CMS Higgs Results: Status and Prospects

HEPAP Meeting

August 27, 2012

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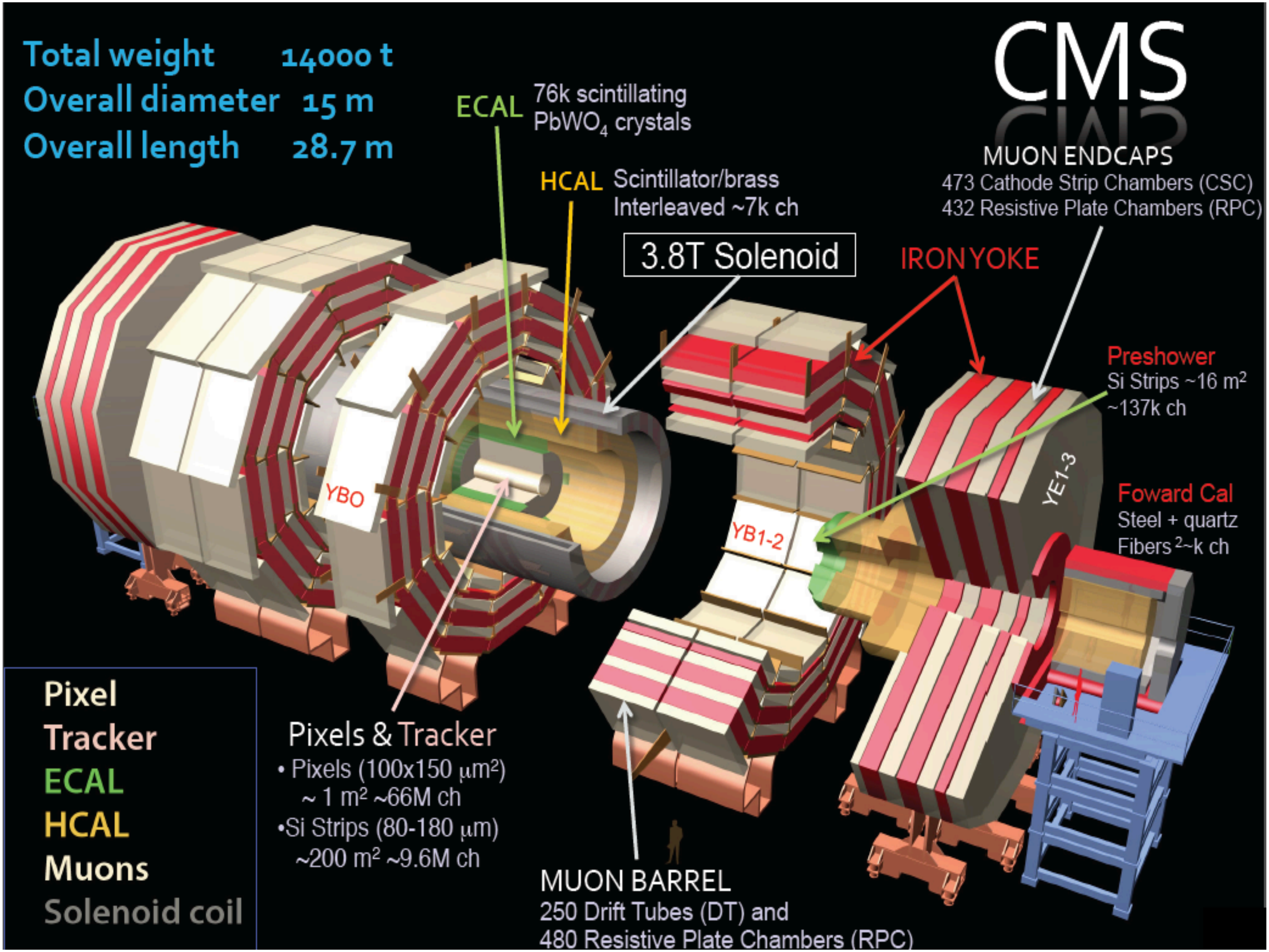
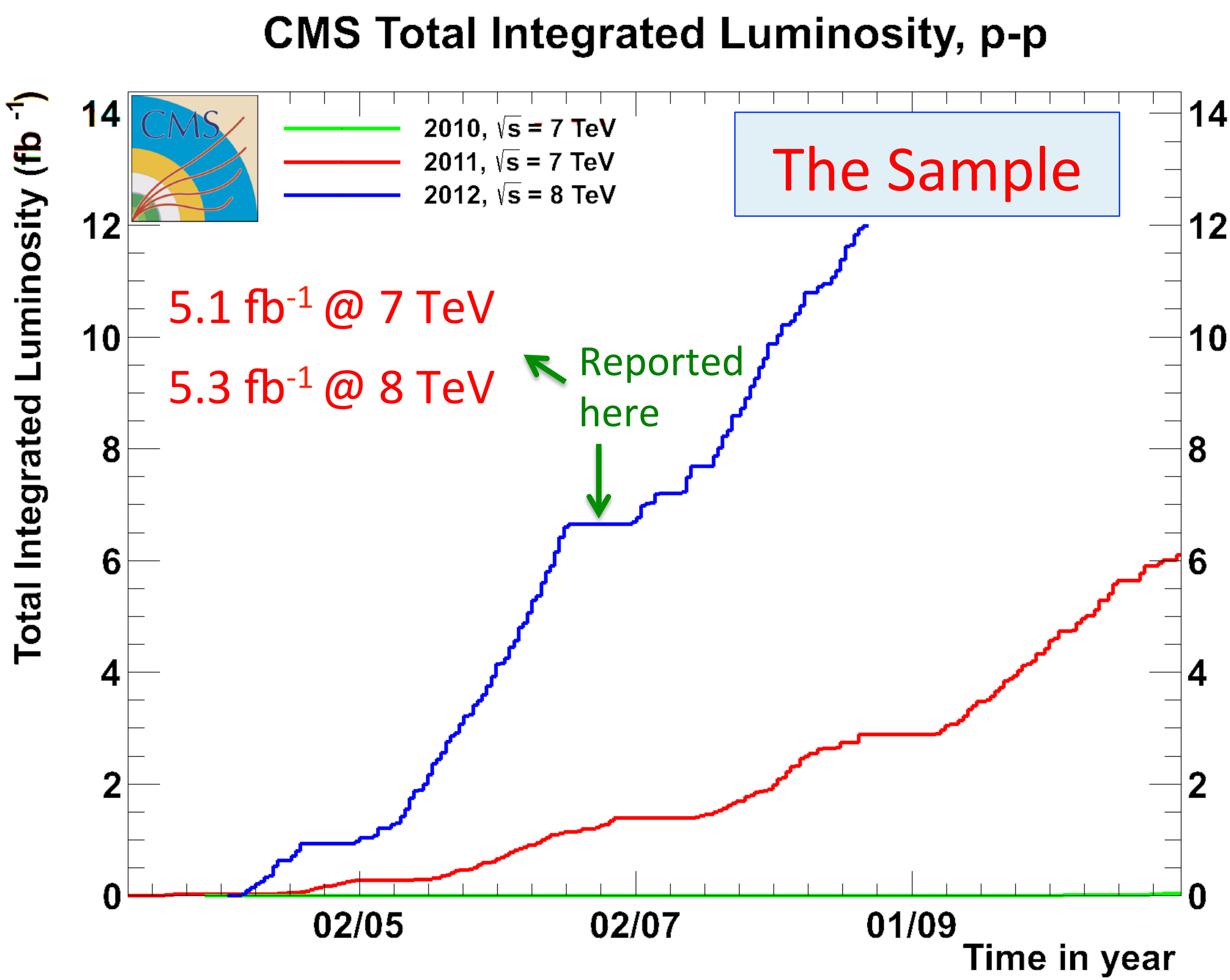
for the

CMS Collaboration

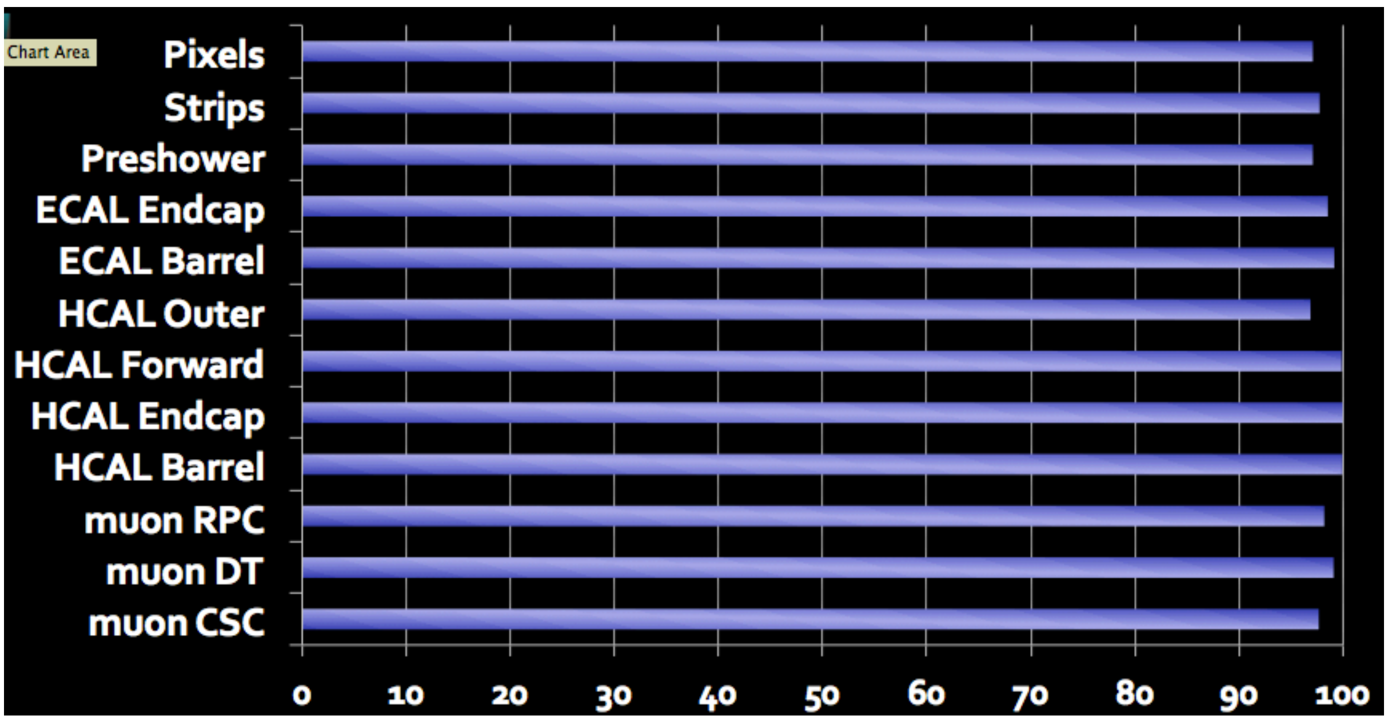
The CMS Collaboration


Total weight 14000 t
Overall diameter 15 m
Overall length 28.7 m
CMS
ECAL 76k scintillating PbWO4 crystals
HCAL Scintillator/brass Interleaved ~7k ch
3.8T Solenoid
IRON YOKE
MUON ENDCAPS
473 Cathode Strip Chambers (CSC)
432 Resistive Plate Chambers (RPC)
Preshower
Si Strips ~16 m2
~137k ch
Foward Cal
Steel + quartz
Fibers 2~k ch
YB0
YB1-2
YE1-3
Pixel
Tracker
ECAL
HCAL
Muons
Solenoid coil
Pixels & Tracker
• Pixels (100x150 μm2)
~ 1 m2 ~66M ch
•Si Strips (80-180 μm)
~200 m2 ~9.6M ch
MUON BARREL
250 Drift Tubes (DT) and
480 Resistive Plate Chambers (RPC)


CMS Total Integrated Luminosity, p-p
Total Integrated Luminosity (fb^{-1})
CMS
2010, $\sqrt{s}$ = 7 TeV
2011, $\sqrt{s}$ = 7 TeV
2012, $\sqrt{s}$ = 8 TeV
The Sample
5.1 fb^{-1} @ 7 TeV
5.3 fb^{-1} @ 8 TeV
Reported here
0
2
4
6
8
10
12
14
02/05
02/07
01/09
Time in year

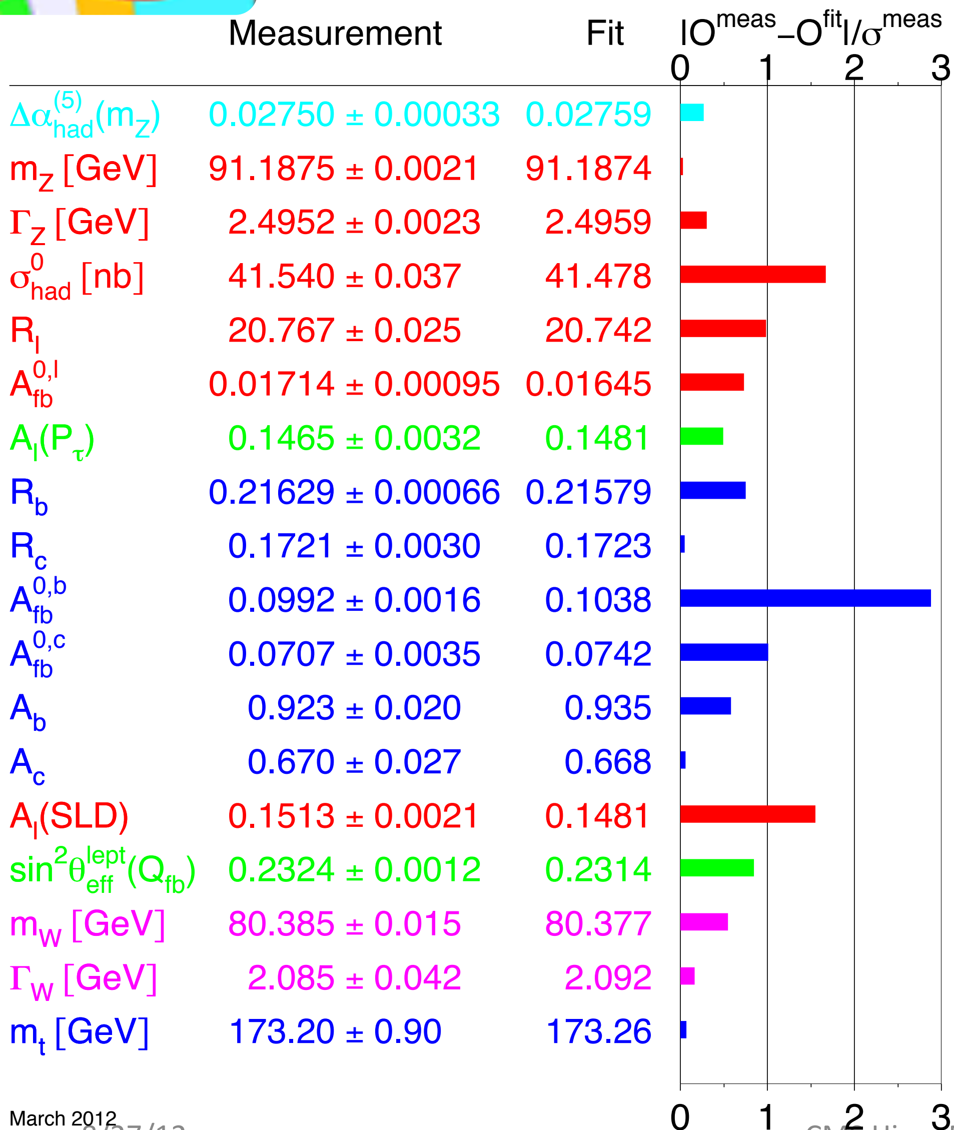
Operational Efficiency

Thus far in 2012, CMS has recorded 93% of the luminosity delivered by the LHC. Of that 85% is certified as "golden" (good for physics).



The fraction of working channels is >98%

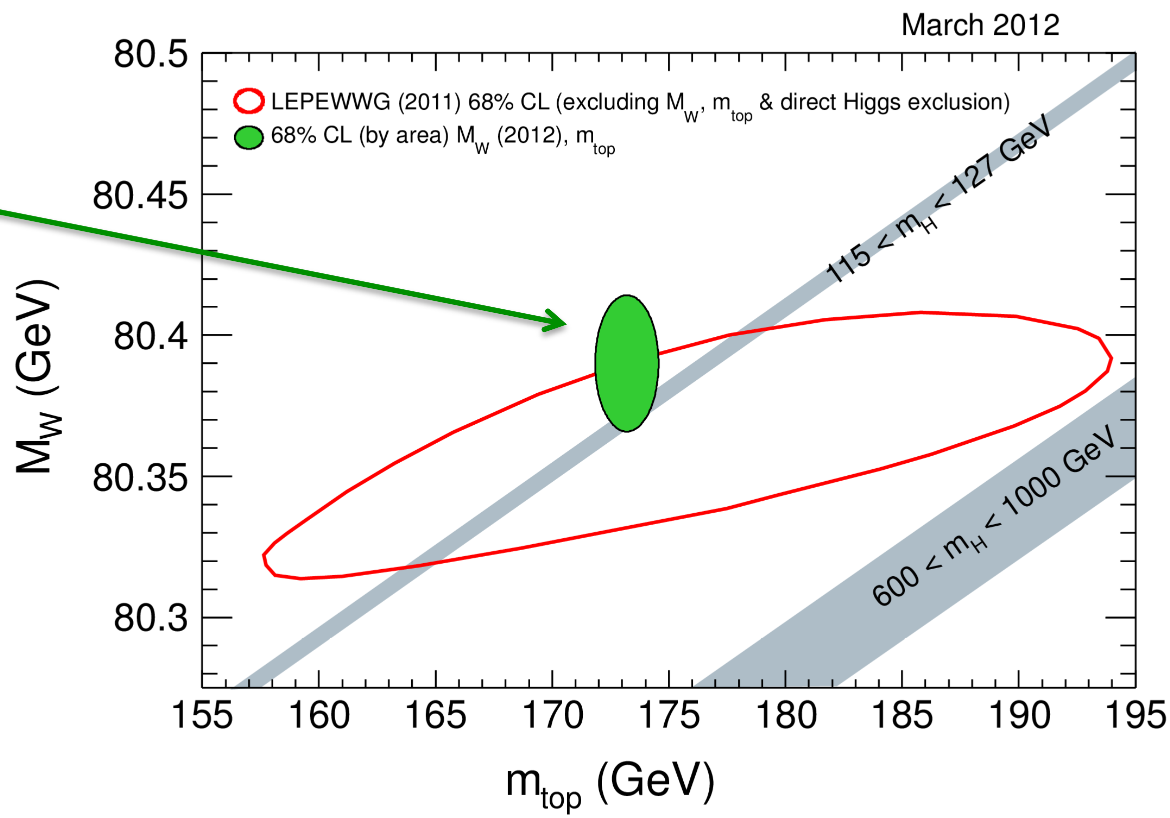
Shoulders of Giants



Studies at the LHC build on a beautiful series of previous EWSB measurements at the Tevatron, LEP, and SLC. These measurements provide a lot of guidance of where and how to look.

