Discovery of a (possible) Higgs Boson at the LHC

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Statement by CERN DG on 7/4

Global Effort → Global Success

Results today only possible due to extraordinary performance of accelerators – experiments – Grid computing

Observation of a new particle consistent with a Higgs Boson (but which one…?)

Historic Milestone but only the beginning

Global Implications for the future

R-D Heuer

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What’ he talking about?

Obse

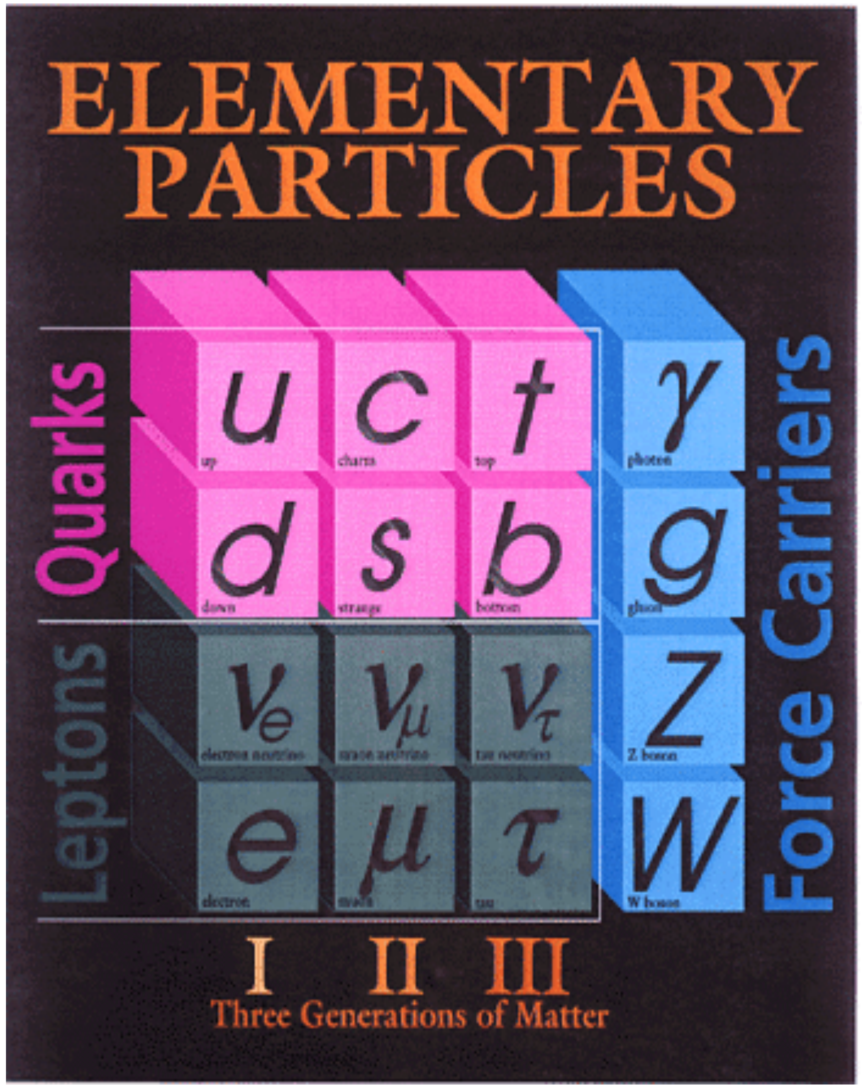
a Higgs Boson (but which one…?)

Historic Milestone but only the beginning

Global Implications for the future

R-D Heuer

Why do we need the Higgs Boson?



Isn't this good enough?

Go back 100+ years . . .

$$\nabla \cdot \vec{E} = \rho / \varepsilon_0$$

$$\nabla \cdot \vec{B} = 0$$

$$\nabla \times \vec{E} = -\frac{d\vec{B}}{dt}$$

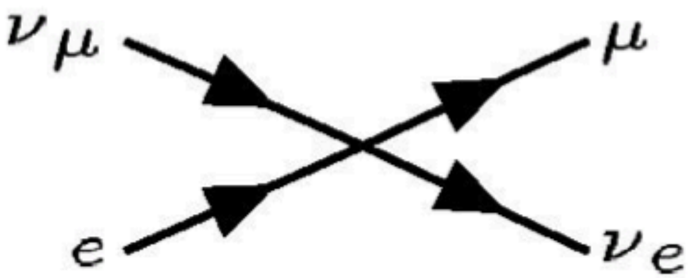
$$\nabla \times \vec{B} = \mu_0 \vec{j} + \varepsilon_0 \mu_0 \frac{d\vec{E}}{dt}$$

$$\vec{F} = q\left(\vec{E} + \vec{v} \times \vec{B}\right)$$

Isn't this good enough?

Nonsensical predictions, and solutions

Fermi theory of the 1930's

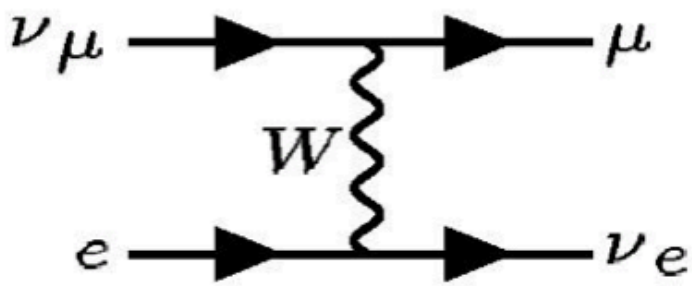


This process violates unitarity at high energies

What do we do?

Modify the diagram to cancel the divergence

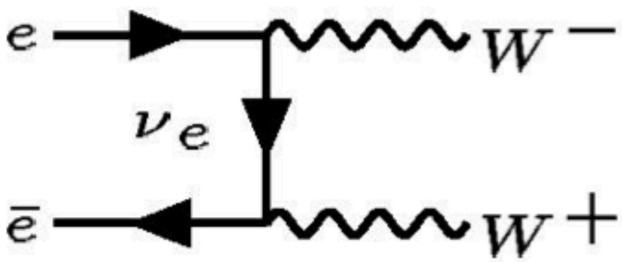
The *Glashow-Weinberg-Salaam* theory



the W boson

(observed at CERN in 1983)

Nonsensical predictions, and solutions cont.



But now this process violates unitarity at high energies!

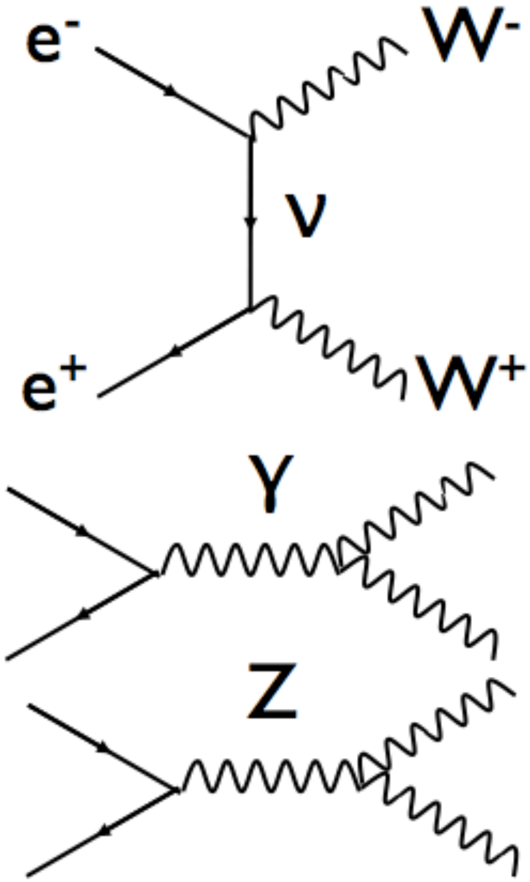
What do we do?

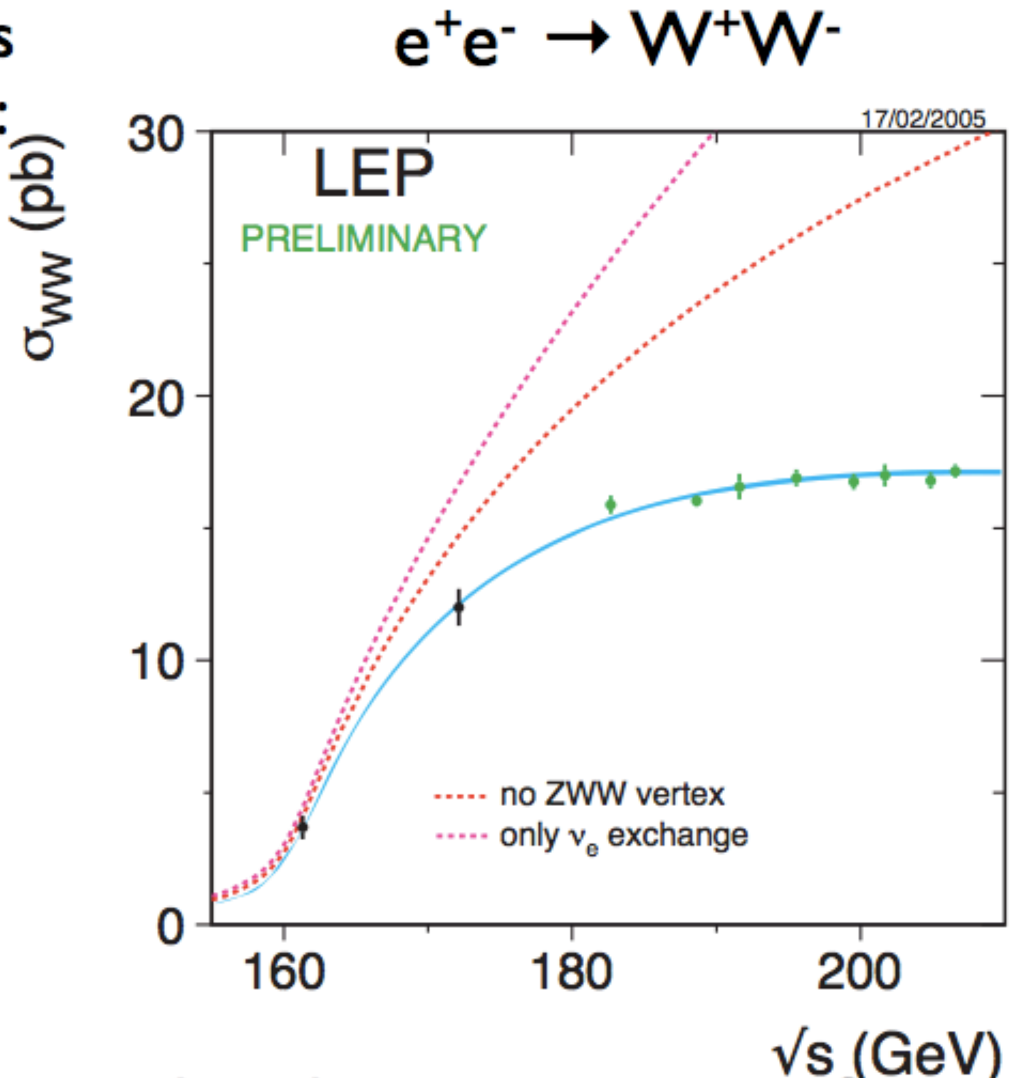
Introduce another diagram that cancels the divergence

the Z boson

(also observed at CERN in 1983)

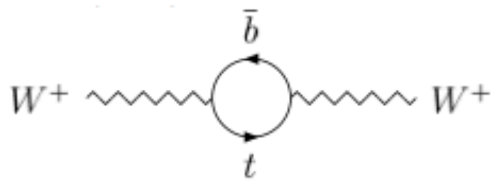
- Each of these diagrams leads to a divergent cross section:

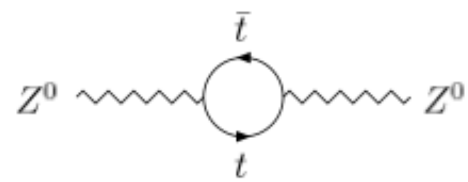




- But when all three are taken together, the cross section is finite.

- W and Z masses both have quantum corrections from top-quark interactions:



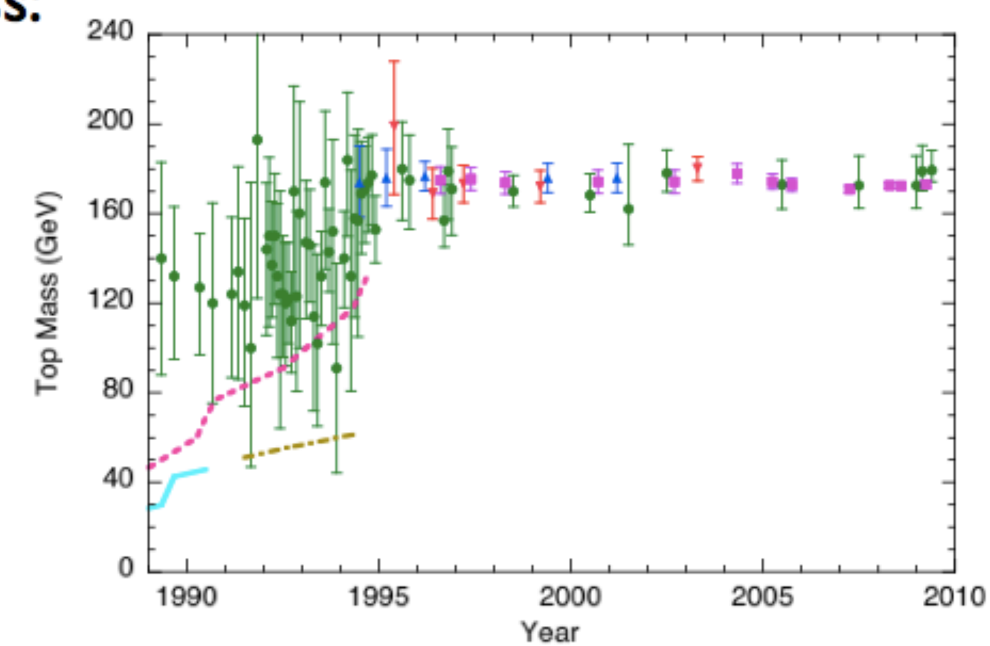


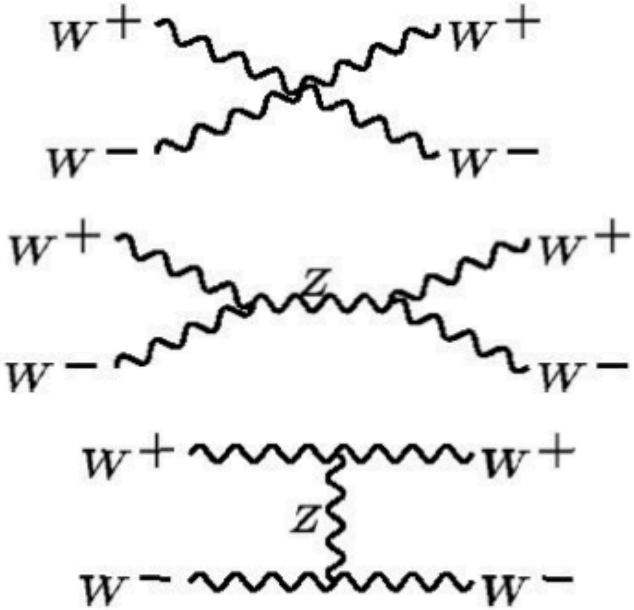
- As a result, measurements of the W and Z masses give an estimate of the top-quark mass:

$$M_W^2 = M_Z^2 \left(1 - \sin^2\theta_{\mathrm{W}}\right)(1 + \Delta\rho) \ ,$$

where

$$\Delta\rho \approx \Delta\rho^{(\mathrm{quarks})} = \frac{3G_{\mathrm{F}} m_t^2}{8\pi^2\sqrt{2}} \ .$$

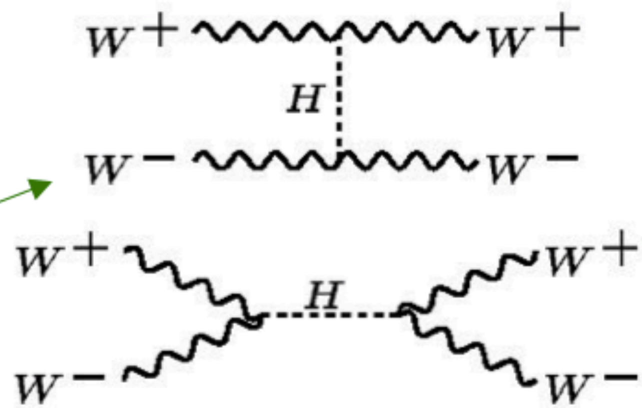




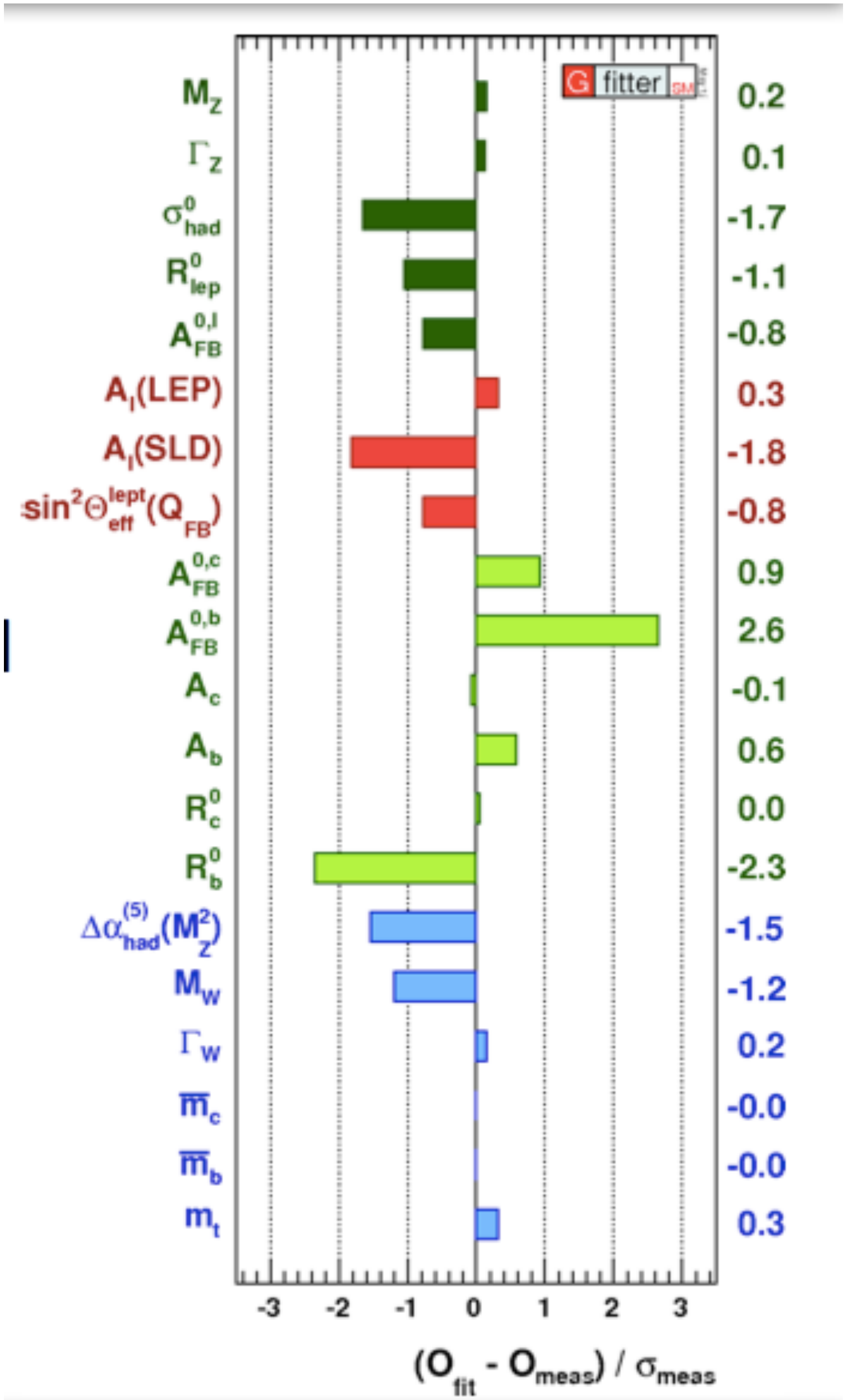
But now *these* processes violate unitarity at high energies!

