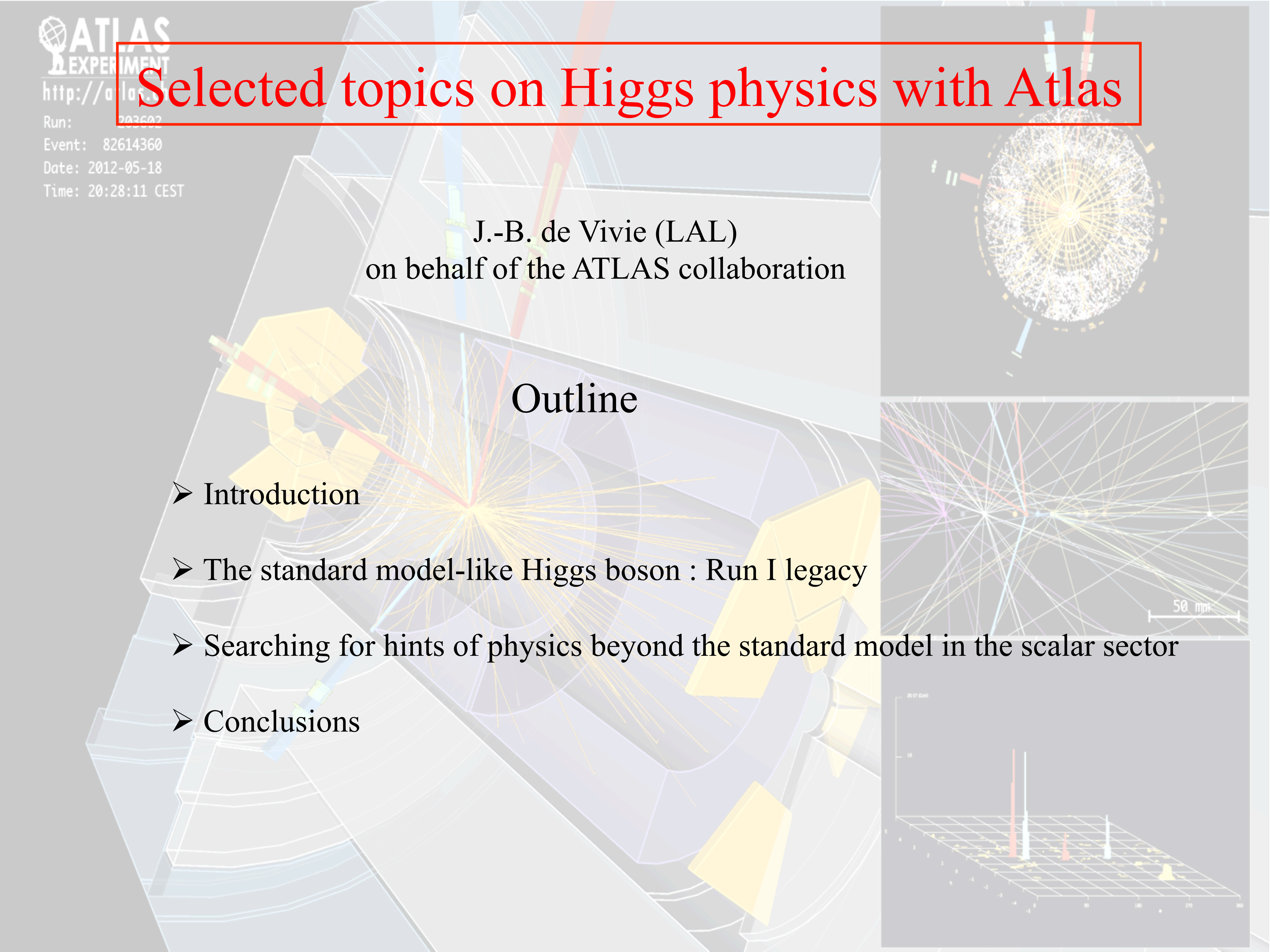


Selected topics on Higgs physics with Atlas

J.-B. de Vivie (LAL)
on behalf of the ATLAS collaboration

Outline

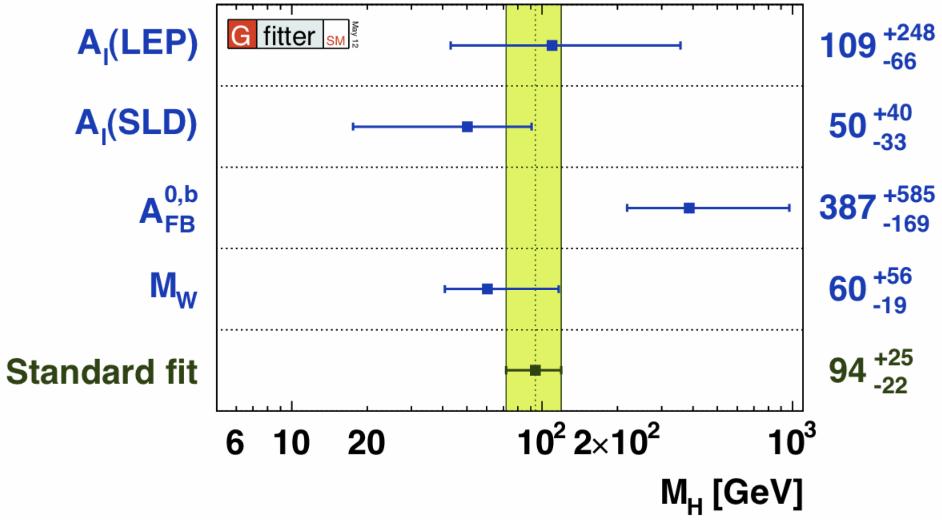
- Introduction
- The standard model-like Higgs boson : Run I legacy
- Searching for hints of physics beyond the standard model in the scalar sector
- Conclusions

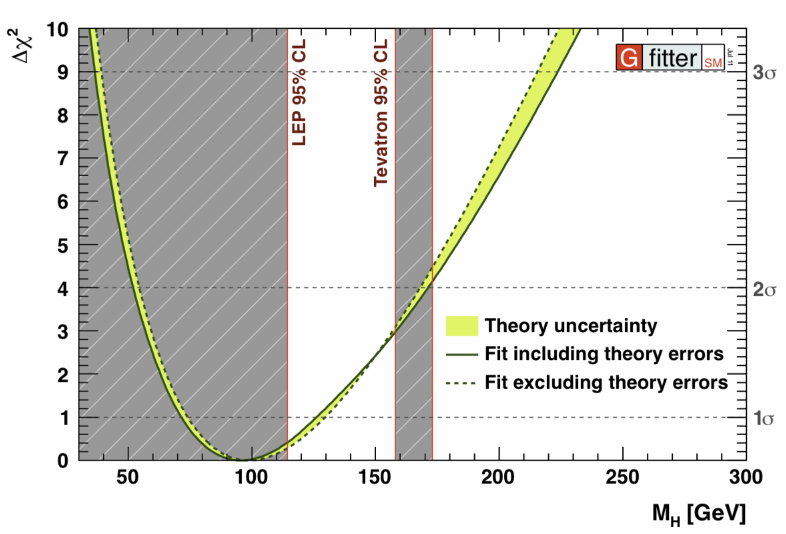
Introduction

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

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 governs
electroweak symmetry breaking

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



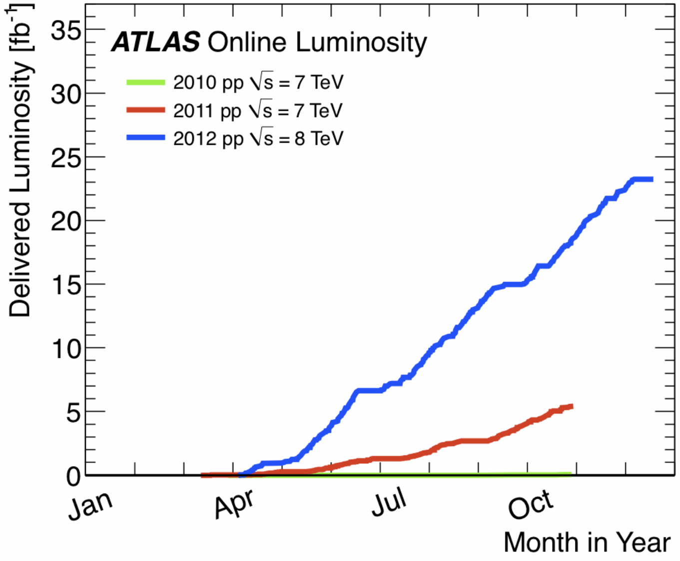


+ theory arguments : pertubative unitarity
triviality

⇒ H_{SM} should be light (but not too light, vacuum stability)

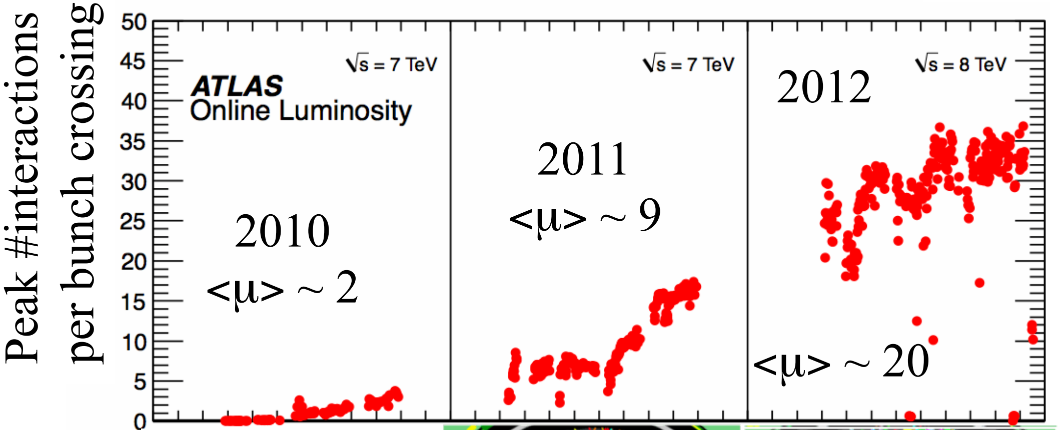
Experimental context

Rare processes ⇒ Need high luminosity :



Peak instantaneous lumi. in 2012 ~ 7. 10^{33} cm^{-2}s^{-1}
(October 2015 : ~ 4. 10^{33} cm^{-2}s^{-1})

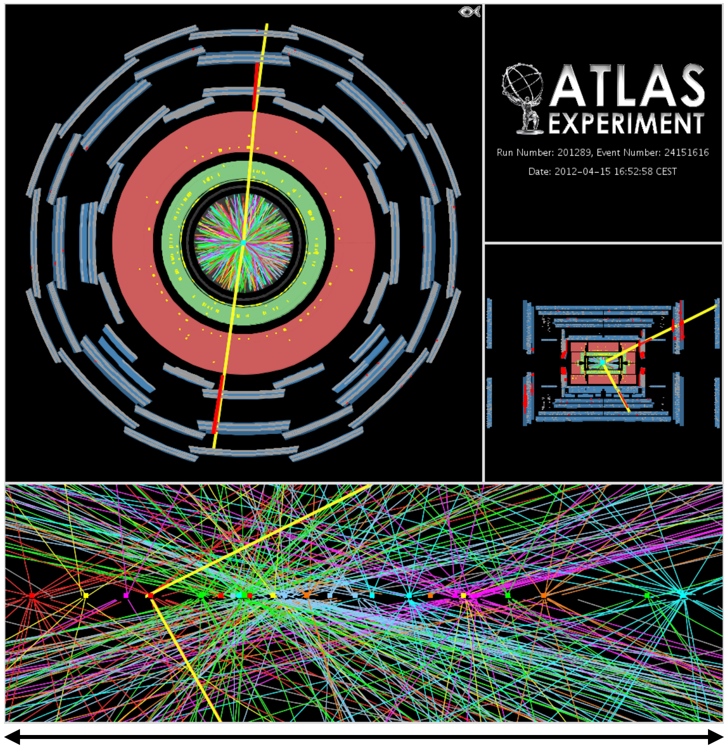
~ 23 fb^{-1} delivered at 8 TeV
⊗ data taking efficiency
⊗ data quality
⇒ 90 % usable for physics [4.5 + 20.3 fb^{-1} at 7 +8 TeV]



2010
<μ> ~ 2

2011
<μ> ~ 9

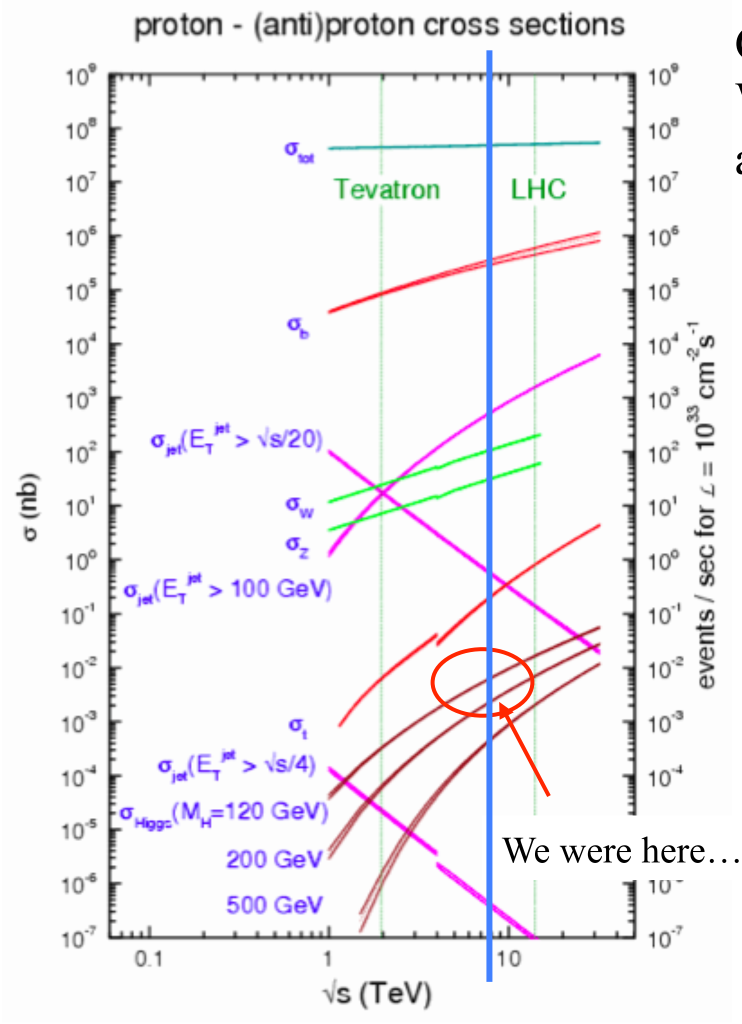
2012
<μ> ~ 20



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

Higgs boson production : 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

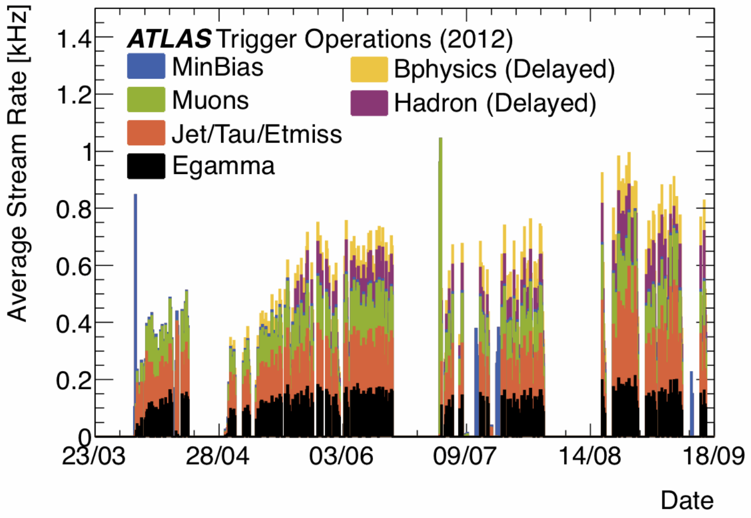


We were here…

Can only record ~ 500 Hz (peak at 0.8-1 kHz)
Wants to keep most of this observable cross-section
and get rid of not interesting events

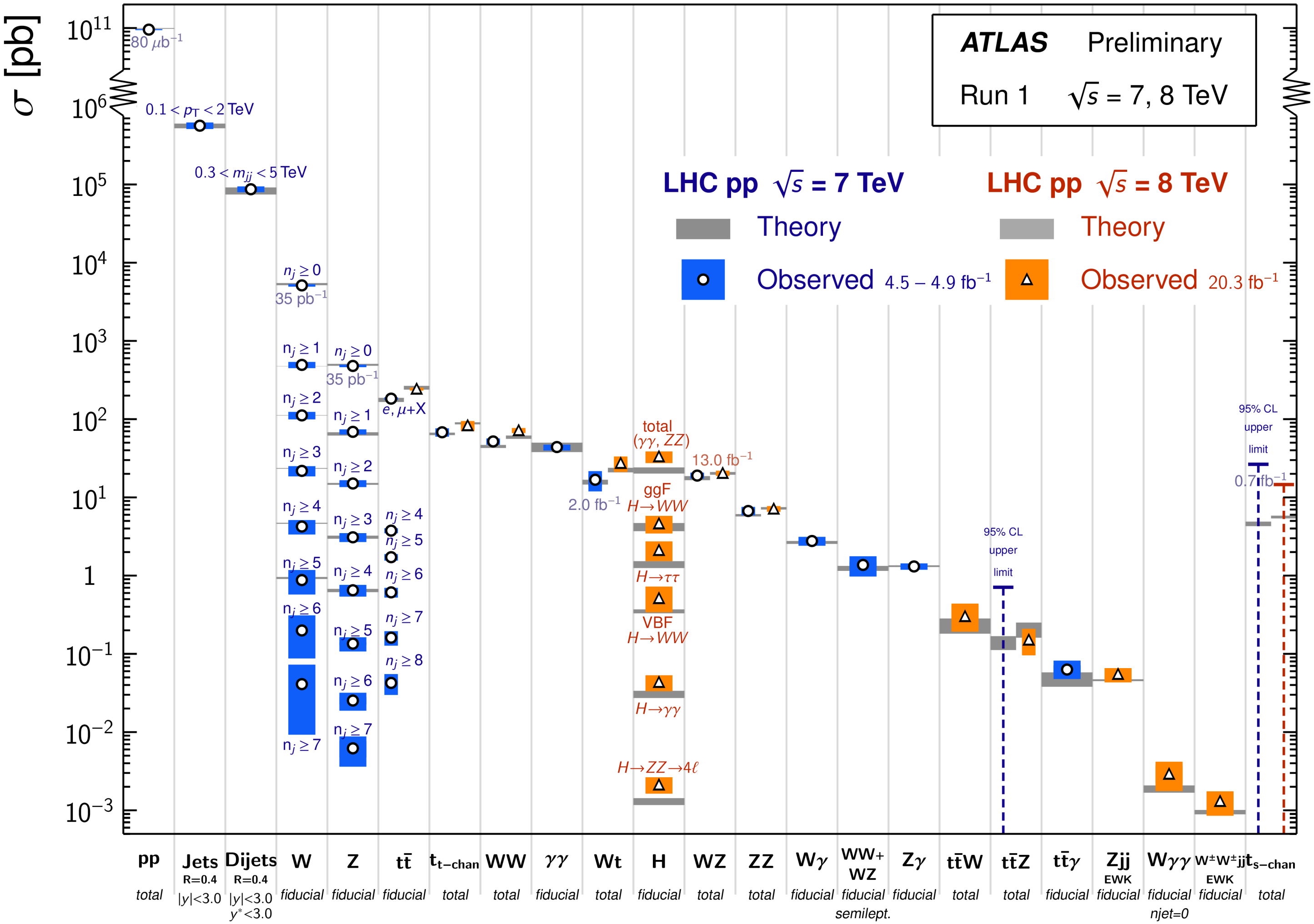
⇒ maintain **good trigger performance**
in a harsh pile-up environment
keeping thresholds as low as possible

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 SM processes have been measured with great precision

→ precision measurements (QCD and EW gauge bosons, top sector, TGC, etc…)



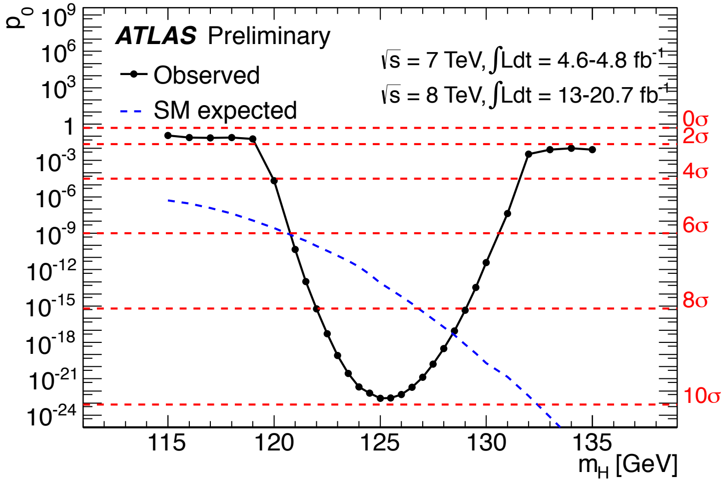
→ standard candles for calibration and alignment (e.g. $Z \rightarrow e^+e^-$, $\mu^+\mu^-$)

→ control backgrounds to searches (and Monte Carlo tunings)

→ validate search techniques

The standard model(-like) Higgs boson : Run I legacy

The *old p_0 era* : March 2013 : a 10 sigmas discovery !



The Higgs boson mass

The last **SM** parameter to be measured : once known, fixes the H_{SM} phenomenology

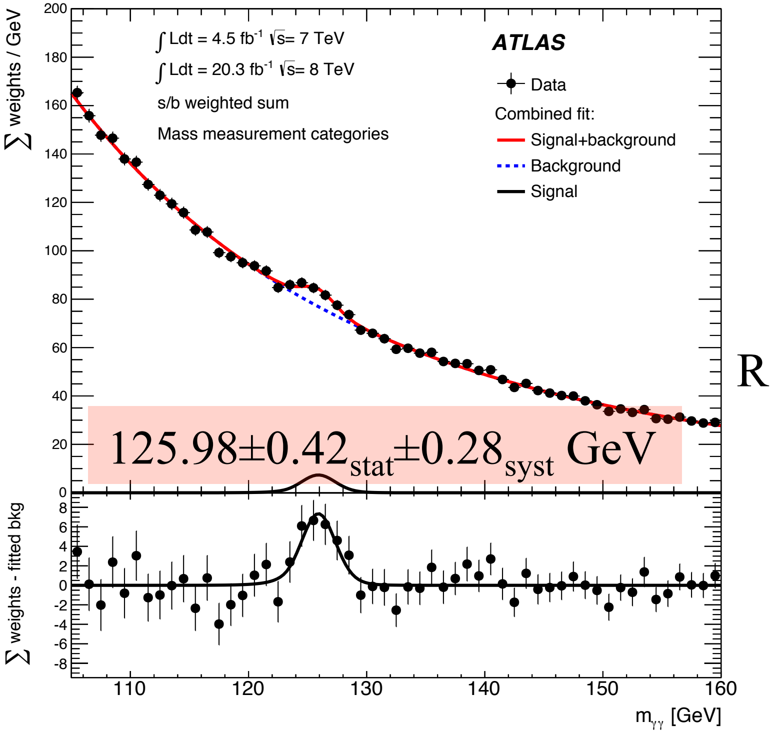
+ important for quantum level tests of SM

+ could allow to constrain many BSM models, e.g. if $m_H > 150$ GeV/c^2, MSSM is killed !

Two channels with excellent mass resolution for an almost model independent measurement :

$H \rightarrow \gamma\gamma$ and $H \rightarrow 4\ell$

benefiting from very precise EM object energy and muon momentum calibration

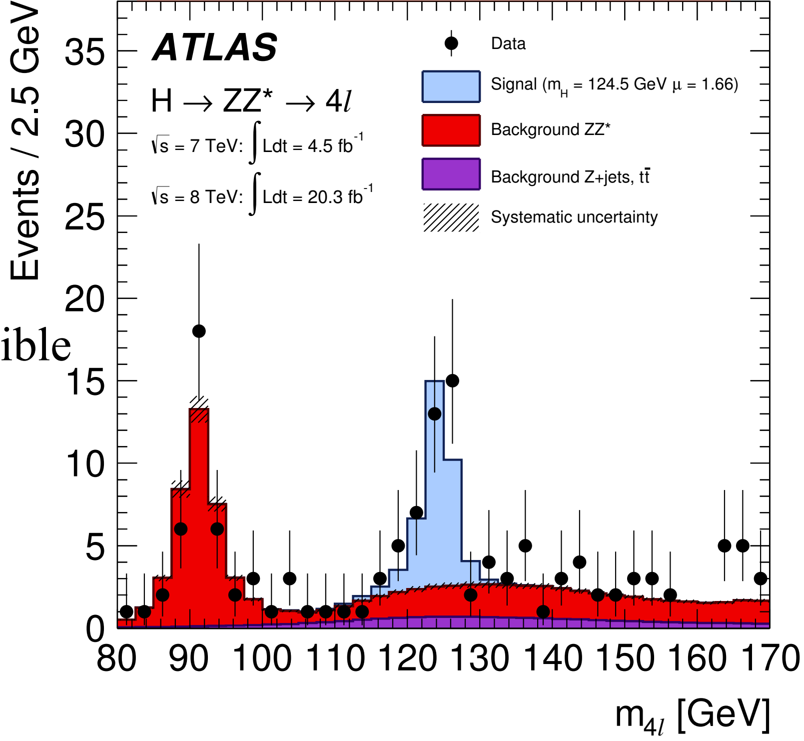


$125.98 \pm 0.42_{stat} \pm 0.28_{syst}$ GeV

Roughly compatible

$\sim 2\sigma$

$124.51 \pm 0.52_{stat} \pm 0.06_{syst}$ GeV

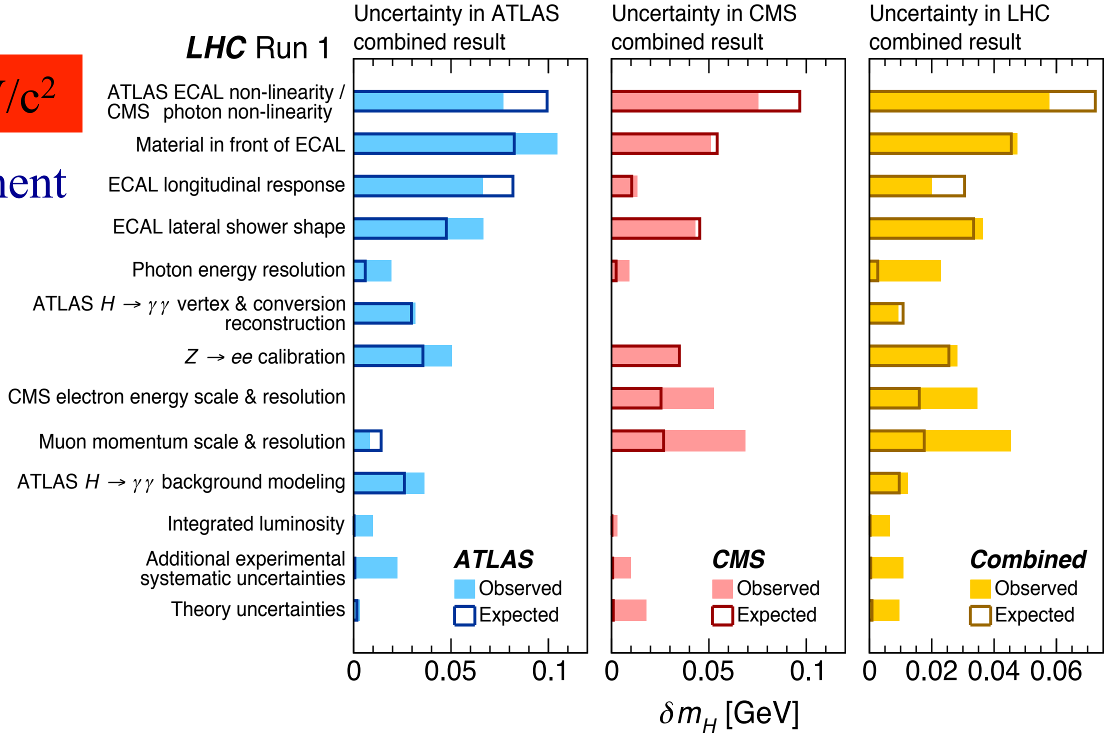


Combined : $125.36 \pm 0.37_{stat} \pm 0.18_{syst}$ GeV

ATLAS-CMS combination :

$m_H^{RunI} = 125.09 \pm 0.21_{stat} \pm 0.11_{syst}$ GeV/c^2

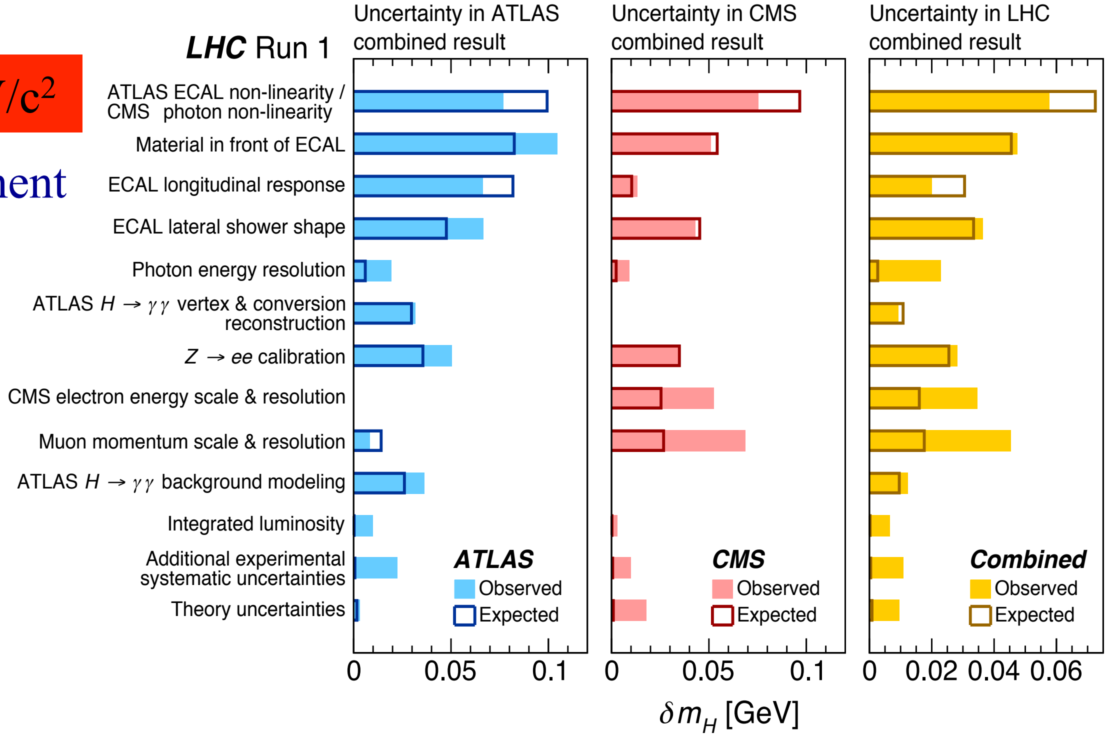
The most precise LHC Run I measurement outside the B-physics sector !



