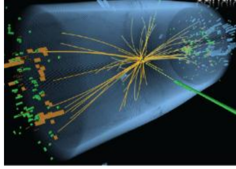


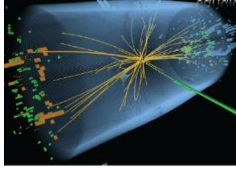
CMS Higgs Results

Ren-Yuan Zhu

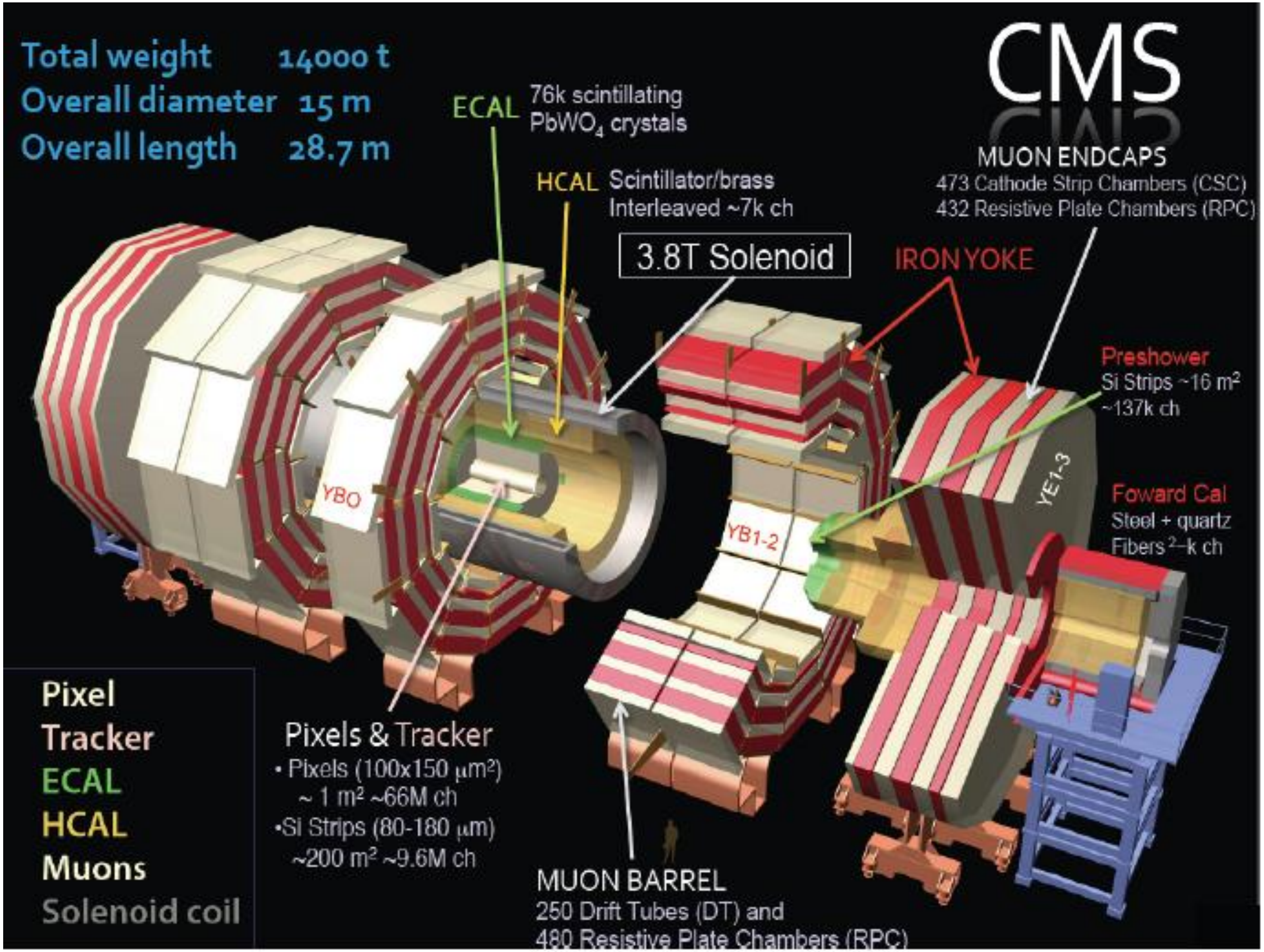
California Institute of Technology

November 14, 2012

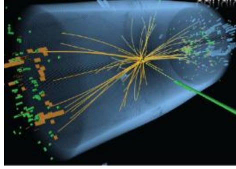
CMS Week in June, 2012

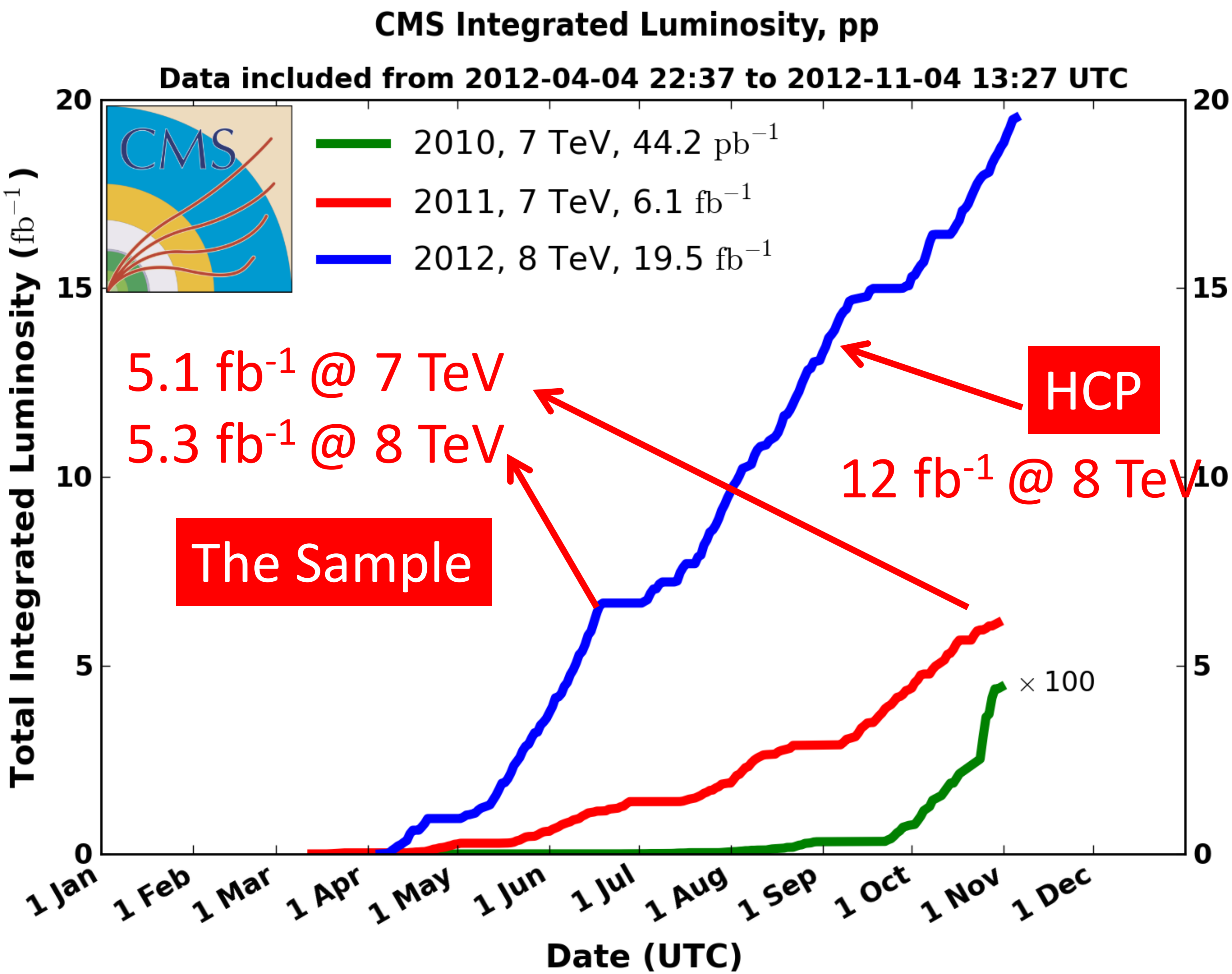


The CMS Detector

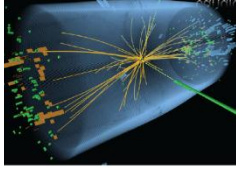


Total Integrated Luminosity, pp

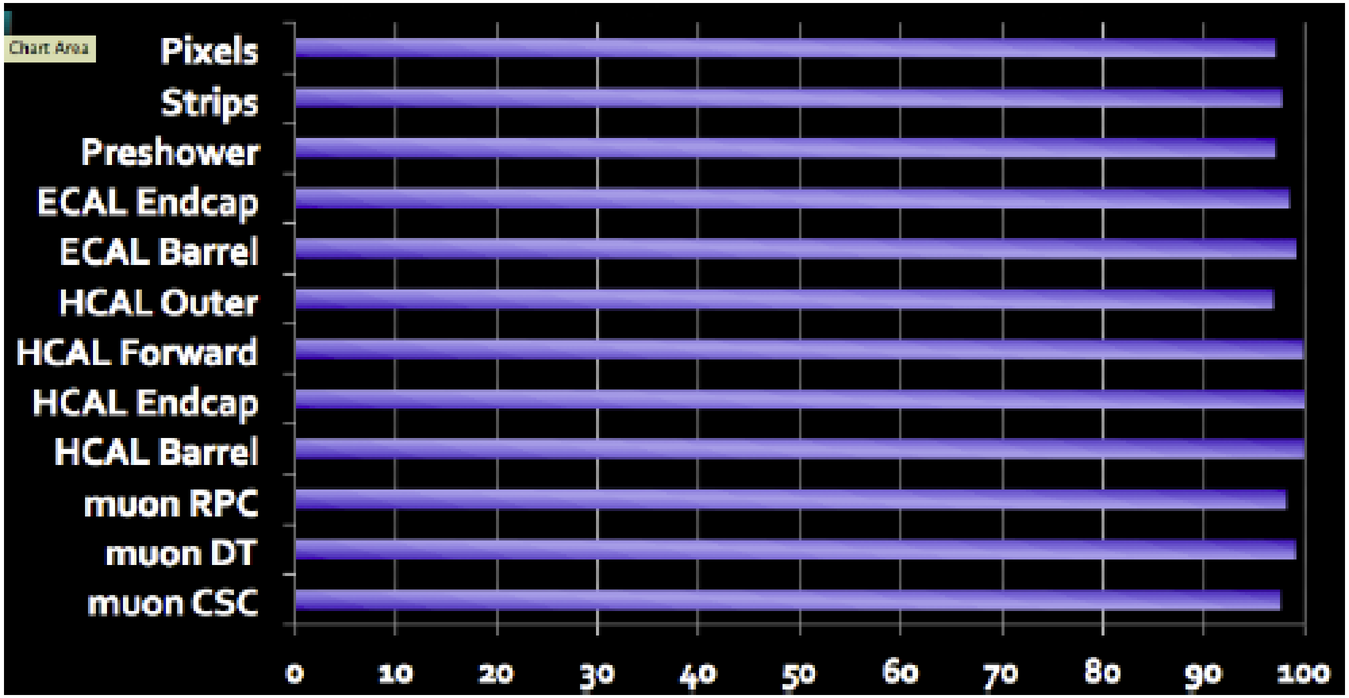




Operation Efficiencies

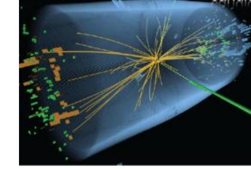


Thus far in 2012, CMS has recorded 93% of the luminosity delivered by the LHC. Of that 85% is certified as “golden” (good for physics).



The fraction of working channels is >98%

CMS Higgs Results at HCP



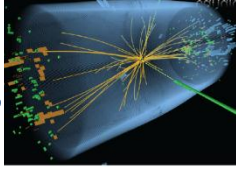
Primary Higgs talk:

- C. Paus: Latest on the Higgs from CMS

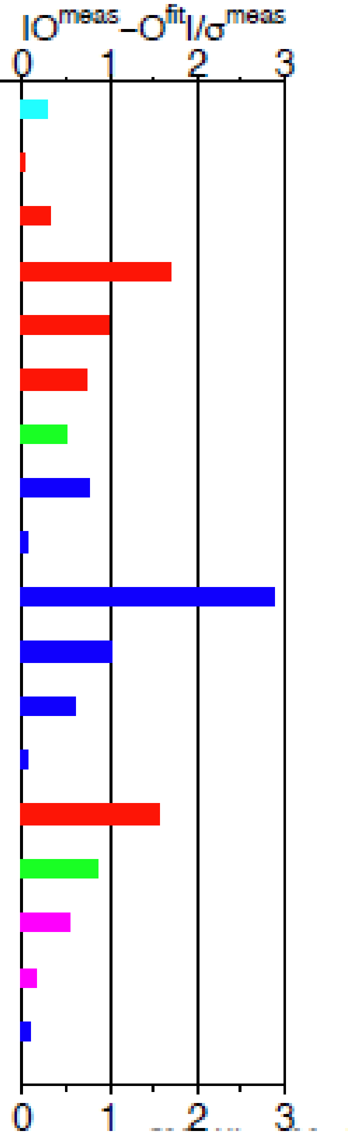
Parallel Higgs talks by CMS collaborators

- N. Marinelli: Search for the Higgs boson decaying in two photons at CMS
- A. Drozdetzki: Search for SM Higgs boson decaying to ZZ at CMS
- P. Dudero: Search for Higgs decaying to WW at CMS
- R. Wolf: Search for SM Higgs boson decaying to a pair of taus at CMS
- R. Rangel: Search for Higgs decaying to bb at CMS
- M. Zanetti: Properties of the new discovered boson and fermiophobic Higgs search with CMS

