Higgs Production at LHC

Vittorio Del Duca
INFN LNF

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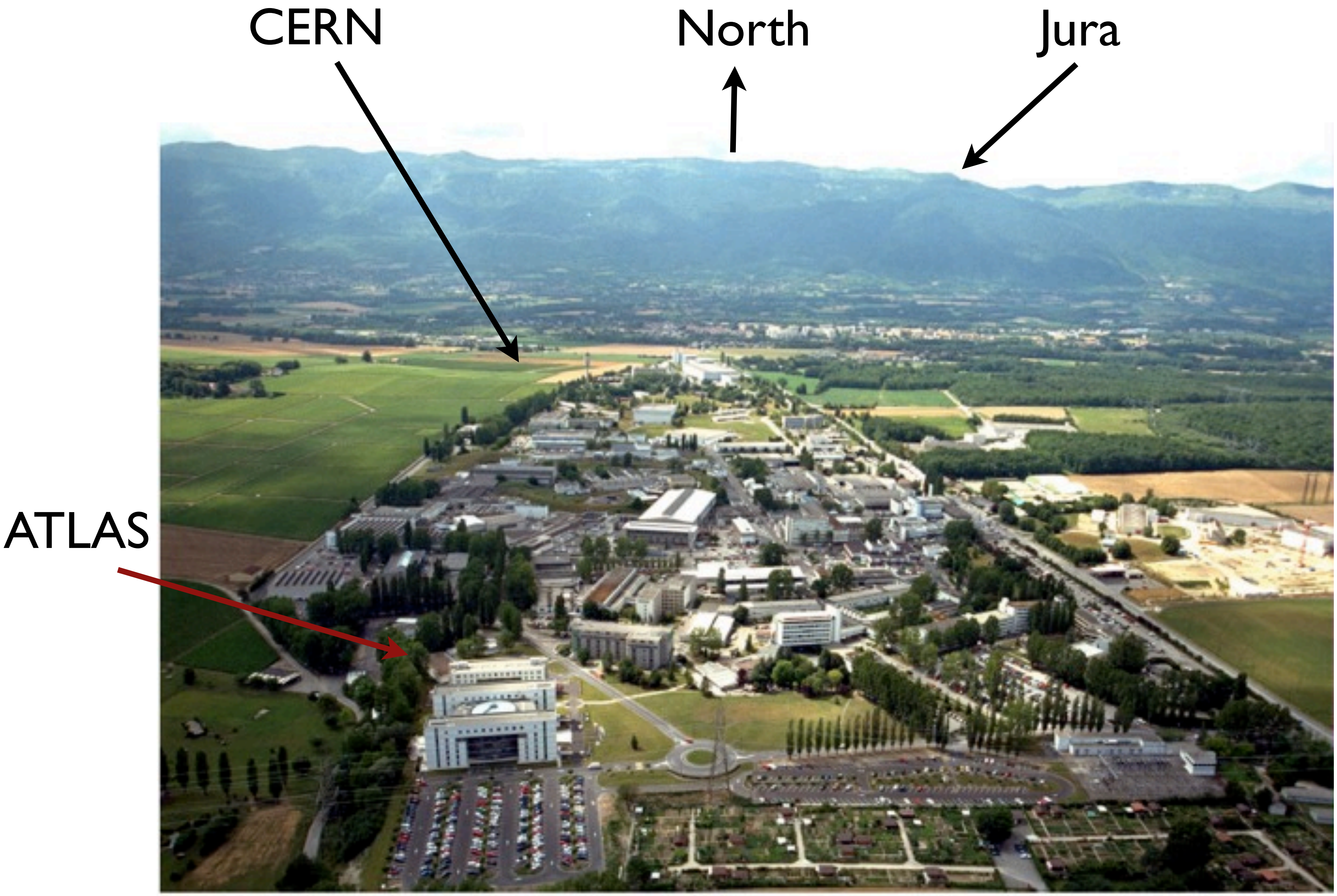
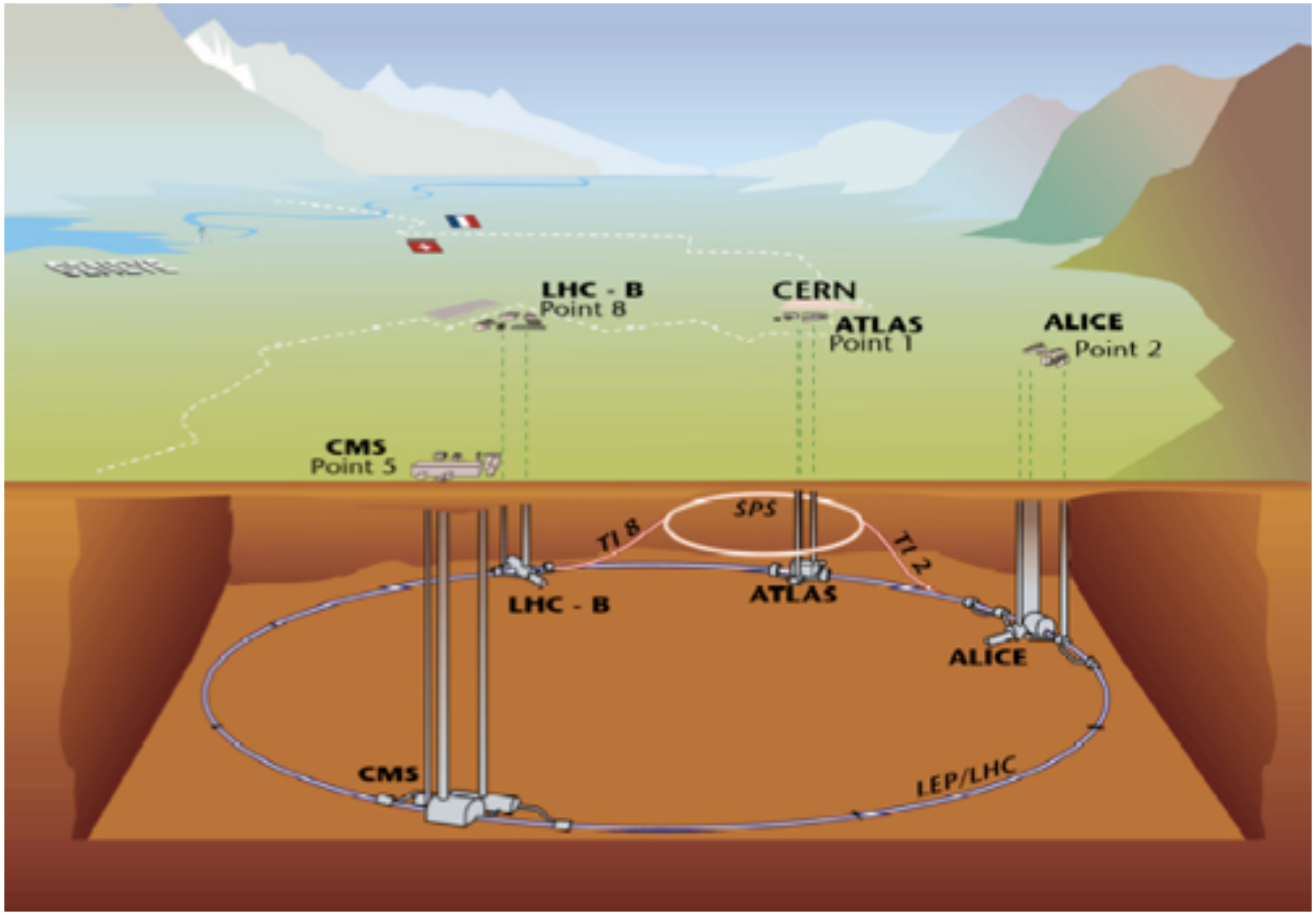
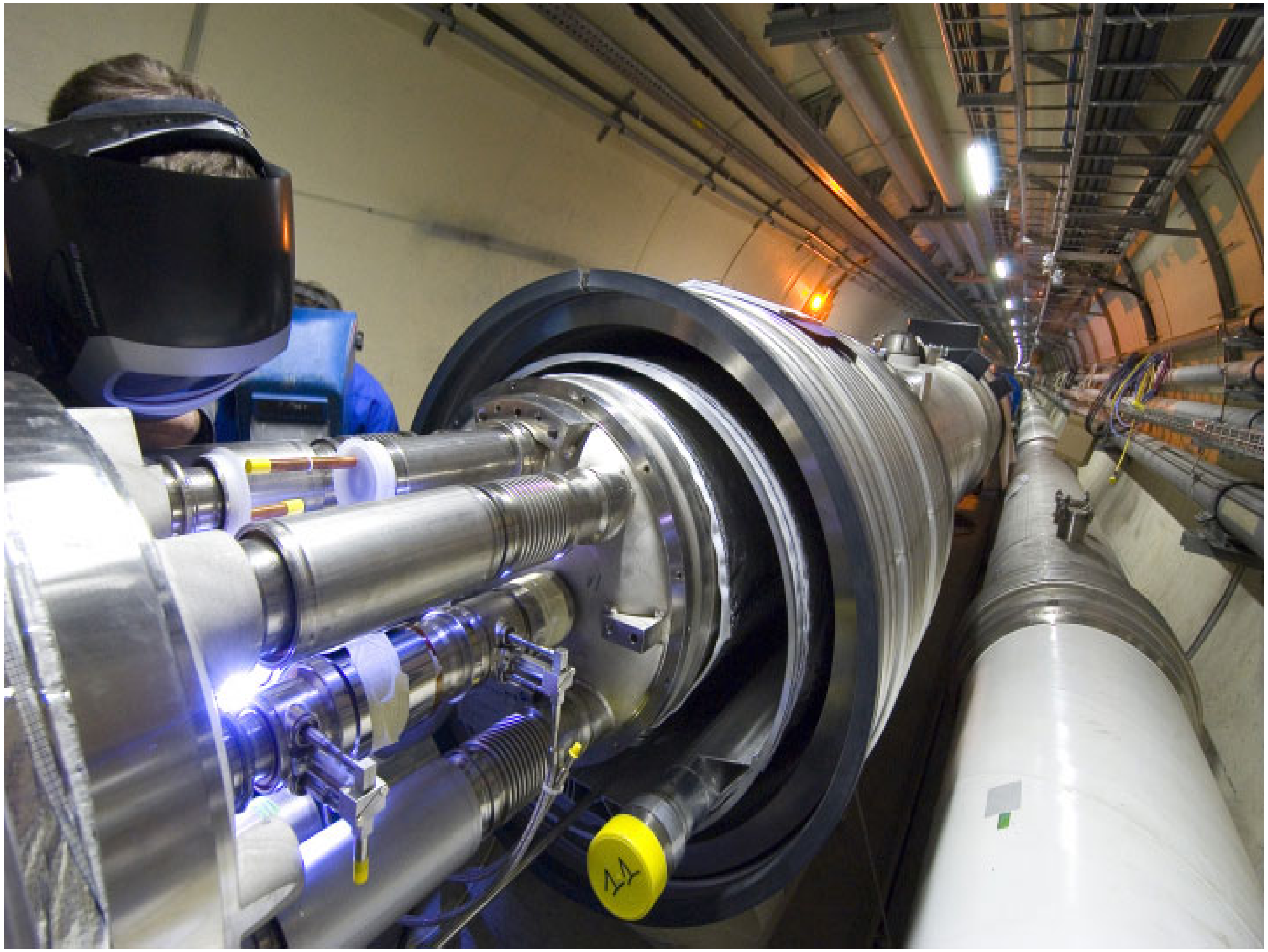

CERN
North
Jura
ATLAS

Sketch of LHC



→ North

- Ring 26,6 Km long and 3,8 m of diameter, made of 8 arches connected by 8 straight sections
- Located 50-175 m underground below the border between France & Switzerland, between Geneva & the Jura range



LHC commissioning

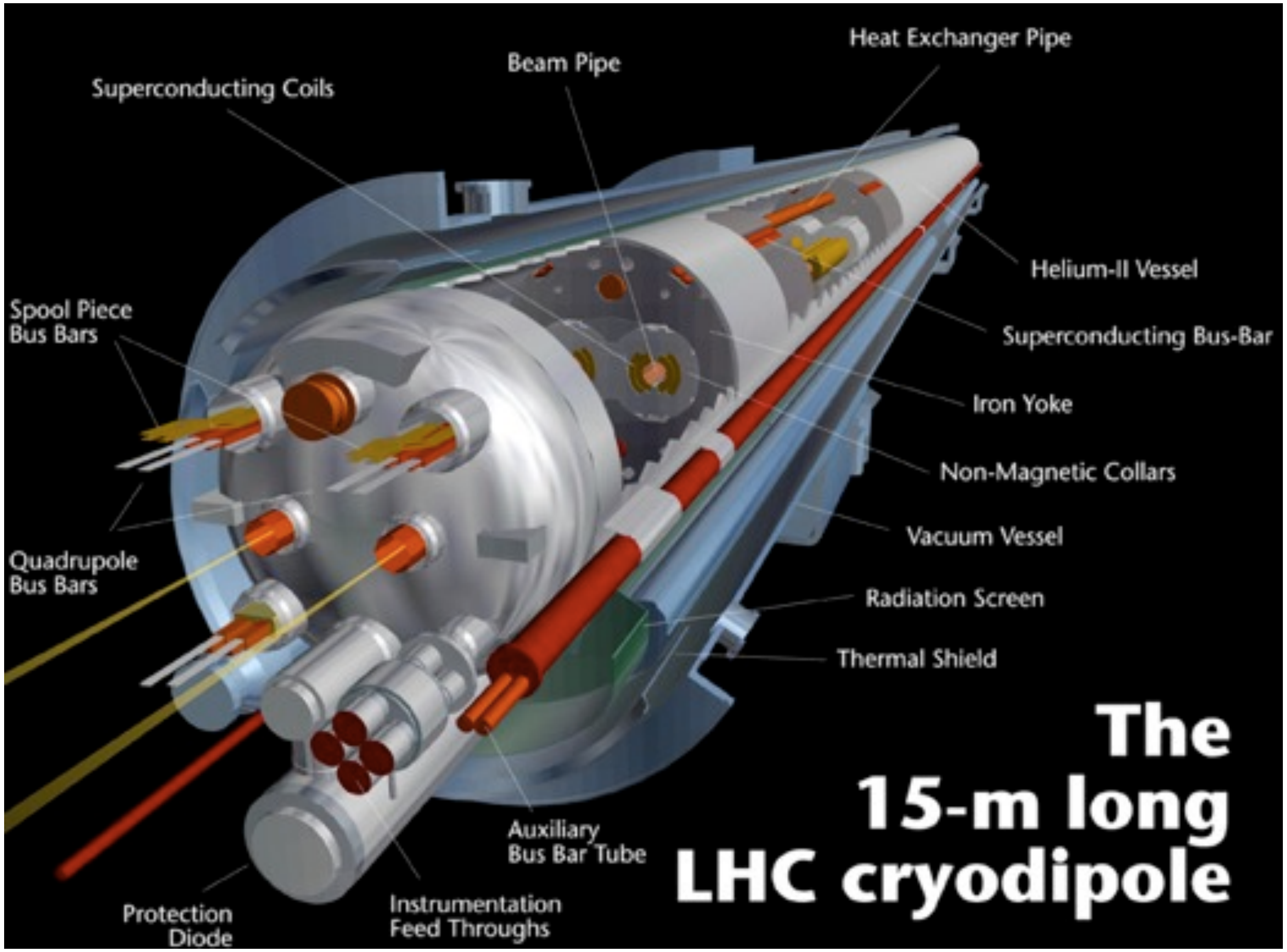
- In the tunnel, 2 proton beams are injected, circulating in opposite directions

- each beam is about 1 micron wide and is designed to be made of 2808 proton bunches, each bunch with $1.15\ 10^{11}$ protons, for a total of $3.22\ 10^{14}$ protons
(in 2012, up to 1380 bunches were injected)

- the energy of a beam of $3.22\ 10^{14}$ protons running at 7 TeV is 360 MJ (about the same as the kinetic energy of a 400t train running at 150 km/h)