Situation in Early 2012

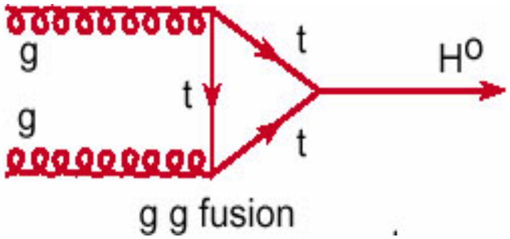
Exquisitely precise measurement of M_W = 80.390 ± 0.016 GeV, driven mainly by the Tevatron.



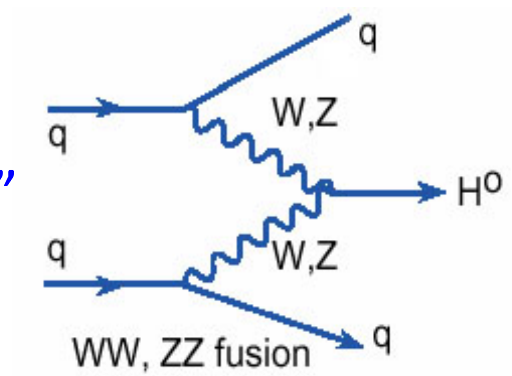
Much of the SM Higgs range had been ruled out by 2011 LHC running.

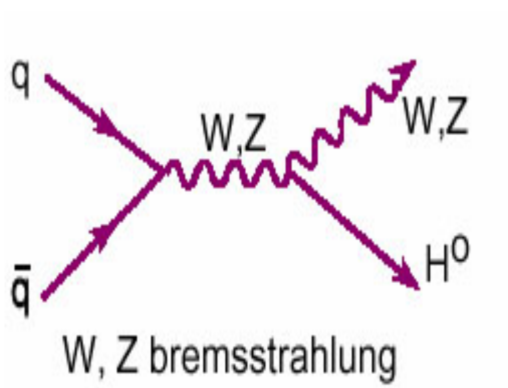
Exclusions of M_H:
– LEP < 114 GeV (arXiv:0602042v1)
– Tevatron [156,177] GeV (arXiv:1107.5518)
– LHC [~127, 600] GeV arXiv:1202.1408 (ATLAS)
arXiv:1202.1488 (CMS)

Higgs Production



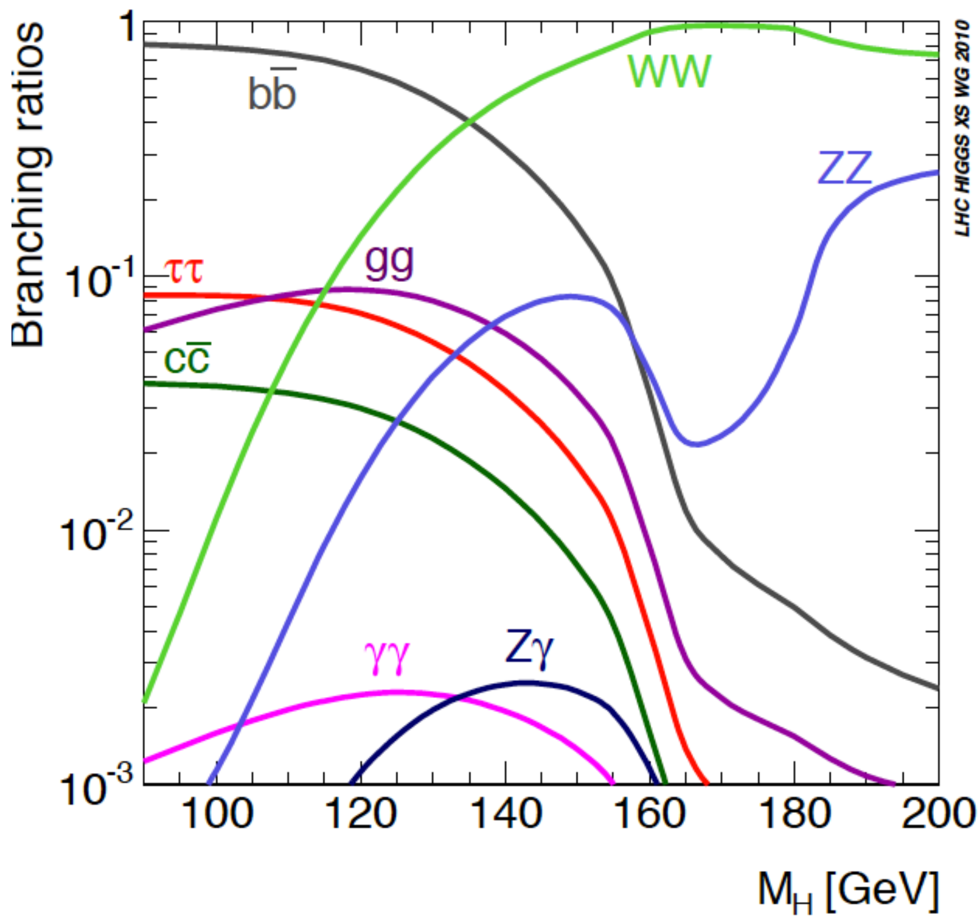
"VBF"





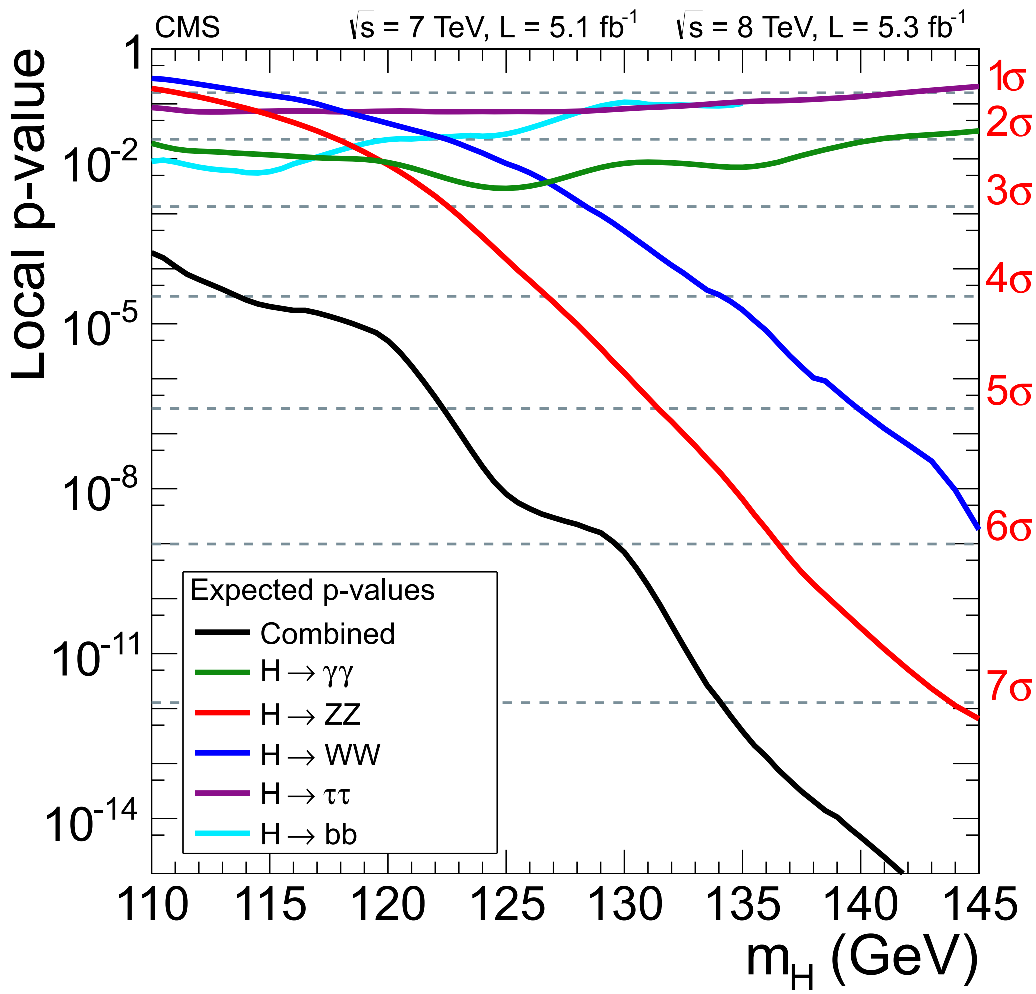
- Cross section ≈20 pb, dominated by gg fusion
- 8 TeV cross sections 25%-30% higher
- All production modes used
  - gg, VBF, VH, ttH (not shown)
  - Last three have smaller rates, but better S/B.

Higgs Decay



- Five modes studied
  - γγ, ZZ, WW, $\tau^+\tau^-$, bb
- The branching ratio plot, however, tells only part of the story—i.e., it's quality, not quantity.

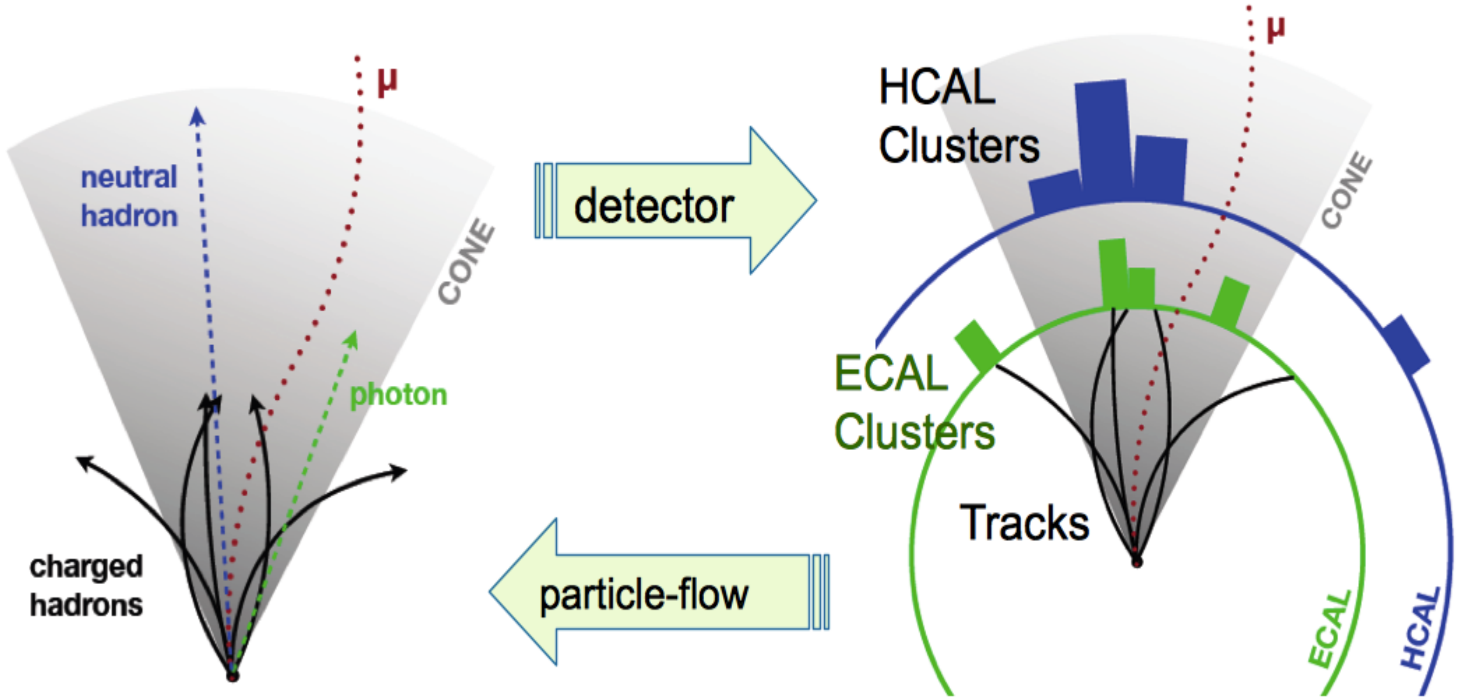
Higgs Decay



Most of the heavy lifting is done by γγ and ZZ, since those modes exploit the excellent mass resolution (~1%) of CMS. This talk will focus on those.

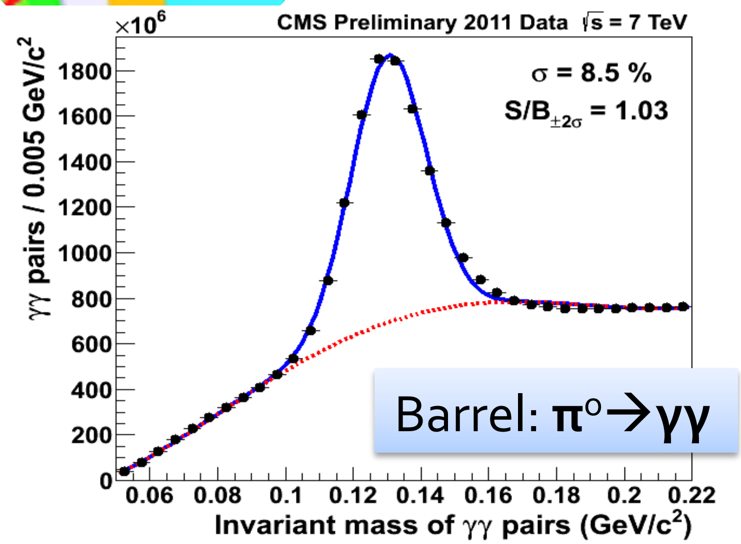
Event Reconstruction

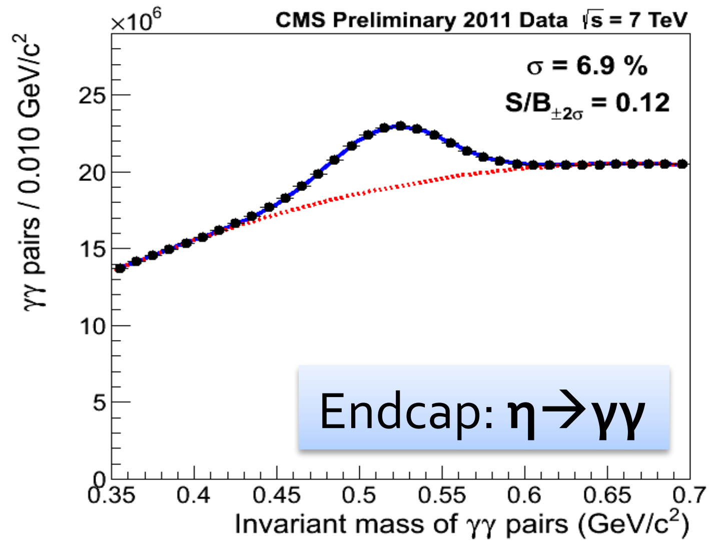
Particle Flow

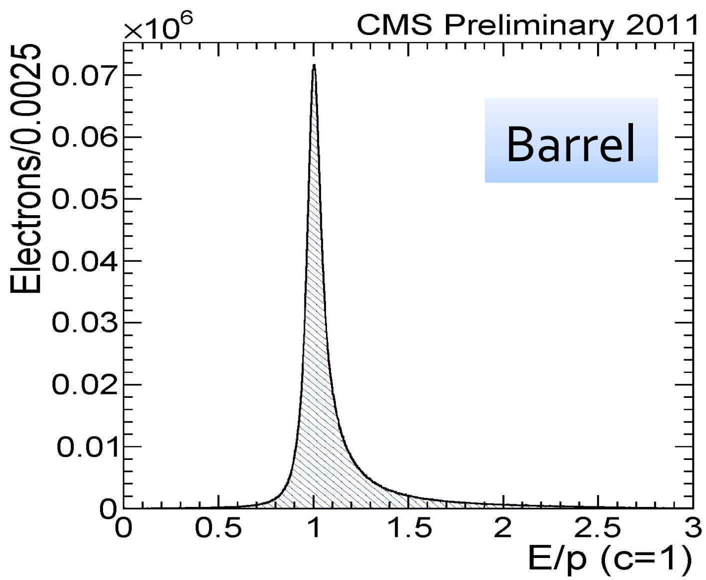


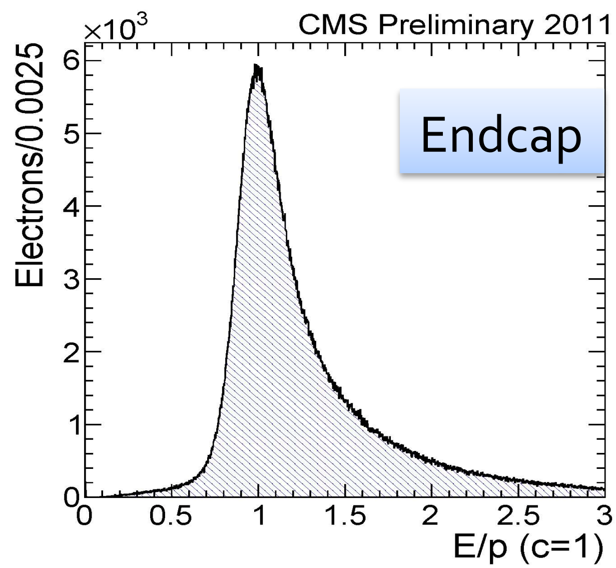
Stable particles in the event are reconstructed by a sophisticated algorithm that combines information from all sub-detectors. This exploits the fine-grained nature of CMS. The particles thus reconstructed are then combined into jets.

