A boost to Higgs Physics: new regimes at high energy

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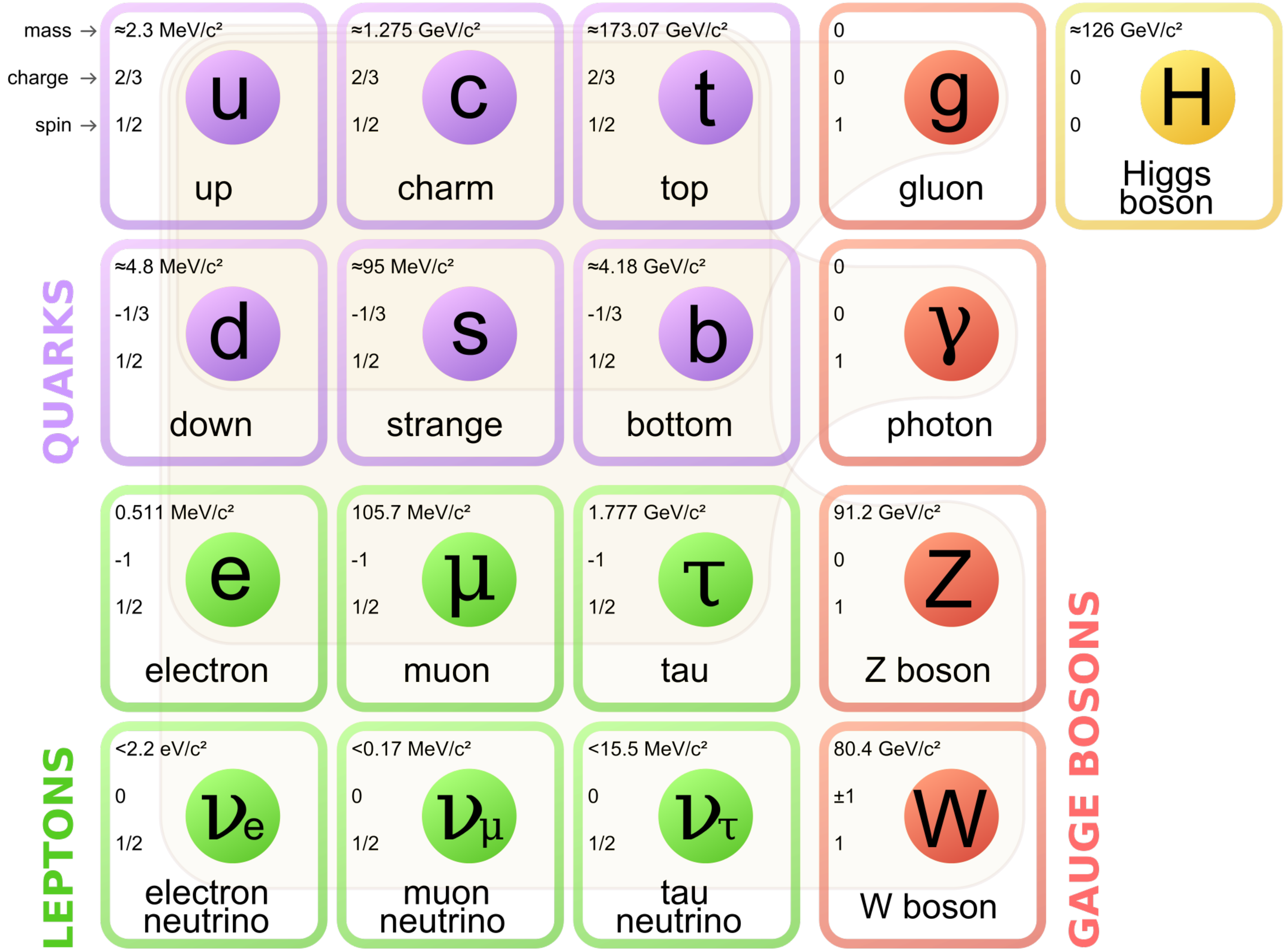
Corso di Dottorato - 2019/2020

Course outline

- **Theory reminder**
- **Higgs boson production and decay modes**
- **Higgs boson discovery by ATLAS and CMS**
- Higgs boson mass measurement by ATLAS and CMS
- Overview of ATLAS and CMS analyses about Higgs
- Signal/background discrimination techniques
  - boosted regimes
    - tagging, large-radius jets substructure, re-clustering
  - multivariate analysis and deep neural network
- Signal extraction techniques
  - likelihood and test statistic
  - CLs method
- ttH analysis: an example

Theory reminder

Reminder: Standard Model



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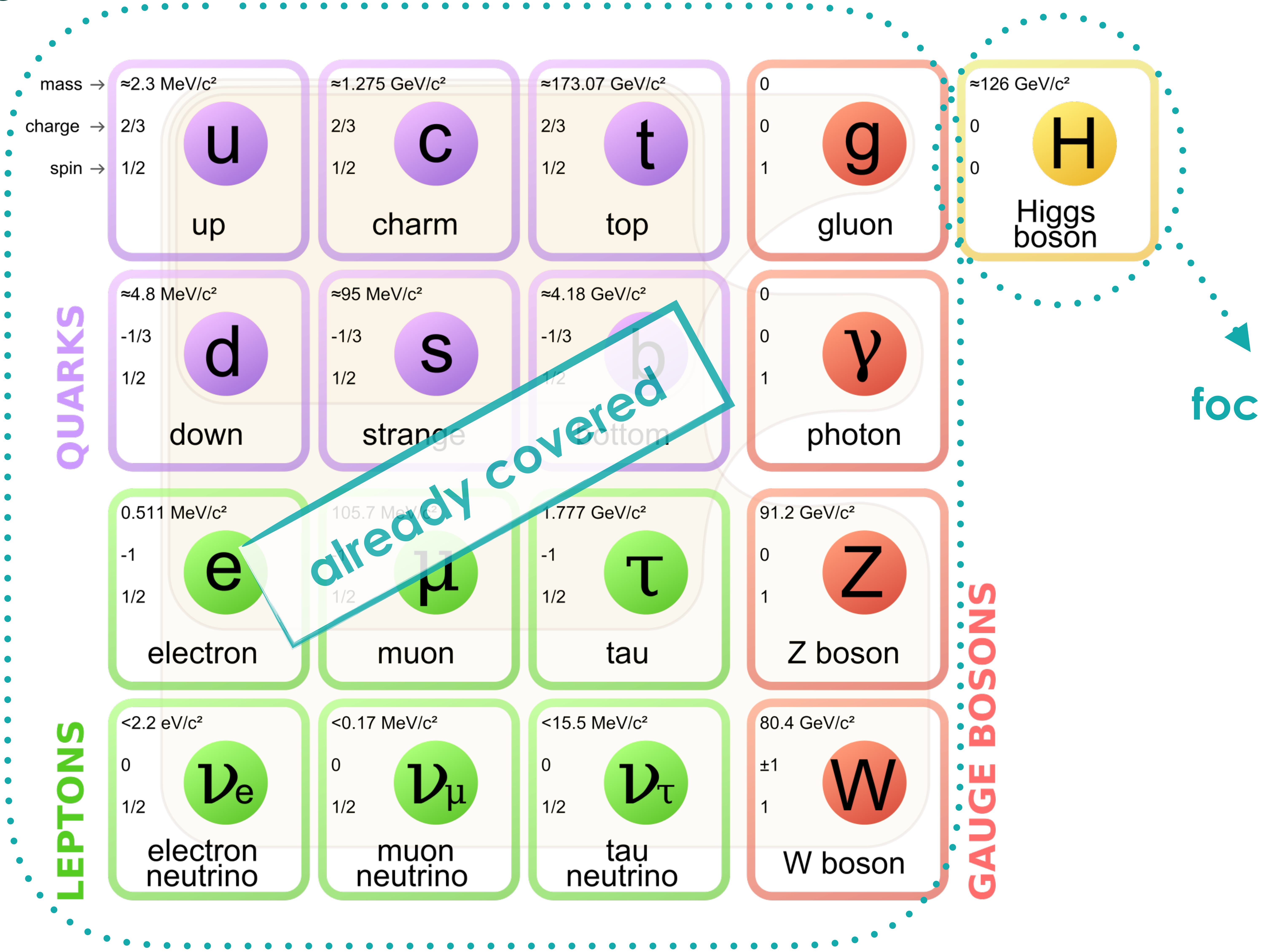
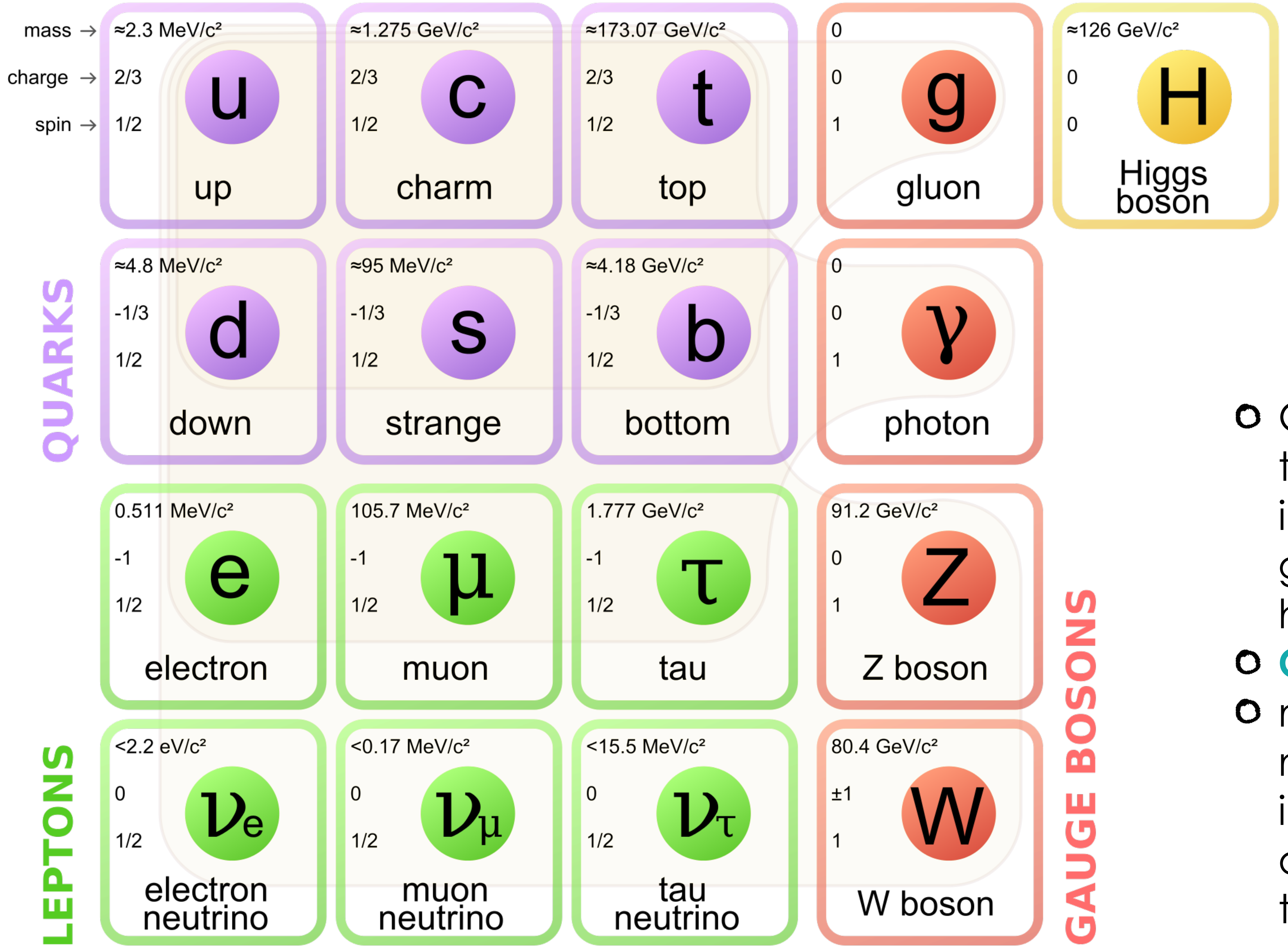


focus of this course

Reminder: Standard Model



$$SU(3)_C \otimes SU(2)_L \otimes U(1)_Y$$

- Group associated to the strong interaction between gluons and quarks in hadrons
- **C** = color charge
- mediators: 8 massless **gluons**, interacting with quarks according to the QCD.

- Group associated to the electroweak (EW) interaction
- **L** = left-handed weak-isospin I_3 doublets
- **Y** = weak hypercharge ($Q = I_3 + 1/2\ Y$)
- mediators: **W±, Z, γ**
- they arise from a linear combination of a representation of these groups.

Reminder: why do we need a Higgs boson?

The Standard Model Lagrangian

$$\mathscr{L} = -\frac{1}{4}\boldsymbol{W}_{\mu\nu} \cdot \boldsymbol{W}^{\mu\nu} - \frac{1}{4}B_{\mu\nu}B^{\mu\nu}$$

$$+\bar{L}\gamma^{\mu}(i\partial_{\mu} - g\frac{1}{2}\boldsymbol{\tau} \cdot \boldsymbol{W}_{\mu} - g'\frac{Y}{2}B_{\mu})L + \bar{R}\gamma^{\mu}(i\partial_{\mu} - g'\frac{Y}{2}B_{\mu})R$$

$+$ something is missing here

Glossary

W_μ = isotriplet vector field coupled to the weak isospin current with coupling factor **g**

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SPOILER ALERT

- kinetic energy and self-coupling of W_μ fields and kinetic energy of B_μ field;
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Reminder: why do we need a Higgs boson?

The Glashow-Weinberg-Salam model

In ‘60s, Glashow-Weinberg-Salam model allows to unify the electromagnetic and weak forces;

↓

electroweak interaction with two couplings and four mediating bosons

BUT

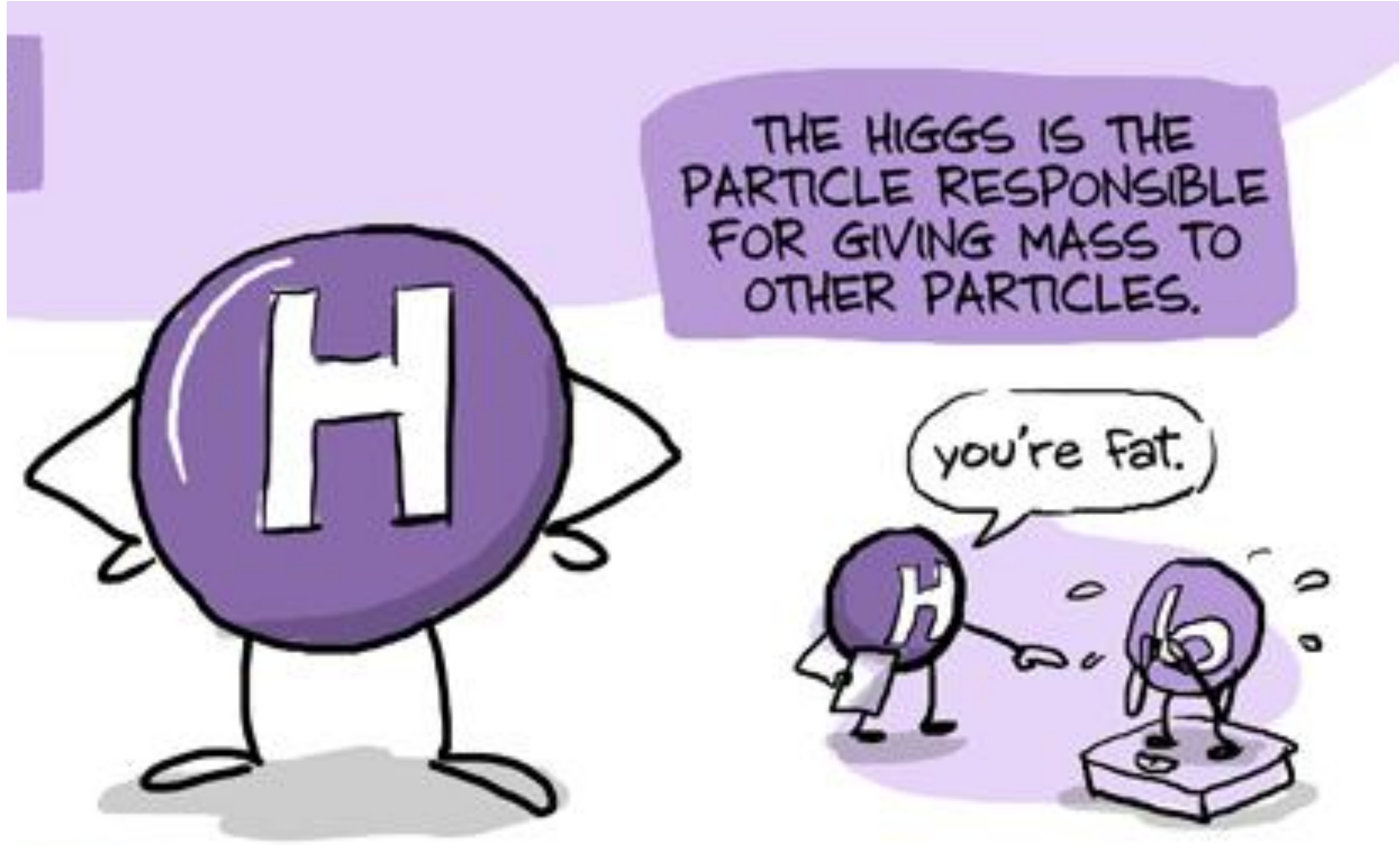
↓

- mass of mediators of the weak field should be zero for a gauge field theory and with an infinite interaction range;
- in contrast with **experimental observations that mediators do have a mass** and, consequently, a short range for the weak interactions.
- According to GWS model, the symmetry between electromagnetic and weak interactions would be manifest at very large momentum transfers ($q^2 >> 10^4$ GeV^2), while at low energies it would be a **spontaneous symmetry breaking**, that provides a mass to the bosons without spoiling the renormalisability of the theory.

Reminder: the Higgs mechanism

- In 1964 by Higgs, Englert and Brout postulated the **existence of a scalar field responsible for this spontaneous symmetry breaking**.

- Consider a system described by a Lagrangian and its symmetries:
  - in each system, the lowest level of energy is the **ground state** (or vacuum);
    - if it is **non-degenerate** it will possess the same symmetries of L;
    - if its is **degenerate**, there will not be only one eigenstate for the representation of the lowest energy level:
      - any of the degenerate states of the fundamental level might not possess the symmetries of the L anymore;
      - **the realisation of an asymmetric state is known as spontaneous symmetry breaking**.



Reminder: Higgs mechanism

less generic case, just to start

- Consider a **scalar field ϕ that interacts with itself**

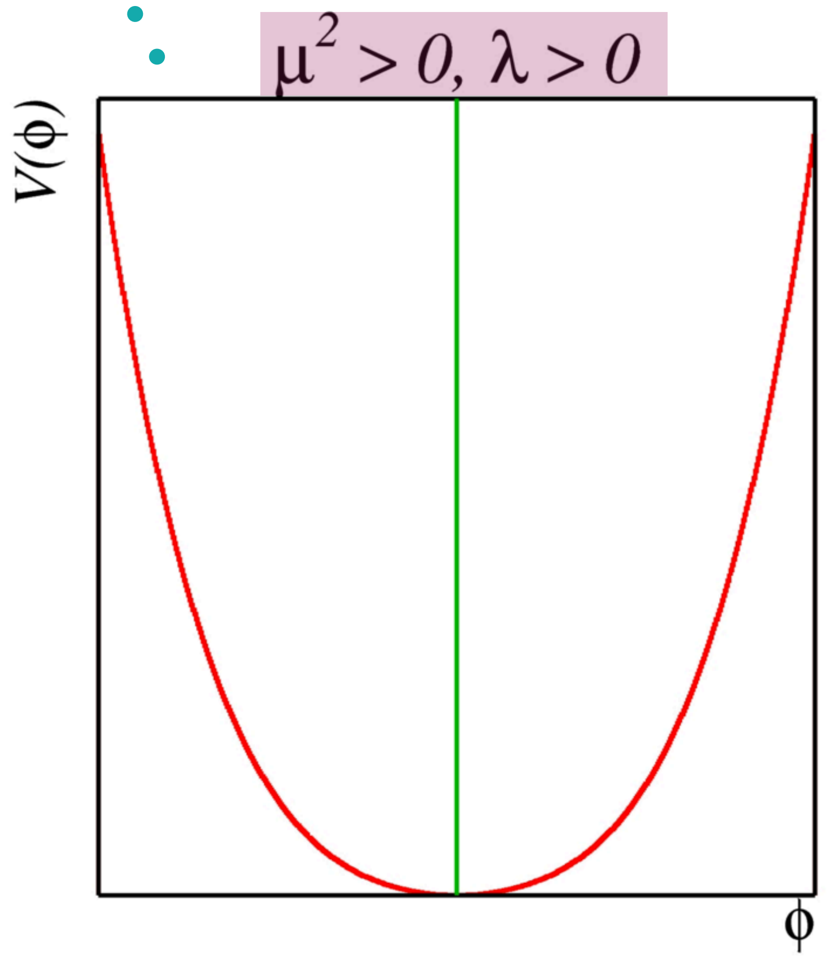
$$\mathbf{L} = \frac{1}{2}(\partial_\mu \phi)^2 - \mathbf{V}(\phi)$$

- where V is invariant under L symmetry operation ($\phi \to -\phi$)

