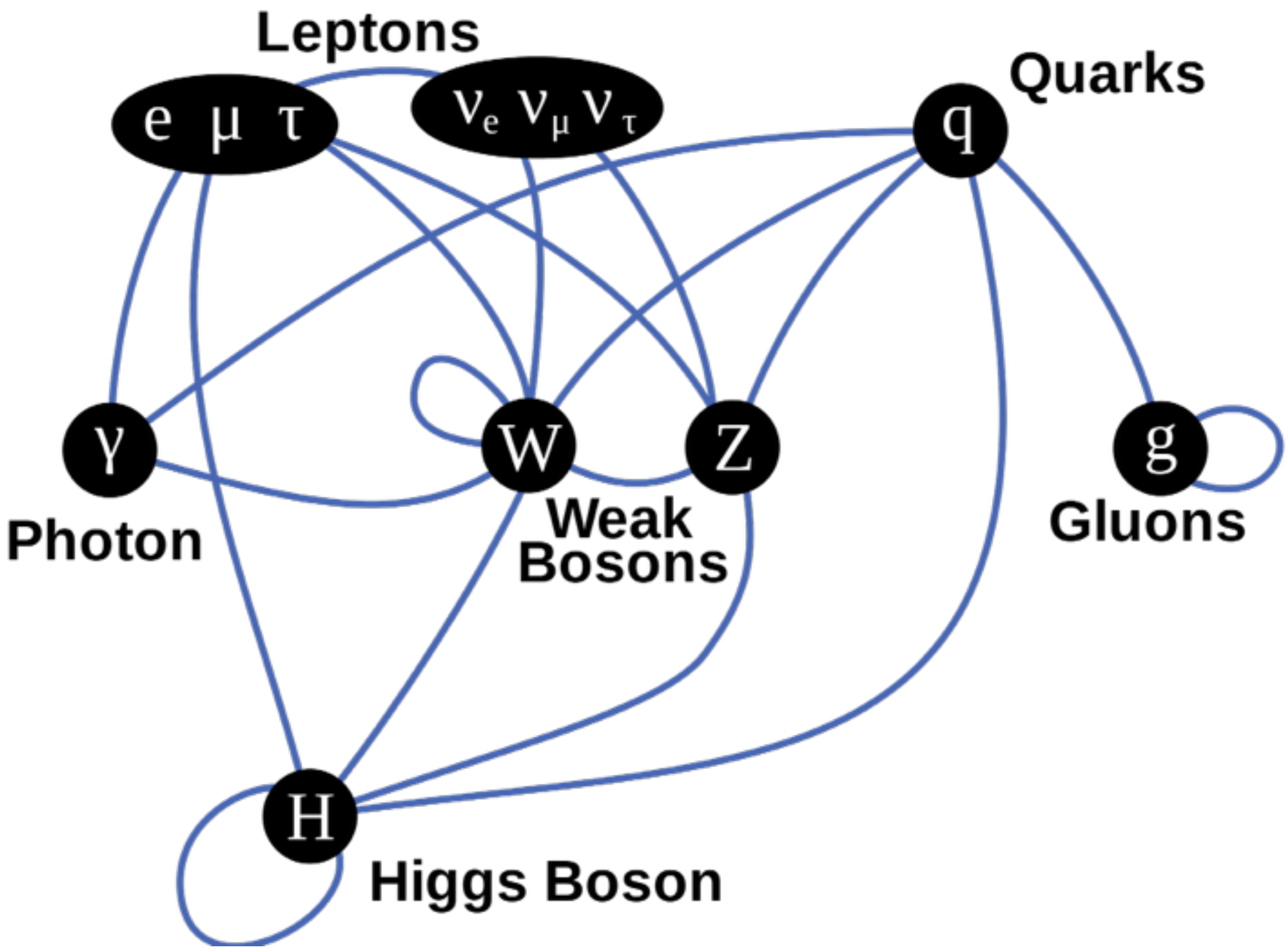
Lecture 2: Higgs

S.Xella

Standard Model Reminder



Higgs field and particle

after Spontaneous Symmetry Breaking (SSB), $\Phi^0 = v/\sqrt{2}$,
and

$$m_W = \tfrac{1}{2} v \, |g| \, ,$$

$$m_Z = \tfrac{1}{2} v \sqrt{g^2 + g'^2},$$

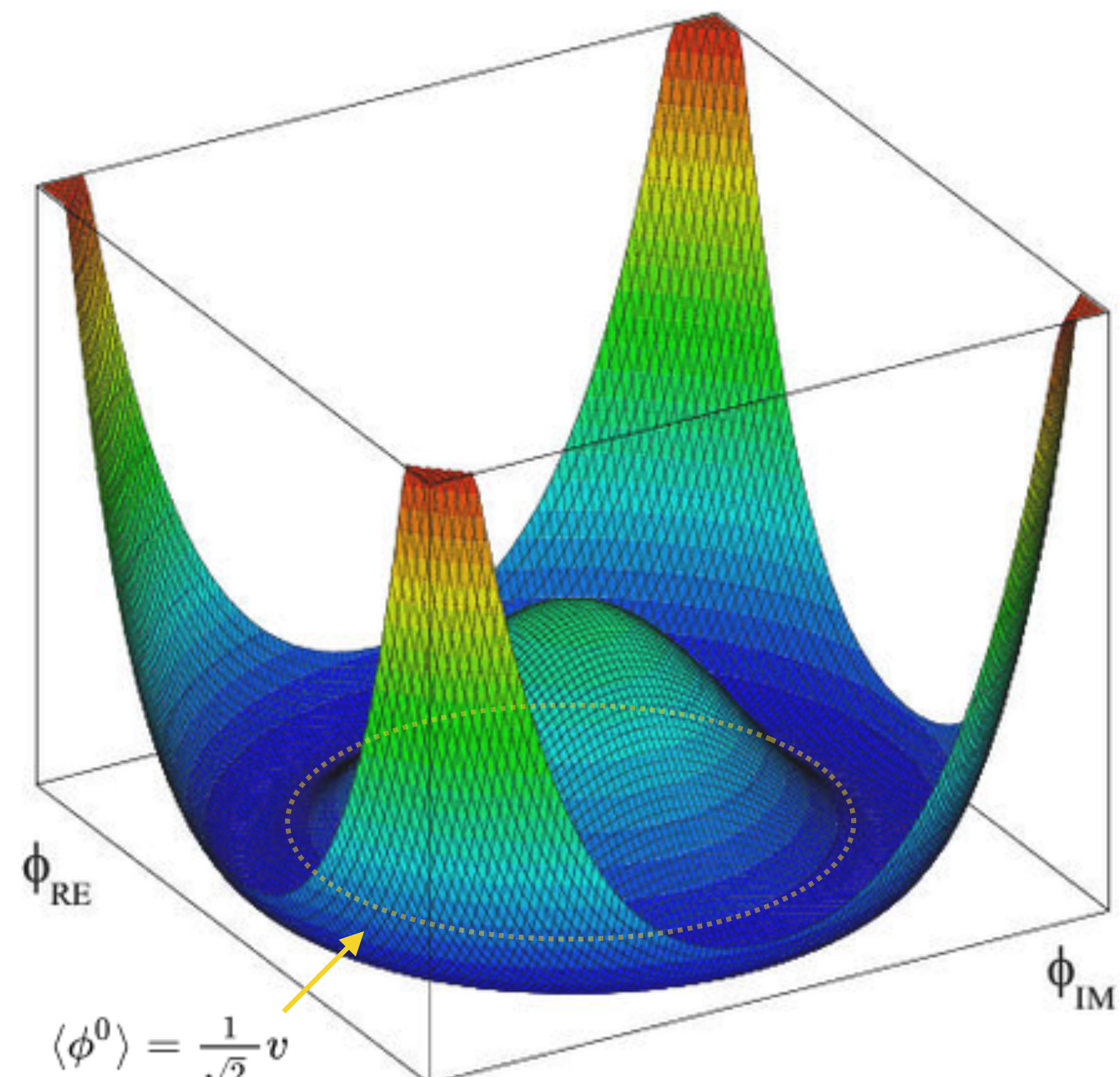
$$\cos\theta_W = \frac{m_W}{m_Z} = \frac{|g|}{\sqrt{g^2 + g'^2}}$$

$$m_H = \sqrt{2\mu^2} \equiv \sqrt{2\lambda v^2}.$$

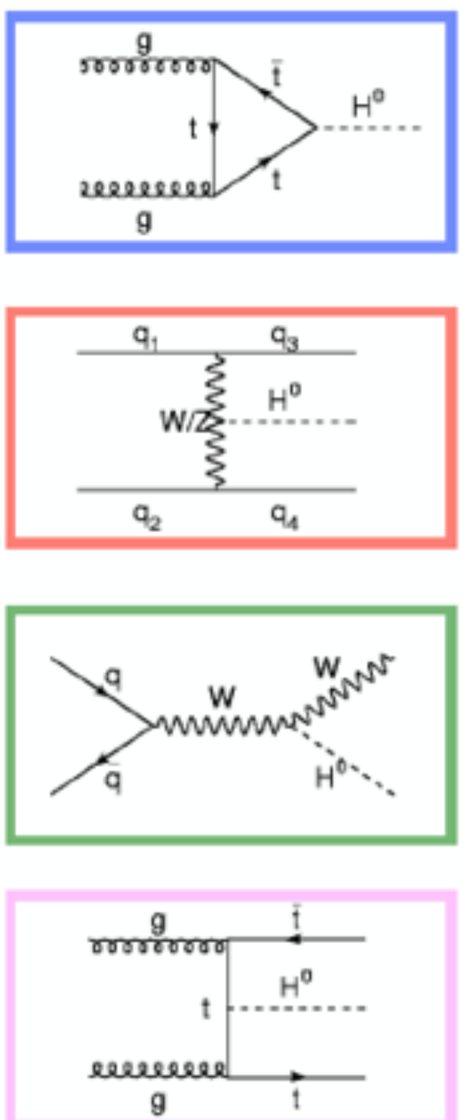
$$m^i_{u,d,e} = \frac{1}{\sqrt{2}} \lambda^i_{u,d,e} v$$

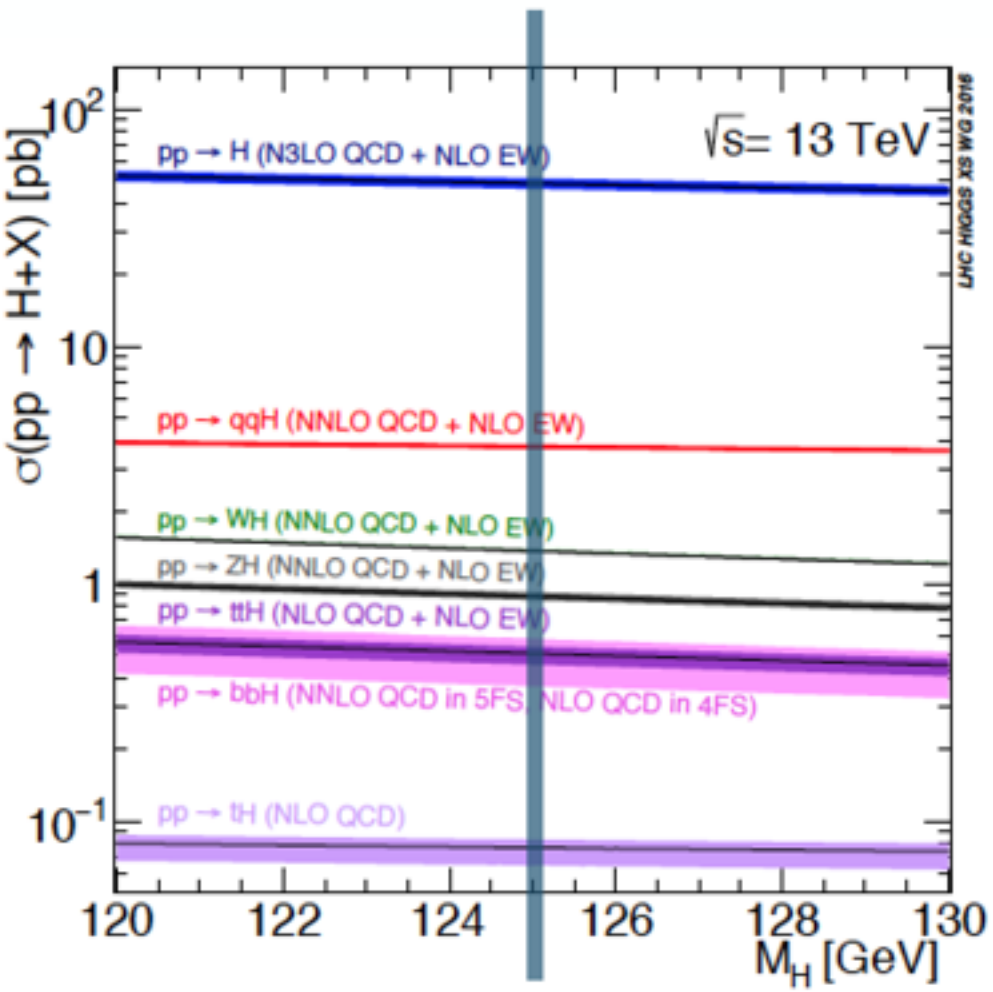
$$\boldsymbol{m^2_{Z,W} = \lambda_{Z,W}\, v}$$

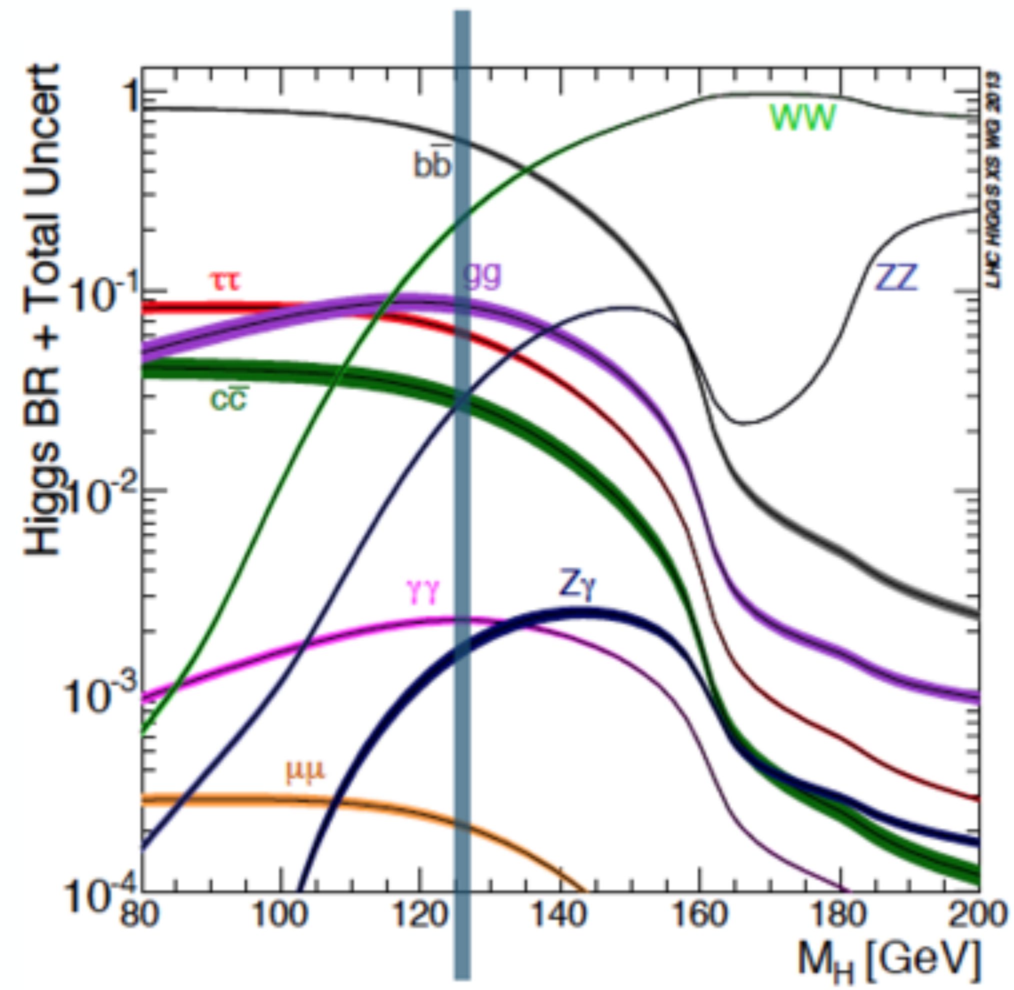
$$\mathcal{L}_H = \left| \left(\partial_\mu - i g W^a_\mu \tau^a - i \frac{1}{2} g' B_\mu \right) \phi \right|^2 + \underline{\mu}^2 \phi^\dagger \phi - \underline{\lambda} (\phi^\dagger \phi)^2,$$



Higgs production/decay @ LHC







once the mass of the Higgs is known then one can predict strength of Higgs field coupling to fermions and bosons

How can we be sure it is the SM Higgs we see ?

confirming the SSB mechanism of the Standard Model means:

measuring the Higgs boson mass, width, spin, charge, CP quantum numbers,

AND

observing the existence of HHH interaction ,

AND

measuring all couplings to fermions and bosons (via production and decay). In particular, fermions-Higgs interaction is a bit ad-hoc added to the SM: Important to test it well

AND

ensure everything consistently points to the same picture (i.e. fit results wrt SM points to 1 in all parameters).

How can we be sure it is the SM Higgs we see ?

confirming the SSB mechanism of the Standard Model means:

measuring the I ... um numbers,

AND

observing the e ...

AND

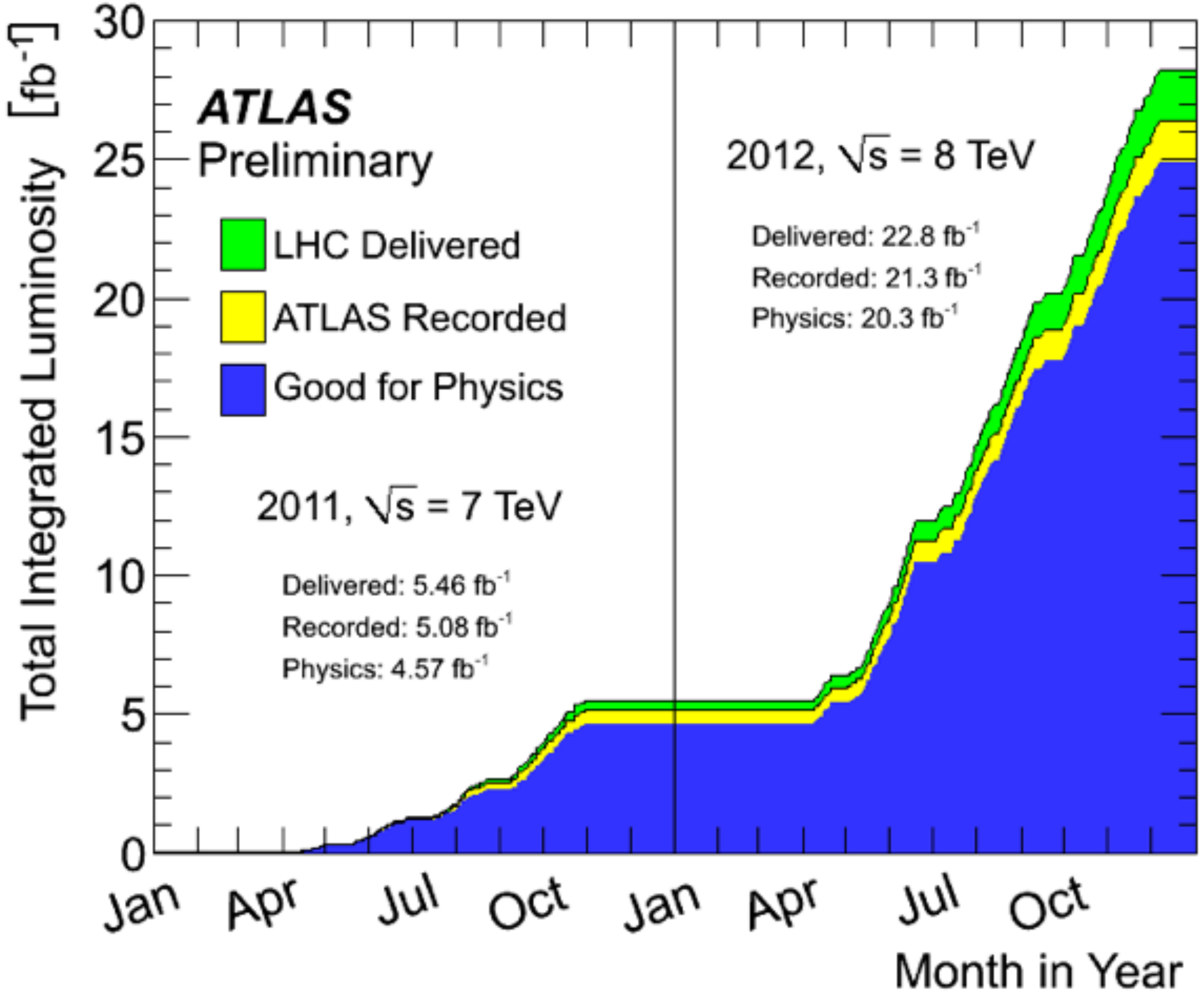
measuring all c ... and decay). In
particular, ferm ... he SM:
Important to tes ...

AND

ensure everything consistently points to the same picture (i.e. fit results wrt SM points to 1 in all parameters).

there is a new particle.
now is no time to get sloppy.
we need to measure everything about it !