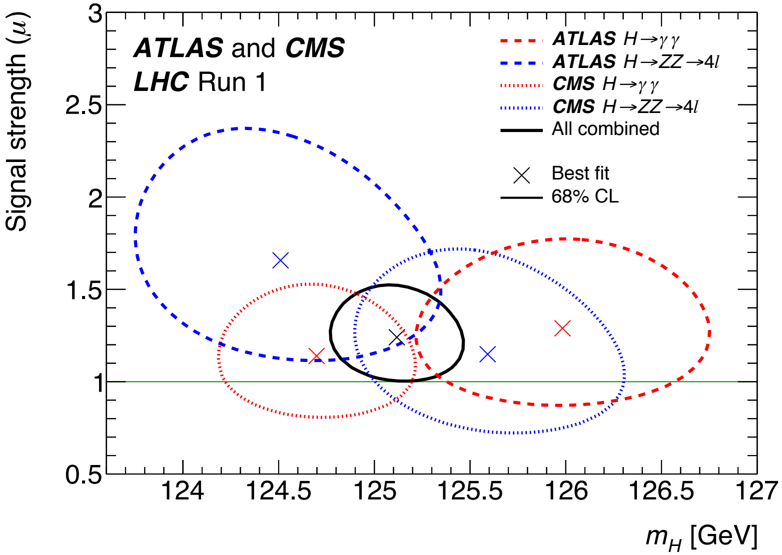
ATLAS-CMS combination :

$$m_H^{\mathrm{RunI}} = 125.09 \pm 0.21_{\mathrm{stat}} \pm 0.11_{\mathrm{syst}}\ \mathrm{GeV}/c^2$$

The most precise LHC Run I measurement outside the B-physics sector !



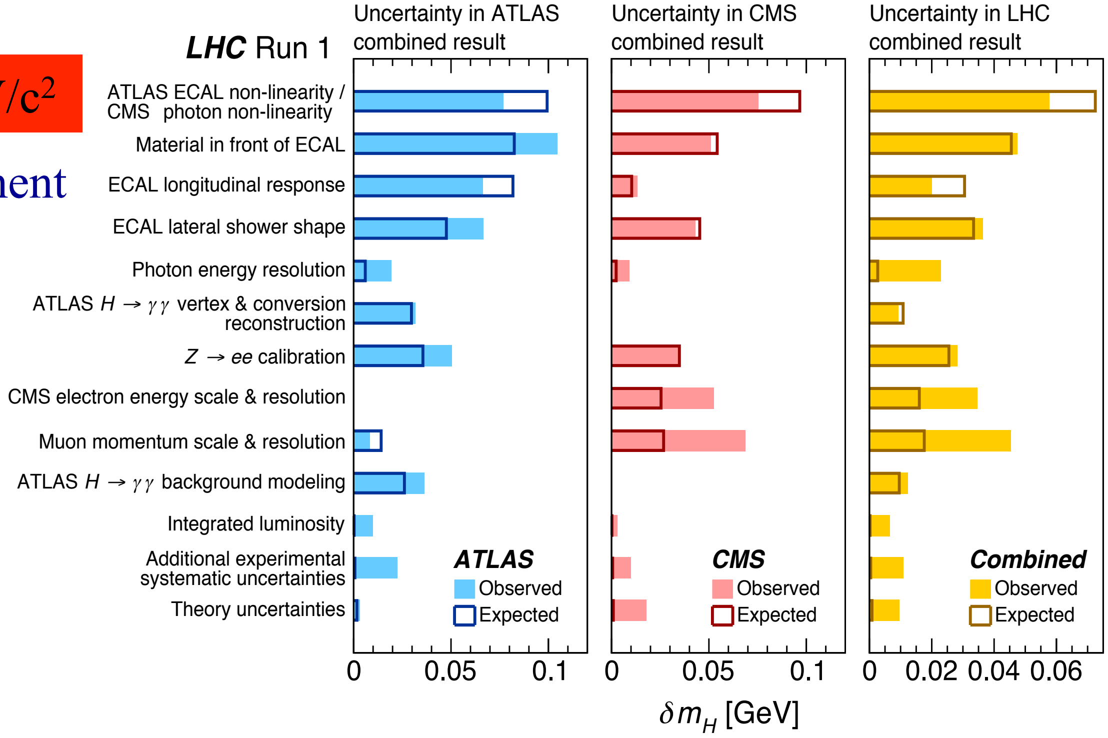
Yet, the 4 masses are slightly scattered :



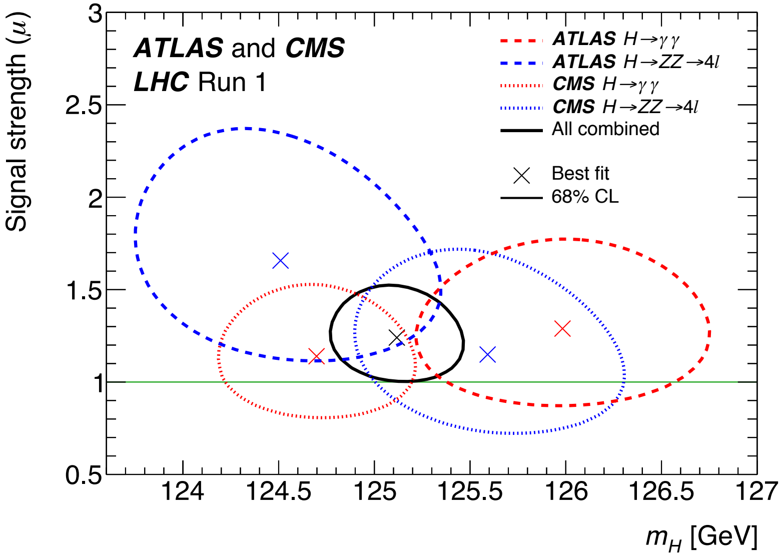
ATLAS-CMS combination :

$$m_H^{RunI} = 125.09 \pm 0.21_{stat} \pm 0.11_{syst}\ \mathrm{GeV}/c^2$$

The most precise LHC Run I measurement outside the B-physics sector !



Yet, the 4 masses are slightly scattered :



Although an improved mass measurement will not result in a physics revolution, it should help to clarify this…

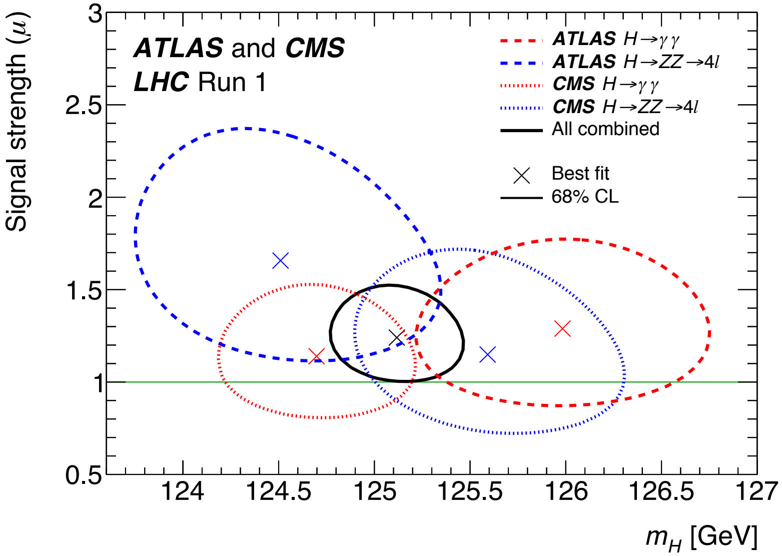
This is not an early measurement though !

ATLAS-CMS combination :

$m_H^{RunI} = 125.09 \pm 0.21_{stat} \pm 0.11_{syst}$ GeV/c^2

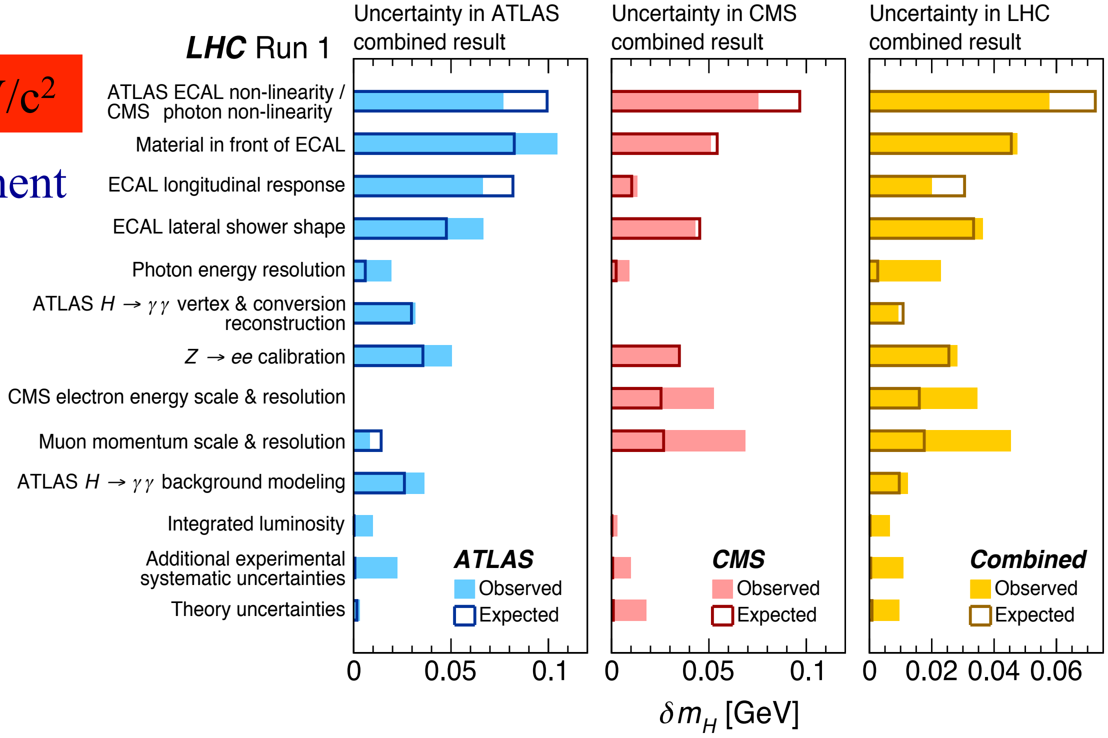
The most precise LHC Run I measurement outside the B-physics sector !

Yet, the 4 masses are slightly scattered :



Although an improved mass measurement will not result in a physics revolution, it should help to clarify this…

This is not an early measurement though !



The ATLAS-CMS combination work allowed to think about new ideas for Run II (100 fb^{-1}) :

e.g. in the ATLAS H → γγ side,
- mitigate impact of background modelling
- improve categorization (VBF, better use of per event resolution, …)

stat. uncertainty expected to be divided by ~ 3

⇒ smaller than Run I syst.

Systematics become limiting factor in H → γγ

H → 4ℓ still statistics limited

The Higgs boson width

Low mass, expect tiny width : very difficult to determine at LHC since on-peak measure σ × Br

⇒ From γγ and 4ℓ line shapes (Breit-Wigner ⊗ resolution) : $\Gamma_H < 5_{\gamma\gamma}$ / $2.6_{4\ell}$ (6.2) GeV (exp.)
~ 3 orders of magnitude above SM width

⇒ From off shell, from H → 4ℓ (ZZ), ℓℓνν (ZZ+WW), using

$m_{4\ell}$ / m_T ($\ell^+\ell^- E_T^{miss}$) >> $2m_Z$, signal xs ~ independent on Γ_H :

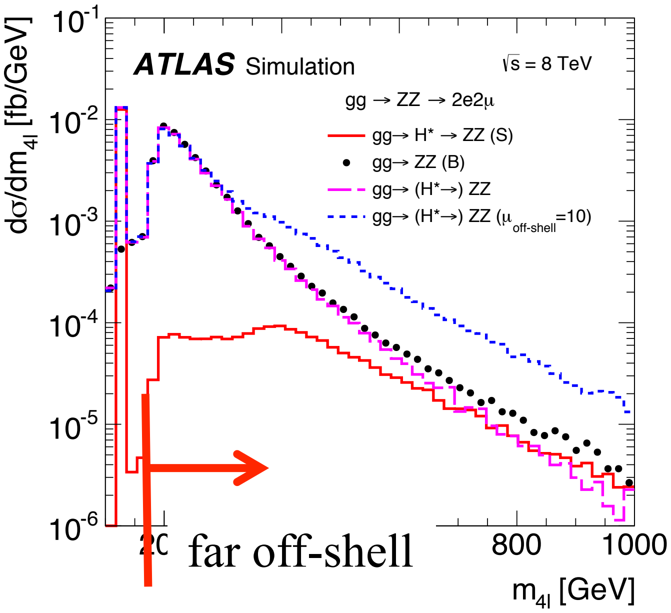
The Higgs boson width

Low mass, expect tiny width : very difficult to determine at LHC since on-peak measure $\sigma \times Br$

⇒ From $\gamma\gamma$ and 4ℓ line shapes (Breit-Wigner $\otimes$ resolution) : $\Gamma_H < 5_{\gamma\gamma}$ / $2.6_{4\ell}$ (6.2) GeV (exp.)
~ 3 orders of magnitude above SM width

⇒ From off shell, from $H \rightarrow 4\ell$ (ZZ), $\ell\ell\nu\nu$ (ZZ+WW), using

$m_{4\ell}$ / m_T ($\ell^+\ell^- E_T^{miss}$) >> $2m_Z$, signal xs ~ independent on Γ_H :



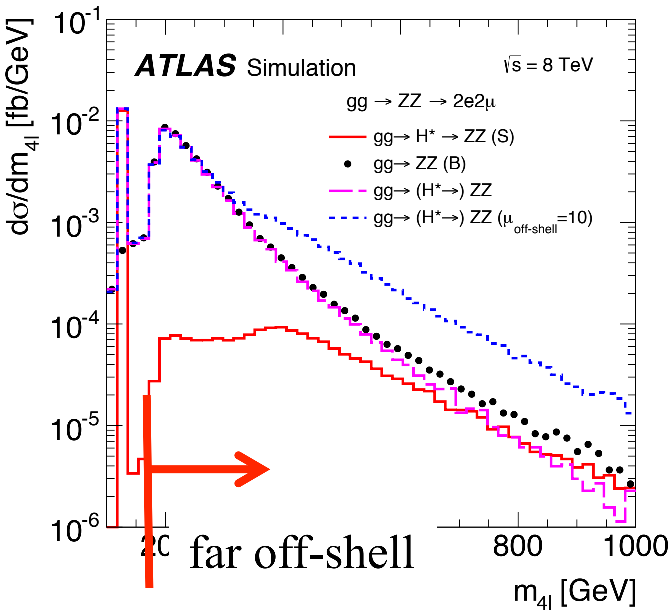
far off-shell

The Higgs boson width

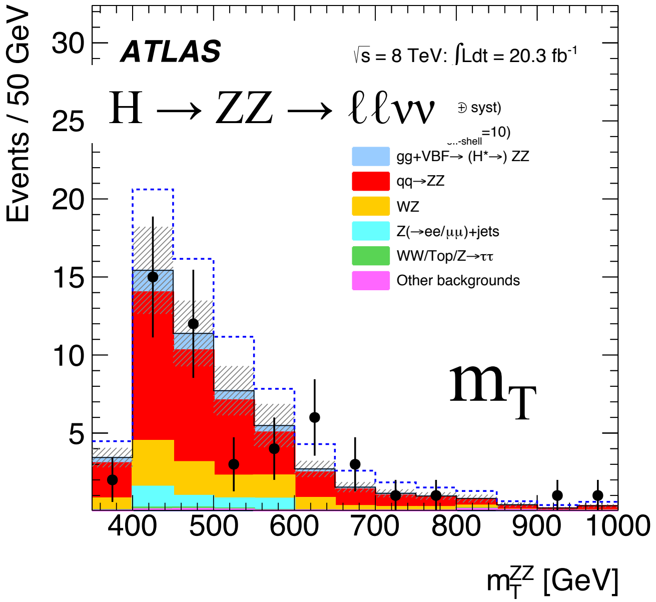
Low mass, expect tiny width : very difficult to determine at LHC since on-peak measure $\sigma \times \mathrm{Br}$

⇒ From $\gamma\gamma$ and 4ℓ line shapes (Breit-Wigner $\otimes$ resolution) : $\Gamma_H < 5_{\gamma\gamma}$ / $2.6_{4\ell}$ (6.2) GeV (exp.)
$\sim$ 3 orders of magnitude above SM width

⇒ From off shell, from $H \to 4\ell$ (ZZ), $\ell\ell\nu\nu$ (ZZ+WW), using



$m_{4\ell}$ / m_T ($\ell^+\ell^- E_T^{miss}$) >> $2m_Z$, signal xs ~ independent on Γ_H :

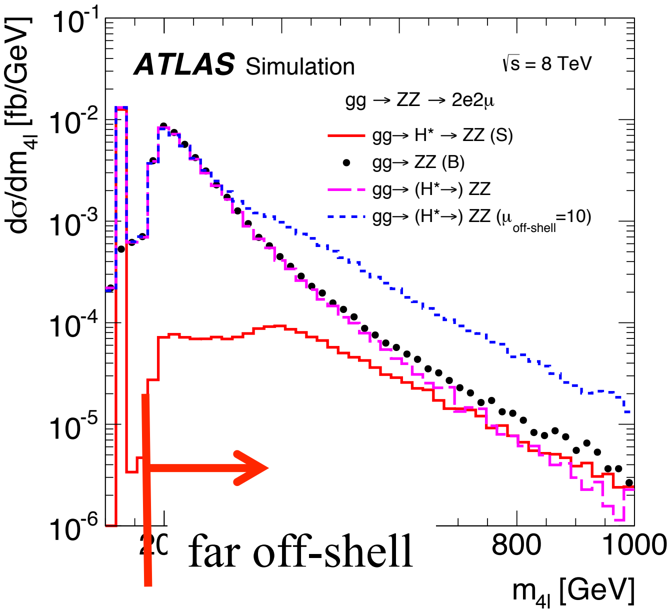


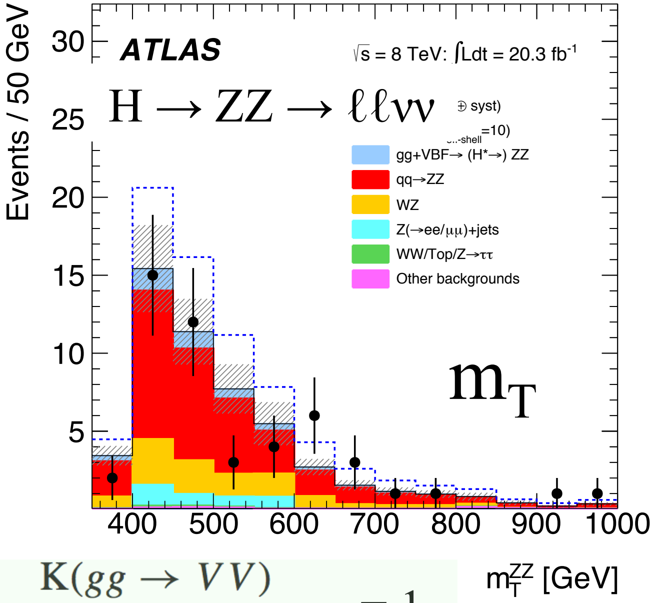
The Higgs boson width

Low mass, expect tiny width : very difficult to determine at LHC since on-peak measure σ × Br

- ⇒ From γγ and 4ℓ line shapes (Breit-Wigner ⊗ resolution) : $\Gamma_H < 5_{\gamma\gamma}$ / $2.6_{4\ell}$ (6.2) GeV (exp.)
  ~ 3 orders of magnitude above SM width
- ⇒ From off shell, from H → 4ℓ (ZZ), ℓℓνν (ZZ+WW), using

$m_{4\ell}$ / m_T ($\ell^+\ell^- E_T^{miss}$) >> $2m_Z$, signal xs ~ independent on Γ_H :





$$\mu_{\text{off}} = \kappa^2_{g,\text{off-shell}}(\hat{s}) \cdot \kappa^2_{V,\text{off-shell}}(\hat{s}) < 6.2 \text{ for } R^B_{H^*} = \frac{K(gg \to VV)}{K(gg \to H^* \to VV)} = 1$$

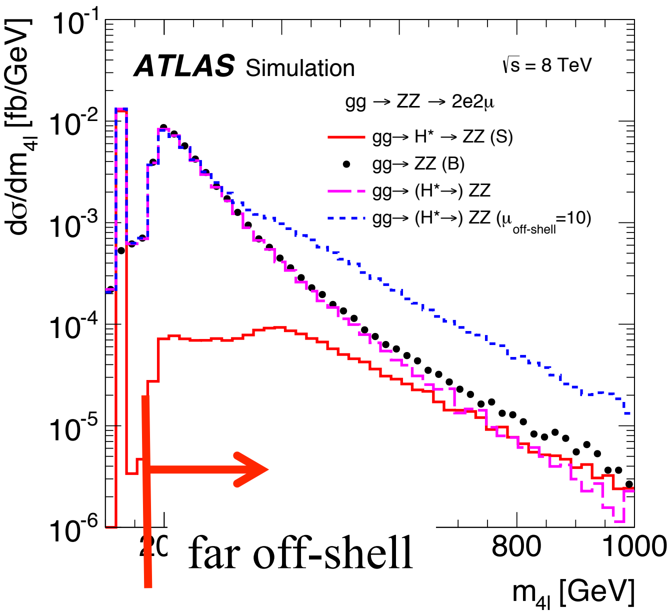
(5.1 / 8.6 for $R_{H^*}{}^B = 0.5 / 2$)

The Higgs boson width

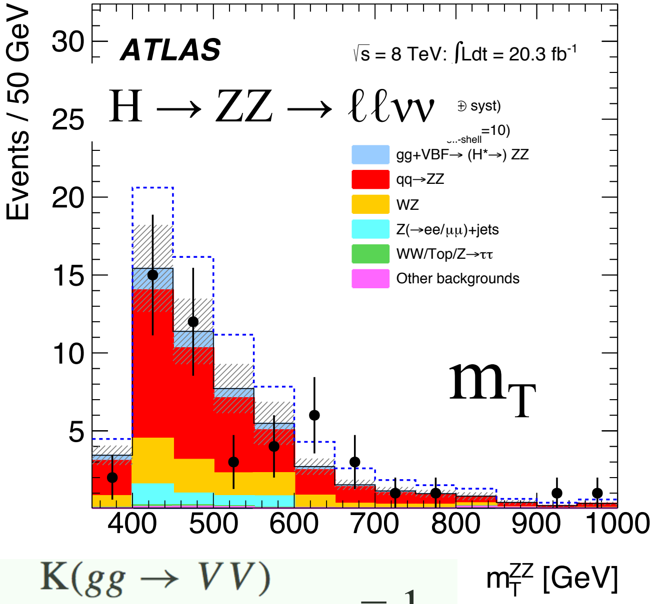
Low mass, expect tiny width : very difficult to determine at LHC since on-peak measure σ × Br

- ⇒ From γγ and 4ℓ line shapes (Breit-Wigner ⊗ resolution) : $\Gamma_H < 5_{\gamma\gamma} \,/\, 2.6_{4\ell}$ (6.2) GeV (exp.)
  ~ 3 orders of magnitude above SM width
- ⇒ From off shell, from H → 4ℓ (ZZ), ℓℓνν (ZZ+WW), using

$m_{4\ell}$ / m_T ($\ell^+\ell^- E_T^{miss}$) >> $2m_Z$, signal xs ~ independent on Γ_H :



far off-shell



H → ZZ → ℓℓνν

m_T

$$\mu_{\text{off}} = \kappa^2_{g,\text{off-shell}}(\hat{s}) \cdot \kappa^2_{V,\text{off-shell}}(\hat{s}) < 6.2 \text{ for } R^B_{H^*} = \frac{K(gg \to VV)}{K(gg \to H^* \to VV)} = 1$$

(5.1 / 8.6 for $R_{H^*}^B$ = 0.5 / 2)

Assuming negligible (SM) running*, and combining with

$$\mu_{\text{on}} = \frac{\kappa^2_{g,\text{on-shell}} \cdot \kappa^2_{V,\text{on-shell}}}{\Gamma_H / \Gamma_H^{SM}}$$

$\Gamma_H/\Gamma_H^{SM} <$ 5.5 ($R_{H^*}^B = 1$)

* Among other strong assumptions.
Nonetheless still a very good consistency test !