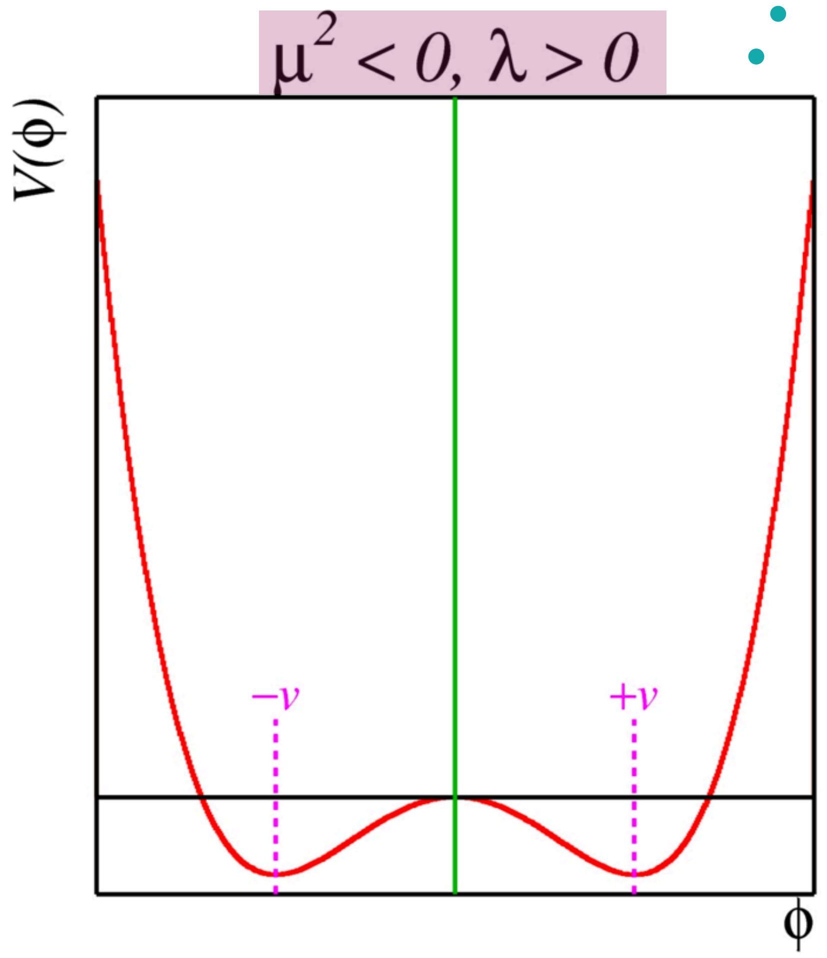
$$\mathbf{V}(\phi) = \frac{1}{2}\mu^2\phi^2 + \frac{1}{4}\lambda\phi^4$$

- μ = scalar particle mass
- λ = dimensionless positive constant representing the coupling of the 4-boson vertex

- the minimum value of V occurs at $\phi = \phi_{min}$, corresponding to $\partial V/\partial\phi = 0$: $\phi(\mu^2 + \lambda\phi^2) = 0$



- ☑ **ground state on the origin at $\phi_{min} = 0$**
- ☑ **scalar field with mass μ**



- ☑ **potential has minima at $\phi_{min} = \pm\sqrt{\frac{-\mu^2}{\lambda}} = \pm \mathbf{v}$**
- ☑ **applying perturbative calculations around the minimum (chosen without loss of generality), scalar field with mass $\mathbf{m} = \sqrt{2\lambda \mathbf{v}^2} = \sqrt{-2\mu^2}$**

Reminder: Higgs mechanism

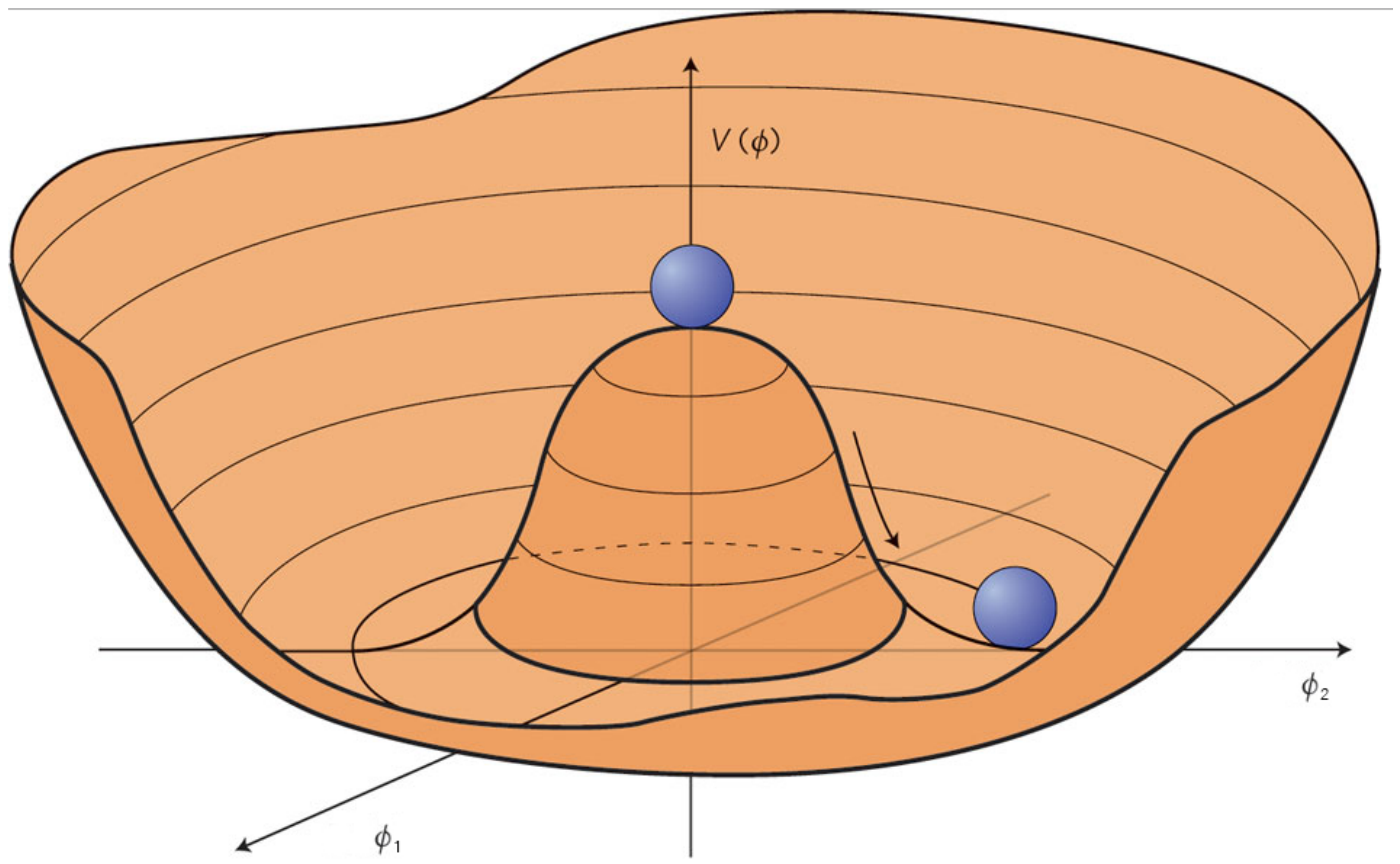
more generic case

- The mechanism to generate a mass for the gauge bosons can be generalised to a **complex scalar field**

$$\phi = \frac{1}{\sqrt{2}}(\phi_1 + i\phi_2)$$

- described by the Lagrangian, invariant under the **U(1) global gauge symmetry** $\phi \to e^{i\alpha}\phi$

$$L = (\partial_\mu \phi)^*(\partial^\mu \phi) - V(\phi) = (\partial_\mu \phi)^*(\partial^\mu \phi) - \frac{1}{2}\mu^2\phi^*\phi - \frac{1}{4}\lambda(\phi^*\phi)^2$$



- **circle of radius *v* of degenerate minima of the potential in φ1φ2 plane, such that $\phi_1^2 + \phi_2^2 = v^2$, with $v^2 = -\mu^2/\lambda$**
- **as before, expanding the field around a minimum energy position, scalar field with mass $m = \sqrt{-2\mu^2}$**

Reminder: Higgs mechanism

the most generic case

- Consider a **complex doublet scalar field** $\phi \equiv \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix} = \sqrt{\frac{1}{2}} \begin{pmatrix} \phi_1 + i\phi_2 \\ \phi_3 + i\phi_4 \end{pmatrix}$

- described by the Lagrangian, invariant under the **SU(2) global gauge symmetry** $\phi \rightarrow e^{i\alpha \frac{\tau_a}{2}} \phi$

$$\mathbf{L} = (\partial_\mu \phi)^\dagger (\partial^\mu \phi) - \mathbf{V}(\phi) = (\partial_\mu \phi)^\dagger (\partial^\mu \phi) - \frac{1}{2}\mu^2 \phi^\dagger \phi - \frac{1}{4}\lambda(\phi^\dagger \phi)^2$$

$$D_\mu = \partial_\mu + ig\frac{\tau_a}{2}W_\mu^a$$

- Applying perturbative calculations and keeping the L invariant also under the **local SU(2) symmetry**:

$$L = (\partial_\mu \phi + ig\frac{1}{2}\boldsymbol{\tau} \cdot \boldsymbol{W_\mu} \phi)^\dagger (\partial^\mu \phi + ig\frac{1}{2}\boldsymbol{\tau} \cdot \boldsymbol{W^\mu} \phi) - \frac{1}{2}\mu^2 \phi^\dagger \phi - \frac{1}{4}\lambda(\phi^\dagger \phi)^2 - \frac{1}{4}\boldsymbol{W_{\mu\nu}} \cdot \boldsymbol{W^{\mu\nu}}$$

☑ **if $\mu^2>0$: L describes a system of 4 scalar particles, each of mass μ, interacting with 3 massless gauge bosons (W_μ^a)**

☑ **if $\mu^2<0$: the potential has its minimum at**

$$\phi^\dagger \phi = \frac{1}{2}(\phi_1^2 + \phi_2^2 + \phi_3^2 + \phi_4^2) = -\frac{\mu^2}{2\lambda}$$

without loss of generality, we can choose

$$\phi_1 = \phi_2 = \phi_4 = 0$$

$$\phi_3^2 = -\frac{\mu^2}{2\lambda} \equiv v^2$$

Reminder: Higgs mechanism

- The expansion about this particular vacuum state $\phi_0 \equiv \sqrt{\frac{1}{2}}\begin{pmatrix} 0 \\ v \end{pmatrix}$ can be described as

$$\phi(x) \equiv \sqrt{\frac{1}{2}}\begin{pmatrix} 0 \\ v + h(x) \end{pmatrix}$$

the Higgs field h(x) is the only one remaining out of four fields

- substituting ϕ_0 in the Lagrangian and keeping only the relevant term, we can determine the **3 gauge bosons**!

$$|(i\partial_\mu - g\frac{1}{2}\boldsymbol{\tau}\cdot\boldsymbol{W_\mu} - g'\frac{Y}{2}B_\mu)\phi|^2 - \frac{1}{2}\mu^2\phi^\dagger\phi - \frac{1}{4}\lambda(\phi^\dagger\phi)^2$$

neglecting the intermediate steps

$$m_\gamma = 0 \qquad m_W = \frac{1}{2}vg \qquad m_Z = \frac{1}{2}v\sqrt{g^2 + g'^2}$$

where $v \simeq 246$ GeV

Reminder: the Higgs mechanism

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$$+|(i\partial_{\mu} - g\frac{1}{2}\boldsymbol{\tau}\cdot\boldsymbol{W}_{\mu} - g'\frac{Y}{2}B_{\mu})\phi|^2 - V(\phi)$$

$$-(G_1\bar{L}\phi R + G_2\bar{L}\phi_C R + \text{hermitian conjugate})$$

- kinetic energy and self-coupling of W_μ fields and kinetic energy of B_μ field;
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$G_{1,2}$ = matrices of Yukawa coupling

φ = 4 real scalar fields

V(φ) = Higgs potential

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- **Higgs mechanism**: $W^{\pm}$ and Z become massive, while γ remains massless.
- lepton and quark coupling to the Higgs field to generate their masses.

$$\mathbf{m_f} = \frac{\mathbf{g_{ffH}}}{\sqrt{2}}\mathbf{v}$$

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Higgs boson: production and decays

Higgs boson: production modes

⭐ **Study of the Higgs production is very important because it can provide fundamental measurements for the determination of the parameters of the SM Lagrangian**

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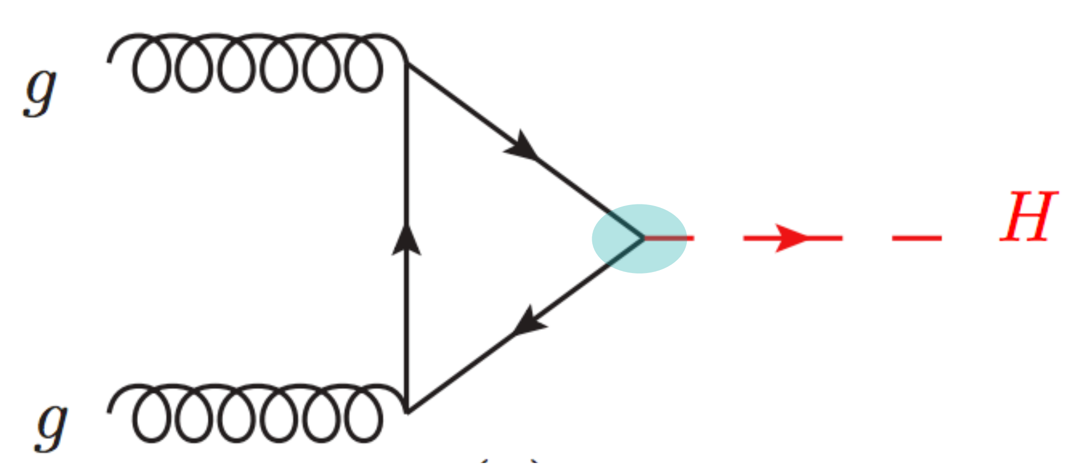
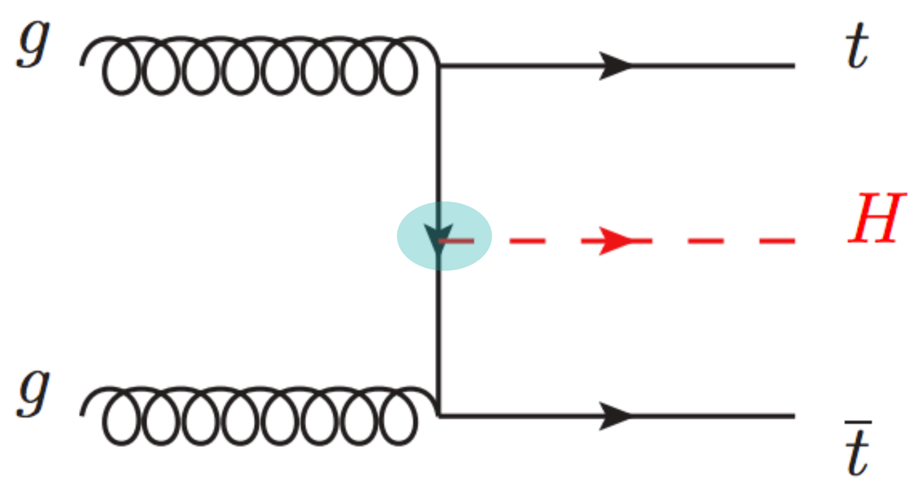
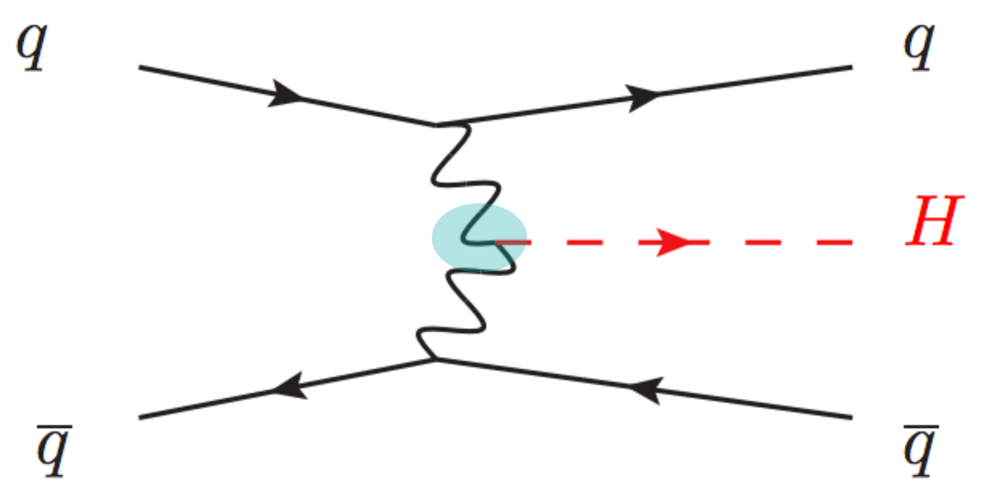
$$+\left|(i\partial_{\mu} - g\frac{1}{2}\boldsymbol{\tau}\cdot\boldsymbol{W}_{\mu} - g'\frac{Y}{2}B_{\mu})\phi\right|^{2} - V(\phi)$$
$$-(G_1\bar{L}\phi R + G_2\bar{L}\phi_C R + \text{hermitian conjugate})$$

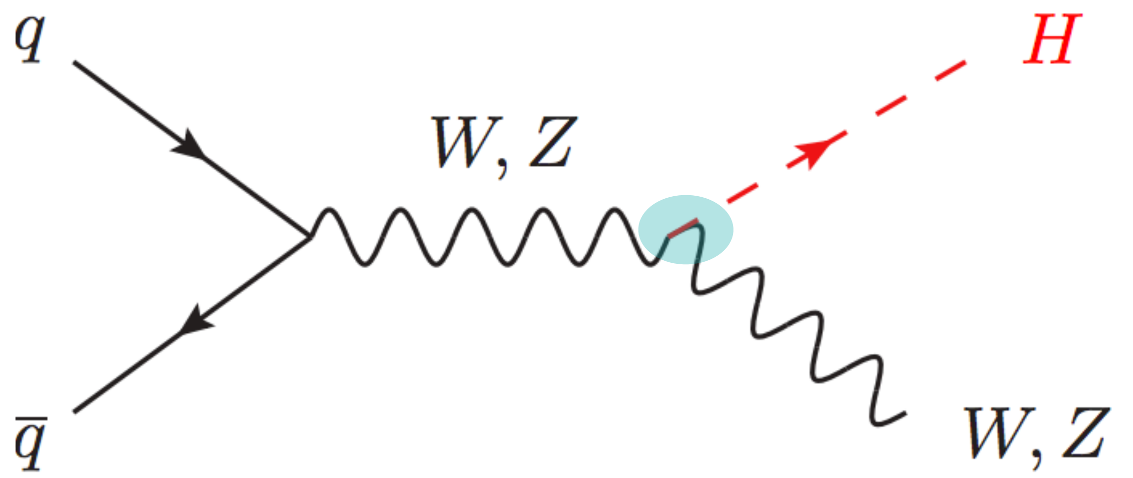
ggF and **ttH** help the determination of the **Yukawa couplings (leptons and quarks)** with the Higgs boson

VBF and **VH** help the determination of the **vector boson couplings** with the Higgs boson









Higgs boson: production modes

~88%

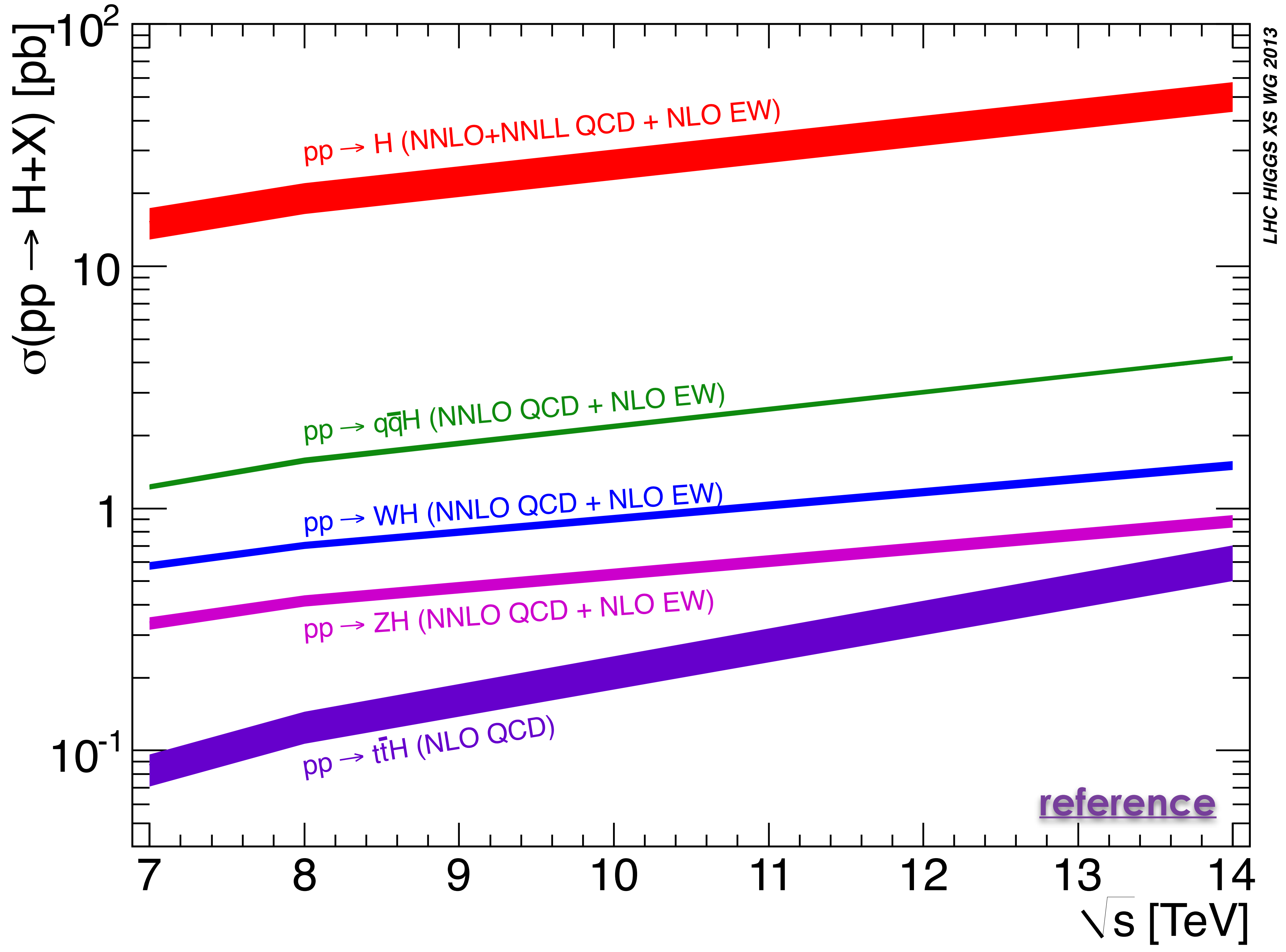
ggF - gluon-gluon fusion

- mediated by the exchange of a virtual top quark;

