The nature of the 125 GeV boson: SM or else ?

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*On leave of absence from INFN, Sezione di Firenze

Outline

- Introduction
- Higgs boson production in the SM
  - Benchmark cross sections
  - Theoretical Uncertainties
- Higgs properties
  - Spin and CP properties
  - Coupling extraction
- Summary and Outlook

The heritage

Standard Electroweak theory based on $SU(2)_L \otimes U(1)_Y$ gauge theory

A. Salam

S. Weinberg

S. Glashow

Quantum Chromo Dynamics (QCD): $SU(3)_c$ gauge theory

D. Gross

F. Wilczek

D. Politzer

Altogether a beautiful theory describing high-energy phenomena at a surprising level of accuracy

But how do elementary particles acquire their mass ?

The "last" mistery

- The standard solution: masses are generated by the Higgs boson (scalar particle) through Spontaneous Symmetry Breaking

- The mass of the Higgs boson is not predicted by the theory

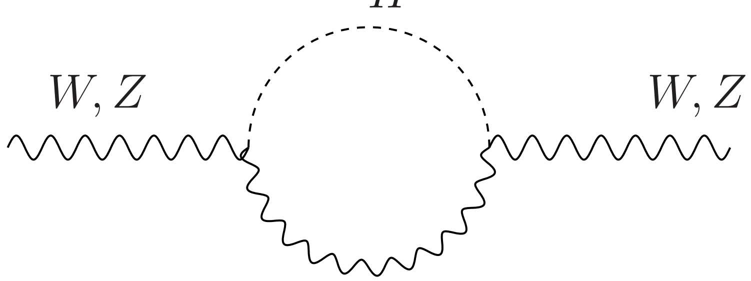
- Theoretical arguments (or prejudices) suggest $50\,\mathrm{GeV} \lesssim m_H \lesssim 800\,\mathrm{GeV}$ (with new physics at the TeV scale)

- LEP has put a lower limit on the mass of the SM Higgs boson at $m_H \geq 114.4$ GeV at 95% CL

- The most sought particle in history (LEP, Tevatron, LHC) !

Other constraints come from:

- **Precision electroweak data: radiative corrections are sensitive to the mass of virtual particles**



$$m_H = 92^{+34}_{-26}\ \text{GeV}$$

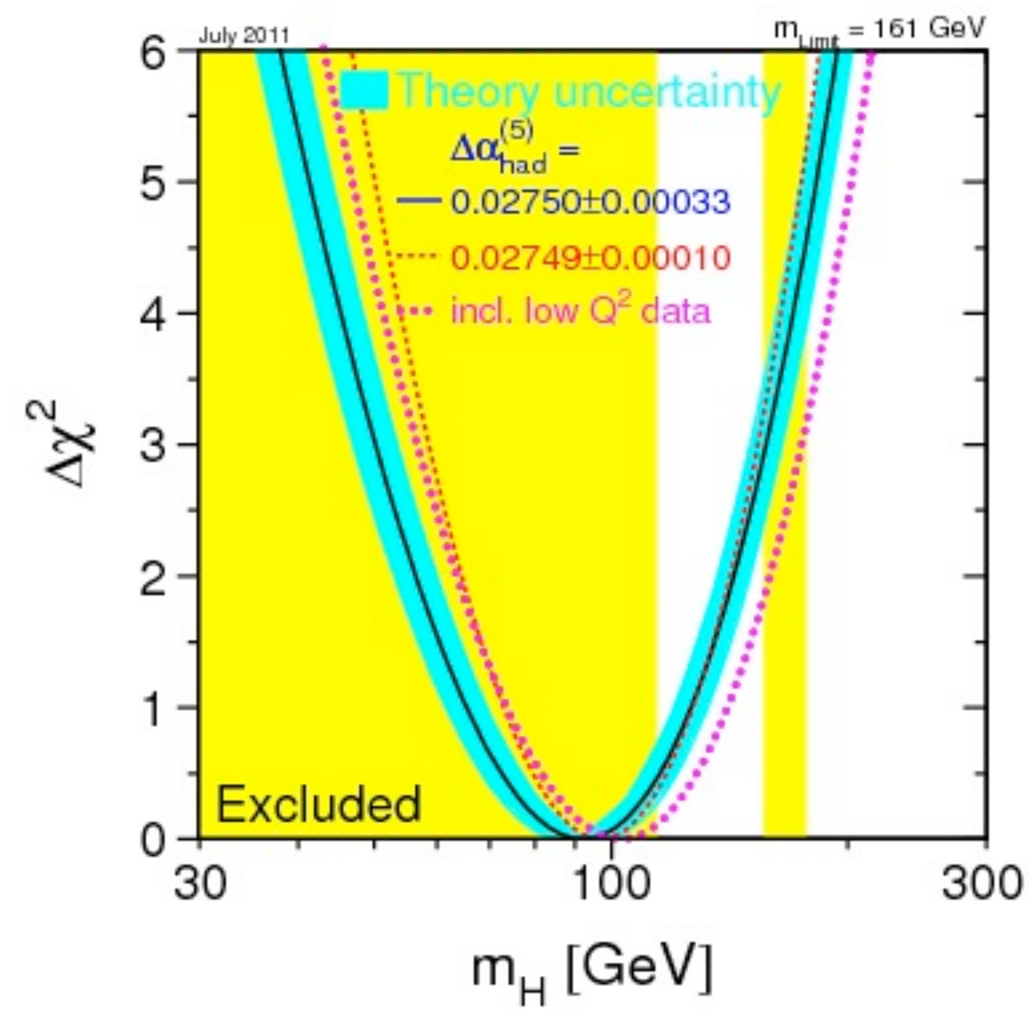
$$m_H < 157\ \text{GeV}$$ at 95 % CL

LEP EWWG, july 2011

Taking into account LEP limit:

$$m_H < 185\ \text{GeV}$$ at 95 % CL

.... but screening effect: the dependence is only logarithmic at one loop (for top quark the dependence is quadratic → m_{top} predicted before discovery !)



The “Higgs” discovery

- On July 4th 2012 ATLAS and CMS have announced the observation of a new neutral state with mass

ATLAS	m_H=126.0 ± 0.4(stat) ± 0.4(sys) GeV
CMS	m_H=125.3 ± 0.4(stat) ± 0.5(sys) GeV

compatible with the production and decay of the SM Higgs boson

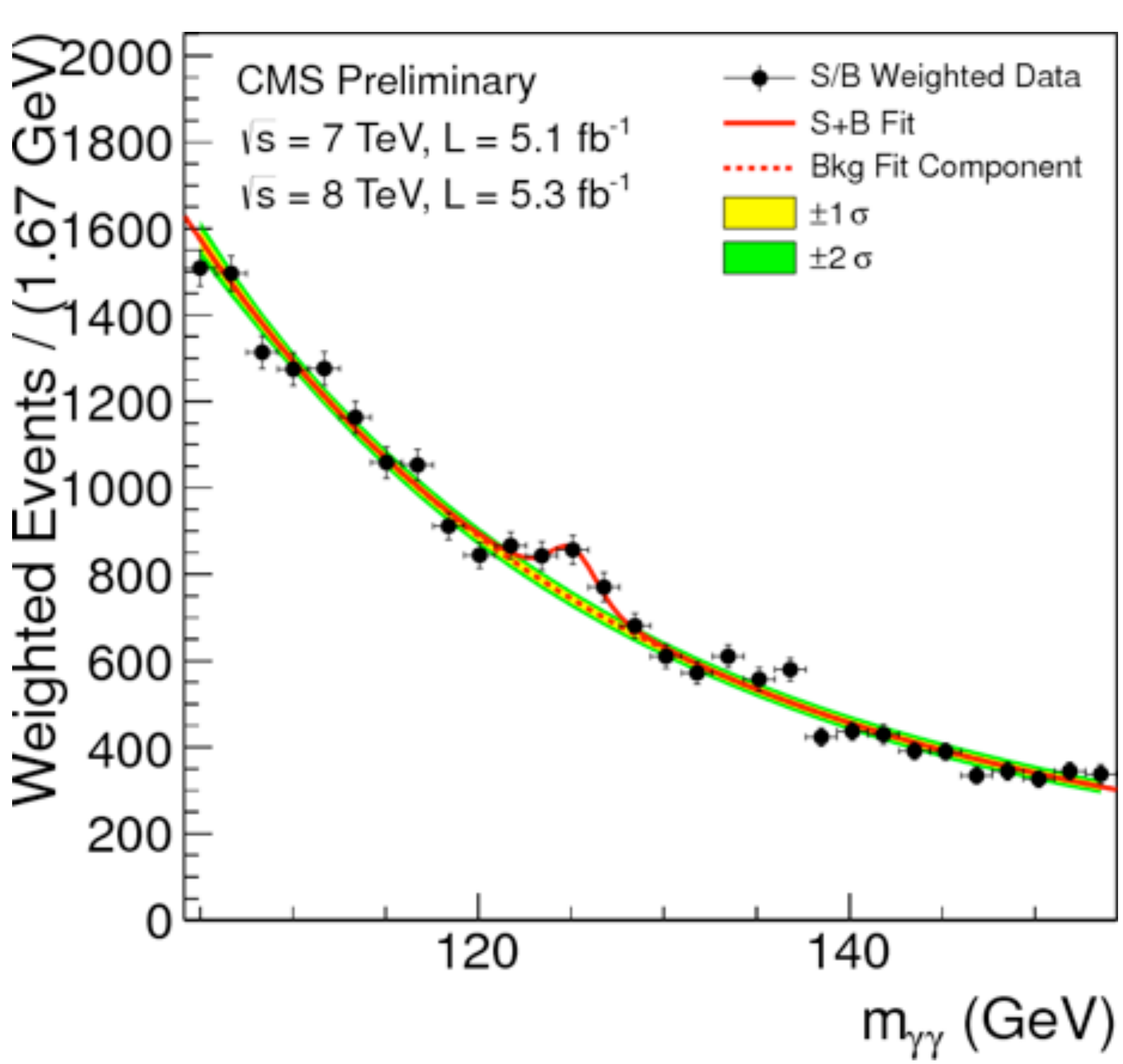
- Right where precision tests like the SM model Higgs to be !

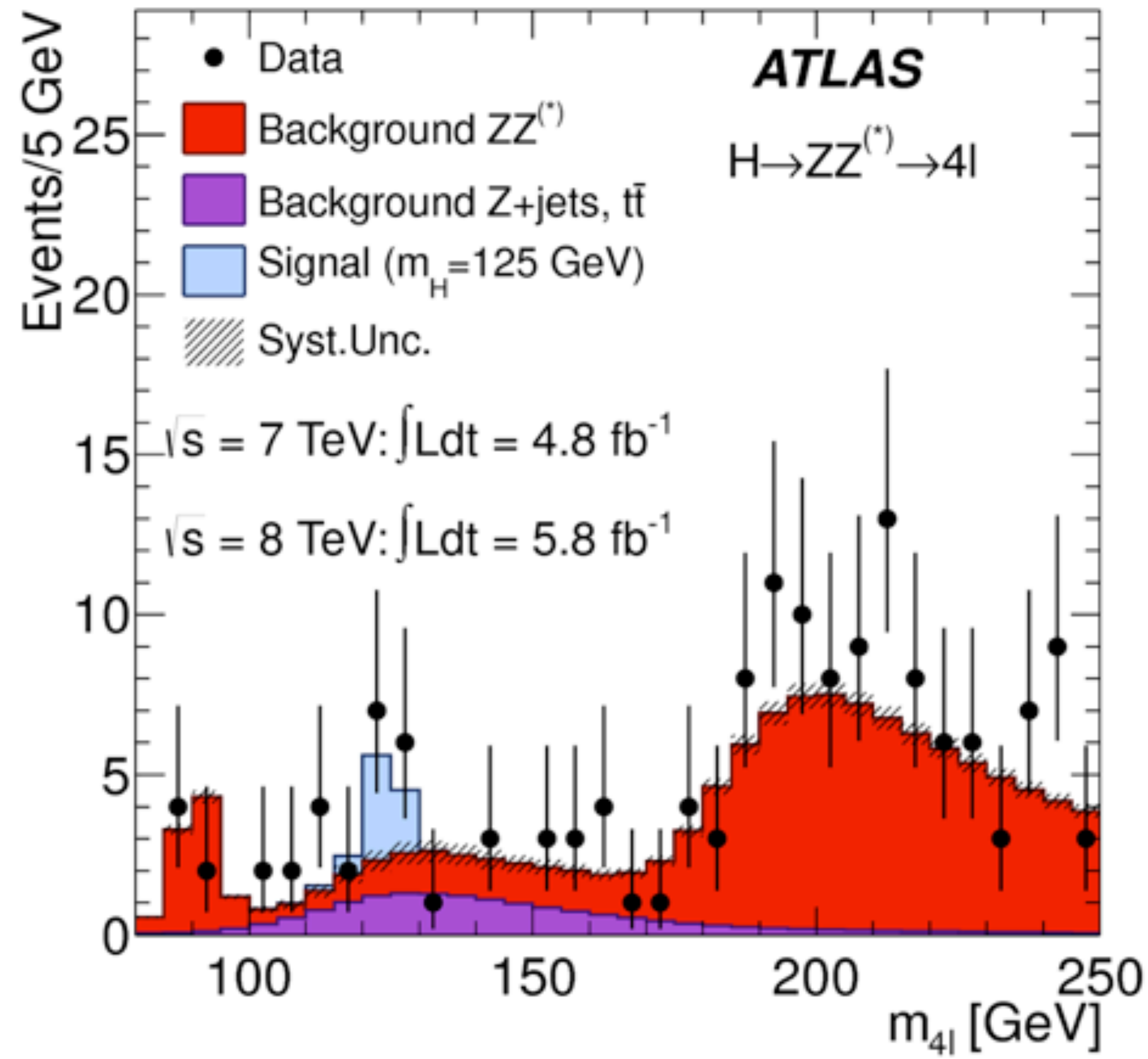
- Probably the most difficult and long sought discovery in the history of particle physics

