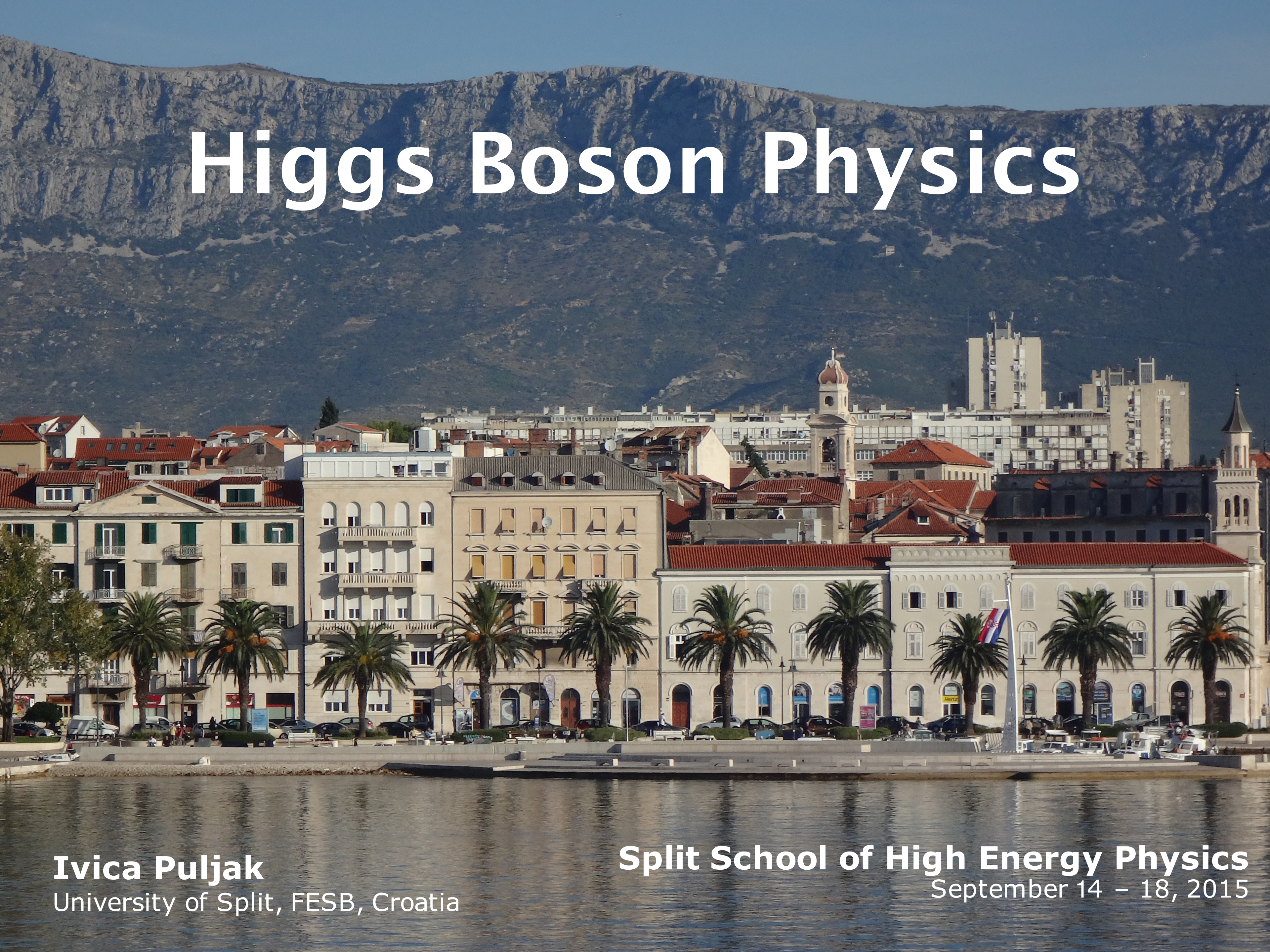
Higgs Boson Physics



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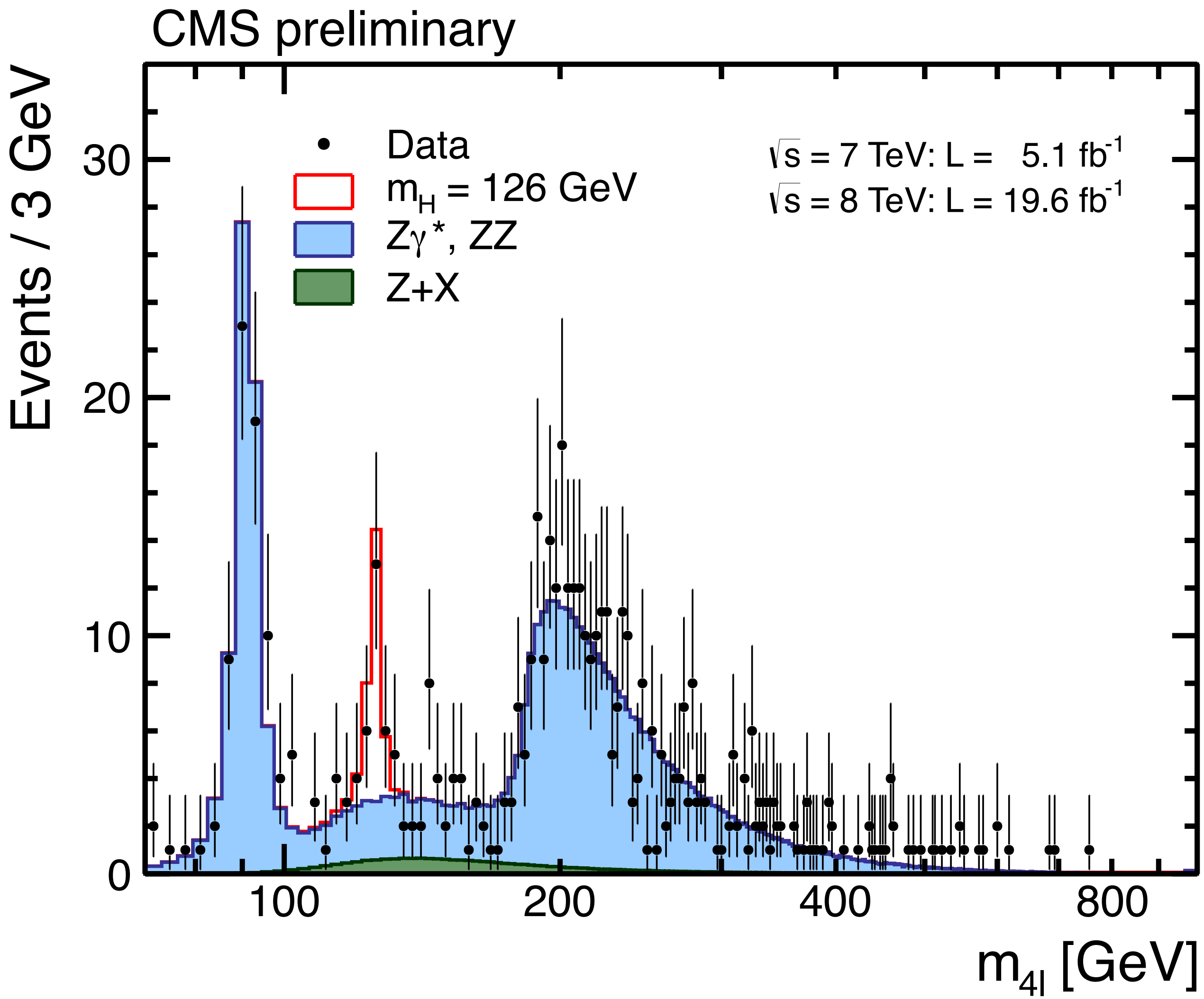
Split School of High Energy Physics
September 14 – 18, 2015

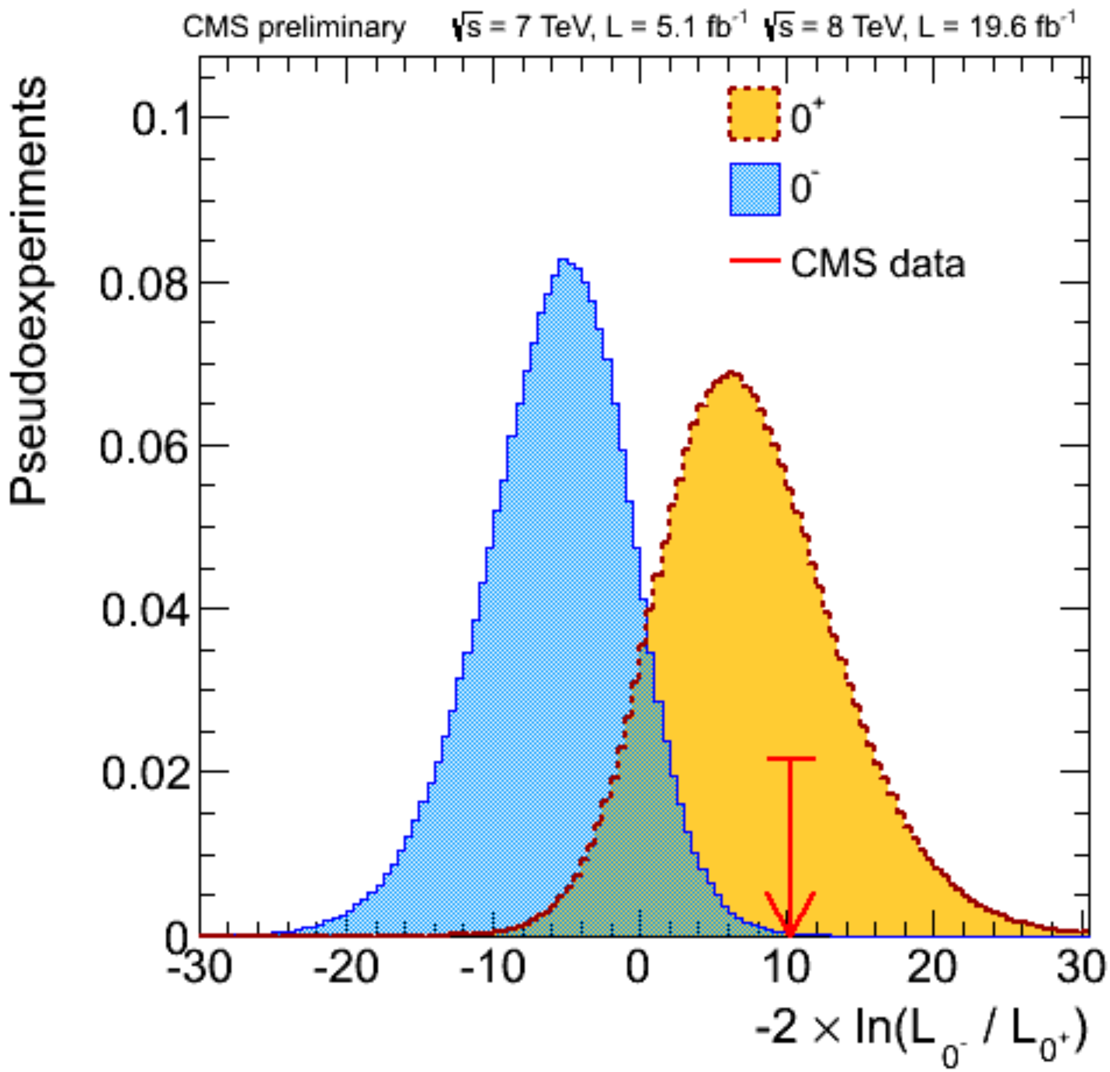
Part 1 – How did we find it?

And how sure are we about it ...



Part 2 – What did we really find?

And how do we know that …



The Higgs boson

Standard Model of

FUNDAMENTAL PARTICLES AND INTERACTIONS

The Standard Model summarizes the current knowledge in Particle Physics. It is the quantum theory that includes the theory of strong interactions (quantum chromodynamics or QCD) and the unified theory of weak and electromagnetic interactions (electroweak). Gravity is included on this chart because it is one of the fundamental interactions even though not part of the "Standard Model."

FERMIONS

matter constituents
spin = 1/2, 3/2, 5/2, ...

Leptons spin = 1/2

Flavor	Mass GeV/c^2	Electric charge
ν_e electron neutrino	$<1\times10^{-8}$	0
e electron	0.000511	–1
ν_μ muon neutrino	<0.0002	0
μ muon	0.106	–1
ν_τ tau neutrino	<0.02	0
τ tau	1.7771	–1

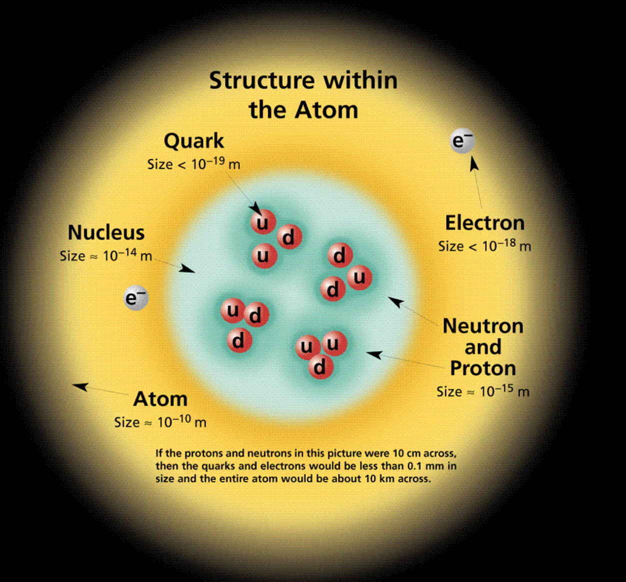
Quarks spin = 1/2

Flavor	Approx. Mass GeV/c^2	Electric charge
u up	0.003	2/3
d down	0.006	–1/3
c charm	1.3	2/3
s strange	0.1	–1/3
t top	175	2/3
b bottom	4.3	–1/3

Spin is the intrinsic angular momentum of particles. Spin is given in units of ħ, which is the quantum unit of angular momentum, where $\hbar = h/2\pi = 6.58\times10^{-25}$ GeV s = 1.05×10^{-34} J s.

Electric charges are given in units of the proton's charge. In SI units the electric charge of the proton is 1.60×10^{-19} coulombs.

The **energy** unit of particle physics is the electronvolt (eV), the energy gained by one electron in crossing a potential difference of one volt. **Masses** are given in GeV/c^2 (remember $E = mc^2$), where 1 GeV = 10^9 eV = 1.60×10^{-10} joule. The mass of the proton is 0.938 GeV/c^2 = 1.67×10^{-27} kg.



If the protons and neutrons in this picture were 10 cm across, then the quarks and electrons would be less than 0.1 mm in size and the entire atom would be about 10 km across.

BOSONS

force carriers
spin = 0, 1, 2, ...

Unified Electroweak spin = 1

Name	Mass GeV/c^2	Electric charge
γ photon	0	0
W^-	80.4	–1
W^+	80.4	+1
Z^0	91.187	0

Strong (color) spin = 1

Name	Mass GeV/c^2	Electric charge
g gluon	0	0

Color Charge

Each quark carries one of three types of "strong charge," also called "color charge." These charges have nothing to do with the colors of visible light. There are eight possible types of color charge for gluons. Just as electrically-charged particles interact by exchanging photons, in strong interactions color-charged particles interact by exchanging gluons. Leptons, photons, and ***W*** and ***Z*** bosons have no strong interactions and hence no color charge.

Quarks Confined in Mesons and Baryons

One cannot isolate quarks and gluons; they are confined in color-neutral particles called **hadrons**. This confinement (binding) results from multiple exchanges of gluons among the color-charged constituents. As color-charged particles (quarks and gluons) move apart, the energy in the color-force field between them increases. This energy eventually is converted into additional quark-antiquark pairs (see figure below). The quarks and antiquarks then combine into hadrons; these are the particles seen to emerge. Two types of hadrons have been observed in nature: **mesons** $q\bar{q}$ and **baryons** qqq.

Residual Strong Interaction

The strong binding of color-neutral protons and neutrons to form nuclei is due to residual strong interactions between their color-charged constituents. It is similar to the residual electrical interaction that binds electrically neutral atoms to form molecules. It can also be viewed as the exchange of mesons between the hadrons.

PROPERTIES OF THE INTERACTIONS

Property \ Interaction	Gravitational	Weak (Electroweak)	Electromagnetic (Electroweak)	Strong: Fundamental	Strong: Residual
Acts on:	Mass – Energy	Flavor	Electric Charge	Color Charge	See Residual Strong Interaction Note
Particles experiencing:	All	Quarks, Leptons	Electrically charged	Quarks, Gluons	Hadrons
Particles mediating:	Graviton (not yet observed)	W^+ W^- Z^0	γ	Gluons	Mesons
Strength relative to electromag for two u quarks at: 10^{-18} m	10^{-41}	0.8	1	25	Not applicable to quarks
Strength relative to electromag for two u quarks at: 3×10^{-17} m	10^{-41}	10^{-4}	1	60	
for two protons in nucleus	10^{-36}	10^{-7}	1	Not applicable to hadrons	20

Baryons qqq and Antibaryons $\bar{q}\bar{q}\bar{q}$

Baryons are fermionic hadrons.
There are about 120 types of baryons.

Symbol	Name	Quark content	Electric charge	Mass GeV/c^2	Spin
p	proton	uud	1	0.938	1/2
$\bar{p}$	anti-proton	$\bar{u}\bar{u}\bar{d}$	–1	0.938	1/2
n	neutron	udd	0	0.940	1/2
Λ	lambda	uds	0	1.116	1/2
Ω^-	omega	sss	–1	1.672	3/2

Mesons $q\bar{q}$

Mesons are bosonic hadrons.
There are about 140 types of mesons.

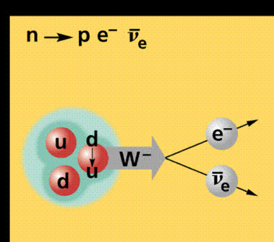
Symbol	Name	Quark content	Electric charge	Mass GeV/c^2	Spin
π^+	pion	$u\bar{d}$	+1	0.140	0
K^-	kaon	$s\bar{u}$	–1	0.494	0
ρ^+	rho	$u\bar{d}$	+1	0.770	1
B^0	B-zero	$d\bar{b}$	0	5.279	0
η_c	eta-c	$c\bar{c}$	0	2 .980	0

Matter and Antimatter

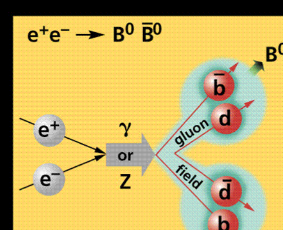
For every particle type there is a corresponding antiparticle type, denoted by a bar over the particle symbol (unless + or – charge is shown). Particle and antiparticle have identical mass and spin but opposite charges. Some electrically neutral bosons (e.g., Z^0, γ, and $\eta_c = c\bar{c}$, but not $K^0 = d\bar{s}$) are their own antiparticles.

Figures

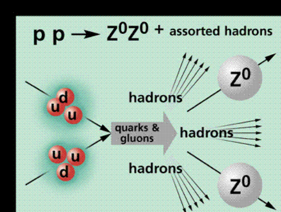
These diagrams are an artist's conception of physical processes. They are *not* exact and have *no* meaningful scale. Green shaded areas represent the cloud of gluons or the gluon field, and red lines the quark paths.



A neutron decays to a proton, an electron, and an antineutrino via a virtual (mediating) W boson. This is neutron β decay.



An electron and positron (antielectron) colliding at high energy can annihilate to produce B^0 and $\bar{B}^0$ mesons via a virtual Z boson or a virtual photon.



Two protons colliding at high energy can produce various hadrons plus very high mass particles such as Z bosons. Events such as this one are rare but can yield vital clues to the structure of matter.

The Particle Adventure

Visit the award-winning web feature *The Particle Adventure* at
http://ParticleAdventure.org

This chart has been made possible by the generous support of:
U.S. Department of Energy
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Lawrence Berkeley National Laboratory
Stanford Linear Accelerator Center
American Physical Society, Division of Particles and Fields
BURLE INDUSTRIES, INC.

http://CPEPweb.org

THE MYSTERY OF MASS

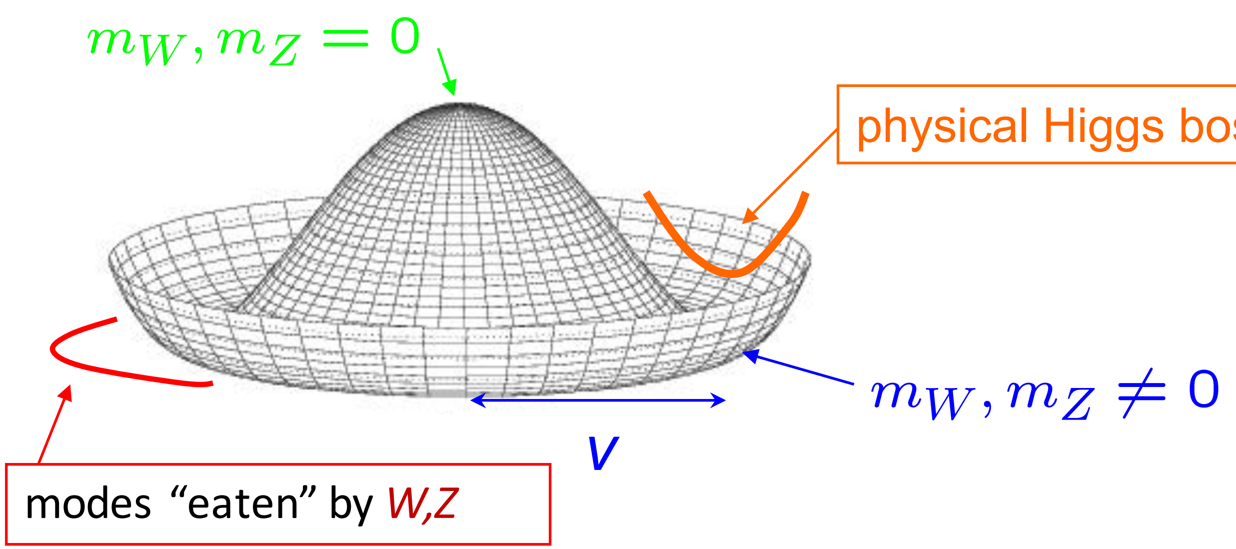
quarks leptons

The reason **could** be the existence of a new particle, called the **“Higgs boson”**

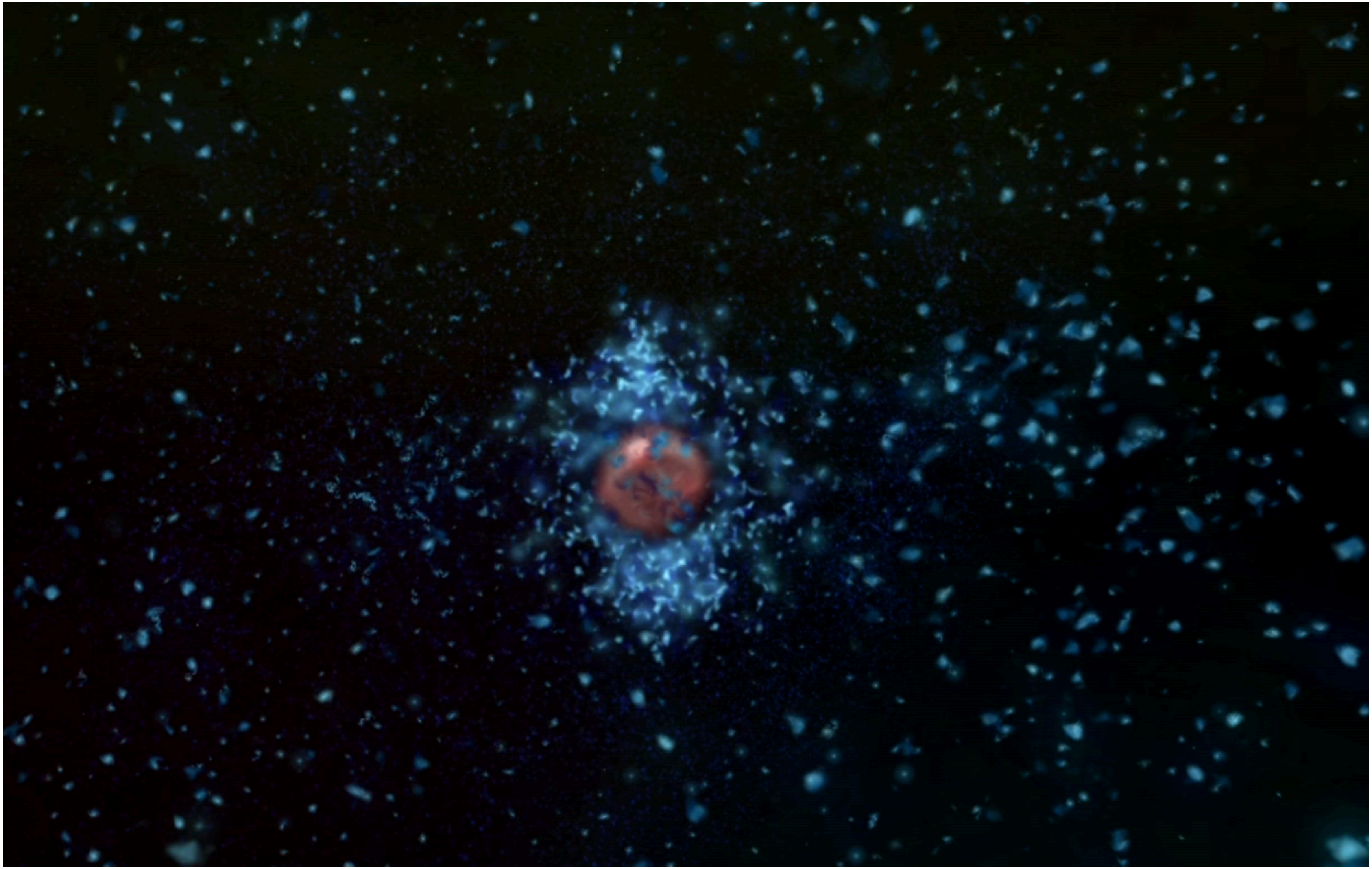
Standard model and Higgs boson

- The Standard Model SU(3)×SU(2)×U(1) of electroweak and strong interactions extermly well confirmed and measured since ~ 30 years
  - But still incomplete and non-satisfactory …
- All particles acquire mass by interaction with scalar particle → Higgs boson
- Higgs mechanism

Brout, Englert, Guralnik, Hagen, Higgs, Kibble (1964)

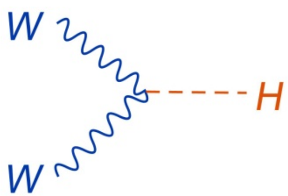


The Higgs mechanism

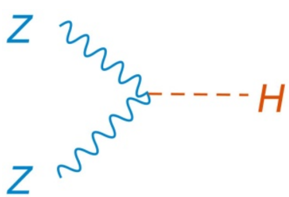


Basic Higgs Properties

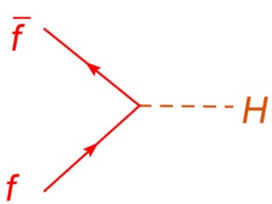
- Spin = 0 particle
- Giving masses to all particles
  - Coupling proportional to particle masses



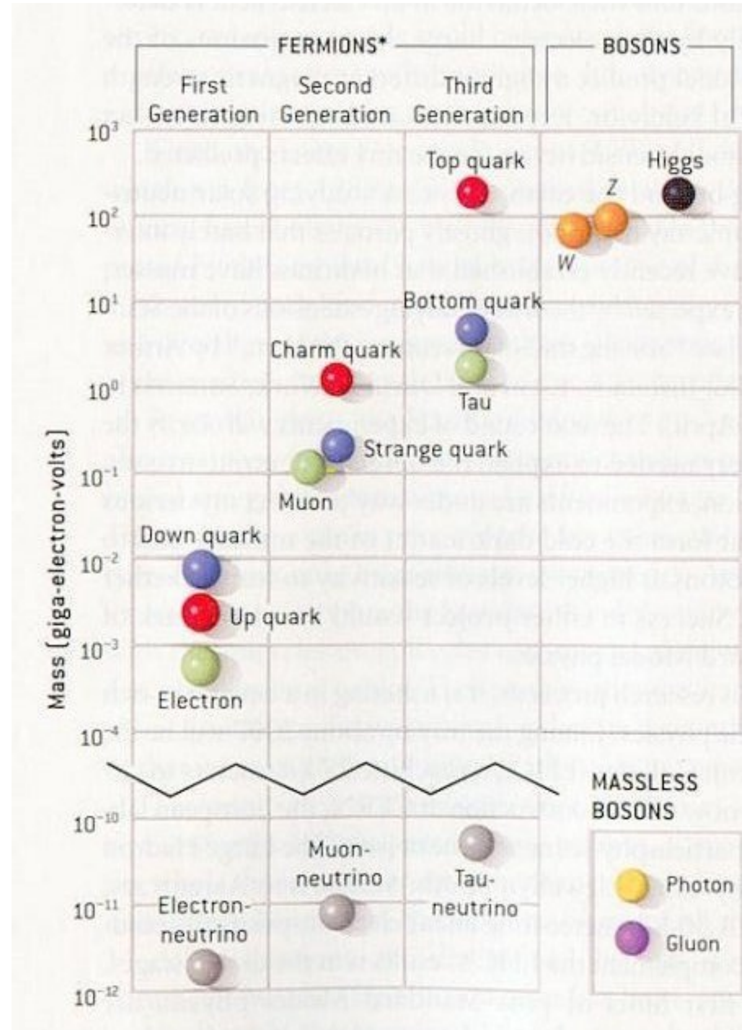
$$2\frac{m_W^2}{v}\eta^{\mu\nu}$$



$$2\frac{m_Z^2}{v}\eta^{\mu\nu}$$



$$\frac{m_f}{v}$$



- Self interaction
  - Self interacting term in the Lagrangian

Higgs mass: theoretical constraints

- Problem: Higgs mass is free parameter

$$M_H^2 = 2\lambda v^2 \quad \ldots\ldots \quad v = 246\ \mathrm{GeV}$$

- Theoretical constraints
  - **Unitarity** (no probabilities > 1)

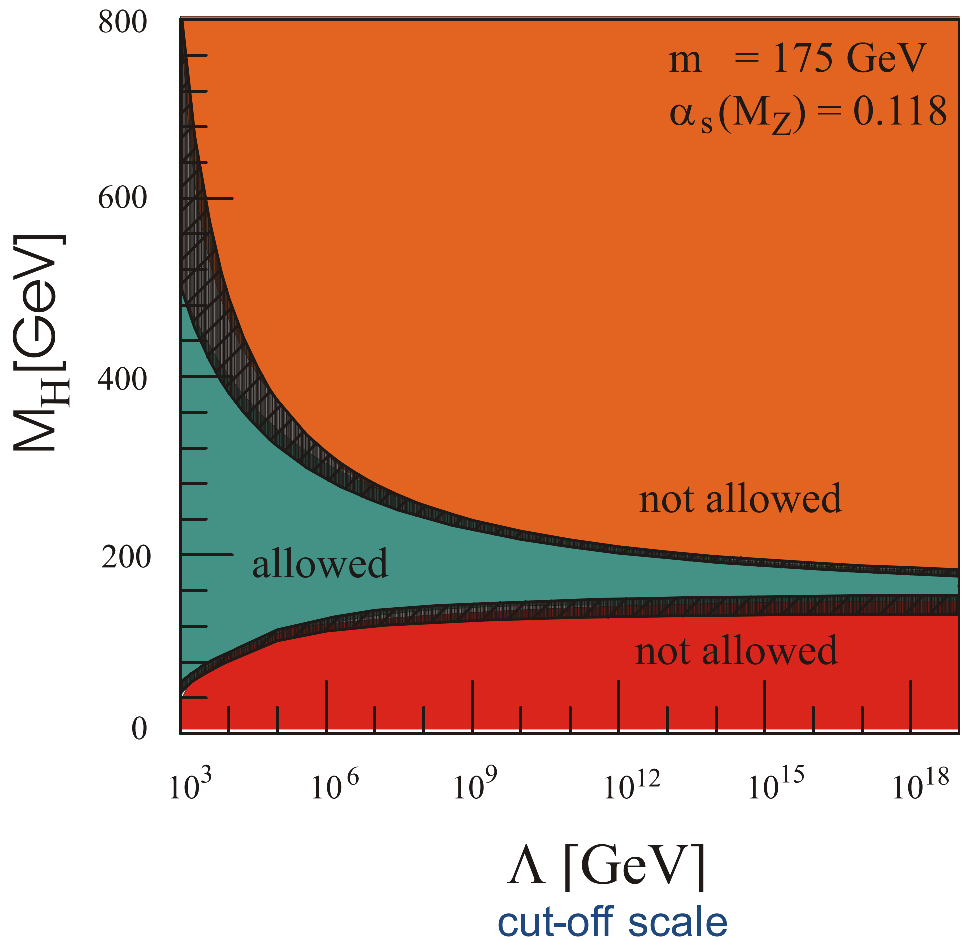
$$M_{\mathrm{H}} < 700 - 800\ \mathrm{GeV}$$

  - **Triviality**
    (Higgs self coupling remains finite)

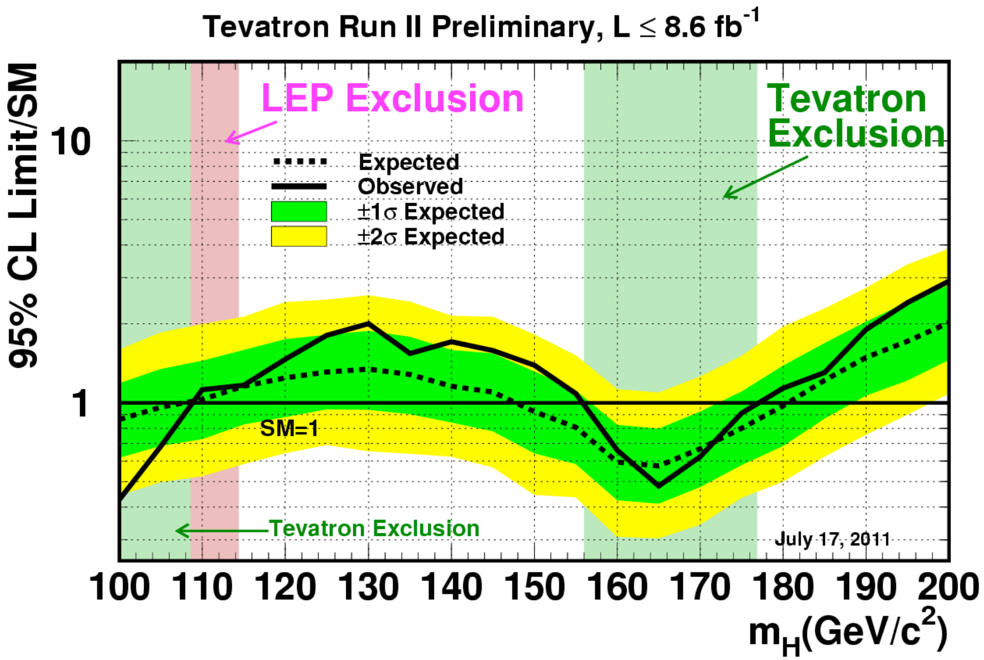
$$M_H^2 < \frac{4\pi v^2}{3\ln(\Lambda/v)}$$

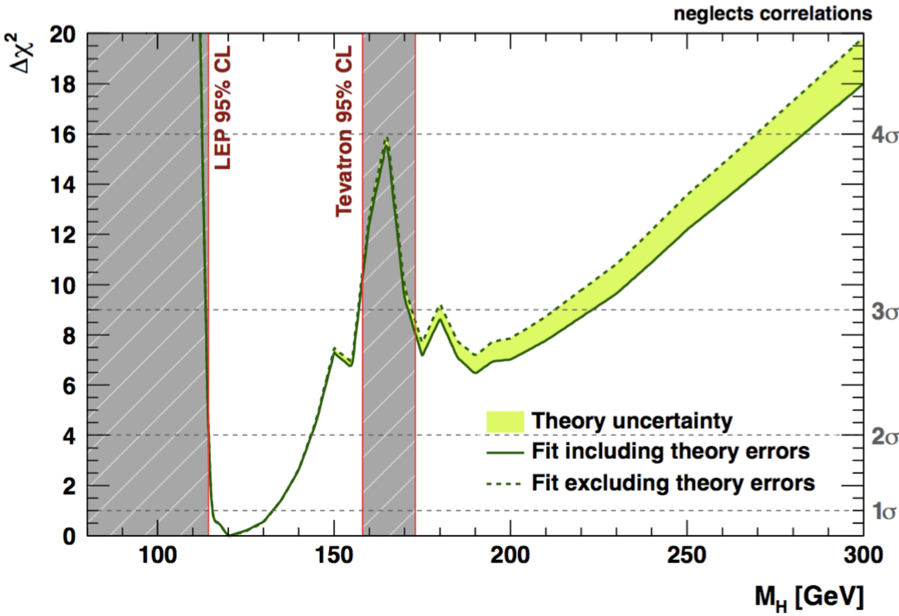
  - **Stability** (of vacuum)

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



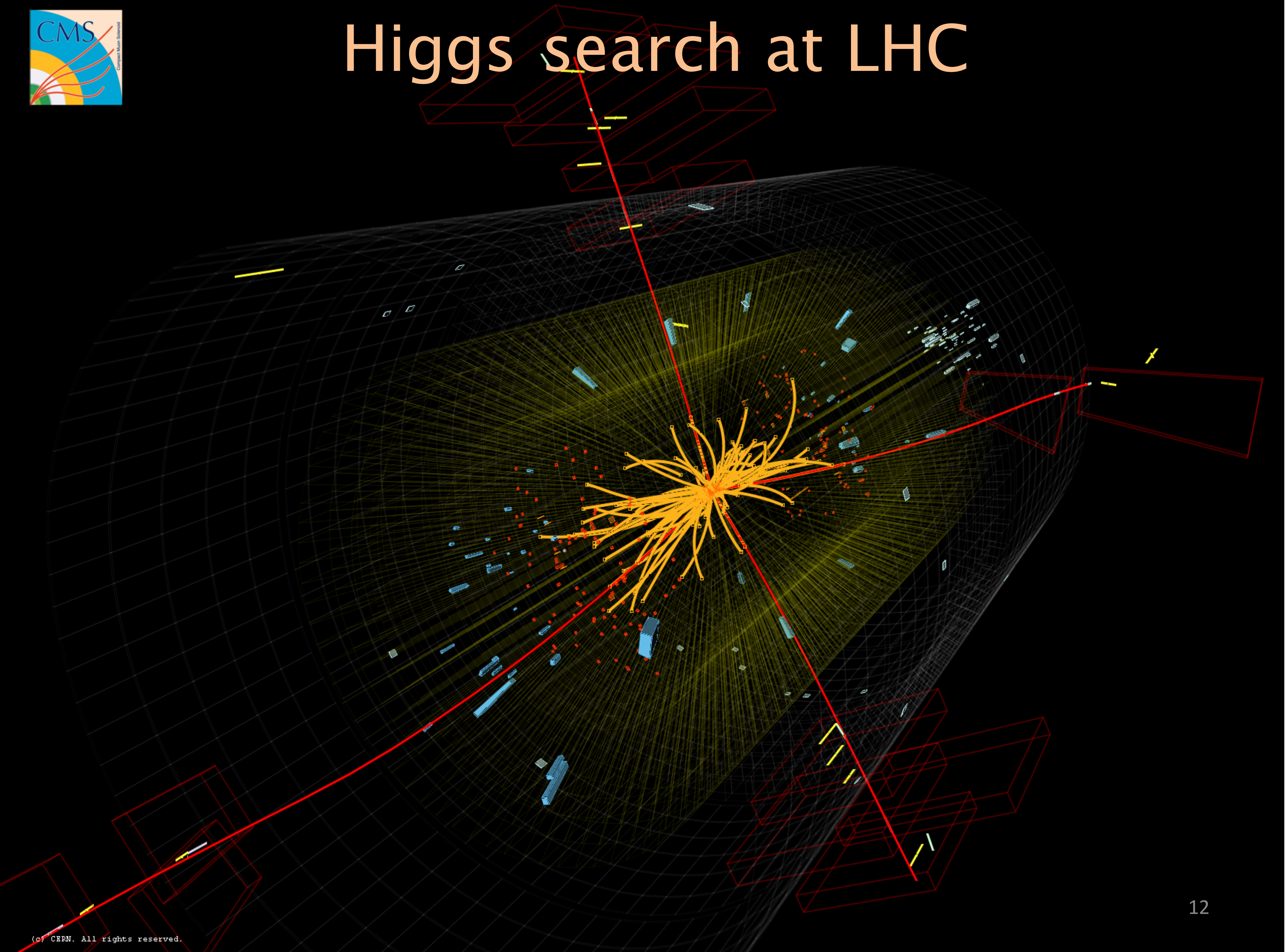
SM Higgs before LHC





- Direct searches
  - LEP: $M_H > 114.4$ GeV
  - Tevatron: 156 GeV < M_H <176 GeV
- Indirect limits from electroweak searches
  - $M_H = 96^{+31}_{-24}$ GeV, M_H<169 GeV at 95% CL (standard fit)
  - $M_H = 120^{+12}_{-5}$ GeV ,M_H<143 GeV at 95% CL (including direct searches)
- SUSY prefers light Higgs boson (<~140 GeV)

Higgs search at LHC

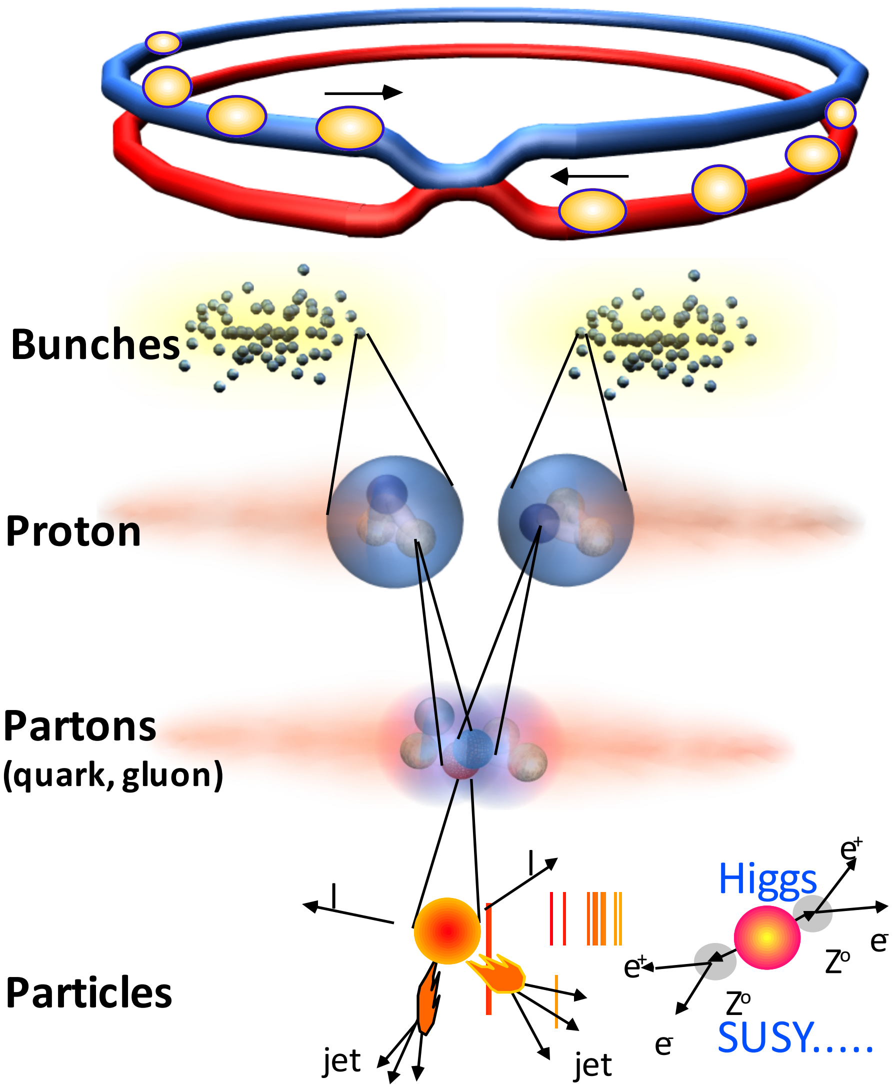


Some of the physicists' jargon

- **Cross section** (σ)
  - A measure of 'frequency' of the physical process
  - Units: barns (10^{-28} m^2)
    - Typical values: femtobarns (fb), picobarns (pb)
- **Luminosity** (L)
  - Or *instantenous luminosity*
  - A measure of collisions 'frequency'
    - Typical at LHC: $L = 10^{34}\ cm^{-2}s^{-1}$
- **Integrated luminosity** ($\mathcal{L} = \int L dt$)
  - A measure of number of accumulated collisions after a certain time period
  - Units: $(\text{cross section})^{-1}$ …. E.g. $1\ fb^{-1} = 1000\ pb^{-1}$
    - Tipical at LHC: few fb^{-1}
- **Number of events** (N)
  - Number of (expected) events (N) after a certain time of running

$$N = \sigma \cdot \mathcal{L}$$

Collisions in LHC

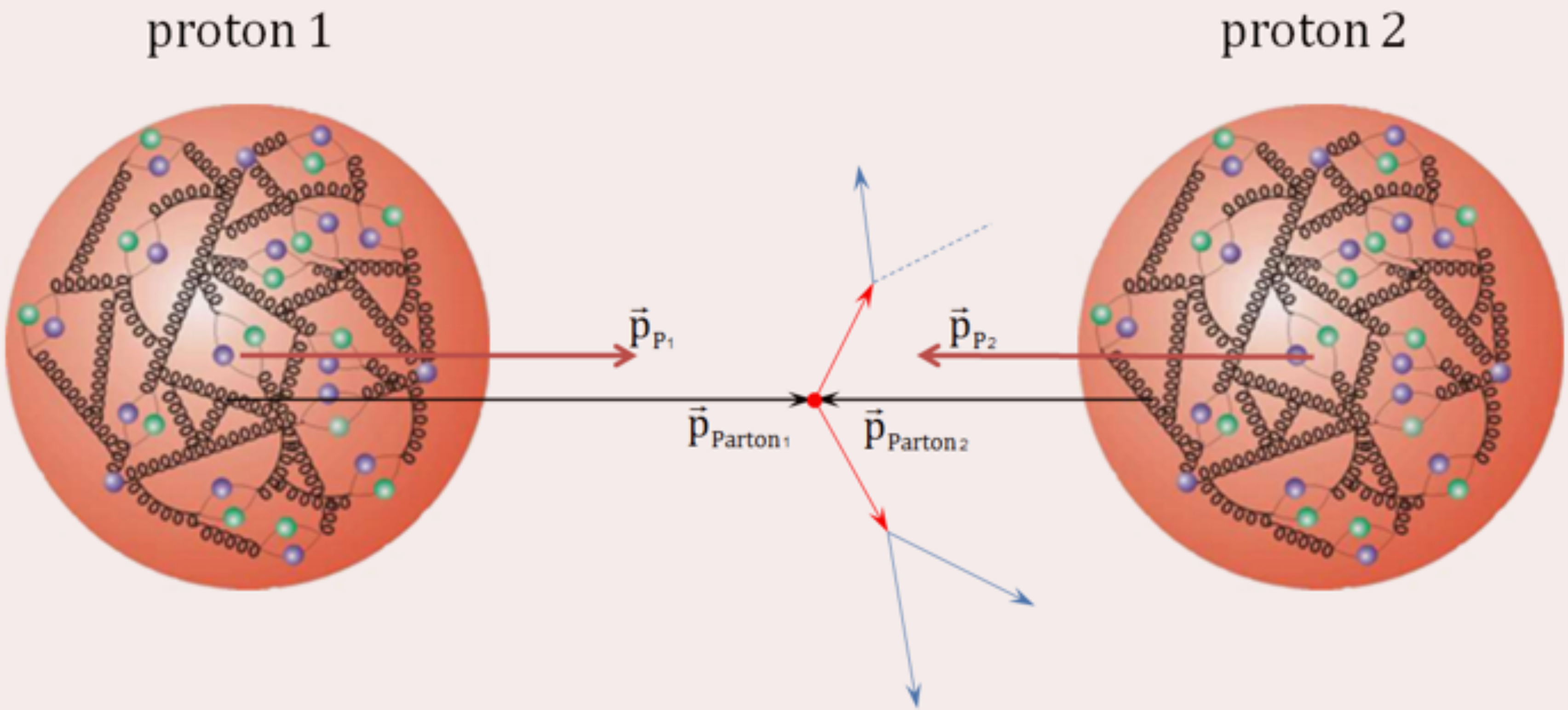


Proton - Proton	1300 bunches/beam
Protons/bunch	10^{11}
Beam energy	4 TeV (7×10^{12} eV)
Luminosity	10^{34} cm^{-2} s^{-1}
Bunch collision frequency	20 MHz
Proton collision frequency	10^{7} - 10^{9} Hz

