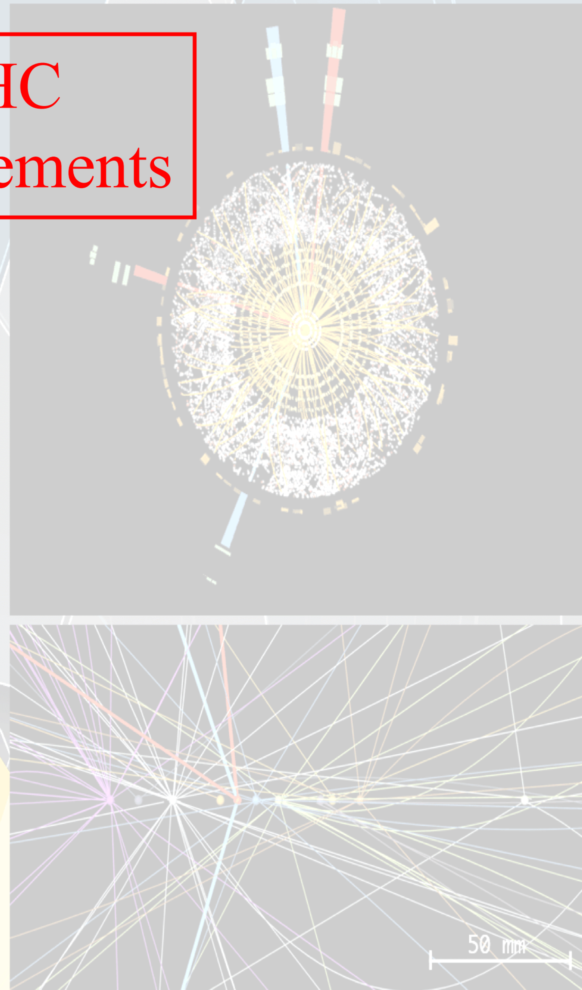
ATLAS EXPERIMENT
http://atlas.ch
Run: 203602
Event: 82614360
Date: 2012-05-18
Time: 20:28:11 CEST

Higgs boson searches at the LHC
from discovery to property measurements



A few selected topics

Outline :

- Context
- Discovery
- Characterisation

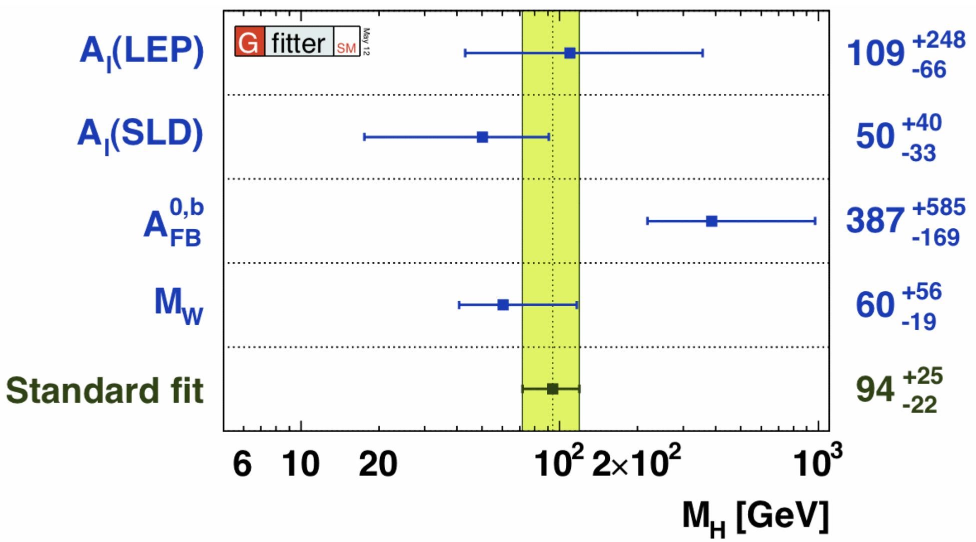
Completely biased towards ATLAS results
Apologize to CMS !

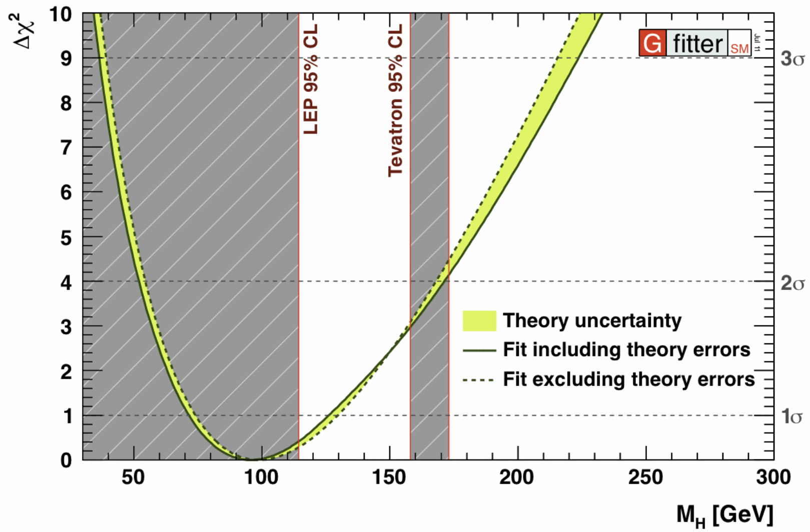
Context

Before 2011… Standard model almost complete but still misses its ***Clé de voûte***
the SM Higgs boson $\mathbf{H_{SM}}$

The least elegant sector of the SM : a scalar particle (not natural), no gauge principle to dictate its dynamic, linked to 15 out of the 19 free parameters
and yet it is a mandatory consequence of the mechanism that triggers electroweak symmetry breaking

If H_{SM} exists, most measurements point to a low mass $m_H < 150$ GeV/c^2



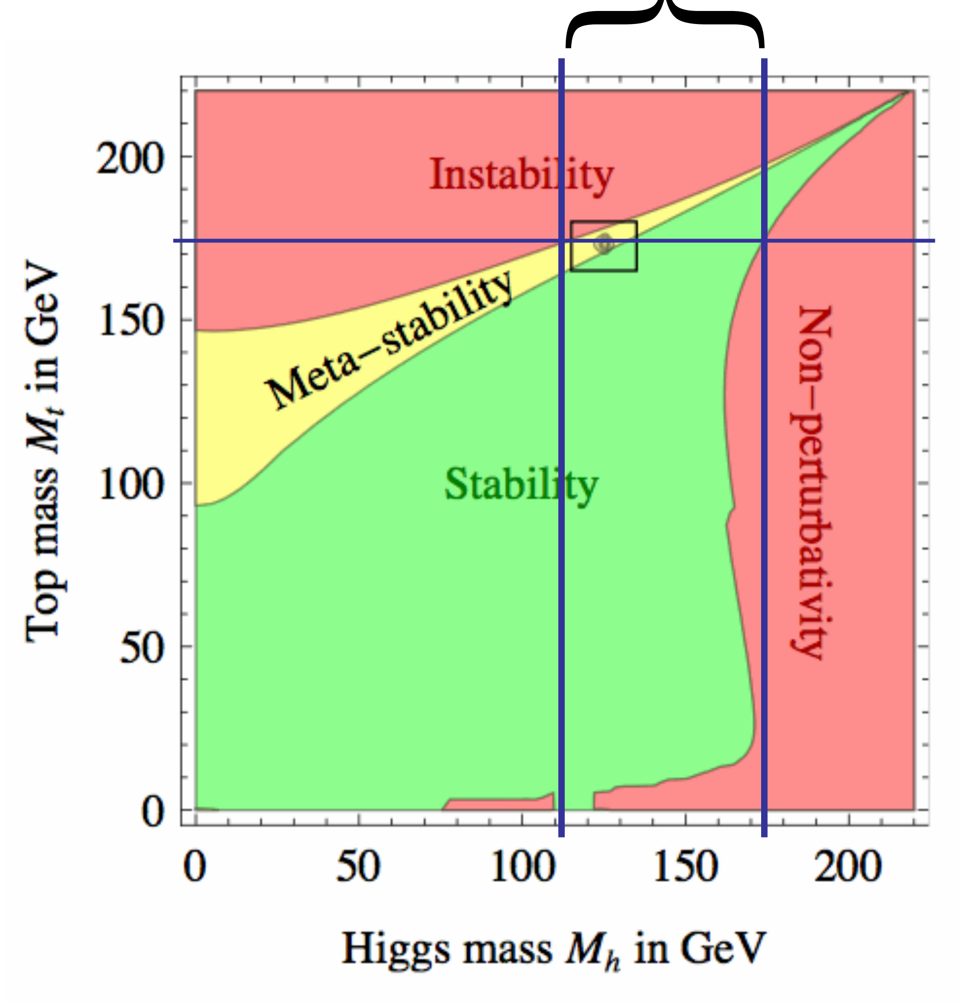


A light H_{SM} is also favoured by theory :

→ needed to regularize longitudinal weak boson scattering
(not that constraining : m_H <~ 800 GeV/c^2 but
gave the reference energy scale for high energy colliders : ~ TeV)

→ if the SM is to be valid (perturbative) up to a very high scale :

110 <~ m_H <~ 175 GeV/c^2 (accepting a meta-stable EW vacuum)



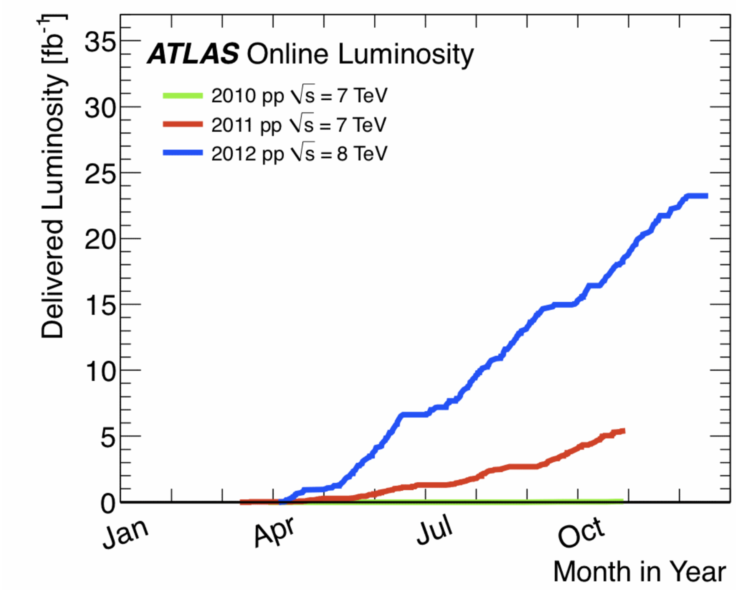
m_t ~ 173 GeV/c^2

Again the good old reassuring message :
one ***has to*** find something at LHC !

It might be

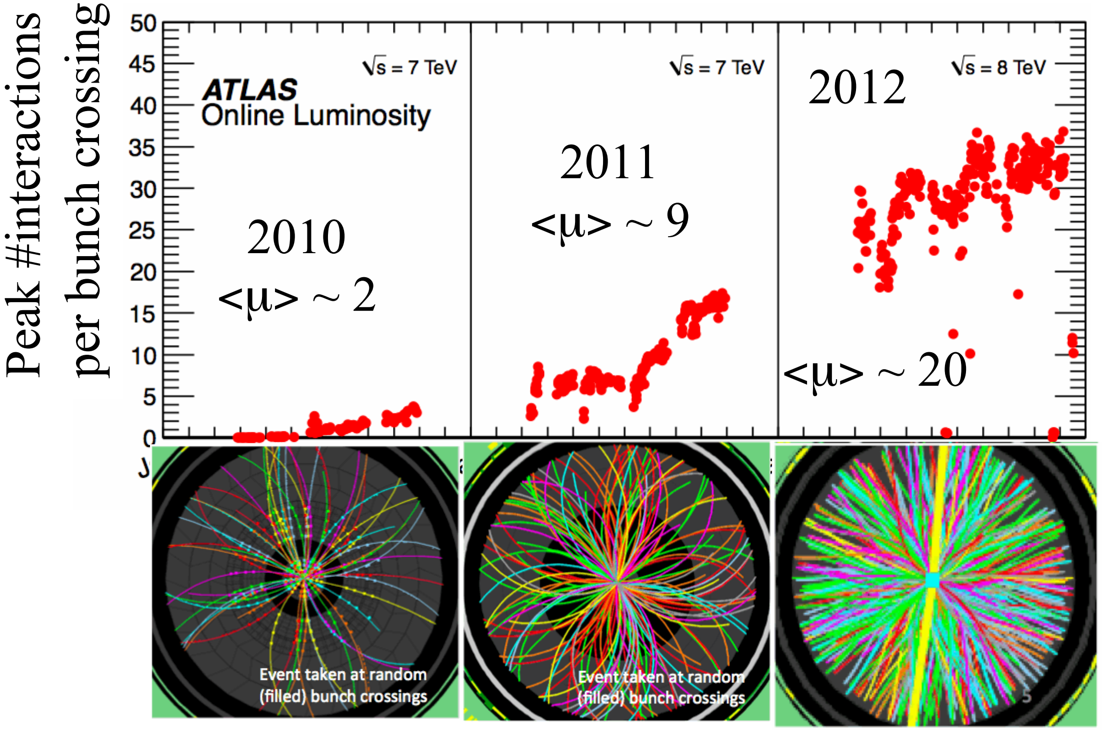
- tough, e.g. a light SM Higgs boson
- very tough, e.g. strange behaviour of weak boson scattering
- easy ? A nice surprise ?

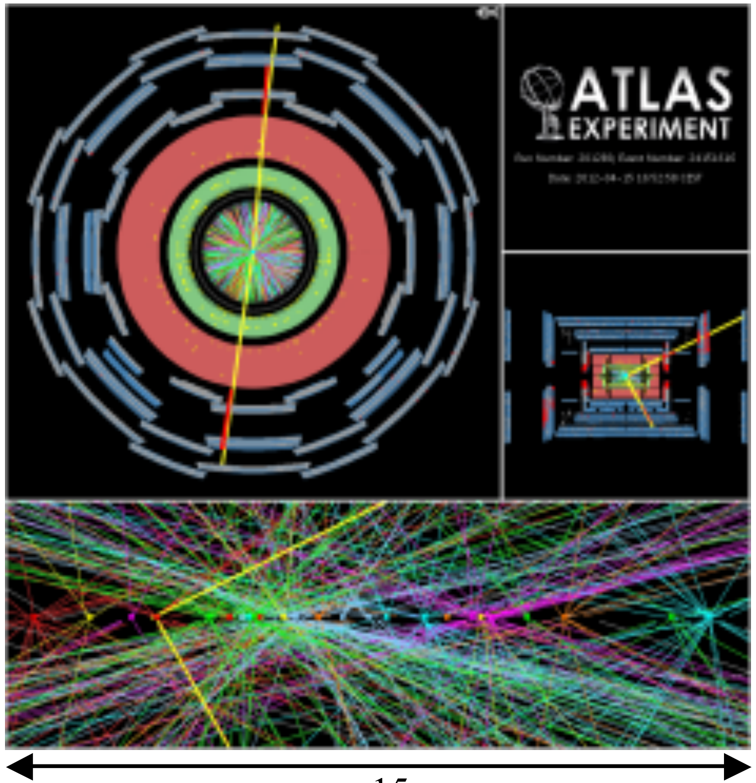
Rare processes ⇒ Needs high luminosity :



Peak instantaneous lumi in 2012 ~ 7 10^{33} $cm^{-2}s^{-1}$

~ 23 fb^{-1} delivered at 8 TeV
+ data taking efficiency
+ data quality
⇒ 90 % usable for physics



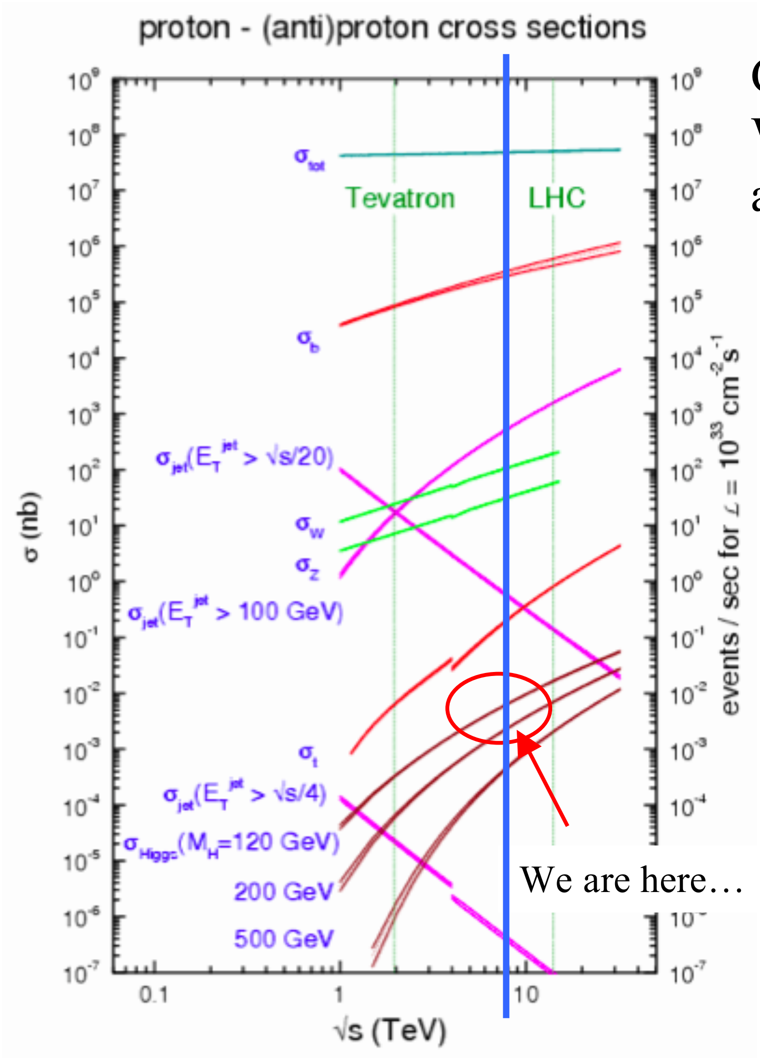


~ 15 cm

A Z →$\mu^+\mu^-$ event with
25 reconstructed vertices

Small cross-section ~ 22.3 pb @ 125 GeV/c^2 on top of a huge background

⇒ only ~ 15% of the cross-section is observable with manageable backgrounds

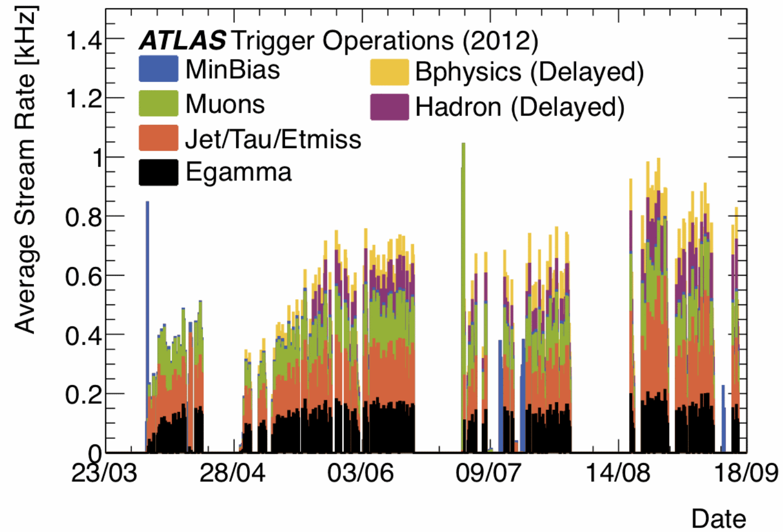


Can only record ~ 400 Hz

Wants to keep most of this observable cross-section and get rid of not interesting events

⇒ maintain **good trigger performance**
in a harsh pile-up environment
keeping thresholds as low as possible

e.g. inclusive electron (muon) p_T > 24 GeV/c : 70(45) Hz
di-photon (p_T > 35/25 GeV/c) : 10 Hz
E_T^{mis} > 80 GeV : 18 Hz @ $L = 5\ 10^{33}$cm^{-2}s^{-1}



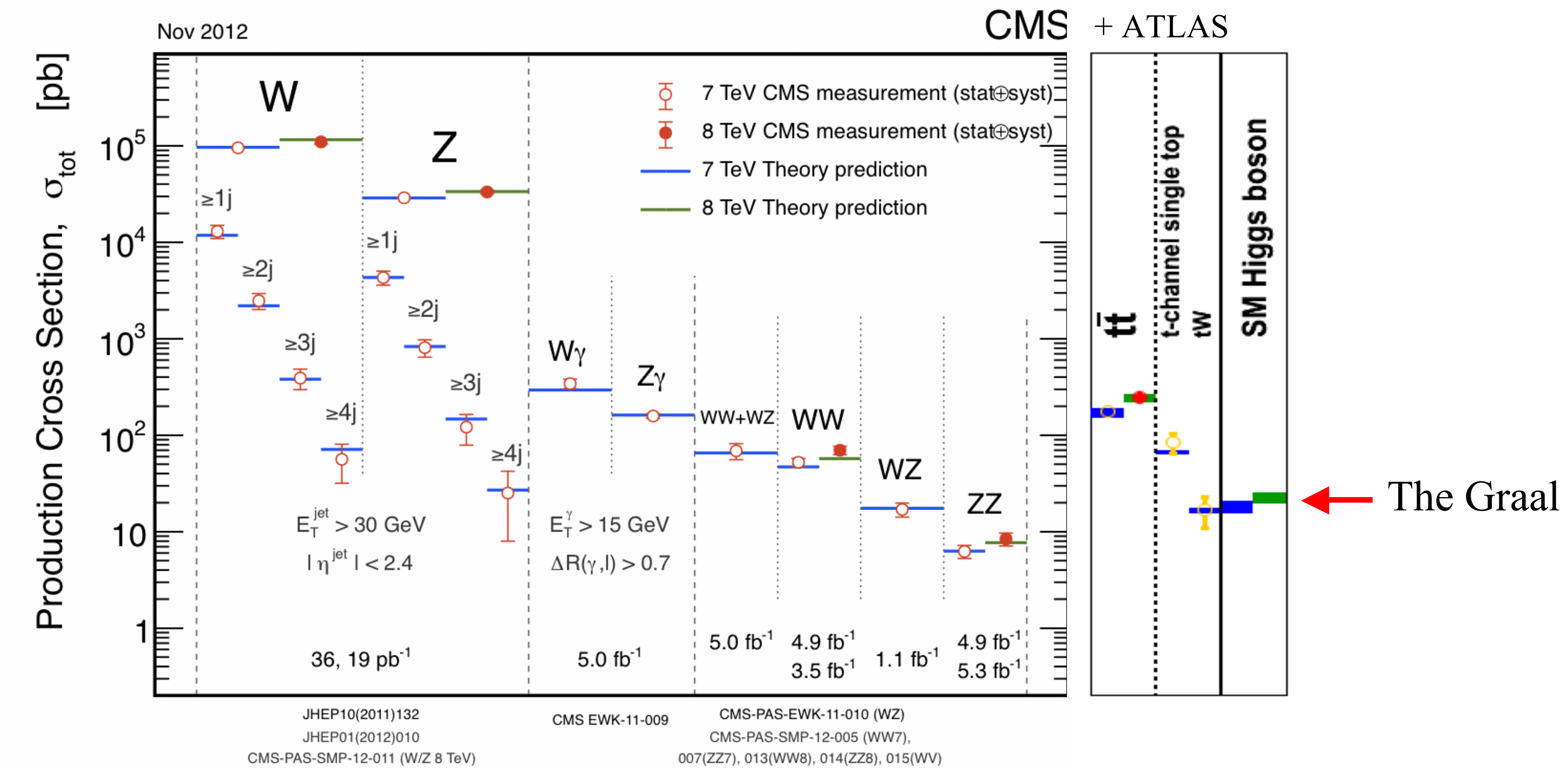
Many *"interesting"* SM processes have been measured with great precision

→ standard candles for calibration and alignment (e.g. $Z \rightarrow e^+e^-$, $\mu^+\mu^-$)

→ control backgrounds to searches (and Monte Carlo tunings)

→ validate search techniques

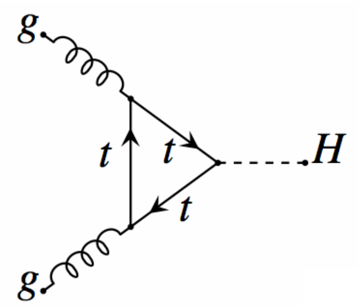
Examples for single boson + jets, di-bosons, top :



+ many more : QCD, photons, …

The Higgs Quest

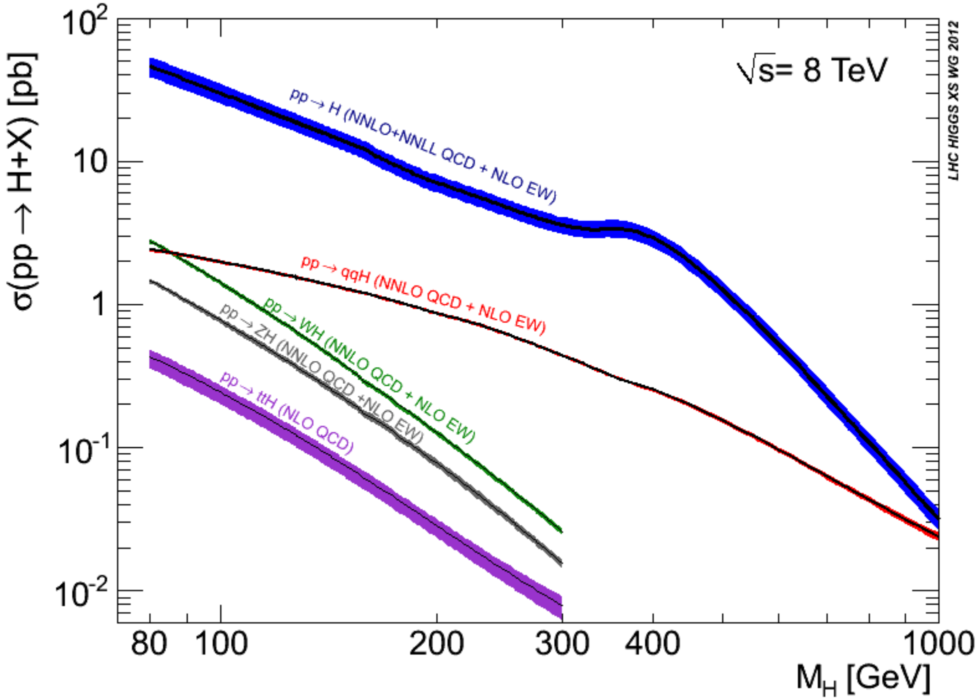
(Numbers @ m_H = 125 GeV/c^2, 25 fb^{-1} at $\sqrt{s}$ 8 TeV)



gluon fusion ggF :

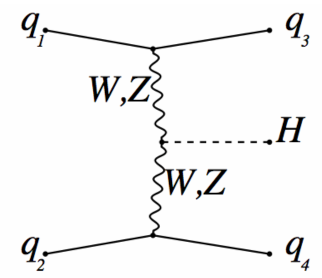
largest yield with ~ 0.5 M event produced !

but needs clean (lepton, photon) H decays



Weak boson fusion VBF :

~ 40 K events



Distinctive event topology :

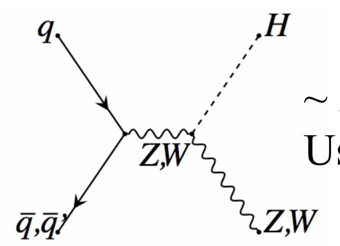
forward medium p_T jets + rapidity gap

Cross-sections known at NNLO QCD + NLO EW

(except ttH, NLO QCD only)

theory uncertainties from 5% to ~ 20%

Associated production with a W/Z (V)



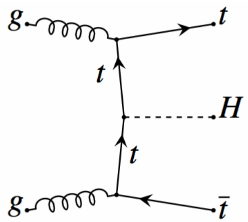
~ 25 K events

Use leptonic V decays

Associated production with a top pair ~ 3.3 K

Important to directly access the top Yukawa coupling.

