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Latest status of the Higgs measurement with the ATLAS detector

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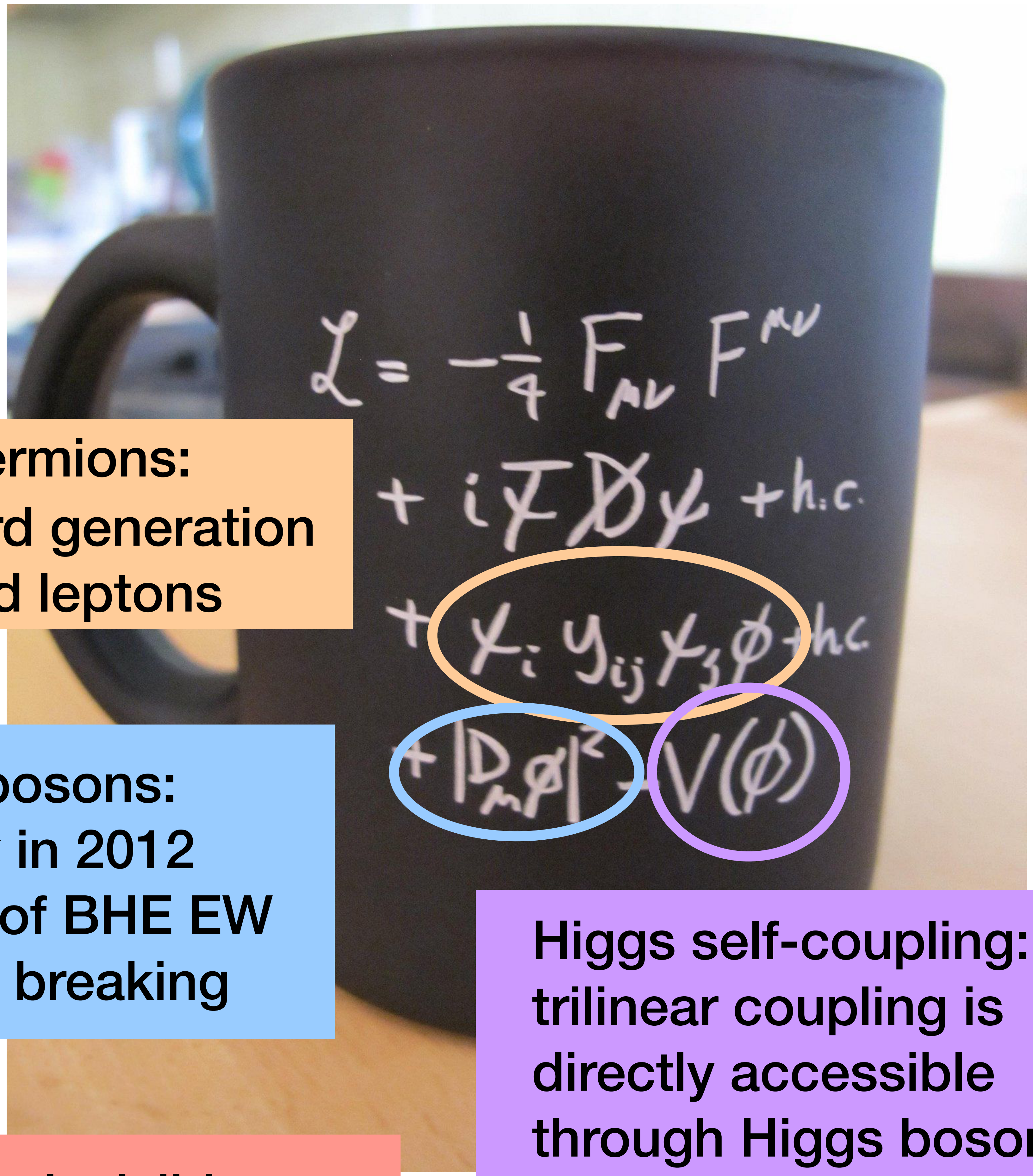
Online Seminar Talk at USTC

Apr. 15th, 2022

Introduction

- A central feature of the SM is the existence of a spineless quantum field that permeates the universe and gives mass to massive elementary particles
- One of main goals of particle physics is testing the existence and properties of the Higgs boson
- Three types of interactions (“couplings”) between Higgs and massive particles:
  - Gauge couplings to the mediator of the weak force, the W and Z bosons
  - The Yukawa interaction to fermions
  - “Self-couplings” of the Higgs to itself
- Experimental determination of these couplings
  - A powerful test of nature of Higgs
  - A possible portal to new physics (coupling structure)



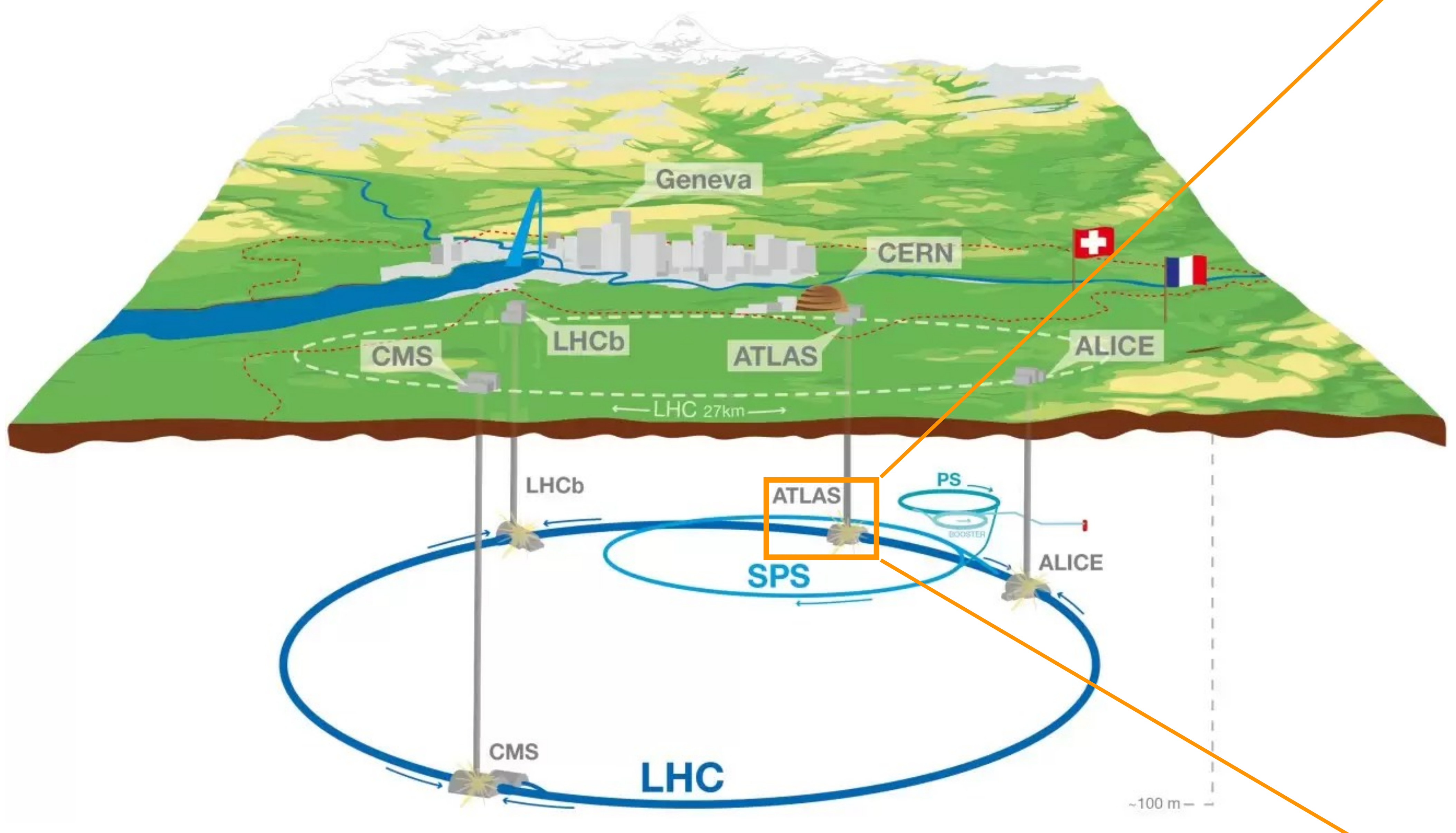
Higgs to fermions:
2nd and 3rd generation Quarks and leptons

Higgs to bosons:
Discovery in 2012
Evidence of BHE EW symmetry breaking

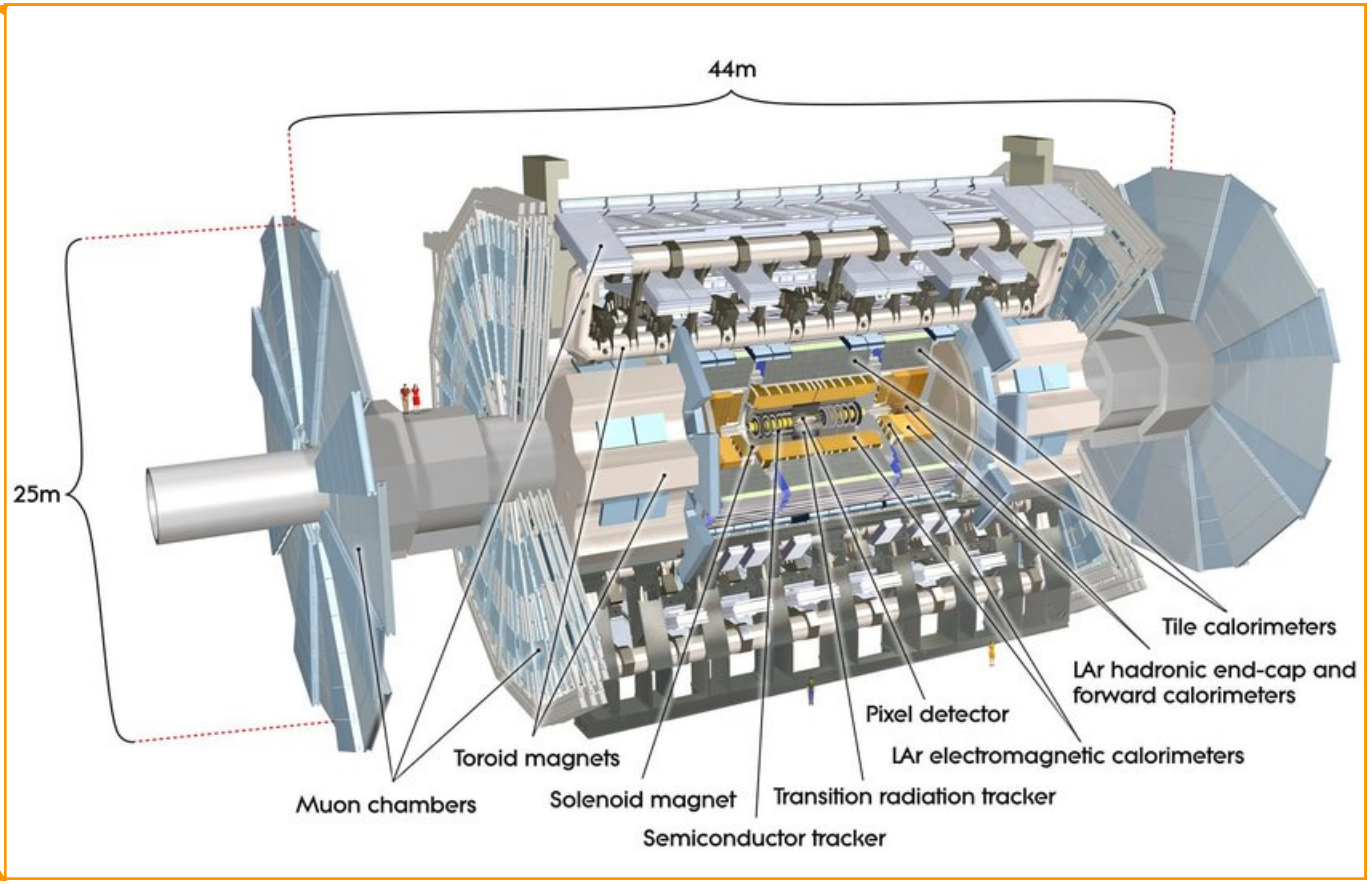
Higgs self-coupling:
trilinear coupling is directly accessible through Higgs boson pair production

Higgs to invisible:
Higgs coupling to neutrinos or dark matter?

LHC and ATLAS detector



The world's largest and highest-energy particle collider.



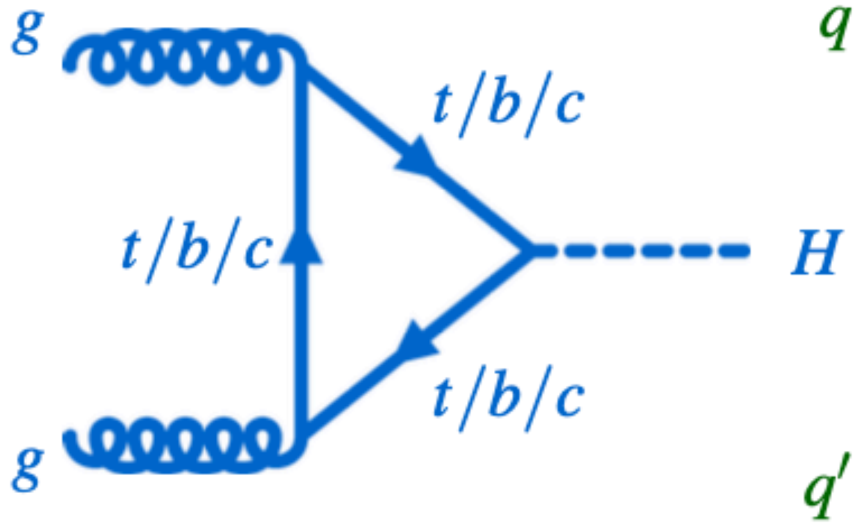
The one of two general-purpose detectors at the LHC

A new schedule for the LHC and its successor

SM Higgs boson production at LHC

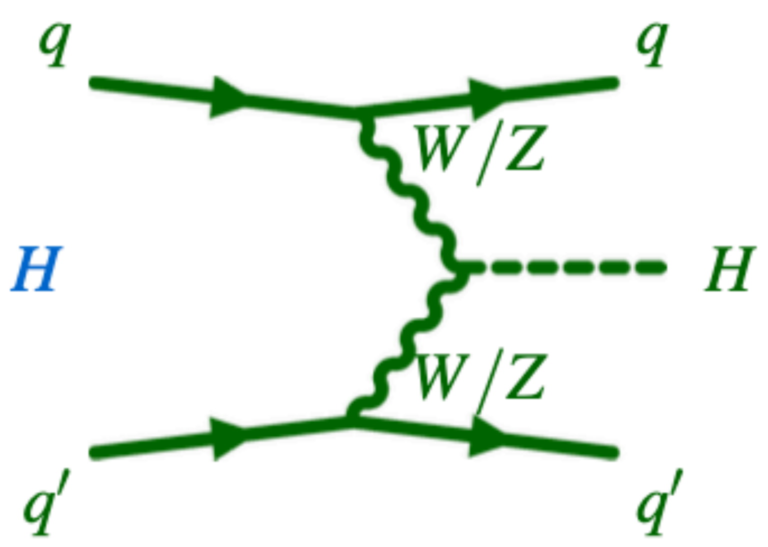
Main

48.5 pb



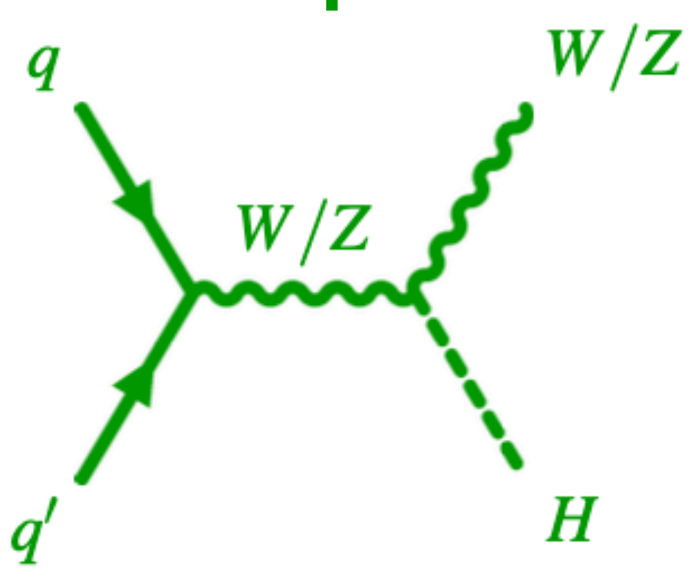
Gluon-fusion ggF (~87%)

3.78 pb



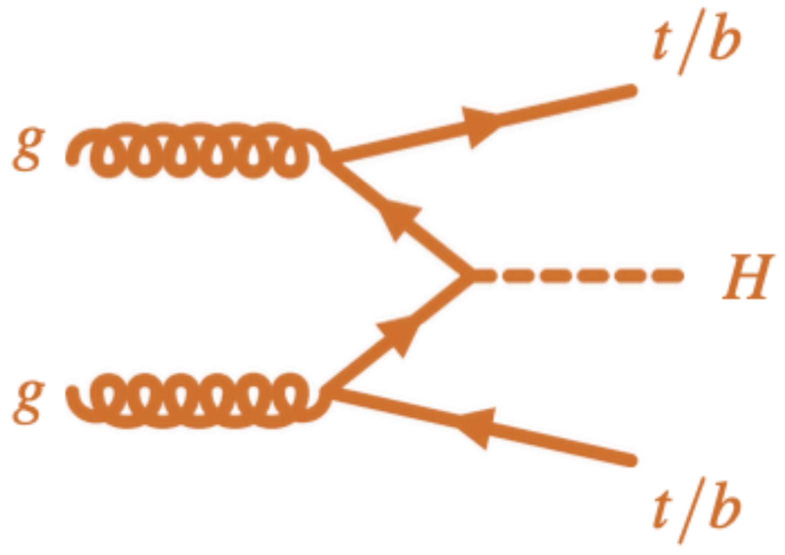
Vector boson fusion (VBF) (~7%)

2.25 pb



VH (~4%)

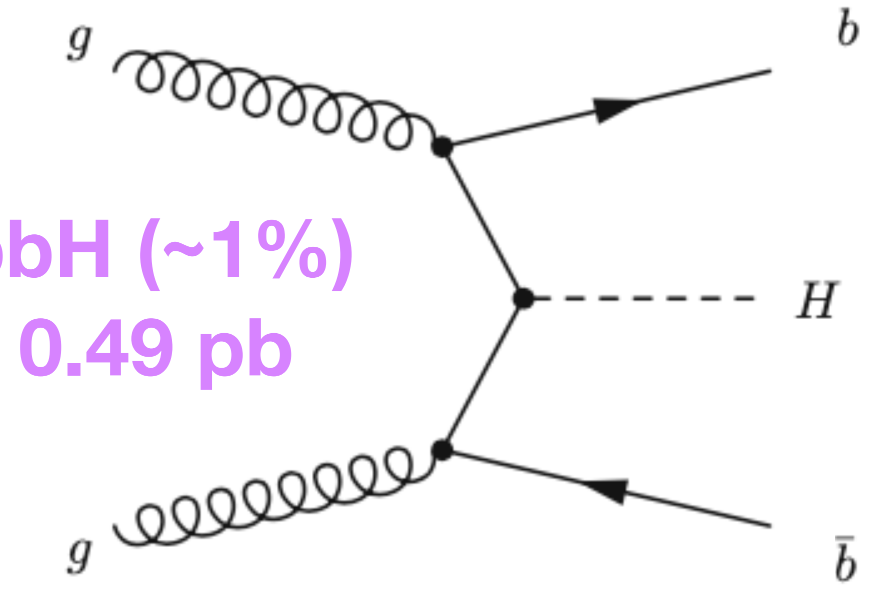
0.51 pb



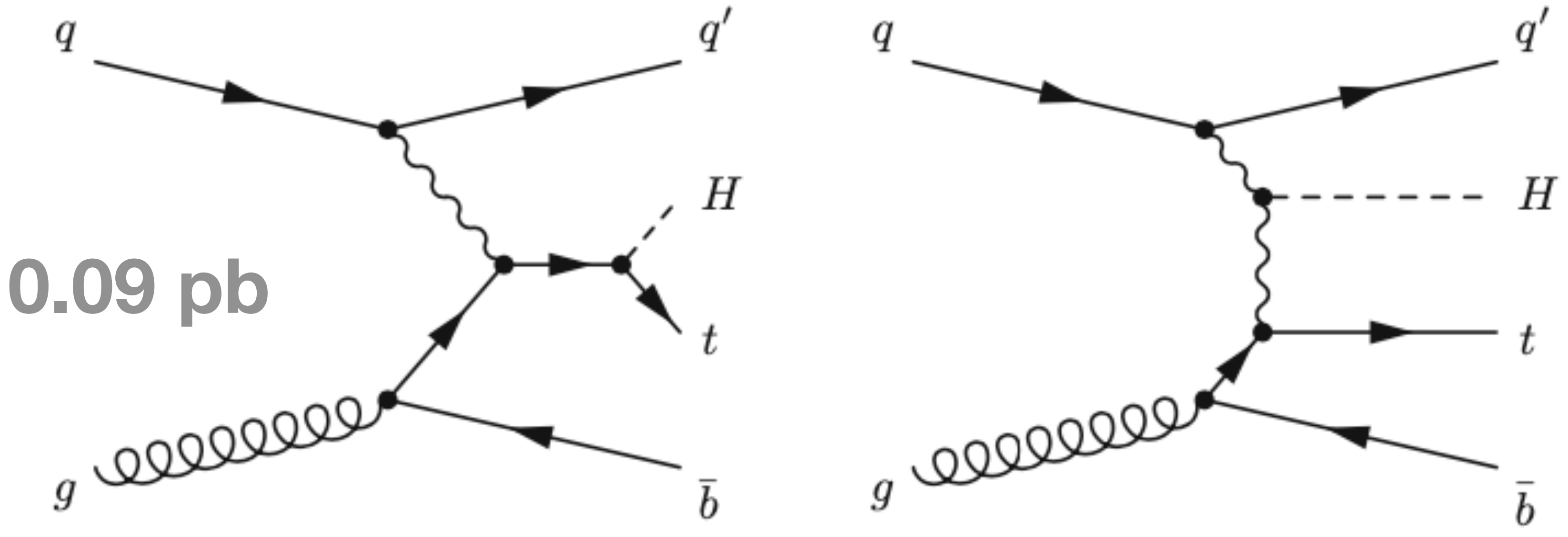
ttH (~1%)

Difficult/Rare

bbH (~1%)
0.49 pb



tH (~0.1%) 0.09 pb

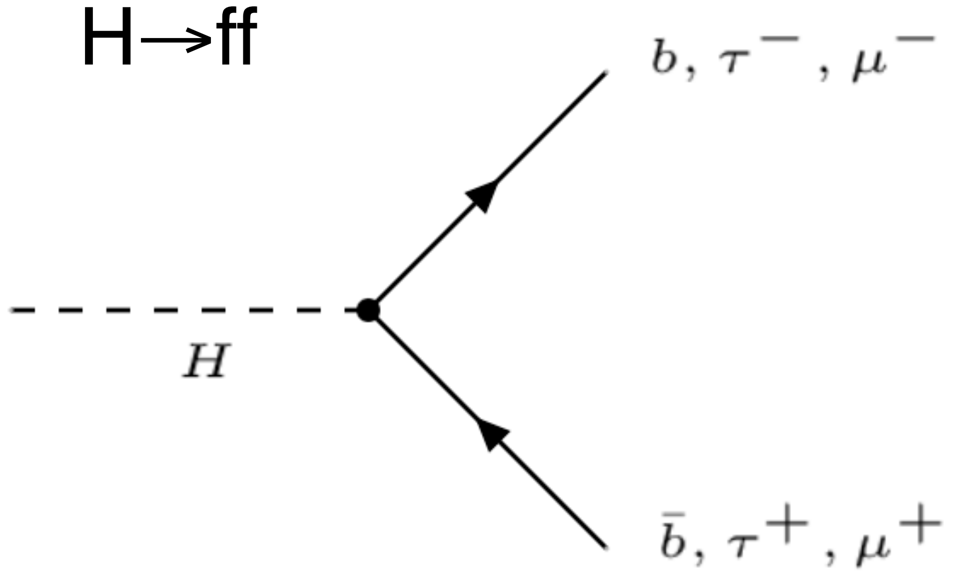


- Distinct topology from many production modes
- Rare/difficult production modes are important for beyond the SM (BSM) scenarios
- Accuracy from theory calculations: inclusive σ (ggF) calculated at N^3LO in QCD and NLO in EW, with 5% uncertainty

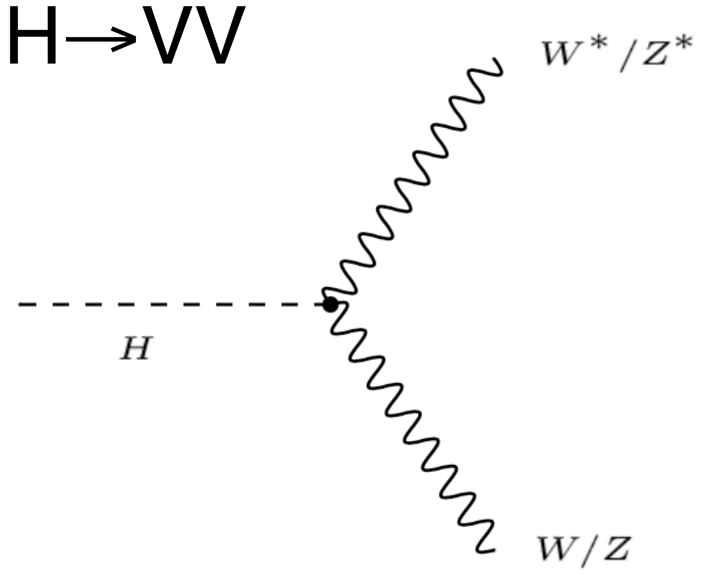
Higgs boson decay

- The SM predicts **4MeV** total width: far below detector resolution!