~7%

VBF - vector boson fusion

- mediated by the exchange of a W or Z boson (via quark scattering)
- Higgs boson radiated off the weak-boson propagator
- scattered quarks give rise to two hard jets in the forward and backward regions of detector
  - clean signature not only for Higgs searches but also for the Higgs couplings at LHC



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VH - associated production with a vector boson (Higgs-Strahlung)

- Higgs boson irradiated through an off-shell W/Z boson
- relatively clean environment for studying the decay H->bb

~1%

ttH - associated production with a top quark pair

- fundamental to directly probe the Yukawa coupling between the quark-top and the Higgs
- Due to its large mass, the top quark Yukawa coupling is expected to be near one (≥ 0.99), differently by the other quarks that have a coupling of ≥ 10^{-2}.

expected cross section (pb)			
channel	7 TeV	8 TeV	13 TeV
ggH	15	19	43
VBF	1.2	1.6	3.7
WH	0.5	0.7	1.4
ZH	0.3	0.4	0.9
ttH	0.09	0.13	0.50

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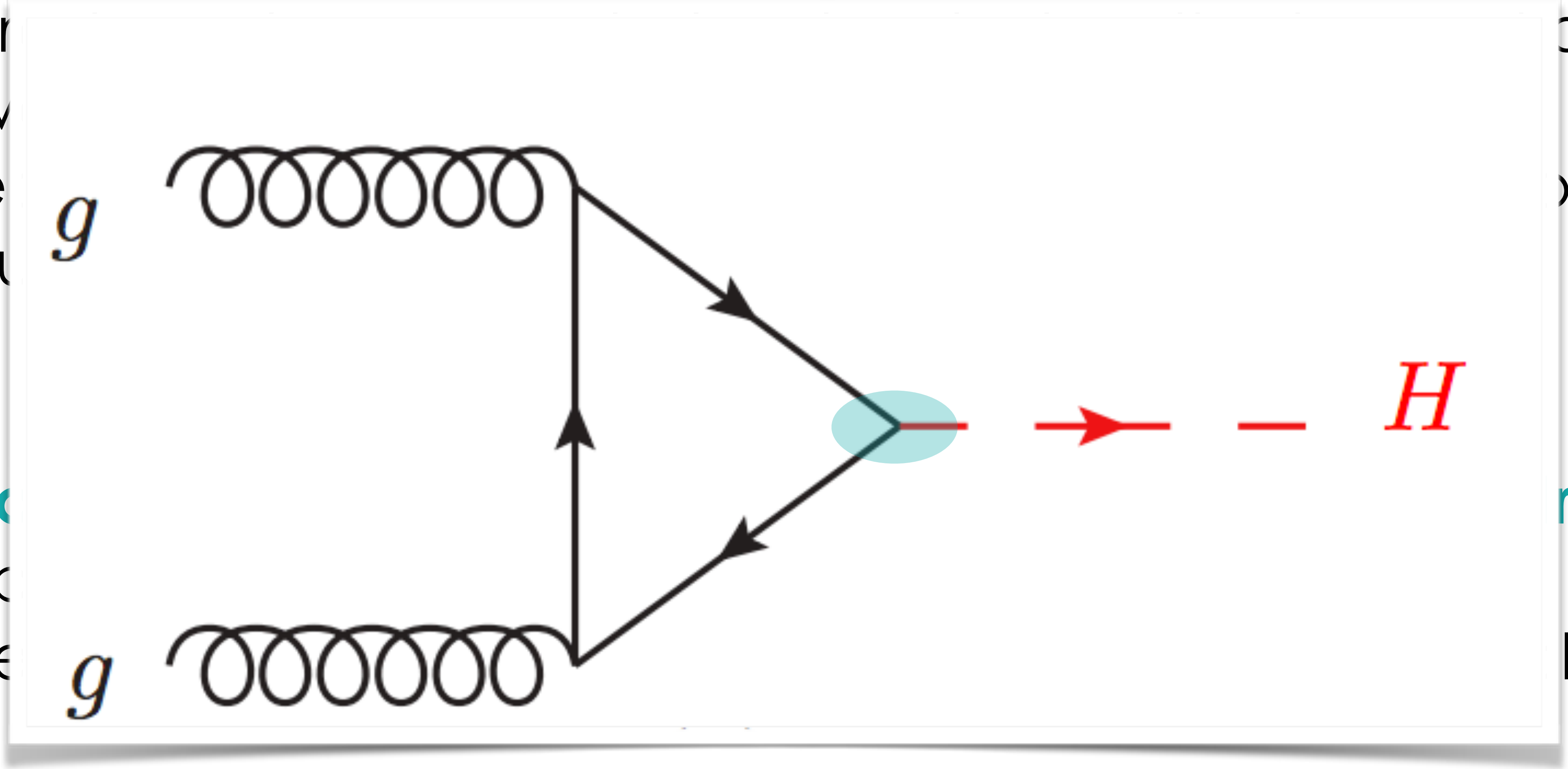

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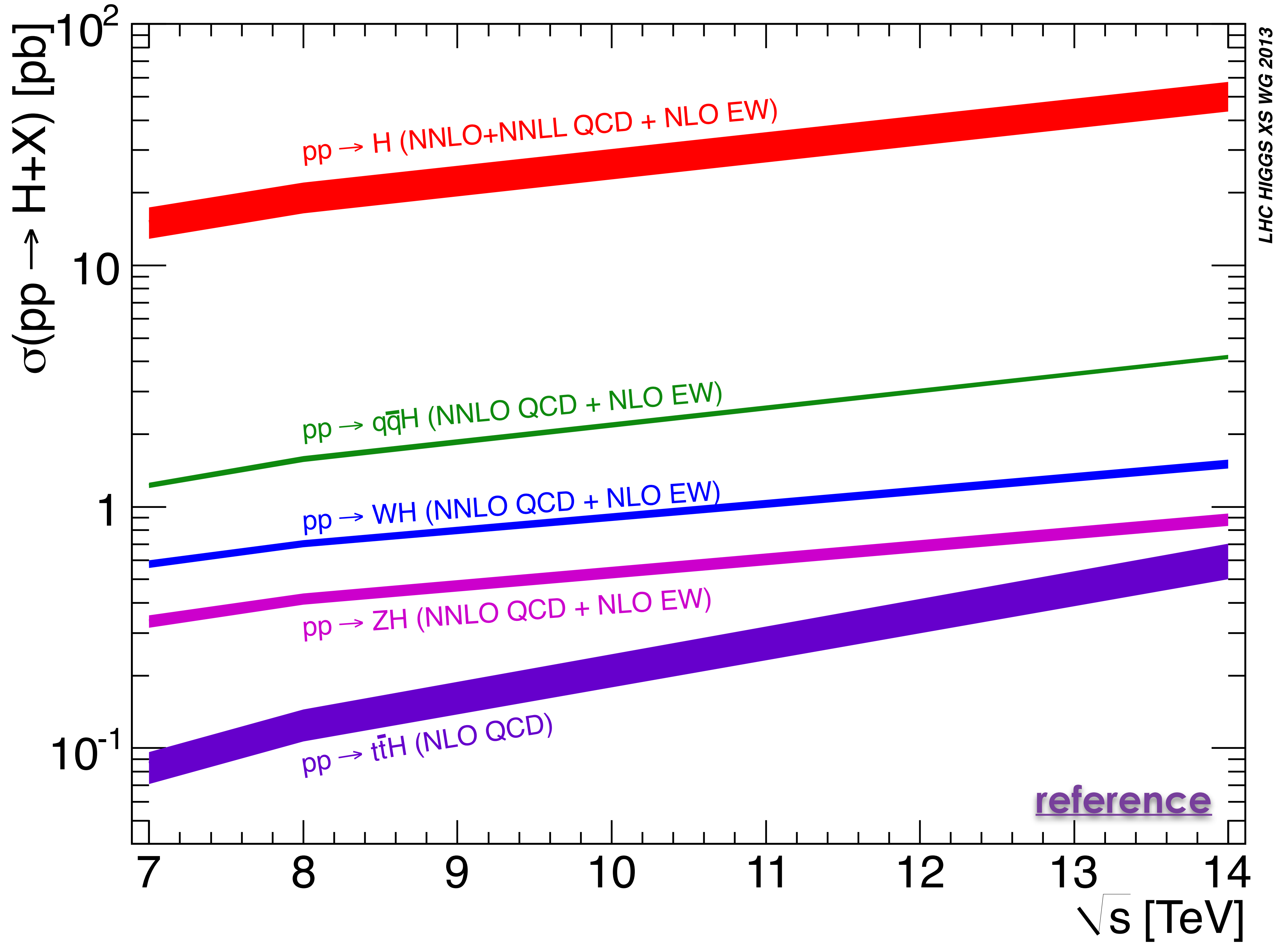

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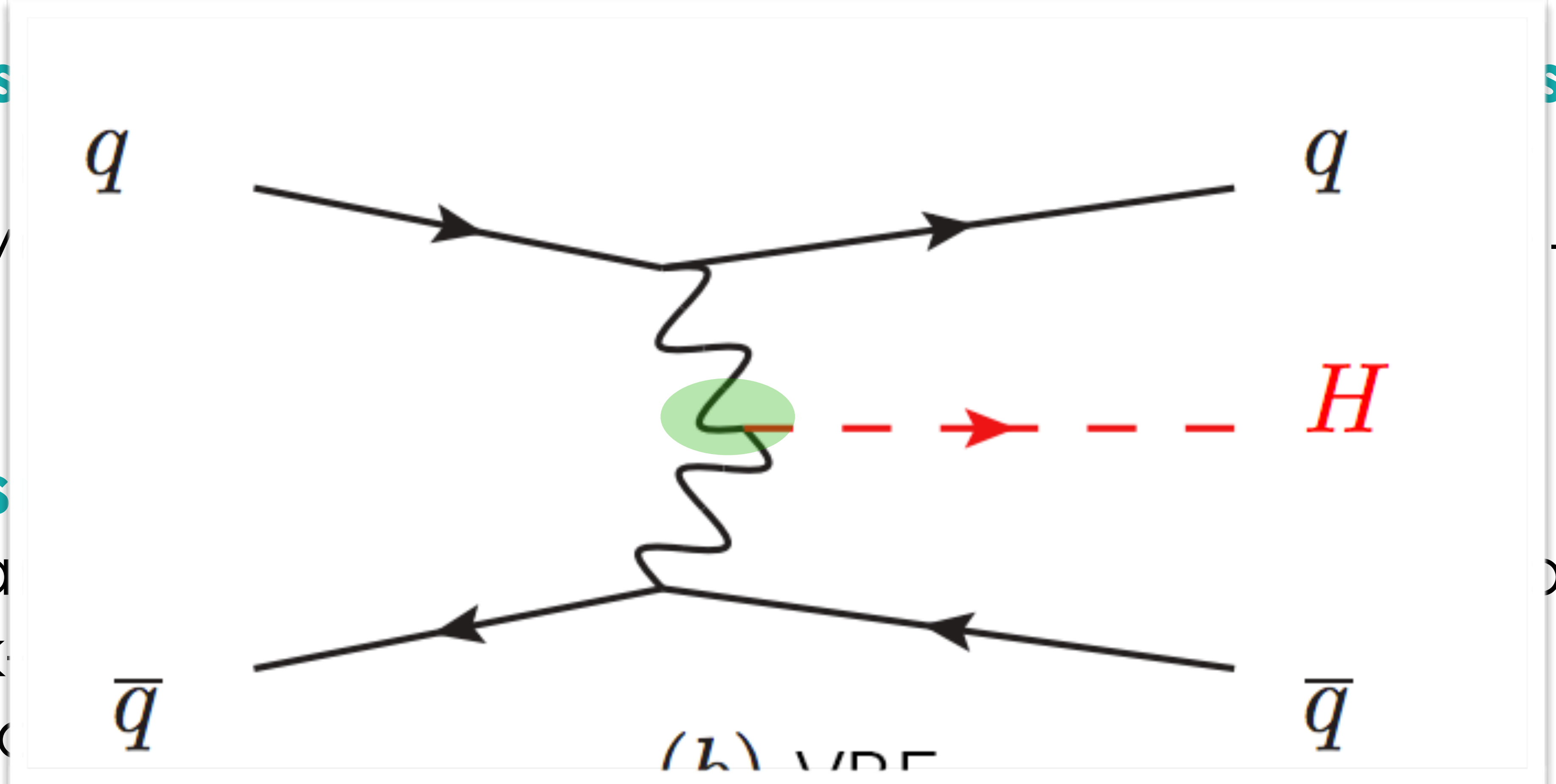

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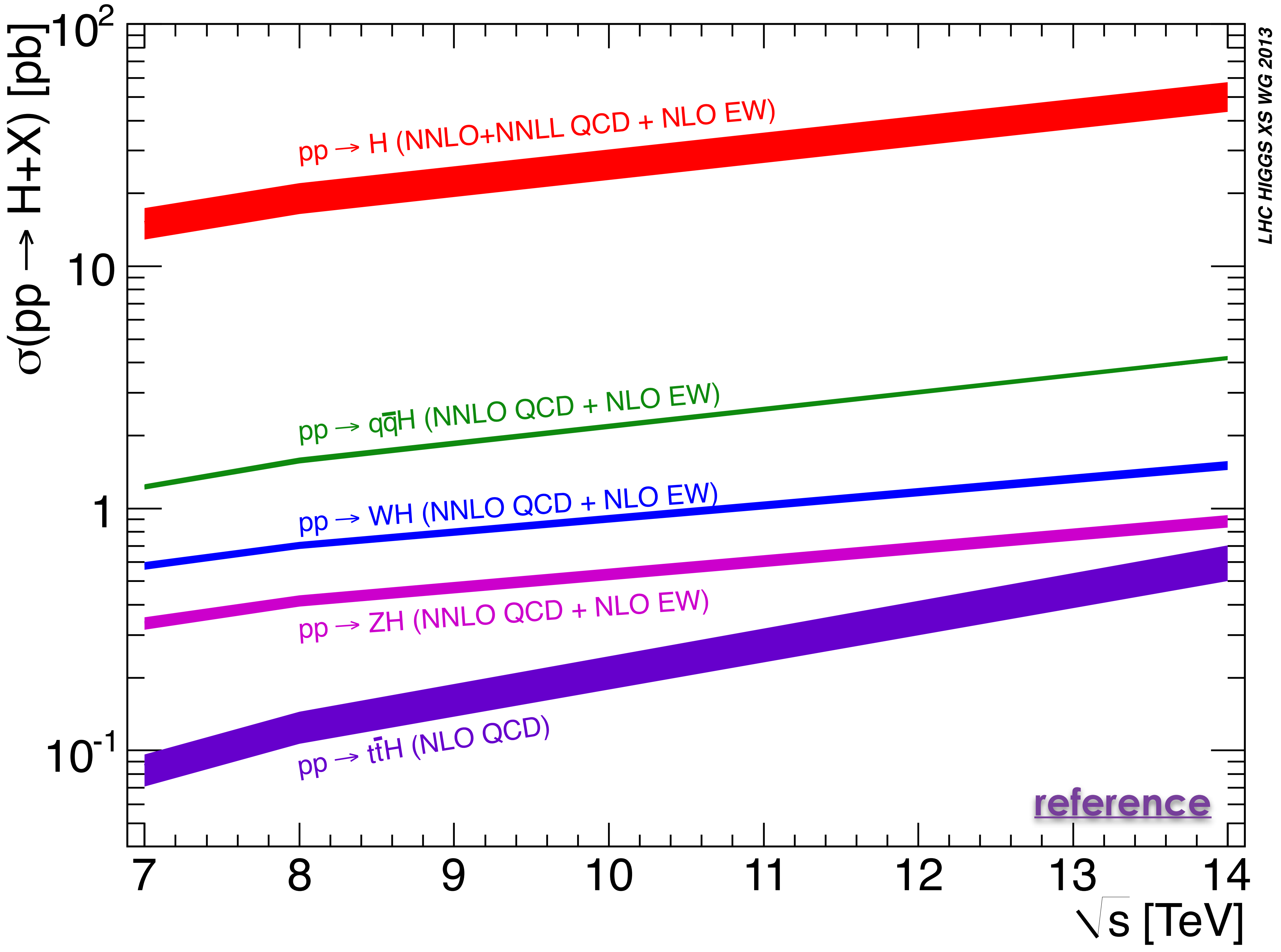

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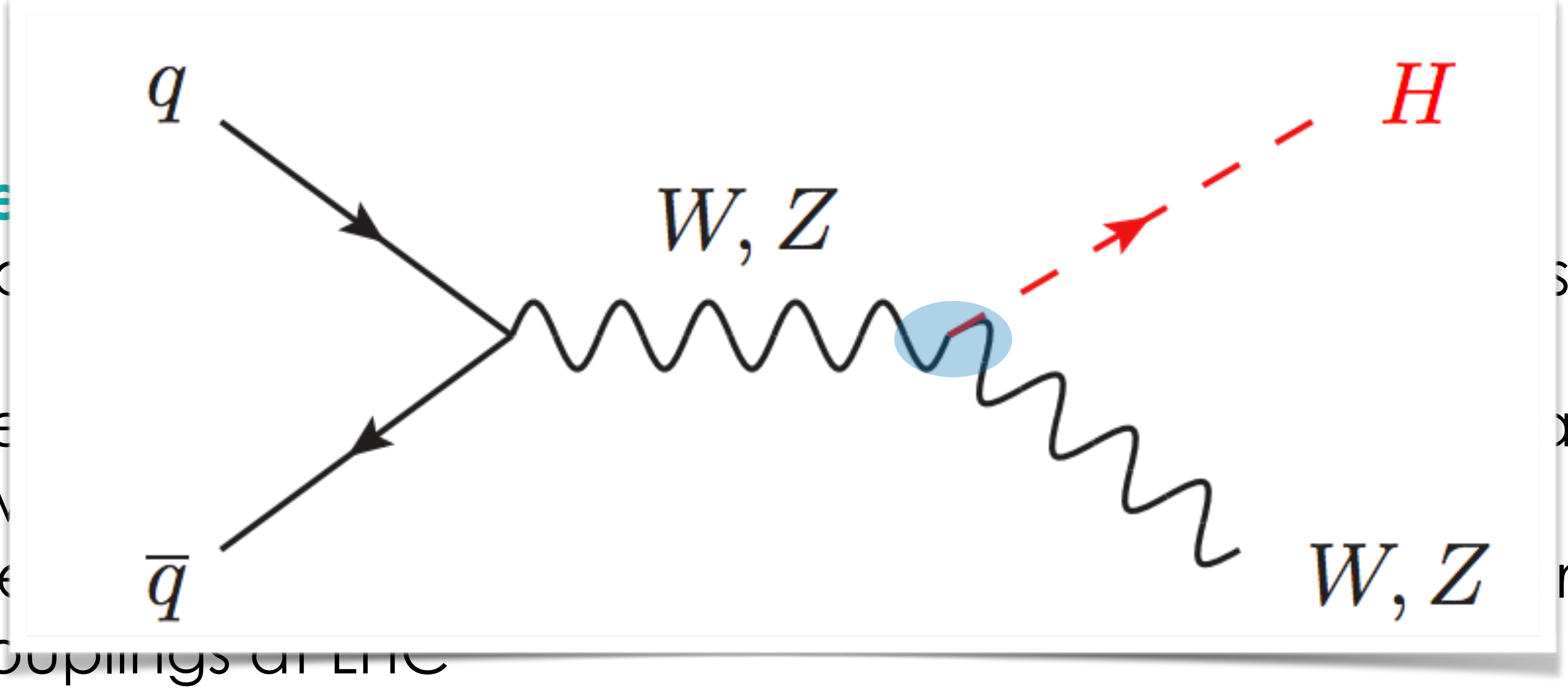

