Collider Physics - Chapter 5b

LHC – Higgs discovery

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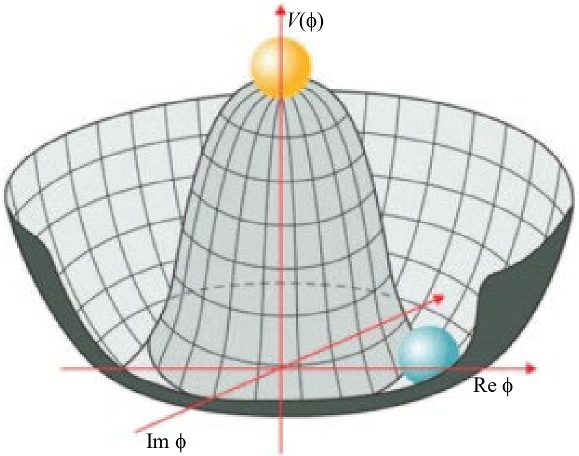
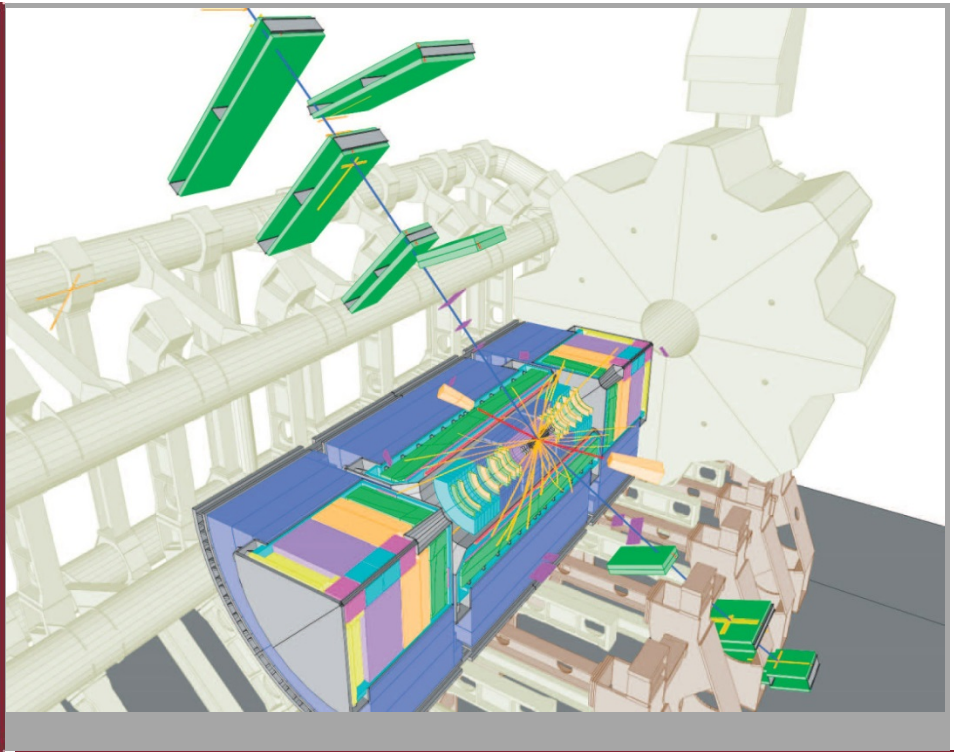
AA 21-22

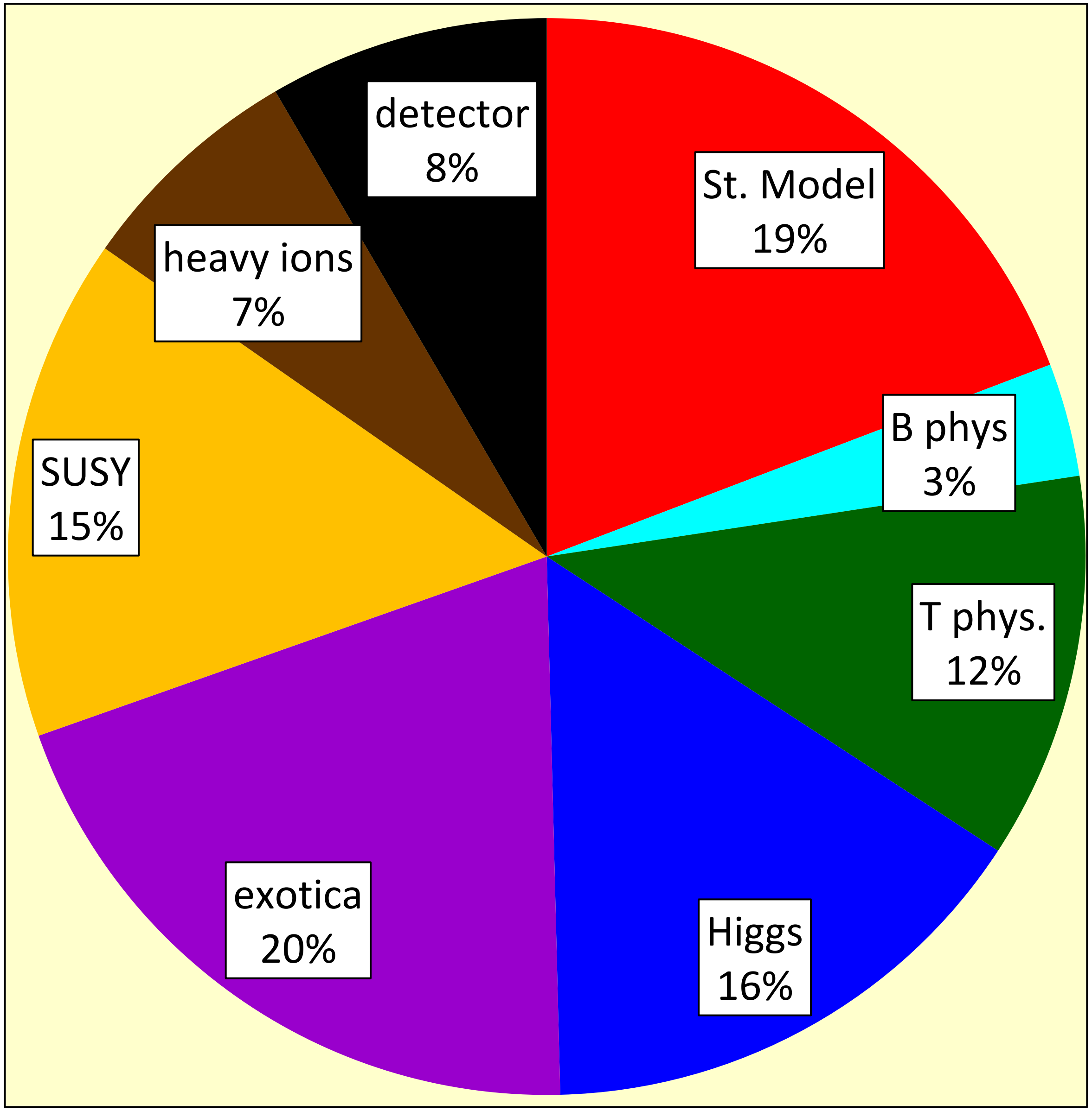
last mod.
1-Dec-21

5 – LHC – Higgs discovery





LHC papers

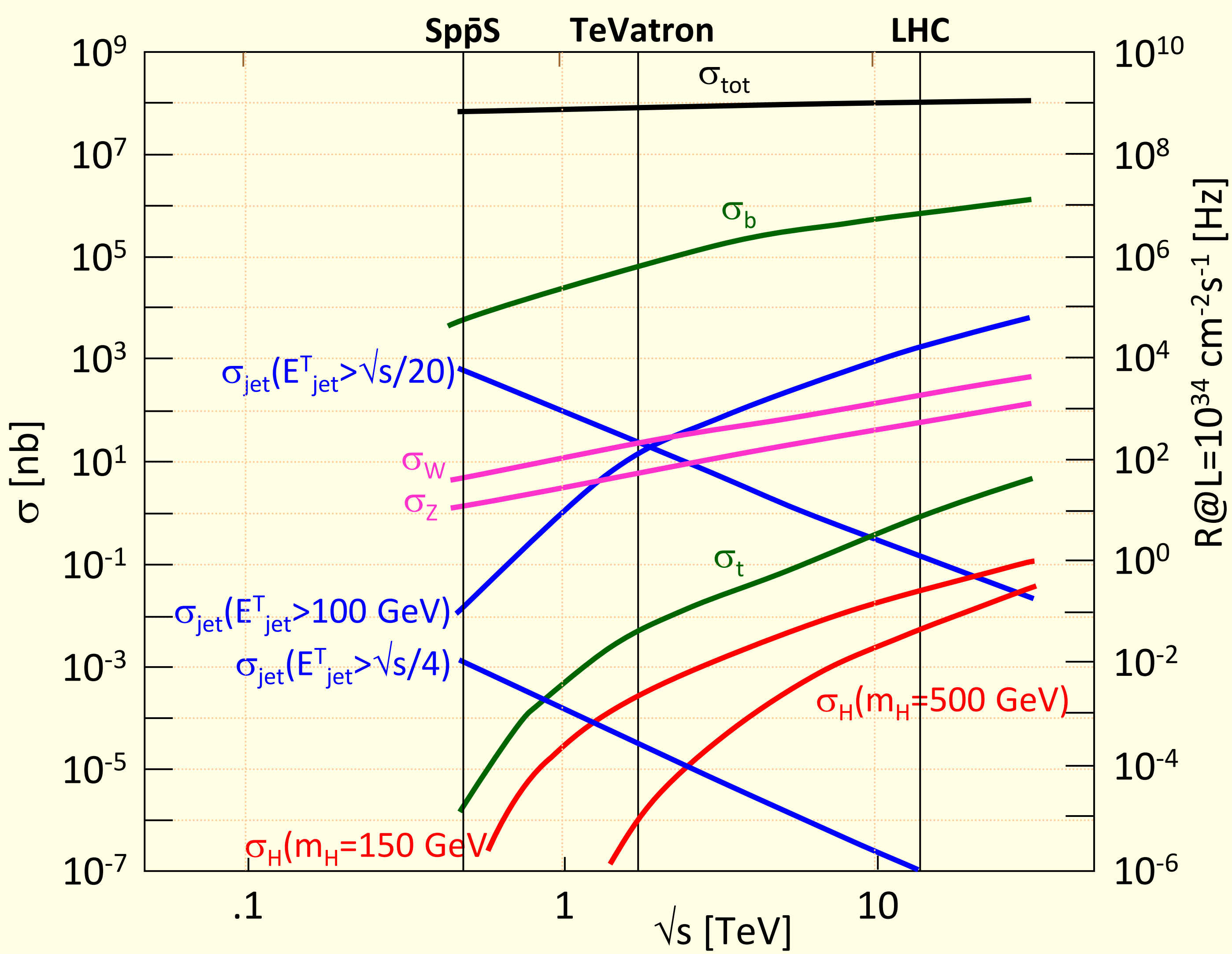


ATLAS < April 2021

- ~ 1000 papers;
- > 100 papers/year;
- [arbitrarily] divided into 8 subjects;
- bSM searches > ⅓;
- in the future [*probably*]:
  - slower rate (dominated by stat + sys.);
  - more bSM.

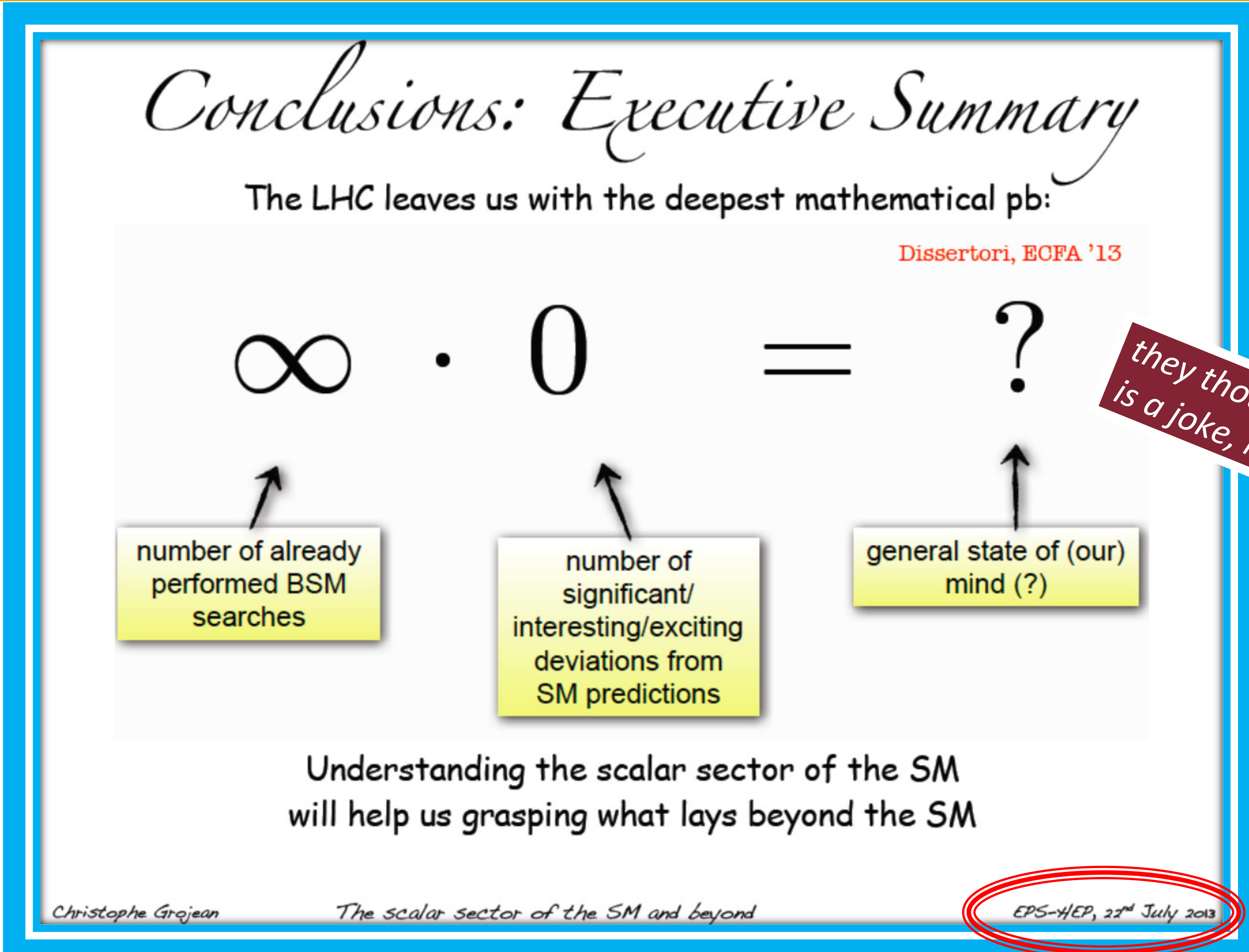
[*NB too boring to repeat it for CMS, but must be very similar*]

LHC processes



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

NB. Spp̄S and Tevatron are p̄p, LHC is pp. *However, no difference within the accuracy of this plot.*



they thought it is a joke, really

LHC results: jet spectrum

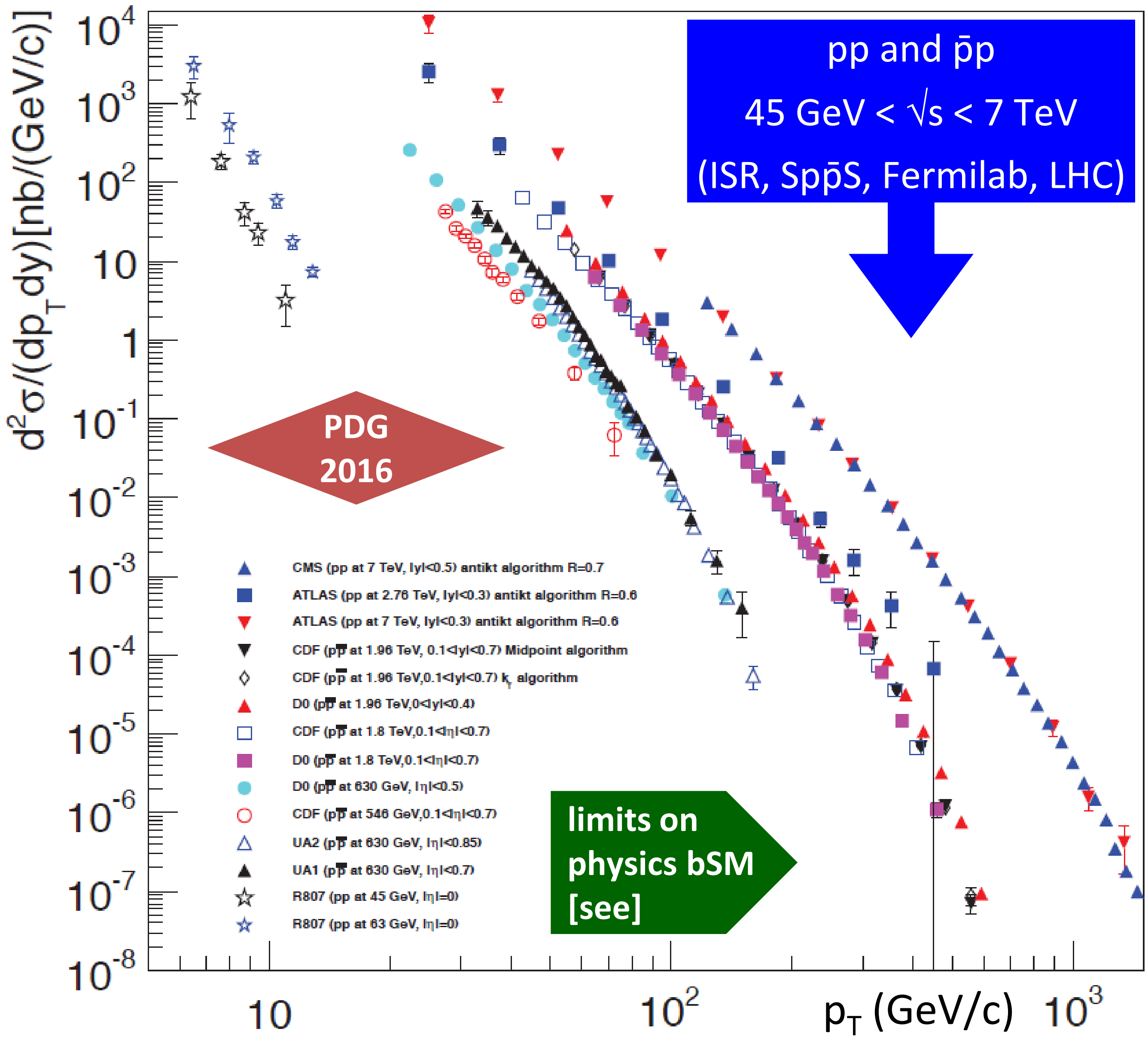
"Simple" explanation:

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.

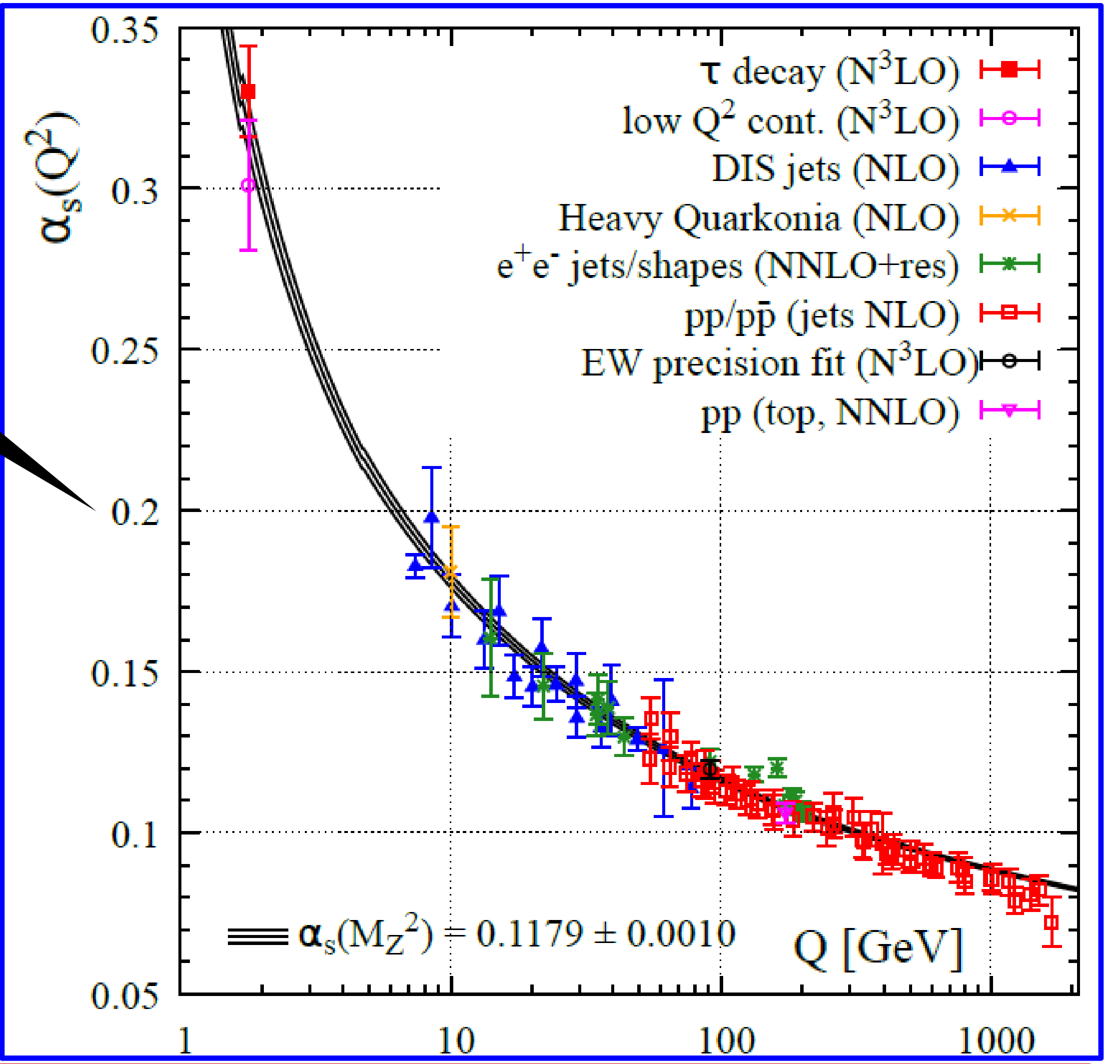
The CDF and D0 measurements use jet sizes of 0.7 (JetClu for CDF Run 1, and Midpoint and kT for CDF Run 2, a cone algorithm for D0 in Run 1 and the Midpoint algorithm in Run 2). The ATLAS results are plotted for the antikT algorithm for R=0.4, while the CMS results also use antikT, but with R=0.5. NLO 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.



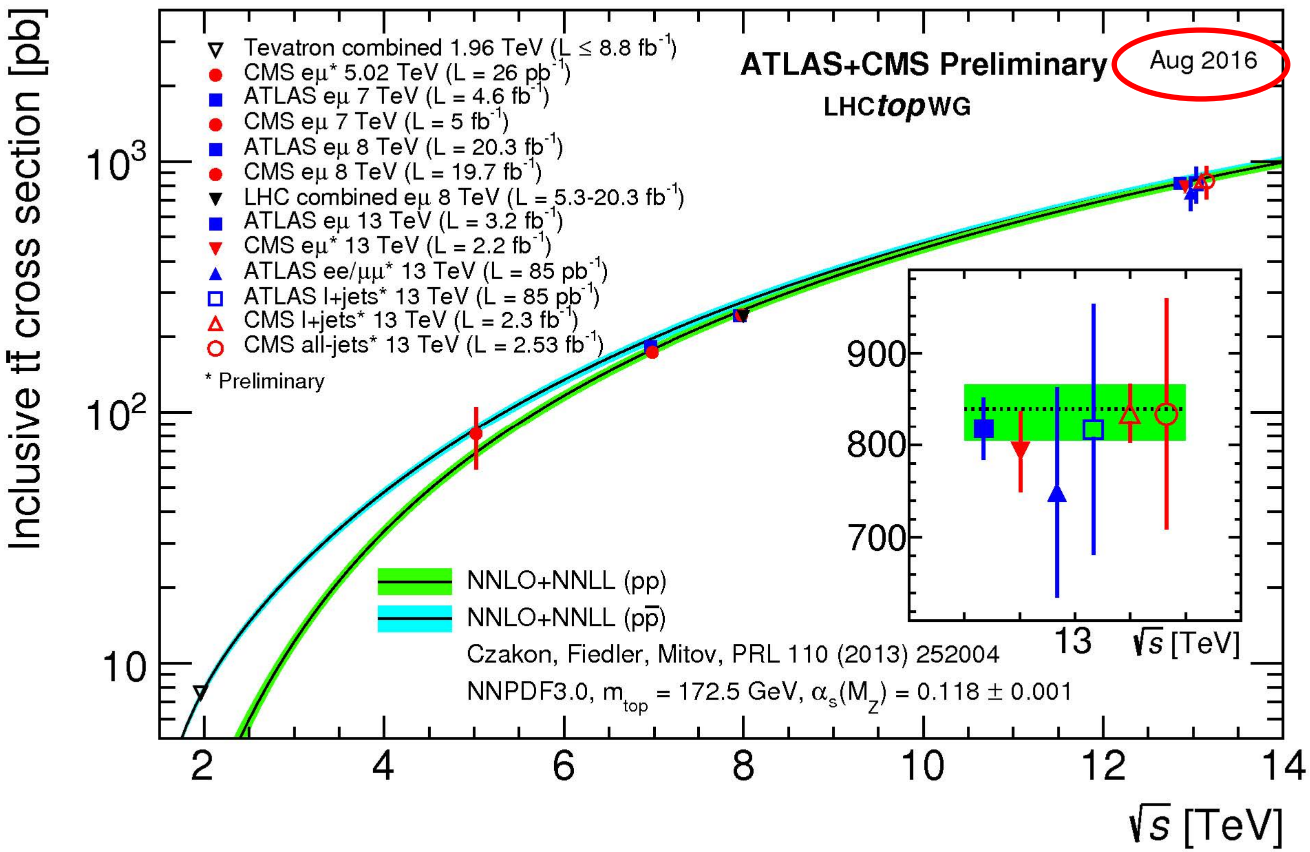
LHC results: α_s running

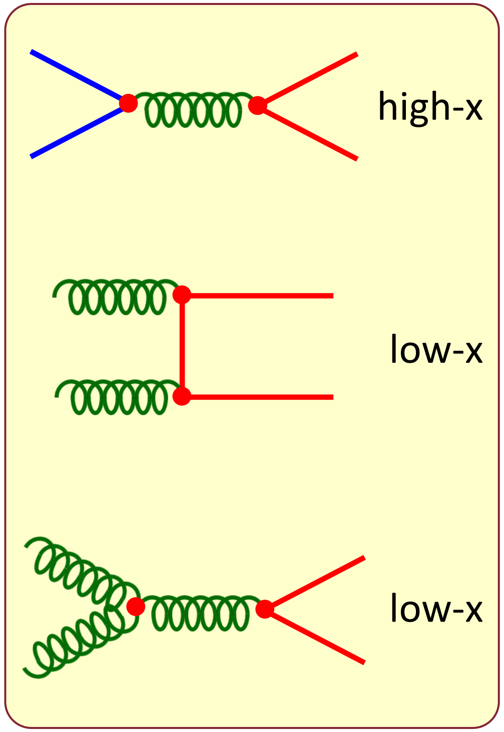
PDG 2020, an update of the plot shown in PP-§6, with many more points.



$$\alpha_s\left(Q^2\right)=\alpha_s\left(Q_0^2\right)\Big/\left[1+\alpha_s\left(Q_0^2\right)\frac{11N_c-2N_f}{12\pi}\ln\left(\frac{Q^2}{Q_0^2}\right)\right];\qquad N_c=3;\qquad N_f=3\to 4\to 5\to 6.$$

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

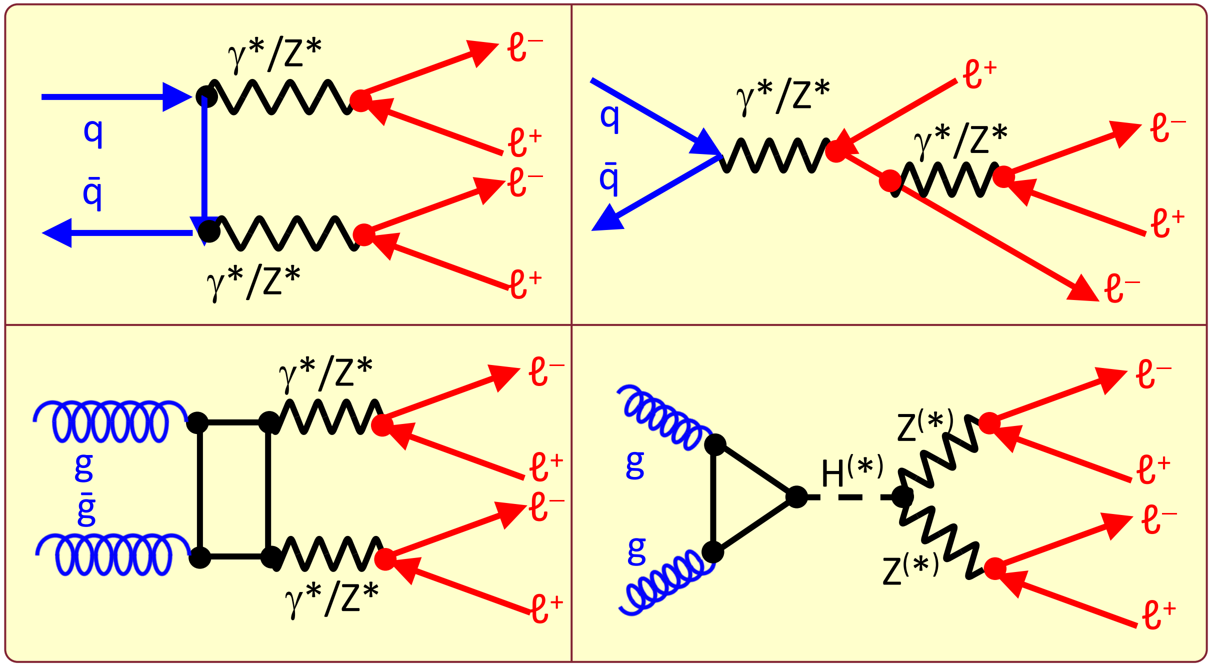


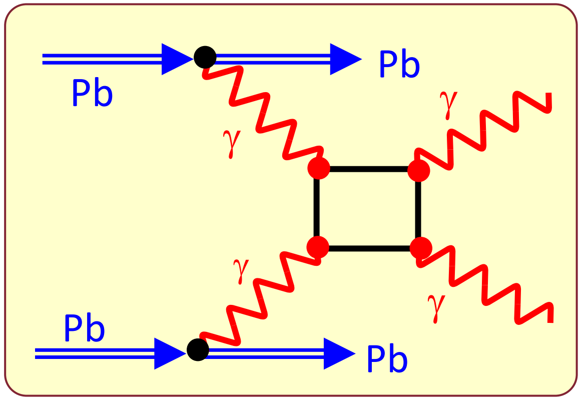


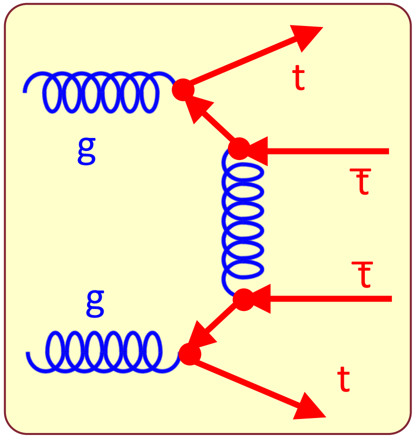
- technically a difficult analysis (secondary verteces + leptons + multijets + $\not{E}_T$);
- agreement ATLAS ↔ CMS and QCD ↔ data;
- [as seen in PP-§3] p̄p larger at small √s, but pp similar when √s increases, due to gluon dominance in PDF at small x;
- another perfect agreement, textbook-like.