Previous EWSB Measurements



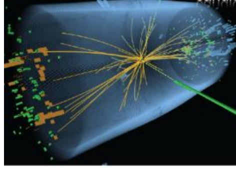
	Measurement	Fit
$\Delta\alpha_{had}^{(5)}(m_Z)$	0.02750 ± 0.00033	0.02759
m_Z [GeV]	91.1875 ± 0.0021	91.1874
Γ_Z [GeV]	2.4952 ± 0.0023	2.4959
σ_{had}^{0} [nb]	41.540 ± 0.037	41.478
R_l	20.767 ± 0.025	20.742
$A_{fb}^{0,l}$	0.01714 ± 0.00095	0.01645
$A_l(P_\tau)$	0.1465 ± 0.0032	0.1481
R_b	0.21629 ± 0.00066	0.21579
R_c	0.1721 ± 0.0030	0.1723
$A_{fb}^{0,b}$	0.0992 ± 0.0016	0.1038
$A_{fb}^{0,c}$	0.0707 ± 0.0035	0.0742
A_b	0.923 ± 0.020	0.935
A_c	0.670 ± 0.027	0.668
A_l(SLD)	0.1513 ± 0.0021	0.1481
$\sin^2\theta_{eff}^{lept}(Q_{fb})$	0.2324 ± 0.0012	0.2314
m_W [GeV]	80.385 ± 0.015	80.377
Γ_W [GeV]	2.085 ± 0.042	2.092
m_t [GeV]	173.20 ± 0.90	173.26



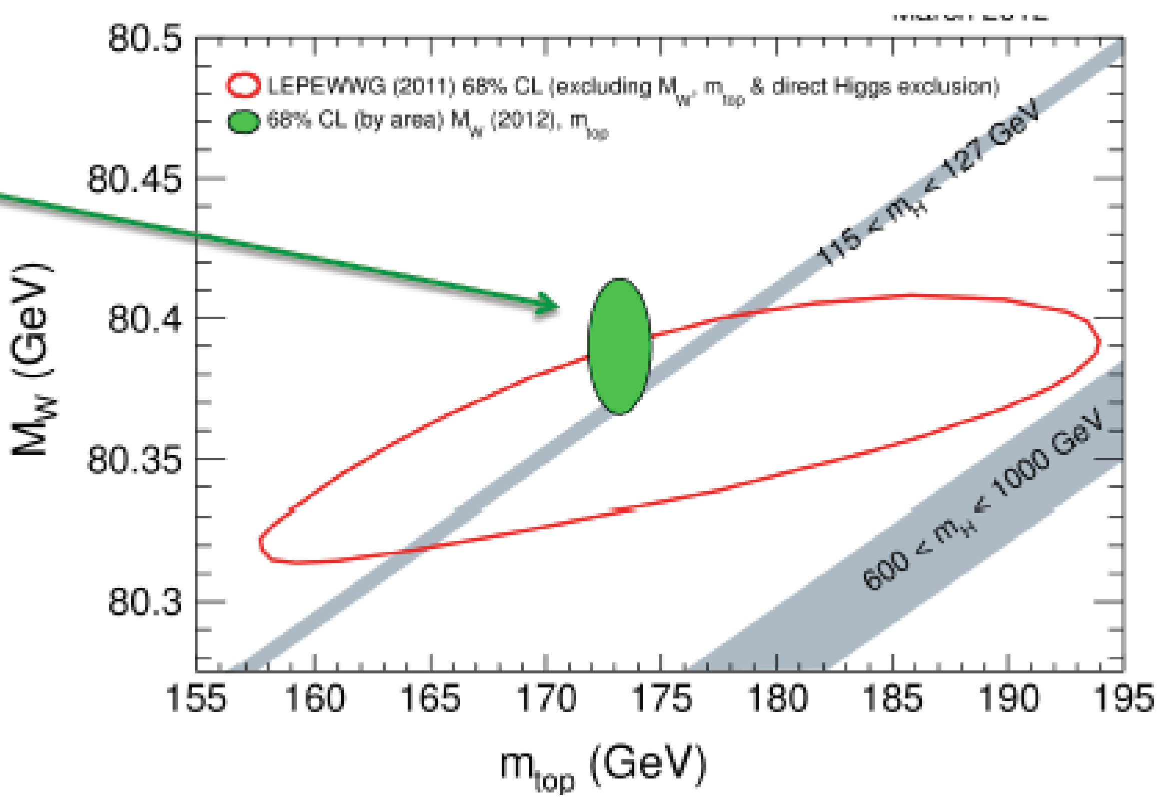
March 2012

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.

Higgs Situation in Early 2012



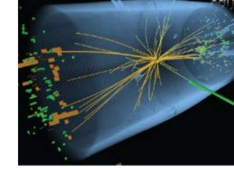
Exquisitely precise measurement of M_W = 80.390 ± 0.016 GeV, driven mainly by the Tevatron.

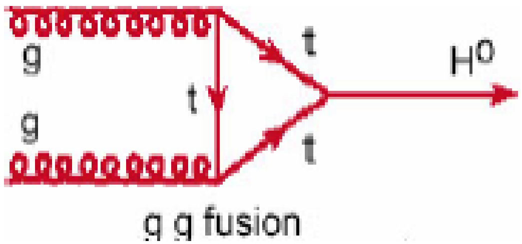


Much of the SM Higgs range had been ruled out by 2011 LHC running.

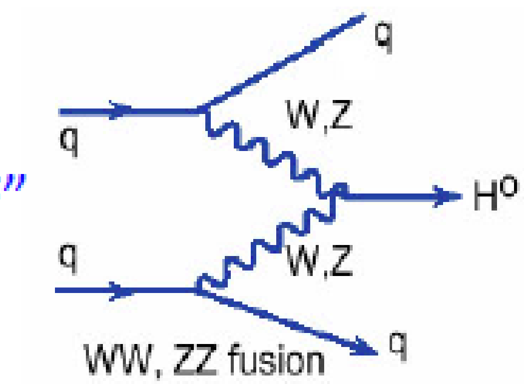
Exclusions of M_H:
– LEP < 114 GeV (arXiv:0602042v1)
– Tevatron [156,177] GeV (arXiv:1107.5518)
– LHC [~127, 600] GeV arXiv:1202.1408 (ATLAS) arXiv:1202.1488 (CMS)

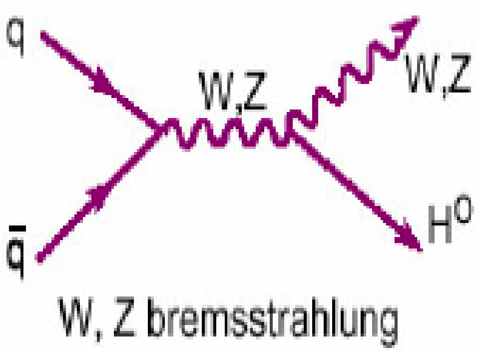
Higgs Production





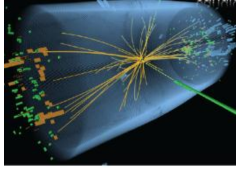
"VBF"

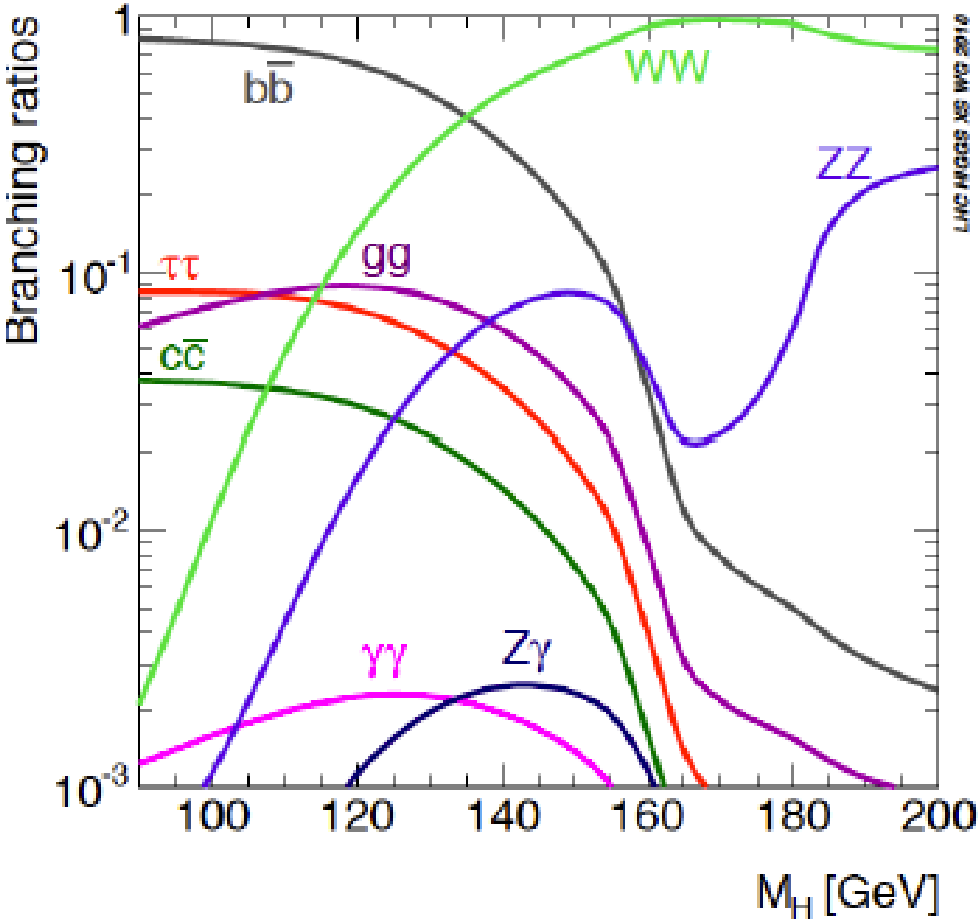




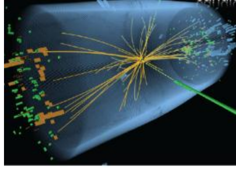
- Cross section ≈20 pb, dominated by gg fusion
- 8 TeV cross sections 25%-30% higher
- All production modes used
  - gg, VBF, VH, ttH (not shown)
  - Last three have smaller rates, but better S/B.

Higgs Decay



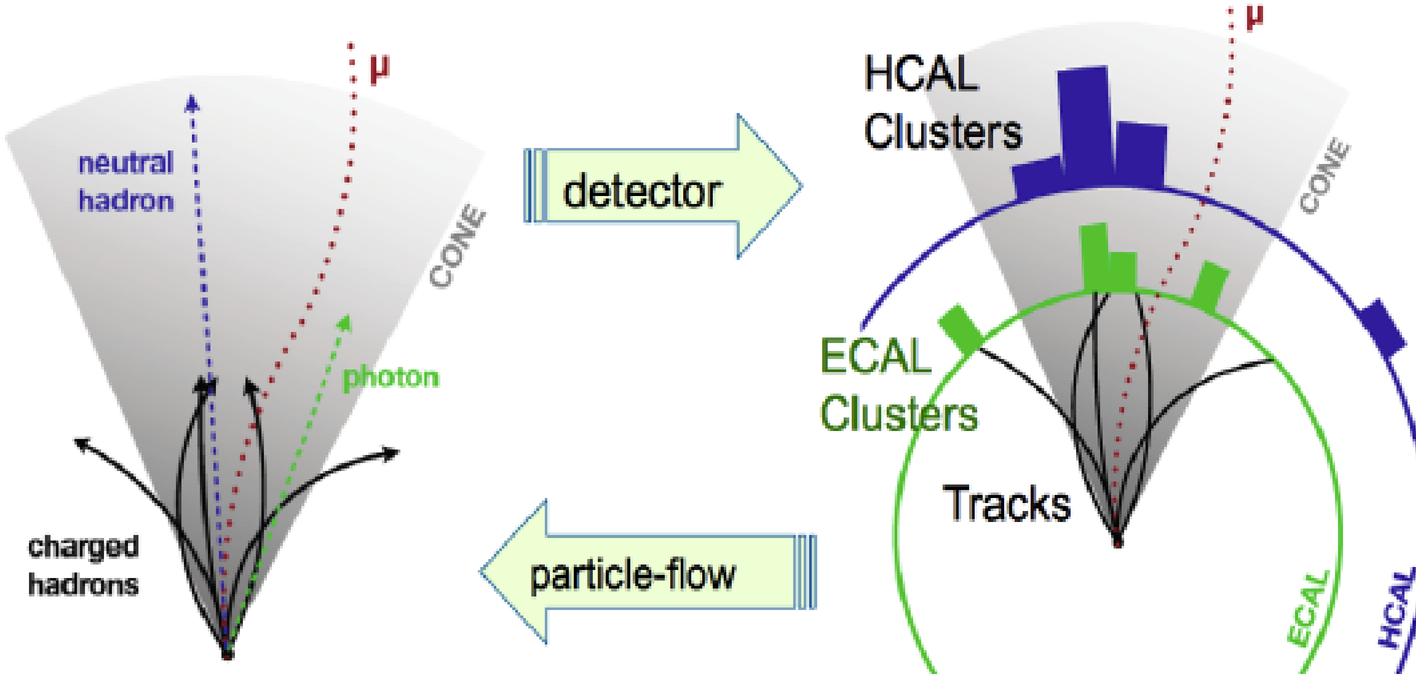


- Five modes studied
  - $\gamma\gamma$, ZZ, WW, $\tau^+\tau^-$, bb
- The branching ratio plot, however, tells only part of the story —i.e., it's quality, not quantity.