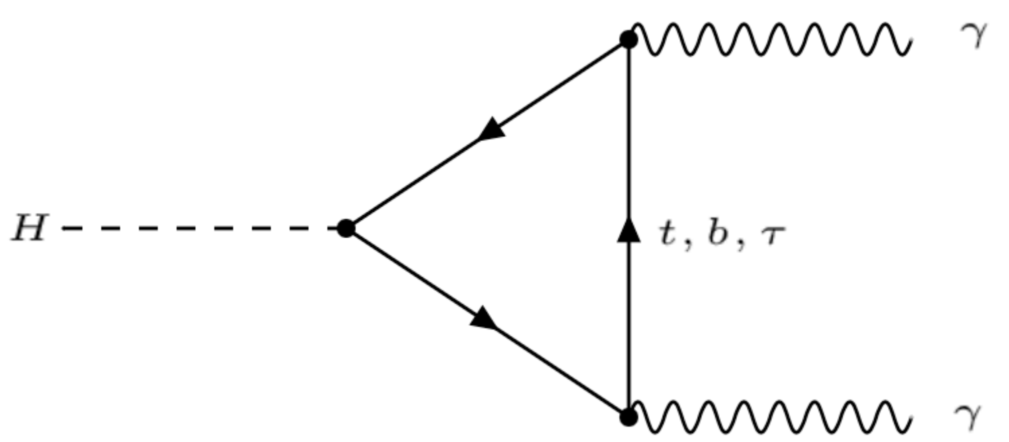
H→ff

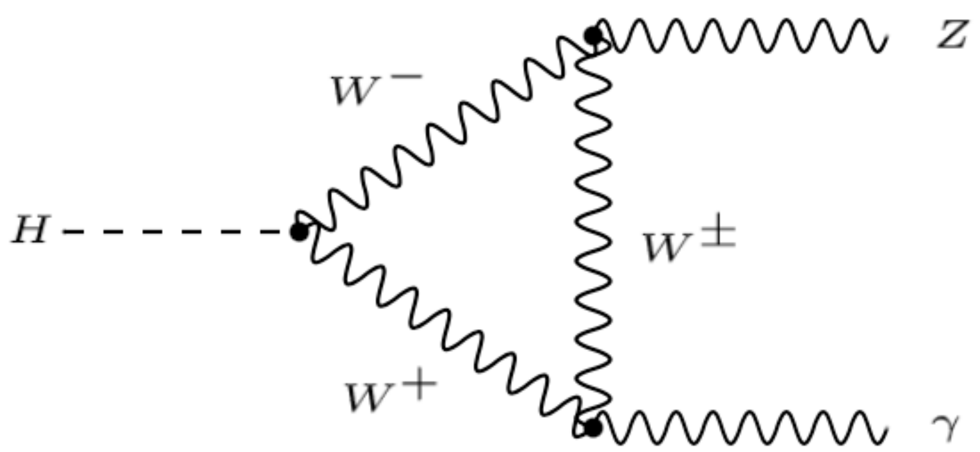


H→VV



H→$\gamma\gamma$/Zγ



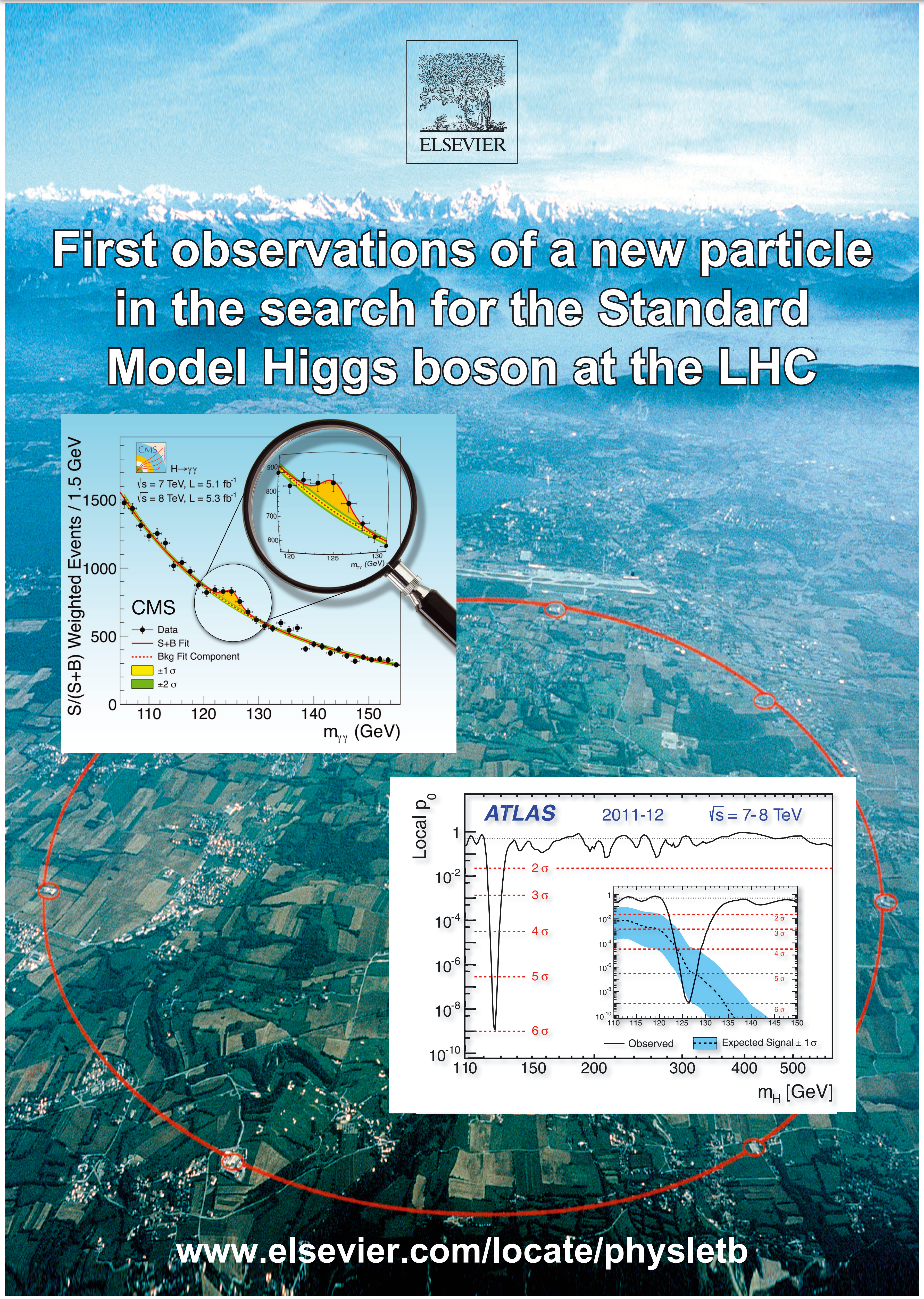


- **Most sensitive decay modes: $\gamma\gamma$, ZZ, WW, $\tau\tau$, bb**
  - High invariant mass resolution in $\gamma\gamma$ and ZZ→4l
- More difficult channels: $\mu\mu$, Zγ, cc,…

Decay channel	SM BR [%] with mH = 125.09 GeV
H→bb	58.1
H→WW	21.5
H→ττ	6.26
H→ZZ	2.64
H→$\gamma\gamma$	0.23
H→μμ	0.022
H→Zγ	0.154
H→cc	2.88
H→gg	8.18

Yellow Report 4

Discovery of SM-like Higgs boson



Nobel Prize 2013

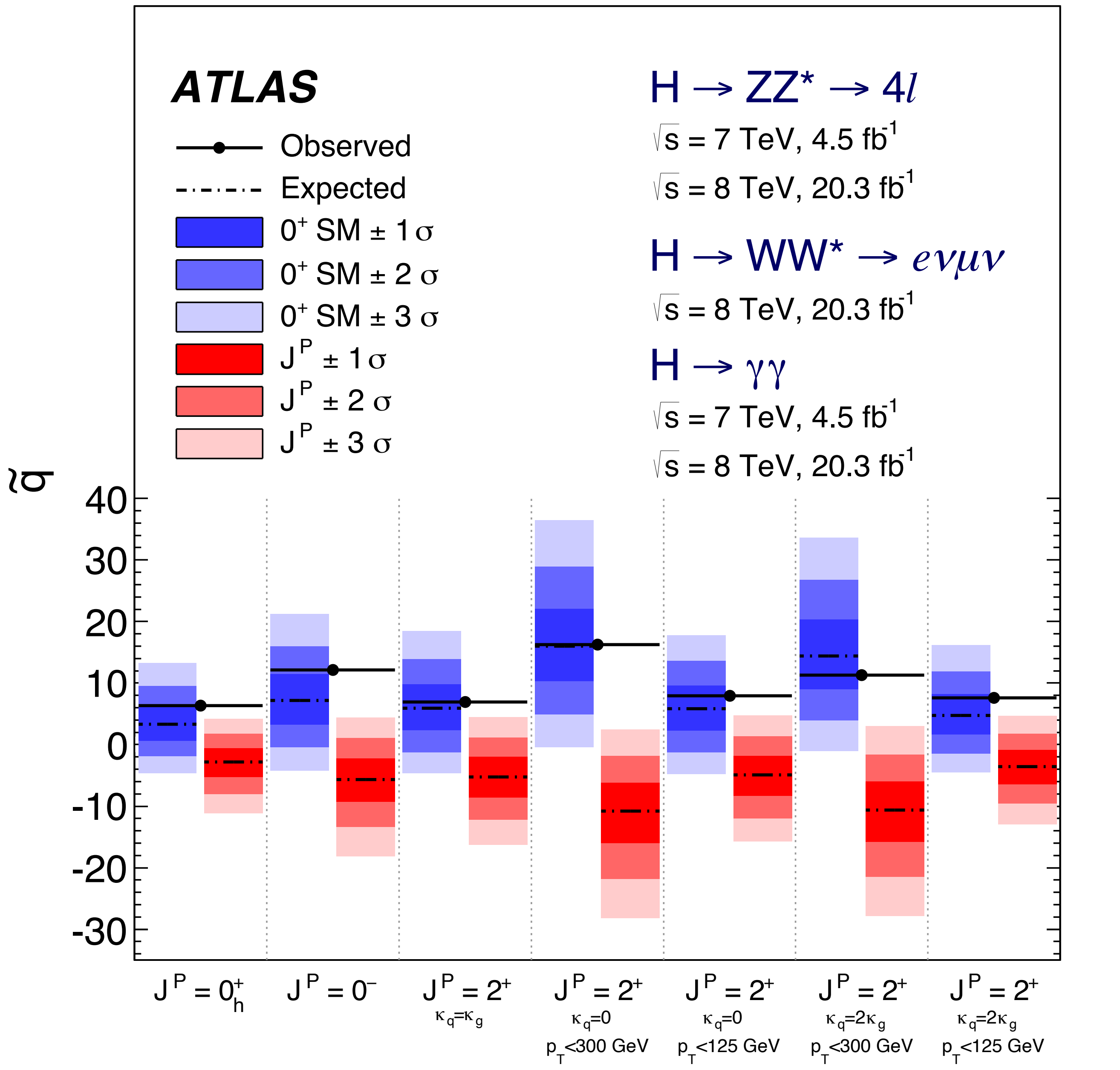
The Nobel Prize in Physics 2013 was awarded jointly to François Englert and Peter W. Higgs "for the theoretical discovery of a mechanism that contributes to our understanding of the origin of mass of subatomic particles, and which recently was confirmed through the discovery of the predicted fundamental particle, by the ATLAS and CMS experiments at CERN's Large Hadron Collider."

Discovery opened a new era of particle physics: detailed measurements of the Higgs sector at the LHC

What we got from Run1 (partial)

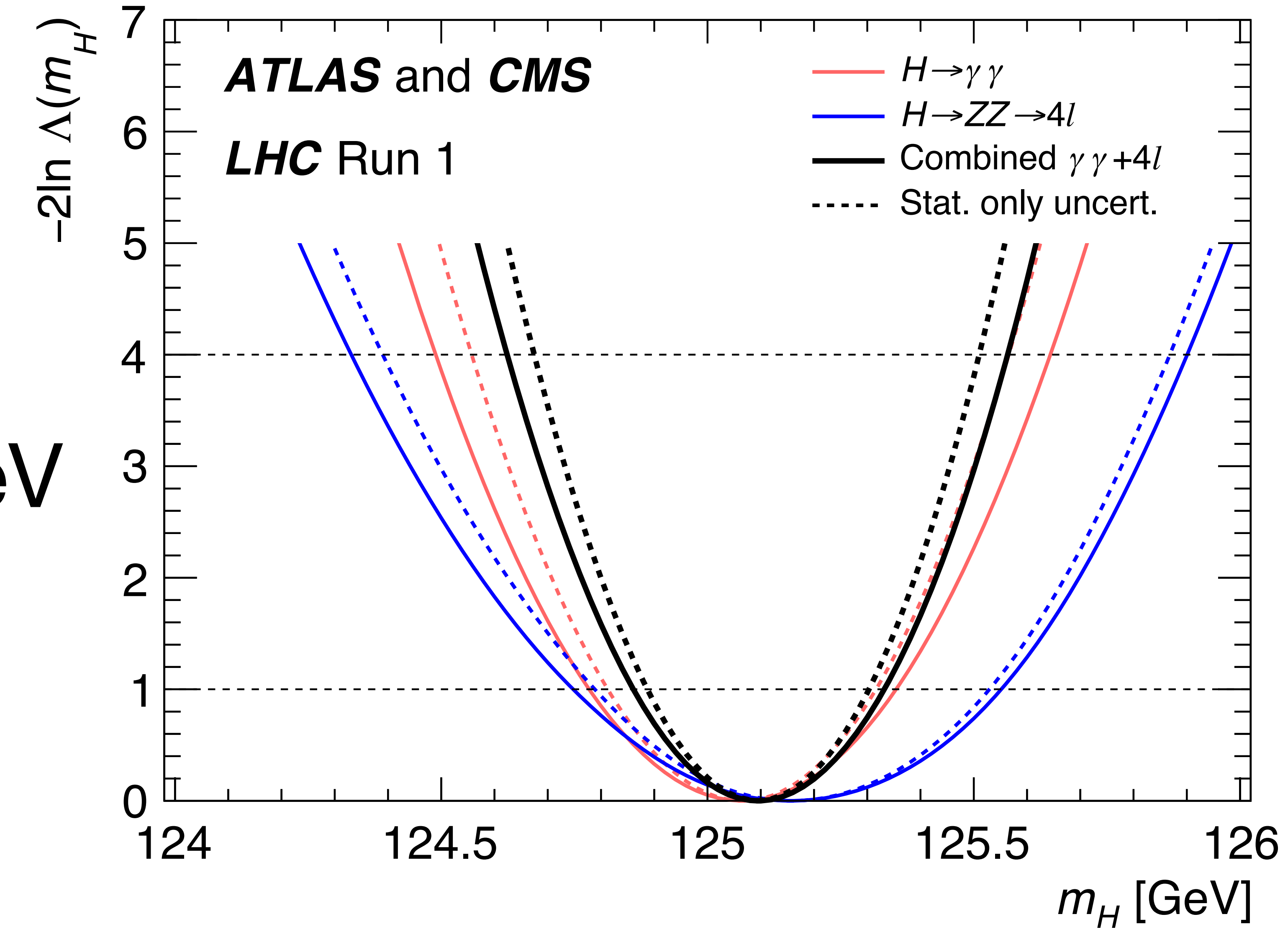
- Spin-0
- Compatible with CP even

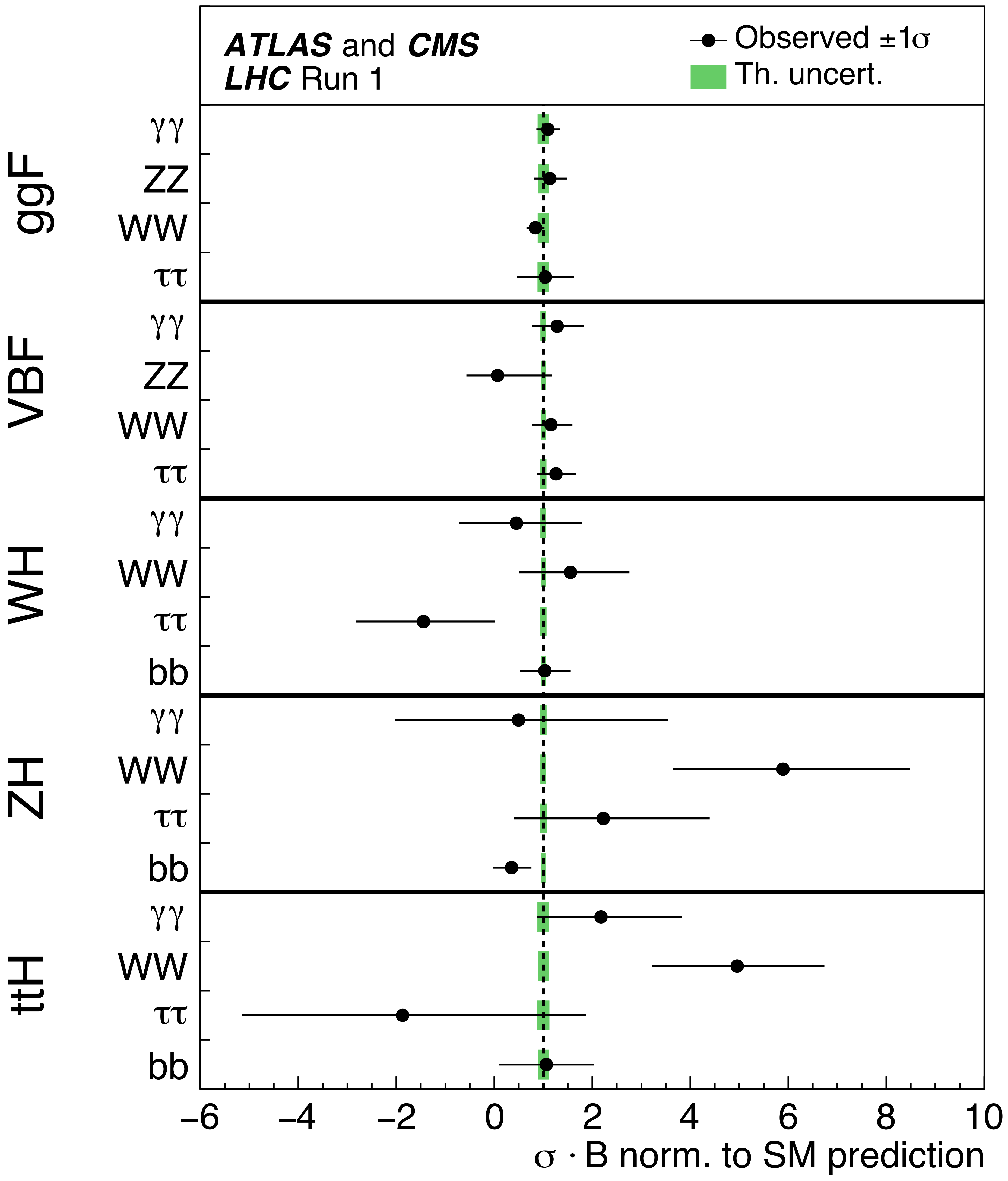
Eur. Phys. J. C 75 (2015) 476



- Mass known
  125.09 ± 0.24 GeV

Phys. Rev. Lett. 114, 191803



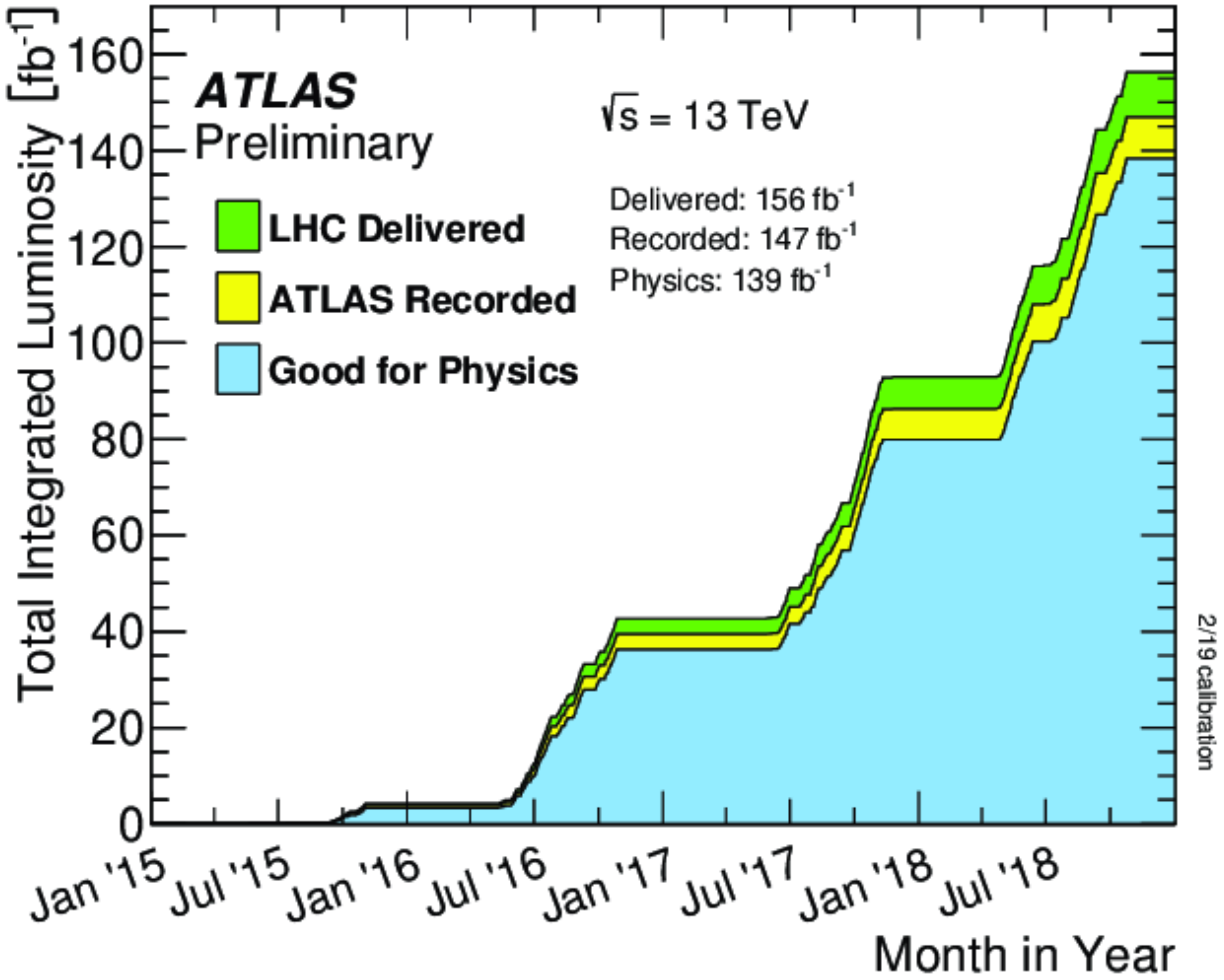


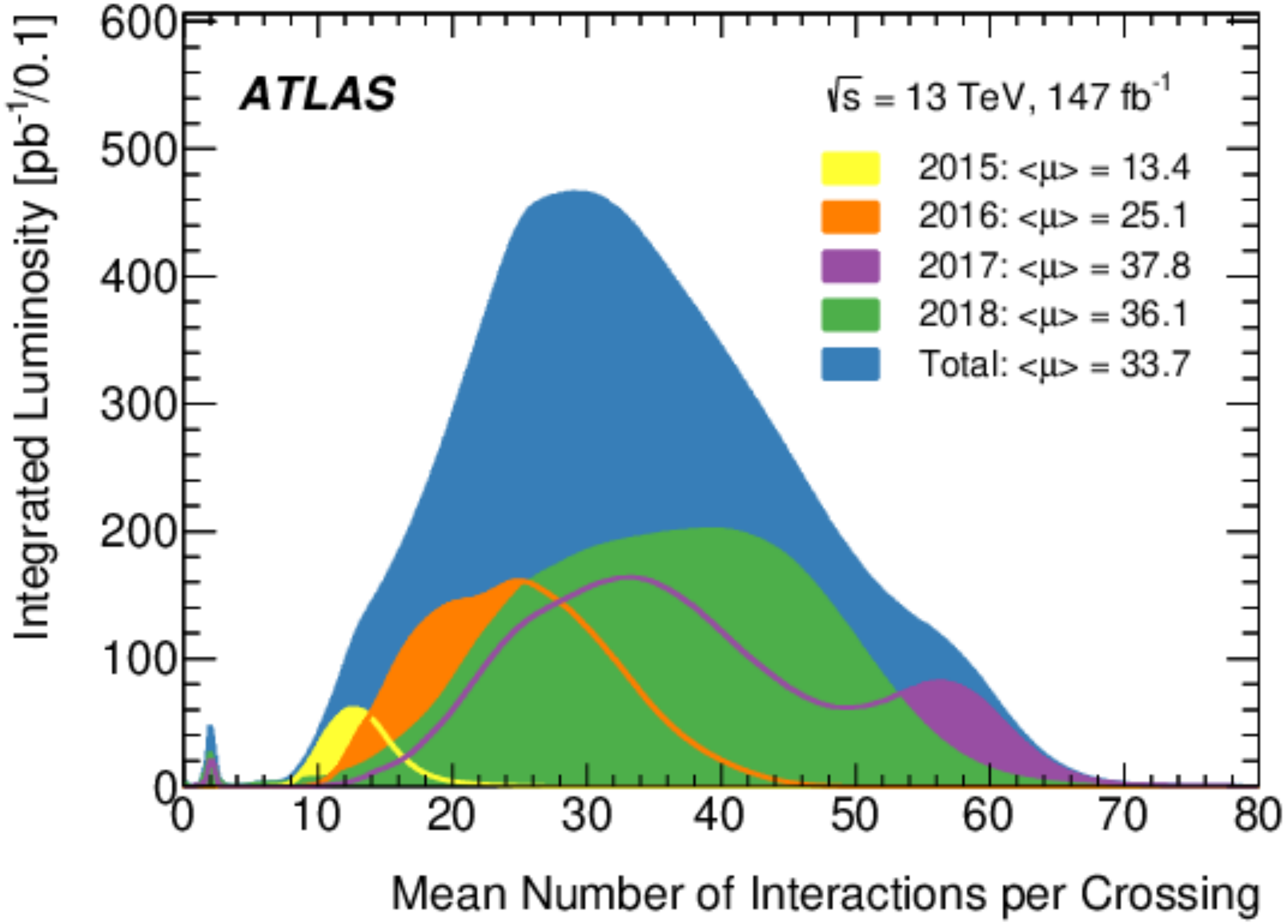
- SM like couplings

JHEP 08 (2016) 045

Run2 data taking

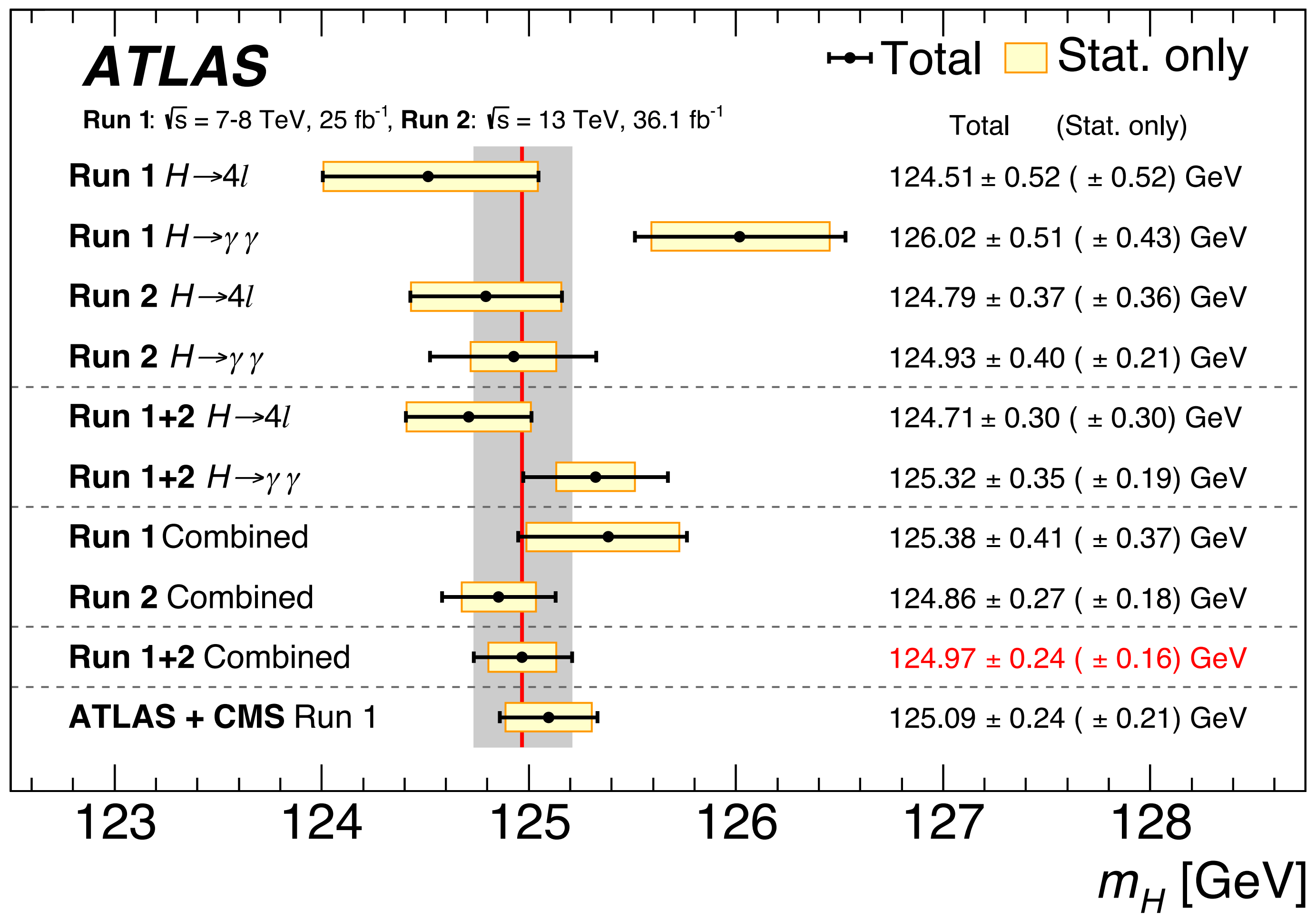
- Run2 data-taking successfully finished in 2018
- 139 fb^{-1} of 13 TeV proton-proton collision data collected by ATLAS in total after data quality (DQ) requirements thanks to the excellent LHC performance





