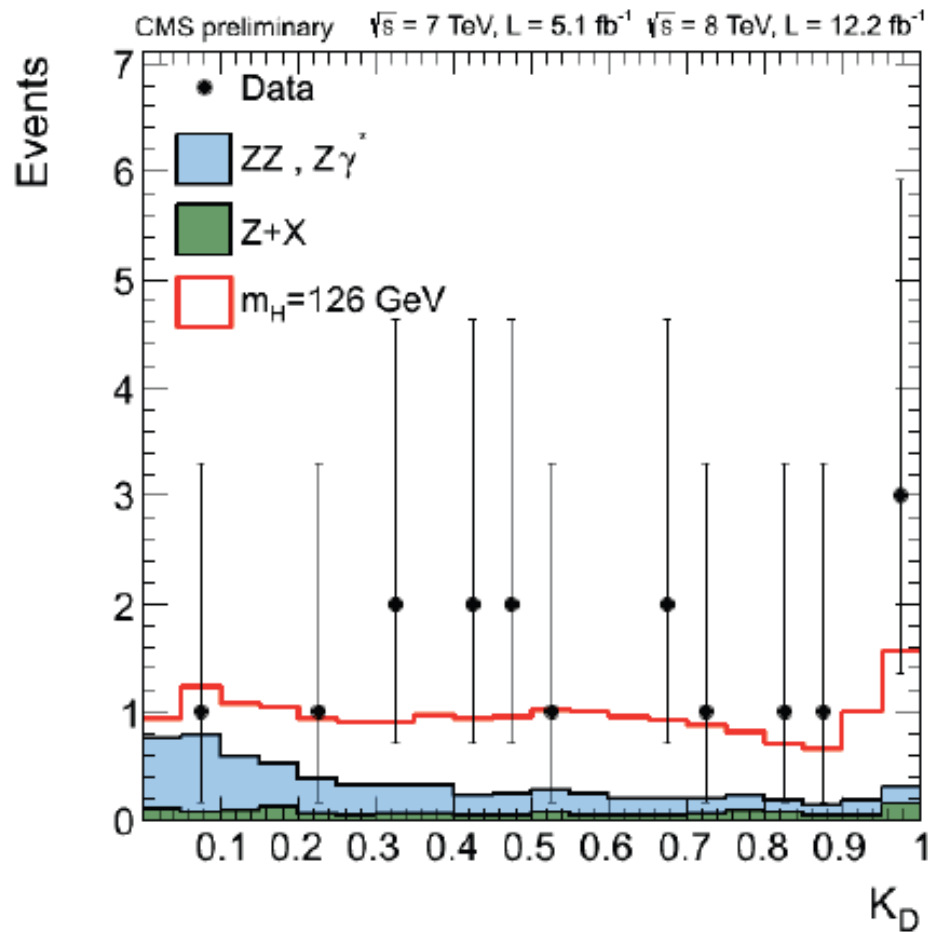
Results: M(4l) spectrum (2)



- With MELA discriminant K_D
- Per-event mass uncertainties
- Color: expected for SM 126 GeV Higgs



Results: M(4l) spectrum and using MELA



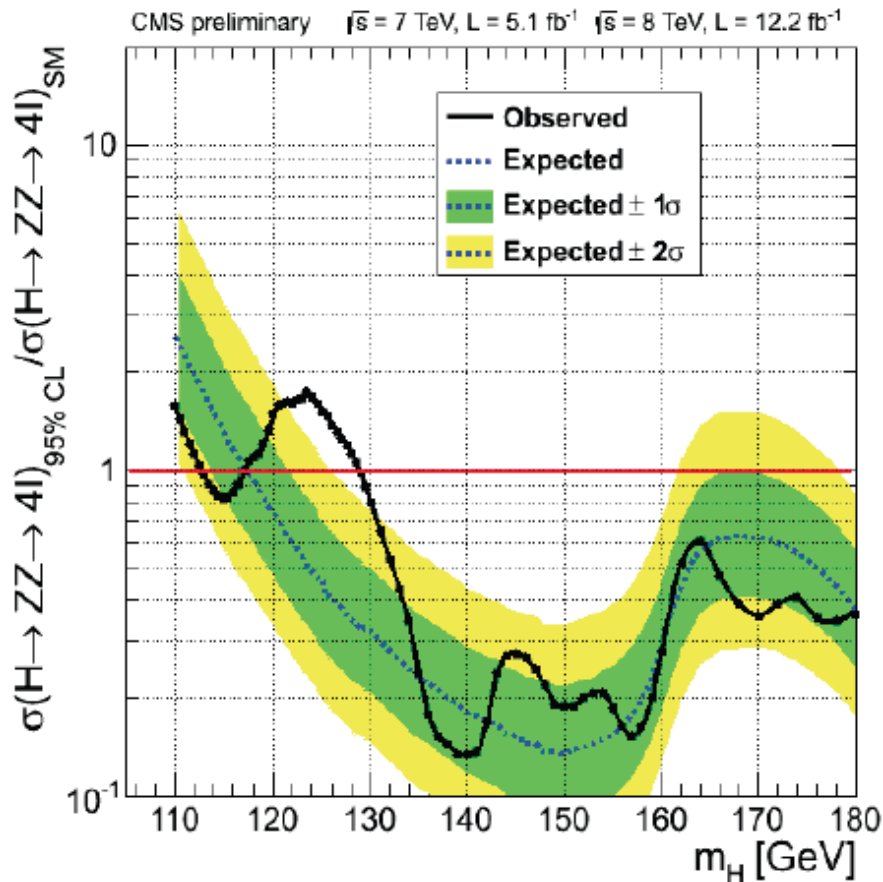
MELA discriminant $K_D > 0.5$

(for the illustration)

BG under peak ~ 3 time lower



Limits and p-values

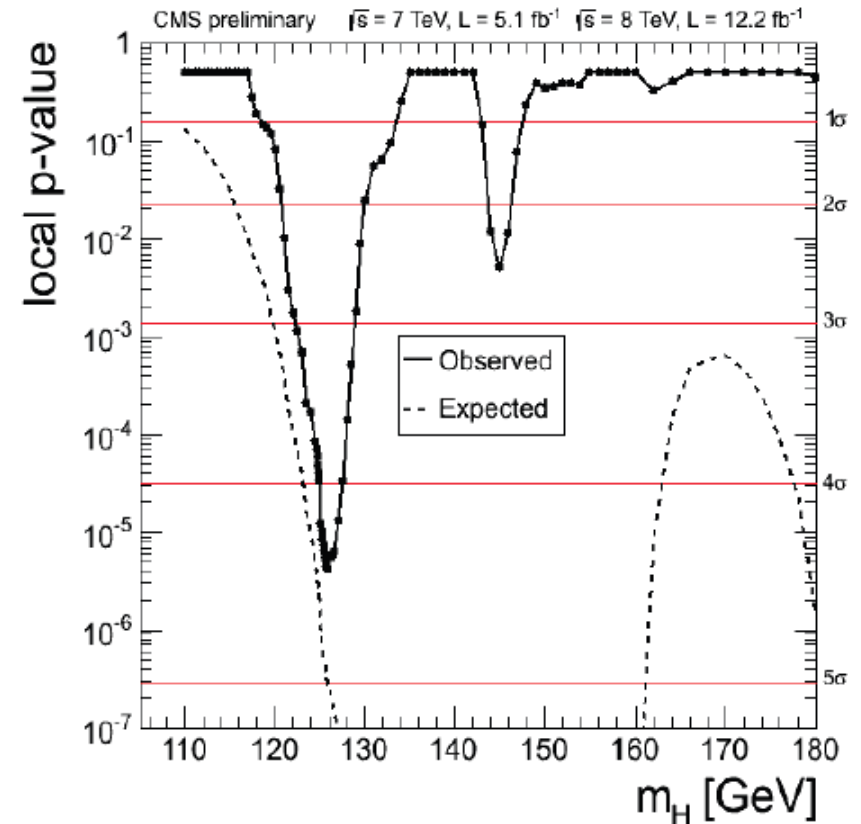


Expected exclusion at 95% CL :

118-670 GeV

Observed exclusion at 95% CL :

113-116 GeV and 129-720 GeV



Expected significance at 125.5 GeV :

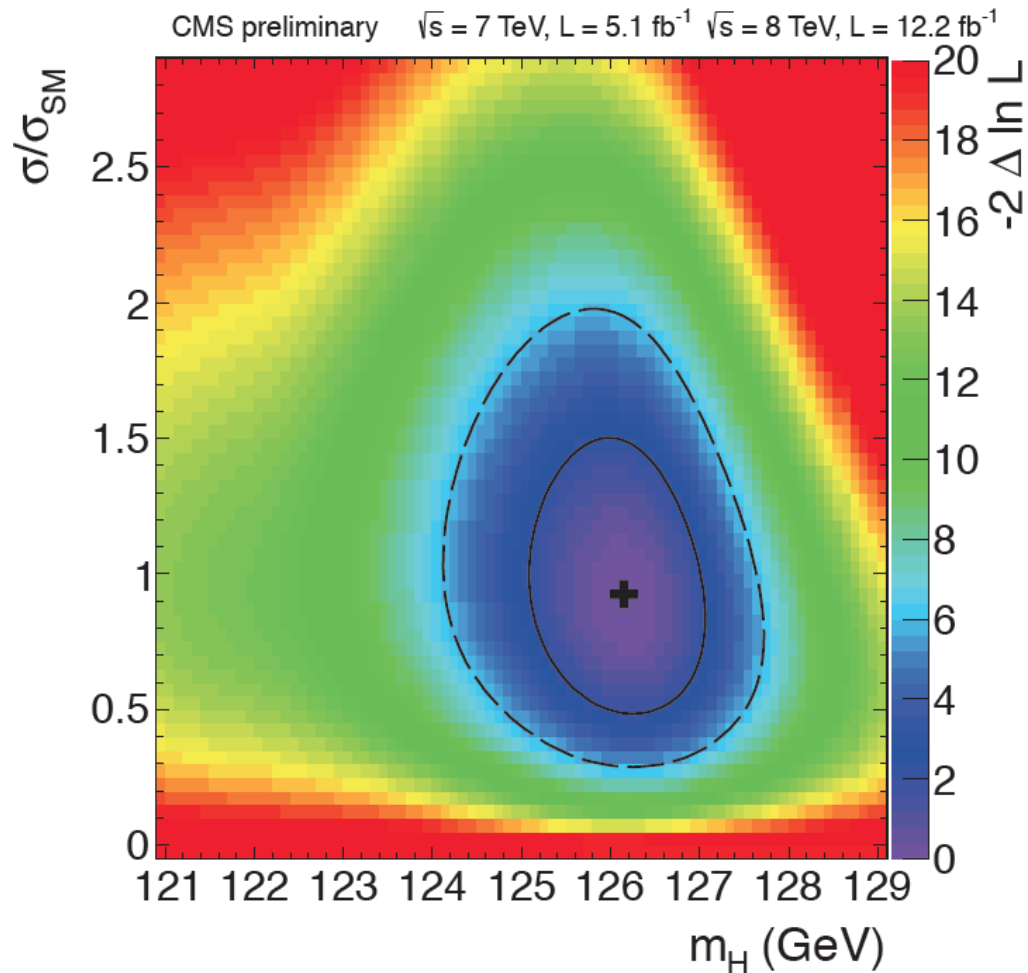
5 σ

Observed significance at 125.5 GeV:

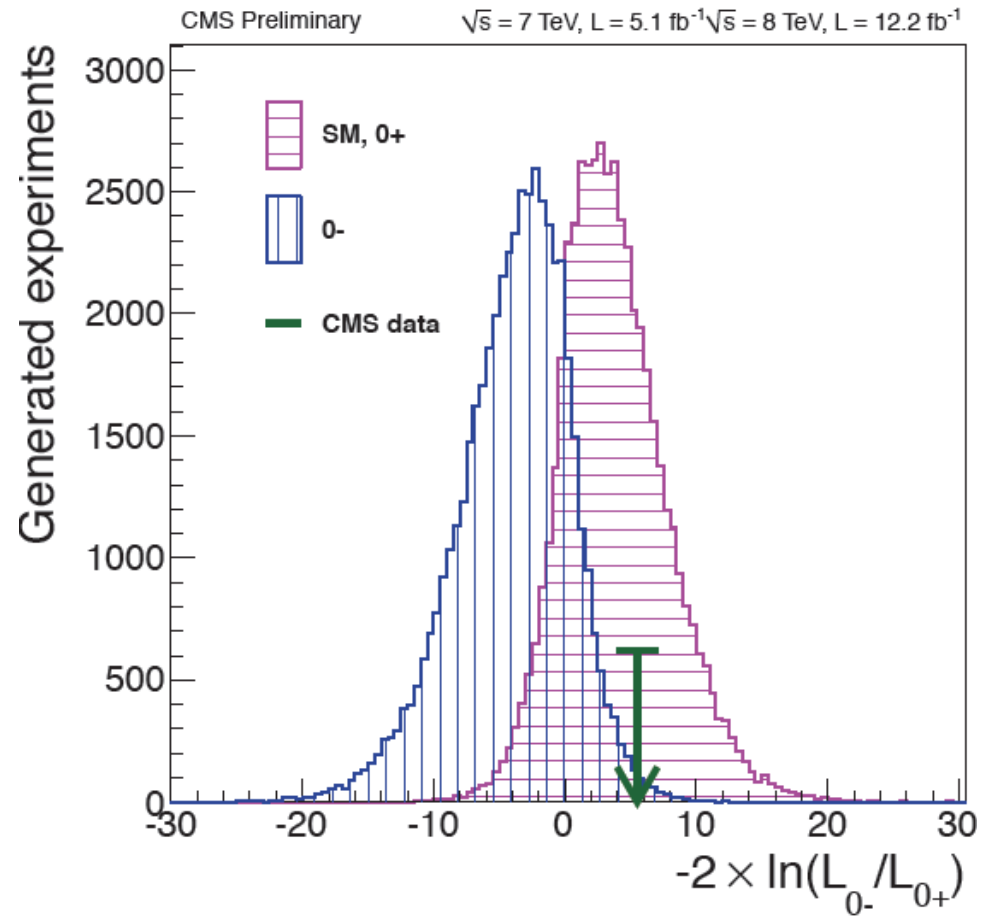
4.5 σ



Rate and parity measurements



$$\sigma/\sigma_{\text{SM}} = 0.8^{+0.35}_{-0.28}$$
$$M = 126.2 \pm 0.6 \text{ (stat)} \pm 0.2 \text{ (syst) GeV}$$

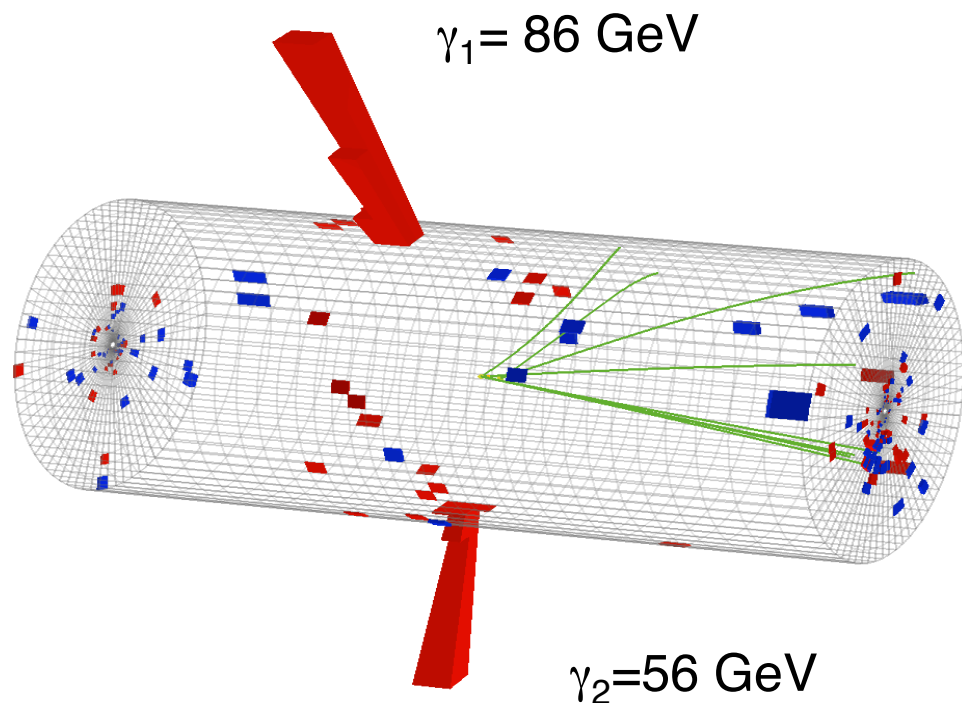


Pseudoscalar disfavoured on the level of
 2.5σ



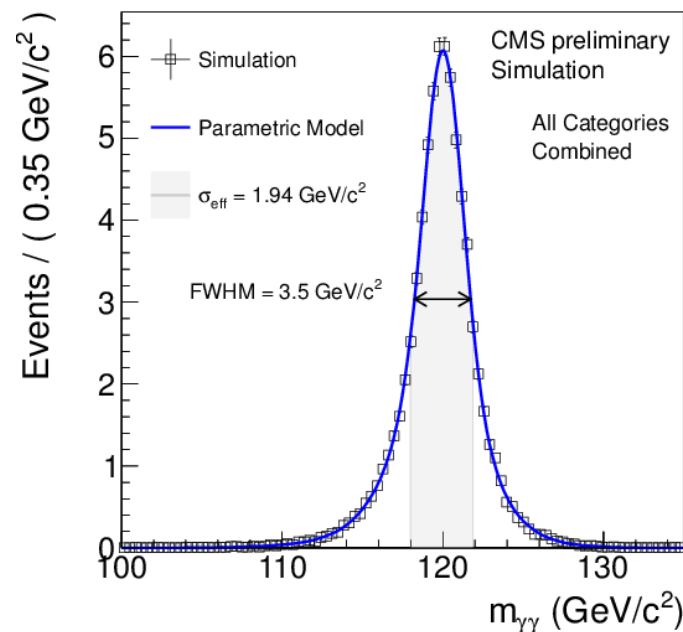
The specialist of the Low Mass: $H \rightarrow \gamma\gamma$

**Signal: 2 energetic, isolated γ .
Search for a narrow mass excess over
a smoothly falling background.**



Excellent resolution: 1-2%

Challenges: vertexing with PU,
calibration of the
electromagnetic calorimeters.
Calibration constants derived
from $Z \rightarrow ee$ data.

