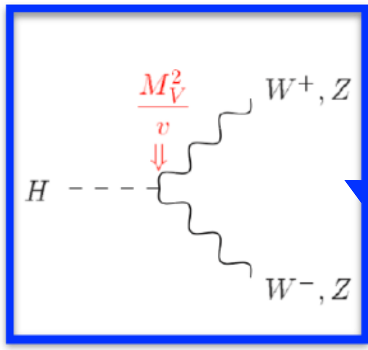
Overview of the ATLAS Higgs boson results

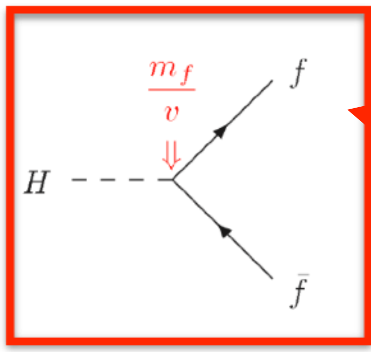
Valerio Dao *on behalf of the ATLAS collaboration*
CERN

excited QCD - Schladming

30-01-2019

The Higgs boson





$$\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} + i \bar{\Psi} \not{D} \Psi + |D_\mu \phi|^2 - V(\phi) + \bar{\Psi}_i y_{ij} \Psi_j \phi + h.c.$$

- With the discovery of a SM-like Higgs boson in 2012, the SM is now complete
- The Higgs boson provides tree level interactions with fermions and vector bosons which are also linked to the generation of their masses

- LHC Run1 left a strong legacy of Higgs boson measurements:
  - *mass (125 GeV) known to 0.2%*
  - *spin 0 and CP parity*
  - *coupling to vector bosons and taus established*
  - *measurements driven by leading production modes*

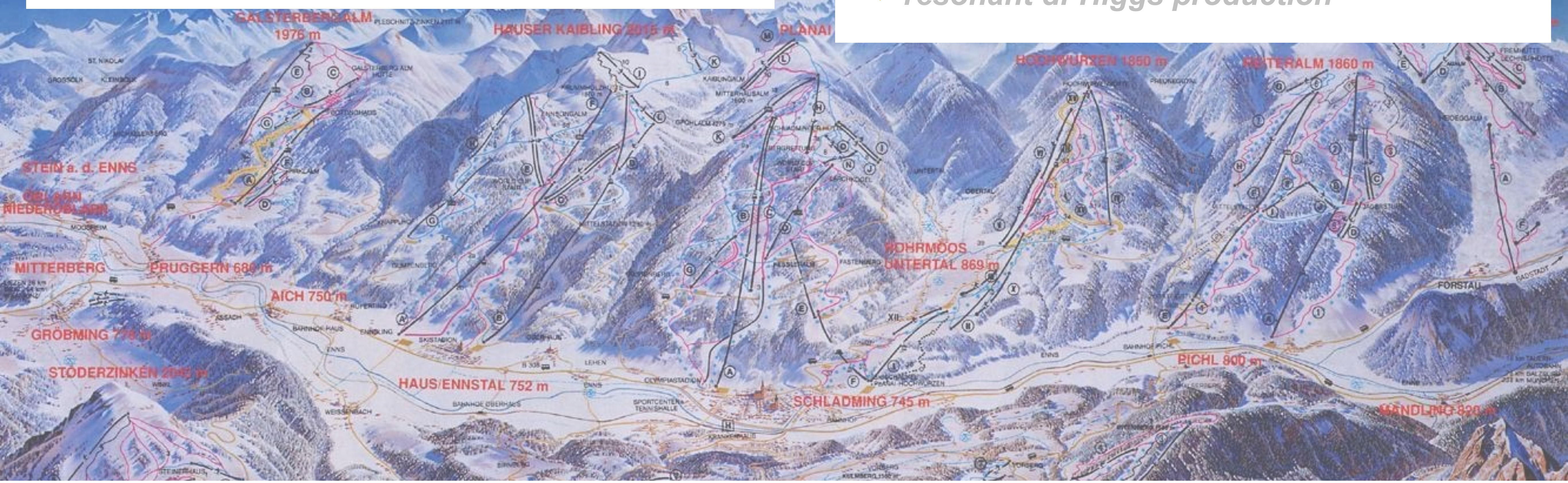
So far, no sign of deviation with respect to the Standard Model Higgs boson

The Higgs boson measurement/search maps

- Higgs boson physics represents the newer and fresher playground at LHC Run2 to understand the consistency of the SM and explore new physics effects

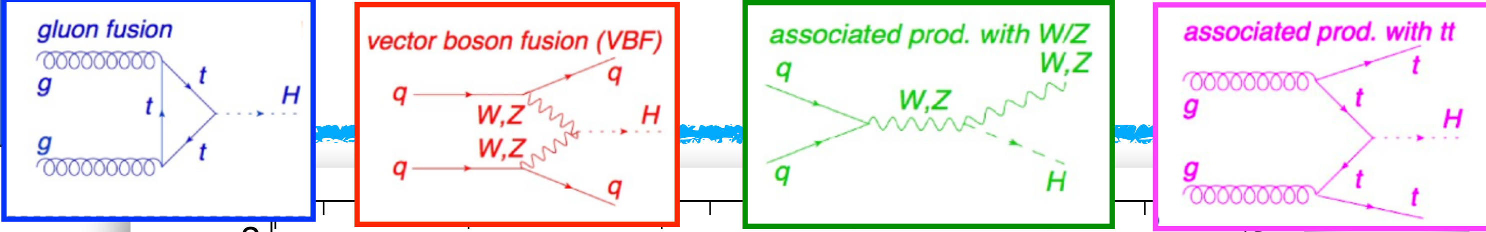
- indirect searches:
  - ***precise measurement of production and decays***
  - ***(pseudo) differential production measurement***
  - ***EFT coupling interpretation***
  - ***rare Higgs boson decays***
  - ***measurement of decay kinematics***

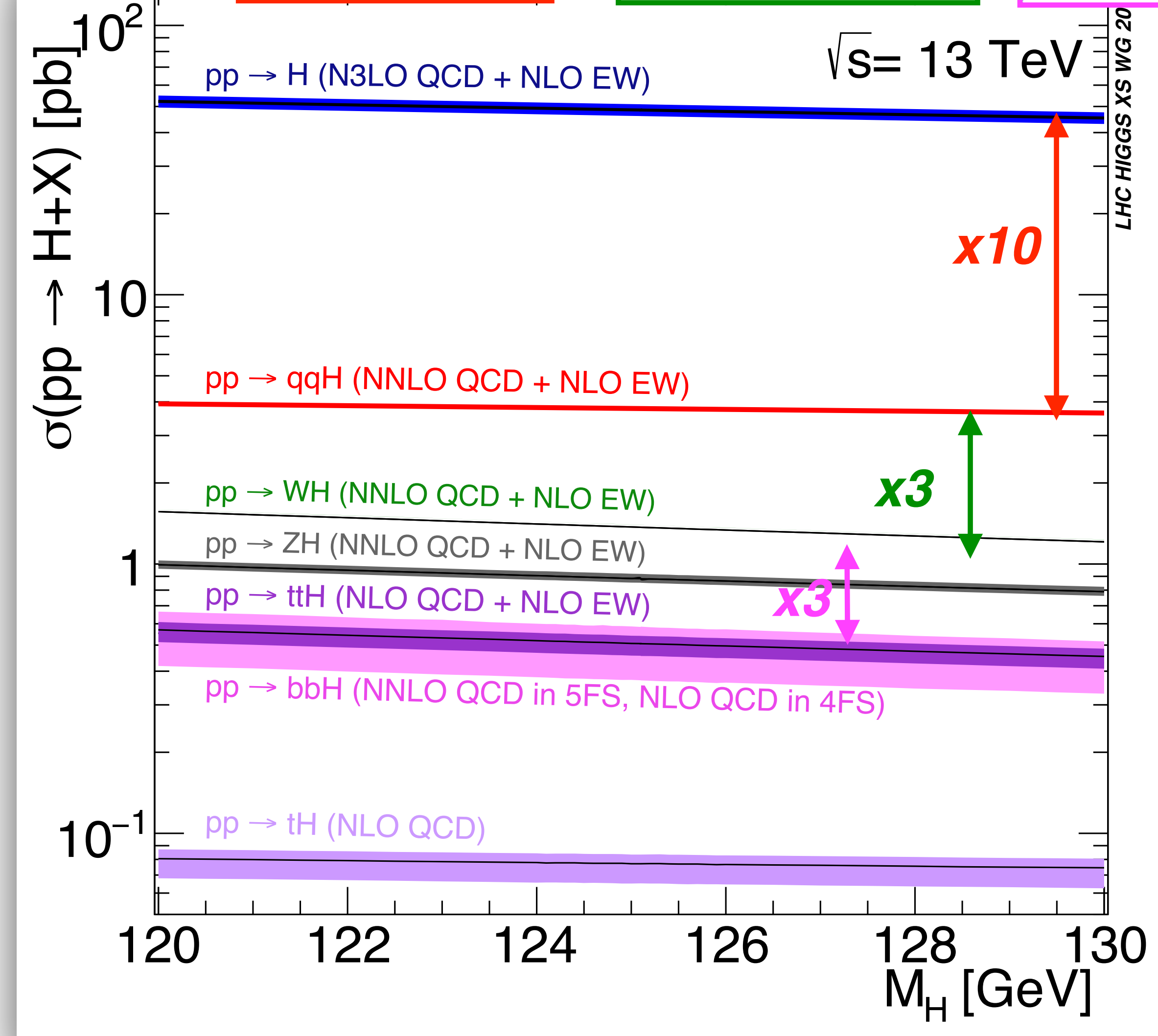
- direct searches:
  - ***extended Higgs sector both at high and low masses (new scalars, pseudo scalars)***
  - ***charged Higgs***
  - ***exotics decays***
  - ***new states producing Higgs boson in decays (SUSY, heavy resonance)***
  - ***resonant di-Higgs production***

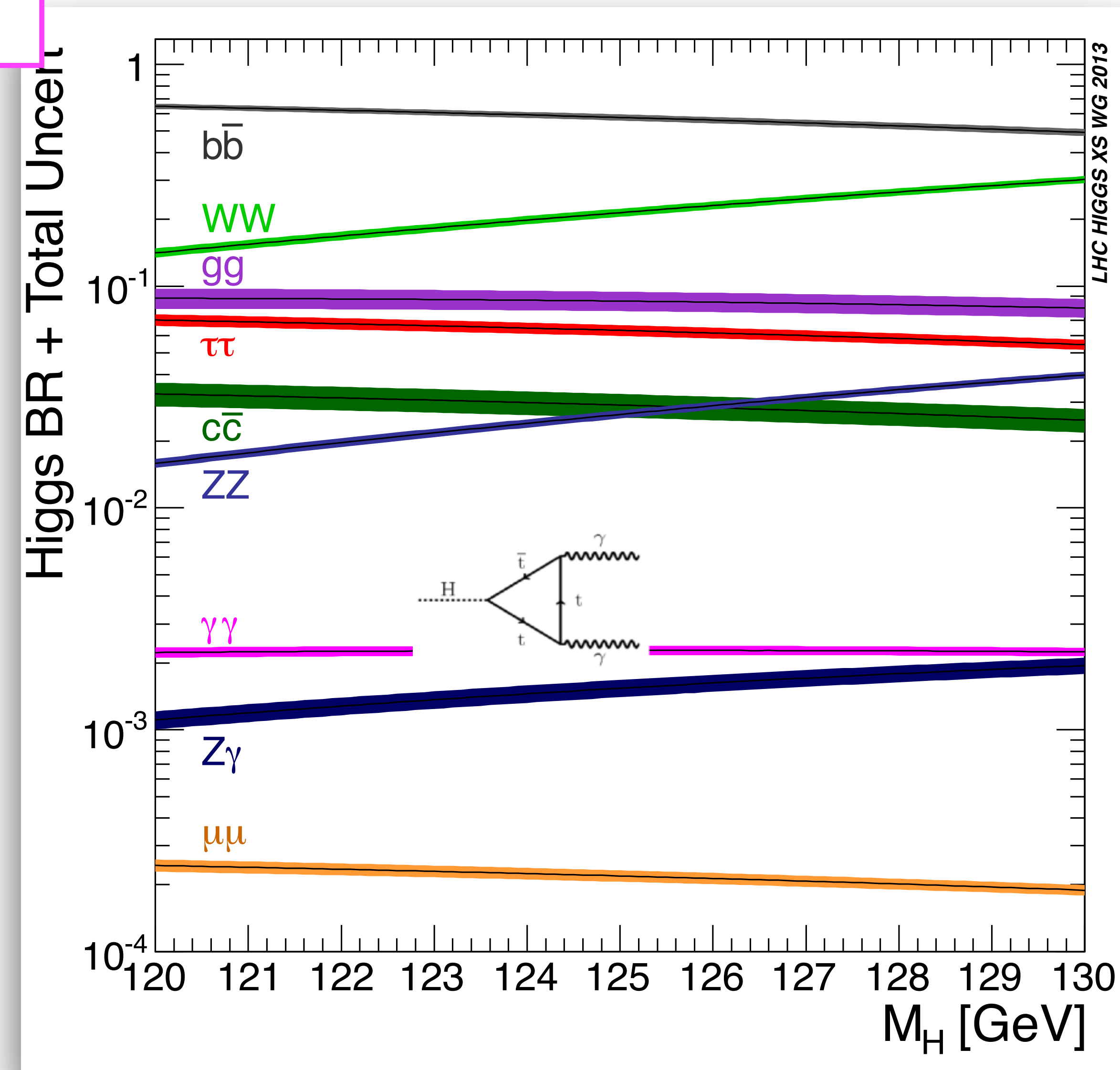


- An incredibly large amount of material … concentrating on some key aspects (personal choice)

Higgs phenomenology



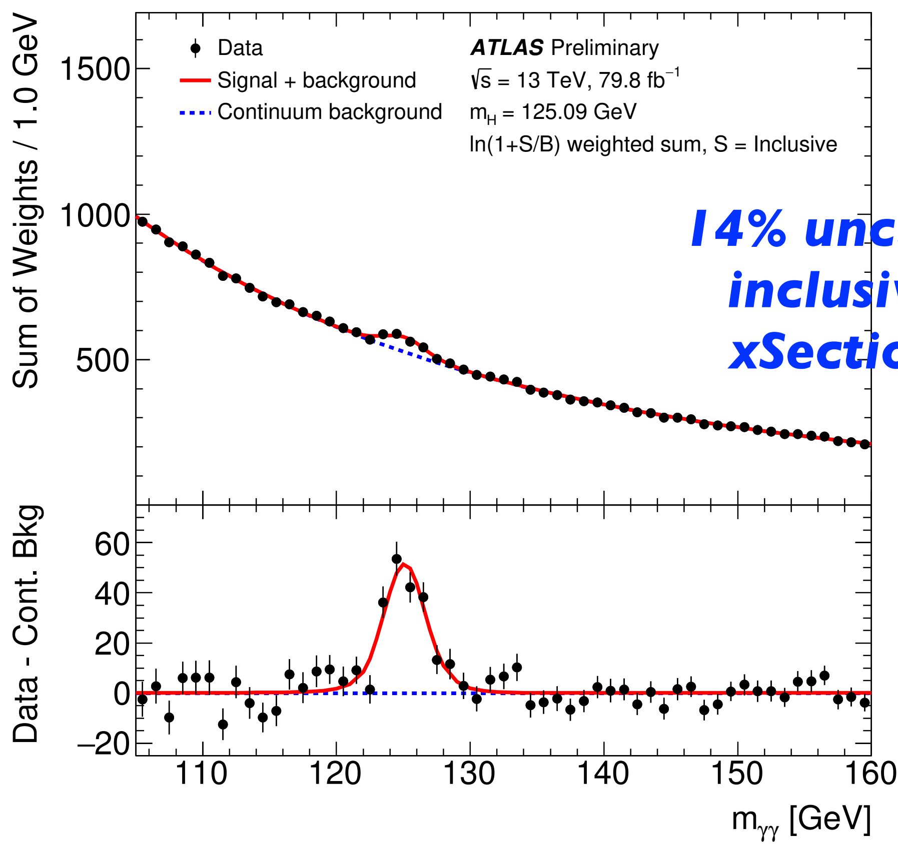




- Extremely rich phenomenology both in production and decay: a lot of handles to test the consistency of the model and probe for new physics effects
- large variety of physics objects involved: need an excellent multipurpose detector
- good complementarity: cleanest final state have lower cross section or Br. Channels with higher cross section usually more challenging experimentally due to background

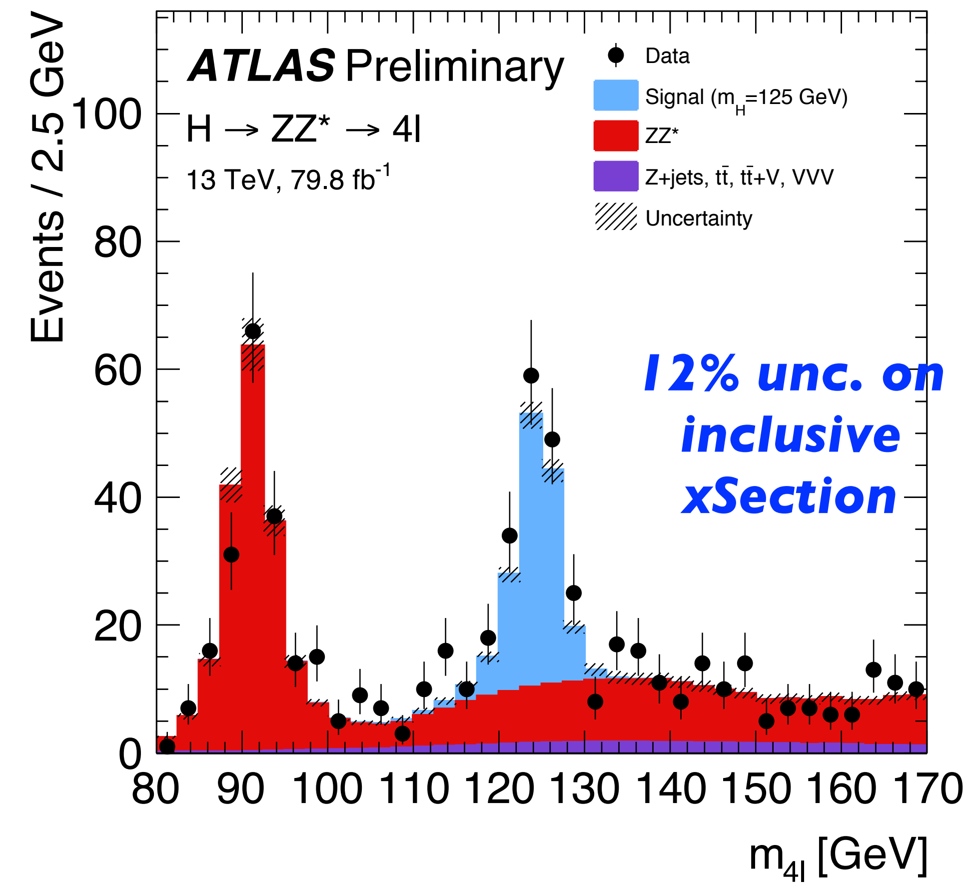
The golden channels

H->$\gamma\gamma$

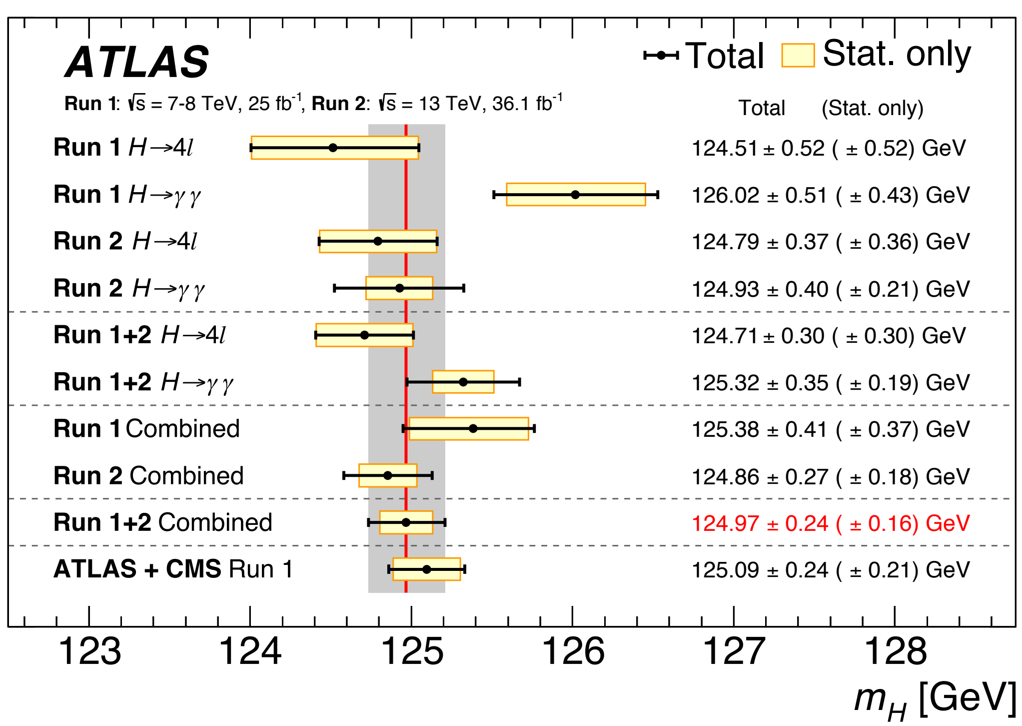


14% unc. on inclusive xSection

H->ZZ*->4l



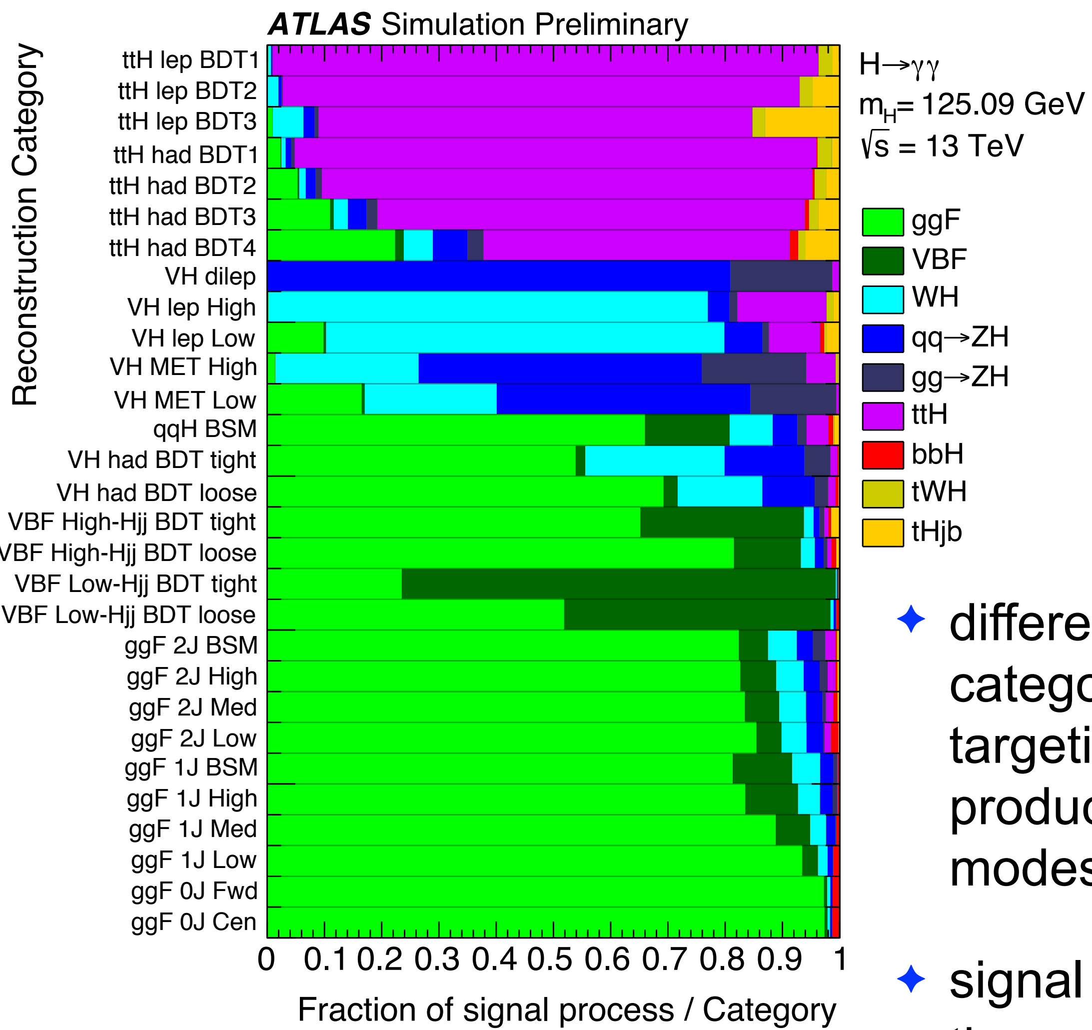
12% unc. on inclusive xSection



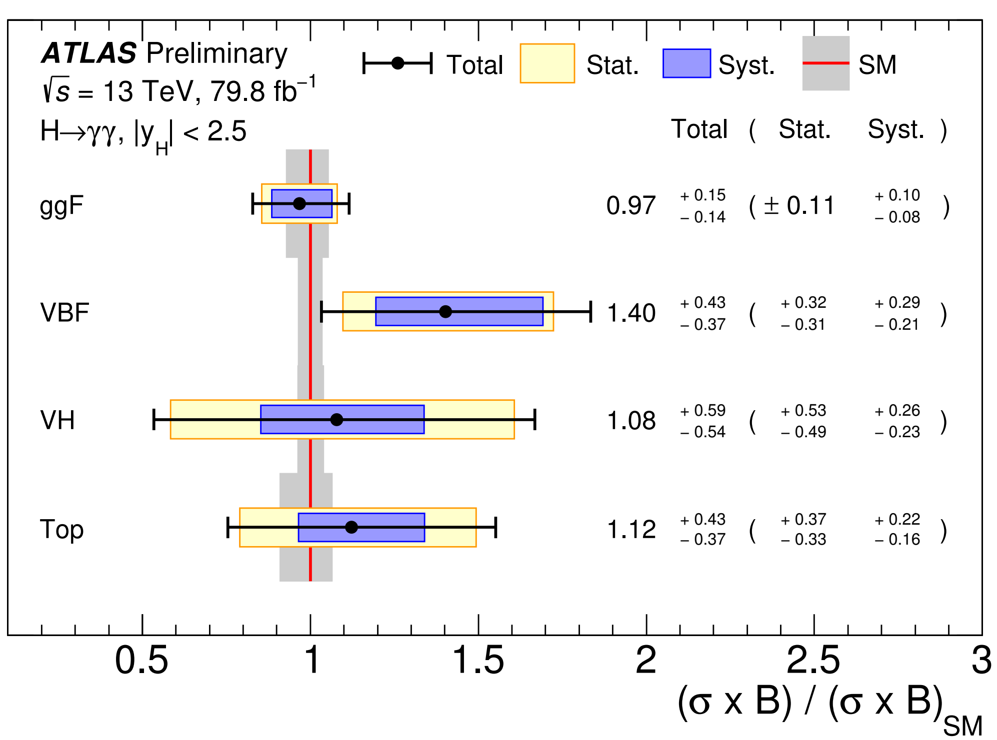
- <0.2% uncertainty on Higgs boson mass
- partial Run2 result competitive with final Run1 LHC combination

Phys. Lett. B 784 (2018) 345

The golden channels

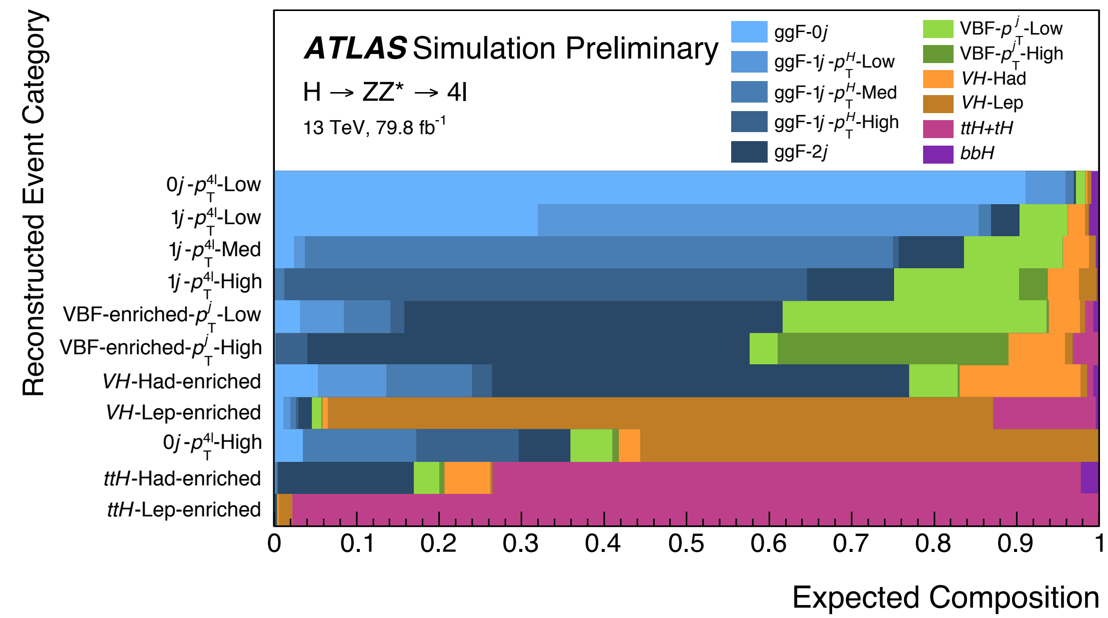


- different categories targeting production modes
- signal extracted through fit to $m_{\gamma\gamma}$

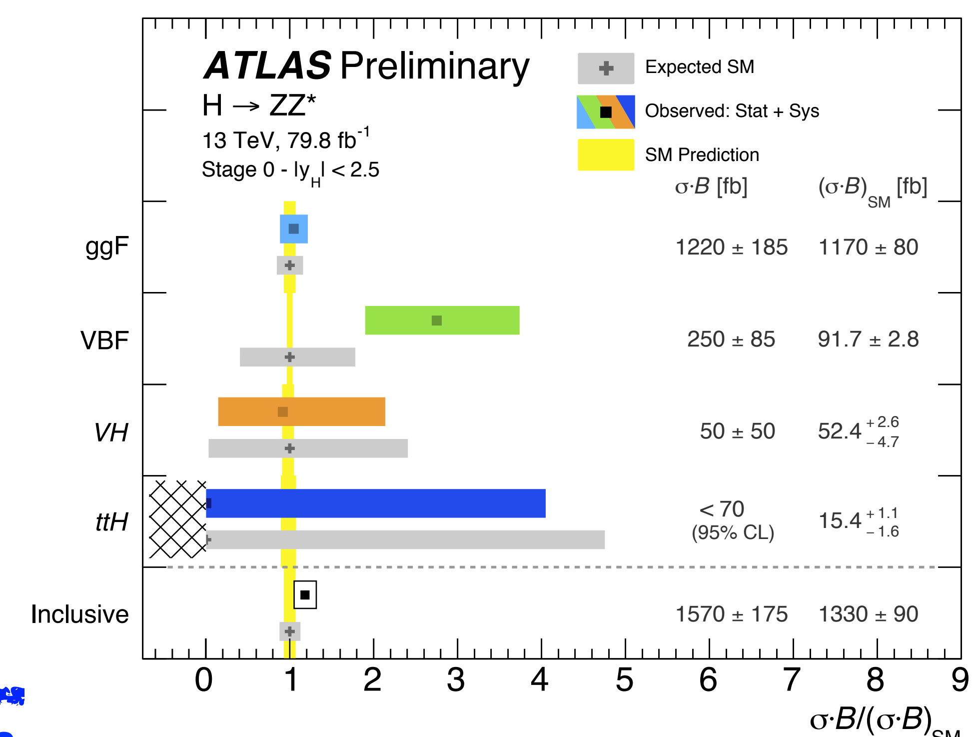


H->ZZ*->4l

- select events with 114 GeV<m_{4L}<130 GeV
- different categories targeting production modes



- signal extracted with multivariate discriminant

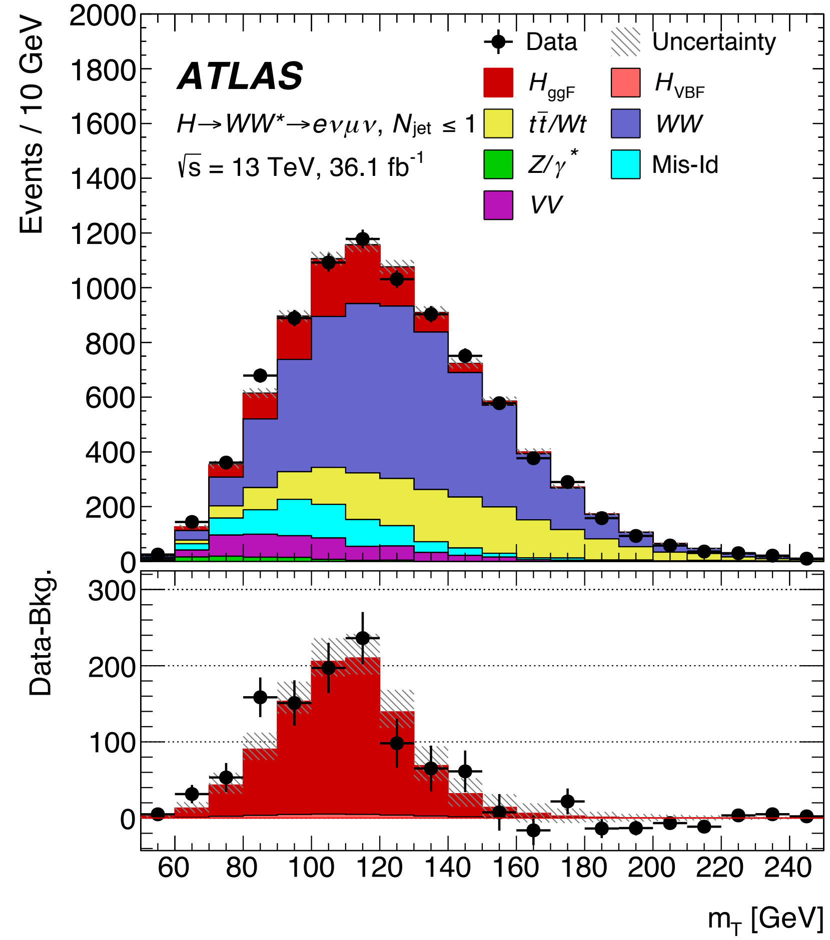


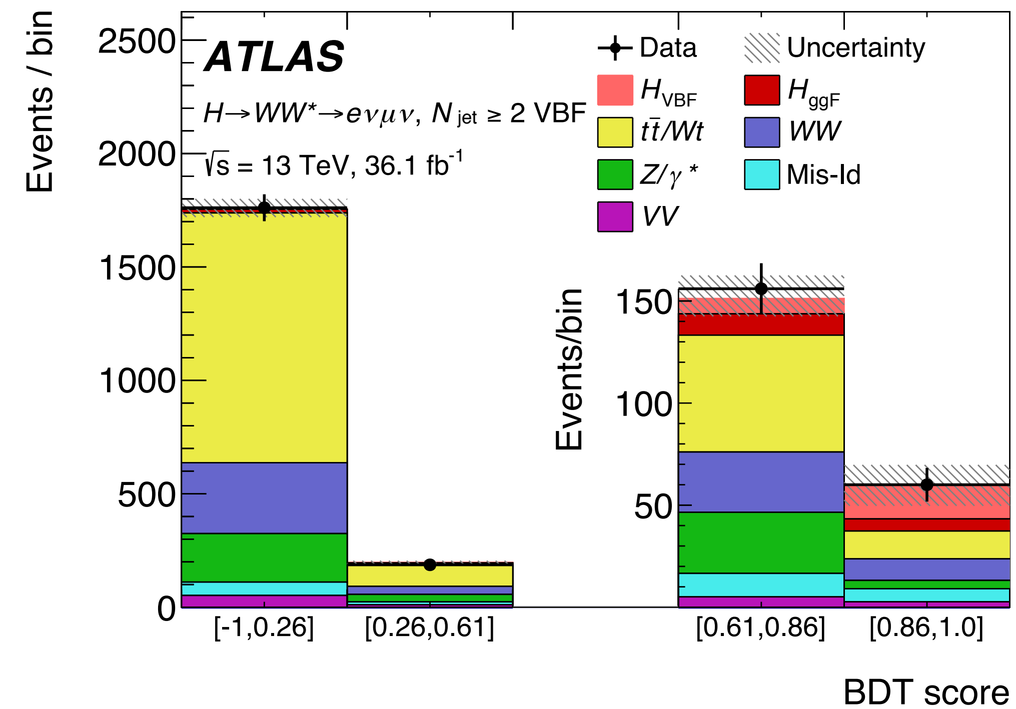
more on coupling to bosons: H->WW

Phys. Lett. B 789 (2019) 508

e+μ + MET events only:

most sensitive final state due to reduced Z background

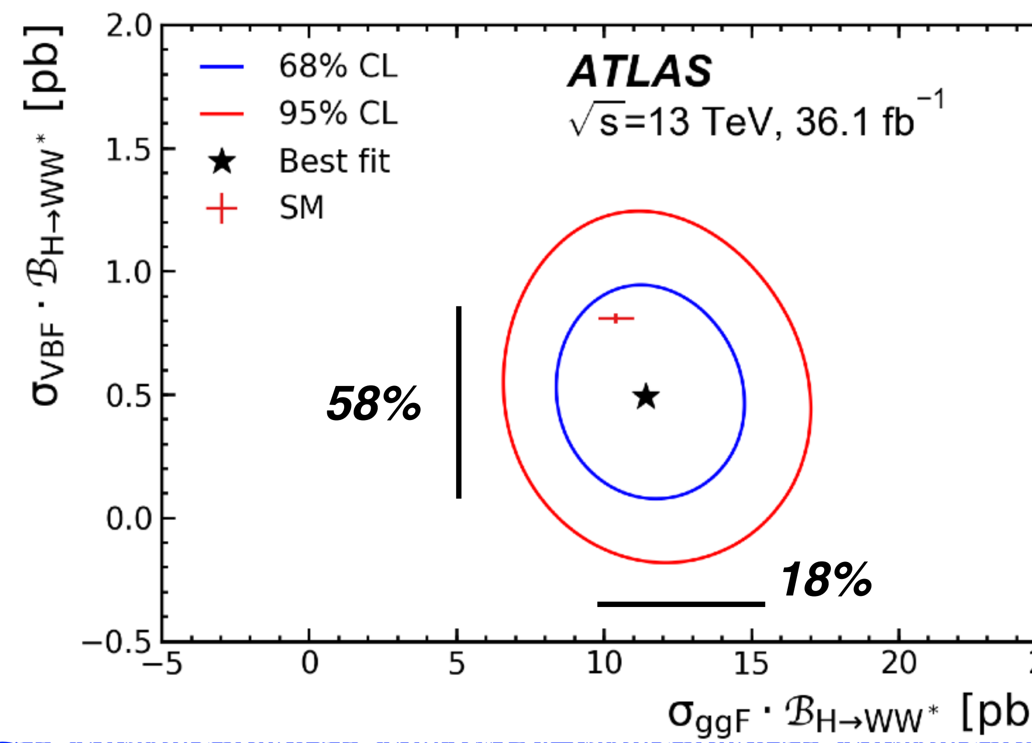




- *2j events sensitive to VBF production (fit to BDT)*
- *0-1j events used to measure ggF production: fit to m_T in multiple categories*

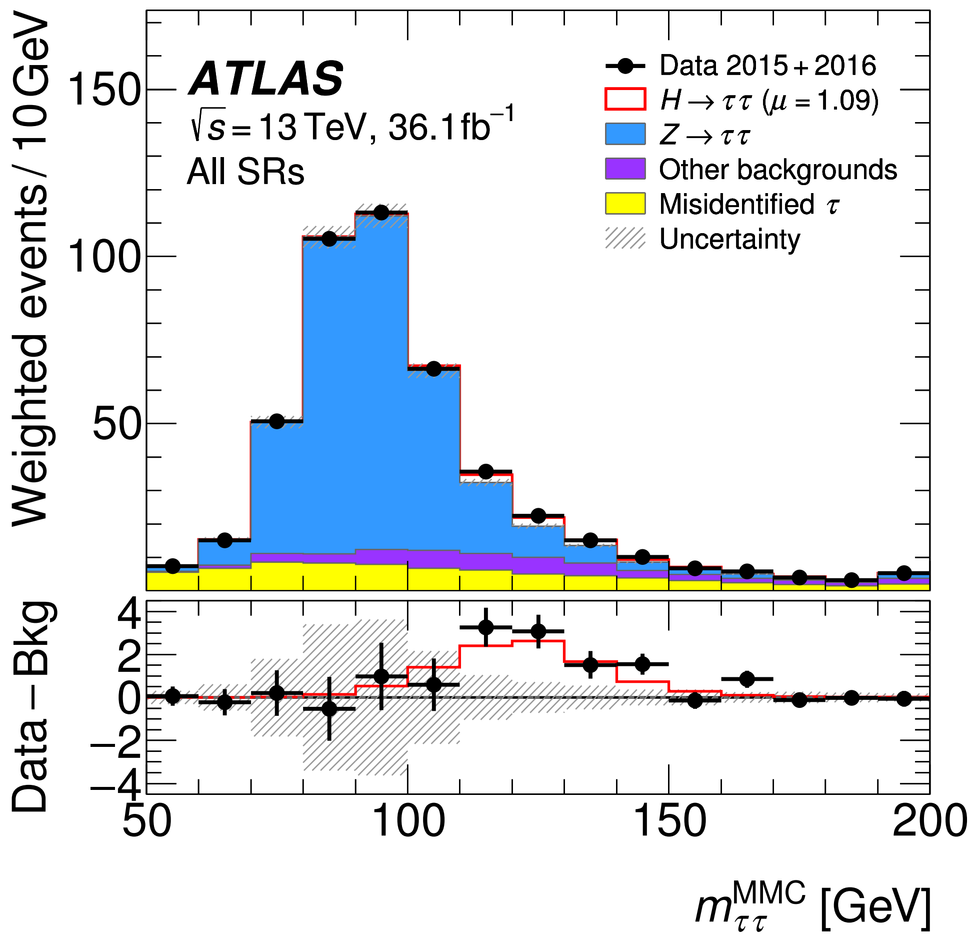
$$\sigma_{\rm ggF} \cdot \mathcal{B}_{H\to WW^*} = 11.4^{+1.2}_{-1.1}({\rm stat.})^{+1.2}_{-1.1}({\rm theo\ syst.})^{+1.4}_{-1.3}({\rm exp\ syst.})$$

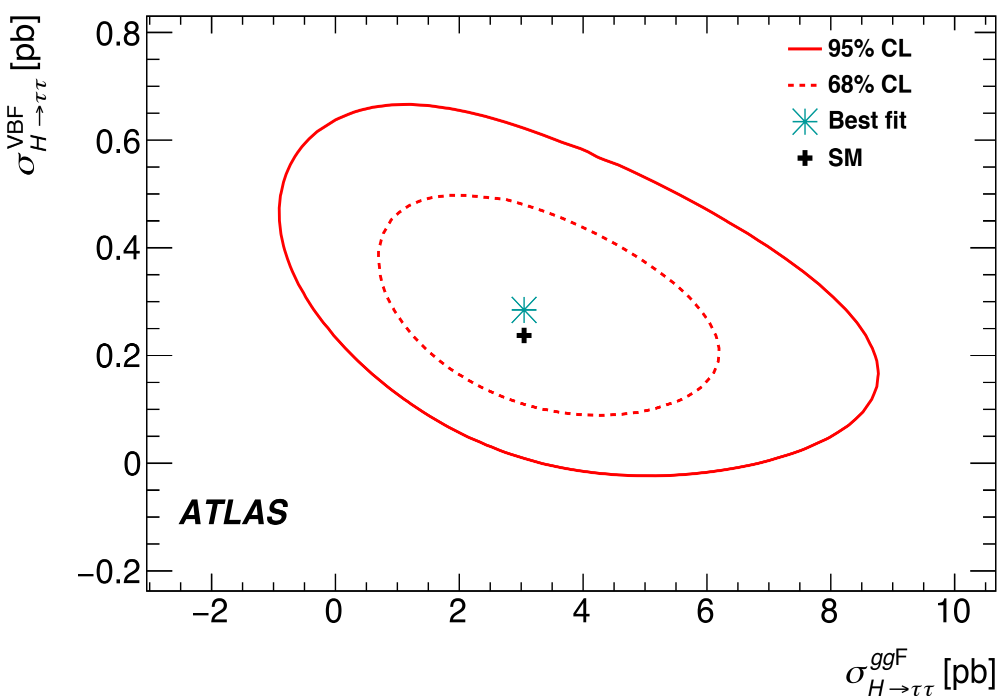
$$\sigma_{\rm VBF} \cdot \mathcal{B}_{H\to WW^*} = 0.50^{+0.24}_{-0.22}({\rm stat.}) \pm 0.10({\rm theo\ syst.})^{+0.12}_{-0.13}({\rm exp\ syst.})\ {\rm pb}$$



arXiv:1811.08856 (submitted to PRD)

- Exploiting all the di-tau decay modes:
  - *had-had, lep-had, lep-lep*
- 2 main categories, each split into tight and loose part:
  - *VBF: >=2j , m_{jj}>400GeV*
  - *boosted ggF: !VBF , >=1j and p_T^{tt}>100 GeV*
- sensitivity strongly increases with p_T^H: most favourable region above 140 GeV





$$\sigma^{ggF}_{H\to\tau\tau} = 3.1 \pm 1.0(\text{stat.})\,^{+1.6}_{-1.3}(\text{sys.})\text{ pb}$$

$$\sigma^{VBF}_{H\to\tau\tau} = 0.28 \pm 0.09(\text{stat.})\,^{+0.11}_{-0.09}(\text{sys.})\text{ pb}$$

correlation: 52%

Run2 signal significance: 4.4 s.d. obs. , 4.1 s.d. exp.

