University of Rochester — Physics Colloquium

October 24, 2012

Discovery of a new boson

Part I: Experimental analysis: mass measurement

Part II: Measurement of properties

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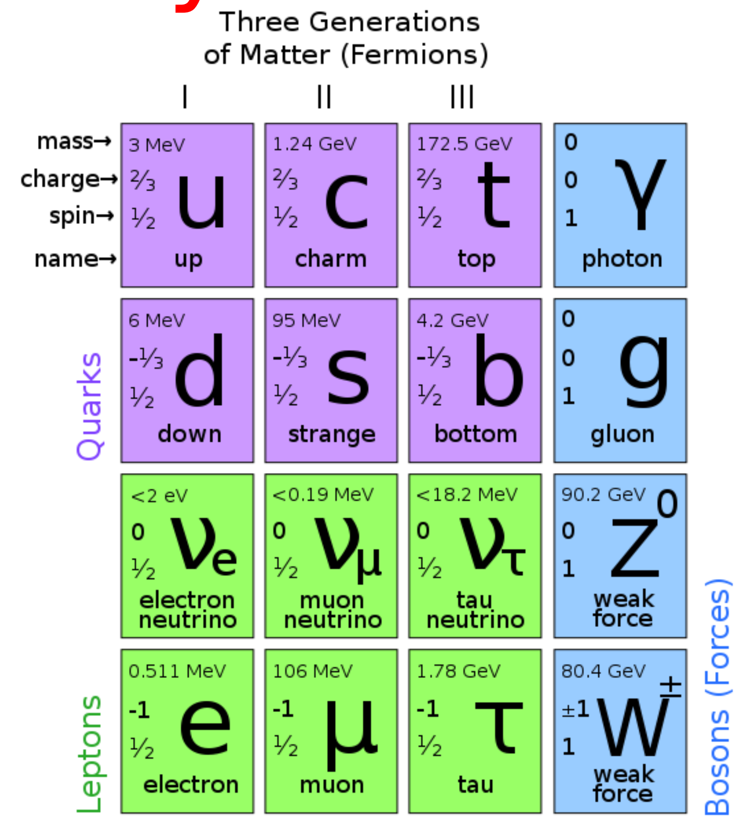
A massless theory

The standard model describes the interactions between matter and forces

- Gauge invariance plays a crucial role
  $\psi(x) \rightarrow e^{i\alpha}\psi(x)$
  - Gauge bosons, conserved "charges"

Forces:	E&M	Weak	Strong
Group	U(1)	SU(2)	SU(3)
Conserved	Q	isospin	color
Mediators	γ	$W^{\pm}$, Z	gluons
couple to	charge	fermions	color



$$\mathcal{L}_{SM} = \frac{1}{4} W_{\mu\nu} W^{\mu\nu} - \frac{1}{4} B_{\mu\nu} B^{\mu\nu} - \frac{1}{4} G^{a}_{\mu\nu} G^{\mu\nu}_{a}$$

kin. en. and self−int. of gauge bosons

$$+\bar{L}\gamma^{\mu}\left(i\partial_{\mu} - \frac{1}{2} g\,\tau \cdot W_{\mu} - \frac{1}{g}' Y B_{\mu}\right) L + \bar{R}\gamma^{\mu}\left(i\partial_{\mu} - \frac{1}{2} g' Y B_{\mu}\right) R$$

kin. en. and EW interactions of fermions

$$+g''(\bar{q}\gamma^{\mu} T_{a} q) G^{a}_{\mu}$$

interactions between quarks and gluons

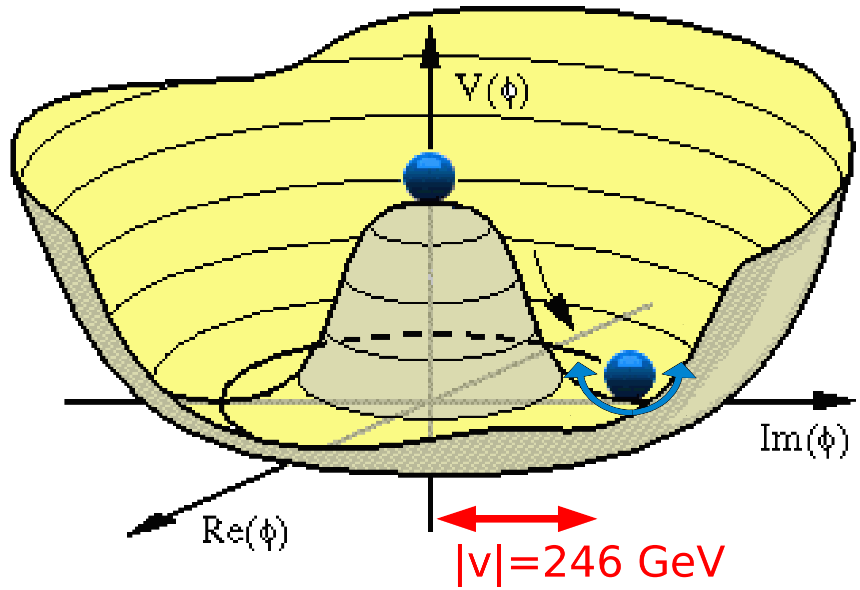
- Adding a mass term $m^2 W^{\mu} W_{\mu}$ makes $\mathcal{L}$ not gauge-invariant, but the W and Z have mass!
- Need to break SU(2)xU(1) keeping gauge invariance
- Spontaneous symmetry breaking: symmetric $\mathcal{L}$, ground state is not

Electroweak symmetry breaking

- Add ϕ, a new (complex doublet) scalar field with potential:

$$\phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix} \qquad V(\phi) = \lambda \left(\phi^\dagger \phi - \frac{v^2}{2} \right)^2$$

  - Breaks SU(2)xU(1) → U(1)
  - 4 d.o.f → 3 longitudinal polarizations of W^+, W^-, Z^0 + 1 new scalar boson: H
  - Lowest energy of vacuum $v/\sqrt{2}$

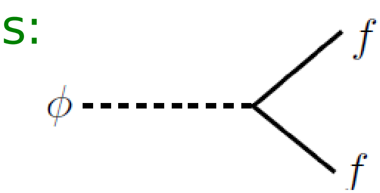


- The scalar's kinetic energy includes a term that becomes:

$$\frac{1}{4} g^2 W^\mu \phi^\dagger W_\mu \phi \rightarrow \frac{1}{8} g^2 v^2 W^\mu W_\mu = \frac{1}{2} M_W^2 W^\mu W_\mu$$

A mass term for the W and Z bosons!

- Interactions with fermions:
  - Fermion masses are generated in a gauge invariant way by arbitrary coupling, proportional to mass:

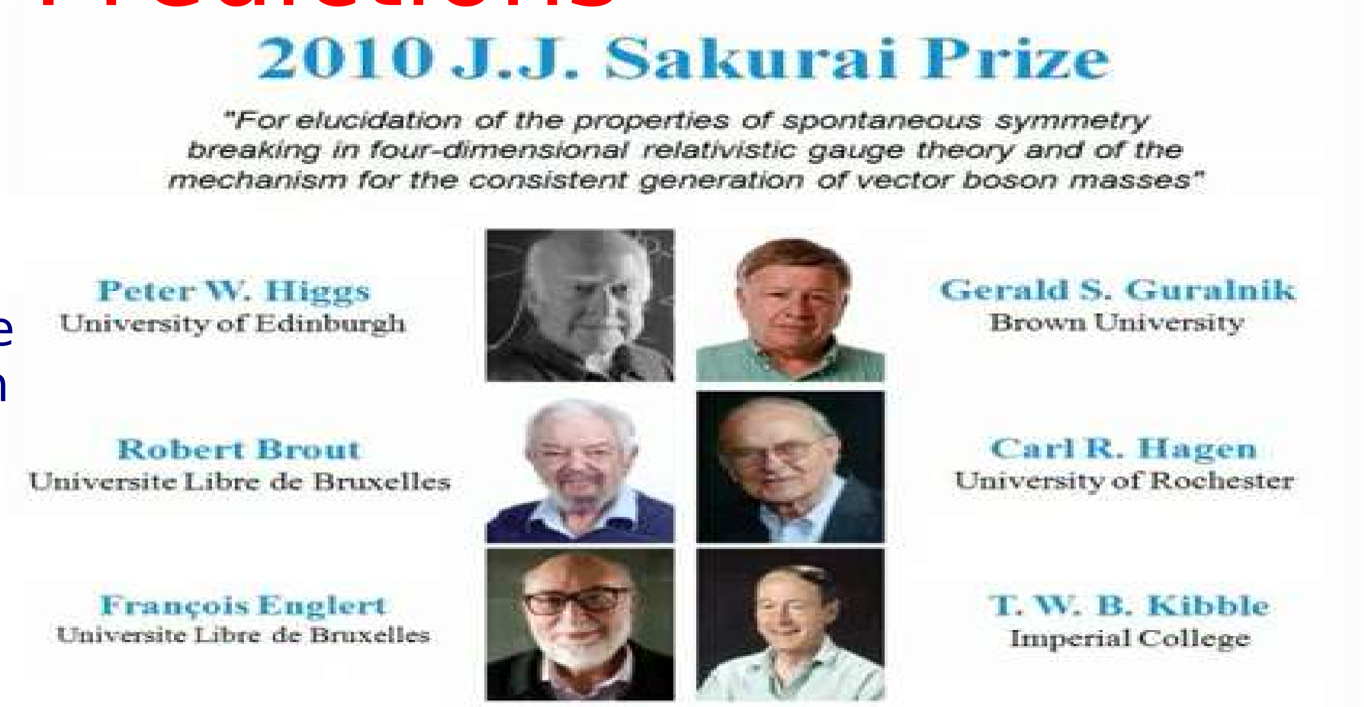


$$y \, f \phi f \;\longrightarrow\; \underbrace{\frac{yv}{\sqrt{2}}}_{m_f} f f + \underbrace{\frac{y}{\sqrt{2}} f h f}_{\text{interaction}}$$

F. Englert and R. Brout, Phys. Rev. Lett. 13 (1964) 321
P. Higgs, Phys. Rev. Lett. 13 (1964) 508,
G. Guralnik, C. R. Hagen, and T. Kibble, Phys. Rev. Lett. 13 (1964) 585

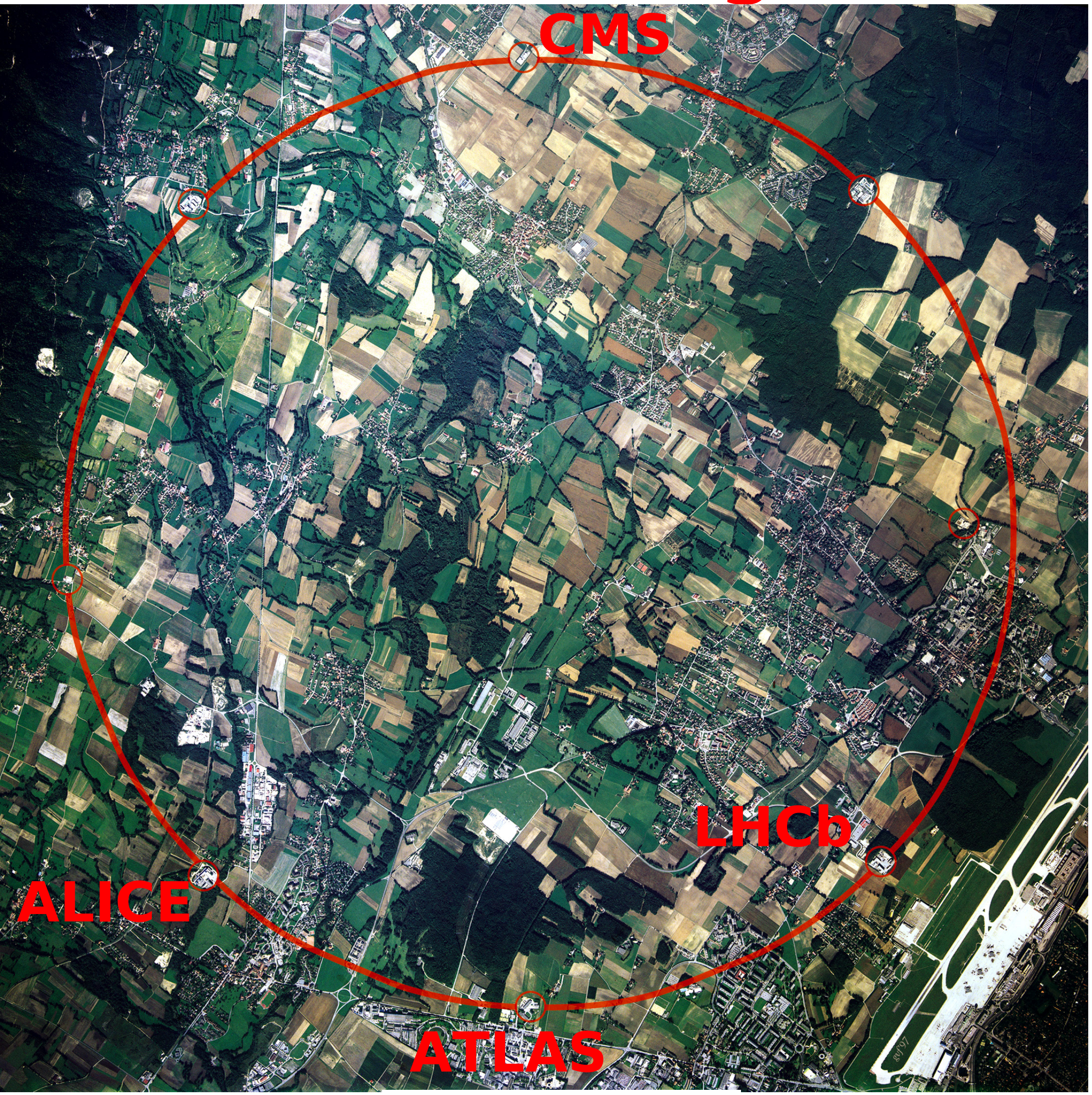
Predictions

2010 J.J. Sakurai Prize
“For elucidation of the properties of spontaneous symmetry breaking in four-dimensional relativistic gauge theory and of the mechanism for the consistent generation of vector boson masses”

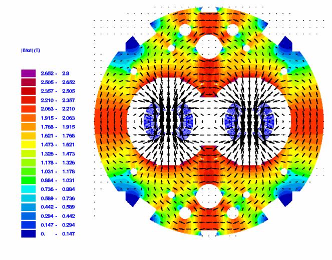


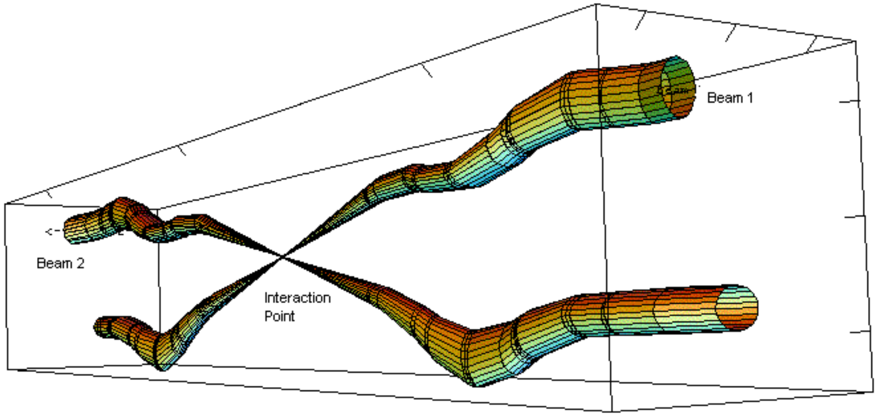
- A new scalar boson s=0, P=+1, $m_H=\sqrt{2\lambda}\,v$
  - Discover resonance, measure its mass ✔
  - Measure its properties (spin, parity)
- Couplings to bosons
  - Test relative strength between γ, W, Z
- Couplings to fermions
  - Perhaps something else gives rise to the fermion masses?
- Self coupling
  - Test strength (will need lots of data!)