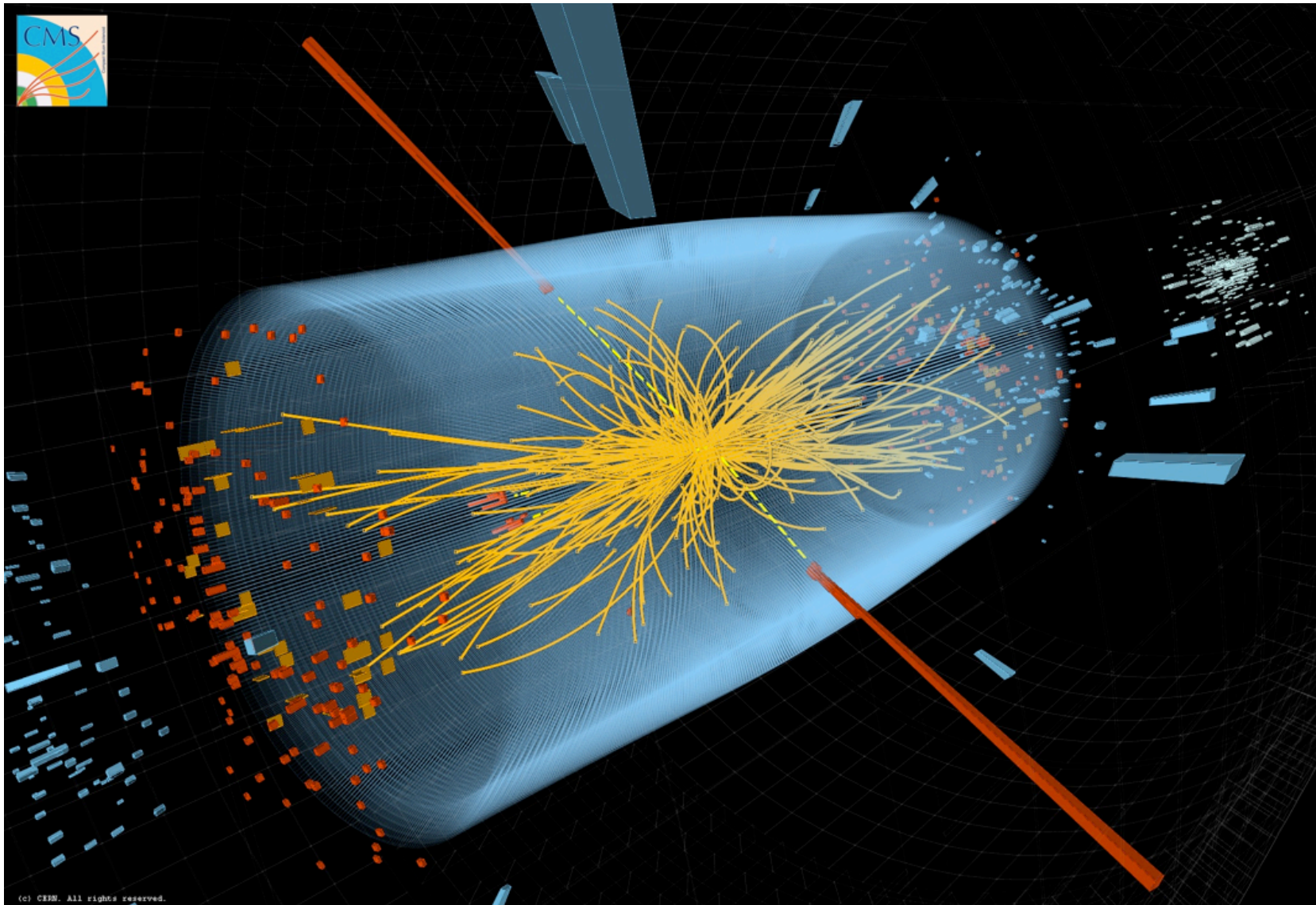


Background: Large and mostly irreducible QCD di-photons.
Measured from $M_{\gamma\gamma}$ sidebands in data

Phys. Lett. B 710 (2012) 403-425



Clean, spectacular events.





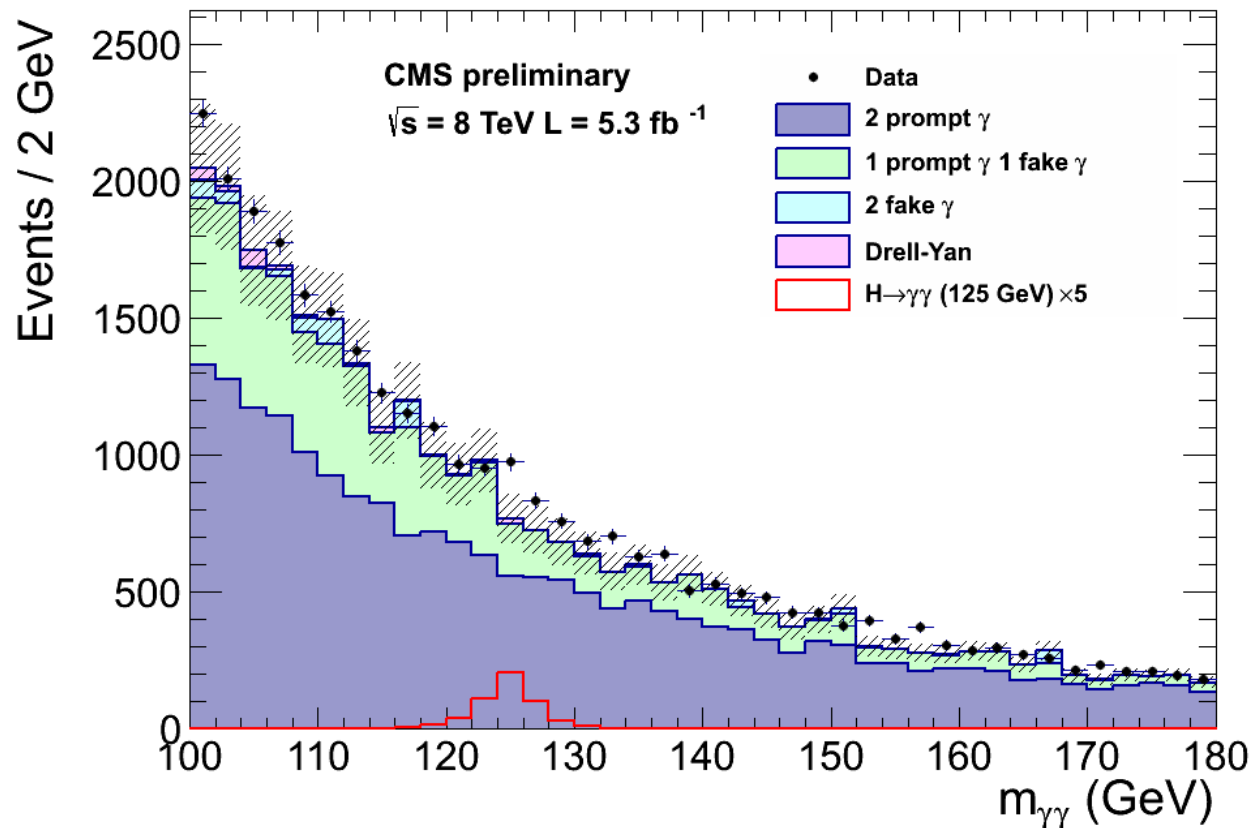
$H \rightarrow \gamma\gamma$ Overview

- Main analysis is a Multi-Variate-Analysis (MVA)
 - MVAs for photon ID and event classification
 - Fit mass distribution in 4 event classes based on a diphoton MVA output + 2 di-jet categories
 - Improvement in expected limit $\sim 15\%$ over cut-based analysis
 - **Cross-checked with an alternative background model extraction:**
 - Fit output of a 2nd MVA combining diphoton MVA and $m_{\gamma\gamma}$ using data in mass sidebands to construct the background model
- Also cross-checked with a cut based analysis
 - Simple and robust
 - Cut based photon ID and event classification
 - Fit data mass distribution in 2 rapidity x 2 shower shape = 4 categories with different Signal over Background (S/B) + 2 di-jet categories
 - Published for 2011 data
 - Phys.Lett. B710 (2012) 403-425 arXiv:1202.1487



Search for a narrow mass peak with two isolated high Et photons

2012 8 TeV

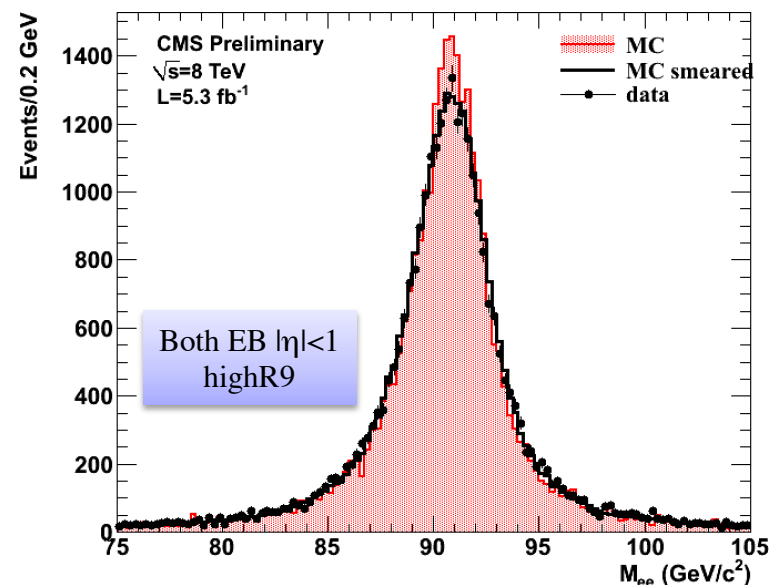
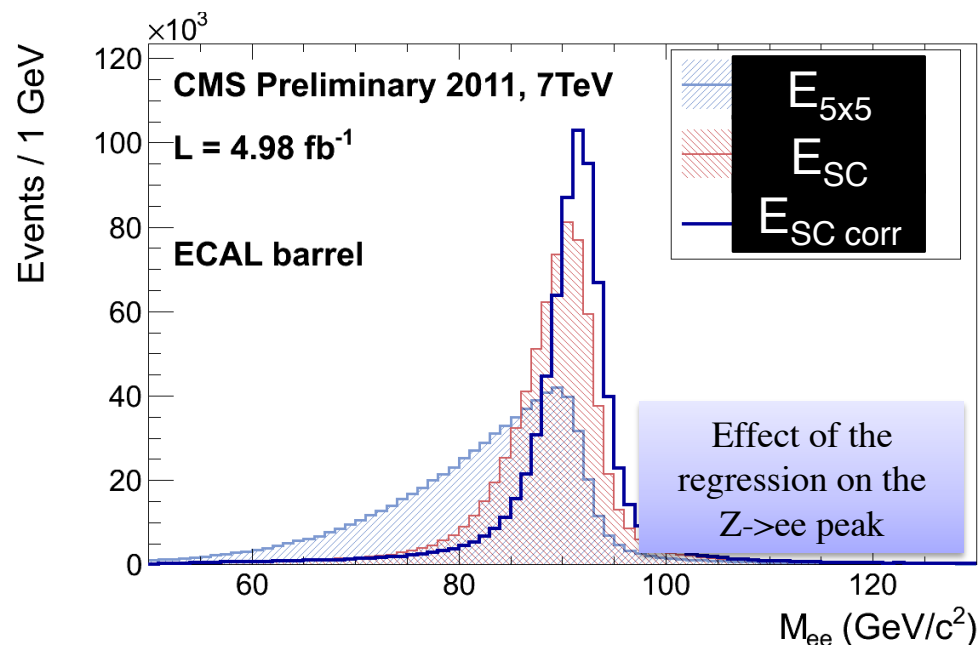


- Blind analysis in 2012
- Re-reco 2011 data into unchanged 2011 analysis
- Background MC only used for analysis optimization, $Z \rightarrow ee$ also to measure photon efficiencies and resolution with data