What do we do?

Introduce *other* diagrams to cancel the divergence



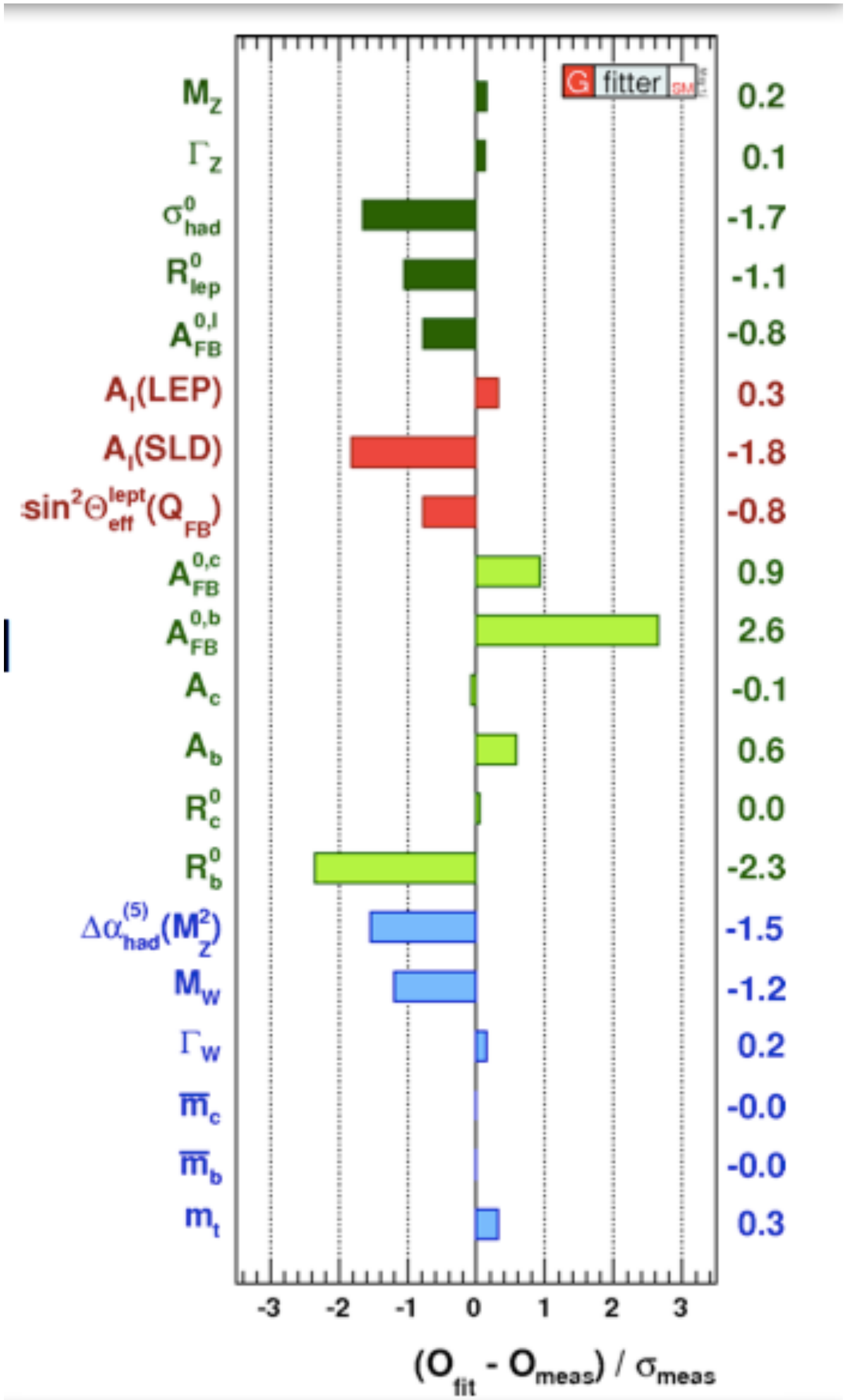
the Higgs boson



These are high precision Electro-Weak measurements.

They give you the top mass.

If you already know the top mass, then…



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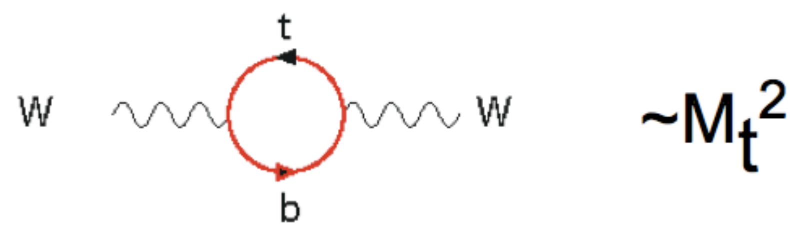
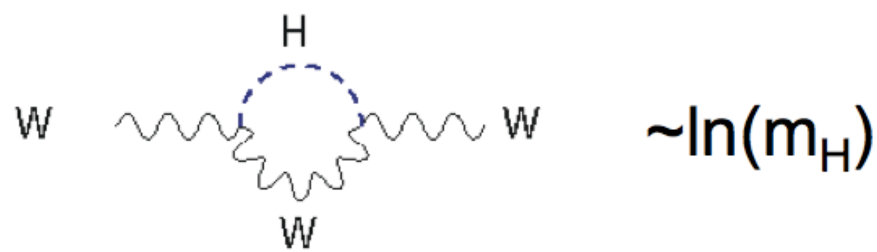
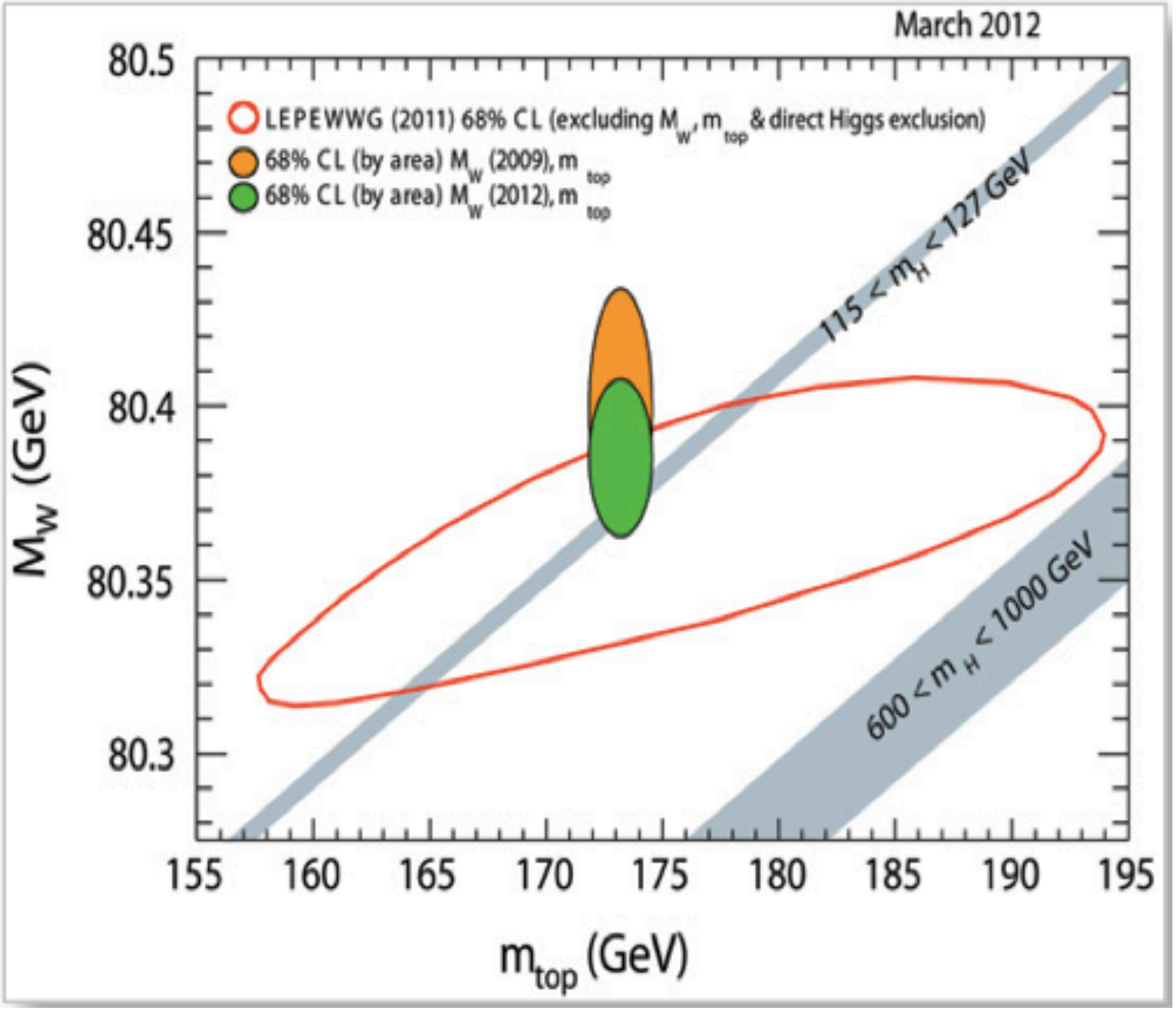
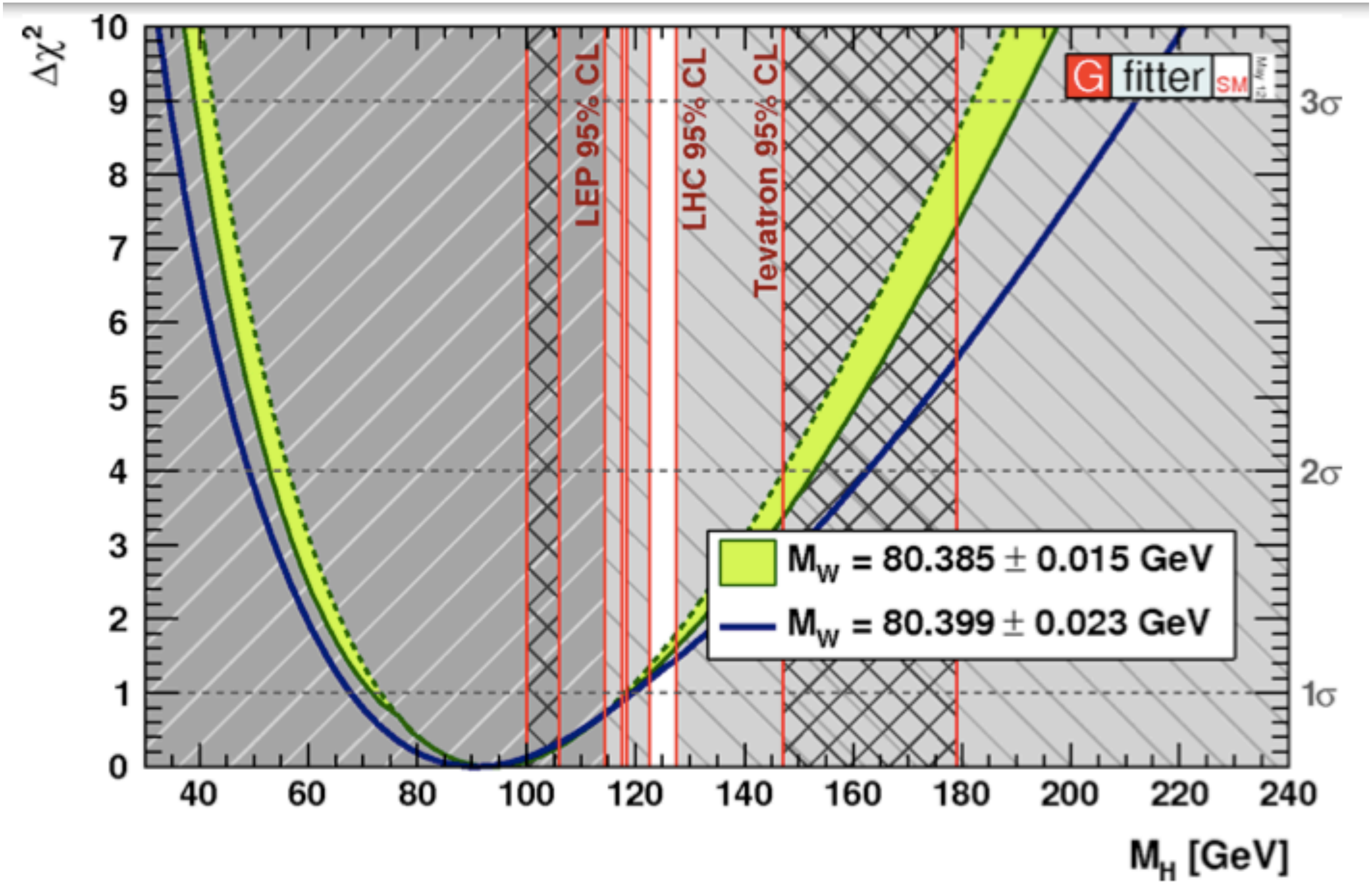




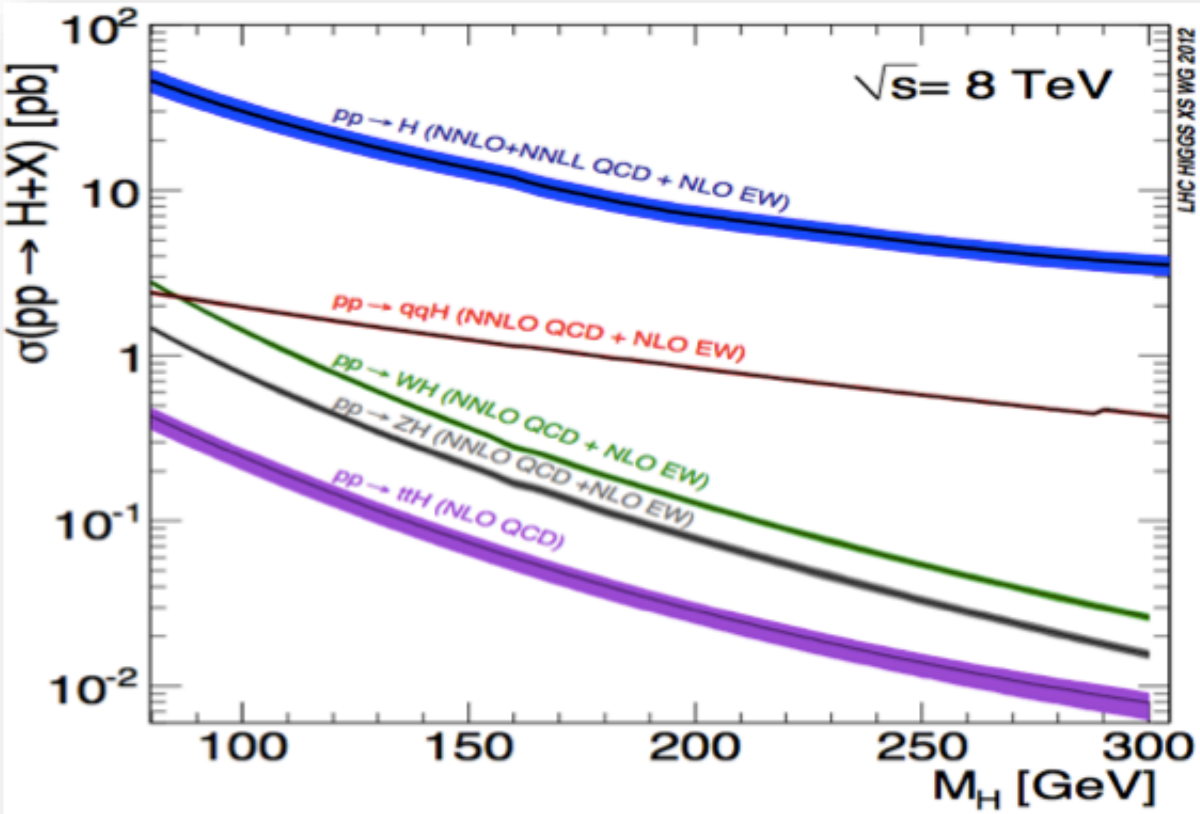


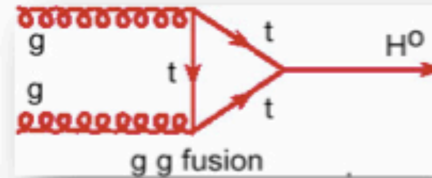
March 2012
LEPEWWG (2011) 68% CL (excluding M_W, m_{top} & direct Higgs exclusion)
68% CL (by area) M_W (2009), m_{top}
68% CL (by area) M_W (2012), m_{top}
$115 < m_H < 127$ GeV
$600 < m_H < 1000$ GeV
80.5
80.45
80.4
80.35
80.3
M_W (GeV)
155
160
165
170
175
180
185
190
195
m_{top} (GeV)

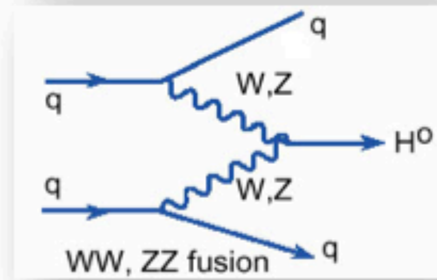


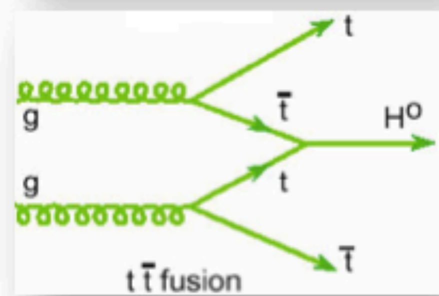
Precision Electro-Weak gives nice "window" on the Higgs Mass.

