Particle Physics - Chapter 12b

LHC – Higgs discovery

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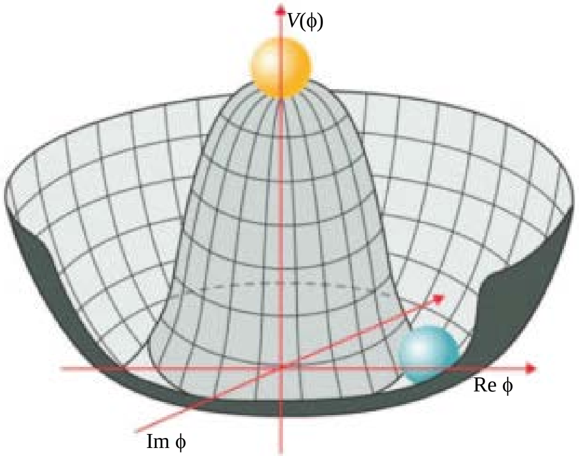
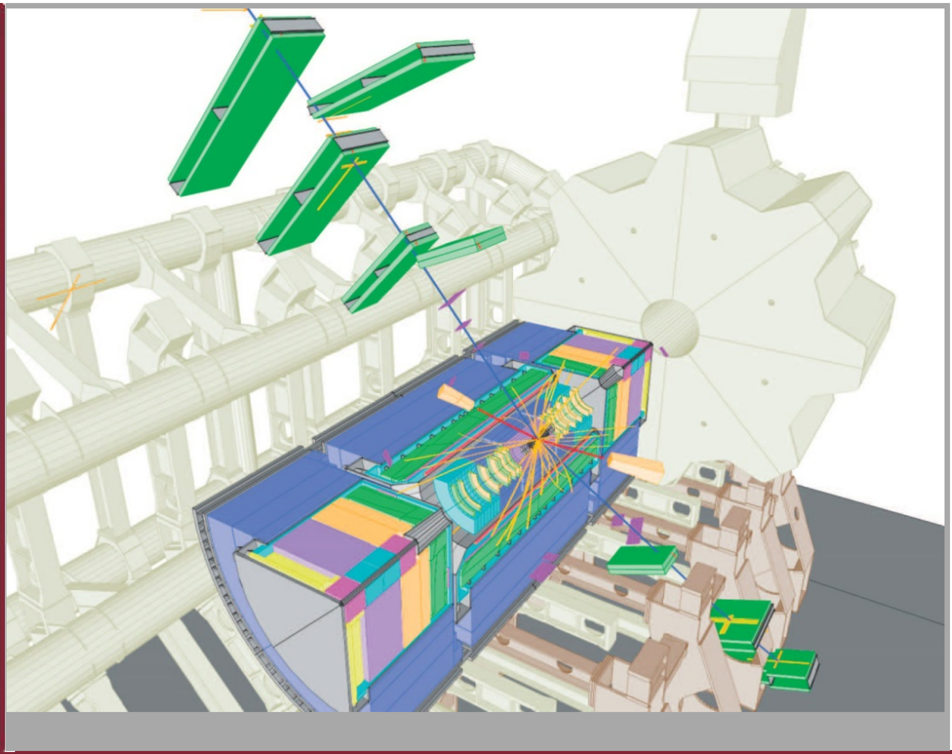
AA 18-19

last mod.
31-May-19

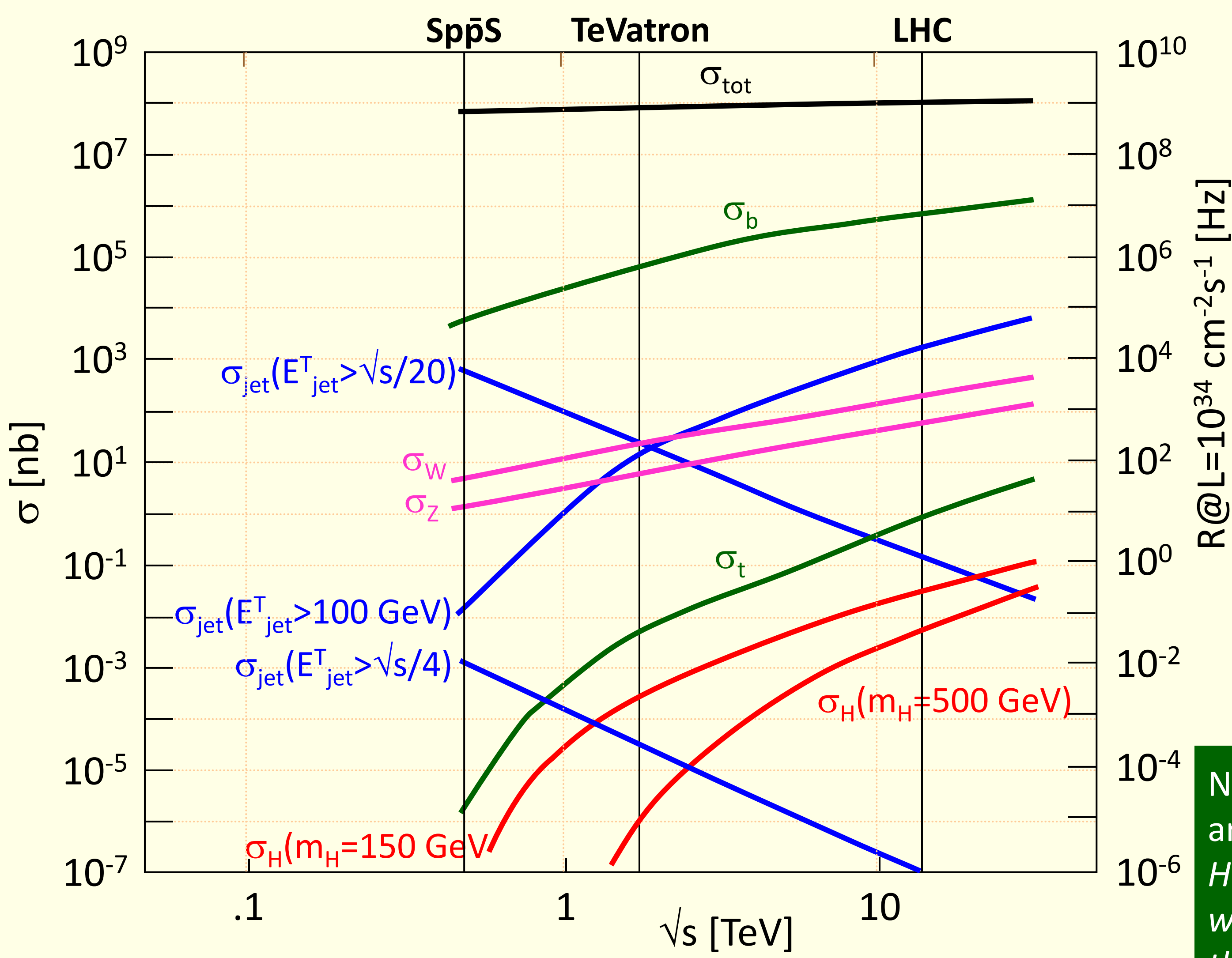
12 – LHC – Higgs discovery



1. LHC results [non-Higgs]
2. the MSM Higgs boson
3. Higgs properties
4. Higgs – pre-LHC
5. Higgs – LHC predictions
6. Higgs discovery
7. Higgs – current status
8. SM today



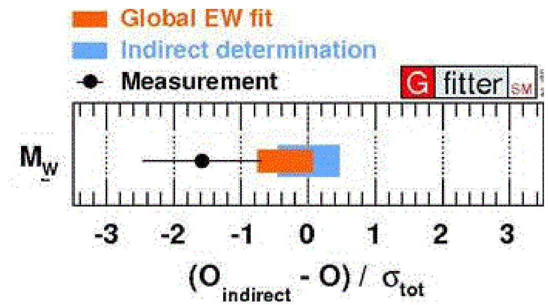
LHC results



- some examples only;
- only show the results;
- no unfair comparison ATLAS ↔ CMS;
- analyses in progress, no attempt to follow the frequent updates.

NB. Sp$\bar{p}$S and Tevatron are $\bar{p}$p, LHC is pp. *However, no difference within the accuracy of this plot.*

LHC results: Rosetta stone of the SM fit



M. Baak et al., arXiv: 1407.3792 [hep-ph] : "Comparison of the fit results with the indirect determination in units of the total uncertainty, defined as the uncertainty of the direct measurement and that of the indirect determination added in quadrature. The indirect determination of an observable corresponds to a fit without using the corresponding direct constraint from the measurement".

I.e. (see the example for M_W) :

- O_{exp} : exp. measurement;
- O_{fit} : result of the complete e.w. fit *;
- $O_{indirect}$: e.w. fit, with all meas, BUT the plotted one;
- σ_{exp} : error on O_{exp} (stat $\oplus$ sys $\oplus$ theo);
- σ_{tot} : $\sigma_{exp} \oplus \sigma_{indirect}$.

$= 0 \pm \sigma_{indirect}/\sigma_{tot}$

Then, for all quantities:

- blue strip : $(O_{indirect} - O_{indirect}) / \sigma_{tot} \pm \sigma_{indirect}/\sigma_{tot}$;
- orange strip : $(O_{indirect} - O_{fit}) / \sigma_{tot} \pm \sigma_{fit}/\sigma_{tot}$;
- points : $(O_{indirect} - O_{exp}) / \sigma_{tot} \pm \sigma_{exp}/\sigma_{tot}$.

roughly speaking:

- blue width : error of indirect fit;
- orange displacement : how much a point moves its fit;
- orange width : error of full fit;
- points : uncorrelated wrt blue;
- points + err : pull.

[a lot of info, main result:

SM = ok $\rightarrow$ all within errors]

"$\oplus$" = "in quadrature";

* the e.w. fit gets (using higher orders) m_H, m_z, couplings, fermion masses; then all e.w. quantities can be computed.

LHC results: SM fits

- in the past the main interest was:
  - ➢ possible deviations from SM;
  - ➢ predict unseen particles (top, Higgs) via rad. corrections;
- now the fit is over-constrained: look for bad pulls → physics bSM;
- perfect agreement (see figs.), textbook-like.

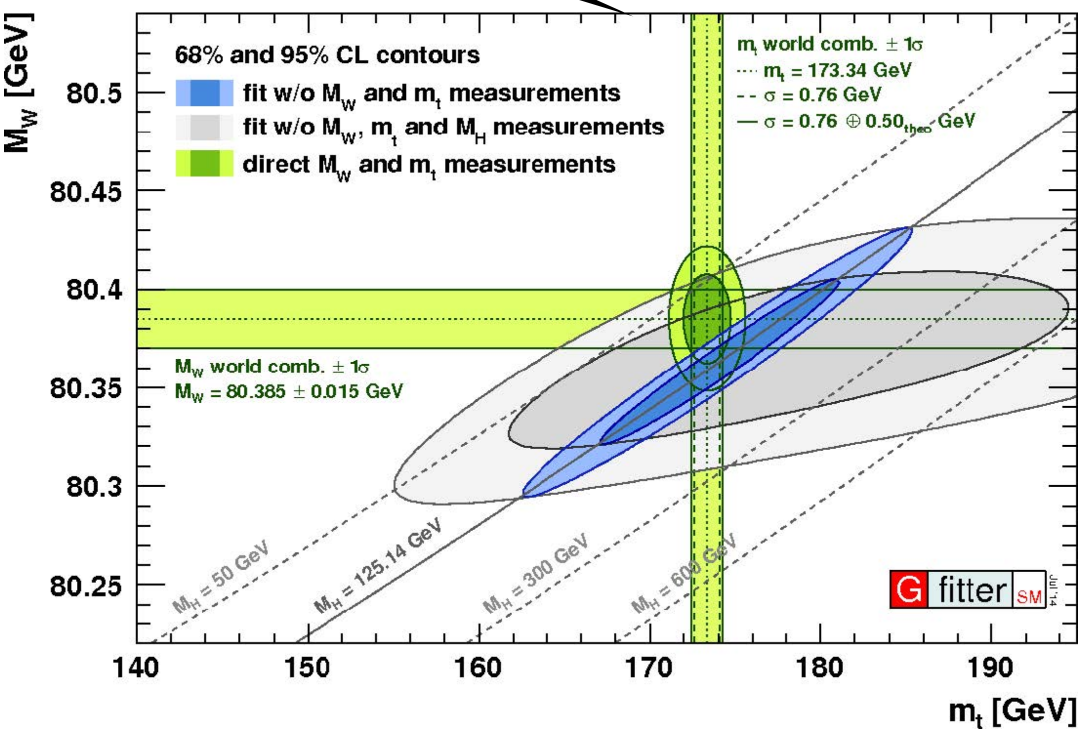
In simpler words :

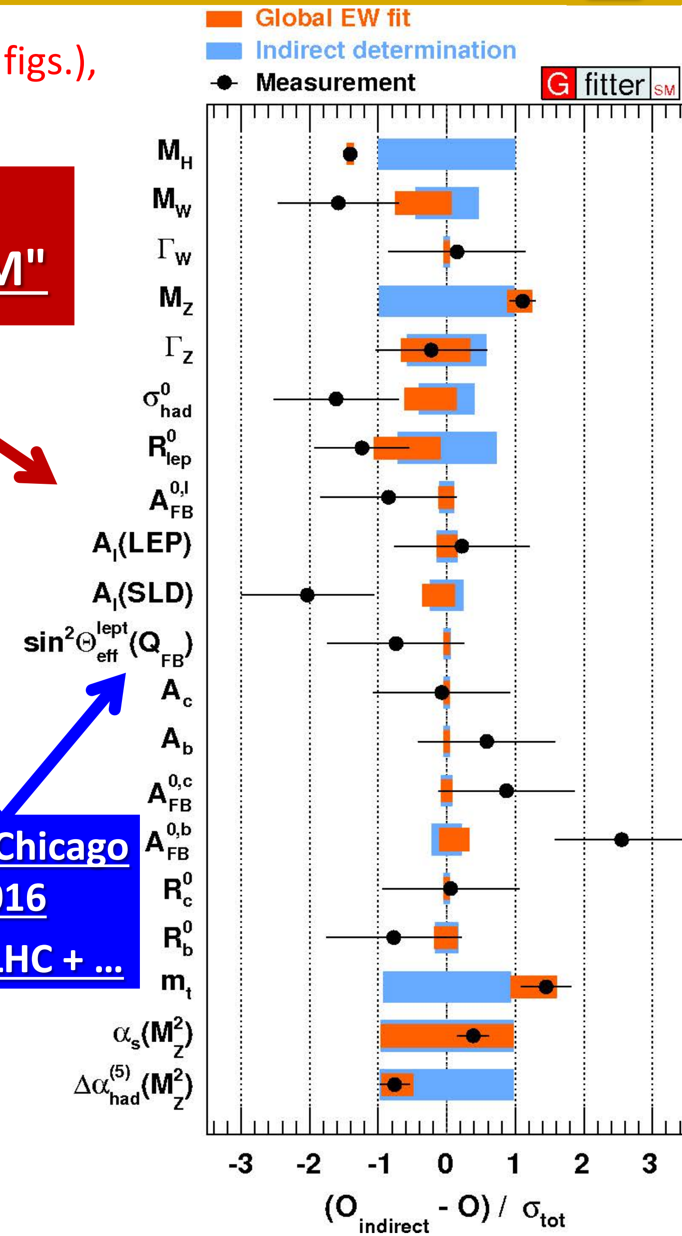
"triumph of the SM"

the glorious end of a 25-years story

ICHEP Chicago 2016

LEP + LHC + ...





LHC results: jet spectrum

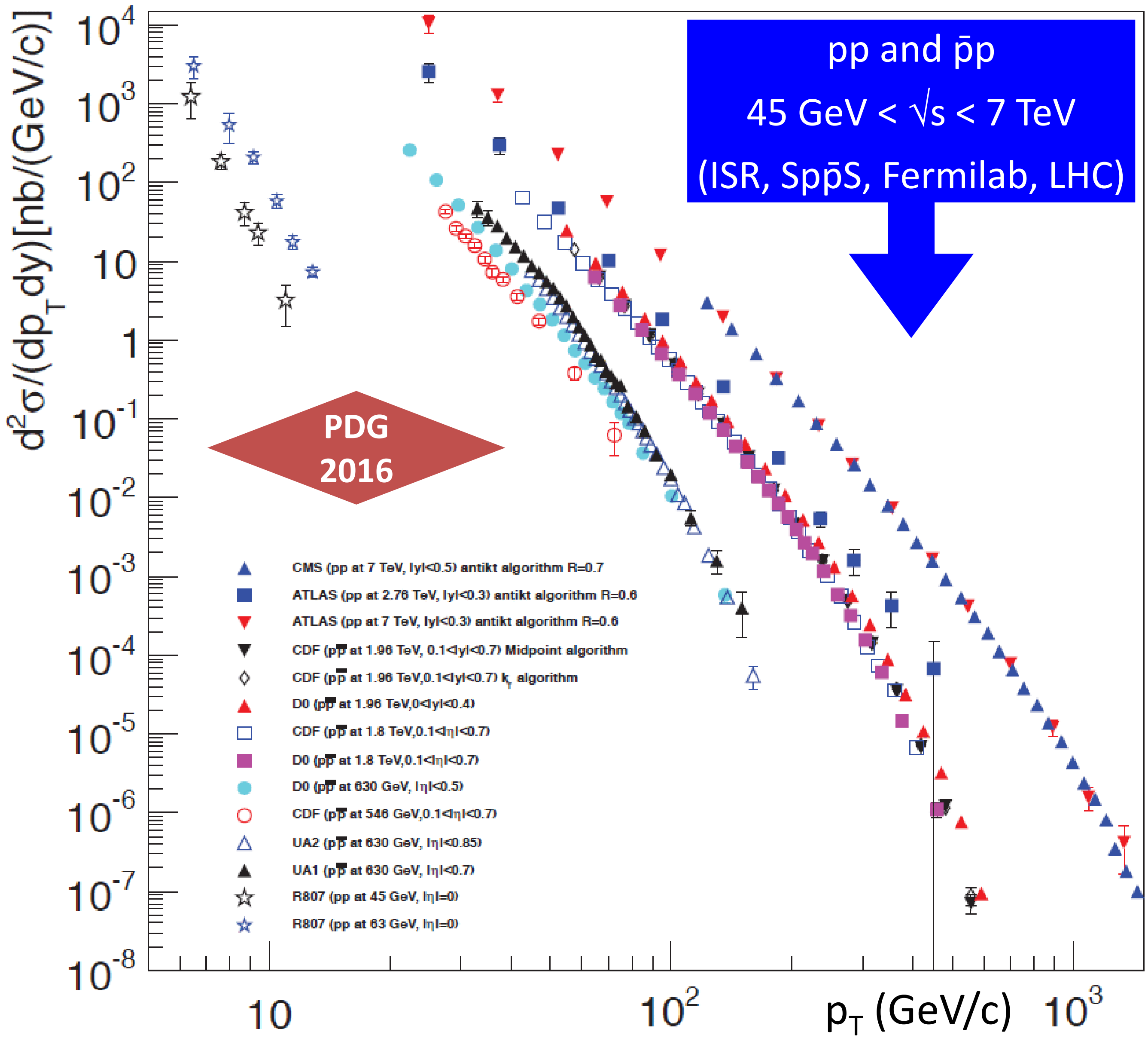
"Simple" explanation:

Inclusive differential jet cross sections, in the central rapidity region, plotted as a function of the jet transverse momentum.

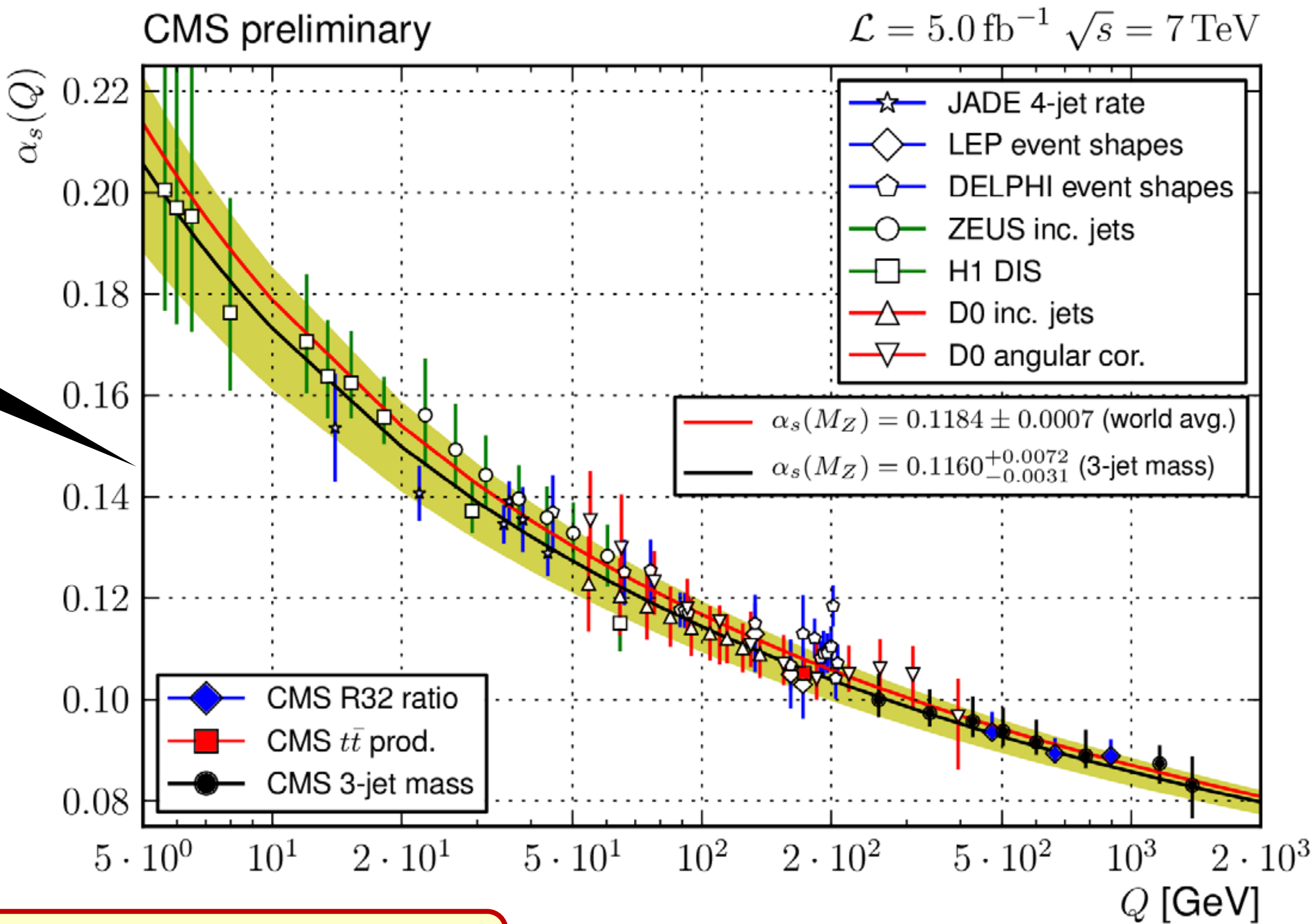
Results earlier than from the Tevatron Run 2 used transverse energy rather than transverse momentum and pseudo-rapidity η rather than rapidity y, but p_T and y are used for all results shown here for simplicity. The error bars plotted are in most cases the experimental stat. and syst. errors added in quadrature.

The CDF and D0 measurements use jet sizes of 0.7 (JetClu for CDF Run 1, and Midpoint and kT for CDF Run 2, a cone algorithm for D0 in Run 1 and the Midpoint algorithm in Run 2). The ATLAS results are plotted for the antikT algorithm for R=0.4, while the CMS results also use antikT, but with R=0.5. NLO QCD predictions in general provide a good description of the Tevatron and LHC data; the Tevatron jet data in fact are crucial components of global PDF fits, and the LHC data are starting to be used as well.

Comparisons with the older cross sections are more difficult due to the nature of the jet algorithms used.



LHC results: α_s running

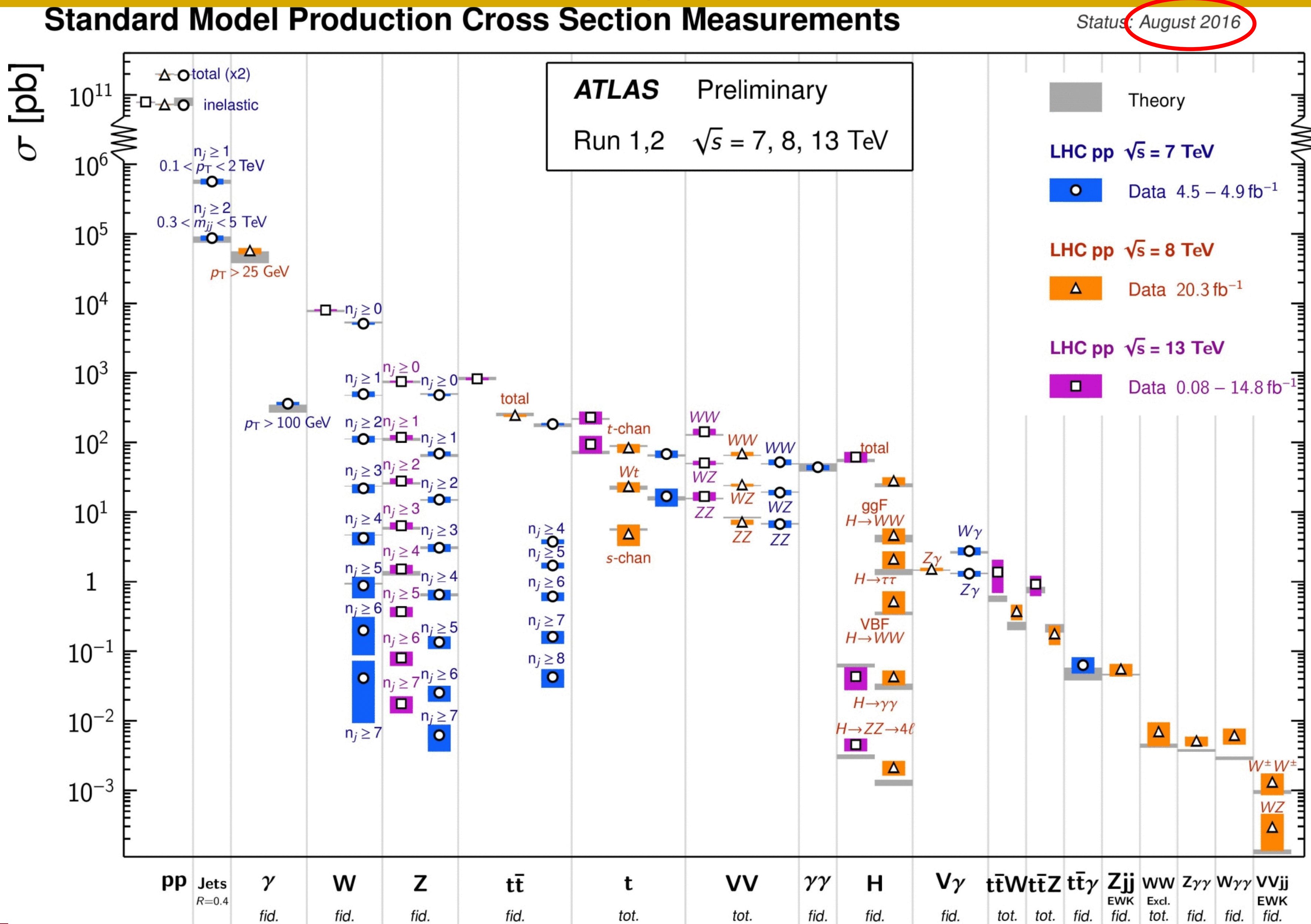


an update of the plot shown in § 6, with many more points.

