



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:

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

decay width:

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

with N_c = number of colors

Bulk of QCD corrections for decays to quarks are mapped into

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

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

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 ($M_H > 2M_V$):

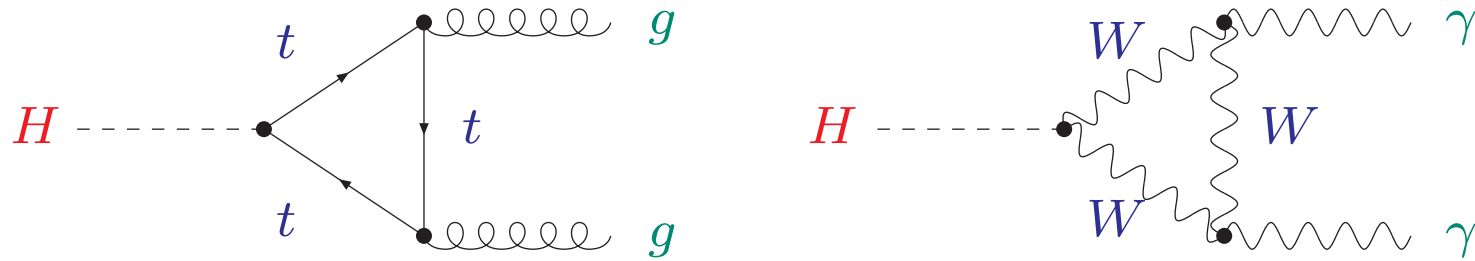
$$\Gamma(H \rightarrow VV) = \delta_V \frac{G_\mu M_H^3}{16 \sqrt{2} \pi} \left(1 - 4 \frac{M_V^2}{M_H^2} + 12 \frac{M_V^4}{M_H^4} \right) \left(1 - 4 \frac{M_V^2}{M_H^2} \right)^{1/2}$$

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

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

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

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



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

via the top quark loop with

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

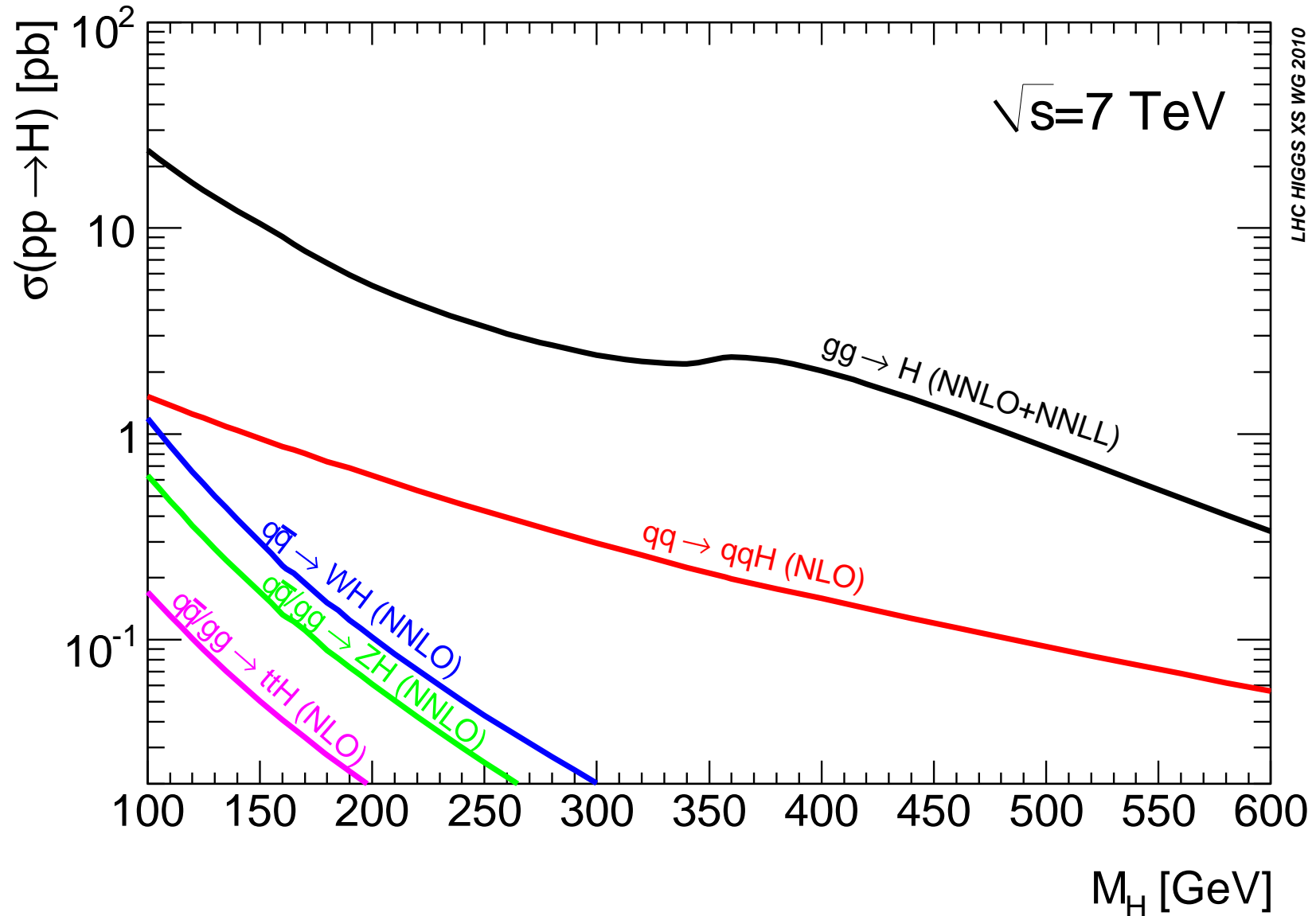
⇒ huge QCD corrections

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

via the top quark and W boson loop

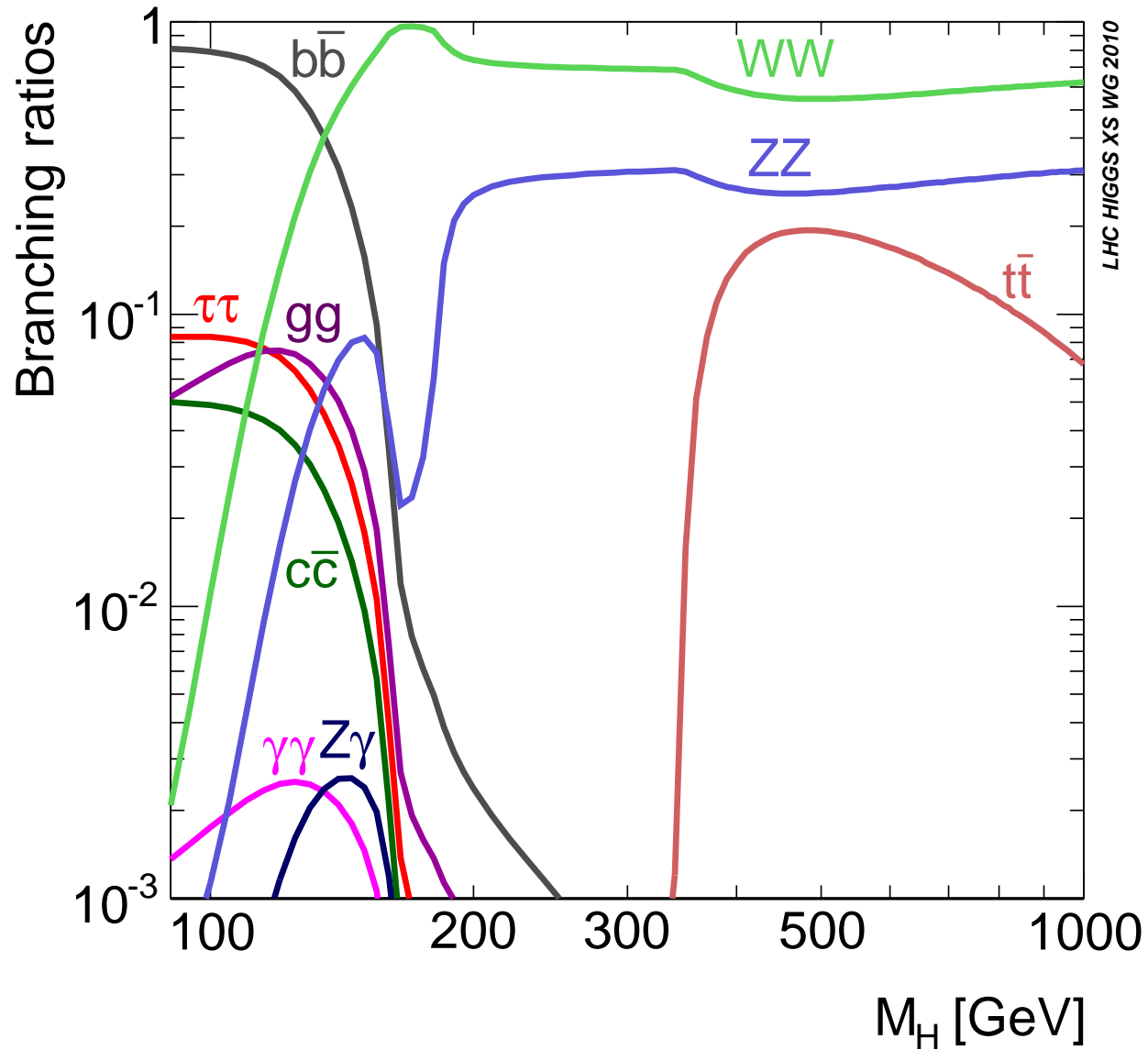
Latest theory predictions for the SM Higgs: LHC production XS

[LHC Higgs XS WG '10]



Latest theory predictions for the SM Higgs: branching ratios

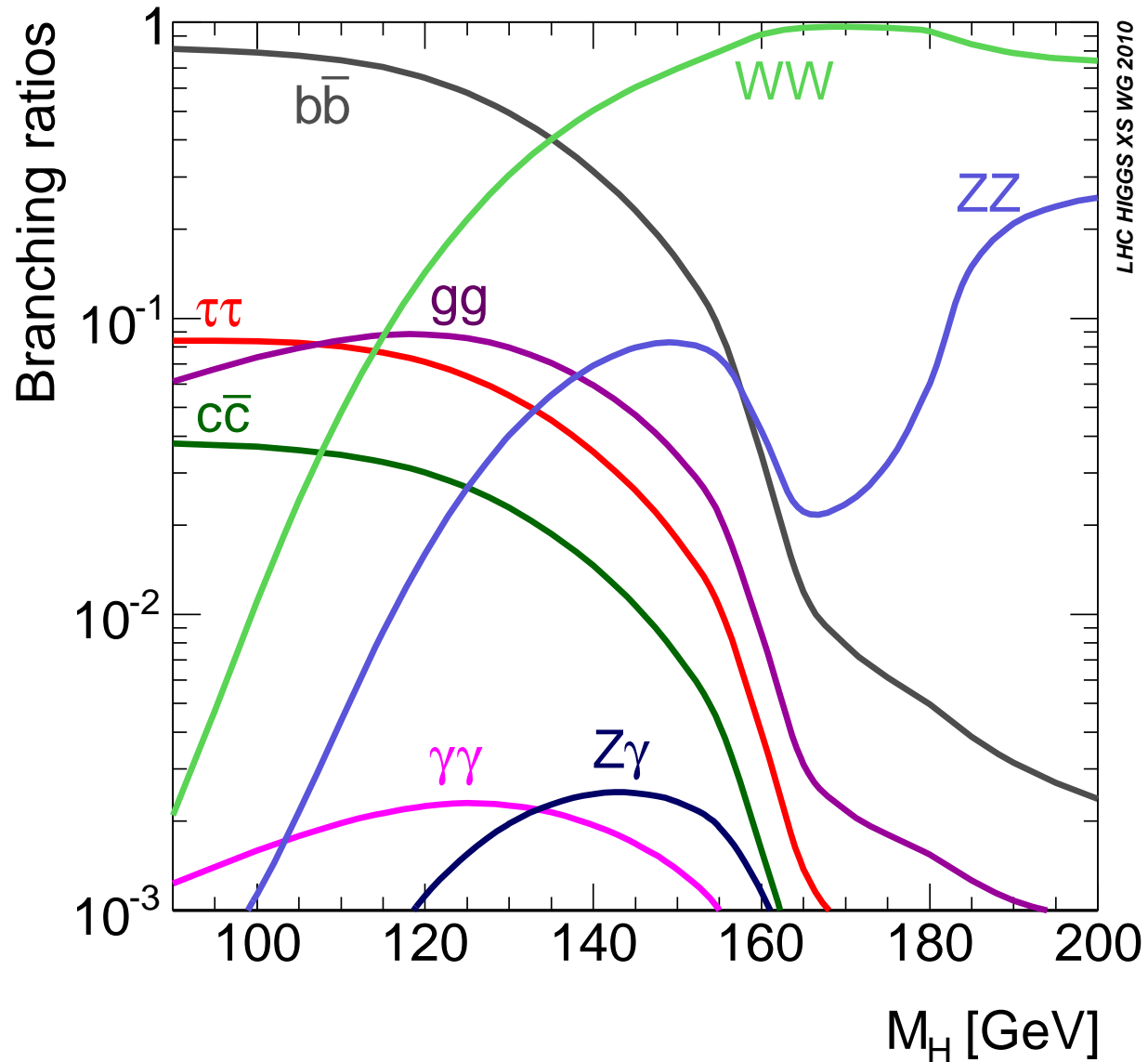
[LHC Higgs XS WG '10]



LHC HIGGS XS WG 2010

Latest theory predictions for the SM Higgs: branching ratios

[LHC Higgs XS WG '10]



Do never forget the **UNCERTAINTIES!**

Three different types of uncertainties:

Experimental error (→ Bill Murray's, Peter Maettig's lecture):

- current error
 - future expectations
- ⇒ sets the scale, has to be matched by other errors

Theory uncertainty:

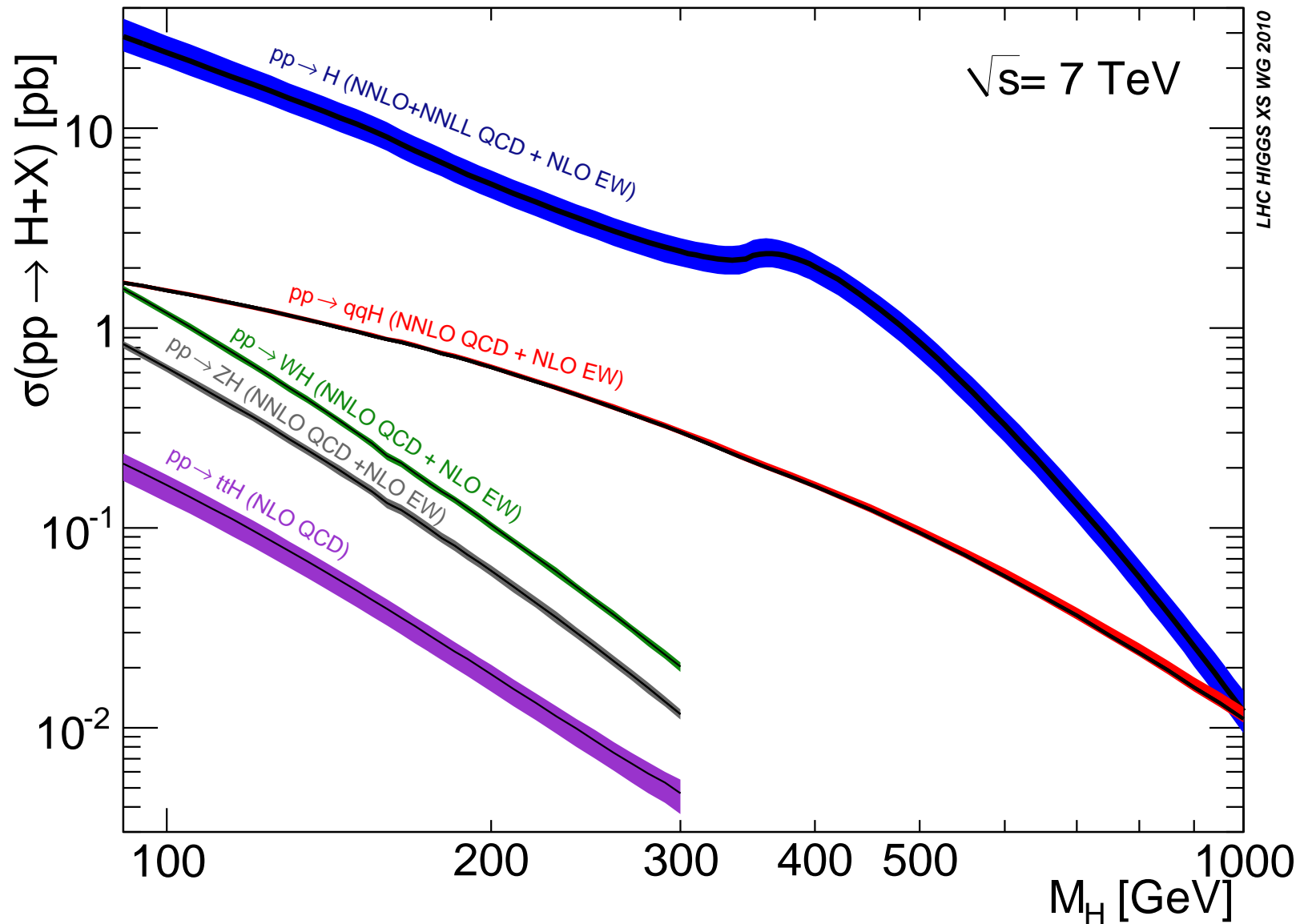
- ⇒ uncertainty due to missing higher order corrections
- only estimates possible
 - even more complicated for the future

Parametric uncertainty:

- current uncertainty in the prediction due to error in the input parameters
- m_t , α_s , PDFs, ...
- future expectations?

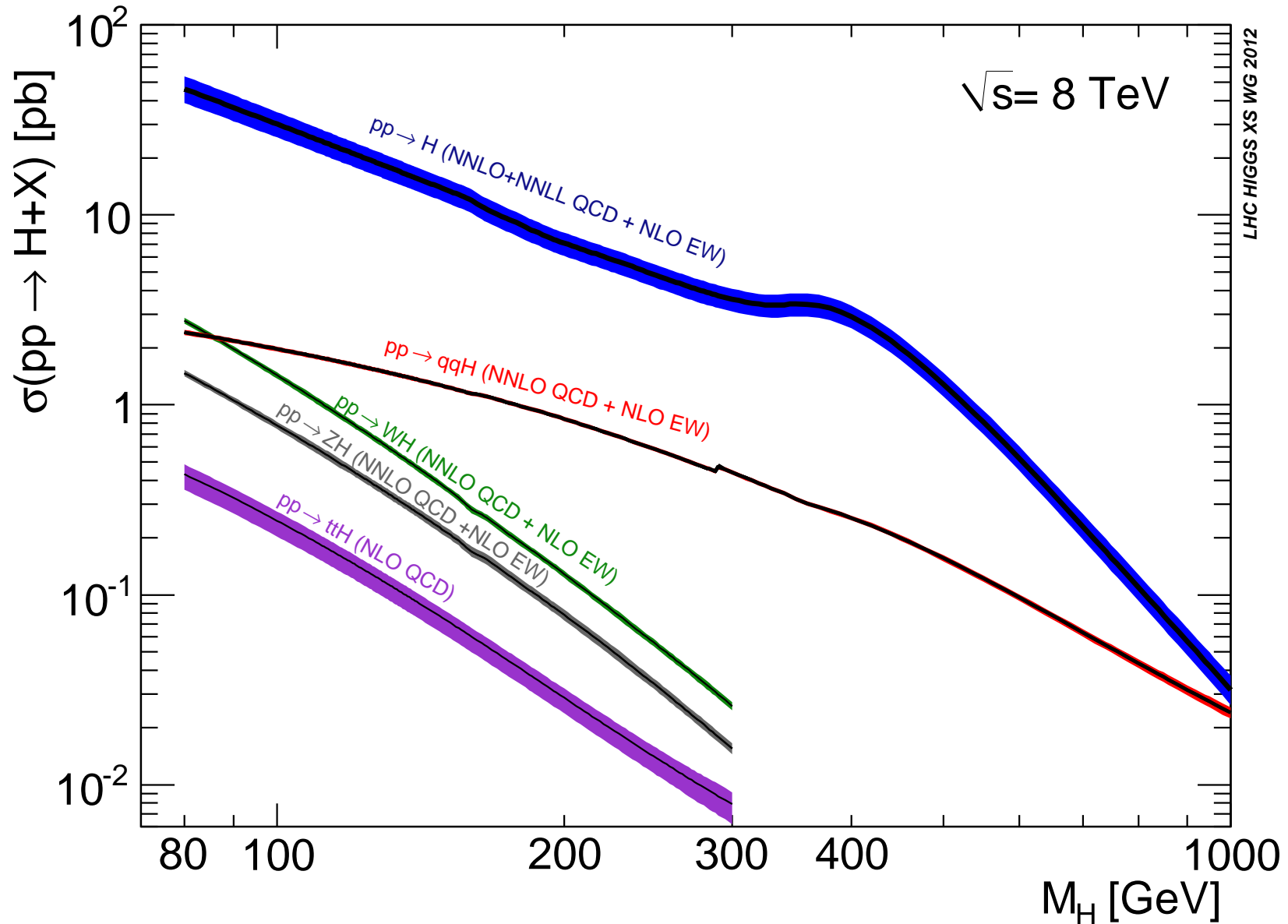
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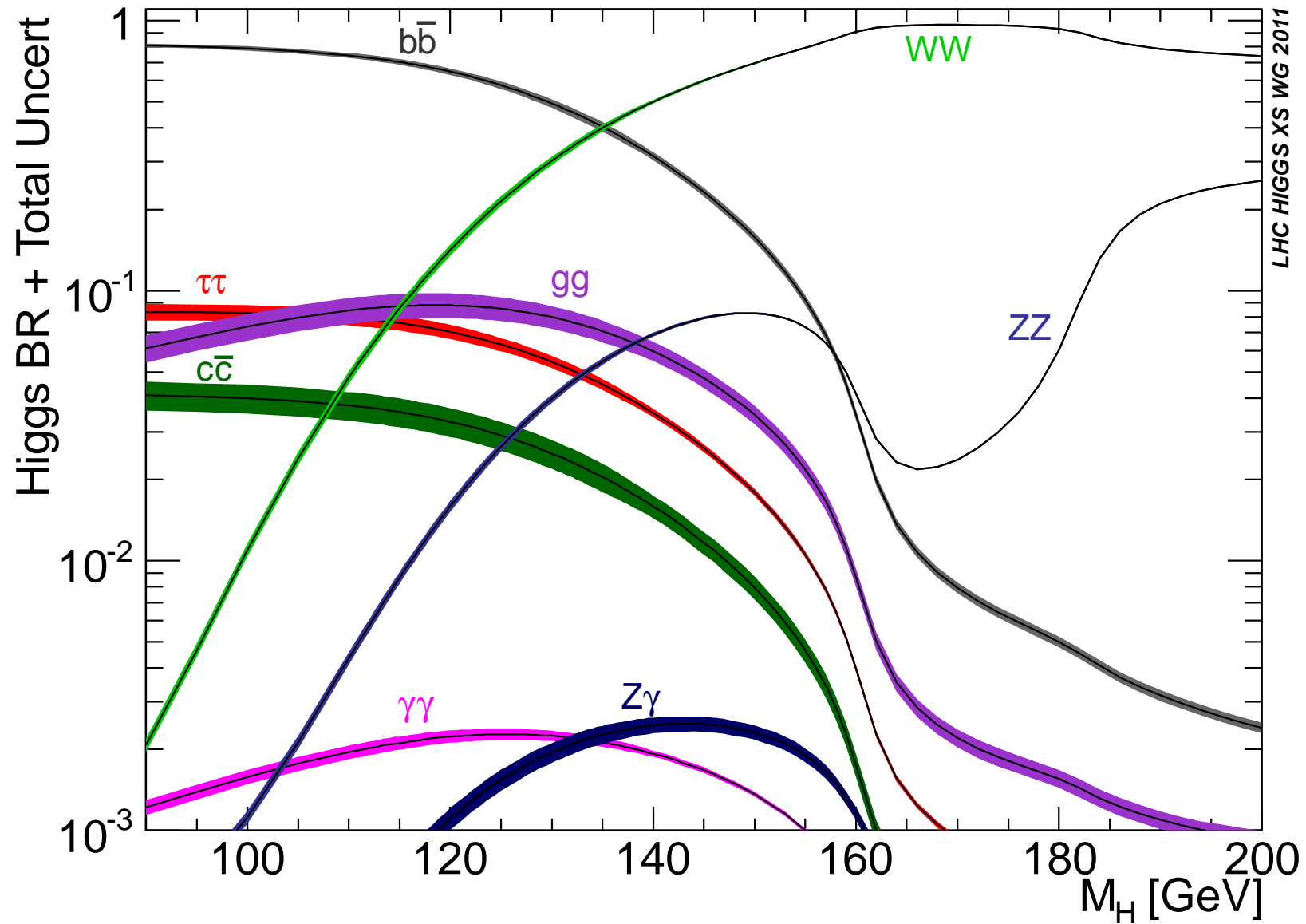
Latest theory predictions for the SM Higgs: LHC production XS

[LHC Higgs XS WG '12]



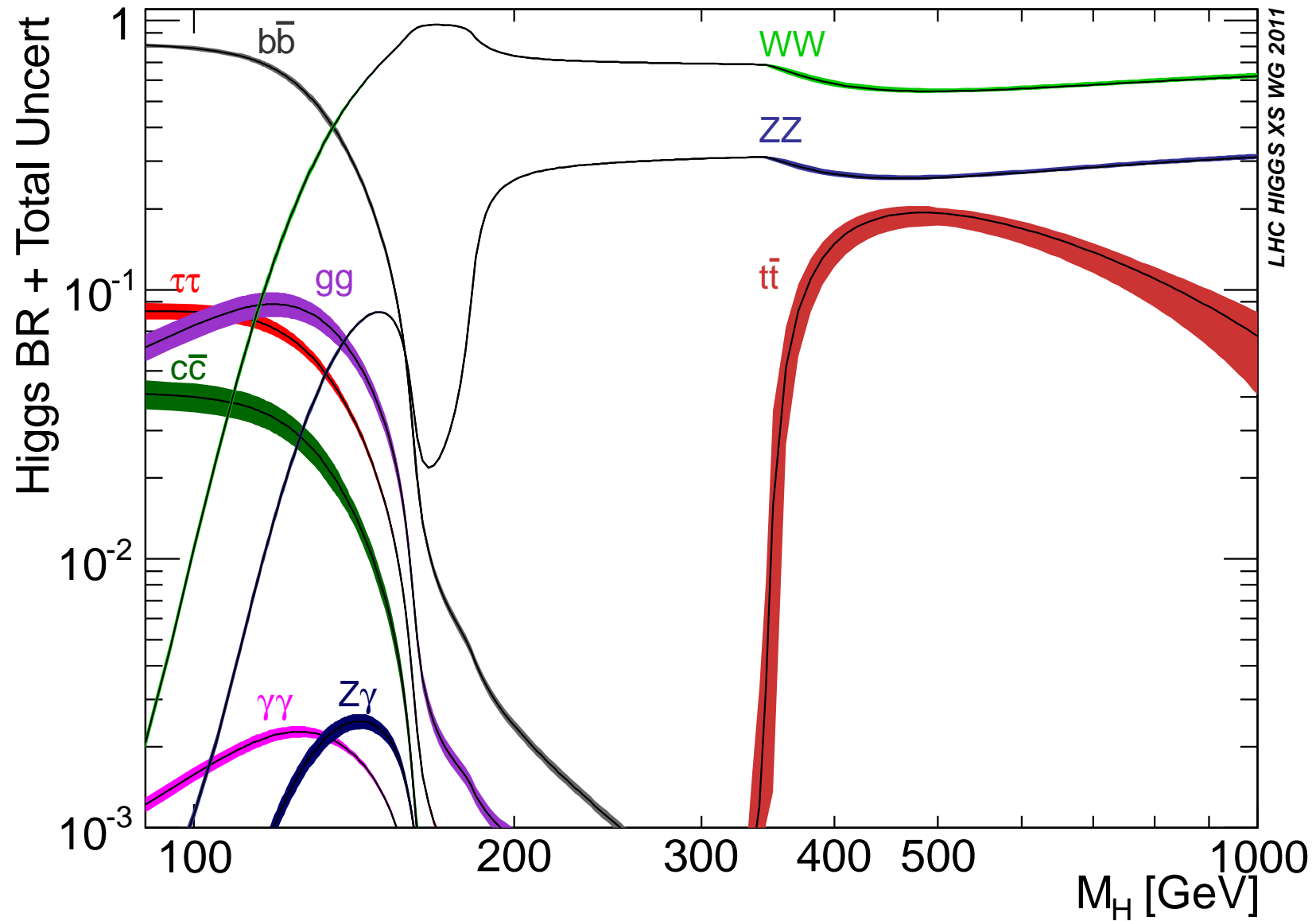
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[LHC Higgs XS WG '11]



Latest theory predictions for the SM Higgs: branching ratios

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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
 - ...
- ⇒ more workforce always appreciated!

Discovering the Higgs boson

What has to be done?

1. Find the new particle

Discovering the Higgs boson

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2. measure its mass (\Rightarrow ok?)

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4. measure couplings to fermions

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5. measure self-couplings
6. measure spin, . . .

Discovering the Higgs boson

What has to be done?

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

T = Tevatron,

Discovering the Higgs boson

What has to be done?

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

T = Tevatron, L = LHC,

Discovering the Higgs boson

What has to be done?