Higgs Production







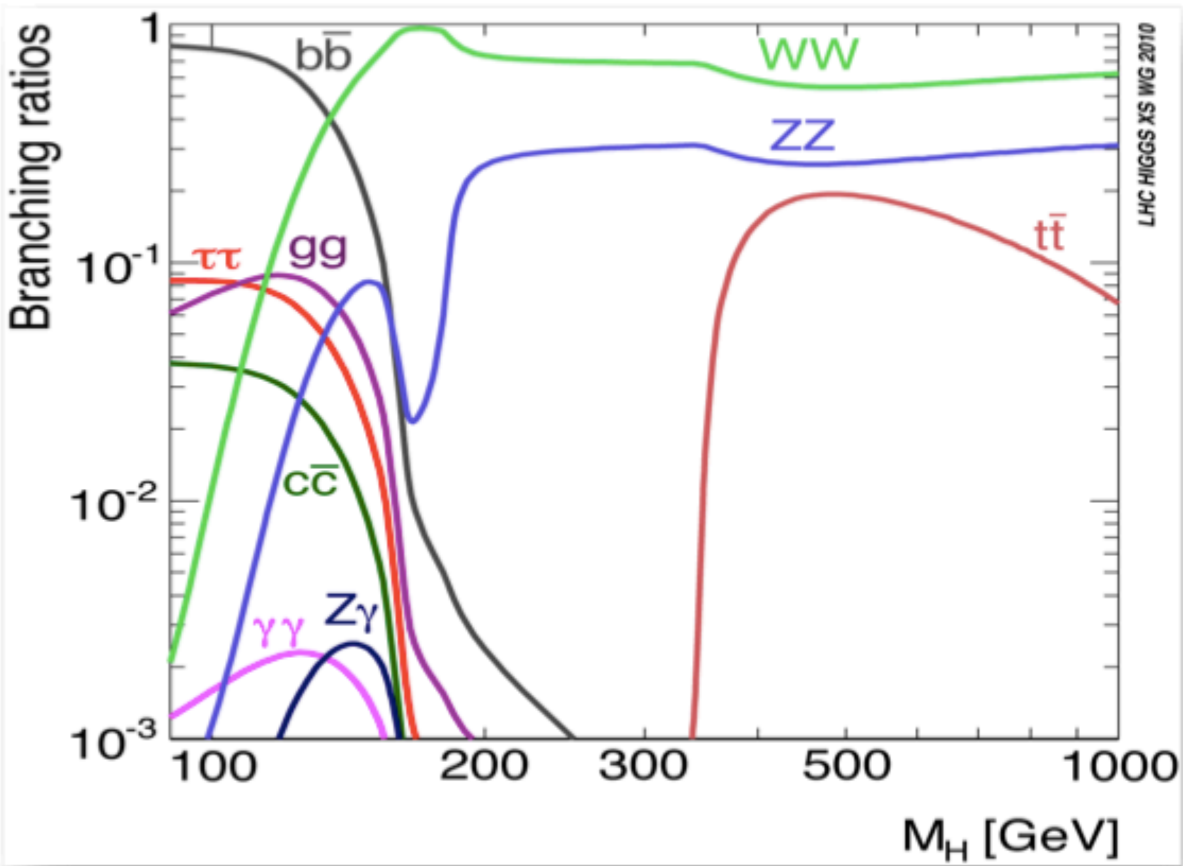


Cross section at 8 TeV is 25-30% higher than at 7 TeV -- 2012 run was crucial

Higgs Decay

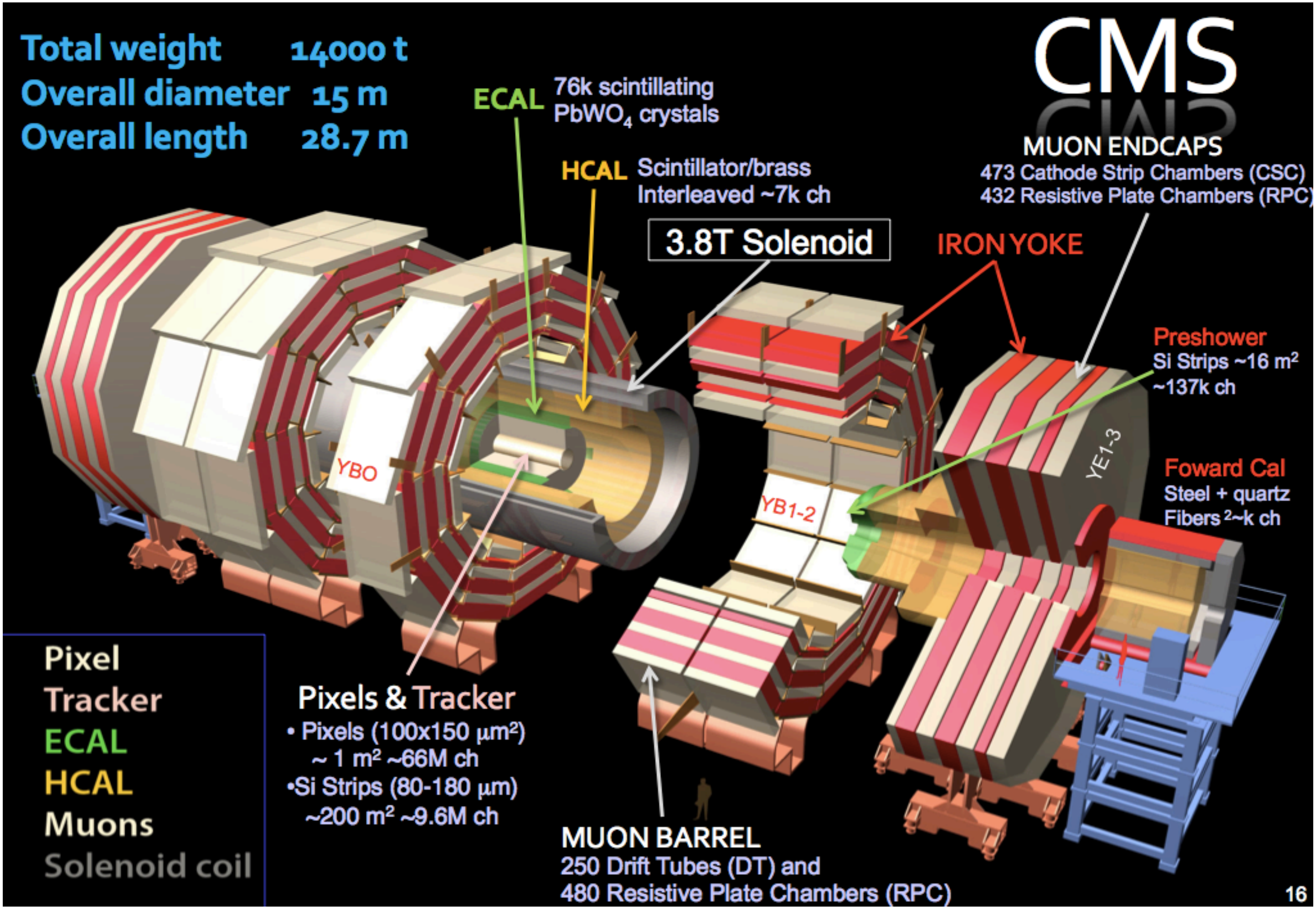
- Since Higgs is really about mass, the Higgs decays to the heaviest particles kinematically accessible to it
  - To good approximation, bb for light Higgs and WW for heavy Higgs
  - A 125 GeV Higgs happens to have a nice variety of decay modes

logarithmic scale!



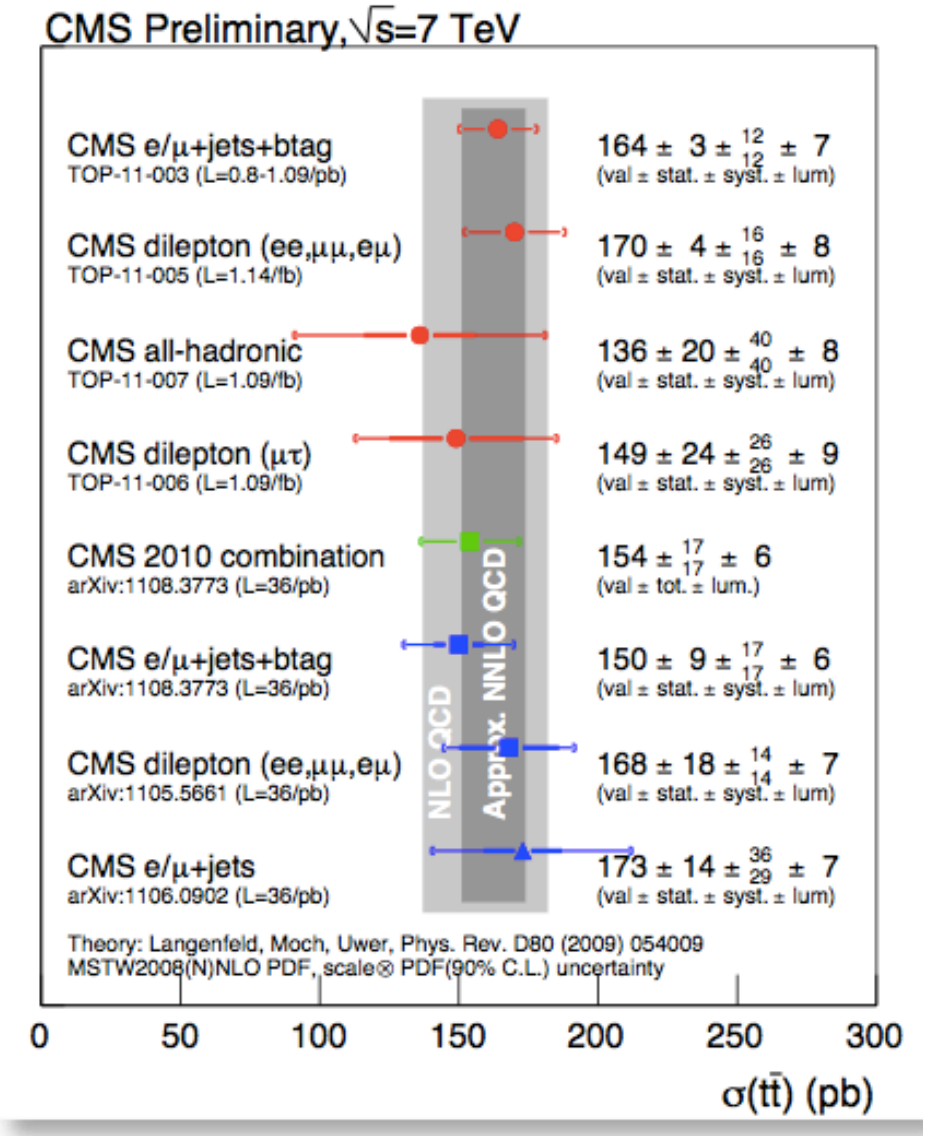
Higgs hunting strategy

- Look in all possible decay modes:
  - $\gamma\gamma$: Less than 1% BR, but very clean and excellent mass resolution at CMS. Look for a bump in diphoton mass spectrum.
  - ZZ: Small BR at low mass, but also excellent mass resolution. But Z to leptons BR is ~3%, so need very high detection efficiency.
  - bb: Largest BR at low mass, but huge dijet background. Need something else in the event, e.g. VH, ttH. So-so mass resolution.
  - WW: Good BR and low background. Poor mass resolution because of neutrinos in W to leptons decay.
  - $\tau\tau$: Few % BR, big background from Z, so-so mass resolution.
- Important: to say that we see a SM Higgs, need to observe the right branching fractions to all of these final states.



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
YE1-3
YB0
YB1-2
Foward Cal
Steel + quartz Fibers 2~k ch
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)
16

Can we measure Standard Model stuff well?



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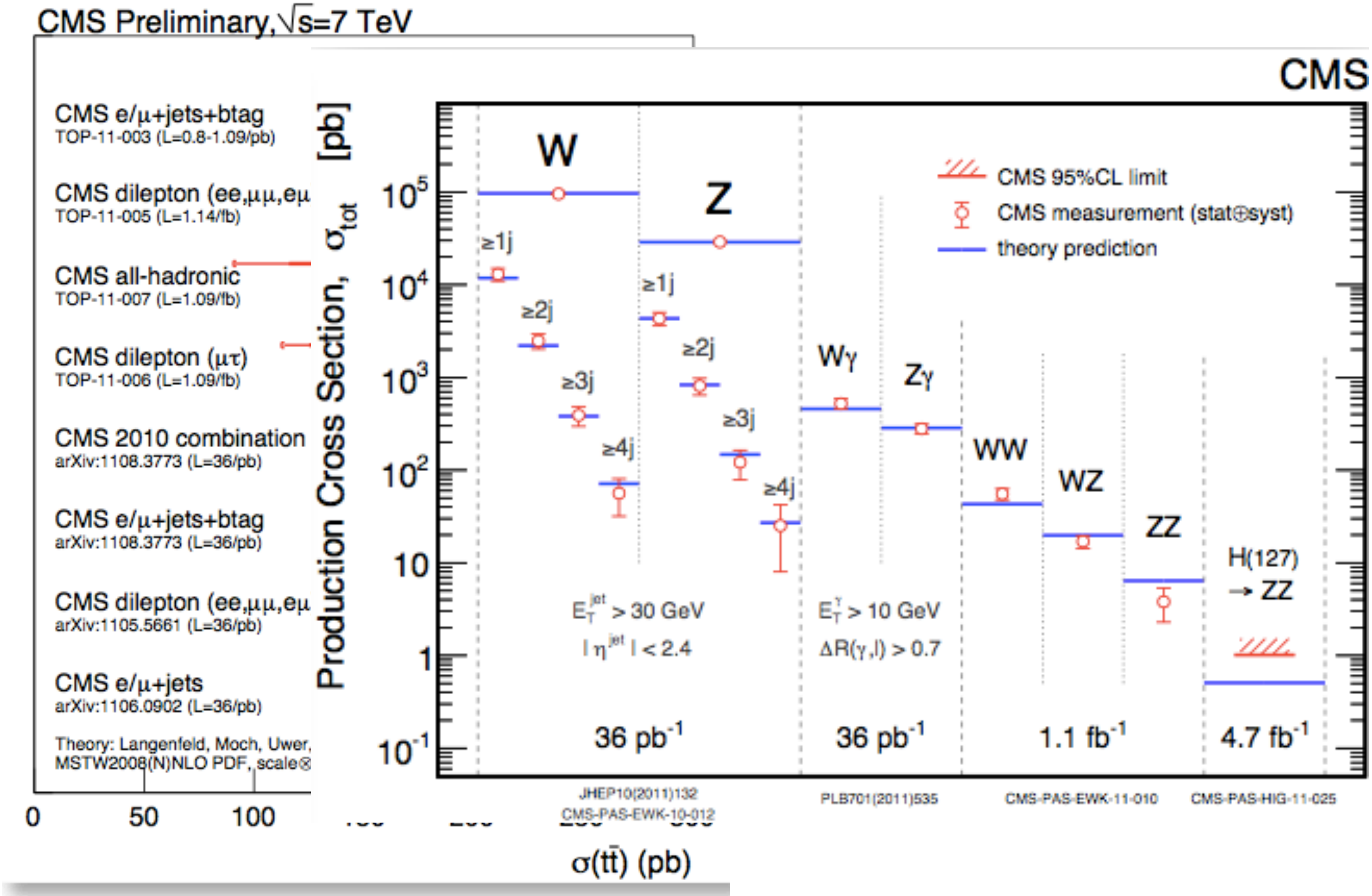

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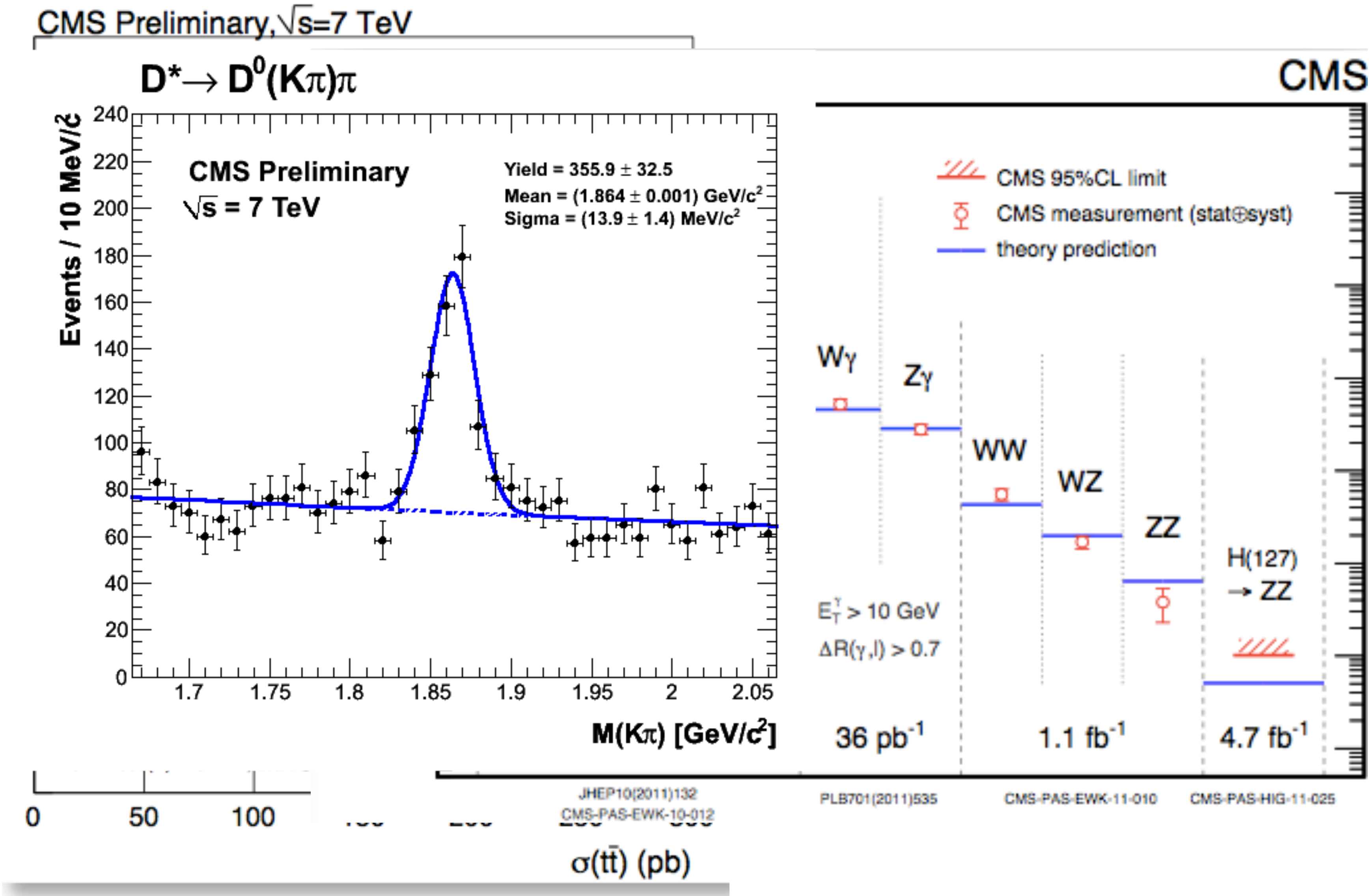