The Large Hadron Collider



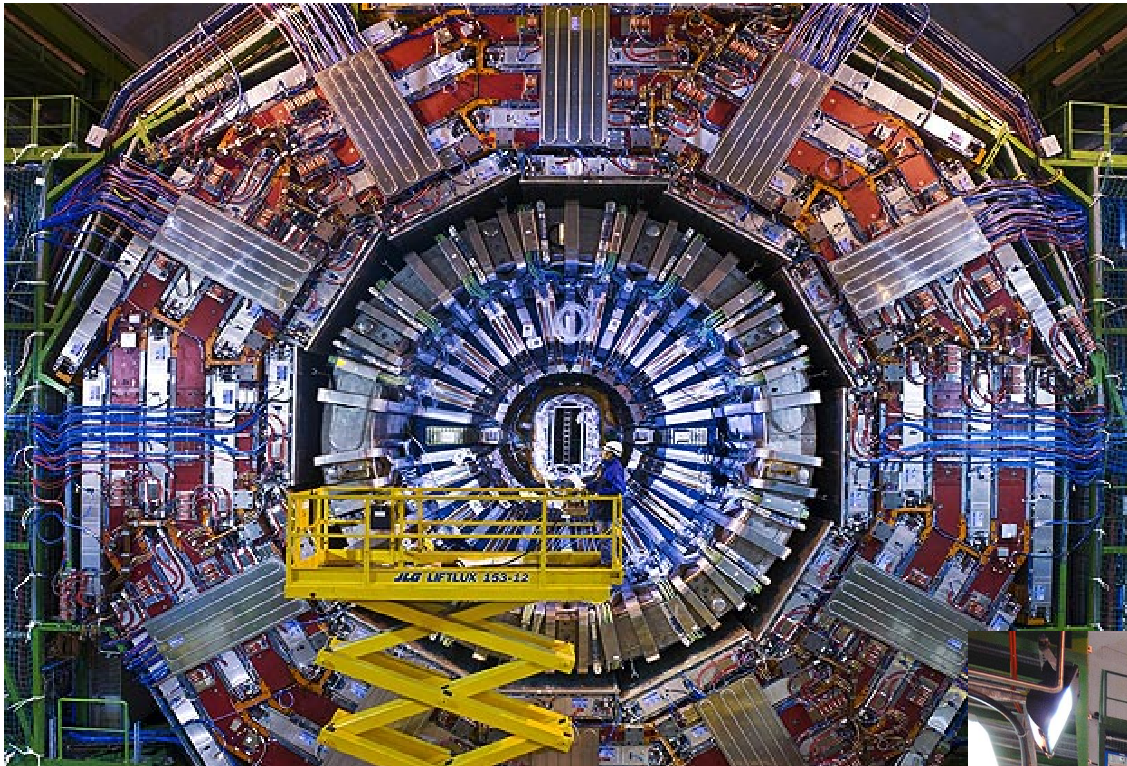
- p-p collider at $\sqrt{s}$=7, 8 TeV
- 26 km long, 100m underground
- Delivered luminosity: 18 fb^{-1}
- Peak luminosity: $7 \cdot 10^{33}$ $cm^2 s^{-1}$
- Crossing rate: 40 MHz
- Rare processes: 1 in 10^{13}

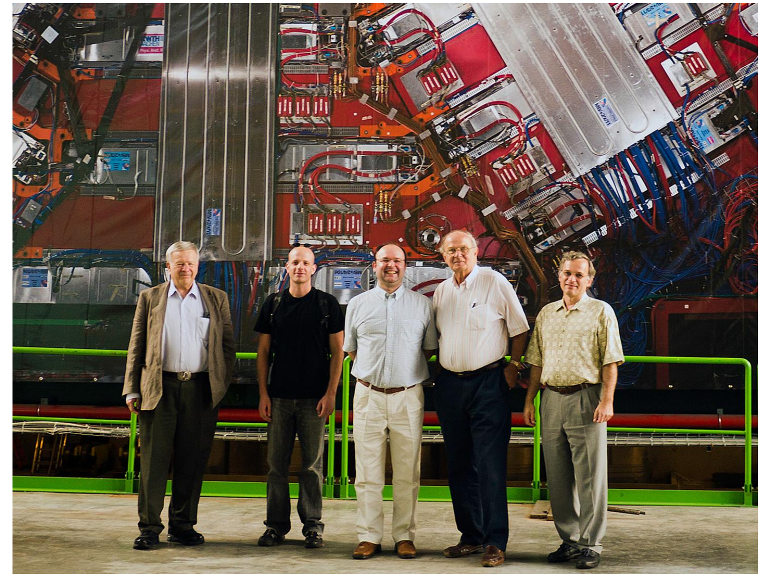


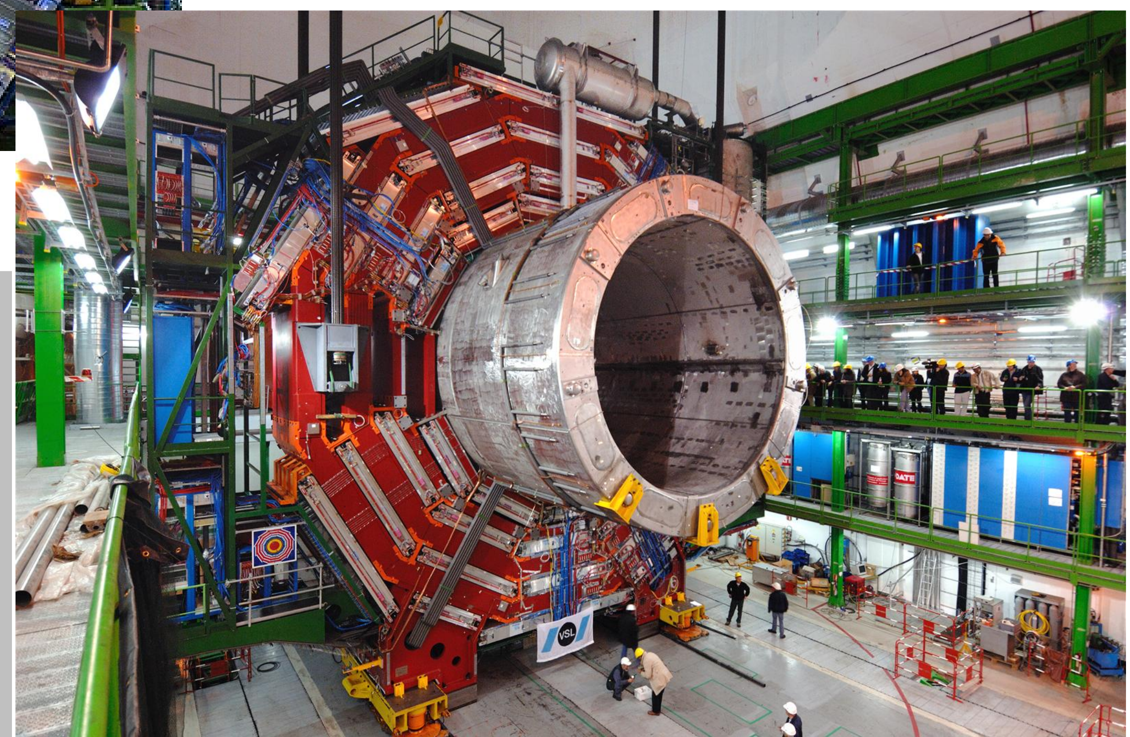


Relative beam sizes around IP1 (Atlas) in collision

The CMS detector



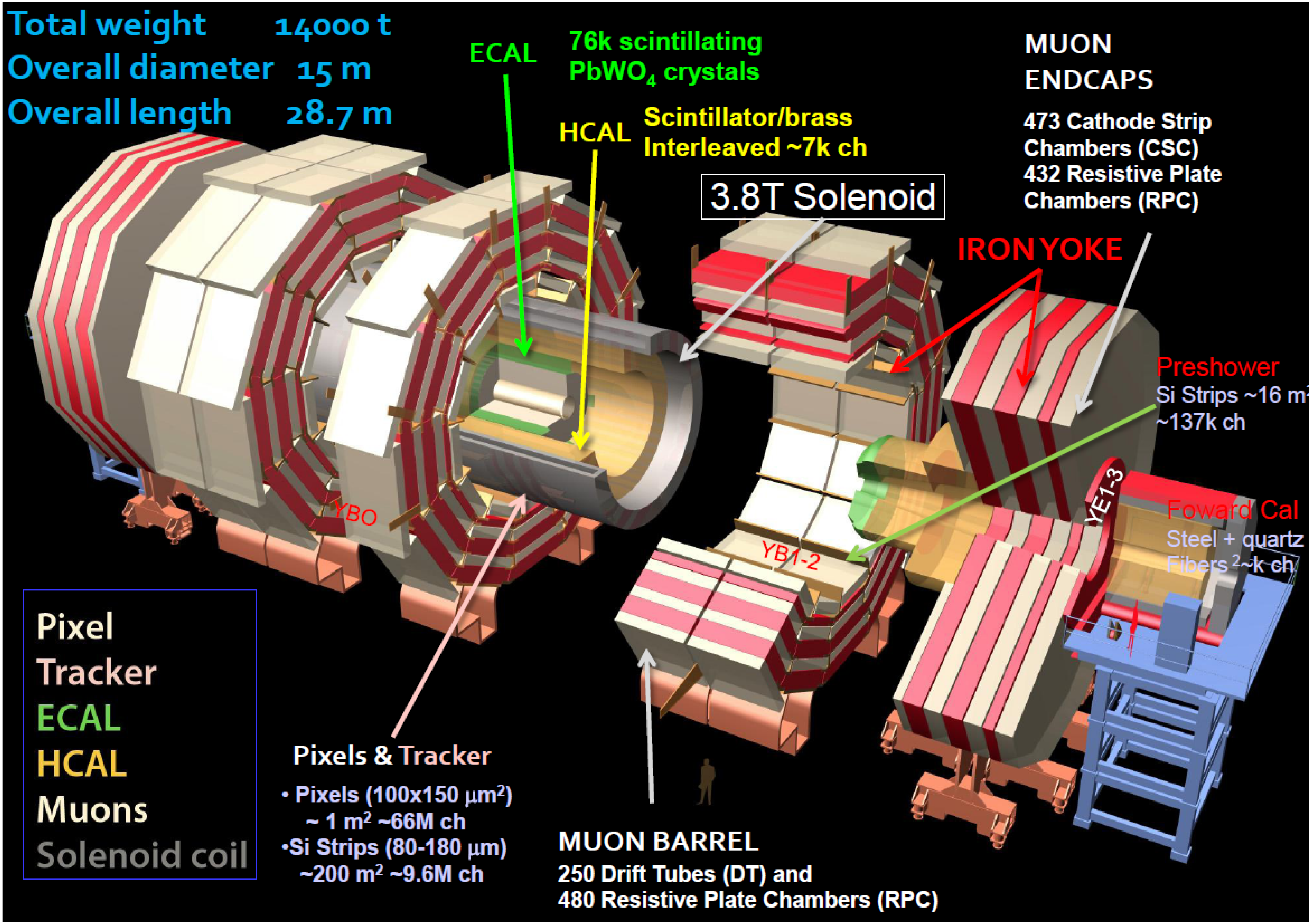




The CMS solenoid magnet:

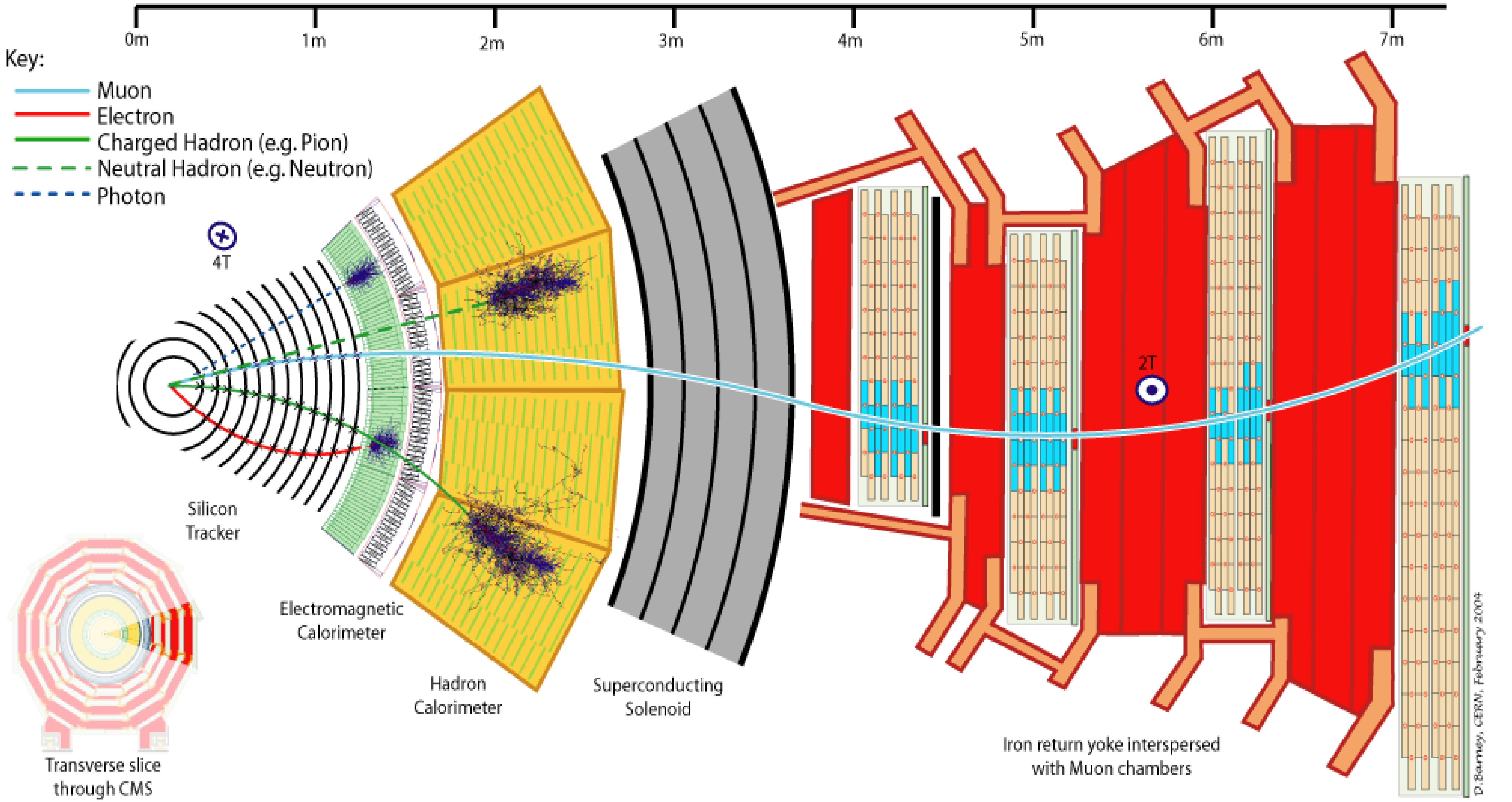
Magnetic length	12.5 m
Free bore diameter	6 m
Central B Field	4 T
Weight	12,000 ton
Temperature	4.2^{o} K
Nominal current	20 kA
Radial Pressure	64 atm
Stored energy	*2.7 GJ*