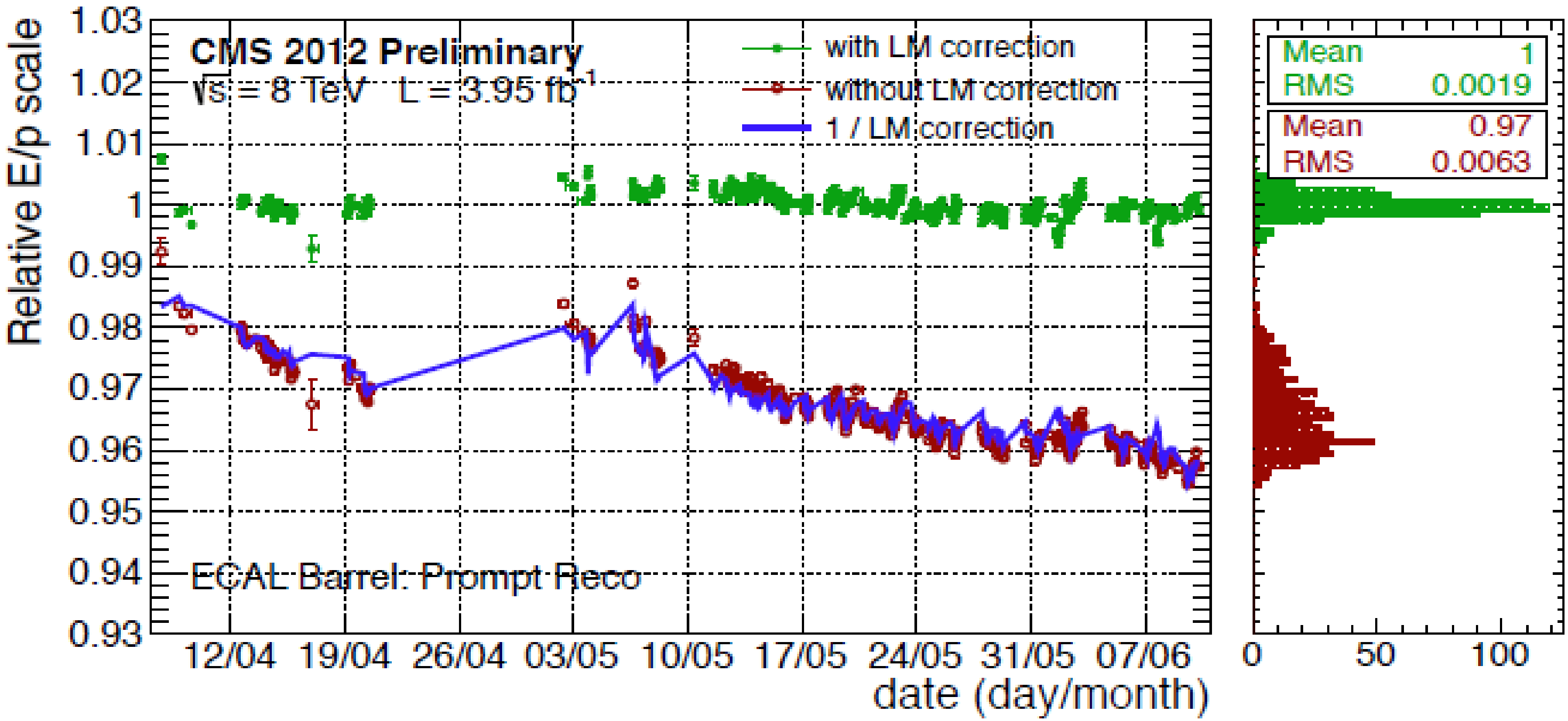
Events Reconstruction

Particle Flow



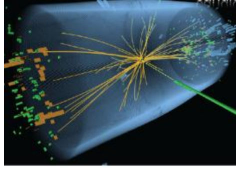
Stable particles in the event are reconstructed by a sophisticated algorithm that combines information from all sub-detectors. This exploits the fine-grained nature of CMS. The particles thus reconstructed are then combined into jets.

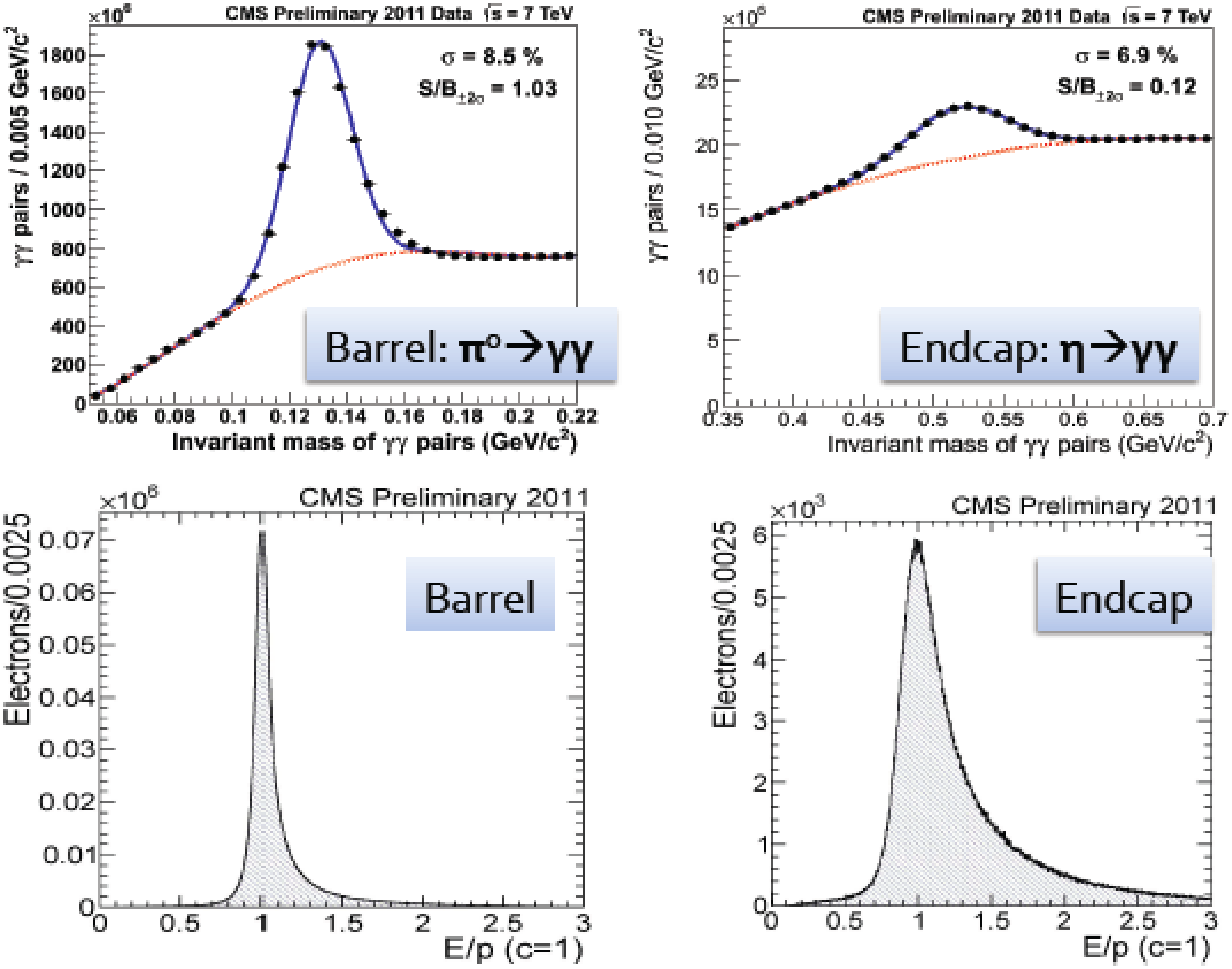
Light Monitoring Correction



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

Photons: PWO Crystal ECAL





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

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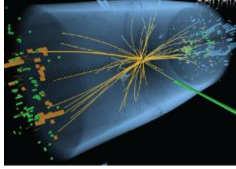
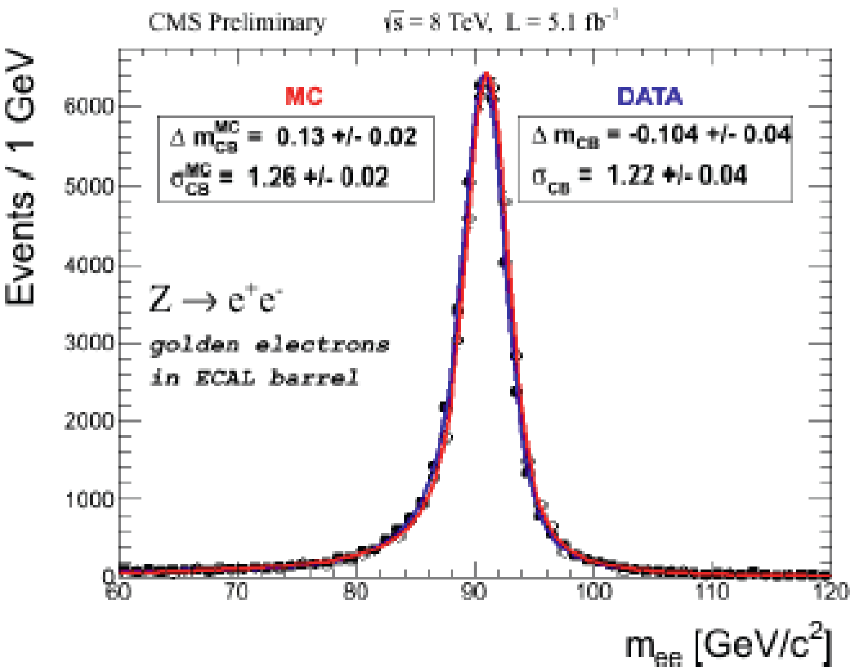
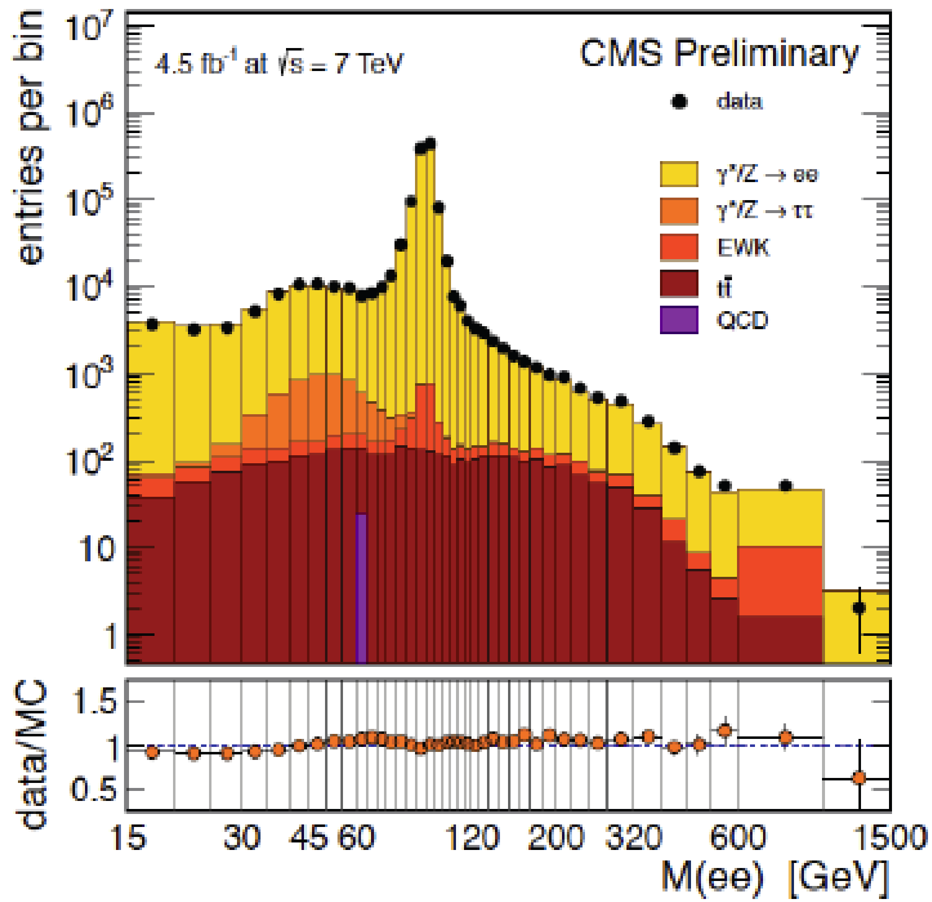
Electrons