Dipoles

- To keep the protons on the trajectory, 1232 dipoles are used



current i = 12000 A

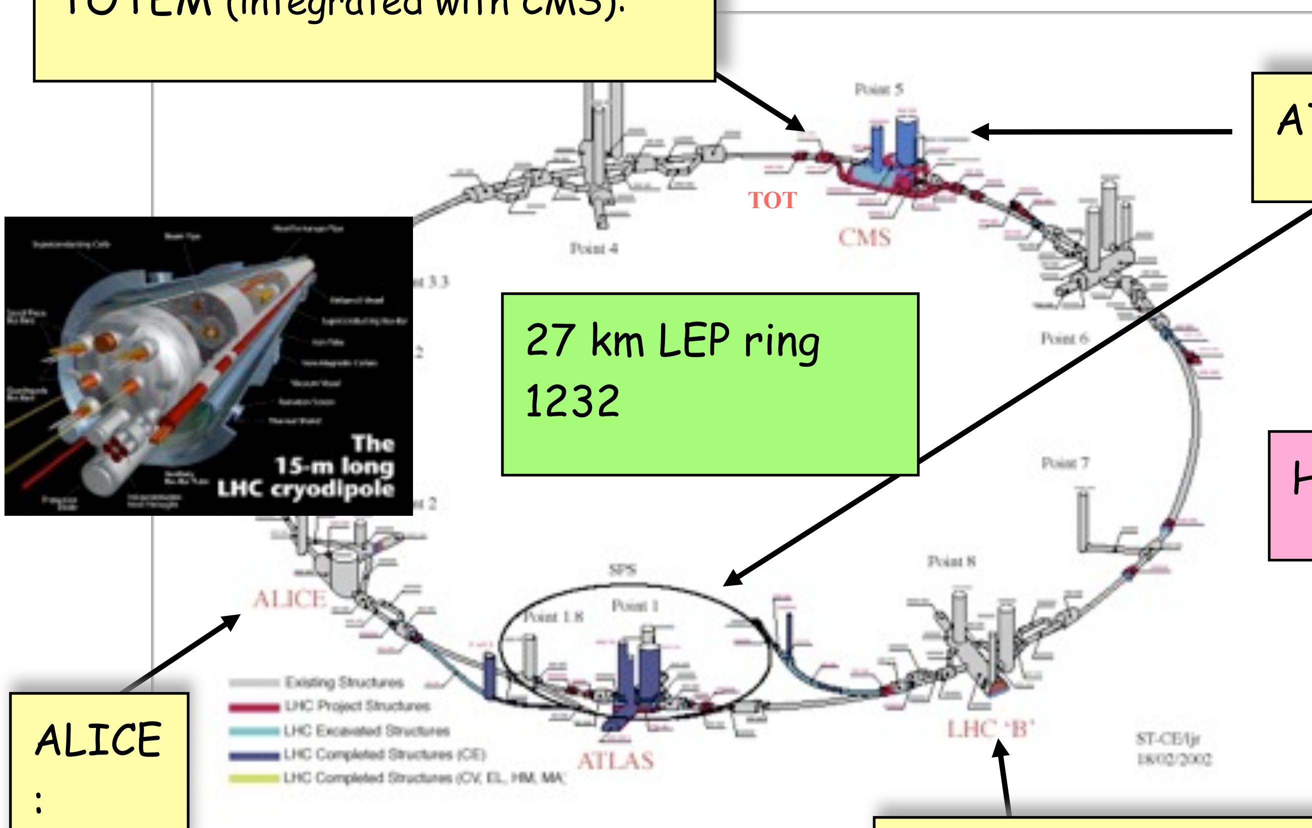
magnetic field B = 8.3 Tesla

LHC performance

- pp $\sqrt{s}$ = 7 TeV $L_{initial} \leq 3.5 \times 10^{33}$ cm^{-2} s^{-1} (2010-2011)
  $\sqrt{s}$ = 8 TeV $L_{2012} \leq 7.7 \times 10^{33}$ cm^{-2} s^{-1} (2012)
  $\sqrt{s}$ = 14 TeV $L_{design} = 10^{34}$ cm^{-2} s^{-1} (after 2014)
- Heavy ions (e.g. Pb-Pb at $\sqrt{s}$ ~ 1000 TeV)

TOTEM (integrated with CMS):

ATLAS and



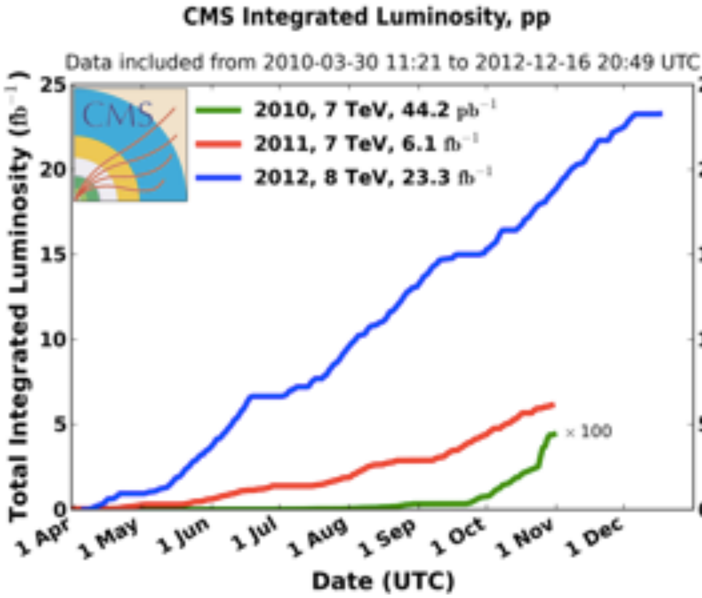
27 km LEP ring
1232

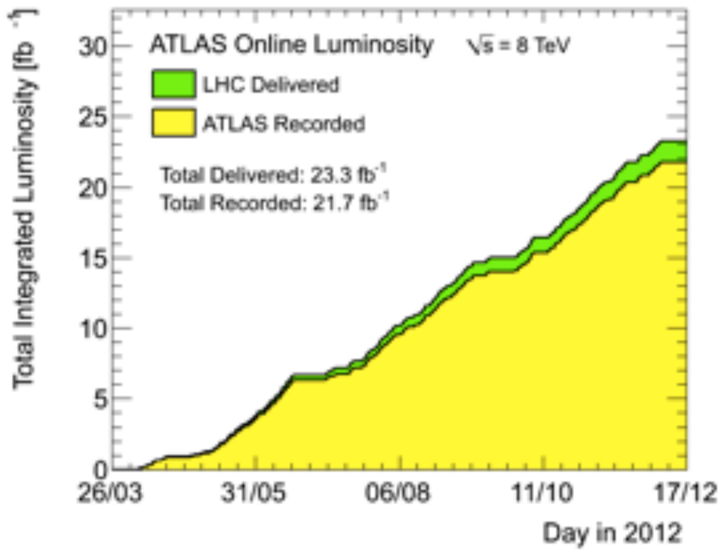
Here:

ALICE
:

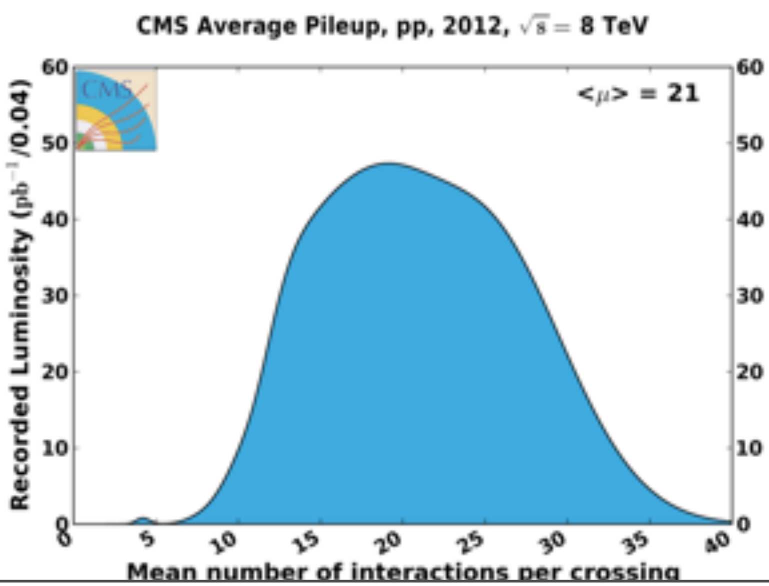
LHCb :

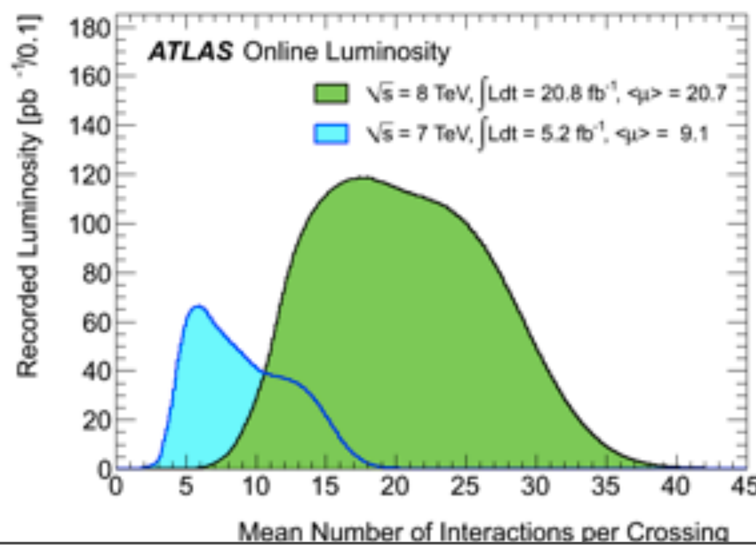
LHC performance





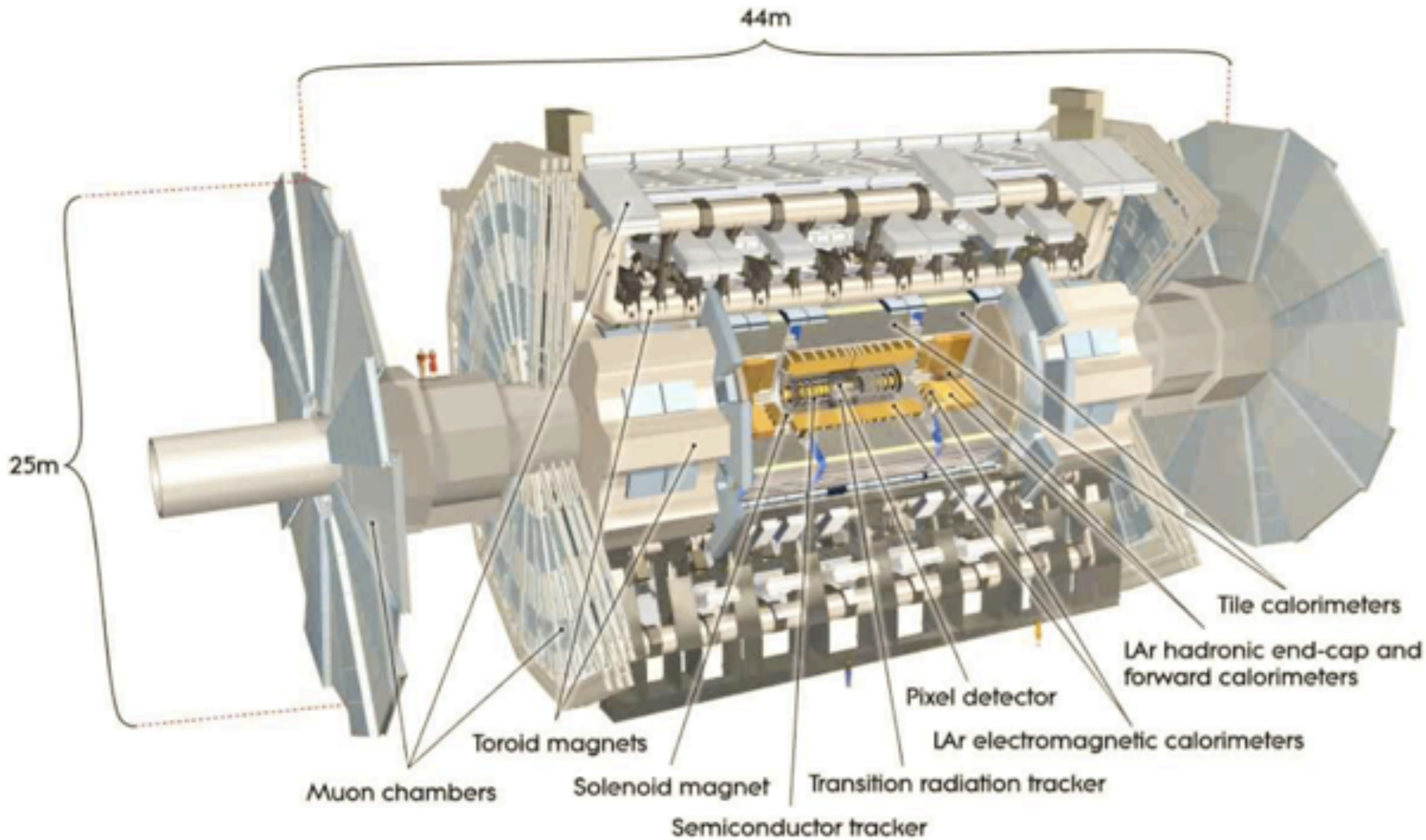
- Bunch crossing = 50 ns → 20M crossings s^{-1}
  ~21 interactions in the same bunch crossing (*pile-up*)
  >400M interactions s^{-1}