- Search for very rare events with tiny cross sections

- Clever analyses to isolate signal over huge backgrounds

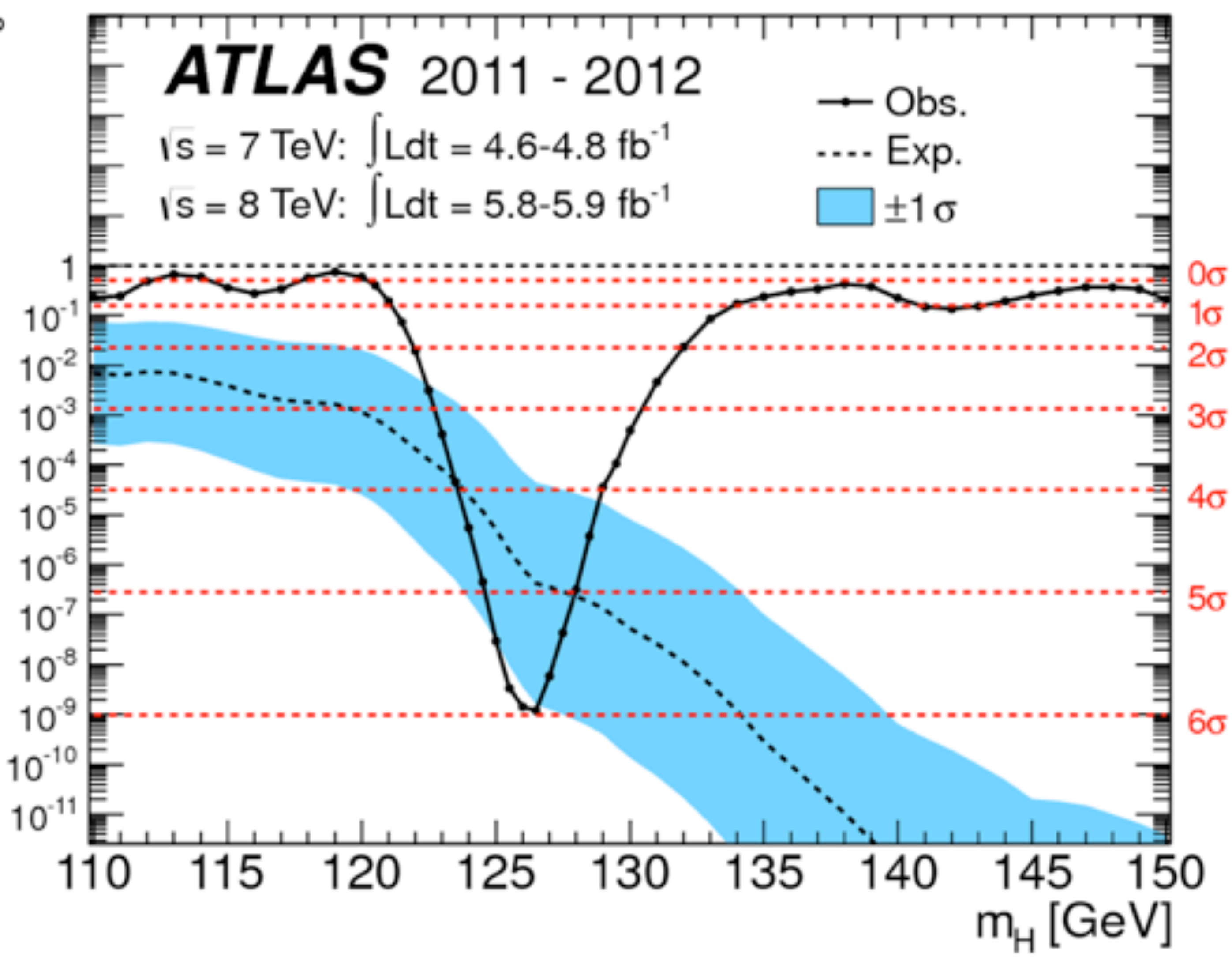
The "Higgs" discovery

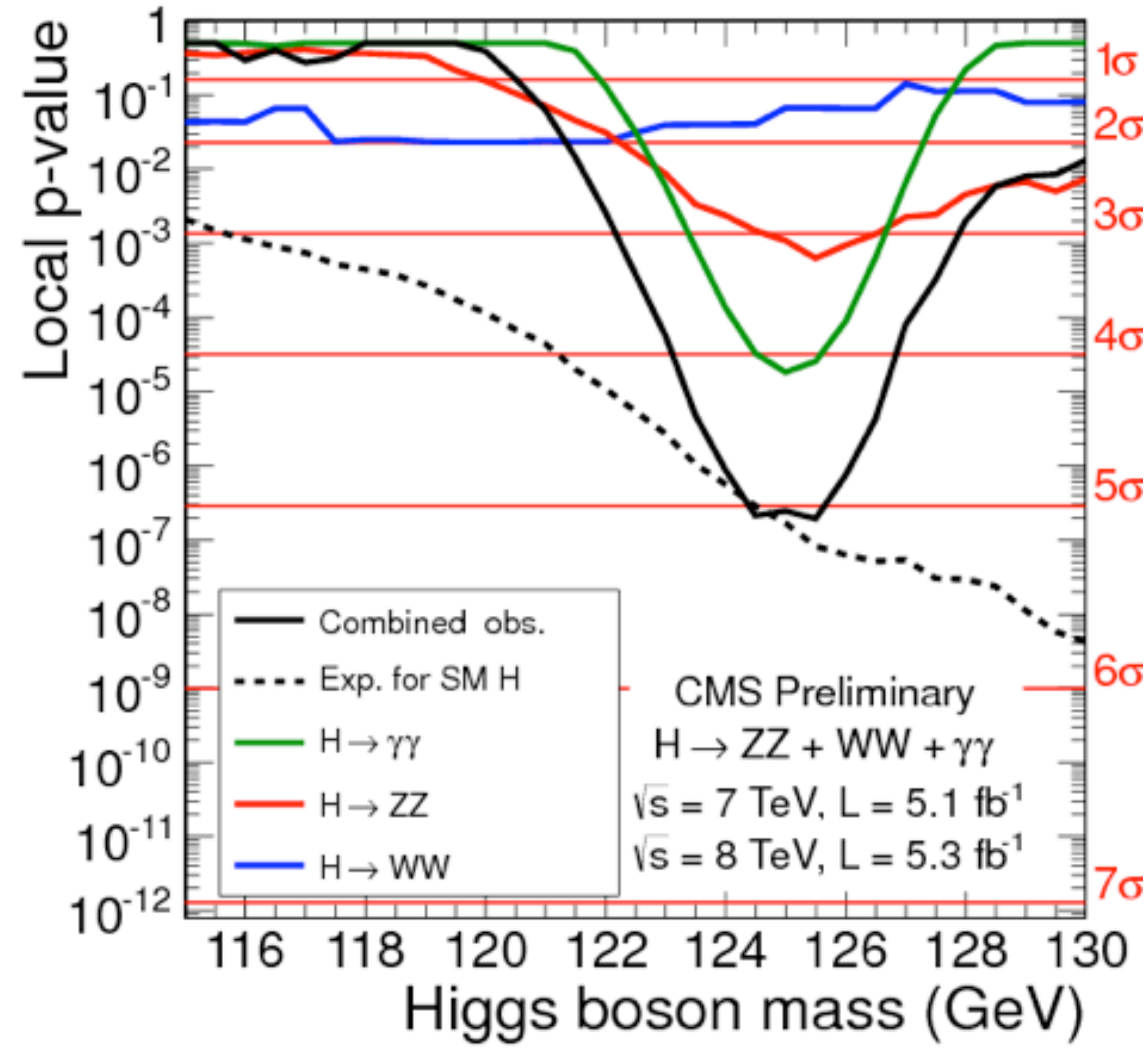




Observation driven by high-resolution channels: H→γγ, H→ZZ

The “Higgs” discovery



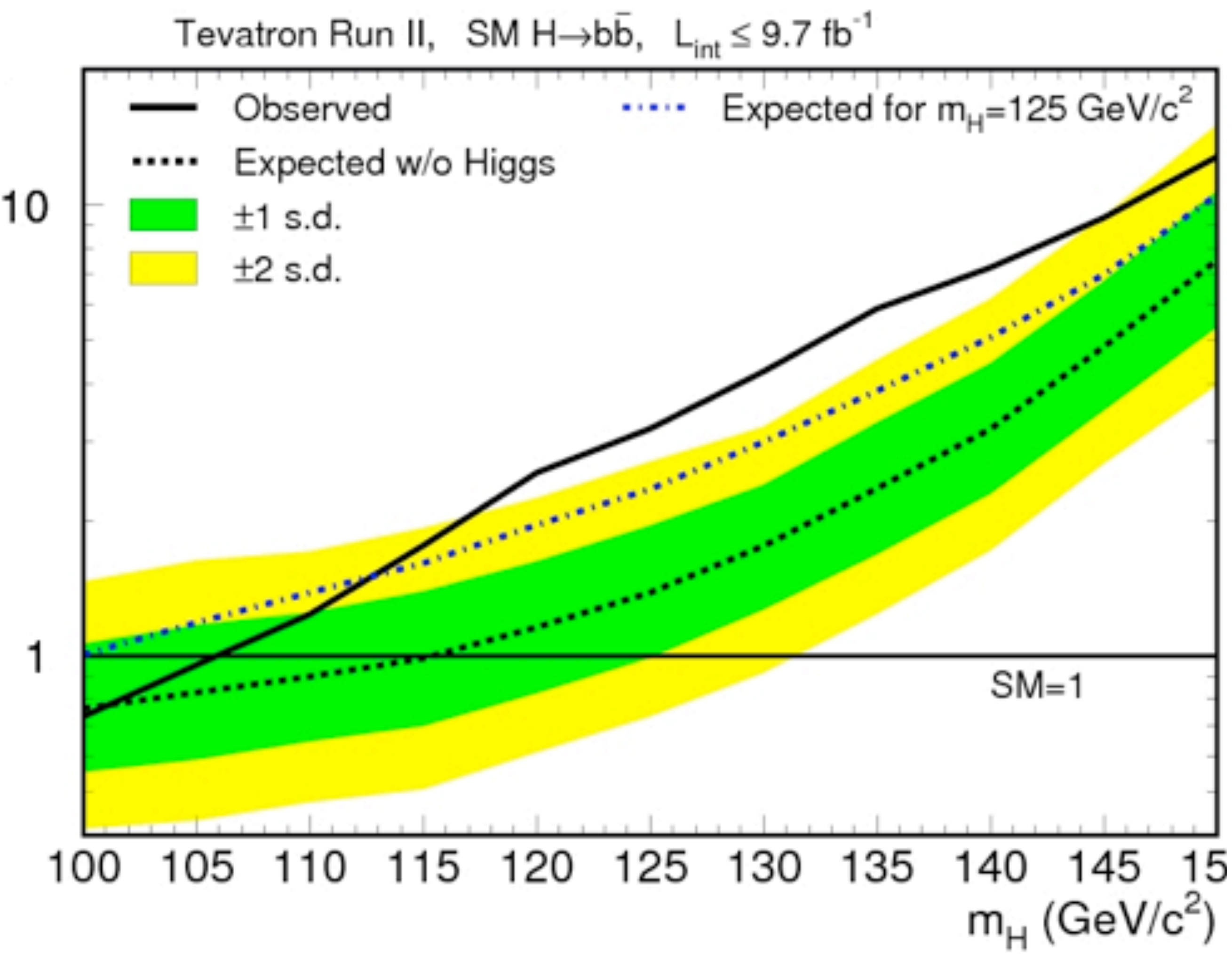


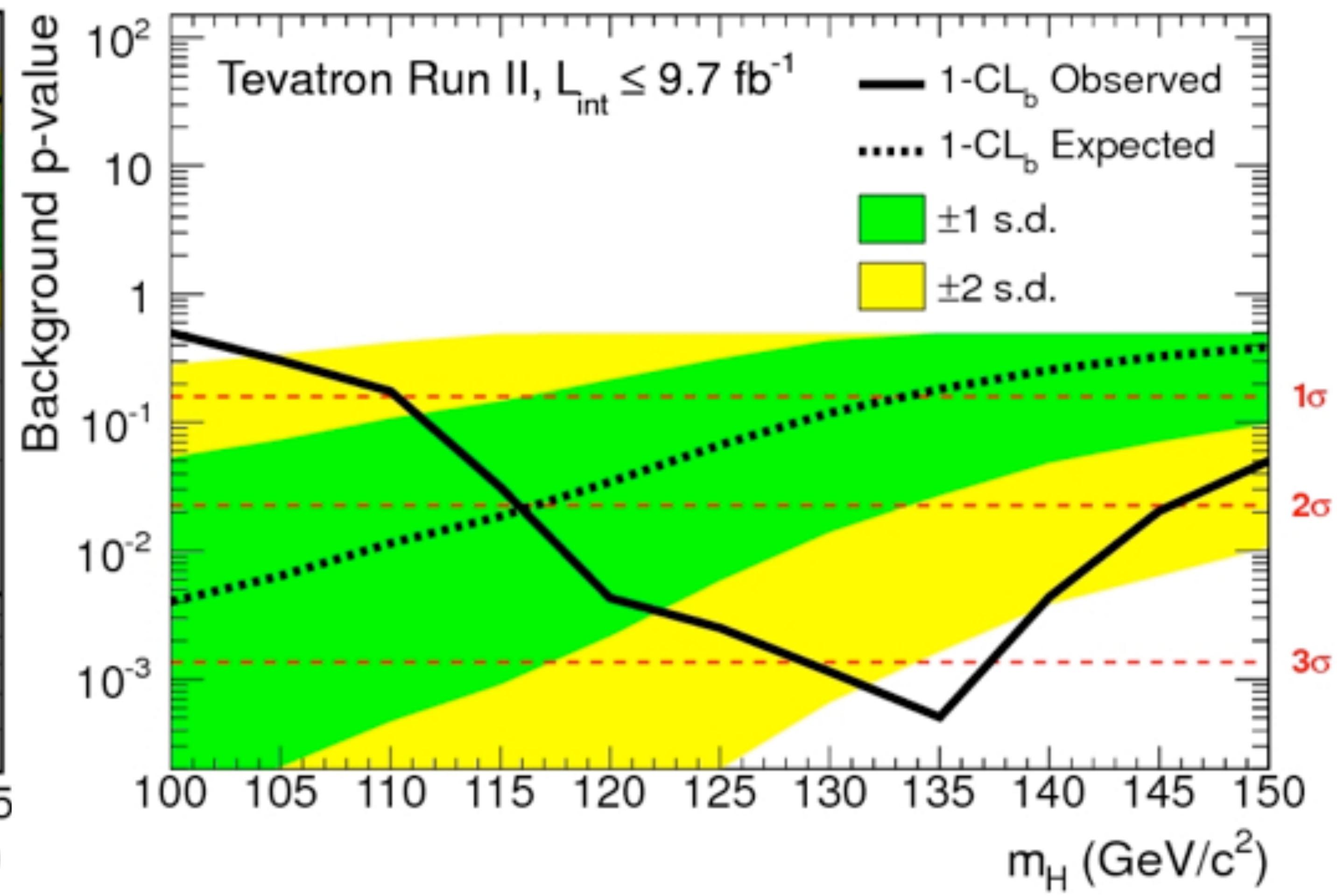
Local significance:

ATLAS: 5.9 σ   CMS 5.0 σ

The “Higgs” discovery

These results are further corroborated by the broad excess seen at the Tevatron



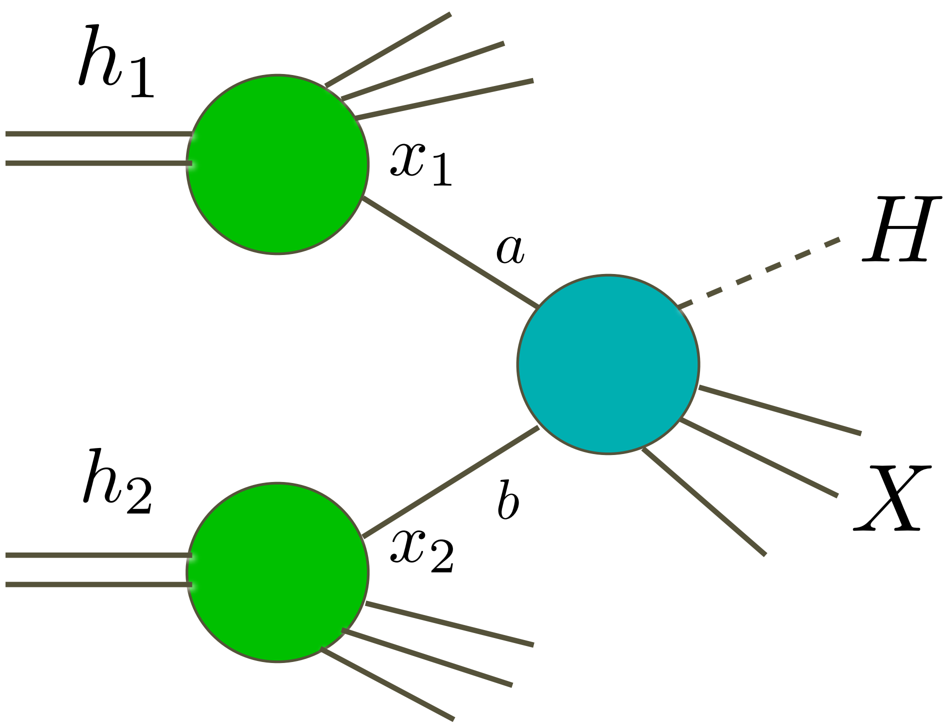