Photon Energy Scale and Resolution

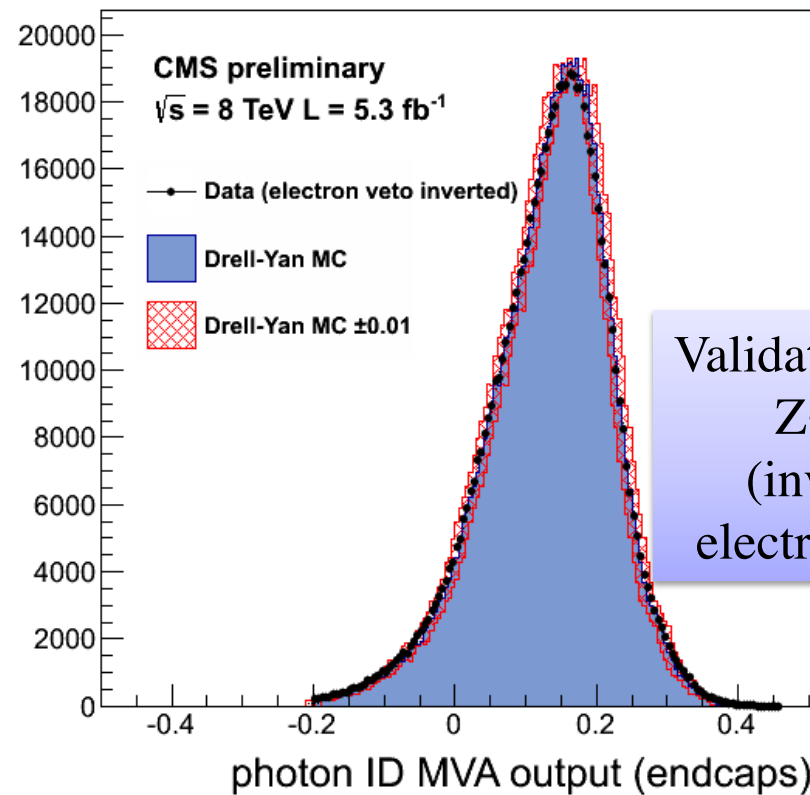
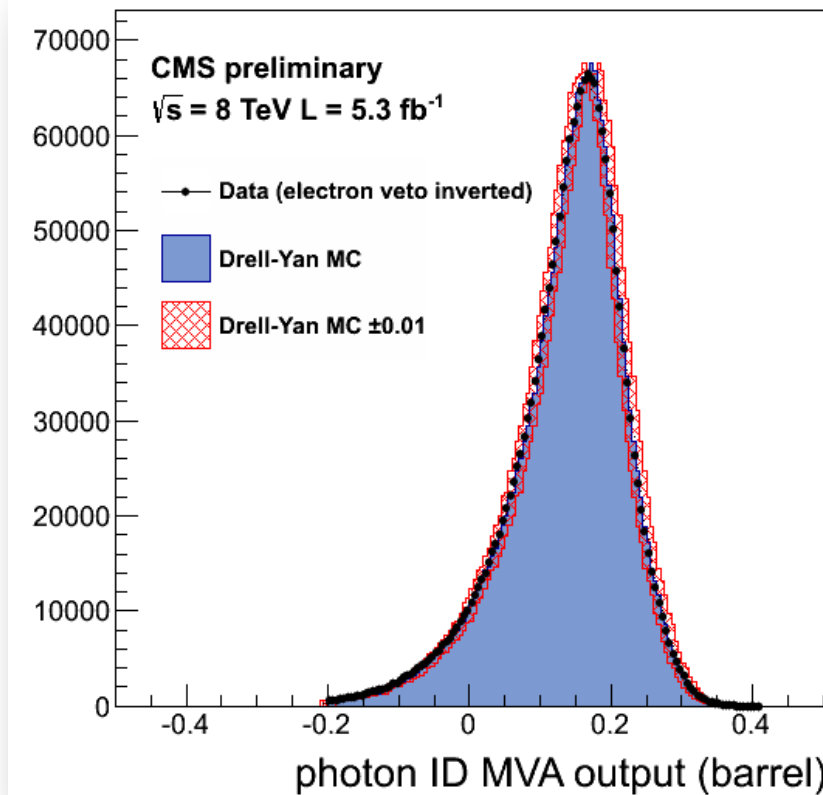
- ECAL cluster energies corrected using a MC trained multivariate regression
 - Improves resolution and restores flat response of energy scale versus pileup
 - Inputs: Raw cluster energies and positions, lateral and longitudinal shower shape variables, local shower positions w.r.t. crystal geometry,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





Photon ID

- **Photon pre-selection:**
 - $E_{\text{TY}1}/m_{\text{YY}} > 3$, $E_{\text{TY}2}/m_{\text{YY}} > 4$
 - Photon ID a bit tighter than trigger selection and MC EM enrichment filters
 - Efficiency measured using tag and probe with $Z \rightarrow ee$
 - Electron veto: Efficiency measured using tag and probe with $Z \rightarrow \mu\mu\gamma$
- **MVA based photon ID discriminates photons from fakes:**
 - Inputs: isolation, shower shape, per event energy density, pseudorapidity

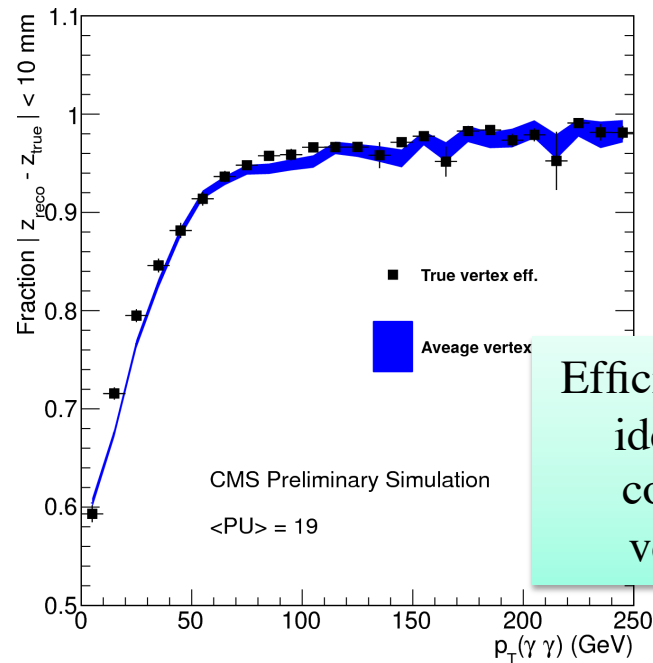


Validation with
 $Z \rightarrow ee$
(inverted
electron veto)

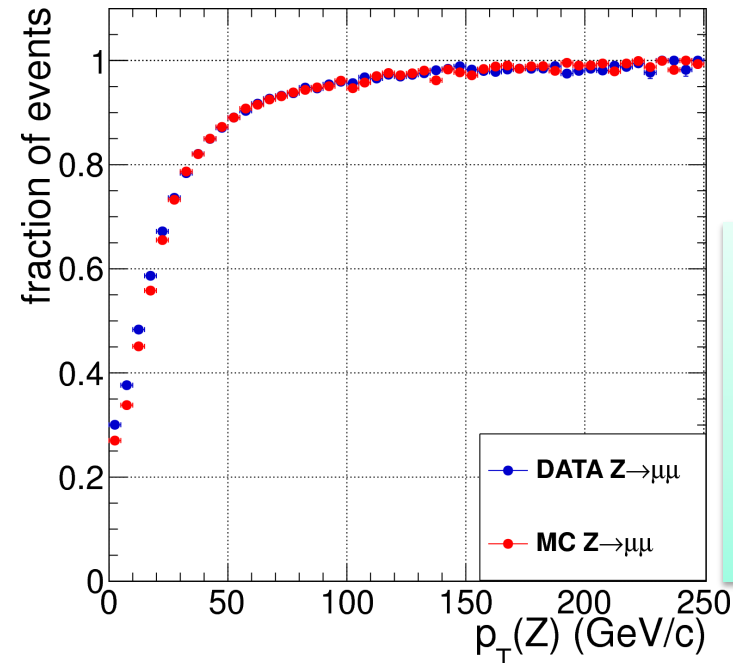


The $\gamma\gamma$ Vertex Choice

- Mass reconstruction
 - Depends on the correct position of the primary vertex
- Interaction vertex is identified using tracks from recoiling jets and underlying event plus conversions
 - correct in ~83% of cases for pileup in 2011 sample.
 - correct in ~80% of cases for pileup in 2012 sample.
- Vertex identification with a BDT
 - Input variables: Σp_t^2 , Σp_t projected onto the $\gamma\gamma$ transverse direction, p_t asymmetry and conversions
- Correct vertex finding probability also estimated using a BDT



Efficiency to
identify
correct
vertex

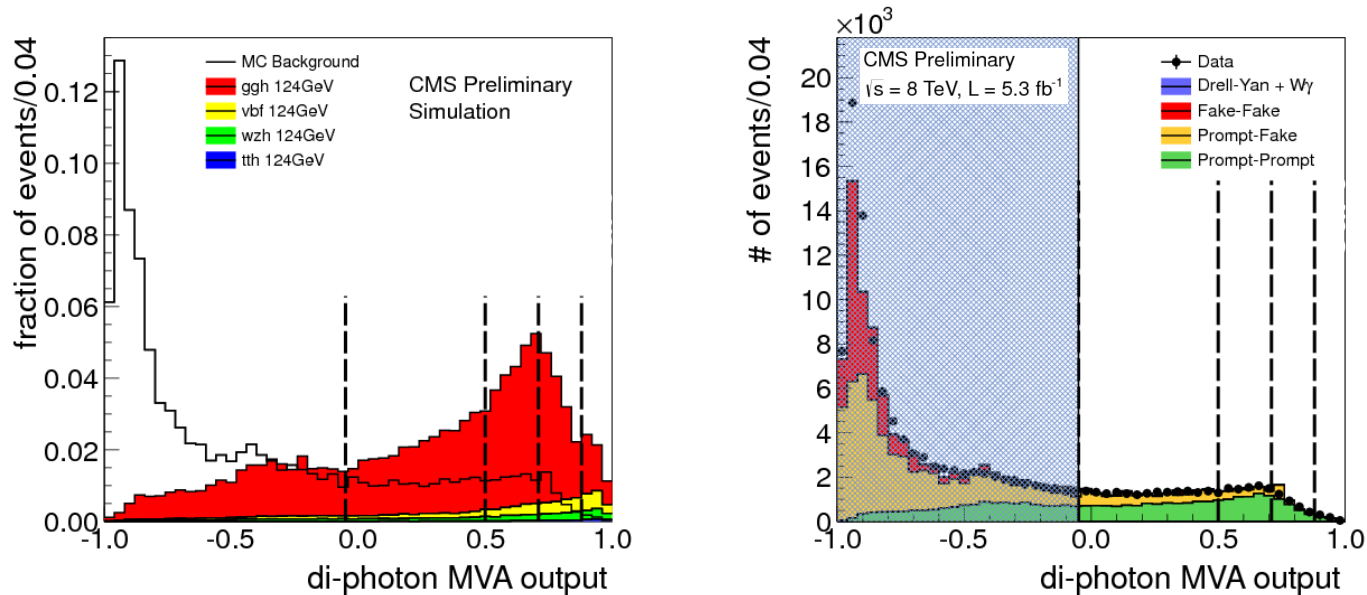


Data-MC
efficiency
for $Z \rightarrow \mu\mu$
After
removing the
 μ tracks



Diphoton MVA

- Diphoton MVA trained on signal and background MC with input variables largely independent of $m_{\gamma\gamma}$
 - Kinematics: p_T and η of each photon, and $\cos\Delta\phi$ between the 2 photons
 - Photon ID MVA output for each photon
 - per-event mass resolution and vertex probability
- Encode all relevant information on signal vs background discrimination (aside from $m_{\gamma\gamma}$ itself) into a single di-photon MVA output to first order independent of $m_{\gamma\gamma}$



- Residual data-MC disagreement
 - For BG only make analysis sub-optimal
 - For signal would cause some category migration included in the systematic errors

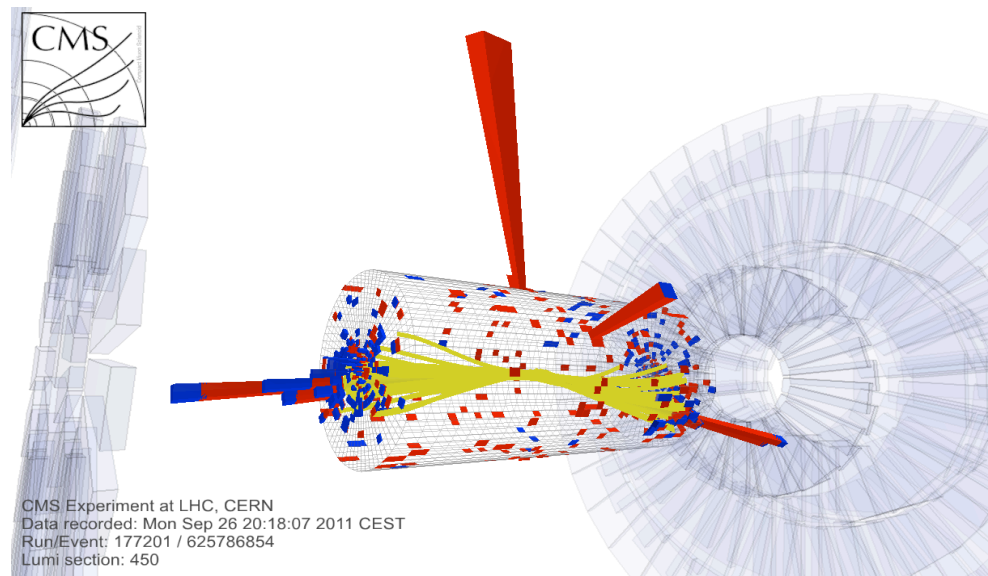


Di-jet Tagging

- Exclusive selection of di-photon events with VBF-like topology:
 - Two high p_T jets with large pseudo-rapidity difference and invariant mass
- High S/B
- ~80%-pure VBF events for large di-jet invariant masses

Di-jet event with:

- diphoton mass 121.9 GeV
 - dijet mass 1460 GeV
- jet p_T : 288.8 and 189.1 GeV
 - jet η : -2.022 and 1.860





Di-jet Tagging: selection

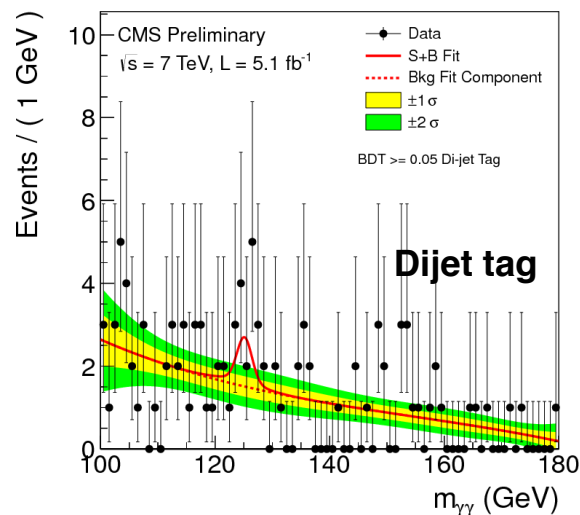
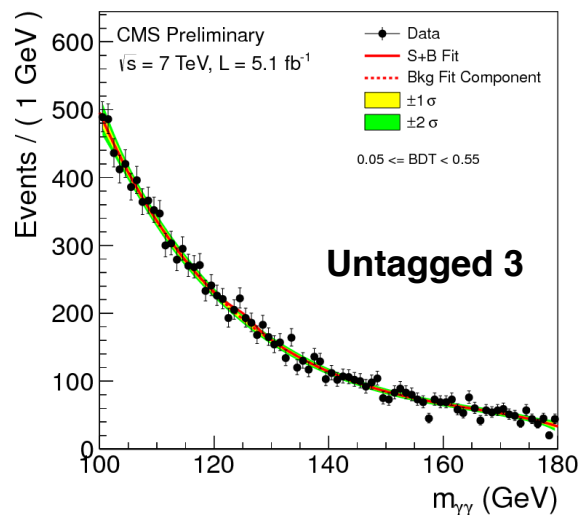
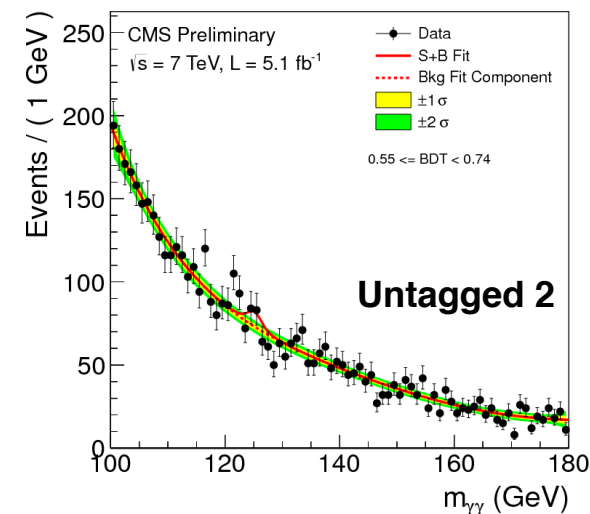
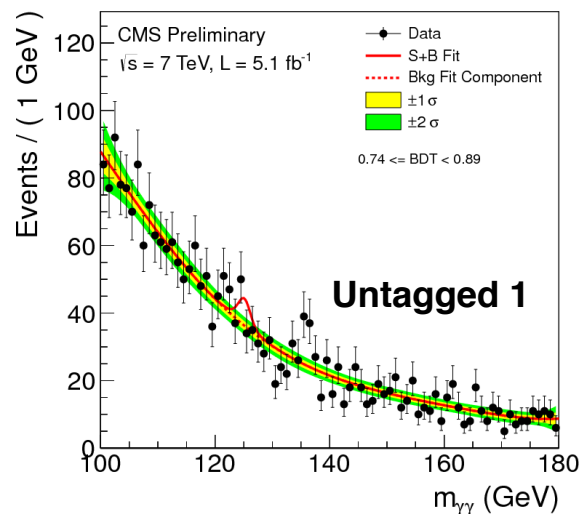
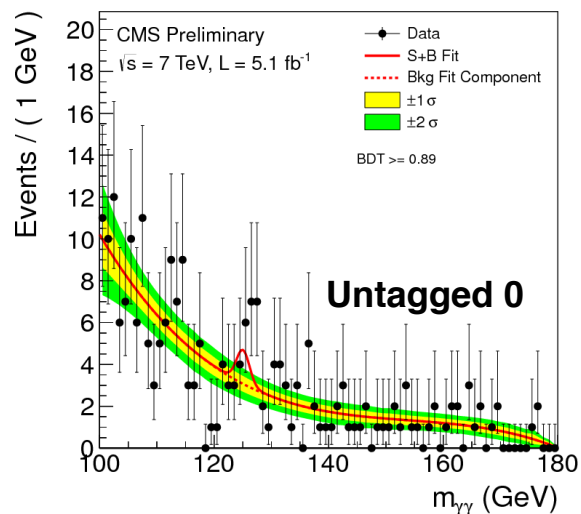
- Split di-jet tagged events in two categories based on M_{jj} and jet p_T
 - ~15% improvement in sensitivity for dijet category
 - better sensitivity to separate different Higgs production modes
 - Based on the jet shape variables, tracks in jet and vertexing
 - Cross-checked using Z+jet and γ +jet events