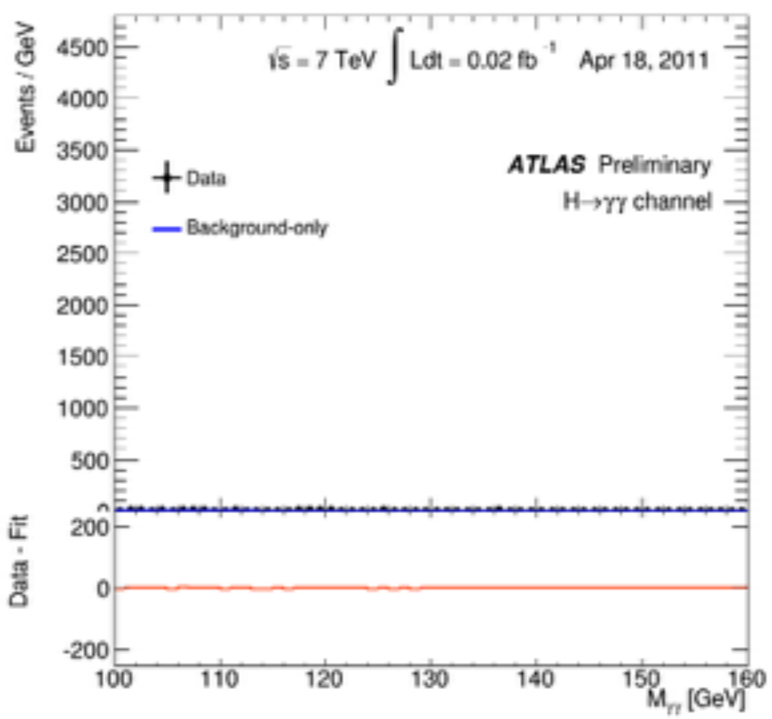
LHC Run-1 dataset



LHC has delivered twice more data, at four times higher energy, in one year than all Tevatron in 20 years

Higgs discovery with bosons

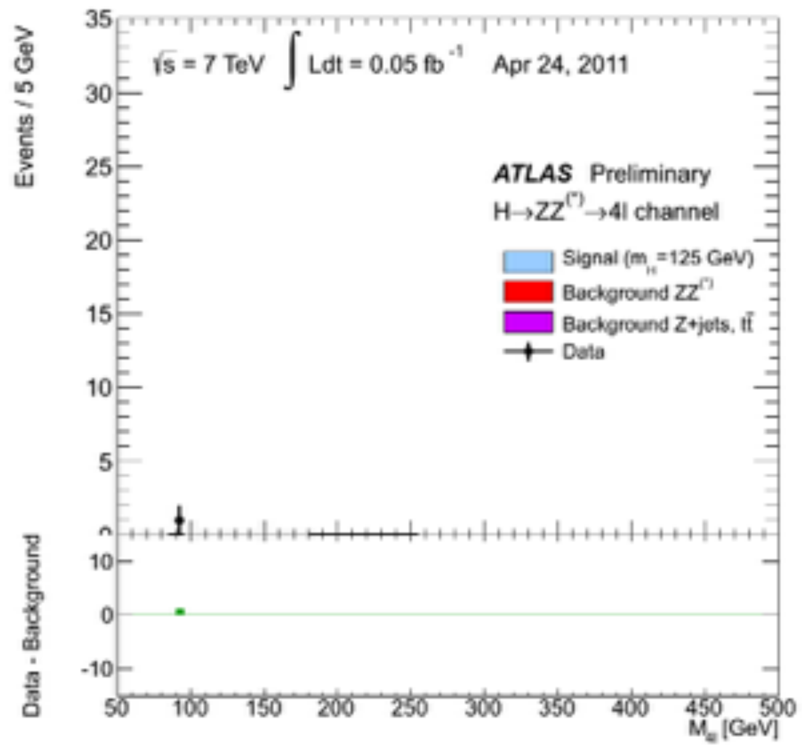
H to γγ



Observed 105-160 GeV	Expected signal
13196	468

Phys. Rev. D 90, 112015 (2014)

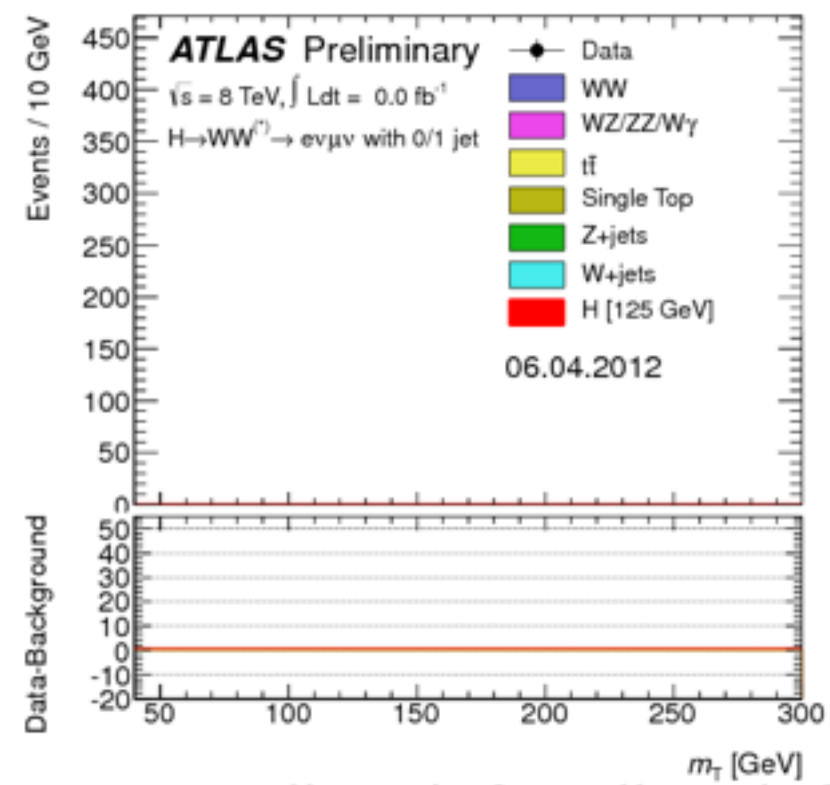
H to ZZ to 4l



Observed 120-130 GeV	Expected signal
37	18.2

Phys. Rev. D 91, 012006 (2015)

H to WW

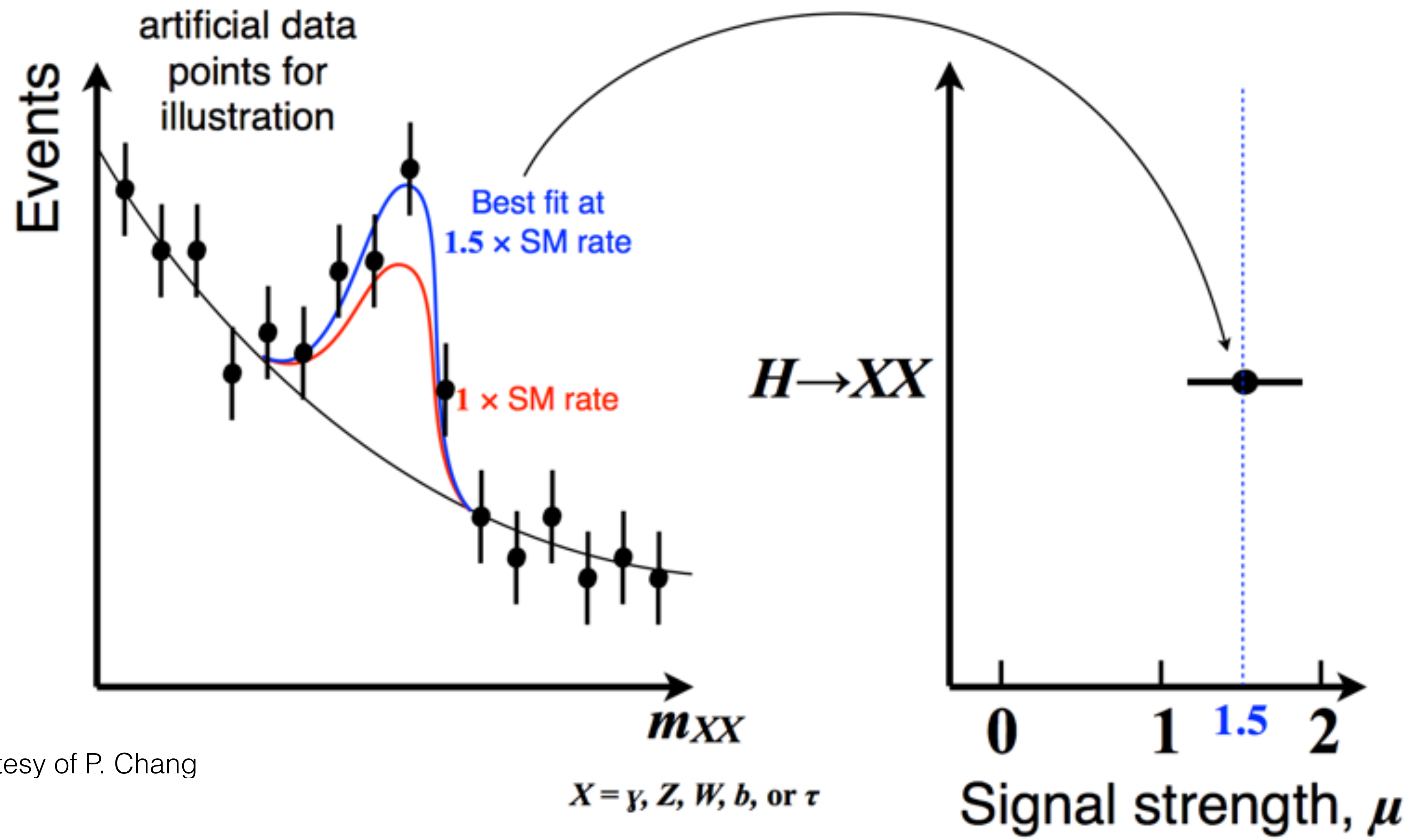


$$m_{\mathrm{T}} = ((E_{\mathrm{T}}^{\ell\ell} + E_{\mathrm{T}}^{\mathrm{miss}})^2 - |\,\mathbf{p}_{\mathrm{T}}^{\ell\ell} + \mathbf{E}_{\mathrm{T}}^{\mathrm{miss}}\,|^2)^{1/2}$$

Observed N(jet) 0,1,>1	Expected signal
831, 309, 55	100, 41, 10.9

Phys. Lett. B 726 (2013) 88

SM Higgs signal



courtesy of P. Chang

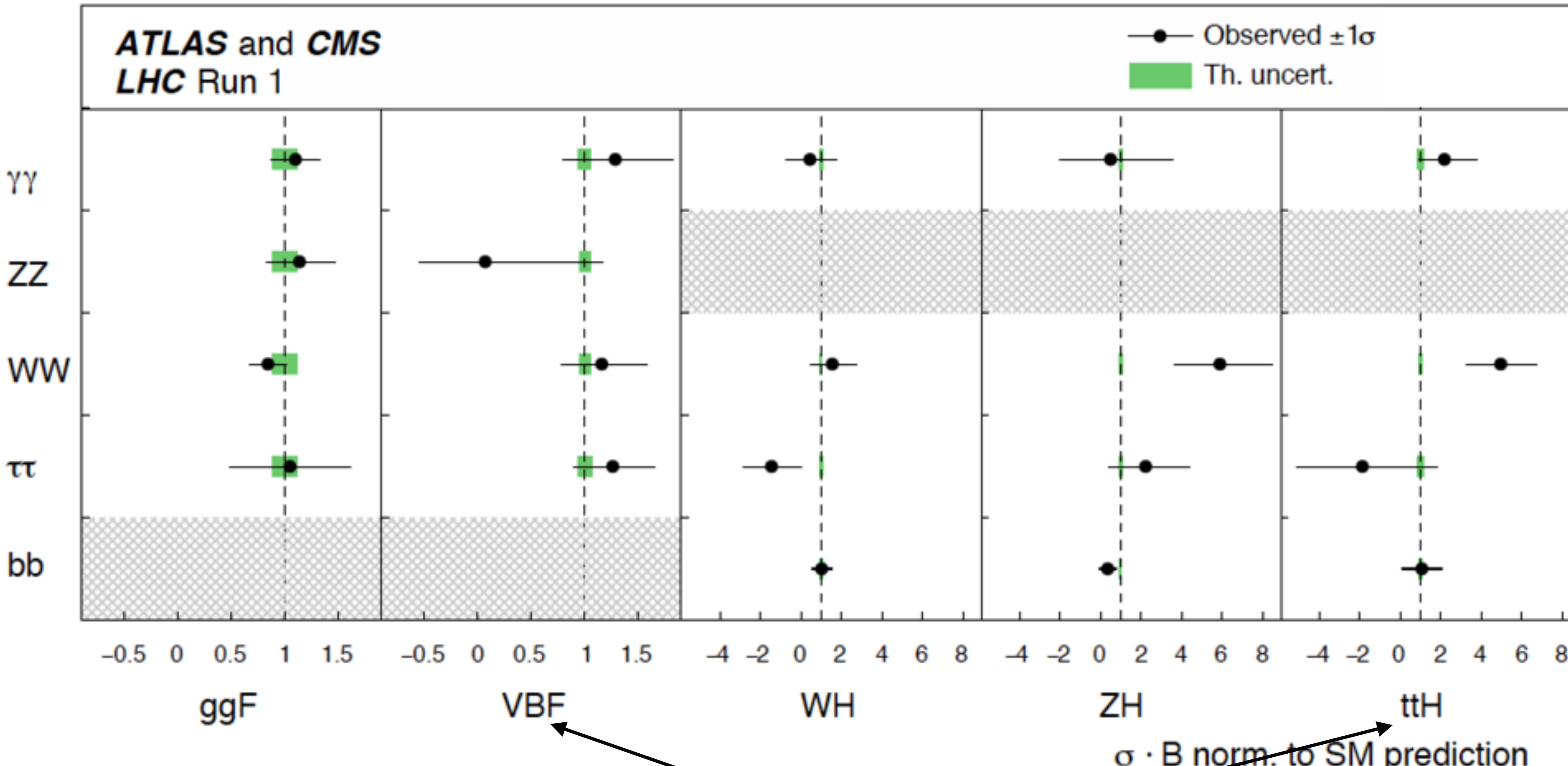
Signal strength → $\mu_{P,X} \sim \dfrac{\left.\sigma_P \times \mathrm{Br}_X\right|_{\text{Data}}}{\left.\sigma_P \times \mathrm{Br}_X\right|_{\text{Theory}}}$

$P \in \{ggF, VBF, VH, ttH\}$

$X \in \{\gamma\gamma, ZZ, WW, bb, \tau\tau\}$

μ=1 means data matches theory (=SM for example)

After Run–1 :



not yet observed (not yet > 5 sigma away from 0) : VBF difficult, ttH rare

bb, ττ : no evidence or just evidence : difficult final states to use

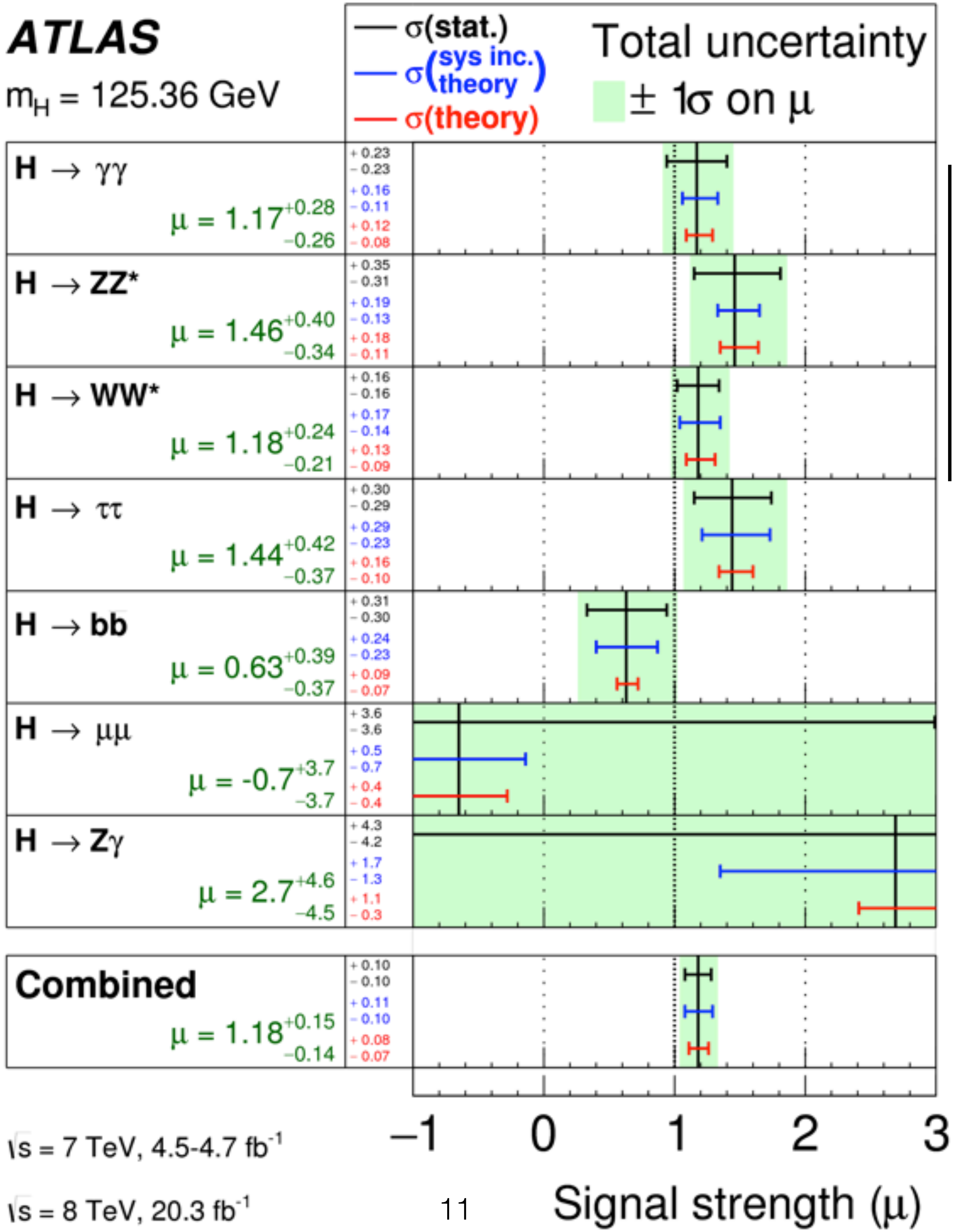
After Run-1:

quantifies our degree of belief

$\mu_{\text{All},X=\gamma\gamma,ZZ,WW}$

$\mu_{\text{All},X=\tau\tau}$

$\mu_{\text{All},X=bb}$



observation (5σ away from 0)

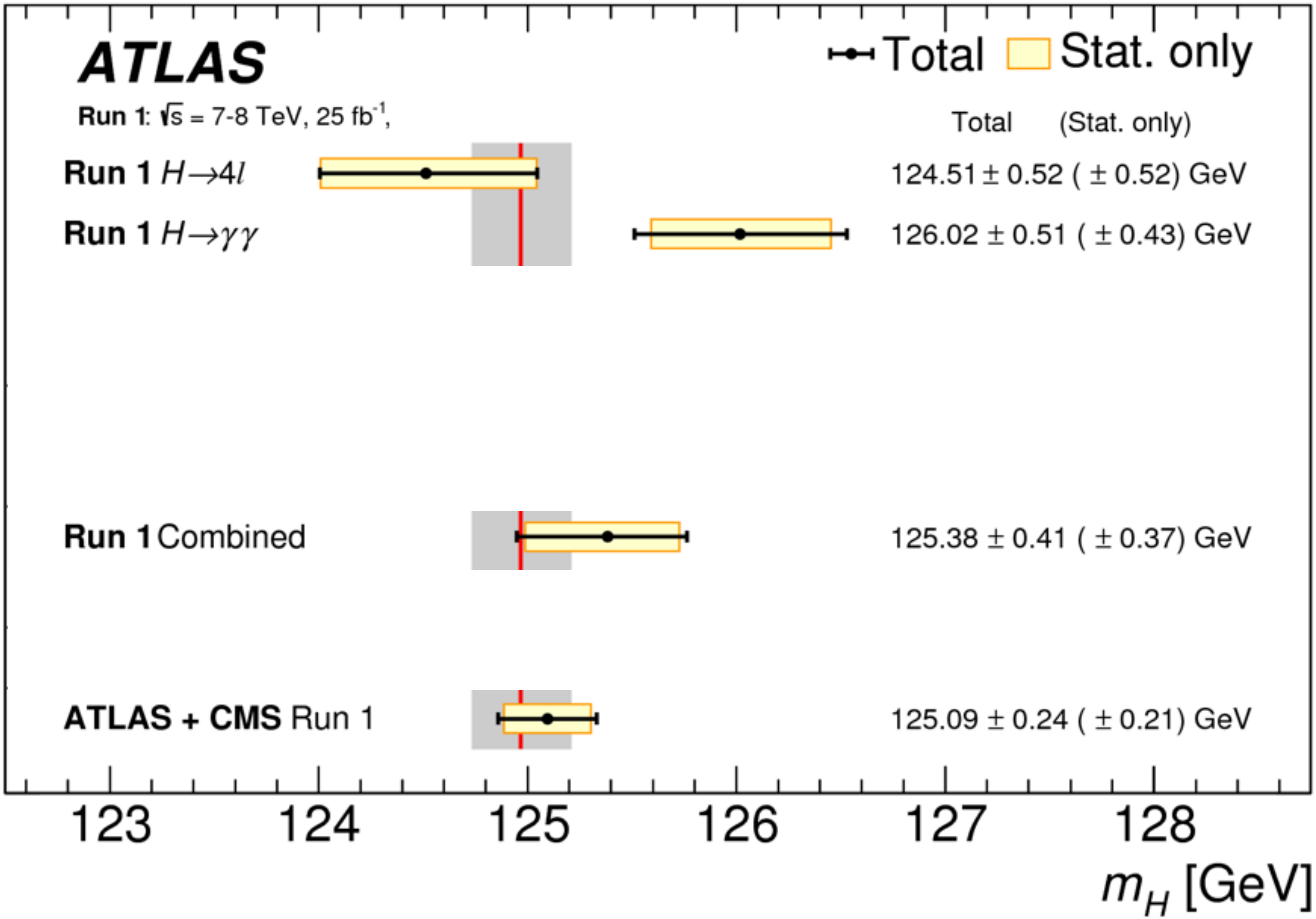
evidence (3σ away from 0)

:(

:(

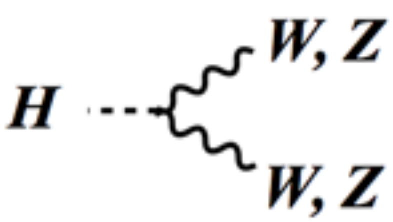
:(

After Run-1 :