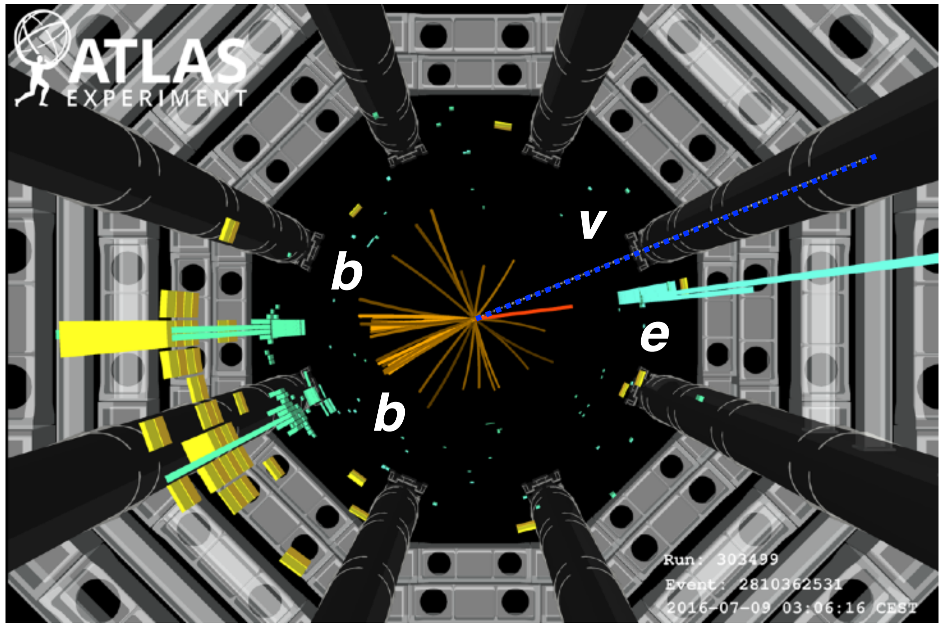
Run1+Run2 signal significance: 6.4 s.d. obs. , 5.4 s.d. exp.

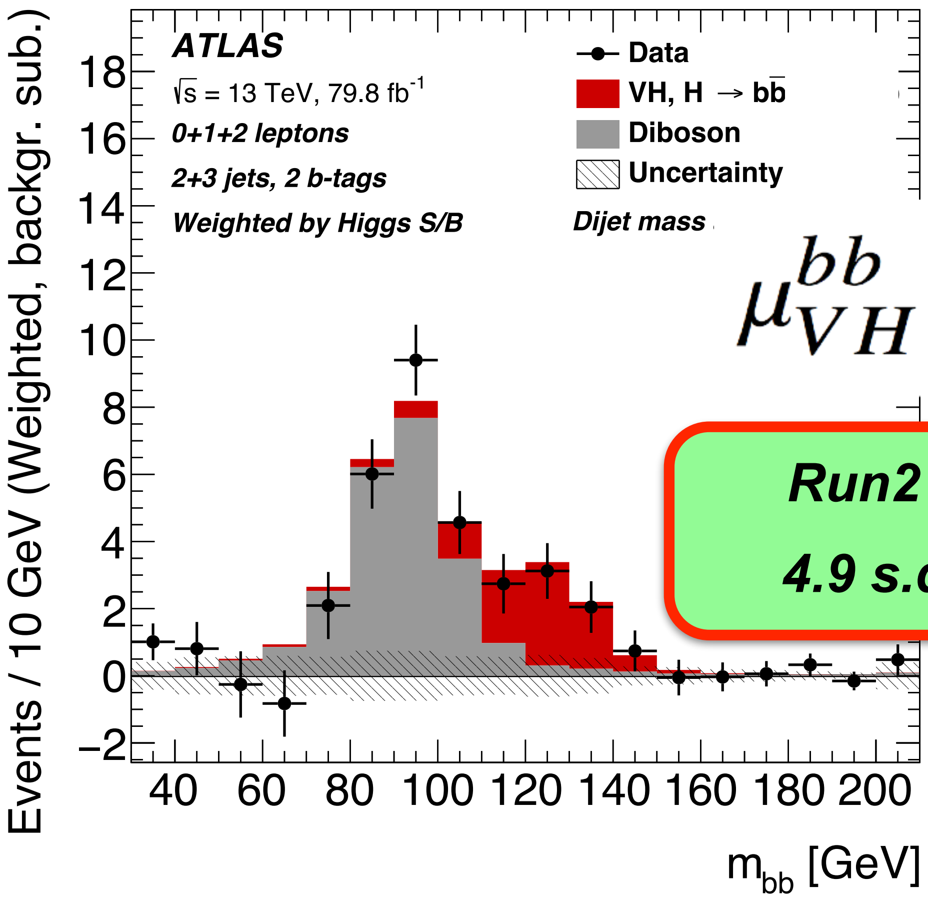
!!! OBSERVATION of H->$\tau\tau$!!!

H->bb: VH as key channel

- Exploiting leptonic vector boson decay:
  - *background reduction easier to collect events*
- Three main channels used on the number of reconstructed leptons (0L, 1L, 2L):
  - *main sensitivity from V p_T>150 GeV*
  - *using multivariate techniques for signal extraction*
  - *cross check with fit to m_{bb} distribution*

WH -> lvbb

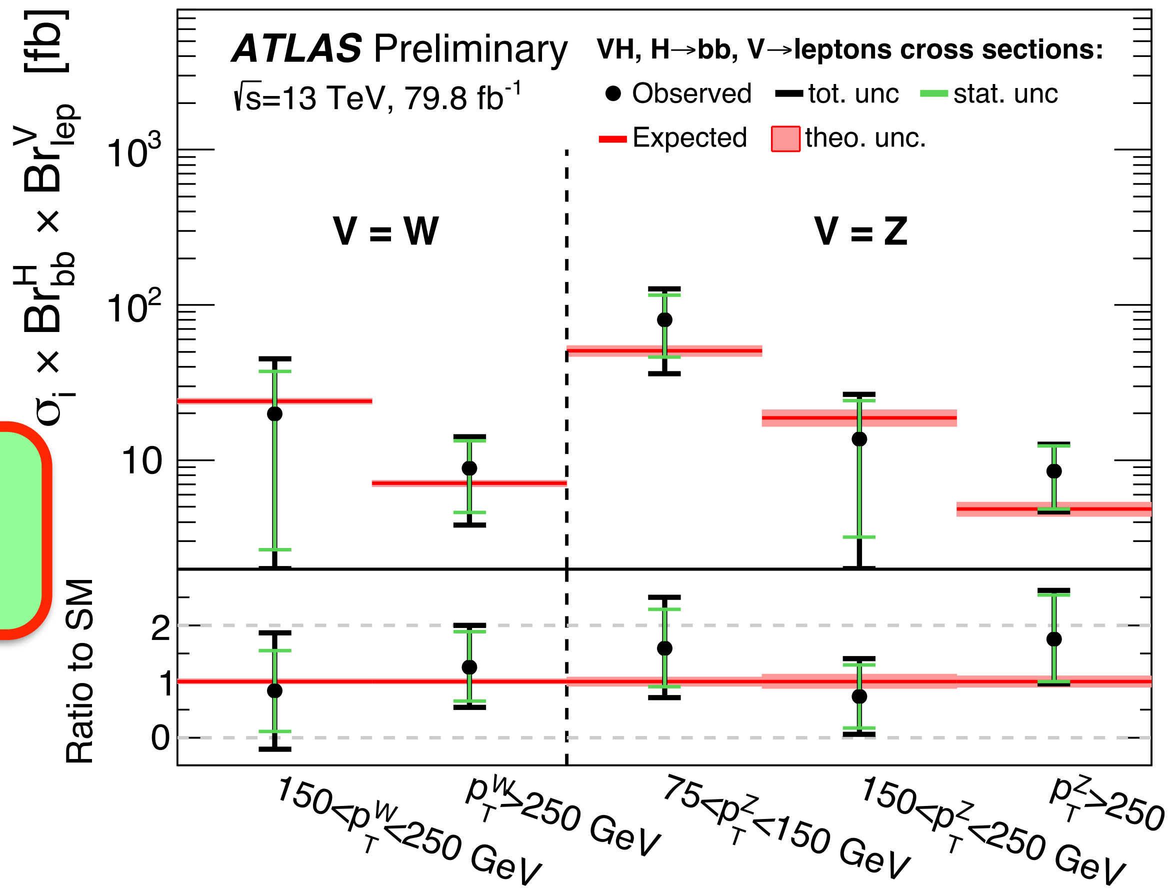




$$\mu_{VH}^{bb} = 1.16^{+0.27}_{-0.25}$$

Run2 signal significance:

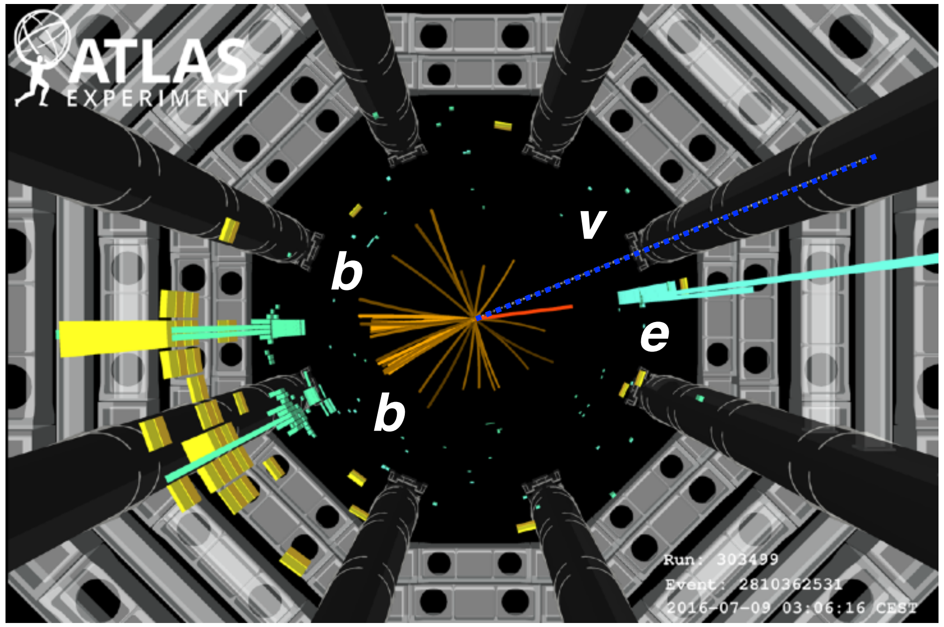
4.9 s.d. obs. , 4.3 s.d. exp.

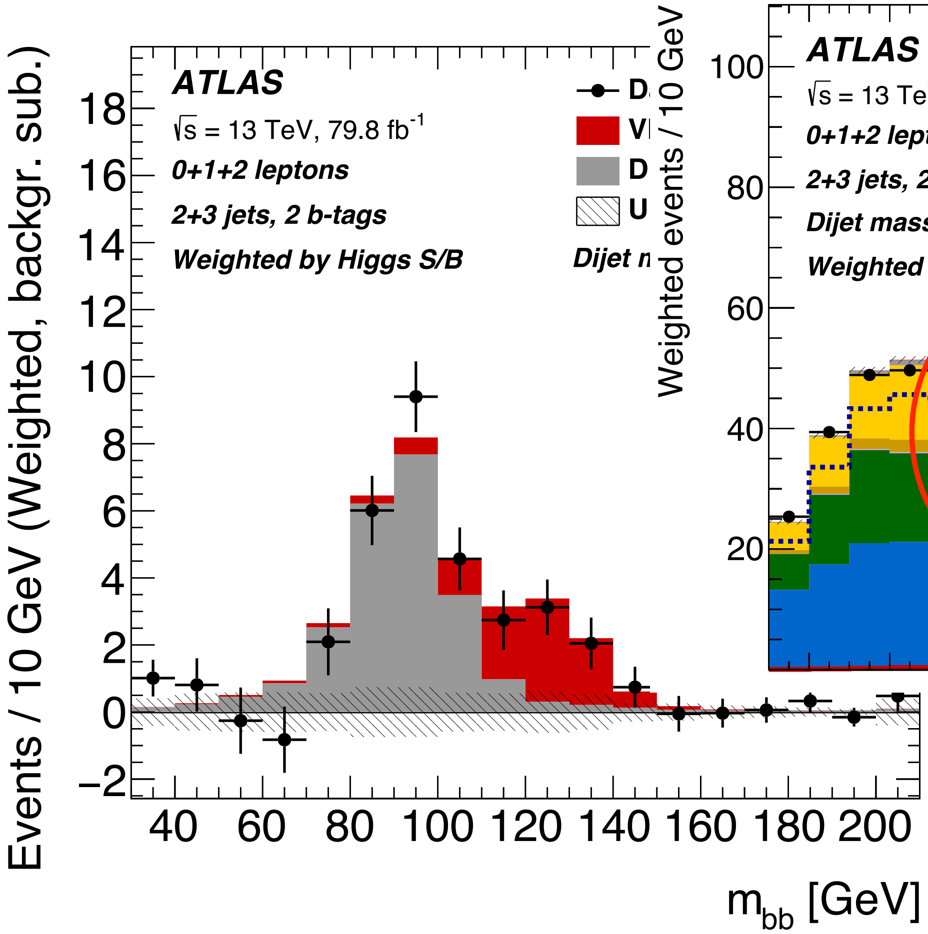


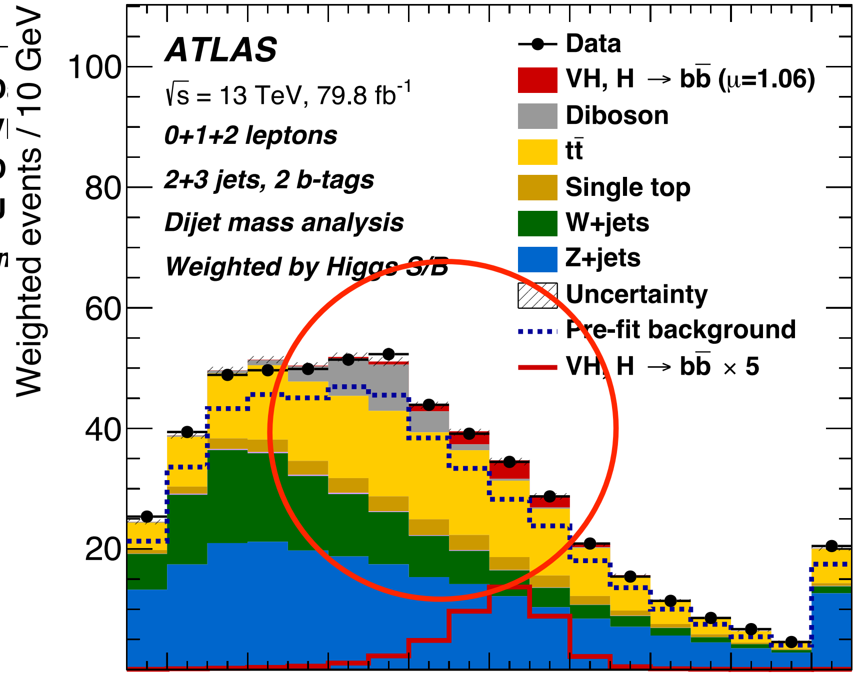
H->bb: VH as key channel

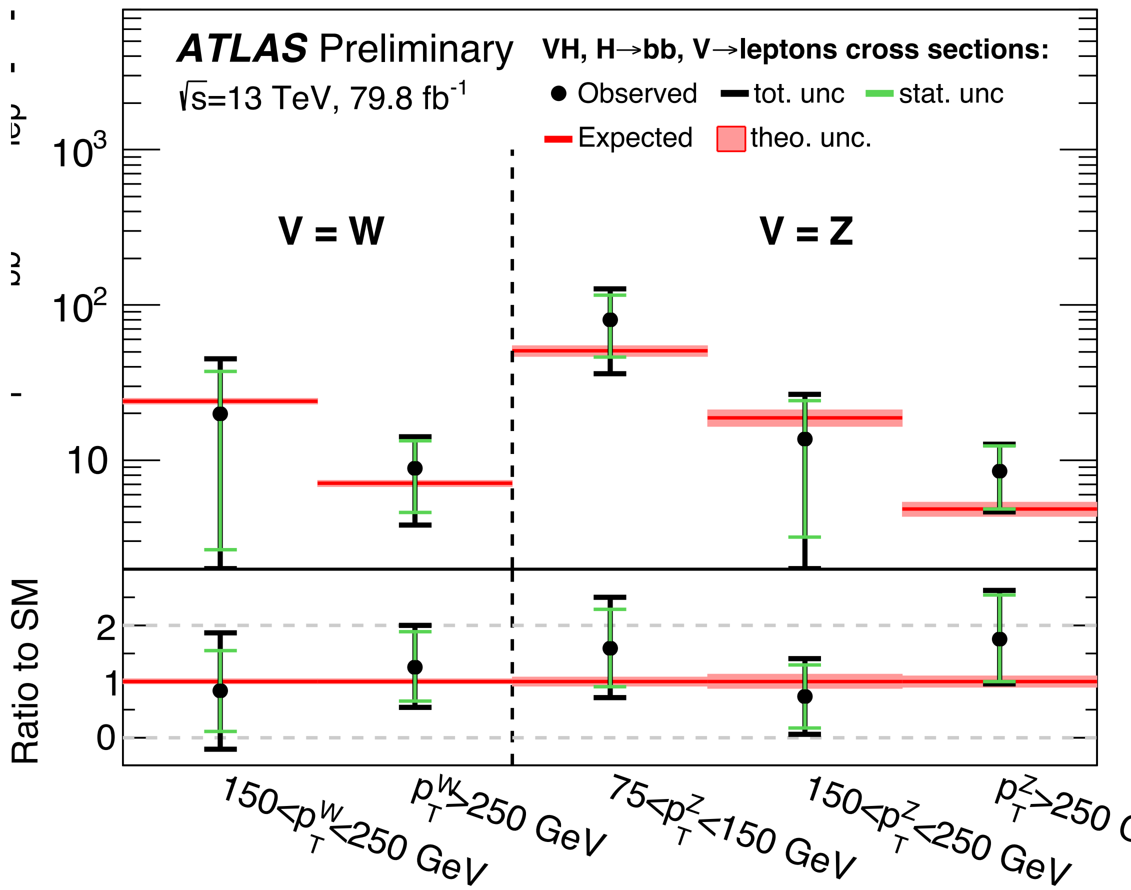
- Exploiting leptonic vector boson decay:
  - *background reduction easier to collect events*
- Three main channels used on the number of reconstructed leptons (0L, 1L, 2L):
  - *main sensitivity from V p_T>150 GeV*
  - *using multivariate techniques for signal extraction*
  - *cross check with fit to m_{bb} distribution*

WH -> lνbb







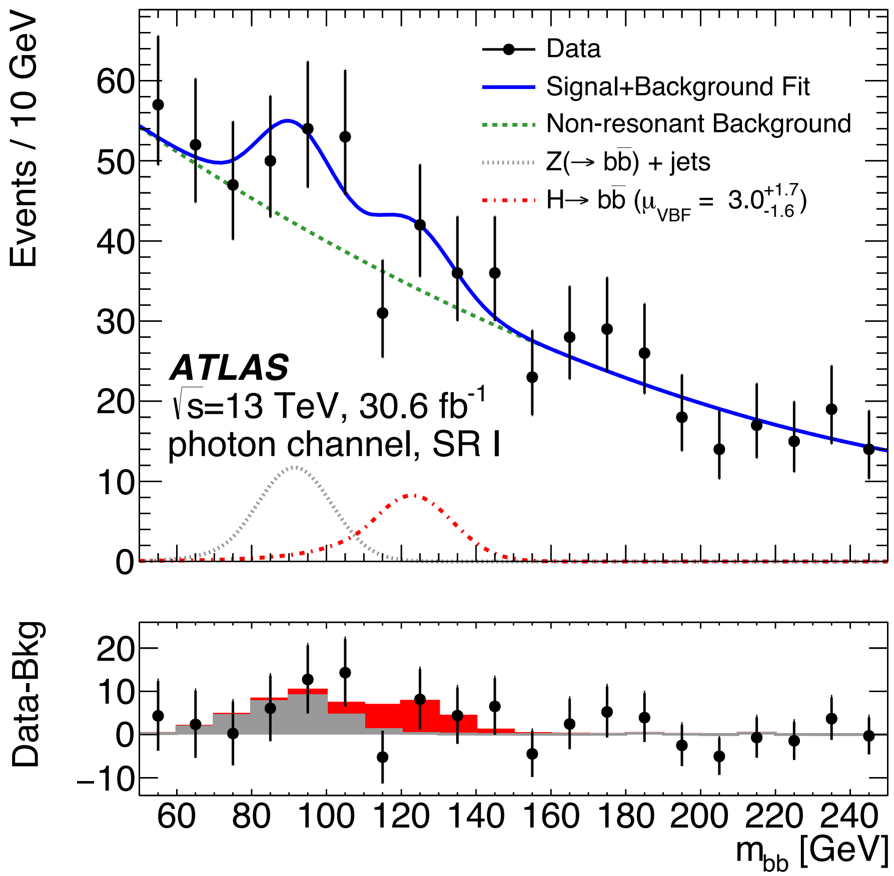


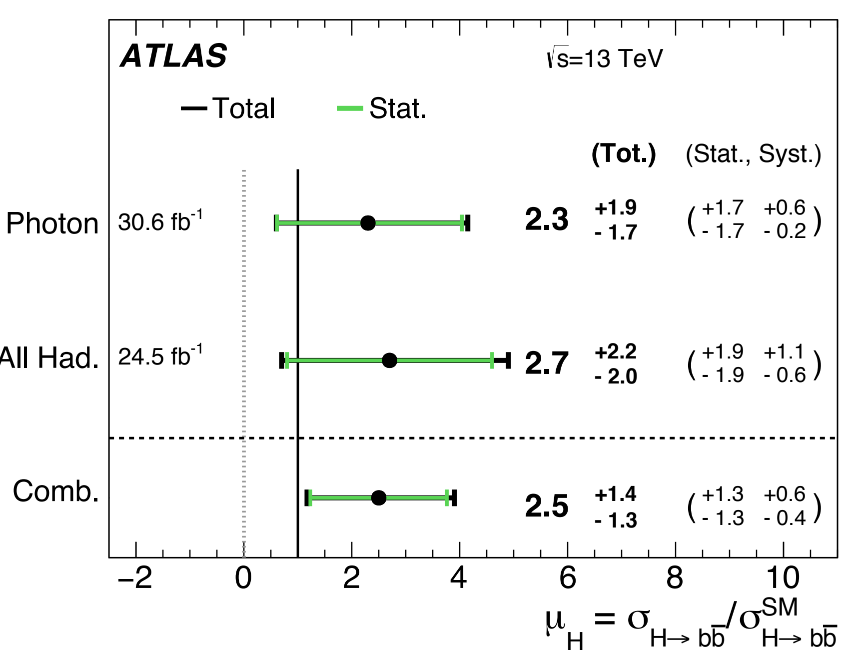
H->bb: “all hadronic”

VBF

2 b-jets + 2jets (+photon):

- *the photon reduces bkgd and ease triggering*



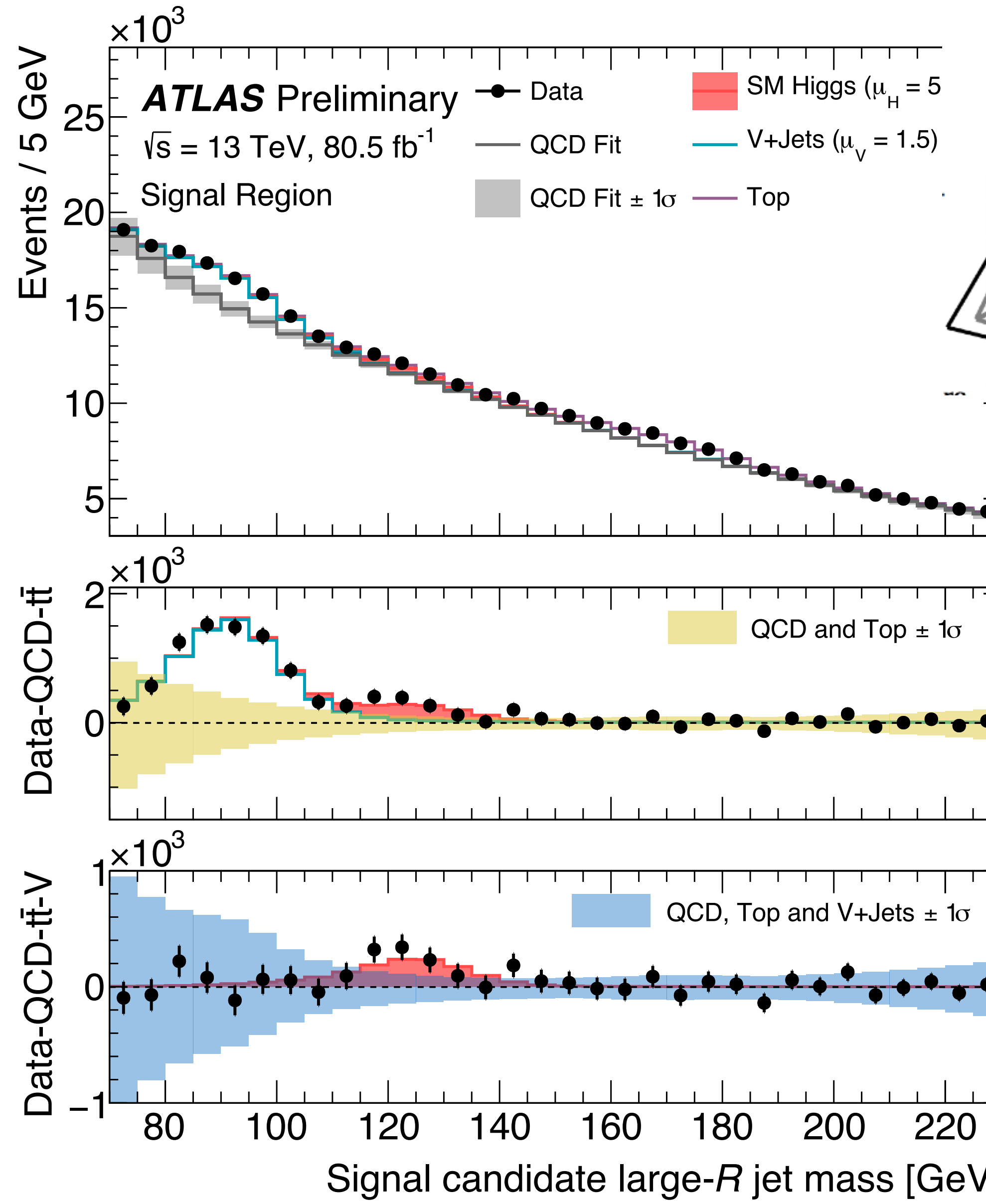


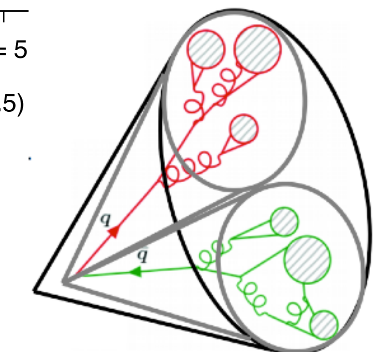
~1.2 s.d. obs
~0.6 s.d. exp

ggH

Higgs candidate reconstructed as large R jet (p_T>480 GeV):

- *relying critically on double b-tagging inside jet*

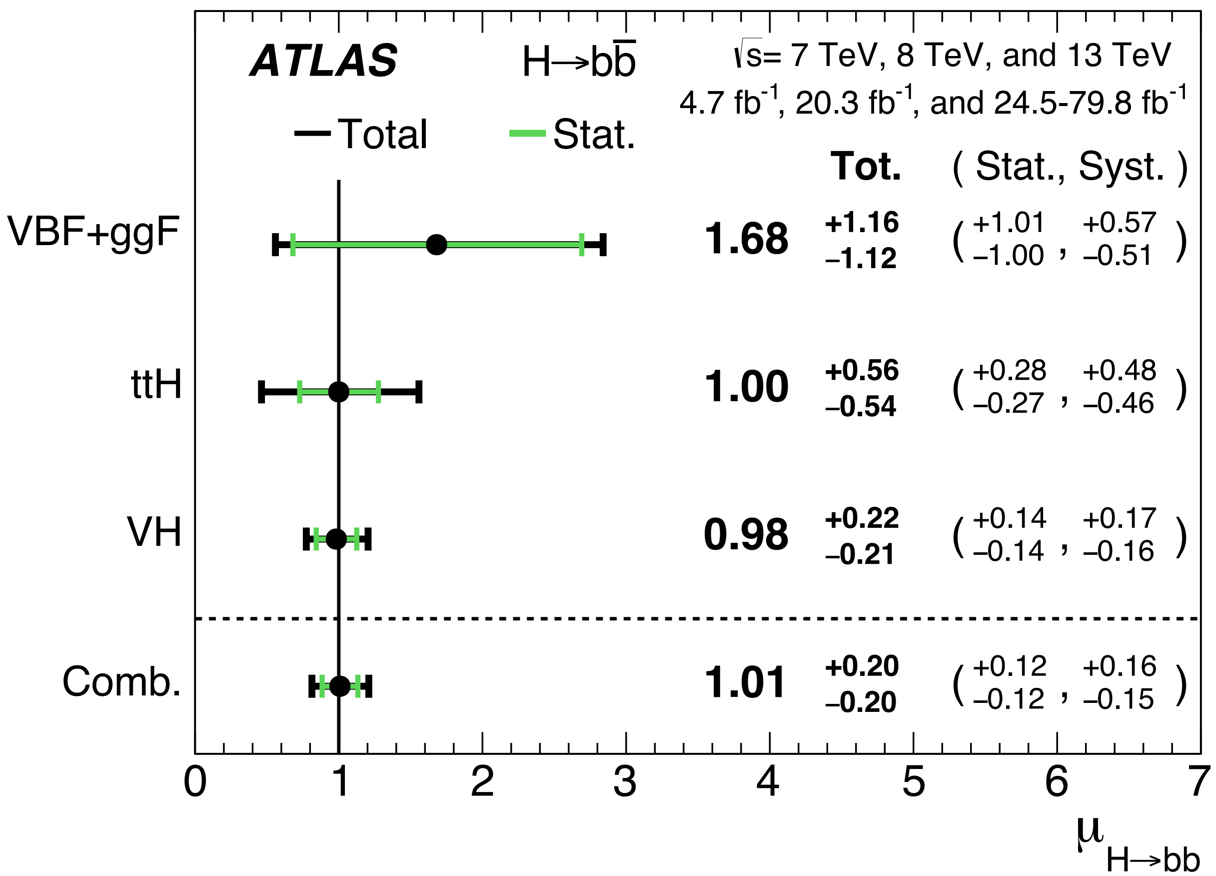


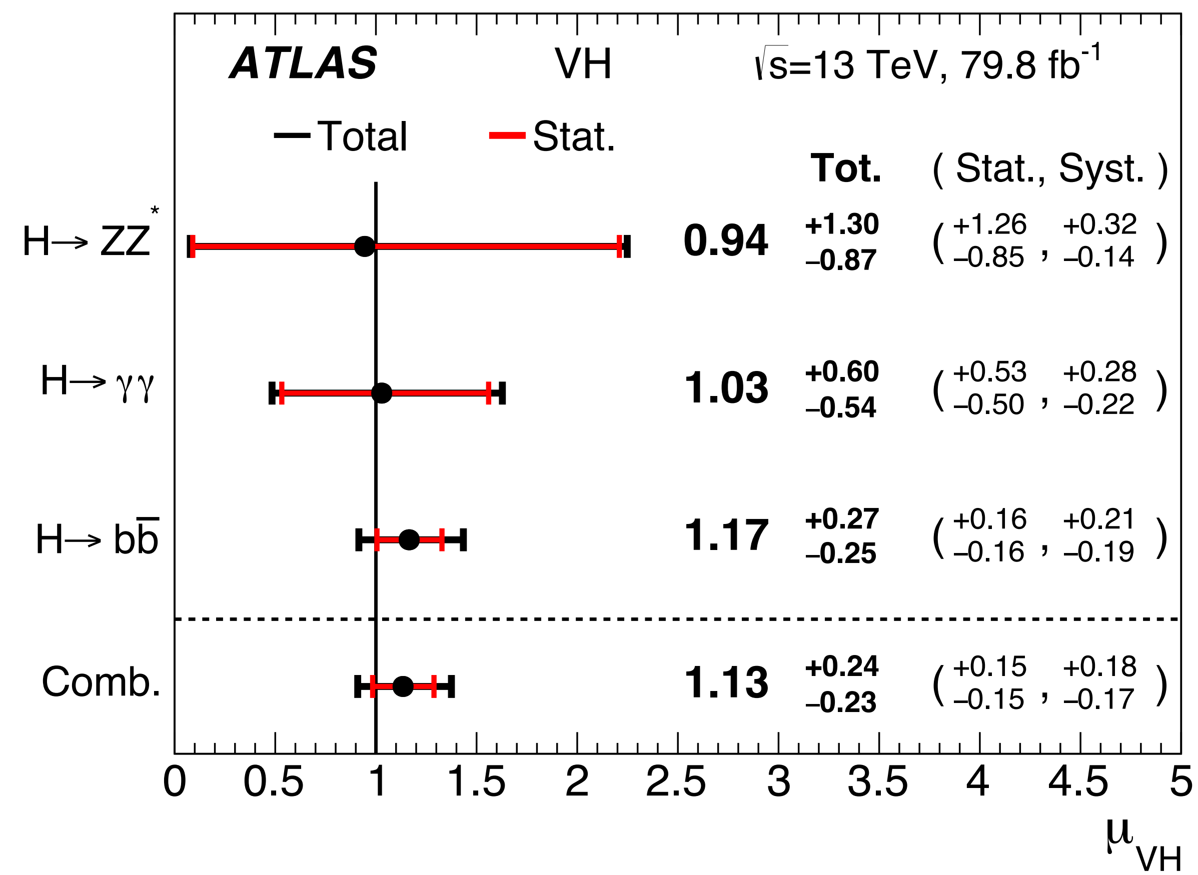


$$\mu_H = 5.8 \pm 3.1\,(\text{stat.}) \pm 1.9\,(\text{syst.}) \pm 1.7\,(\text{th.})$$

observed significance: ~1.6 s.d.

important Run2 milestones





Run1+Run2 significance: 5.4 s.d. obs. *, 5.5 s.d. exp.*

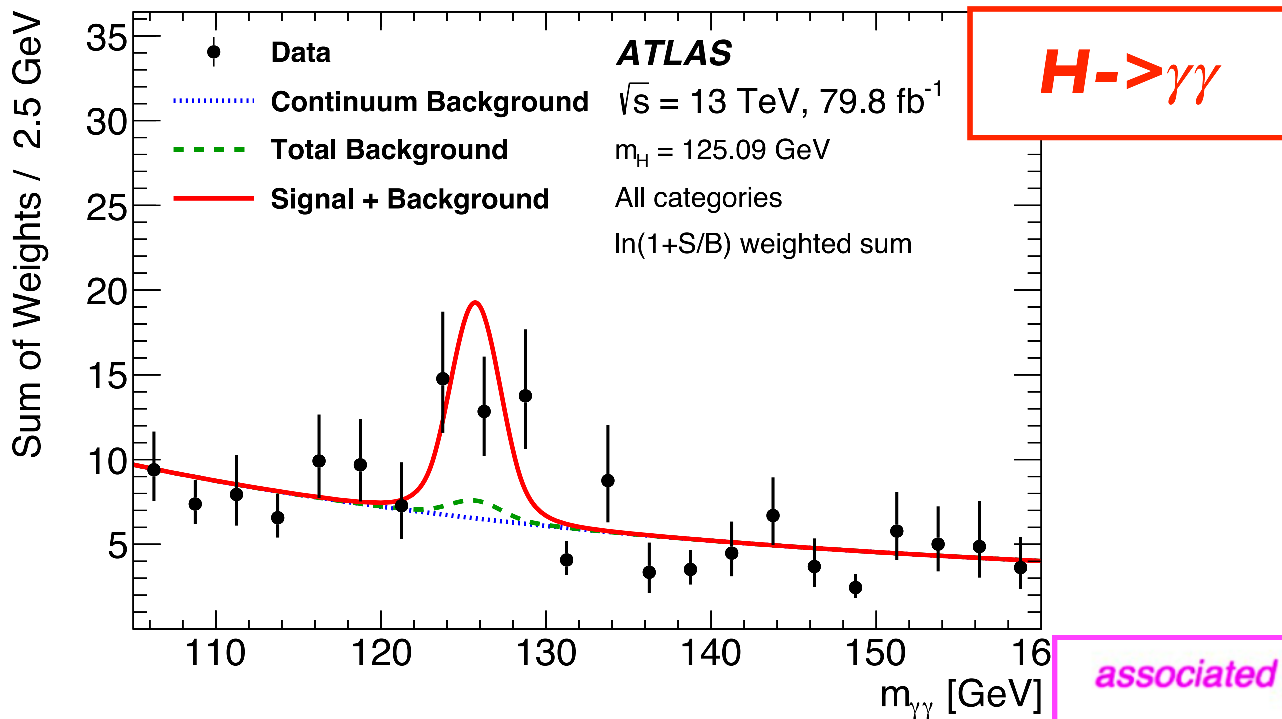
Run2 significance: 5.3 s.d. obs. *, 4.8 s.d. exp.*

!!! OBSERVATION of H->bb !!!

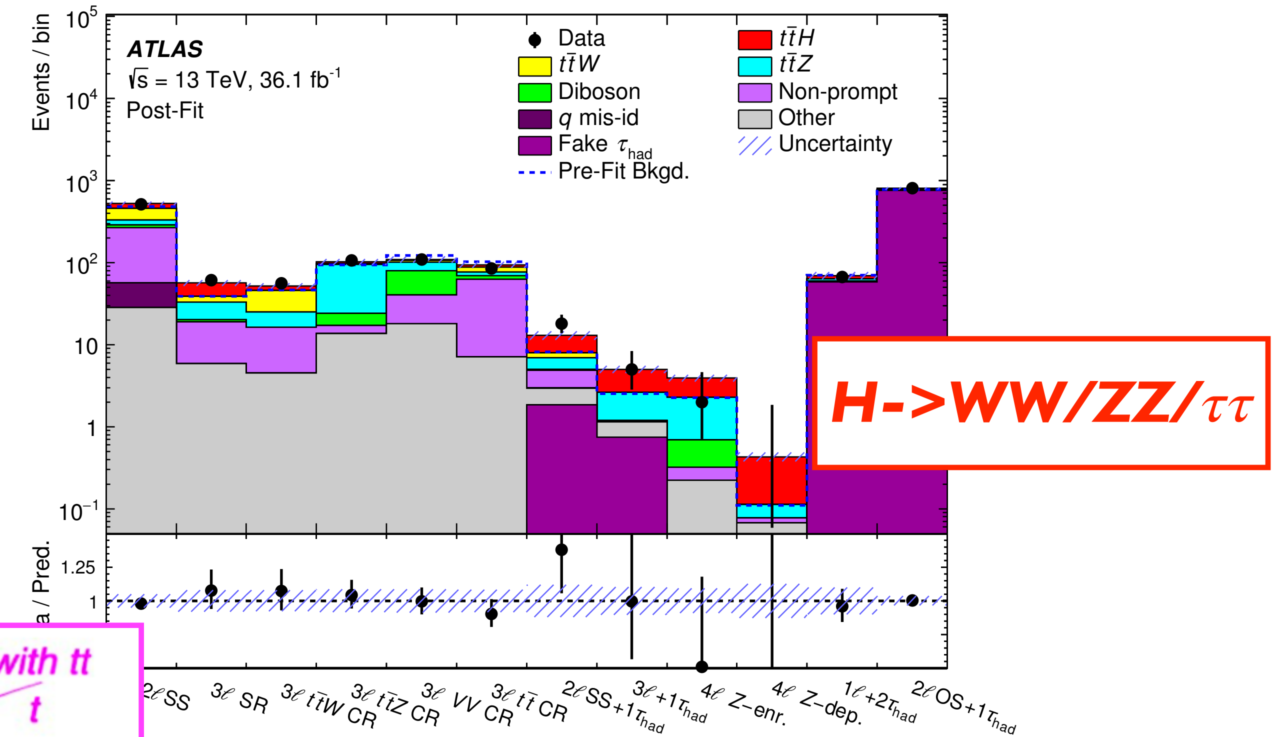
!!! OBSERVATION of VH production !!!