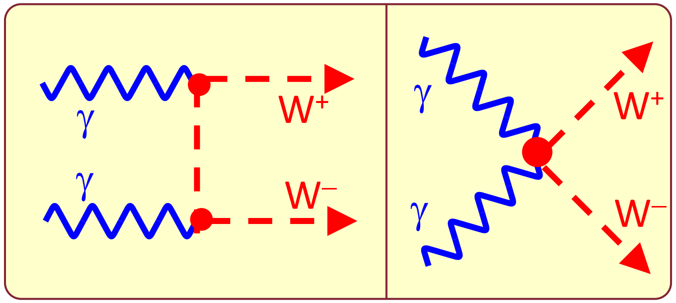
LHC results: nice SM rare processes (1)

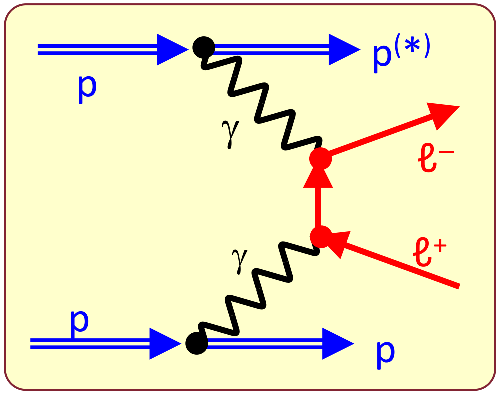
only diagram at tree level for some very smart analyses; interested readers are kindly invited to look at the Prague 2020 material, e.g. the talk of Bogdan Malaescu.



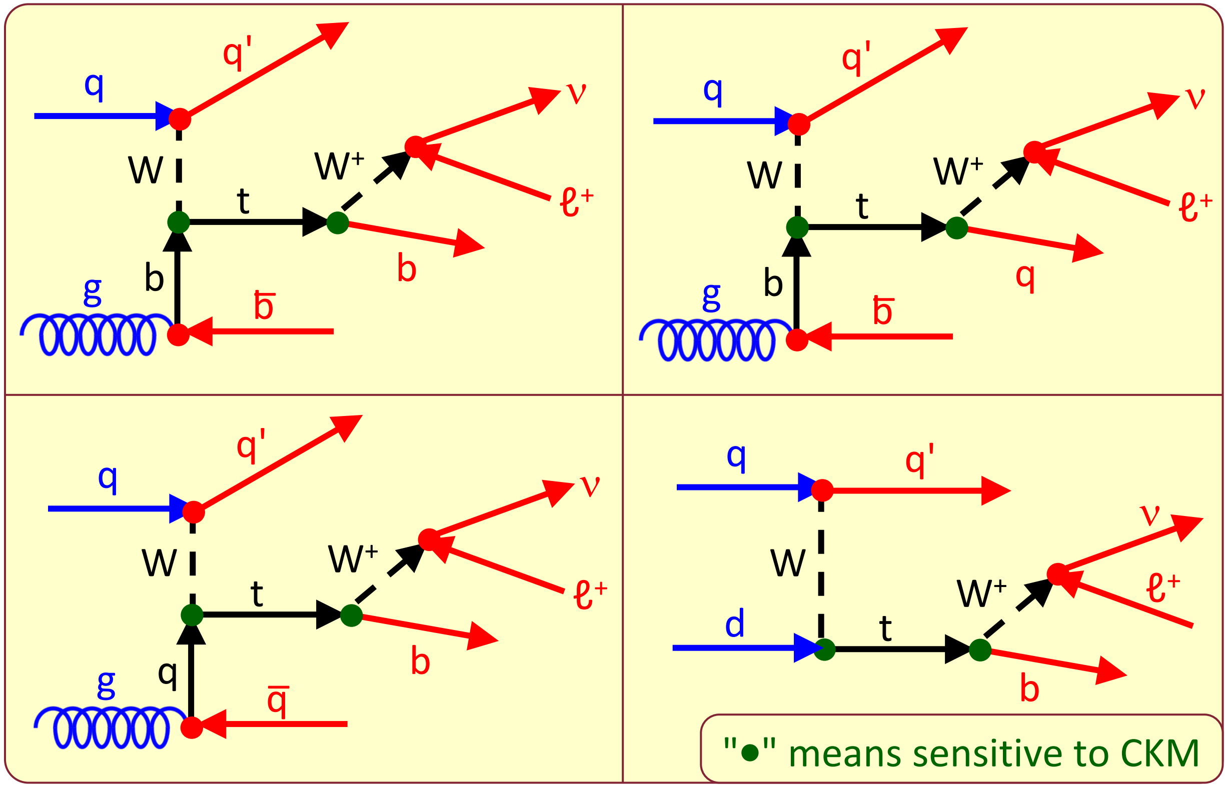


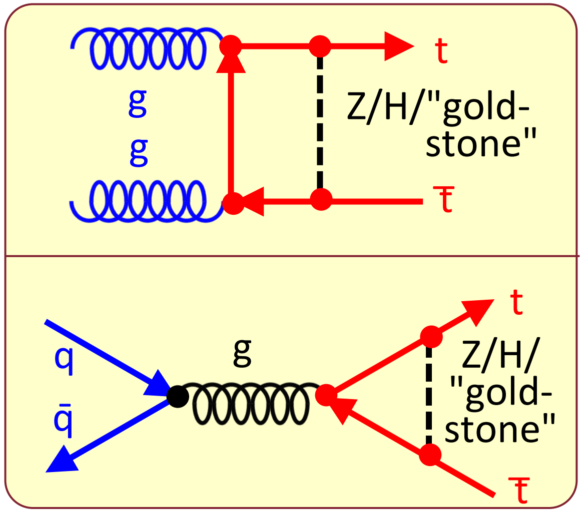


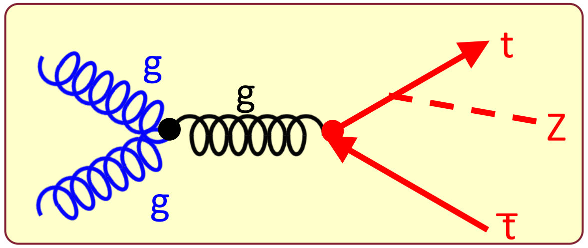


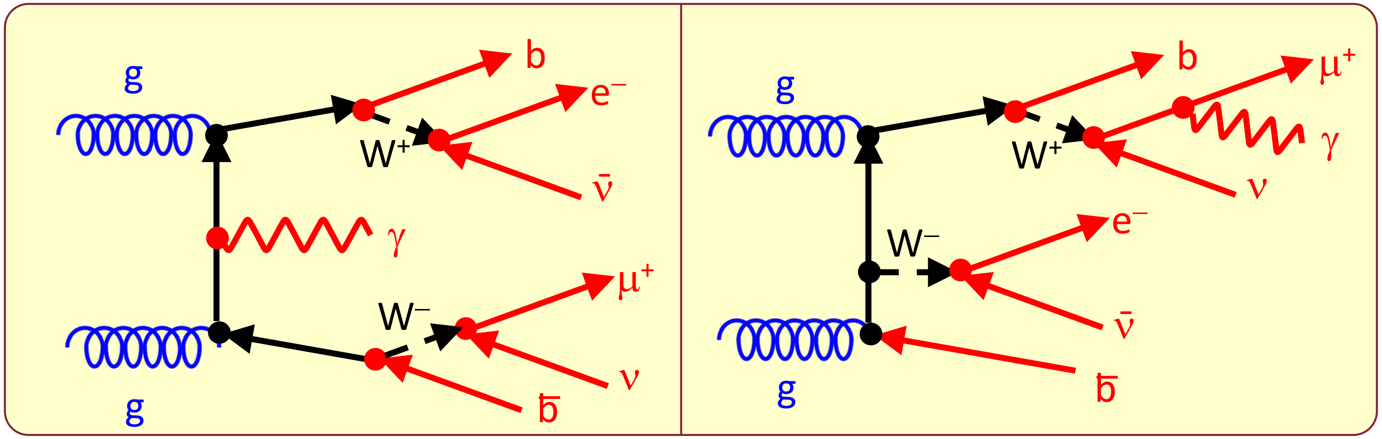


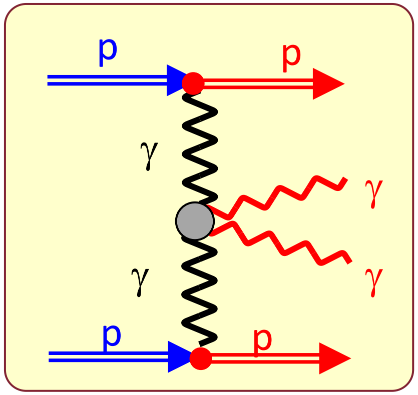
LHC results: nice SM rare processes (2)





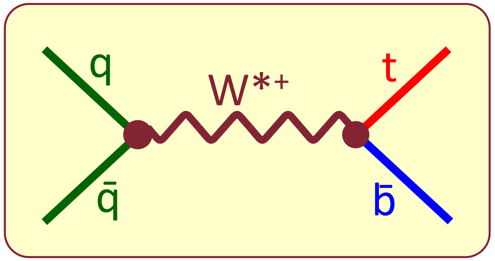




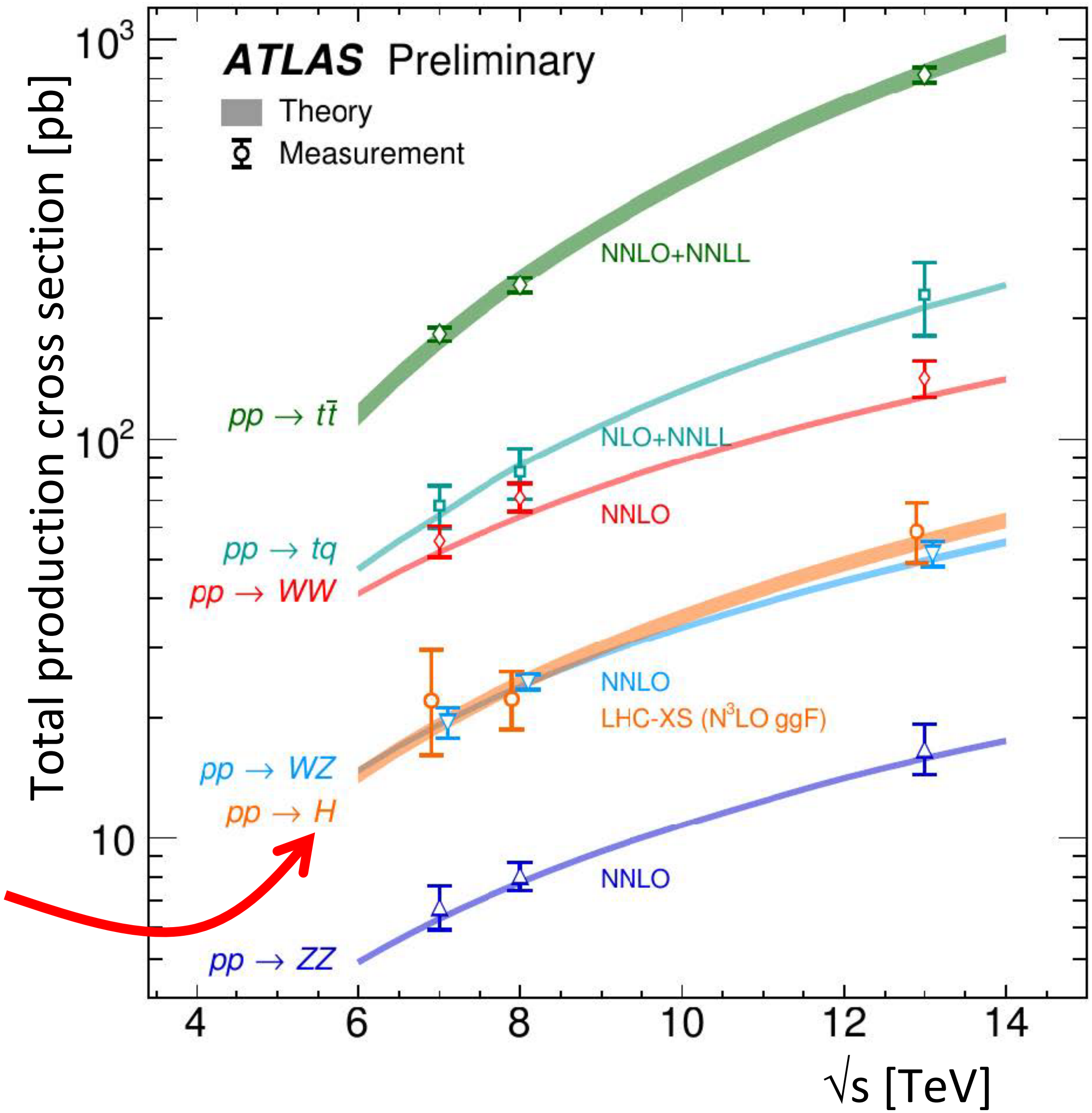


LHC results: small-σ processes

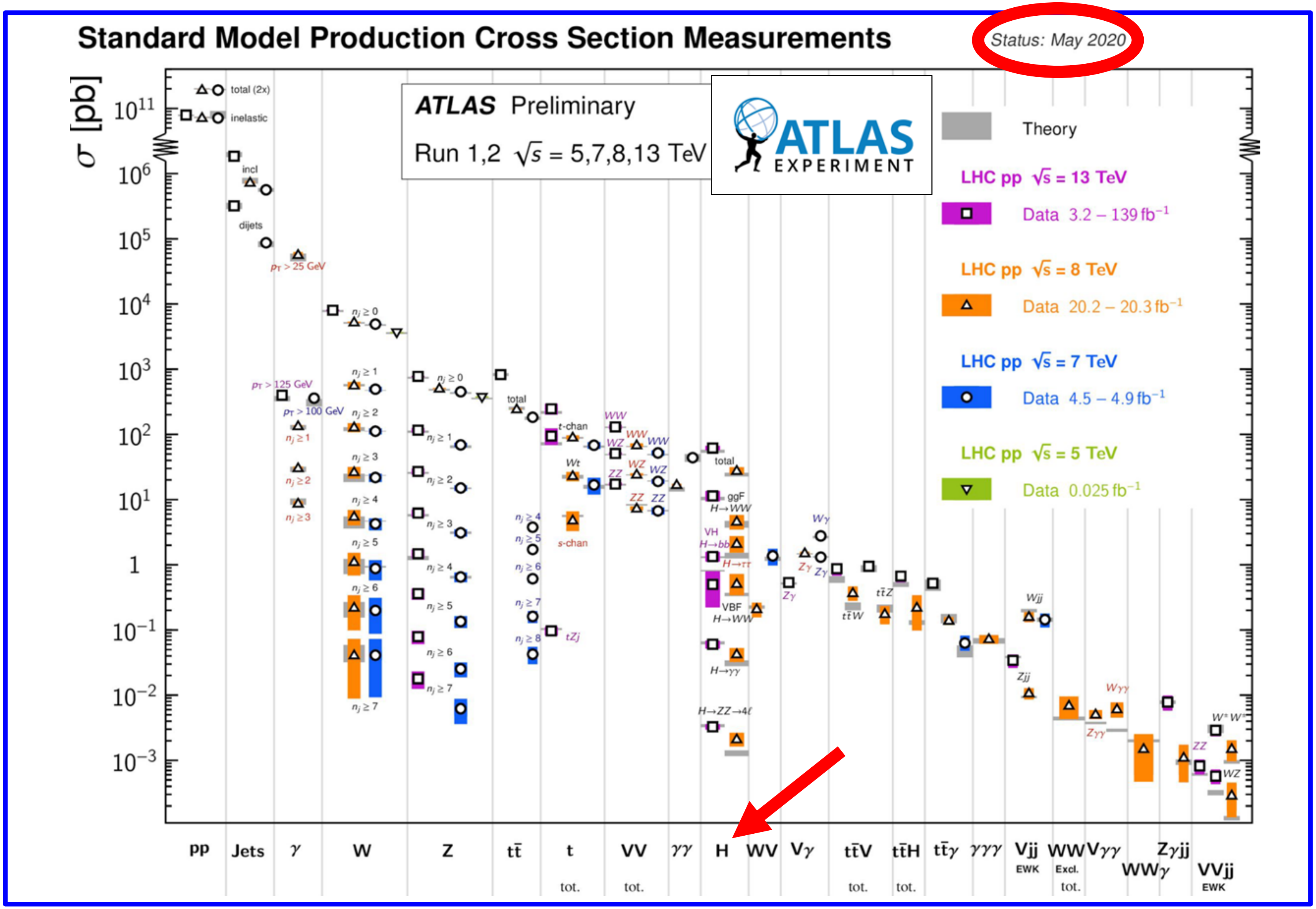
- the "heavy flavor/boson" sector:
  - $t\bar{t}$ (QCD);
  - single top (ew) [*example below*];



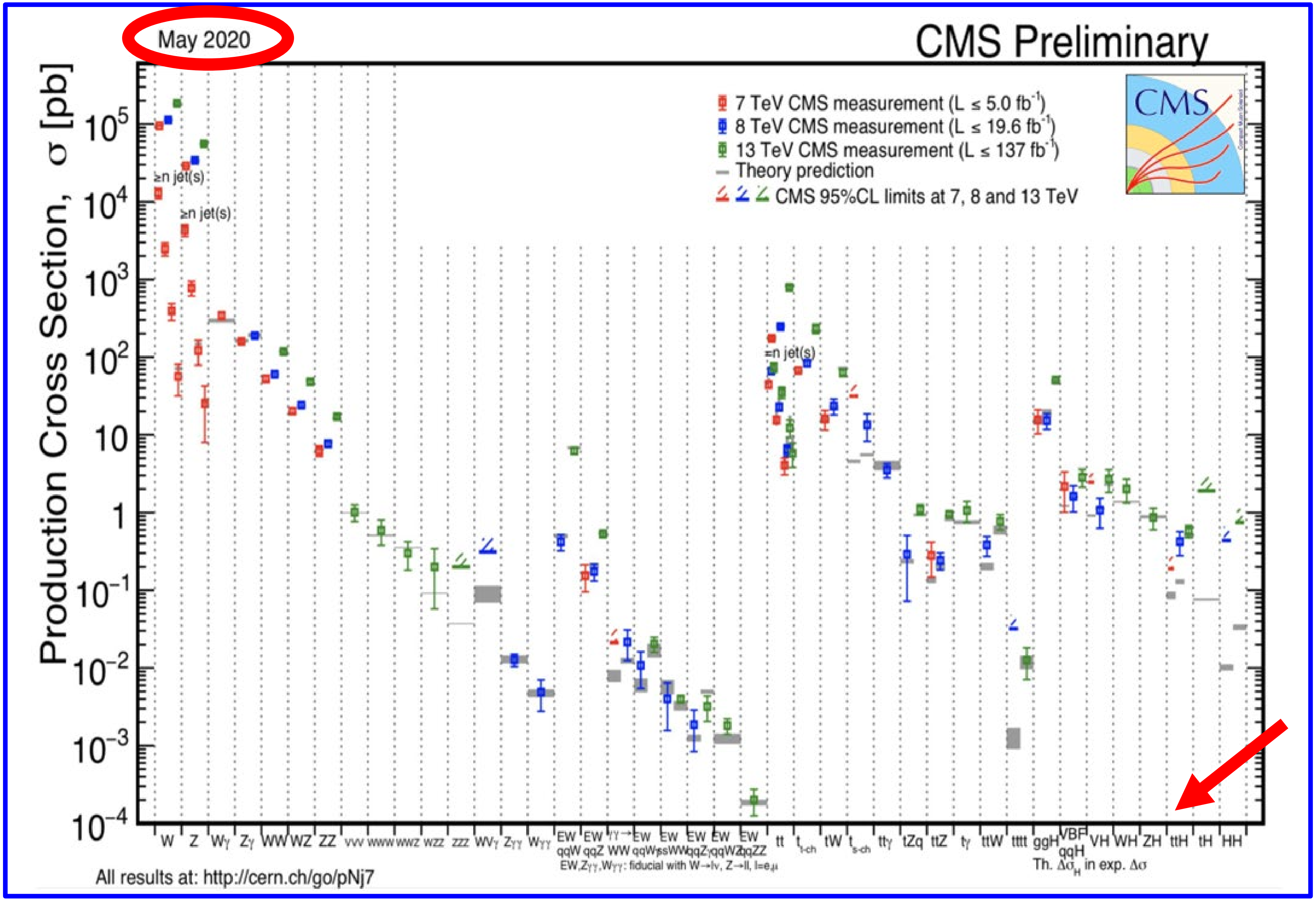
  - WW, WZ, ZZ (ew);
  - H (ew);
- shown vs √s;
- notice:
  - LHC "sees" well at the pb level;
  - H is not very different from ZW / WW / ZZ channels, neither as mass, nor as σ, nor as √s dependence;
- SM (qpm + pQCD + ew) works well.



LHC results: SM processes (ATLAS)

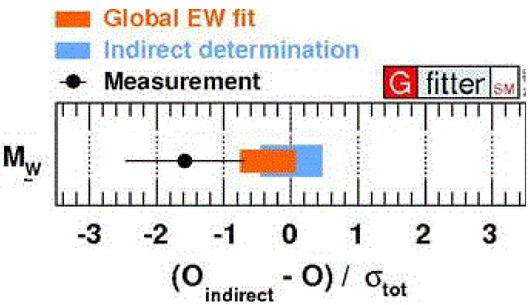


LHC results: SM processes (CMS)



LHC fits: Rosetta stone of the SM fit

J. Haller et al., arXiv: 1803.01853 [hep-ph] : "Comparison of the fit results and the input measurements with the indirect determinations in units of the total uncertainties. Analog results for the indirect determinations illustrate the impact of their uncertainties on the total uncertainties. The indirect determination of an observable corresponds to a fit without using the constraint from the corresponding input 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} : $\sigma_{exp} \oplus \sigma_{indirect}$.

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 : $(O_{indirect} - O_{exp}) / \sigma_{tot} \pm \sigma_{exp}/\sigma_{tot}$.

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

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]

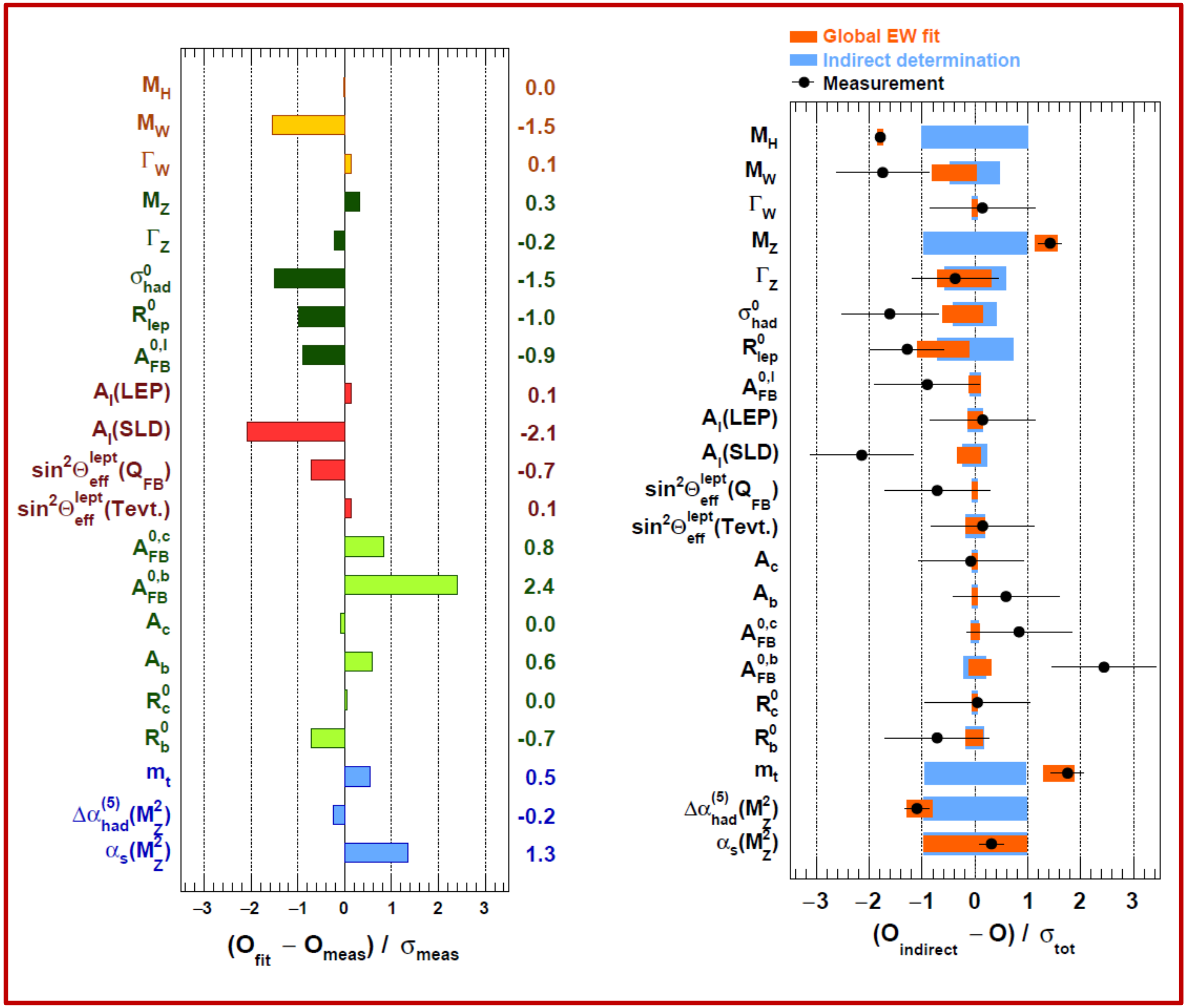
———————————————

"$\oplus$" = "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 fits: results

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



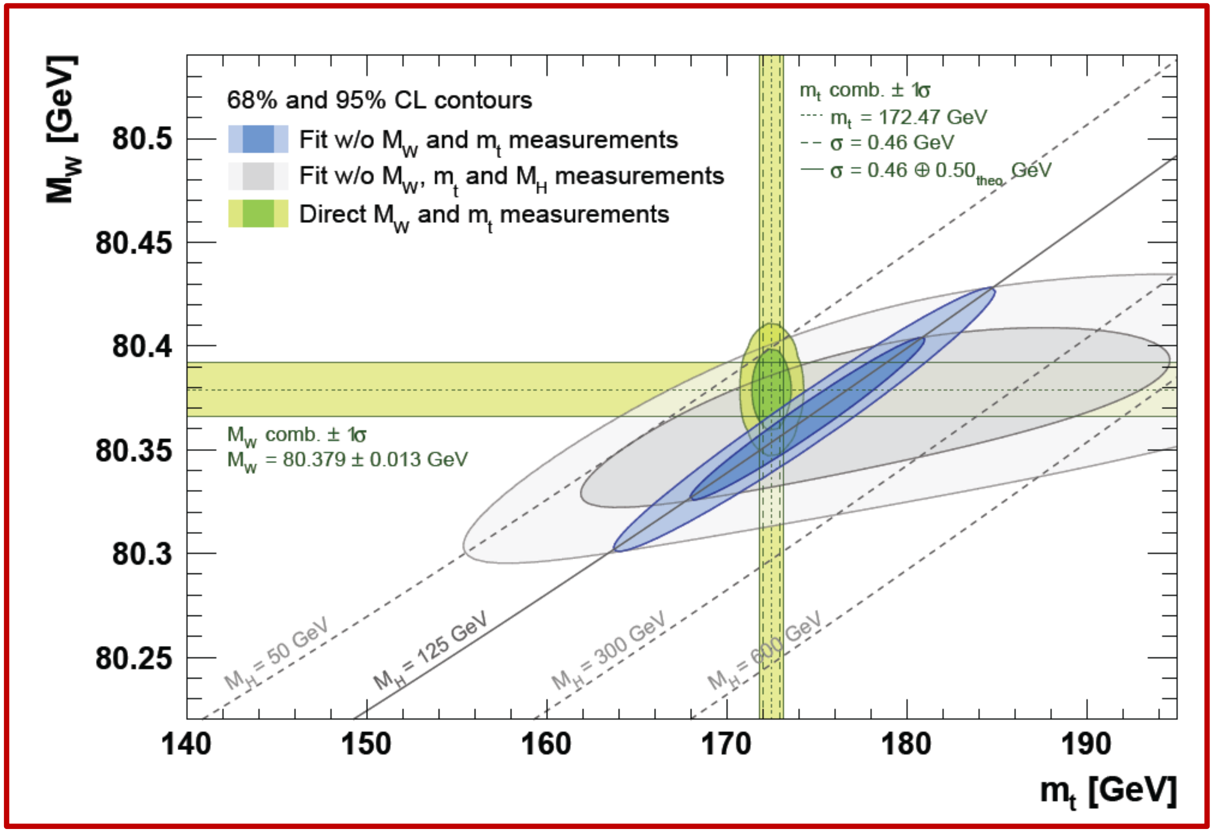
LHC fits: m_w vs m_t

The LHC version of an old plot: m_w vs m_t for few values of m_H;

- supposed to be very sensitive to physics bSM (and to exp. mistakes !);
- watch the blue and green ellipses ...
- ... and fear (*hope* ?) they move apart;
- it would show that m_H is inconsistent with the other masses → the 125 GeV particle is NOT the SM Higgs.

any
hope
?

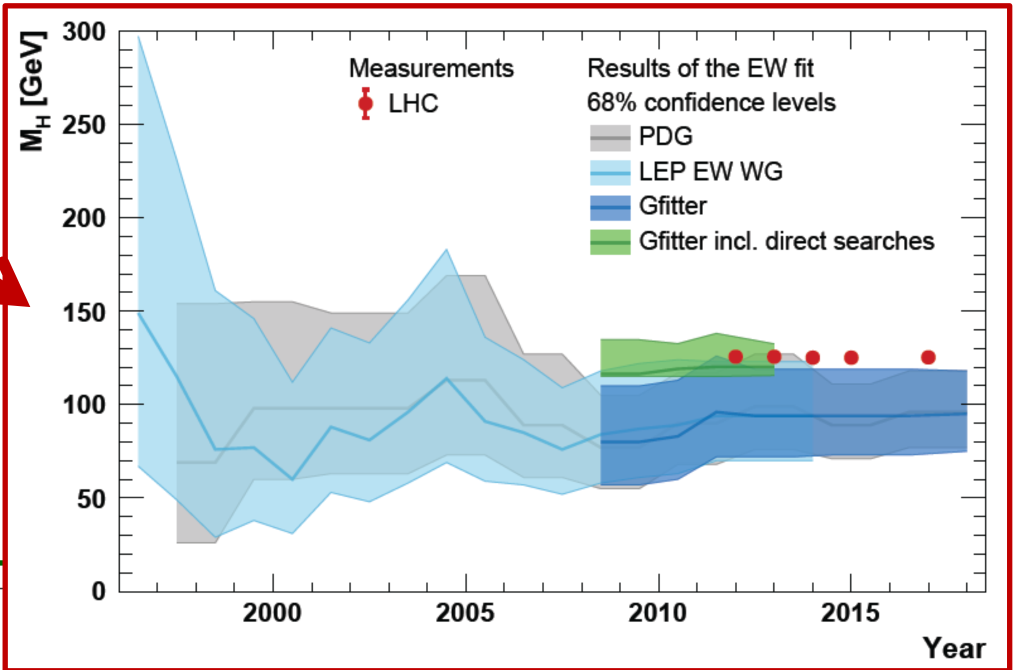
keep improving !!!
[especially m_w !!!]