"New physics" frequency .00001 Hz

Event selection:
1 u 10 000 000 000 000

Interactions of constituents of the colliding protons, the so called partons (quarks, gluons)



$\vec{p}_{P_1}$ ... momentum proton 1

$\vec{p}_{P_1}$ ... momentum proton 2

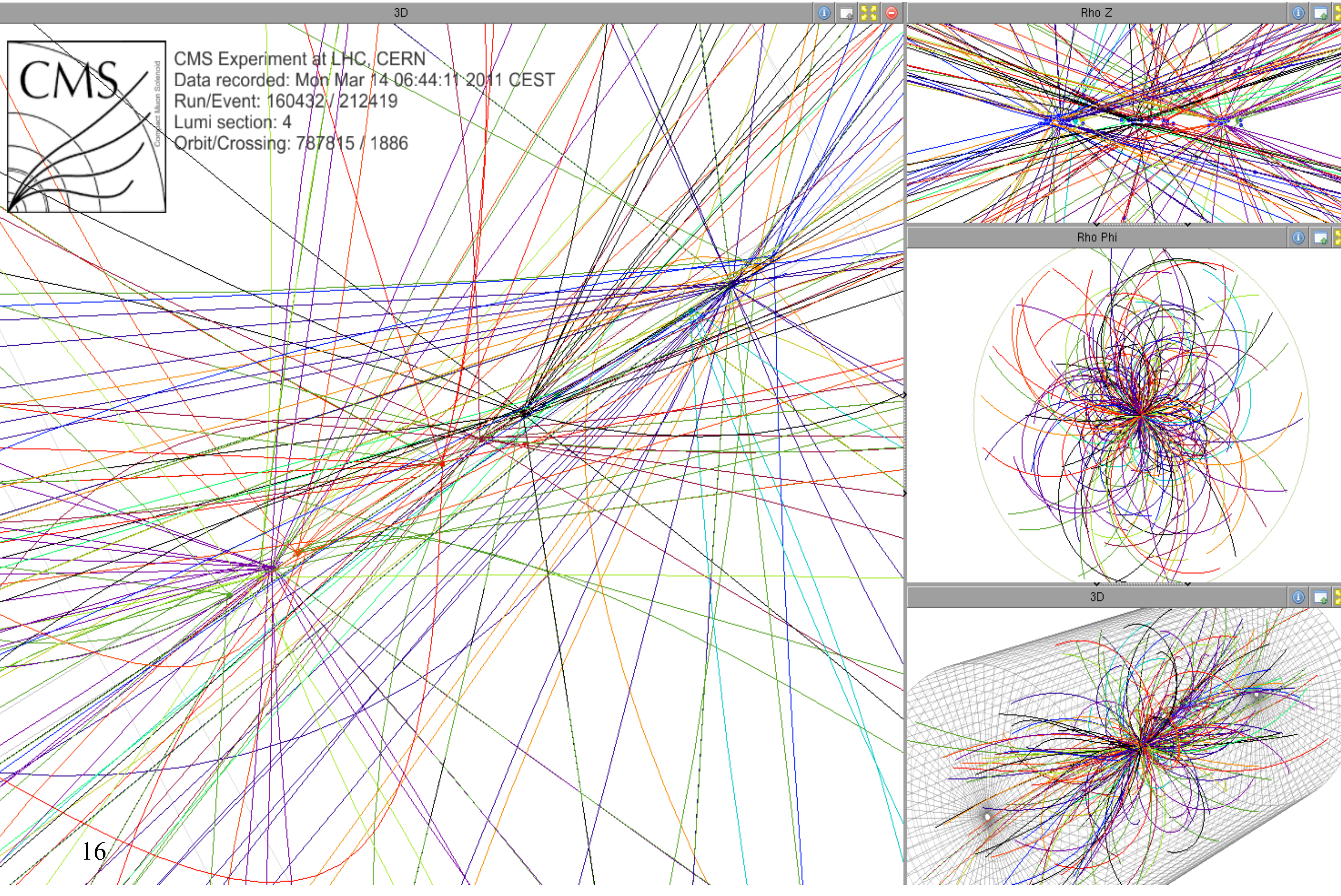
• interaction vertex

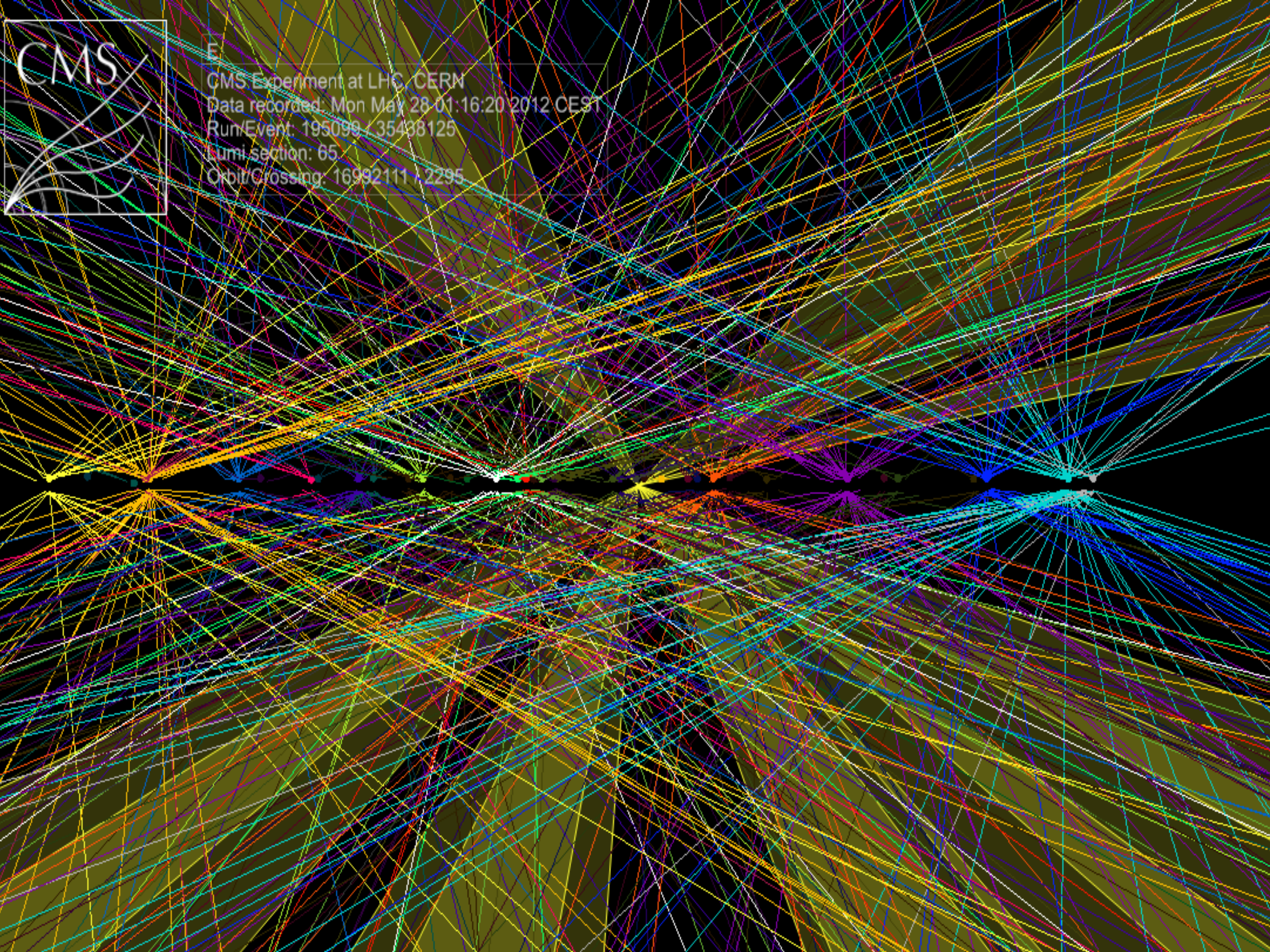
$\vec{p}_{Parton_1}$ ... momentum parton 1

$\vec{p}_{Parton_2}$ ... momentum parton 2

High luminosity: multiple interactions

PILE-UP




CMS
E
CMS Experiment at LHC, CERN
Data recorded: Mon May 28 01:16:20 2012 CEST
Run/Event: 195099 / 35438125
Lumi section: 65
Orbit/Crossing: 16992111 / 2295

Our main goal

- Finding something new

- But:
  - New things are very rare
  - Otherwise someone else would have found them already

Data analysis – general picture

1 **Physical phenomena**

Described by a theory

Described by PDFs, depending on p **uknown** parameters with **true values**

$$\boldsymbol{\theta}^{true} = (\theta_1^{true}, \theta_2^{true}, \ldots, \theta_p^{true})$$

For example:

$$\boldsymbol{\theta}^{true} = (m_H^{true}, \Delta m_s^{true}, \ldots, \sigma_{tot}^{true})$$

2 **Sampling a reality**

Experiment

3 **Data sample**

$$\boldsymbol{x} = (x_1, x_2, \ldots, x_N)$$

For example:

$$\boldsymbol{x} = (event_1, \ldots, event_N)$$

In statistics $\boldsymbol{x}$ is a multivariate **random variable** *(each event has many properties, all potential variables)*

4 **Data analysis**

5 **Results**

- parameter estimates
- confidence limits
- hypothesis tests

Data analysis – another look

The main goal:
learn more about NATURE

Make an experiment and obtain a DATA SAMPLE

For example, let's suppose the TRUE state of nature is:
Higgs boson exists with the mass of m_H(true) = 134.26 GeV

Use data sample to examine this!

Events collected after some time of LHC running
Event 1
Event 2
...
Event N

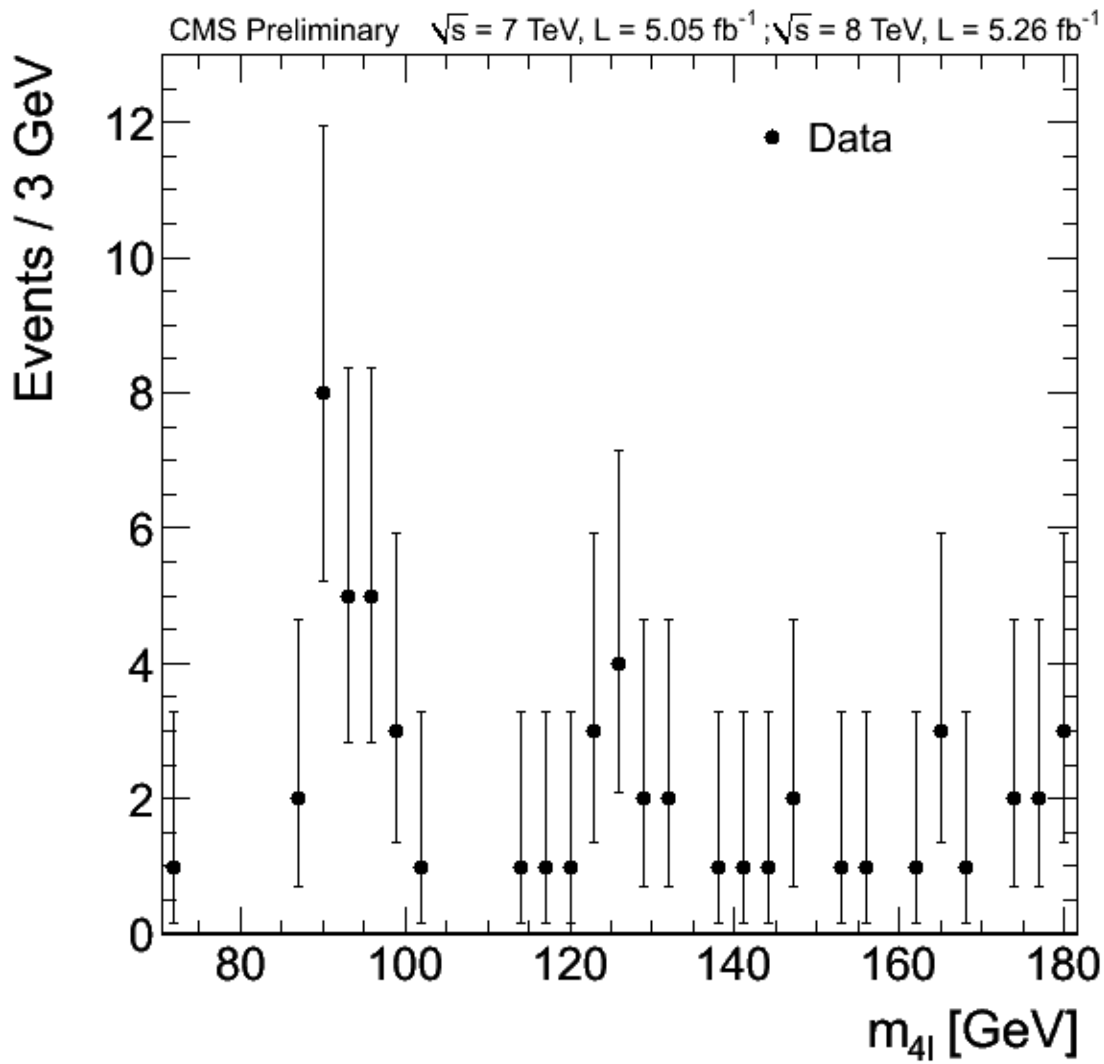
Event 1
Object 1
Object 2
...
Object k

If Object 1 == electron
p_x
p_y
p_z
E
...

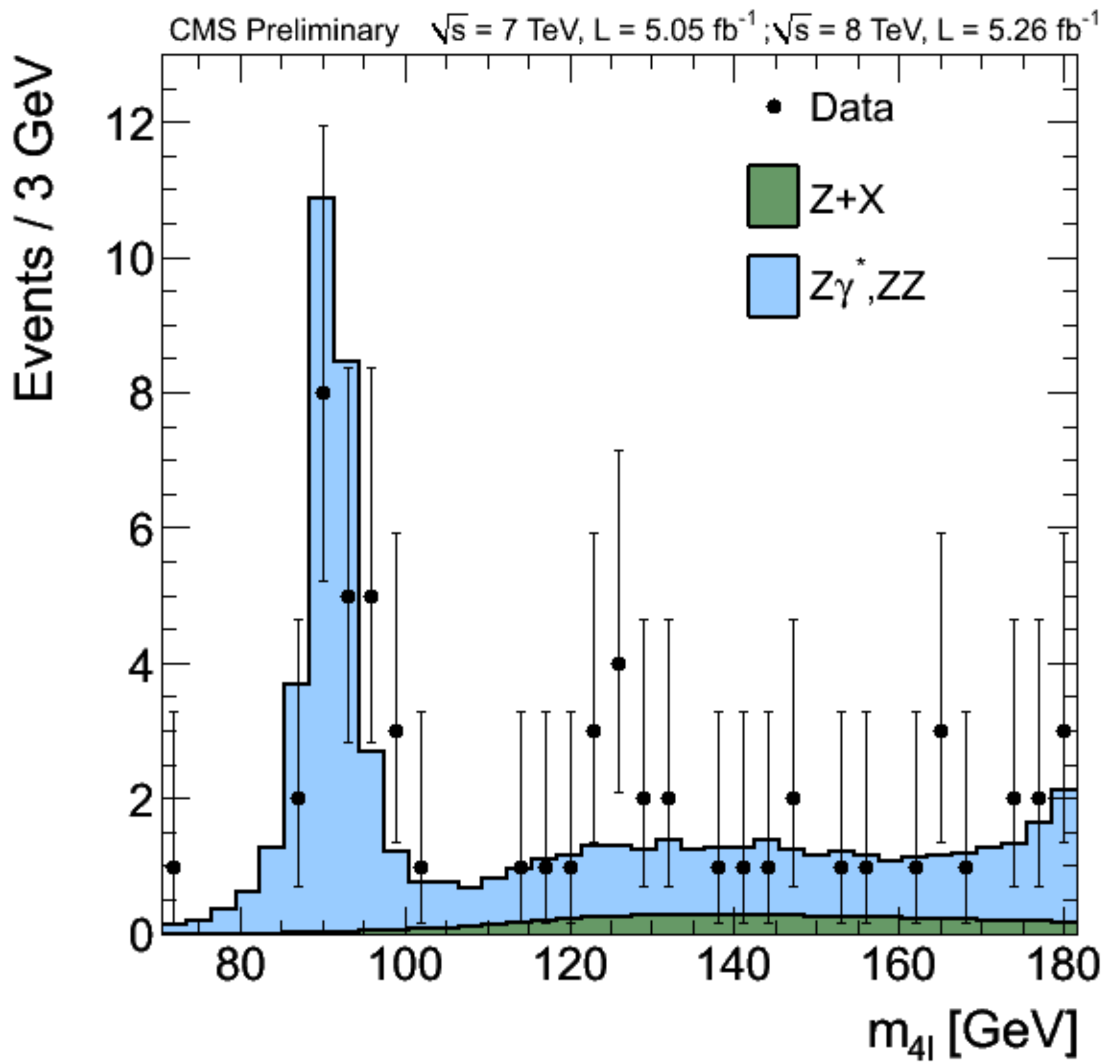
N ~ 100/s x 10^7 s/year
N ~ 10^9 events per year

Objects ≡ reconstructed objects
i. e. electrons, photons, jets, muons ...

Measured


CMS Preliminary √s = 7 TeV, L = 5.05 fb-1 ; √s = 8 TeV, L = 5.26 fb-1
Events / 3 GeV
Data
0
2
4
6
8
10
12
80
100
120
140
160
180
m4l [GeV]

Measured + predicted/expected



Measurements vs predictions

Predictions/Simulation	Measurements
Event Generation	**Collisions**
Tools: **MC** generators (PYTHIA, ...)	*Tools:* Accelerator (LHC, Tevatron ...)
Output: final state particles	*Output:* final state particles
↓	↓
Detector simulation	**Data acquisition**
Tools: **MC** simulators (GEANT)	*Tools:* Detectors (CMS, ATLAS,...)
Output: simulated detector response	*Output:* detector response
↓	↓

Event reconstruction

Tools: Detectors' software packages (custom made; **MC** used in algorithms)

Output: reconstructed physical objects (electrons, muons, jets ...)

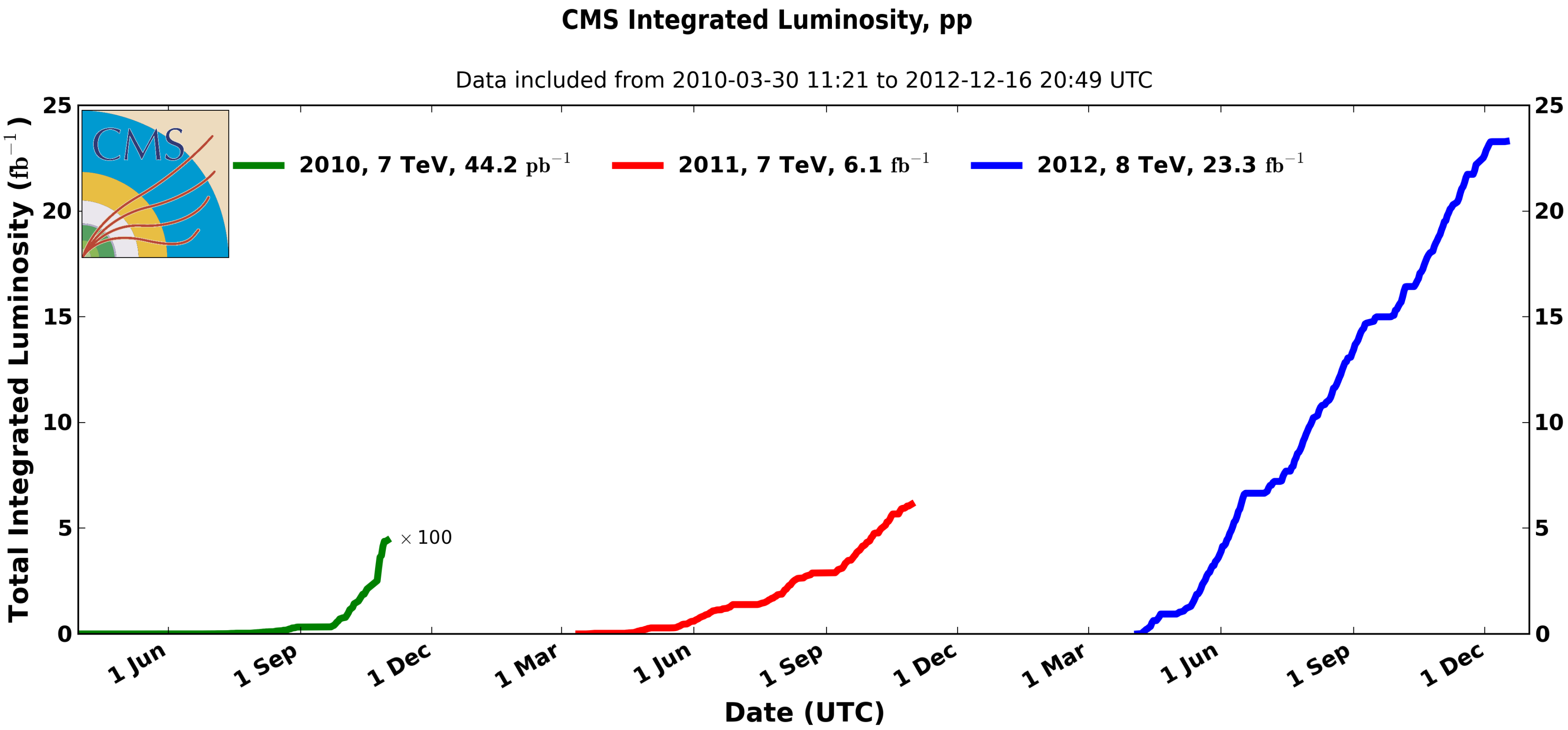
↓ ↓

Data analysis

Tools: Statistics (ROOT, ...; **MC** used in algorithms; f.g. **Toy MC**)

Output: new knowledge (parameter/interval estimates, hypothesis tests, article, talks ...)

Data collected by CMS



When we see something interesting

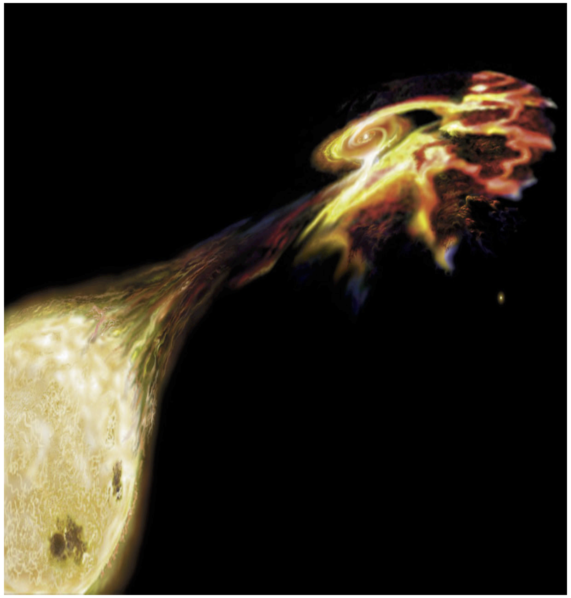
- Is it something new?
- Or it can be explain with what we already know ?
- Use the **Occam's razor** as a guideline

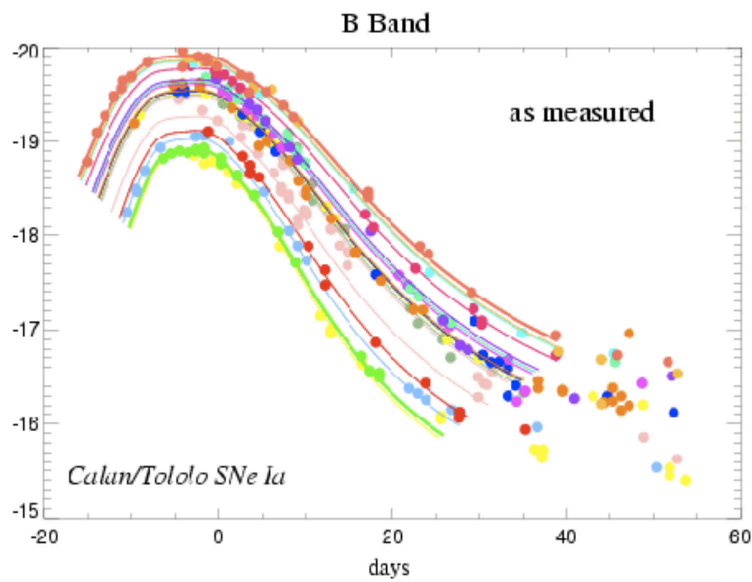
What does it mean for our instruments?

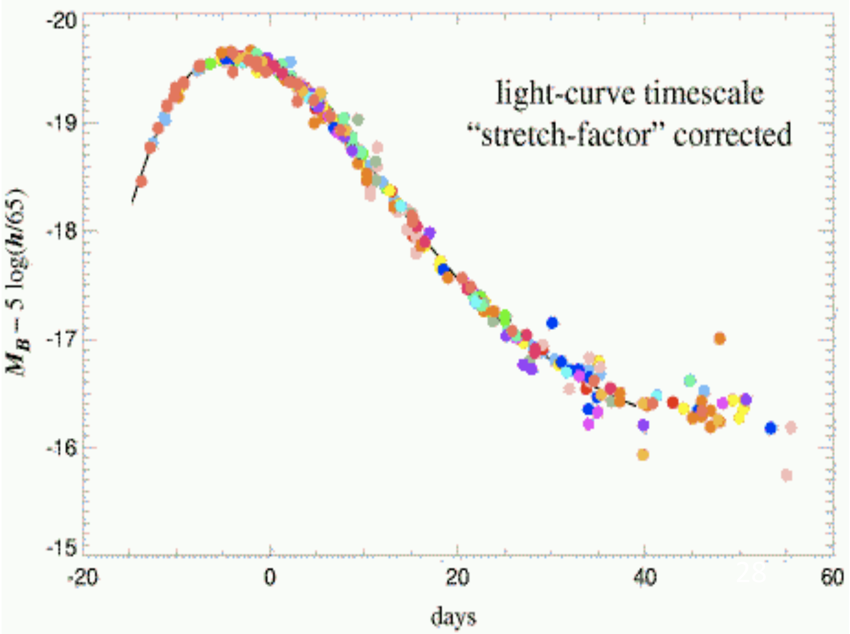
- We need to calibrate them
  - By mesuring something we know very well
- Then when we see someting interesting → chances that it is something new are much larger
  - With respect to chances that it’s a simple bug ☺
- Be aware:
  - we will never be **absolutely** sure
  - But we can be **pretty** sure
  - What does the “pretty” really mean?

Standard candle

Type Ia Super Novae as standard candles



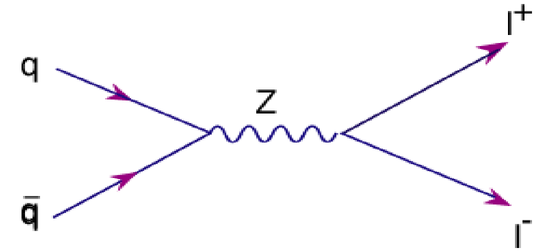


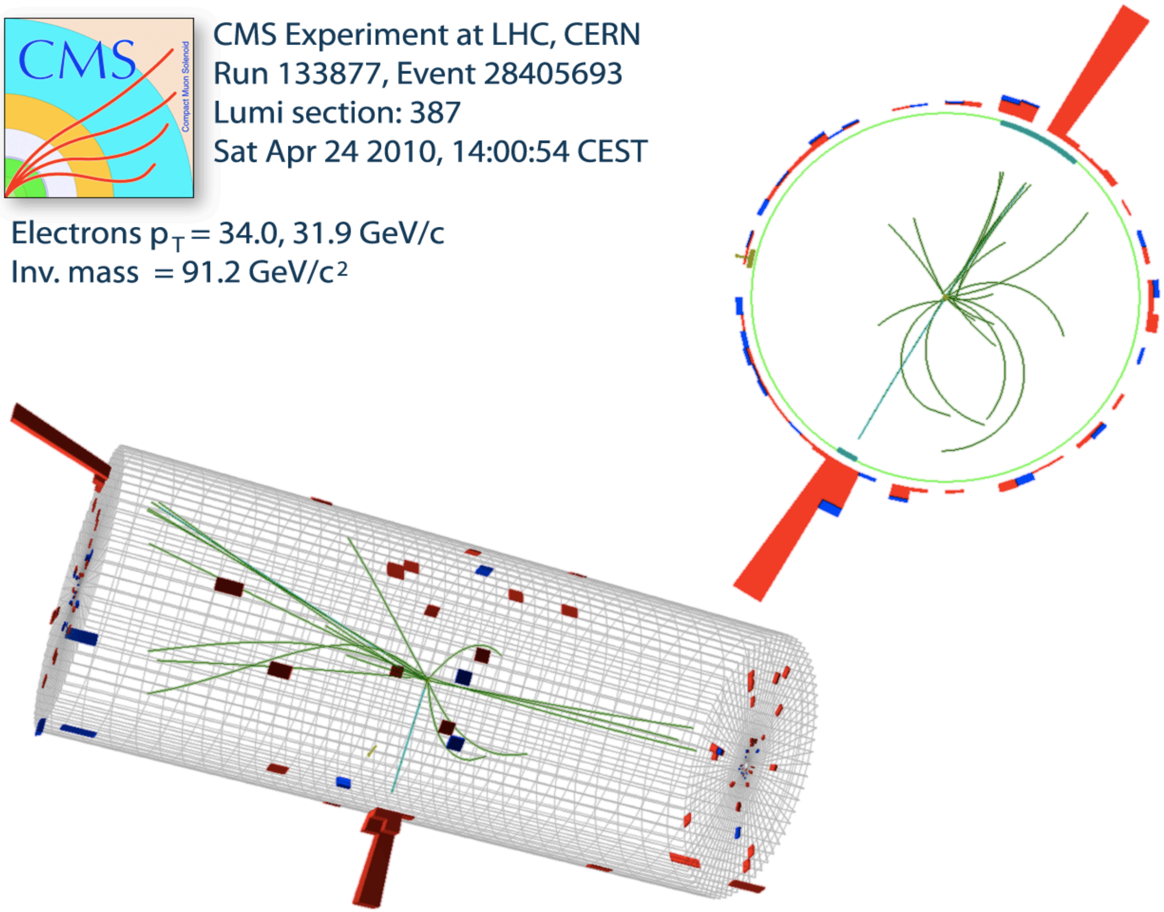


- They show a light curve shape - luminosity relation : brighter – slower
- They also exhibit a color-luminosity relation: brighter-bluer
- Standardisation : after empirical correction :
    - 16% dispersion on L_{peak}
    - 8% precision on distance d_L

From D. Denegri

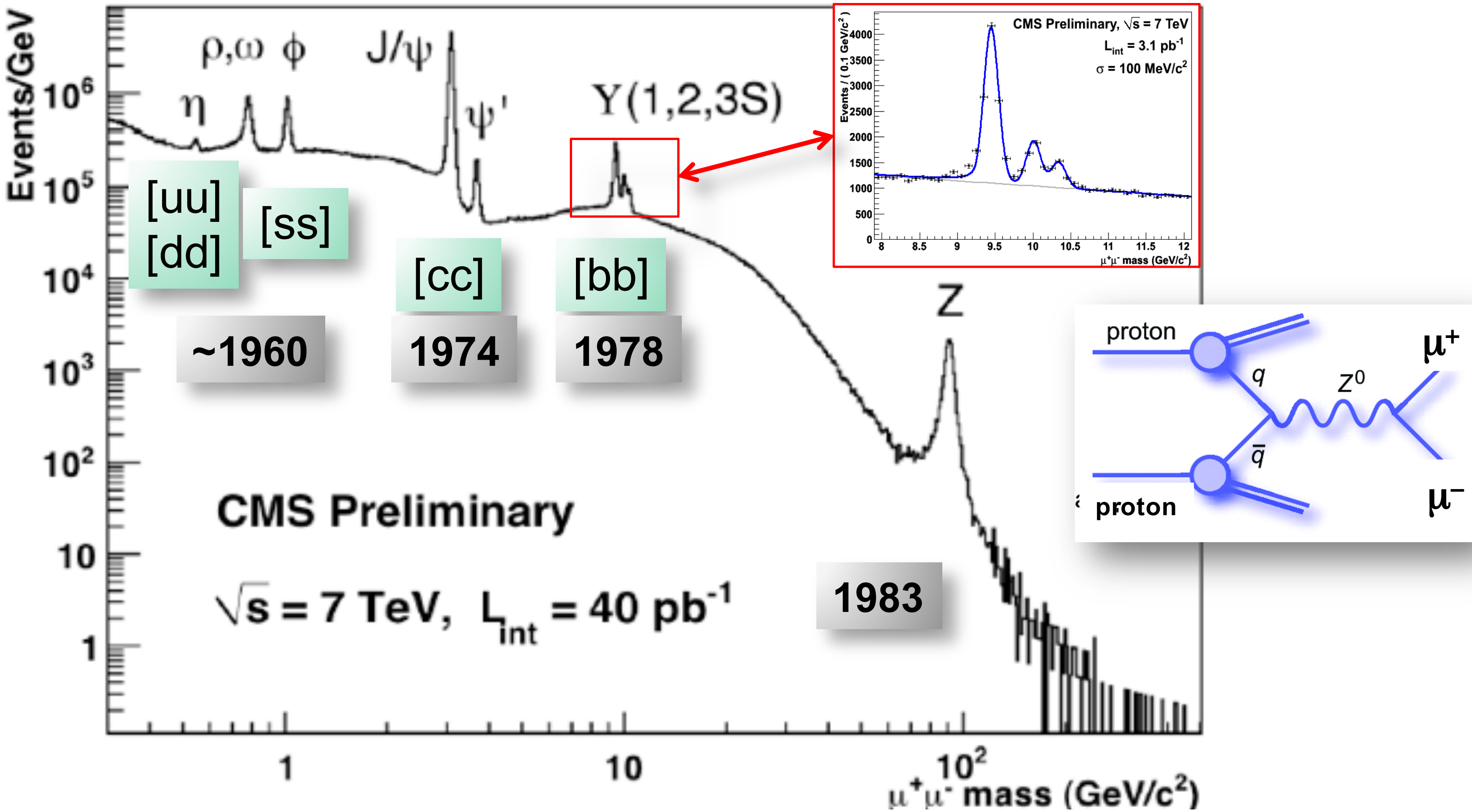
Standard candle at LHC





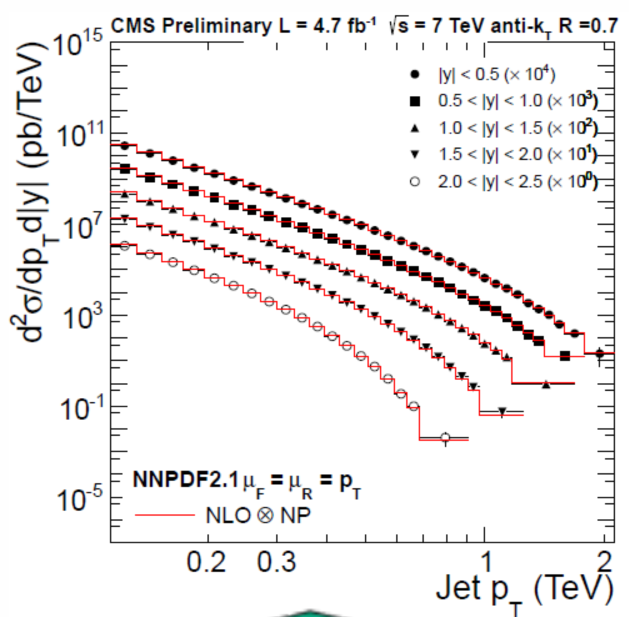
From D. Denegri

Re-discovery of the Standard Model



40 pb^{-1} collected in 2010

Standard Model: Precision Jets, W, and γ^*/Z

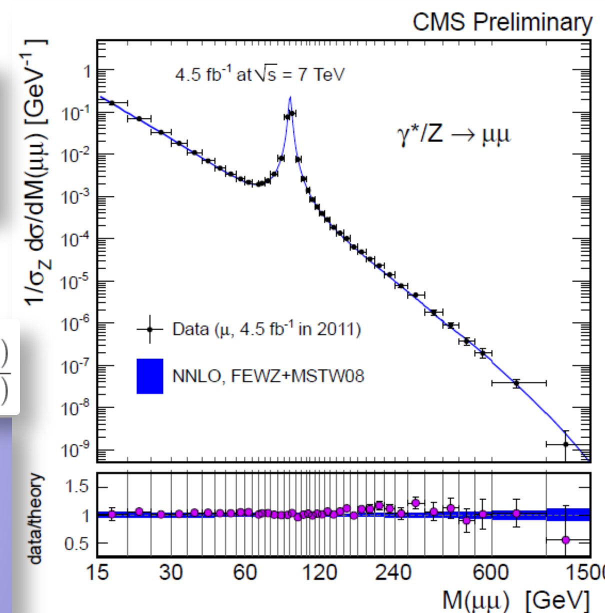


See talk Maria Cepeda Hermida
W and Z physics at the LHC

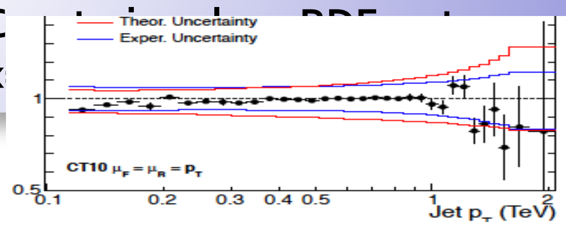
CMS-PAS-SMP-12-001

$$A(\eta) = \frac{d\sigma/d\eta(W^+ \to \ell^+\nu) - d\sigma/d\eta(W^- \to \ell^-\bar{\nu})}{d\sigma/d\eta(W^+ \to \ell^+\nu) + d\sigma/d\eta(W^- \to \ell^-\bar{\nu})}$$

W electron charge asymmetry measured to 0.5-1% per bin of 0.1 in Δη. Constrains u/d PDF ratio

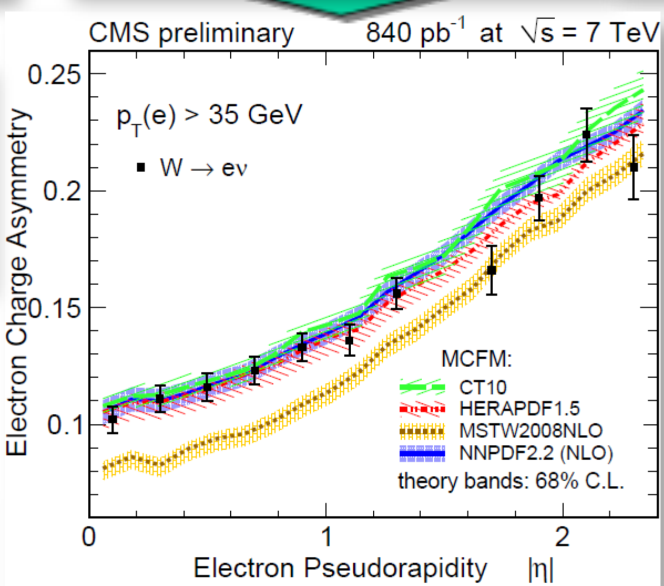


Inclusive jet and dijets. 2-4% JES.