Dijet selection cuts

Variable	2011	2012	
		Loose	Tight
$p_T(j_1)$	$> 30 \text{ GeV}$		
$p_T(j_2)$	$> 20 \text{ GeV}$	$> 30 \text{ GeV}$	
$\Delta\eta(j_1, j_2)$	> 3.5	> 3.0	
$ \eta_{\gamma\gamma} - \frac{1}{2}(\eta_{j1} + \eta_{j2}) $	< 2.5		
$\Delta\phi(jj, \gamma\gamma)$	> 2.6		
m_{jj}	$> 350 \text{ GeV}$	$> 250 \text{ GeV}$	$> 500 \text{ GeV}$



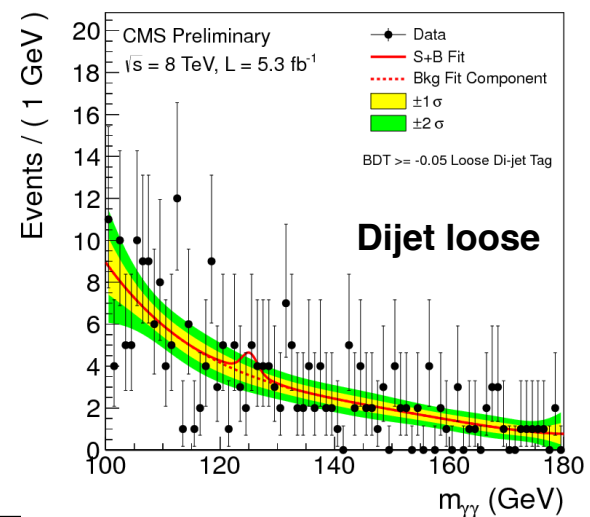
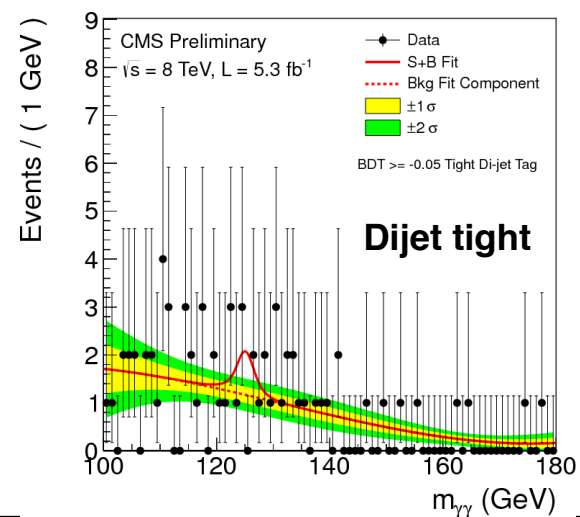
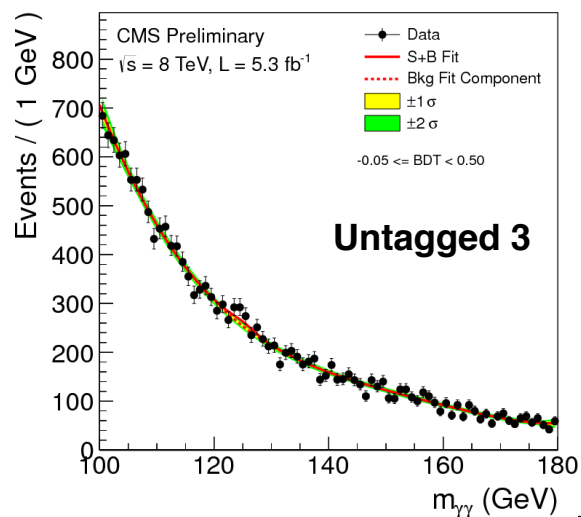
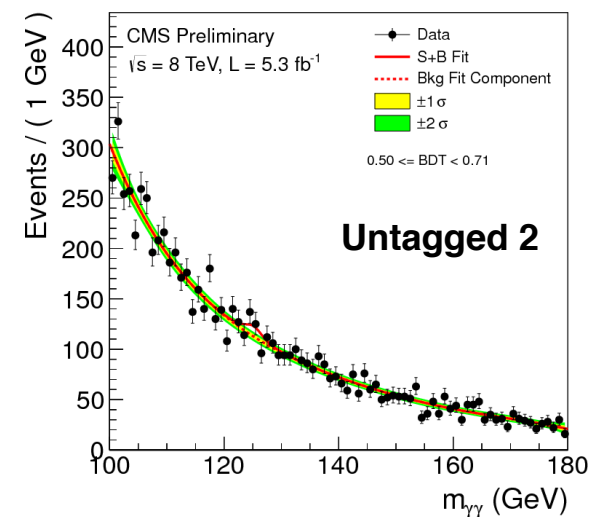
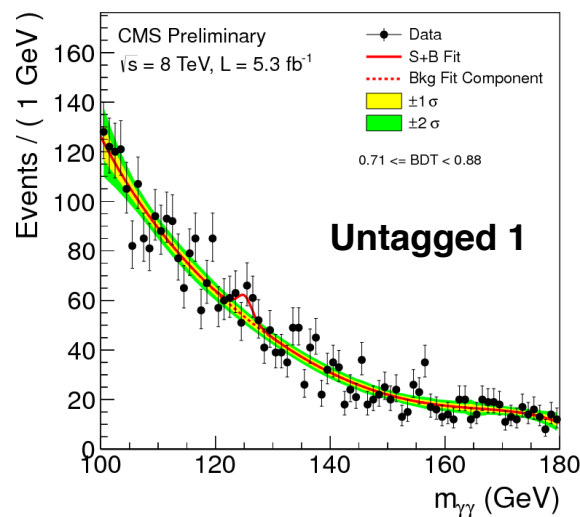
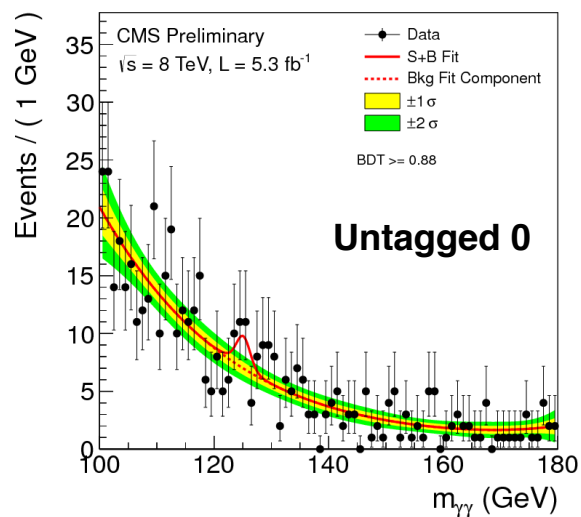
7 TeV Mass Distribution in Categories



- Background model is entirely from data.
- Fit to mass distribution in each category with polynomial functions (3rd to 5th degree)
 - keep bias below 20% of fit error.
 - causes some loss of performance due to number of parameters in fit function.



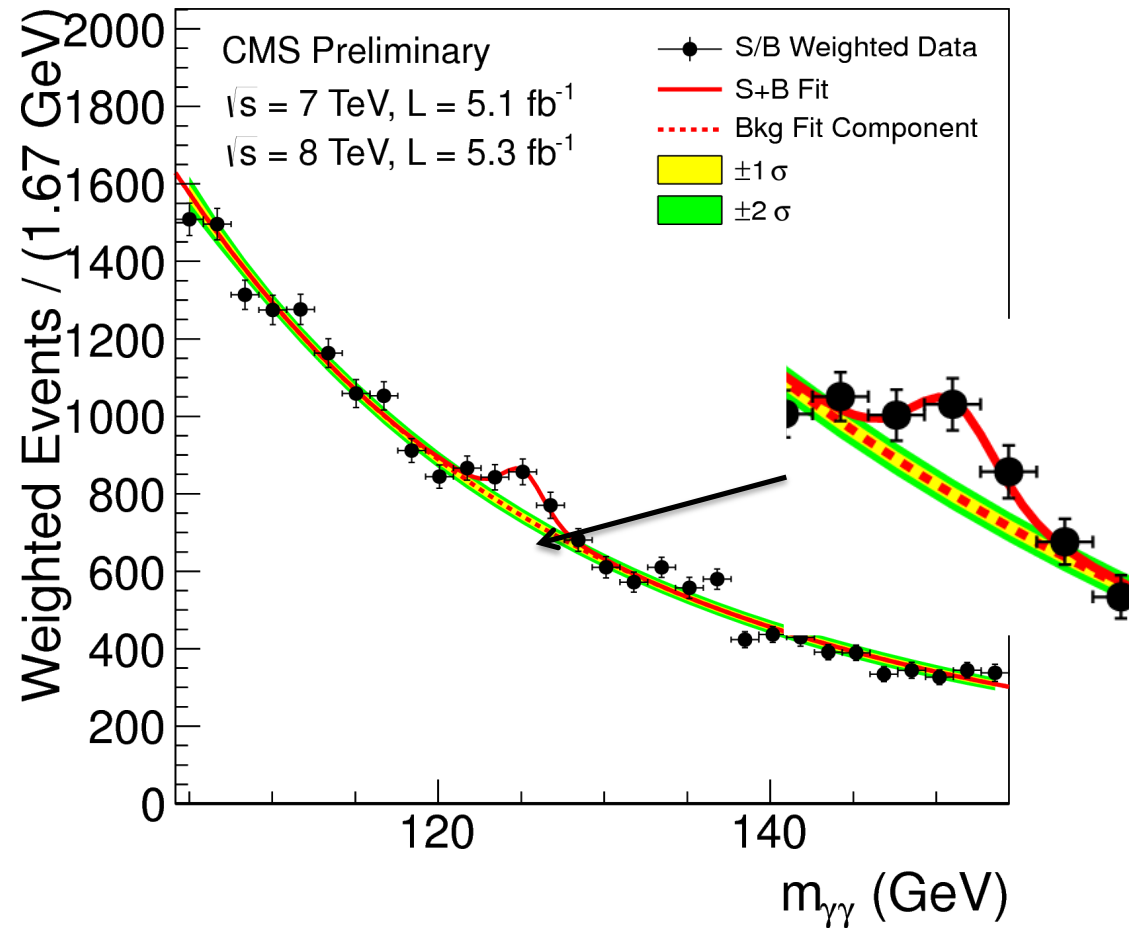
8 TeV Mass Distribution in Categories





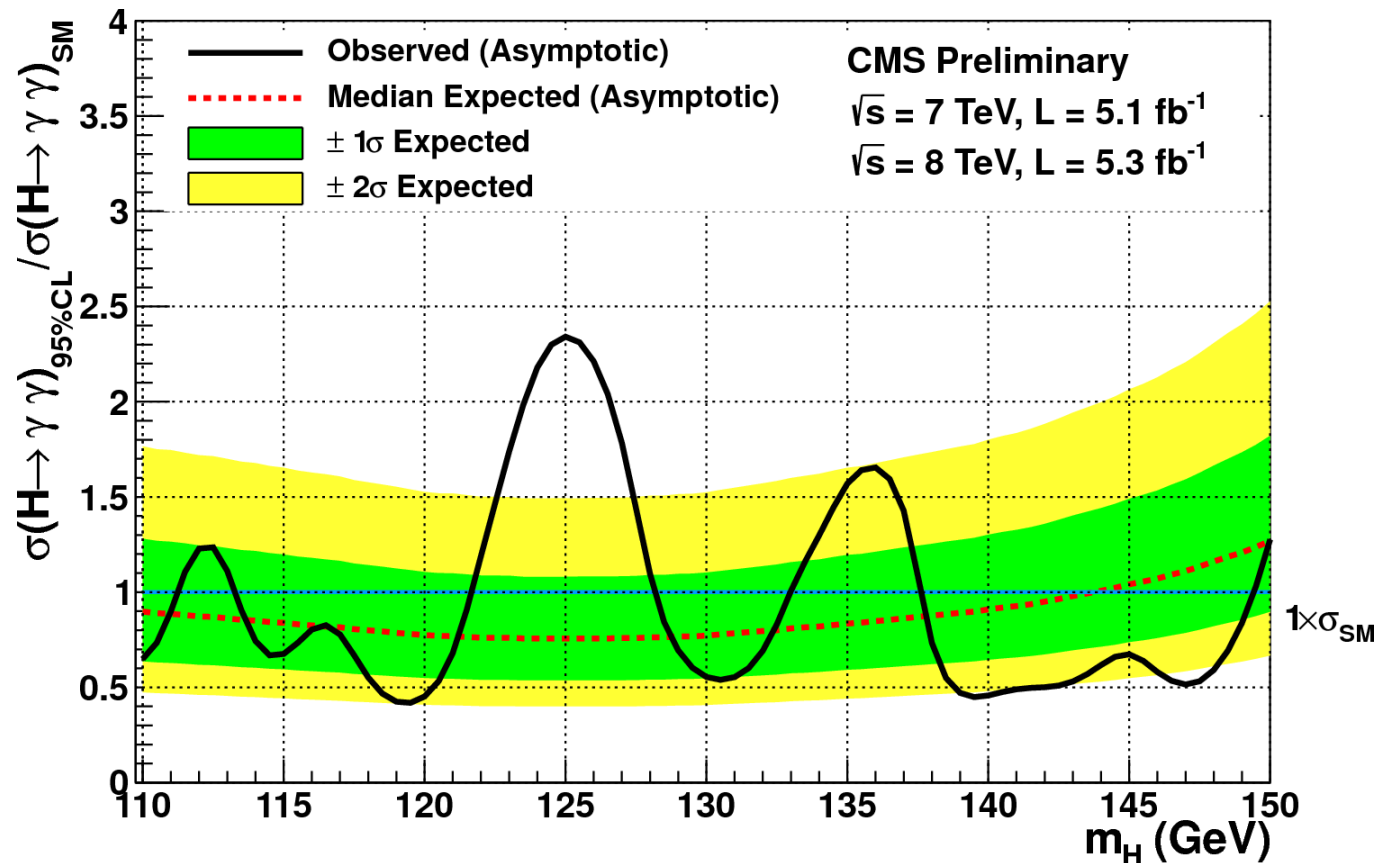
S/B Weighted Mass Distribution

- Sum of mass distributions for each event class, weighted by S/B
 - B is integral of background model over a constant signal fraction interval