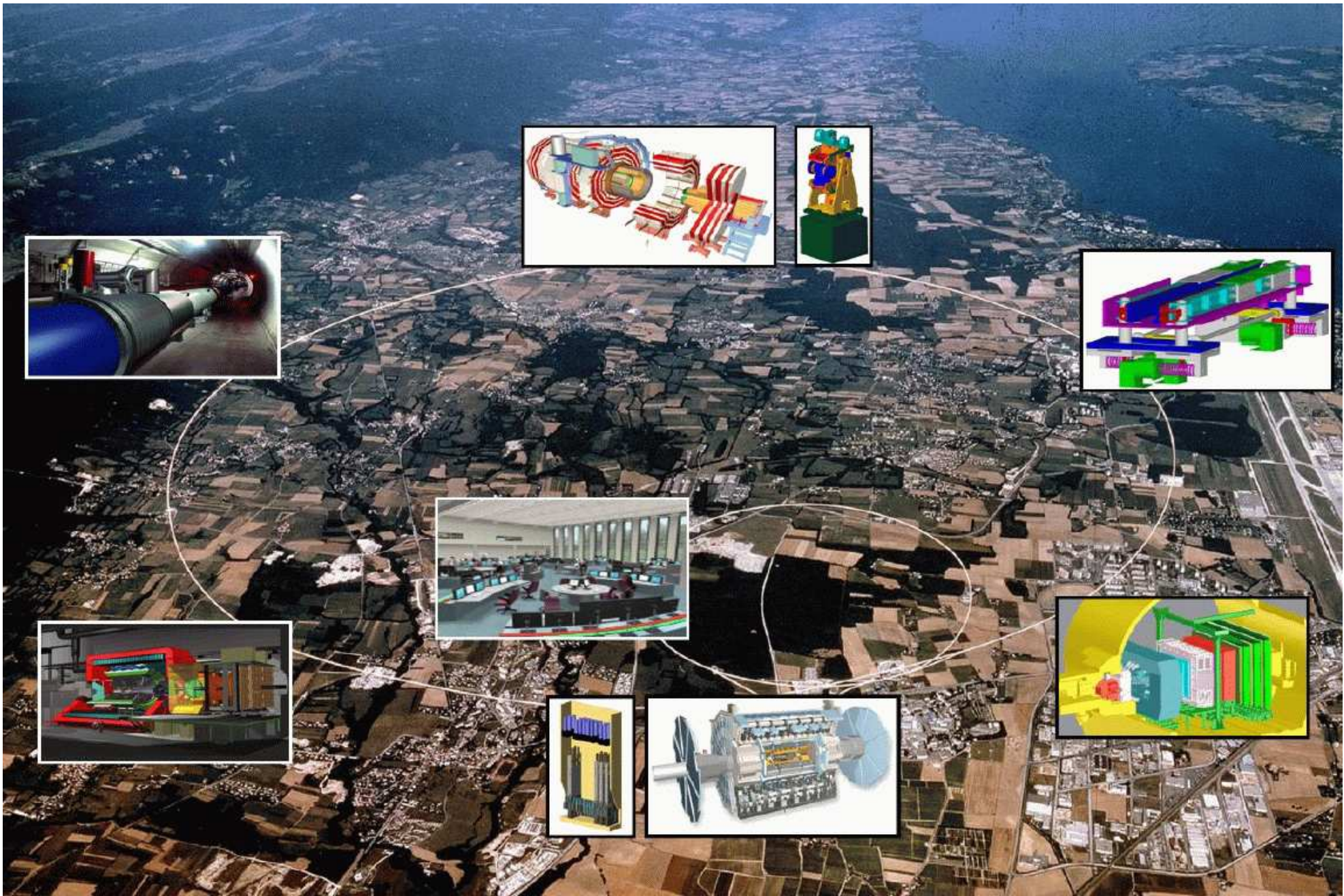
- | | | | |
|--|---|---|---|
| 1. Find the new particle | T | L | I |
| 2. measure its mass (\Rightarrow ok?) | T | L | I |
| 3. measure coupling to gauge bosons | | L | I |
| 4. measure couplings to fermions | | L | I |
| 5. measure self-couplings | | | I |
| 6. measure spin, ... | | L | I |

T = Tevatron, L = LHC, I = ILC

We need the **ILC** to find the Higgs
and to establish the Higgs mechanism!

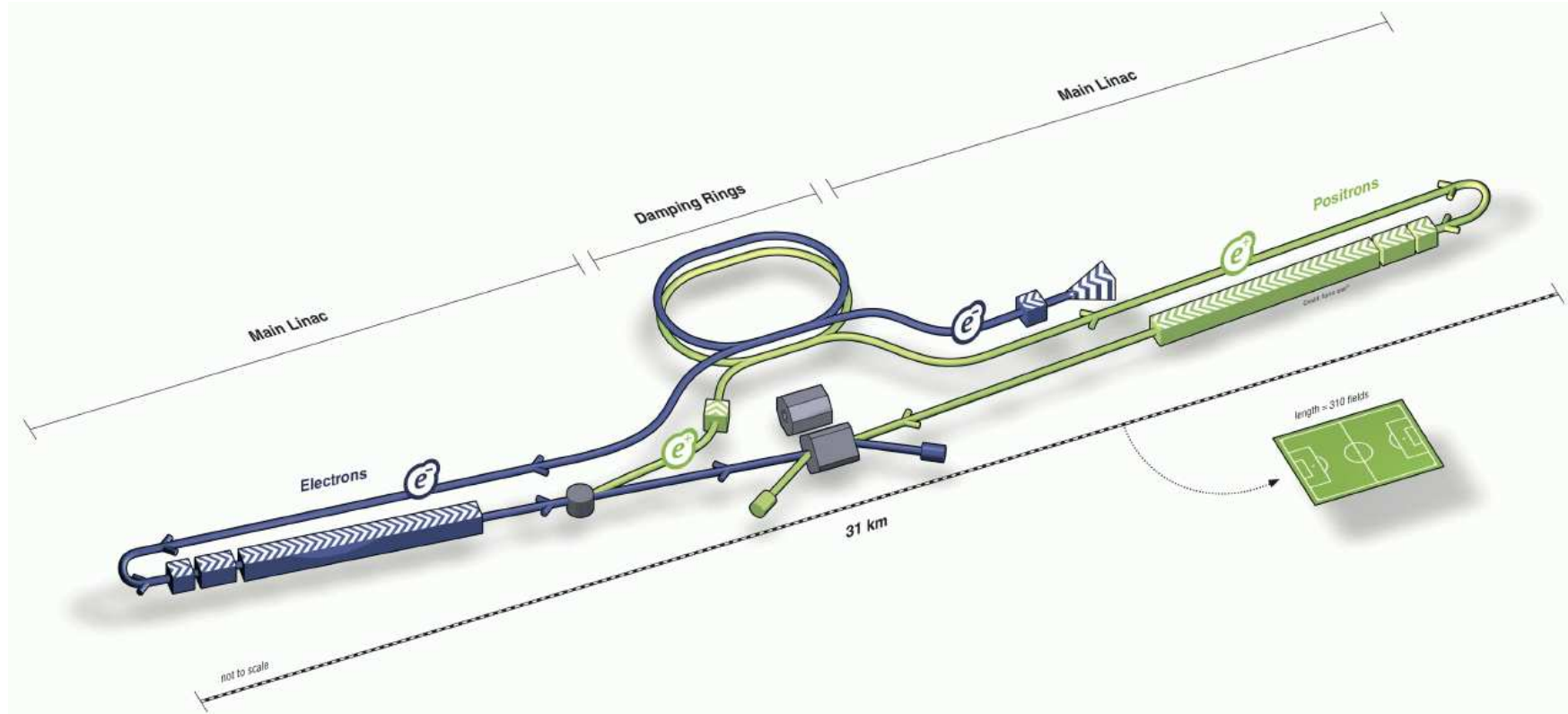
But the **LHC** can do a crucial part already!





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

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

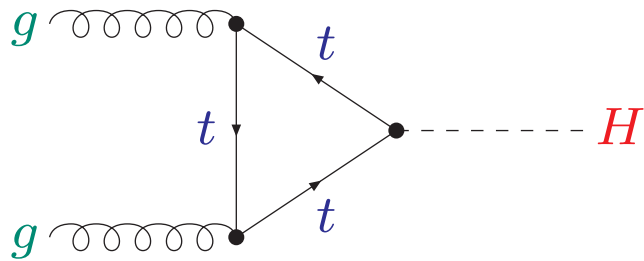


- two detectors in one interaction region (push-pull)
 - undulator based e^+ source
 - polarized beams for e^- and e^+ ($P_{e^-} = 80\%$, $P_{e^+} = 60\%$)
- ⇒ clearly defined and tunable initial state
⇒ extremely “clean” physics

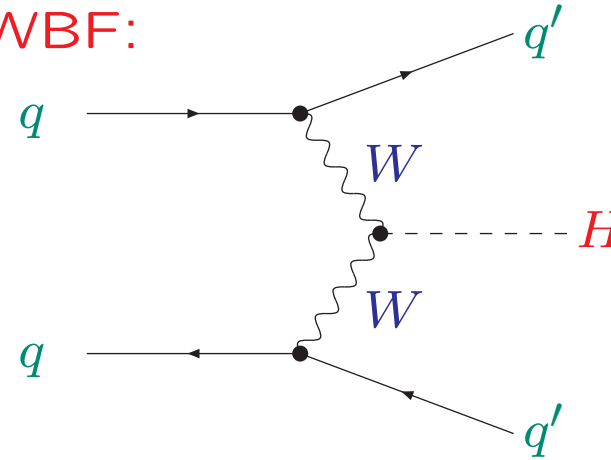
Comparison to “the discovery”:

Important SM production channel at the LHC:

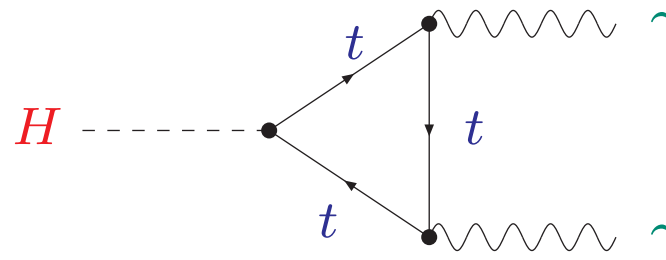
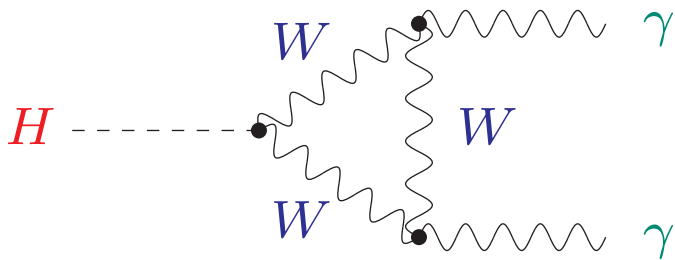
Gluon-Fusion:

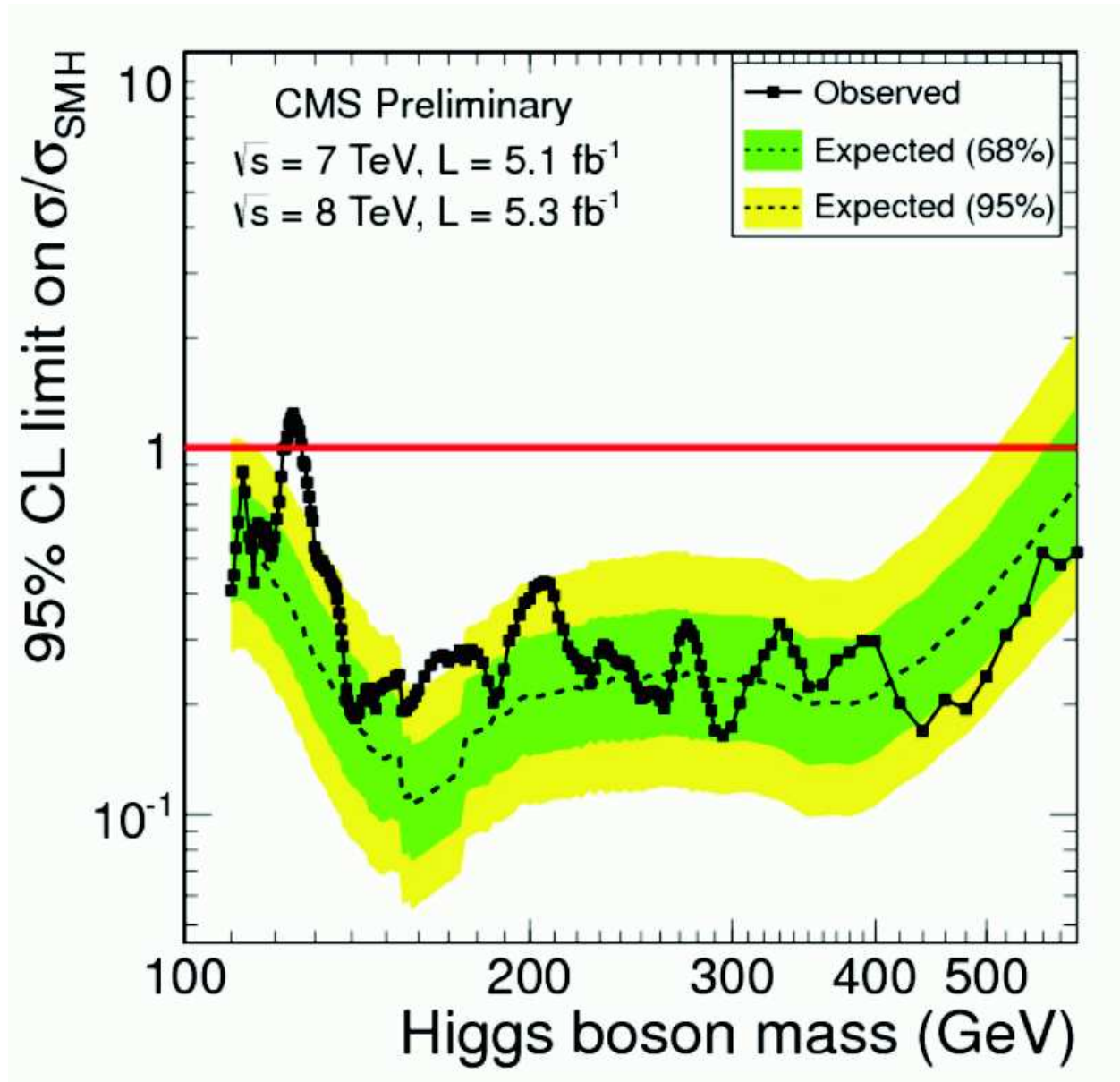


WBF:

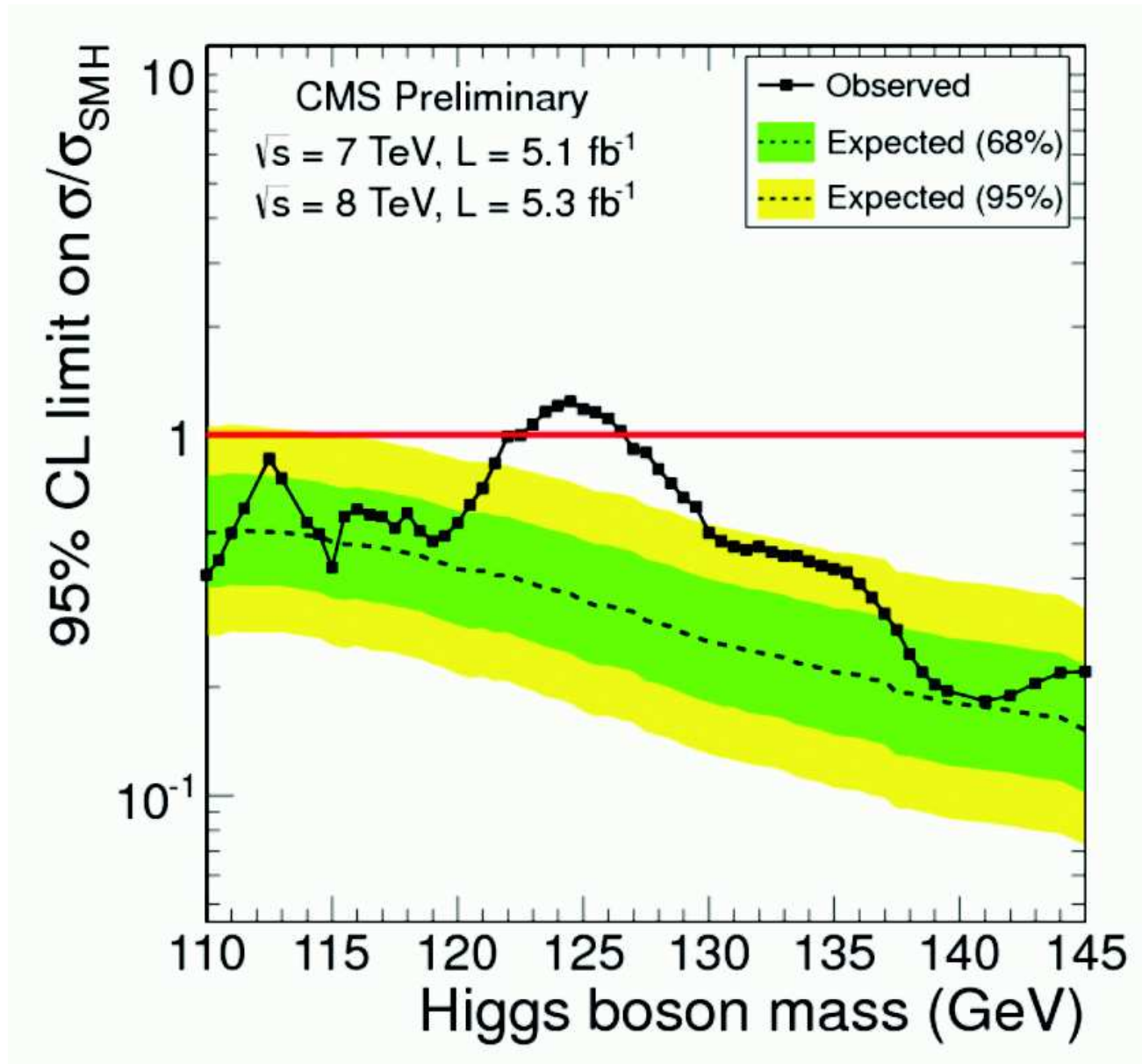


Important decay for Higgs mass measurement:

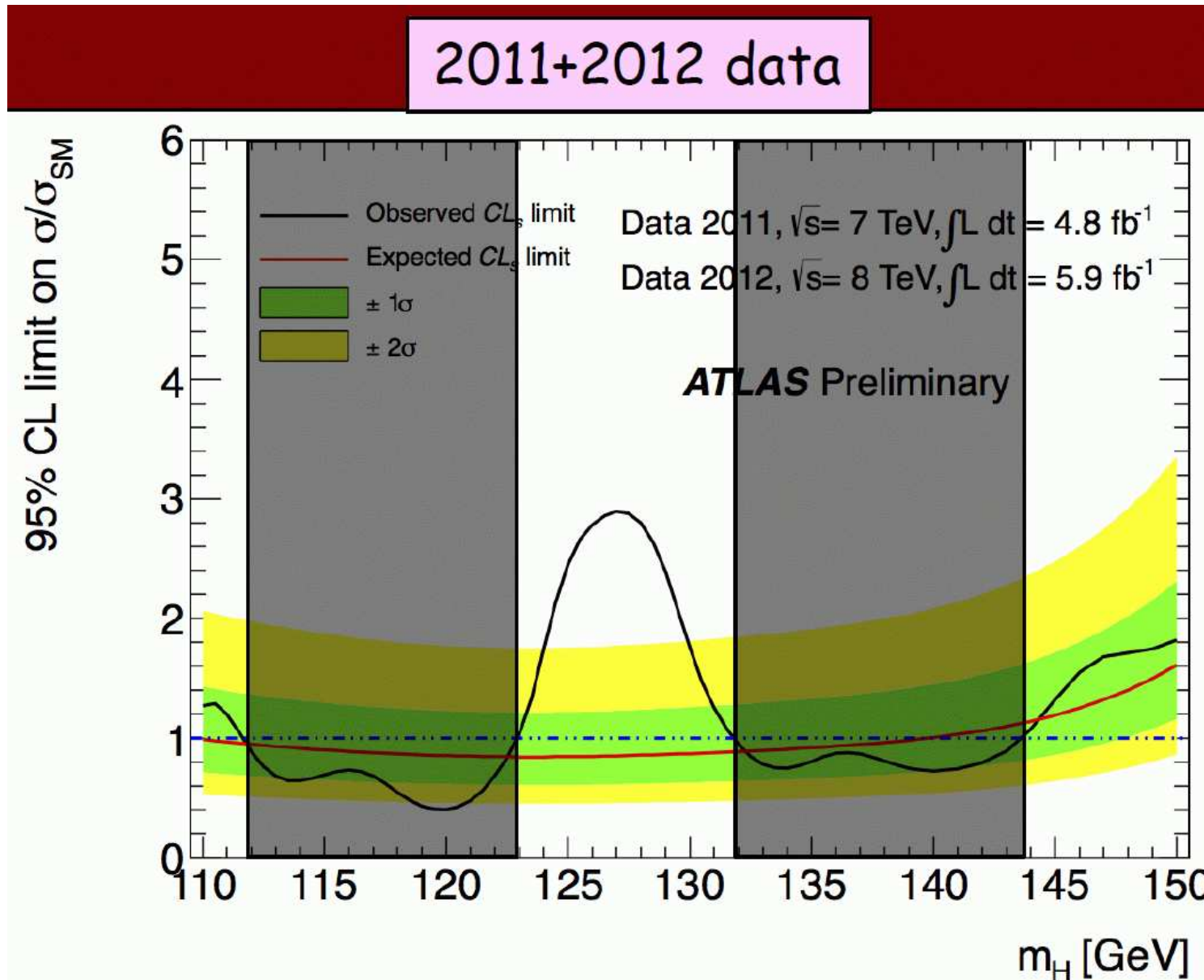




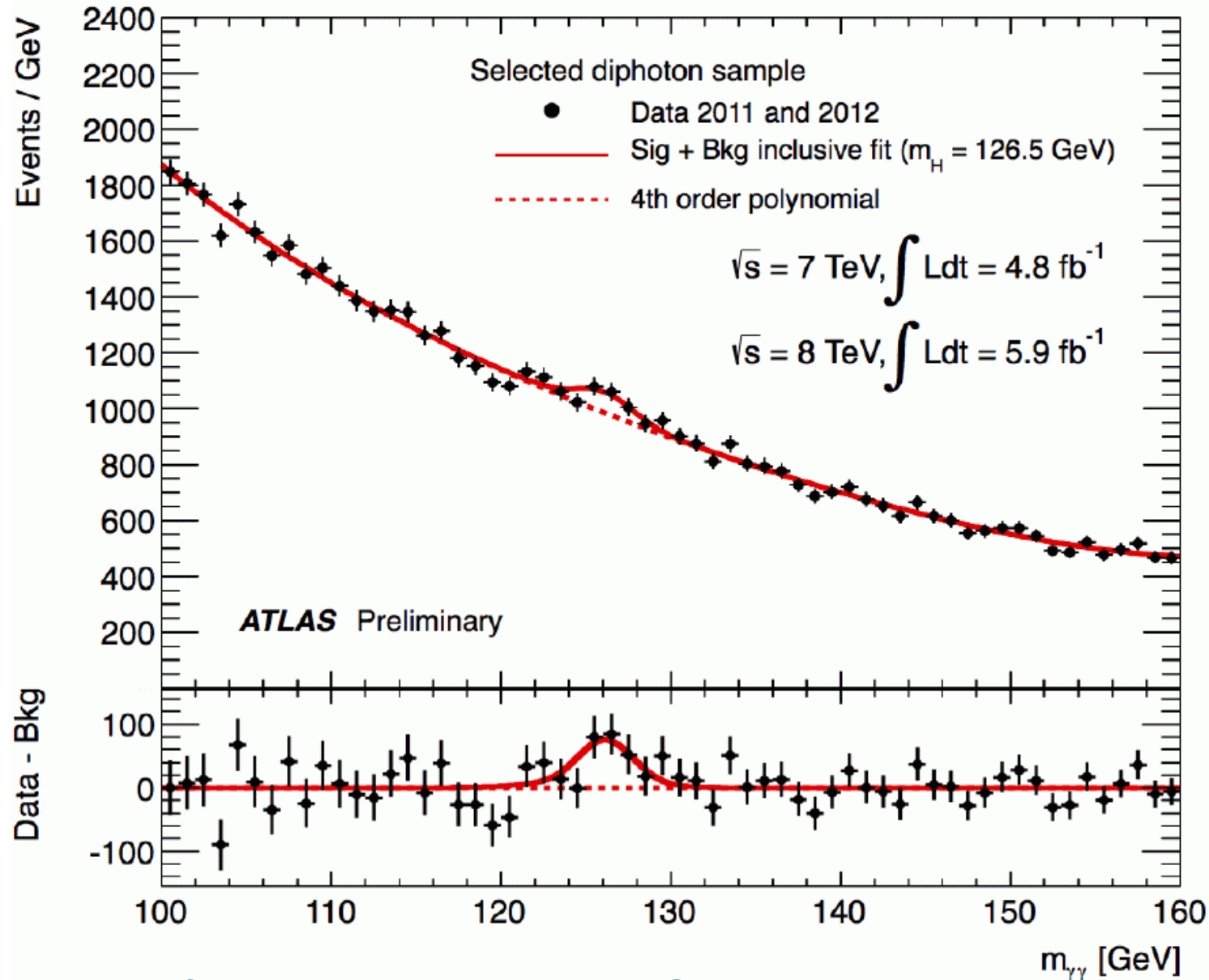
⇒ clear excesses for around $M_H \simeq 125 \text{ GeV}$



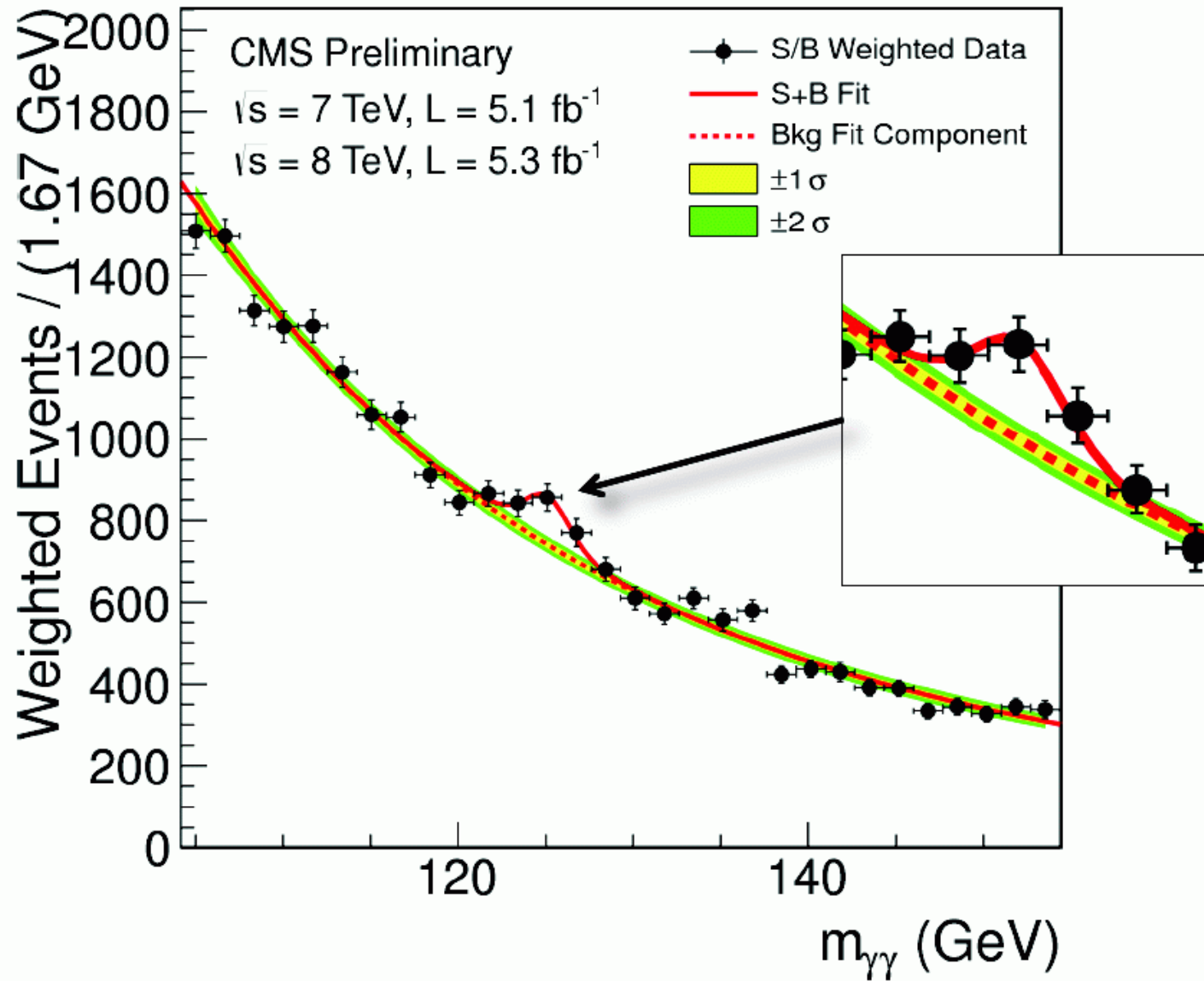
⇒ clear excesses for around $M_H \simeq 125 \text{ GeV}$