Global significance in the range m_H=115-150 GeV is 3.1 σ

Important because it is in the H→bbar channel on which LHC is poorly sensitive at present

Theoretical predictions

The framework: QCD factorization theorem



$$\sigma(p_1, p_2; M_H) = \sum_{a,b} \int_0^1 dx_1 dx_2\, f_{h_1,a}(x_1, \mu_F^2)\, f_{h_2,b}(x_2, \mu_F^2) \times \hat{\sigma}_{ab}(x_1 p_1, x_2 p_2, \alpha_S(\mu_R^2); \mu_F^2)$$

Theoretical predictions

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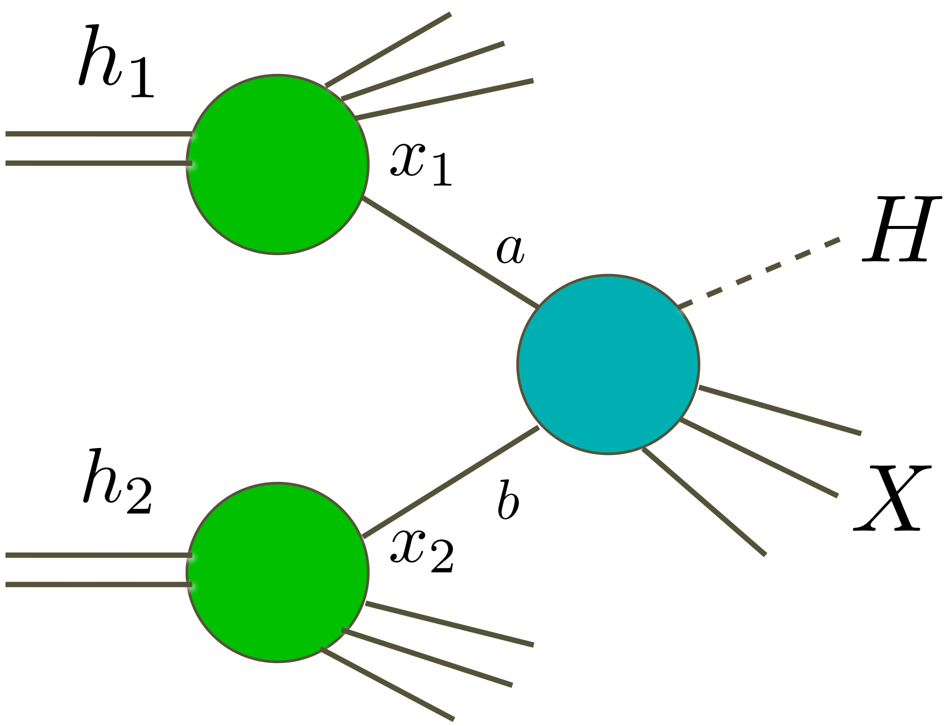

Parton distributions

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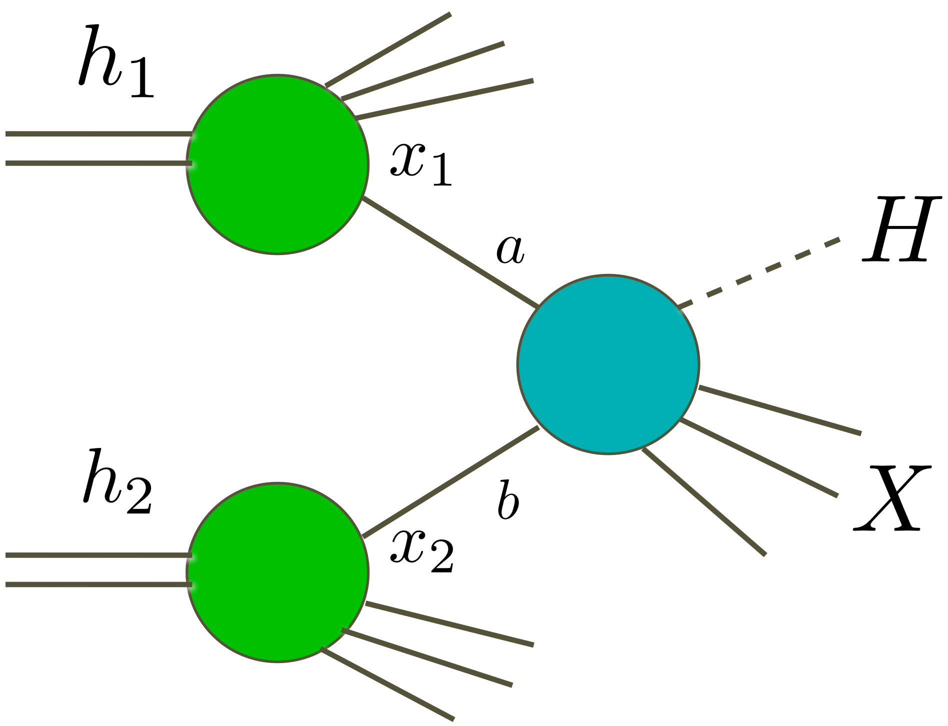

