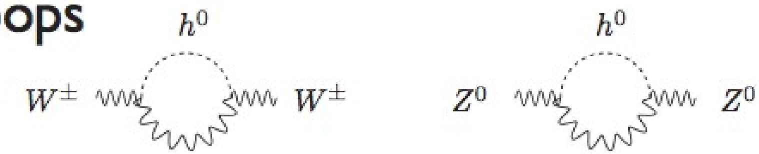
Experimental Tests of the Standard Model (4)

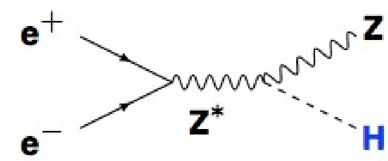
- Measurements of the Weinberg angle
- $W^{\pm}$ and Z^0 discovery
- Precision measurements of the Z^0
- Precision measurements of the W
- Discovery/measurements of the top
- **Discovery of the Higgs**

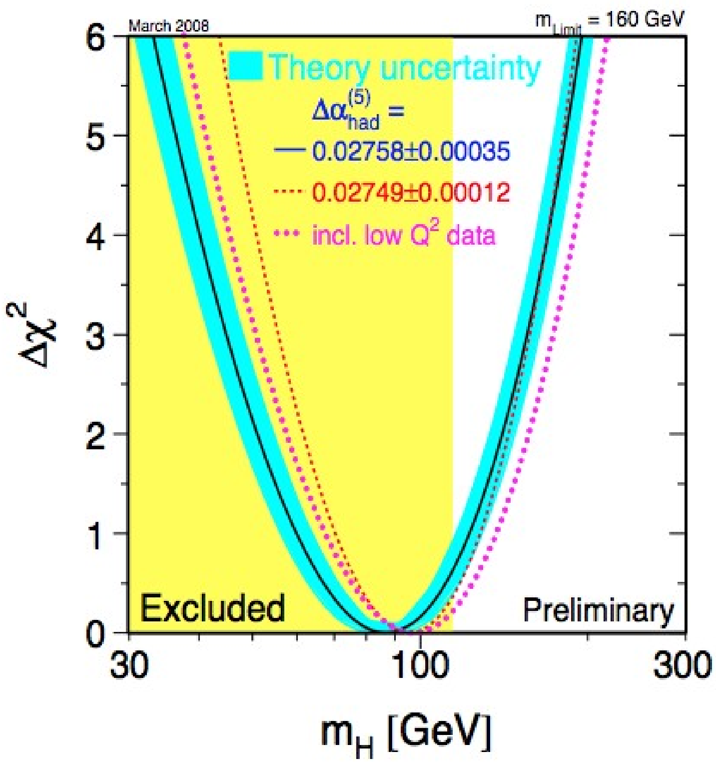
Experimental constraints on M_{Higgs}

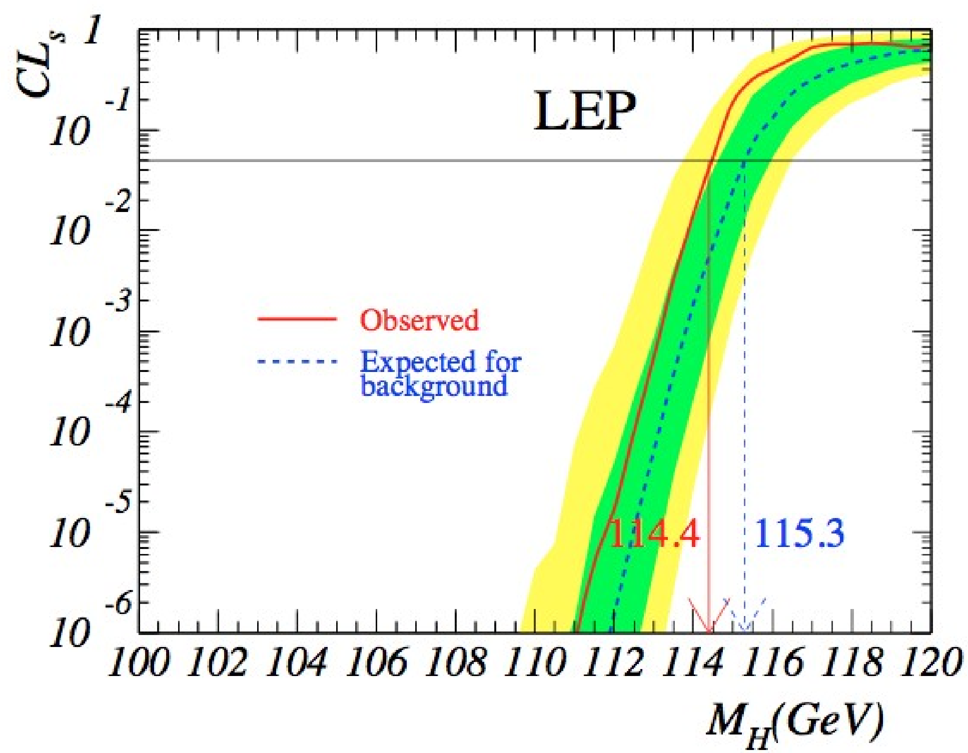
- Indirect search through precision measurement of SM sensitive to radiative corrections to Higgs in loops



- Direct search at LEP in Higgs-strahlung production channel

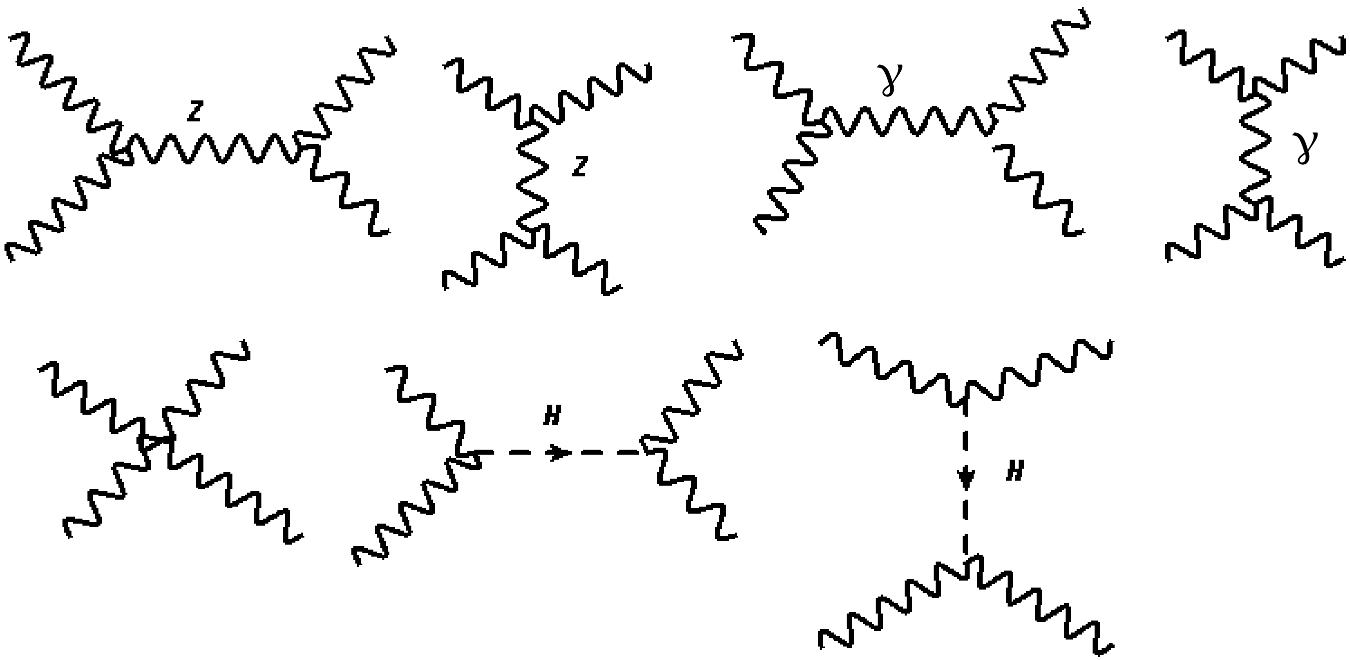






Theoretical constraints on the Higgs mass

- **Upper limits on the Higgs mass**
  One considers the scattering process: *WW* → *WW*



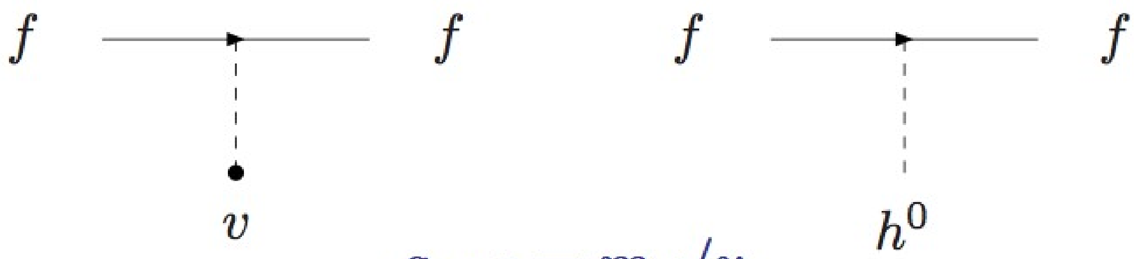
There is a strong cancellation summing up all the graphs, an essential role is given by the graphs with the Higgs bosons. The remaining amplitude depends on the Higgs mass.
Using the unitarity limit constraint one obtains the following condition:

$$M_H < \left(\frac{8\sqrt{2}\pi}{3\,G_F} \right)^{\frac{1}{2}} \approx 1\,TeV$$

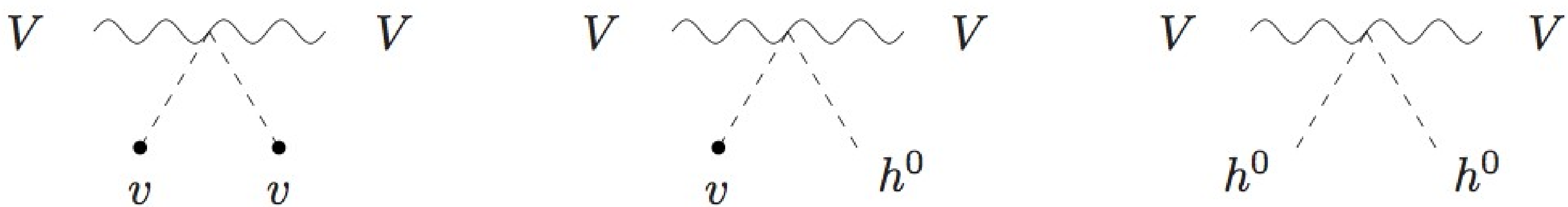
Theoretical constraints on the Higgs mass

- Trepassing this limit the weak interaction will become not more weak but strong.
  In other words the scattering at high energy of the weak interacting bosons are no more correctly described by the perturbative theory.
  The Higgs mass can exceed this limit, but in this case its properties cannot be obtained from the pertubative theory

Higgs coupling



$$g_{hf\bar{f}} = m_f/v$$



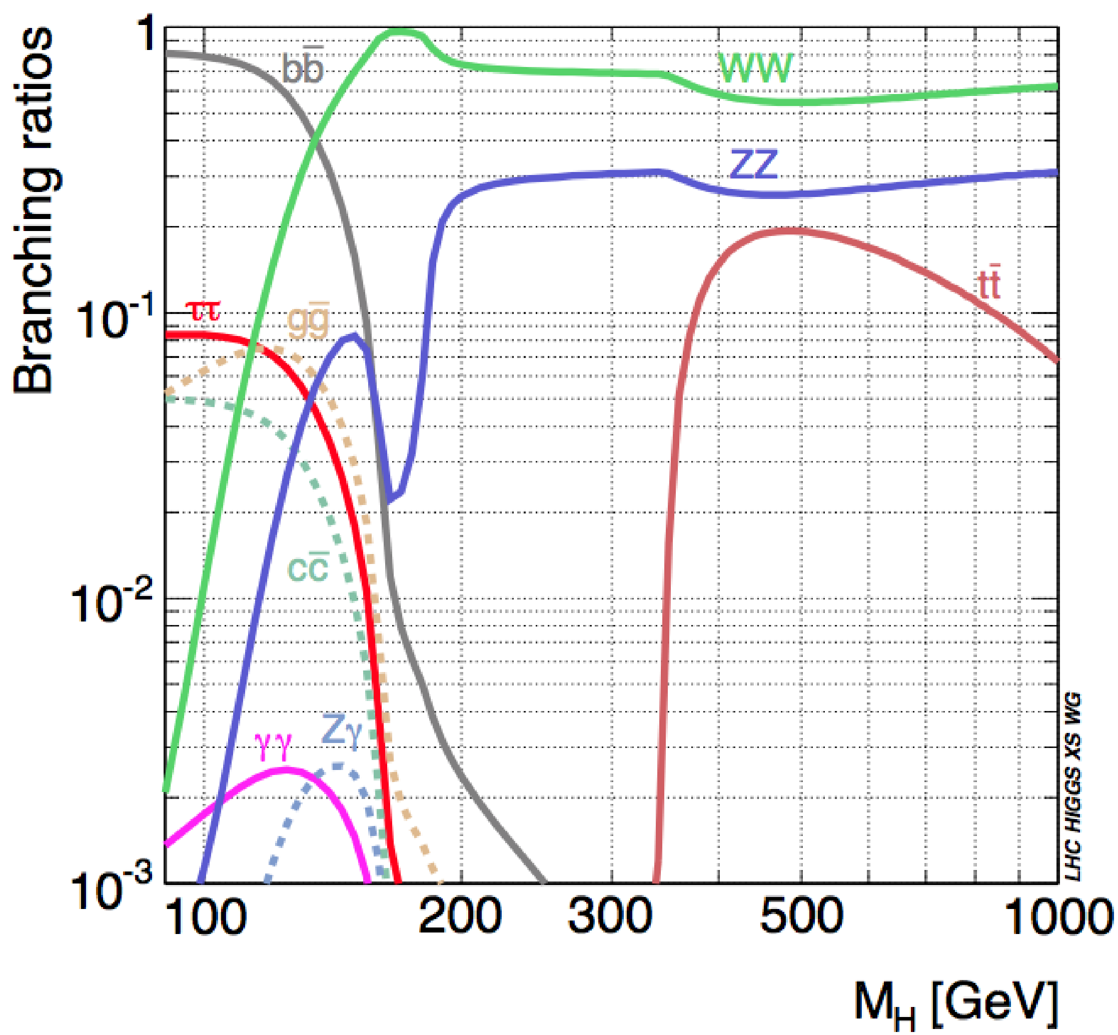
$$g_{hVV} = 2m_V^2/v \qquad g_{hhVV} = 2m_V^2/v^2$$

- Higgs coupling enhanced for heavier particles
- Vector bosons always preferred to fermions
  - But must be kinematically allowed
- Fixing mass of Higgs fixes decay rates for all final states

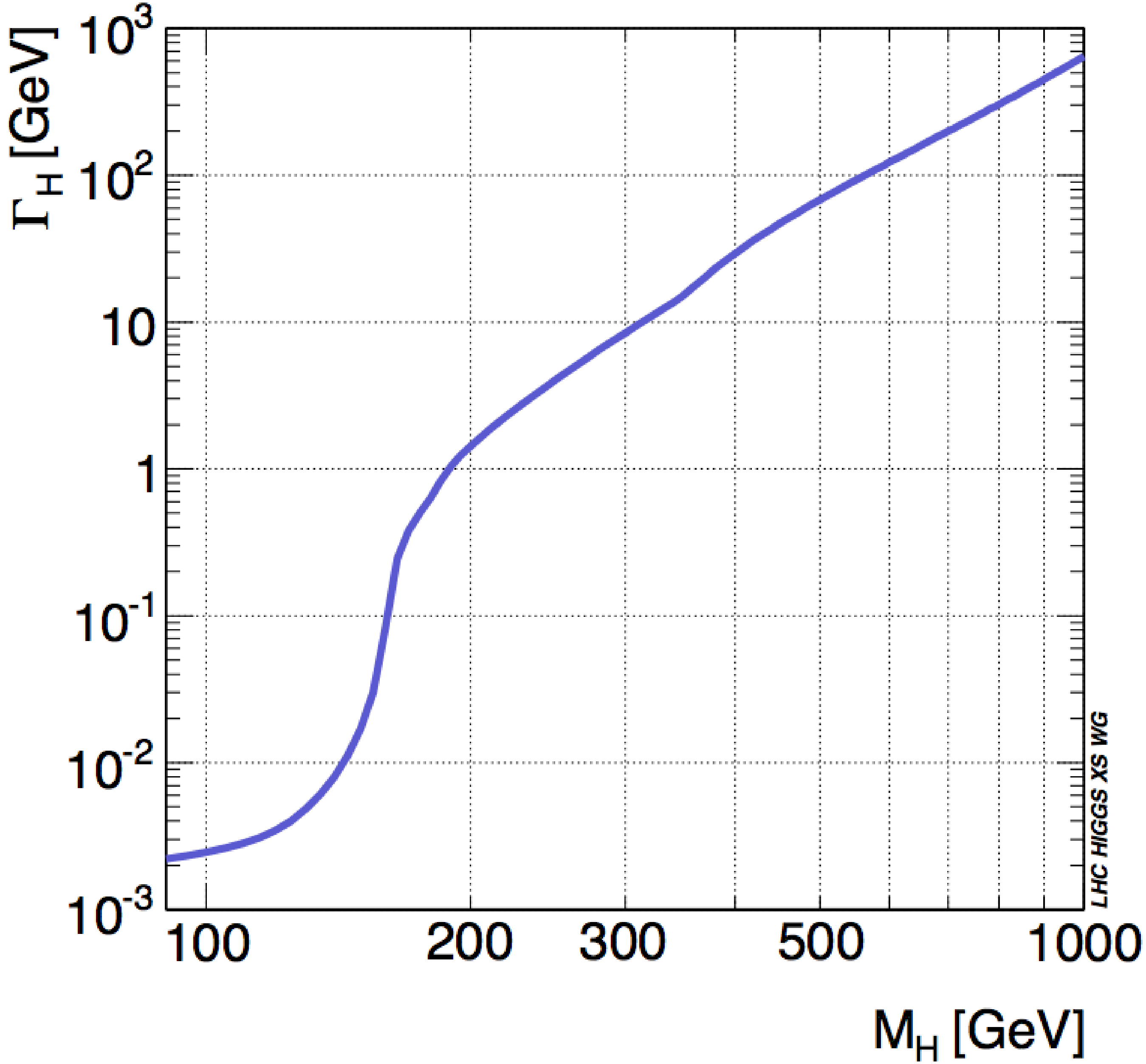
Higgs branching ratios

- Low Mass < 140 GeV
  - $H \to b\bar{b}$ dominant, BR = 60–90%
  - $H \to \tau^+\tau^-, c\bar{c}, gg$ BR= a few %
  - $H \to \gamma\gamma, \gamma Z$, BR = a few permille

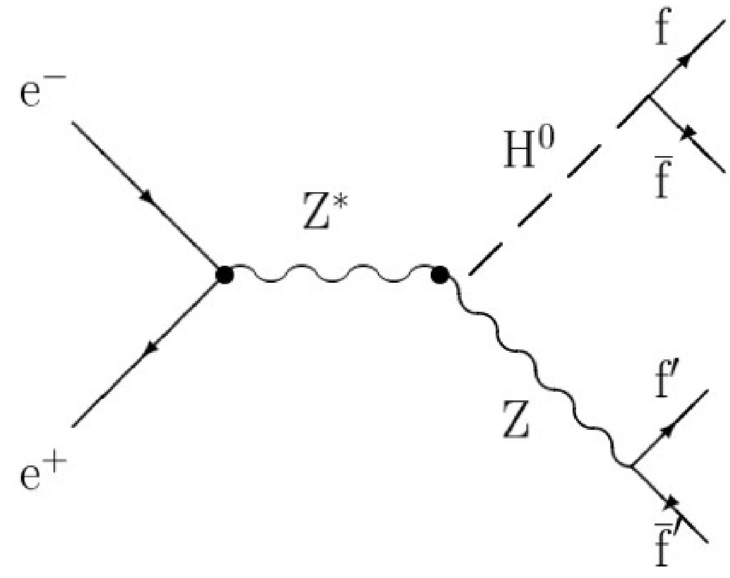
- High Mass > 140 GeV
  - $H \to WW^*, ZZ^*$ up to $\gtrsim 2M_W$
  - $H \to WW, ZZ$ above (BR $\to \frac{2}{3}, \frac{1}{3}$)
  - $H \to t\bar{t}$ for high M_H; BR $\lesssim 20\%$.