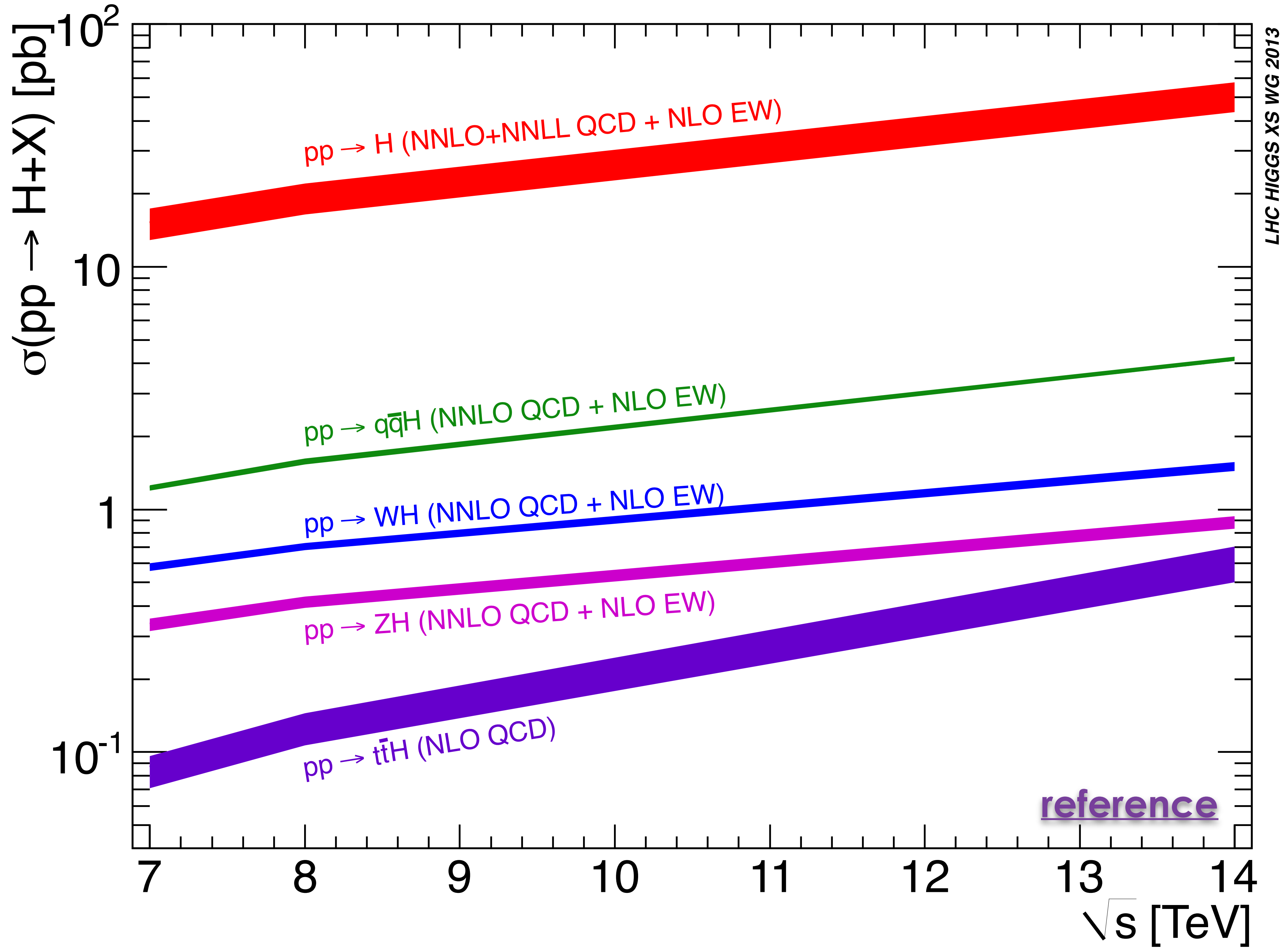

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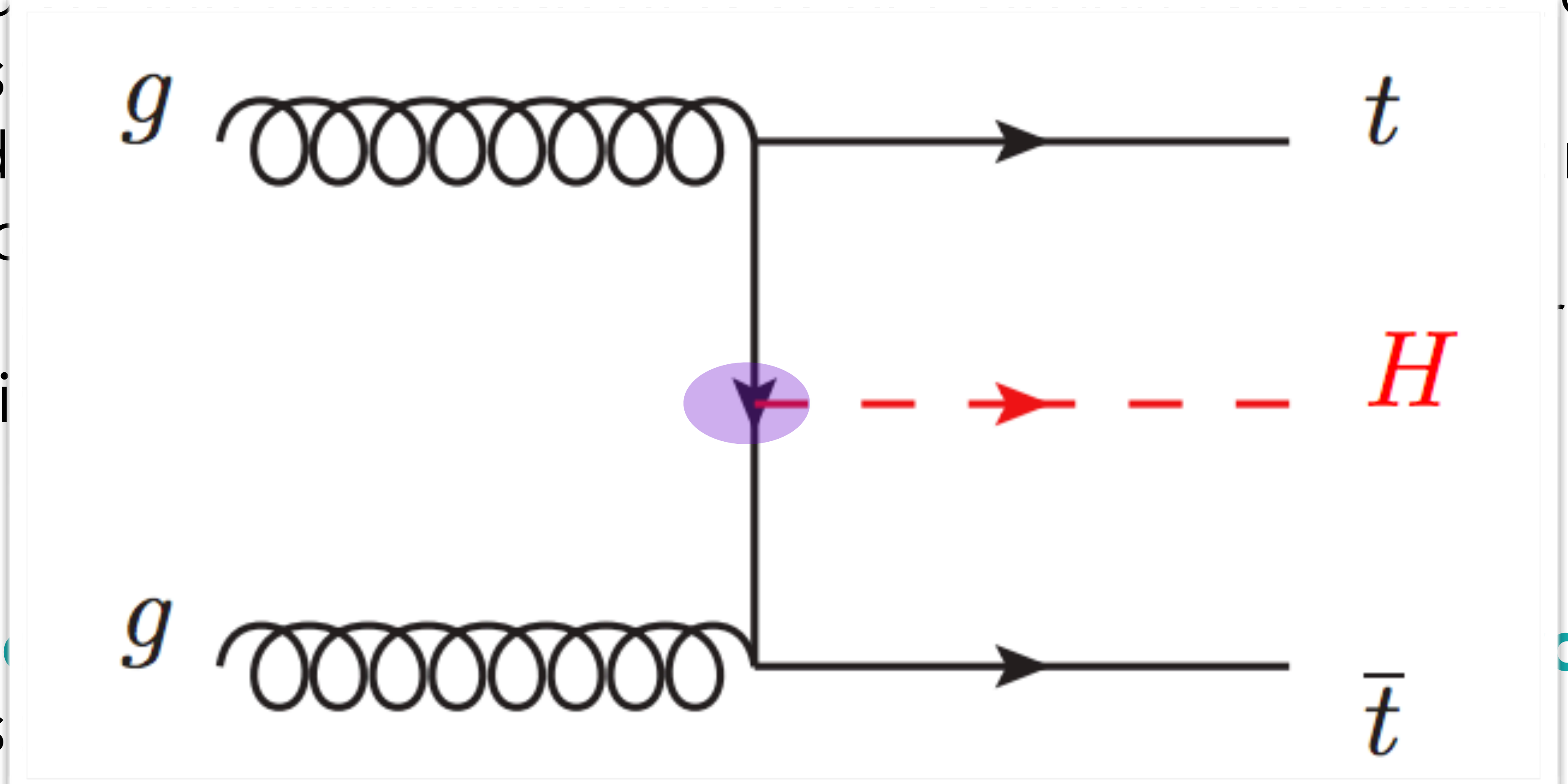

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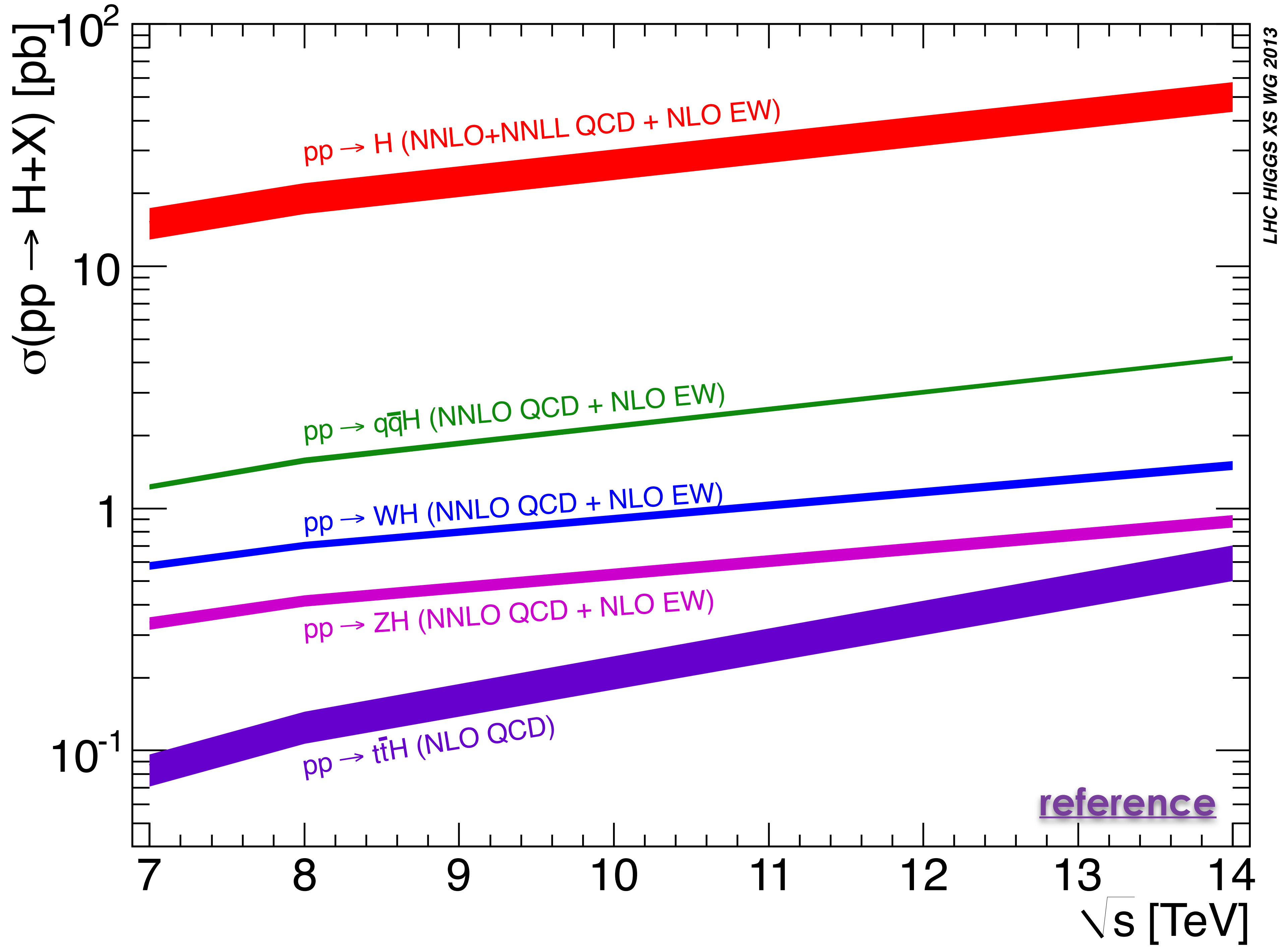

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Higgs boson production cross section

Challenge of the Higgs boson

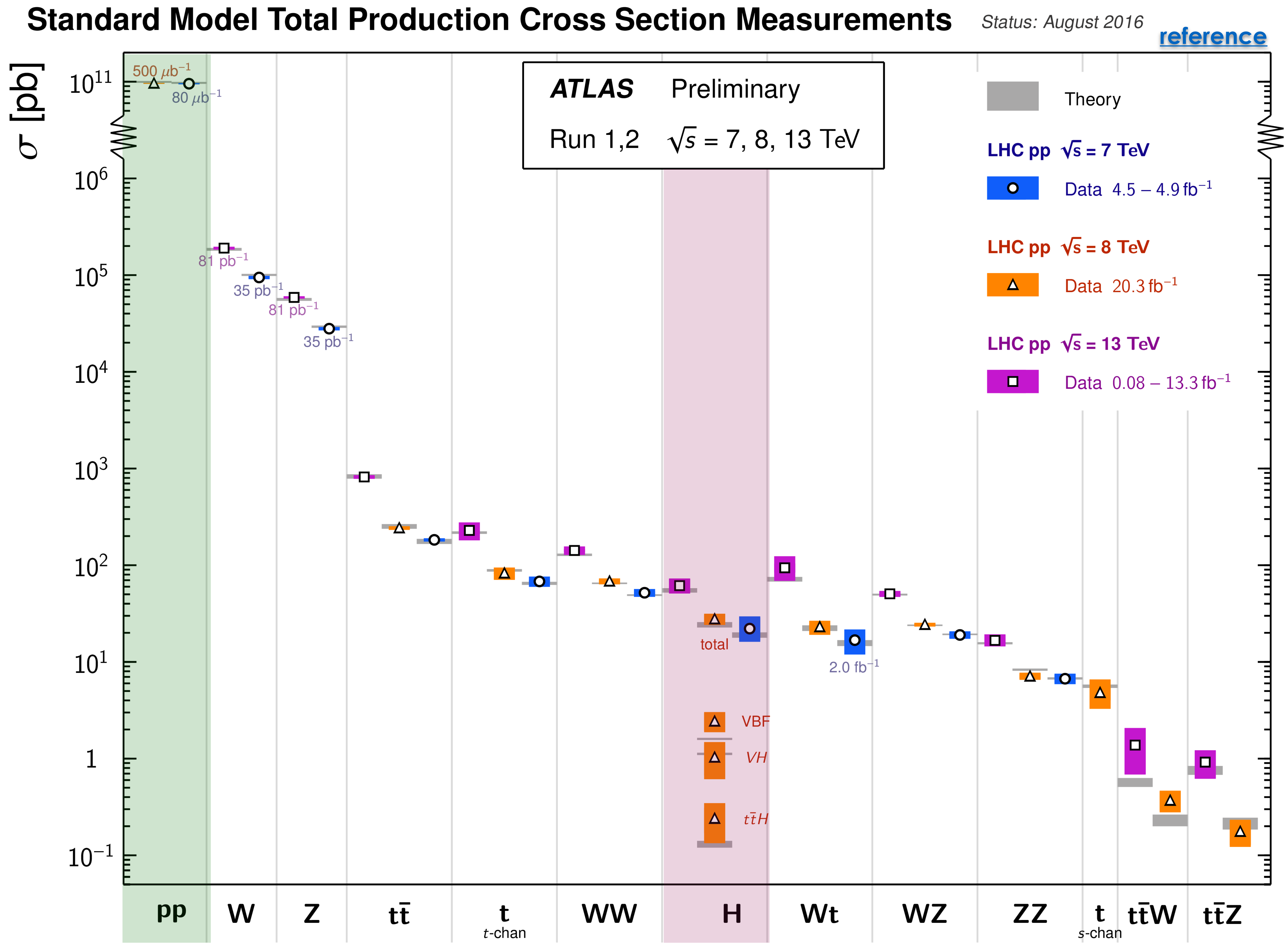
- low production processes probability wrt the total pp collision production at LHC
- precision measurements on its properties difficult if low statistics

Total pp production

- ~10^{11} pb

Higgs production cross section

- ~50 pb



Higgs boson: decay modes

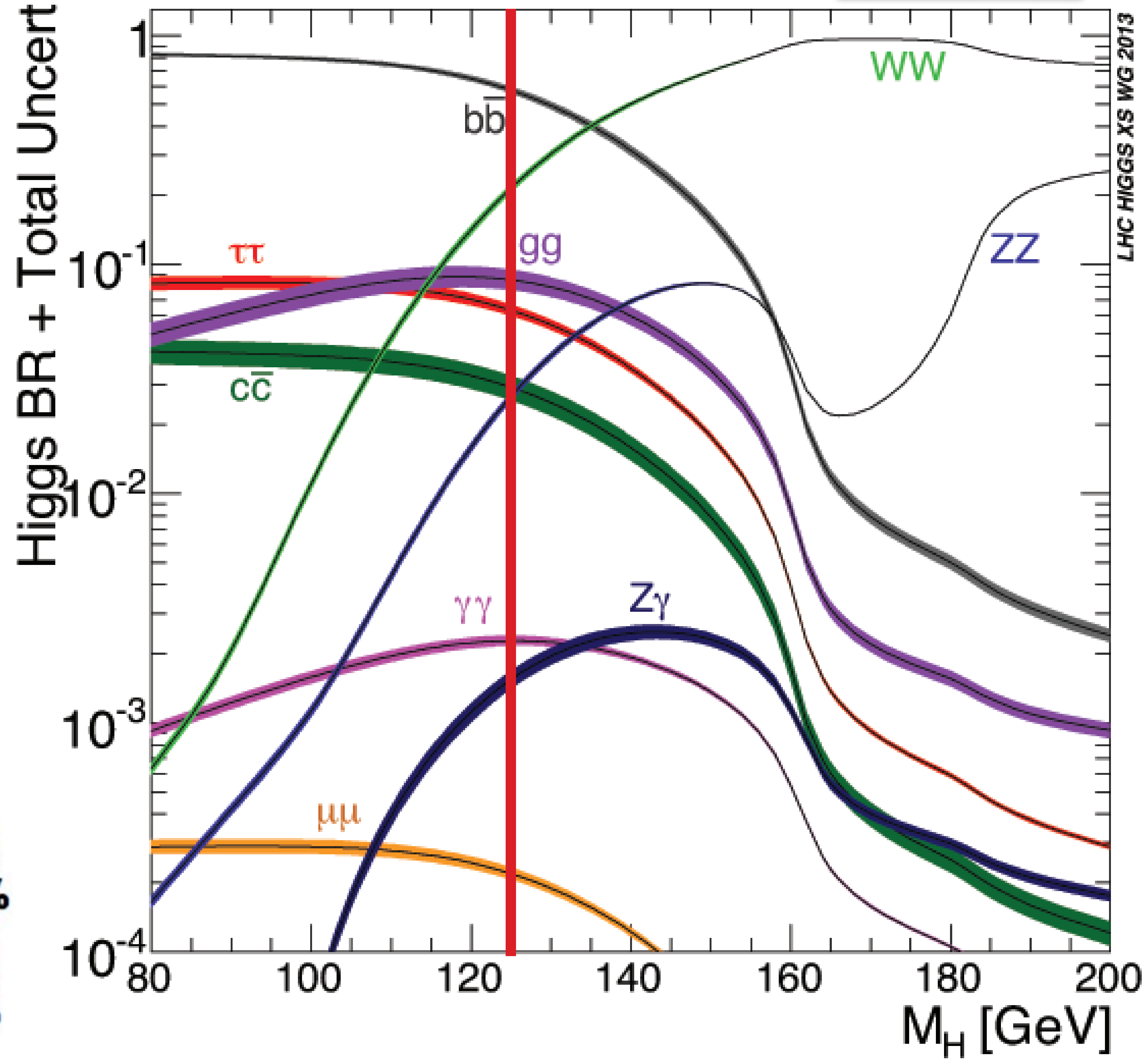
Lepton and quark pair decay channels

$$\Gamma(H \to l^+l^-) = \frac{G_F m_l^2}{4\sqrt{2}\pi} m_H \beta^3 \qquad \Gamma(H \to q\bar{q}) = \frac{3 G_F m_q^2}{4\sqrt{2}\pi} m_H \beta^3 \left[1 + \frac{3}{4}\frac{\alpha_s}{\pi}\Delta_H^{QCD}\right]$$

* $\beta = (1 - 4m_f^2/m_H^2)^{1/2}$

- Among the quark decay channels, the **bb has the highest BR, but it is not measurable in all the production mechanisms**;
- in the ggF production, for example, it would be totally overwhelmed by background processes, such as Z→qq and qq→bb, whose cross sections are many orders of magnitude larger

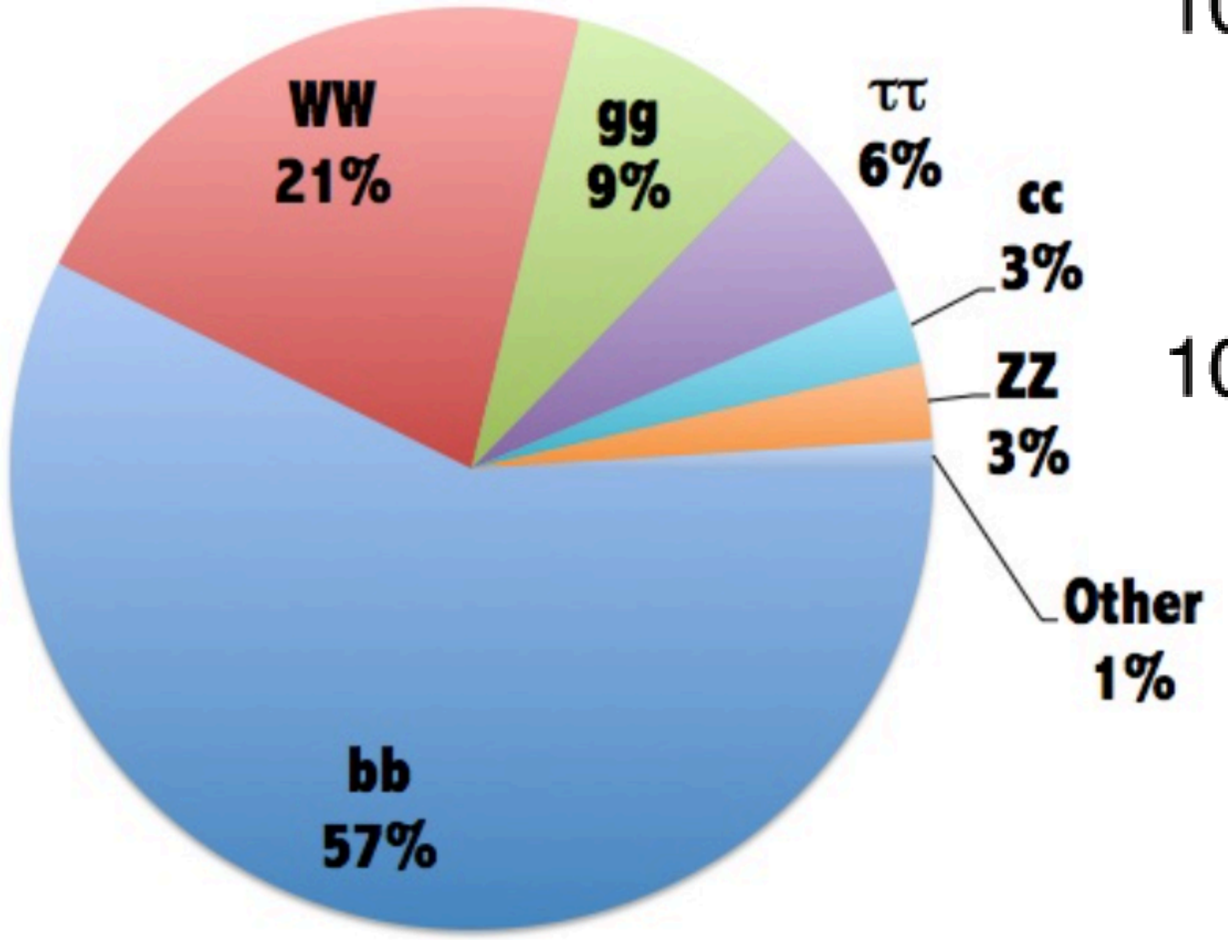
reference



W, Z and γ decay channels

$$\Gamma(H \to VV^*) = \delta_V \frac{\sqrt{2} G_F}{32\pi} m_H^3 (1 - 4x + 12x^2)\beta$$