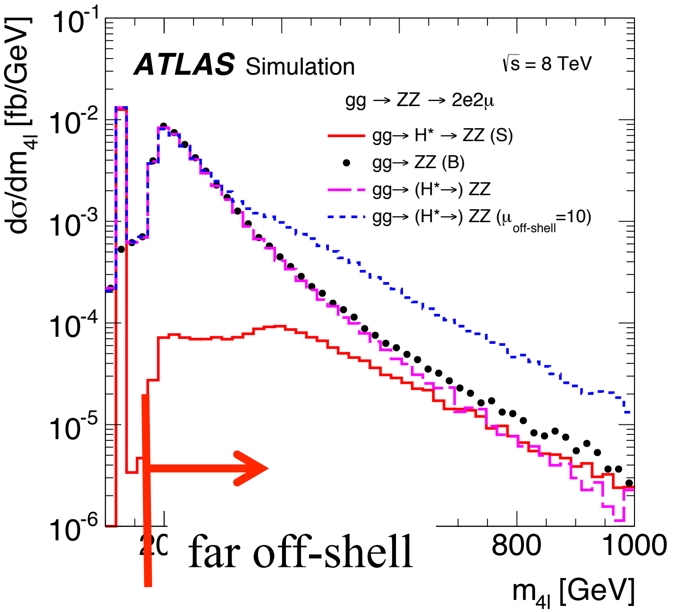
The Higgs boson width

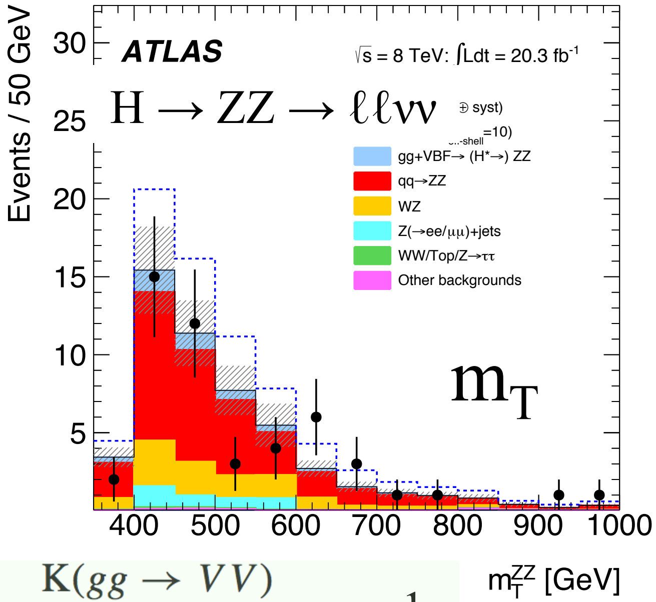
Low mass, expect tiny width : very difficult to determine at LHC since on-peak measure σ × Br

⇒ From γγ and 4ℓ line shapes (Breit-Wigner ⊗ resolution) : $\Gamma_H < 5_{\gamma\gamma} \,/\, 2.6_{4\ell}$ (6.2) GeV (exp.)
~ 3 orders of magnitude above SM width

⇒ From off shell, from H → 4ℓ (ZZ), ℓℓνν (ZZ+WW), using

$m_{4\ell} / m_T (\ell^+\ell^- E_T^{miss}) >> 2m_Z$, signal xs ~ independent on Γ_H :





$$\mu_{\text{off}} = \kappa^2_{g,\text{off-shell}}(\hat{s}) \cdot \kappa^2_{V,\text{off-shell}}(\hat{s}) < 6.2 \text{ for } R^B_{H^*} = \frac{K(gg \to VV)}{K(gg \to H^* \to VV)} = 1$$

(5.1 / 8.6 for $R_{H^*}^B$ = 0.5 / 2)

Assuming negligible (SM) running*, and combining with

$$\mu_{\text{on}} = \frac{\kappa^2_{g,\text{on-shell}} \cdot \kappa^2_{V,\text{on-shell}}}{\Gamma_H / \Gamma_H^{SM}}$$

$\Gamma_H/\Gamma_H^{SM} < 5.5 \ (R_{H^*}^B = 1)$

A **measurement** might be feasible at HL-LHC
$\Gamma_H = 4.2^{+1.5}_{-2.1}$ MeV using same technique !

* Among other strong assumptions.
Nonetheless still a very good consistency test !

Differential cross-sections and quantum numbers

The already large Run I data sample allows us to measure differential cross-sections

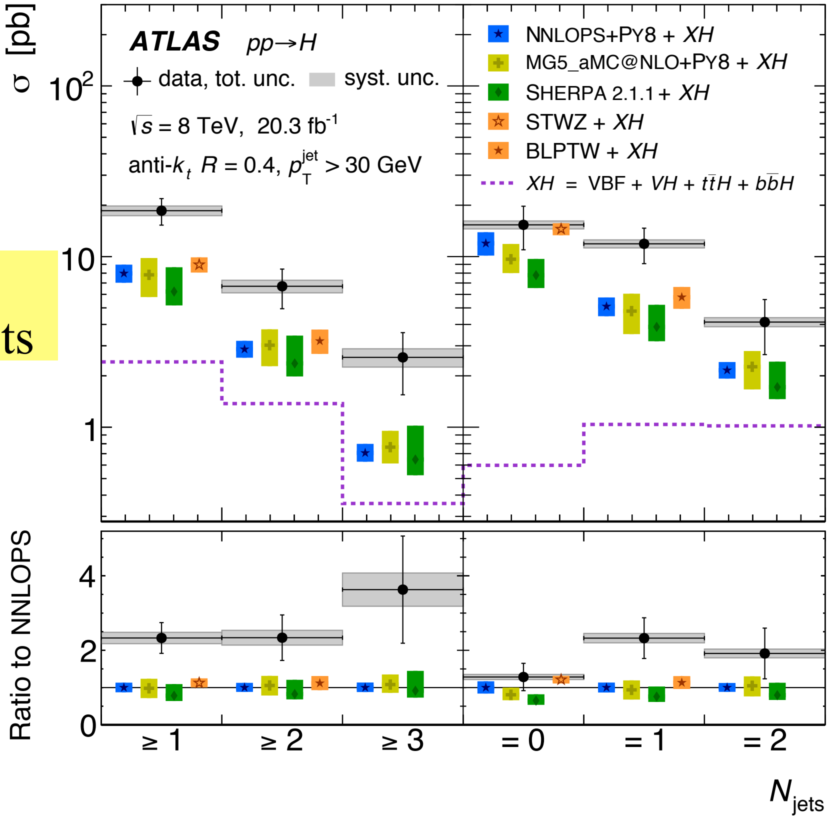
→ study different production mechanisms (e.g. p_T^H, N_{jet}) and sensitivity to loop content

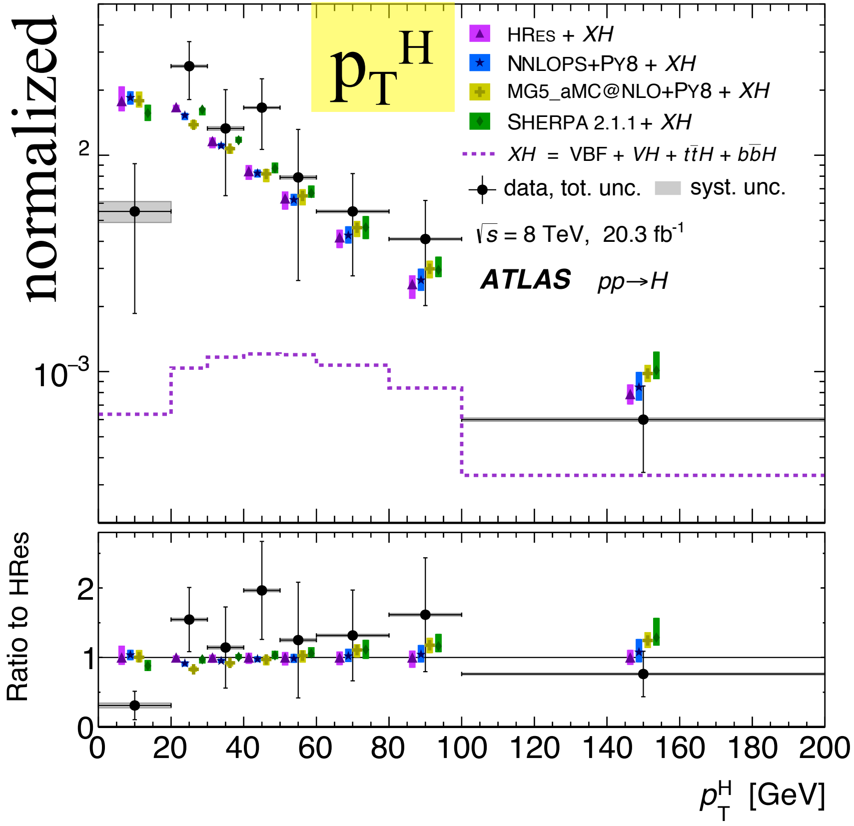
→ sensitivities to quantum J^{CP} numbers (e.g. cosθ* in H → γγ for J, $\Delta\varphi_{jj}$ for CP)

Combine fully reconstructed final states (γγ, 4ℓ)

(partially reconstructed WW* in progress…)

N_{jets}





p_T^H

Large overall yield (remember signal strength…) and slightly higher jets multiplicity but still statistically limited…

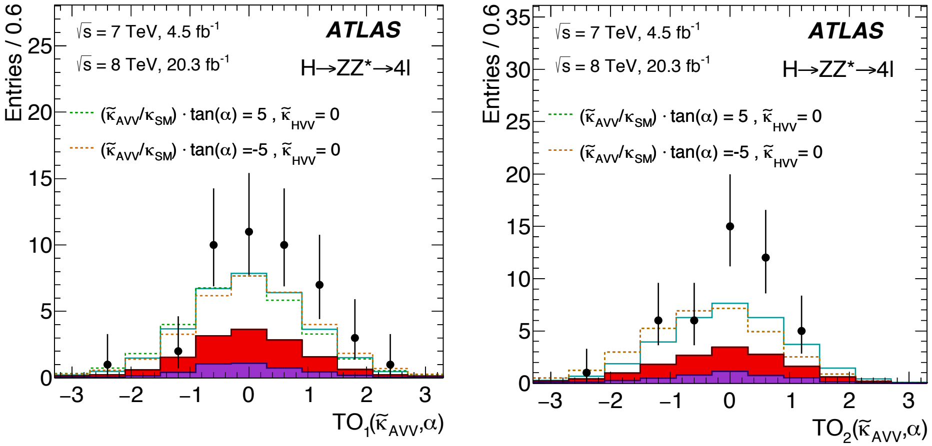
Quantum numbers :

- ➢ Landau-Yang + observation of H → γγ : J = 0 or ≥ 2.
  Data excludes "almost reasonable" J = 2 models in favour of 0 at very high confidence level
  (from couplings but also using only kinematic properties)
- ➢ CP-admixture much more interesting but tougher and suffering from low statistics
  ⇒ pave the way to Run II studies

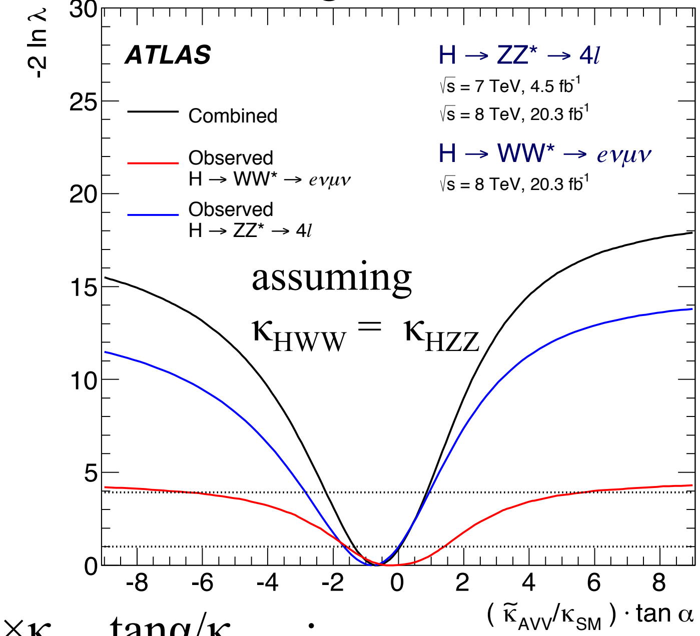
$$\mathcal{L} = \cos\alpha\,\kappa_{SM}\left[g_{HVV}\underbrace{V_\mu V^\mu}_{\text{SM (CP-even)}} - \frac{1}{4\Lambda\kappa_{SM}}\left(\kappa_{HVV}\underbrace{V^{\mu\nu}V_{\mu\nu}}_{\text{CP-even, H.O.}} + \kappa_{AVV}\tan\alpha\,\underbrace{V^{\mu\nu}\tilde{V}_{\mu\nu}}_{\text{CP-odd}}\right)\right]H$$

Compare SM to mixture of SM+BSM operators

e.g. in the 4l final state, SM vs SM+CP-odd
using optimal observables (ratios of ME w/wo BSM)



Combining with H → WW*



assuming $\kappa_{HWW} = \kappa_{HZZ}$

Allowed range @ 95% CL for $\kappa_{AVV} \equiv v/4\Lambda \times \kappa_{AVV}\tan\alpha/\kappa_{HSM}$:

[-2.18,0.83] ([-2.33,2.3] expected)

⇒ no sign of a CP-odd component

⇒ We have a light CP-even scalar with a narrow width

Basic assumption for coupling measurements

Reconstruct effective Lagrangian :

$$\mathcal{L} = \kappa_{\mathrm{W}} \frac{2m_{\mathrm{W}}^2}{v} \mathrm{W}^{+,\mu}\mathrm{W}_{\mu}^{-}\mathrm{H} + \kappa_{\mathrm{Z}} \frac{m_{\mathrm{Z}}^2}{v} \mathrm{Z}^{\mu}\mathrm{Z}_{\mu}\mathrm{H} - \sum_{\mathrm{f}} \kappa_{\mathrm{f}} \frac{m_{\mathrm{f}}}{v} \mathrm{f}\bar{\mathrm{f}}\mathrm{H}$$

SM, tree level

$$+ c_{\mathrm{g}} \frac{\alpha_s}{12\pi v} \mathrm{G}^{\mu\nu,a}\mathrm{G}_{\mu\nu}^{a}\mathrm{H} + c_{\gamma} \frac{\alpha}{\pi v} \mathrm{A}^{\mu\nu}\mathrm{A}_{\mu\nu}\mathrm{H} + c_{\mathrm{Z}\gamma} \frac{\alpha}{\pi v} \mathrm{A}^{\mu\nu}\mathrm{Z}_{\mu\nu}\mathrm{H}$$

SM, loop level

$$+\mathcal{O}_{\mathrm{inv}}\mathrm{H}$$

BSM

$\kappa_{g/\gamma/Z\gamma}$ equivalent to $c_{g/\gamma/Z\gamma}$ but defined by $\kappa_{ij}^2 = \Gamma_{ij} / \Gamma_{SM}$

from measured signal yields :

$$n_s^c = \sum_i \sum_f \mu_i(\sigma_i)_{SM} \times \mu_f(BR_f)_{SM} \times \underbrace{A_{if}^c \times \varepsilon_{if}^c}_{\text{Efficiency (MC)}} \times \mathcal{L}^c$$

Event category

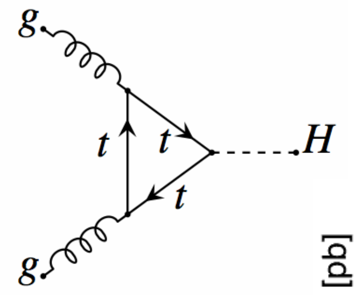
Production mode

decay mode

Luminosity

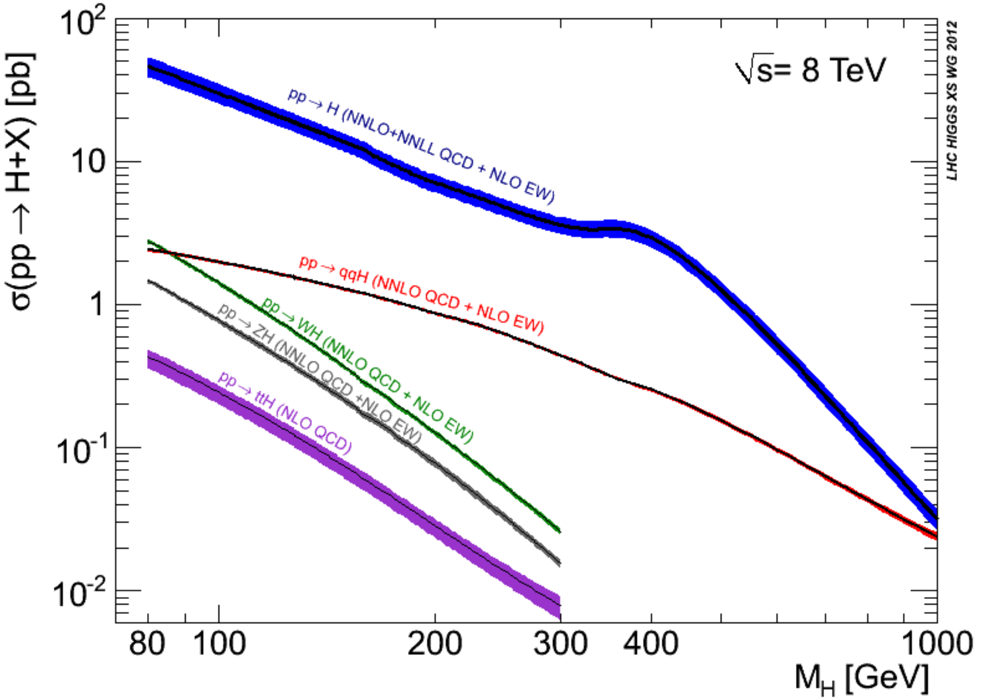
Higgs boson production

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



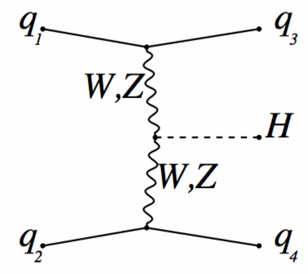
gluon fusion ggF : ~ 0.5 M events, δσ/σ (th.) ~ 11%

$$\kappa_g^2 \sim \quad 1.06 \cdot \kappa_t^2 + 0.01 \cdot \kappa_b^2 - 0.07 \cdot \kappa_t \kappa_b$$



Weak boson fusion VBF :

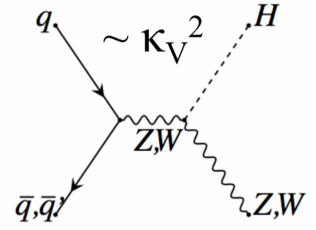
~ 40 K events, δσ/σ (th.) ~ 5%



~ κ_V^2

Distinctive event topology :
forward medium p_T jets + rapidity gap

Associated production with a W/Z (V)



~ κ_V^2

~ 25 K events, δσ/σ (th.) ~ 5%

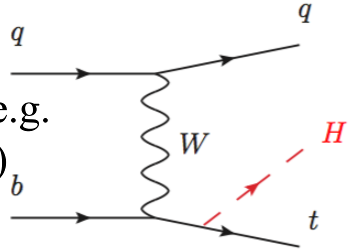
gg → HZ (box + triangle) included
~ 8% of pp → HZ, sensitivity to κ_Z and κ_t

+ other rare production modes

$$\text{tqH} \sim \quad 3.4 \cdot \kappa_t^2 + 3.56 \cdot \kappa_W^2 - 5.96 \cdot \kappa_t \kappa_W$$

(also gb →WtH)

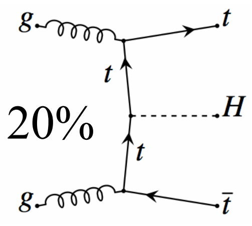
Sensitivity to sign(κ_t,κ_W) : e.g.
σ(κ_t = -1,κ_W =1) ~ 2 σ(ttH)



Associated production with a top/bottom pair

~ 3.3 K / 5 K, δσ/σ (ttH, th.) ~ 20%

~ κ_t^2, κ_b^2



Higgs boson decay

In %, expected for SM $m_H = 125.4$ GeV/c^2

To fermion pairs :

bb	ττ	μμ	cc
57.1	6.3	0.022	2.9
κ_b^2	κ_τ^2	κ_μ^2	κ_c^2

Ultra hard :
need to be very smart
(H → J/ψγ, etc…)

For beyond Run II if SM

To boson pairs :

WW*	22.0	κ_W^2
gg	8.6	Resolved : $\kappa_g^2 = 1.06\kappa_t^2 - 0.07\kappa_b\kappa_t + 0.01\kappa_b^2$
ZZ*	2.7	κ_Z^2
γγ	0.23	Resolved : $\kappa_\gamma^2 = 1.59\kappa_W^2 - 0.66\kappa_W\kappa_t + 0.07\kappa_t^2$
Zγ	0.16	Resolved : $\kappa_\gamma^2 = 1.12\kappa_W^2 - 0.12\kappa_W\kappa_t + 0.0004\kappa_t^2$

(Not doable)

For beyond Run II if SM

Plus scaling factor for SM part of width :

$$\kappa_H^2 \sim \begin{array}{l} 0.57 \cdot \kappa_b^2 + 0.22 \cdot \kappa_W^2 + 0.09 \cdot \kappa_g^2 + \\ 0.06 \cdot \kappa_\tau^2 + 0.03 \cdot \kappa_Z^2 + 0.03 \cdot \kappa_c^2 + \\ 0.0023 \cdot \kappa_\gamma^2 + 0.0016 \cdot \kappa_{Z\gamma}^2 + 0.00022 \cdot \kappa_\mu^2 \end{array}$$

Including undetected/invisible decay :

$$\Gamma_H(\kappa_j, \mathrm{BR}_{\mathrm{i.,u.}}) = \frac{\kappa_H^2(\kappa_j)}{(1 - \mathrm{BR}_{\mathrm{i.,u.}})} \Gamma_H^{\mathrm{SM}}$$

Summary of the considered channels

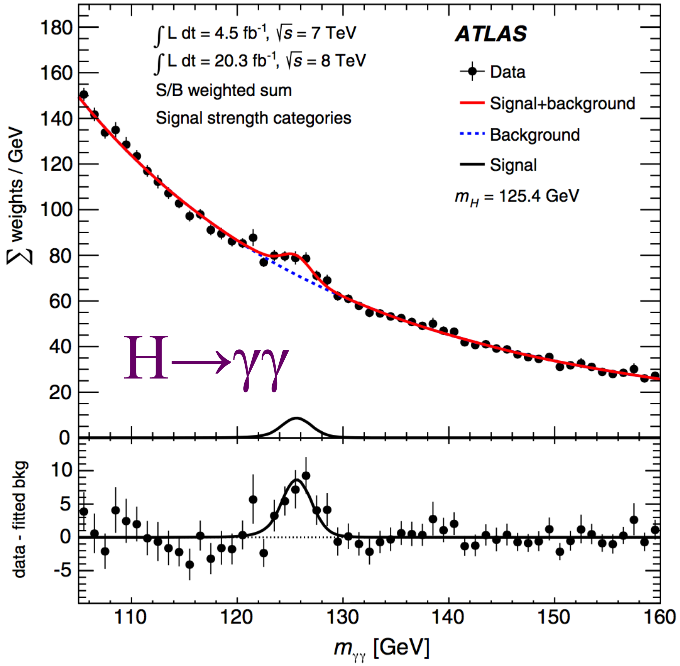
(dedicated to the SM)

At 125 GeV/c^2, for ~ 4.5 + 20.3 fb^{-1} at $\sqrt{s}$ = 7 + 8 TeV

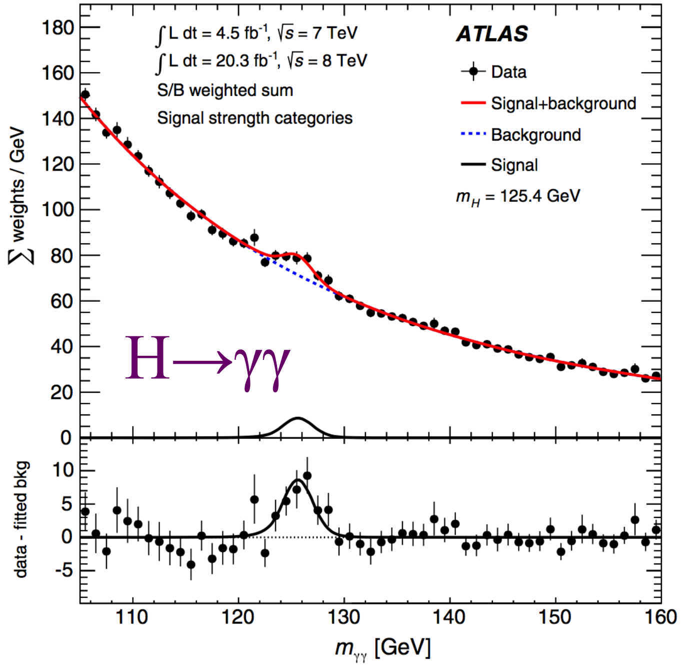
channel	ggF	VBF	VH	ttH	Signal yield	S/B	Mass resolution (GeV/c^2)
$\gamma\gamma$	✓	✓	✓	✓	~ 470	1 → 20%	1.6
$\tau\tau$	✓	✓	✓	✓	~ 180 (ggF + VBF)	0.5 → 80%	~ 20
bb		(CMS)	✓	✓	~ 390 (in VH)	0.3 → 70%	~ 15
ZZ → 4l	✓	✓	✓	✓	~ 18	~ 1.5	2.2
WW → $l\nu l\nu$	✓	✓	✓	✓	~ 550 (ggF + VBF)	5 → 30%	Very poor

+ dedicated searches for ttH, H → $\gamma\gamma$, WW^*+ZZ^* +$\tau\tau$ (multi-leptons), bb