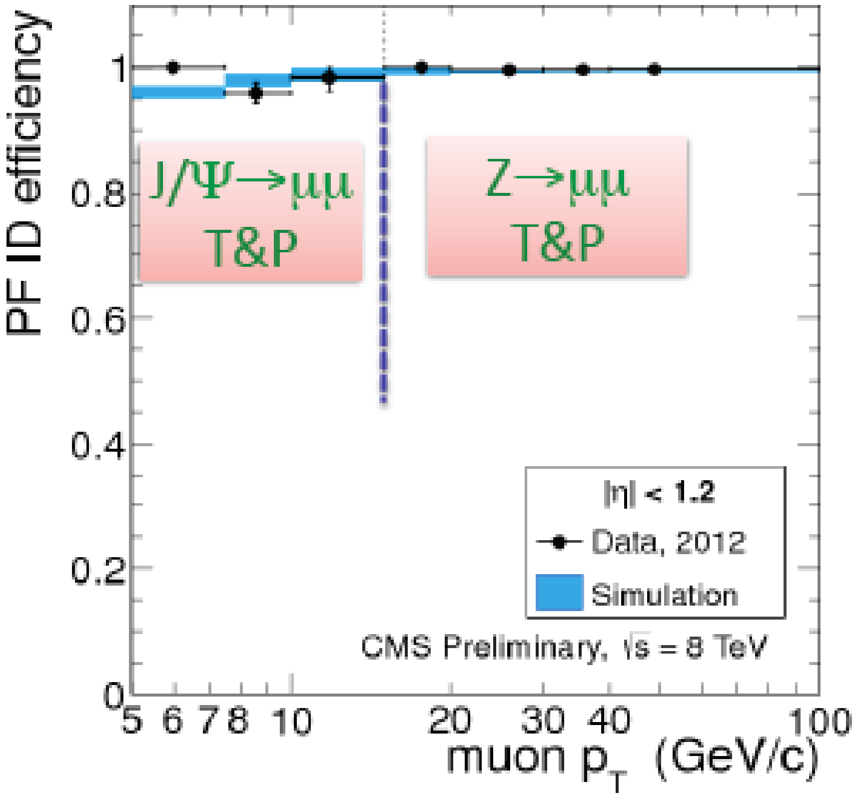


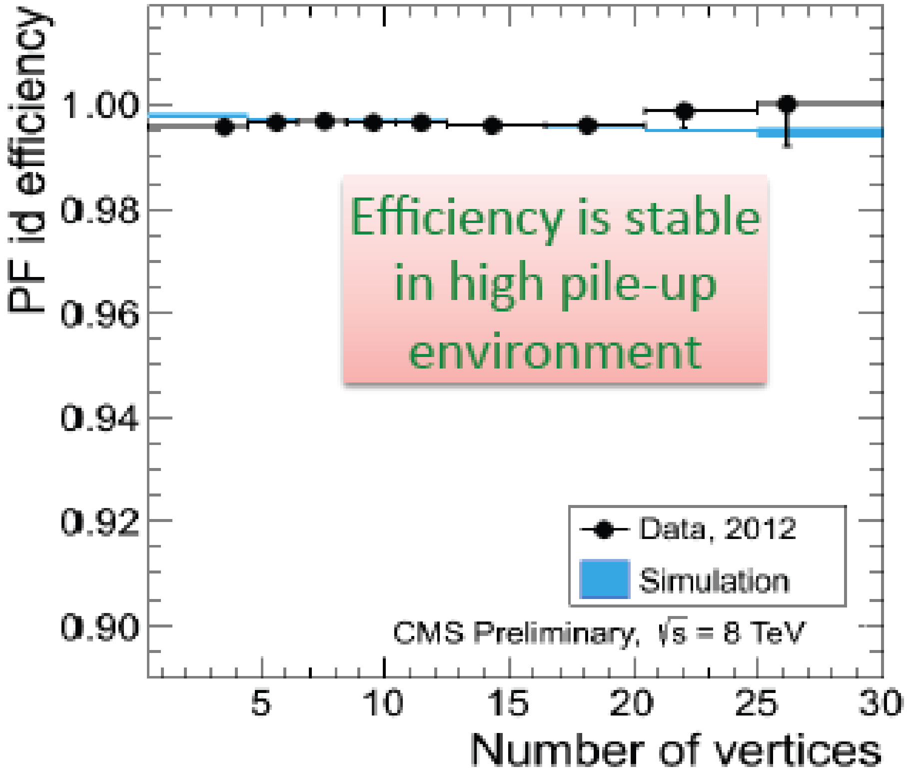
Z peak from golden electrons



Drell-Yan Spectrum

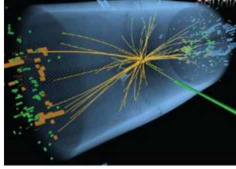
Muons

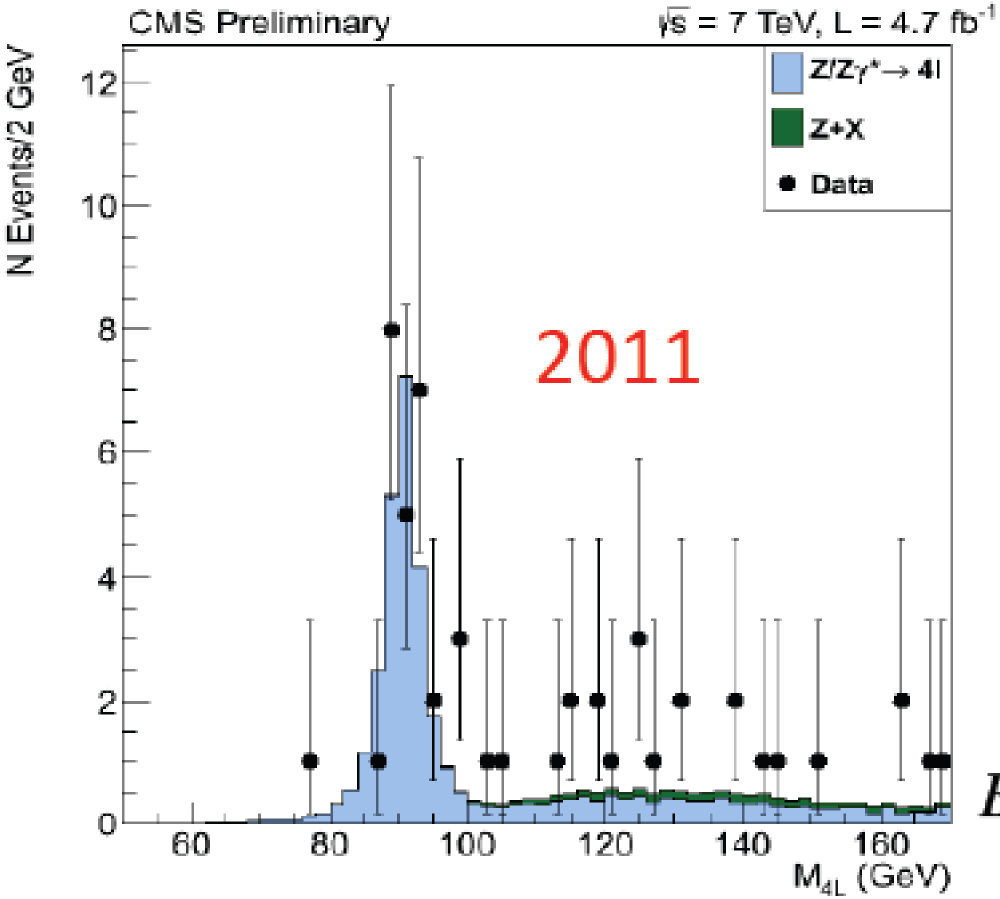


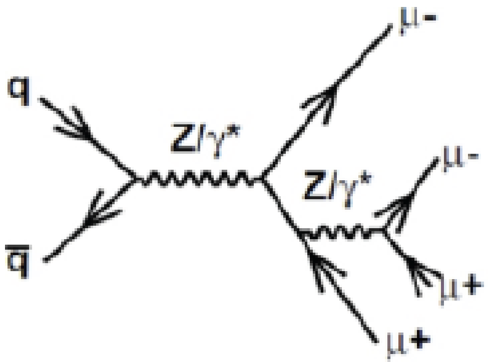


- High efficiency down to $p_T = 15$ GeV
  - Exploit also tracker-based muon ID
  - Important for H->ZZ->4l

Leptons



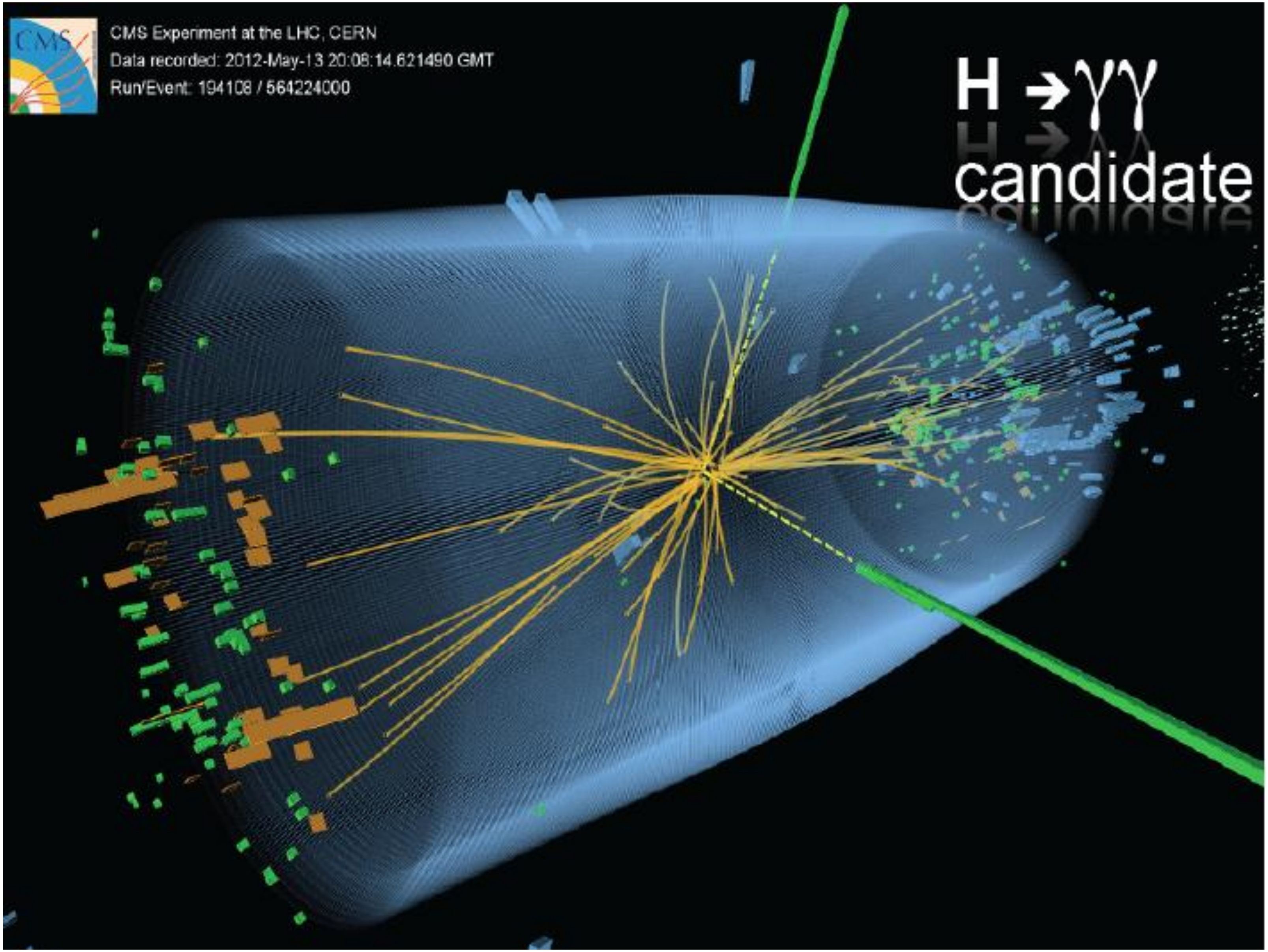




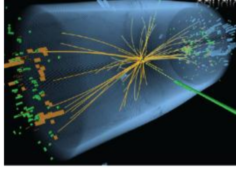
CMS and LHC are good enough to allow for the search (and discovery!) of rare Z decays.

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

Higgs → γγ

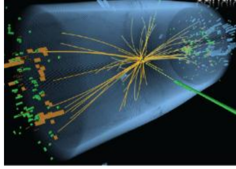

CMS Experiment at the LHC, CERN
Data recorded: 2012-May-13 20:08:14.621490 GMT
Run/Event: 194108 / 564224000
H →γγ
candidate

Higgs → γγ Strategy

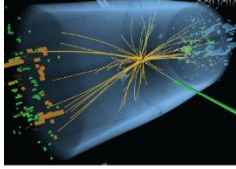


- Multi-Variate Analysis (MVA) for photon ID and event classification
  - Divide events into non-overlapping samples of varying S/B based on properties of the reconstructed photons and presence of di-jets from VBF process
- Cross check with cut-based analysis
  - MVA and cut-based results consistent
  - 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 and Jet Selection

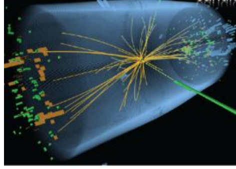


- Photons
  - $|\eta_\gamma| < 2.5$ and not in $1.44 < |\eta_\gamma| < 1.57$
  - Leading photon $p_T > M_{\gamma\gamma}/3$
  - Other photon $p_T > M_{\gamma\gamma}/4$
  - Leading photon in di-jet case $p_T > M_{\gamma\gamma}/2$
- Jets (VBF)
  - $|\eta_{jet}| < 4.7$
  - Leading jet $p_T > 30$ GeV, other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



Event Selection

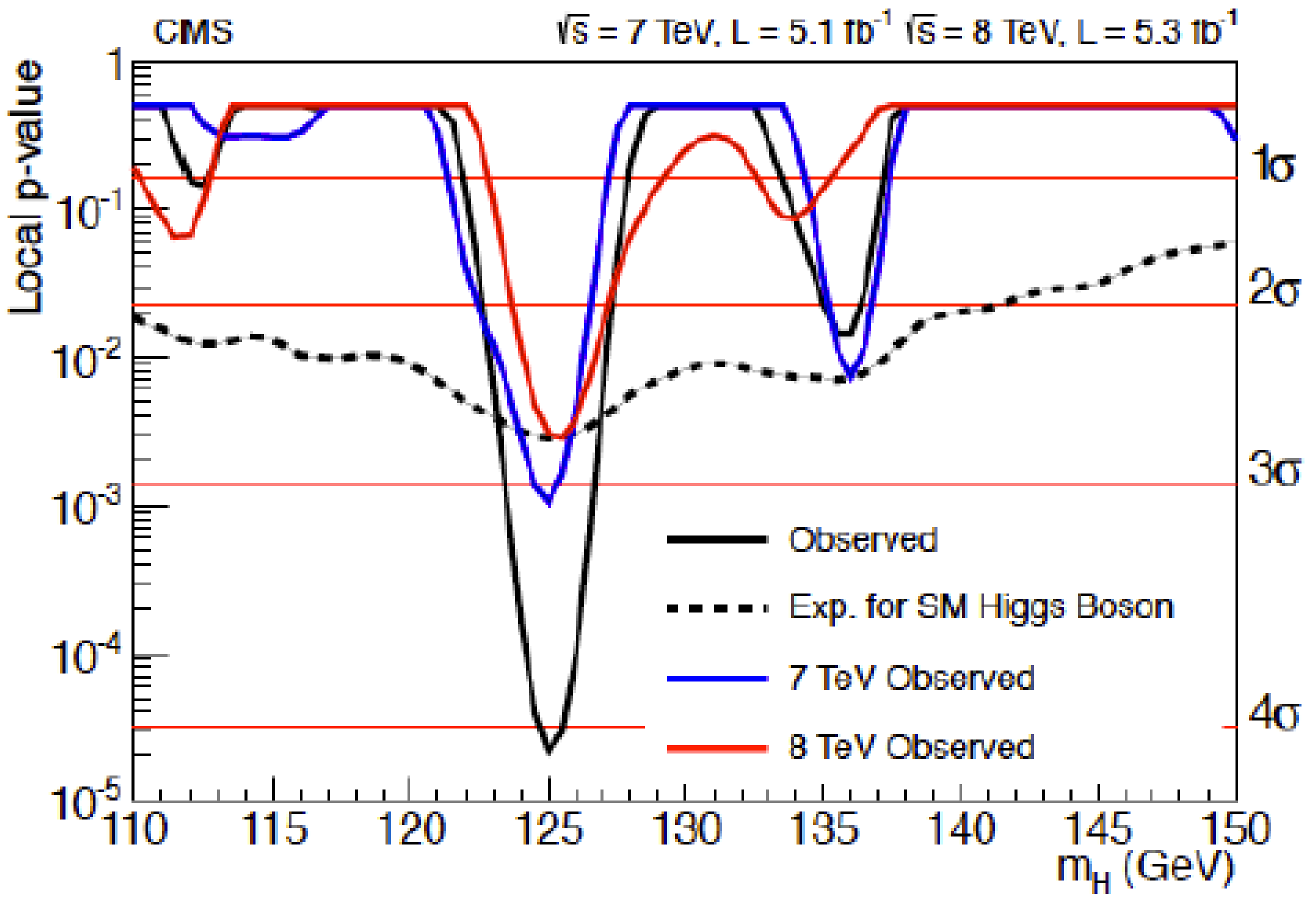
- Use a boosted decision tree to classify events based on
  - Photon quality (shape and isolation)
  - Expected mass resolution
  - Probability of correct vertex assignment
  - Kinematic characteristics of photons (excluding invariant mass)
- Divide events into five categories, dropping those in the 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