However very tough…



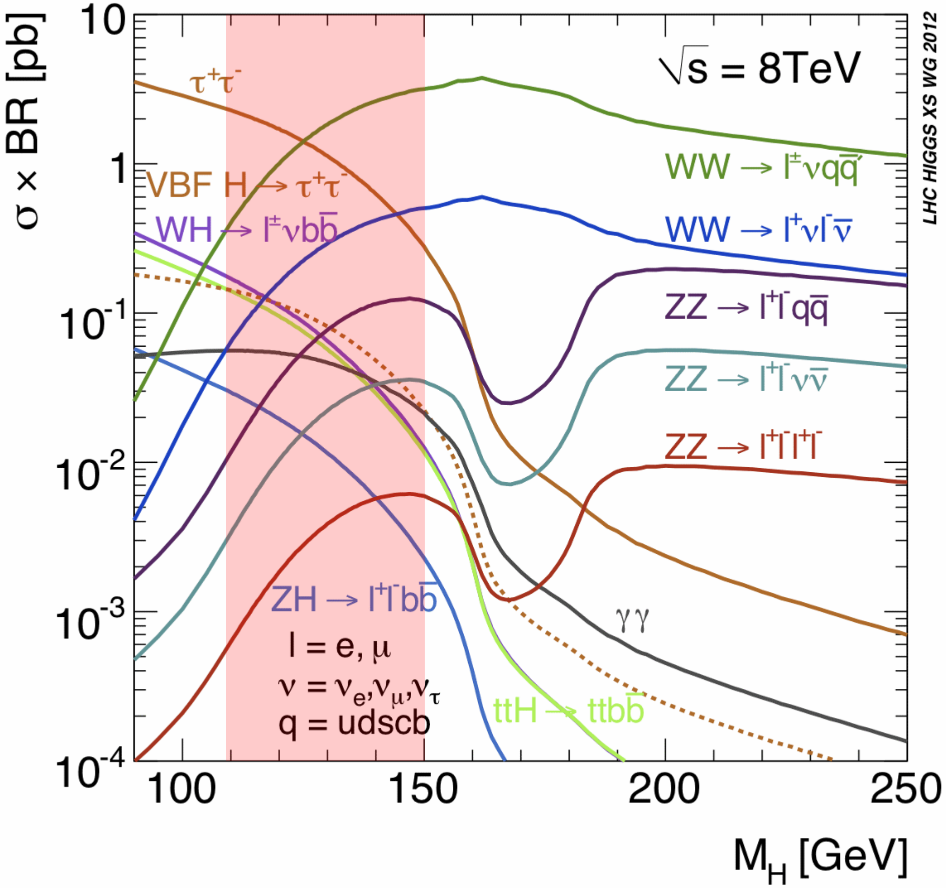
125 GeV/c^2 is a nice value !

With 2011 + 2012 data, ATLAS and CMS are sensitive to 4 out of 5 production processes

Search channels :

The low mass region ~ [120,150] GeV/c^2 is also nice from the decay point of view

- ✓ Dominant bb decays :
  accessible via VH (and ttH) production
  (background much too large in ggF and VBF)
- ✓ $\tau^+\tau^-$: also VBF, VH
- ✓ WW → lνlν ~ clean,
  but ~ no mass reconstruction
- ✓ γγ : clean, large background (bkg)
  but narrow mass peak
- ✓ ZZ → llll : Golden !
  Small background, narrow mass peak
  but tiny yield



The variety of search channels at low mass will allow
interesting measurements in the coupling and spin/parity sector already
with the 2011 and 2012 data set…

Summary of the considered search channels

(dedicated to the low mass domain; other channels at high mass)

channel	ggF	VBF	VH	ttH	Mass range (GeV/c^2)	Signal yield*	S/B (%)	Mass resolution (GeV/c^2)
$\gamma\gamma$	✓	✓	✓	✓	110-150	~ 250	1 → 20%	1.6
$\tau\tau$	✓	✓	✓		110-140	~ 240	0.5 → 10%‡	~ 20
bb			✓	✓	110-130	~ 60	0.3 → 3%‡	~ 15
ZZ → 4l	✓				120-500	~ 8	~ 1.3	2.2
WW → $l\nu l\nu$	✓	✓			120-600	~ 111	10%	Very poor

(* At 125 GeV/c^2, for ~ 13 fb^{-1} at $\sqrt{s}$ = 8 TeV

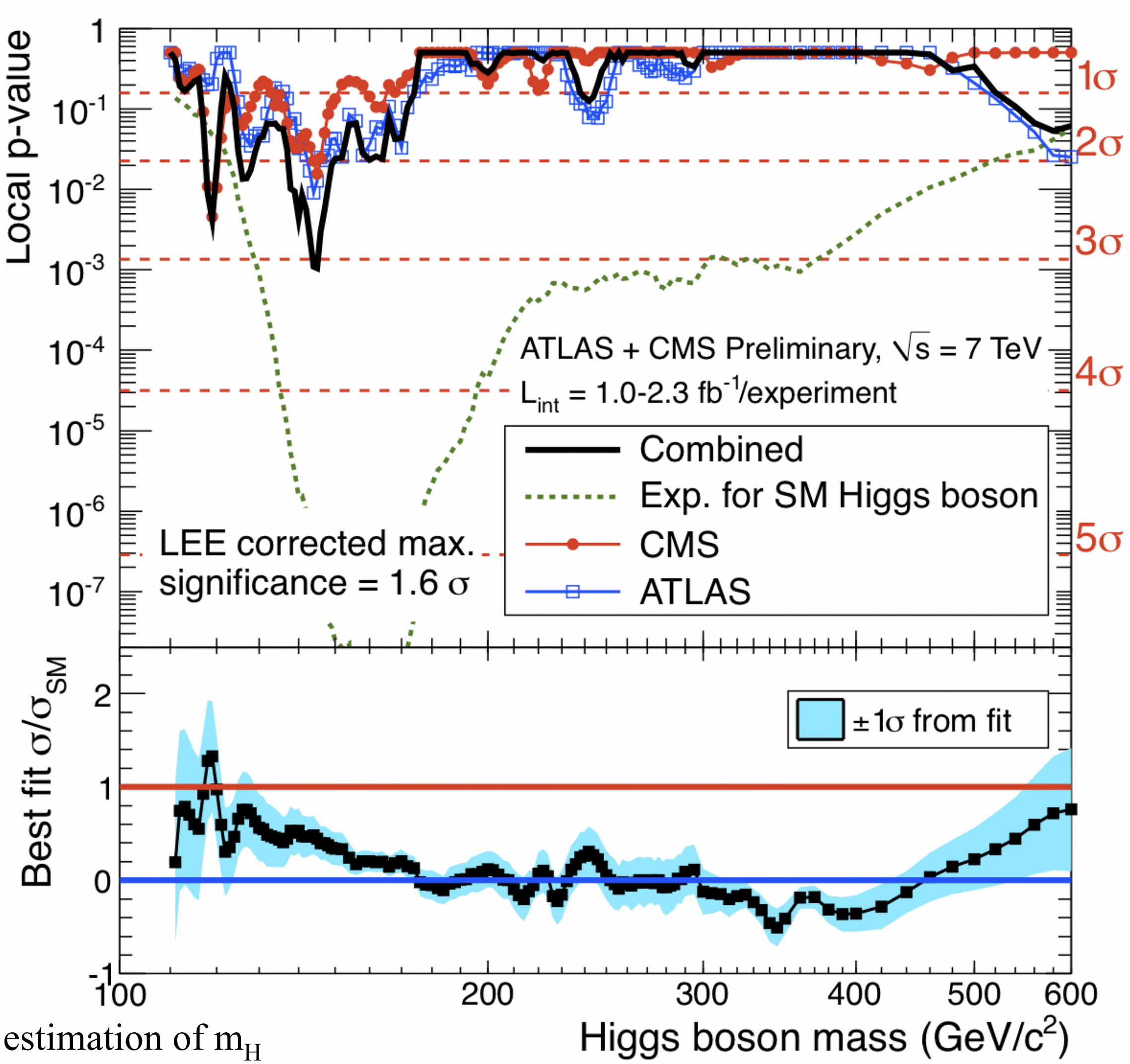
‡ not completely fair since there is some crude information in the mass)

Discovery   Panorama in November 2011 :

Basically, want to *measure* the ***signal strength*** or Parameter of Interest (poi)
Or test some hypothesized values :

$$\mu = \frac{\sigma(pp \to H)\mathrm{BR}}{[\sigma(pp \to H)\mathrm{BR}]_{SM}}$$

- $\mu \leq 0$, no signal
- SM Higgs : $\mu = 1$
- $\mu >> 1$: more fun !



p_0 : compatibility of the observation with bkg only : test $\mu = 0$

~ fraction of toy bkg experiments that are less bkg-like than the data

5 sigmas discovery ⇔ $p_0 = 2.85\ 10^{-7}$

$\hat{\mu}$: best fit value of μ

it is ***not*** an accurate cross-section measurement
the mass at which it is maximum is ***not*** an accurate estimation of m_H

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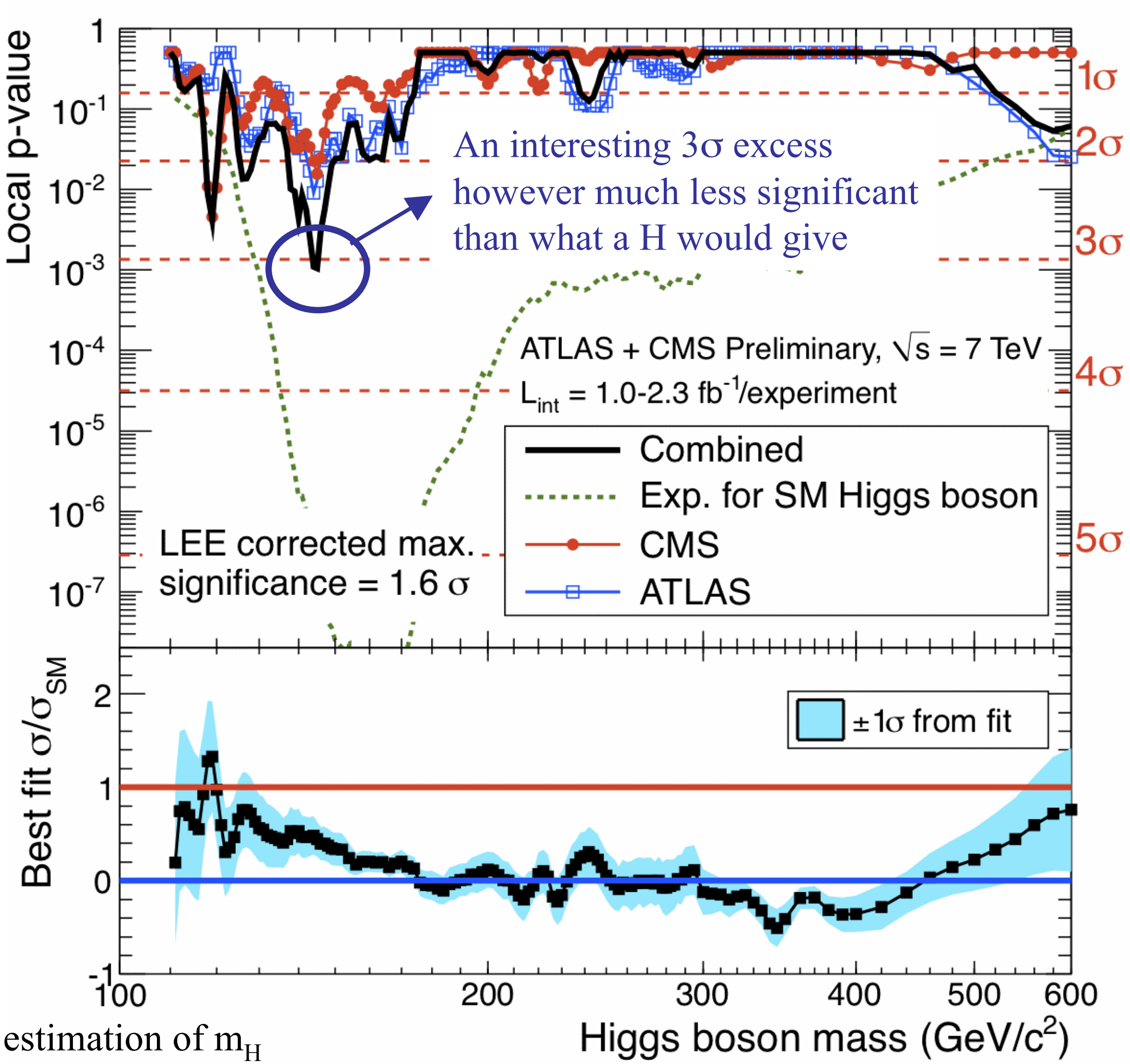

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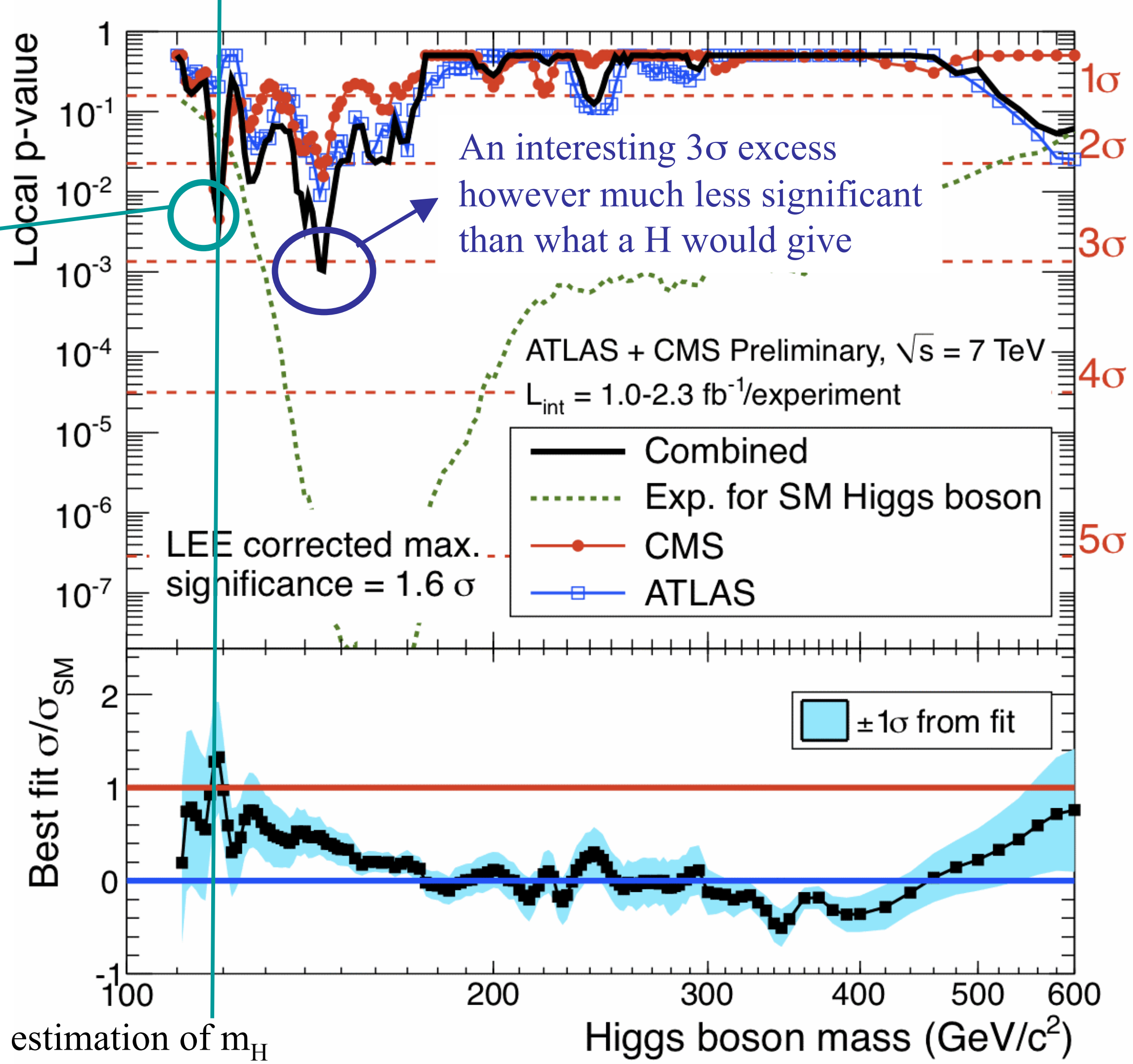
A ~ 2.5 σ excess, larger than what can be expected from H at that mass correlated to a measured μ of ~ 1.4



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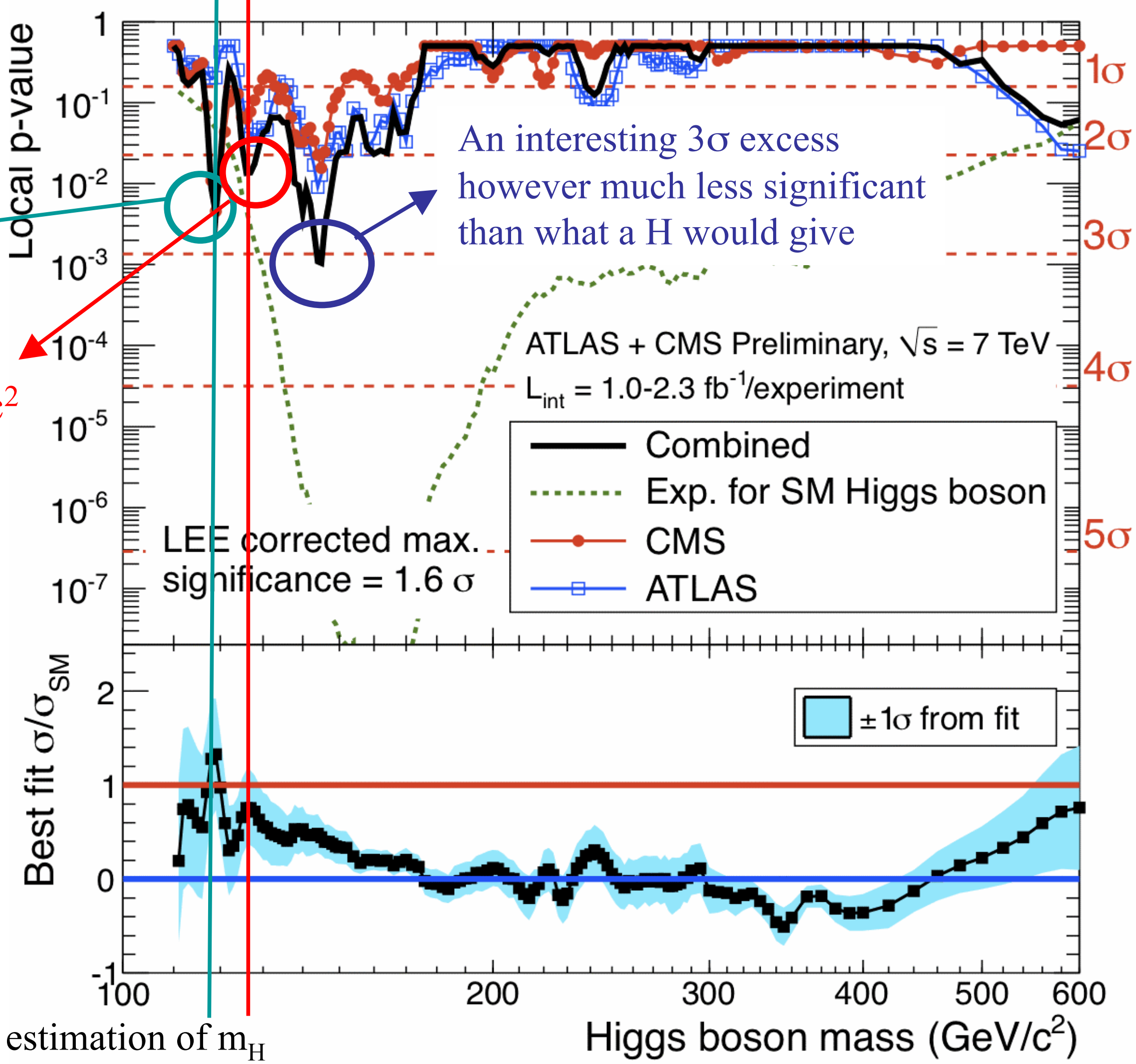
A ~ 2.1 σ excess, similar to what can be expected from H at m_H ~ 126 GeV/c^2

An interesting 3σ excess however much less significant than what a H would give



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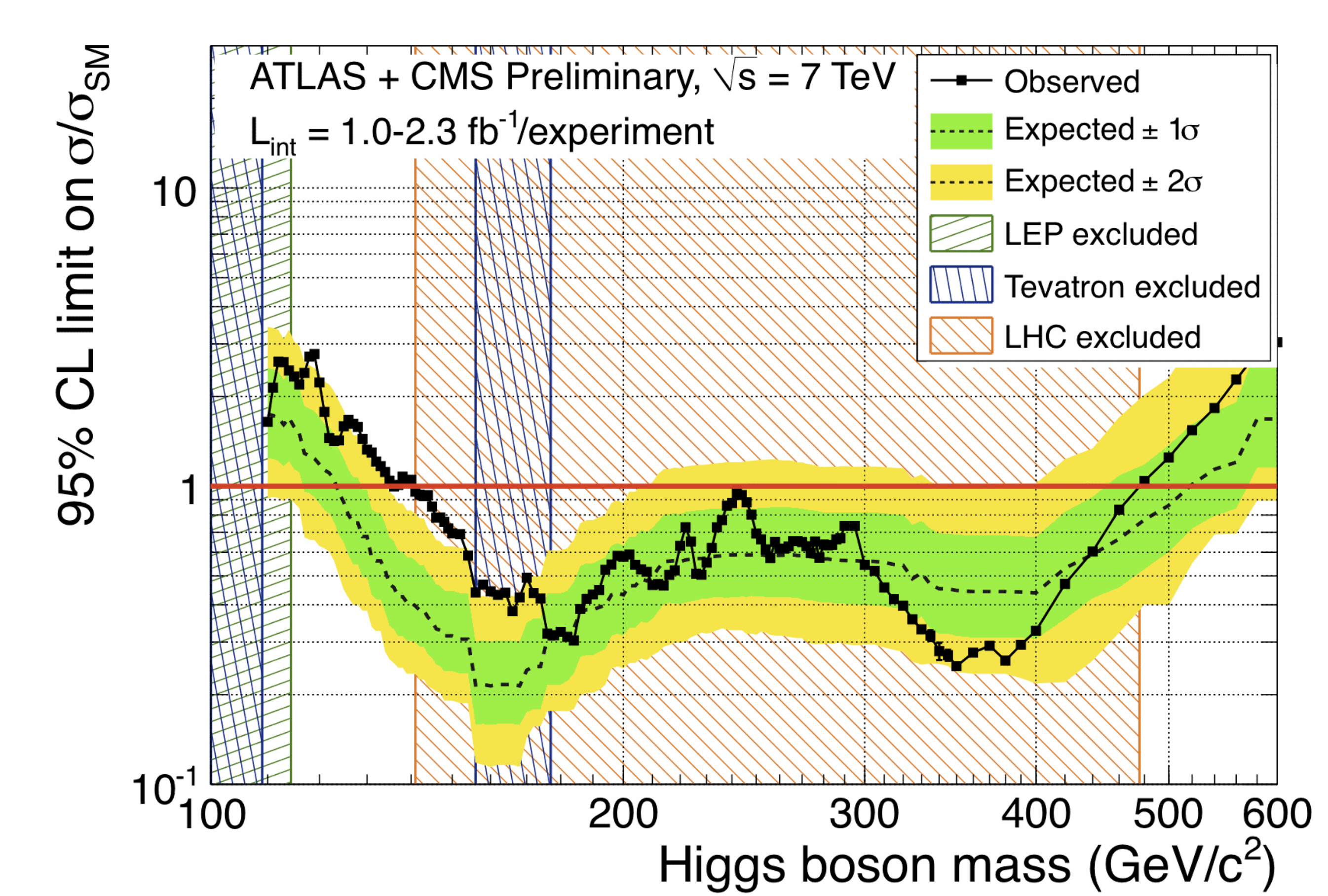
⇒ Some relatively small excesses at low mass, all compatible with bkg fluctuations

