Electroweak and Theory

(SM and MSSM)

Sven Heinemeyer, IFCA (CSIC, Santander)

St. Andrews, 08/2012

1. Higgs and Electroweak in The Standard Model (I)

2. Higgs and Electroweak in The Standard Model (II)

3. Higgs and Electroweak in the MSSM

Electroweak and Theory (II):
Higgs and Electroweak in the SM (II)

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1. Properties of the SM Higgs boson

2. Comparison to "the discovery"

3. Implications for future colliders

Properties of the SM Higgs boson

1.) Decay to fermions:

coupling:

$$g_{f\bar{f}H} = \left[\sqrt{2}\, G_\mu\right]^{1/2} m_f$$

decay width:

$$\Gamma(H \to f\bar{f}) = N_c \frac{G_\mu\, M_H}{4\sqrt{2}\,\pi} m_f^2(M_H^2) \left(1 - 4\frac{m_f^2}{M_H^2}\right)^{3/2}$$

with N_c = number of colors

Bulk of QCD corrections for decays to quarks are mapped into

$$m_q^2(\text{pole}) \to m_q^2(M_H^2)$$

Dominant decay process: $H \to b\bar{b}$

2.) Decay to heavy gauge bosons ($V = W, Z$):

coupling:

$$g_{VVH} = 2 \left[\sqrt{2}\, G_\mu\right]^{1/2} M_V^2$$

on-shell decay width ($M_H > 2M_V$):

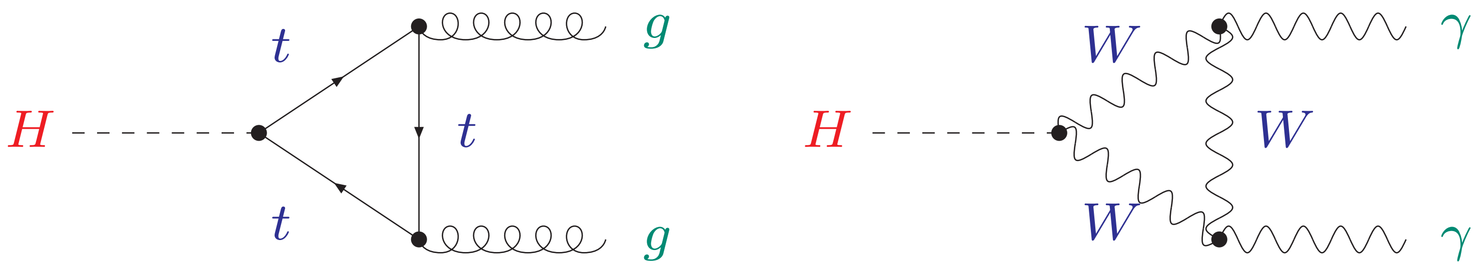
$$\Gamma(H \to VV) = \delta_V \frac{G_\mu M_H^3}{16\sqrt{2}\,\pi} \left(1 - 4\frac{M_V^2}{M_H^2} + 12\frac{M_V^4}{M_H^4}\right) \left(1 - 4\frac{M_V^2}{M_H^2}\right)^{1/2}$$

with $\delta_{W,Z} = 2, 1$

off-shell decay width ($M_H < 2M_V$):

$$\Gamma(H \to VV^*) = \delta'_V \frac{3G_\mu^2 M_H}{16\,\pi^3} M_V^4 \times \text{Integral}$$

3.) Decay to massless gauge bosons (gg, $\gamma\gamma$):



$$\Gamma(H \to gg) \;=\; \frac{G_\mu\, \alpha_s^2(M_H^2)\, M_H^3}{36\,\sqrt{2}\,\pi^3}\left[1 + C\frac{\alpha_s(\mu)}{\pi}\right]$$

via the top quark loop with

$$C = \frac{215}{12} - \frac{23}{6}\log\left(\frac{\mu^2}{M_H^2}\right) + \mathcal{O}(\alpha_s)$$

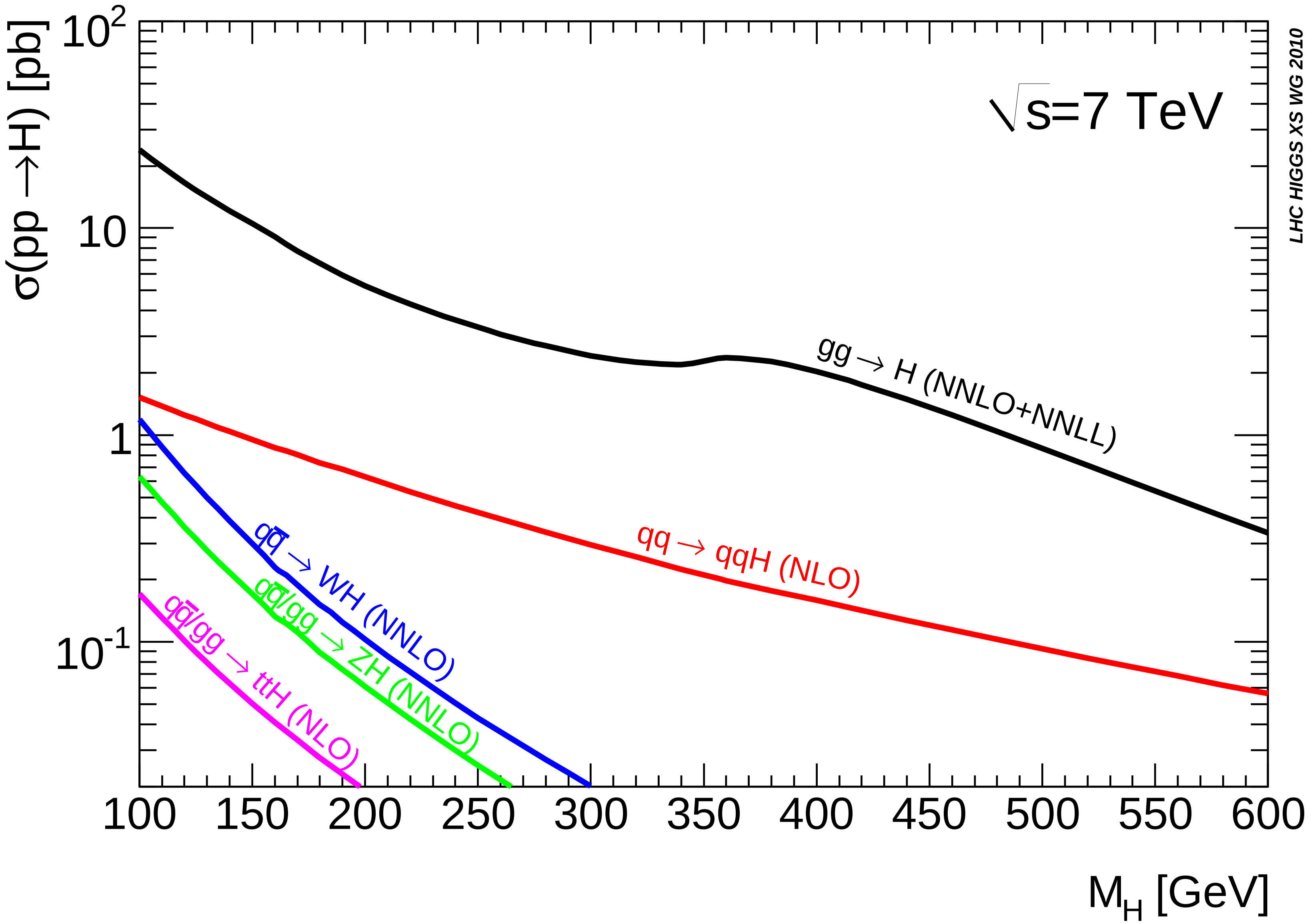
$\Rightarrow$ huge QCD corrections

$$\Gamma(H \to \gamma\gamma) \;=\; \frac{G_\mu\, \alpha^2\, M_H^3}{128\,\sqrt{2}\,\pi^3}\left|\frac{4}{3}e_t^2 - 7\right|^2$$

via the top quark and W boson loop

Latest theory predictions for the SM Higgs: LHC production XS

[*LHC Higgs XS WG '10*]



Latest theory predictions for the SM Higgs: branching ratios

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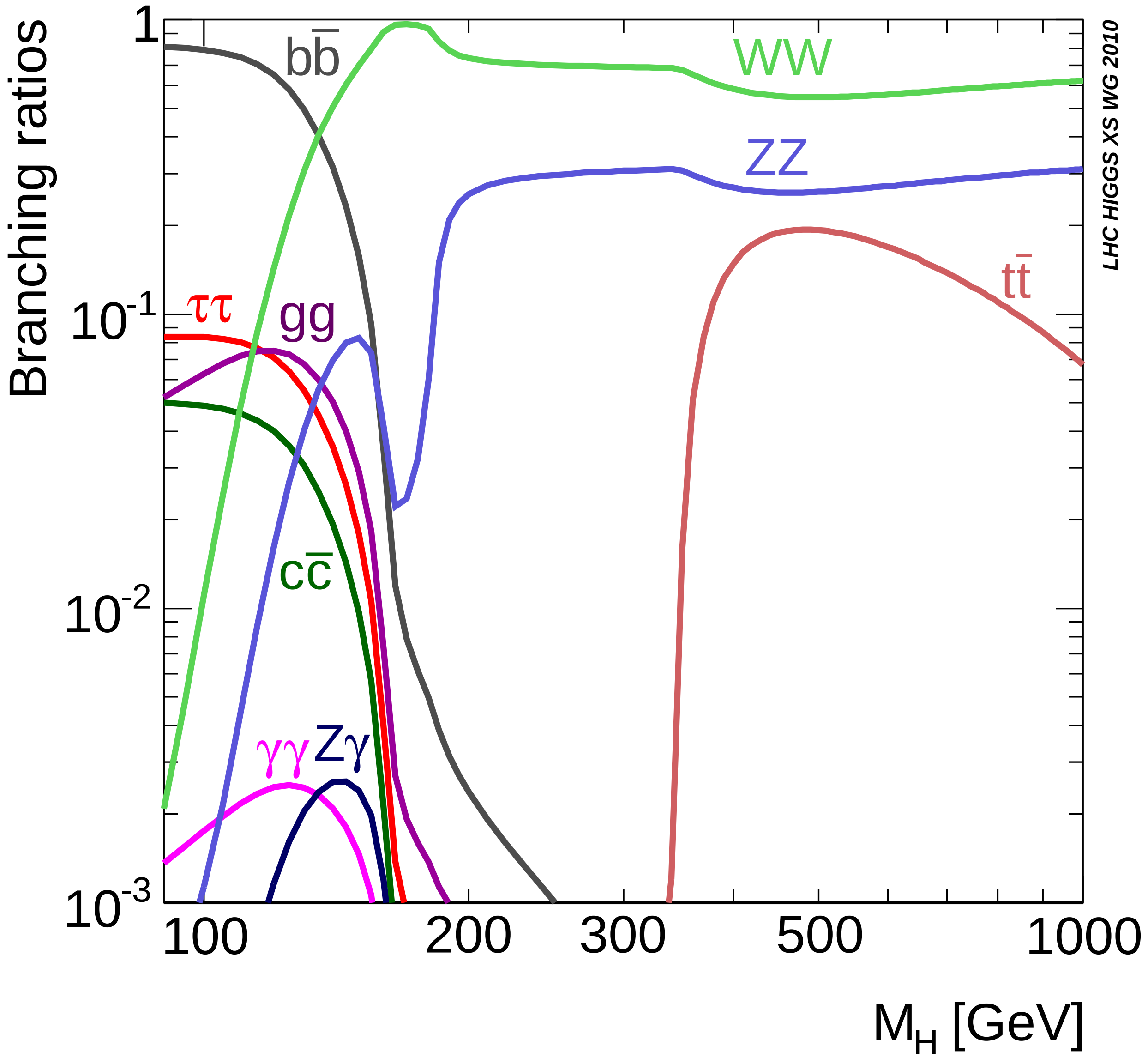

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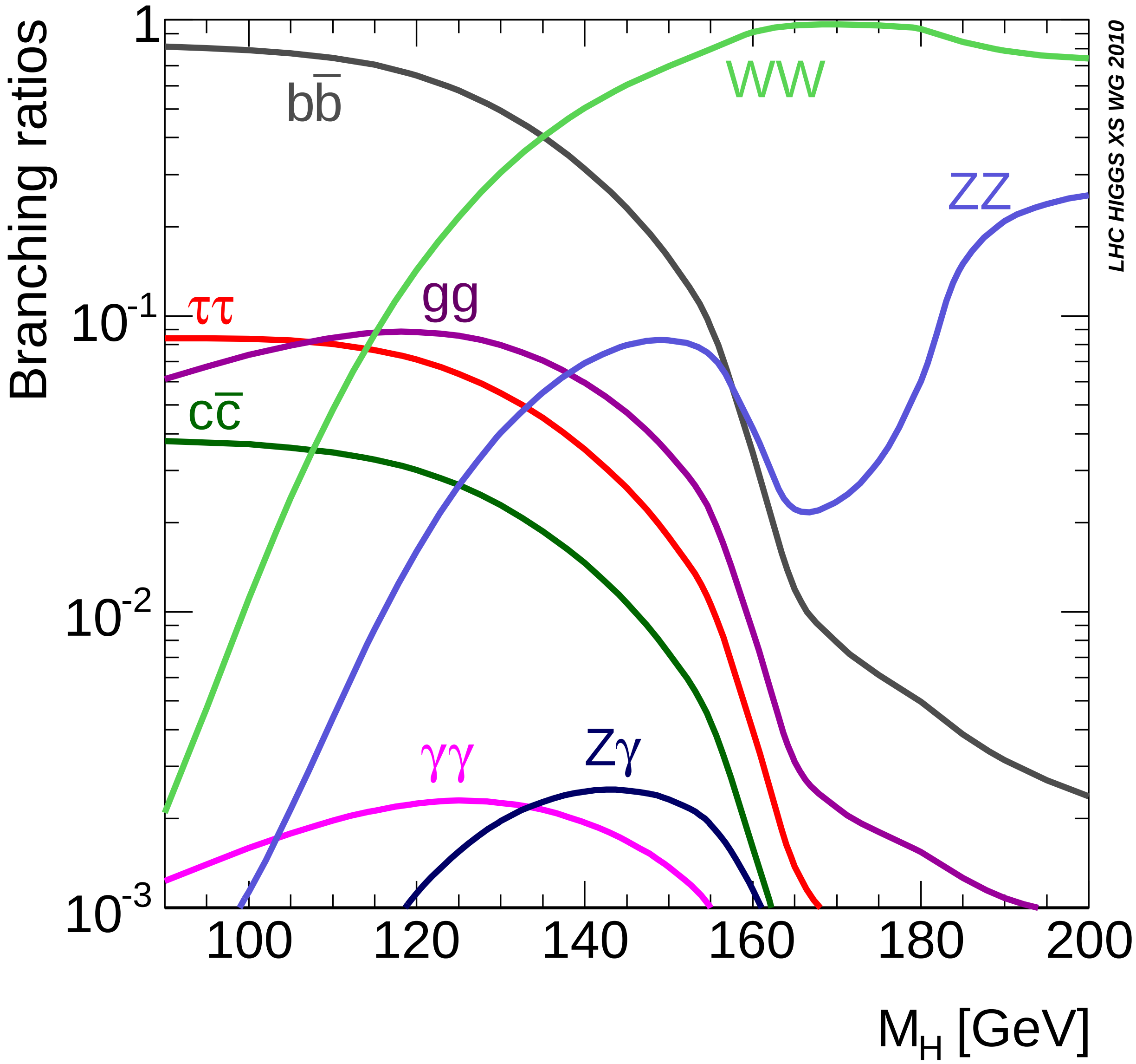

Do never forget the **UNCERTAINTIES!**

Three different types of uncertainties:

Experimental error ($\to$ Bill Murray's, Peter Maettig's lecture):

– current error

– future expectations

$\Rightarrow$ sets the scale, has to be matched by other errors

Theory uncertainty:

$\Rightarrow$ uncertainty due to missing higher order corrections

– only estimates possible

– even more complicated for the future

Parametric uncertainty:

– current uncertainty in the prediction due to error in the input parameters

– m_t, α_s, PDFs, . . .