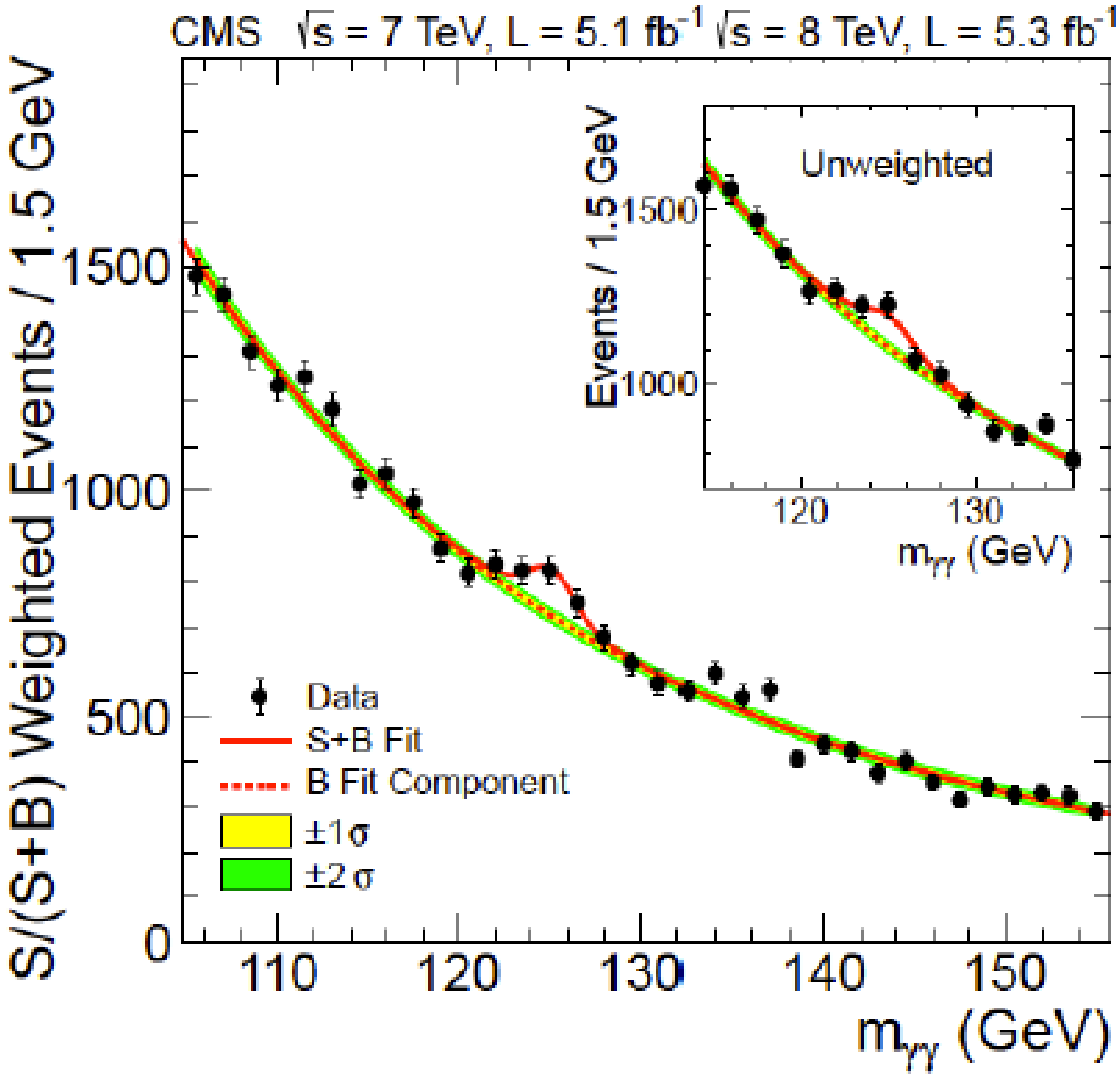


Significance based on local p-value: 4.1σ

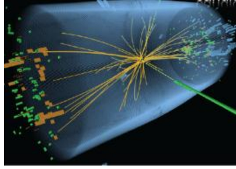
Significance based on global p-value: 3.2σ (110-150) GeV

Old Fashion Spectrum

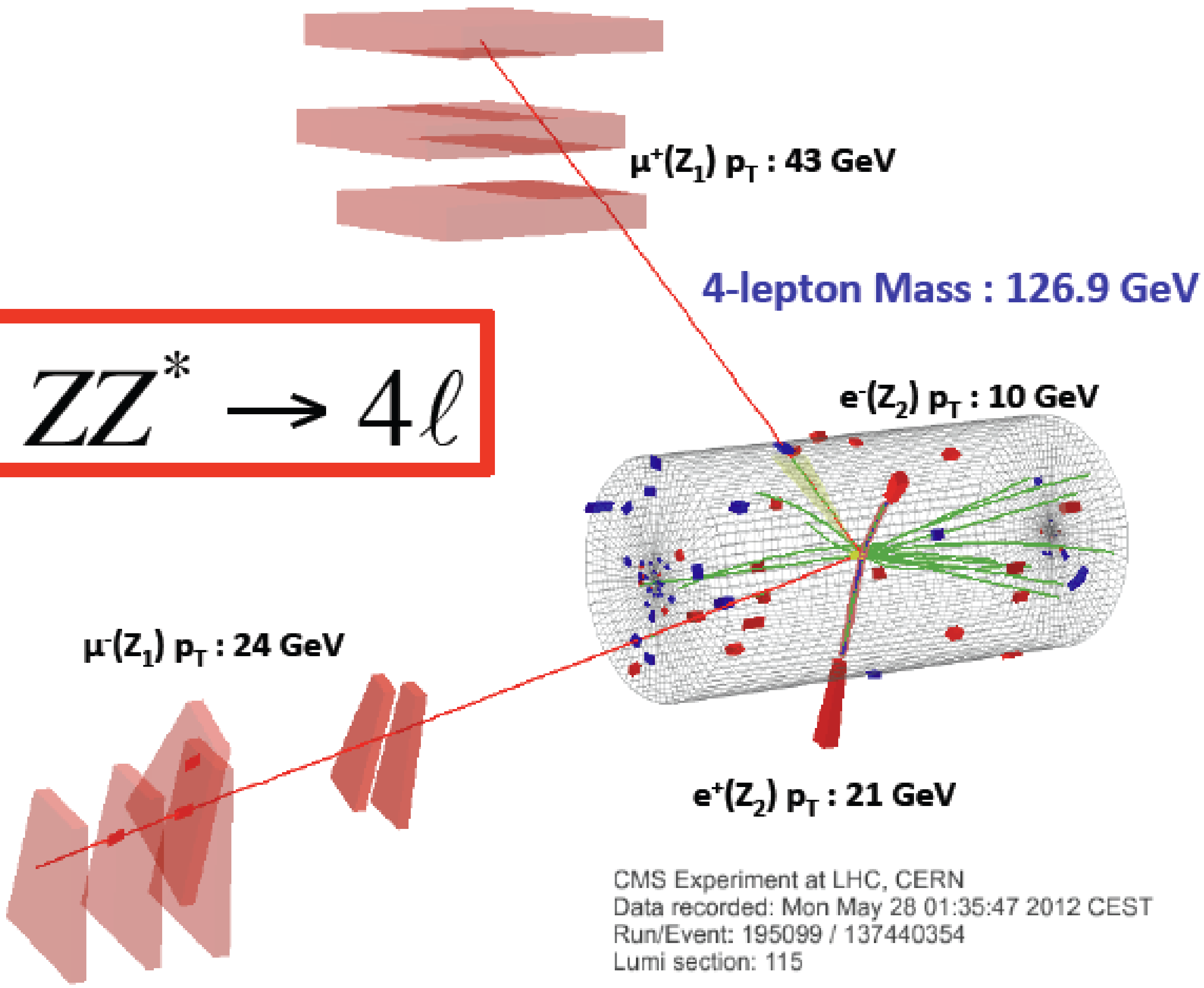
Event weights according to BDT class.



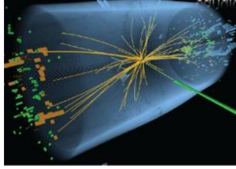
Higgs →ZZ*→ 4 Leptons



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

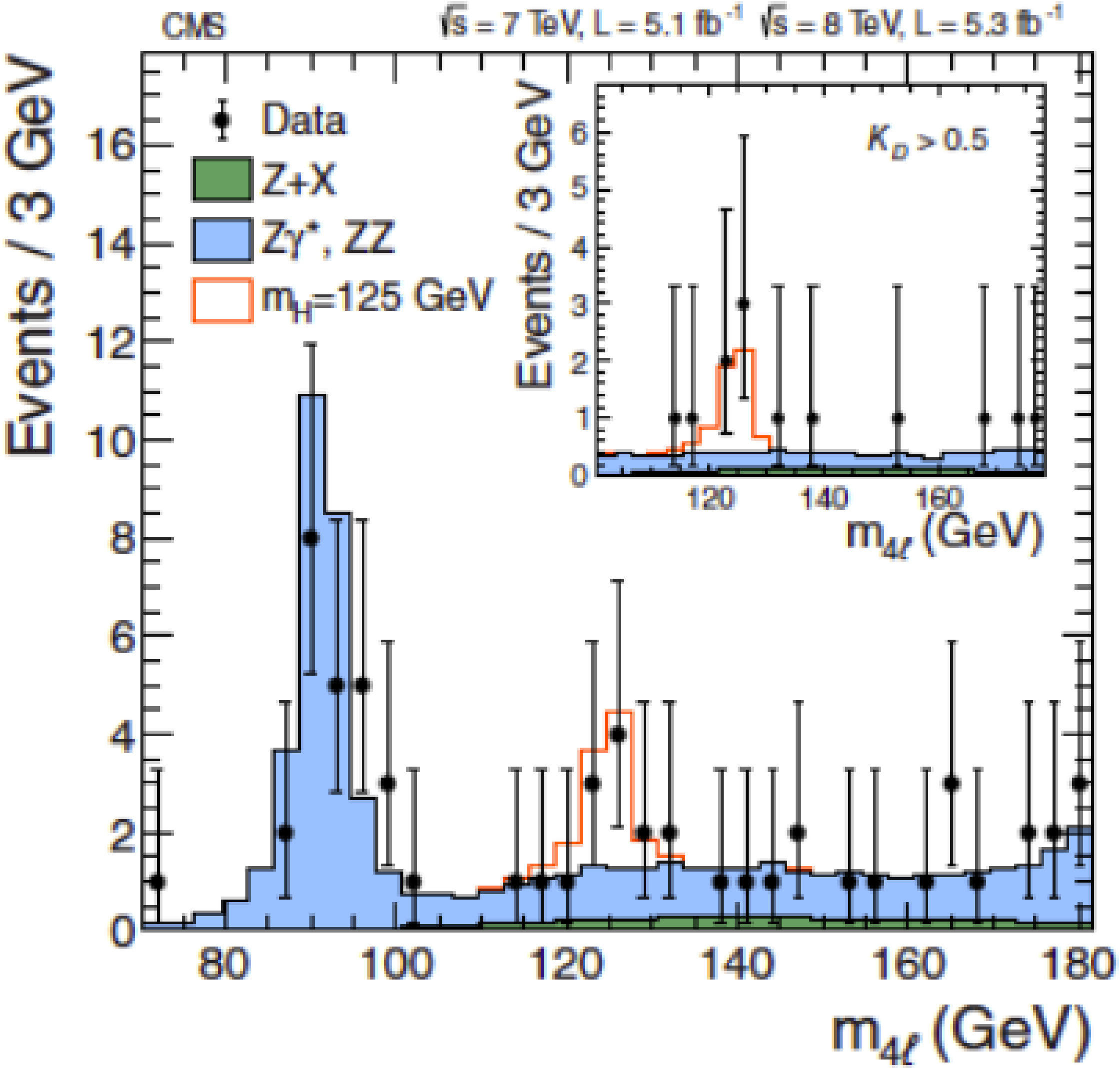


Higgs → ZZ* Selection



- 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

Higgs → 4l Mass Spectrum



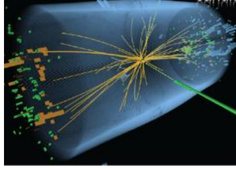
K_D is kinematic discriminate from MELA

Excess:

3.2σ @ 125.6 GeV

vs. 3.8σ expected

Higgs → ZZ* Signal & Background

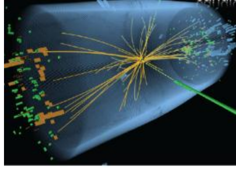


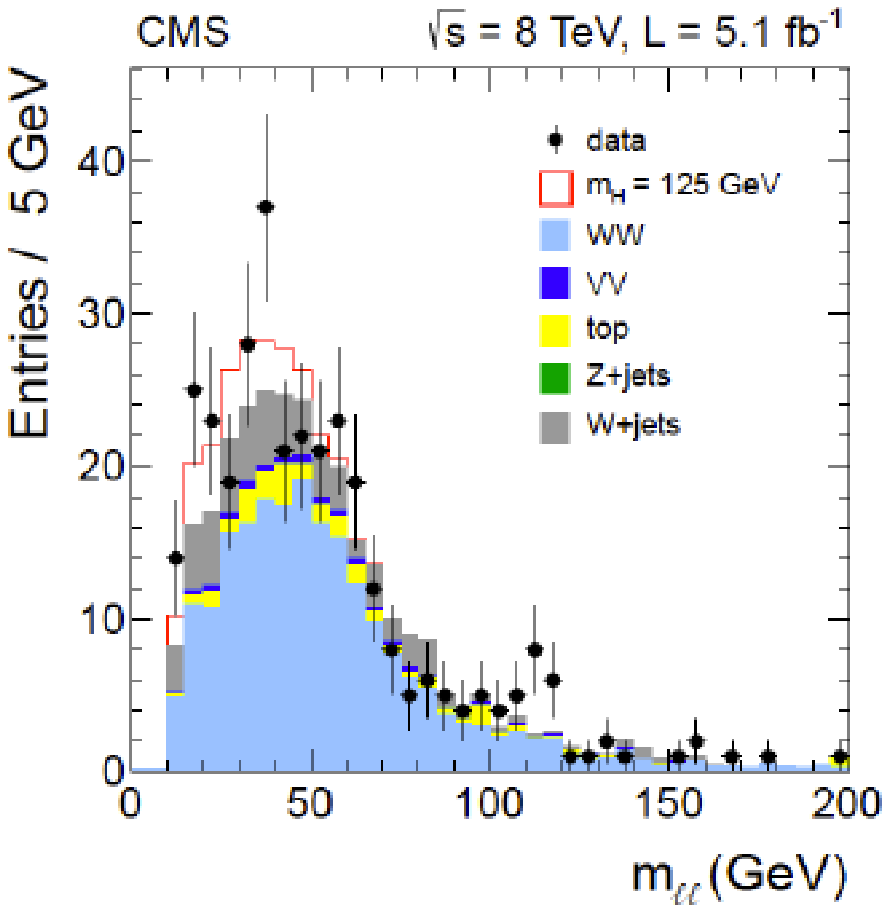
Channel	4e	4μ	$2e2\mu$	4ℓ
ZZ background	2.7 ± 0.3	5.7 ± 0.6	7.2 ± 0.8	15.6 ± 1.4
Z + X	$1.2^{+1.1}_{-0.8}$	$0.9^{+0.7}_{-0.6}$	$2.3^{+1.8}_{-1.4}$	$4.4^{+2.2}_{-1.7}$
All backgrounds ($110 < m_{4\ell} < 160\,\mathrm{GeV}$)	4.0 ± 1.0	6.6 ± 0.9	9.7 ± 1.8	20 ± 3
Observed ($110 < m_{4\ell} < 160\,\mathrm{GeV}$)	6	6	9	21
Signal ($m_H = 125\,\mathrm{GeV}$)	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

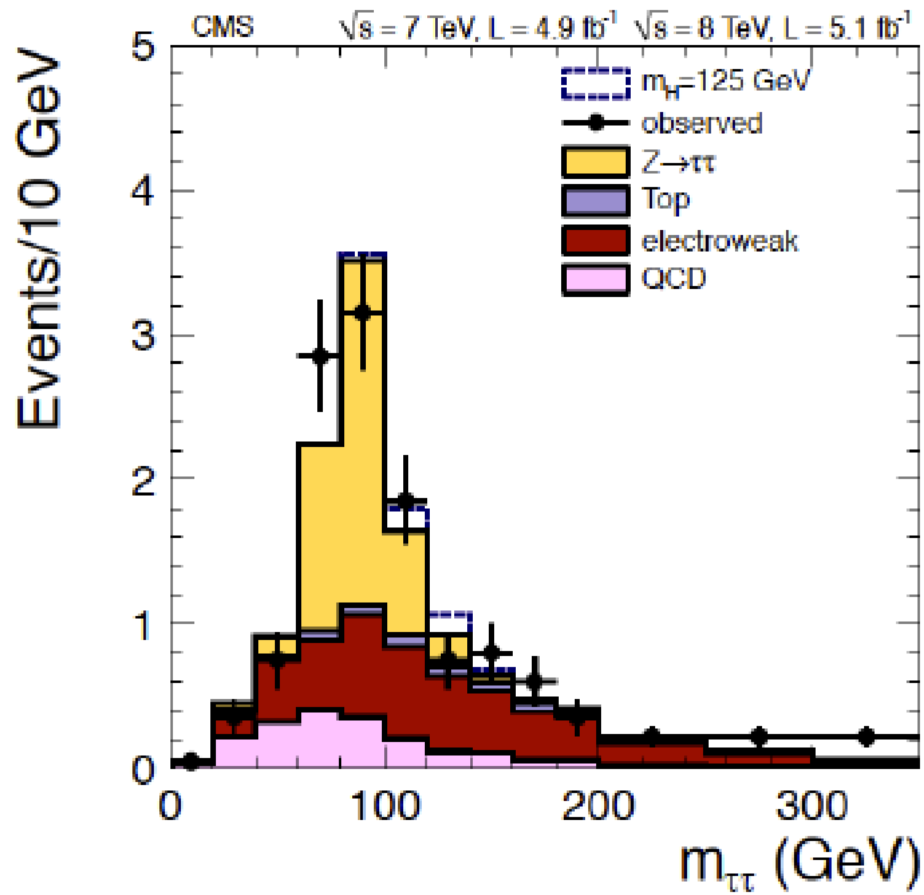
Observed significance at M_H = 125.6 GeV:
3.2σ (vs 3.8σ expected for SM Higgs)

Other Higgs Decay Modes



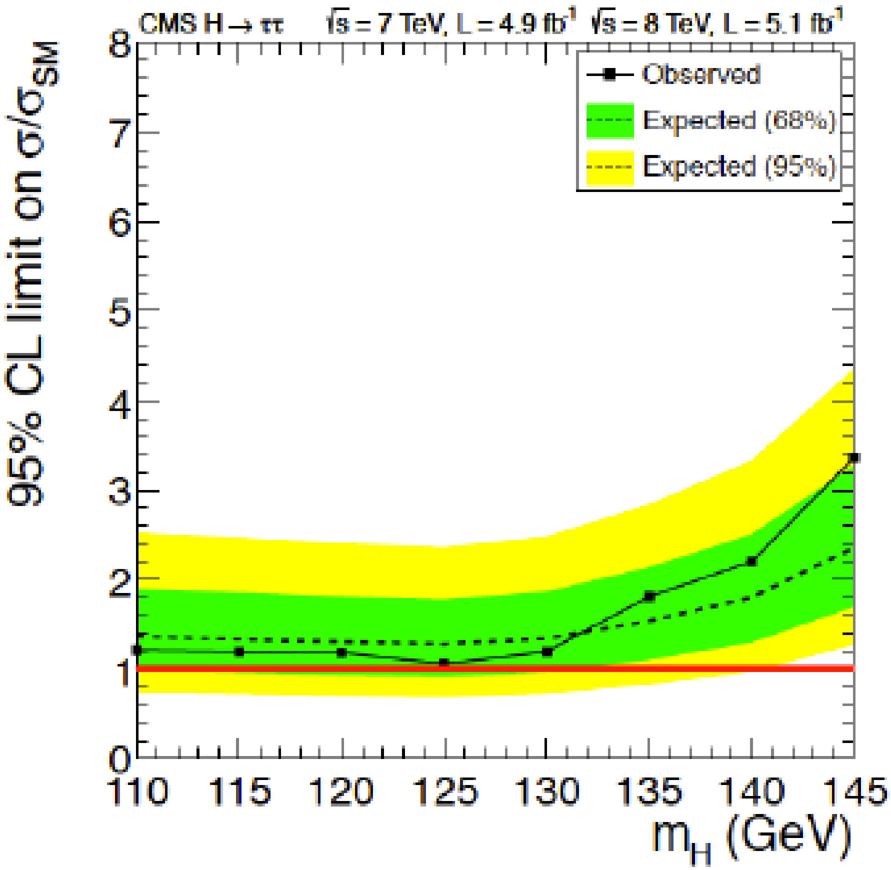


$H \rightarrow WW \quad$ (0-jet $e\mu$)

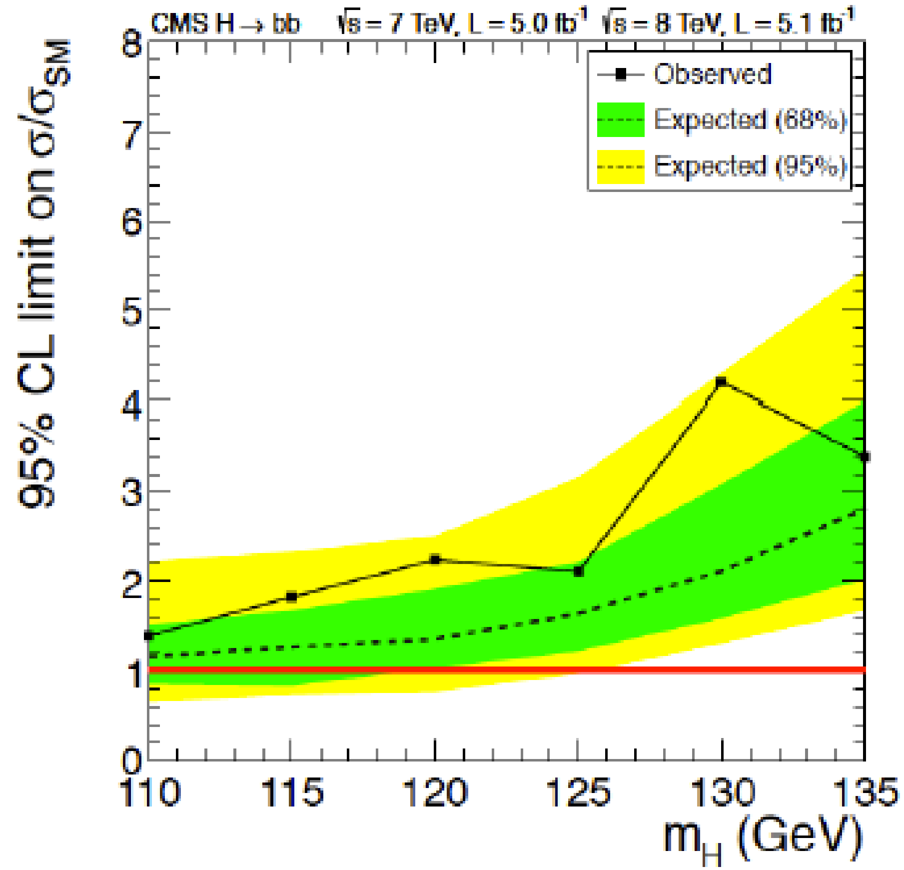


$H \rightarrow \tau\tau \quad (\mu\tau_h \;\; \text{VBF})$

Other Modes

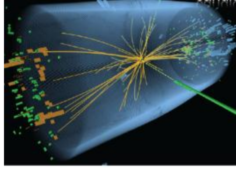


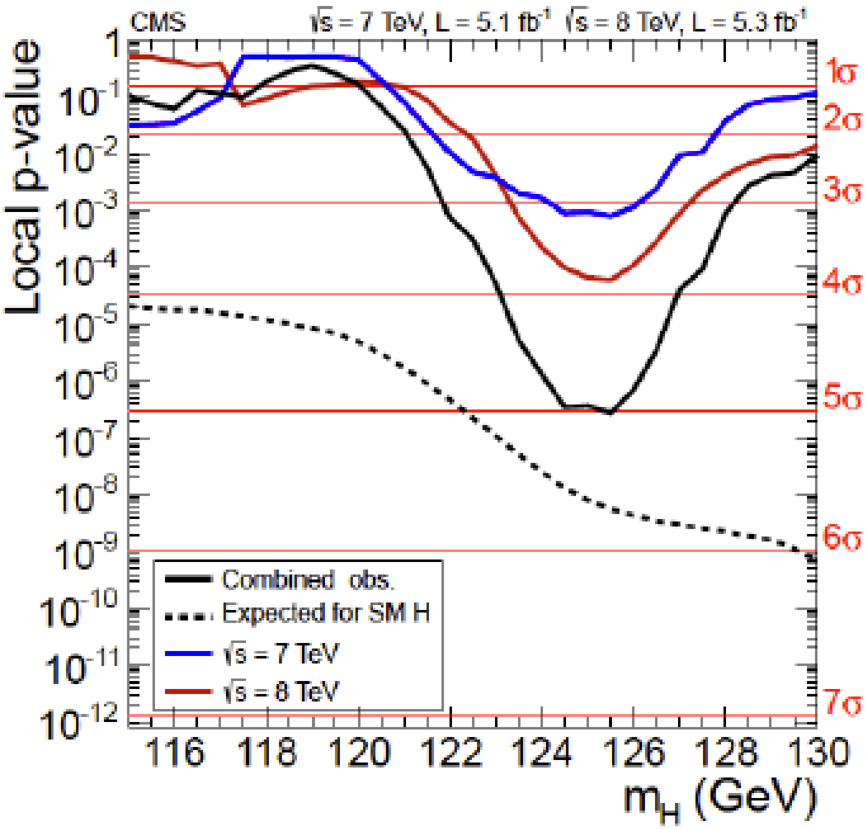
$H \to \tau\tau$ (combined)



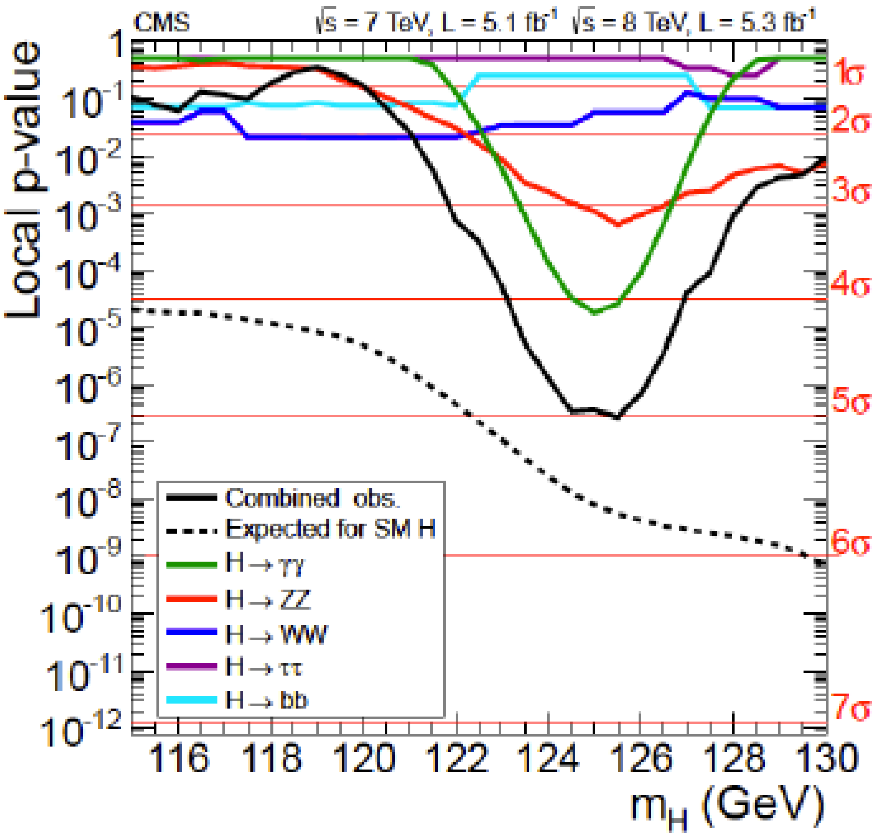
$H \to bb$ (combined)