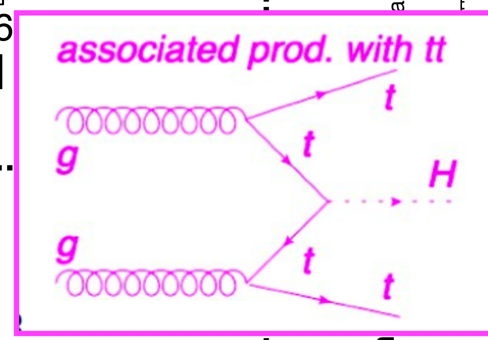
more on third generation: ttH

Phys. Rev. D 97 (2018) 072003

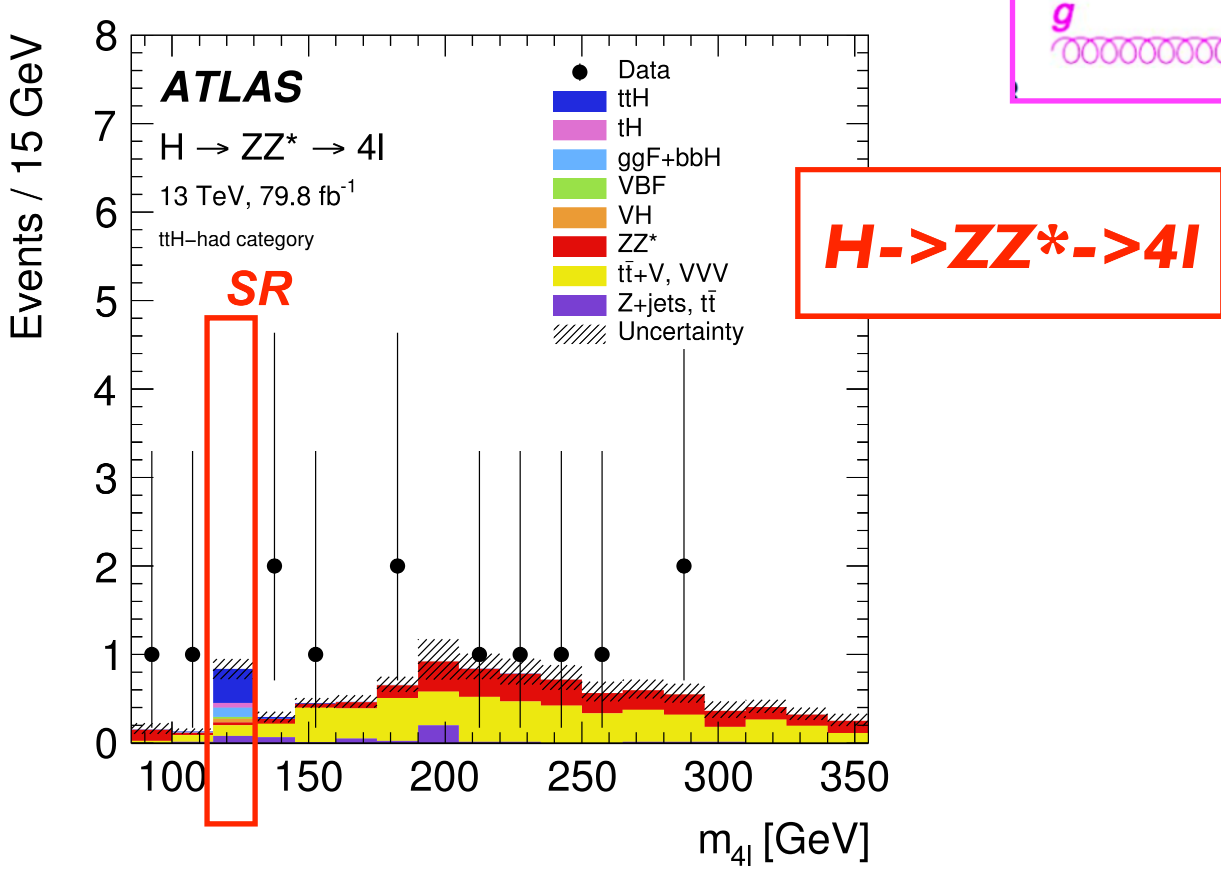


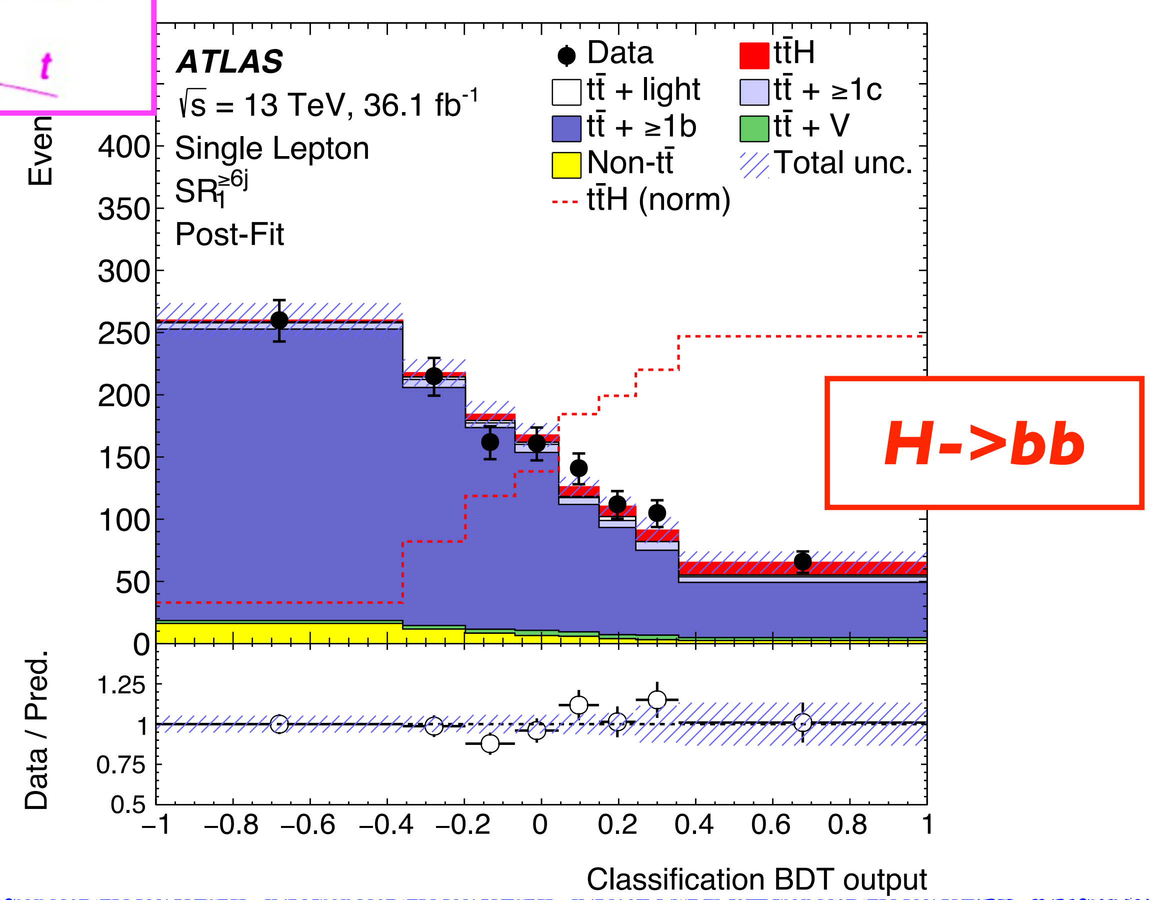
Phys. Lett. B 784 (2018) 173





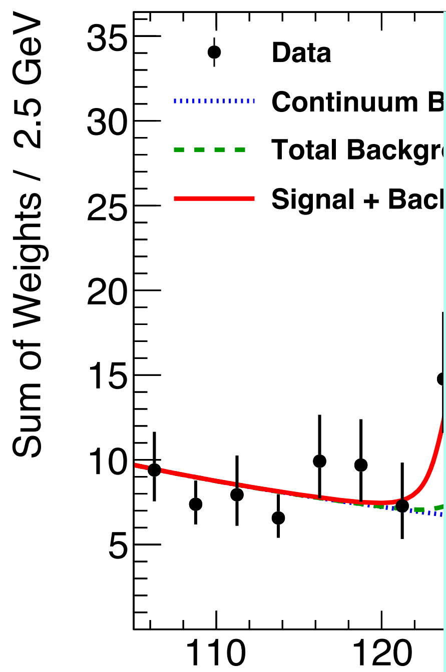
Phys. Rev. D 97 (2018) 072016



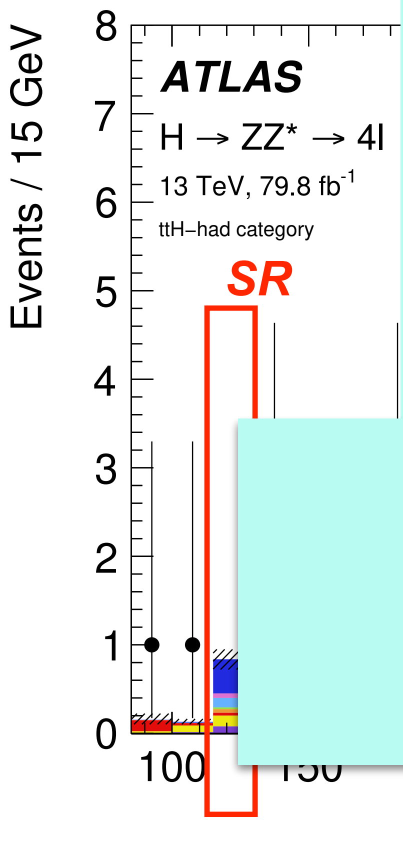


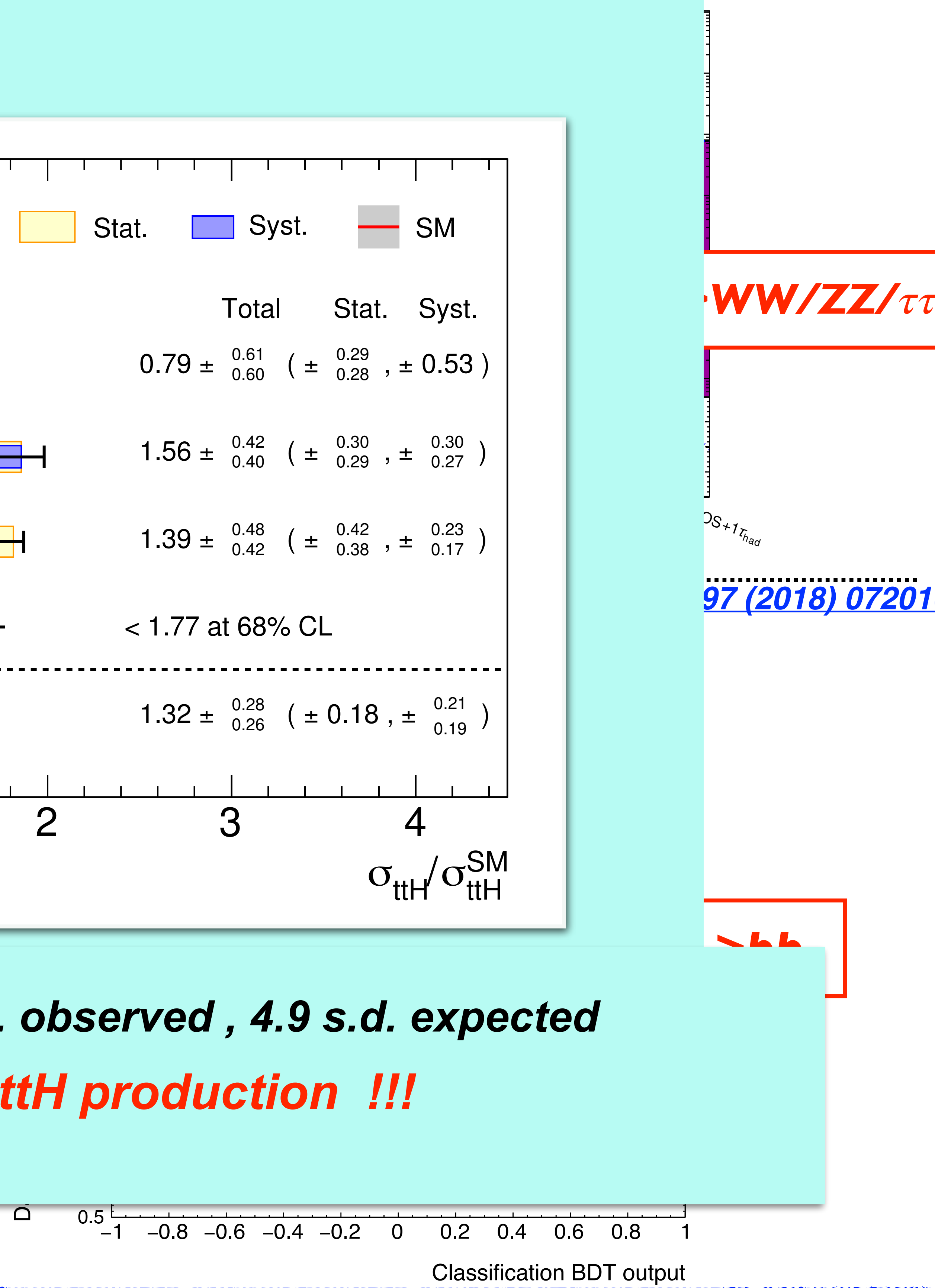
more on third generation: ttH

Phys. Rev. D 97 (2018) 072003

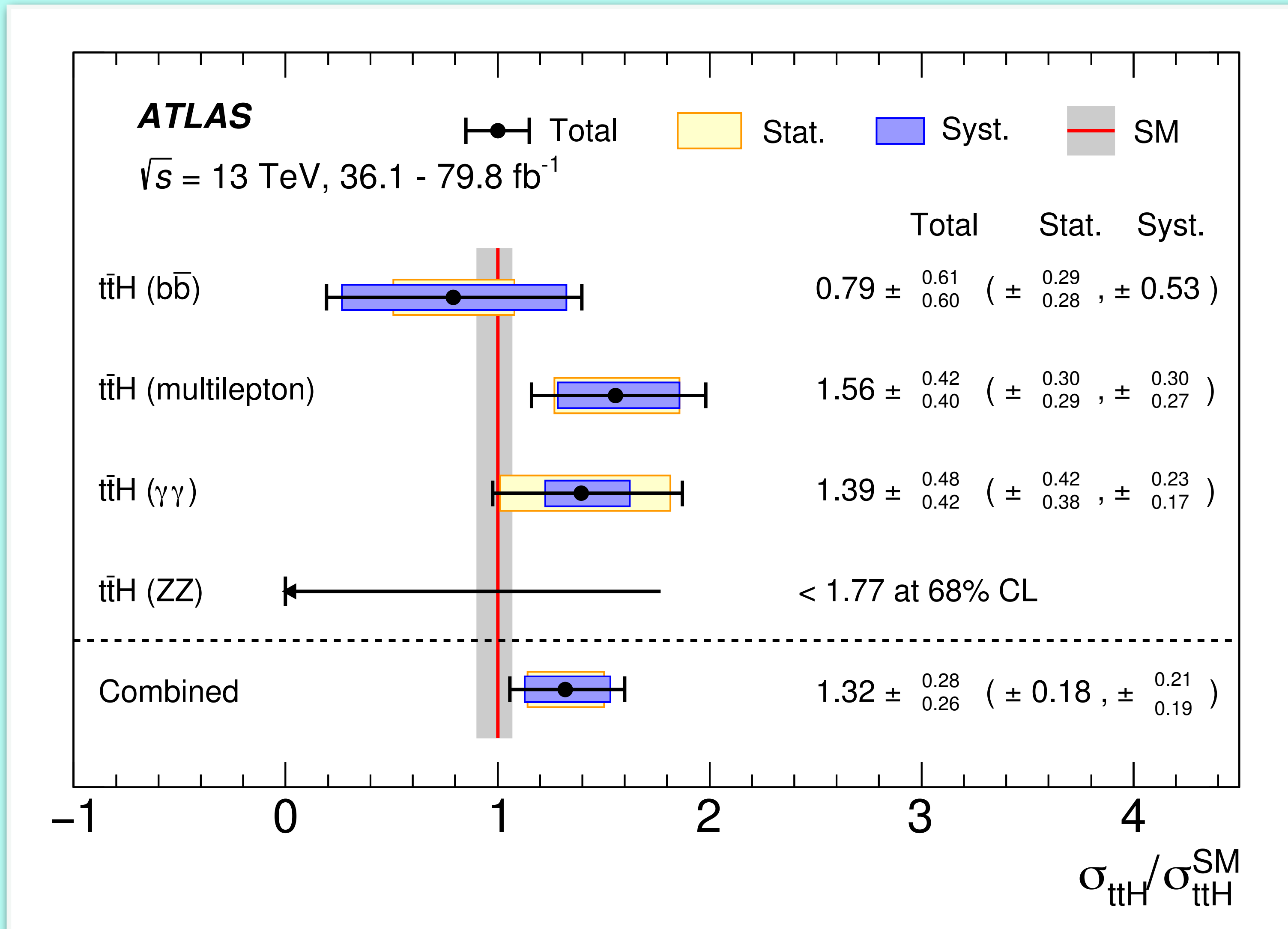


Phys. Lett. B 784 (2018)





97 (2018) 072016



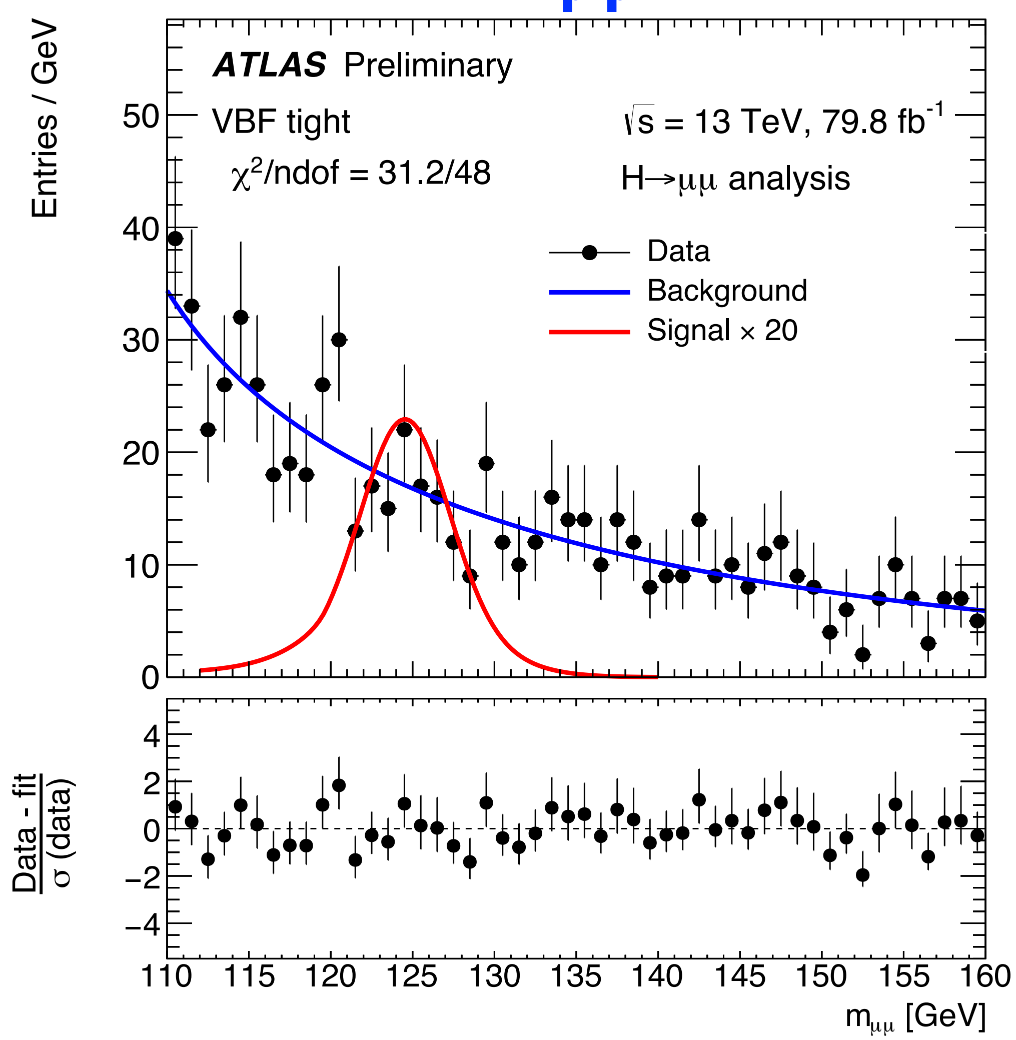
Run2 signal significance: 5.8 s.d. observed , 4.9 s.d. expected

!!! OBSERVATION of ttH production !!!

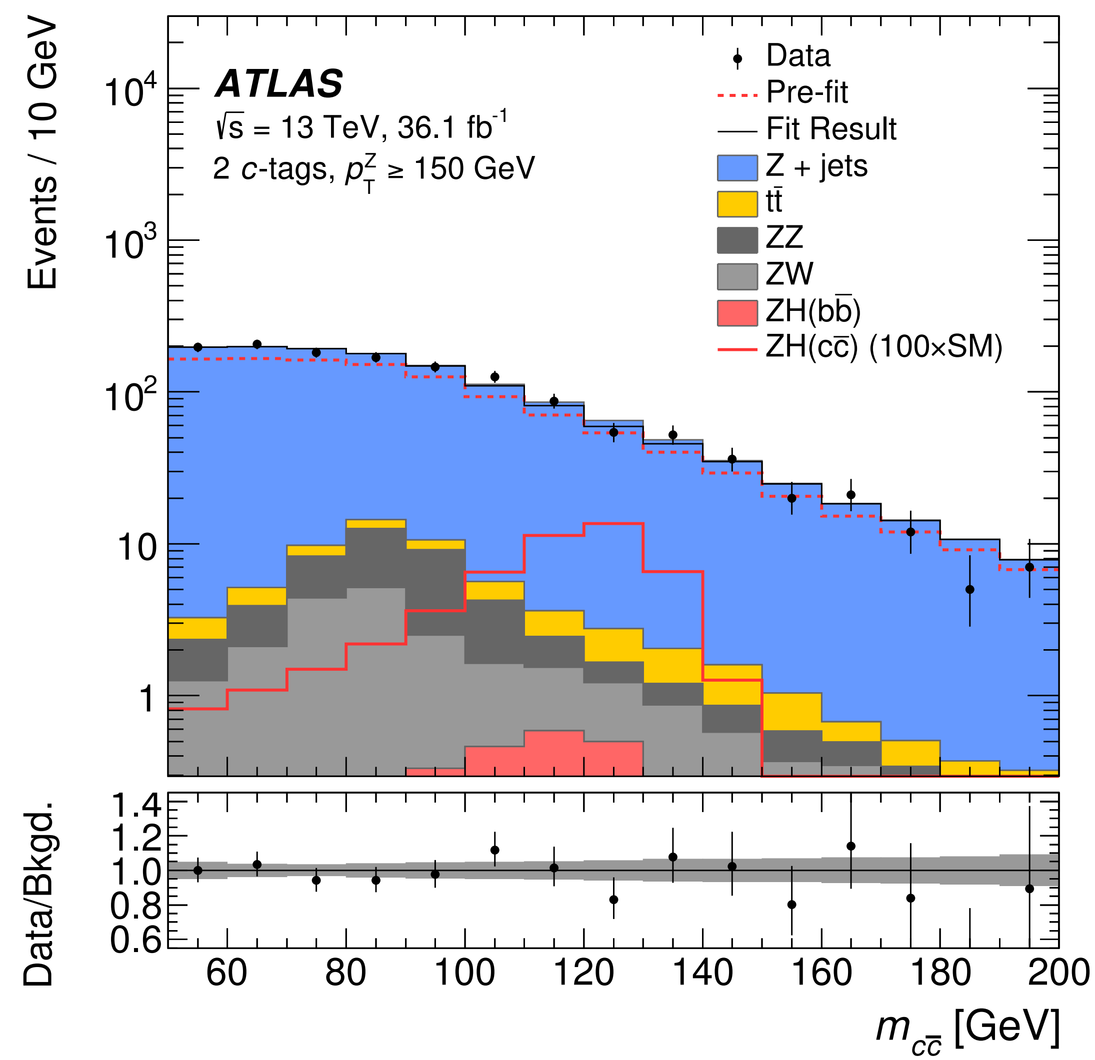
ATLAS-CONF-2018-026

Phys. Rev. Lett. 120 (2018) 211802

H->μμ



H->cc



- Fitting di-muon mass in several analysis regions with different detector resolution and production modes

observed σ*BR/(σ*BR)$_{SM}$ < 2.1

*expected σ*BR/(σ*BR)$_{SM}$ < 2.0*

- Exploiting ZH->llcc production (similar to VHbb analysis)
- Fitting di c-jets invariant mass in 2 Z pT categories

observed σ_{ZH}*BR$_{cc}$ < 2.7 pb

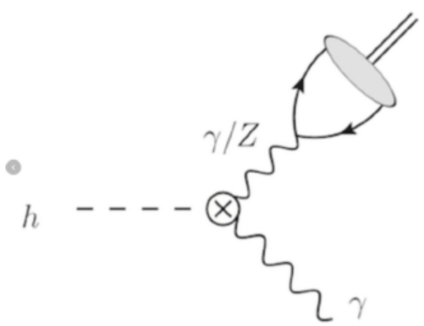
*expected σ_{ZH}*BR$_{cc}$ < 3.9 pb*

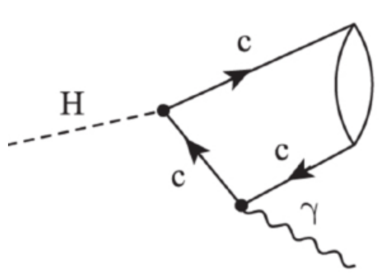
~ x100 SM

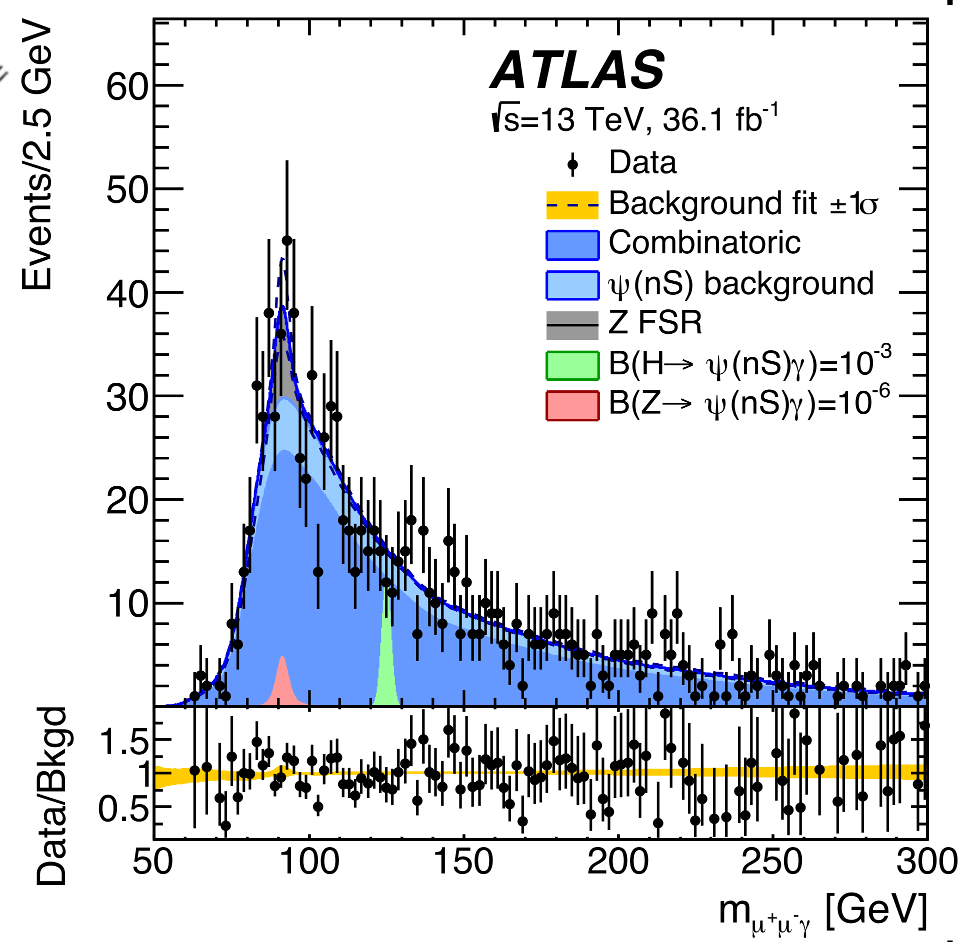
going even more rare

H->meson+γ

- indirect sensitivity to c and b Yukawa couplings
- meson identified through excellent performance of muon reconstruction

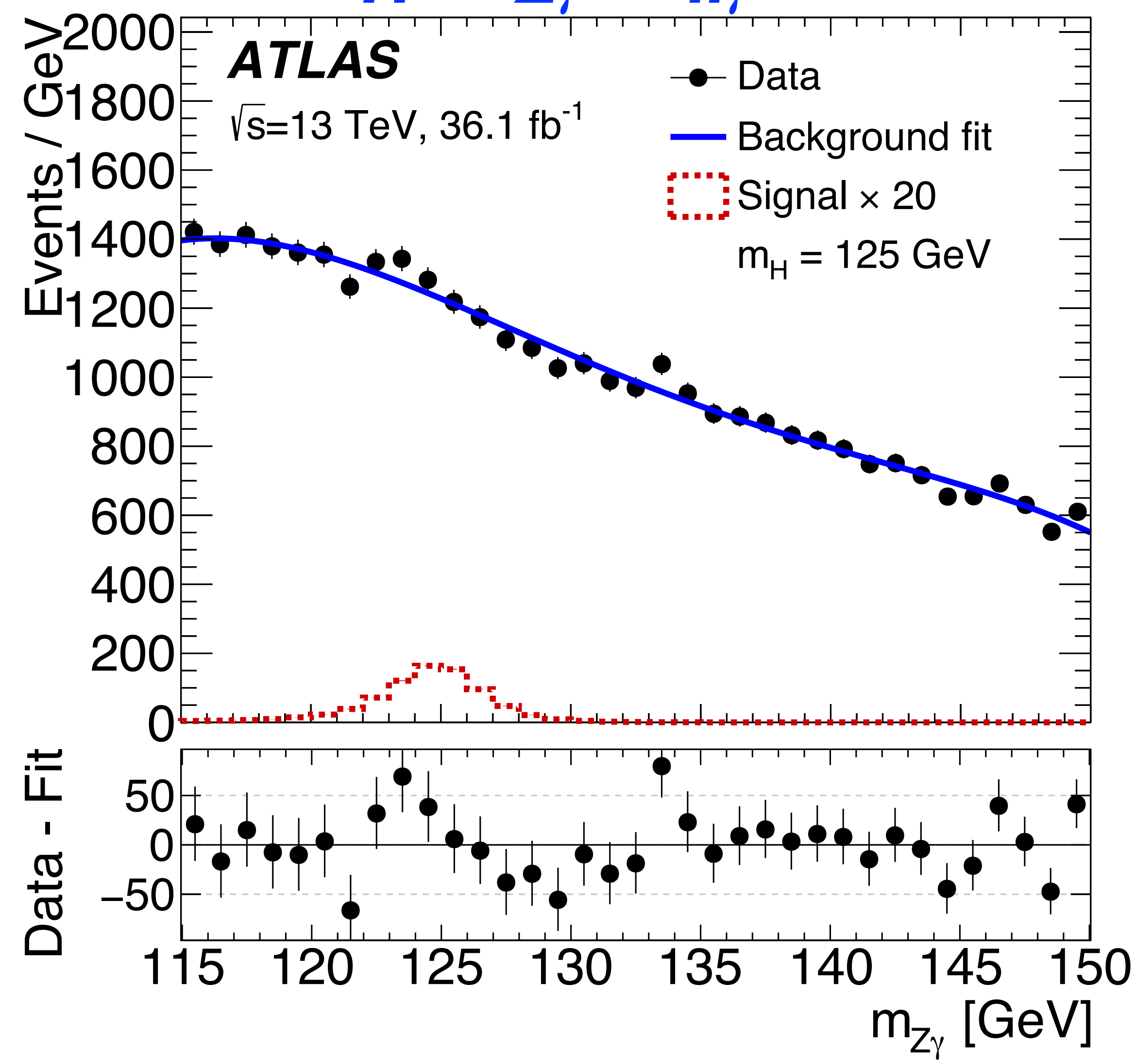






Branching fraction limit (95% CL)	Expected	Observed
$\mathcal{B}(H \to J/\psi\,\gamma)$ [10^{-4}]	$3.0^{+1.4}_{-0.8}$	3.5
$\mathcal{B}(H \to \psi(2S)\,\gamma)$ [10^{-4}]	$15.6^{+7.7}_{-4.4}$	19.8
$\mathcal{B}(Z \to J/\psi\,\gamma)$ [10^{-6}]	$1.1^{+0.5}_{-0.3}$	2.3
$\mathcal{B}(Z \to \psi(2S)\,\gamma)$ [10^{-6}]	$6.0^{+2.7}_{-1.7}$	4.5
$\mathcal{B}(H \to \Upsilon(1S)\,\gamma)$ [10^{-4}]	$5.0^{+2.4}_{-1.4}$	4.9
$\mathcal{B}(H \to \Upsilon(2S)\,\gamma)$ [10^{-4}]	$6.2^{+3.0}_{-1.7}$	5.9
$\mathcal{B}(H \to \Upsilon(3S)\,\gamma)$ [10^{-4}]	$5.0^{+2.5}_{-1.4}$	5.7

H—>Zγ—>llγ



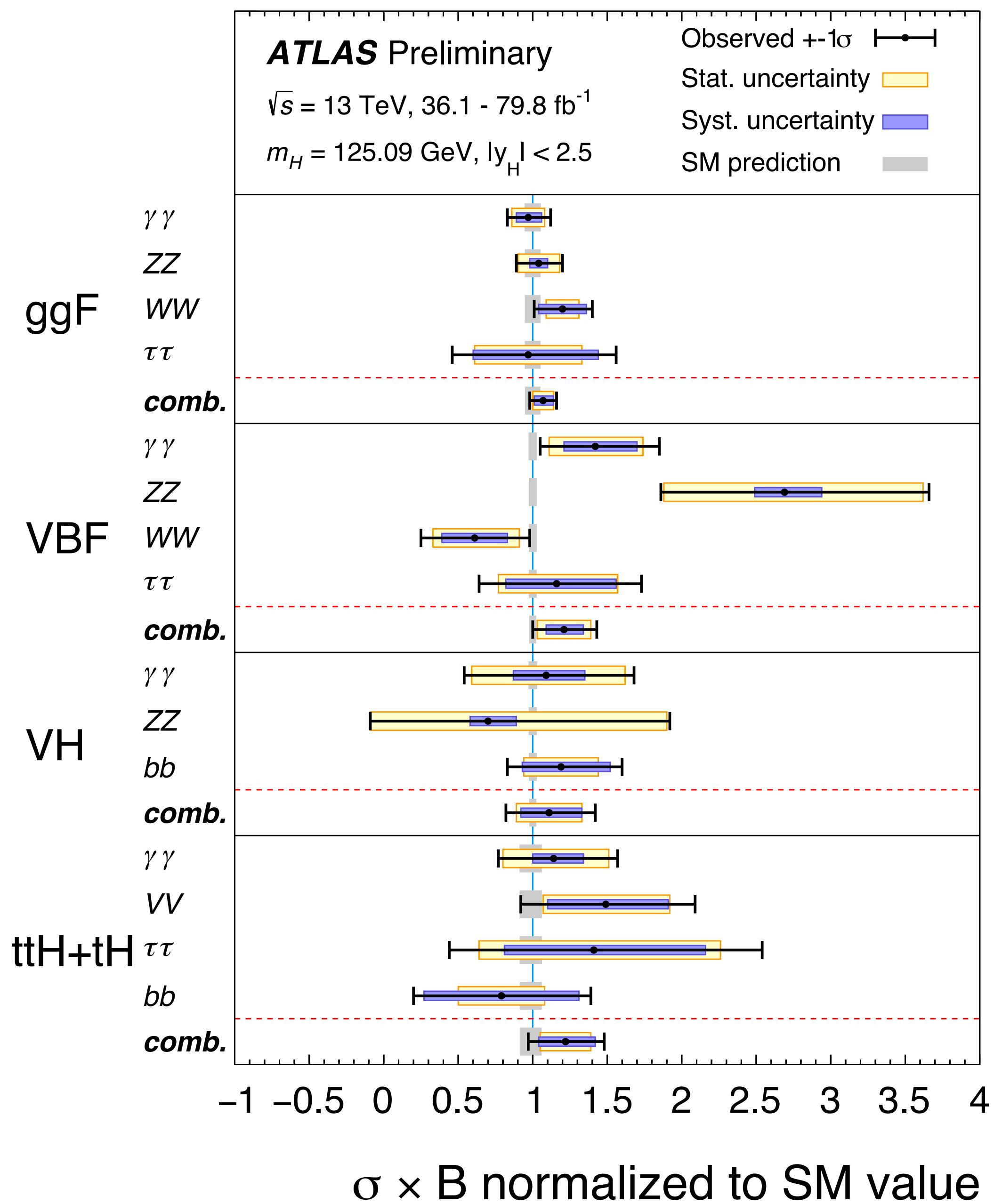
- 6 categories targeting different production mode (VBF more sensitive), photon p_T and lepton flavour

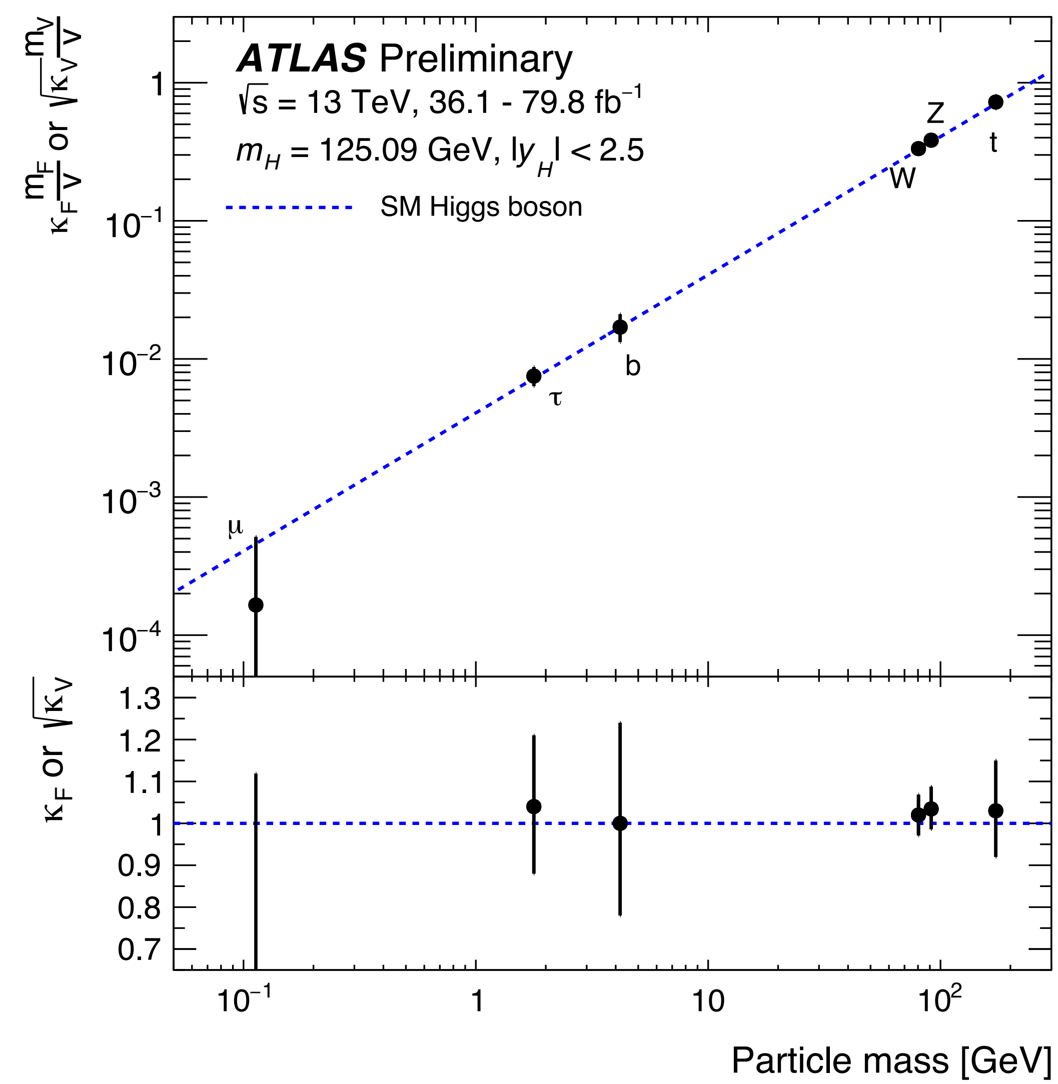
observed σ*BR/(σ*BR)$_{SM}$ < 6.6

*expected σ*BR/(σ*BR)$_{SM}$ < 5.2*

putting it all together (*)

- Good complementarity and consistence among the various analyses
- ***Leading production and decay mode established at more than 5 sigma***: no major deviation from SM.