⇒ Set limits on μ :

compatibility of the observation with S+B experiments : test hypothesized μ values



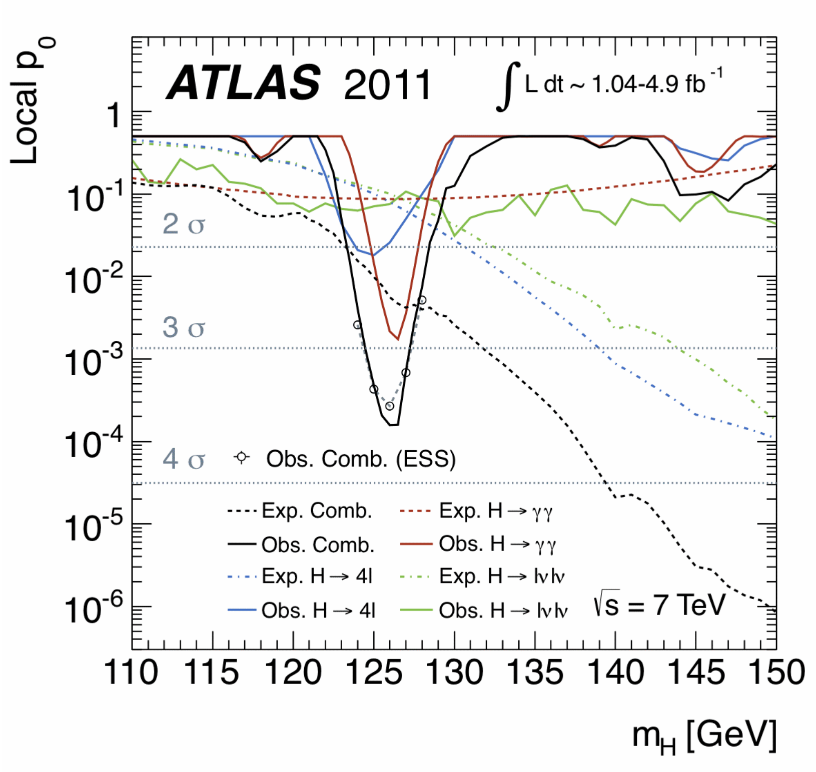
Most of the interesting range covered, two not excluded domains

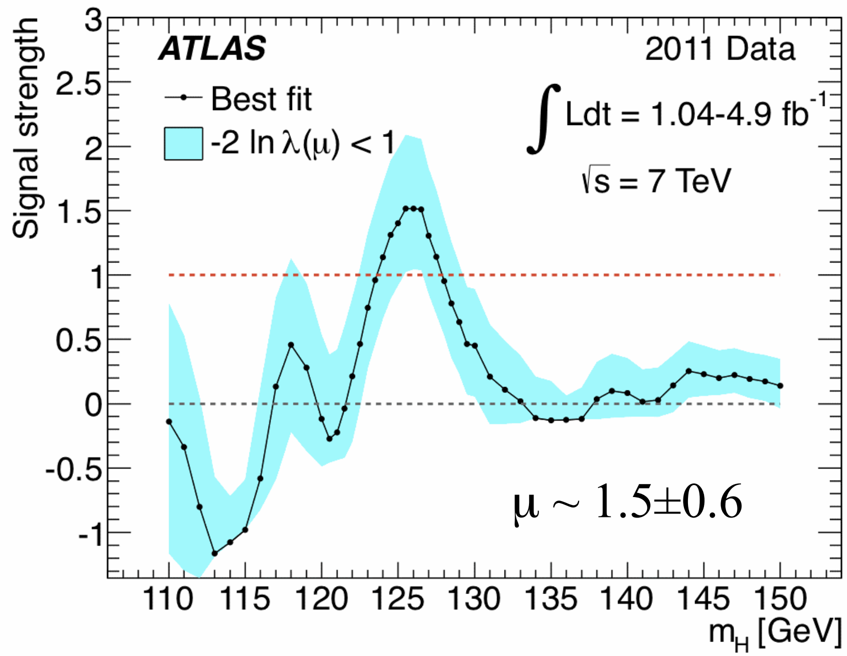
→ [115,141] GeV/c^2

→ High mass (less motivated) > 476 GeV/c^2

Concentrate on the low mass region, where some ~ 2 σ excesses are observed

The December 2011 update and winter 2012 results : evidence (?) for a new boson





At $m_H \sim 126$ GeV/c^2
local$^{(*)}$ $p_0 \sim 3\ 10^{-4} \Leftrightarrow 3.5\sigma$

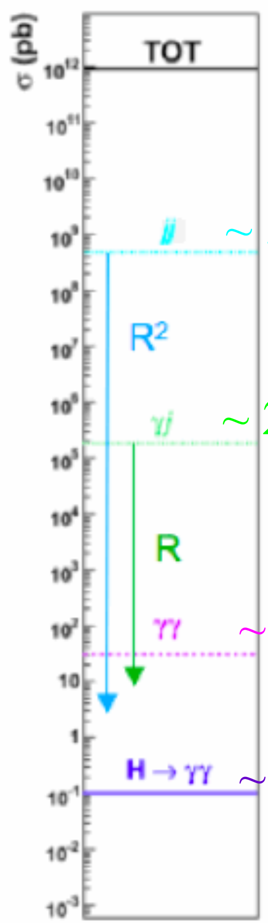
Something is emerging
at a mass ~ 126 GeV/c^2
with a *global* significance of ~ 2.2σ

* OK, you get an excess, but it's likely to find one because your search region is large !
Rescale by the probability to find an excess *anywhere* in this mass region,
e.g. intuitively ***but* very roughly :**
resolution σ_m, search region $\Delta m \Rightarrow p_0 \rightarrow p_0 \times \Delta m/\sigma_m$

The two most powerful channels

$H \rightarrow \gamma\gamma$

Large bkg but narrow mass peak : key ingredients
- Understand fake photon rejection
- Photon precise energy and direction measurements for $m_{\gamma\gamma}$ estimation



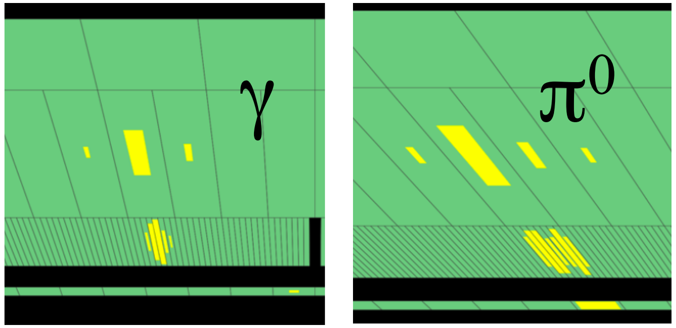
~ 500 μb

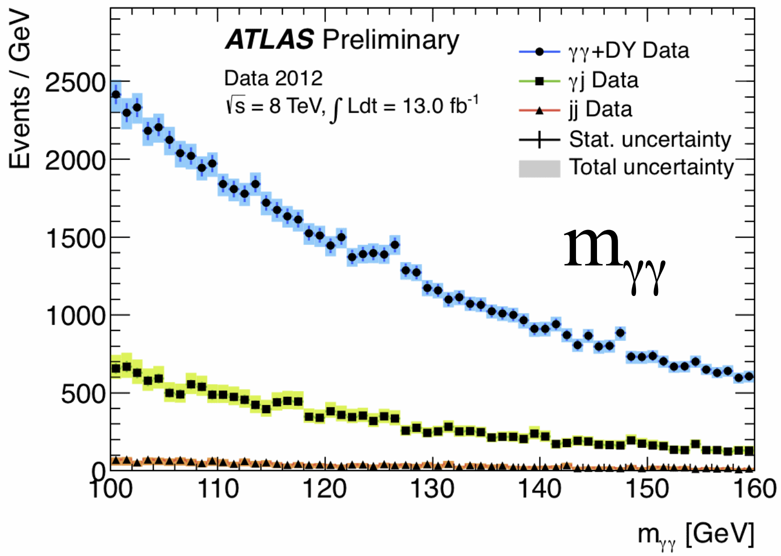
~ 200 nb

~ 30 pb

~ 45 fb

Benefiting from the highly granular EM calorimeter :
jet rejection ~ 8000





$m_{\gamma\gamma}$

~ 80% irreducible γγ

~ 20% γ-jet, di-jet

(just shown to illustrate the good understanding of the bkg composition, not used in the final results)

Back to the $m_{\gamma\gamma}$ estimation $m^2_{\gamma\gamma} = 2E_{\gamma_1}E_{\gamma_2}(1-\cos\theta_{12})$

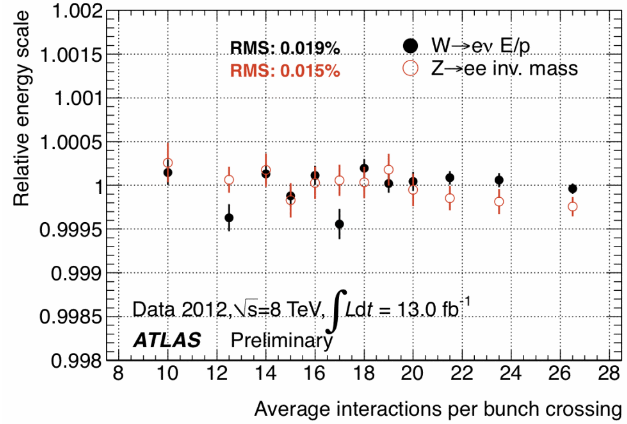
→ accurate photon energy scale : from $Z \to e^+e^-$ data and extrapolation $e \to \gamma$

require excellent material budget knowledge

(+ control from radiative decays $Z \to e^+e^-\gamma$,

limited by statistics and to low energy)

Also very good stability w.r.t.
Number of interactions / bunch crossing



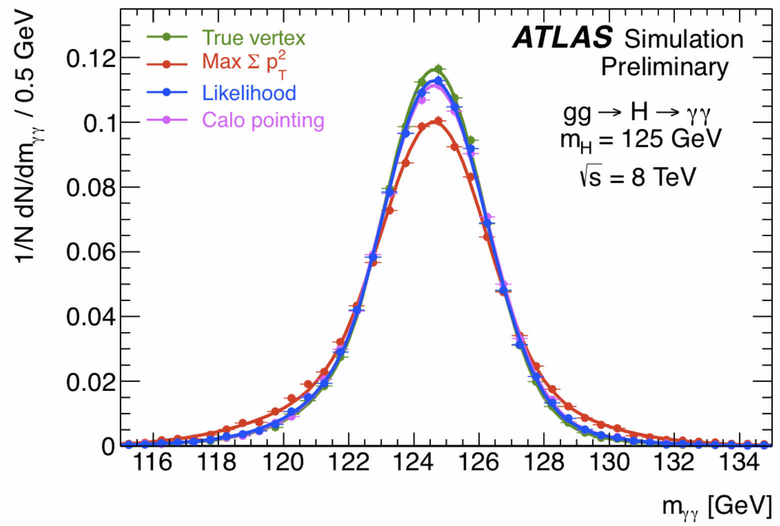
→ accurate direction :

pile-up ! ~ 20 soft interactions overlaid and longitudinal beam spot size ~ 45 mm

have to choose the right interaction point (PV)…

calorimeter pointing (longitudinal segmentation) +

photon conversion (if any) + recoiling tracks



If no measured PV, would add ~ 1.3 GeV/c^2 to the mass resolution

instead : negligible contribution from direction to mass resolution

driven by energy resolution

(sampling term ~ 10%/√E +

constant term ~ 1% not at design yet)

Improving inclusive search with ***categorisation***

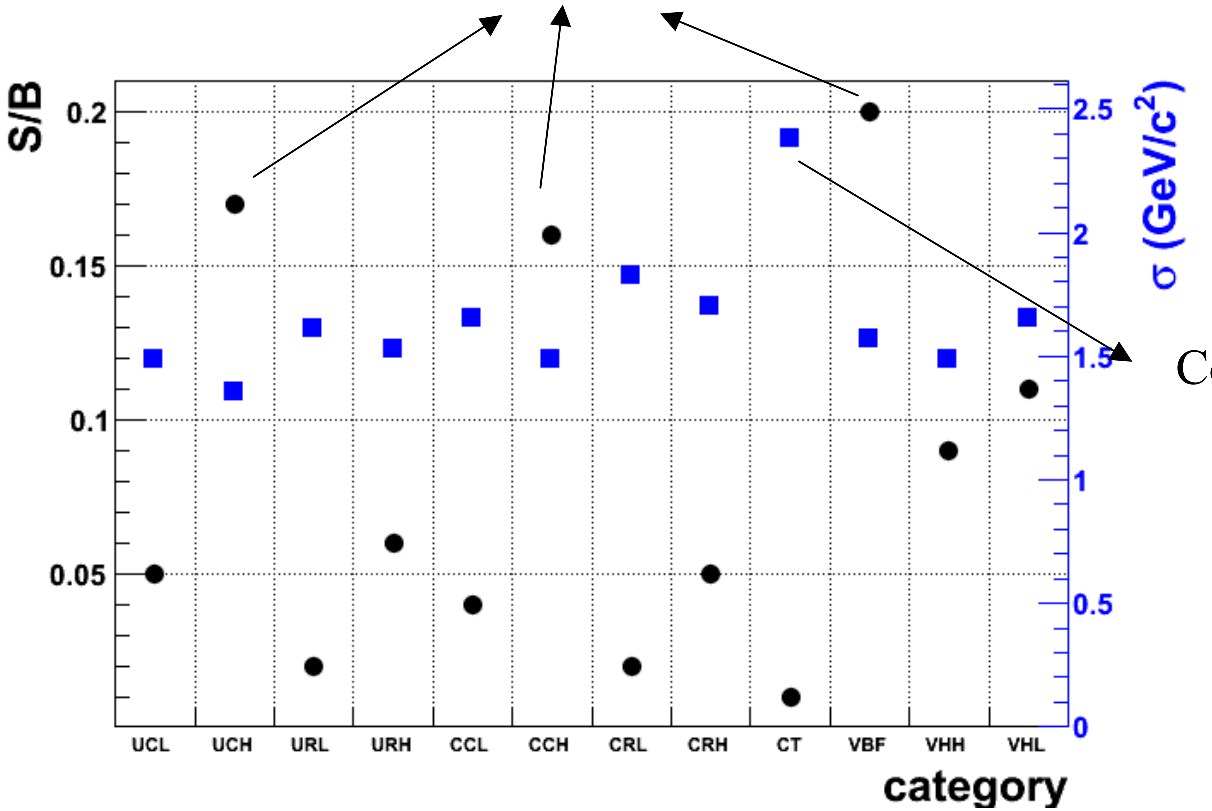
Events with rather different purity are mixed together

⇒ sorting them in different categories can increase the sensitivity

From 9 categories (central/forward and converted/not converted photons, p_{Tt} ($\gamma\gamma$)) for Winter 2012 to 10 (+ tagging jets, better S/B, disentangling VBF) for Summer 2012 to 12 (+low mass di-jet, +lepton, better S/B, disentangling VH) for Fall 2012

Final analysis : 10 (2011) + 12 (2012) categories

High p_T and di-jet tag : “high” S/B



Converted, transition barrel/endcap poor S/B and mass resolution

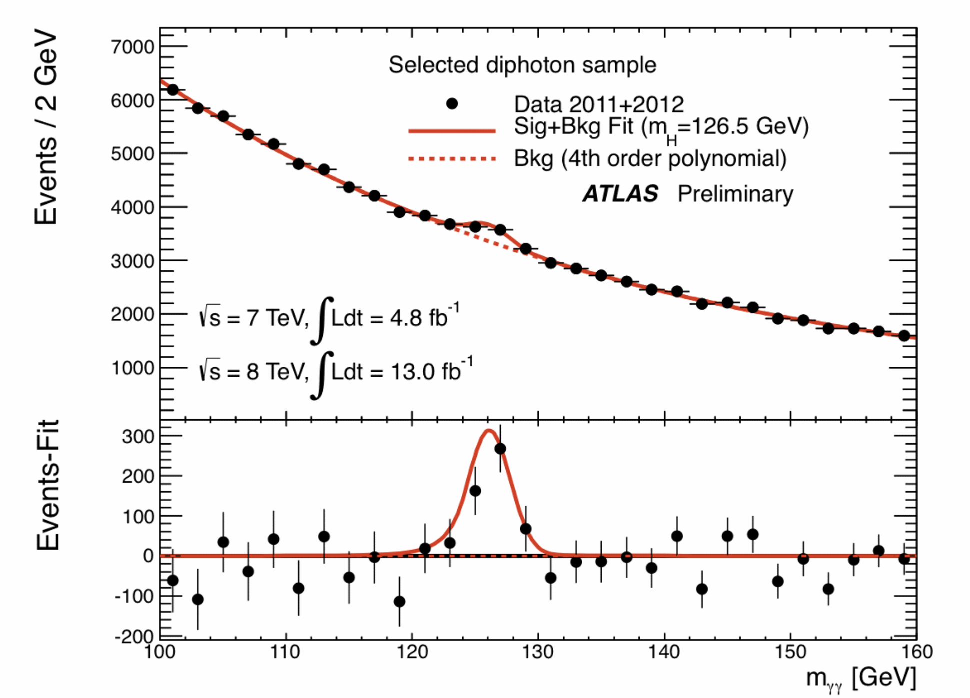
Final “mass plots” :

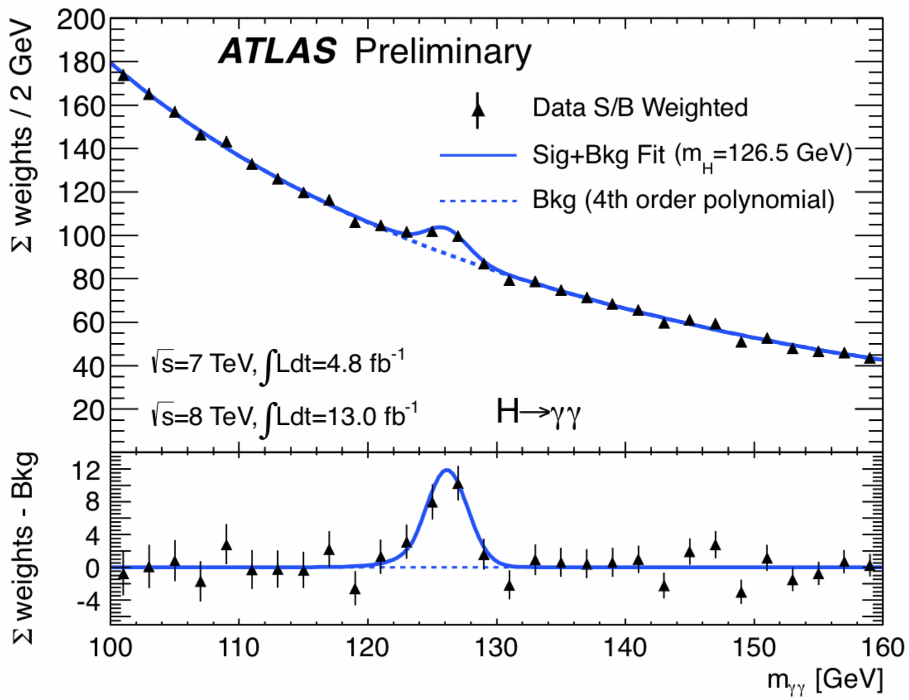
Only $m_{\gamma\gamma}$
far from the full power of the categorisation
bump clearly visible anyway

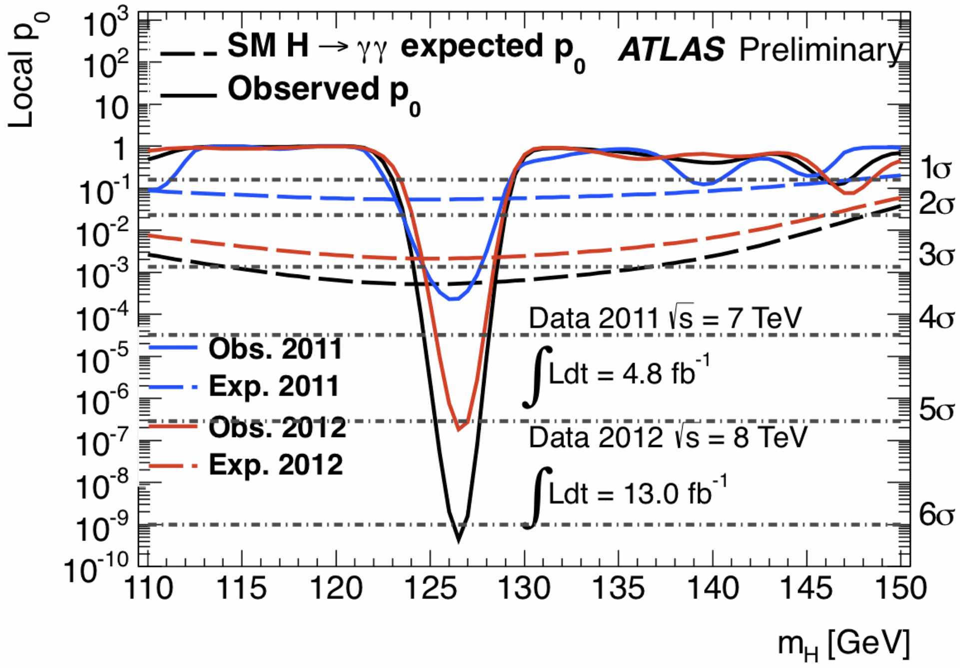
➔

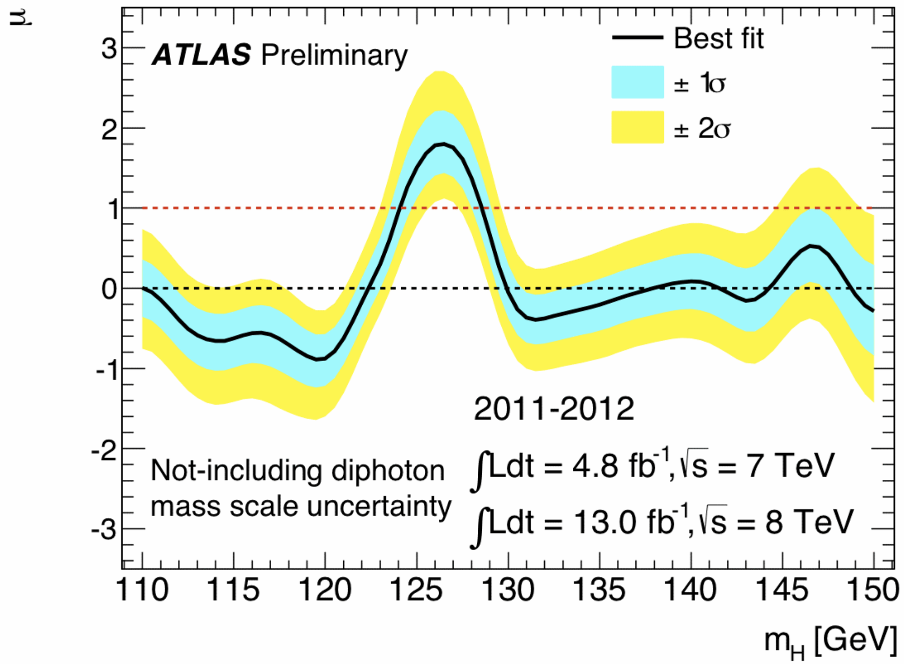
Weighting events by category
$w_i = \ln(1+S_i/B_i)$

bump clearer, as it should if it is a real signal





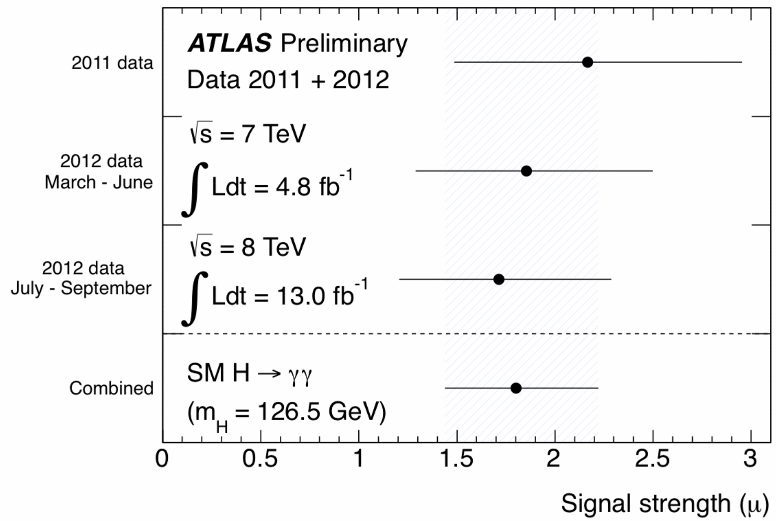




~ 6σ *local* significance (3.3σ expected) at m_H = 126.5 GeV/c² ⇒ first standalone discovery !