Higgs width


Γ_H [GeV]
10^3
10^2
10
1
10^{-1}
10^{-2}
10^{-3}
100
200
300
500
1000
M_H [GeV]
LHC HIGGS XS WG

Higgs production at LEP



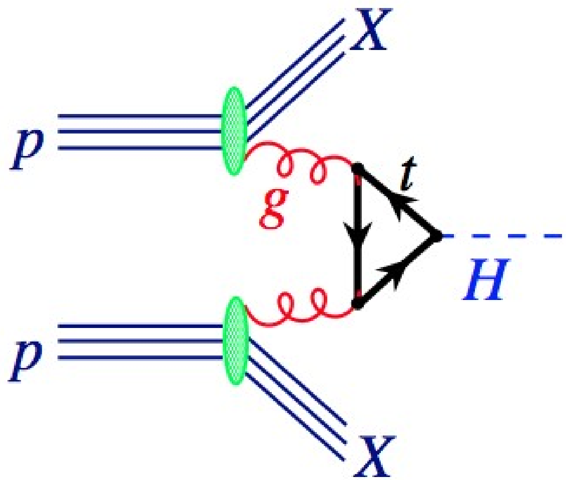
$H^0 \to b\bar{b}$ dominant (BR $\approx 84\%$)

$H^0(\to b\bar{b})Z(\to q\bar{q}) \sim 60\%$

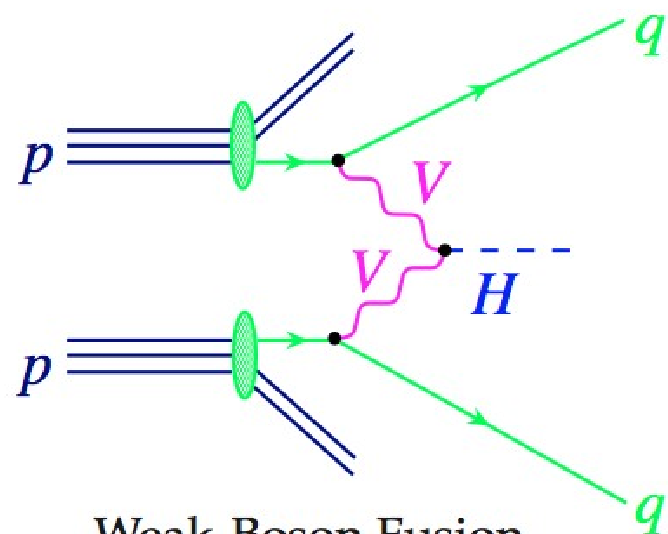
$H^0(\to b\bar{b})Z(\to \nu\bar{\nu}) \sim 17\%$

$H^0(\to b\bar{b})Z(\to \ell^+\ell^-)$ and $H^0(\to \tau^+\tau^-)Z(\to q\bar{q}) \sim 14\%$

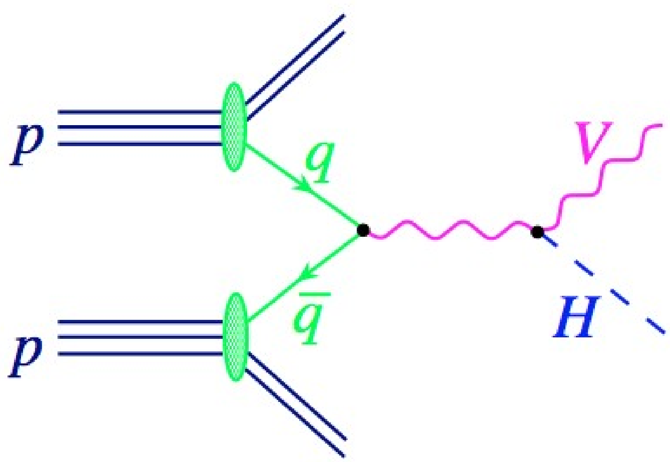
Higgs production at hadron colliders



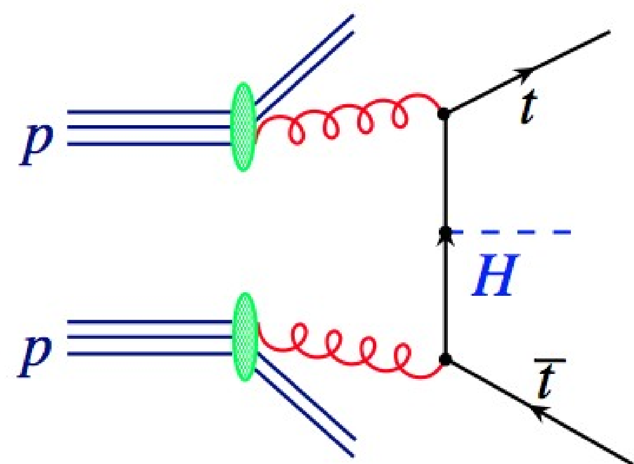
Gluon fusion



Weak-Boson Fusion

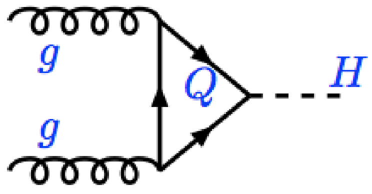


Higgs Strahlung



$t\bar{t}H$

gluon-gluon fusion



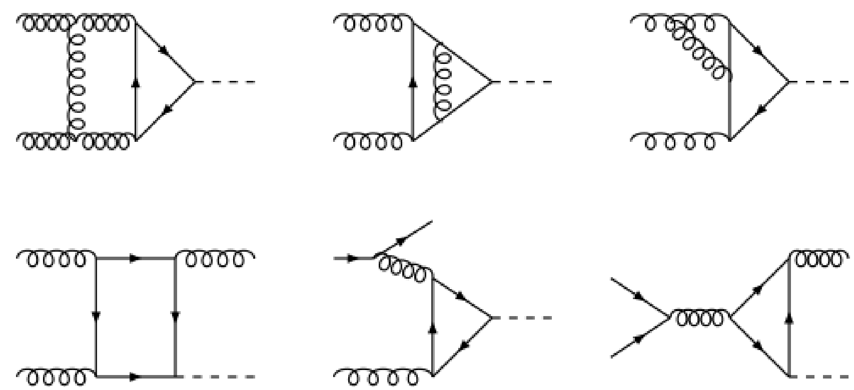
$$\hat{\sigma}_{LO}(gg \to H) = \frac{\pi^2}{8M_H}\Gamma_{LO}(H \to gg)\,\delta(\hat{s} - M_H^2)$$

$$\Gamma_{LO} = \frac{G_\mu \alpha_s^2(\mu_R^2)}{288\sqrt{2}\pi}\left|\frac{3}{4}\sum_q A_{1/2}^H(\tau_Q)\right|^2$$

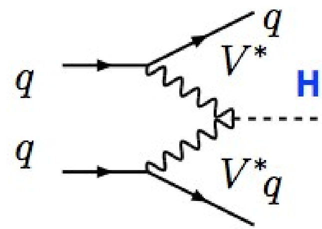
$$A_{1/2}^H(\tau) = 2[\tau + (\tau - 1)f(\tau)]\,\tau^{-2}$$

$$f(\tau) = \arcsin^2\sqrt{\tau} \text{ for } \tau = M_H^2/4m_Q^2 \leq 1$$

- Leading production mechanism at LHC
  - Recall: parton luminosity highest for gluons
- In Standard Model only top quark matters
  - b quark contribution ~5%
  - In models beyond SM other particles could enter the loop
    - modification to expected cross section
- Cross section known with uncertainty at the level of 5%
  - many additional radiative terms included



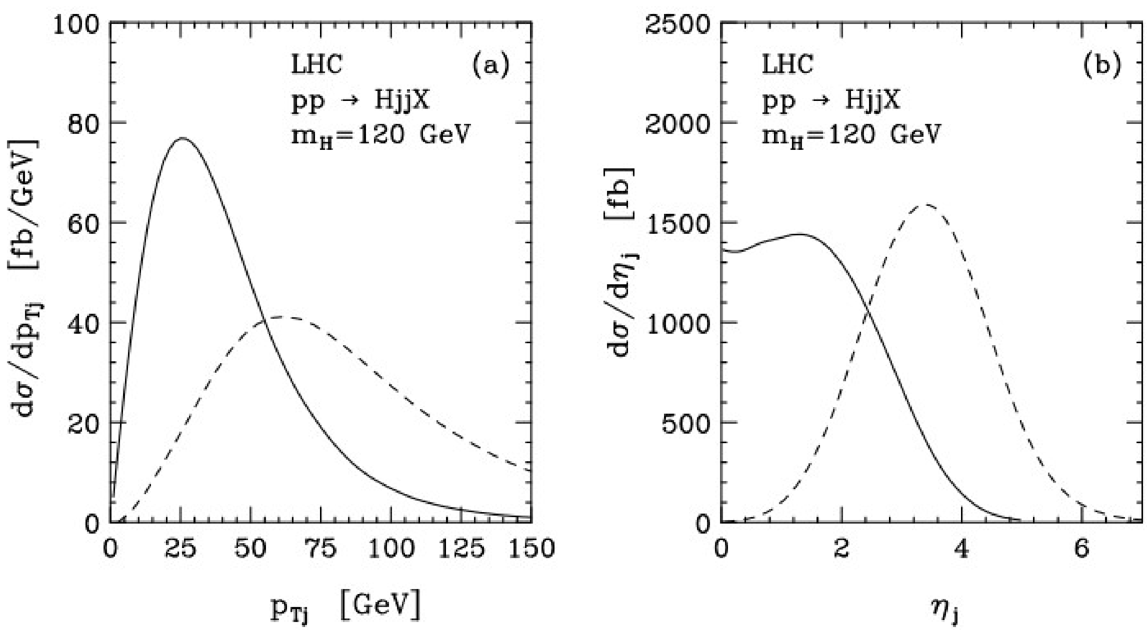
Vector Boson fusion



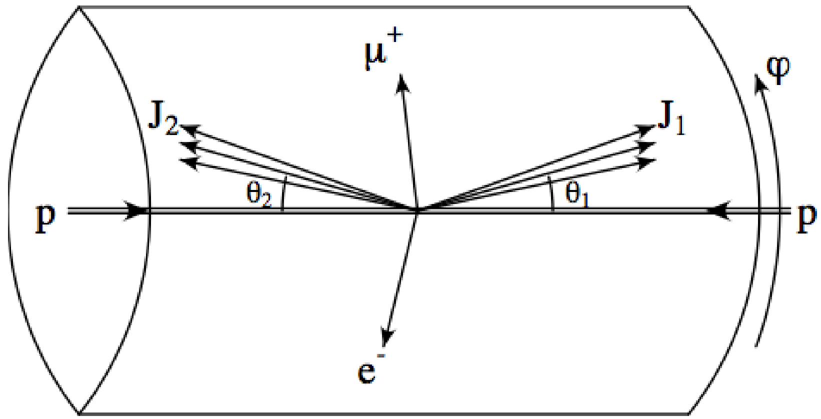
$$\hat{\sigma}_{\rm LO} = \frac{16\pi^2}{M_H^3}\Gamma(H \to V_L V_L)\frac{d\mathcal{L}}{d\tau}\Big|_{V_L V_L/qq}$$

$$\frac{d\mathcal{L}}{d\tau}\Big|_{V_L V_L/qq} \sim \frac{\alpha}{4\pi^3}(v_q^2 + a_q^2)^2 \log\left(\frac{\hat{s}}{M_H^2}\right)$$

- Cross section grows with center-of-mass energy
- Process becomes more important at higher energy and for lighter Higgs
- Radiative corrections relatively small at 10% level
- Distinctive kinematic signature: forward jets with high transverse momentum

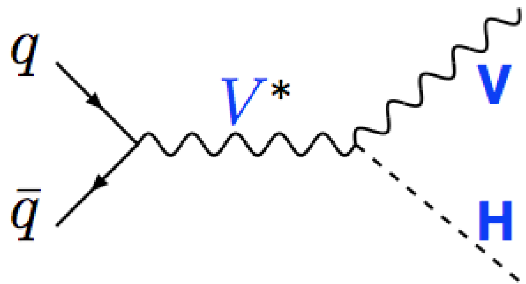


Vector Boson fusion : kinematics



- Energetic jets in forward and backward regions ($p_T > 20$ GeV)
  - tagging jets
- Large rapidity separation between two leading jets which leads to high invariant mass
  - rapidity gap
- Higgs and its decay products typically produce in rapidity gap between jets
  - more isolation for Higgs products except for underlying event
- Little gluon radiation in central rapidity region since W/Z exchange is colorless
  - require no jets in central region between two tagging jets

Higgs-strahlung



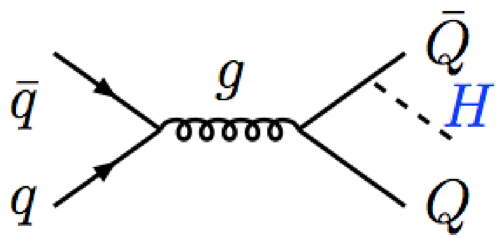
$$\hat{\sigma}_{LO}(q\bar{q} \to VH) = \frac{G_\mu^2 M_V^4}{288\pi\hat{s}} \times (\hat{v}_q^2 + \hat{a}_q^2)\lambda^{1/2}\frac{\lambda + 12M_V^2/\hat{s}}{(1 - M_V^2/\hat{s})^2}$$

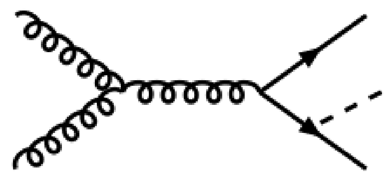
Cross section $\propto \hat{s}^{-1}$ sizable only for low $M_H \lesssim 200$ GeV values.

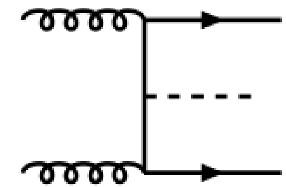
Cross section for $W^{\pm}H$ approximately 2 times larger than ZH.

- Minor role at LHC because of parton luminosity
  - anti-quark from sea
- Cross section favored mostly in low mass region where WW and ZZ final states are still small
- Important production mechanism at Tevatron
  - valence anti-quarks in anti-proton

Associated production







- Higgs production associated with pair of fermions in final state
  - useful experimental signature to recognize (tag) events
- top dominates because of its much larger coupling to Higgs
  - b quark also contributes
- different diagrams imply different kinematics
  - recall:VBF very different from gluon-gluon fusion
- top decays require dedicated or at least b- tagging
- Non-leptonic Higgs decays rather challenging when combined with two top quarks

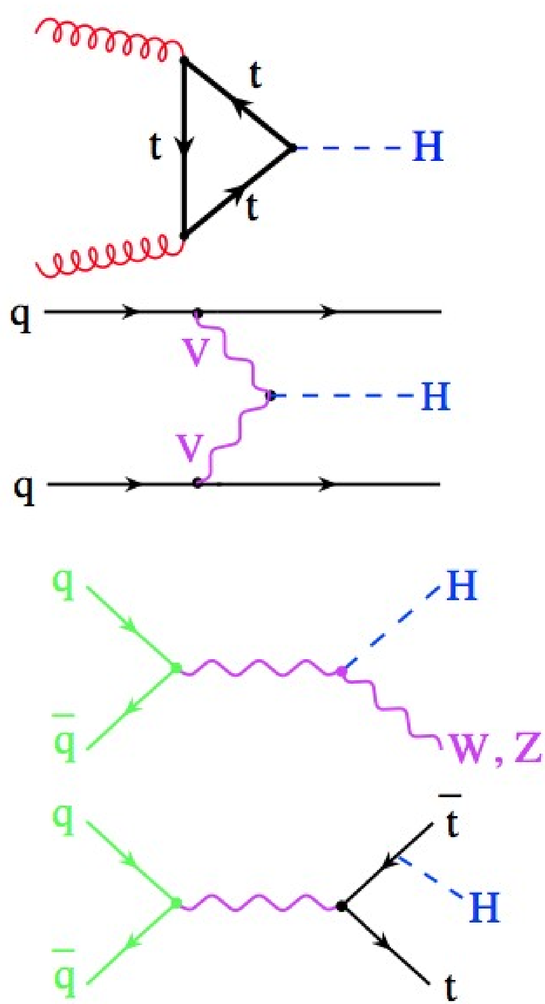
Comparison between the processes

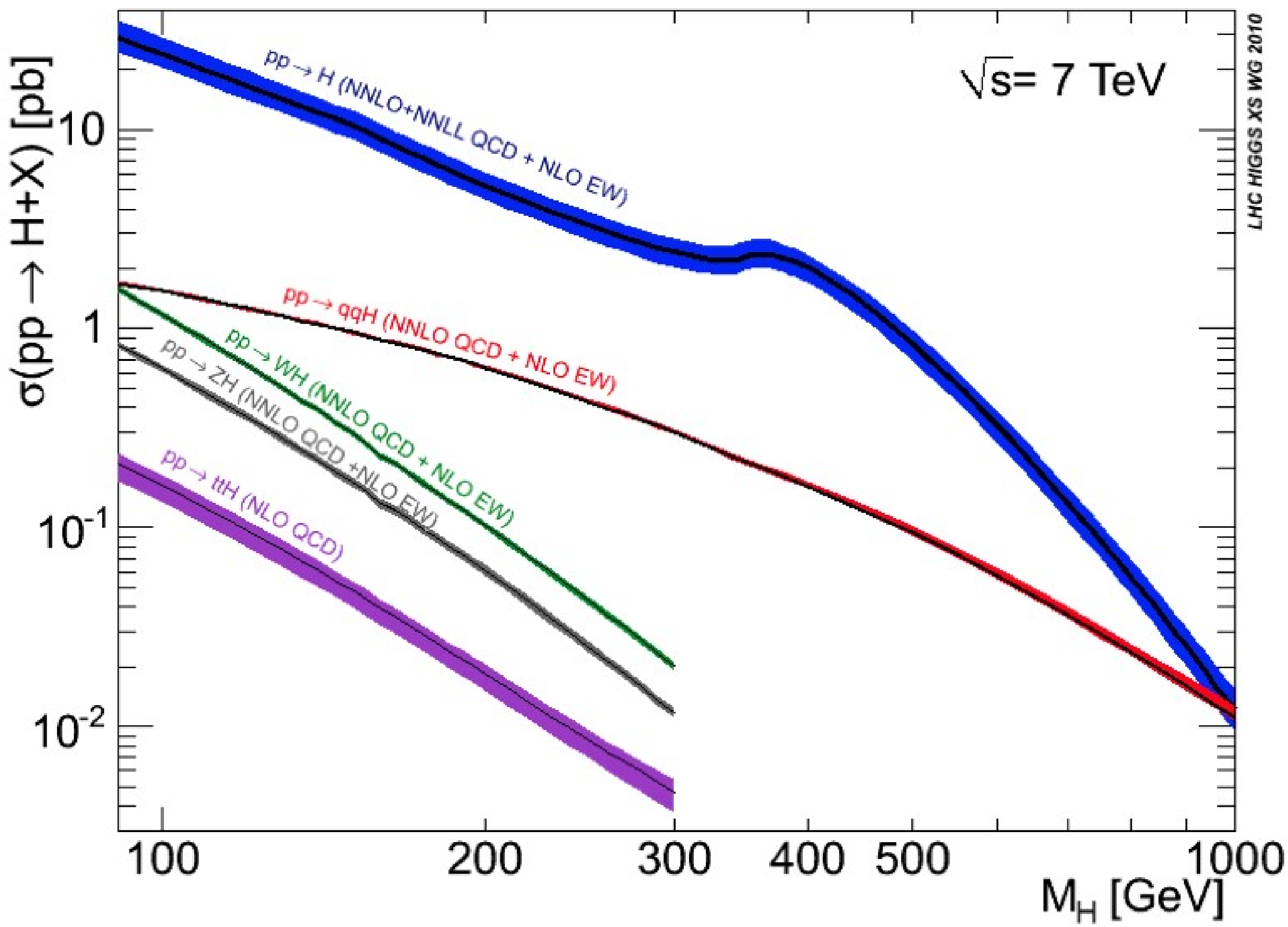
- gluon-gluon fusion relevant for any Higgs mass and hence relevant for all decay channels

- Vector boson fusion most important for mid-high Higgs mass
  - distinctive kinematic signature with accompanying forward-backward jets
  - beneficial for WW final state that suffers from more background because of missing particles in final state

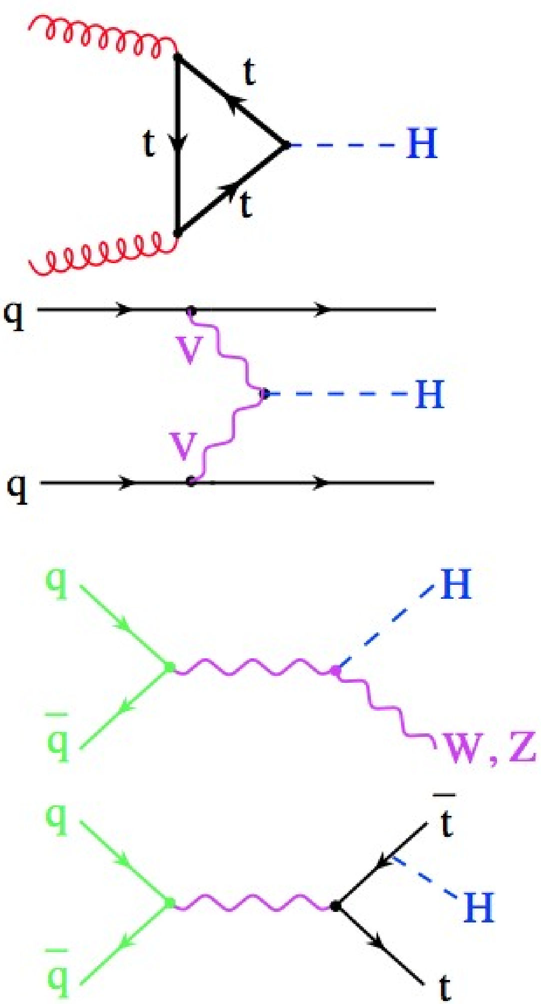
- Higgs-strahlung most important for low mass region