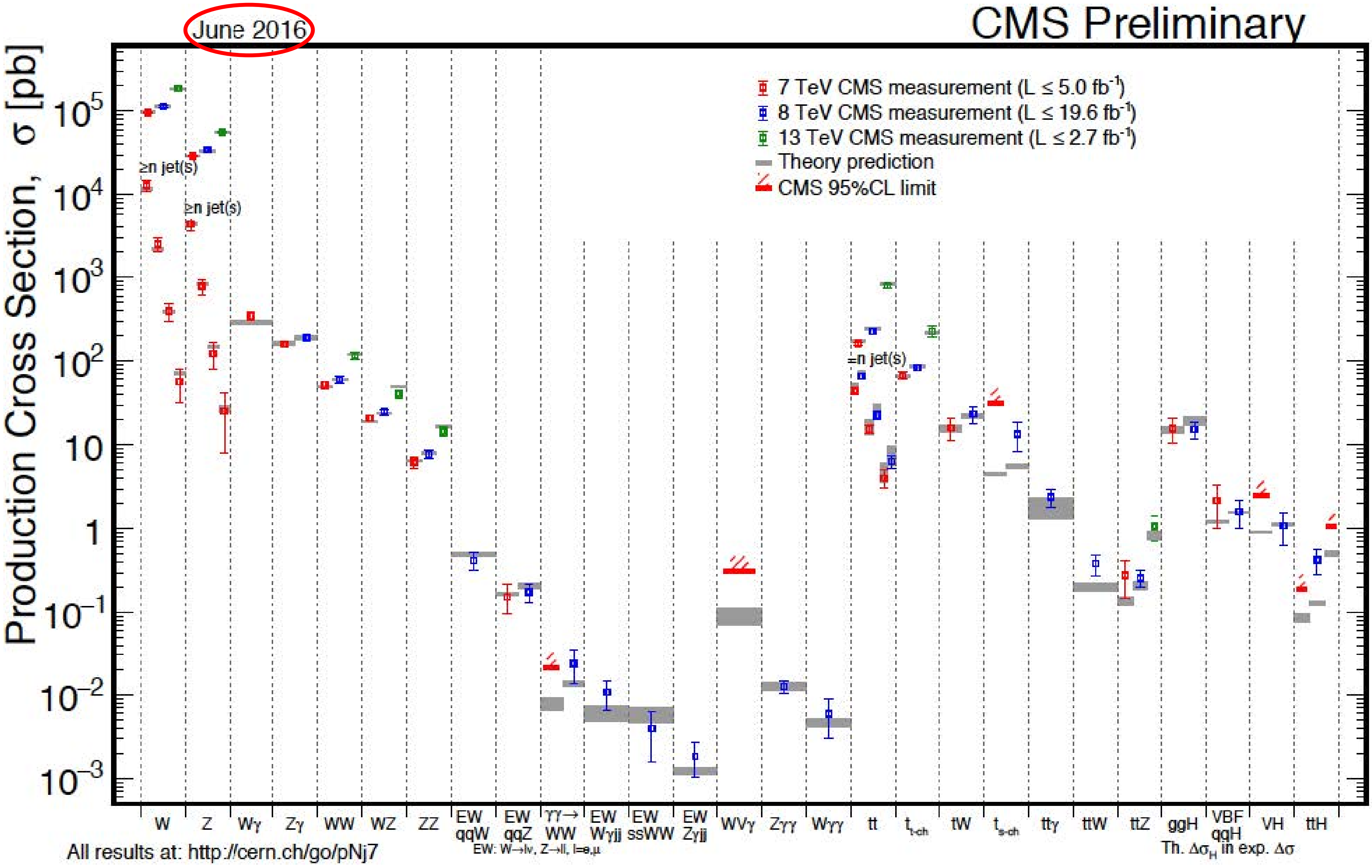
$$\alpha_s\left(Q^2\right) = \alpha_s\left(Q_0^2\right) \Big/ \left[1 + \alpha_s\left(Q_0^2\right) \frac{11N_c - 2N_f}{12\pi} \ln\left(\frac{Q^2}{Q_0^2}\right)\right];$$

$N_c = 3$; $N_f = 3 \to 4 \to 5 \to 6.$

LHC results: SM processes (ATLAS)

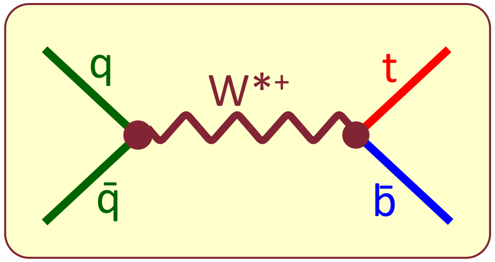


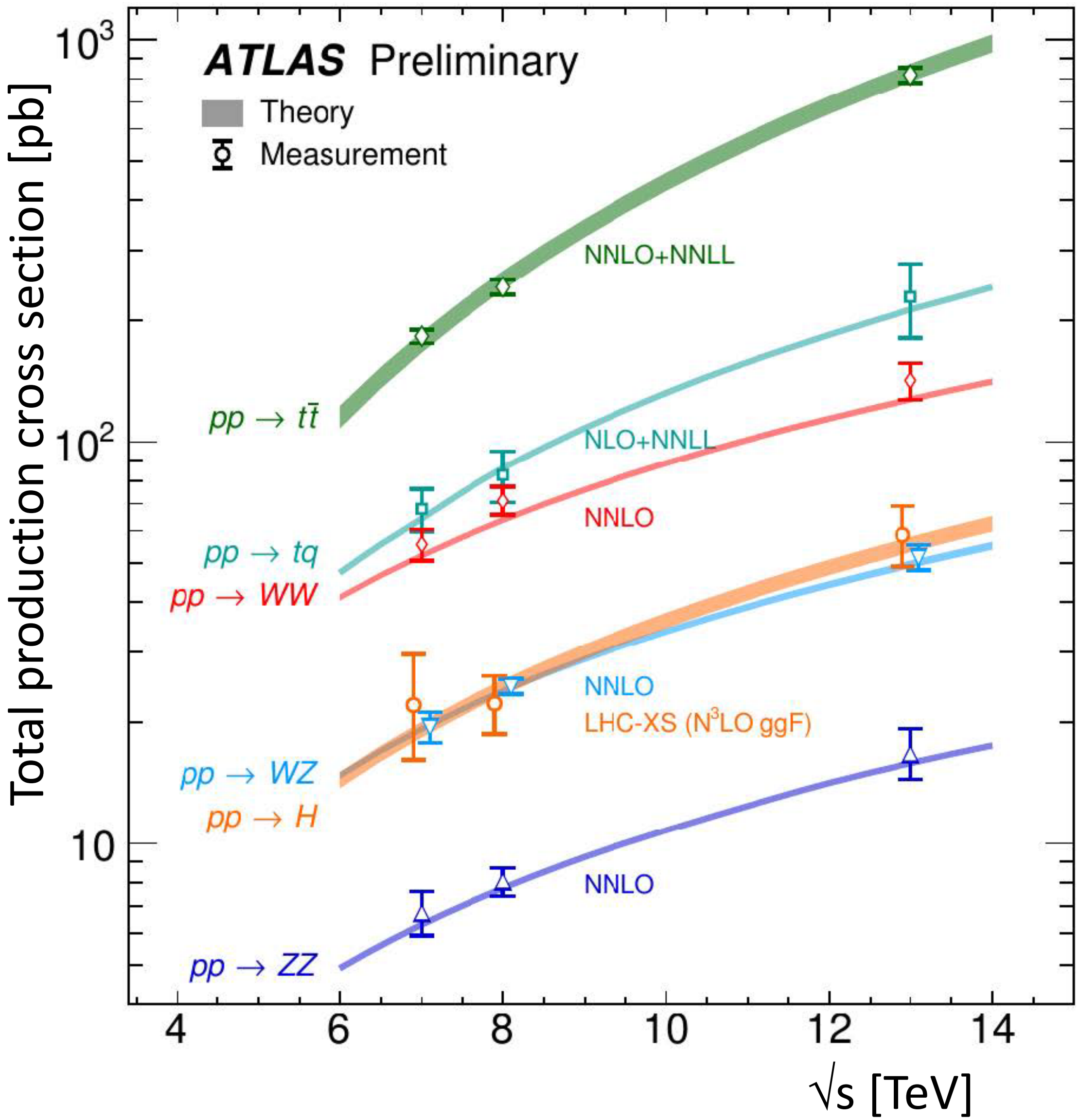
LHC results: SM processes (CMS)



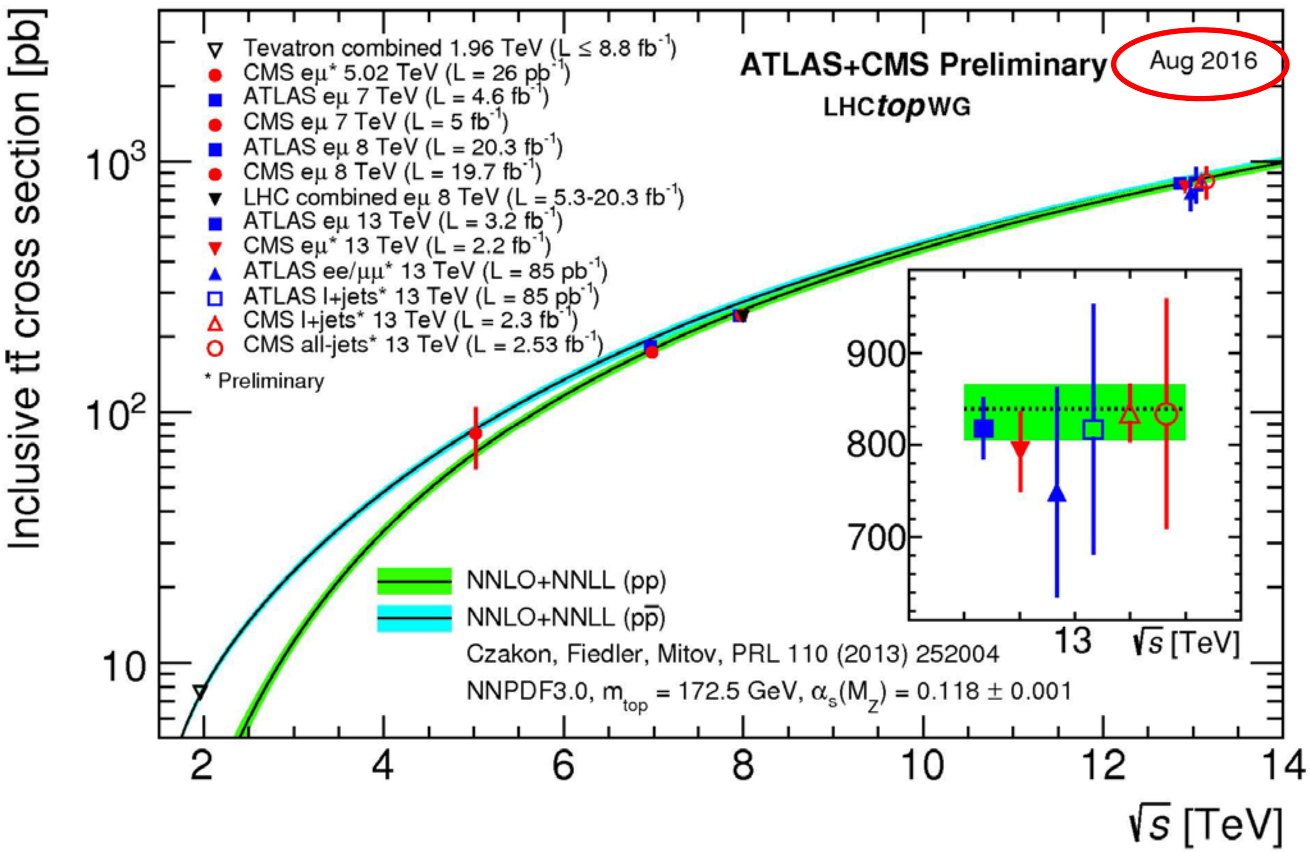
LHC results: small-σ processes

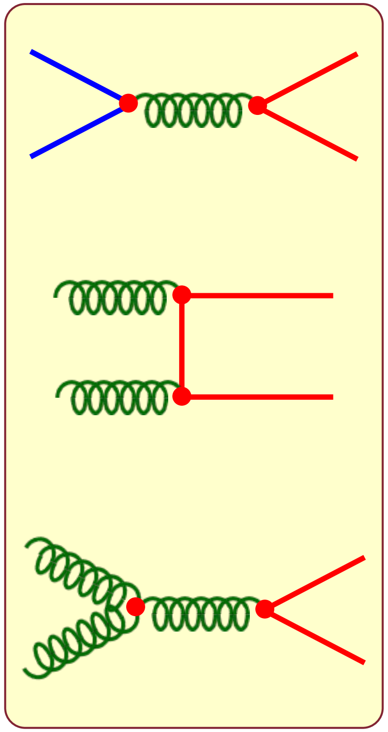
- the "heavy flavor/boson" sector:
  - ➢ $t\bar{t}$ (QCD);
  - ➢ single top (ew) [*example below*];
  - ➢ WW, WZ, ZZ (ew);
  - ➢ H (ew);
- shown vs √s;
- lessons:
  - ➢ LHC "sees" well at the pb level;
  - ➢ H is not very different from ZW / WW / ZZ channels, neither as mass, nor as σ, nor as √s dependence;
- as usual, SM (QCD+ew) works well.





LHC results: $\sigma_{t\bar{t}}$ vs $\sqrt{s}$



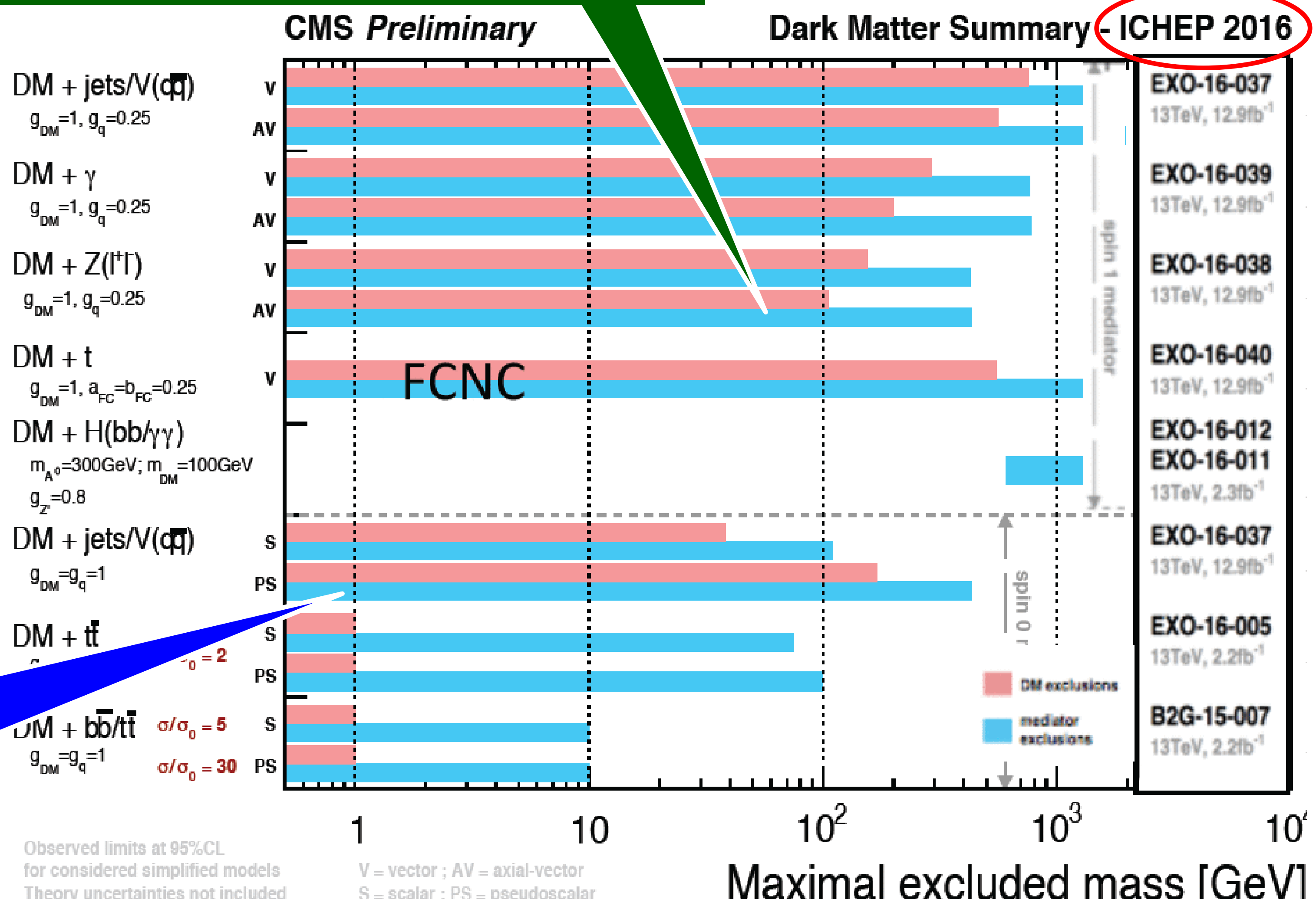


- technically a difficult analysis (secondary verteces + leptons + multijets + $\not{E}_T$);
- agreement ATLAS ↔ CMS and QCD ↔ data;
- [as seen in § 3] p̄p larger at small √s, but pp equivalent when √s increases, due to gluon dominance in PDF at small x;
- another perfect agreement, textbook-like.

LHC results: bSM (CMS DM)

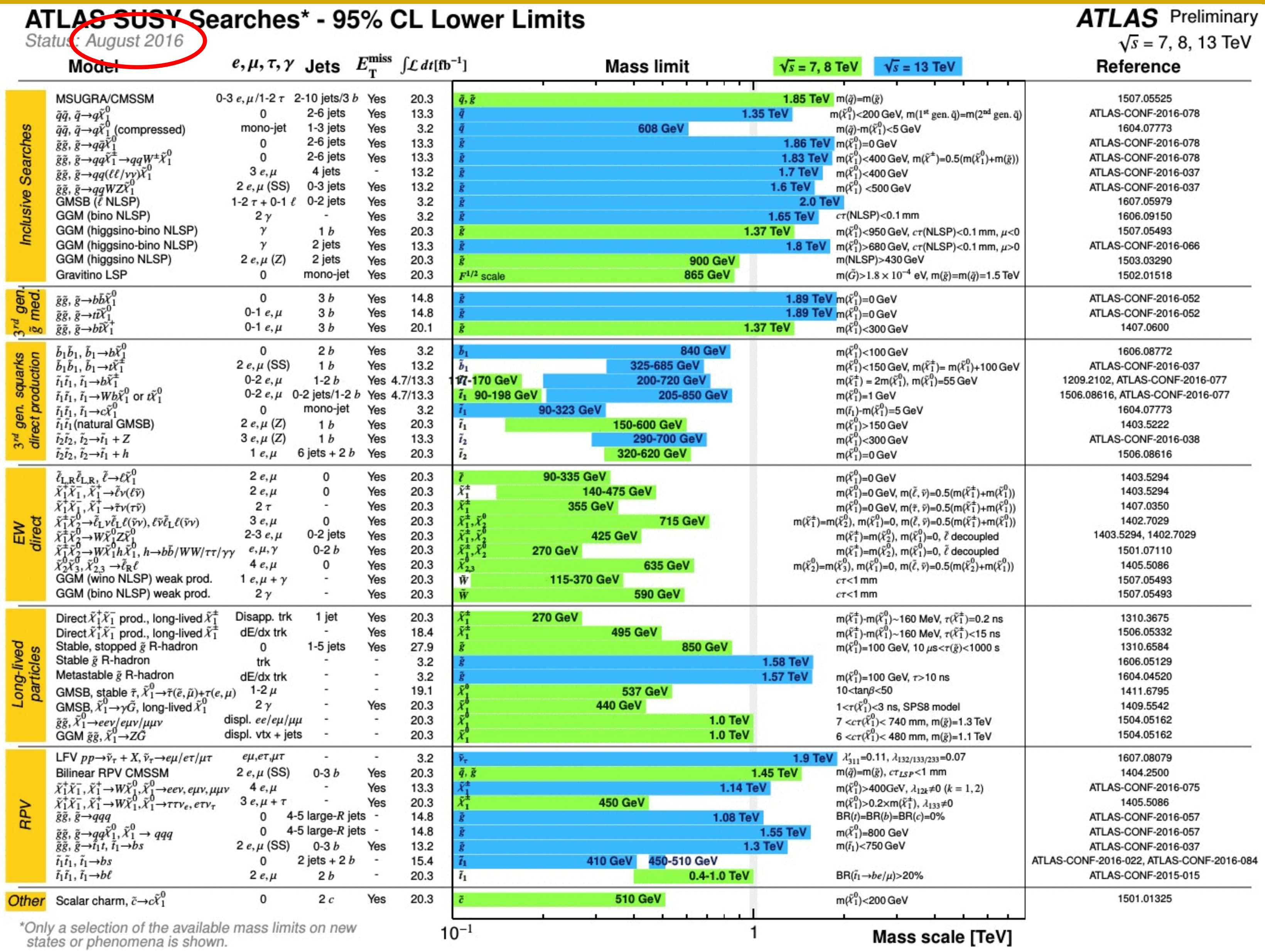
just as examples, "CMS dark matter" and "ATLAS supersymmetry" searches

[ATLAS-DM and CMS-SUSY are not too different]

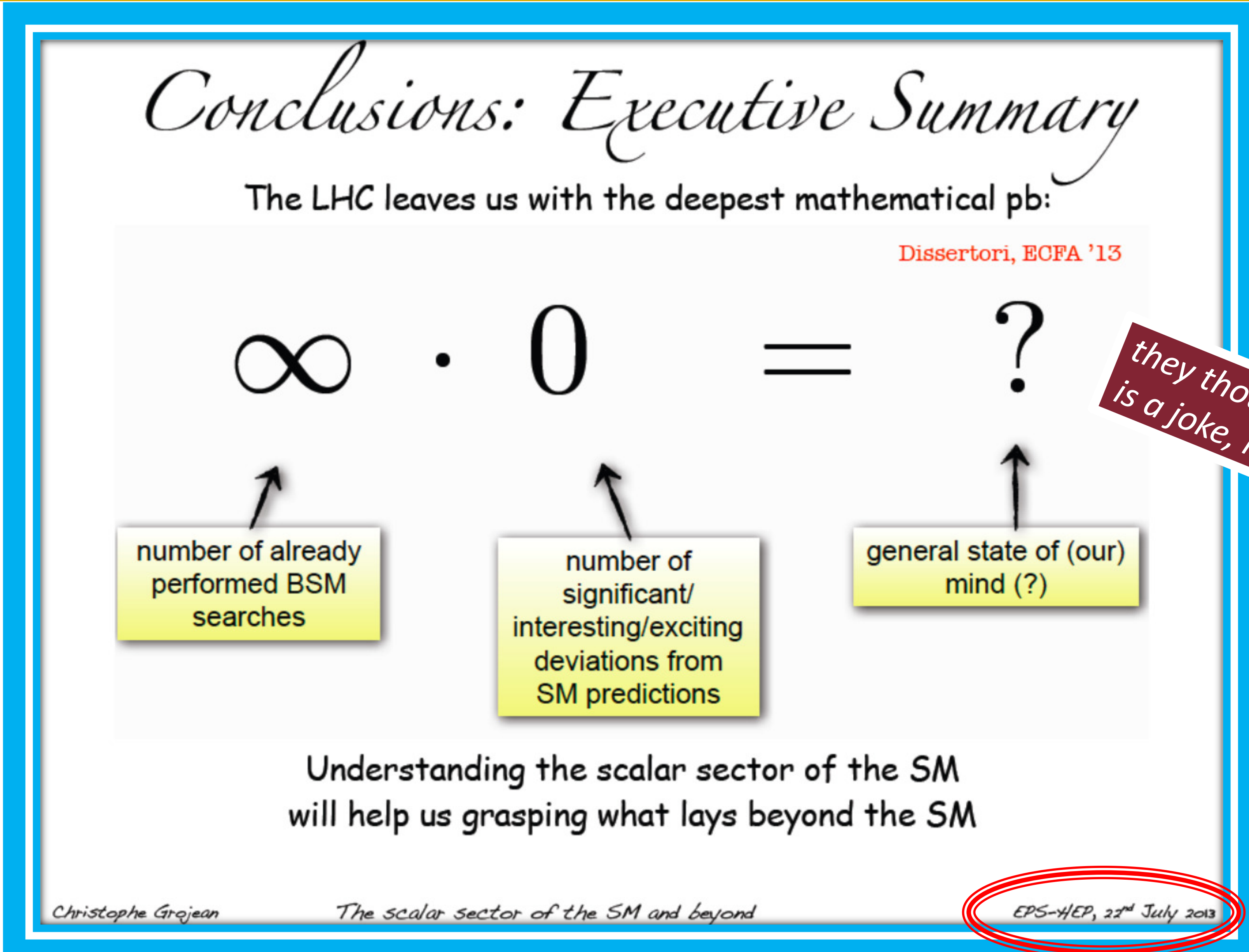


nothing found until now, but we know that something is hidden somewhere, so please continue …

LHC results: bSM (ATLAS SUSY)