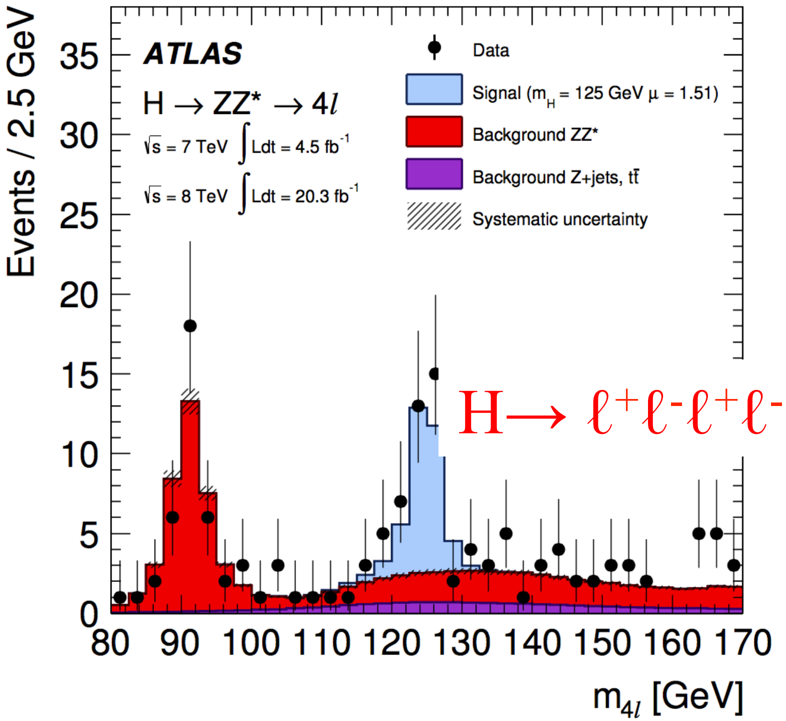
Measurements



Measurements

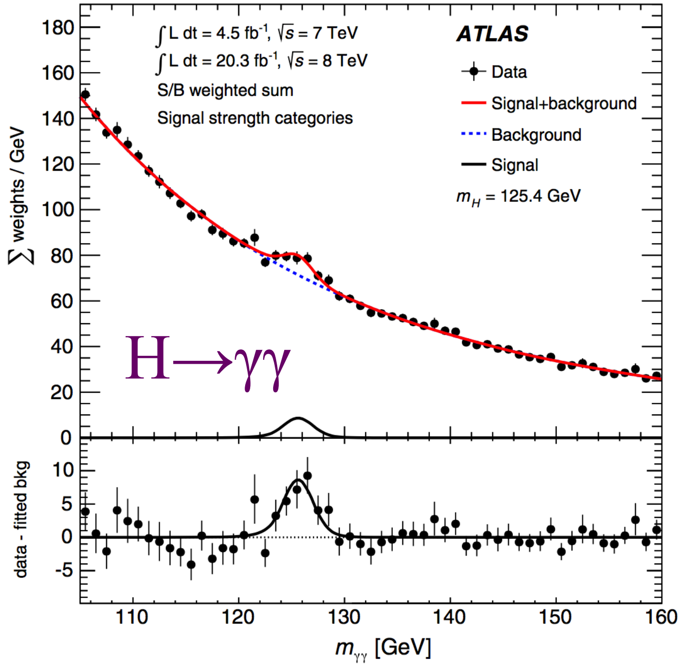


H→γγ

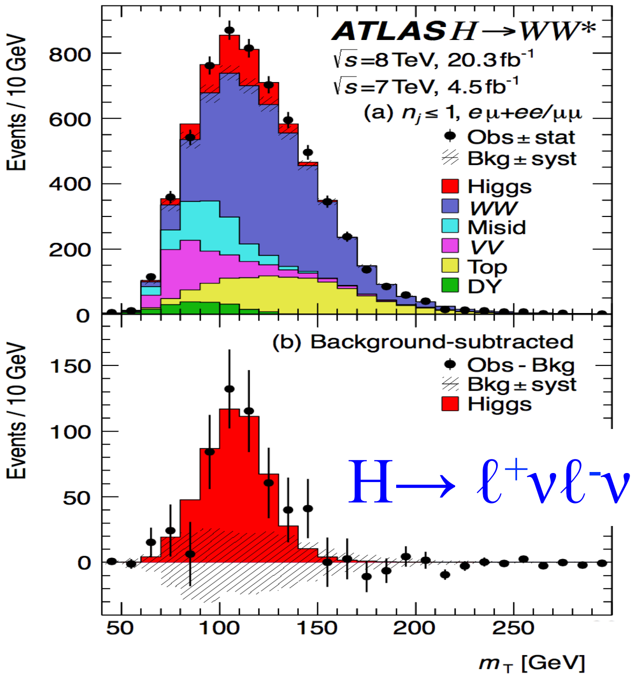


H→ $\ell^+\ell^-\ell^+\ell^-$

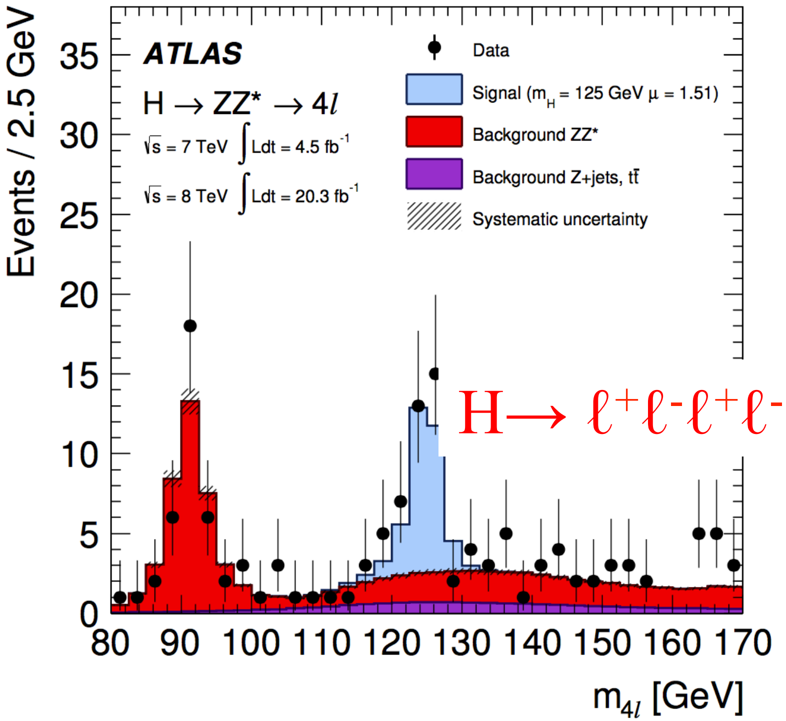
Measurements



$H \to \gamma\gamma$

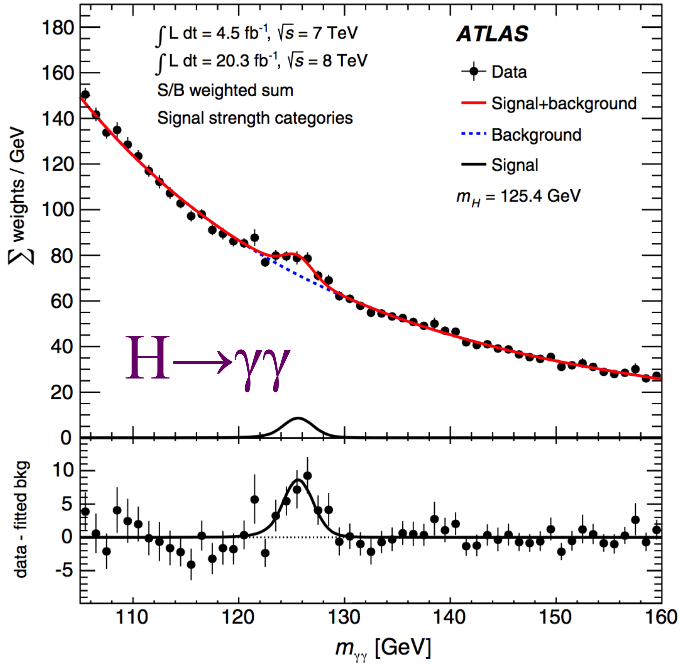


$H \to \ell^+\nu\ell^-\nu$

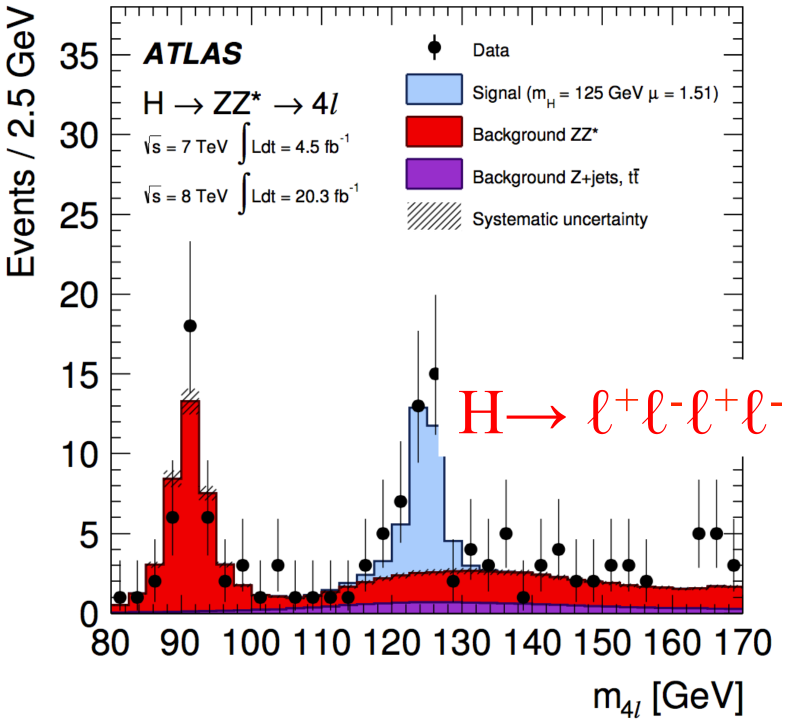


$H \to \ell^+\ell^-\ell^+\ell^-$

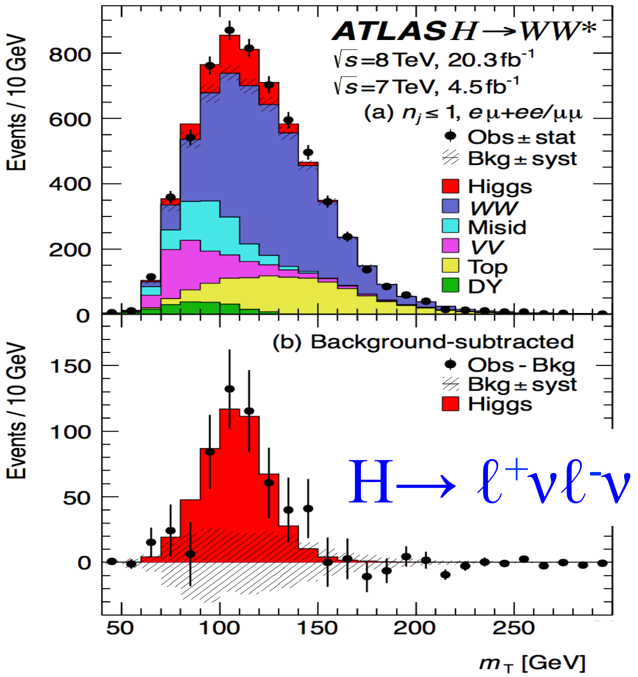
Measurements



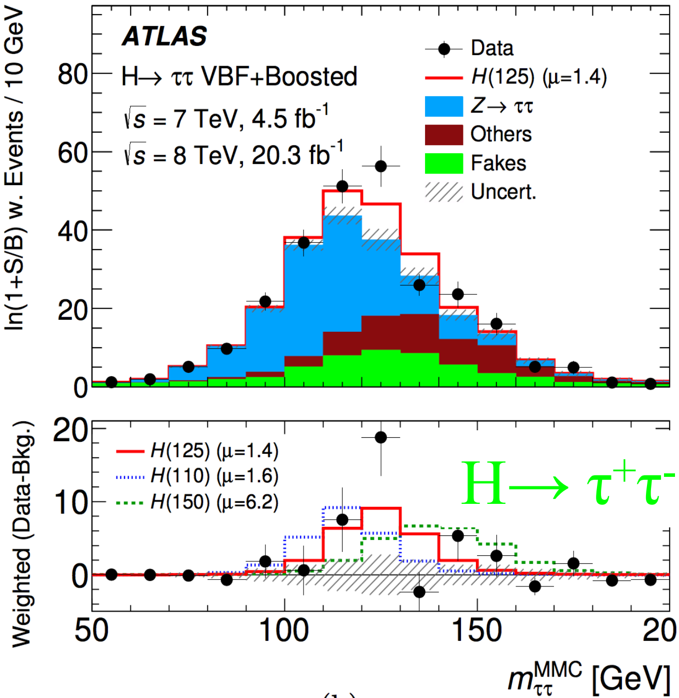
H→γγ



H→ $\ell^+\ell^-\ell^+\ell^-$

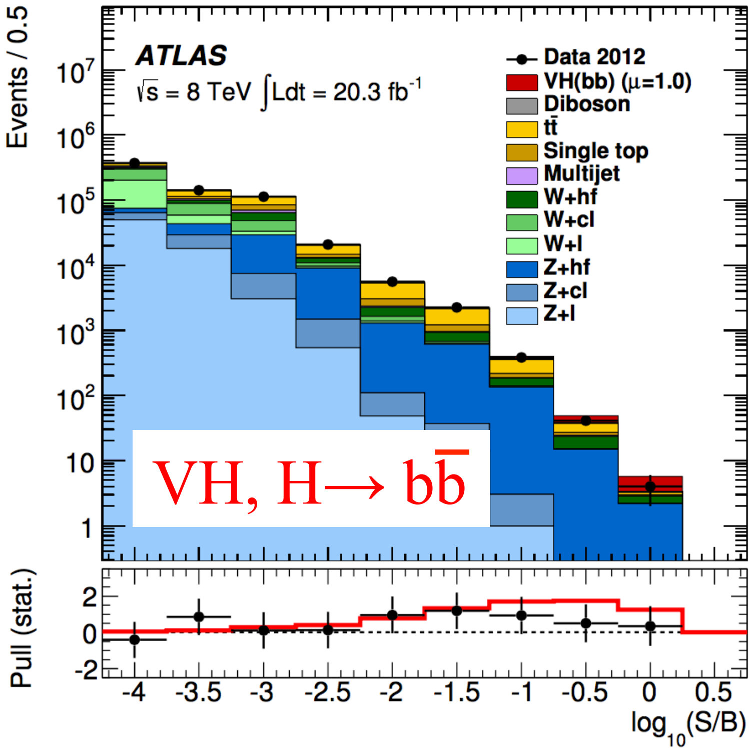


H→ $\ell^+\nu\ell^-\nu$



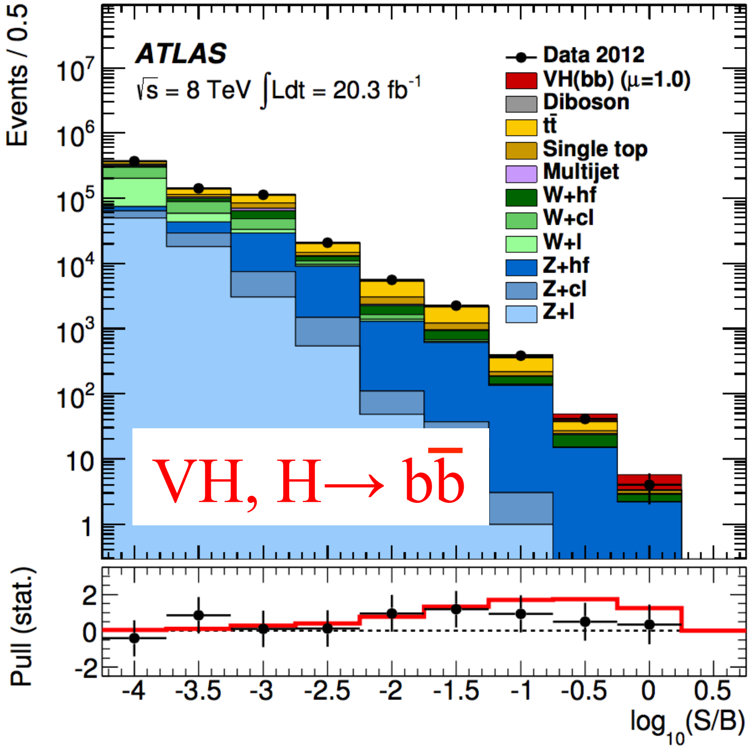
H→ $\tau^+\tau^-$

Measurements

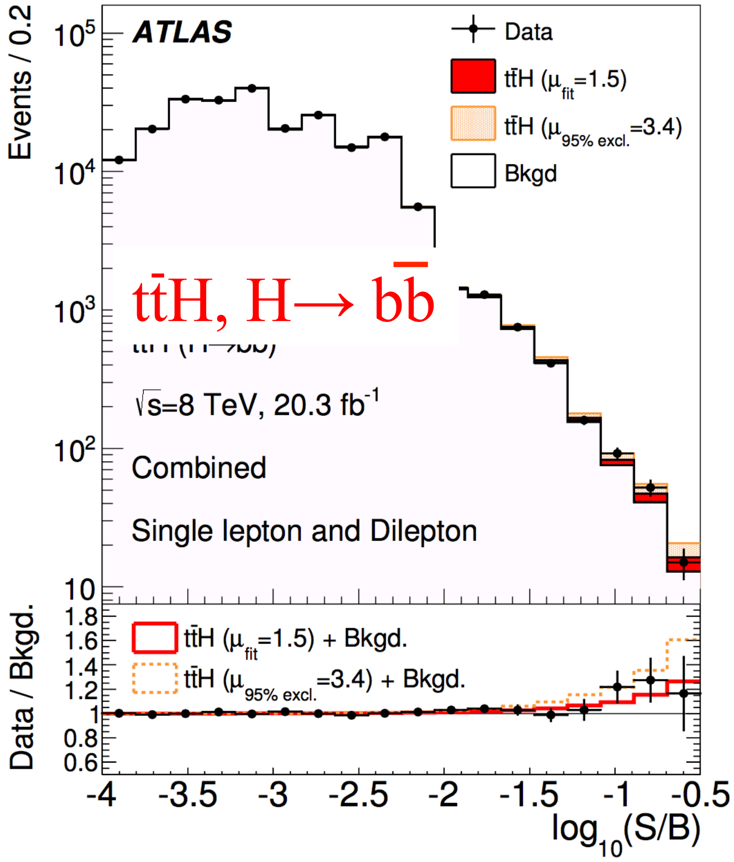


VH, $H \rightarrow b\bar{b}$

Measurements

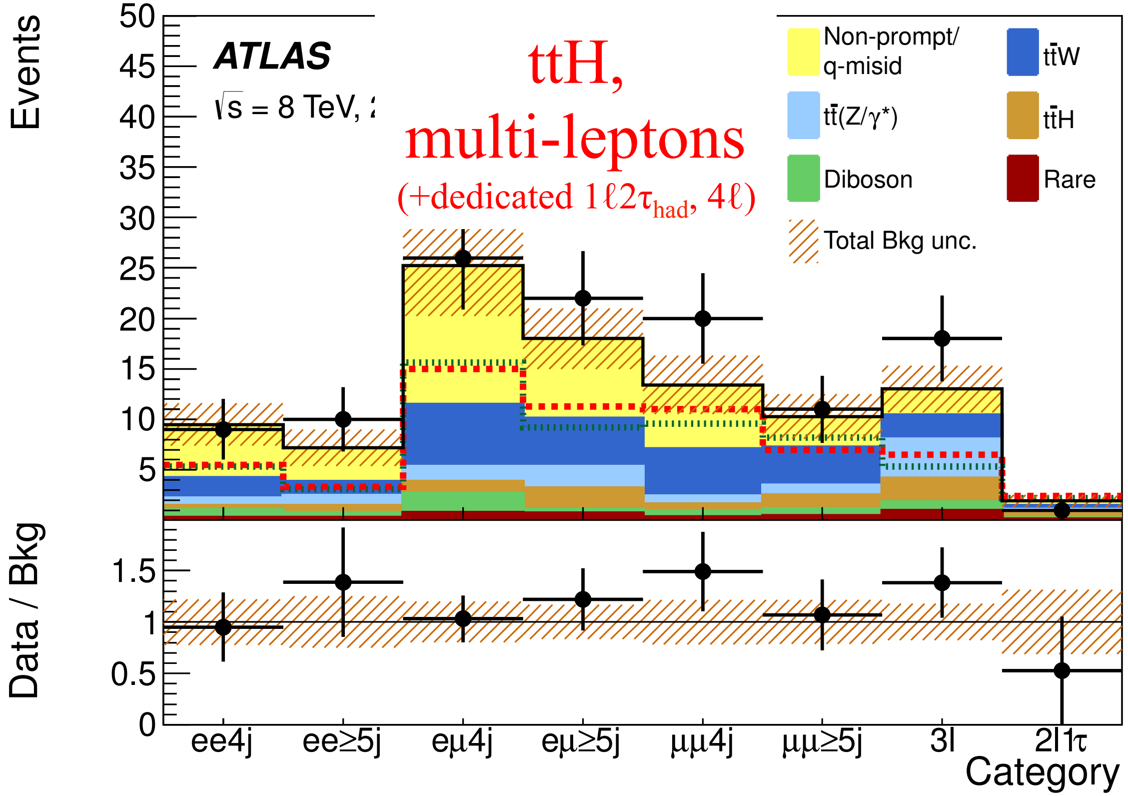


VH, H→ bb̄



tt̄H, H→ bb̄

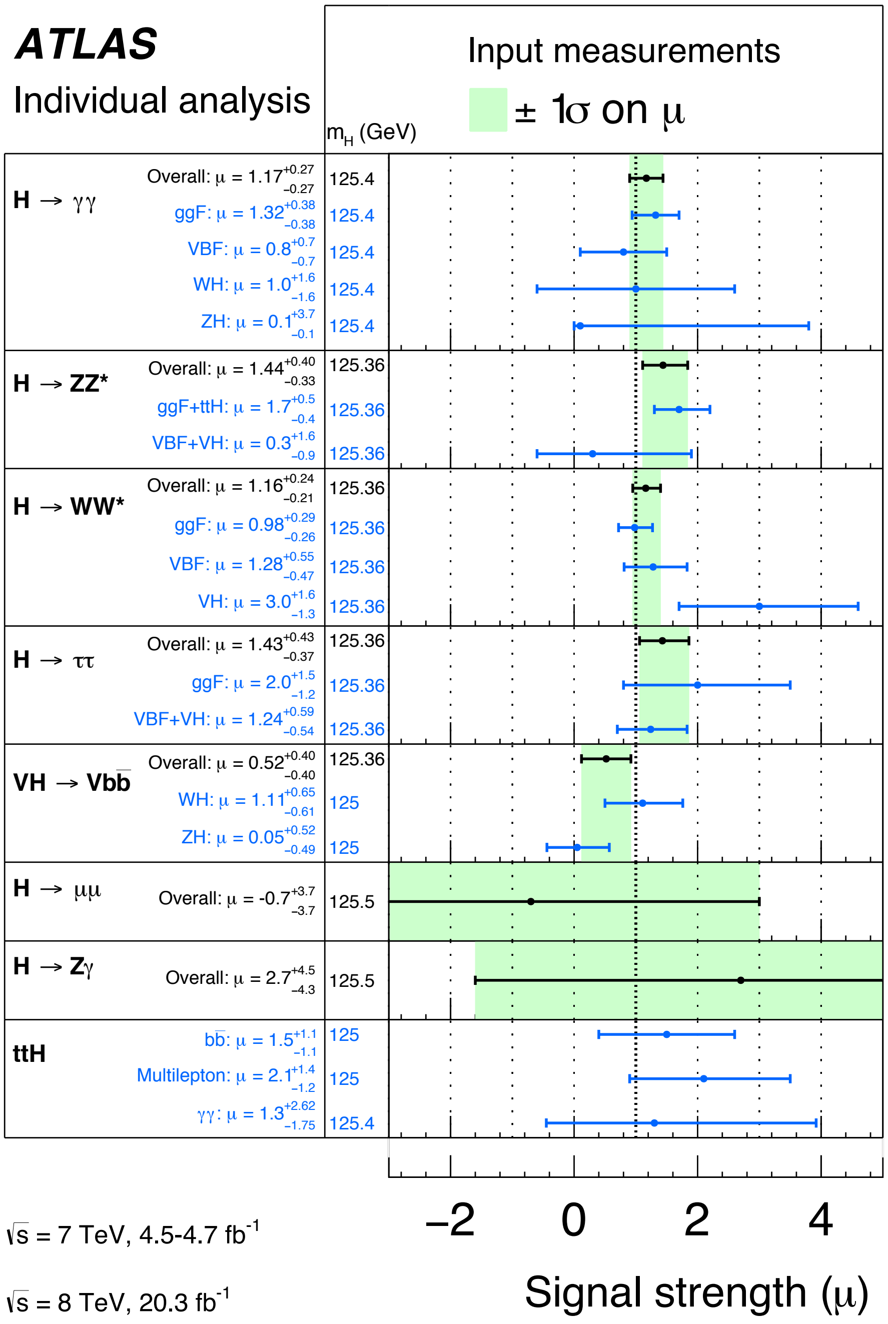
… to measurements



ttH, multi-leptons

(+dedicated $1\ell 2\tau_{had}$, 4ℓ)

Input to combinations : ATLAS example



- ➢ All signal strengths compatible with 1 within less than 2 sigmas

- ➢ Interesting (but not significant) excess in ttH, seen in both experiments, especially in multi-leptons :

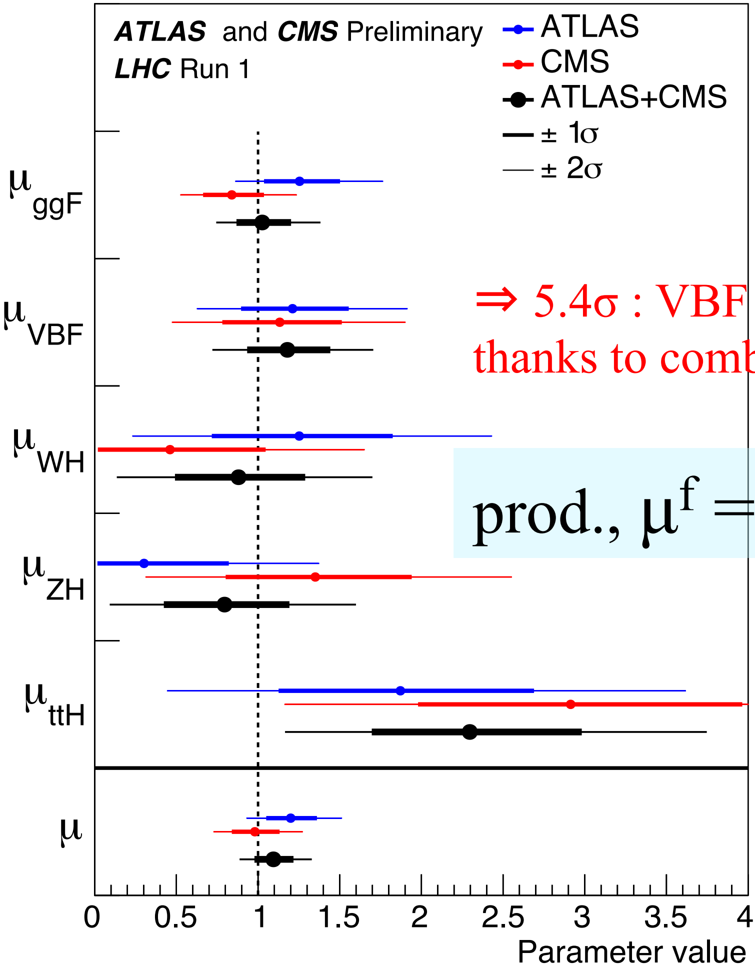
ATLAS : μ(ttH, leptons) $= 2.1^{+1.4}_{-1.2}$
CMS : μ(ttH, WW*-tag) $\sim 4.0^{+1.7}_{-1.6}$

⇒ Eagerly waiting for run II results on ttH, which benefits the most of √s increase (Signal × 3.9) !