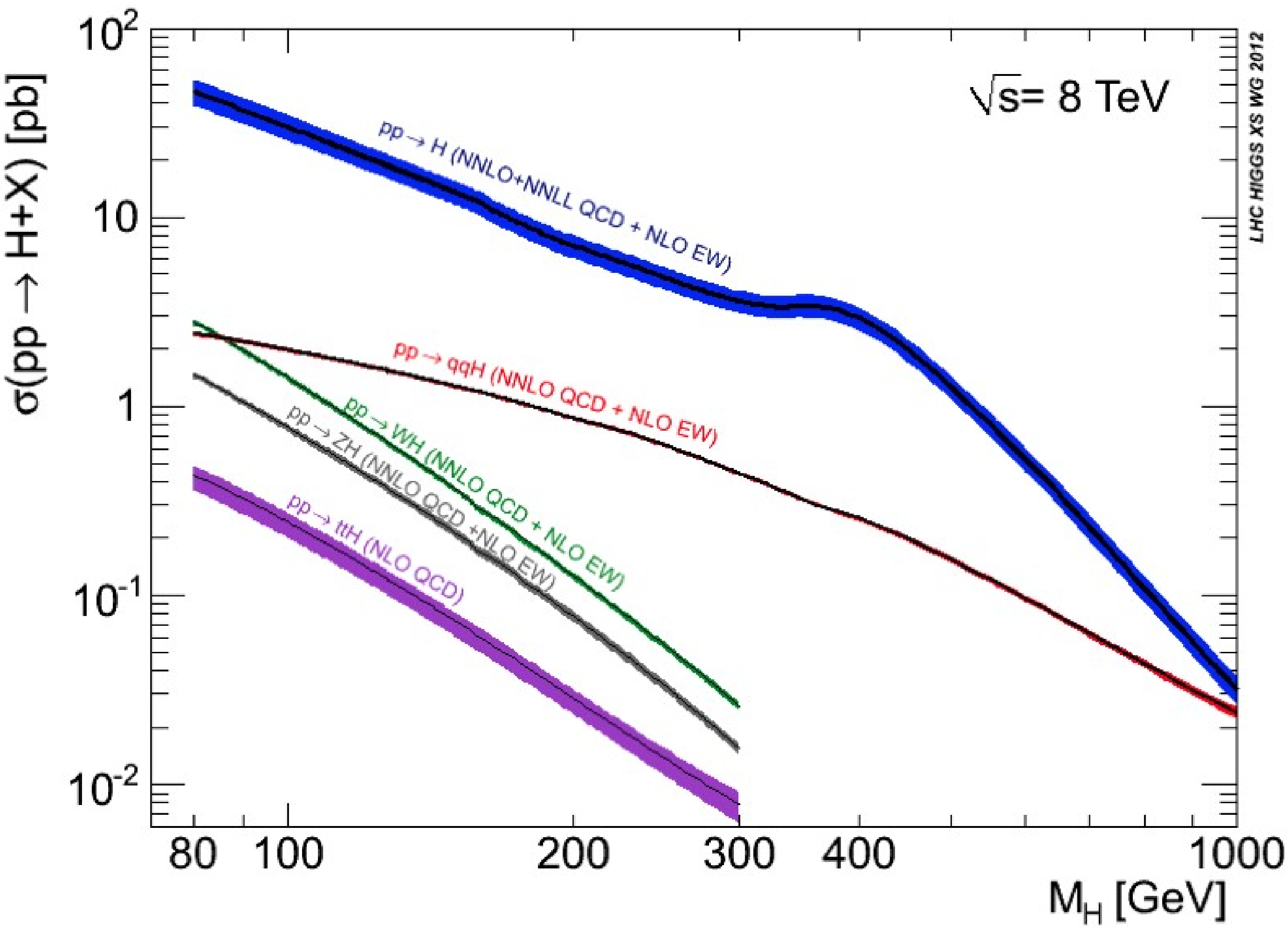
Higgs production cross section @ 7 TeV



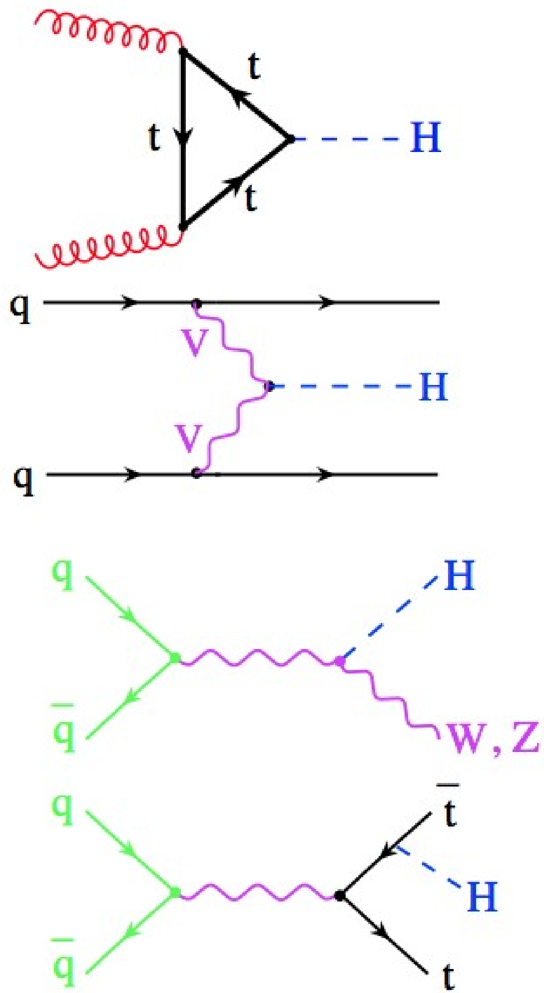


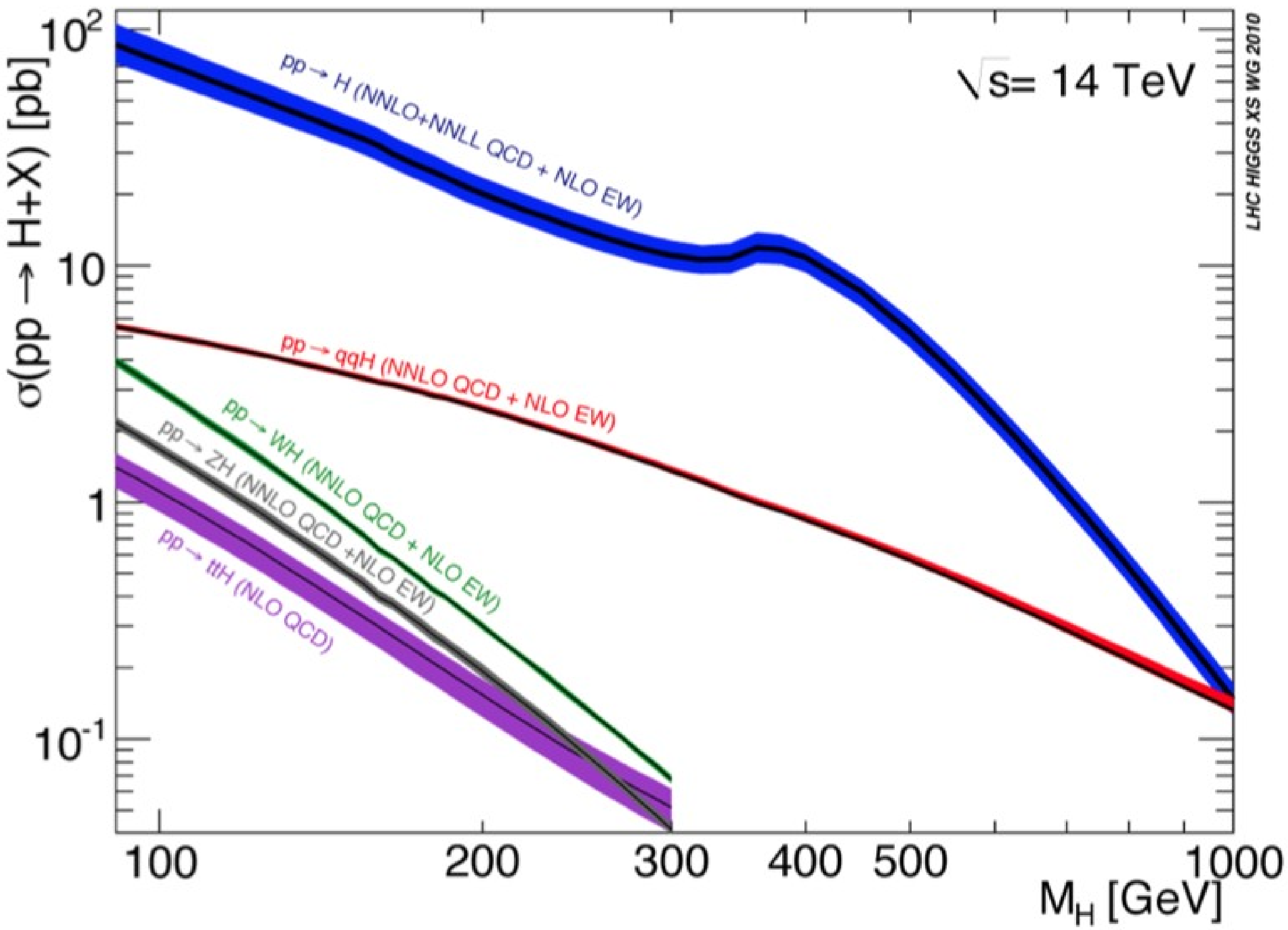
Higgs production cross section @ 8 TeV

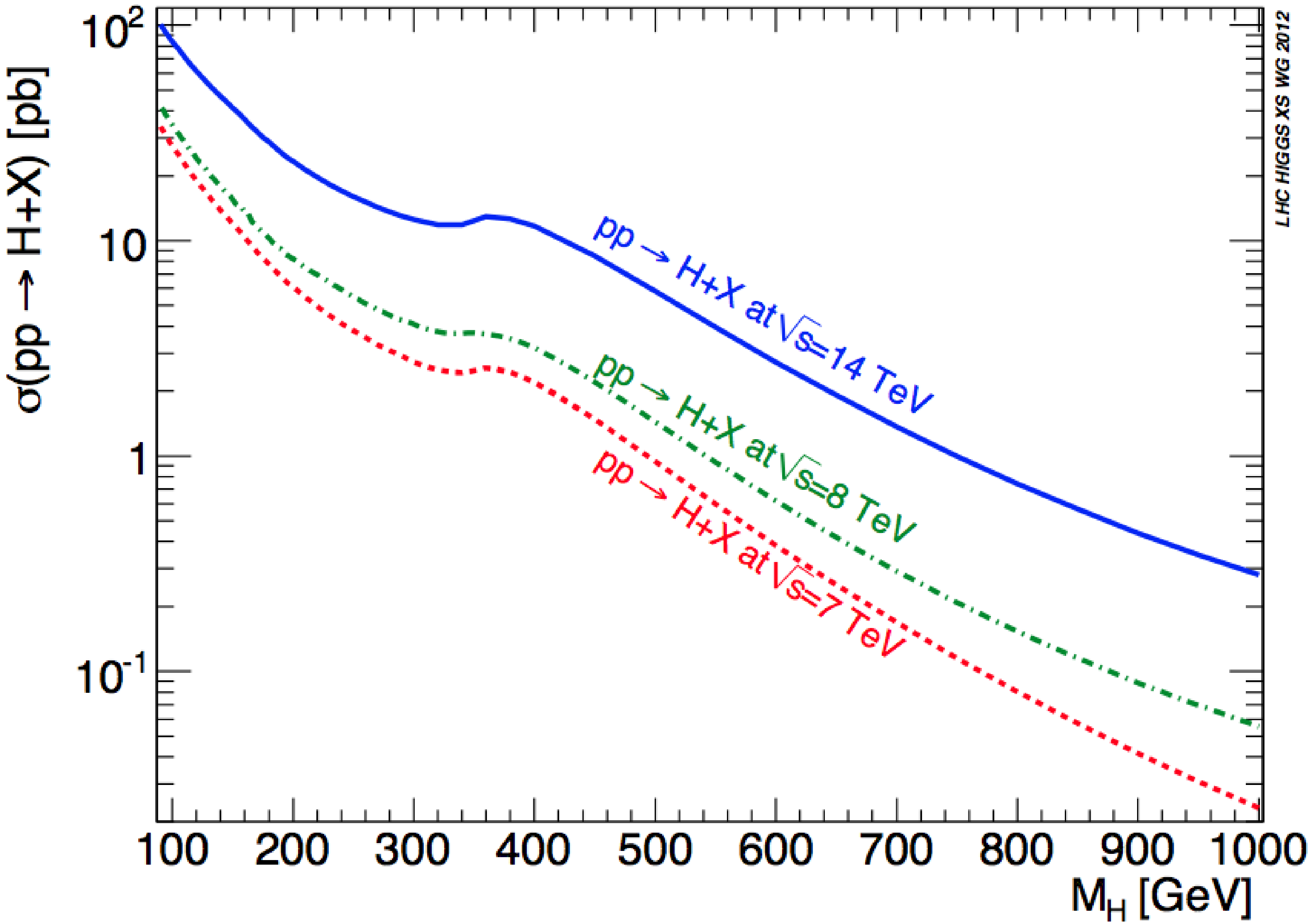




Higgs production cross section @ 14 TeV

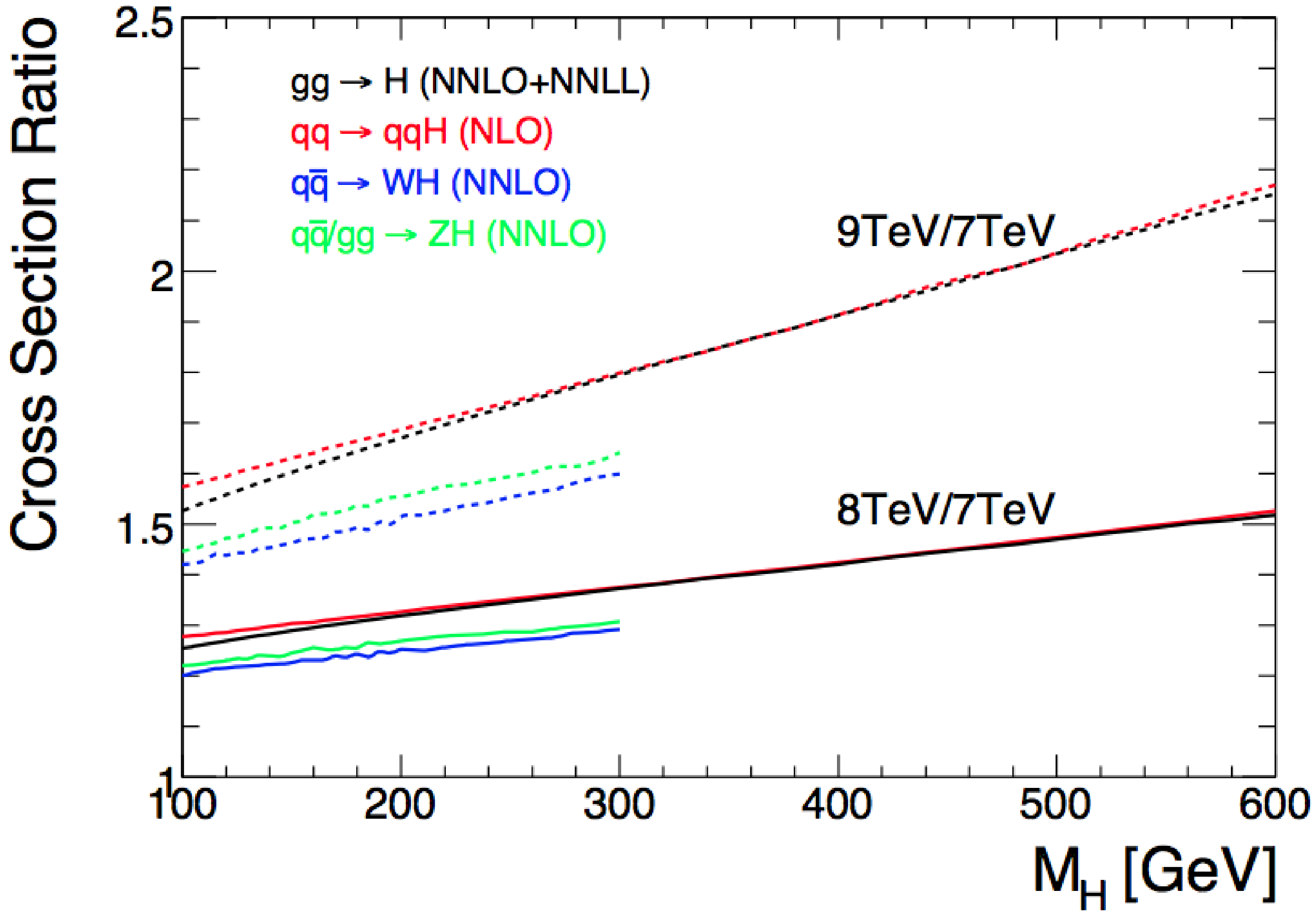






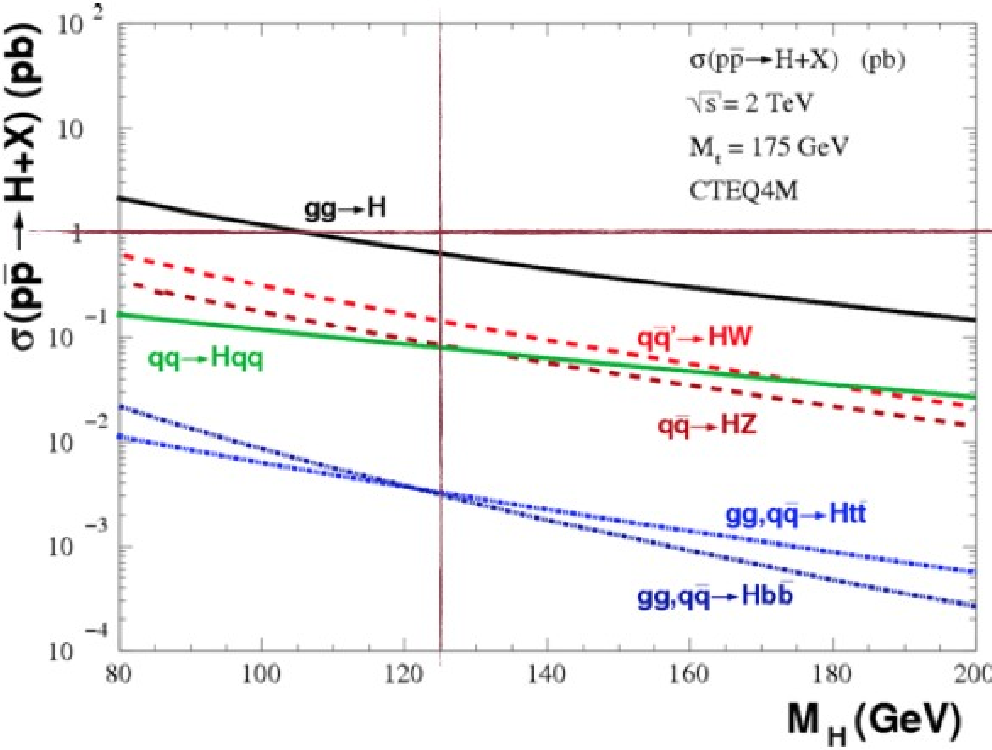
10^2
10
1
10^{-1}
σ(pp → H+X) [pb]
100
200
300
400
500
600
700
800
900
1000
M_H [GeV]
pp → H+X at √s=14 TeV
pp → H+X at √s=8 TeV
pp → H+X at √s=7 TeV
LHC HIGGS XS WG 2012

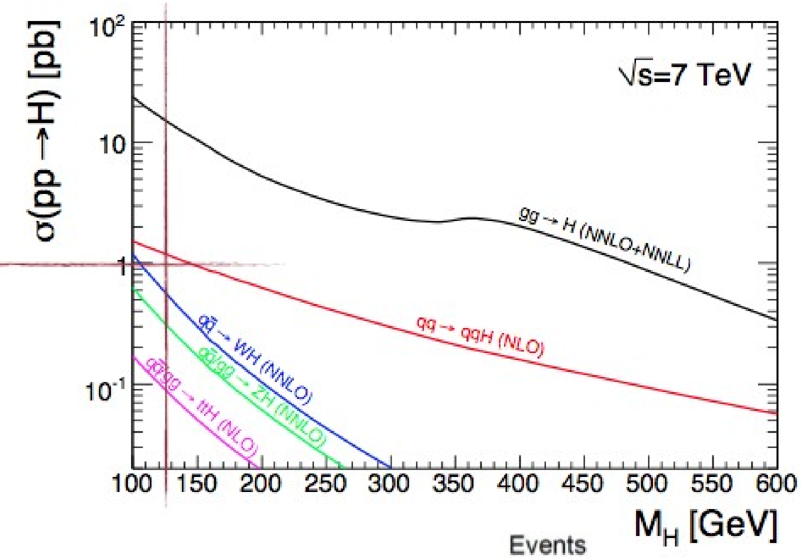
Effect of the increasing of the energy

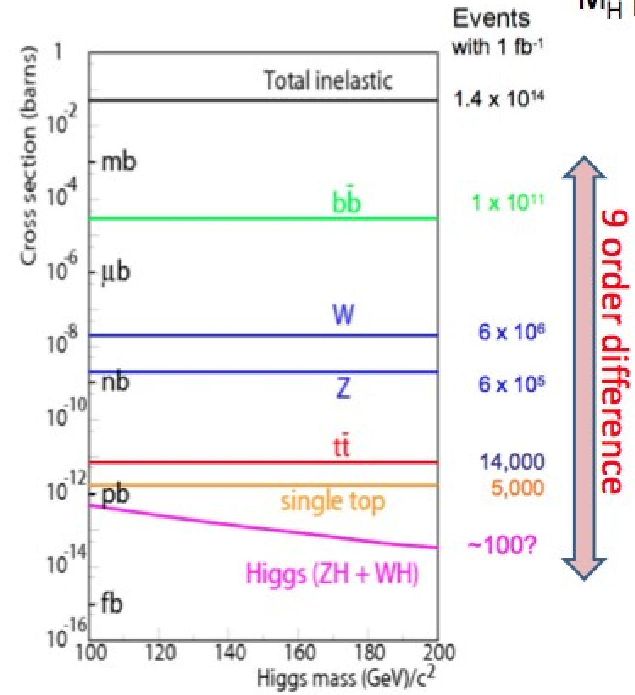


- 25% higher cross section at 8 TeV
  - 25% more data compared to running at 7 TeV
  - or 25% less running time to have same sensitivity

Cross section at TEVATRON

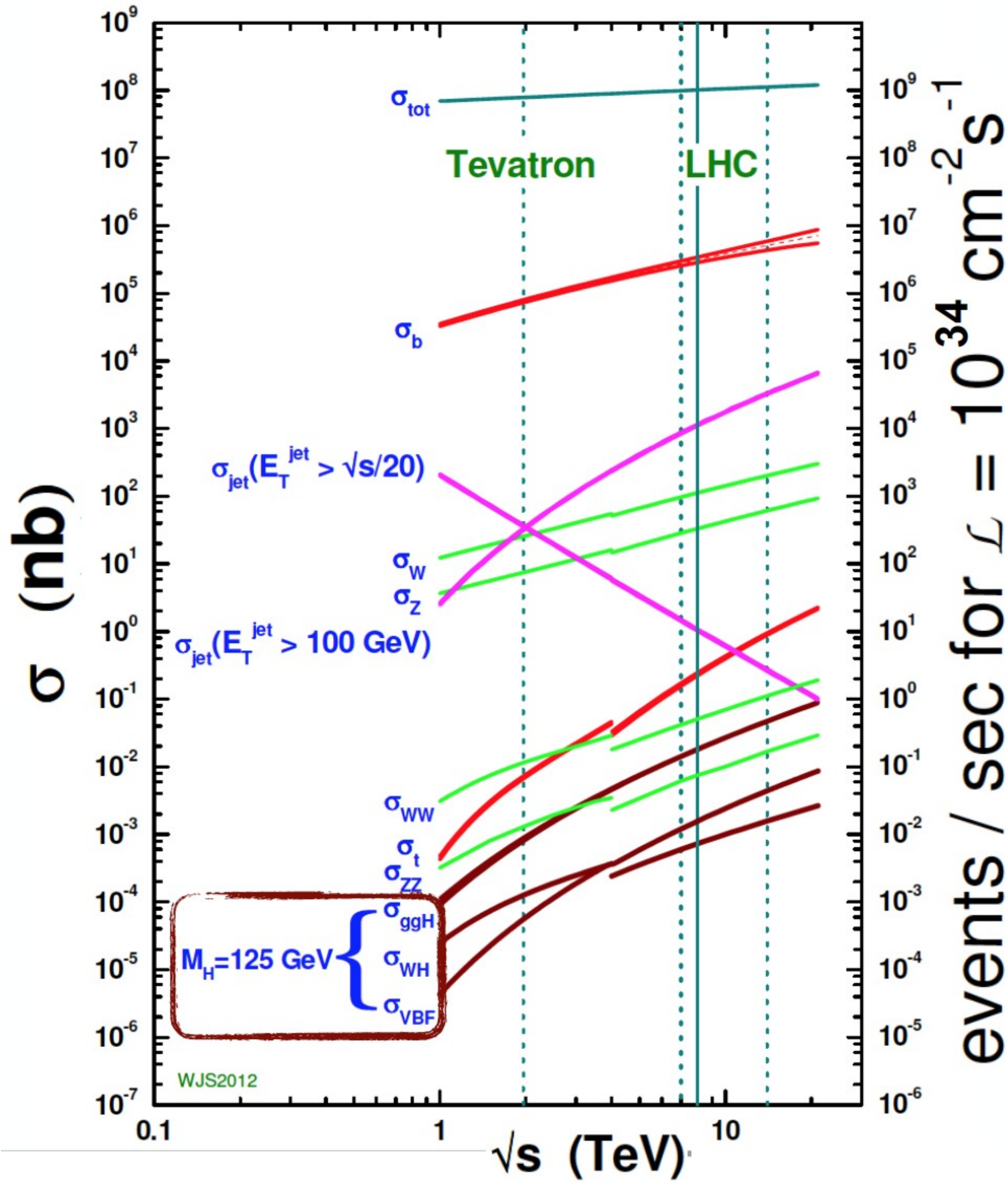






- almost x10 difference between Tevatron and LHC in some mass regions
- In addition signal efficiency and acceptance also different between experiments