* $x = m_V^2/m_H^2 \qquad \beta = (1-4x)^{1/2} \qquad \delta_V = 2\,(1)$ for V = W (Z)

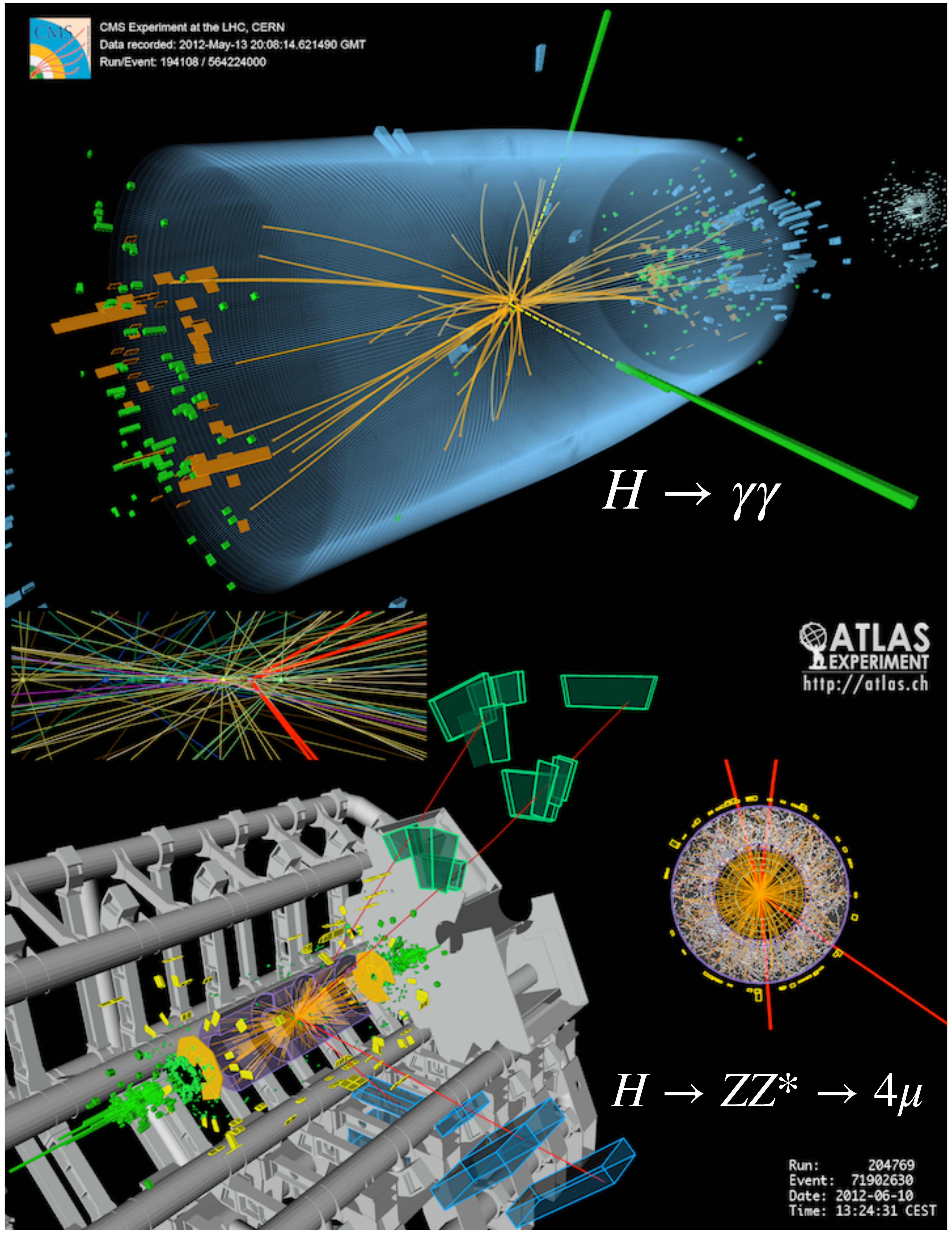


Higgs boson discovery

The discovery of the Higgs boson

- As a confirmation of the prediction, **the discovery of a new boson was announced by ATLAS and CMS experiments on 4th of July 2012 at CERN**.

François Englert and Peter Higgs during the celebration of the Higgs boson discovery, at CERN.



The discovery of the Higgs boson: decay modes

- Observation of a new particle in the search for the Standard Model Higgs boson with the ATLAS detector at the LHC
- Observation of a new boson at a mass of 125 GeV with the CMS experiment at the LHC

ATLAS

8 TeV
5.8 fb^{-1}

$$H \to ZZ^* \to 4l$$
$$H \to \gamma\gamma$$
$$H \to WW^* \to e\nu\mu\nu$$

7 TeV
4.8 fb^{-1}

$$H \to b\bar{b}$$
$$H \to \tau^+\tau^-$$
$$H \to ZZ^* \to 4l$$
$$H \to \gamma\gamma$$

CMS

$$H \to ZZ^* \to 4l$$
$$H \to \gamma\gamma$$
$$H \to WW^* \to e\nu\mu\nu$$
$$H \to b\bar{b}$$
$$H \to \tau^+\tau^-$$

8 TeV + 7 TeV
4.8 fb^{-1} + 5.8 fb^{-1}

The discovery of the Higgs boson: decay modes

- [Observation of a new particle in the search for the Standard Model Higgs boson with the ATLAS detector at the LHC]
- [Observation of a new boson at a mass of 125 GeV with the CMS experiment at the LHC]

ATLAS

8 TeV
5.8 fb^{-1}

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

$H \to \gamma\gamma$

$H \to WW^* \to e\nu\mu\nu$

7 TeV
4.8 fb^{-1}

$H \to b\bar{b}$

$H \to \tau^+\tau^-$

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

$H \to \gamma\gamma$

improved

CMS

8 TeV + 7 TeV
4.8 fb^{-1} + 5.8 fb^{-1}

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

$H \to \gamma\gamma$

$H \to WW^* \to e\nu\mu\nu$

$H \to b\bar{b}$

$H \to \tau^+\tau^-$

The discovery of the Higgs boson: $H \rightarrow 4l$

ATLAS | **CMS**

Main backgrounds

continuum ZZ* (irreducible), Z + jets and tt production (reducible)

ATLAS

- wide mass range (**110–600 GeV**);
- selecting **two pairs of isolated leptons with same flavour and opposite charge** ($\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} > 0.1$ if the same flavour, $\Delta R > 0.2$ otherwise)

Selection and categorisation of events:

- combination of the lepton quadruplet in the event, categorised in terms of **p_T** and **invariant mass** (the closest to the Z mass);
- all possible selected lepton pairs must satisfy **$m_{ll} > 5$ GeV** (to reject J/ψ mesons backgrounds)
- **4 sub-channels**: 4e, 2e2μ, 2μ2e and 4μ, arranged by the flavour of the leading lepton pair.

CMS

- low-mass range (**110–160 GeV**);
- selecting **two pairs of isolated leptons with same flavour and opposite charge** ($\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} > 0.3/0.4$)

Selection and categorisation of events:

- pair with invariant mass closest to the Z boson mass is required to have a mass in the range **40–120 GeV**;
- the other pair is required to have a mass in the range **12–120 GeV**;
- **3 sub-channels**: 4e, 2e2μ and 4μ, arranged by the flavour of the leading lepton pair;
- **kinematic discriminant** is constructed based on the probability ratio of the signal and background hypotheses (five angles and the invariant masses of the two lepton pairs): **$K_D = P_{sig}/(P_{sig}+P_{bkg}) > 0.5$** .

The discovery of the Higgs boson: H → 4*l*

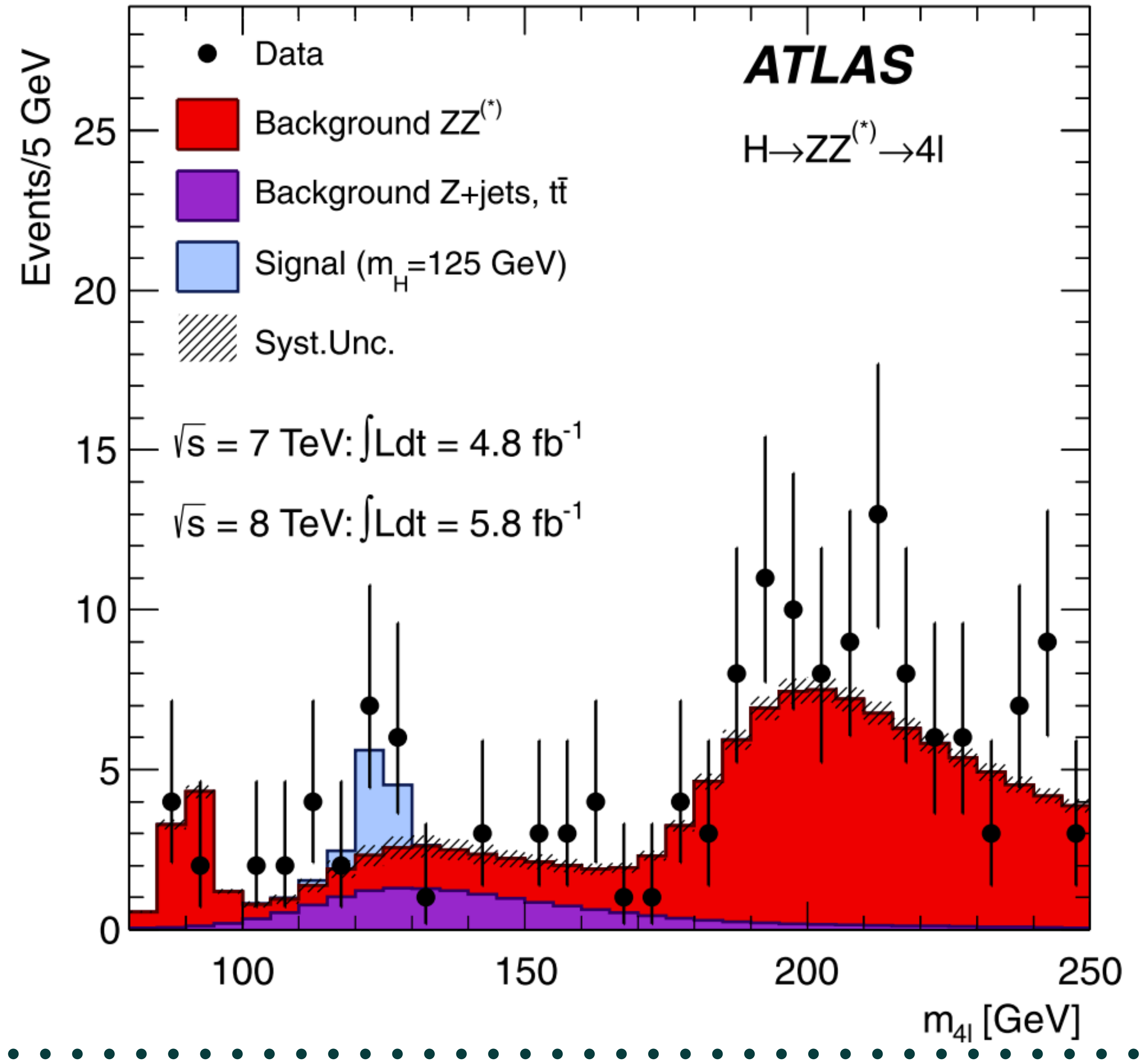
ATLAS

MC simulation normalised to the theoretical cross section

normalisation factors fitted in control regions from data

	Signal	$ZZ^{(*)}$	$Z+$jets, $t\bar{t}$	Observed
4μ	2.09 ± 0.30	1.12 ± 0.05	0.13 ± 0.04	6
$2e2\mu/2\mu2e$	2.29 ± 0.33	0.80 ± 0.05	1.27 ± 0.19	5
$4e$	0.90 ± 0.14	0.44 ± 0.04	1.09 ± 0.20	2

Systematic uncertainties:
- integrated luminosity;
- lepton reco, ID and resolution;
- lepton energy scale;
- jet energy scale and ETmiss;
- theory uncertainties, affecting mainly the signal predictions

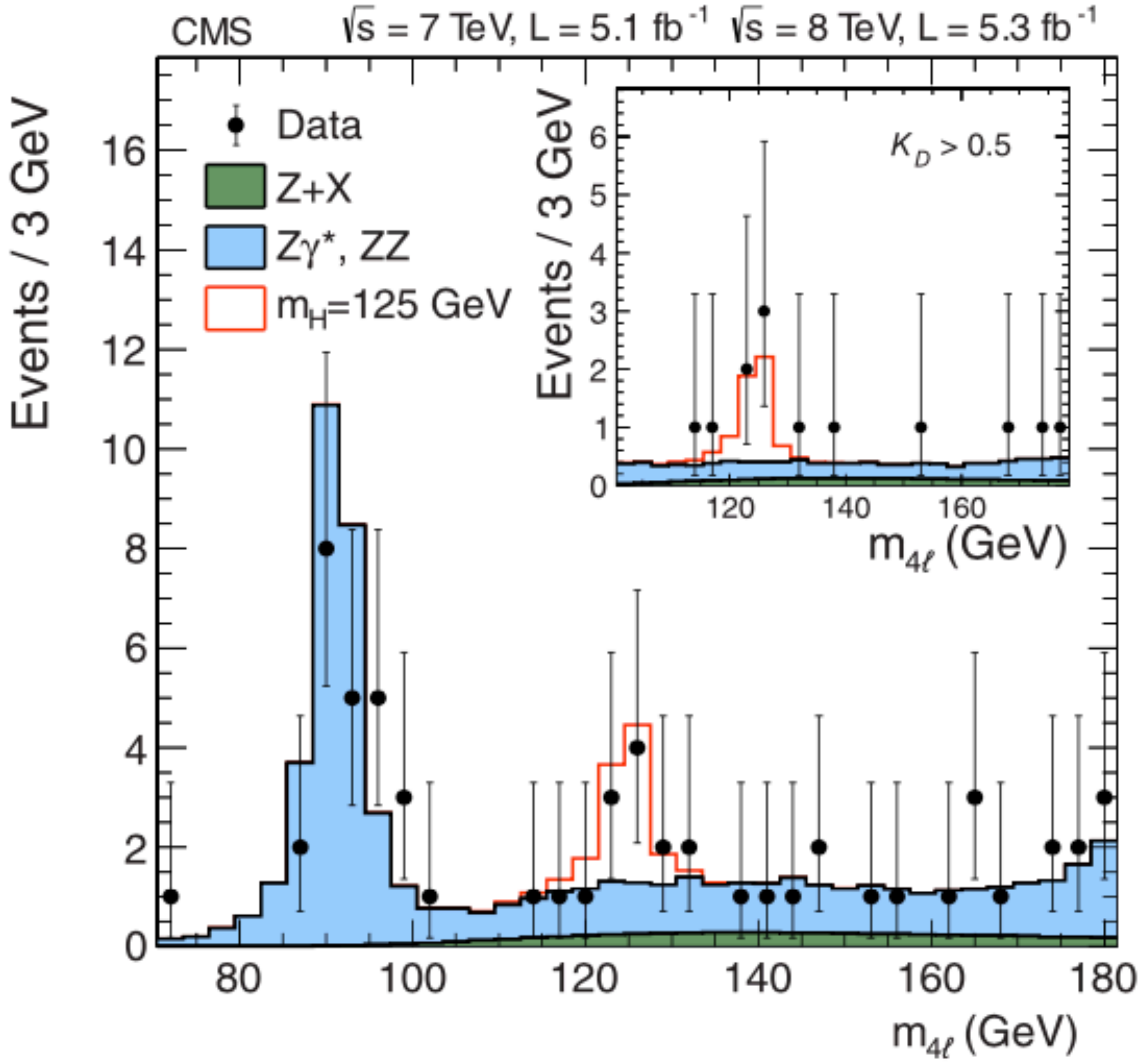


CMS

MC simulation normalised to the theoretical cross section

normalisation factors fitted in control regions from data

Channel	4e	4μ	$2e2\mu$	4ℓ
ZZ background	2.7 ± 0.3	5.7 ± 0.6	7.2 ± 0.8	15.6 ± 1.4
$Z+X$	$1.2^{+1.1}_{-0.8}$	$0.9^{+0.7}_{-0.6}$	$2.3^{+1.8}_{-1.4}$	$4.4^{+2.2}_{-1.7}$
All backgrounds ($110 < m_{4\ell} < 160$ GeV)	4.0 ± 1.0	6.6 ± 0.9	9.7 ± 1.8	20 ± 3
Observed ($110 < m_{4\ell} < 160$ GeV)	6	6	9	21
Signal ($m_H = 125$ GeV)	1.36 ± 0.22	2.74 ± 0.32	3.44 ± 0.44	7.54 ± 0.78
All backgrounds (signal region)	0.7 ± 0.2	1.3 ± 0.1	1.9 ± 0.3	3.8 ± 0.5
Observed (signal region)	1	3	5	9



Systematic uncertainties:
- integrated luminosity;
- lepton reco, ID and resolution;
- lepton energy scale;
- jet energy scale and ETmiss;
- limited statistical precision in the reducible background control regions.

The discovery of the Higgs boson: $H \to \gamma\gamma$

ATLAS | **CMS**

Main backgrounds

QCD production of two photons (irreducible), reconstructed photon candidates from jet fragments misidentification (reducible)

ATLAS

- mass range: **100-160 GeV**;
- **$m_{\gamma\gamma}$** evaluated using the photon energies measured in the calorimeter, the azimuthal angle φ between the photons in calo and the values of η calculated from the position of the identified primary vertex and the impact points of the photons in the calorimeter.

Selection and categorisation of events:

- Photon candidates requirements: **|η|<2.37**, (excluding the calorimeter barrel/end-cap transition region 1.37<|η|<1.52), **E_T>40 GeV (30 GeV)** for leading (sub-leading);
- **10 mutually exclusive categories** with different mass resolutions and S/B ratios:
  - 1 exclusive category with 2 jets (improves the sensitivity to VBF);
  - 9 categories defined by the presence or not of converted photons, η of the selected photons and p_{Tt}*

* the component of the diphoton p_T, orthogonal to the axis defined by the difference between the two photon momenta

$$p_{Tt} = \frac{|(\mathbf{p}_T^{\gamma_1} + \mathbf{p}_T^{\gamma_2}) \times (\mathbf{p}_T^{\gamma_1} - \mathbf{p}_T^{\gamma_2})|}{\mathbf{p}_T^{\gamma_1} - \mathbf{p}_T^{\gamma_2}}$$

CMS

- mass range: **100-150 GeV**;
- Boosted Decision Tree (**BDT**) trained to enhance the signal-like events:
  - photon quality, expected mass resolution, per-event estimate of the probability of locating the diphoton vertex within 10 mm of its true location along the beam direction, kinematic characteristics of the photons and the diphoton system.

Selection and categorisation of events:

- Photon candidates requirements: **|η|<2.5**, (excluding the calorimeter barrel/end-cap transition region 1.44<|η|<1.57), **p_T>$m_{\gamma\gamma}$/3 ($m_{\gamma\gamma}$/4)** for leading (sub-leading) γ;
- **6 mutually exclusive categories** with different S/B ratios and jets:
  - 4 categories based on BDT output and no jets;
  - 2 categories with 2 jets (tight: m_{jj}>500 GeV and p_T>30 GeV).