$$\hat{\mu} = 1.80 \pm 0.30(stat.)^{+0.21}_{-0.15}(syst.)^{+0.20}_{-0.14}(theo.) \quad @\ 126.6\ \mathrm{GeV/c^2}$$

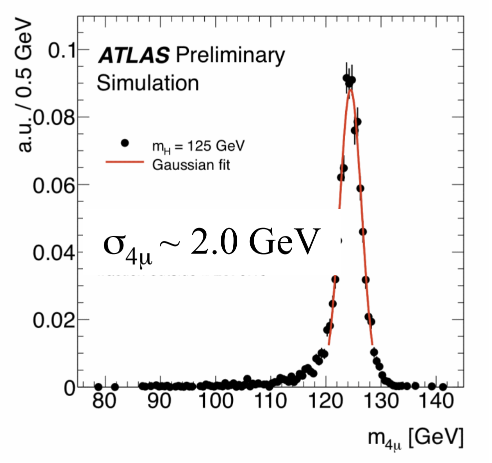
Best fit value of μ ~ 2.4σ *above* the SM hypothesis, a feature ~ constant in time

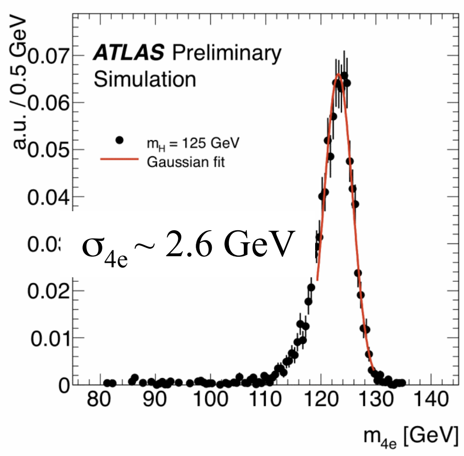


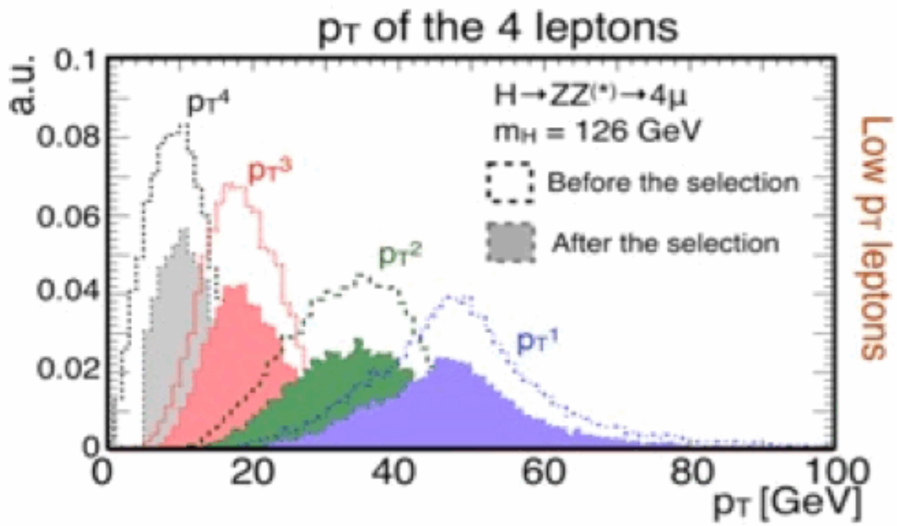
$H \to ZZ^* \to 4\mu$ / $2\mu2e$ / $4e$

4 leptons, one pair OS-SF compatible with an on-shell Z

- Small yield : < 1 evt / fb^{-1} but small bkg
- Excellent mass resolution (tracking+calo)
- Key ingredient : low p_T lepton identification



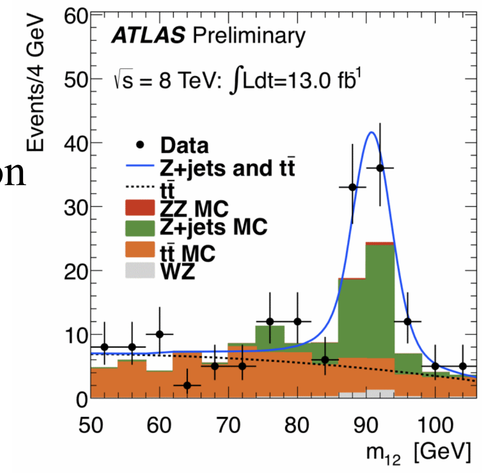




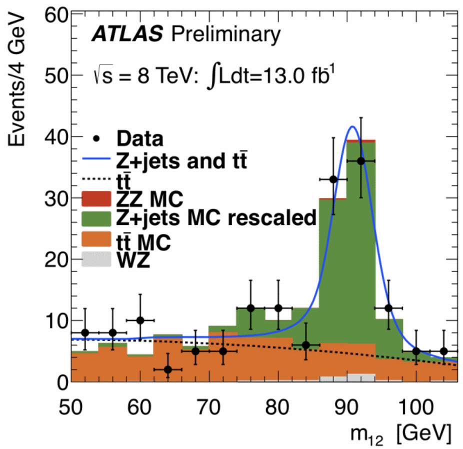
Reducible bkg from b/c → l : isolation (pile up !) + impact parameter

Data driven estimation : example for tt and Z+jets determination in ll $+\mu^+\mu^-$

Control region



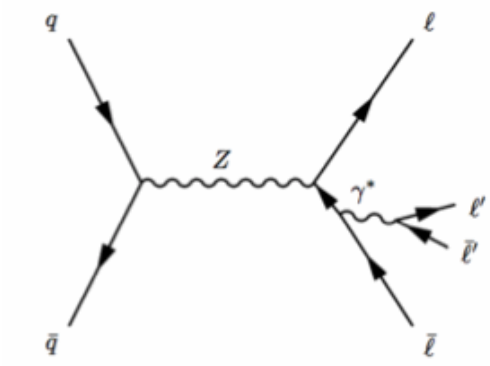
Scaling factor → to apply on MC

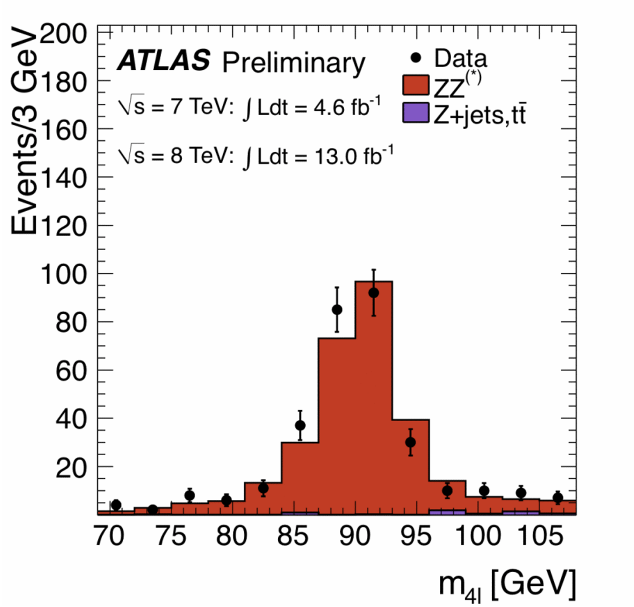


Extrapolation → to signal region

Dress rehearsal :

Dealing with very low p_T leptons to search for a known resonance decaying to 4 leptons : the Z !





⇒ Final mass plot :

In the range [120,130] GeV/c^2

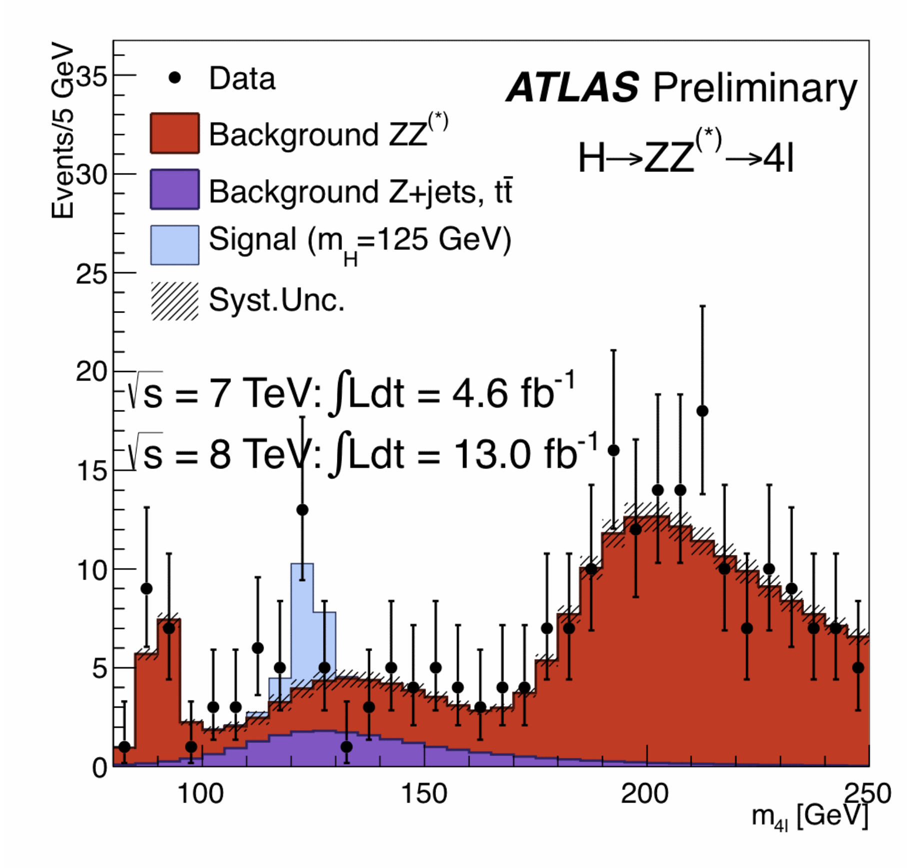
S = 9.9±1.3

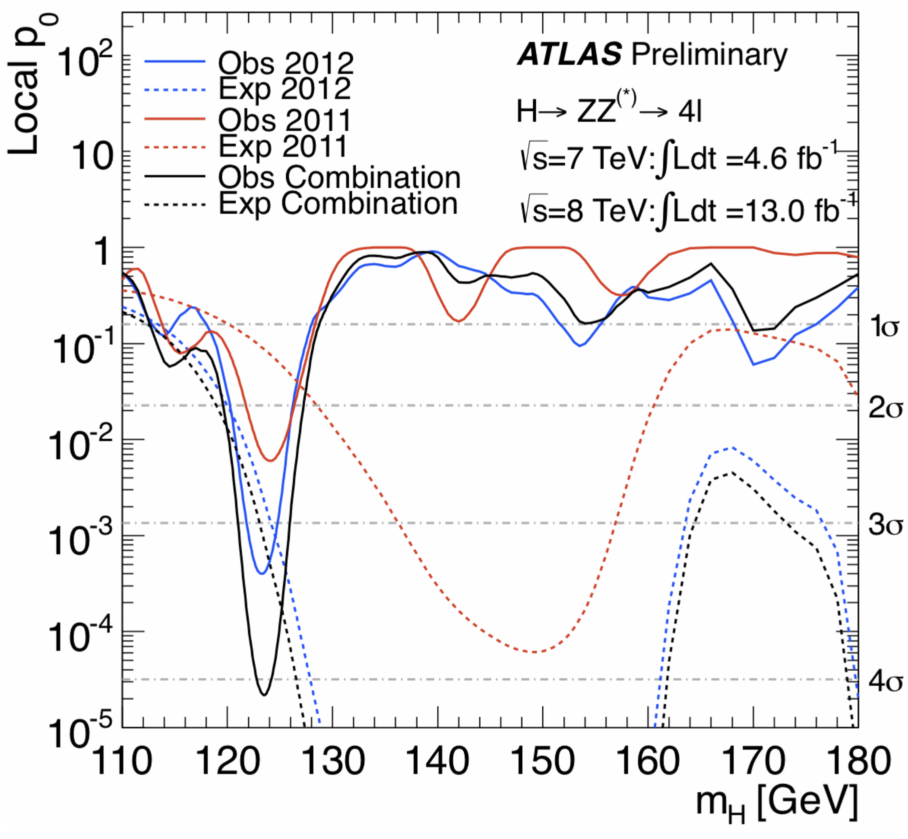
(40%/40%/20% 4μ/2μ2e/4e)

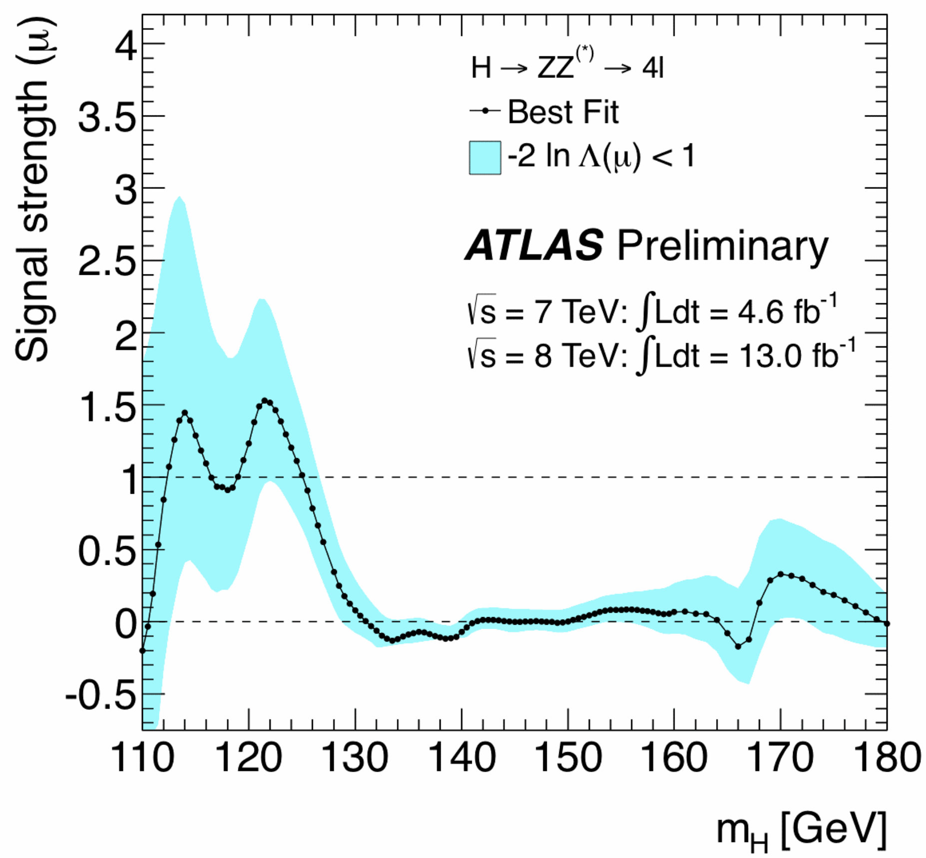
B = 8.3±0.5

N_{obs} = 18

(8/6/4 4μ/2μ2e/4e)







4.1σ *local* significance (3.1σ expected) at m_H = 123.5 GeV/c^2

$$\hat{\mu} = 1.3^{+0.5}_{-0.4}$$

WW, bb and ττ in two slides !

H → WW → eνμν

Large yield and S/B, but no mass peak

→ Need good understanding of missing transverse energy (pile-up !)

→ Good control of bkg : data driven with different control regions

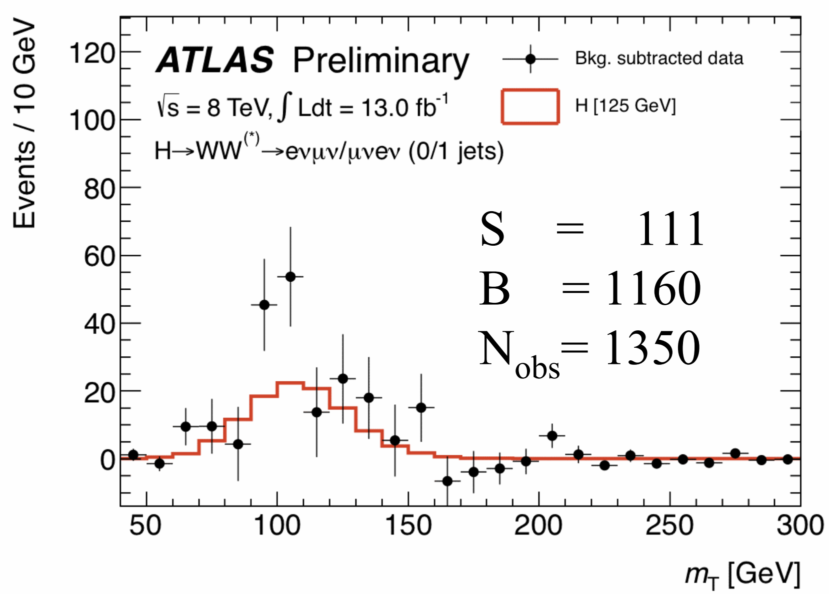
(e.g. same sign leptons : W+jets; b-tagging : top)

→ Spin correlation used to define the signal region : model dependence (spin 0)

(leptons preferentially emitted in the same direction)

→ Two jet bins : 0 or at most 1 jet

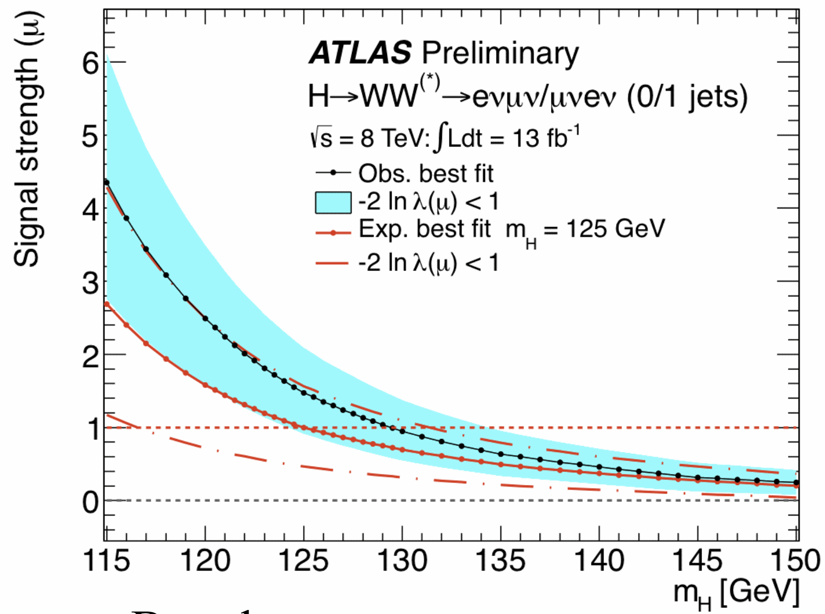
→ Some discrimination in the transverse mass



$S = 111$

$B = 1160$

$N_{obs} = 1350$



Broad excess,
2.8 (2.6) σ at 111 (125) GeV/c²

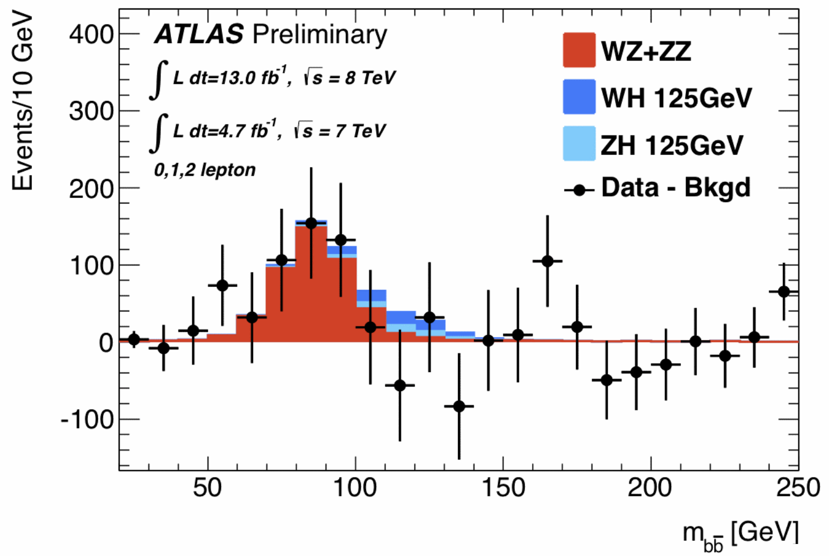
$$\hat{\mu} = 1.48^{+0.35}_{-0.33}(stat.)^{+0.28}_{-0.27}(syst.)^{+0.41}_{-0.36}(theo.)$$

$VH \rightarrow ll/\nu\nu/l\nu + bb$

Paramount for precise coupling measurements ($H \rightarrow bb$ drive the total width) but tough !

Not yet sensitive to the SM Higgs boson

promising 4σ observation of the companion processes $H \leftrightarrow Z$, $Z \rightarrow bb$



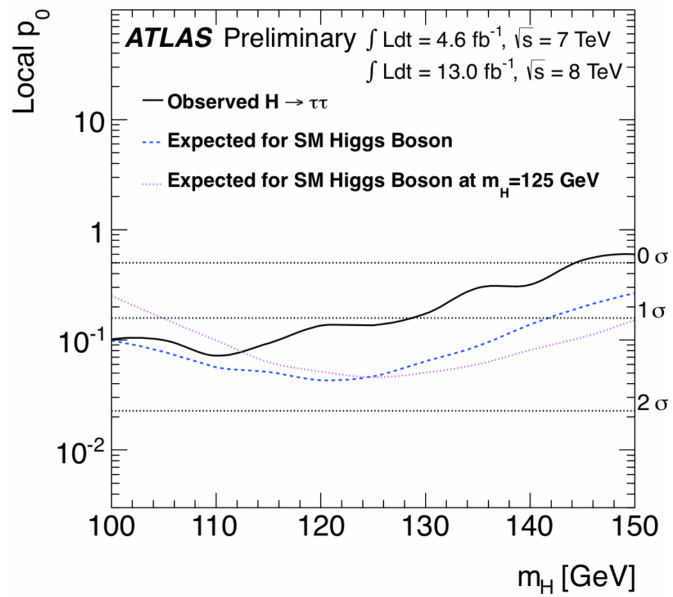
$H \rightarrow \tau\tau$ (VBF, boosted)