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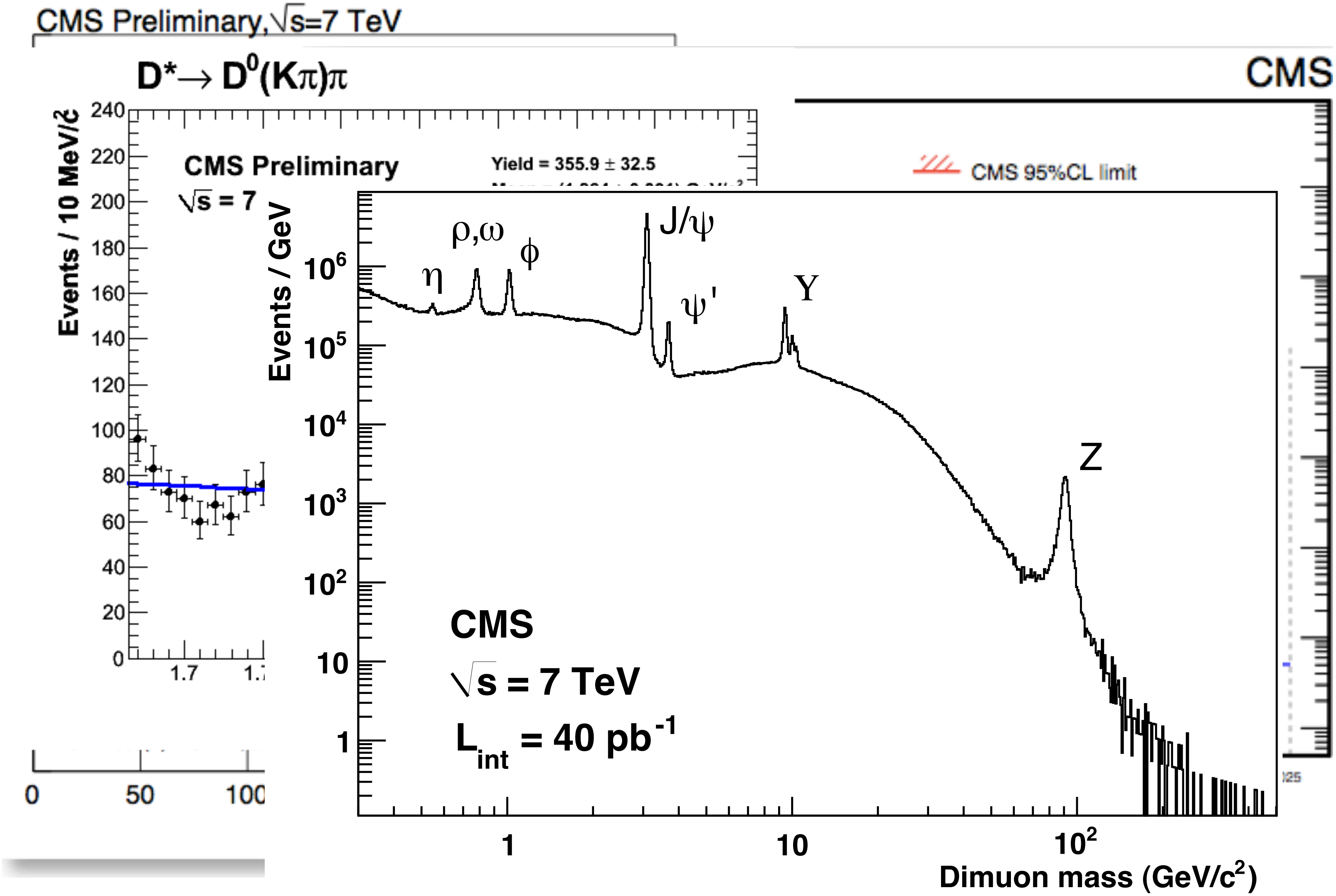

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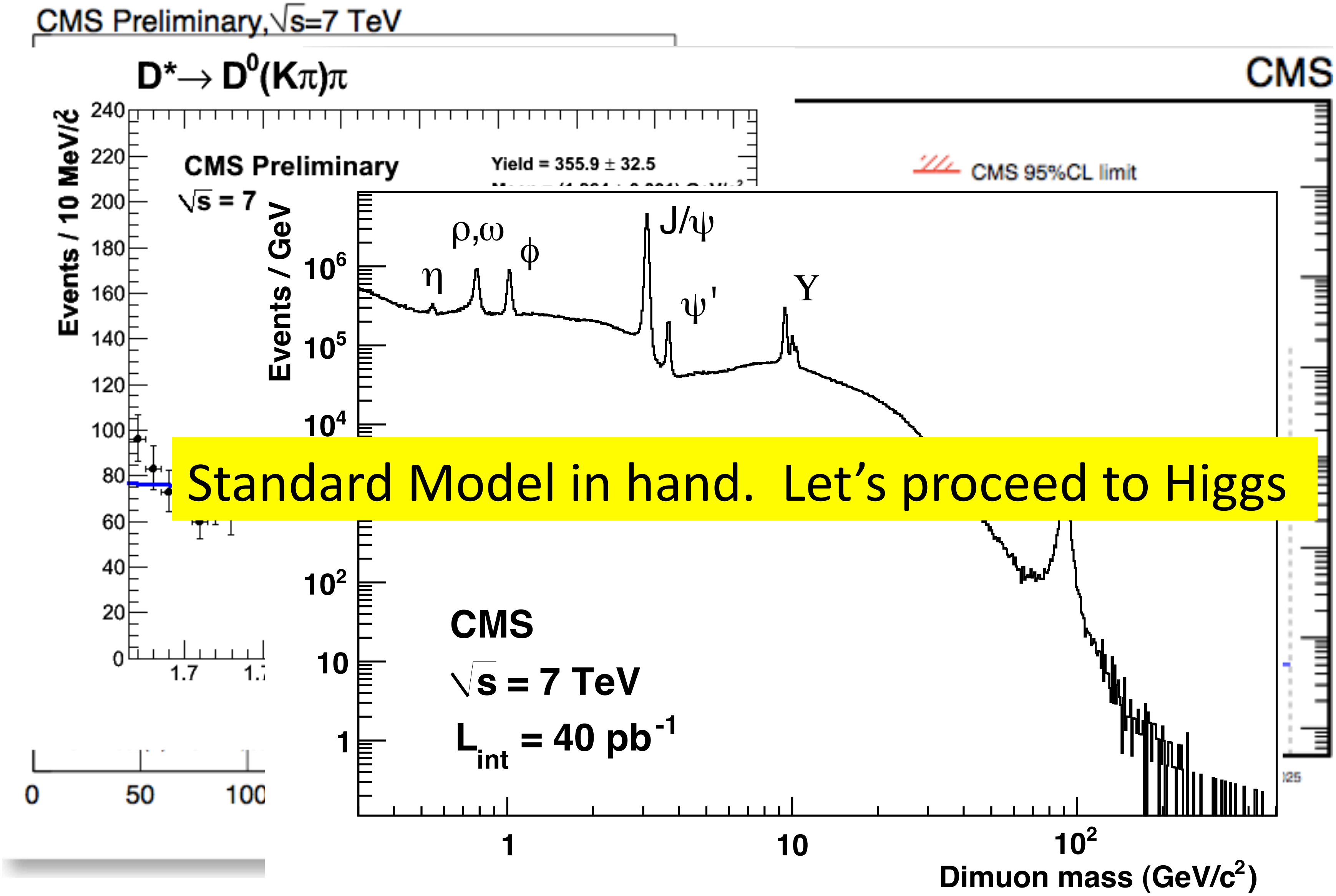
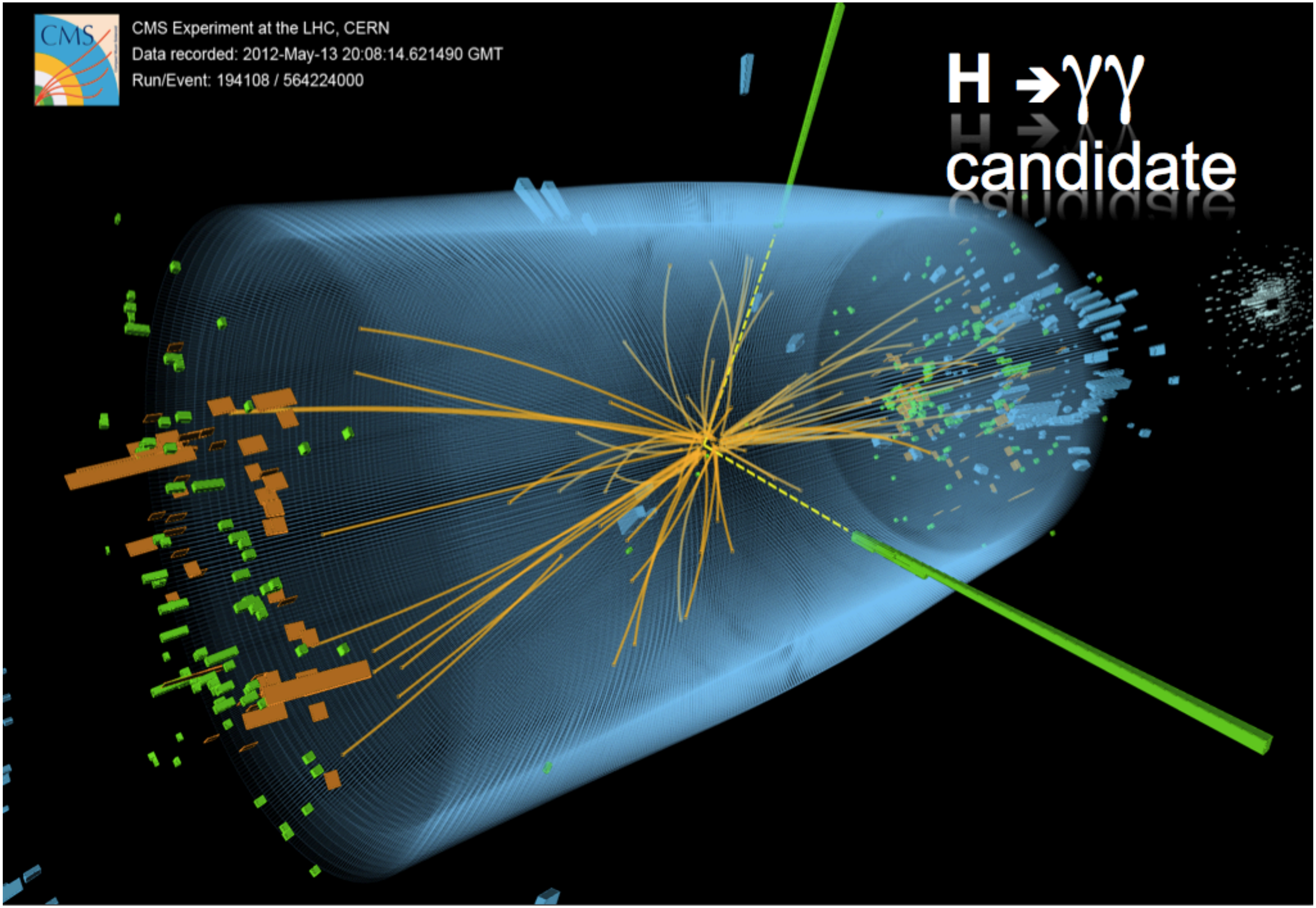
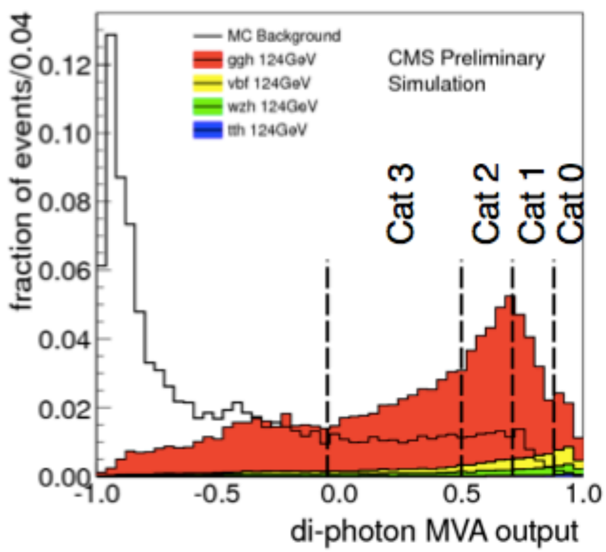


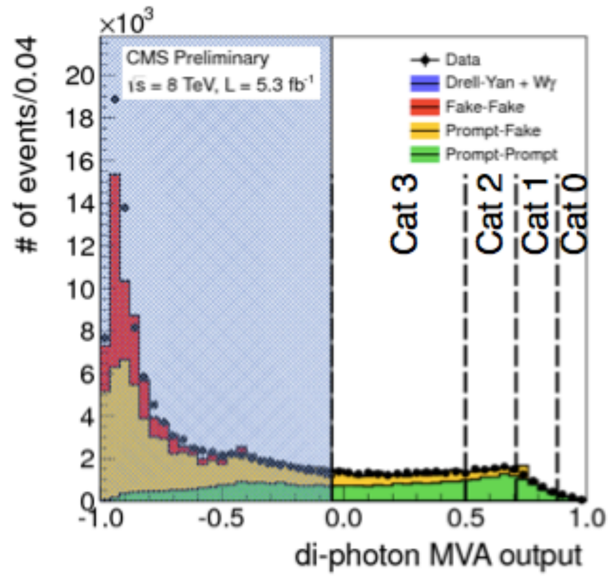
Standard Model in hand. Let's proceed to Higgs


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

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 $m_{\gamma\gamma}$



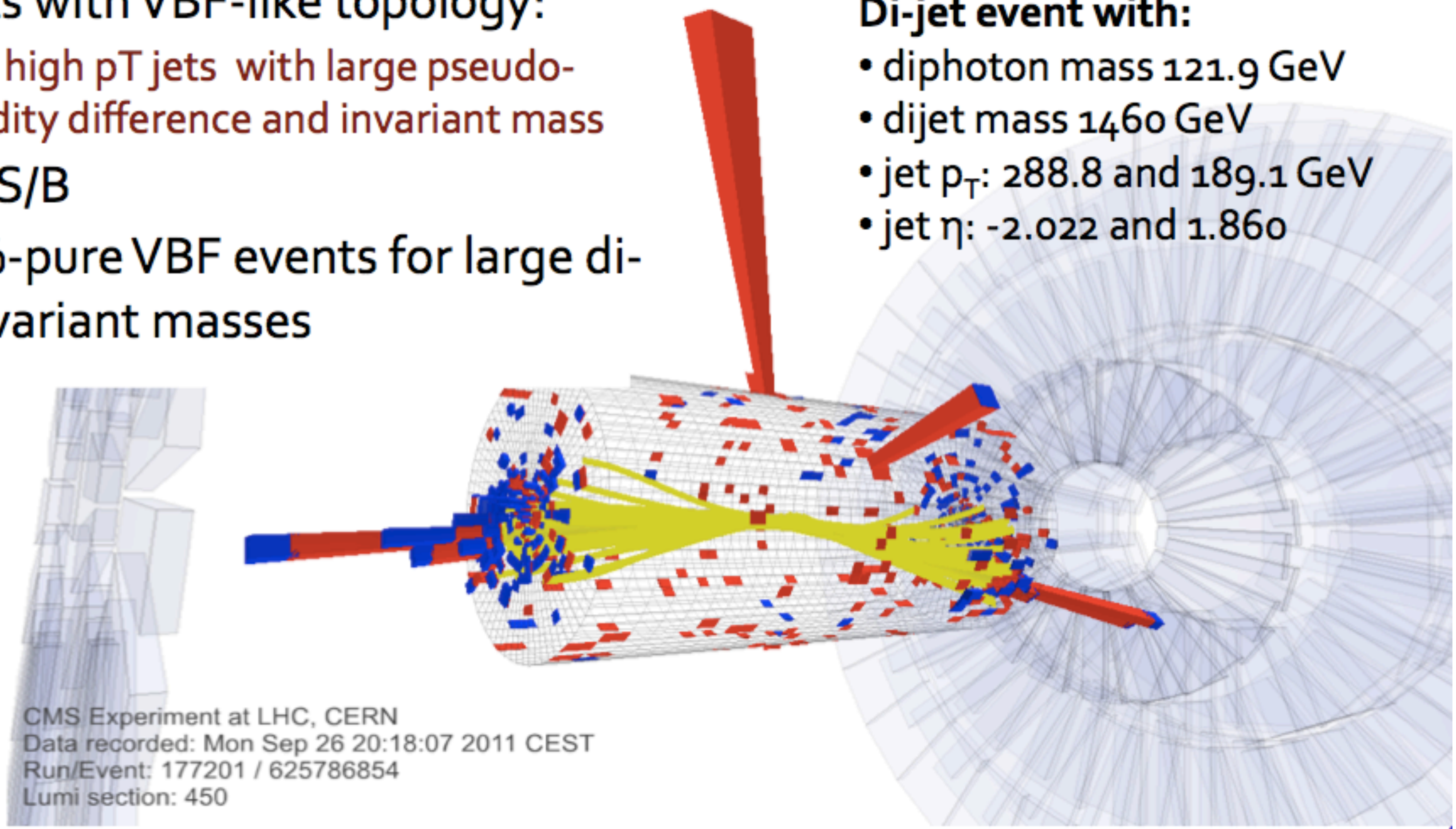


- Residual data-MC disagreement
  - For BG only make analysis sub-optimal
  - For signal would cause some category migration included in the systematic errors

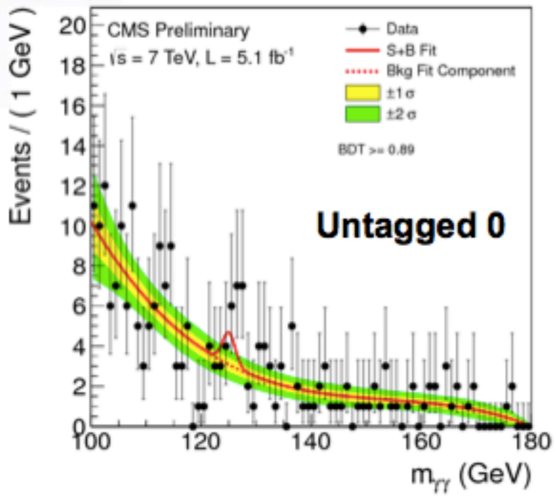
Di-jet Tagging

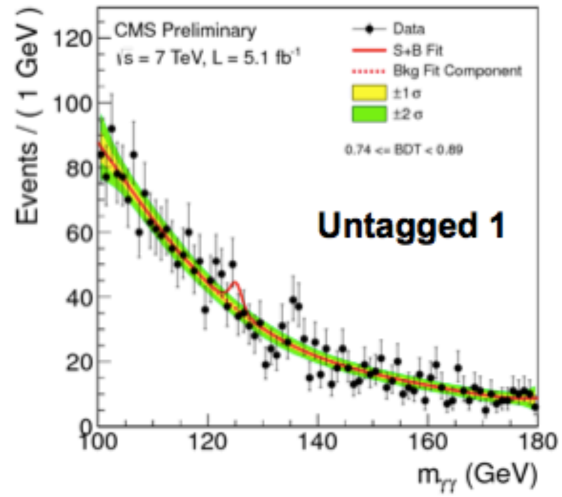
- Exclusive selection of di-photon events with VBF-like topology:
  - Two high pT jets with large pseudo-rapidity difference and invariant mass
- High S/B
- ~80%-pure VBF events for large di-jet invariant masses

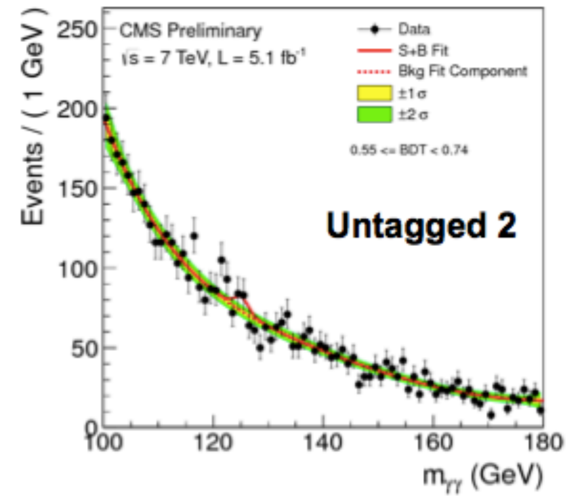
Di-jet event with:
- diphoton mass 121.9 GeV
- dijet mass 1460 GeV
- jet p_T: 288.8 and 189.1 GeV
- jet η: -2.022 and 1.860