– future expectations?

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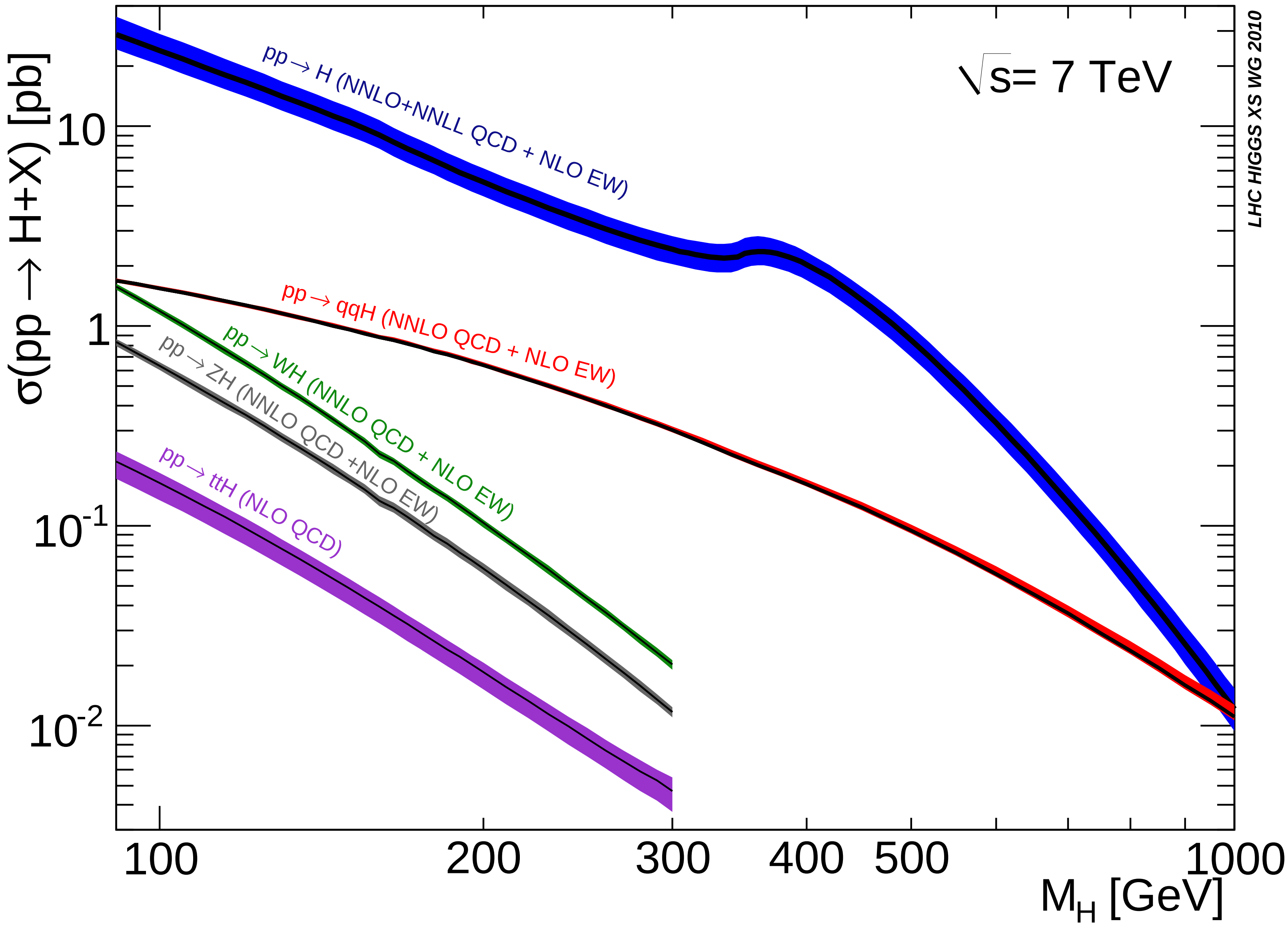
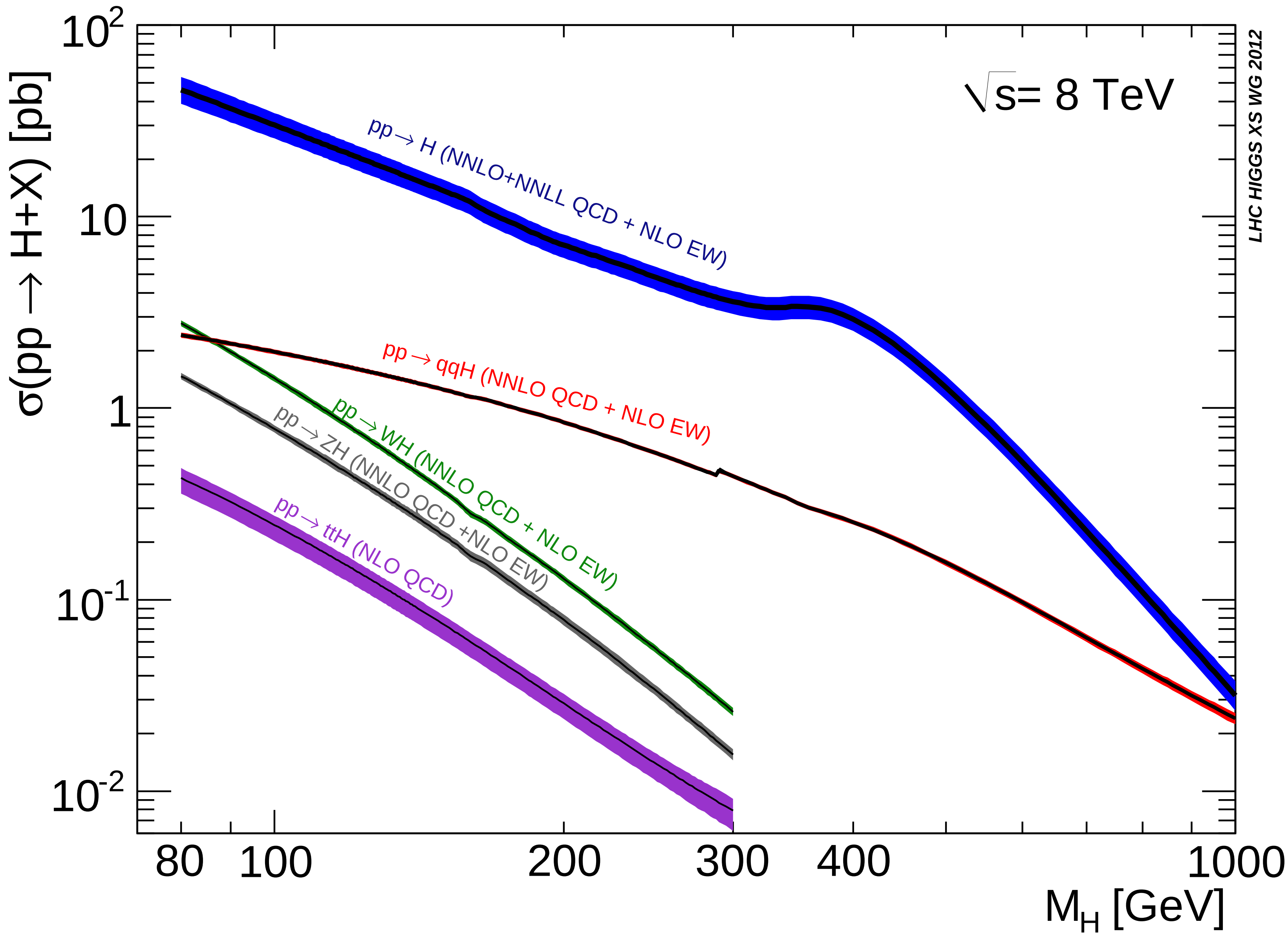
[*LHC Higgs XS WG '10*]



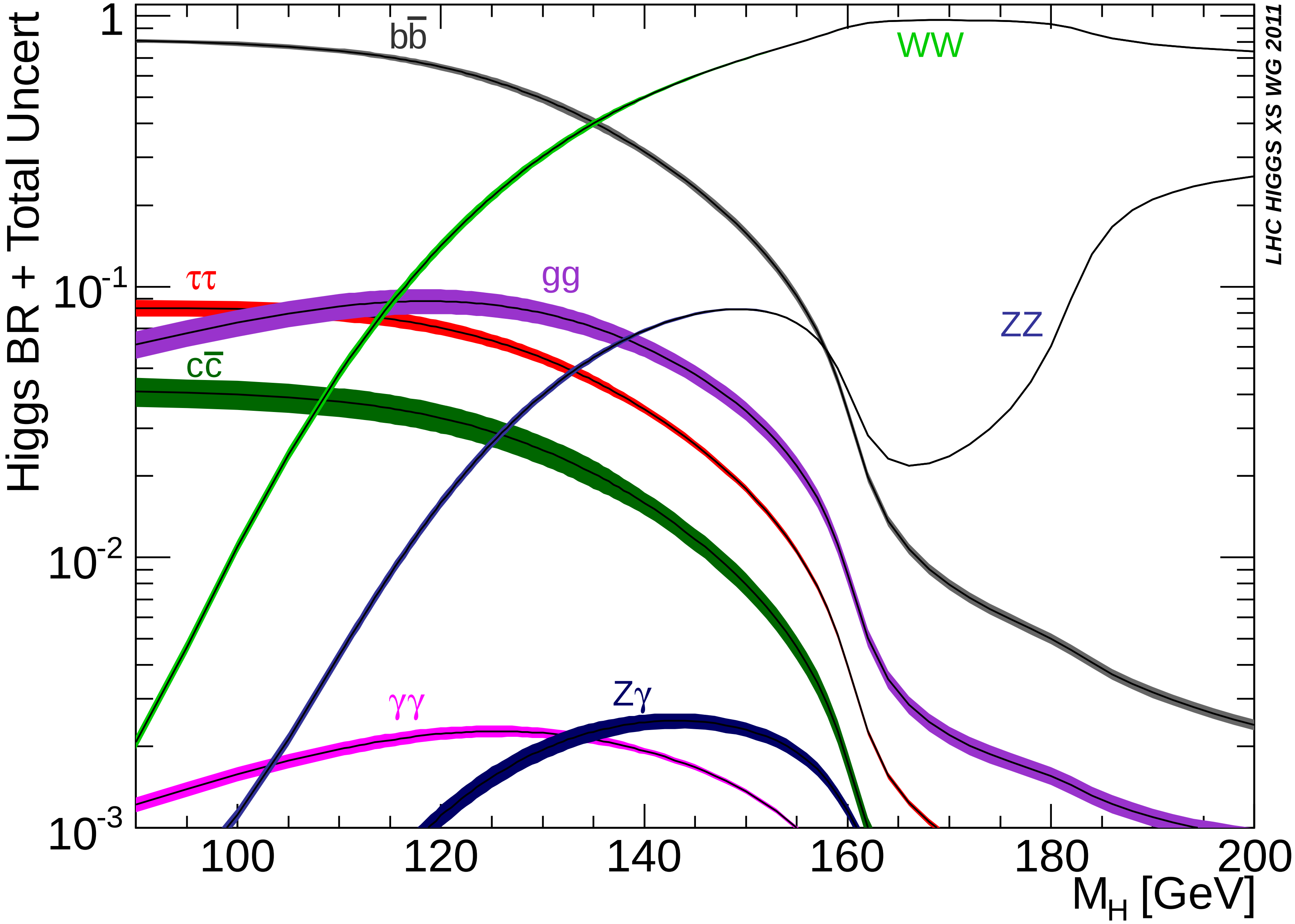
Latest theory predictions for the SM Higgs: LHC production XS

[*LHC Higgs XS WG '12*]



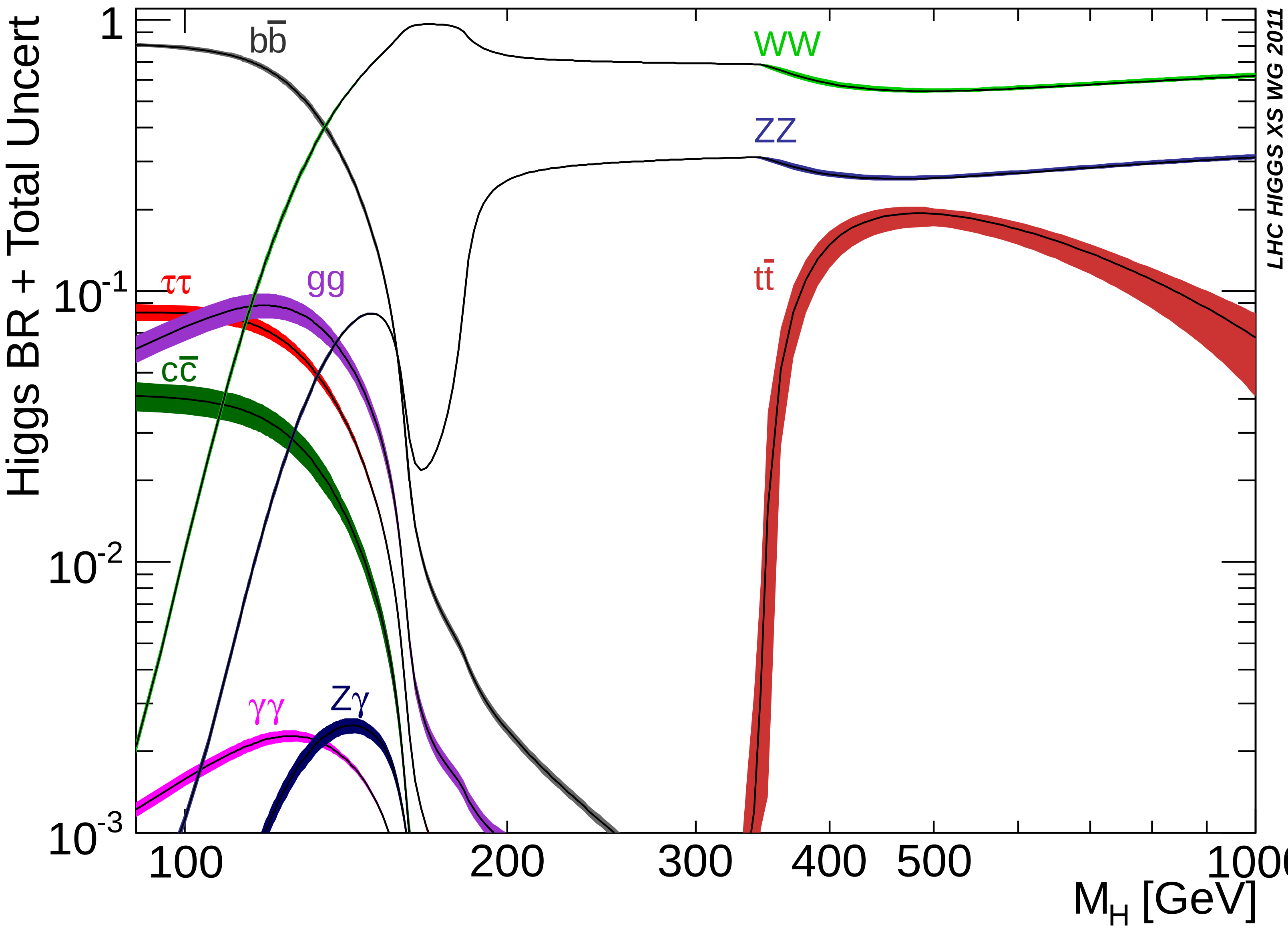
Latest theory predictions for the SM Higgs: branching ratios