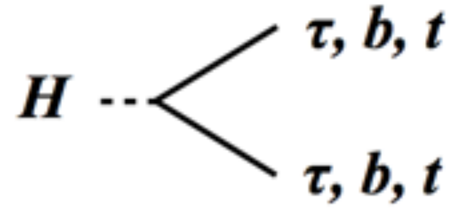


these are the final states with the best energy resolution

couplings H-to-X in decay/production

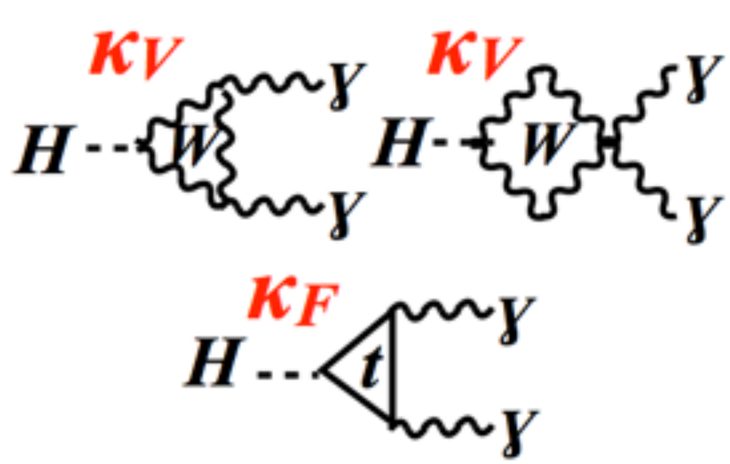


$$g_V \sim \kappa_V \frac{2M_V^2}{v}$$

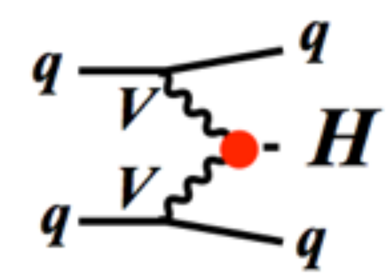


$$g_F \sim \kappa_F \frac{M_F}{v}$$

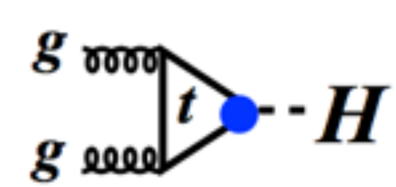
$v =$ v.e.v

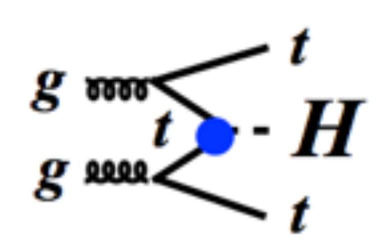


$$\kappa_\gamma^2 \sim 1.59\,\kappa_V^2 - 0.66\,\kappa_V\kappa_F + 0.07\,\kappa_F^2$$



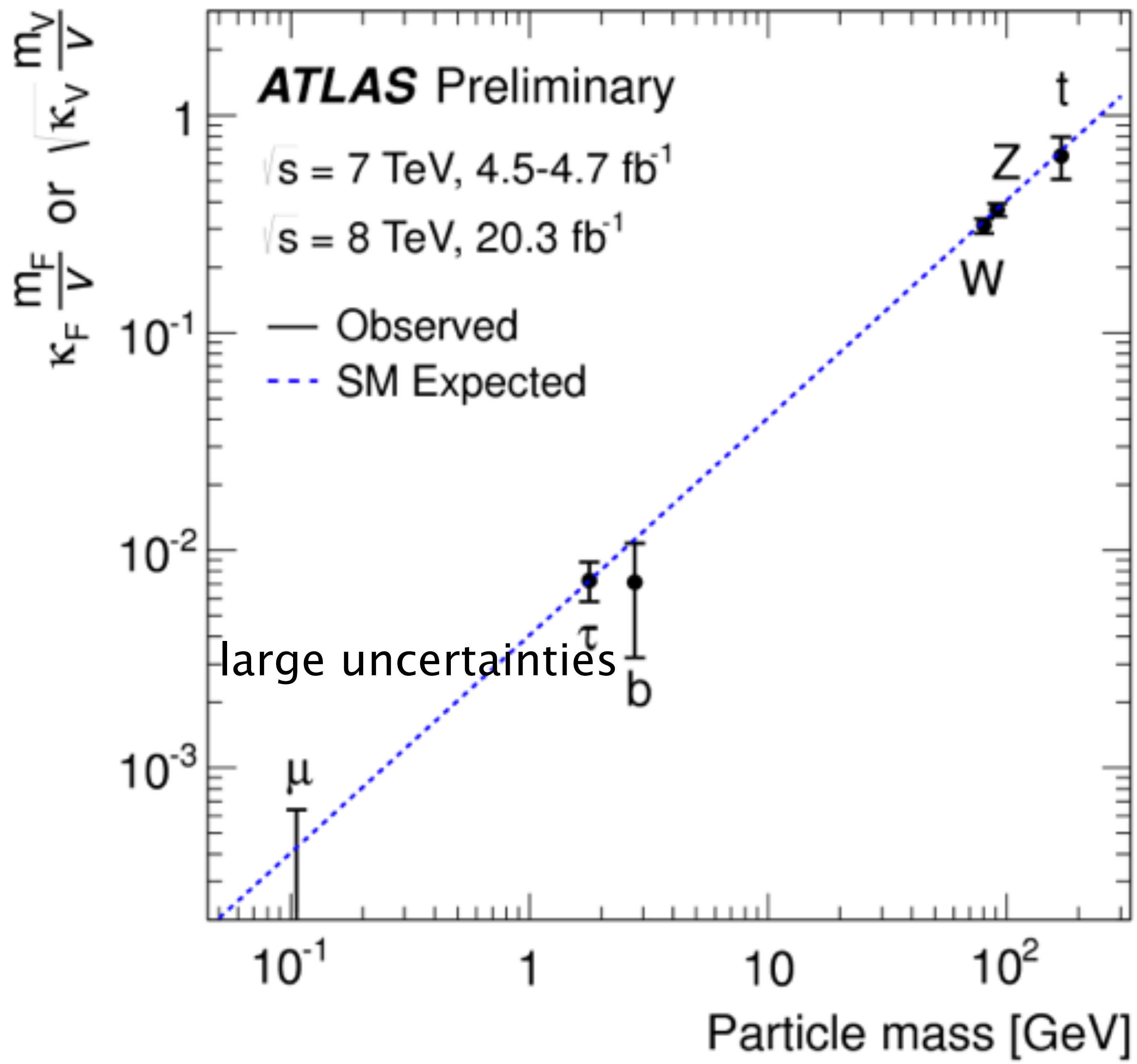
K_V





K_F

Higgs couplings- Run-1



large uncertainties

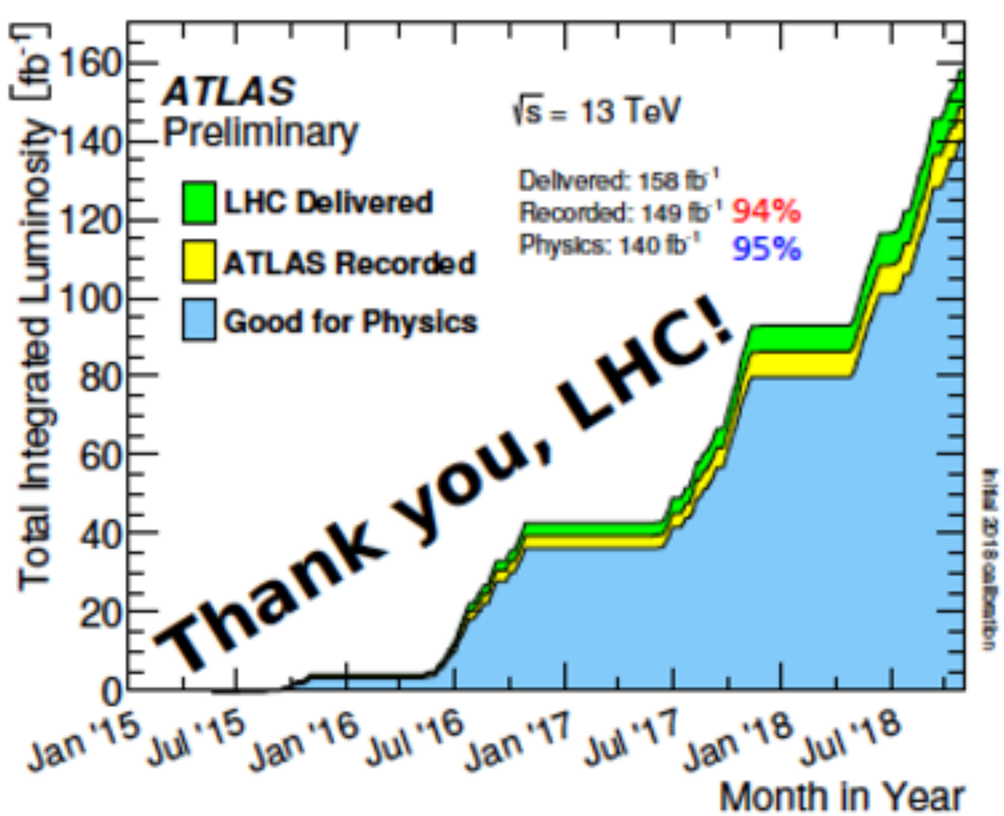
~ok
could be better

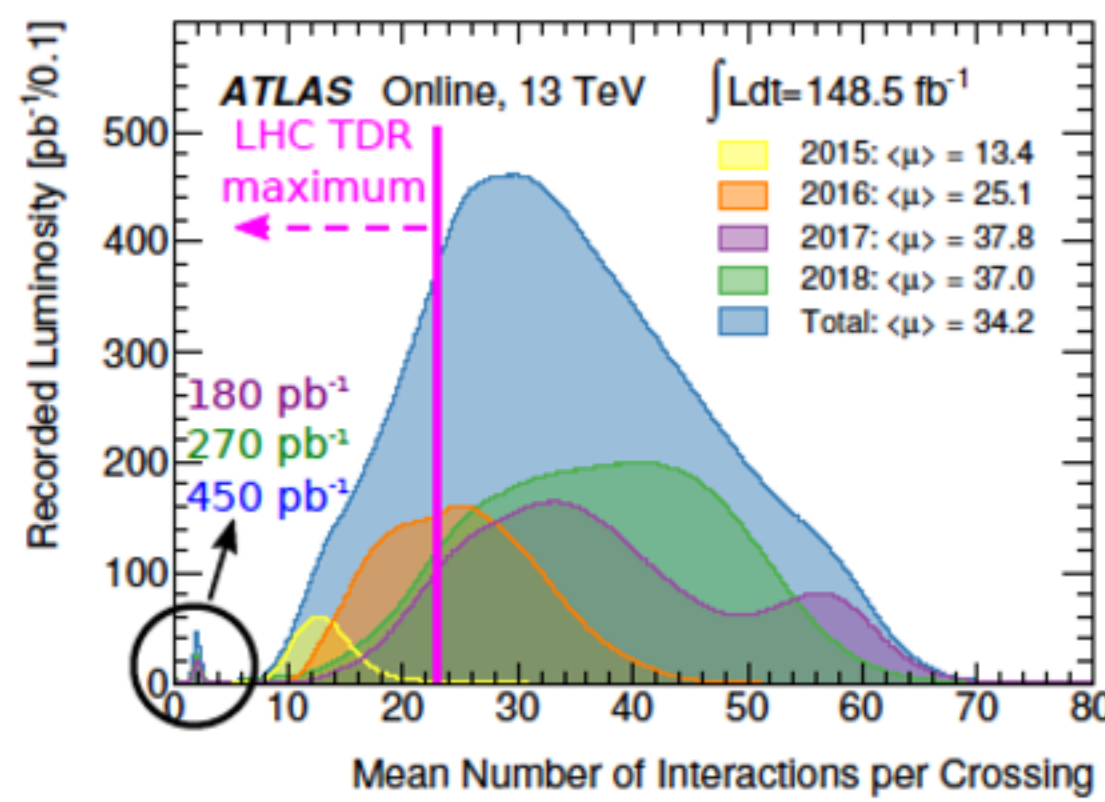
LHC Run-2 dataset

- ATLAS recorded nearly 150 fb^{-1} of *pp* data in Run 2 (6 times Run-1 data)
  - Continually improving data taking efficiency and data quality!

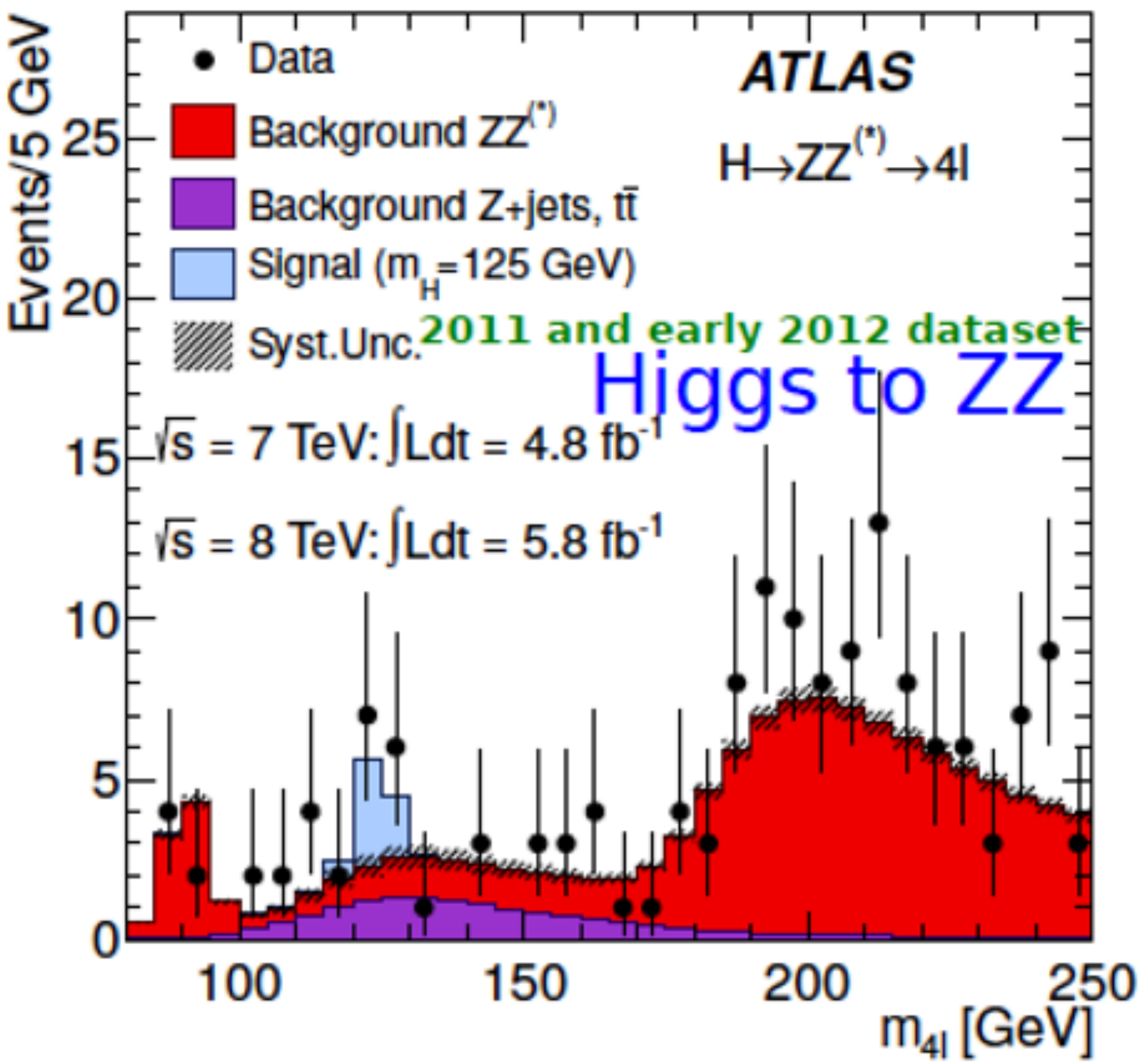
	2015	2016	2017	2018	Run 2
Data taking	92.4%	92.5%	93.4%	95.7%	94%
Data quality	87.1%	92.8%	93.6%	97.5%	95%

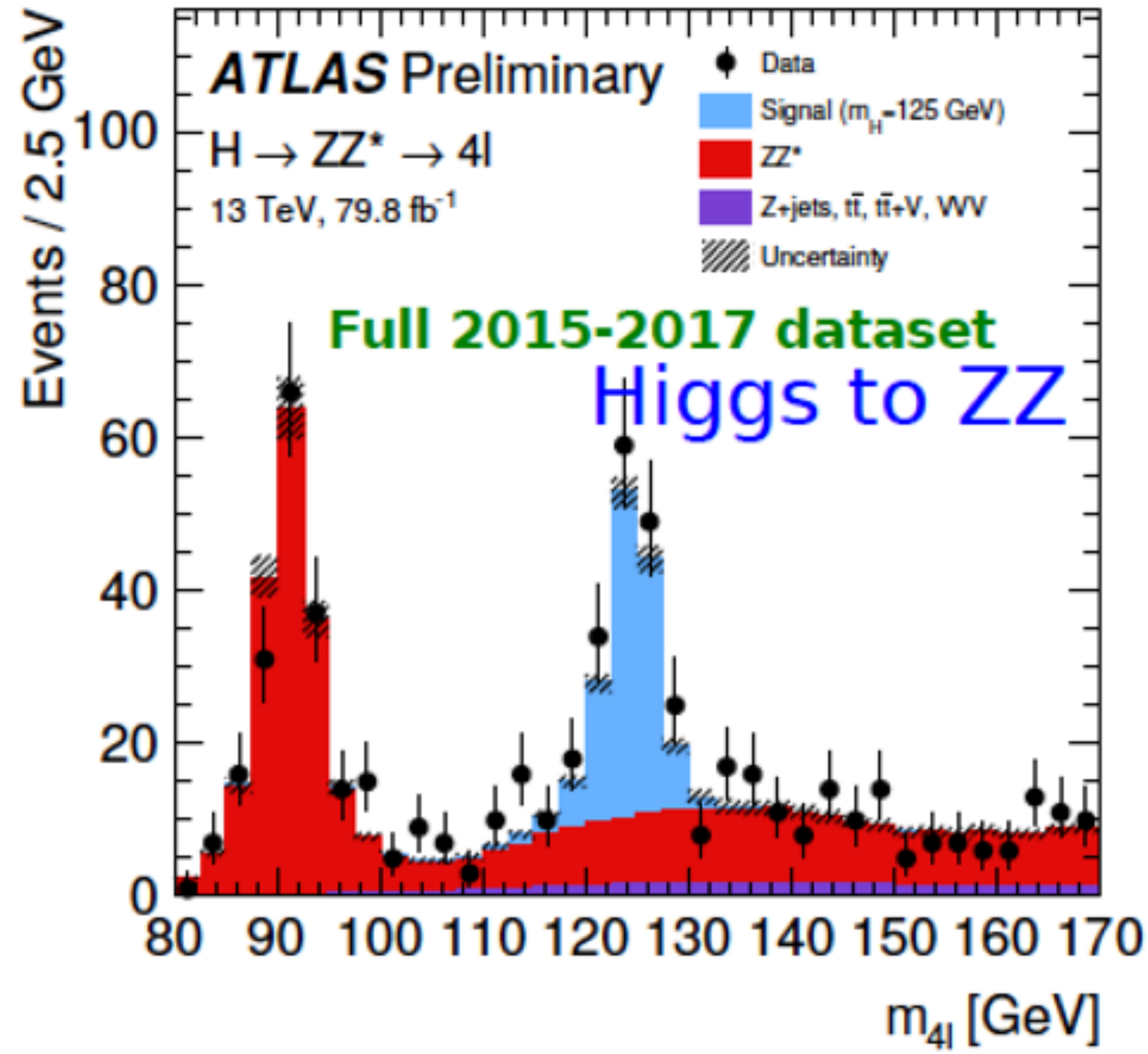
- Excellent performance, beyond expected LHC conditions
  - Also an active "special runs" program, refines precision measurements





Run-2 H→ZZ

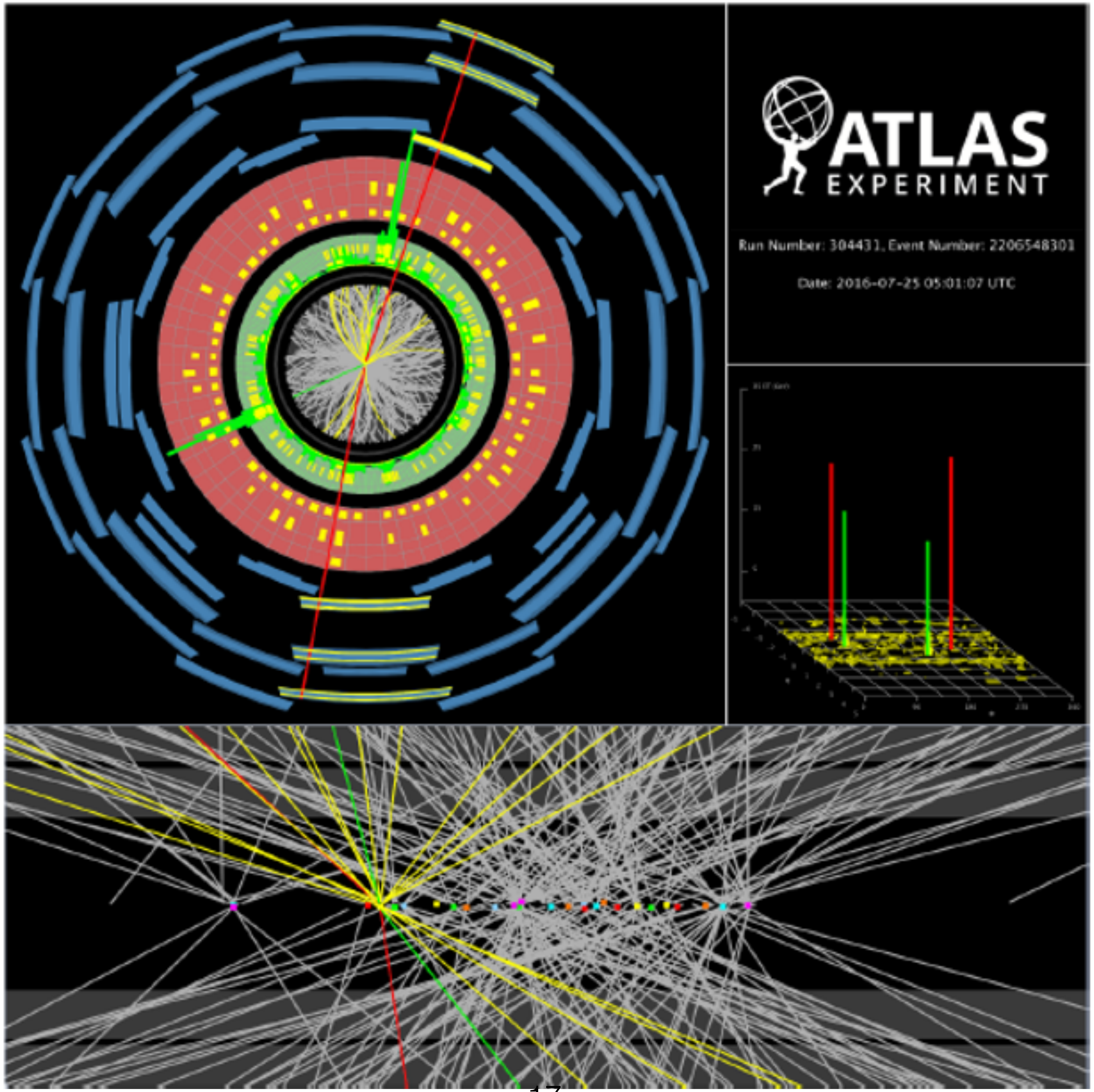




beautiful ! and there is still more data to analyze !