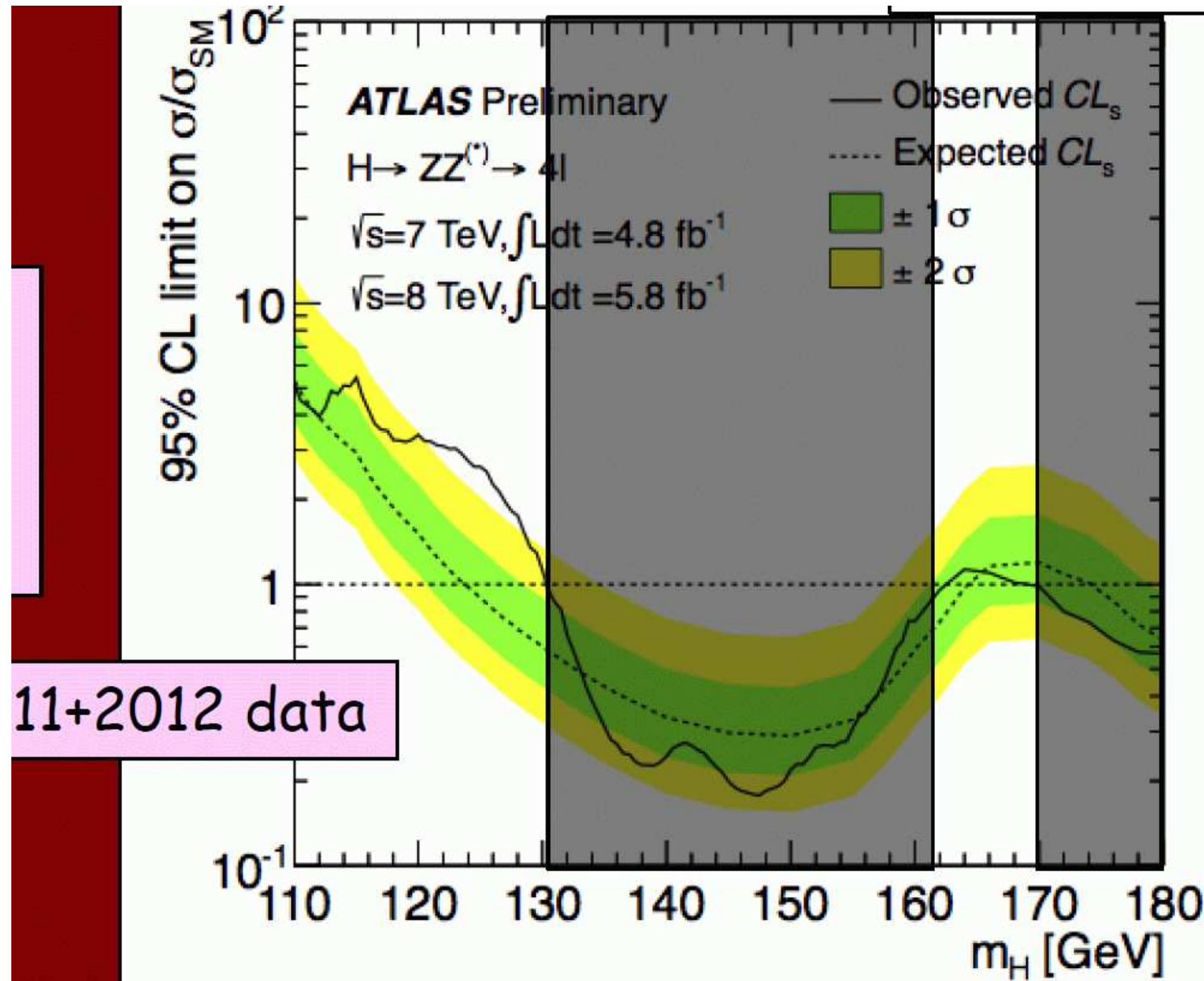
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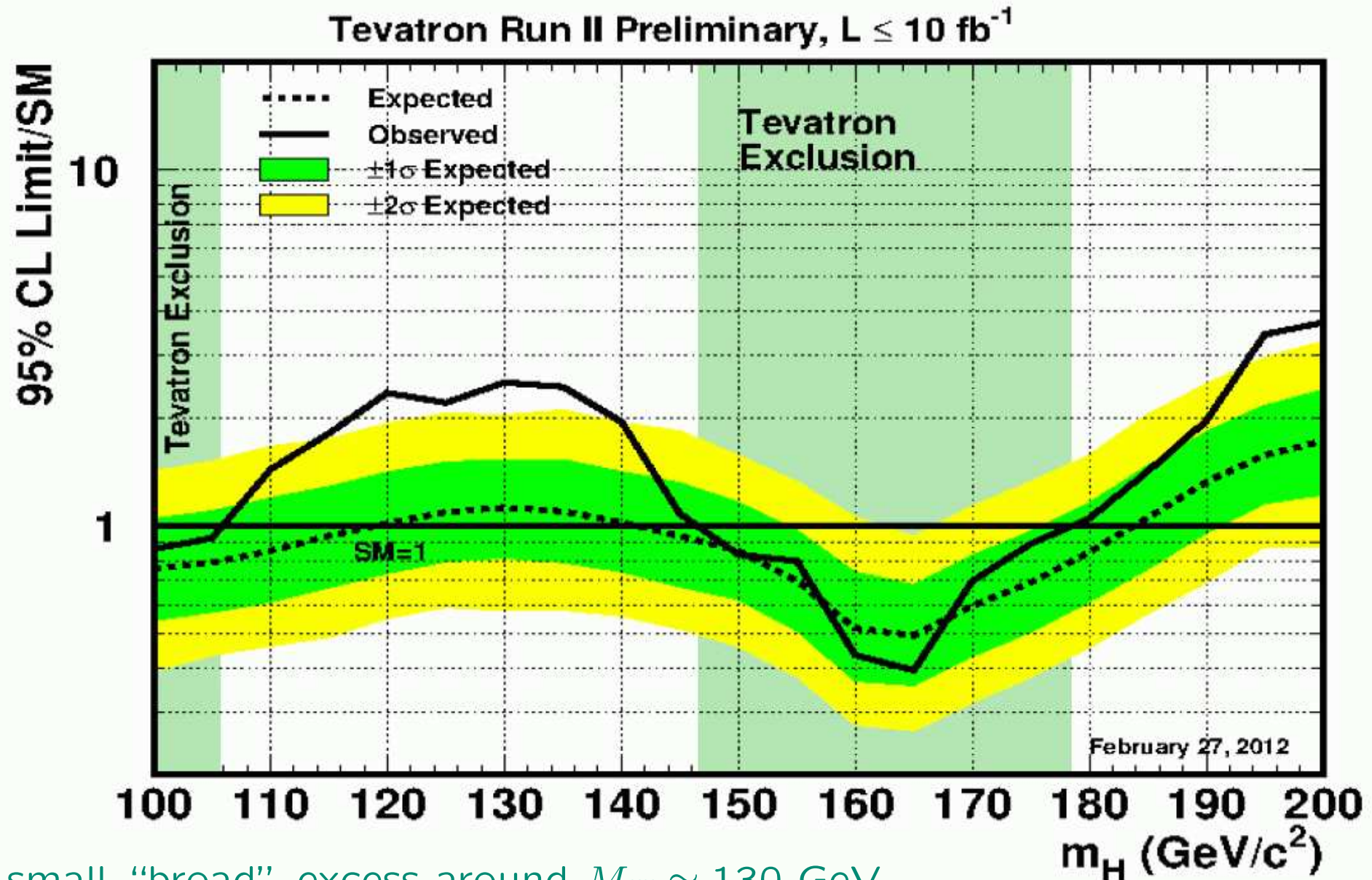


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Do not forget the final result of SM Higgs searches at the Tevatron:



⇒ small “broad” excess around $M_H \simeq 130 \text{ GeV}$

Results for the combination of all experiments:

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Official combination does not exist :-)

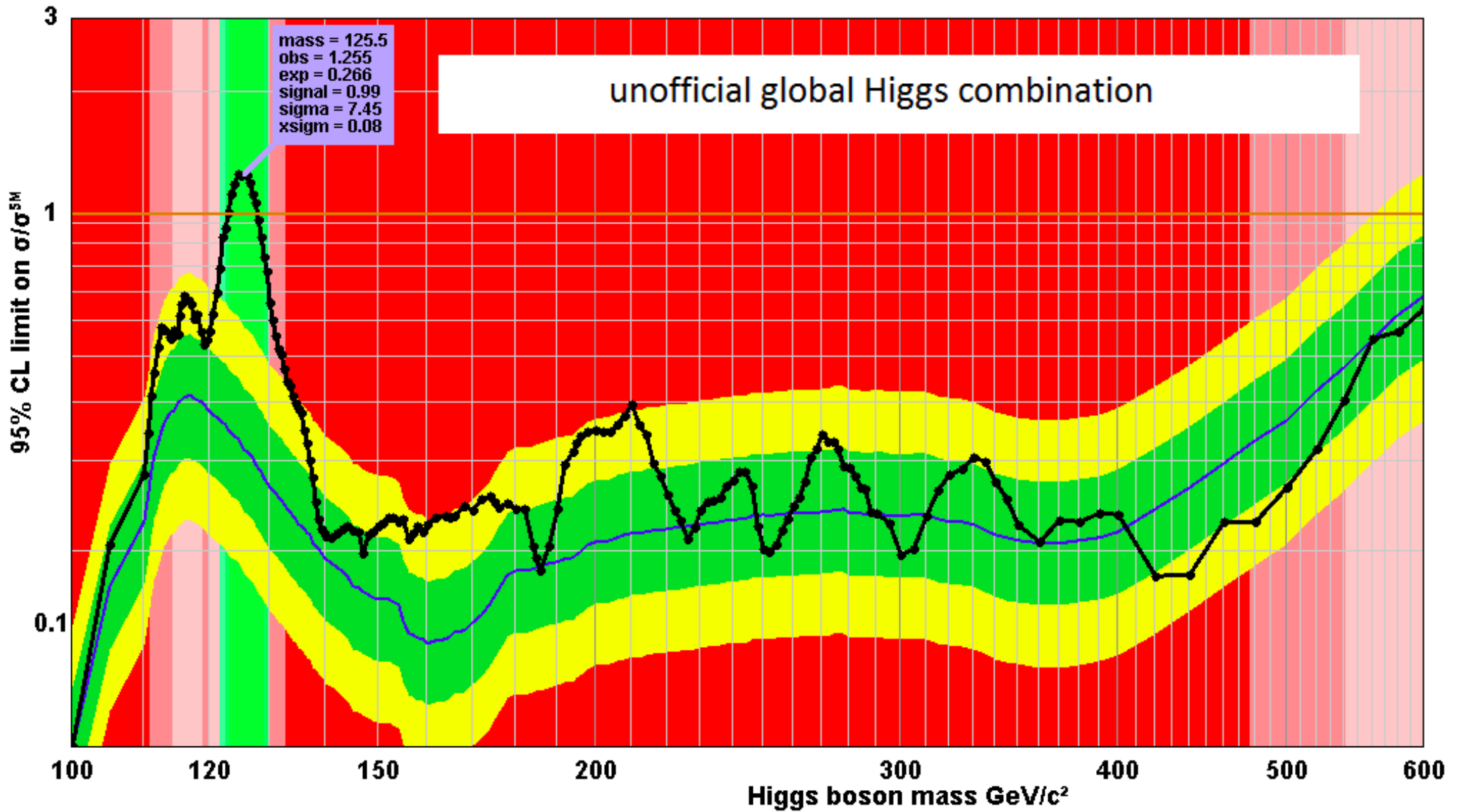
Results for the combination of all experiments:

Official combination does not exist :-)

However: unofficial combination exists . . .

1/fb - 10/fb

04/07/2012



Comparison to SM prediction:

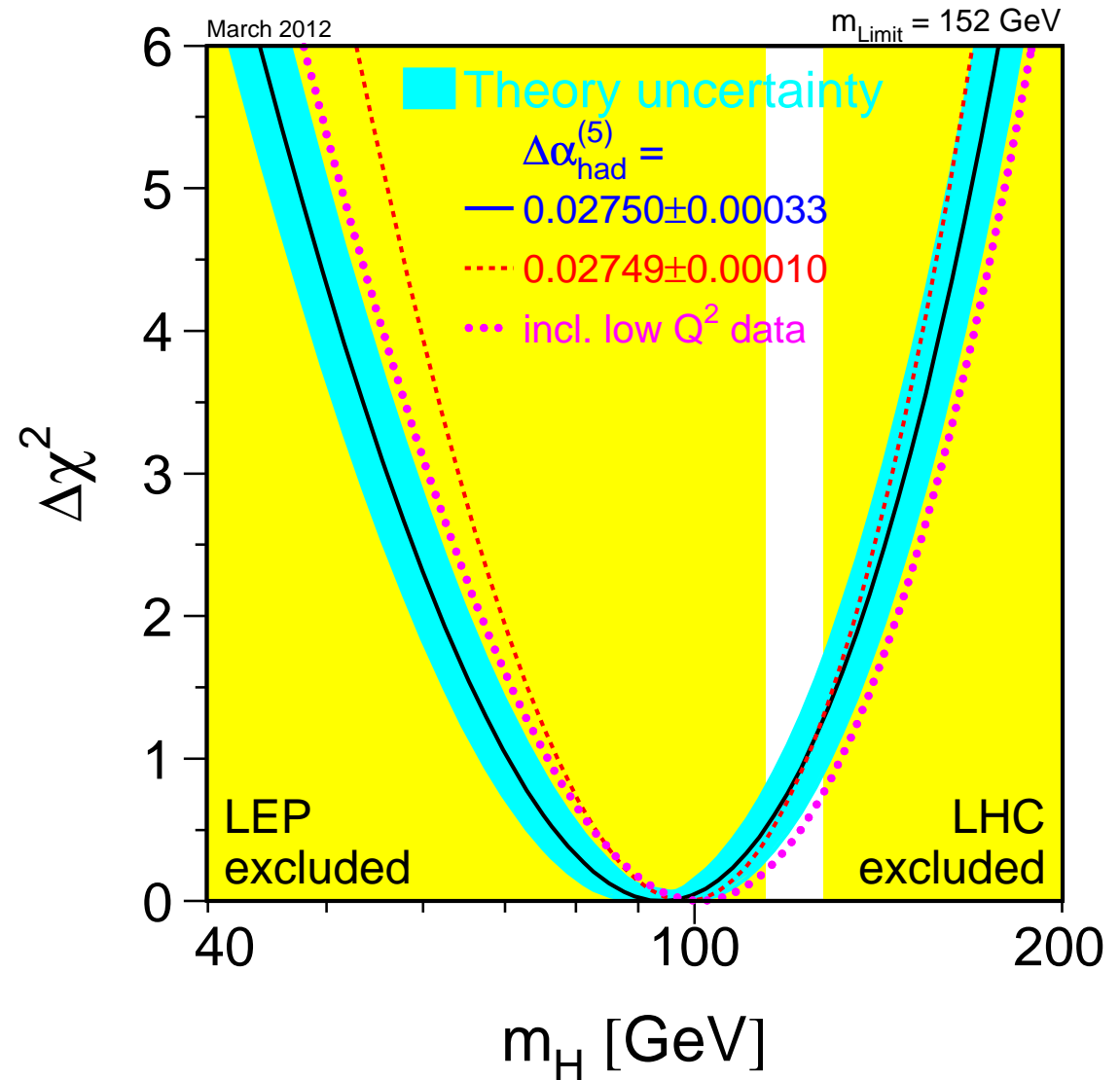
[LEPEWWG '12]