USS Ronald Reagan (88,000 tons) at 20 mph



Total weight 14000 t
Overall diameter 15 m
Overall length 28.7 m
ECAL
76k scintillating
$PbWO_4$ crystals
HCAL
Scintillator/brass
Interleaved ~7k ch
MUON
ENDCAPS
473 Cathode Strip
Chambers (CSC)
432 Resistive Plate
Chambers (RPC)
3.8T Solenoid
IRON YOKE
Preshower
Si Strips ~16 m^2
~137k ch
YBO
YB1-2
YE1-3
Foward Cal
Steel + quartz
Fibers ~2k ch
Pixel
Tracker
ECAL
HCAL
Muons
Solenoid coil
Pixels & Tracker
• Pixels (100x150 μm^2)
~ 1 m^2 ~66M ch
•Si Strips (80-180 μm)
~200 m^2 ~9.6M ch
MUON BARREL
250 Drift Tubes (DT) and
480 Resistive Plate Chambers (RPC)

Particle detection in CMS

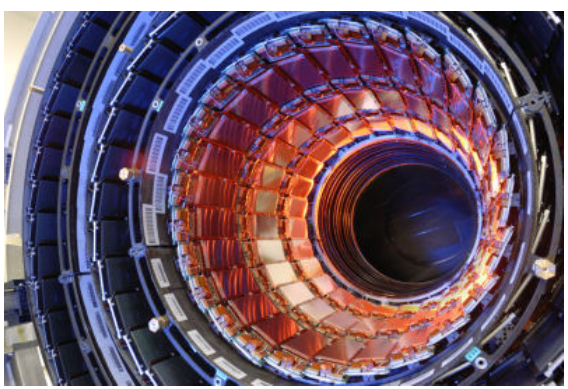


https://cms-docdb.cern.ch/cgi-bin/PublicEPPOGDocDB/RetrieveFile?docid=97&version=1&filename=CMS_Slice_elab.swf

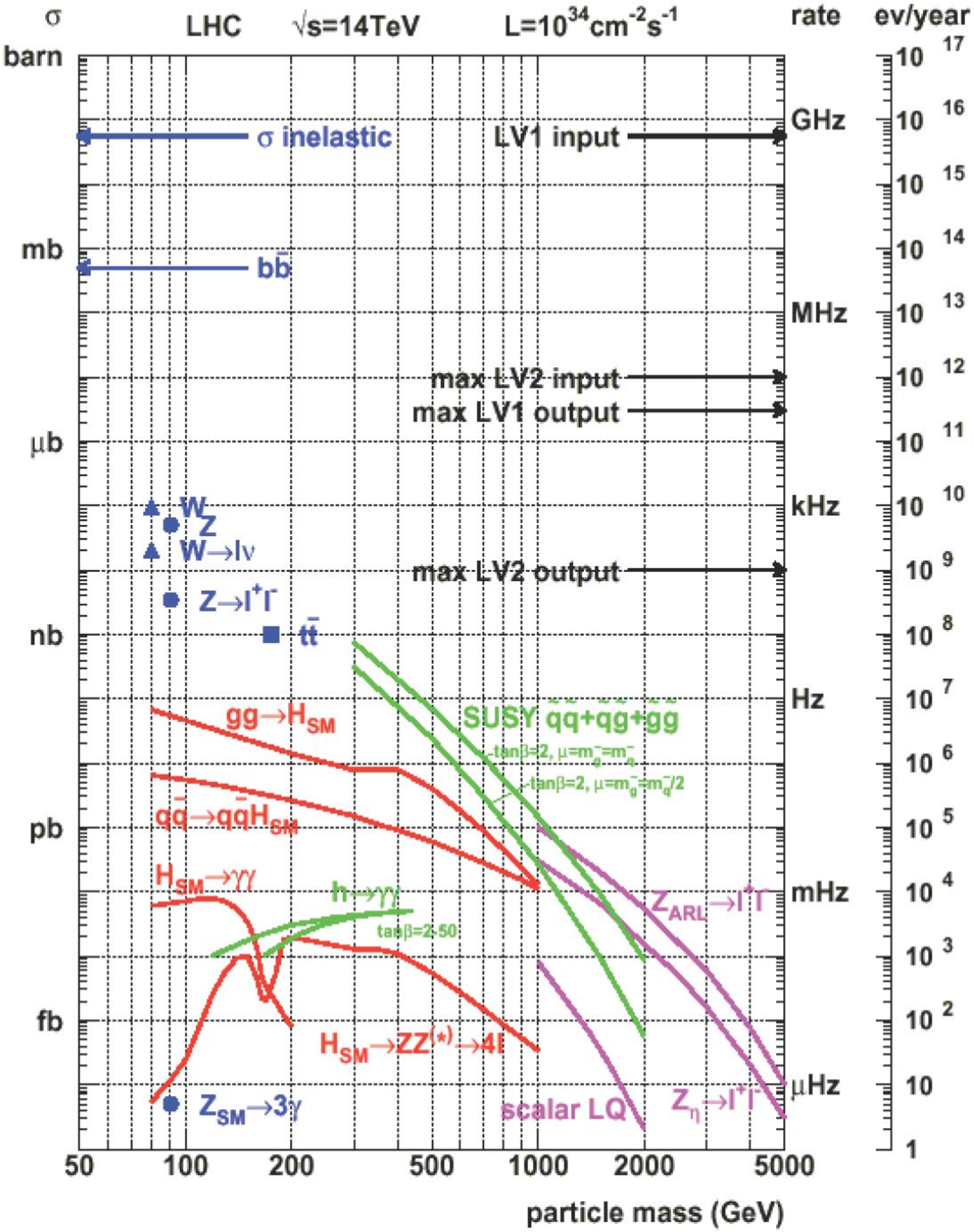
UR contributions to CMS

- **Hadronic calorimeter**: design, construction, commissioning
  - 70,000 plastic scintillator tiles
- **Silicon detector**: prototyped, tested, and commissioned Si modules
  - 200 square meters of Si (100 kg)
- **Objects**: tracks, μ, jets, b-jets
- **Physics**: W, Z, top, searches, H



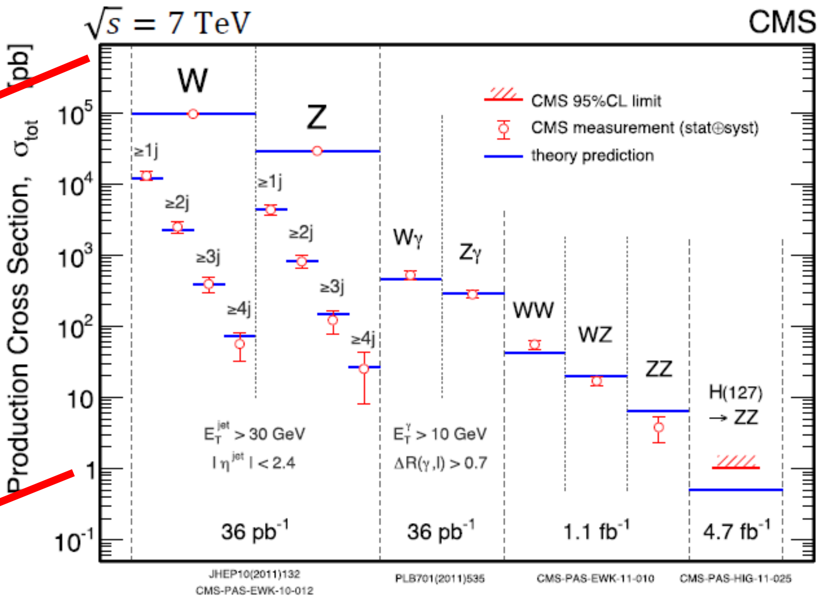




Physics at a hadron collider is like... drinking from a fire hose



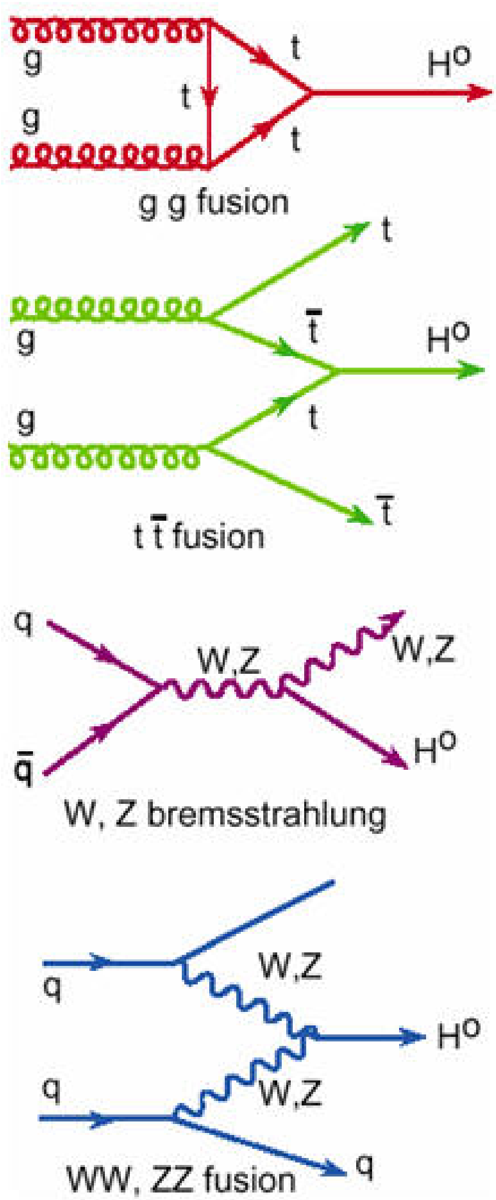
$$N = \sigma[cm^2]L[cm^{-2}s^{-1}] \sim MHz$$

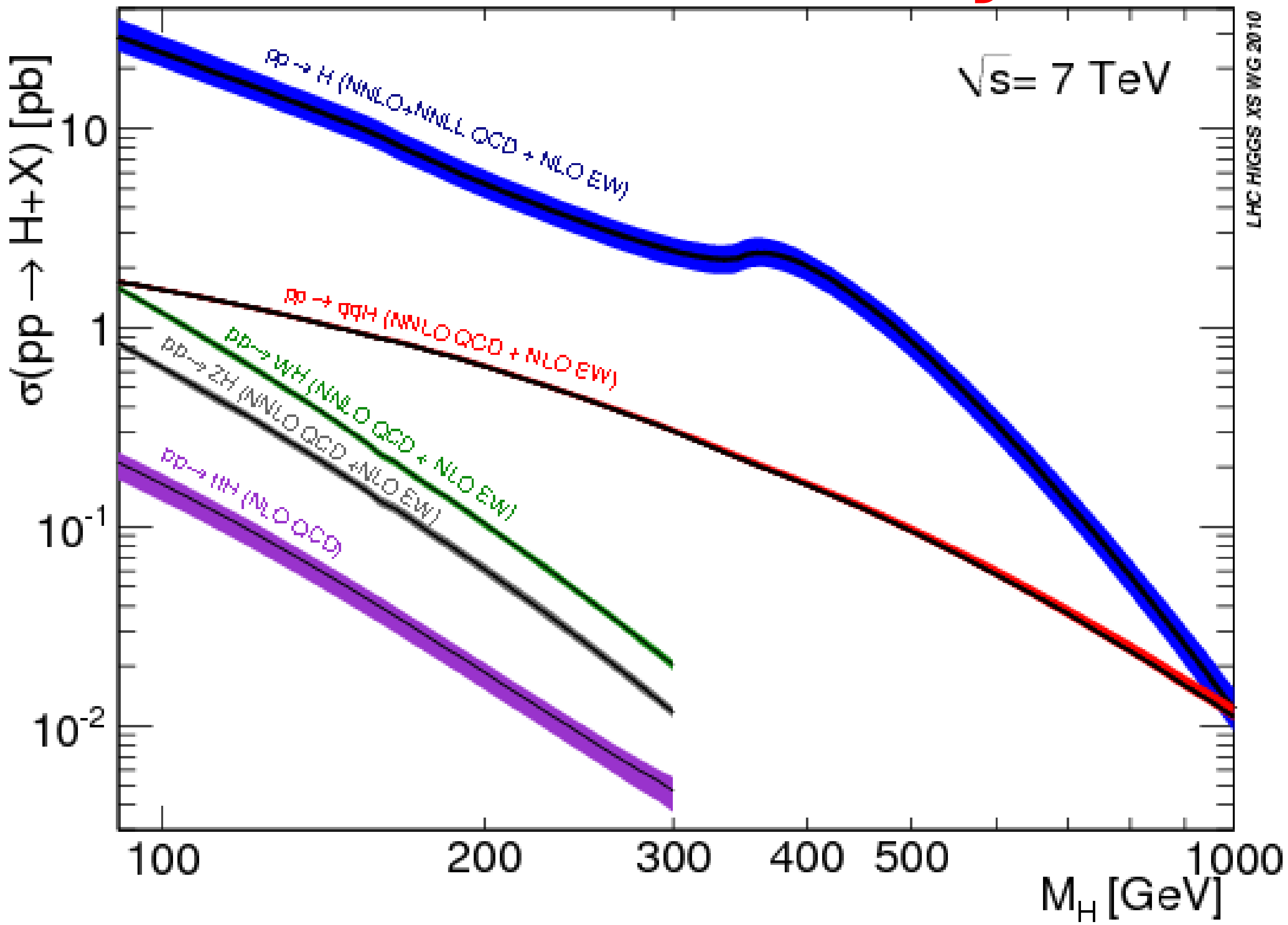
LHC at 8TeV and $L=7\cdot10^{33}cm^{-2}s^{-1}$ produces ~750 H/hour



~70 papers published on standard model physics at 7 and 8 TeV:
no deviations from predictions have been observed