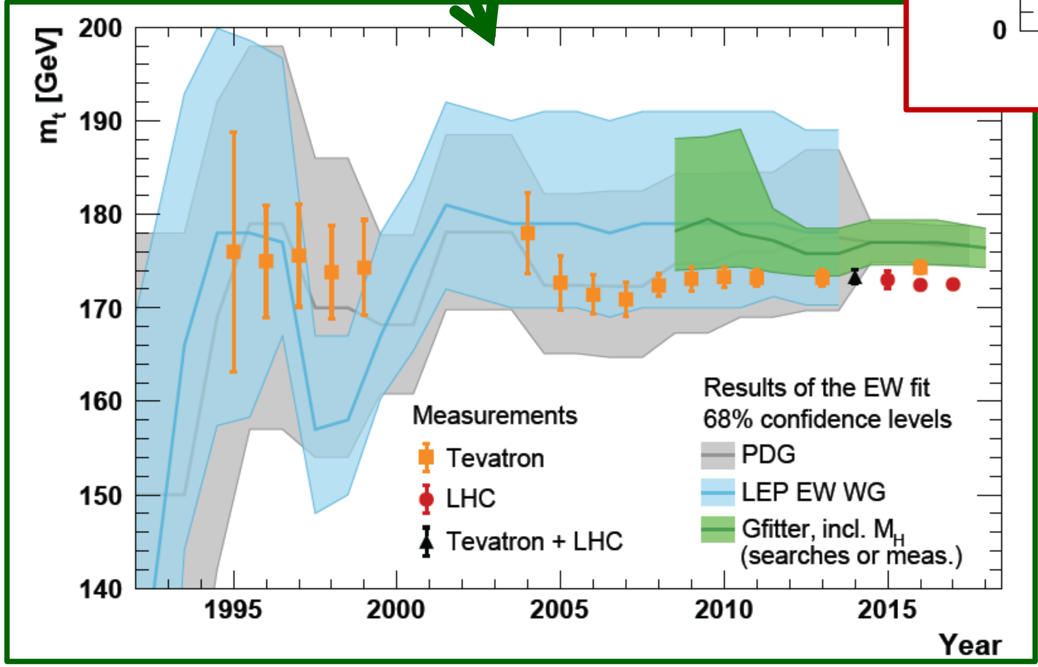


LHC fits: fits vs discoveries

The prediction from SM fits and the direct observation vs year for:

- m_H, the Higgs mass (indirect data from LEP, Fermilab, LHC, direct observation at Fermilab+LHC));
- m_t, the top quark mass (ditto for i.d., d.o. at LHC).





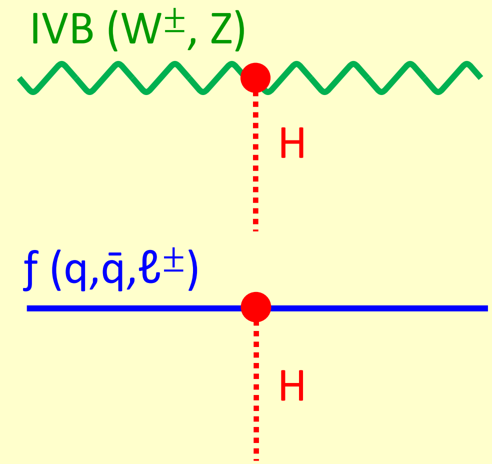
Why show these plots ?

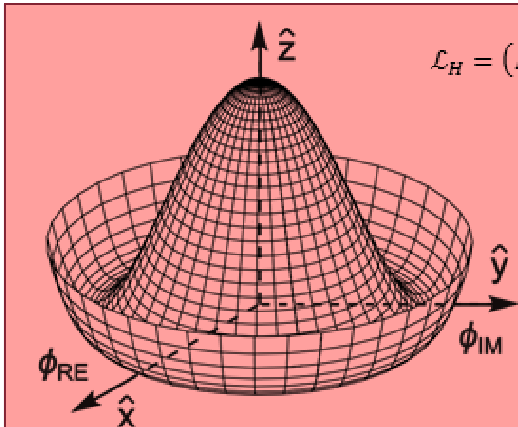
- irrelevant for physics, which is independent of discovery time and method;
- **NOT** for parochial feuds ("*who really made the discovery* ?");
- ... but to give confidence on the quality and reliability of the fits;
- ... which however require a lot of tech. skill (... *and are less convincing*...)

the MSM Higgs

$\not{m}_H$

- [*the symbol* $\not{m}_H$ *means that in the slide the value of the mass of the Higgs is unknown and 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..





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

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

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

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

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

H(MSM): potential V_H

Define the SM parameters (as in PDG 2020 §11):

$V_H(\phi) = \mu^2\phi^\dagger\phi + \lambda(\phi^\dagger\phi)^2 + \cancel{const.}$;

$V_H = 0 \rightarrow \phi(V_H = 0) \equiv \upsilon = \sqrt{-\mu^2/\lambda} = \left(\sqrt{2}G_F\right)^{-1/2}$;

$m_H^2 = 2\lambda\upsilon^2 = -2\mu^2$;

ⓘ notice: $\mu^2 < 0$ (!)

$m_W^2 = \dfrac{g^2\upsilon^2}{4}$; $m_Z^2 = \dfrac{\left(g^2 + g'^2\right)\upsilon^2}{4} = \dfrac{m_W^2}{\cos^2\theta_W}$; $m_\gamma^2 = 0$;

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

$\mathscr{L}^{coupling}_{Higgs} = -g_f\overline{\psi}_f\psi_f H + \delta_V g_V V_\mu V^\mu H + [...]$;

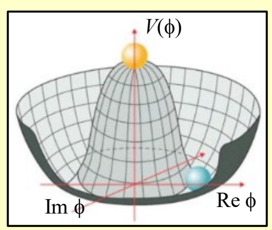
$[V = W/Z;\quad \delta_W = 1;\quad \delta_Z = ½]$

$g_f = m_f/\upsilon$; $g_V = 2m_V^2/\upsilon$;

PDG § 11, YN3, Degrassi : this def;

PDG § 10: $\mu^2\phi^2$ + ½□ ^{4};

Thomson: ½$\mu^2\phi^2$ + ¼□ ^{4}; etc etc



$\upsilon \approx 246.6$ GeV (indep. of m_H);

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

$\lambda^{exp} = \dfrac{m_H^2}{2\upsilon^2} \approx 0.128$;

$\left|\mu^{exp}\right| = \dfrac{m_H}{\sqrt{2}} \approx 88$ GeV.

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

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

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

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

and adjust κ_f and κ_W to the data;

$\kappa_j^2 = \dfrac{\sigma_j^{exp}}{\sigma_j^{SM}}$; or $\kappa_j^2 = \dfrac{\Gamma_j^{exp}}{\Gamma_j^{SM}}$;

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

H(MSM): function V(φ)

Study the function $V=V(|\phi|)$:

$$V_H(\phi) = \mu^2\left(\phi^\dagger\phi\right) + \lambda\left(\phi^\dagger\phi\right)^2 =$$

$$= \mu^2\left(|\phi|^2 + \frac{\lambda}{\mu^2}|\phi|^4\right) =$$

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

$\mu^2 < 0$

$$|\mu| = \frac{m_H}{\sqrt{2}}; \qquad \lambda = \frac{m_H^2 G_F}{\sqrt{2}};$$

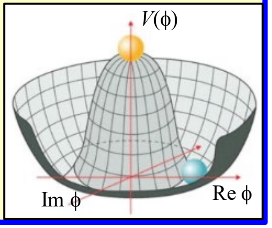
$$\upsilon = \left(\sqrt{2}G_F\right)^{-1/2} \approx 246.6 \text{ GeV};$$

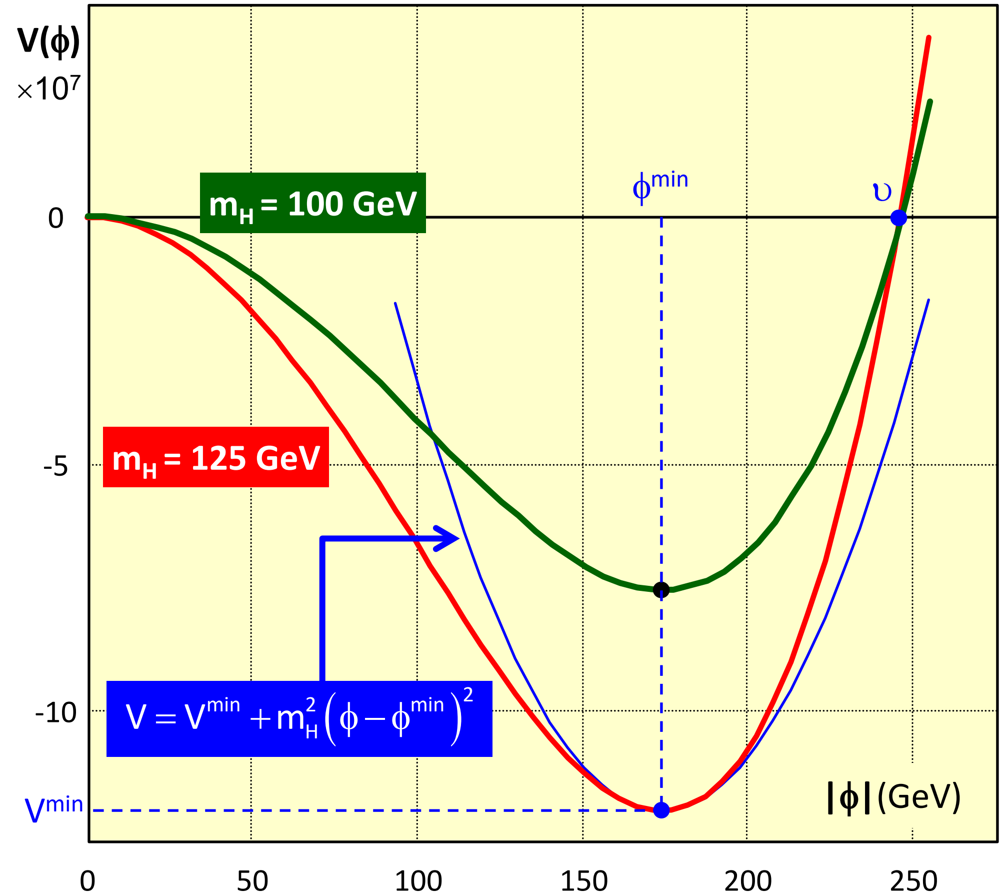
(prev. page)

$$\frac{\partial V_H}{\partial \phi} = 0 \rightarrow \phi^{min} = \frac{|\mu|}{\sqrt{2\lambda}} = \frac{\upsilon}{\sqrt{2}} \approx 174 \text{ GeV};$$

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

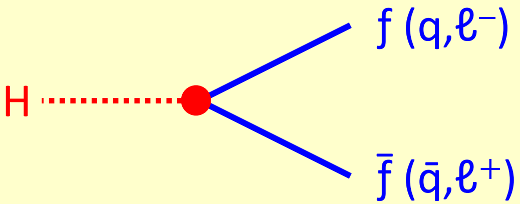
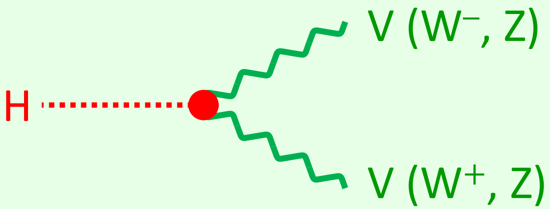
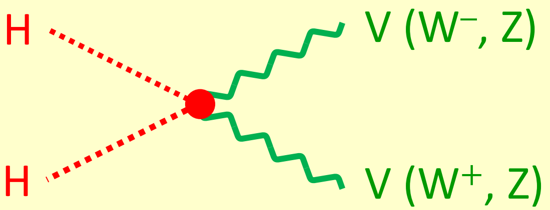
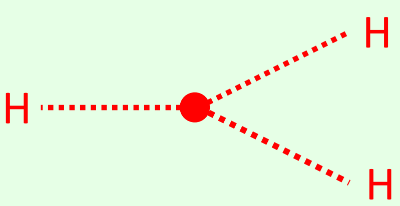
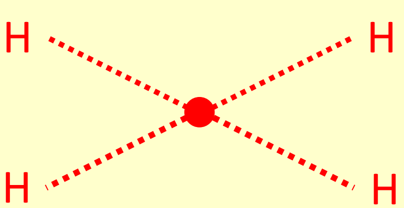
$$\left.\frac{\partial^2 V_H}{\partial \phi^2}\right|_{\phi=\phi^{min}} = 2m_H^2.$$





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

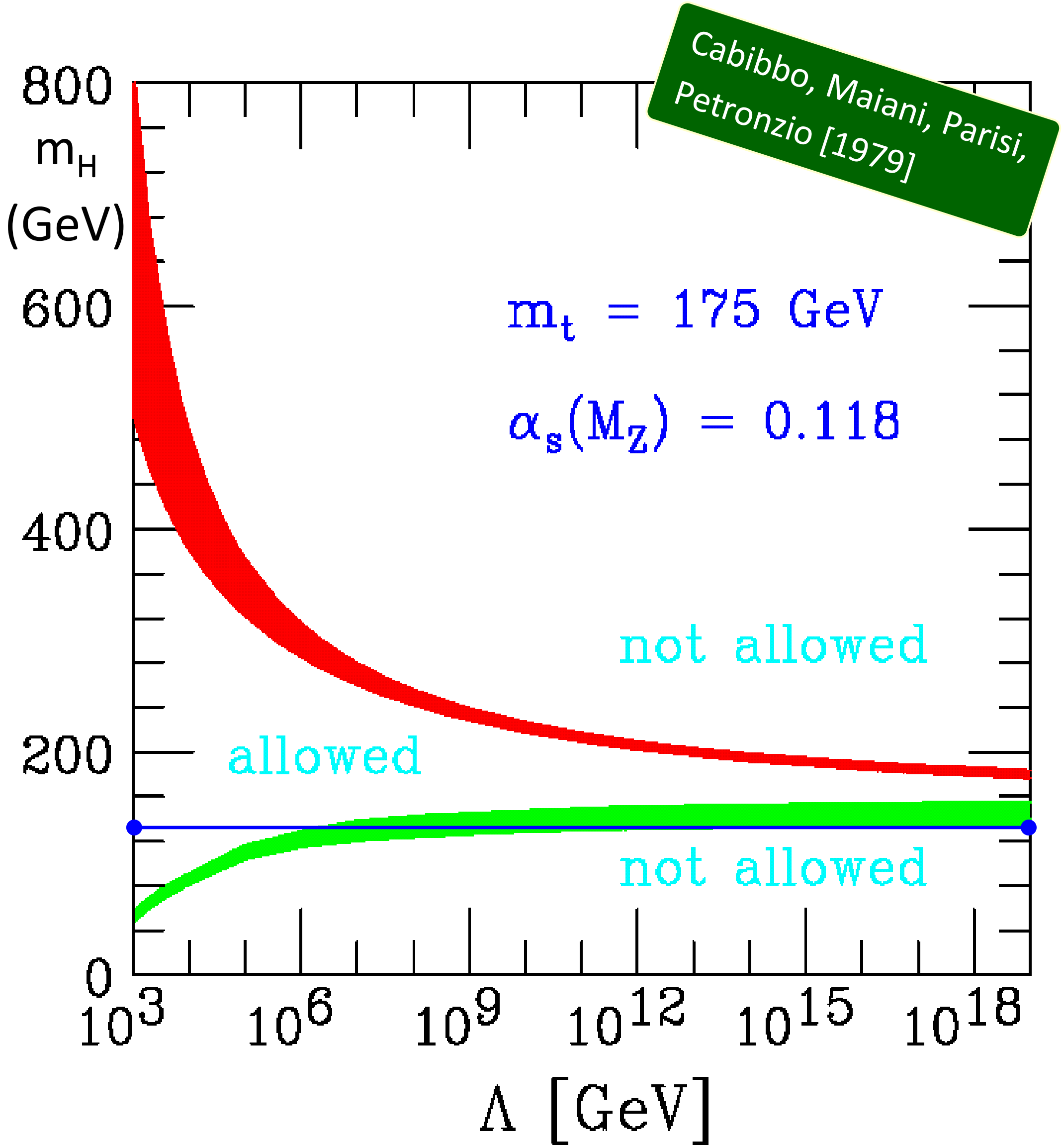
H(MSM): all SM couplings

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

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

H(MSM): mass limits

- in the SM the Higgs mass is a free parameter; however its value is limited by the consistency of the theory [*more on next page*];
- the *vacuum stability* limits m_H vs the scale Λ of hypothetical new physics (**green line**);
- the non-violation of the unitarity puts a limit $m_H \leq 1$ TeV (approx.);
- if the SM has to be consistent, the *triviality* puts another limit on m_H, as a function of Λ (**red line**);
- all together, if $\Lambda = m_{Planck}$, then $130 < m_H < 180$ GeV [approx.];
- the blue line corresponds to $m_H = 125$ GeV [*quite puzzling*].



H(MSM): vacuum and triviality

Vacuum stability (**green line**) roughly means the following:

- the parameter "λ" is a constant at tree level only;
- when higher orders are considered, λ becomes a variable, which follows an appropriate equation (*renormalization group equation*, r.g.e.);
- λ is required to be +ve for all the values of the scale Q;
- if, for a given value Q = Λ, the value of λ becomes –ve, the SM breaks;
- the only way to restore λ, is to assume that, for $Q \geq \Lambda$, some new physics appear in the equation, such that λ remains +ve;
- therefore Λ is NOT a precise value in some process, but a scale for new physics;
- Λ depends on m_H and the H couplings; the most important (and unknown) is m_t.

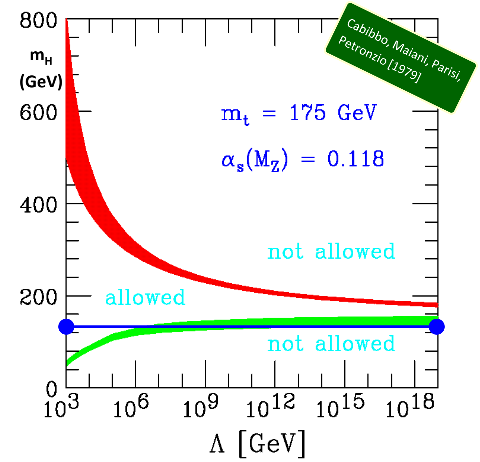
Triviality (**red line**) means:

- from the r.g.e. equation, one gets:

$$\frac{1}{\lambda(Q)} = \frac{1}{\lambda(\upsilon)} - \frac{3}{4\pi^2}\ell n\left(\frac{Q^2}{\upsilon^2}\right)$$

- to be consistent, $\lambda(Q)$ must be small and only vanish if $Q = \infty$; in this case, the H gets no interaction (*trivial solution*);
- to avoid $\lambda(Q) \to \infty$ (*Landau pole*), with a similar argument as before, $\lambda(Q=\Lambda) < \infty$;
- this requirement puts a limit on m_H vs the scale Λ of possible new physics:

$$m_H^2 = 2\upsilon^2\lambda \leq \leq 2\upsilon^2\lambda_{max} = = \frac{8\pi^2\upsilon^2}{3\ell n\left(\Lambda^2/\upsilon^2\right)}.$$

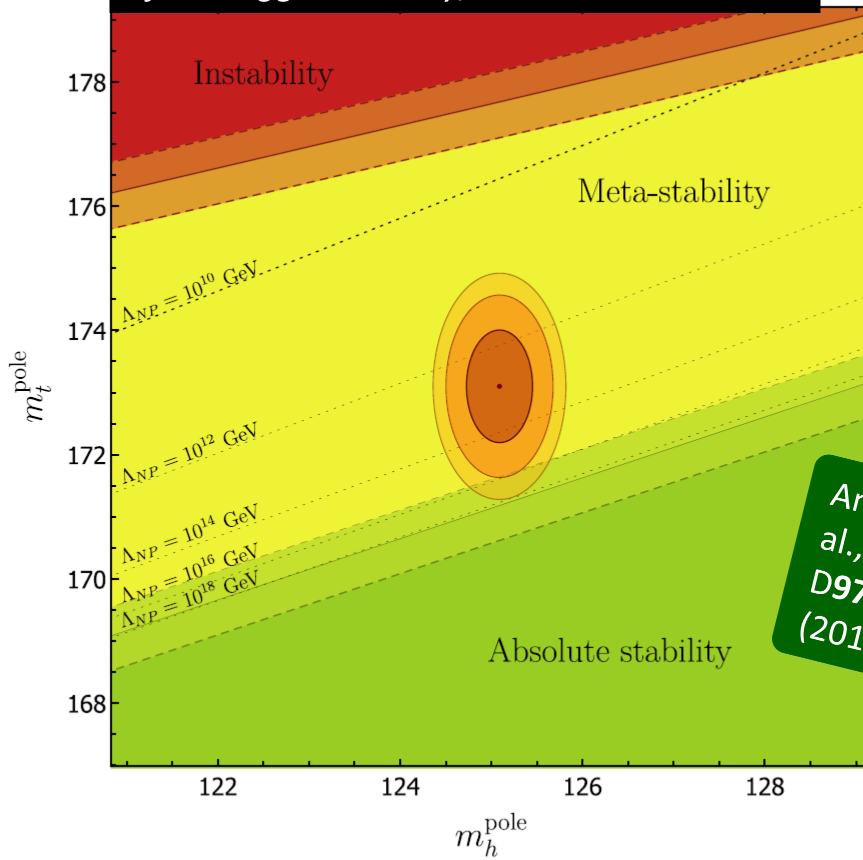


H(MSM): vacuum stability

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), the present error does not answer the question;
- only a future, more precise measurement will solve it;
- notice in the plot (year 2018 !!!):
  - the error on the top quark mass is VERY important;
  - the scale of "new physics" necessary to get stability is very large: > 10^{10} GeV;



Andreassen et al., Phys. Rev. D**97**, 056006 (2018).

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

H(MSM): is the universe decaying ?

From the same paper:

Thus, the lifetime of the Standard Model universe is

$$\tau_{SM} = [...]\ 10^{161^{+160}_{-59}}\ \text{years.}$$

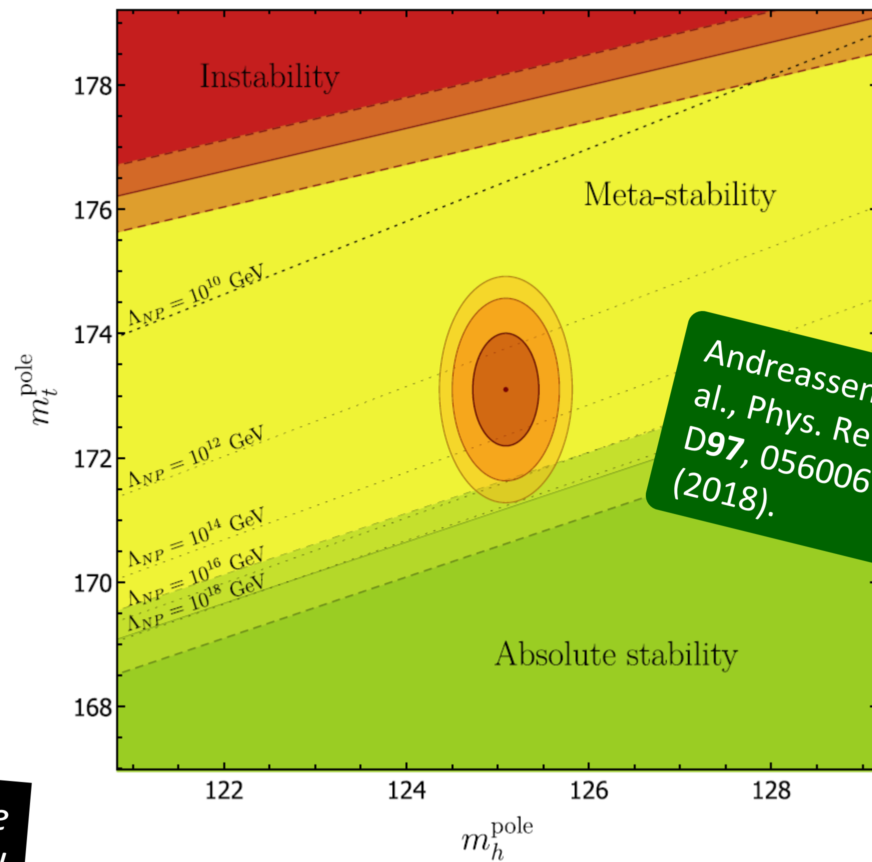
That is, to 68% confidence, $10^{102} < \tau_{SM}/\text{years} < 10^{321}$. To 95% confidence $10^{65} < \tau_{SM}/\text{years} < 10^{1383}$.

To be more clear about what the lifetime means, we can ask a related question: what is the probability that we would have seen a bubble of a decaying universe by now? Using the space-time volume of our past lightcone [...] and the Hubble constant [...], the probability that we should have seen a bubble by now is

$$P = \frac{\Gamma}{V}(VT)_{light-cone} = 10^{-606^{-638}_{+239}}.$$

[just as an amusement, go to arXiv and check these numbers across the 4 versions of this paper … and then be really concerned … Ah, the theorists !!!]

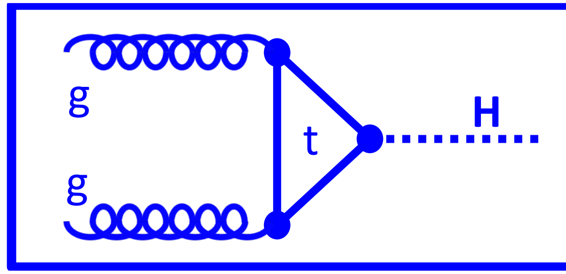
Since the bubbles expand at the speed of light, chances are if we saw such a bubble we would have been destroyed by it; thus it is reassuring to find the probability of this happening to be "quite small".



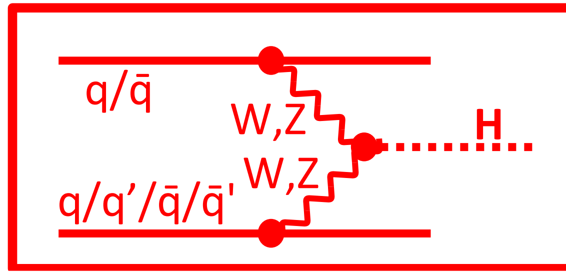
Andreassen et al., Phys. Rev. D**97**, 056006 (2018).

Higgs properties: production dictionary

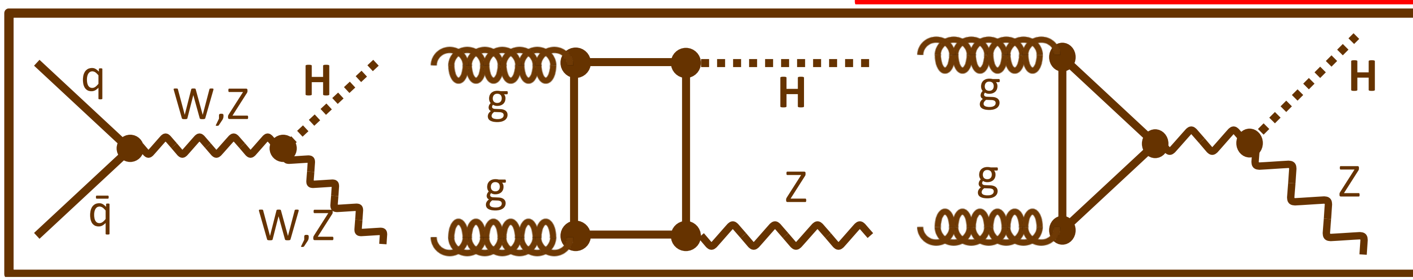
- Higgs production processes in hadron colliders, with their usual names;
- only main diagrams, many others less important (e.g. single top);
- emphasis on detectability → some particles in final state may help it;
- here, when relevant, also virtual particles [e.g. W = W$^{(*)}$, Z = Z$^{(*)}$].



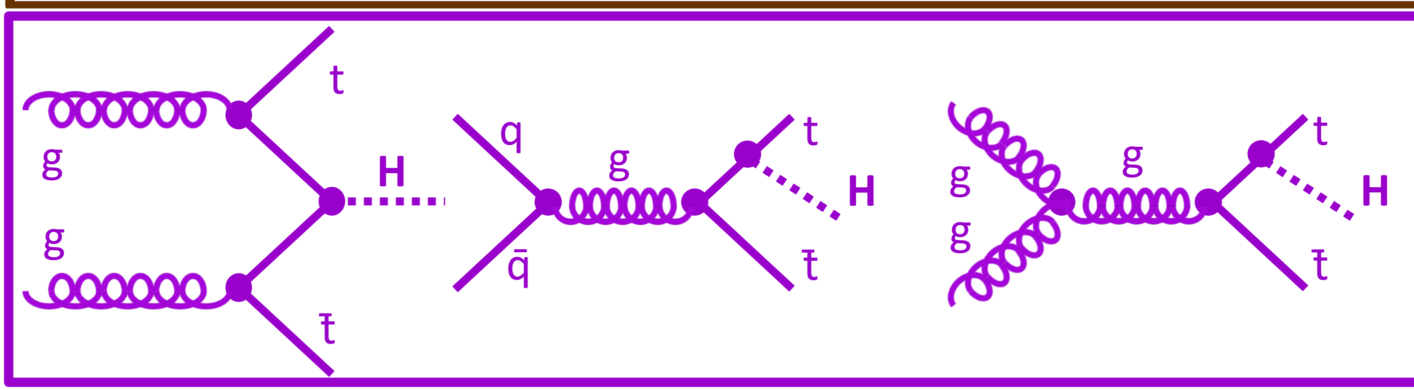
ggF — gluon gluon fusion



VBF — vector boson fusion



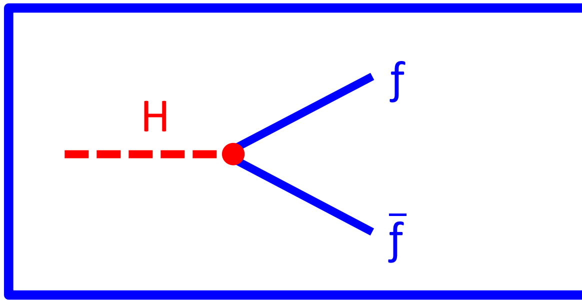
VH [= WH + ZH] — VH production



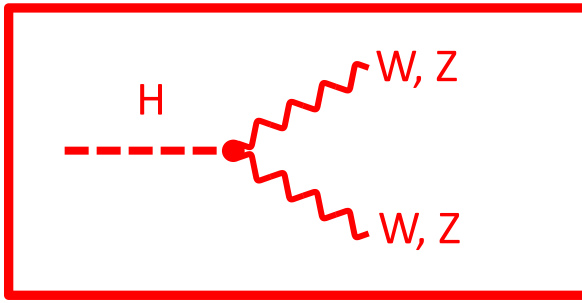
tt̄H — tt̄H process

Higgs properties: decay dictionary

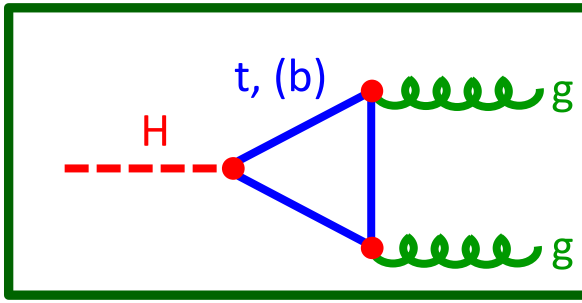
- Higgs decay modes;
- "f" = any fermion (q, ℓ, <u>NOT</u> ν) ; the coupling (therefore the BR) is strongly dependent on its mass;
- as usual, e.g. $W = W^{(*)}$, $Z = Z^{(*)}$ [but, for m_H = 125 GeV, $H \to WW^*$, ZZ^* only !!!].