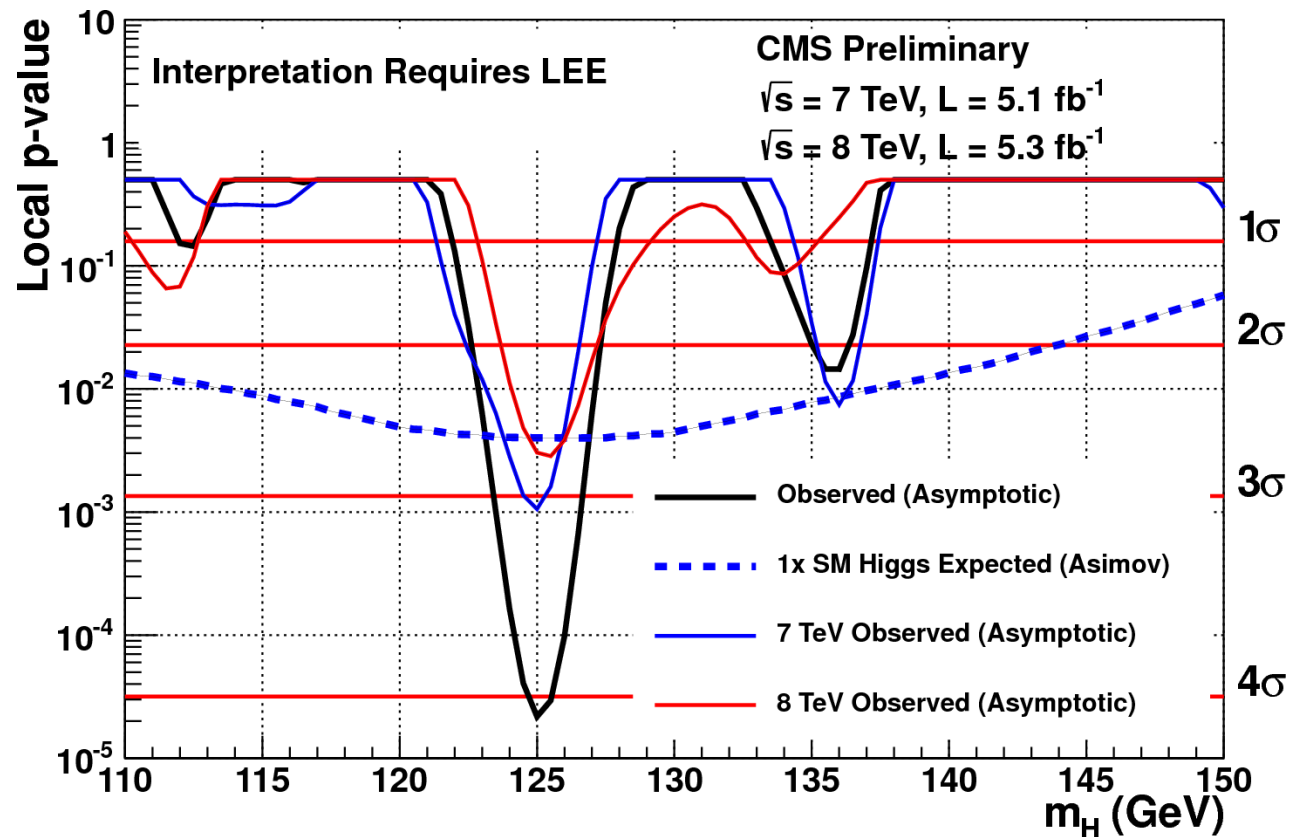
95% CL Exclusion for SM Higgs



- Expected 95% CL exclusion 0.76 times SM at 125 GeV
- Large range with expected exclusion below σ_{SM}
- Largest excess at 125 GeV



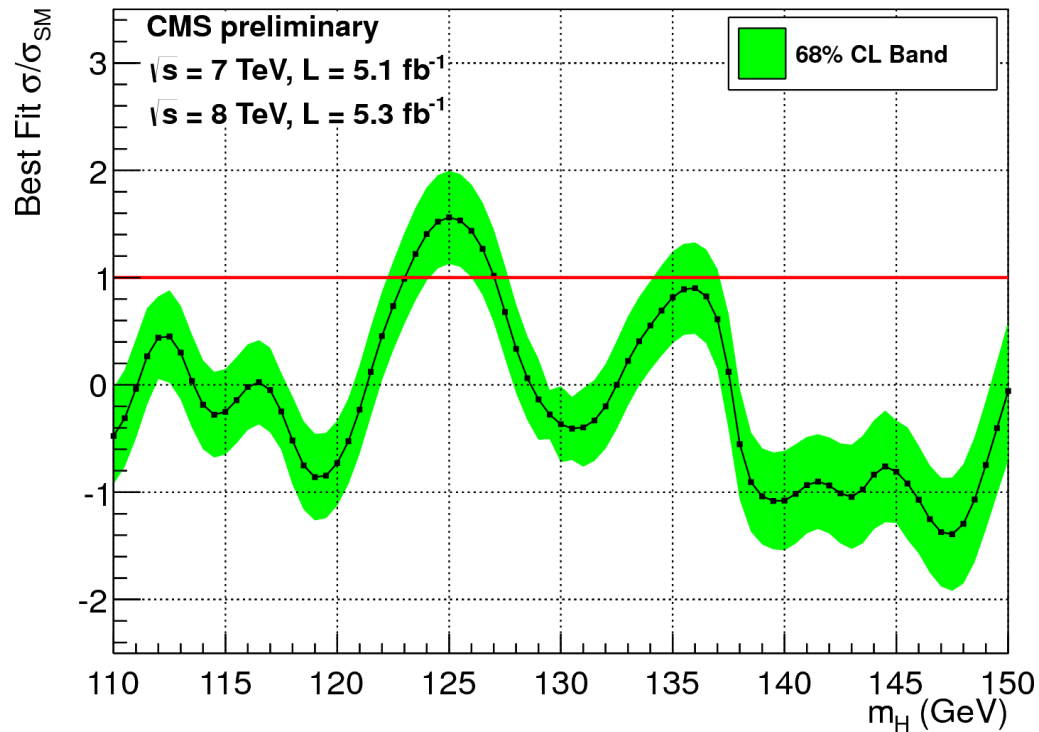
P-Values



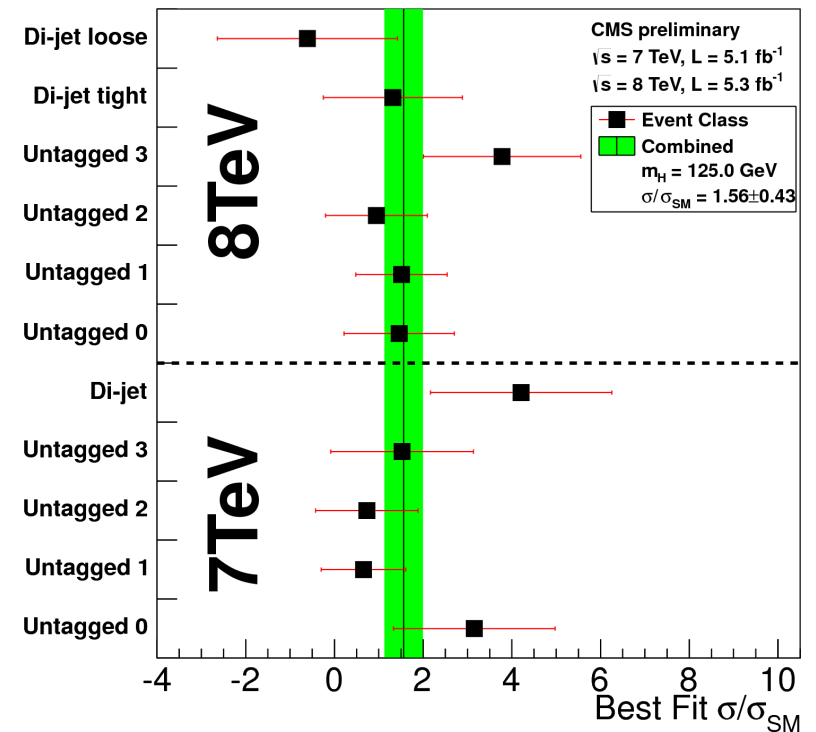
- Minimum local p-value at 125 GeV with a local significance of 4.1σ
- Similar excess in 2011 and 2012
- Independent cross check analyses give similar results
- Global significance in the full search range (110-150 GeV) 3.2σ



Fitted Signal Strength



Combined best fit signal strength
 $\sigma/\sigma_{\text{SM}} = 1.56 \pm 0.43 \times \text{SM}$,
consistent with SM.

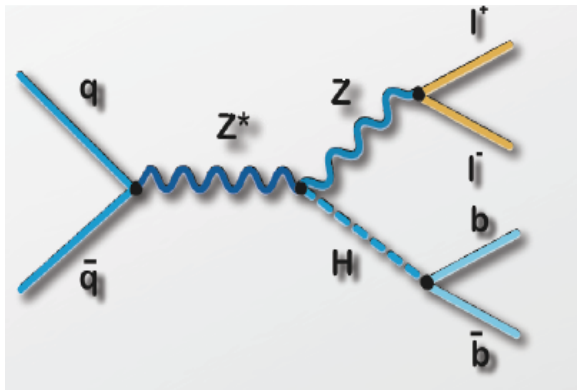


Best fit signal strength
consistent between different
classes



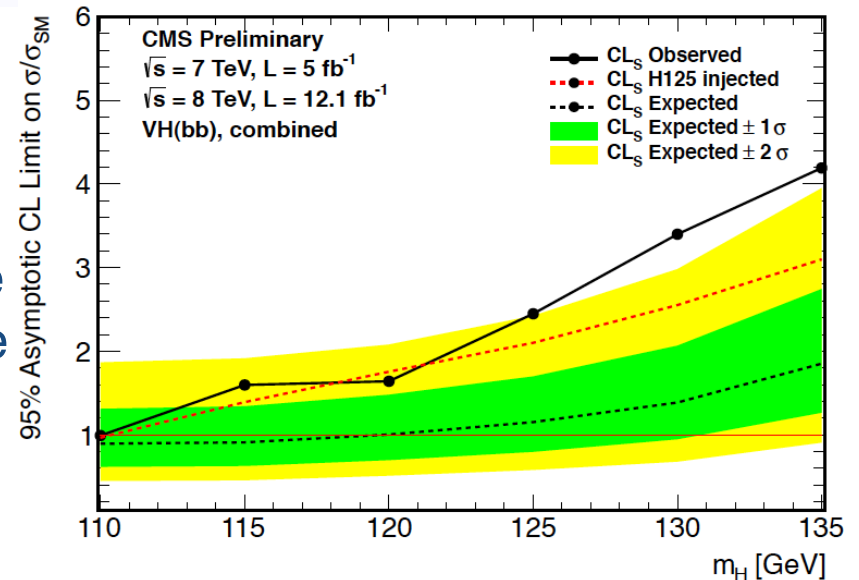
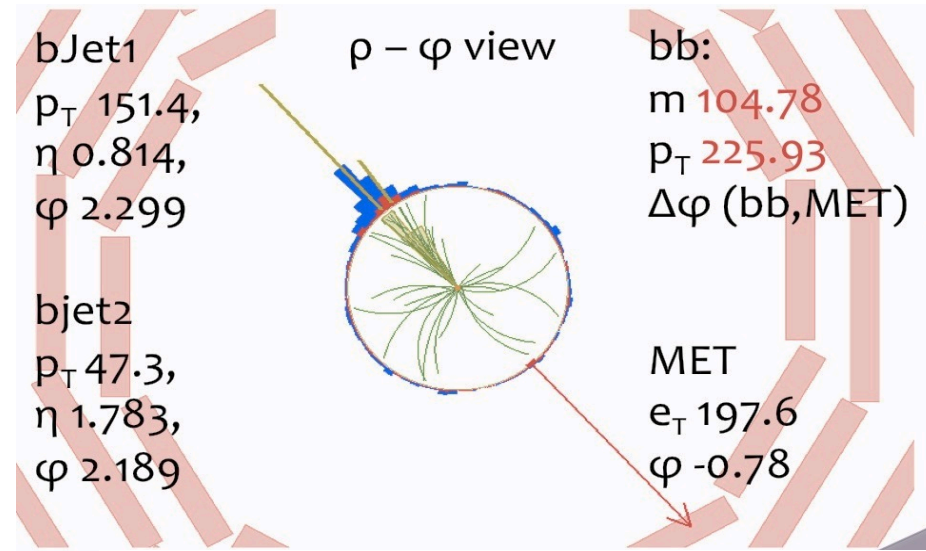
Low mass: $H \rightarrow bb$

- $gg \rightarrow H \rightarrow bb$ and VBF are dominant production modes but overwhelmed by enormous QCD di-jet background
- Best option: $qq \rightarrow VH; H \rightarrow bb$**
 - Major backgrounds are V +jets, VV , $t\bar{t}$
- Use
 - VH topology : $\Delta\Phi(V,H) > 3$**
 - $P_T(V) > 100\text{-}160$ GeV (boosted W/Z)**
 - Tight b-tagging & MET quality
 - Backgrounds estimated from control data**



5 sub channels

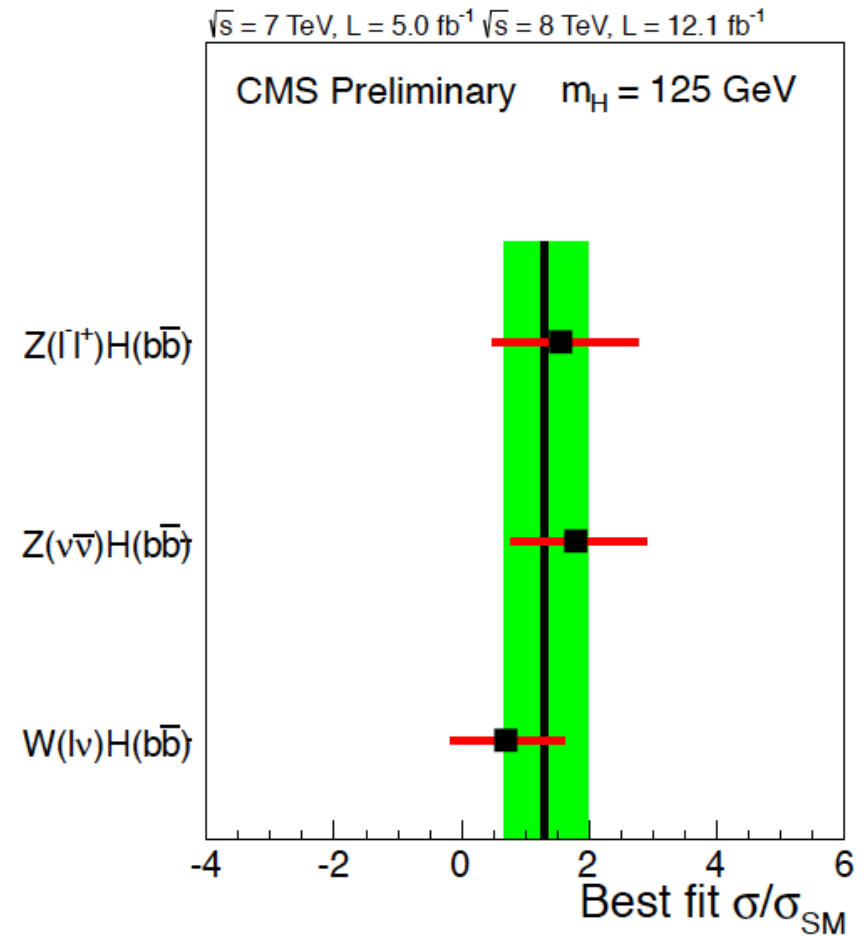
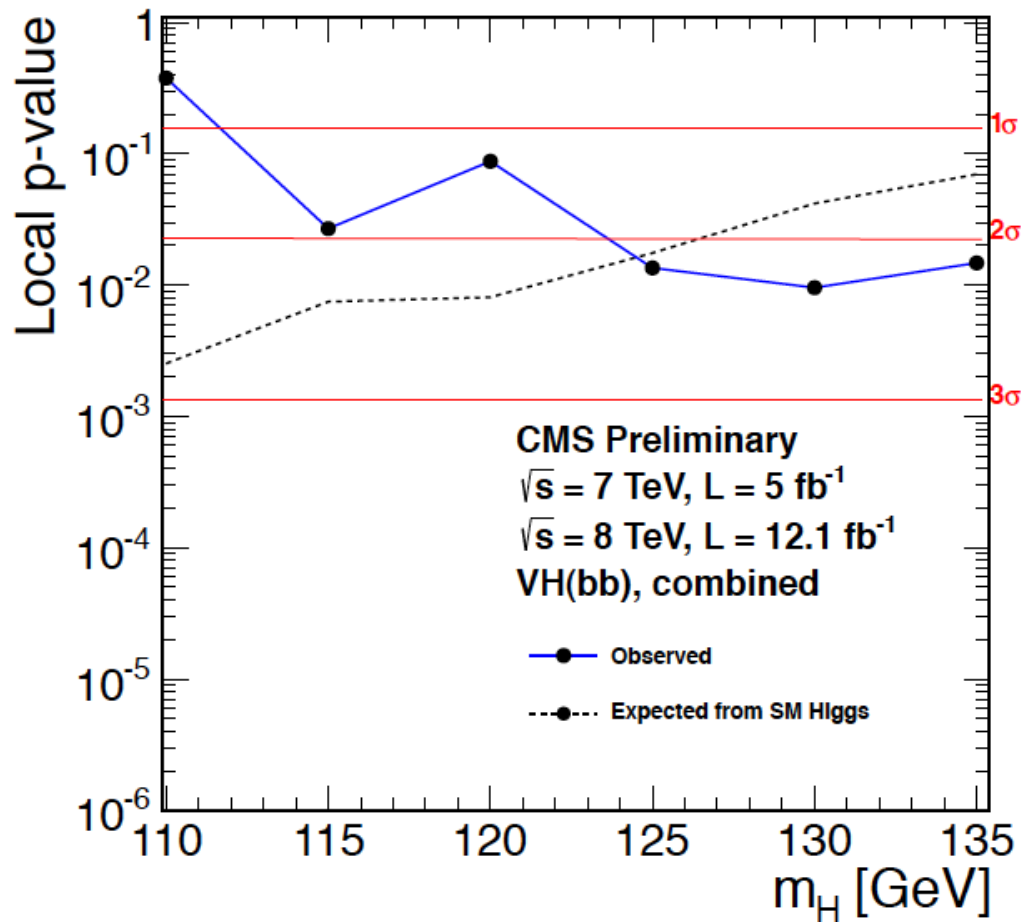
$Z(\rightarrow ll); H \rightarrow bb, l = \mu, e$
 $W(\rightarrow lv); H \rightarrow bb, l = \mu, e$
 $Z(\rightarrow \nu\nu); H \rightarrow bb$