Combined Results



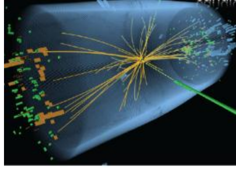


By dataset



By mode

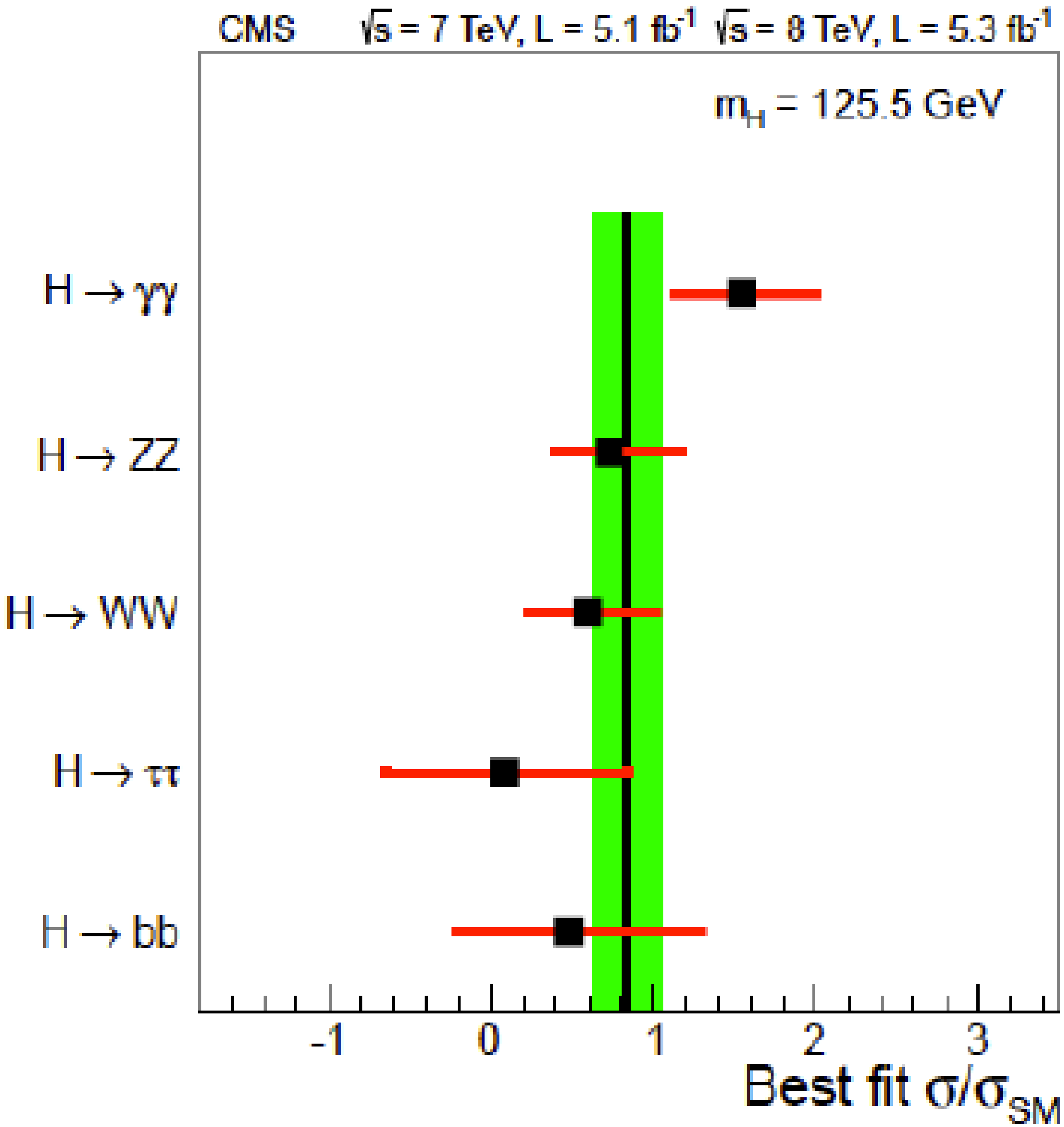
Combined Results



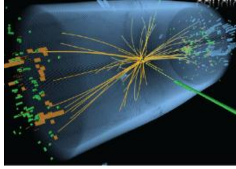
Decay mode/combination	Expected (σ)	Observed (σ)
$\gamma\gamma$	2.8	4.1
ZZ	3.6	3.1
$\tau\tau$ + bb	2.4	0.4
$\gamma\gamma$ + ZZ	4.7	5.0
$\gamma\gamma$ + ZZ + WW	5.2	5.1
$\gamma\gamma$ + ZZ + WW + $\tau\tau$ + bb	5.8	5.0

Overall significance 5.0σ versus 5.8σ expected.

Signal Strength in Channels



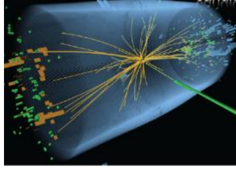
Properties of the Particle



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

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

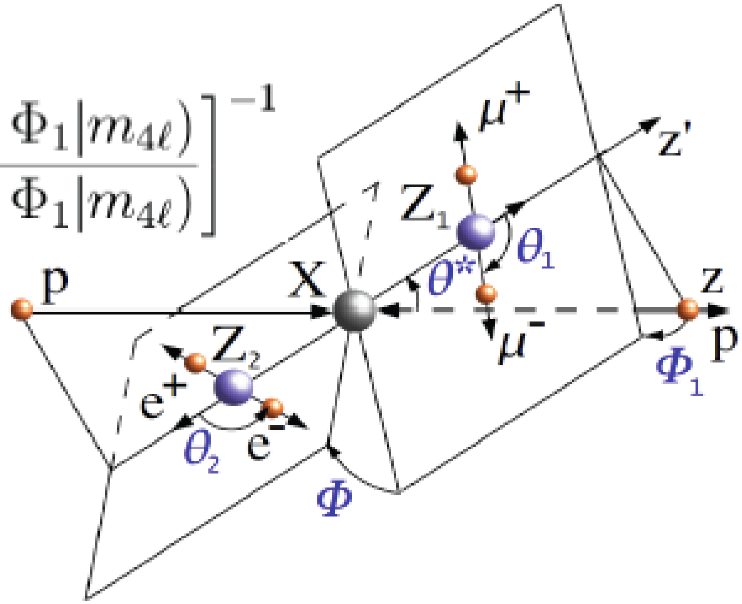
- Spin-parity
  - Spin one ruled out by 2γ decay
  - Assuming S=0, one can use H→ZZ to distinguish between parity states

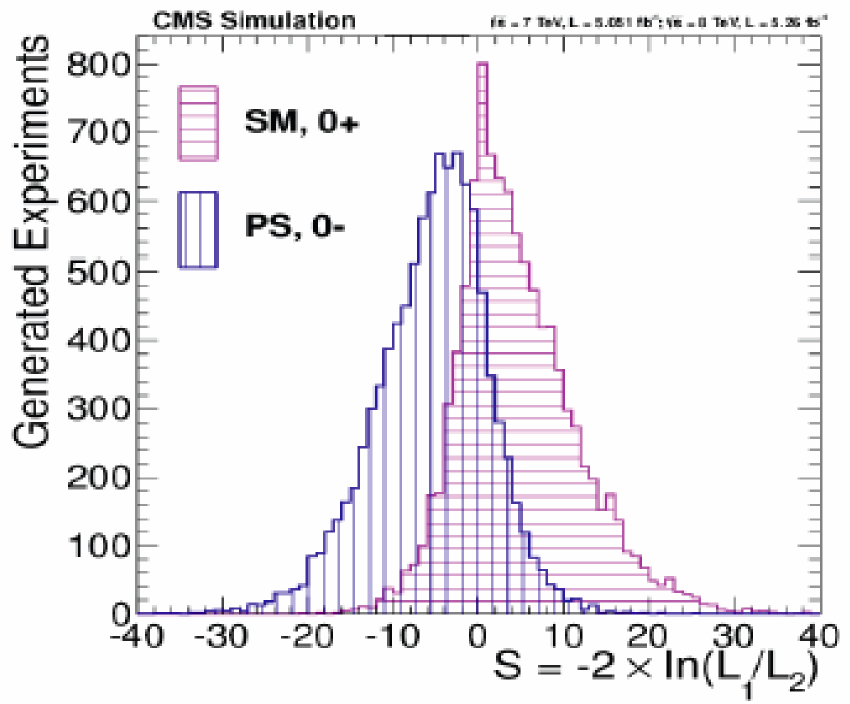


Parity from MELA

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

Matrix Element Likelihood Analysis: uses kinematic inputs to form likelihood



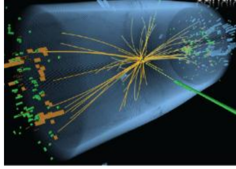


gs Marlow 35

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

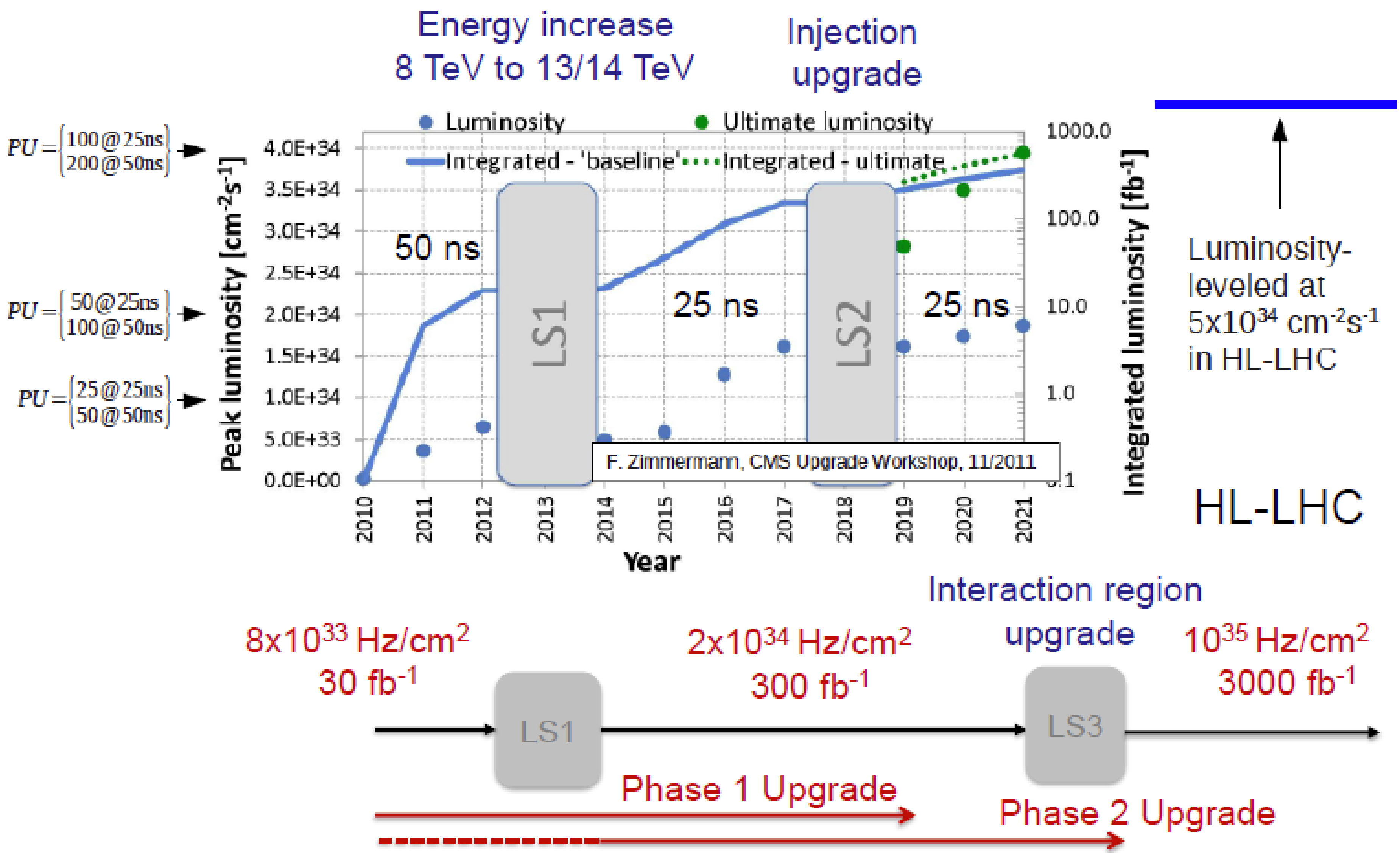
1.6σ with current sample
3.1σ with 5+30 fb^{-1} sample expected by end of 2012 run

LHC Upgrade

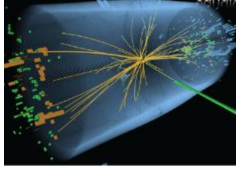


- General need for upgrade understood for some time now, given excellent performance of LHC. But . . .
- The recent discovery has brought new focus to plans for the near- and long-term future.
- The studies are rapidly advancing, and one can expect significant improvements over the snapshot to be presented.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