[LHC Higgs XS WG '11]



Latest theory predictions for the SM Higgs: branching ratios

[*LHC Higgs XS WG '11*]



LHC Higgs Cross Section Working Group

https://twiki.cern.ch/twiki/bin/view/LHCPhysics/CrossSections

- Mixed group of ATLAS/CMS experimentalists and theorists (crucial!)
- Subgroups for each LHC Higgs production cross section or BRs
- Goal: obtain best theory predictions to facilitate
  - "best" Higgs boson search
  - "best" combination of ATLAS and CMS
  - "best" extraction of parameters
- Much to do for theorists:
  - improve cross section/BR calculation
  - calculation of distributions
  - extract/fit Higgs couplings
  - ...
- $\Rightarrow$ more workforce always appreciated!

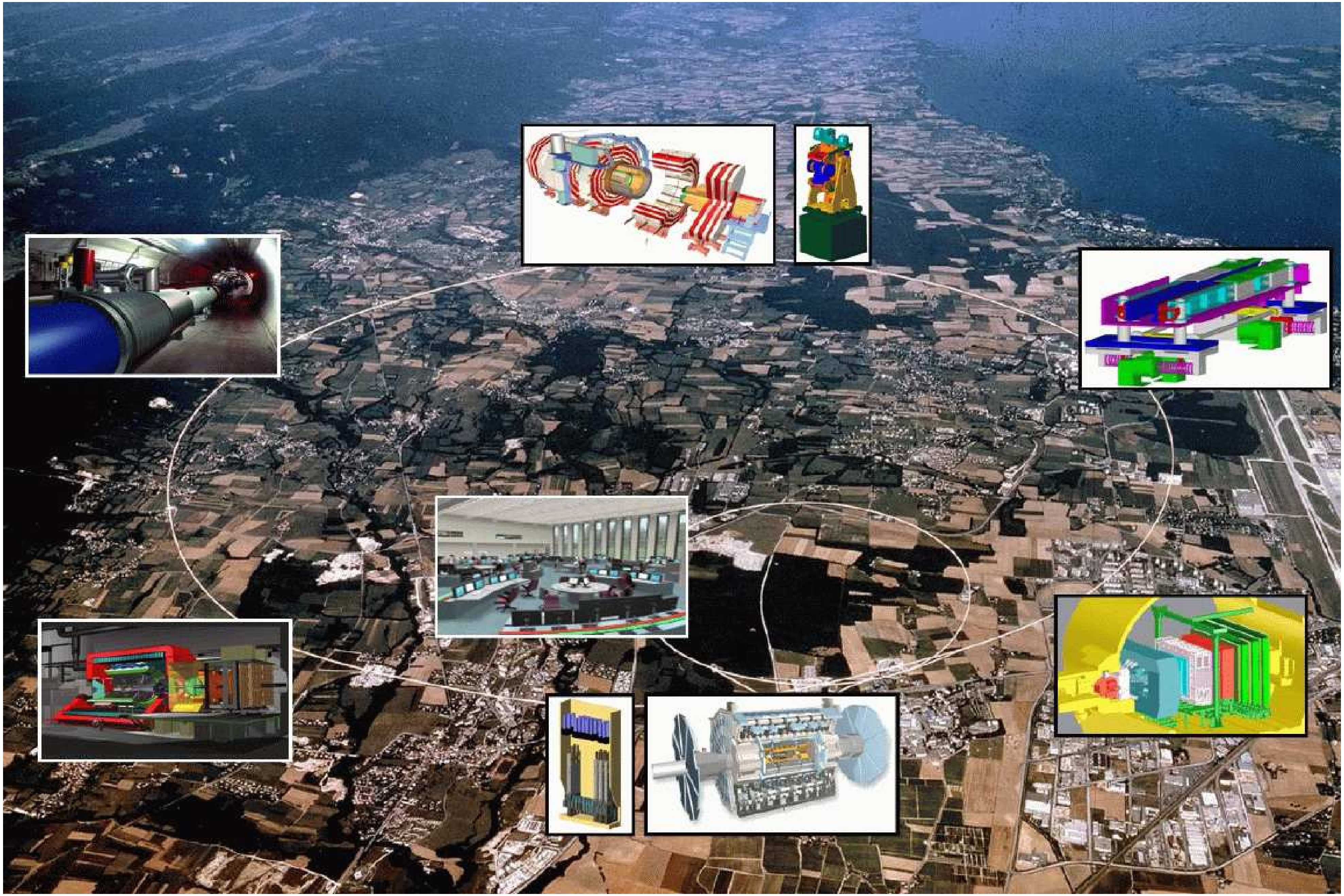
Discovering the Higgs boson

What has to be done?

1. Find the new particle	T	L	I
2. measure its mass ($\Rightarrow$ ok?)	T	L	I
3. measure coupling to gauge bosons		L	I
4. measure couplings to fermions		L	I
5. measure self-couplings			I
6. measure spin, . . .		L	I

T = Tevatron, L = LHC, I = ILC

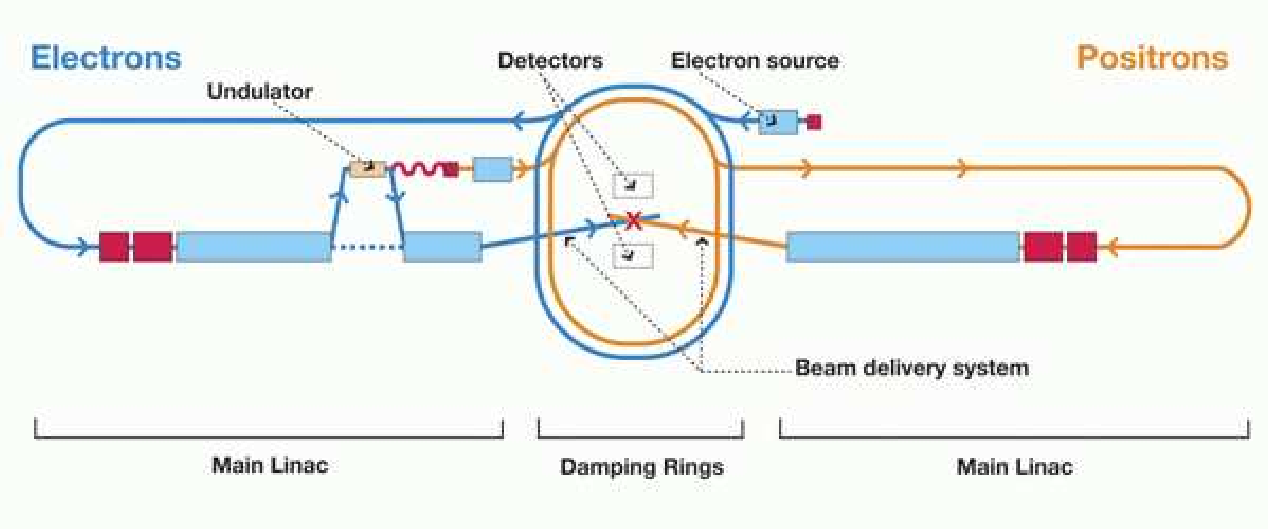
We need the ILC to find the Higgs
and to establish the Higgs mechanism!
But the LHC can do a crucial part already!



Linear e^+e^- collider, $\sqrt{s} = 500 - 1000$ GeV

based on superconducting cavities (cold technology) (ITRP decision 2004)

Schematic:



– two detectors in one interaction region (push-pull)

– undulator based e^+ source

– polarized beams for e^- and e^+ ($P_{e^-} = 80\%$, $P_{e^+} = 60\%$)

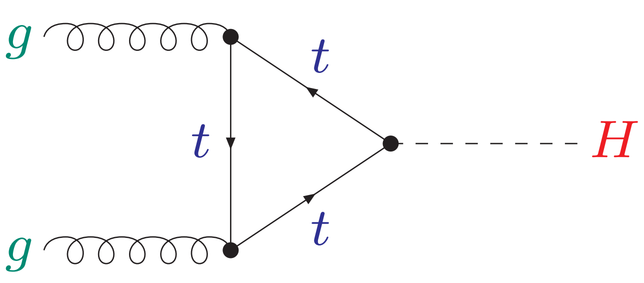
⇒ clearly defined and tunable innitial state

⇒ extremely "clean" physics

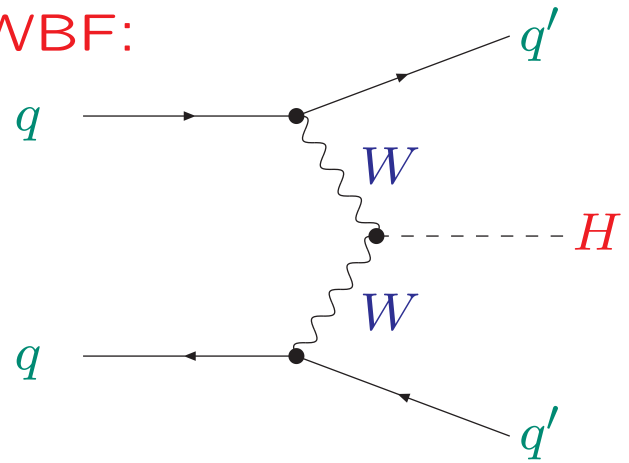
Comparison to "the discovery":

Important SM production channel at the LHC:

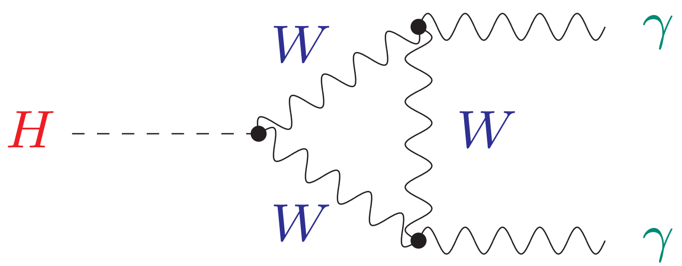
Gluon-Fusion:

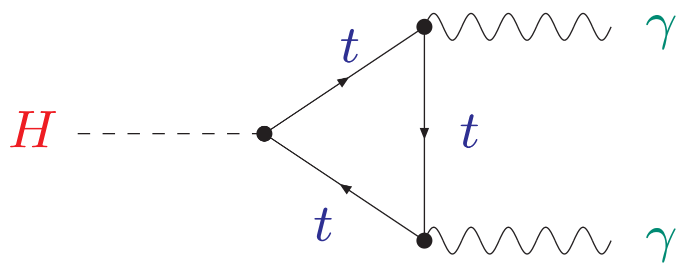


WBF:

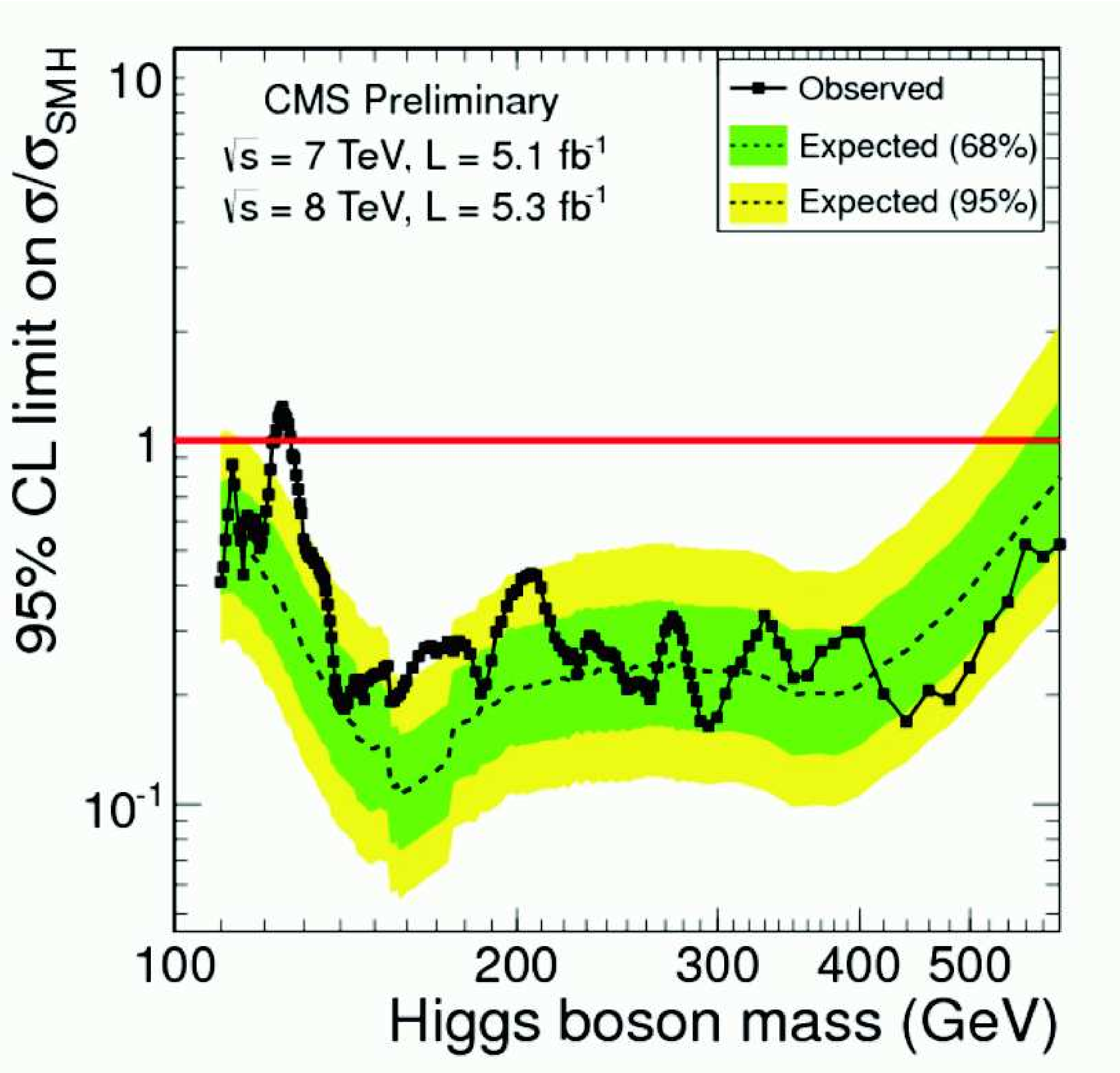


Important decay for Higgs mass measurement:

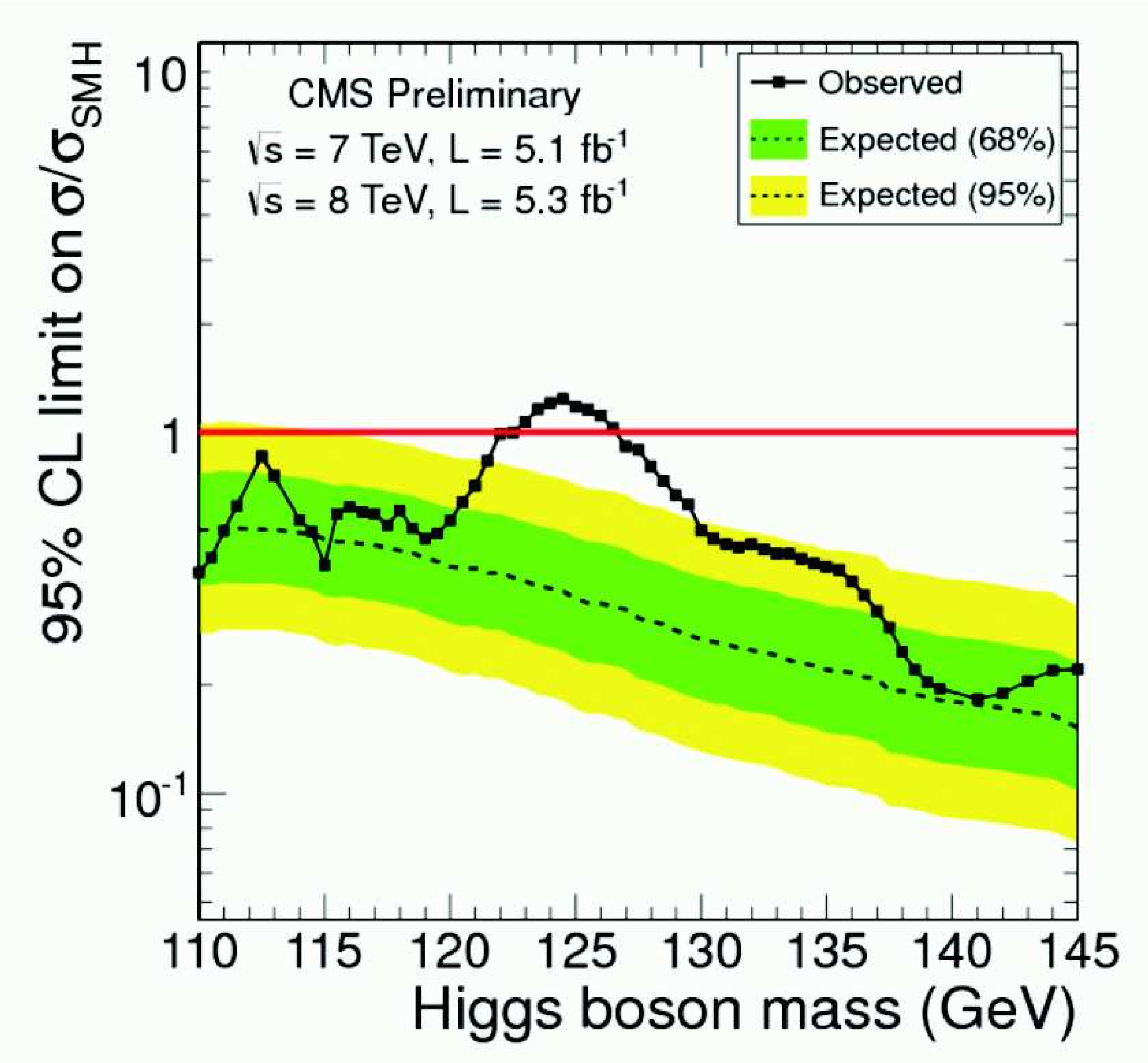




Latest CMS results in search for a SM Higgs: [*CMS '12*]



$\Rightarrow$ clear excesses for around $M_H \simeq 125$ GeV



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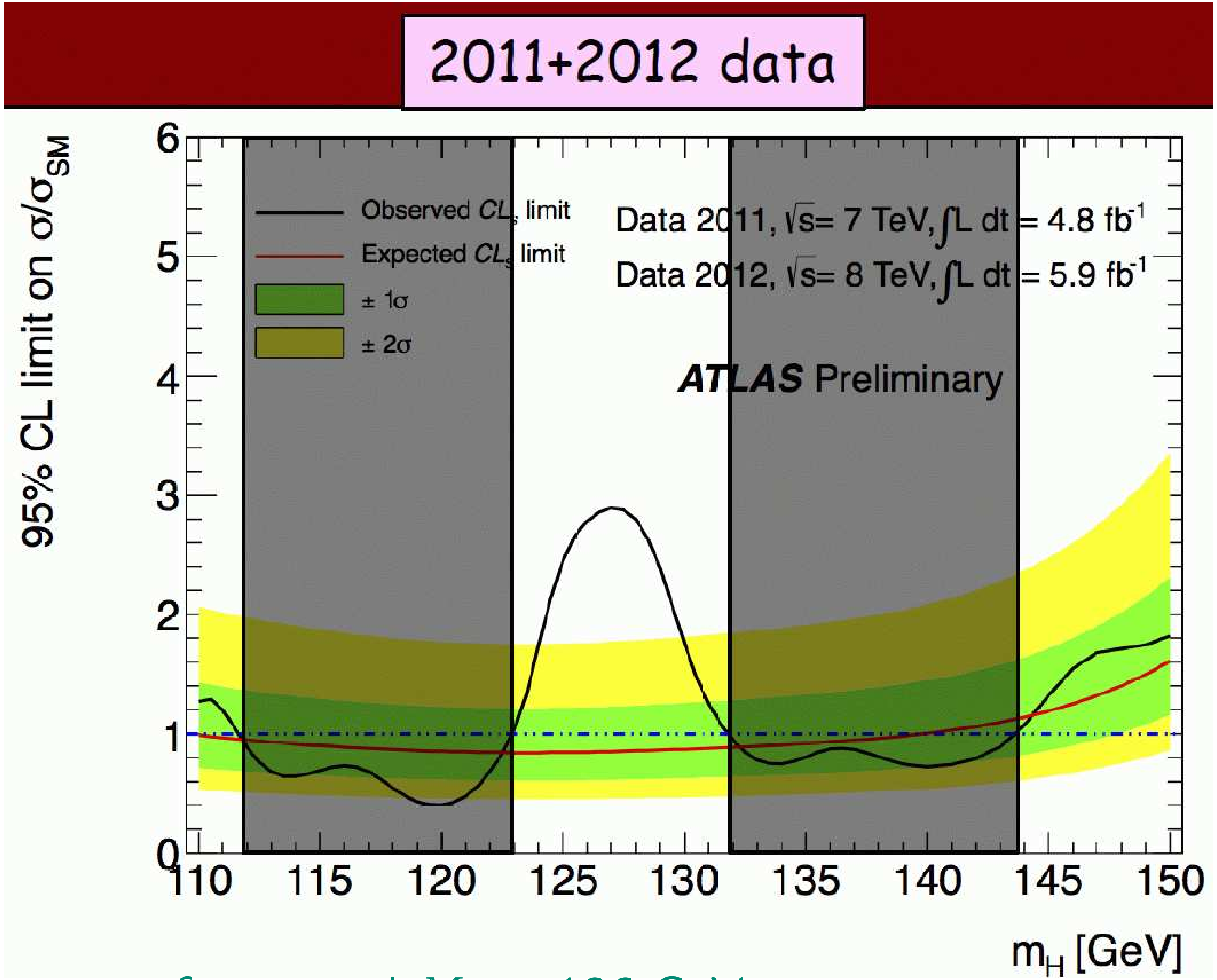
Latest ATLAS results in search for a SM Higgs in $\gamma\gamma$: [ATLAS '12]



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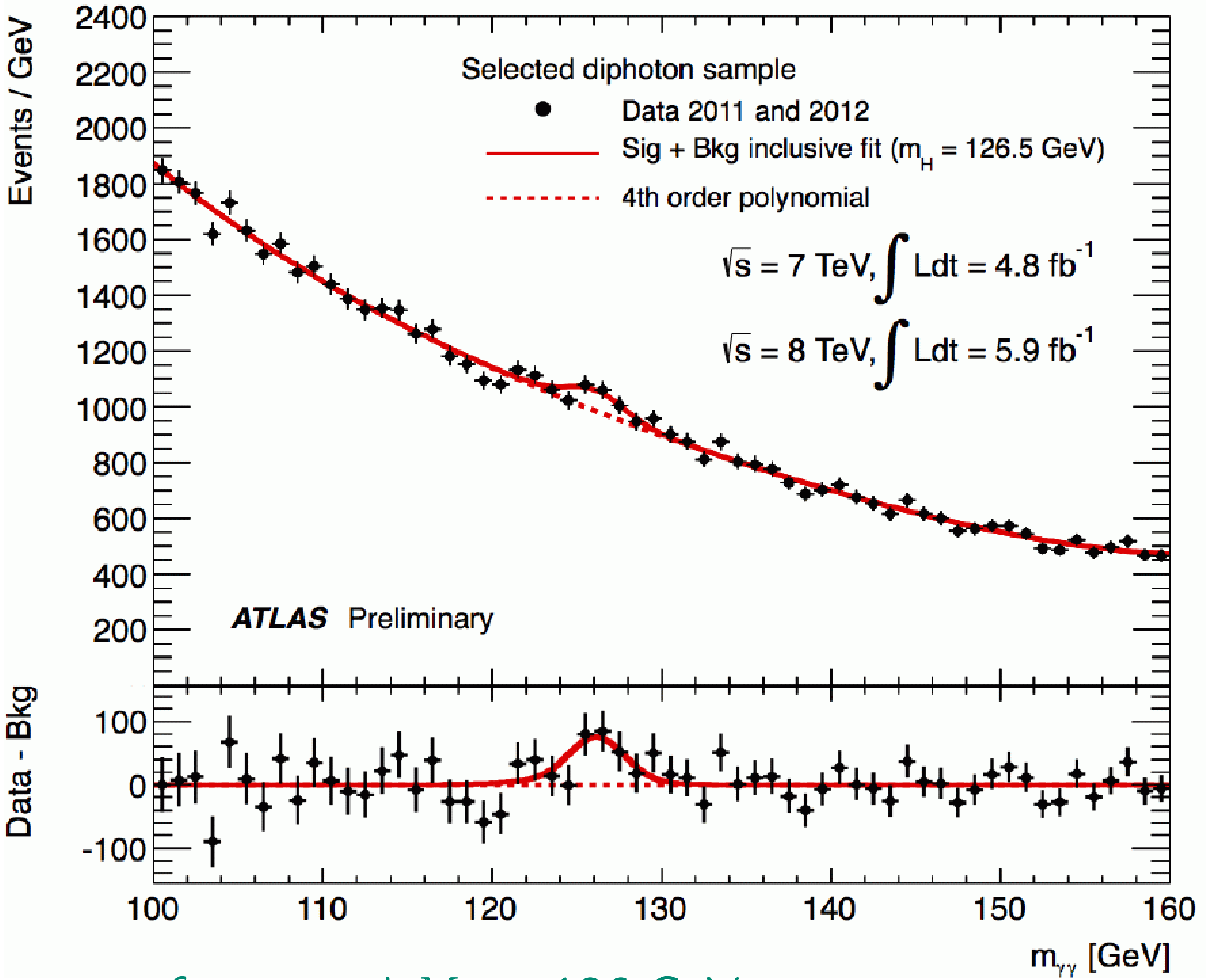