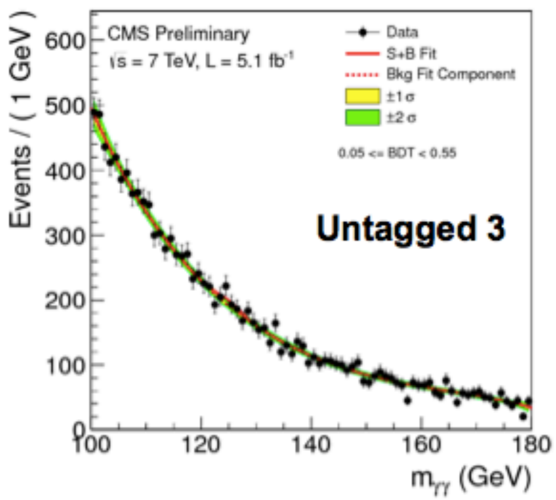


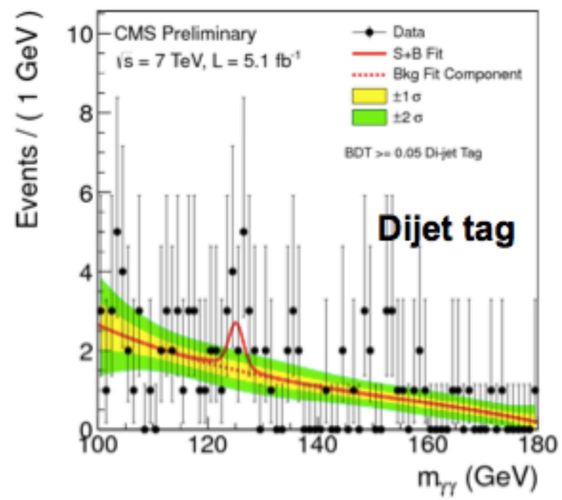
7 TeV Mass Distribution in Categories





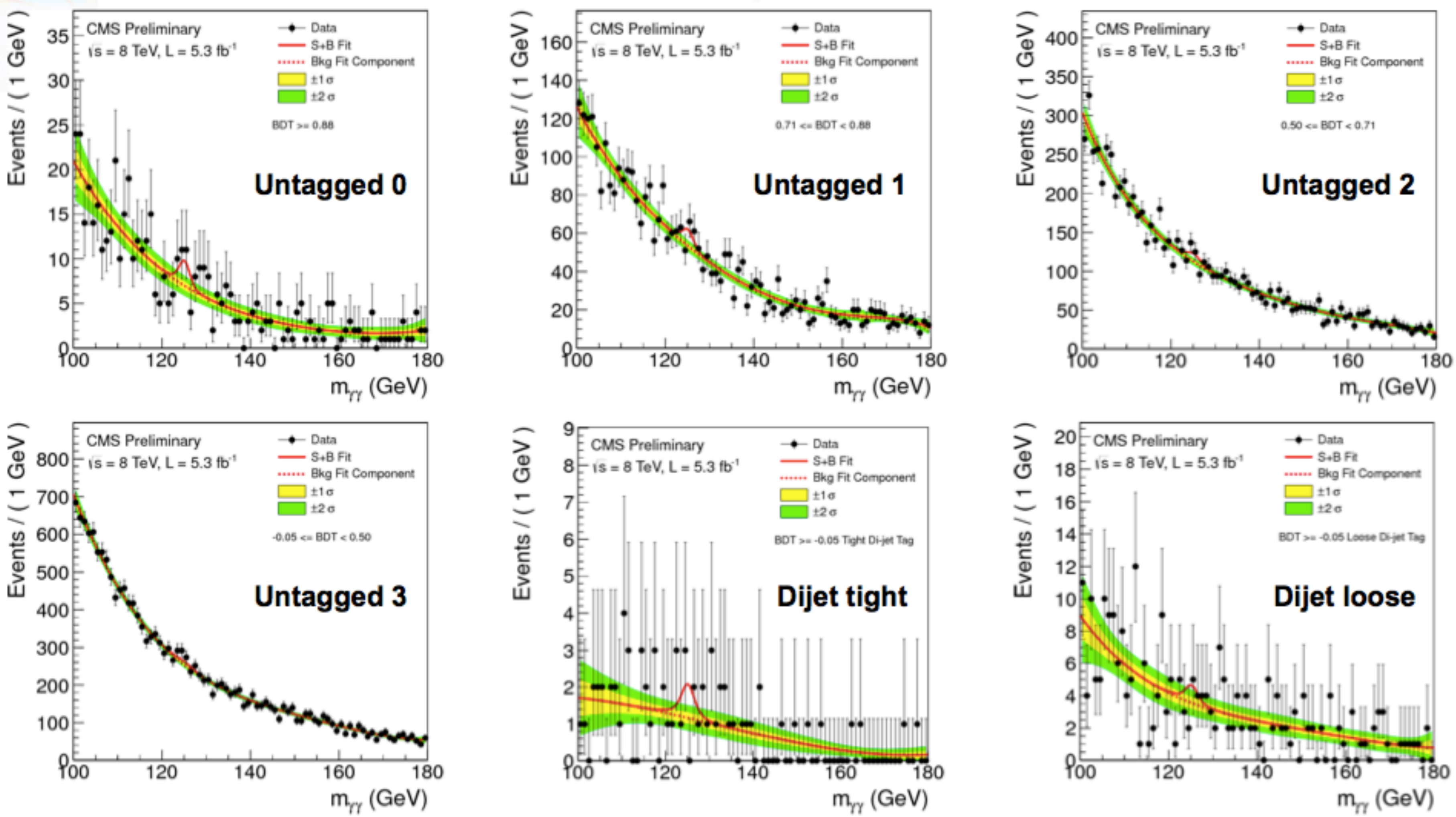






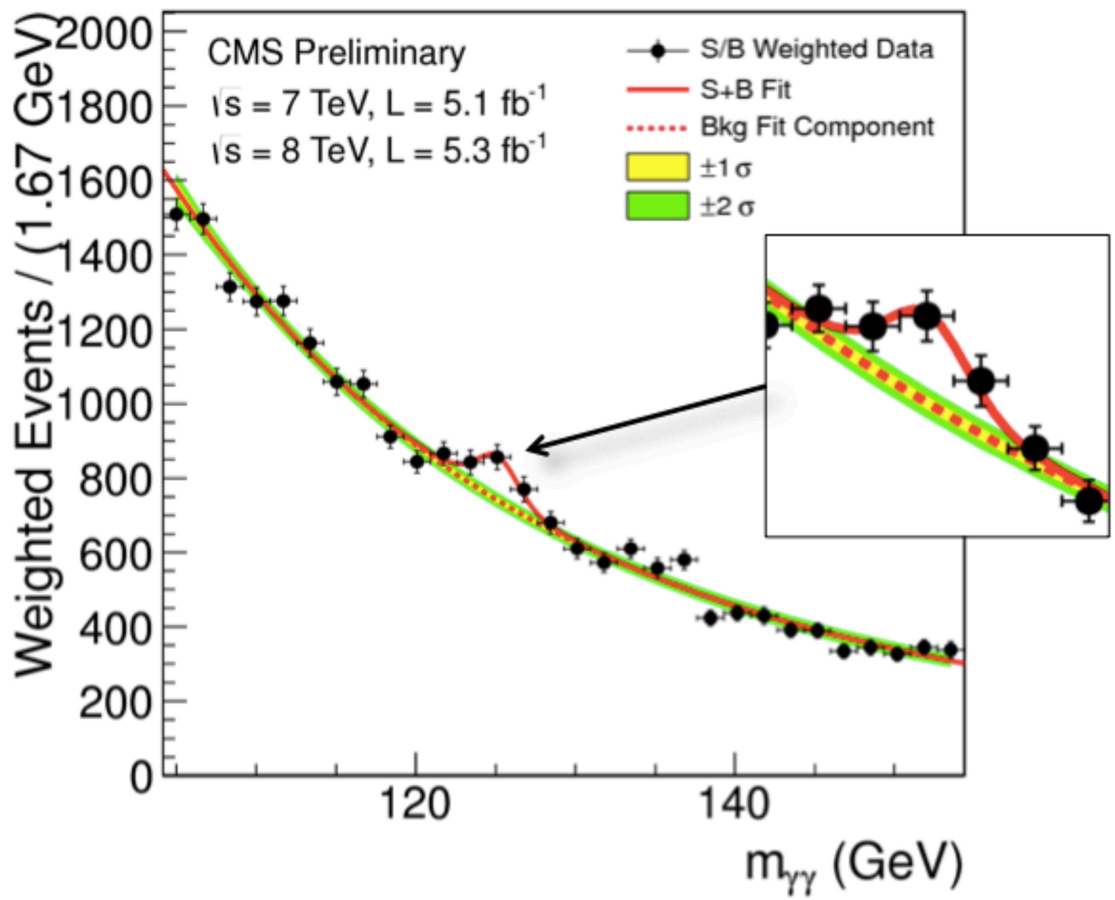
- Background model is entirely from data.
- Fit to mass distribution in each category with polynomial functions (3rd to 5th degree)
  - keep bias below 20% of fit error.
  - causes some loss of performance due to number of parameters in fit function.

8 TeV Mass Distribution in Categories

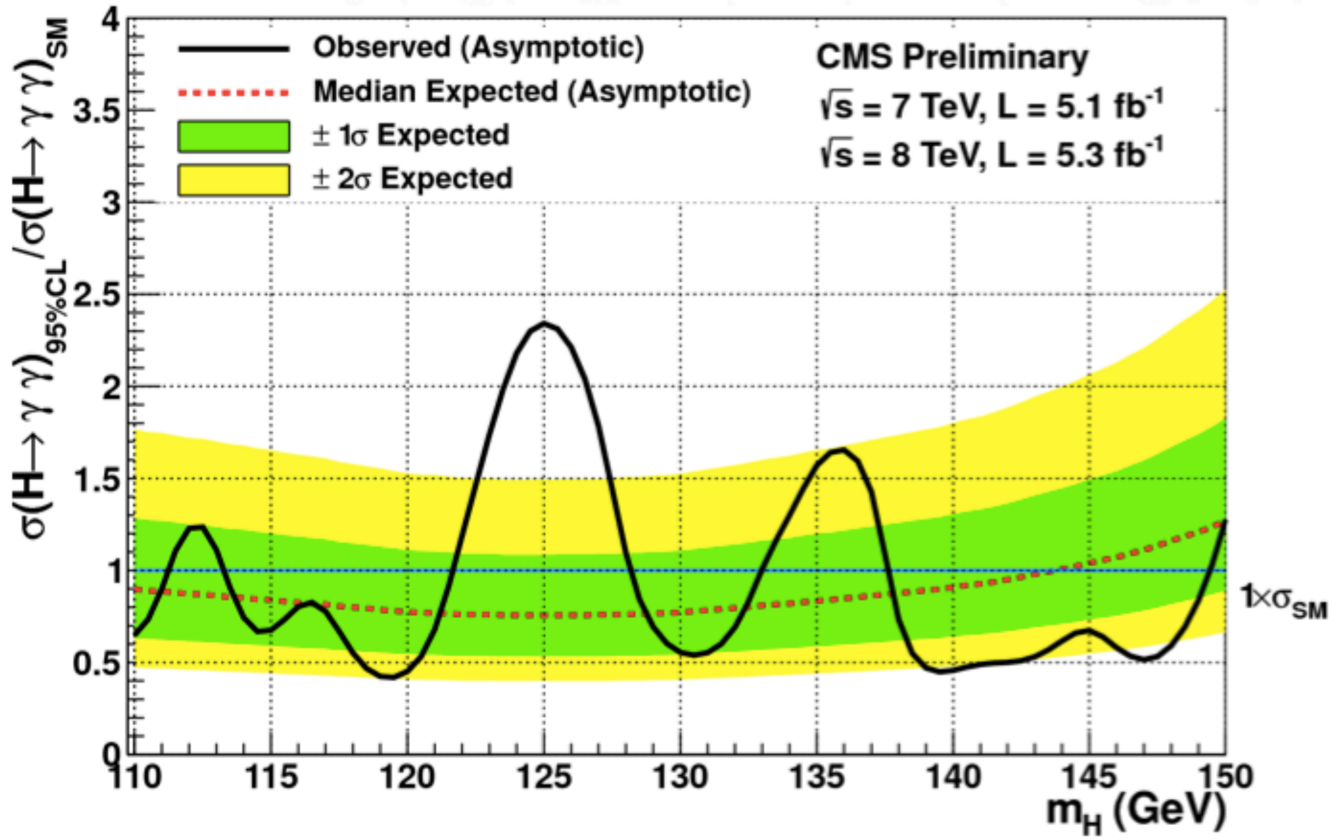


S/B Weighted Mass Distribution

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

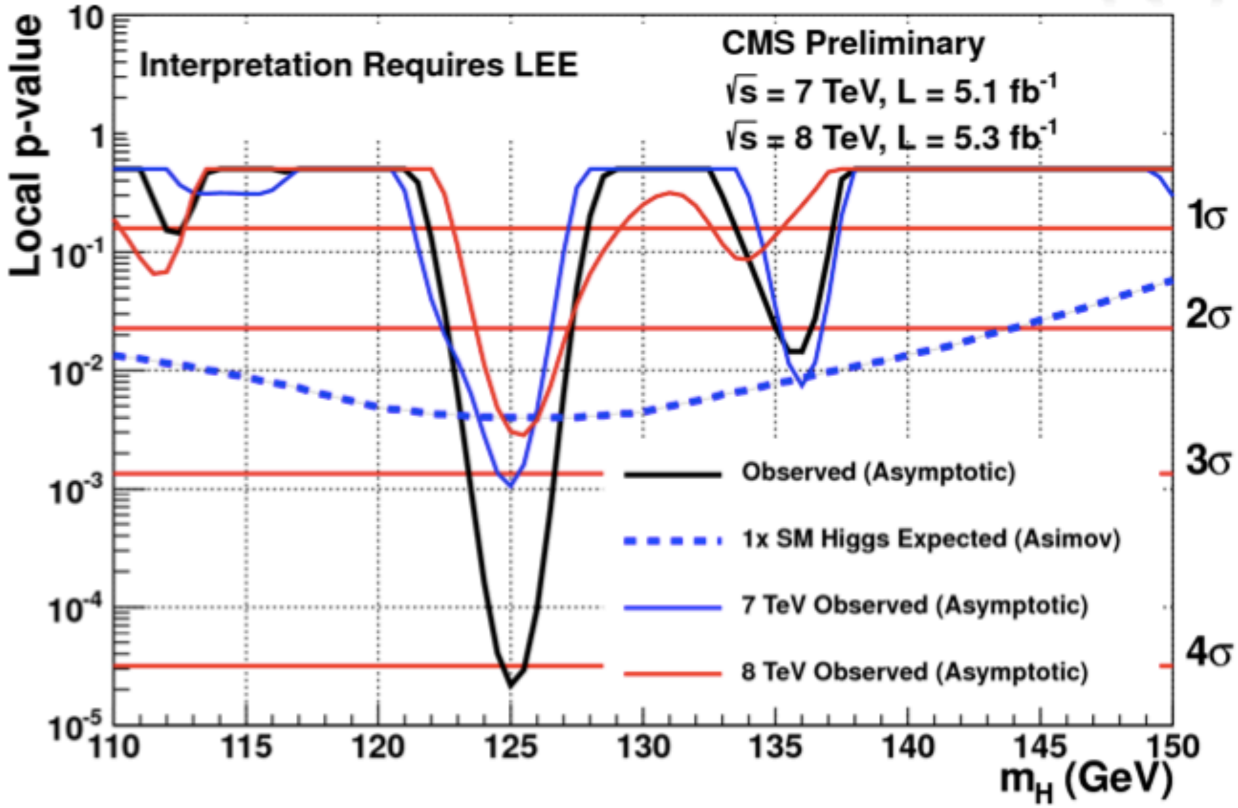


95% CL Exclusion for SM Higgs



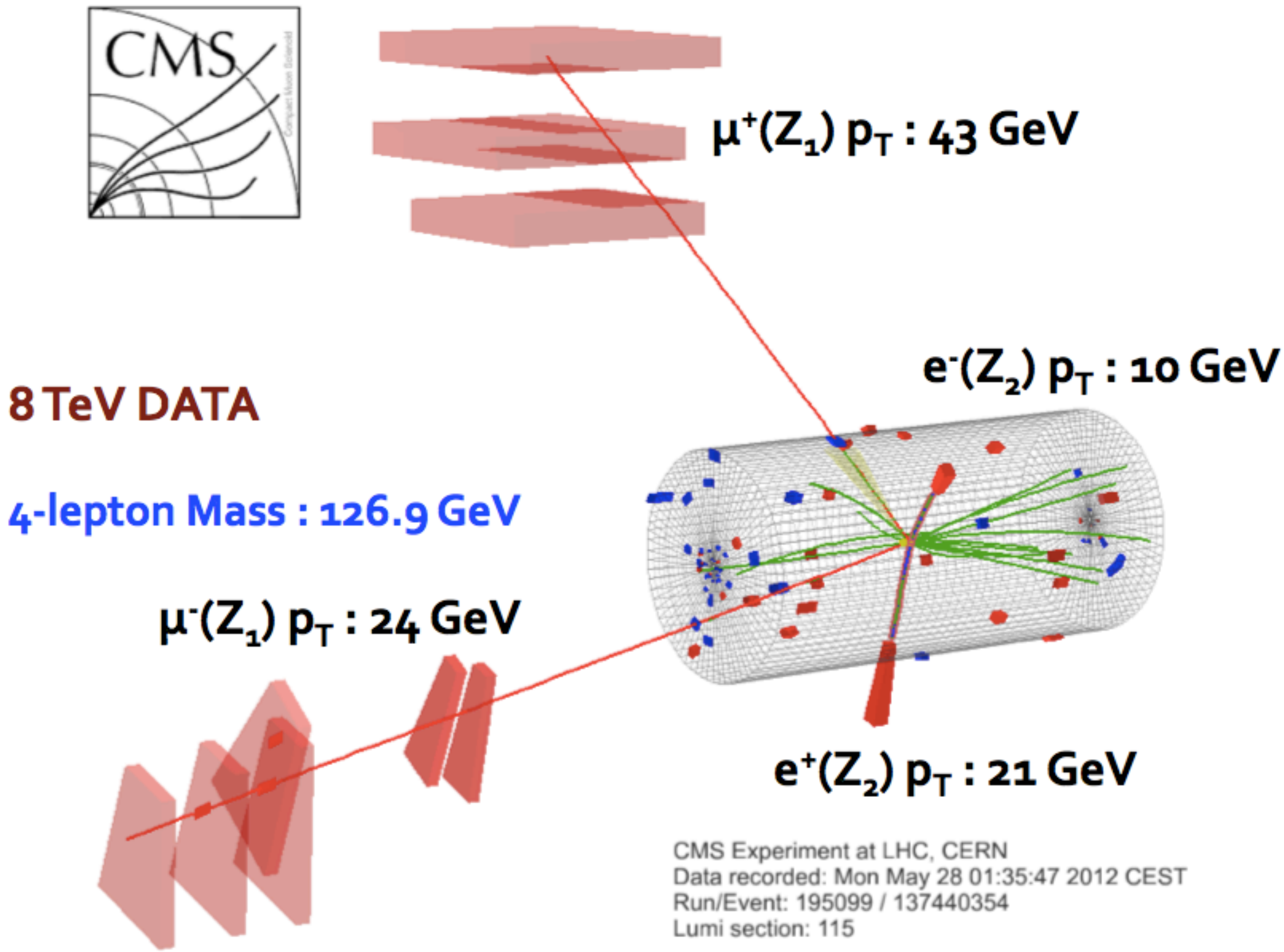
- Expected 95% CL exclusion 0.76 times SM at 125 GeV
- Large range with expected excusion below σ_{SM}
- Largest excess at 125 GeV