Parton distributions

Partonic cross section

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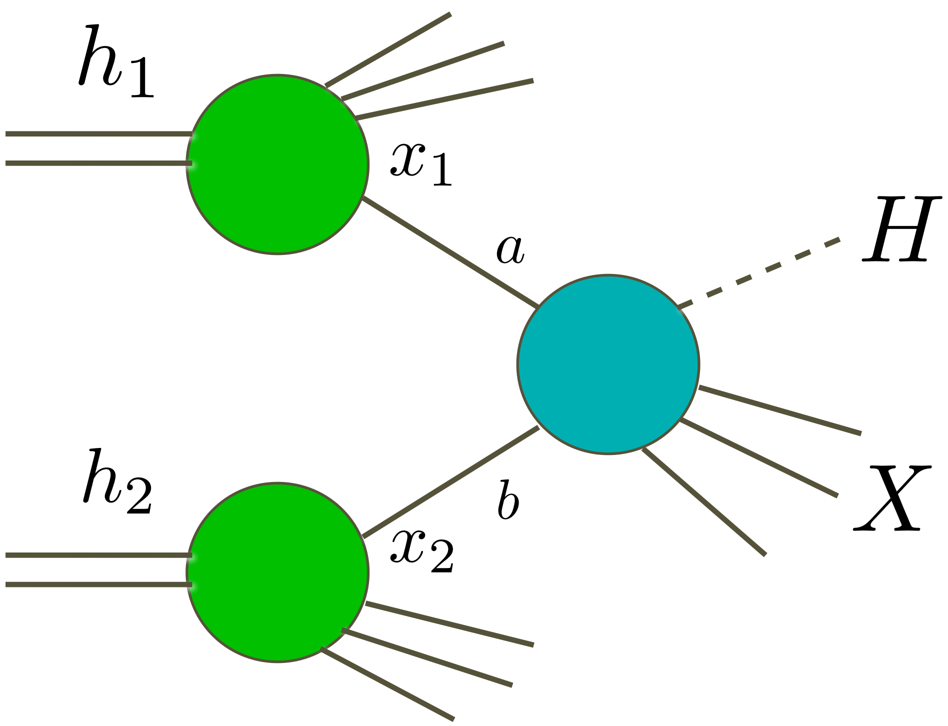

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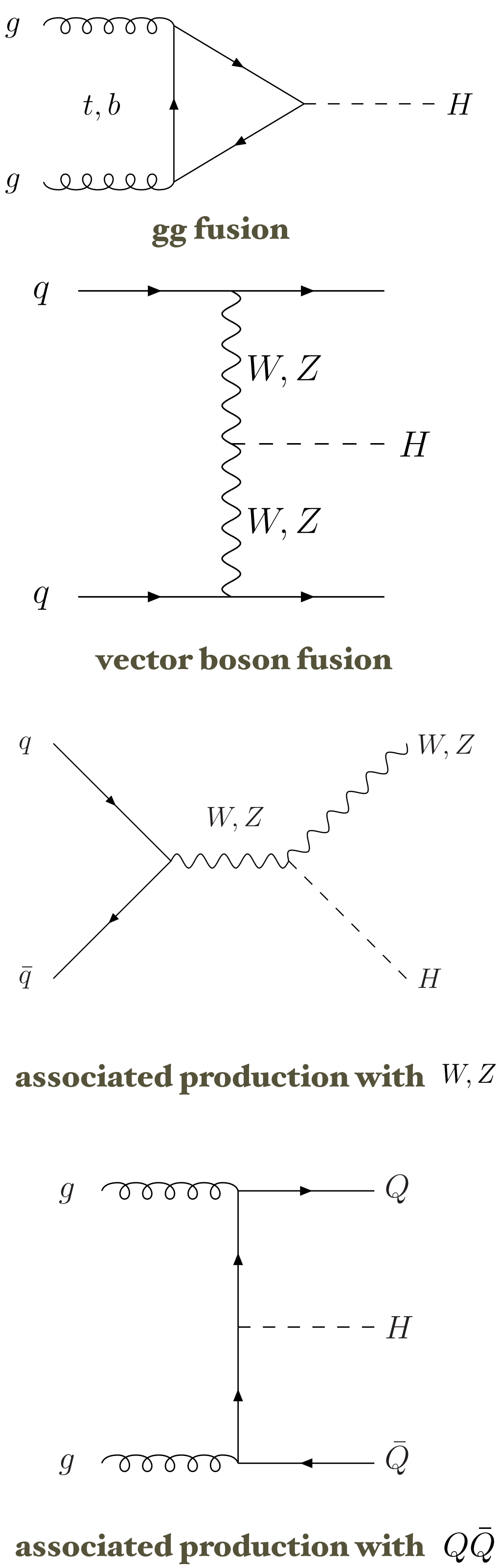
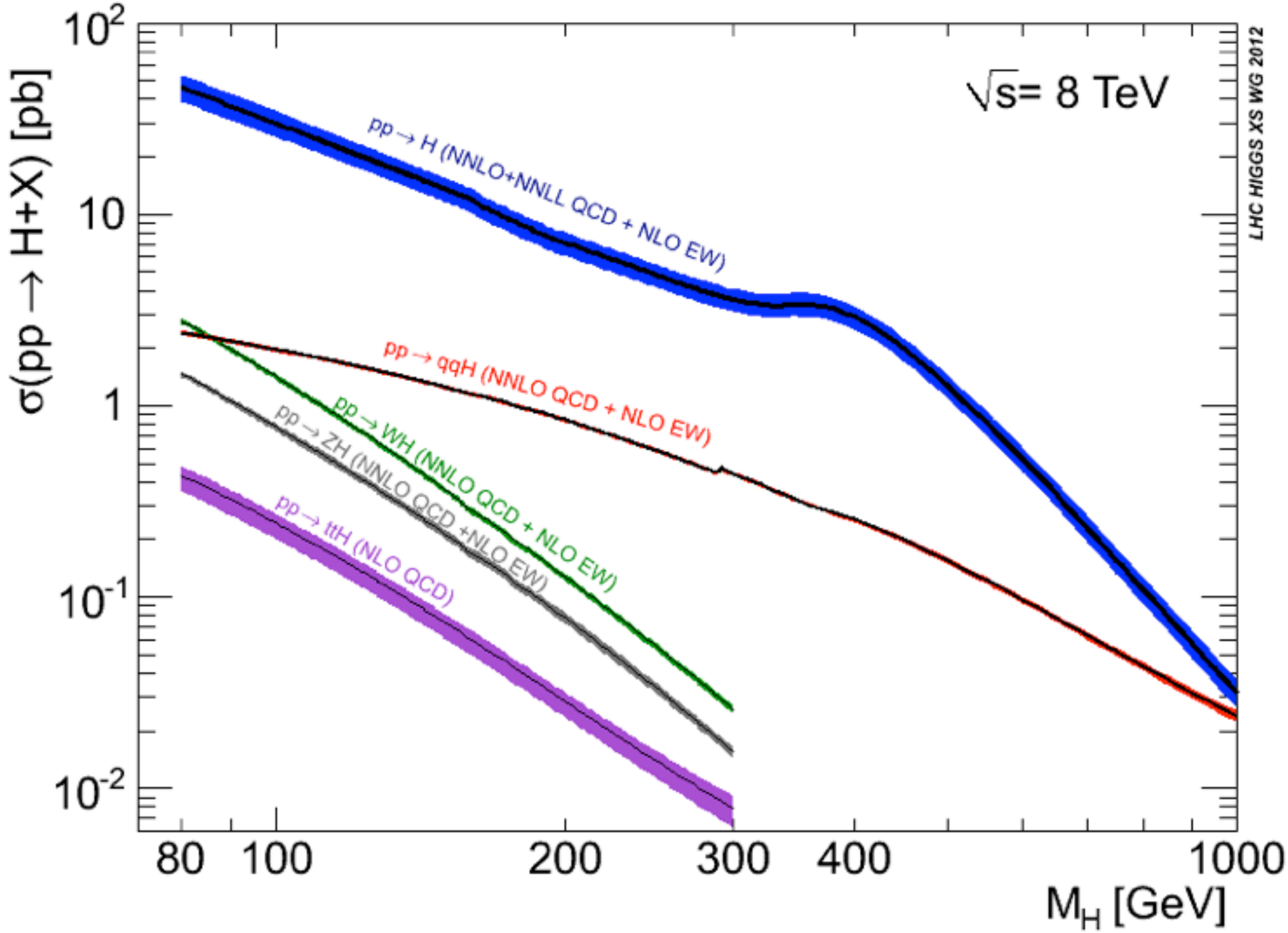
Precise predictions for σ depend on good knowledge of BOTH $\hat{\sigma}_{ab}$ and $f_{h,a}(x, \mu_F^2)$

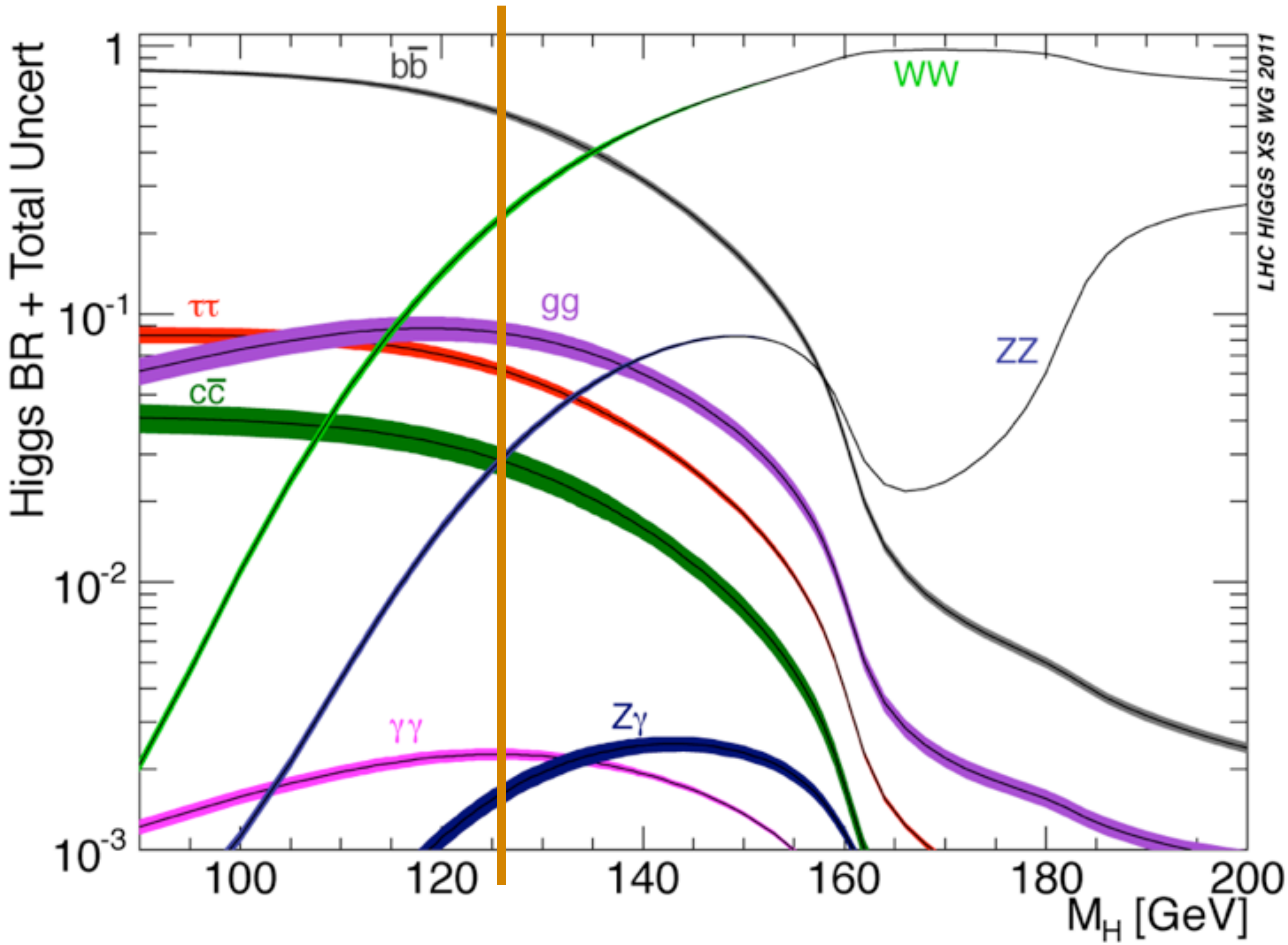
Higgs production in the SM





Large gluon luminosity → gg fusion is the dominant production channel over the whole range of m_H