Photons (EM Calorimetry)



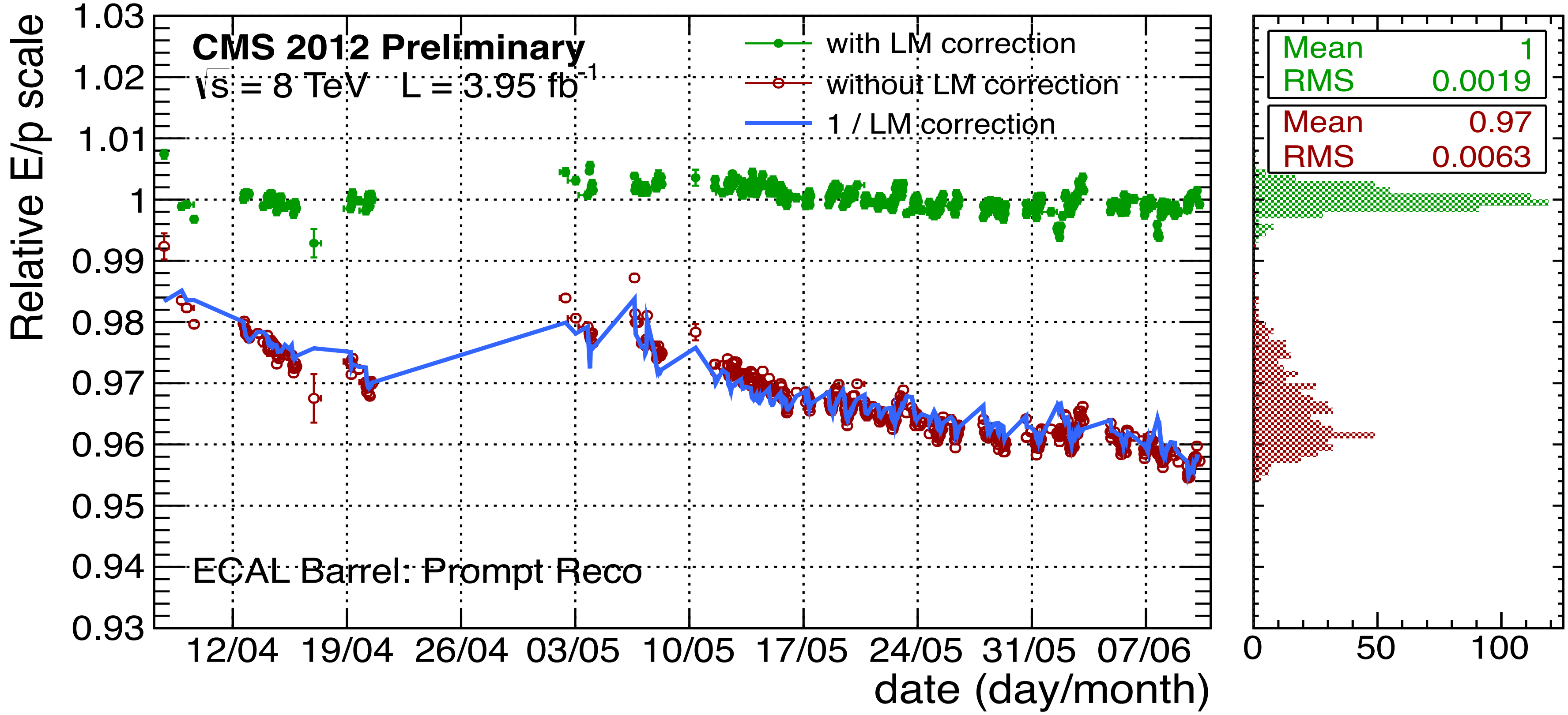






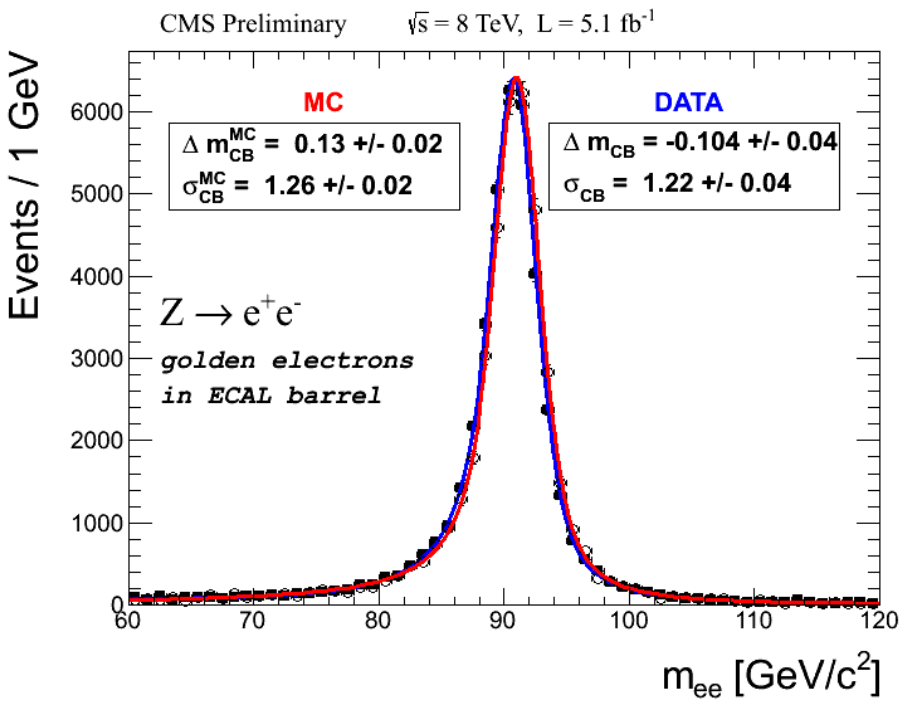
Calibration is a key issue for $H \rightarrow \gamma\gamma$

EM Calorimetry

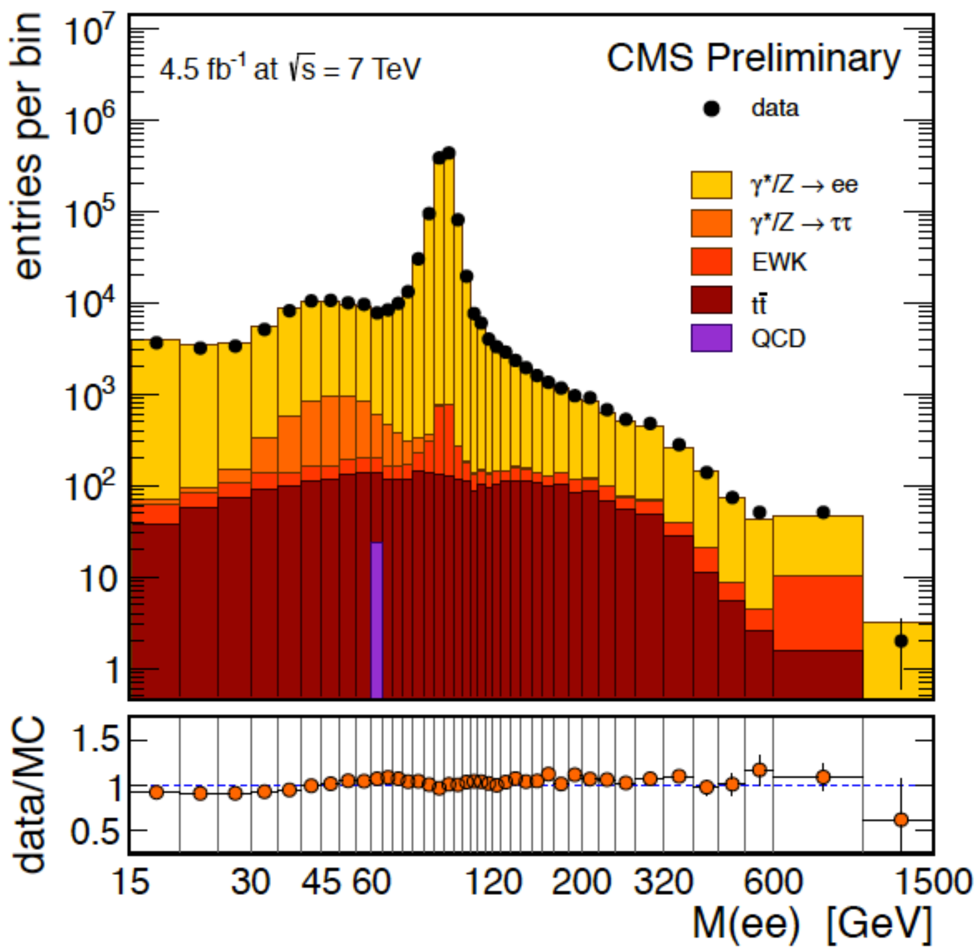


Light monitoring (LM) corrections are used to greatly improve the temporal stability.

Electrons

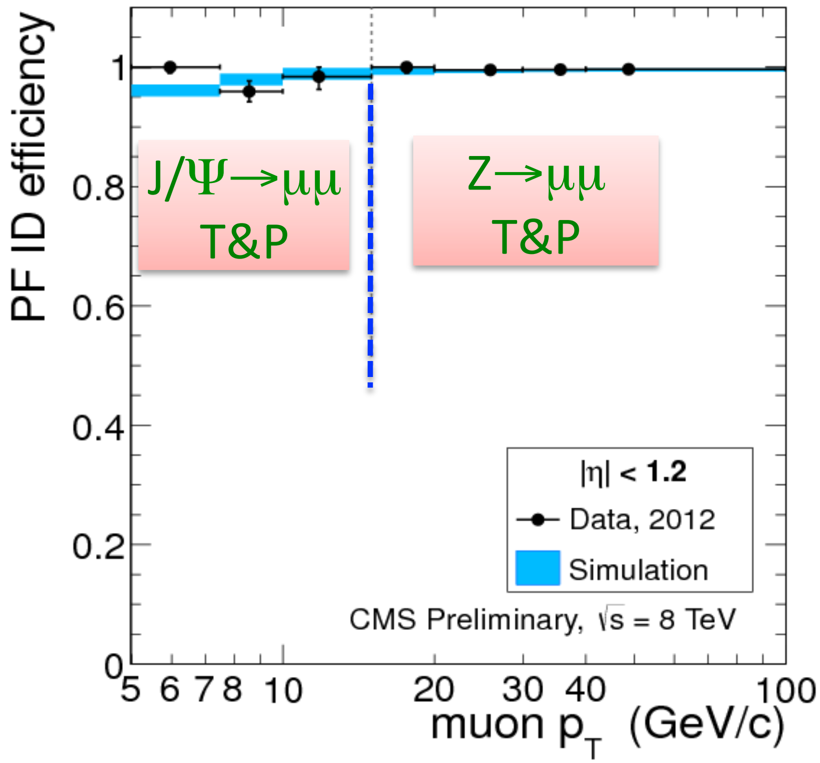


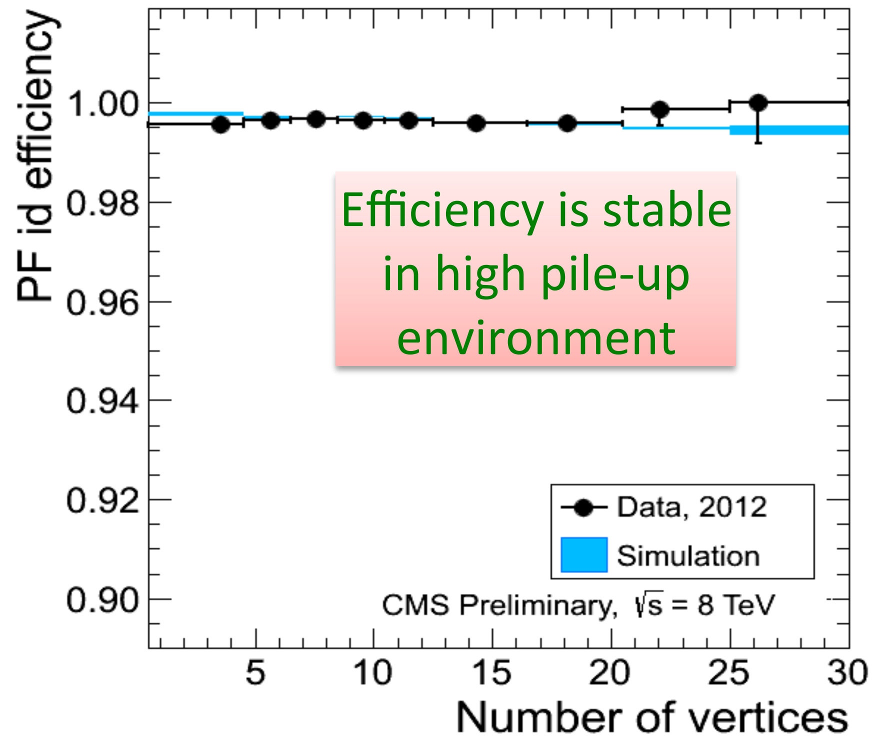
Z peak from golden electrons



Drell-Yan Spectrum

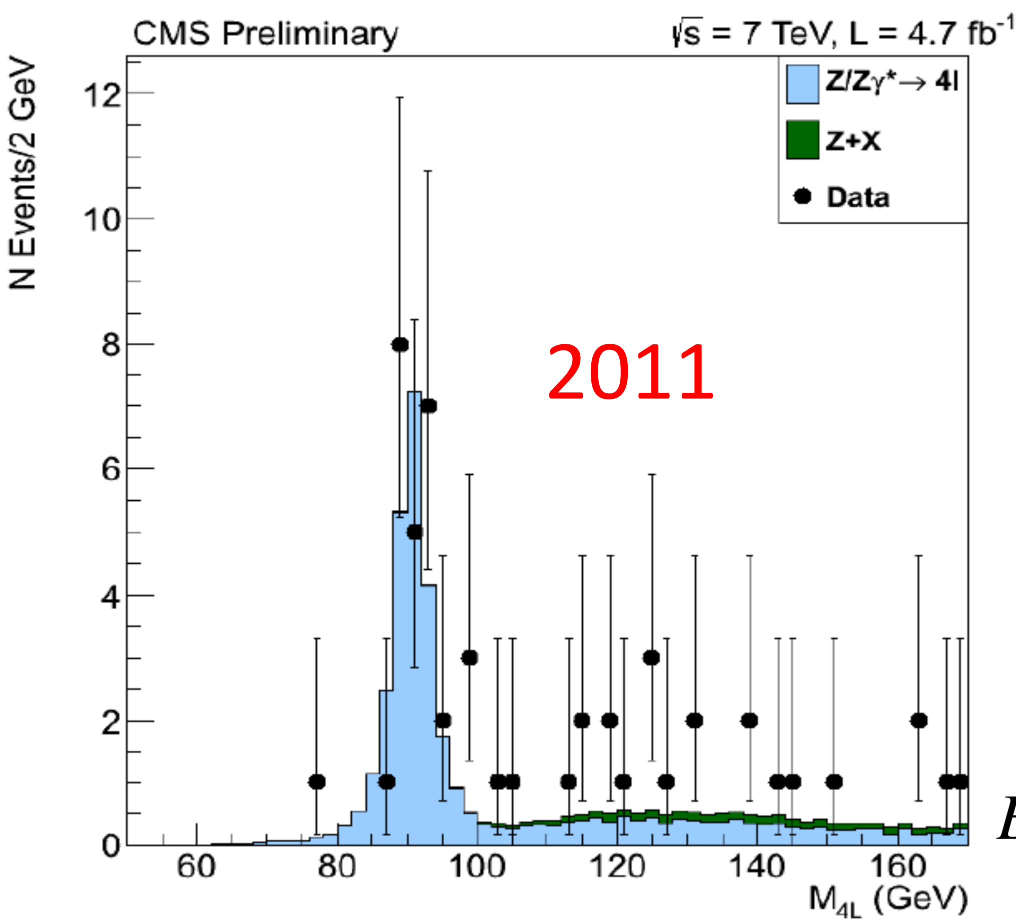
Muons

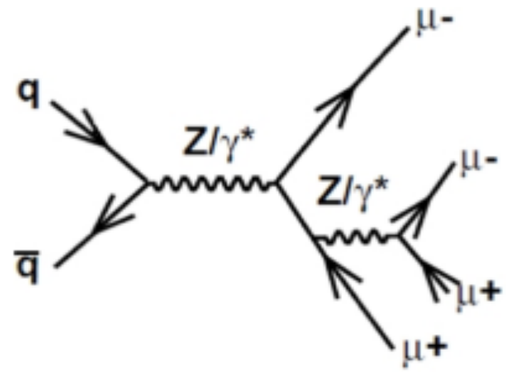




- High efficiency down to p_T = 15 GeV
  - Exploit also tracker-based muon ID
  - Important for H->ZZ->4l

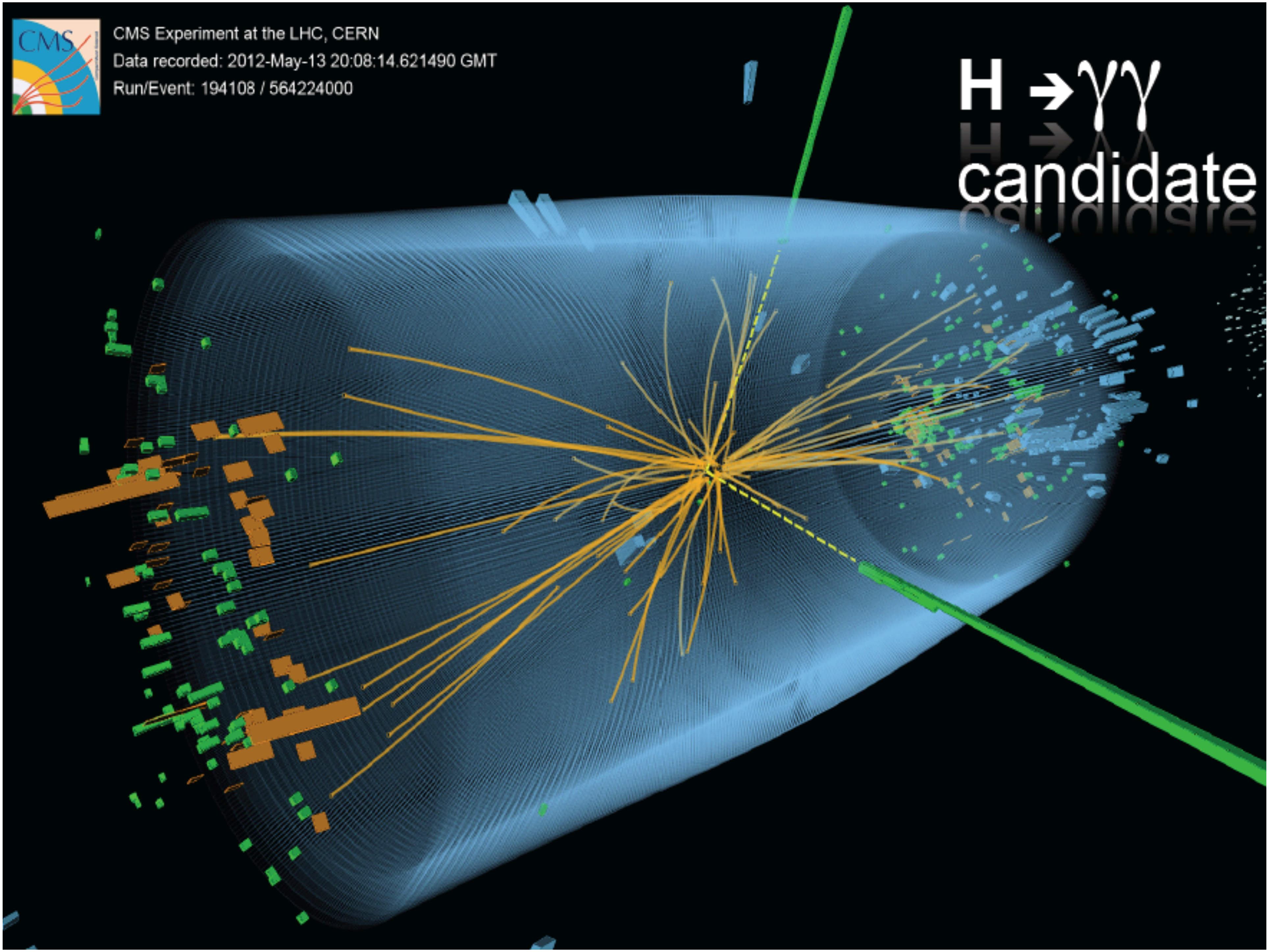
Leptons





CMS and LHC are good enough to allow for the search (and discovery!) of rare Z decays.