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

$$M_H < 152 \text{ GeV, 95\% C.L.}$$

Assumption for the fit:
SM incl. Higgs boson

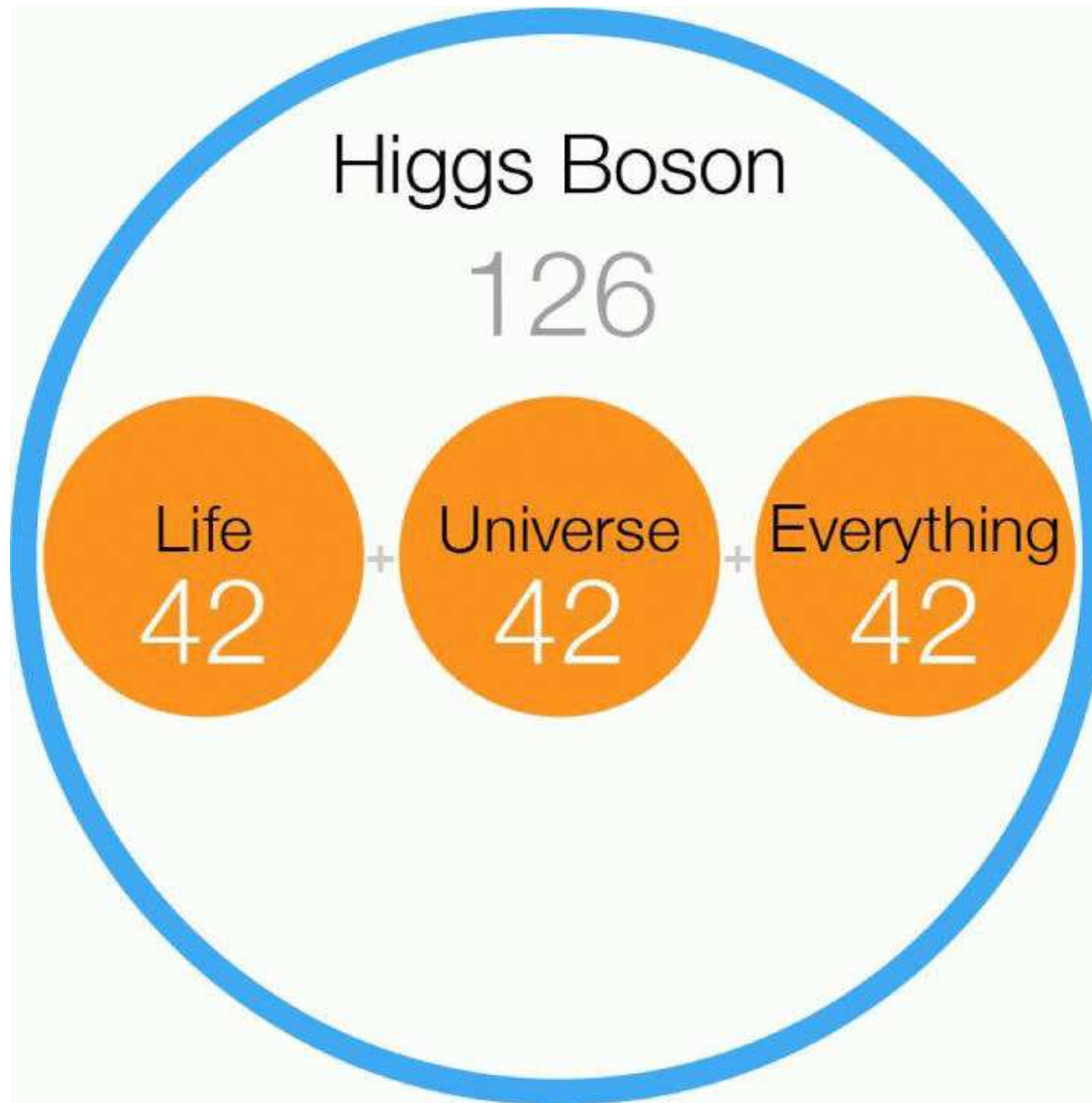
\Rightarrow no confirmation of
Higgs mechanism



\Rightarrow Observed excess well compatible with SM prediction

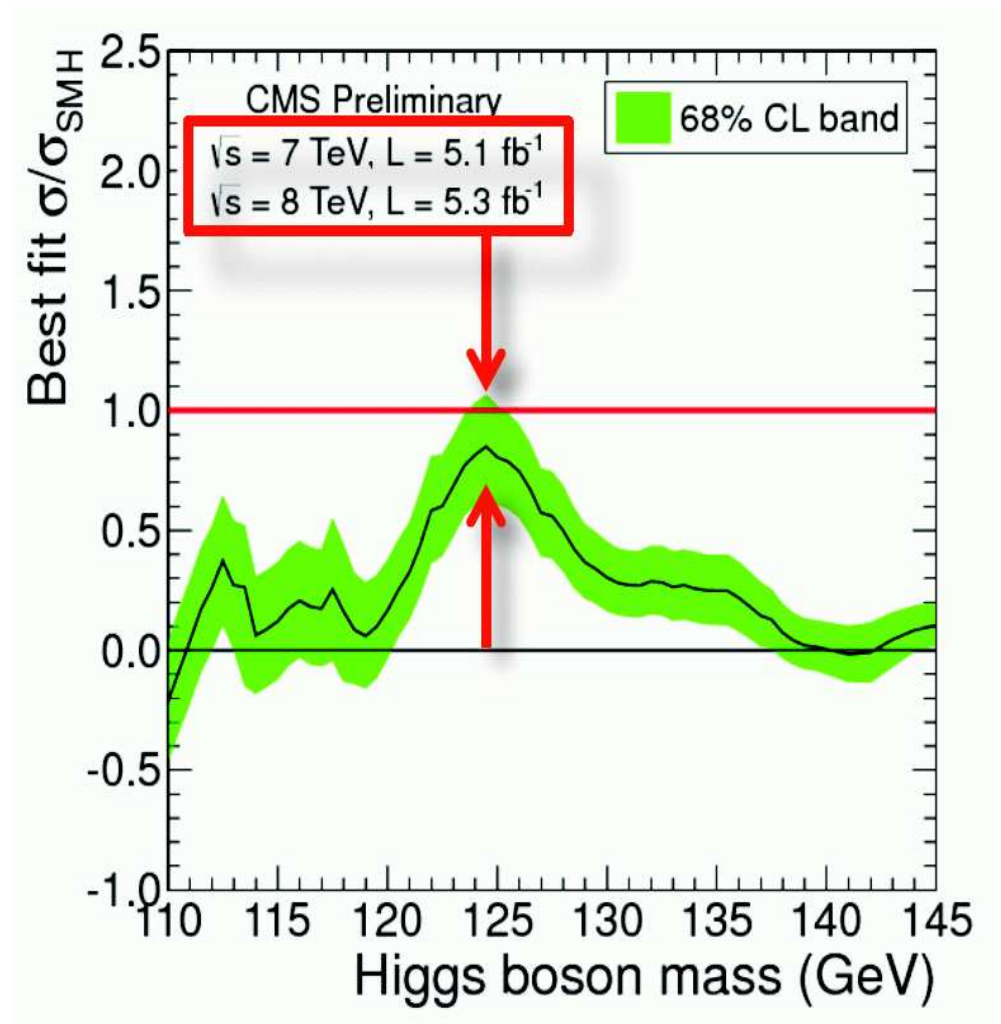
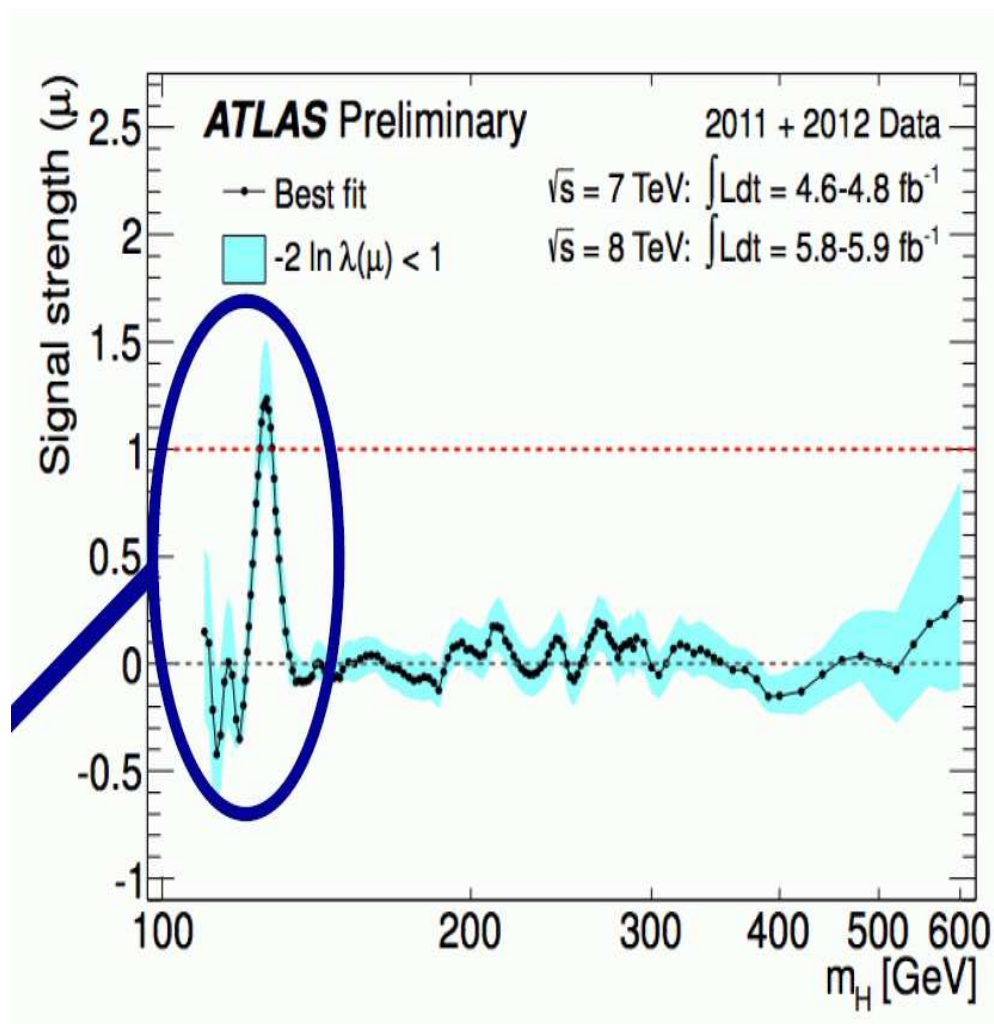
Comparison to Douglas Adam's prediction:

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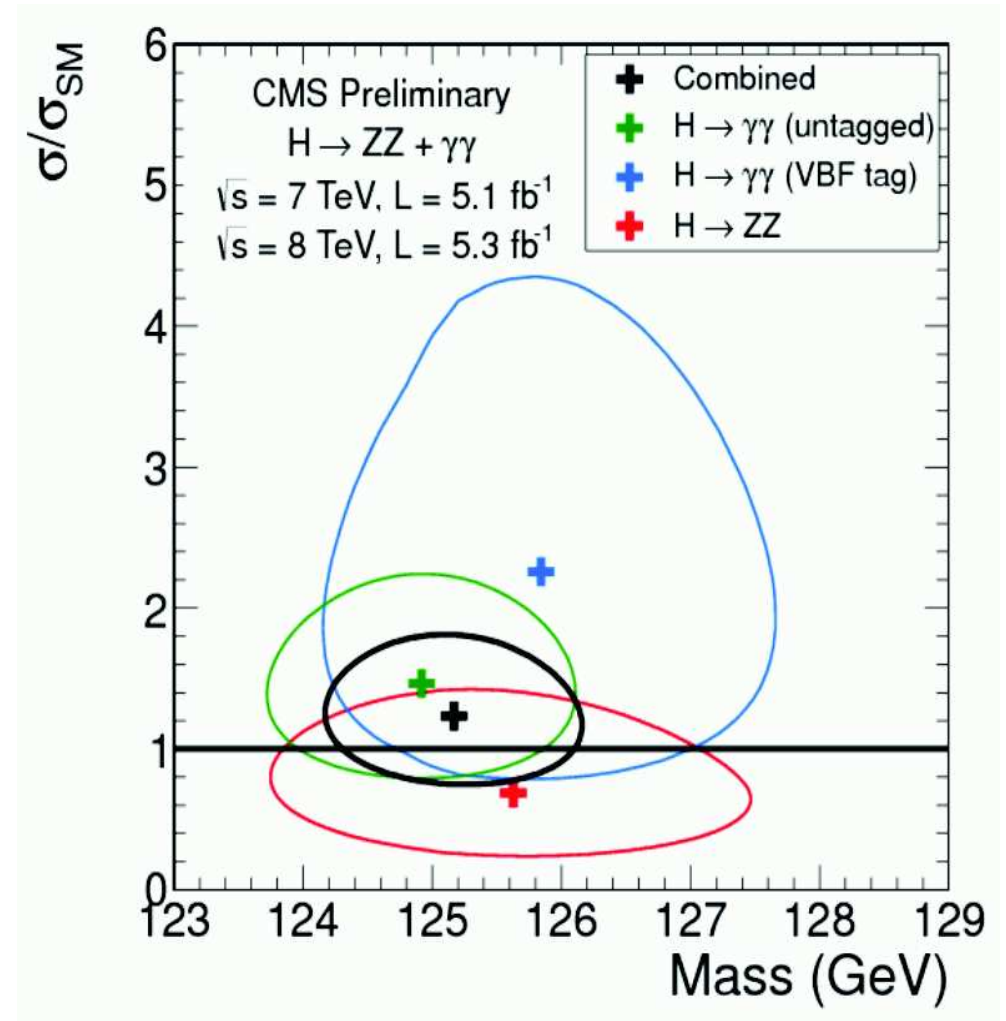
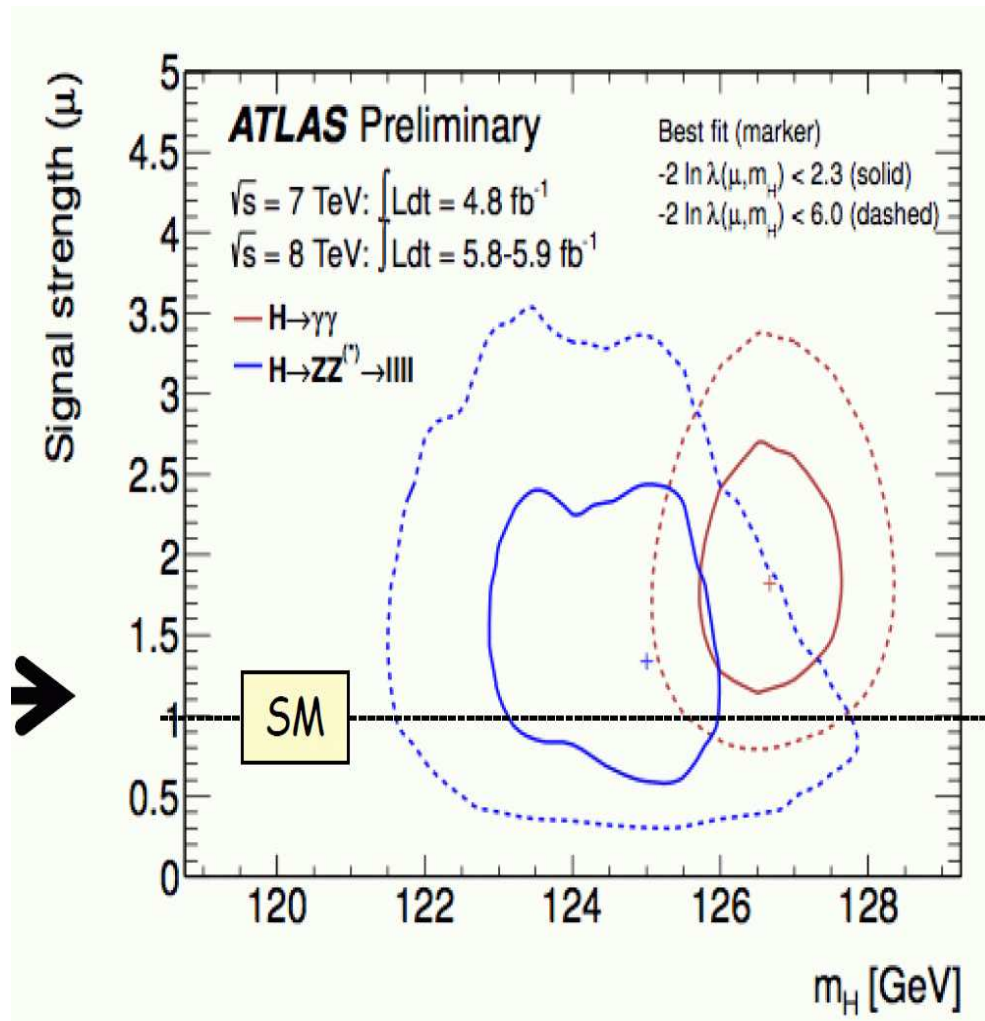
⇒ right on the spot!