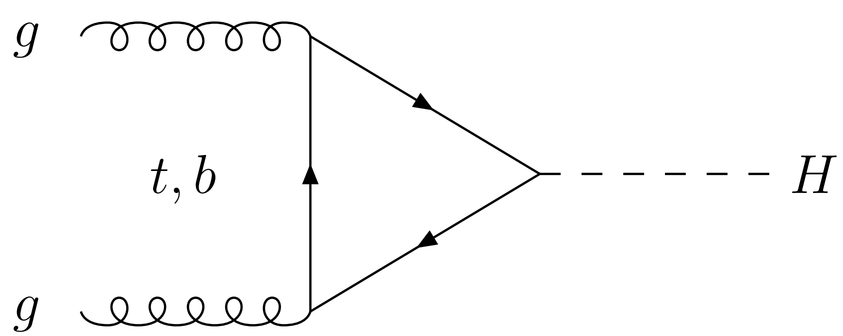
Higgs decay in the SM



For $m_H \sim 125$ GeV many decay modes are relevant

$H \to \gamma\gamma$, $H \to WW$, ZZ, $H \to bb$, $H \to \tau\tau$

gg fusion

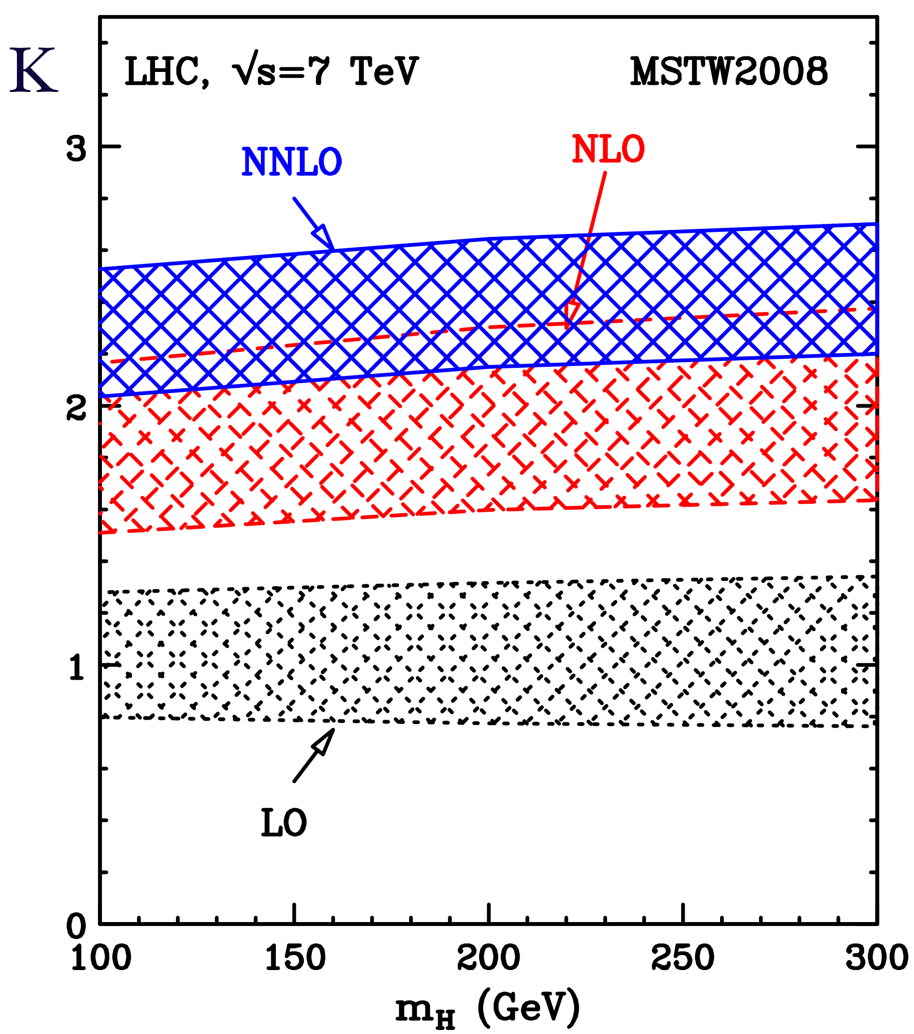


The Higgs coupling is proportional to the quark mass

→ top-loop dominates

QCD corrections to the total rate computed 20 years ago and found to be large → O(100 %) effect !

A. Djouadi, D. Graudenz, M. Spira, P. Zerwas (1991)



Next-to-next-to leading order (NNLO) corrections computed in the large-m_{top} limit (+25 % at the LHC, +30 % at the Tevatron)

R.Harlander (2000); S. Catani, D. De Florian, MG (2001)
R.Harlander, W.B. Kilgore (2001,2002)
C. Anastasiou, K. Melnikov (2002)
V. Ravindran, J. Smith, W.L.Van Neerven (2003)

scale uncertainty computed with $m_H/2 < \mu_F, \mu_R < 2\, m_H$ and $1/2 < \mu_F/\mu_R < 2$

The large-m_{top} approximation

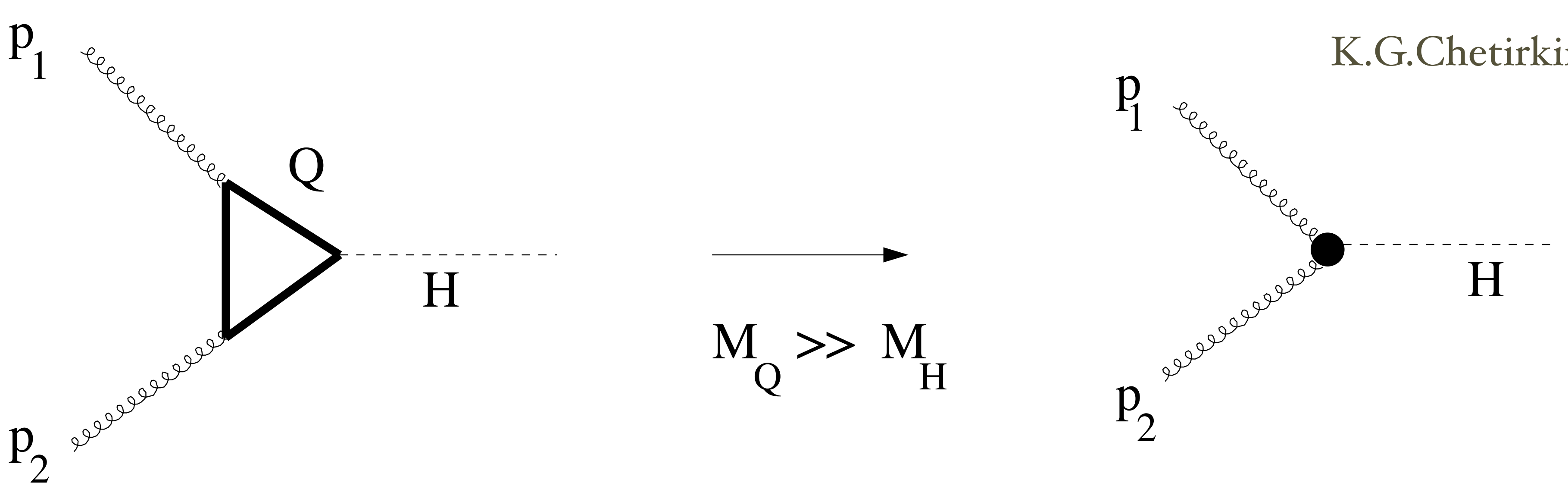
For a light Higgs it is possible to use an effective lagrangian approach obtained when $m_{top} \to \infty$

J.Ellis, M.K.Gaillard, D.V.Nanopoulos (1976)
M.Voloshin, V.Zakharov, M.Shifman (1979)

$$\mathcal{L}_{eff} = -\frac{1}{4}\left[1 - \frac{\alpha_S}{3\pi}\frac{H}{v}(1+\Delta)\right] \mathrm{Tr}\, G_{\mu\nu}G^{\mu\nu}$$

Known to $\mathcal{O}(\alpha_S^3)$

K.G.Chetirkin, M.Steinhauser, B.A.Kniehl (1997)



Effective vertex: one loop less !

Recently the subleading terms in large-m_{top} limit at NNLO have been evaluated

R.Harlander et al. (2009,2010)
M.Steinhauser et al. (2009)

The approximation works to better than 0.5 % for $m_H < 300$ GeV

gg fusion

Effects of soft-gluon resummation at Next-to-next-to leading logarithmic (NNLL) accuracy (about +9-10% at the LHC, +13% at the Tevatron, with slight reduction of scale unc.)

S. Catani, D. De Florian, P. Nason, MG (2003)

→ Nicely confirmed by computation of soft terms at N^3LO

S. Moch, A. Vogt (2005), E. Laenen, L. Magnea (2005)

Two-loop EW corrections are also known (effect is about O(5%))

U. Aglietti et al. (2004)
G. Degrassi, F. Maltoni (2004)
G. Passarino et al. (2008)

Mixed QCD-EW effects evaluated in EFT approach (effect O(1%))

Anastasiou et al. (2008)

→ support "complete factorization": EW correction multiplies the full QCD corrected cross section

EW effects for real radiation (effect O(1%))

W.Keung, F.Petriello, (2009)
O.Brein (2010)
C.Anastasiou et al. (2011)

Results

Quite an amount of work has been done recently to provide updated results that include all the available theoretical information

- Our calculation: D. de Florian, MG (2009,2012)

  Update of NNLL+NNLO calculation of Catani et al. (2003)

  - Start from exact NLO result and add soft-gluon resummation at NLL
  - Perform NNLL+NNLO calculation in the large-m_{top} limit
  - Include two-loop EW effects
  - Include finite width effects within the complex-mass scheme G. Passarino et al. (2011)

Online calculator available at: http://theory.fi.infn.it/grazzini/hcalculators.html

→ **Recommended result by the LHC Higgs XS WG and used as reference theoretical prediction by ATLAS and CMS**

(corresponding results for the Tevatron still used by CDF+D0)

$m_H = 125$ GeV

- Our calluation:

D. de Florian, MG (2009,2012)

PDF uncertainties computed with PDF4LHC recommendation (roughly equivalent to consider 90% CL)

Scale uncertainties computed with $m_H/2 < \mu_F, \mu_R < 2\, m_H$ and $1/2 < \mu_F/\mu_R < 2$

$$\sigma = 19.52^{+7.2\%}_{-7.8\%}\,(\text{scale})^{+7.5\%}_{-6.9\%}\,(\text{PDF} + \alpha_S)\ \text{pb}$$

- Independent calculation by Anastasiou et al (no soft-gluon resummation and $\mu_F = \mu_R = m_H/2$): implemented in iHixs

Anastasiou et al. (2012)

$$\sigma = 20.69^{+8.4\%}_{-9.3\%}\,(\text{scale})^{+7.8\%}_{-7.5\%}\,(\text{PDF} + \alpha_S)\ \text{pb}$$

→ 6% higher than our result but still compatible within scale uncertainties

Other Results

- Calculation by Baglio-Djouadi

J.Baglio,A.Djouadi (2010)

- Detailed (and very) conservative study of the various sources of uncertainties → about±25-30 % at 7 TeV

- Further update for the Tevatron uses $\mu_F = \mu_F = m_H/2$ as central scale: agreement with the other calculations

→ Recently used to provide possible explanation of $\gamma\gamma$ excess

A.Djouadi (2012)

- Calculation by Neubert et al.