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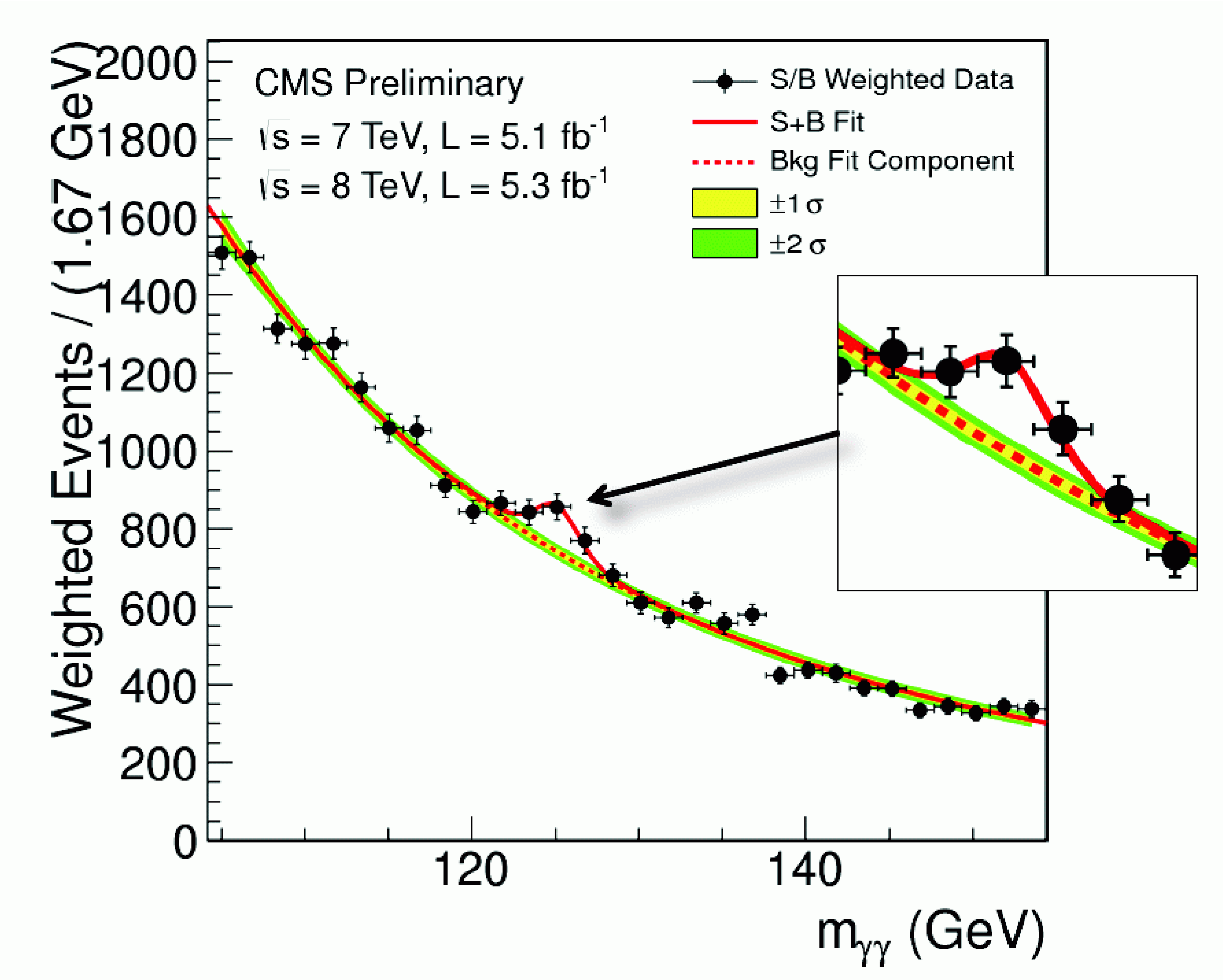
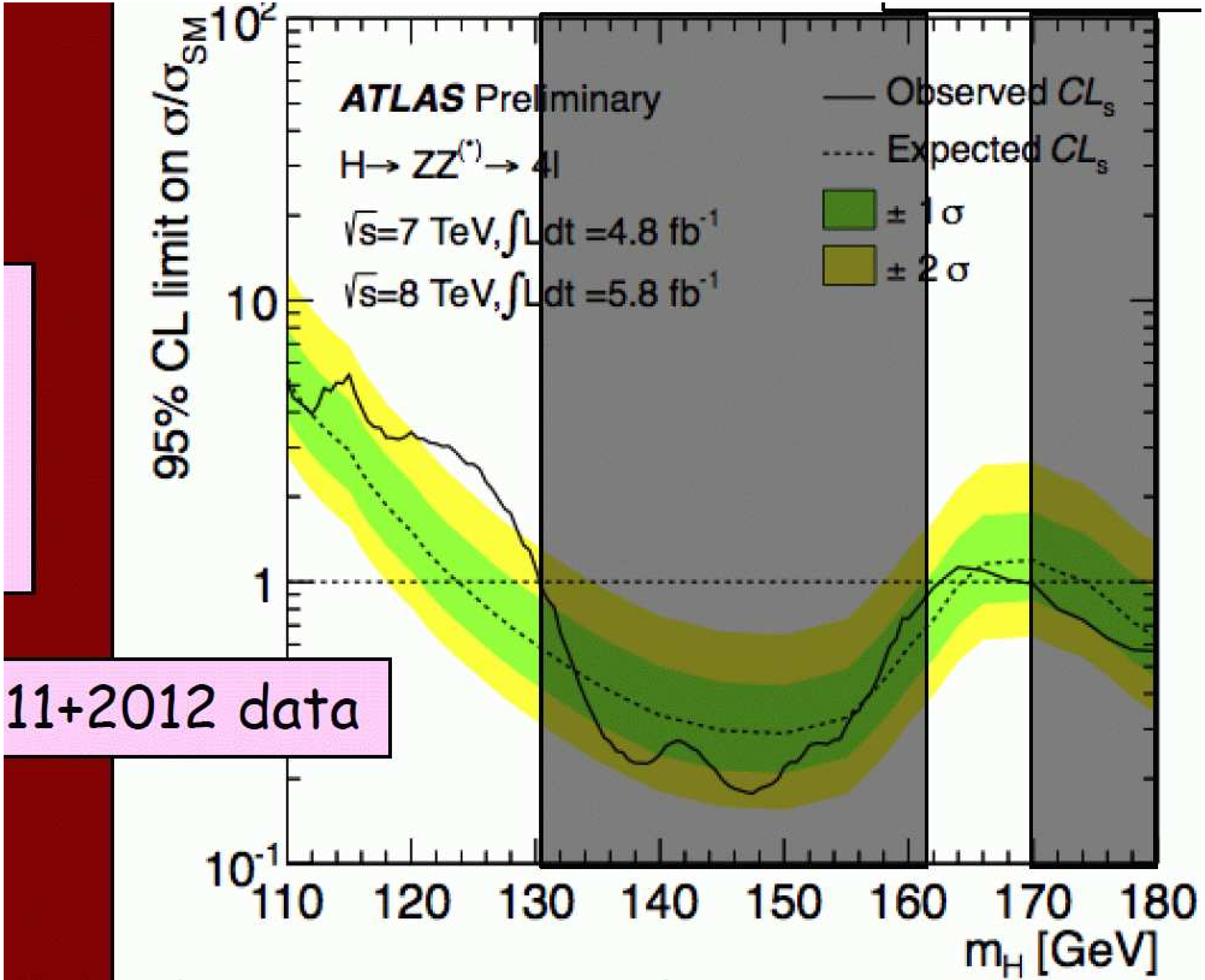


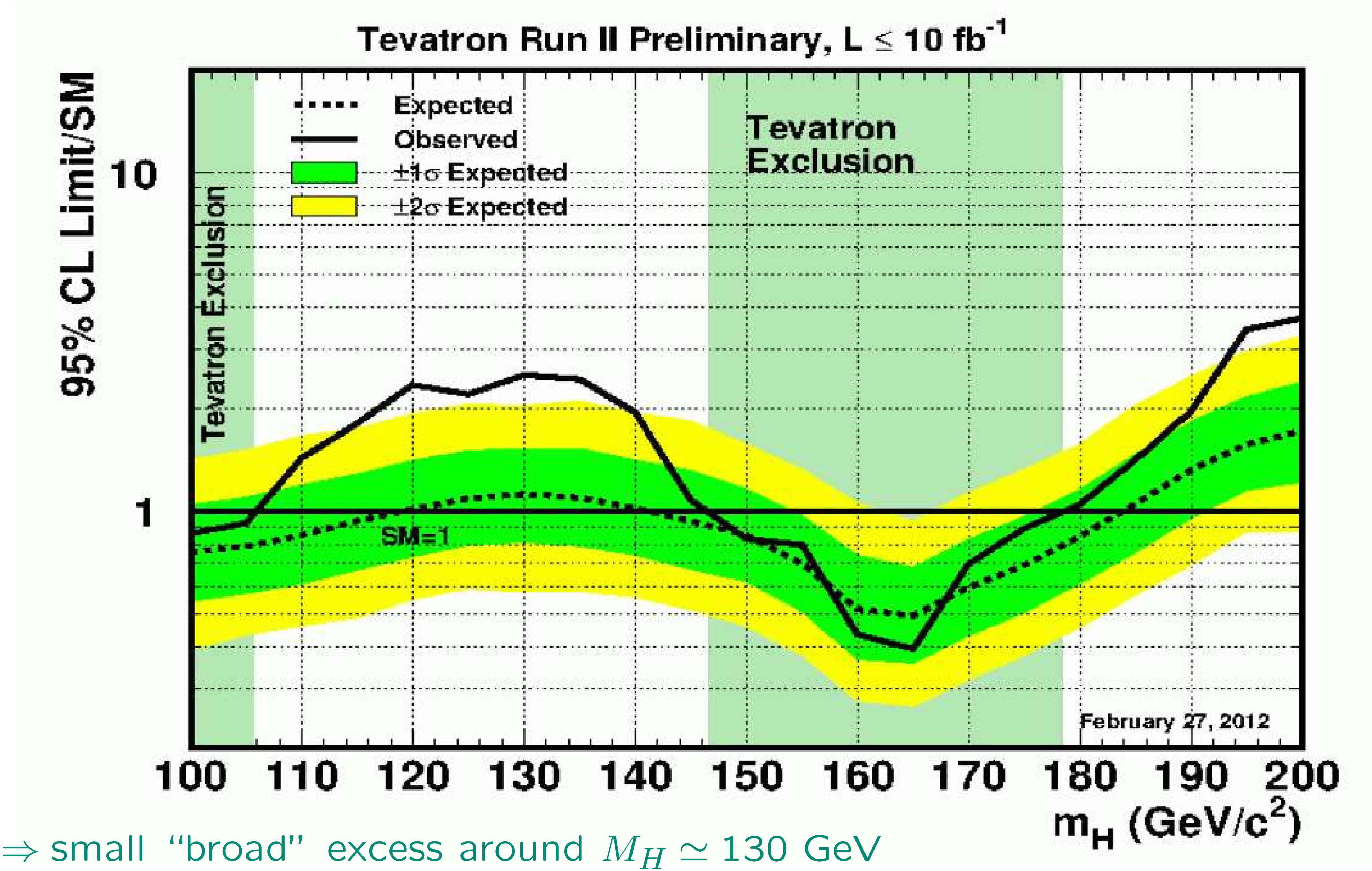
$\Rightarrow$ clear excesses for around $M_H \simeq 125$ GeV

Latest ATLAS results in search for a SM Higgs in ZZ^*: [ATLAS '12]



⇒ clear excesses for around $M_H \simeq 125$ GeV

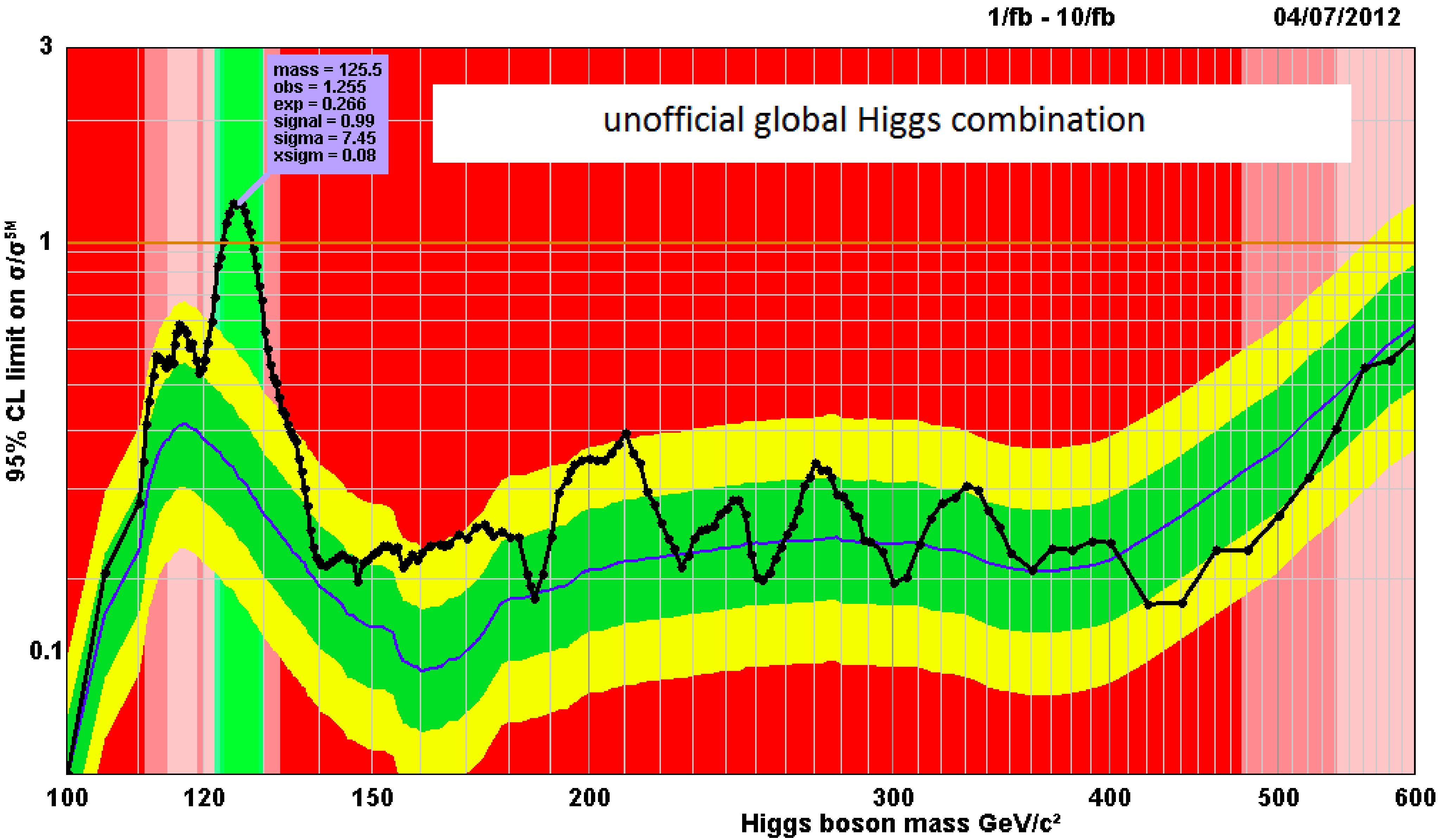
Do not forget the final result of SM Higgs searches at the Tevatron:



⇒ small "broad" excess around $M_H \simeq 130$ GeV

Results for the combination of all experiments:

Unofficial(!) LHC combination: [vixra.org]