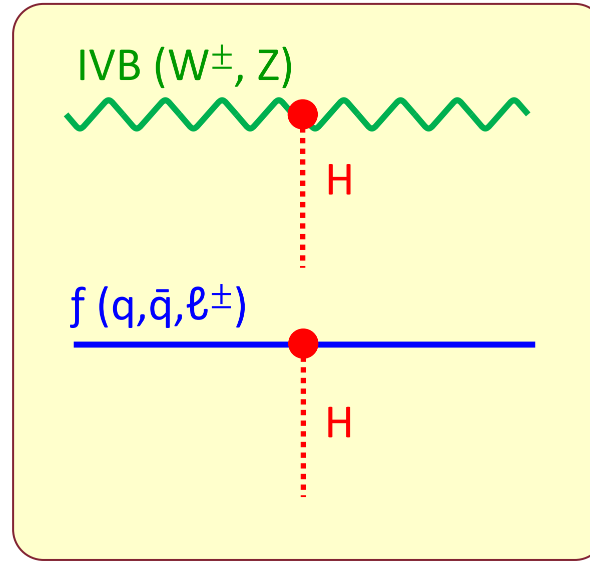
LHC results: bSM results

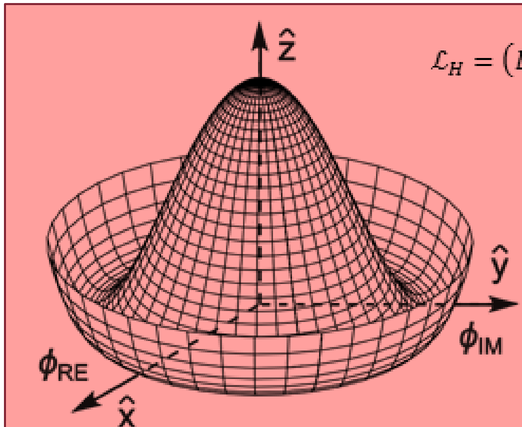


they thought it is a joke, really

the MSM Higgs boson

- [*the symbol* ~~m~~$_H$ *means that in the slide the value of the mass of the Higgs may vary:*
  - *for didactic reasons,*
  - *because the analysis is still in progress,*
  - *because of a possible larger H sector*]
- [at least] one H boson in SM;
- just one Higgs in "minimal standard model" MSM [*MSM assumed in the following*];
- [> 1 in theories bSM, e.g. in SUSY: h, H, A, $H^\pm$]
- charge : 0; spin : 0; $J^P = 0^+$ [other H may have different q.n.];
- in MSM directly coupled with all massive particles, i.e. all but γ, g, ν's (if massless);
- it behaves like a normal particle (with exotic couplings): it is produced, it decays, etc etc.
- [*more on this subject later in the chapter*]





$$\mathcal{L}_H = (D_\mu\phi)^* D_\mu\phi - V(\phi) - \tfrac{1}{4}F_{\mu\nu}F^{\mu\nu}$$

$$D_\mu\phi = \partial\phi + ieA_\mu\phi$$

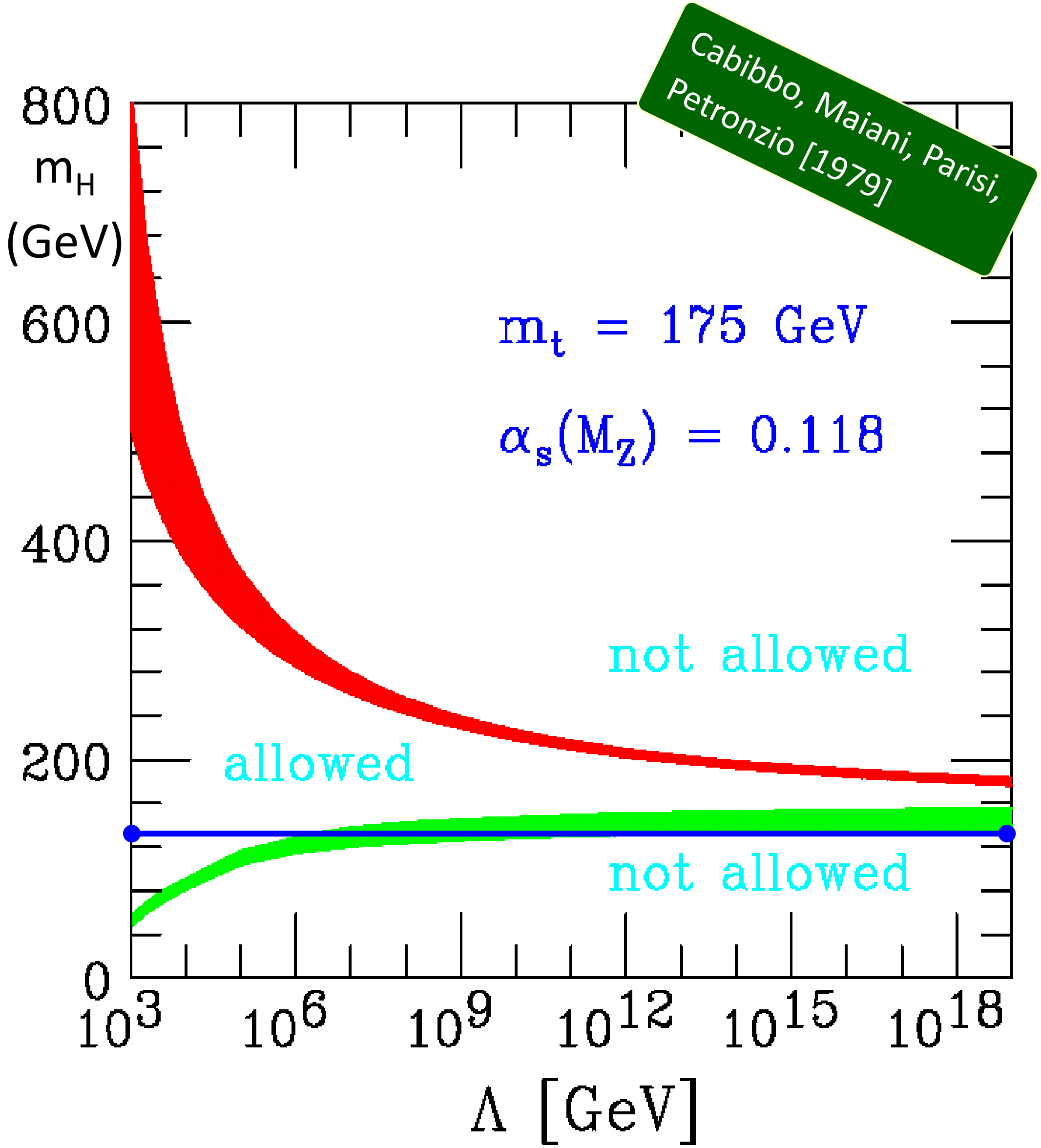
$$F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu$$

$$V(\phi) = \alpha\phi^*\phi + \beta(\phi^*\phi)^2$$

$$\alpha < 0, \qquad \beta > 0$$

the MSM Higgs boson: mass limits

- the Higgs mass is a free parameter of the SM [sometimes another correlated parameter chosen as "fundamental"];
- however, the non-violation of the unitarity puts a limit $m_H \leq 1$ TeV (approx.);
- the further demand that the SM be consistent up to a given scale Λ (triviality bound) puts another limit on m_H, function of Λ **(red line)**;
- the vacuum stability also limits m_H (stability bound, **green line)**;
- considering all together, $\Lambda = m_{Planck}$ $\rightarrow 130 < m_H < 180$ GeV;
- the blue line corresponds to m_H = 125 GeV [*quite puzzling*].

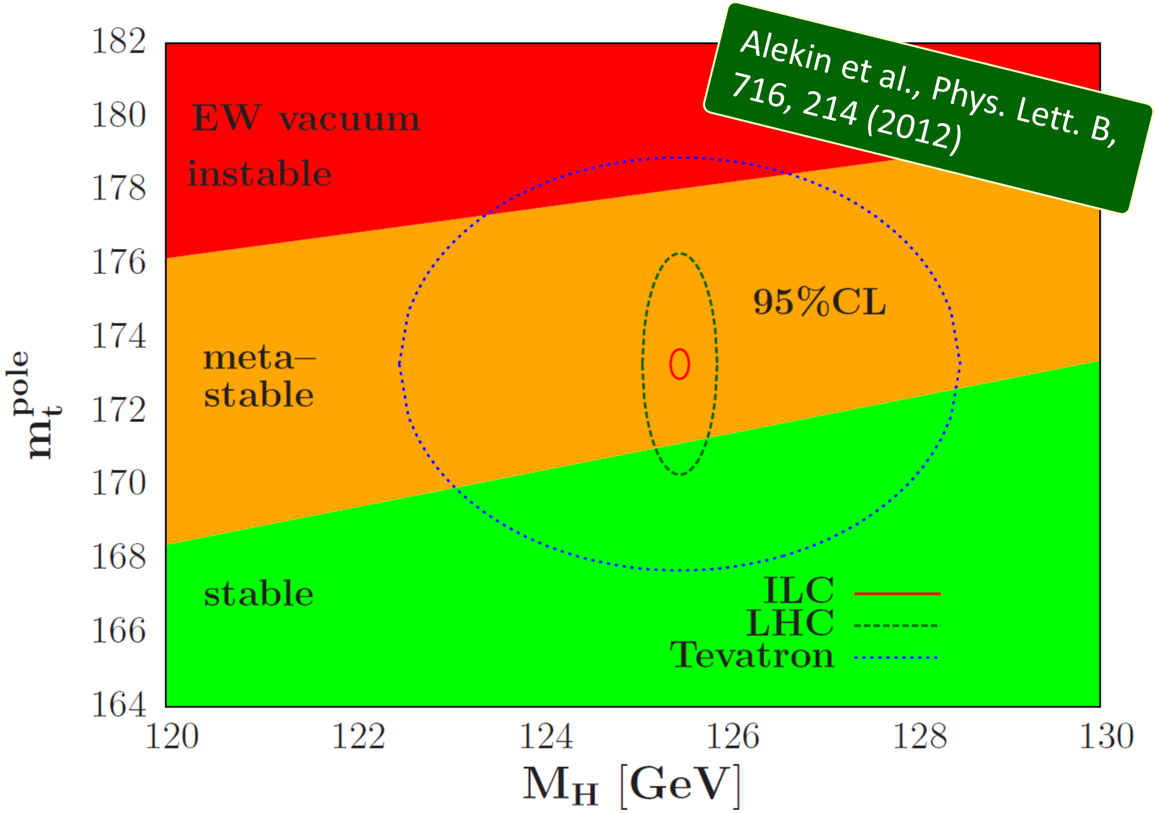


the MSM Higgs boson: vacuum stability

this page should appear after the discussion of the Higgs discovery, but here it is easier.

Assume the Higgs has been found at ~125 GeV:

- according to the previous argument, the universe is **stable**, **meta-stable**, or **in-stable** ?
- even with the MSM assumption (particle found at LHC = MSM Higgs), present error ("LHC") does not solve the question;
- only a future, more precise measurement ("ILC"), will solve it;
- notice in the plot:
  - ➢ the value of the top quark mass is VERY important;
  - ➢ the "ILC" value is arbitrarily put at the LHC/ TeVatron measurement: only look to the size of the error;



- however, if one takes the LHC measurement at face value, the universe is **metastable**, but its lifetime may exceed its age (~ 10^{10} years);
- so, do not panic, but **improve the measurement** !!!

the MSM Higgs boson: potential V_H

Define the SM parameters (PDG 2016 §10):

$$V_H(\phi) = -\mu^2 \phi^\dagger \phi + \lambda^2 (\phi^\dagger \phi)^2 / 2;$$

$$V_H = 0 \rightarrow \phi(V_H = 0) \equiv \upsilon = \frac{\sqrt{2}\mu}{\lambda} = \sqrt{\frac{1}{\sqrt{2}G_F}} \approx 246 \text{ GeV};$$

ⓘ other definitions :
$\lambda^2/2 \rightarrow \lambda, \lambda^2, \lambda/2, \lambda/4, \ldots$
$-\mu^2 \rightarrow \mu^2, \ldots$

$$m_H = \lambda\upsilon; \quad m_W = \frac{1}{2} g\upsilon;$$

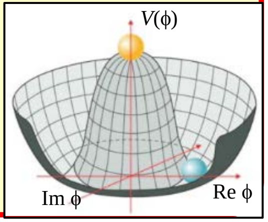
$$m_Z = \frac{1}{2}\sqrt{g^2 + g'^2}\,\upsilon = \frac{m_W}{\cos\theta_W}; \quad m_\gamma = 0;$$

$$g = \frac{2m_W}{\upsilon} \approx 0.65; \quad g' = \frac{2\sqrt{m_Z^2 - m_W^2}}{\upsilon} \approx 0.35;$$

$$\mathcal{L}^{\text{coupling}}_{\text{Higgs}} = -g_f \bar{\psi}_f \psi_f H + \delta_V g_V V_\mu V^\mu H + [\ldots];$$

$$[V = W/Z; \quad \delta_W = 1; \quad \delta_Z = ½]$$

$$g_f = \frac{m_f}{\upsilon}; \qquad g_V = \frac{2m_V^2}{\upsilon};$$



$$m_H^{exp} \approx 125 \text{ GeV} \rightarrow$$

$$\lambda^{exp} = \frac{m_H}{\upsilon} \approx 0.51;$$

$$\mu^{exp} = \frac{m_H}{\sqrt{2}} \approx 88 \text{ GeV}.$$

imho (λ, μ) neither theor. clear, nor exp clean.

To test the SM couplings, redefine g_f and g_V with "modifiers" κ's:

$$g_f = \frac{m_f}{\upsilon} \rightarrow \kappa_f \frac{m_f}{\upsilon};$$

$$g_V = \frac{2m_V^2}{\upsilon} \rightarrow \kappa_V \frac{2m_V^2}{\upsilon};$$

and adjust κ_f and κ_W to the data;

$$\kappa_j^2 = \frac{\sigma_j}{\sigma_j^{SM}}; \quad \text{or} \quad \kappa_j^2 = \frac{\Gamma_j}{\Gamma_j^{SM}};$$

$$SM \rightarrow \kappa_f = \kappa_V = 1.$$

the MSM Higgs boson: function V(ϕ)

Study the function V=V(ϕ):

$$V_H(\phi) = -\mu^2\phi^\dagger\phi + \frac{\lambda^2}{2}(\phi^\dagger\phi)^2 =$$

$$= m_H^2\left(-\frac{1}{2}|\phi|^2 + \frac{1}{\sqrt{2}}G_F|\phi|^4\right);$$

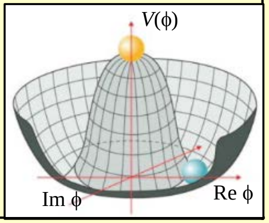
$$\left[\mu = \frac{m_H}{\sqrt{2}}; \quad \lambda = m_H\sqrt{\sqrt{2}G_F}\right]$$

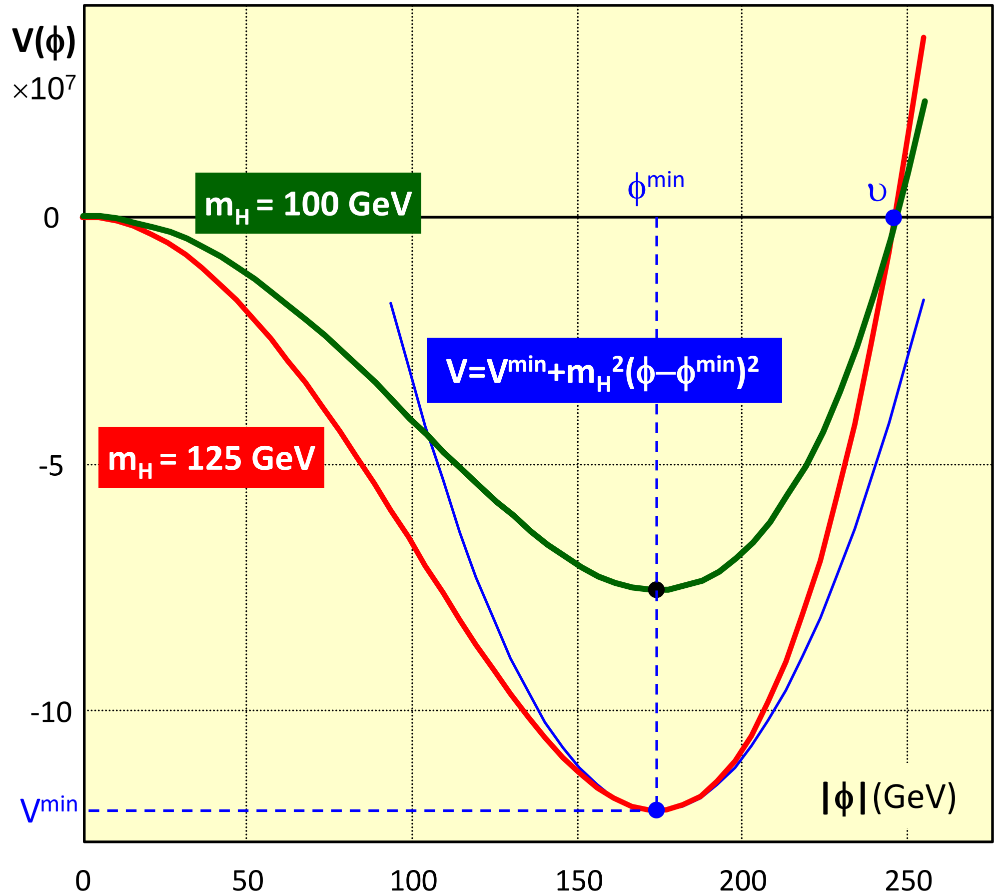
$$\upsilon = \sqrt{\frac{1}{\sqrt{2}G_F}} \approx 246 \text{ GeV};$$

$$\left.\frac{\partial V_H}{\partial\phi}\right|_{\phi=\phi^{min}} = 0 \rightarrow \phi^{min} = \sqrt{\frac{1}{2\sqrt{2}G_F}} \approx 174 \text{ GeV};$$

$$V_H^{min} = V_H\left(\phi^{min}\right) = \frac{-m_H^2}{8\sqrt{2}G_F};$$

$$\left.\frac{\partial^2 V_H}{\partial\phi^2}\right|_{\phi=\phi^{min}} = 2m_H^2.$$





- the horizontal shape of V_{Higgs} (e.g. ϕ^{min}, υ) does NOT depend on m_H;
- the vertical shape is $\propto m_H^2$ (show m_H = 100 / 125 GeV);
- the parabola at ϕ_{min} represents a particle of mass m_H = the Higgs boson !

the MSM Higgs boson: all SM couplings

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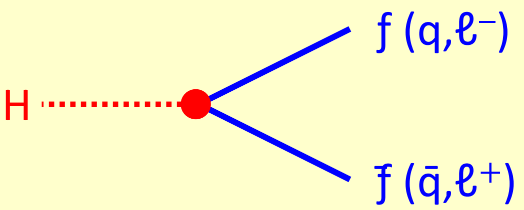
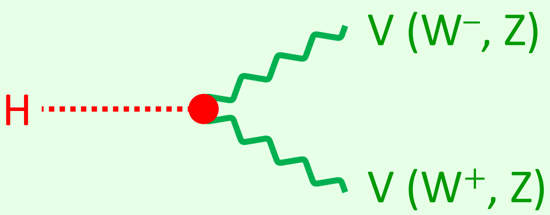
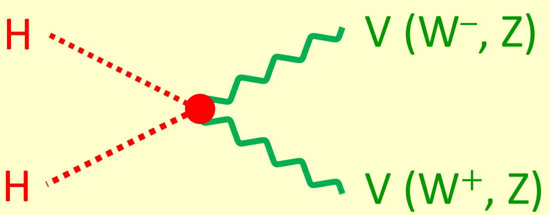
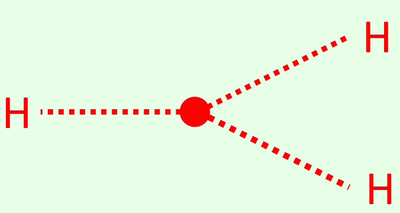
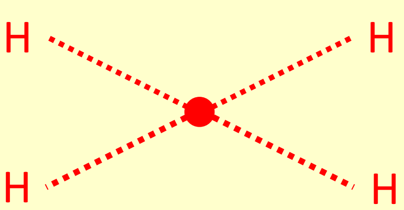
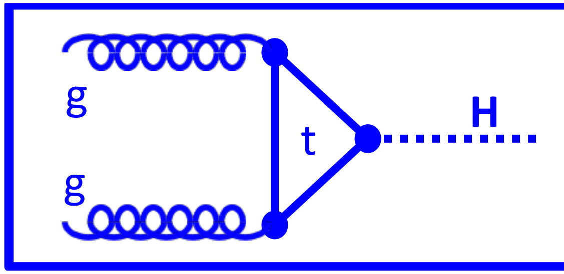
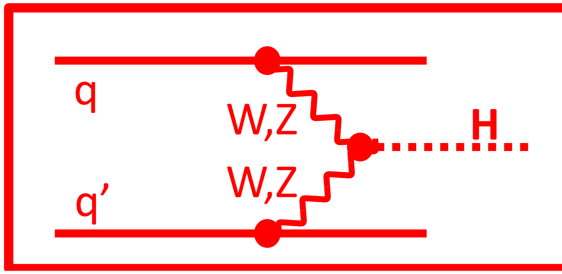
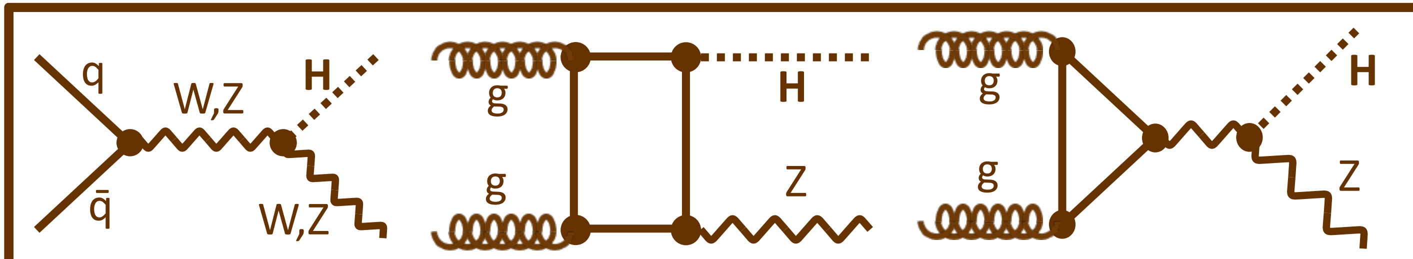
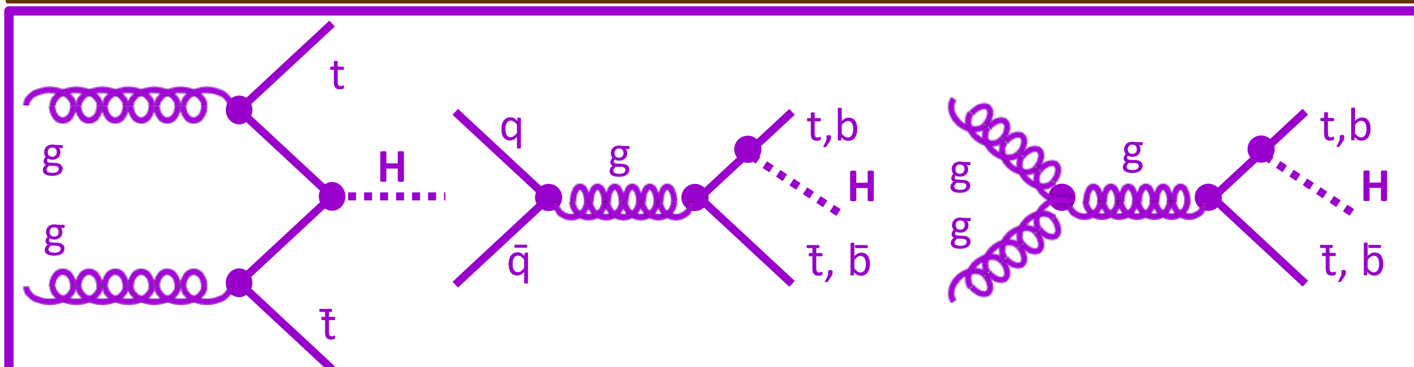
<tr><td>
</td><td>Hff</td><td>g_{Hff}</td><td>$= m_f / \upsilon$</td><td>$= (\sqrt{2}\, G_F)^{½}\, m_f$</td><td>$\times (-i)$</td></tr>
<tr><td>
</td><td>HVV</td><td>g_{HVV}</td><td>$= 2m_V^2/\upsilon$</td><td>$= 2(\sqrt{2}\, G_F)^{½}\, m_V^2$</td><td>$\times (ig_{\mu\nu})$</td></tr>
<tr><td>
</td><td>HHVV</td><td>g_{HHVV}</td><td>$= 2m_V^2/ \upsilon^2$</td><td>$= 2\sqrt{2}\, G_F\, m_V^2$</td><td>$\times (ig_{\mu\nu})$</td></tr>
<tr><td>
</td><td>HHH</td><td>g_{HHH}</td><td>$= 3m_H^2 / \upsilon$</td><td>$= 3(\sqrt{2}\, G_F)^{½}\, m_H^2$</td><td>$\times (-i)$</td></tr>
<tr><td>
</td><td>HHHH</td><td>g_{HHHH}</td><td>$= 3m_H^2 / \upsilon^2$</td><td>$= 3\sqrt{2}\, G_F\, m_H^2$</td><td>$\times (-i)$</td></tr>
</table>

A. Djouadi, Phys. Rep., 457 (2008) 1.

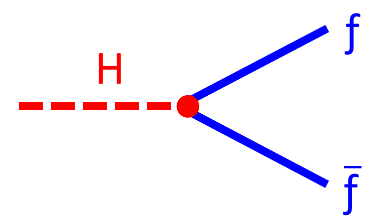
Higgs properties: production dictionary

- Higgs production processes in hadron colliders, with their usual names;
- only main diagrams, many others less important (e.g. single top);
- emphasis on detectability → some particles in final state may help;
- in the following, W and W* both appear as W [same for Z/Z*].

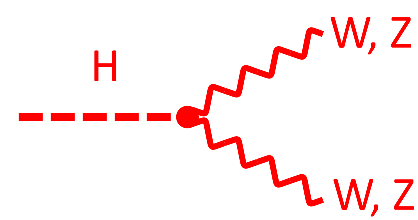
	**ggF**	gluon gluon fusion
	**VBF**	vector boson fusion
	**VH** [= WH + ZH]	VH production
	**tt̄H**	tt̄H process

Higgs properties: decay dictionary

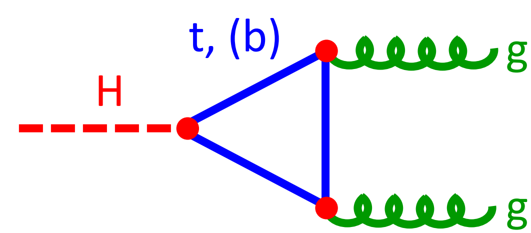
- Higgs decay modes;
- in the diagrams, "f" represents any fermion; however the coupling (and therefore the BR) is strongly dependent on its mass;
- here W and W* both appear as W [same for Z/Z*].



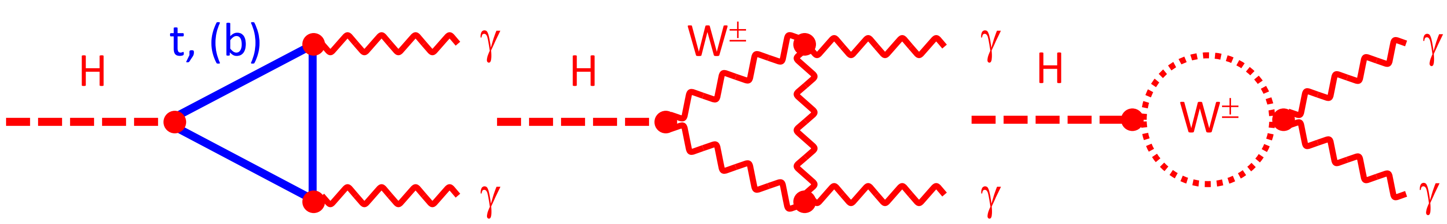
$H \to f\bar{f}$



$H \to WW / ZZ$



$H \to gg$



$H \to \gamma\gamma$

Higgs properties: decays f, W, Z

- at "tree level" the partial width for the Higgs decay into a pair of real fermions (f=quarks, leptons) or real gauge bosons (V = W, Z) is given by :

$$\Gamma(H\to f\bar{f}) = \frac{c_f}{4\pi\sqrt{2}} G_F m_H m_f^2 \beta_f^3;$$

$$\beta_f = \sqrt{1-\frac{4m_f^2}{m_H^2}}\ ;\quad c_f = \begin{cases} 1\ [\text{leptons}] \\ 3\ [\text{quarks}] \end{cases};$$

$$\Gamma(H\to VV) = \delta_V \frac{G_F m_H^3}{64\pi\sqrt{2}} \beta_V (4 - 4x_V + 3x_V^2);$$

$$\beta_V = \sqrt{1-\frac{4m_V^2}{m_H^2}}\ ;\ x_V = \frac{4m_V^2}{m_H^2};\ \delta_V = \begin{cases} 2\ [W^\pm] \\ 1\ [Z] \end{cases};$$

- therefore, for m_H small (m_H < 110 GeV), $H\to b\bar{b}$ dominates (see § LEP);
- if $m_H > 2\ m_{W,Z}$, the largest BR would be for $H \to W^+W^-$, $H \to ZZ$;
- in the region m_H = 110 ÷ 180 GeV, the decays into W*W and Z*Z are important (also because of their detectability); but the formula with β_V assumes real W/Z; when virtual W*/Z* are required, the computation is different; for m_H=125 GeV, results are reported below;
- when m_H increases, new decay channels open; moreover, the partial widths also increase; therefore Γ_{tot} is a strong function of m_H :

$$\Gamma_{tot}(m_H) = \sum_j \Gamma(H\to f_j\bar{f}_j) + \sum_k \Gamma(H\to V_k^{(*)}V_k);$$

$$BR(H\to X) = \Gamma(H\to X)/\Gamma_{tot} = BR(m_H);$$

both Γ_{tot} and BR function of m_H.