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?

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[SUSSP65 '09]



Has the Higgs particle been discovered?

We have

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

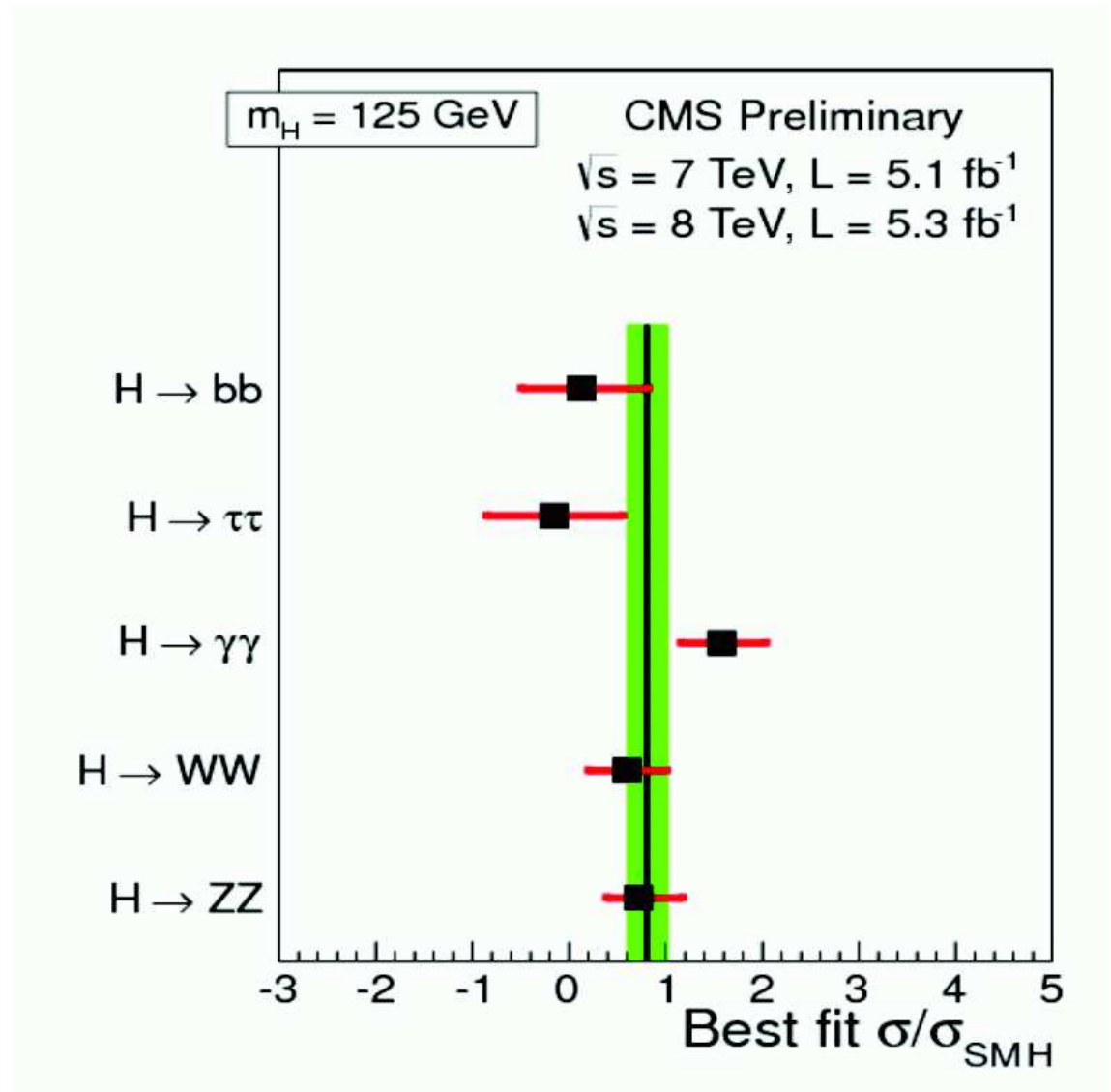
How can we be sure about SM?

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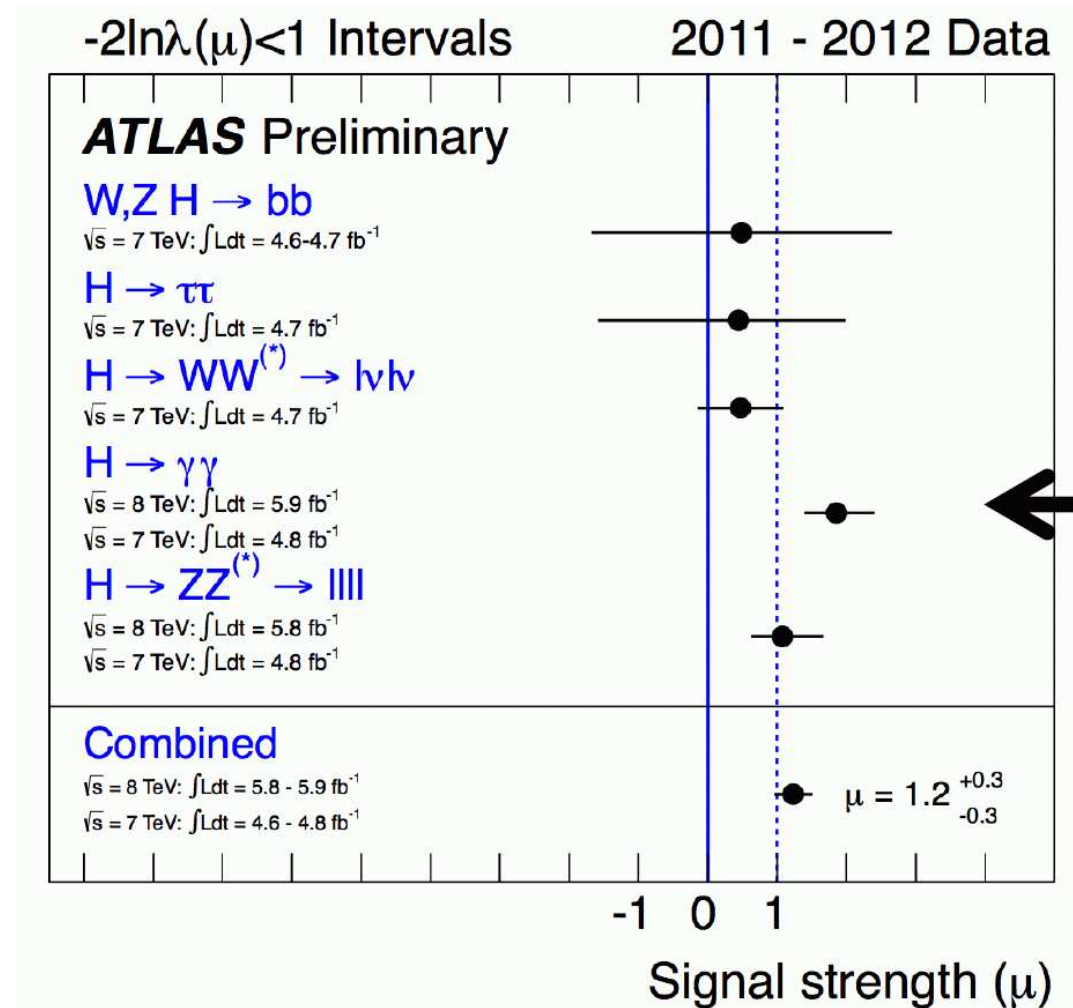
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$$g_x = g_x^{\text{SM}} (1 + \Delta_x)$$

Fit 1:

One coupling modifier for everything: Δ_H

Fit 2:

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

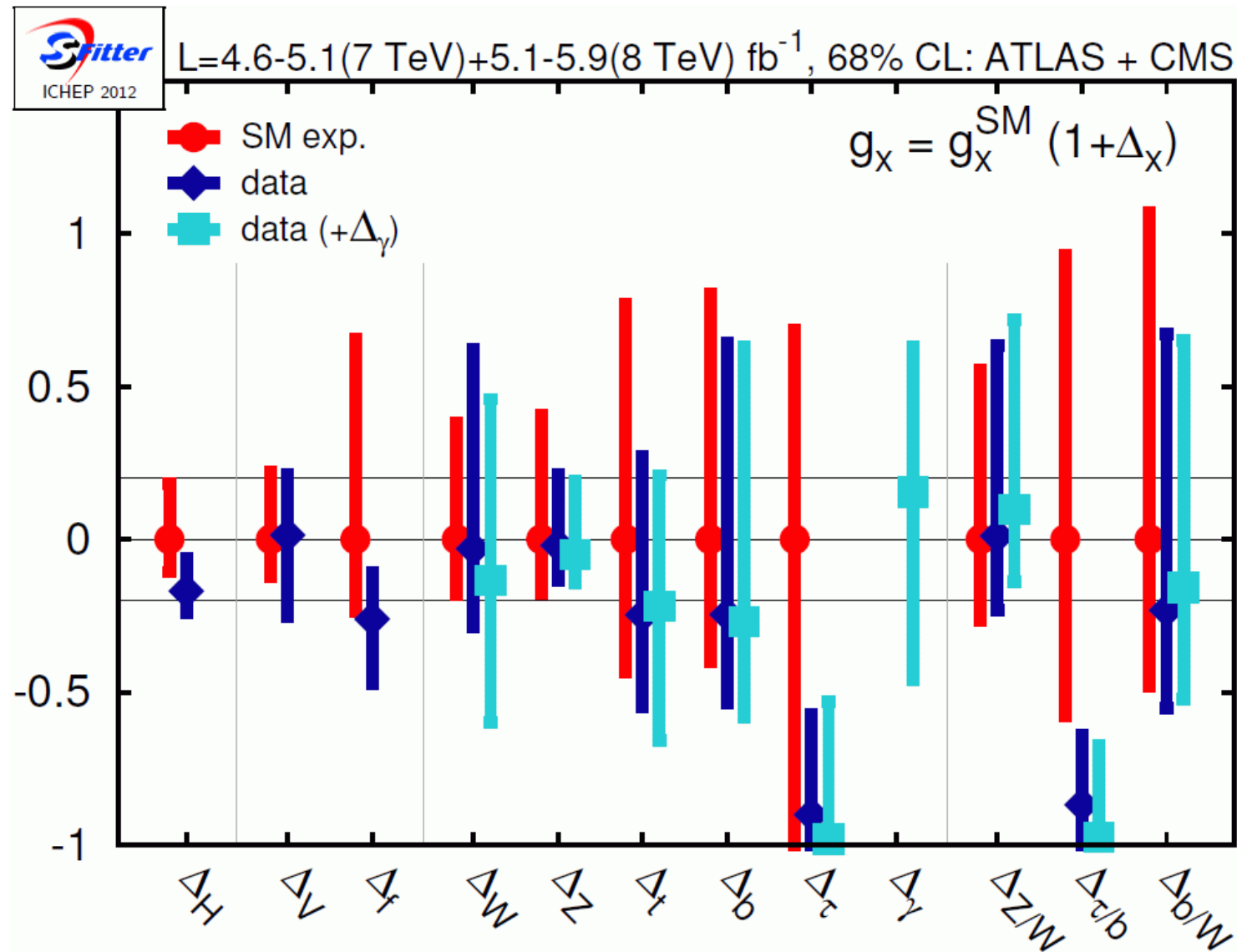
Fit 3:

Fit individual couplings: $\Delta_W, \Delta_Z, \Delta_t, \Delta_b, \Delta_\tau$

⇒ theory assumptions on total width necessary!