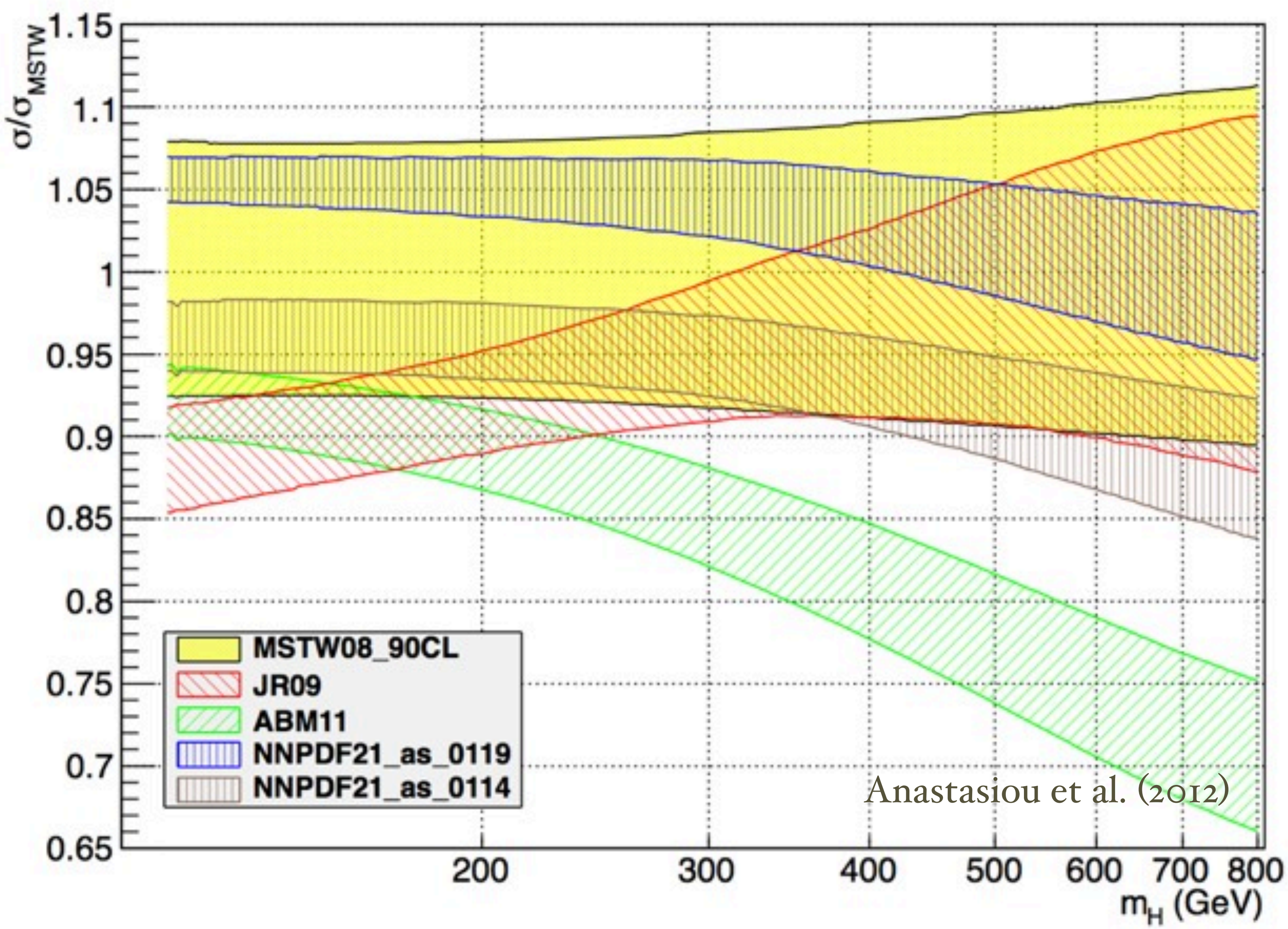
V.Ahrens et al. (2010)

- Based on the so called "π^2-resummation"

- Numerical results agree with the other calculations

- Perturbative uncertainties of about 3% or smaller → largely underestimated !

The gluon density issue



Various NNLO sets have become available in the last few years

New CT10 NNLO fit agrees with MSTW within 5 %

At m_H=125 GeV things appear under control

ABM11 set does not include Tevatron jet data and it has α_S much smaller than the world average → large difference at high m_H (relevant for exclusion)

Improvements will come from precise measurements of top and other SM cross sections at the LHC

Higgs properties

What do we know about the newly discovered resonance ?

It manifests itself in three decay channels: ZZ, WW and $\gamma\gamma$

Its width is consistent with being smaller than the experimental resolution

Landau Yang theorem → Since it decays in $\gamma\gamma$ it cannot have spin one (caveat $H \to aa \to 4\gamma$ with two photon pairs too close to be distinguished)

It has significant decay fraction in WW and ZZ

→ Likely to play a role in EWSB

→ very likely to have a significant CP even component, since the couplings of a pseudoscalar to VV are loop induced, and thus expected to be small.........

but difficult to rule out the existence of a (small) CP odd component !

Spin CP properties

The methods to determine the properties of a resonance through its decays to gauge bosons and then into four leptons date back to more than 50 years ago

Photon polarization can be used to determine π^0 parity in $\pi^0 \to \gamma\gamma$

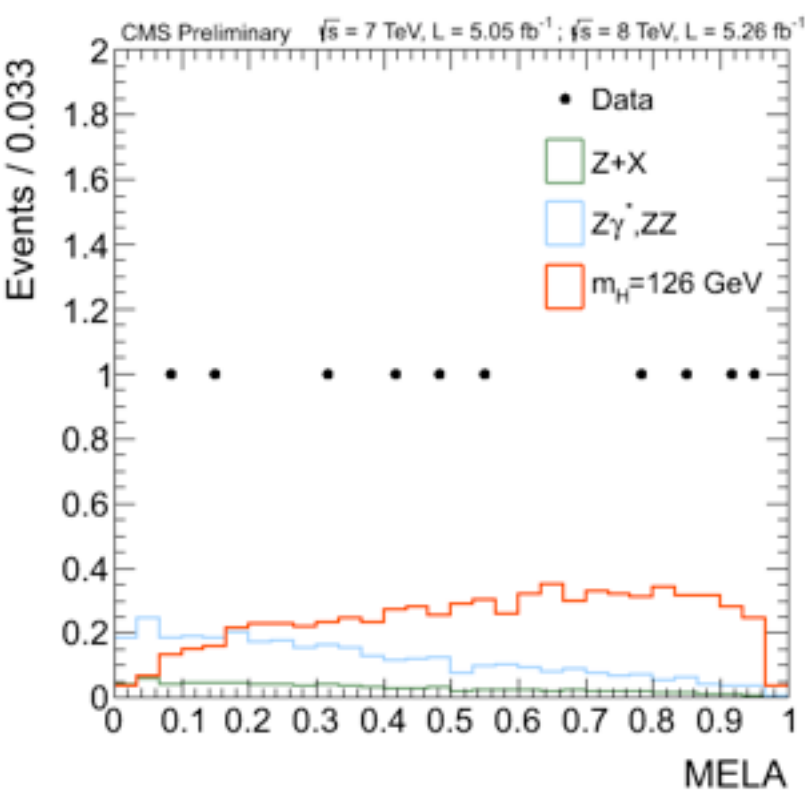
(unfeasible for the Higgs but maybe possible to look at converted photons)

C.N. Yang (1950)

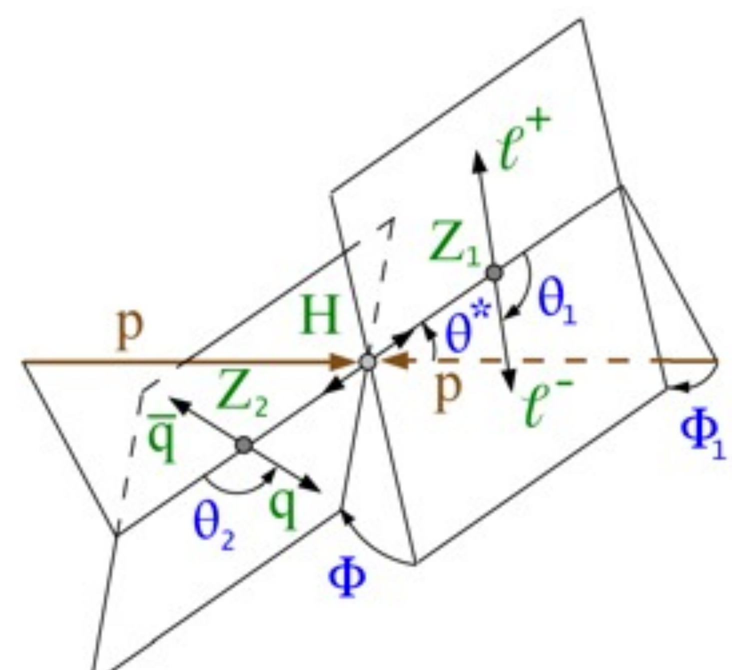
Easier to use orientation in Dalitz pairs in $\pi^0 \to e^+ e^- e^+ e^-$

R.H. Dalitz (1951)

MELA (Matrix Element Likelihood Analysis)



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

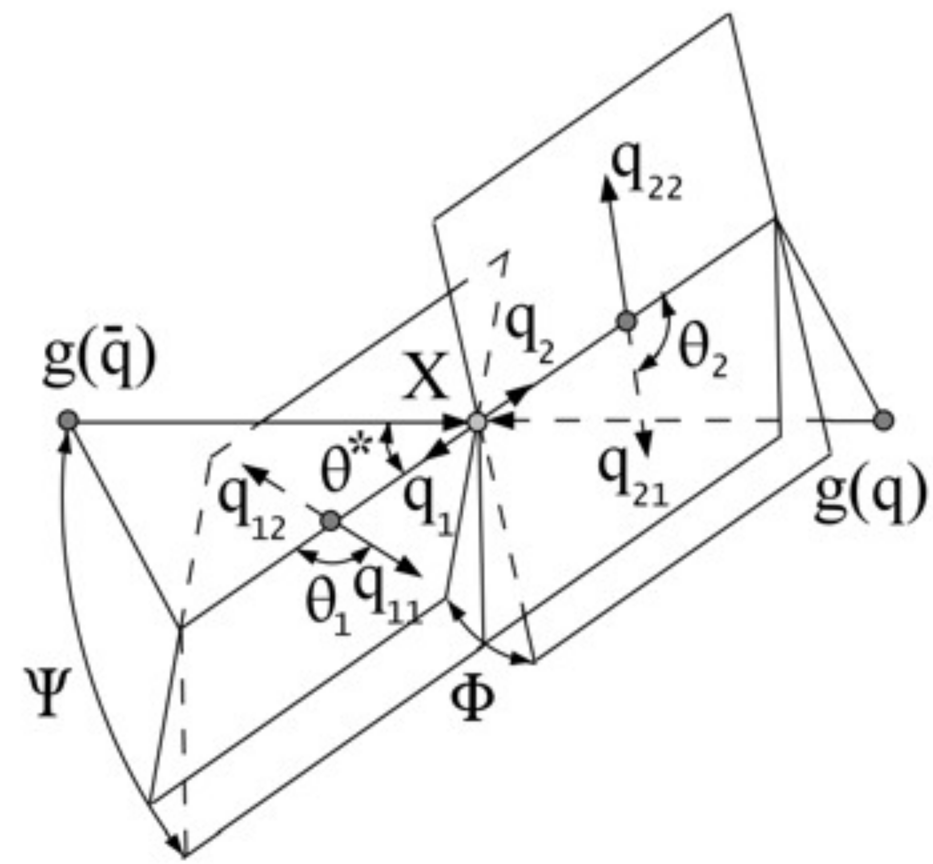


Spin CP properties

JHU generator:

K.Melnikov et al. (2009, 2012)

Model independent production of a resonance X followed by its decay in two vector bosons and in four fermions