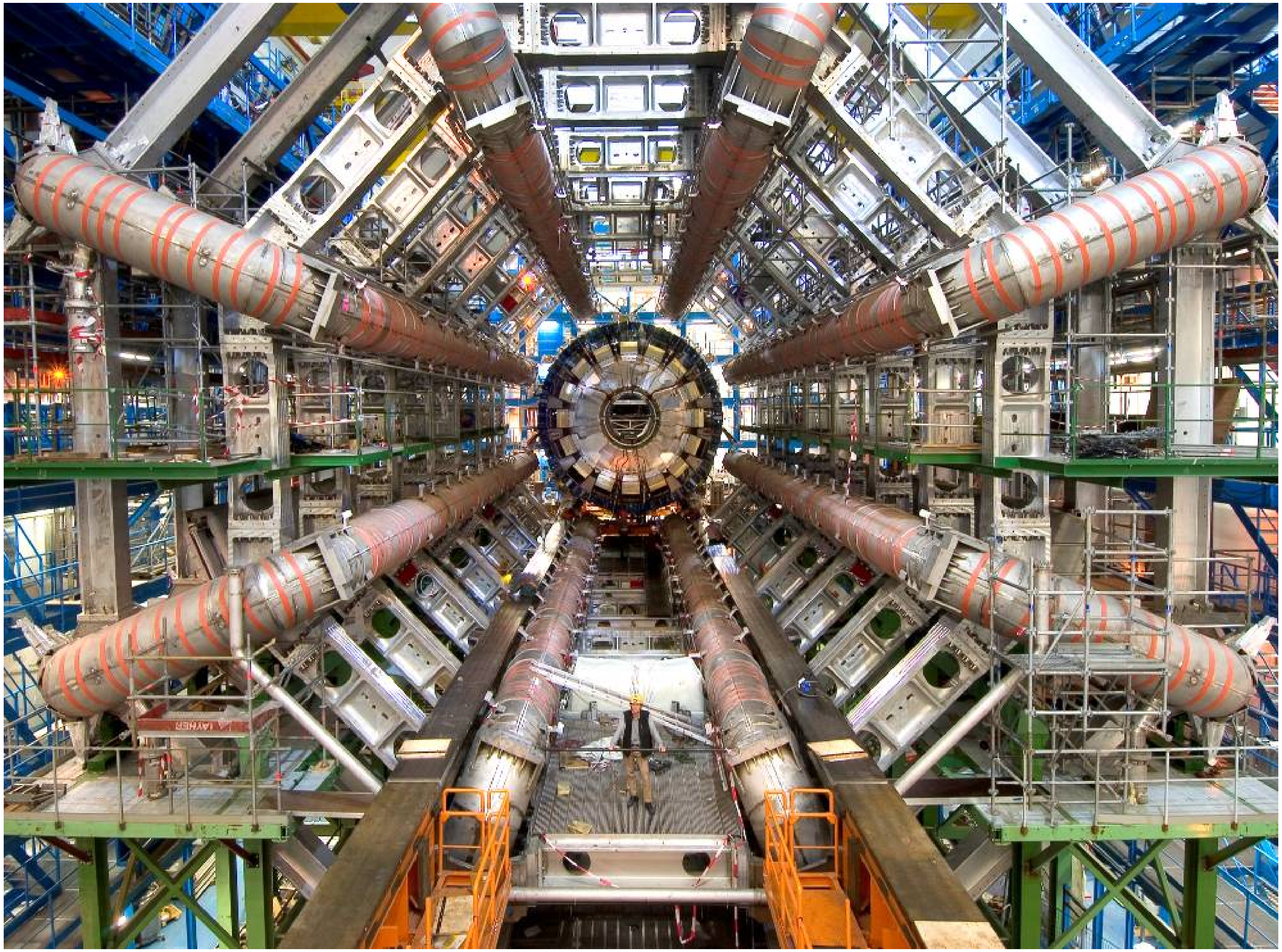
A Toroidal Lhc ApparatuS

investigates Higgs, SM, Supersymmetry, New Physics models



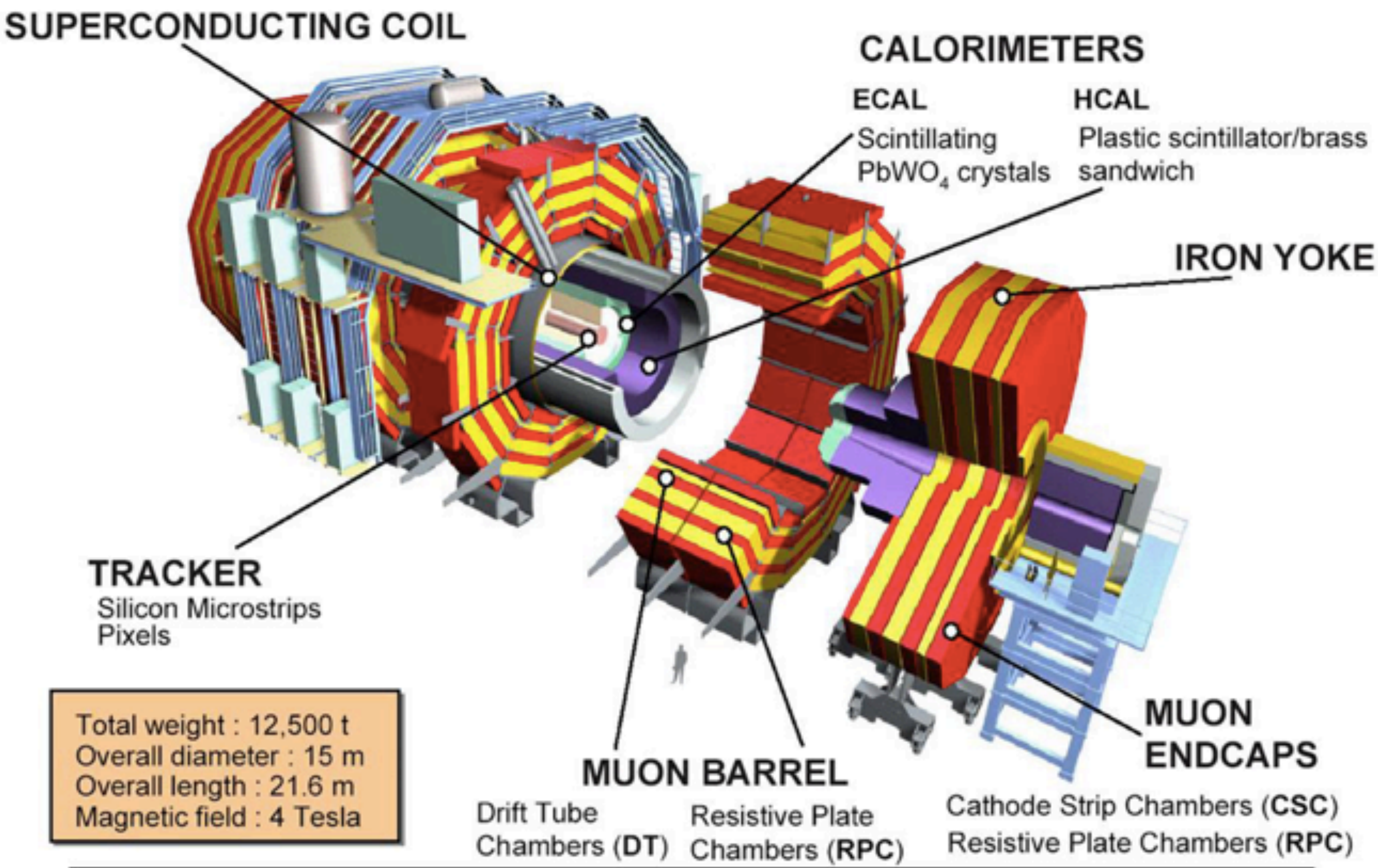
magnet length:	26 m
weight:	7.000 t

ATLAS magnet



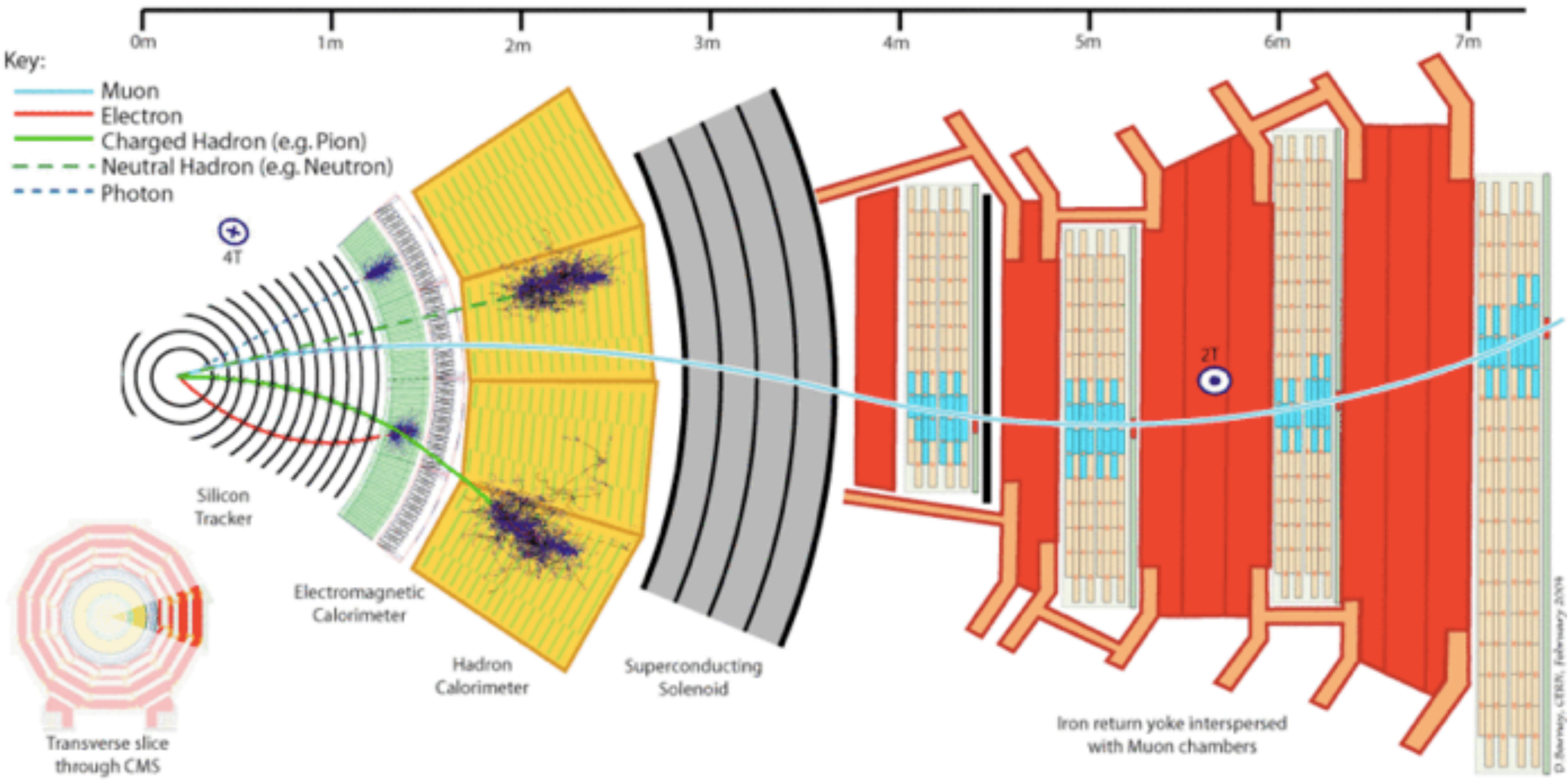
Compact Muon Solenoid

investigates Higgs, SM, Supersymmetry, New Physics models



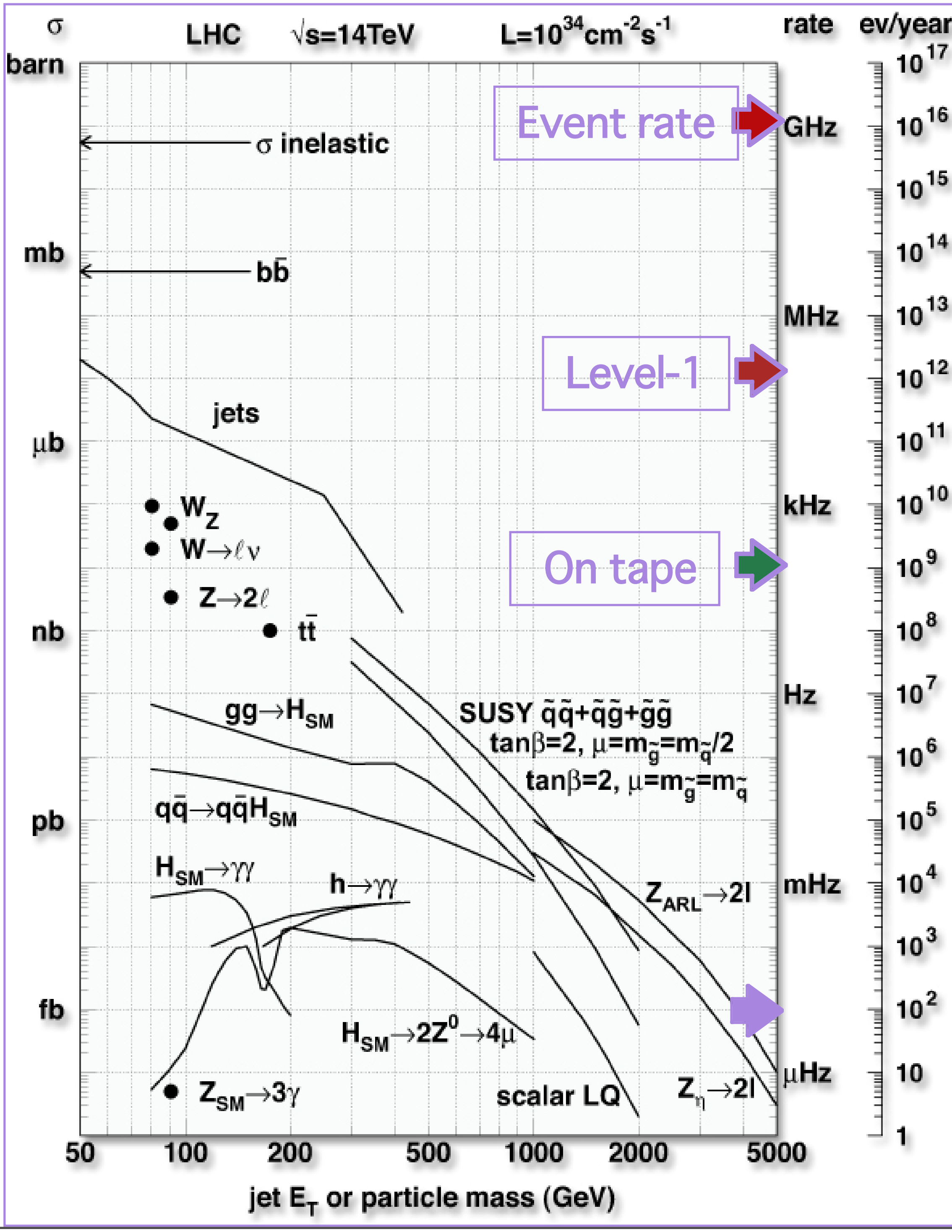
June 2008 - CMS construction

Particle reconstruction at CMS



beampipe and CMS tracker

LHC at design energy and luminosity



the LHC is a SM factory which can detect (hopefully) **New Physics signals**

design luminosity

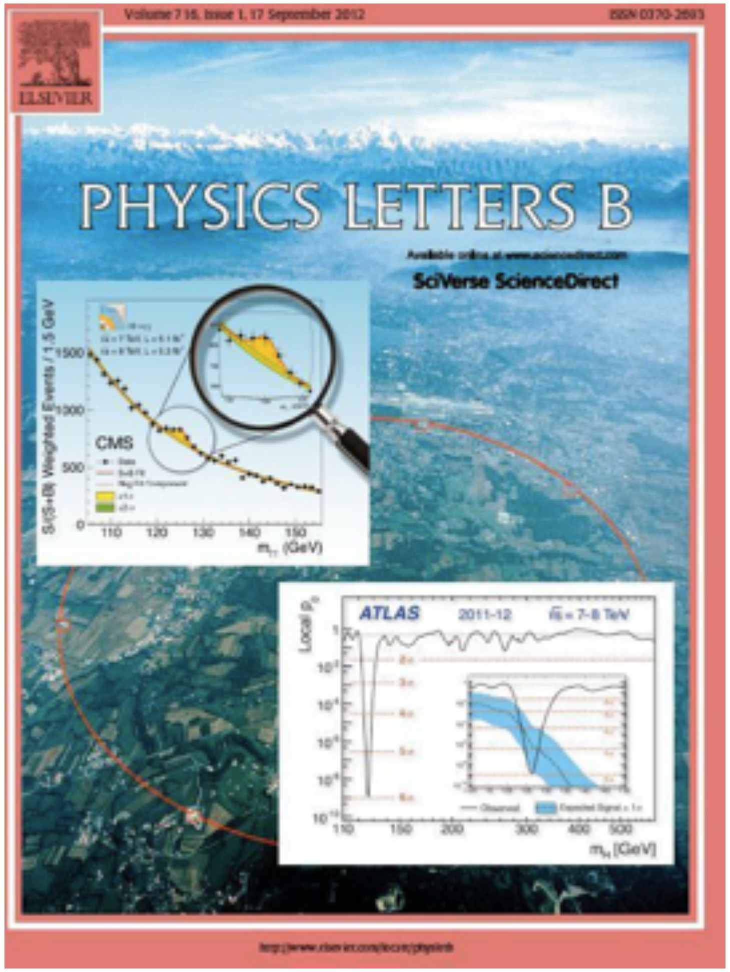
$$L = 10^{34}\ \mathrm{cm}^{-2}\,\mathrm{s}^{-1} = 10^{-5}\ \mathrm{fb}^{-1}\,\mathrm{s}^{-1}$$

integrated luminosity (per year)

$$L \approx 100\ \mathrm{fb}^{-1}\,\mathrm{yr}^{-1}$$

New boson

4 July 2012,
ATLAS & CMS announce the observation of a new particle



discovery based on data samples of
5.1fb^{-1} at 7 TeV and 5.3fb^{-1} at 8 TeV (CMS)
4.8fb^{-1} at 7 TeV and 5.8fb^{-1} at 8 TeV (ATLAS)

discovery channels

$H \to \gamma\gamma$

$H \to ZZ \to 4l$

$H \to WW \to l\nu\ l\nu$

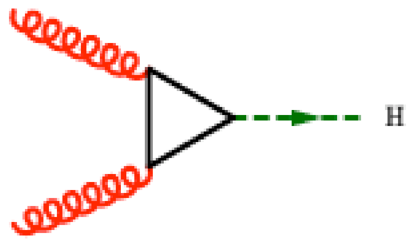
Observation of a new particle in the search for the Standard Model Higgs boson with the ATLAS detector at the LHC, ATLAS Collaboration, Phys. Lett. B 716 (2012), 1-29

Observation of a new boson at a mass of 125 GeV with the CMS experiment at the LHC, CMS Collaboration, Phys. Lett. B 716 (2012), 30-61

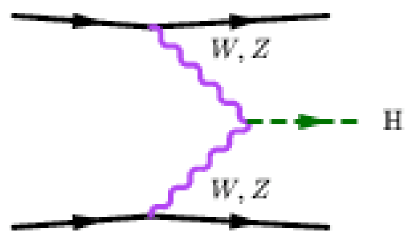
Higgs production modes at LHC

In proton collisions, the Higgs boson is produced mostly via

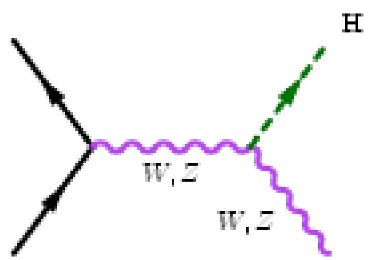
- gluon fusion $gg \to H$
  - largest rate for all M_H
  - proportional to the top Yukawa coupling y_t



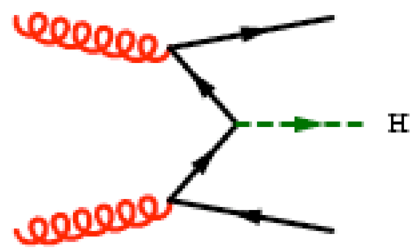
- vector-boson fusion (VBF) $qq \to qqH$
  - second largest rate (mostly $u\,d$ initial state)
  - proportional to the VVH coupling



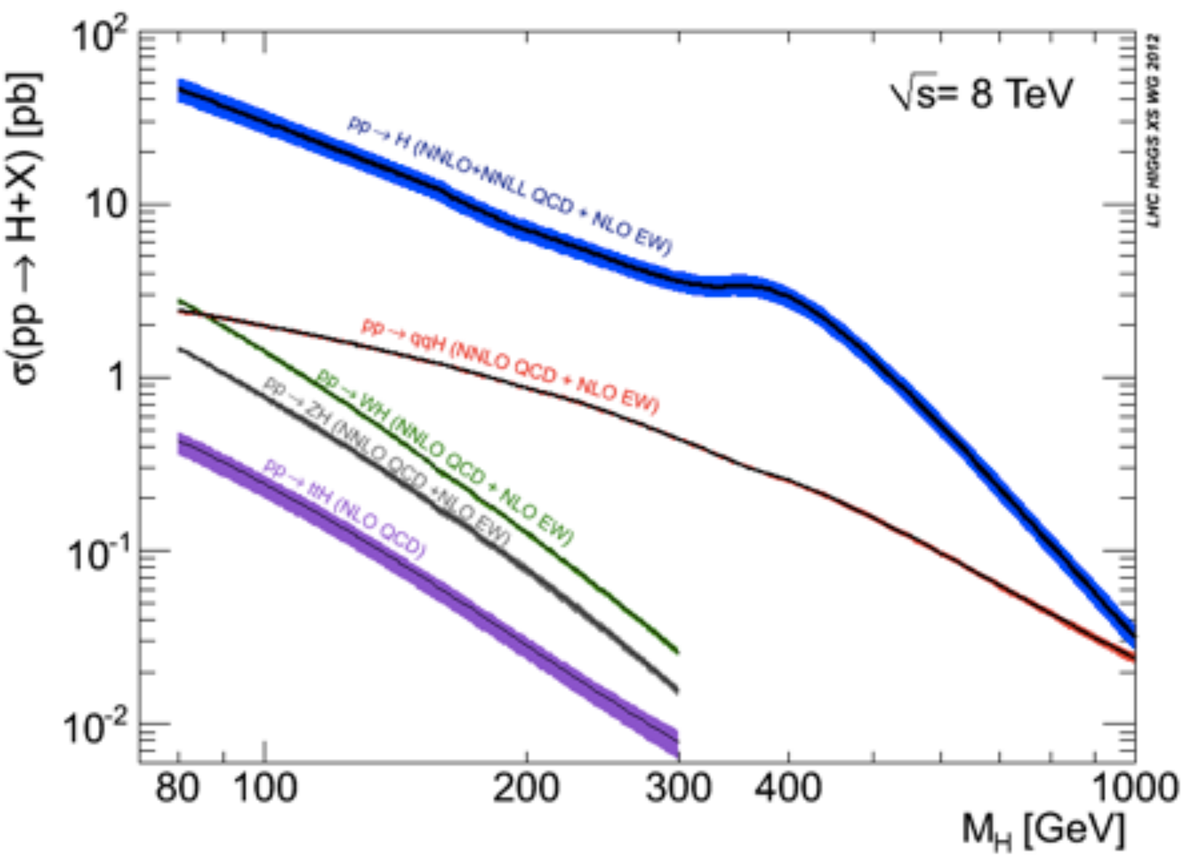
- Higgs-strahlung $q\bar{q} \to W(Z)H$
  - third largest rate
  - same coupling as in VBF



- $t\bar{t}(b\bar{b})H$ associated production
  - same initial state as in gluon fusion, but higher x range
  - proportional to the heavy-quark Yukawa coupling y_Q