Phys. Lett. B 710 (2012) 284-306, arXiv:1202.4195



H → bb

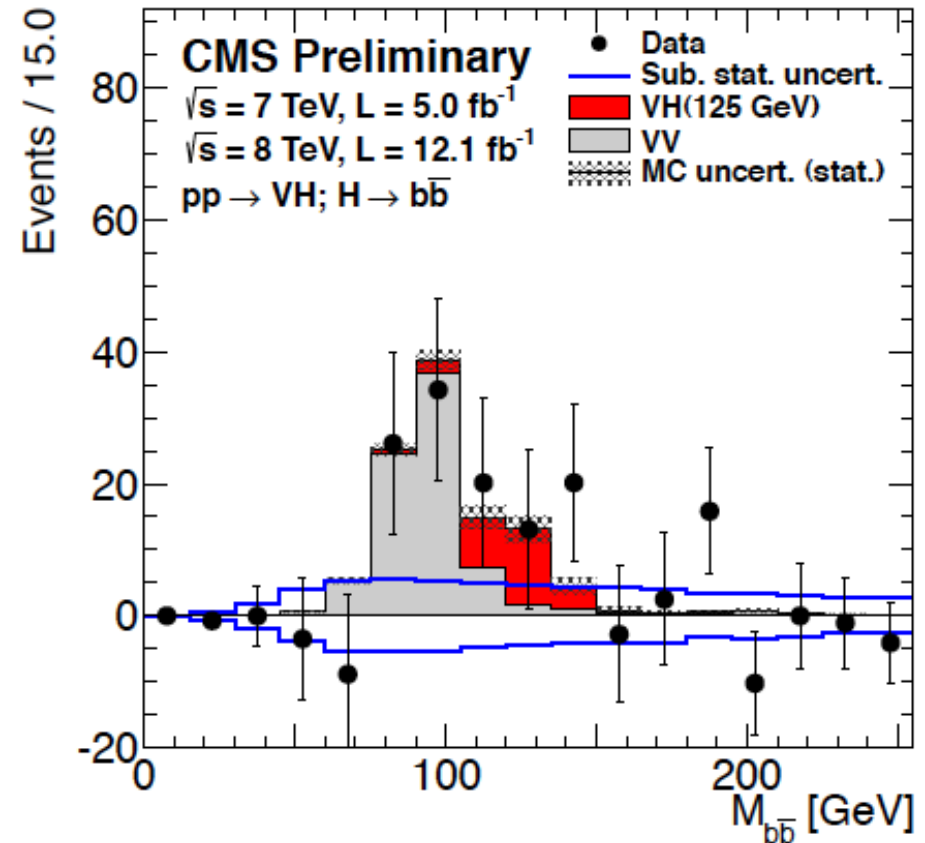
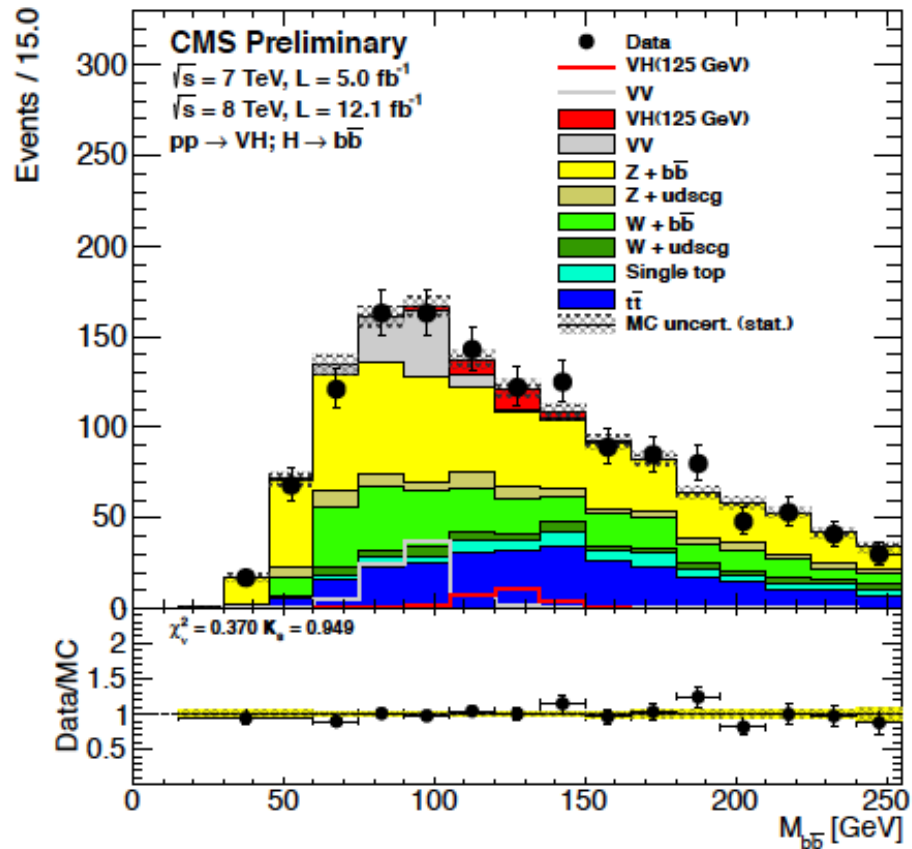


Excess compatible with SM starts to build up, 2.2 sigma



H → bb

BG subtracted:

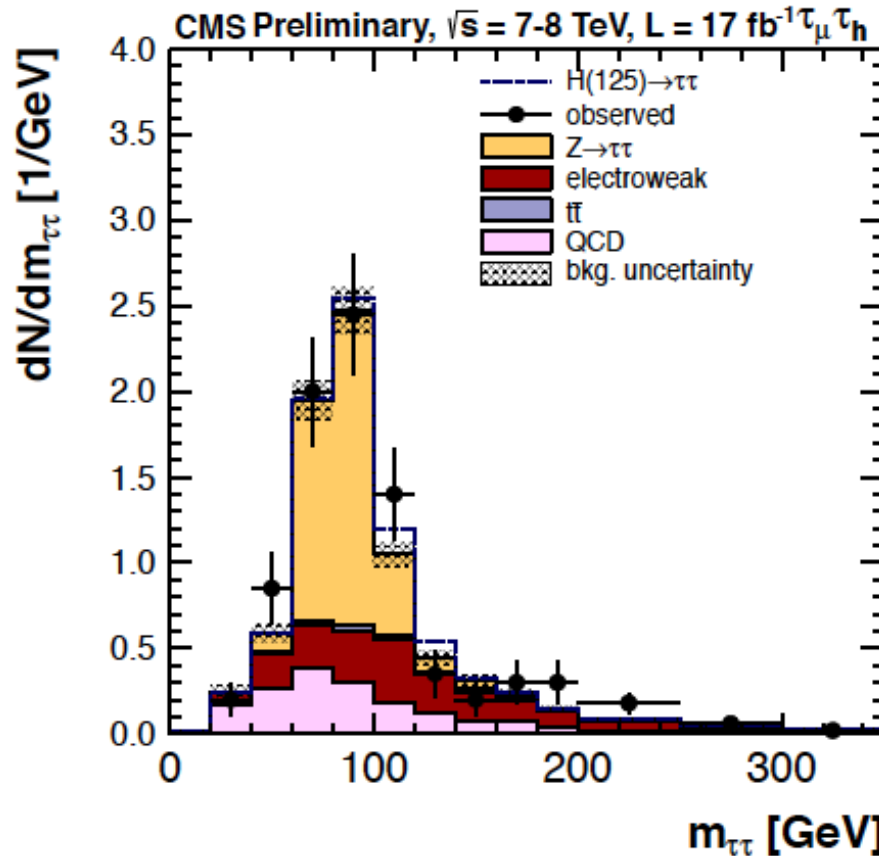




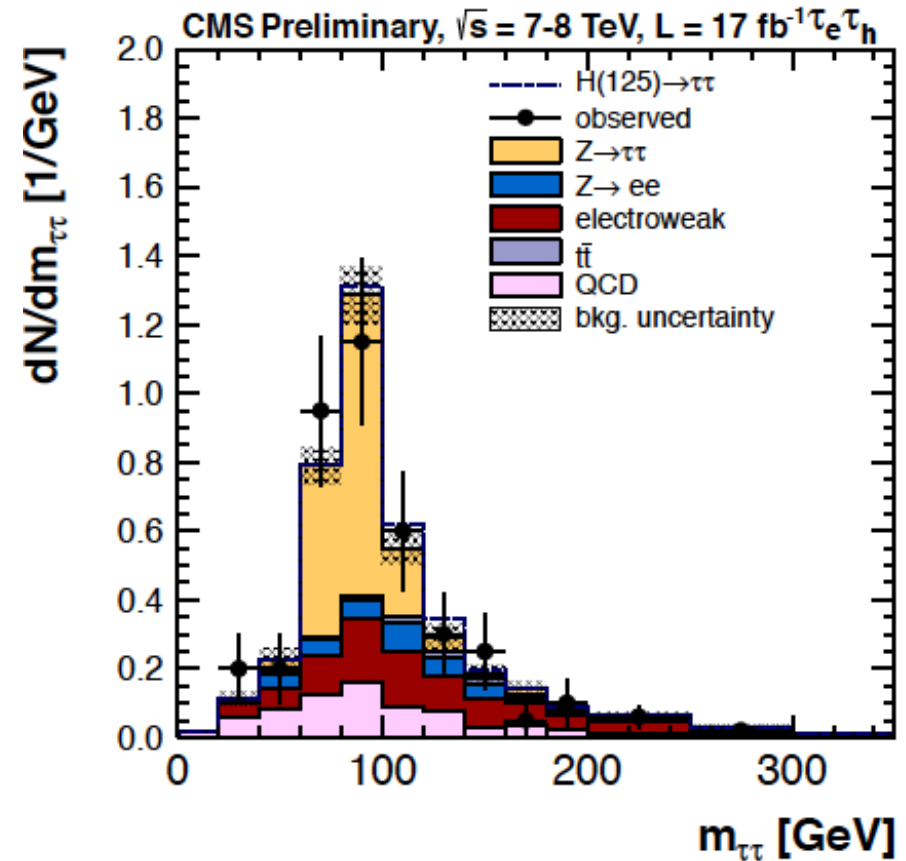
$H \rightarrow \tau\tau$

Improvements: MVA PF missing E_T ; VBF selection optimized

VBF with a muon



VBF with an electron

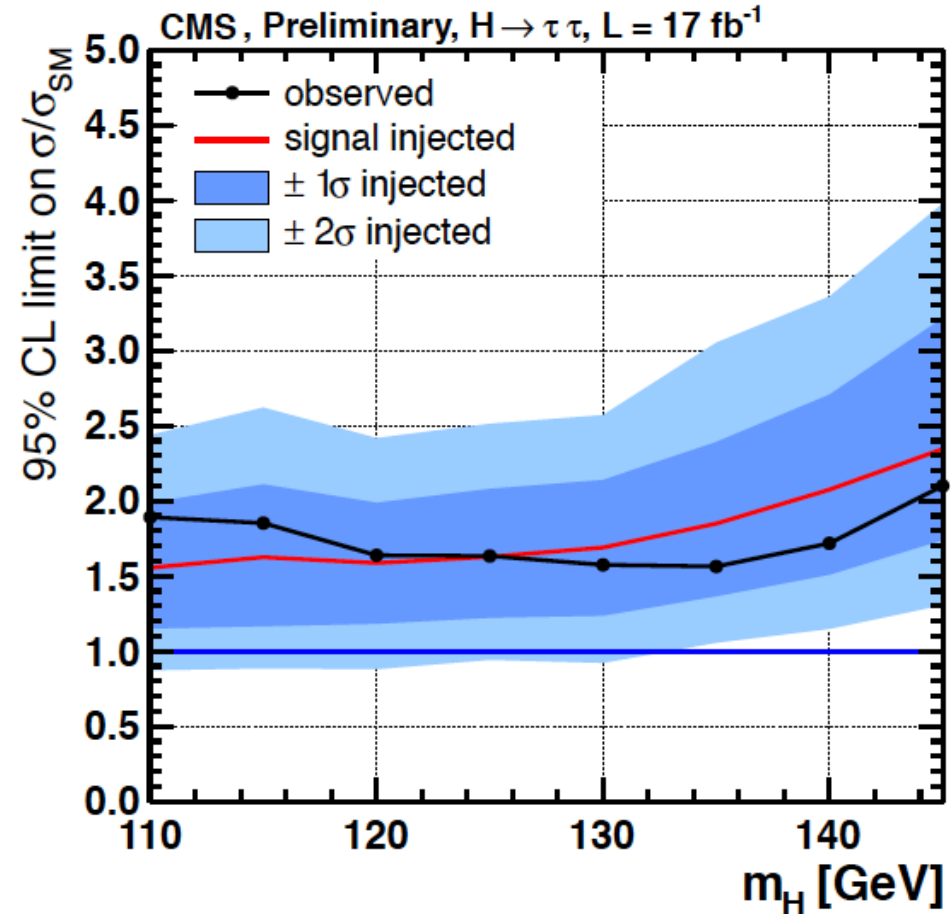
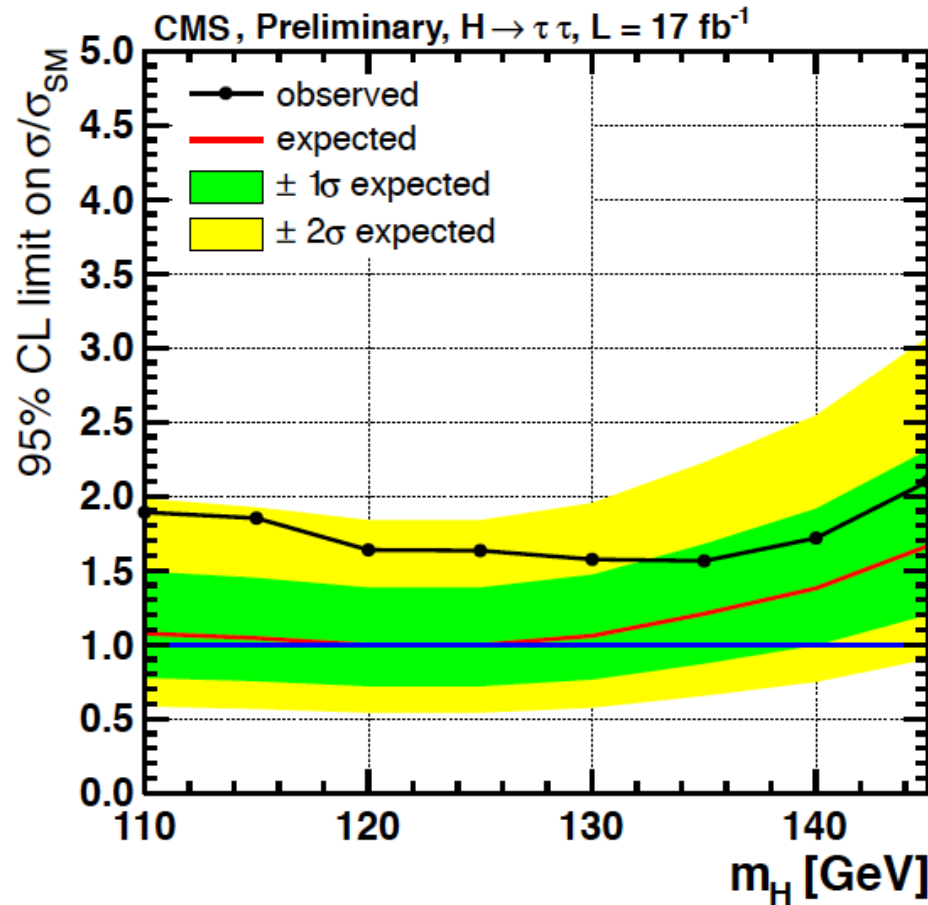