Higgs properties: decays gg, γγ

- in addition, also few "higher order" decays (γγ, Zγ, gg);
- the decays $H\to gg$ and $H\to\gamma\gamma$ (much less $H\to Z\gamma$) are important for the discovery :
  - the decay $H\to gg$ is large, although not easy to identify (→ 2 jets, large QCD bckgd);
  - the decay $H\to\gamma\gamma$ is rare, but has high efficiency and little bckgd (see later);
- complete formulas in references :

$$\Gamma(H\to gg)=\frac{1}{36\pi^3\sqrt{2}}\alpha_s^2 G_F m_H^3 \left|I_{gg}\right|^2;$$

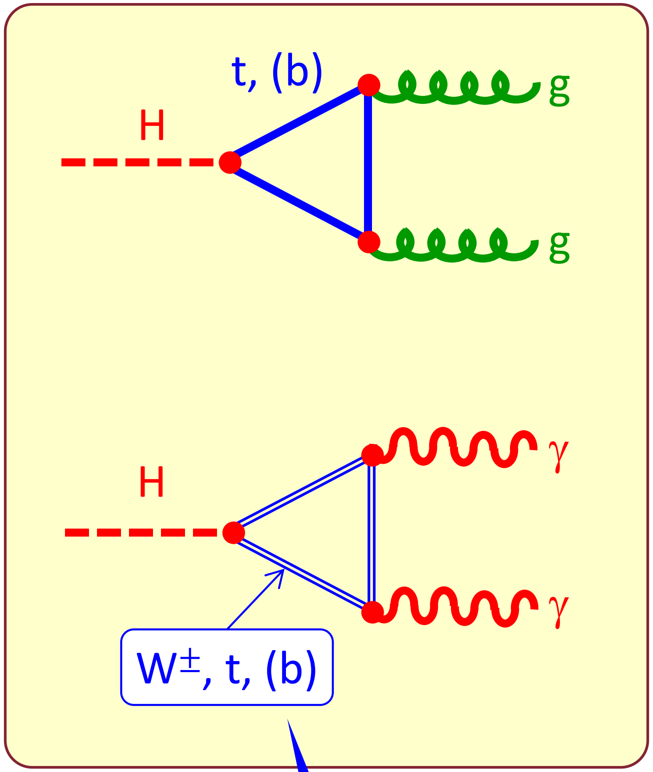
$$I_{gg}=\sum_q I_q(m_q^2/m_H^2)=f(m_H)\sim 0.1\div 1;$$

(sum over quarks, important for q=t);

$$\Gamma(H\to\gamma\gamma)=\frac{1}{8\pi^3\sqrt{2}}\alpha_{em}^2 G_F m_H^3 \left|I_{\gamma\gamma}\right|^2;$$

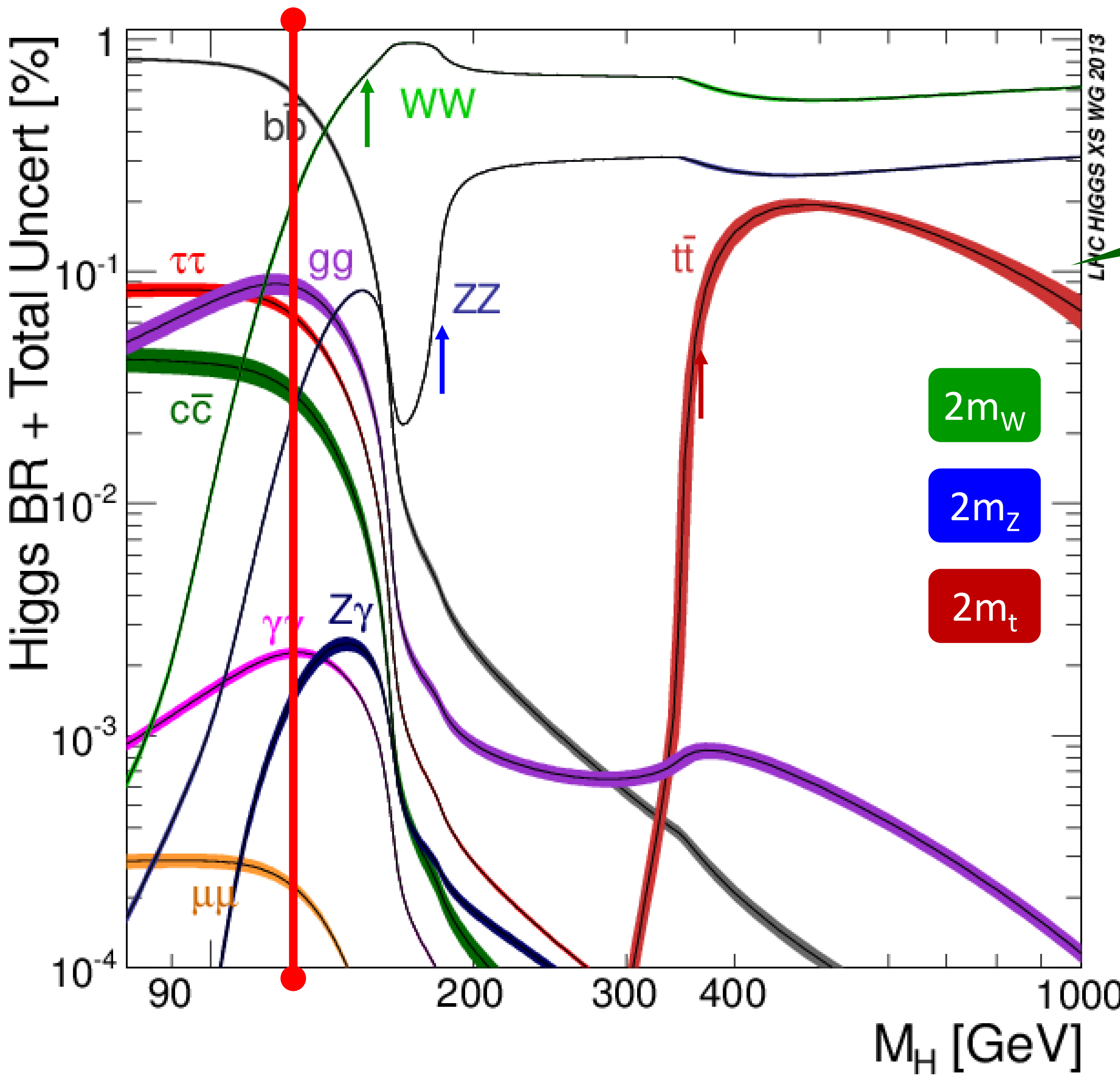
$$I_{\gamma\gamma}=\sum_f c_f q_f^2 I_f(m_f^2/m_H^2)+I_W=f(m_H)\sim 1\div 10;$$

[sum over charged fermions f, c_f=1($\ell^\pm$) or 3(q)].



for γγ, interference W ↔ t large and negative (a nice test of the SM).

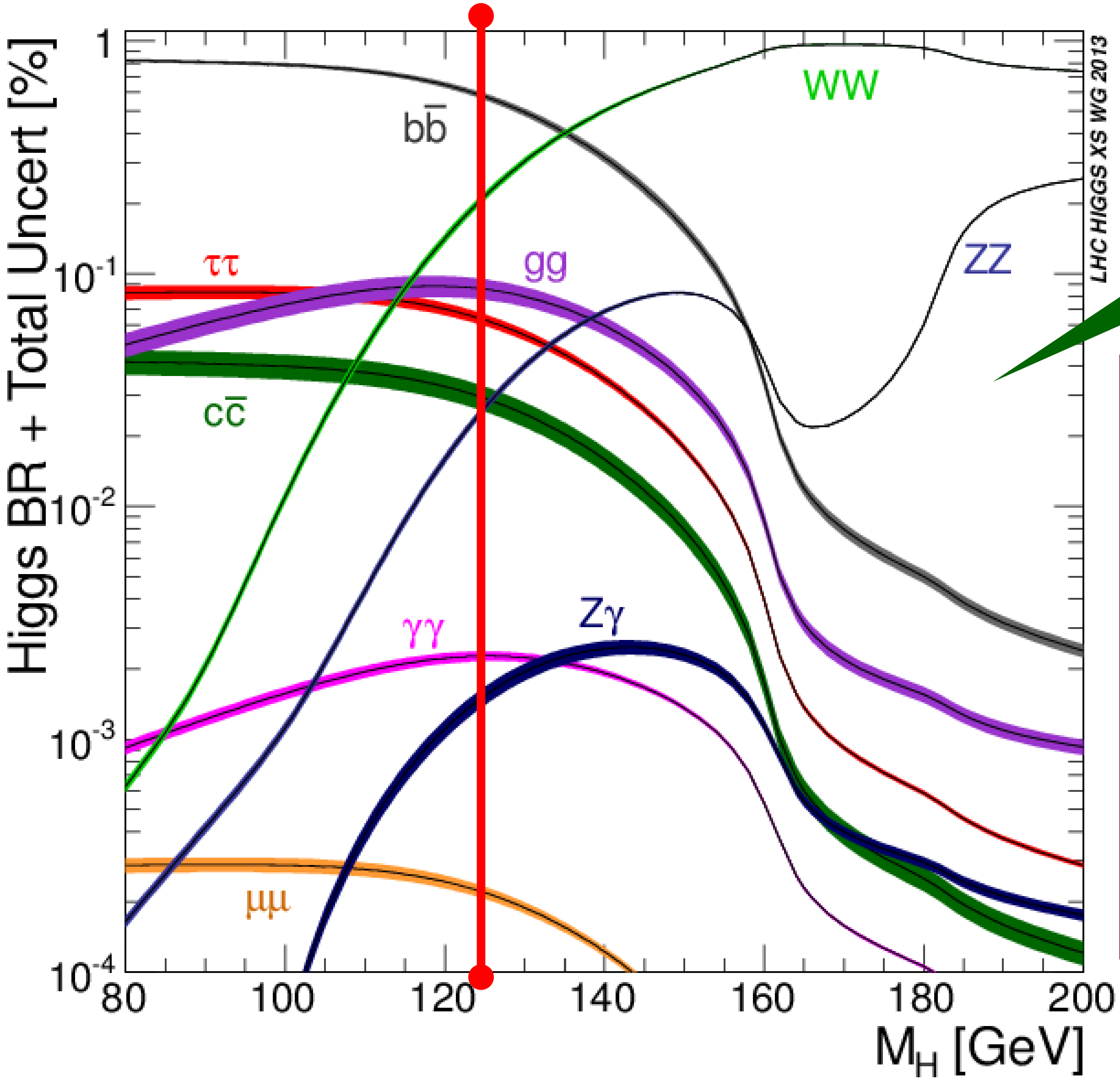
Higgs properties: decay BR vs H mass



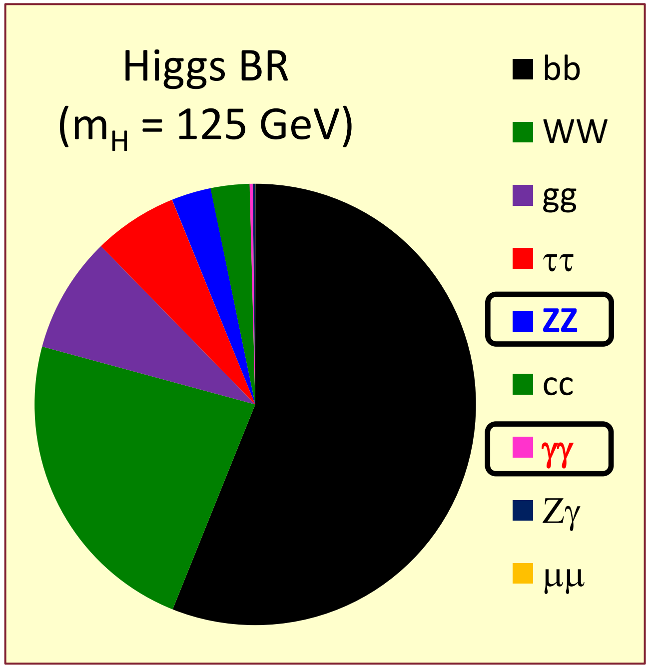
Unlike LEP2, in the LHC energy range, the Higgs boson decay mode is highly variable
→ challenge for the experiments.

m_H = 125 GeV [*CERN-2013-004*]		
decay mode	Γ (MeV)	BR (%)
$b\bar{b}$	2.35	57.5
$W^{\pm}W^{\mp *}$	0.886	21.7
gg	0.349	8.6
$\tau^+\tau^-$	0.257	6.3
ZZ*	**0.110**	**2.7**
$c\bar{c}$	0.118	2.9
γγ	**9.3E-03**	**0.23**
Zγ	6.3E-03	0.15
$\mu^+\mu^-$	8.9E-04	0.022
sum	4.08	100

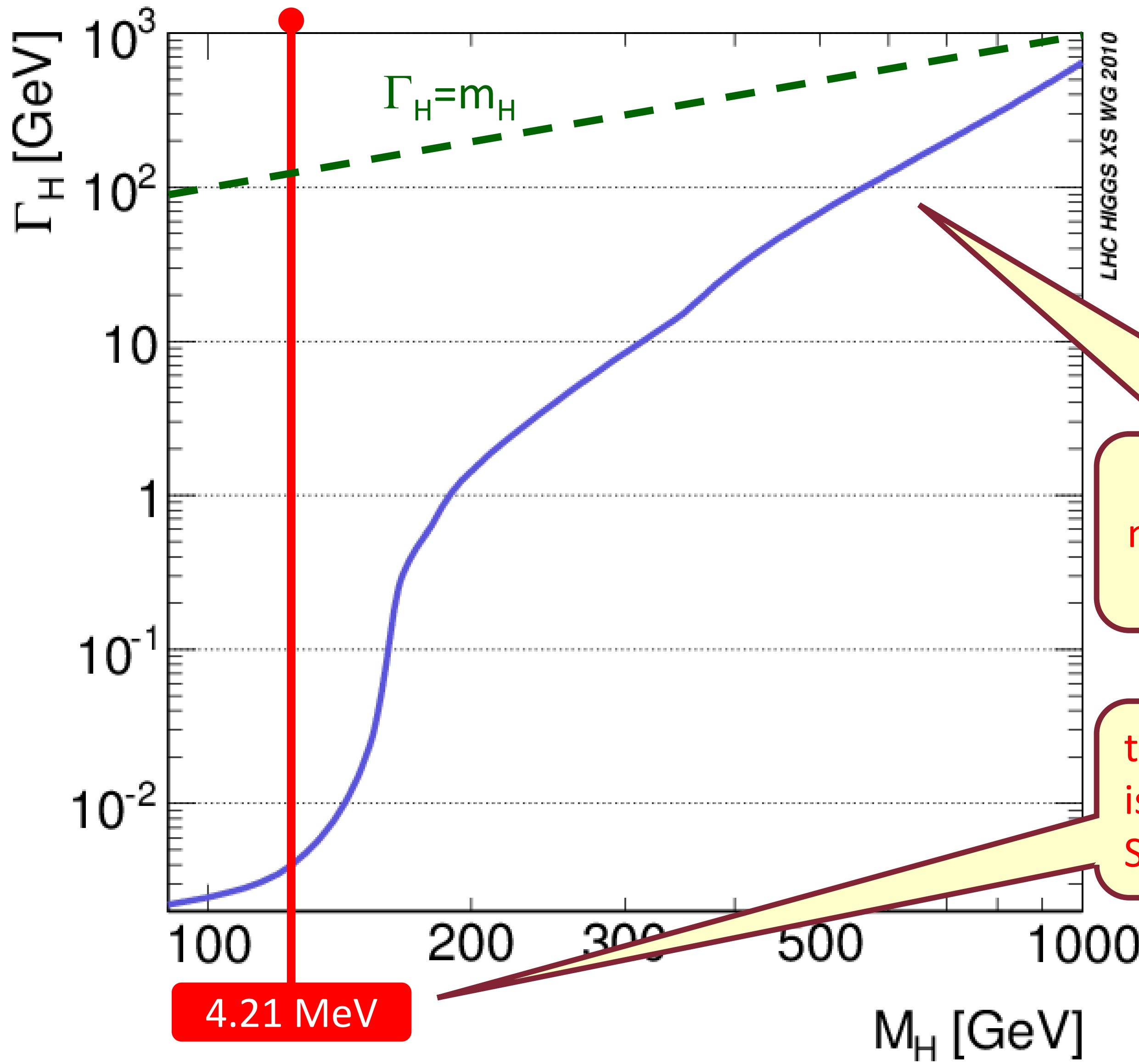
Higgs properties: BR(80 < m_H < 200 GeV)



enlarge for 80 < m_H < 200 GeV.



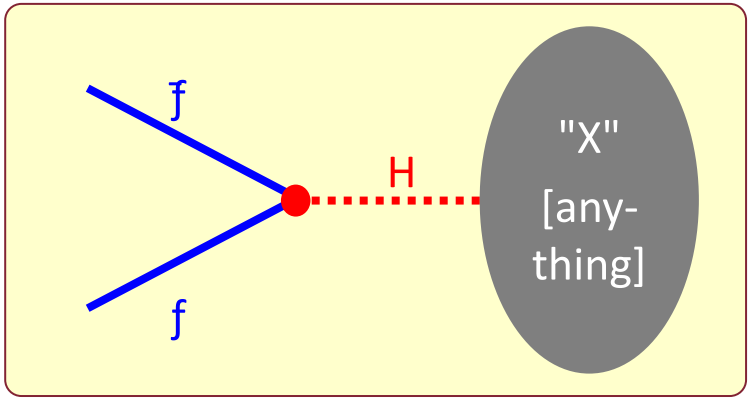
Higgs properties: full width vs m_H



roughly $\propto m_H^3$
$m_H \approx 1.4$ TeV $\rightarrow \Gamma_{tot} \approx m_H$,
not anymore a particle

the direct measure of Γ_H is a powerful test of the SM: ideas are welcome

Higgs properties: formation in $\ell^+\ell^-$



Question (for a lepton collider, not for LHC): what about the direct formation ($f\bar{f} \to H \to X$) in the s channel ?

Answer: it is depressed by the H coupling with low-mass fermions ($\Gamma_f \propto m_f^2$).

Compute it for a hypotetical $\mu^+\mu^-$ machine:

$$\sigma(f\bar{f} \to H \to X) = \frac{4\pi\Gamma_f\Gamma_X}{\left(s - m_H^2\right)^2 + \Gamma_H^2 m_H^2} = \frac{4\pi\Gamma_f\Gamma_X}{\Gamma_H^2 m_H^2}\left[\frac{\Gamma_H^2 m_H^2}{\left(s - m_H^2\right)^2 + \Gamma_H^2 m_H^2}\right]$$

$$\xrightarrow{X=\text{all}} \frac{4\pi}{m_H^2}\frac{\Gamma_f}{\Gamma_H}\left[\frac{\Gamma_H^2 m_H^2}{\left(s - m_H^2\right)^2 + \Gamma_H^2 m_H^2}\right] \xrightarrow[f\bar{f}=\mu^-\mu^+,\ \sqrt{s}=m_H=125\text{ GeV}]{} 64\text{ pb.}$$

see § 3 [quoted for $e^+e^- \to J/\psi$] :

$$\sigma(ab \to J/\psi \to f\bar{f}, \sqrt{s}) = \frac{16\pi}{s}\frac{(2J_R+1)}{(2S_a+1)(2S_b+1)}\left[\frac{\Gamma_{ab}}{\Gamma_R}\right]\left[\frac{\Gamma_{f\bar{f}}}{\Gamma_R}\right]\left[\frac{\Gamma_R^2/4}{\left(\sqrt{s}-M_R\right)^2 + \Gamma_R^2/4}\right]$$

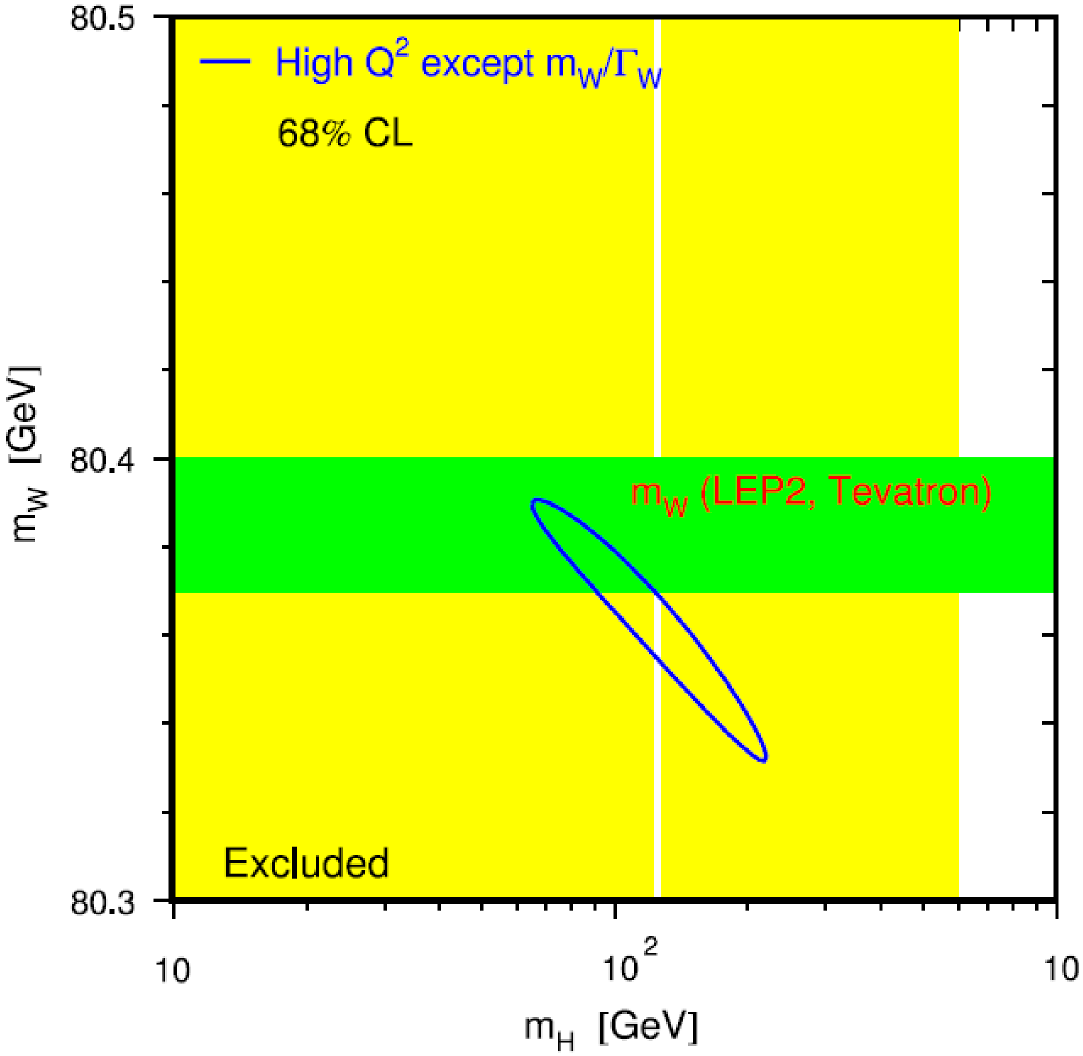
for e^+e^-, factor $(m_e/m_\mu)^2 \approx 1/40{,}000$:

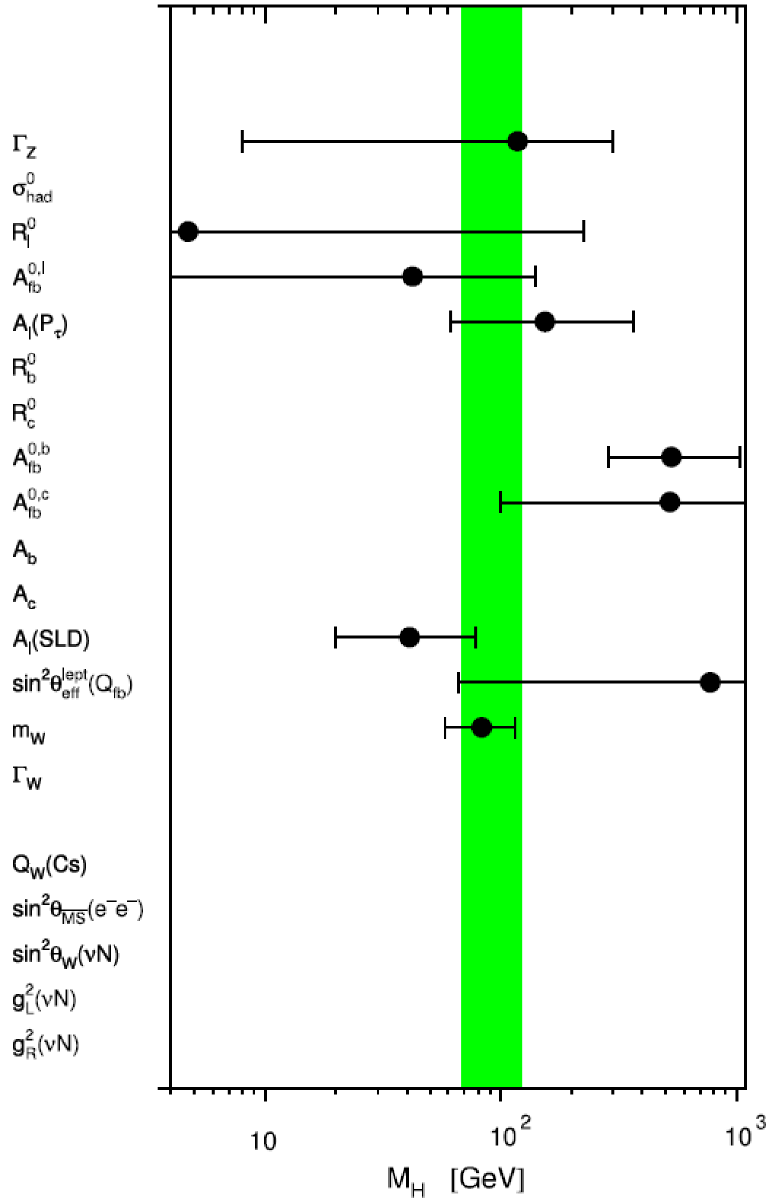
- $\to$ impossible for electron colliders;
- $\to$ one of the main motivations for muon colliders.