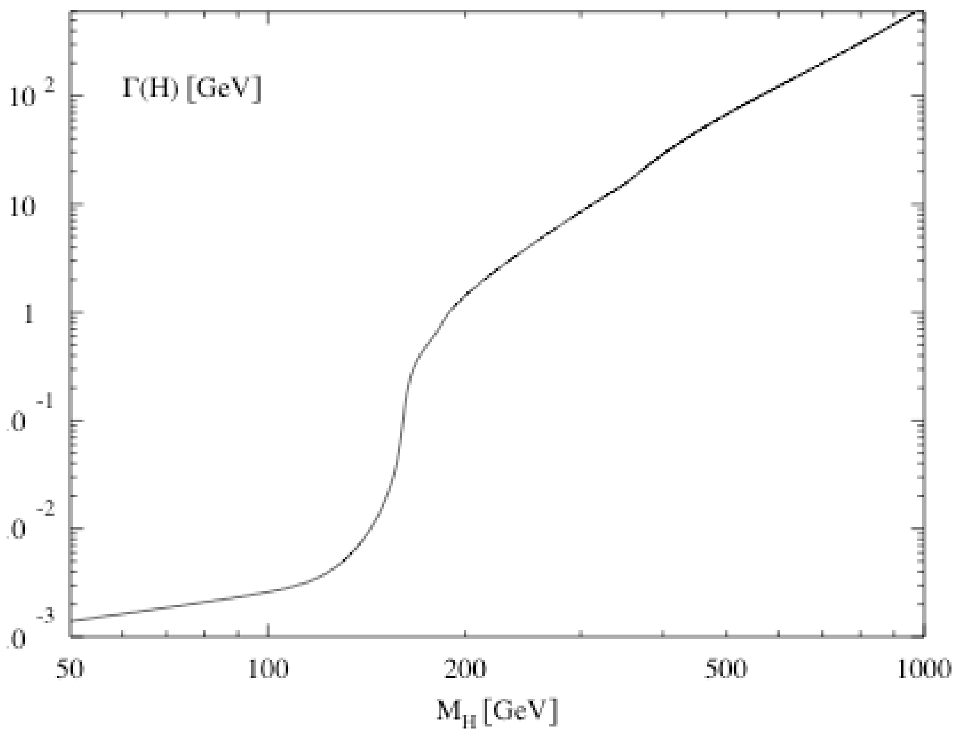


Higgs production at LHC

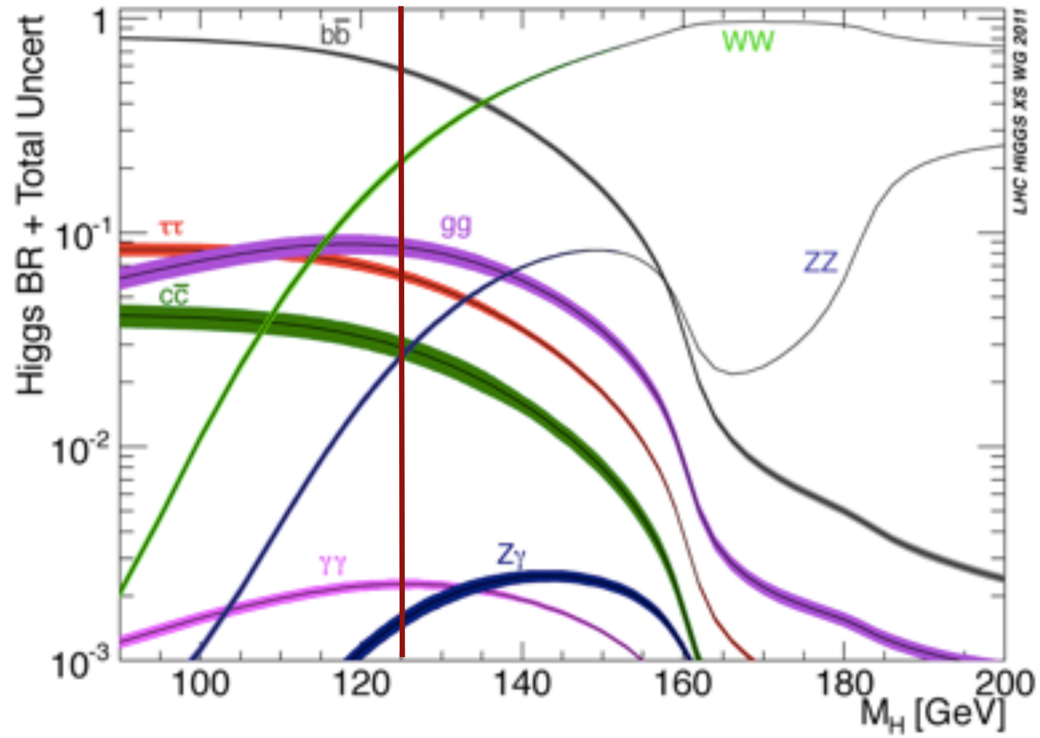


- At 8 TeV, and m_H = 125 GeV
  - gluon fusion cross section is σ = 19.5 pb, Δσ = 15-20%
  - VBF cross section is σ = 1.6 pb, Δσ = 5%
  - *WH/ZH* cross section is σ = 0.7/0.4 pb, Δσ = 5%
  - *ttbarH* cross section is σ = 0.13 pb, Δσ = 15%

Higgs decay at LHC



total width

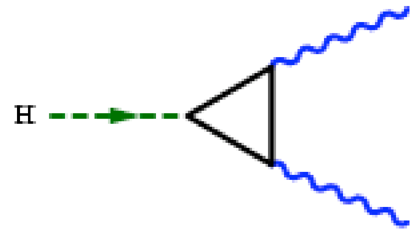


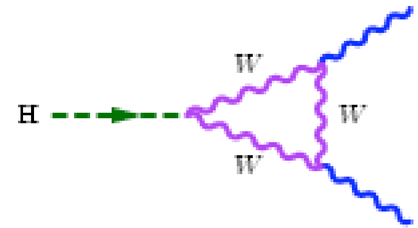
branching ratios

Higgs decay modes at LHC

- $H \to \gamma\gamma$

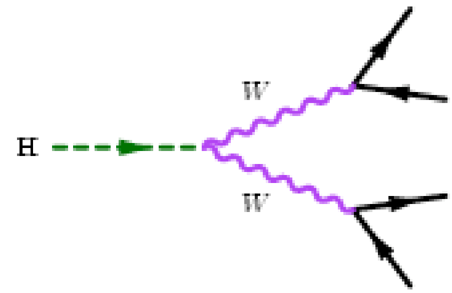
low mass, high bkg and mass resolution dominated by EW coupling





- $H \to ZZ \to 4l$

full mass range, low BR, high mass resolution

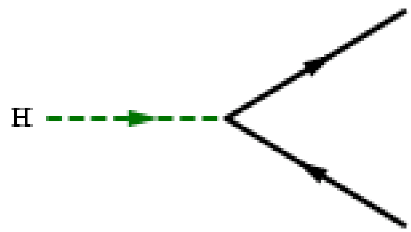


- $H \to WW \to l\nu\, l\nu$

full mass range, high BR, low mass resolution

- $H \to \tau\tau$

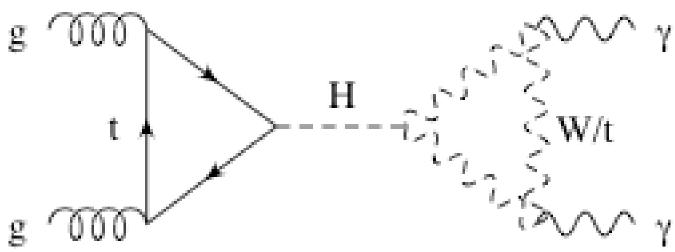
low mass, probes the Yukawa coupling

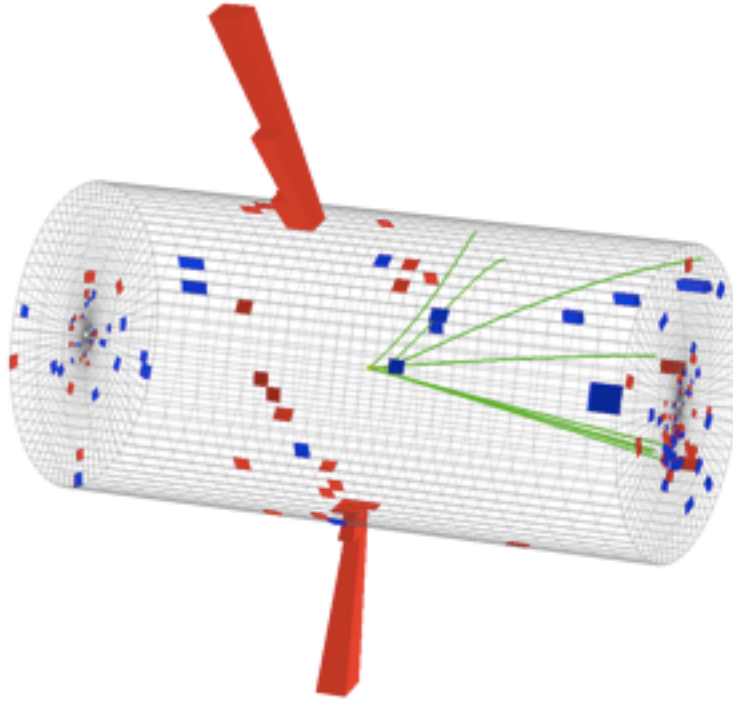


- $VH \to Vbb$

boosted Higgs from associated production

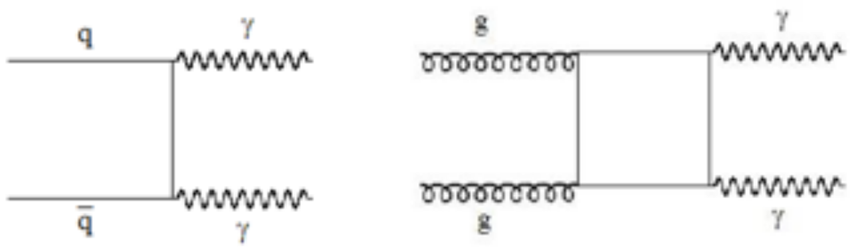
$H \rightarrow \gamma\gamma$



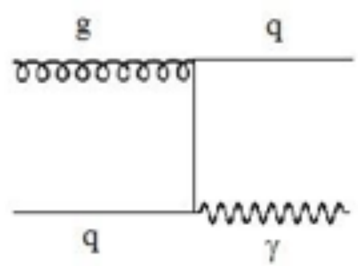


- BR: ~ 10^{-3} (at m_H = 125 GeV)
- Clean signature: two isolated, high-p_T γ narrow peak in $m_{\gamma\gamma}$ over decreasing bkg
- Backgrounds: γγ (irreducible), γ jet & jet jet (~ 25%)