In other categories S/B is much lower



$H \rightarrow \tau\tau$

Signal injected:



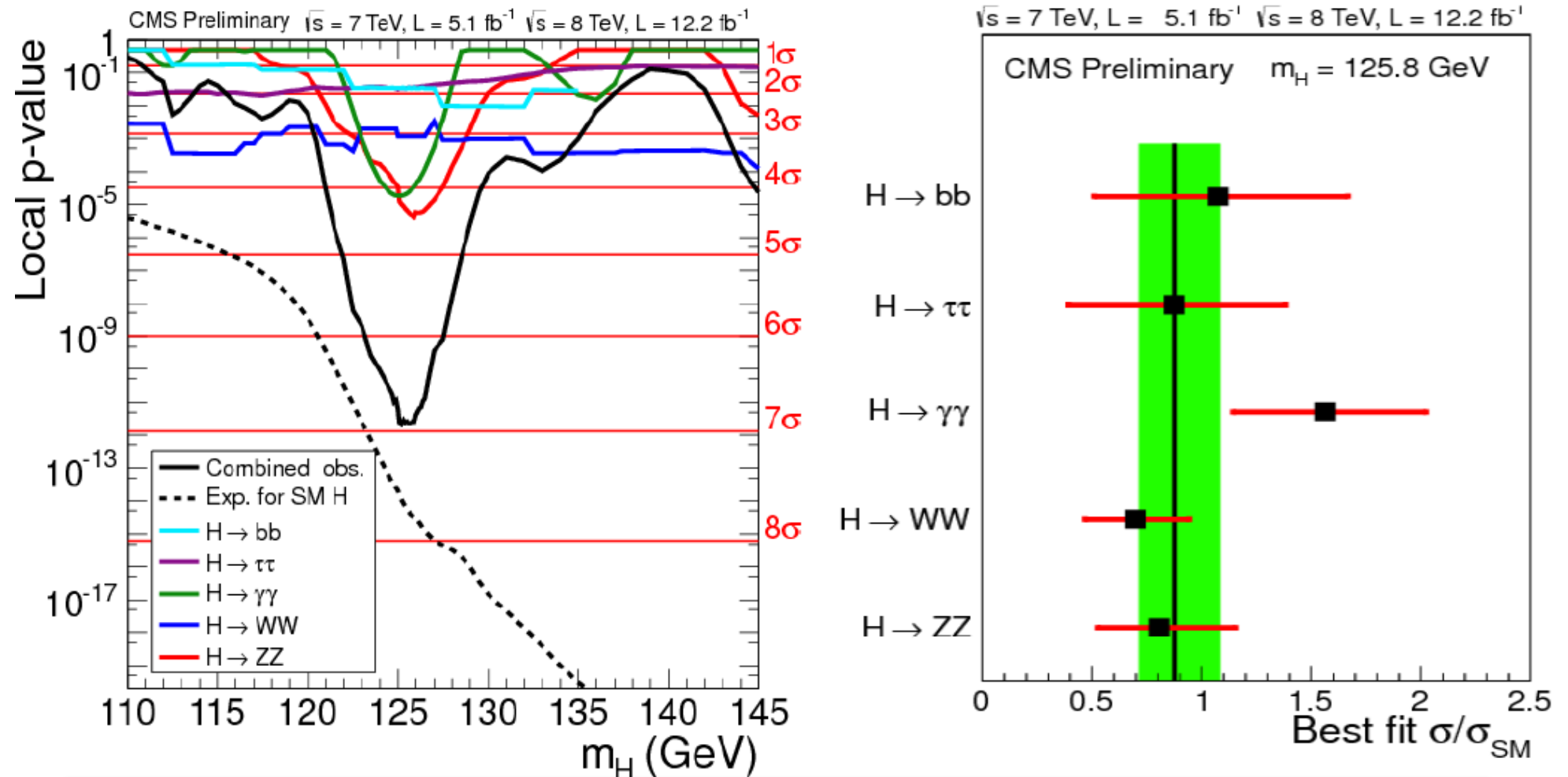
Combined excess slightly above 1 sigma



Combination of the results



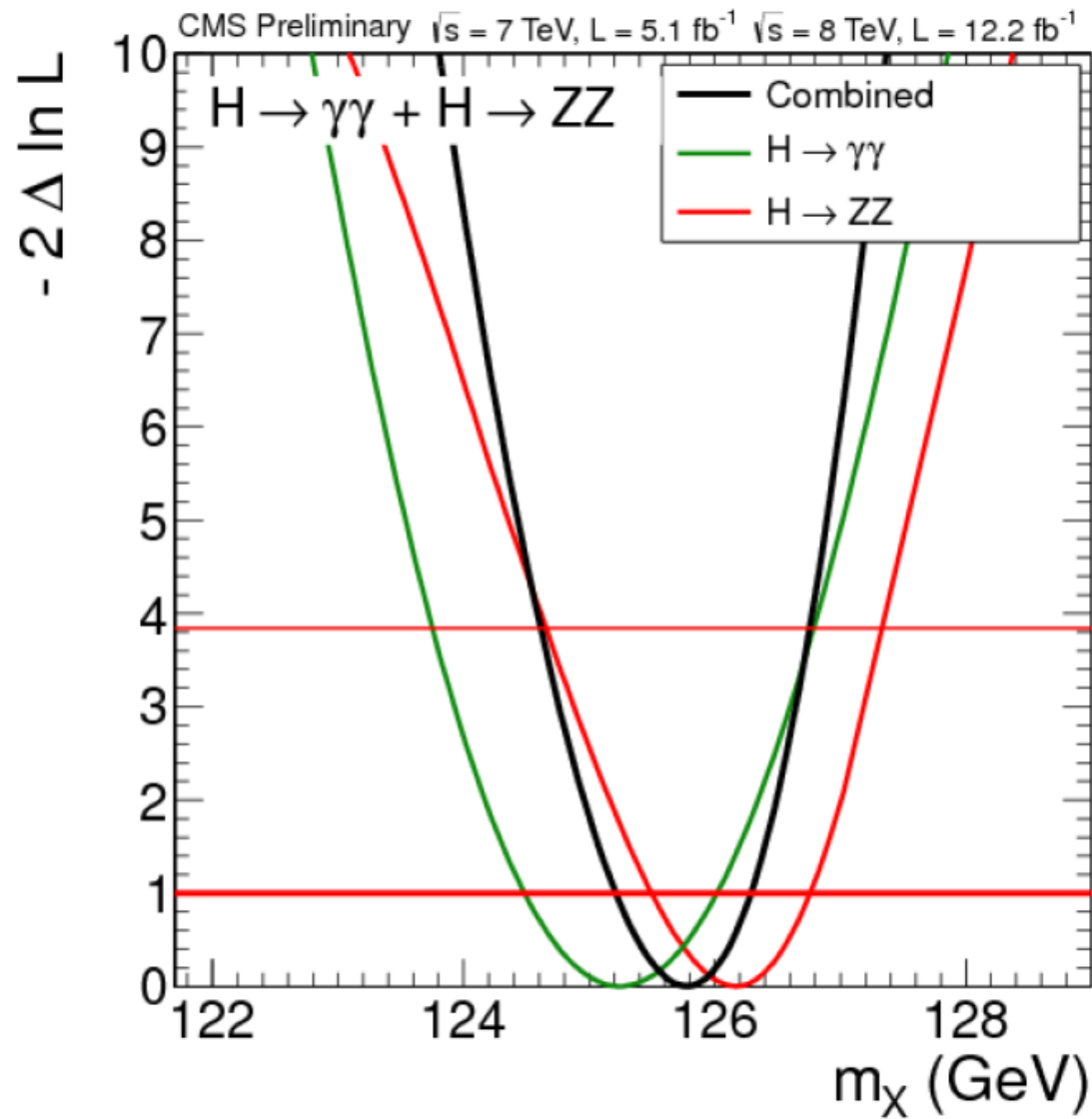
Combination



Expected significance: 7.8σ Observed 6.9σ
Signal strength: 0.88 ± 0.21



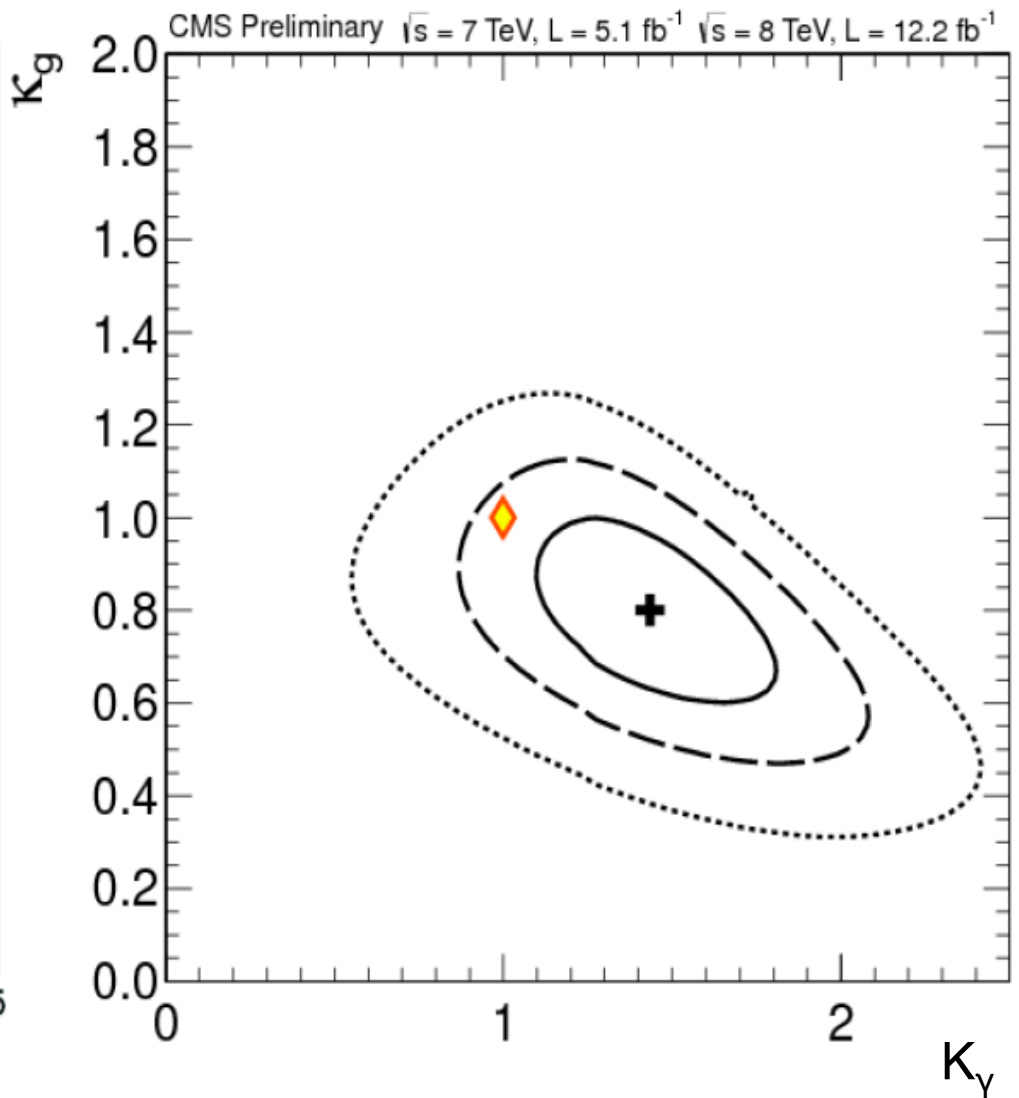
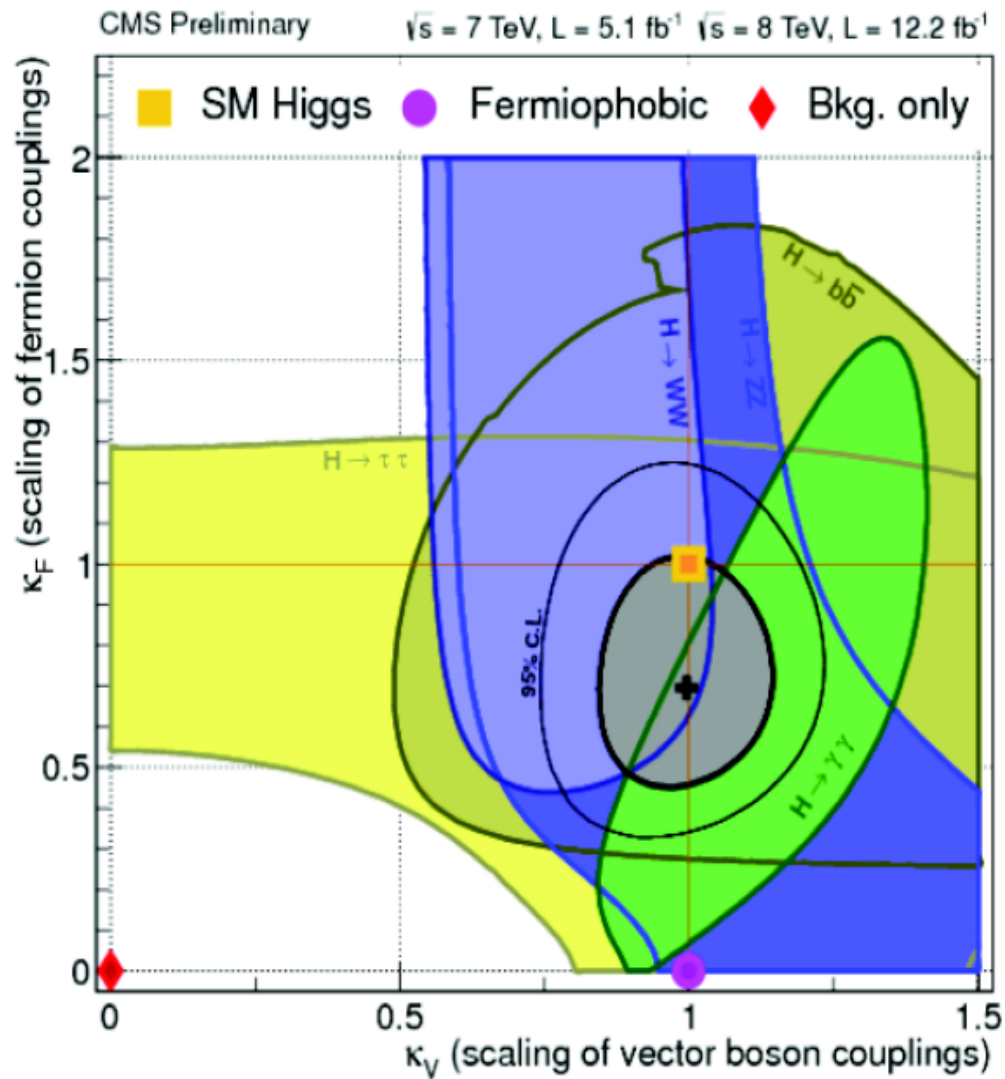
Mass measurements



$$M_H = 125.8 \pm 0.4 \text{ (stat)} \pm 0.4 \text{ (syst)}$$



Couplings





Conclusion

- New results consistent with publications
- Particle behaves even more like SM Higgs compared to ICHEP
- More data by winter conferences