P-Values

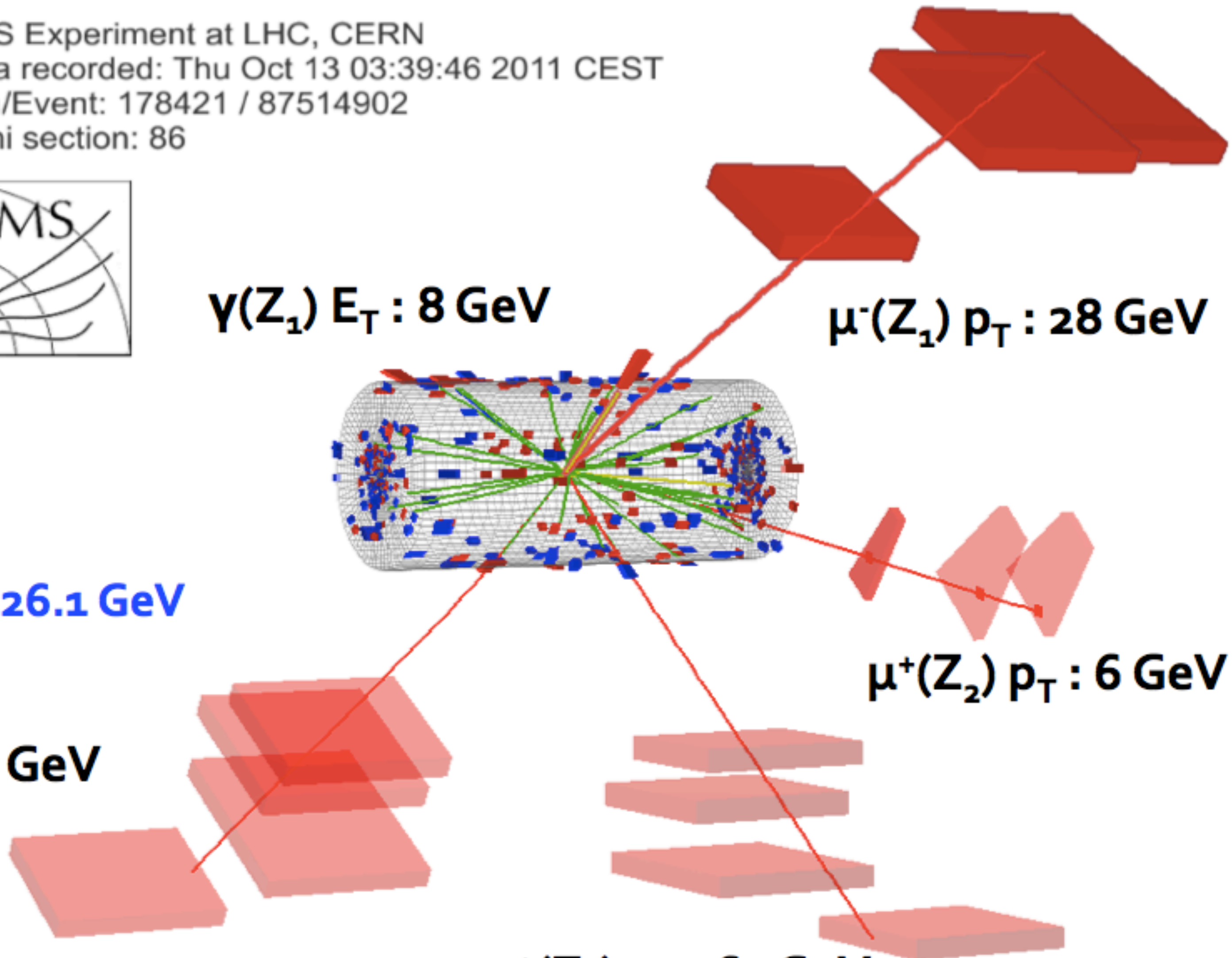


- Minimum local p-value at 125 GeV with a local significance of 4.1 σ
- Similar excess in 2011 and 2012
- Independent cross check analyses give similar results
- Global significance in the full search range (110-150 GeV) 3.2 σ

$H \rightarrow ZZ \rightarrow 4leptons$



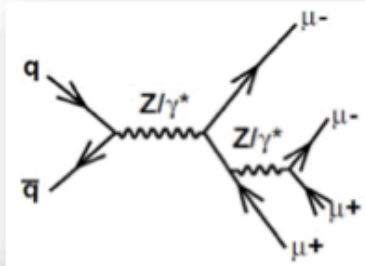
8 TeV DATA
4-lepton Mass : 126.9 GeV
μ⁺(Z₁) p_T : 43 GeV
e⁻(Z₂) p_T : 10 GeV
μ⁻(Z₁) p_T : 24 GeV
e⁺(Z₂) p_T : 21 GeV
CMS Experiment at LHC, CERN
Data recorded: Mon May 28 01:35:47 2012 CEST
Run/Event: 195099 / 137440354
Lumi section: 115

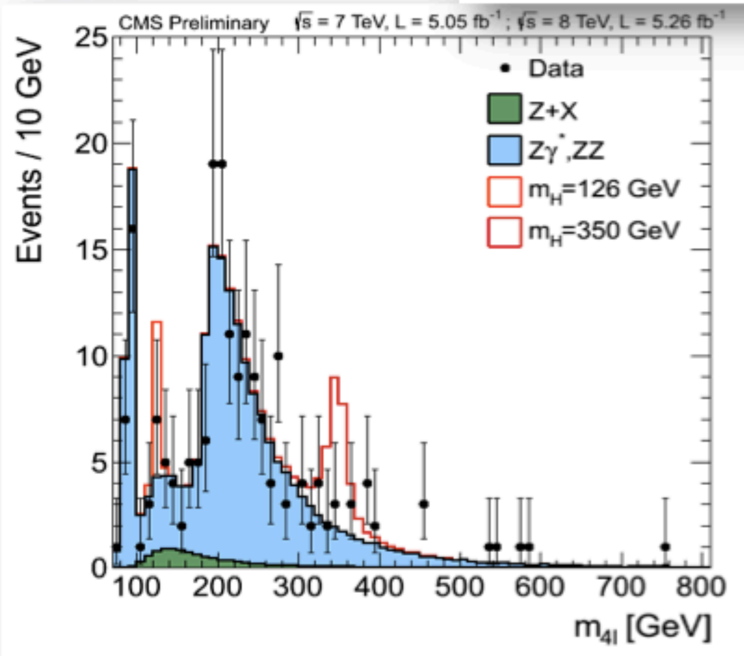


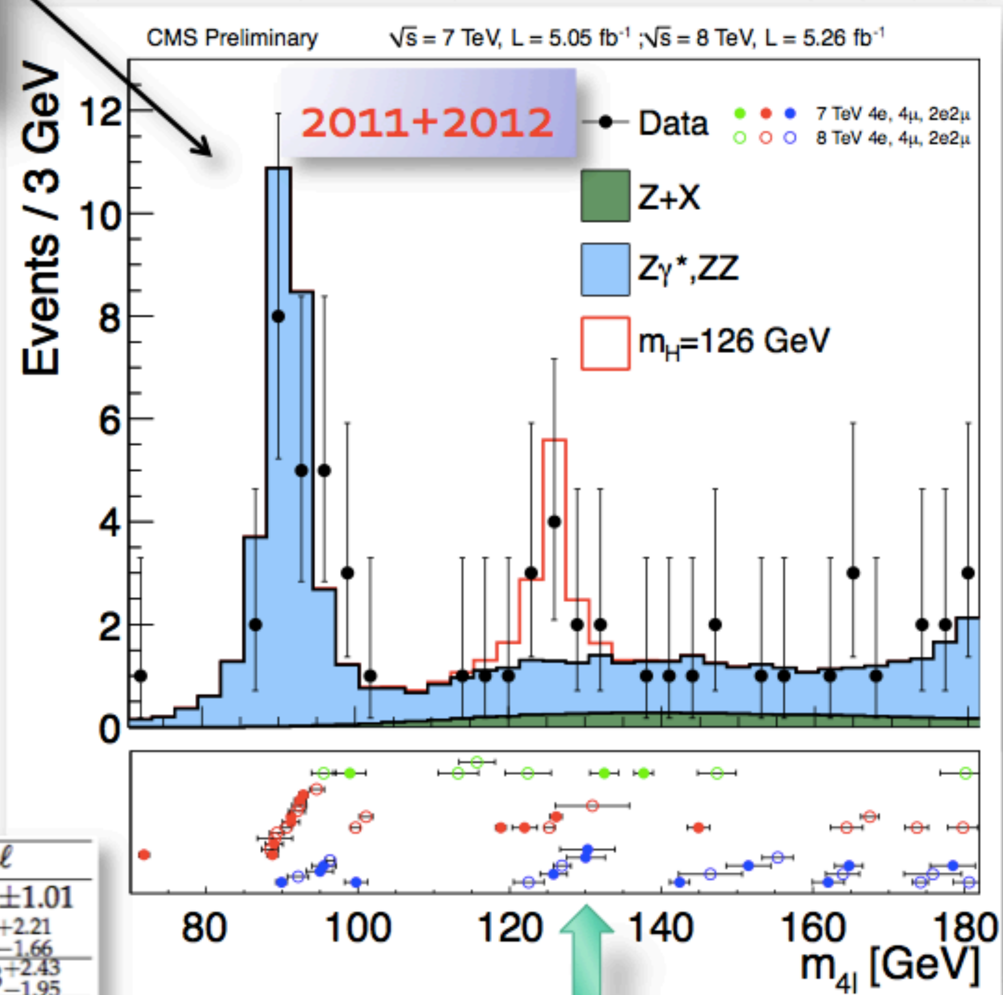
7 TeV DATA

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

Results: m(4l) spectrum







Yields for m(4l)=110..160 GeV

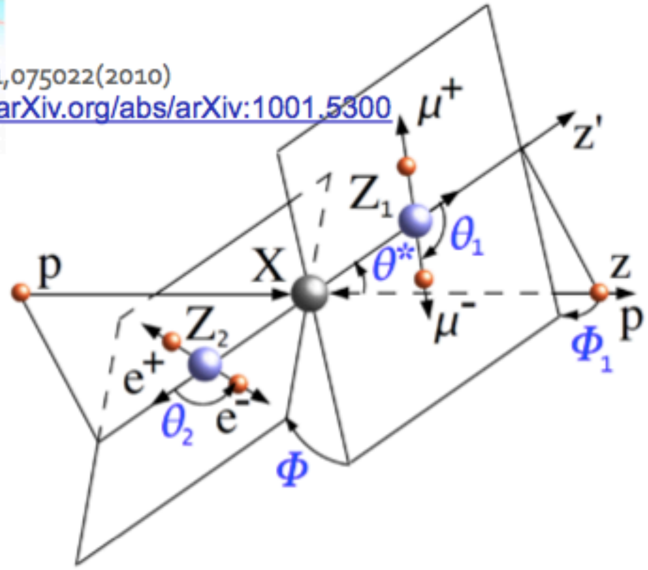
Channel	4e	4μ	$2e2\mu$	4ℓ
ZZ background	2.65 ± 0.31	5.65 ± 0.59	7.17 ± 0.76	15.48 ± 1.01
Z+X	$1.20^{+1.08}_{-0.78}$	$0.92^{+0.65}_{-0.55}$	$2.29^{+1.81}_{-1.36}$	$4.41^{+2.21}_{-1.66}$
All backgrounds	$3.85^{+1.12}_{-0.84}$	$6.58^{+0.88}_{-0.81}$	$9.46^{+1.96}_{-1.56}$	$19.88^{+2.43}_{-1.95}$
$m_H = 126\,\mathrm{GeV}$	1.51 ± 0.48	2.99 ± 0.60	3.81 ± 0.89	8.31 ± 1.18

164 events expected in [100, 800 GeV]
172 events observed in [100, 800 GeV]

Event-by-event errors

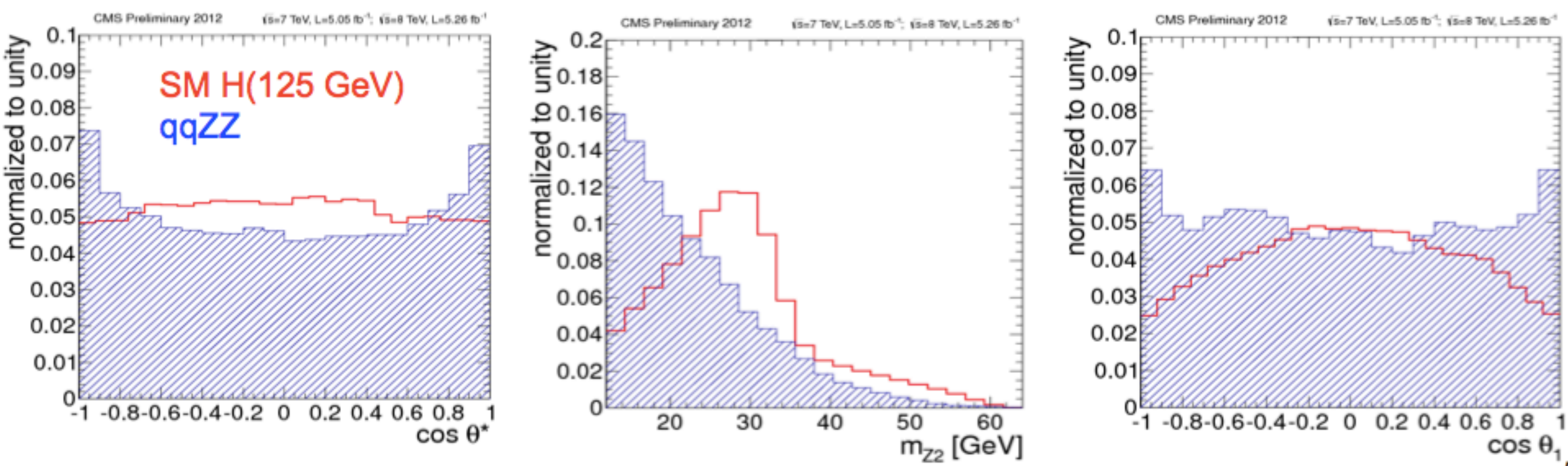
MELA

PRD81,075022(2010)
http://arXiv.org/abs/arXiv:1001.5300



Matrix Element Likelihood Analysis:
uses kinematic inputs for
signal to background discrimination
$\{m_1, m_2, \theta_1, \theta_2, \theta^*, \Phi, \Phi_1\}$

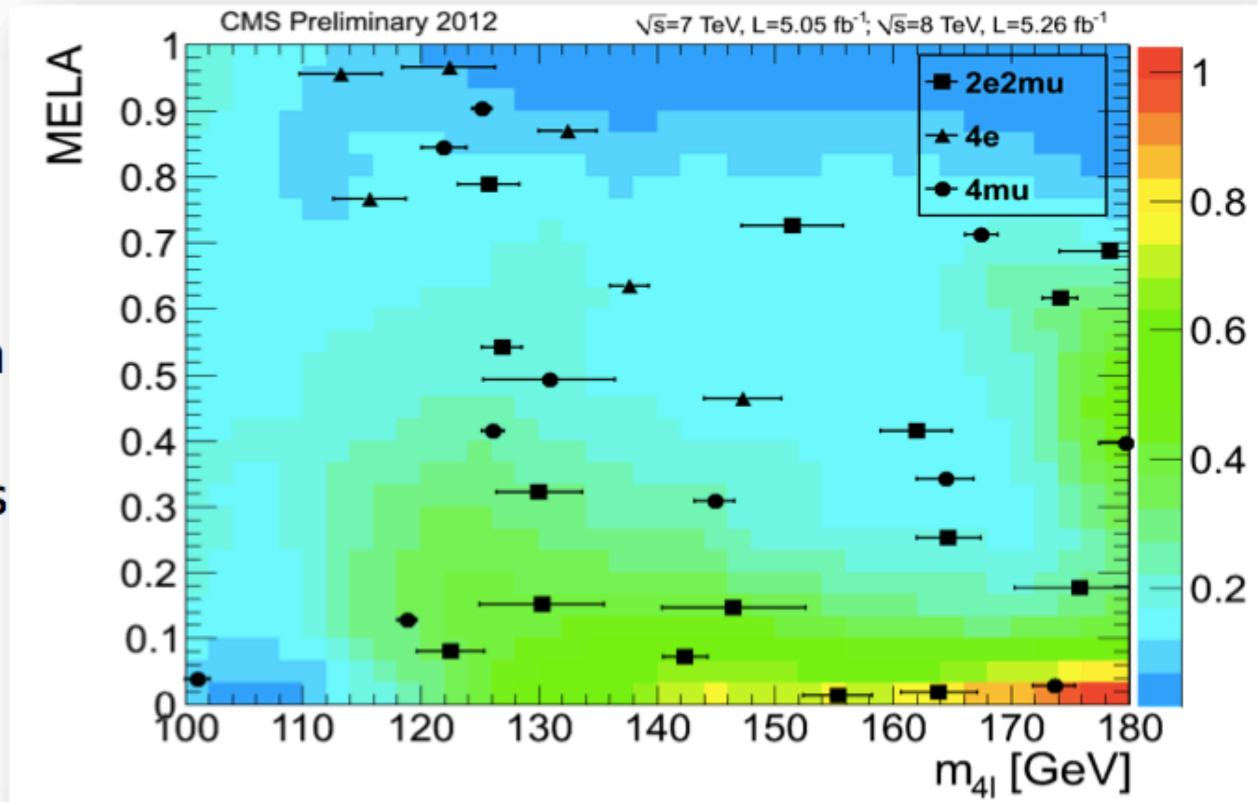
$$\mathrm{MELA} = \left[1 + \frac{\mathcal{P}_{\mathrm{bkg}}(m_1, m_2, \theta_1, \theta_2, \Phi, \theta^*, \Phi_1 | m_{4\ell})}{\mathcal{P}_{\mathrm{sig}}(m_1, m_2, \theta_1, \theta_2, \Phi, \theta^*, \Phi_1 | m_{4\ell})}\right]^{-1}$$



Results: MELA 2D plots

Perform 2D fit

- MELA discriminant versus m_{4l}
  - Data points shown with per-event mass uncertainties