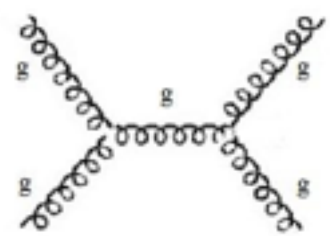
$pp \rightarrow \gamma\gamma$



$pp \rightarrow \gamma$ jet



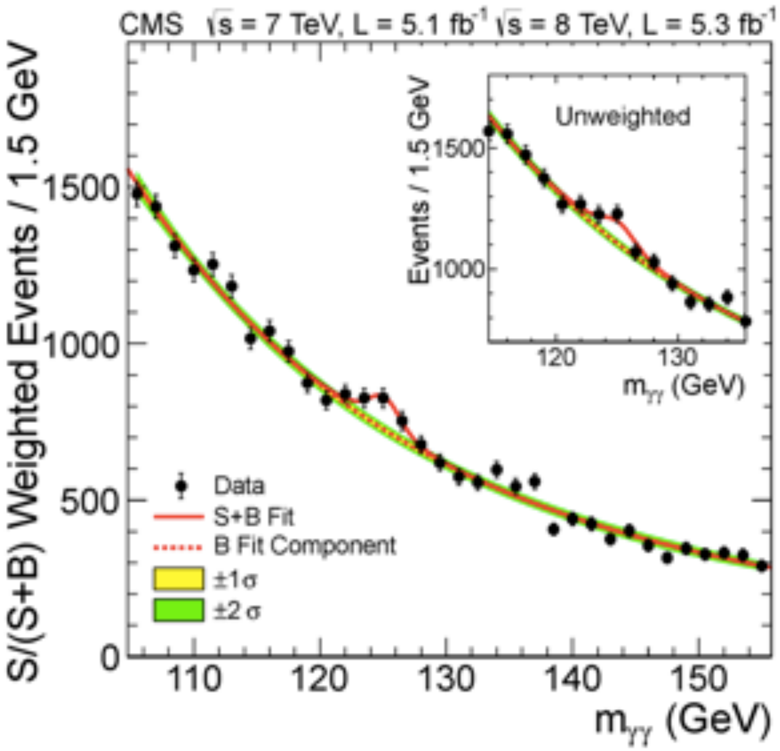
$pp \rightarrow$ jet jet

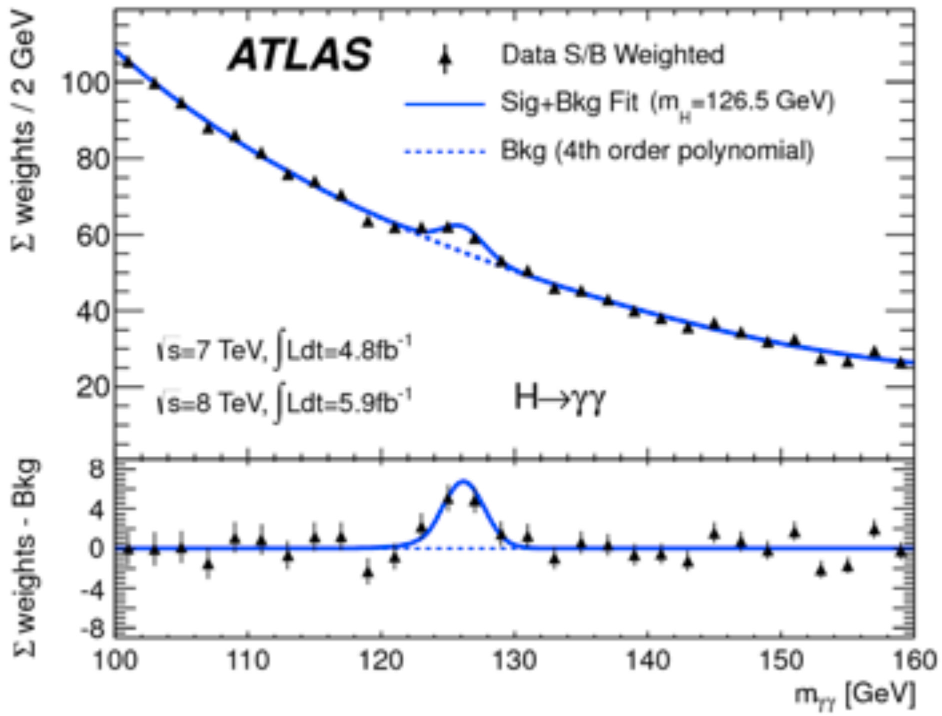


$H \to \gamma\gamma$

- Background is smooth: extrapolate it into the signal region from the sidebands

4 July 2012

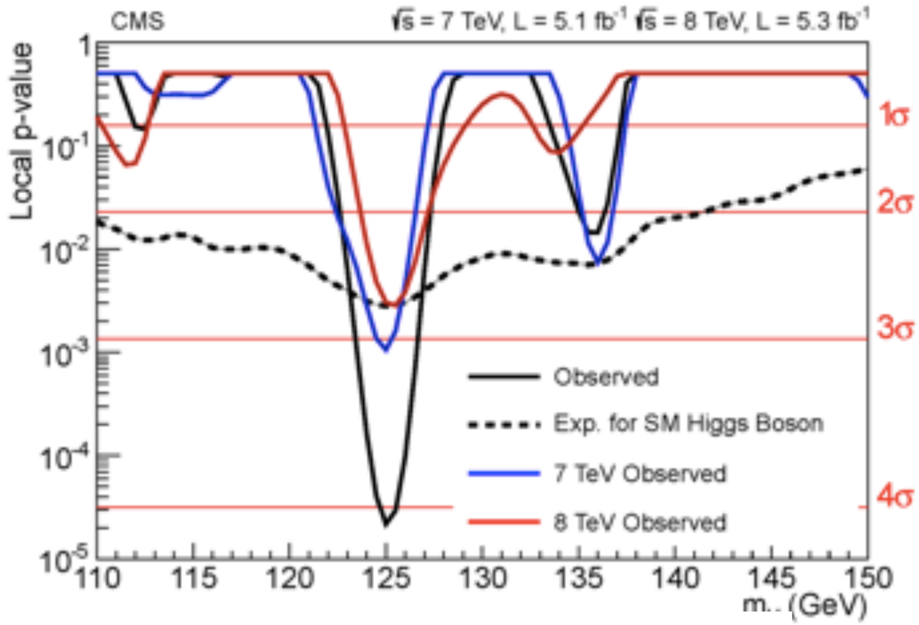


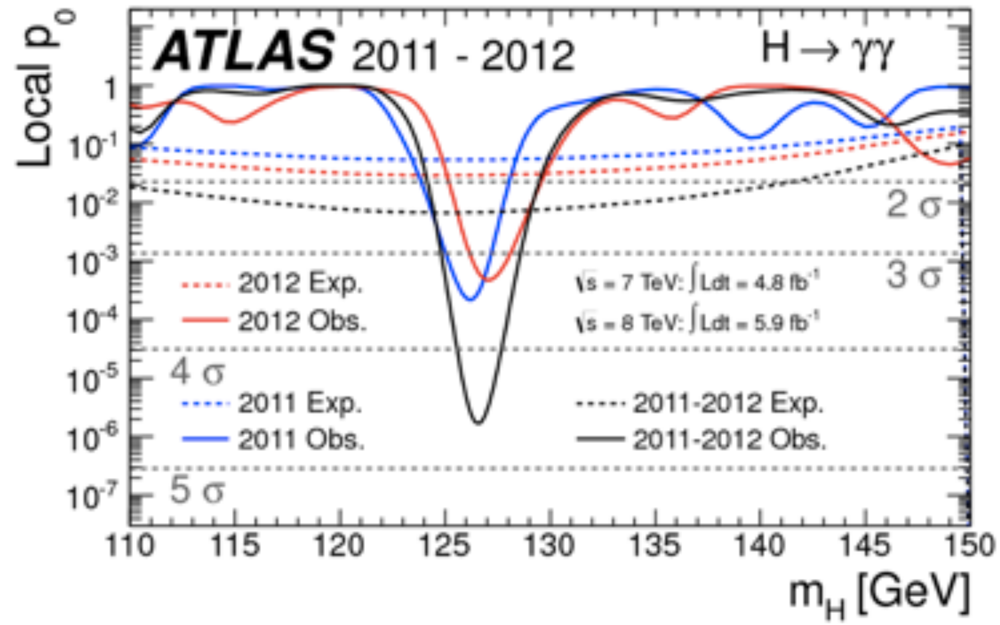


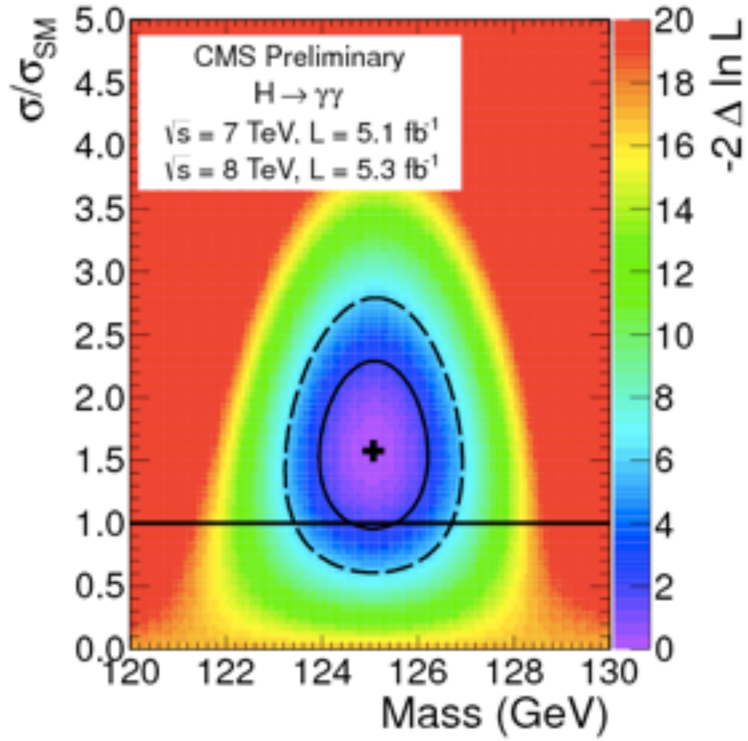
events in the plot weighted by *S/(S+B)* of each category

events in the plot weighted by *ln*[*(S+B)/B*] of each category

$H \to \gamma\gamma$







4 July 2012

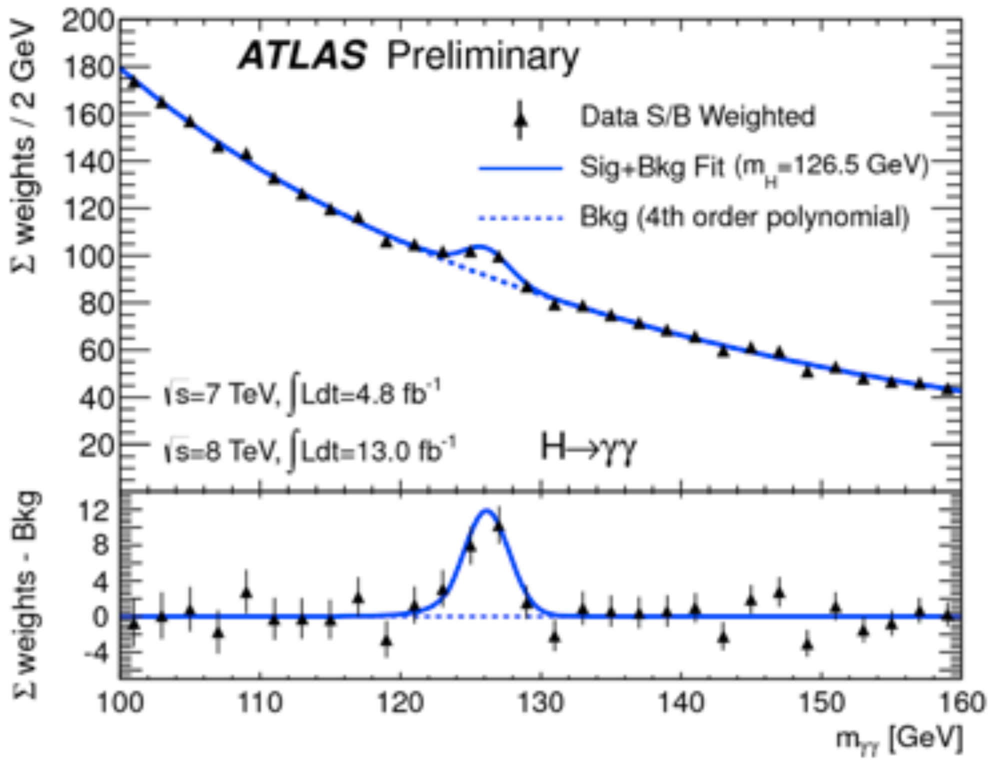
CMS: 4σ excess at m_H = 125 GeV
ATLAS: 4.5σ excess at m_H = 126.5 GeV

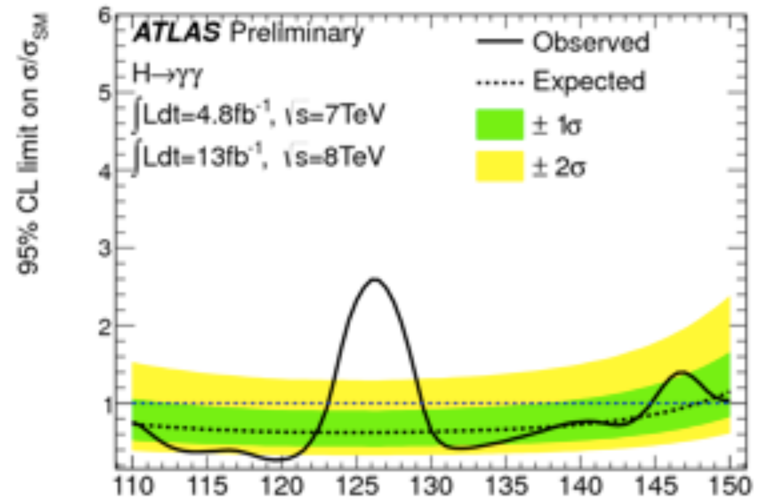
CMS: signal strength σ/σ_{SM} = 1.56 ± 0.45
ATLAS: signal strength σ/σ_{SM} = 1.9 ± 0.5

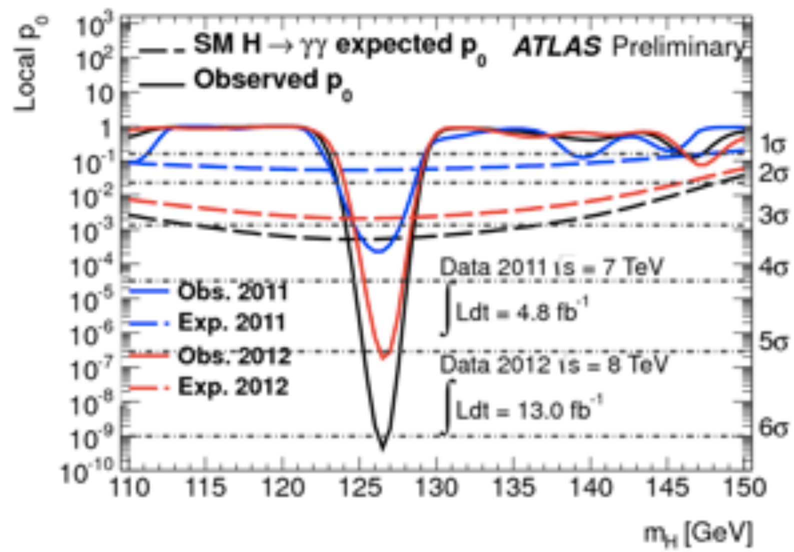
$H \rightarrow \gamma\gamma$

December 2012

- ATLAS: data samples of 4.8fb^{-1} at 7 TeV and 13.0fb^{-1} at 8 TeV
- SM Higgs boson excluded at 95% CL: 110-122.5 and 129.5-144.5 GeV
- 6.1σ excess at m_H = 126.6 GeV
- signal strength σ/σ_{SM} = 1.8 ± 0.4

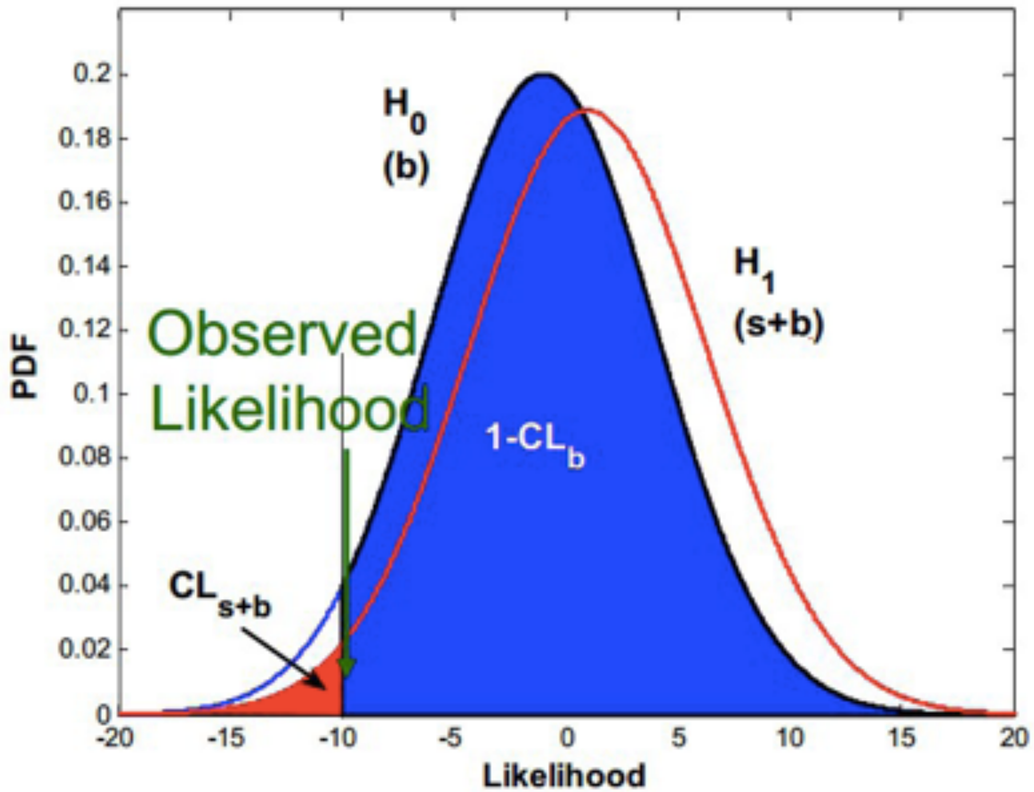






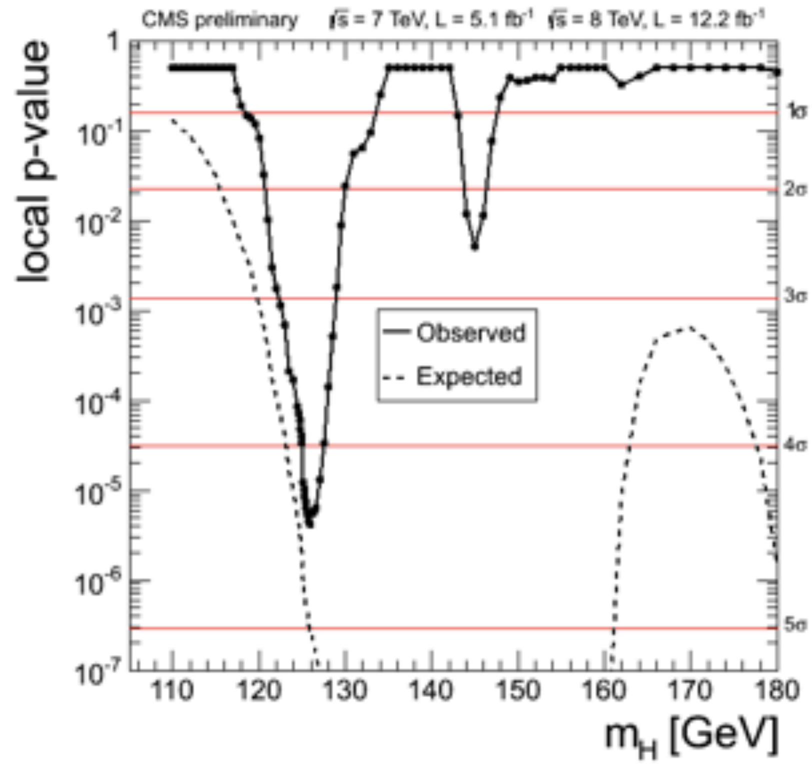
Upper limit on a cross section

- estimate signal BR x σ
- estimate SM background
- do a likelihood fit for each mass bin
- H_0 → background
- $H_1 + H_0$ → signal + background
- vary signal cross section until $CL_{s+b}/CL_b = 0.05$
- the value you get is the upper limit of the signal σ at 95% CL



p-value

- how do we estimate an excess on the upper limit of the signal σ ?
- assume that the background has a statistical fluctuation such as to show the observed excess
- p-value is: $1\text{-}CL_b$



for example, compute the p-value
to get 8 heads out of 10 coin flips

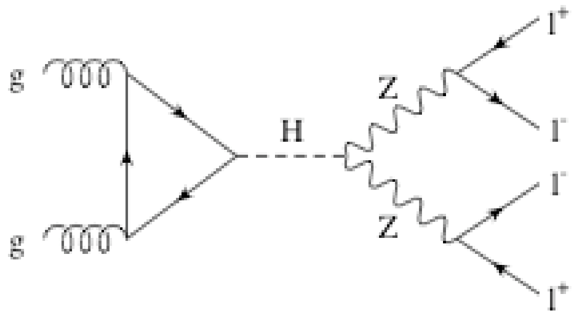
Probability of at least 8 heads

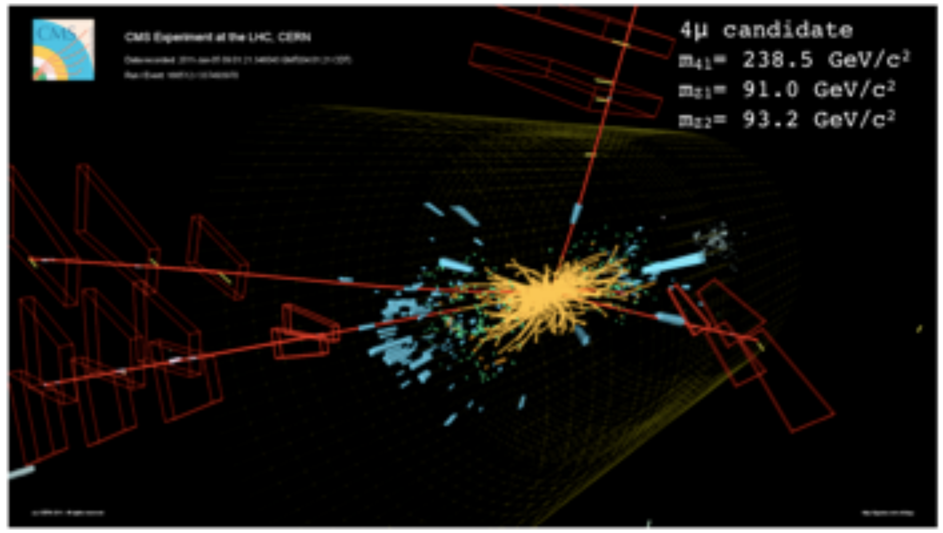
$$\frac{1}{2^{10}}\left[\binom{10}{8}+\binom{10}{9}+\binom{10}{10}\right]=\frac{56}{2^{10}}=0.055$$

p-value = Prob (≥8 heads or ≥8 tails) = 2* Prob (≥8 heads) = 2*(1- Prob (≤8 heads)) = 0.11

p-value(≥8 heads) exceeds 0.05, falls within the range of what would happen 95% of the time: deviation from expected outcome small enough to be consistent with chance
but p-value(≥9 heads) = 0.02 would let us reject chance at 95% CL

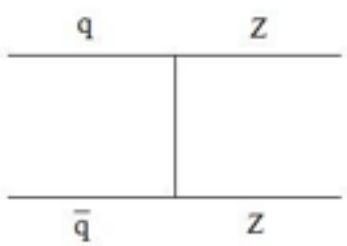
$H \to ZZ \to 4l$

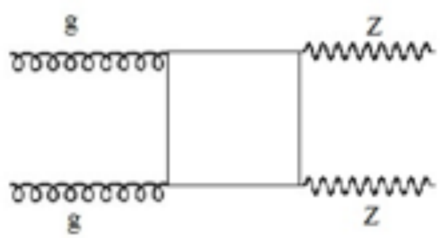




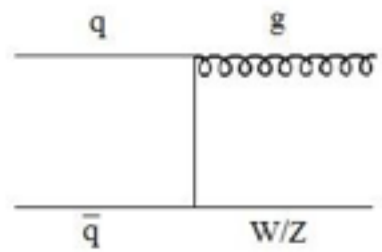
- BR: ~ 10^{-4} (at m_H = 125 GeV)
- signature: two pairs of isolated, high-p_T leptons originating from the primary vertex
- $4l$ = 4μ, 2e2μ, 4e
- signal purity: S/B ~ 1
- Backgrounds: ZZ (irreducible), Z jet & ttbar (~ 30%)