$$B(Z \to 4\ell) = (4.2 \pm 0.9 \pm 0.2) \times 10^{-6}$$


CMS
CMS Experiment at the LHC, CERN
Data recorded: 2012-May-13 20:08:14.621490 GMT
Run/Event: 194108 / 564224000
H →γγ
candidate

$H \rightarrow \gamma\gamma$ Strategy

- Multi-Variate Analysis (MVA) for photon ID and event classification
  - Divide events into non-overlapping samples of varying S/B based on properties of the reconstructed photons and presence of di-jets from VBF process
- Cross check with cut-based analysis
  - MVA and cut-based results consistent
  - MVA gives 15% better sensitivity
- Primary vertex selection, which is needed for $M_{\gamma\gamma}$ calculation, is based on consistency with di-photon kinematics (p_T balance etc.)
  - Correct assignment 83% (80%) in 2011 (2012)

Photon/Jet Selection

- Photons
  - $|\eta_\gamma| < 2.5$ and not in $1.44 < |\eta_\gamma| < 1.57$
  - Leading photon $p_T > M_{\gamma\gamma}/3$
  - Other photon $p_T > M_{\gamma\gamma}/4$
  - Leading photon in di-jet case $p_T > M_{\gamma\gamma}/2$
- Jets (VBF)
  - $|\eta_{jet}| < 4.7$
  - Leading jet $p_T > 30$ GeV, other jet $p_T > 20$ GeV
  - $\Delta\eta > 3.5$
  - $M_{jj} > 250$ GeV @ 8 TeV

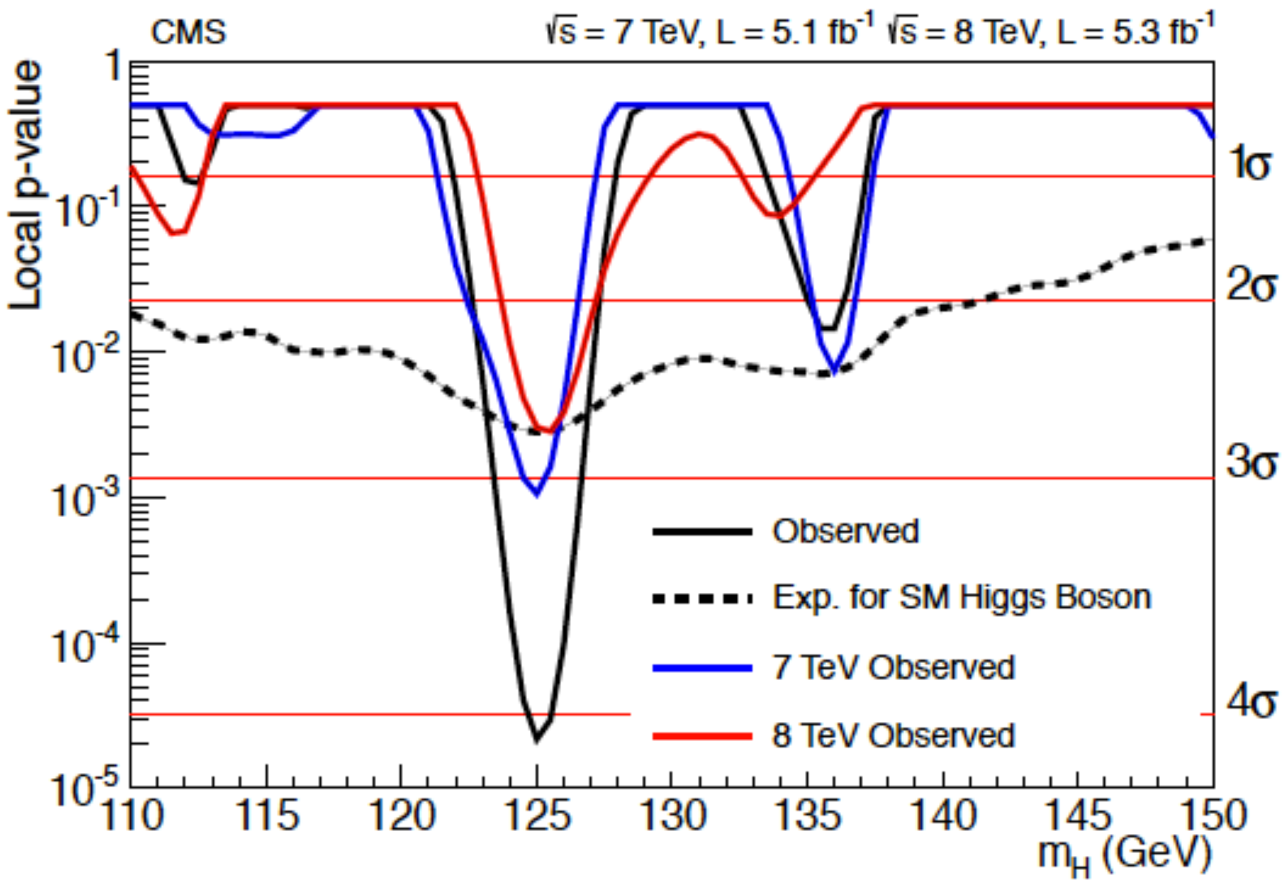
Event Selection

- Use a boosted decision tree to classify events based on
  - Photon quality (shape and isolation)
  - Expected mass resolution
  - Probability of correct vertex assignment
  - Kinematic characteristics of photons (excluding invariant mass)
- Divide events into five categories, dropping those in the lowest category
- Create additional category for di-jet tagged events
- See table next page

Expected Yield for SM Higgs

Event categories		SM Higgs boson expected signal ($m_H = 125$ GeV)							Background $m_{\gamma\gamma} = 125$ GeV (events/GeV)
		Events	ggH	VBF	VH	ttH	σ_{eff} (GeV)	FWHM/2.35 (GeV)	
7 TeV, 5.1 fb^{-1}	BDT 0	3.2	61%	17%	19%	3%	1.21	1.14	3.3 ± 0.4
	BDT 1	16.3	88%	6%	6%	–	1.26	1.08	37.5 ± 1.3
	BDT 2	21.5	92%	4%	4%	–	1.59	1.32	74.8 ± 1.9
	BDT 3	32.8	92%	4%	4%	–	2.47	2.07	193.6 ± 3.0
	Dijet tag	2.9	27%	72%	1%	–	1.73	1.37	1.7 ± 0.2
8 TeV, 5.3 fb^{-1}	BDT 0	6.1	68%	12%	16%	4%	1.38	1.23	7.4 ± 0.6
	BDT 1	21.0	87%	6%	6%	1%	1.53	1.31	54.7 ± 1.5
	BDT 2	30.2	92%	4%	4%	–	1.94	1.55	115.2 ± 2.3
	BDT 3	40.0	92%	4%	4%	–	2.86	2.35	256.5 ± 3.4
	Dijet tight	2.6	23%	77%	–	–	2.06	1.57	1.3 ± 0.2
	Dijet loose	3.0	53%	45%	2%	–	1.95	1.48	3.7 ± 0.4

Local p Values

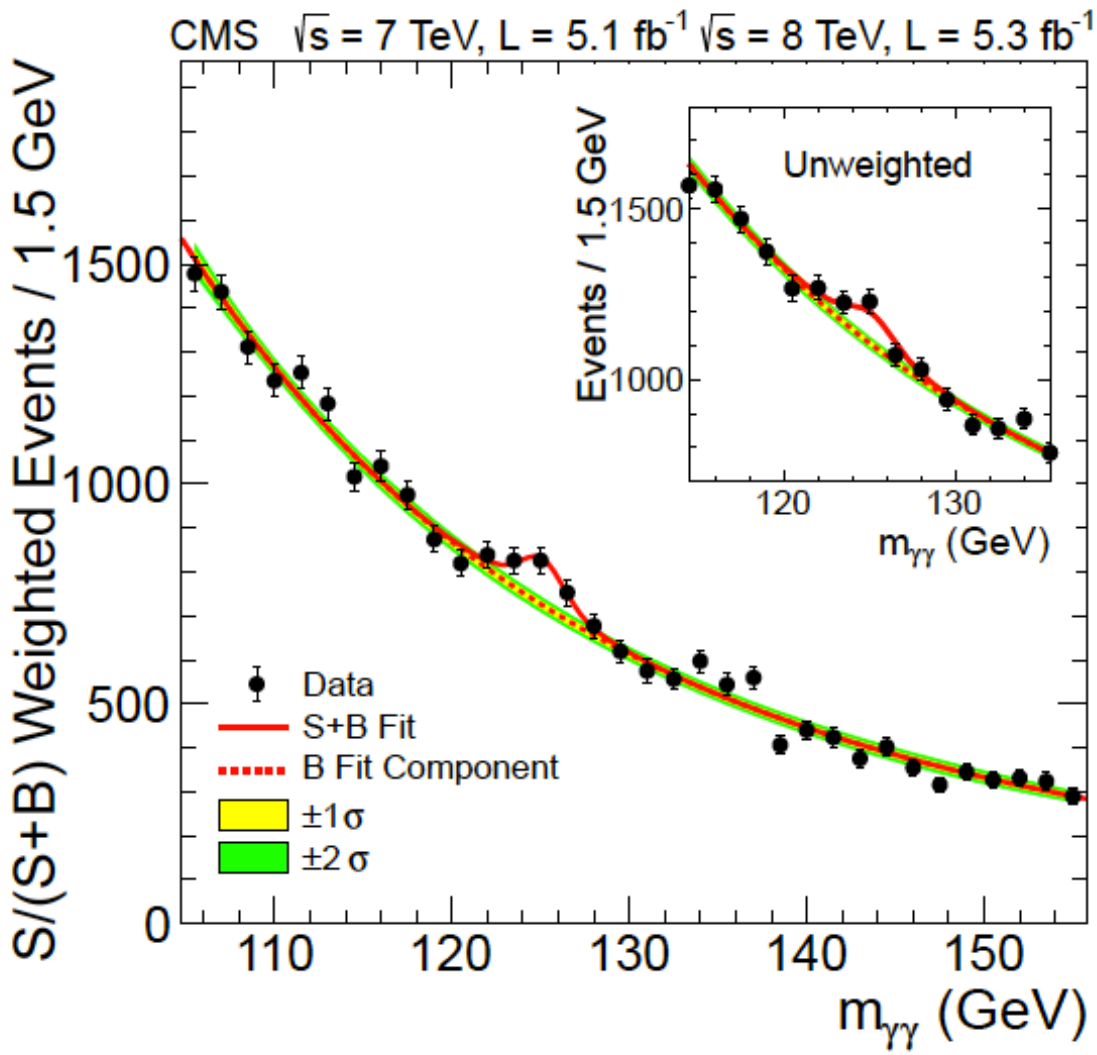


Significance based on local p-value: 4.1σ

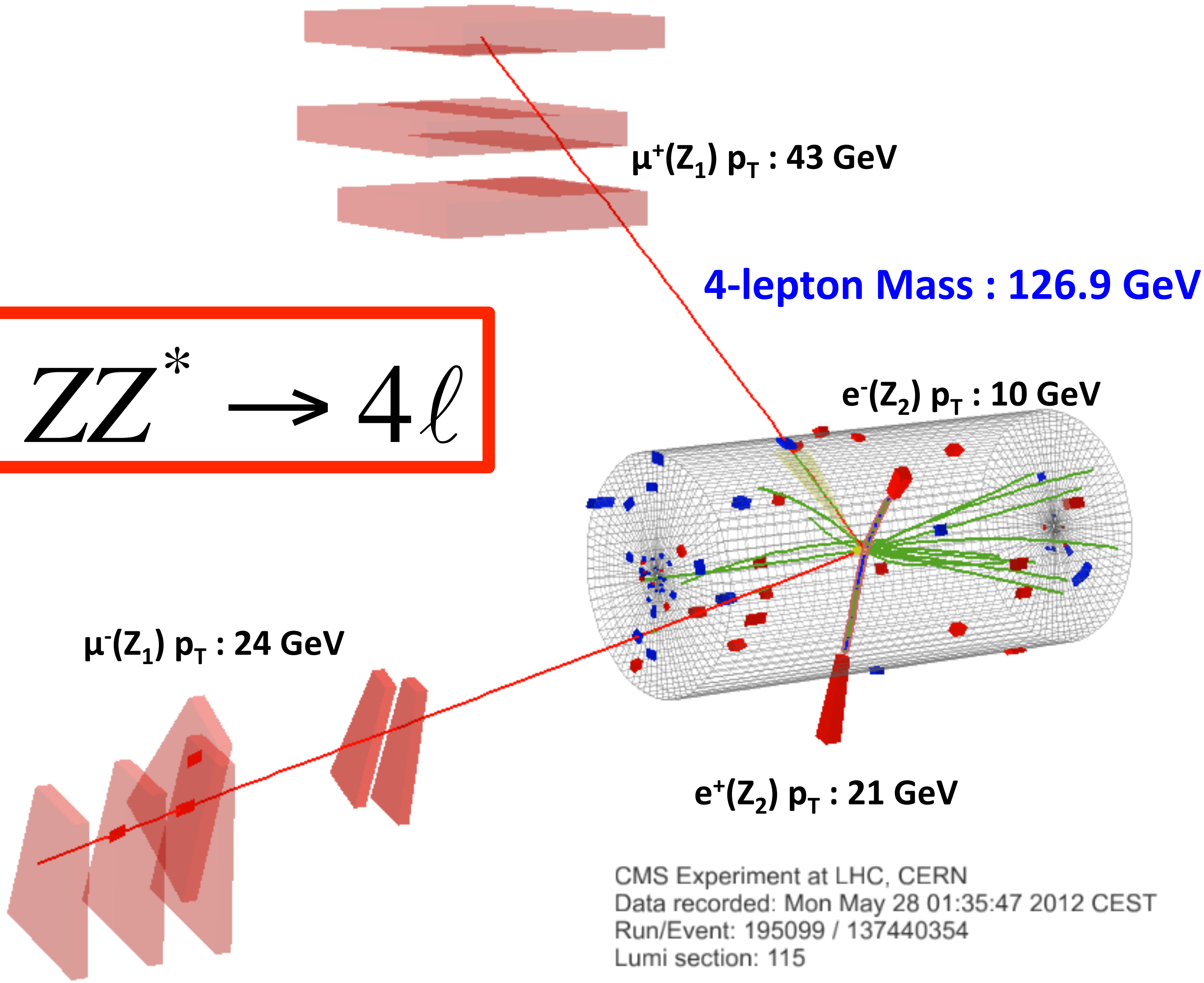
Significance based on global p-value: 3.2σ (110-150) GeV

Old Fashioned Spectrum

Event weights according to BDT class.



$$H \rightarrow ZZ^{*} \rightarrow 4\ell$$



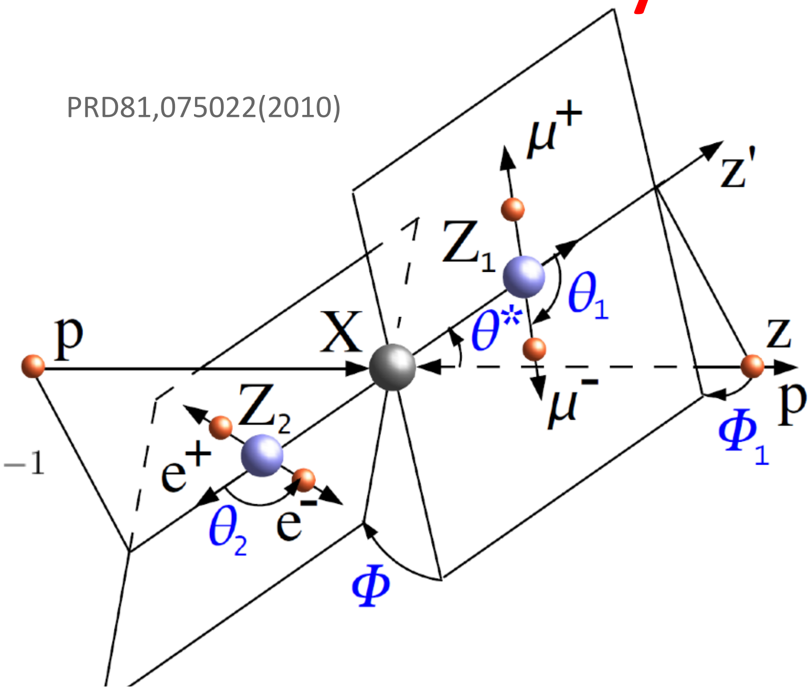
H→ZZ Selection

- 4e, 4μ, 2e2μ cases handled separately
- Backgrounds
  - Direct ZZ production (irreducible)
  - Z+bb, Z+tt (real leptons)
  - Z+jets, WZ+jets (jet misID as lepton)
- Final state radiation (FSR) recovery
- Lepton Requirements
  - Electrons: $p_T > 7$ GeV, $|\eta|<2.5$
  - Muons: $p_T > 5$ GeV, $|\eta|<2.4$
  - Isolation for both e's and μ's
  - Leptons must come from common vertex
- Di-lepton mass
  - Closest match: $40 < M_{ll} < 120$ GeV
  - Other pair: $12 < M_{ll} < 120$ GeV

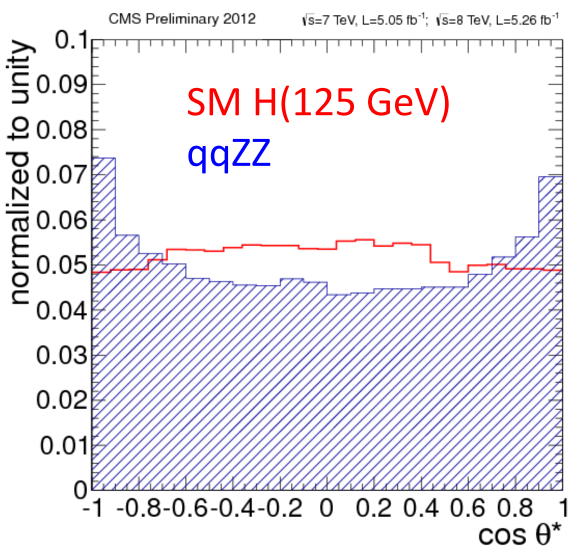
Matrix Element Likelihood Analysis

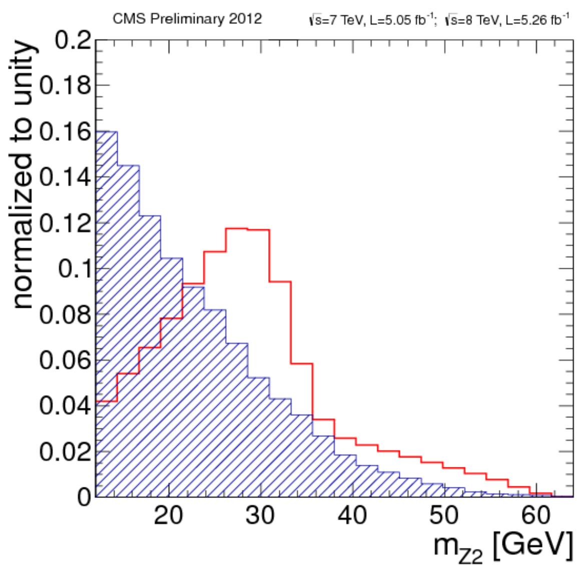
MELA uses kinematic inputs for signal to background discrimination $\{m_1, m_2, \theta_1, \theta_2, \theta^*, \Phi, \Phi_1\}$