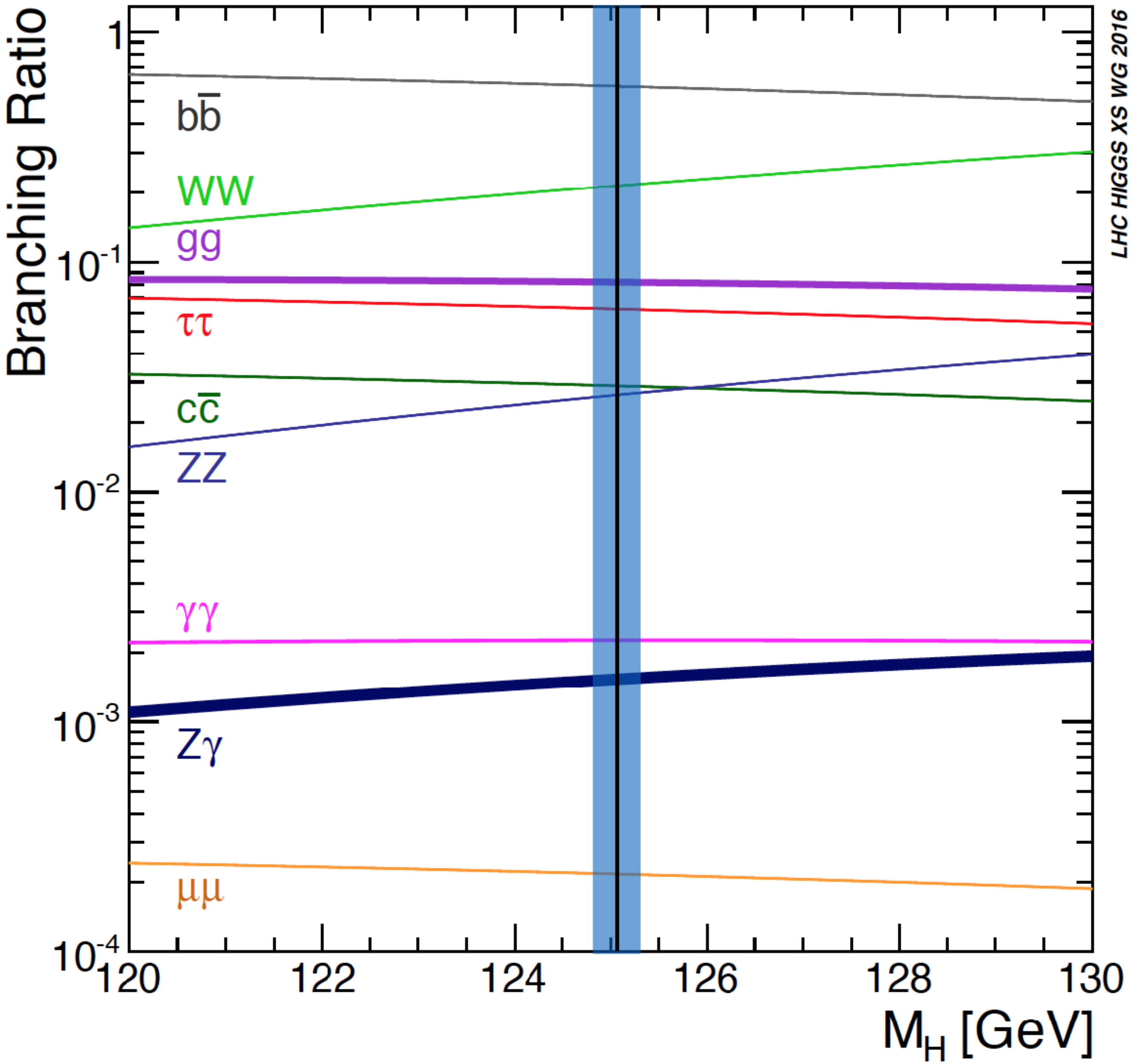
Higgs Boson Production: a Rare Process



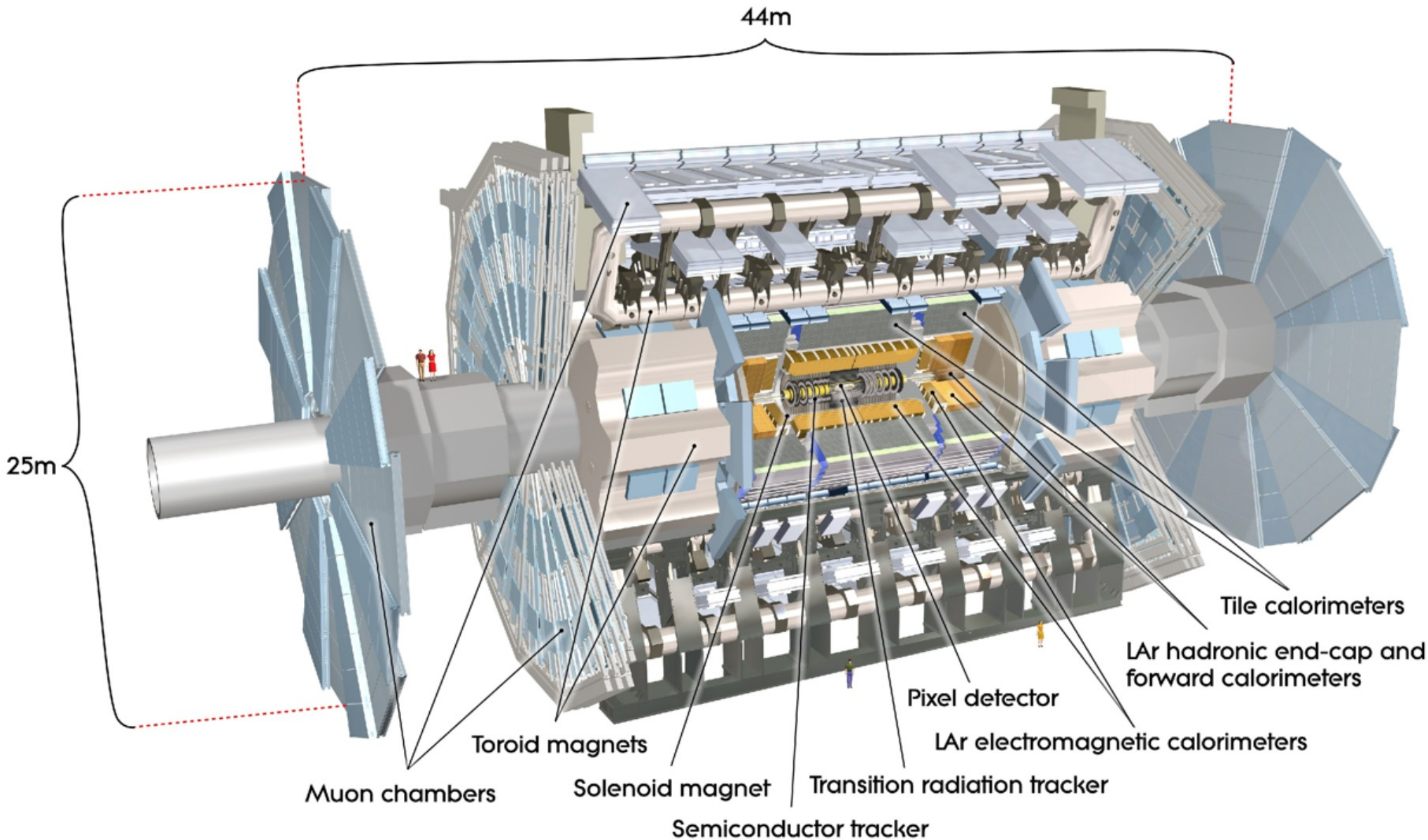
Proton-(anti)proton cross sections

A Higgs boson is produced in only 1 out of 10^9 events

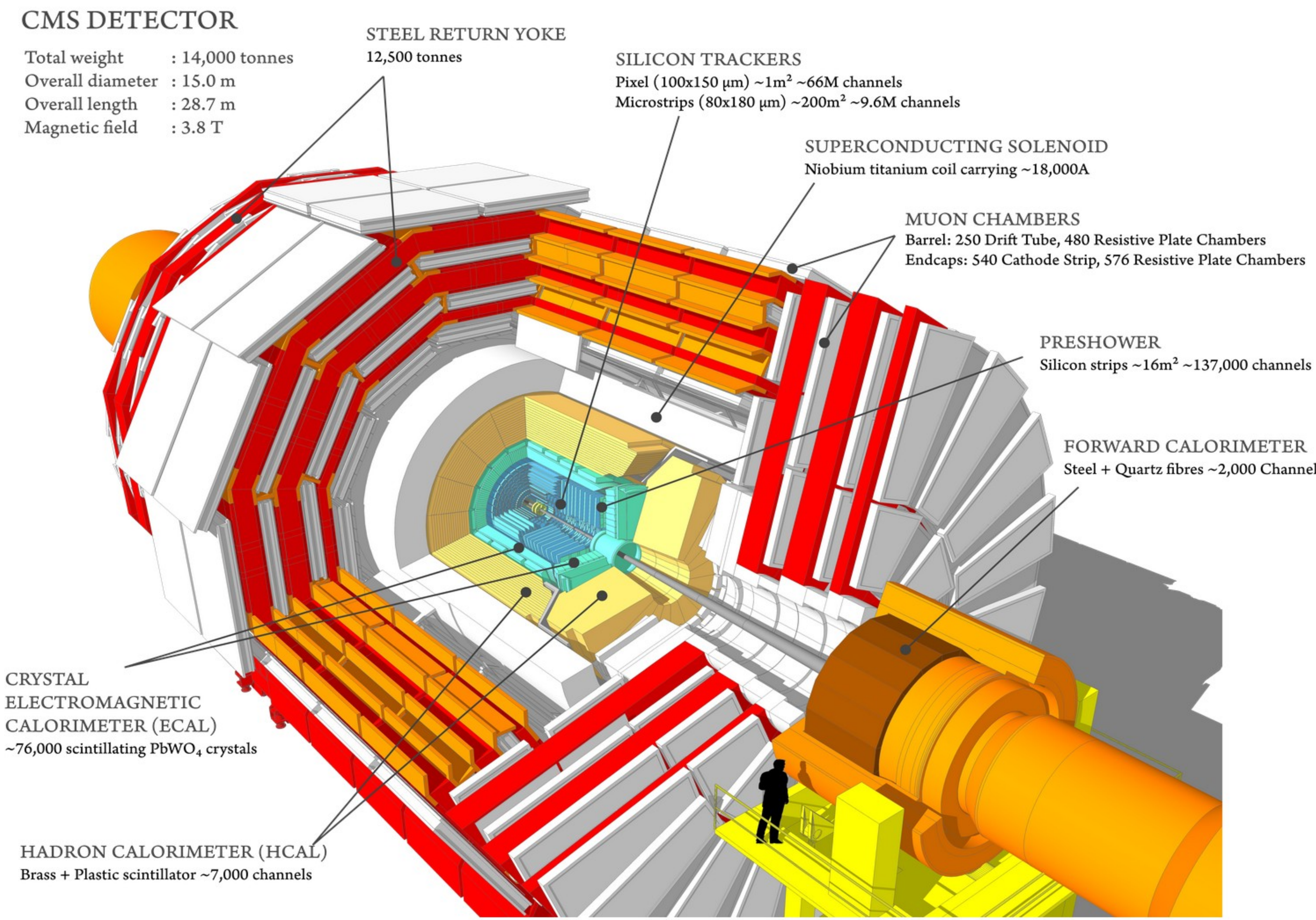
Higgs Boson Decay



The ATLAS detector



The CMS detector

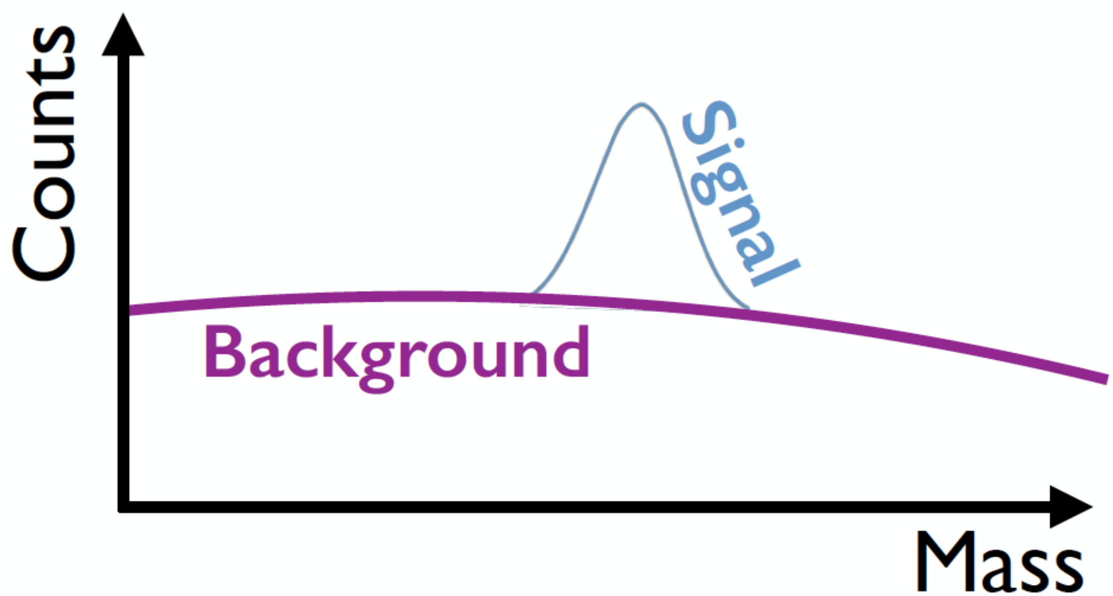


How do we find the Higgs Boson?

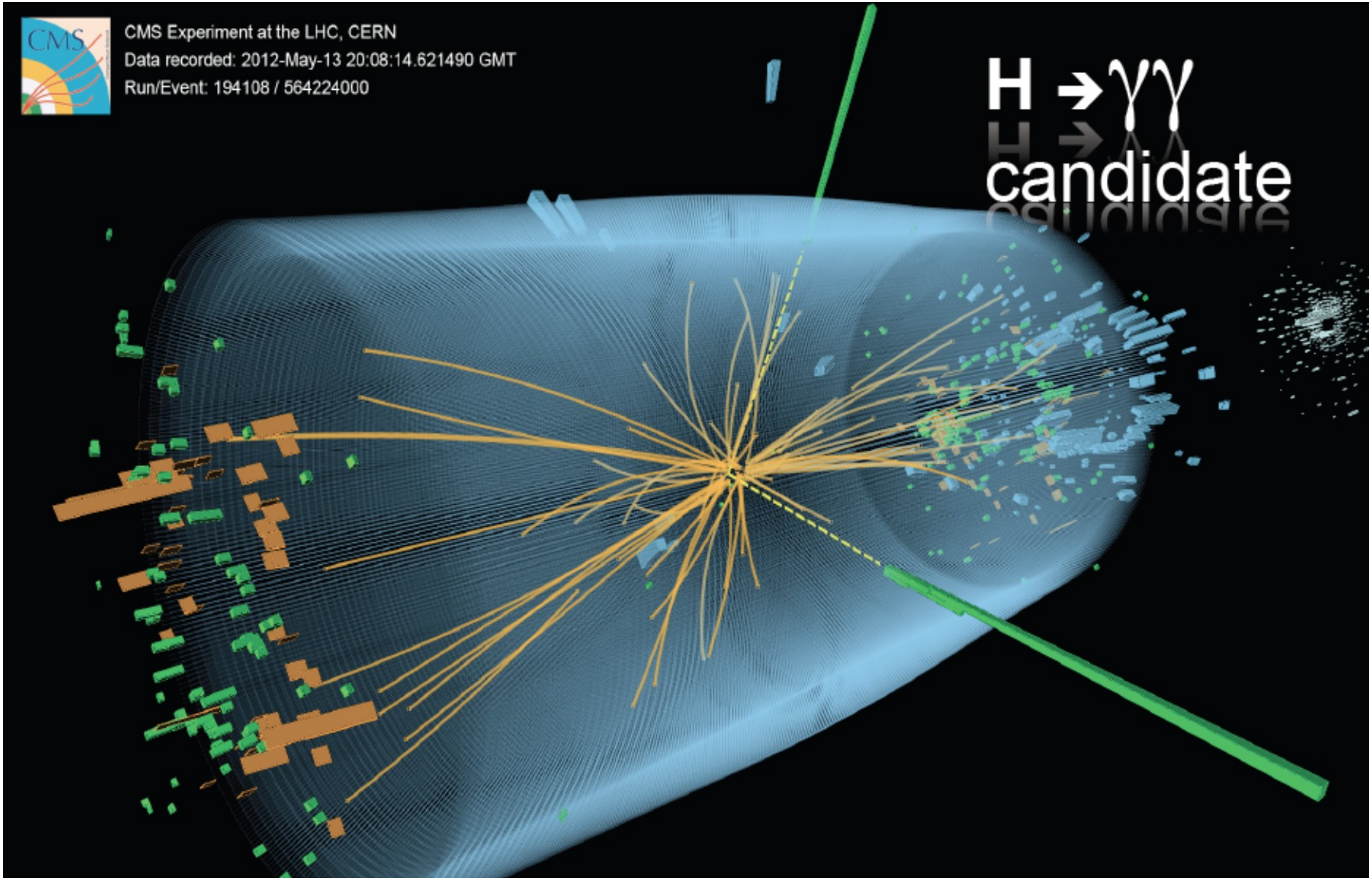
- Search in "clean" signatures: leptons or photons
- Calculate "invariant mass" of decay products

$$m^2 = |\mathbf{p}_1 + \mathbf{p}_2|^2 = (E_1 + E_2)^2 - |\vec{p}_1 + \vec{p}_2|^2$$

- Plot mass of every selected event into histogram and look for signal peak over background

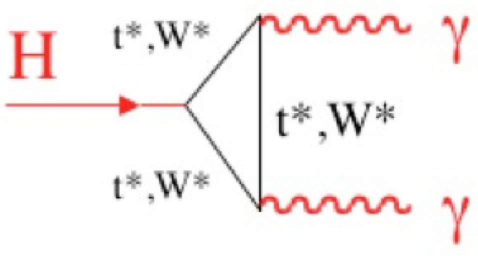


H →γγ

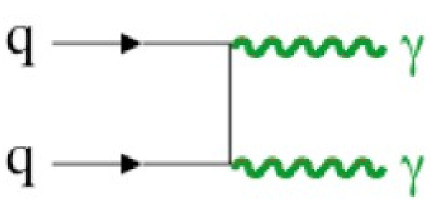

CMS
CMS Experiment at the LHC, CERN
Data recorded: 2012-May-13 20:08:14.621490 GMT
Run/Event: 194108 / 564224000
H →γγ
candidate

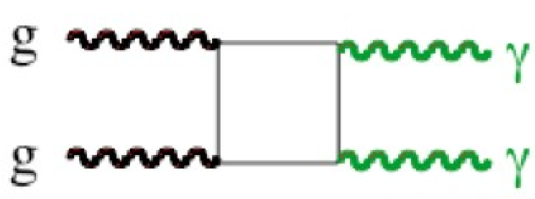
$H \to \gamma\gamma$

- Signal
  - nice mass peak
  - energy and angular resolution are critical ingredients
  - Selection: isolated high p_T photons

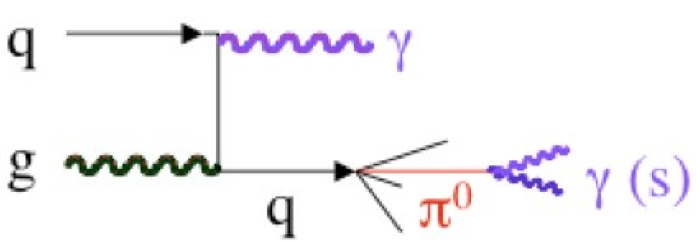


- Irreducible background: direct production of di-photon events in Standard Model
  - Any signal selection selects also these events
  - no peak in invariant mass but lots and lots of then