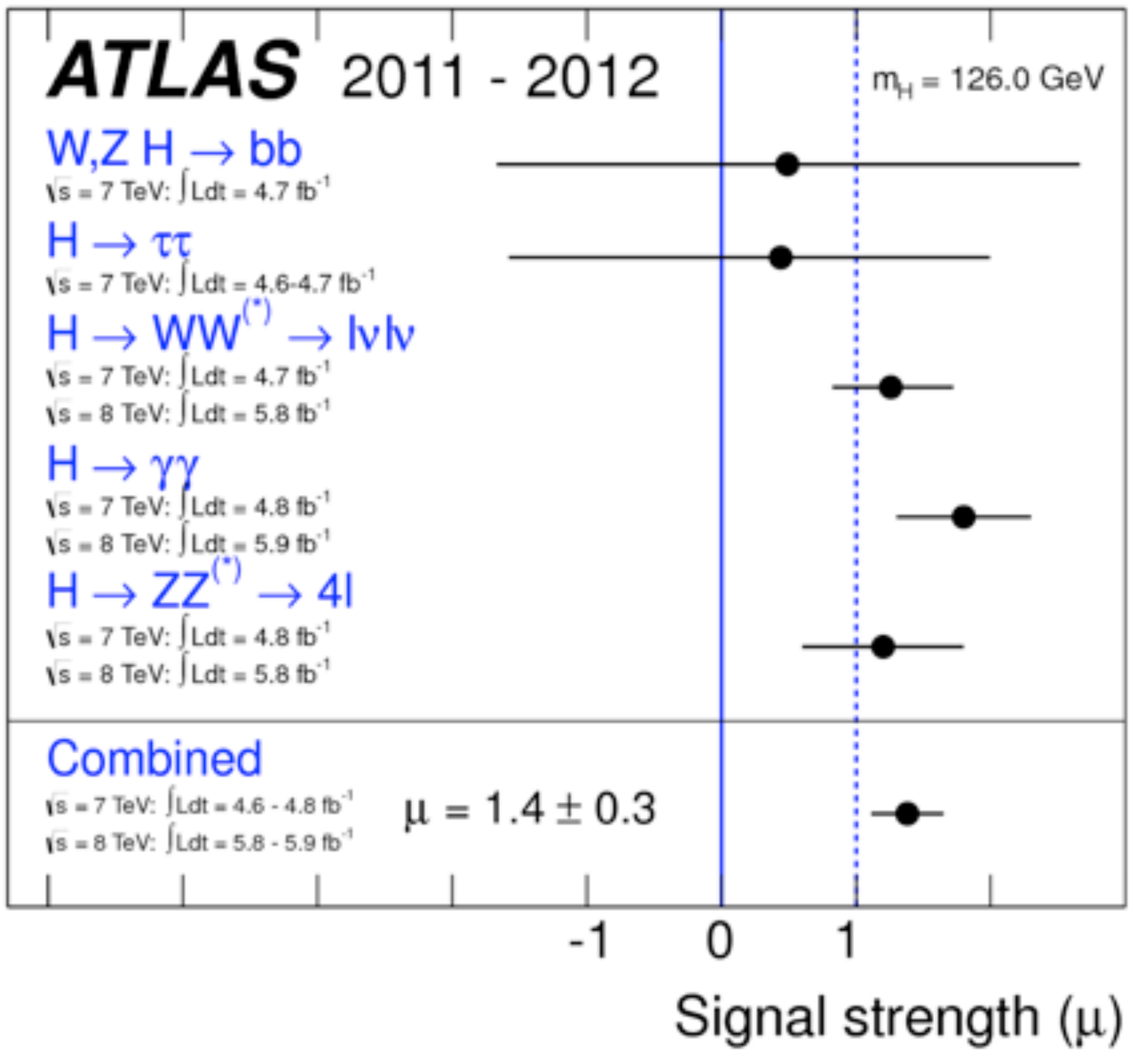
Results of this study show good discriminating power against pseudoscalar and spin 2 hypotesis

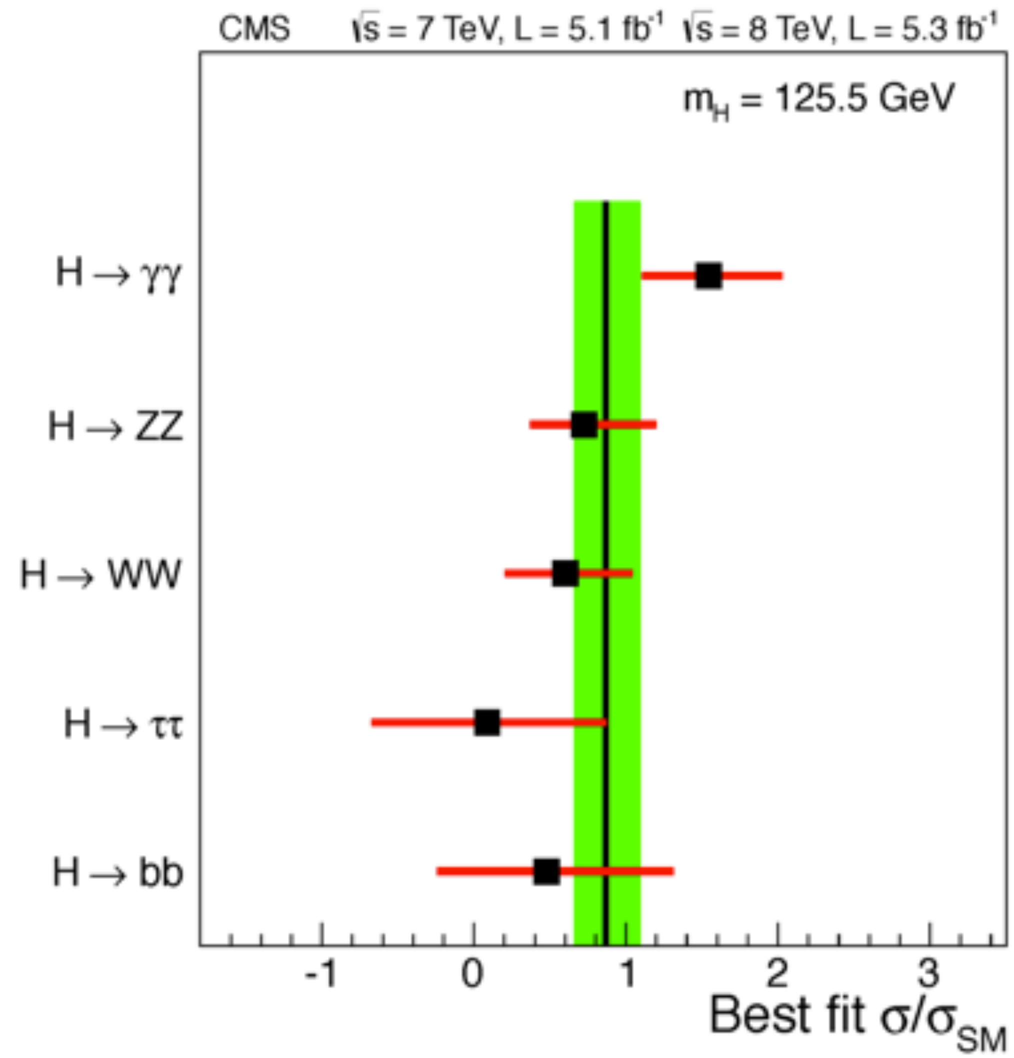
Expected separation significance with 35 fb⁻¹

scenario	$X \to ZZ$	$X \to WW$	$X \to \gamma\gamma$	combined
0^+_m vs background	7.1	4.5	5.2	9.9
0^+_m vs 0^-	4.1	1.1	0.0	4.2
0^+_m vs 2^+_m	1.6	2.5	2.5	3.9

But: LO only !
Issue to be investigated:
impact of Higgs pt

SM or else ?





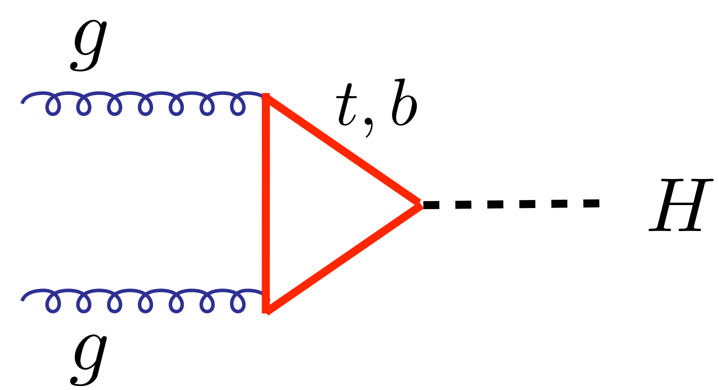
$H \to \gamma\gamma$ rate higher than (but still compatible with) what expected in the SM

$H \to \tau\tau$ quite low (CMS)

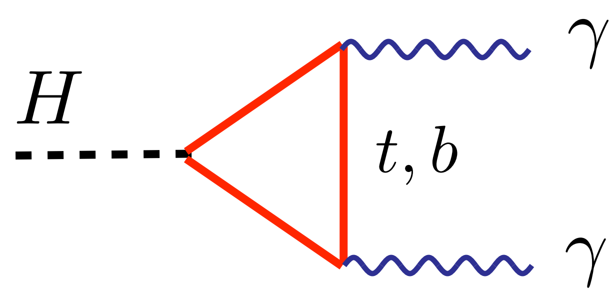
O(100) theory paper with possible interpretations !

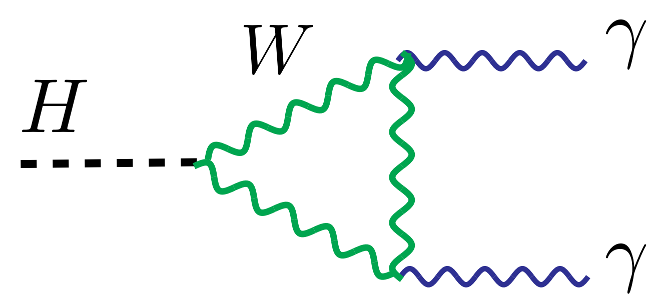
SM or else ?

Higgs production sensitive to heavy colored particles



Higgs decay to two photons sensitive to both colored and colorless particles





→ To preserve the SM predictions in the other channels there should be new colorless states with large couplings to the Higgs.......

....or the Higgs coupling to heavy fermions should change sign ! (to make the interference of top and W loop positive)

A.Azatov et al. (2012)
J. Espinosa et al. (2012)
P.P.Giardino et al (2012)

Chiral lagrangian for a light Higgs

Start from chiral lagrangian for the Goldstone bosons

$$\mathcal{L} = \frac{v^2}{4}\mathrm{Tr}\left(D_\mu \Sigma^\dagger D^\mu \Sigma\right) \qquad \Sigma = \exp\{i\sigma_a \pi_a / v\}$$

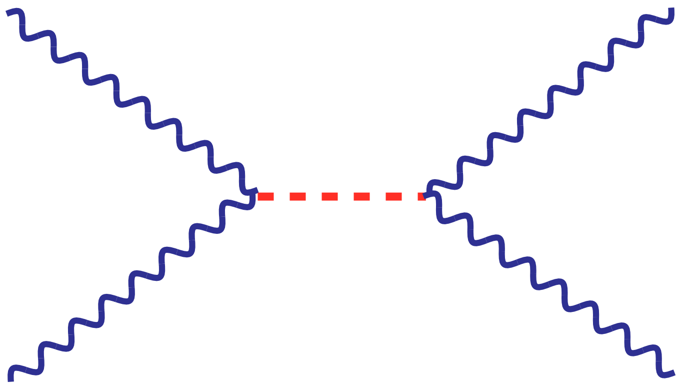
→ unitarity violations at the TeV scale

Let us introduce the Higgs boson as scalar degree of freedom neutral under $SU(2)_L \otimes SU(2)_R / SU(2)_V$

G.Giudice, C.Grojean, A.Pomarol, R.Rattazzi (2007)
R.Contino, C.Grojean, M.Moretti, F.Piccinini, R.Rattazzi (2010)

$$\mathcal{L} = \frac{1}{2}(\partial_\mu h)^2 - V(h) + \frac{v^2}{4}\mathrm{Tr}\left(D_\mu \Sigma^\dagger D^\mu \Sigma\right)\left(1 + 2a\frac{h}{v} + b\frac{h^2}{v^2}\right)$$
$$-\lambda \bar{\psi}_L \Sigma \psi_R \left(1 + c\frac{h}{v}\right)$$