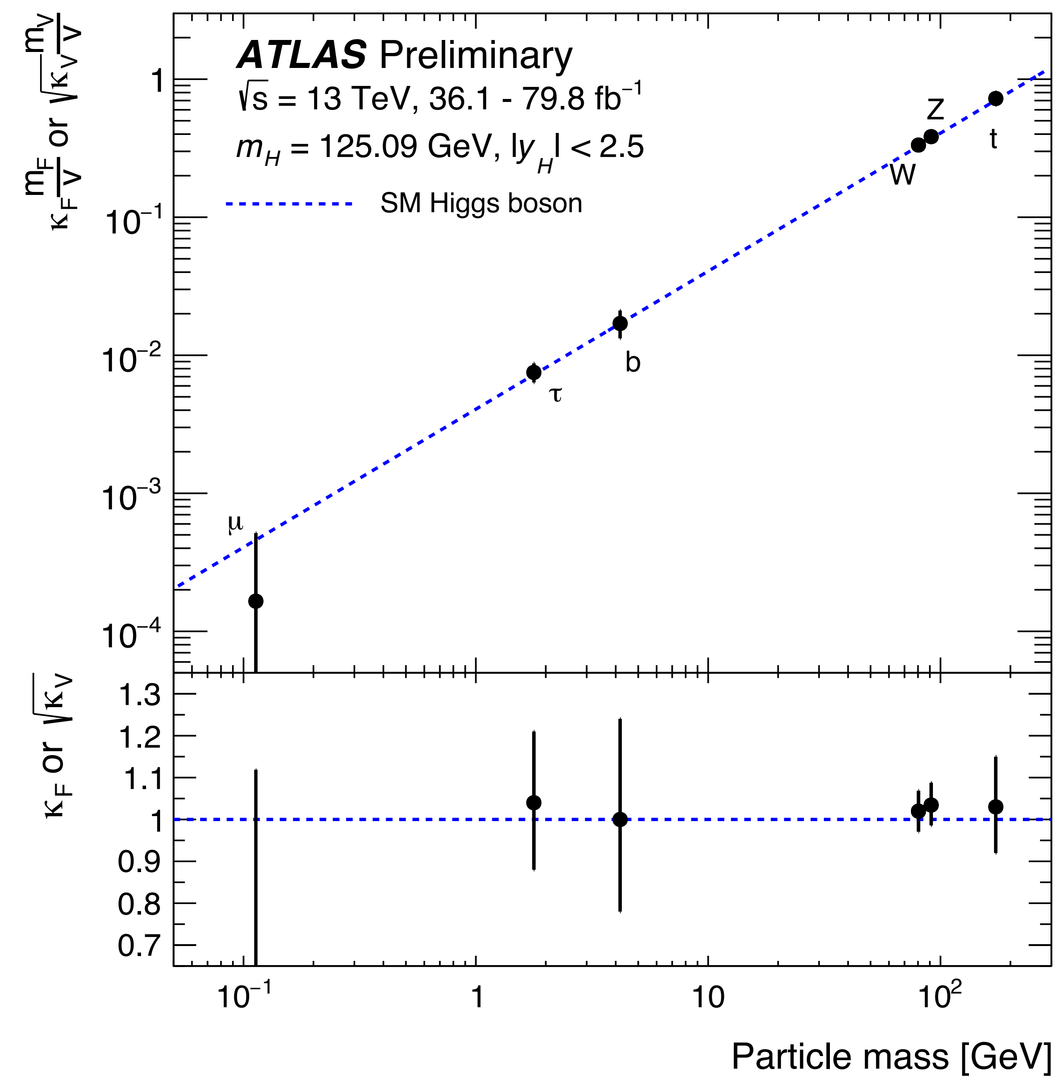
- reaching very high precision in determination of coupling to SM particles

(*) not including the latest Hbb results

putting it all together (*)

- Good complementarity and consistence among the various analyses
- ***Leading production and decay mode established at more than 5 sigma***: no major deviation from SM.

Production	Loops	Interference	Expression in fundamental coupling-strength s
$\sigma(ggF)$	✓	b–t	$\kappa_g^2 \sim 1.06\cdot\kappa_t^2 + 0.01\cdot\kappa_b^2 - 0.07\cdot\kappa_t\kappa_b$
$\sigma(VBF)$	-	-	$\sim 0.74\cdot\kappa_W^2 + 0.26\cdot\kappa_Z^2$
$\sigma(WH)$	-	-	$\sim \kappa_W^2$
$\sigma(q\bar{q}\to ZH)$	-	-	$\sim \kappa_Z^2$
$\sigma(gg\to ZH)$	✓	Z–t	$\kappa_{ggZH}^2 \sim 2.27\cdot\kappa_Z^2 + 0.37\cdot\kappa_t^2 - 1.64\cdot\kappa_Z\kappa_t$
$\sigma(bbH)$	-	-	$\sim \kappa_b^2$
$\sigma(ttH)$	-	-	$\sim \kappa_t^2$
Partial decay width			
$\Gamma_{b\bar{b}}$	-	-	$\sim \kappa_b^2$
Γ_{WW}	-	-	$\sim \kappa_W^2$
Γ_{ZZ}	-	-	$\sim \kappa_Z^2$
$\Gamma_{\tau\tau}$	-	-	$\sim \kappa_\tau^2$
$\Gamma_{\mu\mu}$	-	-	$\sim \kappa_\mu^2$
$\Gamma_{\gamma\gamma}$	✓	W–t	$\kappa_\gamma^2 \sim 1.59\cdot\kappa_W^2 + 0.07\cdot\kappa_t^2 - 0.66\cdot\kappa_W\kappa_t$
$\Gamma_{Z\gamma}$	✓	W–t	$\kappa_{Z\gamma}^2 \sim 1.12\cdot\kappa_W^2 + 0.00035\cdot\kappa_t^2 - 0.12\cdot\kappa_W\kappa_t$
Total decay width			
Γ_H	✓	$W-t$, $b-t$	$\kappa_H^2 \sim 0.57\cdot\kappa_b^2 + 0.22\cdot\kappa_W^2 + 0.09\cdot\kappa_g^2 + 0.06\cdot\kappa_\tau^2 + 0.03\cdot\kappa_Z^2 + 0.03\cdot\kappa_c^2 + 0.0023\cdot\kappa_\gamma^2 + 0.0016\cdot\kappa_{Z\gamma}^2 + 0.00022\cdot\kappa_\mu^2$

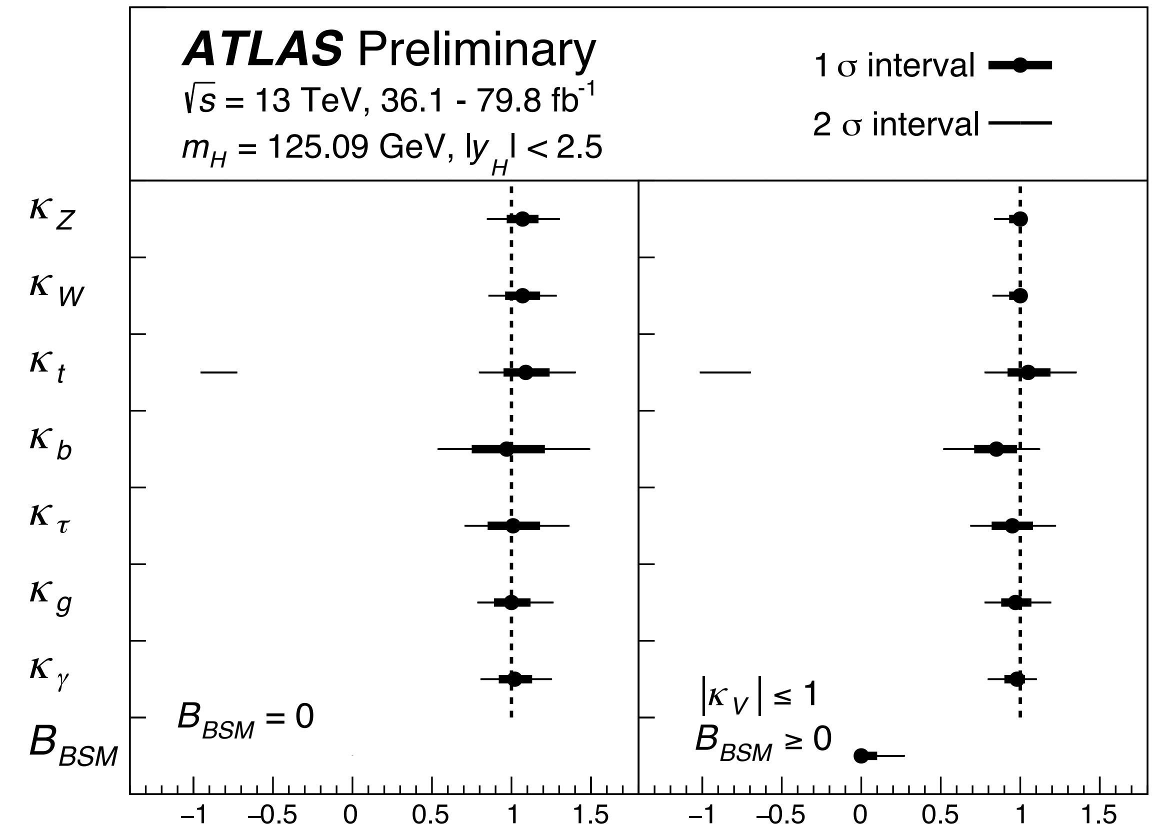


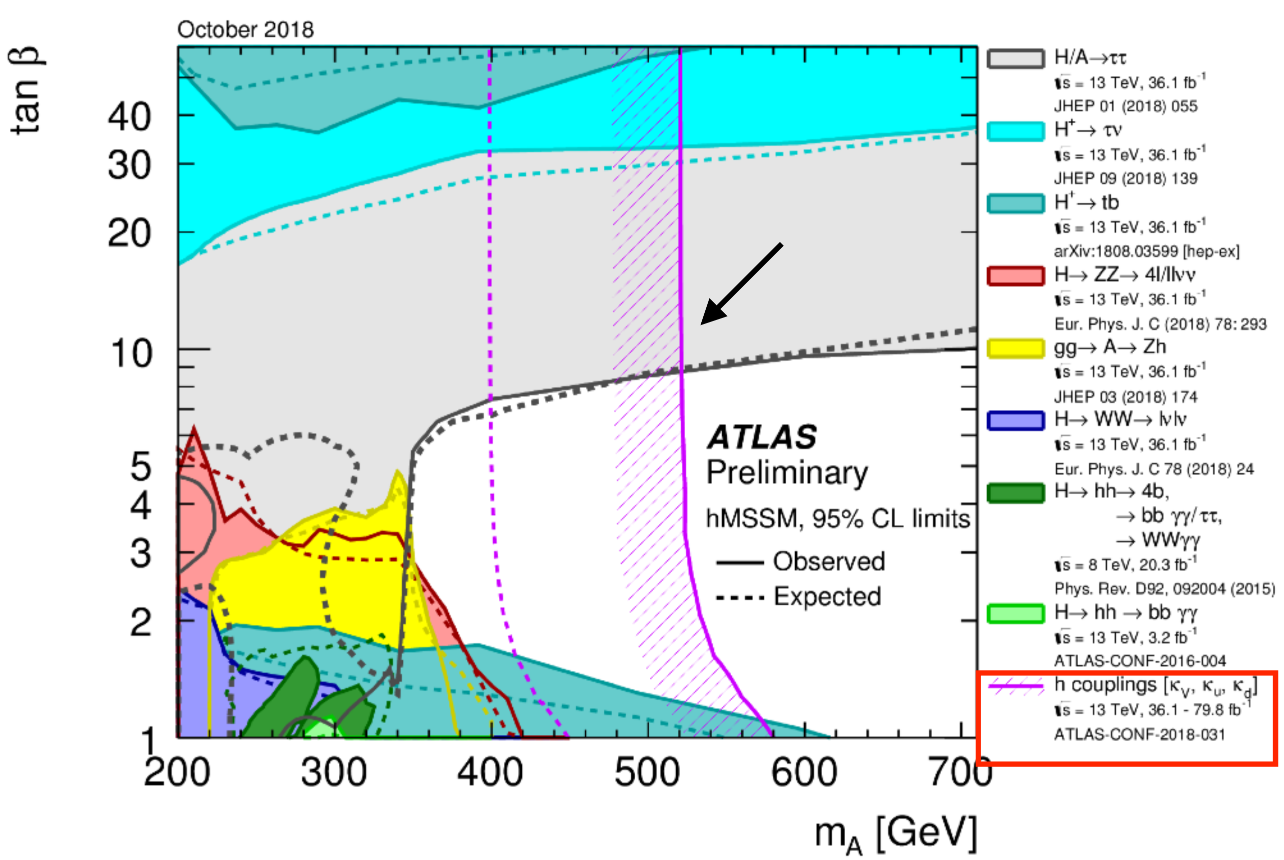
- reaching very high precision in determination of coupling to SM particles

(*) not including the latest Hbb results

putting it all together (2)

- Large amount of information allow to probe more general scenarios/assumptions:
  - *independent coupling modifiers for ggH and Hγγ loops (sensitive to BSM particles)*
  - *allowing Higgs boson to decay to non SM particles*
- Clear assumptions: only modification of the strength of the coupling is considered and not a change in their structure



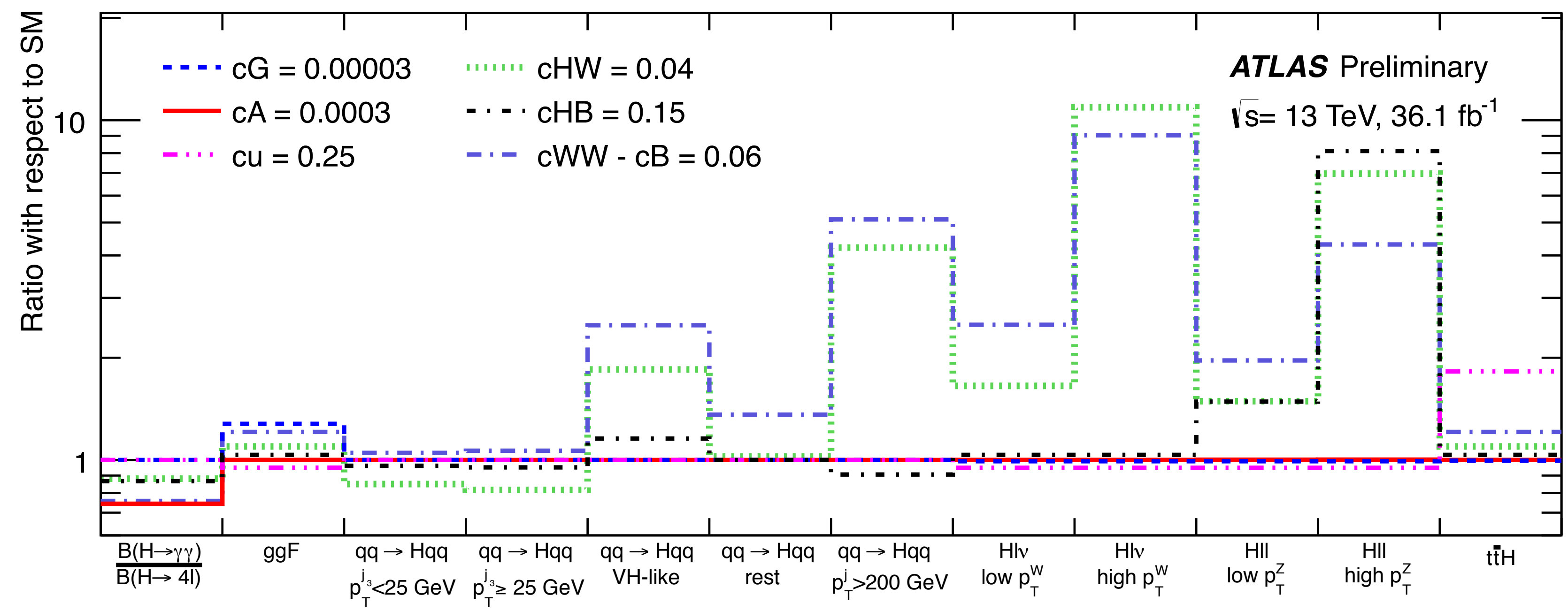


- results could be used to set limits on new physics models that predicts modifications of the couplings
- example on hMSSM: *results complementary to direct searches*

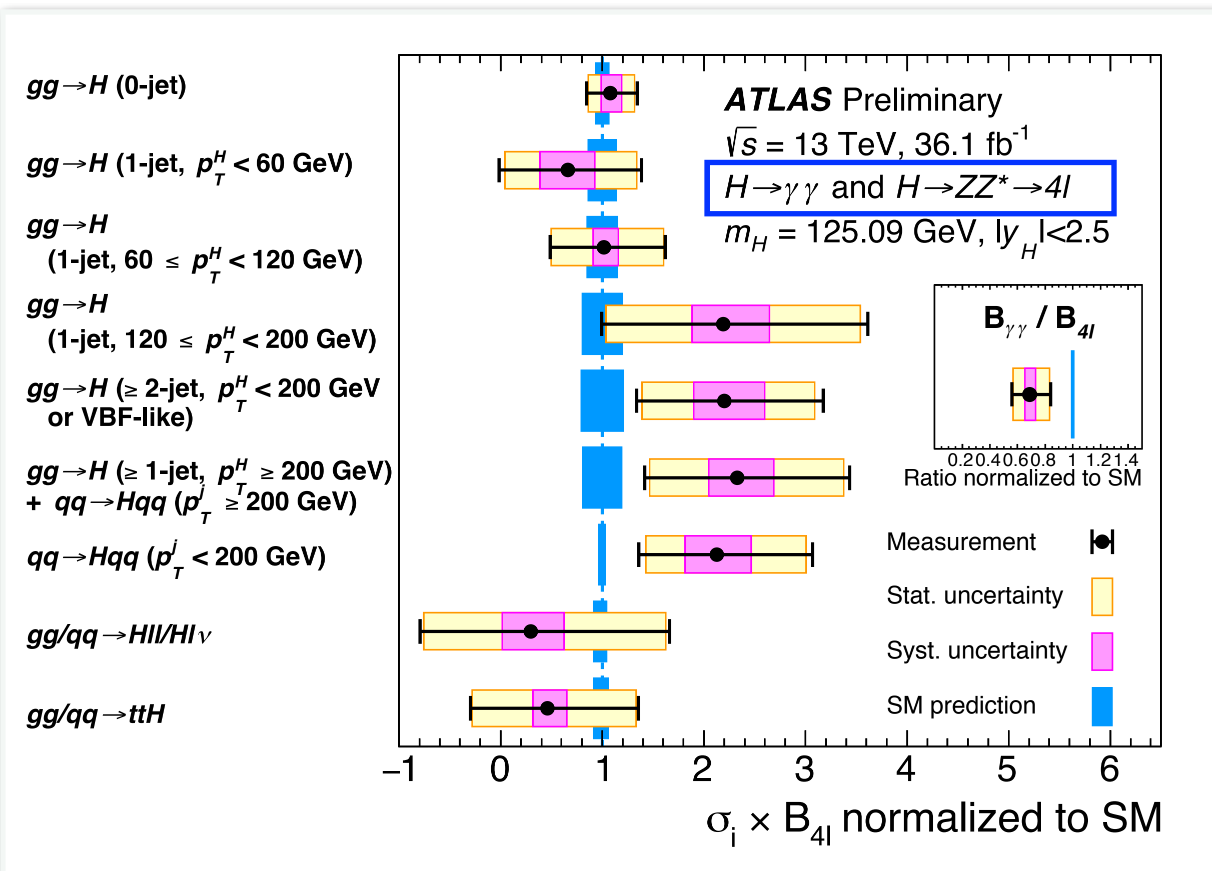
beyond coupling modifiers

- New physics effect can go beyond simple coupling modifications.
- Effective Field Theory approach for indirect BDSM effects

$$\mathcal{L} = \mathcal{L}_{SM} + \sum_i c_i^{(6)} O_i^{(6)} / \Lambda^2$$



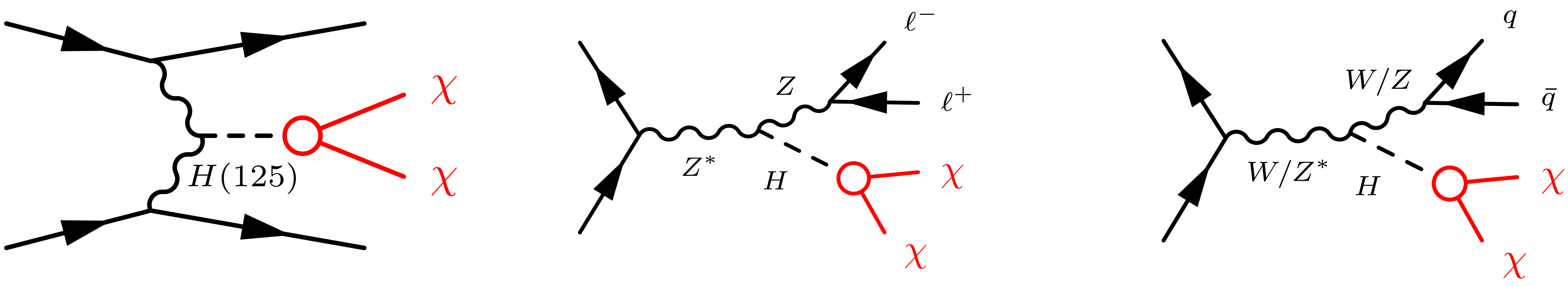
- Effects of EFT operators can alter the kinematics of the Higgs production (and decay)
  - *in general, larger deviations at higher p_T*
- Important to measure the process more differentially:
  - *fully differential distributions only possible the the "golden channels"*
  - *Simplified Template Cross Section (STXS): bin the production modes in key kinematic quantities*
  - *also helps reducing theory uncertainties*



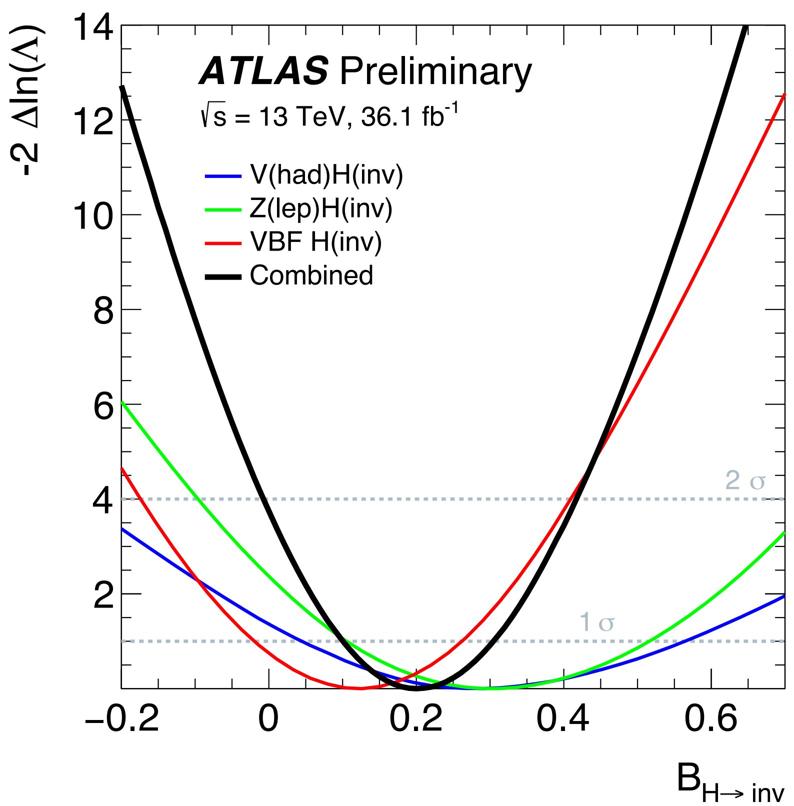
(similar approach in H->bb and H->tautau)

H->invisible

- Direct search for Higgs decaying into "non detectable particles" (dark matter candidates)
- need to rely on associated Higgs production (predictions): missing E_T + X final state



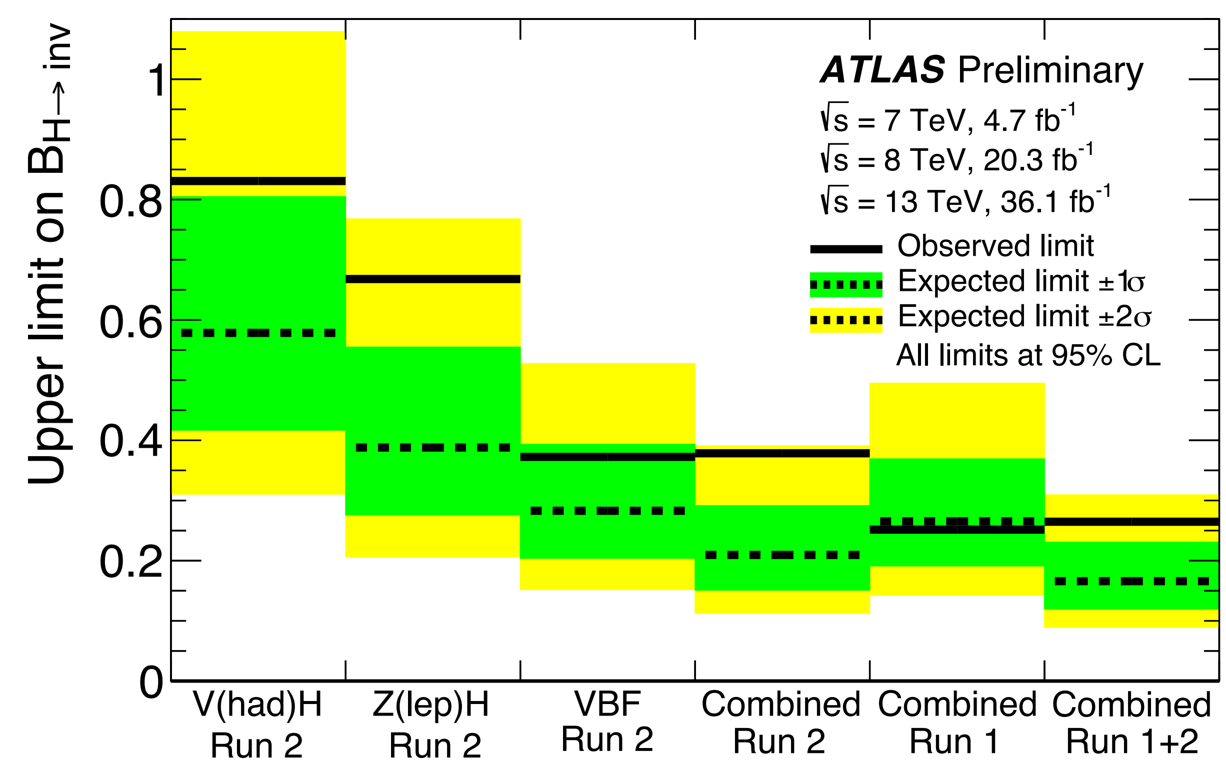
- Key requirement: missing E_T > 90-120 GeV



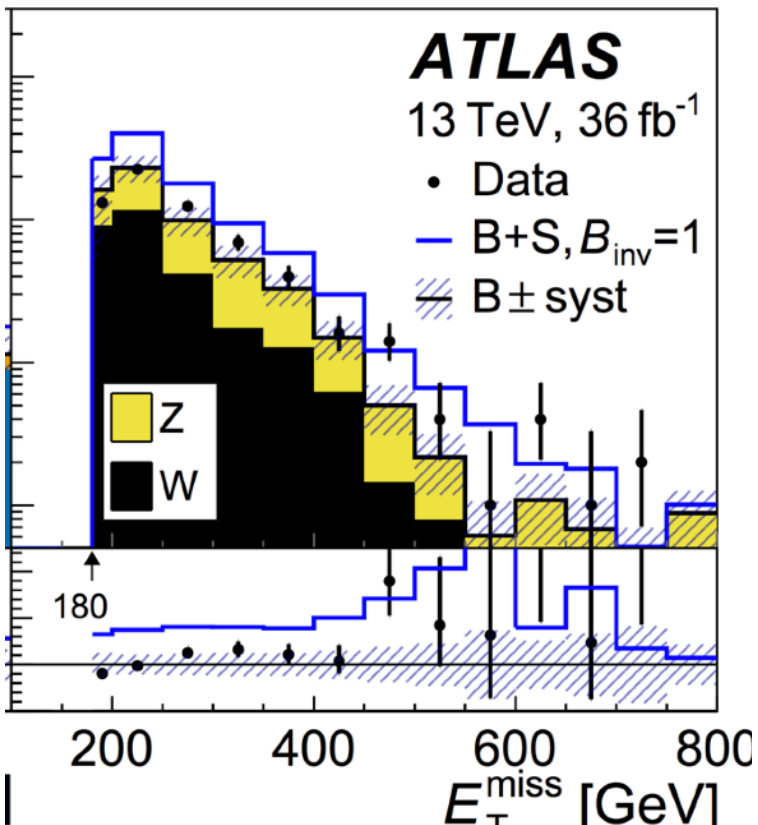
Run1+Run2:

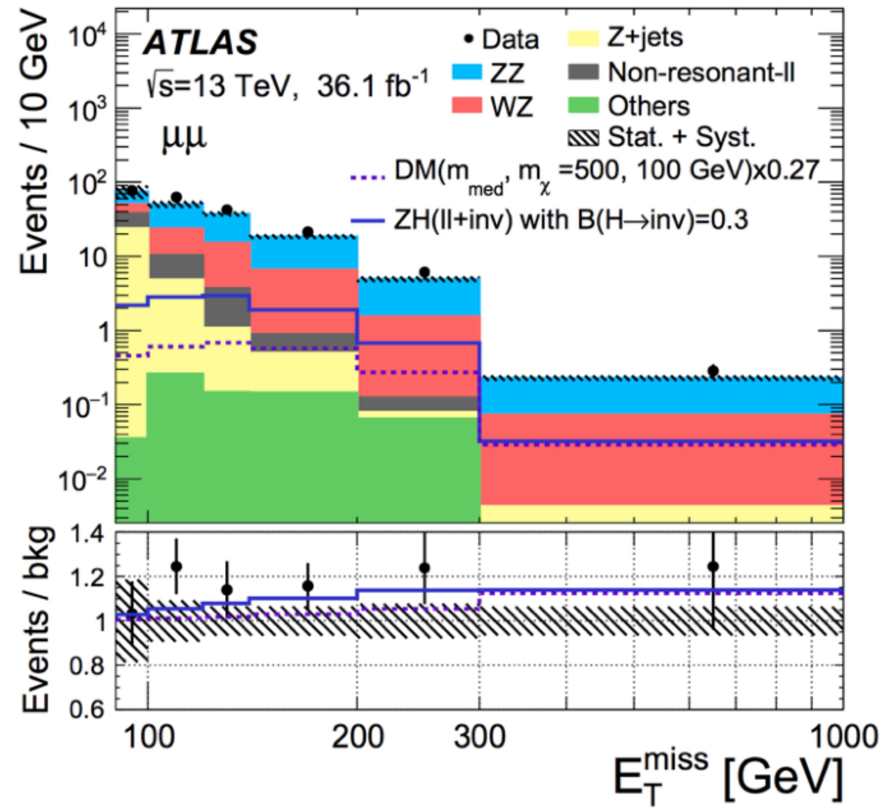
Br(inv) < 26% obs

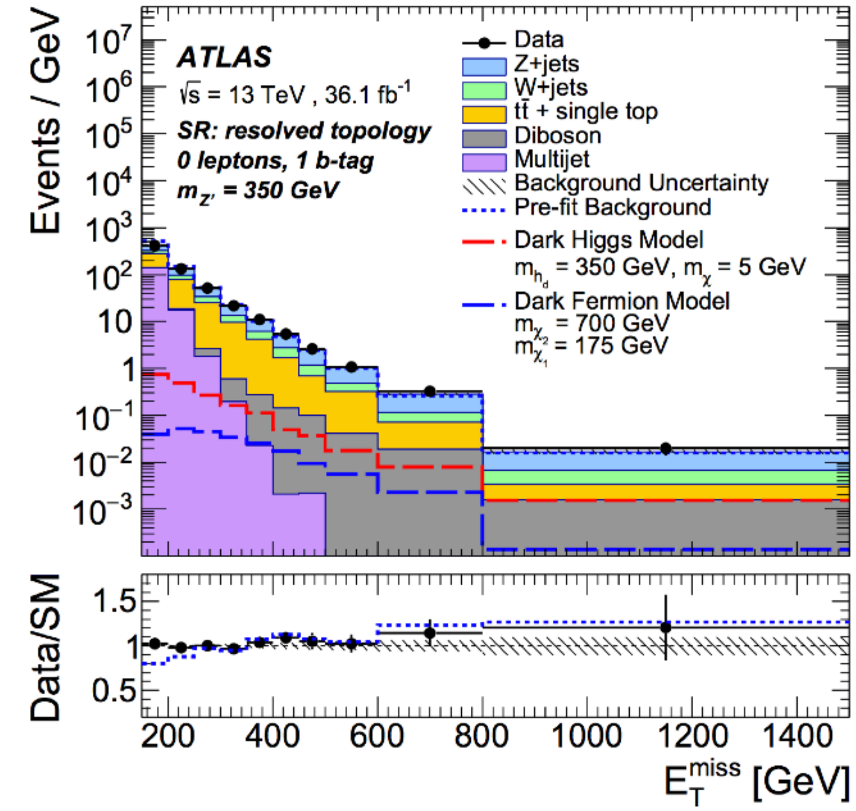
Br(inv)<17% exp

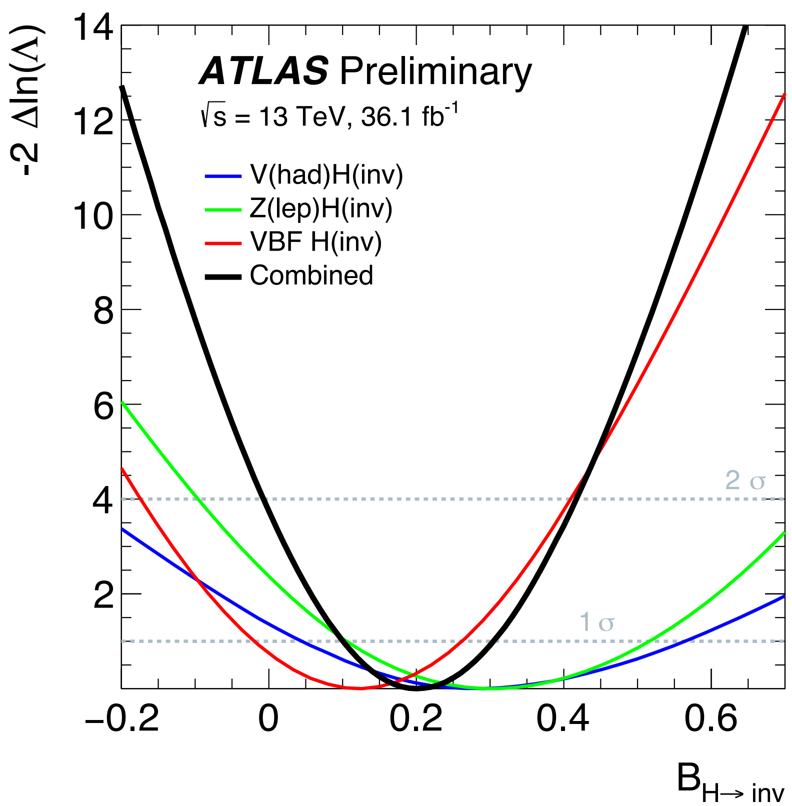


H->invisible





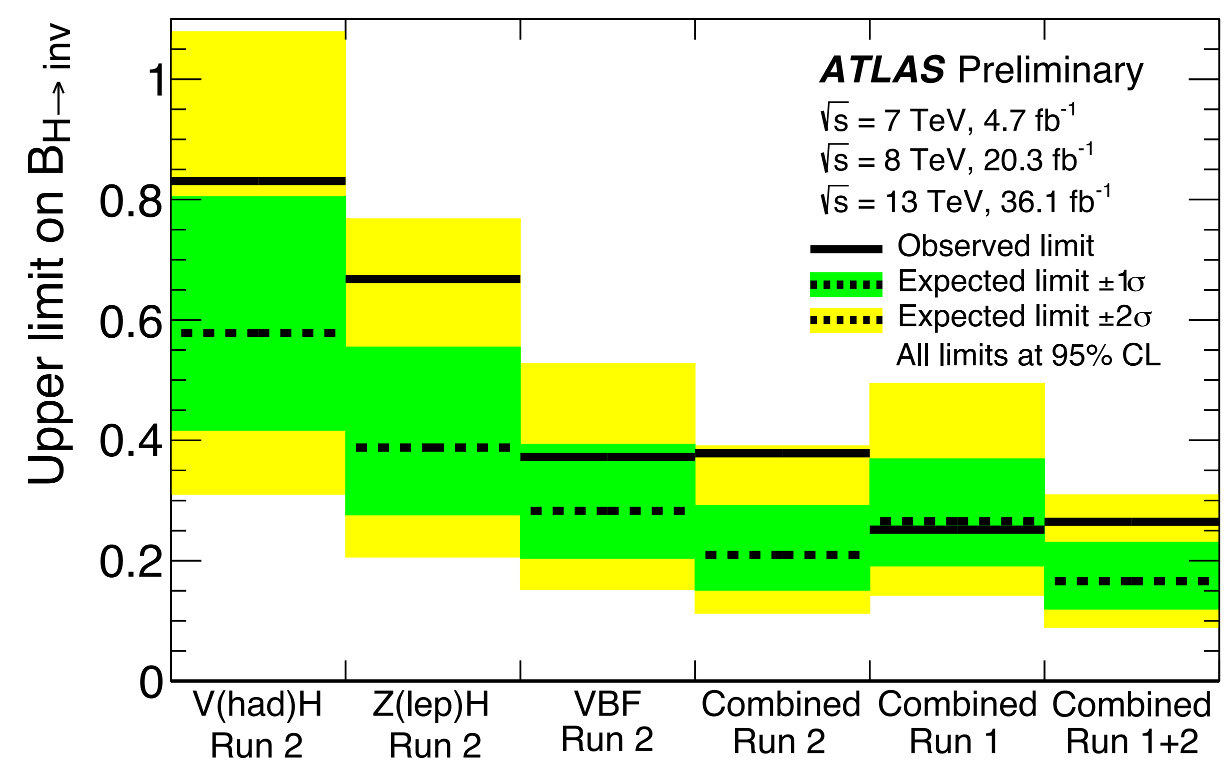




Run1+Run2:

Br(inv) < 26% obs

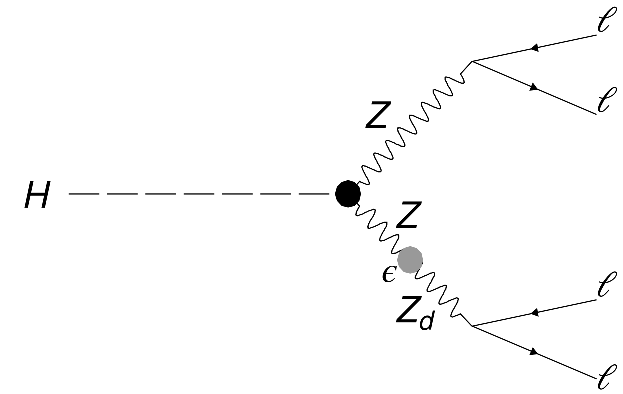
Br(inv)<17% exp

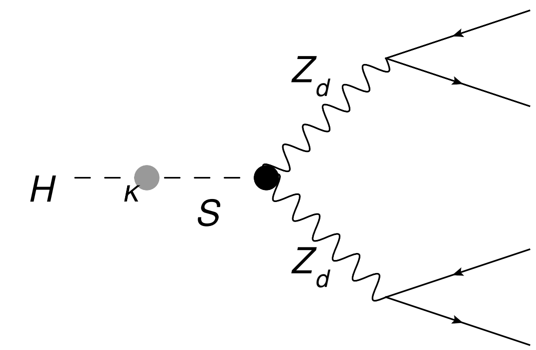


$H \to Z_d Z_{(d)}$

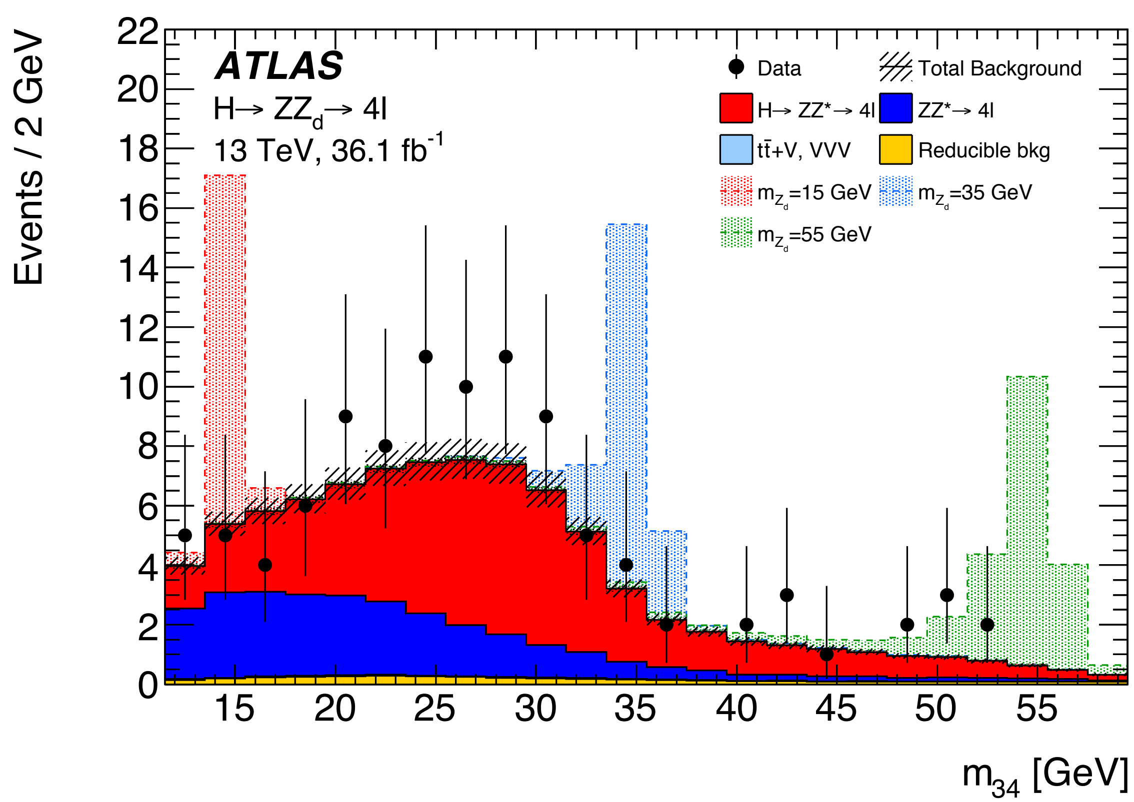
JHEP 06 (2018) 166

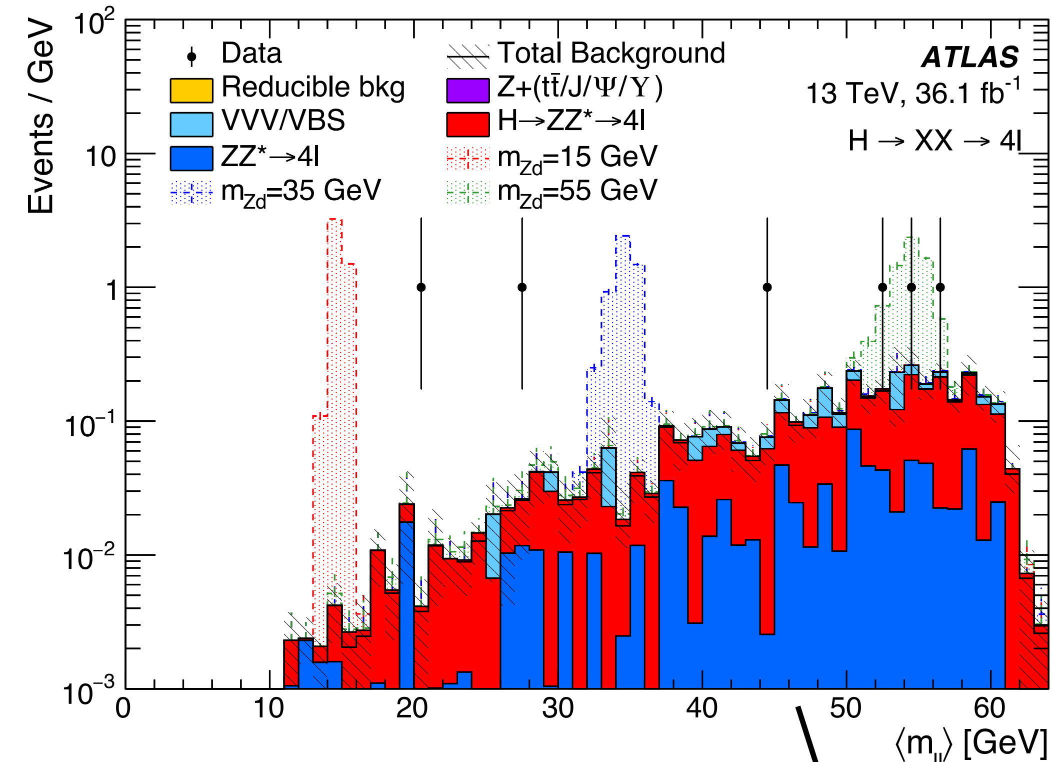
- Exploiting excellent lepton performance to look for new resonance in Higgs decay: *dark sector model interpretation*