CMS-PAS-QCD-11-004

See talk by Darko Mekterovic
Direct photon and jet properties



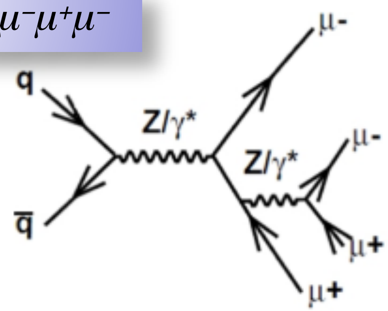
Differential Drell-Yan cross section: 2.5M μμ pairs tests NNLO cross sections and PDFs

CMS-PAS-EWK-11-007

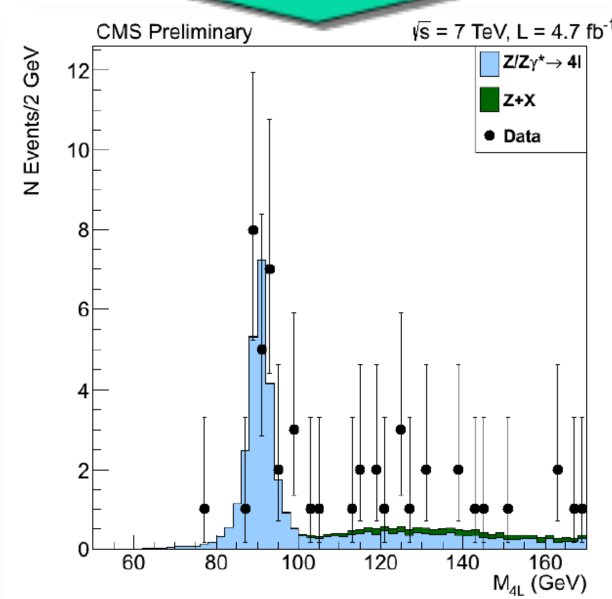
See talk by Norbert Neumeister
Measurement of Drell-Yan Cross Section

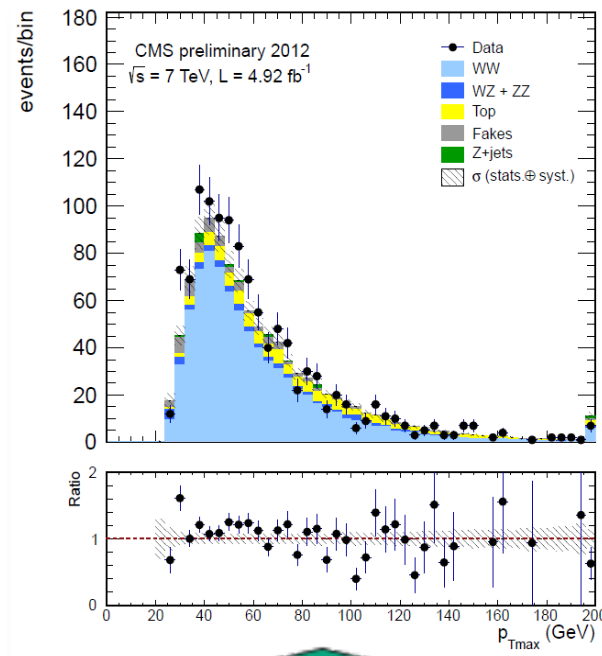
Standard Model: ‘rare’ processes

$Z \rightarrow \mu^+\mu^-\mu^+\mu^-$



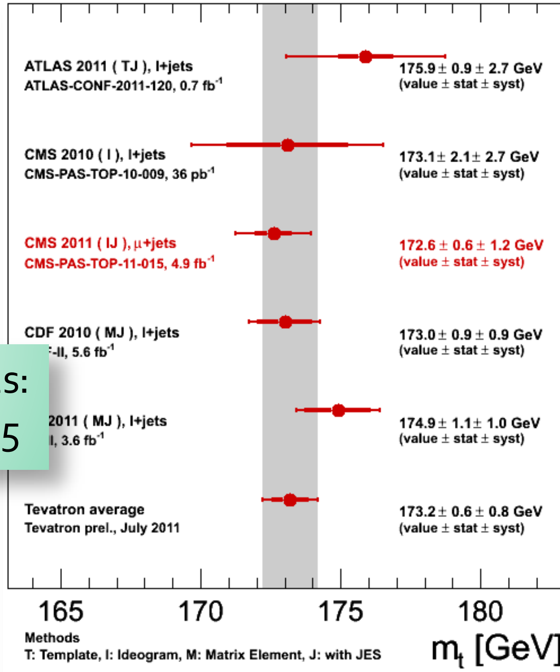
4-fermion *Z→llll* decays observed at a hadron collider! (BR = $4.4 \cdot 10^{-6}$), $\sigma \approx 125 \pm 26$ fb





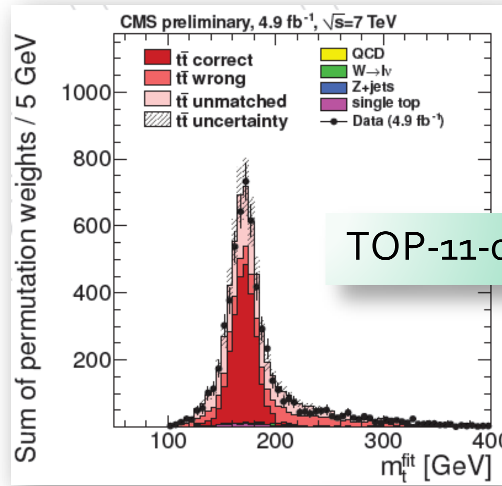
800 *WW→lνlν* events observed in 2011, ±10% xsec precision. Constrains Higgs backgrounds and anomalous trilinear electroweak couplings

Top mass

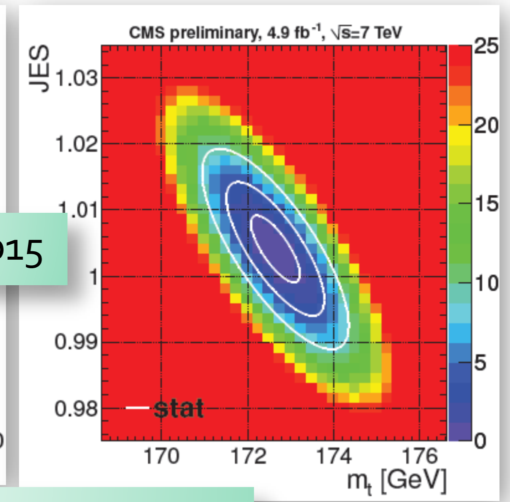


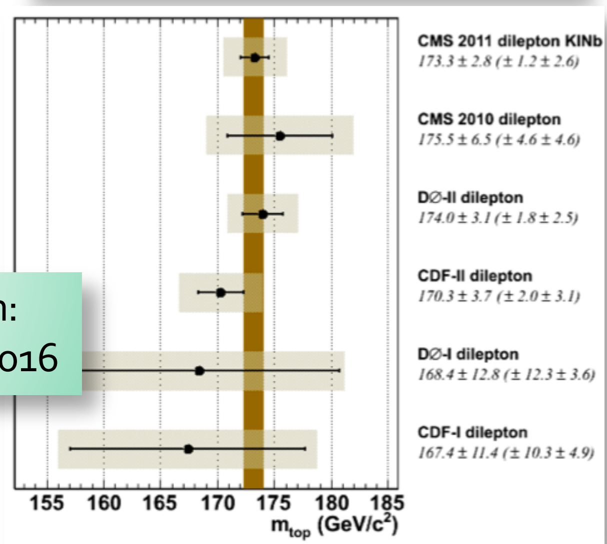
Lepton+jets: TOP-11-015

CMS average: 172.6 ± 0.4 ± 1.2 GeV



TOP-11-015





Dilepton: TOP-11-016

CMS μ+Jets analysis

m_t = ... (syst) GeV

JES = 1.004 ± 0.005(stat) ± 0.012(syst)

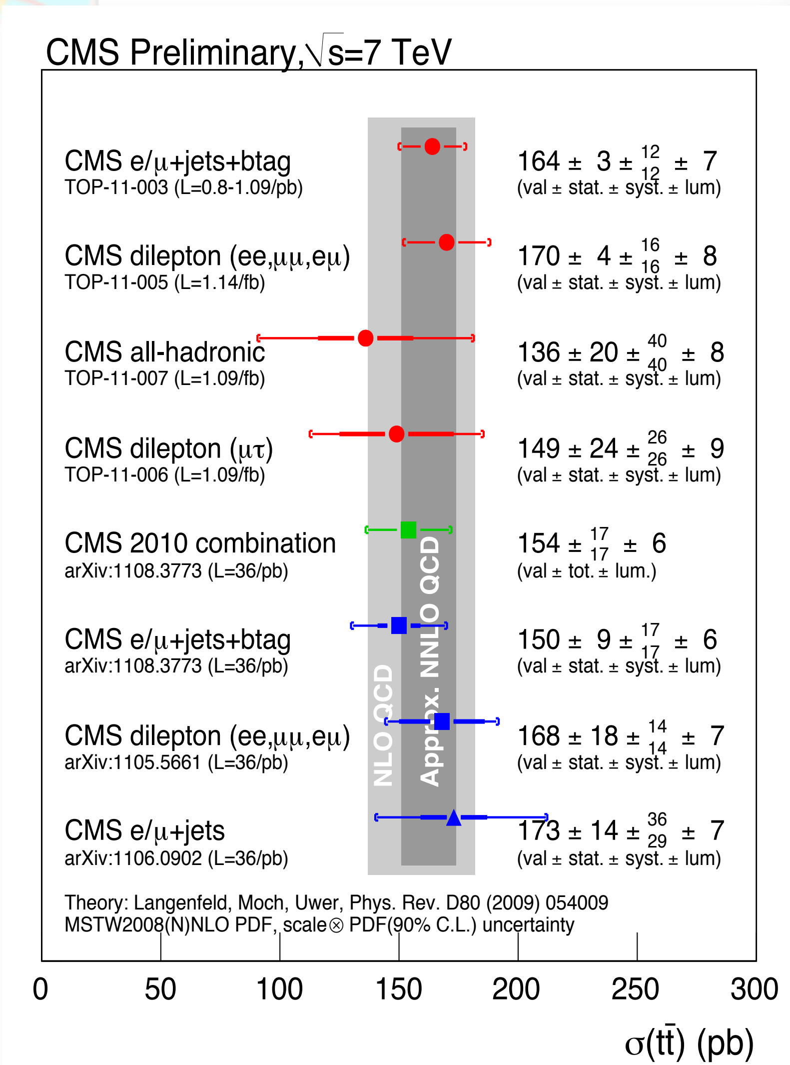
~1.3 (syst) GeV including color reconnection

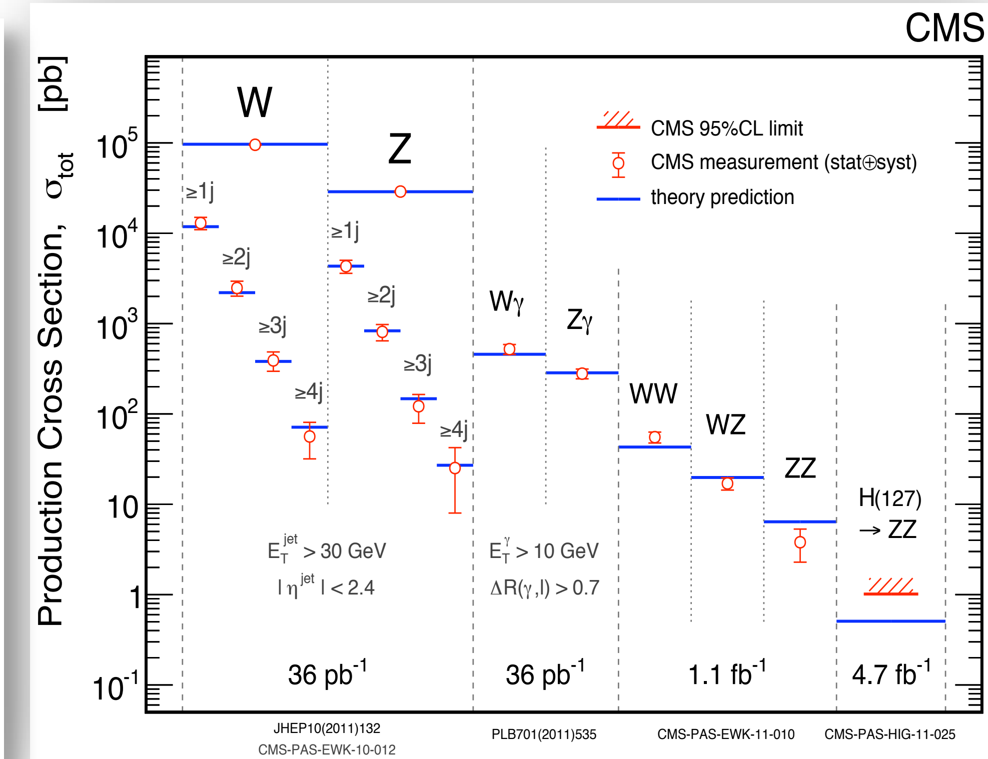
Underlying Event expected to be small

Cross-check: 44660

After applying the calibration, we obtain a top quark mass from 44660 events of $m_t = 172.6 \pm 0.2$ (stat) ± 1.8 (syst) GeV which confirms the result obtained in the main analysis.

Standard Model at 7 TeV 2010-2012

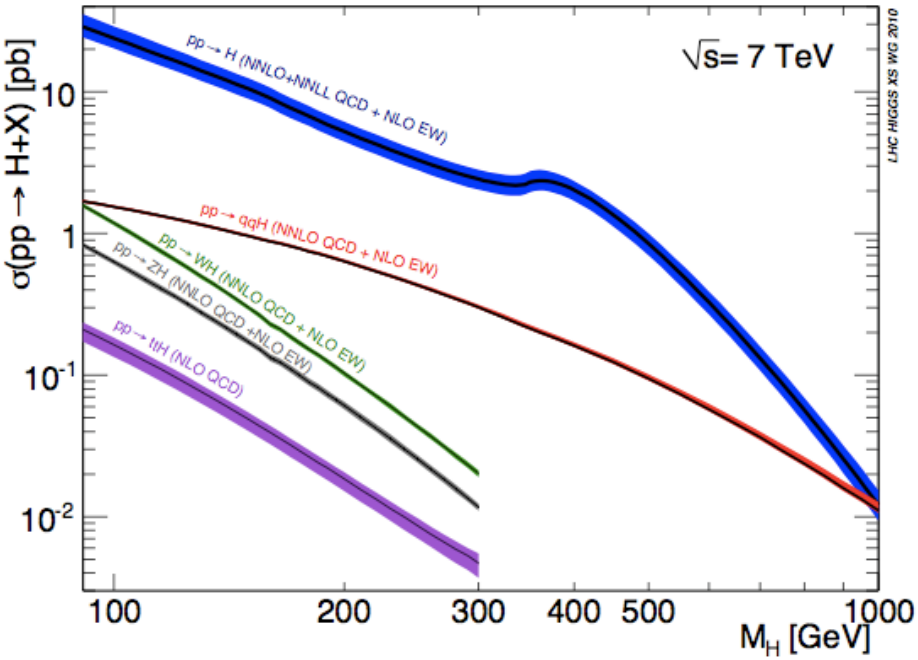


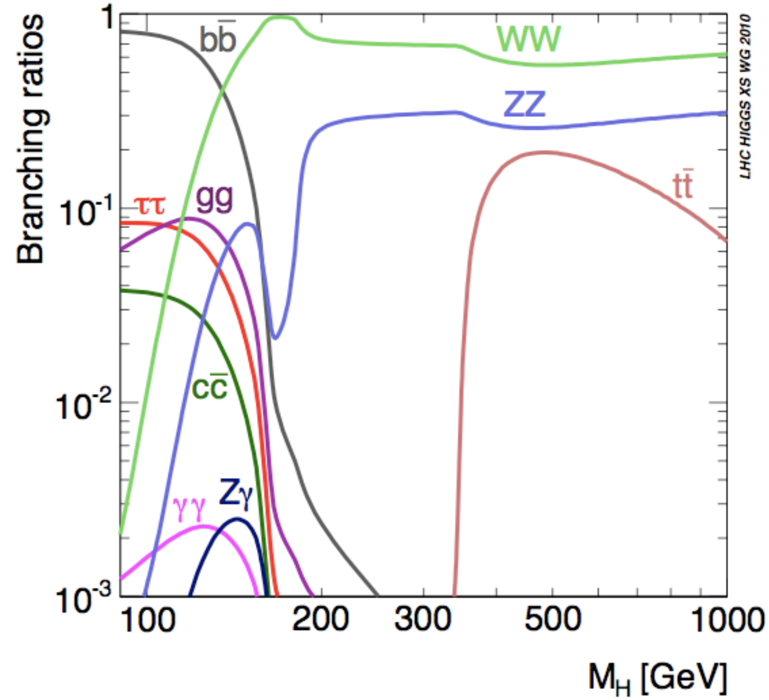


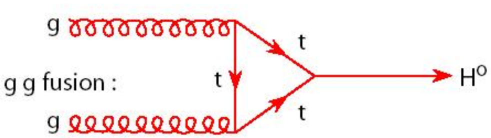
- Fabulous agreement
- Lot's of data

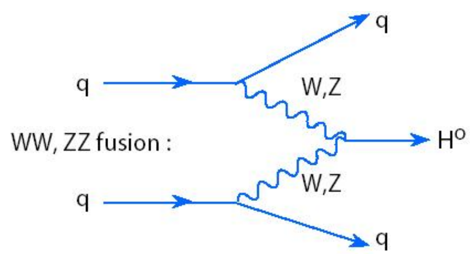
... onto the Higgs...

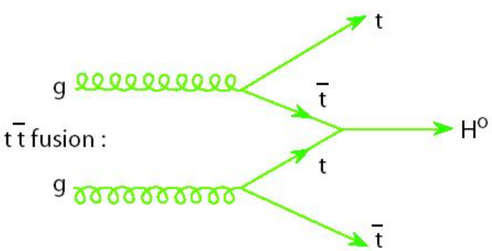
Higgs boson at LHC

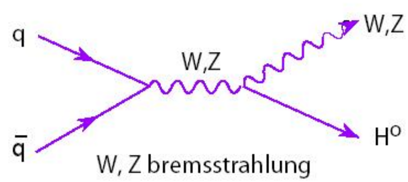








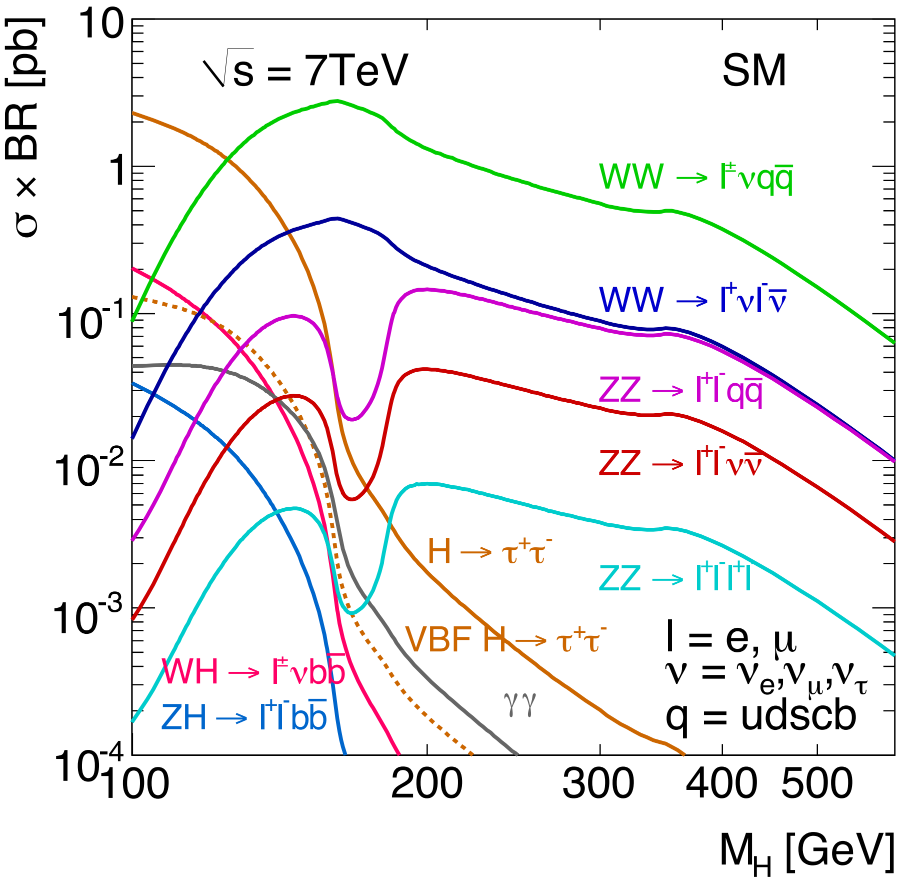




Higgs boson (M_H ~120 GeV) produced every **~10 seconds** @ L=5x10^{33} cm^{-2} s^{-1}

- If it exists ☺

Higgs boson: decay channels



Decay channel	Mass region
$H \to \gamma\gamma$	110–150
$H \to bb$	110–135
$H \to \tau\tau$	110–140
$H \to WW \to 2l\ 2\nu$	110–600
$H \to ZZ \to 4l$	110–600
$H \to ZZ \to 2l2\tau$	180–600
$H \to ZZ \to 2l2j$	226–600
$H \to ZZ \to 2l2\nu$	250–600

Signal at 1 fb^{-1}

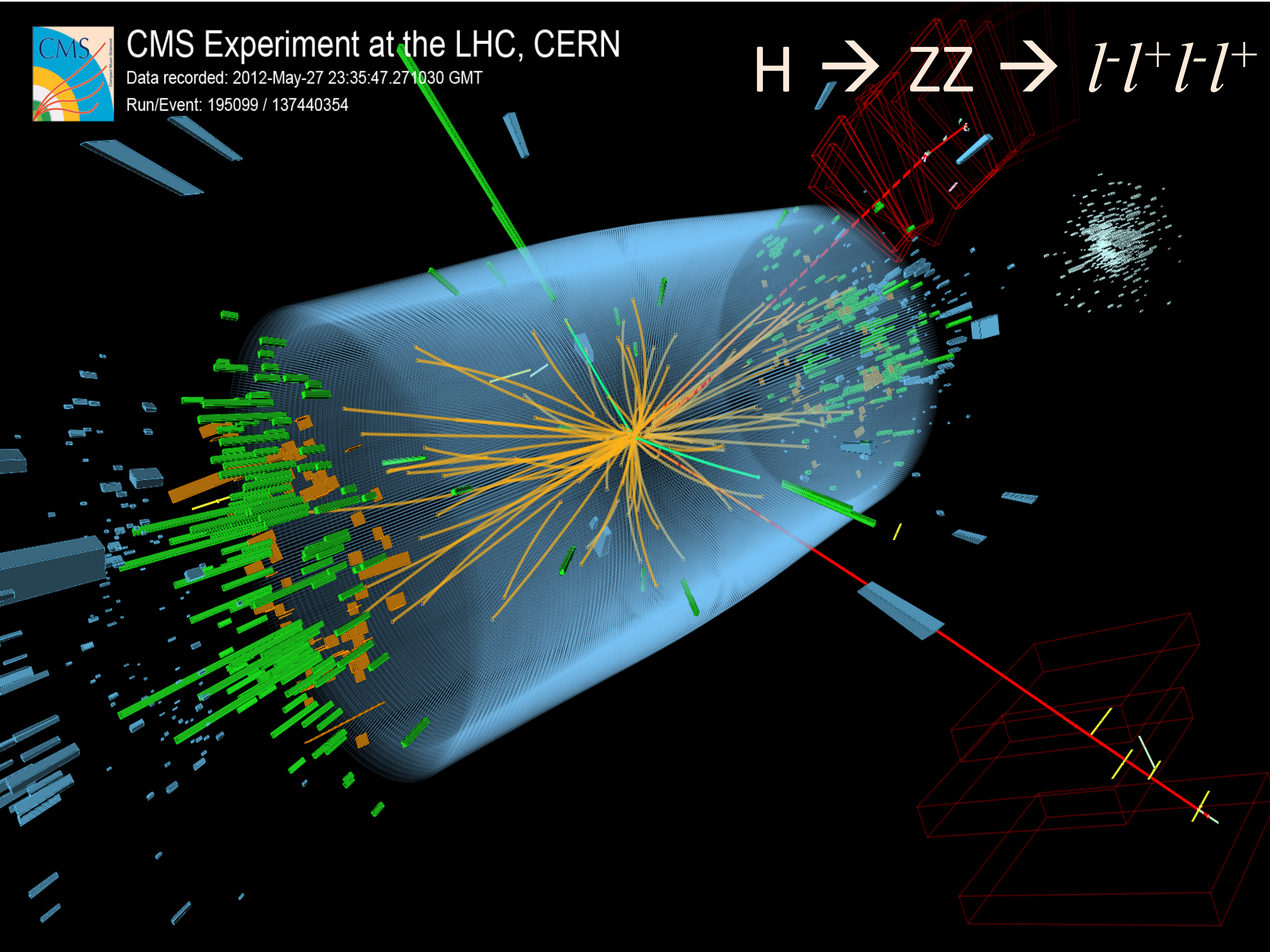
m_H, GeV	$WW \to 2l2\nu$	$ZZ \to 4l$	$\gamma\gamma$
120	127	1.5	43
150	390	4.6	16
300	89	3.8	0.04

Most sensitive channels for low mass Higgs:

$H \to \gamma\gamma$

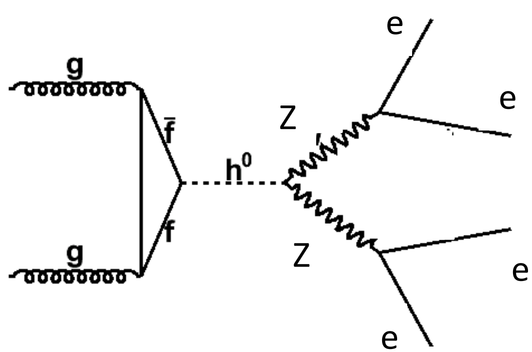
$H \to WW \to l^-\nu l^+\nu$,

$H \to ZZ \to l^-l^+l^-l^+$

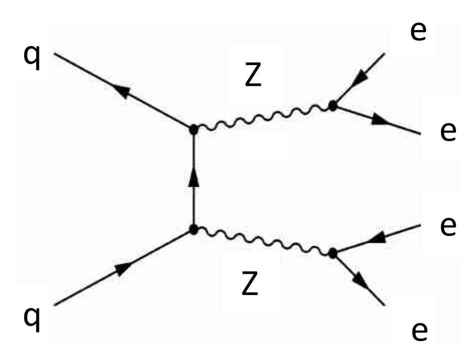

CMS
CMS Experiment at the LHC, CERN
Data recorded: 2012-May-27 23:35:47.271030 GMT
Run/Event: 195099 / 137440354
$H \rightarrow ZZ \rightarrow l^-l^+l^-l^+$

Signal vs background(s)

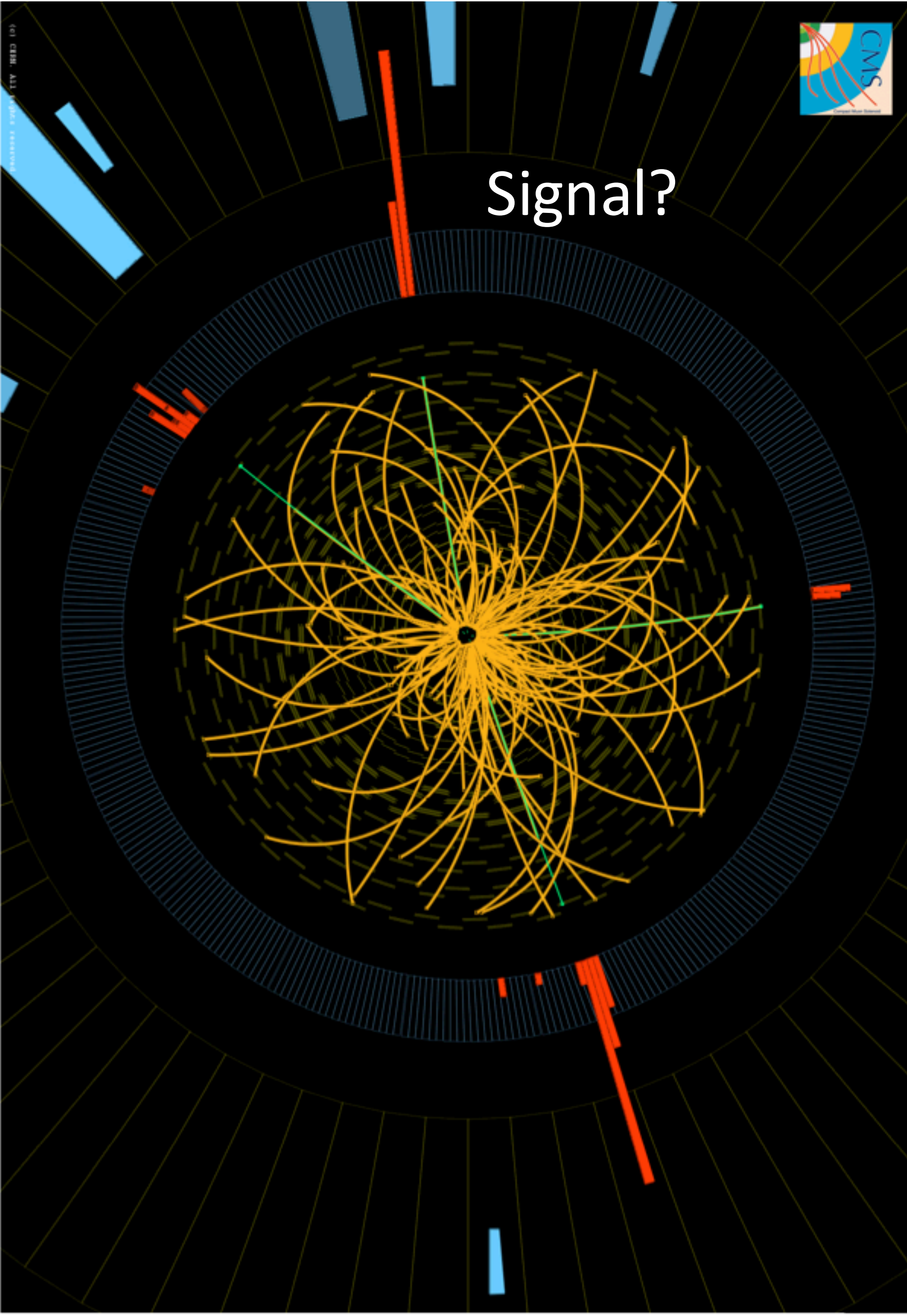
- **Signal**: an event coming from the physical process under study
  - Example: $H \rightarrow ZZ \rightarrow e^+e^-e^+e^-$
- **Background**: any other event
  - 'Trivial' backgrounds are all other backgrounds and are easily *rejected* by a simple requirement of having at least 4 electrons in the final state
  - 'Dangerous' background is any other process giving at least 4 electrons in the final state

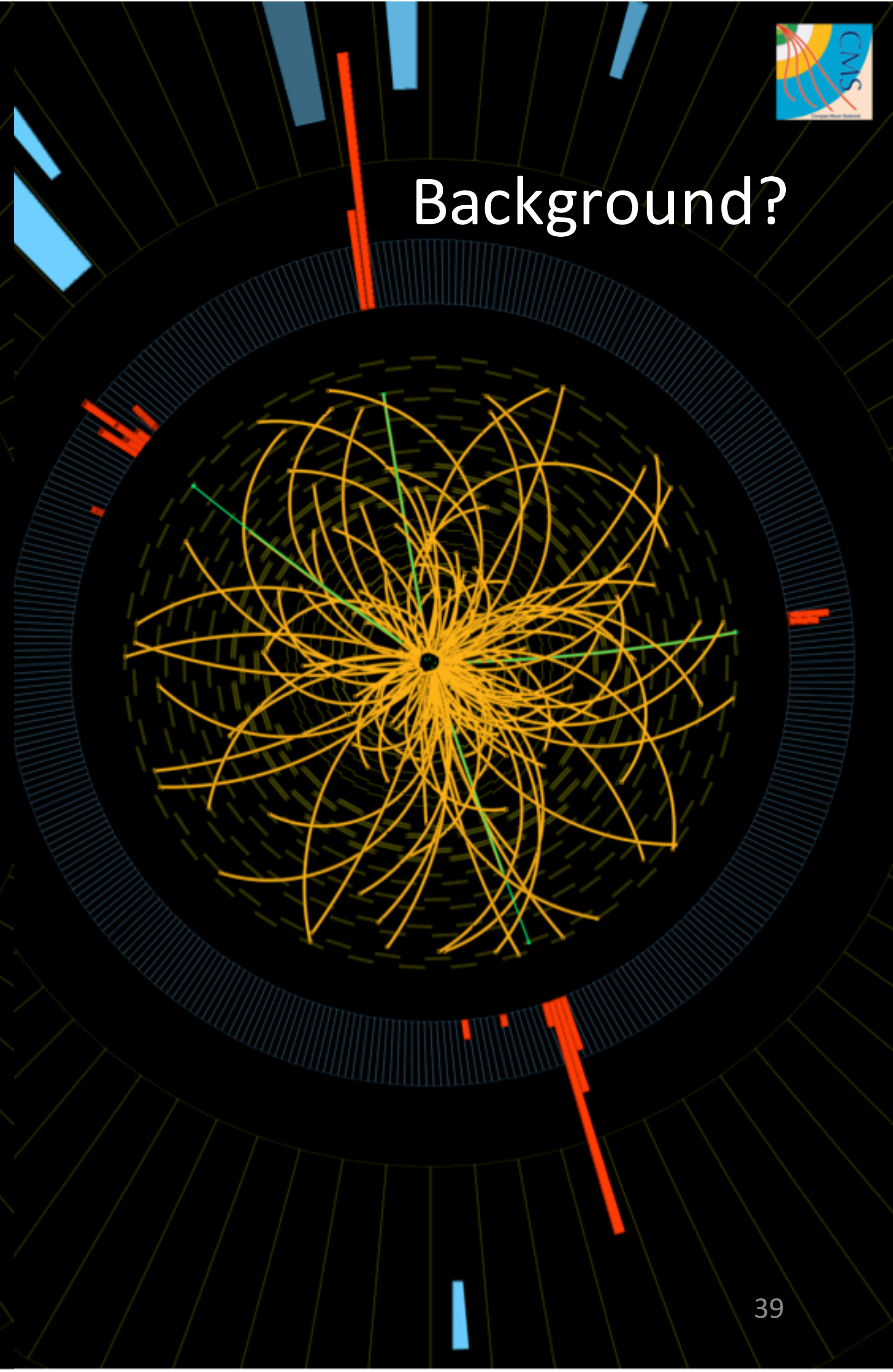


Signal: pp→H→ZZ→4e

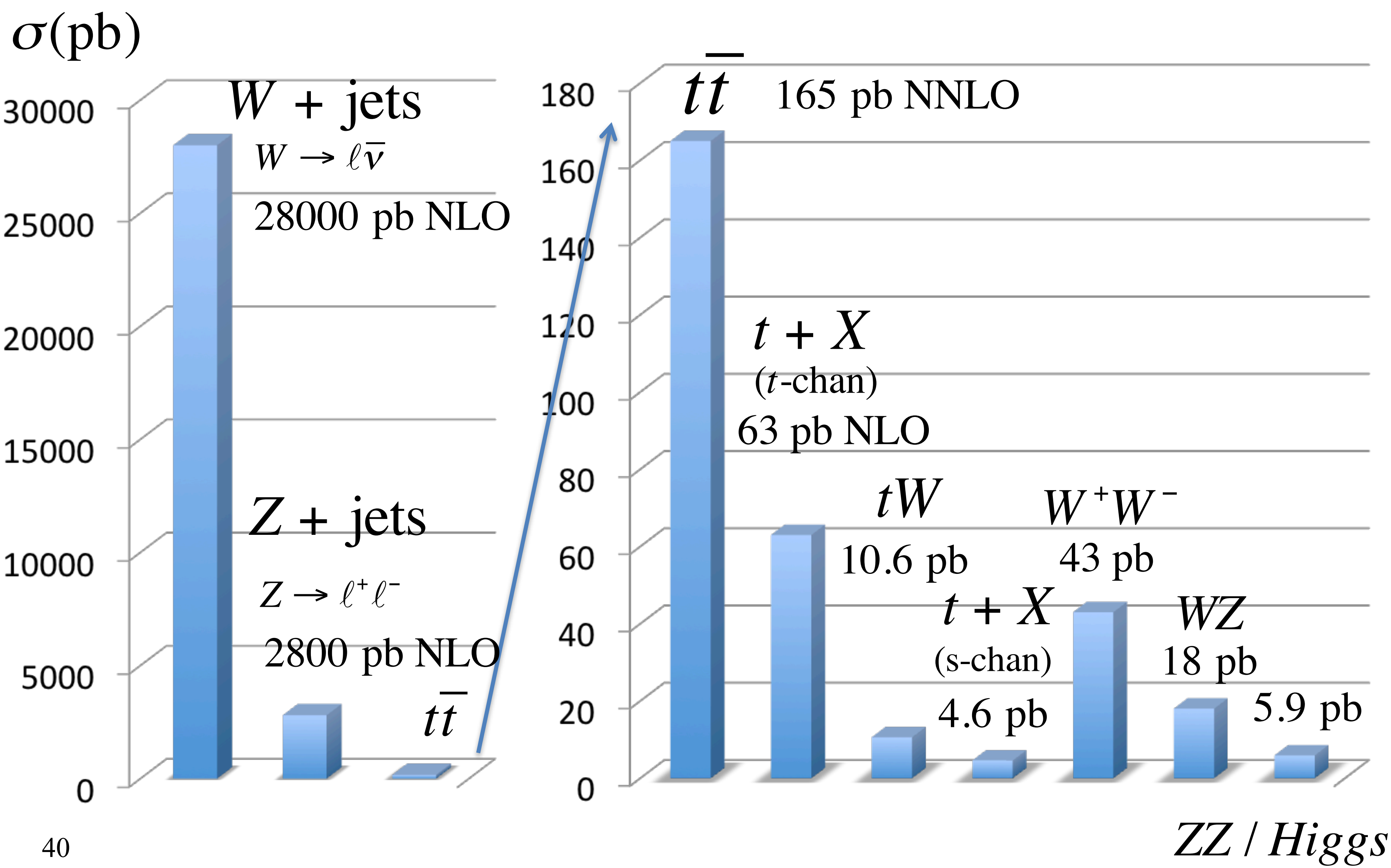


'Dangerous' background: pp→ZZ→4e

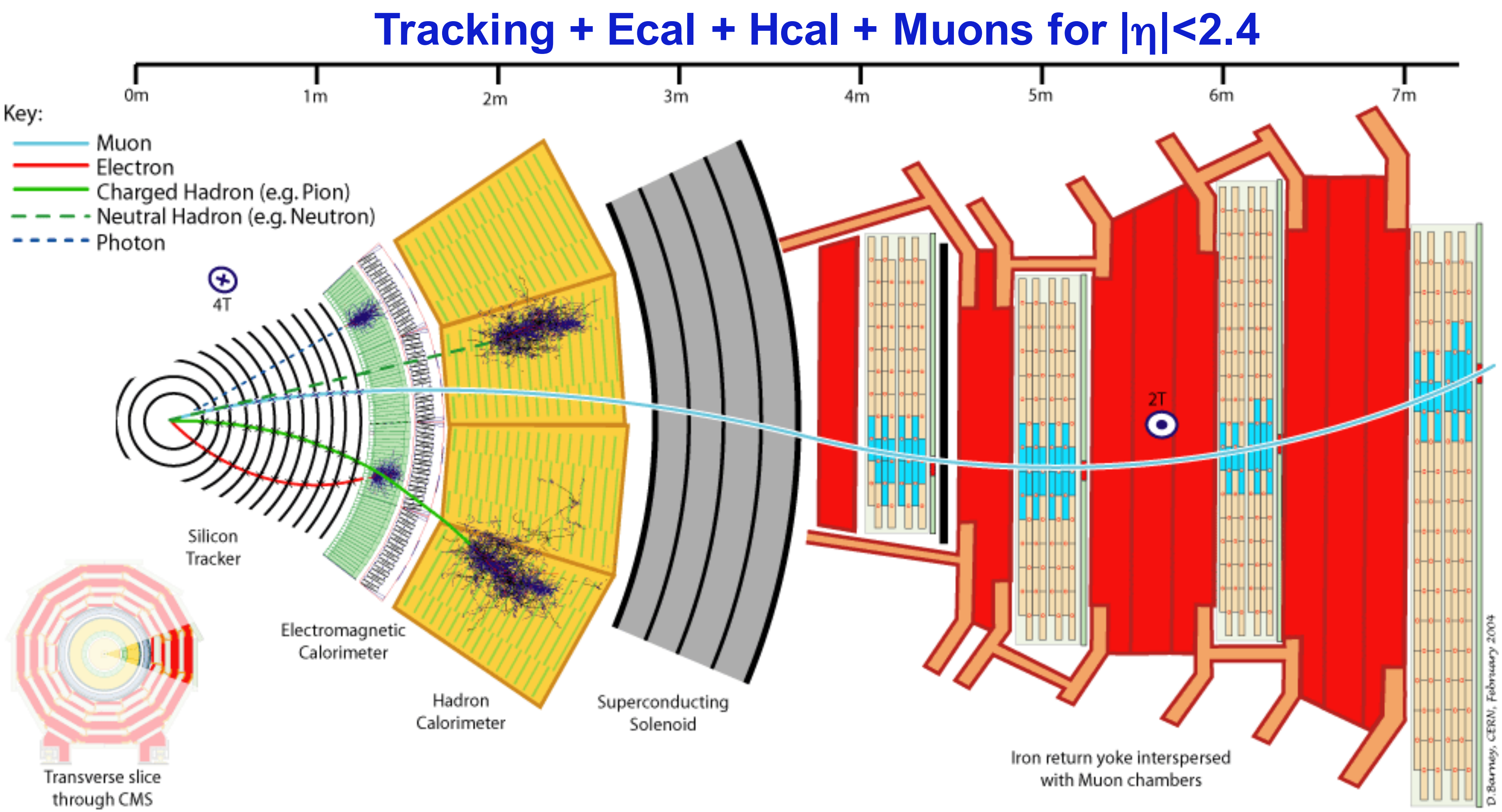

Signal?


Background?

Signal vs backgrounds



How to detect particles?