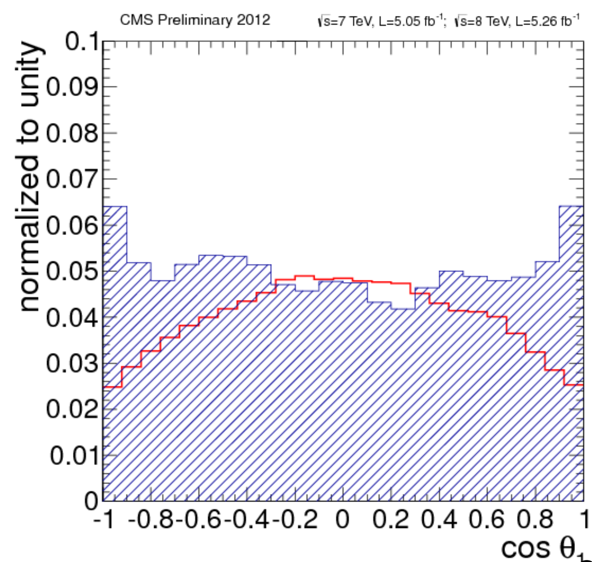
PRD81,075022(2010)



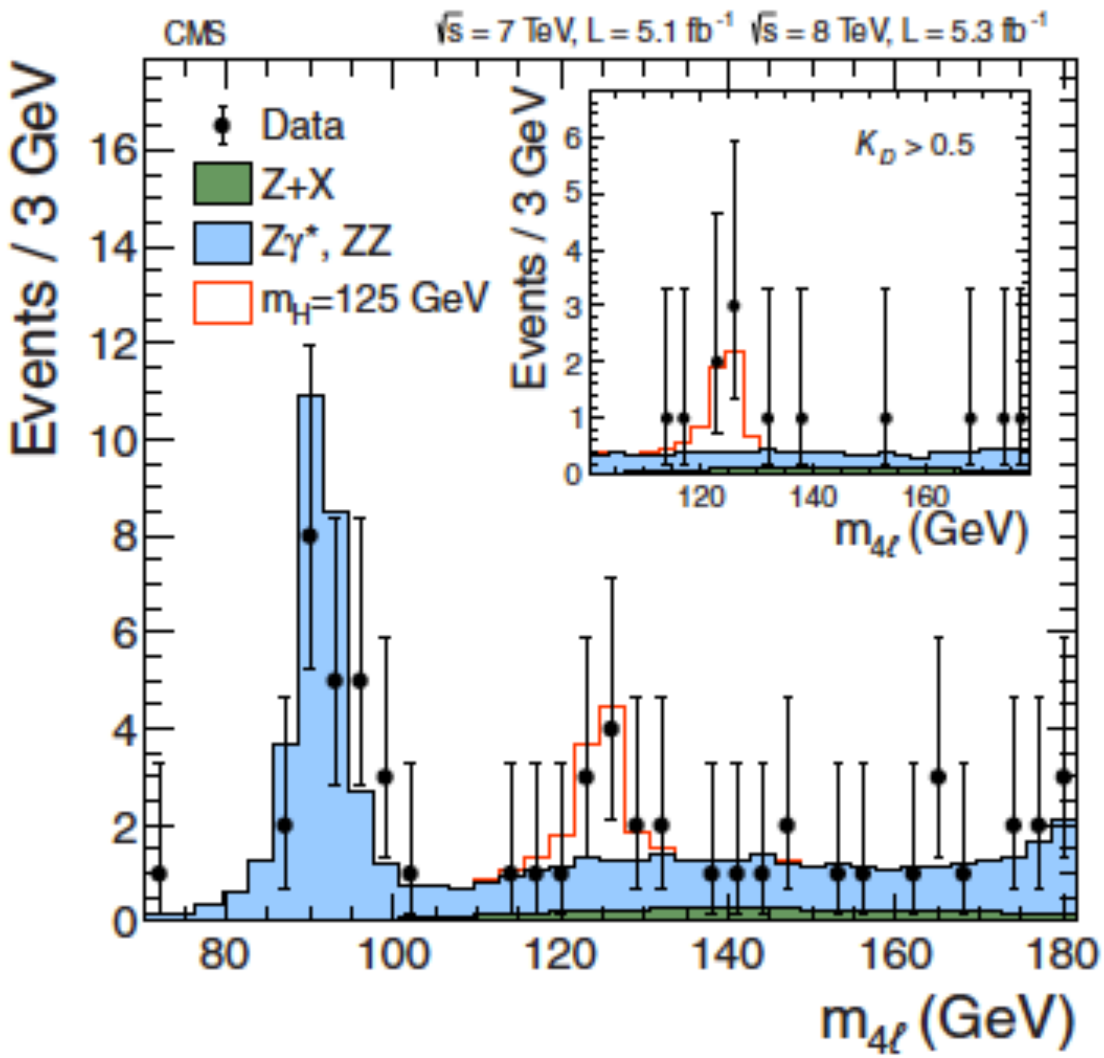
$$\mathrm{MELA} = \left[1 + \frac{\mathcal{P}_{\mathrm{bkg}}(m_1, m_2, \theta_1, \theta_2, \Phi, \theta^*, \Phi_1 | m_{4\ell})}{\mathcal{P}_{\mathrm{sig}}(m_1, m_2, \theta_1, \theta_2, \Phi, \theta^*, \Phi_1 | m_{4\ell})}\right]^{-1}$$







4l Mass Spectrum



K_D is kinematic discriminate from MELA

Excess:
3.2σ @ 125.6 GeV
vs. 3.8σ expected

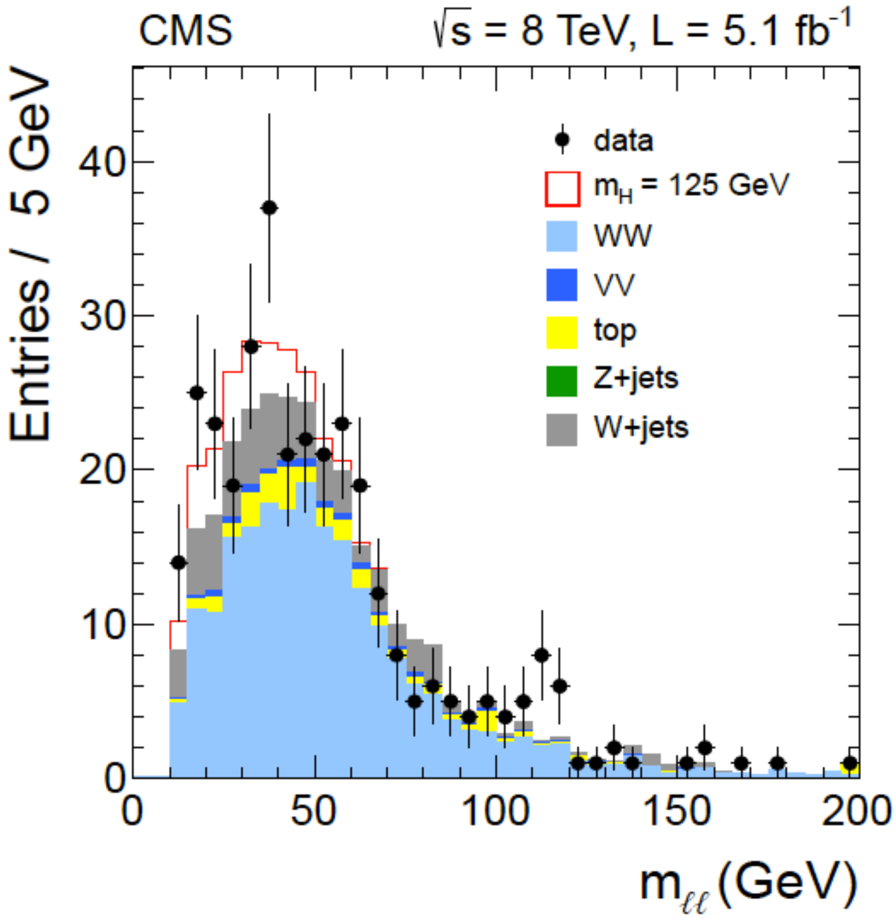
$H \rightarrow ZZ$ Signal and Background

Channel	4e	4μ	$2e2\mu$	4ℓ
ZZ background	2.7 ± 0.3	5.7 ± 0.6	7.2 ± 0.8	15.6 ± 1.4
$Z + X$	$1.2^{+1.1}_{-0.8}$	$0.9^{+0.7}_{-0.6}$	$2.3^{+1.8}_{-1.4}$	$4.4^{+2.2}_{-1.7}$
All backgrounds ($110 < m_{4\ell} < 160$ GeV)	4.0 ± 1.0	6.6 ± 0.9	9.7 ± 1.8	20 ± 3
Observed ($110 < m_{4\ell} < 160$ GeV)	6	6	9	21
Signal ($m_H = 125$ GeV)	1.36 ± 0.22	2.74 ± 0.32	3.44 ± 0.44	7.54 ± 0.78
All backgrounds (signal region)	0.7 ± 0.2	1.3 ± 0.1	1.9 ± 0.3	3.8 ± 0.5
Observed (signal region)	1	3	5	9

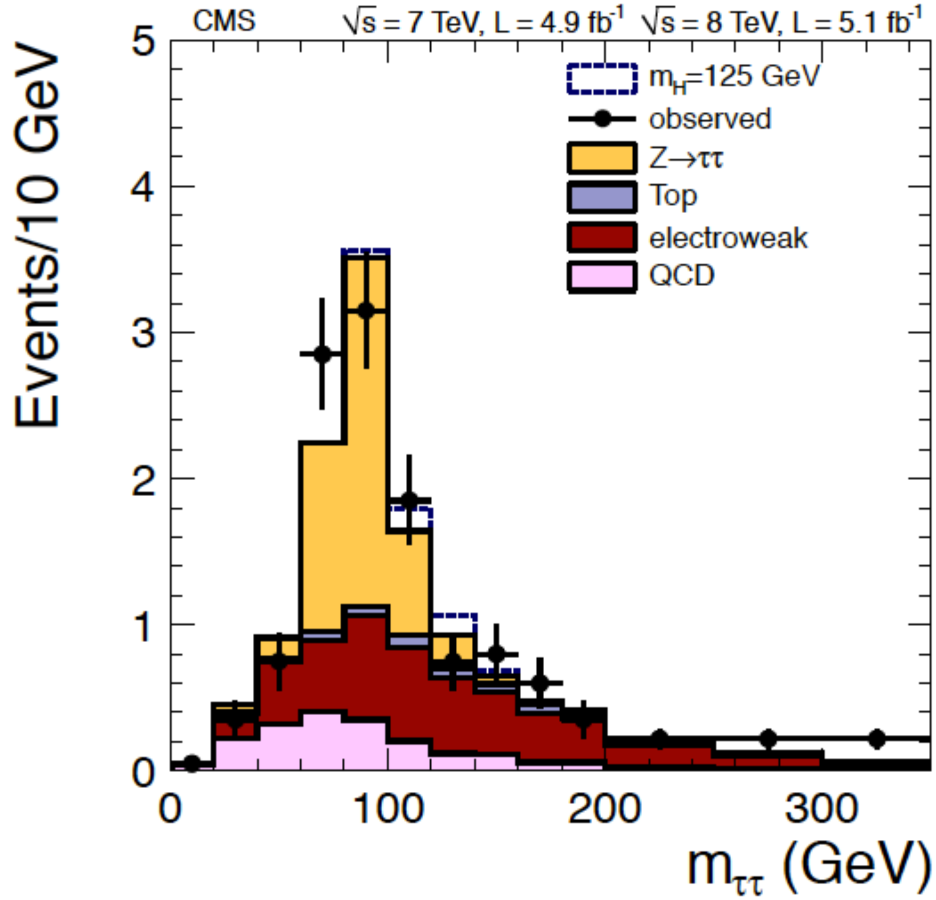
Signal Region: $121.5 < M_{4\ell} < 130.5$ GeV

Observed significance at M_H = 125.6 GeV:
3.2σ (vs 3.8σ expected for SM Higgs)

Other Modes

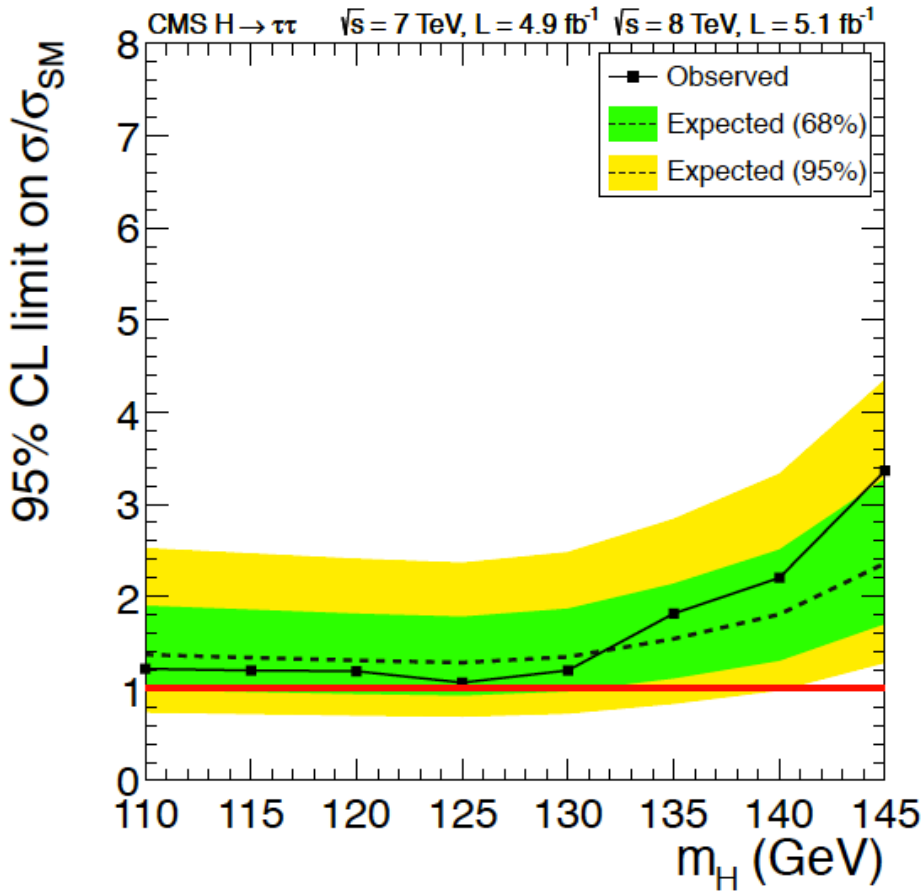


$H \rightarrow WW \quad$ (0-jet $e\mu$)

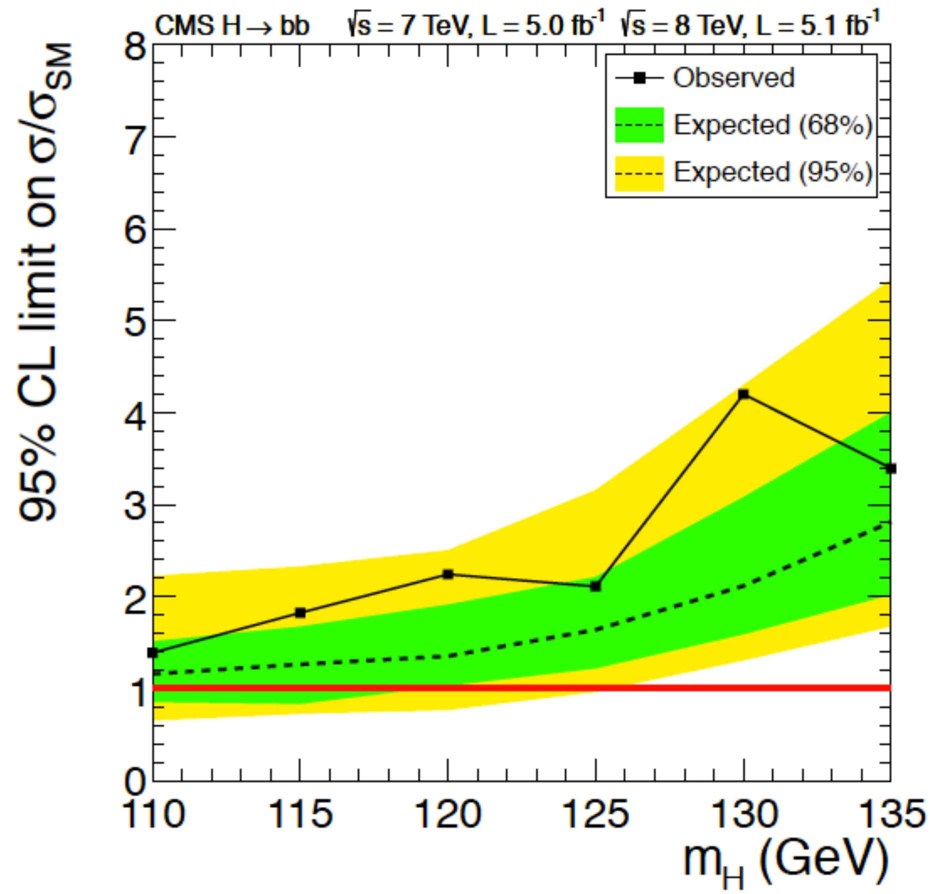


$H \rightarrow \tau\tau \quad (\mu\tau_h \;\; \mathrm{VBF})$

. . . Other Modes

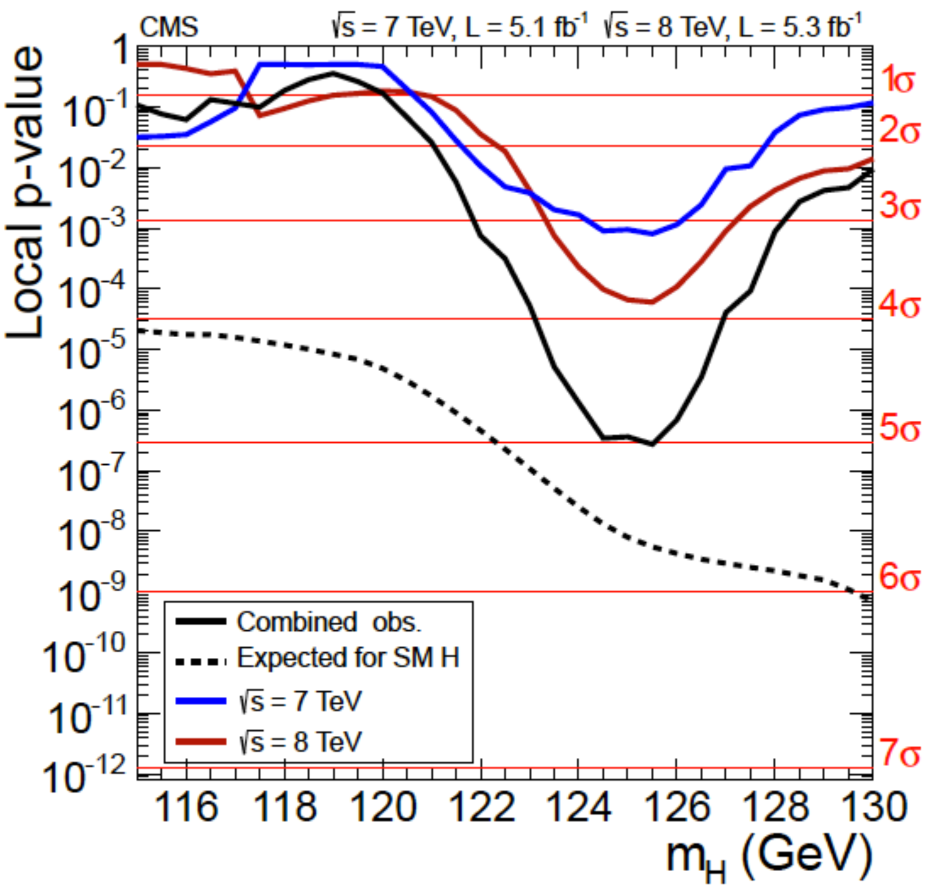


$H \to \tau\tau$ (combined)