Higgs — pre-LHC : LEP legacy

bottom : m_W vs m_H (strong correlation);

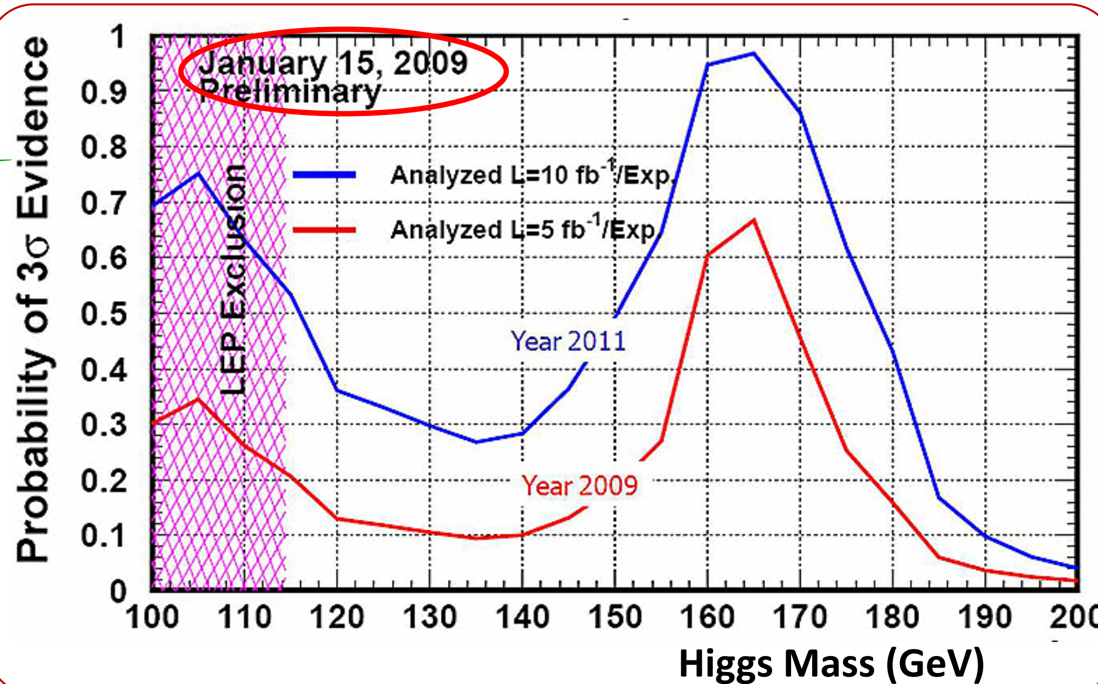
right : individual meas. contribution;

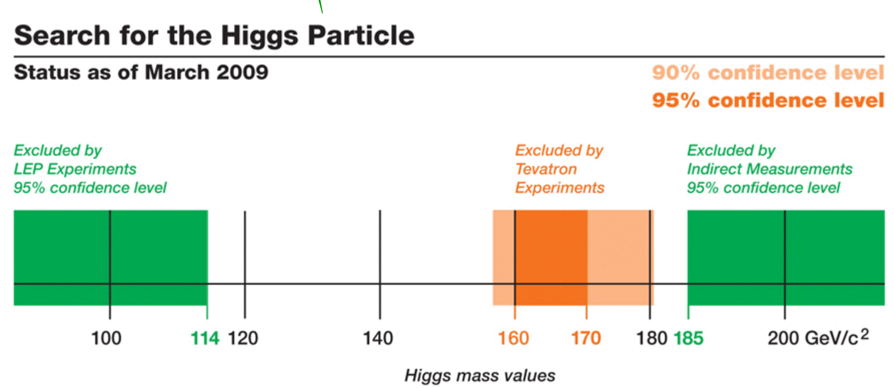




Higgs — pre-LHC : Tevatron legacy (1)

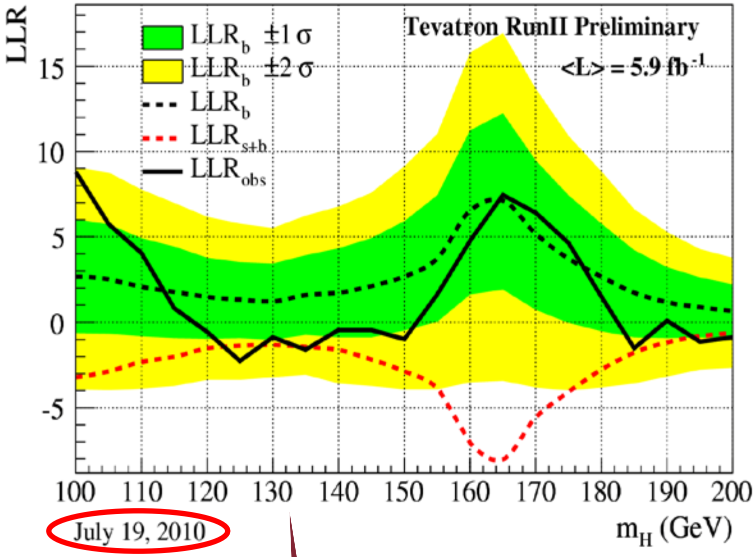
CDF + D0 combined





"3σ evidence" has **<u>never</u>** been used at LEP or at LHC; although well defined and politically understandable, it is a useless complication.

Higgs — pre-LHC : Tevatron legacy (2)

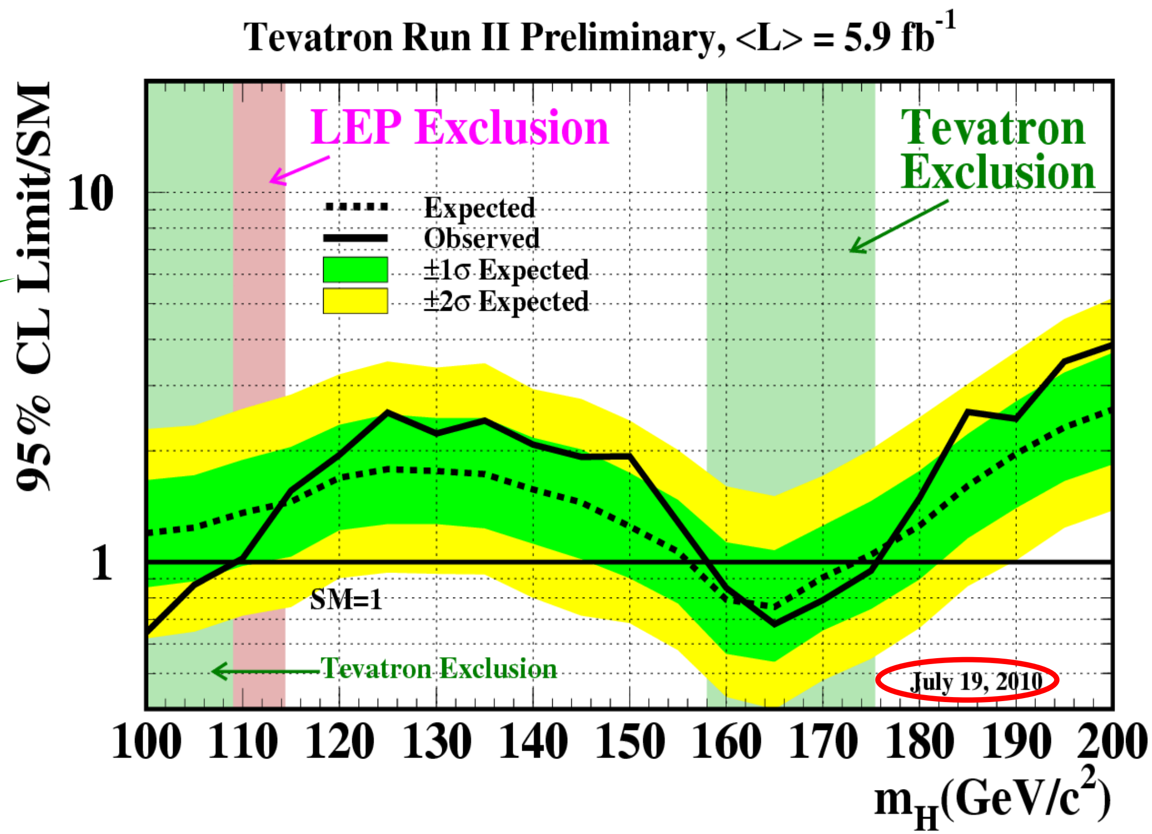


at LEP, for m_H < 115 GeV, the value of n (= $\mathscr{L}_{int}\ \varepsilon_s\ \sigma_s$) was monotonic and strongly decreasing with m_H;

on the contrary, for higher m_H, due to the different decay modes with different efficiency, n has various maxima; the exclusion interval breaks accordingly.

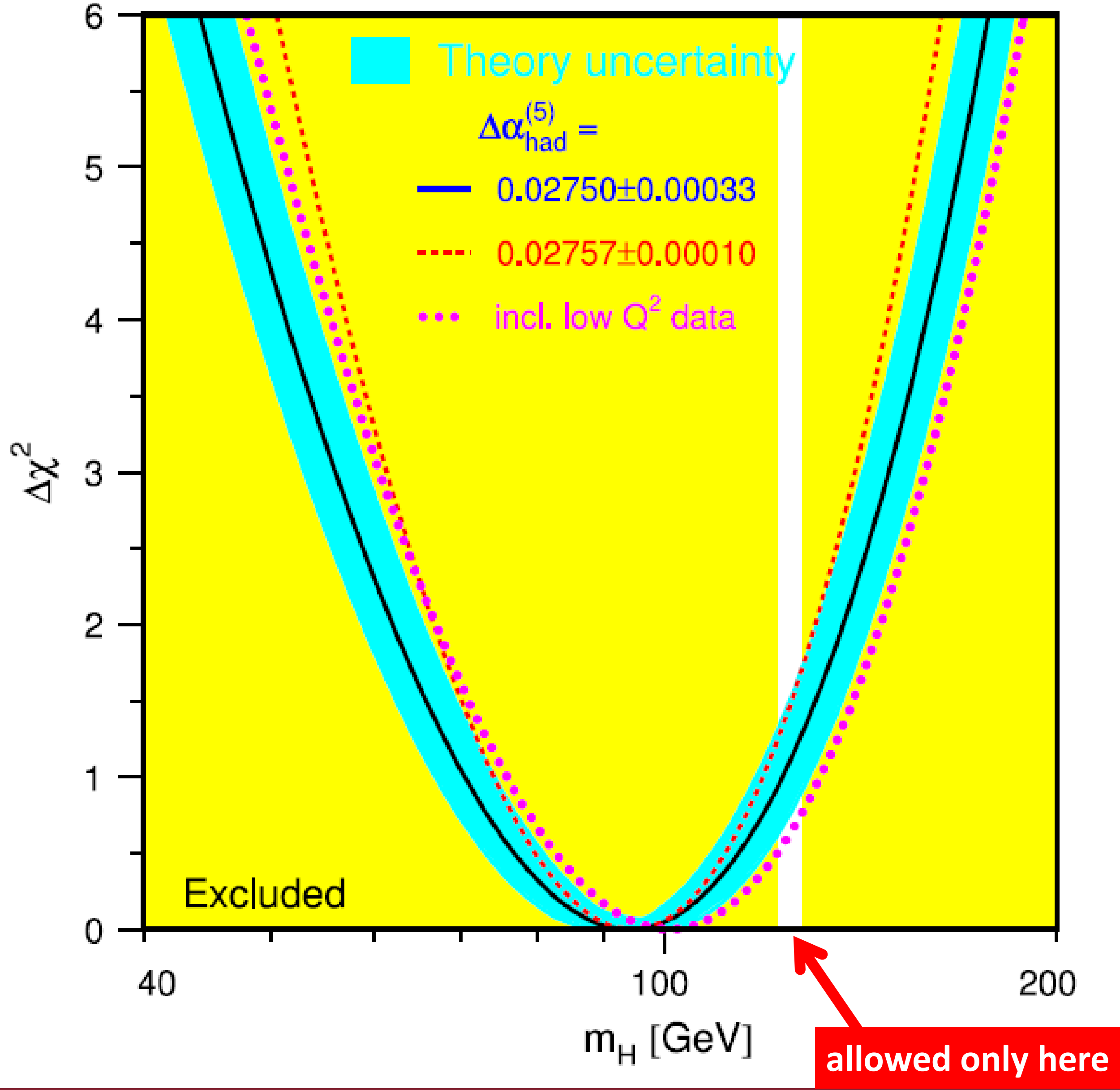
i.e. "μ"

"LLR" ≡ log likelihood ratio = $-2\ell n(\Lambda_s/\Lambda_b)$



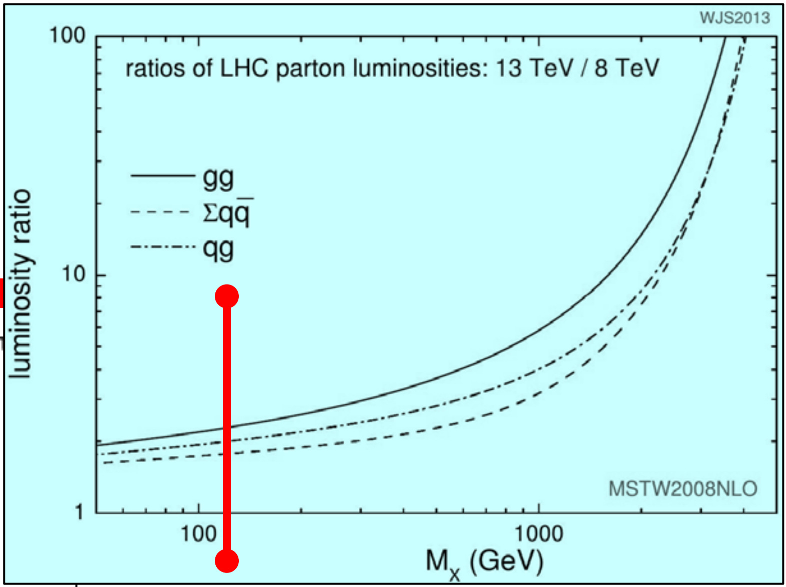
Higgs — pre-LHC : complete legacy

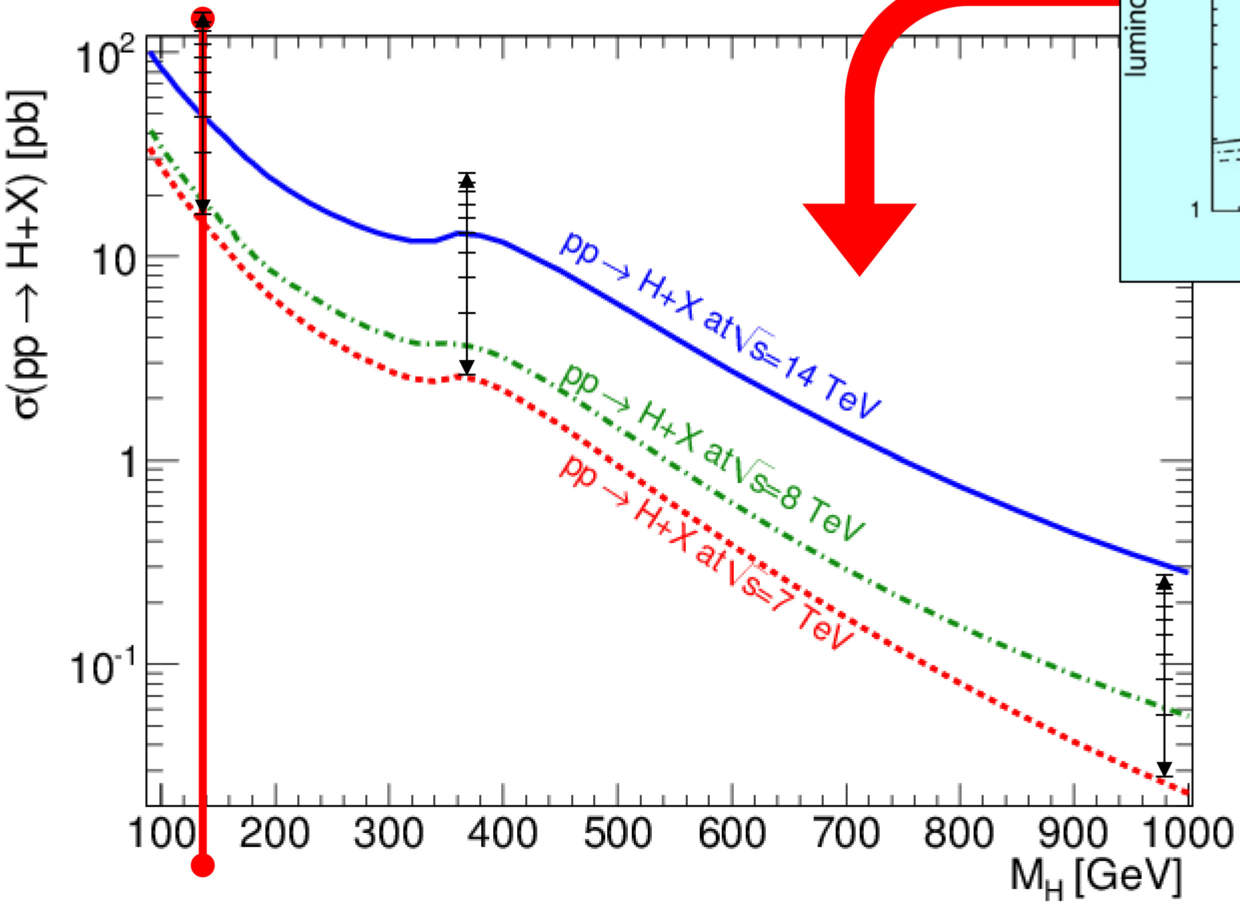
- the (in)famous "blueband", already discussed, wants a light Higgs; it includes all the known info, BUT the direct search at LEP, Tevatron and LHC, shown separately;
- instead, the yellow bands represent the result of the direct searches [NB : no experimental correlation with the blueband];
- the yellow bands varied a lot with time; the present figure refers to just before 2012; it includes TeVatron (160-170 GeV excluded) and the first LHC data;
- everything is now ready to show the direct LHC search.



Higgs — LHC predictions : production

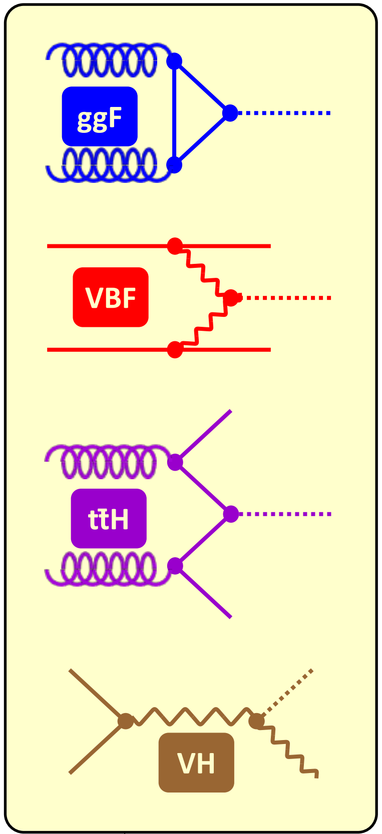
- the real process is at partonic level;
- parton densities (= PDF) at fixed x, depend on $\sqrt{s}$;
- they are strong functions of $\hat{s}$ (= M_x).



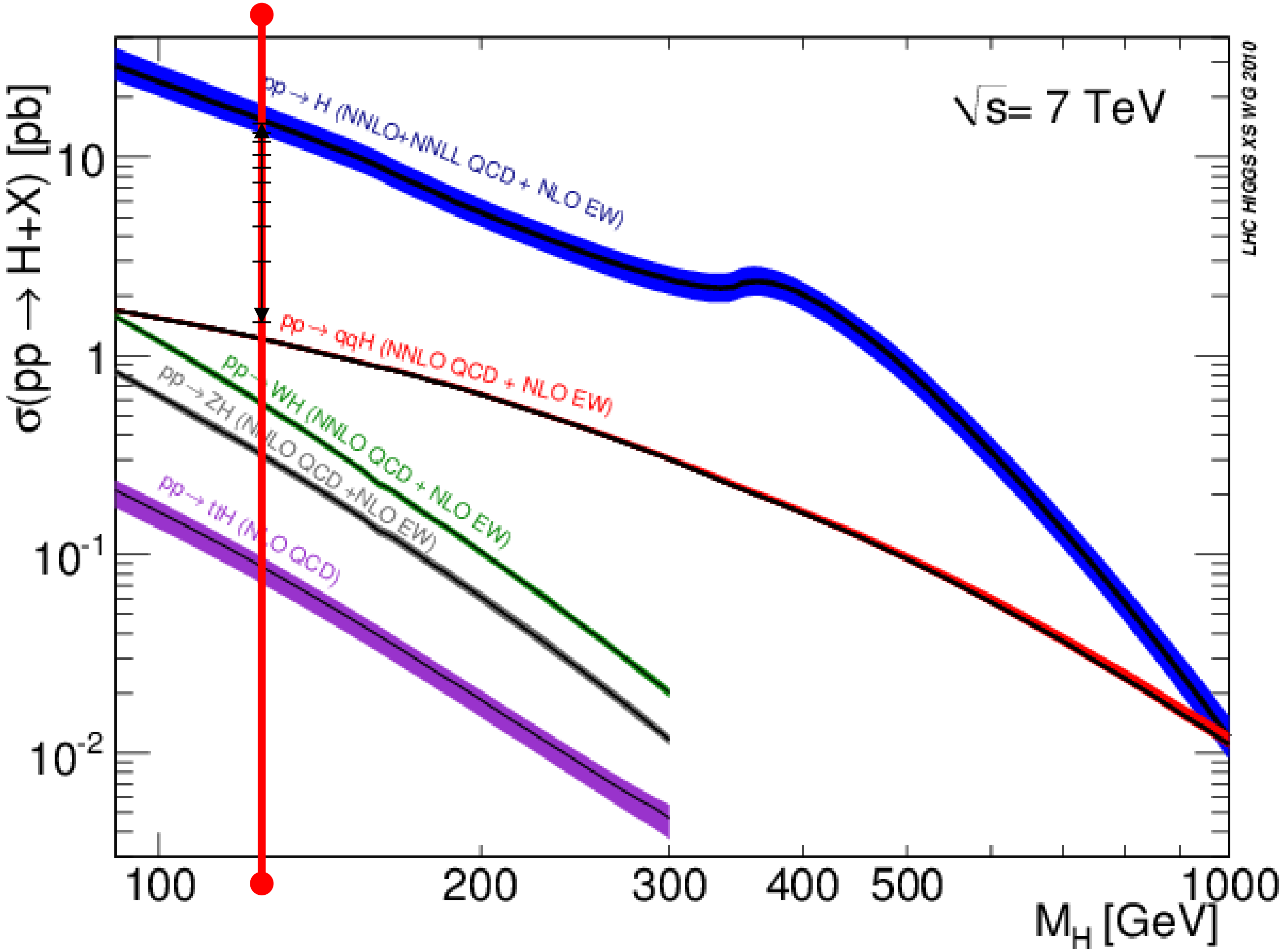


- σ_{125} = few × 10 pb;
- many BR decays, some unmeasurable;
- only observables $\sigma \times BR_i$;
- notice the scales.

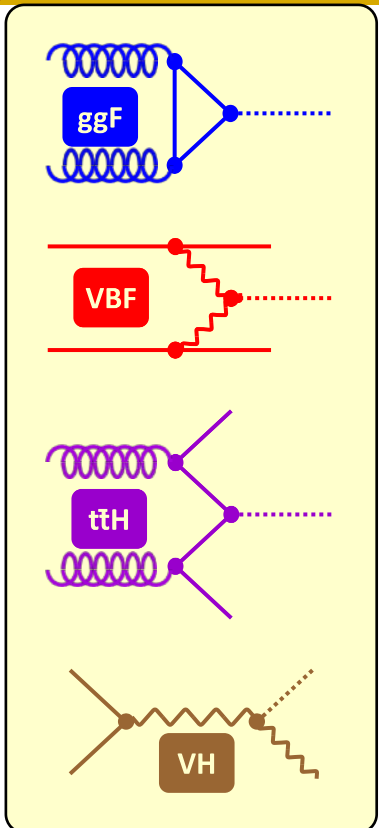
Higgs – LHC predictions : σ_H @ 7 TeV



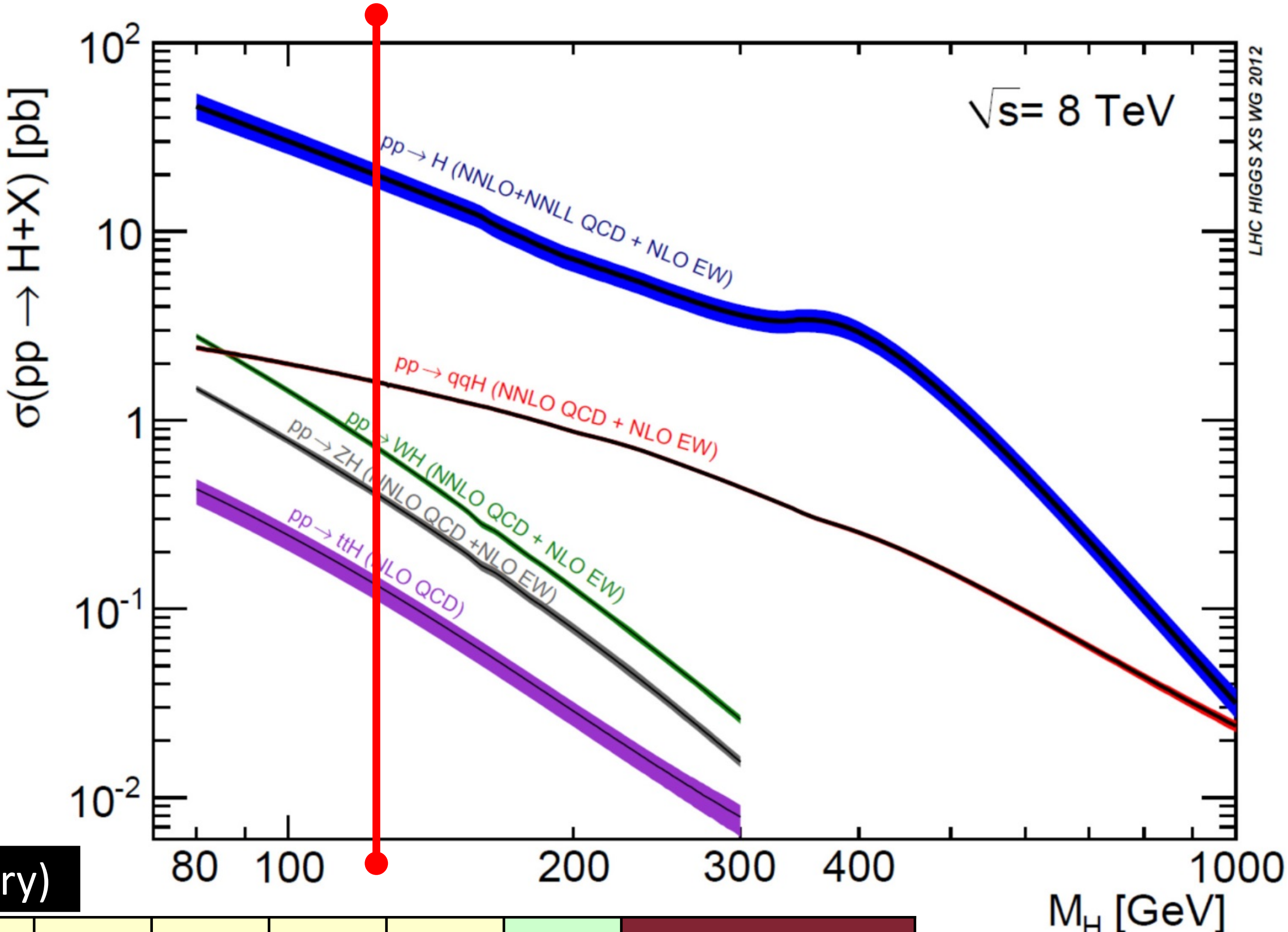
(see dictionary)