Sensitivity to H_{SM} almost there : ~ 1.2 x SM

Very slight excess :

at $m_H = 125$ GeV/c², ~ 1.1σ local significance

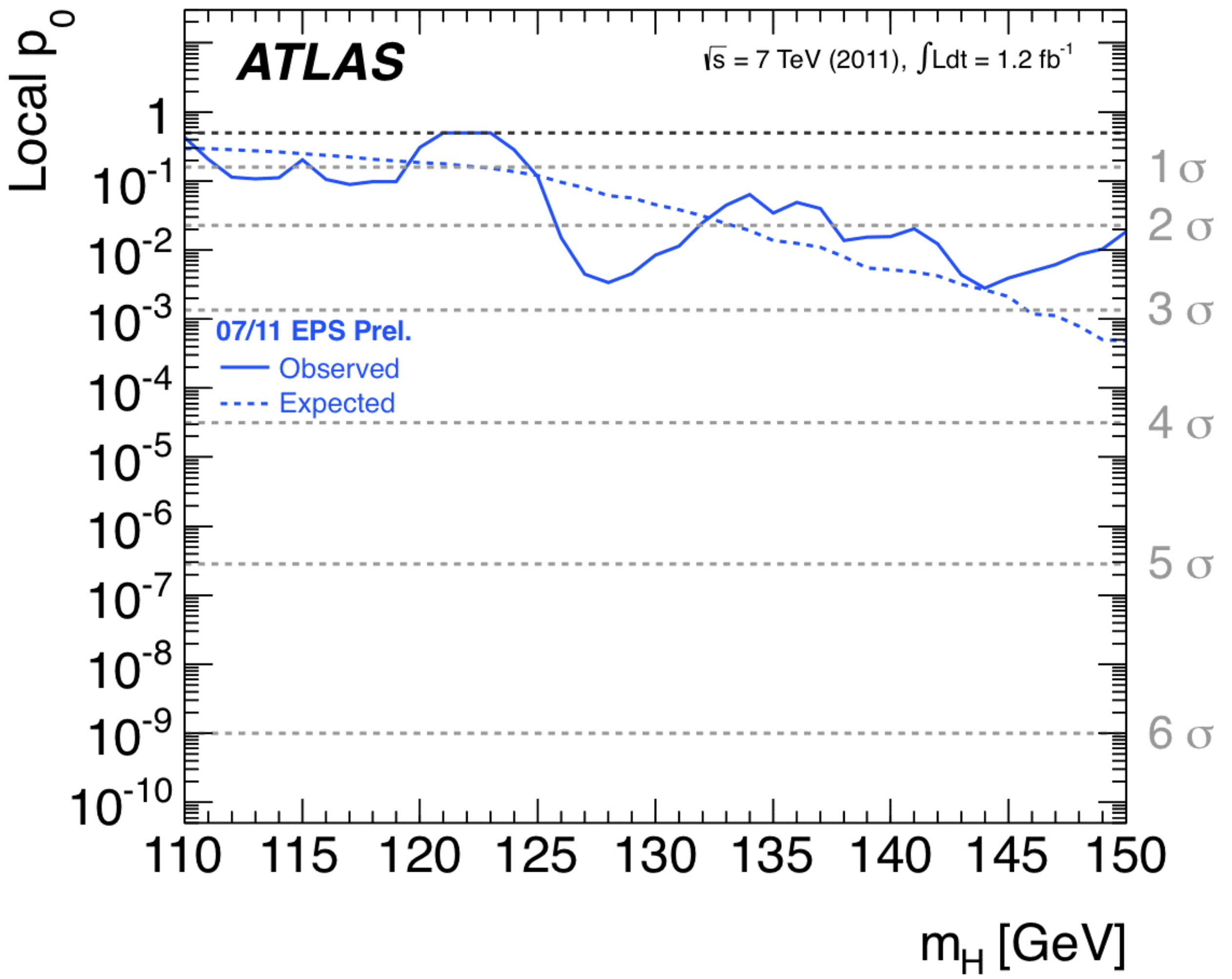
$$\hat{\mu} = 0.7 \pm 0.7$$



The Experimental Birth of a New Particle

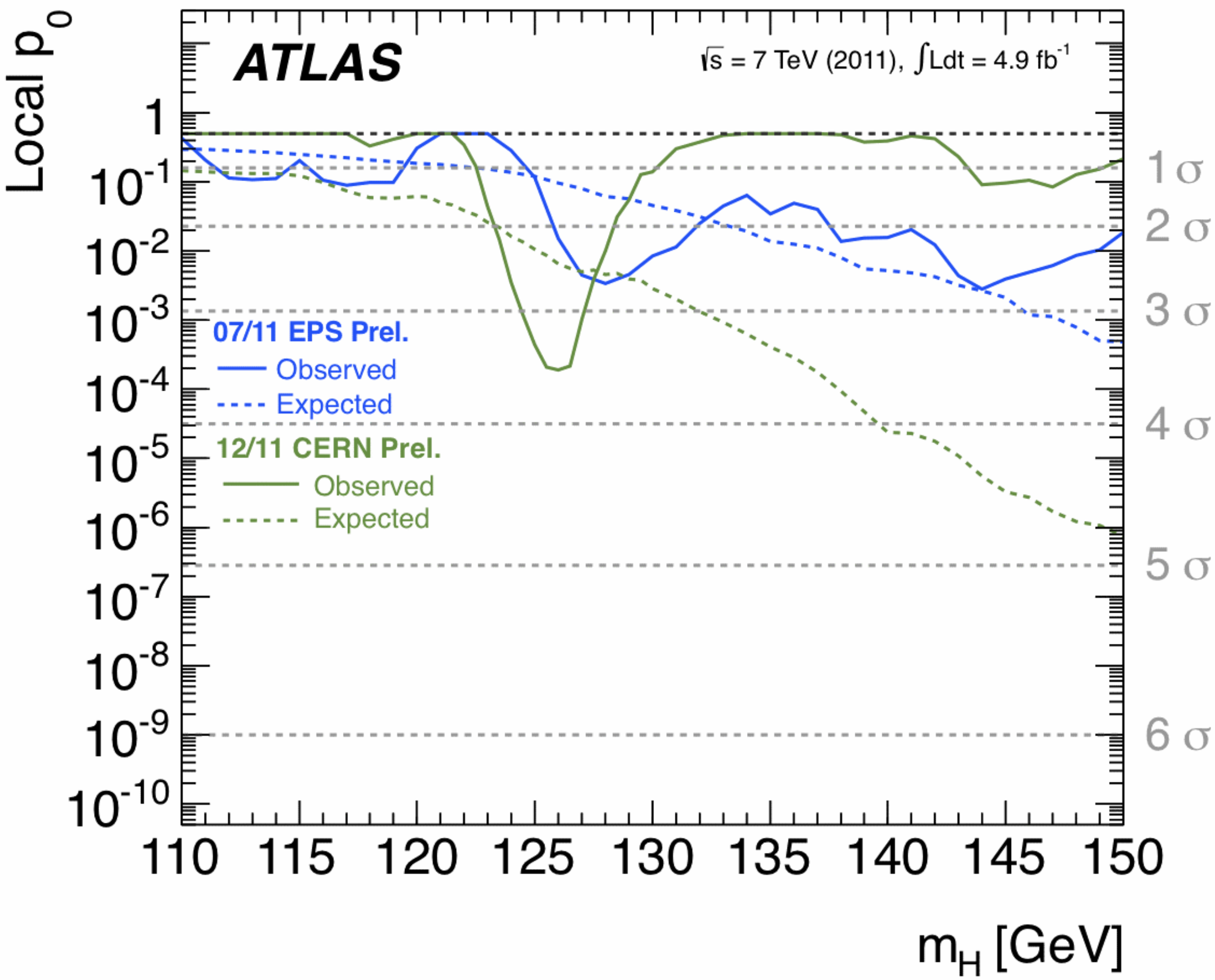
The Experimental Birth of a New Particle

July 2011 (EPS)



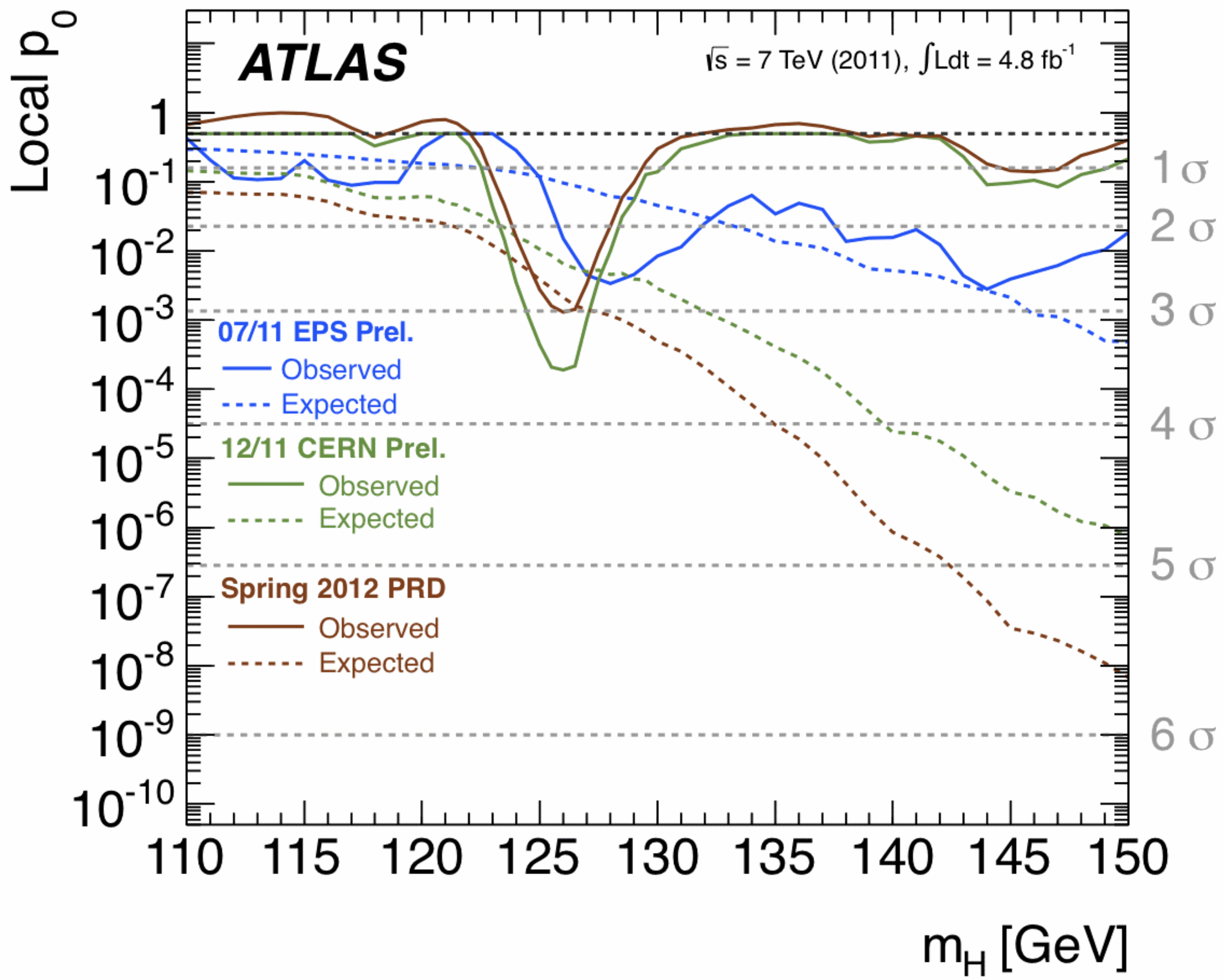
The Experimental Birth of a New Particle

December 2011 (Council)



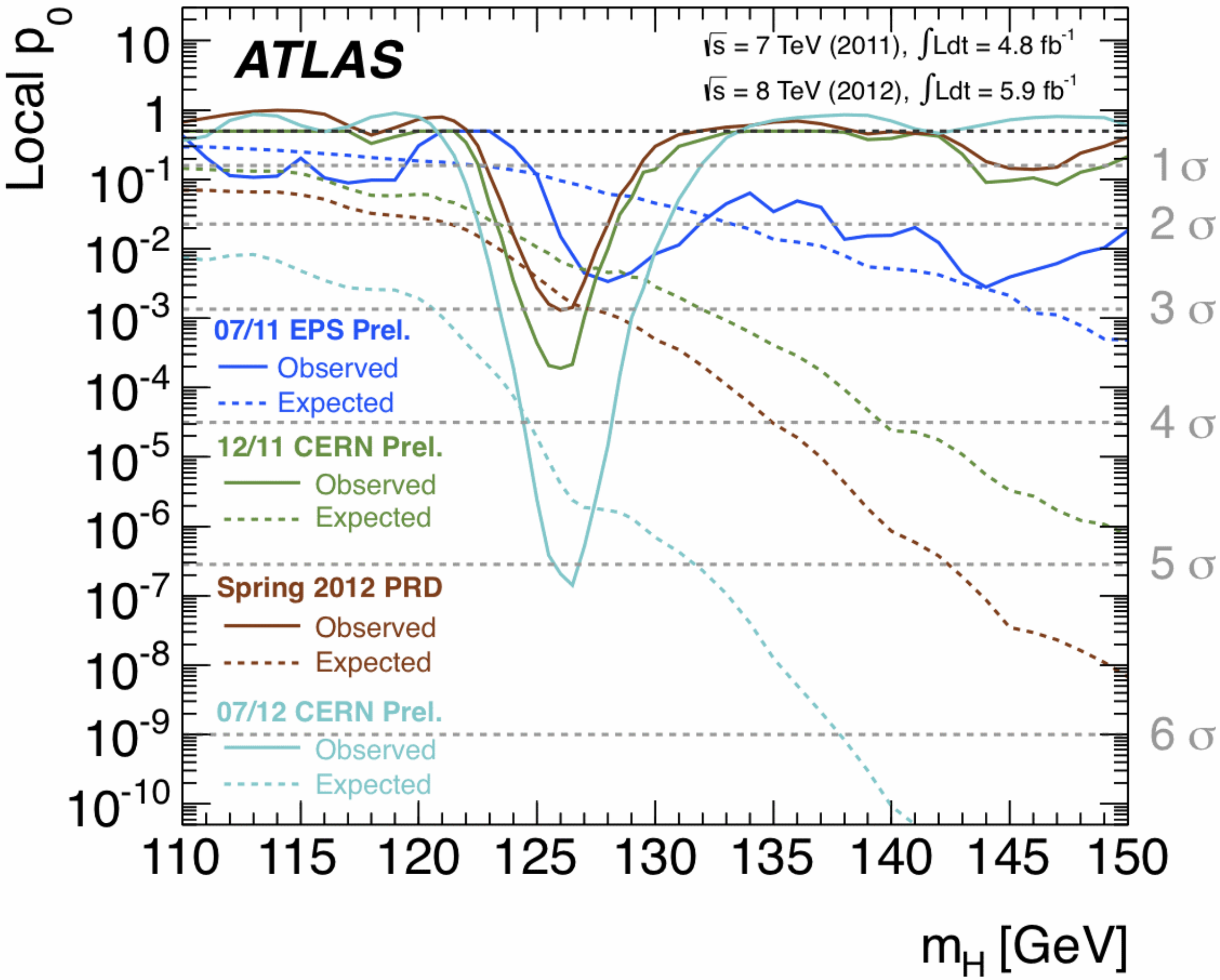
The Experimental Birth of a New Particle

February 2012



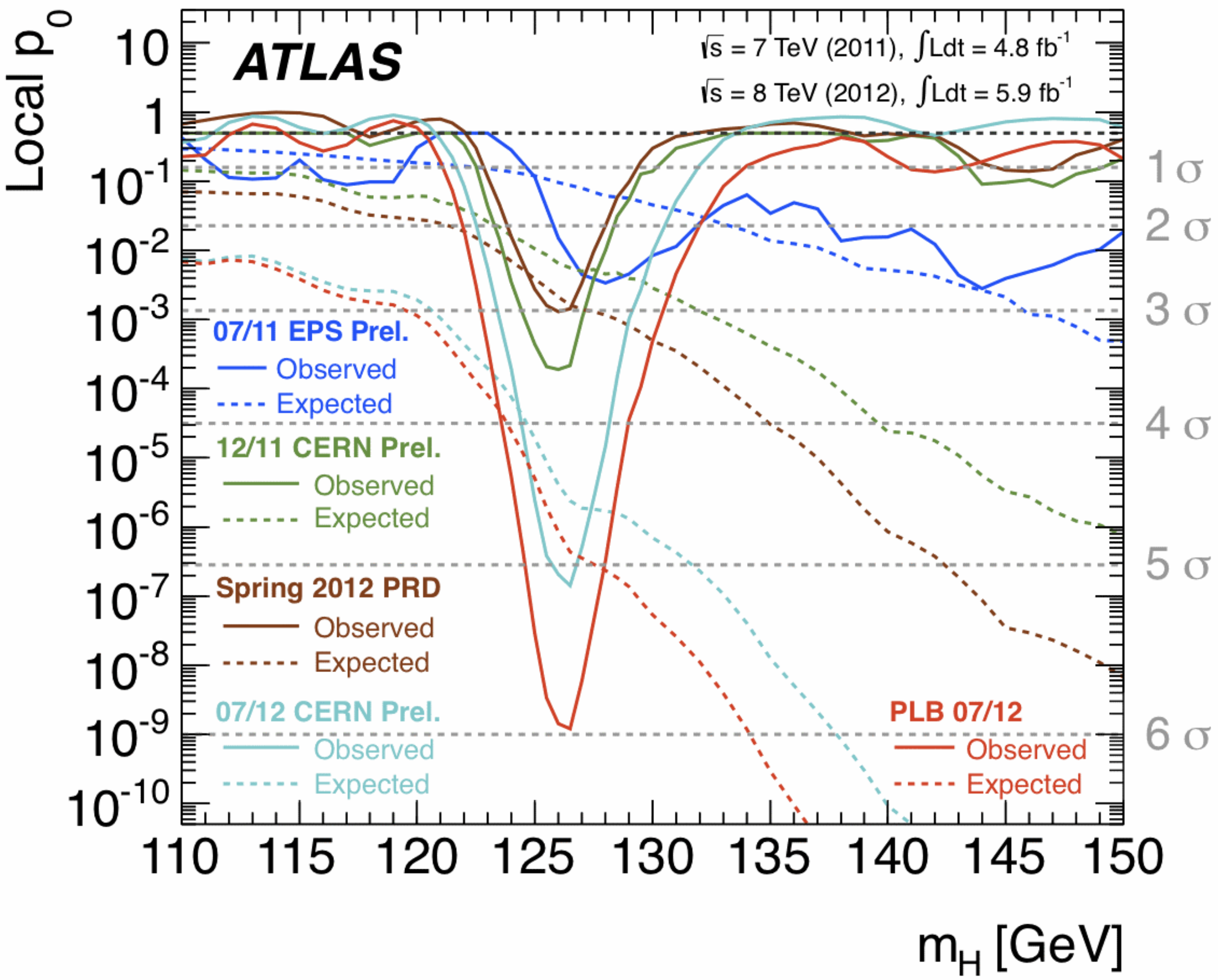
The Experimental Birth of a New Particle

July 2012 (ICHEP)



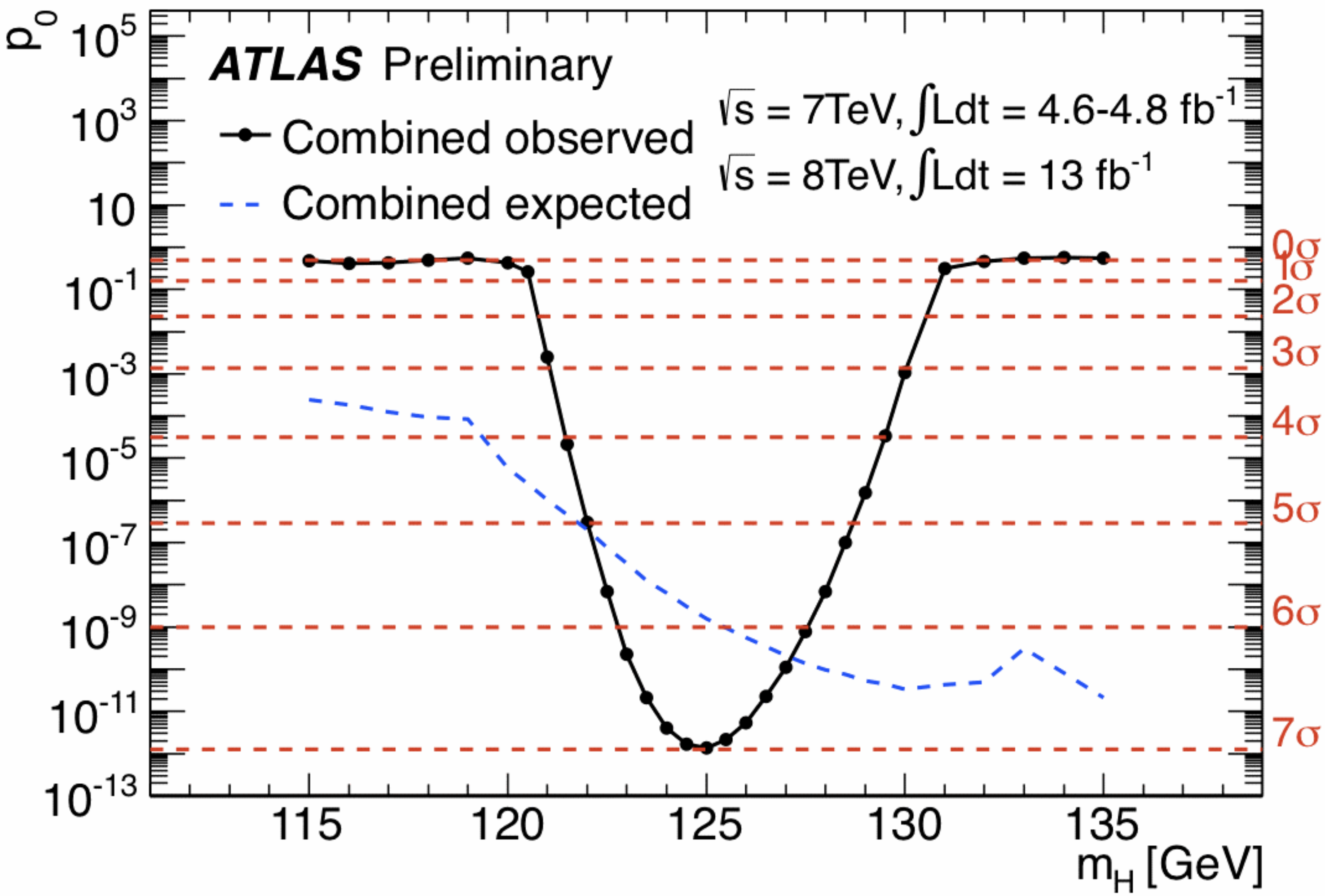
The Experimental Birth of a New Particle

August 2012 : Discovery paper

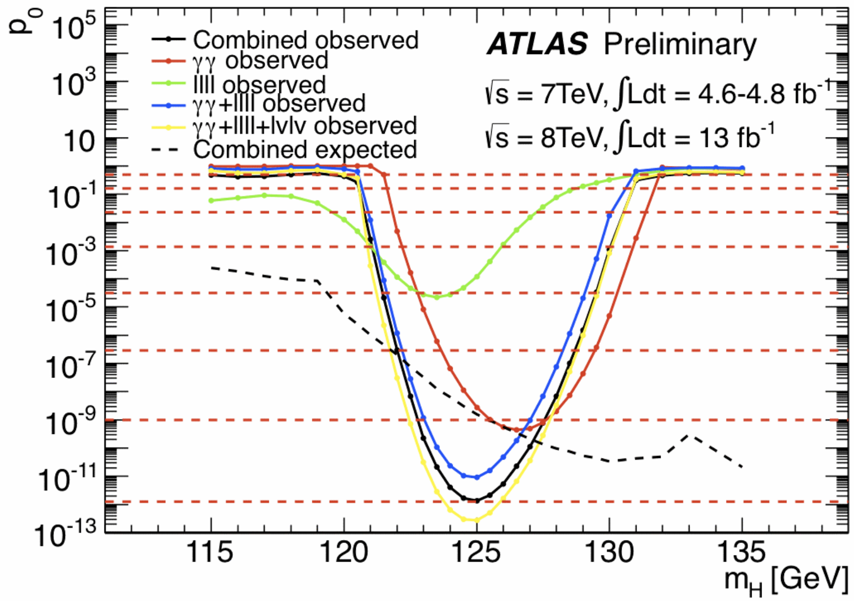


The Experimental Birth of a New Particle

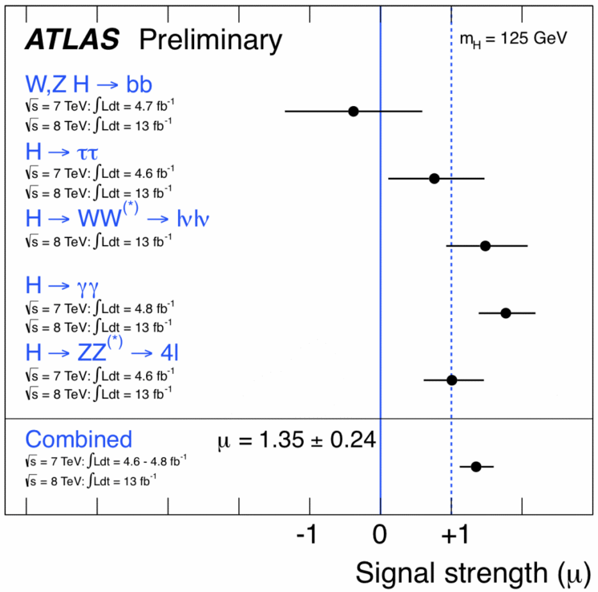
From the combination of 95 sub-channels
December 2012 (CERN Council)

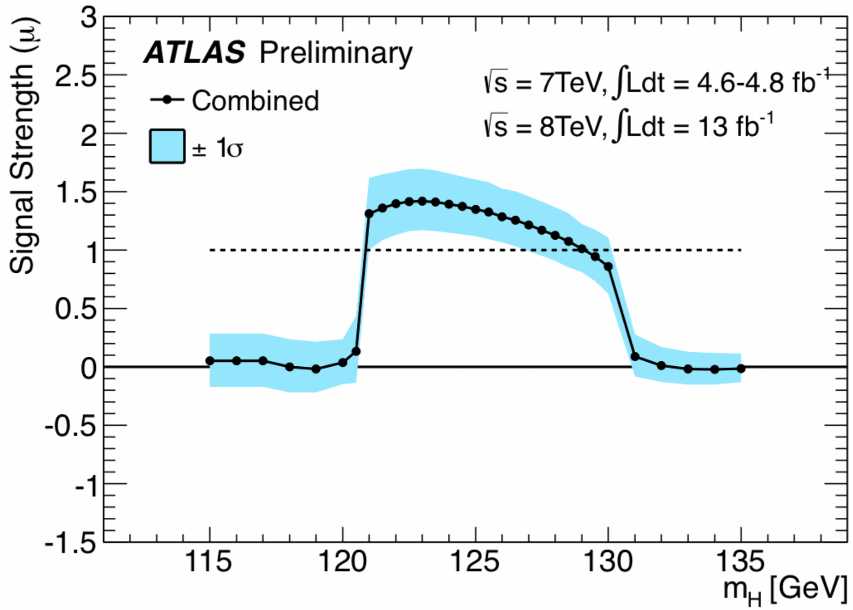


(one of the last p_0 plot in the SM context ?)



7σ *local* significance (5.9σ expected) at 125 GeV/c^2





μ rather stable w.r.t. hypothesised mass

(and illustration* that this is
definitively not a mass measurement !)