$pp \to ZZ$

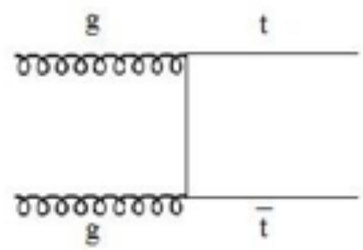




$pp \to Z$ jet

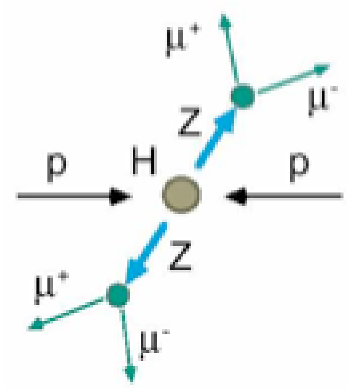


$pp \to$ ttbar

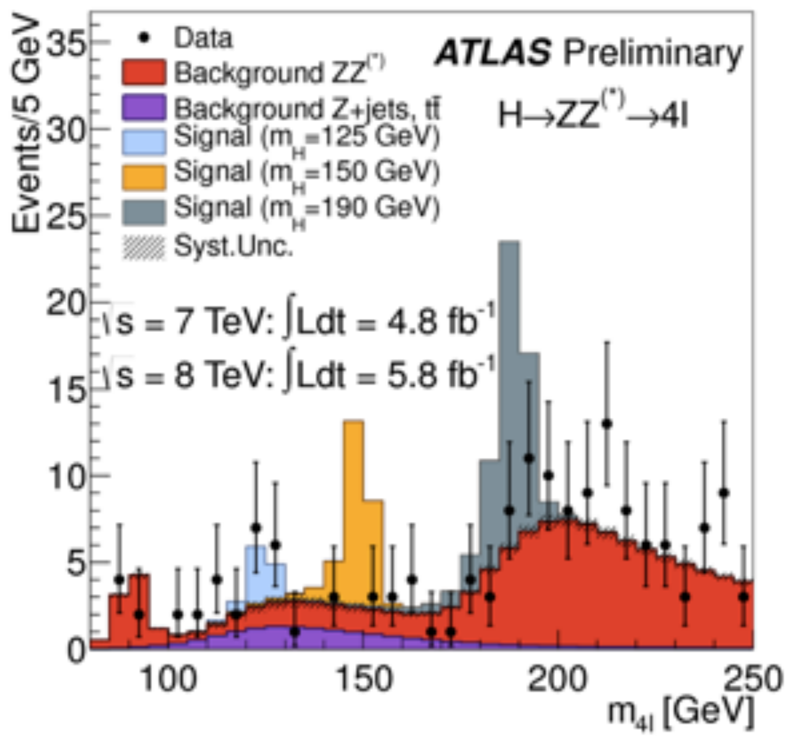


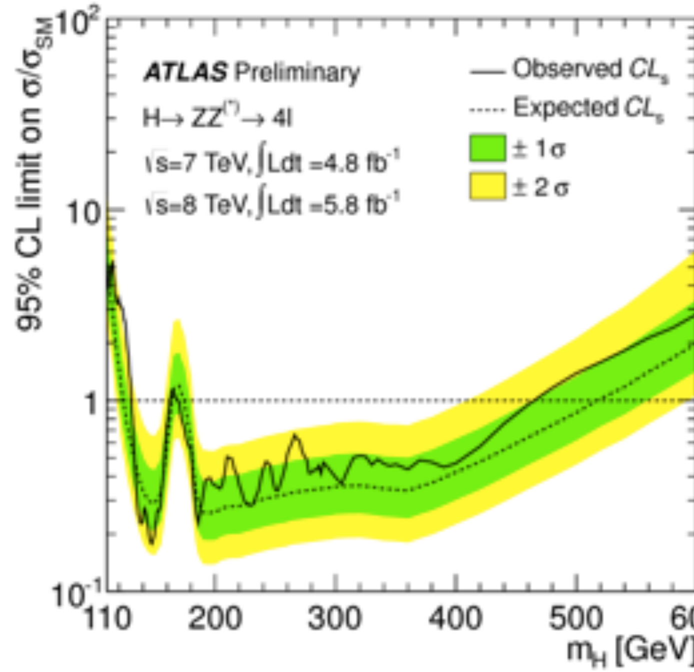
$H \rightarrow ZZ \rightarrow 4l$

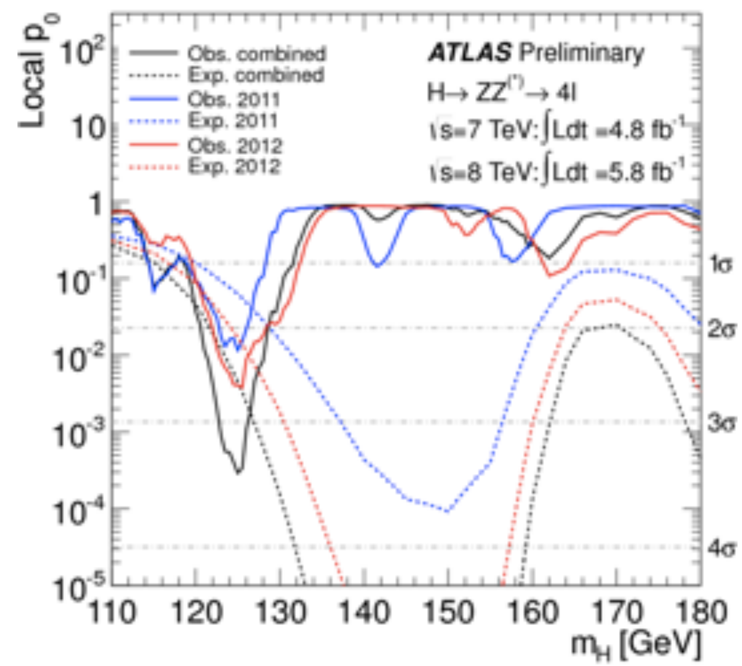
4 July 2012



m_{4l} distribution







- ATLAS: 3.6σ excess at m_H = 126.5 GeV

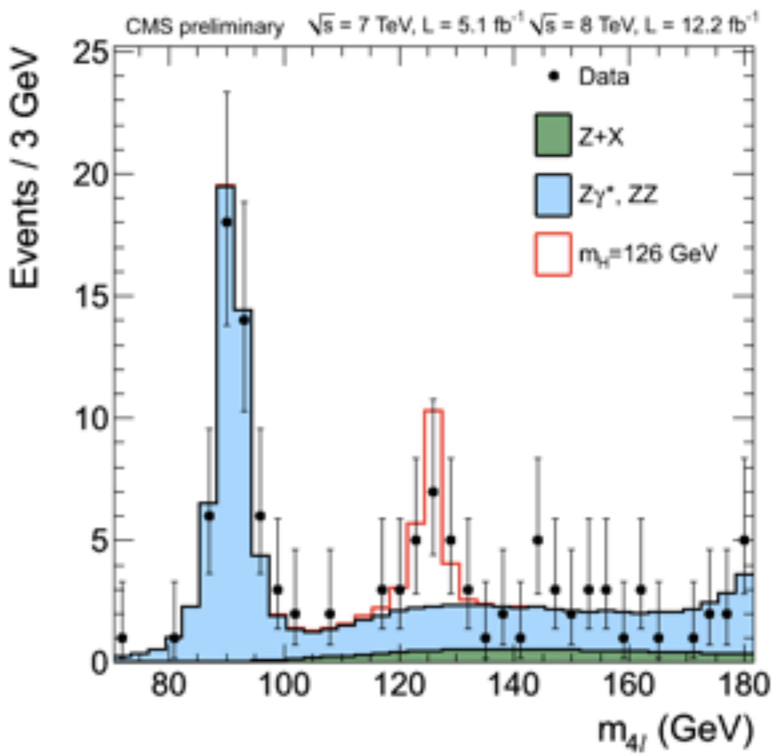
  signal strength $\sigma/\sigma_{SM} = 1.2 \pm 0.6$

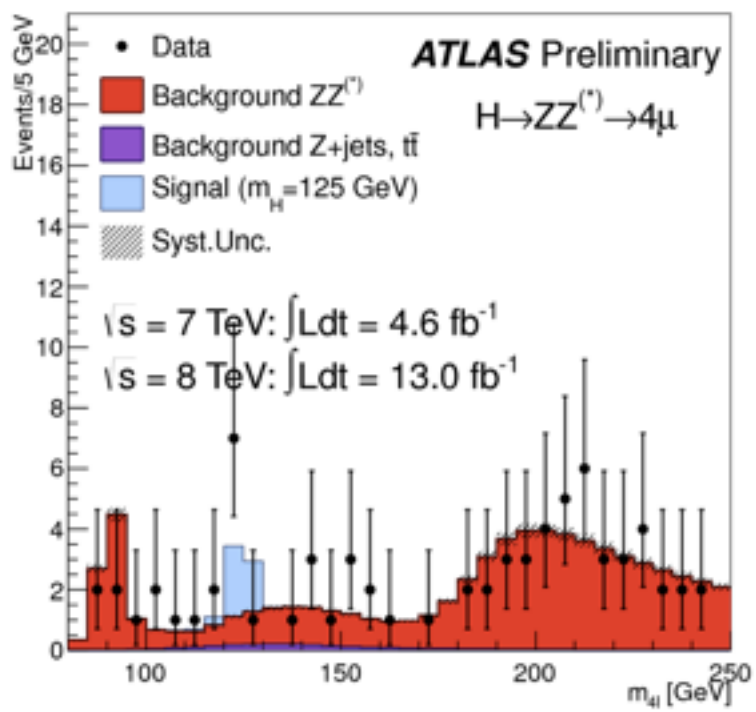
$H \to ZZ \to 4l$

December 2012

ATLAS: data samples of $4.8fb^{-1}$ at 7 TeV and $13.0fb^{-1}$ at 8 TeV
CMS: data samples of $5.1fb^{-1}$ at 7 TeV and $12.2fb^{-1}$ at 8 TeV

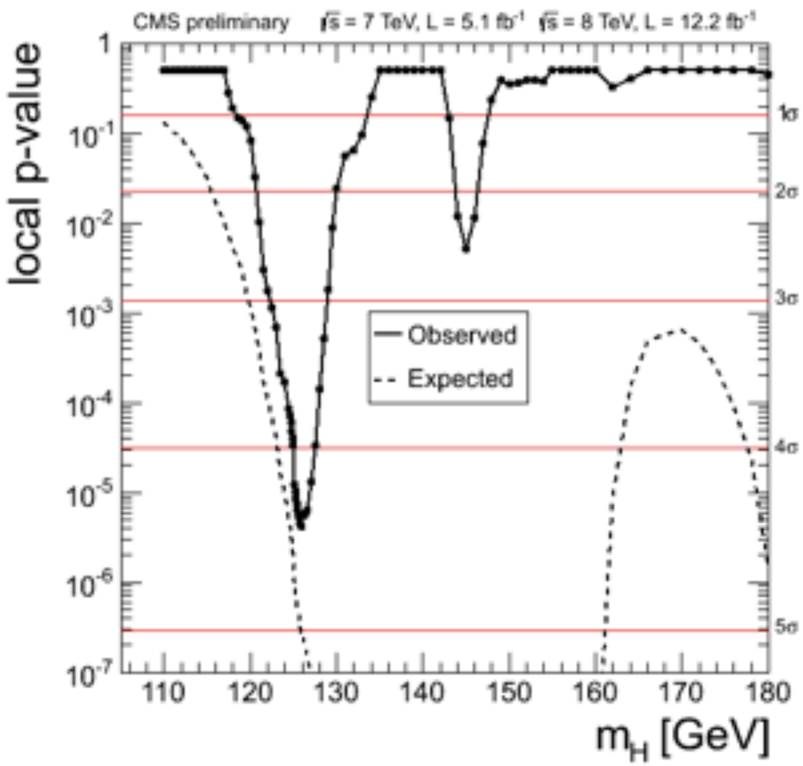
m_{4l} distribution

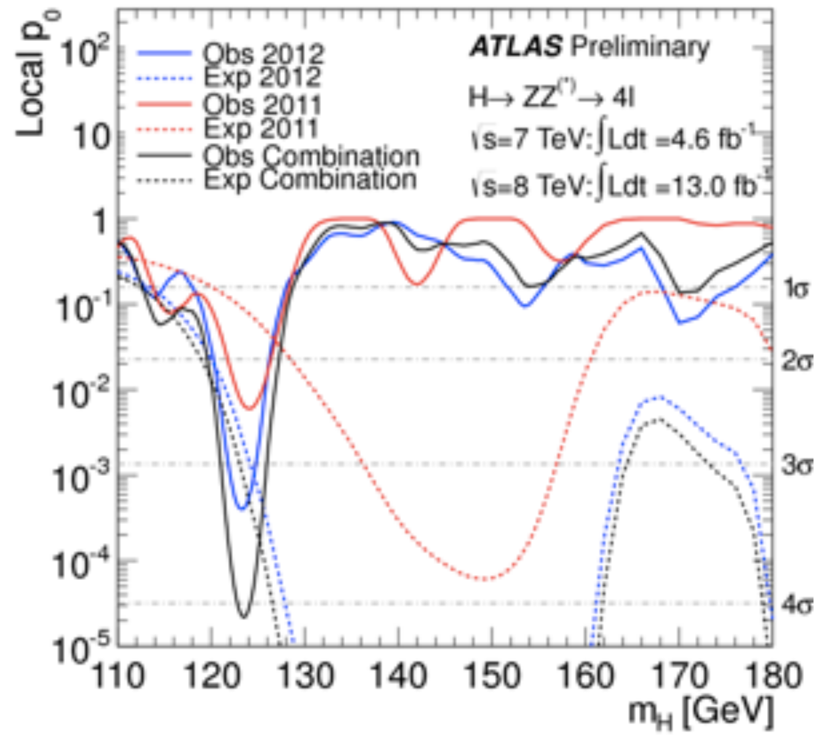




$H \to ZZ \to 4l$

December 2012

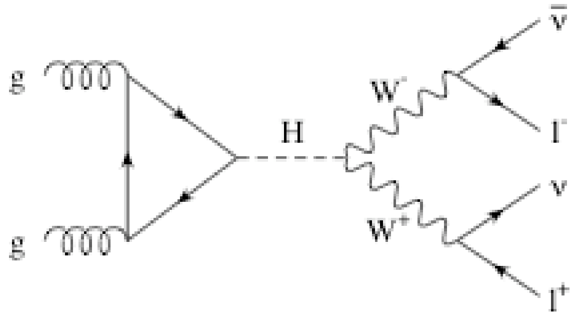


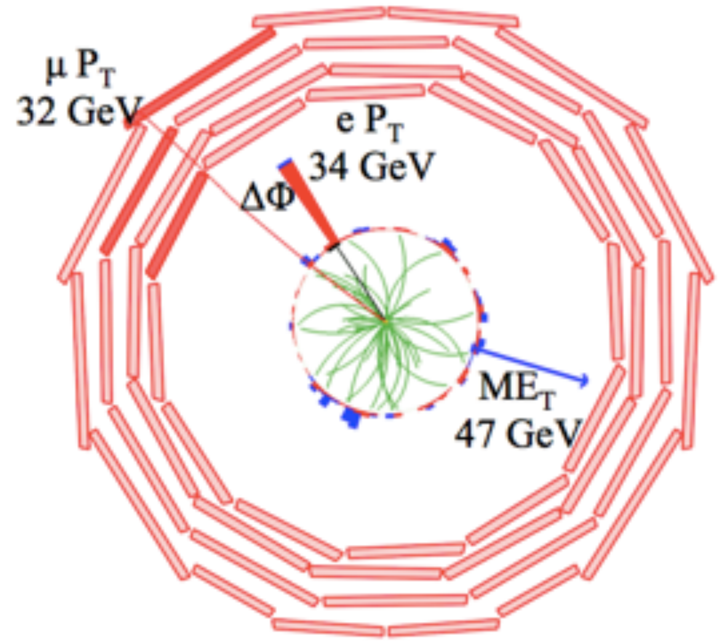


ATLAS: 4.1σ excess at m_H = 123.5 GeV
CMS: 4.5σ excess at m_H = 126 GeV

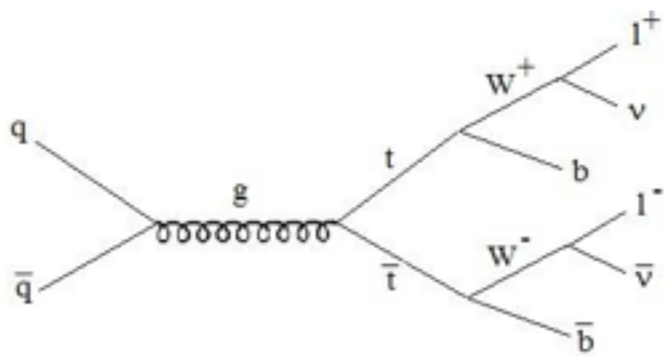
ATLAS: signal strength σ/σ_{SM} = 1.3 ± 0.4
CMS: signal strength σ/σ_{SM} = 0.8 ± 0.35