The discovery of the Higgs boson: H → γγ

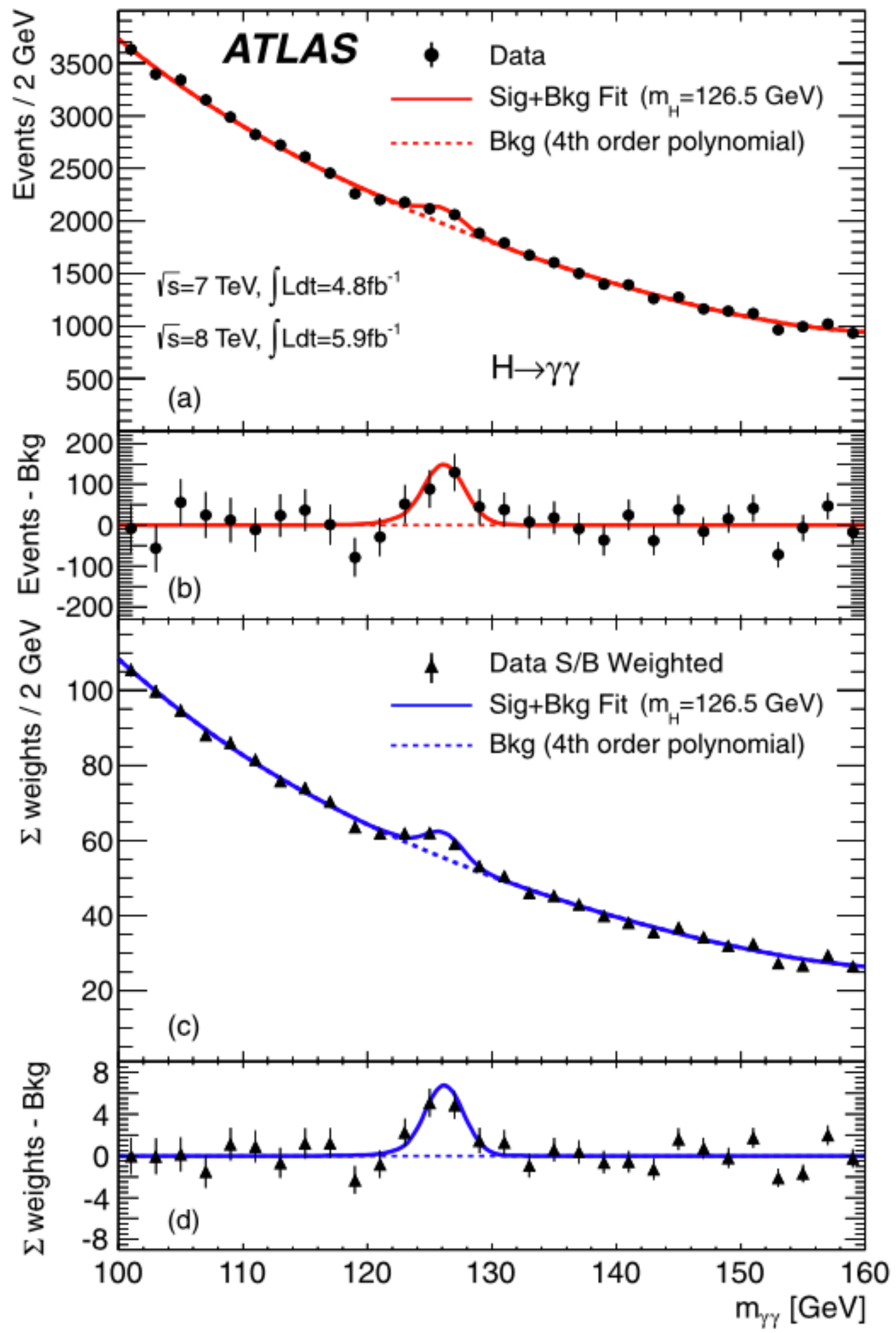
ATLAS

Background estimation:

- in each category, **from data by fitting the diphoton mass spectrum** with free parameters of shape and normalisation
- different models for the different categories to limit a potential bias and keep good statistical power

Systematic uncertainties:

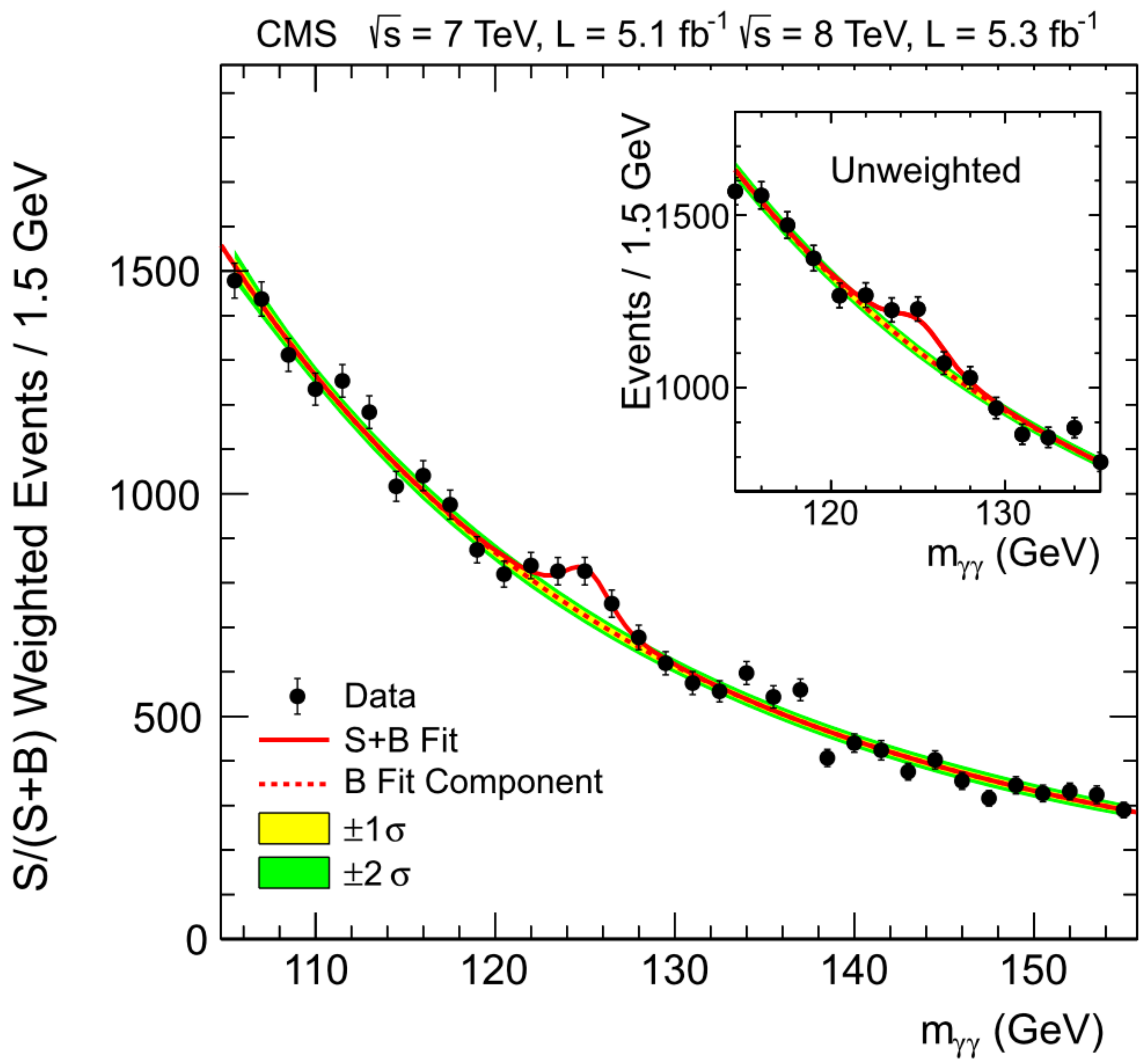
- integrated luminosity;
- photon reconstruction and identification efficiency;
- pile-up modelling;
- photon isolation;
- theory uncertainties, affecting mainly the signal predictions



CMS

Background estimation:

- in each category, **from data by fitting the diphoton mass spectrum** in an extended mass range (100-180 GeV)
- **independent analysis performed** using a different approach to the background modelling:
  - fit to the output of an additional BDT taking as input the diphoton invariant mass and the diphoton BDT output;
  - background model derived from the sidebands of the invariant mass distribution;
  - fit used to obtain the background normalisation.



Systematic uncertainties:

- integrated luminosity;
- photon reconstruction and identification efficiency;
- pile-up modelling;
- photon isolation;
- theory uncertainties, affecting mainly the signal predictions

The discovery of the Higgs boson: results

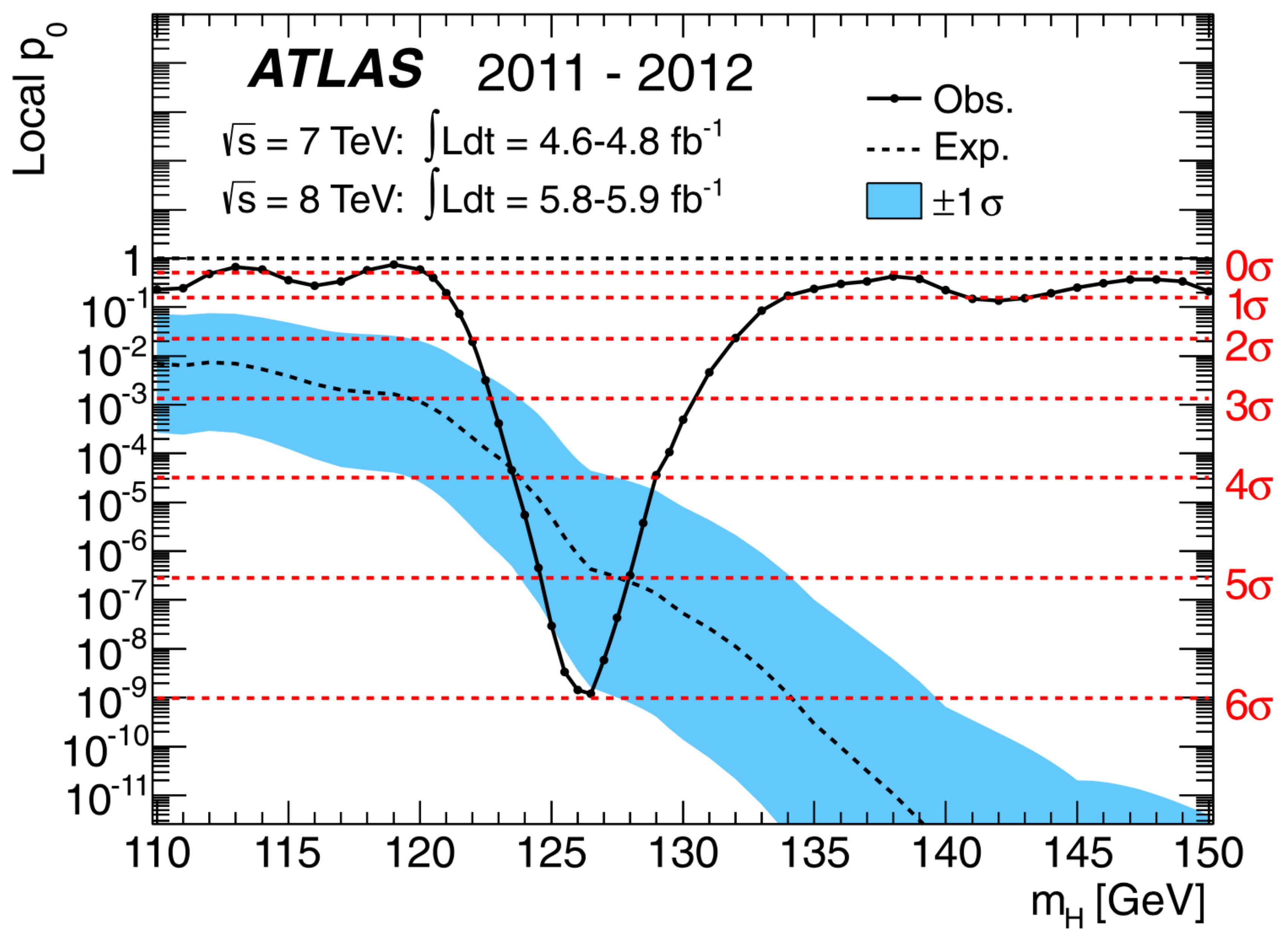
ATLAS **CMS**

$$\mu = \frac{\sigma_{\text{observed}}}{\sigma_{\text{SM}}}$$

Statistical procedure:

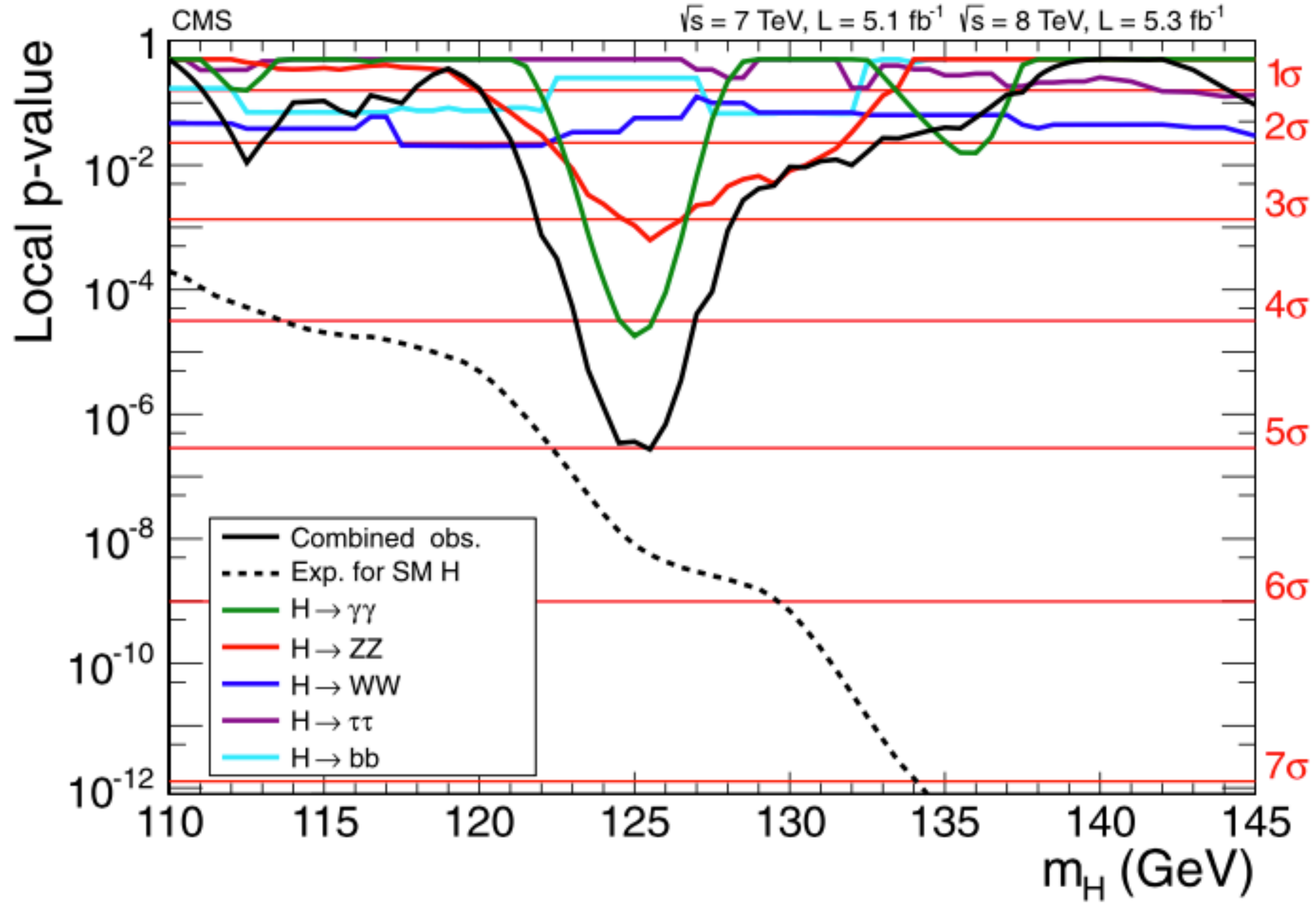
- full likelihood fit to the data, including all the parameters that describe the systematic uncertainties and their correlations

- A SM Higgs boson with a certain mass m_H is considered **excluded at 95% confidence level (CL) when μ = 1 is excluded at that mass**:
  - The significance of an excess in the data is first quantified with the **local p_0**, the probability that the background can produce a fluctuation greater than or equal to the excess observed in data.
  - The equivalent formulation in terms of number of standard deviations, **Z_l**, is referred to as the **local significance**.
  - the **"look elsewhere" effect** used to calculate the ratio global/local probabilities for the most significant excess to be observed anywhere.



Systematic treatment:

- uncorrelated systematic: background normalisations or background model parameters, the MC simulation statistical uncertainties and the theoretical uncertainties affecting the background processes
- correlated systematic: all the others



The discovery of the Higgs boson: results

ATLAS

Excluded mass regions:

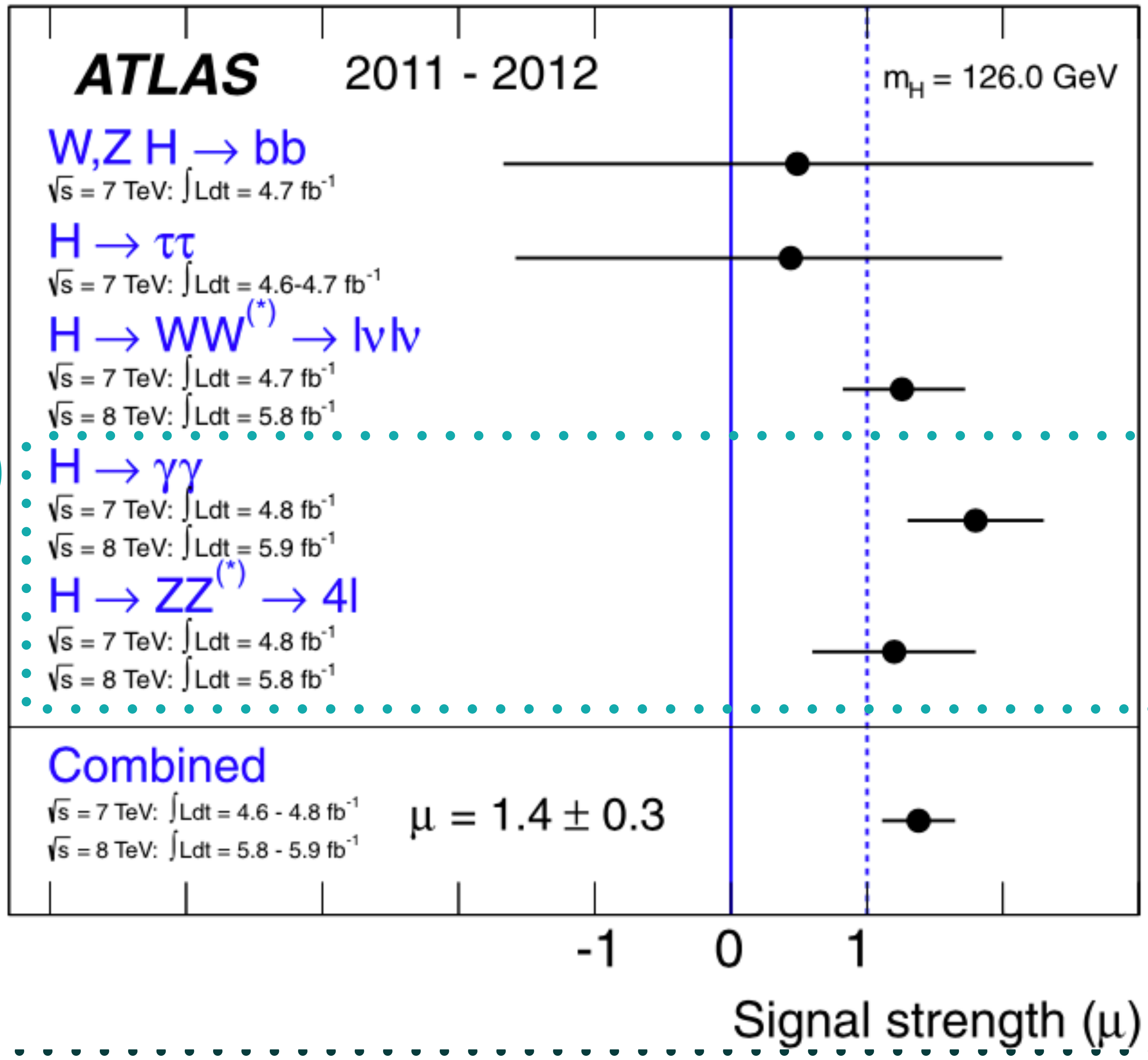
- Three mass regions are excluded at 99% CL, **113–114, 117–121 and 132–527 GeV**.

Observation of an excess of events:

- Clear evidence for the production of a neutral boson with a measured mass of **126.0±0.4 (stat)±0.4 (sys) GeV**
- **local significance of 6.0σ (4.9σ expected)**, at a mass near 125 GeV

4.5σ (2.5σ)

3.6σ (2.7σ)



most significant excess in the two decay modes with the best mass resolution, γγ and ZZ

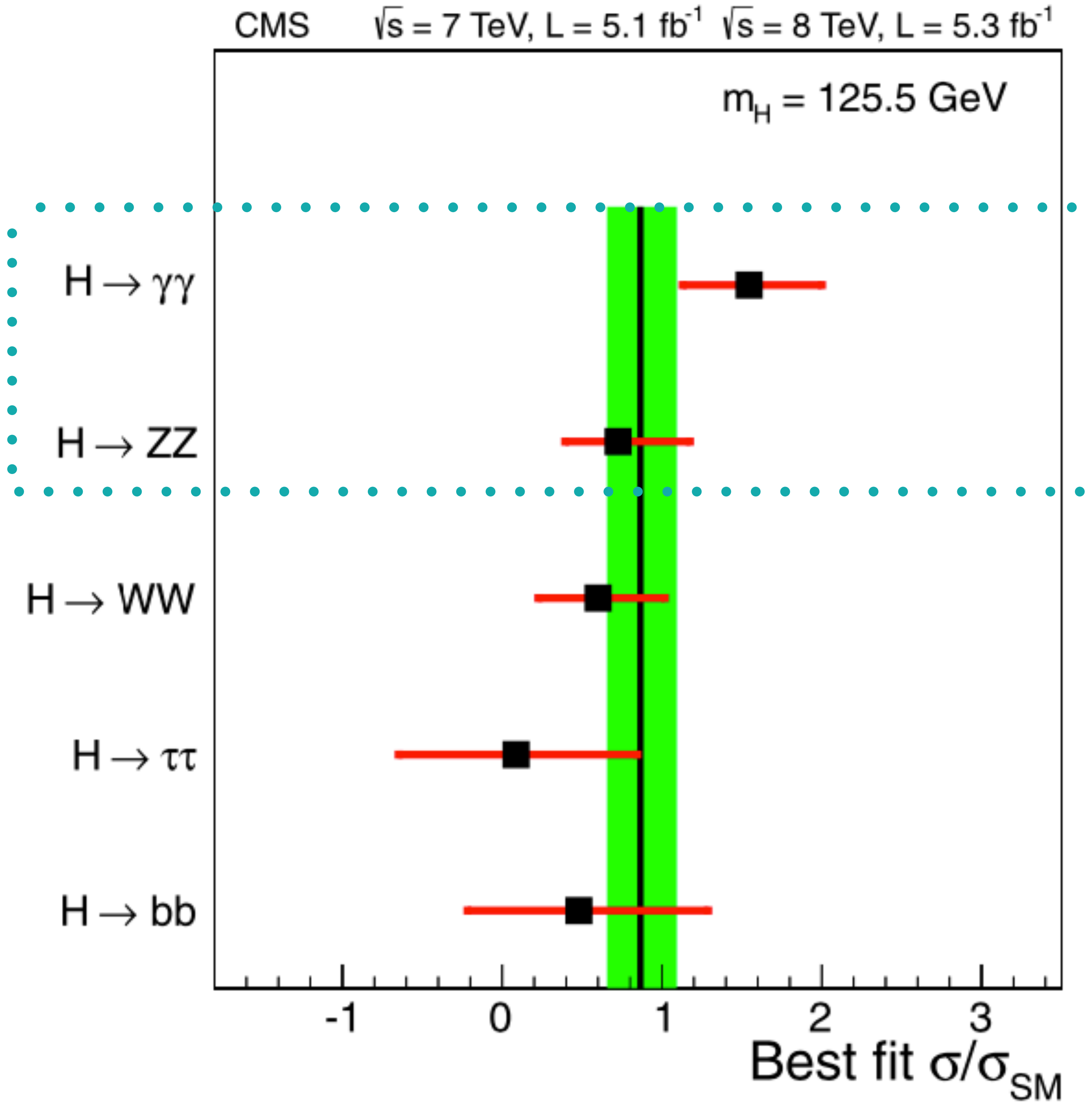
CMS

Excluded mass regions:

- Mass regions excluded at 99% CL: **110–121.5 and 128–600 GeV**.