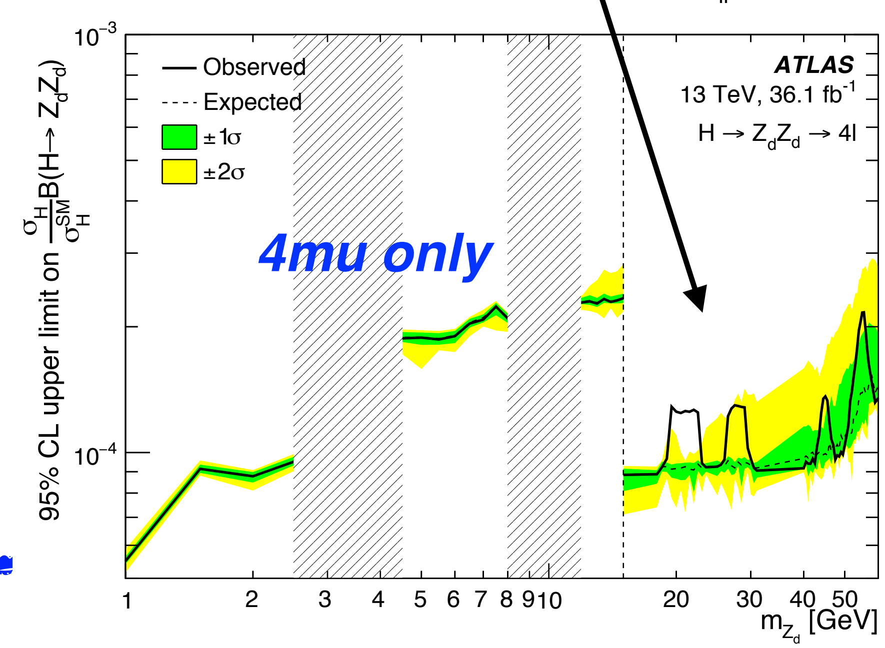




- Single resonance (ZZ_d): closely following SM H->ZZ* analysis
- Double resonance (Z_dZ_d): pair OS SF leptons minimising the difference between reconstructed masses of the two candidates







- Very low mass region (muons only) also interpret in the context of H->aa searches

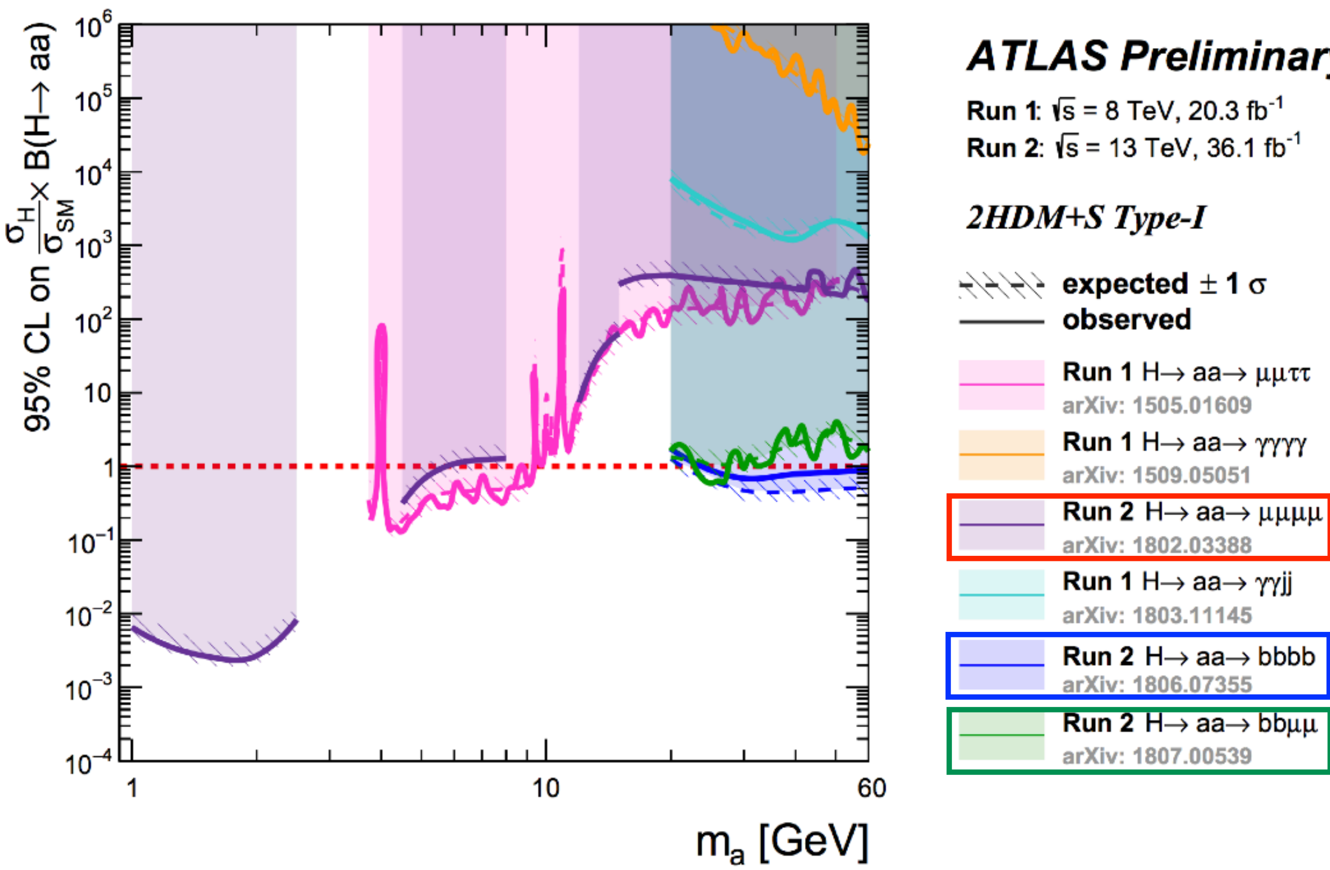
H->aa

arXiv:1807.00539

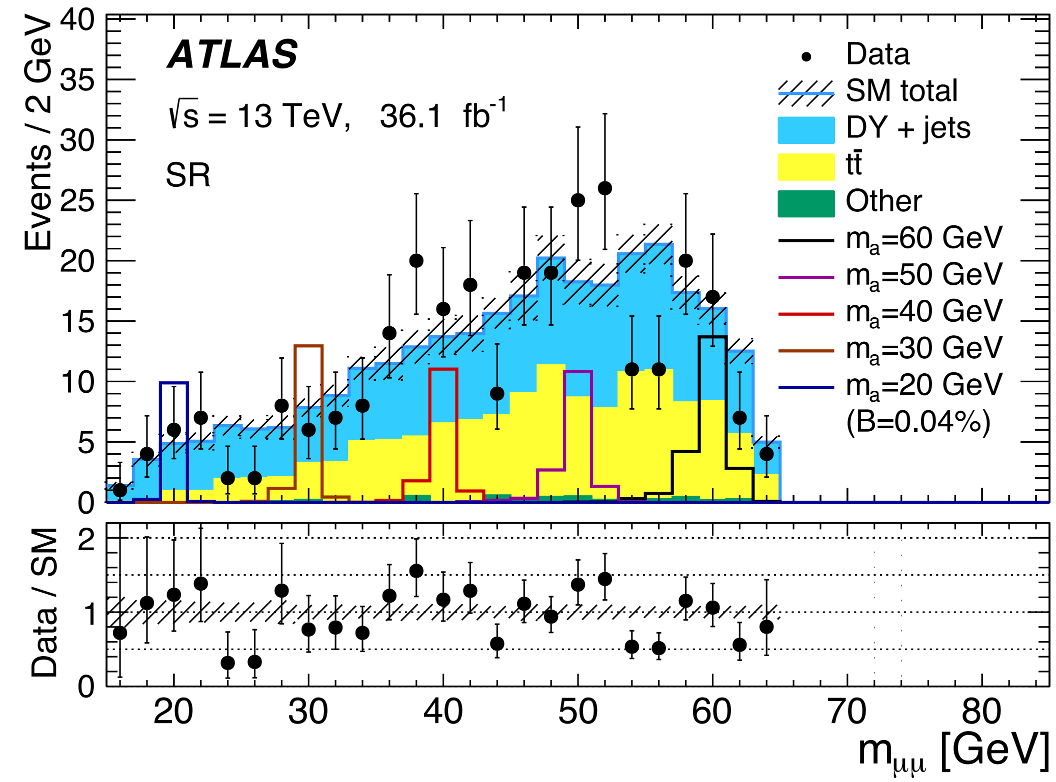
- Search for decay into pair of *spin 0 particles* subsequently decaying into SM particles: *key experimental challenge is handling of low p_T objects*

- Assuming SM production; model independent limits in each decay

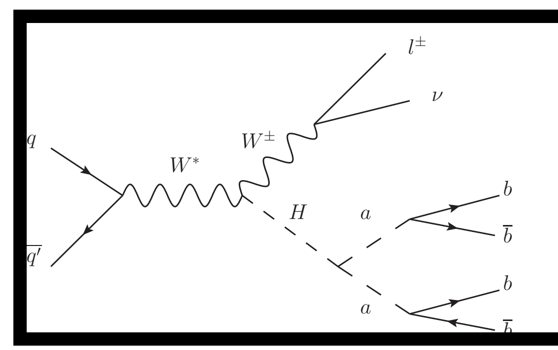
- Comparison of analyses in 2HDM+a model:
  - *Br of a strongly depends no the model parameters*
  - *good complementarity of final states in the full parameter phase space*

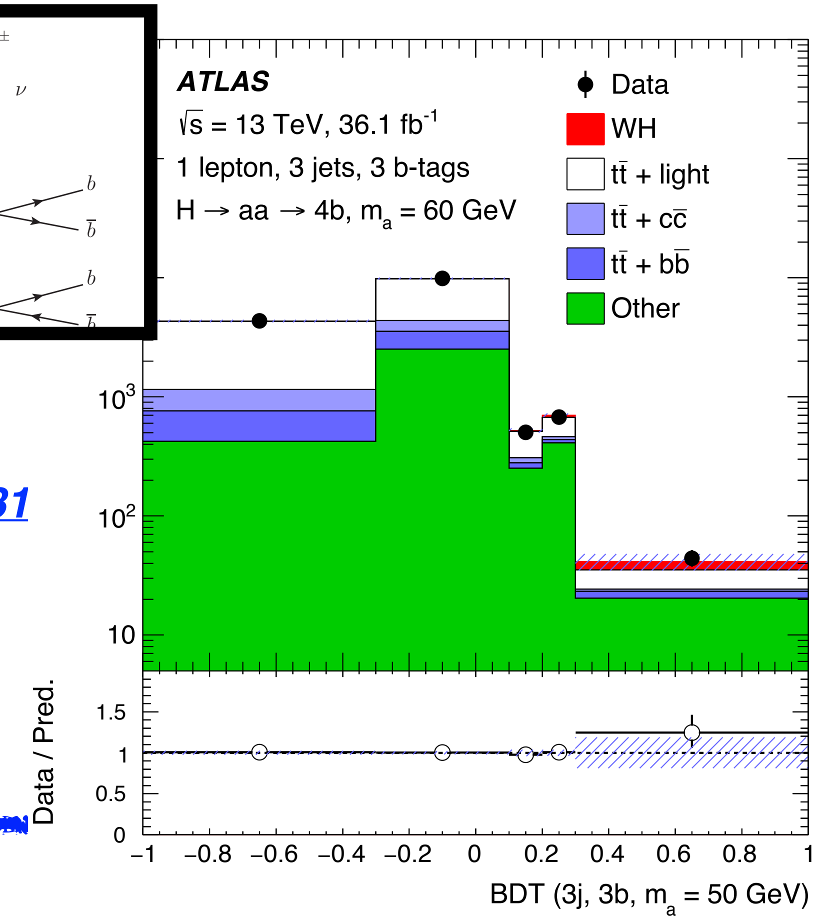


bbμμ ***$m_{bb\mu\mu}$~125 GeV , m_{bb}~$m_{\mu\mu}$***



bbbb: *VH production*



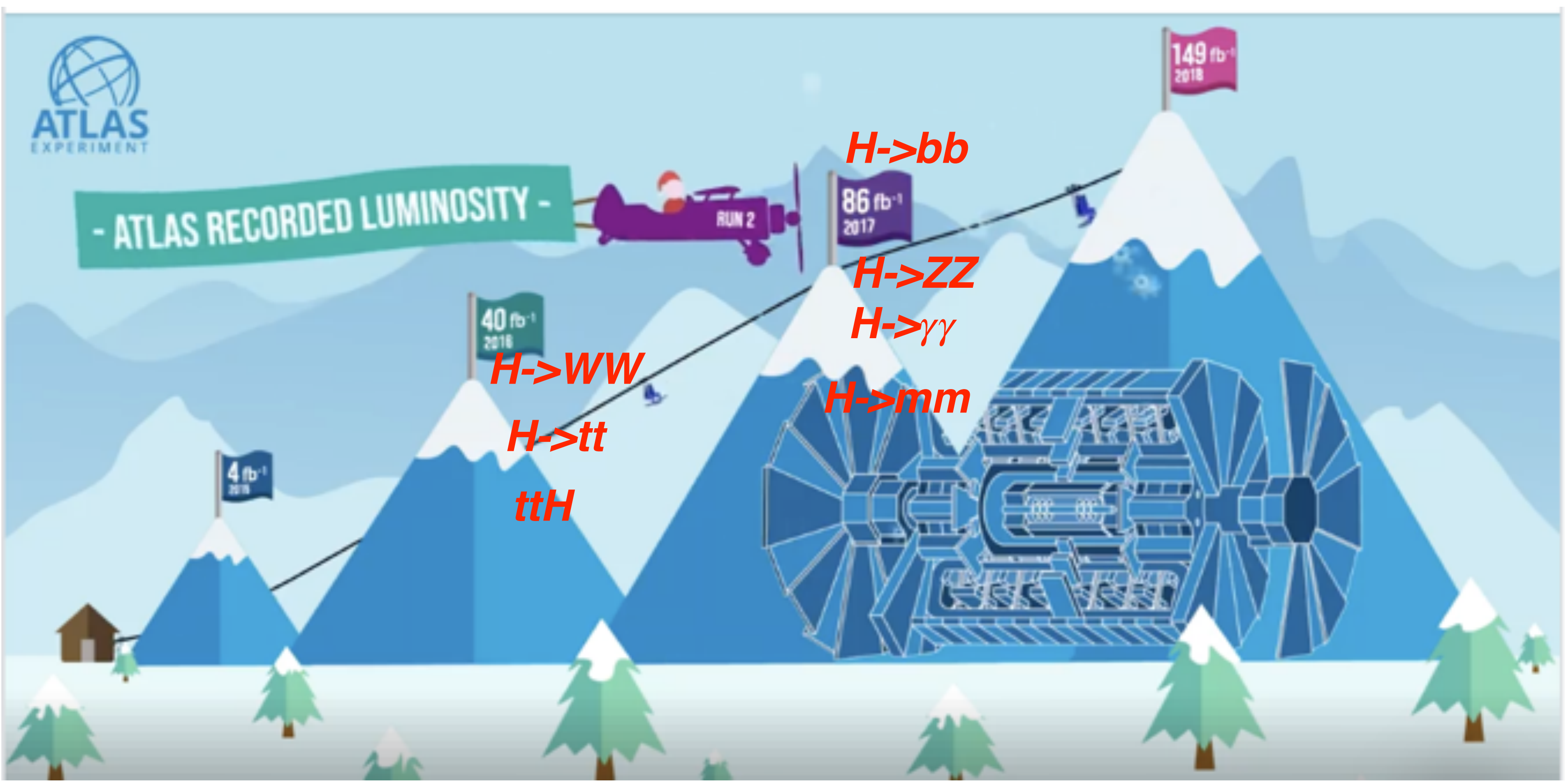


JHEP 10 (2018) 031

- 30/01/2019

Summary and Conclusions

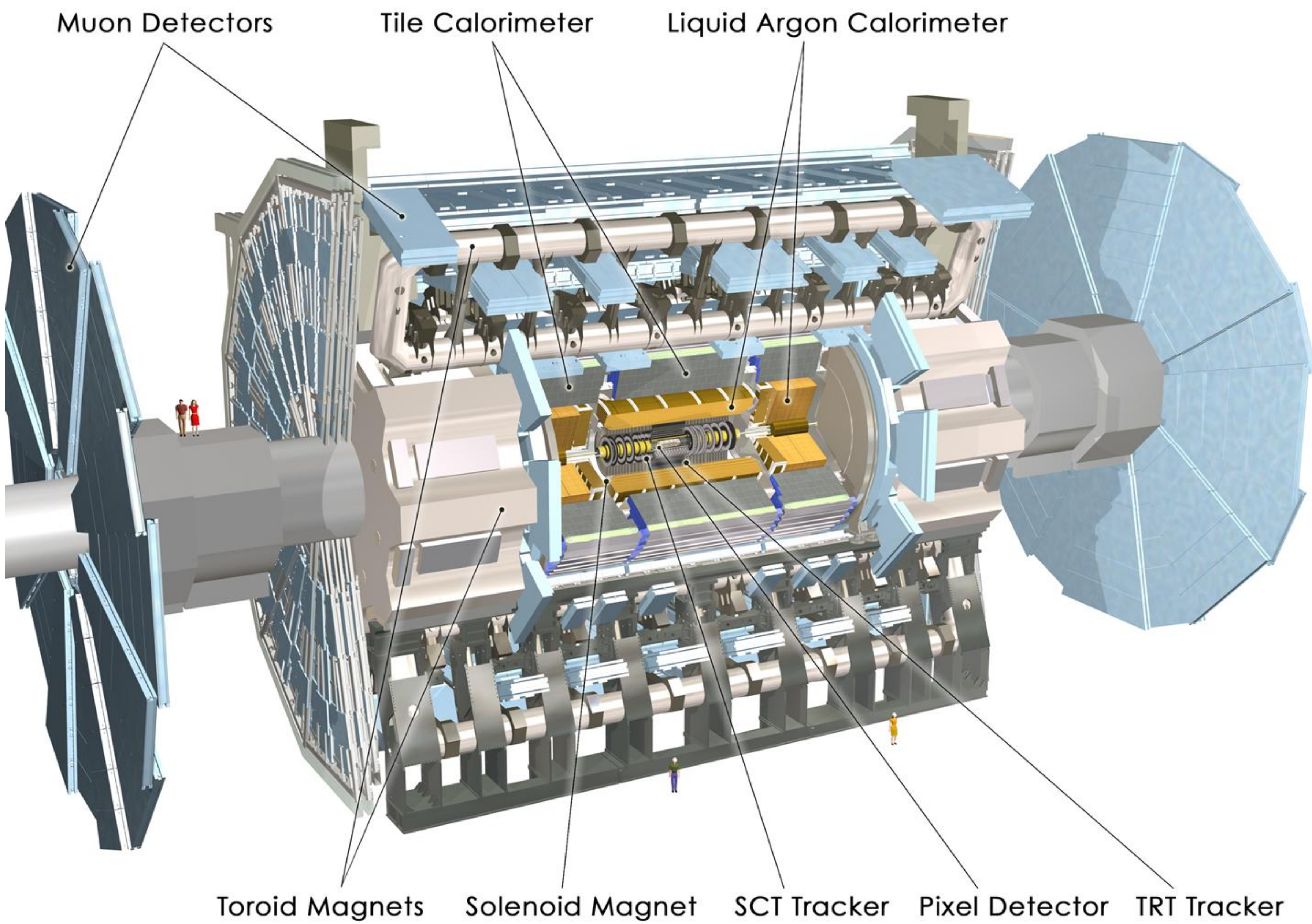
- This was a partial (and biased) overview of the landscape of Higgs boson analyses at ATLAS
- First part of LHC Run2 dataset already brought some important milestones*:*
  - *observation of H->bb decay*
  - *observation of ttH production*
- No significant deviation from SM prediction has been found but ATLAS continues to improve the precision of the measurements and to provide unexplored opportunities for searches that could be used to constrain new physics predictions



- ***much more data already on tape to be analysed (and event more to come, see Pedrag's talk)***

!!!! Stay tuned for upcoming results !!!!

“would you like to know more?”



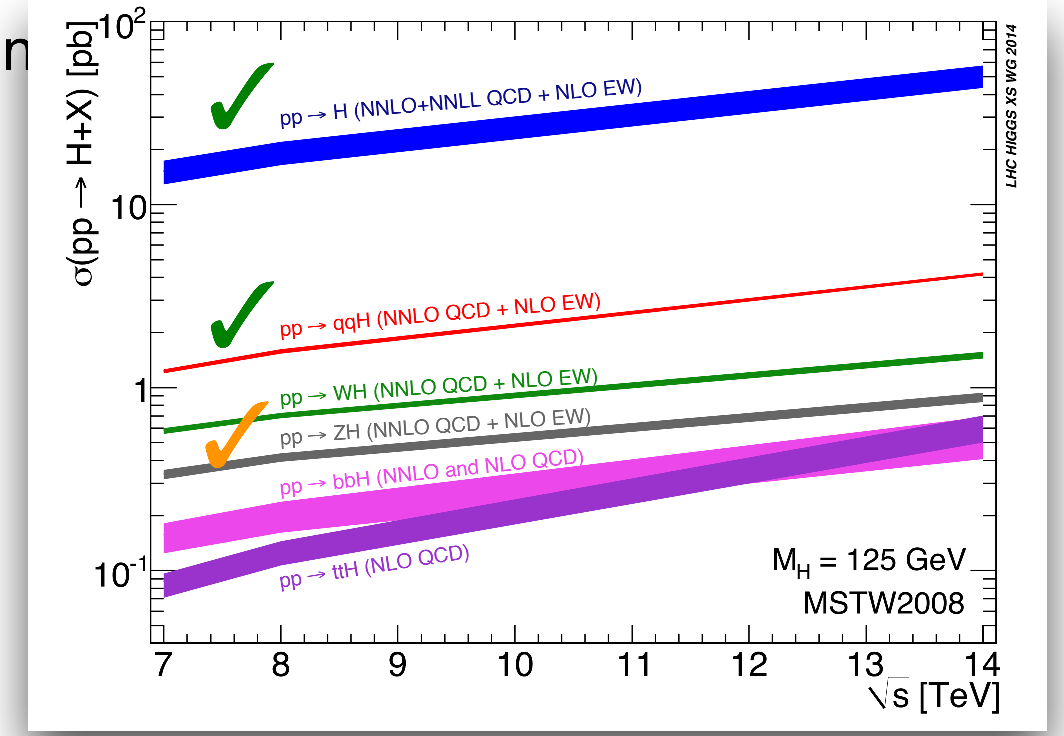
https://twiki.cern.ch/twiki/bin/view/AtlasPublic/HiggsPublicResults

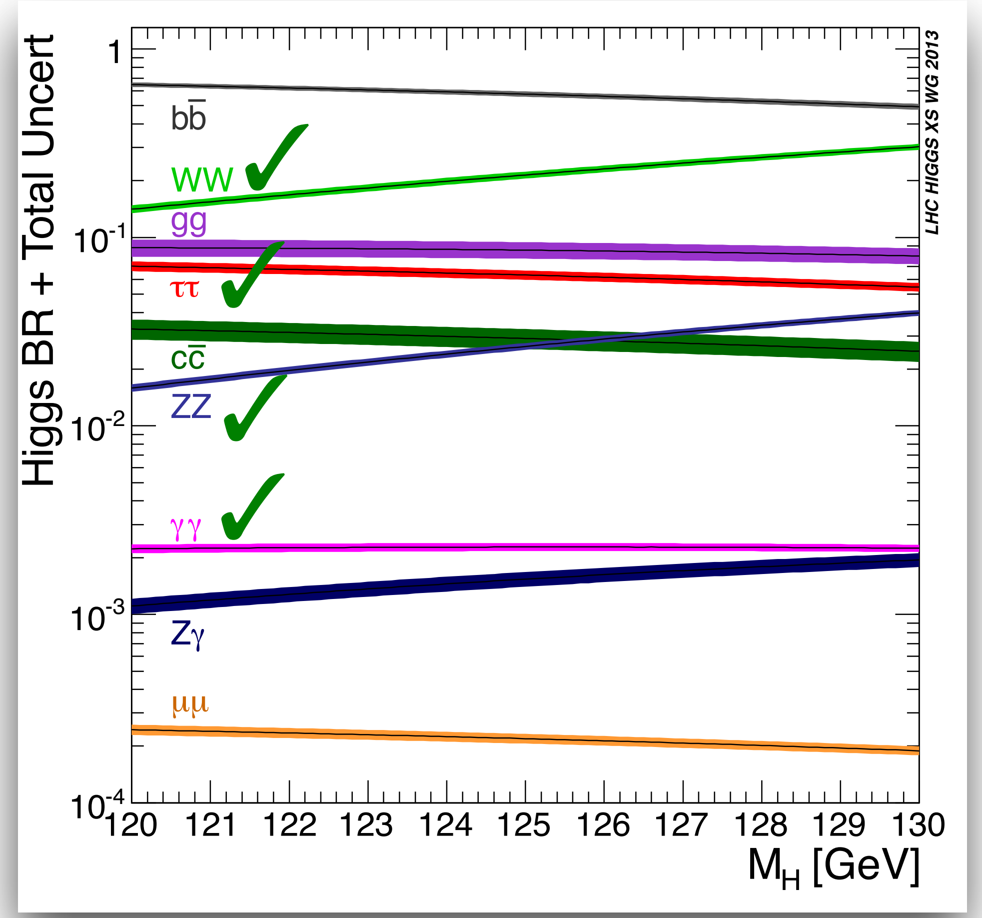
BackUp

Current experimental status

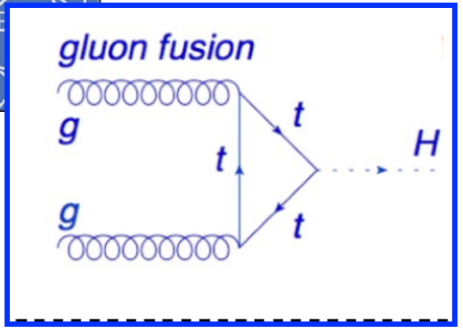
✦ ***Run1 legacy results:*** being confirmed by Run2 measurements

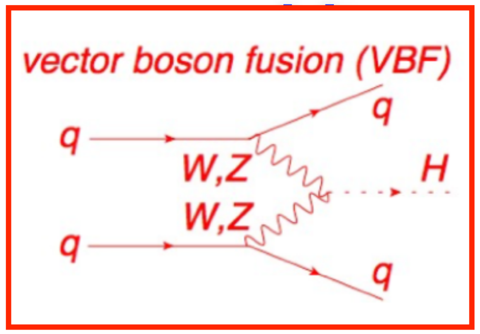
- 2012 discovery and precise measurement driven by *gluon fusion* production mode [indirect probe of coupling to quarks]
- 5.4 s.d. observation of *vector boson fusion production*
- 3.5 s.d. evidence for *VH production*
- observation of *direct decay into bosonic final states* (WW,ZZ,γγ) well established
- observation of *decay into tau pair* confirmed coupling to fermions (leptons)
- mass measurement now at <3% uncertainty
- spin / parity
- “re-discovery” of Higgs boson signal at 13TeV started with bosonic channels (ZZ and γγ)

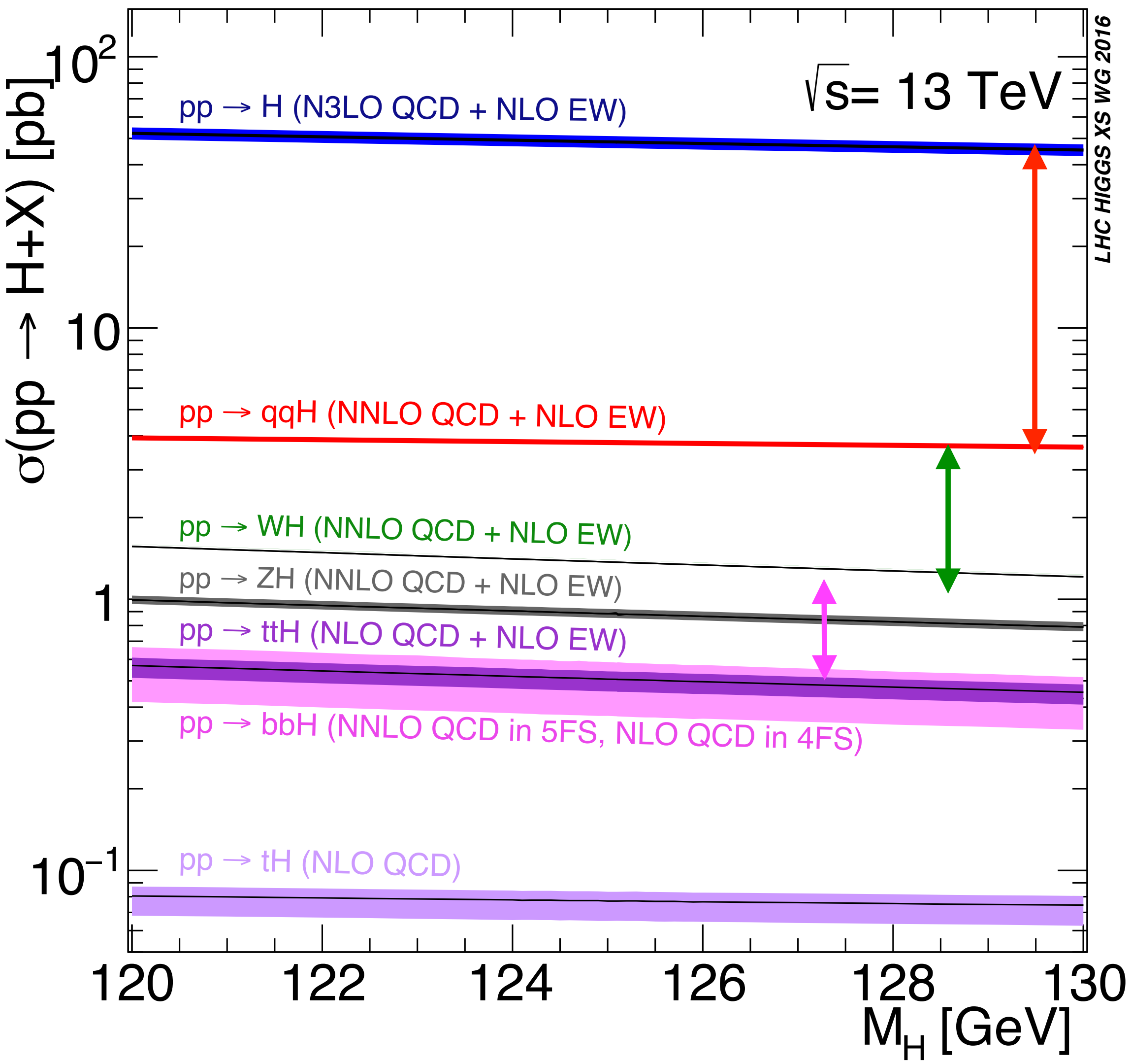


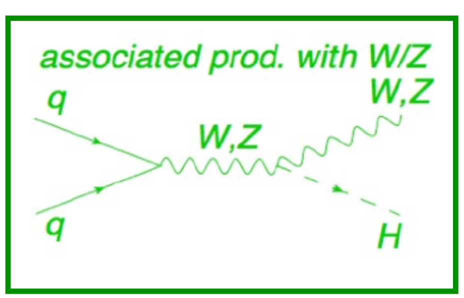


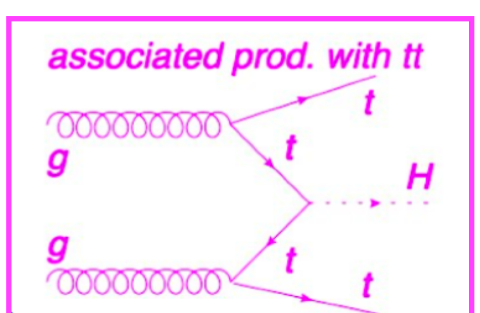
phenomenology











- production and decay with statement on complete sophisticated analyses***gluon fusion***:
  - overwhelming multi-jet background
  - only limited to very high p_T

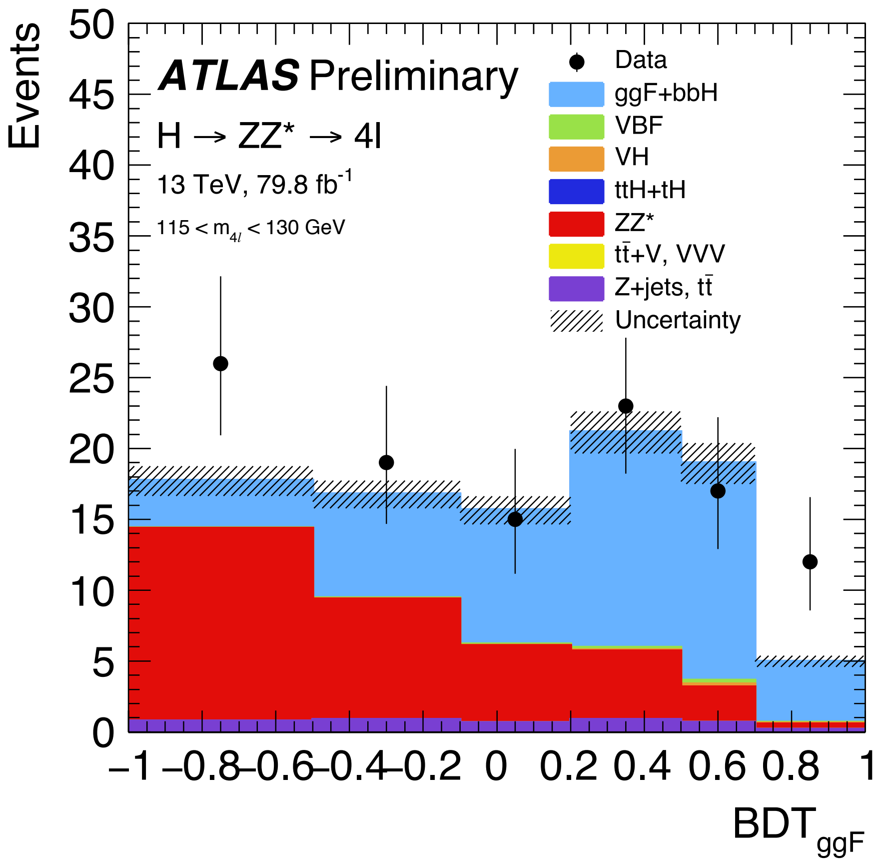
- ***Vector Boson Fusion***: 1/10 of total cross section
  - forward jets topology helps reducing the background
  - fully hadronic final state still maintain many experimental difficulties (trigger)

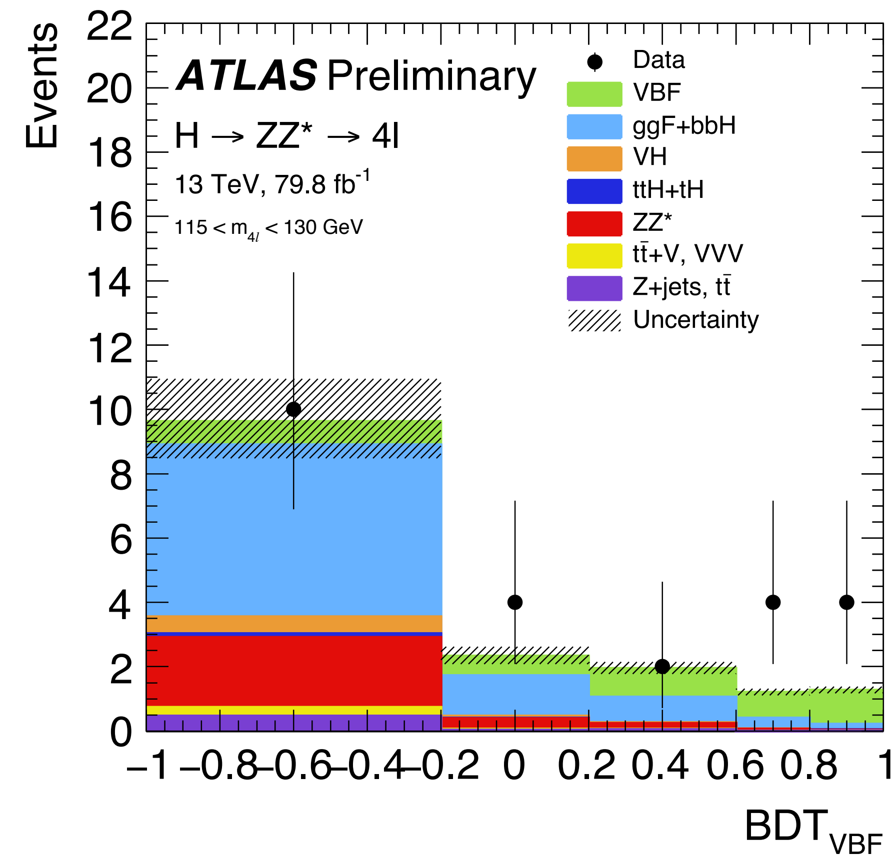
- ***VH production***: 1/20 of total cross section
  - can use leptonic decays of V for triggering/background reduction
  - *GOLDEN H->bb channel at hadronic machines*

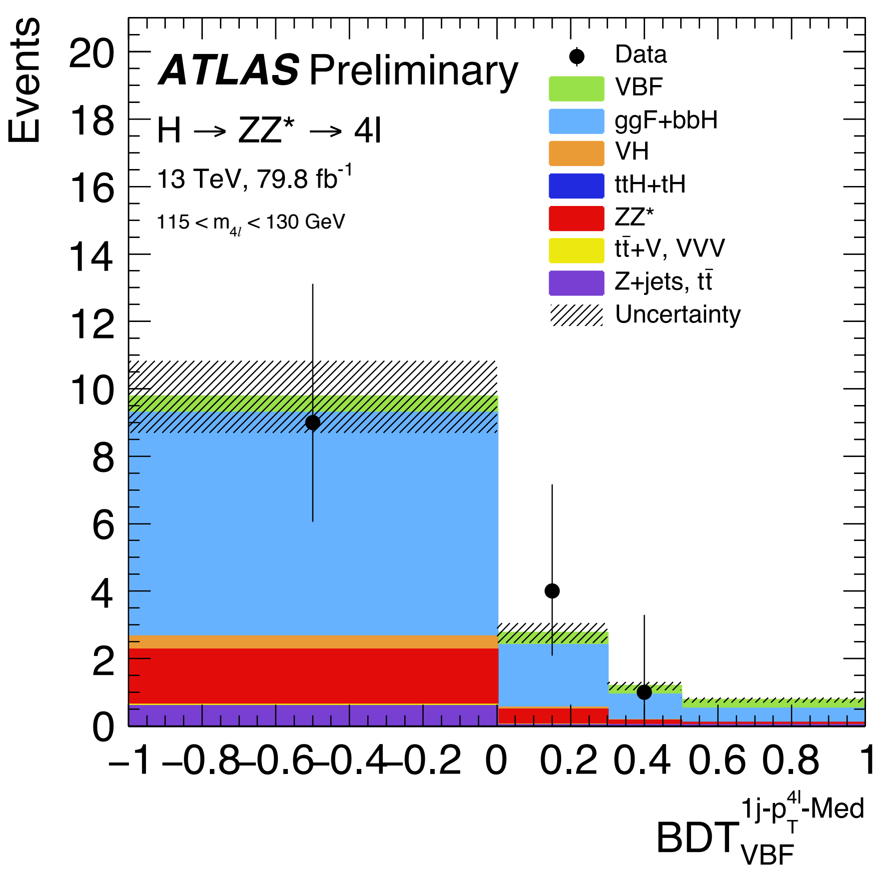
- ***ttH***: 1/100 of total cross section
  - can rely on leptonic decays of top quarks for triggering/ background reduction
  - complicated combinatorics: difficult to extract a mass peak already for the signal