Si TRACKER

Silicon Microstrips and Pixels

CALORIMETERS

ECAL

Scintillating $PbWO_4$ crystals

HCAL

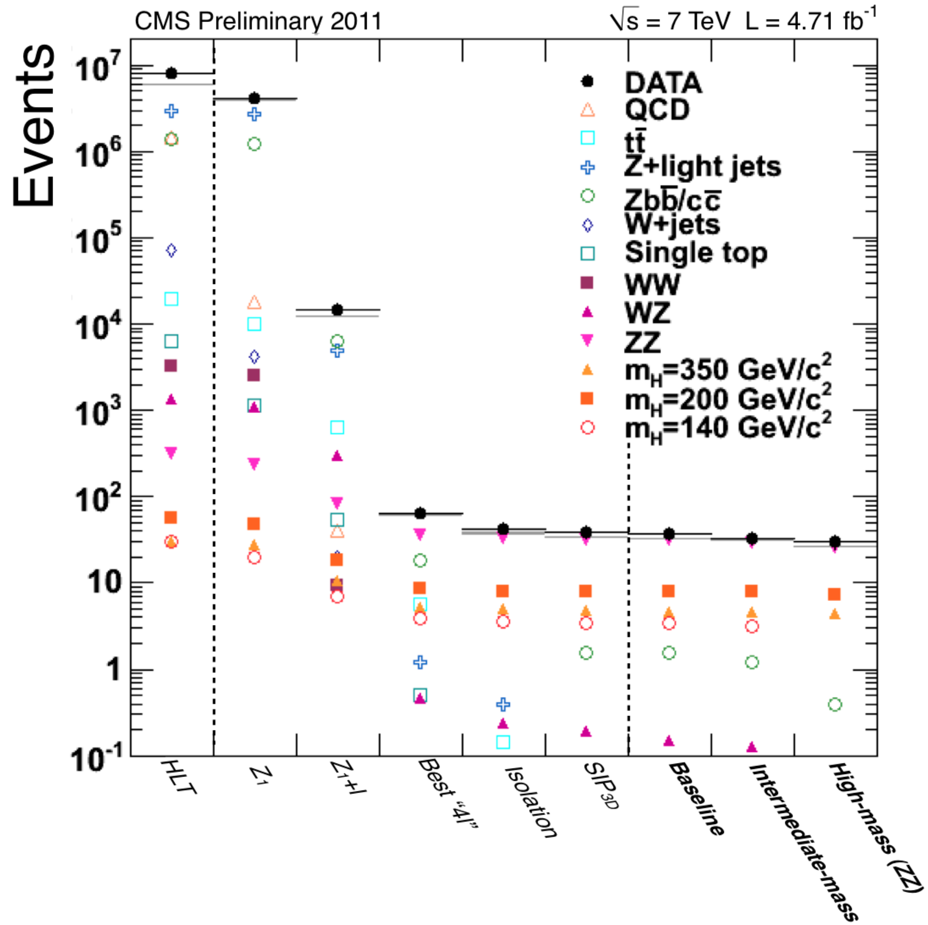
Plastic scintillator/brass sandwich

MUON BARREL

Drift Tube Chambers (**DT**)

Resistive Plate Chambers (**RPC**)

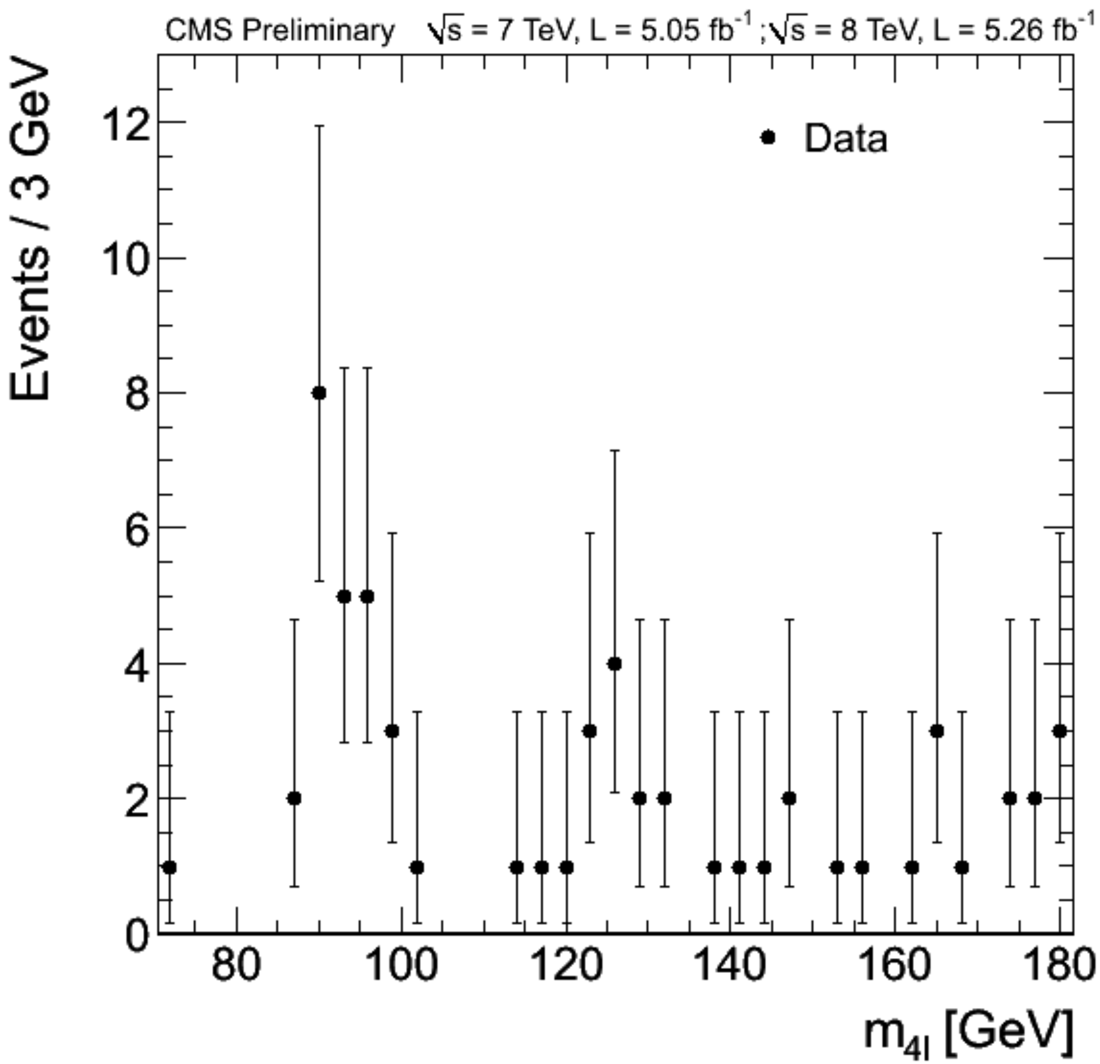
H → ZZ → $l^-l^+l^-l^+$ event selection



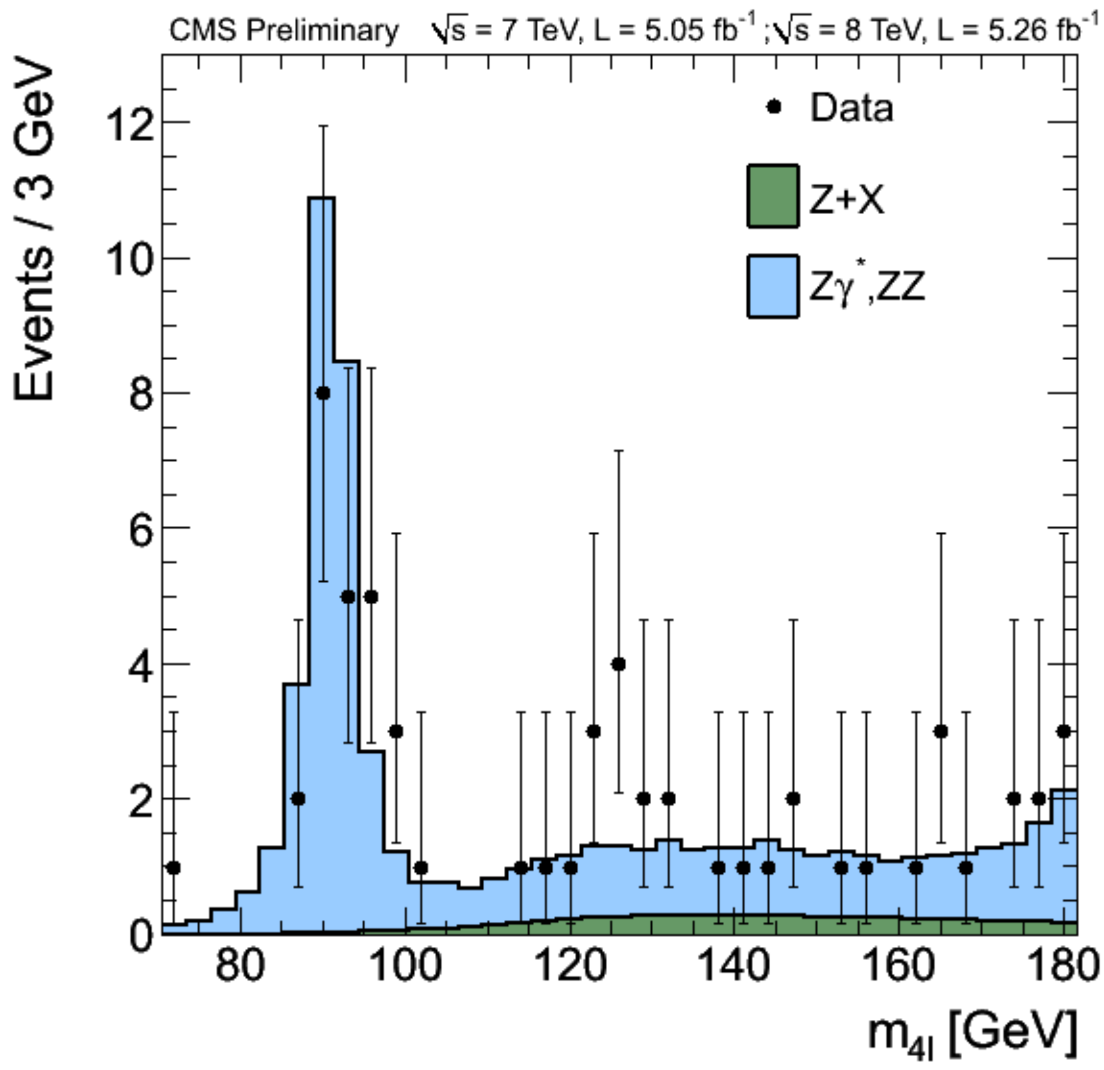
- Best 4l candidate choice
  - Two lepton pairs of opposite charge, p_T> 20, 10, 7, 5 GeV
  - Z hypothesis for at least on pair
  - M_{4l}>100 GeV
- Background rejection with isolation and impact parameter requirement
- M_{ll}>12 GeV requirement on 2nd lepton pair
- Event distribution consistent with SM ZZ*

- Event count (example from 2011):
  - **data: 72, expected background: 67.1±6.0**
  - 13 events below M_H=160, 9.5±1.3 expected

Measured

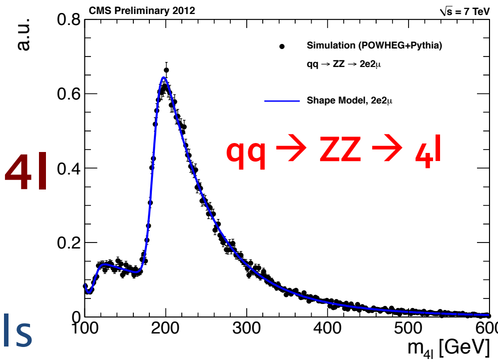

CMS Preliminary $\sqrt{s}$ = 7 TeV, L = 5.05 fb^{-1} ; $\sqrt{s}$ = 8 TeV, L = 5.26 fb^{-1}
Data
Events / 3 GeV
0
2
4
6
8
10
12
80
100
120
140
160
180
m_{4l} [GeV]

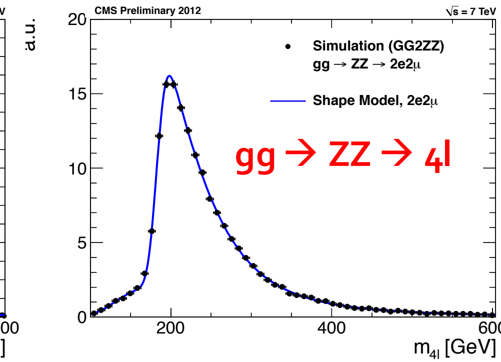
Measured + predicted/expected



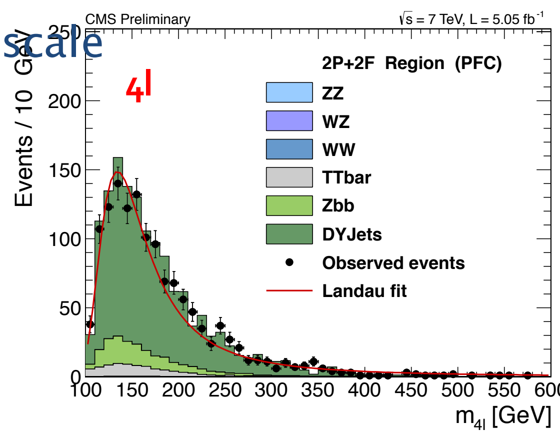
Background models

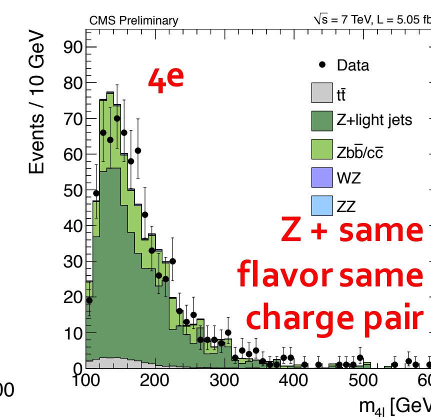
- **Irreducible background ZZ $\rightarrow$ 4l**
  - Estimated **using simulation**
  - Phenomenological shape models
  - Corrected for data/simulation scale

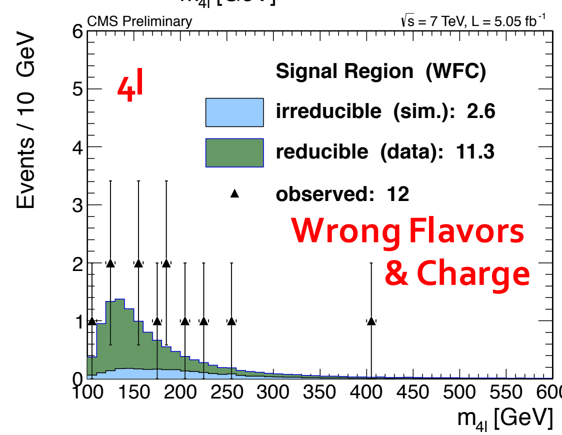




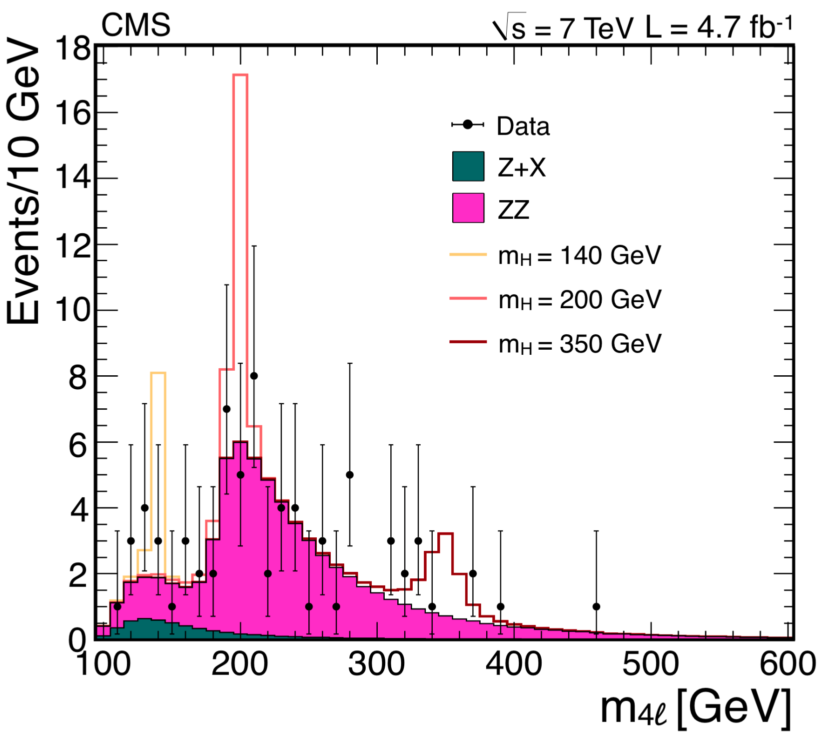
- **Reducible background**
  - Estimated **from data**
    - Measure probabilities for lepton misidentification
    - Extrapolate from control samples enriched with mis-identified leptons
  - **Validation in data** using "wrong flavors & charges" events
  - Total uncertainty ~50%

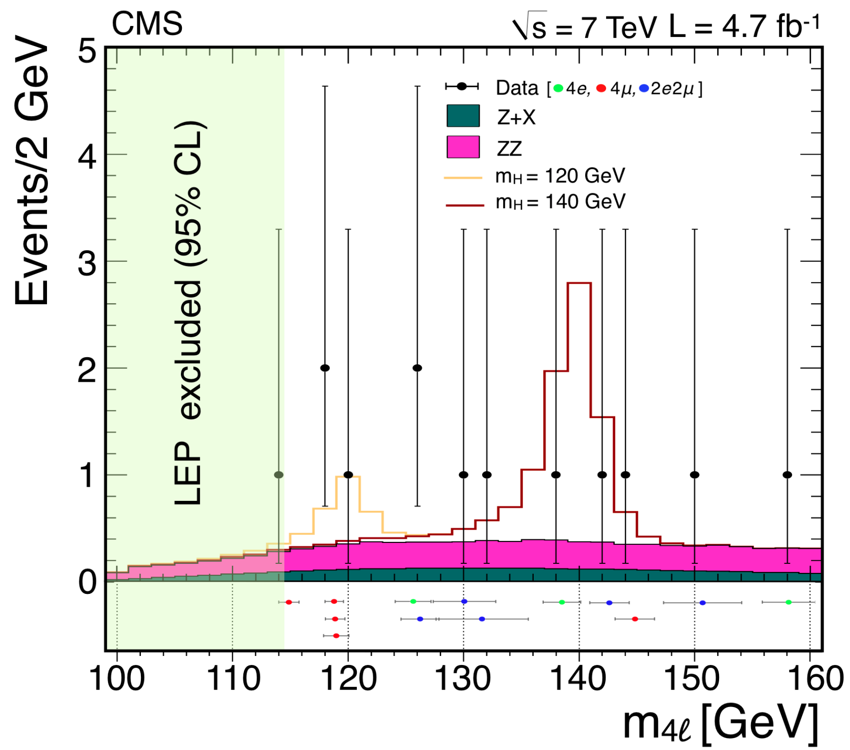






Situation in 2011

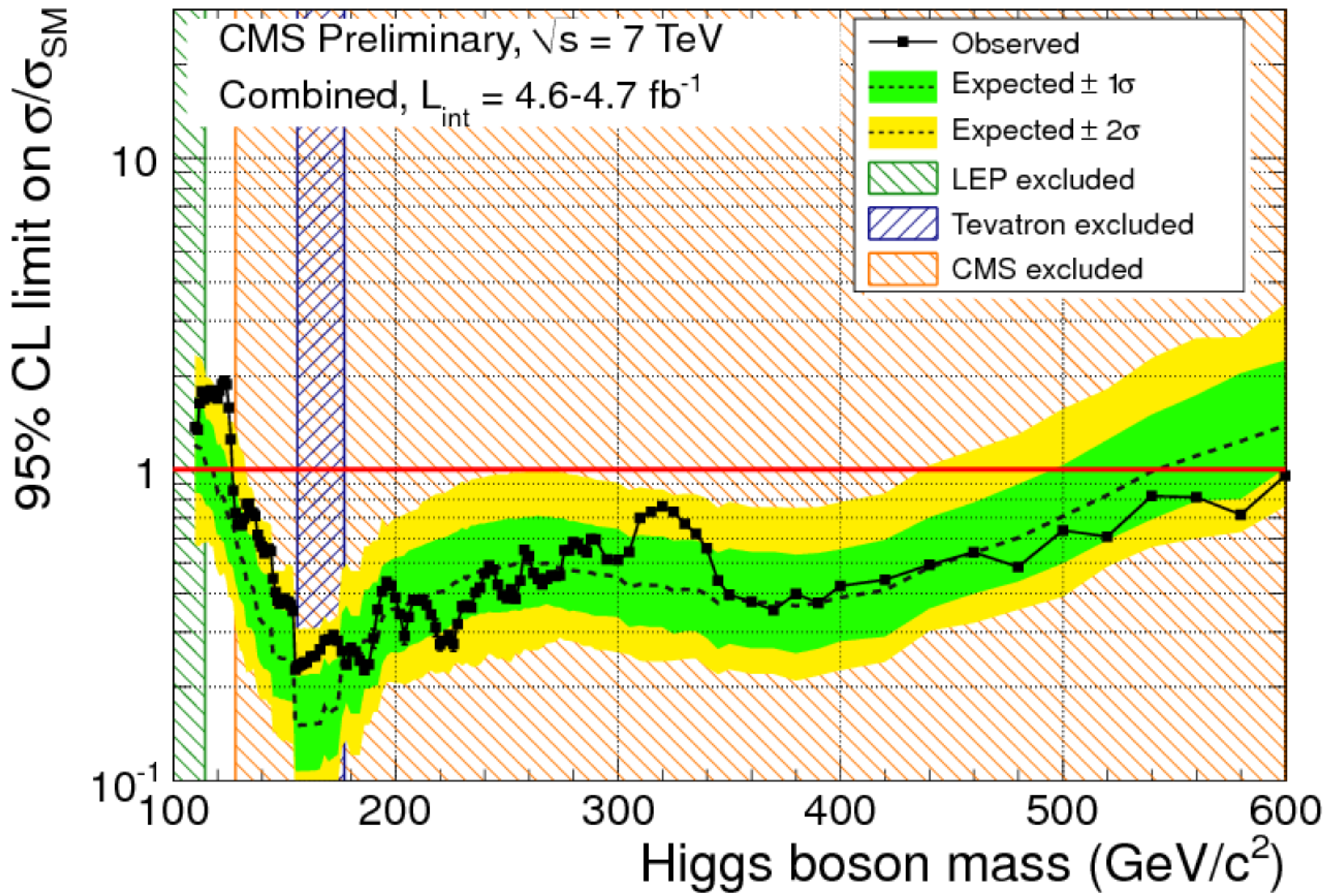




Accepting or rejecting theories?

- Image we make an experiment and obtain data
  - Theory 1 agrees with data
  - Theory 2 also agrees
  - Theory 3 also agrees
  - …
  - Theory n also agrees
  - Than the statement that "*Theory 1 is acceptable*" is not so strong
    - Not wrong either
- But imagine this scenario
  - Theory 1 gives precise prediction
  - Experiment doesn't quite agree with that prediction
  - Than the statement "*Theory 1 is not acceptable*" is rather strong
  - Therefore **we better reject than accept theories**

Search for SM Higgs: limits from 2011



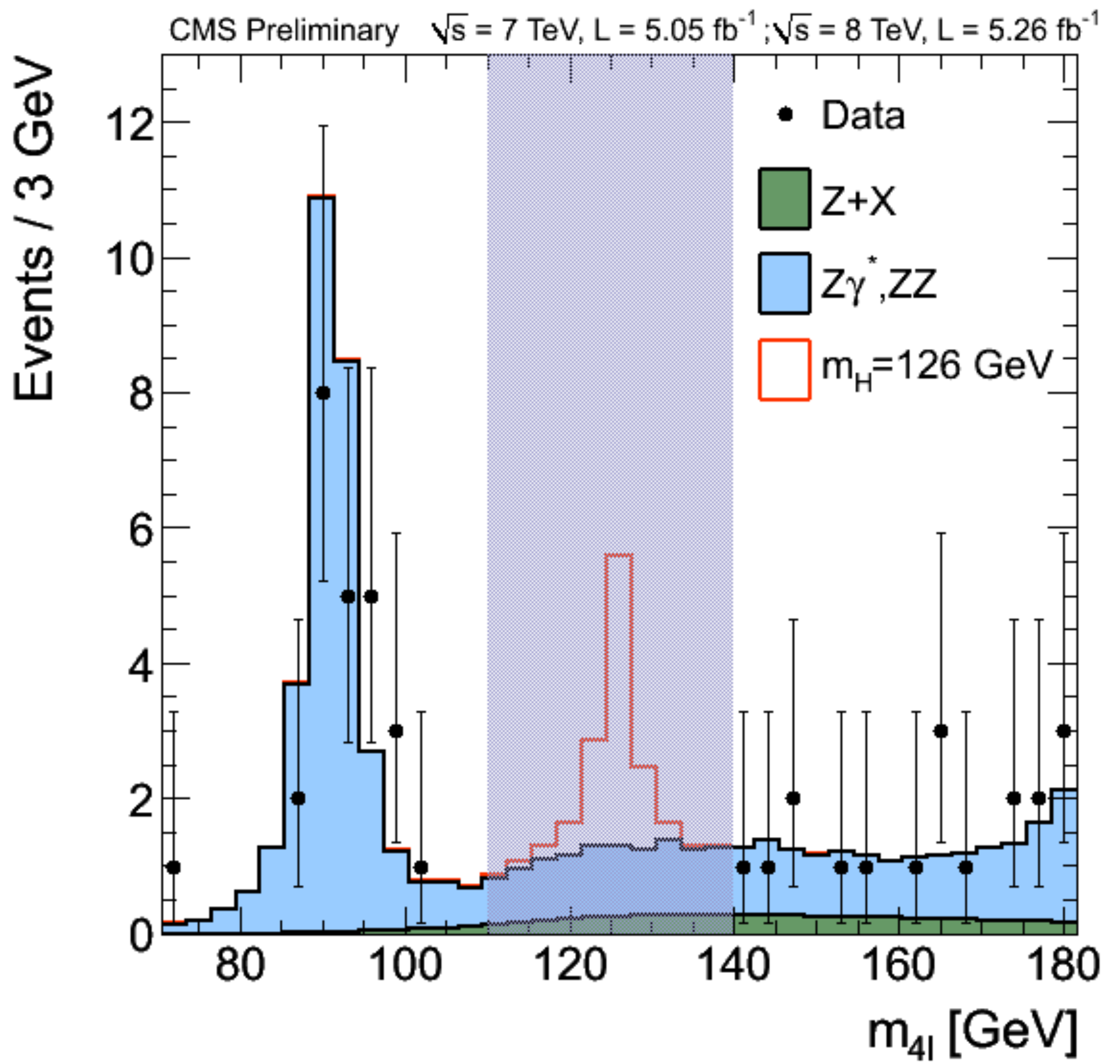
- Higgs boson excluded everywhere except [114.5 – 127] GeV

Two options for 2012


DON'T LOOK
AT ME DON'T
TALK TO ME

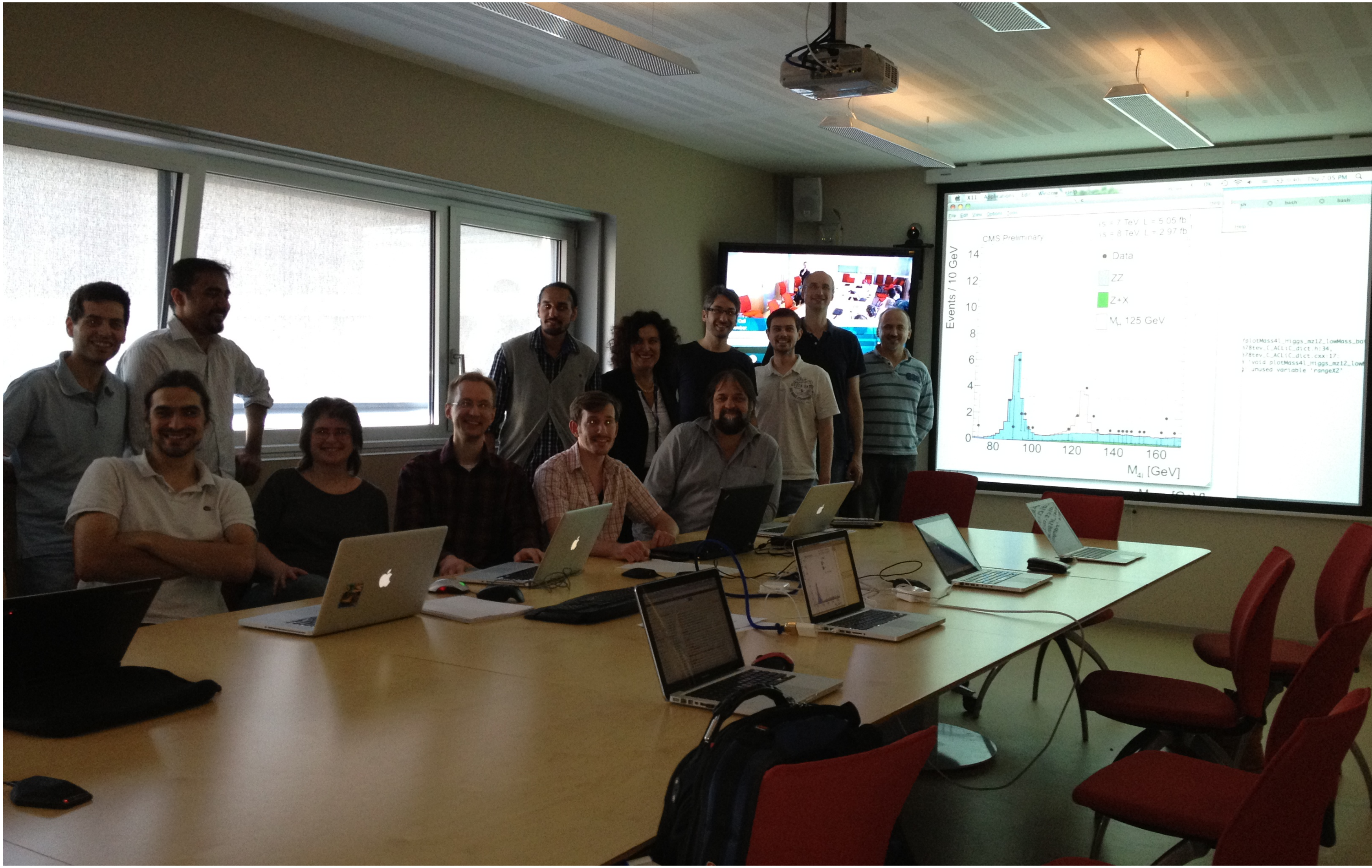
Blind analysis

H → ZZ → $l^-l^+l^-l^+$ events distribution

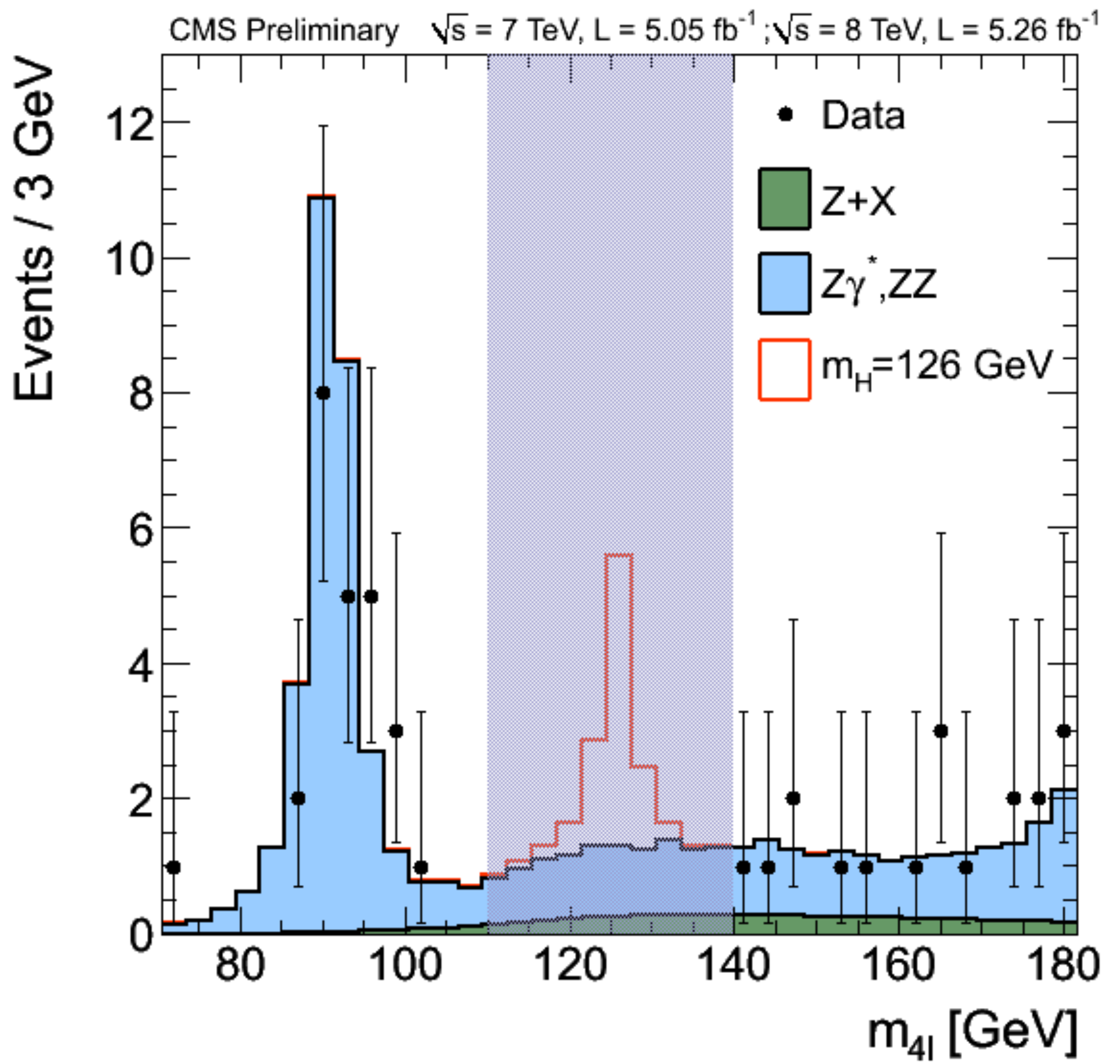


The day we looked at signal region

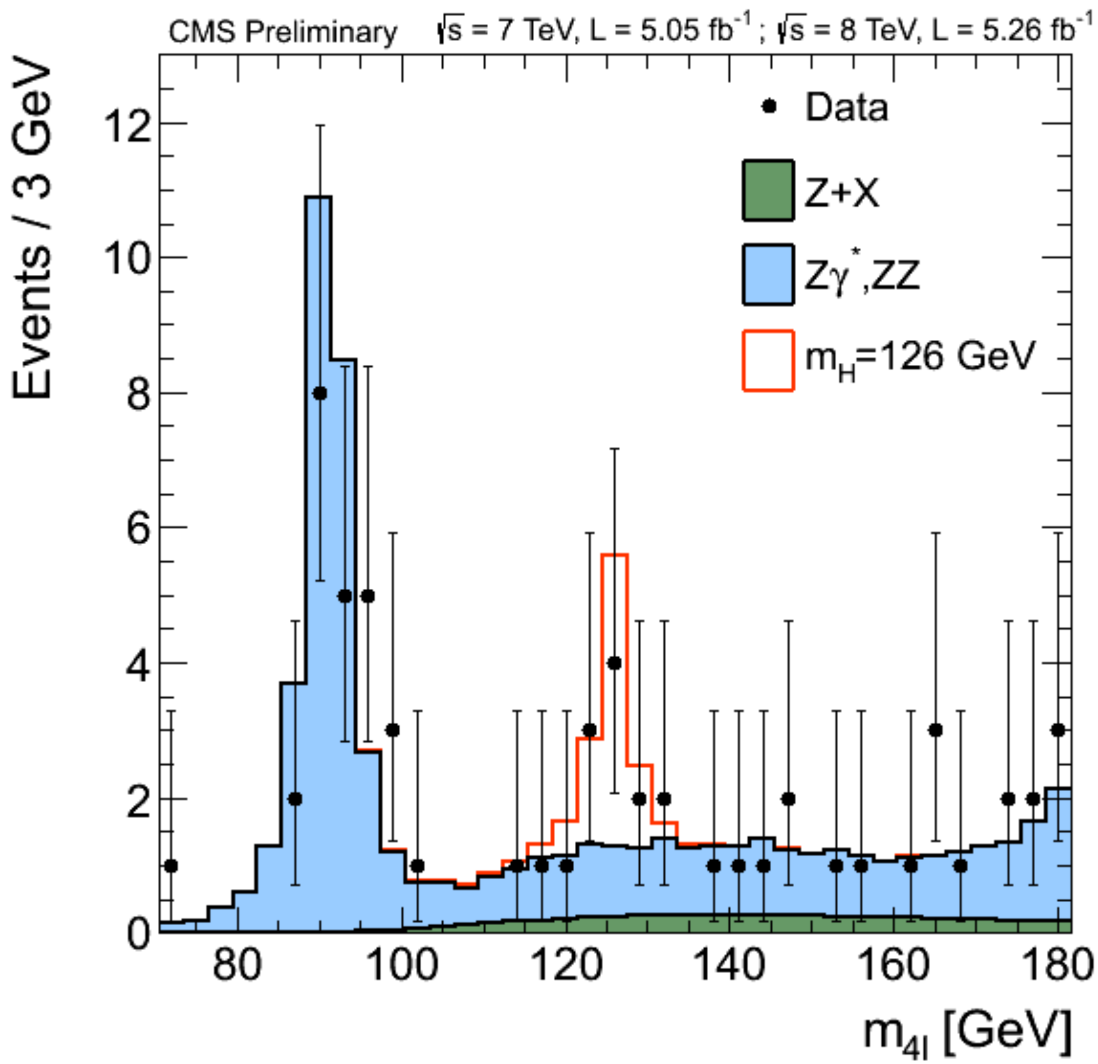
14 June 2012 @ 18h00



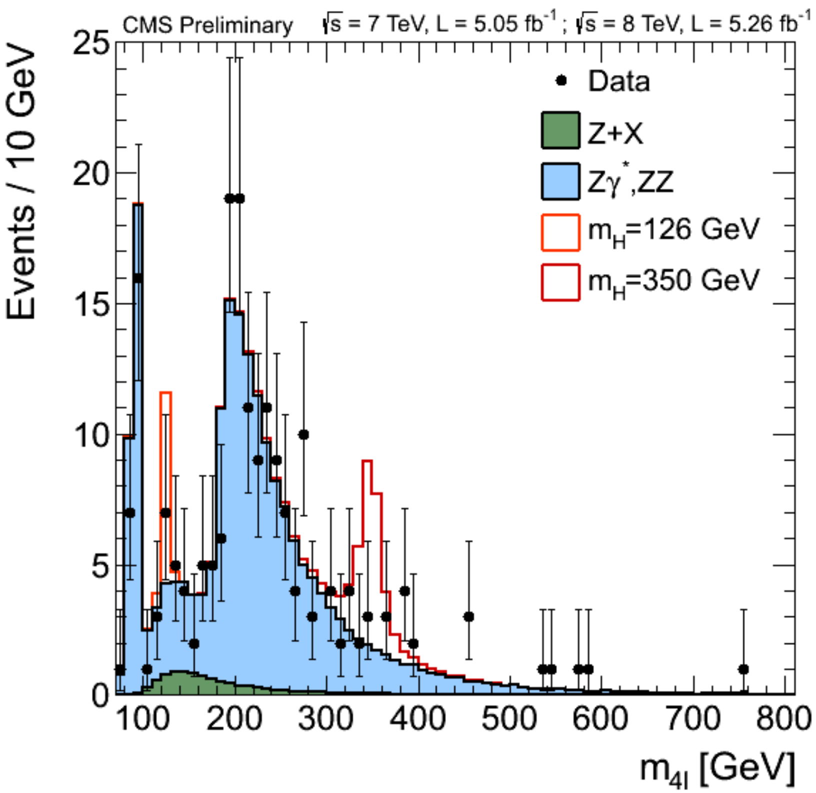
H → ZZ → $l^-l^+l^-l^+$ events distribution

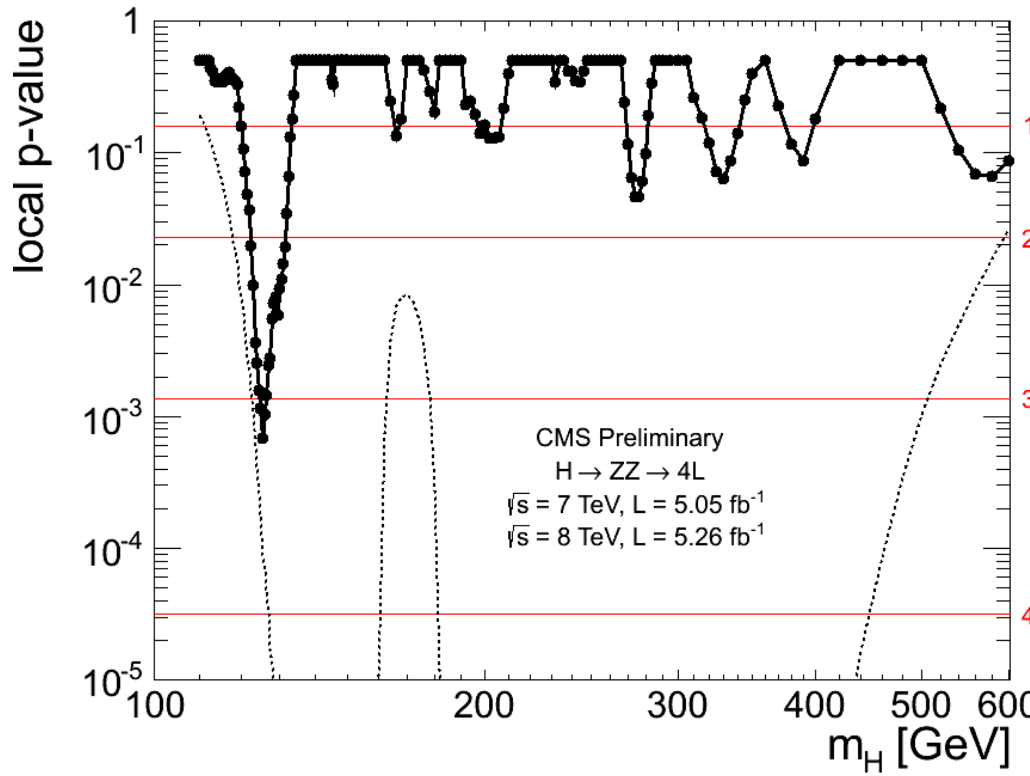


H → ZZ → $l^- l^+ l^- l^+$ events distribution



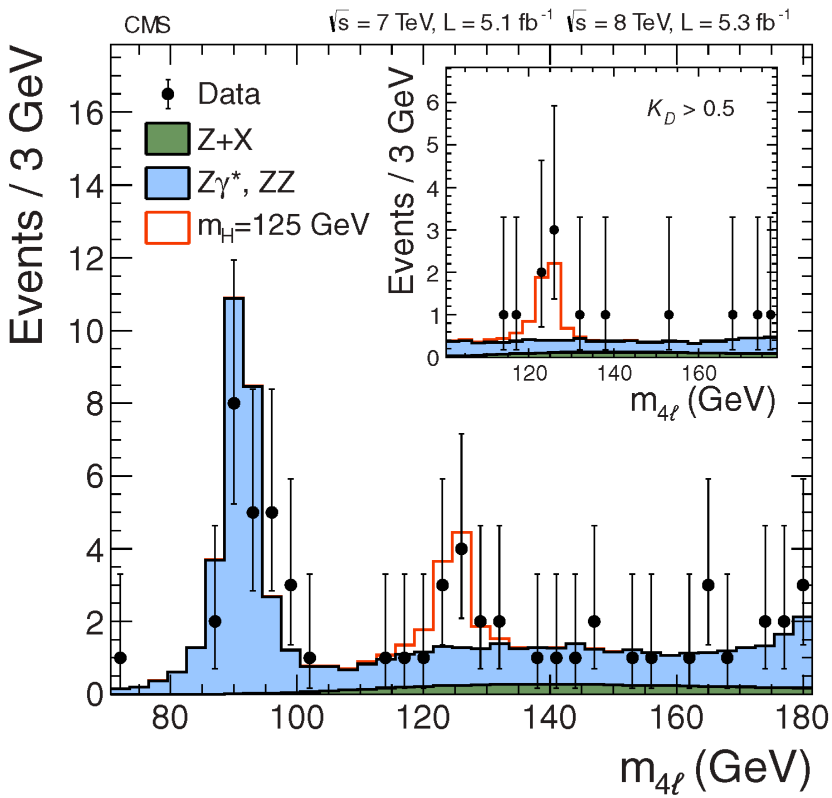
H → ZZ → $l^- l^+ l^- l^+$ results

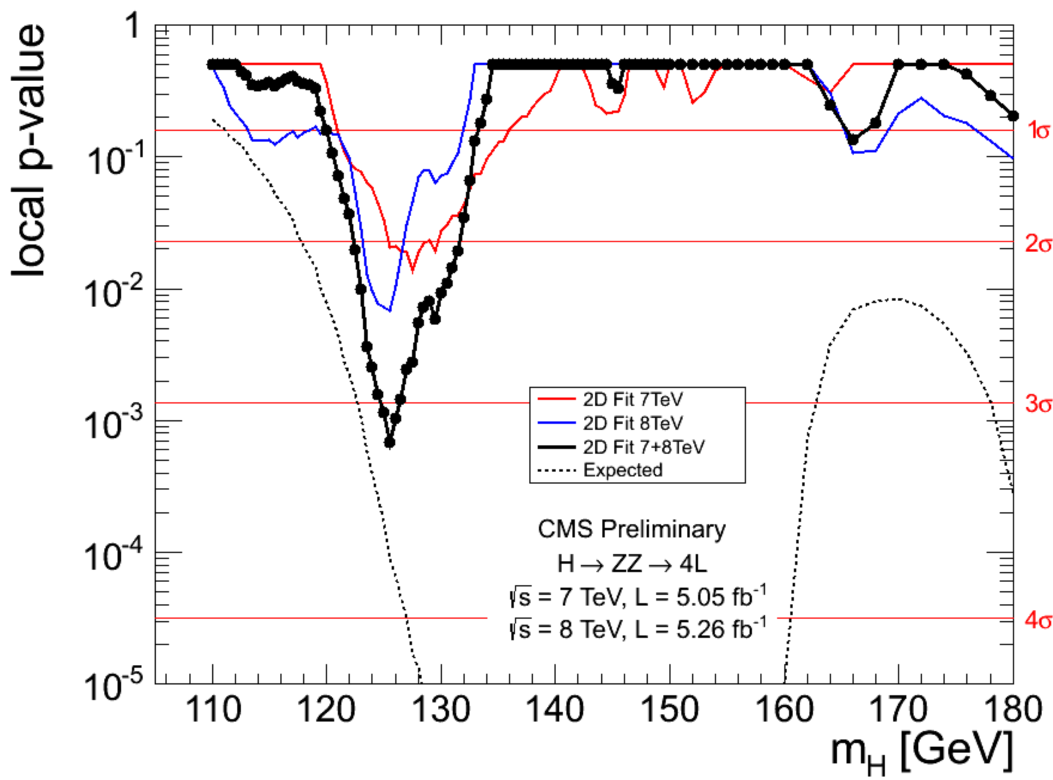




From PDG: "*... p-value is defined as the probability to find t in the region of equal and lesser compatibility with H_0 than the level of compatibility observed with actual data ...*"

$H \rightarrow ZZ \rightarrow l^- l^+ l^- l^+$ results



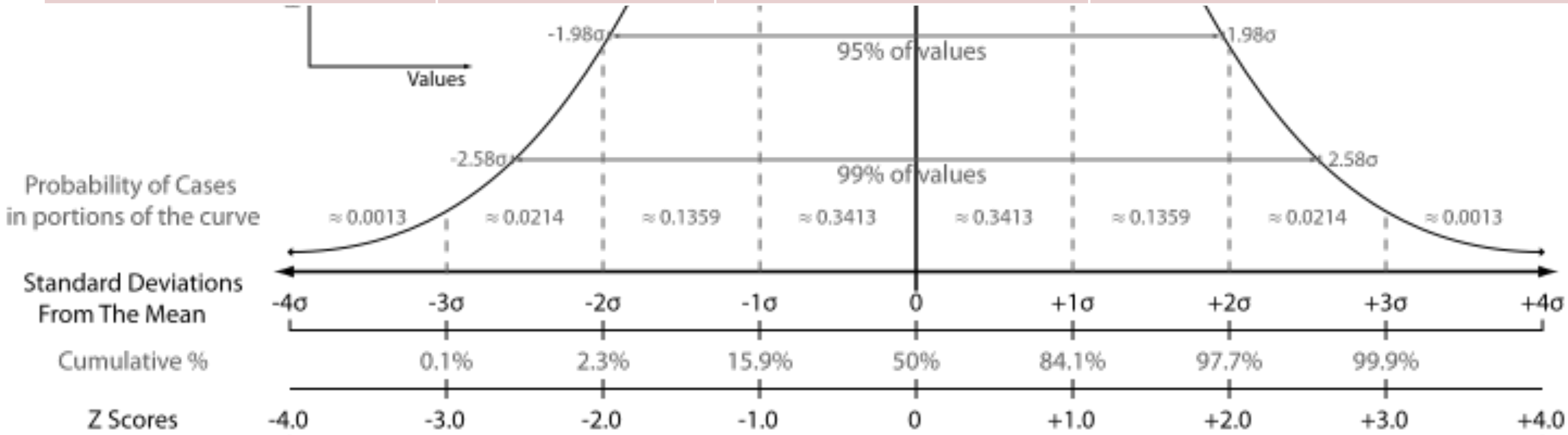


When do we claim a discovery?