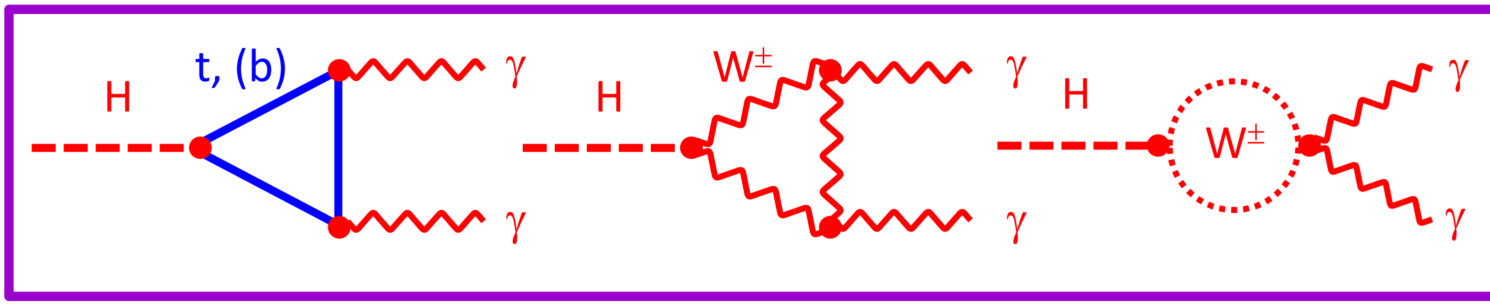
$H \to f\bar{f}$



$H \to WW$ / ZZ



$H \to gg$



$H \to$ □

Higgs properties: decays ƒ, W, Z

- at "tree level" the partial width for the Higgs decay into a pair of real fermions (ƒ=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;

in principle correct, but useless

- 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→gg and H→γγ (much less H→Zγ) are important for the discovery :
  - the decay H→gg is large, although not easy to identify (→ 2 jets, large QCD bckgd);
  - the decay H→γγ is rare, but has high efficiency and little bckgd (see later);
- complete formulas in references :

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

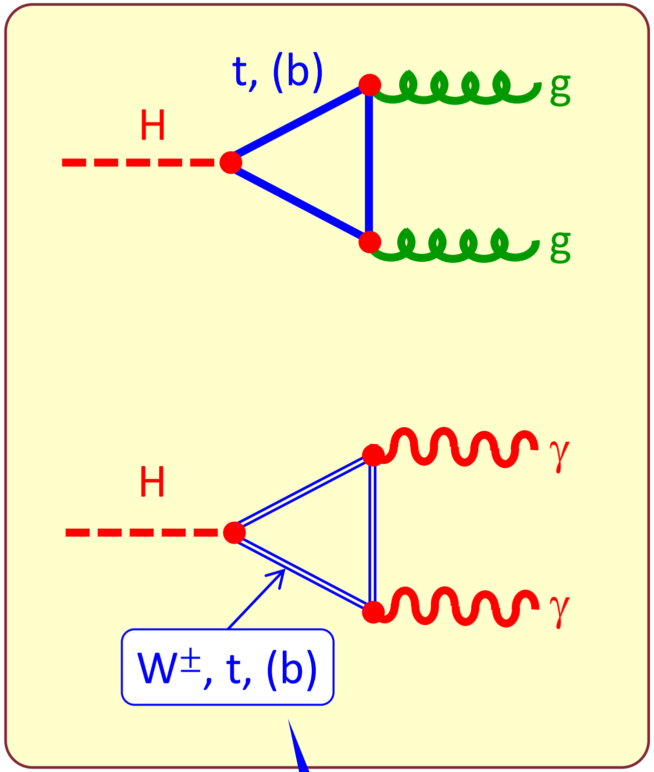
$$I_{gg} = \sum_q I_q(m_q^2/m_H^2) = f(m_H) \sim 0.1 \div 1;$$

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

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

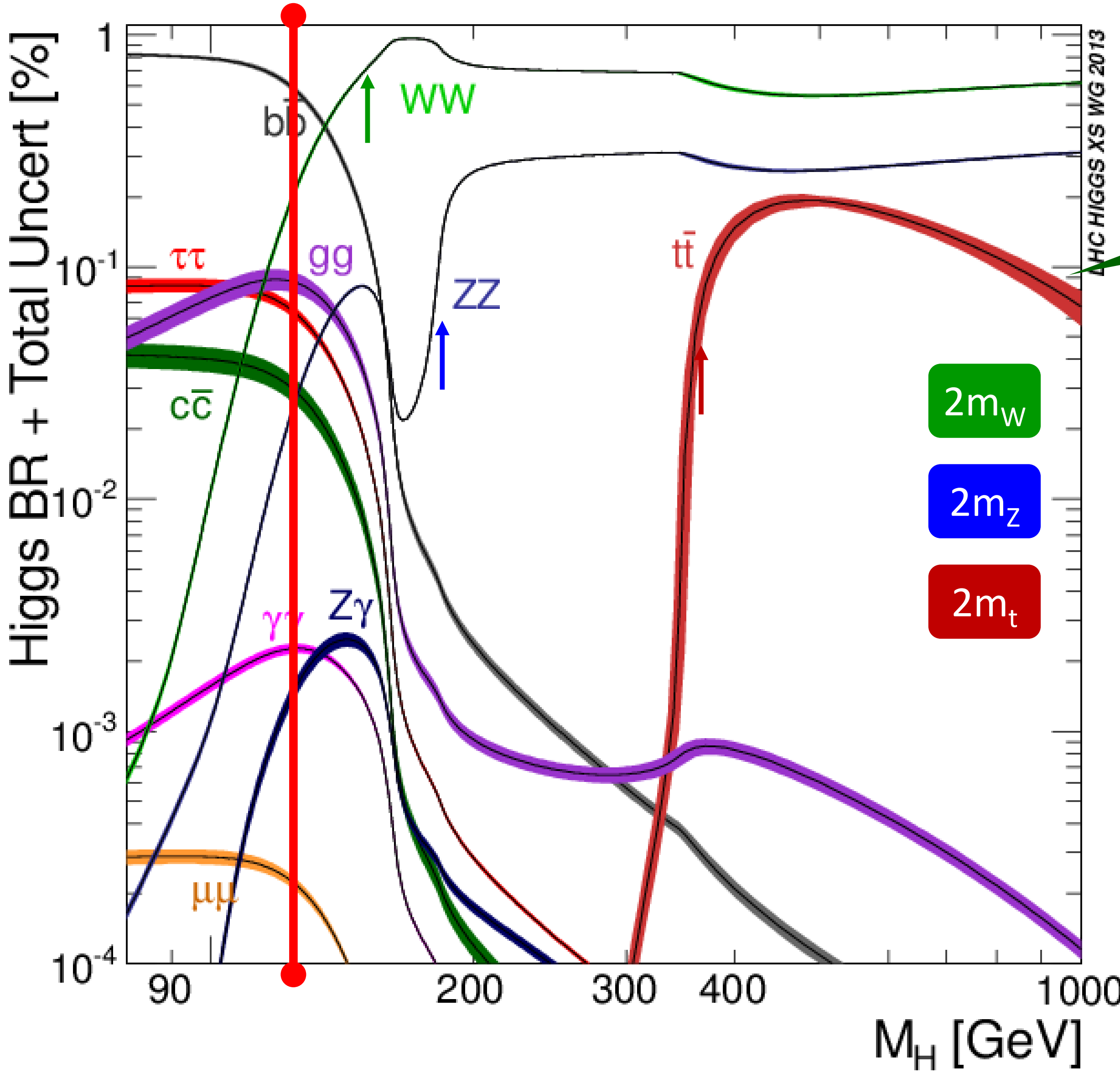
$$I_{\gamma\gamma} = \sum_f c_f q_f^2 I_f(m_f^2/m_H^2) + I_W = f(m_H) \sim 1 \div 10;$$

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



for □ , interference W ↔ t large and <u>negative</u> (a nice test of the SM).

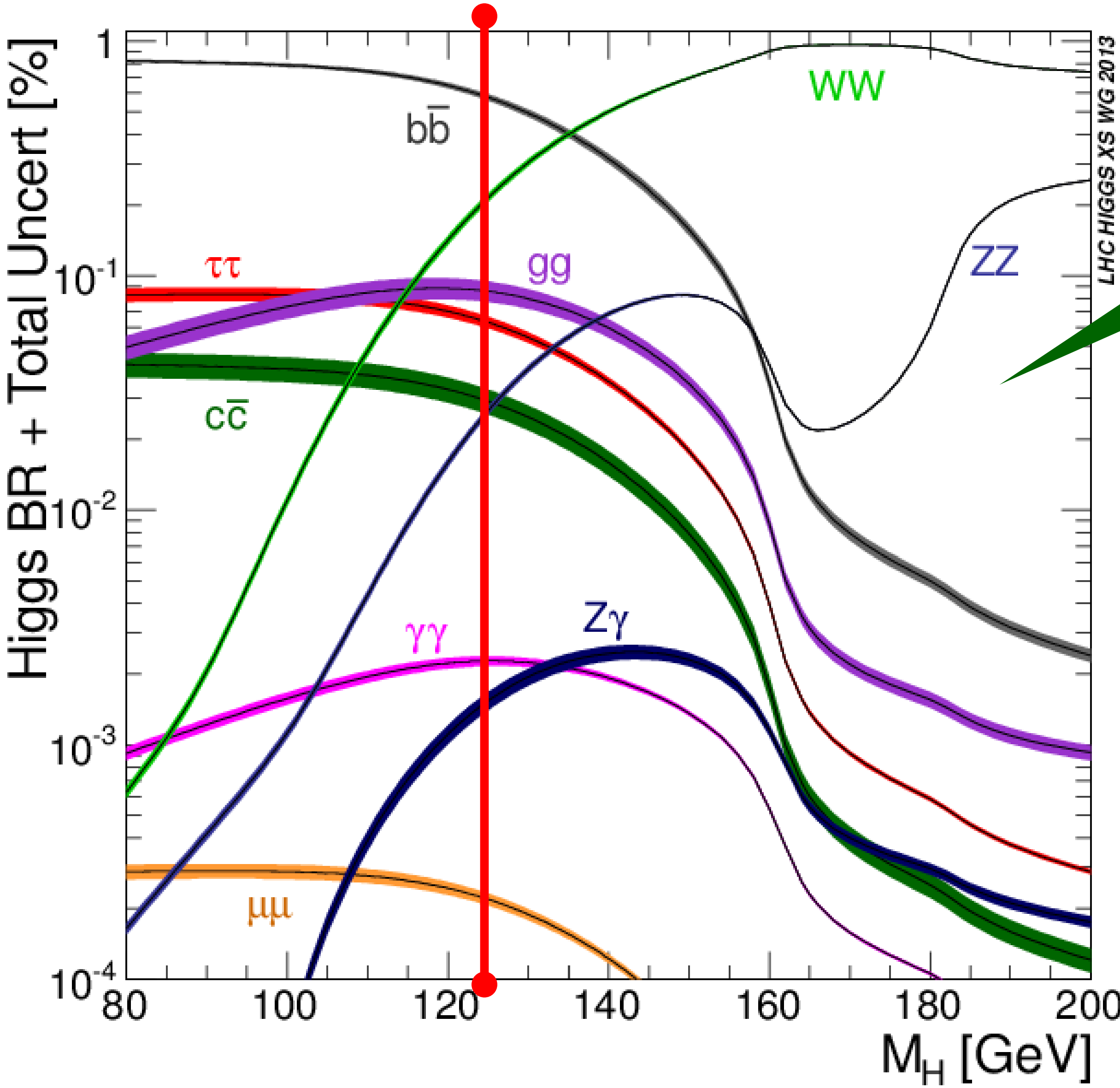
Higgs properties: decay BR vs H mass



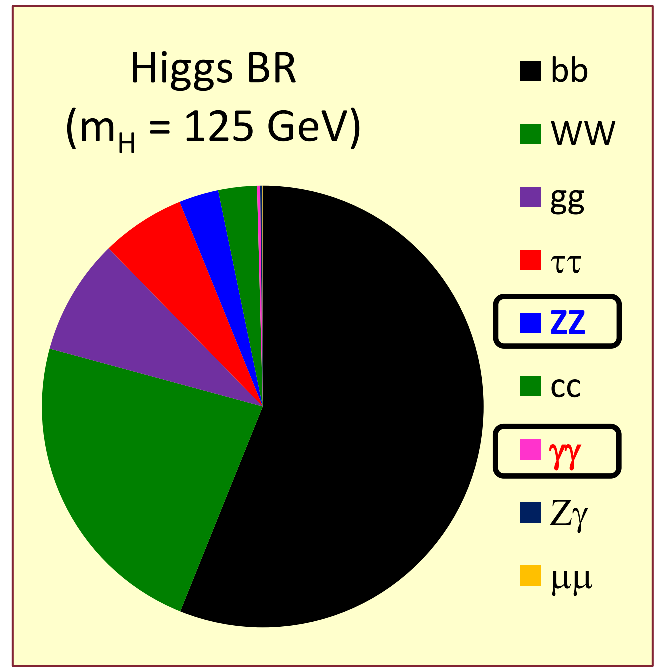
Unlike LEP2, in the LHC energy range, the Higgs boson decay mode is highly variable
→ a challenge for the experiments.

m_H = 125 GeV [*CERN-2013-004*]		
decay mode	Γ (MeV)	BR (%)
$b\bar{b}$	2.37	58.2
$W^{\pm}W^{\mp *}$	0.871	21.4
gg	0.334	8.2
$\tau^+\tau^-$	0.255	6.3
ZZ*	**0.107**	**2.6**
$c\bar{c}$	0.118	2.9
γγ	**9.2E-03**	**0.23**
Zγ	6.2E-03	0.15
$\mu^+\mu^-$	8.9E-04	0.022
sum	4.07	100

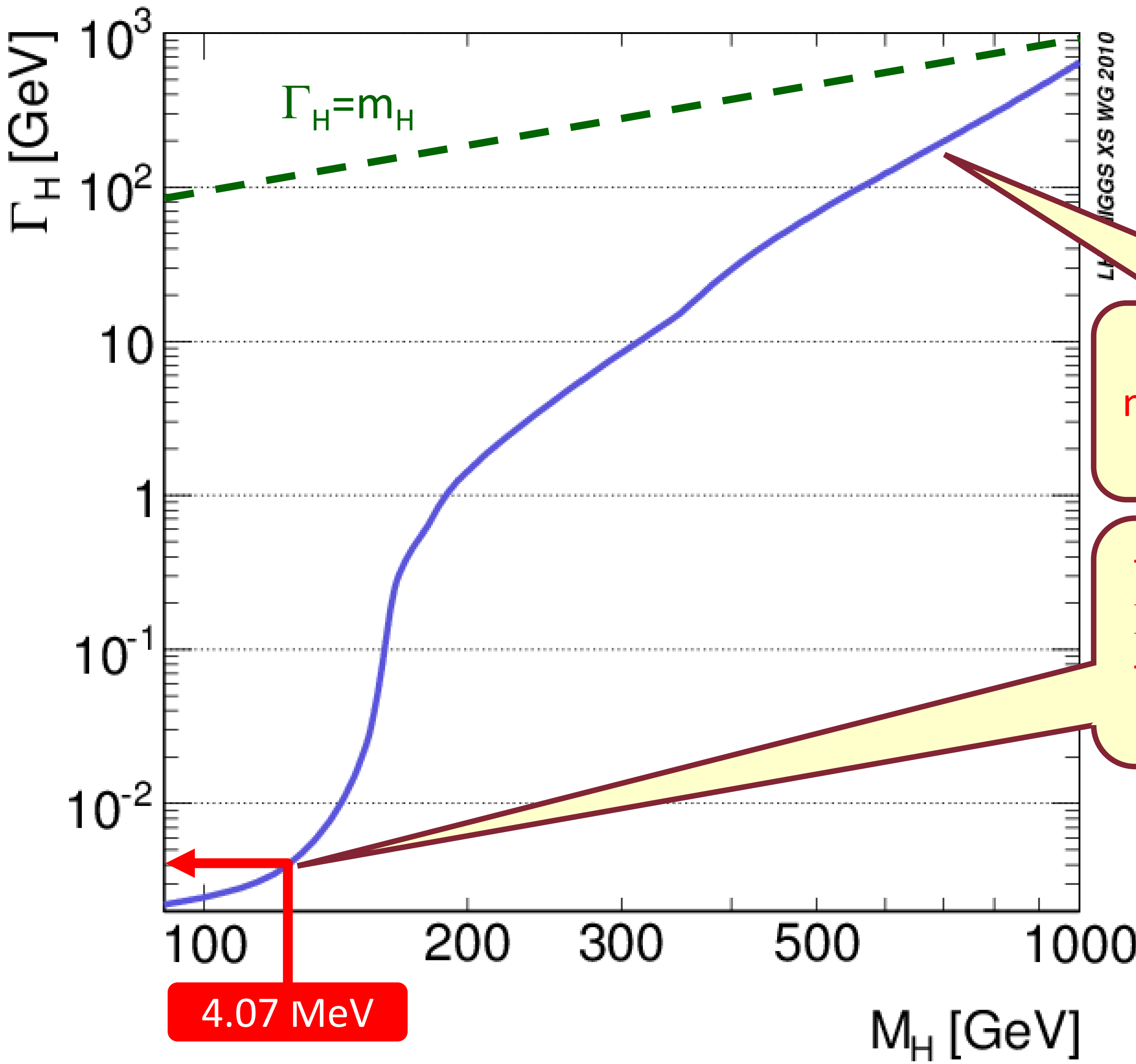
Higgs properties: BR($80 < m_H < 200$ GeV)



enlarge for $80 < m_H < 200$ GeV.



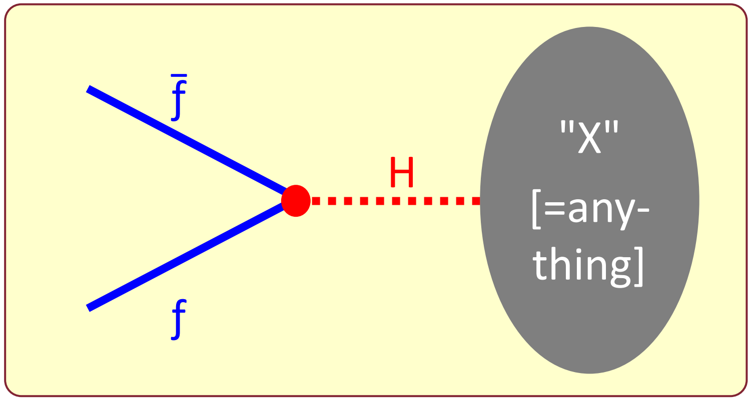
Higgs properties: full width vs m_H



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. How measure it ? ideas welcome !

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



Question (for a lepton collider, not for LHC): why not a direct formation from (spin ½) - fermions ($f\bar{f} \to H \to X$) 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 hypothetical $\mu^+\mu^-$ machine:

$$\sigma(f\bar{f} \to H \to X) = \left[\frac{16\pi}{s}\right] \left[\frac{1}{4}\right] \left[\frac{\Gamma_{f\bar{f}}}{\Gamma_H}\right] \left[\frac{\Gamma_X}{\Gamma_H}\right] \left[\frac{\Gamma_H^2/4}{\left(\sqrt{s}-M_H\right)^2 + \Gamma_H^2/4}\right]$$

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

[see Introduction, or the J/ψ in PP]

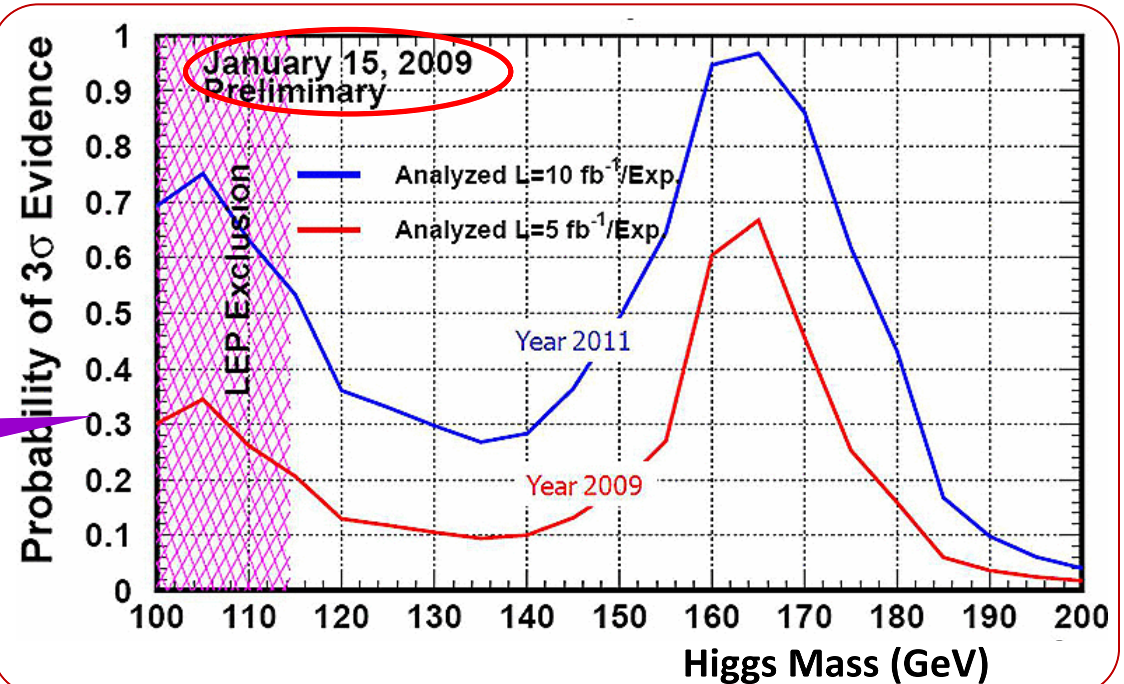
$$\sigma(ab \to R \to X, \sqrt{s}) =$$

$$= \left[\frac{16\pi}{s}\right] \left[\frac{(2J_R+1)}{(2S_a+1)(2S_b+1)}\right] \left[\frac{\Gamma_{ab}}{\Gamma_R}\right] \left[\frac{\Gamma_X}{\Gamma_R}\right] \left[\frac{\Gamma_R^2/4}{\left(\sqrt{s}-M_R\right)^2 + \Gamma_R^2/4}\right]$$

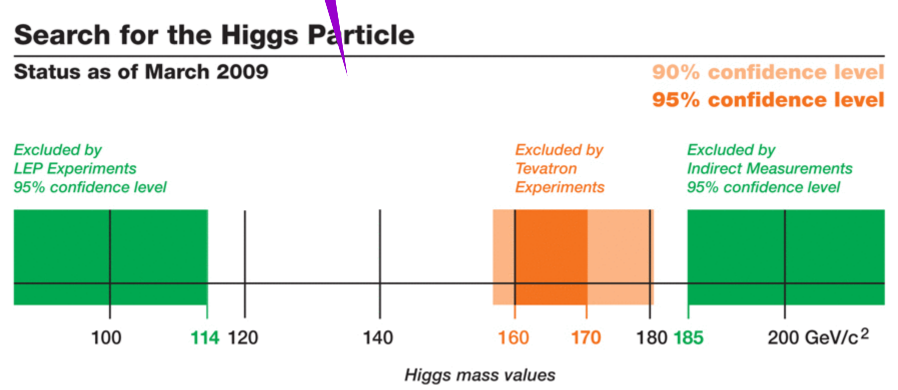
for e^+e^-, factor $(m_e/m_\mu)^2 \approx 1/40{,}000$:

- → impossible for electron colliders;
- → one of the main motivations for muon colliders.

Higgs — pre-LHC : Tevatron legacy (1)

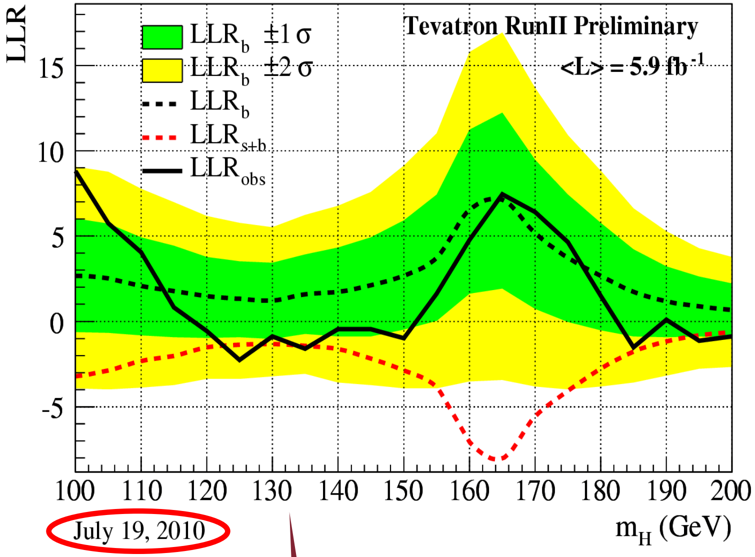


The "American dream" in 2009: get the Higgs before LHC, by combining CDF + D0.



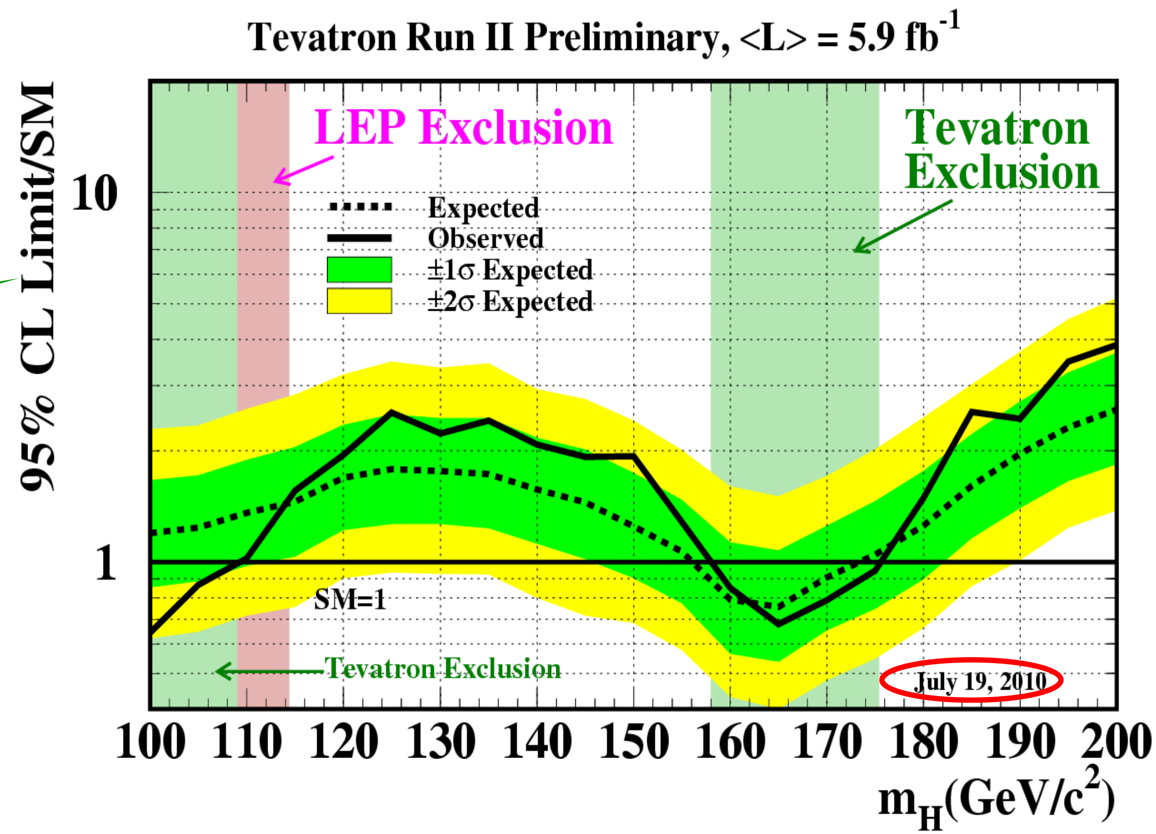
"3σ evidence" has **never** been used at LEP or at LHC; although well defined and politically understandable, a posteriori it is a useless complication.

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.

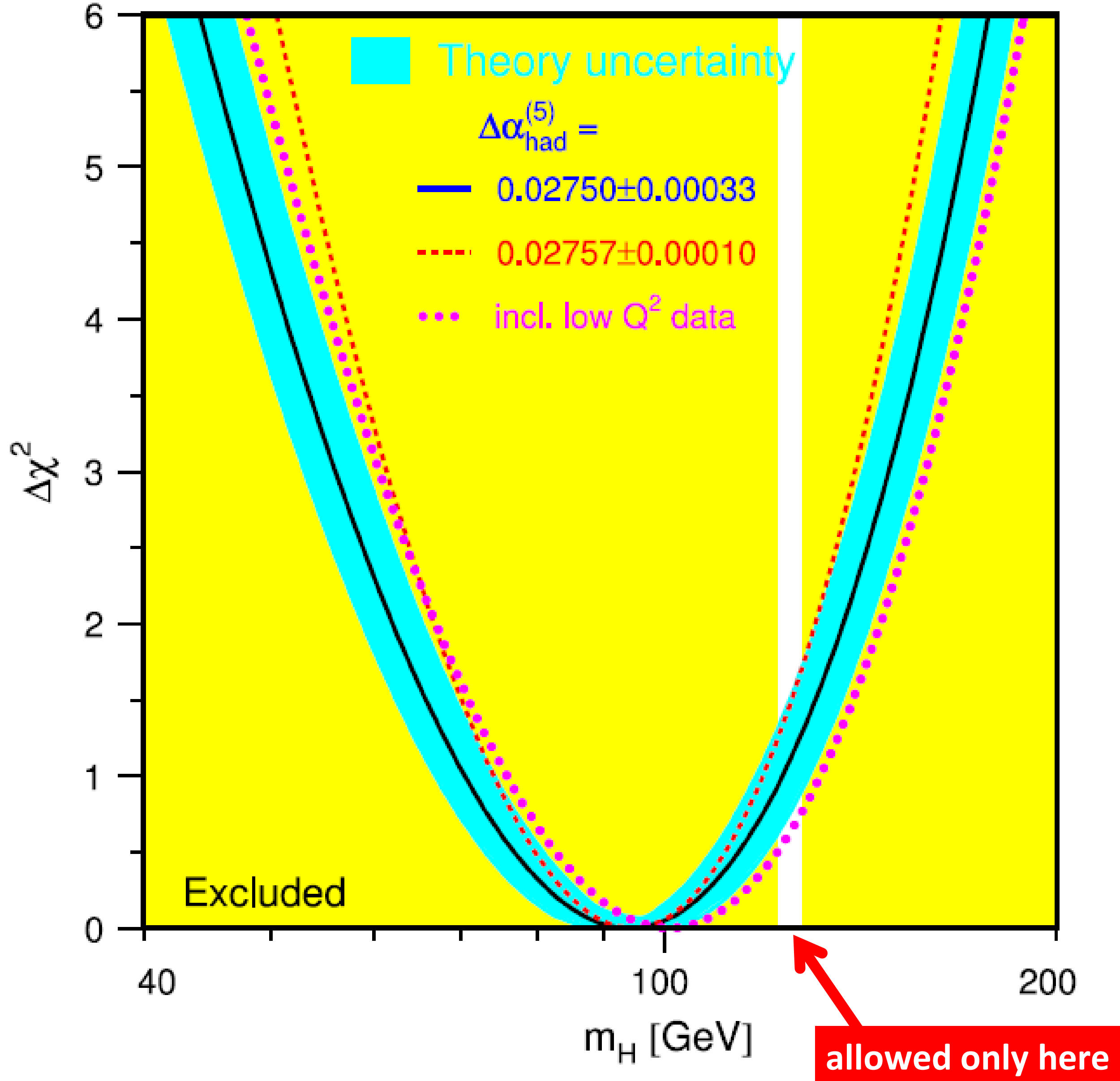


i.e. "μ"

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

Higgs — pre-LHC : complete legacy (1)

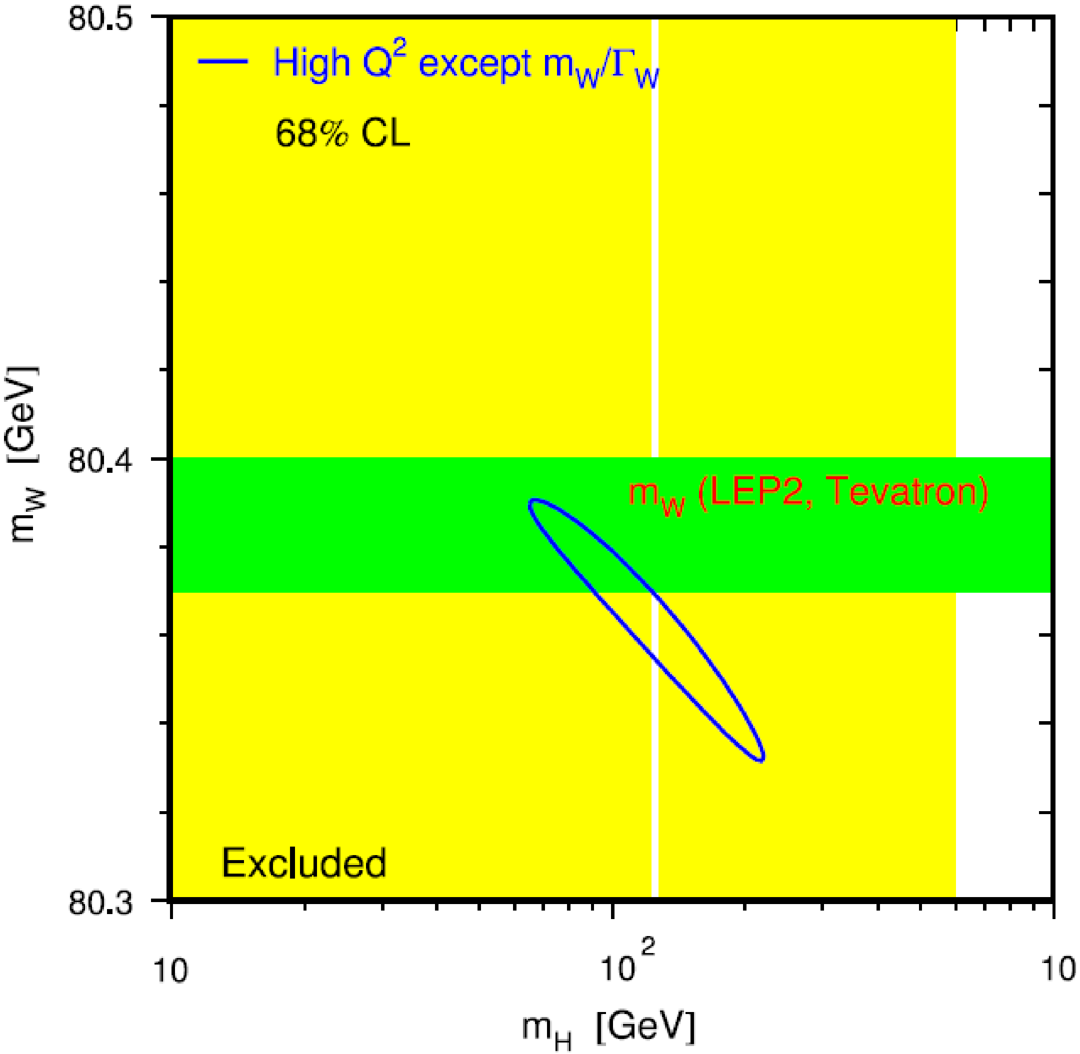
- the (in)famous "blueband", already discussed, wants a light Higgs; it includes all the known info, BUT the direct search at LEP, Tevatron and LHC, shown separately;
- instead, the yellow bands represent the result of the direct searches [NB : no experimental correlation with the blueband];
- the yellow 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.