H production and decay

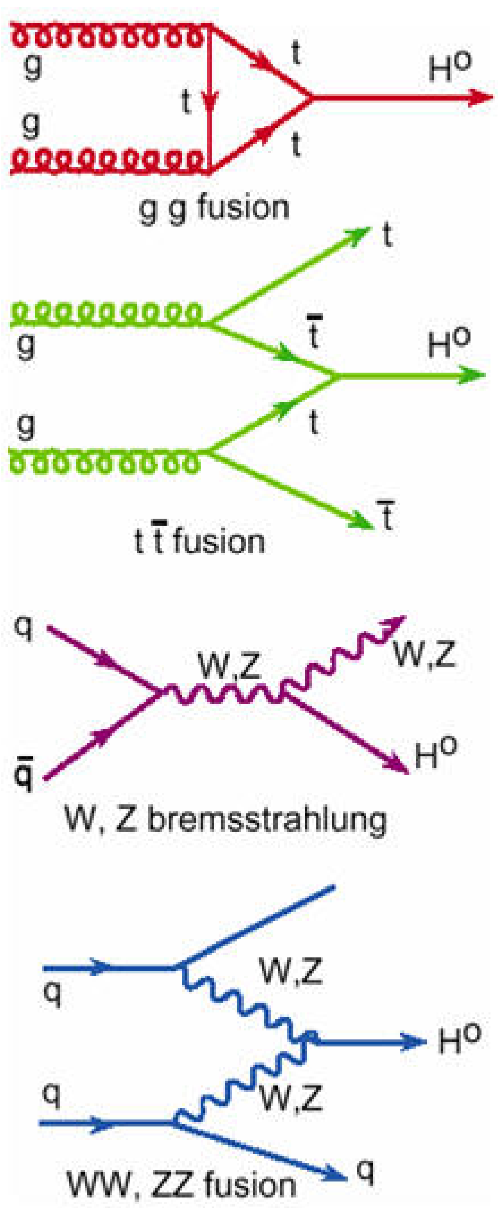


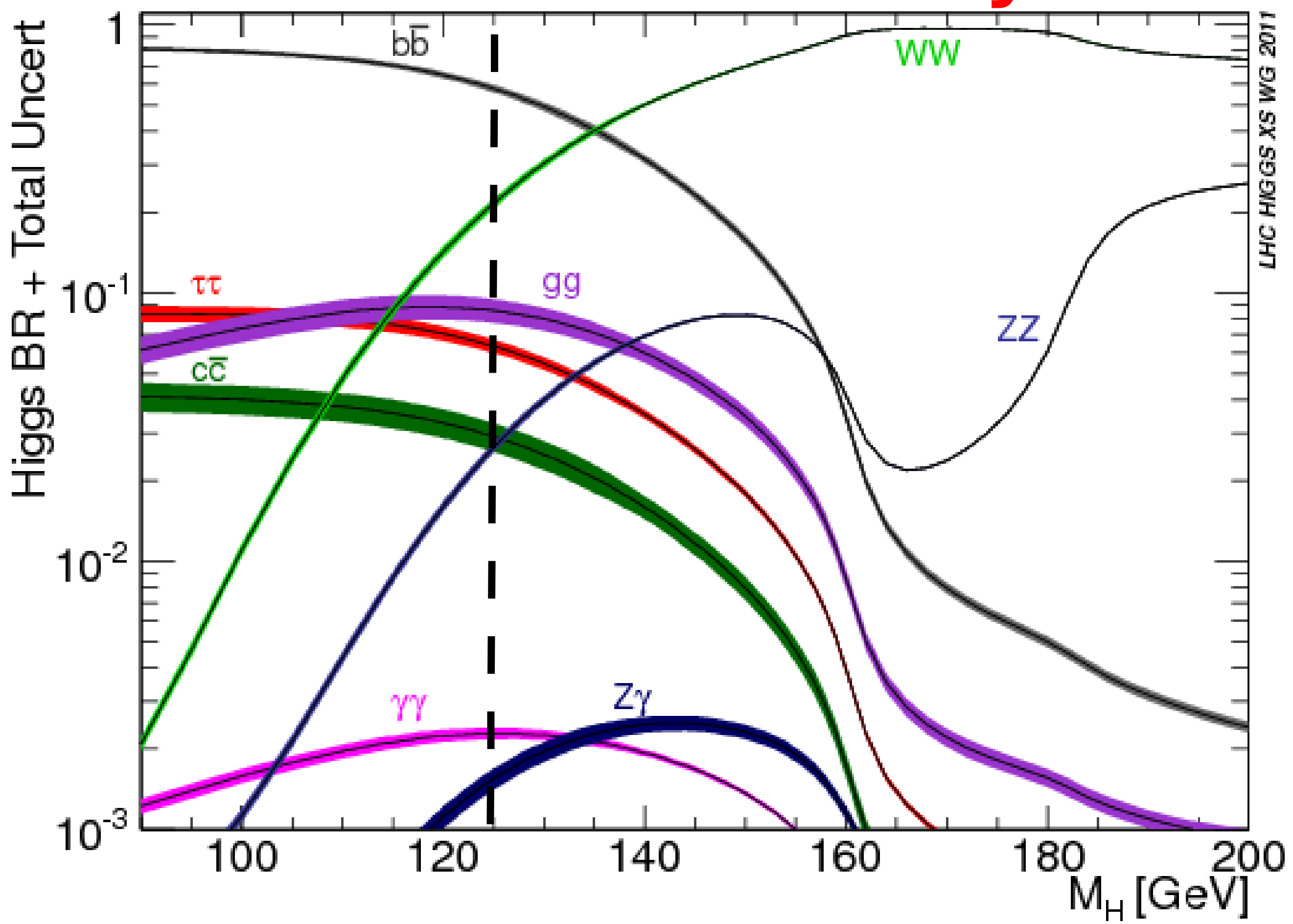


The scalar can be produced via different interactions (protons at 4 TeV mostly contain gluons)

Production cross section σ depends on the unknown H mass

H production and decay





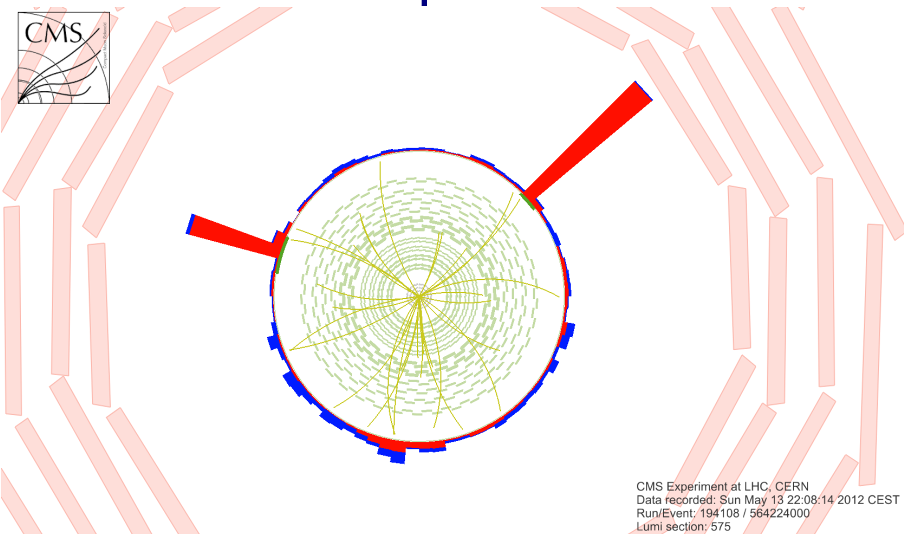
The scalar then decays in one of several final states: the fraction of each decay also depends on on the unknown H mass

All channels are needed to establish the nature of the new particle

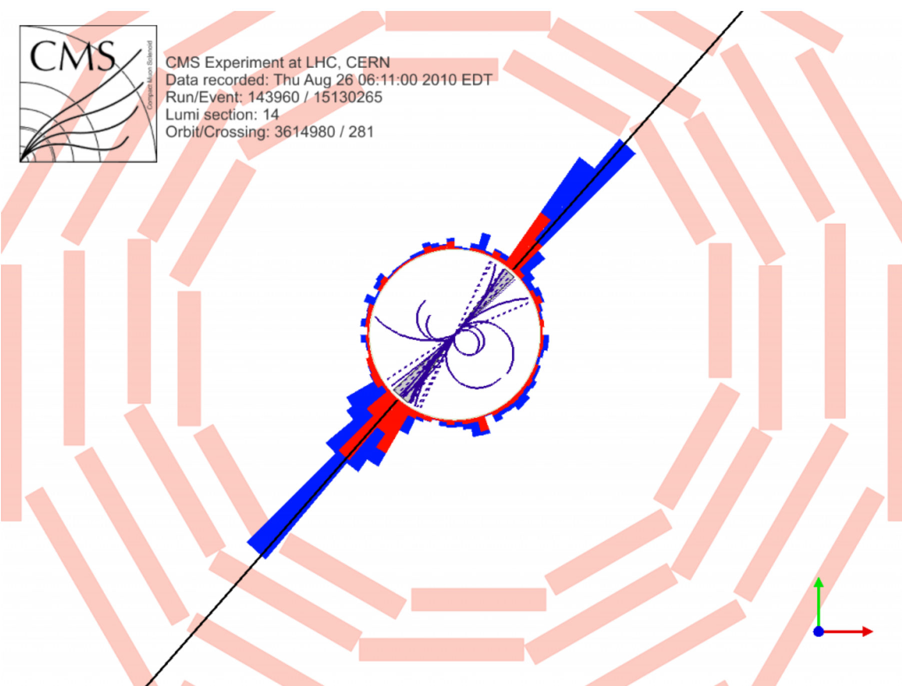
M_H = 125 GeV: all decays possible!

Search for H → γγ

We need to separate this:

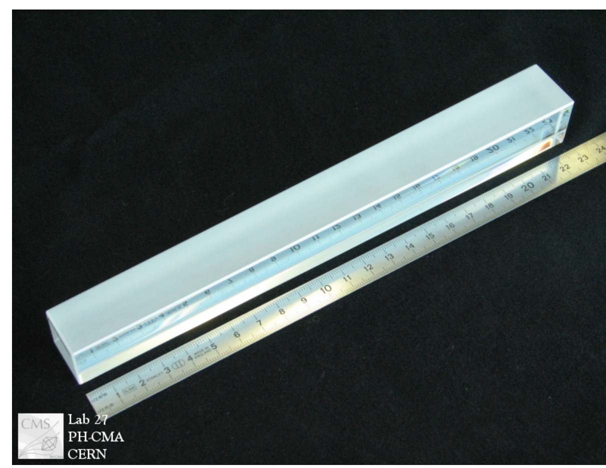


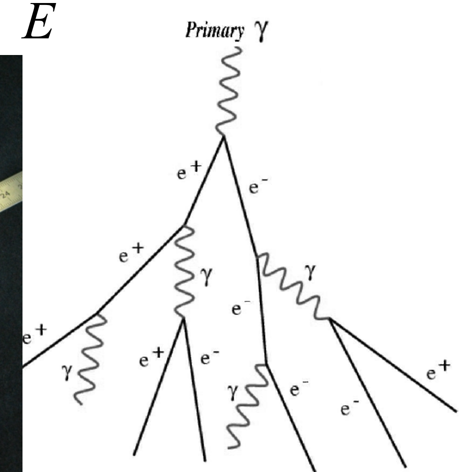
From this:



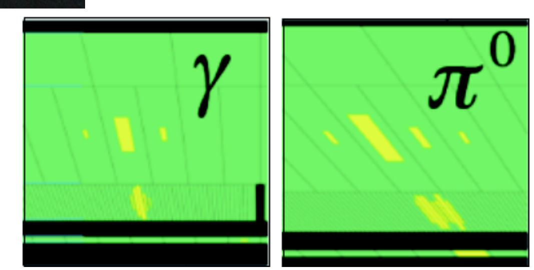
- Only a small fraction of jets can mimic a photon – but there are a lot of jets!
- Channel with tiny decay width, but small backgrounds
- Scintillator Electromagnetic calorimeter designed to achieve:

$$\frac{\delta E}{E} = \frac{2.7\%}{\sqrt{E}} \oplus 0.55\% \oplus \frac{0.16\,\mathrm{GeV}}{E}$$





- Use shape info to separate from $\pi \to \gamma\gamma$

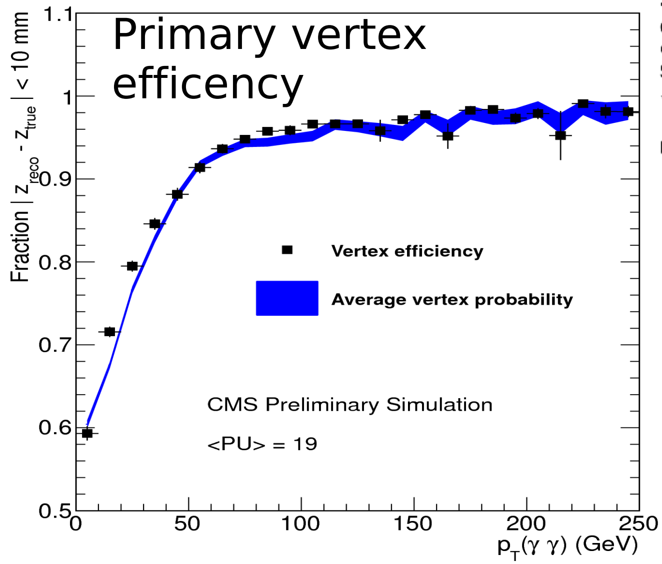


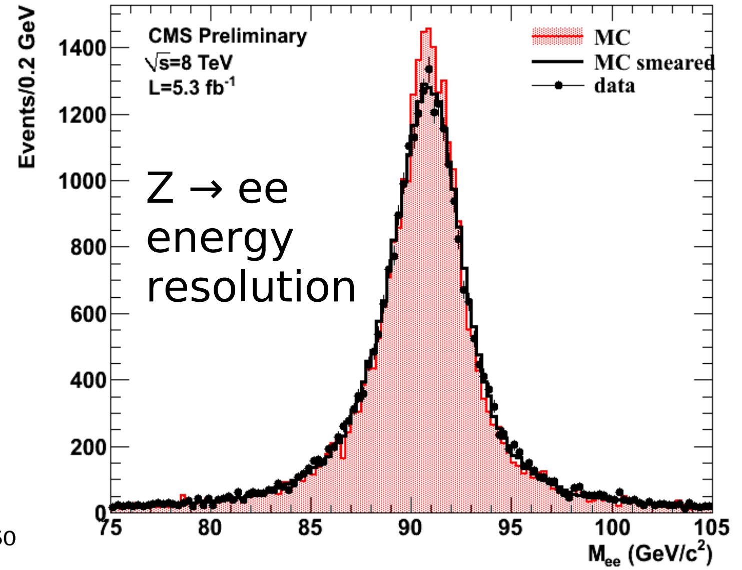
Diphoton analysis

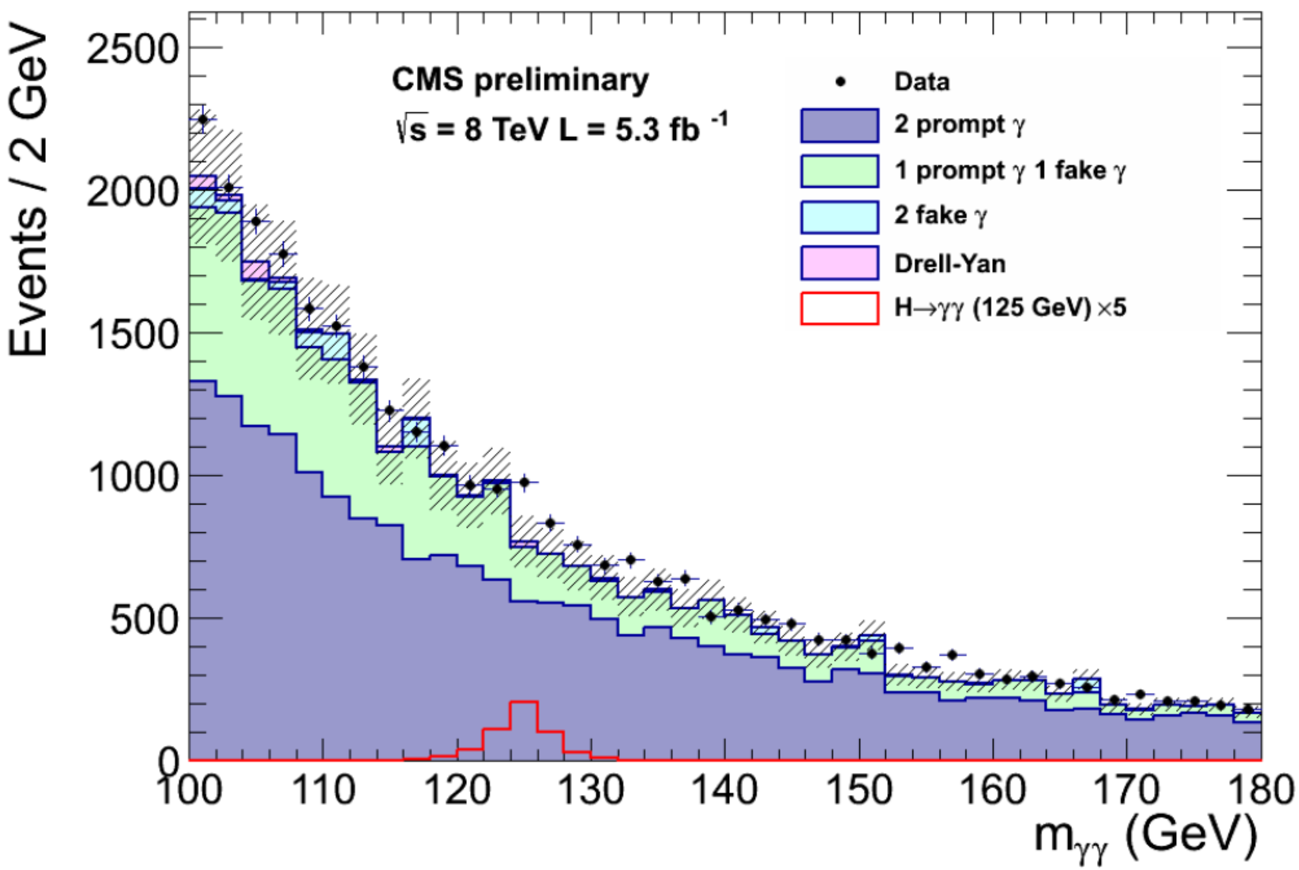
$$E^2=(mc^2)^2+(|\vec{p}|c)^2$$

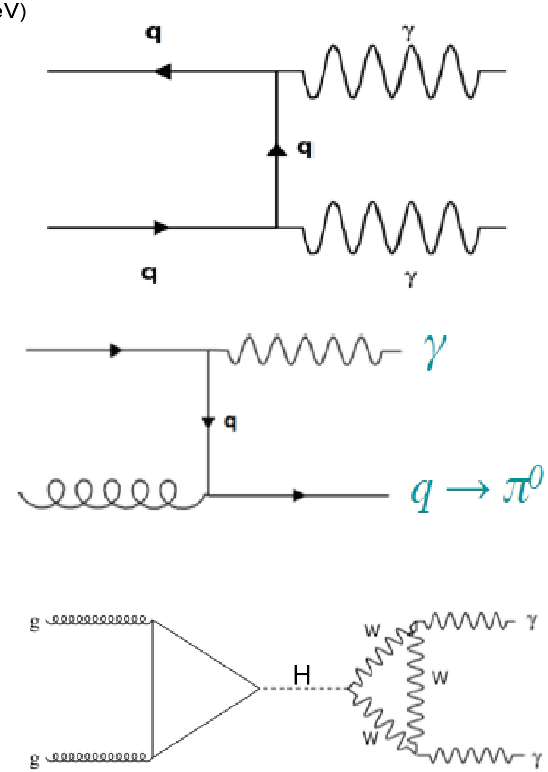
$$m_H=\sqrt{\left(\frac{\sum E_i}{c^2}\right)^2-\left|\frac{\sum \vec{p}_i}{c}\right|^2}$$