- Claiming discovery is a serious issue
  - It should stay with us for a long long time (if not forever ☺)
- So, when do we claim a discovery?
  - When we are sure.
  - But we are never sure!
  - That's right, but we can be pretty sure ☺
  - 'Pretty' is not a scientific term!?
  - That's right, therefore we addopted some kind of a convention:
    - Make a hypothesis that the result you obtain is due to the fluctuation of the background (i.e. already know processes)
    - Calculate a probability for that hypothesis
    - Reject the hypothesis if that probability is smaller than 0.000000287 (significance > 5)

Converting p-values to significances

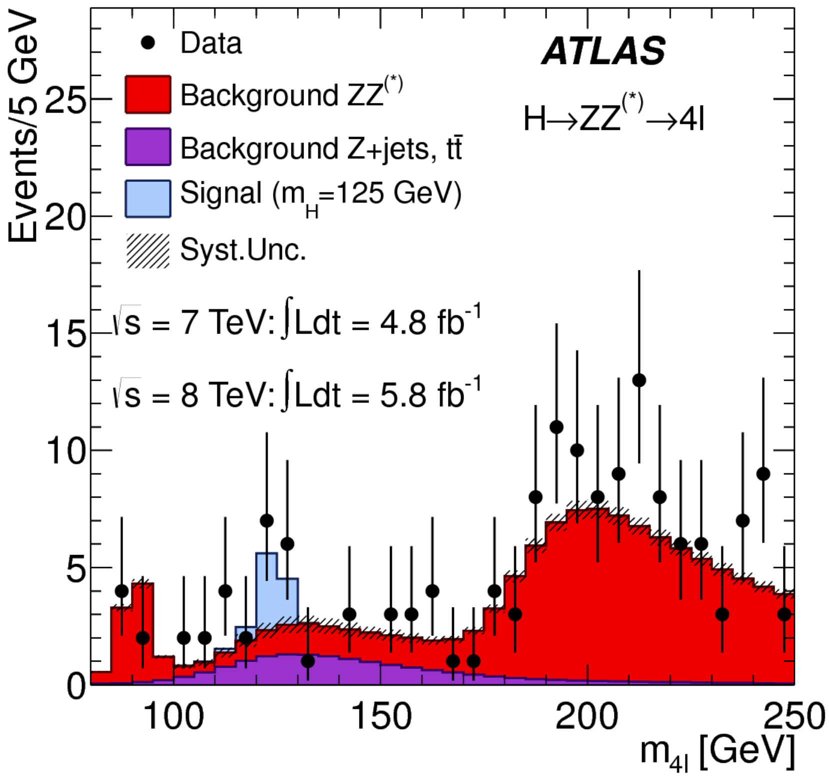
p-value	Zscore / significance	Area ±nσ	Probability of outcome: 1 in …
0.159	1	0.68268949	3.15
0.023	2	0.95449974	22.0
1.35E-03	3	0.99730020	370
3.17E-05	4	0.99993666	15,787
2.87E-07	5	0.99999943	1,744,278

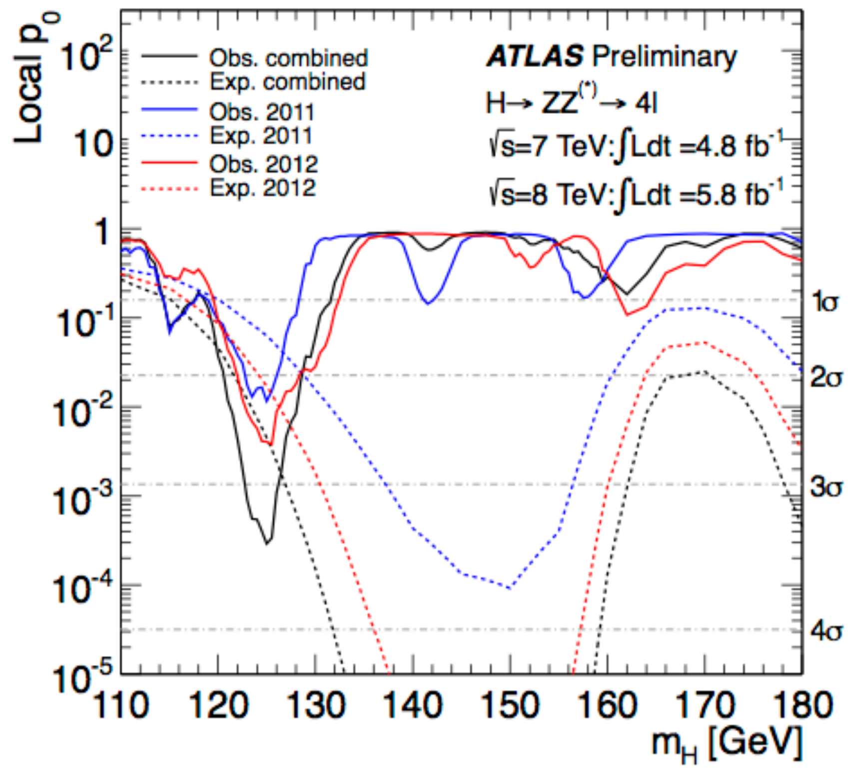



LHC prsten:
Opseg od 27 km
LHCb
ATLAS
CMS
ALICE
CERN

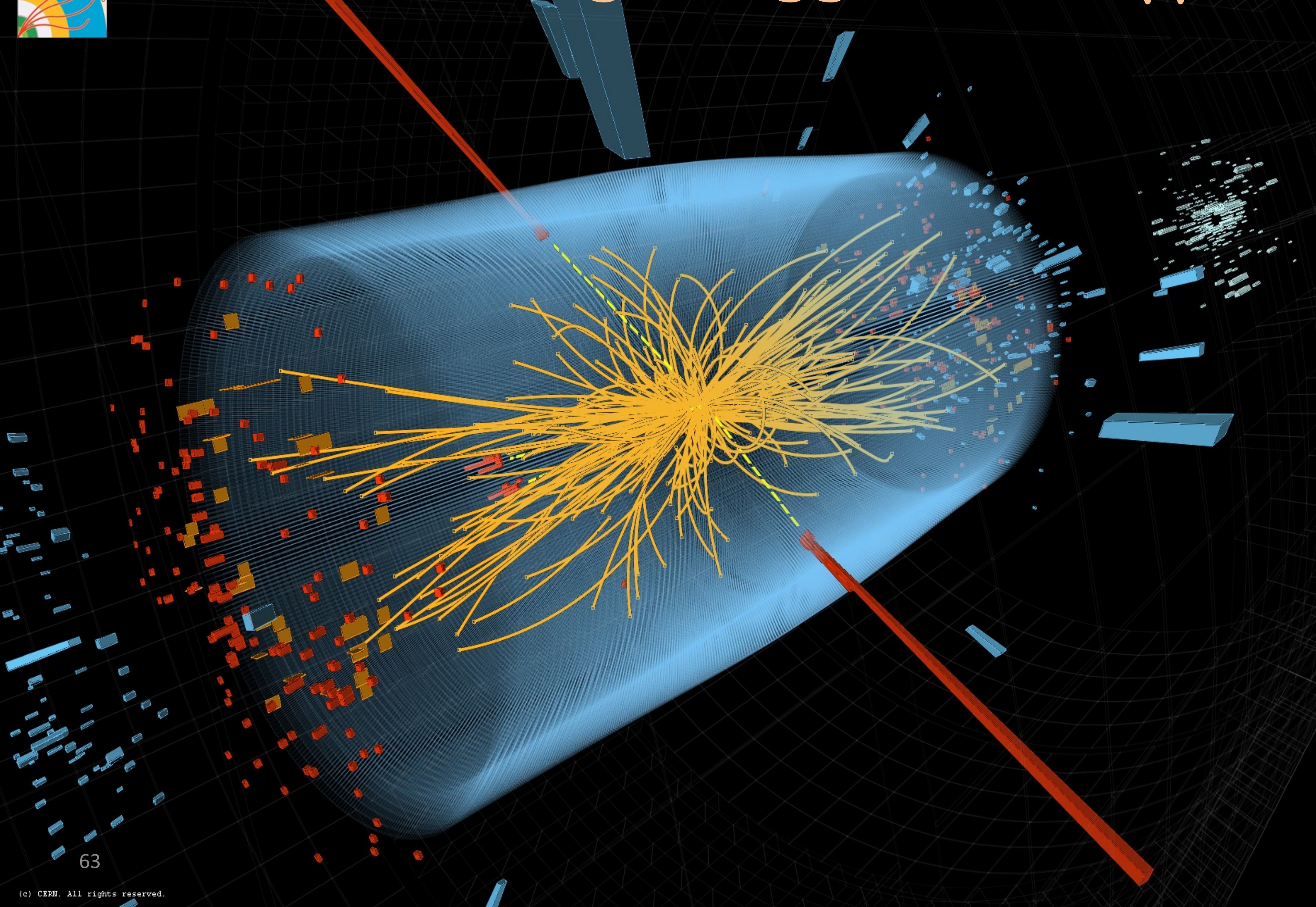

WHEN I DON'T WANT TO TALK TO PEOPLE
I DON'T
memegenerator.net

ATLAS H → ZZ → $l^-l^+l^-l^+$ results

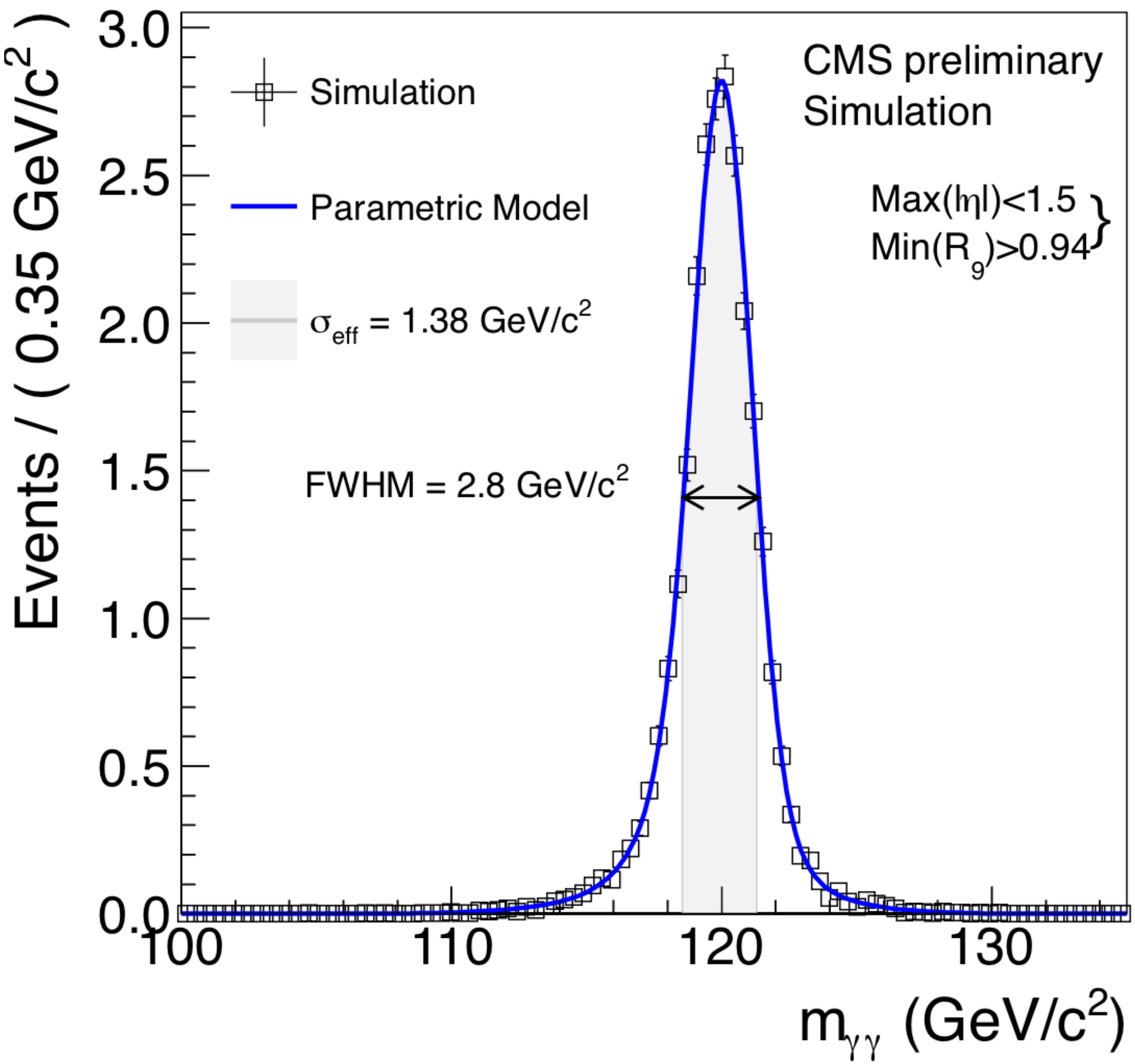




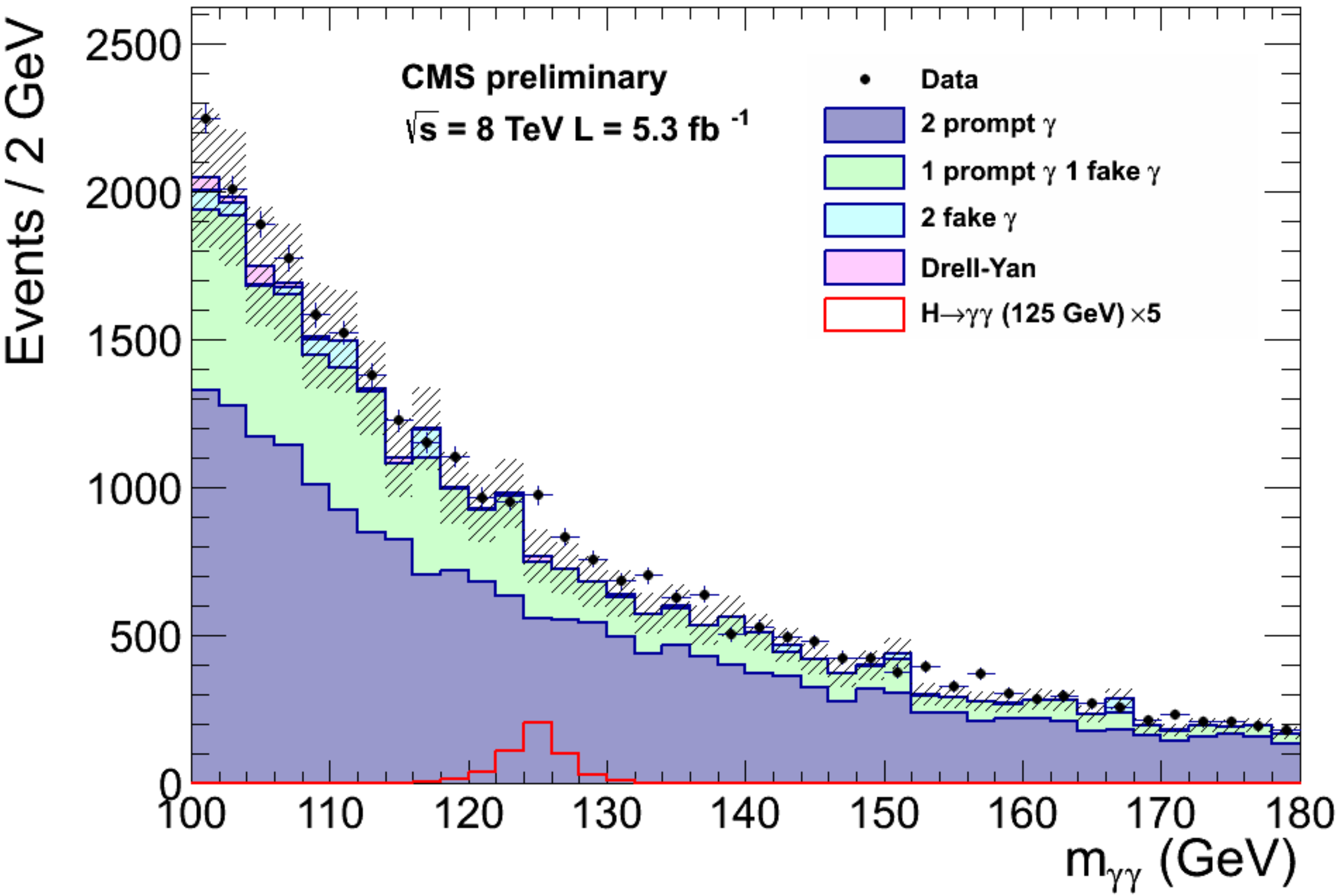
Search for light higgs: H → $\gamma\gamma$



H → γγ: Search for a narrow mass peak with two isolated high E_T photons

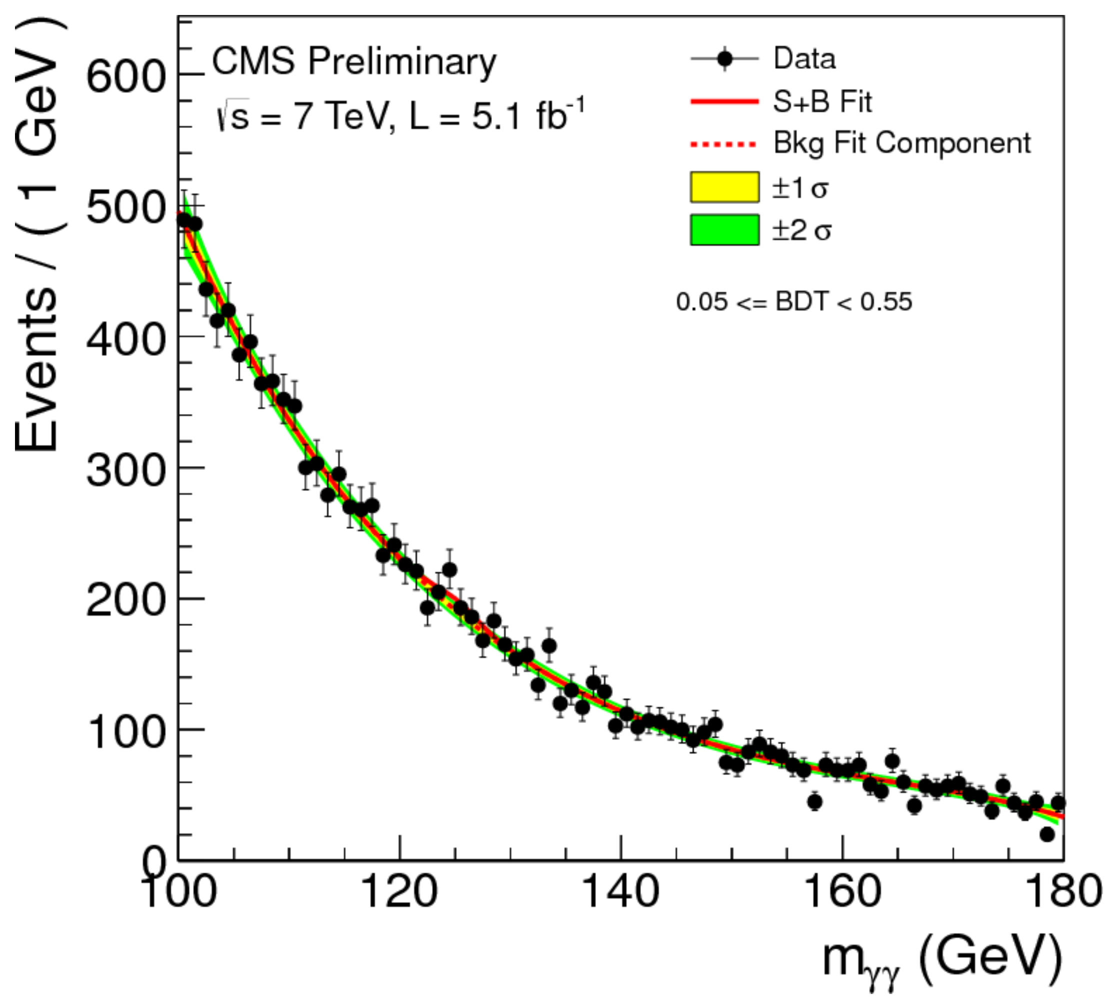


H → γγ: Search for a narrow mass peak with two isolated high E_T photons

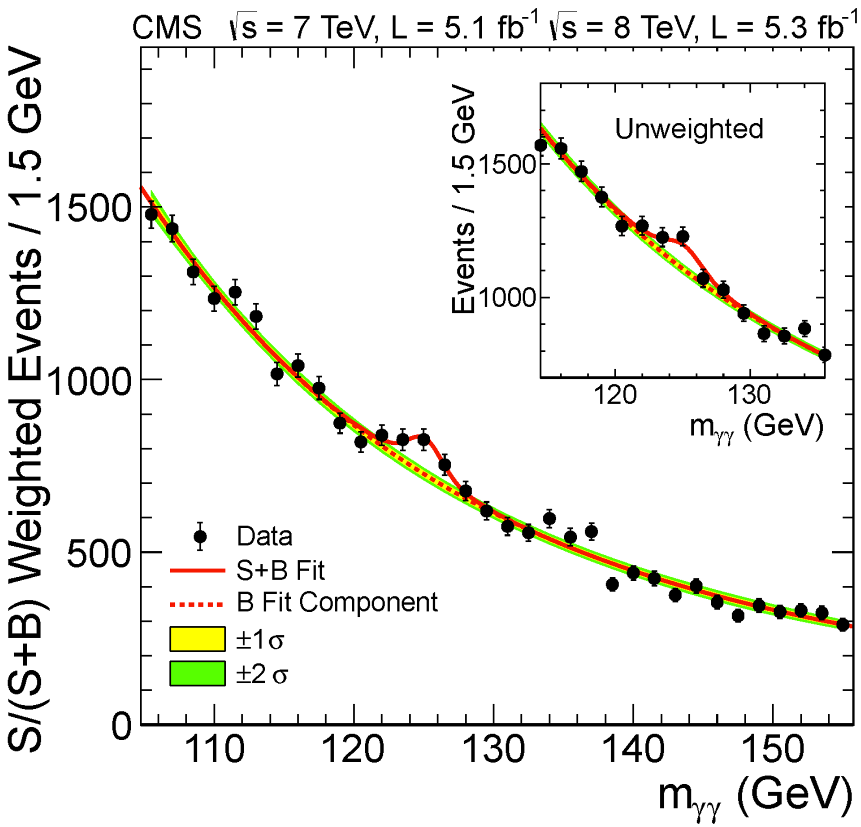


H → γγ selection

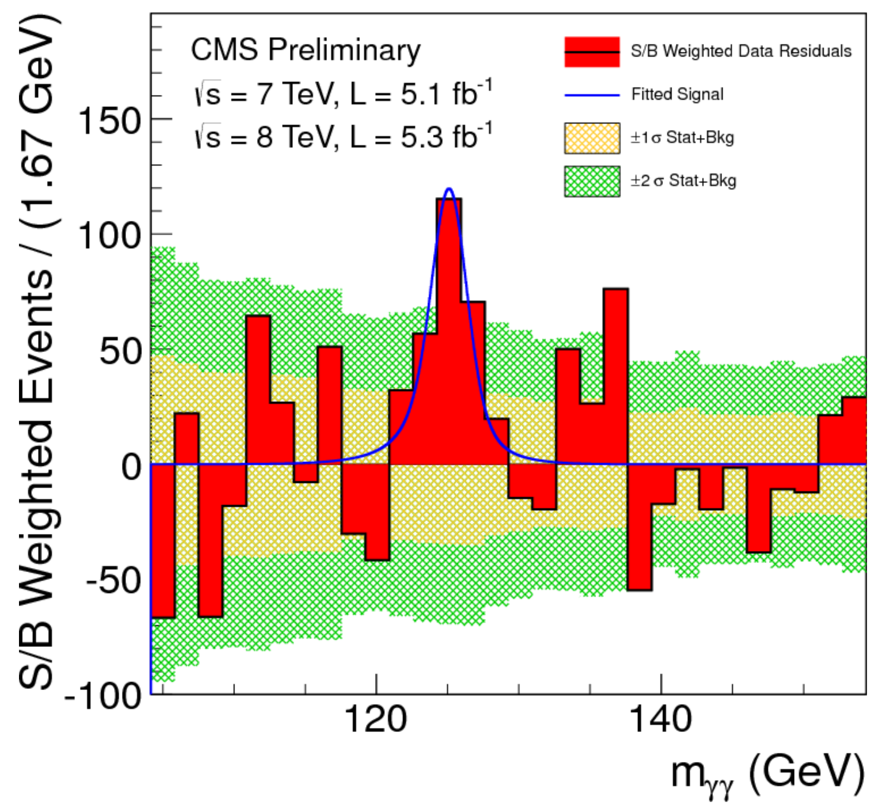
- Background: direct QCD photons and fake photons from jets
- p_T> (40,30) GeV for two photon candidates
- Photon identification based on categories based on η_γ i conversion probability:
  - Isolation
  - Shape of electromagnetic calorimeter to reject $\pi^0 \rightarrow \gamma\gamma$
  - Electron veto



H → γγ

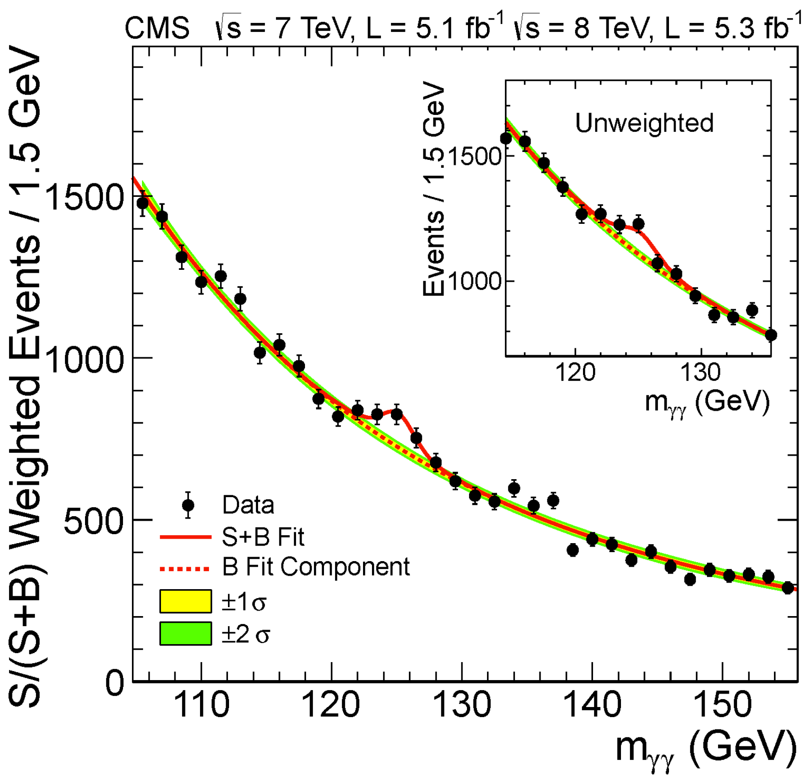


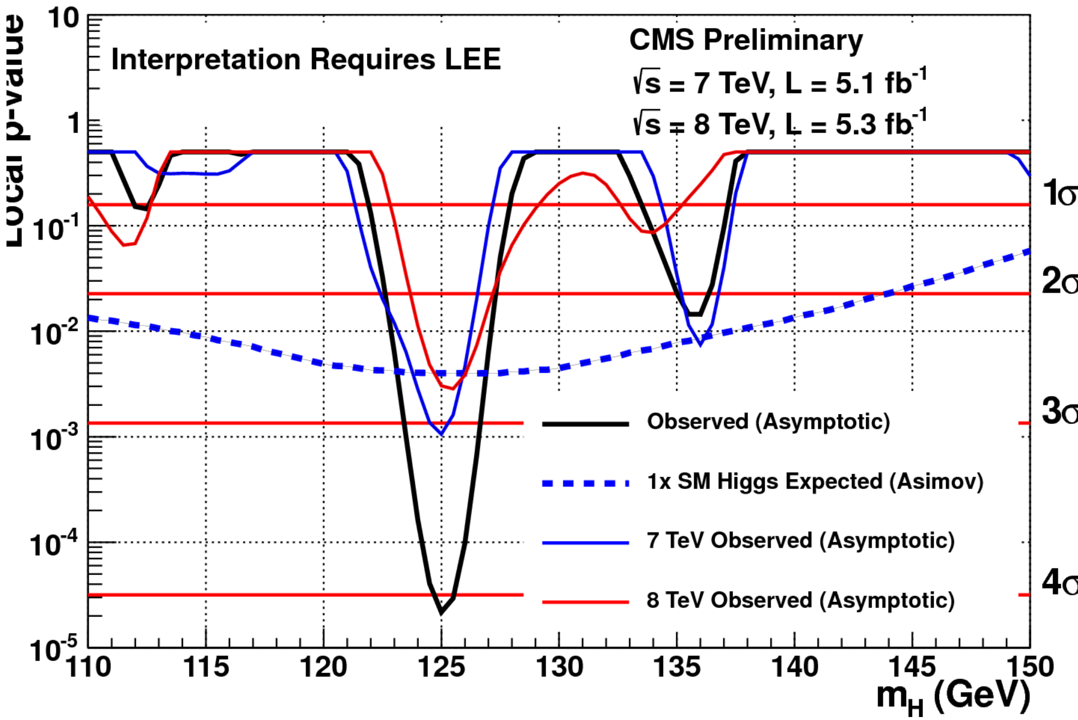
CMS √s = 7 TeV, L = 5.1 fb^-1 √s = 8 TeV, L = 5.3 fb^-1
S/(S+B) Weighted Events / 1.5 GeV
Unweighted
Events / 1.5 GeV
mγγ (GeV)
Data
S+B Fit
B Fit Component
±1σ
±2 σ



CMS Preliminary
√s = 7 TeV, L = 5.1 fb^-1
√s = 8 TeV, L = 5.3 fb^-1
S/B Weighted Data Residuals
Fitted Signal
±1σ Stat+Bkg
±2 σ Stat+Bkg
S/B Weighted Events / (1.67 GeV)
mγγ (GeV)

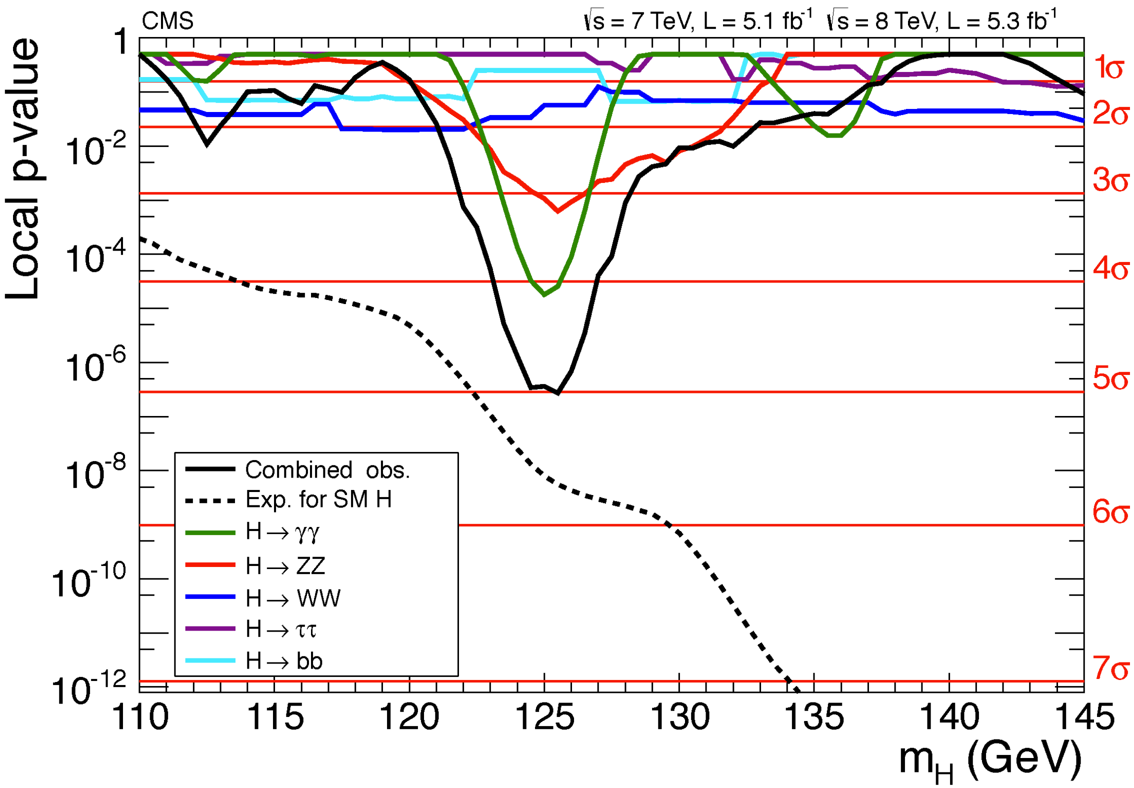
p-value

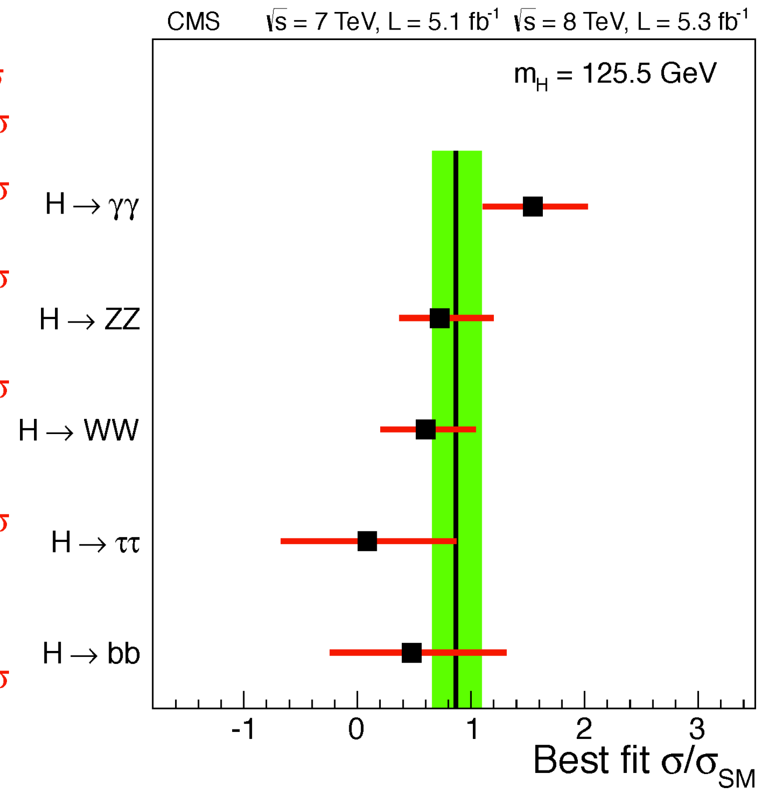

CMS √s = 7 TeV, L = 5.1 fb-1 √s = 8 TeV, L = 5.3 fb-1
Unweighted
Events / 1.5 GeV
$m_{\gamma\gamma}$ (GeV)
Data
S+B Fit
B Fit Component
±1σ
±2 σ
S/(S+B) Weighted Events / 1.5 GeV
$m_{\gamma\gamma}$ (GeV)


Interpretation Requires LEE
CMS Preliminary
√s = 7 TeV, L = 5.1 fb-1
√s = 8 TeV, L = 5.3 fb-1
Local p-value
1σ
2σ
3σ
4σ
Observed (Asymptotic)
1x SM Higgs Expected (Asimov)
7 TeV Observed (Asymptotic)
8 TeV Observed (Asymptotic)
m_H (GeV)

Combination and interpretation

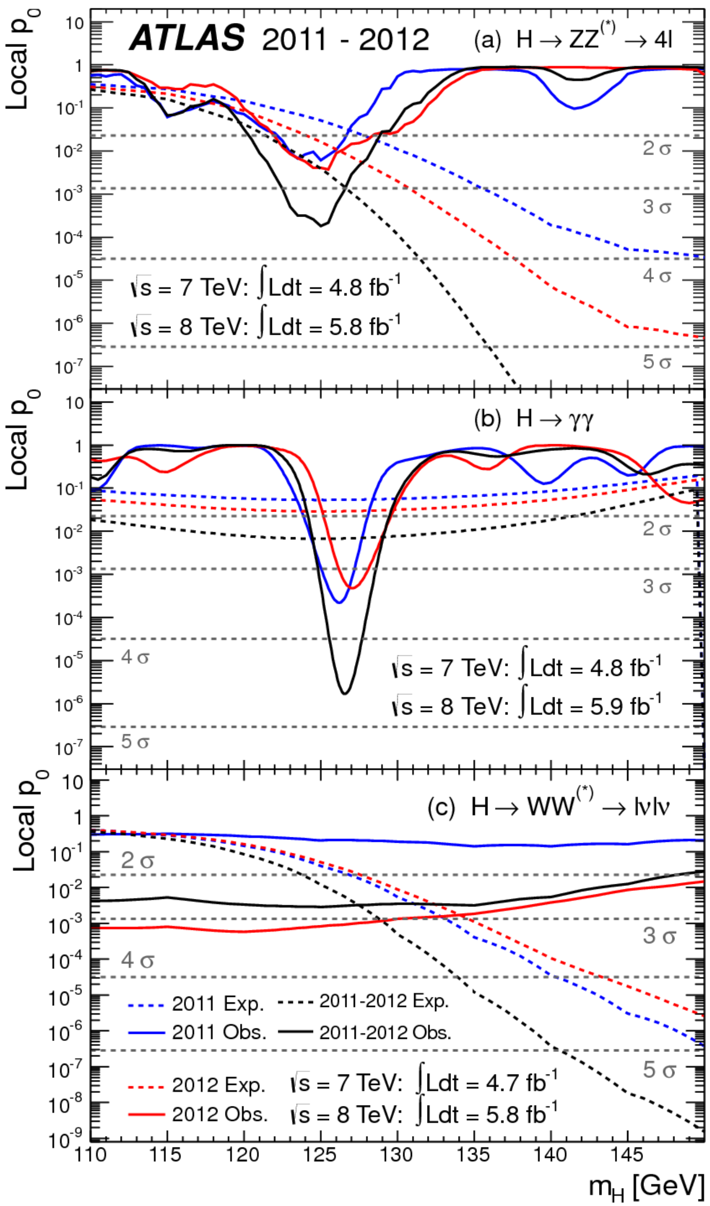
A new Higgs-like boson: CMS

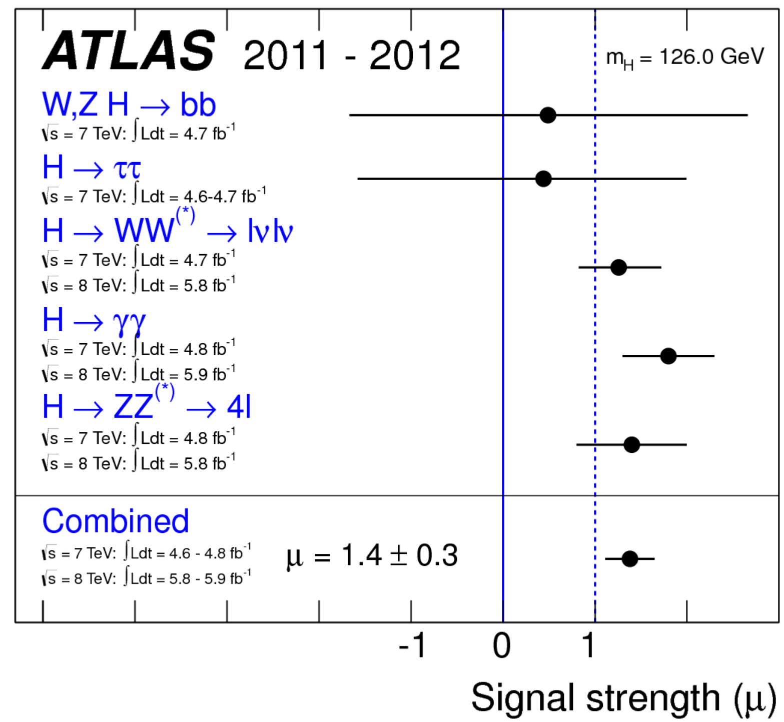




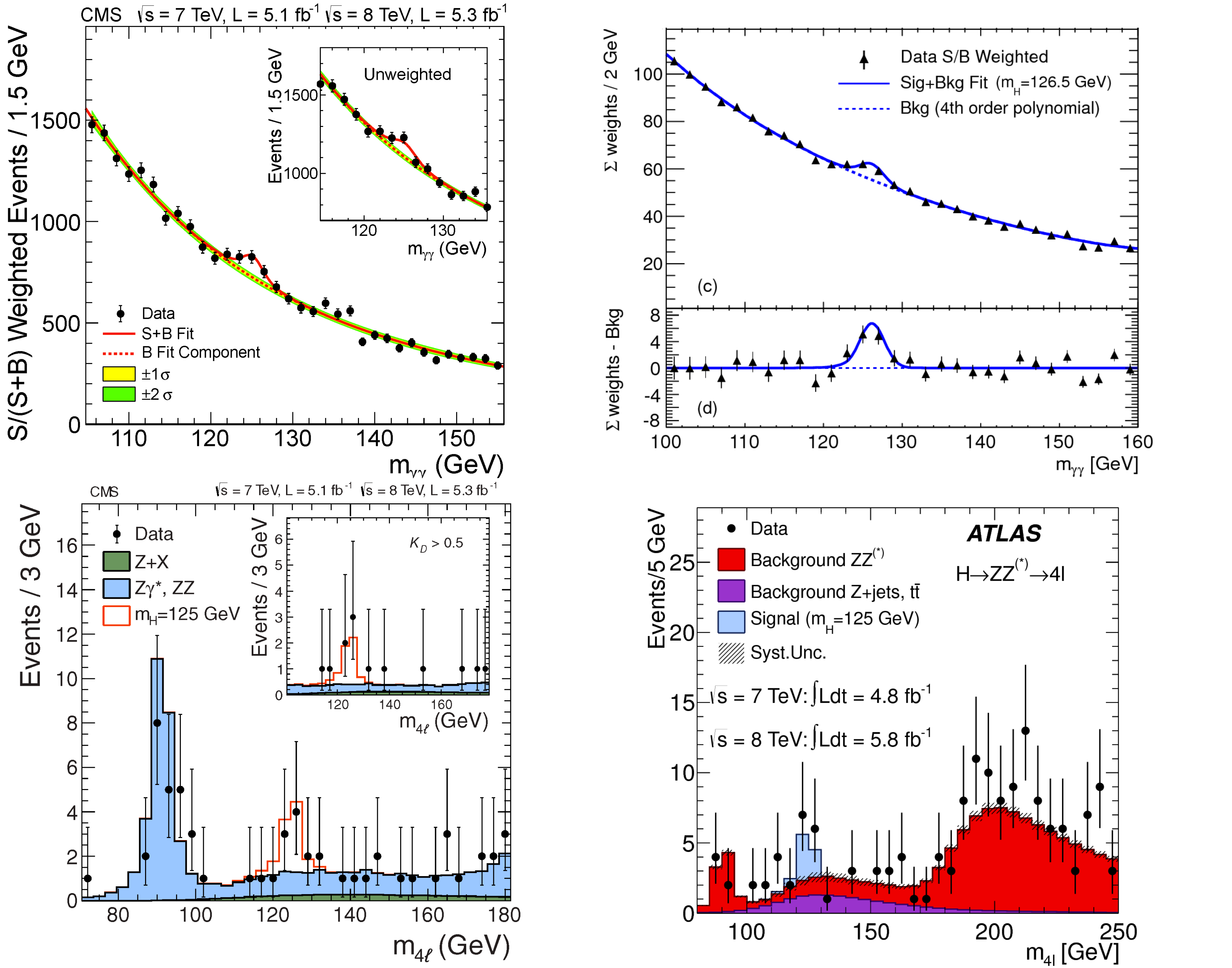
Significance = 5σ @ 125.5 GeV

A new Higgs-like boson: ATLAS

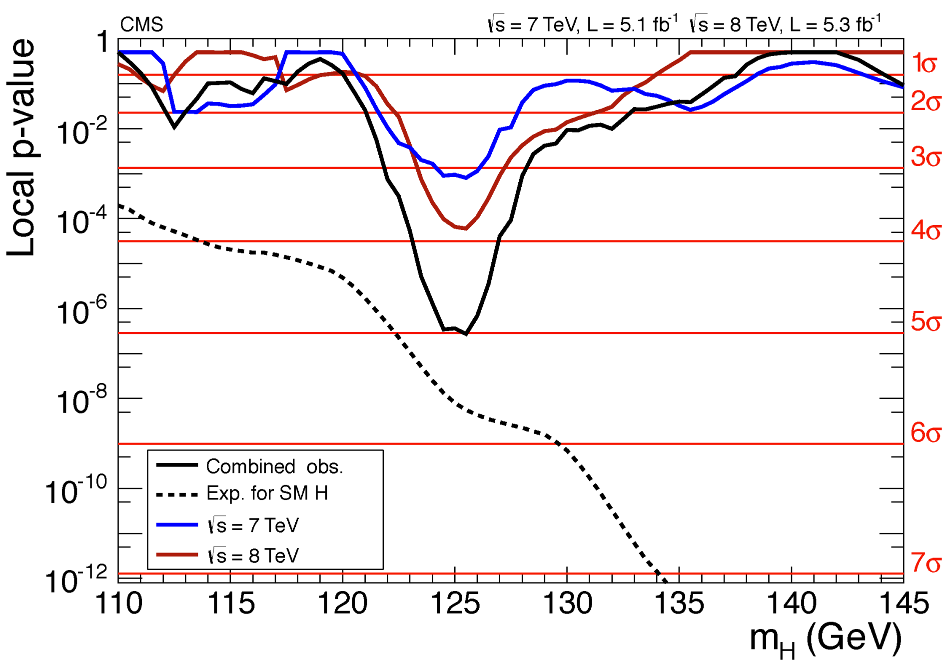


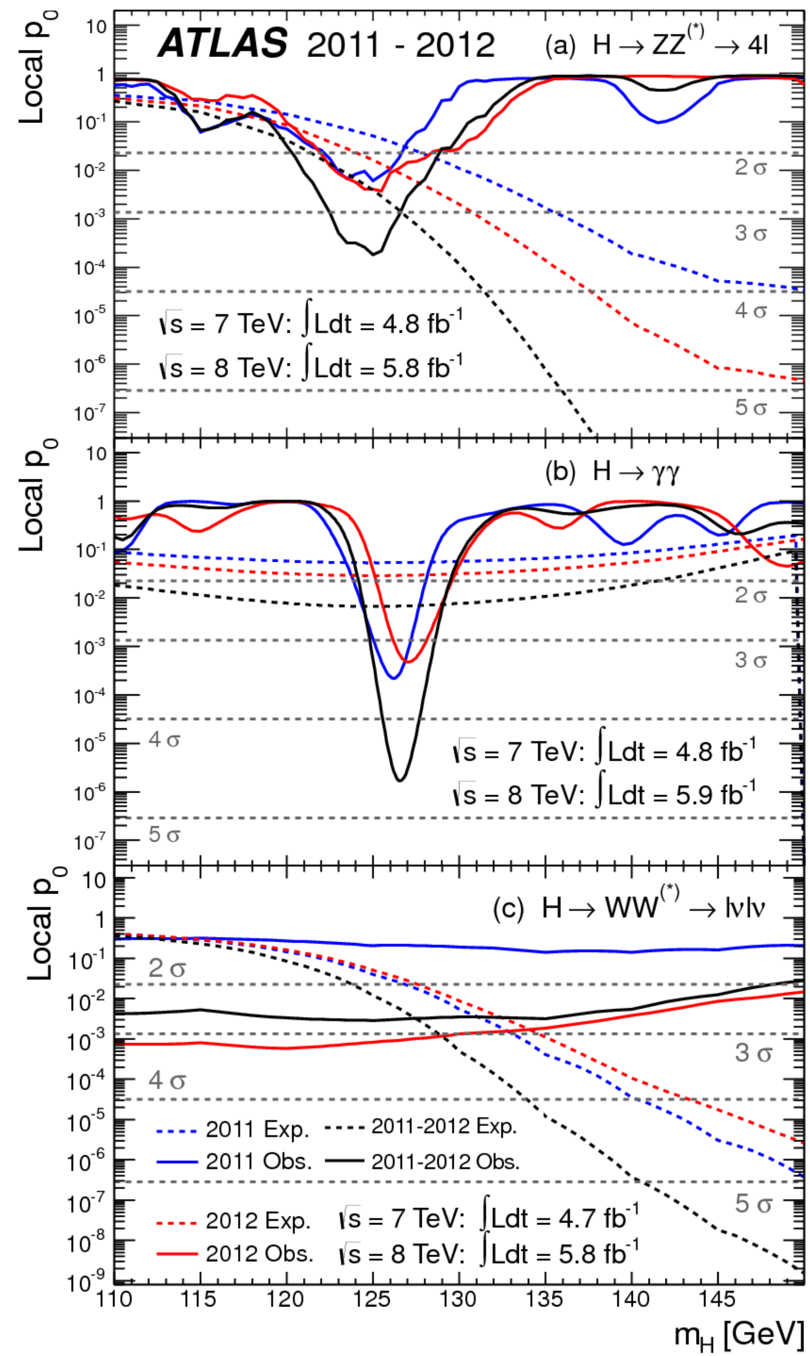


Significance = 5.9σ @ 126.5 GeV


CMS √s = 7 TeV, L = 5.1 fb-1 √s = 8 TeV, L = 5.3 fb-1
S/(S+B) Weighted Events / 1.5 GeV
Unweighted
Events / 1.5 GeV
mγγ (GeV)
Data
S+B Fit
B Fit Component
±1σ
±2 σ
Data S/B Weighted
Sig+Bkg Fit (mH=126.5 GeV)
Bkg (4th order polynomial)
Σ weights / 2 GeV
(c)
Σ weights - Bkg
(d)
mγγ [GeV]
CMS √s = 7 TeV, L = 5.1 fb-1 √s = 8 TeV, L = 5.3 fb-1
Events / 3 GeV
Data
Z+X
Zγ*, ZZ
mH=125 GeV
KD > 0.5
m4ℓ (GeV)
Events/5 GeV
Data
Background ZZ(*)
Background Z+jets, tt̄
Signal (mH=125 GeV)
Syst.Unc.
ATLAS
H→ZZ(*)→4l
√s = 7 TeV: ∫Ldt = 4.8 fb-1
√s = 8 TeV: ∫Ldt = 5.8 fb-1
m4l [GeV]

Excess of data at about the same place … in two years





Observation of a new boson at a mass of 125 GeV with the CMS experiment at the LHC

The CMS Collaboration*

Abstract

Results are presented from searches for the standard model Higgs boson in proton-proton collisions at $\sqrt{s} = 7$ and 8 TeV in the CMS experiment at the LHC, using data samples corresponding to integrated luminosities of up to 5.1 fb^{-1} at 7 TeV and 5.3 fb^{-1} at 8 TeV. The search is performed in five decay modes: $\gamma\gamma$, ZZ, WW, $\tau^+\tau^-$, and bb. An excess of events is observed above the expected background, a local significance of 5.0 standard deviations, at a mass near 125 GeV, signalling the production of a new particle. The expected significance for a standard model Higgs boson of that mass is 5.8 standard deviations. The excess is most significant in the two decay modes with the best mass resolution, $\gamma\gamma$ and ZZ; a fit to these signals gives a mass of $125.3 \pm 0.4\,(\mathrm{stat.}) \pm 0.5\,(\mathrm{syst.})$ GeV. The decay to two photons indicates that the new particle is a boson with spin different from one.