Higgs — LHC predictions : σ_H @ 8 TeV



(see dictionary)

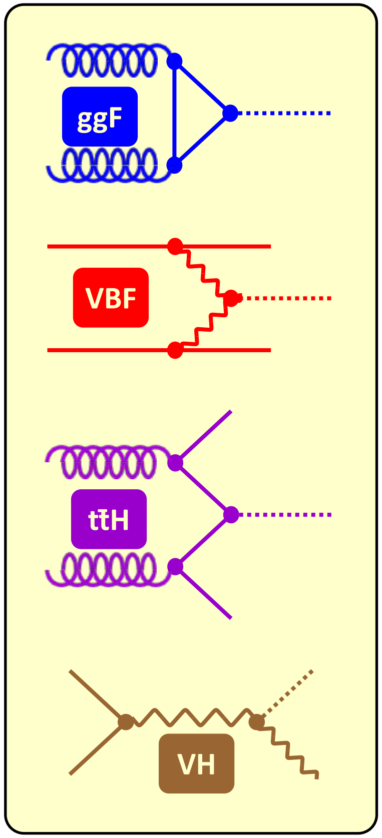


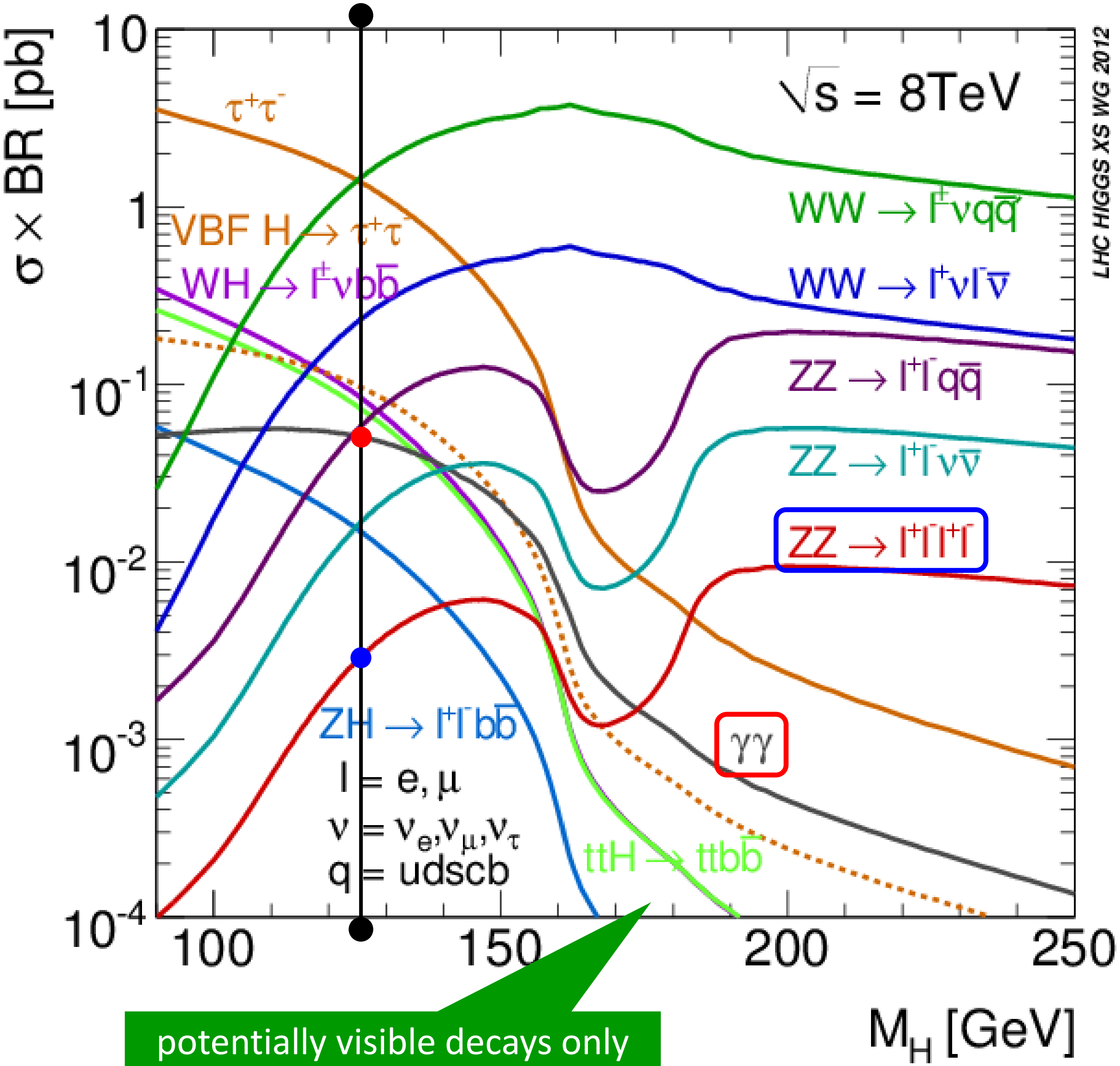
√s (TeV)	ggF	VBF	WH	ZH	tt̄H	(…)	Sum
7	15.0	1.22	0.58	0.33	0.09	0.2	17.4
8	19.2	1.58	0.70	0.41	0.13	0.3	22.3
14	49.2	4.15	1.47	0.86	0.59	…	56.3

$\sigma(pp \to HX)$ (pb)

[computed for m_H = 125 GeV]

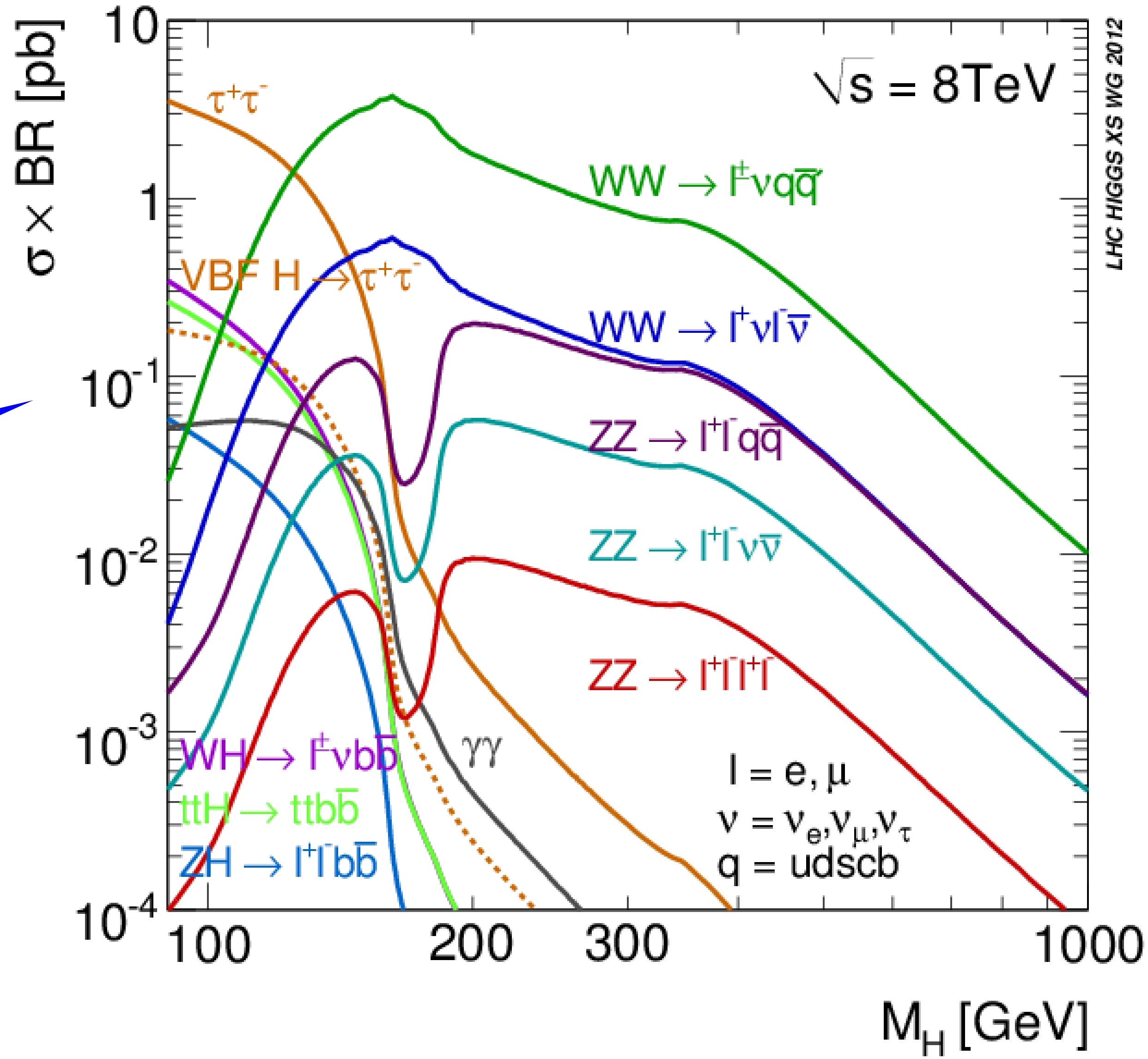
Higgs — LHC predictions : $\sigma_H \times BR$





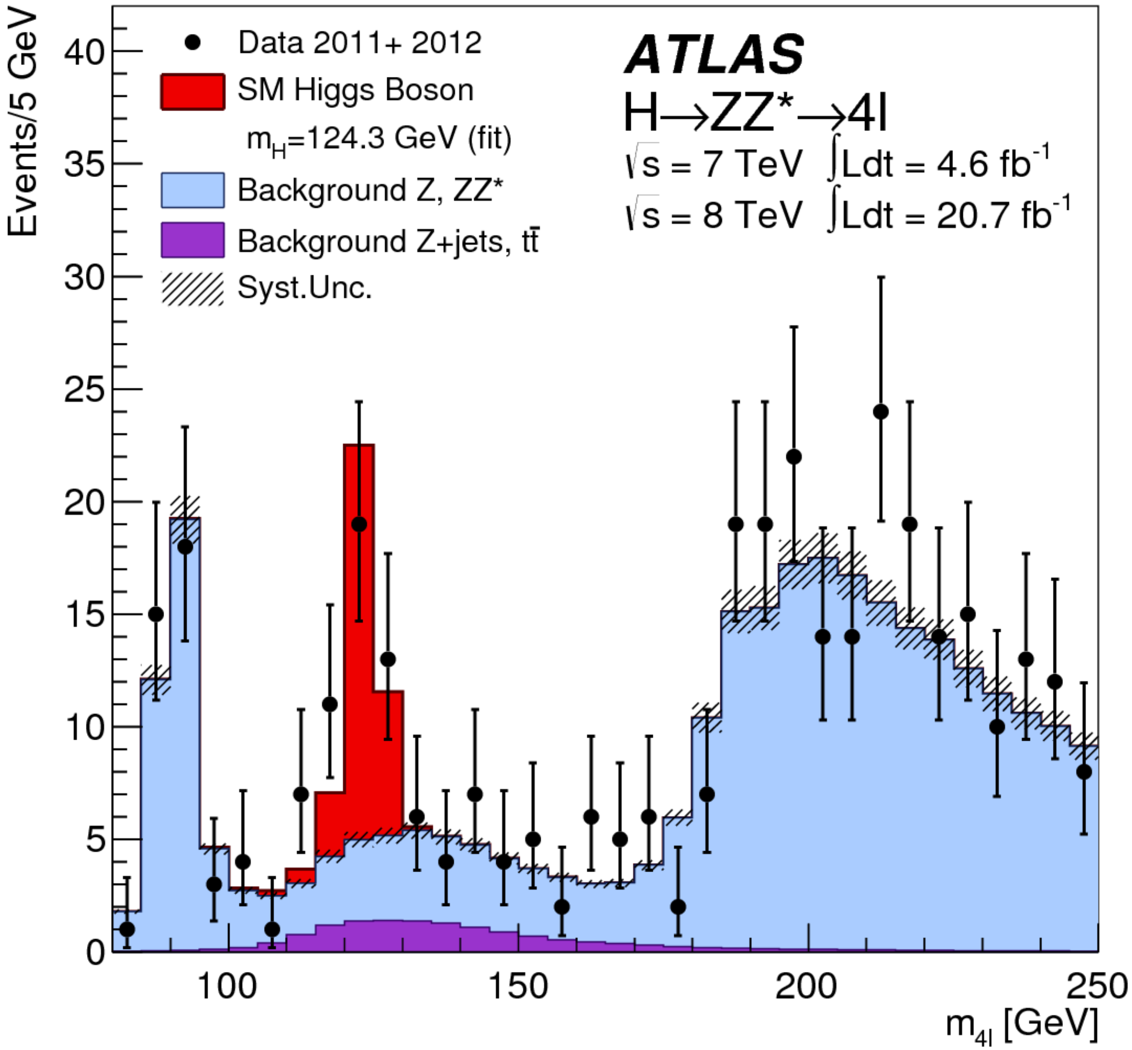
potentially visible decays only
[e.g. WW → qq̄qq̄ is missing]

Higgs — LHC predictions : $\sigma_H \times BR$



same plot, different scale, to show the high m_H behavior (not irrelevant, even after Higgs discovery, because of possible extensions of the Higgs sector, even in **<u>non-minimal SM</u>**).

Higgs discovery : H → ZZ* - ATLAS



looking for the Higgs boson !!!

$H \to ZZ^* \to \ell^+\ell^-\ell^+\ell^-$

Test mass ~ 125 GeV

(exact values from mass fits, small variations – within errors)

more results in >2013, some shown below.

1. ATLAS animated gifs: https://twiki.cern.ch/twiki/bin/view/AtlasPublic/HiggsPublicResults#Animations
2. ditto for CMS: https://twiki.cern.ch/twiki/bin/view/CMSPublic/Hig13002TWiki

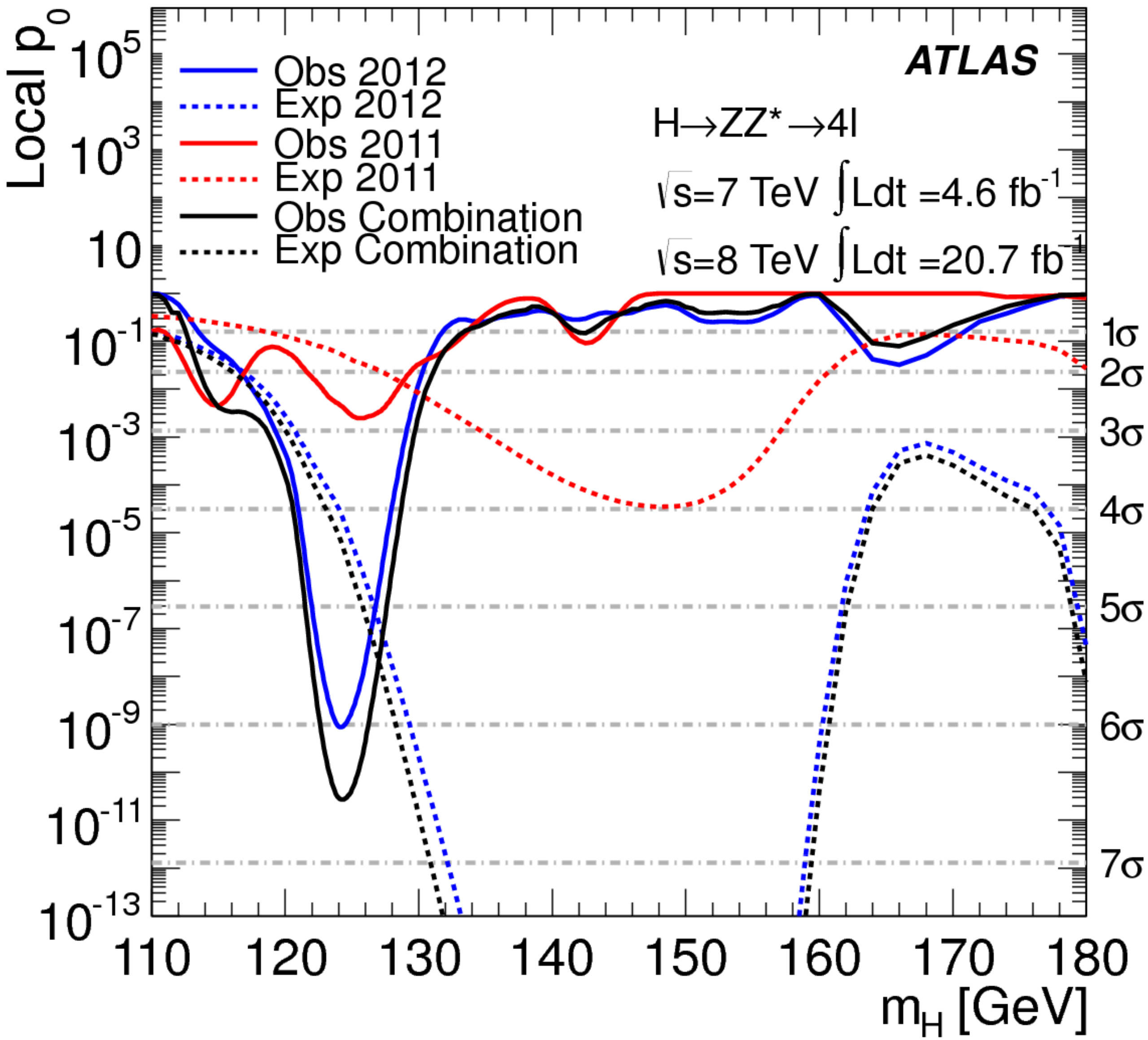
Higgs discovery : H → ZZ* - ATLAS p-value

ATLAS 4 ℓ±

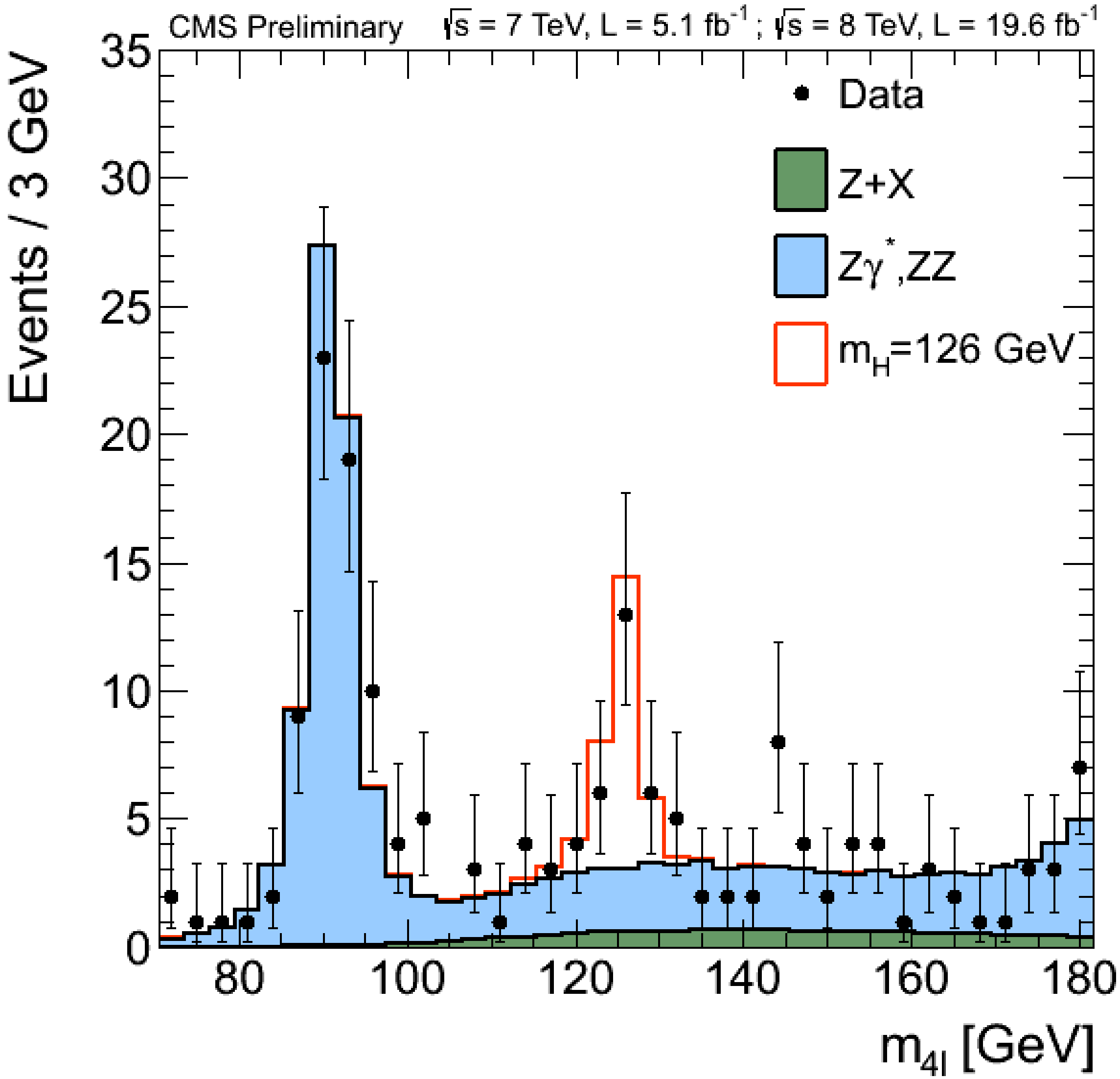
- 2011 : some excess, below 3σ;
- **2012 : ~ 6 σ;**
- combined : between 6 and 7 σ.

more than expected, but **not incompatible**.

NB. obs (–) and exp (- -) are expected to agree ONLY at m_H^{obs}.



Higgs discovery : H → ZZ* - CMS



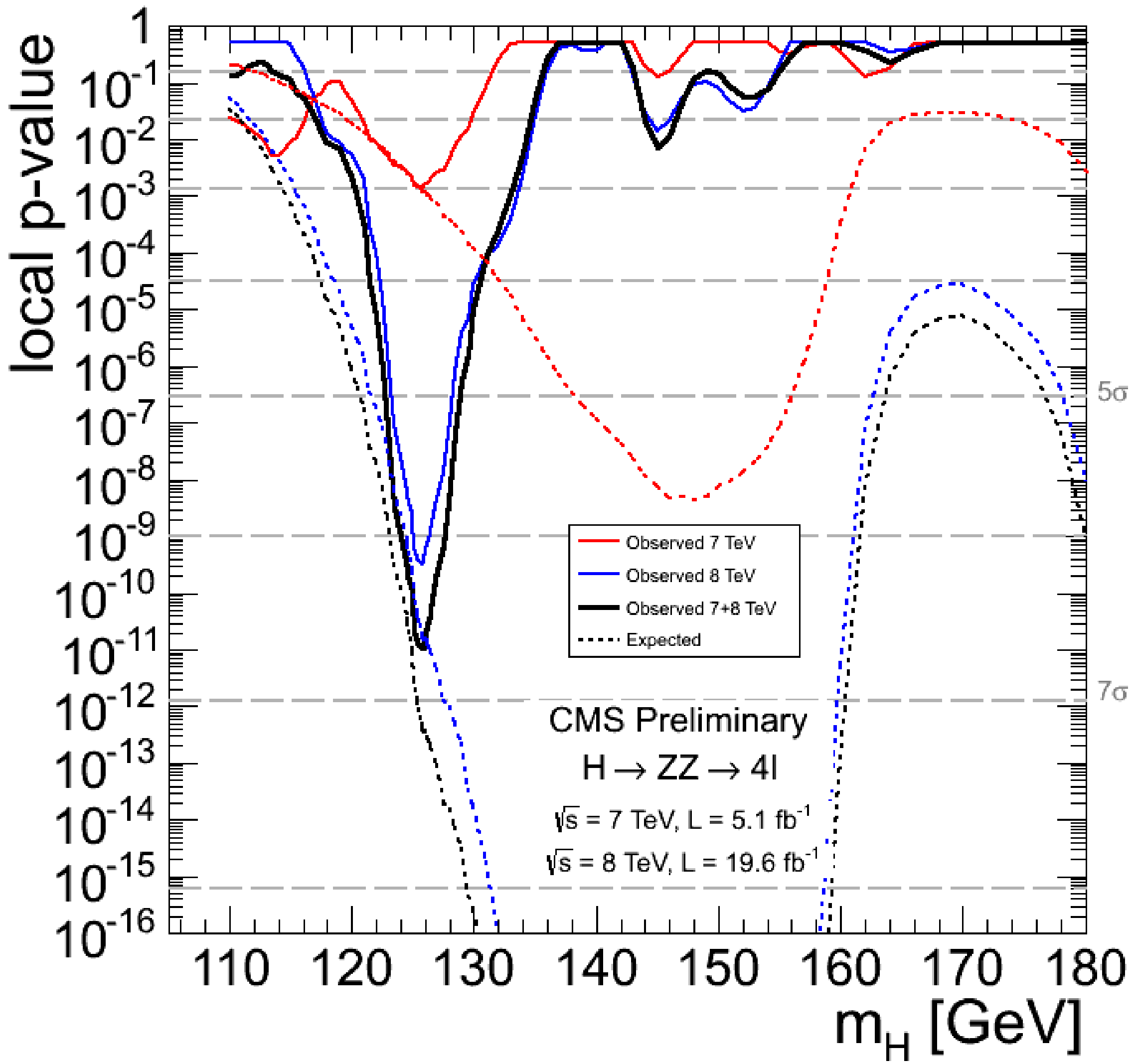
$H \rightarrow ZZ^* \rightarrow \ell^+\ell^-\ell^+\ell^-$

Test mass ~ 125 GeV

(exact values from mass fits,

small variations – within errors)

Higgs discovery : H → ZZ* - CMS p-value



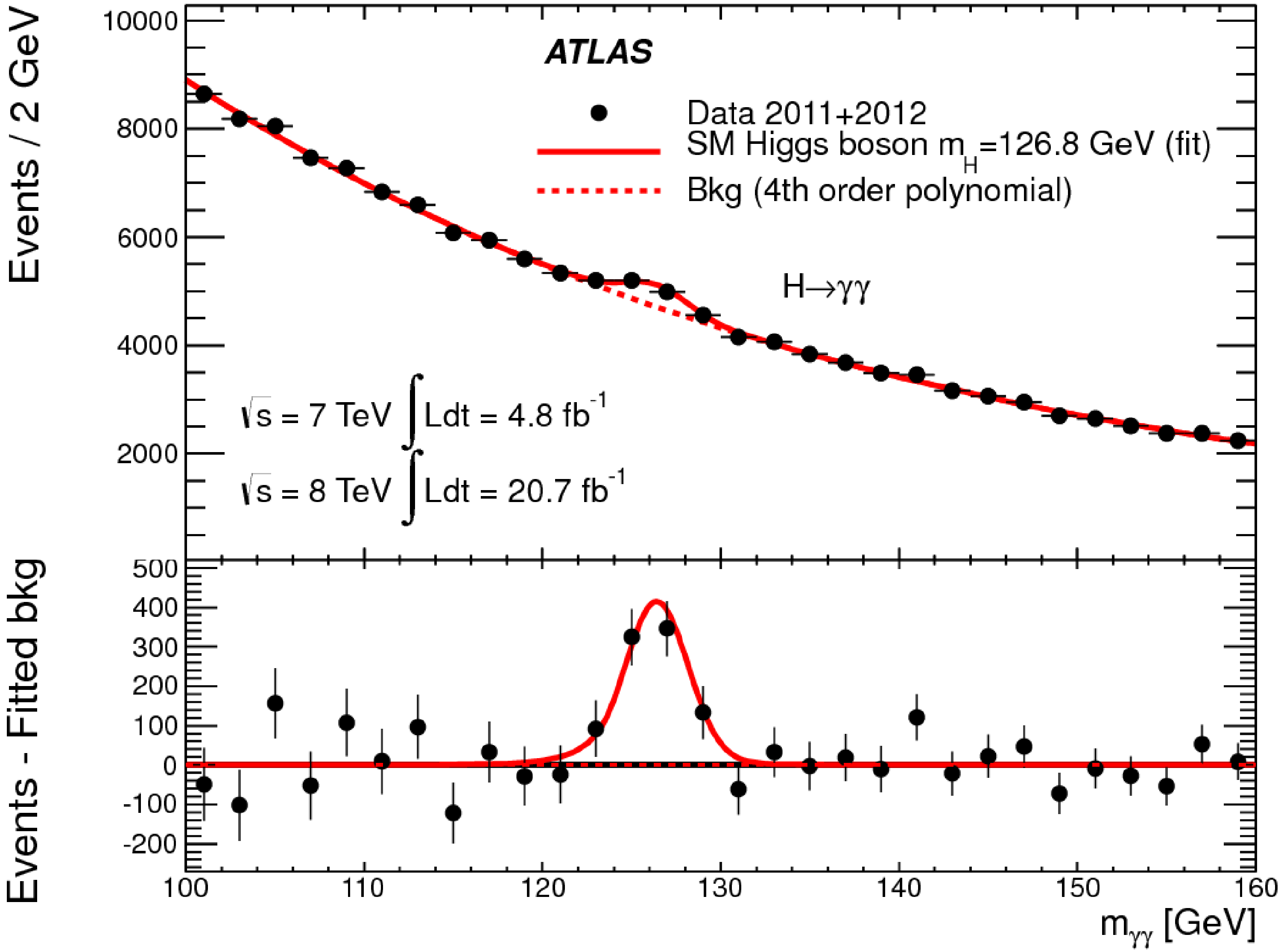
CMS 4 ℓ±

- 2011 : some excess, ~3 σ;
- **2012 : > 6 σ;**
- combined : between 6 and 7 σ.