- Unitarity restored in WW scattering for a=1



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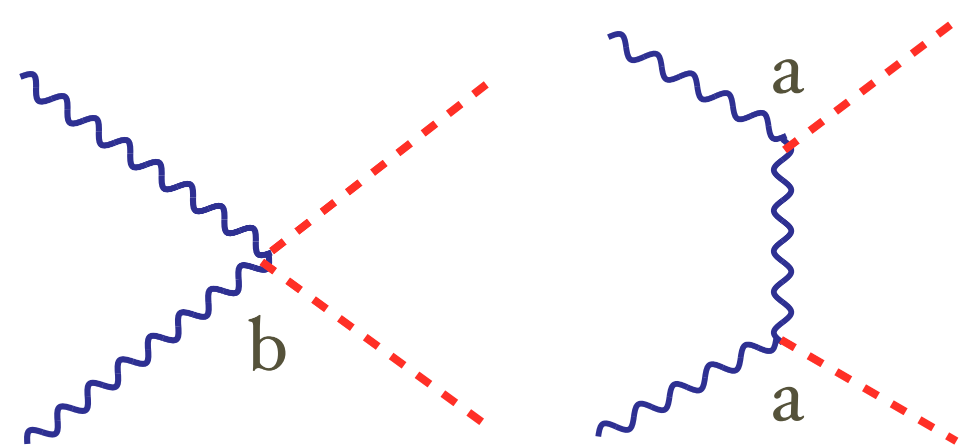
- Unitarity restored in WW→hh for $b=a^2$



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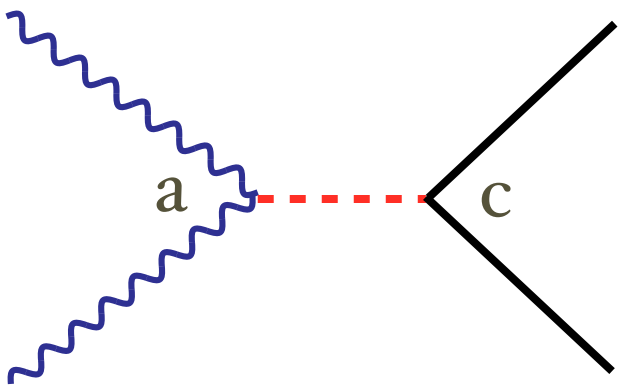
- Unitarity restored in $WW \to \psi\psi$ for ac=1



Chiral lagrangian for a light Higgs

The choice a=b=c=1 corresponds to the SM Higgs sector

$$H = \frac{1}{\sqrt{2}} e^{i\sigma_i \pi_i / v} \begin{pmatrix} 0 \\ v+h \end{pmatrix} \qquad \mathcal{L} \to (D_\mu H)^\dagger D^\mu H$$

Deviations from the SM can be explored with a,b,c≠ 1 and including higher dimensional operators

$$\left(\frac{g}{4\pi}\right)^2 \left(c_{WW} W_{\mu\nu}^2 + c_{ZZ} Z_{\mu\nu}^2 + c_{Z\gamma} Z_{\mu\nu} F^{\mu\nu} + c_{\gamma\gamma} F_{\mu\nu}^2 + c_{gg} G_{\mu\nu}^2\right) \frac{h}{v} + \ldots\ldots$$

Still too much freedom:
we need additional assumptions on possible operators

Higgs couplings

Interim framework for coupling exploration

LHCHXSWG, A. David et al (2012)

Assumptions:

- The signal observed originate from a single narrow resonance of mass around 125 GeV
- The width of the resonance can be neglected (i.e. the narrow width approximation can be used)
- Only (small) modifications of the coupling strength are taken into account, while the tensor structure is assumed to be the same as in the SM

Predicted SM cross sections (including all available radiative corrections) are dressed with scale factors $\varkappa_i$

Higgs couplings

- Simplest approach: one common scale factor $\varkappa$

  → Equivalent to fit overall signal strength

  ATLAS finds $\mu=1.4 \pm 0.3$ at $m_H=126.0$

  CMS finds $\mu=0.87 \pm 0.23$ at $m_H=125.5$

- Scaling of vector ($\varkappa_V=\varkappa_W=\varkappa_Z$) and fermion couplings ($\varkappa_f=\varkappa_t=\varkappa_b$)

$$(\sigma \text{ x BR})(gg \to H \to \gamma\gamma) = \varkappa_f^2 \varkappa_\gamma^2 / \varkappa_H^2$$

$\varkappa_\gamma = \varkappa_\gamma(\varkappa_f, \varkappa_V)$ loop coupling to the photons (involves W, heavy quarks)

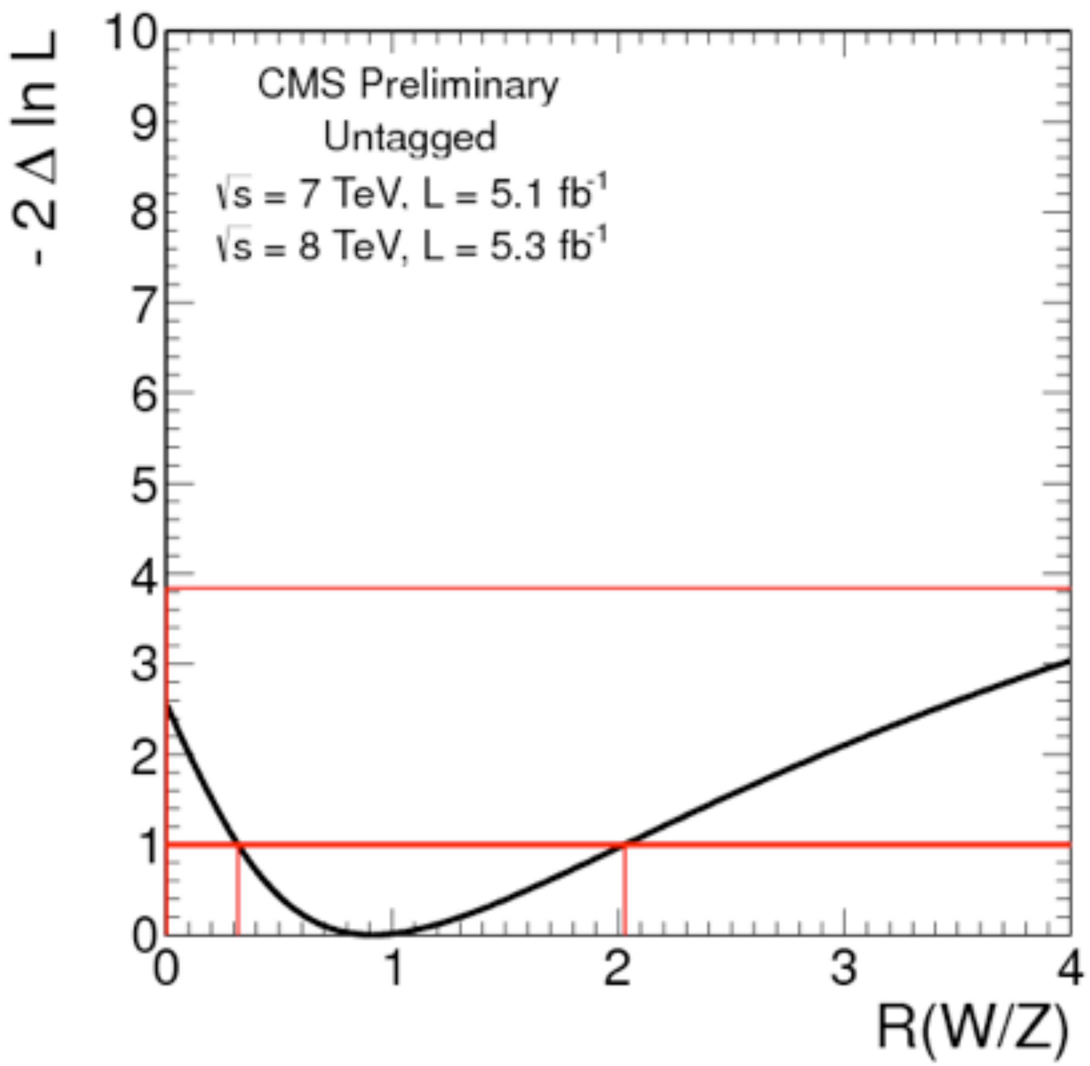
$\varkappa_H = \varkappa_H(\varkappa_f, \varkappa_V)$ scaling factor for the total width

→ implies no invisible or undetectable widths

this assumption can be relaxed and the width treated as a free parameter

Higgs couplings

- Probing custodial symmetry: one more parameter R_{WZ} ($=\varkappa_W/\varkappa_Z$) besides $\varkappa_f$ and $\varkappa_Z$



$R(W/Z) = 0.9^{+1.1}_{-0.6}$

→ **More data are needed !**

Increasing the number of parameters the model becomes more realistic but experimental uncertainties in the fit will rapidly grow

Higgs couplings

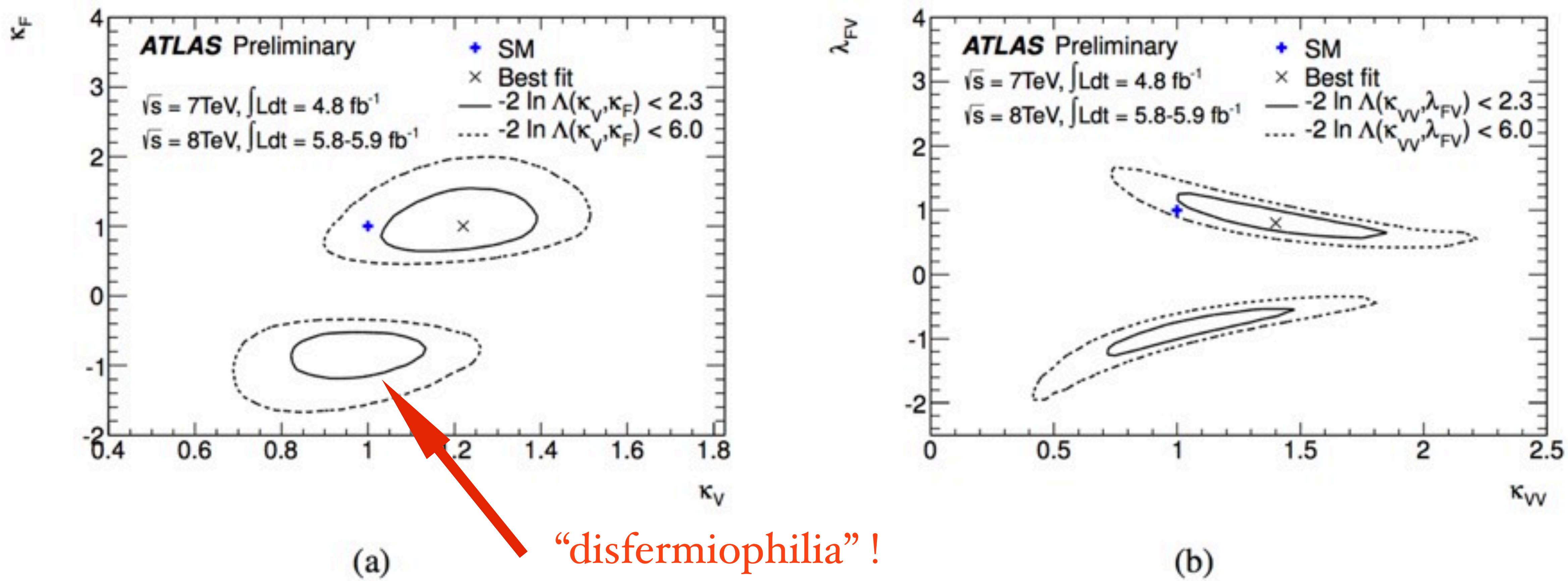


Figure 4: Fits for 2-parameter benchmark models probing different coupling strength scale factors for fermions and vector bosons: (a) Correlation of the coupling scale factors κ_F and κ_V, assuming no non-SM contribution to the total width; (b) Correlation of the coupling scale factors $\lambda_{FV} = \kappa_F/\kappa_V$ and $\kappa_{VV} = \kappa_V \cdot \kappa_V/\kappa_H$ without assumptions on the total width.

Very recent ATLAS analysis uses this set up and confirms previous findings: present data indicate possible negative coupling with heavy fermions ! (but best fit still SM like....)

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Summary & Outlook

- It is a very exciting moment for particle physics:
  a new particle consistent with the long sought Higgs boson has been discovered

- Difficult to overstate the importance of this discovery for a generation of physicists !

- Current data are in agreement with the SM (with some interesting hint here and there....)

- The exploration of the properties of the new resonance has already started

- Next update is expected for the Hadron Collider Physics symposium in Kyoto (november 2012) with about 15 fb^{-1} per experiment

→ **Stay tuned !**

Buon compleanno !