(run II : ~ 125 fb^{-1} by the end of 2018)

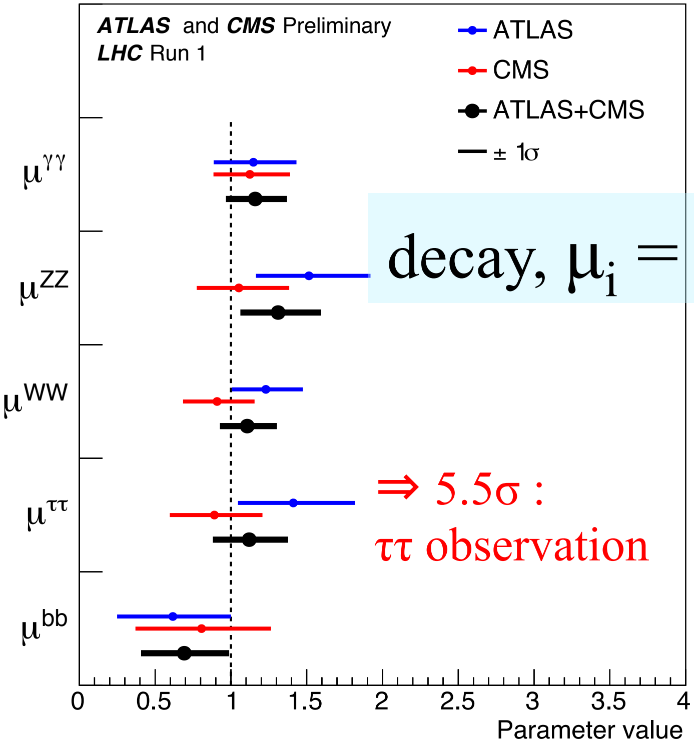
ATLAS + CMS combination

Disentangling production (assuming same strength at 7 and 8 TeV) and decay in the global fit :



⇒ 5.4σ : VBF observation thanks to combination

prod., $\mu^f = 1$



decay, $\mu_i = 1$

⇒ 5.5σ : ττ observation

The rather low μ^{bb} has a large impact on the interpretation since it enters the width with the leading coefficient…

$$\mu = 1.09 \pm 0.07_{stat} \pm 0.04_{exp} \pm 0.03_{bkgth} \pm 0.07_{sigth}$$

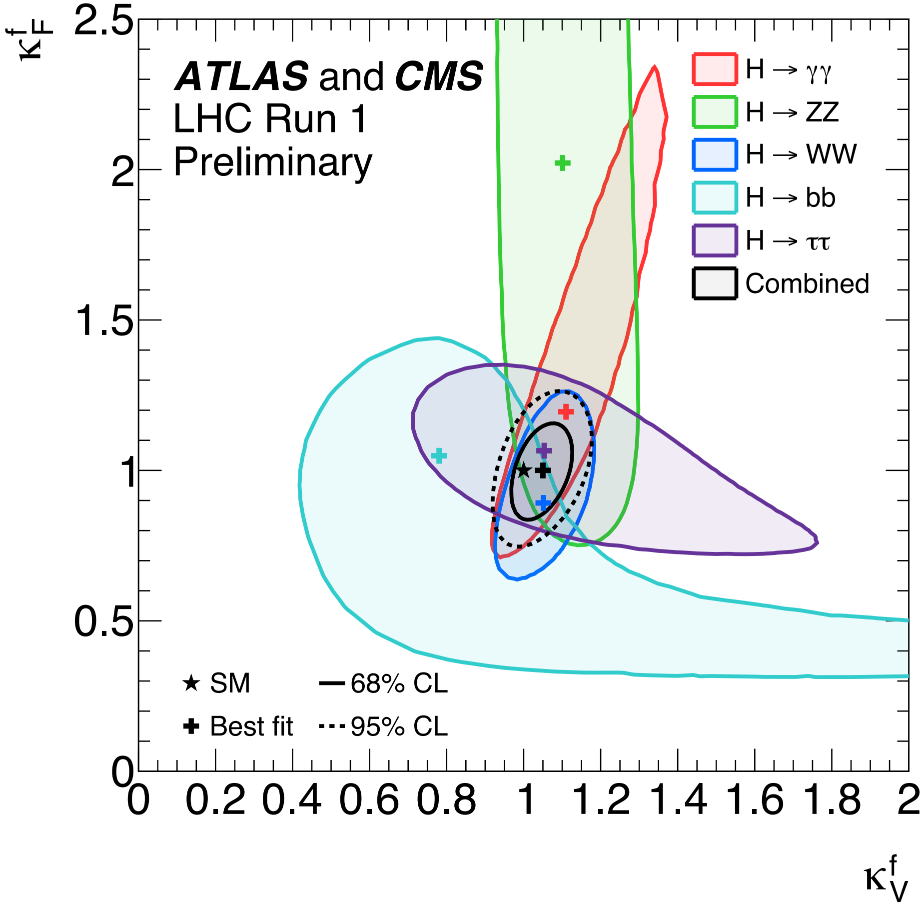
⇒ Very constraining for singlet extension or minimal composite (MCHM4) models : from ATLAS alone : f > 710 GeV

Comparable signal theory uncertainty (dominated by ggF cross-section) and stat. uncertainty : call for improved predictions…

Already there with N^3LO for ggF, improved pdf (agreement) !

Going to coupling modifiers : different tests following different assumptions can be performed

Example 1 : no BSM in loops nor decay, a single modifier for W/Z κ_V and fermions κ_F



Convention $\kappa_V > 0$

Some channels are sensitive to sign(κ_V,κ_F)

- especially $\gamma\gamma$ decay
- also single top-associated production

- and bb through $gg \rightarrow ZH$!

(each decay channel but bb slightly prefers $\kappa_F < 0$ but the overlap is by far not as good as for $\kappa_F > 0$
⇒ the positive solution is highly favoured,
$\kappa_F < 0$ excluded @ ~ 5σ)

Same model used to constrain
next-to-minimal composite (MCHM5) model :
from ATLAS alone : f > 780 GeV (600 GeV exp.)

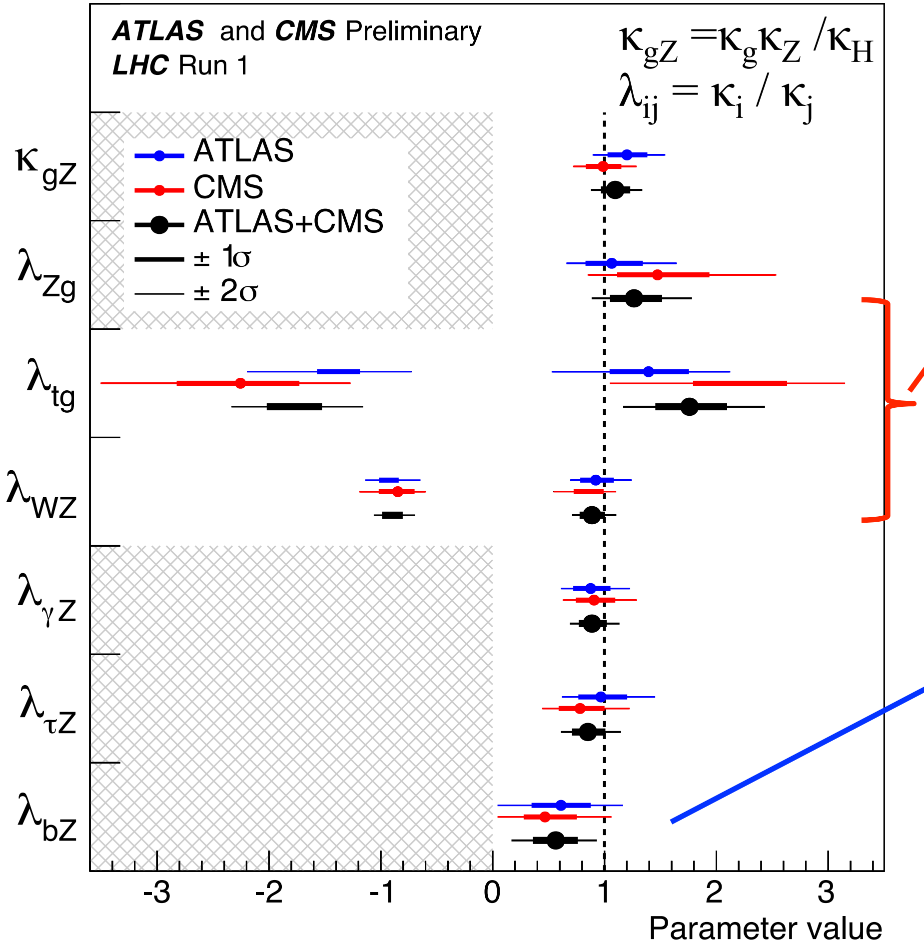
Example 2 : going outside SM, no assumptions on BSM decays or in loops

→ κ_γ, κ_g ($\kappa_{Z\gamma}$) are effective couplings (κ_{ggZH} always treated as resolved)

→ B(invisible/undetected) ≥ 0

⇒ the most generic parameterisation in terms of kappa factors

- without any further assumption, only ratio of kappas can be determined
- additional *reasonable* assumptions could be $\kappa_V < 1$ or $\kappa_{\text{on-shell}} = \kappa_{\text{off-shell}}$



Sign sensitivity through tH + ggZH (resolved in this analysis)

positive solutions very slightly favoured

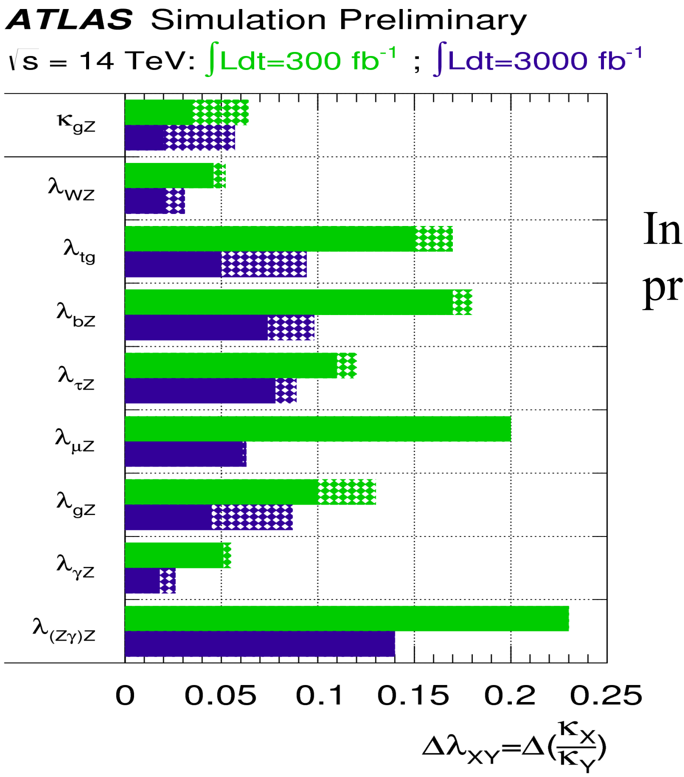
λ_{bZ} rather low : conspiracy of

- a high σ(ttH) /σ_{ggF} (multi-lep.)
- a high σ(ZH)/σ_{ggF} (CMS, dijet cat.)
- low VH, H → bb

whereas ttH, H → bb is not that high

Some expectations for beyond run II

→ most prospects have been considering integrated luminosities of 0.3 ab^{-1} (~2024)
or 3.0 ab^{-1} (~2035)



In particular for 0.3 ab^{-1} factor ~ 2 gain on precision for $\lambda_{\gamma Z}$: ~ 5% accuracy assuming 2014 theory uncertainties

⇒ sensitivity to new charged particles in the loop ?

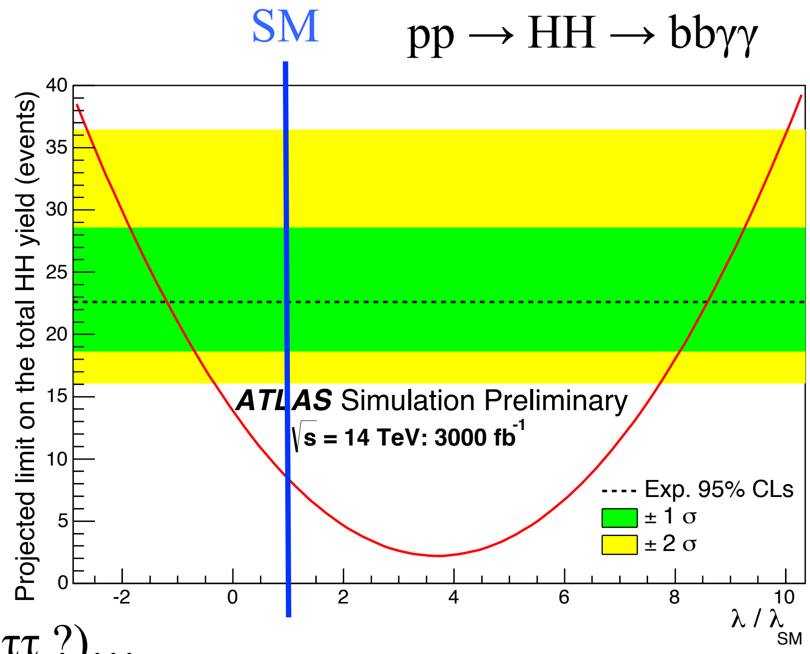
- What about the trilinear λ_{3H} coupling ?

$$V_{SM}(H) = \lambda v^2 H^2 + \lambda v H^3 + \frac{\lambda}{4} H^4$$

$\lambda = m_H^2 / 2v^2 \sim 0.13$, $\lambda_{3H} = 3m_H^2 / 2v \sim 191$ GeV

Very very hard, needs HL-LHC : e.g. in bbγγ
S ~ 8.4, B ~ 47.1, $\lambda/\lambda_{SM} \in [-1.3, 8.7]$ @ 95%CL

pp → HH → bbγγ



Work in progress to try to include more final states (bbττ ?)…

⇒ Most of the measurements aiming at characterizing the new boson discovered by ATLAS and CMS point to a particle ***very compatible with the SM Higgs boson***

a light, narrow width, elementary at the TeV scale, CP-even scalar particle coupling to massive particles

In the most simple test (a single modifier) a precision of order O(10%) has been reached with similar contributions from stat. and theory systematic uncertainties

Precisions on constraints obtained on ratios of cross-sections or branching ratios are at the O(30%) level

Most results from the ATLAS+CMS combination as expected from naïve combination but the huge combination work was needed to make sure this is indeed the case when taking properly correlations into account

Both experiments and the theory community are actively working to beyond the kappa framework

→ simplified / differential cross-sections
→ Higgs-Effective-Field theory

A huge success and yet a small disappointment :
no sign of new physics in the characterization yet !

⇒ decoupling ? alignment ? Nothing ? ☹

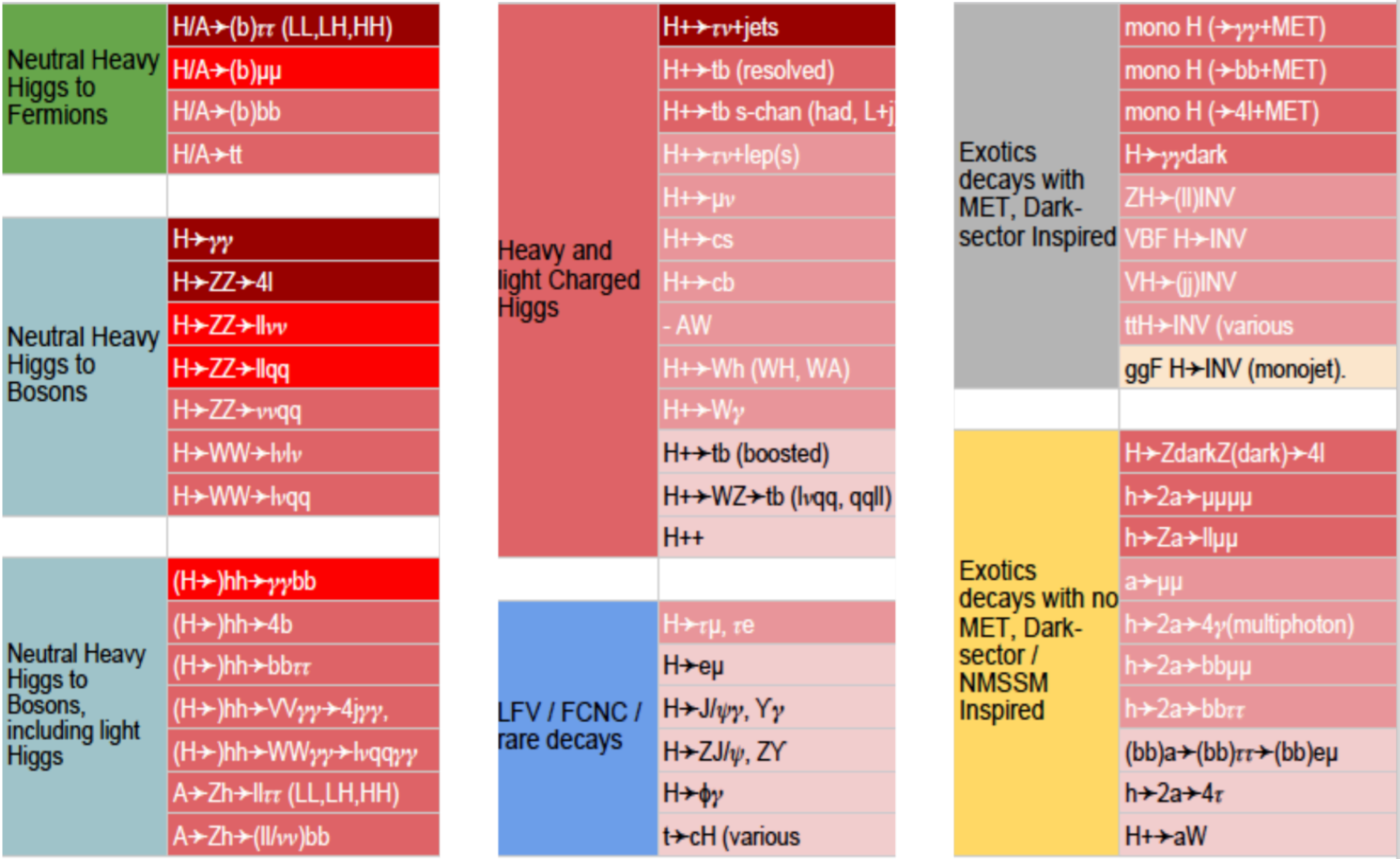
Searching for hints of physics beyond the standard model in the scalar sector

A huge number of possible analyses to corner the BSM+Higgs sector

- rare decays barely accessible at HL-LHC : e.g. Quarkonium+γ, $VP^{(*)}$ e.g. $W^{\pm}\rho^{\mp}$
- 125 GeV Higgs as a portal to new physics : BSM production and decays
- Additional Higgs bosons : singlets, nHDM, triplets

The Run I panorama : a (probably) not exhaustive list

(Courtesy of P. Savard)



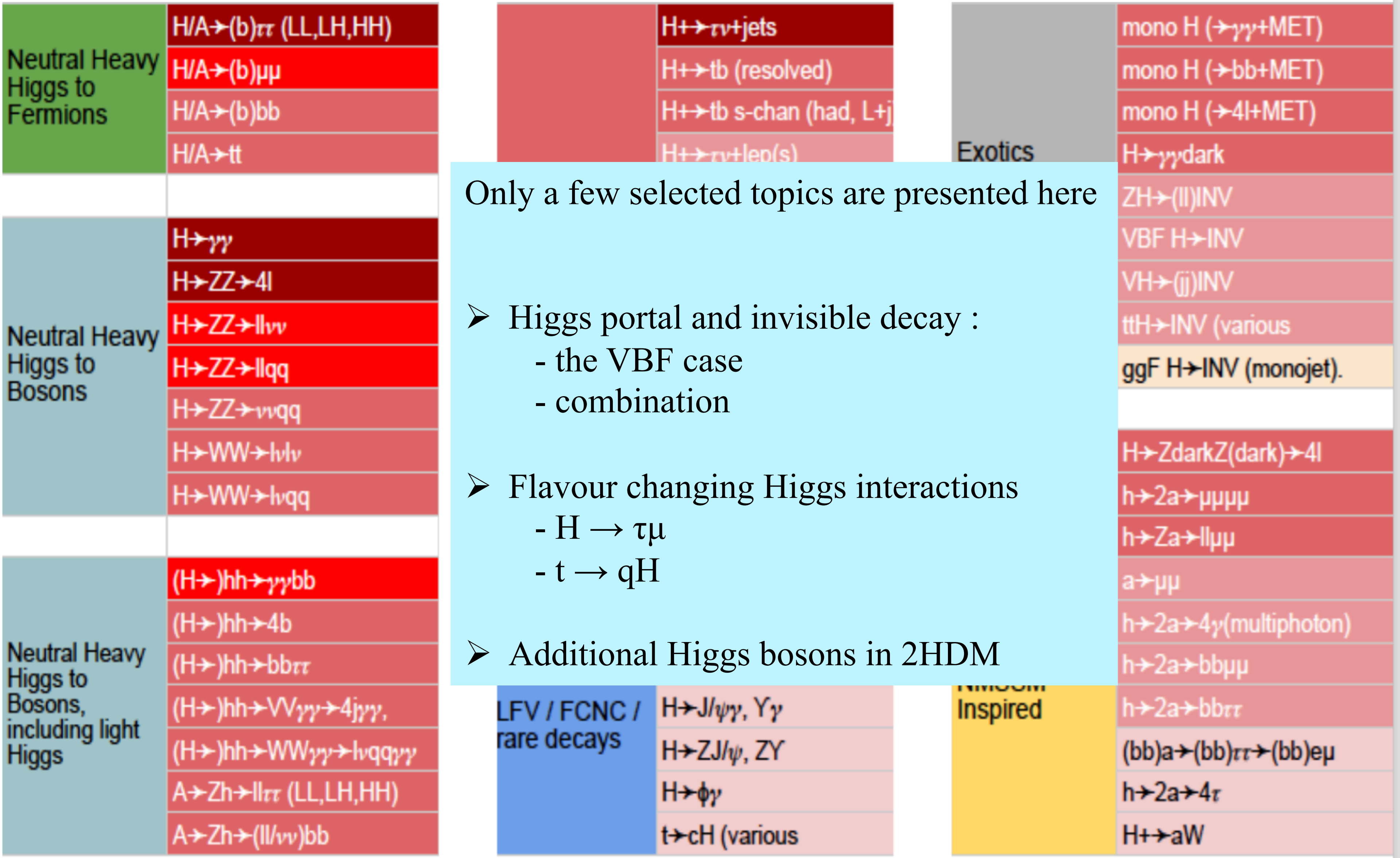
Neutral Heavy Higgs to Fermions	H/A→(b)ττ (LL,LH,HH)
	H/A→(b)μμ
	H/A→(b)bb
	H/A→tt
Neutral Heavy Higgs to Bosons	H→γγ
	H→ZZ→4l
	H→ZZ→llνν
	H→ZZ→llqq
	H→ZZ→ννqq
	H→WW→lνlν
	H→WW→lνqq
Neutral Heavy Higgs to Bosons, including light Higgs	(H→)hh→γγbb
	(H→)hh→4b
	(H→)hh→bbττ
	(H→)hh→VVγγ→4jγγ,
	(H→)hh→WWγγ→lνqqγγ
	A→Zh→llττ (LL,LH,HH)
	A→Zh→(ll/νν)bb

Heavy and light Charged Higgs	H+→τν+jets
	H+→tb (resolved)
	H+→tb s-chan (had, L+j
	H+→τν+lep(s)
	H+→μν
	H+→cs
	H+→cb
	- AW
	H+→Wh (WH, WA)
	H+→Wγ
	H+→tb (boosted)
	H+→WZ→tb (lνqq, qqll)
	H++
LFV / FCNC / rare decays	H→τμ, τe
	H→eμ
	H→J/ψγ, Υγ
	H→ZJ/ψ, ZΥ
	H→ϕγ
	t→cH (various

Exotics decays with MET, Dark-sector Inspired	mono H (→γγ+MET)
	mono H (→bb+MET)
	mono H (→4l+MET)
	H→γγdark
	ZH→(ll)INV
	VBF H→INV
	VH→(jj)INV
	ttH→INV (various
	ggF H→INV (monojet).
Exotics decays with no MET, Dark-sector / NMSSM Inspired	H→ZdarkZ(dark)→4l
	h→2a→μμμμ
	h→Za→llμμ
	a→μμ
	h→2a→4γ(multiphoton)
	h→2a→bbμμ
	h→2a→bbττ
	(bb)a→(bb)ττ→(bb)eμ
	h→2a→4τ
	H+→aW

The Run I panorama : a (probably not exhaustive list)

Courtesy of P. Savard)



Neutral Heavy Higgs to Fermions	H/A→(b)ττ (LL,LH,HH)
	H/A→(b)μμ
	H/A→(b)bb
	H/A→tt
Neutral Heavy Higgs to Bosons	H→γγ
	H→ZZ→4l
	H→ZZ→llνν
	H→ZZ→llqq
	H→ZZ→ννqq
	H→WW→lνlν
	H→WW→lνqq
Neutral Heavy Higgs to Bosons, including light Higgs	(H→)hh→γγbb
	(H→)hh→4b
	(H→)hh→bbττ
	(H→)hh→VVγγ→4jγγ,
	(H→)hh→WWγγ→lνqqγγ
	A→Zh→llττ (LL,LH,HH)
	A→Zh→(ll/νν)bb

	H+→τν+jets
	H+→tb (resolved)
	H+→tb s-chan (had, L+j
	H+→τν+lep(s)
LFV / FCNC / rare decays	H→J/ψγ, Υγ
	H→ZJ/ψ, ZΥ
	H→φγ
	t→cH (various

Exotics	mono H (→γγ+MET)
	mono H (→bb+MET)
	mono H (→4l+MET)
	H→γγdark
	ZH→(ll)INV
	VBF H→INV
	VH→(jj)INV
	ttH→INV (various
	ggF H→INV (monojet).
	H→ZdarkZ(dark)→4l
	h→2a→μμμμ
	h→Za→llμμ
	a→μμ
	h→2a→4γ(multiphoton)
	h→2a→bbμμ
Inspired	h→2a→bbττ
	(bb)a→(bb)ττ→(bb)eμ
	h→2a→4τ
	H+→aW

Only a few selected topics are presented here

- Higgs portal and invisible decay :
  - the VBF case
  - combination
- Flavour changing Higgs interactions
  - H → τμ
  - t → qH
- Additional Higgs bosons in 2HDM

Higgs portal and invisible decays

Indirect limit on the invisible (/undetected) branching ratio can be determined from the coupling fits. In the most generic model tested, the

$$\kappa_W, \kappa_Z, \kappa_t, \kappa_b, \kappa_\tau, \kappa_\mu, \kappa_g, \kappa_\gamma, \kappa_\tau, \kappa_{Z\gamma}, \mathcal{B} = \mathrm{Br}(H\rightarrow \mathrm{inv})$$

model, and assuming $\kappa_W, \kappa_Z < 1$ to lift the model degeneracy

$\mathcal{B} < 0.49$ @ 95% CL (assuming $\kappa_{\text{on-shell}} = \kappa_{\text{off-shell}}$ gives $\mathcal{B} < 0.68$)

Direct search for invisible decay $H \rightarrow \chi\chi$, where χ is a generic (quasi-) stable neutral and weakly interacting particle (e.g. the lightest neutralino in R_p-conserving SUSY)

⇒ use Higgs boson associated production VBF or VH, V = W/Z
(ttH might also be used)