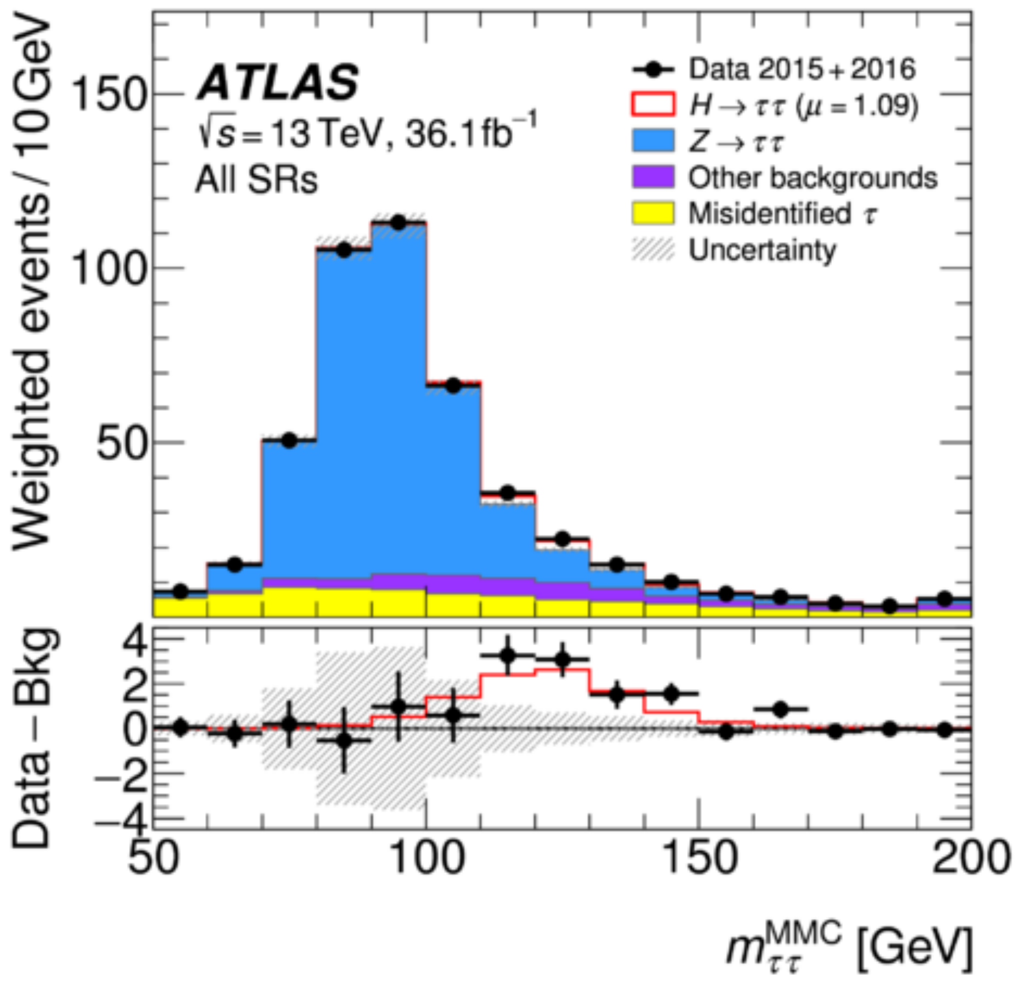
ATLAS Run 2 Higgs boson property studies

Phys. Lett. B 784 (2018) 345



m$_H$ measurements updated

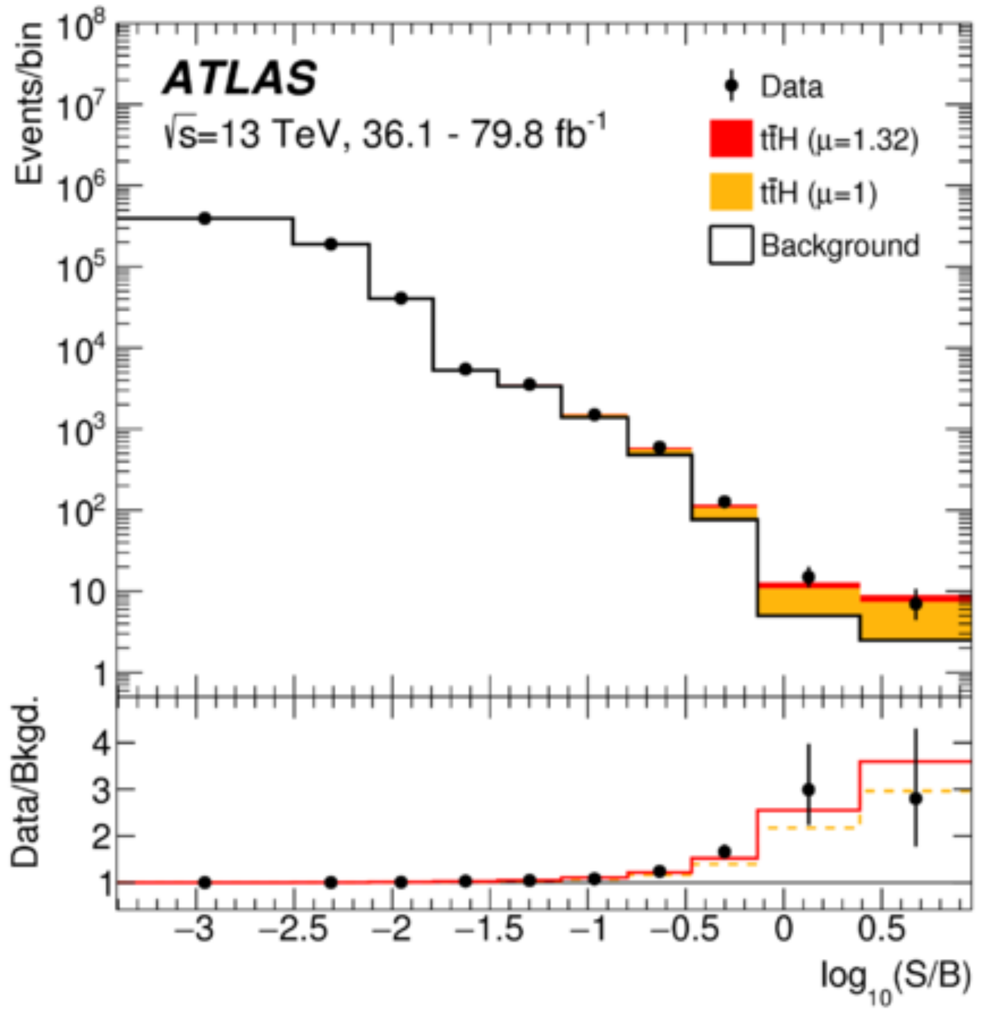
Phys. Rev. D 99 (2019) 072001



observation of H→ττ

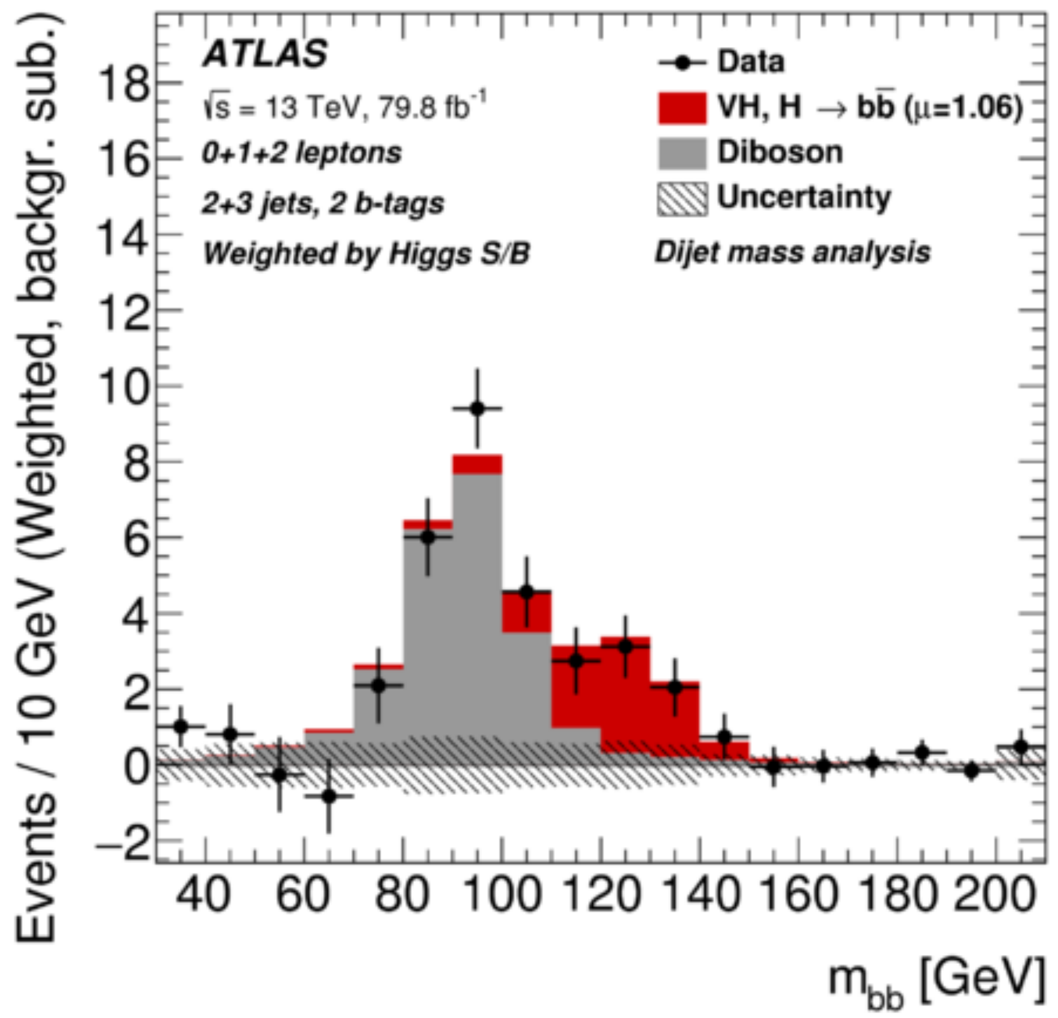
by a single experiment

Phys. Lett. B 784 (2018) 173



observation of ttH

Phys. Lett. B 786 (2018) 59



observation of H→bb/VH

- Just with partial Run2 statistics
- Our focus will be on the combined measurement of production cross-sections and decay rates of the Higgs boson, and various interpretations of the results

Many hands (from Run2) make light work

- Rich pool of analyses performed by ATLAS
- Major improvements in performance and analysis methodologies (a lot of MVA)
- Every measurement consists of one or more signal regions, designed to selected target **Higgs production** / **decay**
- Analyses trying to provide more granular information on the Higgs

Decay channel	Target Production Modes	$\mathcal{L}$ [fb^{-1}]
$H \to \gamma\gamma$	ggF, VBF, WH, ZH, $t\bar{t}H$, tH	139
$H \to ZZ^*$	ggF, VBF, WH, ZH, $t\bar{t}H$(4ℓ)	139
	$t\bar{t}H$	36.1
$H \to WW^*$	ggF, VBF	139
	$t\bar{t}H$	36.1
$H \to \tau\tau$	ggF, VBF, WH, ZH, $t\bar{t}H$($\tau_{\rm had}\tau_{\rm had}$)	139
	$t\bar{t}H$	36.1
$H \to b\bar{b}$	WH, ZH	139
	VBF	126
	$t\bar{t}H$	139
$H \to \mu\mu$	ggF, VBF, VH, $t\bar{t}H$	139
$H \to Z\gamma$	ggF, VBF, VH, $t\bar{t}H$	139
$H \to inv$	VBF	139

Higgs 2021 Conf. note:

Inclusive measurement:

- Cross sections (σ)
- Signal Strengths ($\mu = \sigma \cdot \mathrm{Br.}^{\mathrm{obs.}} / \sigma \cdot \mathrm{Br.}^{\mathrm{SM}}$)
- Coupling strength scale factor relative to SM (κ framework, κ = 1 for SM)

Differential measurements:

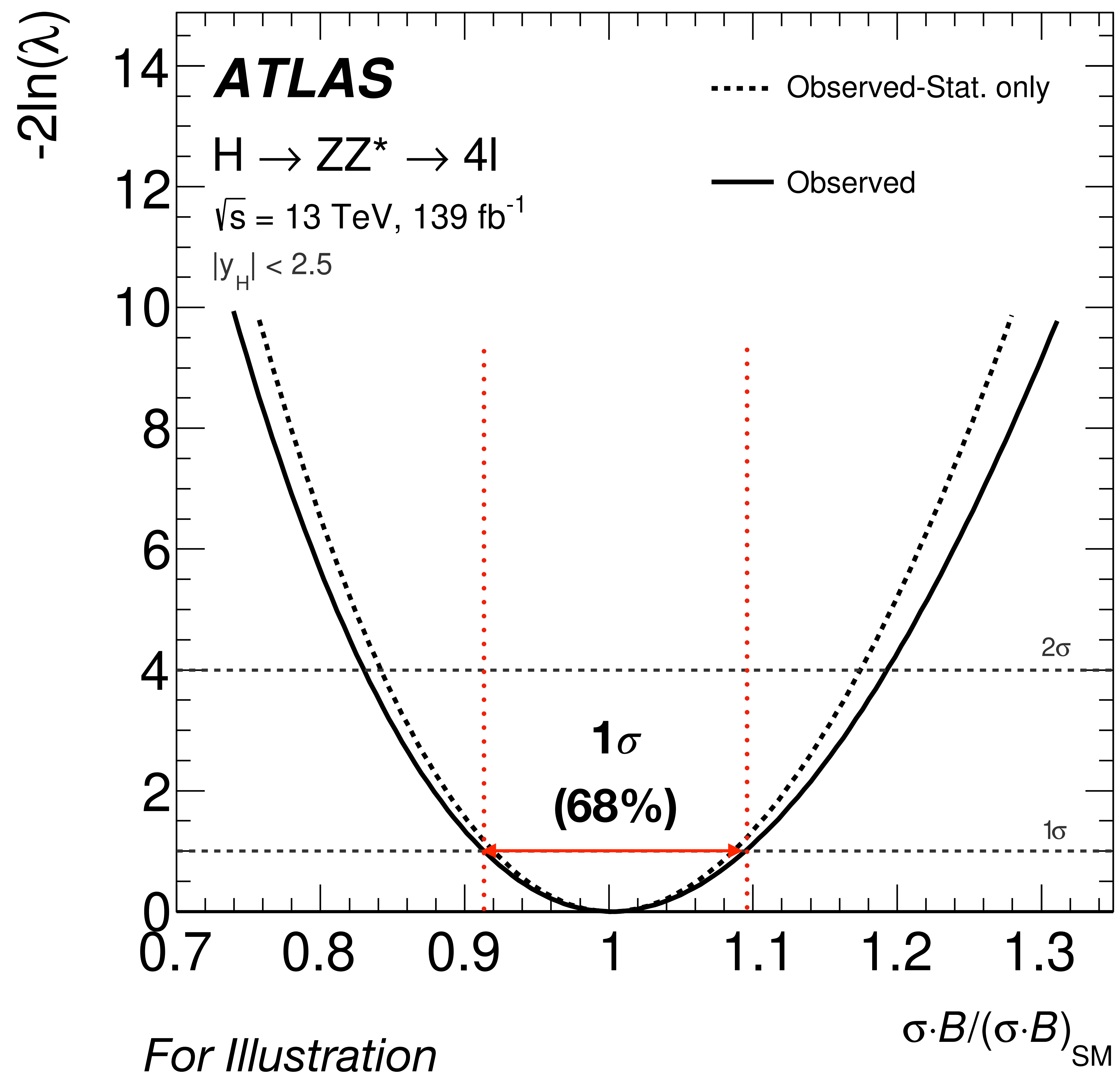
- Simplified Template Cross Sections (STXS) framework

Combination

- Why combination?
  - The individual analyses is probing different production processes, decays and also different kinematic regions
  - We can obtain the best results from the combination of the individual.
- Construct combined likelihood model as **multiplication of individual channel likelihoods**
- Common parameters, e.g. **signal cross-sections** and **nuisance parameters** for the same systematic uncertainties, are shared between likelihood of individual channels
- Use profile likelihood ratio Λ as **test statistic**:

$$\Lambda(\alpha) = \frac{L(\alpha, \hat{\hat{\theta}}(\alpha))}{L(\hat{\alpha}, \hat{\theta})}$$

- 1-D 68% confidence interval defined by $-2\ln\Lambda$ increasing by 1 (asymptotic limit)



For Illustration

Eur. Phys. J. C 80 (2020) 957

Inclusive signal strength

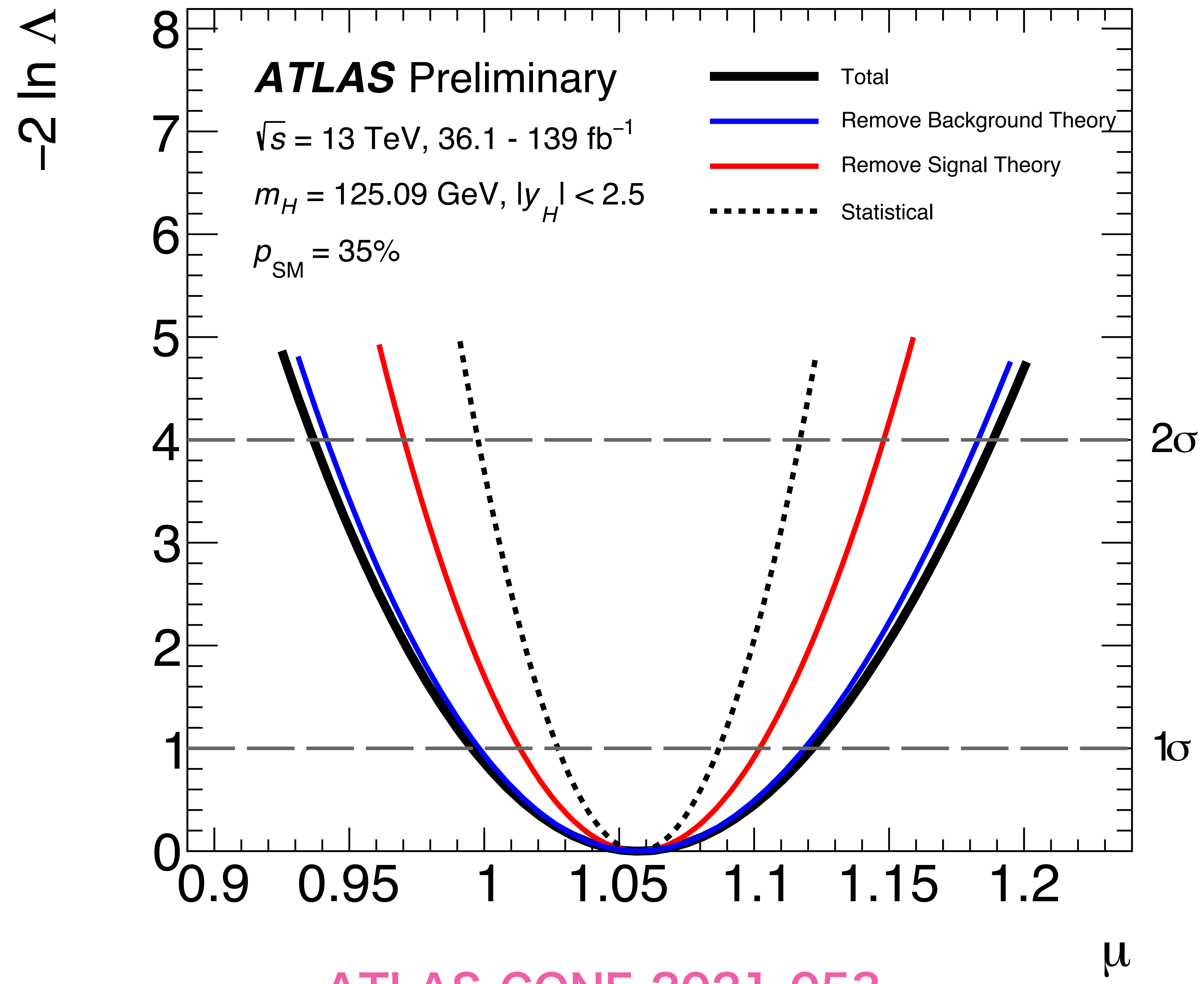
- Global signal strength $(\sigma \cdot \text{Br.})^{\text{obs.}} / (\sigma \cdot \text{Br.})^{\text{SM}}$, assuming a common scaling for all production processes and decays

  $\mu = 1.06 \pm 0.06 = 1.06 \pm 0.03\,(\text{stat.}) \pm 0.03\,(\text{exp.}) \pm 0.04\,(\text{sig . th.}) \pm 0.02\,(\text{bkg . th.})$

- The uncertainties on $(\sigma \cdot \text{Br.})^{\text{SM}}$ taken into account
- Comparable contribution from statistical, experimental, and signal/bkg. theory uncertainty components

- **10%** improvement in accuracy comparing to ATLAS- CONF-2020-027, **44%** improvement comparing to Run1

- Consistent with the SM: p_{SM} = 35 %
- The precision is dominantly constrained by the syst. unc.



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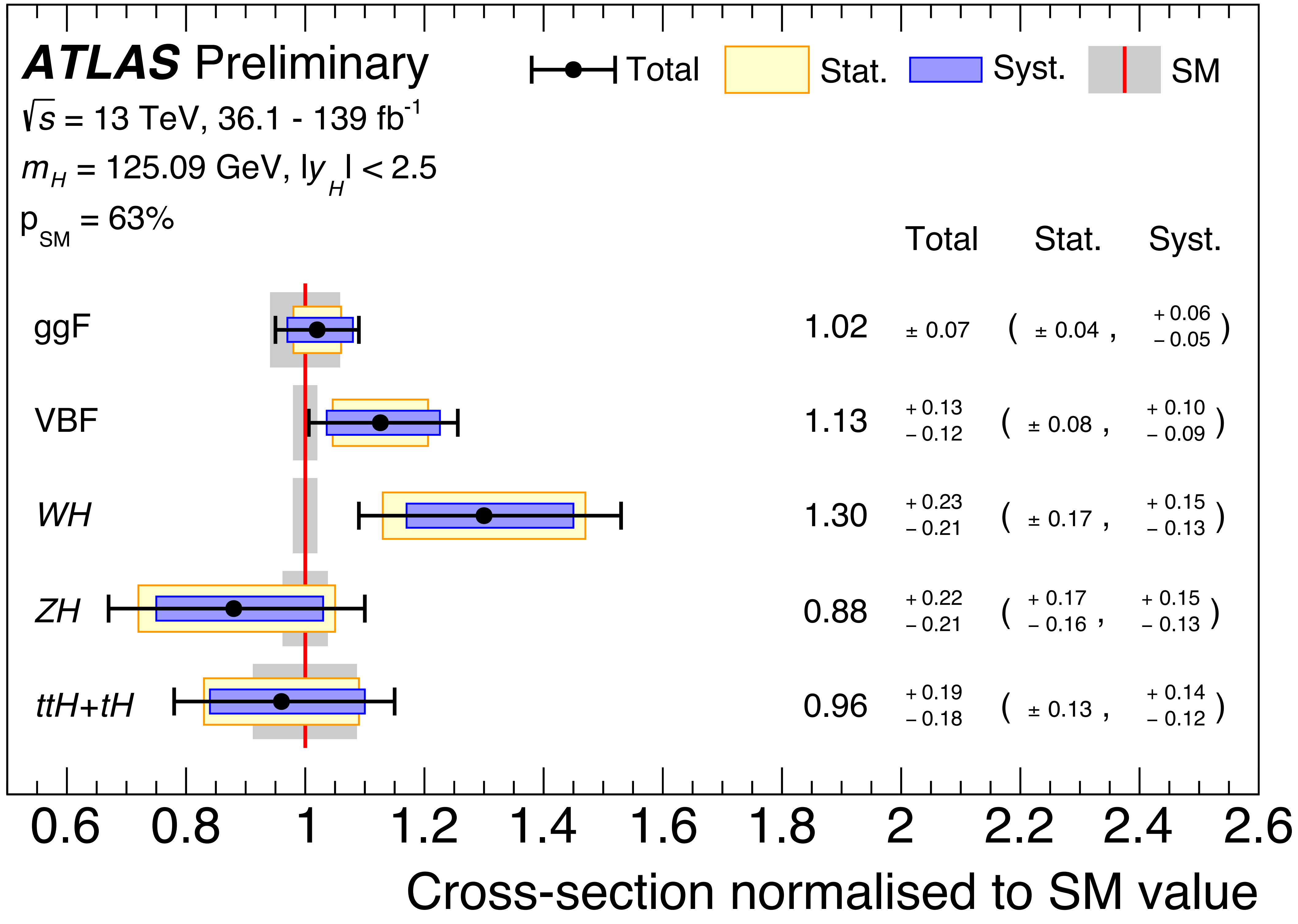
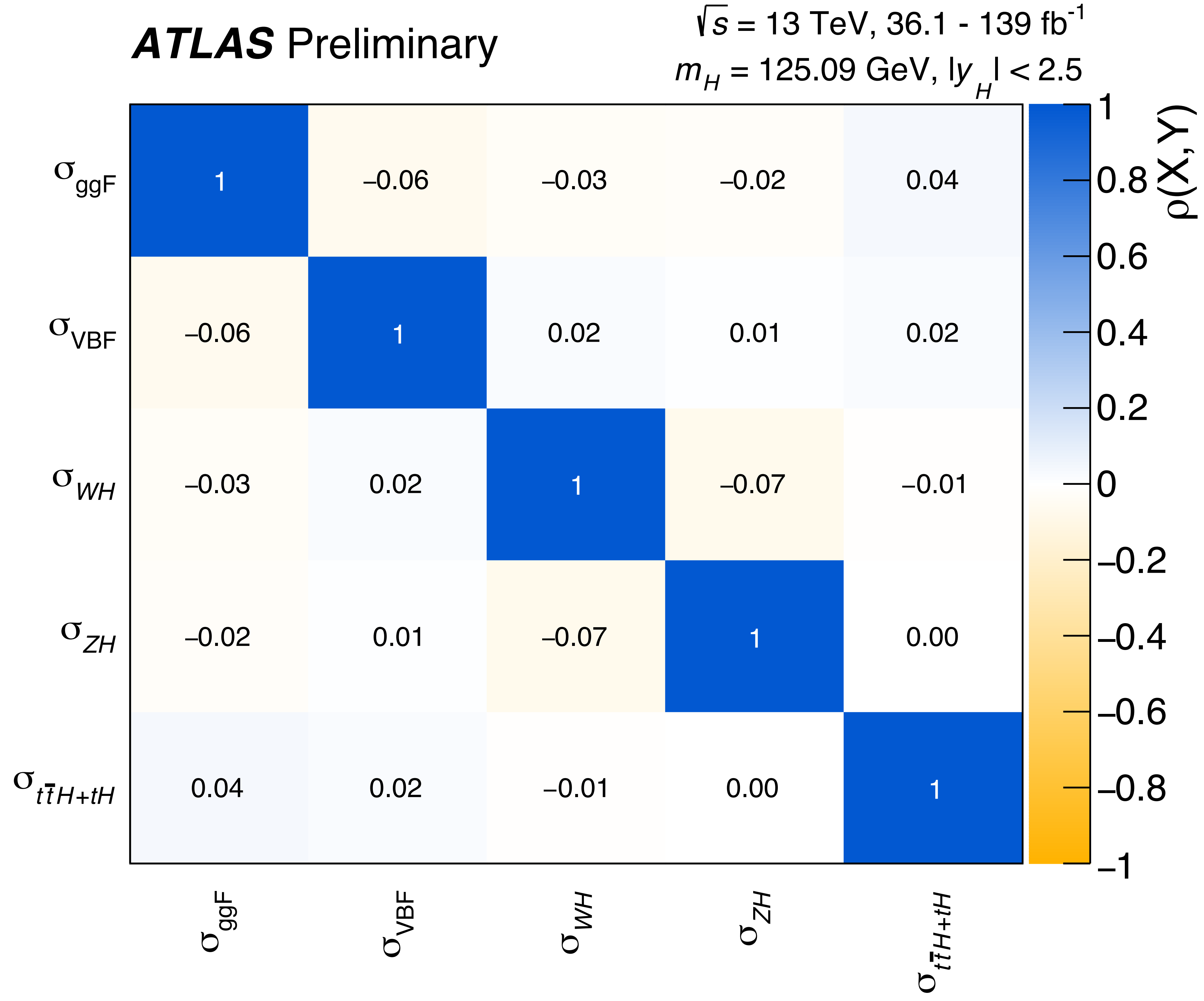
Production mode cross-sections (assuming the SM BRs)