Observation of an excess of events:

- Clear evidence for the production of a neutral boson with a measured mass of **125.3 ± 0.4(stat.) ± 0.5(syst.) GeV**
- **local significance of 5.0σ (5.8σ expected)**, at a mass near 125 GeV



4.1σ (2.8σ)

3.2σ (3.8σ)

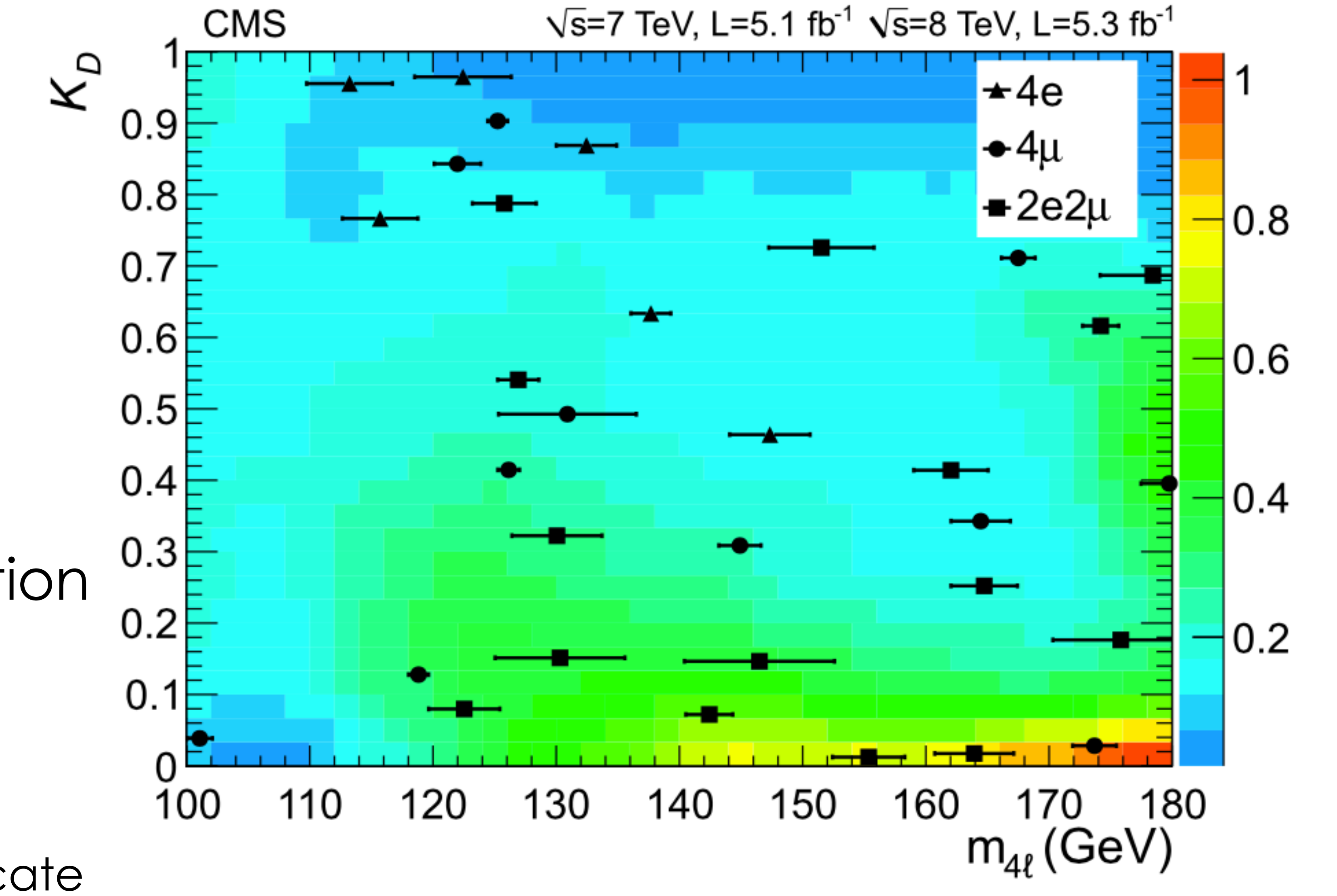
Supporting material

The discovery of the Higgs boson: H → 4l

ATLAS

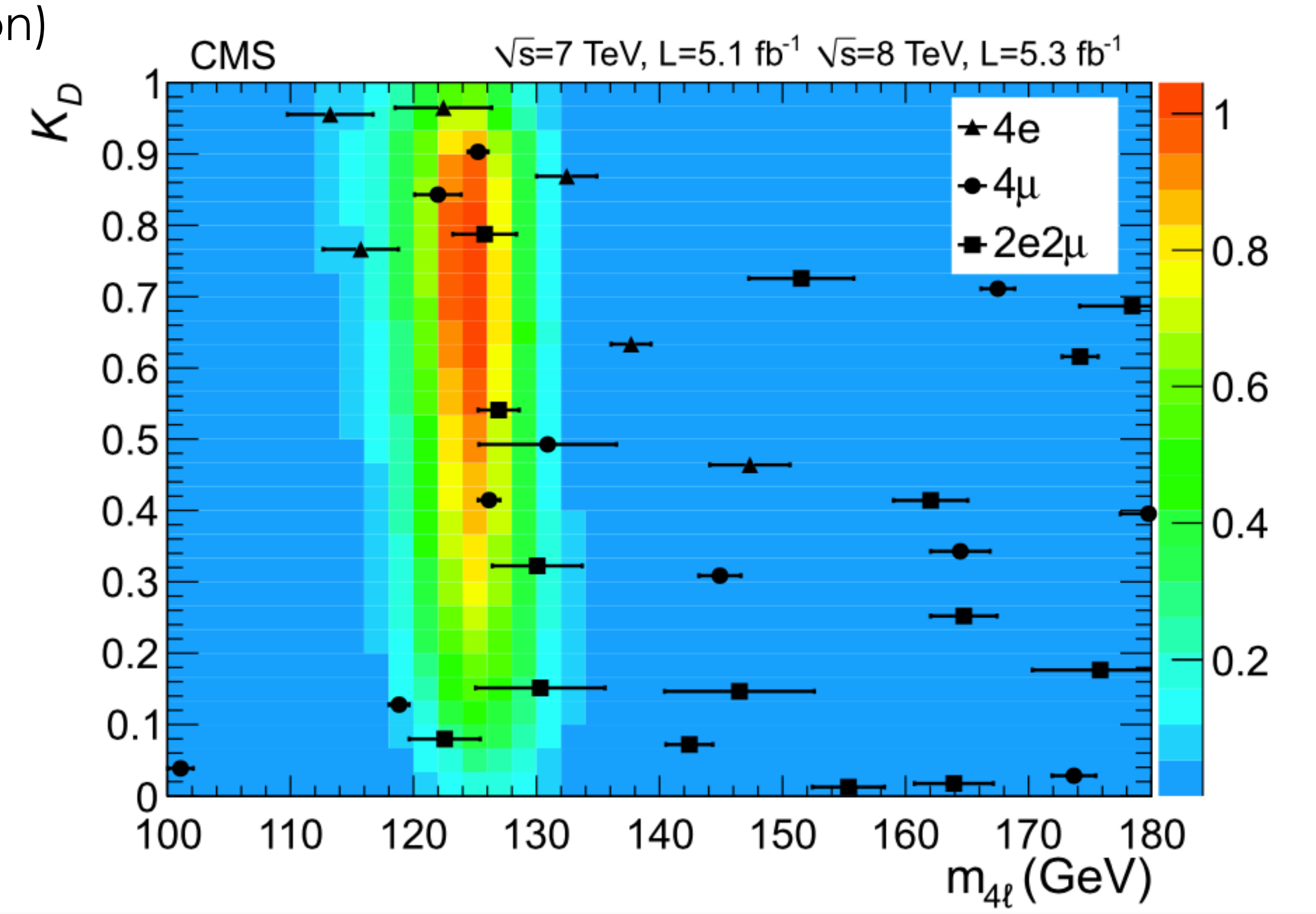
CMS

background expectation



(horizontal error bars indicate the estimated mass resolution)

event density expected from a SM Higgs boson



The discovery of the Higgs boson: H → γγ

ATLAS

$\sqrt{s}$	7 TeV		8 TeV		
$\sigma \times B(H \to \gamma\gamma)$ [fb]	39		50		FWHM [GeV]
Category	N_D	N_S	N_D	N_S	
Unconv. central, low p_{Tt}	2054	10.5	2945	14.2	3.4
Unconv. central, high p_{Tt}	97	1.5	173	2.5	3.2
Unconv. rest, low p_{Tt}	7129	21.6	12 136	30.9	3.7
Unconv. rest, high p_{Tt}	444	2.8	785	5.2	3.6
Conv. central, low p_{Tt}	1493	6.7	2015	8.9	3.9
Conv. central, high p_{Tt}	77	1.0	113	1.6	3.5
Conv. rest, low p_{Tt}	8313	21.1	11 099	26.9	4.5
Conv. rest, high p_{Tt}	501	2.7	706	4.5	3.9
Conv. transition	3591	9.5	5140	12.8	6.1
2-jet	89	2.2	139	3.0	3.7
All categories (inclusive)	23 788	79.6	35 251	110.5	3.9

N_D = events in data
N_S = expected events
FWHM = mass resolution

(1% stat uncertainty)

CMS

Event categories		SM Higgs boson expected signal ($m_H = 125$ GeV)							Background $m_{\gamma\gamma} = 125$ GeV (events/GeV)
		Events	ggH	VBF	VH	ttH	σ_{eff} (GeV)	FWHM/2.35 (GeV)	
7 TeV, 5.1 fb^{-1}	BDT 0	3.2	61%	17%	19%	3%	1.21	1.14	3.3 ± 0.4
	BDT 1	16.3	88%	6%	6%	–	1.26	1.08	37.5 ± 1.3
	BDT 2	21.5	92%	4%	4%	–	1.59	1.32	74.8 ± 1.9
	BDT 3	32.8	92%	4%	4%	–	2.47	2.07	193.6 ± 3.0
	Dijet tag	2.9	27%	72%	1%	–	1.73	1.37	1.7 ± 0.2
8 TeV, 5.3 fb^{-1}	BDT 0	6.1	68%	12%	16%	4%	1.38	1.23	7.4 ± 0.6
	BDT 1	21.0	87%	6%	6%	1%	1.53	1.31	54.7 ± 1.5
	BDT 2	30.2	92%	4%	4%	–	1.94	1.55	115.2± 2.3
	BDT 3	40.0	92%	4%	4%	–	2.86	2.35	256.5 ± 3.4
	Dijet tight	2.6	23%	77%	–	–	2.06	1.57	1.3 ± 0.2
	Dijet loose	3.0	53%	45%	2%	–	1.95	1.48	3.7 ± 0.4

The discovery of the Higgs boson: H → WW

ATLAS

The expected numbers of signal ($m_H = 125$ GeV) and background events after all selections, including a cut on the transverse mass of $0.75\,m_H < m_T < m_H$ for $m_H = 125$ GeV. The observed numbers of events in data are also displayed. The $e\mu$ and μe channels are combined. The uncertainties shown are the combination of the statistical and all systematic uncertainties, taking into account the constraints from control samples. For the 2-jet analysis, backgrounds with fewer than 0.01 expected events are marked with '–'.

	0-jet	1-jet	2-jet
Signal	20 ± 4	5 ± 2	0.34 ± 0.07
WW	101 ± 13	12 ± 5	0.10 ± 0.14
$WZ^{(*)}/ZZ/W\gamma^{(*)}$	12 ± 3	1.9 ± 1.1	0.10 ± 0.10
$t\bar{t}$	8 ± 2	6 ± 2	0.15 ± 0.10
$tW/tb/tqb$	3.4 ± 1.5	3.7 ± 1.6	–
$Z/\gamma^* +$ jets	1.9 ± 1.3	0.10 ± 0.10	–
$W +$ jets	15 ± 7	2 ± 1	–
Total background	142 ± 16	26 ± 6	0.35 ± 0.18
Observed	185	38	0

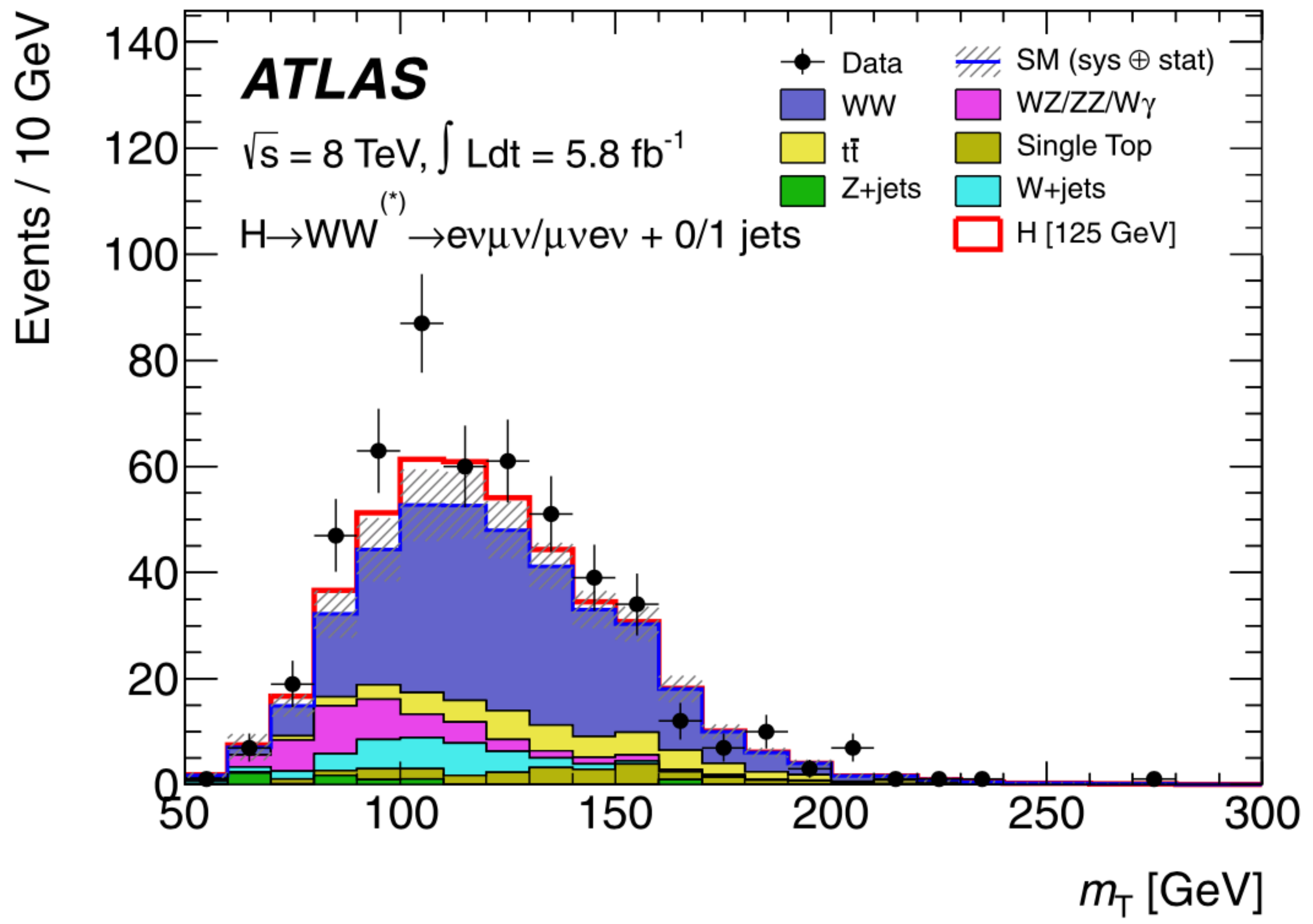


Fig. 6. Distribution of the transverse mass, m_T, in the 0-jet and 1-jet analyses with both $e\mu$ and μe channels combined, for events satisfying all selection criteria. The expected signal for $m_H = 125$ GeV is shown stacked on top of the background prediction. The $W +$ jets background is estimated from data, and WW and top background MC predictions are normalised to the data using control regions. The hashed area indicates the total uncertainty on the background prediction.

CMS

Observed number of events, background estimates, and signal predictions for $m_H = 125$ GeV in each category of the WW analysis of the 8 TeV data set. All the selection requirements have been applied. The combined experimental and theoretical, systematic and statistical uncertainties are shown. The $Z\gamma$ process includes the dimuon, dielectron, and $\tau\tau \to \ell\ell$ final states.

Category:	0-jet $e\mu$	0-jet $\ell\ell$	1-jet $e\mu$	1-jet $\ell\ell$	2-jet $e\mu$	2-jet $\ell\ell$
WW	87.6 ± 9.5	60.4 ± 6.7	19.5 ± 3.7	9.7 ± 1.9	0.4 ± 0.1	0.3 ± 0.1
$WZ + ZZ + Z\gamma$	2.2 ± 0.2	37.7 ± 12.5	2.4 ± 0.3	8.7 ± 4.9	0.1 ± 0.0	3.1 ± 1.8
Top	9.3 ± 2.7	1.9 ± 0.5	22.3 ± 2.0	9.5 ± 1.1	3.4 ± 1.9	2.0 ± 1.2
$W +$ jets	19.1 ± 7.2	10.8 ± 4.3	11.7 ± 4.6	3.9 ± 1.7	0.3 ± 0.3	0.0 ± 0.0
$W\gamma^{(*)}$	6.0 ± 2.3	4.6 ± 2.5	5.9 ± 3.2	1.3 ± 1.2	0.0 ± 0.0	0.0 ± 0.0
All backgrounds	124.2 ± 12.4	115.5 ± 15.0	61.7 ± 7.0	33.1 ± 5.7	4.1 ± 1.9	5.4 ± 2.2
Signal ($m_H = 125$ GeV)	23.9 ± 5.2	14.9 ± 3.3	10.3 ± 3.0	4.4 ± 1.3	1.5 ± 0.2	0.8 ± 0.1
Data	158	123	54	43	6	7