At m_H = 125 GeV/c^2 :

$$\hat{\mu} = 1.35 \pm 0.19(stat.) \pm 0.15(syst.)$$

CMS : 0.88±0.21

* with a little help from a conspiracy ;-) see next slides…

Characterization

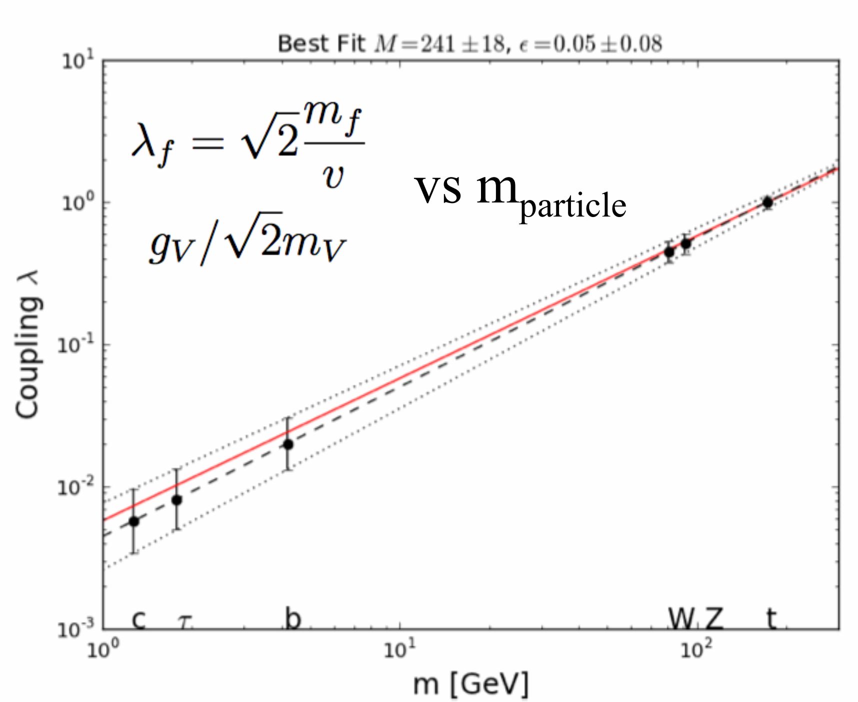
Is this really the "SM Higgs" boson ?

- Mass ~ 125 GeV/c^2 very much consistent with the preferred values from EW fits and theoretical prejudices
- Is it a neutral boson ? Yes : observation of e.g. $H \to \gamma\gamma$ ✓
- Is it $J^{CP} = 0^{++}$? ($H \to \gamma\gamma \Rightarrow C = +$)
- Does it couple to other SM particles ∝ mass ?

Coupling to V $= g_V = 2\frac{m_V^2}{v}$

Coupling to fermion $= \lambda_f = \sqrt{2}\frac{m_f}{v}$

Ellis, You, 1207.1693



Try that ansatz (SM : M = v, ε = 0)

$$\lambda'_f = \sqrt{2}\left(\frac{m_f}{M}\right)^{1+\epsilon}$$

$$g'_V = 2\frac{m_V^{2(1+\epsilon)}}{M^{1+2\epsilon}}$$

Fit (M,ε) with already available data
M = 241±18 GeV/c^2, ε = 0.05±0.08

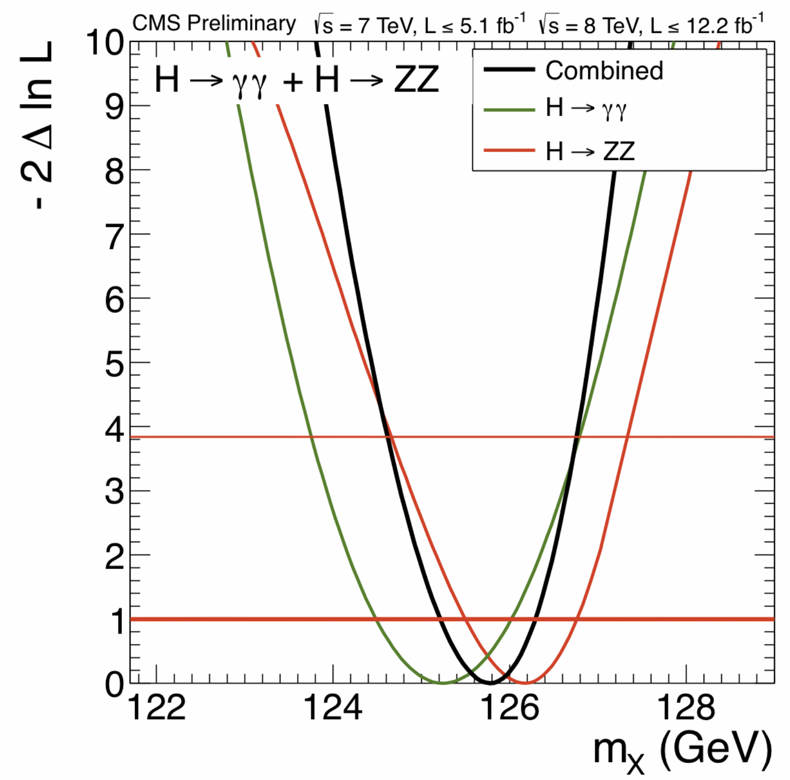
Very consistent with SM…

Mass measurement

Use the two high resolution channels : $H \to \gamma\gamma$, $H \to ZZ \to 4l$

Trying to stay model-independent :
the individual signal strengths can be different,
and are *profiled away* (let the data choose their preferred values)

CMS :



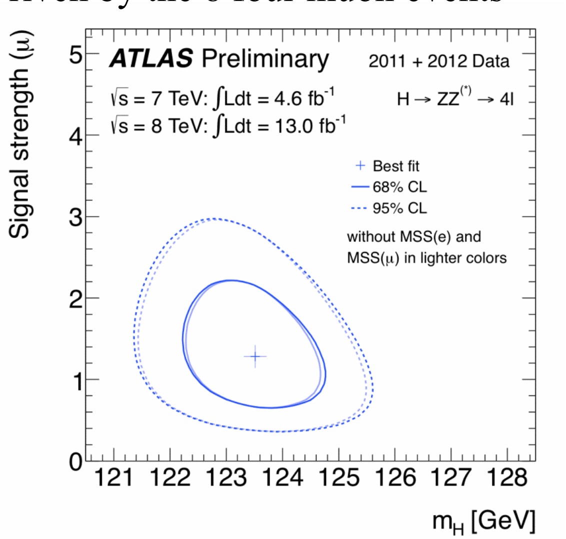
Both channels fully consistent

$m_H = 125.8 \pm 0.4\text{(stat.)} \pm 0.4\text{(syst.)}\ \text{GeV}/c^2$

ATLAS

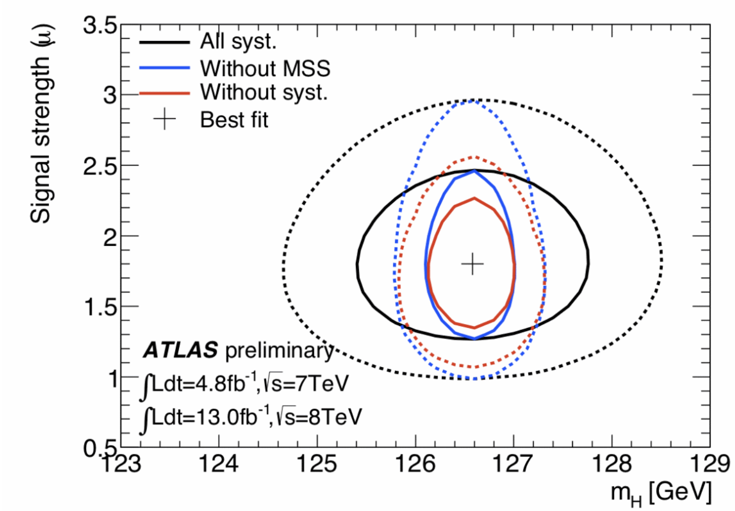
$m_H(4l) = 123.5 \pm 0.9(stat.) \pm 0.3(syst.)$

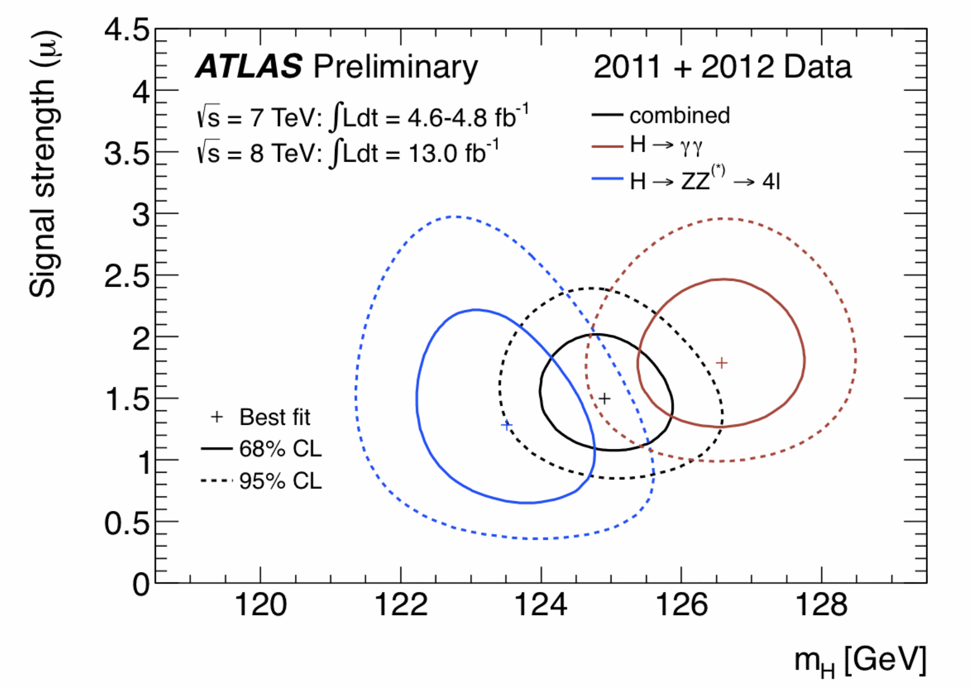
Driven by the 8 four muon events



$m_H(\gamma\gamma) = 126.6 \pm 0.3(stat.) \pm 0.7(syst.)$

Syst. dominated by photon energy scale





Probability for a single particle to produce mass difference between the two channels larger than observed is 0.8% (2.7σ)

Many checks have been performed to understand the origin of this discrepancy

Hopefully the ~ 10 fb^{-1} amount of data still to be analysed will help to clarify this

Meanwhile :

$m_H = 125.2 \pm 0.3(stat.) \pm 0.6(syst.)$ GeV/c^2

Spin and parity

From Resonaances blog (quoted by C. Grojean at HC2012) :
« nice to see progresses on that but
"this question carries a similar potential for surprise as a football game between Brazil and Tonga" »

Do not expect a clear visual impression
Prejudices help !
And… in statistics we trust…

- The low mass region is not very favourable for J^P measurement
  - many information in $H \to ZZ \to 4l$ but tiny yield
  - relatively large yield in $H \to WW \to l\nu l\nu$ but final state not fully reconstructed
  - relatively large yield in $H \to \gamma\gamma$, but huge background

- In addition to parity, concentrate on Spin 0 (SM) vs Spin 2 :
  - Look at *minimal coupling* for the time being ("graviton like", 2^+)
  - no look at higher spin for simplicity
  - Spin 1 forbidden by the Landau/Yang theorem from $H \to \gamma\gamma$ observation

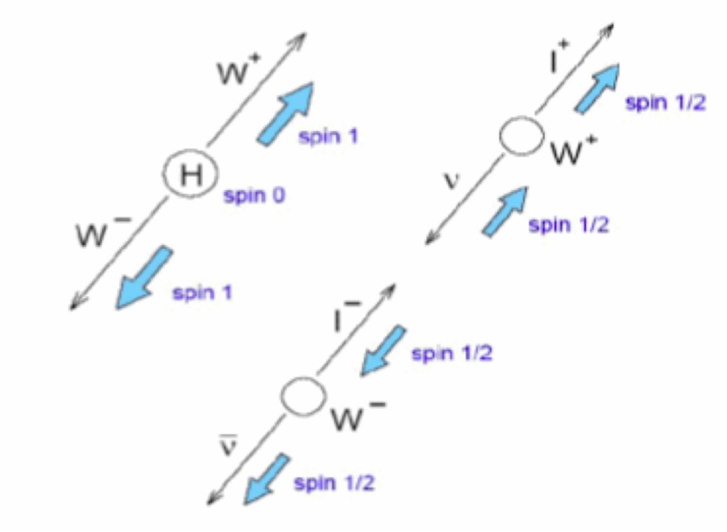
- The analyses are inclusive to stay as model independent as possible
  This is very conservative, e.g. the p_T spectrum of a spin 2 produced in qq annihilation is expected to be much softer than the SM Higgs one. Need to think more about these aspects

- The signal yield is a nuisance parameter,
  forget about the fact that μ is not so far away from the SM expectation

- The WW and ZZ observations already suggest $J^P = 0^+$ as being likely
  (exclude pure CP odd)

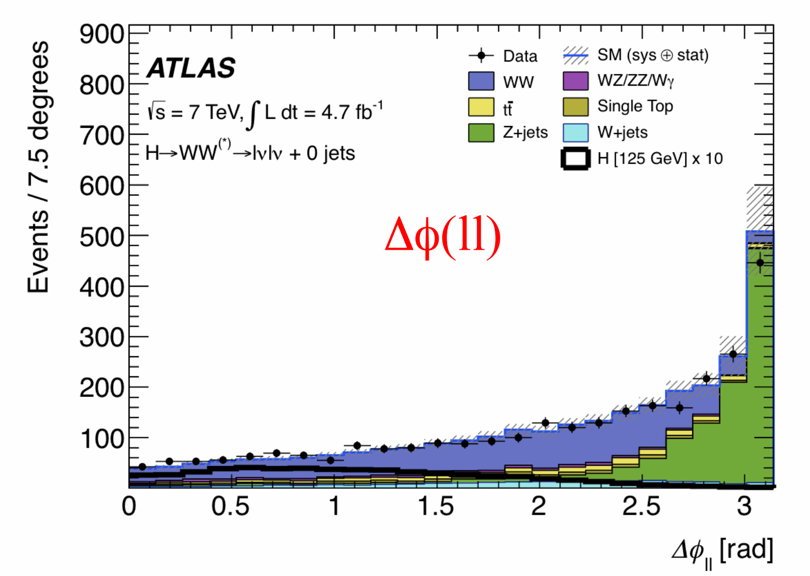
One should keep in mind that if it's not something close to the SM Higgs boson,
it is a ***very smart impostor***

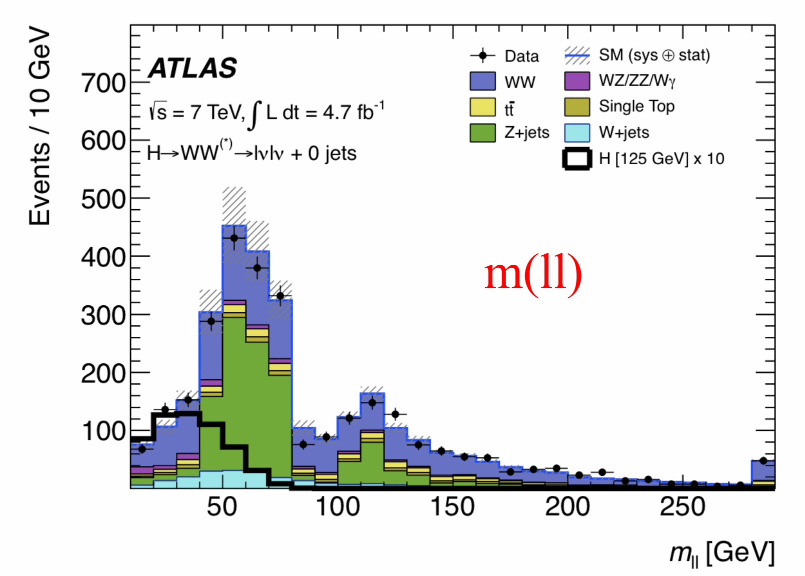
H → WW : Spin 0 property already explicitly included in the search analysis (in association with the V-A nature of the charged currents)



Charged leptons close-by in space
→ small azimuthal separation Δϕ(ll)
→ small di-lepton mass

⇒ Change analysis strategy to exploit this kind of variables without selection bias

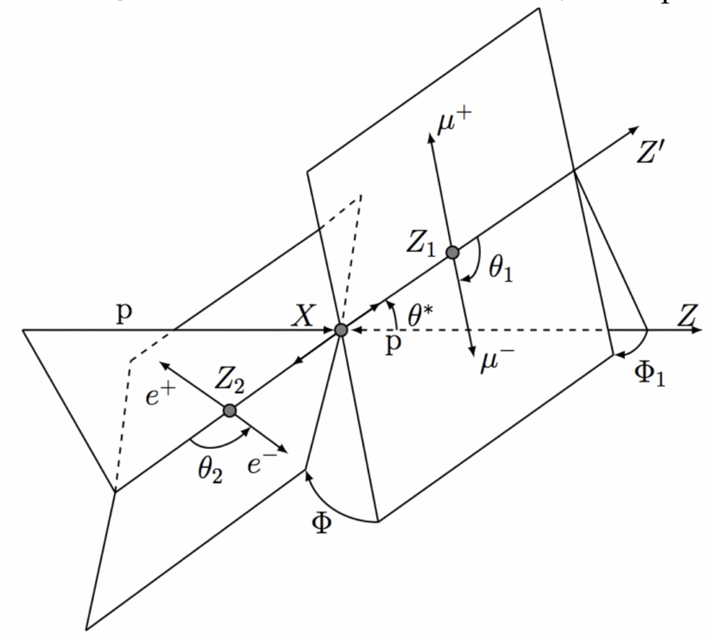




Preliminary analysis hopefully available for Moriond, stay tune…

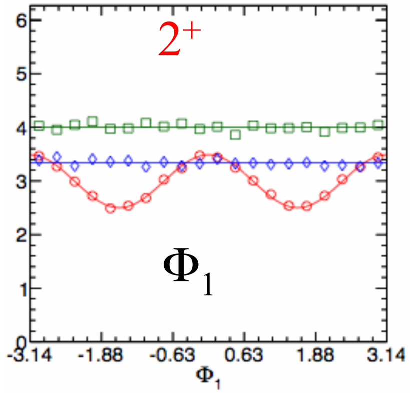
The golden four lepton channel (if only its yields were larger !)

4 body final state, fully reconstructed $\Rightarrow$ many clean variables to disentangle hypotheses
3 angles from the $Z^{(*)}$ decays (θ_1,θ_2,Φ), 2 angles for $Z^{(*)}$ production (θ^*, Φ_1), two masses

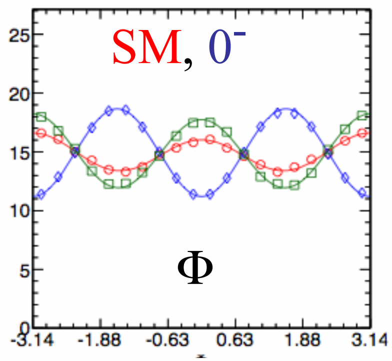


Not very sensitive to SM vs 2^+ yet

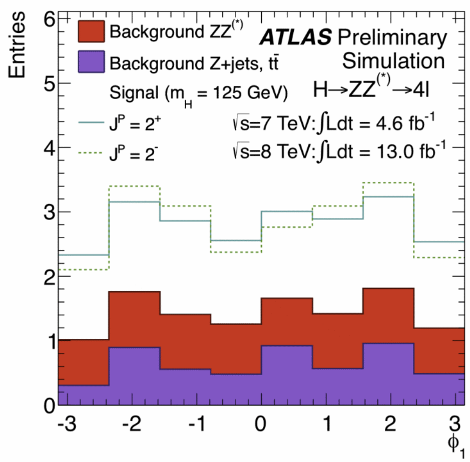
(Flat for SM)



(Almost flat for 2^+)



How Φ_1 looks like in ATLAS
! S and B stacked !

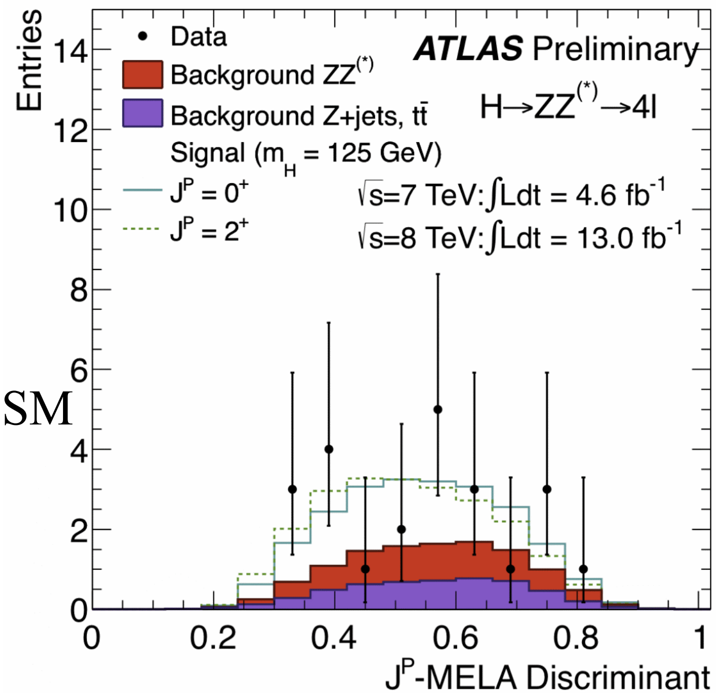


Combine all variables via the matrix element for both production processes (J^+-MELA)

minimal $2^{+\,(\dagger)}$ disfavoured w.r.t. SM @ ~ 1σ

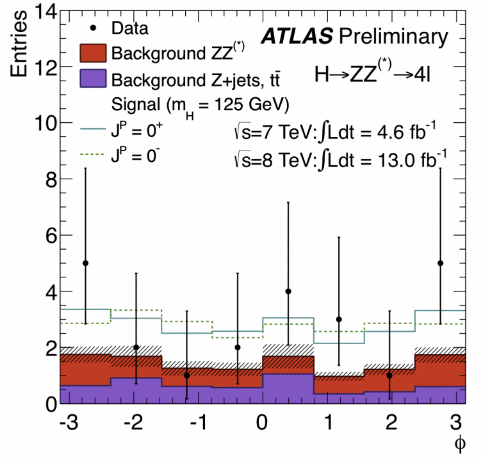
(and data fully compatible with SM)

† a very specific spin 2, produced via gluon fusion only

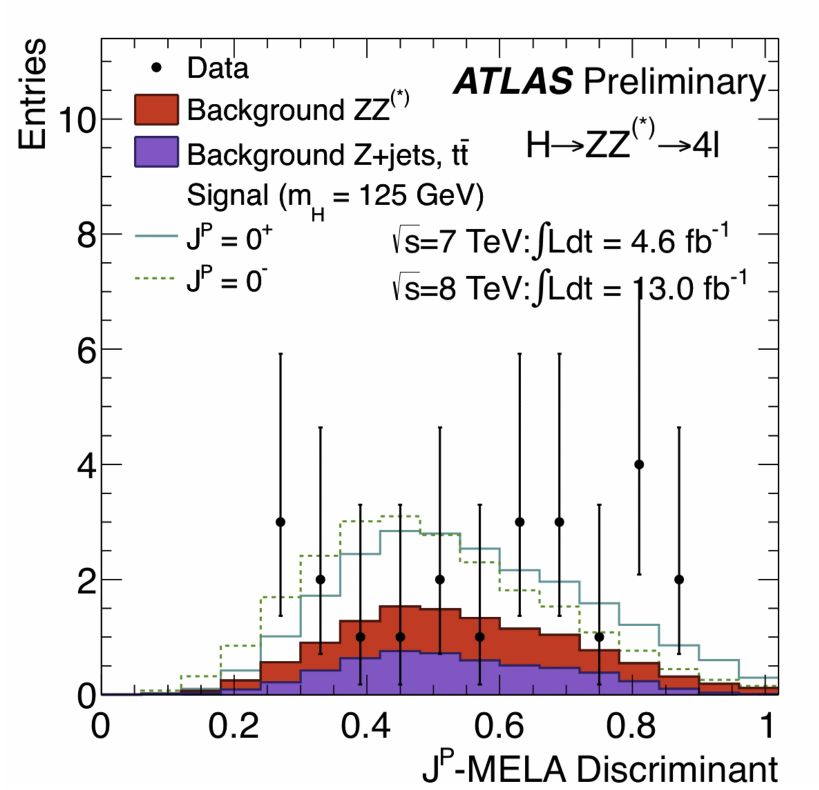


The four lepton channel is more powerful for parity

e.g. Φ angle between the Z decay planes

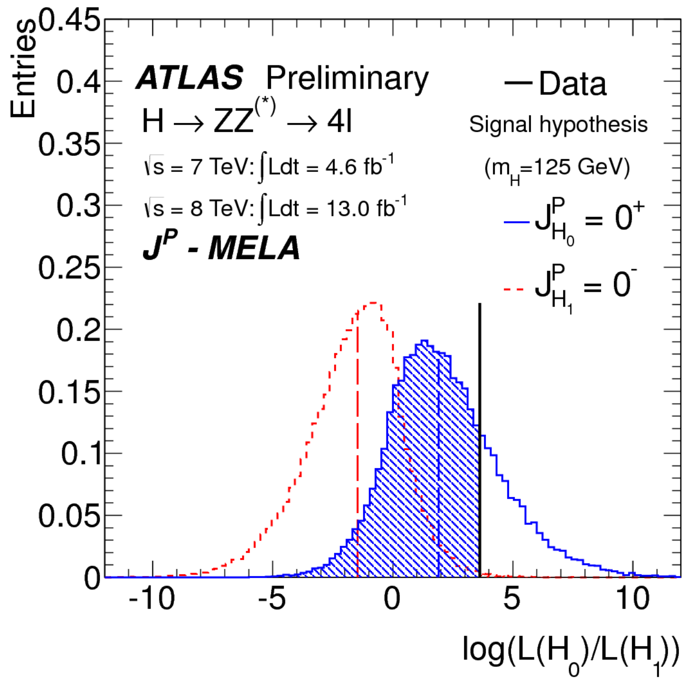


⇒ 5 relevant variables in a 0^P-MELA



Example of statistical treatment :

Ranking experiments with likelihood ratio

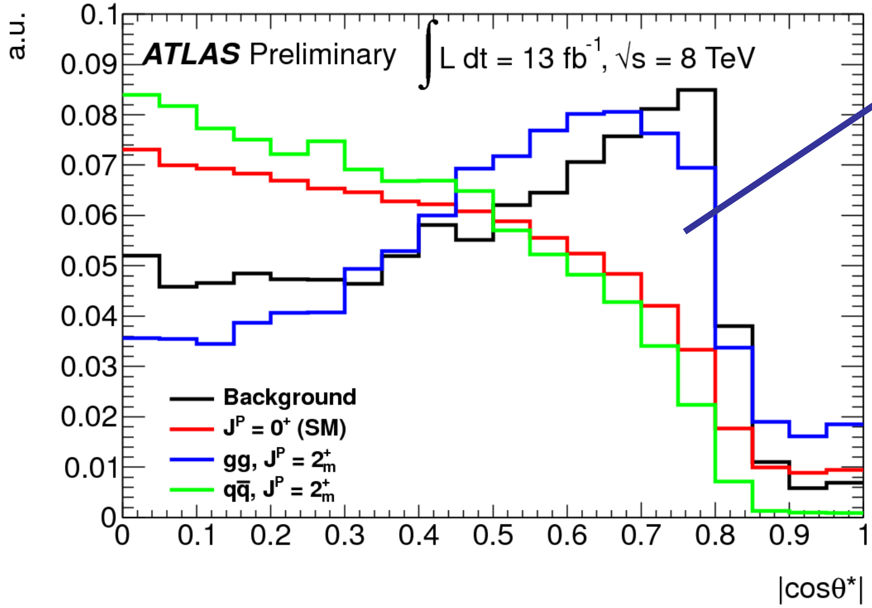


Pseudo-scalar disfavoured w.r.t. SM @ 2.7σ (1.9σ expected)

What does $H \rightarrow \gamma\gamma$ has to say ?