Data w.r.t. background expectation

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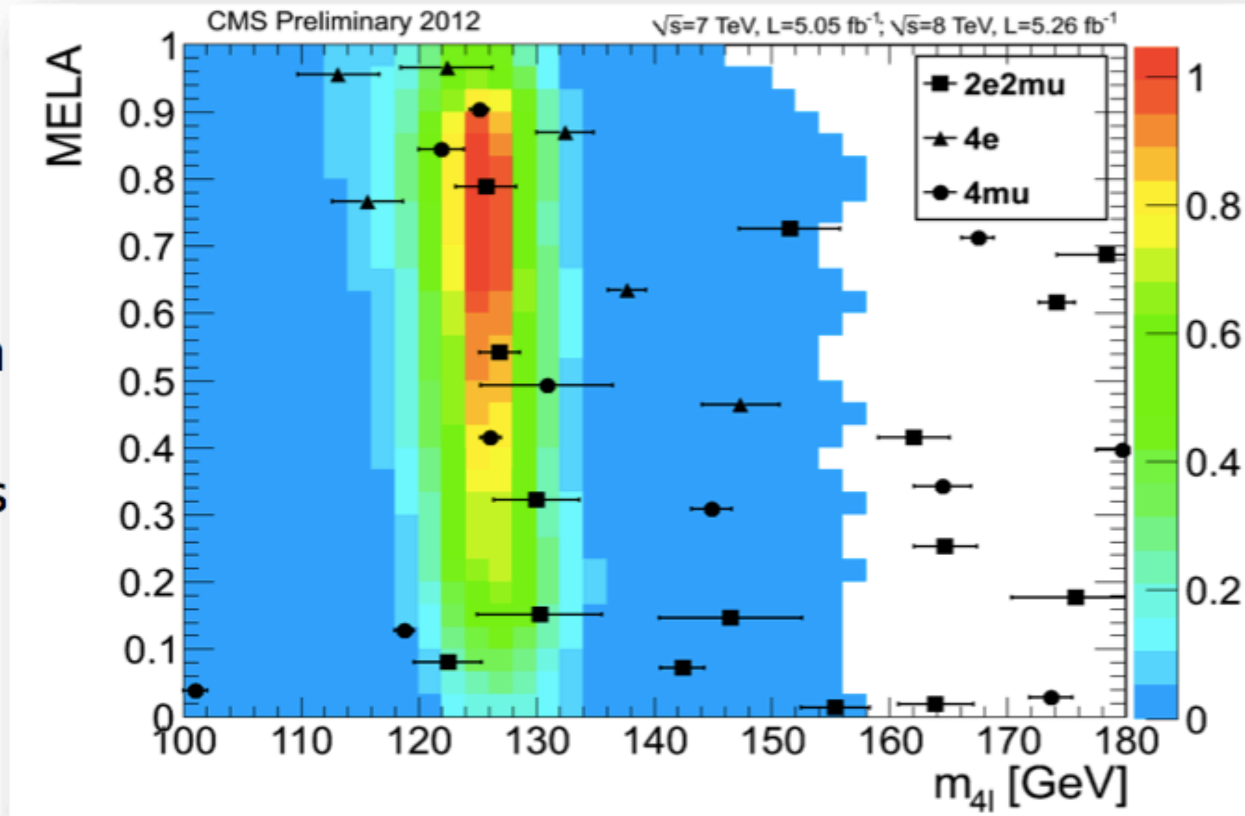
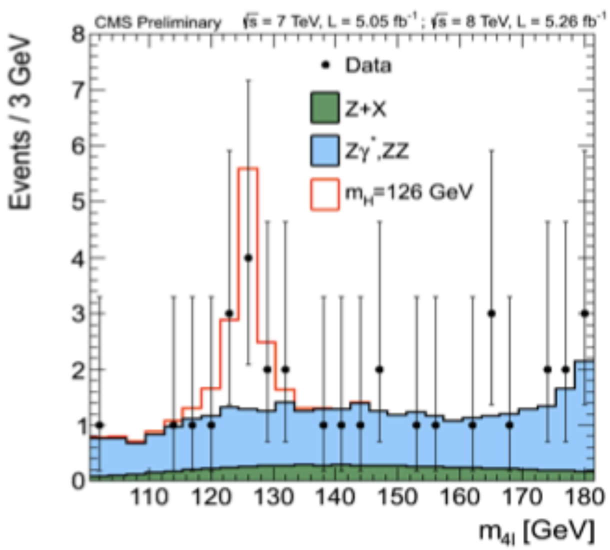
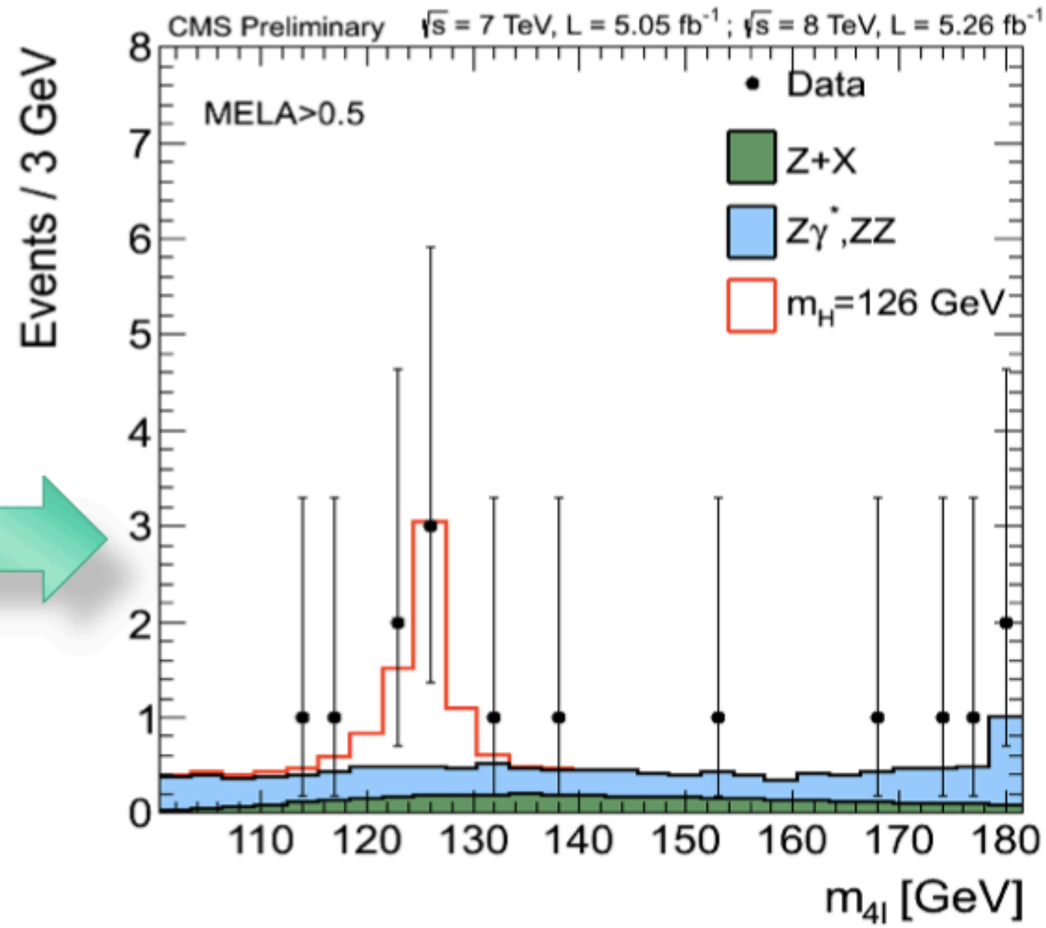


Data w.r.t 126 GeV Higgs Expectation

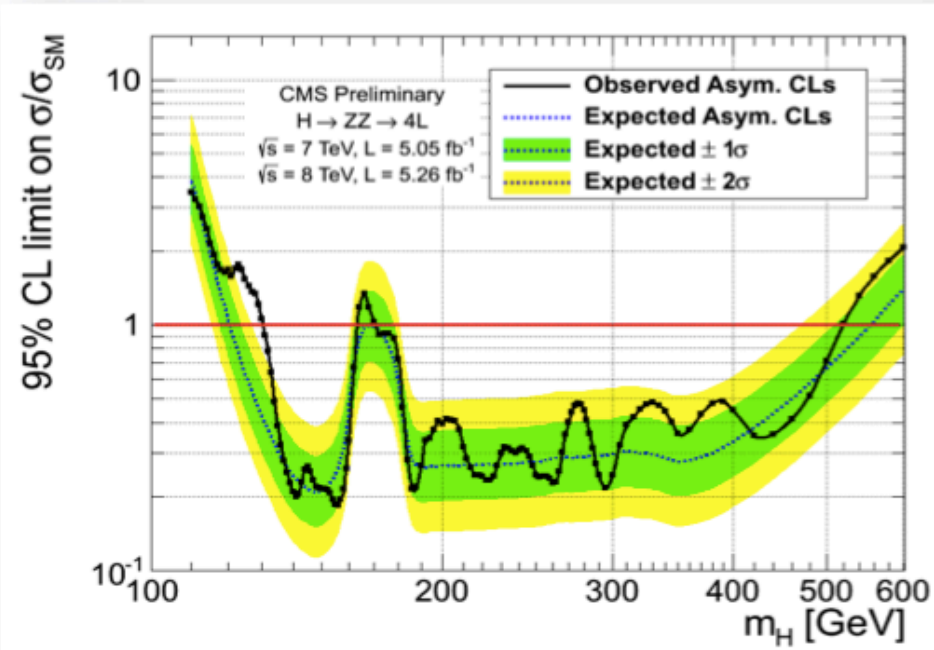
For illustration:
Low mass region with MELA cut

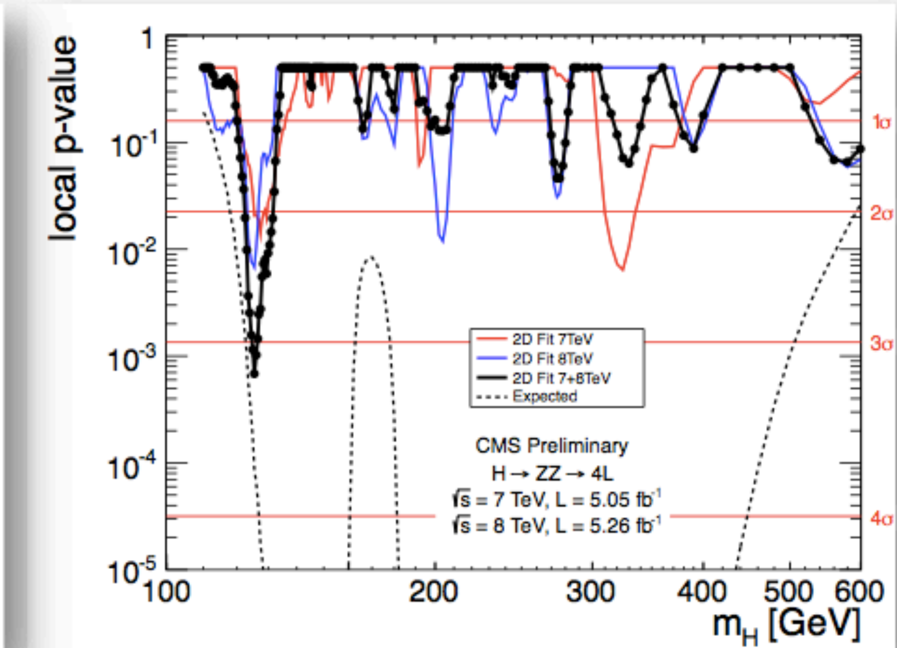
- Enrich the signal content
  - Cut: MELA > 0.5
    - Cut value chosen such that signal probability > background probability





Limits and p-values

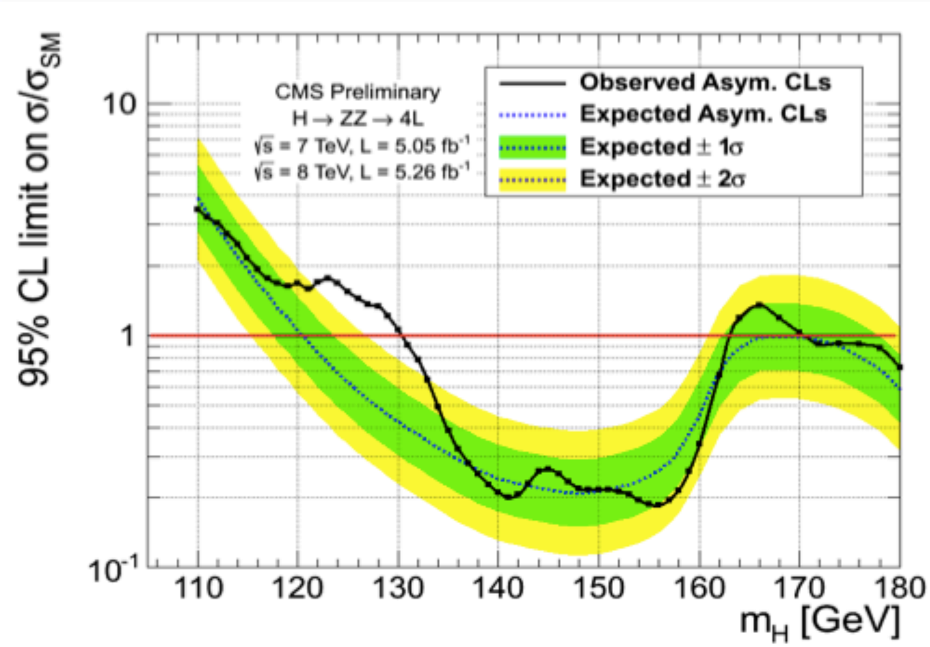


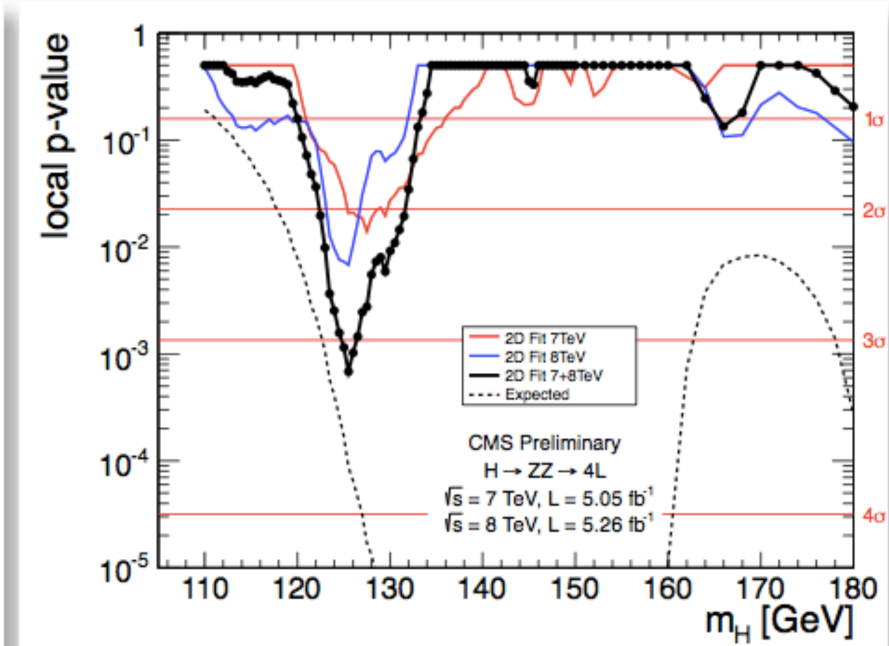


Expected exclusion at 95% CL :
121-550 GeV
Observed exclusion at 95% CL :
131-162 GeV and 172-530 GeV

Expected significance at 125.5 GeV :
3.8 σ
Observed significance at 125.5 GeV:
3.2 σ

Limits and p-values





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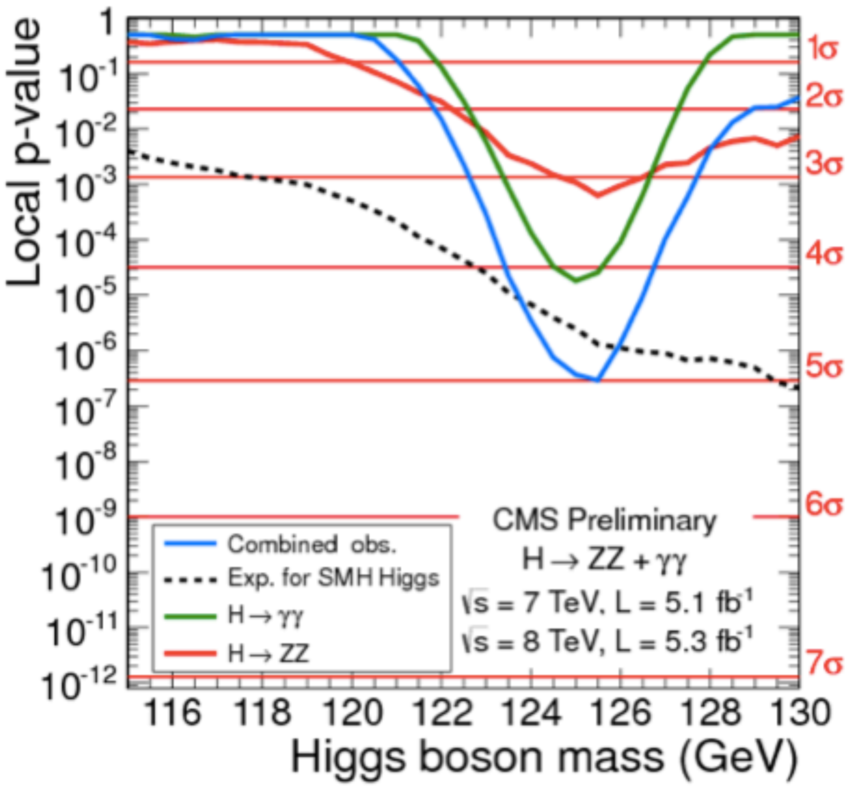
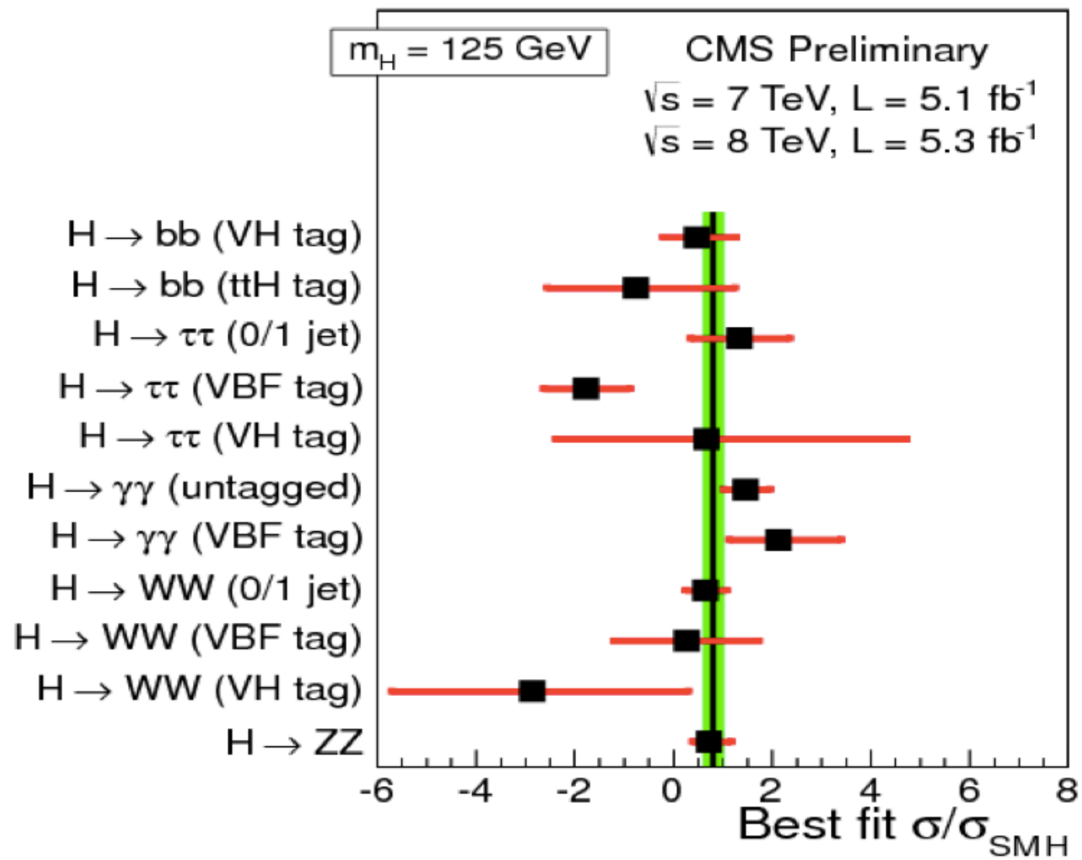
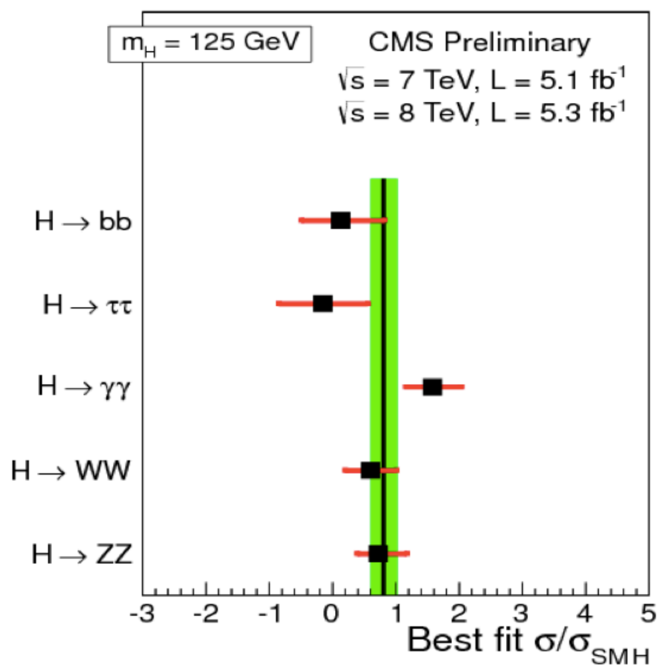
Characterization of excess near 125 GeV