ATLAS-CONF-2021-053

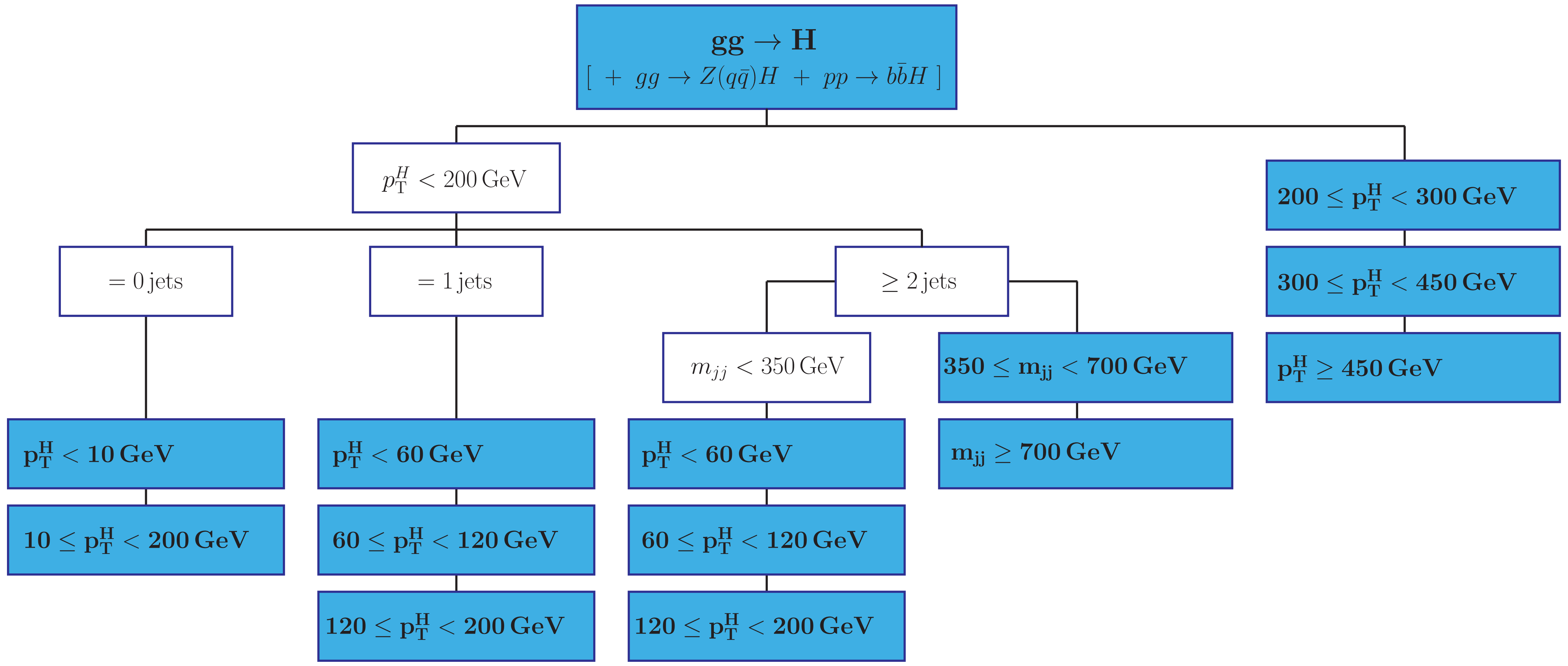
- Precision improves by 2% - 27% thanks to improvements in the individual analyses
- ggF cross-section now measured with precision of 7%, close to 5% uncertainty on the N^{3}LO cross section prediction
- All major production modes observed
- Small correlation between measurements of different production modes

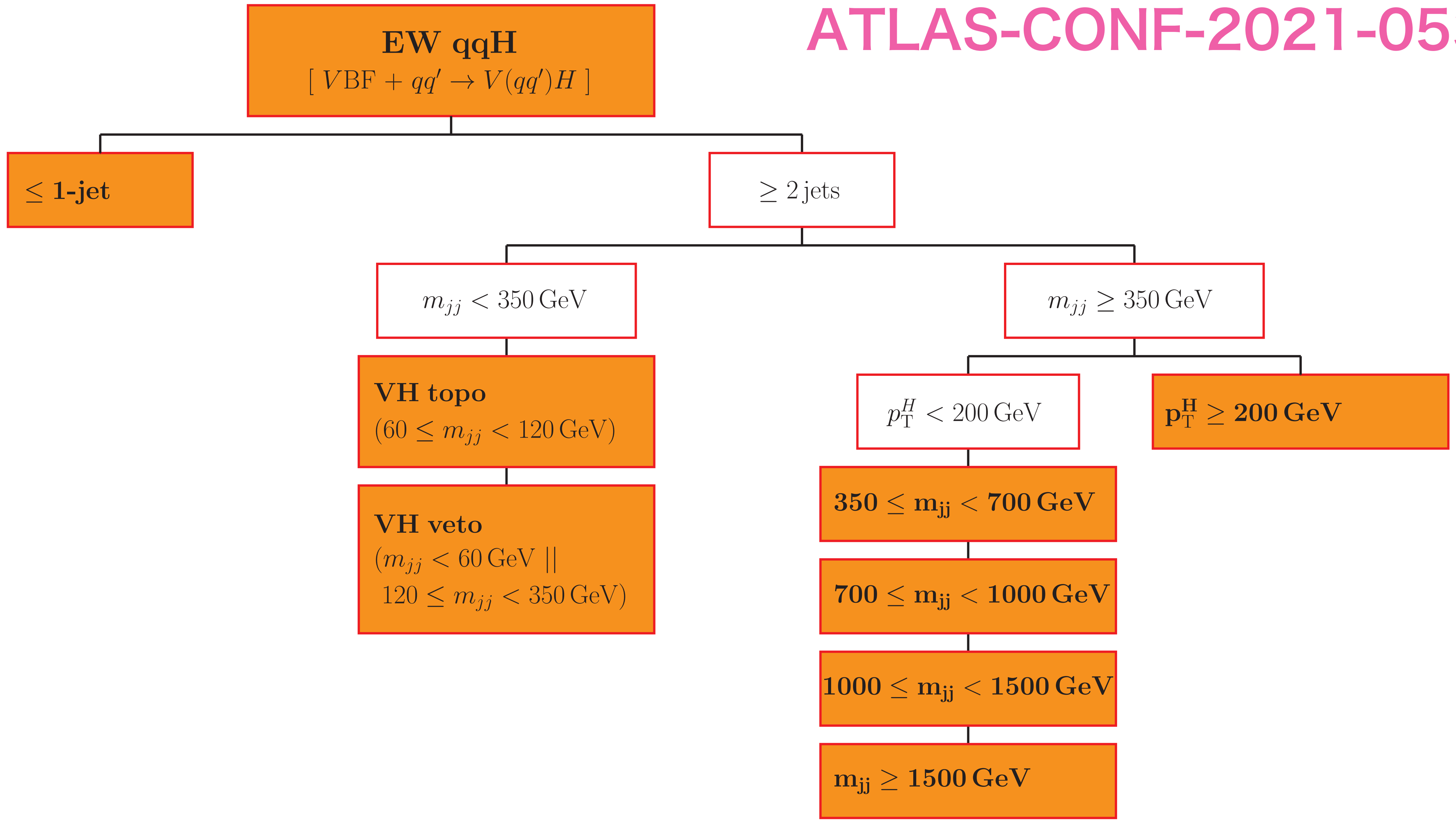




Simplified template cross section (STXS)

- Extension of inclusive-style measurements
- Measure cross-section per production mode in different phase-space regions
  - Reduce model dependence and maximize sensitivity to BSM effects
  - Support kinematic-dependent interpretations (EFT etc.)
- Within each region, use the SM predicted signal templates to fit data
  - Can still exploit powerful analysis techniques (e.g. MVA)





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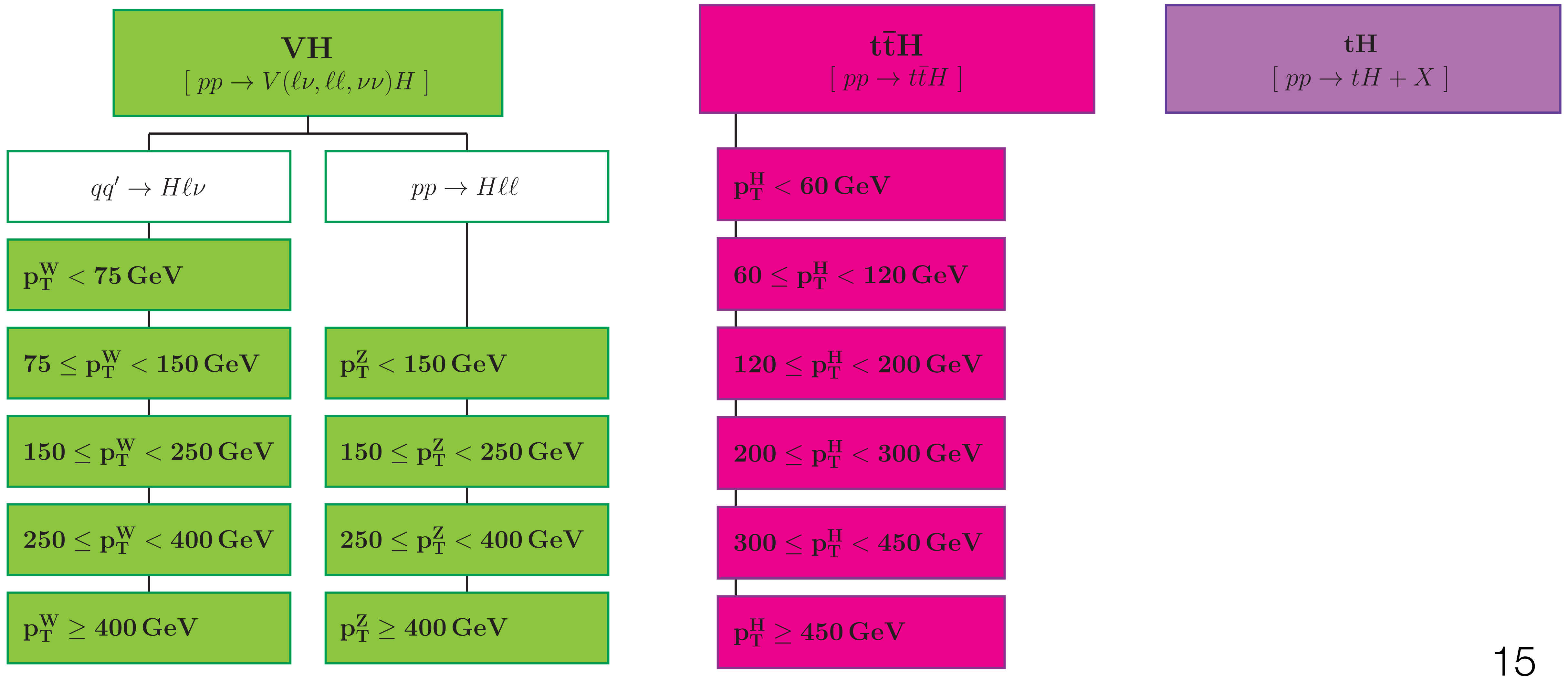
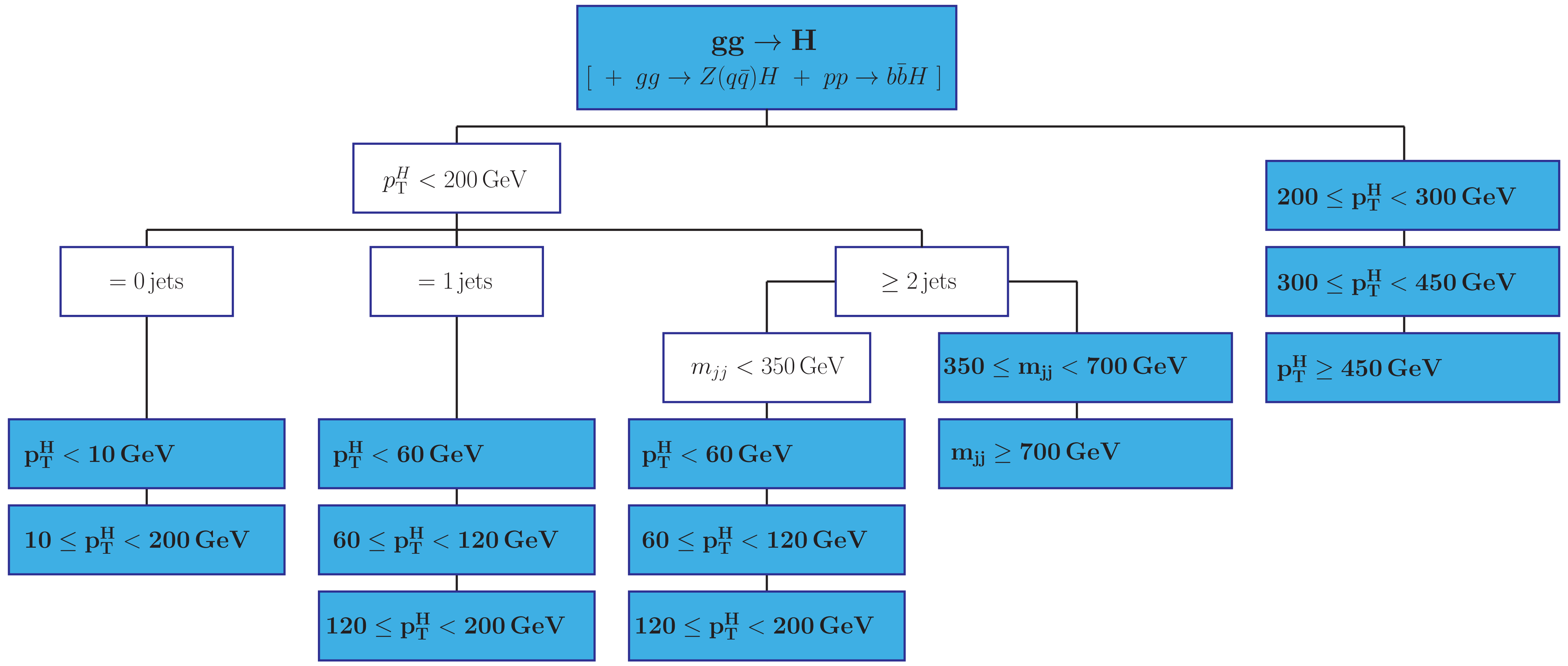
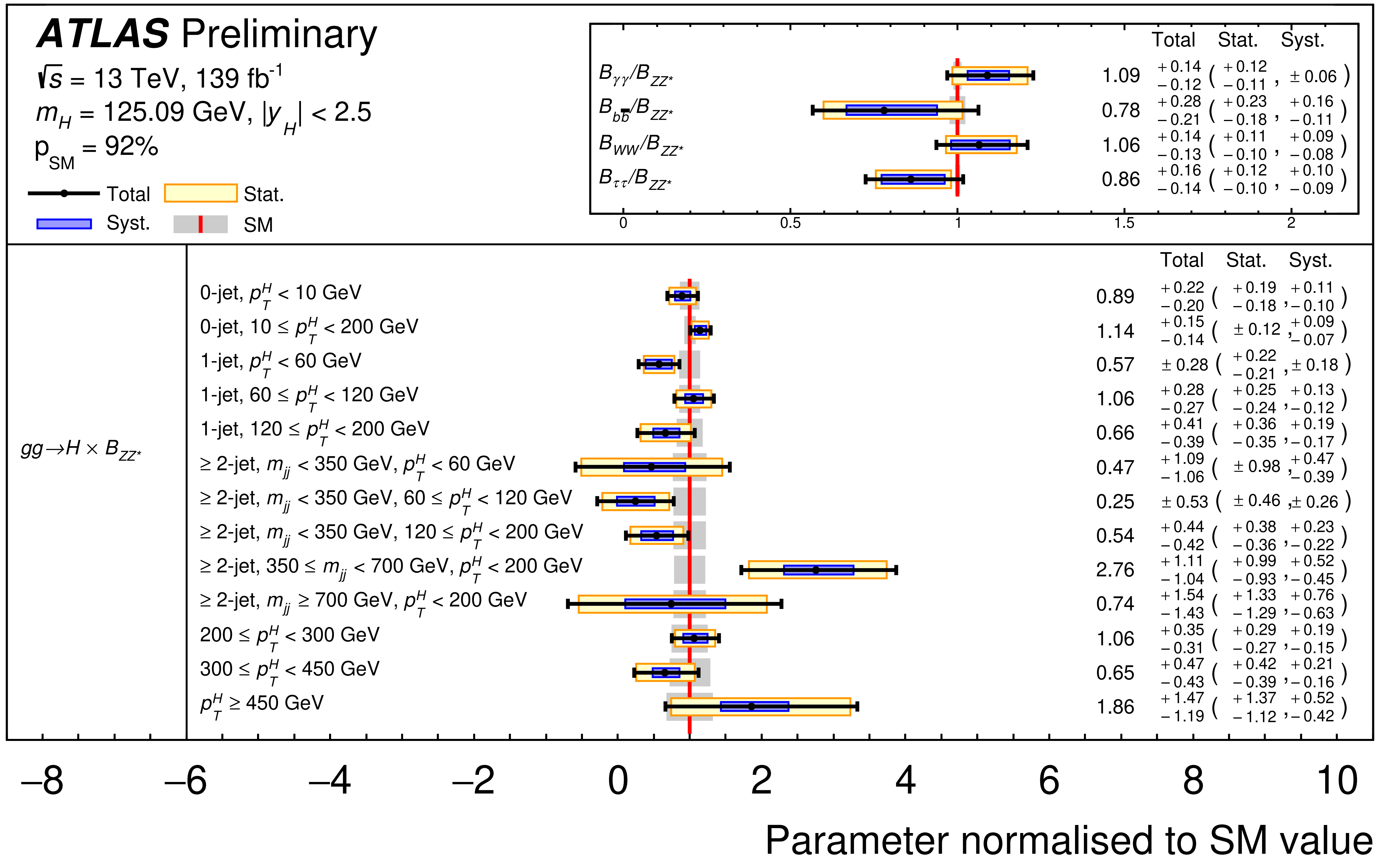
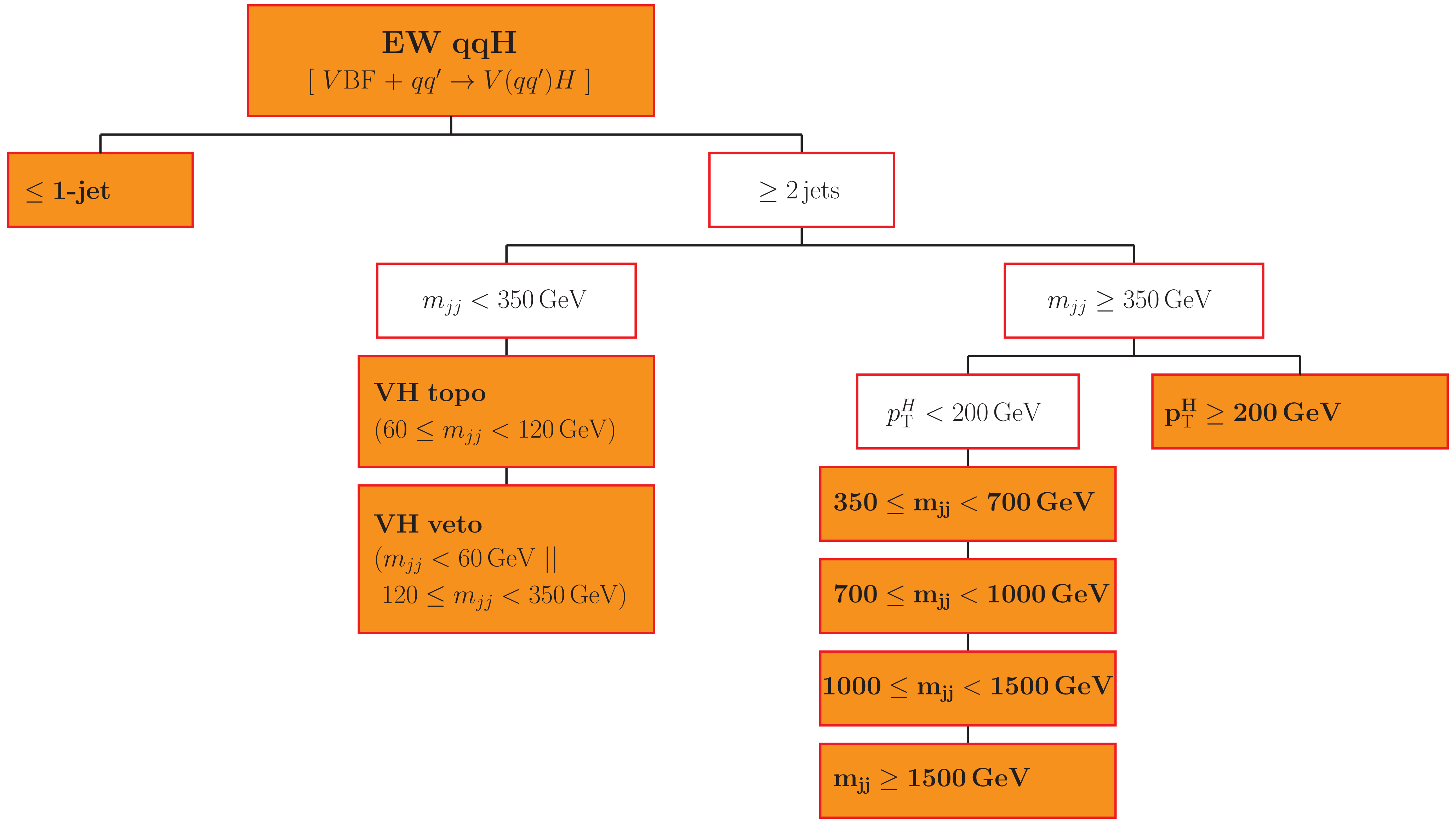
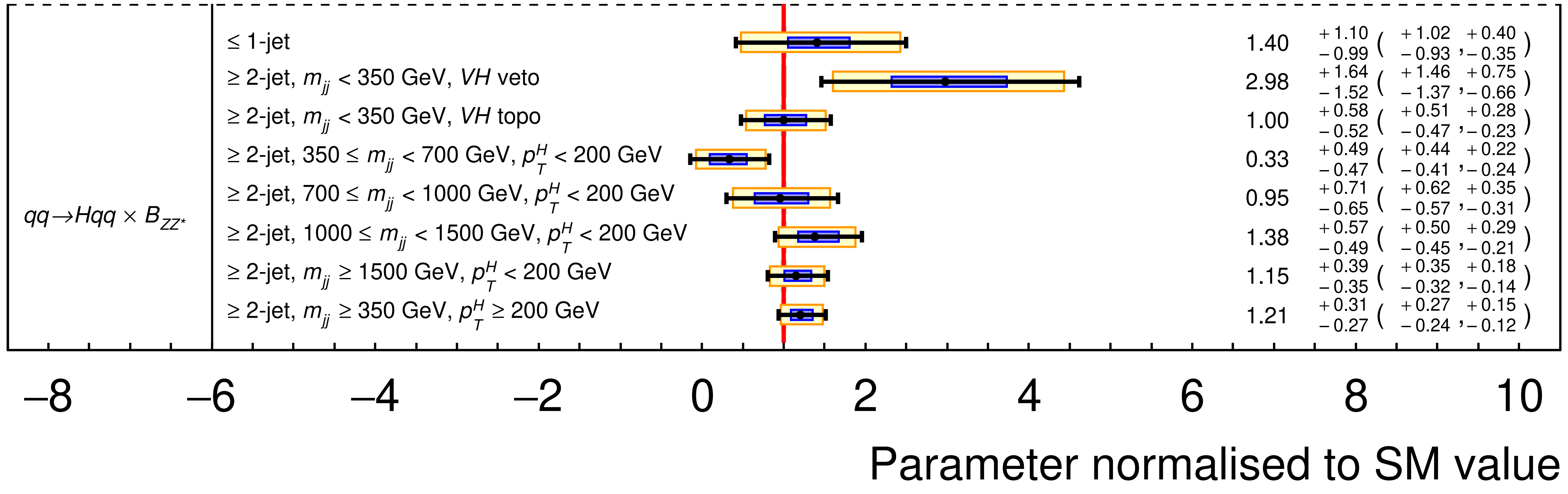