$$m_{\gamma\gamma}=\sqrt{2E_1E_2(1-\cos\theta)}$$



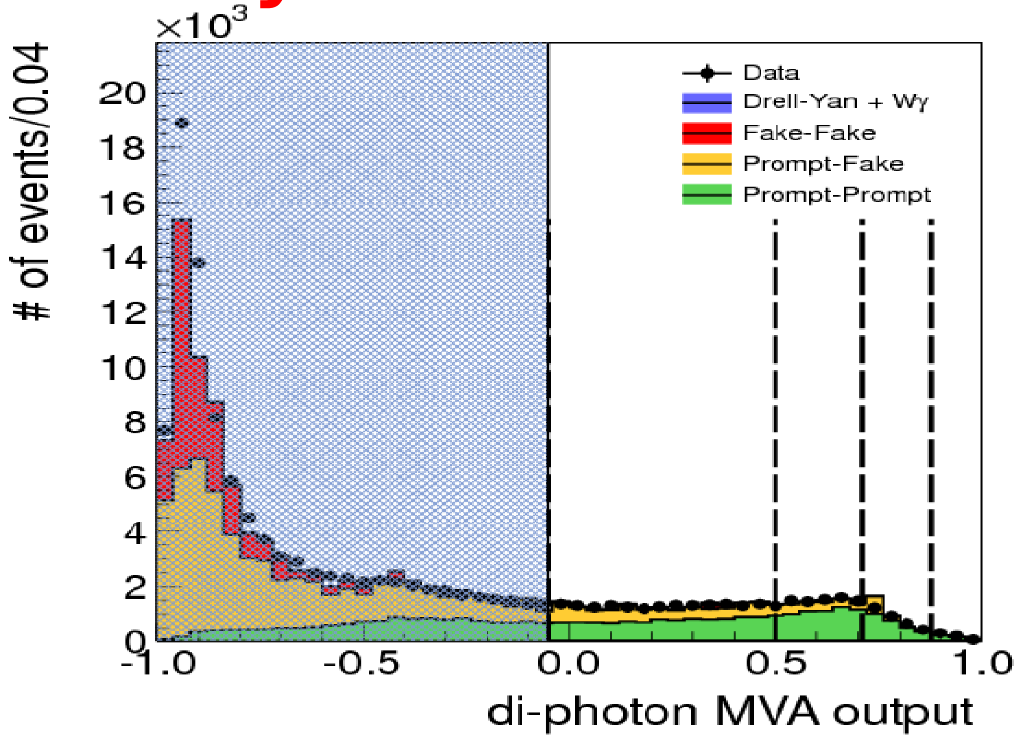


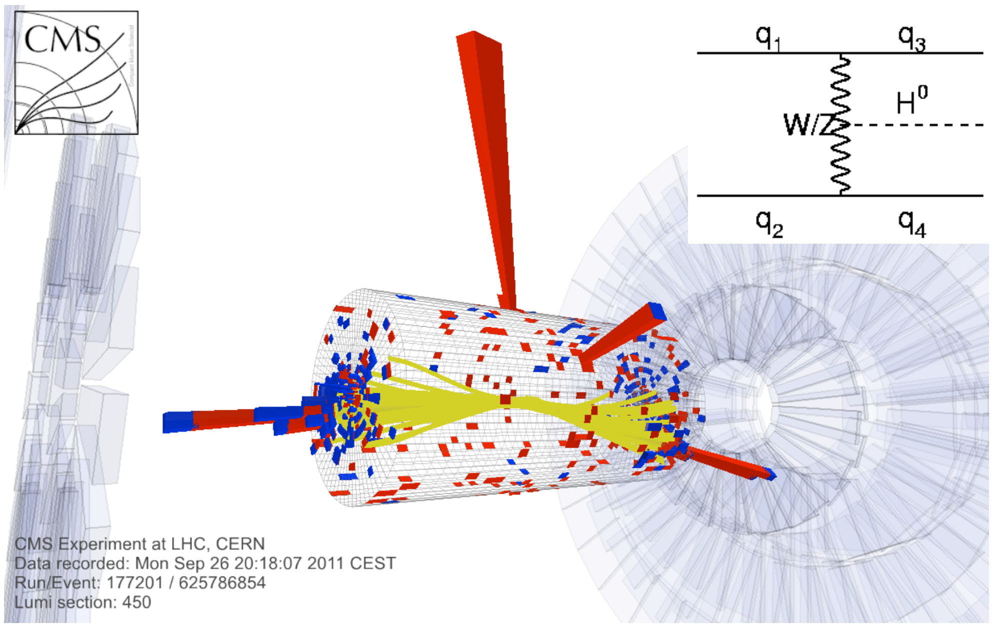




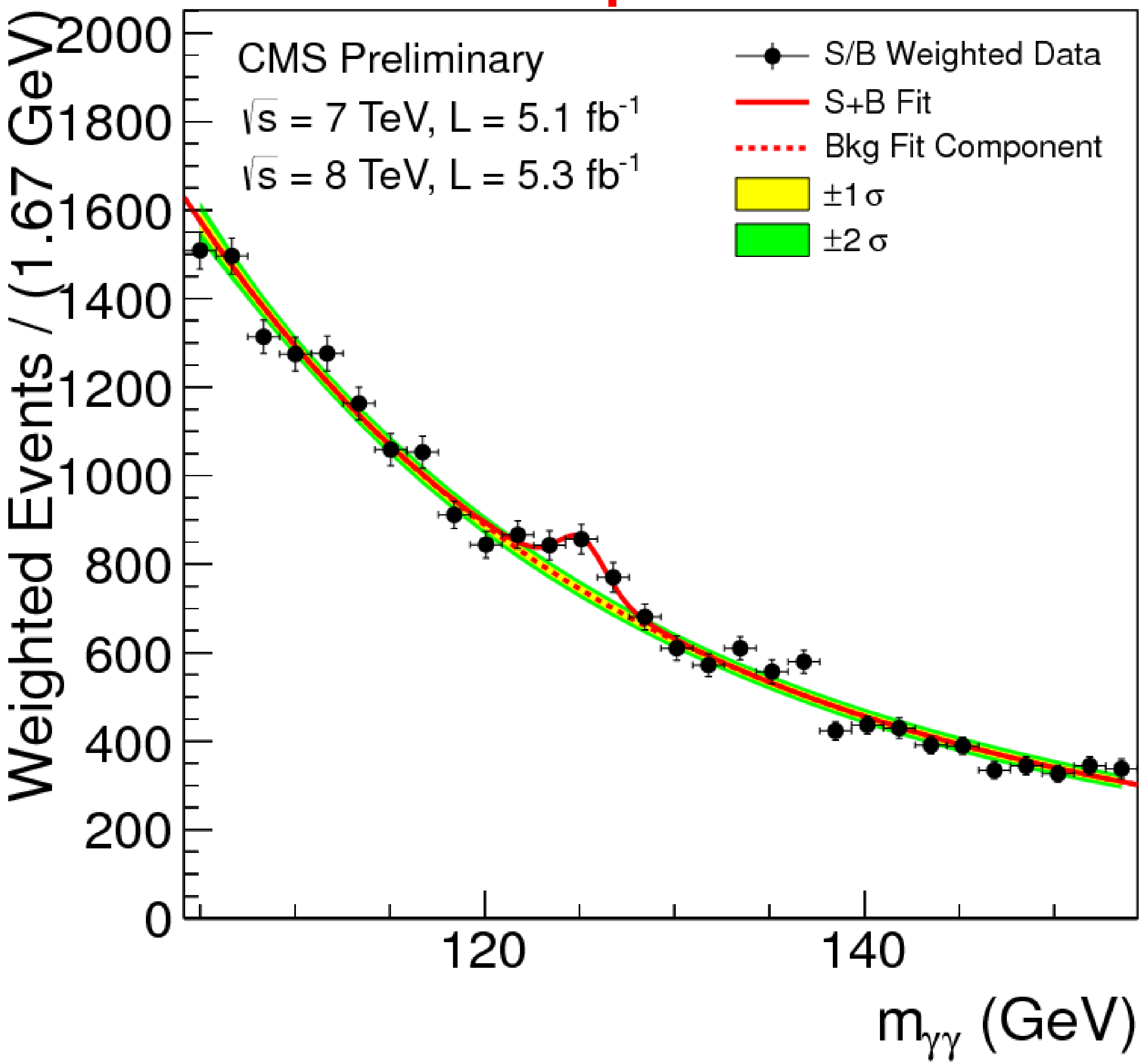
Diphoton analysis

- Select events with 2 photons:
  - Use MVA trained to reject fakes using observed shower-shape differences, isolation
  - Select pair with highest Σp_T
  - $p_T^{\gamma 1} > m_{\gamma\gamma}/3$; $p_T^{\gamma 2} > m_{\gamma\gamma}/4$
  - $|\eta| < 2.5$
- Use MVA to separate H signal from backgrounds
  - Inputs: photon p_T, η, and MVA output, $\cos\Delta\varphi_{\gamma\gamma}$, and per-event mass resolution
- Include VBF channel
  - 2 isolated γ + 2 forward jets
  - Large s/b, but small s
- Cross checks:
  - Mass fits with sidebands
  - Simple cut-based analysis



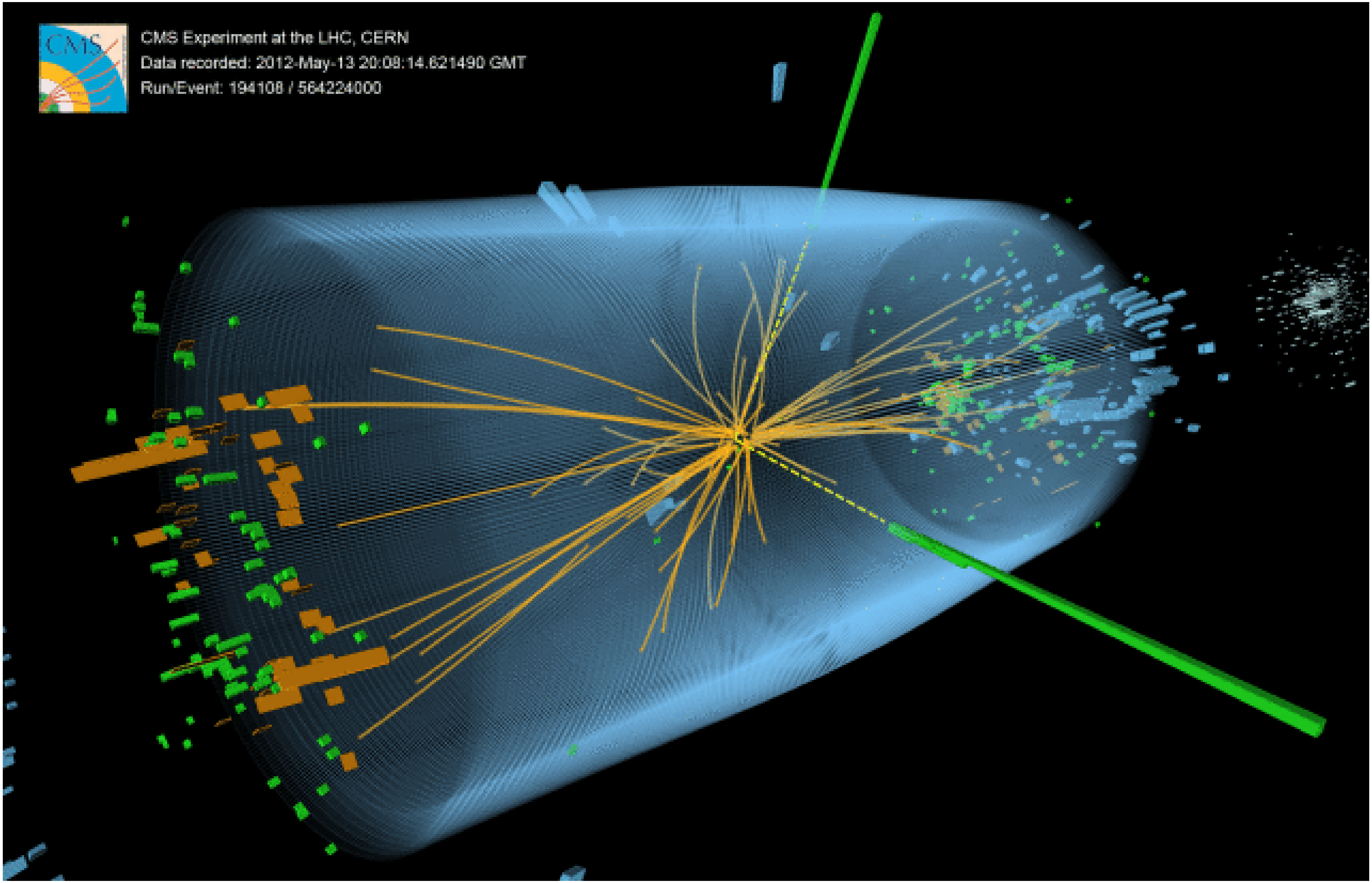


Diphoton results



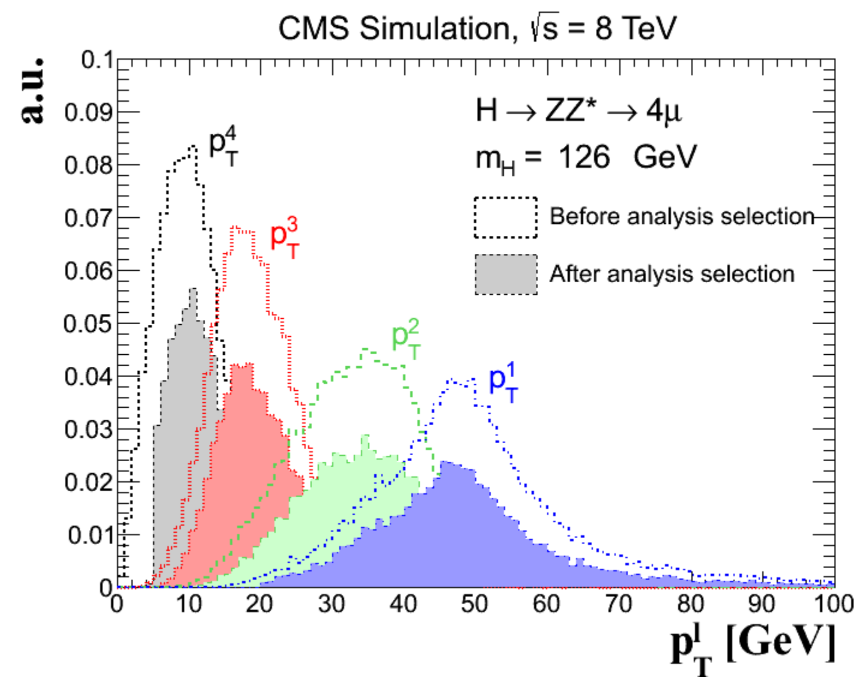
- Combination of 11 different categories
- Events are weighted by S/B
- Fit backgrounds to polynomials
- Clear "bump" seen over falling background
- Here the $m_{\gamma\gamma}$ resolution of ~ 2 GeV is crucial!