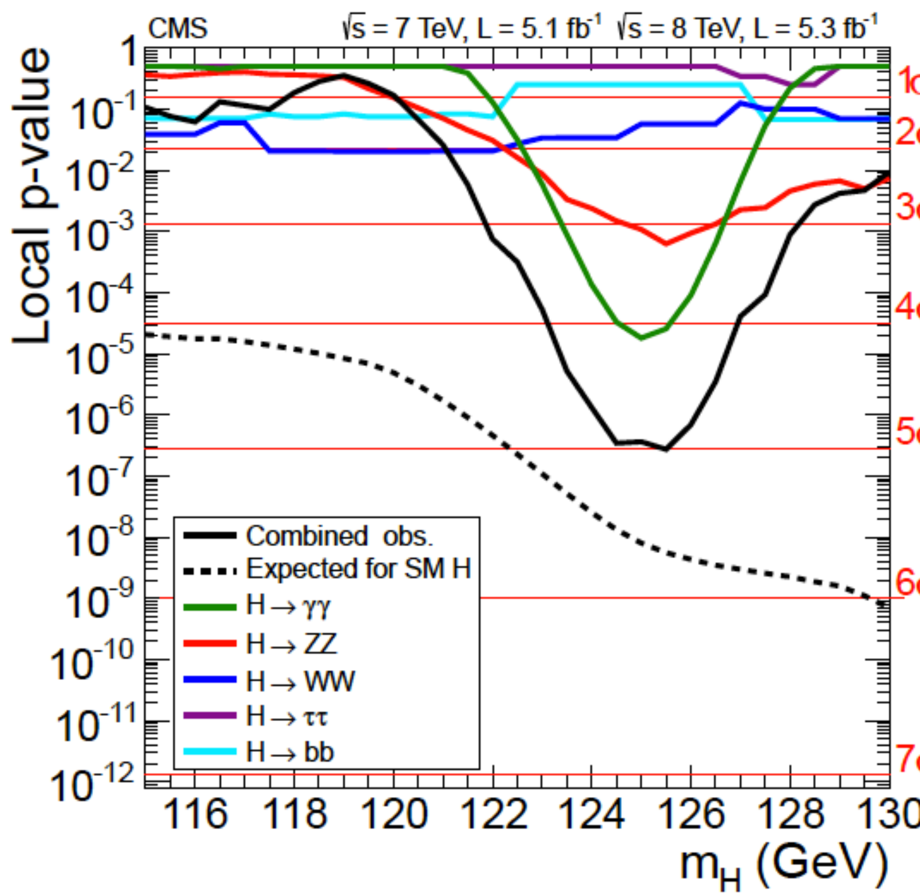


$H \to bb$ (combined)

Combined Results



By dataset



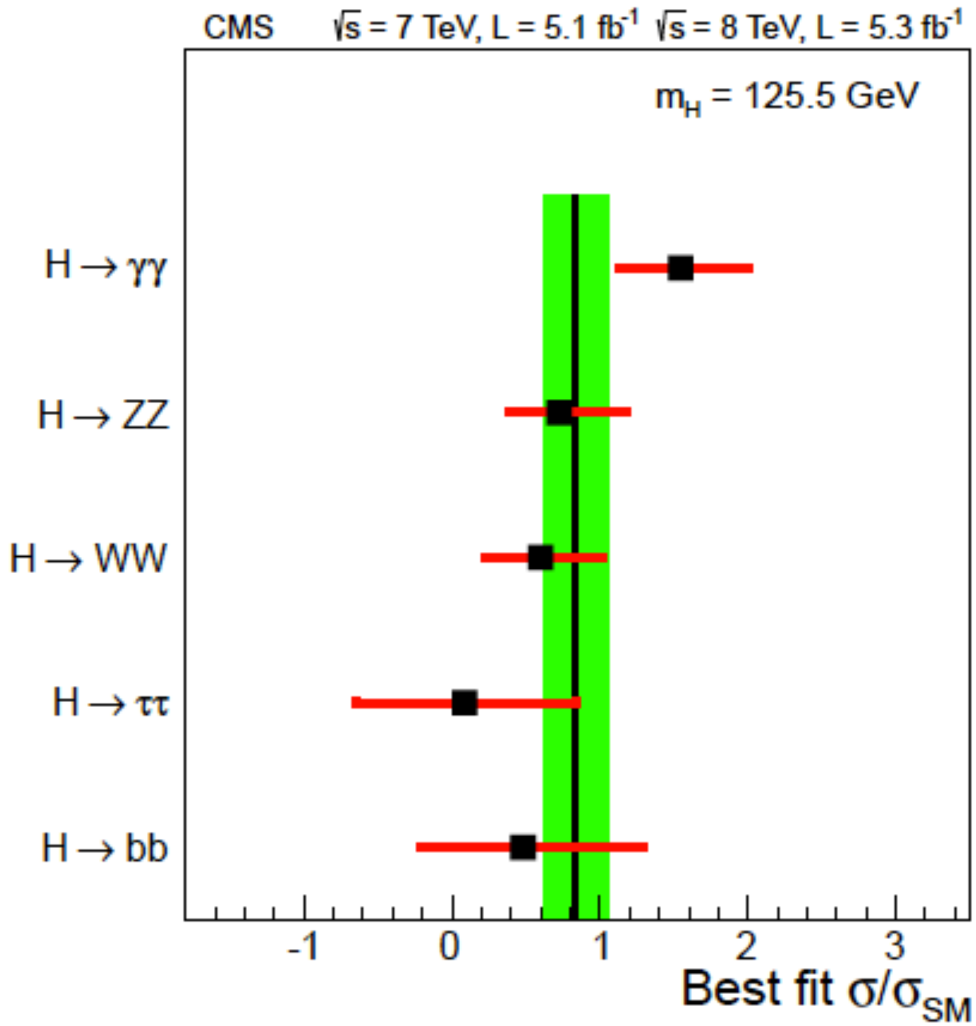
By mode

Combined Results

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

Overall significance 5.0σ versus 5.8σ expected.

Signal Strengths



Properties of New Particle

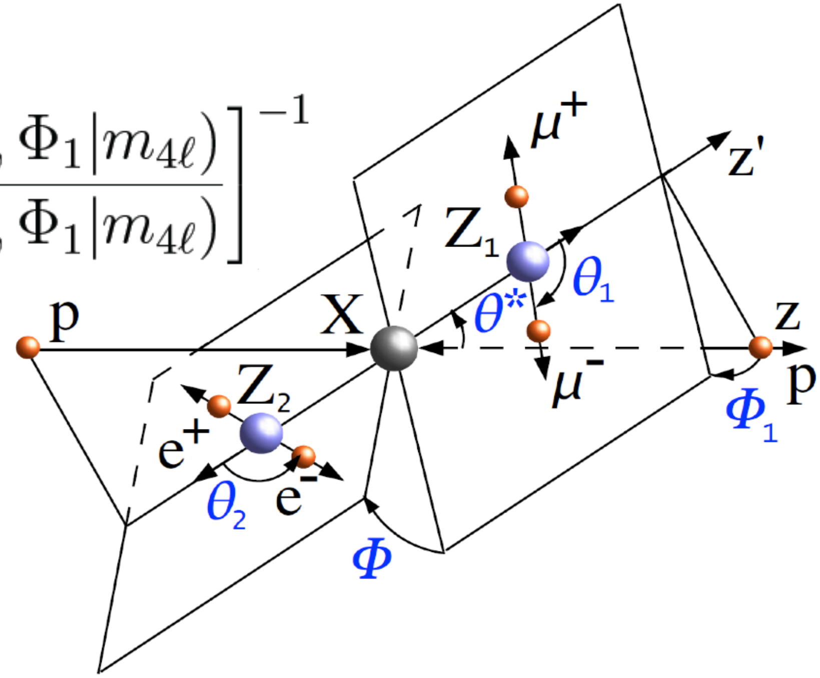
- $M = 125.3 \pm 0.4 \pm 0.5 \text{ GeV}$
- Best-fit signal strength to combined data

$$\frac{\sigma}{\sigma_{\text{SM}}} = 0.87 \pm 0.23$$

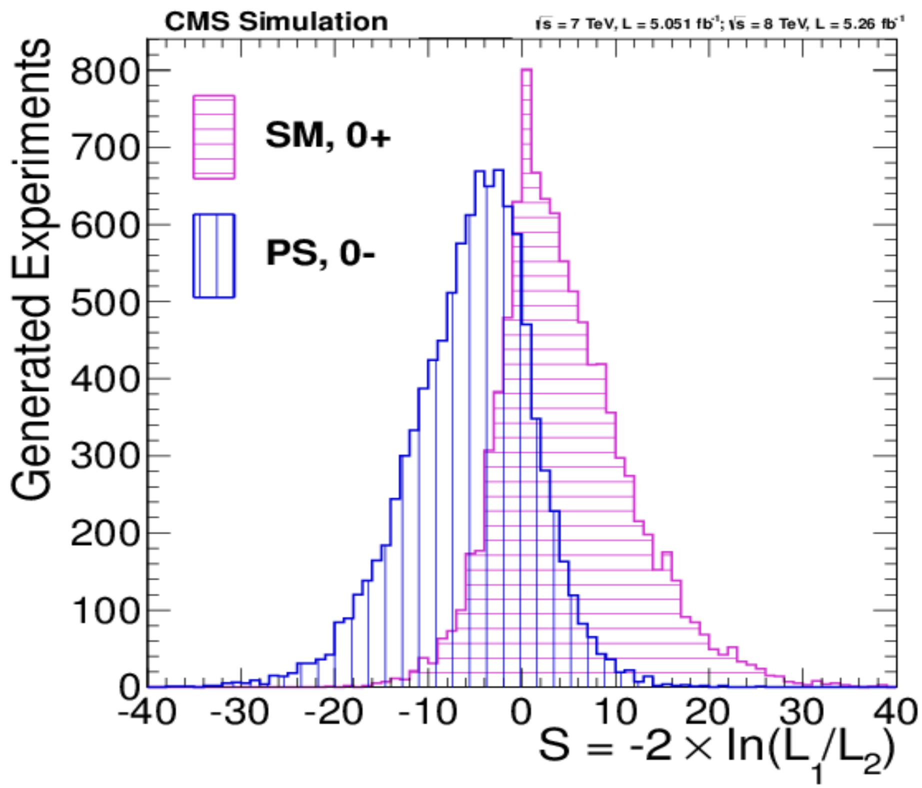
- Spin-parity
  - Spin one ruled out by 2γ decay
  - Assuming S=0, one can use H→ZZ to distinguish between parity states

Parity from MELA

$$\text{psMELA} = \left[1 + \frac{\mathcal{P}_{0-}(m_1, m_2, \theta_1, \theta_2, \Phi, \theta^*, \Phi_1 | m_{4\ell})}{\mathcal{P}_{0+}(m_1, m_2, \theta_1, \theta_2, \Phi, \theta^*, \Phi_1 | m_{4\ell})}\right]^{-1}$$



Matrix Element Likelihood Analysis: uses kinematic inputs to form likelihood



Expected (MC) separation between 0^+ and 0^- hypotheses:

1.6σ with current sample
3.1σ with 5+30 fb^{-1} sample expected by end of 2012 run

Scouting the Energy Frontier

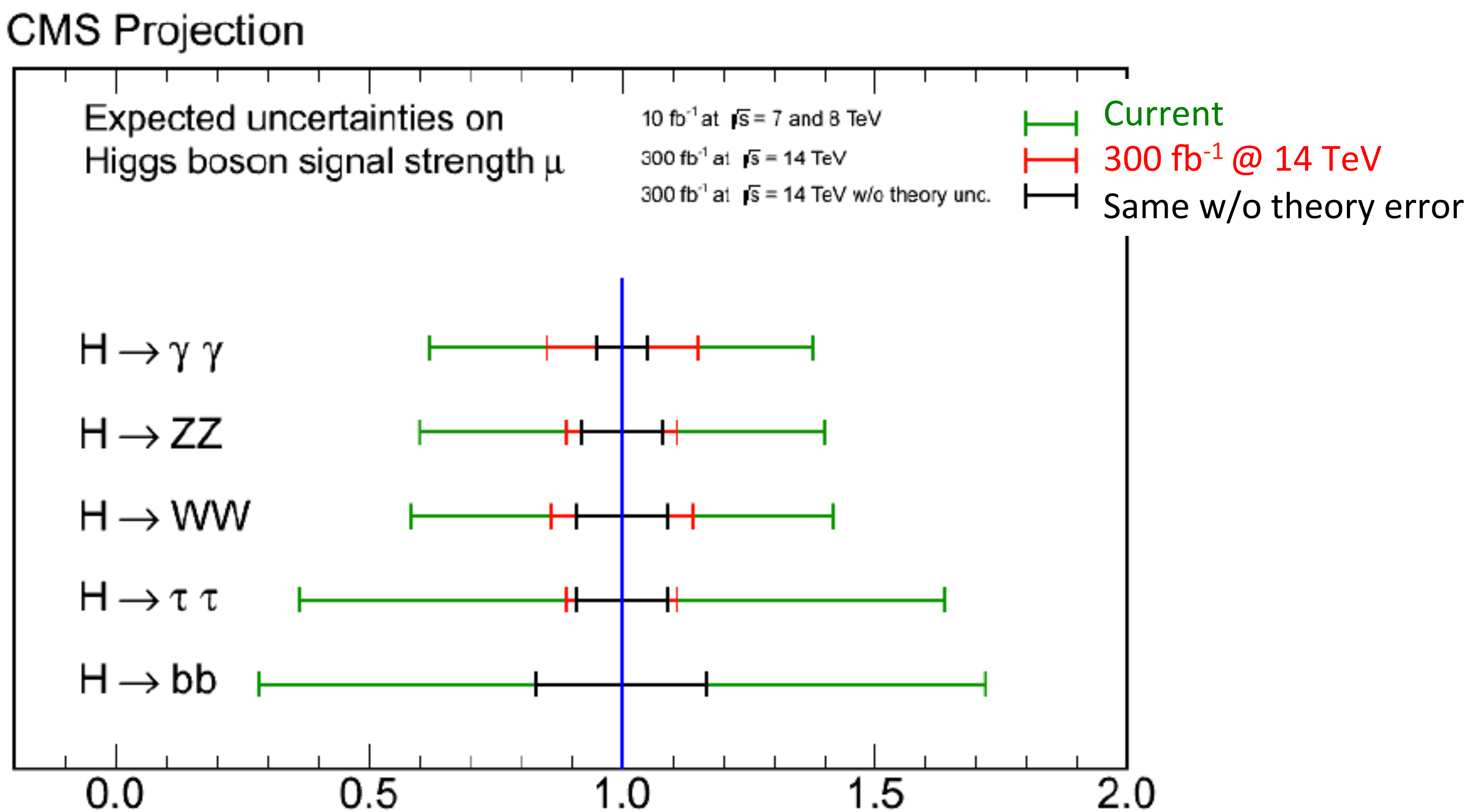
- General need for upgrade understood for some time now, given excellent performance of LHC. But . . .
- The recent discovery has brought new focus to plans for the near- and long-term future.
- The studies are rapidly advancing, and one can expect significant improvements over the snapshot to be presented.
- There are, of course, other topics of interest that can be studied at the energy frontier, but this talk will concentrate on the Higgs.