Despite large bkg and little information, might contribute where golden channel is less sensitive

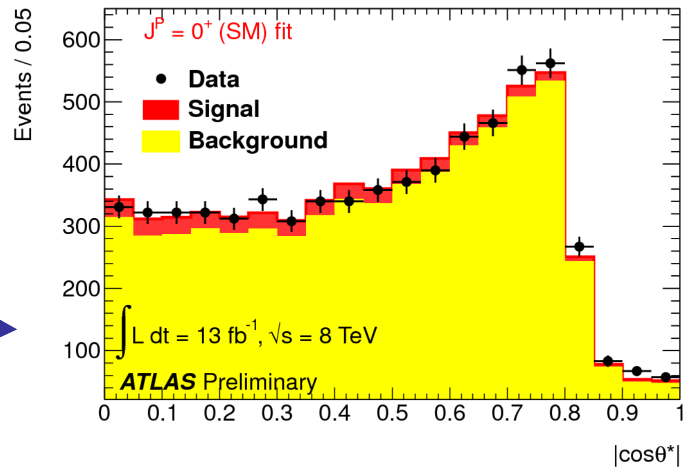
Relevant variable : photon production angle θ^*



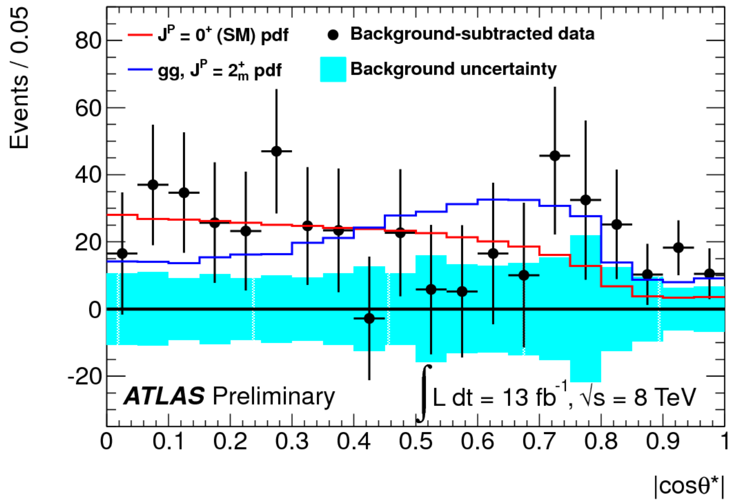
Very different shapes between SM and $gg \rightarrow X(2^+) \rightarrow \gamma\gamma$…

($q\bar{q}$ annihilation much more SM-like)

But this is on top of a huge bkg !



Bkg subtracted :



Data favours the SM w.r.t. to $gg2^+$

p-values : SM : 0.291 (0.6σ)

$gg2^+$: 0.086 (1.4σ)

Couplings

A new portal to new physics (?)

Measure Cross-section x Branching ratio

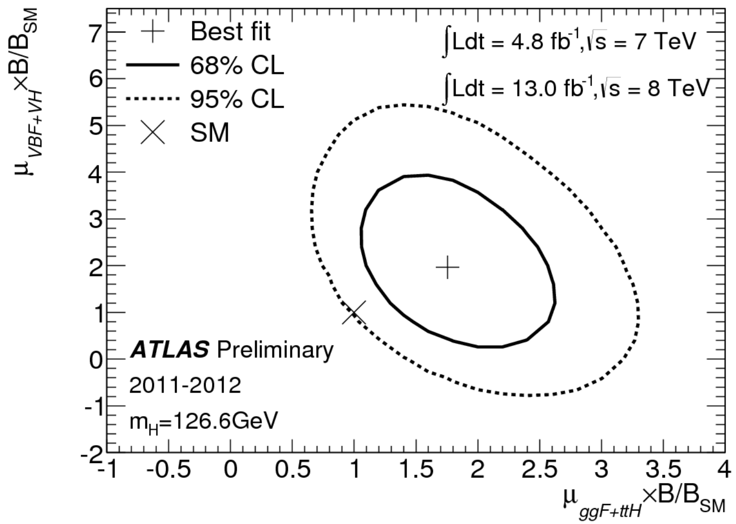
But cannot measure total width and all couplings in a completely model independent way

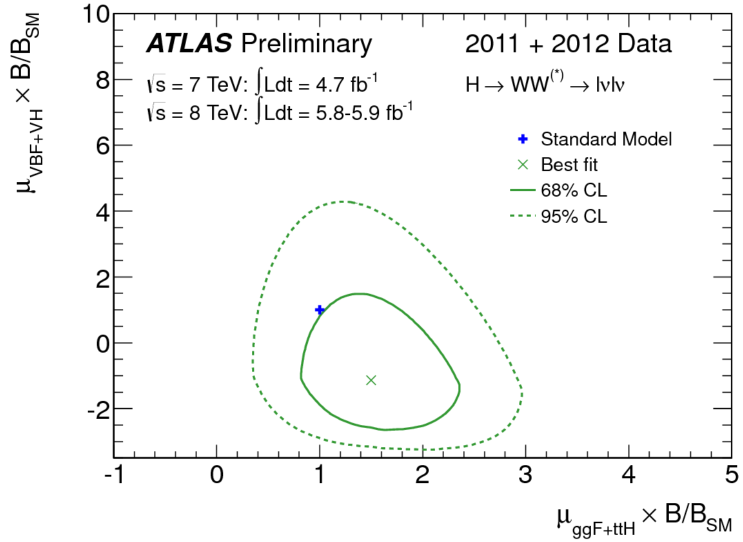
$\Rightarrow$ make drastic but well motivated assumptions

Simplest departure from the global signal strength model :

Two signal strengths : $\mu_{ggF+ttH}$ ($\Leftrightarrow$ coupling to top) and μ_{VBF+VH} (*) ($\Leftrightarrow$ coupling to W/Z)

Thanks to *exclusive categories* in $H \rightarrow \gamma\gamma$ and $H \rightarrow WW \rightarrow l\nu l\nu$ searches





Measurements a little bit high ($\gamma\gamma$) as anticipated from the global μ result but still consistent with the SM @ 1-2σ

* Can also separate μ_{VBF} and μ_{VH} thanks to the 2 new VH cat. in $\gamma\gamma$

Going further…

- ✓ Assuming a single narrow resonance at a mass $m_X \sim 125$ GeV/c^2

  (m_X could also be *profiled away* in the fit)
- ✓ Assume the same tensor structure of the SM Higgs boson : $J^{CP} = 0^{++}$
- ✓ Link to an effective Lagrangian and use scale factors

$$\mathcal{L} = \kappa_W \frac{2m_W{}^2}{v} W^+_\mu W^-_\mu H + \kappa_Z \frac{m_Z{}^2}{v} Z_\mu Z_\mu H - \sum_f \kappa_f \frac{m_f}{v} f\bar{f}H$$
$$+ c_g \frac{\alpha_s}{12\pi v} G^a_{\mu\nu} G^a_{\mu\nu} H + c_\gamma \frac{\alpha}{\pi v} A_{\mu\nu} A_{\mu\nu} H$$

$\kappa_g{}^2 = \sigma(gg \to H)/\ \sigma(gg \to H)_{SM}$, $\kappa_\gamma{}^2 = \Gamma(H \to \gamma\gamma)/\Gamma(H \to \gamma\gamma)_{SM}$, $\kappa_H{}^2 = \Gamma_H/\Gamma_{H,SM}$

$\kappa_{g,}$ κ_γ and κ_H are either free parameter
(e.g. contribution from unknown particles in the loop for $\kappa_{g,}$ κ_γ, or invisible decays for κ_H)
or function of the tree level coupling scale factors $\kappa_{W,Z,f}$

Rewrite $(\sigma \cdot BR)(ii \to H \to ff) = \frac{\sigma_{ii} \cdot \Gamma_{ff}}{\Gamma_H}$ with these scale factors, e.g

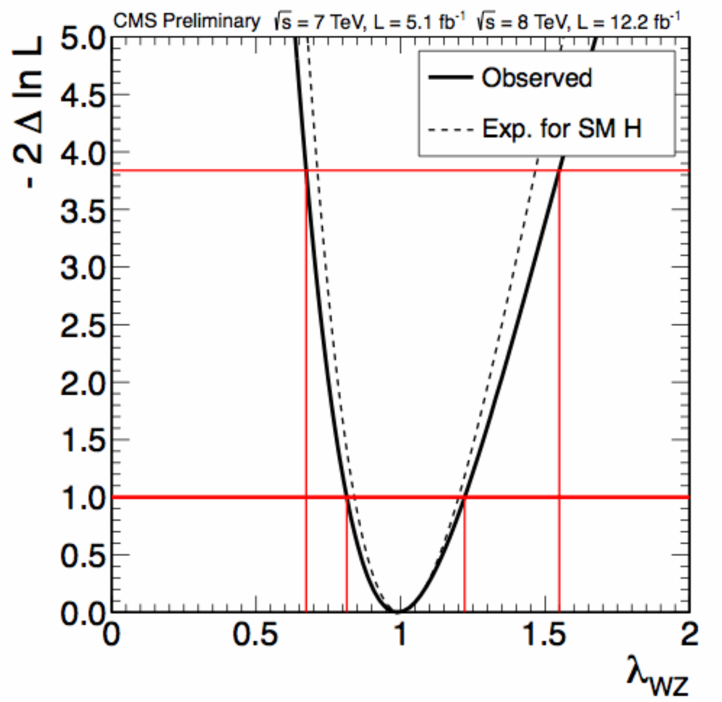
$$(\sigma \cdot BR)(gg \to H \to \gamma\gamma) = \sigma_{SM}(gg \to H) \cdot BR_{SM}(H \to \gamma\gamma) \cdot \frac{\kappa_g^2 \cdot \kappa_\gamma^2}{\kappa_H^2}$$

… and test different well motivated models

- The custodial symmetry : $\kappa_W = \kappa_Z$

No assumption on total width, main poi = $\lambda_{WZ} = \kappa_W/\kappa_Z$
(and two other κ_F/κ_Z and κ_Z^2/κ_H, κ_F is a common fermion scale factor)

Example of result from CMS :



$$\lambda_{WZ} = 1.0^{+0.22}_{-0.19}$$

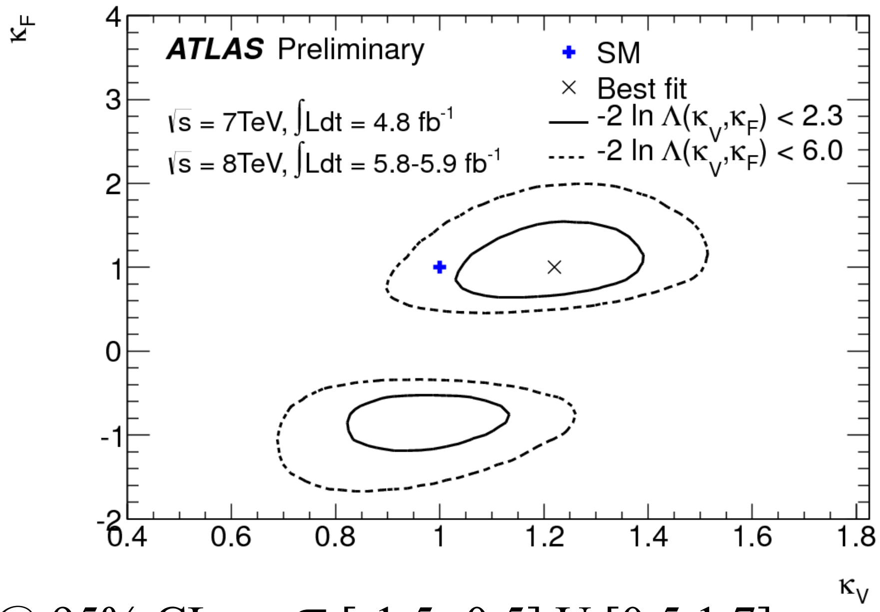
$$\lambda_{WZ} \in [0.67, 1.55]$$

Similar conclusion in ATLAS

$\Rightarrow$ With the available data :
custodial symmetry is also respected
in this newly observed sector

Fermions and Weak bosons rescaling (assuming only SM particles in loops)

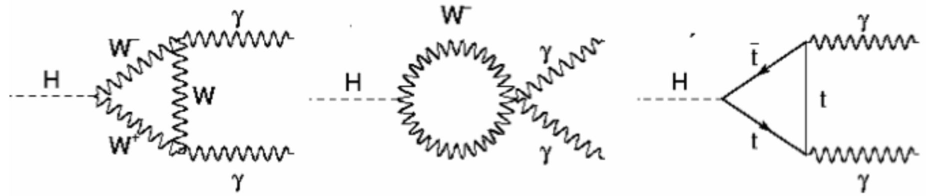
A single fermion κ_F and weak boson κ_V scale factors



One overall not observable sign, choose $\kappa_V > 0$

Difference between $\kappa_F > 0$ and $\kappa_F < 0$

from interference between top and W in $H \rightarrow \gamma\gamma$



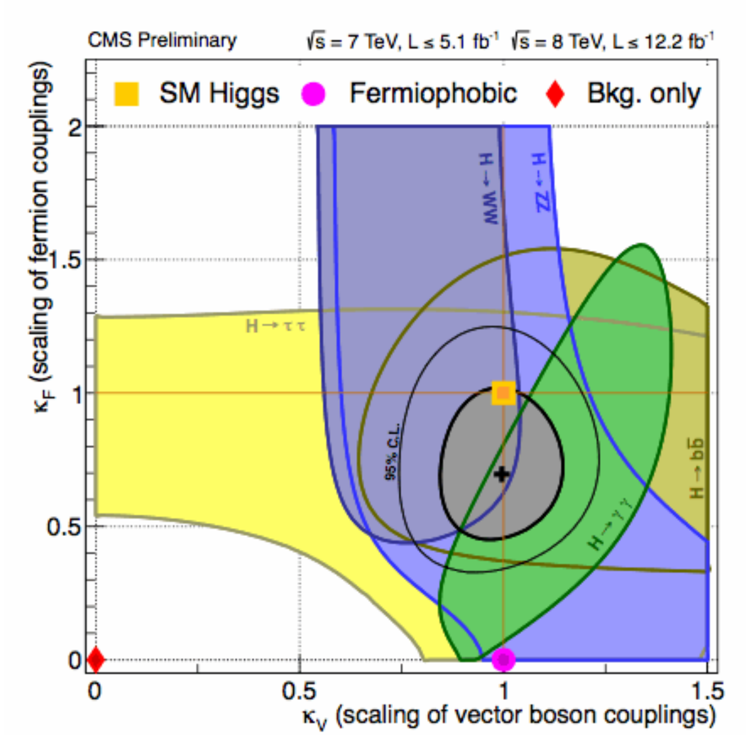
$$\kappa_\gamma^{\ 2} \sim |1.28\ \kappa_W - 0.28\ \kappa_t|^2$$

@ 95% CL $\kappa_F \in [-1.5,-0.5]$ U $[0.5,1.7]$:

$\Rightarrow$ fermiophobic X strongly disfavoured

$\kappa_V \in [0.7,1.4]$

A nice illustration of the interplay between many search channels (CMS) (imposing $\kappa_F > 0$)



A negative solution if preferred would be far away from the SM, invalidating a little bit the basic assumption used in this framework that only small deviations can be searched for

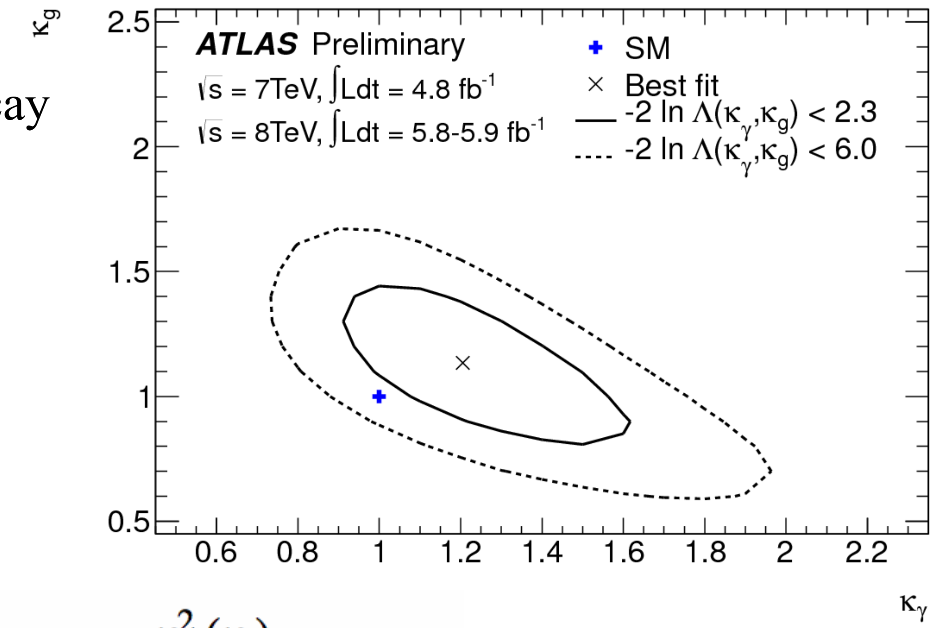
Loop couplings and undetected decays

No significant deviation observed so far : assume all tree level scale factors are 1 and probe κ_g and κ_γ

Assuming no new physics (NP) in decay

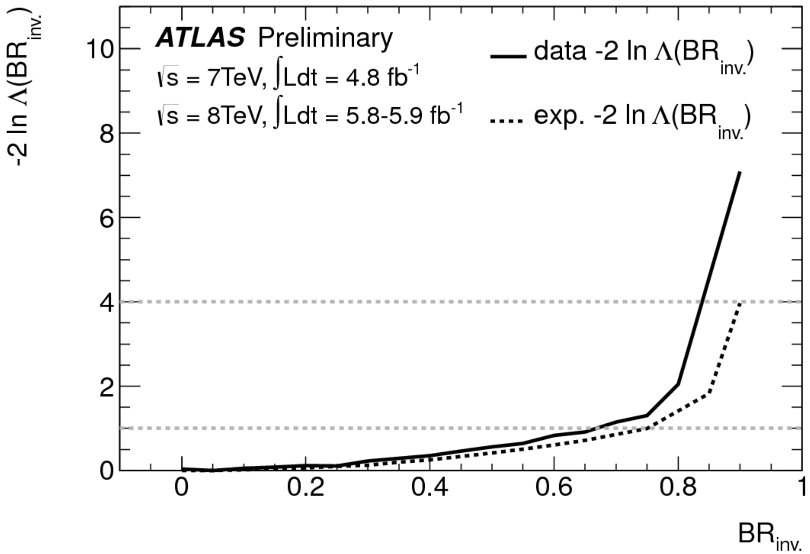
$\kappa_g = 1.1^{+0.2}_{-0.3}$
$\kappa_\gamma = 1.2^{+0.3}_{-0.2}$

Compatibility between best fit and SM ~ 18%



Or assuming undetected decays from NP

$$\Gamma_H = \frac{\kappa_H^2(\kappa_i)}{(1 - BR_{inv.,undet.})}\Gamma_H^{SM}$$



$\kappa_g = 1.1^{+1.4}_{-0.2}$
$\kappa_\gamma = 1.2^{+0.3}_{-0.2}$

$BR_{inv,unded} < 84\%$ @ 95 % CL

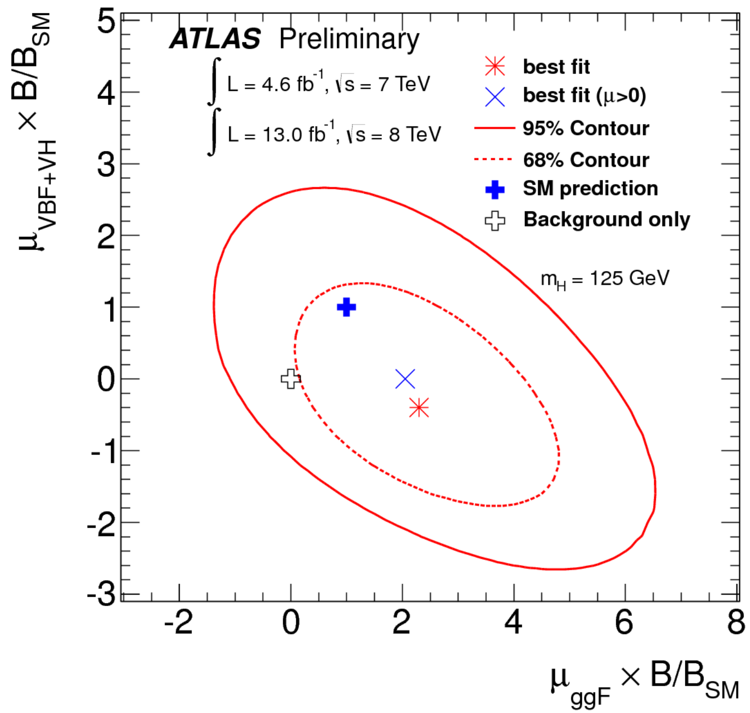
In the fermion sector

→ Test lepton vs quark

→ Test down type vs up type

Before HCP 2012, no direct handle on κ_f ,
only indirect through top quark loop in gluon fusion and di-photon decays

$H \to \tau^+\tau^-$ now entering the game
(but only very mild excess for the time being)



Eagerly waiting for (better) evidences in

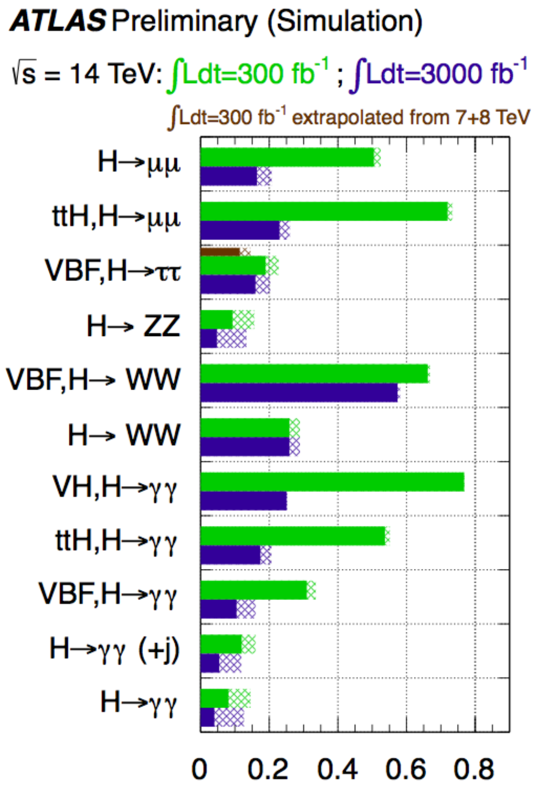
$H \to \tau^+\tau^-$ and $H \to bb$!

What else ?