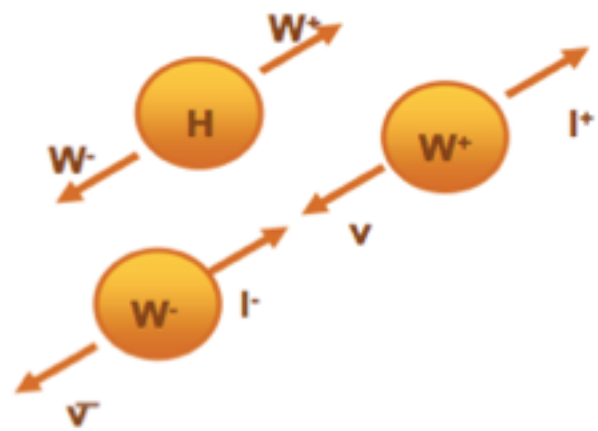
$H \to WW \to l\nu\, l\nu$





- BR: ~ 2.5 10^{-3} (at m_H = 125 GeV)
- signature: two isolated high-p_T leptons (μμ, μe, ee) of opposite sign; large missing E_T
- signal purity: S/B ~ 0.1
- Backgrounds: *WW*, *W* jet, jet jet, ttbar

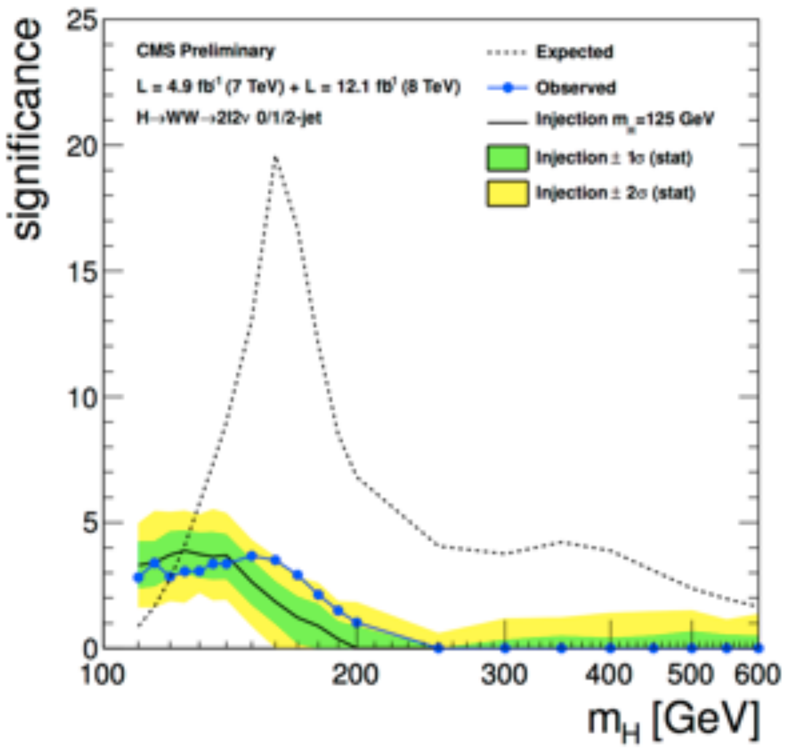




$H \to WW \to l\nu\, l\nu$

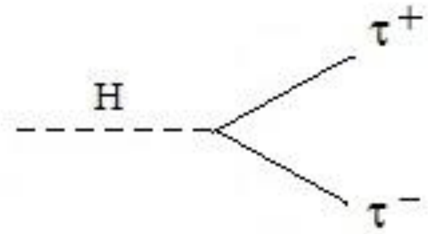
December 2012

- ATLAS: data samples of 4.8fb^{-1} at 7 TeV and 13.0fb^{-1} at 8 TeV
  CMS: data samples of 4.9fb^{-1} at 7 TeV and 12.1fb^{-1} at 8 TeV
- ATLAS: 2.8σ excess at m_H = 125 GeV
  CMS: 3.1σ excess at m_H = 125 GeV
- ATLAS: signal strength σ/σ_{SM} = 1.5 ± 0.6
  CMS: signal strength σ/σ_{SM} = 0.74 ± 0.25

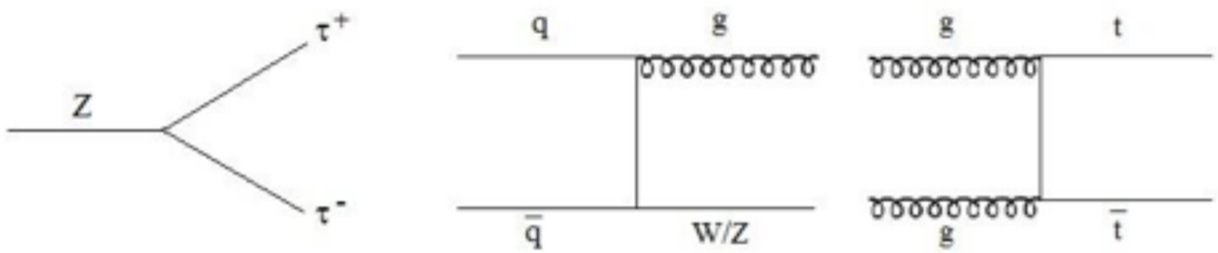


$H \to \tau\tau$

- BR: ~ 0.06 (at m_H = 125 GeV)
- signature: two isolated high-p_T leptons ($\tau\tau$, $\tau\mu$, τe, $\mu\mu$, μe) of opposite sign; large missing E_T

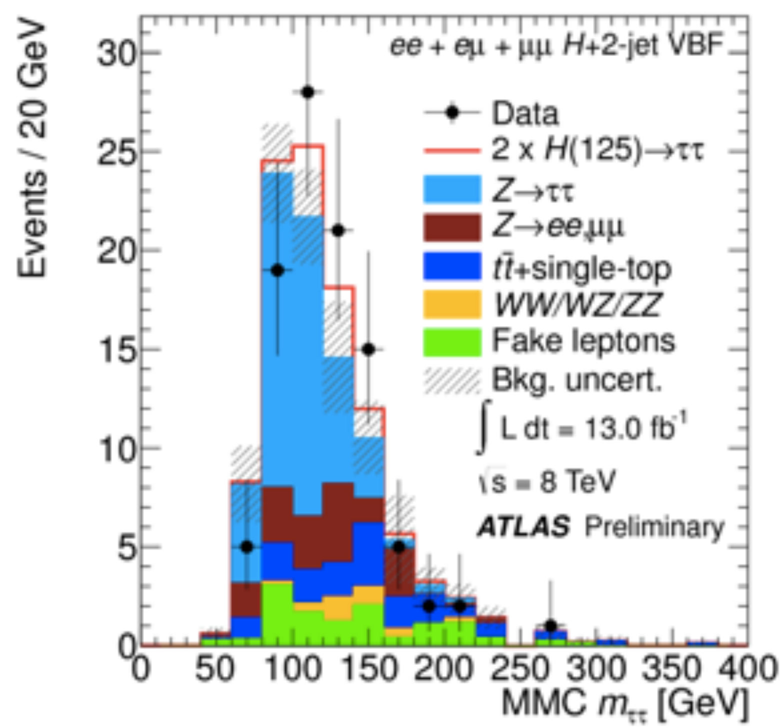


- Backgrounds: DY→Z→ττ (irreducible), Z jet & top



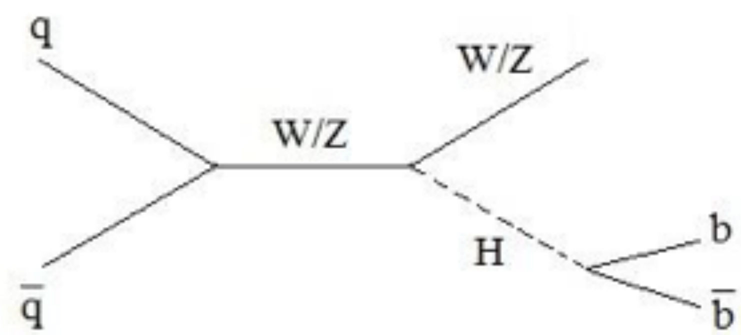
December 2012

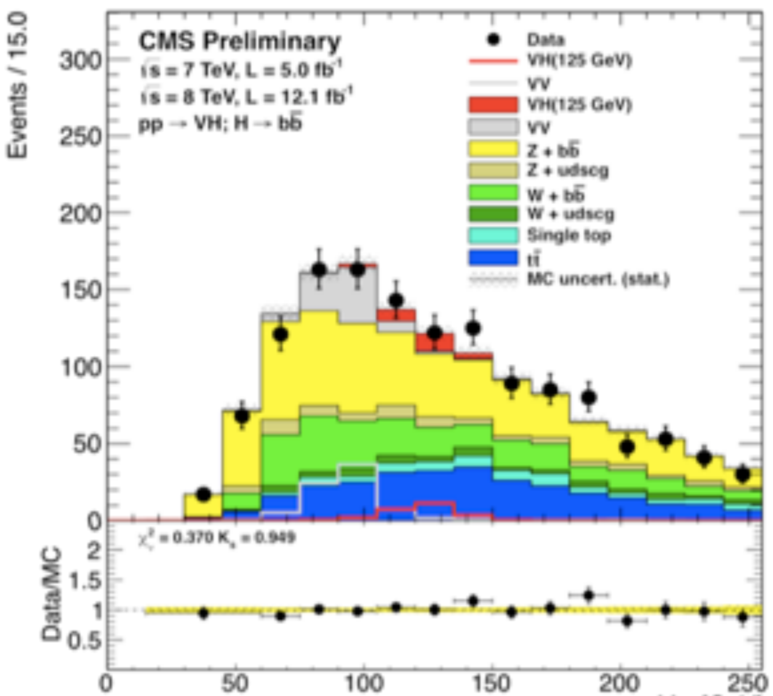
- ATLAS: 13fb^{-1} at 8 TeV
  CMS: 17fb^{-1} at 8 TeV
- ATLAS: 1.1σ excess at m_H = 125 GeV
  CMS: 1.3σ (?) excess at m_H = 125 GeV
- ATLAS: signal strength σ/σ_{SM} = 0.7 ± 0.7
  CMS: signal strength σ/σ_{SM} = 0.7 ± 0.5



$VH \to Vbb$

- huge background in the inclusive channel $H \to bb$ from QCD dijet production
- boosting the Higgs in p_T allows us to distinguish the Higgs from the background using the different profiles of the b jets. That requires using the associated production $VH \to Vbb$
- BR: ~ 0.6 (at m_H = 125 GeV)
- Backgrounds: Vbb, top





December 2012

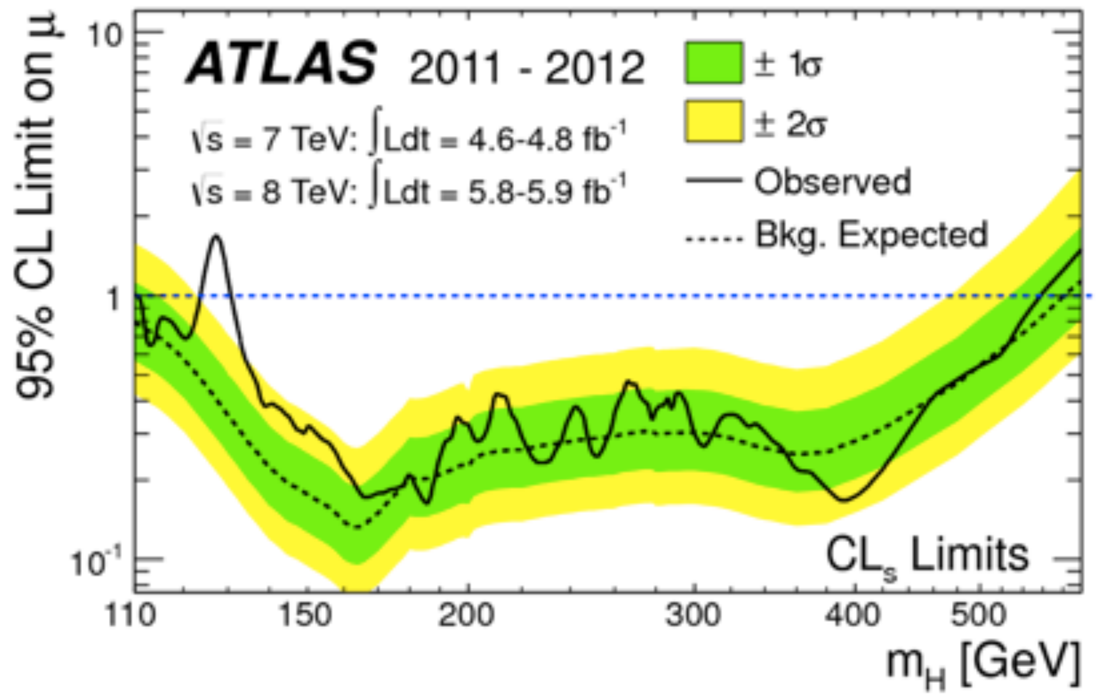
ATLAS: 4.7fb^{-1} at 7 TeV and 13.0fb^{-1} at 8 TeV
CMS: 5.0fb^{-1} at 7 TeV and 12.1fb^{-1} at 8 TeV

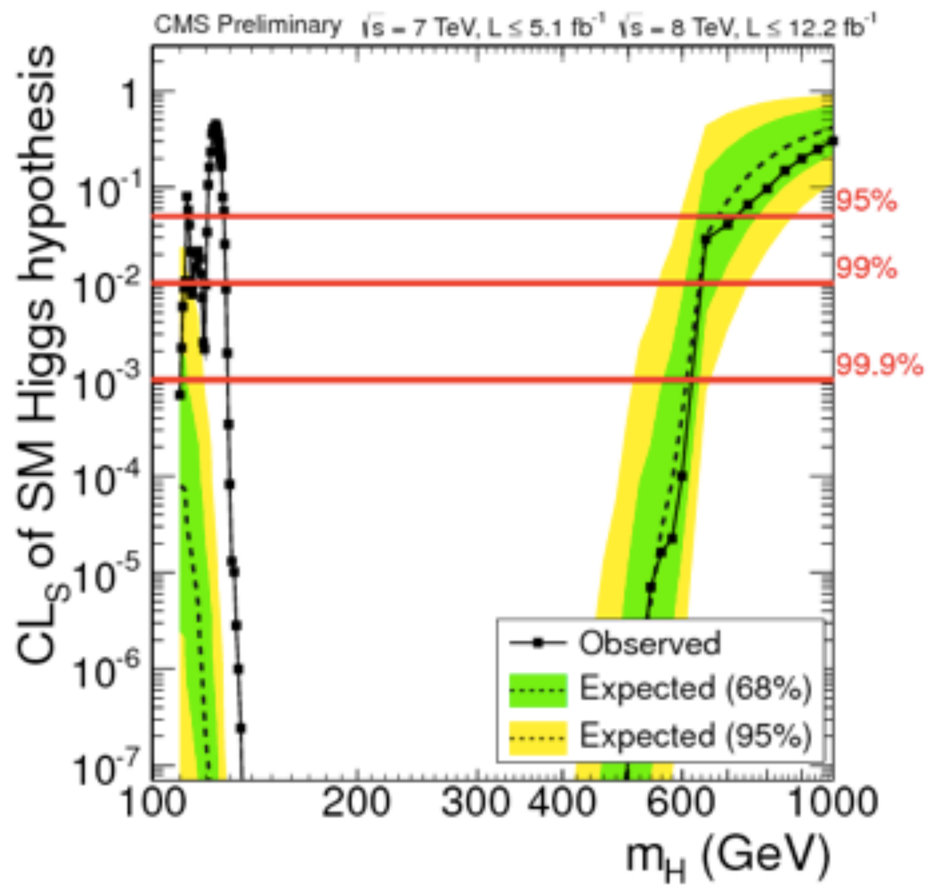
ATLAS: no significant excess observed
CMS: 2.2σ excess at m_H = 125 GeV