Benchmark Data Sets

Scenario	L (fb^{-1})	E (TeV)
LHC	300	14
HL-LHC	3000	14
HE-LHC	300	33

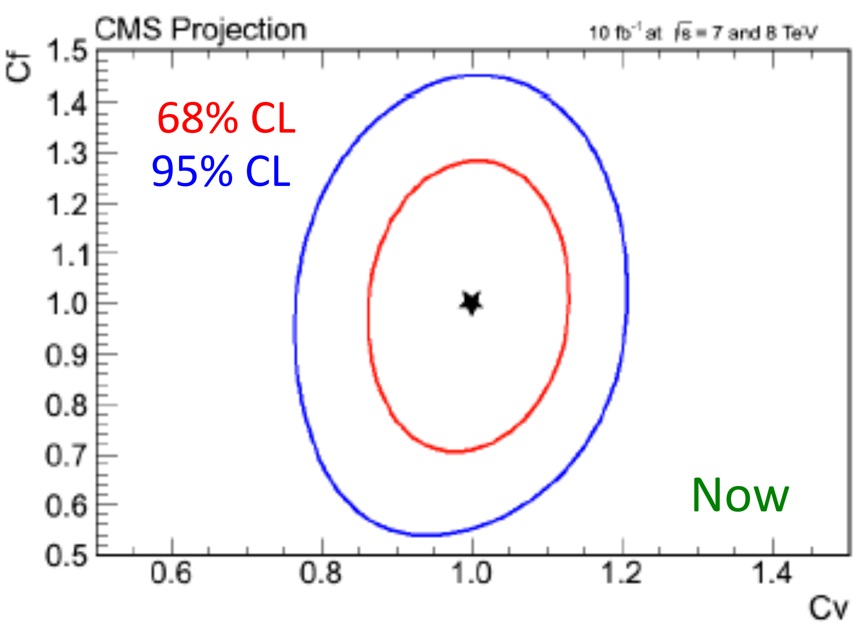
- In terms of parton luminosities, the higher energy (33 TeV) is worth about a factor of two for the creation of 100 GeV objects and a factor of 10 for objects of mass 1 TeV
- Assume trigger and reconstruction performance similar to what CMS currently has at 8 TeV
  - Superficially conservative, but will in fact require *significant detector upgrades* to offset effects of radiation damage and higher pileup

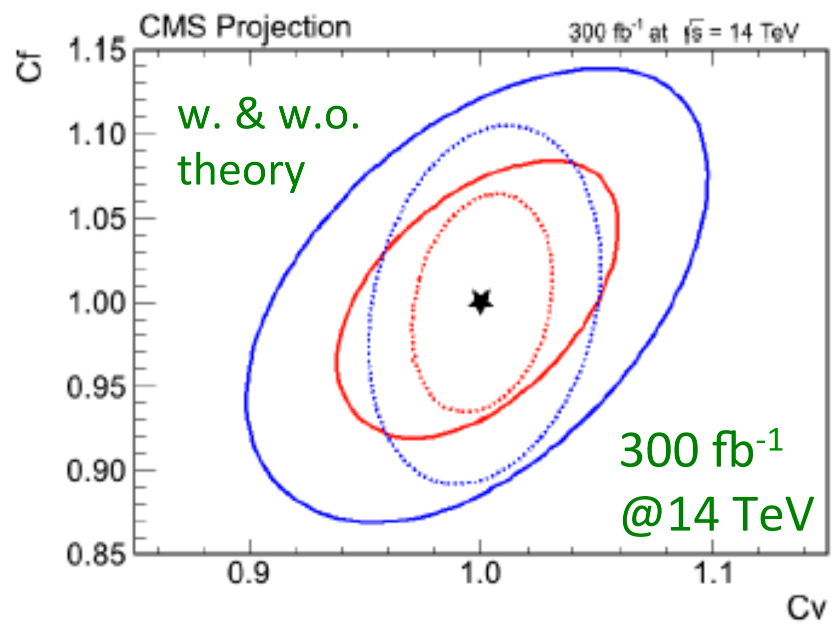
Projected Signal Strength Precision



Higgs Characterization

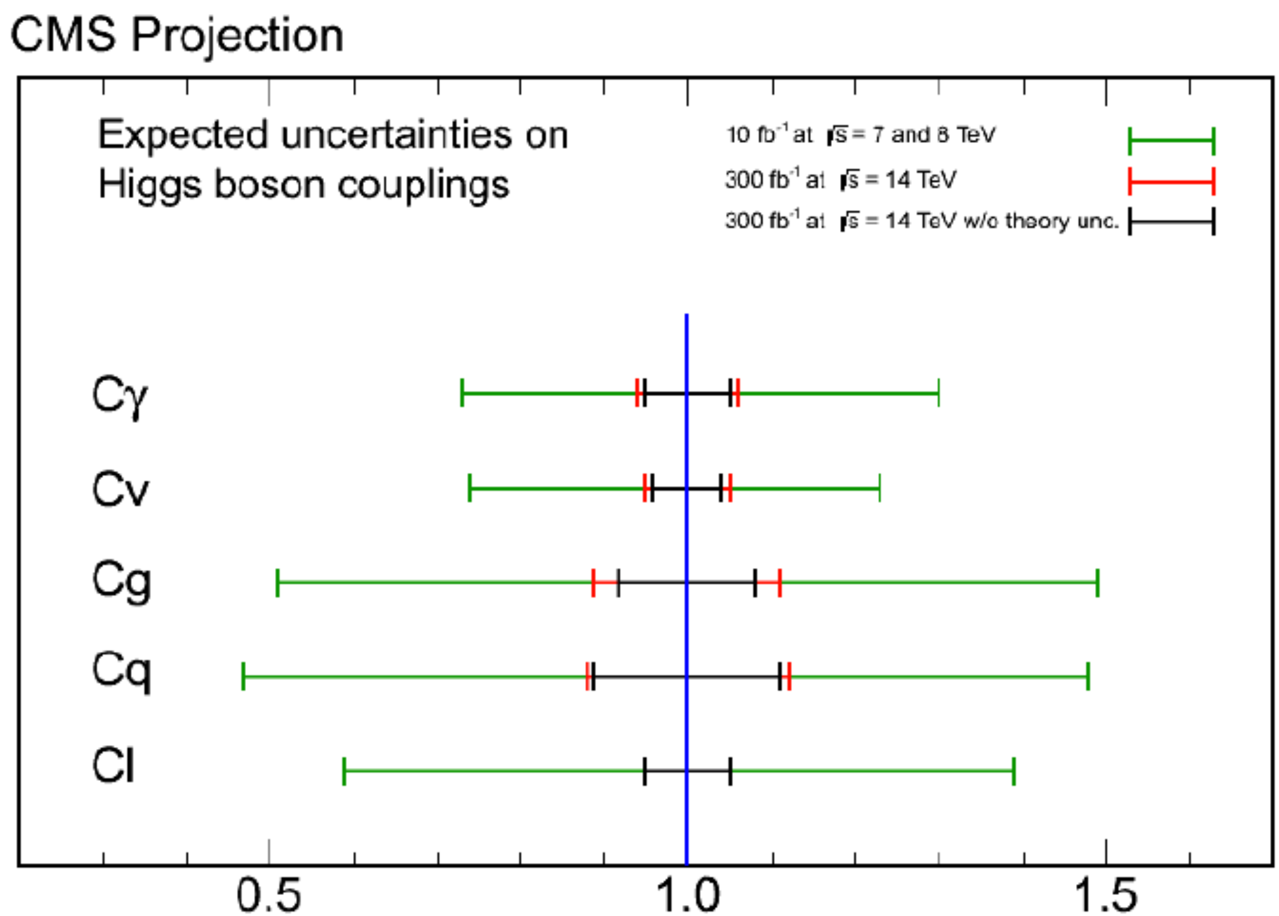
- Consider scenario where SM is extended through an effective-theory approach, wherein modified couplings to vector bosons and fermions are obtained. These are called C_V and C_F, respectively, and are nominally =1 in the SM (although uncertainties exist).





Higgs Characterization

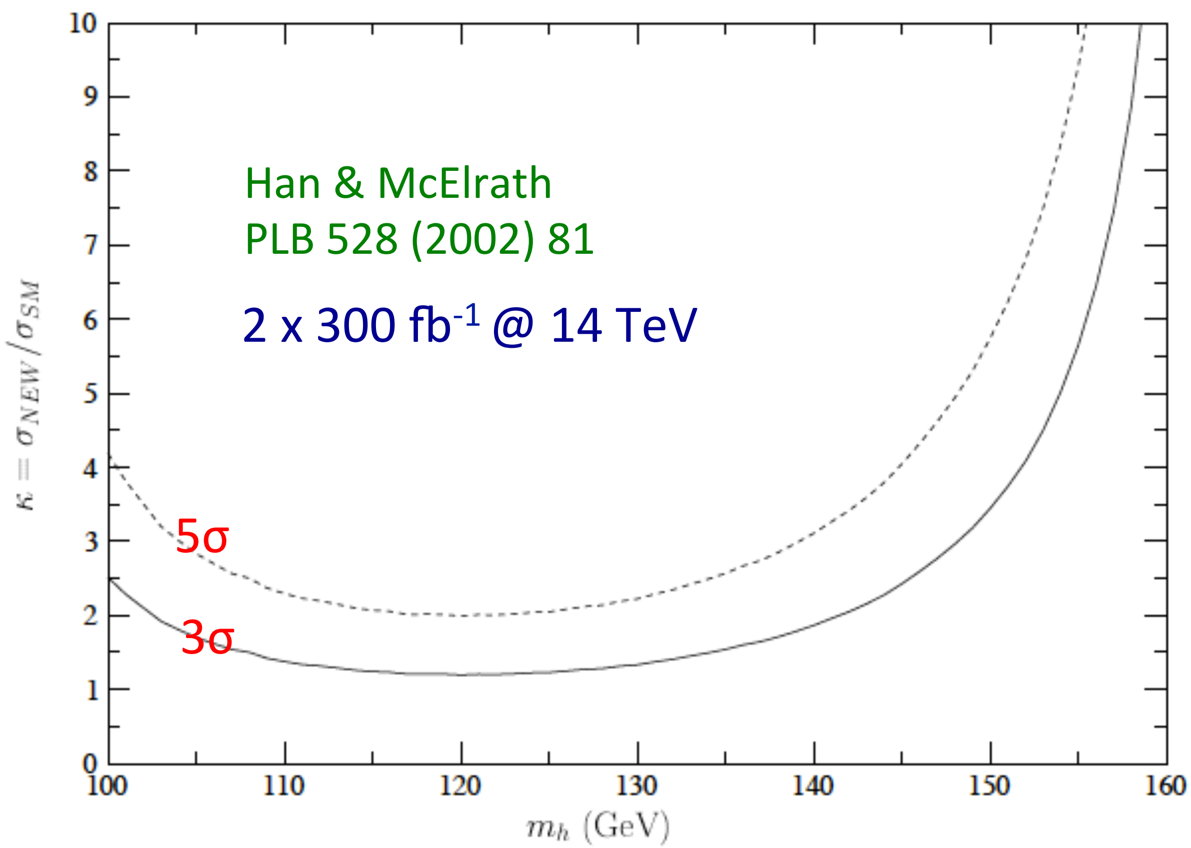
One can go a step farther and introduce additional degrees of freedom in the form of C_γ, C_V, C_g, C_q, and C_l .



H→μμ

Would like to see example of Higgs coupling to a 2nd generation fermion.

Rate predicted by SM is low, but within reach. Moreover, enhancements are possible in beyond the SM scenarios.



Enhancement relative to SM needed to see signal in H→μμ

Higgs Self Coupling

- Probing the Higgs potential itself is an essential piece of the future program.
- Do this through the study of multiple Higgs production.
- Most straightforward approach uses

$$gg \to HH \to W^+W^-W^+W^- \to \ell^\pm \nu jj \ell^\pm \nu jj$$

  but this runs out of gas for M_H < 140 GeV
- For lower M_H=125 GeV use

$$gg \to HH \to \begin{cases} b\bar{b}\gamma\gamma \\ b\bar{b}\mu\mu \end{cases}$$

Likely needs the 33 TeV machine

Conclusions

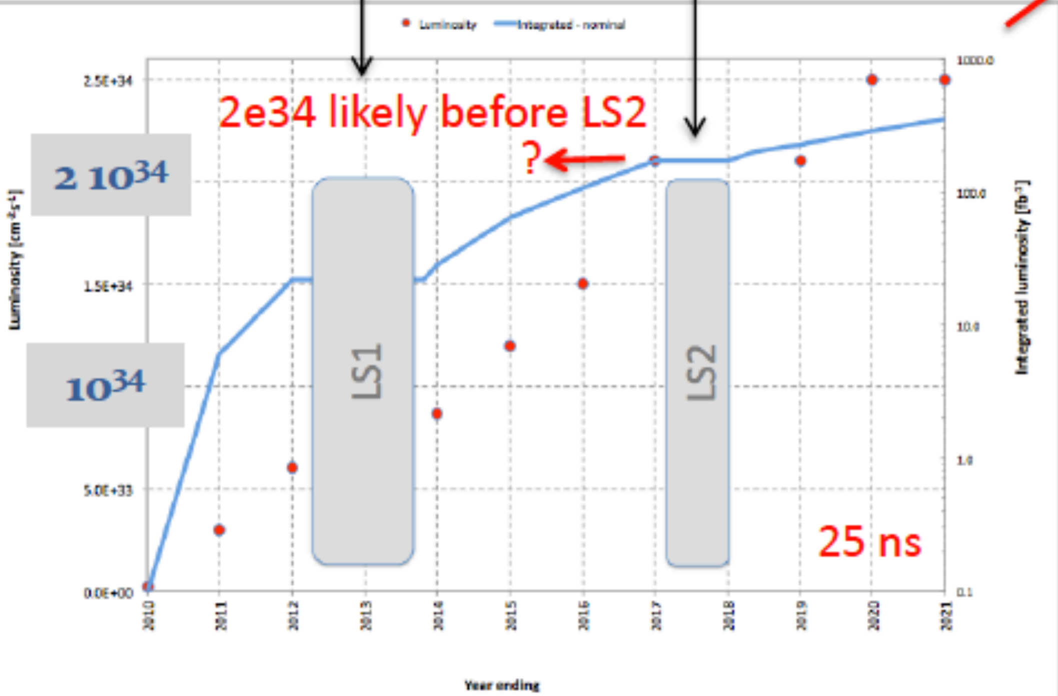
- Discovery of new boson with Higgs-like properties at 125 GeV is a major accomplishment for the field.
- Much remains to be done to confirm (or refute) the SM Higgs interpretation
- An upgraded LHC will play a key role in elucidating the nature of this new particle

Backup

LHC Schedule

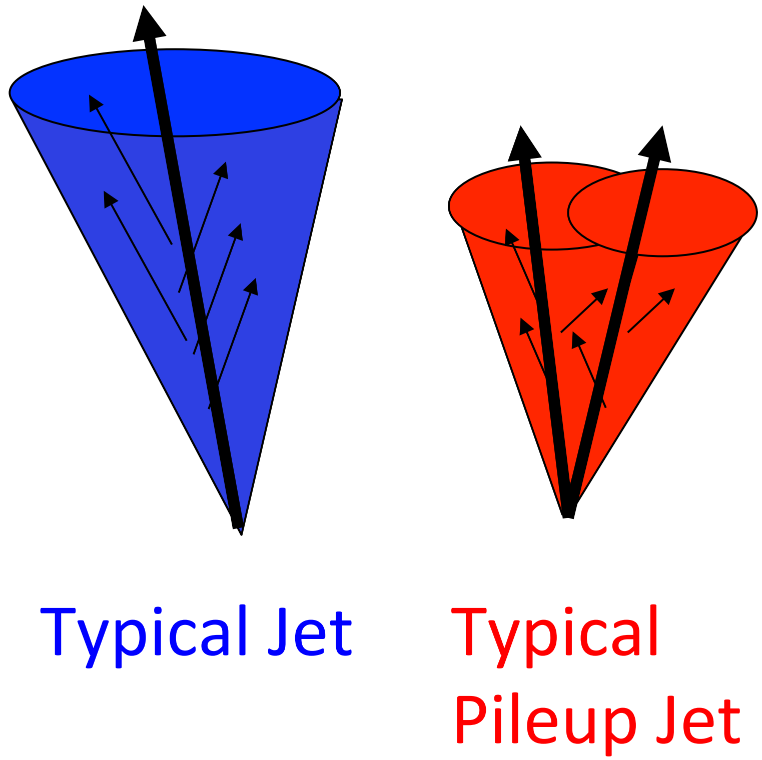
20fb^{-1} → **Phase 1 : 13/14 TeV - 500fb^{-1}** → **Phase 2 : 13/14 TeV - 3000fb^{-1}**

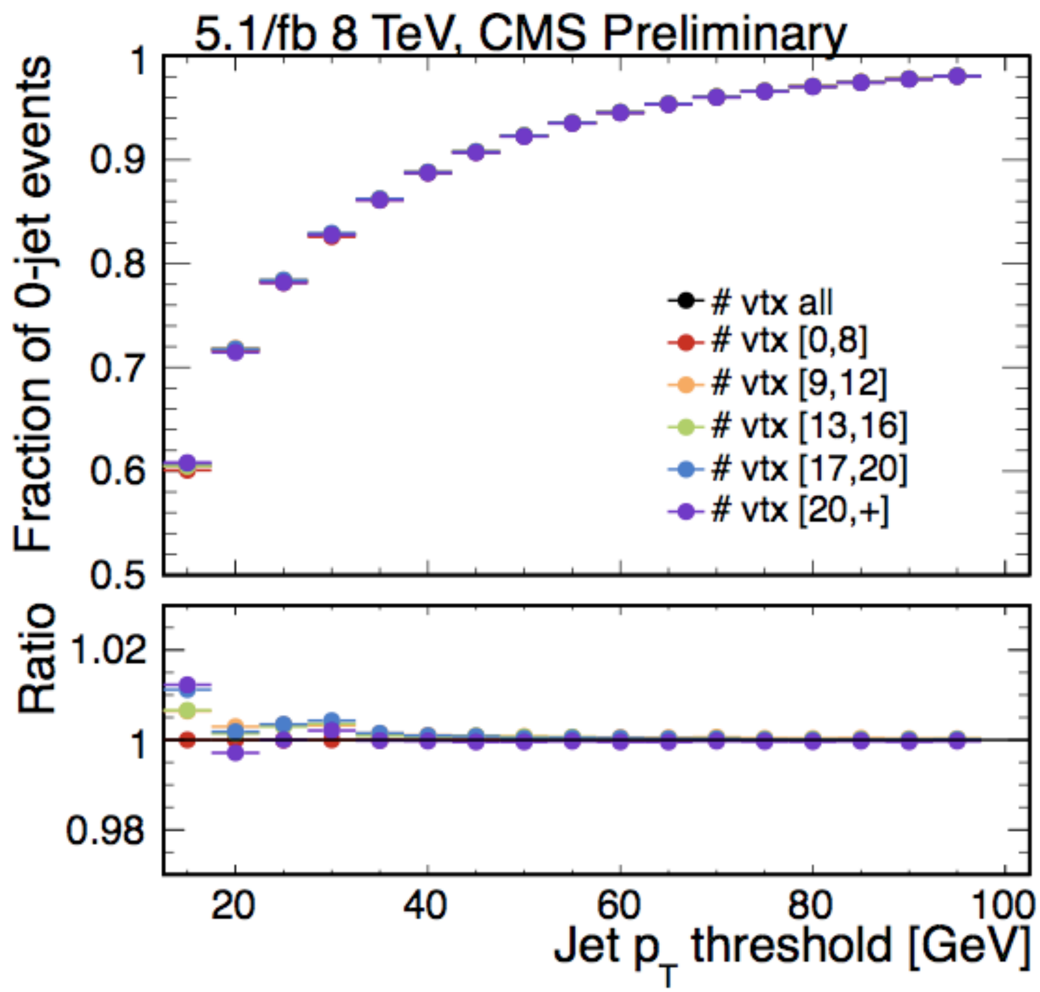
12	LS1 13-14	LS2 18 (19?)	LS3 22-23	>30…
7 10^{33}Hz/cm^2 @50 ns	8→13/14 TeV Injection upgrade: PS batch compression SPS scrubbing	Injection upgrade: Linac4 (H^-) PSB-PS 1.4→2GeV RF upgrades PS - SPS aC coating SPS (?)	LHC Interaction region upgrade: Triplets (lower β*) Crab cavities (beam crossing leveling) b-b compensation (lower beam loss) L_{peak} 10^{35} Hz/cm^2 $L_{leveled}$ 5 10^{34} Hz/cm^2	



- Goal is 25ns, 50ns not ruled out
- Performance projection and schedule will likely not be well known before restarting in 2015
- Leveling mitigates pile-up but integrated luminosity could be limited due to SEE & UFOs effects

Jets


Typical Jet
Typical
Pileup Jet


5.1/fb 8 TeV, CMS Preliminary
Fraction of 0-jet events
1
0.9
0.8
0.7
0.6
0.5
vtx all
vtx [0,8]
vtx [9,12]
vtx [13,16]
vtx [17,20]
vtx [20,+]
Ratio
1.02
1
0.98
20
40
60
80
100
Jet p_T threshold [GeV]