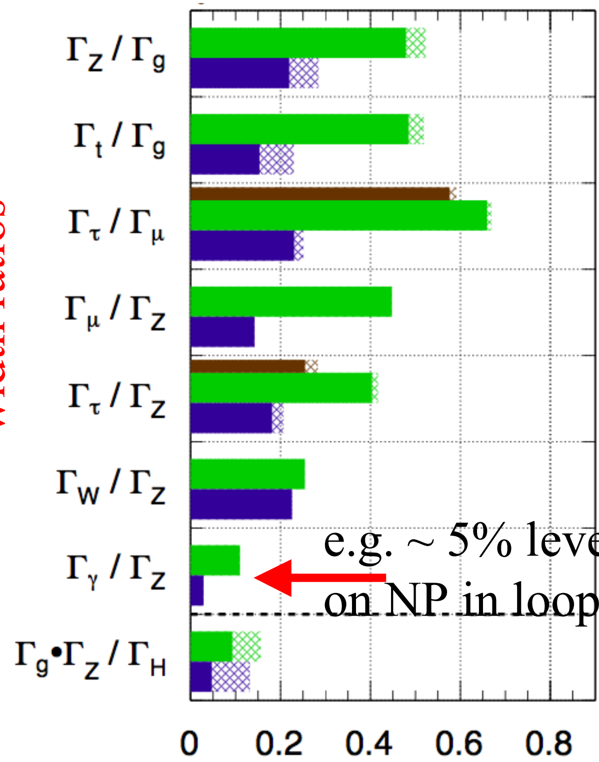
✓ Short term (2013) : improve all analyses and especially the tough ones H → $\tau^+\tau^-$ / bb

✓ Projection in the (more or less far) future :

Uncertainty on signal strengths



Uncertainty on width ratios



e.g. ~ 5% level constraint on NP in loops

✓ Determination of the scalar potential, an essential missing ingredient : **self couplings** !

$\lambda_3 H^3 + \lambda_4 H^4$: are they as predicted by the SM potential *i.e.* $\lambda_3 \sim m_H^2/(2v)$, $\lambda_4 \sim m_H^2/(8v^2)$?

λ_4 : hopeless in any planed experiment (?)

λ_3 : very very hard but some hope, e.g.

pp → HH → bbγγ (S ~ 15, B ~ 21 for 3 ab^{-1} ! Need to have faith…) bb$\tau^+\tau^-$ (under study)

⇒ 30% measurement of λ_3 with ATLAS+CMS combined at 13 TeV and 3 ab^{-1} ?

Conclusion

* The kill joy comment
when I arrived in ATLAS, it was foreseen to have $30\ fb^{-1}$ at 14 TeV by 2008 and $300\ fb^{-1}$ by 2012…

- Thanks to excellent LHC operations (*) with $25\ fb^{-1}$ @ 8 TeV delivered to ATLAS and CMS …

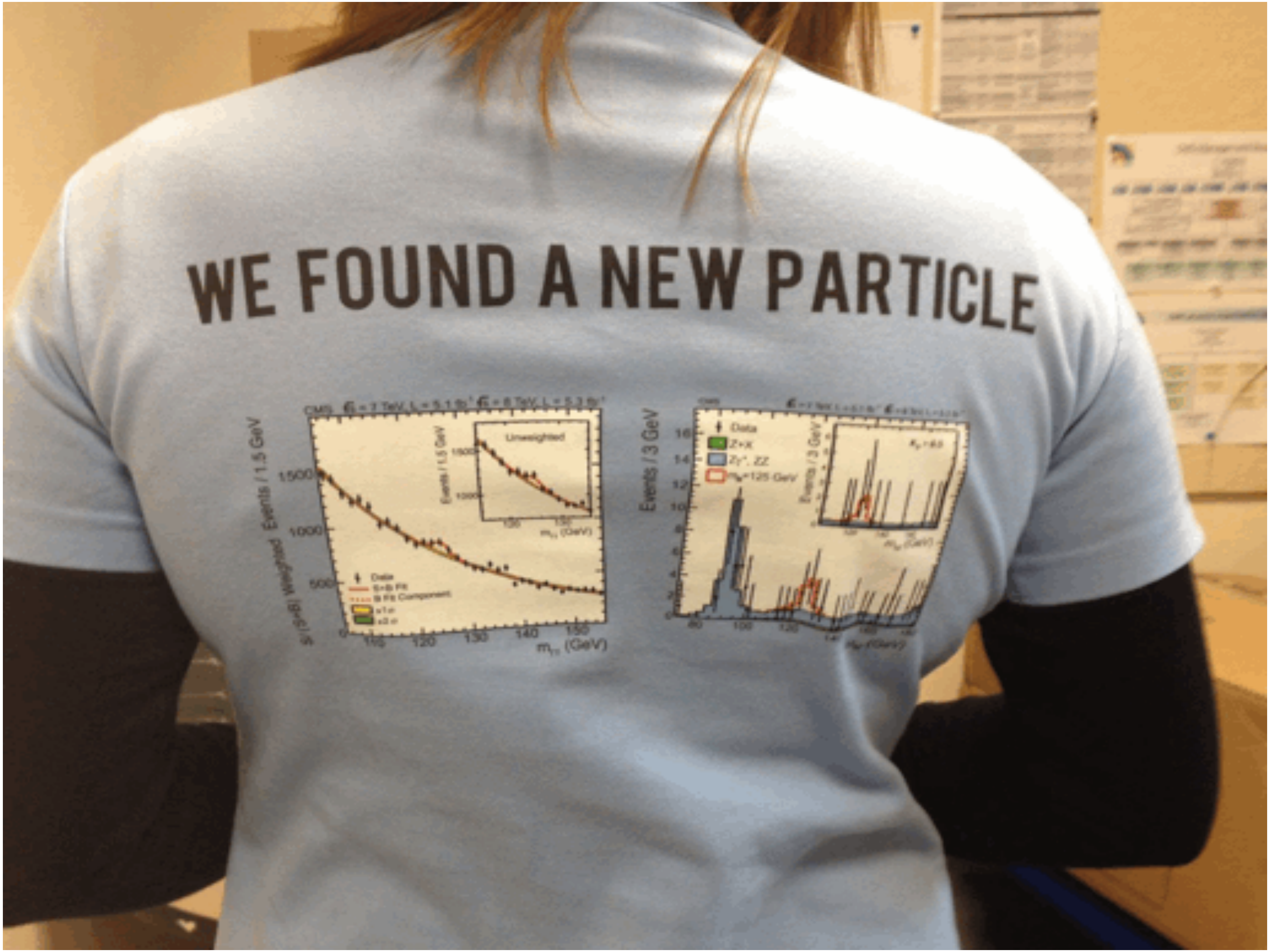
- and excellent performance of CMS/ATLAS …
  Trigger/DAQ
  + "*robustification*" of reconstruction algorithms to cope with very high pile-up
    (and also efficient computing !)

- The year 2012 was a fantastic year for Particle Physics !
  At last the discovery of a Higgs-boson like resonance

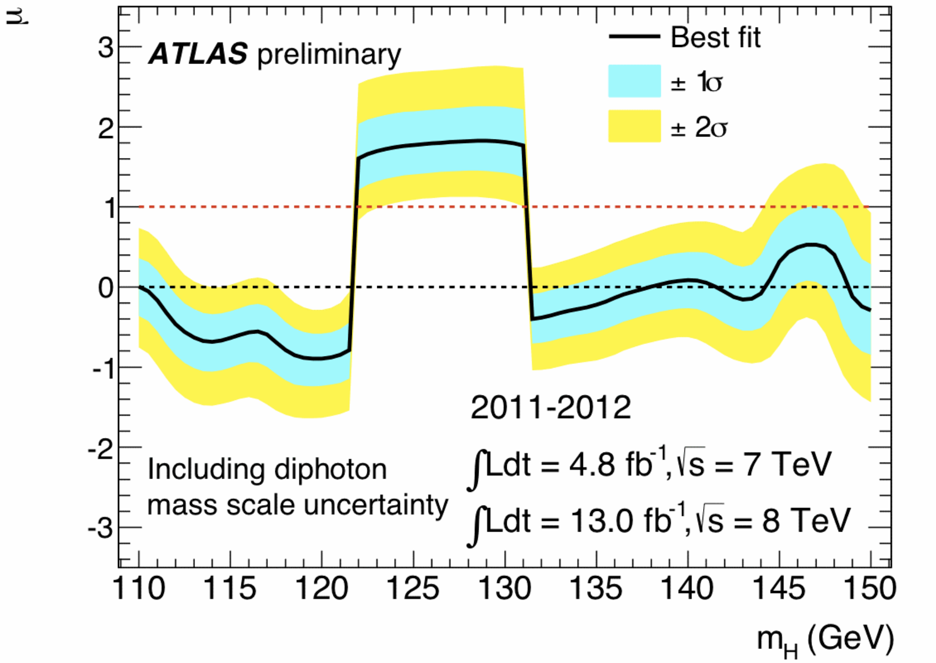
  All measurements up to now are consistent with SM but surprises might occur…
  (e.g. persistent excess in $H \rightarrow \gamma\gamma$ in both experiments (waiting for CMS update)
  actually nice ! Could be a portal to New Physics ?)

- Beginning of a new era :
  from searches to "precision" measurements in the Higgs sector

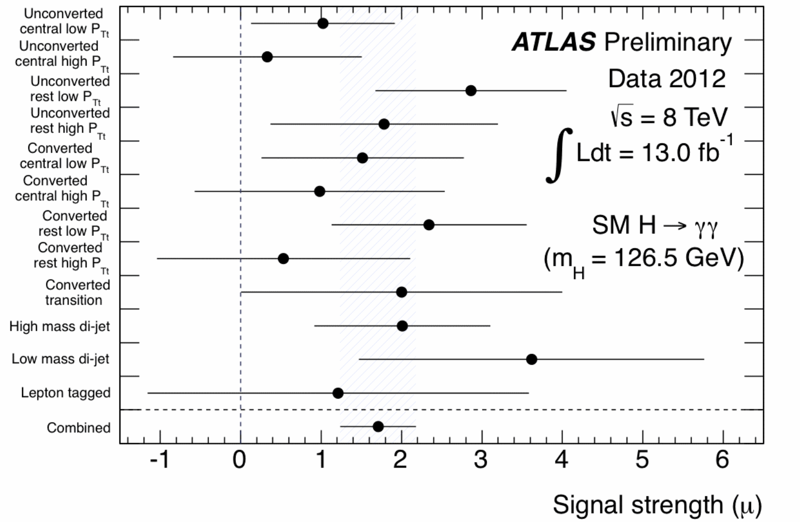
  → Exploit all 2012 data with refined strategies optimized for measurements
  → Consolidate all preliminary measurements
  → Go forward : prepare for 13 TeV collisions after LS1 in 2015


WE FOUND A NEW PARTICLE
Events / 3 GeV
Data
Z+X
m (GeV)

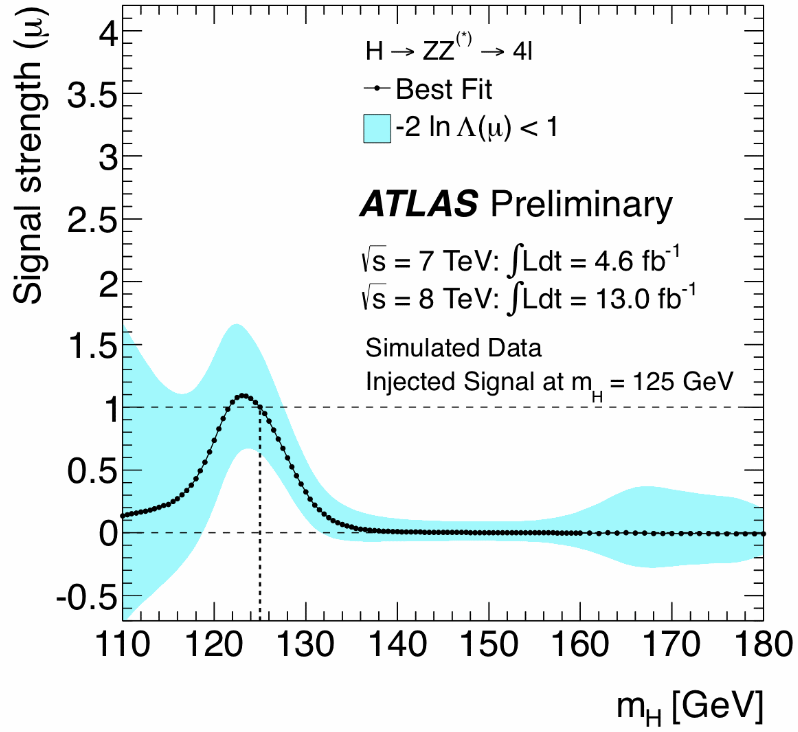
Backup



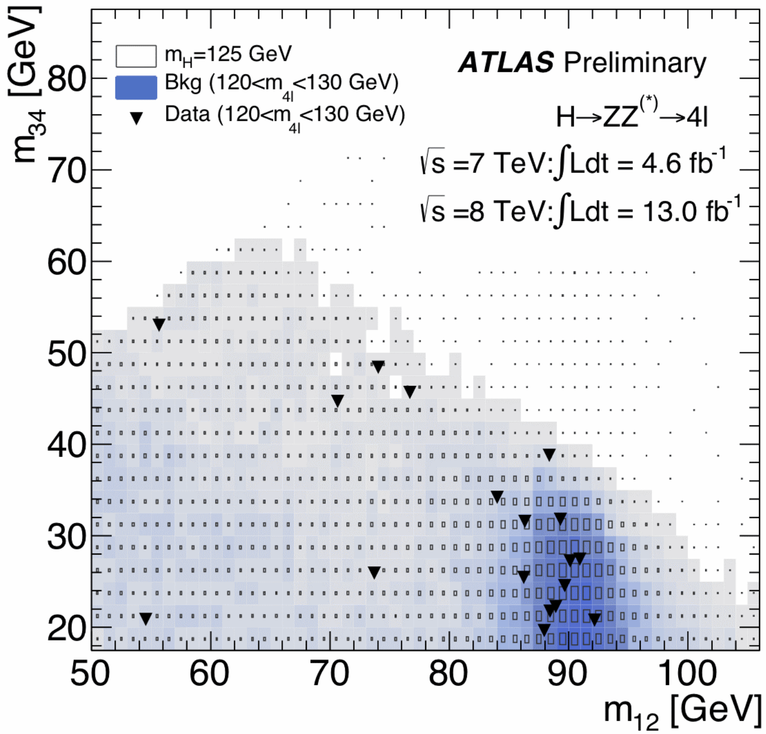
μ
ATLAS preliminary
Best fit
± 1σ
± 2σ
2011-2012
Including diphoton
mass scale uncertainty
∫Ldt = 4.8 fb-1,√s = 7 TeV
∫Ldt = 13.0 fb-1,√s = 8 TeV
mH (GeV)



Unconverted central low PTt
Unconverted central high PTt
Unconverted rest low PTt
Unconverted rest high PTt
Converted central low PTt
Converted central high PTt
Converted rest low PTt
Converted rest high PTt
Converted transition
High mass di-jet
Low mass di-jet
Lepton tagged
Combined
ATLAS Preliminary
Data 2012
√s = 8 TeV
∫Ldt = 13.0 fb-1
SM H → γγ
(mH = 126.5 GeV)
Signal strength (μ)



Signal strength (μ)
H → ZZ(*) → 4l
Best Fit
-2 ln Λ(μ) < 1
ATLAS Preliminary
√s = 7 TeV: ∫Ldt = 4.6 fb-1
√s = 8 TeV: ∫Ldt = 13.0 fb-1
Simulated Data
Injected Signal at mH = 125 GeV
mH [GeV]



m_H=125 GeV
Bkg (120<m_4l<130 GeV)
Data (120<m_4l<130 GeV)
ATLAS Preliminary
H→ZZ(*)→4l
√s =7 TeV: ∫Ldt = 4.6 fb-1
√s =8 TeV: ∫Ldt = 13.0 fb-1
m_34 [GeV]
m_12 [GeV]
20
30
40
50
60
70
80
50
60
70
80
90
100

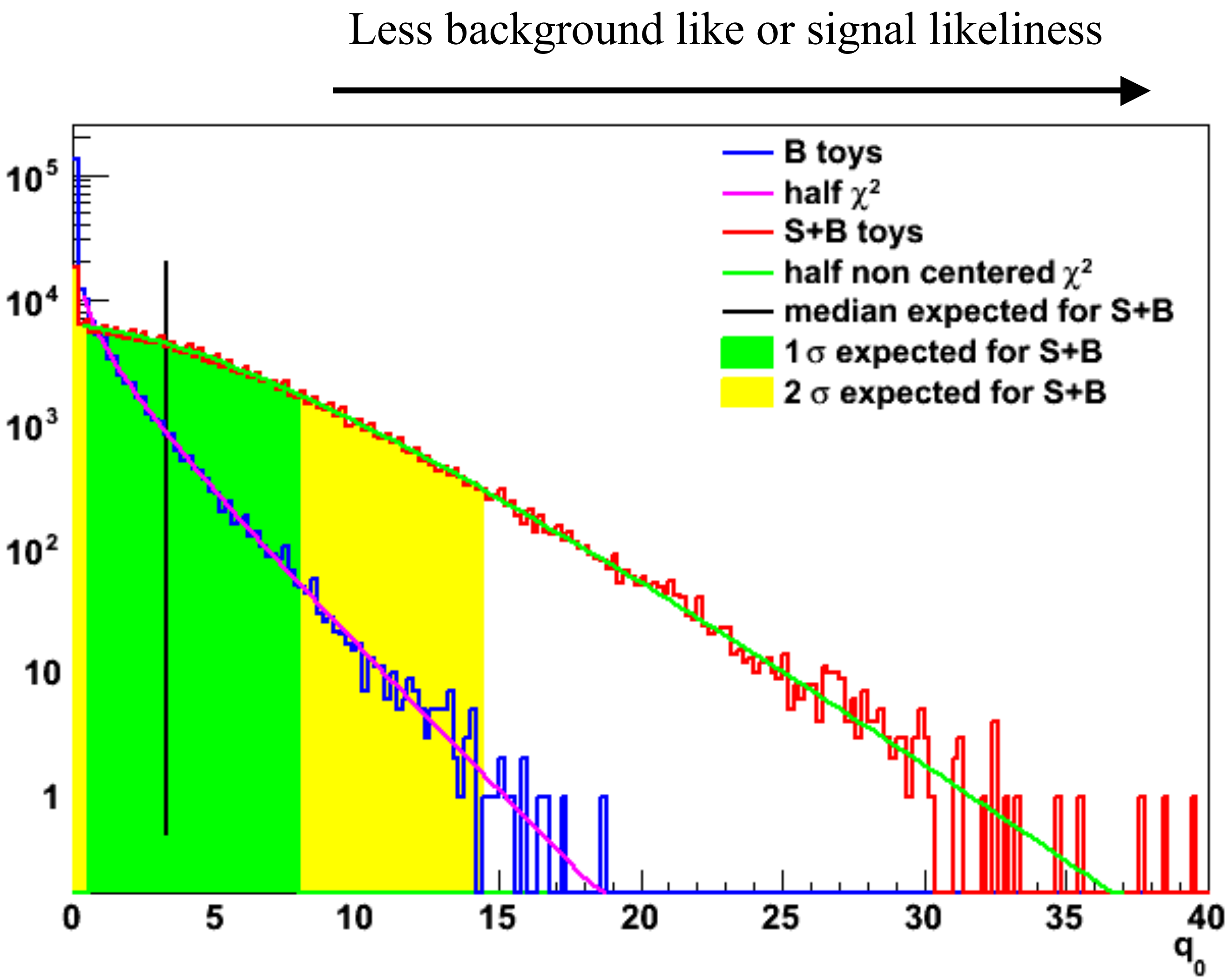
Stats : the famous profile likelihood ratio

$$q_L = -2\ln\frac{\mathcal{L}(\mathbf{p}_A, \hat{\hat{\theta}}_A)}{\mathcal{L}(\hat{\mathbf{p}}, \hat{\theta})}$$

p : vector of poi, e.g. κ_F and κ_V
θ : vector of nuisance parameter (could be m_X)
A : label of an hypothesis, e.g. $\kappa_F = 1 = \kappa_V$
$\boldsymbol{\theta}_A$: nuisance parameters that minimize *L* given A
hat notation : values at the absolute minimum

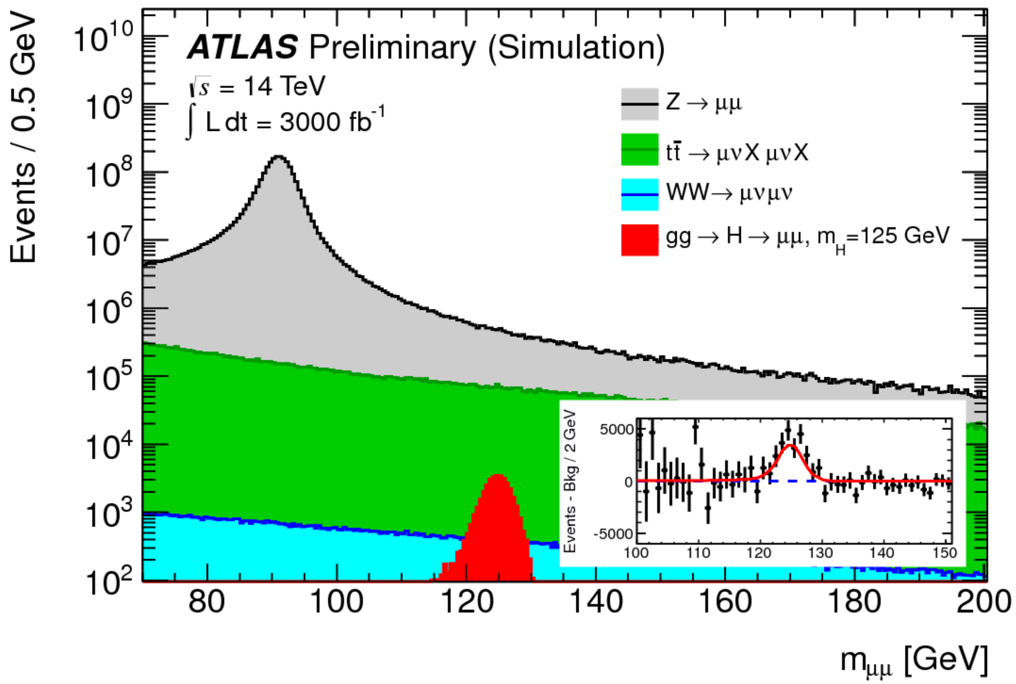
If some limits (often met) q_L is distributed at a χ^2 for dim(***p***) degrees of freedom

Discover : q_0 and p_0



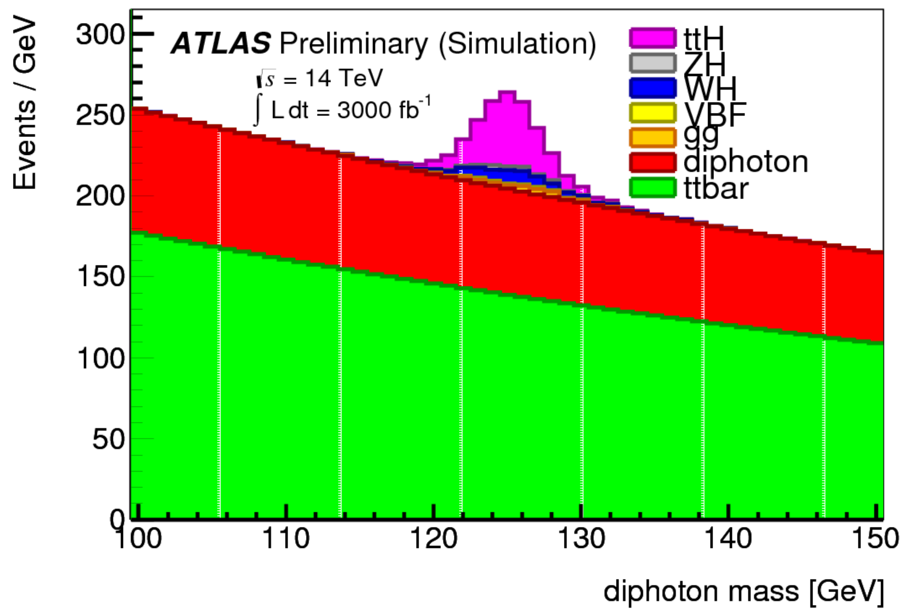
Ultra rare : H → $\mu^+\mu^-$!

Br = 0.02%



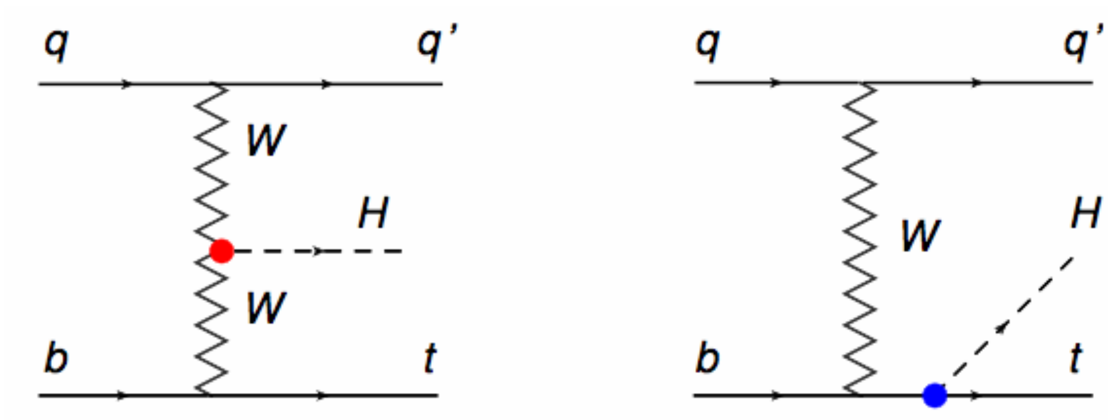
Top Yukawa coupling

ttH, H → γγ



Probing the “sign” of top quark Yukawa coupling with tH production

Thanks to the interference between two processus



No expected visible signal in SM
But already sensitive with 8 TeV data if “wrong” sign