STXS results I









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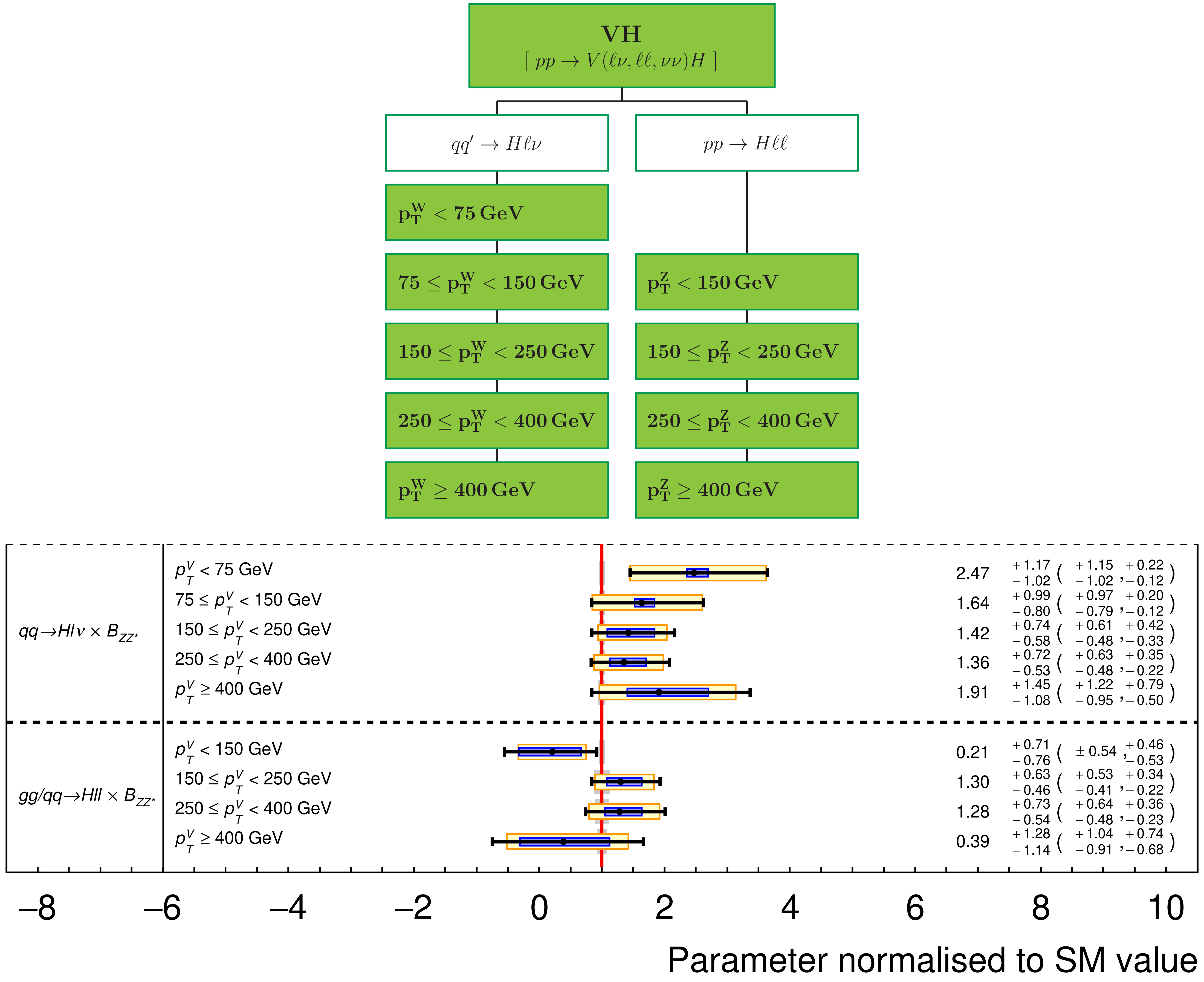
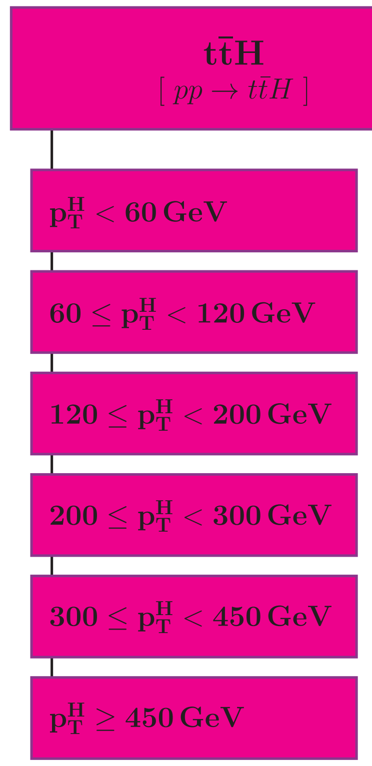
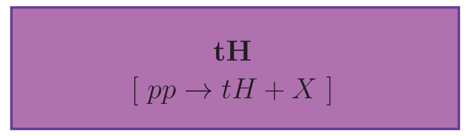
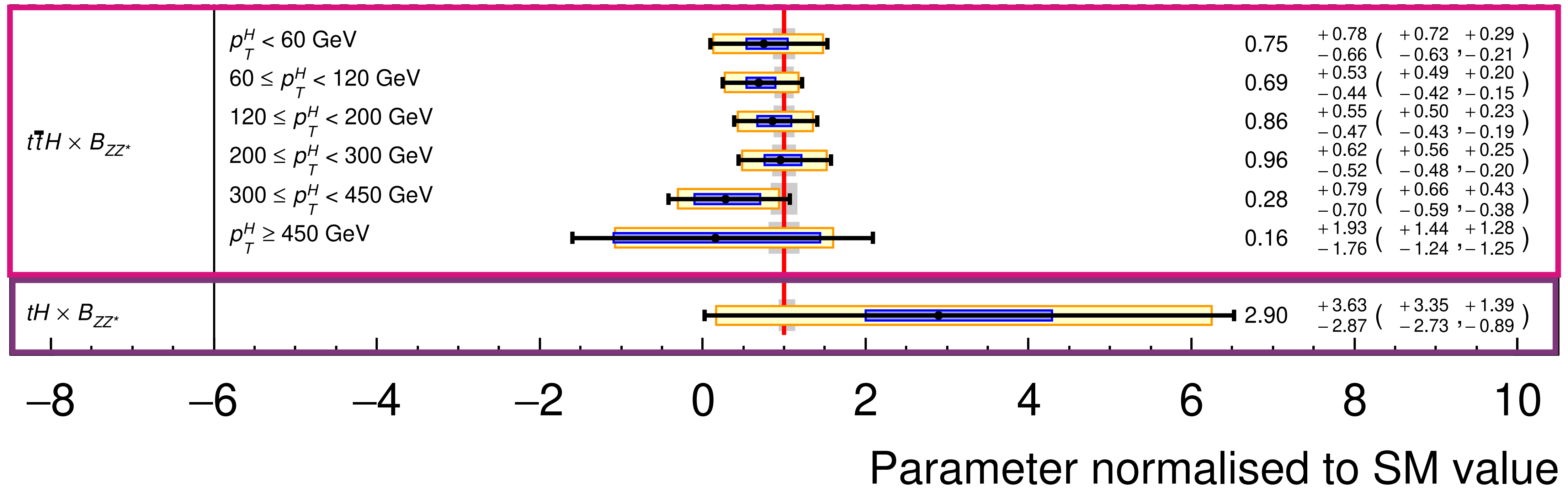
STXS results II







- The obs. (exp.) sig. for **tH** STXS bin: 1.0 σ (0.4 σ)
- The obs. (exp.) upper limit is **9.3** (**6.7**) times the SM prediction at 95% CL
- observed limit 10% higher than the previous due to the larger obs. best-fit value



- Most granular, simultaneous measurement (41 POIs: 37 STXS bins for all production modes + 4 BR. ratios)
  - For all bins **stat. unc. dominating;** only in few syst. unc. matters
  - Overall good compatibility with SM (p_{SM} = 92%)
  - Statistical precision, in particular in most BSM sensitive regions is still limited: more data to help

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SMEFT

- Introduce new effective operators with free coefficients to capture new physics appearing beyond scale Λ (typically chosen as 1 TeV)
- New heavy internal particles are integrated out and are represented as vertices in the new effective theory
- Most common: Warsaw-basis (JHEP 10 (2010) 085) forming a complete set of all dim-6 operators allowed by the SM gauge symmetries
- Interpretation performed in SMEFT framework

$$\mathcal{L}_{\text{SMEFT}} = \mathcal{L}_{\text{SM}} + \sum_{i}^{N_{d6}} \frac{c_i}{\Lambda^2} \mathcal{O}_i^{(6)} + \sum_{j}^{N_{d8}} \frac{b_i}{\Lambda^4} \mathcal{O}_i^{(8)} + \ldots$$

- SMEFT in a nutshell:
  - $\mathscr{L}_{\text{SM}}$ is dim-4, high orders only valid in the low-energy regime $E \ll \Lambda$
  - terms with odd dimensionality violate lepton and/or baryon symmetry and are usually not considered for LHC physics
  - Wilson coefficients $c \equiv 0$ for SM, deviations might indicate new physics

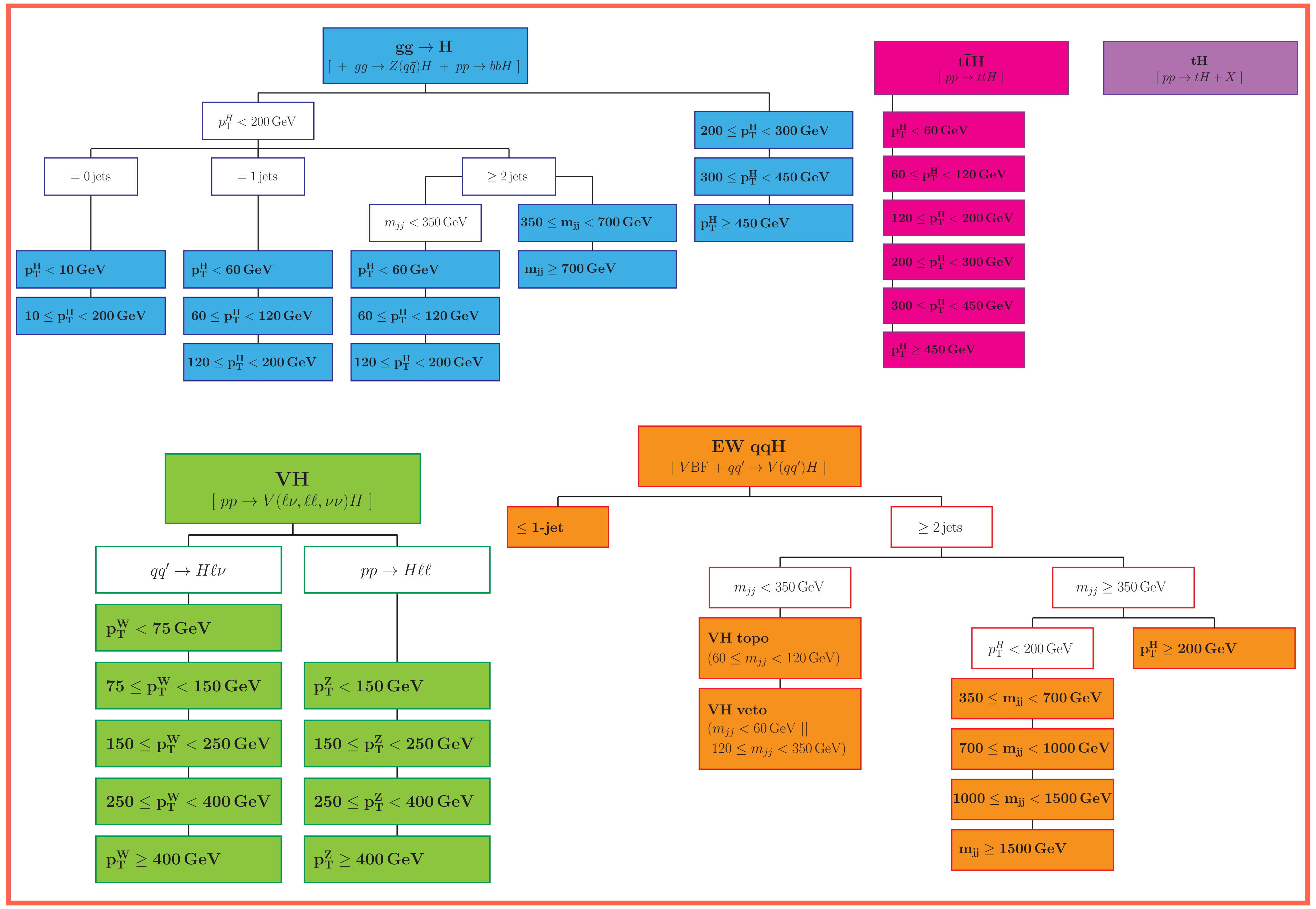
SMEFT Interpretation: operators

- $\Lambda = 1$TeV and Warsaw-basis

Wilson coefficient	Operator	Wilson coefficient	Operator
$c_{H\square}$	$(H^\dagger H)\square(H^\dagger H)$	c_{uG}	$(\bar{q}_p\sigma^{\mu\nu}T^A u_r)\widetilde{H}\,G^A_{\mu\nu}$
c_{HDD}	$\left(H^\dagger D^\mu H\right)^*\left(H^\dagger D_\mu H\right)$	c_{uW}	$(\bar{q}_p\sigma^{\mu\nu}u_r)\tau^I\widetilde{H}\,W^I_{\mu\nu}$
c_{HG}	$H^\dagger H\,G^A_{\mu\nu}G^{A\mu\nu}$	c_{uB}	$(\bar{q}_p\sigma^{\mu\nu}u_r)\widetilde{H}\,B_{\mu\nu}$
c_{HB}	$H^\dagger H\,B_{\mu\nu}B^{\mu\nu}$	c'_{ll}	$(\bar{l}_p\gamma_\mu l_t)(\bar{l}_r\gamma^\mu l_s)$
c_{HW}	$H^\dagger H\,W^I_{\mu\nu}W^{I\mu\nu}$	$c^{(1)}_{qq}$	$(\bar{q}_p\gamma_\mu q_t)(\bar{q}_r\gamma^\mu q_s)$
c_{HWB}	$H^\dagger\tau^I H\,W^I_{\mu\nu}B^{\mu\nu}$	$c^{(3)}_{qq}$	$(\bar{q}_p\gamma_\mu\tau^I q_r)(\bar{q}_s\gamma^\mu\tau^I q_t)$
c_{eH}	$(H^\dagger H)(\bar{l}_p e_r H)$	c_{qq}	$(\bar{q}_p\gamma_\mu q_t)(\bar{q}_r\gamma^\mu q_s)$
c_{uH}	$(H^\dagger H)(\bar{q}_p u_r\widetilde{H})$	$c^{(31)}_{qq}$	$(\bar{q}_p\gamma_\mu\tau^I q_t)(\bar{q}_r\gamma^\mu\tau^I q_s)$
c_{dH}	$(H^\dagger H)(\bar{q}_p d_r\widetilde{H})$	c_{uu}	$(\bar{u}_p\gamma_\mu u_r)(\bar{u}_s\gamma^\mu u_t)$
$c^{(1)}_{Hl}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{l}_p\gamma^\mu l_r)$	$c^{(1)}_{uu}$	$(\bar{u}_p\gamma_\mu u_t)(\bar{u}_r\gamma^\mu u_s)$
$c^{(3)}_{Hl}$	$(H^\dagger i\overleftrightarrow{D}^I_\mu H)(\bar{l}_p\tau^I\gamma^\mu l_r)$	$c^{(1)}_{qu}$	$(\bar{q}_p\gamma_\mu q_t)(\bar{u}_r\gamma^\mu u_s)$
c_{He}	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{e}_p\gamma^\mu e_r)$	$c^{(8)}_{ud}$	$(\bar{u}_p\gamma_\mu T^A u_r)(\bar{d}_s\gamma^\mu T^A d_t)$
$c^{(1)}_{Hq}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{q}_p\gamma^\mu q_r)$	$c^{(8)}_{qu}$	$(\bar{q}_p\gamma_\mu T^A q_r)(\bar{u}_s\gamma^\mu T^A u_t)$
$c^{(3)}_{Hq}$	$(H^\dagger i\overleftrightarrow{D}^I_\mu H)(\bar{q}_p\tau^I\gamma^\mu q_r)$	$c^{(8)}_{qd}$	$(\bar{q}_p\gamma_\mu T^A q_r)(\bar{d}_s\gamma^\mu T^A d_t)$
c_{Hu}	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{u}_p\gamma^\mu u_r)$	c_W	$\epsilon^{IJK}W^{I\nu}_\mu W^{J\rho}_\nu W^{K\mu}_\rho$
c_{Hd}	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{d}_p\gamma^\mu d_r)$	c_G	$f^{ABC}G^{A\nu}_\mu G^{B\rho}_\nu G^{C\mu}_\rho$

- Considering only EFT contributions from the interference between the SM and the dim-6 SMEFT operators
    - pure dim-6 BSM not considered: as being suppressed by a factor $1/\Lambda^4$, expected to be small

impact



STXS bins

$\otimes$

$$H \to \tau\tau$$
$$H \to bb$$
$$H \to \gamma\gamma$$
$$H \to WW$$
$$H \to ZZ$$

Decay BR.

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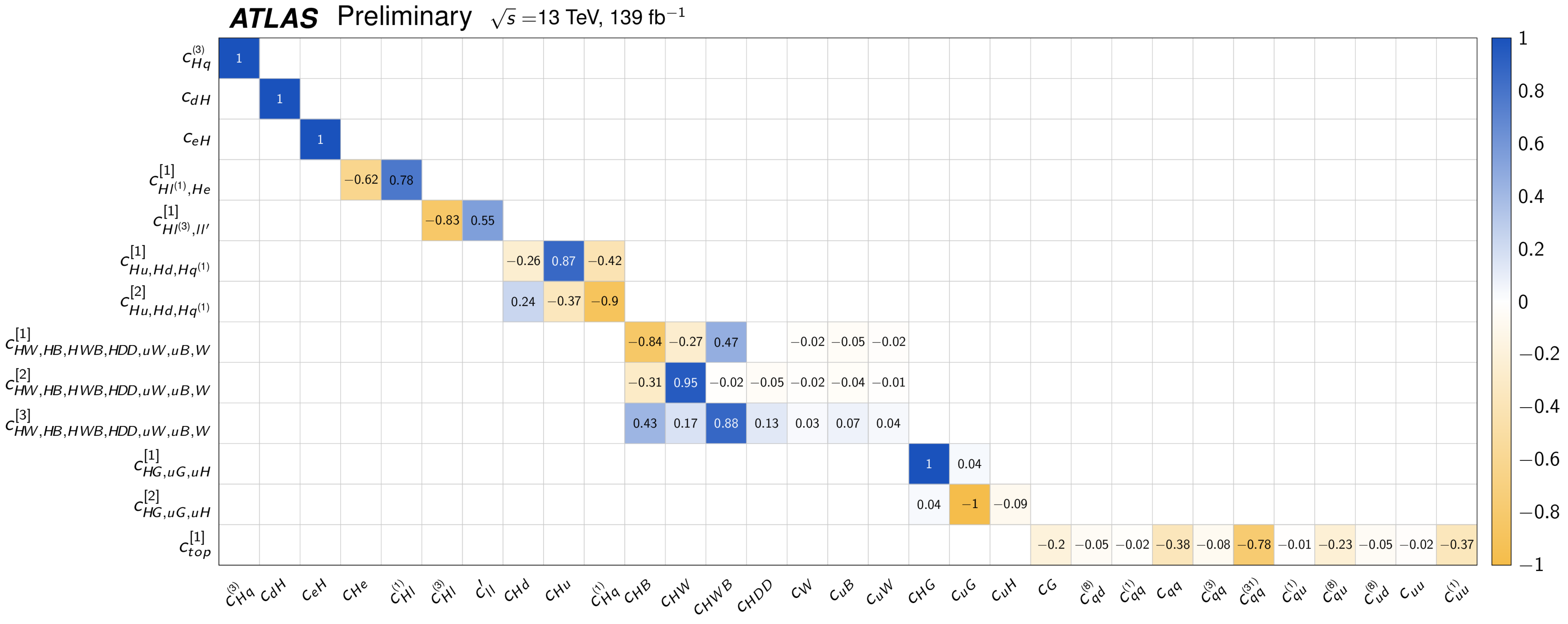
SMEFT Interpretation: measured parameters

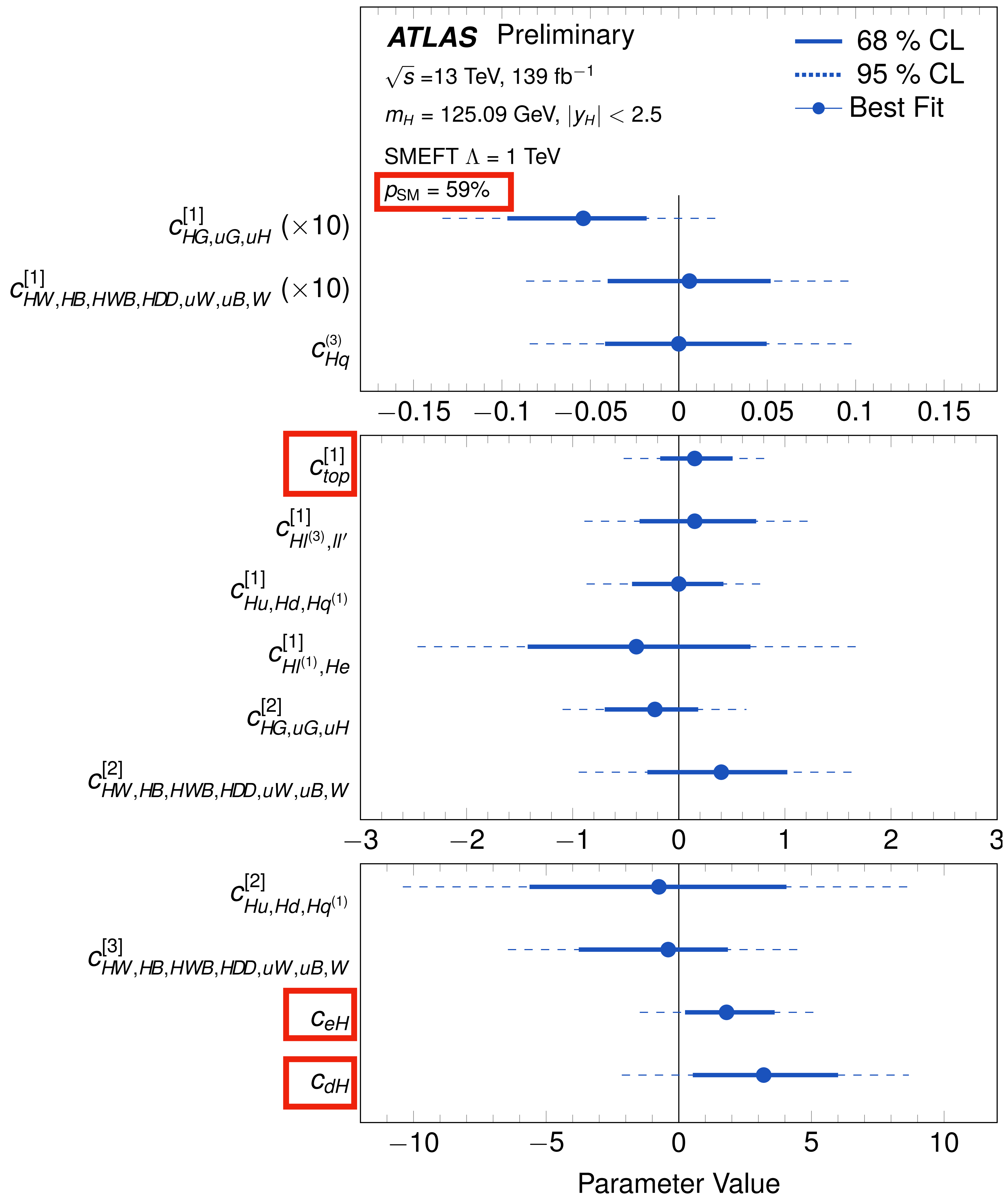
- Due to large number of parameters with complicated correlation, Cannot separately constrain all parameters
- Decompose into subspaces, motivated by correlations and physics concerns
- Set parameters with weak eigenvalues to 0 and fit resulting parameter set



SMEFT Interpretation: results

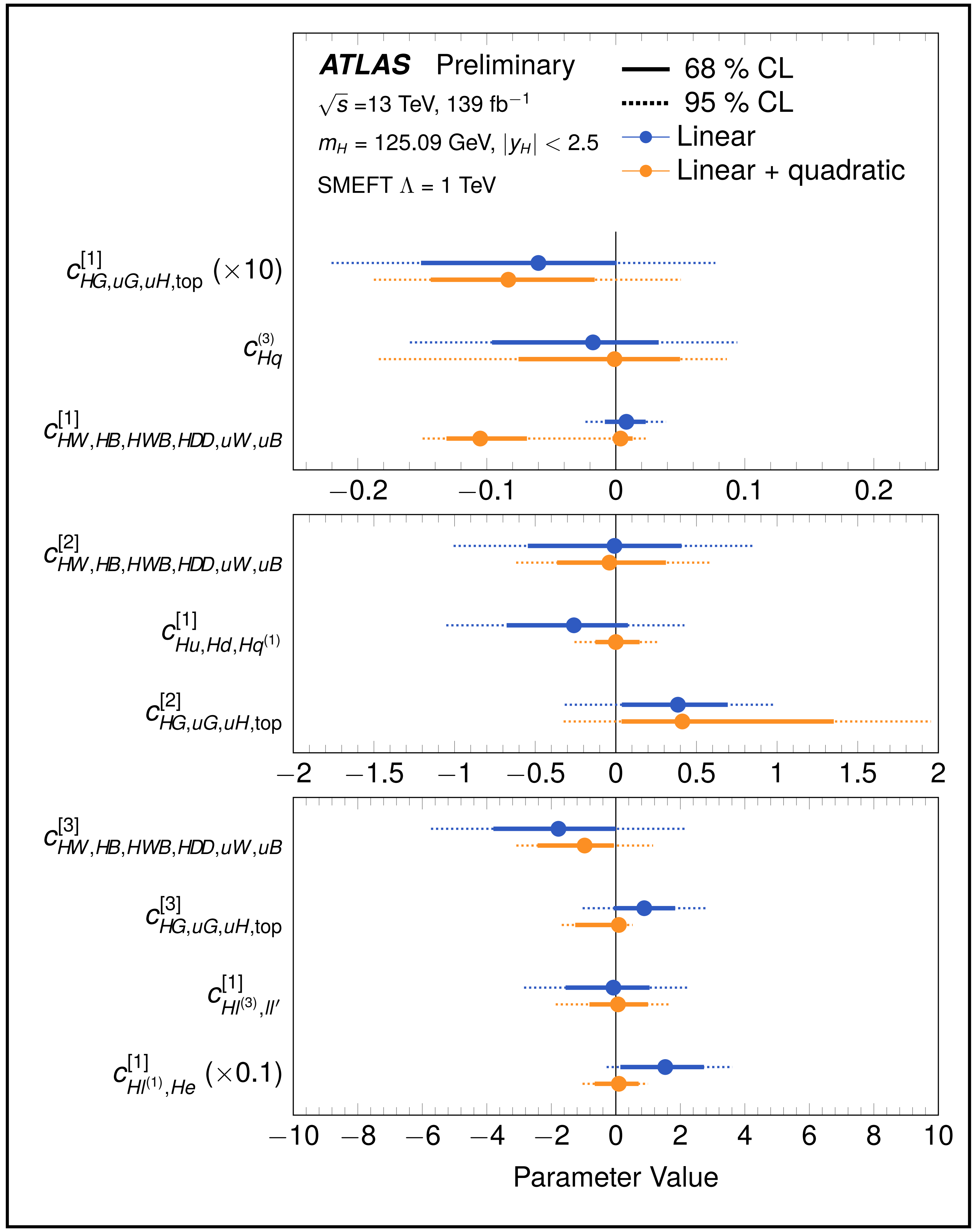
ATLAS-CONF-2021-053

- Parameter measurements



ATLAS-CONF-2020-053

- Previous measurements



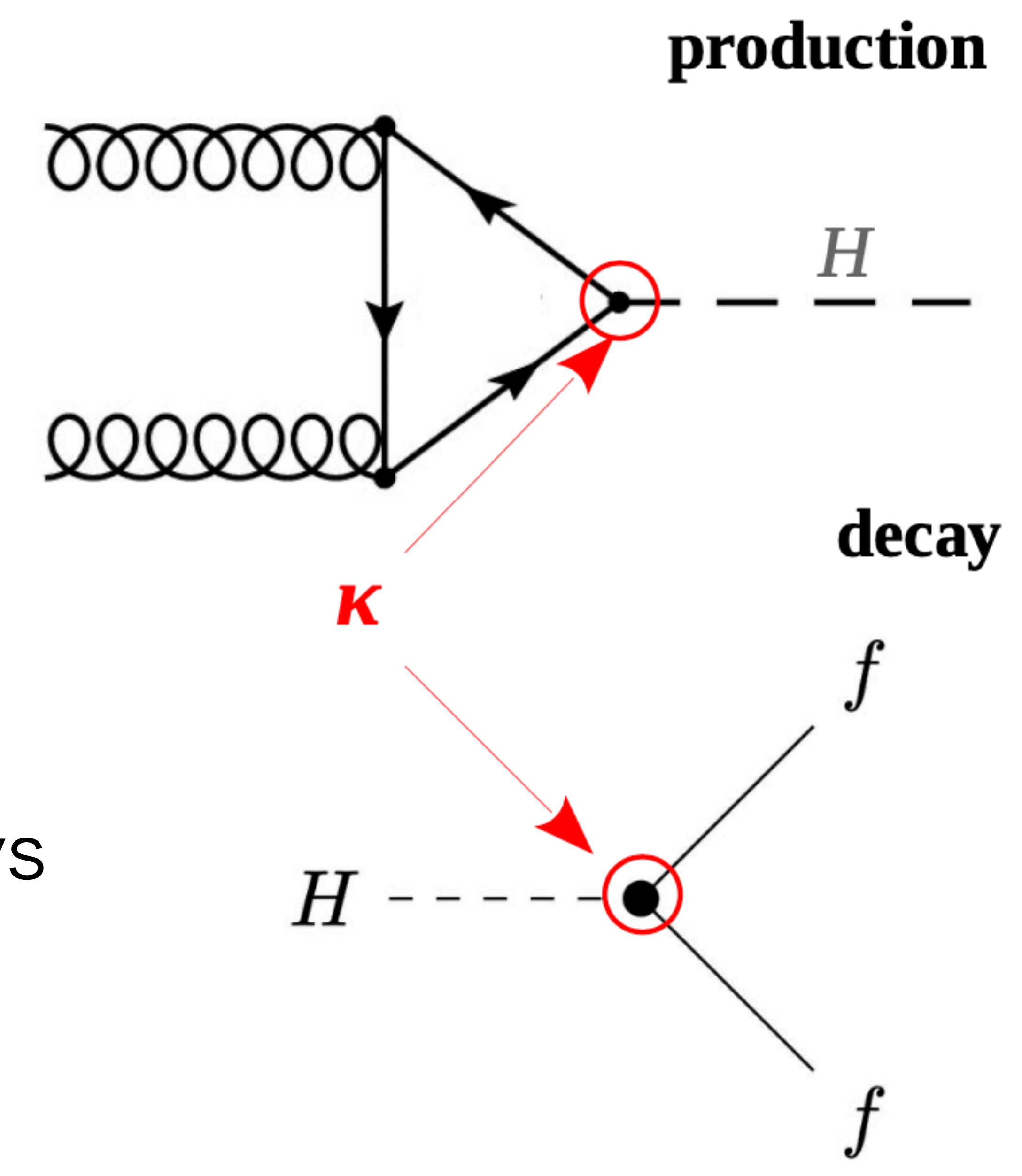
Compared with the previous results:

- Updated H→$\tau\tau$ result, c_{eH} can now be constrained
- VBF and ttH with H→bb: c_{dH} and c_{top}

Interpretation in the κ framework

- Assumption: BSM physics modifies only the strength of the Higgs-boson coupling
- Introduce **coupling-strength modifiers** $\boldsymbol{\kappa}$ to the leading-order contributions to each production and decay

$$\sigma_i \times B_f = \frac{\sigma_i(\boldsymbol{\kappa}) \times \Gamma_f(\boldsymbol{\kappa})}{\Gamma_H}$$



- Modifiers on Cross-section and partial decay width for SM process j:

$$\kappa_j^2 = \frac{\sigma_j}{\sigma_j^{\mathrm{SM}}} \quad \text{or} \quad \kappa_j^2 = \frac{\Gamma_j}{\Gamma_j^{\mathrm{SM}}}$$

- Higgs total decay width: $B_{\mathrm{i./u.}}$: branching ratio of invisible/undetected BSM decays

$$\Gamma_H(\boldsymbol{\kappa}, B_{\mathrm{i.}}, B_{\mathrm{u.}}) = \kappa_H^2(\boldsymbol{\kappa}, B_{\mathrm{i.}}, B_{\mathrm{u.}})\, \Gamma_H^{\mathrm{SM}}$$

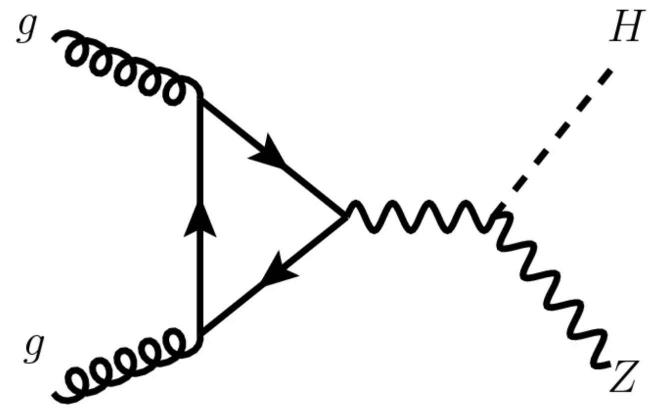
where
$$\kappa_H^2(\boldsymbol{\kappa}, B_{\mathrm{i.}}, B_{\mathrm{u.}}) = \frac{\sum_j B_j^{\mathrm{SM}} \kappa_j^2}{(1 - B_{\mathrm{i.}} - B_{\mathrm{u.}})}$$

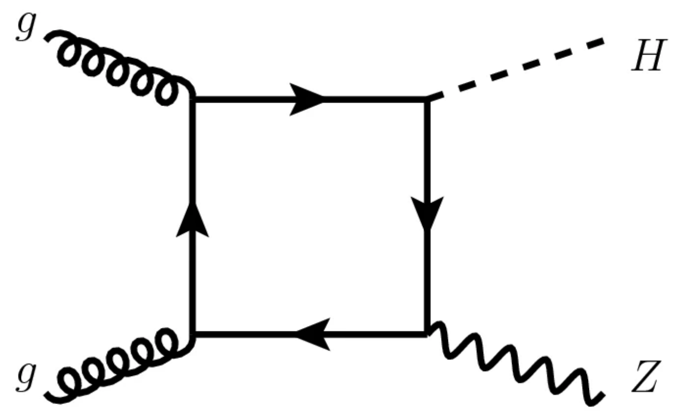
- BSM contributions may manifest themselves as $\kappa_j \neq 1$ or $B_{\mathrm{i./u.}} \neq 0$.

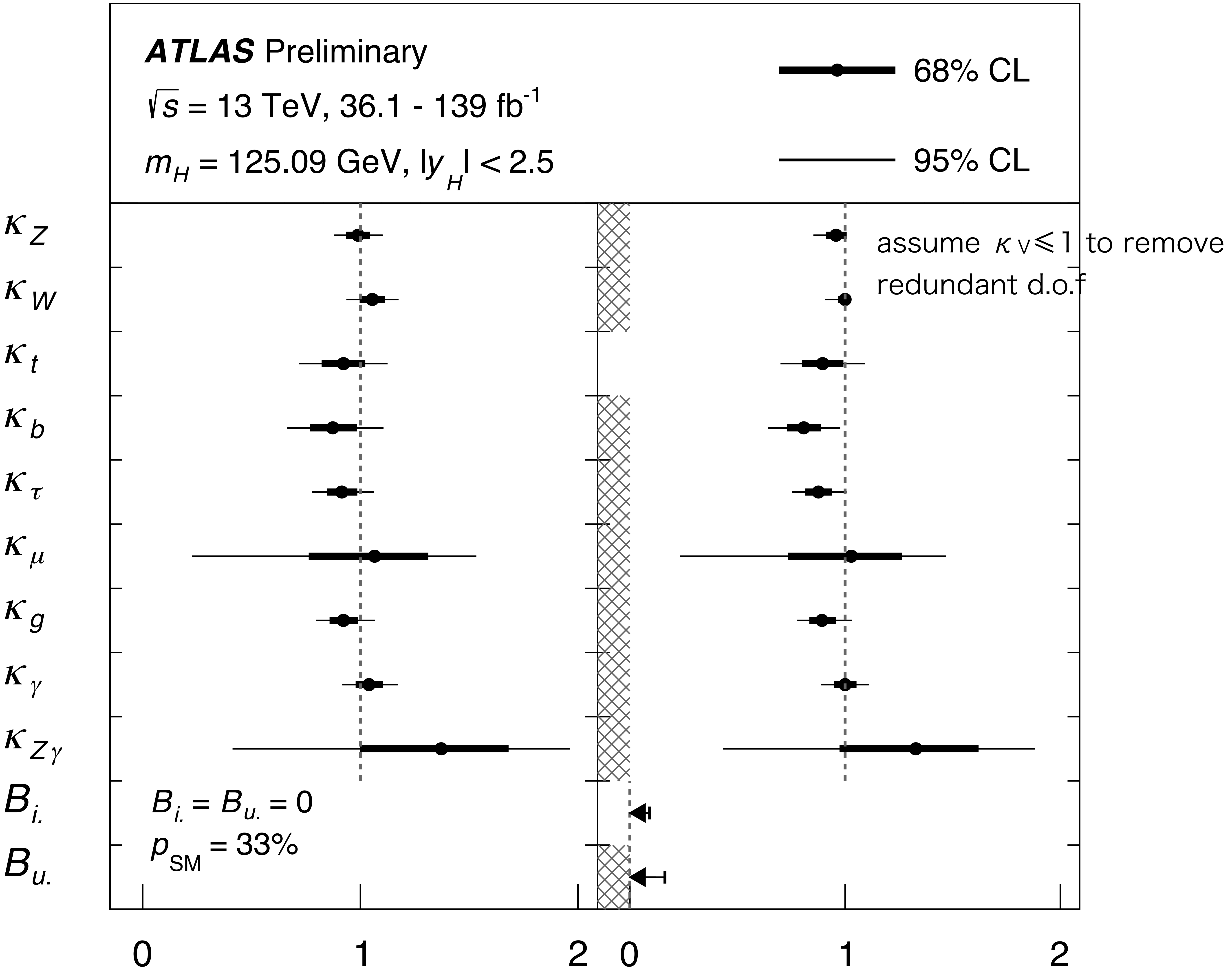
ATLAS-CONF-2021-053

Generic parameterization

- Introduce coupling scale factors for the SM particles where there is sensitivity. Not resolving ggF and $H\gamma\gamma$ effective vertices
- $\kappa_{Z\gamma}$: first time included as effective $H \to Z\gamma$ vertex in the Run2 combination
- Two scenarios for Higgs boson width
  A. No BSM contributions ($B_{i.} = B_{u.} = 0$) (left)
  B. $B_{i.}$ and $B_{u.}$ free parameters and include VBF, $H \to$ invisible to constraint $B_{i.}$, $\kappa_V \leqslant 1$ to constrain $B_{u.}$ (assumed to be positive) (right)
- Using tH and gg→ZH process to constrain relative sign of t-H coupling κ_t w.r.t. κ_W and κ_Z excluding the negative κ_t: 4.3σ in scenario (A).







ATLAS-CONF-2021-053

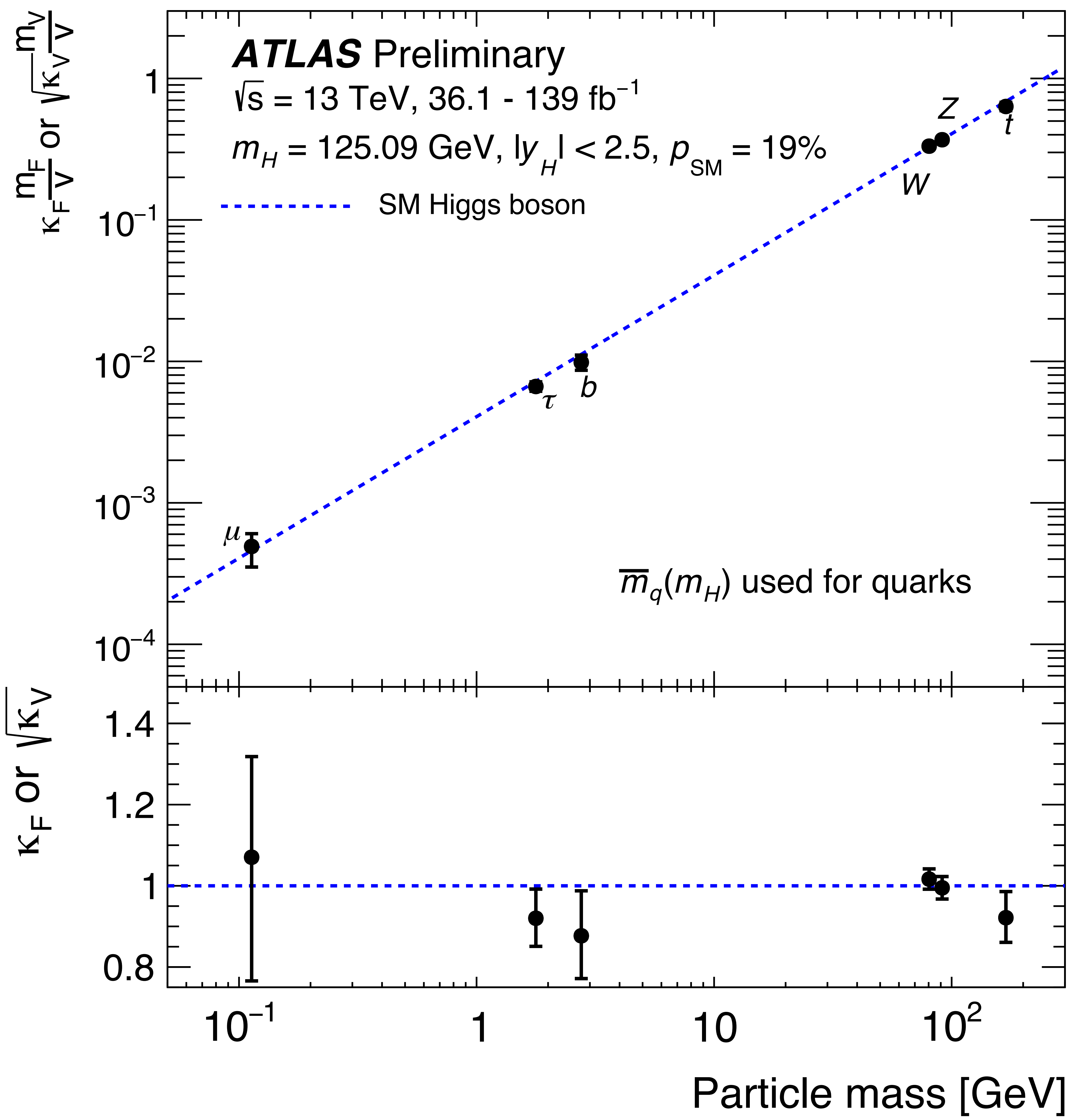
Coupling modifier vs. particle mass

- Assume no BSM contribution in loop-induced processes (ggF, H→$\gamma\gamma$ etc.) or total width
- Probe all the coupling strengths for which there is sensitivity
- Best fitted values:

improved by 9%~44% thanks to newly updated updated H → WW, (VBF, VH, ttH) bb and H → τ τ comparing to ATLAS- CONF-2020-027

Parameter	Result
κ_Z	0.99 ± 0.06
κ_W	1.03 ± 0.05
κ_b	0.88 ± 0.11
κ_t	0.92 ± 0.06
κ_τ	0.92 ± 0.07
κ_μ	$1.07\ ^{+0.25}_{-0.31}$

- **Good agreement with the SM within uncertainties across 3 orders of magnitude in particle mass!**

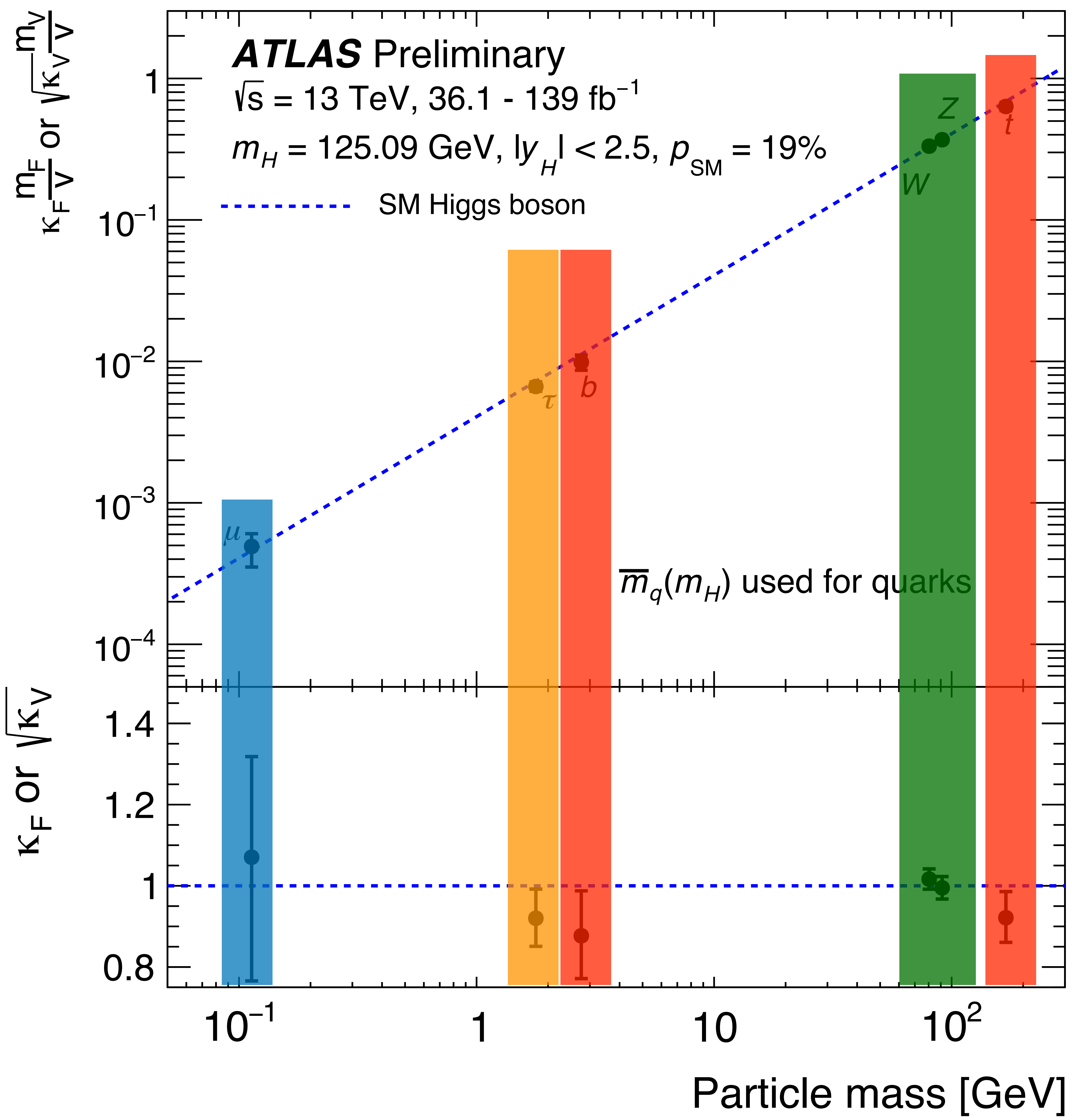


ATLAS-CONF-2021-053

Not enough!

- Coupling to Vector Bosons
- **Coupling to 3rd-gen. quarks and lepton**
- Coupling to 2nd-gen. lepton
- It is also accessible to 2nd-gen. quark, c quark as well:
    - Targeting VH, categories based on # of leptons and (c-)jet
    - Challenging: high QCD background / modelling / c-tag
    - μ < 26(31) x SM obs.(exp.) @ 95% CL and $|\kappa_c|<8.5$
    - Included in "ATLAS Higgs combination nature paper" for 10th anniversary for the Higgs discovery
    - Submitted to Nature, coming soon!

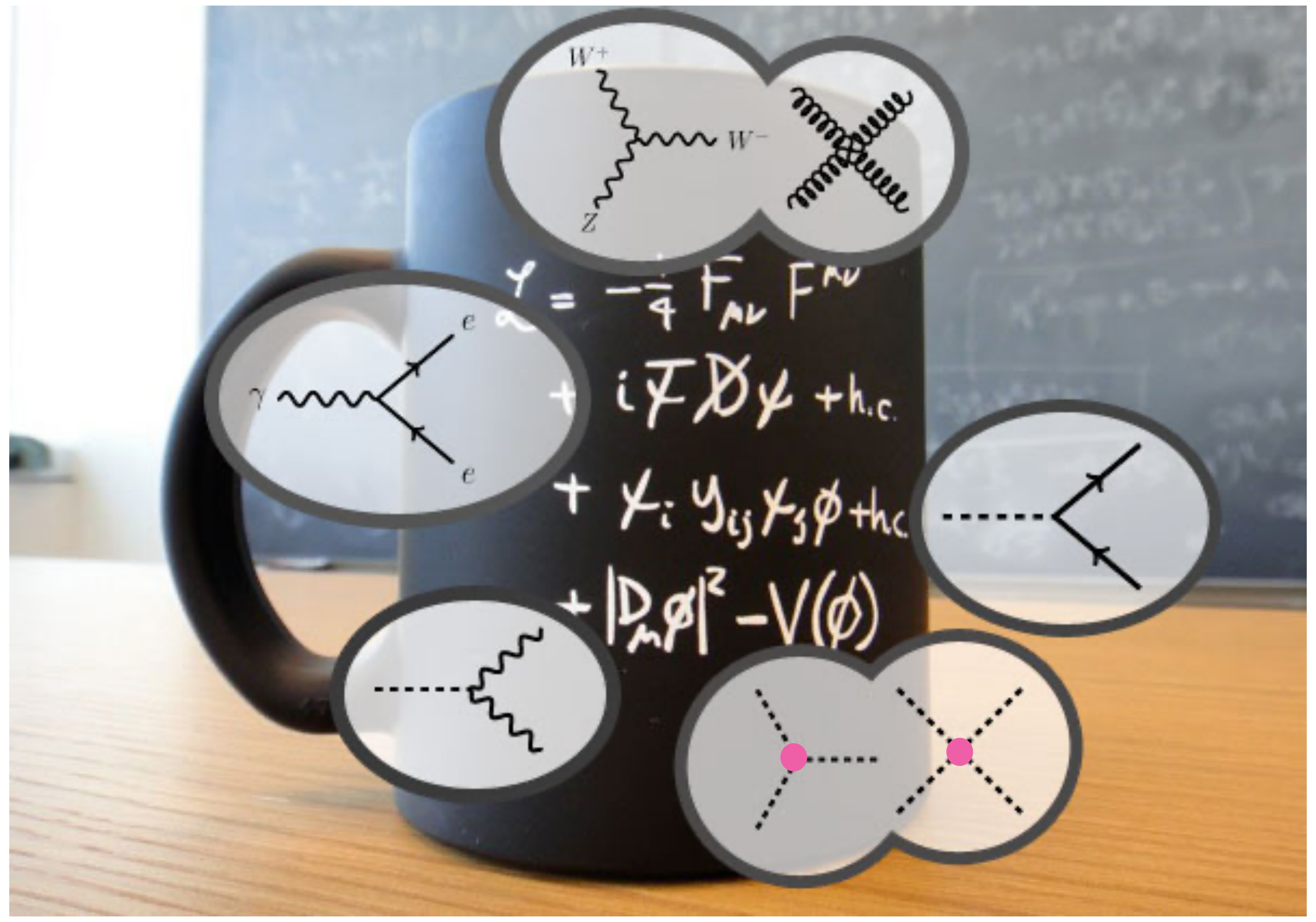
One may wonder how about Higgs self-coupling?