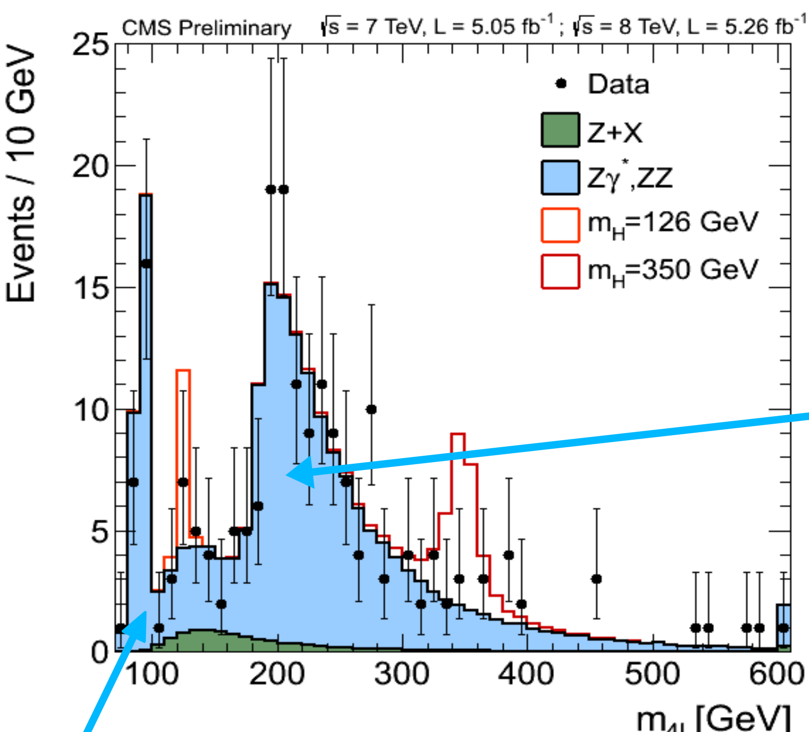
H → γγ candidate event

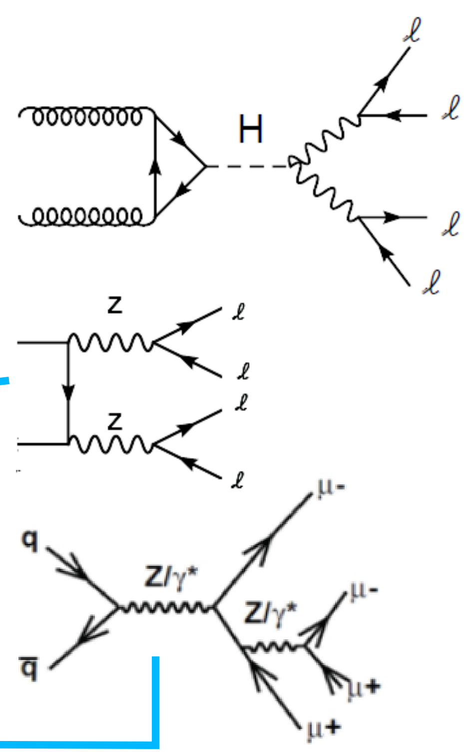


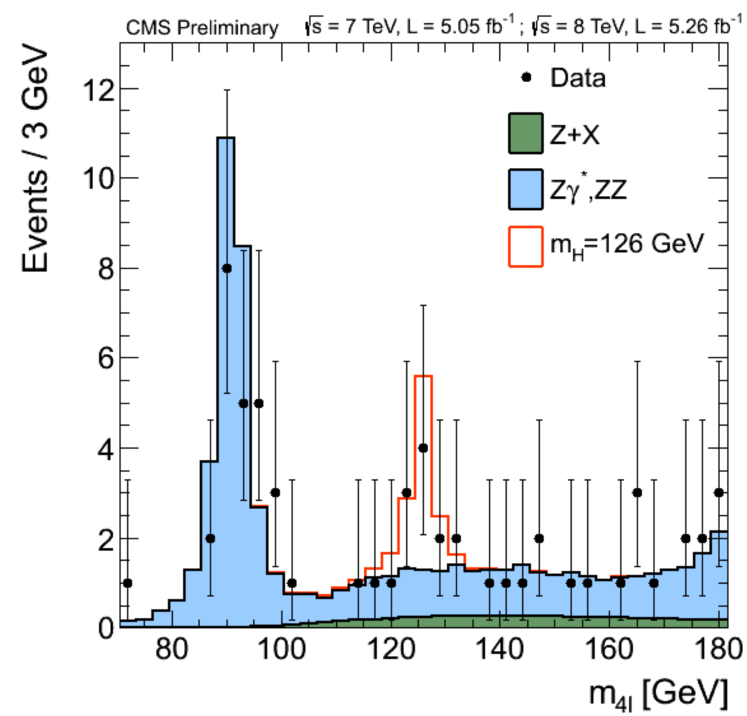
$H \rightarrow ZZ^* \rightarrow \ell\ell\ell\ell$

- Golden channel:
  - Very good mass resolution
  - Low (real) backgrounds
  - Need high efficiency: decay width ~ 0.06^2
  - Very small statistics
- Expect 164±11, observe 172 events in [70-800] GeV



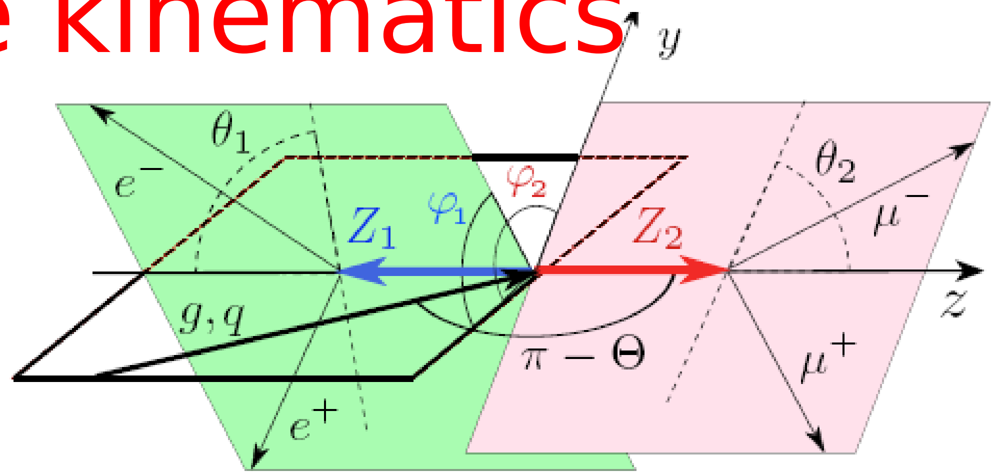


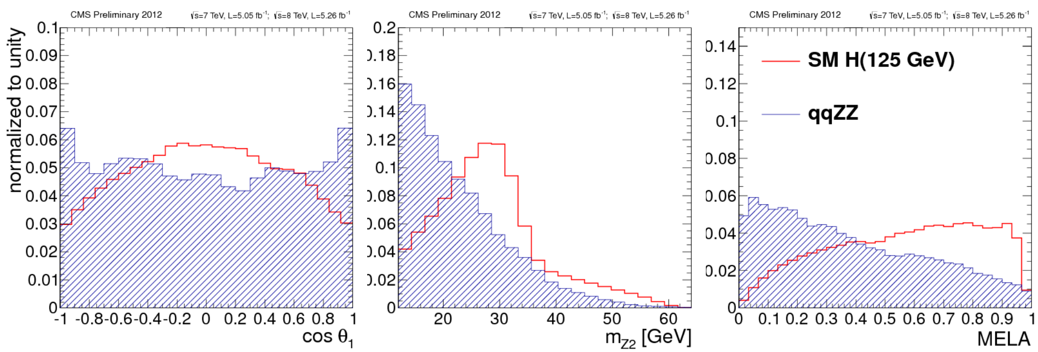


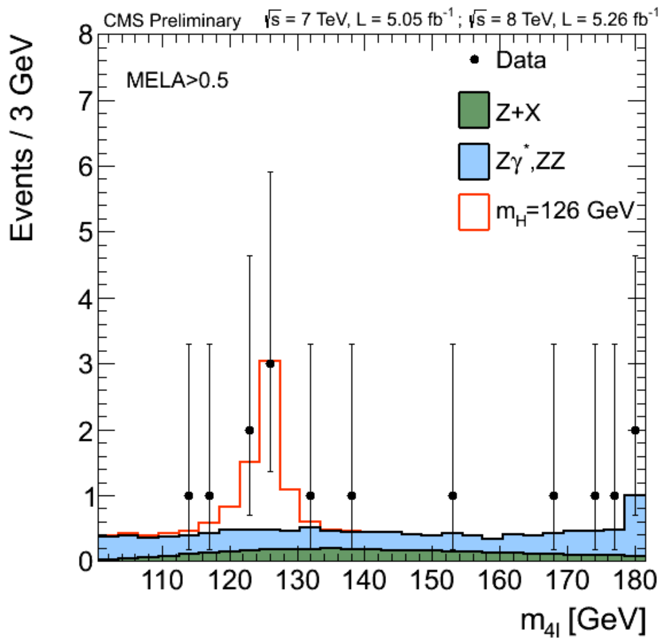


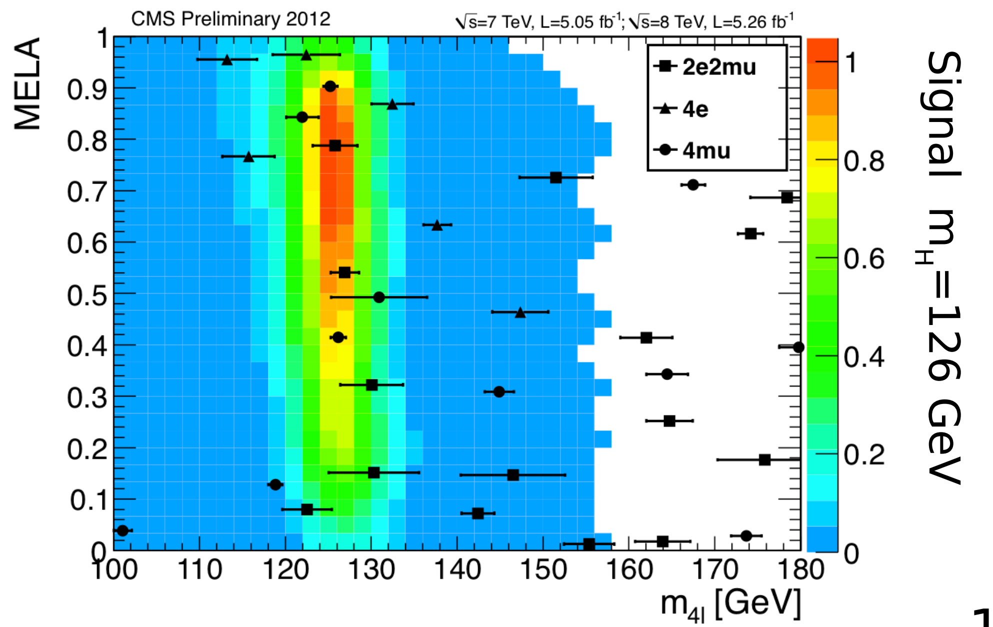
We can use kinematics

- MELA discriminant
  - Exploit decay of scalar X into two heavy Z bosons that then decay to two charged leptons
- Significant gain in S/B: most sensitive channel
- MELA is mostly insensitive to the spin of the H: relies on character of backgrounds
- MELA>0.5 consistent with S+B