Higgs boson to $ee\mu\mu$ candidate in large pileup

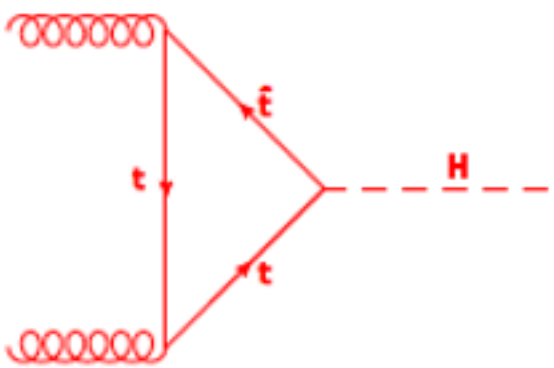
ATLAS EXPERIMENT



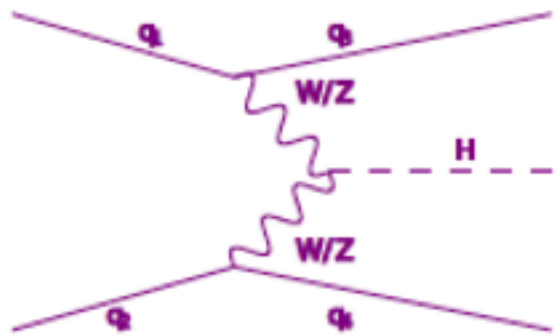
Run-2 has been more challenging due to the higher pile-up

Observed Higgs interactions

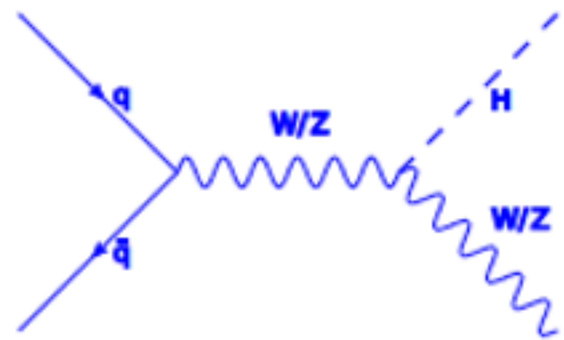
Higgs production mechanisms



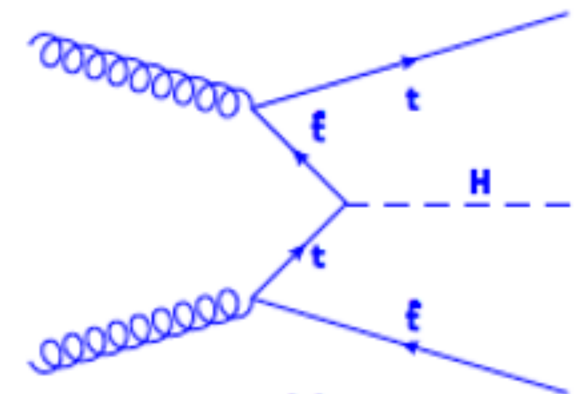
ggF
Run 1



VBF
Run 1 (ATLAS+CMS)
Run 2 (ATLAS alone)

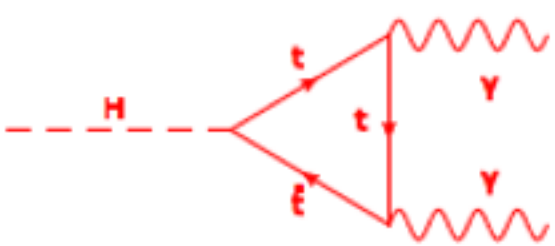


VH
2018



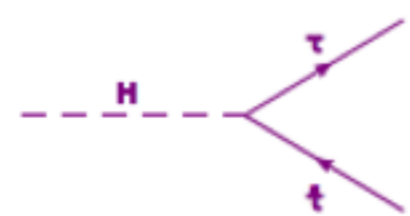
ttH
2018

Higgs decay modes

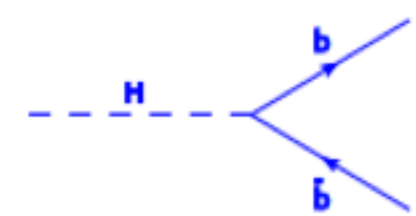


Hγγ
Run 1

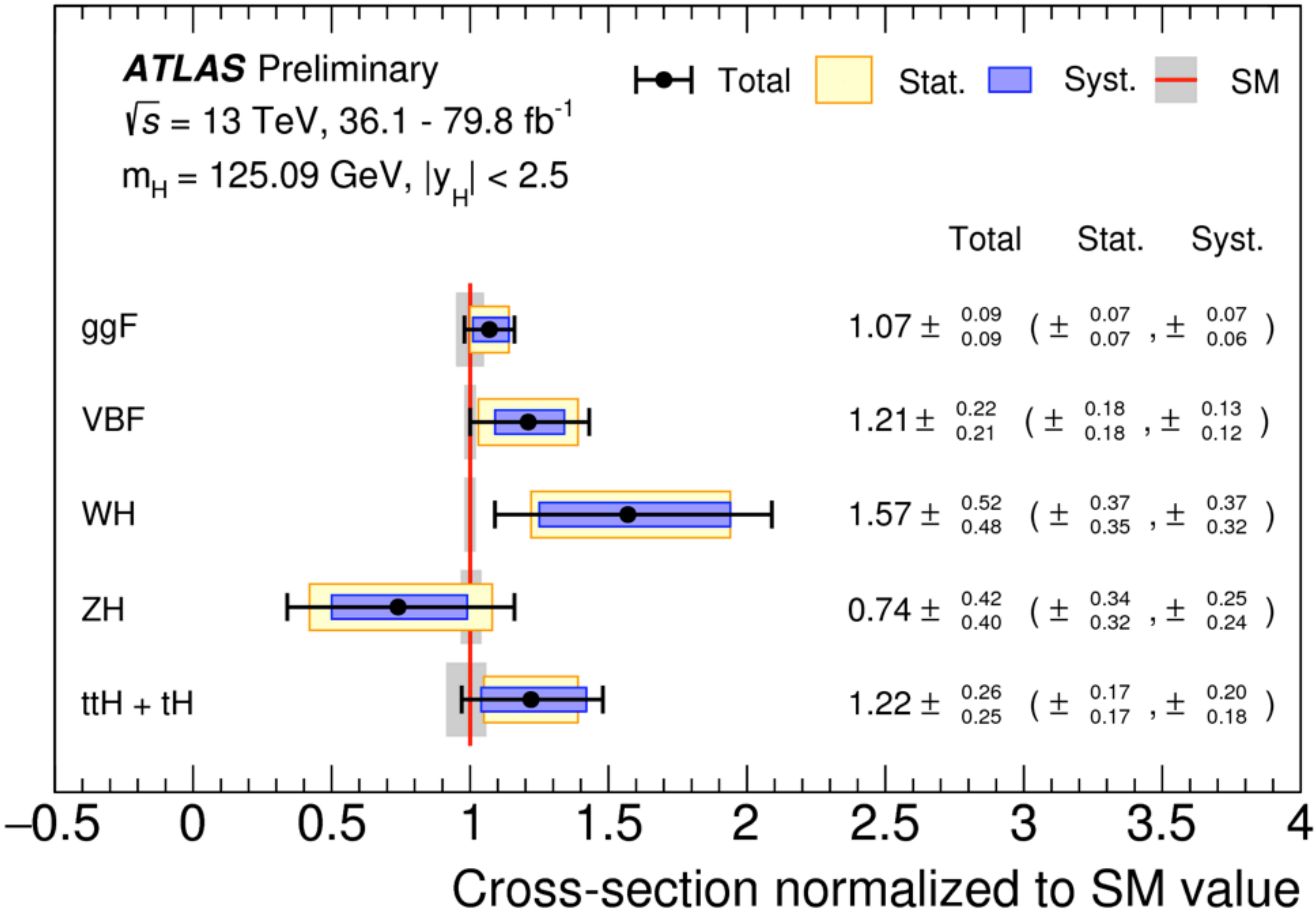
HWW/HZZ
Run 1



Hττ
Run 1 (ATLAS+CMS)
2018 (ATLAS alone)



Hbb
2018


ATLAS Preliminary
√s = 13 TeV, 36.1 - 79.8 fb-1
mH = 125.09 GeV, |yH| < 2.5
Total
Stat.
Syst.
SM
Total Stat. Syst.
ggF 1.07 ± 0.09 0.09 (± 0.07 0.07 , ± 0.07 0.06)
VBF 1.21 ± 0.22 0.21 (± 0.18 0.18 , ± 0.13 0.12)
WH 1.57 ± 0.52 0.48 (± 0.37 0.35 , ± 0.37 0.32)
ZH 0.74 ± 0.42 0.40 (± 0.34 0.32 , ± 0.25 0.24)
ttH + tH 1.22 ± 0.26 0.25 (± 0.17 0.17 , ± 0.20 0.18)
−0.5
0
0.5
1
1.5
2
2.5
3
3.5
4
Cross-section normalized to SM value

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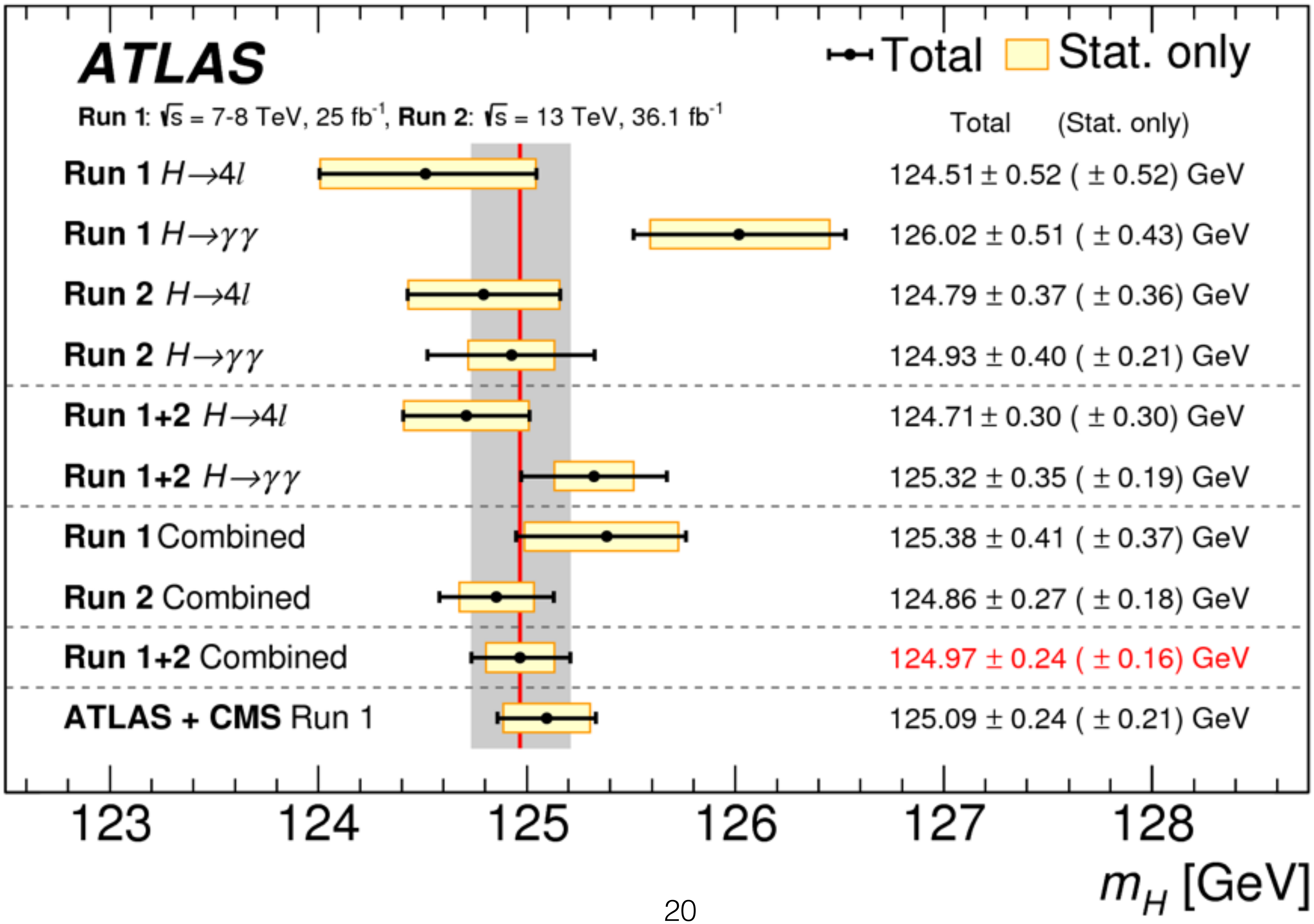
Higgs mass

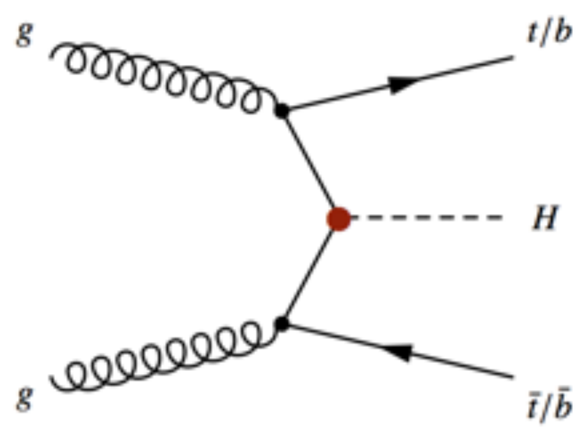


down
to per-mille
precision

H–top coupling

In SM the top-Higgs Yukawa coupling is strongest one ($\lambda_t \propto m_{top}/v \approx 1$). It is important in several production and decay processes.

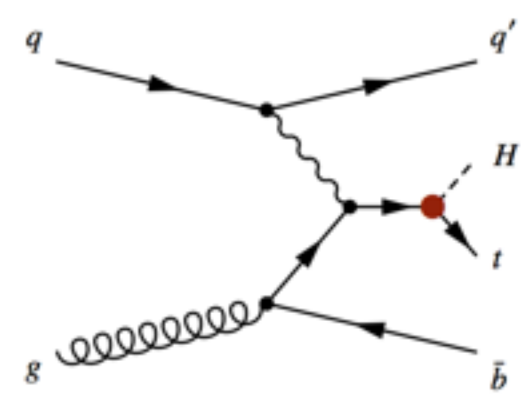
The top-Higgs vertex (●) is only directly accessible when H is produced in association with one or more top quarks.



σ(pp → ttH) = 0.507 pb @ 13 TeV

~1/96th of ggH production

Probes the modulus of λ_t



σ(pp → tH) = 0.074 pb @ 13 TeV

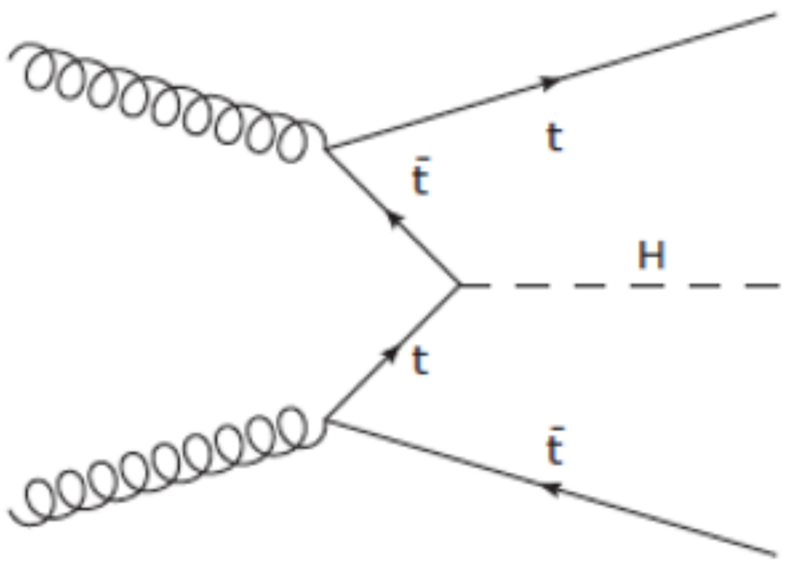
~1/15th of ttH production

Probes the relative sign of λ_t

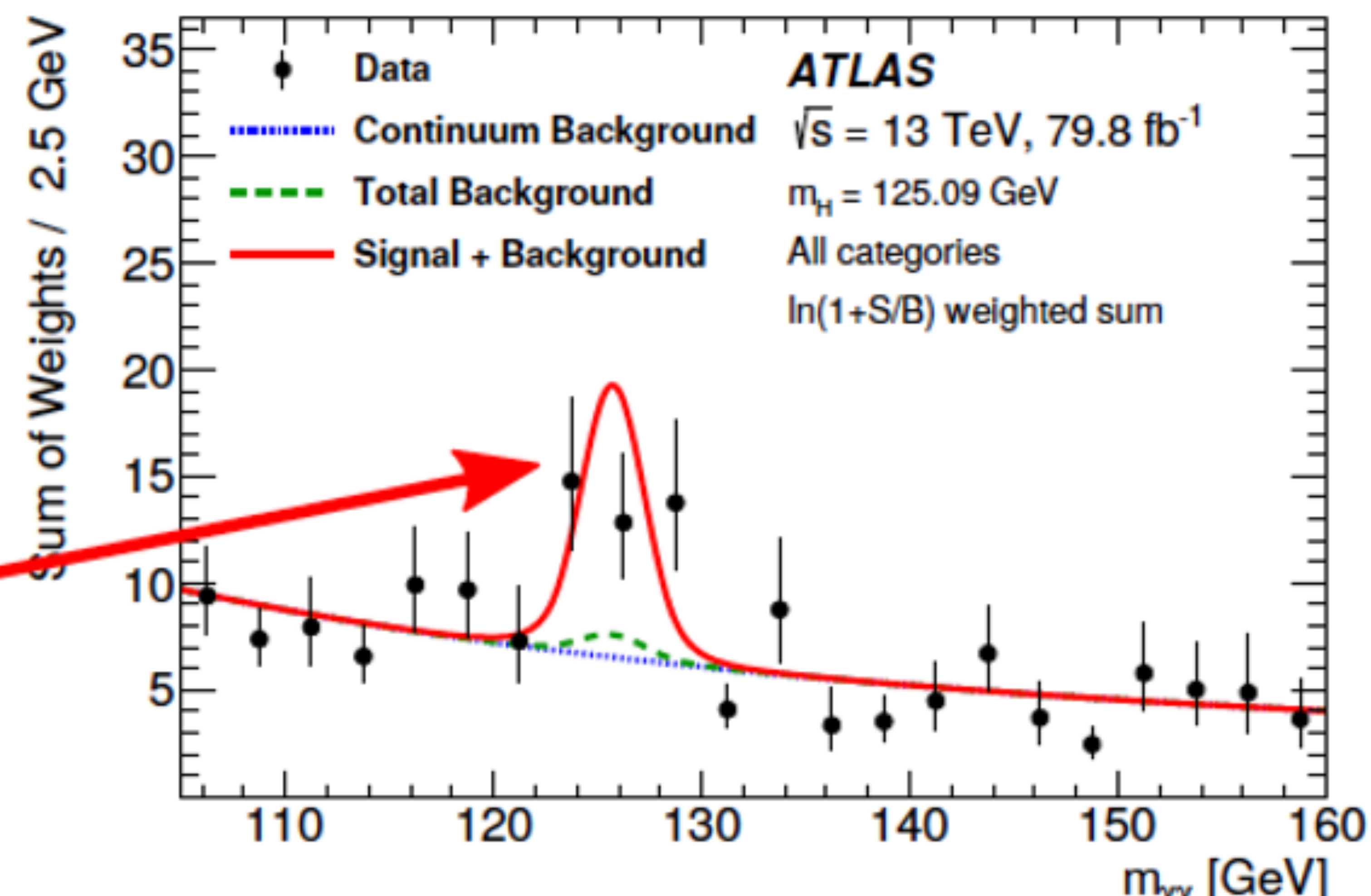
The comparison of the direct measurement of λ_t with the one from the loop-induced ggH can constrain contributions from NP in the gluon fusion loop

H–top coupling

- ATLAS observed the ttH production mechanism in 2018
  - Confirms Yukawa coupling (Higgs + fermion interactions)



Process	Obs. Sig.
H to γγ	4.1
H to multilep	4.1
H to bb	1.4
H to ZZ to 4l	0
Comb (13 TeV)	5.8
Comb (7, 8, 13 TeV)	**6.3**



not a lot of events
but quite clean !