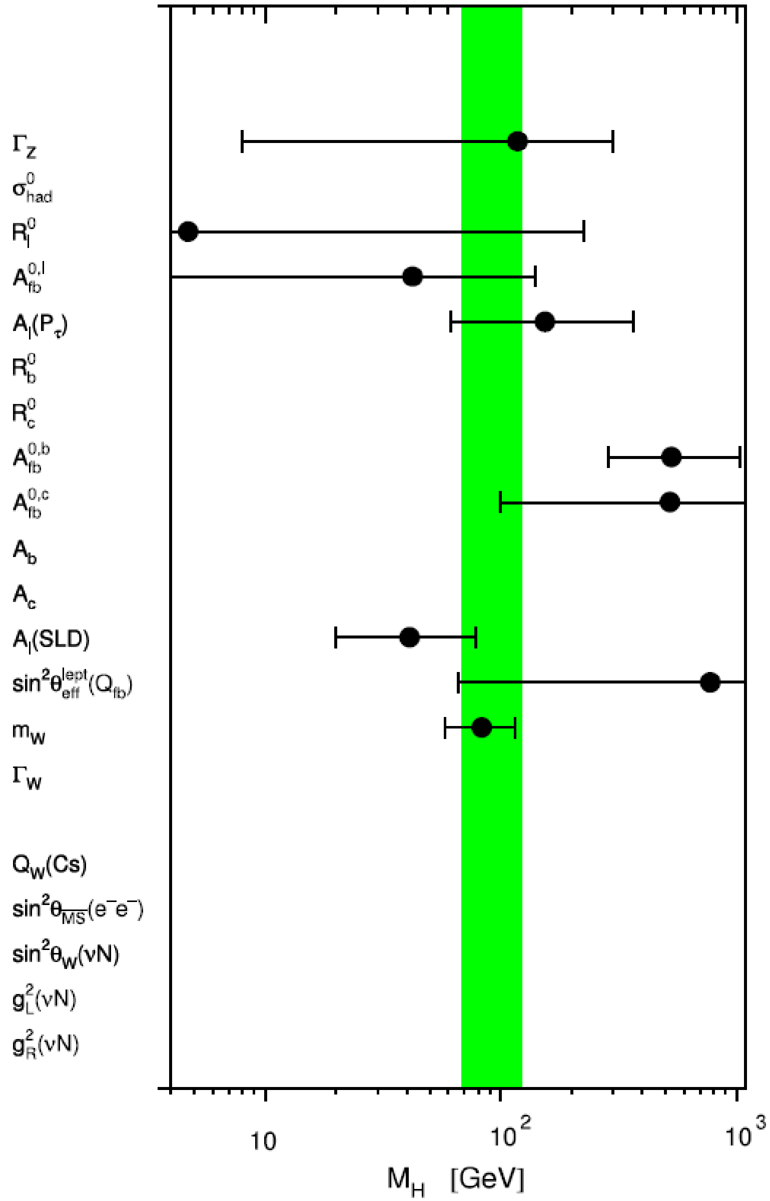


Higgs — pre-LHC : complete legacy (2)

bottom : m_W vs m_H (strong correlation);

right : individual meas. contribution;





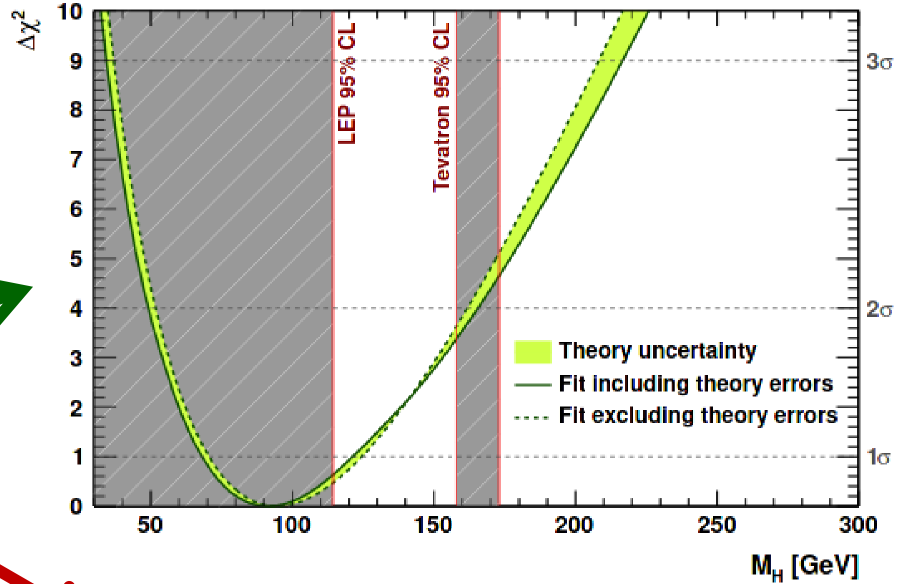
Higgs — pre-LHC : radiative corrections

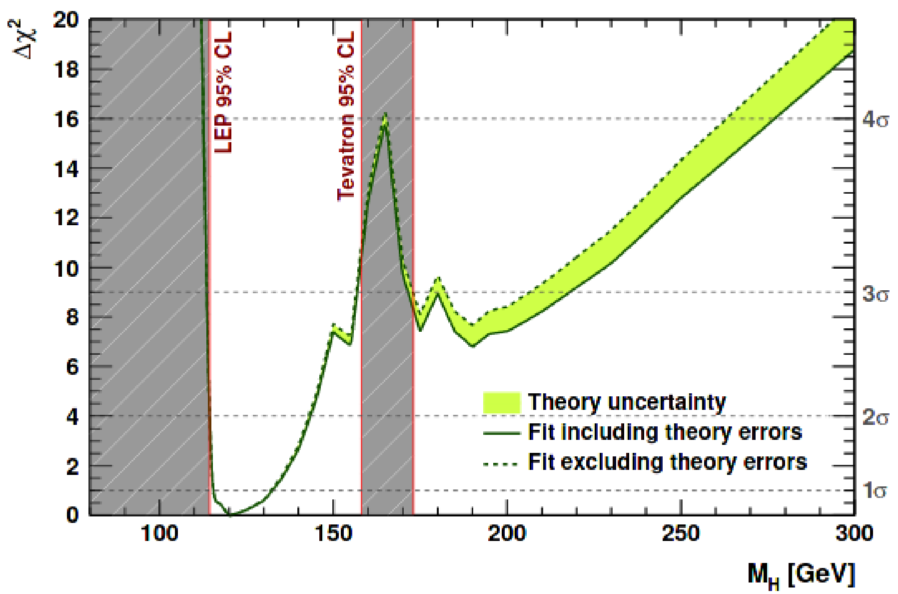
m_H

Already in 2010, radiative corrections + direct searches allowed for a very precise determination of m_H.
[Gfitter, Eur.Phys.J. C72 (2012), 2003]

w/o direct search: $m_H = 91^{+30\ [+74]}_{-23\ [-42]}$ GeV

direct search in: $m_H = 120^{+12\ [+23]}_{-05\ [-06]}$ GeV





more formally, the radiative correction are:

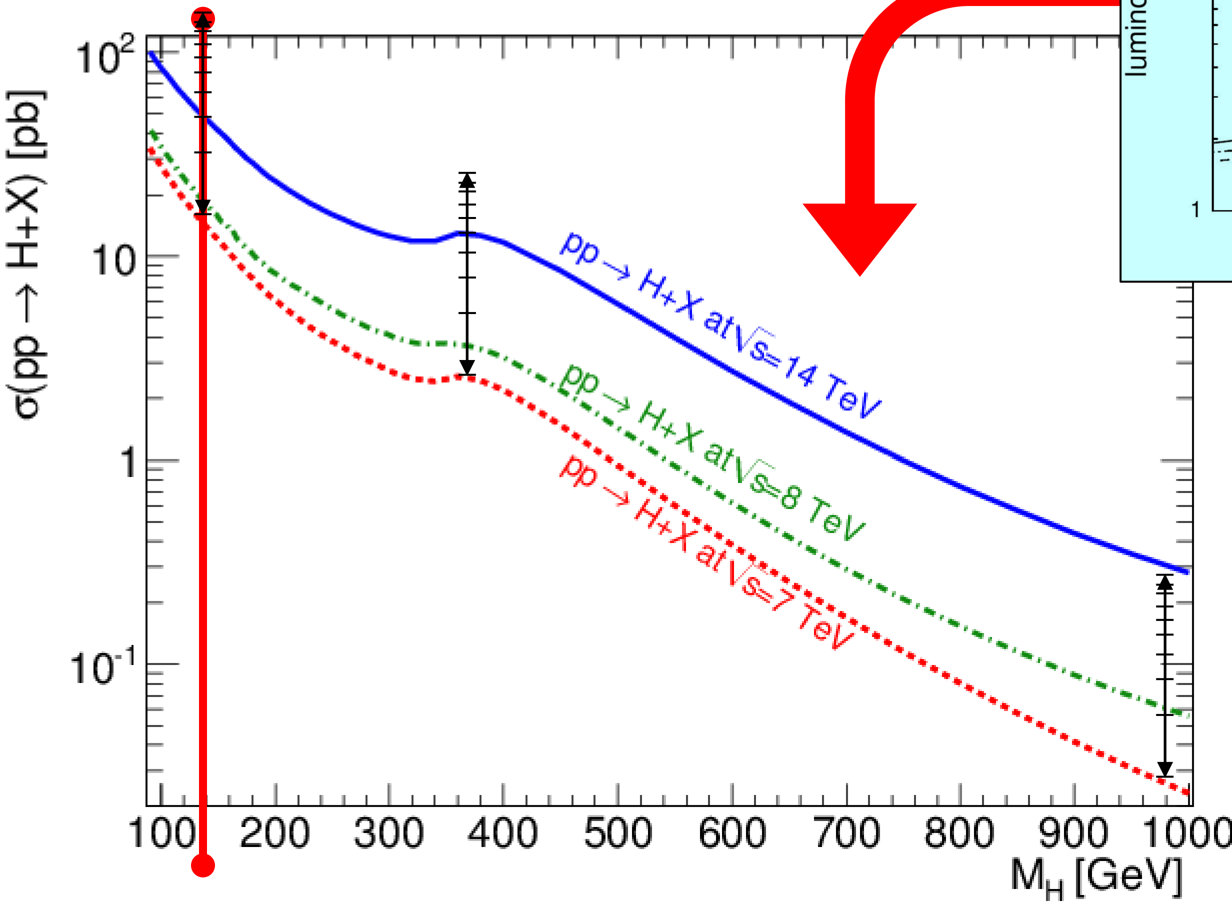
$$\rho = \frac{m_W^2}{m_Z^2 \cos^2\theta_W} \approx \rho_0 \left(1 + \delta\rho_t + \delta\rho_H + \ldots\right);$$

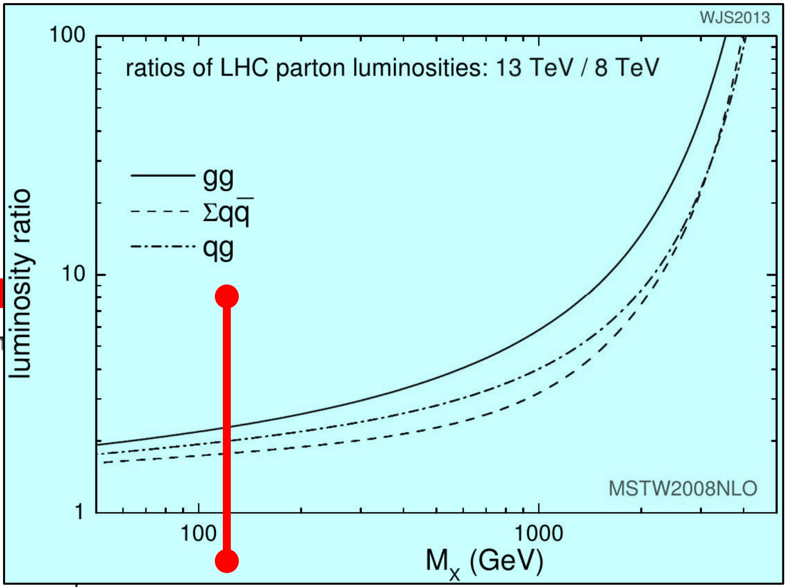
$$\delta\rho_t \approx \frac{3 G_F m_t^2}{8\sqrt{2}\pi^2} \approx 0.0096 \left(\frac{m_t}{173\ \text{GeV}}\right)^2;$$

$$\delta\rho_H \approx -\frac{3 G_F m_Z^2 \sin^2\theta_W}{8\sqrt{2}\pi^2} \left(\ell n \frac{m_H^2}{m_W^2} - \frac{5}{6}\right).$$

Higgs — LHC predictions : production

- real process at parton level;
- PDFs depend on M_H and $\sqrt{s}$, (i.e. $\sqrt{\hat{s}}$ and x);
- σ_{125} = few × 10 pb;
- observables = $\sigma \times Br_i$, but some decays not measurable, some difficult.

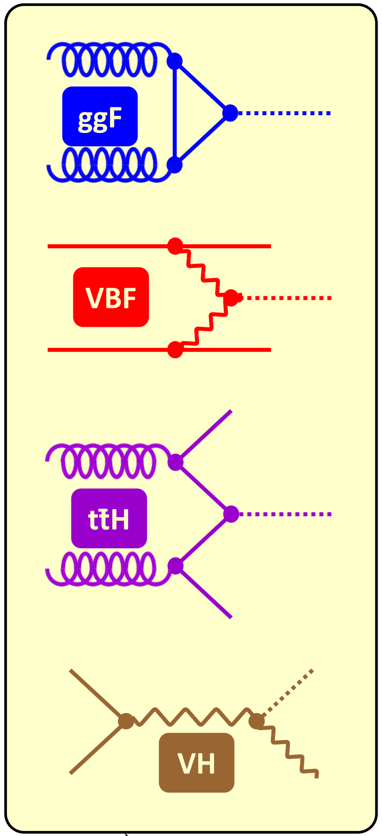


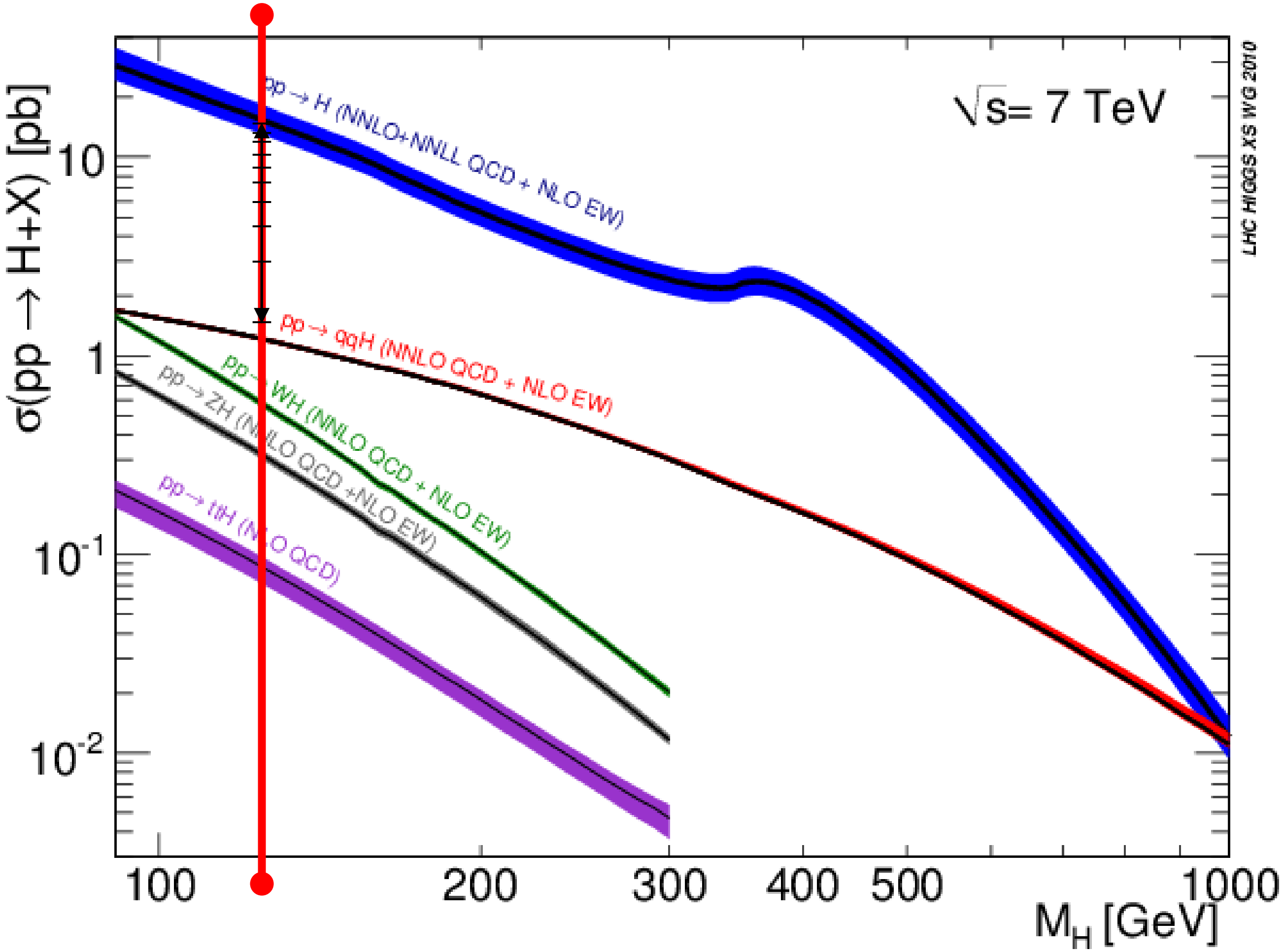


to be compared with:

Luminosity (fb^{-1}) ℒ / √s / exp			
√s (TeV)	7 TeV	8 TeV	7,8,13
ATLAS	4.7	20.7	139
CMS	5.1	19.6	137

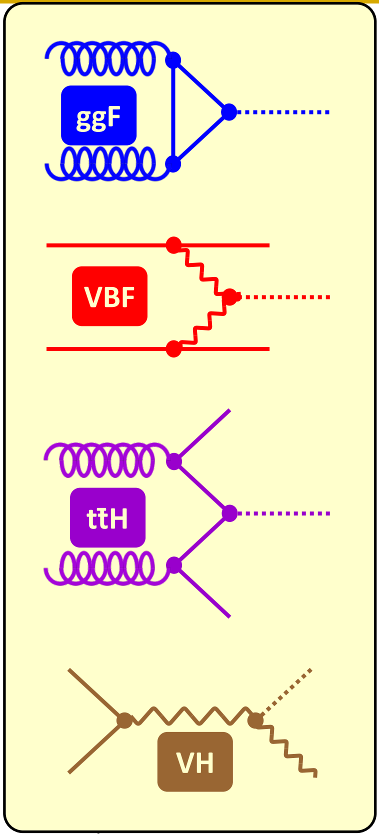
Higgs — LHC predictions : σ_H @ 7 TeV



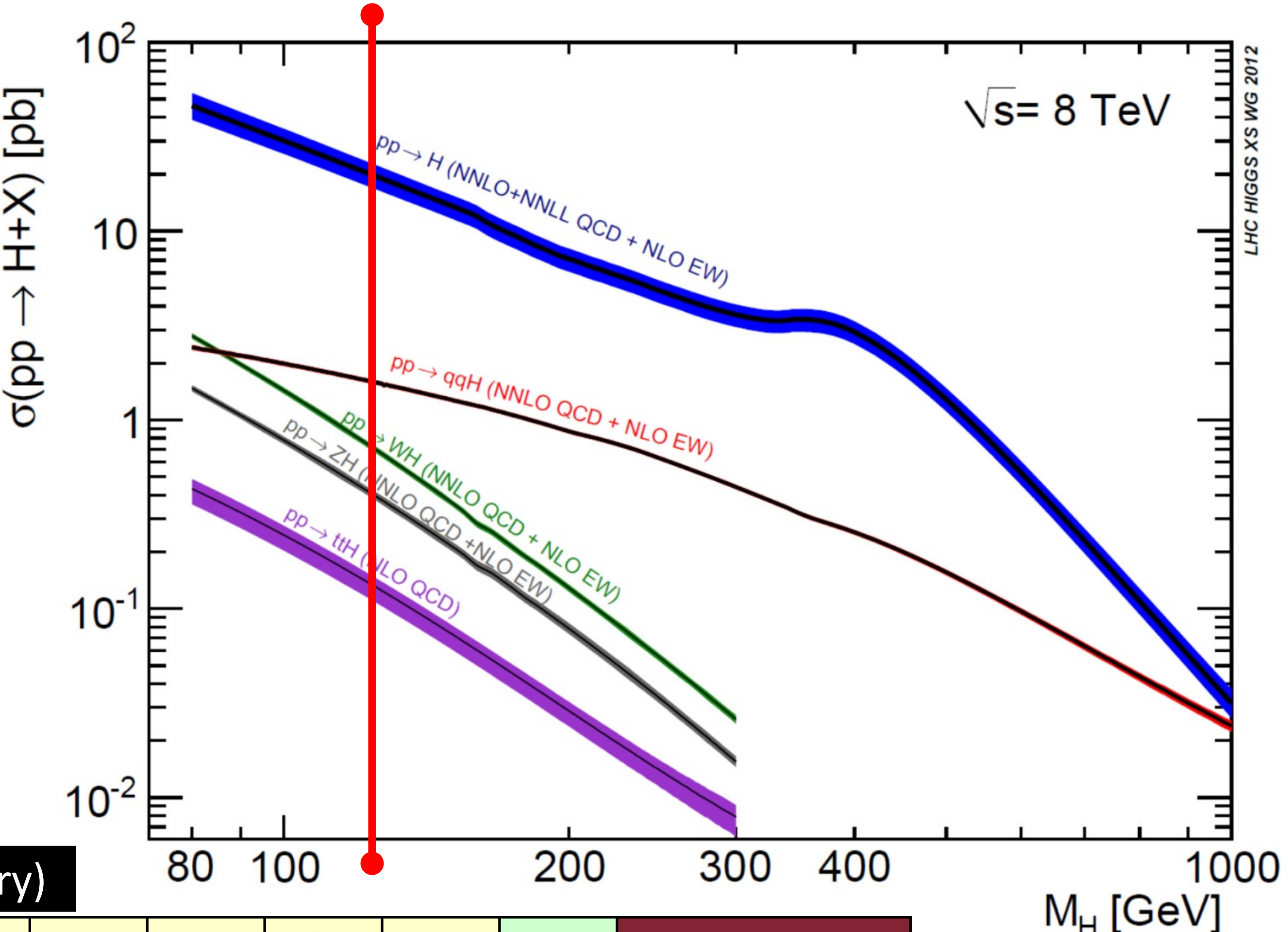


(see dictionary)

Higgs — LHC predictions : σ_H @ 8 TeV

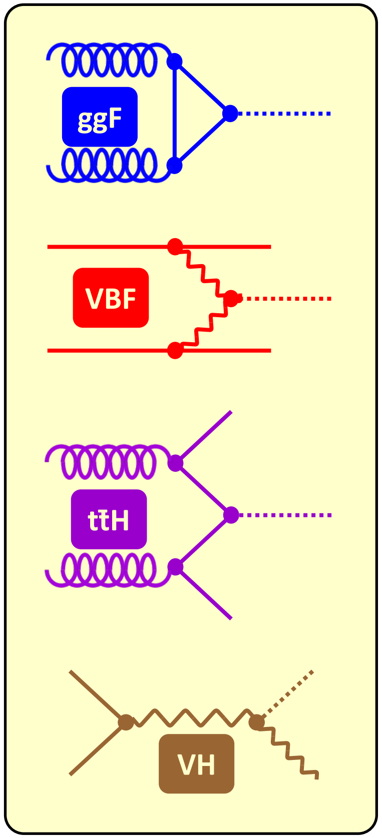


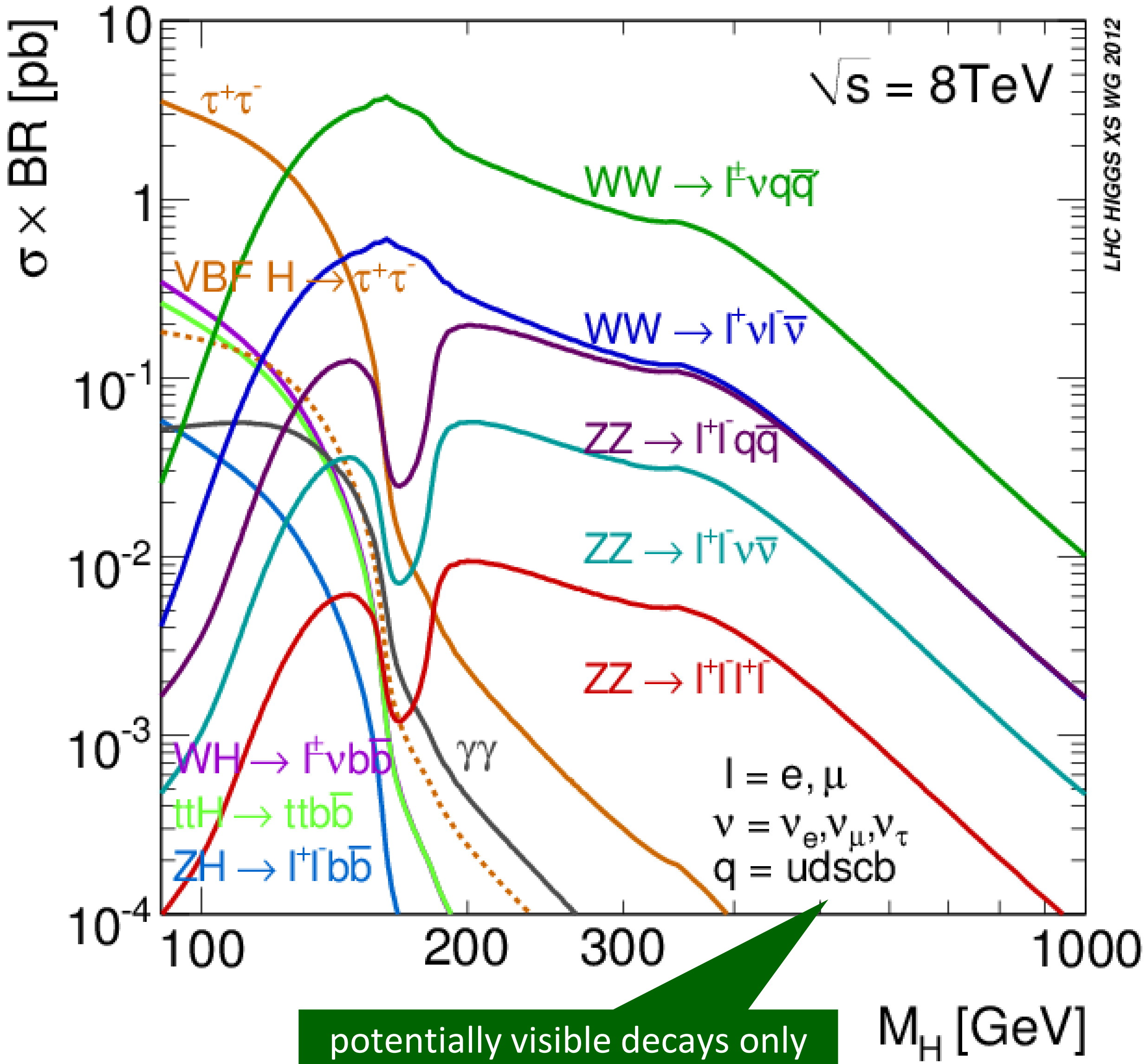
(see dictionary)



√s (TeV)	ggF	VBF	WH	ZH	tt̄H	(…)	Sum	σ(pp → HX) (pb) [computed for m_H = 125 GeV]
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	

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





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

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

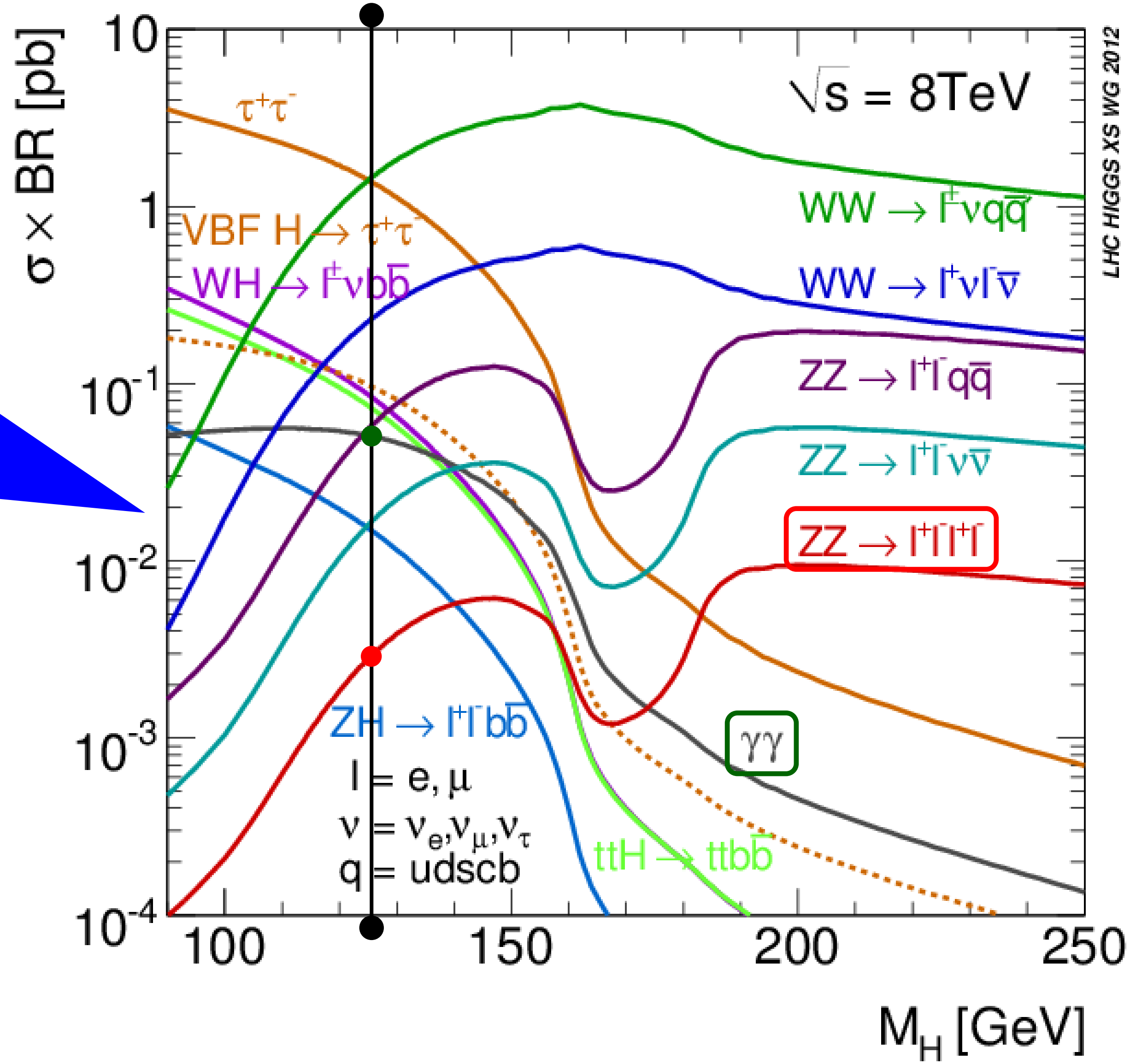
Same plot, different scale, to show the low m_H behavior.