ATLAS-CONF-2021-053

Higgs self-couplings

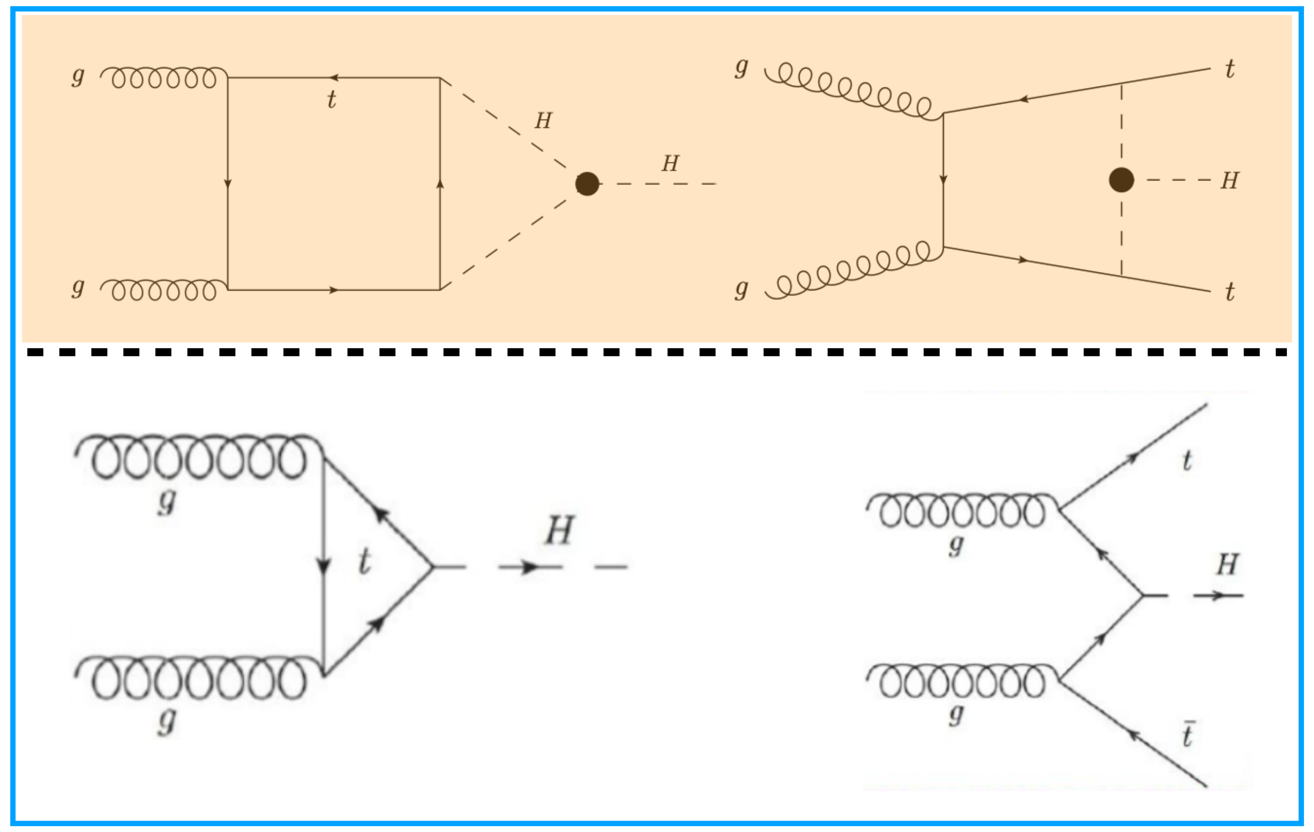
- Higgs couplings with the elemental particles (μ, τ, **b, W, Z, t**), compatible with SM prediction, as shown previously
- Higgs self-coupling is also crucial
  - Probe of the shape of the Higgs potential

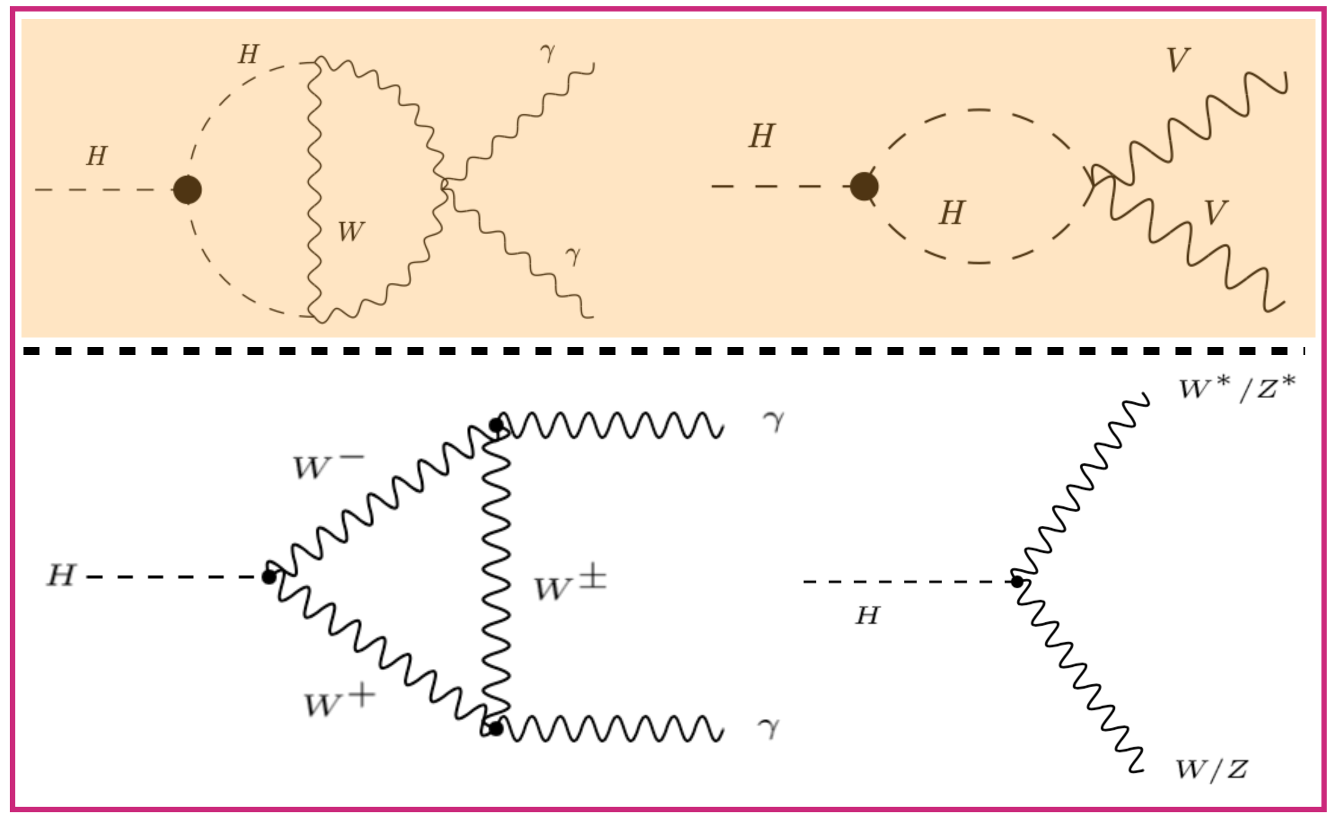


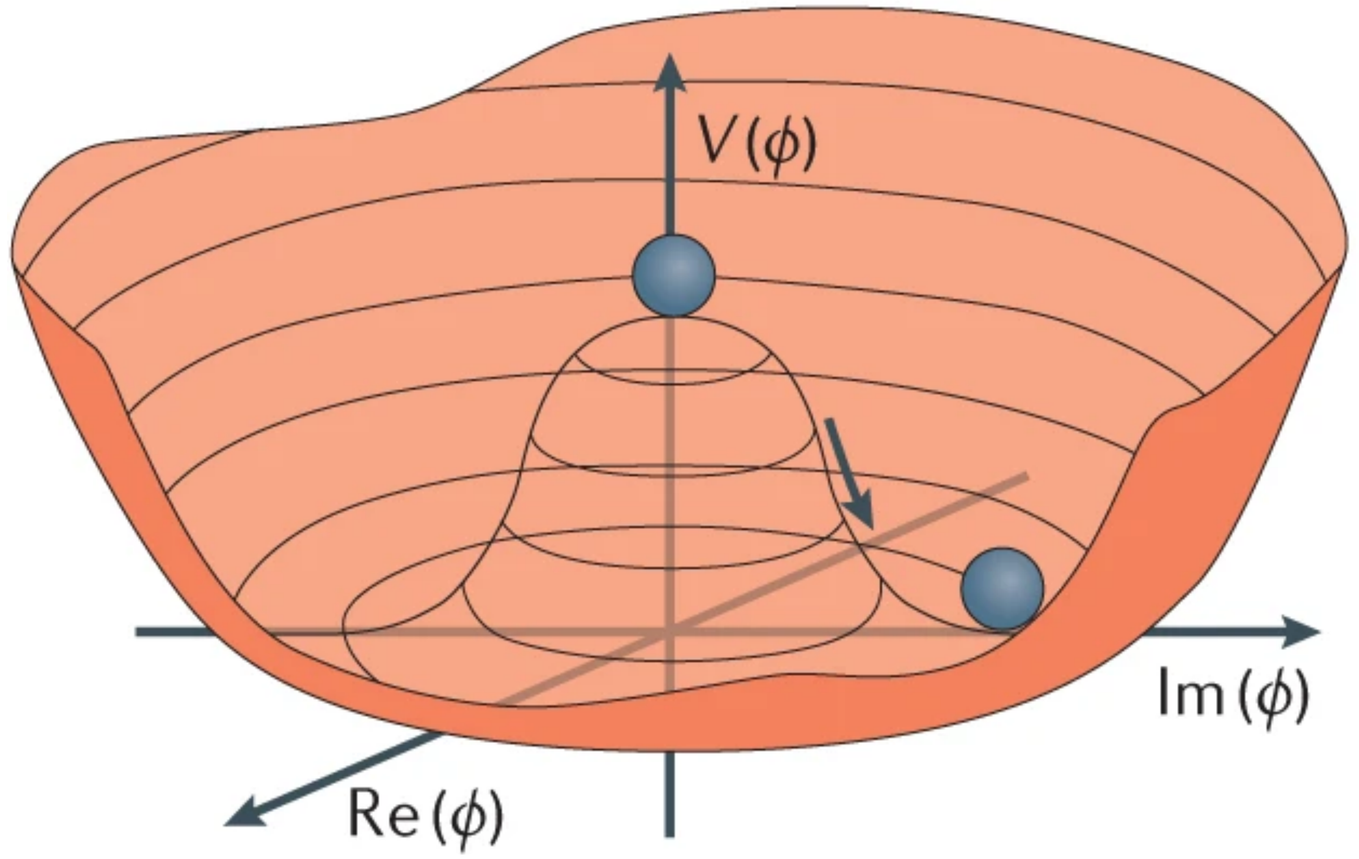
$$V = V_0 + \lambda v^2 h^2 + \lambda v h^3 + \frac{\lambda}{4} h^4 \qquad \lambda_{hhh} = \frac{m_h^2}{2v^2}$$

$$= V_0 + \frac{1}{2} m_h^2 h^2 + \frac{m_h^2}{2v^2} v h^3 + \frac{1}{4} \frac{m_h^2}{2v^2} h^4 \qquad \kappa_\lambda = \kappa_3 = \frac{\lambda_{HHH}}{\lambda_{HHH}^{SM}}$$

  - Standard Model (SM) prediction: the Higgs boson self coupling λ = ~ 0.13
  - However, the new physics can alter λ, thus measuring κ_λ is important for both studying the Higgs boson and probing physics Beyond the SM (BSM)
  - Single Higgs prod. / decay: self-coupling presents in **higher order diagram**





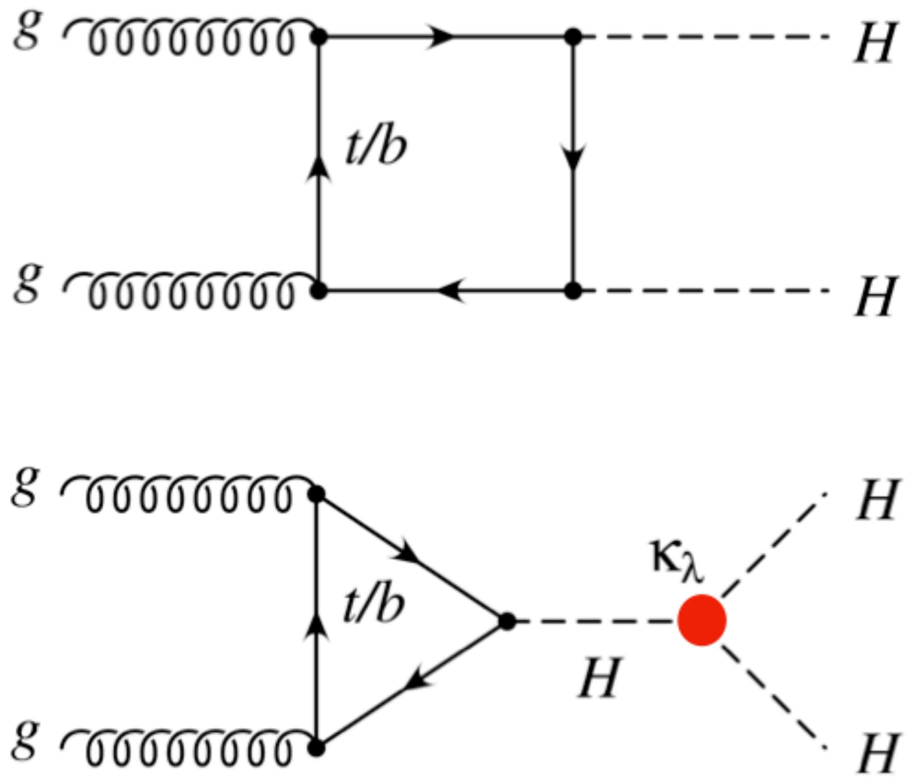


Indirect!

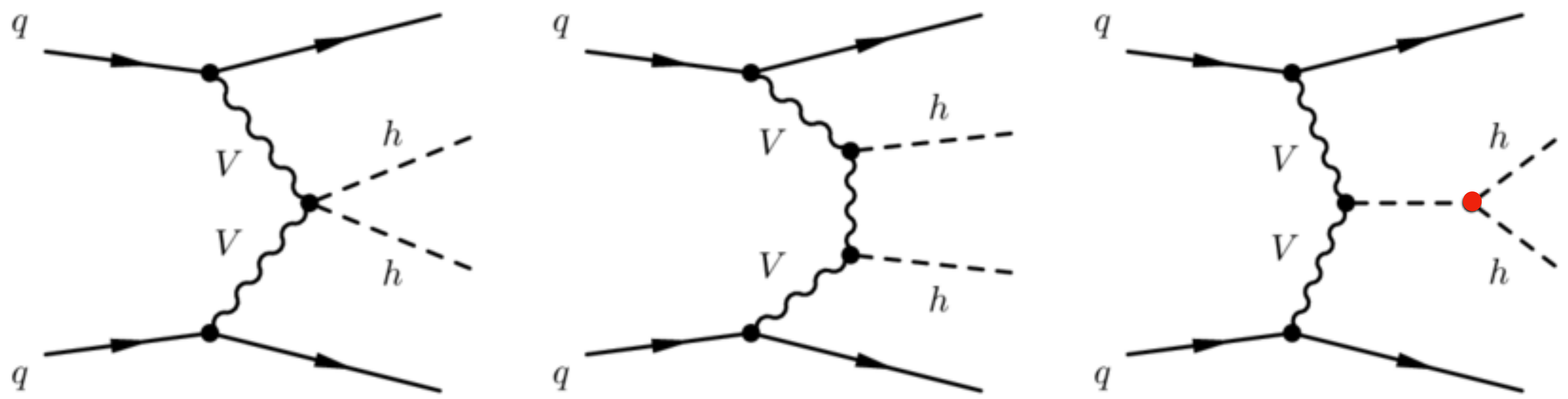
κ_λ in Di-Higgs production

- Di-Higgs production provides a direct access to λ

ggF HH
31.05 fb



VBF HH
1.73 fb



- Around 4k HH events expected to be produced during the Run 2, complementarity and combination of various decay channels to maximize the sensitivity

	bb	WW	ττ	ZZ	γγ
bb	33%				
WW	25%	4.6%			
ττ	7.4%	2.5%	0.39%		
ZZ	3.1%	1.2%	0.34%	0.076%	
γγ	0.26%	0.10%	0.029%	0.013%	0.0005%

Measurement performed by recent ATLAS Di-Higgs analysis:

- **HH→bbγγ** : ATLAS-CONF-2021-016
- **HH→bbττ** : ATLAS-CONF-2021-030

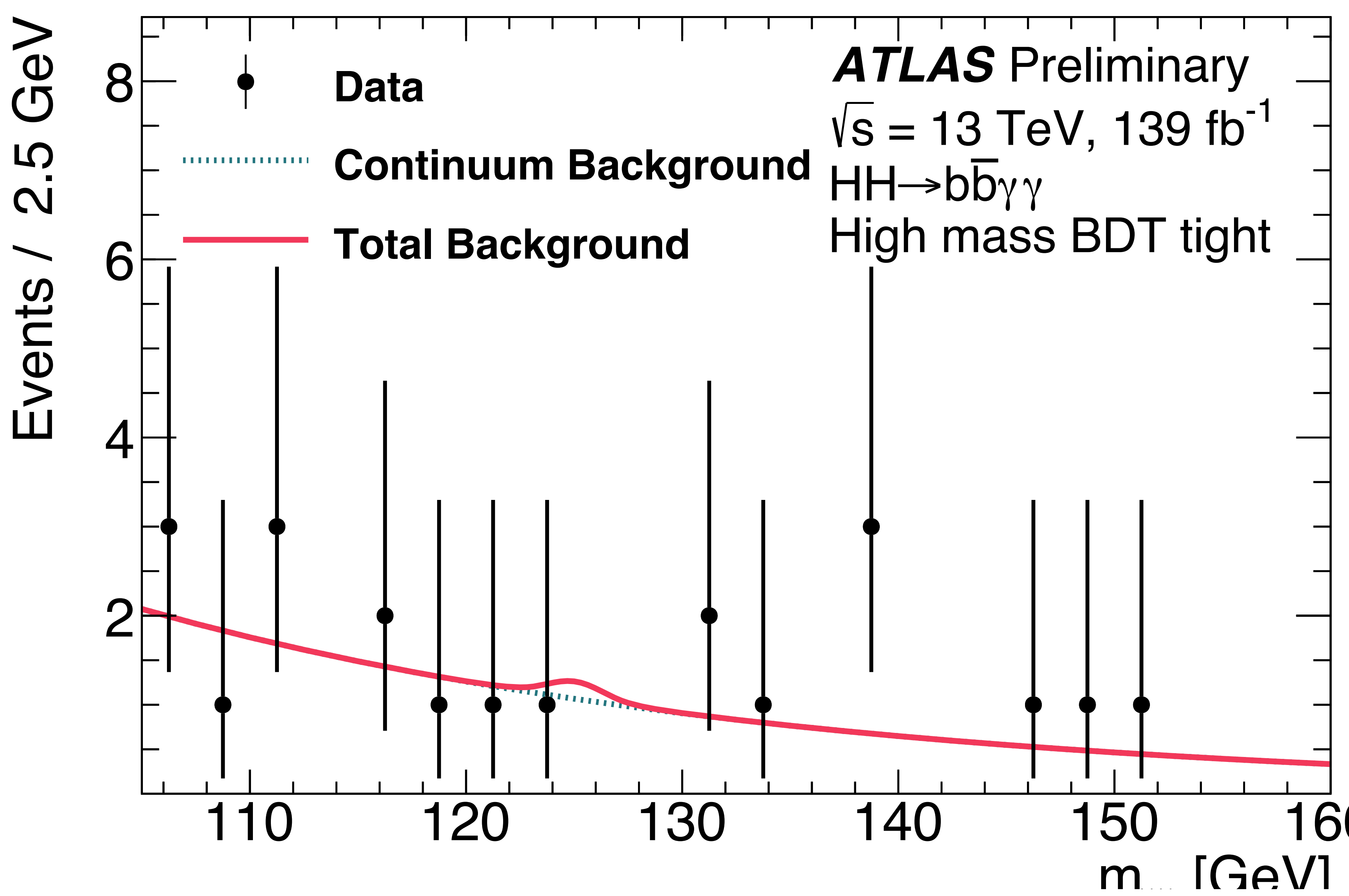
And:

- **Combination**: ATLAS-CONF-2021-052

HH→bbγγ

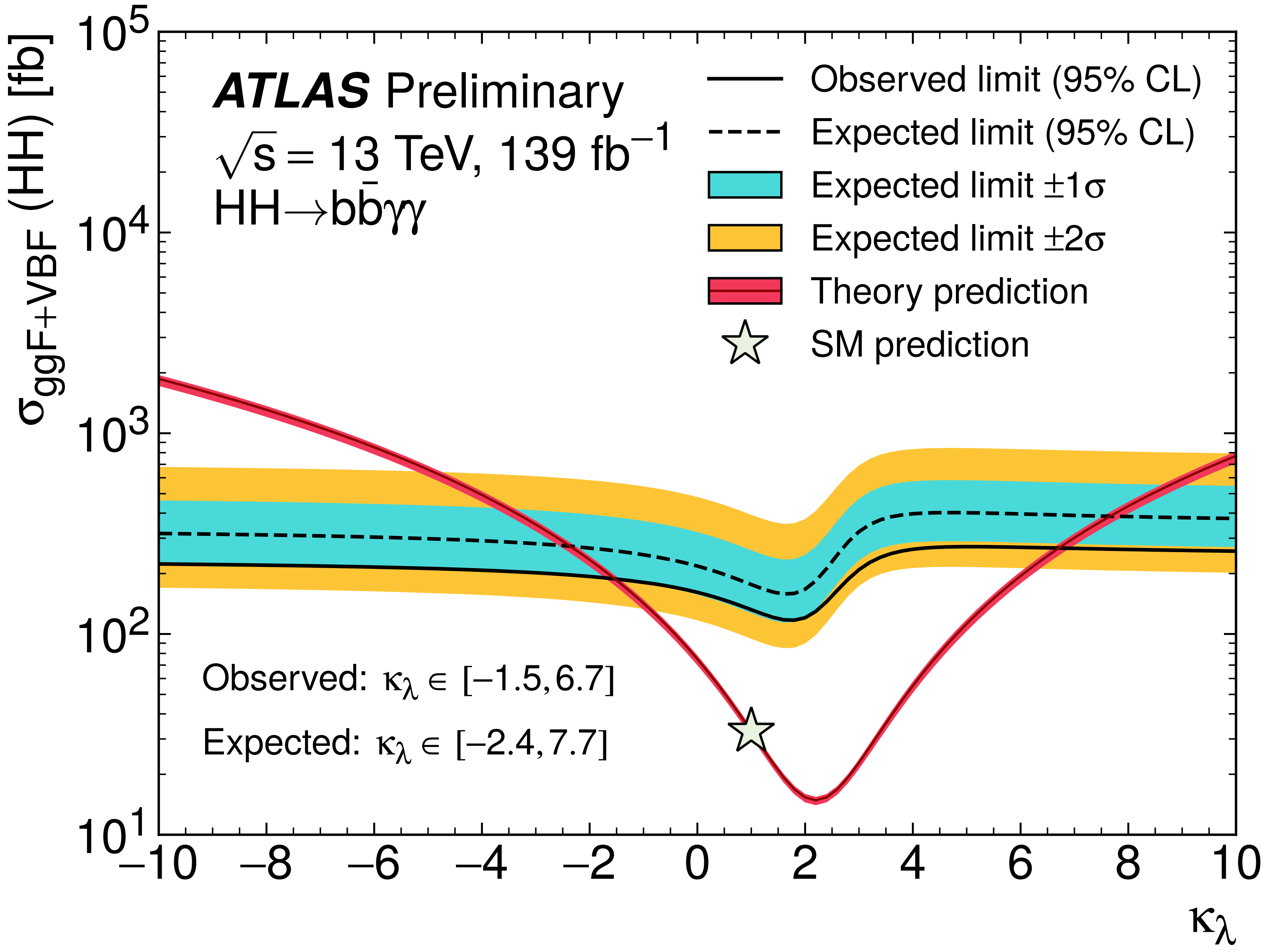
ATLAS-CONF-2021-016

- 0.26% of total HH BR, clean H→$\gamma\gamma$ signature for the trigger, selection and excellent resolution
- 2 photons with E_T > 35 (25) GeV; 2b- jets (DL1r, 77%)
- 105 GeV < $m_{\gamma\gamma}$ < 160 GeV → final discriminant for fitting simultaneously in 4 categories:
  - split by $m^*_{bb\gamma\gamma}$ ($= m_{bb\gamma\gamma} - m_{bb} - m_{\gamma\gamma} + 250$ **GeV**) at 350 GeV, and then further split by BDT into tight and loose



Obs. (exp.) upper limits on σ_{HH} are set as 4.1 (5.5) times the SM prediction at 95% CL

5× improvement comparing with previous result (25×SM), 3× due to analysis improvement



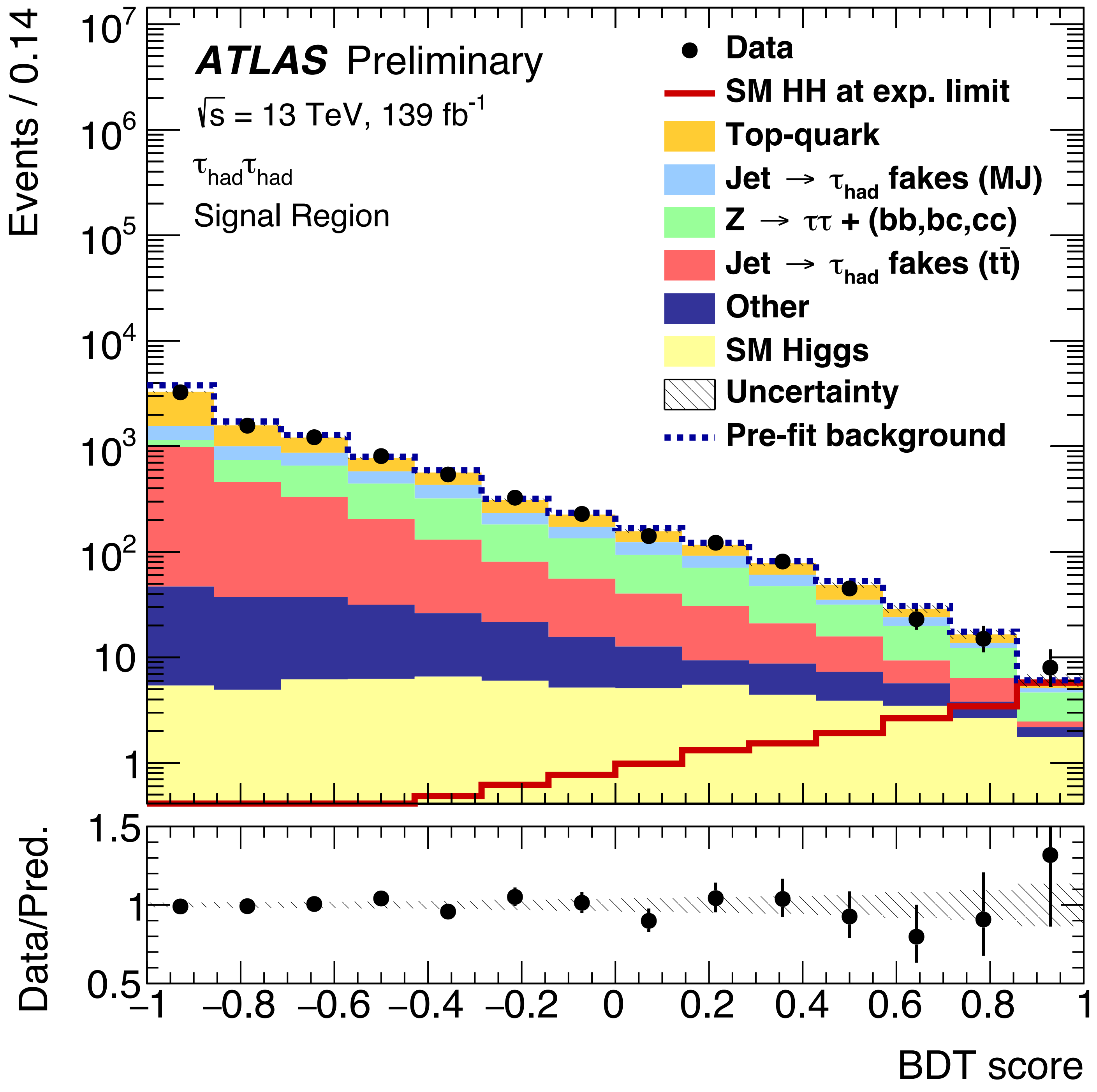
Obs. (exp.) constraint on κ_λ is $-1.5 \leq \kappa_\lambda \leq 6.7$ ($-2.4 \leq \kappa_\lambda \leq 7.7$) at 95%CL