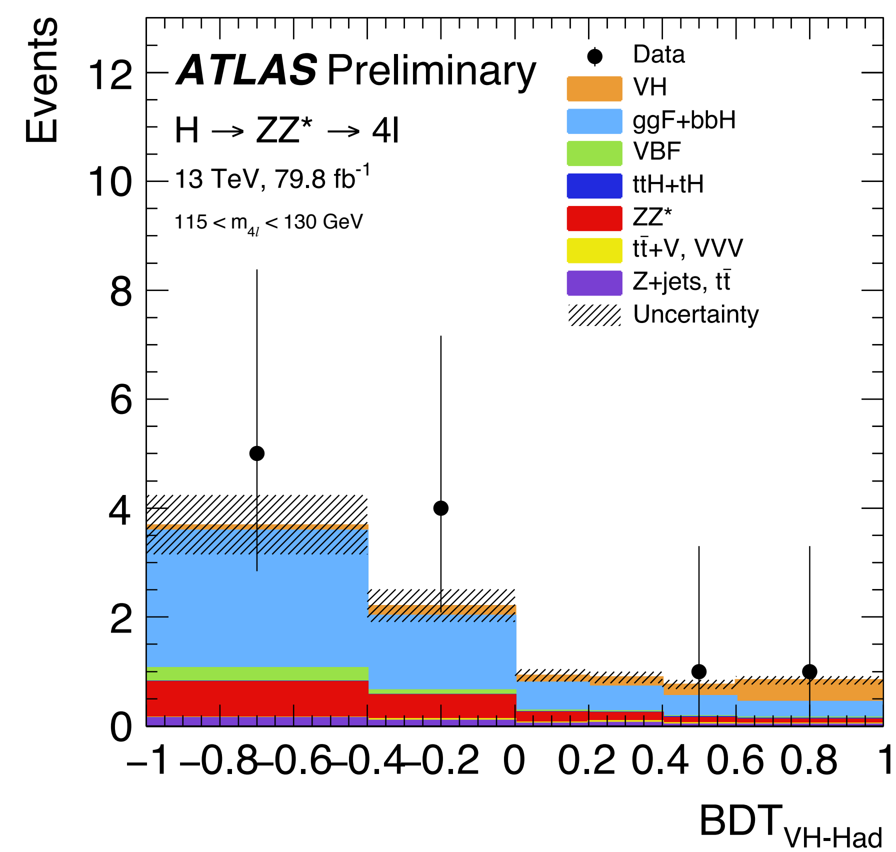
ATLAS-CONF-2018-018

The golden channels: ZZ

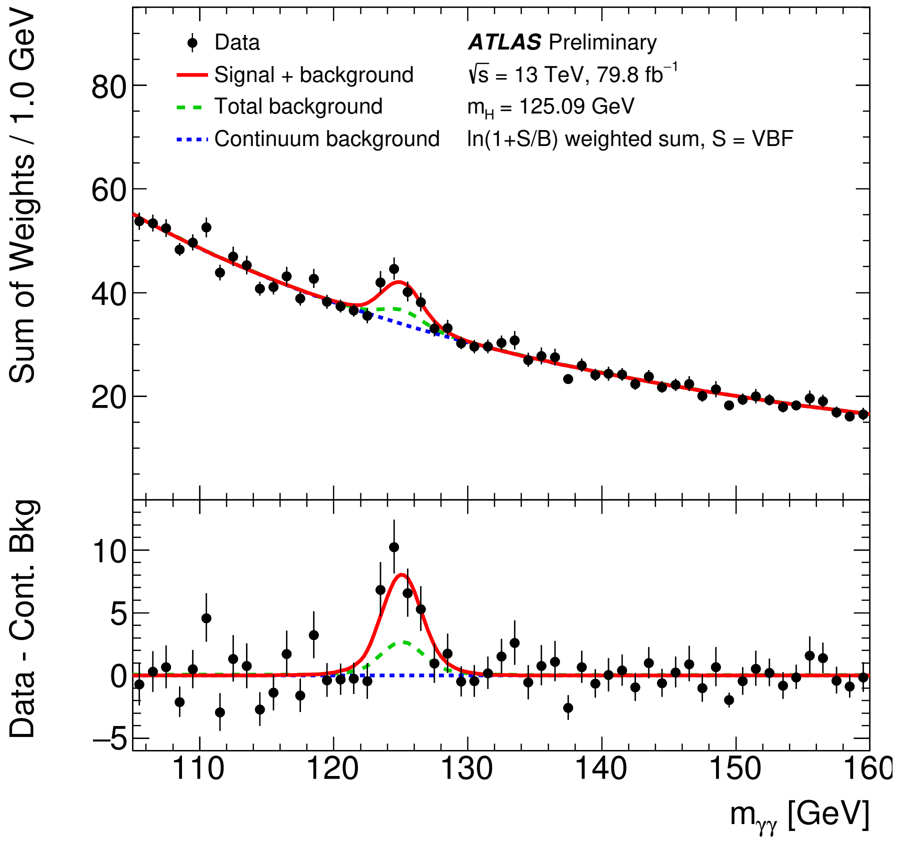


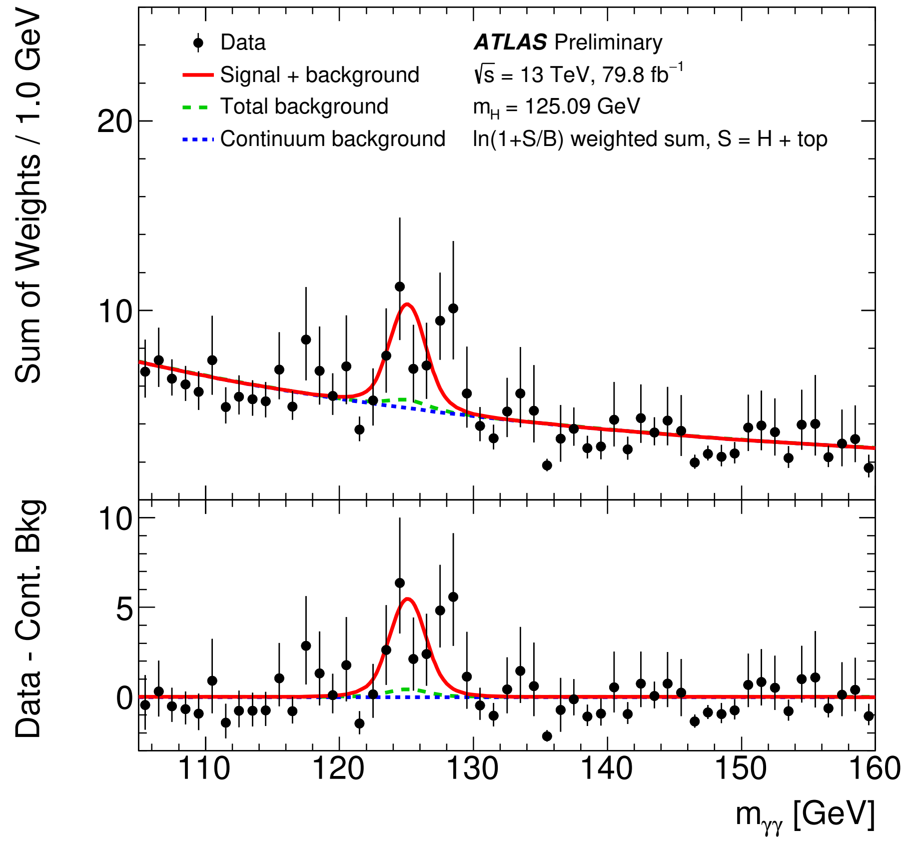


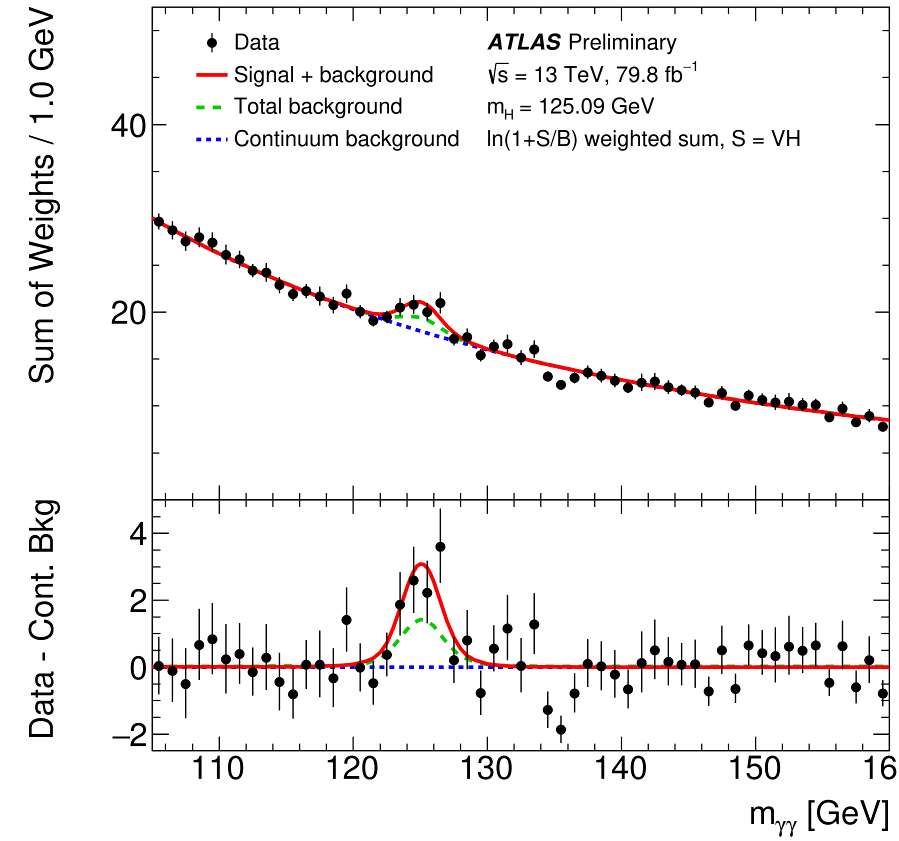


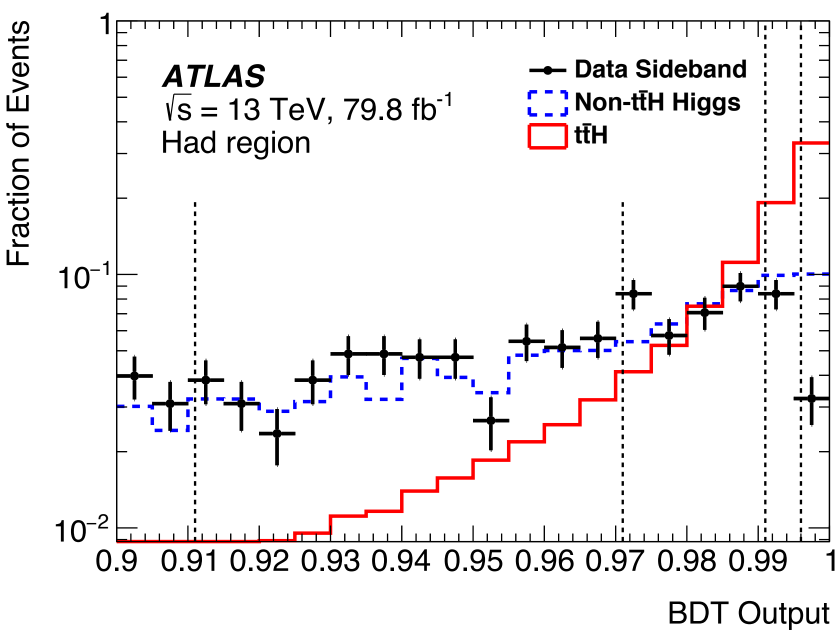


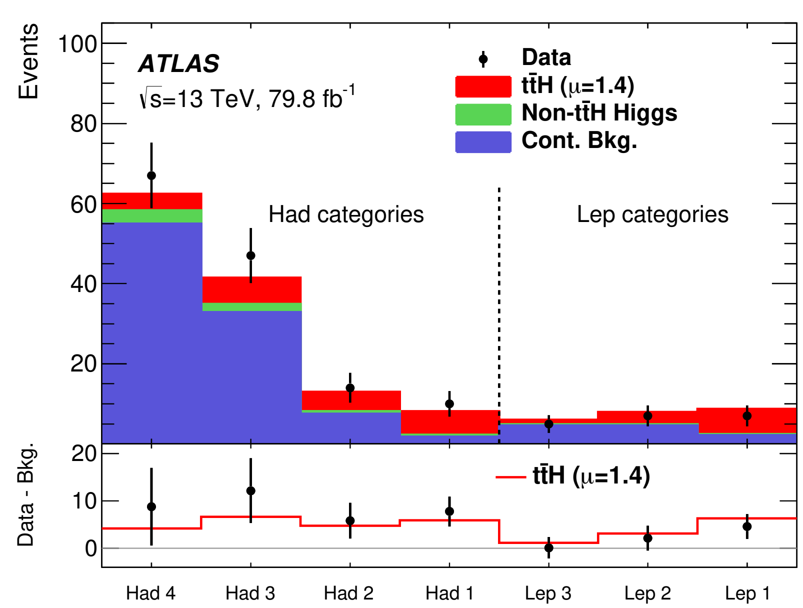
The golden channels: γγ

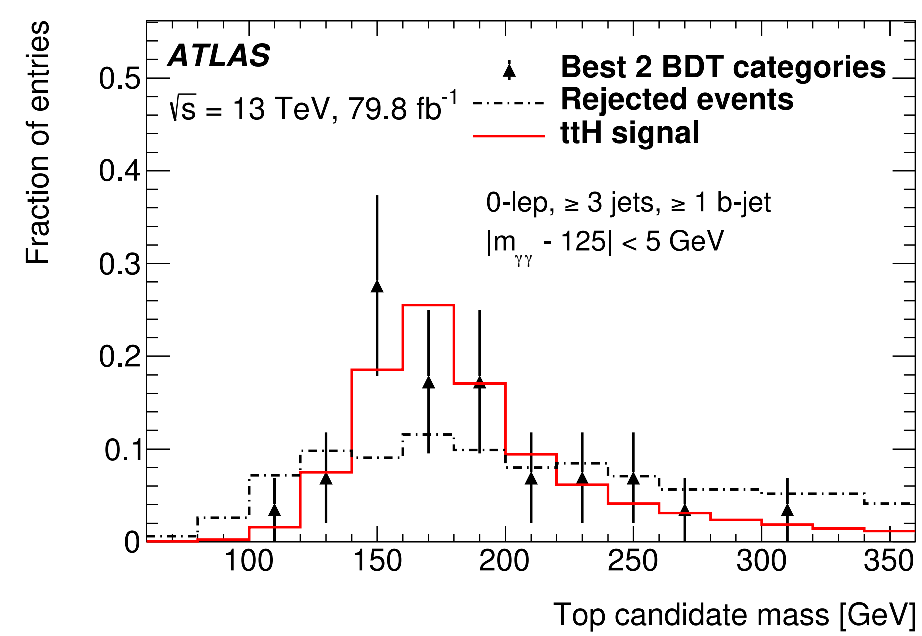






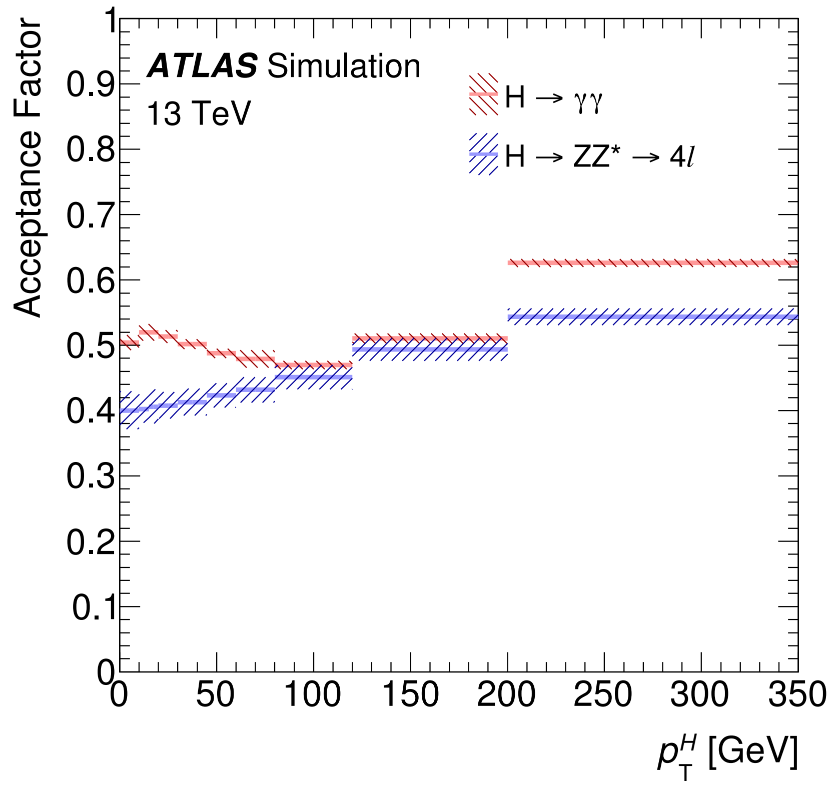


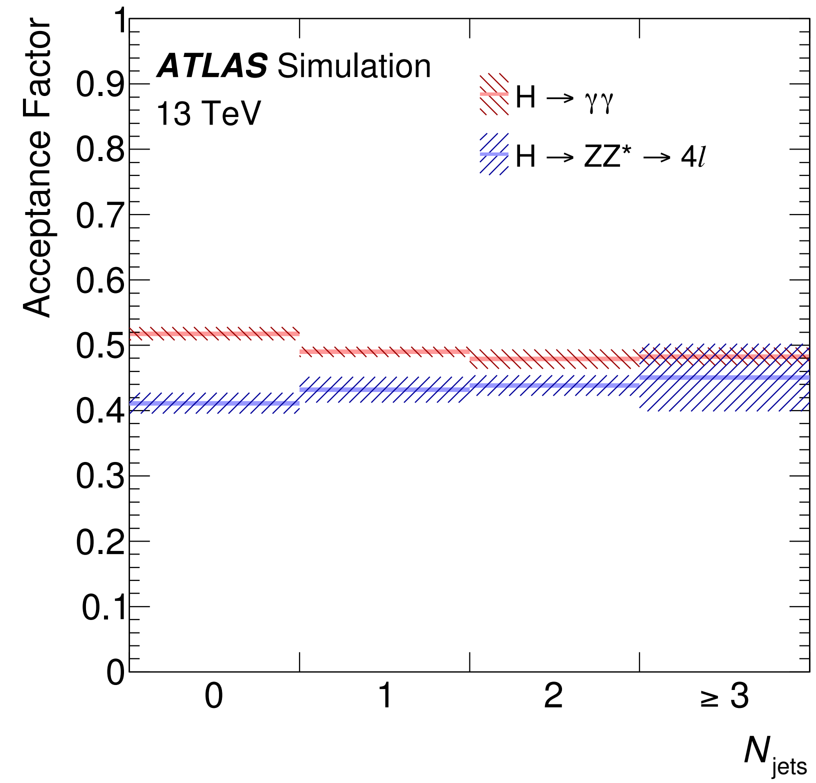


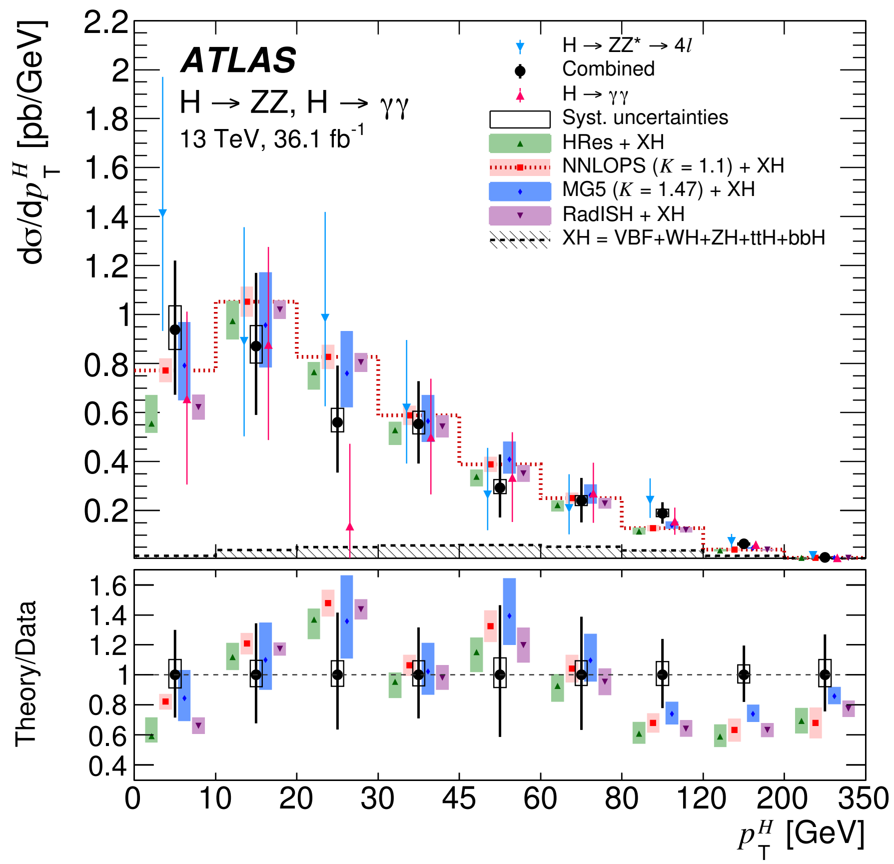


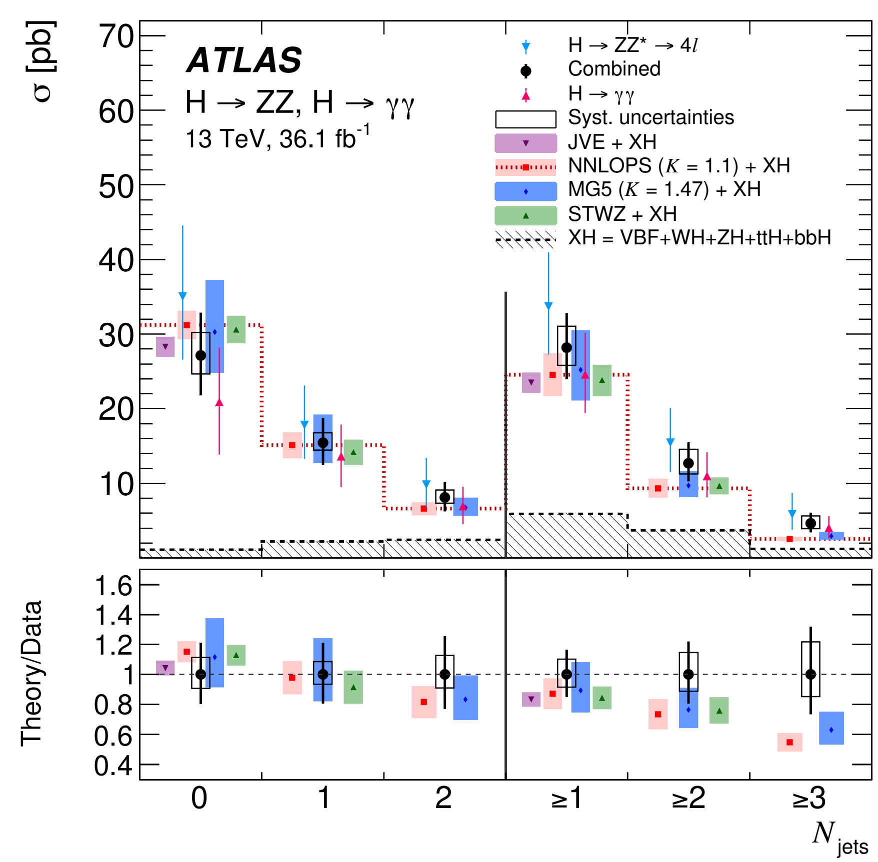
The golden channels: differential cross-section

- Backup on inclusive xSection, differential combination; HIGG-2017-11/



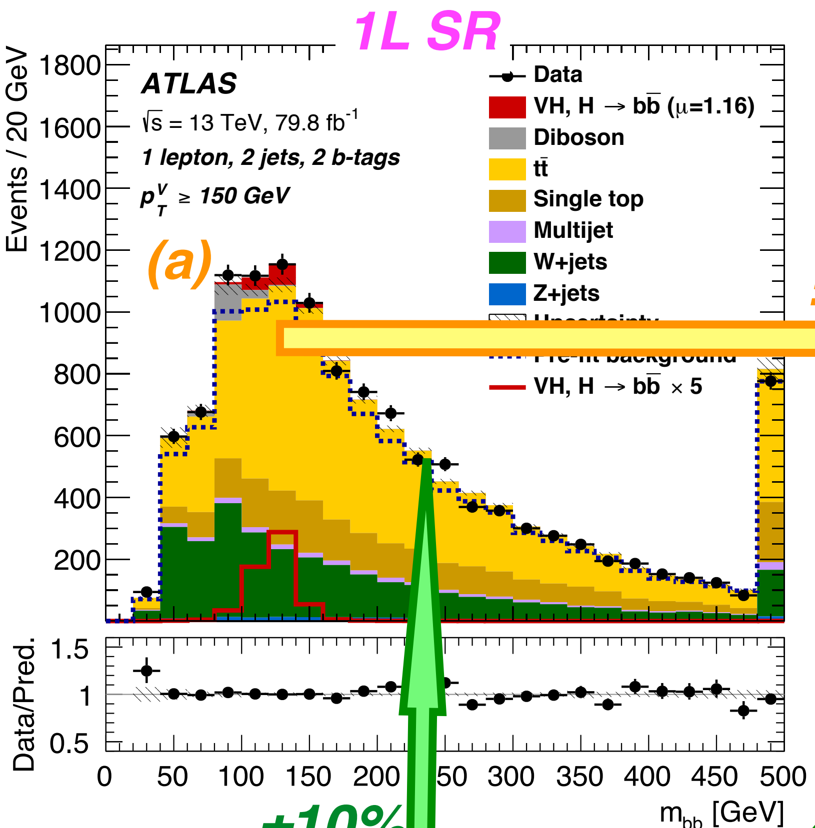


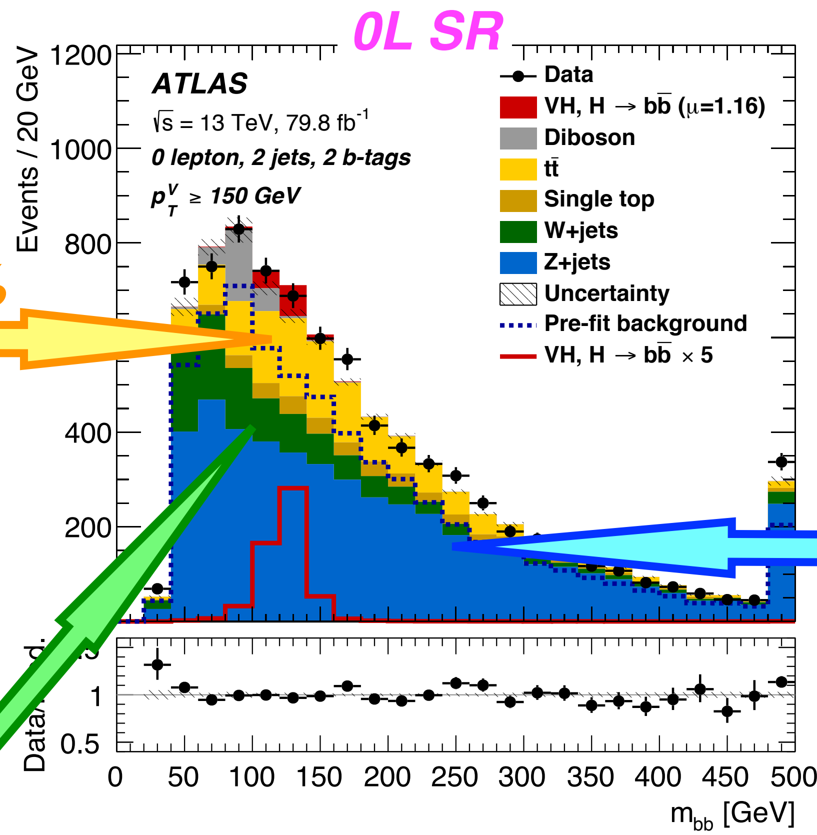


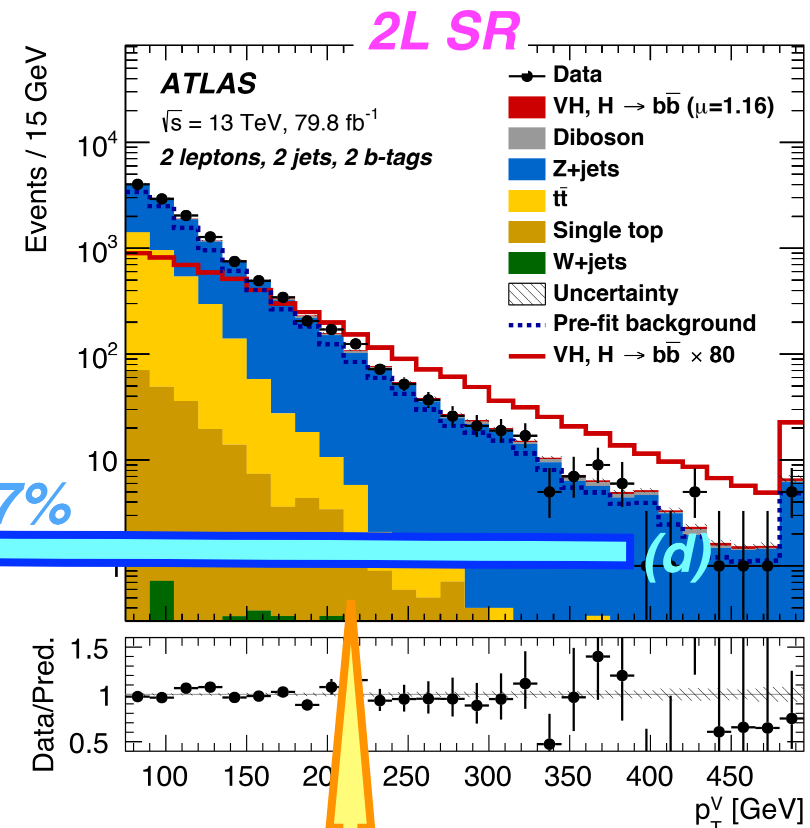


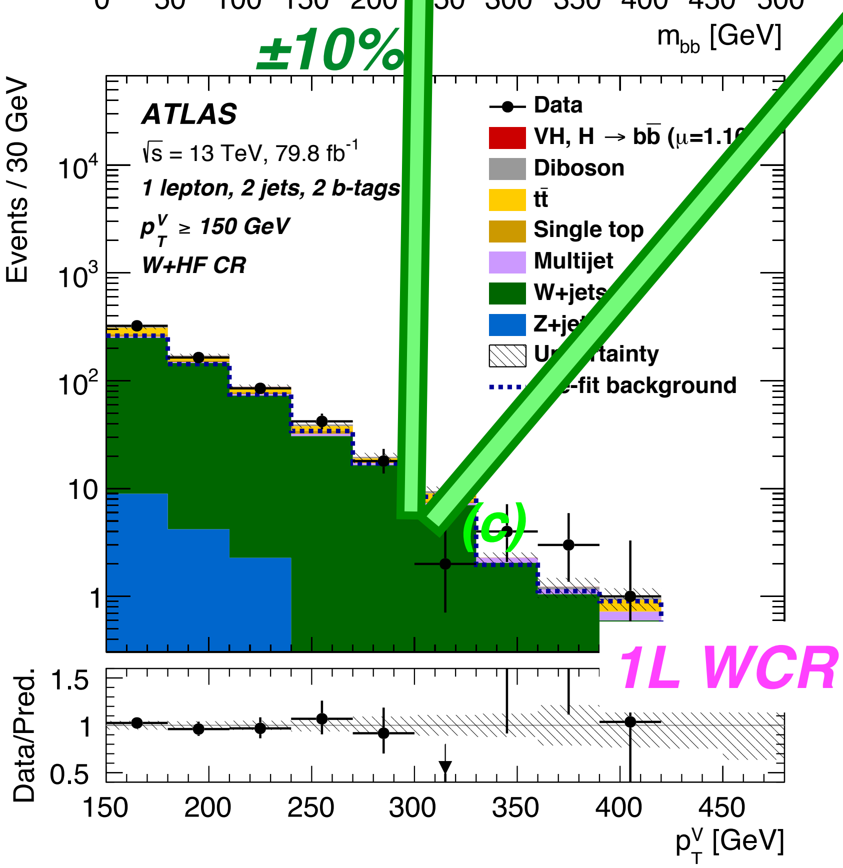
H->bb: VH

- Warning: slightly simplified version, only 1 jet multiplicity bin shown

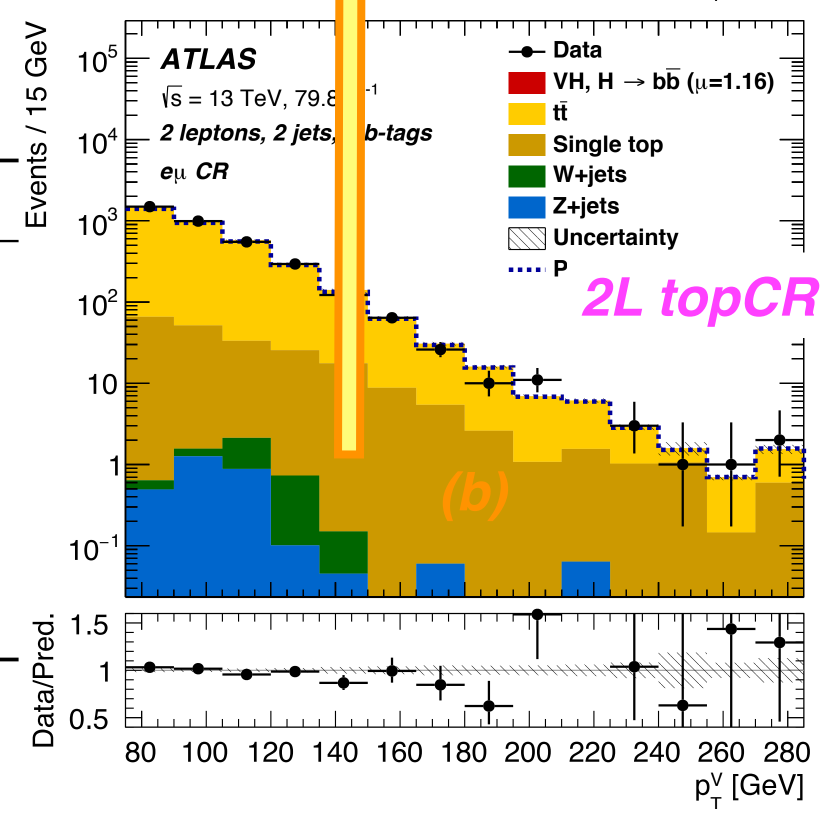






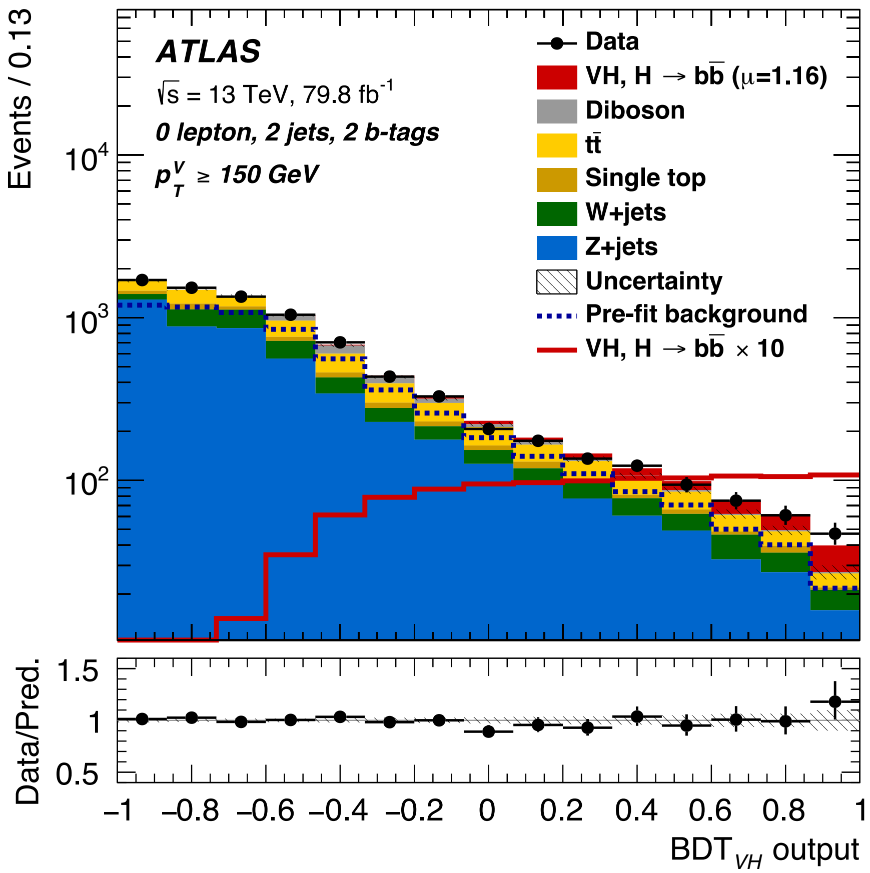


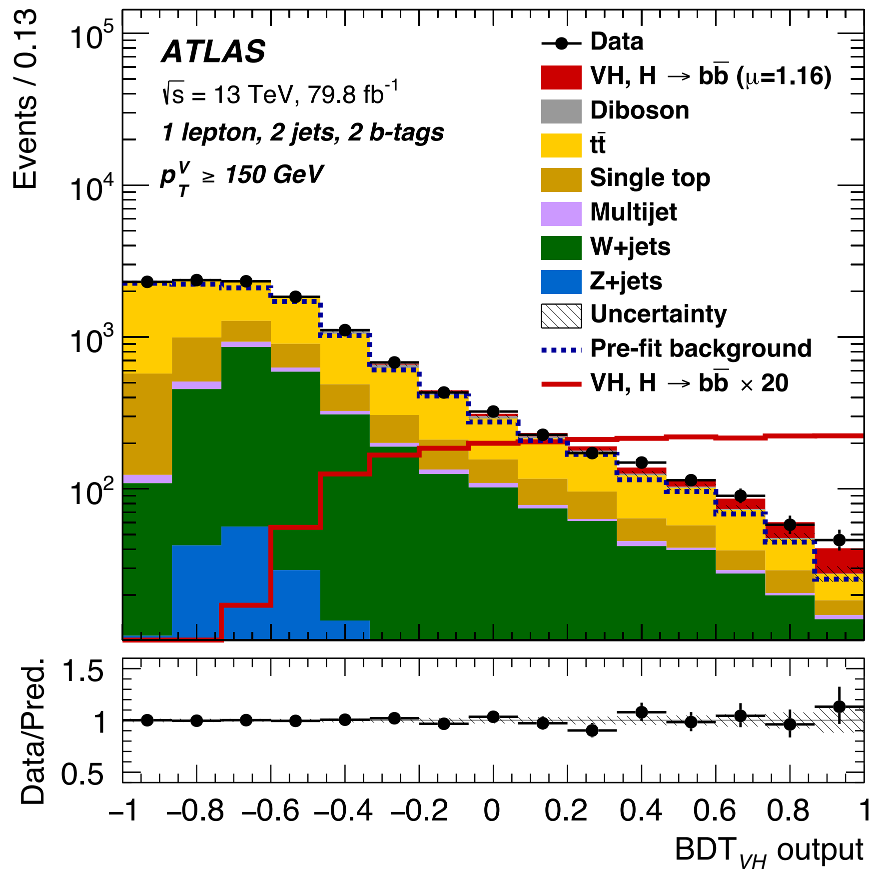
	Process	Normalisation factor
(a)	$t\bar{t}$ 0- and 1-lepton	0.98 ± 0.08
(b)	$t\bar{t}$ 2-lepton 2-jet	1.06 ± 0.09
	$t\bar{t}$ 2-lepton 3-jet	0.95 ± 0.06
(c)	$W+$HF 2-jet	1.19 ± 0.12
	$W+$HF 3-jet	1.05 ± 0.12
(d)	$Z+$HF 2-jet	1.37 ± 0.11
	$Z+$HF 3-jet	1.09 ± 0.09