The dots are the "golden channels":

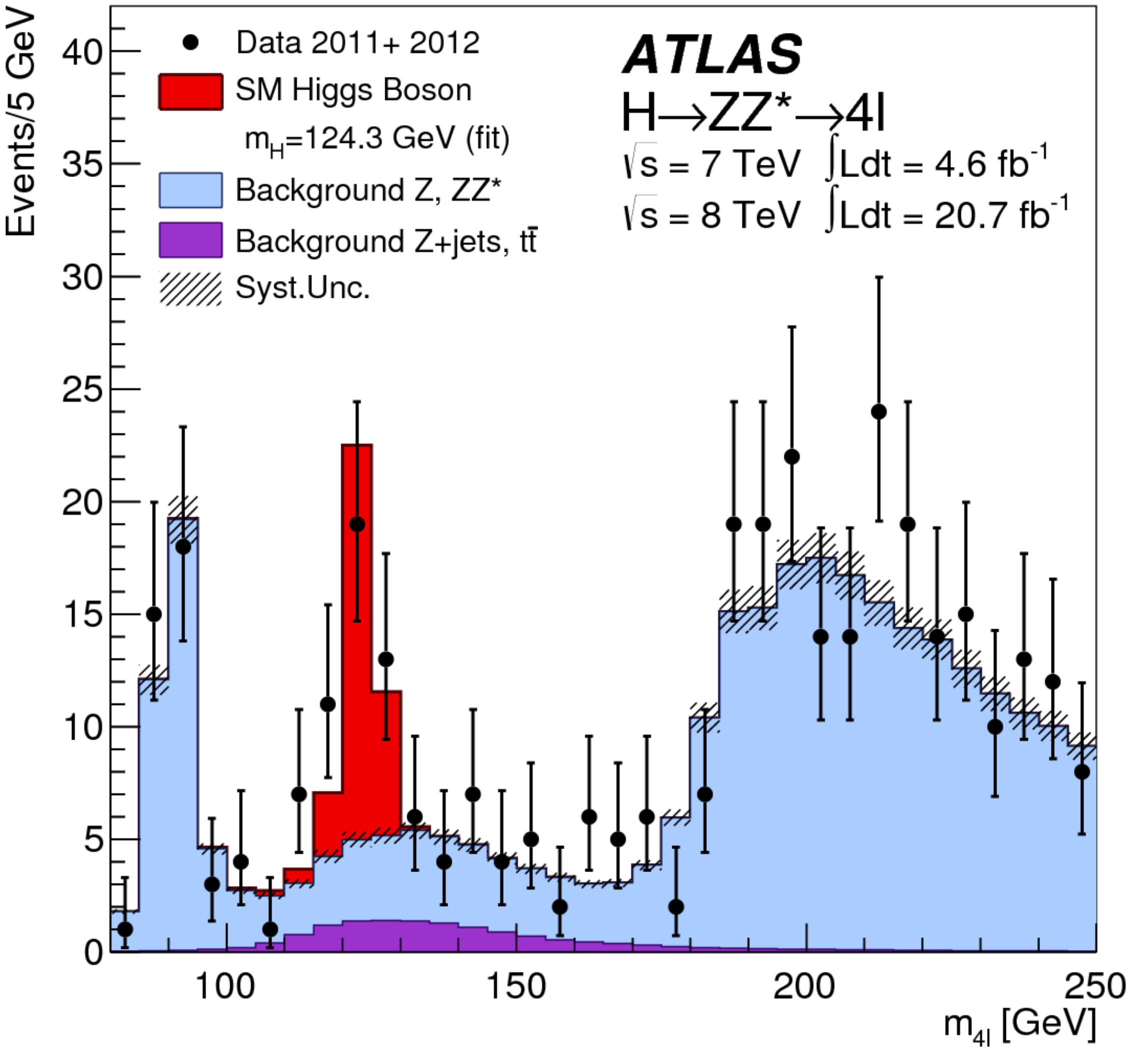
a) □ ;

b) $\ell^+\ell^-\ell^+\ell^-$.

i.e. a compromise between yield and observability.



Higgs discovery : H → ZZ* - ATLAS



looking for the Higgs boson !!!

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

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 : $H \to ZZ^*$ - ATLAS p-value

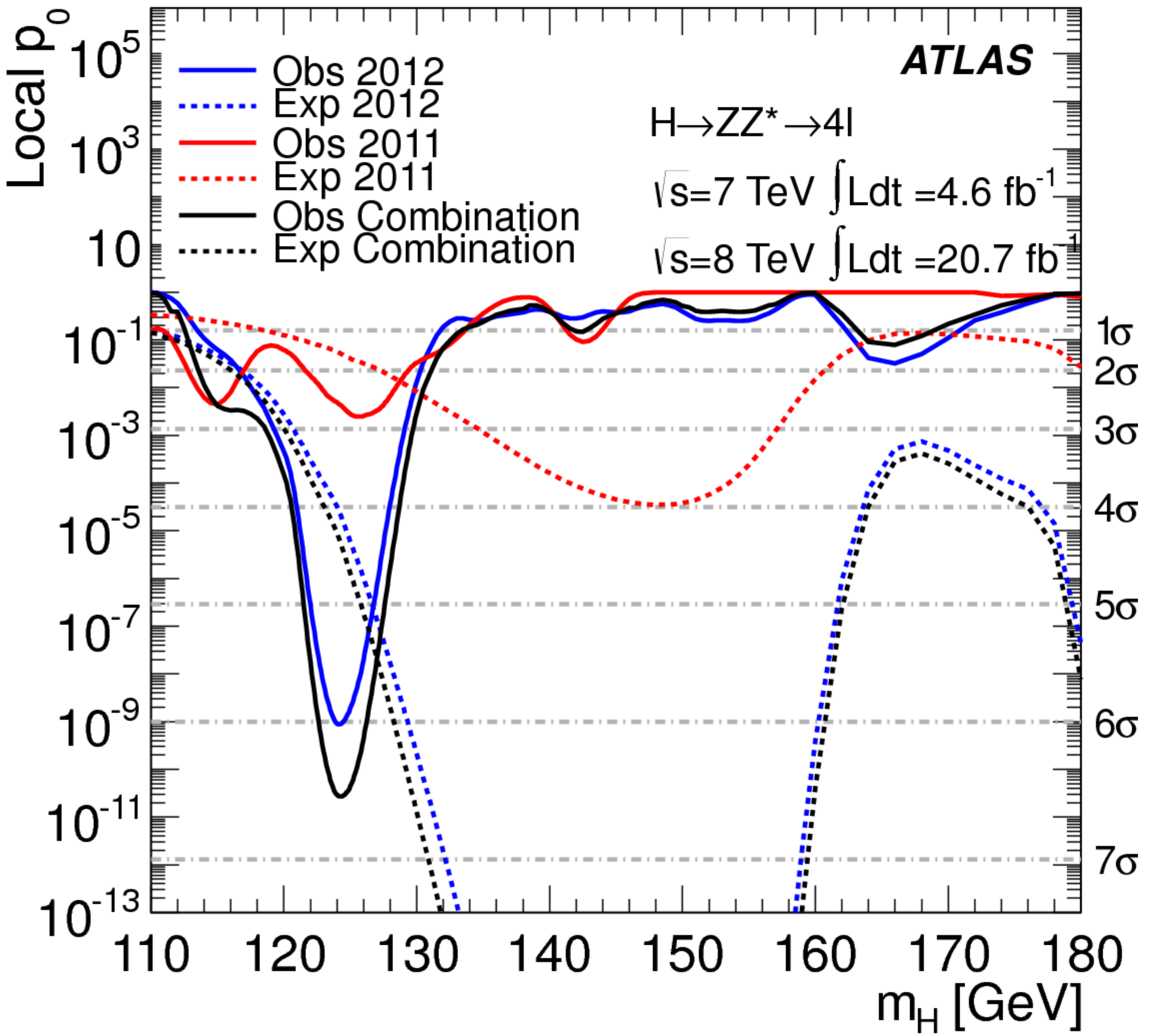
ATLAS 4 $\ell^\pm$

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

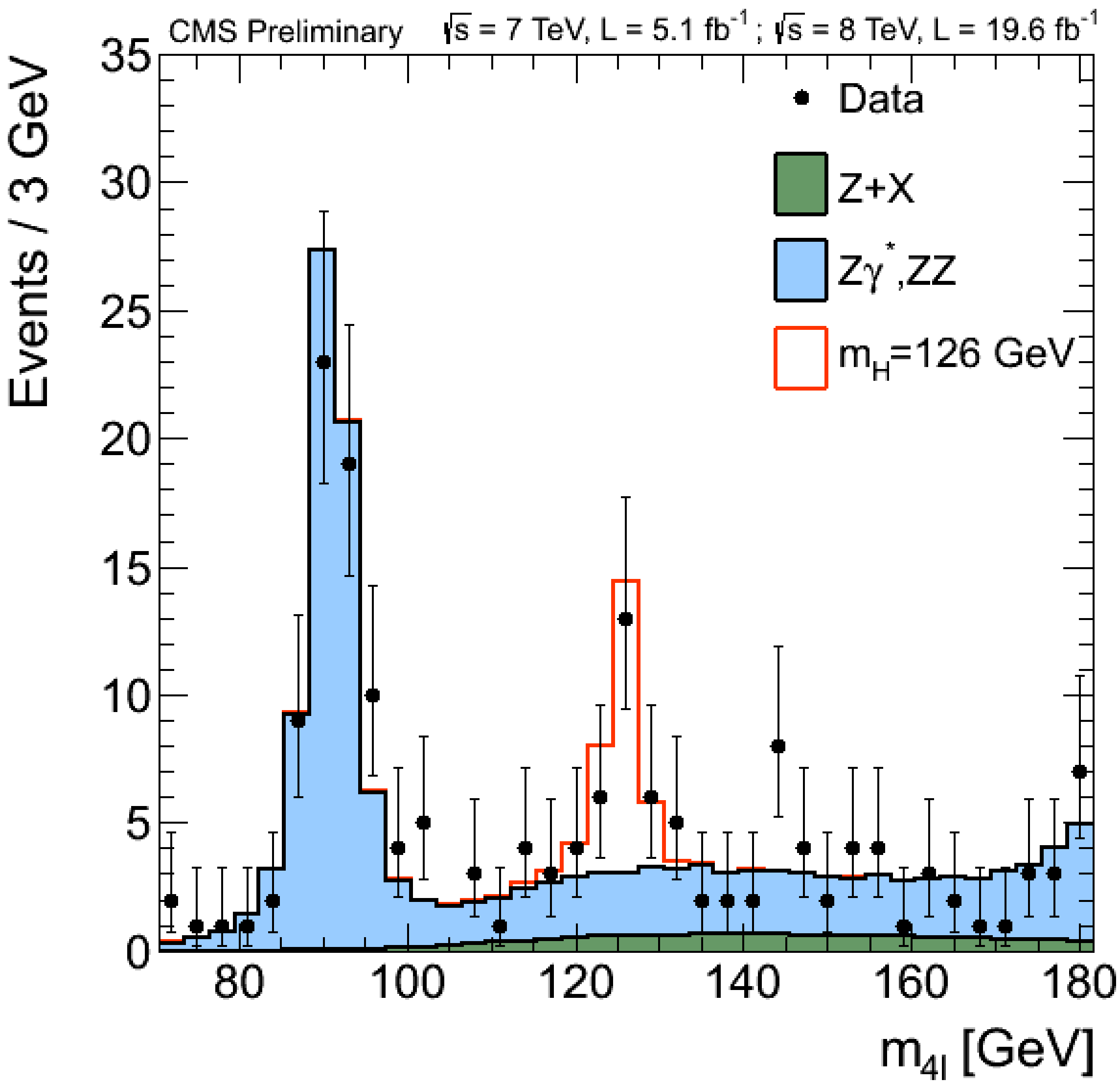
more than expected, but **not incompatible**.

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

definition of p-value ???



Higgs discovery : H → ZZ* - CMS

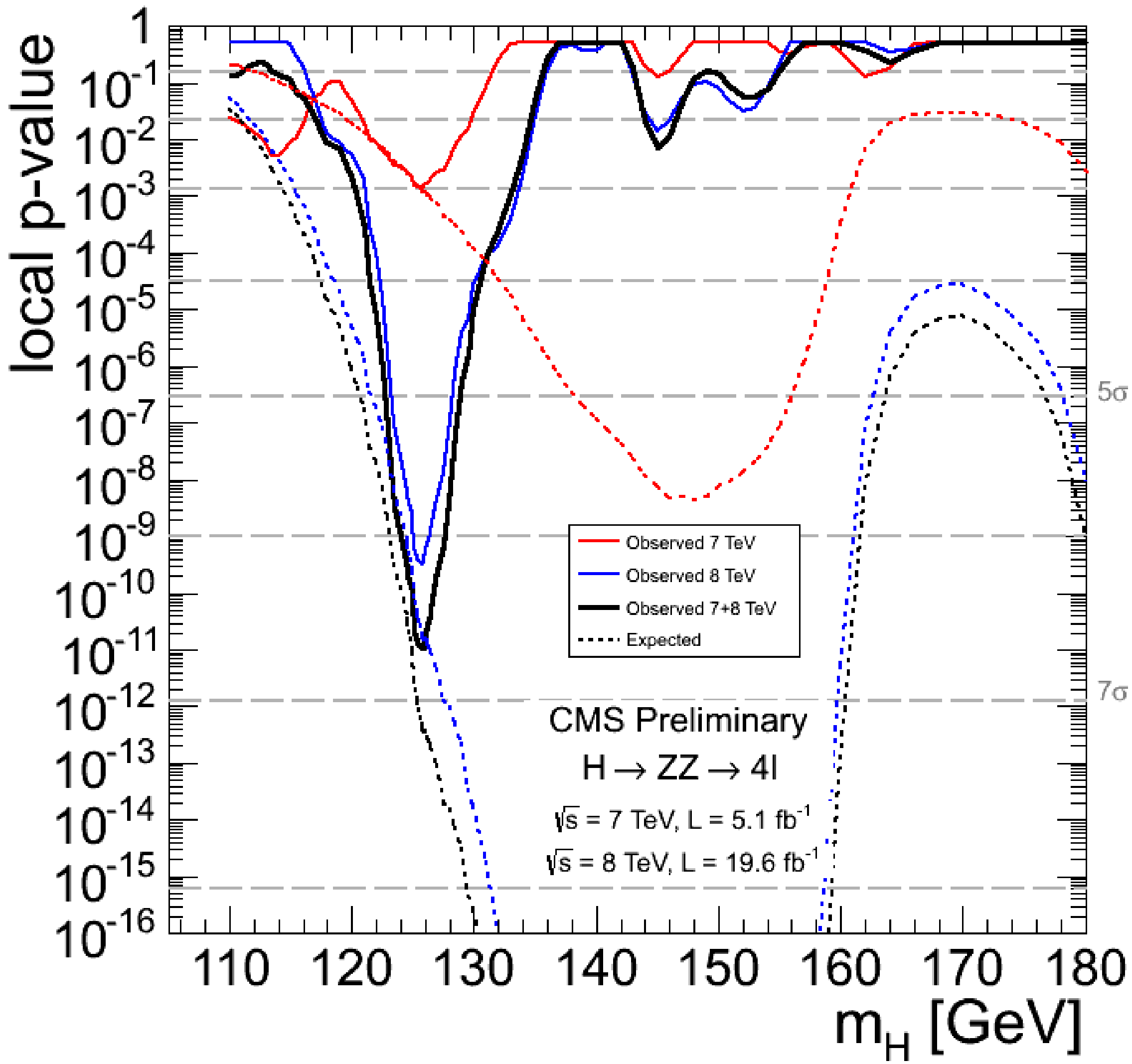


$H \to ZZ^* \to \ell^+\ell^-\ell^+\ell^-$

Test mass ~ 125 GeV

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

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



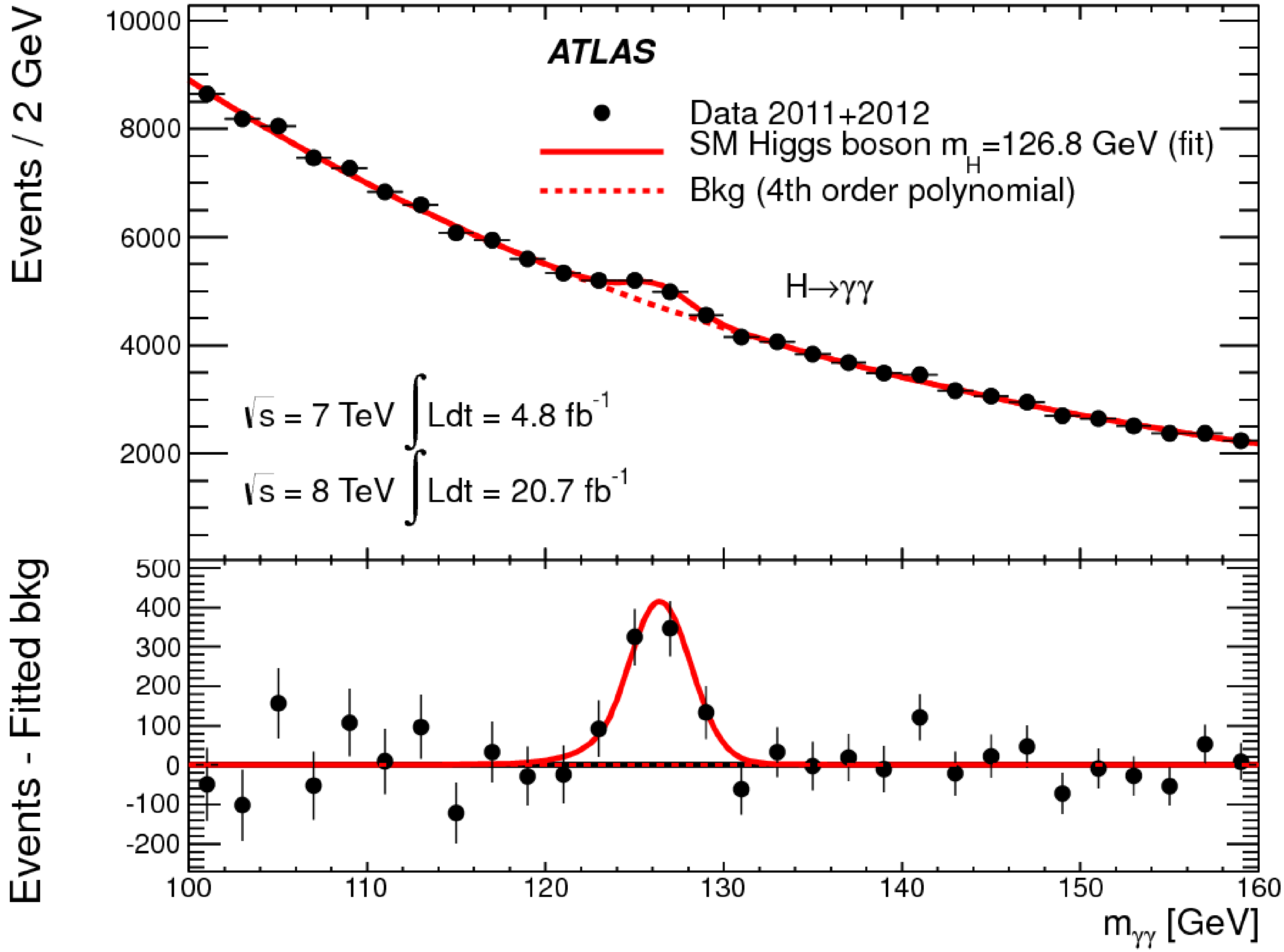
CMS 4 ℓ±

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

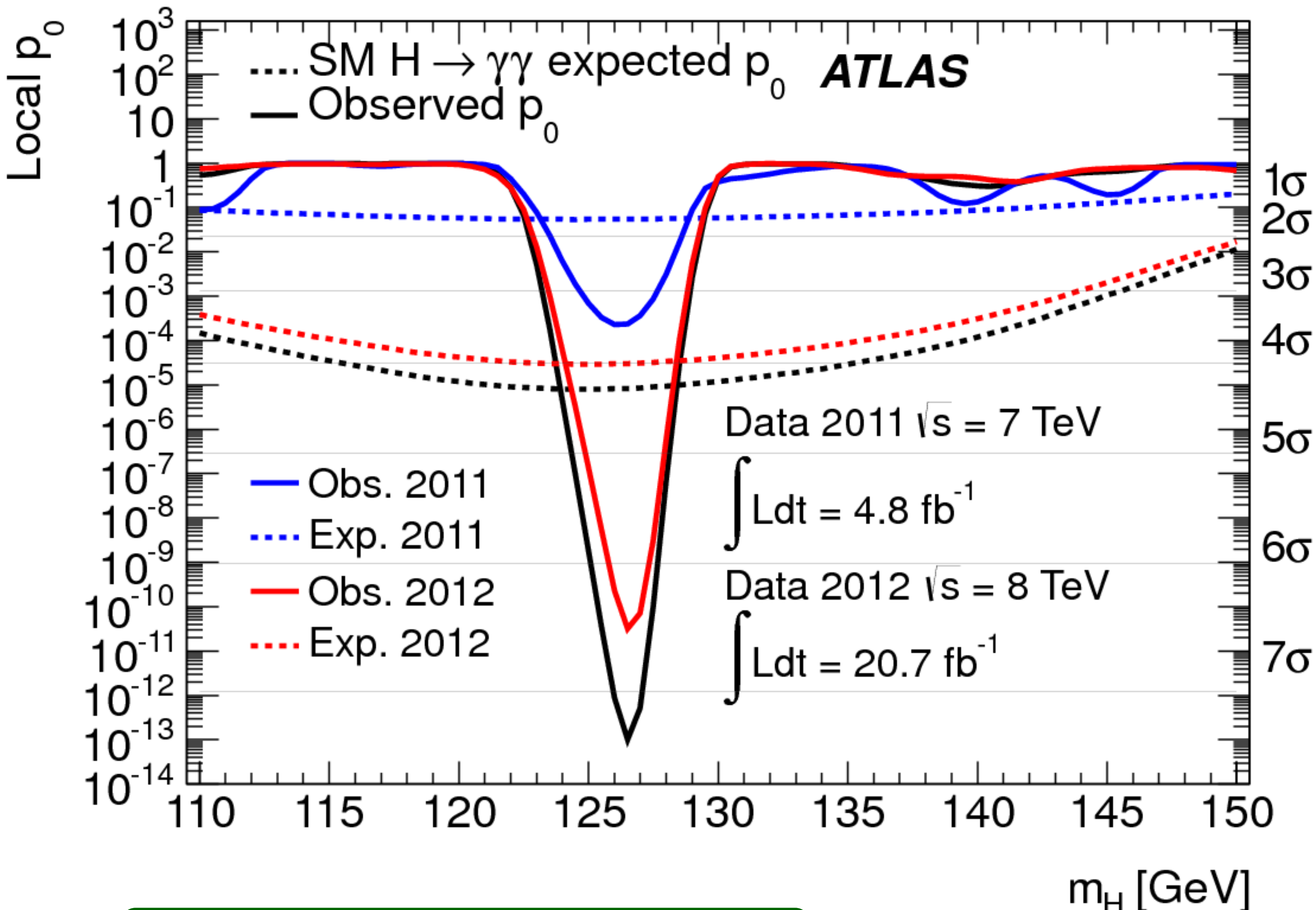
well compatible with expected.

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

Higgs discovery : H → γγ - ATLAS



Higgs discovery : H → □ - ATLAS p-value



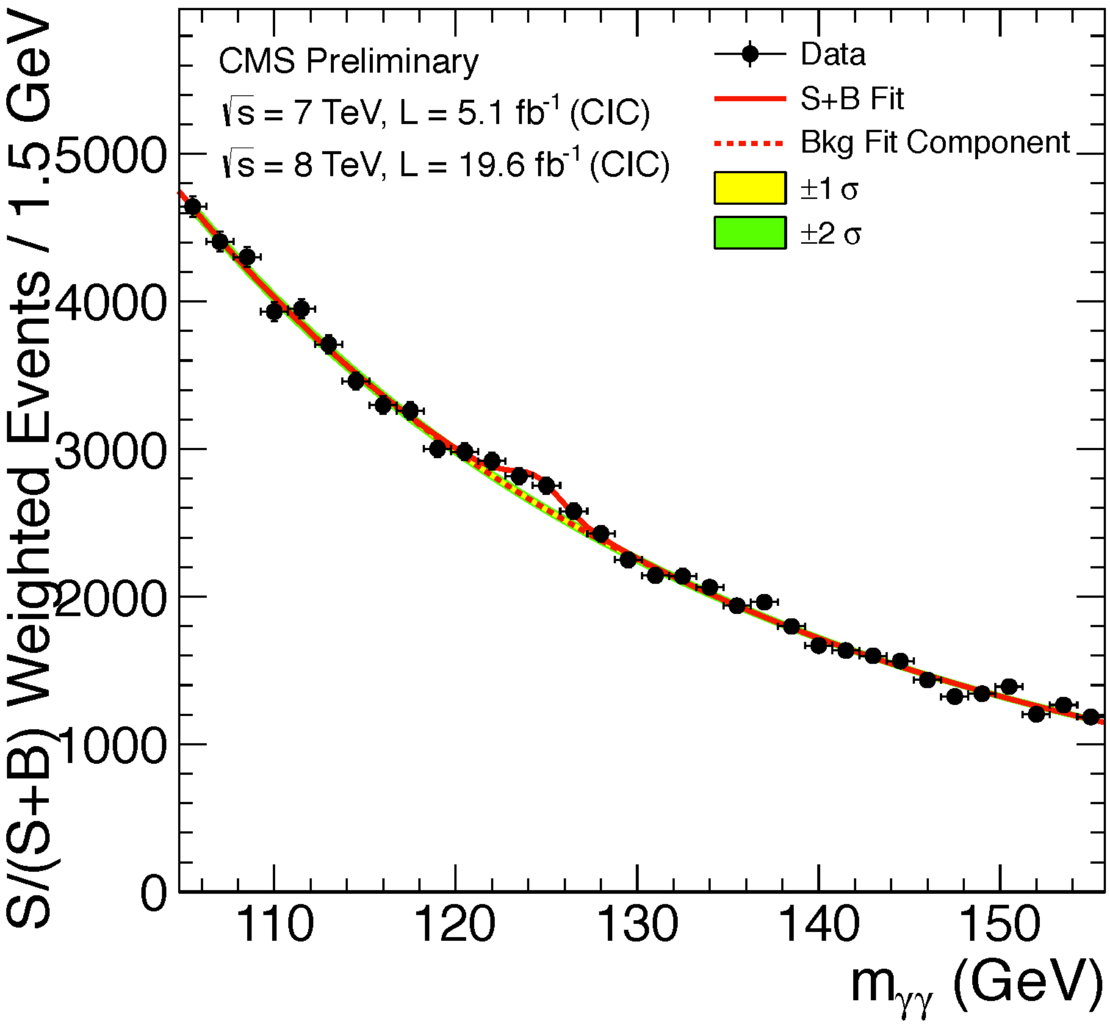
NB. obs (–) and exp (- -) are expected to agree ONLY at m_H^{obs}.

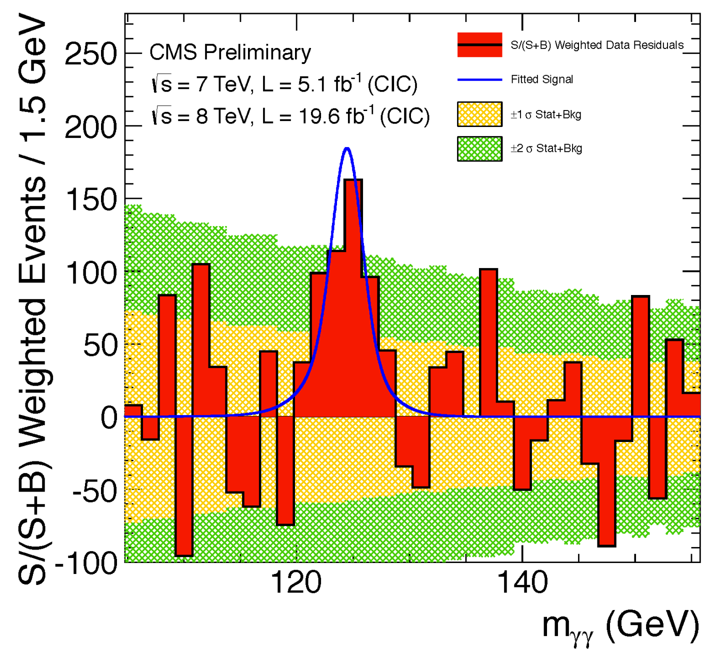
ATLAS γγ

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

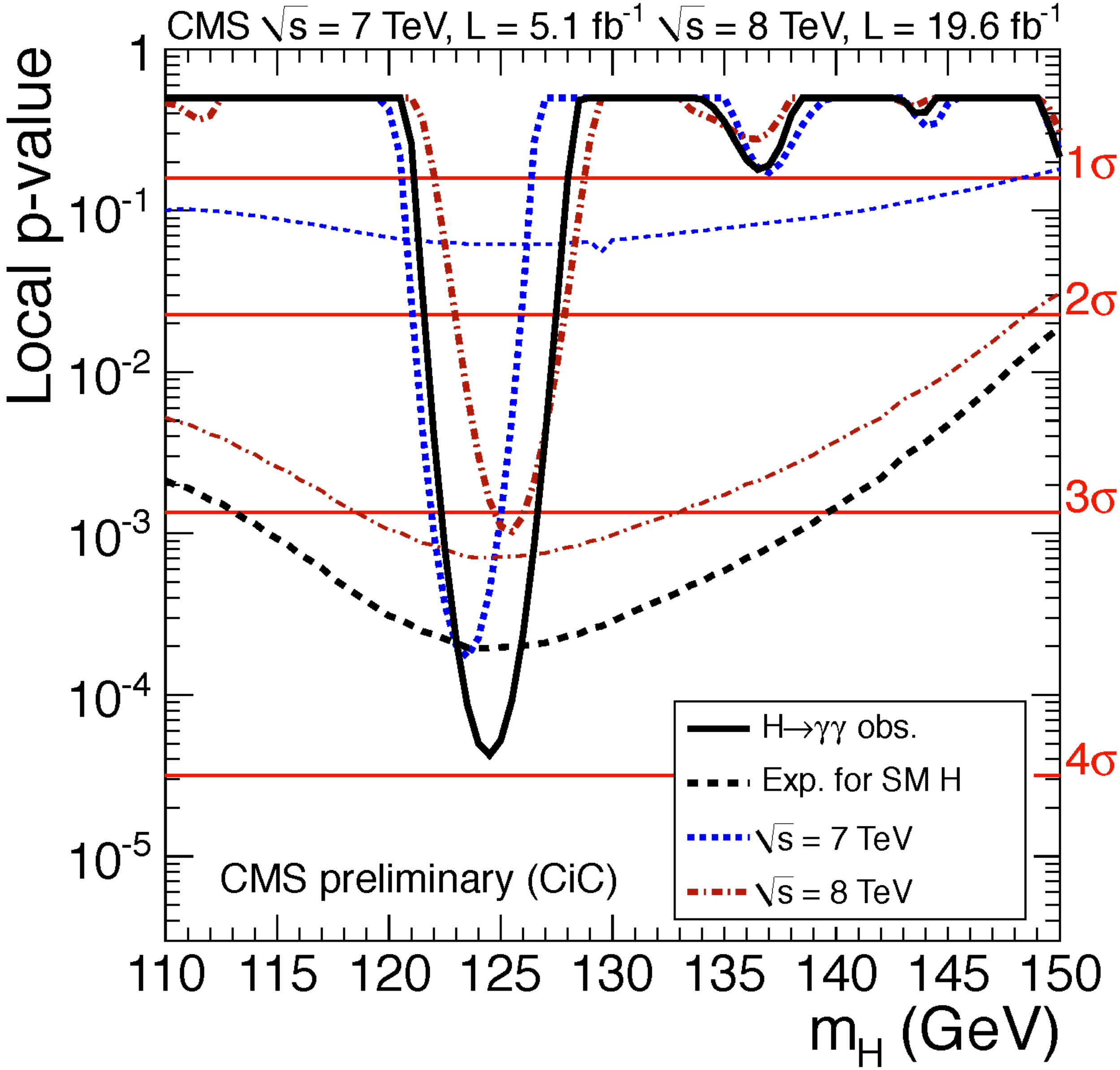
more than expected, but **not incompatible**.