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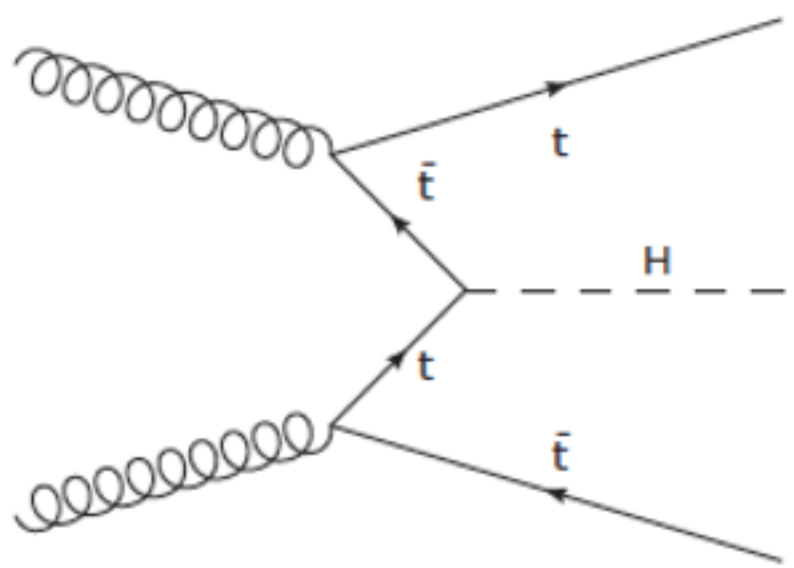

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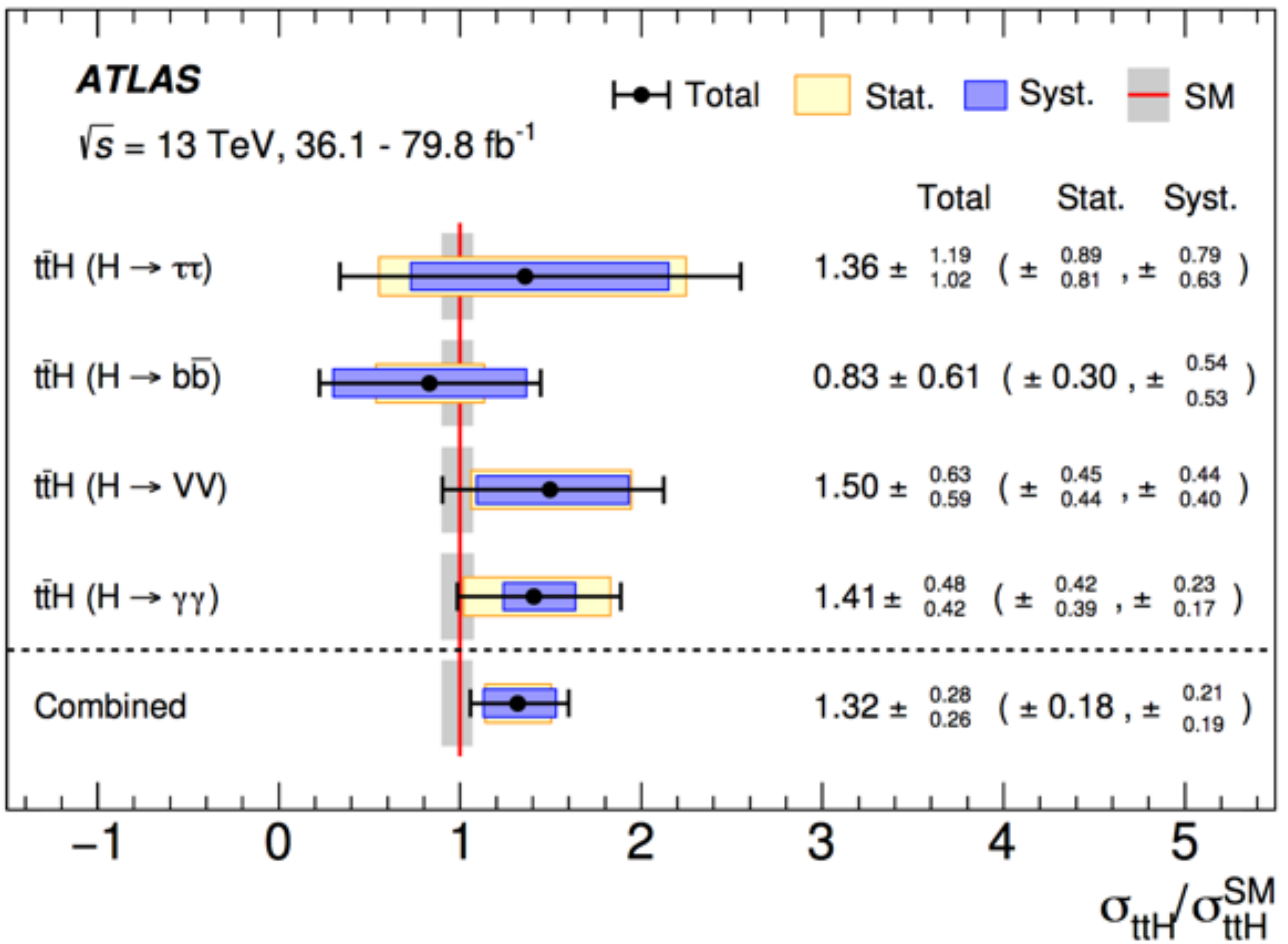
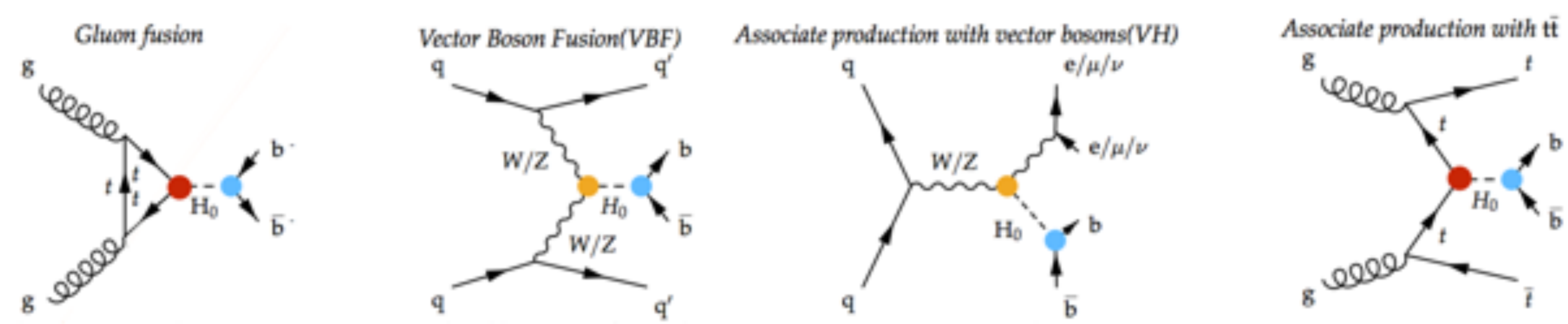


H–bottom coupling

(Probably) the only Yukawa coupling to a down-type quark within LHC reach

Direct observation of the bottom-Higgs vertex (●) via **H→bb decay**
Largest BR among all the decays, dominates total width of SM Higgs

All the production mechanisms are exploited

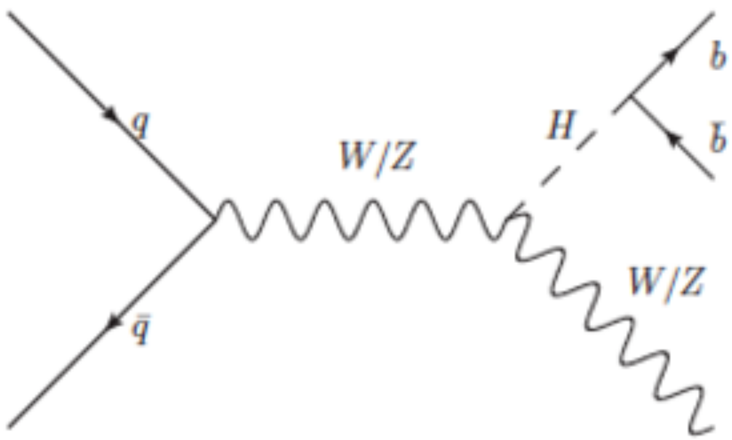


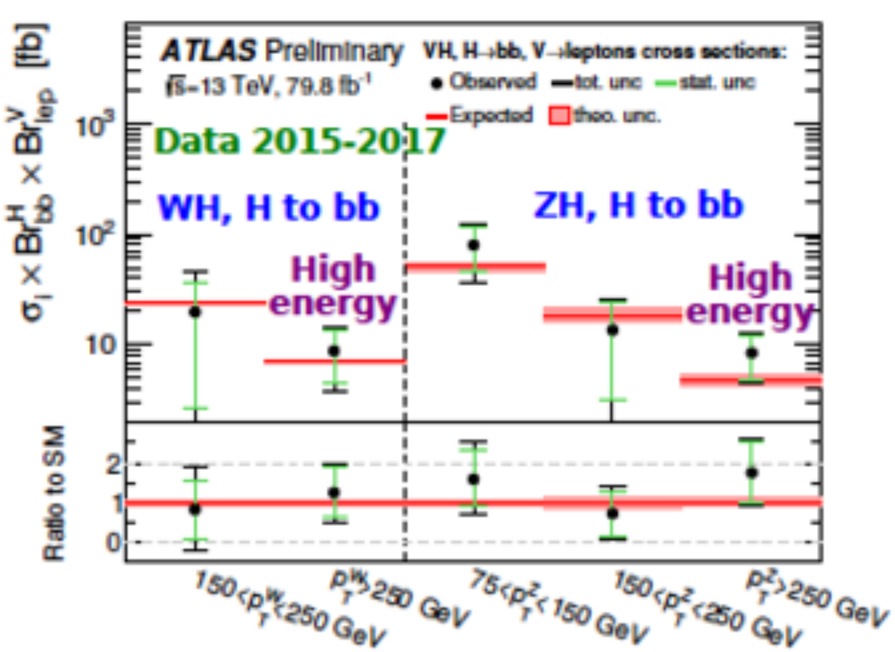
87% of total cross section	7% of total cross section	4% of total cross section **Most sensitive**	1% of total cross section

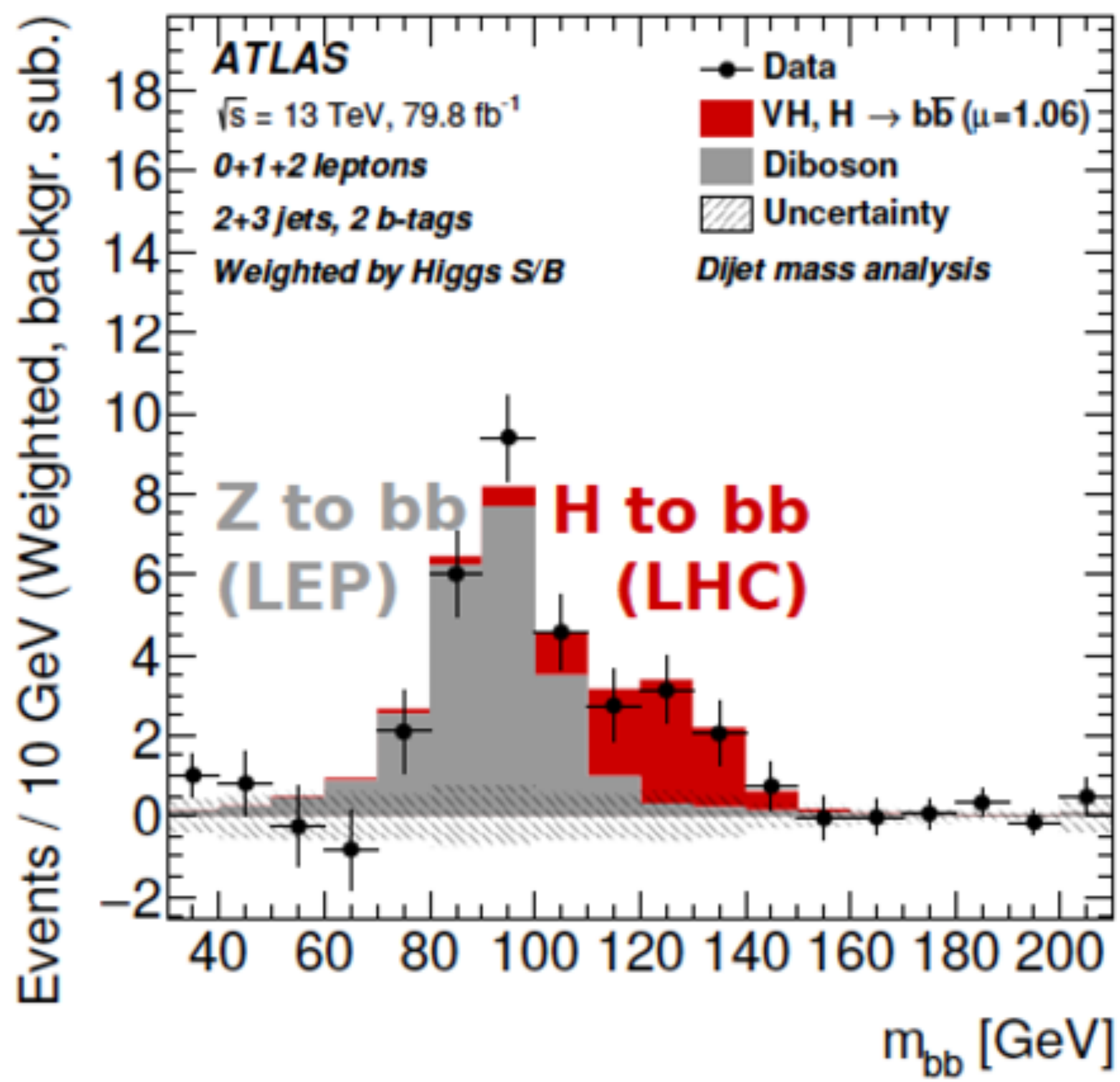
Despite the high BR an analysis with many challenges: b-tag, E_T^{miss}, back. modelling (V+HF), trigger, …

H–bottom coupling

- Observed VH production (5.3σ) and H→bb decay modes (5.4σ)
- Higgs to *bb* is the most common Higgs decay, but very hard to study
  - Just observed, but already performing differential measurements!







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H–bottom coupling

$$
\begin{aligned}
qq &\to WH \\
&\to \ell\nu b\bar{b} \\
qq &\to ZH \\
&\to \nu\nu b\bar{b}/\ell\ell b\bar{b} \\
gg &\to ZH \\
&\to \nu\nu b\bar{b}/\ell\ell b\bar{b}
\end{aligned}
$$

many category of events designed, to exploit the best events to spot Higgs decay into b quarks

multi-variate selection used

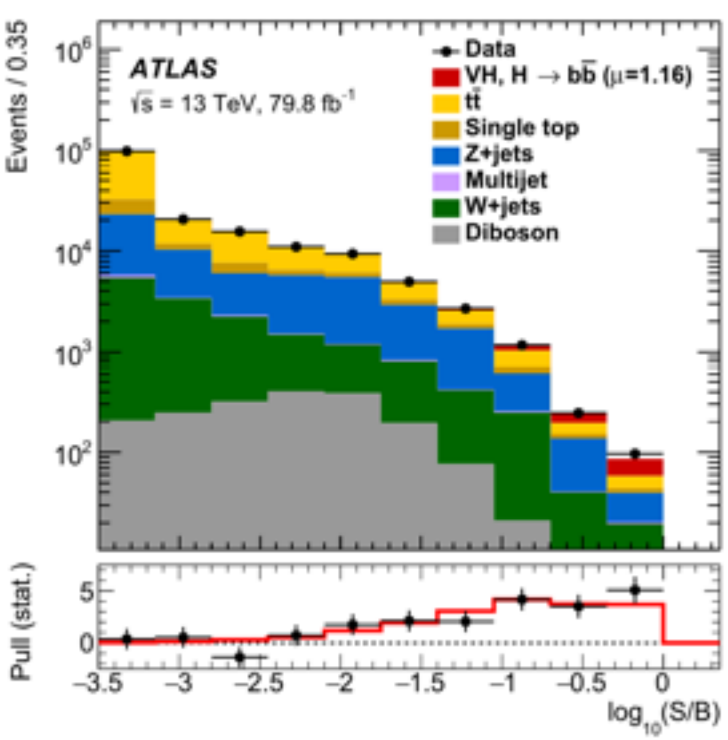
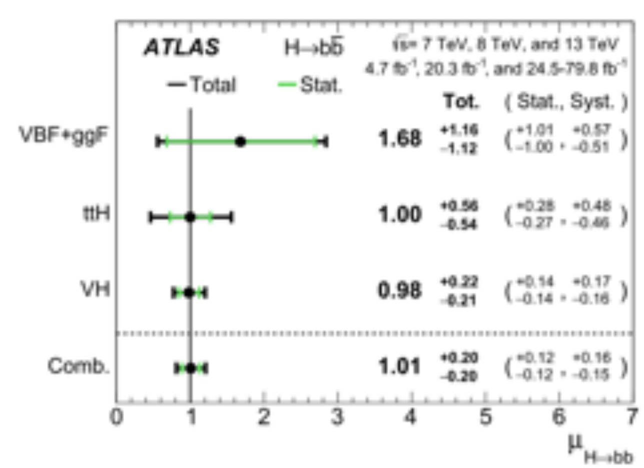
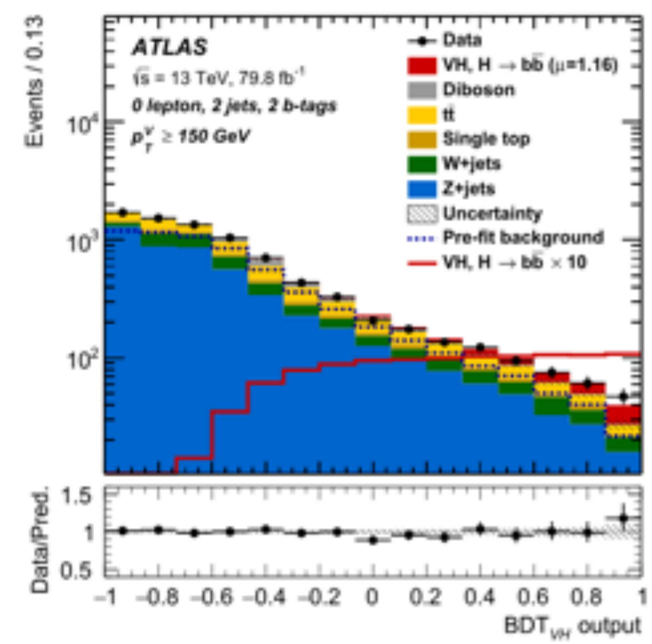
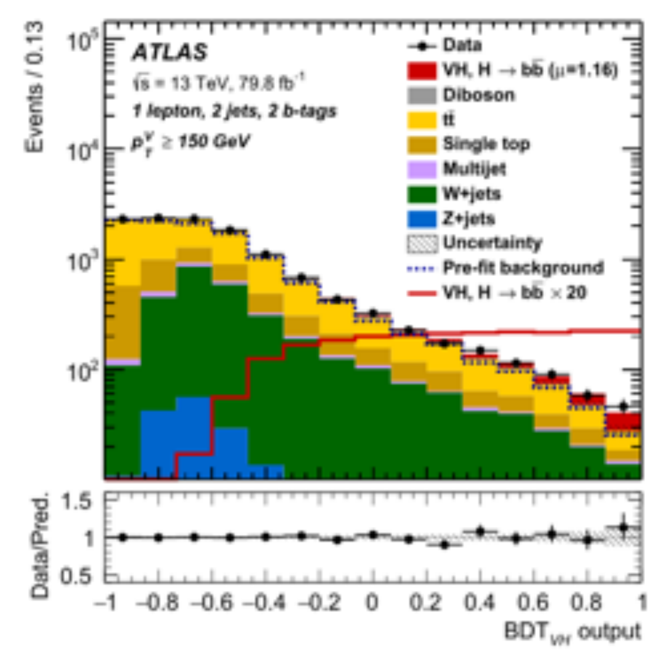


Table 12
Expected and observed significance values (in standard deviations) for the $H \to b\bar{b}$ channels fitted independently and their combination using the 7 TeV, 8 TeV and 13 TeV data.

Channel	Significance	
	Exp.	Obs.
VBF+ggF	0.9	1.5
$t\bar{t}H$	1.9	1.9
VH	5.1	4.9
$H \to b\bar{b}$ combination	5.5	5.4







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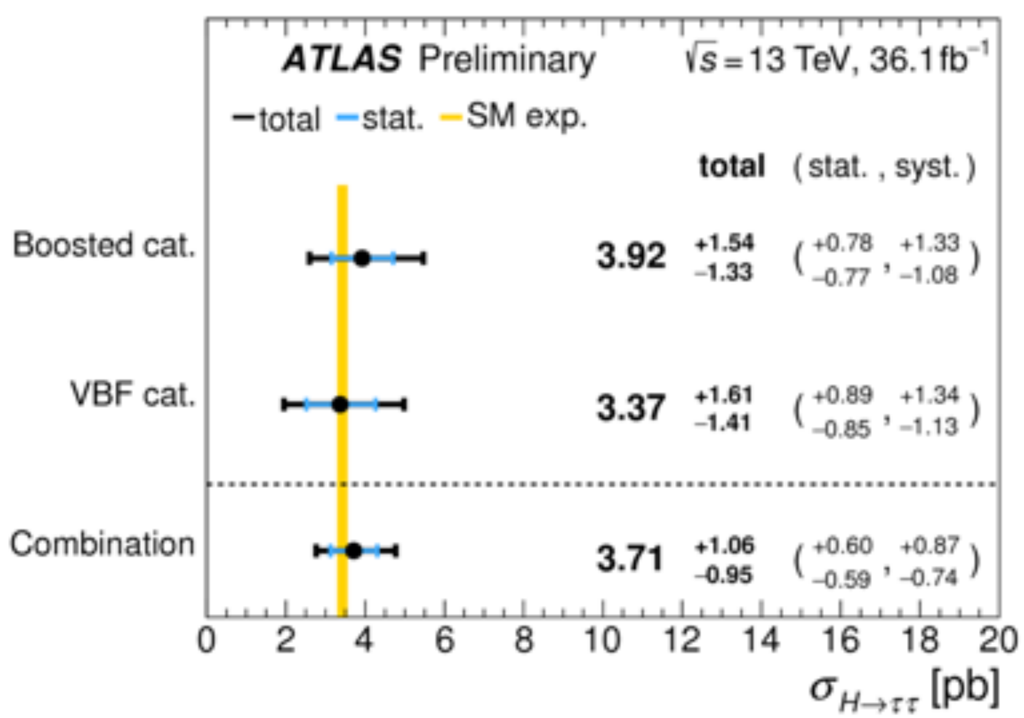
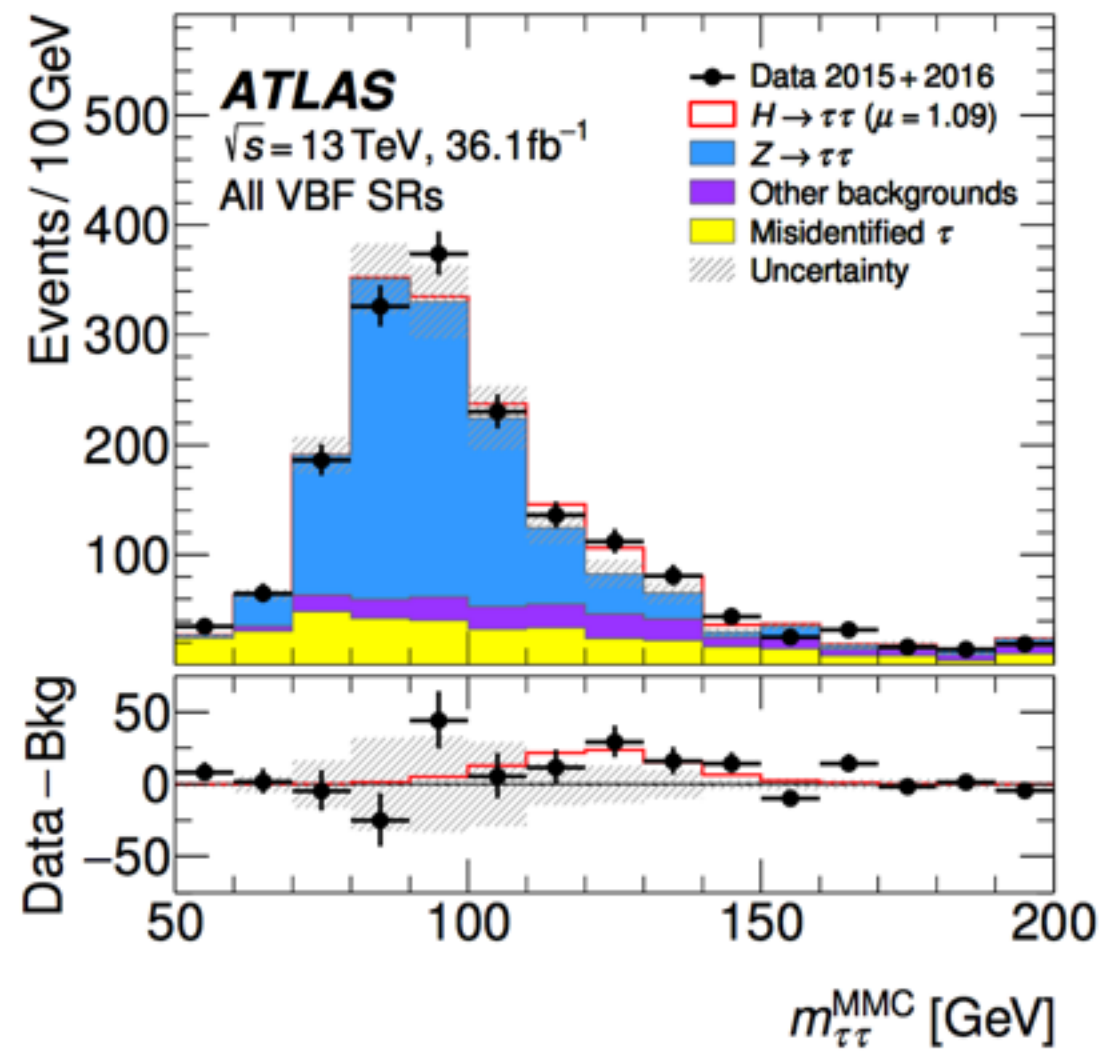
arXiv:1811.08856