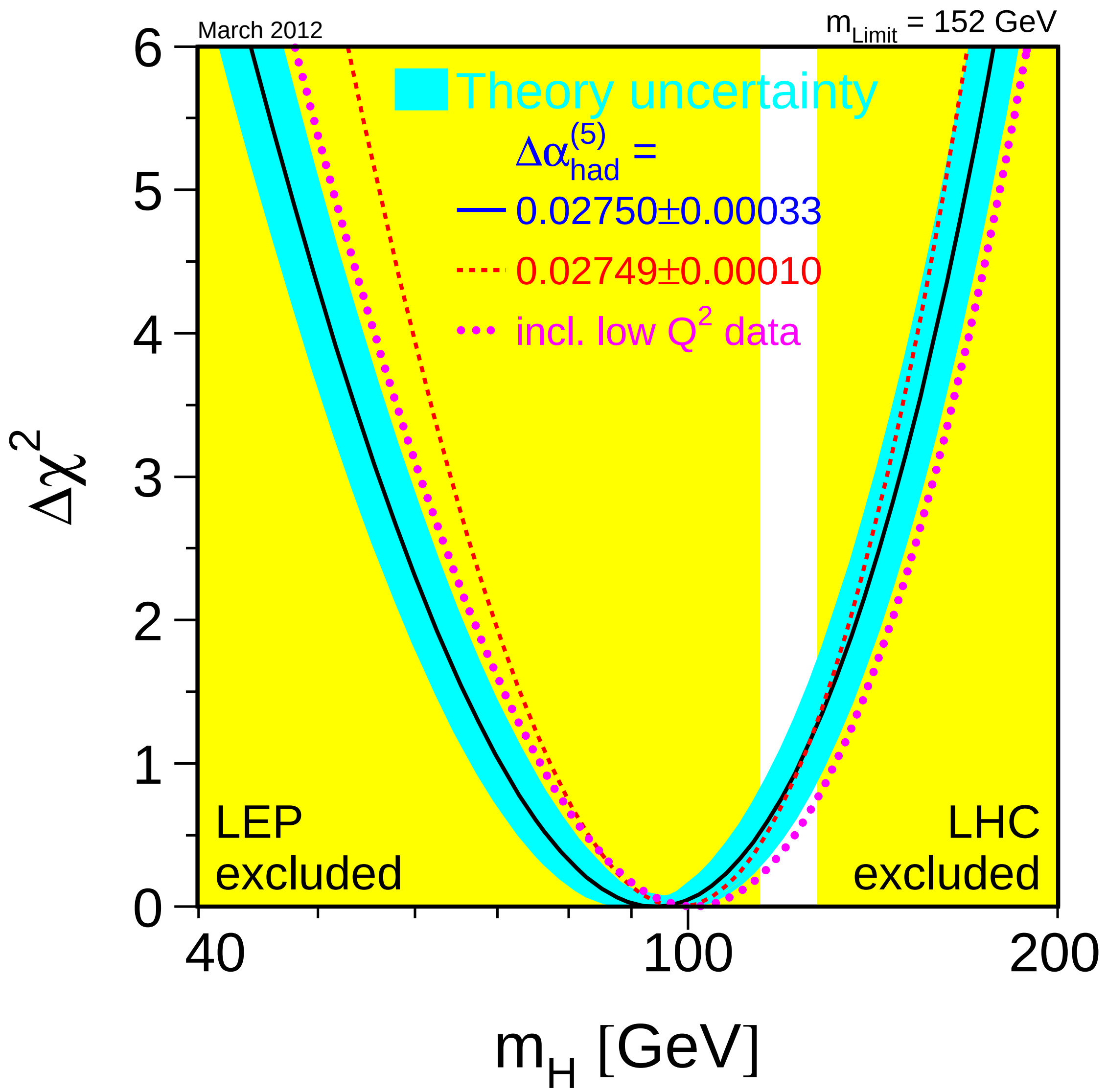


Comparison to SM prediction:

[*LEPEWWG '12*]

$\Rightarrow M_H = 94^{+29}_{-24}$ GeV

$M_H < 152$ GeV, 95% C.L.



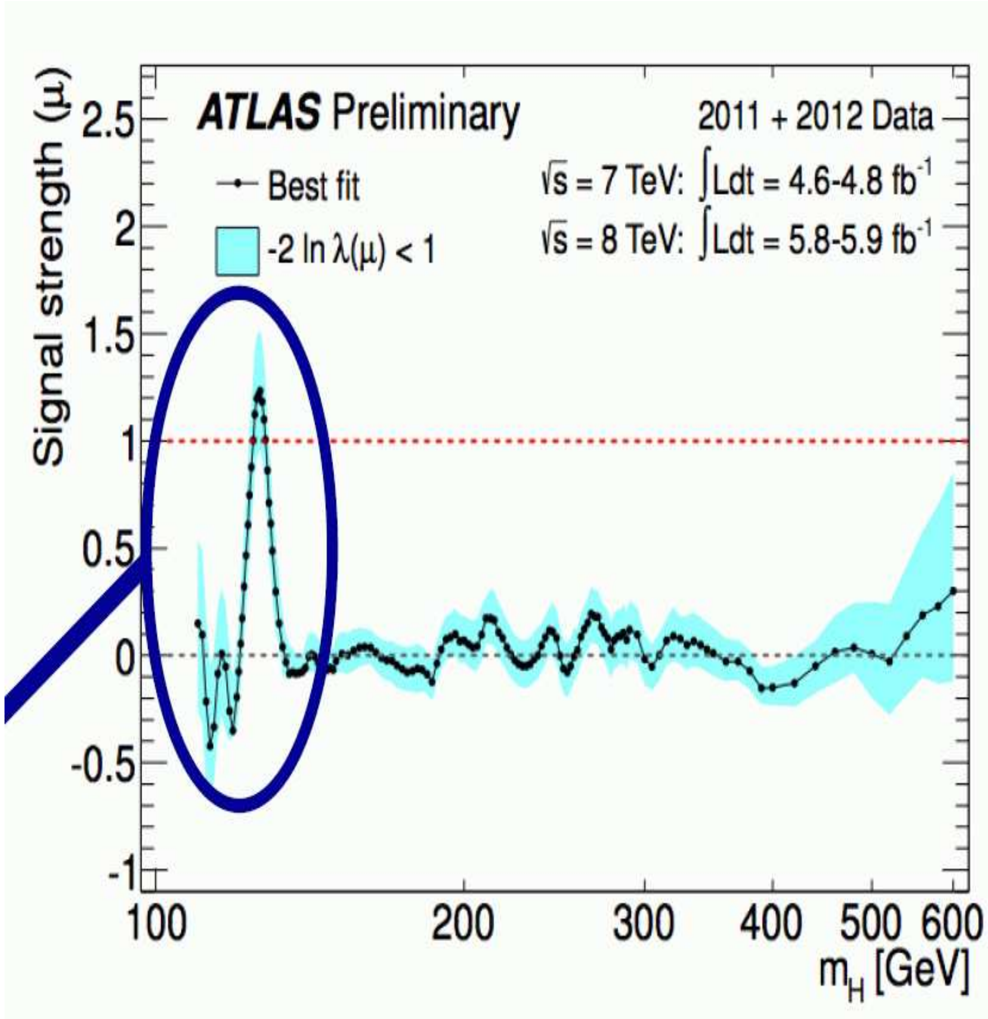
Assumption for the fit:
SM incl. Higgs boson

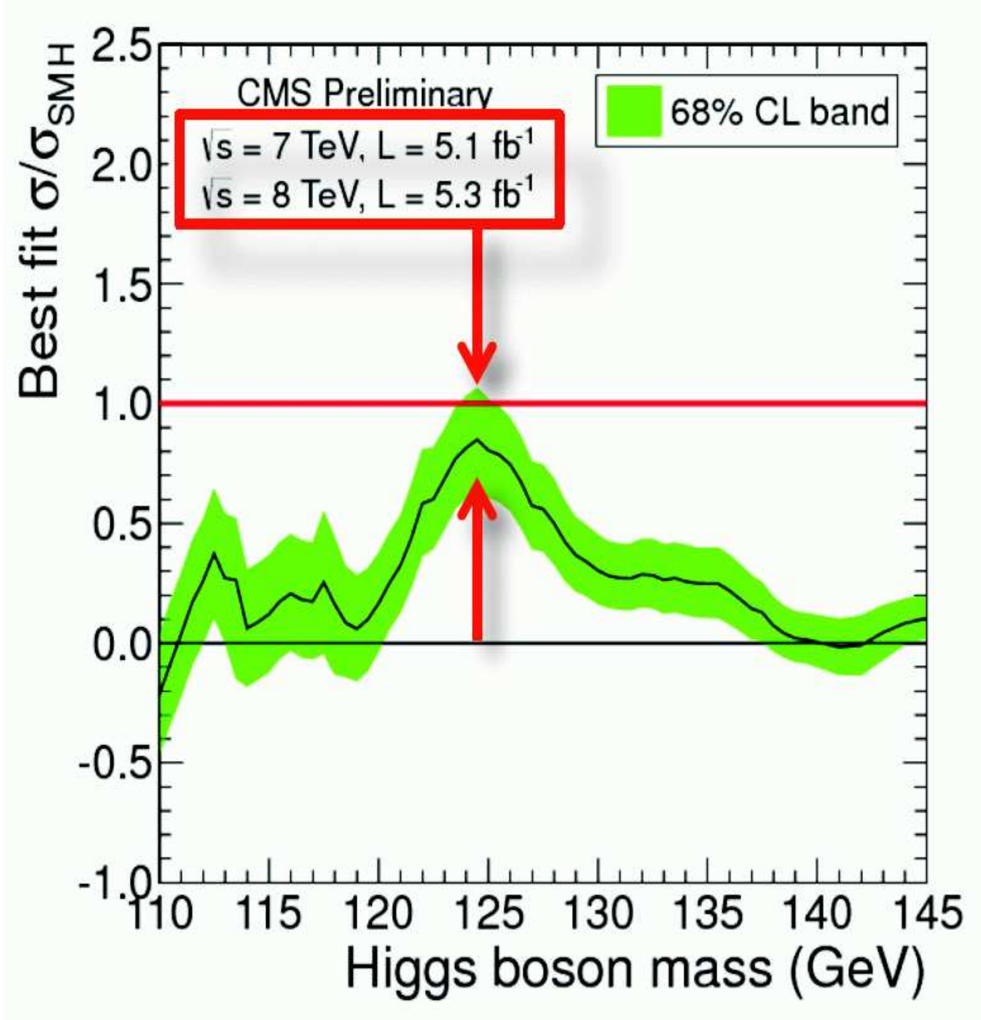
$\Rightarrow$ no confirmation of Higgs mechanism

$\Rightarrow$ Observed excess well compatible with SM prediction

Comparison to Douglas Adam's prediction:

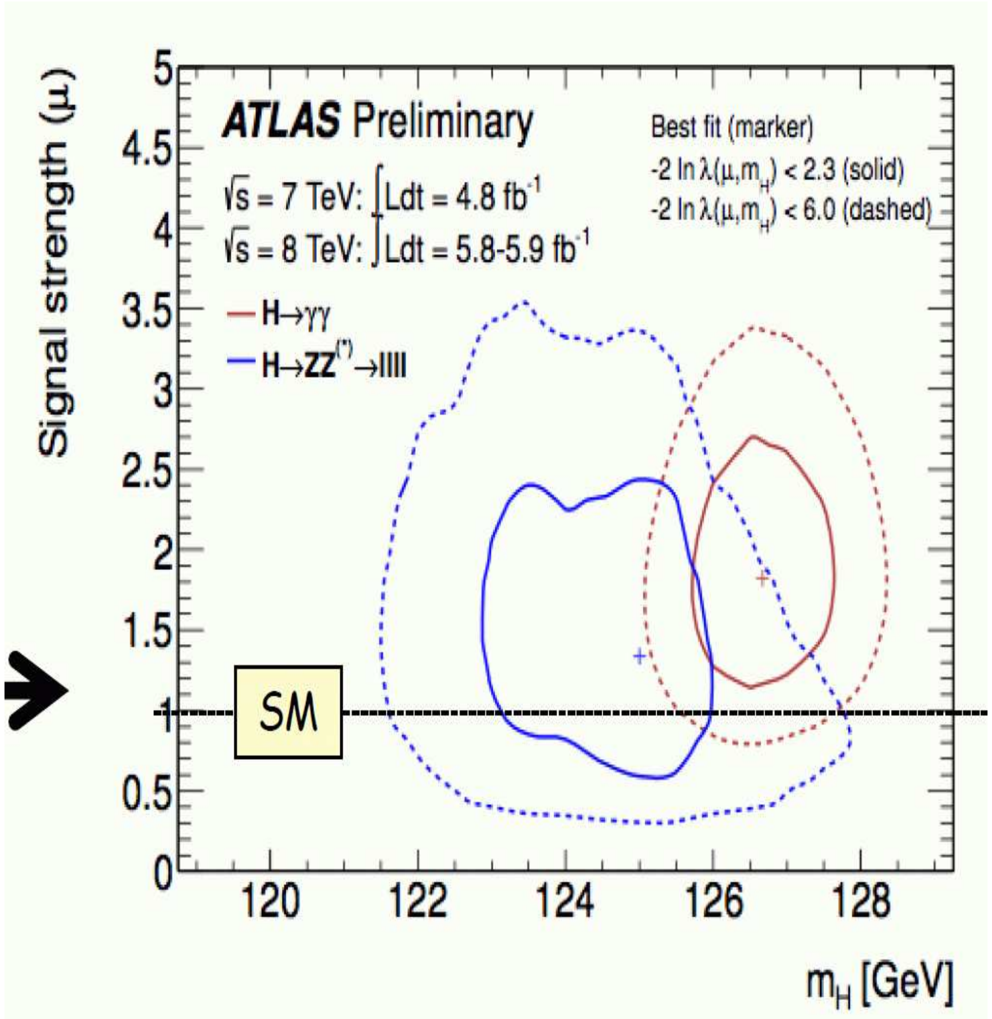
Towards a coupling measurement: signal strength:

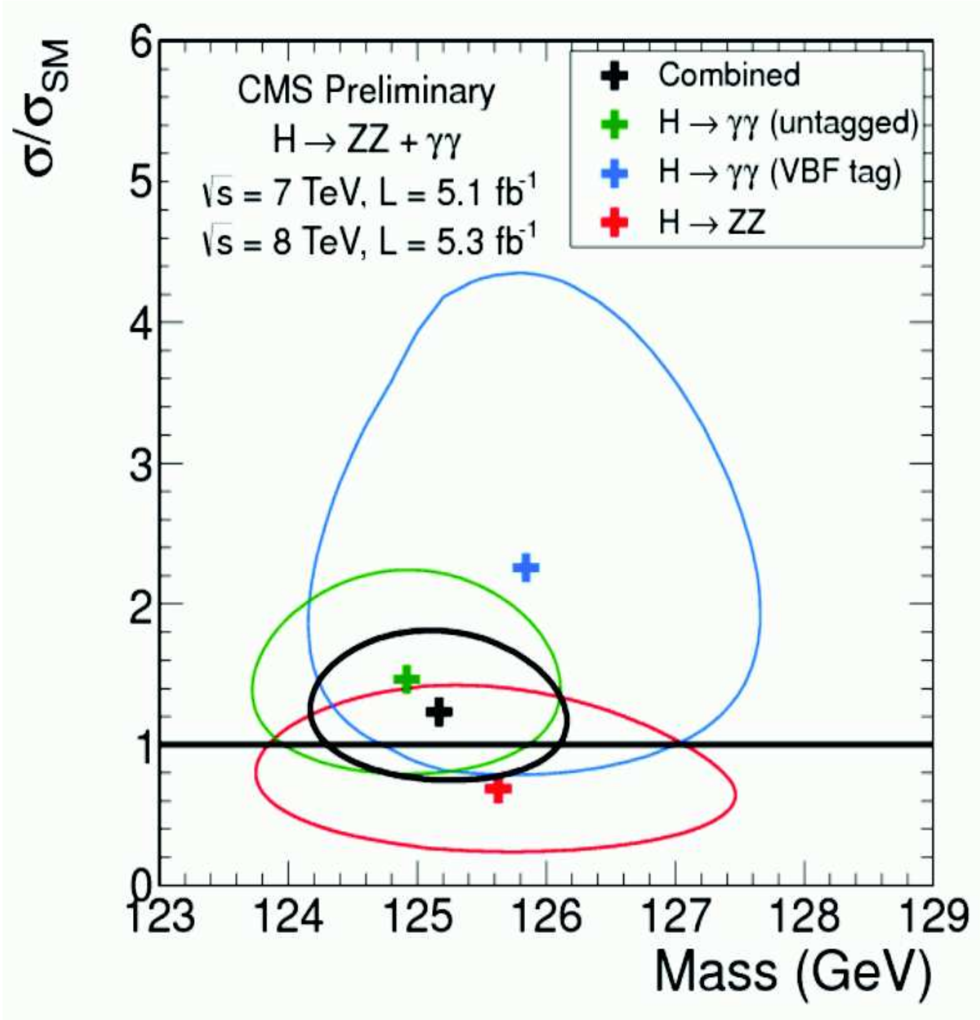




⇒ looks well compatible with the SM Higgs!