Higgs discovery : H → □ - CMS





Higgs discovery : H → □ - 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 today

After discovery, what next ?

[*the new particle exists, but must check whether it is exactly the SM Higgs*]

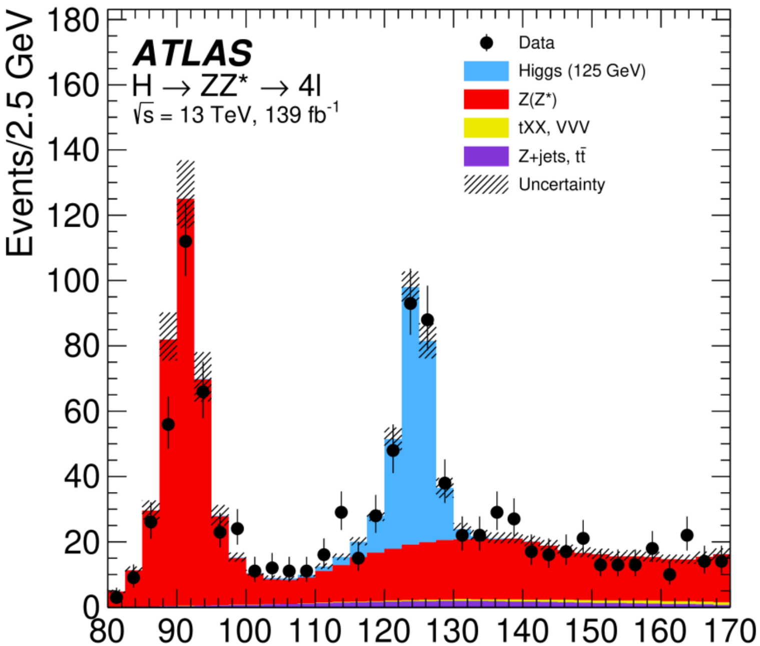
Strategy :

- measure as many as possible H properties :
  - mass (→ masses in all decays);
  - production rates (→ vs $\sqrt{s}$);
  - production mechanisms and decay BR's (→ couplings);
  - angular distr. of decay products;
- 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 and J^{CP});*
- *no discussion of bSM analyses (actually most studies, but none successful, until now…, see next chapter);*
- *a neverending work in progress …*

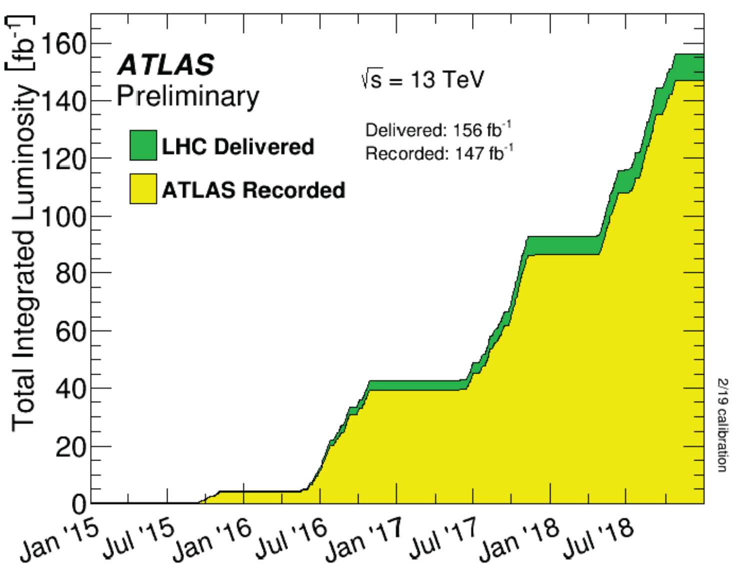
Higgs today: $4\ell^{\pm}$ mass - plot 2020

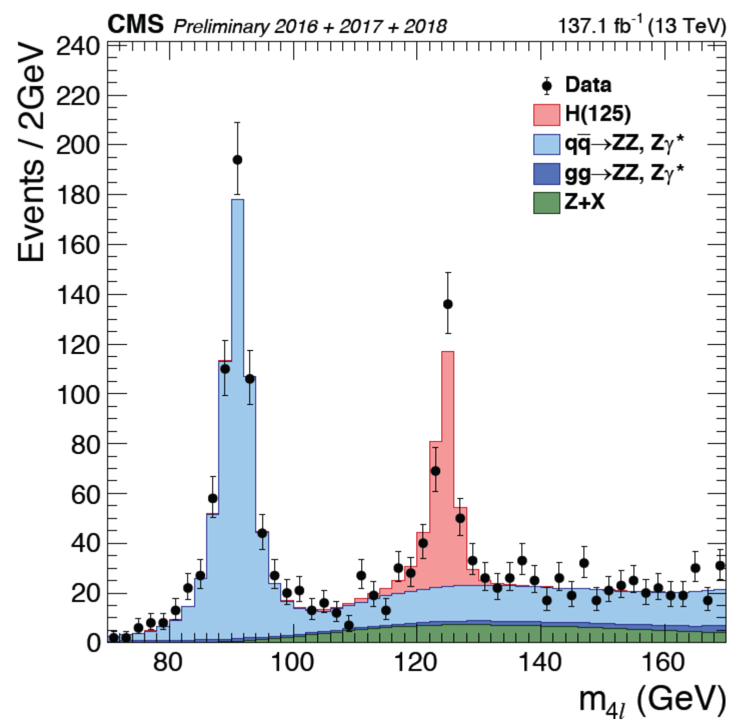


A fresh look to new data at 13 TeV for H → $4\ell^{\pm}$ (see $\mathscr{L}$ plot).

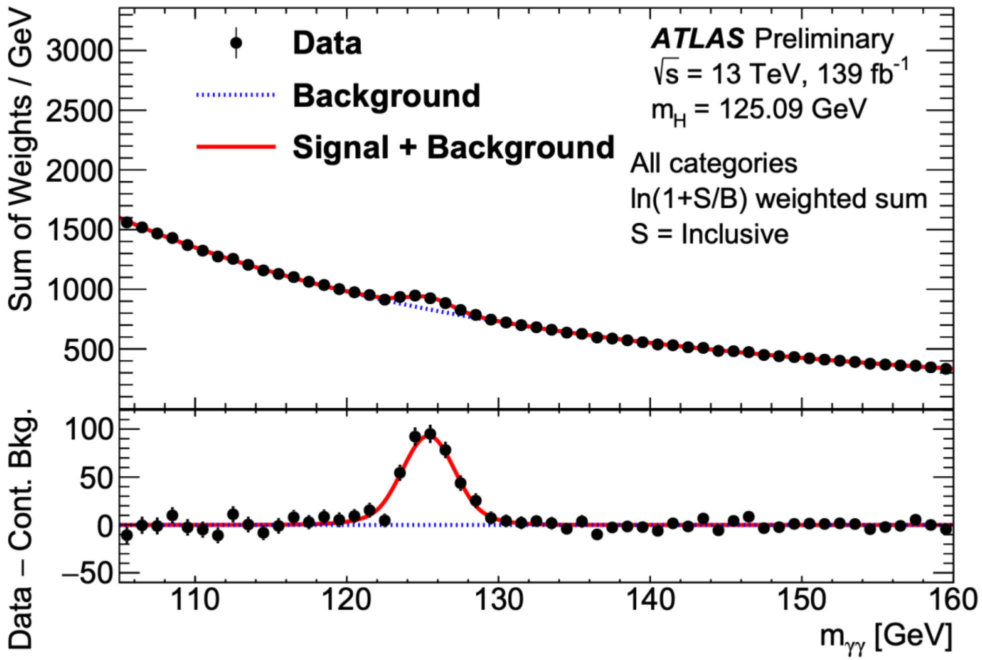
The data size has strongly improved: just look at the discovery plots.

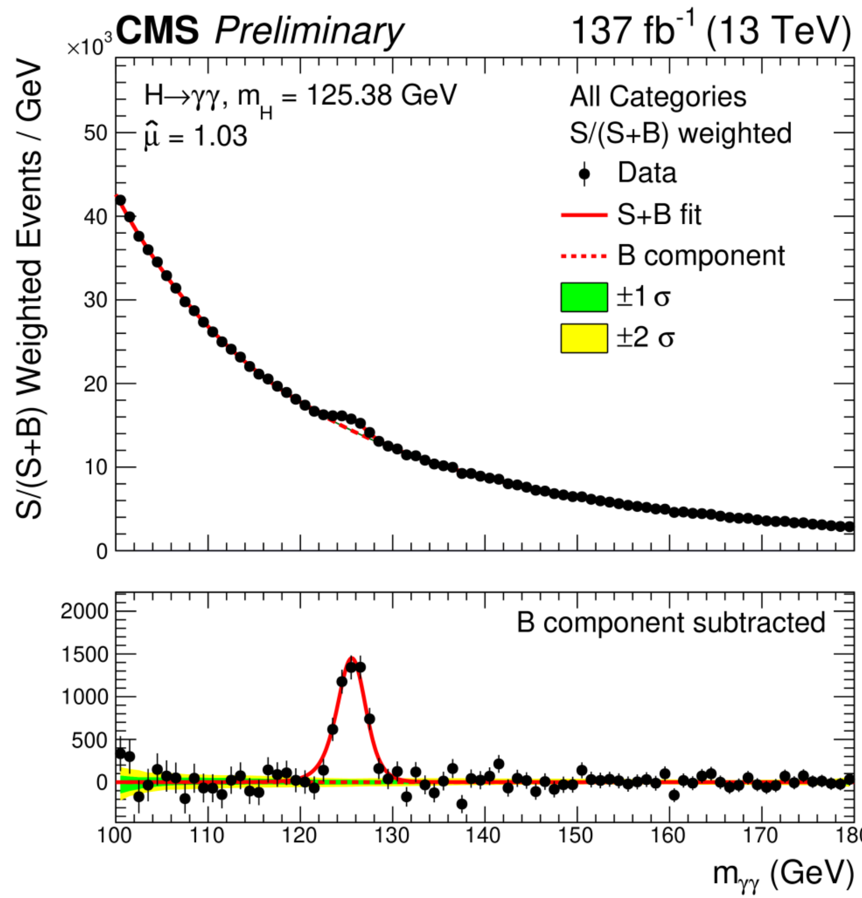
The exact p-value looks irrelevant, we are back to the old-fashioned regime "*the presence of the effect is obvious*" [<u>but NOT the interpretation</u> !]





Higgs today: γγ mass - plot 2020

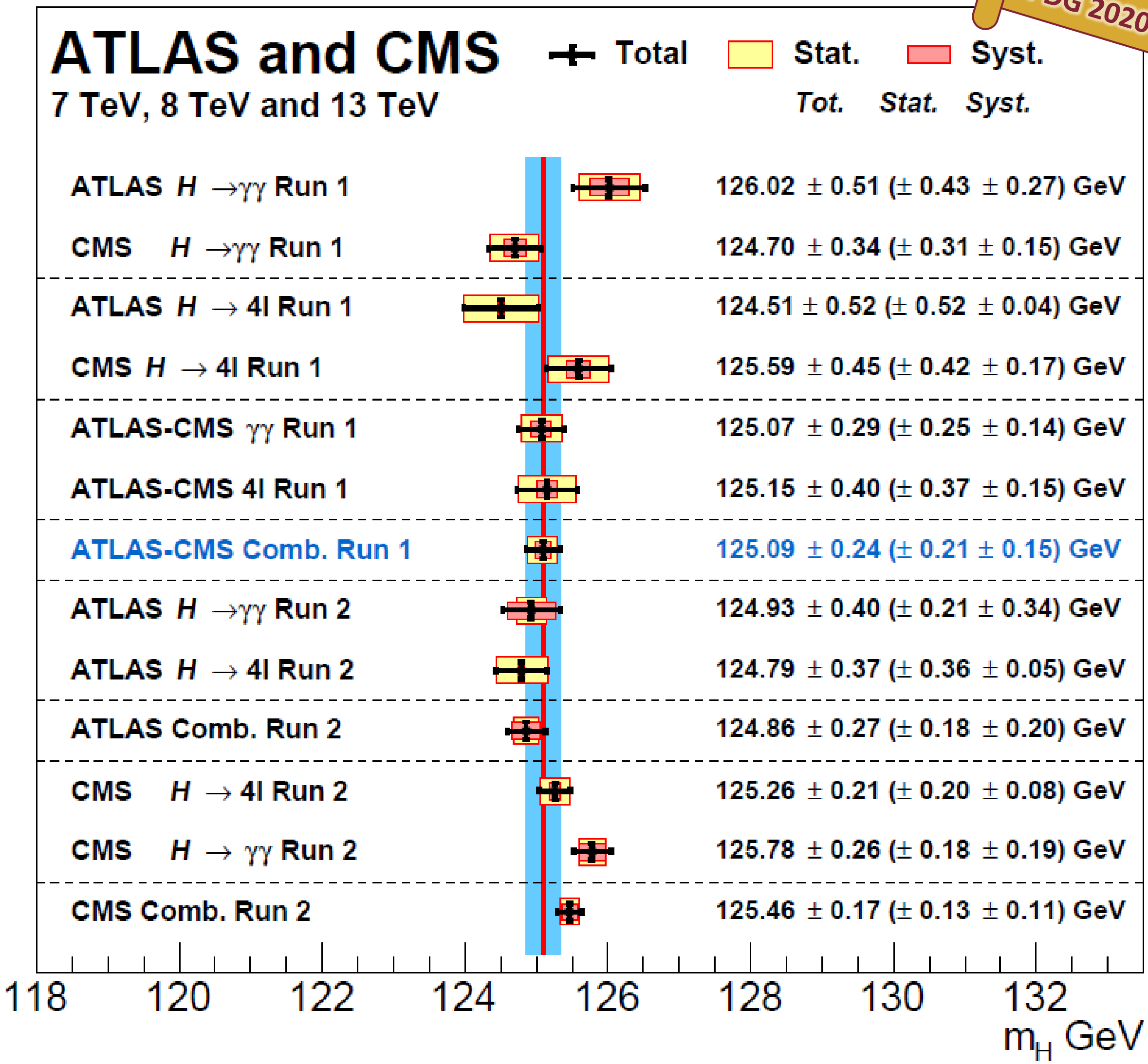




... and for H → γγ.

[*same comment on p-value*]

Higgs today: mass(es ?)



PDG 2020

Fot the (□) and (4ℓ) channels $\Delta m_H/m_H < 1\%$ (very precise):

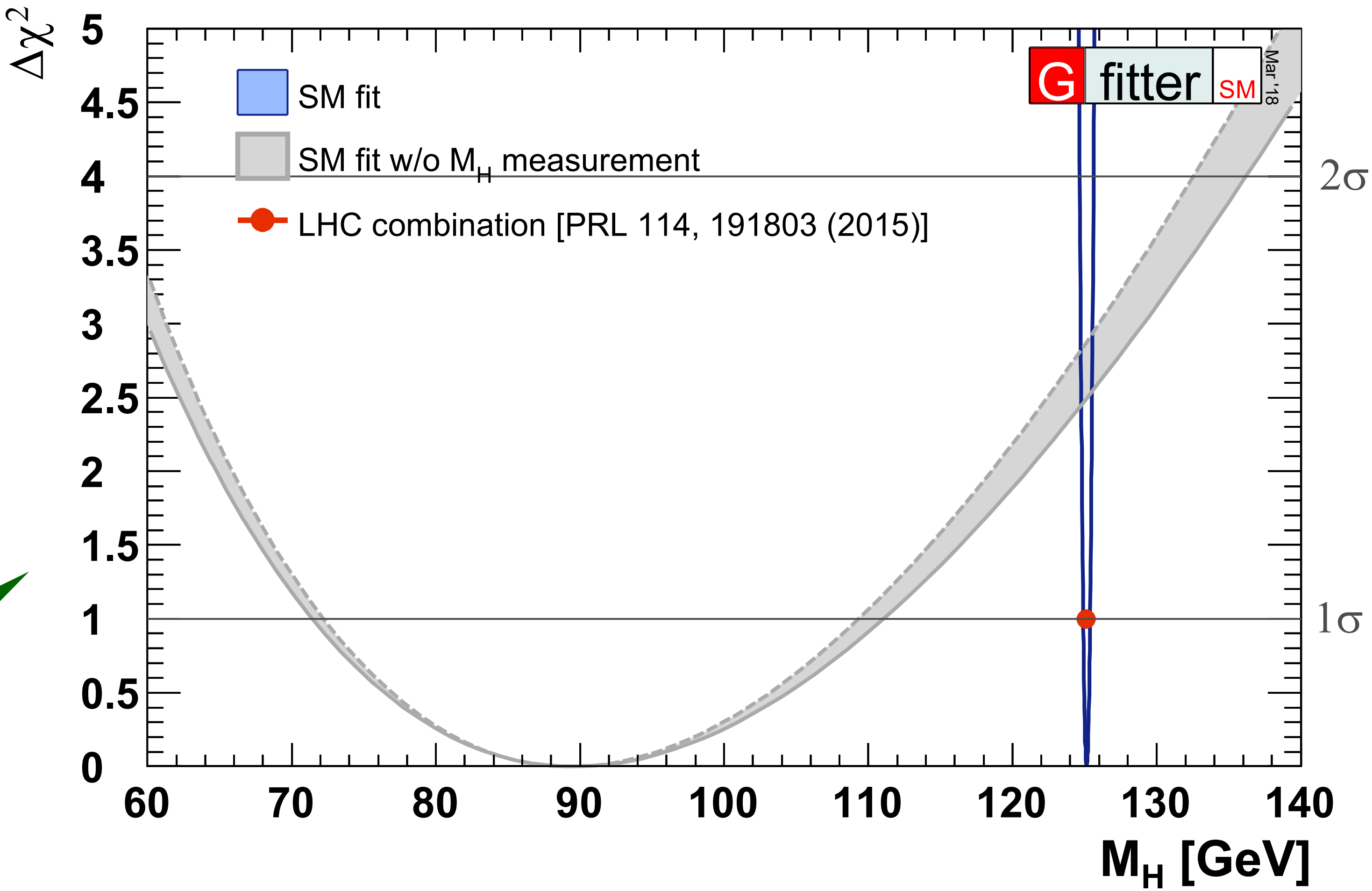
- if particle NOT the SM H → m(□) and m(4ℓ) could be different;
- but in the data their mass is compatible;
- and ATLAS and CMS are fully compatible;
- assuming combination, the PDG 2020 estimation has the error at 10^{-3} level:

  $m_H = 125.10 \pm 0.14$ GeV

  [*an unprecedented success, just go back and look for W/Z at the Sp$\bar{p}$S*].

Higgs today: mass SM vs direct

- the indirect measurement still likes a low-mass Higgs;
- [*but be aware that* "2σ" *is NOT* "2 × 1σ";]
- stat. fluctuation [*most likely imho*] or real hint of new physics ?
- "ai posteri l'ardua sentenza" ["*sentence waits posterity*", *really ?*]



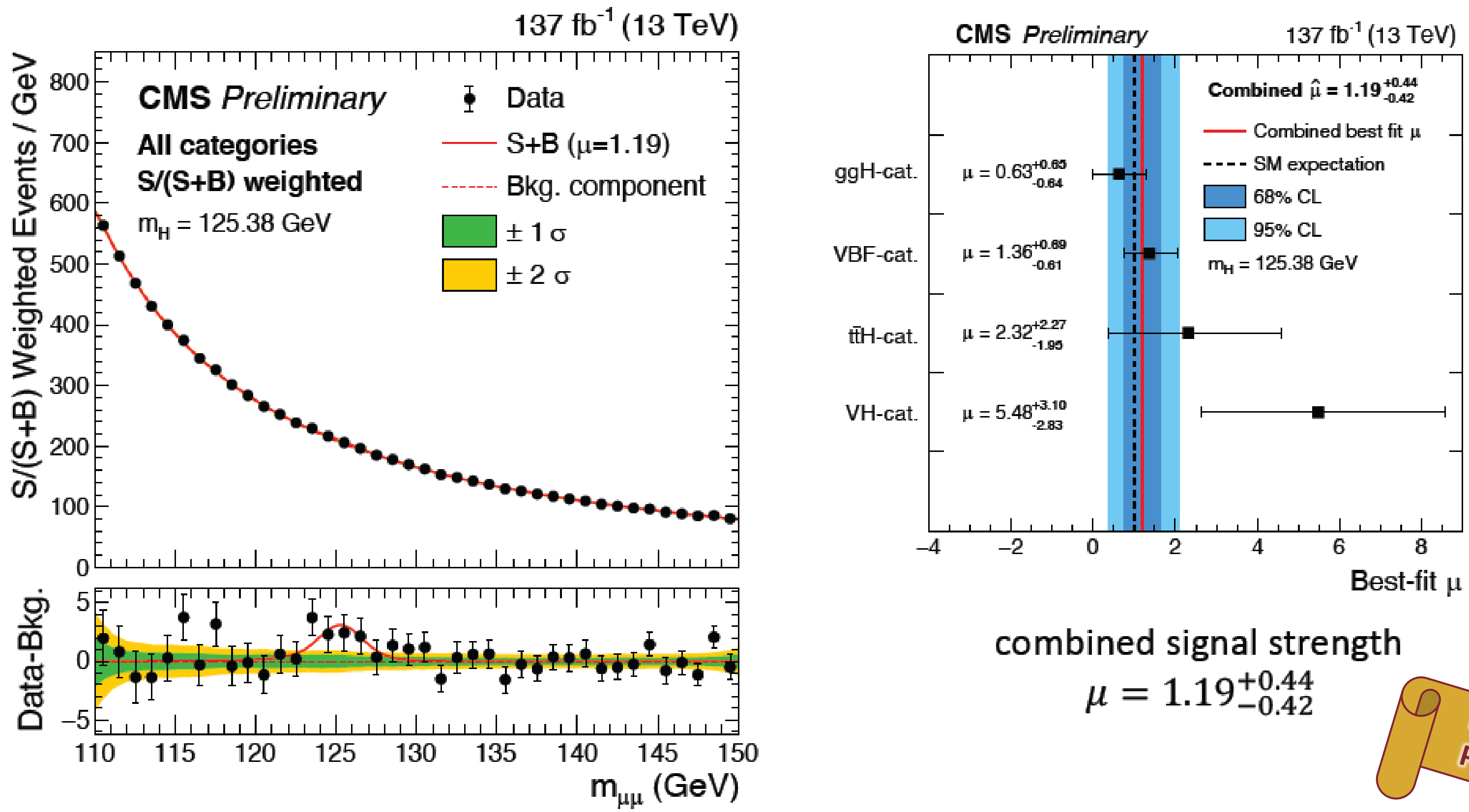
I love this plot, I've shown it 5 or 6 times.

Higgs today: $H \to \mu^+\mu^-$

One of the highlights of the last year:

$H \to \mu^+\mu^-$

- the coupling is very small (BR 2×10^{-4}) $\to$ difficult;
- before it, only 3rd family + IVB's, this is the 1st fermion of the 2nd family;
- in the SM the coupling is NOT a function of the family [*but you never know*].



combined signal strength

$\mu = 1.19^{+0.44}_{-0.42}$

R.Carlin Prague2020

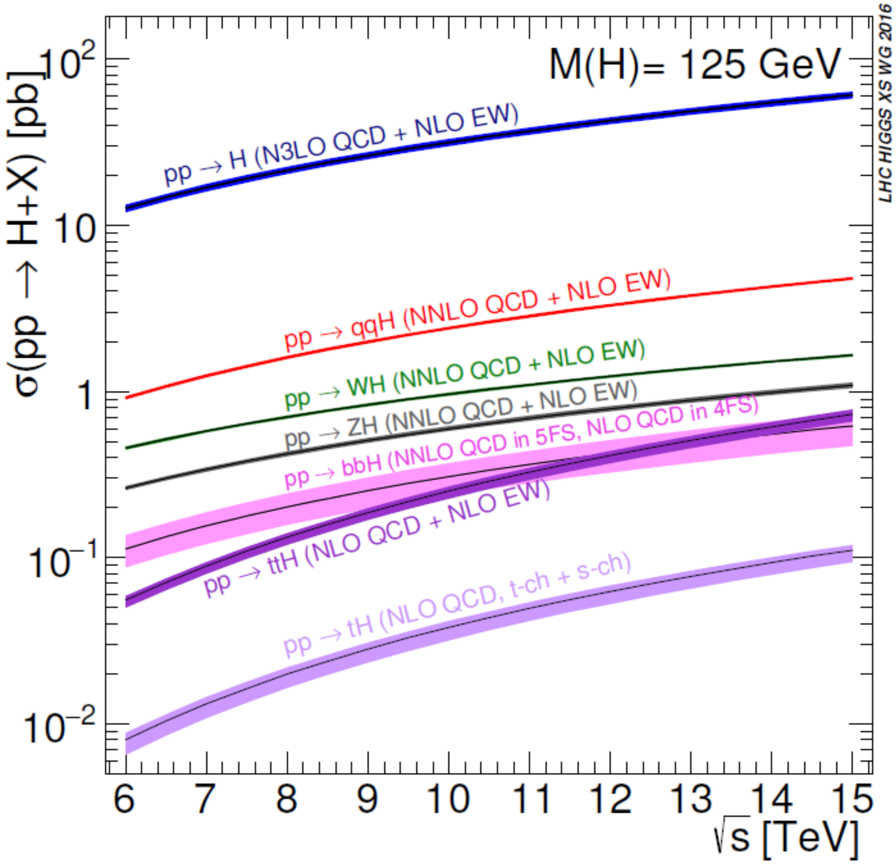
Higgs couplings: new SM predictions

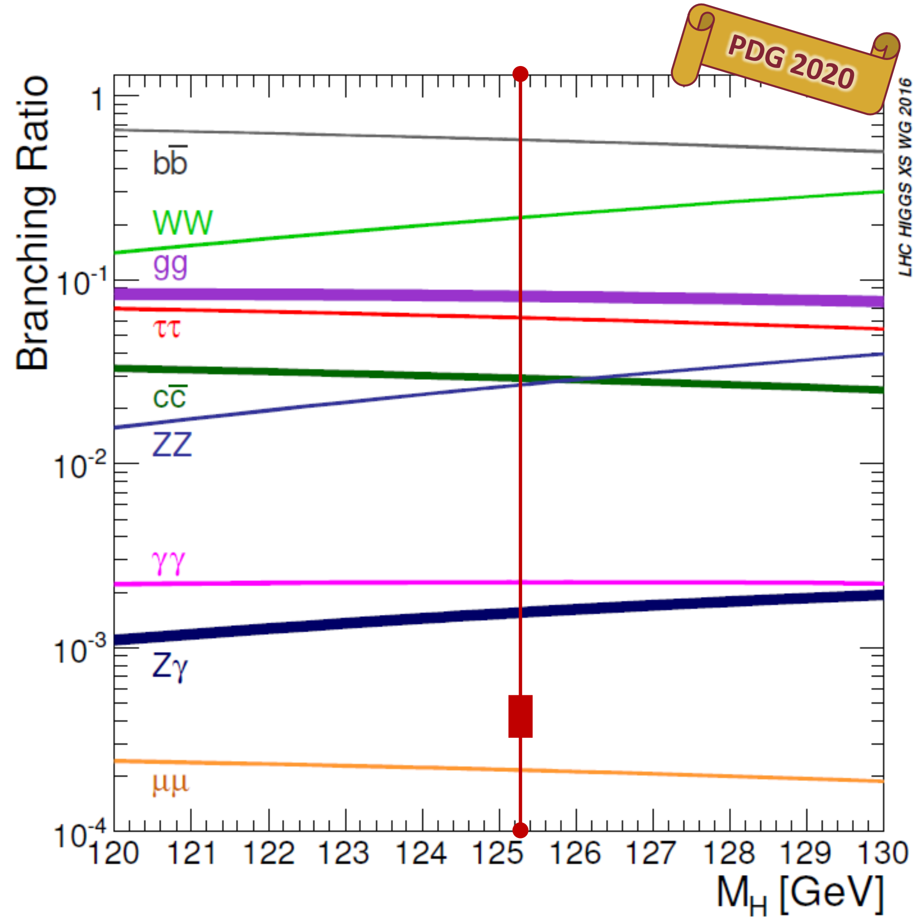
For production/decay precision meas., better SM predictions are needed.

Calculations of Higgs properties vs m_H up to m_H = 1 TeV are now useless (they are used to look for a larger Higgs sector).

New calculations for:

- σ_H vs $\sqrt{s_{LHC}}$ for m_H = 125 GeV;
- BR(H $\rightarrow$X).





Higgs couplings: Γ's

- Γ(H→fermions/IVBs/…) ≡ $\Gamma_{ff/WW/ZZ/...}$ completely specified in SM, once m_H fixed [see plot before and IE, § 14];
- **very** different if real/virtual W/Z ($H_{125} \to$ W*W or Z*Z only);
- computable 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 theory ↔ exp. [*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^*}, i.e. $m_H < 2m_{W,Z}$:

$$\Gamma_{WW} = \frac{3G_F^2 m_H m_W^4}{2\pi^3} \times J_W\left(\frac{m_W}{m_H}\right);$$

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

$$\Gamma_{ZZ} = \frac{3G_F^2 m_H m_Z^4}{2\pi^3} \times g_Z\left(\sin^2\theta_W\right) \times J_Z\left(\frac{m_W}{m_H}\right);$$

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

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

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

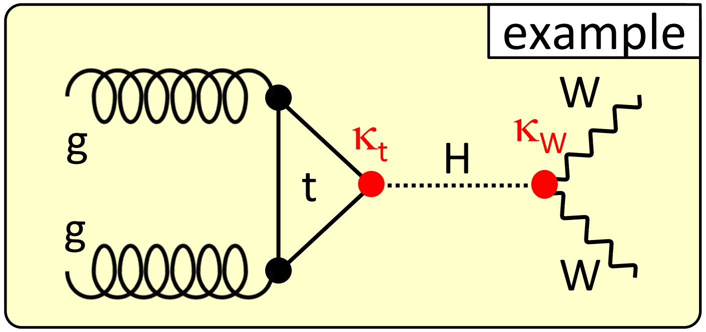
Higgs couplings: modifiers κ

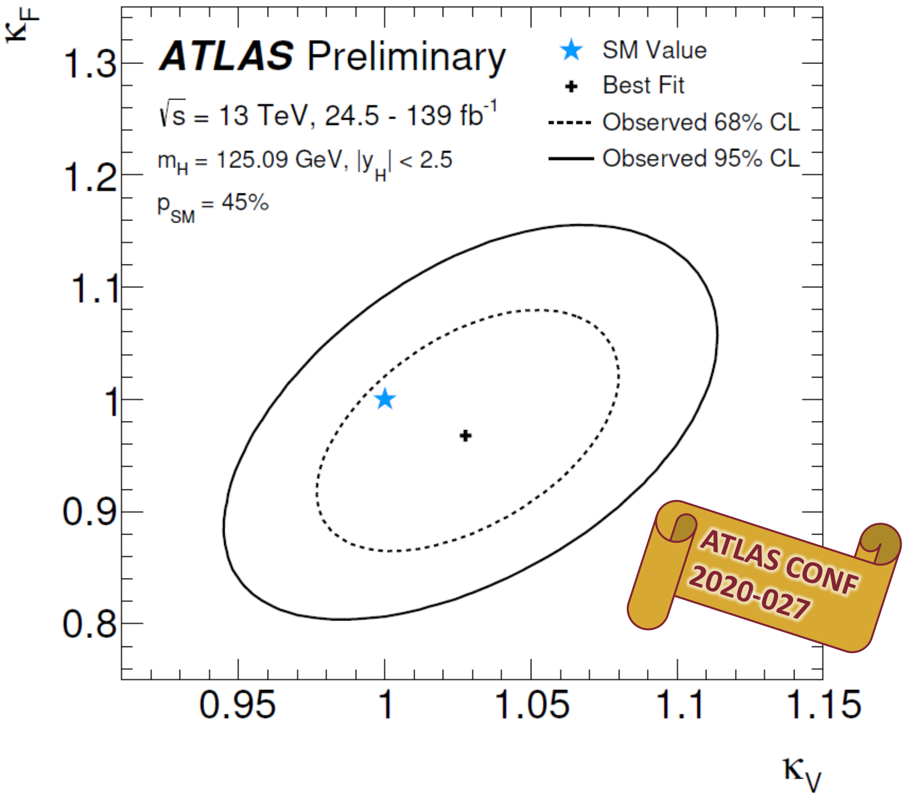
The modifiers κ already defined; in practice:

- $\kappa_j^2 = \dfrac{\Gamma^j_{exp}}{\Gamma^j_{SM}}$ [j = all particles (f / V)];
- [simpler: only two: κ_f for fermions; κ_V for IVBs];

"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.