H-tau coupling

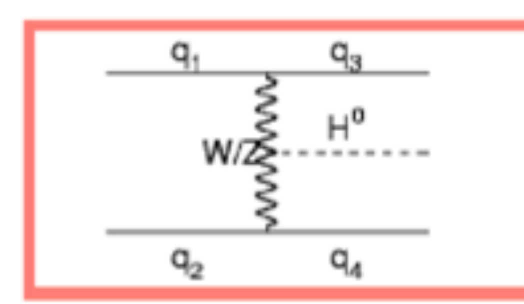
First individual fermion coupling to be established with ≥5σ significance (Run1+Run2 ATLAS, alone)



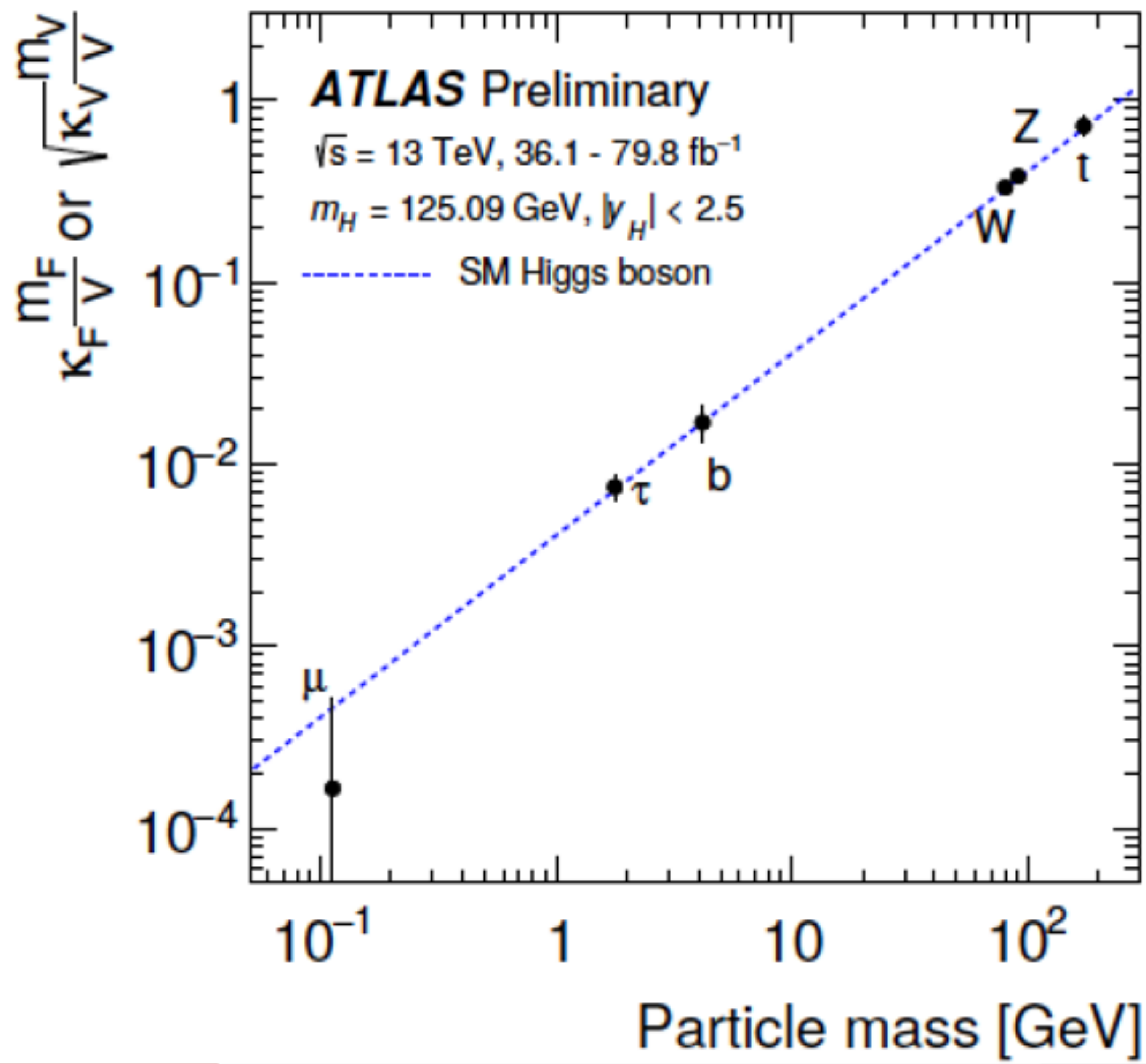


There is more data avaiable, not yet used.

Can start measuring the CP properties of the Higgs boson (is it a pure CP-even state, or mixes with another one?), and probe anomalous HVV couplings in VBF production.



Higgs couplings – Run-2

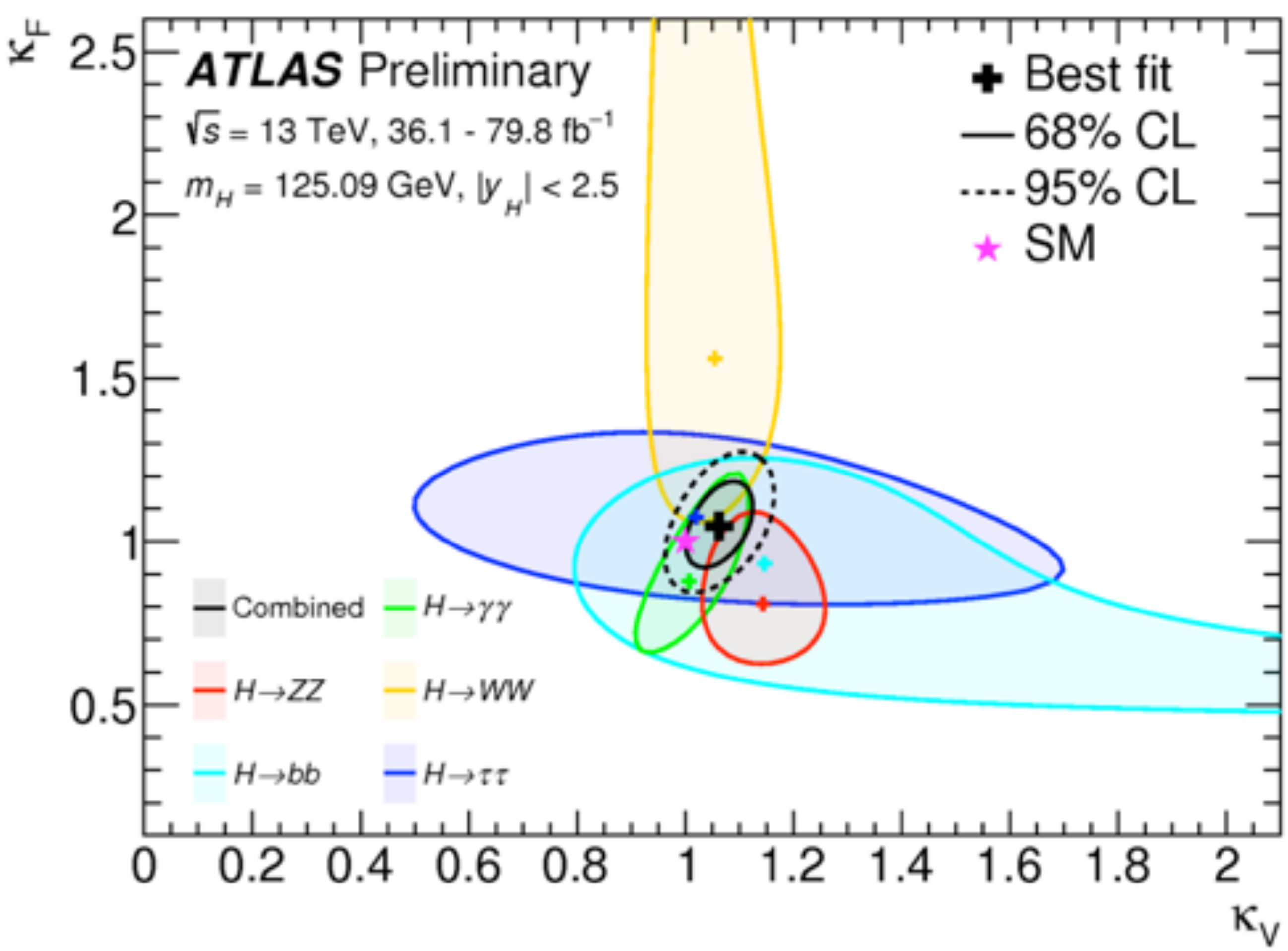


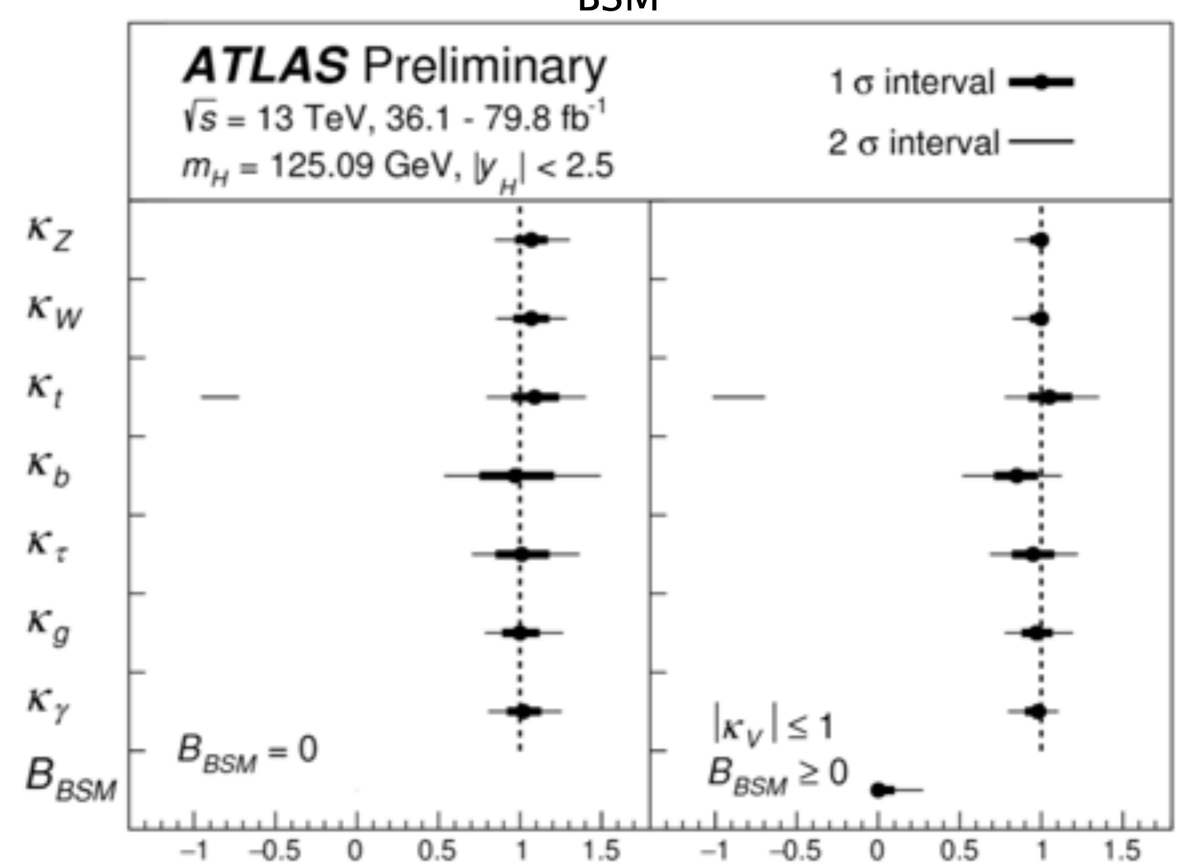
much better everywhere

Higgs couplings – Run-2

probe for invisible/undetectable decays with possibility of new particles in gg → H production and H → γγ decay i.e. κ_g and κ_γ modifiers left free in the fit

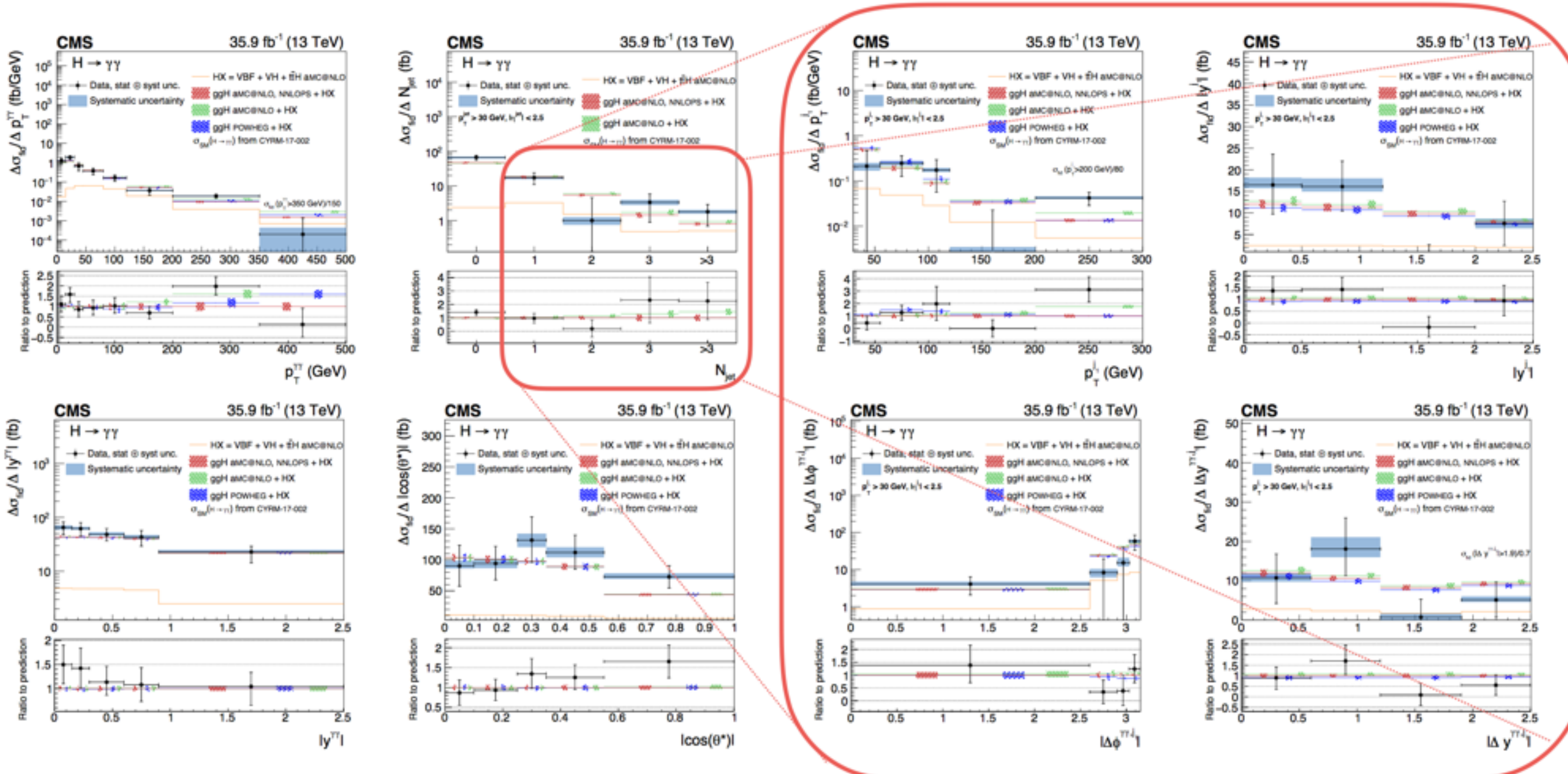
Result : $B_{BSM} < 0.26$ at 95% CL





arXiv: 1807.03825

H differential Xsections



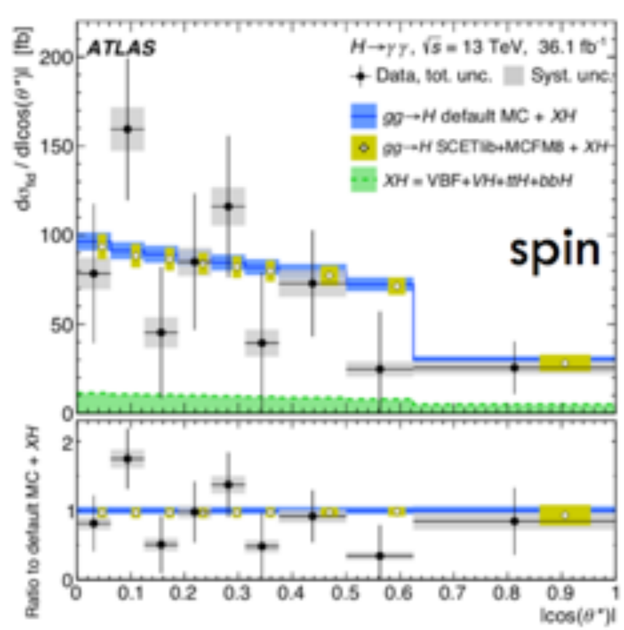
remarkable results (and there is 3 times more data to use!)
Precision tests on Higgs achievable already now.

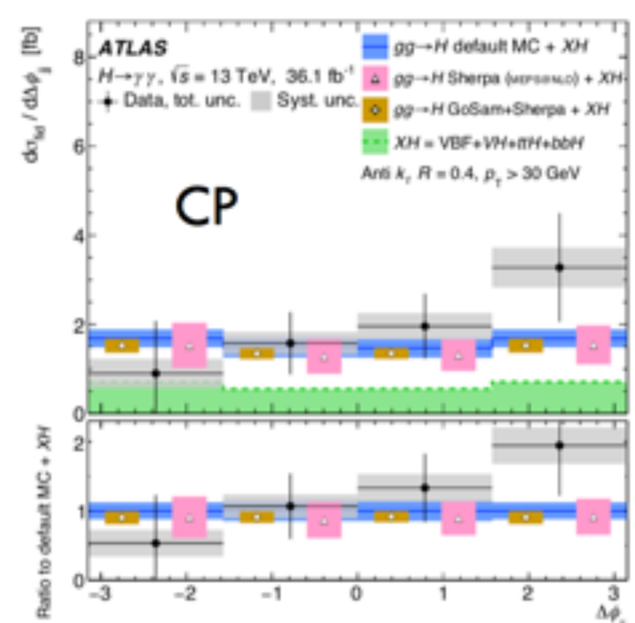
spin/CP H

- Spin and Parity of the Higgs boson measured in WW*/ZZ* final states using Run-I 7 TeV and 8 TeV data (~25/ fb). SM Higgs boson hypothesis, $J^P = 0^+$, tested against alternative spin scenarios, which were excluded at 99.9% CL

- In Run2 Higgs boson spin-CP tested, e.g. in $\gamma\,\gamma$ decays, with angle distributions of photons and jets sensitive to these properties
  - For a scalar particle $|\cos\,\theta^*|$ shows a strong drop around 0.6

$$|\cos\theta^*| = \frac{|\sinh(\Delta\eta^{\gamma\gamma})|}{\sqrt{1+\left(p_T^{\gamma\gamma}/m_{\gamma\gamma}\right)^2}}\,\frac{2p_T^{\gamma_1}p_T^{\gamma_2}}{m_{\gamma\gamma}^2}$$

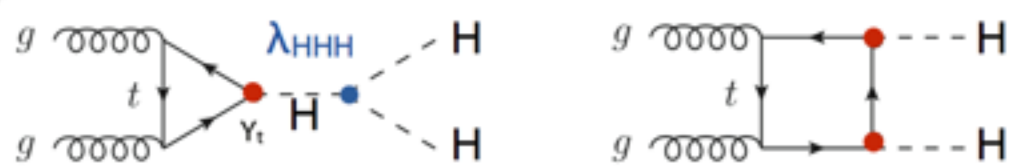




in VBF and ggF, different dependencies depending on CP of Higgs

H^3

Higgs boson self coupling is essential in EWSB, need to measure the Higgs boson trilinear coupling (λ_{HHH}). To measure ***nH*** coupling need to measure ***(n-1)H*** production