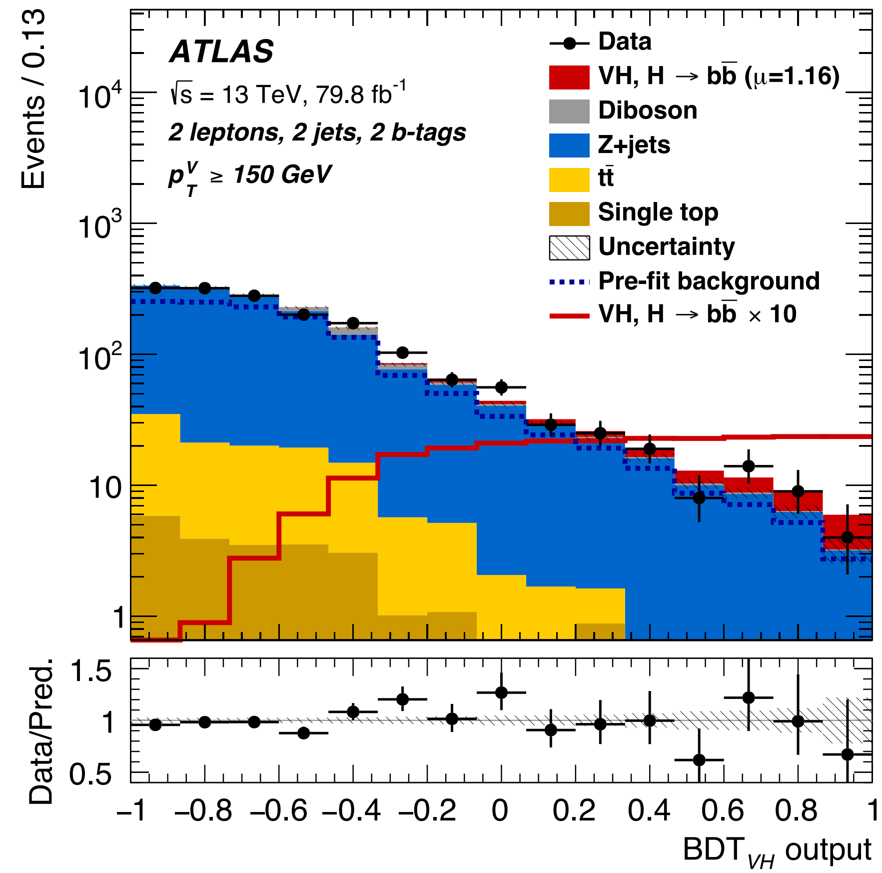


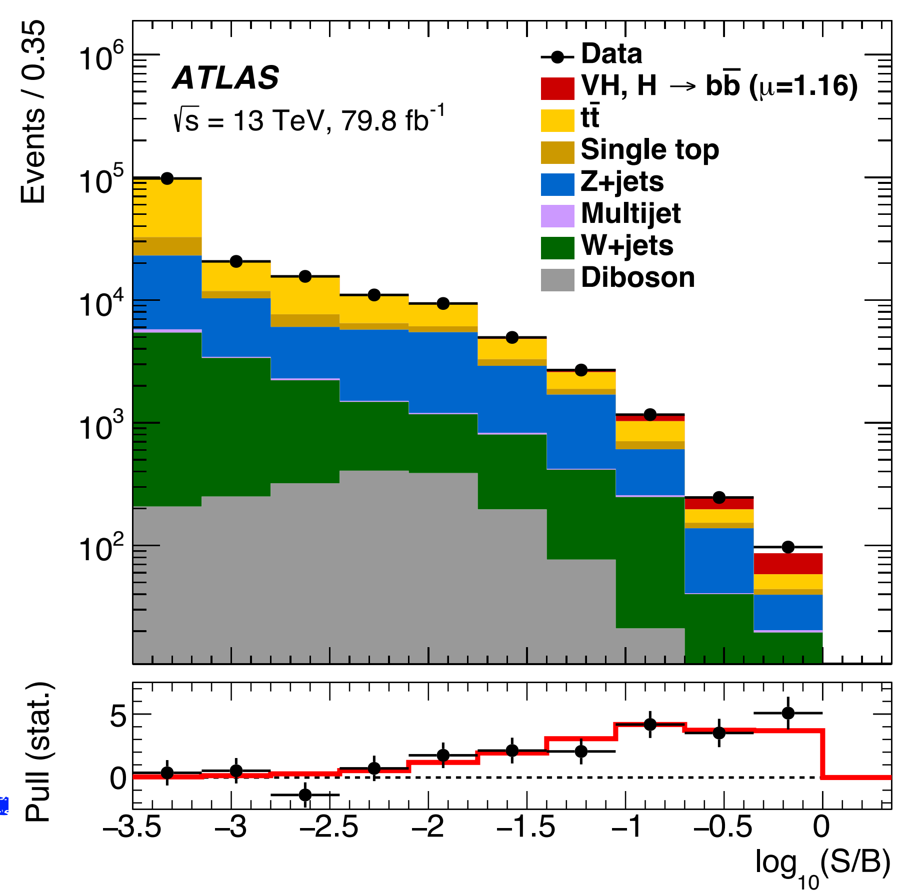
H->bb: VH

Phys. Rev. D 98 (2018) 052003

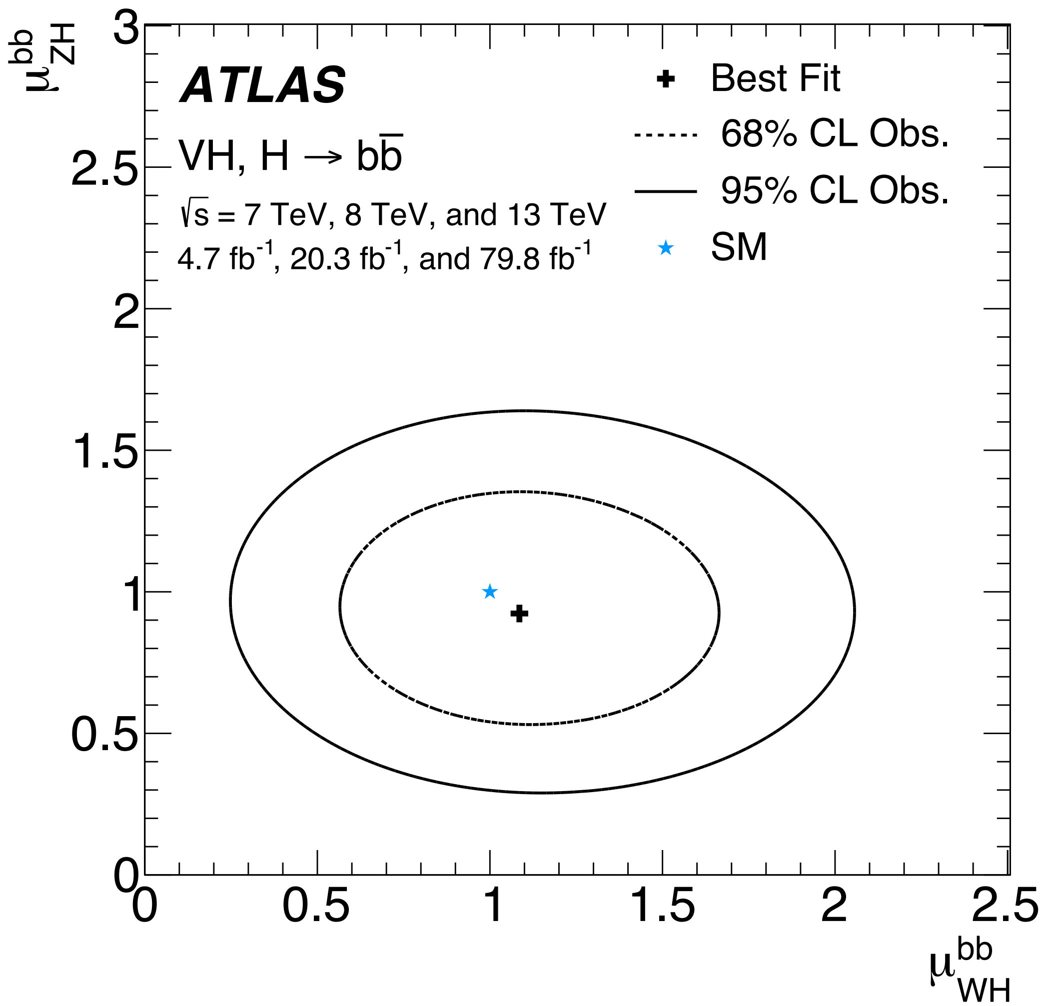


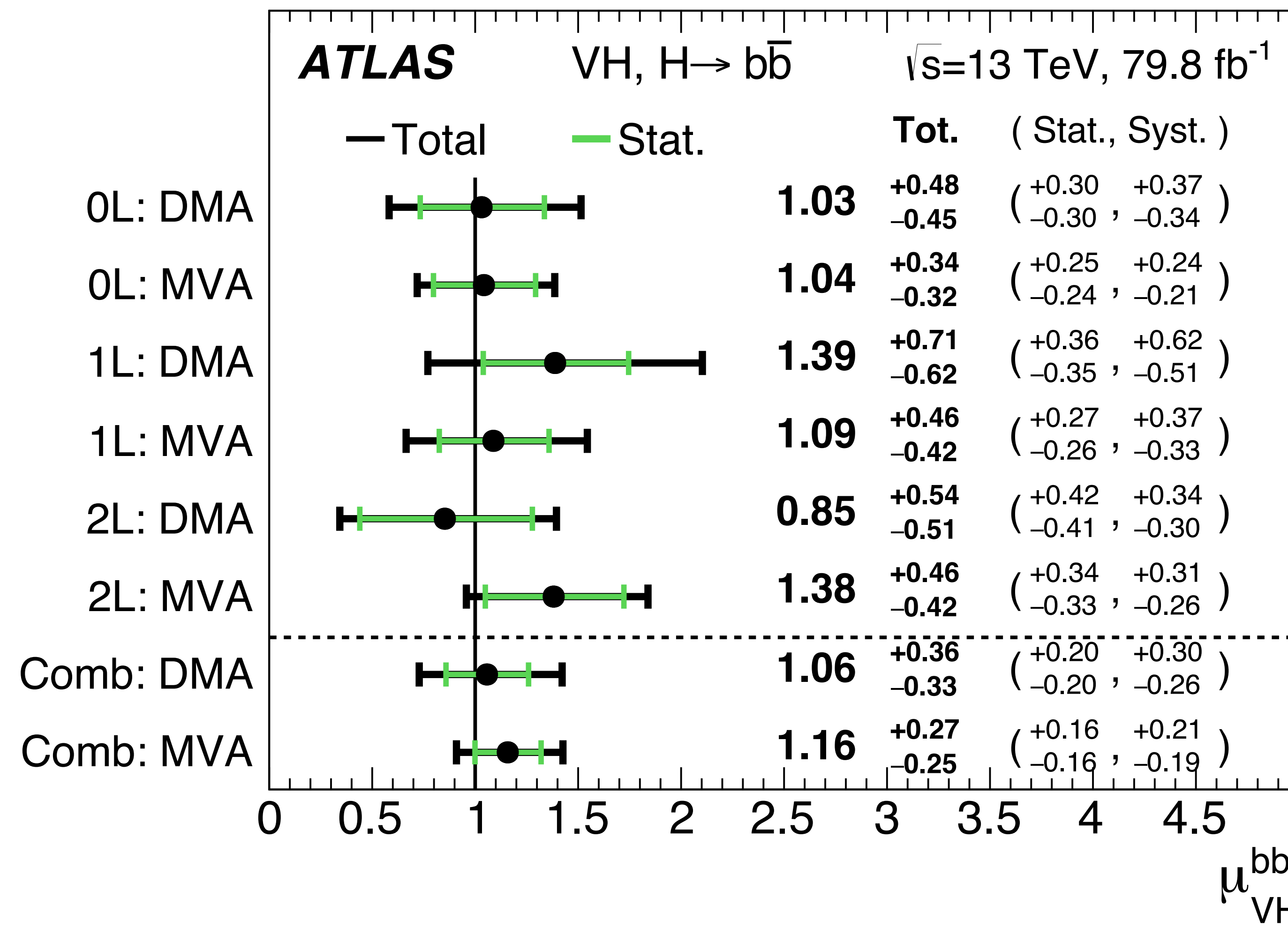






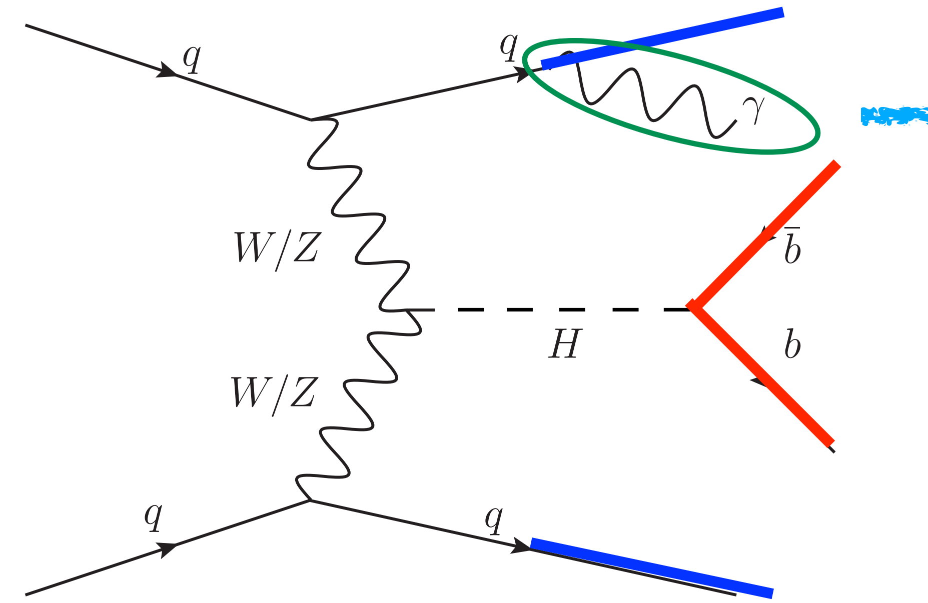
H->bb: VH


ATLAS
VH, H → bb̄
√s = 7 TeV, 8 TeV, and 13 TeV
4.7 fb-1, 20.3 fb-1, and 79.8 fb-1
Best Fit
68% CL Obs.
95% CL Obs.
SM
μbb ZH
μbb WH


ATLAS
VH, H→ bb̄
√s=13 TeV, 79.8 fb-1
Total
Stat.
Tot.
(Stat., Syst.)
0L: DMA 1.03 +0.48 −0.45 (+0.30 −0.30 , +0.37 −0.34)
0L: MVA 1.04 +0.34 −0.32 (+0.25 −0.24 , +0.24 −0.21)
1L: DMA 1.39 +0.71 −0.62 (+0.36 −0.35 , +0.62 −0.51)
1L: MVA 1.09 +0.46 −0.42 (+0.27 −0.26 , +0.37 −0.33)
2L: DMA 0.85 +0.54 −0.51 (+0.42 −0.41 , +0.34 −0.30)
2L: MVA 1.38 +0.46 −0.42 (+0.34 −0.33 , +0.31 −0.26)
Comb: DMA 1.06 +0.36 −0.33 (+0.20 −0.20 , +0.30 −0.26)
Comb: MVA 1.16 +0.27 −0.25 (+0.16 −0.16 , +0.21 −0.19)
μbb VH

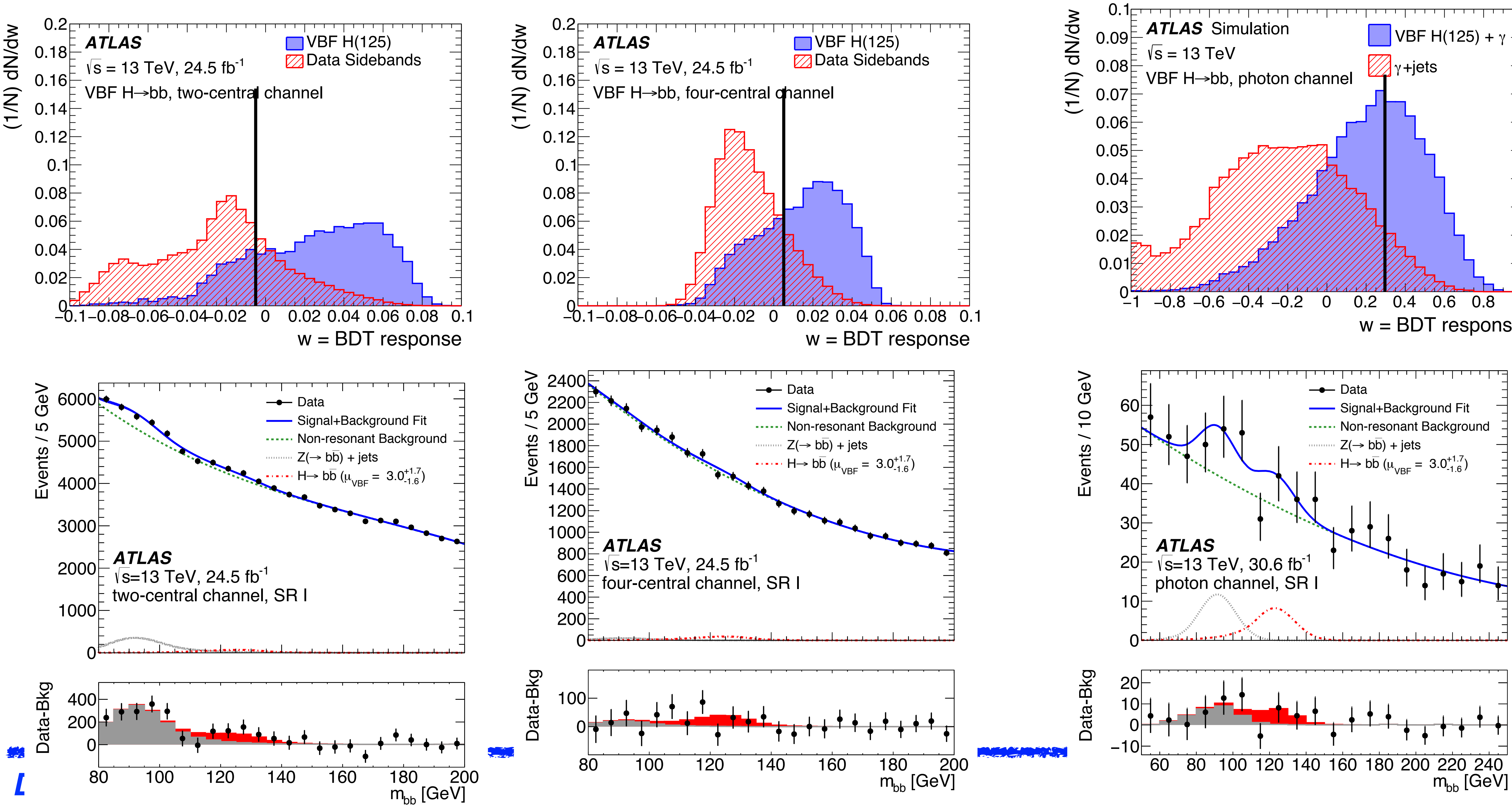
Phys. Rev. D 98 (2018) 052003

H->bb: VBF

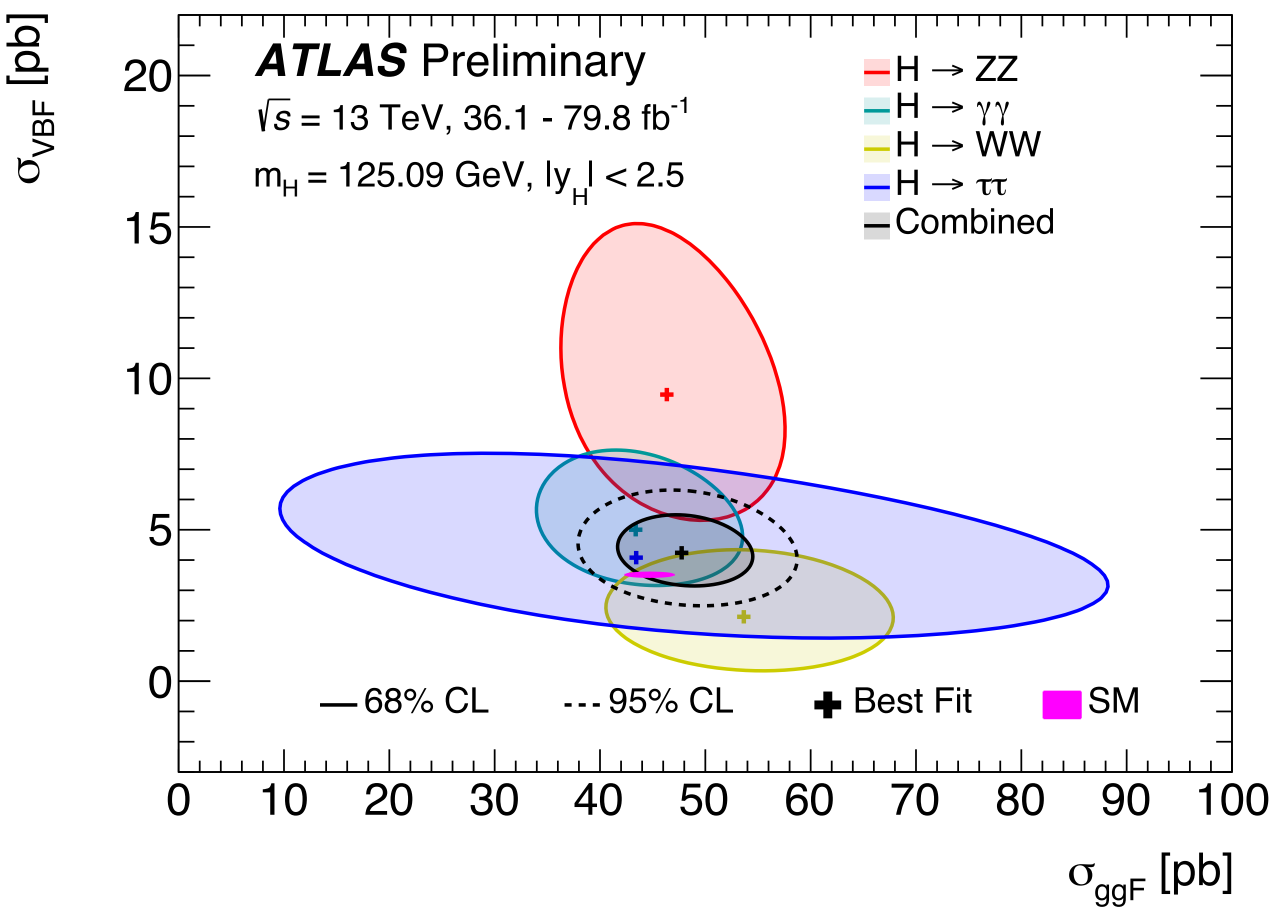


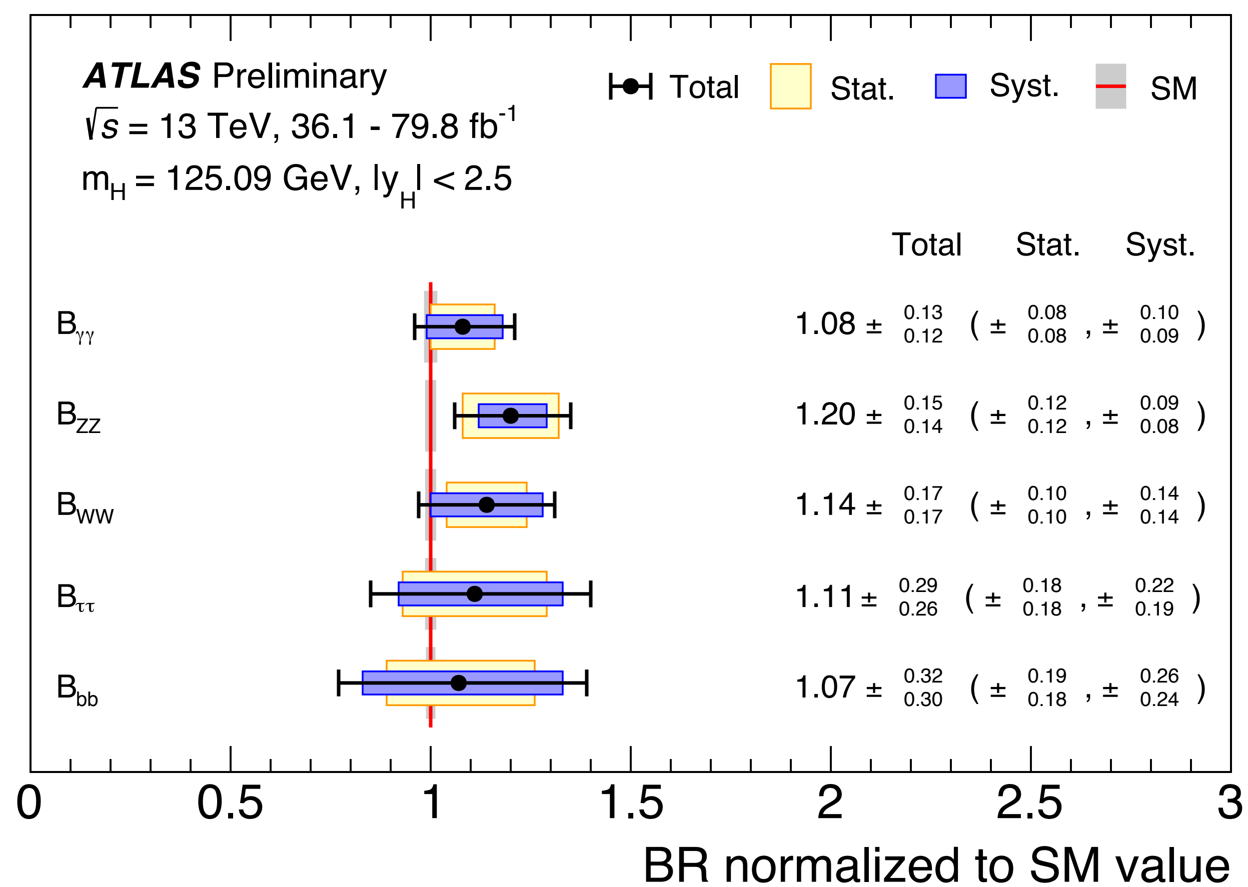
2 b-jets + 2jets (+photon):

- *the photon reduces bkgd and ease triggering*

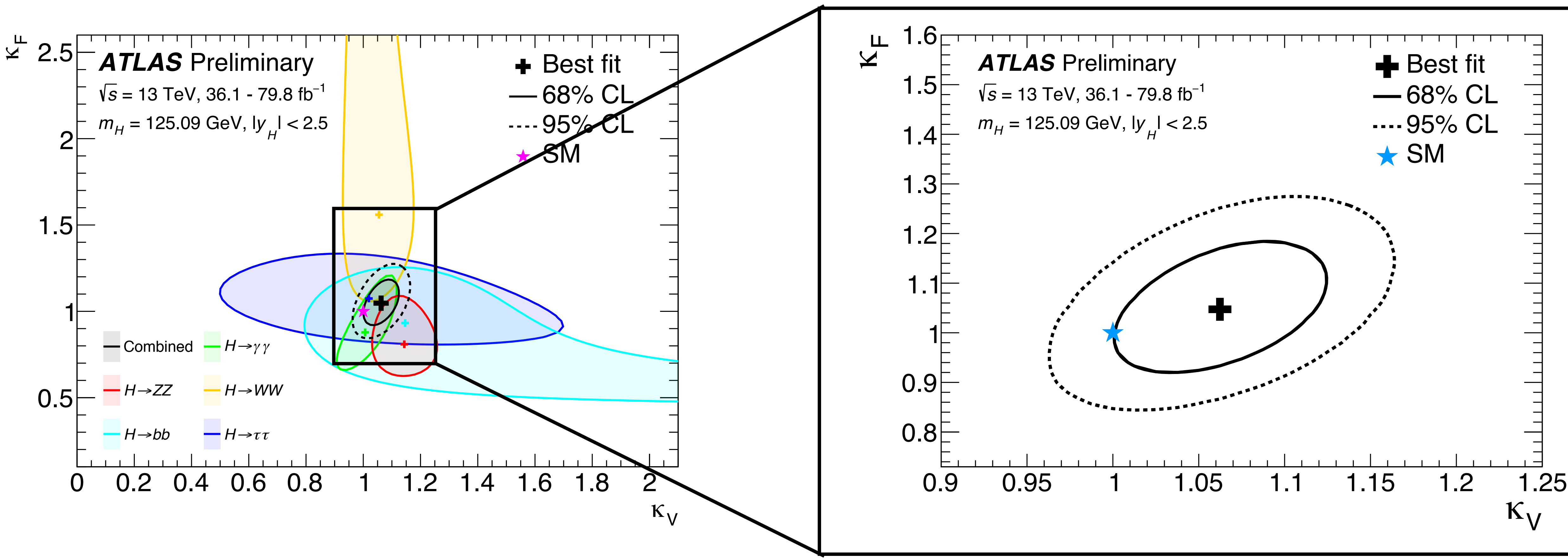


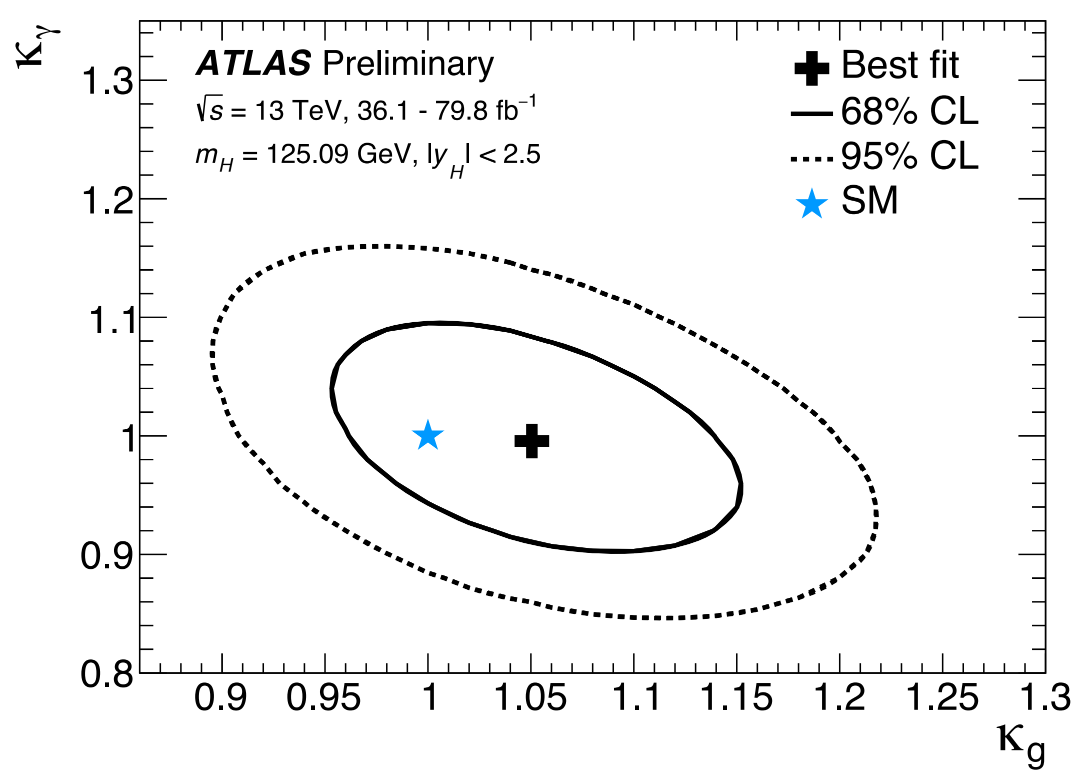
More on combination





Coupling parameterisation (2)

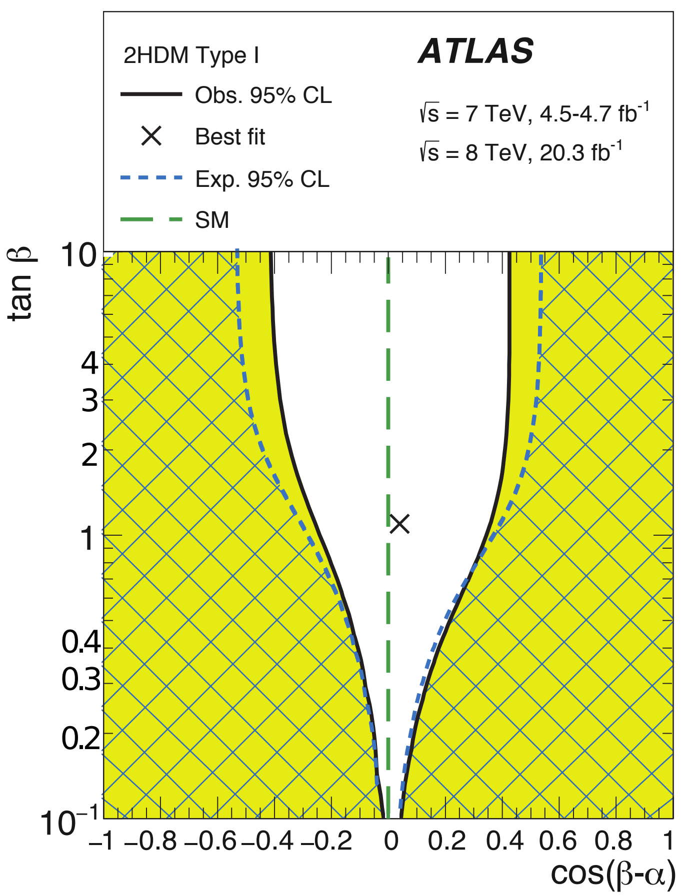


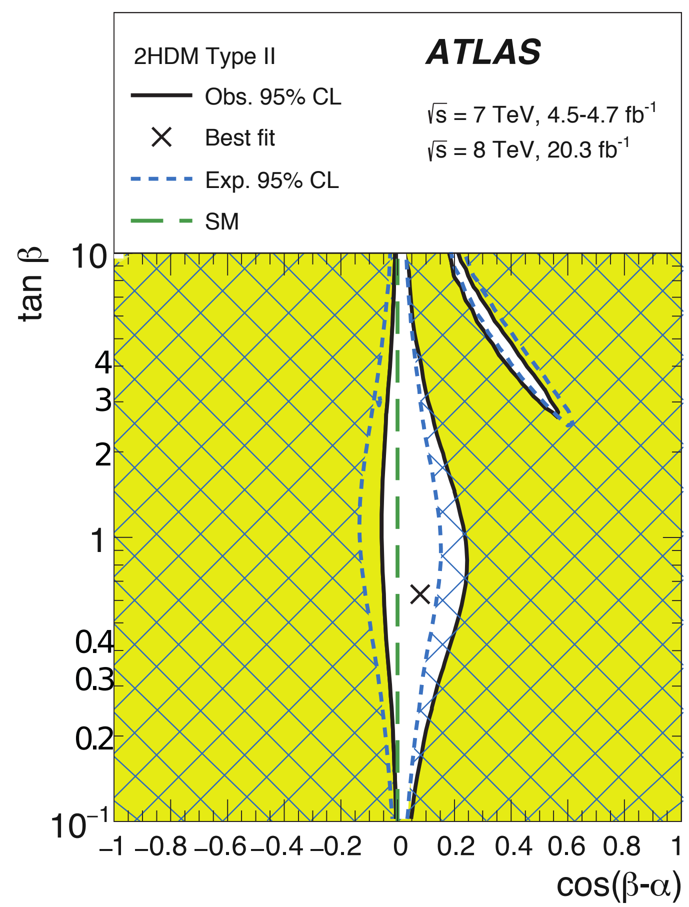


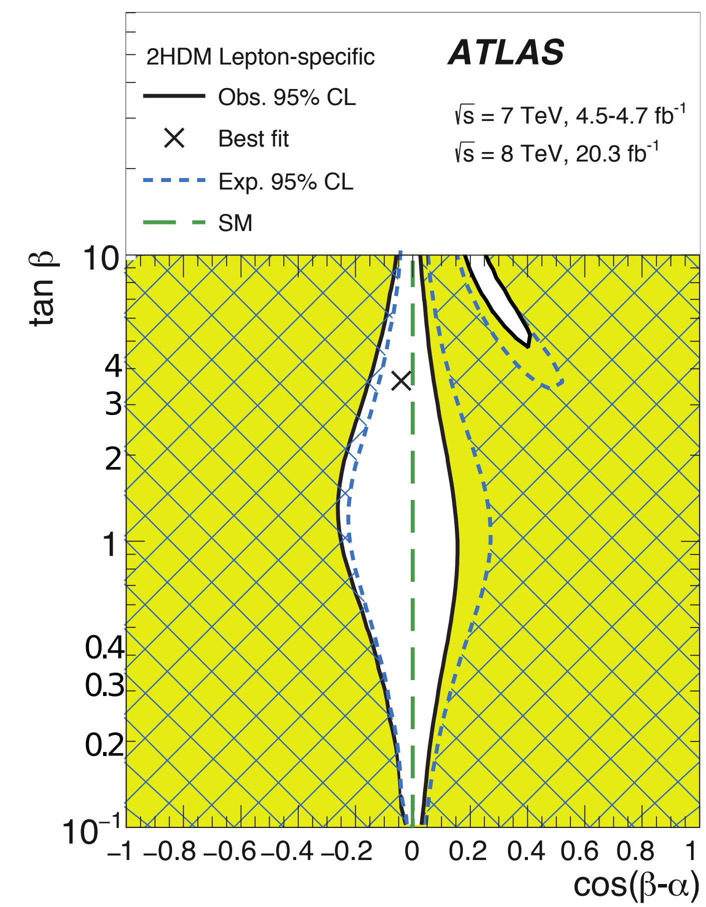
Coupling parameterisation (2)

- 2HDM: extension of the SM to 5 Higgs bosons (2 CP-even, 1 CP-odd, 2 charged)
- *h = lightest CP-even*. Can parameterise deviation of couplings as a function of 2 mixing parameters

	2HDM type I	type II	Type III	Type IV
κ_V	$\sin(\beta-\alpha)$	$\sin(\beta-\alpha)$	$\sin(\beta-\alpha)$	$\sin(\beta-\alpha)$
κ_u	$\cos(\alpha)/\sin(\beta)$	$\cos(\alpha)/\sin(\beta)$	$\cos(\alpha)/\sin(\beta)$	$\cos(\alpha)/\sin(\beta)$
κ_d	$\cos(\alpha)/\sin(\beta)$	$-\sin(\alpha)/\cos(\beta)$	$\cos(\alpha)/\sin(\beta)$	$-\sin(\alpha)/\cos(\beta)$
κ_ℓ	$\cos(\alpha)/\sin(\beta)$	$-\sin(\alpha)/\cos(\beta)$	$-\sin(\alpha)/\cos(\beta)$	$\cos(\alpha)/\sin(\beta)$



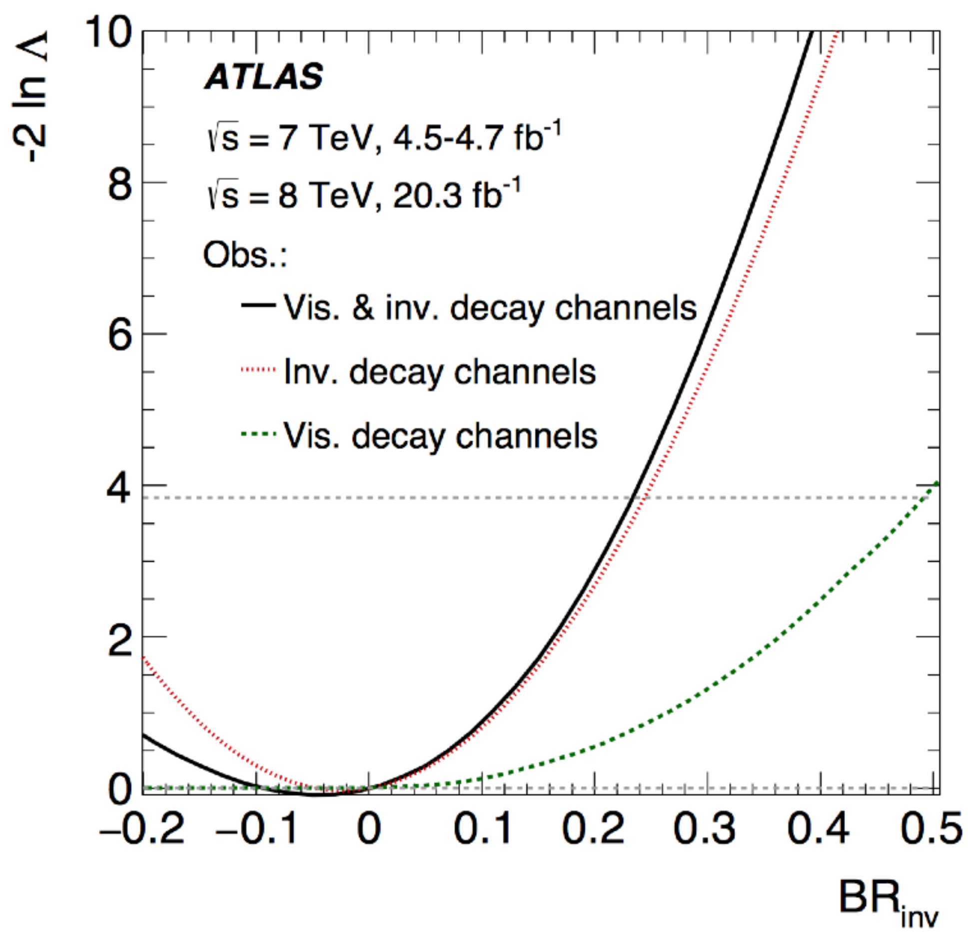




- Express production and decay of Higgs boson in terms of simple modifiers of couplings with known SM particles: *assuming that effect of new physics modifies the rate but not the type of interaction*

Production	Loops	Interference	Expression in fundamental coupling-strength s	
$\sigma(ggF)$	✓	b–t	$\kappa_g^2 \sim$	$1.06 \cdot \kappa_t^2 + 0.01 \cdot \kappa_b^2 - 0.07 \cdot \kappa_t \kappa_b$
$\sigma(VBF)$	-	-	$\sim$	$0.74 \cdot \kappa_W^2 + 0.26 \cdot \kappa_Z^2$
$\sigma(WH)$	-	-	$\sim$	κ_W^2
$\sigma(q\bar{q} \to ZH)$	-	-	$\sim$	κ_Z^2
$\sigma(gg \to ZH)$	✓	Z–t	$\kappa_{ggZH}^2 \sim$	$2.27 \cdot \kappa_Z^2 + 0.37 \cdot \kappa_t^2 - 1.64 \cdot \kappa_Z \kappa_t$
$\sigma(bbH)$	-	-	$\sim$	κ_b^2
$\sigma(ttH)$	-	-	$\sim$	κ_t^2

Partial decay width				
$\Gamma_{b\bar{b}}$	-	-	$\sim$	κ_b^2
Γ_{WW}	-	-	$\sim$	κ_W^2
Γ_{ZZ}	-	-	$\sim$	κ_Z^2
$\Gamma_{\tau\tau}$	-	-	$\sim$	κ_τ^2
$\Gamma_{\mu\mu}$	-	-	$\sim$	κ_μ^2
$\Gamma_{\gamma\gamma}$	✓	W–t	$\kappa_\gamma^2 \sim$	$1.59 \cdot \kappa_W^2 + 0.07 \cdot \kappa_t^2 - 0.66 \cdot \kappa_W \kappa_t$
$\Gamma_{Z\gamma}$	✓	W–t	$\kappa_{Z\gamma}^2 \sim$	$1.12 \cdot \kappa_W^2 + 0.00035 \cdot \kappa_t^2 - 0.12 \cdot \kappa_W \kappa_t$
Total decay width				
Γ_H	✓	$W-t$ $b-t$	$\kappa_H^2 \sim$	$0.57 \cdot \kappa_b^2 + 0.22 \cdot \kappa_W^2 + 0.09 \cdot \kappa_g^2 +$ $0.06 \cdot \kappa_\tau^2 + 0.03 \cdot \kappa_Z^2 + 0.03 \cdot \kappa_c^2 +$ $0.0023 \cdot \kappa_\gamma^2 + 0.0016 \cdot \kappa_{Z\gamma}^2 + 0.00022 \cdot \kappa_\mu^2$



- Introducing new parameter for Higgs-to-invisible branching ratio:

$$Br(H\to xx) = \kappa^2_{xx} / \kappa^2_H * (1 - \mathbf{Br_{inv}})$$

- Simultaneous fit to all Higgs boson production and decay measurements can help setting upper limit Br_{inv}:
  - ***Br_{inv}<49% @ 95% CL level***
  - *improving by 10%* the limit from direct H->invisible searches …. and making it less model dependent

The push for high p_T: theory

"***Sensitivity*** might not require extreme ***Precision***"

M. Mangano's talk

$$\delta O_Q \sim \left(\frac{Q}{\Lambda}\right)^2$$

size of deviation — δO_Q

scale of your analysis — Q

NP scale — Λ

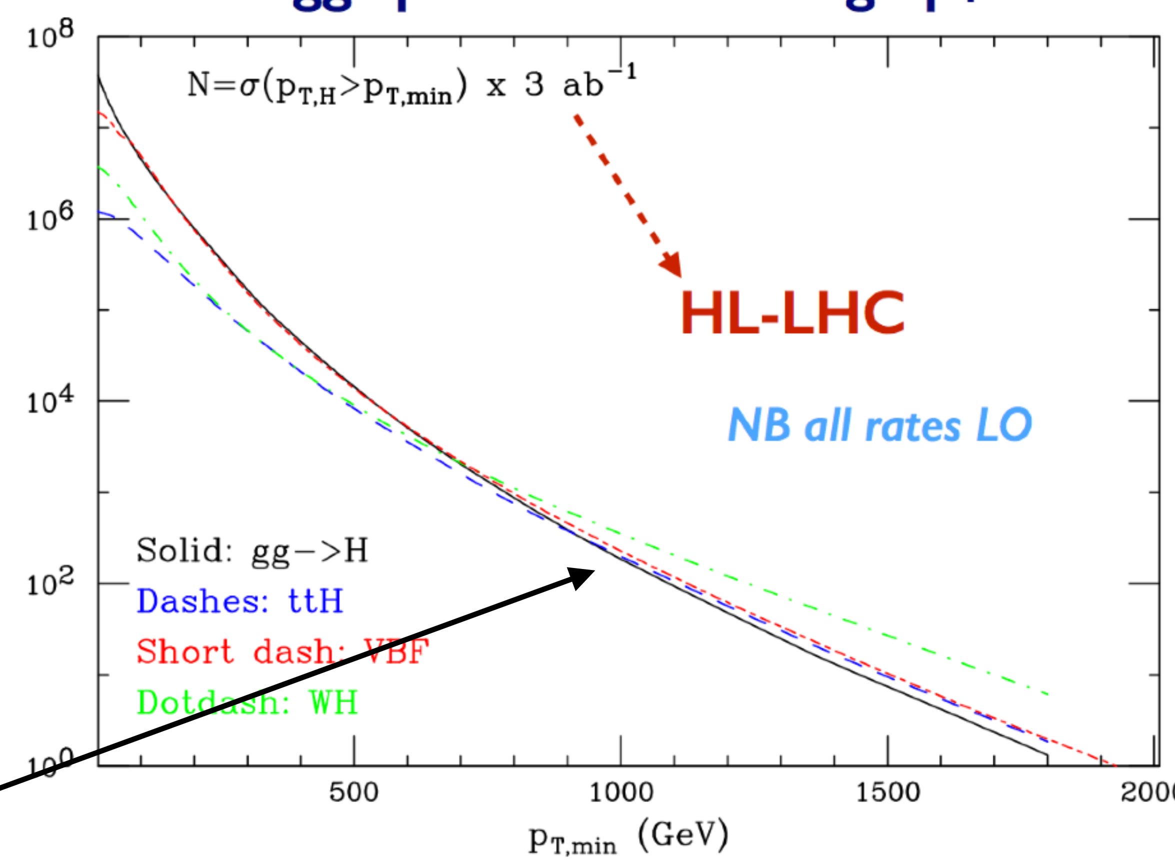
- Probing higher scale in the analysis makes you mode ***sensitive*** to NP therefore you can afford to be less **precise**

- One example:
  - *3% uncertainty for p_T>150GeV : probes scales up to 890 GeV*
  - *10% uncertainty for p_T>600GeV : probes scales up to 1800 TeV*
  - *an analysis 3 times less precise has twice the sensitivity*