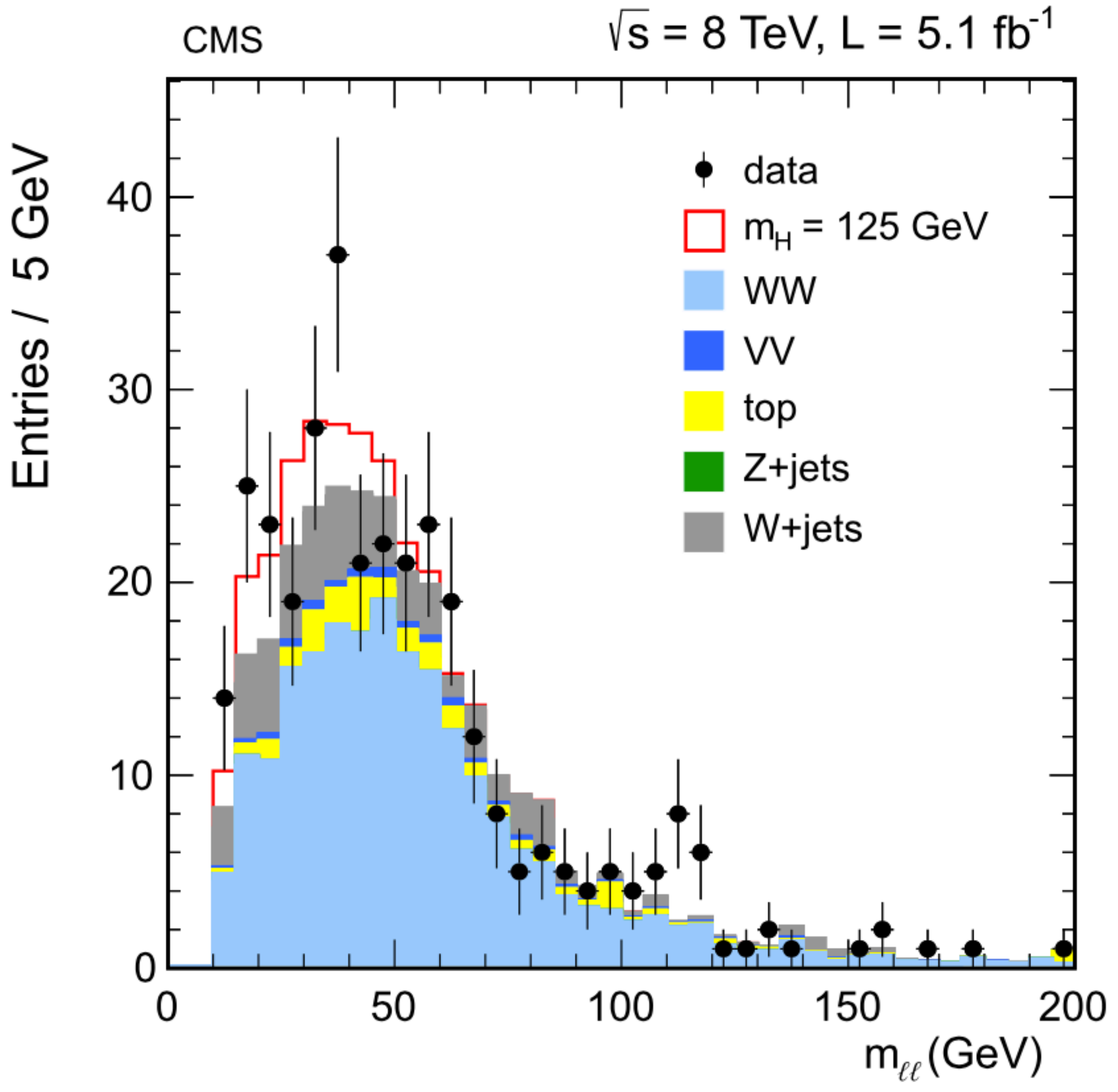
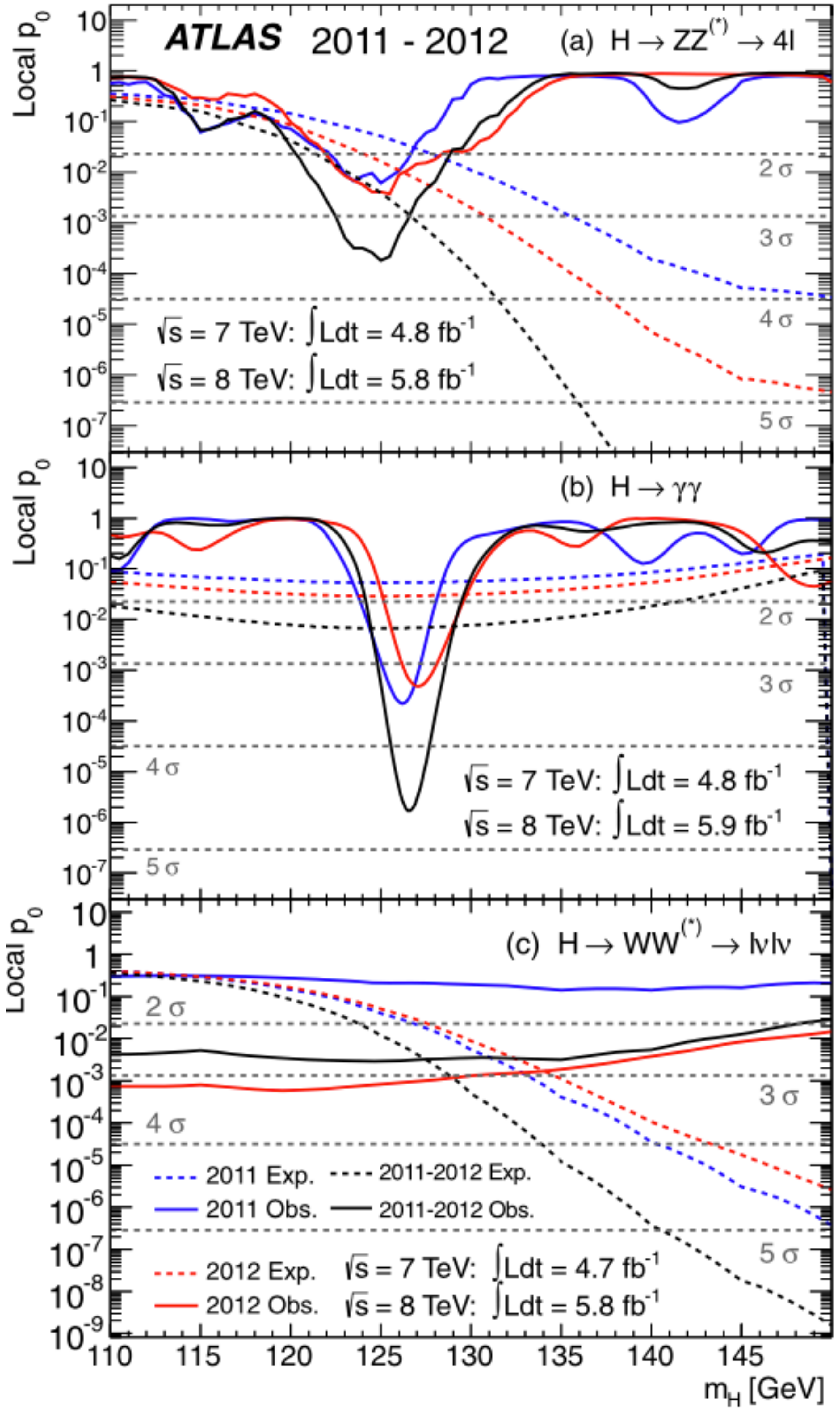
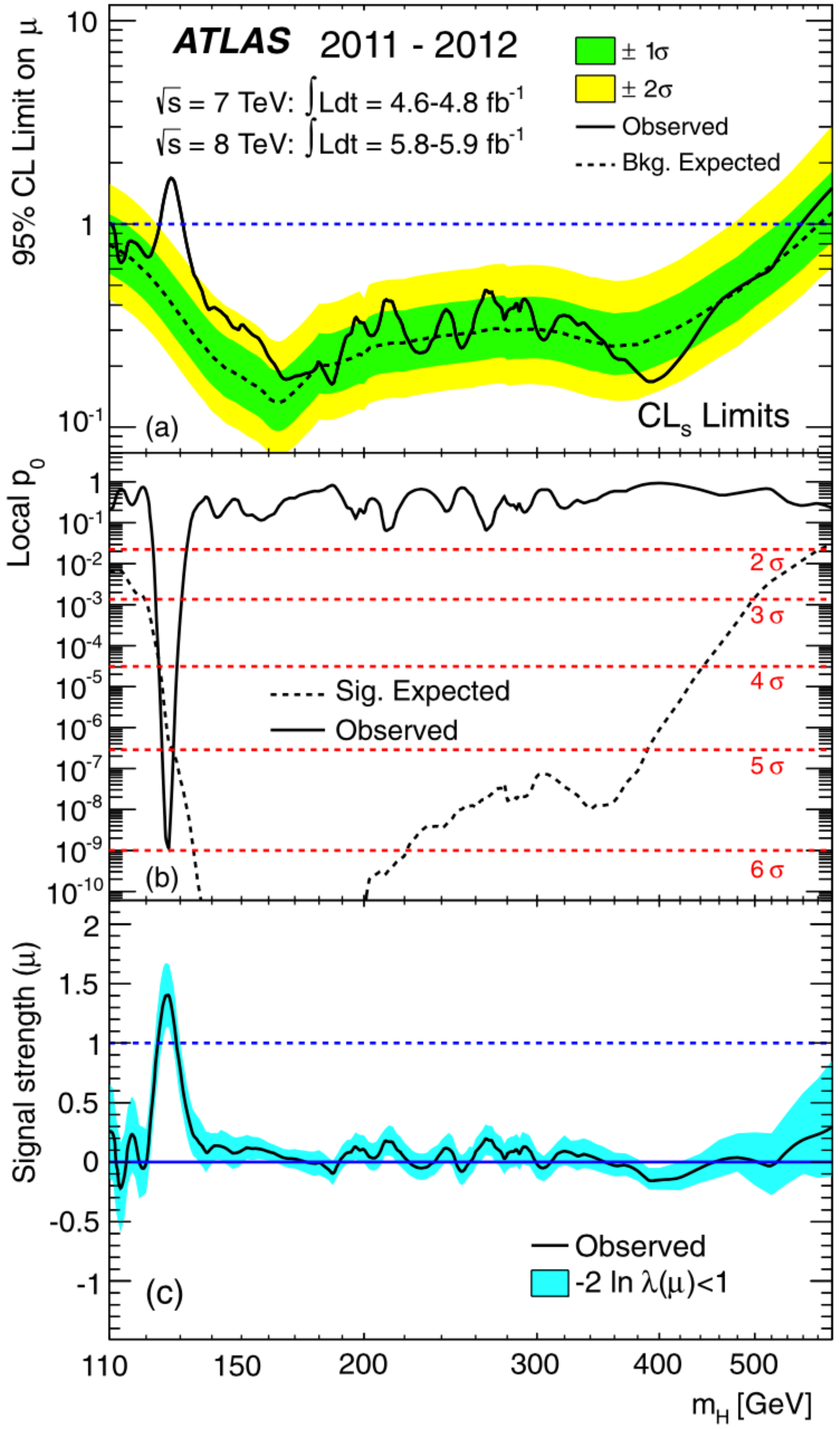


Fig. 7. Distribution of $m_{\ell\ell}$ for the zero-jet $e\mu$ category in the $H \to WW$ search at 8 TeV. The signal expected from a Higgs boson with a mass $m_H = 125$ GeV is shown added to the background.

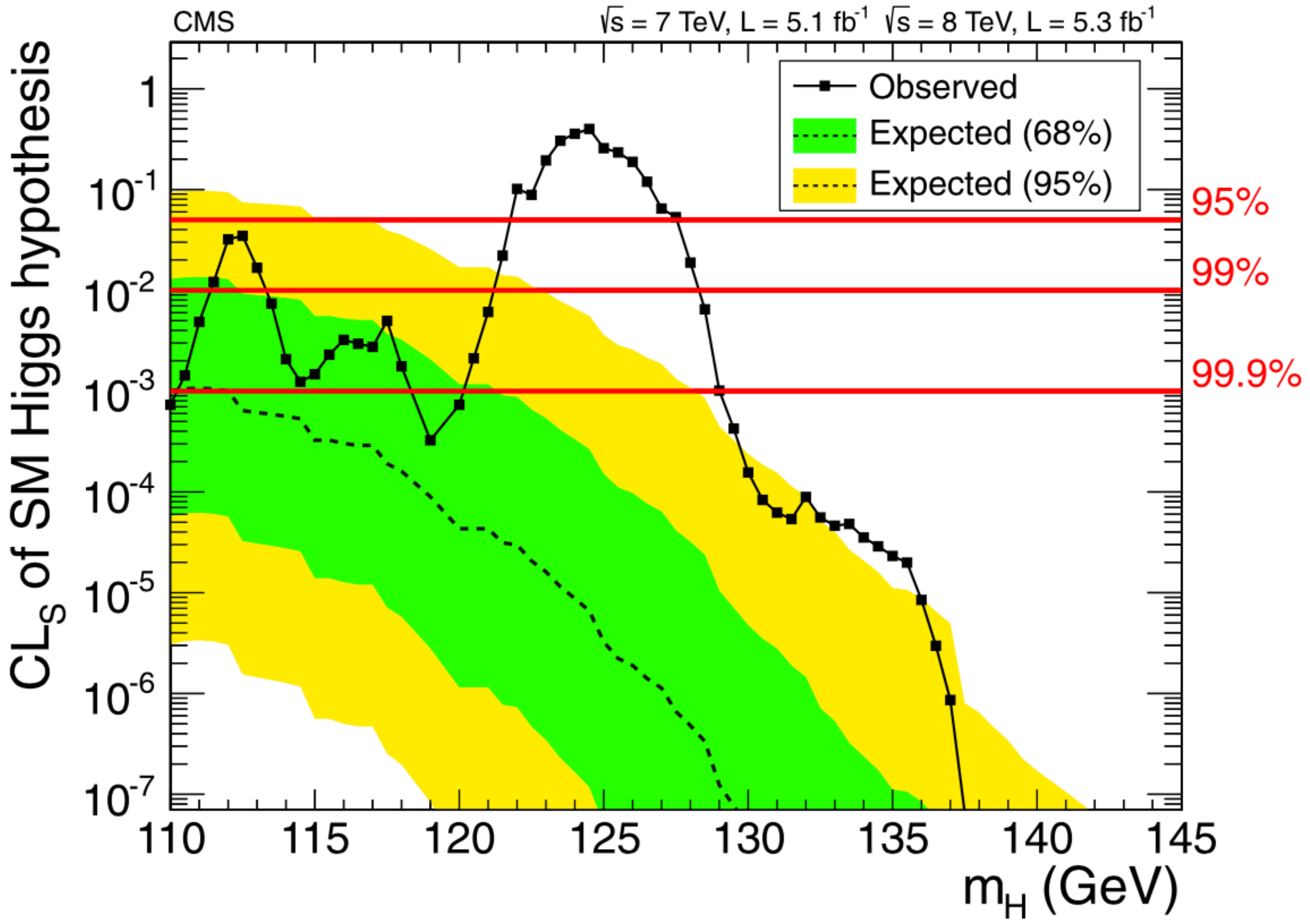
The discovery of the Higgs boson: results

ATLAS





CMS



Decay mode/combination	Expected (σ)	Observed (σ)
$\gamma\gamma$	2.8	4.1
ZZ	3.8	3.2
$\tau\tau$ + bb	2.4	0.5
$\gamma\gamma$ + ZZ	4.7	5.0
$\gamma\gamma$ + ZZ + WW	5.2	5.1
$\gamma\gamma$ + ZZ + WW + $\tau\tau$ + bb	5.8	5.0

The discovery of the Higgs boson: results

ATLAS

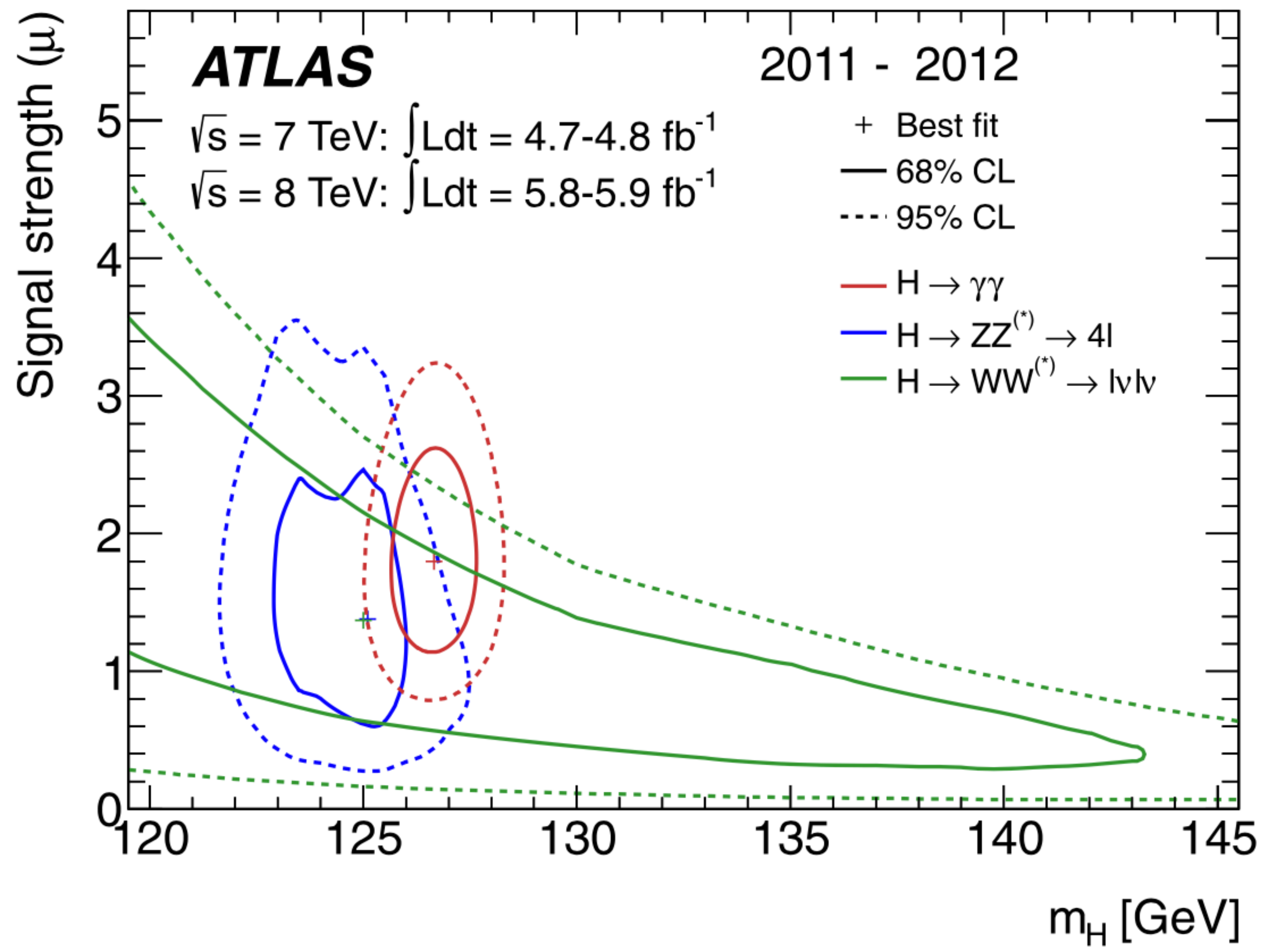


Fig. 11. Confidence intervals in the (μ, m_H) plane for the $H \to ZZ^{(*)} \to 4\ell$, $H \to \gamma\gamma$, and $H \to WW^{(*)} \to \ell\nu\ell\nu$ channels, including all systematic uncertainties. The markers indicate the maximum likelihood estimates $(\hat{\mu}, \hat{m}_H)$ in the corresponding channels (the maximum likelihood estimates for $H \to ZZ^{(*)} \to 4\ell$ and $H \to WW^{(*)} \to \ell\nu\ell\nu$ coincide).

CMS

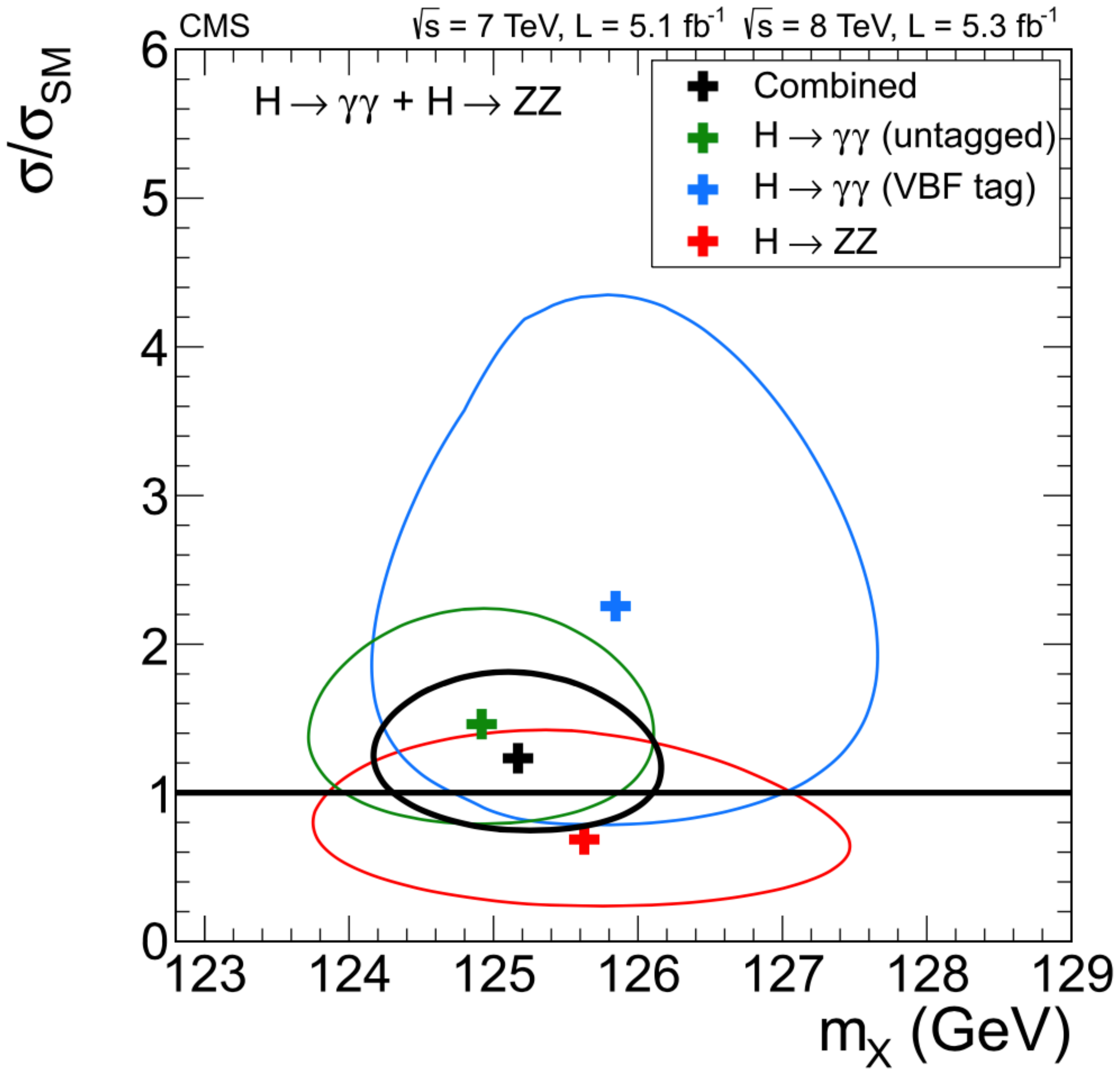


Fig. 17. The 68% CL contours for the signal strength σ/σ_{SM} versus the boson mass m_X for the untagged $\gamma\gamma$, $\gamma\gamma$ with VBF-like dijet, 4ℓ, and their combination. The symbol σ/σ_{SM} denotes the production cross section times the relevant branching fractions, relative to the SM expectation. In this combination, the relative signal strengths for the three decay modes are constrained by the expectations for the SM Higgs boson.