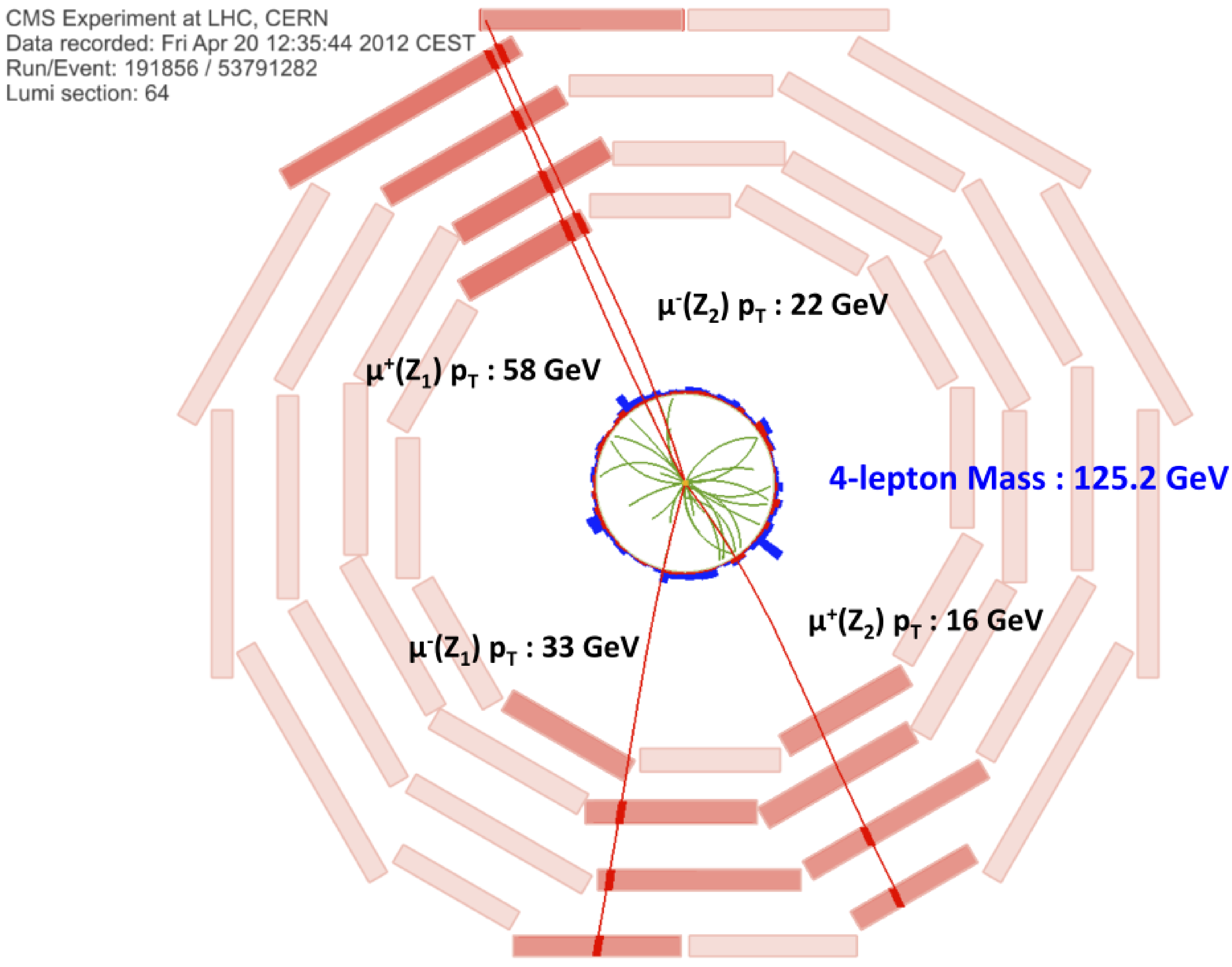




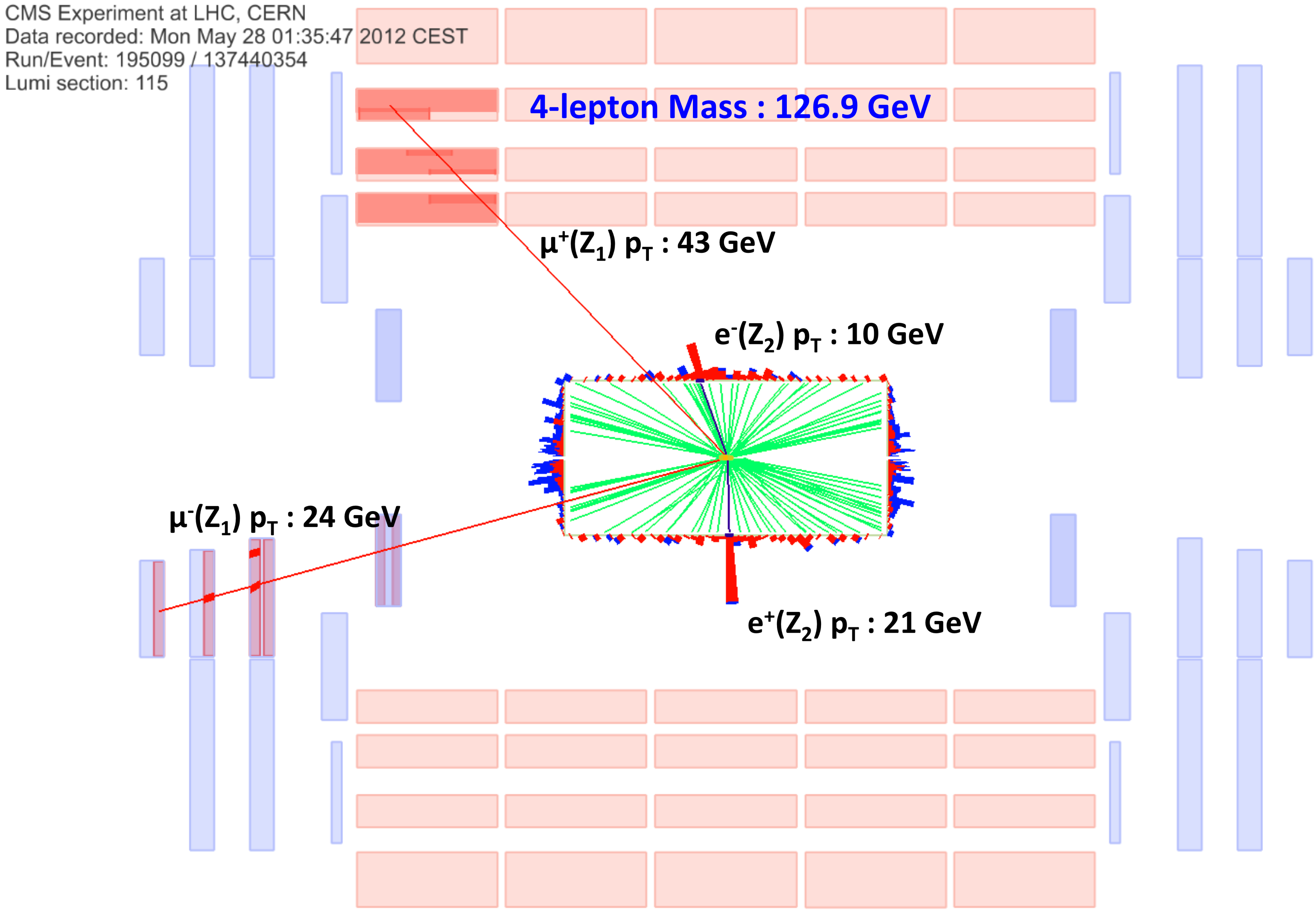




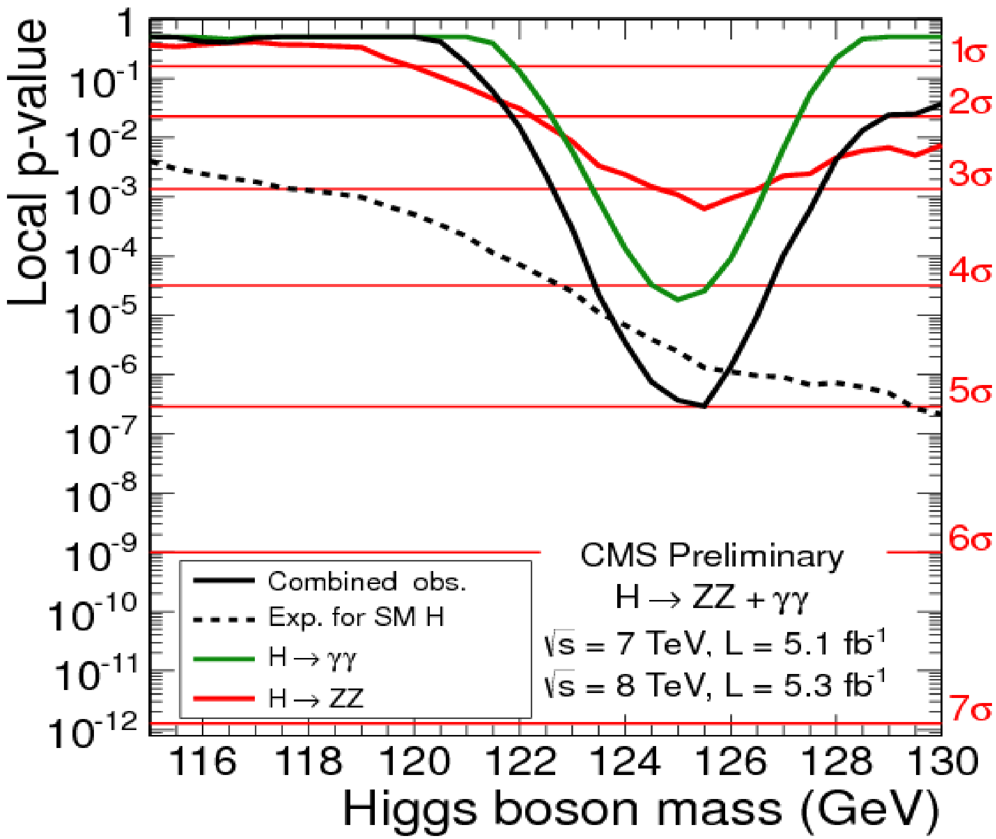
Candidate event $H \rightarrow ZZ^* \rightarrow \mu\mu\mu\mu$



Candidate event $H \to ZZ^* \to ee\mu\mu$



Combined significance



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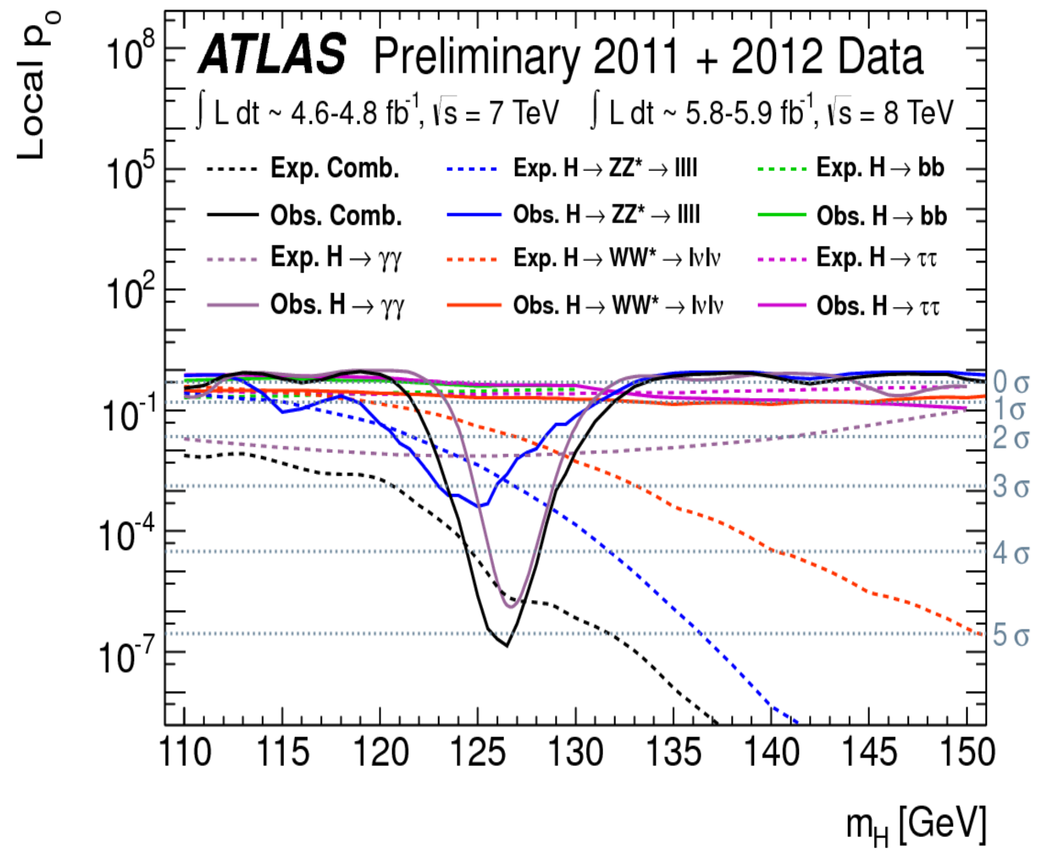
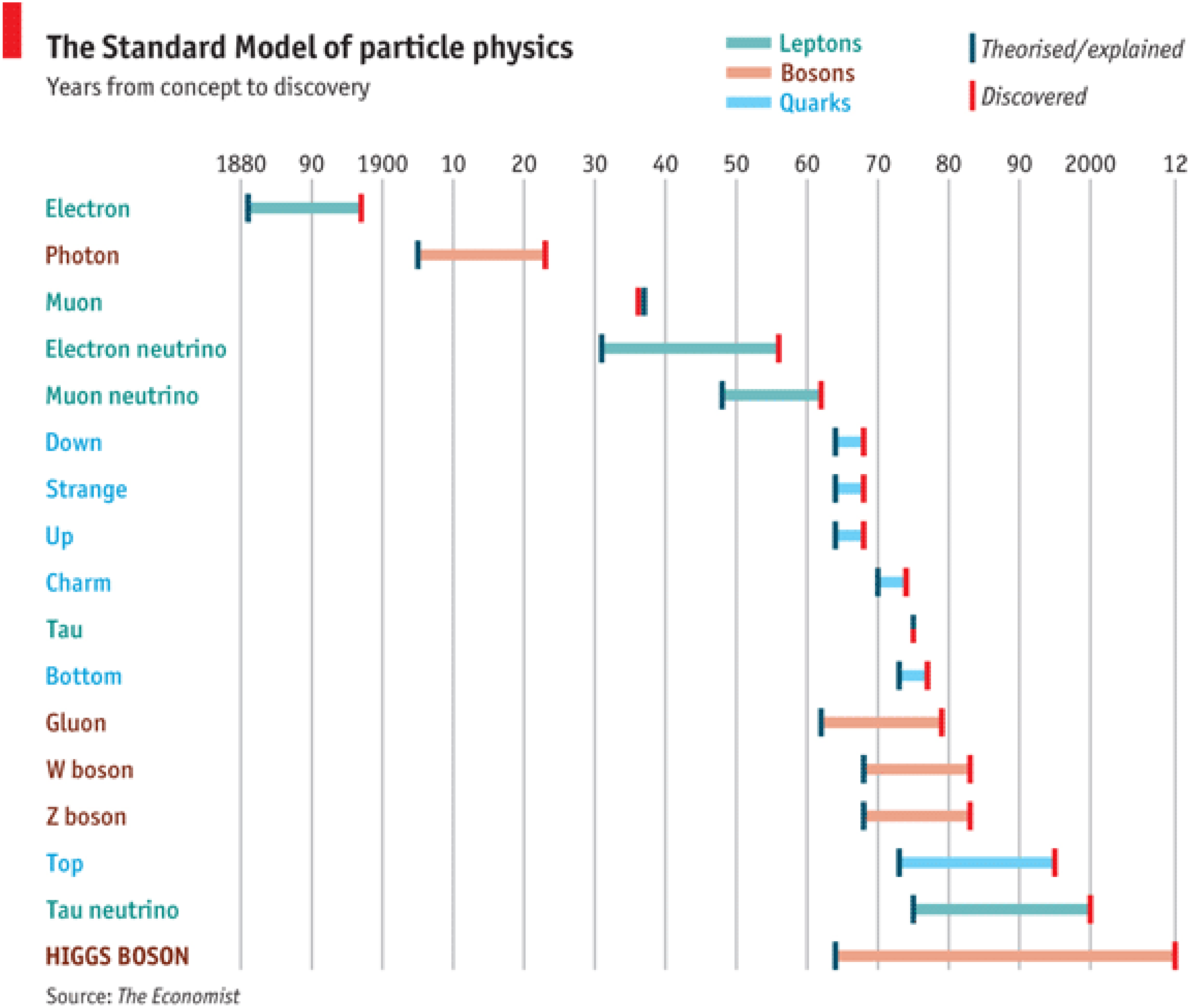


Phys. Lett. B 716 (2012) 1-29

- CMS expected: 4.7σ CMS observed: 5.0σ
  - 1 in $3.5 \cdot 10^6$ chance of a background fluctuation
  - m_H = 125.3 ± 0.4 (stat.) ± 0.5 (sys.) GeV
- ATLAS expected: 4.6σ ATLAS observed: 5.0σ
  - m_H = 126.0 ± 0.4 (stat.) ± 0.4 (sys.) GeV



The Standard Model of particle physics
Years from concept to discovery
Leptons
Bosons
Quarks
Theorised/explained
Discovered
1880
90
1900
10
20
30
40
50
60
70
80
90
2000
12
Electron
Photon
Muon
Electron neutrino
Muon neutrino
Down
Strange
Up
Charm
Tau
Bottom
Gluon
W boson
Z boson
Top
Tau neutrino
HIGGS BOSON
Source: The Economist

Conclusions

- Observation in CMS, and independently in ATLAS, of a new boson with a mass of roughly 125 GeV decaying to vector bosons
- It is certainly looking and walking like the SM scalar boson. Does it also quack like the SM Higgs boson?
- Some questions:
  - Are the relative signal strengths and couplings consistent? Maybe!
  - We know it's a boson, we also know it is not spin 1. Is it spin 0? Maybe!
  - If it is spin 0, is it a scalar or a pseudoscalar? Maybe!
  - Does it couple to fermions? Maybe!
  - Is the width accounted for in the accessible channels? Maybe!