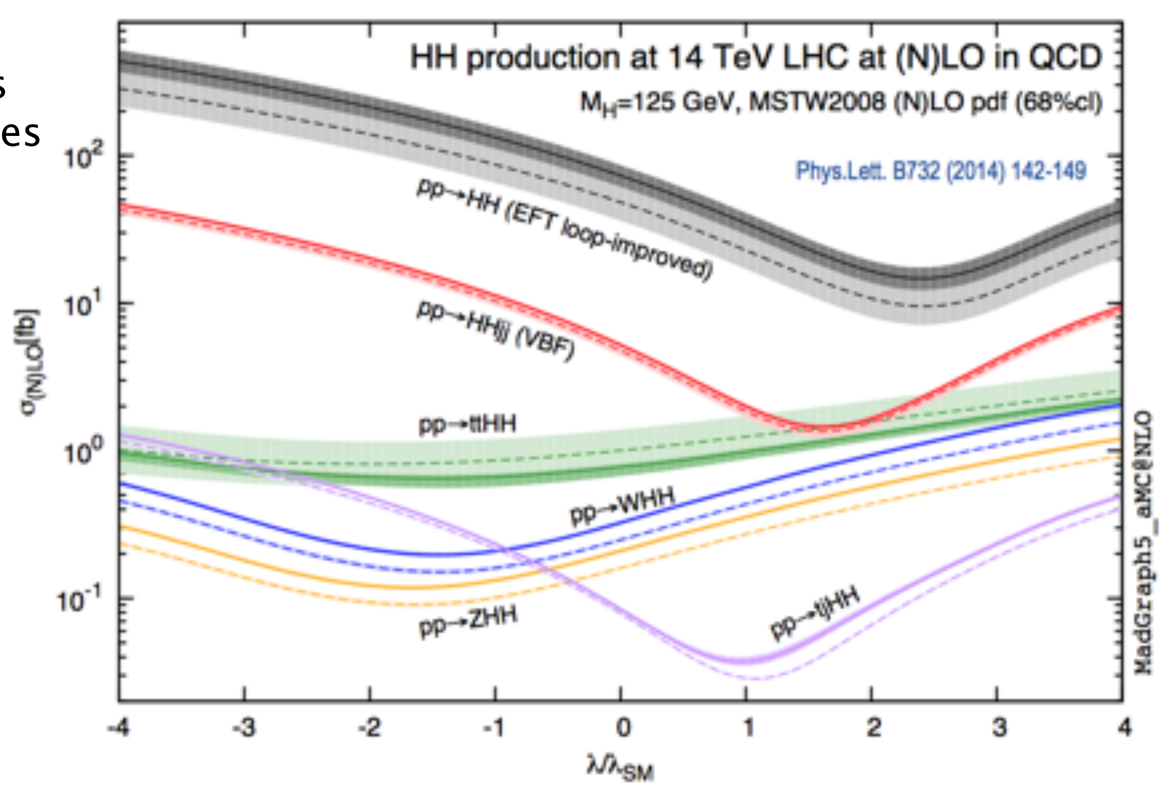
$\sigma_{gg\to HH} = 33.49^{+4.3}_{-6.0}$ (scale) ± 2.1 (PDF) ± 2.3 (α_s) fb

[13 TeV, NNLO + NNLL with top mass effects, HXSWG, arXiv:1610.07922]

Smallness of production cross section and destructive interference

other couplings affect HH too (y_t + other HH diagrams with higher order operators)

pp→H is 1000 times larger



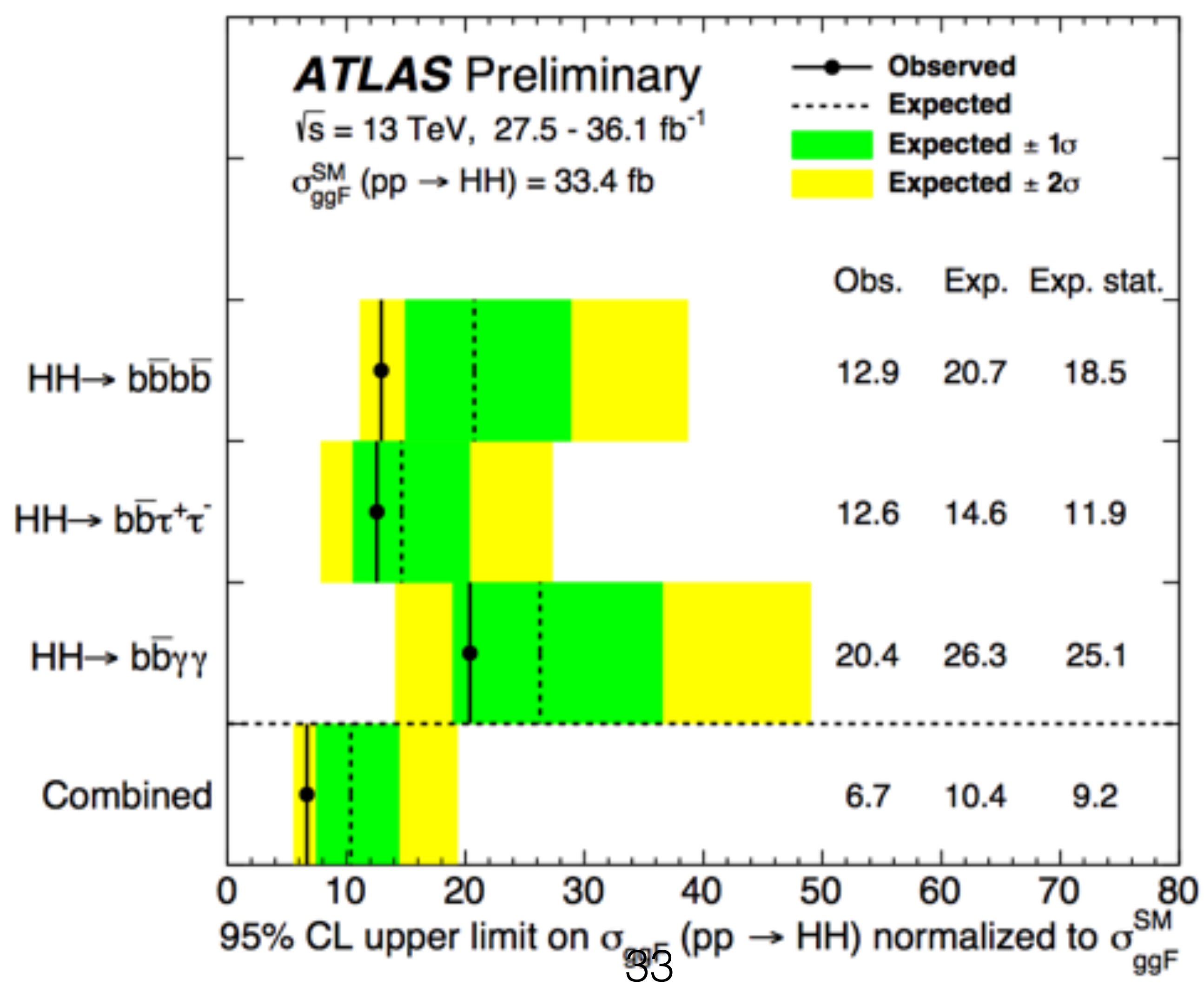
$\sigma/\sigma_{SM} \sim 2.09\kappa_t^4 - 1.36\kappa_\lambda\kappa_t^3 + 0.28\,\kappa_\lambda^2\kappa_t^2$

$[\kappa_t := \lambda_t/\lambda_t^{SM}\,;\ \kappa_\lambda := \lambda/\lambda^{SM}]$

ATLAS-CONF-2018-043
arXiv:1811.09689

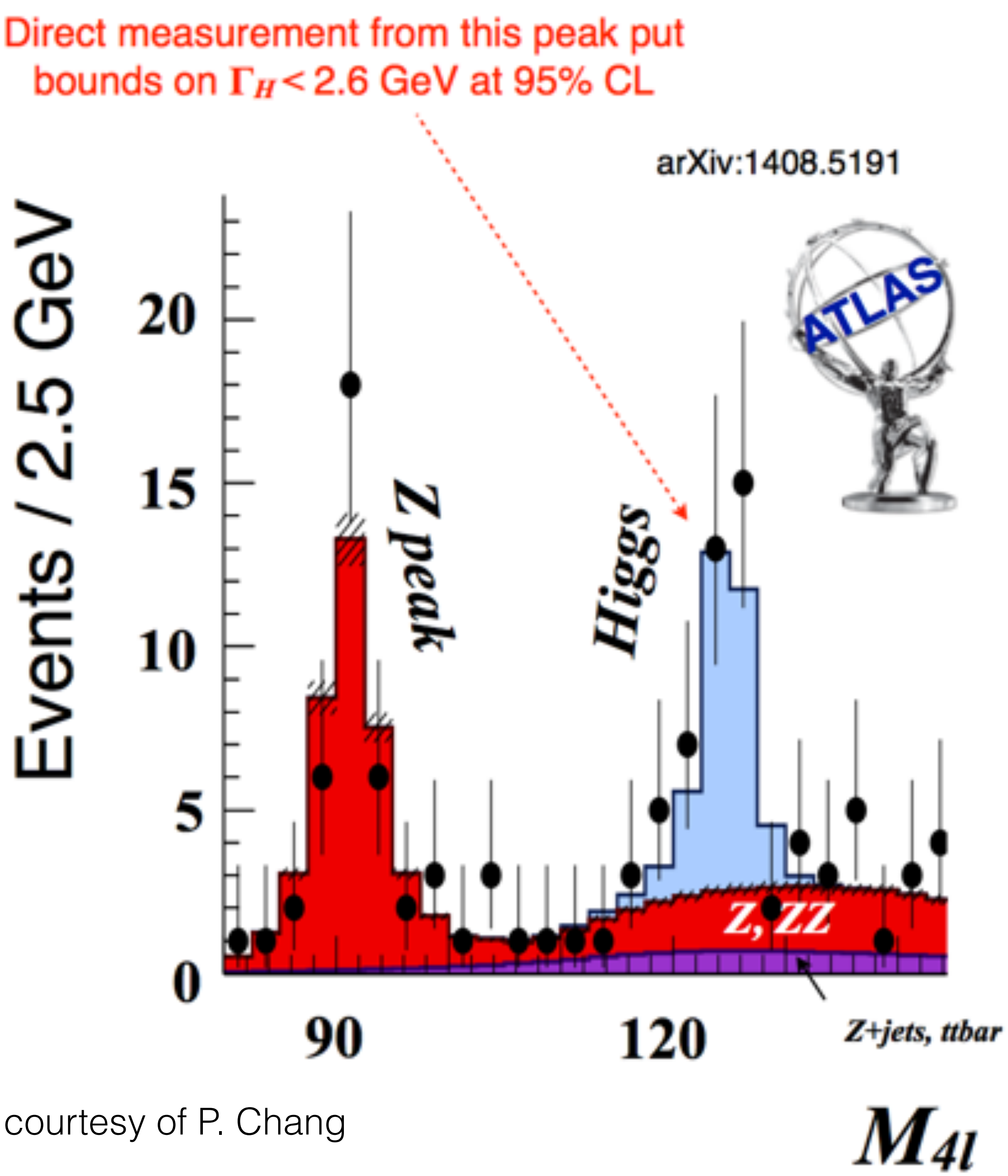
H^3

- smallness of production cross section forces to use difficult final states with highest branching ratio
- several analyses need to be combined.

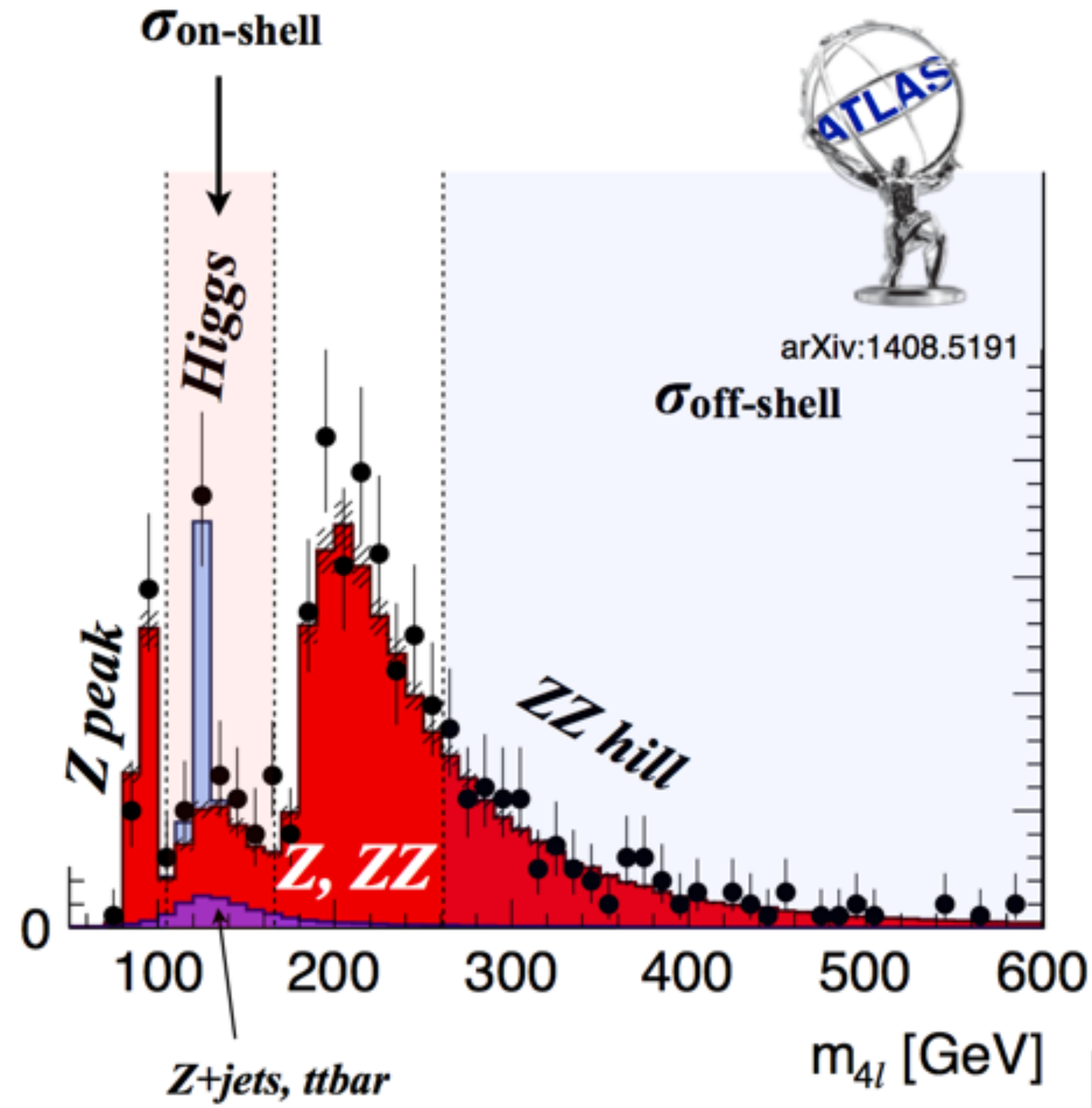


here we need statistics, statistics, statistics.

Higgs total width



courtesy of P. Chang



Standard Model predicts $\Gamma_H = 4.1$ MeV

CMS-PAS-HIG-18-002
PLB 786 (2018) 223

Higgs total width

under the assumption that couplings do not change
when moving from Higgs on-shell to Higgs off-shell

coupling constants

$$\frac{d\sigma}{dM^2} \sim \frac{C_g}{(M^2 - M_H^2)^2 + M_H^2\Gamma_H^2}$$

narrow width approx. off-shell

$$\sigma_{\text{on-shell}} \sim \frac{C_g}{\Gamma_H} \qquad \sigma_{\text{off-shell}} \sim C_g$$

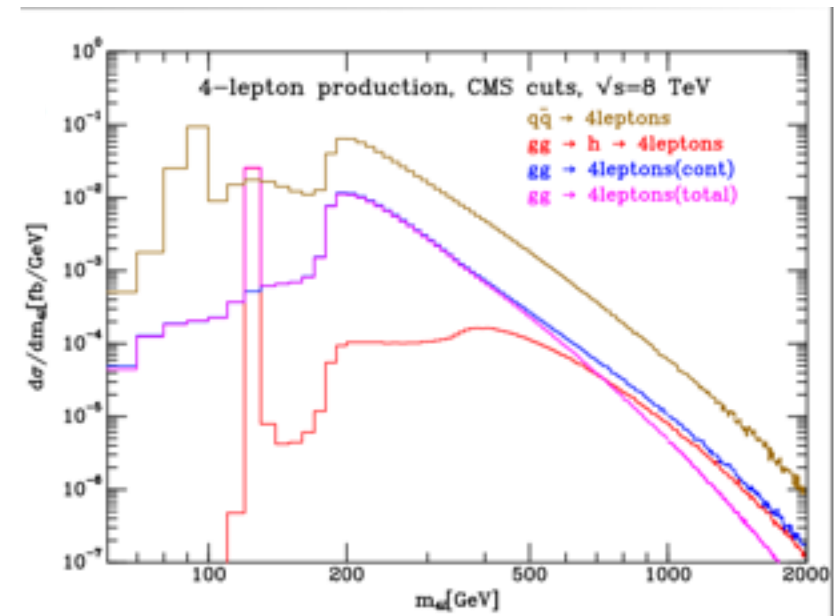
arXiv:1307.4935

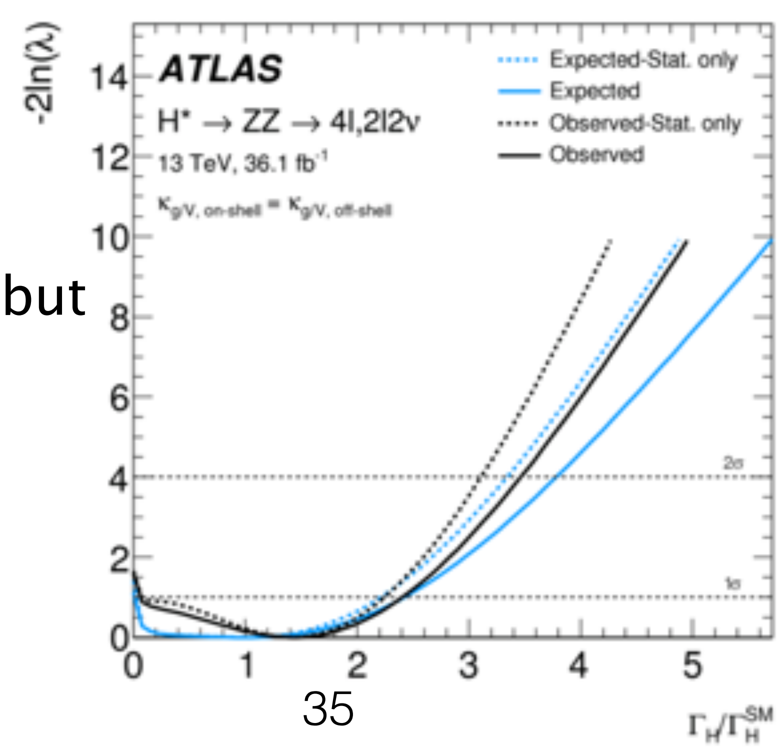
$$\frac{\sigma_{\text{off-shell}}}{\sigma_{\text{on-shell}}} \sim \Gamma_H$$

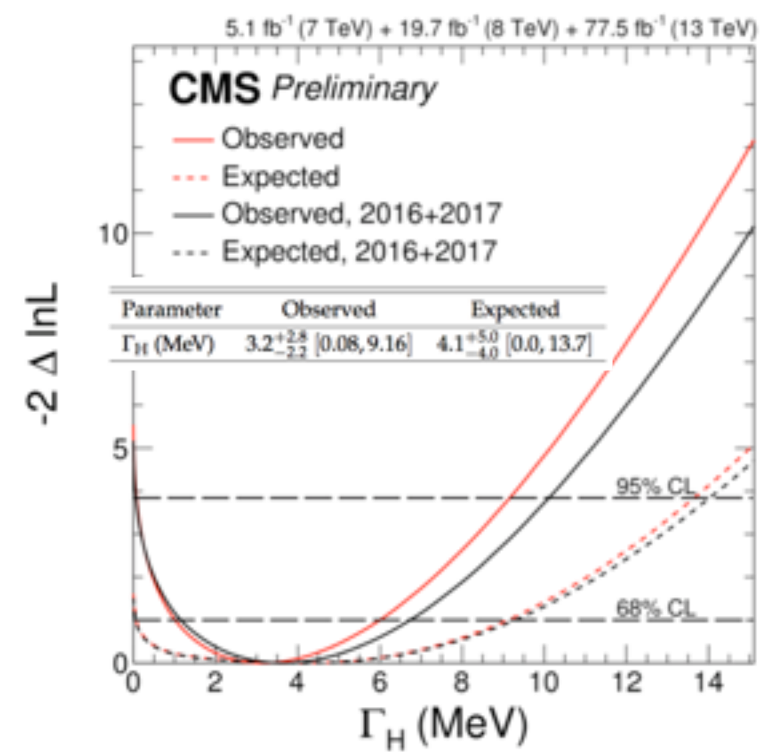
off-shell production ($\sigma^{\text{off-shell}}$) sizeable (~ 10% of total cross section), but can be enhanced by experimental cuts

CMS (Run1+Run2 4l)
Γ_H <9.16 MeV @95% C.L.

ATLAS (Run2 4l+2l2v)
Γ_H <14.4 MeV @95% C.L.