This paper is dedicated to the memory of our colleagues who worked on CMS but have since passed away.

In recognition of their many contributions to the achievement of this observation.

Submitted to Physics Letters B

CERN-PH-EP-2012-218

Submitted to: Physics Letters B

arXiv:1207.7214v1 [hep-ex] 31 Jul 2012

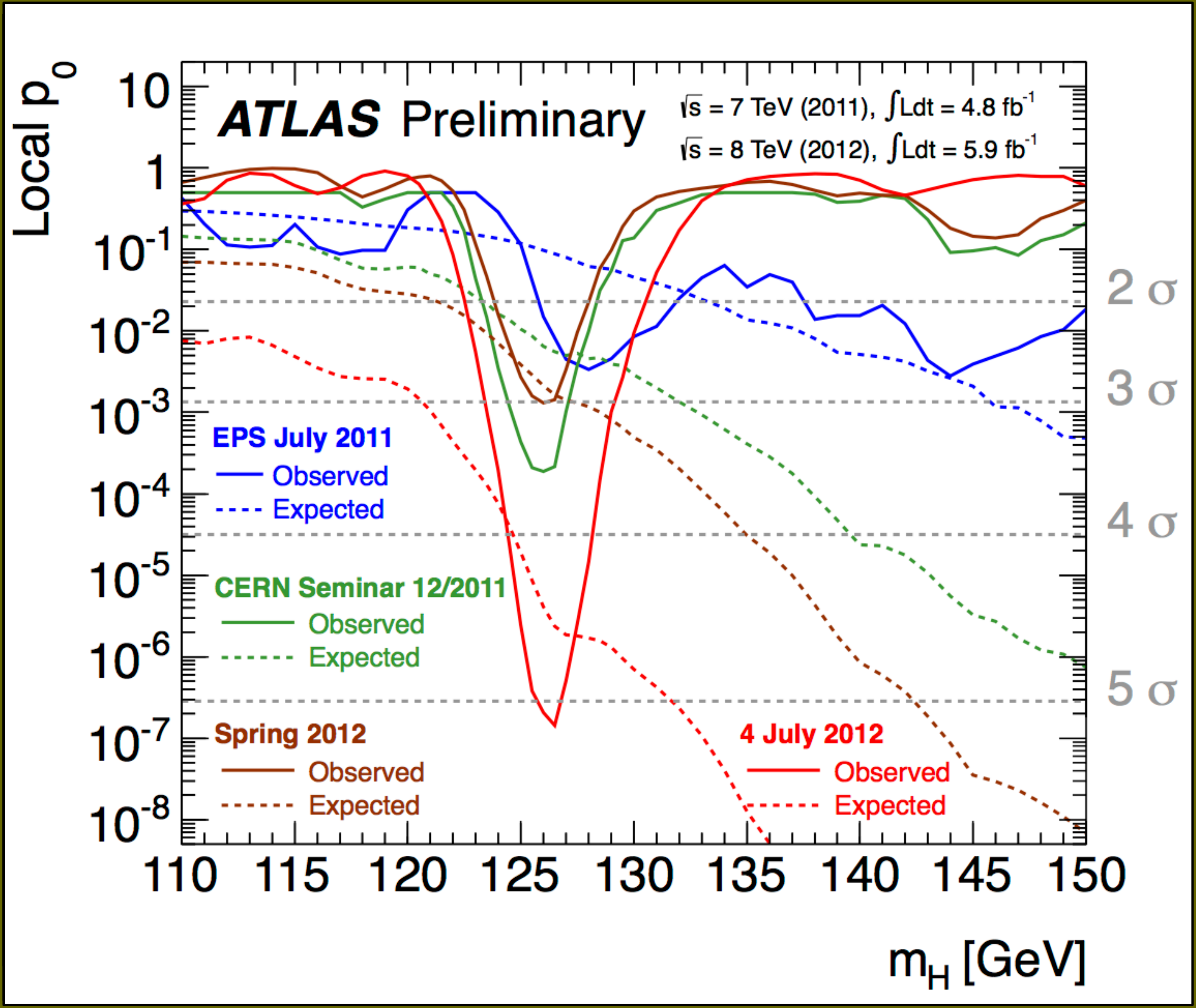
Observation of a New Particle in the Search for the Standard Model Higgs Boson with the ATLAS Detector at the LHC

The ATLAS Collaboration

Abstract

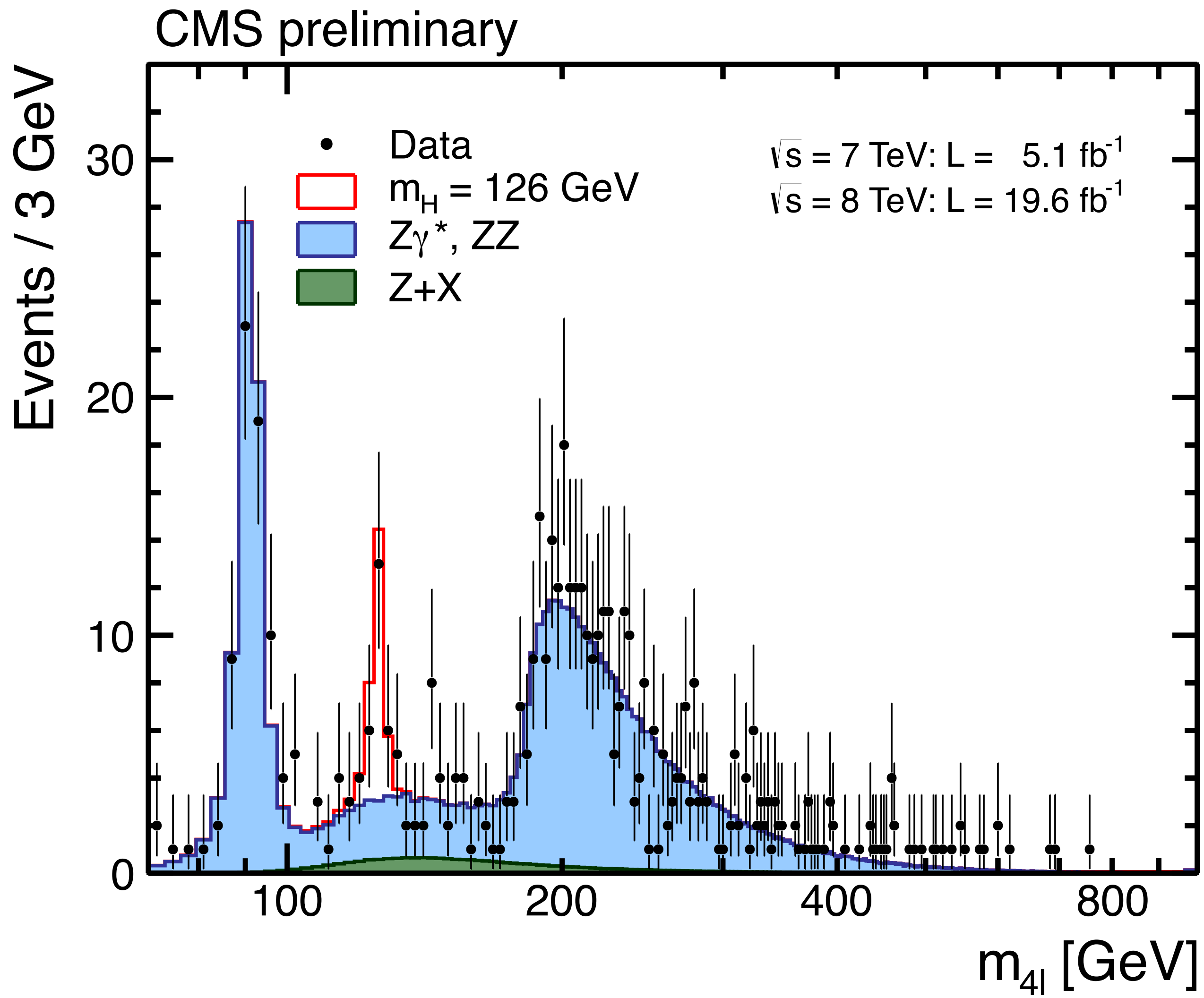
A search for the Standard Model Higgs boson in proton-proton collisions with the ATLAS detector at the LHC is presented. The datasets used correspond to integrated luminosities of approximately 4.8 fb^{-1} collected at $\sqrt{s} = 7$ TeV in 2011 and 5.8 fb^{-1} at $\sqrt{s} = 8$ TeV in 2012. Individual searches in the channels $H \to ZZ^{(*)} \to 4\ell$, $H \to \gamma\gamma$ and $H \to WW^{(*)} \to e\nu\mu\nu$ in the 8 TeV data are combined with previously published results of searches for $H \to ZZ^{(*)}$, $WW^{(*)}$, bb and $\tau^+\tau^-$ in the 7 TeV data and results from improved analyses of the $H \to ZZ^{(*)} \to 4\ell$ and $H \to \gamma\gamma$ channels in the 7 TeV data. Clear evidence for the production of a neutral boson with a measured mass of $126.0 \pm 0.4\,\text{(stat)} \pm 0.4\,\text{(sys)}$ GeV is presented. This observation, which has a significance of 5.9 standard deviations, corresponding to a background fluctuation probability of 1.7×10^{-9}, is compatible with the production and decay of the Standard Model Higgs boson.

Evolution of the excess with time



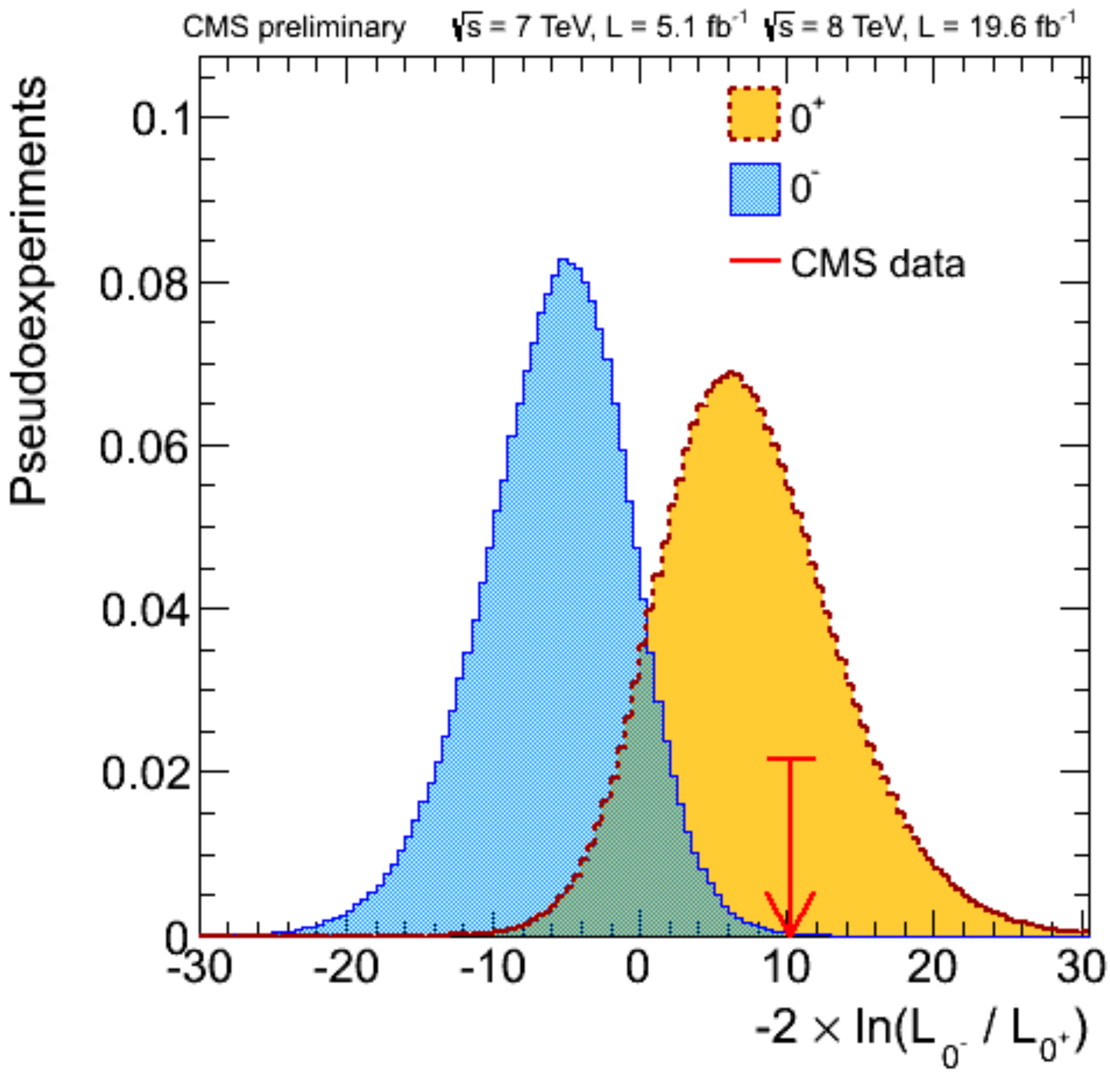
Energy-scale systematics not included

This was
Part 1 – How did we find it?

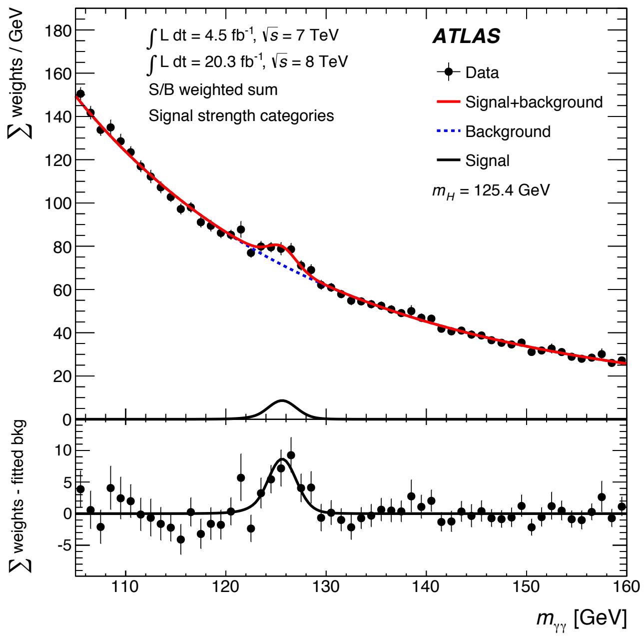


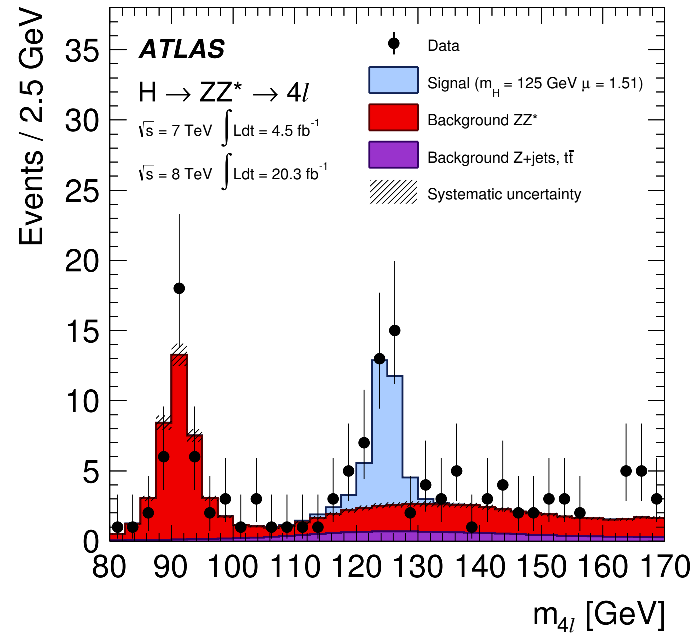
Part 2 – What did we really find?

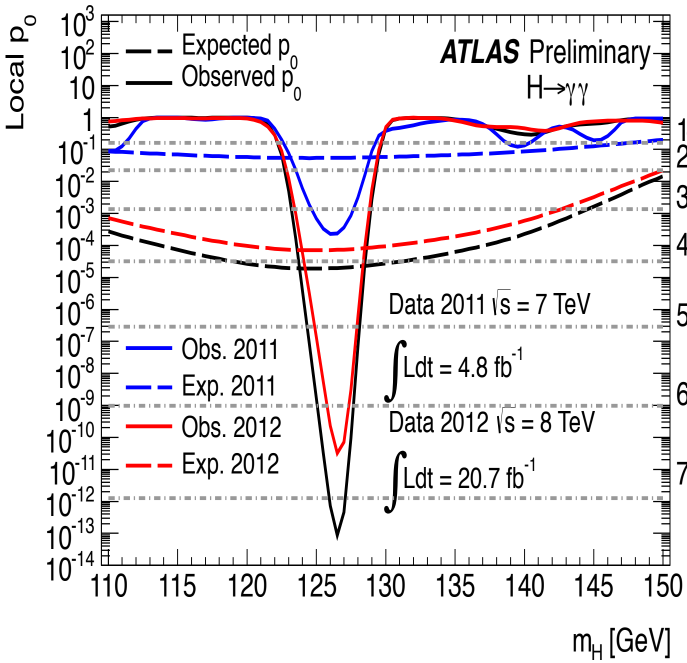
And how do we know that …

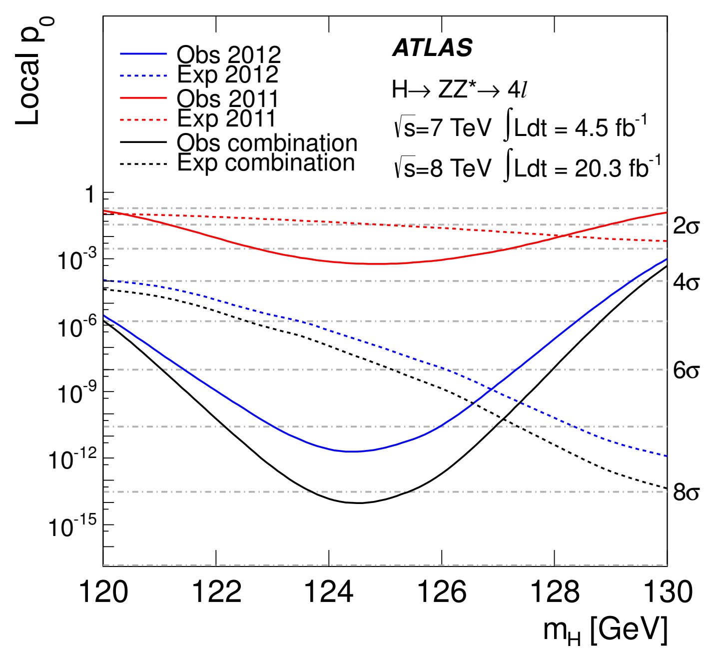


ATLAS – Final results with Run I data

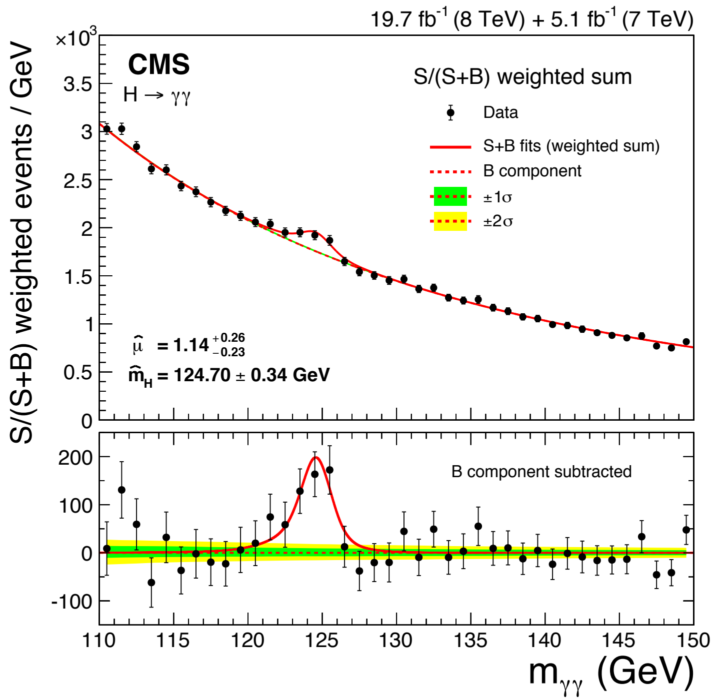


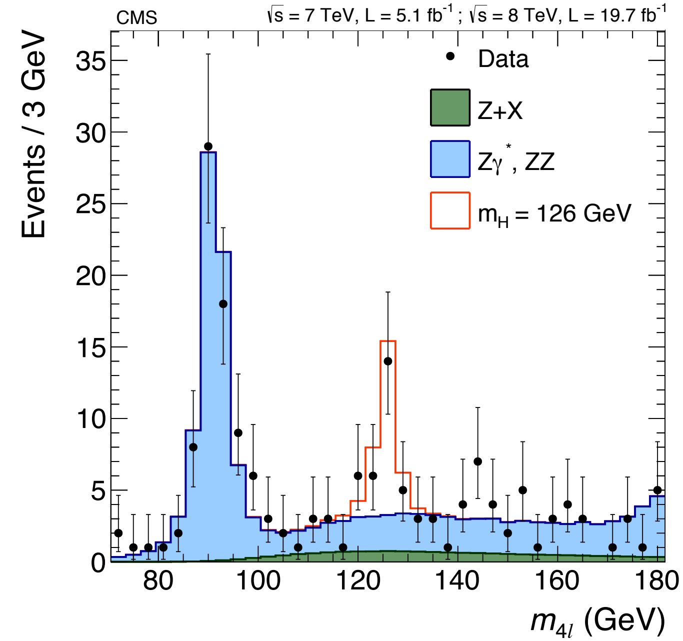


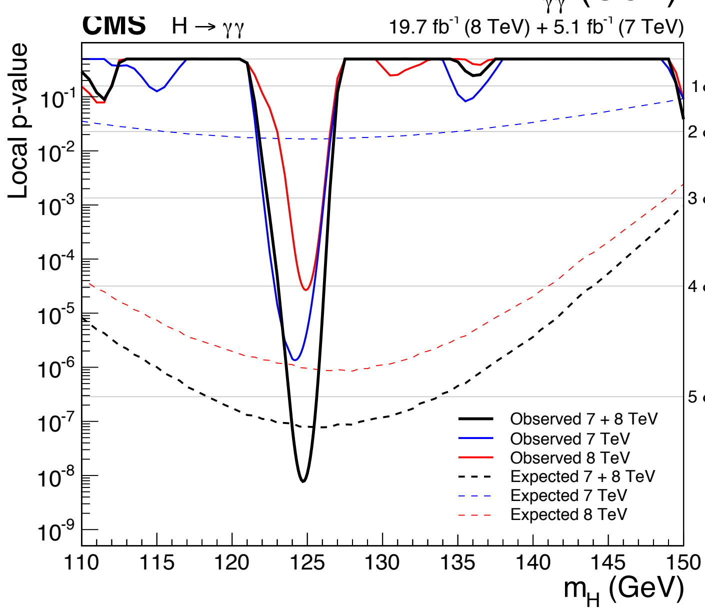


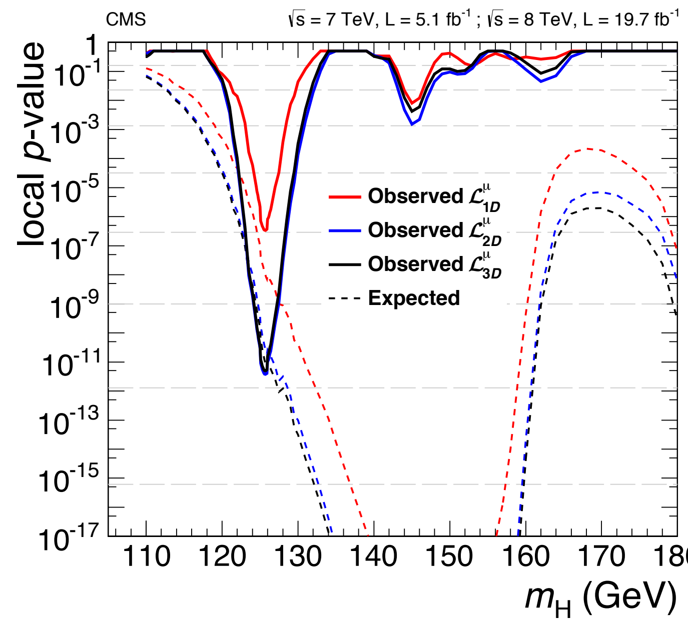


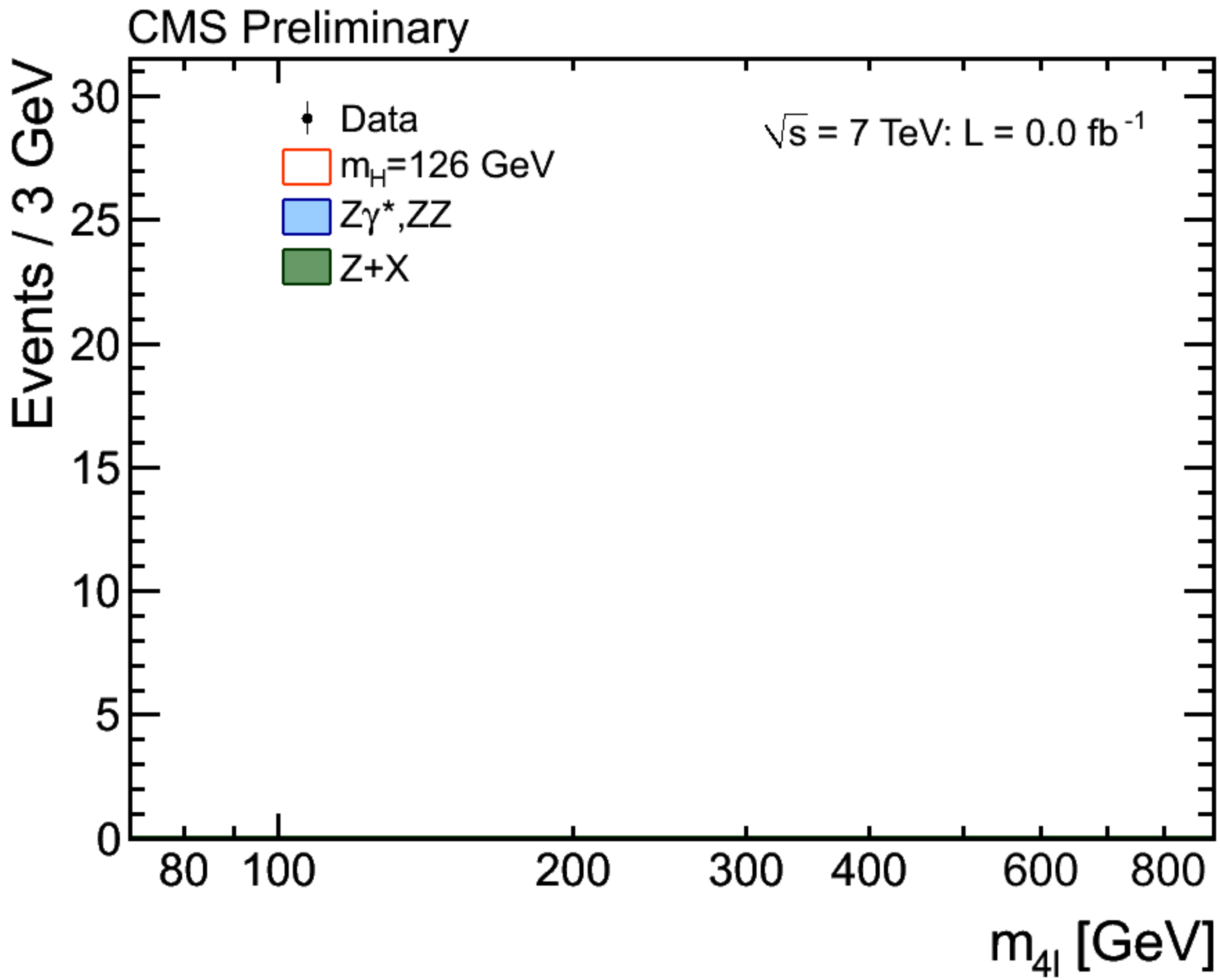
CMS – Final results with Run I data







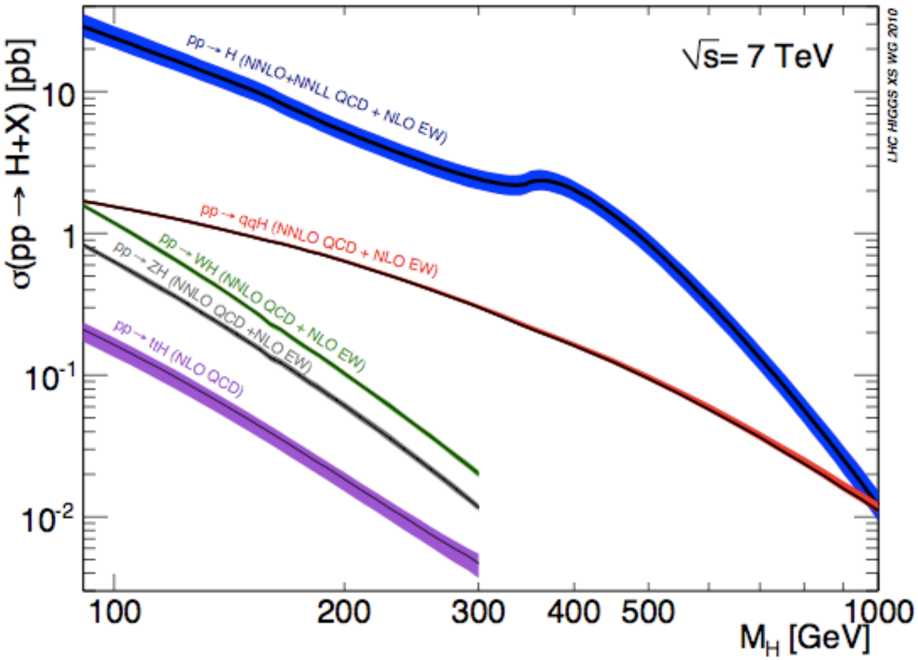


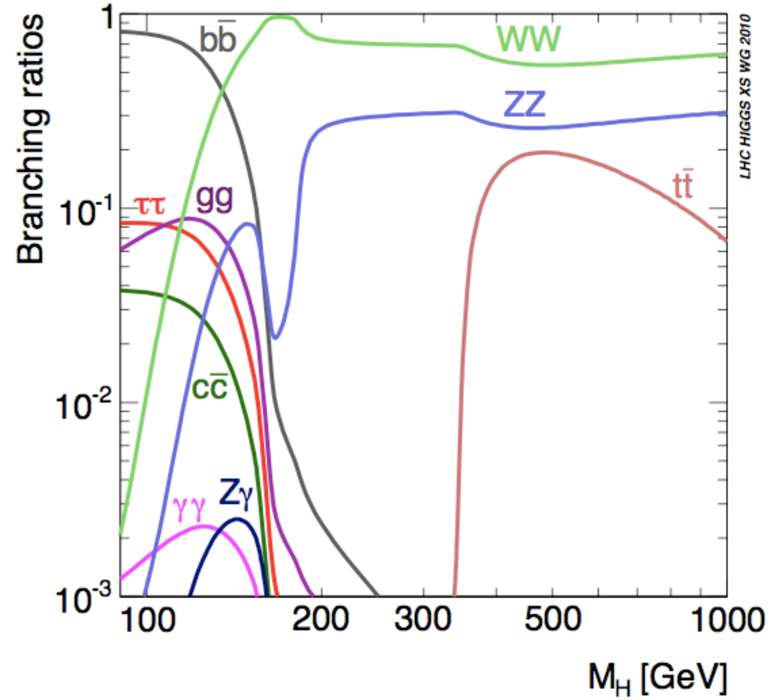

CMS Preliminary
Events / 3 GeV
30
25
20
15
10
5
0
Data
m_H=126 GeV
Zγ*,ZZ
Z+X
√s = 7 TeV: L = 0.0 fb^-1
80
100
200
300
400
600
800
m_4l [GeV]

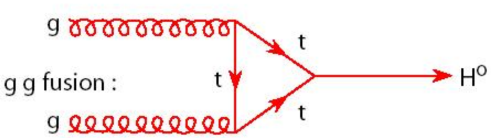
Measuring the properties

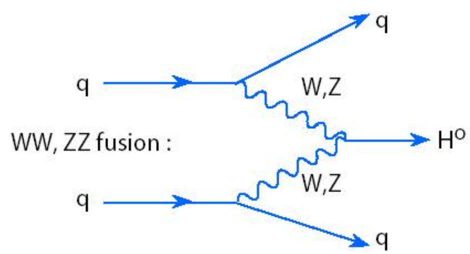
- What kind of objects did we find?
  - Is this the Higgs boson of the Standard Model?
    - Or something else ...
- Remember from the first part of this lecture: we better reject then accept hypotheses
- Let's call this particle "**X particle**", for the moment
- Tests:
  - What is the mass of **X**?
  - Is **X** produced according to the SM Higgs boson predictions?
  - Does **X** decay according to the SM Higgs boson predictions?
  - Does **X** couple to other particles according to the SM Higgs boson predictions?
  - What is the spin and parity of **X**?

Higgs boson at LHC







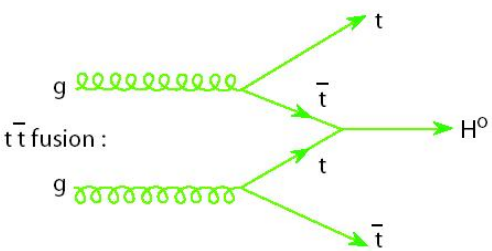


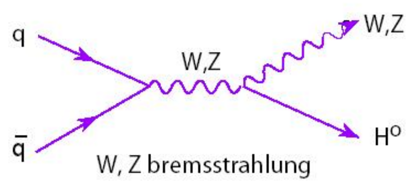
Higgs boson (M_H ~120 GeV)

produced every **~10 sekunds**

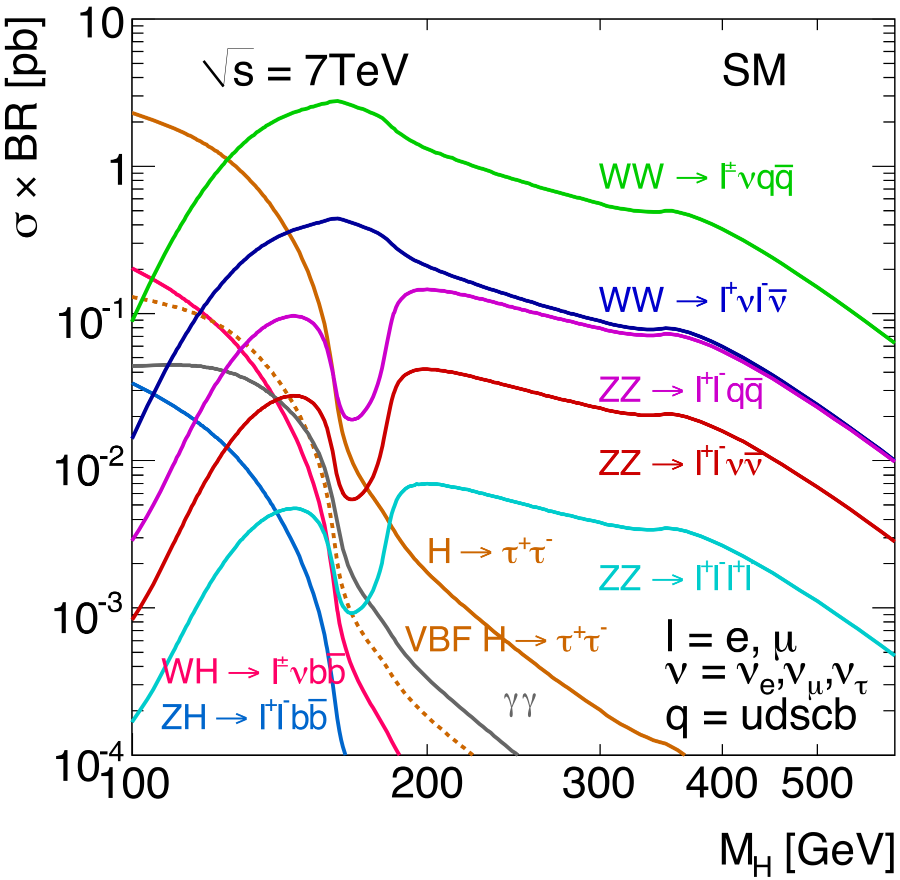
@ L=5x10^{33} cm^{-2} s^{-1}

– If it exists ☺





Higgs boson: decay channels



Decay channel	Mass region
H → γγ	110–150
H → bb	110–135
H → ττ	110–140
H →WW →2l 2ν	110–600
H → ZZ →4l	110–600
H → ZZ →2l2τ	180–600
H → ZZ →2l2j	226–600
H → ZZ →2l2ν	250–600

Signal at 1 fb^{-1}

m_H, GeV	WW→2l2ν	ZZ→4l	γγ
120	127	1.5	43
150	390	4.6	16
300	89	3.8	0.04

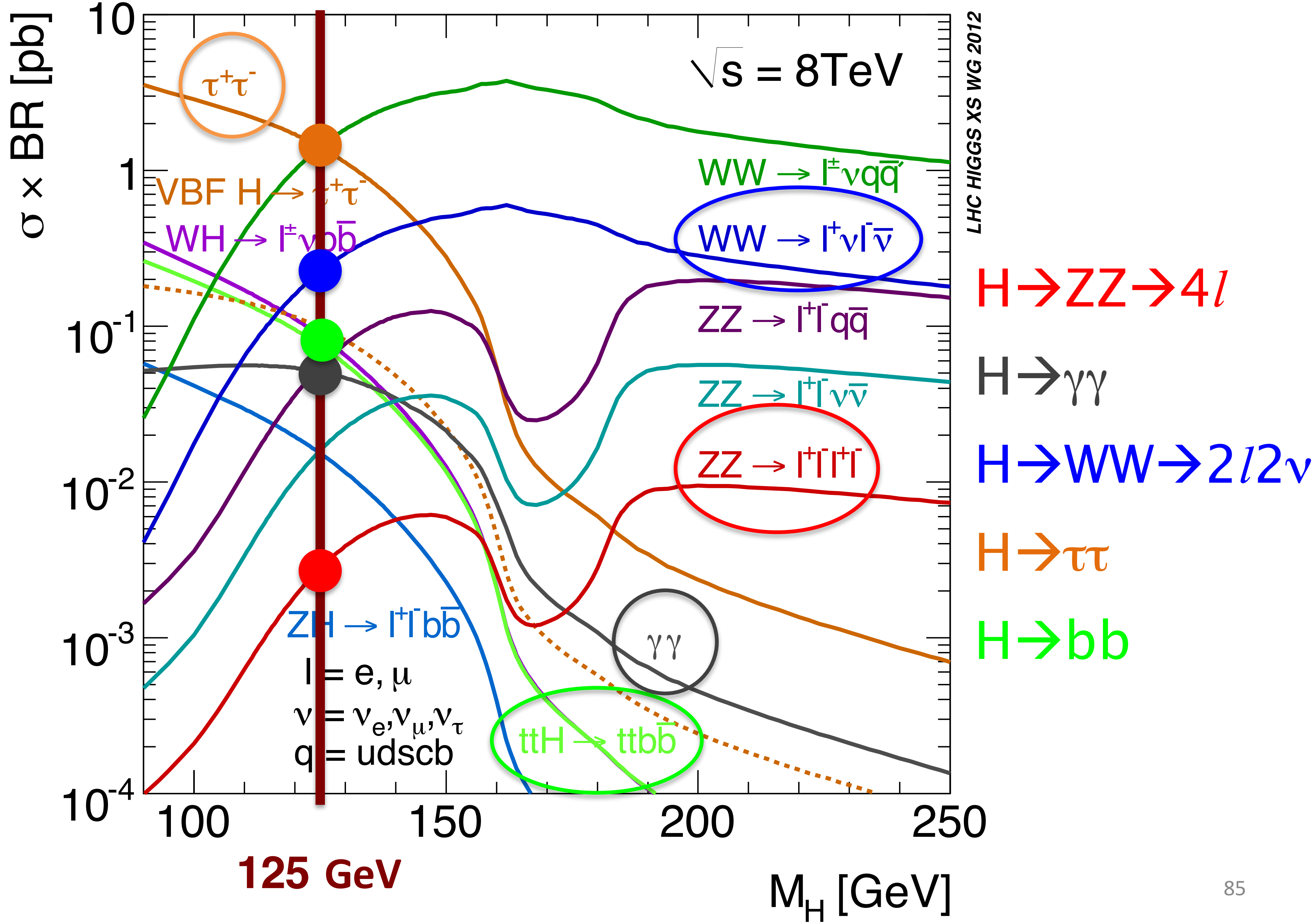
Most sensitive channels for low mass Higgs:

H → γγ

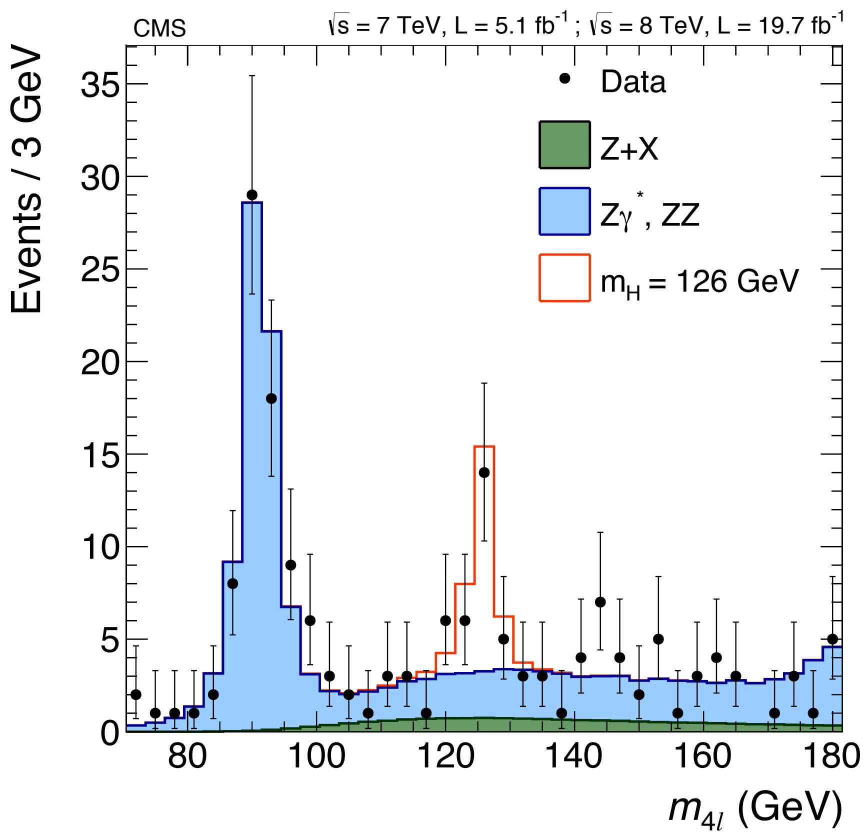
H → WW → $l^-\nu l^+\nu$,

H → ZZ → $l^-l^+l^-l^+$

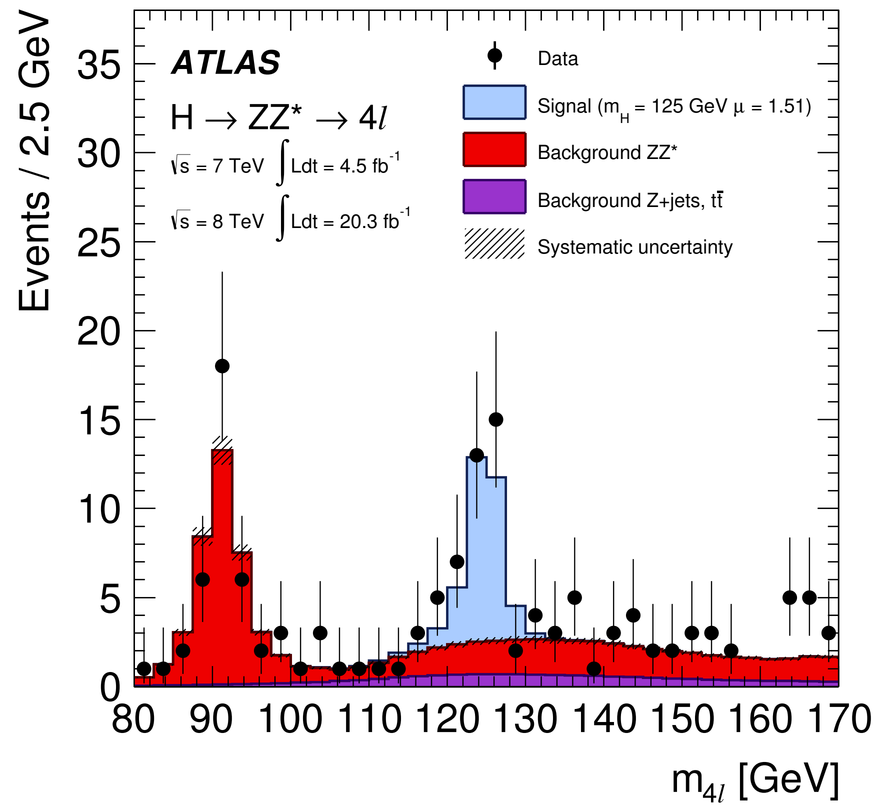
Main channels



H→ZZ→4l

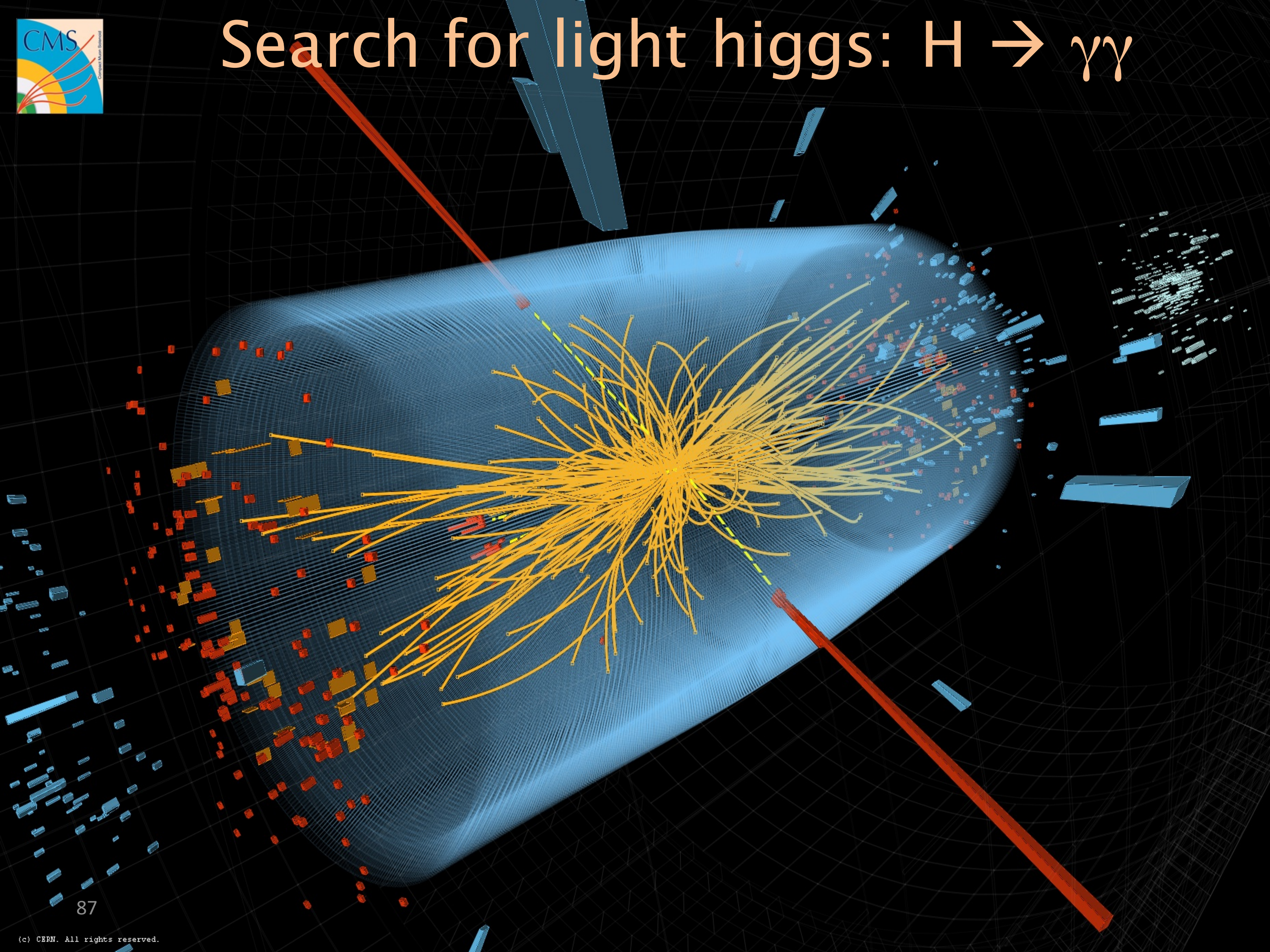


CMS
√s = 7 TeV, L = 5.1 fb⁻¹ ; √s = 8 TeV, L = 19.7 fb⁻¹
Data
Z+X
Zγ*, ZZ
m_H = 126 GeV
Events / 3 GeV
m_4l (GeV)

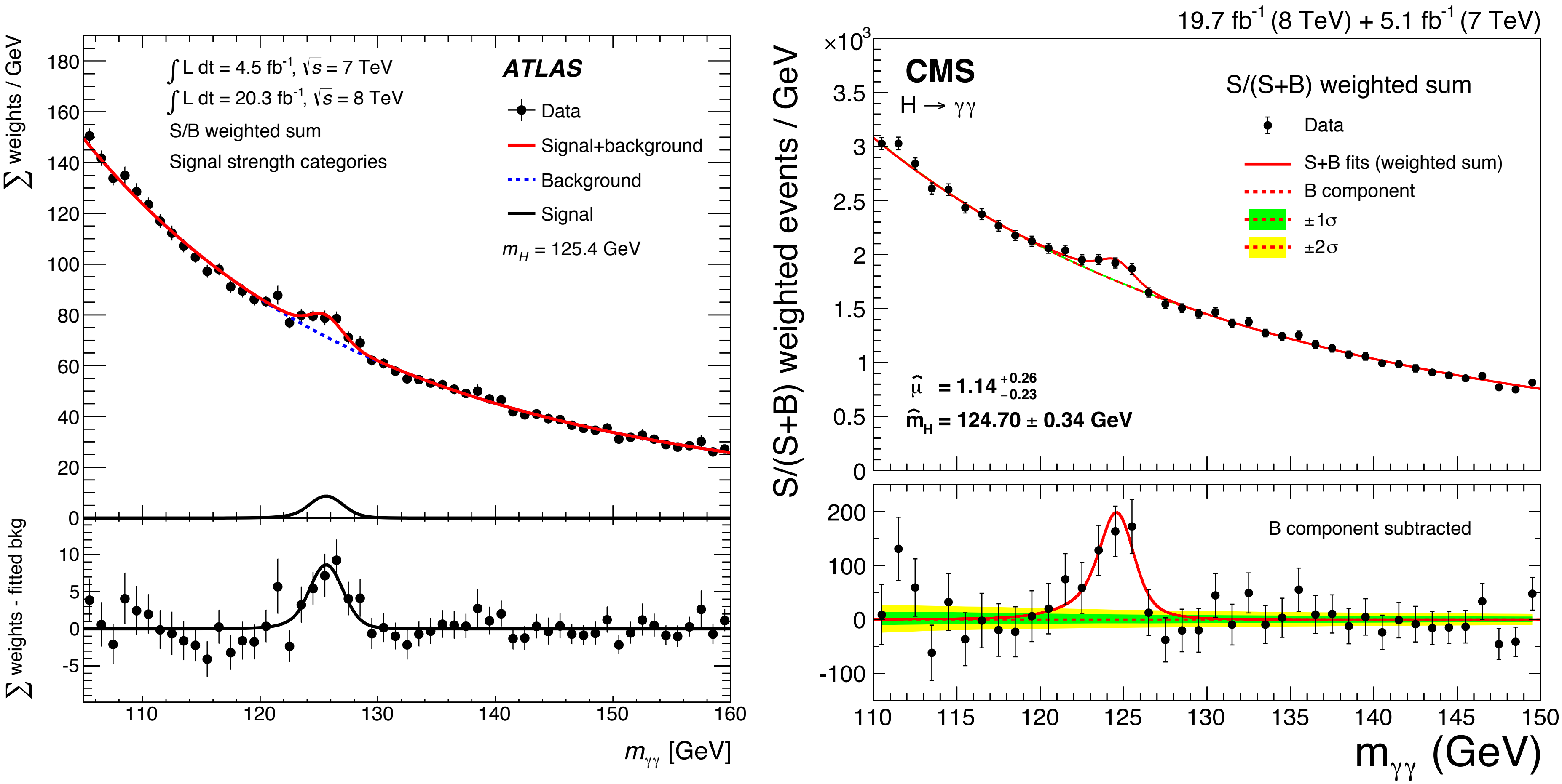


ATLAS
H → ZZ* → 4l
√s = 7 TeV ∫Ldt = 4.5 fb⁻¹
√s = 8 TeV ∫Ldt = 20.3 fb⁻¹
Data
Signal (m_H = 125 GeV μ = 1.51)
Background ZZ*
Background Z+jets, tt̄
Systematic uncertainty
Events / 2.5 GeV
m_4l [GeV]

Search for light higgs: $H \rightarrow \gamma\gamma$

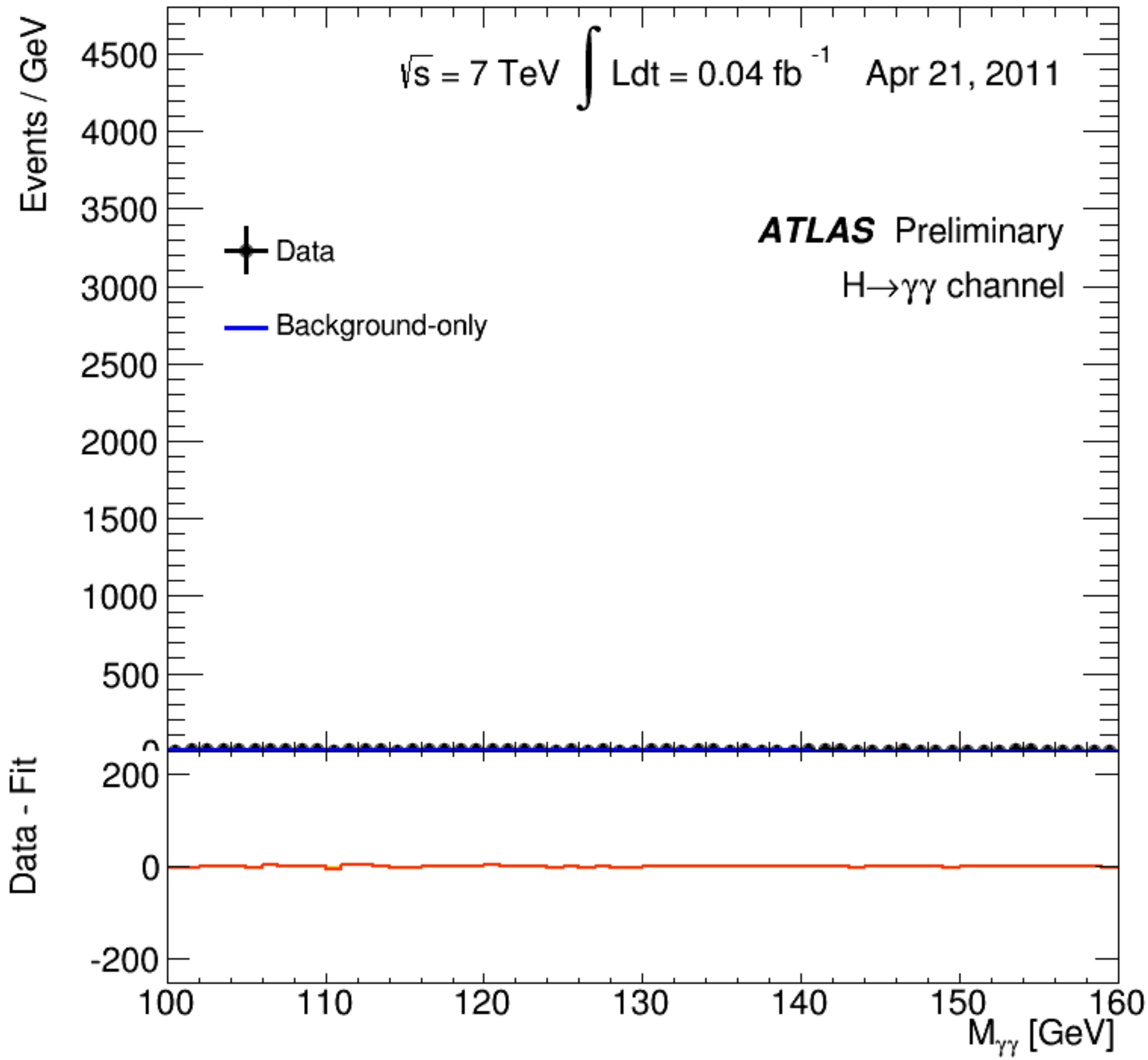


H→γγ



ATLAS
$\int L\,dt = 4.5\ fb^{-1}$, $\sqrt{s} = 7$ TeV
$\int L\,dt = 20.3\ fb^{-1}$, $\sqrt{s} = 8$ TeV
S/B weighted sum
Signal strength categories
Data
Signal+background
Background
Signal
$m_H = 125.4$ GeV
$\sum$ weights / GeV
$\sum$ weights - fitted bkg
$m_{\gamma\gamma}$ [GeV]
$19.7\ fb^{-1}$ (8 TeV) + $5.1\ fb^{-1}$ (7 TeV)
CMS
$H \rightarrow \gamma\gamma$
S/(S+B) weighted sum
Data
S+B fits (weighted sum)
B component
$\pm 1\sigma$
$\pm 2\sigma$
$\hat{\mu} = 1.14^{+0.26}_{-0.23}$
$\hat{m}_H = 124.70 \pm 0.34$ GeV
S/(S+B) weighted events / GeV
B component subtracted
$m_{\gamma\gamma}$ (GeV)

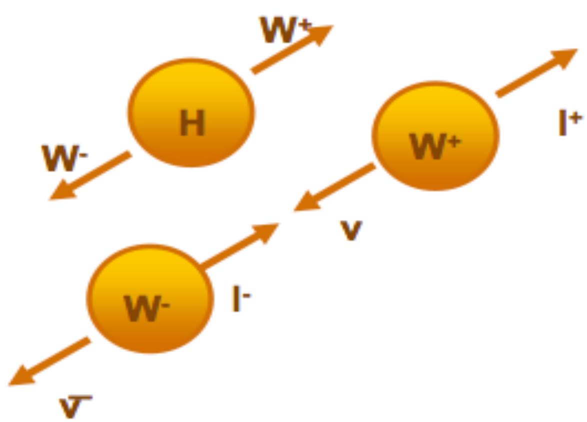
ATLAS H → γγ

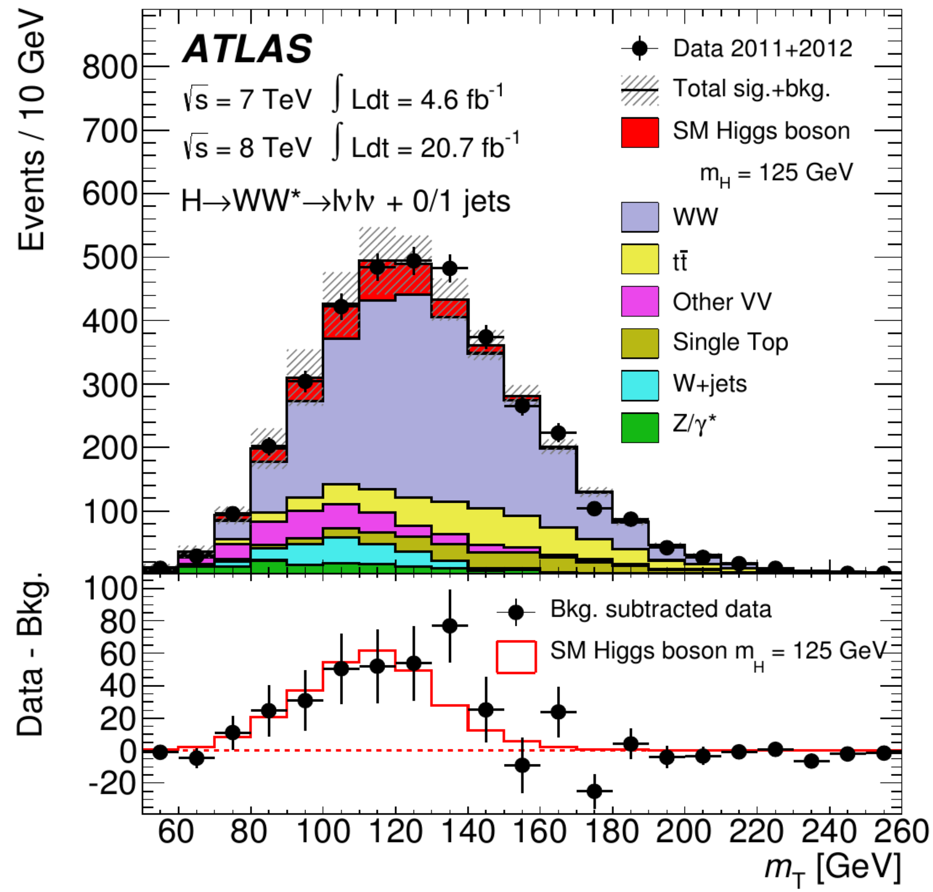


Events / GeV
4500
4000
3500
3000
2500
2000
1500
1000
500
0
√s = 7 TeV ∫Ldt = 0.04 fb -1 Apr 21, 2011
ATLAS Preliminary
H→γγ channel
Data
Background-only
Data - Fit
200
0
-200
100
110
120
130
140
150
160
Mγγ [GeV]

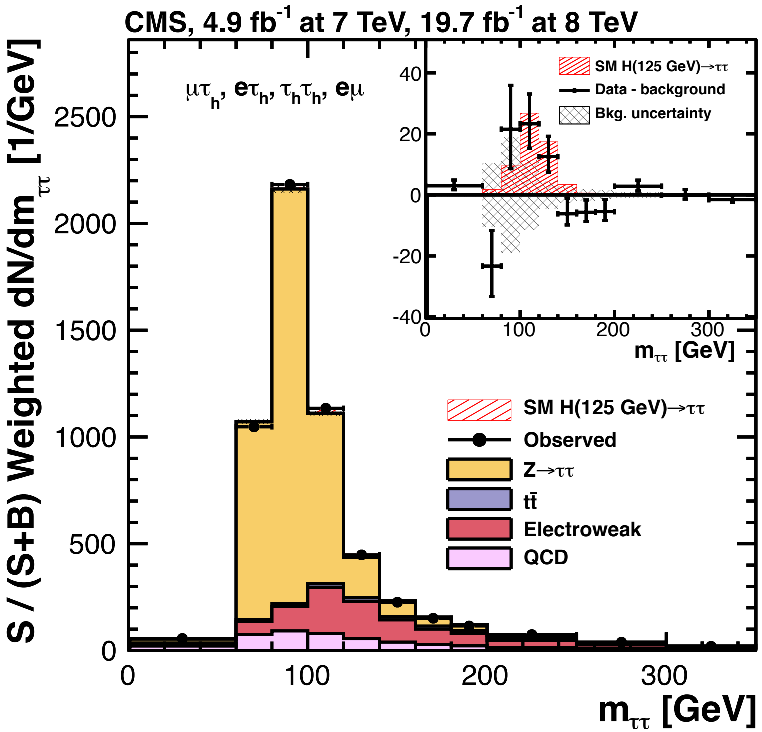
H→WW→2l2ν

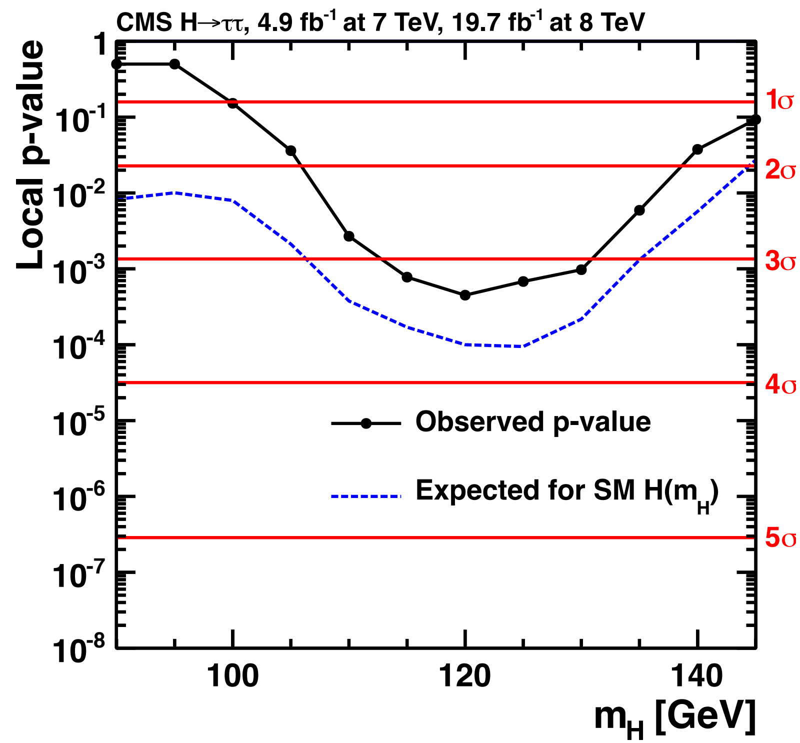
- Signal characteristics:
  - Only 2 opposite sign, isolated leptons
  - significant ME_T→ No mass peak
  - No b-jets, no additional low P_T μ
  - With additional 0, 1 or 2 jets (VBF)
  - Small ΔΦ (l^+l^-) ← Higgs scalarity





H→ττ



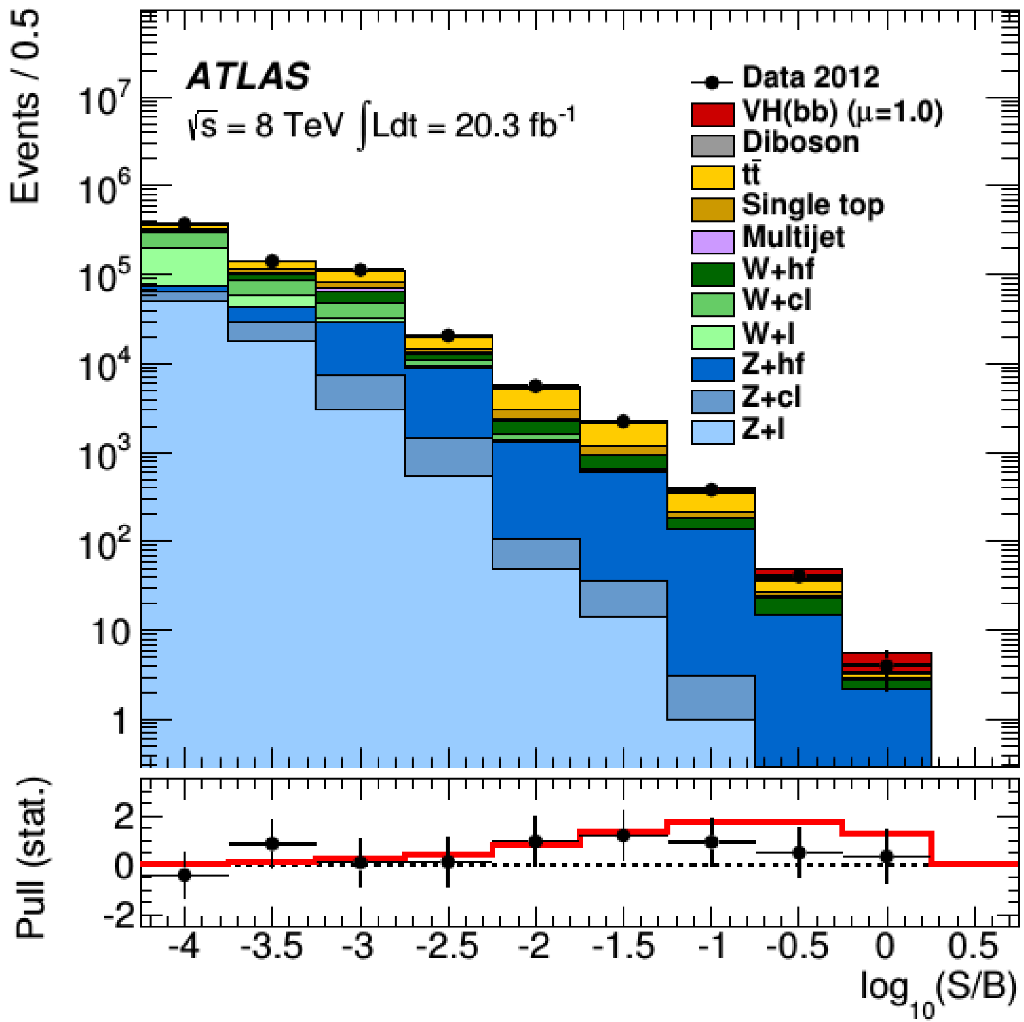


Search H→ ττ in two categories:

- VBF: 2 jets (P_T>30 GeV), $\Delta\eta_{jj}$>3.5
  $\eta_1 \bullet \eta_2 < 0$, M_{jj} > 350 GeV
- Non-VBF: ≤ 1jet , or 2j failing VBF
- In $\tau_e + \tau_h$, $\tau_\mu + \tau_h$, $\tau_e + \tau_\mu$ final states
- Background: top, EWK, Z → ττ (irreducible)

VH→lνbb

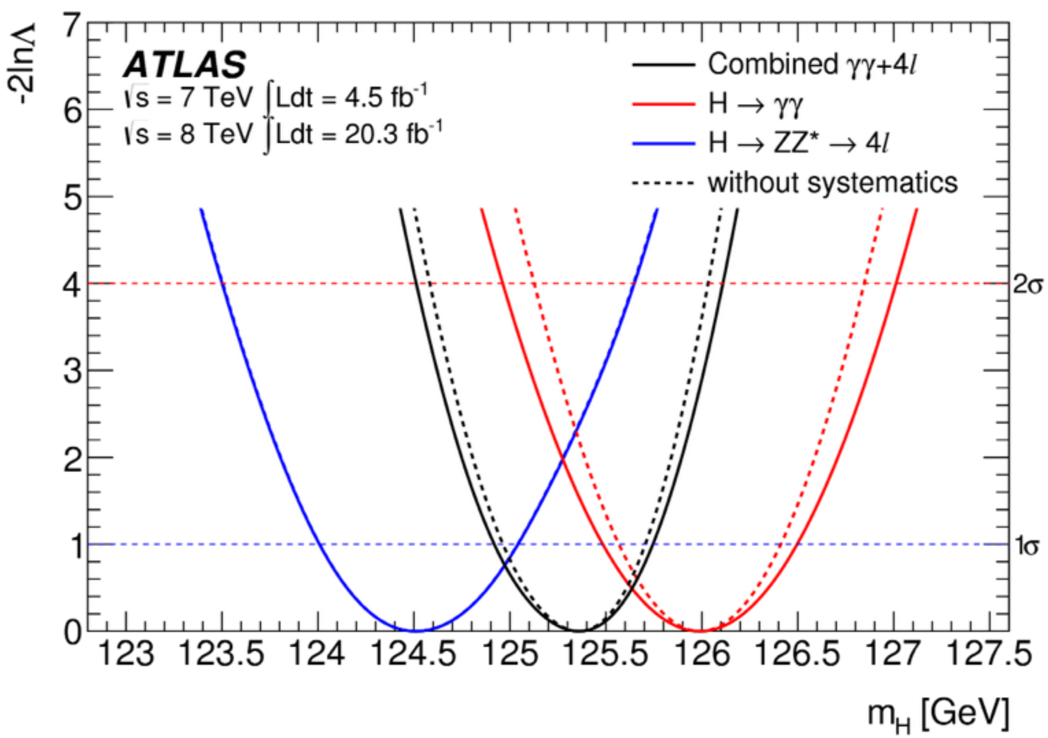
- gg→H→ bb and VBF are dominant production modes
  - but overwhelmed by enormous QCD di-jet background
- Best option: qq→ VH; H → bb
- Use
  - VH topology : ΔΦ(V,H) > 3
  - P_T(V)> 100-160 GeV (boosted W/Z)
  - Tight b-tagging & MET quality
  - Backgrounds estimated from control data

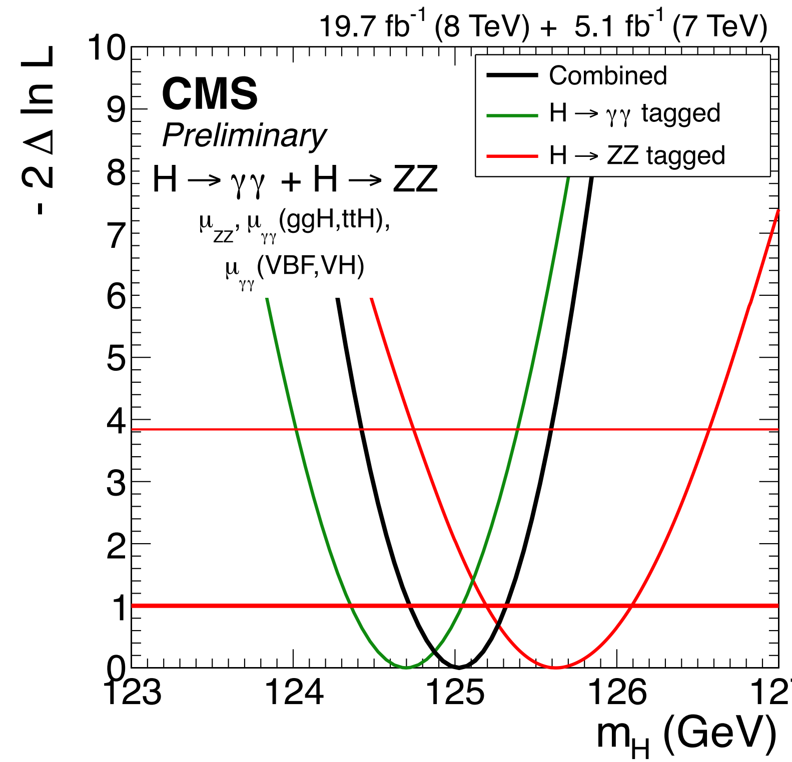


What is the mass of X?

Measure the mass through high precision channels

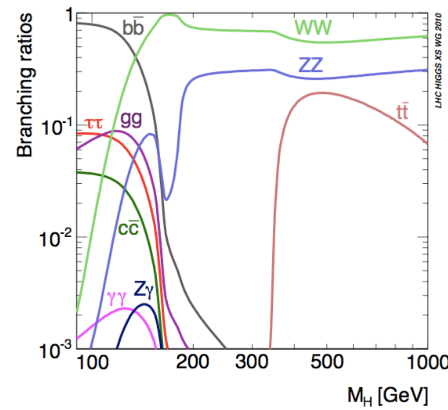
H→γγ and H→ZZ→4l

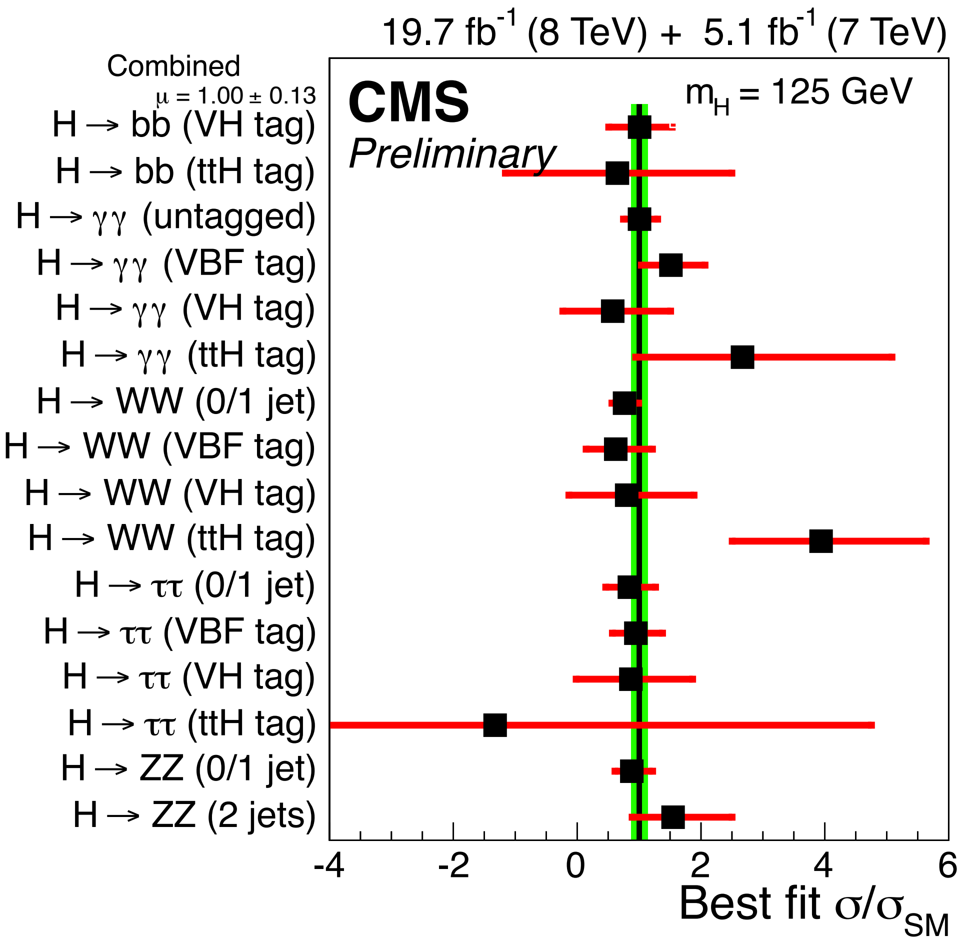


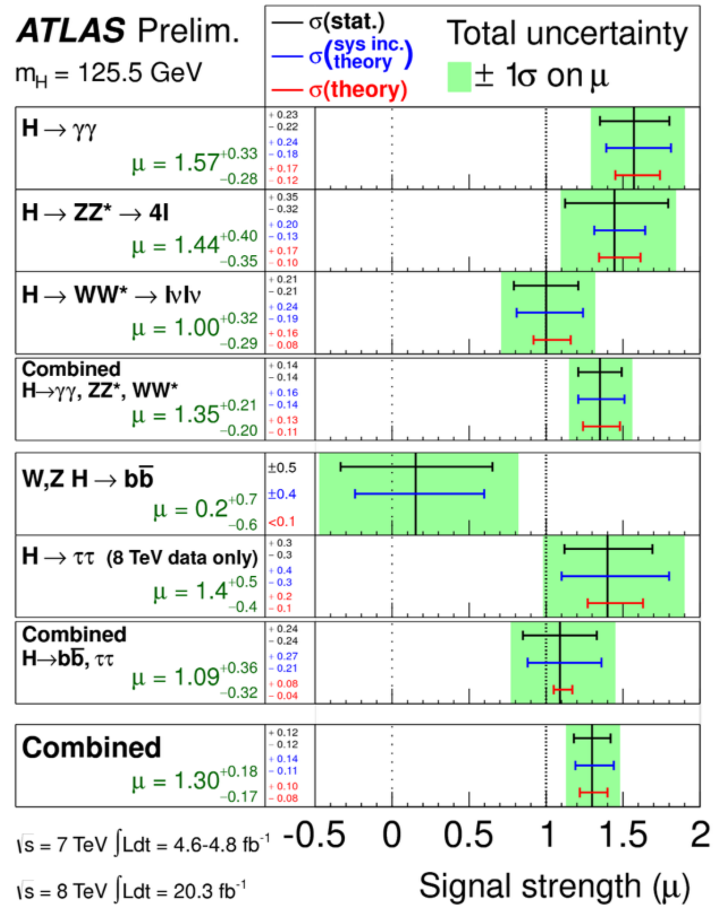


$m_X = 125.36 \pm 0.37\ \text{(stat)} \pm 0.18\ \text{(syst) GeV}$ $m_X = 125.03 \pm^{0.26}_{0.27}\ \text{(stat)} \pm^{0.13}_{0.15}\ \text{(syst) GeV}$

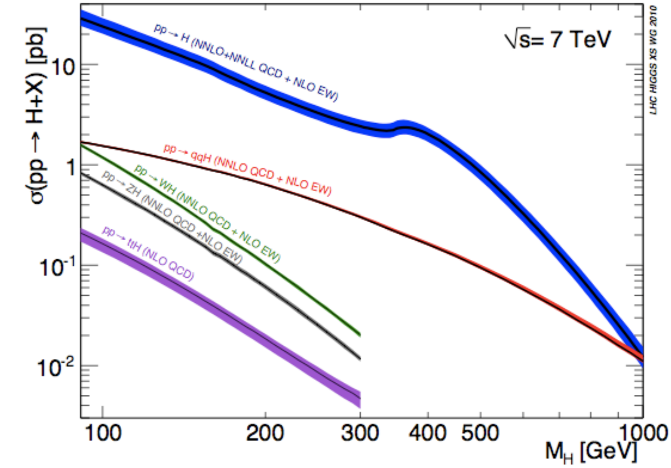
How does X decay?

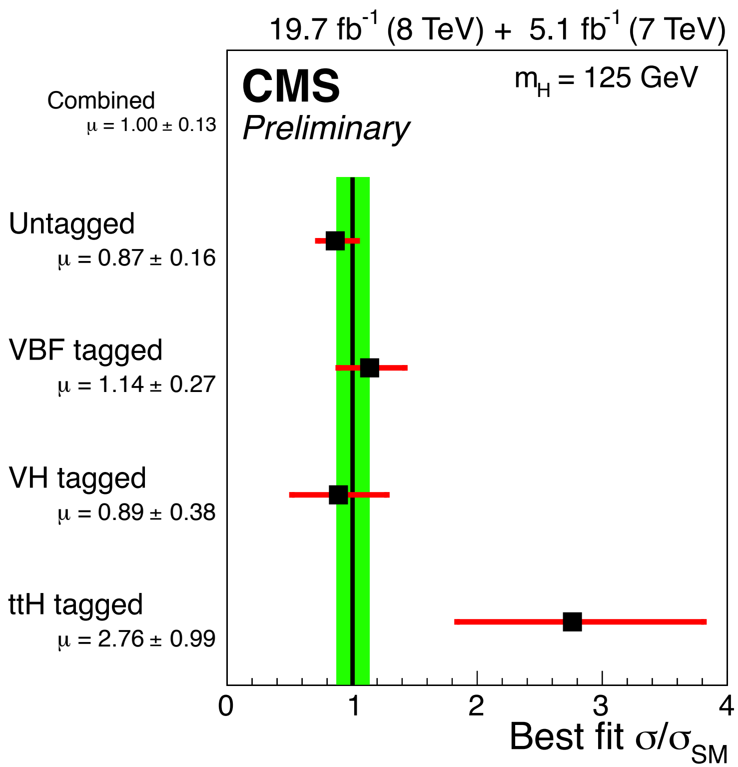


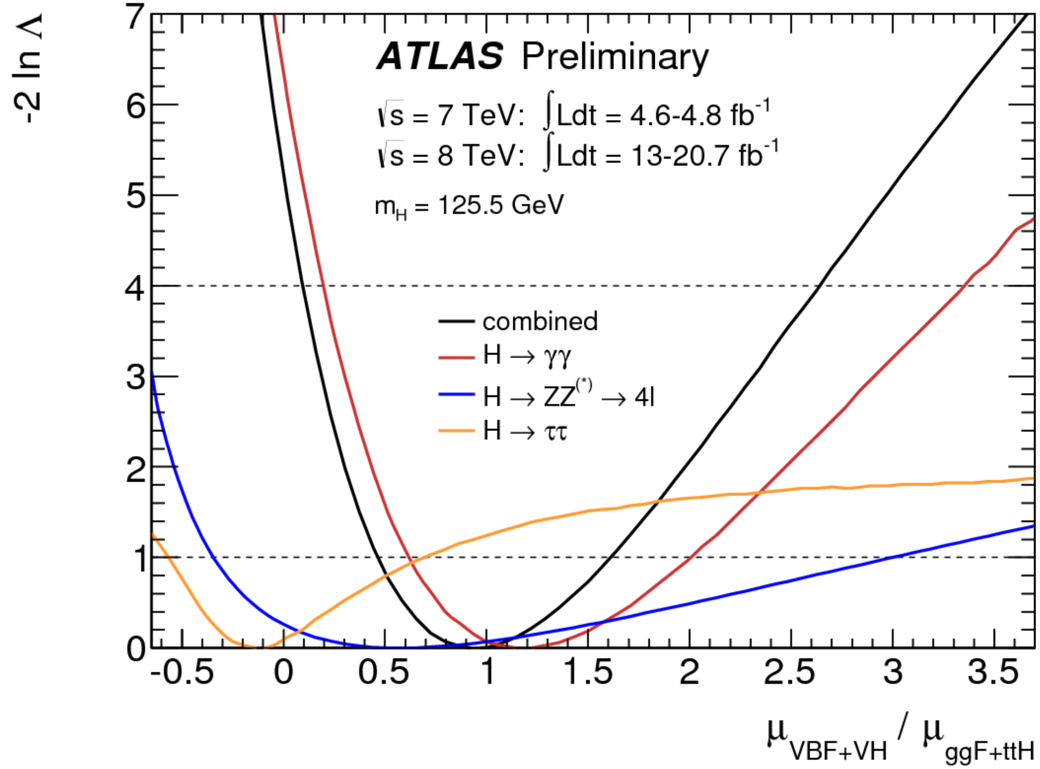




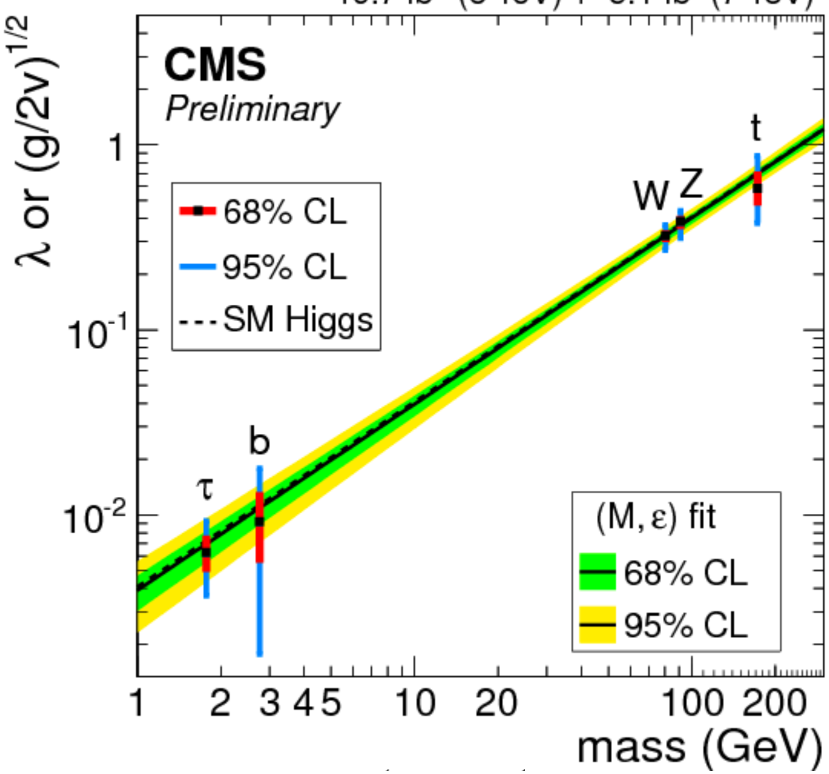
How is X produced?