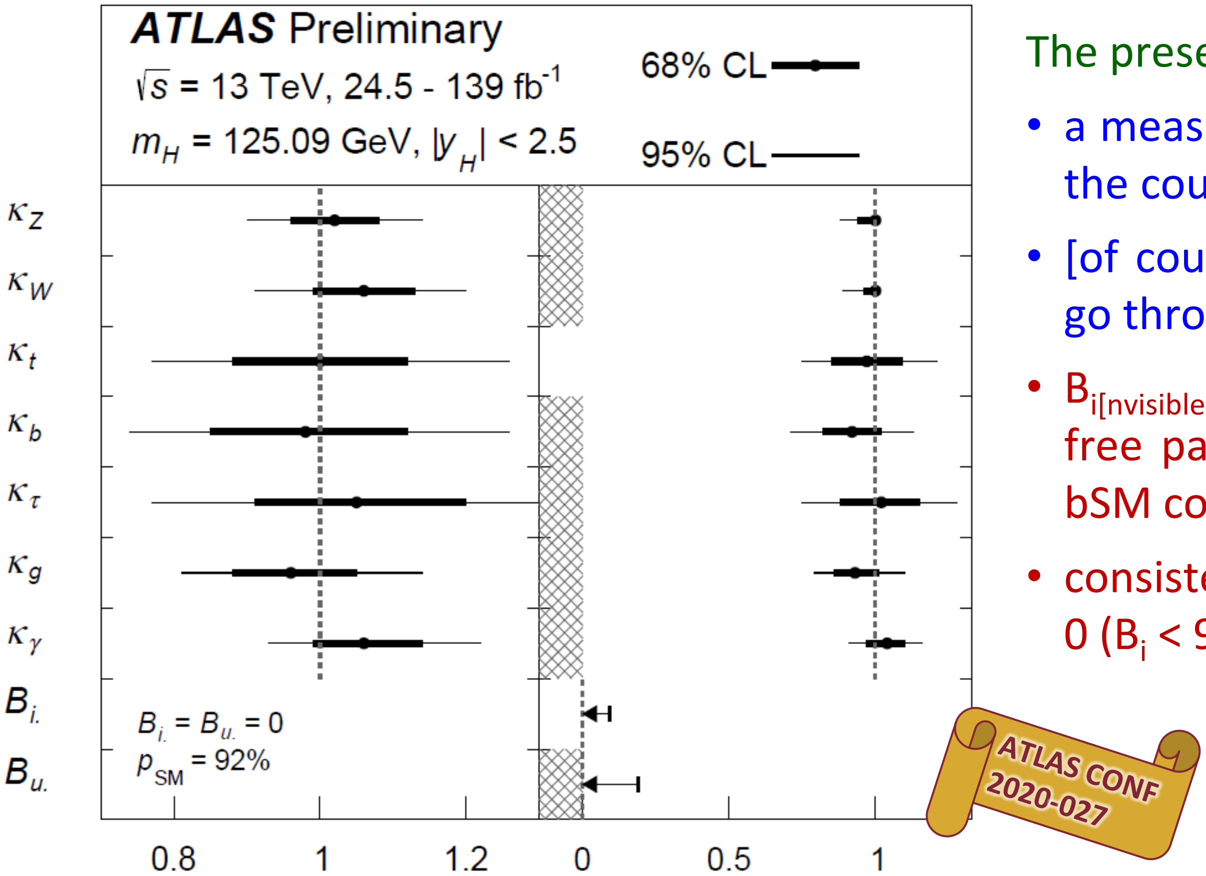




An example of this analysis:

- κ_F vs κ_V (i.e. fermions vs IVBs);
- large errors, but compatible with $\kappa_F = \kappa_V = 1$;
- agreement ATLAS ↔ CMS (not shown).

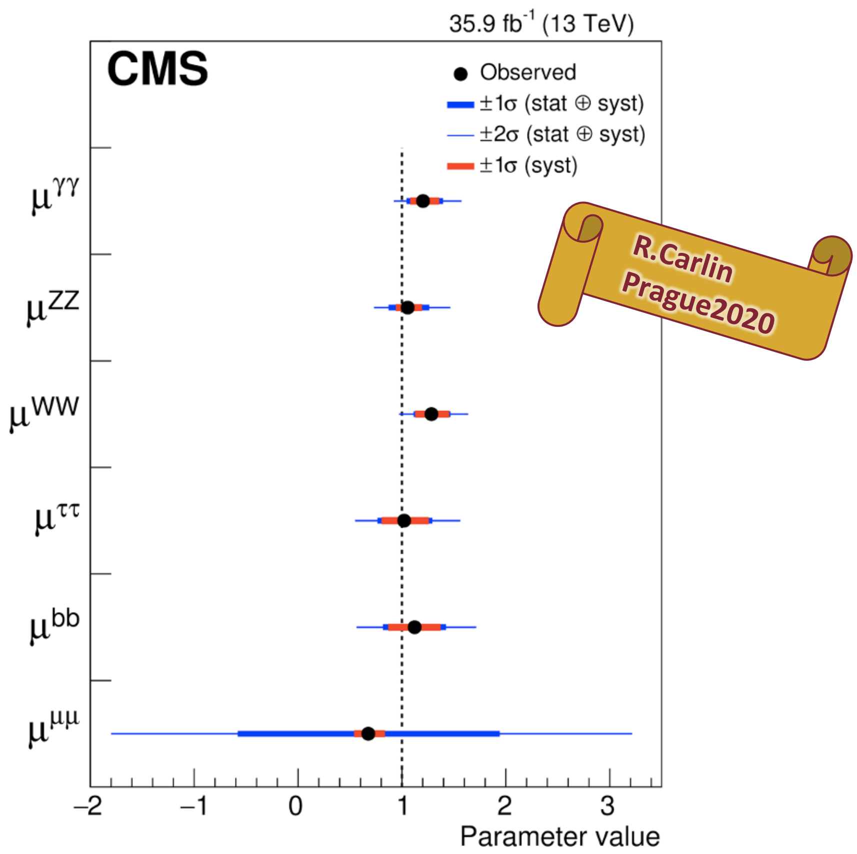
Higgs couplings: results (ATLAS)



The present situation:

- a measurement of the modifiers κ_j for the couplings with Z, W, t, b, τ, g, γ;
- [of course the couplings with g and γ go through loops];
- $B_{i[nvisible]}$ and $B_{u[ndetected]}$ are added as free parameters to allow for possible bSM couplings;
- consistency with SM: all κ's = 1, B's ≈ 0 (B_i < 9% at 95%CL).

Higgs couplings: results (CMS)



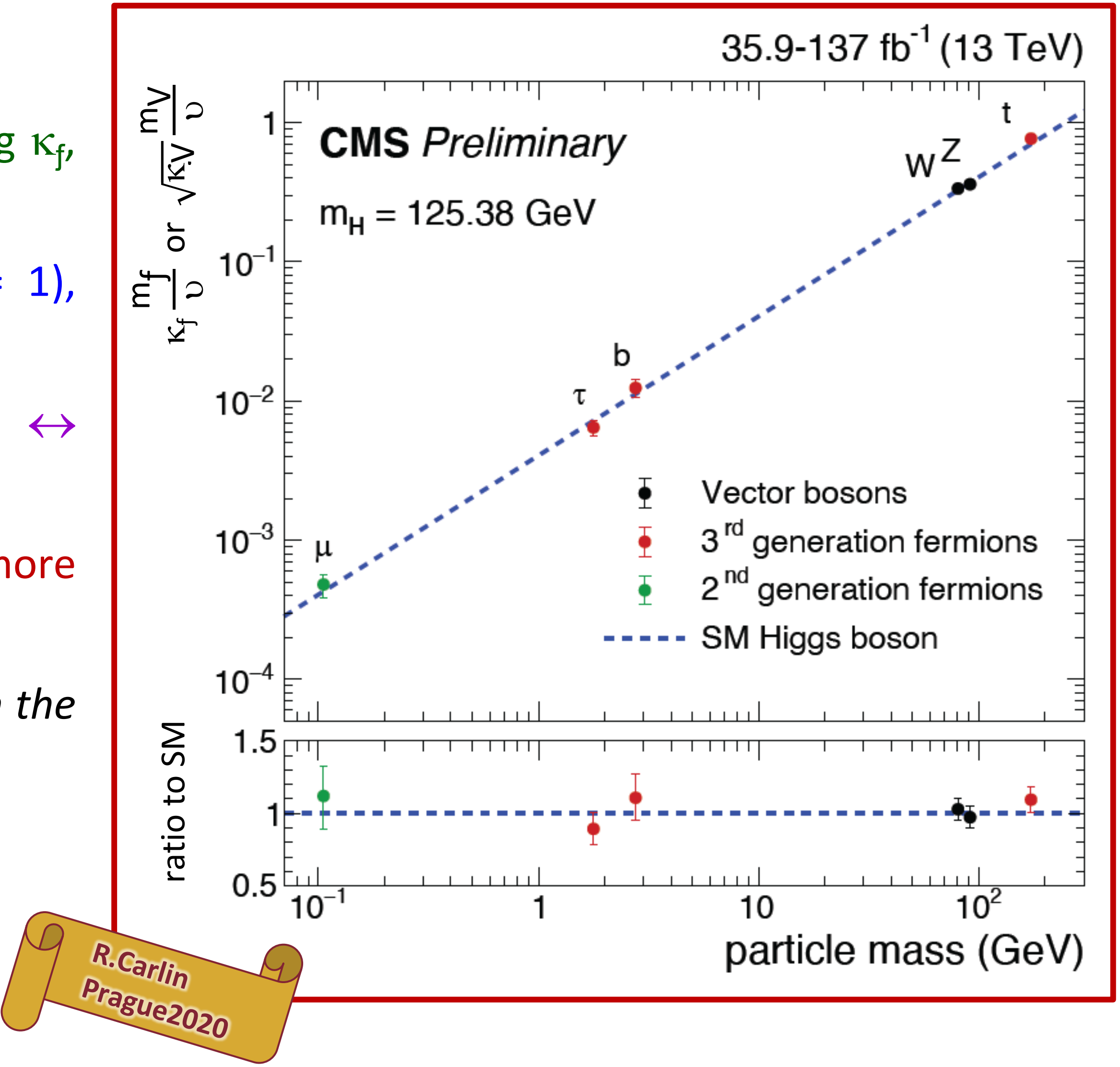
a similar plot for CMS:

- couplings with bosons (γ/Z/W), 3rd gen. fermions (τ,b), 2nd gen. fermions (μ);
- coupling with t also tested via production;
- 1st gen. still missing;
- ="1" → SM ok;
- the physics is VERY clear: no deviation from SM.

Higgs couplings: values vs m_f/m_V

Higgs couplings (measured vs SM):

- plot together couplings (including κ_f, κ_V) vs mass of fermions and IVBs;
- compatible with SM (κ_f = κ_V = 1), represented by the line (- - - -);
- agreement ATLAS (not shown) ↔ CMS;
- impressive, from m_μ to m_t → more than 3 orders of magnitude;
- [*imho the best evidence for SM in the higgs sector*].



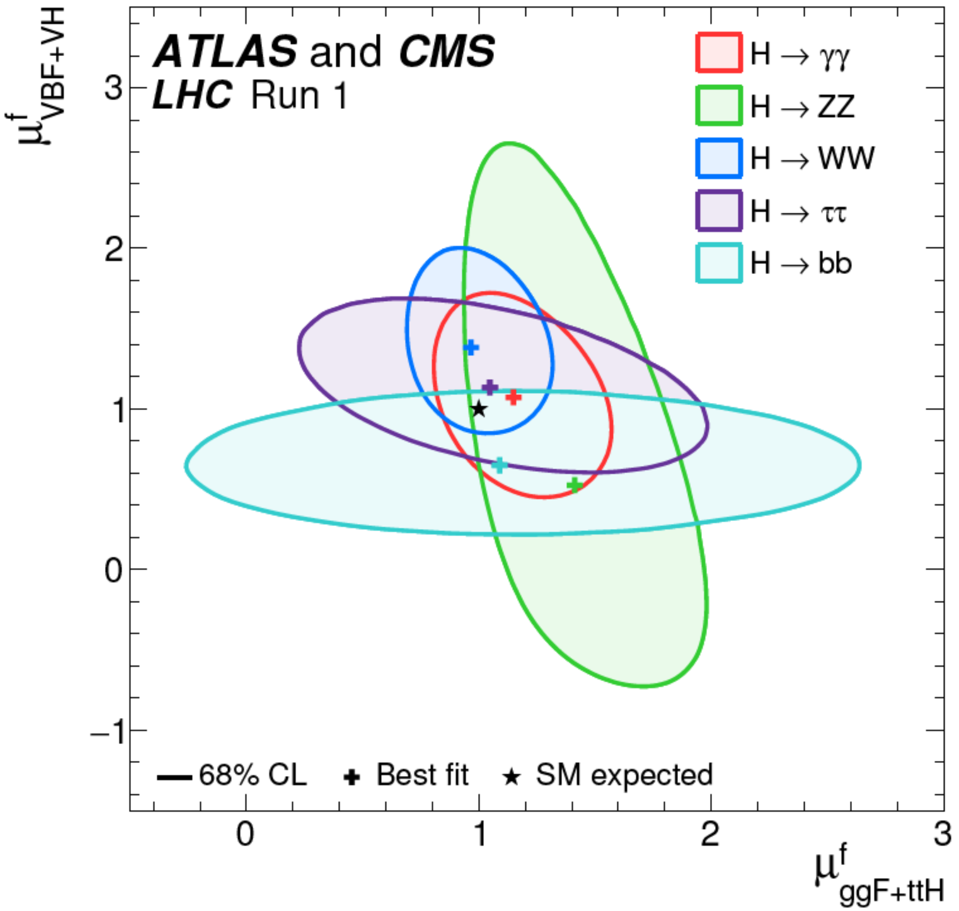
Higgs couplings: σ × BR

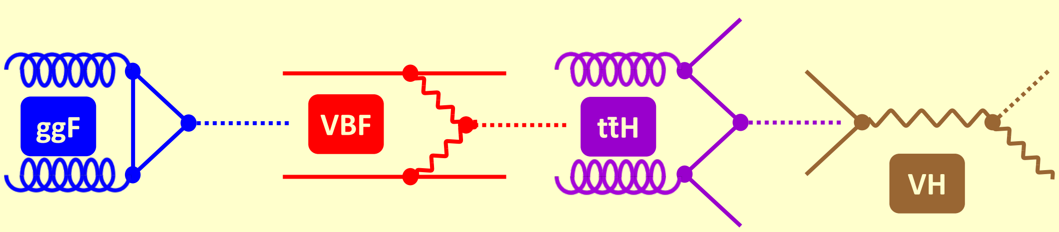
Define :

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

interpretation of result for μ_i^f :

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



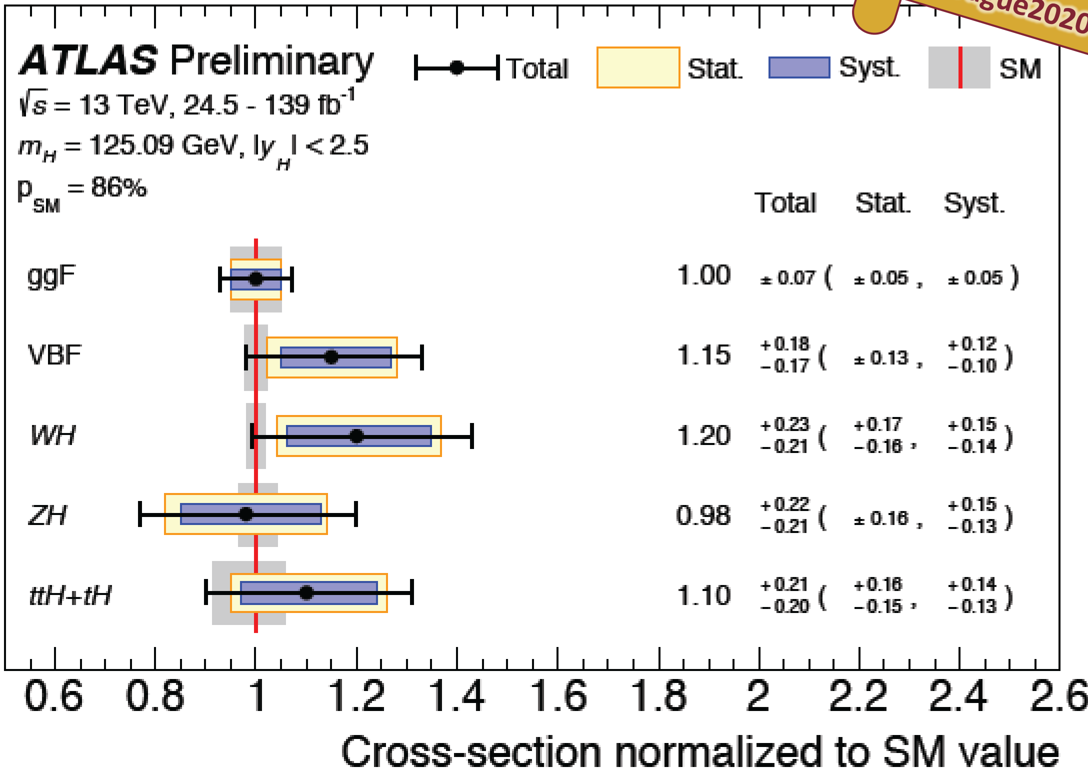


An old example of this analysis:

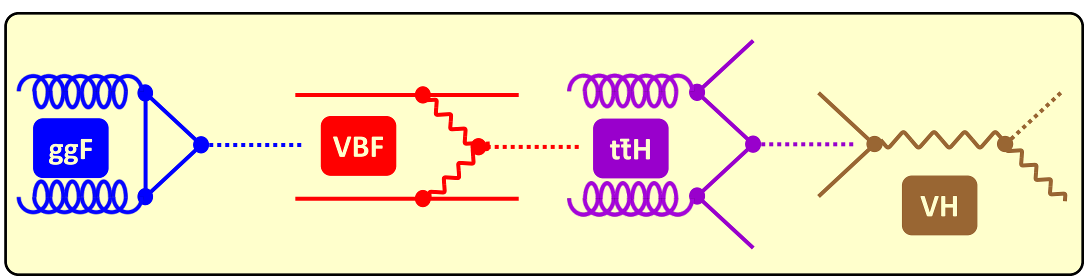
- for all the decays (5 × "f");
- group (VBF+VH) and (ggF+tt̄H), i.e. bosons vs fermions.

Higgs couplings: production mechanisms

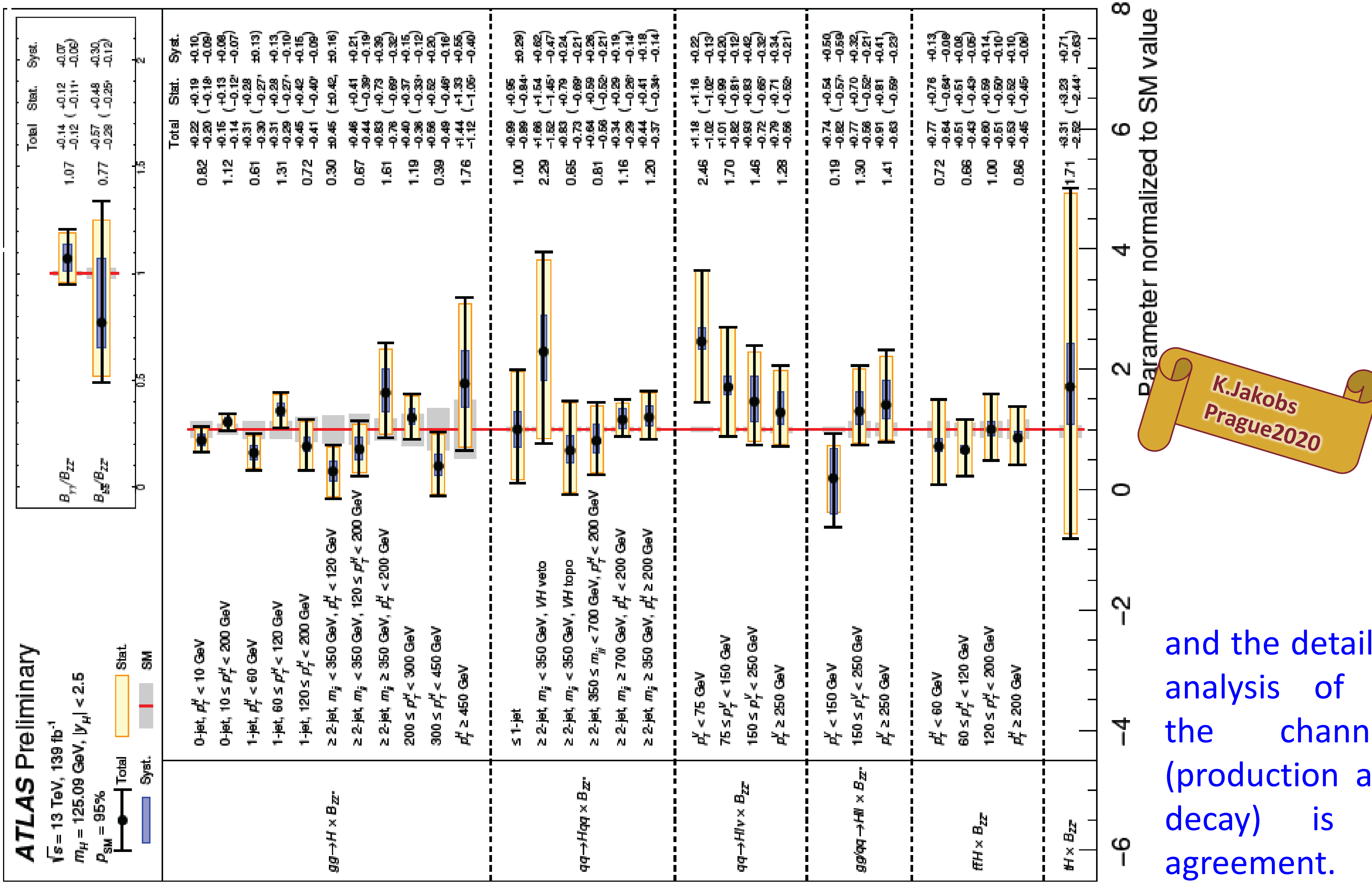
K.Jakobs
Prague2020



All main production mechanisms (see diagrams) observed with significance > 5σ and yields compatible with SM;



Higgs couplings: production & decay



and the detailed analysis of all the channels (production and decay) is in agreement.

Higgs conclusion: (1)

… finally (PDG 2020, slightly simplified):

The discovery of the Higgs boson [H] is a major milestone in the history of particle physics as well as an extraordinary achievement of the LHC machine and the ATLAS and CMS experiments. Seven years after the discovery, substantial progress in the field of H physics has been accomplished and a significant number of measurements probing the nature of this unique particle have been made. They are revealing an increasingly precise profile of the H.

The LHC has now concluded its Run 2, delivering a dataset of 13 TeV pp collisions corresponding to an integrated luminosity of approximately 140 fb^{-1} of data collected by ATLAS and CMS. With the substantial increase in production rates at the higher center-of-mass energy and the larger datasets, new landmark results in Higgs physics have been achieved.

Three new results of fundamental importance have been achieved with partial Run 2 datasets by ATLAS and CMS independently: (i) the clear and unambiguous observation of the Higgs boson decay to taus; (ii) the clear and unambiguous observation of the H decay to a pair of b quarks; (iii) the clear and unambiguous observation of the production of the H through the $t\bar{t}H$ process. These results provide direct evidence for the Yukawa coupling of the H to fermions of the third generation: taus, bottom quarks and top quarks, at rates compatible with those expected in the SM. These, and all other experimental measurements, are consistent with the EWSB mechanism of the SM.

New theoretical calculations and developments in Monte-Carlo simulation pertaining to H physics are still occurring at a rapid pace. [...] With these improvements in the state-of-the-art theory predictions and the increase in luminosity and center-of-mass energy, Higgs physics has definitively entered a precision era. Its impact can already be seen on the latest Run 2 combined measurements of the H couplings.

(continue …)

Higgs conclusion: (2)

(… continue)

Since the discovery of the H, new ideas have emerged to probe its rare decays and production modes. [...] The H has now become part of the standard toolkit in searches for new physics.

[...] The ATLAS and CMS experiments have searched for additional H in the Run 2 data, and have imposed constraints in broad ranges of mass and couplings for various scenarios with an extended Higgs sector.

The landscape of Higgs physics has been extended extraordinarily since its discovery. The current dataset is approximately only five percent of the total dataset foreseen for the HL-LHC project. The current precisions on the measurements of the couplings of the H to gauge bosons and third generation fermions are typically of the order of 10–20%. The uncertainty on the H coupling to the muon is approximately 100%, and the upper limits on the branching fraction to new invisible or undetected particles are approximately 20%. The sensitivity to the H self-coupling has not reached the SM value yet and there is no information on how the Higgs field acquired its VEV in the early times of the Universe. This situation allows for new challenges to ultimately increase further the reach in precision and it also widens the possibilities of unveiling the true nature and the dynamics of the EWSB.

(continue …)

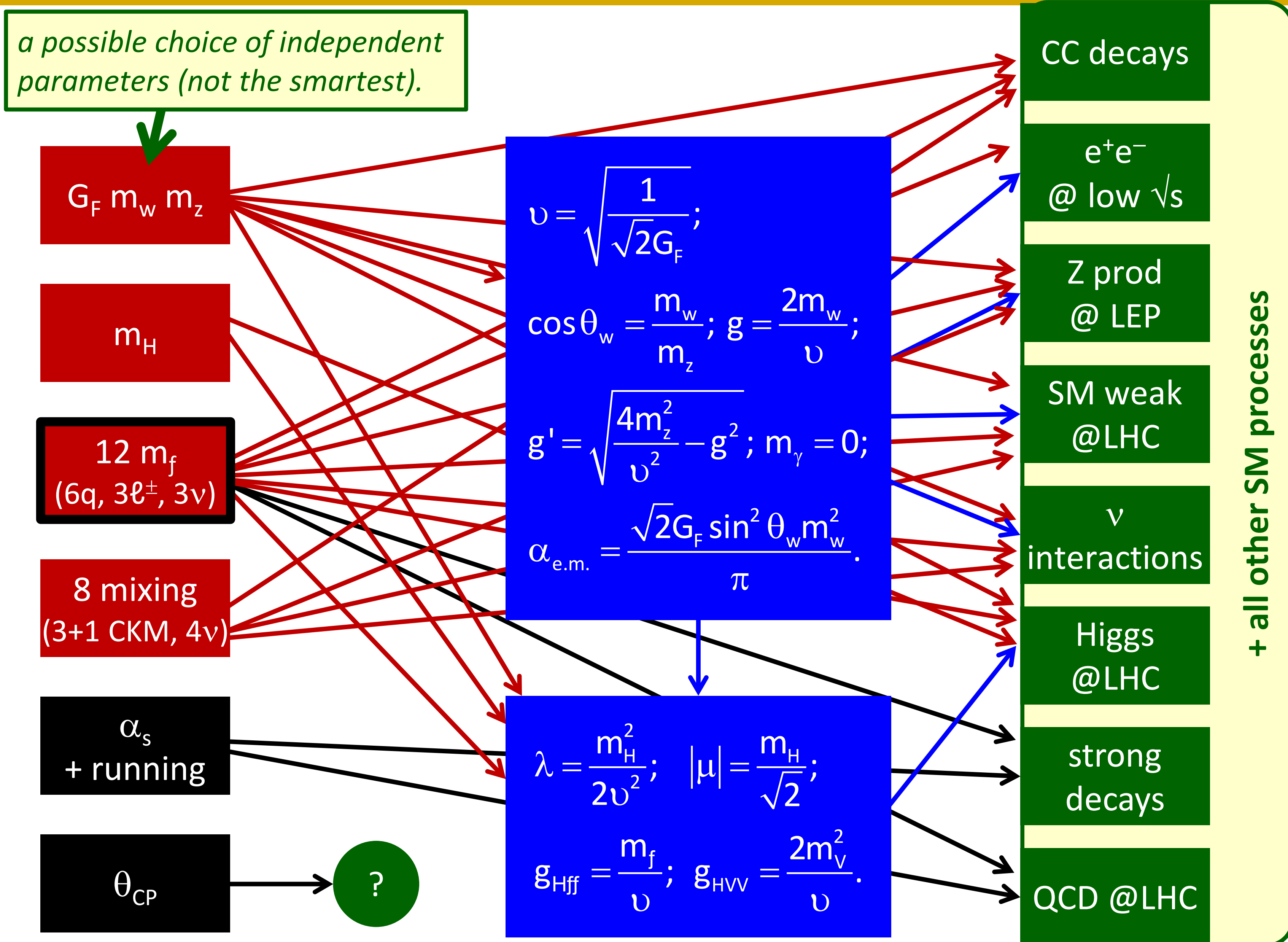
Higgs conclusion: (3)

(... continue)

[...] The fermion-Higgs boson couplings are not governed by 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 scales significantly higher than the EW scale. The non-observation of additional states which could stabilise the H mass is a challenge for natural scenarios [...] 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. With the HL-LHC, the precision will improve by a factor 5–10 on all observables with respect to current data. [... *In this case t*]he experimental systematic uncertainties are similar to the statistical uncertainties, but the dominant source of uncertainty arises from theory, and this remains the case even after assuming that, by the end of the HL-LHC run, the theory uncertainties can be reduced by a factor two compared to the current uncertainties, a hypothesis that appears realistic but still requires dedicated and concerted work. For both hadron and lepton colliders, some theoretical progress is crucial to fully exploit and capitalise on the experimental data. In particular, the expected HL-LHC data together with rapid ongoing progress in theoretical calculations are defining a new era of precision H measurements.

SM today: a simple tree-level flow-diagram



why the SM is not final – (1)

THE SM PROBLEMS [*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*].

Imho 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.

why the SM is not final – (2)

THE SM PROBLEMS [*according to* ***J.Iliopoulos*** *&* ***T.Tomaras****, 2021, slightly simplified*]:

- *Unification*. The Standard Model describes three fundamental interactions in the unified framework of gauge quantum field theories. Nevertheless, it is *not* a unified theory because it contains three independent gauge coupling constants.
- *Quantisation of the electric charge*. For example, the equality of the electric charges of the electron and the muon must be imposed by hand.
- *The three families*. This is part of the general problem of flavour.
- *The large number of arbitrary constants*. A really fundamental theory should be able to predict the values of all its dimensionless constants, or at least to reduce this number considerably.
- *Questions related to astrophysics and cosmology*. Examples are the absence of a dark matter candidate, or an explanation for the observed matter-antimatter asymmetry in the universe.
- *The gravitational interactions are not included*.
- *The particular value of the [Higgs] boson mass*.

I like his style and clarity. Moreover, compared with the previous page, it shows that no real progress on that has been made in the previous years. ***IDEAS, please !!!***

References: results

1. Science, 338 (2012) 1560, 1569, 1576 [simple, divulgative];
2. Higgs (theory) : [IE, 14]; A. Djouadi, Physics Reports, 457 (2008) 1.
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

End of chapter 5b