CMS: signal strength σ/σ_{SM} = 1.3 ± 0.7

Channel combination

- Exclusion limits



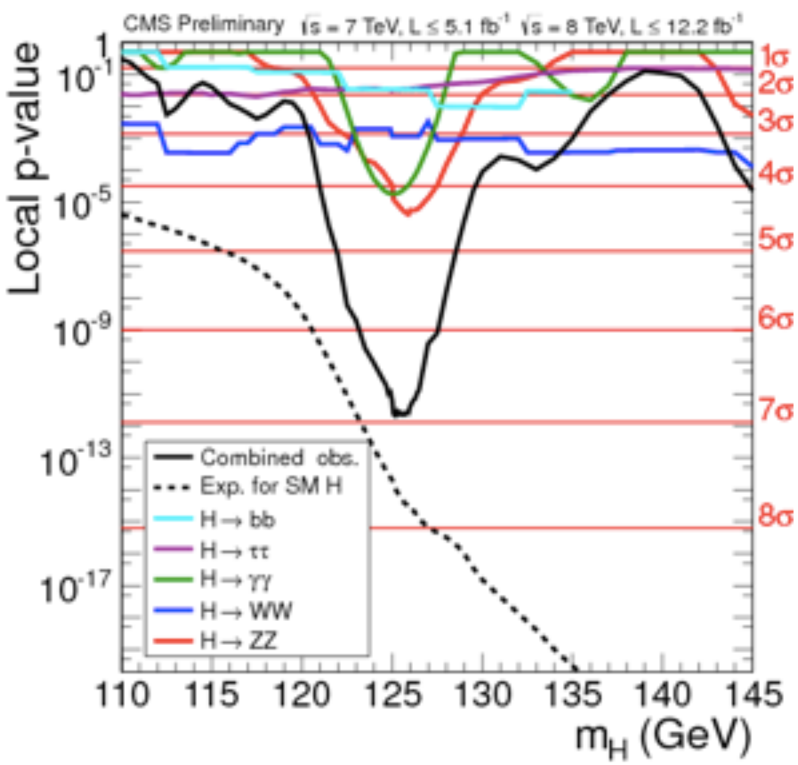


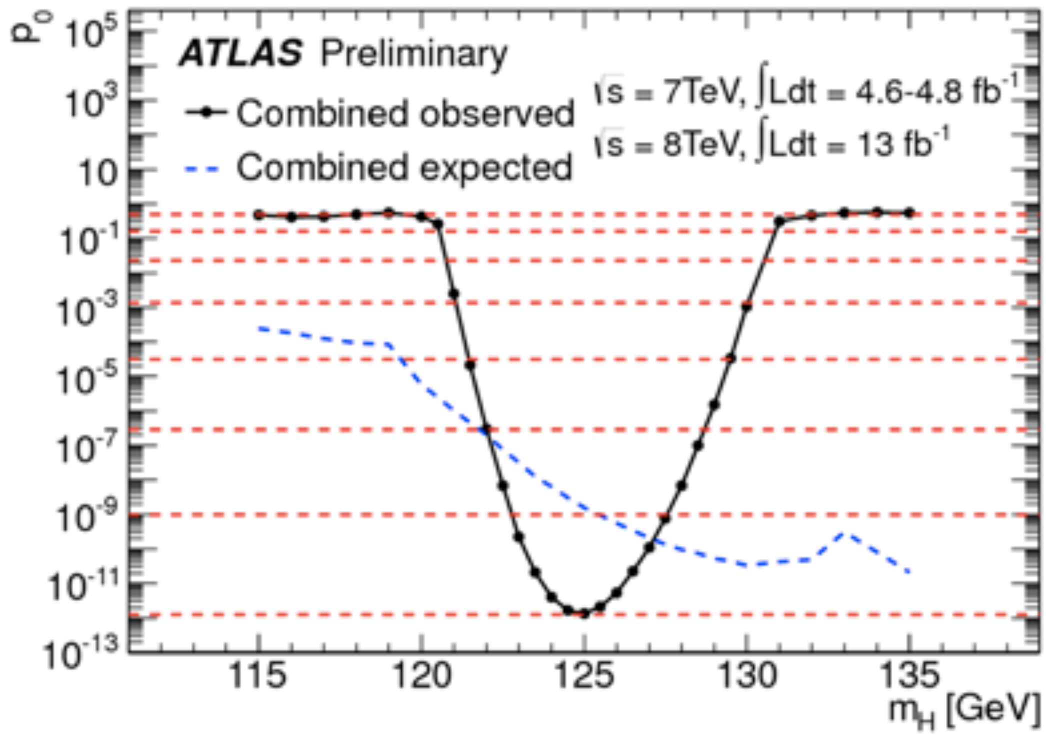
ATLAS: SM Higgs boson excluded at 95% CL: 111-122 and 131-559 GeV (4 July 2012)
CMS: SM Higgs boson excluded at 95% CL: 113-121 and 128-700 GeV (December 2012)

Channel combination

- Significance of the excess

December 2012





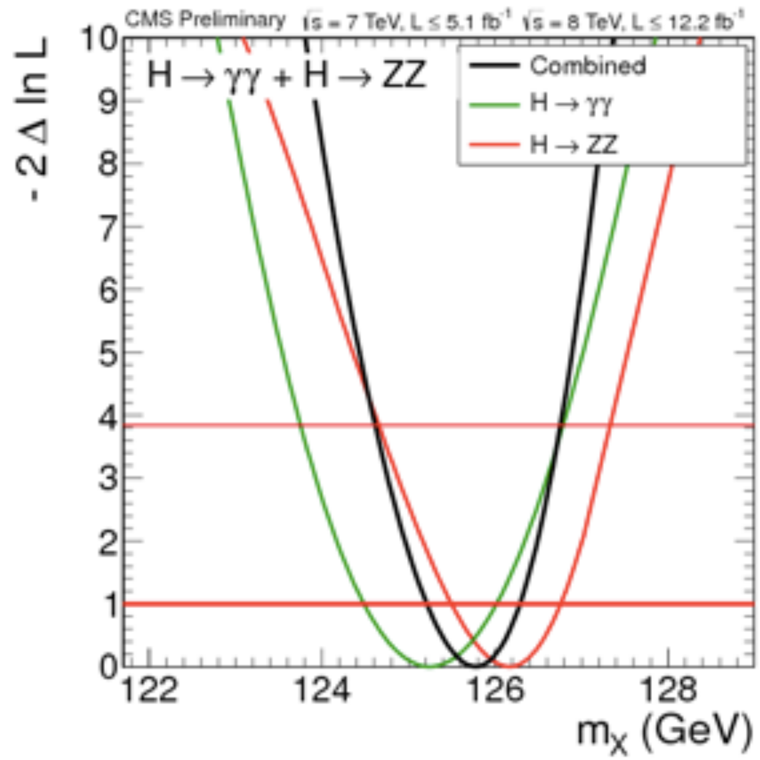
ATLAS: 7.0σ excess at m_H = 125.2 GeV
CMS: 6.9σ excess at m_H = 125.8 GeV (5.8σ from γγ and ZZ channels alone)

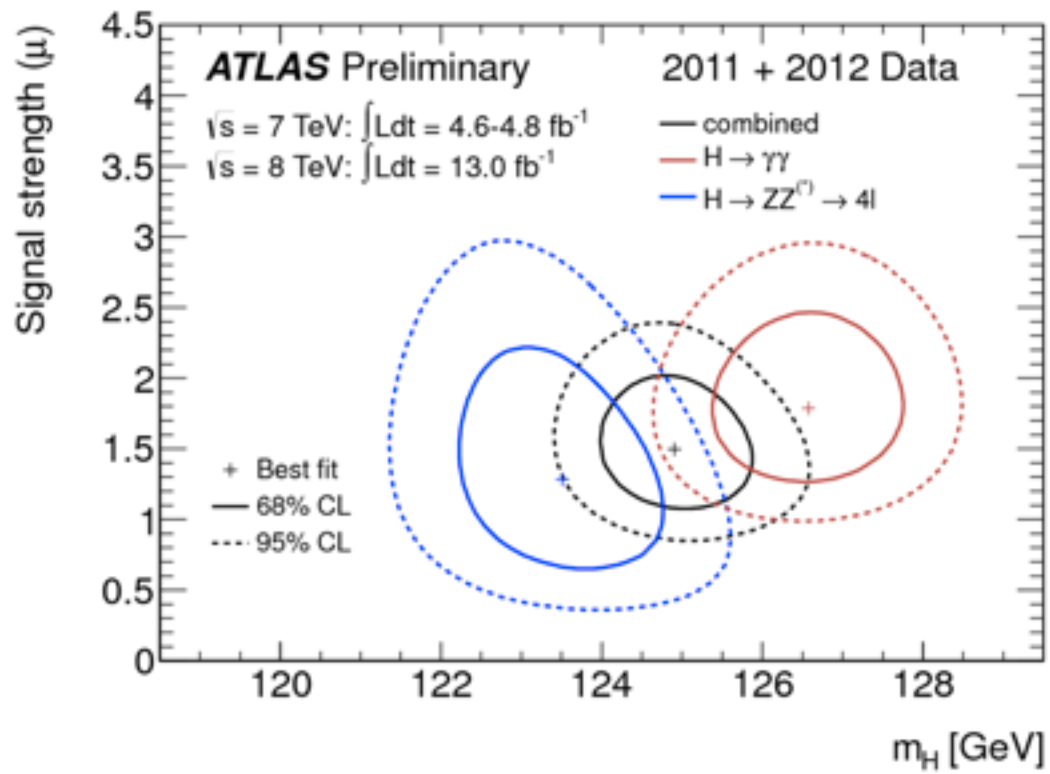
ATLAS: signal strength σ/σ_{SM} = 1.35 ± 0.24
CMS: signal strength σ/σ_{SM} = 0.88 ± 0.21

Channel combination

- Mass measurement:
  combination of γγ and *ZZ* channels

December 2012





ATLAS: m_H = 125.2 ± 0.3 (*stat*) ± 0.6 (*syst*) GeV
CMS: m_H = 125.8 ± 0.4 (*stat*) ± 0.4 (*syst*) GeV

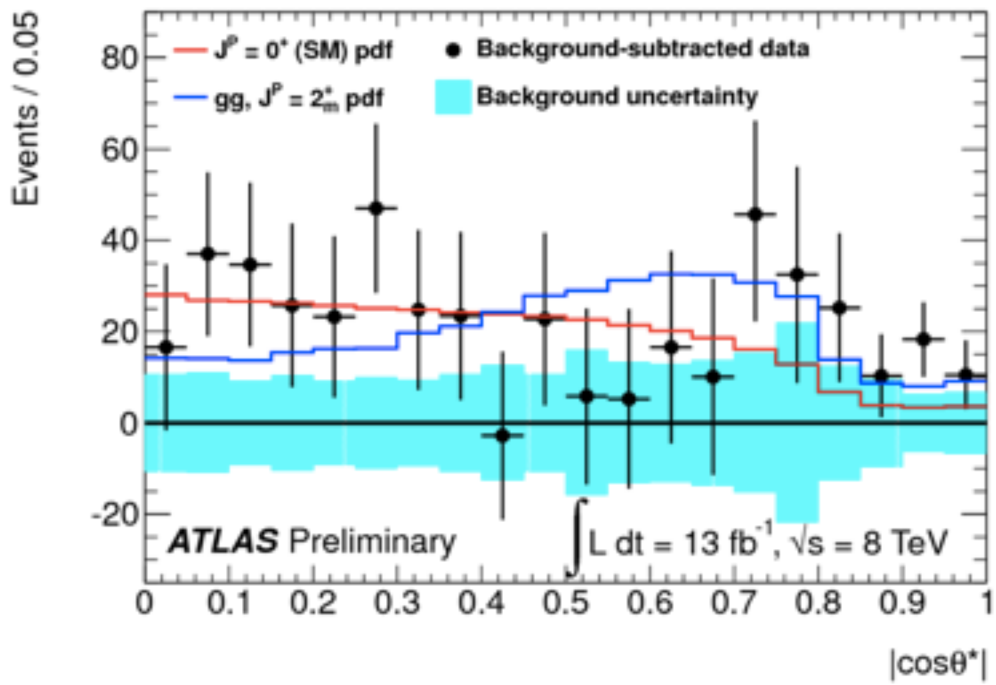
Resonance properties

- Q: Is it a Higgs boson ?

  A: a Higgs boson is a spin-0 scalar with specific couplings in the SM

- Q: So is it a spin-0 scalar particle ?

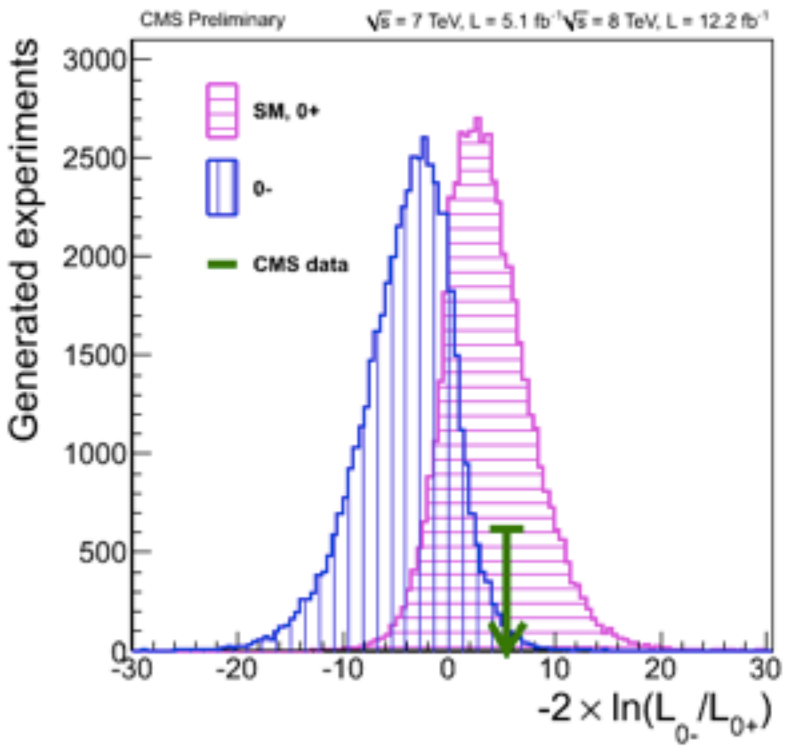
  A: Because it decays into $\gamma\gamma$ it should be either spin 0 or 2

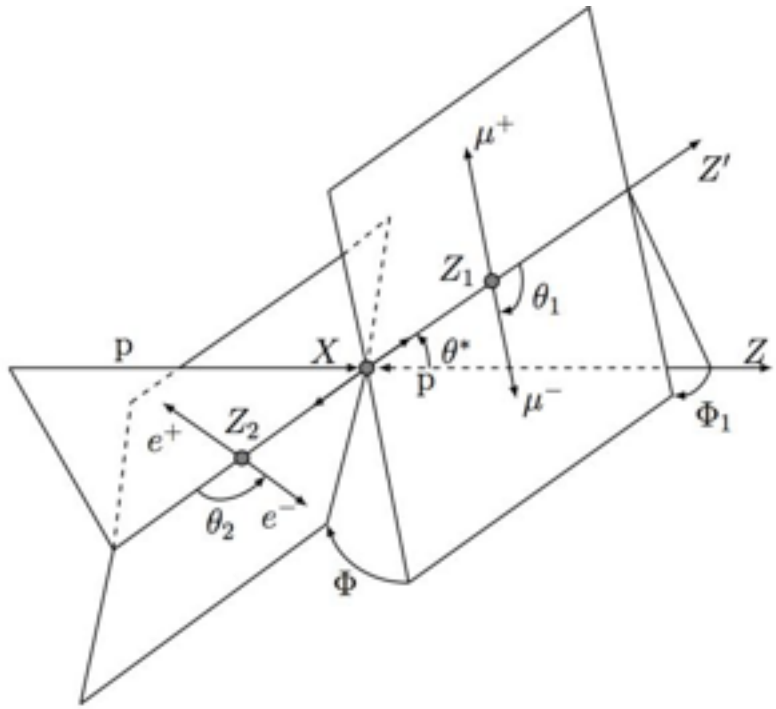


$H \rightarrow \gamma\gamma$ (ATLAS): exclusion of the spin 2^+ (graviton-like tensor) at 91% CL

Resonance properties

- spin 0^+ (scalar) and 0^- (pseudoscalar) can be distinguished using $H \to ZZ \to 4l$ whose kinematics is described by 5 angles and 2 masses m_{12} m_{34}





CMS: spin 0^- disfavoured at 2.4σ level

Higgs couplings

- As couplings, a Higgs-like resonance should have gauge, Yukawa, self-couplings

- we can investigate them under the assumption that:
  - the signals observed originate from a single narrow resonance
  - the width of the resonance is neglected, such that for all channels

$$(\sigma \cdot \mathrm{BR})(ii \to H \to ff) = \frac{\sigma_{ii}\Gamma_{ff}}{\Gamma_H}$$

σ_{ii} production cross section through initial state *ii*

Γ_{ff} partial decay width into state *ff*

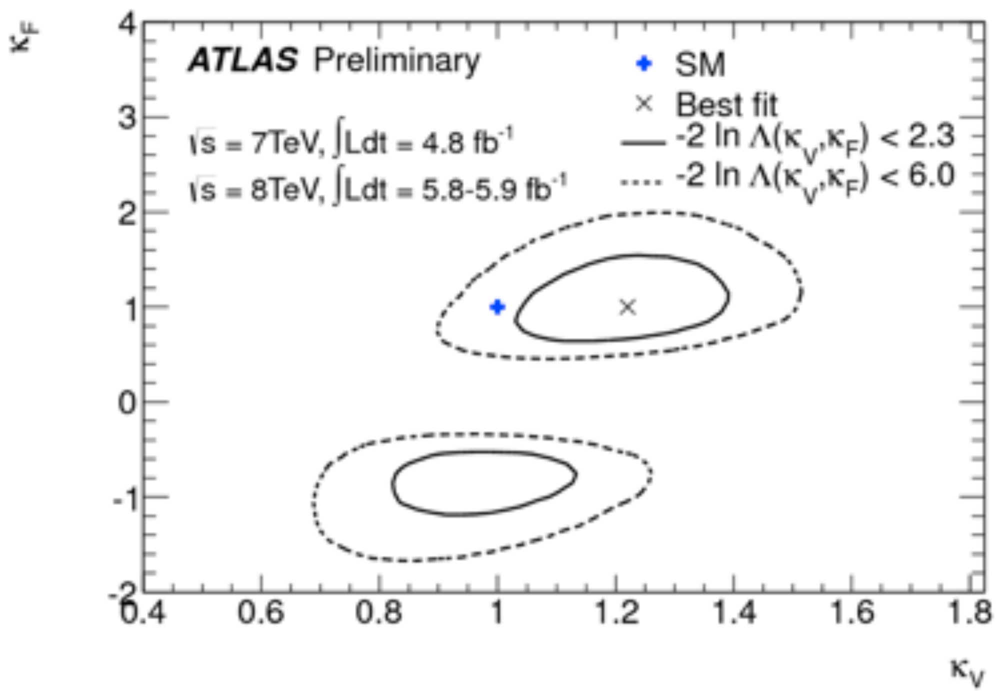
Γ_H total width of Higgs resonance

- suppose that the *true* coupling scales as
  true coupling = κ · SM coupling

$$(\sigma \cdot \mathrm{BR})(ii \to H \to ff) = \sigma_{SM}(gg \to H) \cdot \mathrm{BR}_{SM}(H \to ff) = \frac{\kappa_i^2 \kappa_f^2}{\kappa_H^2}$$

Higgs couplings

- assume
  $\kappa_V = \kappa_W = \kappa_Z$ scale factor for all vectors
  $\kappa_F = \kappa_b = \kappa_\tau = \kappa_t$ scale factor for all fermions



- within the statistical uncertainties, no significant deviations from the SM couplings are observed

Conclusions

- a new resonance has been observed, combining the $\gamma\gamma$, ZZ and WW production channels
- the new resonance has a mass of 125 GeV
- although more data are necessary to establish spin, parity and couplings of the new resonance, the observations make it so far compatible with a SM Higgs boson