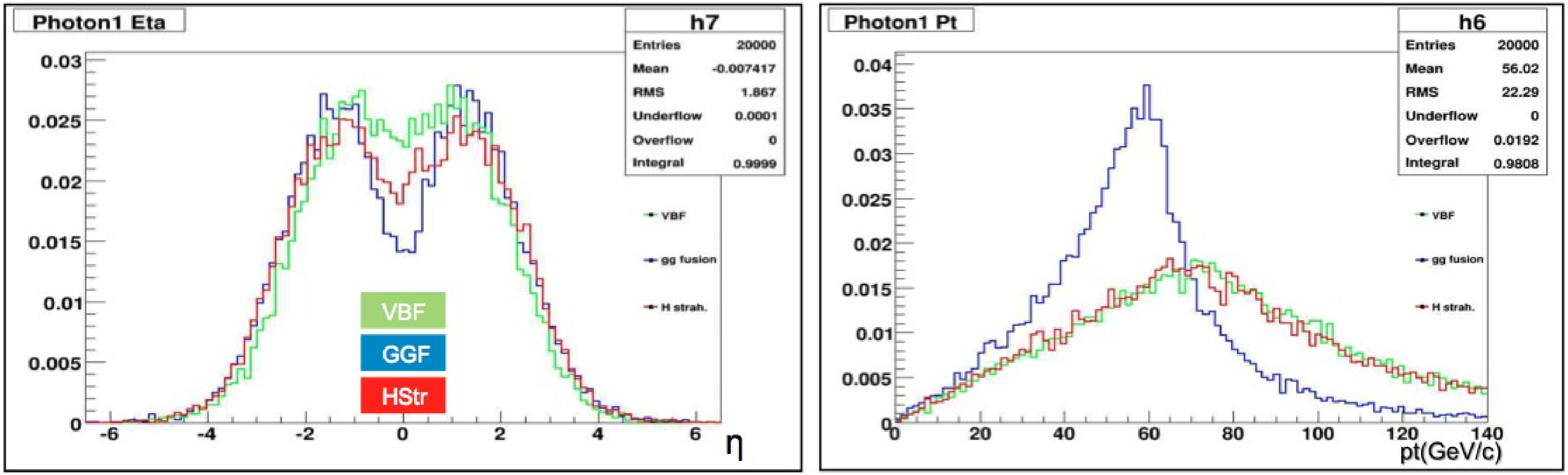




- Reducible background
  - gamma + jet: jet mis-identified as photon
  - di-jet: two jets with misidentified photons

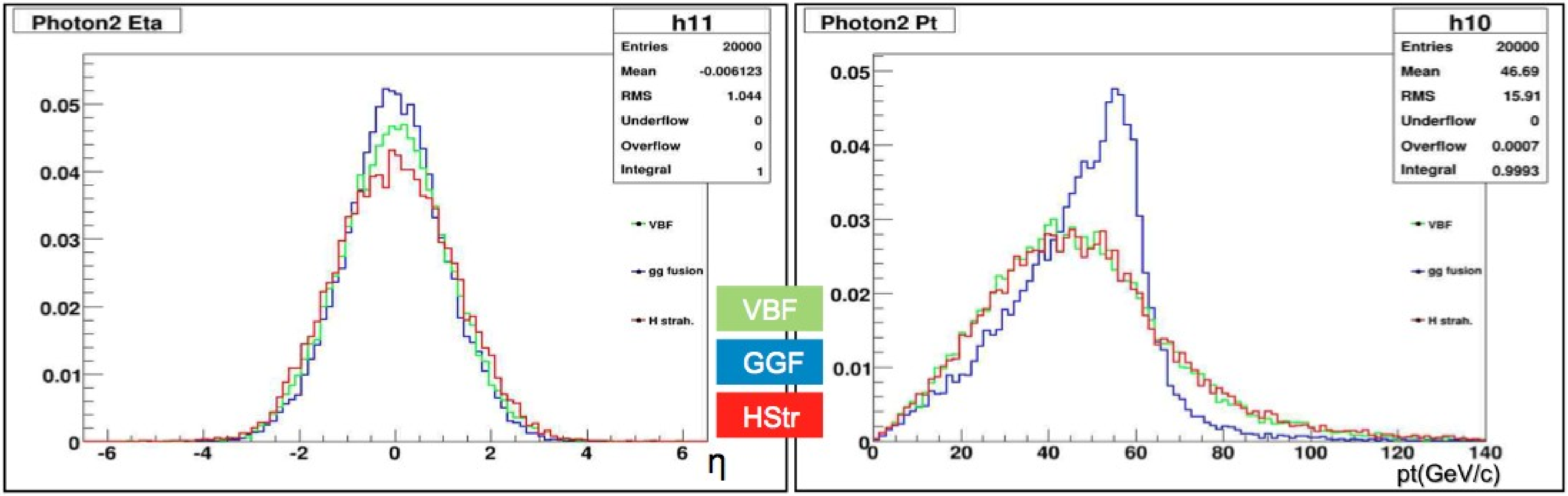


Higgs sons with higher p_T

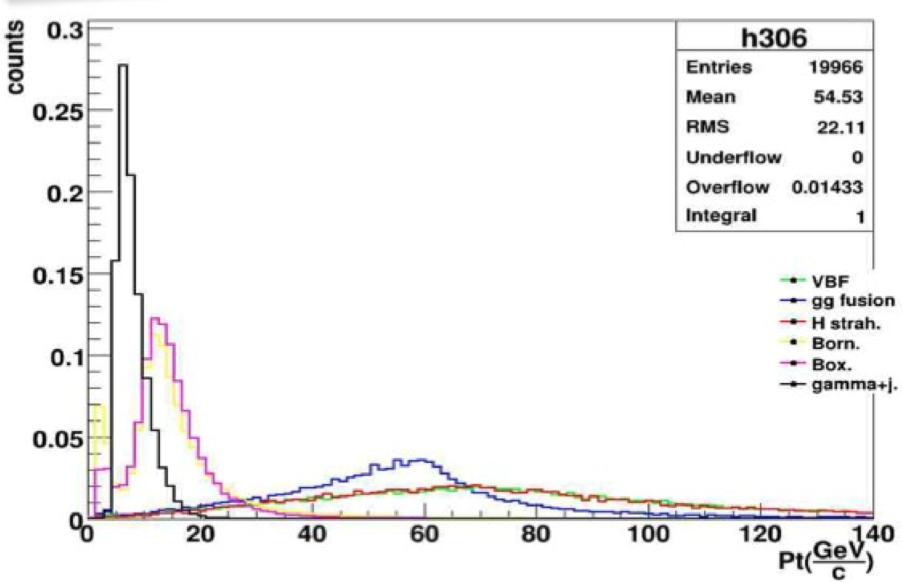


- Higher p_T for VBF and Higgs-strahlung
  - less background from standard model: not many SM particles decaying in high pt photons!
- Unfortunately these are also the modes much smaller than gluon-gluon fusion

Higgs sons with lower p_T

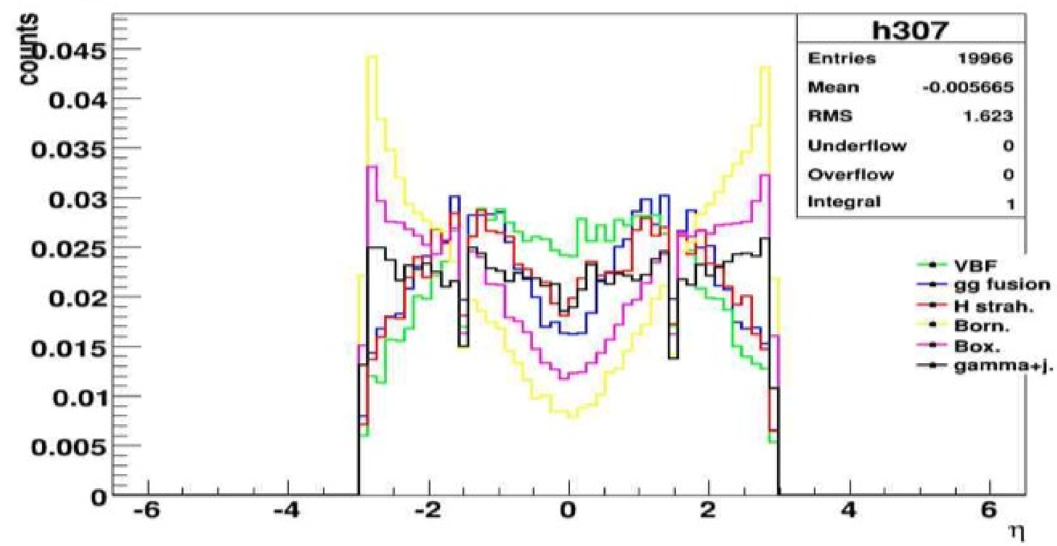


Irriducible background



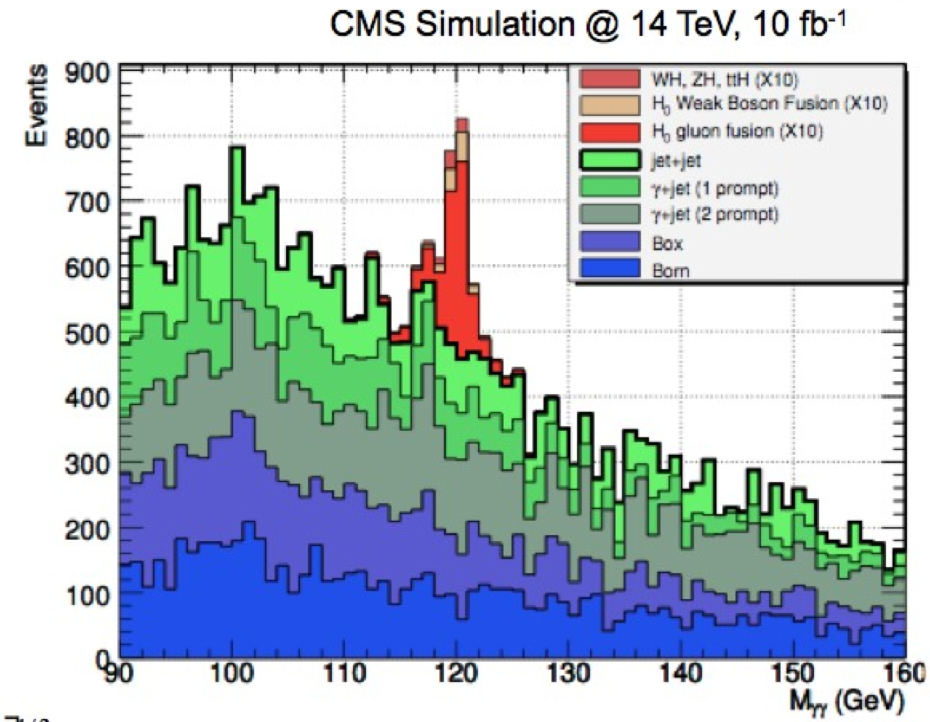
VBF
GGF
HStr
Born
Box
γ+j

- background processes have spectrum more similar to photons from gluon-gluon fusion
  - irreducible background



inclusive H →γγ

- Not very encouraging S/B
  - irreducible background pass all signal criteria
- Optimal and well understood mass resolution essential for observation of this final state
  - S/B drops significantly if resolution worsens



$$m^2_{\gamma\gamma} = 2\,E_1\,E_2\,(1 - \cos\theta_{\gamma\gamma})$$

$$1 - \cos\theta_{\gamma\gamma} = 2\sin^2\theta_{\gamma\gamma}/2$$

$$\frac{\sigma_m}{m} = \frac{1}{2}\left[\left(\frac{\sigma_1}{E_1}\right)^2 + \left(\frac{\sigma_2}{E_2}\right)^2 + \left(\frac{\sigma_\theta}{tg\theta/2}\right)^2\right]^{1/2}$$

- For θ=90° 15 mrad of angular resolution equivalent to 1% of energy resolution!
  - understanding and stability of electromagnetic calorimeter will determine success of discover in this decay mode

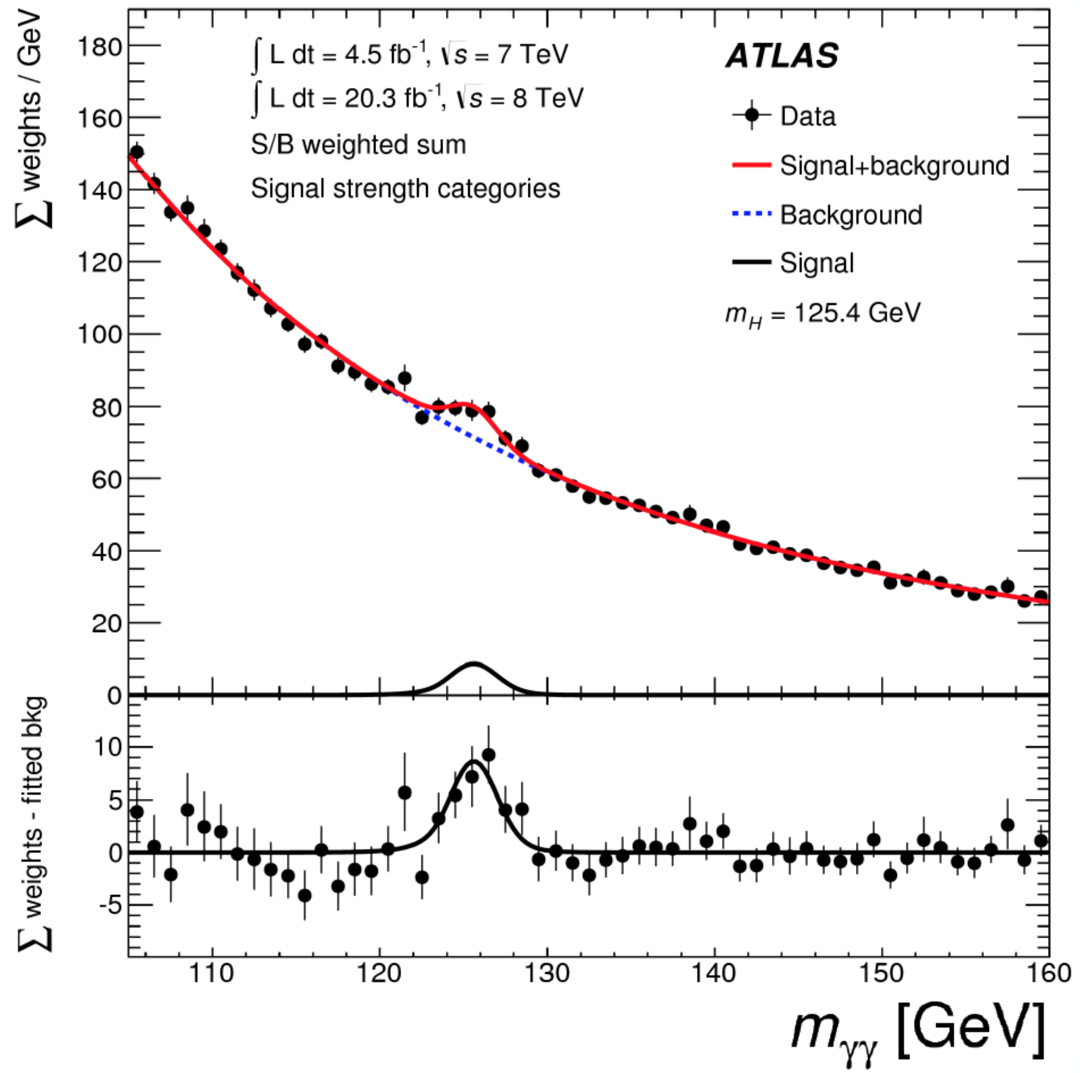
H →γγ

Strategy:

- Select two isolated photons
- Calculate di-photon invariant mass and fit distribution

Complete Run 1 data!

Expect ~1400 Higgs Bosons



Signal strength μ:

$$\mu := \frac{\sigma \cdot \mathcal{B}}{\sigma_{SM} \cdot \mathcal{B}_{SM}} = \frac{\text{observed rate}}{\text{expected rate}}$$

$$= 1.17 \pm 0.27$$

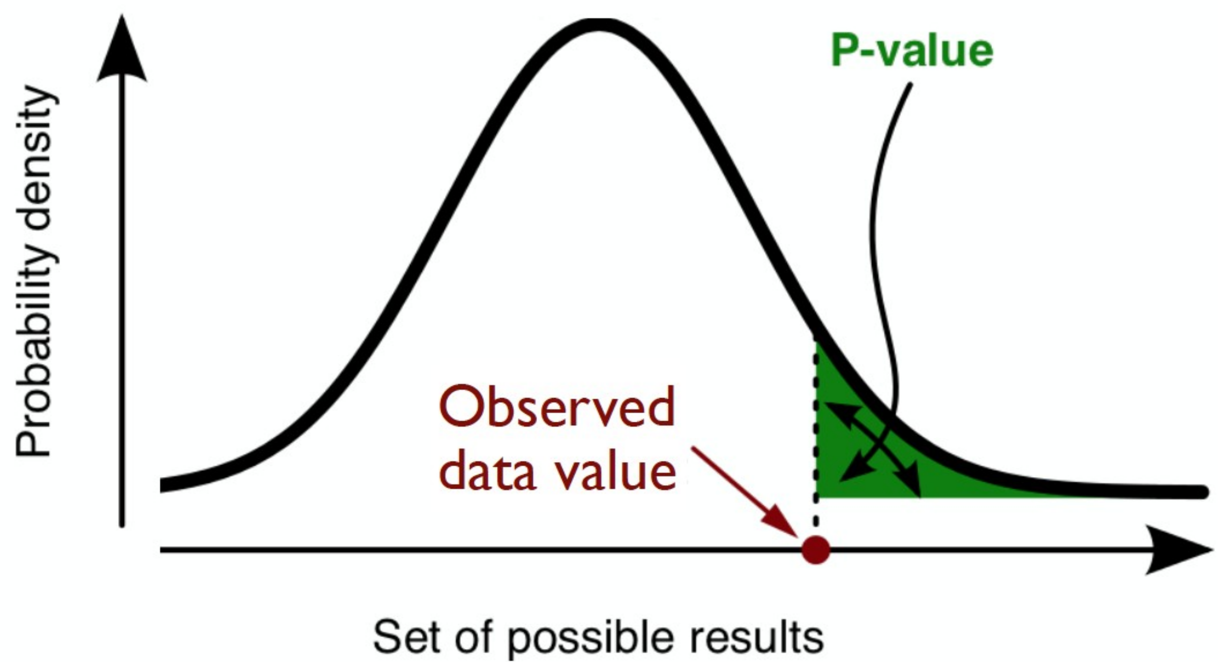
How sure are we ?

- Calculate the "p-value":
  1. Build probability density distribution f for background-only hypothesis H_0: $f(x|H_0)$
  2. Probability to obtain result x_{obs} or less likely, given $f(x|H_0)$:

$$p = \int_{x_{\rm obs}}^{\infty} f\,(x|H_0)dx$$

- Map p-value to Gaussian standard deviations N_σ:

$$p = \int_{N_\sigma}^{\infty} \frac{e^{-2y^2/2}}{\sqrt{2\pi}} dy$$



How sure are we ?

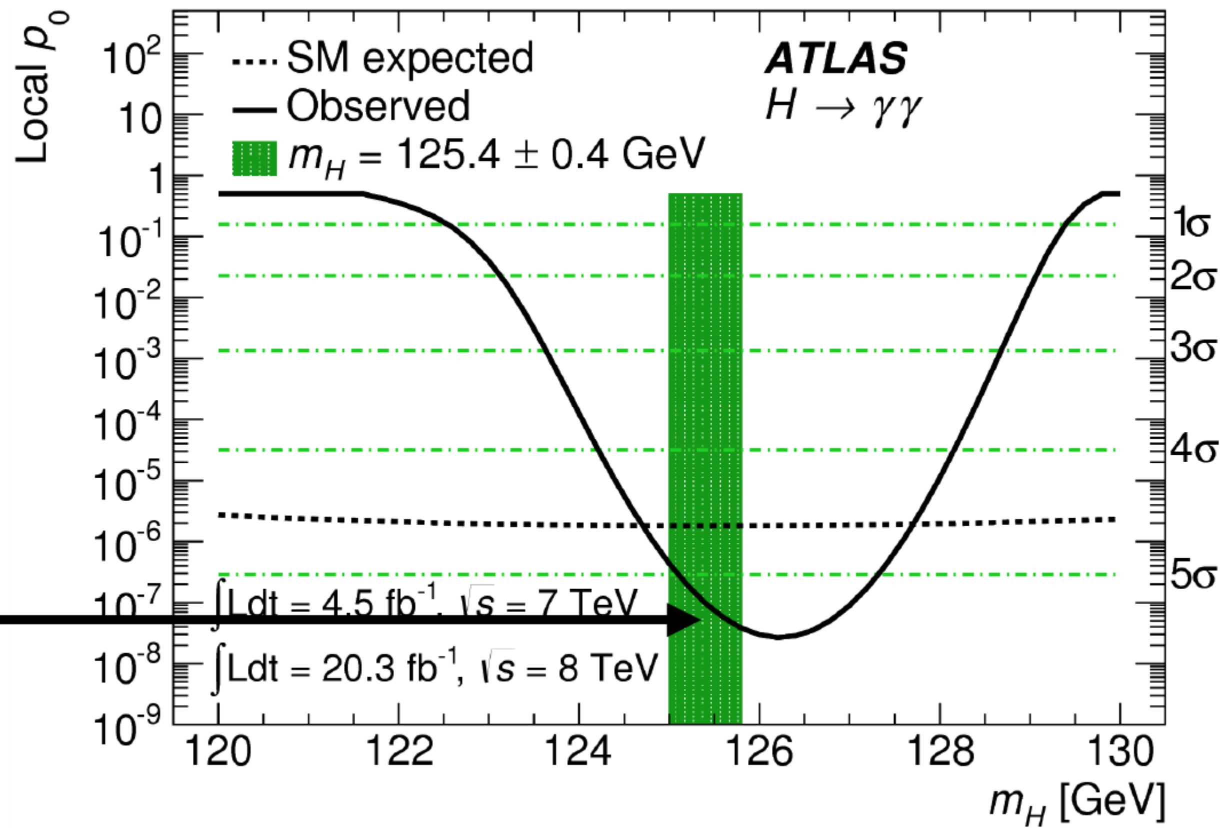
- Calculate the "p-value":
  1. Build probability density distribution f for background-only hypothesis H_0: $f(x|H_0)$
  2. Probability to obtain result x_{obs} or less likely, given $f(x|H_0)$:

$$p = \int_{x_{\rm obs}}^{\infty} f\,(x|H_0)dx$$

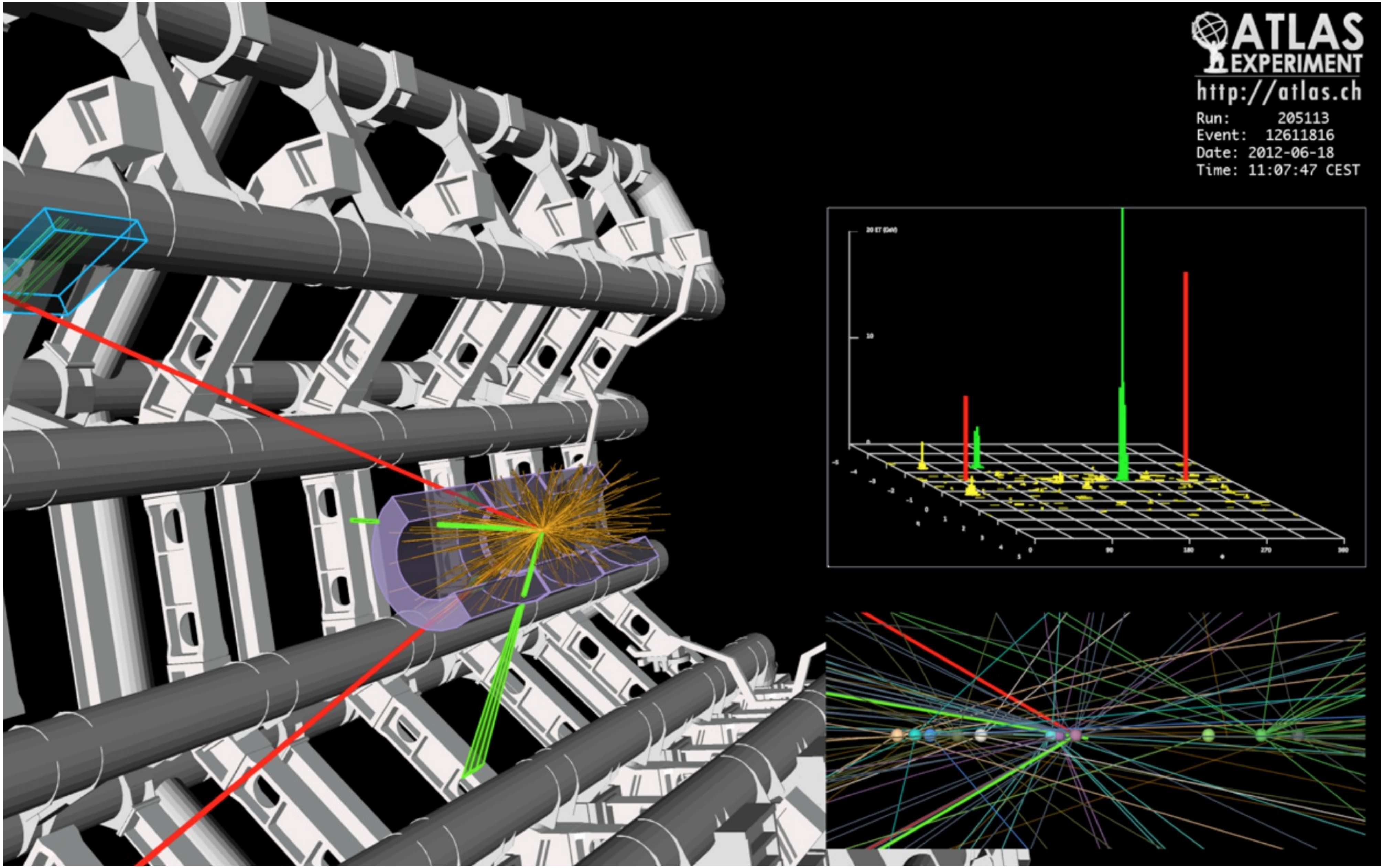
- Map p-value to Gaussian standard deviations N_σ:

$$p = \int_{N_\sigma}^{\infty} \frac{e^{-2y^2/2}}{\sqrt{2\pi}} dy$$

- Significance: **5.2σ**

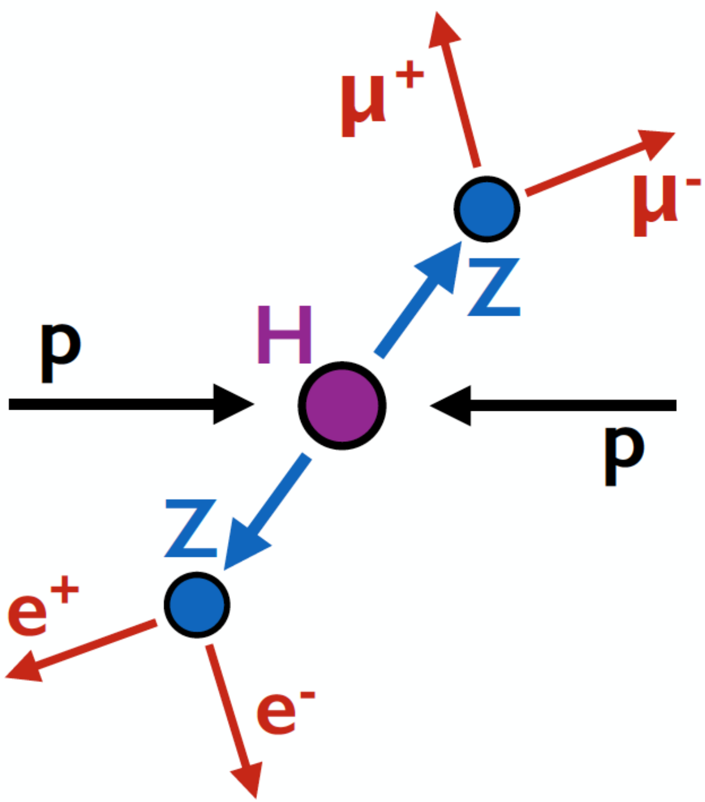


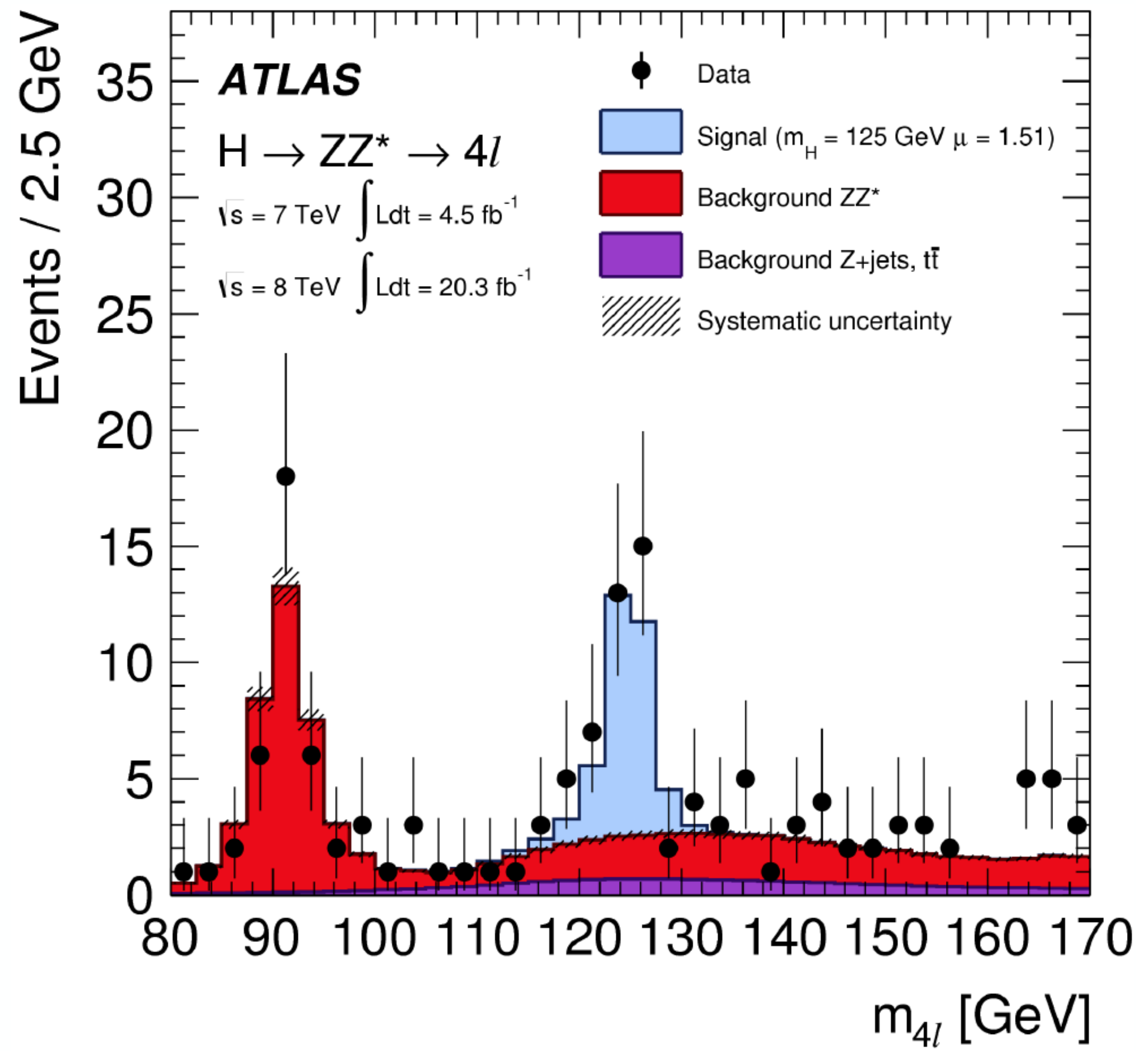
H →ZZ* →4*l*


ATLAS
EXPERIMENT
http://atlas.ch
Run: 205113
Event: 12611816
Date: 2012-06-18
Time: 11:07:47 CEST

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

- Strategy:
  - Identify 4 isolated leptons (electrons, muons)
  - Calculate invariant mass



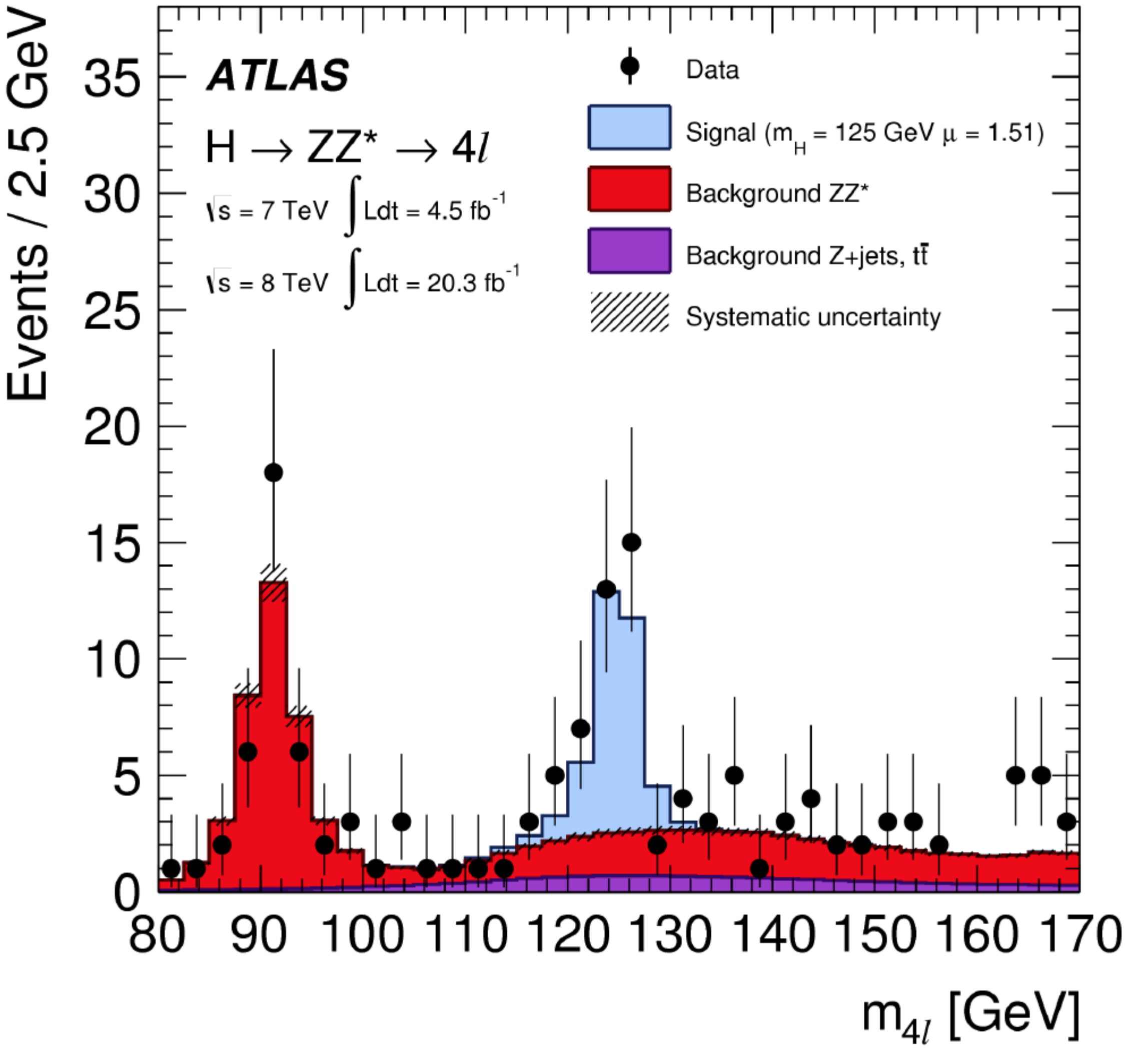


$H \rightarrow ZZ^* \rightarrow 4l$

- Strategy:
  - Identify 4 isolated leptons (electrons, muons)
  - Calculate invariant mass
- Conditions:
  - **Tiny overall branching ratio:**
    - BR($H \rightarrow ZZ^*$) ≈ 2.6%
    - BR($Z \rightarrow \ell\ell$) ≈ 3.4%

  ⇒ Expect ~**75 Higgs bosons in this decay!**
- Result:
  - Significance: 8.2σ
  - Signal strength:

$$\mu = 1.50\ ^{+0.35}_{-0.31}(\text{stat})\ ^{+0.19}_{-0.13}(\text{sys})$$

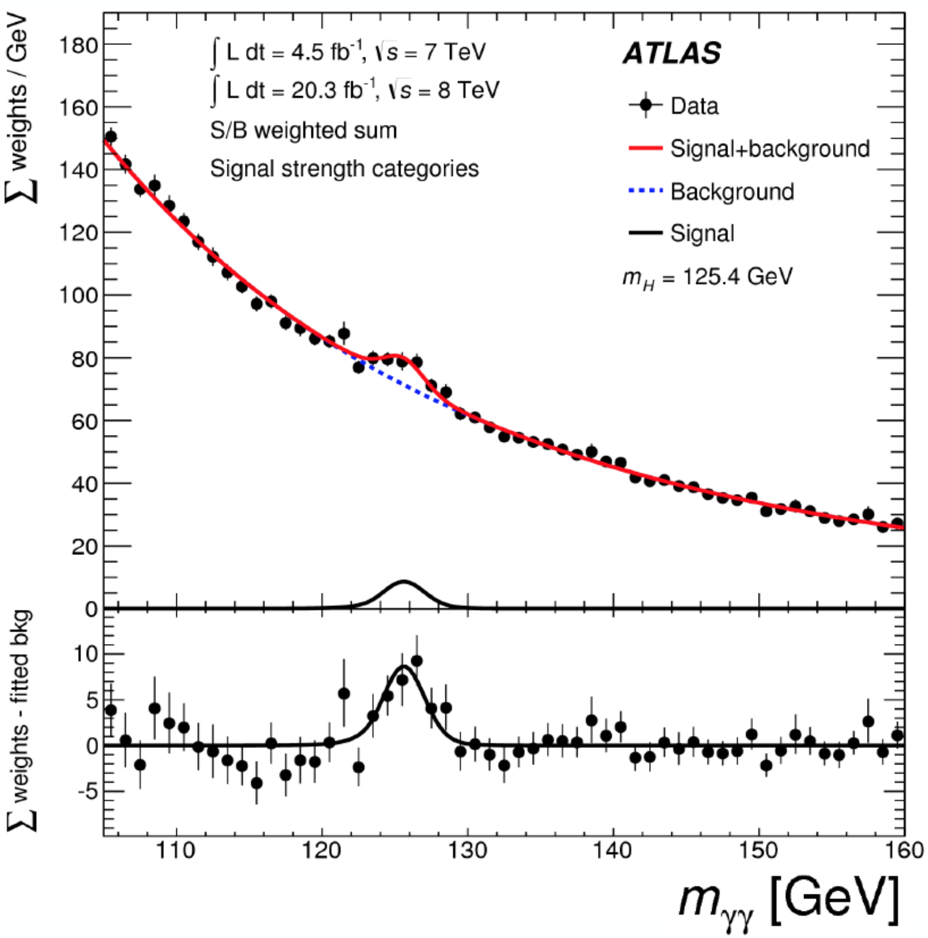


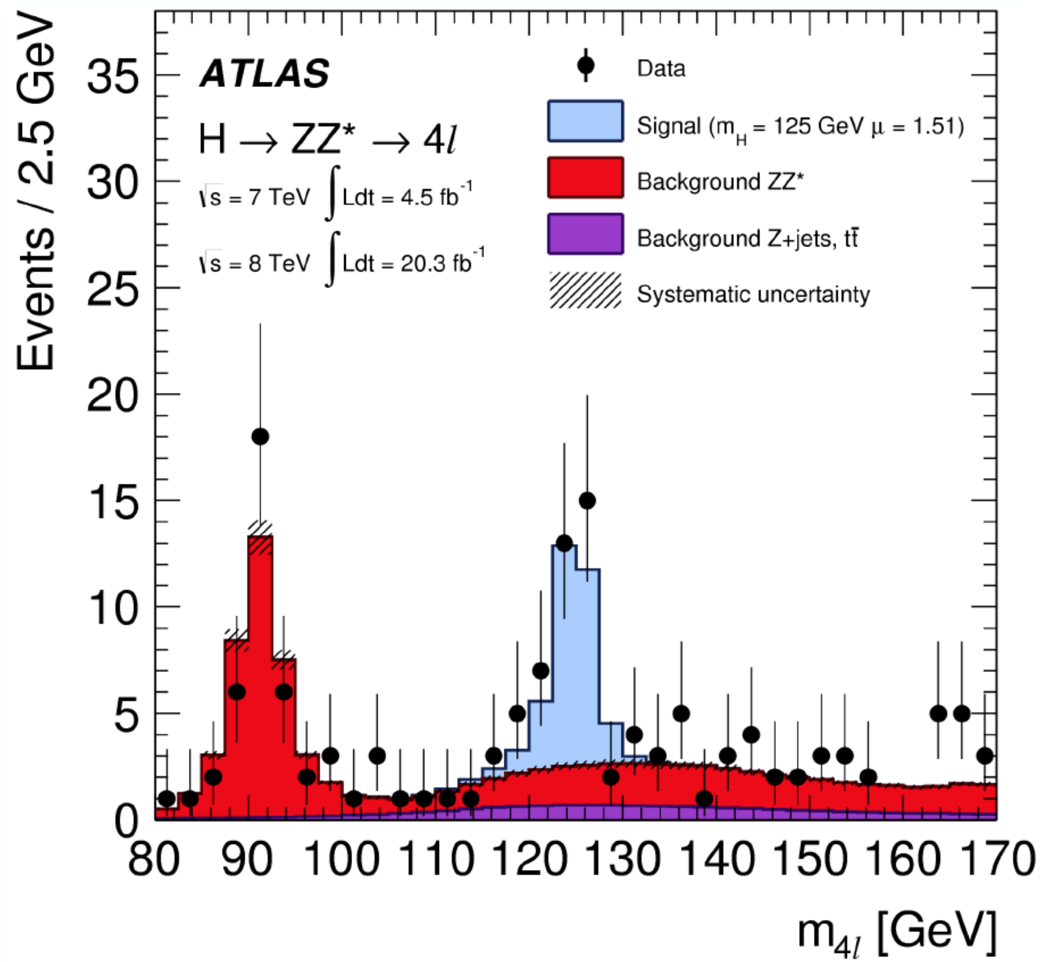
Higgs Boson Properties

- Mass m_H
- Spin and CP
- Interactions with other particles

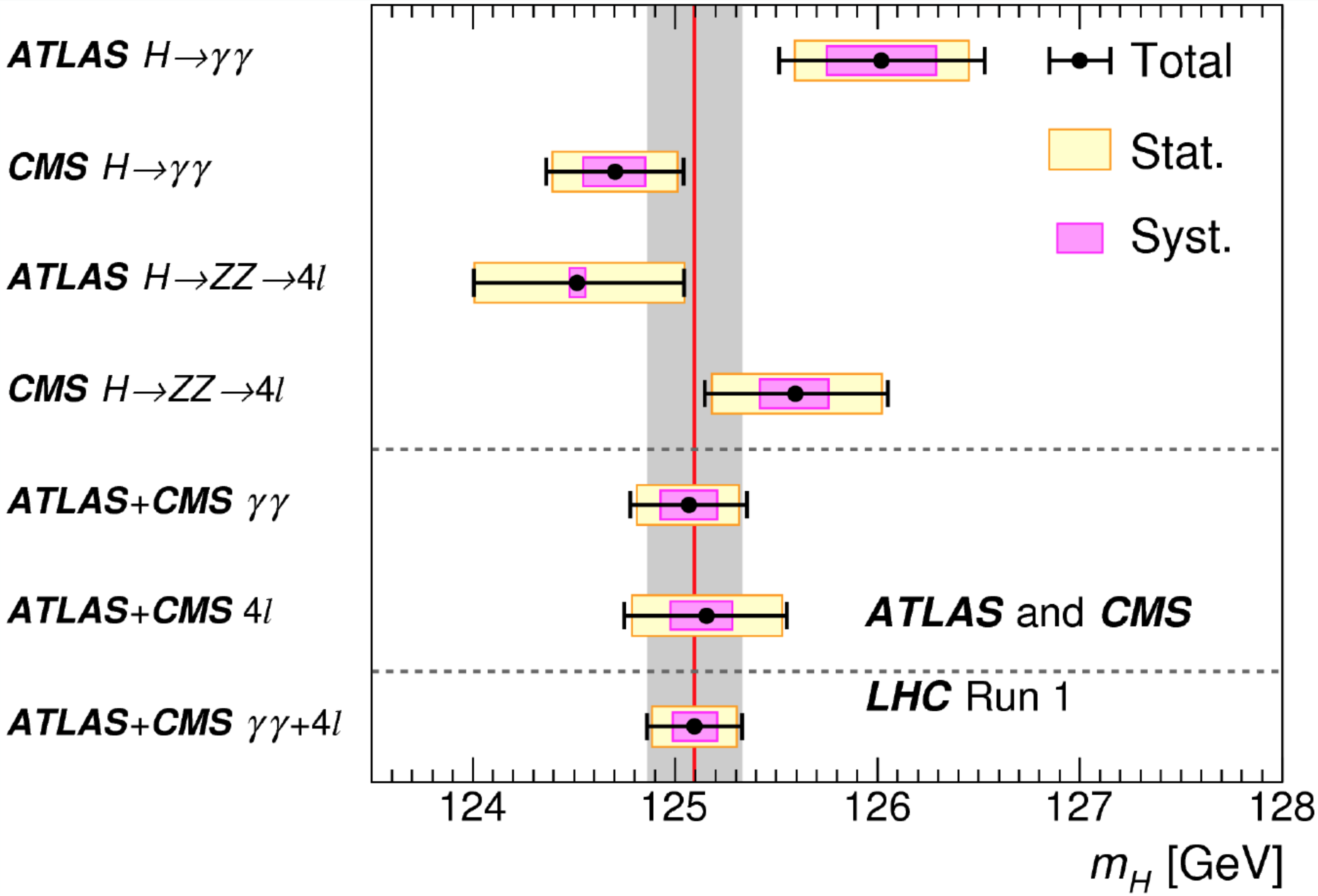
Mass Measurement

- Not predicted by theory
  - Once measured by experiment, everything else is determined
- Use high-resolution **H** → γγ and **H** → **ZZ*** → **4ℓ** channels:





ATLAS + CMS Mass Measurement (Run 1)



- Result: $m_H = 125.09 \pm 0.24\ \text{GeV}$

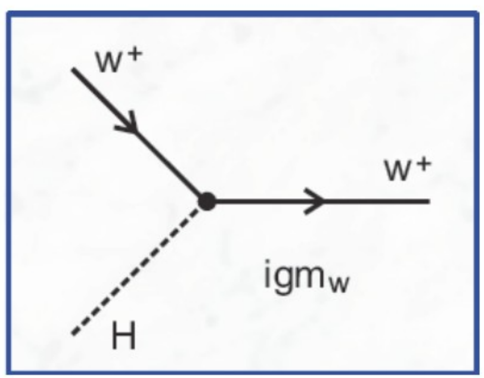
2‰ uncertainty!