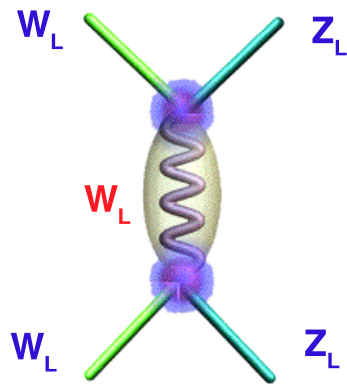


Backup

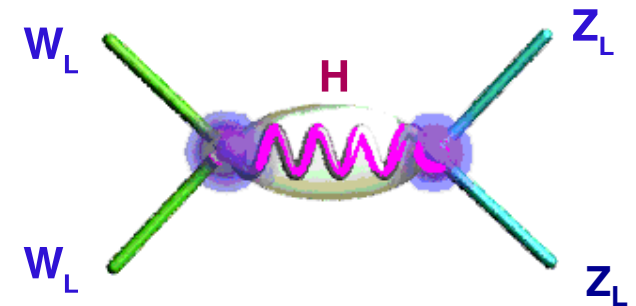


Constraints on the mass of the SM Higgs

Unitarity constraints: the exchange of a Higgs boson would allow to regulate the scattering amplitudes at high energies

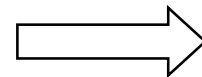


To avoid unitarity violation ($\sigma \sim s$)
un-physical (>1) scattering probability
of longitudinally polarized W bosons



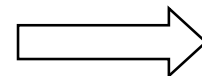
$$A(W_L^+ W_L^- \rightarrow Z_L Z_L) = \frac{G_F E^2}{8\sqrt{2}\pi} \left(1 - \frac{E^2}{E^2 - m_H^2} \right)$$

Without Higgs



SM limited to $E < 1.2-1.4$ TeV

With Higgs the SM is OK but



$M_H < 7-800$ GeV/c²



The Large Hadron Collider: design parameters



Nominal settings	
Beam energy (TeV)	7.0
Number of particles per bunch	$1.15 \cdot 10^{11}$
Number of bunches per beam	2808
Crossing angle (μrad)	285
Norm transverse emittance ($\mu\text{m rad}$)	3.75
Bunch length (cm)	7.55
Beta function at IP 1, 2, 5, 8 (m)	0.55,10,0.55,10

$$L = \frac{N_b^2 n_b f_{\text{rev}} \gamma_r}{4\pi \epsilon_n \beta^*} F$$

Cost 3 G€

**3.2×10^{14} p
/beam**



**25 ns between
crossing**

N_b = number of proton per bunch

n_b = number of bunches

f_{rev} = rotation frequency ($\sim 11\text{Hz}$)

F = crossing angle factor

Rms transverse beam size $= \sqrt{\epsilon_n \beta^*}$

ϵ_n = renorm. transverse emittance

β^* = optics at beam crossing (m)

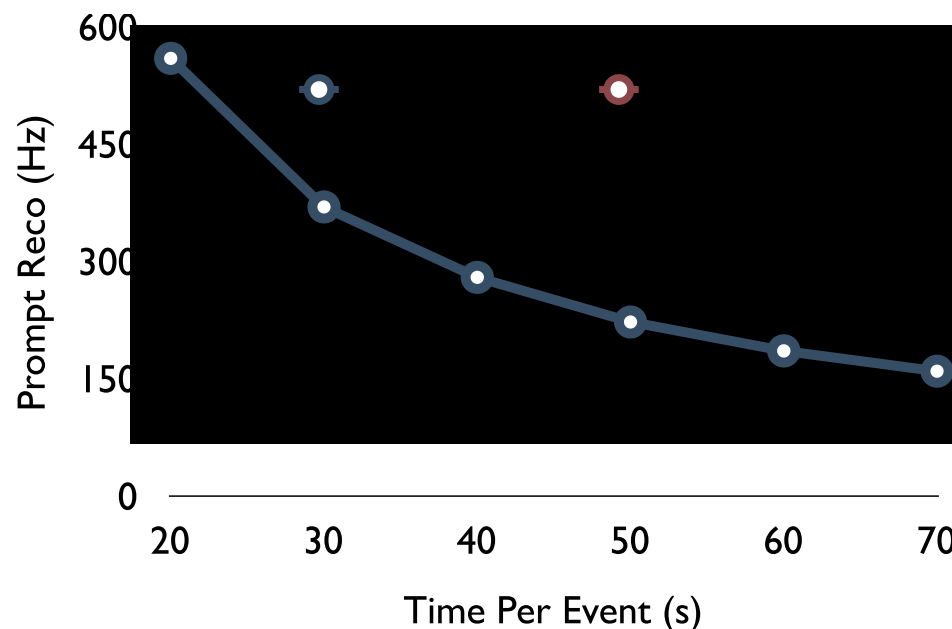
γ_r = relativistic factor

Derived parameters	
Luminosity in IP 1 & 5 ($\text{cm}^{-2} \text{s}^{-1}$)	10^{34}
Luminosity in IP 2 & 8 ($\text{cm}^{-2} \text{s}^{-1}$)*	$\sim 5 \cdot 10^{32}$
Transverse beam size at IP 1 & 5 (μm)	16.7
Transverse beam size at IP 2 & 8 (μm)	70.9
Stored energy per beam (MJ)	362



CMS Preparations for 8 TeV and high PU in 2012

- Last Autumn
 - cpu time for high PU >40 sec/event
 - Memory usage well above 2 GB.
 - Means we cannot use all the cores!
 - Even 200 Hz looked hard!
- Task force started December
 - Major success!
- Improvements
 - A factor 2.5 in speed
 - Under ~15" per event on average
 - Much reduced memory use
 - Well under 2 GB
- Physics performance unchanged
 - Kept our AAA rating:
 - E.g. no explicit p_T threshold on tracks



Prompt Reconstruction at Tier-0:
Limit on our data-taking rate versus event processing time for low and high memory use cases



Higgs hunting basics: μ and CL_s

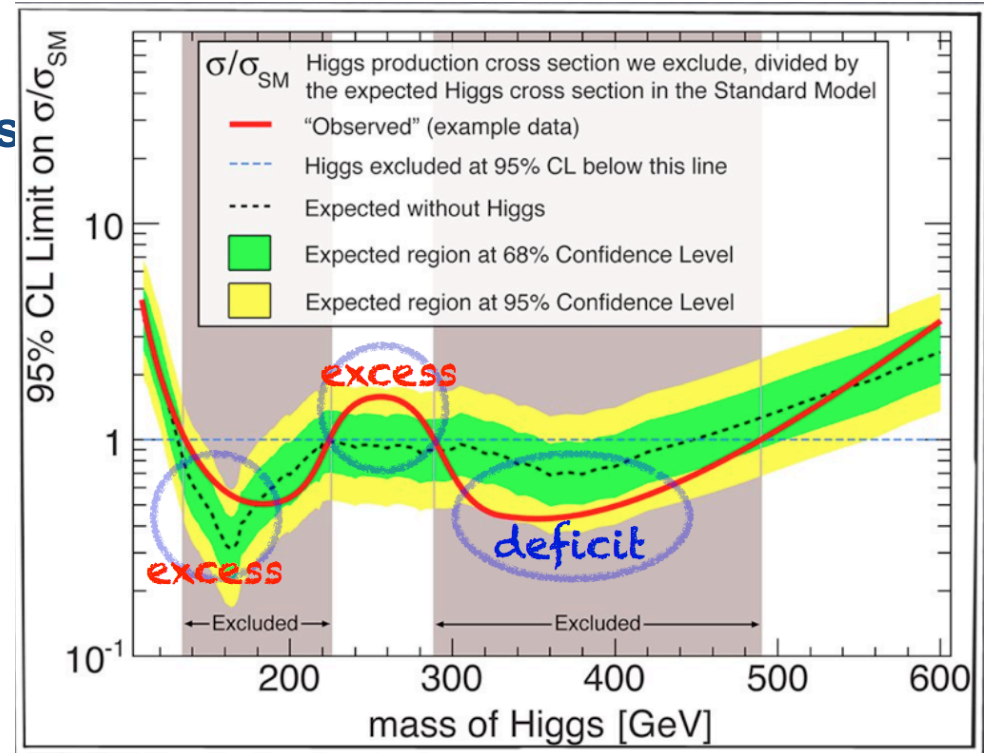
Understanding the yellow and green bands.

μ is the ratio between the measured cross section at a given mass assuming the presence of a SM Higgs signal and the expected cross section at that mass.

$$\mu = \frac{\sigma_{meas}}{\sigma_{SM}(m_H)}$$

CL_s measures the compatibility of the data with the signal hypothesis.

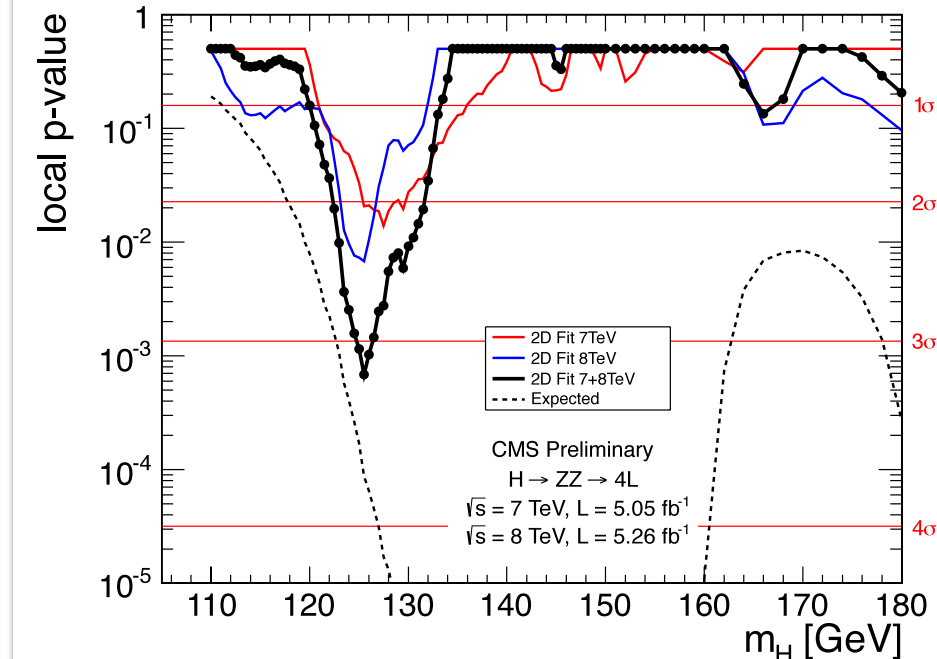
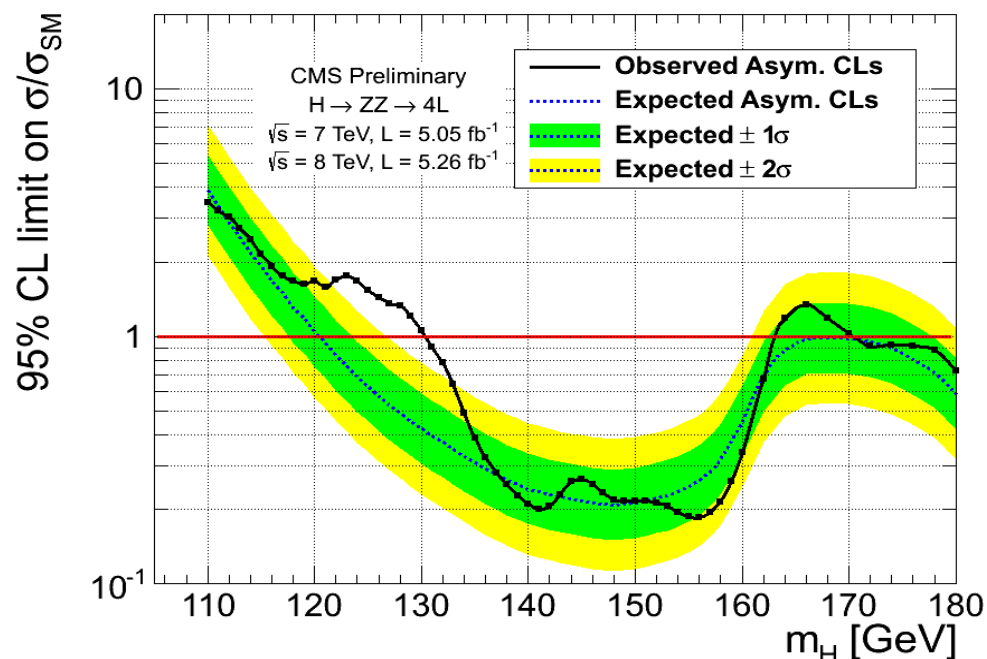
If $CL_s < 5\%$ the signal hypothesis is excluded at the 95% CL.



μ_{up} is the signal strength for which $CL_s = 5\%$. If, for a given mass hypothesis, m_H , $\mu_{up} < 1$ then $\sigma_{meas} < \sigma_{SM}$ and m_H is excluded at 95% CL.



Limits and p-values



Expected exclusion at 95% CL :

121-550 GeV

Observed exclusion at 95% CL :

131-162 GeV and 172-530 GeV

Expected significance at 125.5 GeV :

3.8 σ

Observed significance at 125.5 GeV:

3.2 σ



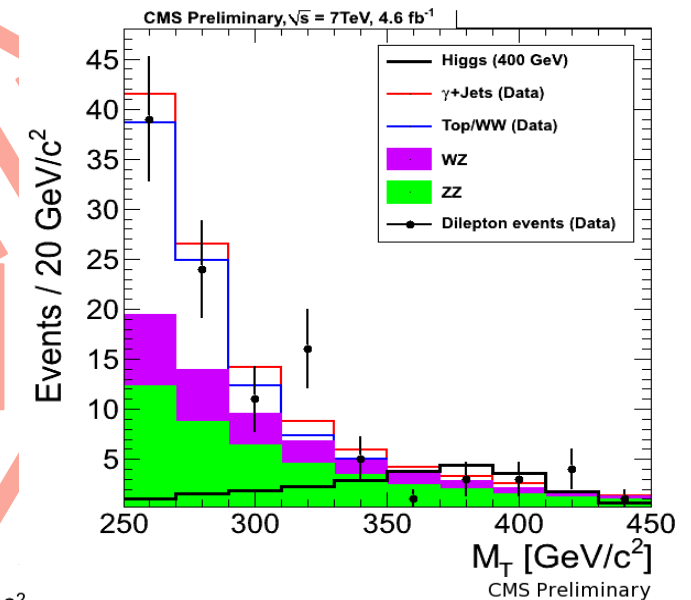
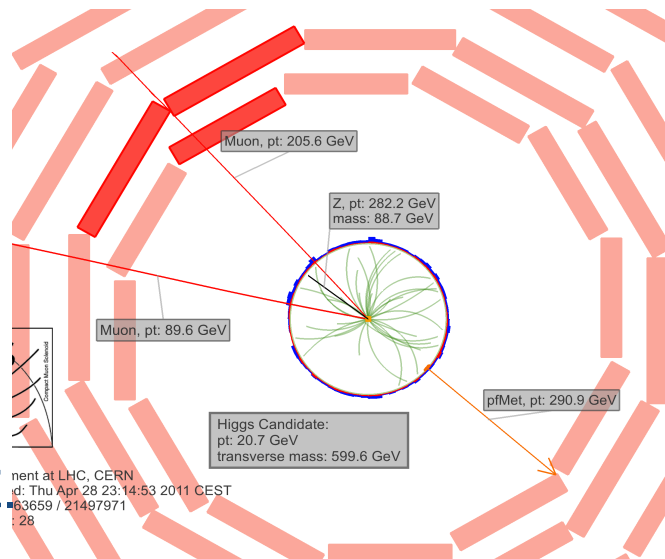
CMS High Mass Higgs: $H \rightarrow ZZ \rightarrow 2l2\nu$

The most sensitive channel in the high mass region.

The presence of neutrinos implies a mass resolution of about 7%.

Main backgrounds:

ZZ irreducible, Z+jets, tt, WZ



The channel is accessible only for high mass (>250GeV) with the two Z bosons selected to be highly boosted and large M_{E_T} present in the event. Discriminating variable for shape analysis, the transverse mass

$$M_T^2 = (\sqrt{P_{TZ}^2 + M_Z^2} + \sqrt{M_{ET}^2 + M_Z^2})^2 - (P_{TZ} + M_{ET})^2$$

95%CL exclusion limits for a SM Higgs boson in range 270-440 GeV arXiv: 1202.3478
J. High Energy Phys. 03 (2012) 040