- High pT VH analysis could become competitive with inclusive H->WW measurement

- ***As Higgs p_T increases, VH becomes more and more competitive with ggF as dominate Higgs production mode***

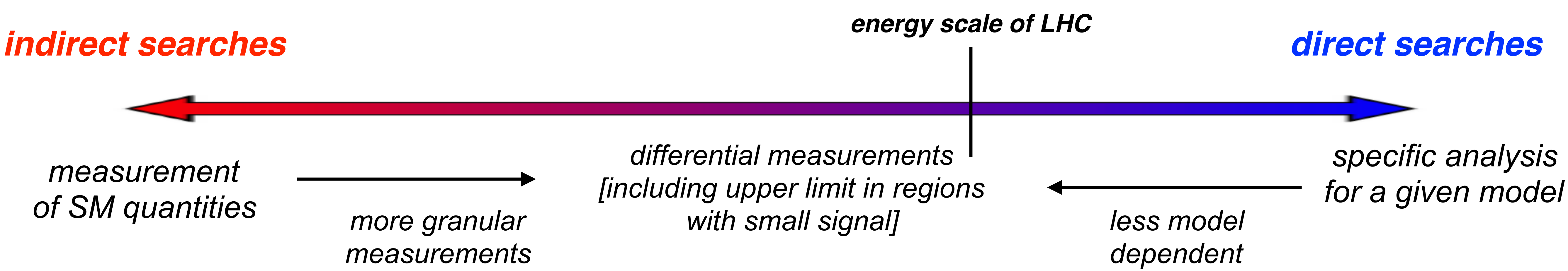
Higgs production at large p_T



H_{bb} as a tool for BSM searches

- ***Direct searches**:*
  - *new physics signature include SM Higgs boson or SM Higgs-boson-like particles in final states:*
  - *consider simplified models as a prototype for a large variety of models: heavy vector triplets, vector-like quarks, Higgs+invisible, SUSY EWK decay chains, di-Higgs resonances*
- ***Indirect searches**:*
  - *modified interaction of Higgs boson can be revealed through deviations of production/decays with respect to SM*
  - *often interpreted in the context of effective field theory (EFT)*

$$\mathcal{L} = \mathcal{L}_{\text{SM}} + \sum_i c_i^{(6)} O_i^{(6)} / \Lambda^2$$



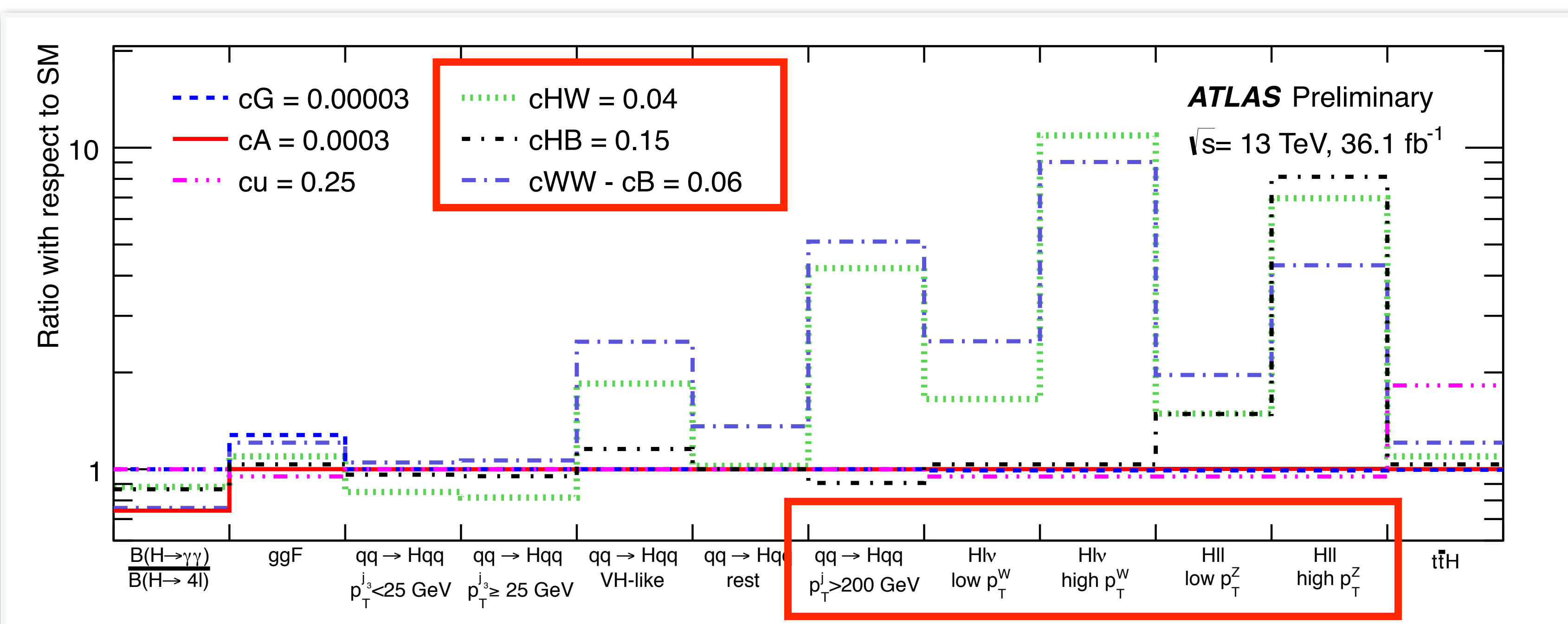
Going more differential: EFT

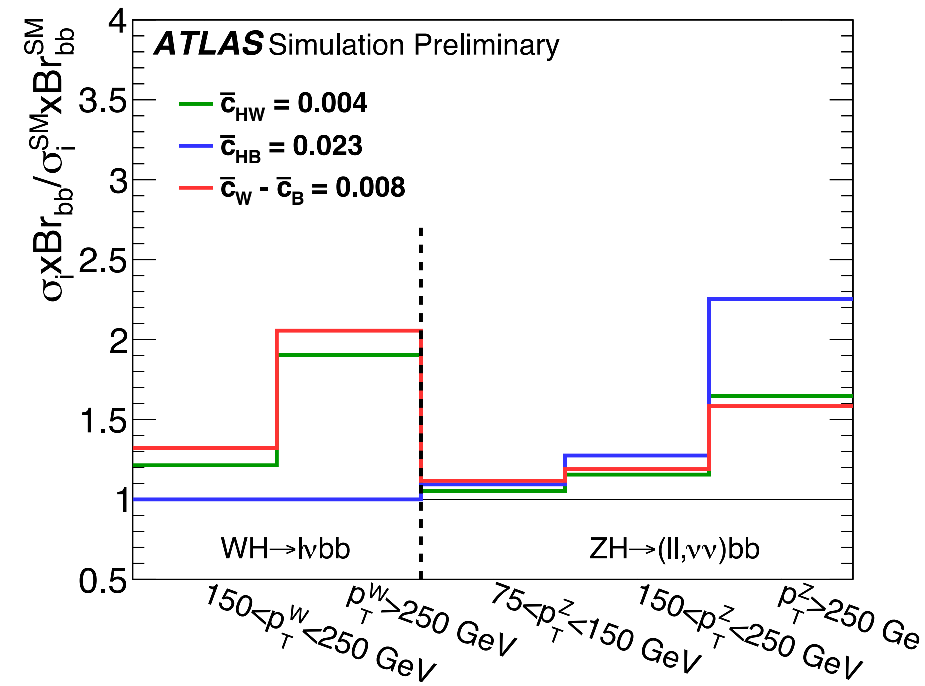
- VH production very sensitive to anomalous Higgs-Vector boson interactions

- ***"Sensitivity" VS "Precision" balance***:
  - *effects are small on quantities we can measure very precisely*
  - *effects are much larger in tails where the precision of the measurements in less high*

7 / 59 dim 6 operators

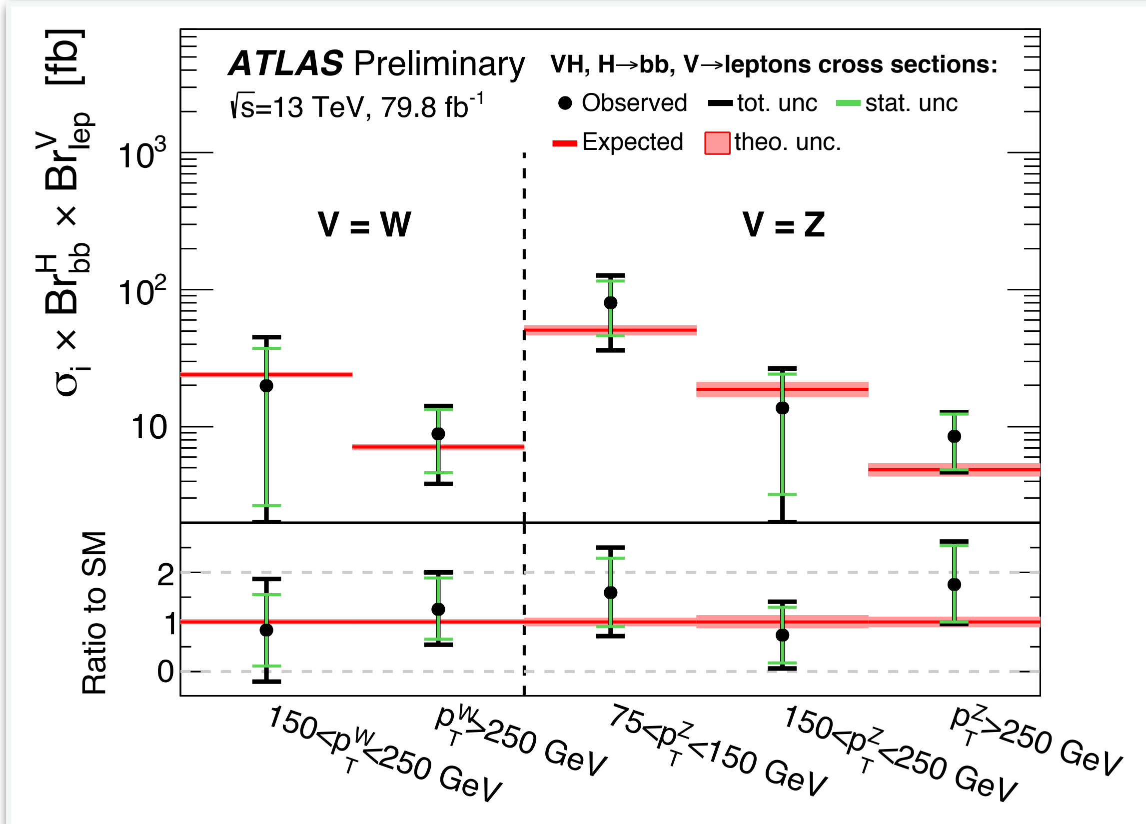
Operator	Expression	HEL coefficient	Vertices
O_g	$\lvert H\rvert^2 G^A_{\mu\nu} G^{A\mu\nu}$	cG $= \frac{m_W^2}{g_s^2}\bar{c}_g$	Hgg
O_γ	$\lvert H\rvert^2 B_{\mu\nu} B^{\mu\nu}$	cA $= \frac{m_W^2}{g'^2}\bar{c}_\gamma$	$H\gamma\gamma, HZZ$
O_u	$y_u \lvert H\rvert^2 \bar{u}_l H u_R +$ h.c.	cu $= v^2 \bar{c}_u$	$Ht\bar{t}$
O_{HW}	$i\,(D^\mu H)^\dagger\, \sigma^a\, (D^\nu H)\, W^a_{\mu\nu}$	cHW $= \frac{m_W^2}{g}\bar{c}_{HW}$	HWW, HZZ
O_{HB}	$i\,(D^\mu H)^\dagger\, (D^\nu H)\, B_{\mu\nu}$	cHB $= \frac{m_W^2}{g'}\bar{c}_{HB}$	HZZ
O_W	$i\,(H^\dagger \sigma^a D^\mu H)\, D^\nu W^a_{\mu\nu}$	cWW $= \frac{m_W^2}{g}\bar{c}_W$	HWW, HZZ
O_B	$i\,(H^\dagger D^\mu H)\, \partial^\nu B_{\mu\nu}$	cB $= \frac{m_W^2}{g'}\bar{c}_B$	HZZ

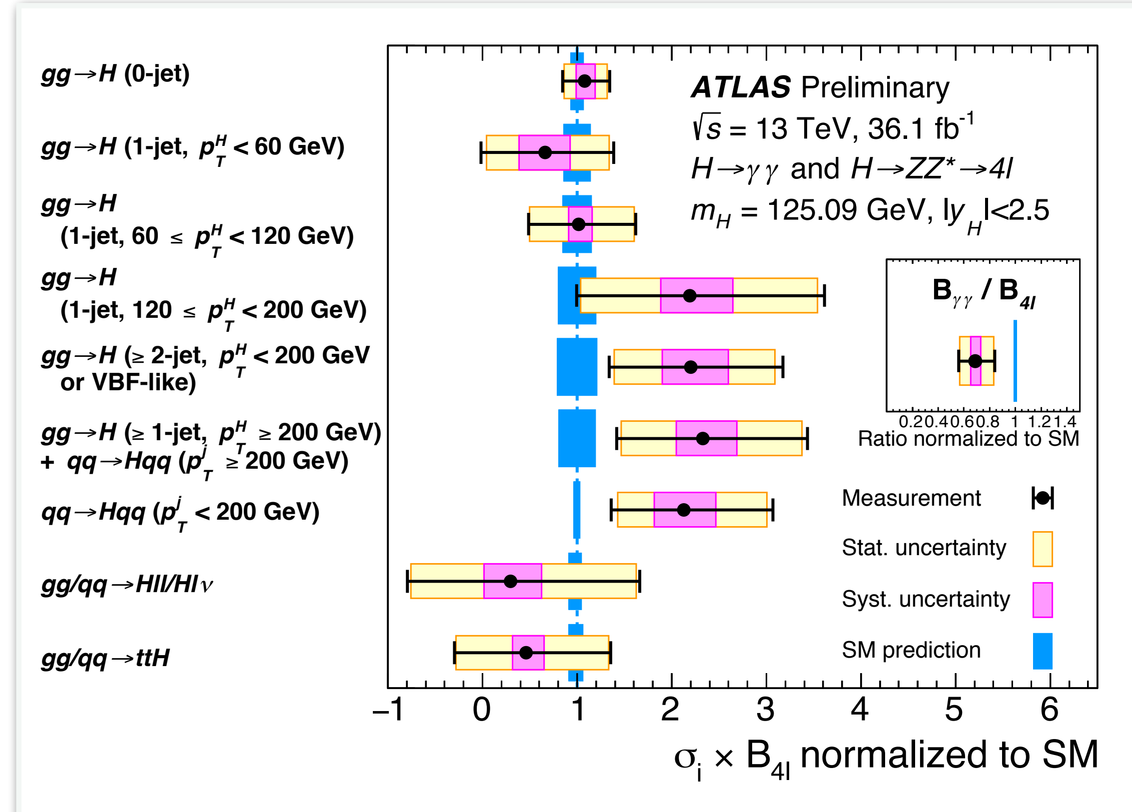


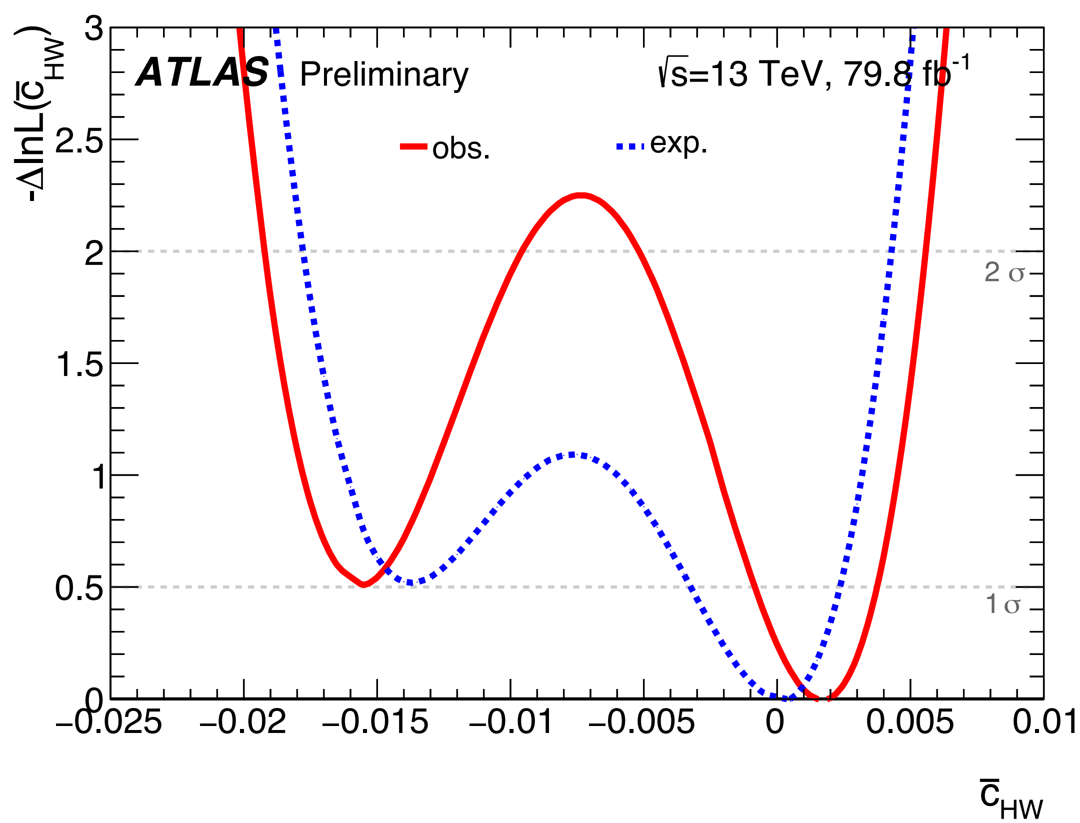


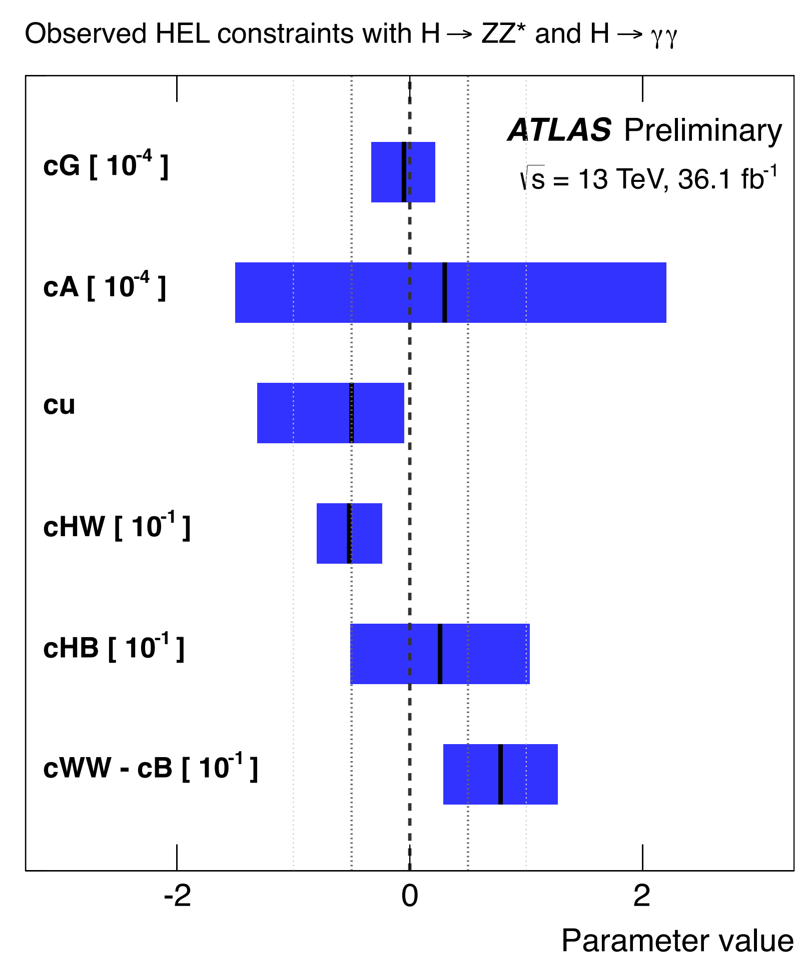
p_T^W>150 *p_T^Z>150*

Going more differential: EFT

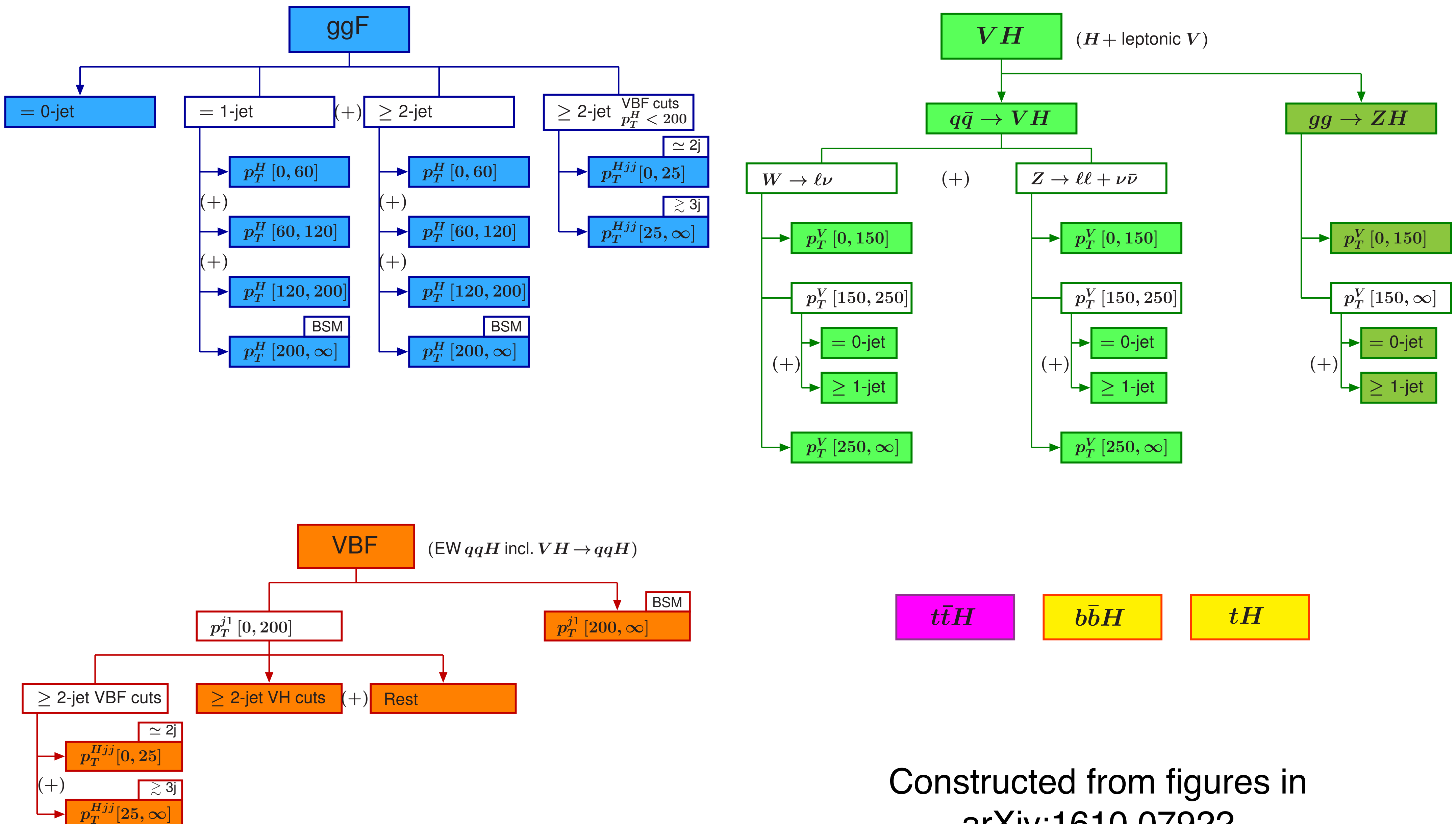








ATLAS Preliminary

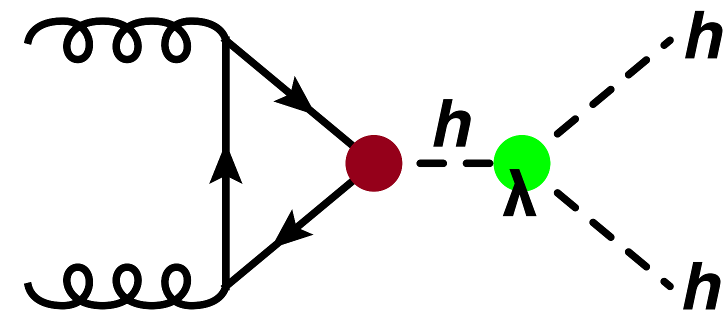


Constructed from figures in
arXiv:1610.07922

Di-Higgs combination

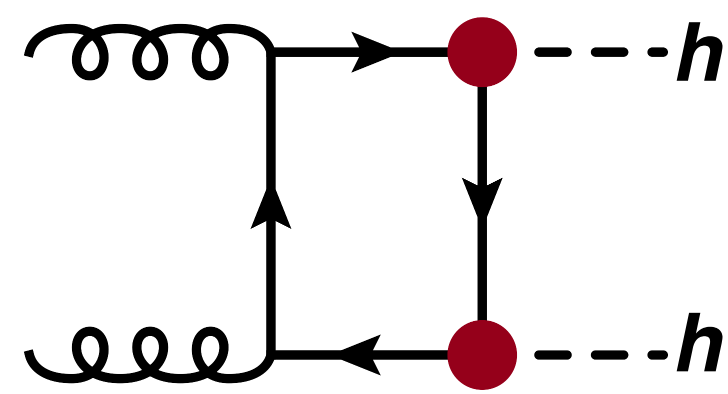
Ultimate goal is the measurement of Higgs boson self coupling:

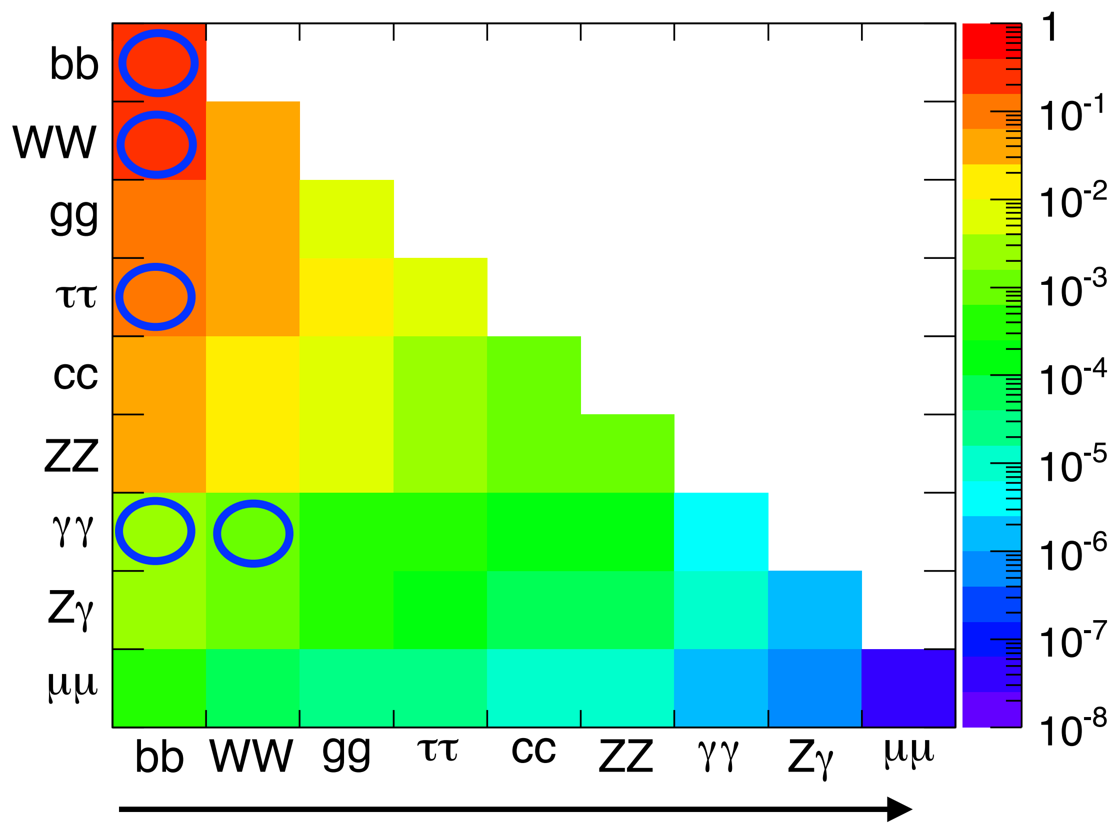
- SM process (σ_{HH}=33fb) way out of reach for current analyses also due to negative interference with "non resonant" production
- Run1 result: σ_{HH}<690 fb



Still many new physics models (2HDM, graviton) ***predict resonant and non resonant enhancement of di-Higgs production:***

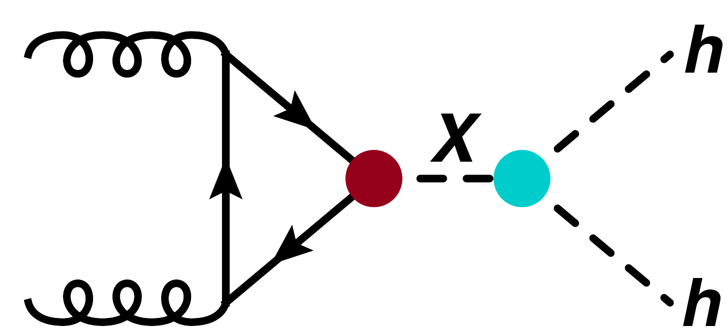
- SM Higgs boson as extra handle to assess presence of new physics
- sensitivity to anomalous triboson coupling: λ



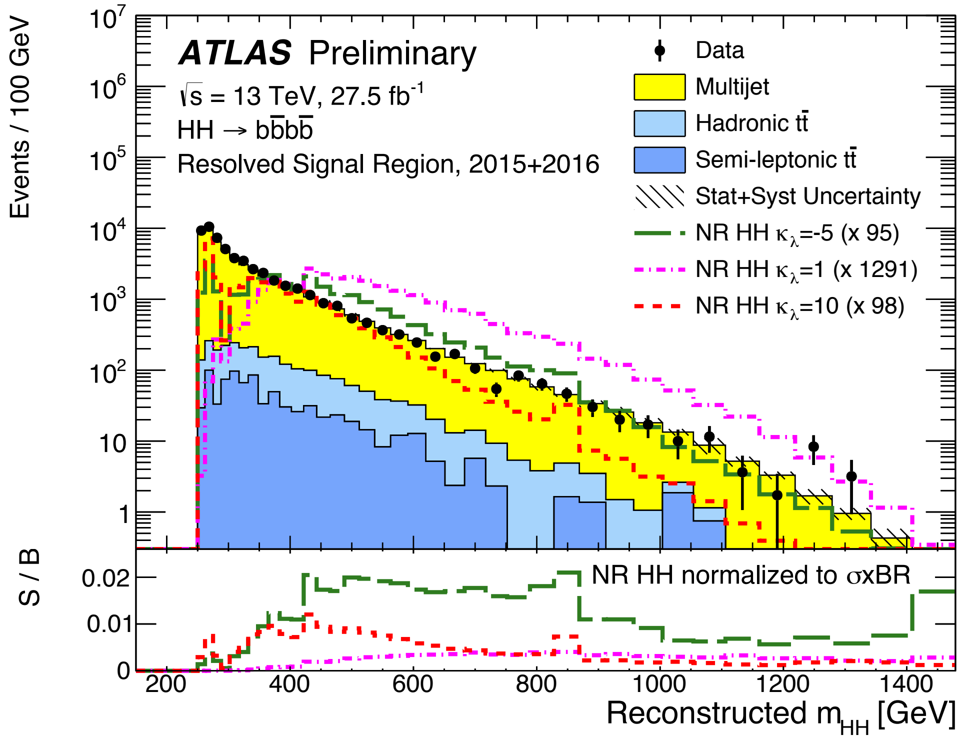


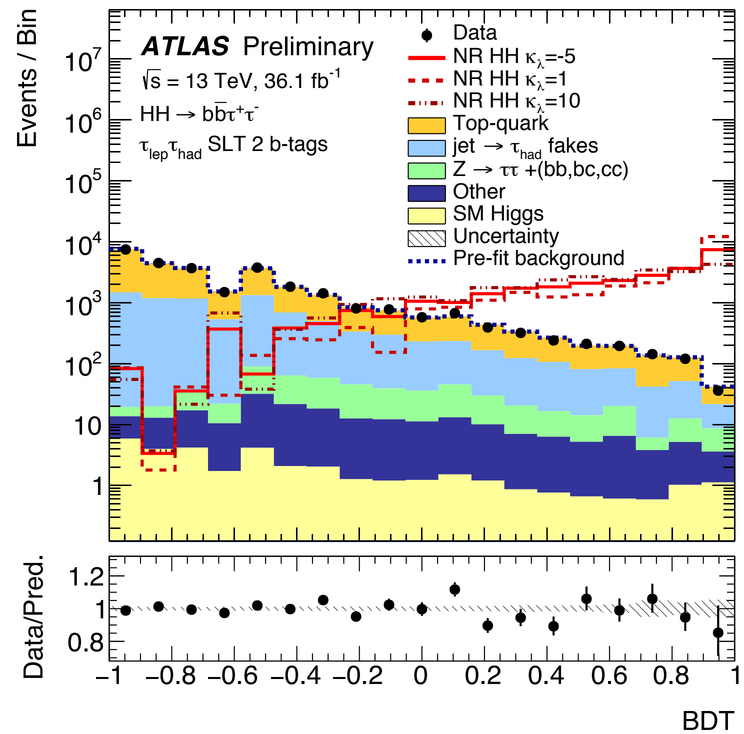
lower background

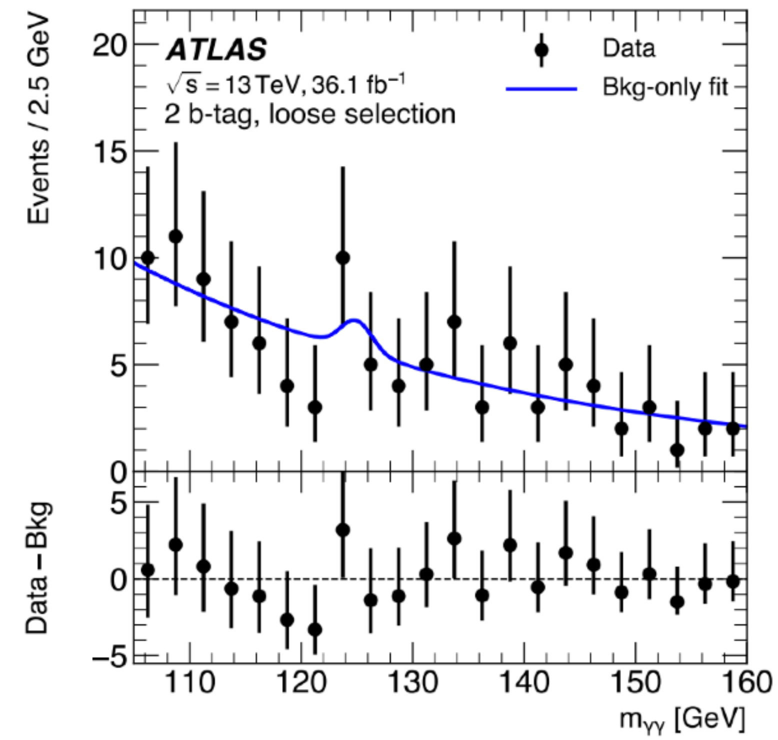
Given the extremely low cross section: ***need to rely to at least one high statistic decay mode***

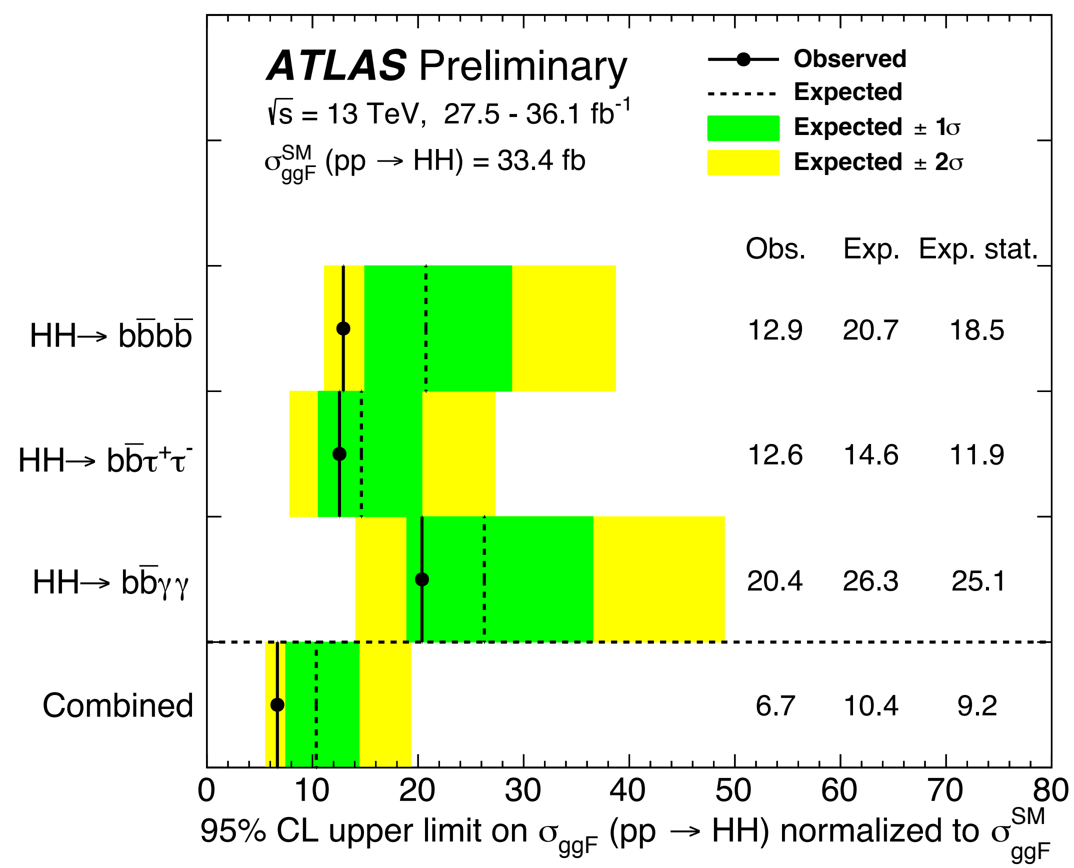


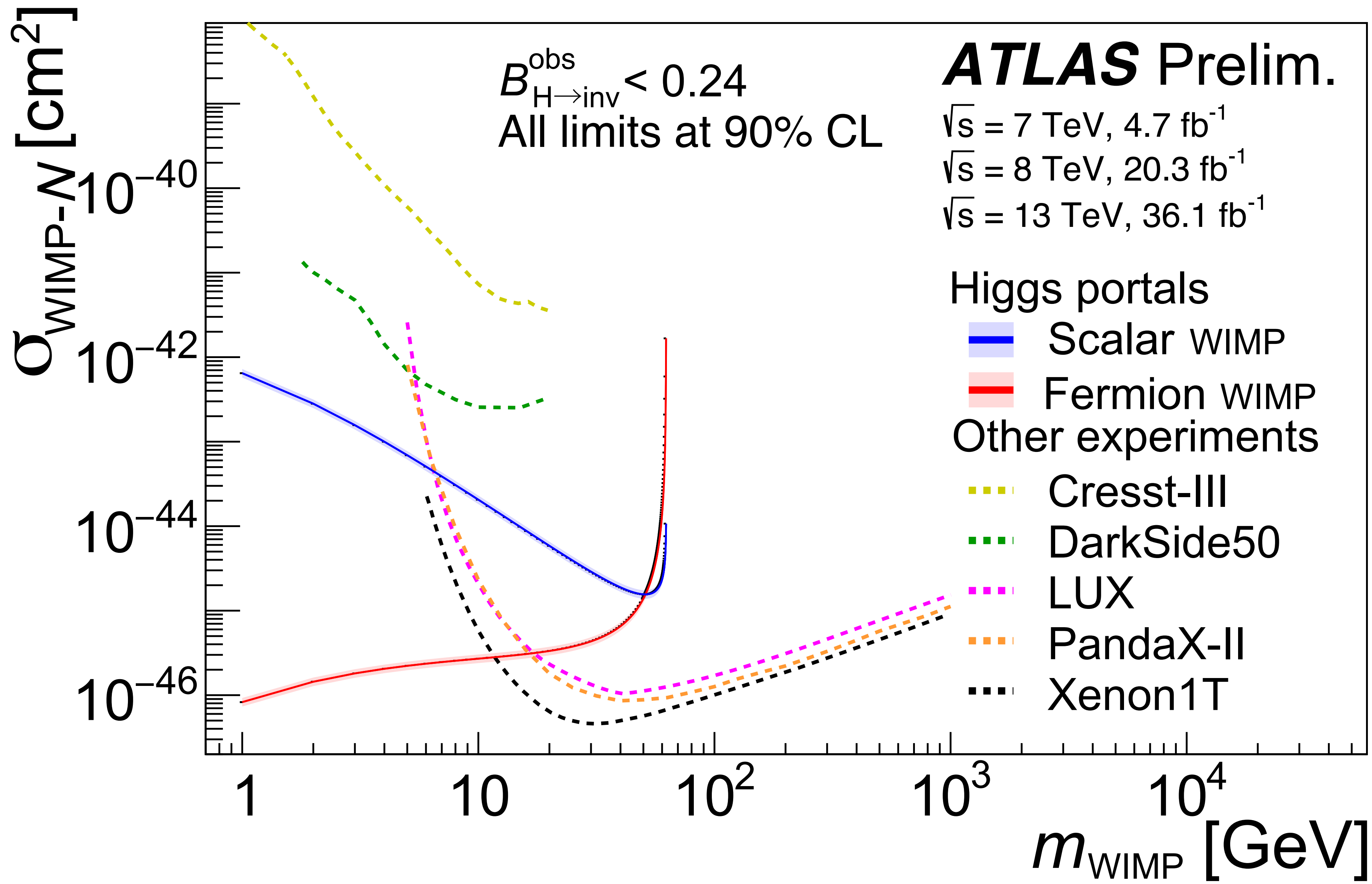
Di-Higgs combination











$B^{obs}_{H\to inv}$ < 0.24
All limits at 90% CL
ATLAS Prelim.
√s = 7 TeV, 4.7 fb-1
√s = 8 TeV, 20.3 fb-1
√s = 13 TeV, 36.1 fb-1
Higgs portals
Scalar WIMP
Fermion WIMP
Other experiments
Cresst-III
DarkSide50
LUX
PandaX-II
Xenon1T
$\sigma_{\text{WIMP-}N}$ [cm^2]
10^{-40}
10^{-42}
10^{-44}
10^{-46}
1
10
10^2
10^3
10^4
m_{WIMP} [GeV]