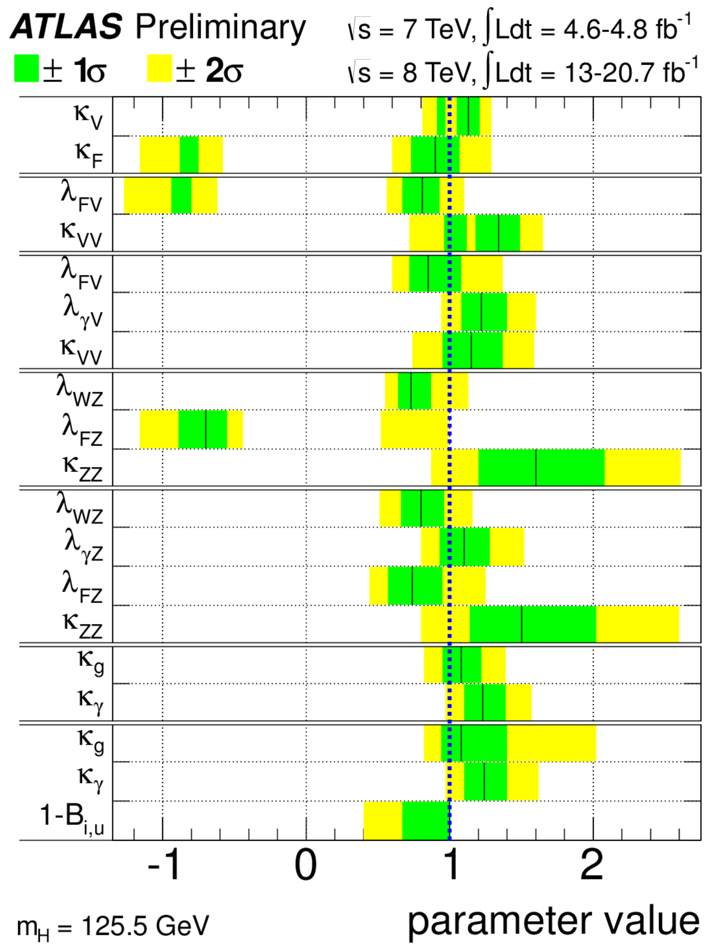






How does X couple to other particles?





$$\frac{\Gamma_{WW^{(*)}}}{\Gamma^{SM}_{WW^{(*)}}} = \kappa_W^2$$

$$\frac{\Gamma_{ZZ^{(*)}}}{\Gamma^{SM}_{ZZ^{(*)}}} = \kappa_Z^2$$

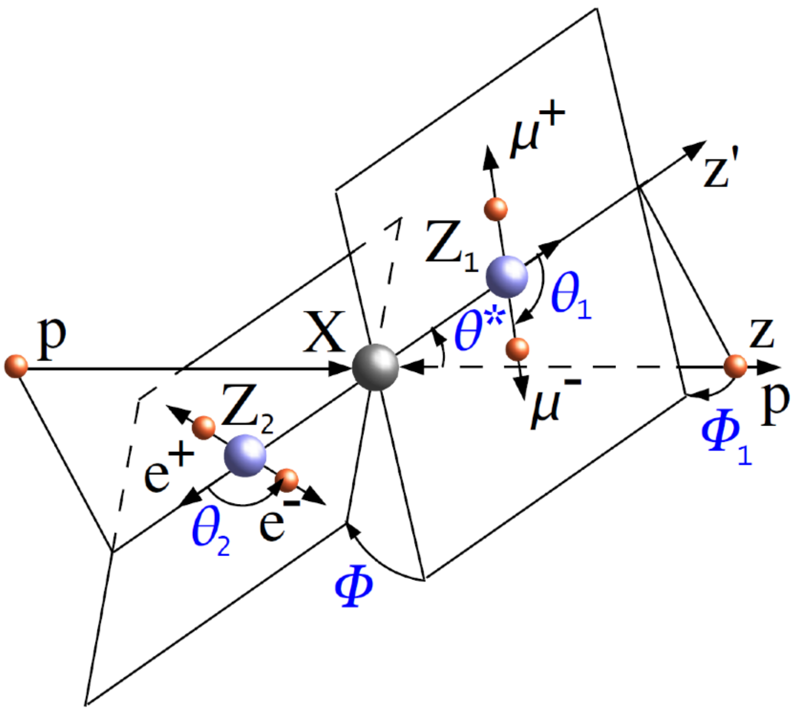
$$\frac{\Gamma_{b\bar{b}}}{\Gamma^{SM}_{b\bar{b}}} = \kappa_b^2$$

$$\frac{\Gamma_{\tau^-\tau^+}}{\Gamma^{SM}_{\tau^-\tau^+}} = \kappa_\tau^2$$

What is the spin and parity of X?

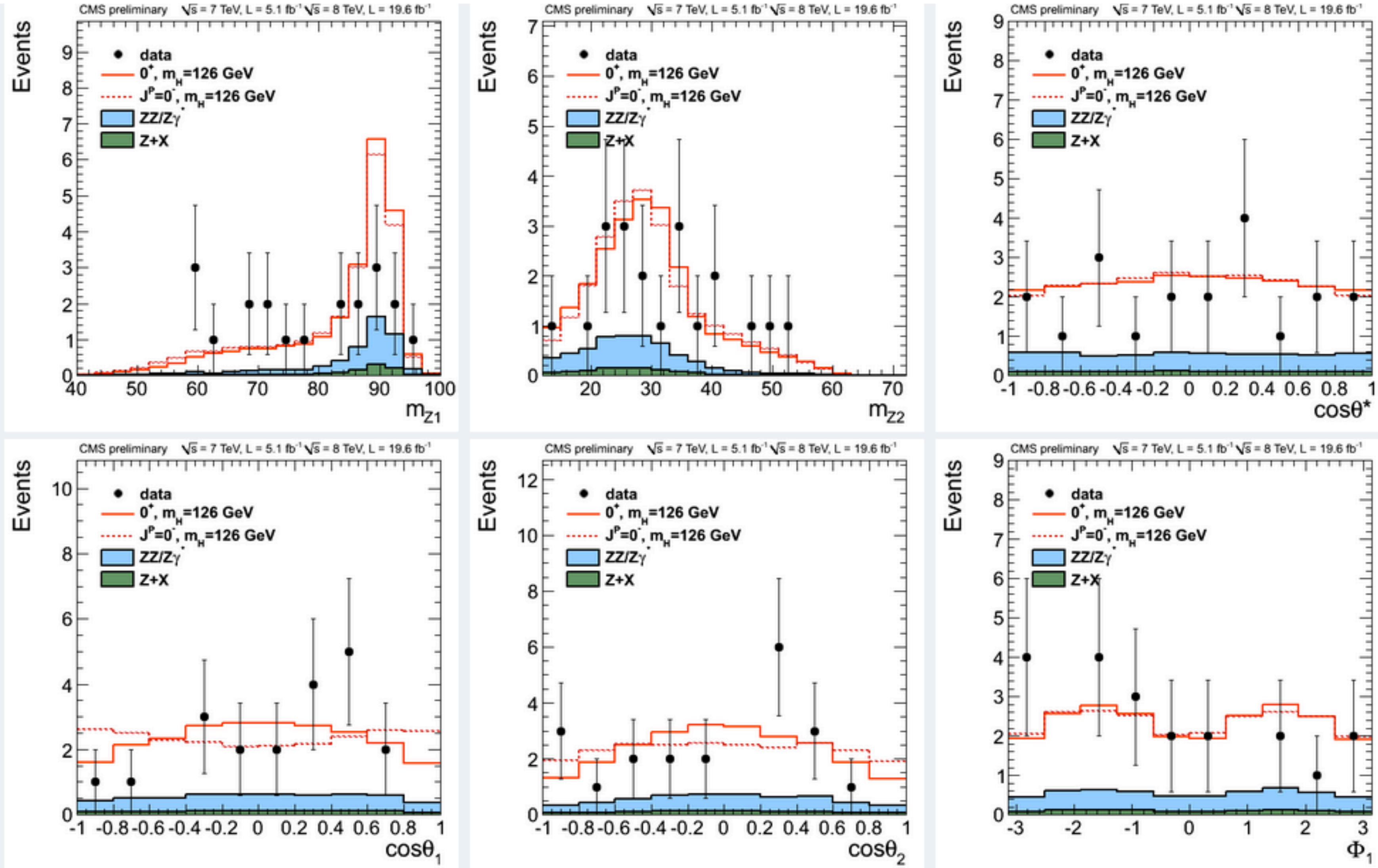
- Use kinematical discriminant (KD) to discriminate against different spin-parity J^P) models

$$\mathcal{D}_{J^P} = \frac{\mathcal{P}_{\mathrm{SM}}}{\mathcal{P}_{\mathrm{SM}} + \mathcal{P}_{J^P}} = \left[1 + \frac{\mathcal{P}_{J^P}(m_1, m_2, \vec{\Omega}|m_{4\ell})}{\mathcal{P}_{\mathrm{SM}}(m_1, m_2, \vec{\Omega}|m_{4\ell})}\right]^{-1}$$

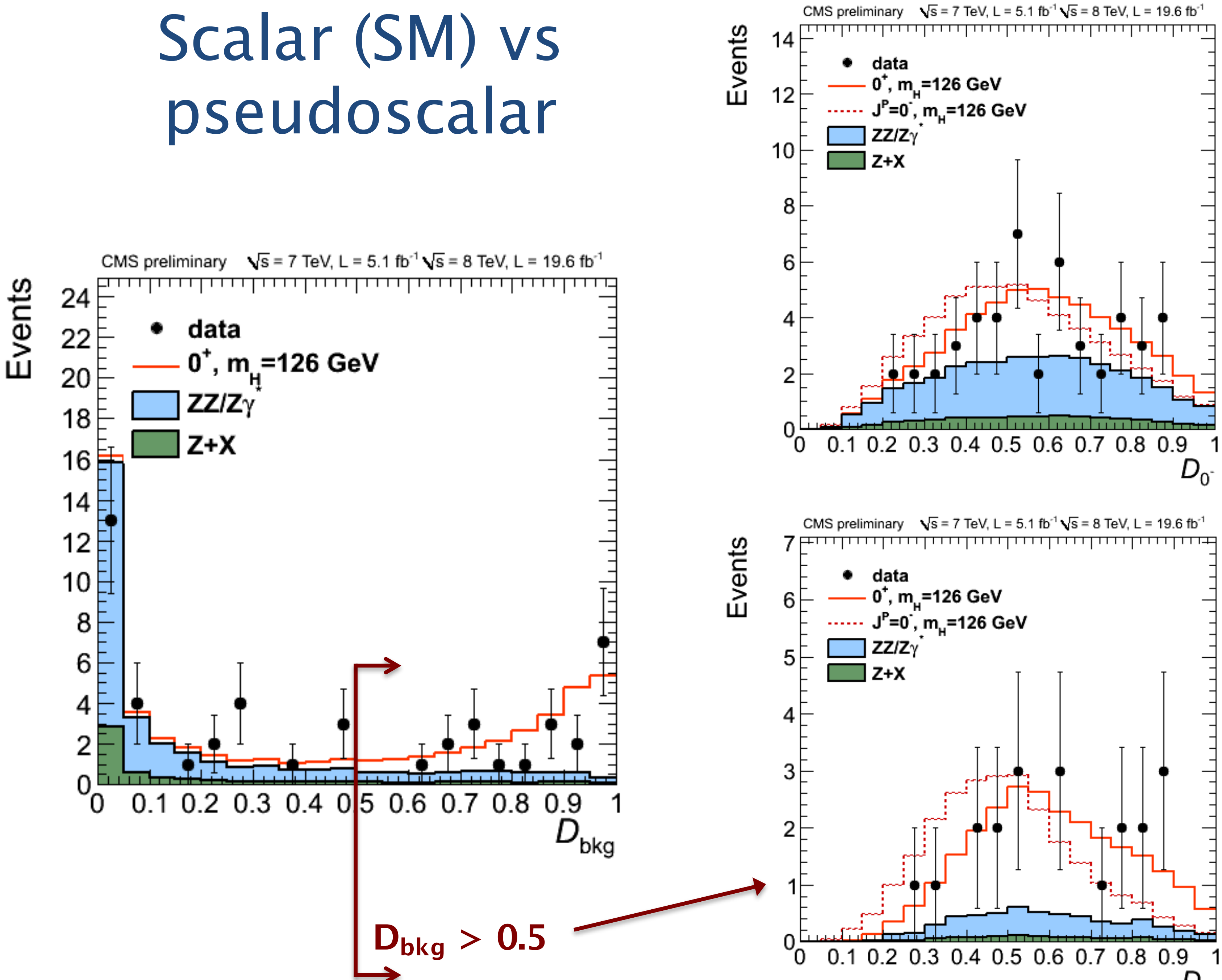


J^P	Model
0^+	SM Higgs boson
0^-	Pseudoscalar
0^+_h	SM with higher dim. operators
1^-	Vector
1^+	Axial vector
2^+_{gg}	gg → graviton
2^+_{qq}	qq → graviton

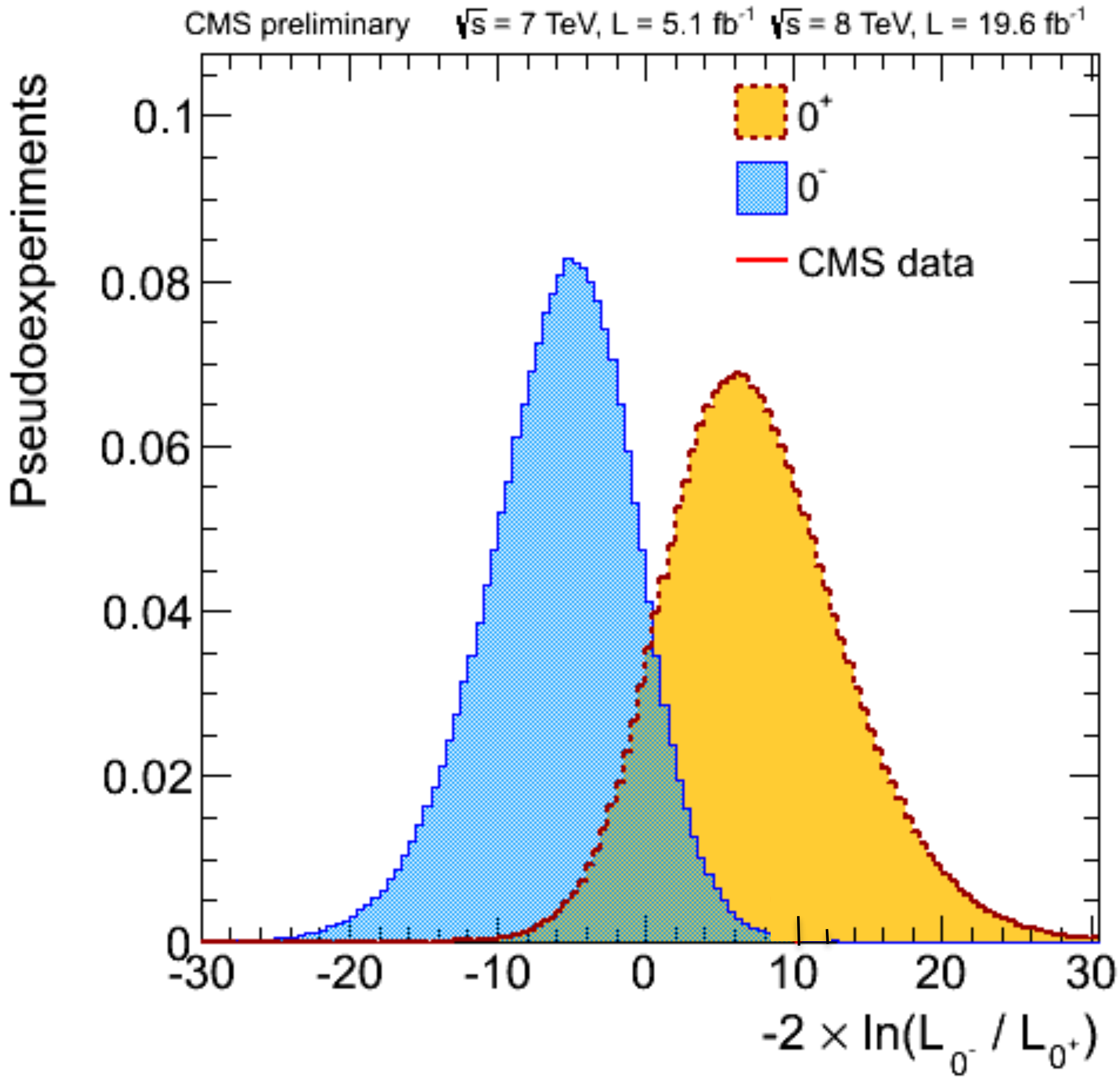
Scalar (SM) vs pseudoscalar



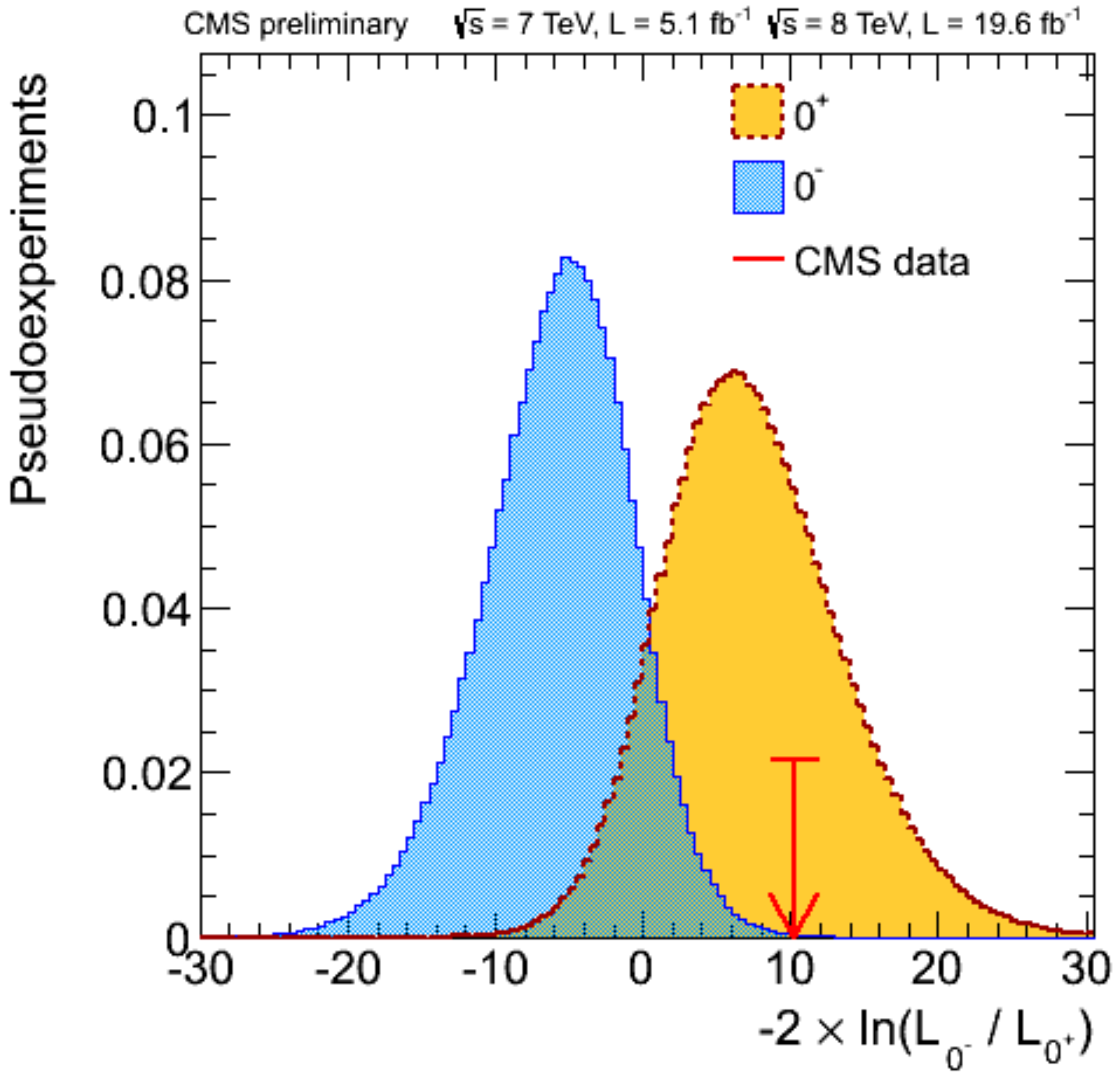
Scalar (SM) vs pseudoscalar



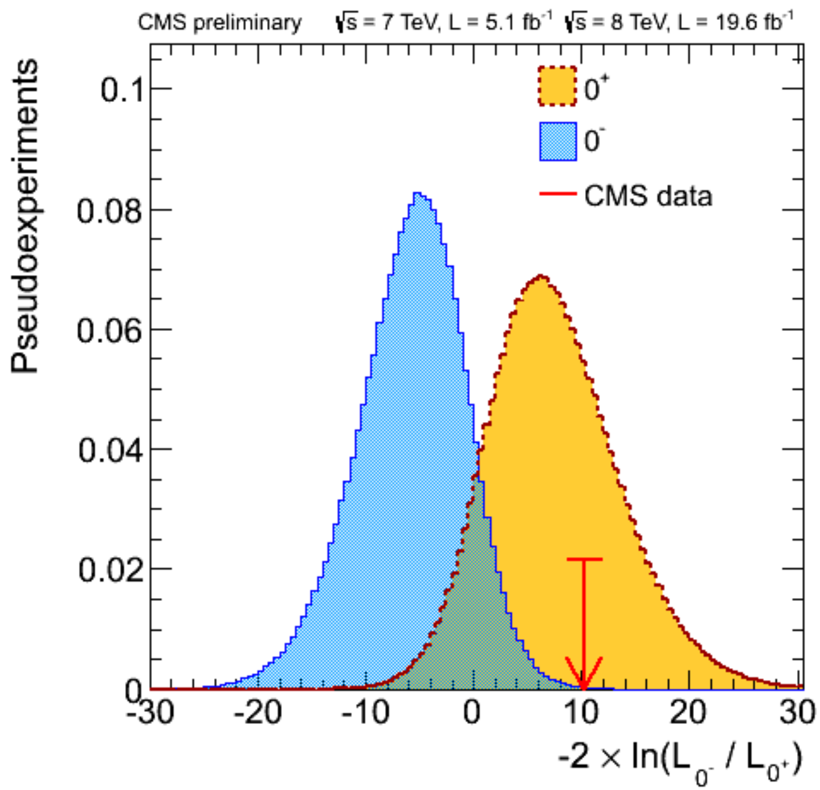
Scalar (SM) or pseudoscalar

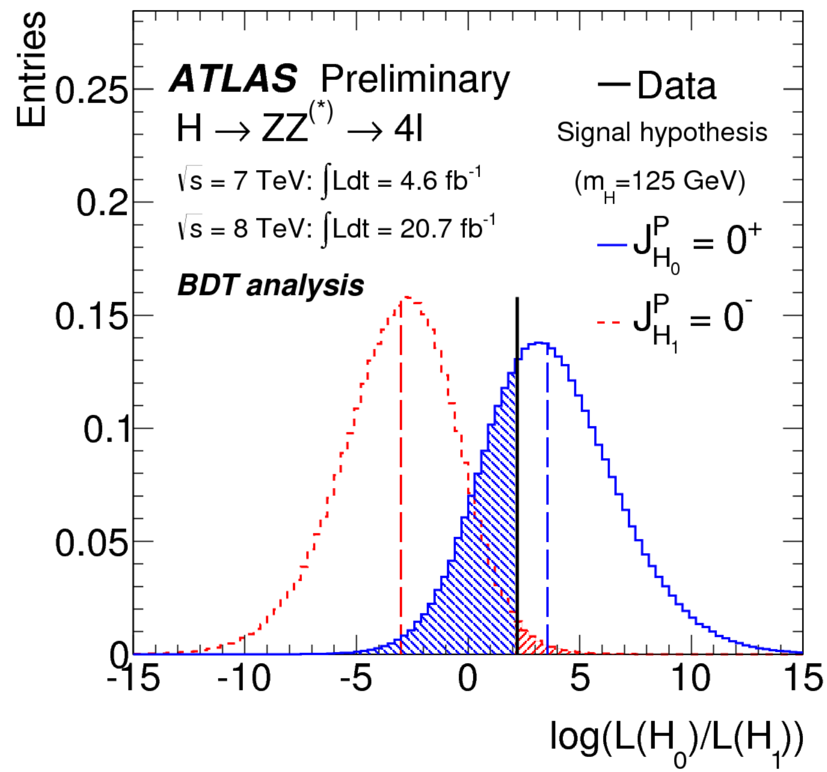


Scalar (SM) or pseudoscalar

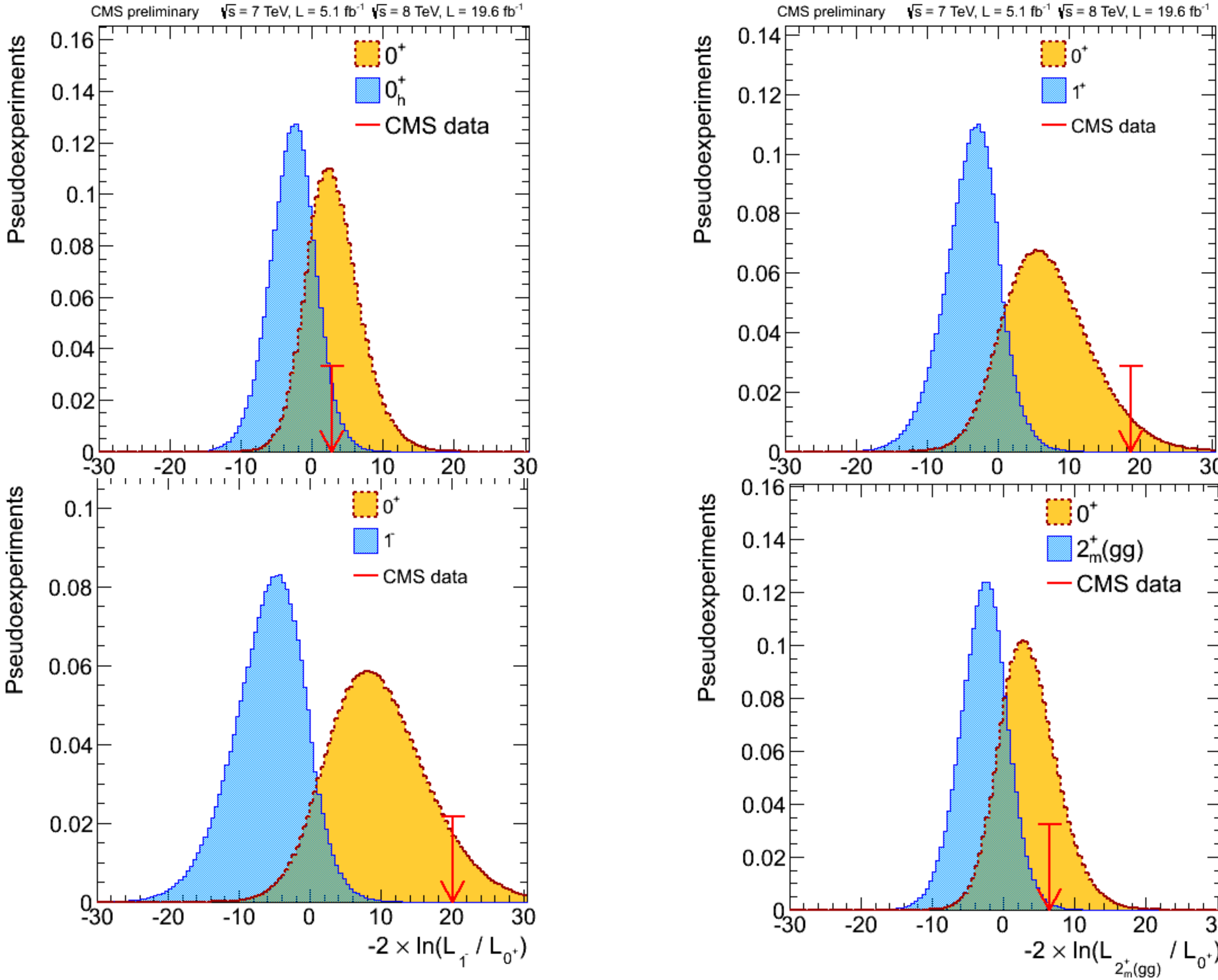


Scalar (SM) vs pseudoscalar

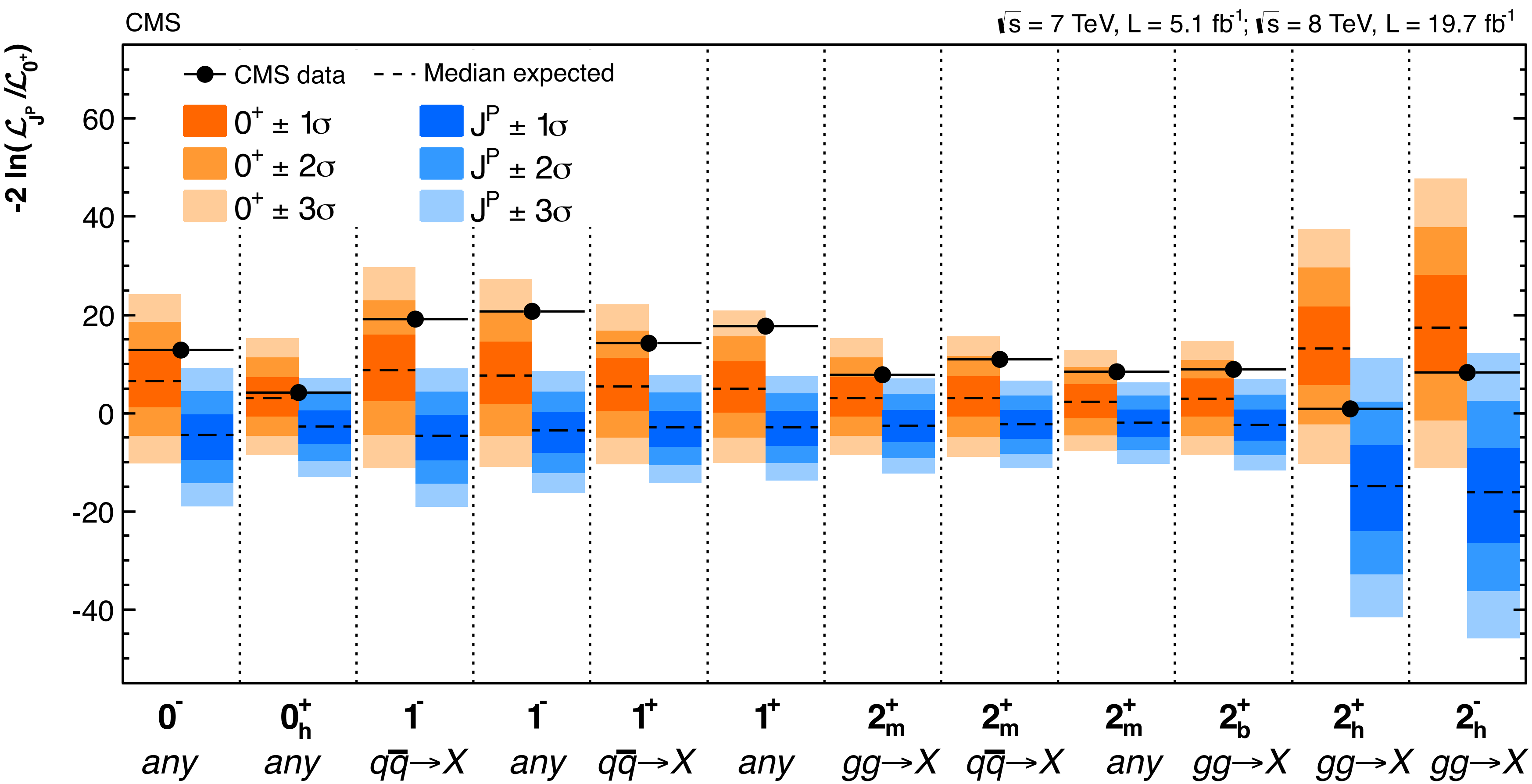




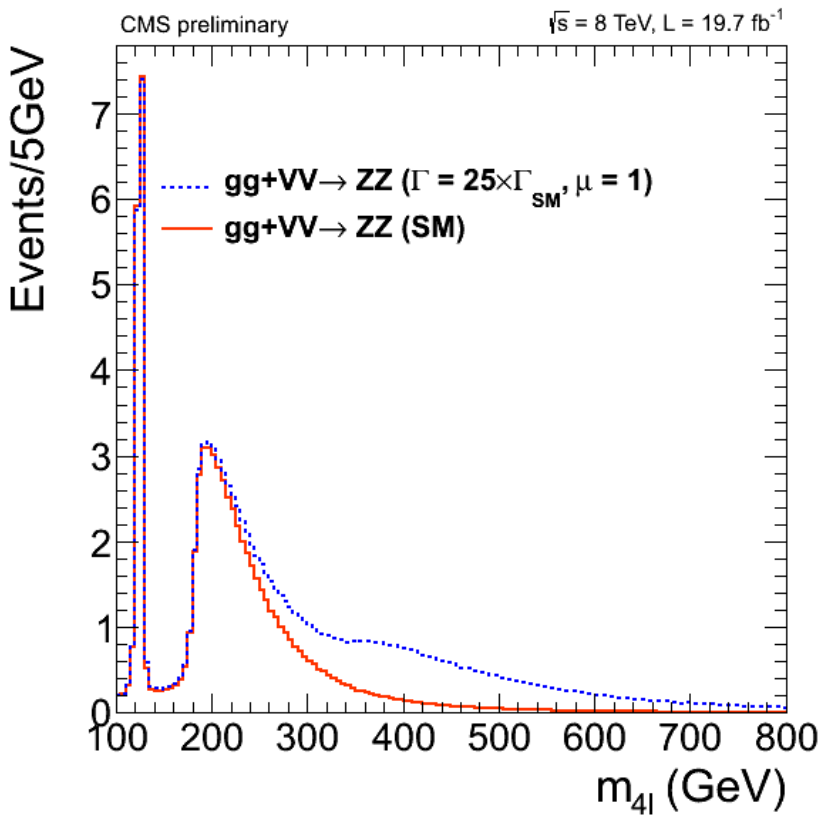
Some other hypotheses

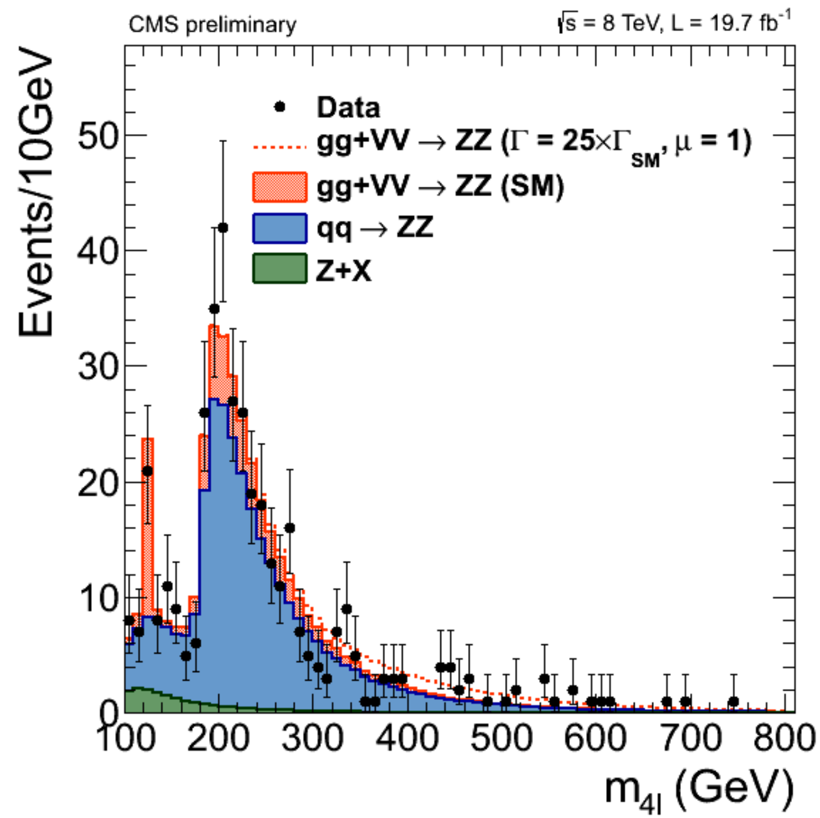


What is the spin and parity of X?

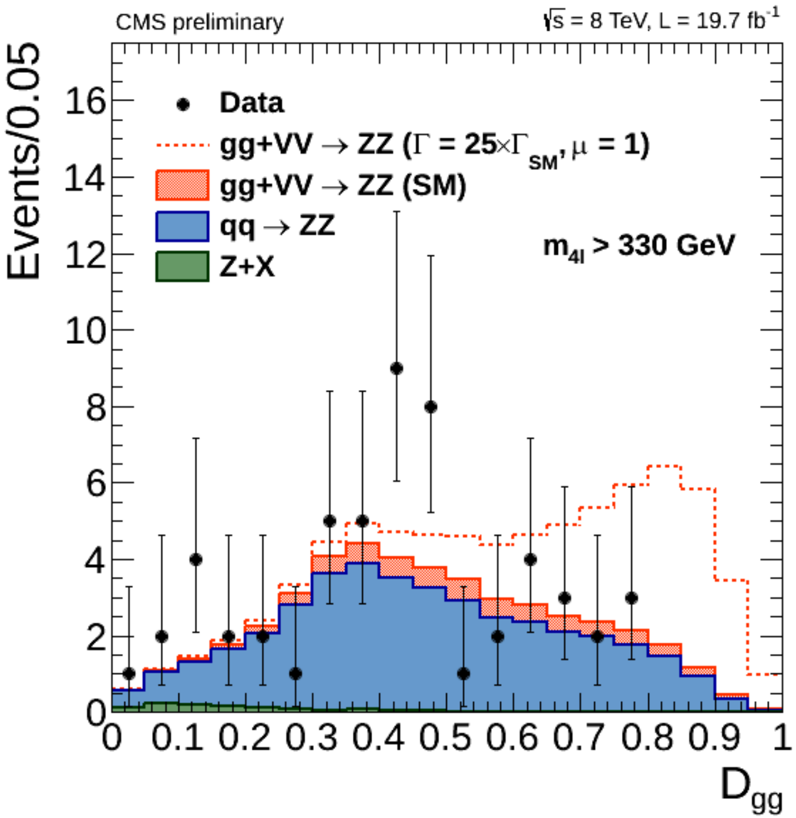


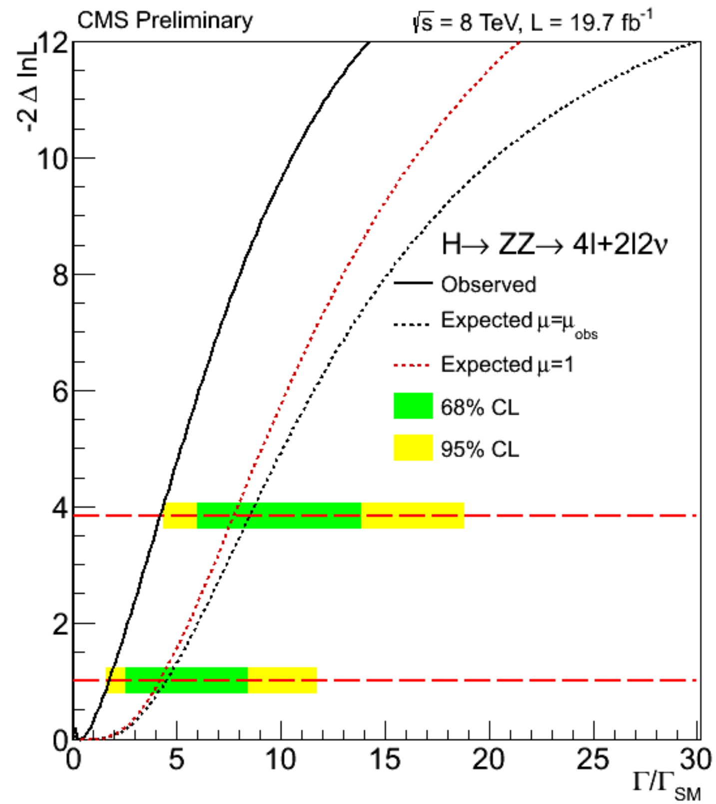
Measuring the width





Measuring the width





	4ℓ	$2\ell 2\nu$	Combined
Expected 95% CL limit, r	11.5	10.7	8.5
Observed 95% CL limit, r	6.6	6.4	4.2
Observed 95% CL limit, Γ_H (MeV)	27.4	26.6	17.4
Observed best fit, r	$0.5^{+2.3}_{-0.5}$	$0.2^{+2.2}_{-0.2}$	$0.3^{+1.5}_{-0.3}$
Observed best fit, Γ_H (MeV)	$2.0^{+9.6}_{-2.0}$	$0.8^{+9.1}_{-0.8}$	$1.4^{+6.1}_{-1.4}$

Summary

- What is the mass of **X**?
  - **Arround 125 GeV**
- Is **X** produced according to the SM Higgs boson predictions?
  - **Yes**
- Does **X** decay according to the SM Higgs boson predictions?
  - **Yes**
- Does **X** couple to other particles according to the SM Higgs boson predictions?
  - **Yes**
- What are the spin and parity of **X**?
  - **We excluded (almost) all the tested options except the SM one**
- So, what is this particle?
  - **Very probably the Higgs boson of the Standard Model**

Evolution of language

- **February 2012**
  - Combined results of **searches for the standard model Higgs boson** in pp collisions at sqrt(s) = 7 TeV
  - By CMS Collaboration, **Phys. Lett. B710 (2012) 26-48**
- **July 2012**
  - **Observation** of a **new boson** with a mass of 125 GeV with the CMS experiment at the LHC
  - By CMS Collaboration, **Phys. Lett. B716 (2012) 30-61**
- **December 2012**
  - Study of the Mass and Spin-Parity of the **Higgs Boson Candidate** Via Its Decays to Z Boson Pairs
  - By CMS Collaboration, **Phys. Rev. Lett. 110 (2013) 081803**
- **July 2013**
  - Measurements of **Higgs boson** production and couplings in diboson final states with the ATLAS detector at the LHC
  - By ATLAS Collaboration, **Phys. Lett. B 726 (2013) 88**
- **March 2015**
  - Combined Measurement of **the Higgs Boson** Mass in pp Collisions at sqrt(s) = 7 and 8 TeV with the ATLAS and CMS Experiments
  - By ATLAS and CMS Collaborations, **Phys.Rev.Lett. 114 (2015) 191803**

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▸ François Englert

▸ Peter Higgs

All Nobel Prizes in Physics

All Nobel Prizes in 2013

The Nobel Prize in Physics 2013
François Englert, Peter Higgs

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The Nobel Prize in Physics 2013

Photo: A. Mahmoud

François Englert

Prize share: 1/2

Photo: A. Mahmoud

Peter W. Higgs

Prize share: 1/2

The Nobel Prize in Physics 2013 was awarded jointly to François Englert and Peter W. Higgs *"for the theoretical discovery of a mechanism that contributes to our understanding of the origin of mass of subatomic particles, and which recently was confirmed through the discovery of the predicted fundamental particle, by the ATLAS and CMS experiments at CERN's Large Hadron Collider"*

Current Higgs questions

- **It is a scalar (0^+) particle, with couplings [to bosons AND fermions] that are proportional to mass.**
  - **It is fully consistent with being the SM Higgs.**

- ***Is it the very Higgs of the Standard Model?***
- **Is it really an elementary particle or a composite one?**
- **Is it the first supersymmetric particle? Perhaps the first of five Higgs bosons?**
- **Is it natural?**
- **Does it couple to Dark Matter as well?**
- **Is it [and the vacuum it pops from] stable?**
- **Is it related to the matter-antimatter asymmetry?**
- **Is it related to inflation – and the Universe-at-large?**

CMS and ATLAS collaborations