Towards a coupling measurement: signal strength vs. M_H:





⇒ looks well compatible with the SM Higgs!

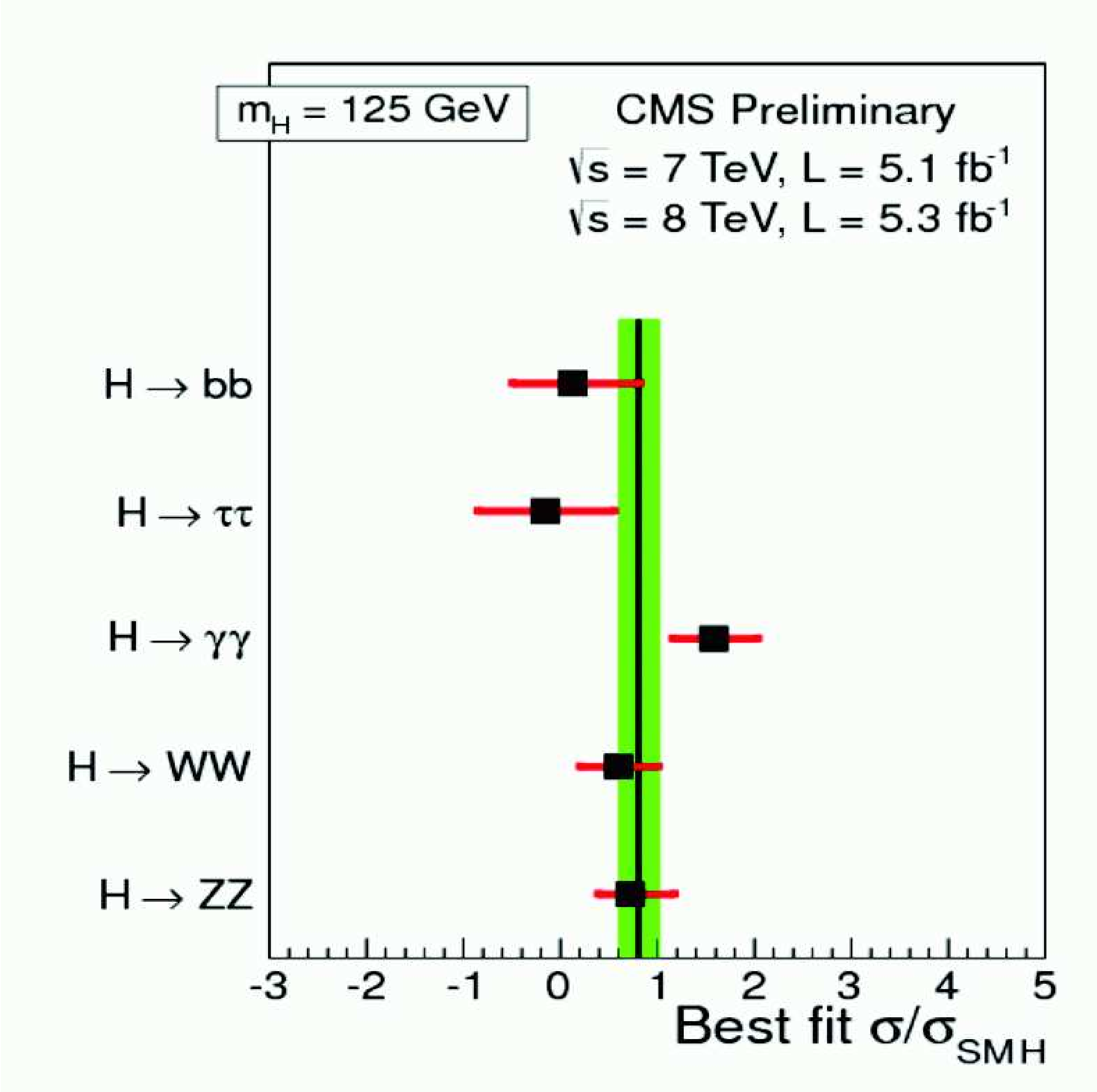
Has the Higgs particle been discovered?

We have
discovered a new particle ,
which is compatible with the
predictions of the SM Higgs boson

How can we be sure about SM?
⇒ we have to measure
all its characteristics
– mass
– couplings to SM particles
– CP, quantum numbers, . . .

⇒ exploit the LHC!

⇒ move on to the ILC!



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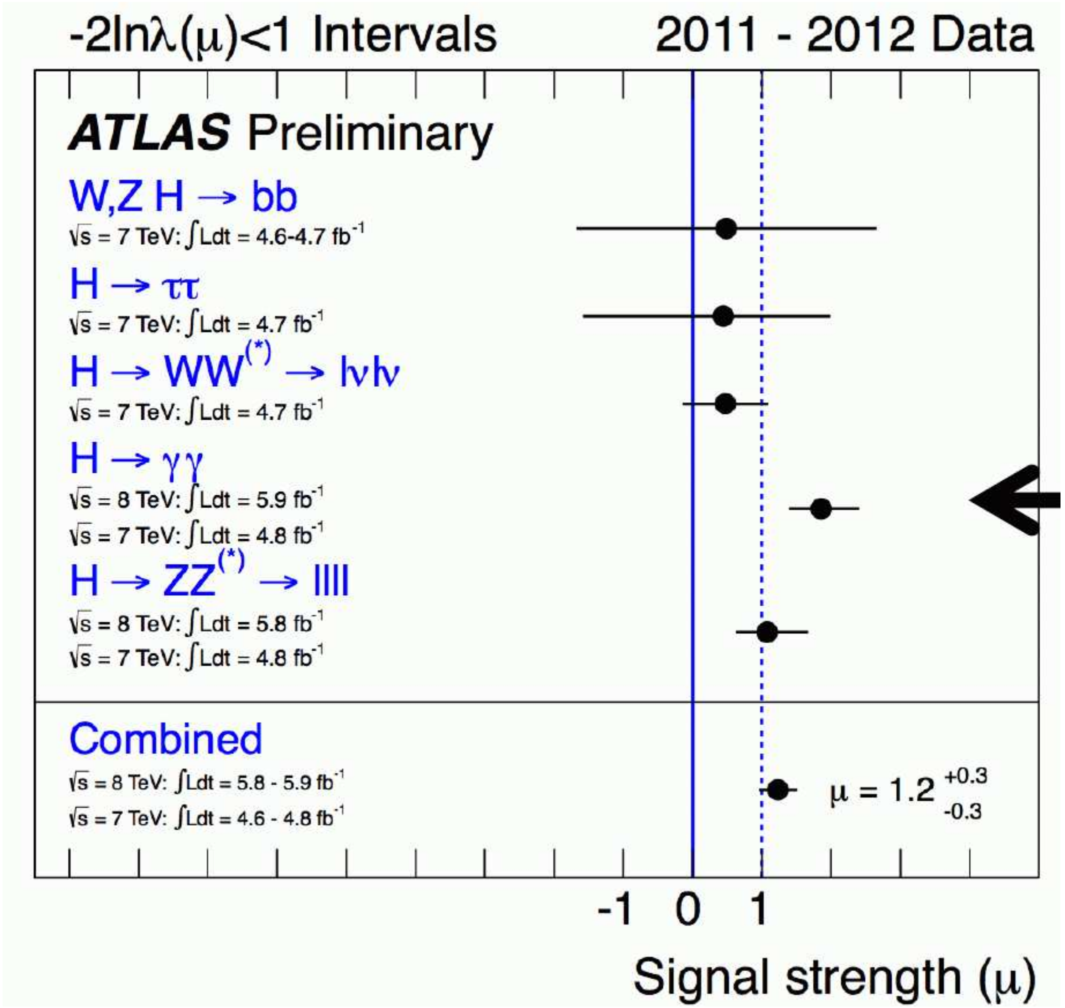


Coupling fits from SFitter:

[*SFitter '12*]

$$g_x = g_x^{\text{SM}} \, (1 + \Delta_x)$$

Fit 1:

One coupling modifier for everything: Δ_H

Fit 2:

One for gauge bosons, Δ_V, one for fermions, Δ_f

Fit 3:

Fit individual couplings: Δ_W, Δ_Z, Δ_t, Δ_b, Δ_τ

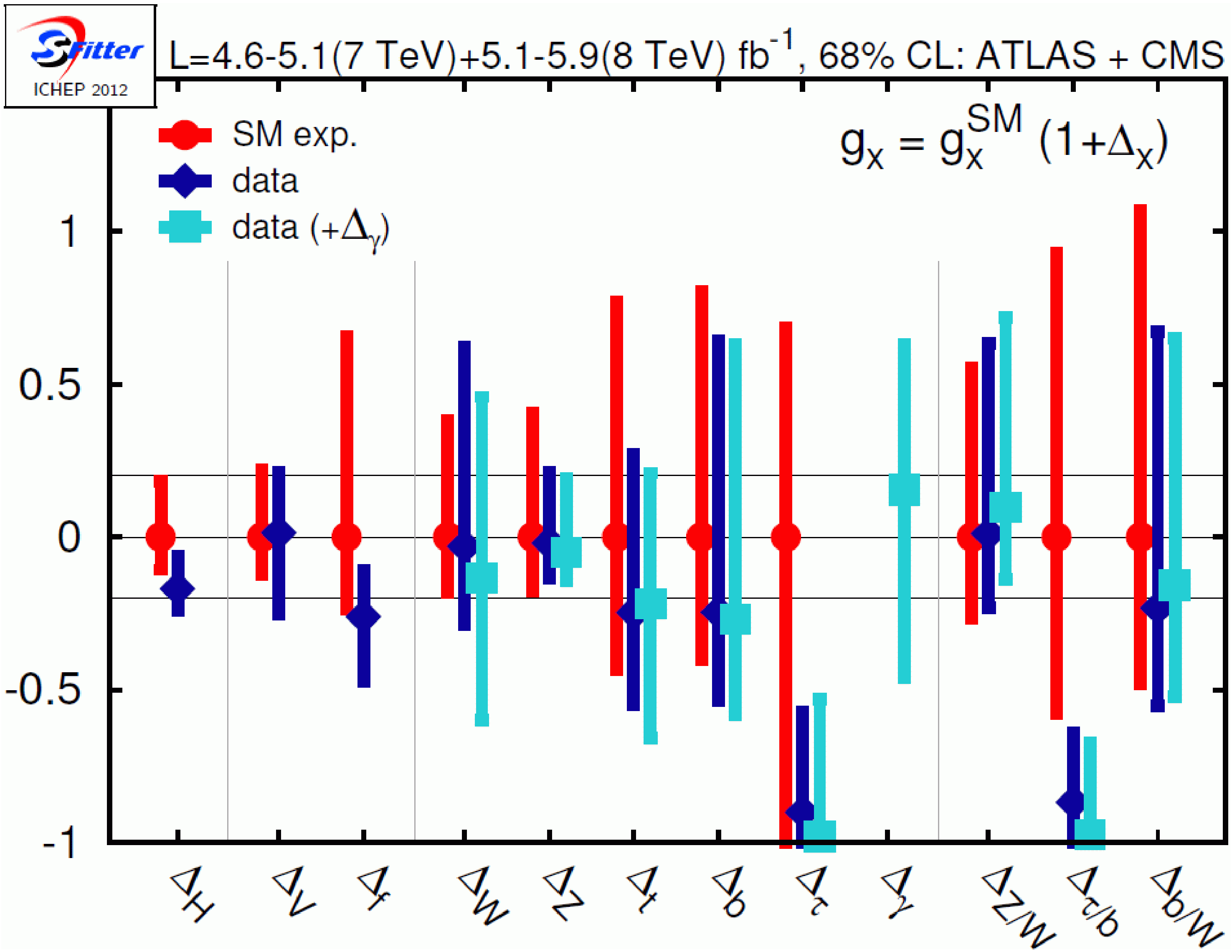
$\Rightarrow$ theory assumptions on total width necessary!