LHC and HL-LHC Projections



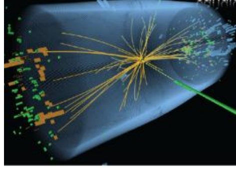
Bench Mark Data Sets

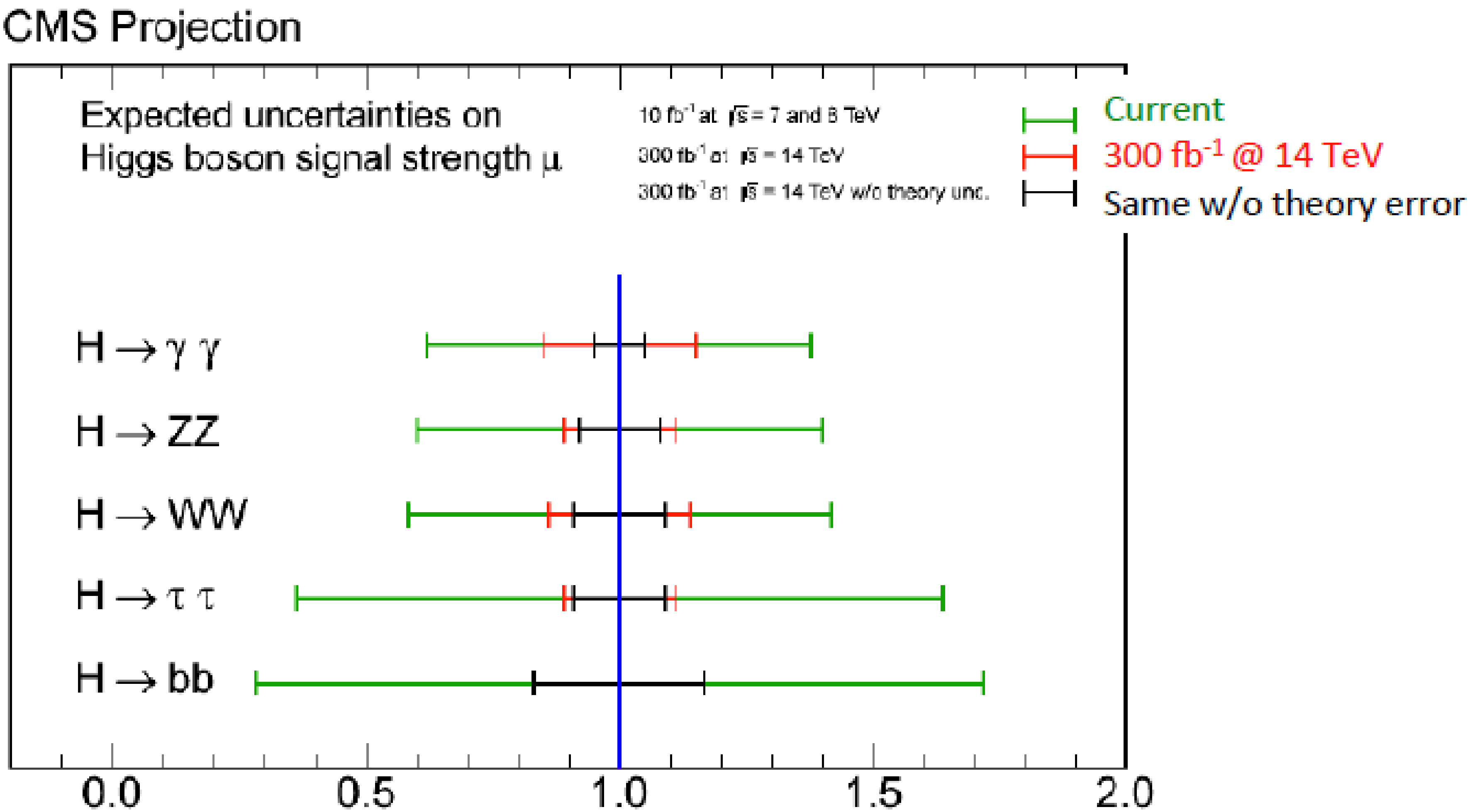


Scenario	L (fb^{-1})	E (TeV)
LHC	300	14
HL-LHC	3000	14
HE-LHC	300	33

- 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.

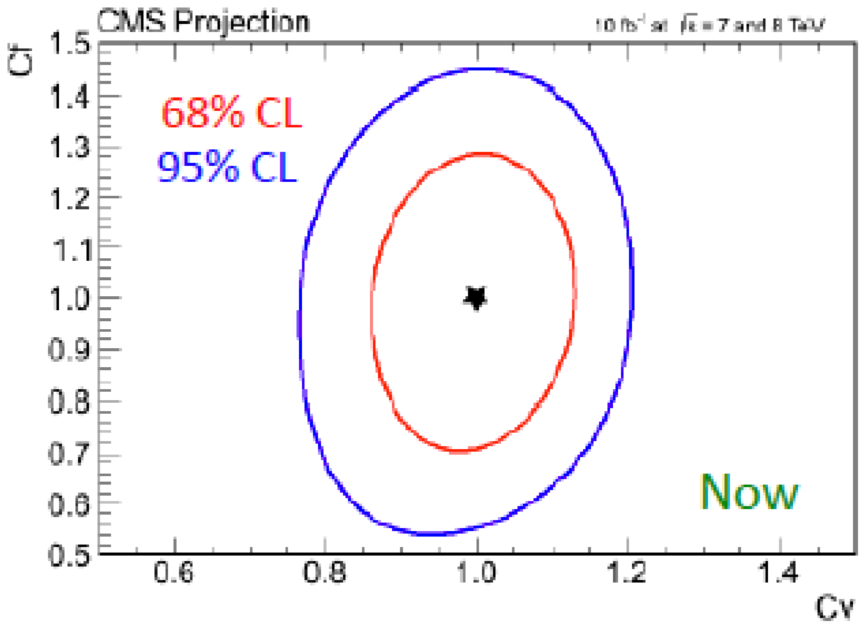
Projected Signal Strength Precision

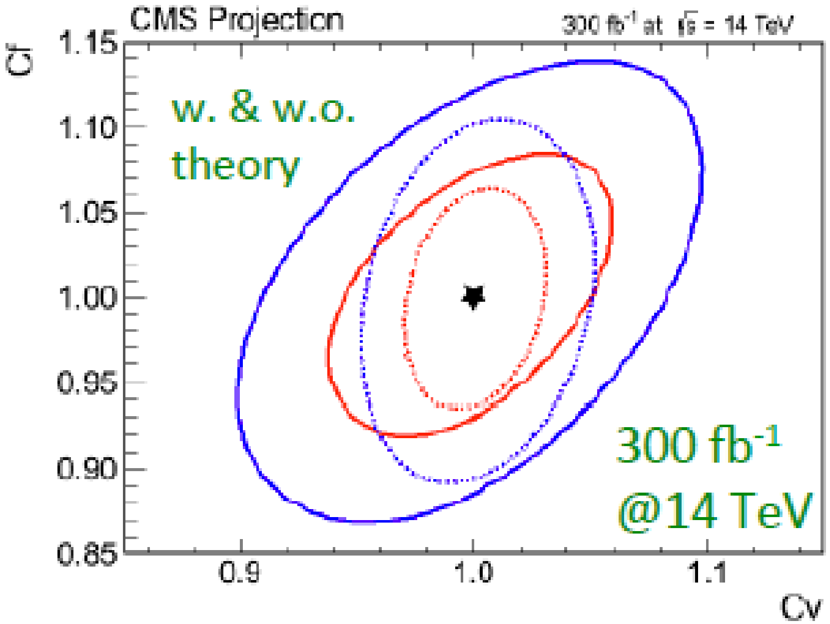




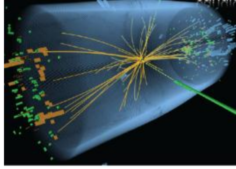
Higgs Characterization

- 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).

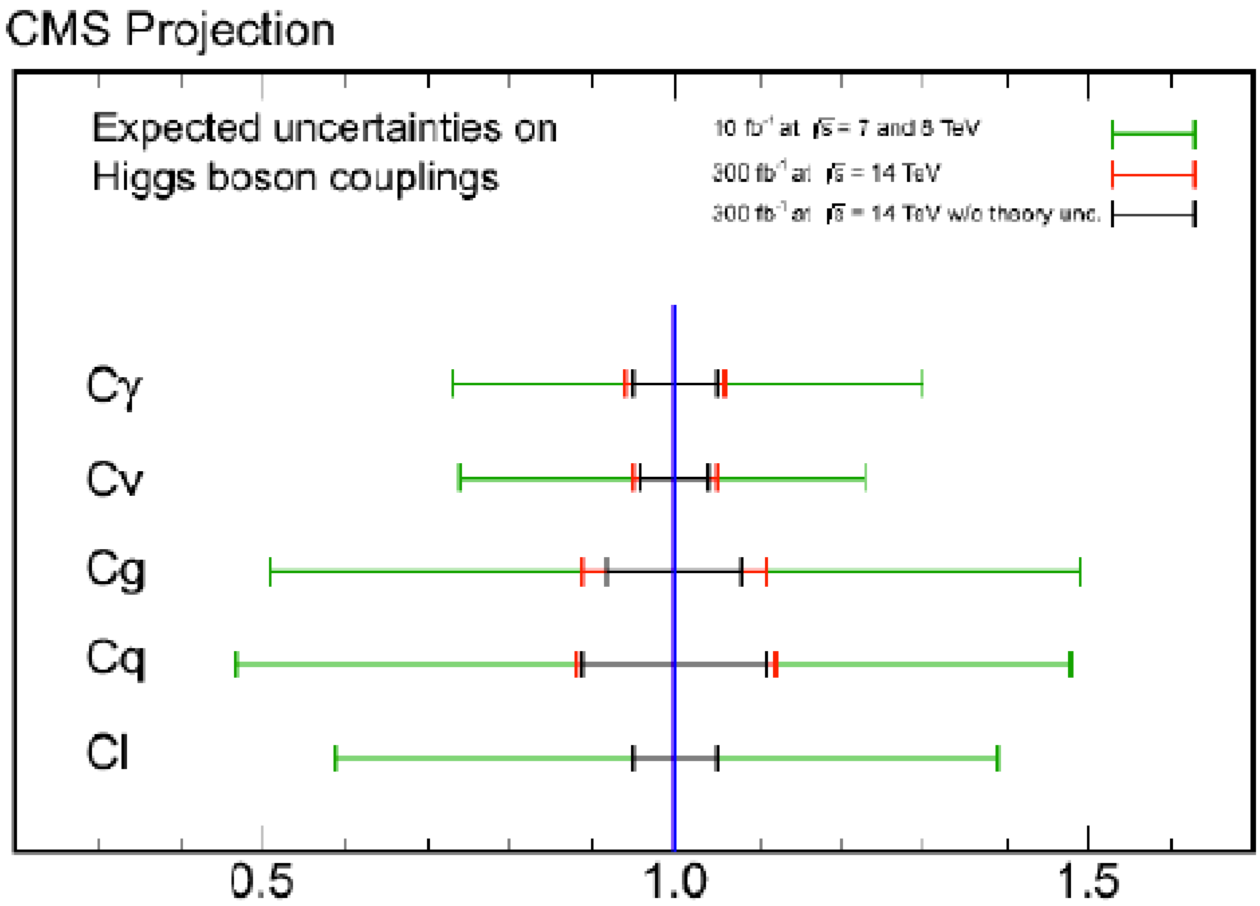




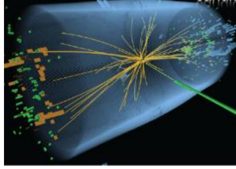
Higgs Characterization



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 .

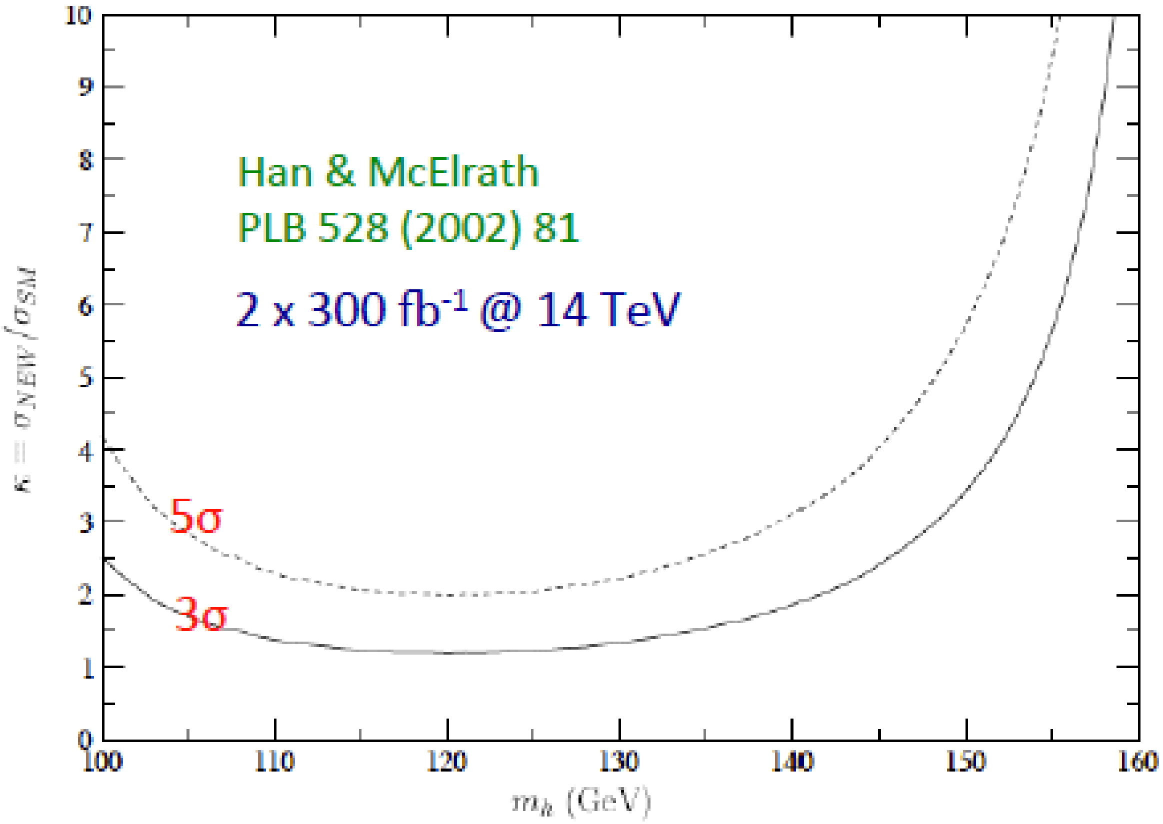


Higgs →μμ

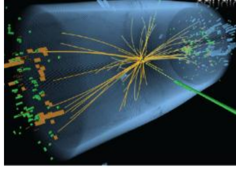


Would like to see example of Higgs coupling to a 2nd generation fermion.

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

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

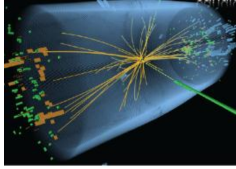
but this runs out of gas for M_H < 140 GeV

- 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