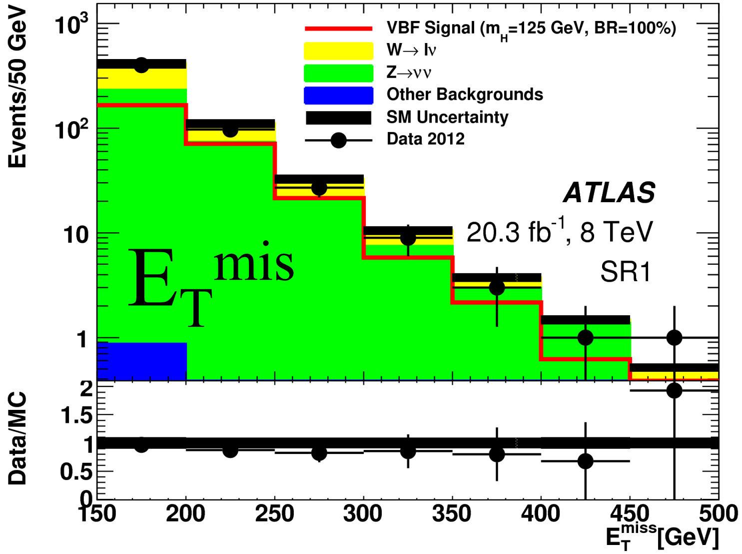
⇒ or single production, relying on ISR tagging
(smaller sensitivity, from mono-jet or mono-V tagging *(unresolved W : fat jet)*
since not specifically designed towards Higgs production)

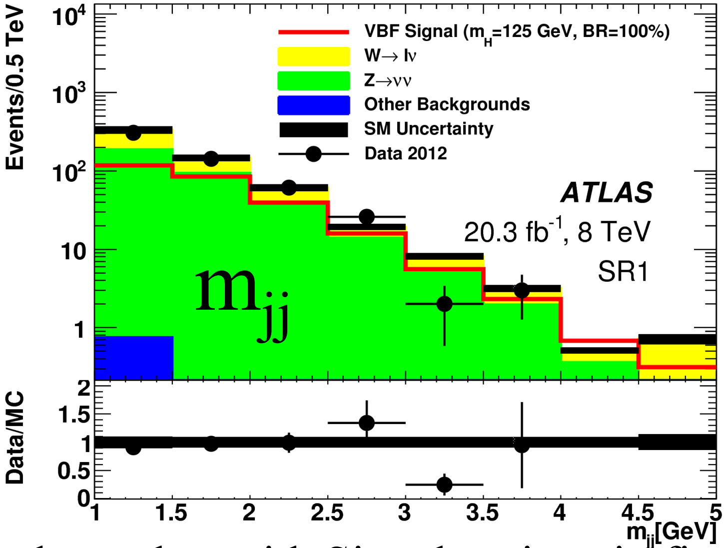
All results quantified in term of $\xi = \dfrac{\sigma \times \mathcal{B}_{inv}}{\sigma_{SM}}$ or $\mathcal{B}$ assuming SM production

Search in VBF production

combine three analysis categories SR1 and SR2a,b which add a 10% sensitivity to SR1

Typical VBF signature : 2 high p_T jets with high m_{jj} (> 1 TeV in SR1), large $\Delta\eta_{jj}$ (> 4.8 in SR1), 3rd jet veto + large E_T^{mis} from H → inv (>150 GeV in SR1) (+ anti-QCD cuts)





Control regions dedicated to Z+jets and W+jets used together with Signal regions in final fit (using 1/2 lepton events, adding lepton in E_T^{mis})

In the most sensitive signal region :

Sig($\mathcal{B}$=1) : N = 306 ± 59 (7% ggH)
Bkg : N = 577 ± 62 (59% Z+jets, 41% W+jets)
N(data) = 539

Combining the three : $\mathcal{B} < 0.28$ (0.31 exp.)
[SR1 alone : 0.30 (0.35 exp)]

The sensitivity in the invisible decay search is a great achievement : before data taking, it was not clear if VBF would be useable at such a large instantaneous luminosity

Combining with (much less sensitive) dedicated VH searches using $Z \to \ell\ell$ and $W/Z \to qq$:

$\mathcal{B} < 0.25$ (0.27 exp.)

The indirect limit ($\mathcal{B} < 0.49$) assumes $\kappa_W, \kappa_Z < 1$

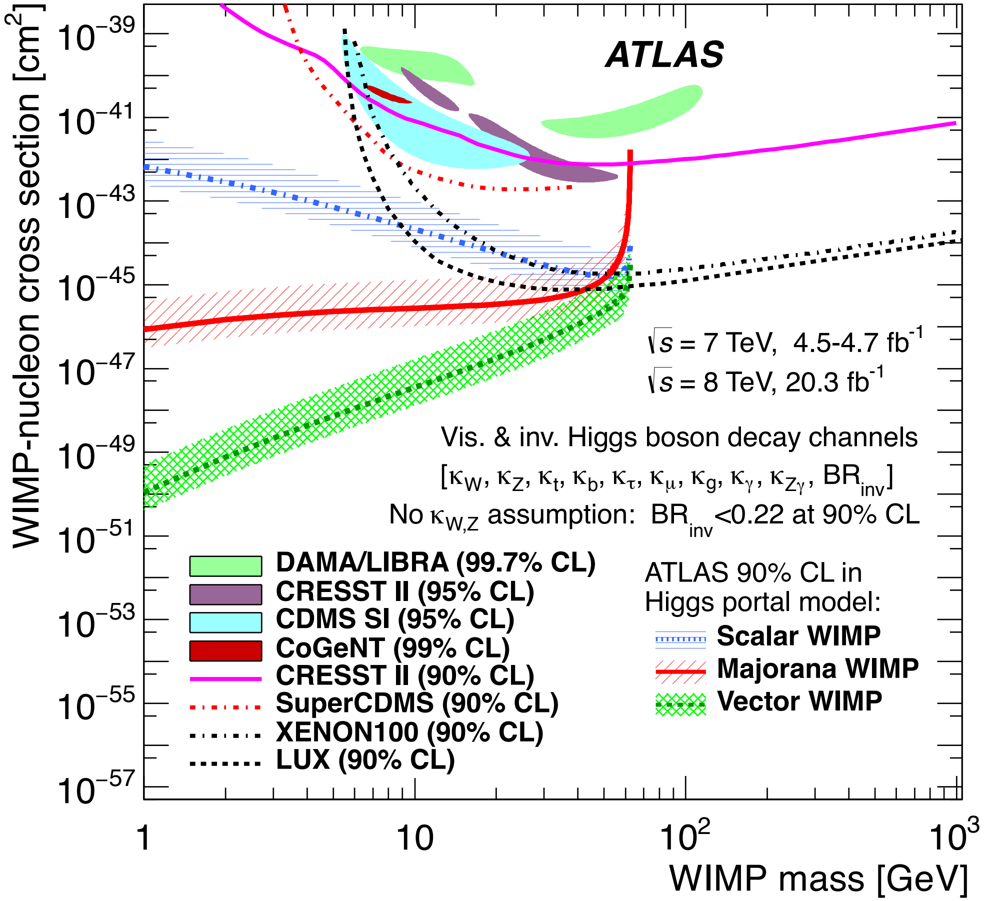
The direct limit ($\mathcal{B} < 0.25$) assumes $\kappa_W = \kappa_Z = \kappa_g = 1$

⇒ Combine both and remove these assumptions !

$\mathcal{B} < 0.23$ (0.24 exp.)

Interpreted as a limit on σ(DM-nucleon)

⇒ very powerful at low DM mass which is very tough for direct detection



Flavour changing Higgs interactions

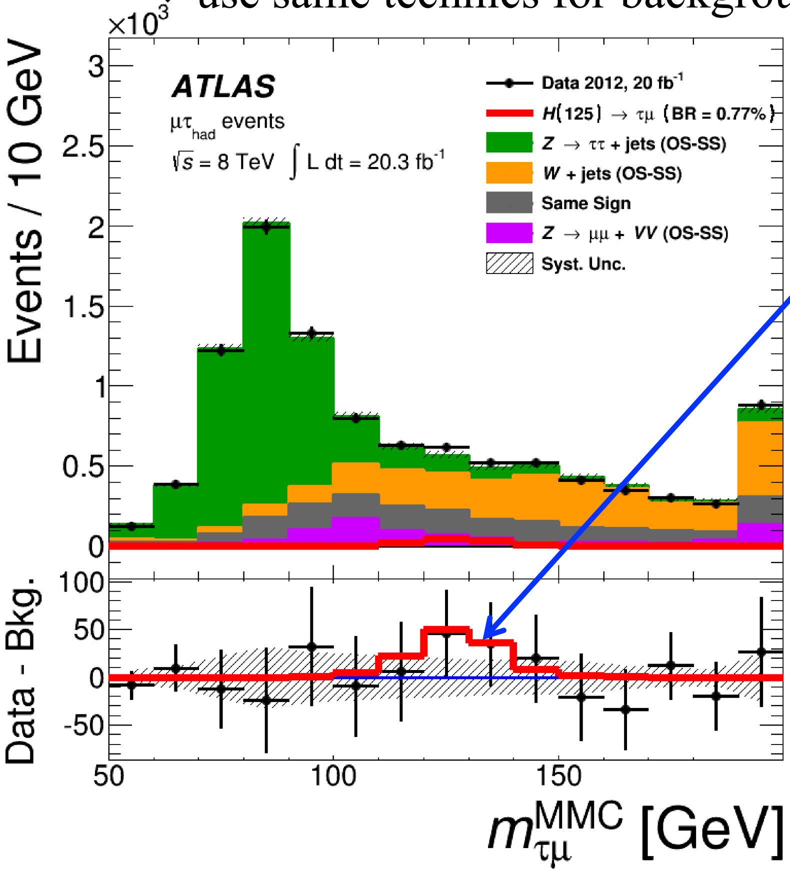
Lepton Flavour Violation $H \to \tau\mu$

- Limits from $\mu \to e\gamma \Rightarrow \mathcal{B}(H\to e\mu) \lesssim 10^{-8}$ but much weaker constrains for $\mathcal{B}(H\to \tau\mu/\tau e)$

- In run I, LHC sensitivity not far away from the "*naturalness limit*" (Cheng-Sher ansatz)
  $\lambda_{\tau\mu} \sim (2m_\tau m_\mu)^{0.5}/v \Rightarrow \mathcal{B} = \mathcal{B}(H\to \tau\mu) \sim m_\mu/m_\tau\, \mathcal{B}(H\to \tau\tau) \sim 0.4\%$

- Small (2.4σ) excess seen in CMS : $\mathcal{B} < 1.57\%$ (0.75% exp.), best fit $\mathcal{B} = 0.84^{+0.39}_{-0.37}\,\%$

- ATLAS performed this search in the $\tau_{had}\mu$; similar to standard $H \to \tau\tau$ search :
  $\Rightarrow$ use same technics for background and systematics uncertainties estimation



Using 20 fb^{-1} of 8 TeV data, very small 1.3σ excess
$\mathcal{B} < 1.85\%$ (1.24% exp.),
best fit $\mathcal{B} = 0.77\pm0.62\ \%$

An interesting $\sim 2.6\sigma$ excess (CMS+ATLAS naïve combination !) to be monitored in run II :
Signal and main bkg increase by ~ 2 :
* in ATLAS expected limit could be

$\mathcal{B} \lesssim 0.7\%$ (0.3%) with 20 fb^{-1} (100 fb^{-1})
$\Rightarrow$ sensitivity to "*naturalness limit*" with $\tau_{had}+\mu$ only without major improvement nor combination with $\tau_{lep}+\mu$

Higgs boson Flavour Changing Neutral production t → qH

Tiny branching ratio in SM : ~ 10^{-15} / 10^{-17} for q = c / u

⇒ Any observation of such processes is a non ambiguous sign of new physics

Some models predict enhancement by several order of magnitude

Benchmark coupling : again *Naturalness limit :* $\lambda_{tcH} \sim 0.086$, $\mathcal{B} \sim 0.2\%$

Both ATLAS and CMS searched for this in top-quark pairs :

$$pp \rightarrow t\bar{t} \rightarrow W^{+}b\ Hq + \text{c.c.}$$

No excess has been observed ⇒ limits :

topology	H → γγ (W→ℓν/qq)		multi-leptons	
(%)	q = c	q = u	q = c	q = u
ATLAS	0.79 (0.51)		0.79 (0.54)	0.78 (0.57)
CMS†	0.47 (0.71)	0.42 (0.65)	0.93 (0.89)	-

† unpublished results with better sensitivity than the published analysis ($\mathcal{B} < 0.56\%$)

- ➢ The ATLAS multi-lepton result is a simple re-interpretation of the SM ttH search in the multi-lepton topology : not optimized for this less busy final state but yet very sensitive !

  ⇒ Might hope for great improvement in run II

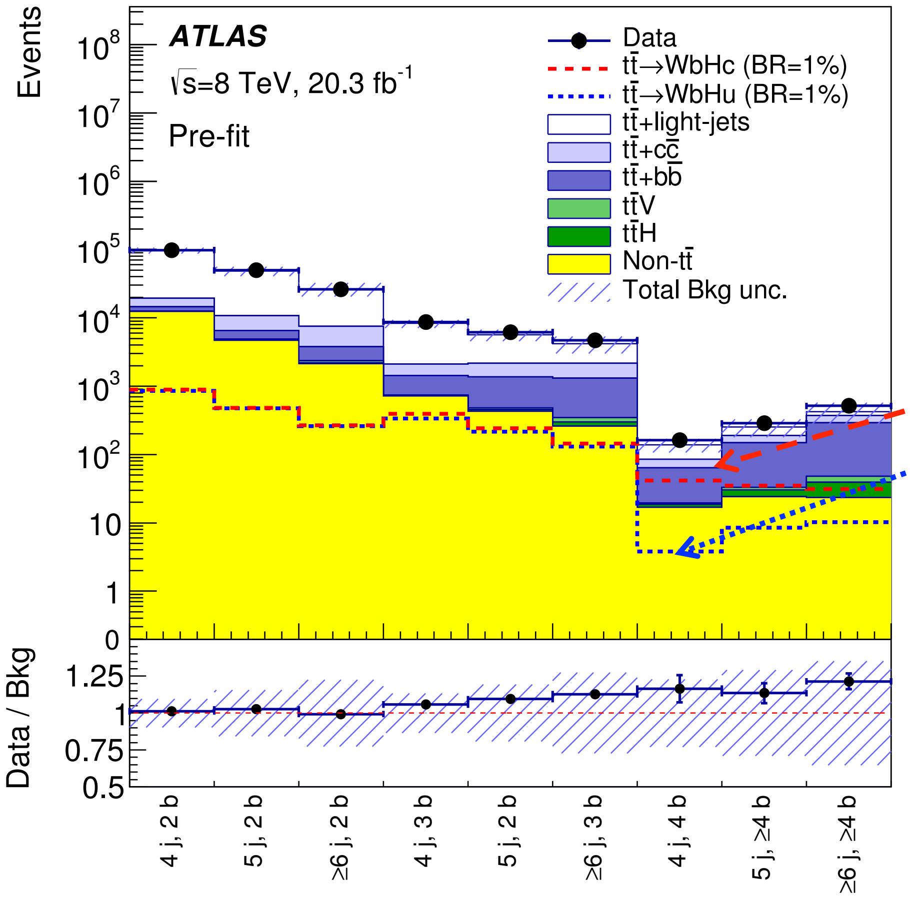
What about H → bb ? A priori very tough !

Signal : ℓνb bbq

vs SM top pair background : ℓνb qqb

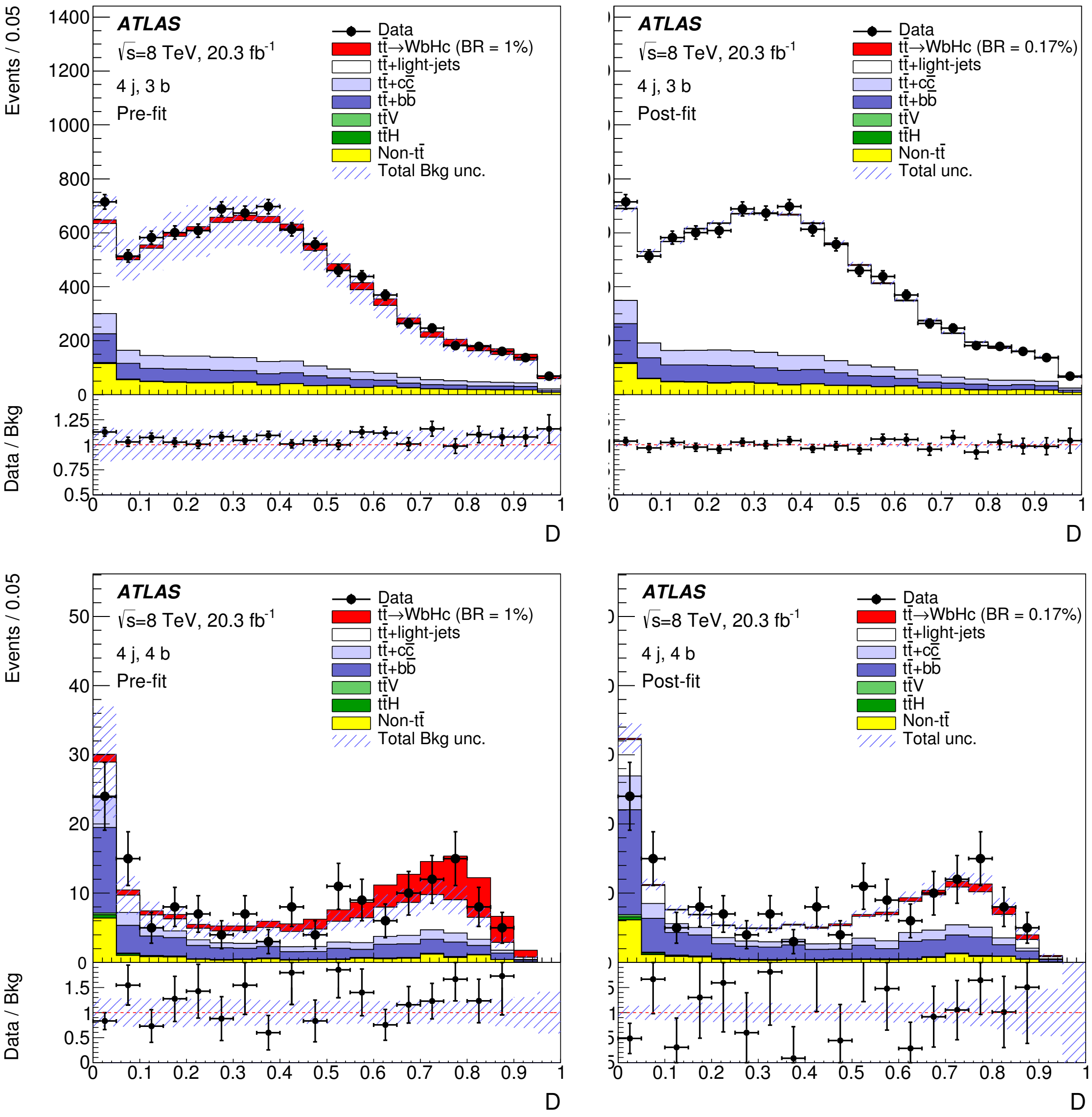
- ➢ Much higher stat. than γγ (× 250)
- ➢ Handles : more b-tags, Higgs boson invariant mass

⇒ Recycle all techniques used for ttH, H → bb :
constrain the background from data via simultaneous fit in categories in
N_{jet}(4, 5, ≥6) and N_{bjet}(2, 3, ≥4)



- ✓ Expect most sensitive categories (N_{jet} N_{bjet}) = (4,3), (4, ≥4)
- ✓ Sensitivity to q= c vs u using ≥4 b categories
- ✓ Final discriminant combines invariant masses (two tops, a Higgs boson) and b-tagging into a likelihood

pre-fit post-fit



No excess :

$\mathcal{B}(t \rightarrow cH) < 0.56\%$ (0.42% exp)

$\mathcal{B}(t \rightarrow uH) < 0.61\%$ (0.64% exp)

Combination with γγ and multi-lep :

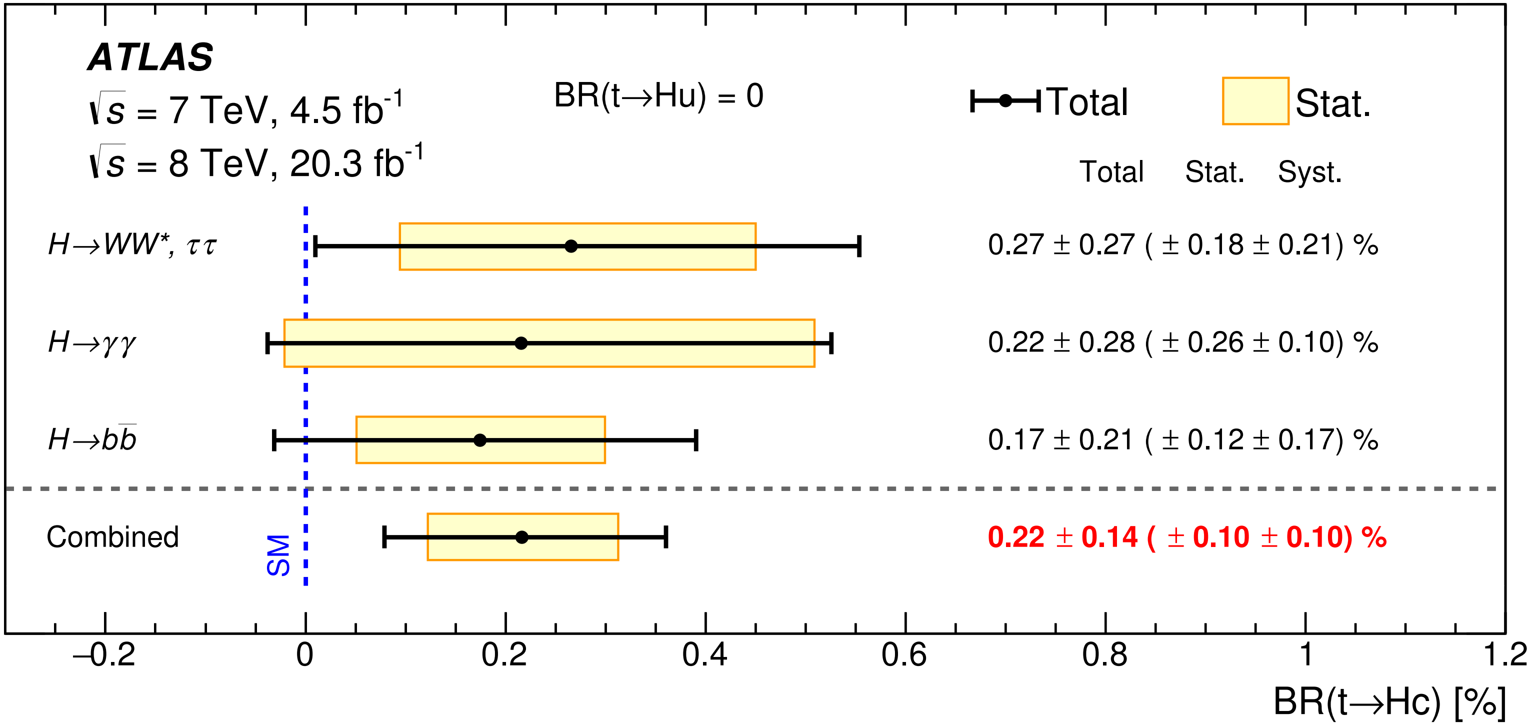
$\mathcal{B}(t \rightarrow cH) < 0.46\%$ (0.25% exp)

$\mathcal{B}(t \rightarrow uH) < 0.45\%$ (0.29% exp)

Intriguingly the three channels observed a slight excess (and for H → bb, in the t → cH decay) corresponding to a best fit value of

$$\mathcal{B}(t \to cH) = 0.22 \pm 0.14\%$$

which matches the *naturalness limit* … 😃



For run II, in the di-photon channel, expect ~ 3.7 events / fb^{-1} for $\mathcal{B} = 0.1\%$:
sensitivity ~ 0.15% with 30 fb^{-1}
⇒ Adding the multi-lepton and bb final state might allow to probe well below the *naturalness limit* before the end of run II

Additional Higgs bosons in 2HDM

Main effort : Two Higgs Doublet Models (2HDM) with CP :
2 CP-even (h/H), 1 CP-odd (A) and a pair of charged ($H^\pm$) Higgs bosons,
most important parameters : tanβ = v_2/v_1 (vev ratio), α : mixing in the CP-even, m_A

The resonance observed at 125 GeV/c^2 (h) is usually assumed to be the lightest CP-even
Strategy :

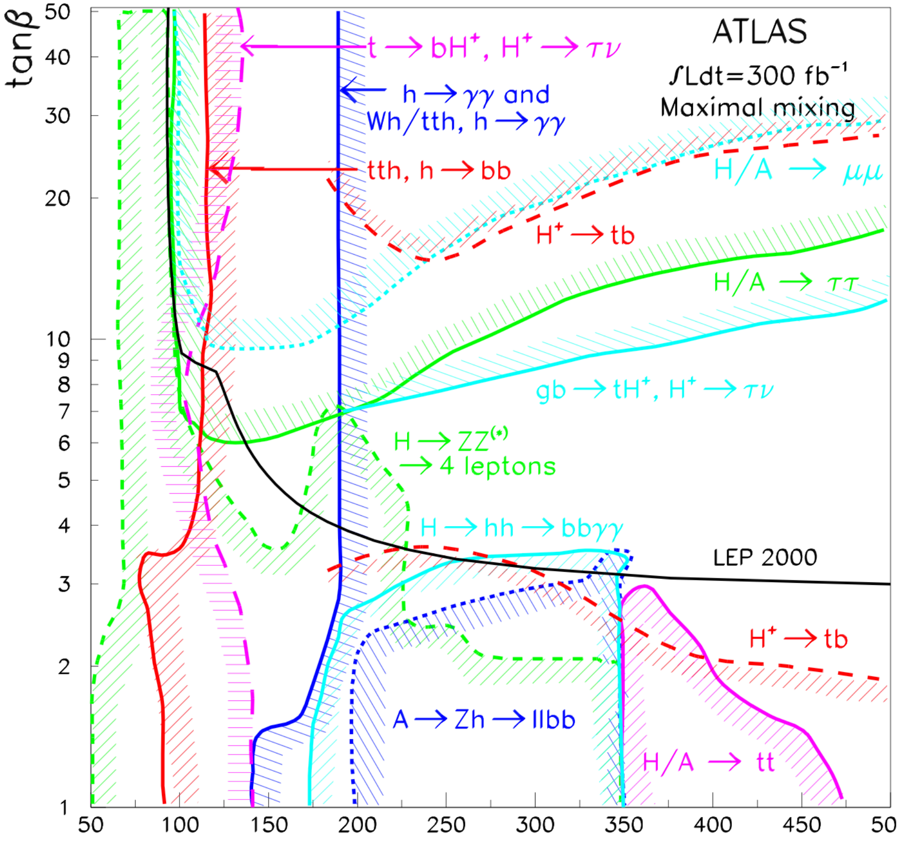
→ redundancy : several topologies can cover the same parameter space in given models

→ stay as model independent as possible (e.g. α is often a free parameter,

$$m_{\mathrm{H}^\pm} \neq \sqrt{m_{\mathrm{A}}^2 + m_{\mathrm{W}}^2}\ \ldots)$$

Particular attention to 2HDM-type II (interpretation in the MSSM within the most recent benchmarks)