- **high sensitivity, high mass resolution channels: γγ+4l**
  - **γγ: 4.1 σ excess**
  - **4 leptons: 3.2 σ excess**
  - **near the <u>same mass</u> 125 GeV**
- **comb. significance: $\boxed{5.0\ \sigma}$**
- **expected significance for SM Higgs: 4.7 σ**

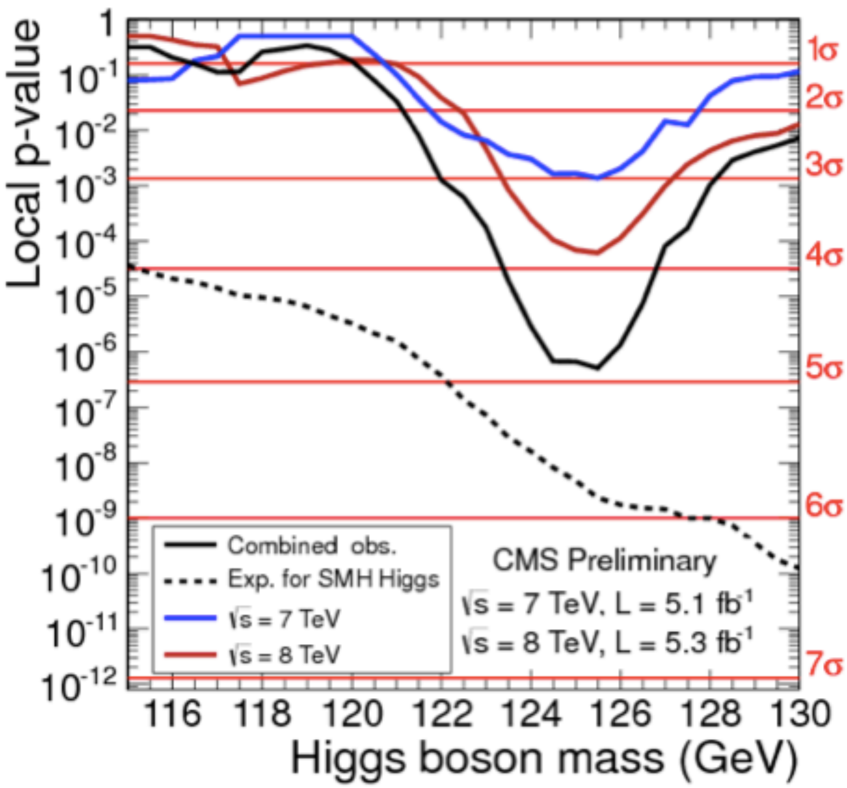
- Event yields in different production times decay modes are self-consistent
  - albeit many modes have not yet reached sensitivity to distinguish SM from Background





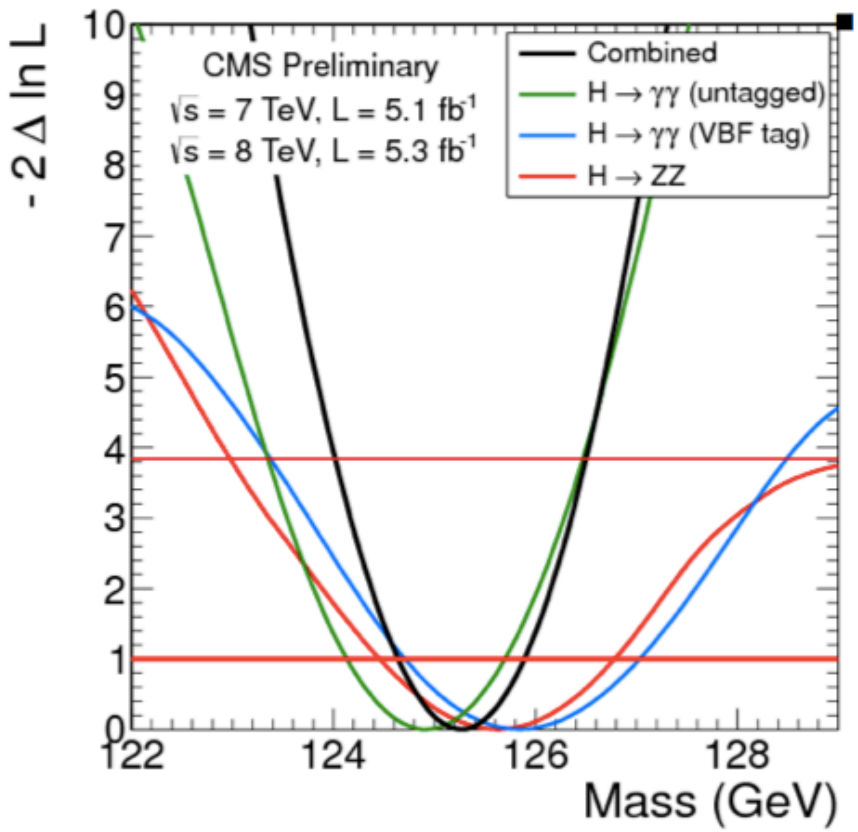
gg, ZZ modes most sensitive

Characterization of excess near 125 GeV



- **Observed significance: $\boxed{4.9\ \sigma}$**
- **Excess seen in both**
  - **7 TeV data (3.0 σ)**
  - **8 TeV data (3.8 σ)**
  - **near the <u>same mass</u> 125 GeV**

Characterization of the excess: mass



- To reduce model dependence, allow for free cross sections in three channels and fit for the common mass:

$m_X = 125.3 \pm 0.6$ GeV

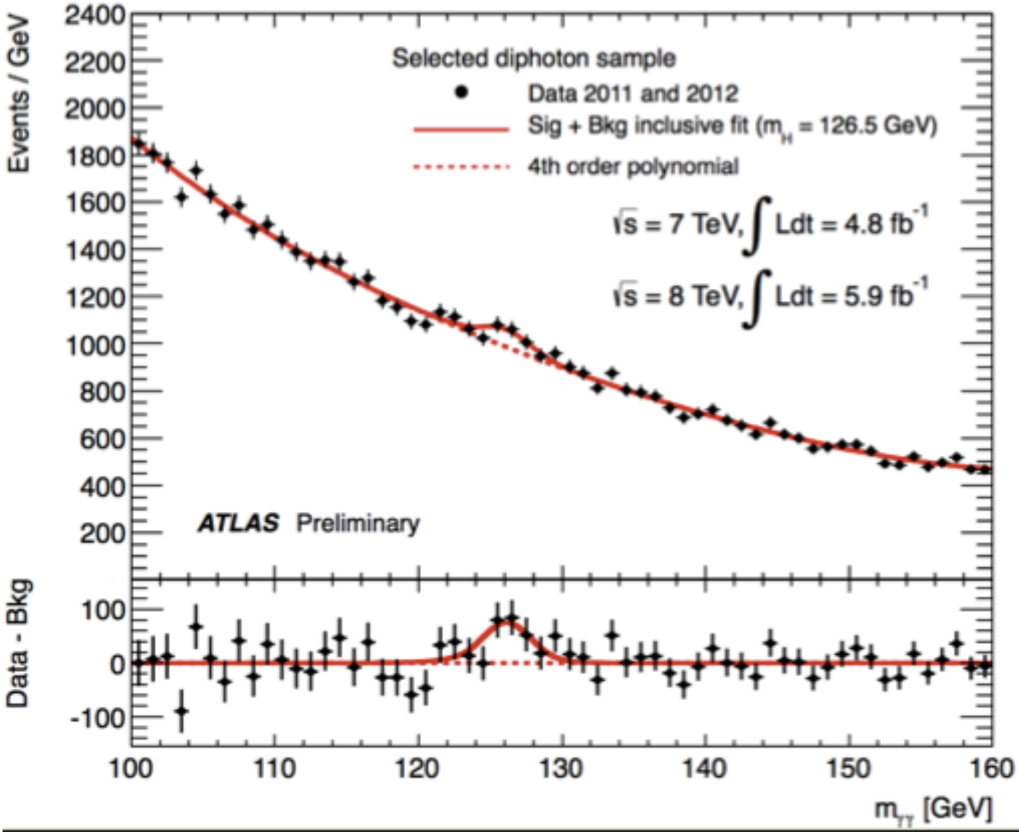
In summary

We have observed a new boson with a mass of

125.3 ± 0.6 GeV

at

4.9 σ significance !



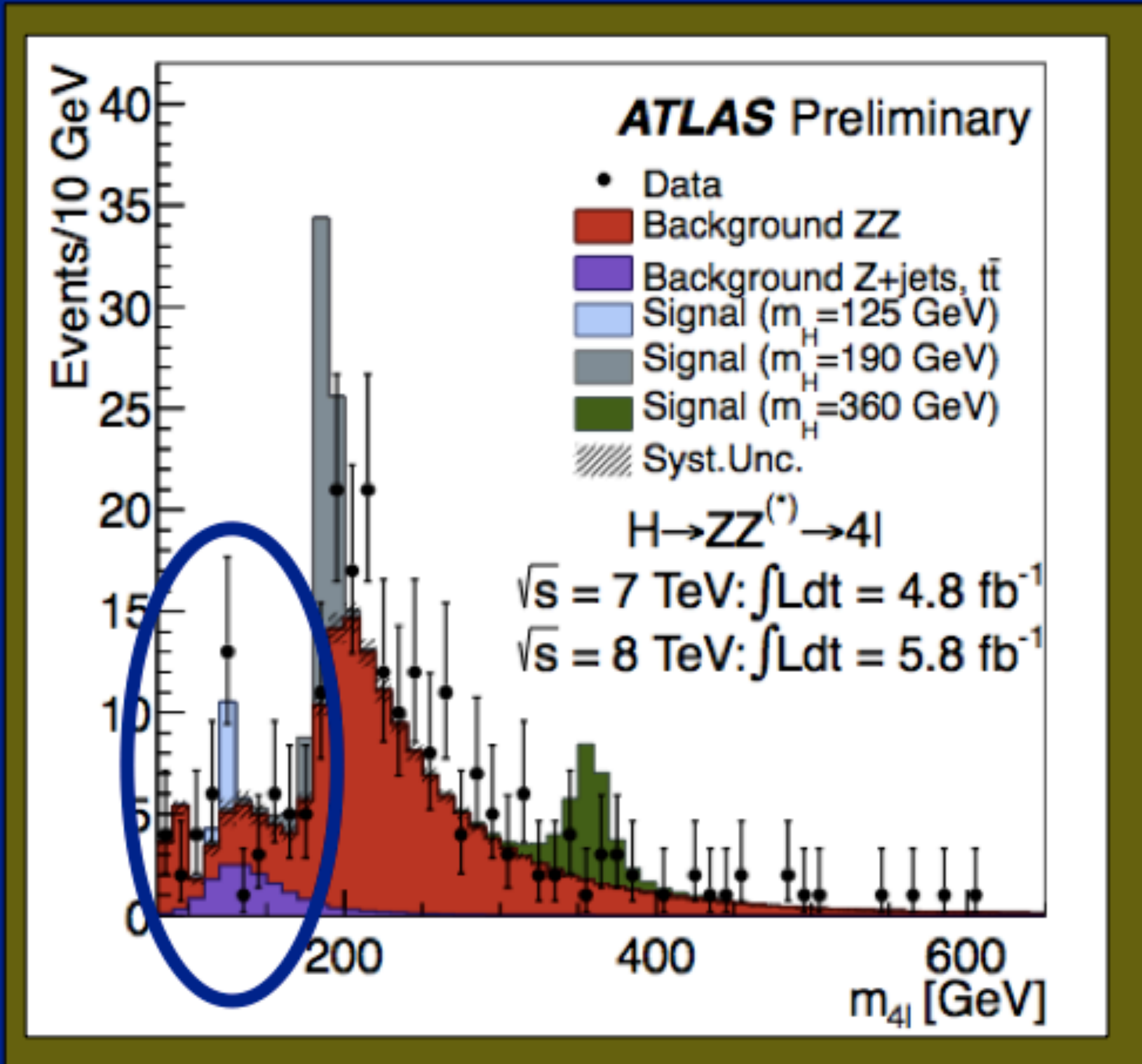
Total after selections: 59059 events

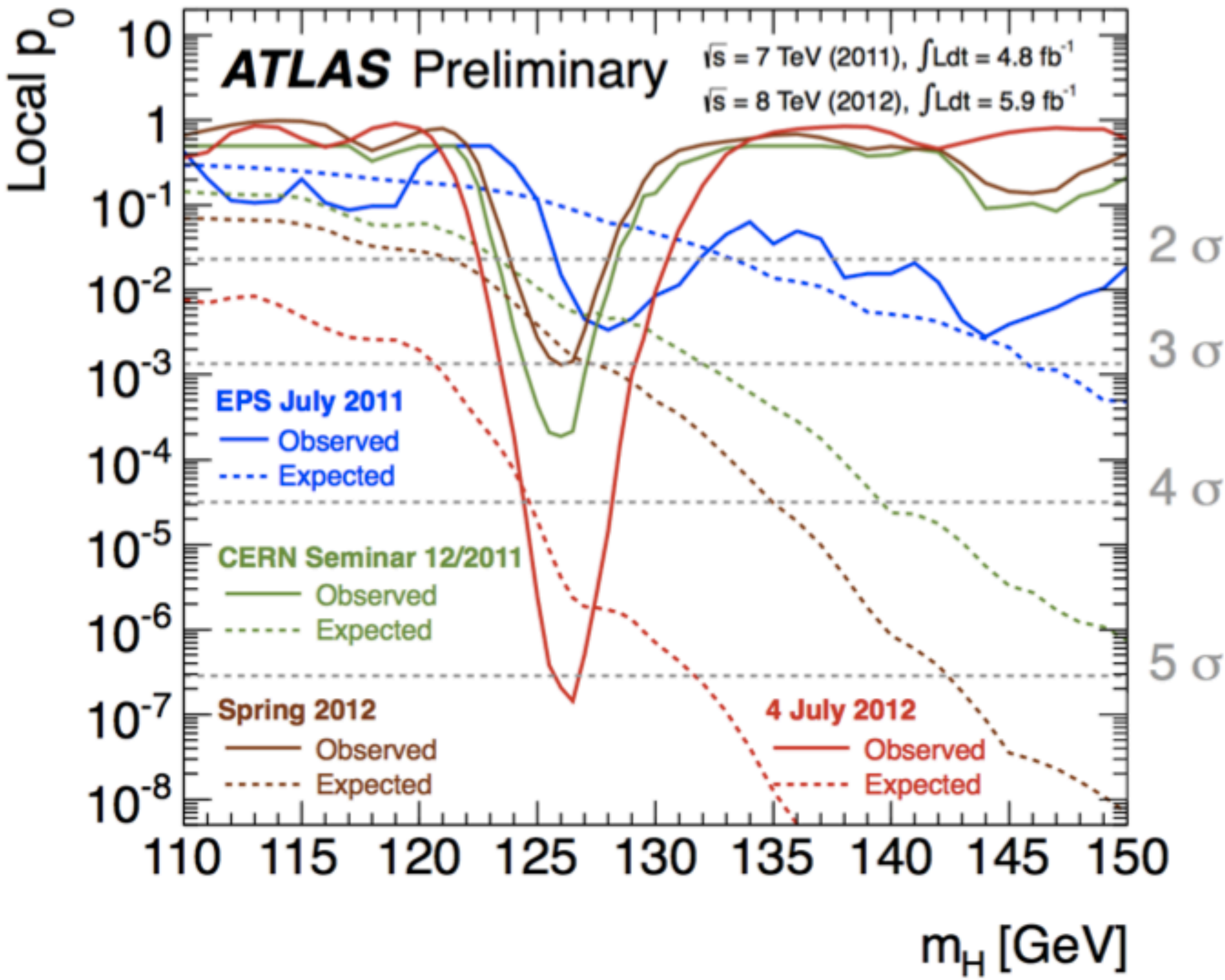
$m_{\gamma\gamma}$ spectrum fit, <u>for each category</u>, with Crystal Ball + Gaussian for signal plus background model optimised (with MC) to minimize biases
Max deviation of background model from expected background distribution taken as systematic uncertainty

Main systematic uncertainties

Signal yield	
Theory	~ 20%
Photon efficiency	~ 10%
Background model	~ 10%
Categories migration	
Higgs p_T modeling	up to ~ 10%
Conv/unconv γ	up to ~ 6%
Jet E-scale	up to 20% (2j/VBF)
Underlying event	up to 30% (2j/VBF)
$H \rightarrow \gamma\gamma$ mass resolution	~ 14%
Photon E-scale	~ 0.6%

H→ 4l mass spectrum after all selections: 2011+2012 data




ATLAS Preliminary
√s = 7 TeV (2011), ∫Ldt = 4.8 fb⁻¹
√s = 8 TeV (2012), ∫Ldt = 5.9 fb⁻¹
Local p0
10
1
10-1
10-2
10-3
10-4
10-5
10-6
10-7
10-8
2 σ
3 σ
4 σ
5 σ
EPS July 2011
Observed
Expected
CERN Seminar 12/2011
Observed
Expected
Spring 2012
Observed
Expected
4 July 2012
Observed
Expected
110
115
120
125
130
135
140
145
150
mH [GeV]

What Now?

- We do not know what it is at 125-126 GeV/c^2.
  - It may be THE Higgs Boson, or
  - It may be A Higgs Boson
- We need to measure its couplings to known particles.
  - It should couple to t, b, W, Z in predictable ways
- We need to measure its spin (Higgs has 0 spin).
  - Note that cosmology needs a scalar (spin 0) field for inflation to work.   But that's another can of worms…