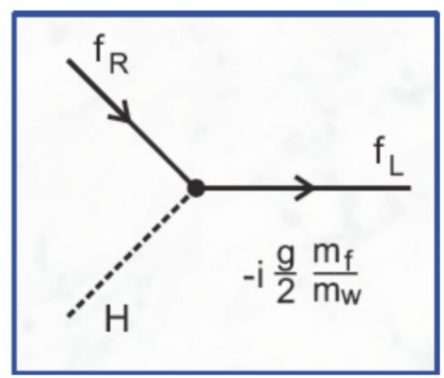
$$= 125.09 \pm 0.21\,(\text{stat.}) \pm 0.11\,(\text{syst.})\ \text{GeV}$$

But is it *THE* Higgs Boson ?

Need to determine its other properties precisely:

- Spin and CP
- Production rates
- Couplings to bosons and fermions
  - According to boson and fermion masses?





Why Spin 0 ?

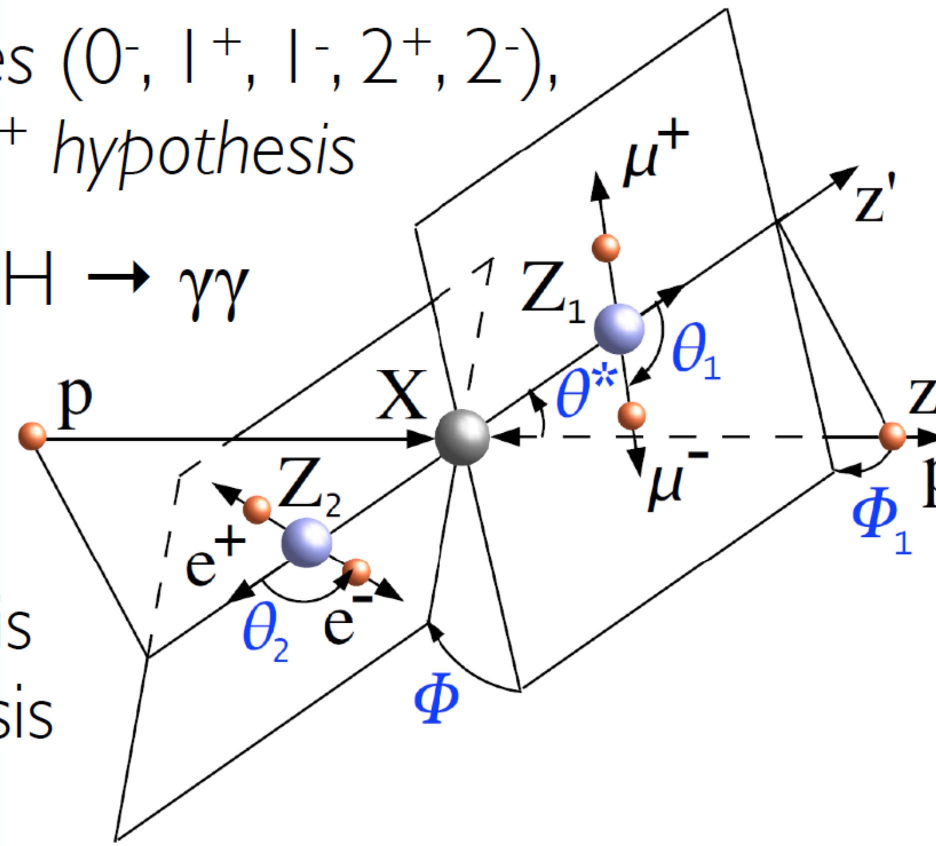
- Vacuum:
  - No charge:
  - Rotationally invariant, *i.e.*, no preferred direction
- Higgs boson should have same quantum numbers as observed vacuum:
  - No charge: 👍
  - Mass cannot depend on direction

    $\Rightarrow$ **Spin 0**

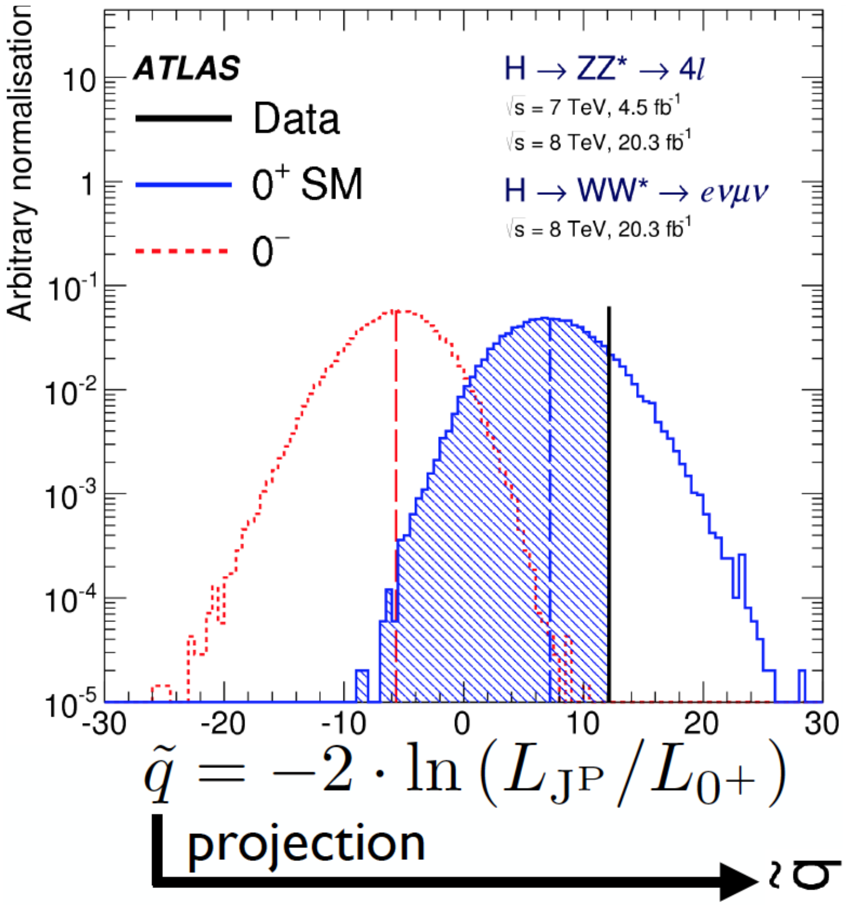
Spin and CP

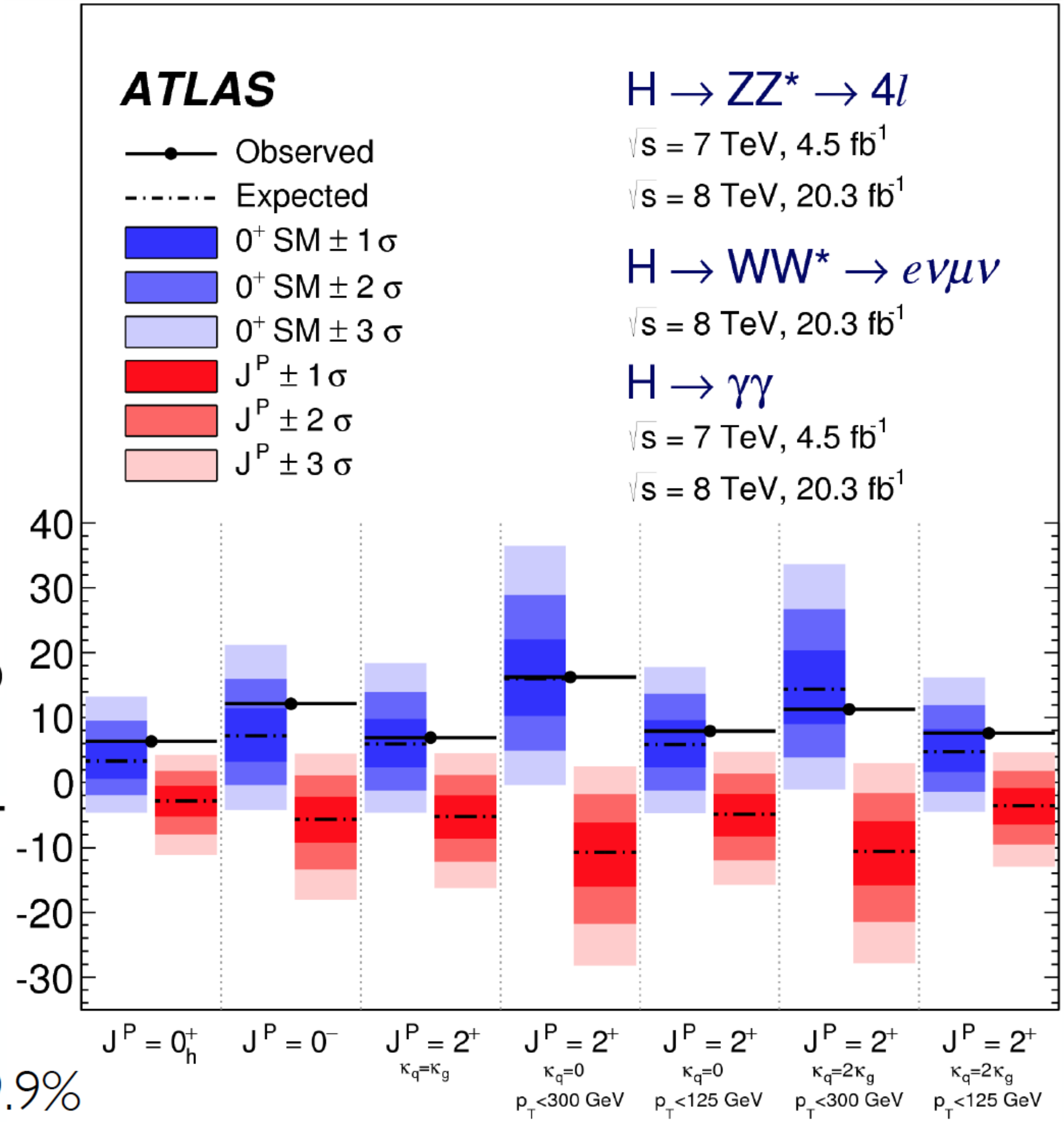
<u>Standard Model Higgs boson: **$J^{PC} = 0^{++}$**</u>

- **C**harge conjugation: change sign of all quantum numbers
- **P**arity ("mirror") transformation": $\hat{P}\ \vec{x} \longrightarrow -\vec{x}$
- Strategy: *falsify other hypotheses* (0^-, 1^+, 1^-, 2^+, 2^-), *demonstrate consistency with 0^+ hypothesis*
- Spin-1 excluded by observed $H \rightarrow \gamma\gamma$
- Use angular variables
- Calculate likelihood ratio between alternative hypothesis and standard $J^P = 0^+$ hypothesis



Spin and CP





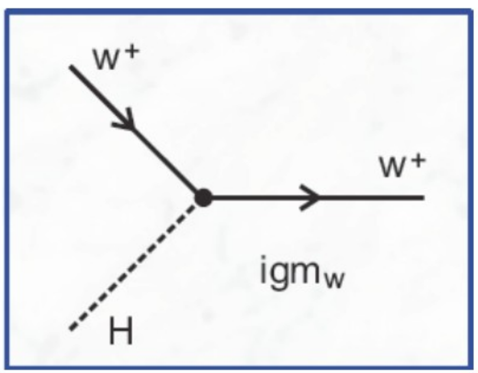
- SM $J^P = 0^+$ favored
- Other models disfavored at >99.9%

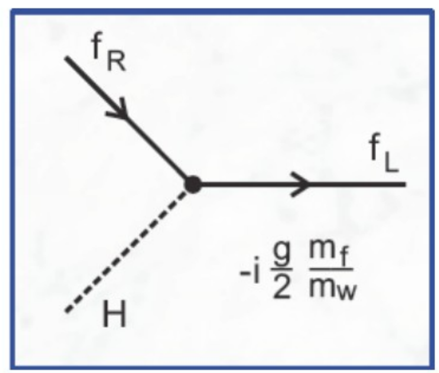
But is it *THE* Higgs Boson ?

Need to determine its other properties precisely:

✔ Spin and CP

- Production rates
- Couplings to bosons and fermions
  - According to boson and fermion masses?





The κ Framework

Model and fit framework:

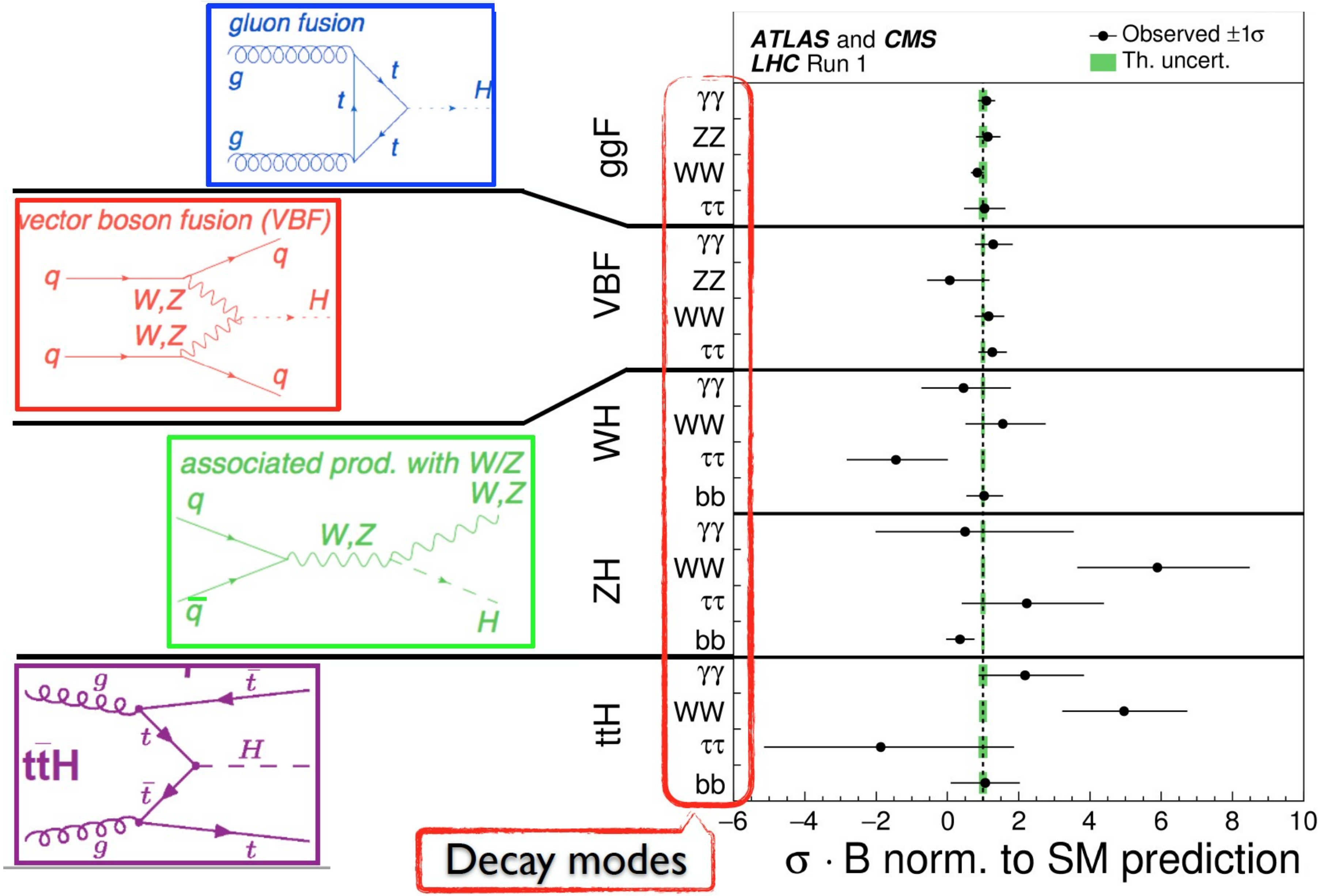
- Once Higgs boson mass is known, all other Higgs-boson parameters are fixed in the SM
- To allow for measurement deviations from SM rates, introduce coupling scale factors: $\kappa = \dfrac{g}{g_{\text{SM}}}$

$$(\sigma \cdot BR)(i \to H \to j) = \frac{\sigma_i^{SM}\,\kappa_i^2 \cdot \Gamma_f^{SM}\,\kappa_f^2}{\Gamma_H^{SM}\,\kappa_H^2} \to \mu_i^f = \frac{\sigma \cdot BR}{\sigma_{SM} \cdot BR_{SM}} = \frac{\kappa_i^2\,\kappa_f^2}{\kappa_H^2}$$

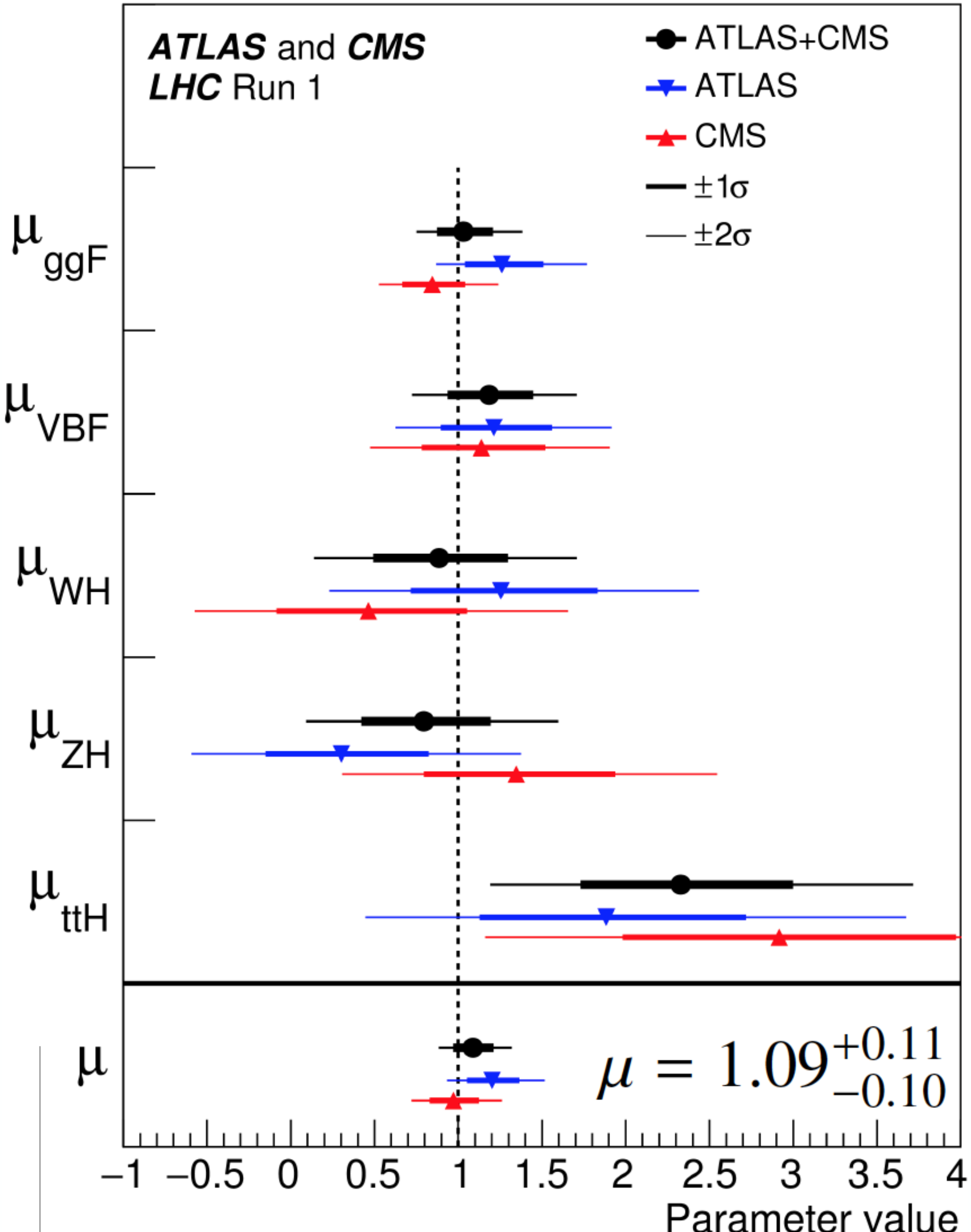
Assumption:

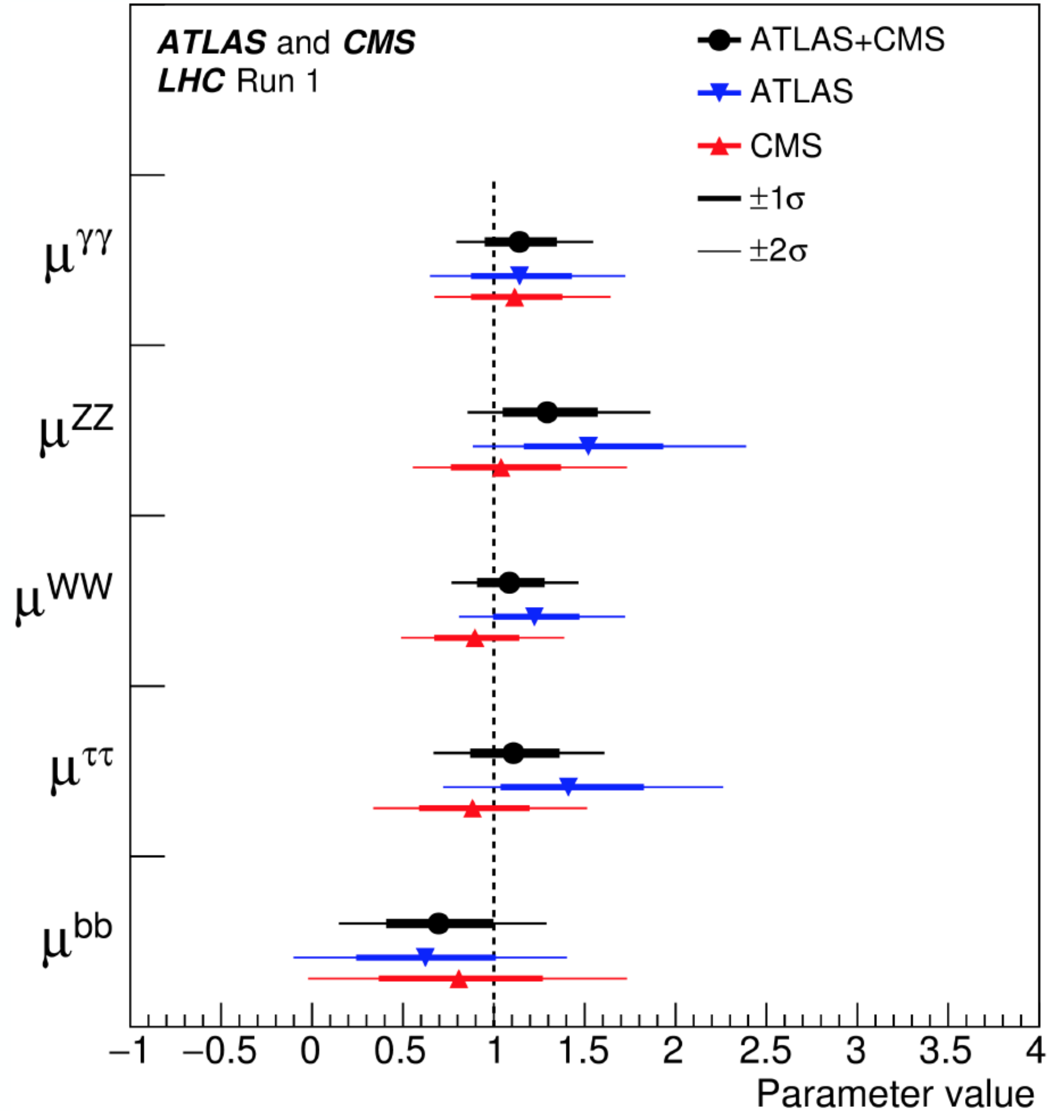
- Only one SM Higgs-like state at ~125 GeV with negligible width

Production and decay Modes



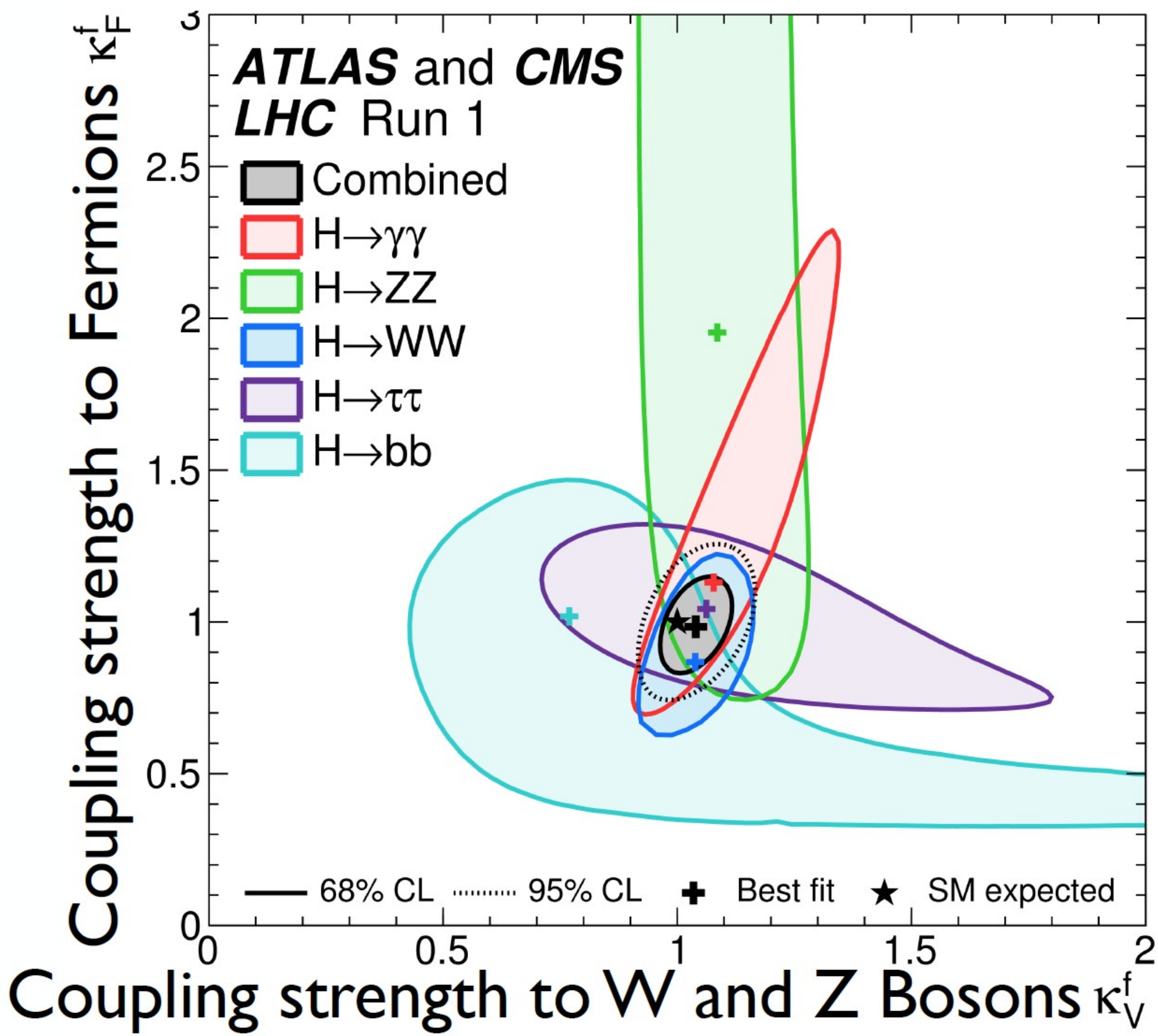
Production and decay Modes



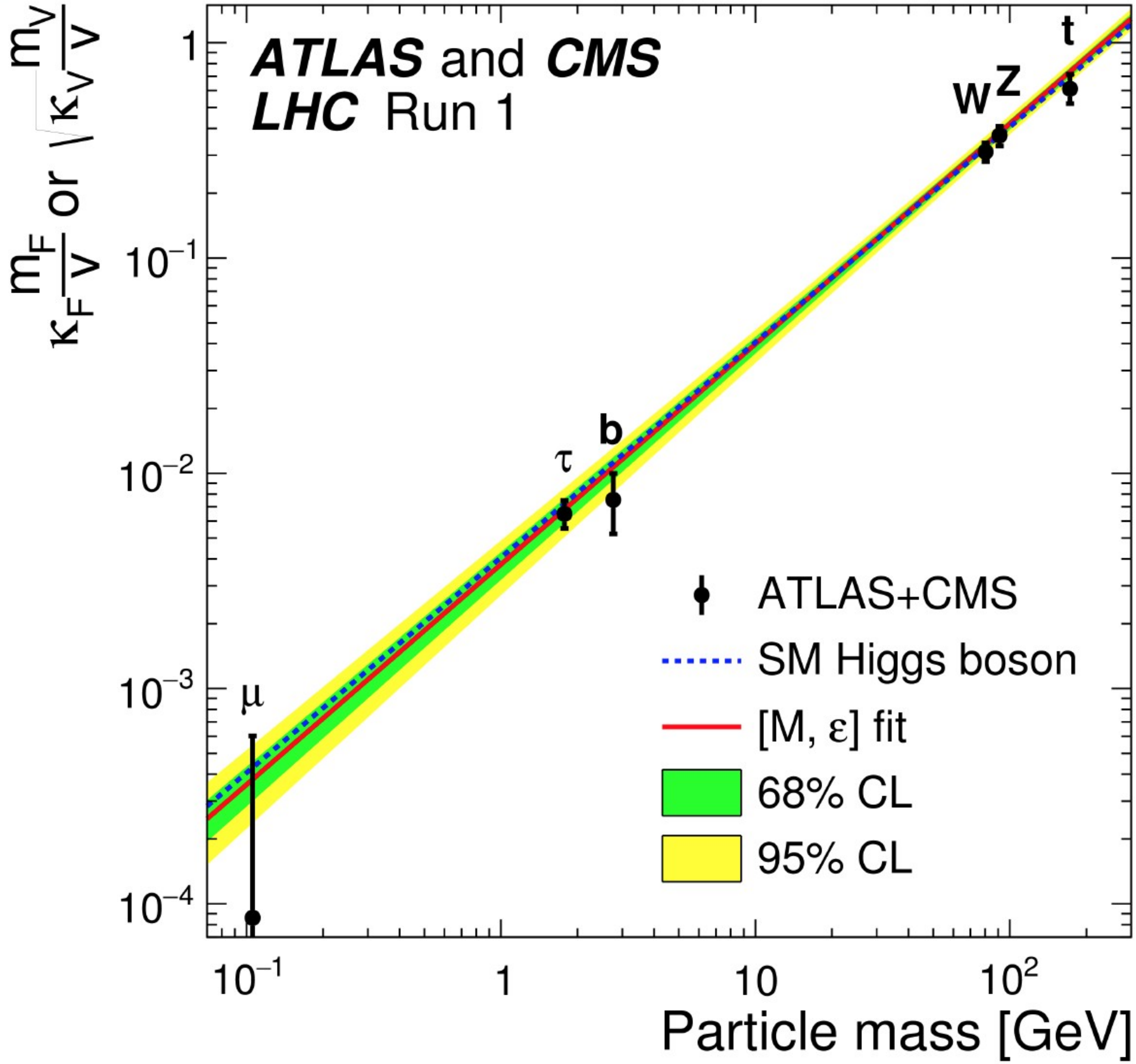


signal strength

Coupling to Fermions and Bosons



Mass ~ Coupling Strength ?



ATLAS and CMS see all measured couplings in agreement with SM expectations

LHC Run 2

$$E_{CM} = 13\,\text{TeV}$$

H →γγ + H →ZZ* →4l

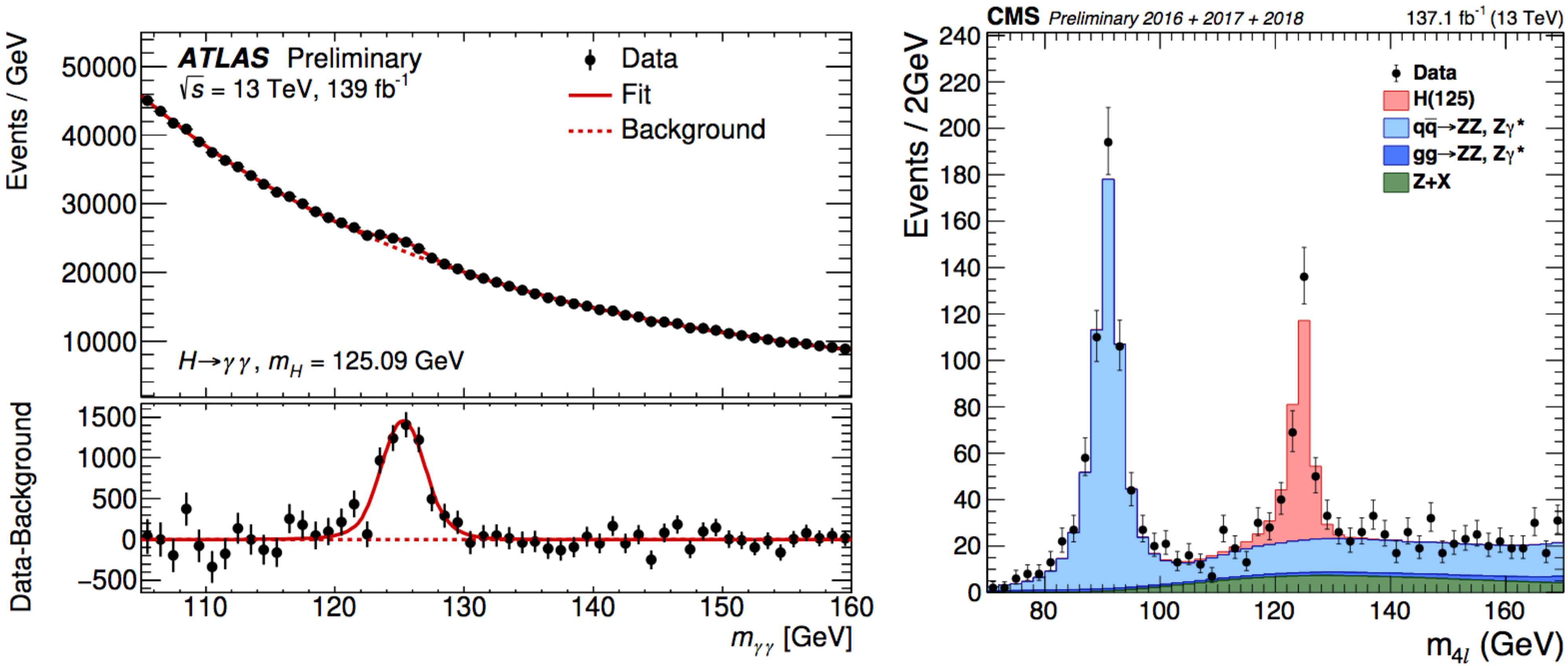
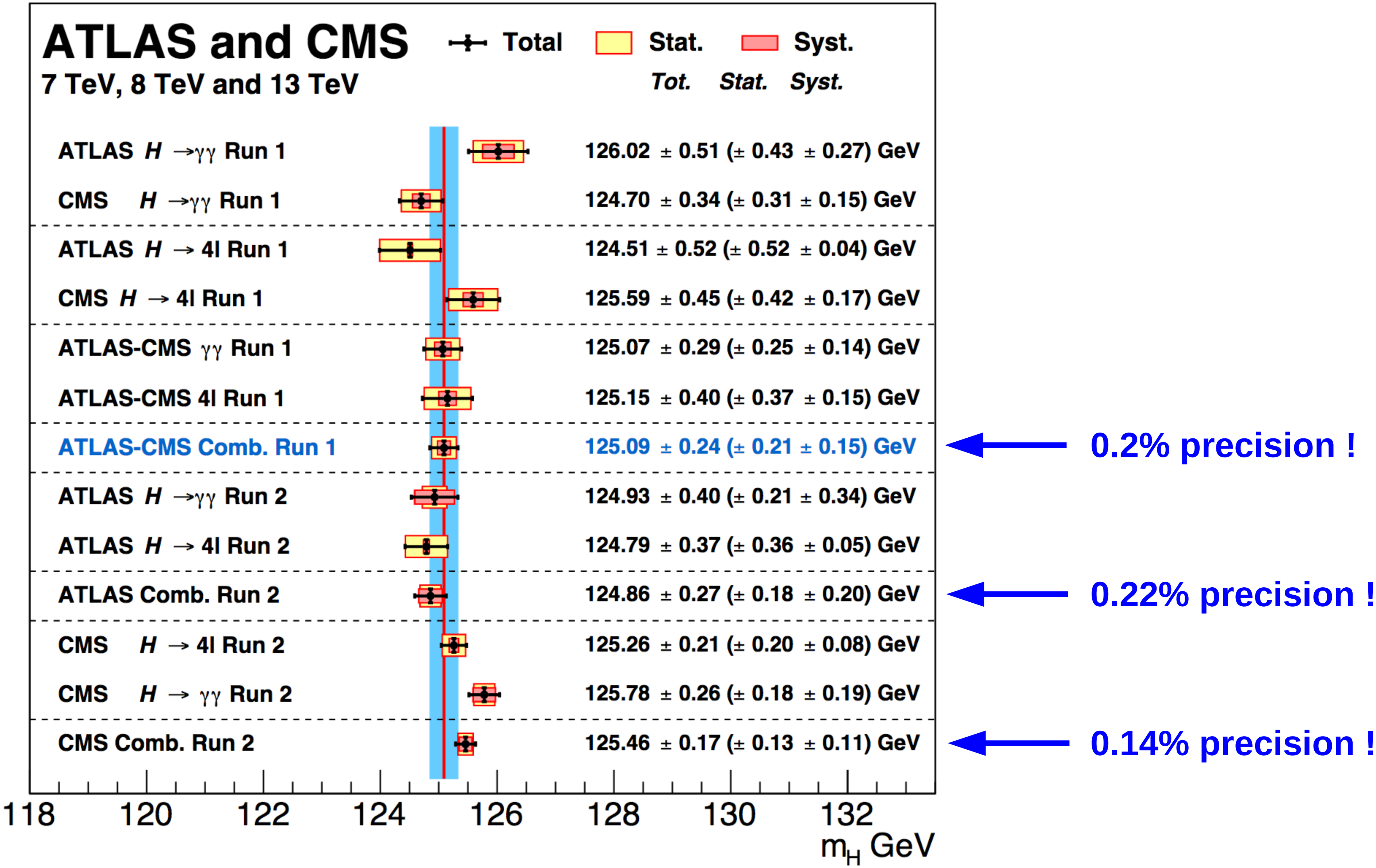


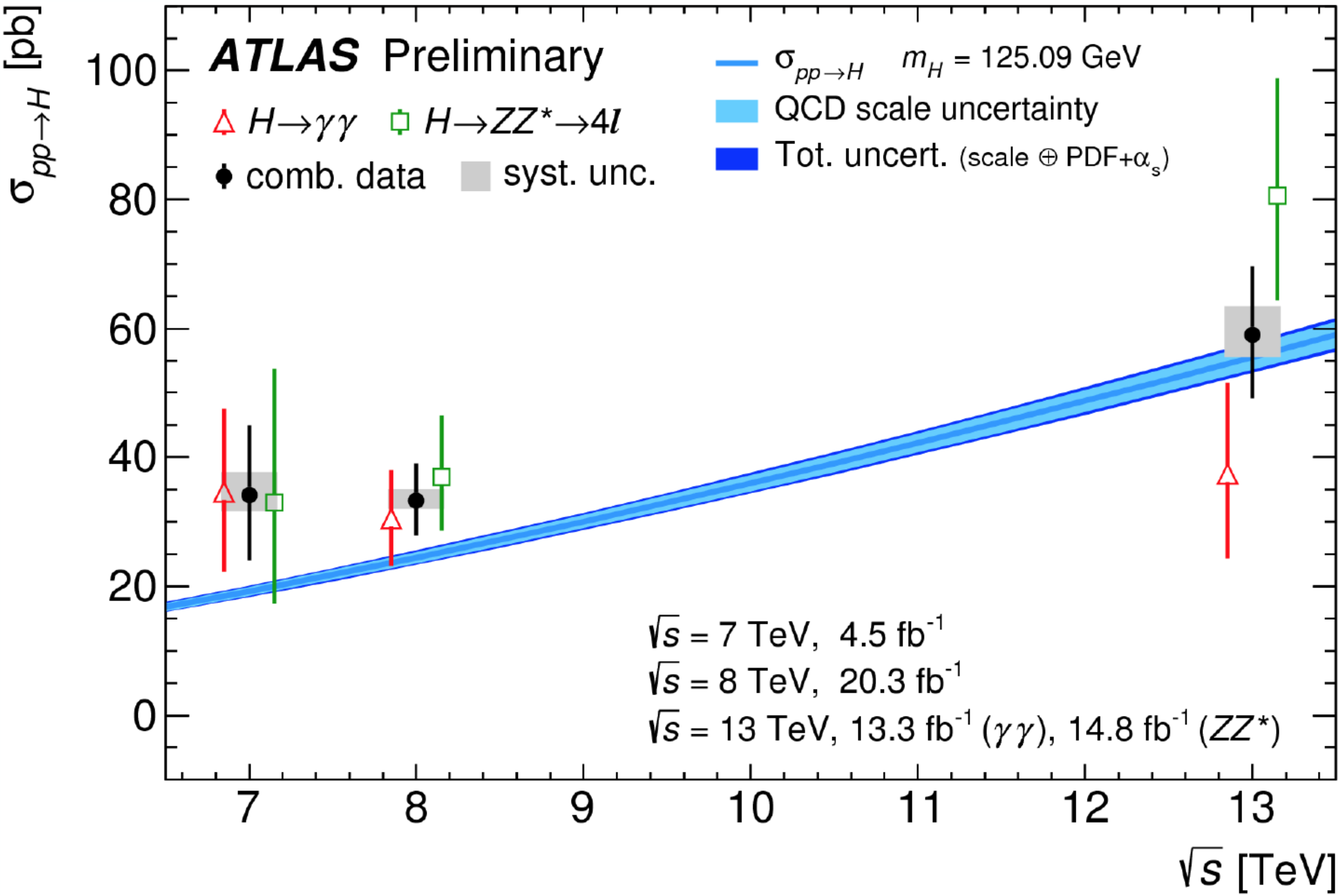
Figure 11.3: (Left) The invariant mass distribution of diphoton candidates, with each event weighted by the ratio of signal-to-background in each event category, observed by ATLAS [125] at Run 2. The residuals of the data with respect to the fitted background are displayed in the lower panel. (Right) The $m_{4\ell}$ distribution from CMS [126] Run 2 data.

ATLAS + CMS Mass Measurement



Combination

Combine H → γγ and H → ZZ* → 4ℓ:



Combination