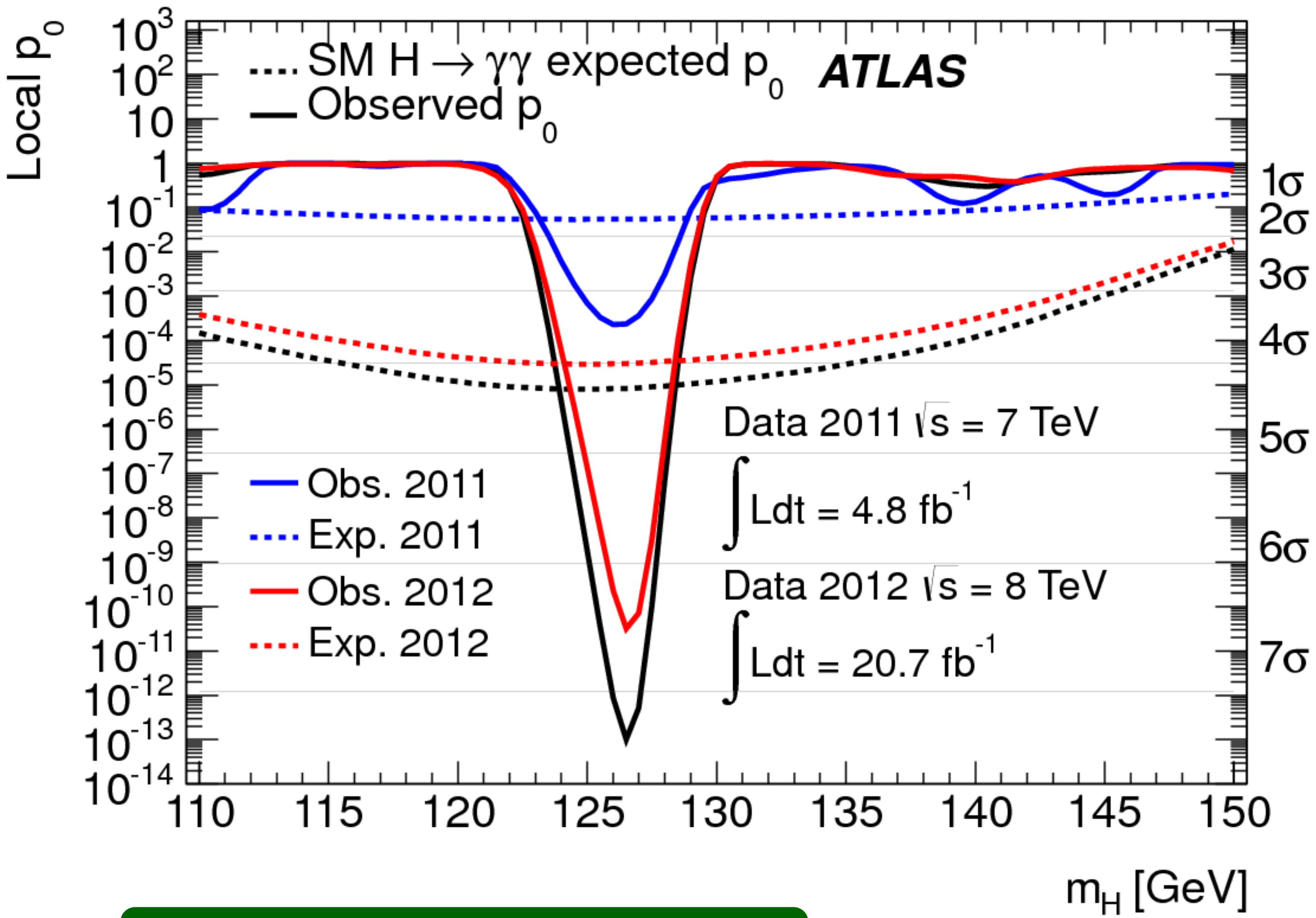
well compatible with expected.

NB. obs (–) and exp (- -) are expected to agree ONLY at m_H^{obs}.

Higgs discovery : H → γγ - ATLAS



Higgs discovery : H → γγ - ATLAS p-value



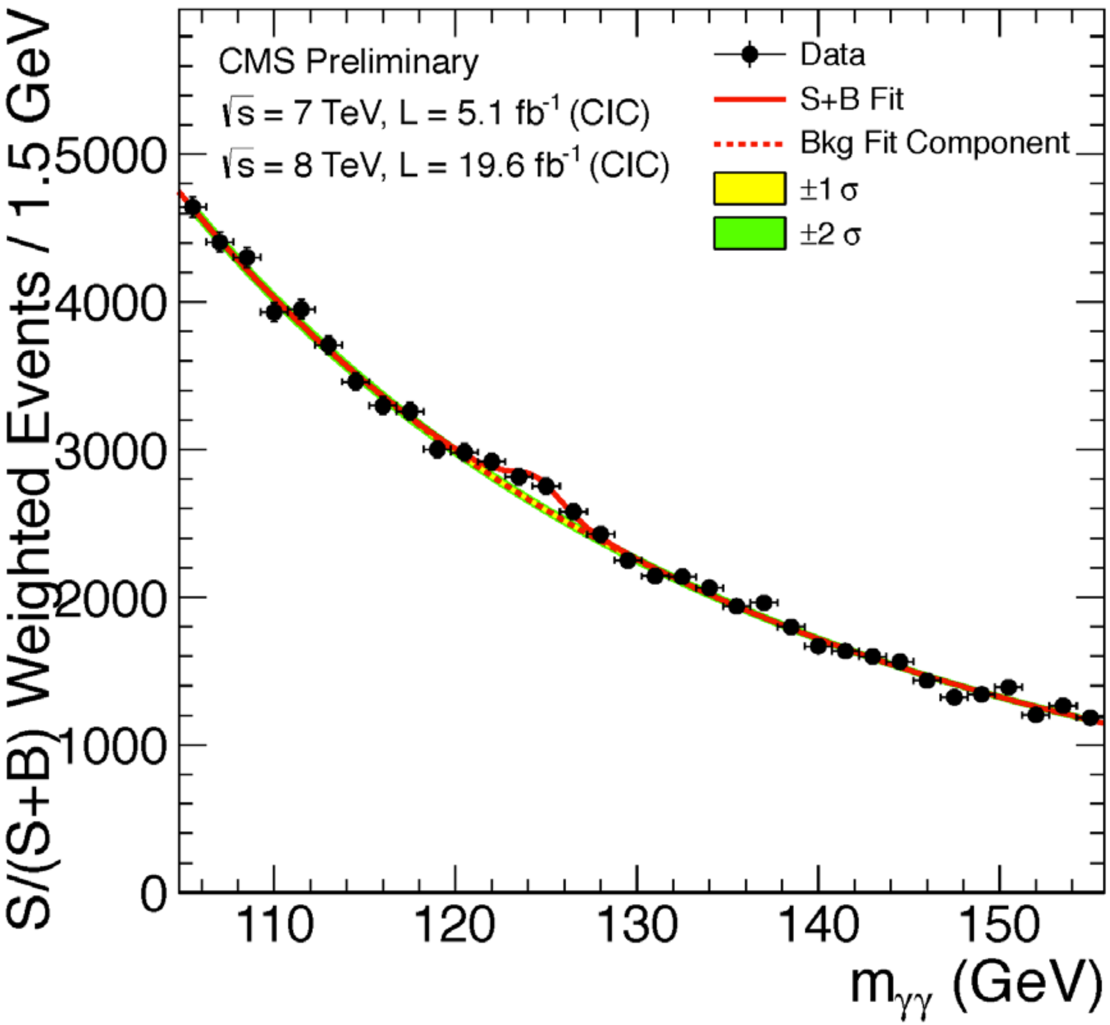
ATLAS γγ

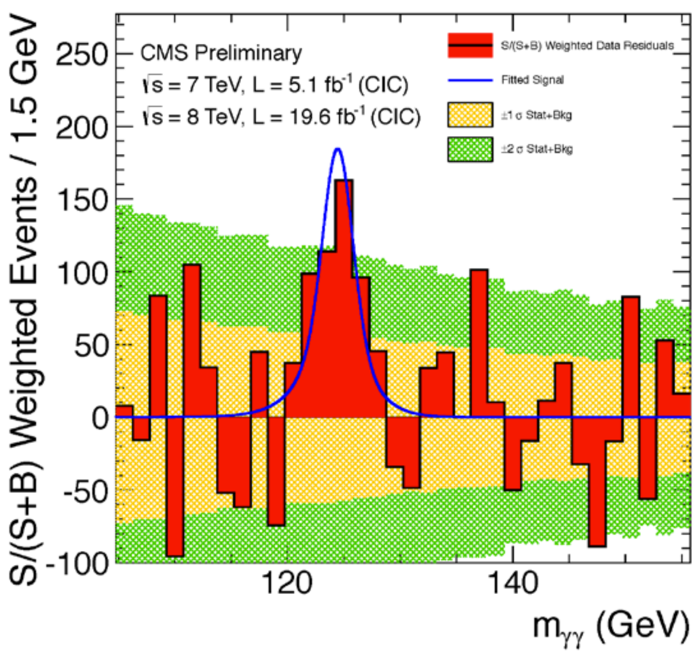
- 2011 : some excess, >3 σ;
- **2012 : > 6 σ;**
- combined : >7 σ.

more than expected, but **not incompatible**.

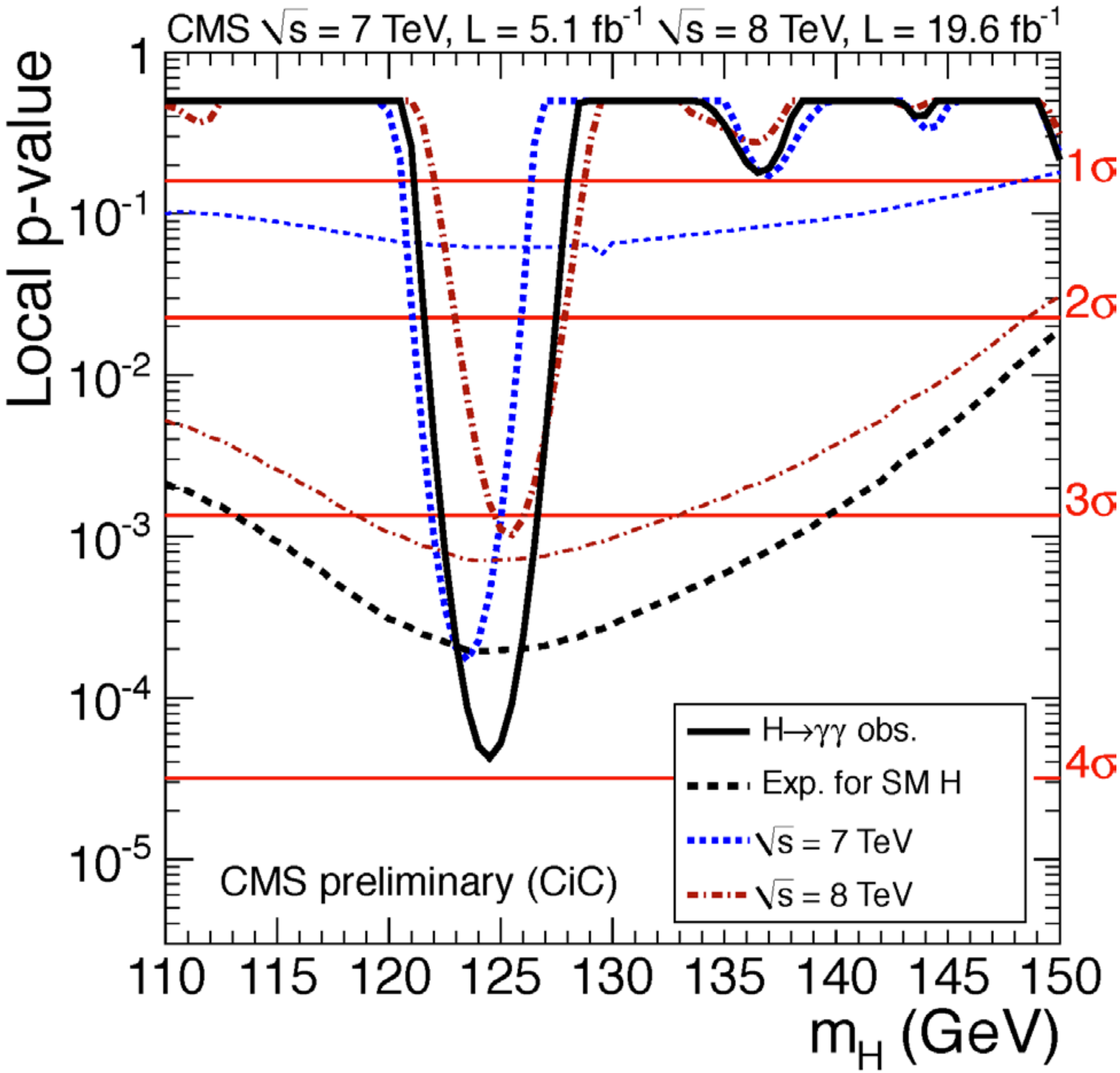
NB. obs (–) and exp (- -) are expected to agree ONLY at m_H^{obs}.

Higgs discovery : $H \to \gamma\gamma$ - CMS





Higgs discovery : H → γγ - CMS p-value



CMS γγ

- 2011 : some excess, >3 σ;
- **2012 : > 3 σ;**
- combined : ~4 σ.

well compatible with expected.

NB. obs (−) and exp (- -) are expected to agree ONLY at m_H^{obs}.

Higgs current status

After discovery, what next ?

[*no possibility for stat. fluctuations, but maybe it is **NOT** the SM Higgs*]

Strategy :

- measure as many as possible H properties :
  - mass (→ masses in all decays);
  - production rates (also vs $\sqrt{s}$);
  - decay BR's;
  - couplings;
  - decay angular distributions;
- compare with SM predictions and check (***hope***) for discrepancies;
- look for the rest of the m_H range, searching for a richer Higgs spectrum;
- [*the same for any other bSM theory*];
- [*also with model-independent analyses*].

Warning:

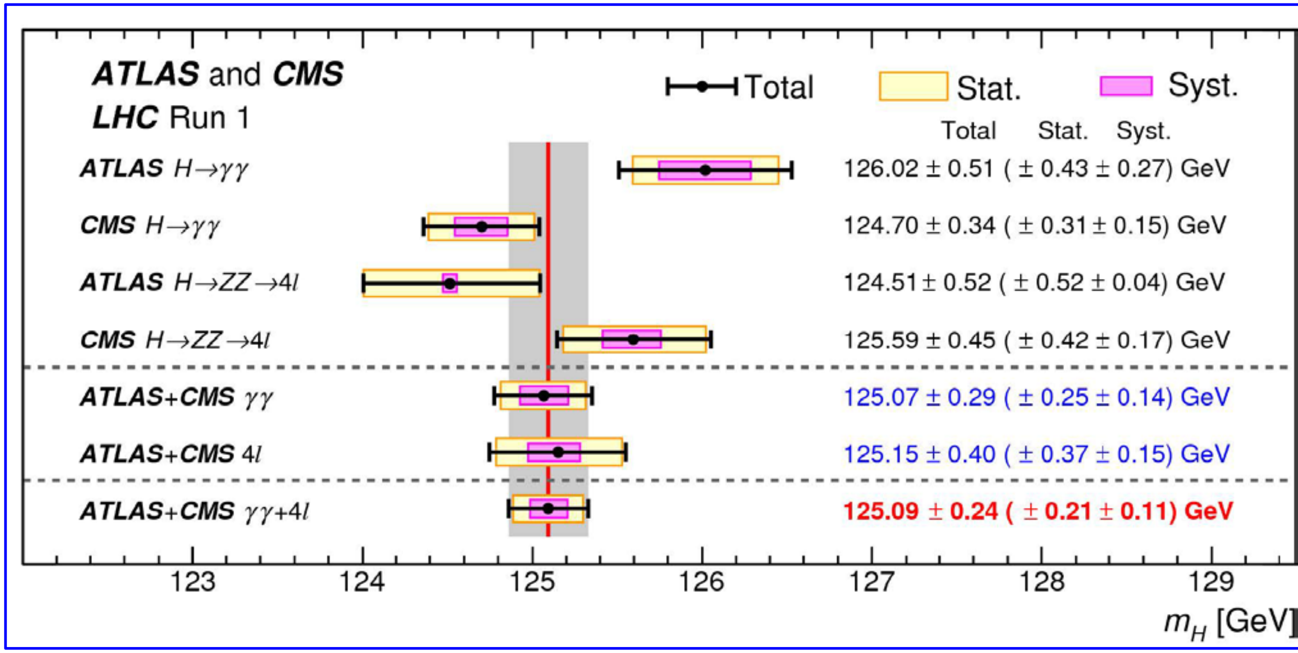
- neither a standard textbook explanation nor a report of present state-of-art results, but an attempt to show the strategy of the current studies;
- best effort to produce updated results and plots, but no guarantee (updates almost daily);
- few properties only (e.g. skip the interesting but complicated attempt to measure H width);
- no discussion of bSM analyses (actually most studies, but none successful, until now…)
- a neverending work in progress …

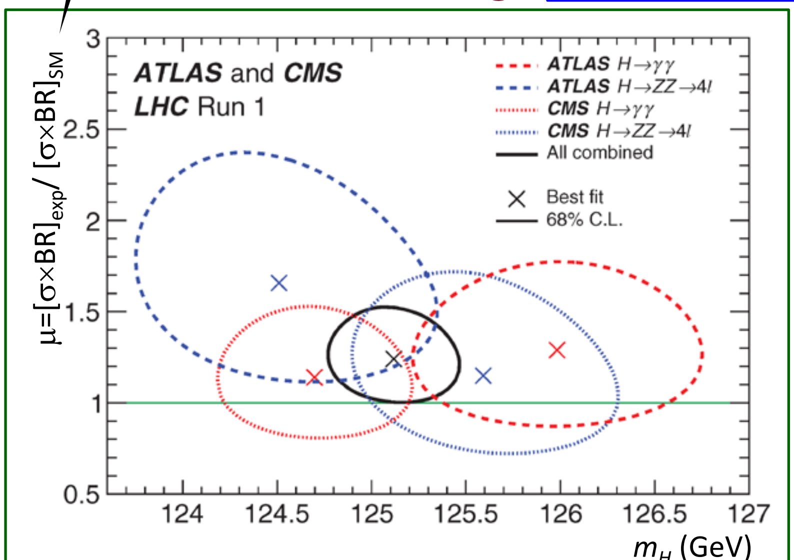
Higgs current status: mass(es)

Data 2011-12	7 TeV	8 TeV
ATLAS	5 fb^{-1}	20 fb^{-1}
CMS	5 fb^{-1}	20 fb^{-1}

As usual, normalize to SM: "$\mu = [\sigma\times BR]_{exp} / [\sigma\times BR]_{SM}$"

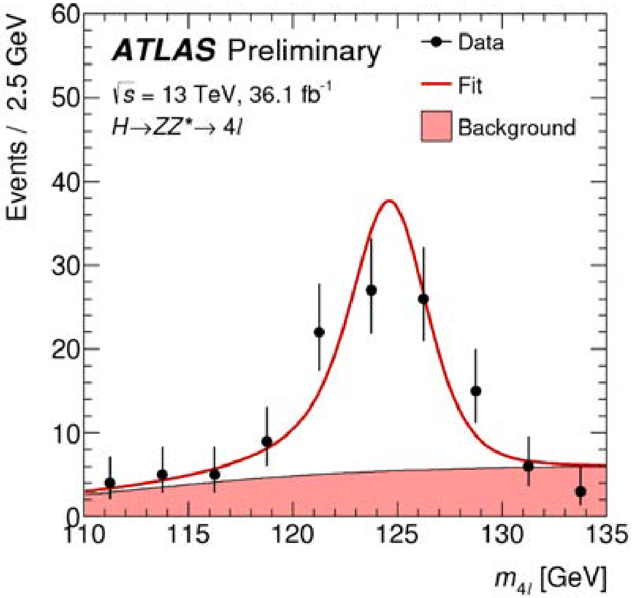
Phys.Rev.Letters, 114, 191803 (2015).

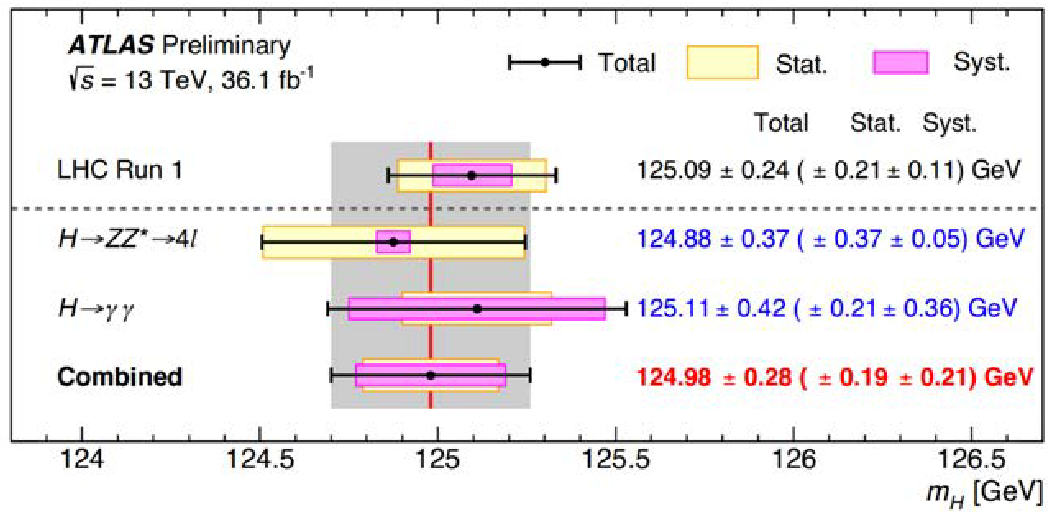


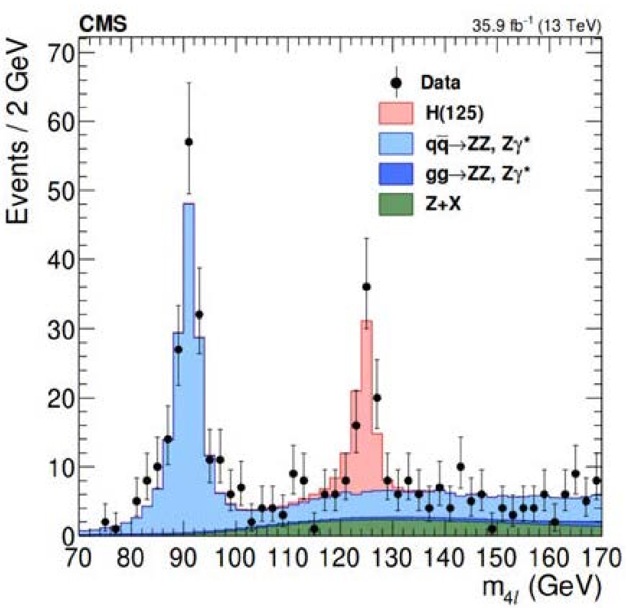


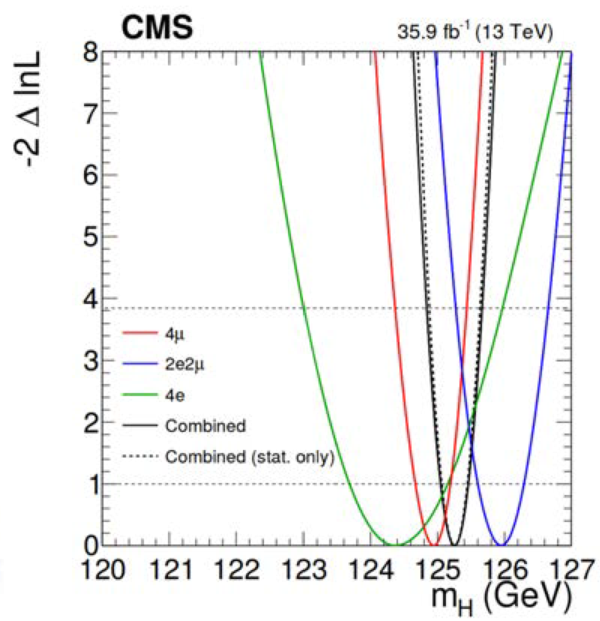
- if it is NOT the SM boson → m(γγ) and m(4ℓ) could be different;
- … and their yield uncorrelated wrt H_{SM};
- but in the data their mass is compatible;
- and their strength is (a bit too large, but still) ok for a SM Higgs of ~125 GeV;
- and ATLAS and CMS are fully compatible. ☺

Higgs current status: mass(es) in 2018









	CMS	ATLAS
m_H	**125.26**	**124.98**
±	**0.21**	**0.28**
[stat]	0.20	0.19
[sys]	0.08	0.21

Moriond February 2018

Higgs current status: Γ's

- Γ(H→fermions/IVBs/…) ≡ $\Gamma_{ff/WW/ZZ/\ldots}$ completely specified in SM, once m_H fixed [see table before and IE, § 14];
- measurable from H production and decay (difficult because of higher orders, loops, …);
- strong function of m_f / m_{IVB};
- [$\mathscr{L}_{INT}$ up → more events → smaller m_f probed];
- wonderful agreement with theory [*as usual … ☺ … ☹*];
- **powerful test of SM : improve accuracy for better test → discrepancies** [*hope … ☹ … ☺*].

$$\Gamma_{f\bar{f}} = \frac{c_f}{4\pi\sqrt{2}} G_F m_H m_f^2 \beta_f^3; \text{ [see before]}$$

$$\beta_f = \sqrt{1 - \frac{4m_f^2}{m_H^2}}; \qquad c_f = \begin{cases} 1 & \text{[leptons]} \\ 3 & \text{[quarks]} \end{cases};$$

for Γ_{ww^*/zz^*} take into account $m_H < 2m_{w,z}$:

$$\Gamma_{ww} = \frac{3G_F^2 m_H m_w^4}{2\pi^3} \times J_w\left(\frac{m_w}{m_H}\right);$$

$$J_w\left(m_H = 125 \text{ GeV}\right) \simeq 0.0227;$$

$$\Gamma_{zz} = \frac{3G_F^2 m_H m_z^4}{2\pi^3} \times g_z\left(\sin^2\theta_w\right) \times J_z\left(\frac{m_w}{m_H}\right);$$

$$g_z\left(x^2\right) = \frac{7}{12} - \frac{10}{9}x^2 + \frac{40}{27}x^4;$$

$$J_z\left(m_H = 125 \text{ GeV}\right) \simeq 0.00366;$$

$\Gamma_{\gamma\gamma}$ and Γ_{gg} : see before.