Fit 4:

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



⇒ 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

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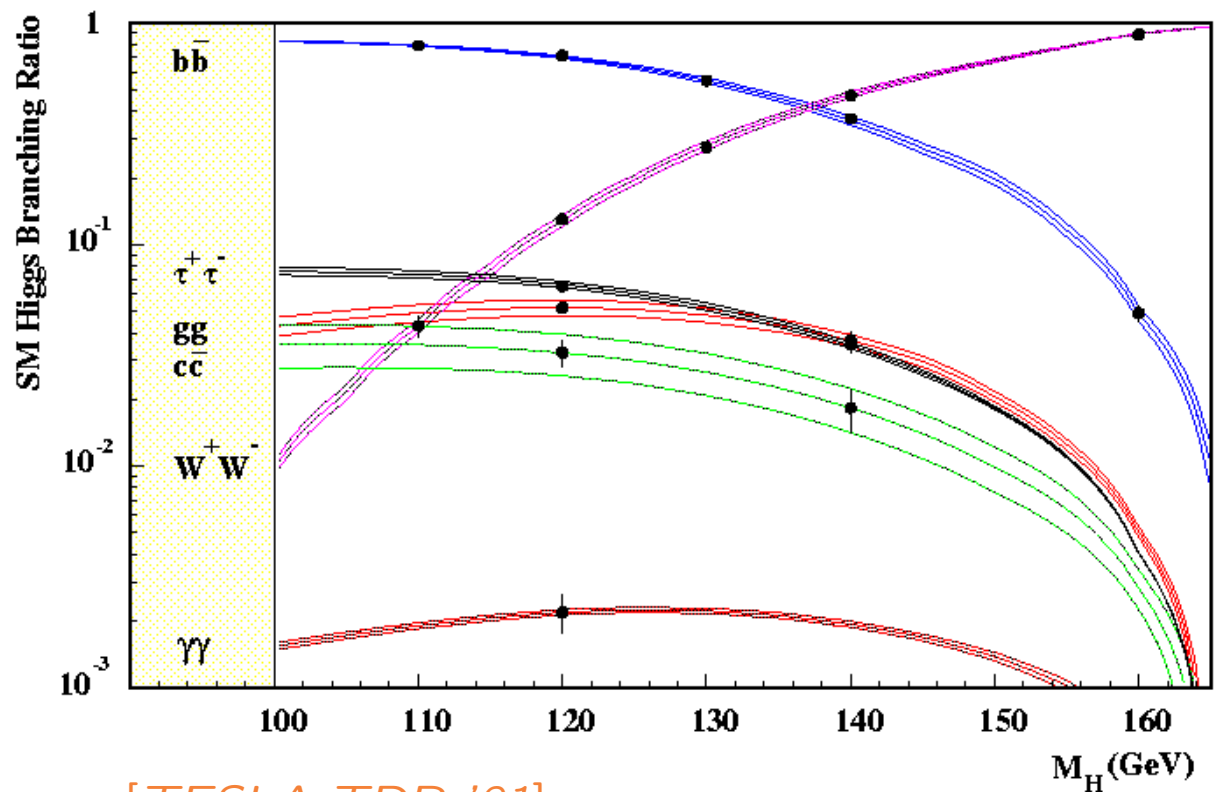
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Higgs physics at the ILC:

SM Higgs @ ILC:

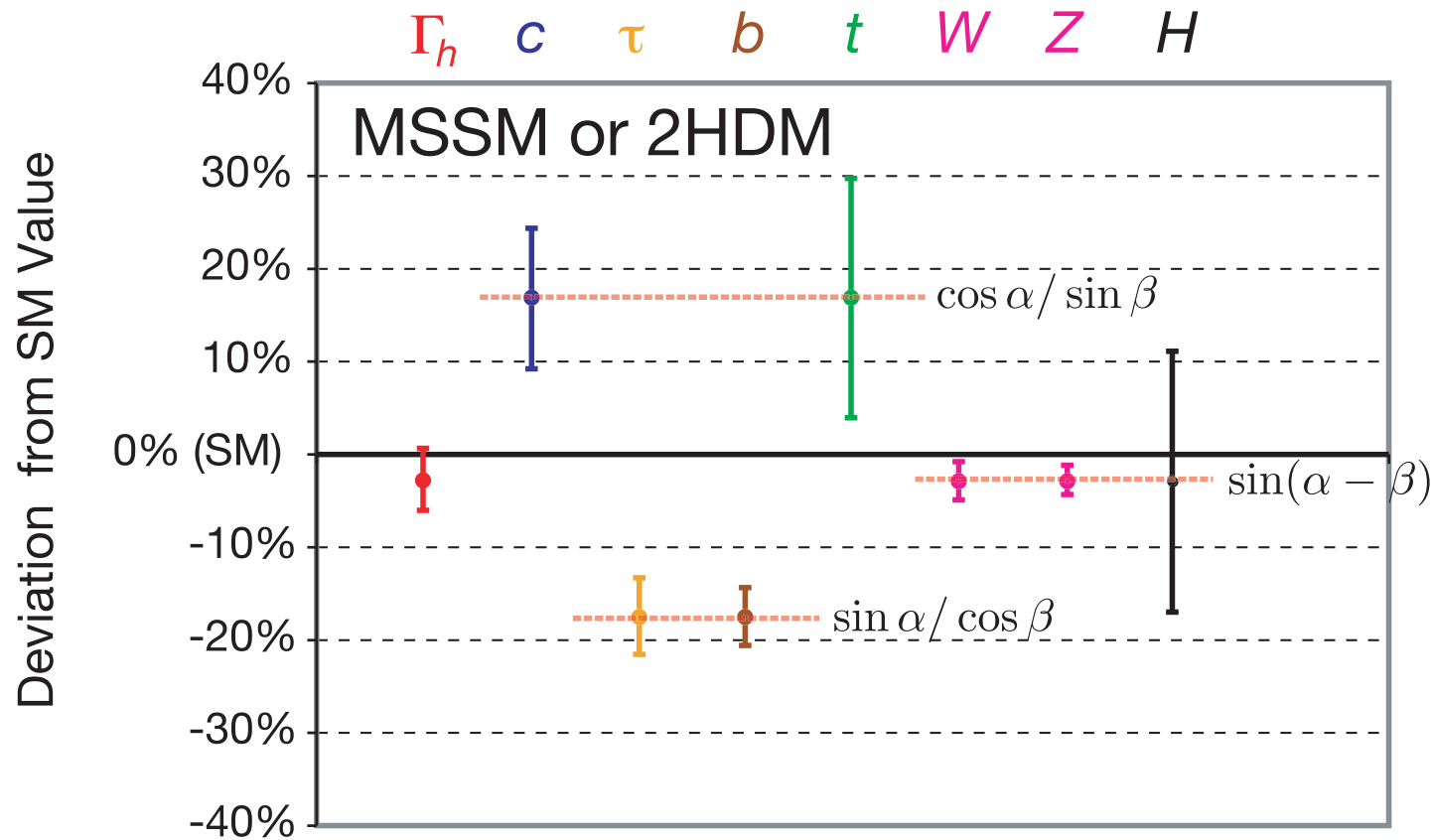
Precise measurement of:

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



Example: Higgs couplings in the MSSM:

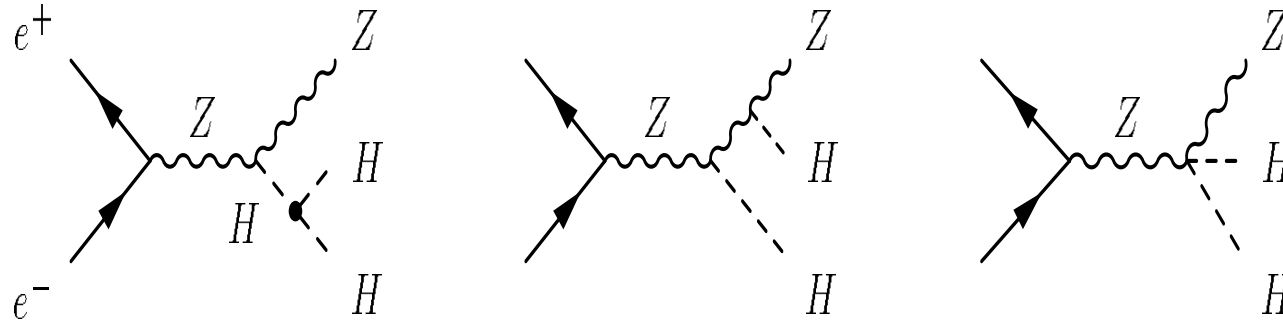
“Normal(?)” MSSM scenario:



⇒ 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:

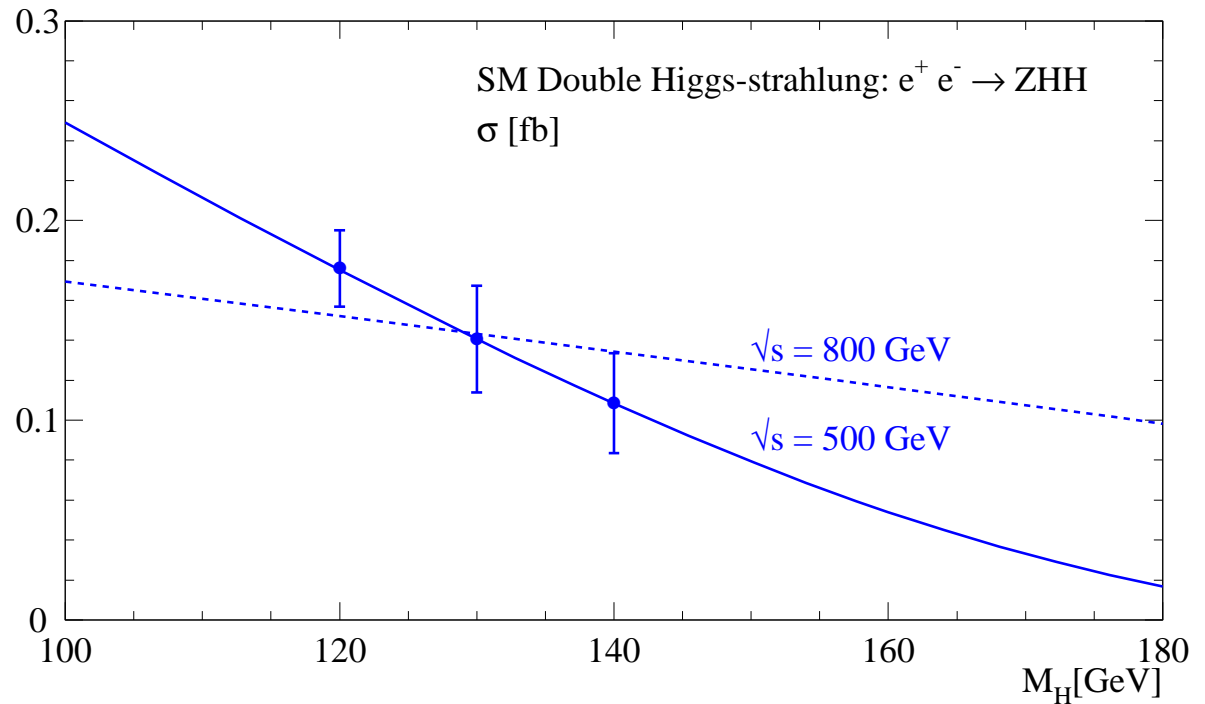
[Djouadi, Kilian, Mühlleitner, Zerwas '99]

$1 \text{ ab}^{-1} \Rightarrow 20\text{--}30\%$

measurement of $\lambda = \lambda_{HHH}$

However:

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



Step 6: measurement of the Higgs boson spin

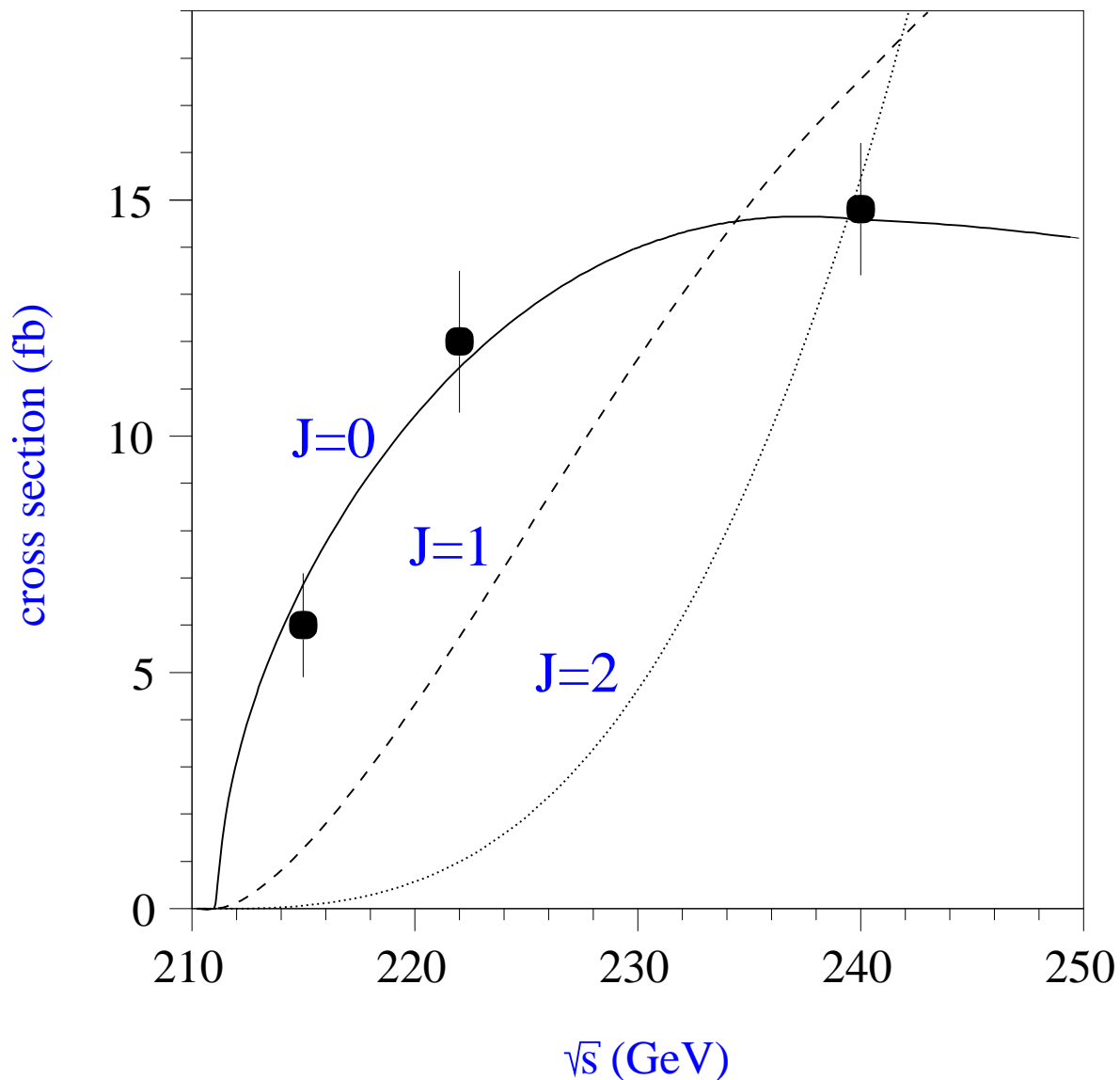
⇒ easy at the ILC

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

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

20 fb^{-1}

⇒ identification easy



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How to go ahead?

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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 $\mathcal{O}(10^5)$ Higgs bosons
 - go to higher energies for top physics
 - go to higher energies for TeV scale exploration
- go to other options: GigaZ, $\gamma\gamma$, ...

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 - go to other options: GigaZ, $\gamma\gamma$, ...
- ⇒ best case scenario the ILC!
- ⇒ We have to use our Annus mirabilis to ensure the (our!) future