Fit 4:

Allow additionally loop contributions in $H \to \gamma\gamma$: Δ_γ

Coupling fits from SFitter:

[SFitter '12]



⇒ no deviation from the SM observed (within the uncertainties)

Implications for future colliders

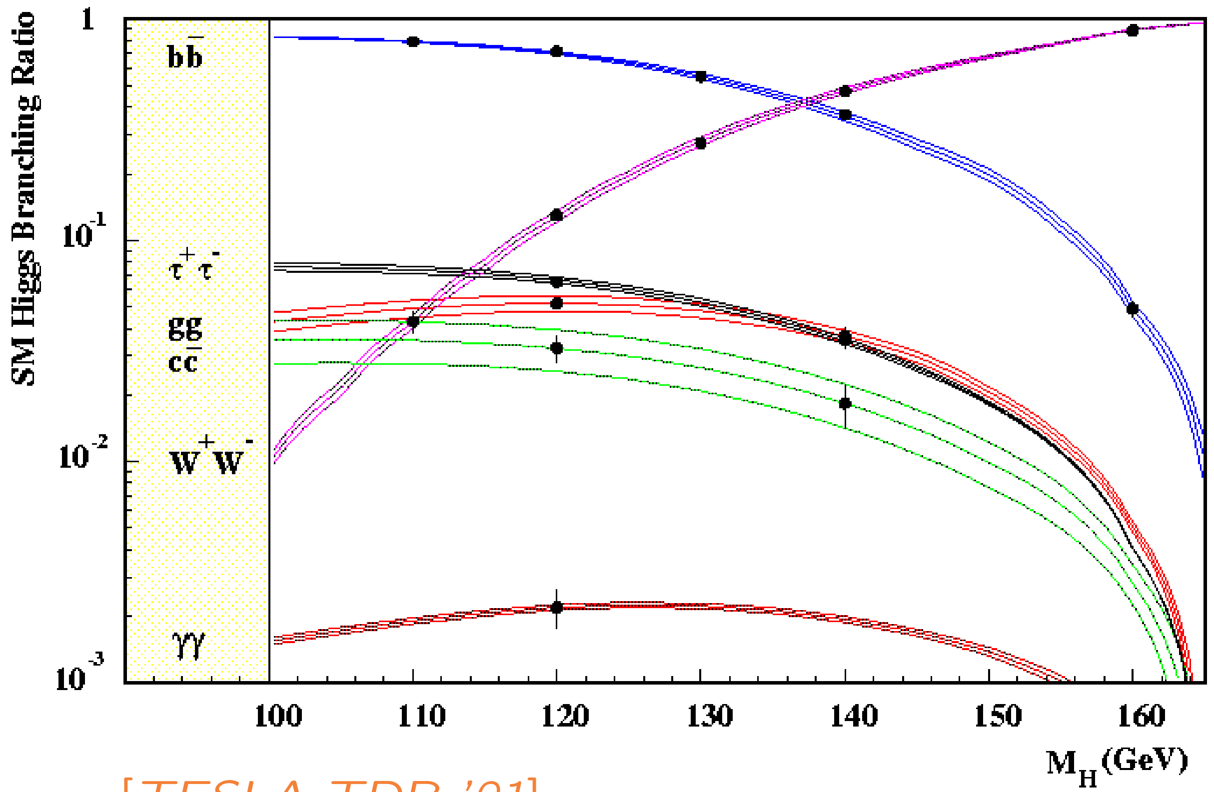
My personal view:

Finding a particle that is compatible with a light (SM-like?) Higgs boson is the **best case** scenario for the ILC

Higgs physics at the ILC:

SM Higgs @ ILC:
Precise measurement of:

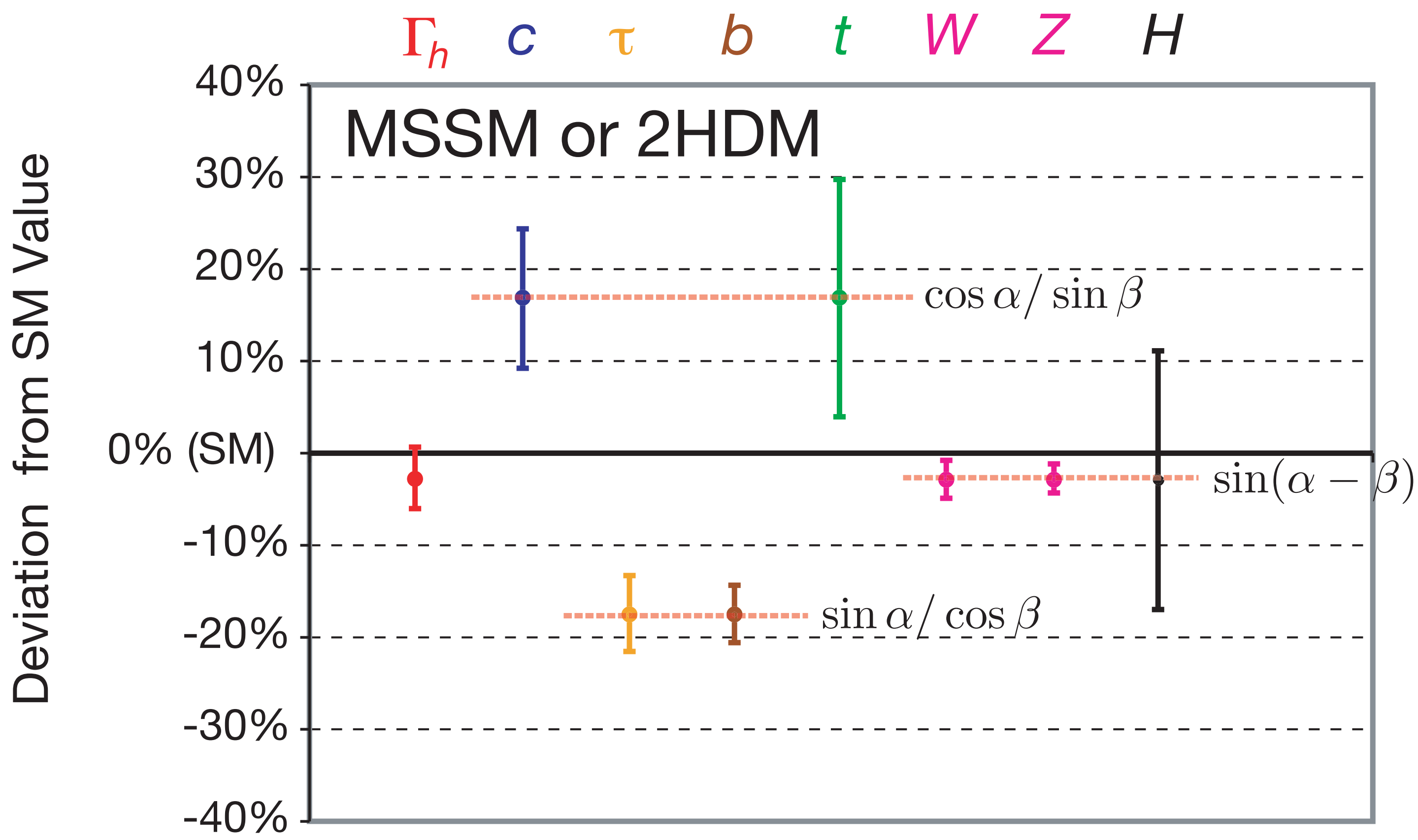
1. Higgs boson mass, $\delta M_H \approx 50$ MeV
2. Higgs boson width (direct/indirect)
3. Higgs boson couplings, $\mathcal{O}$ (few%) $\Rightarrow$
4. Higgs boson quantum numbers: spin, . . .



[*TESLA TDR '01*]

Example: Higgs couplings in the MSSM:

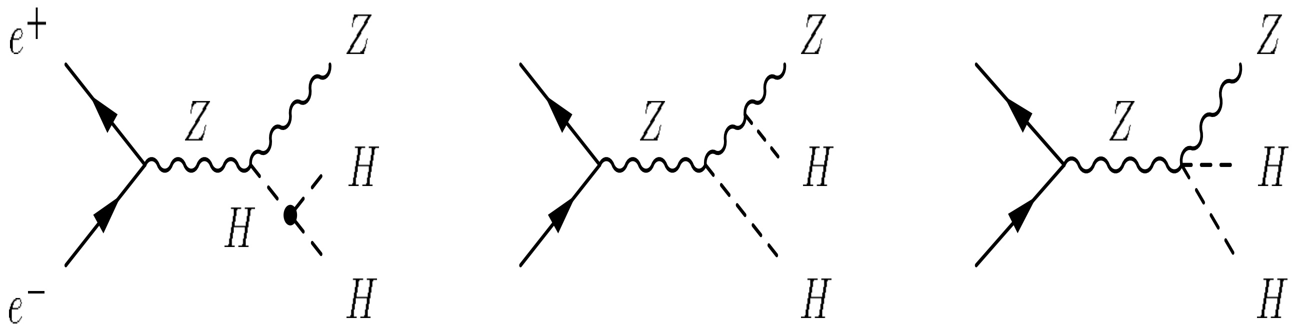
"Normal(?)" MSSM scenario:



$\Rightarrow$ measurable deviations (at least in some parts of the parameter space)

Step 5: measurement of the Higgs boson self-coupling

⇒ only possible at the ILC



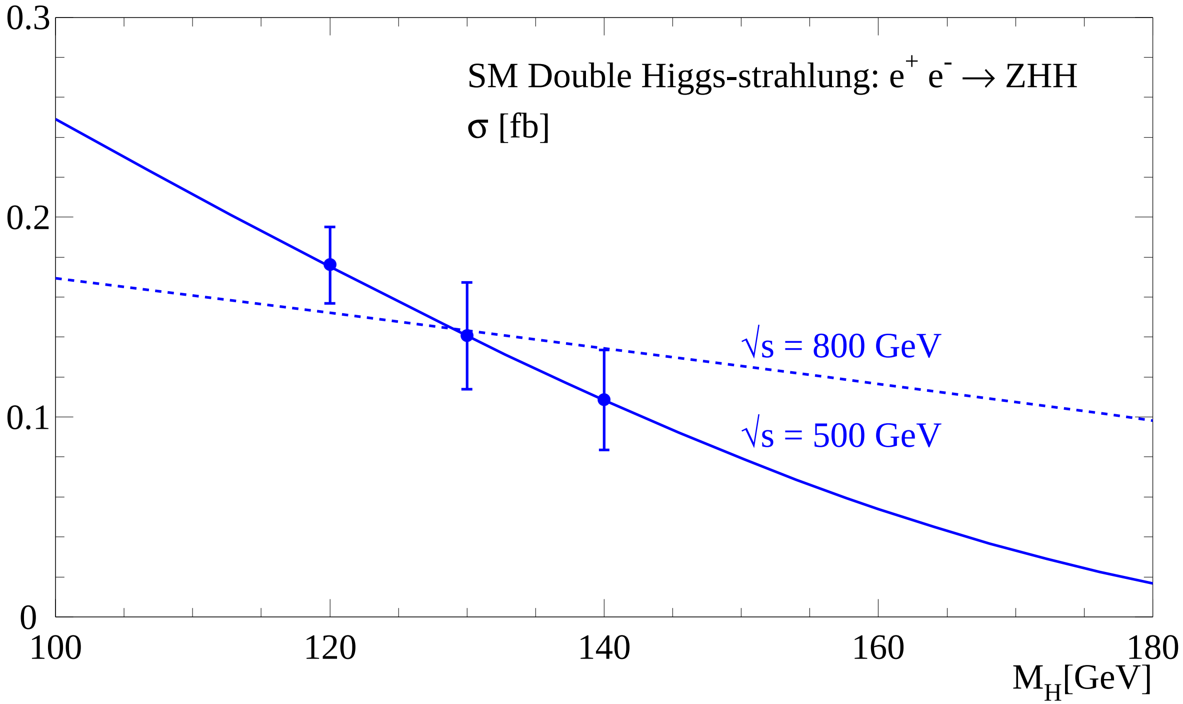
Parton-level study:

[*Djouadi, Kilian, Mühlleitner, Zerwas '99*]

1 ab^{-1} ⇒ 20–30%
measurement of $\lambda = \lambda_{HHH}$

However:

$\lambda = \lambda_{HHHH}$ out of reach
for all foreseeable colliders



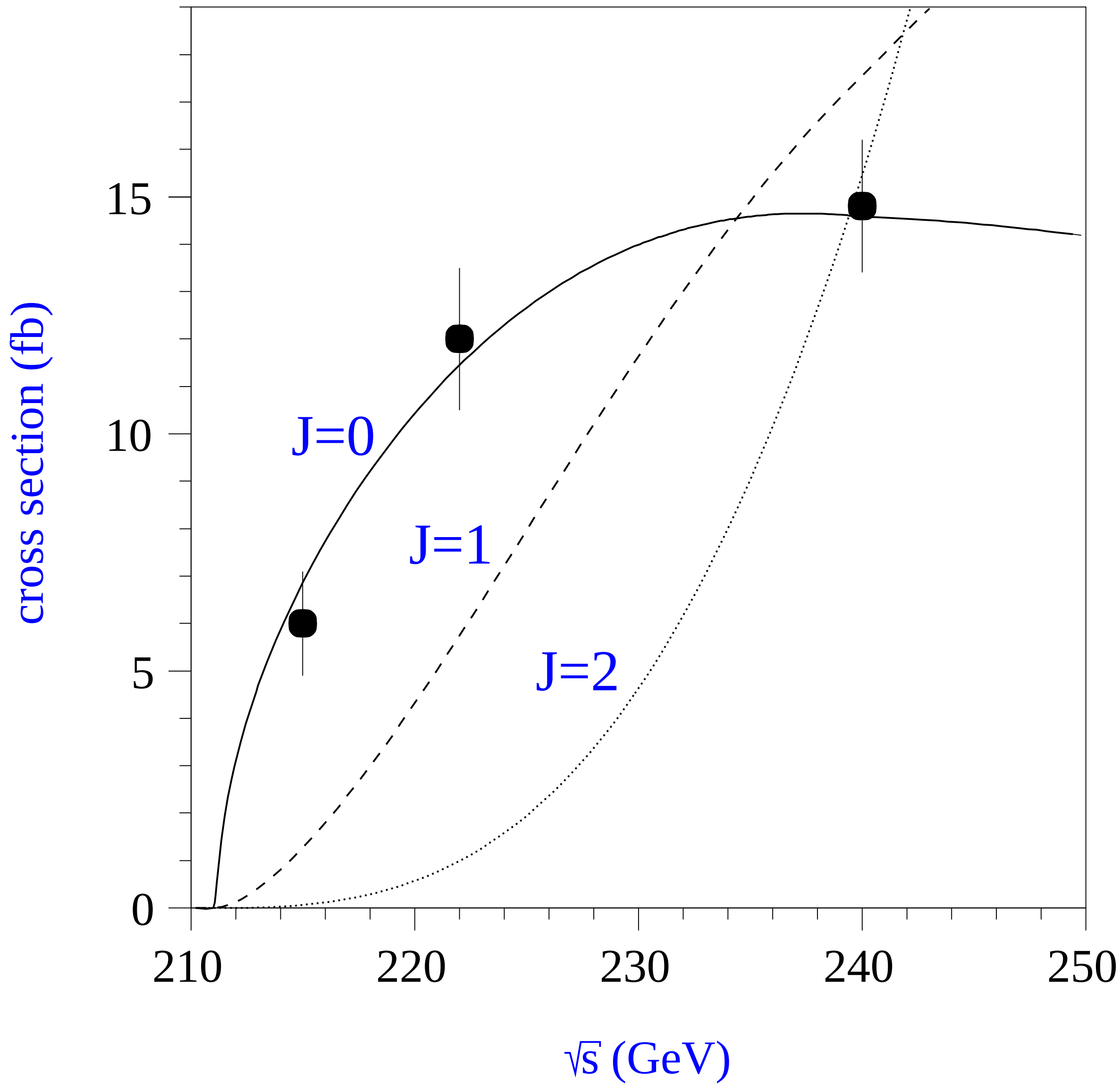
Step 6: measurement of the Higgs boson spin

$\Rightarrow$ easy at the ILC

Threshold scan for
$\sigma(e^+e^- \to ZX)$:

$X = H \Rightarrow \sigma \sim \beta$
(β from kinematics)

$20\,\text{fb}^{-1}$
$\Rightarrow$ identification easy



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> Finding a particle that is compatible with
> a light (SM-like?) Higgs boson
> is the **best case** scenario for the ILC

How to go ahead?

– ILC as a Higgs (and top) factory

– Staged approach?

  – start at lower energies to produce $\mathcal{O}\left(10^5\right)$ Higgs bosons

  – go to higher energies for top physics

  – go to higher energies for TeV scale exploration

– go to other options: GigaZ, $\gamma\gamma$, . . .

⇒ best case scenario the ILC!

⇒ We have to use our Annus mirabilis to ensure the (our!) future