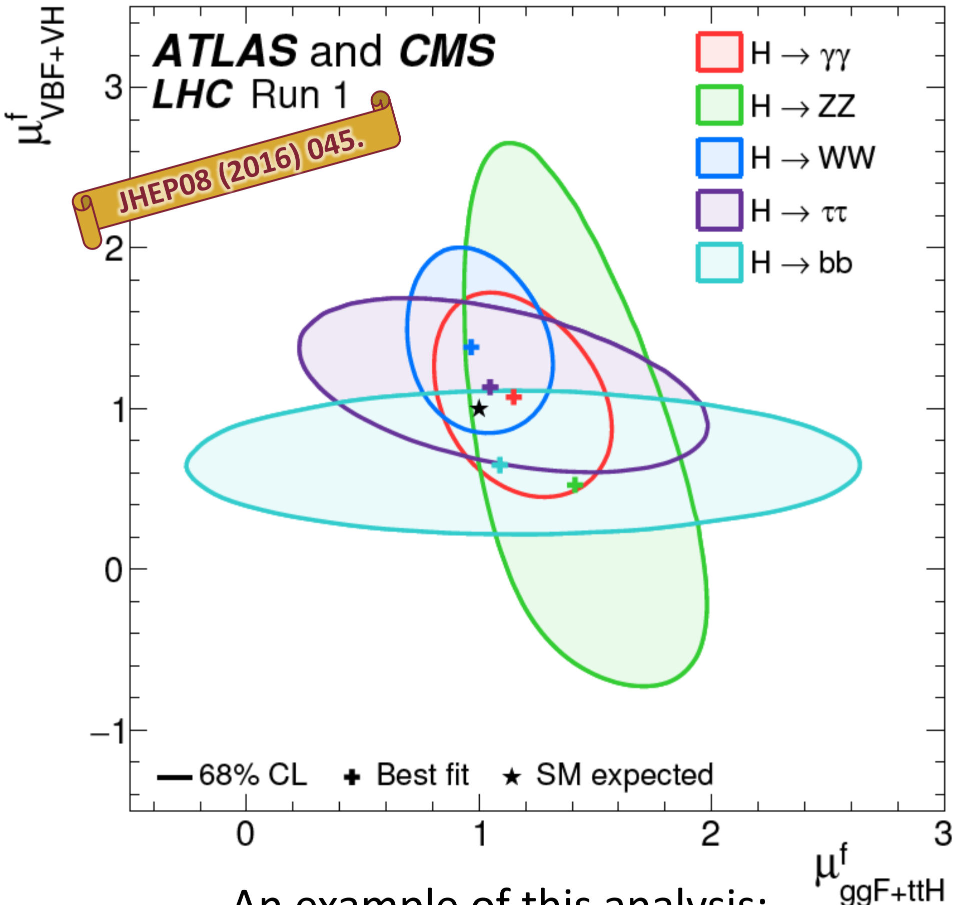
Higgs current status: $\sigma \times BR$

Define:

- $\mu_i = \dfrac{\sigma_i}{\sigma_i^{SM}}$ $\left\{ \begin{array}{l} \text{cross-section for H production} \\ i = \text{ggF, VBF, WH, ZH, ttH} \end{array} \right.$;
- $\mu^f = \dfrac{BR^f}{BR^f_{SM}}$ {branching ratios for H decay;
- $\mu_i^f = \dfrac{\sigma_i \times BR^f}{\sigma_i^{SM} \times BR^f_{SM}}$ $\left\{ \begin{array}{l} \text{only quantity accessible} \\ \text{to experiments} \end{array} \right.$;

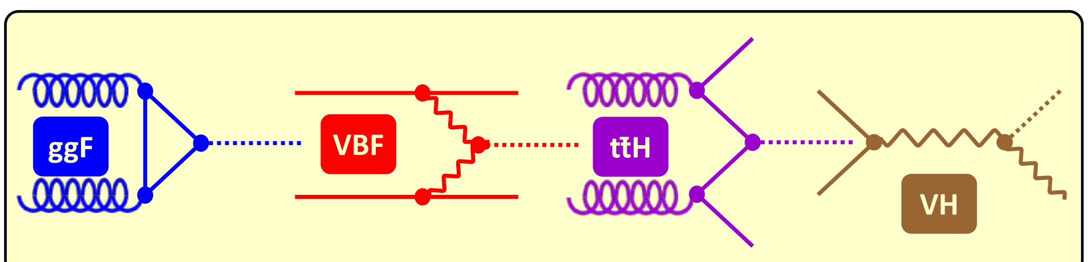
interpretation of result for μ:

- $\mu = 0 \rightarrow$ no signal in this channel;
- $\mu = 1 \rightarrow$ compatible with SM $\rightarrow$ SM ok;
- $\mu > 1 \rightarrow$ too much signal $\rightarrow$ SM wrong.



An example of this analysis:

- for all the decays (5 × "f");
- group (VBF+VH) and (ggF+tt̄H), i.e. bosons vs fermions;
- OK !!!



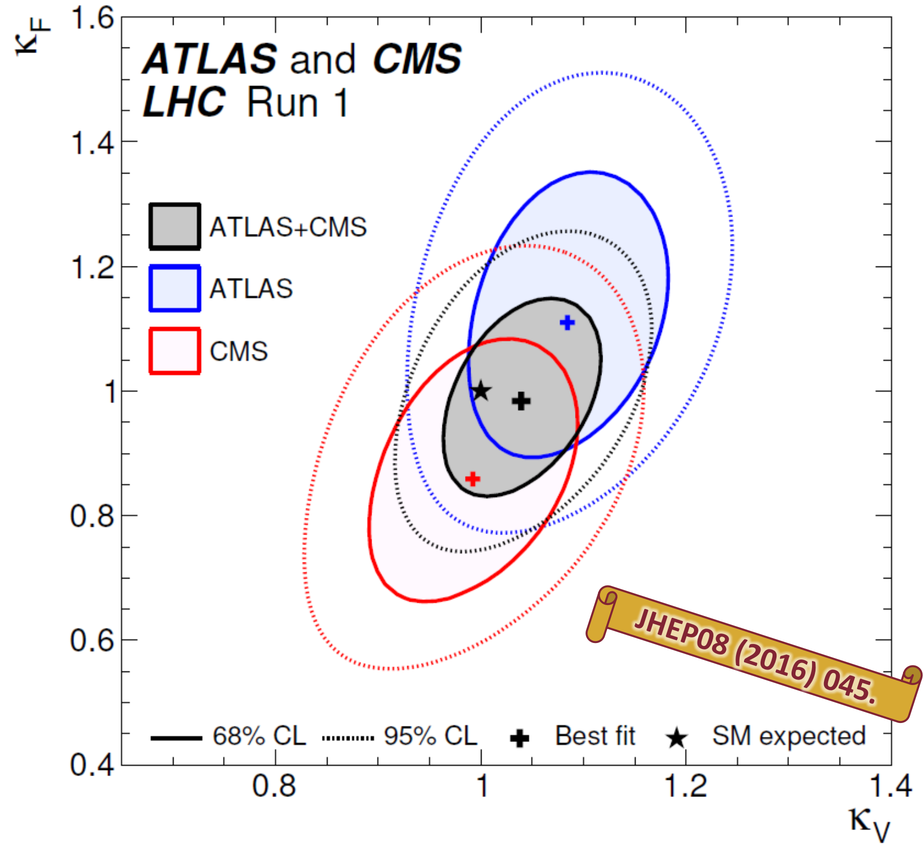
Higgs current status: couplings

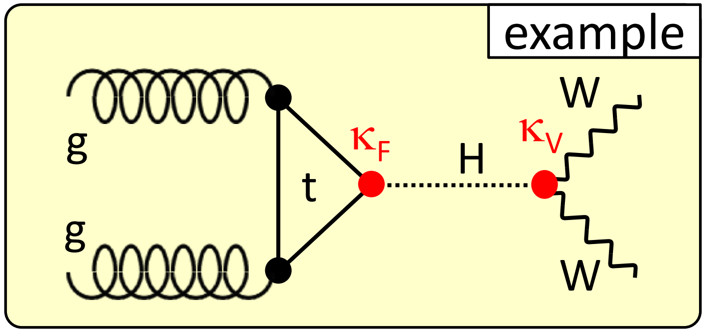
The modifiers κ already defined; in practice:

- $\kappa_j^2 = \dfrac{\Gamma^j}{\Gamma^j_{SM}}$ [j = all particles (f / V)];
- [simpler: only two: $\begin{cases}\kappa_f & \text{for fermions}\\ \kappa_V & \text{for IVBs}\end{cases}$;]

"κ_j" is the "non-SM"-ness of the j-coupling, e.g. :

- $\kappa_j = 0$ → no coupling observed in case "j";
- $\kappa_j = 1$ → compatible with SM → SM ok;
- $\kappa_j \gg 1$ → too large coupling → SM wrong;
- $\kappa_f \neq \kappa_V$ → fermions and IVBs different.





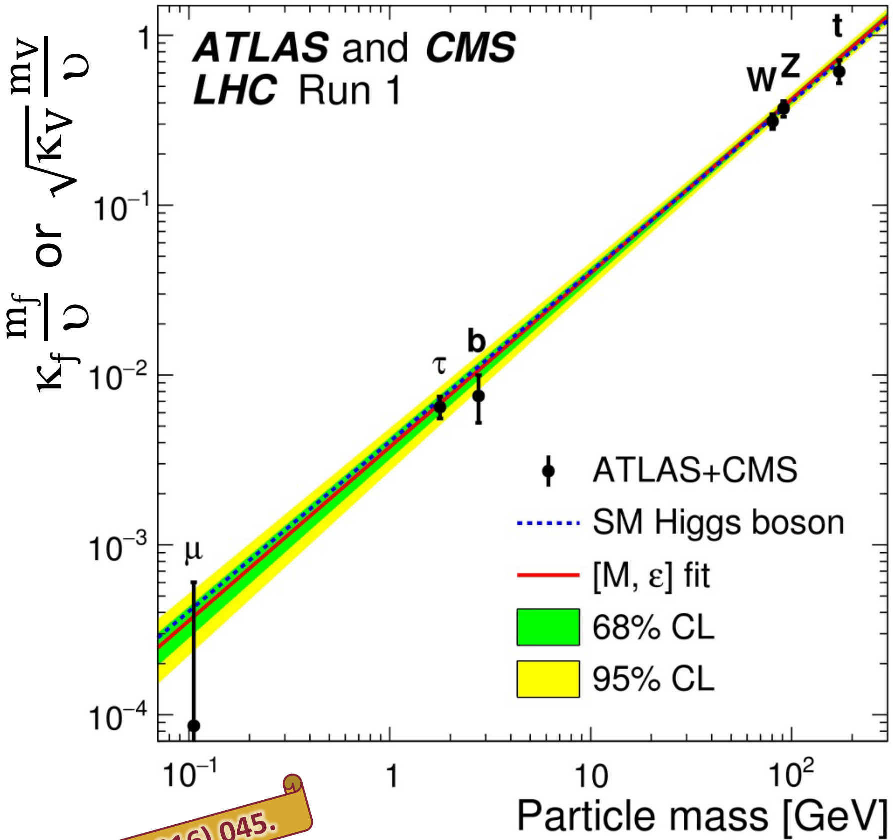
An example of this analysis:

- κ_F vs κ_V (i.e. fermions vs IVBs);
- large errors, but compatible with $\kappa_F = \kappa_V = 1$;
- agreement ATLAS ↔ CMS.

Higgs current status: couplings vs m_f/m_V

Higgs couplings (measured vs SM):

- plot together couplings (including κ_f, κ_V) vs mass of fermions and IVBs;
- clearly compatible with SM ($\kappa_f = \kappa_V = 1$);
- agreement ATLAS ↔ CMS;
- impressive, from m_μ to m_t → more than 3 orders of magnitude.



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The "[M, ε] fit" is another approach:

- redefine g_f and g_V:

$$g_f = \frac{m_f}{\upsilon} \rightarrow \left(\frac{m_f}{M}\right)^{1+\varepsilon};$$

$$g_V = \frac{2m_V^2}{\upsilon} \rightarrow \frac{2m_V^{2(1+\varepsilon)}}{M^{(1+2\varepsilon)}};$$

- fit M and ε from the data:

SM → $\varepsilon = 0$, $M = \upsilon = 246$ GeV.

fit →

$\varepsilon = 0.023 {+0.029} {-0.027}$

$M = 233 {+13} {-12}$ GeV

Higgs current status: other meas

Current status (not in these lectures, but PDG § 11, ICHEP 2016, Moriond '17/'18):

- (H→γγ) and (H→ZZ* → 4ℓ) golden;
- (H→WW* → ℓνℓν) solid;
- (H→ττ / b$\bar{b}$) less significant;
- also ttH / tH, (→ tH coupling);
- H→Zγ, c$\bar{c}$, μμ next in line (?);
- spin-parity: $J^P = 0^+$ (established);
- couplings (some results shown)

→ until now, all **compatible with SM**.

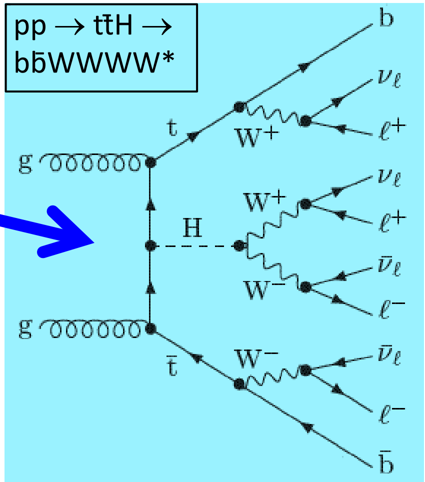
Next (limits on exotica already shown):

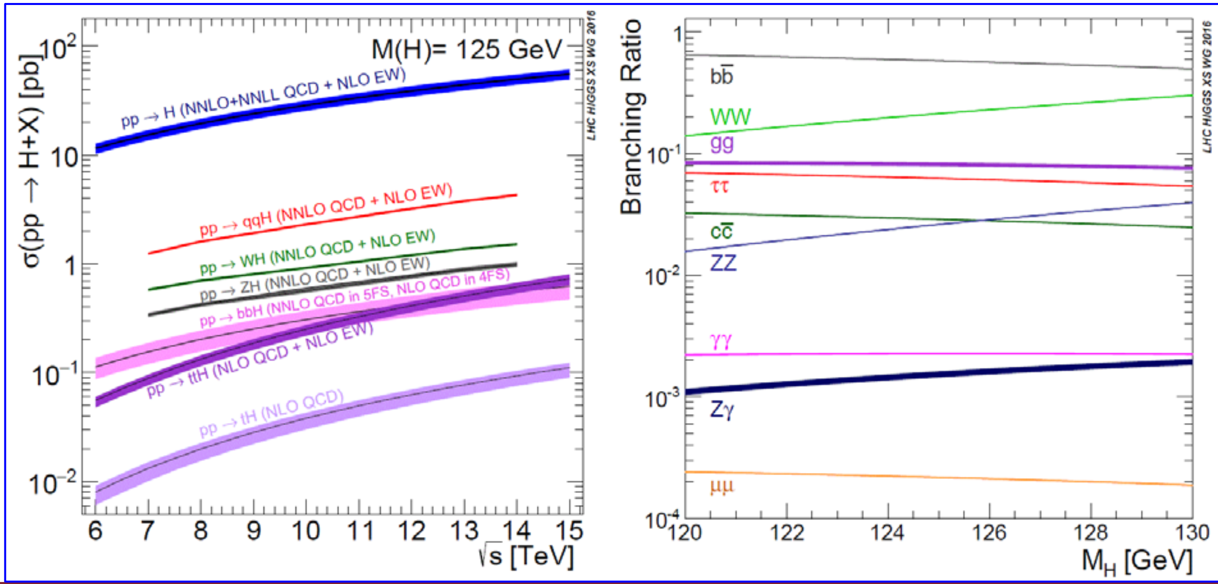
- rarer decays;
- HH (wait for HL-LHC);
- "violating" decays (e.g. lepton flavor);
- decays → dark matter;
- decays bSM (e.g. → SUSY);
- bSM Higgs (e.g. SUSY higgsinos);
- …

nice process:

- ≥ 4 ℓ± (e.g. 3μ 1e);
- ≥ 4 ν ($\not{E}_T$);
- 4 sec. vtx;

pp → t$\bar{t}$H → b$\bar{b}$WWWW*





Higgs current status: conclusion (1)

… finally (PDG 2018, §11.VIII, slightly simplified):

The discovery of the Higgs boson [*H*] is an important milestone in the history of particle physics. Five years after its discovery, a significant number of measurements probing its nature have been made. They are revealing an increasingly precise profile of the H.

The LHC has delivered in Run 2 a luminosity of more than 36 fb^{-1} of data collected by fully operational ATLAS and CMS. Milestone measurements have been performed: (i) H decay to $\tau^+\tau^-$ (CMS); (ii) H decay to $b\bar{b}$ (ATLAS+CMS); (iii) evidence for the production of the H through the $t\bar{t}H$ mechanism (ATLAS+CMS). These and all other experimental measurements are consistent with the EWSB [*ElectroWeak Symmetry Breaking*] mechanism of the SM.

New theoretical calculations are still occurring. With these improvements in the state-of-the-art in theory predictions and the increase in luminosity and energy, Higgs physics has definitively entered a precision era.

Since the discovery of the H, new ideas have emerged to probe its rare decays and production modes, as well as indirectly measure the H width. The H has now become part of the searches for new physics.

Many extensions of the SM at higher energies call for an enlargement of the EWSB sector. Hence, direct searches for additional scalar states can provide valuable insights on the dynamics of the EWSB mechanism. The ATLAS and CMS experiments have searched for additional H's, and imposed constraints in broad ranges of mass and couplings for various extended Higgs scenarios.

The landscape of Higgs physics has been extended extraordinarily since the discovery. The current dataset is approximately one percent of the total dataset foreseen for the High Luminosity-LHC. This perspective brings new challenges to increase further the reach in precision and it also widens the possibilities of unveiling the nature of the EWSB.

(continue …)

Higgs current status: conclusion (2)

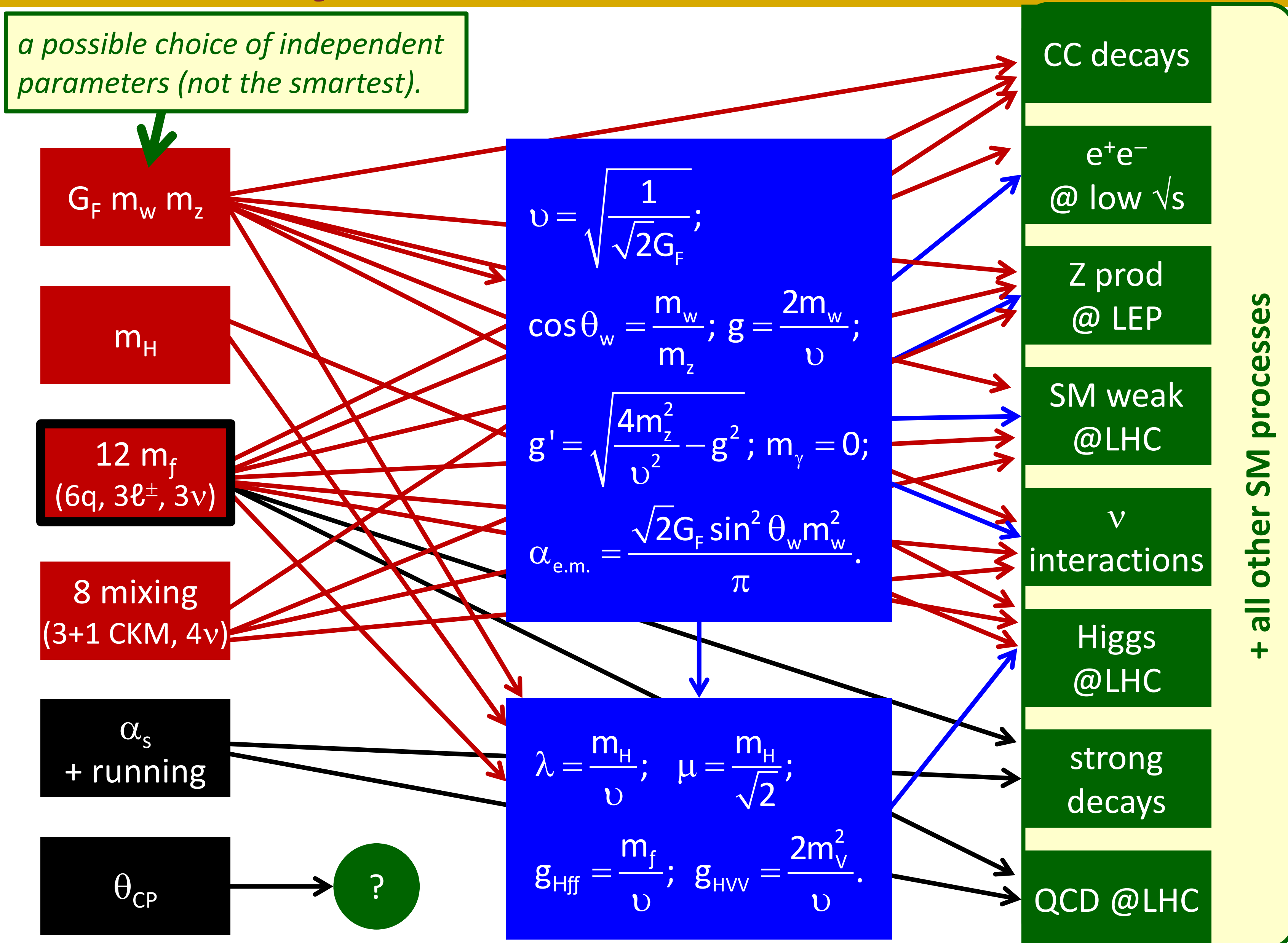
(... continue)

Outlook – The unitarization of the vector boson scattering (VBS) amplitudes was a determining consideration in the building of the accelerator and the detectors. It motivated the existence of a H or the observability of manifestations of strong dynamics at TeV scale. Now that a H has been found and its couplings to gauge bosons are consistent with the SM predictions, perturbative unitarity is preserved to a large amount with the sole exchange of the H, and without the need for any additional states. VBS is, however, still an important channel to investigate further in order to better understand the nature of the Higgs sector and the possible completion of the SM at the TeV scale.

The H couplings are not dictated by any local gauge symmetry. Thus, in addition to a new particle, the LHC has also discovered a new force, different in nature from the other fundamental interactions since it is non-universal and distinguishes between the three families of quarks and leptons. The existence of the H embodies the problem of an unnatural cancellation among the quantum corrections to its mass if new physics is present at scale significantly higher than the EW scale. The non-observation of additional states which could stabilize the H mass is a challenge for natural scenarios like supersymmetry or models with a new strong interaction in which the H is not a fundamental particle. This increasingly pressing paradox starts questioning the principle of naturalness.

The search for the H has occupied the particle physics community for the last 50 years. Its discovery has shaped and sharpened the physics programs of the LHC and of prospective future accelerators. The experimental data together with the progress in theory mark the beginning of a new era of precision H measurements.

SM today: a simple tree-level flow-diagram



a change of perspective

For the first time after (maybe) the birth of quantum mechanics, elementary particle physics is in an uncommon state:

- no major (nor minor) prediction awaits confirmation (e^+, $\bar{p}$, …, $W^{\pm}$, Z, t, …, H all discovered);
- no major (nor minor) observed phenomenon awaits explanation (strong interactions have been tamed, CP violation is under control);
- exceptions : **dark energy + dark matter**;
- hope in the few missing pieces (ν masses and mixing, Higgs precision measurements, QCD @ low Q^2, …);

→ **(personal) conclusion**:

Either we are at the borders of a big desert, or some new physics (e.g. SUSY, extra-dimensions, …) is just above the present limits, but has not given us the slightest hint of a presence:

... however, much indirect evidence that this story has more chapters ...

why the SM is not final

The SM does NOT explain [*SNOWMASS 2013, Energy frontier summary*]:

a. dark matter/energy [*85% of the matter in the universe is "dark" - neutral, weakly interacting*];

b. excess of baryons over antibaryons in the universe [*the SM contains a mechanism to generate baryon number in the early universe, baryon number violation, CP violation, and a phase transition in cosmic history; however it predicts a baryon-antibaryon asymmetry that is too small by ten orders of magnitude*];

c. grand unification [*the quantum numbers of the quarks and leptons under the gauge symmetry SU(3)×SU(2)×U(1) of the SM suggests that these symmetry groups are unified into a larger grand unification group, like SU(5) or SO(10); however, the results of precision measurements of the strengths of the gauge couplings is inconsistent with this hypothesis*];

d. ν masses [*the SM could account for Dirac ν's with few new parameters – technically simple, but intriguing*];

e. fermion mixing [*the pattern of weak interaction mixing among neutrinos is completely different from that observed for quarks*];

f. gravity [*no quantum theory of gravity is incorporated in the SM*].

These difficulties are not equally important [*I am particularly impressed by (a) and (f)*] – However, all together largely justify the claim that the present SM is not the last word of the story.

Thanks for attending

Best wishes !

_P.B._

References: results

1. Science, 338 (2012) 1560, 1569, 1576 [simple, divulgative];
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3. Higgs (predictions) : YR CERN-2011-002, CERN-2012-002, CERN-2013-004;
4. Higgs (exp.) : A.Nisati, G.Tonelli - Riv. Nuovo Cimento, 38 (2015), 507 [clear, detailed];
5. H mass : ATLAS+CMS, Phys. Rev. Lett. 114, 191803 (2015);
6. H production + decay : ATLAS+CMS, JHEP08 (2016) 045.
7. https://twiki.cern.ch/twiki/bin/view/LHCPhysics ;
8. https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CombinedSummaryPlots/ ;
9. https://twiki.cern.ch/twiki/bin/view/AtlasPublic/StandardModelPublicCollisionPlots.

Évrard d'Espinques - The knights and kings of the Round Table experiencing a vision of the Holy Grail, miniature tirée du "Lancelot en prose" a.d. 1474 [French National Library].

References: gif's

1. ATLAS animated gifs:
   https://twiki.cern.ch/twiki/bin/view/AtlasPublic/HiggsPublicResults#Animations
2. ditto for CMS:
   https://twiki.cern.ch/twiki/bin/view/CMSPublic/Hig13002TWiki

Caravaggio (Michelangelo Merisi) – I bari – ca 1594
Kimbell Art Museum, Fort Worth

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End of chapter 12