From the good old ATLAS TDR 1999



Not covered here :

- Most sensitive at high tanβ : A → ττ
- di-Higgs e.g. from H → hh (→ 4b,2b2γ,multi-ℓ+γ)
- H → WW/ZZ
- Charged Higgs

Details on the search for $A \rightarrow Zh$

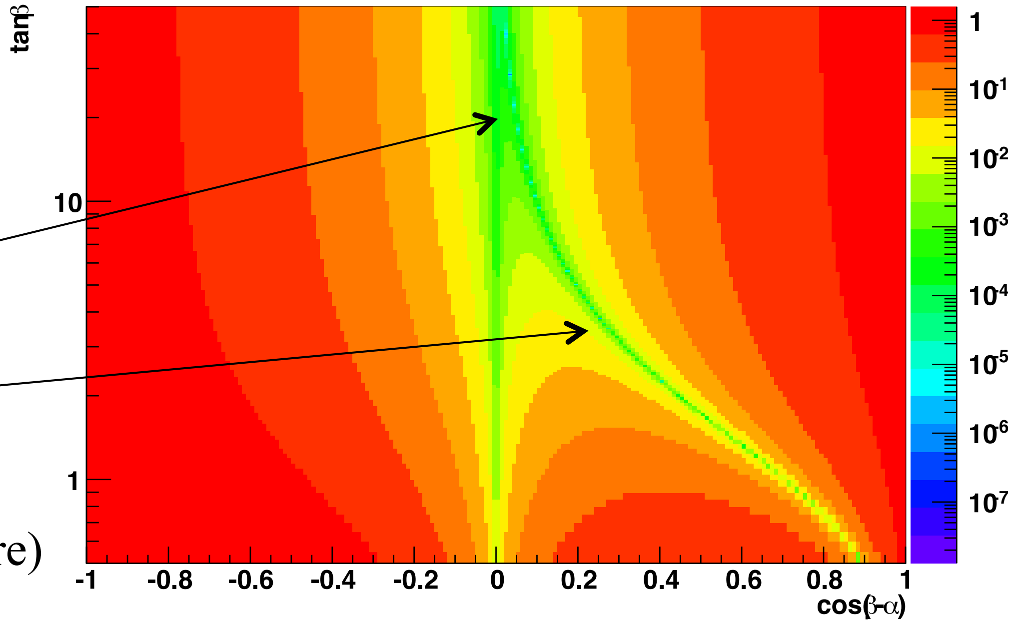
In the MSSM, especially useful at low tanβ, below the tt threshold

For example in type II, using $h \rightarrow$ down-type fermion pair, constraining coupling combination :

- Gluon fusion : $\kappa = [\text{t-t-A} \sim 1/\tan\beta] \times [\text{Z-h-A} \sim \cos(\beta-\alpha)] \times [\text{h-b-b} \sim -\sin\alpha/\cos\beta]$

(• b-associated : $[\text{b-b-A} \sim \tan\beta] \times [\text{Z-h-A} \sim \cos(\beta-\alpha)] \times [\text{h-b-b} \sim -\sin\alpha/\cos\beta]$)

In the (cos(β-α),tanβ) plane,
for ggA :



Z-h-A ~ 0

h-b-b ~ 0

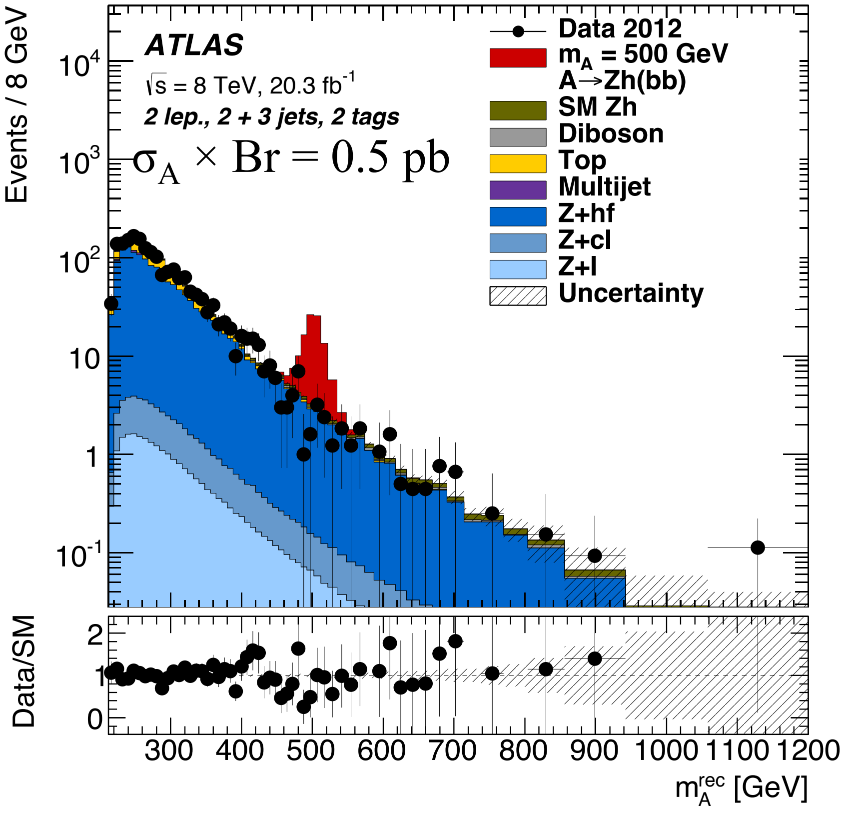
Most promising channels :

- $Z \rightarrow \ell^+\ell^- \; h \rightarrow \tau\tau$ (not described here)
- $Z \rightarrow \ell^+\ell^- \; h \rightarrow bb$

The $h \rightarrow bb$ case profits from the background understanding acquired in the SM associated Zh, $h \rightarrow bb$ production study, especially Z + jets

The $\ell^+\ell^-$ bb channel

Very good four body invariant mass resolution, ranging from 2% to 3% for $m_A \in [0.22,1]$ TeV/c^2



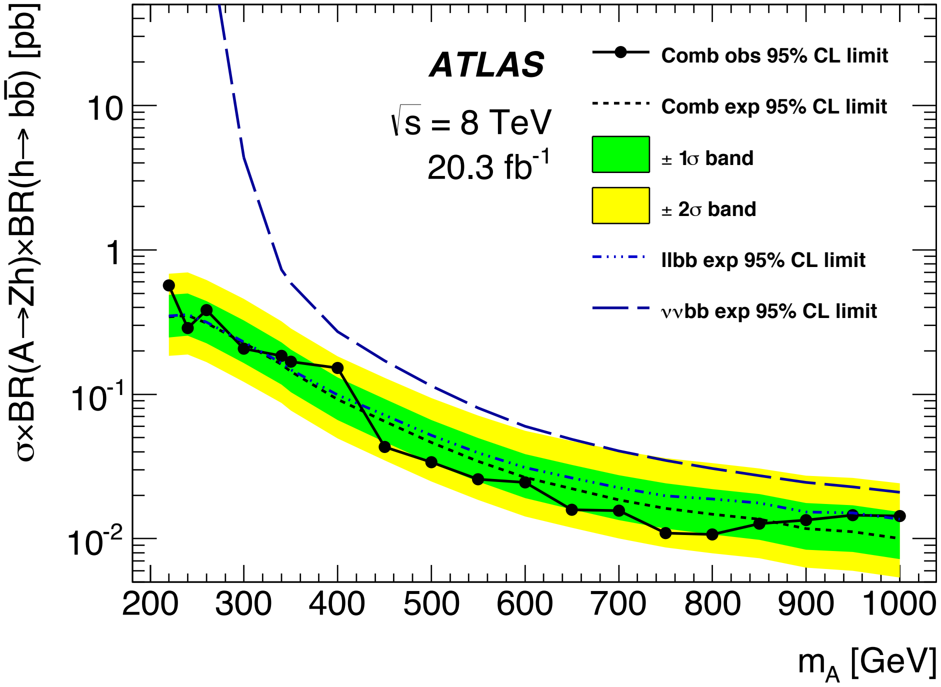
Adding the νν bb channel :

3× yields (before cuts),

but no mass peak, only transverse mass

⇒ add ~ 10% to the combined sensitivity at ~ 500 GeV/c^2 but 50% at 1 TeV/c^2

(assuming narrow width…)

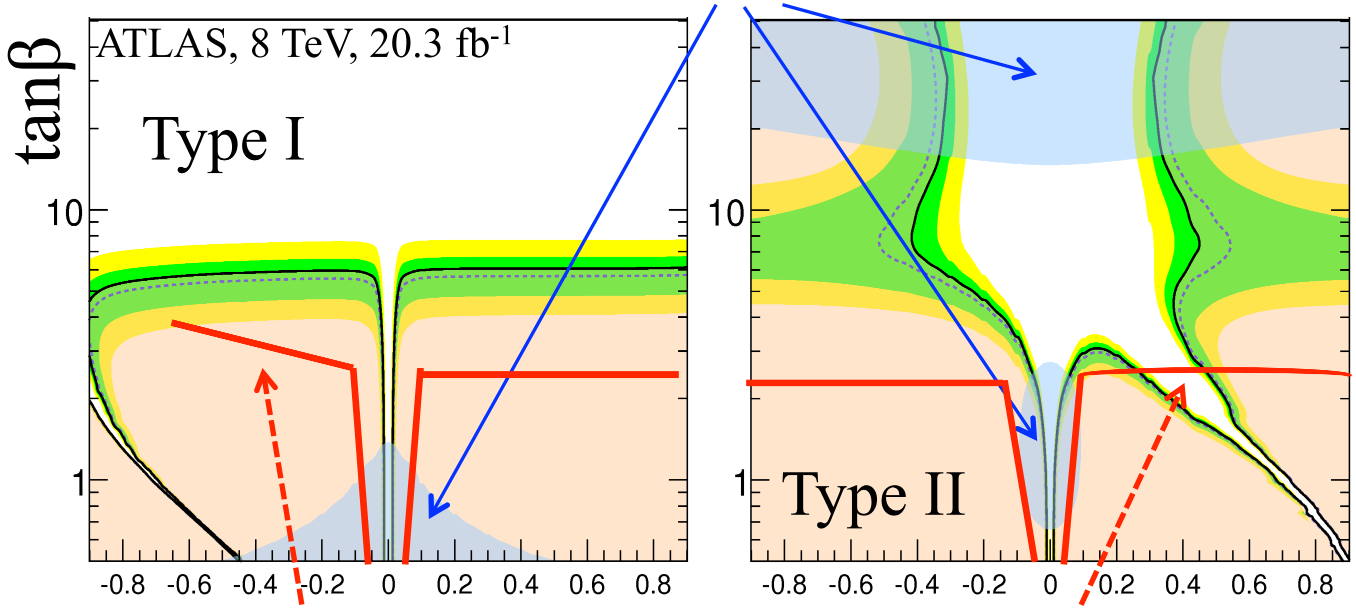


⇒ (almost*) model-independent limit on σ×B(A → Zh) ×B(h → bb) between 570 and 14 fb

(* : above the top threshold, the width can vary a lot and a large width degrades the limit)

Interpretation : example of 2HDM I and II, $m_A = 300$ GeV/c^2
(no combination AZh / Aττ / Hhh)

A → ττ (bbA production included)

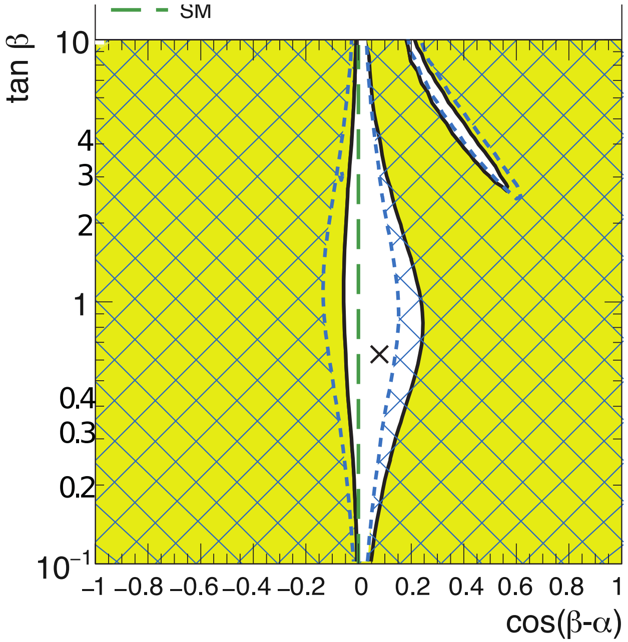


Nice complementarity between
A →Zh and A →ττ
in 2HDM II

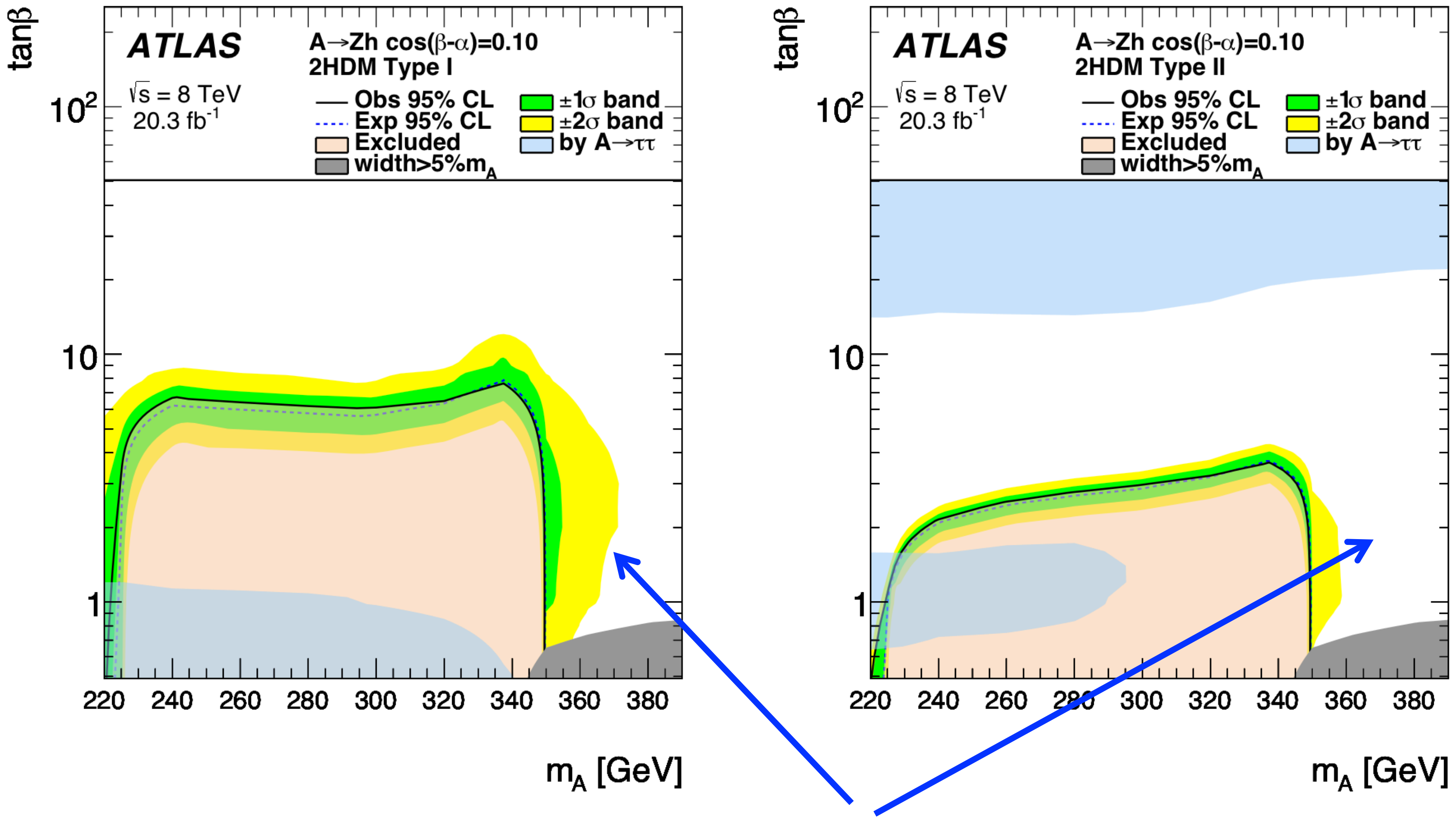
CMS also looked at multi-lepton (≥ 3 including at most 1 τ_{had})
and γγ decays searching for H → hh and A → Zh
⇒ very important to fill the holes when h-b-b ~ 0
(~ h-τ-τ for 2HDM I,II)

(mainly from AZh so only slightly worse if assumption $m_H = m_A$ is relaxed)

Example for 2HDM II
from h coupling measurements
h → ZZ*, WW*, γγ, ττ, bb



In the (m_A,tanβ) plane, for cos(β-α) = 0.1 :



Opening of A → tt

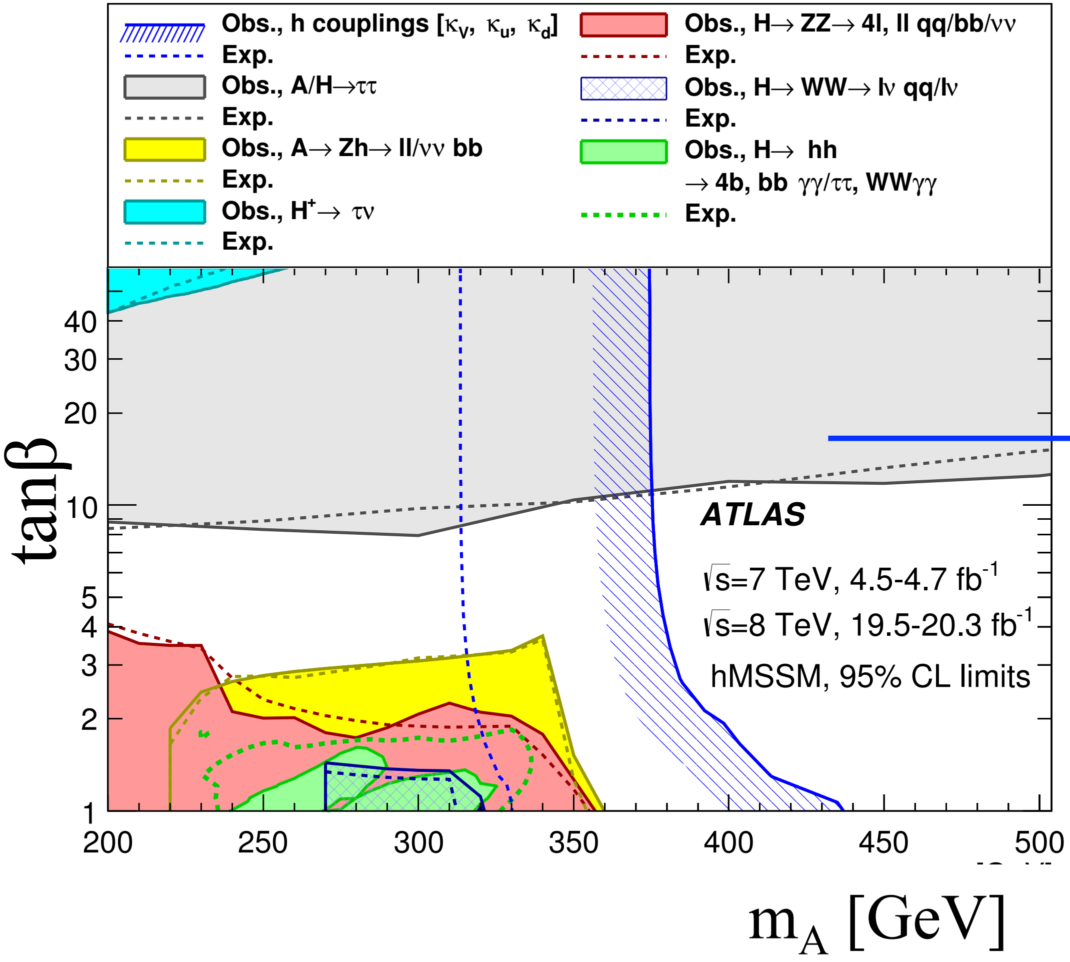
Interpretation in the simplified MSSM

(using $m_H = 125.1\ \mathrm{GeV}/c^2$ to estimate radiative corrections to effective couplings)

Run I analyses not all done yet !
Work in progress for some missing channels

e.g. $pp \rightarrow (b)tH^{\pm}, H^{\pm} \rightarrow tb$ at high $m_{H\pm}$

A simple overlay of all constrains,
not yet a global combination



Remember : the expectation for
$L = 300\ \mathrm{fb}^{-1}$ @ 14 TeV !

- NNLO (+ no decays to gauginos)
- smarter analyses

allowed to get there with 15 less lumi. and a smaller √s !

More channels should be covered in run II benefiting from better tools, e.g. :

$A \rightarrow tt$ for $m_A > 2\ m_{top}$

with proper treatment of the interference with continuum background

Conclusions

- The discovered Higgs particle is ***very*** SM like :
  - * low mass as preferred by SM precision measurements and theory
  - * many measurements pointing to small width
    direct (not very sensitive), off-shell, invisible Higgs exclusions, couplings
    rare decays, …
  - * scalar and no sizeable CP-odd component,
  - * all couplings compatible with 1, typical precision in general fits : ~ 30/40 %

- No sign of BSM in the Higgs sector yet…
  But some small excesses to keep an eye on, e.g. ttH, lepton flavour violation

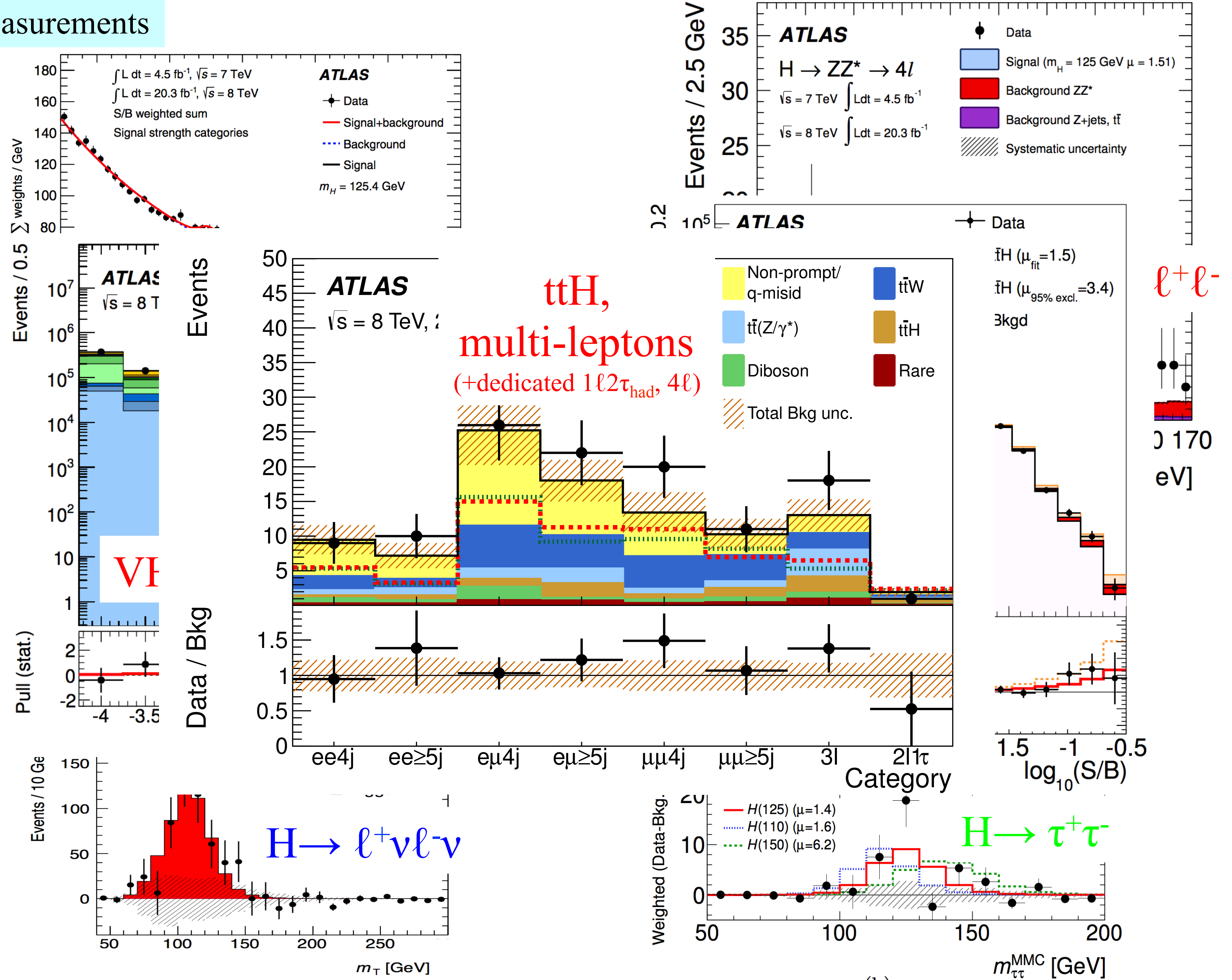
- Run II results might come quickly ! With ~ 4 fb^{-1} (?) of 2015 data at 13 TeV

  ⇒ re-observation of H, especially $\rightarrow \gamma\gamma$, 4ℓ
  (cross-section × 2.3 (3.9 for ttH) w.r.t. 8 TeV)

  ⇒ beyond run I sensitivity for high mass BSM, e.g. $A \rightarrow \tau\tau$

Back-up

Measurements


ttH, multi-leptons

(+dedicated $1\ell 2\tau_{had}$, 4ℓ)