2012 analysis + improvements

5 fb^{-1} @ 7 TeV + 5.3 fb^{-1} @ 8 TeV

Blinding policy:

Analysis is optimized blinding in the signal region
Do NOT look at 110 < m_{4l} <140 GeV, and m_{4l} > 300 GeV

Main changes:

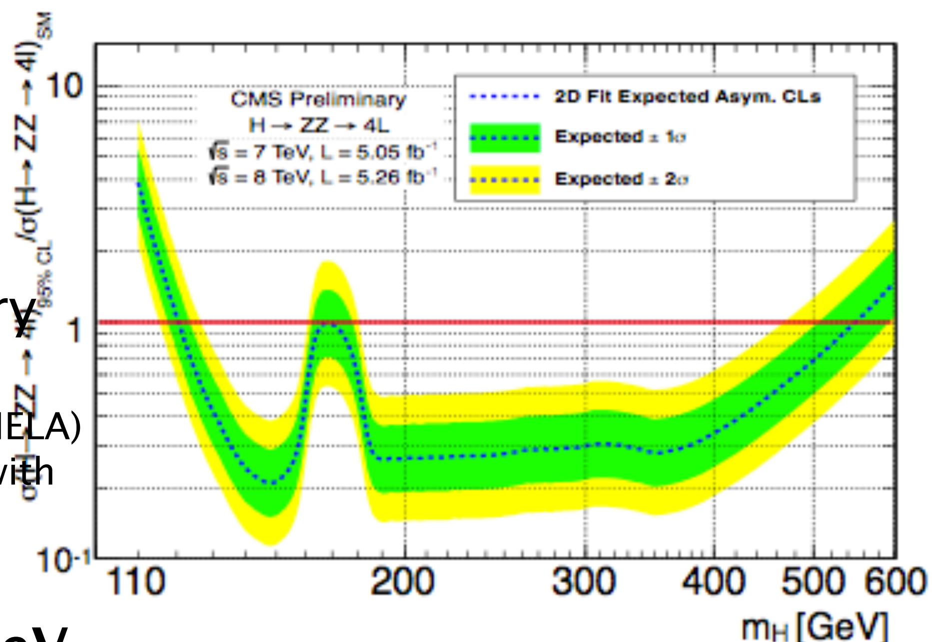
New lepton ID
- multivariate electron ID / PF muon ID

New lepton PF isolation

Final State Radiation (FSR) recovery

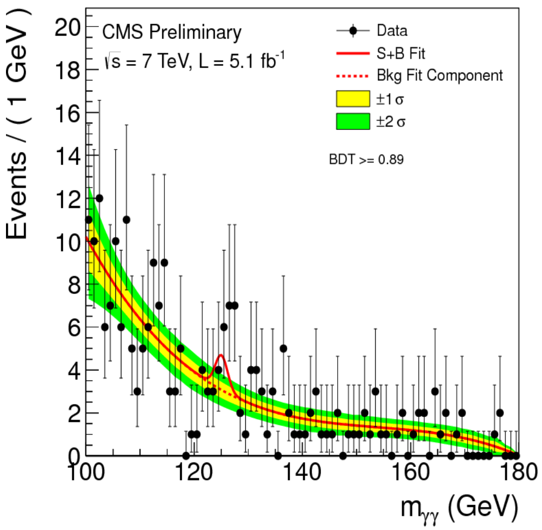
2D analysis: m_{4l} + KD
- using a Matrix Element Likelihood Analysis (MELA) a Kinematic Discriminant (KD) is computed with m_{Z1},m_{Z2}, and angles informations

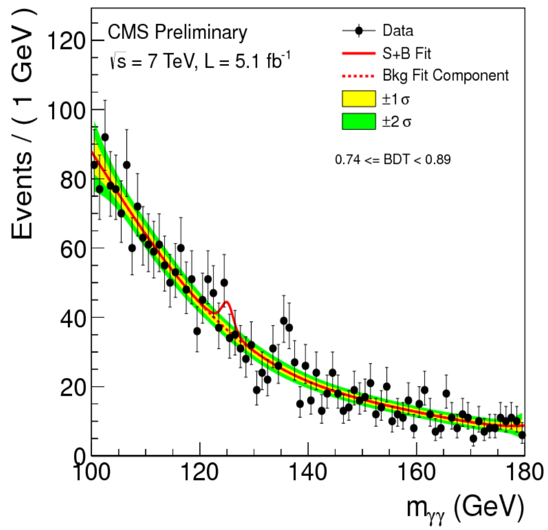
>20% improvement @ m_H = 126 GeV wrt 2011 analysis

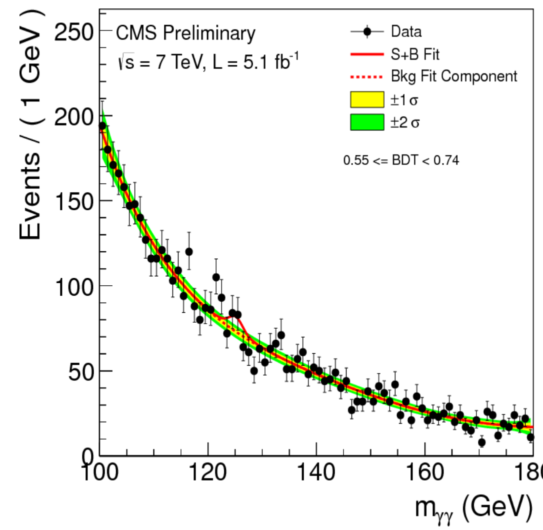


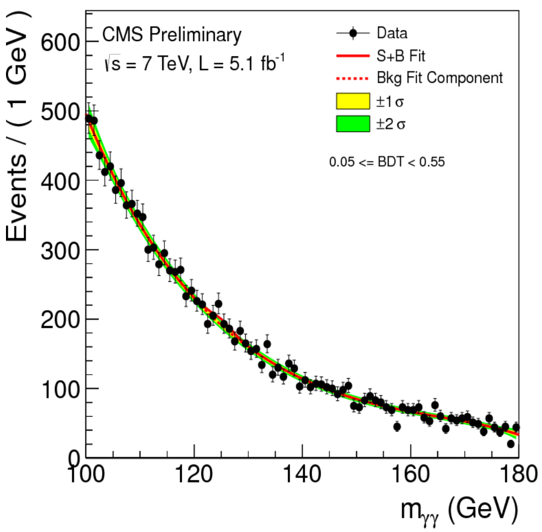
Expected exclusion range
121-540 GeV

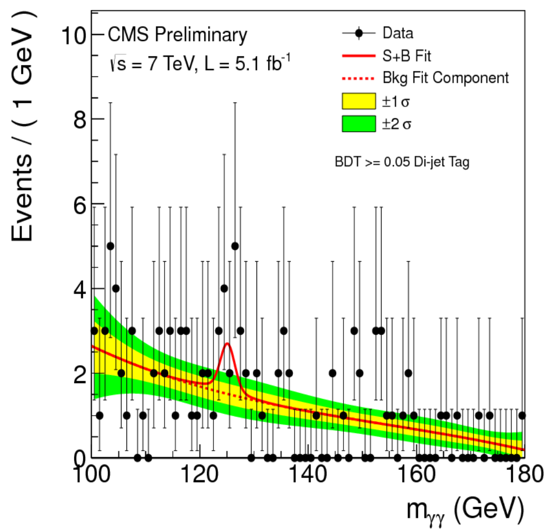
7 TeV Mass Distribution in Categories





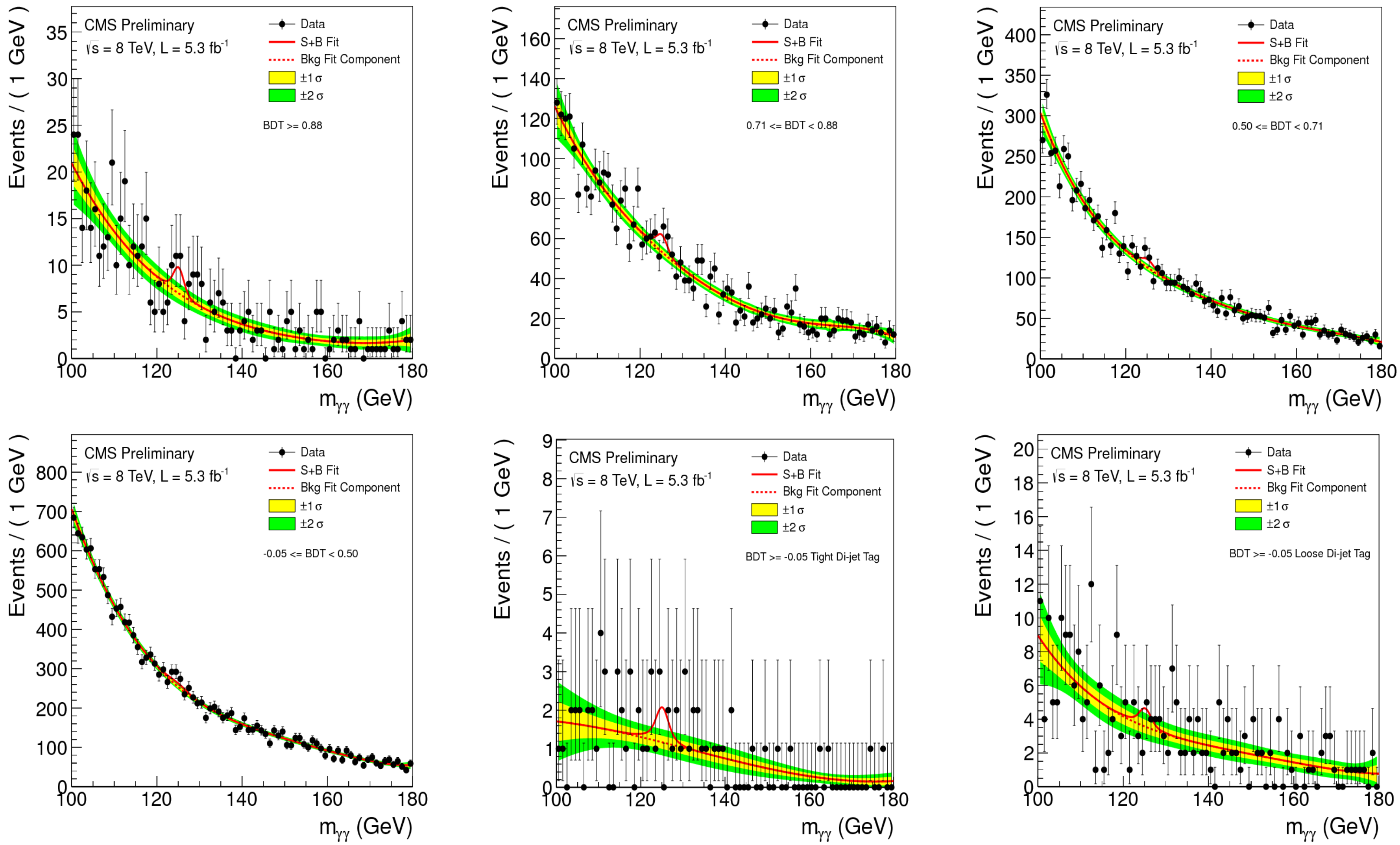




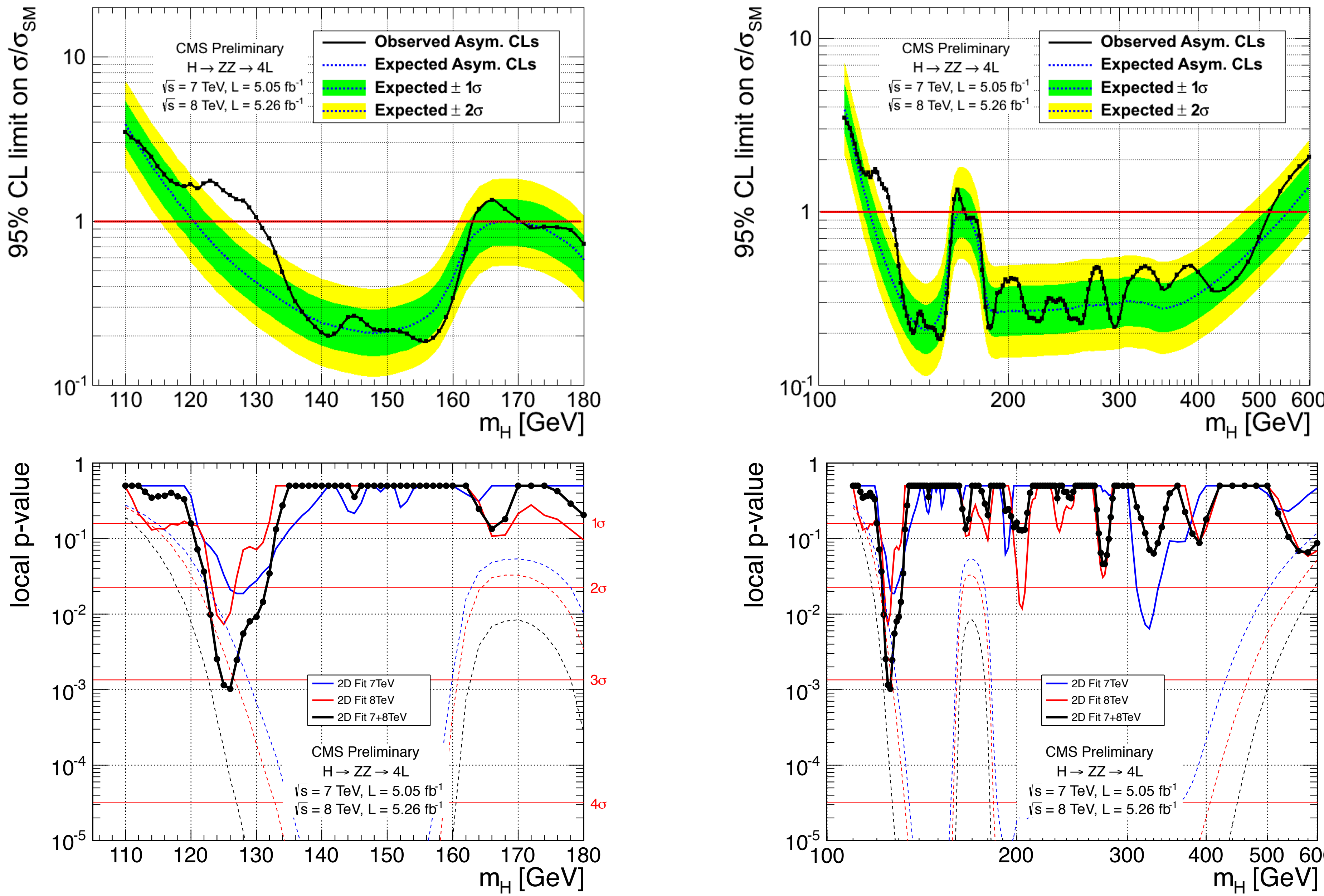


- Background model is entirely from data.
- Fit to mass distribution in each category with polynomial functions (3rd to 5th degree)
  - keep bias below 20% of fit error.
  - causes some loss of performance due to number of parameters in fit function.

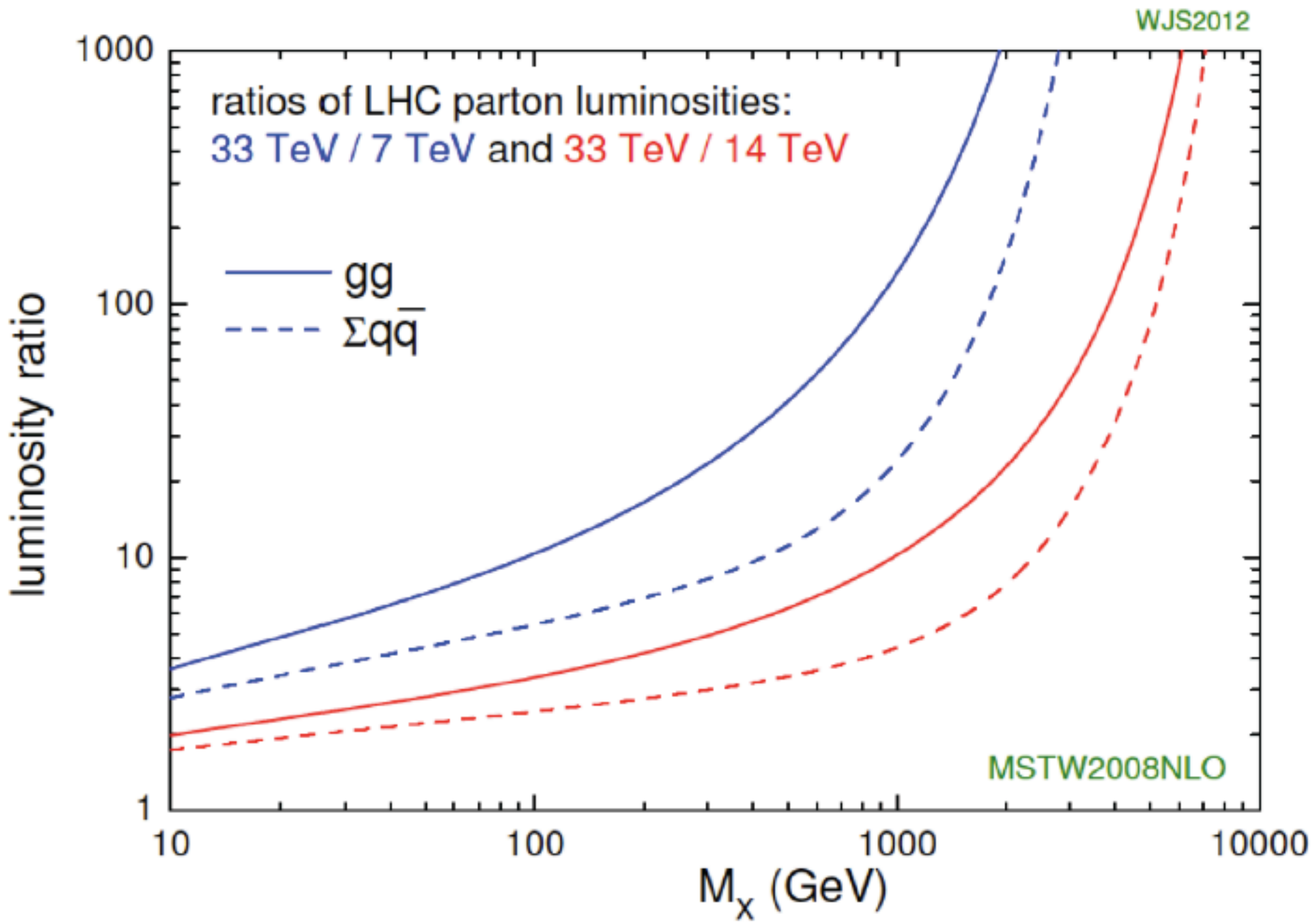
8 TeV Mass Distribution in Categories



H→ZZ Limits and p-values



Parton Luminosities



W.J. Sterling