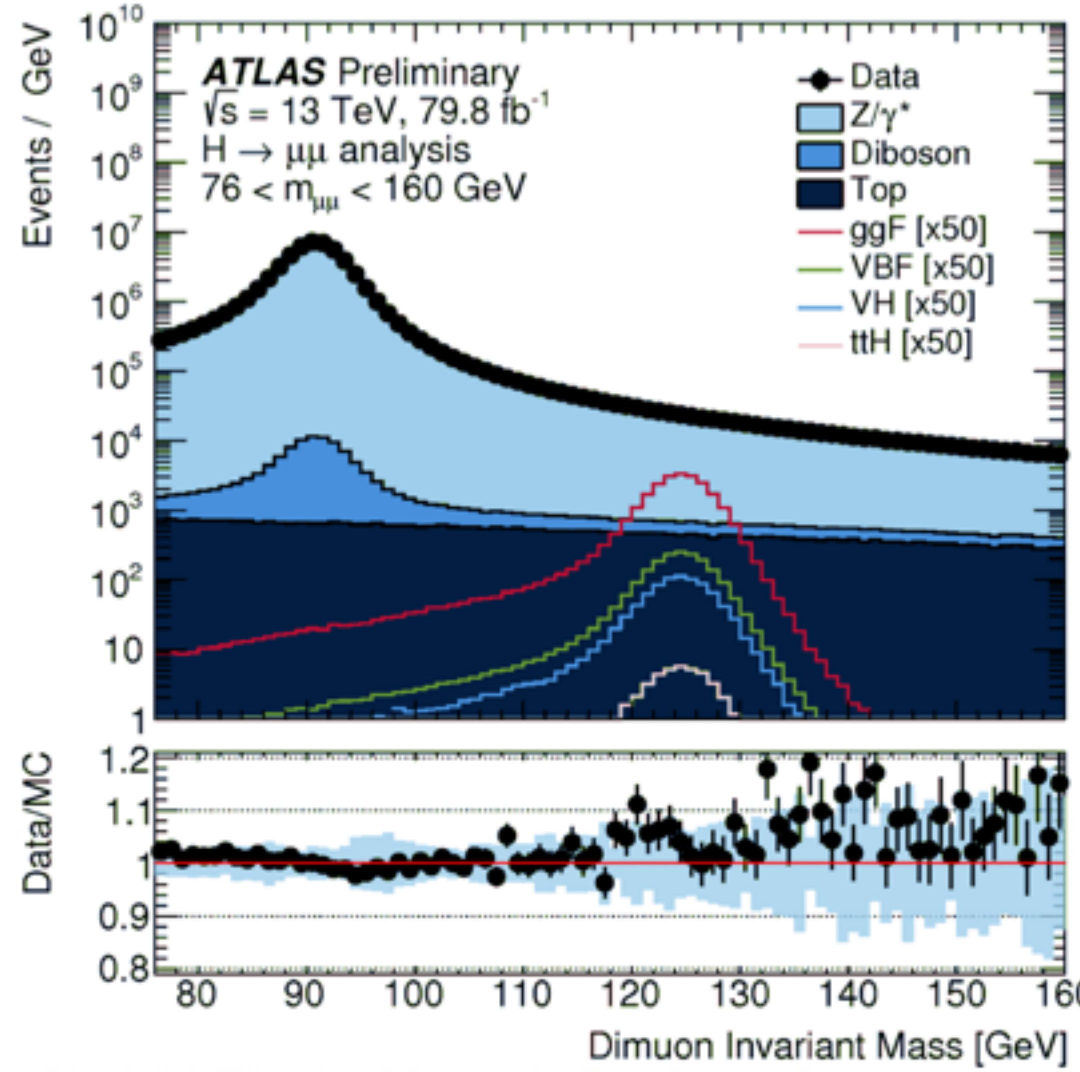




H–muon coupling

Measure via H→μμ decay. In principle an easy analysis: μ are the easiest object to identify and measure, but …

- small BR (2×10^{-4}) → $\boldsymbol{O}$(5-6) evt/fb^{-1}
- large backgrounds (DY,tt)
  - → rapidly falling shape
- small S/(S+B) regime
- small deviations in the background
  - → large difference in the results



H–muon coupling

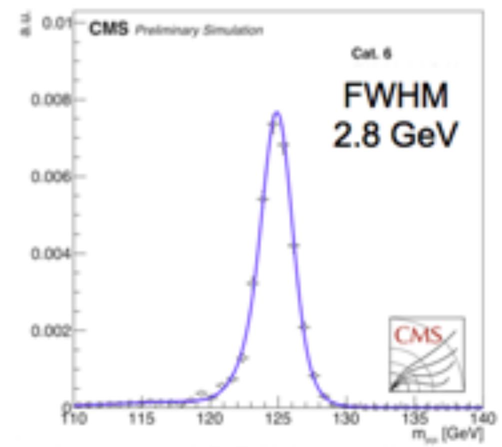
Good muon momentum resolution is critical

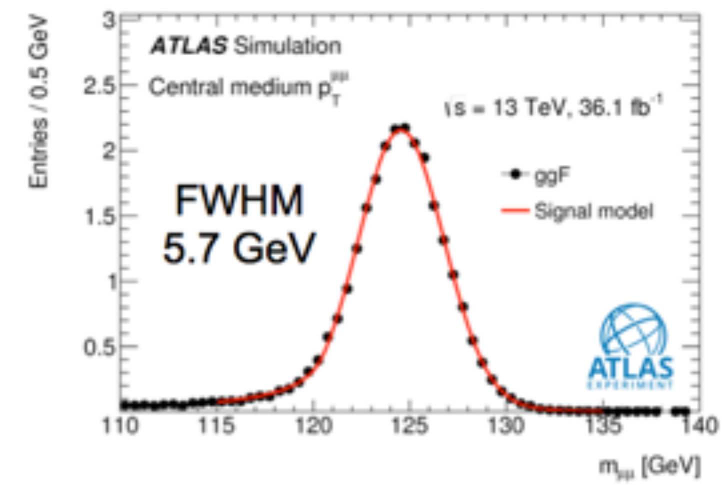
- Categorize events according to muon |η|

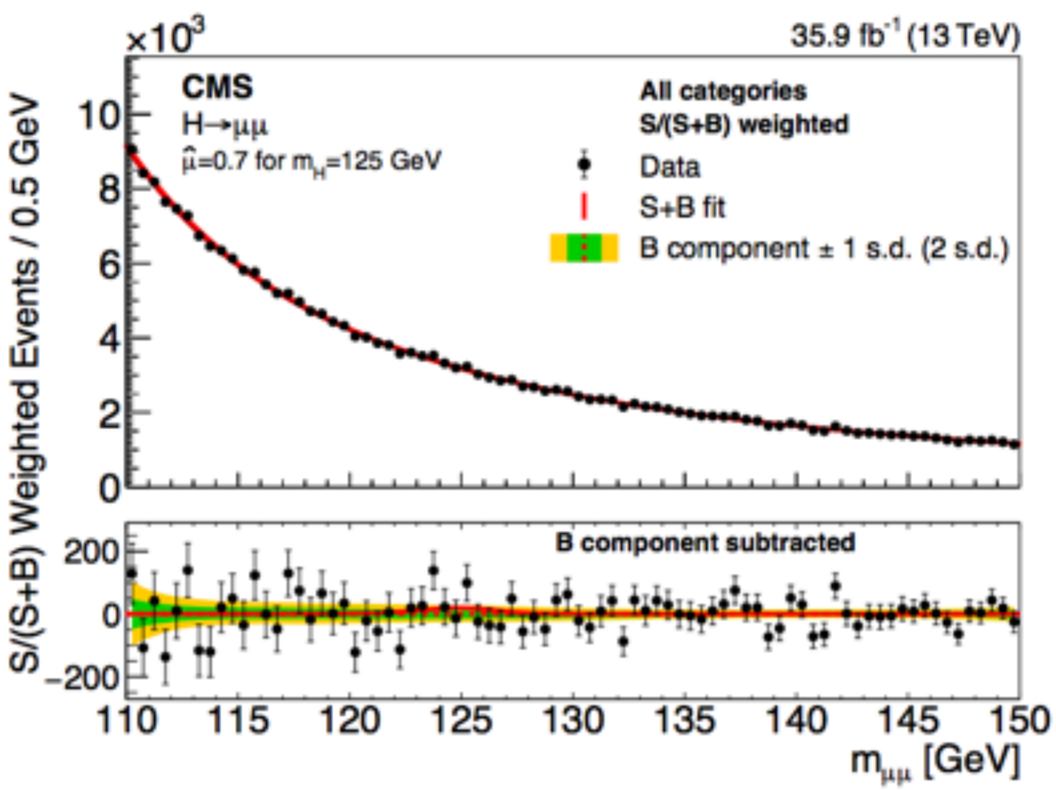
Suppress tt using b-tagging, E_T^{miss}

Select phase space regions with best S/B

- high $p_T(\mu\mu)$ or VBF production







CMS : Run1+2016 dataset

μ = 0.9 ± 1.0

μ < 2.9 obs. (2.2 exp. for μ=0)

ATLAS : Run1+2016+2017 datasets

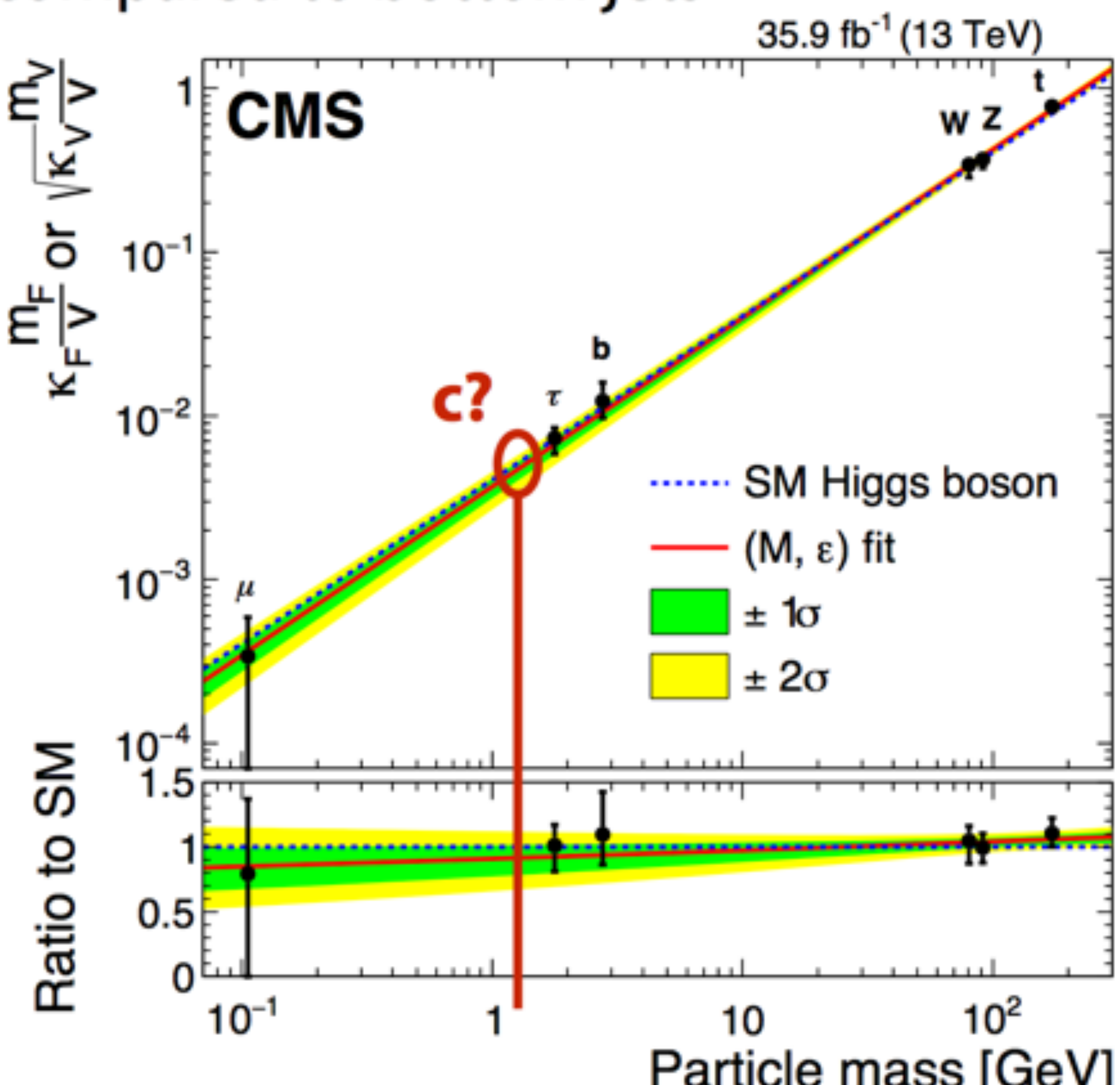
μ = 0.1± 1.0

μ < 2.1 obs. (2.0 exp. for μ=0)

H–charm coupling

Charm coupling $\lambda_c \sim \lambda_{tau}$, but way harder to probe :

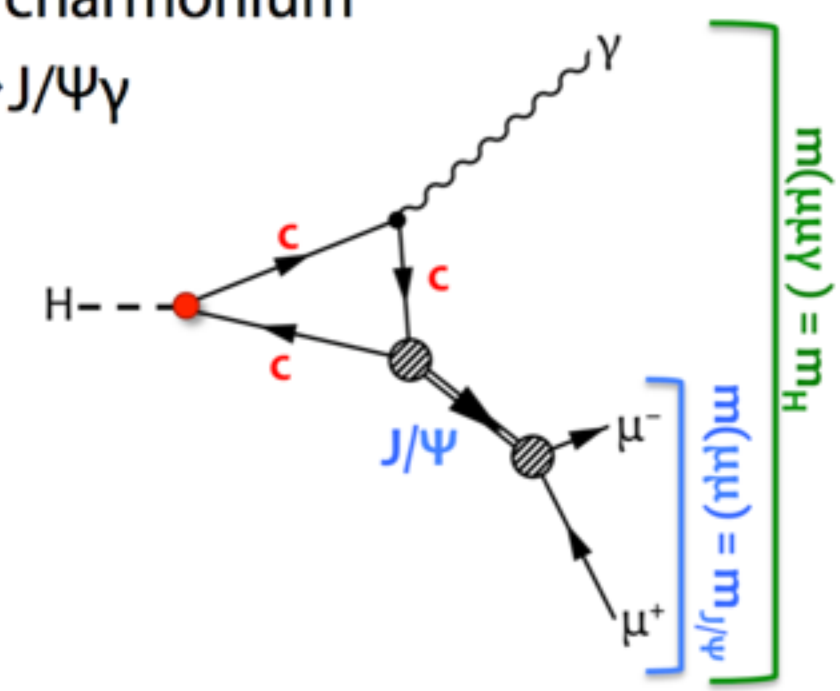
BR(cc)~0.05×BR(bb), H→bb background, and ID of charm jets more challenging compared to bottom jets



arXiv: 1809.10733

Three approaches can be explored

- Direct searches for H→cc decay
- Searches for charmonium decays: H→J/Ψγ



- Extract constraints on λ_c from kinematics

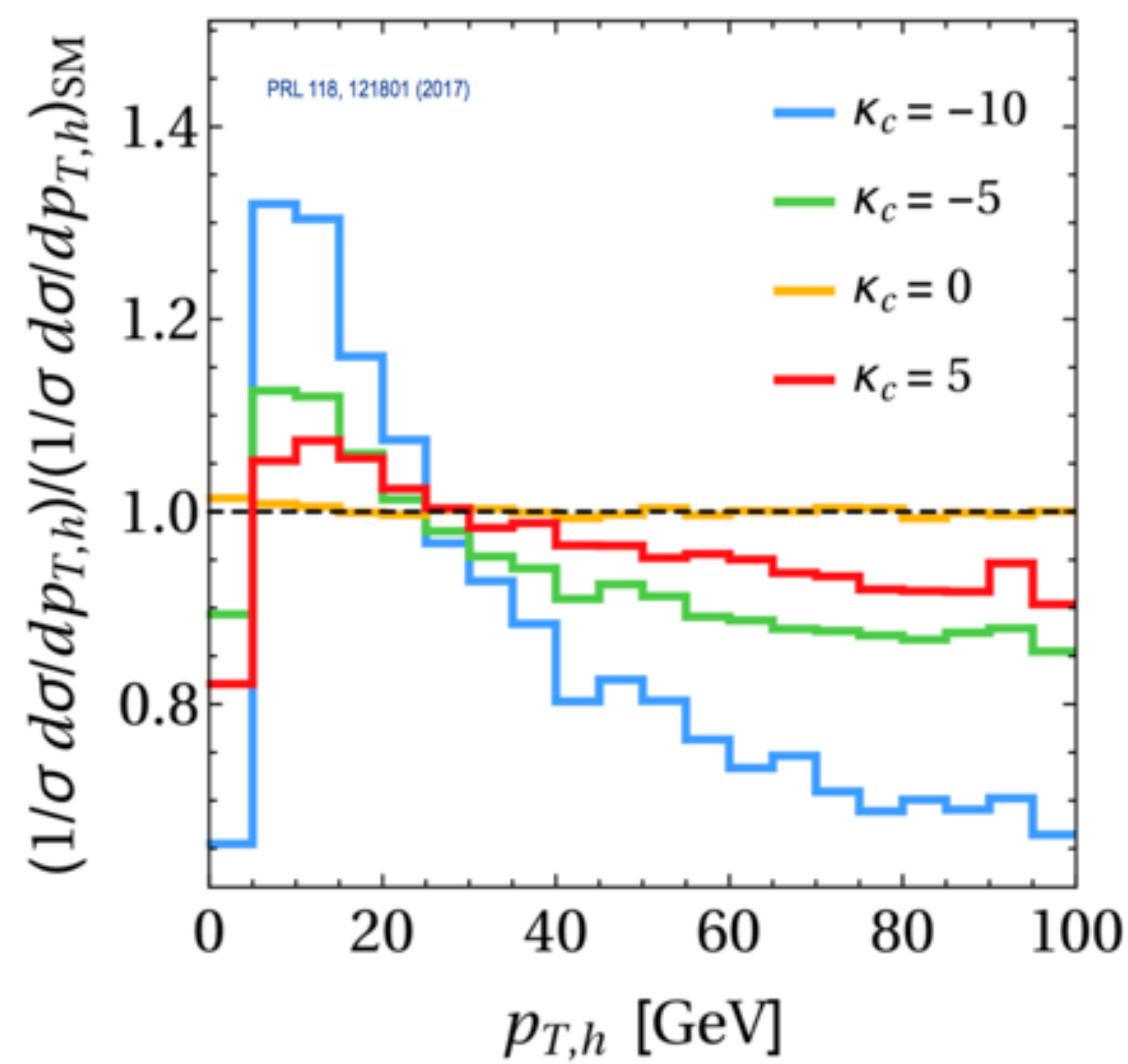
H–charm coupling

constraints on λ_c from kinematics : best limits

Higgs p_T spectrum one of the most important differential observables

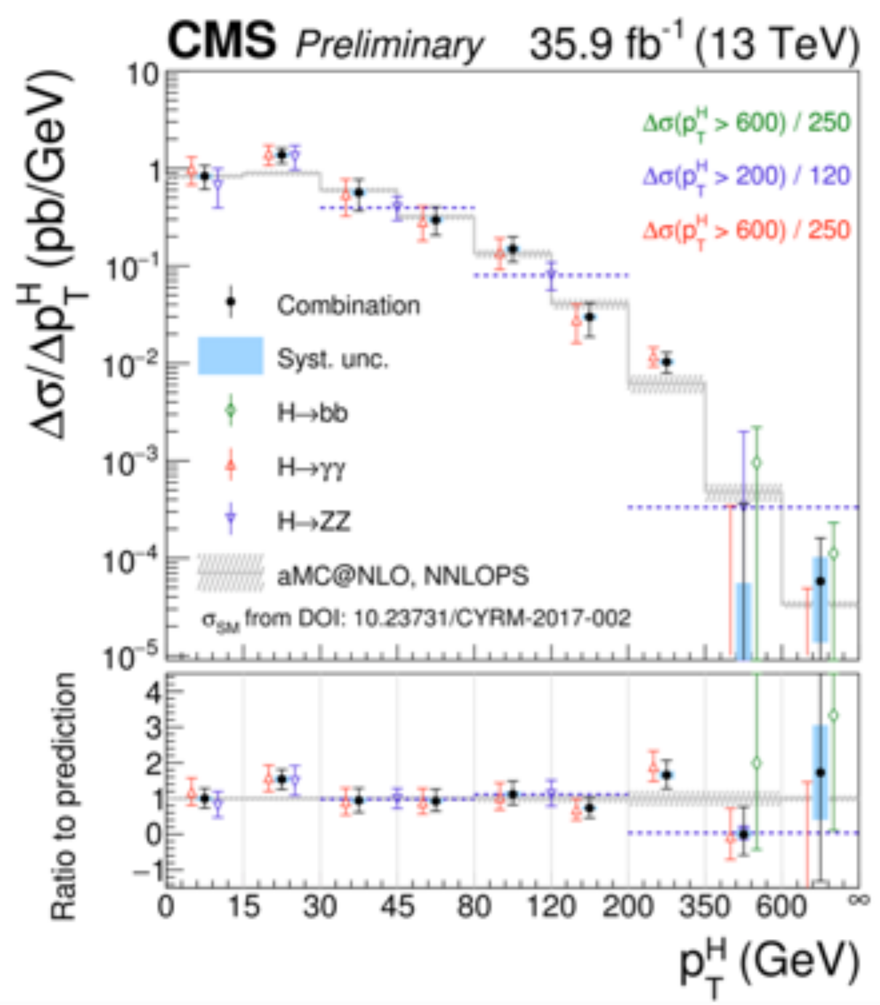
p_T(ggH) predictions provided by theorists in terms of $\kappa_c := \lambda_c/\lambda_c^{SM}$

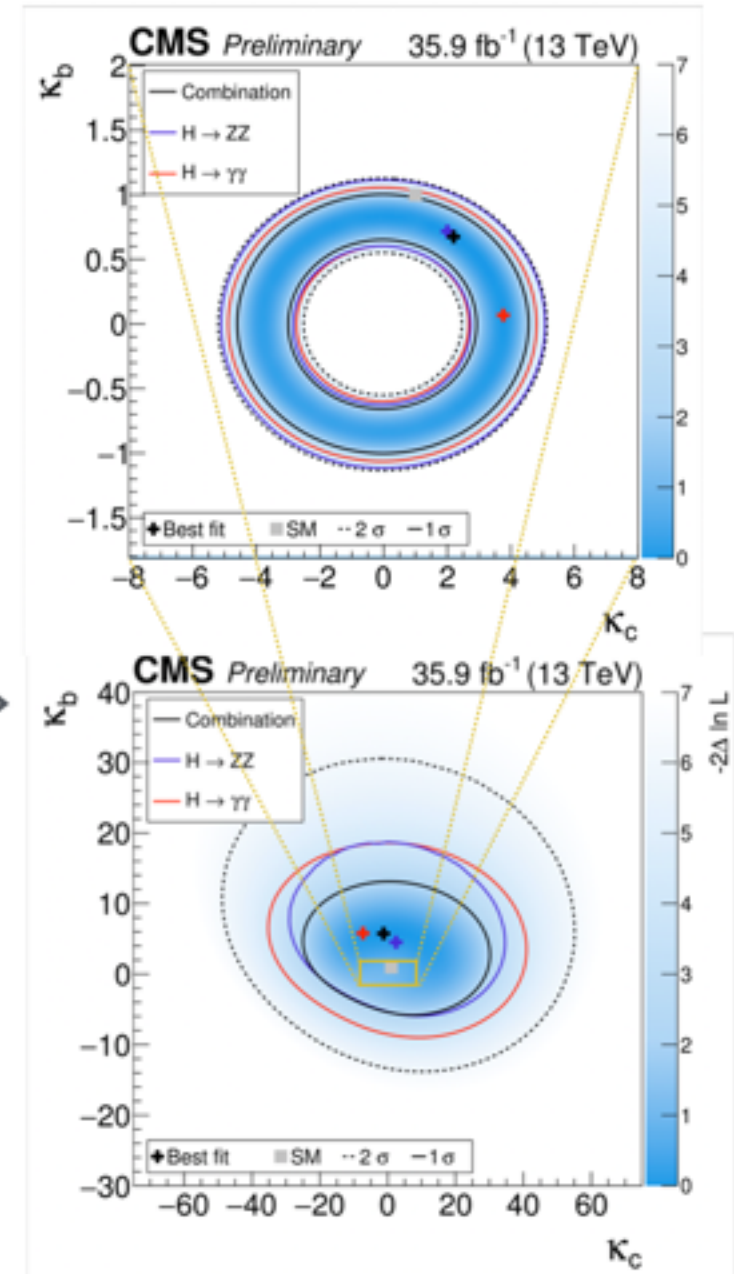
p_T range [0, 120] GeV, well below m_{top}



H–charm coupling

Combined fit of $p_T(H)$ measurements from γγ and ZZ final states.
H→bb measurement starting from 350 GeV





Scenario 1
BR = BR(κ_b, κ_c)

$-4.3 < \kappa_c < 4.3$ observed
($-5.4 < \kappa_c < 5.3$ expected)

Scenario 2
free BR's

$-18 < \kappa_c < 23$ observed
($-16 < \kappa_c < 19$ expected)

Conclusions

- LHC delivers fantastic datasets, always exceeding expectations
- we start to zoom in on the Higgs. We welcome the HL-LHC period to nail down its properties.
- in some channels it is clear that cleaver ideas (in obsrvables choices, analysis methods, …) are needed to beat the difficulty of the small cross sections and/or difficult final states