VH

$H \rightarrow \ell^+\nu\ell^-\nu$

$H \rightarrow \tau^+\tau^-$

$\ell^+\ell^-$

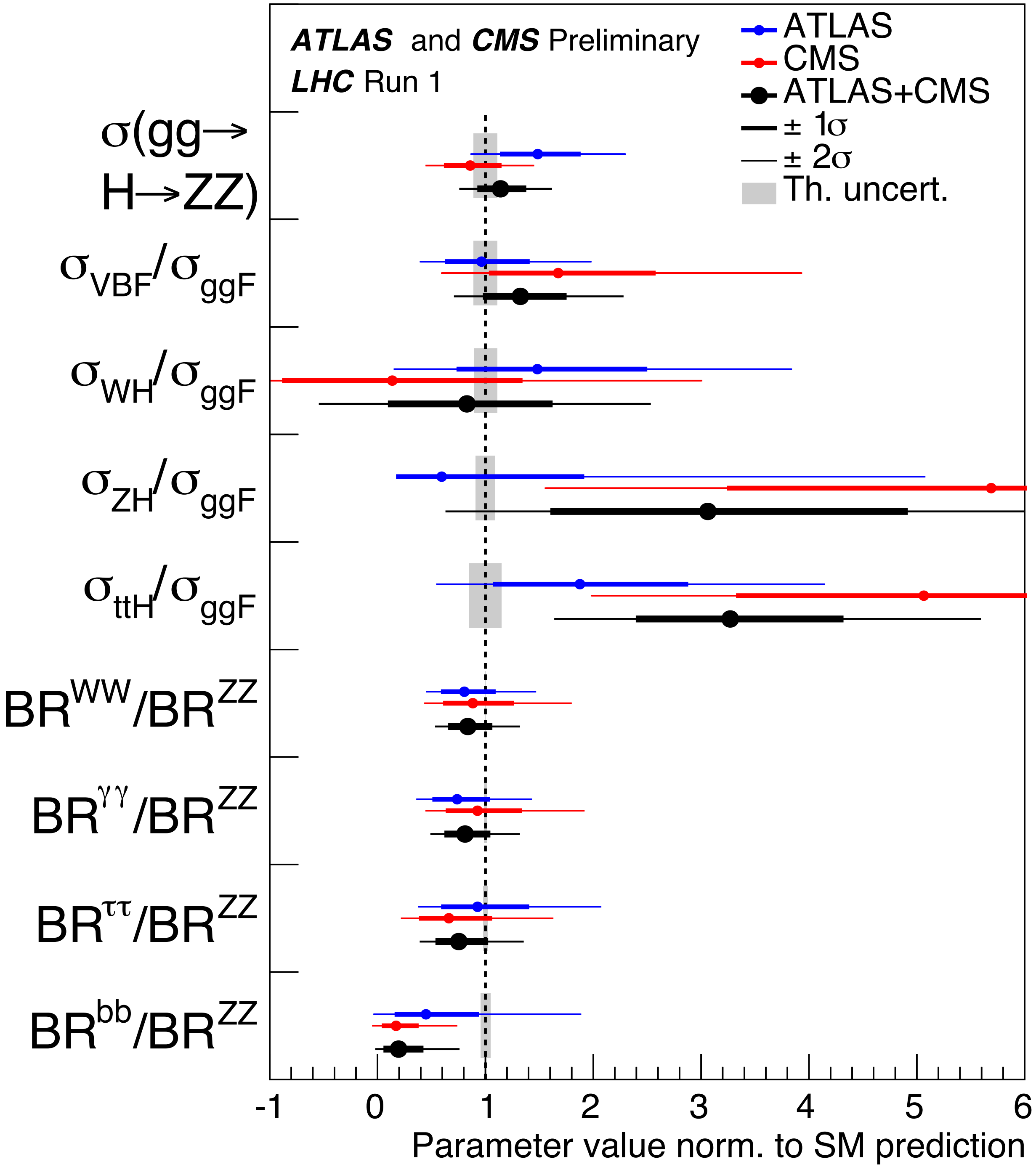
Ratio of cross-section and branching ratios

Br(bb)/Br(ZZ) rather low :

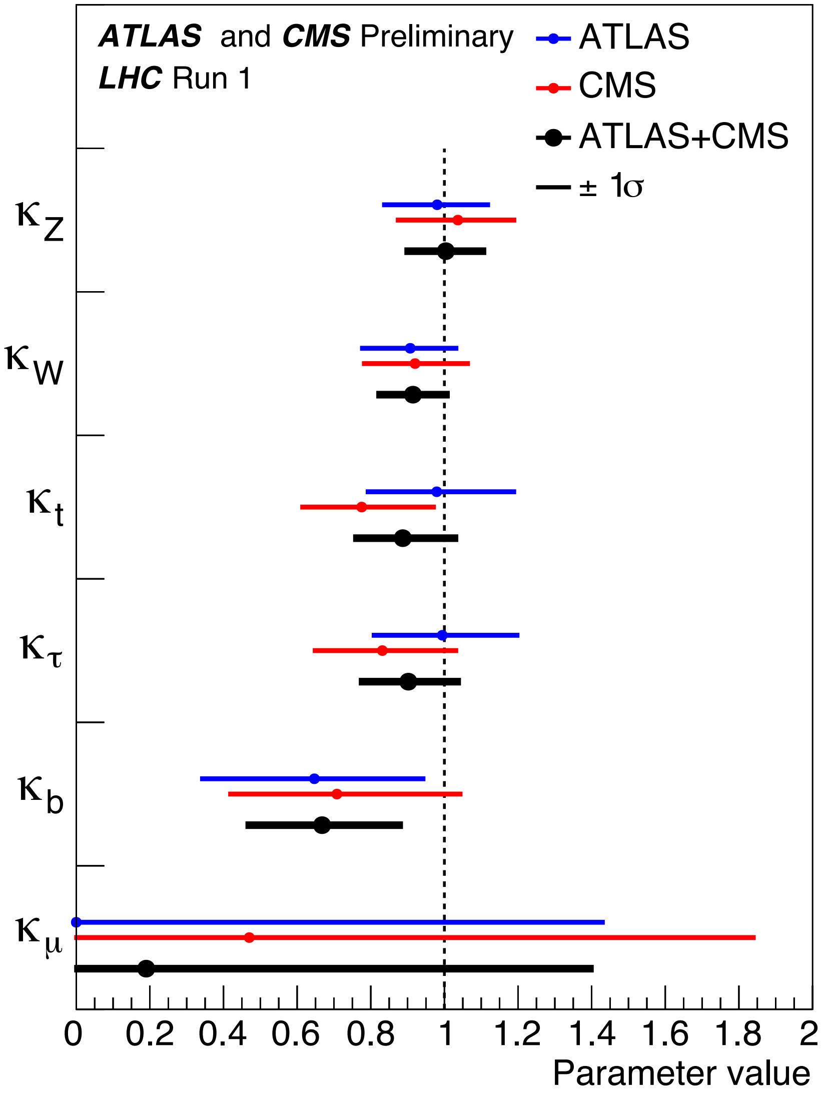
Conspiracy of
- a high $\sigma(ttH)/\sigma_{ggF}$ (multi-lep.)
- a high $\sigma(ZH)/\sigma_{ggF}$ (CMS, dijet cat.)

whereas
- ttH, H → bb
- VH, H → bb

are not high



No BSM, resolved loops, tree level couplings

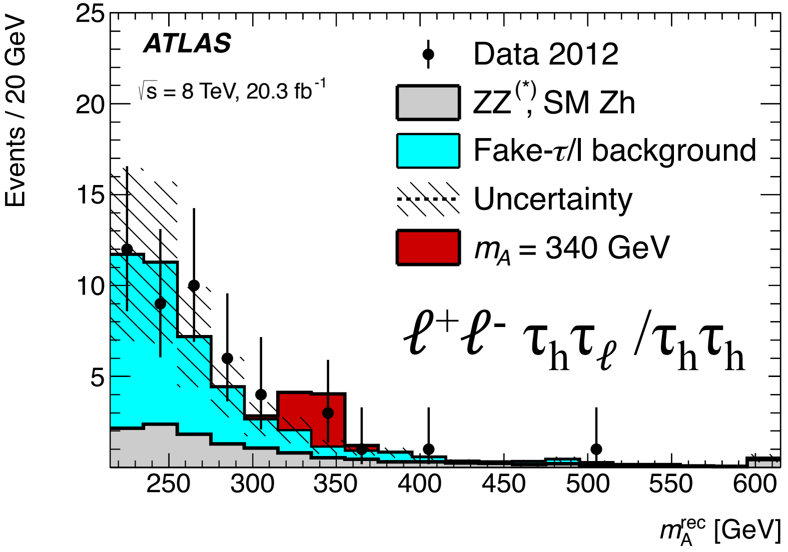


The $\ell^+\ell^-\,\tau\tau$ channel

- Main handle is the 4-body invariant mass estimated as

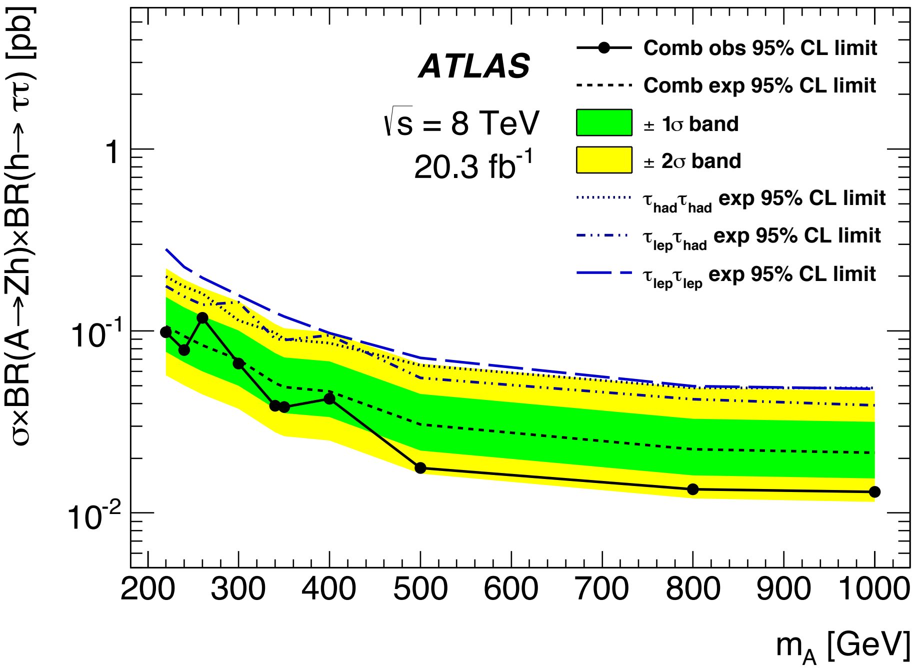
$$m_{rec} = m(\ell^+\ell^-\,\tau\tau) - m_{\ell+\ell-} - m_{\tau\tau} + m_h + m_Z$$

resolution from 3 to 5% for m_A in [0.22,1.00] TeV/c^2



$m_{\tau\tau}$ estimated using the Missing Mass Calculator technic

⇒ No excess…



- Irreducible bkg from ZZ*, SM Zh from simulation
- bkg from fake hadronic tau candidate estimated from data

Rare decays $H \to Q\gamma$, $VP^{(*)}$ ($V = Z/W$)

- Not really BSM but super rare

- Easily enhanced in many BSM frameworks

- Study of the $H \to Vff$ amplitude for cases

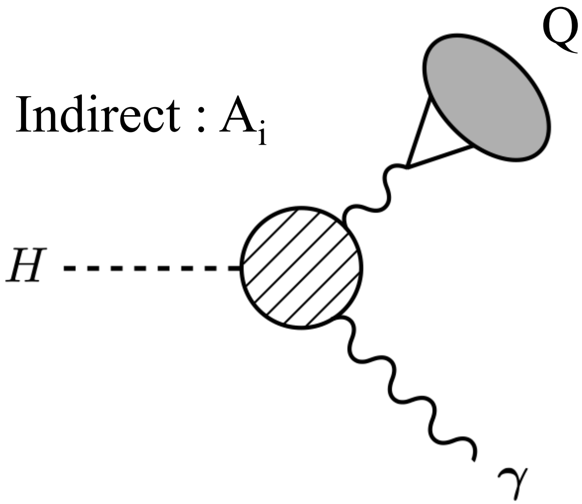
  where *4 leptons* is difficult (low m_{ll})
  where f = quark

$H \rightarrow Q\gamma$: *signal interferometry*

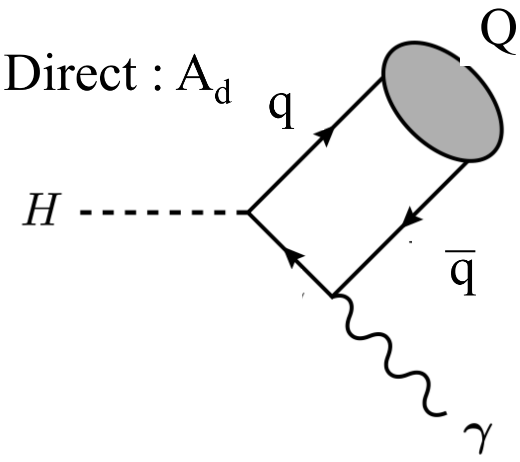
$Q = \Upsilon, \mathbf{J/\psi}, \varphi, \rho$

- Can give a handle on Yukawa couplings of first and second generations
- Rates are tiny.
  Can be viewed as a feasibility study / rehearsal for HL-LHC and beyond
- Idea : interference between two amplitudes gives access to the (normalized) Yukawa coupling κ_q (magnitude **and** sign)

Indirect : A_i



Direct : A_d



$$\Gamma \sim |A_i + A_d\,\kappa_q|^2$$

The most promising channel : $H \to J/\psi\, \gamma \to \mu^+\mu^-\gamma$

$\mathcal{B}(J/\psi \to \mu^+\mu^-) = 5.96\%$

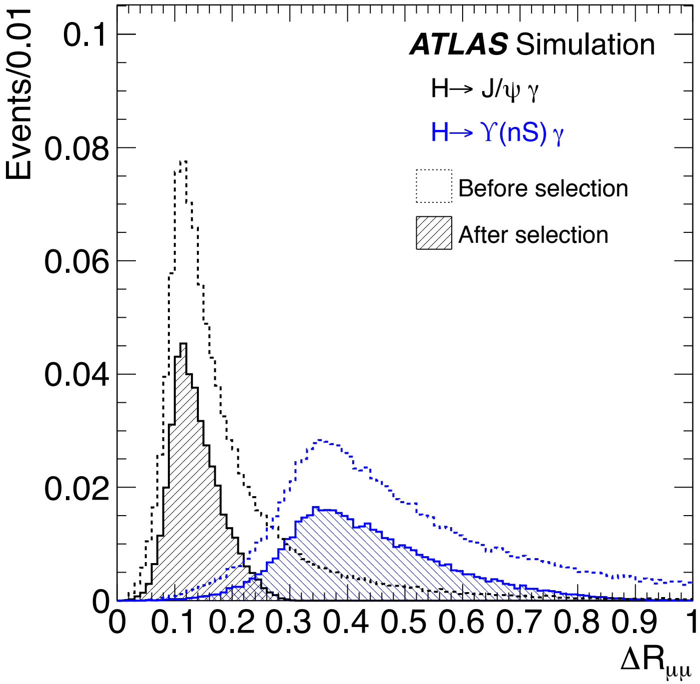
$\Gamma \sim |11.9 - 1.04\, \kappa_c|^2 \times 10^{-10}$ GeV $\Rightarrow$ $\mathcal{B}_{SM} \sim (2.79 \pm 0.16) \times 10^{-6}$ $\Rightarrow$ 20% difference…

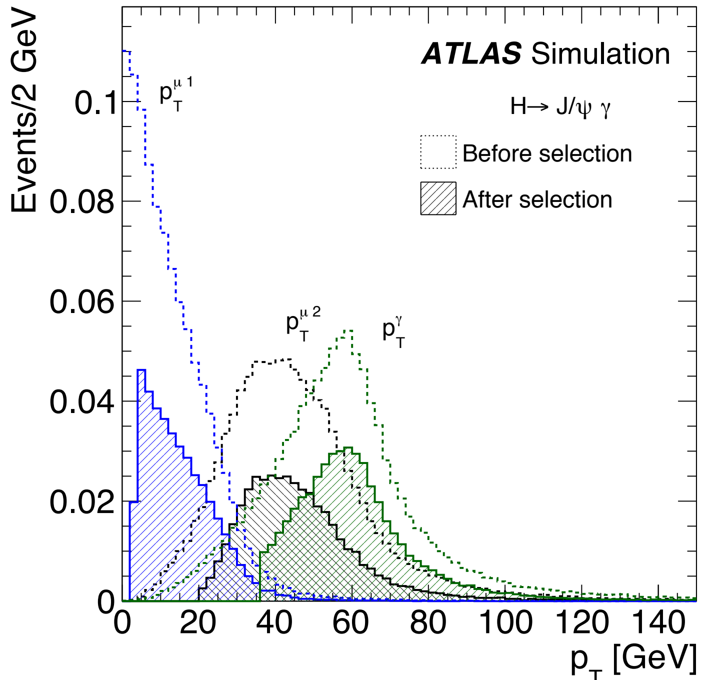
$\mathcal{B}(\kappa_c = 0) \sim 3.38 \times 10^{-6}$

No sensitivity to SM or *"reasonable"* BSM in runI and runII (13 TeV, 100 fb^{-1}), (expect 0.07 and 0.84 event respectively, before selection) but develop baseline for HL-LHC

Clean signature : high p_T isolated photon and di-muon pair (cut 36 GeV/c)
$m_{\mu+\mu-}$ within 150 MeV/c^2 of J/ψ mass (200 MeV/c^2 in endcap categ.)

But cannot use *standard* di-muons or single isolated muon trigger (boosted J/ψ, low $\Delta R(\mu^+,\mu^-)$)



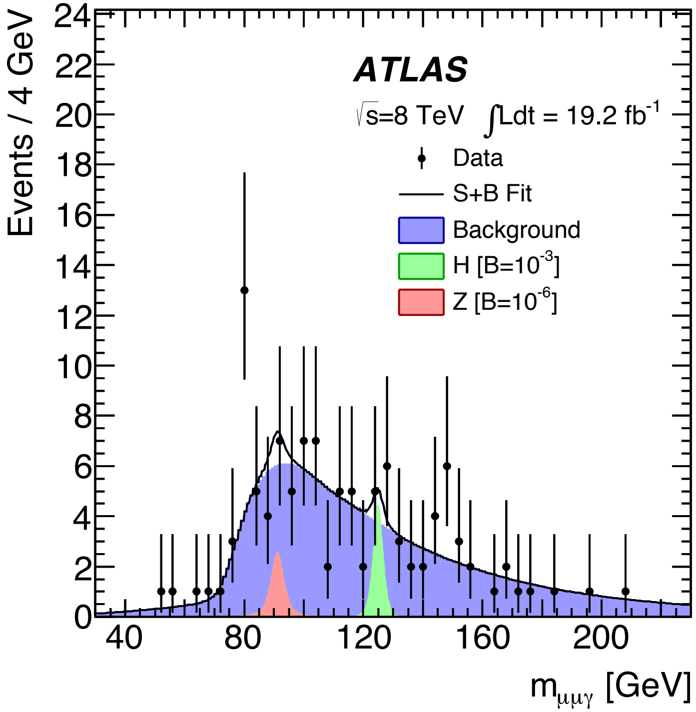


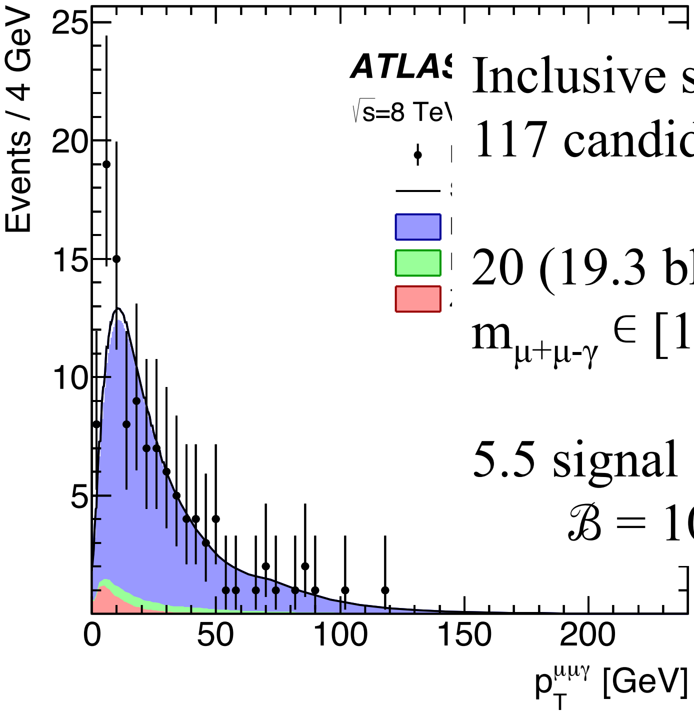
Backgrounds :

- From various QCD processes : prompt J/ψ (~56%),
  non-prompt J/ψ (rejected by a cut on transverse decay length significance, ~3%)
  combinatorial (~41%)
  Shapes estimated with a data driven approach

- Contribution from Dalitz decays $H \rightarrow \gamma^*\gamma \rightarrow \mu^+\mu^-\gamma$ and FSR $Z \rightarrow \mu^+\mu^-\gamma$ negligible with the runI sensitivity.

The background normalisation and signal extraction are done with a 2D fit to the $m_{\mu+\mu-\gamma}$ and $p_T^{\mu+\mu-\gamma}$ distributions (in four different categories)





Inclusive selected sample
117 candidates

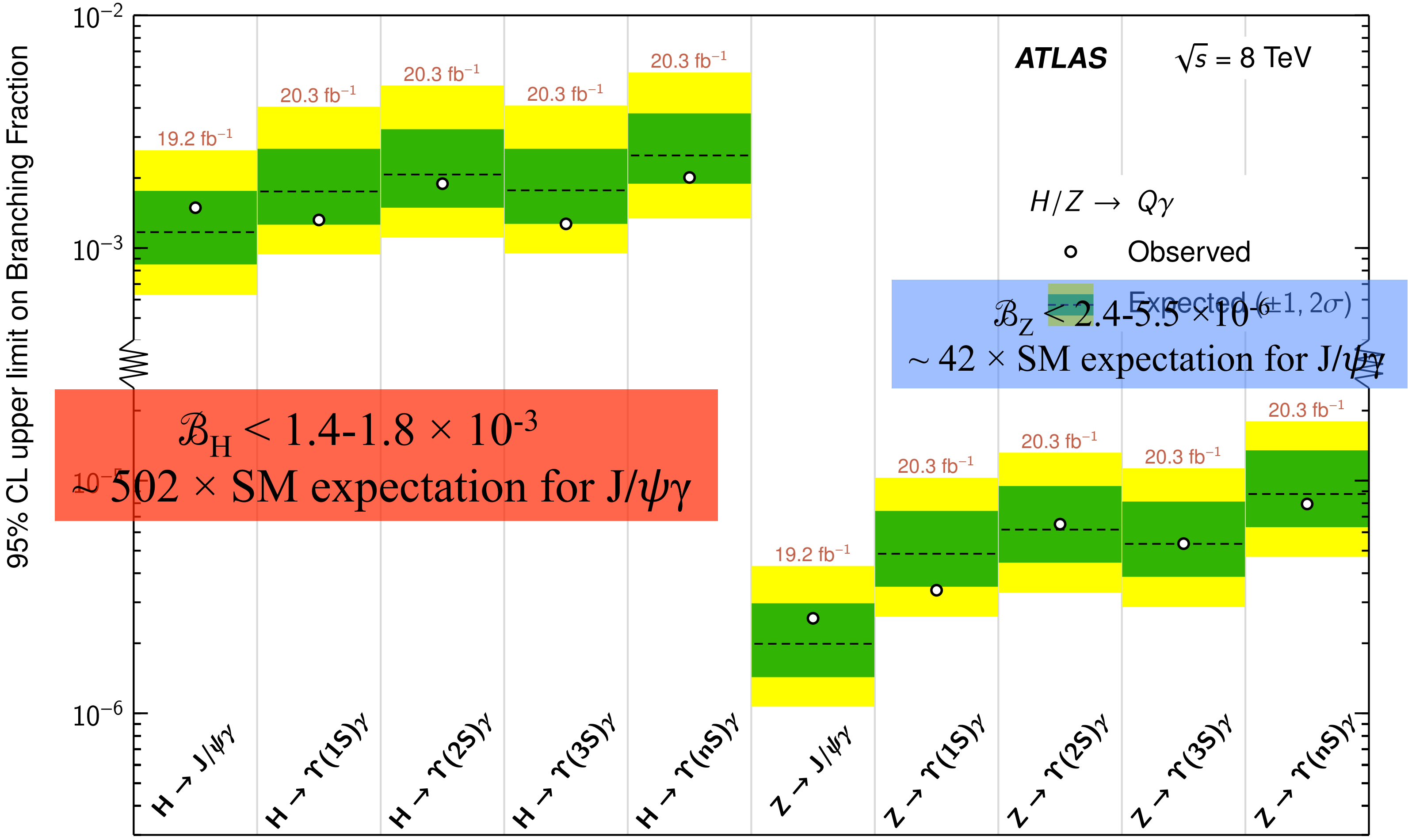
20 (19.3 bkg exp) with
$m_{\mu+\mu-\gamma} \in [115,135]$ GeV/c2

5.5 signal events expected for
$\mathcal{B} = 10^{-3}$

Analysis similar for H → ϒγ :

- SM branching ratio much smaller and uncertain : 8.4 (+19.3,-8.2) × 10^{-10} but highly sensitive to κ_b
- using as additional information $m_{\mu^+\mu^-}$ to handle the $Z \to \mu^+\mu^-\gamma$ normalisation, not negligible in the Y window (and separation of the 3 Υ_{nS}), in a 3D fit

Both analyses are also performed to search for Z → J/ψ (ϒ) + γ ($\mathcal{B} \sim 5.7\ (7.5) \times 10^{-8}$) for which SM sensitivity could be reached at run II, making it a standard candle for the Higgs



$\mathcal{B}_Z < 2.4\text{-}5.5 \times 10^{-6}$

~ 42 × SM expectation for J/ψγ

$\mathcal{B}_H < 1.4\text{-}1.8 \times 10^{-3}$

~ 502 × SM expectation for J/ψγ

Prospects for run II

- Analysis repeated for *"runII"* (14 TeV, 100 fb^{-1}) assuming runI performance and scaling signal and bkg. With a simple 1D ($m_{\mu+\mu-\gamma}$) fit, expect

  $\mathcal{B}(H \rightarrow J/\psi\ \gamma) < 2.6\ 10^{-4}$

  (20-30 % improvement possible with a 2D/3D fit)

  Sensitivity could be improved a little bit going from cut-based to MVA selection

- Issues :

  - **trigger** : muons very collimated → not isolated :

    would topological triggers such as *"2 muons + photon"* help ?

  - SM backgrounds from Higgs (Dalitz decay) : likely not an issue for runII but is larger than signal ⇒ to be dealt with at HL-LHC

  - Is it crazy to try the $e^+e^-\gamma$ final state ?

- What about other Q = φ, ρ ? Would probe κ_s and $\kappa_{u,d}$ (first generation !)

$\mathcal{B}(H \rightarrow \rho\gamma) = (1.9 \pm 0.2) \times 10^{-5}$ and $\mathcal{B}(H \rightarrow \varphi\gamma) = (3.0 \pm 0.2) \times 10^{-6}$
leading to $N(\pi^+\pi^-\gamma) \sim 96$ and $N(K^+K^-\gamma) \sim 7$ events @ 13 TeV, 100 fb^{-1}

$H \rightarrow \rho\gamma$ might seem promising ⇒ perform rough truth-level acceptance study :

- $p_T^\gamma > 50$ GeV/c (very tight ?), $p_T^{trk} > 10$ GeV/c (within std η acceptance)

→ acceptance ~ 31% : $N_{acc} \sim 30$

+ rather clear topology : high p_T isolated photon recoiling against a two track jet

BUT :

- Huge QCD background ! (wide peak in $m_{\pi+\pi-}$?)
- Single photon trigger not useable (too high threshold)
  Would need photon + tau and/or tight isolated photon…

Even more difficult : $H \to VP^{(*)}$, $V = W, Z$, $P^{(*)}$ = pseudo-scalar (vector)

A priori best channels : $\mathcal{B}(H \to W^{\pm}\pi^{\mp}, W^{\pm}\rho^{\mp}) \sim 1.2 \times 10^{-5}$, 1.6×10^{-5}

$\Rightarrow N_{prod}(\ell^{\pm}\nu\pi^{\mp}, \ell^{\pm}\nu\pi^{\mp}\pi^{0}) \sim 13, 17.5$ @ 13 TeV, 100 fb^{-1} ($\ell = e,\mu$)

Rough truth-level acceptance :

- $p_T^{\ell} > 30$ GeV/c, $E_t^{miss} > 40$ GeV, $p_T^{trk} > 20$ GeV/c (huge bkg from W)

$\Rightarrow$ Acceptance ~ 15%, $N(W^{\pm}\pi^{\mp}) \sim 2$

- and no mass peak, only jacobian “peak” in m_T

($W^{\pm}\rho^{\mp}$ even harder because softer charged pion…)

Very very very challenging…