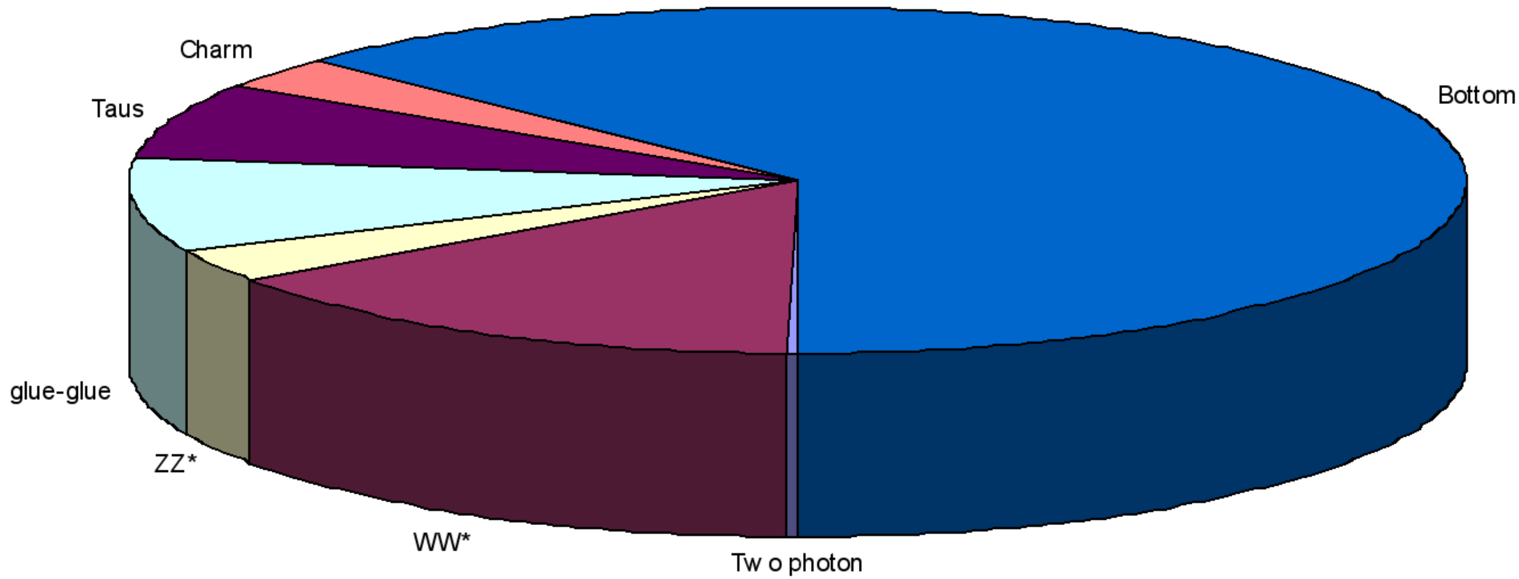
Lots of work still to do!

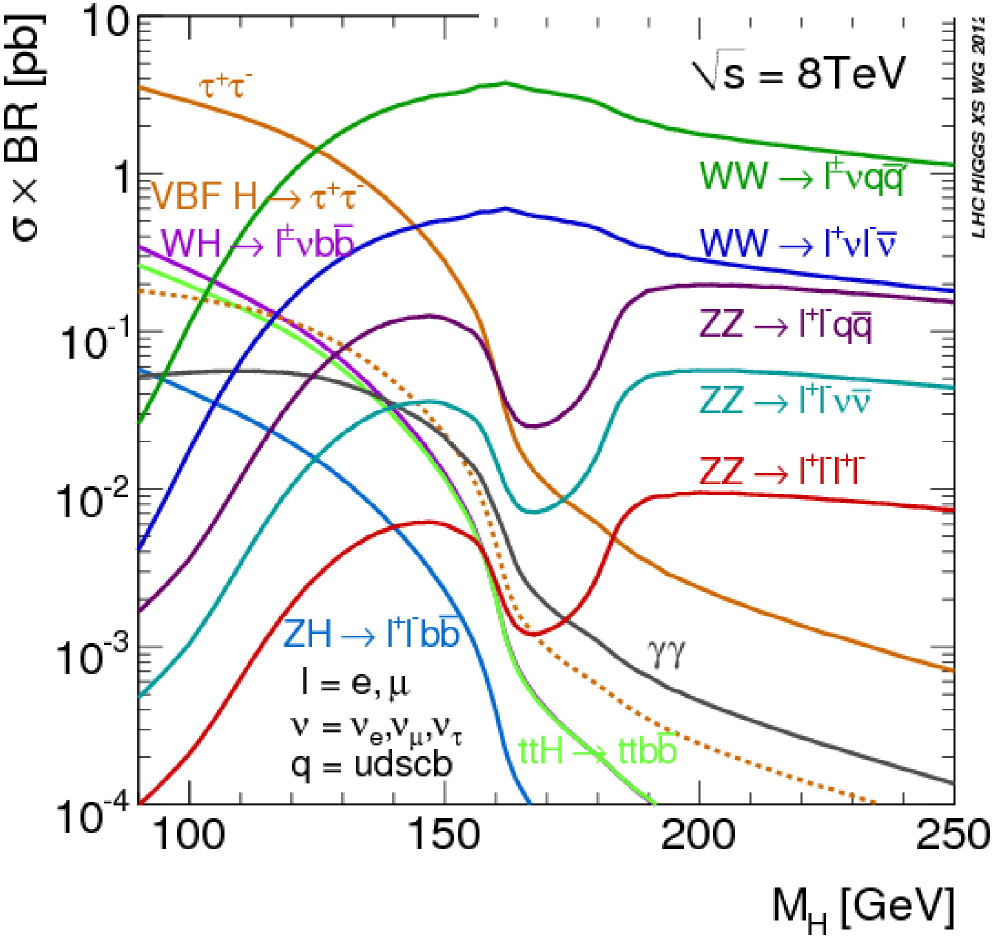
Extra slides

For more information:

http://cms.web.cern.ch/news/observation-new-particle-mass-125-gev

http://www.atlas.ch/news/2012/latest-results-from-higgs-search.html


Charm
Taus
Bottom
glue-glue
ZZ*
WW*
Tw o photon

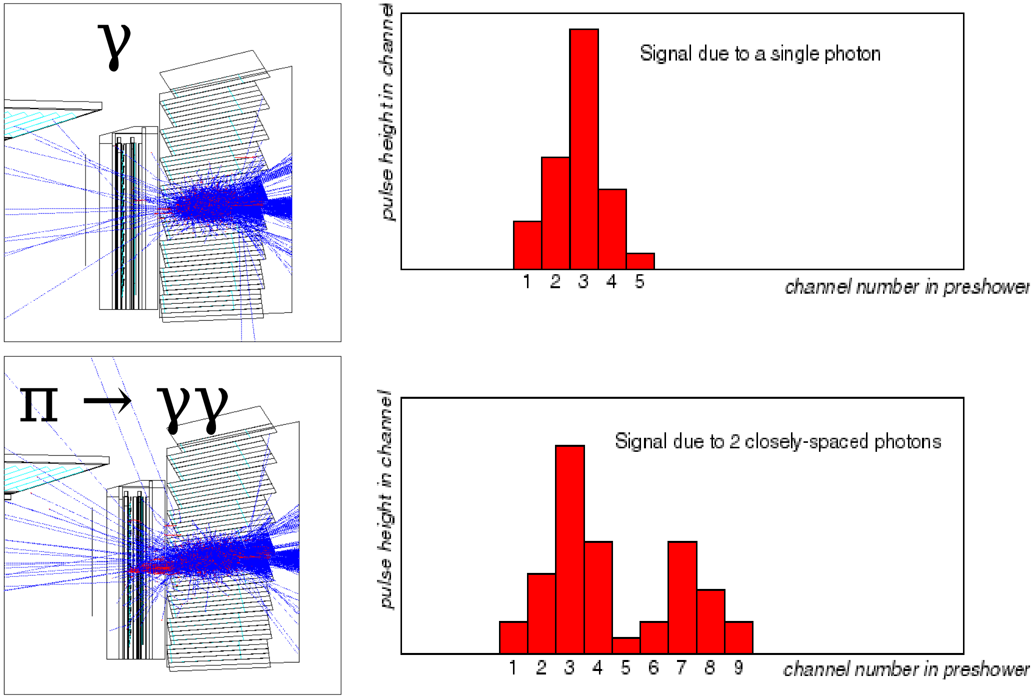

$\sigma \times$ BR [pb]
$\sqrt{s}$ = 8TeV
LHC HIGGS XS WG 2012
$\tau^+\tau^-$
VBF H $\to \tau^+\tau^-$
WH $\to l^\pm\nu b\bar{b}$
WW $\to l^\pm\nu q\bar{q}$
WW $\to l^+\nu l^-\bar{\nu}$
ZZ $\to l^+l^-q\bar{q}$
ZZ $\to l^+l^-\nu\bar{\nu}$
ZZ $\to l^+l^-l^+l^-$
ZH $\to l^+l^-b\bar{b}$
$\gamma\gamma$
l = e, μ
$\nu = \nu_e, \nu_\mu, \nu_\tau$
q = udscb
ttH $\to$ ttb$\bar{b}$
M_H [GeV]

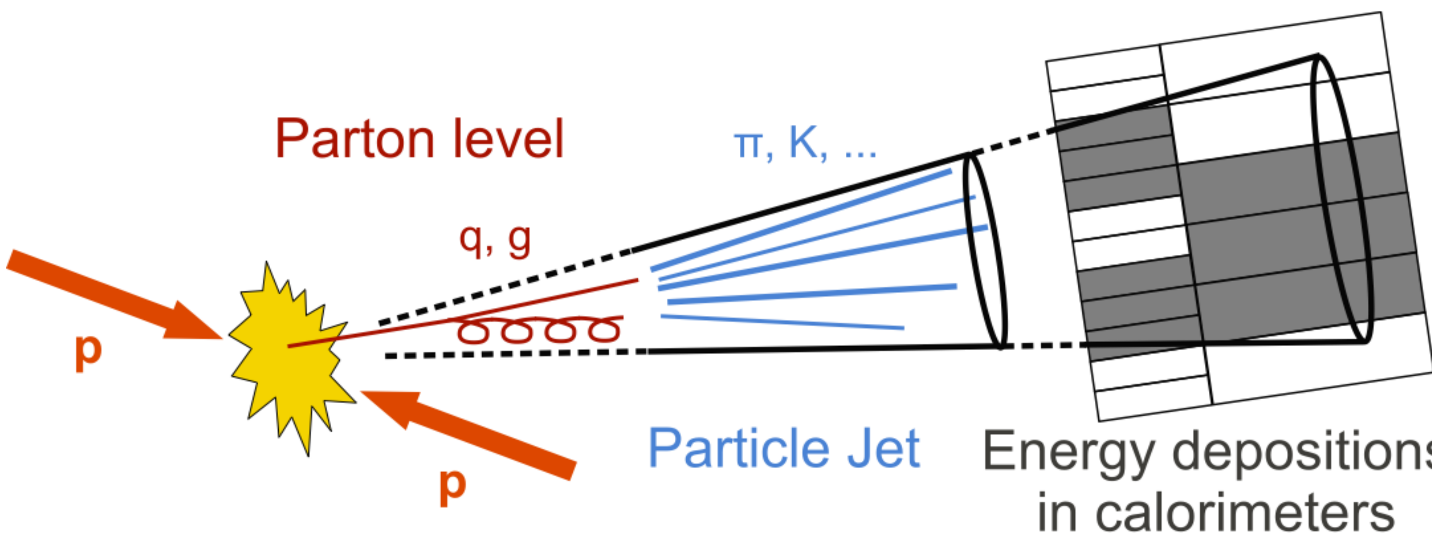
Higgs Decays

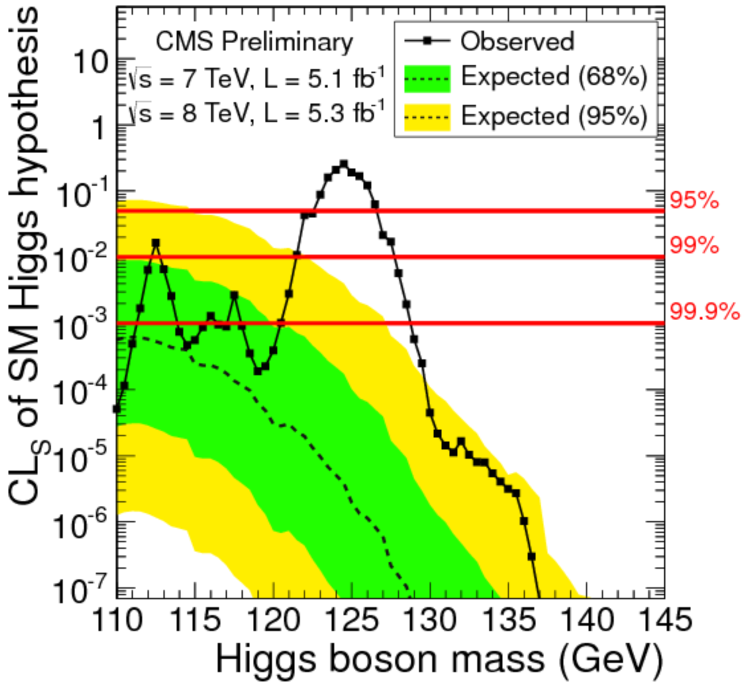
Decay Mode	Branching Fraction	Useful Branching fraction	Background Level
Bottom quarks	60%	30%	Tens of thousands:1
WW*	15%	~2%	Few:1
ZZ*	4%	0.014%	Comparable
gluons	10%	10%	Millions:1
taus	8%	6%	A long story
Charm quarks	6%	3%	Tens of thousands:1
Two photons	0.2%	0.2%	Few:1

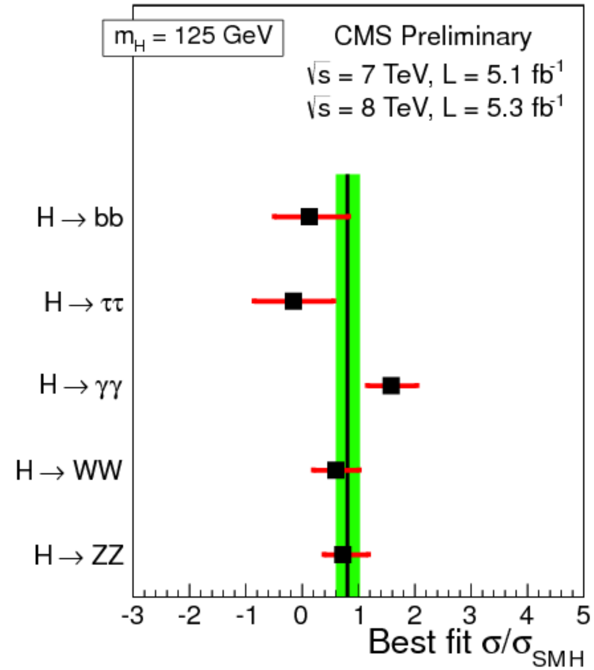
For a ~125 GeV Higgs

The quantity of signal is but one element in designing an analysis. The level of background is at least as important. While I will only barely touch on it, so is triggerability: you cannot analyze an event that you didn't record.


γ
π → γγ
pulse height in channel
Signal due to a single photon
1 2 3 4 5
channel number in preshower
pulse height in channel
Signal due to 2 closely-spaced photons
1 2 3 4 5 6 7 8 9
channel number in preshower


Parton level
π, K, ...
q, g
p
p
Particle Jet
Energy depositions
in calorimeters





Ratio of WW and ZZ couplings:
Both dominated by gluon fusion production
Ratio of signal strengths is therefore dominantly the ratio of couplings to W/Z
Separate fit to WW and ZZ with
M_H = 125.3 ± 0.6 GeV