Previous limits (36.1 fb^{-1} analysis): $-8 < \kappa_\lambda < 13$

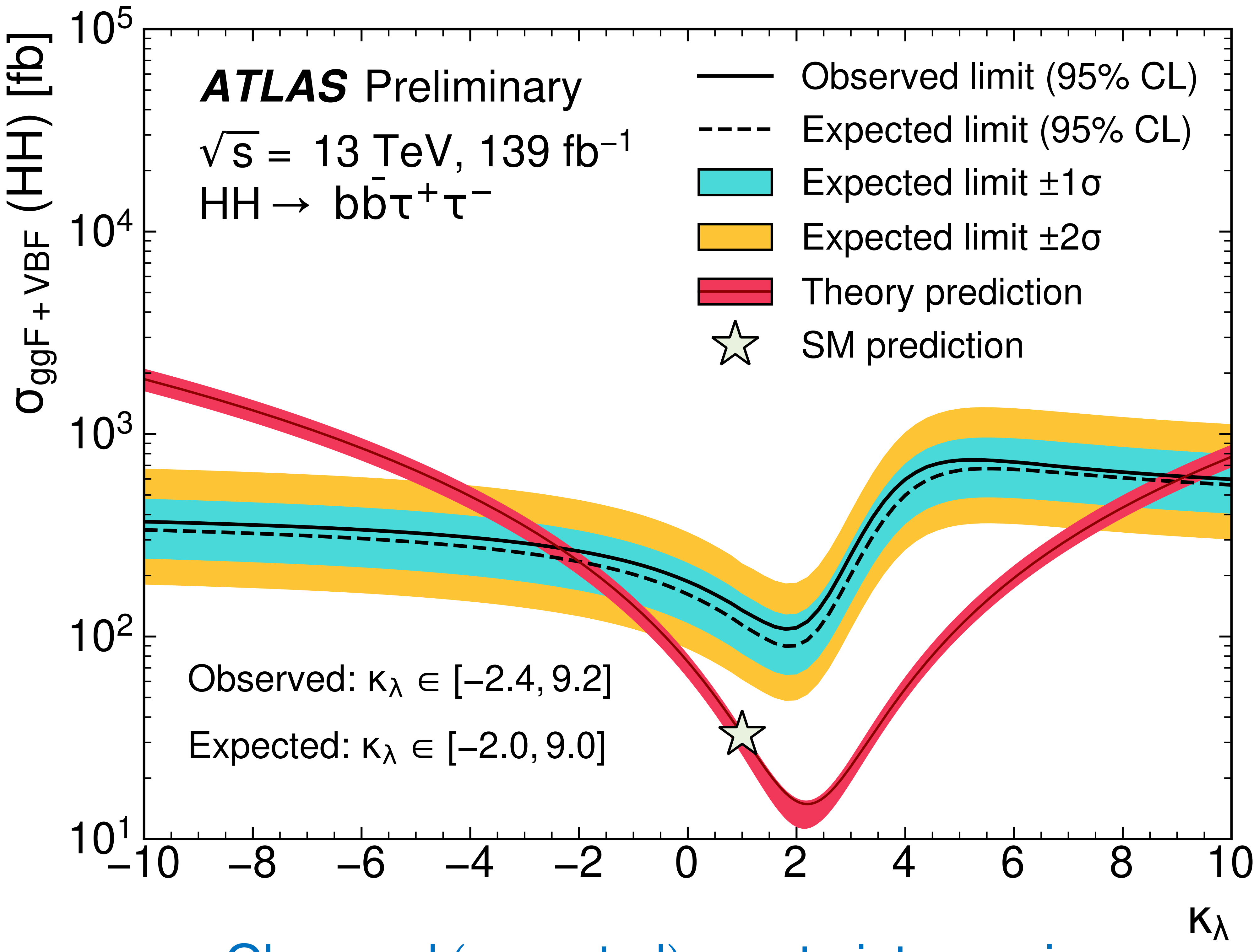
HH→bbττ

ATLAS-CONF-2021-030

- 7.4% of the total HH branching ratio (BR): relatively clean signature and low background
- Signal signature: two b-tagged jets (DL1r tagger, 77%) and $\tau_{had}\tau_{had}$ / $\tau_{lep}\tau_{had}$ with opposite charge
- Multivariate (MVA) method used for signal and background separation



Observed (expected) upper limits on the SM HH production cross-section are set as 4.7 (3.9) times the SM prediction at 95% CL



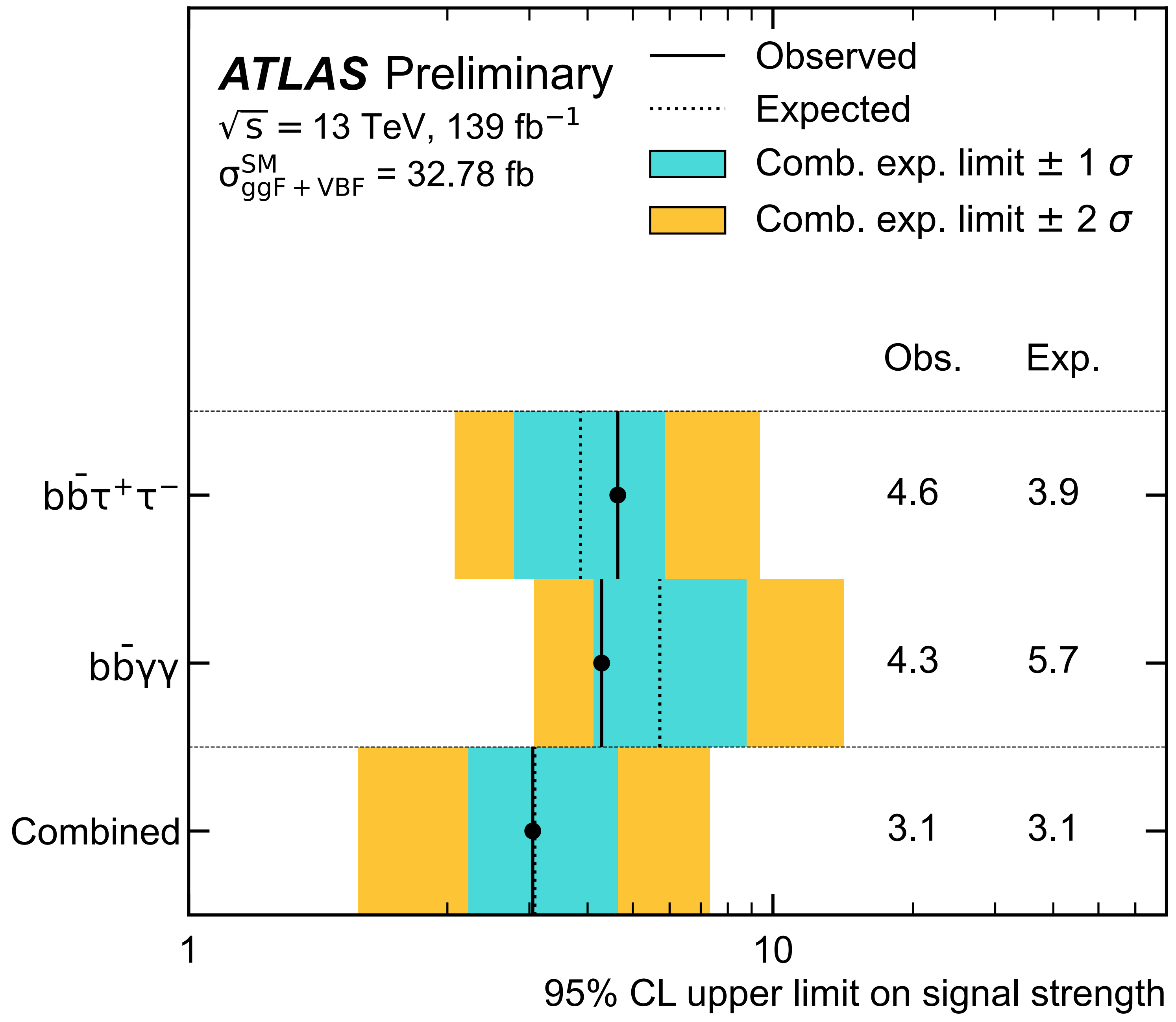
Observed (expected) constraint on κ_λ is $-2.4 \leq \kappa_\lambda \leq 9.2$ ($-2.0 \leq \kappa_\lambda \leq 9.0$) at 95% CL

κ_λ Measurement from the HH combination

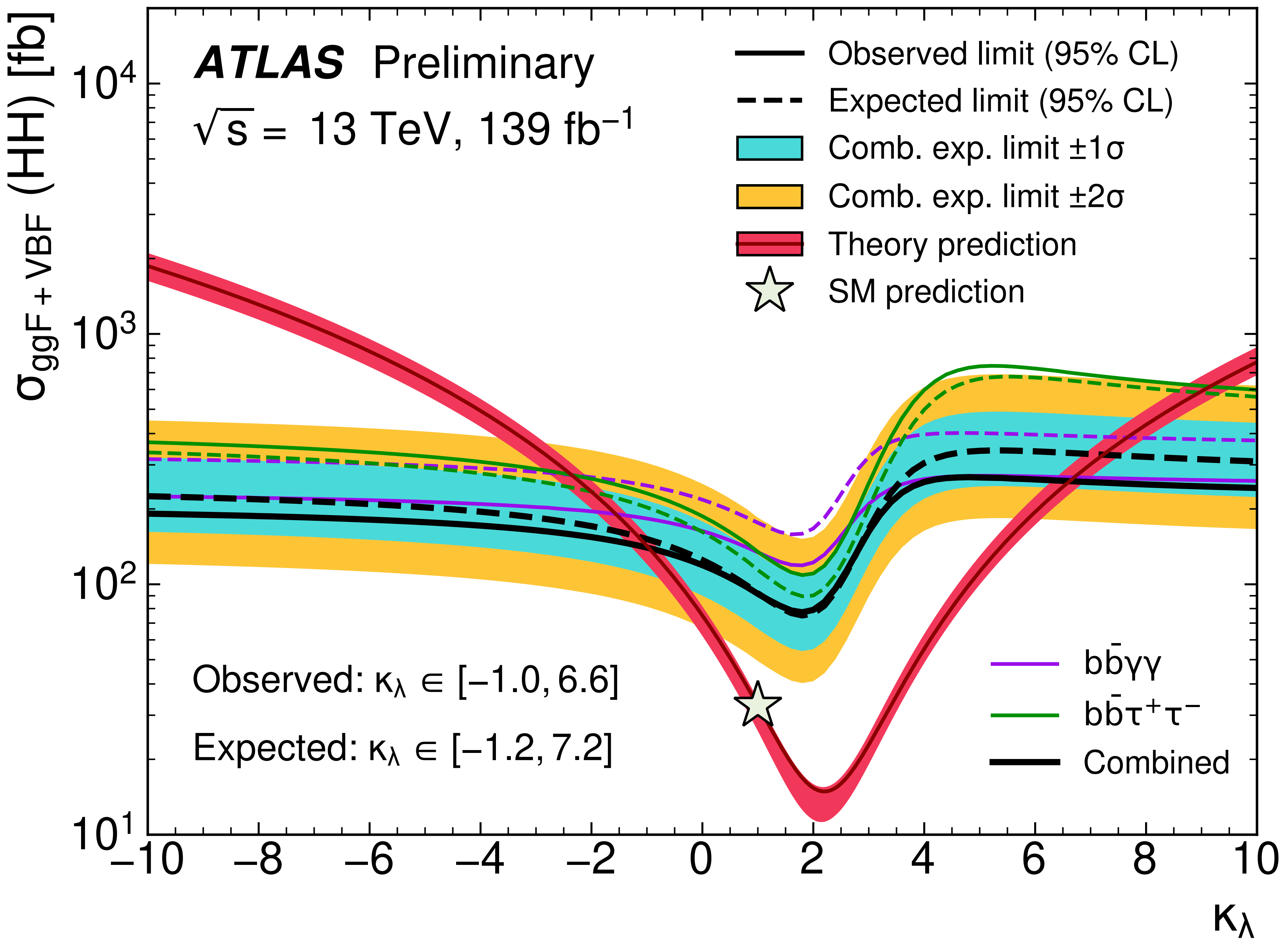
- Performed statistical combination for different HH analyses to maximize sensitivity to SM and BSM HH production
  - including $bb\tau\tau$ and $bb\gamma\gamma$: $bb\tau\tau$ has better sensitivity at around κ_λ = 1 due to more boosted signal and higher BR, while $bb\gamma\gamma$ outperforms at high κ_λ values due to high acceptance

ATLAS-CONF-2021-052

  - Systematics correlated where appropriate (like luminosity, flavor tagging, signal theory uncertainties, etc)



Obs. (exp.) upper limits on σ_{HH} are set as 3.1 (3.1) times SM prediction

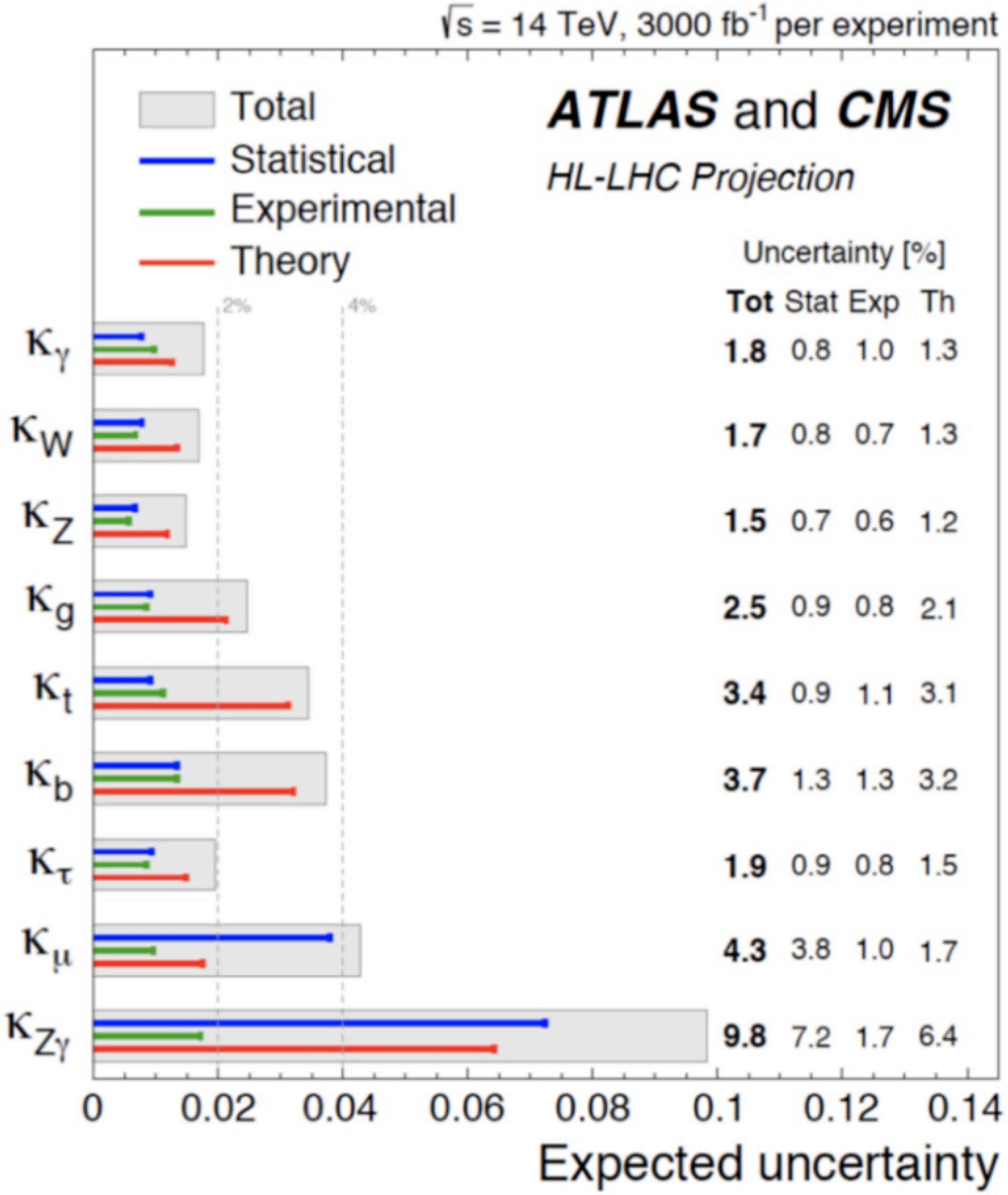


Obs. (exp.) constraint on κ_λ is $-1.0 \leq \kappa_\lambda \leq 6.6 (-1.2 \leq \kappa_\lambda \leq 7.2)$

The best constraints on HH signal strength and κ_λ up to date!

Conclusions and outlook

- Combination of analyses based on up to 139 fb^{-1} of Run 2 data improves precision ATLAS-CONF-2021-053
- All measurements in good agreement with the SM within current uncertainty, but still space for new physics.
- The latest HH searches with bb$\tau\tau$ and bb$\gamma\gamma$ presented, as well as the HH combination ATLAS-CONF-2021-052
- Significant improvement on the results comparing with the previous publications:
  the best constraints on HH signal strength and κ_λ is shown!
- More analyses and combinations in progress using full Run-2 statistics!
  - Full Run-2 and Run-3 will amount to 350-400 fb-1
  - Improvements of analysis methods and treatment of systematics
- The HL-LHC could dramatically expand our Higgs physics reach
  - More challenging environment but 2-4 % precision of the couplings.

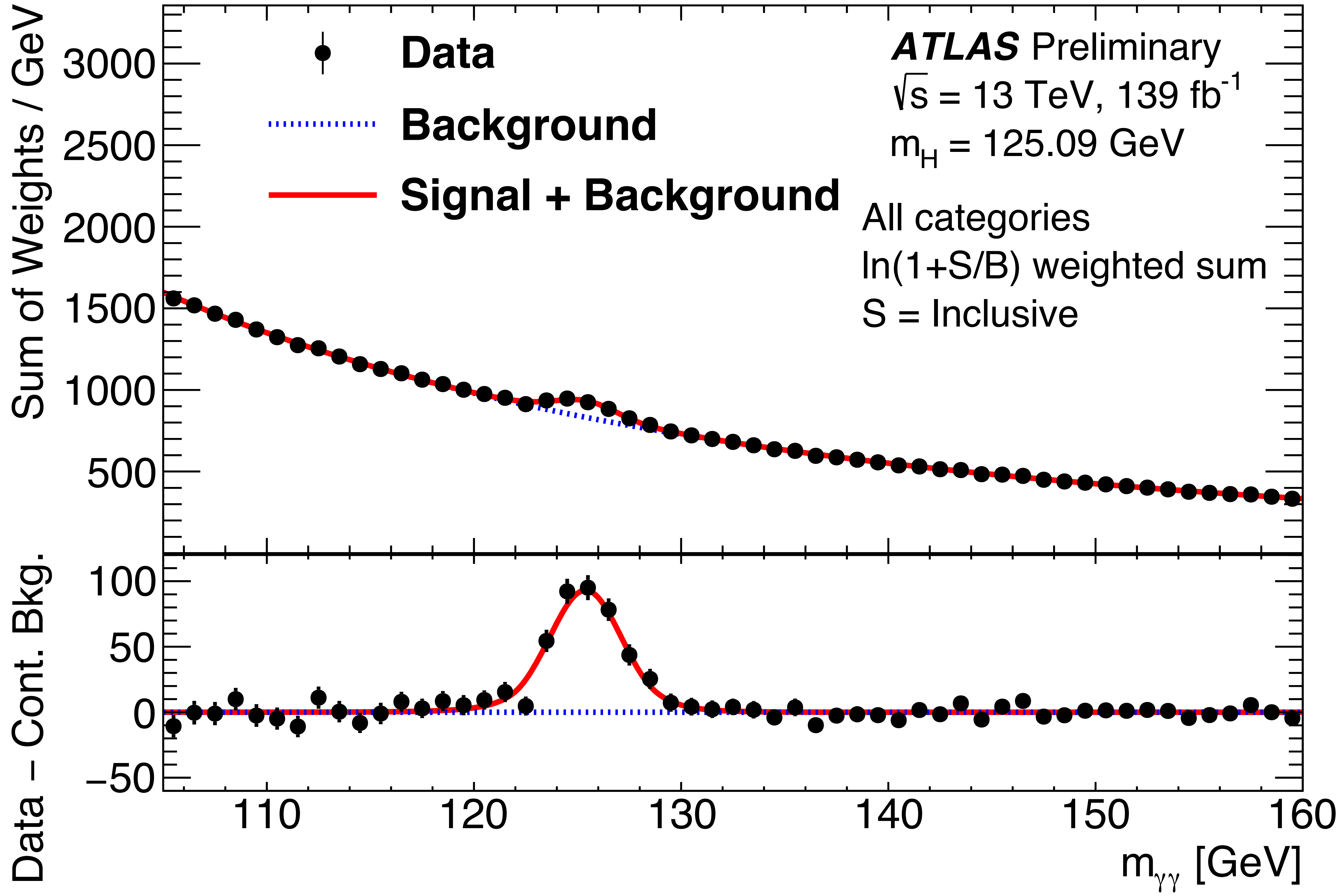


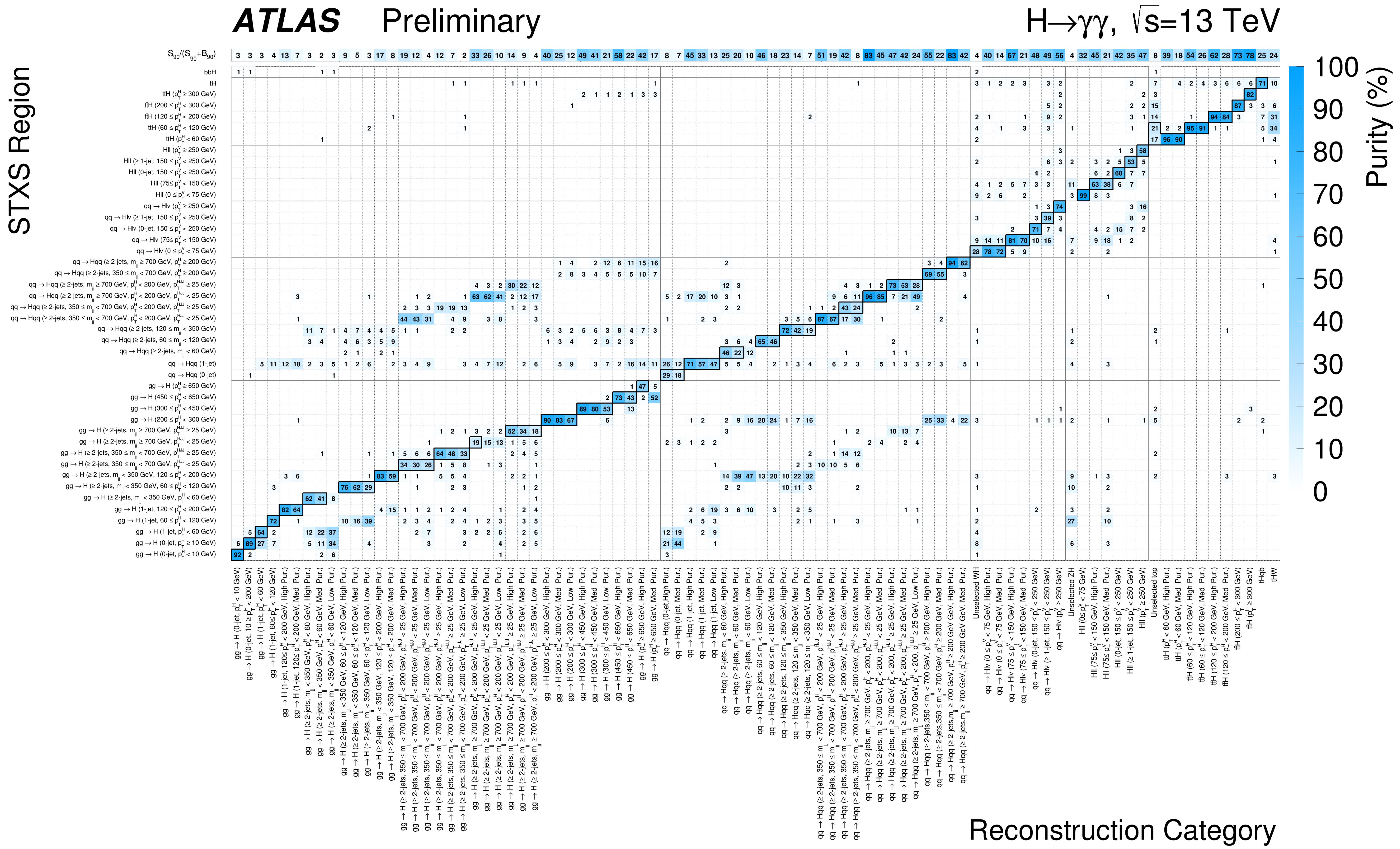
Backup and bonus

Reference

- Combined measurements of Higgs boson production and decay using up to 139-1 of proton - proton collision data at $\sqrt{s}$ = 13 TeV collected with the ATLAS experiment ATLAS-CONF-2021-053
- Hyy: ATLAS-CONF-2020-026
- HZZ: Eur. Phys. J. C 80 (2020) 957
- ttHWW/ZZ/tautau: Phys. Rev. D 97 (2018) 072003
- HWW: ATLAS-CONF-2021-014
- $H \to \tau\tau$: ATLAS-CONF-2021-044
- VHbb: Eur. Phys. J. C 81 (2021) 178 Phys. Lett. B 816 (2021) 136204 ATLAS-CONF-2021-051
- VBFbb: Eur. Phys. J. C. 81 (2021) 537
- ttHbb: CERN-EP-2021-202
- Hmumu: Phys. Lett. B 812 (2021) 135980
- HZy: Phys. Lett. B 809 (2020) 135754
- VBFHinvisible: ATLAS-CONF-2020-008

H→γγ (139 fb^{-1})

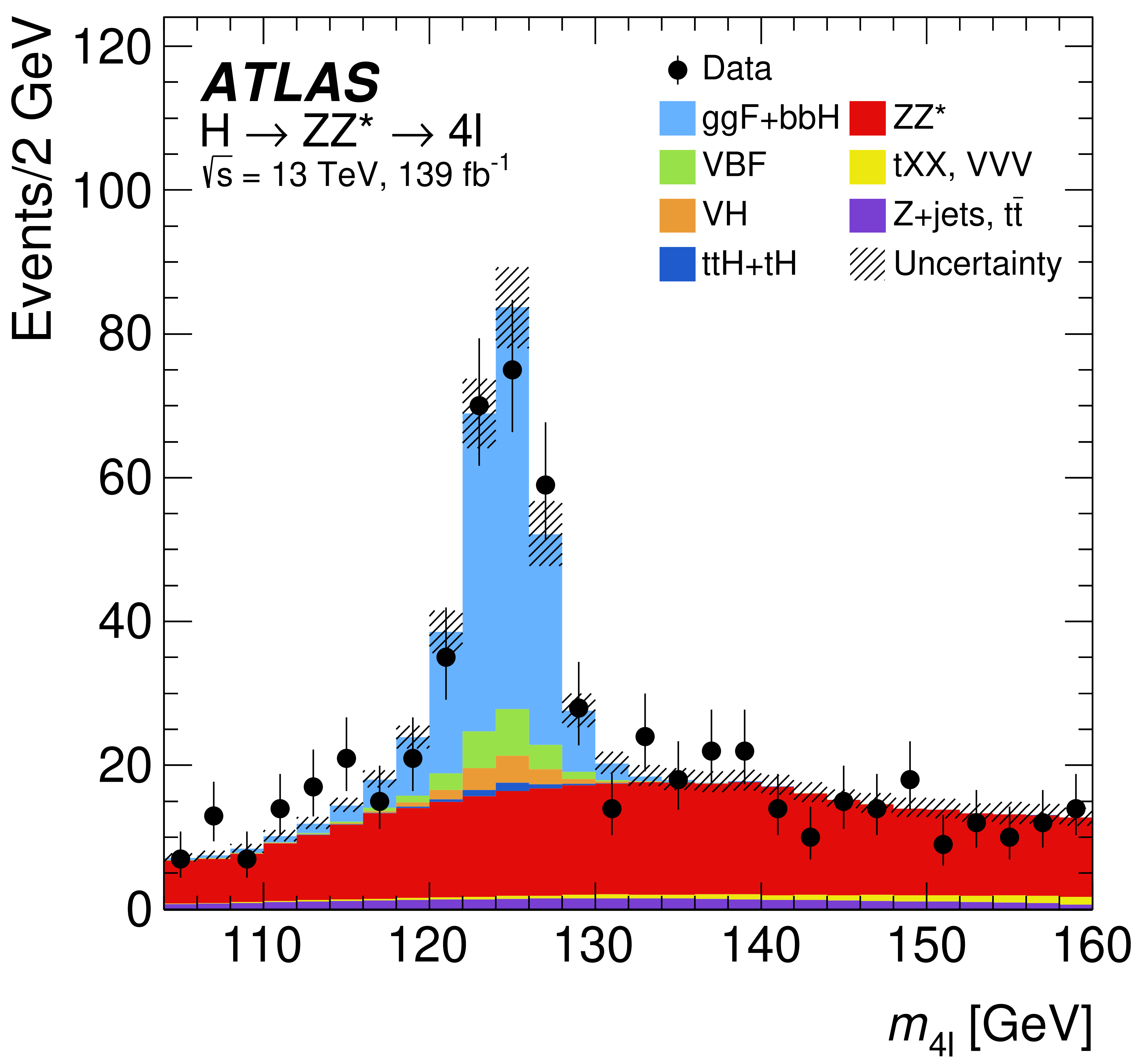


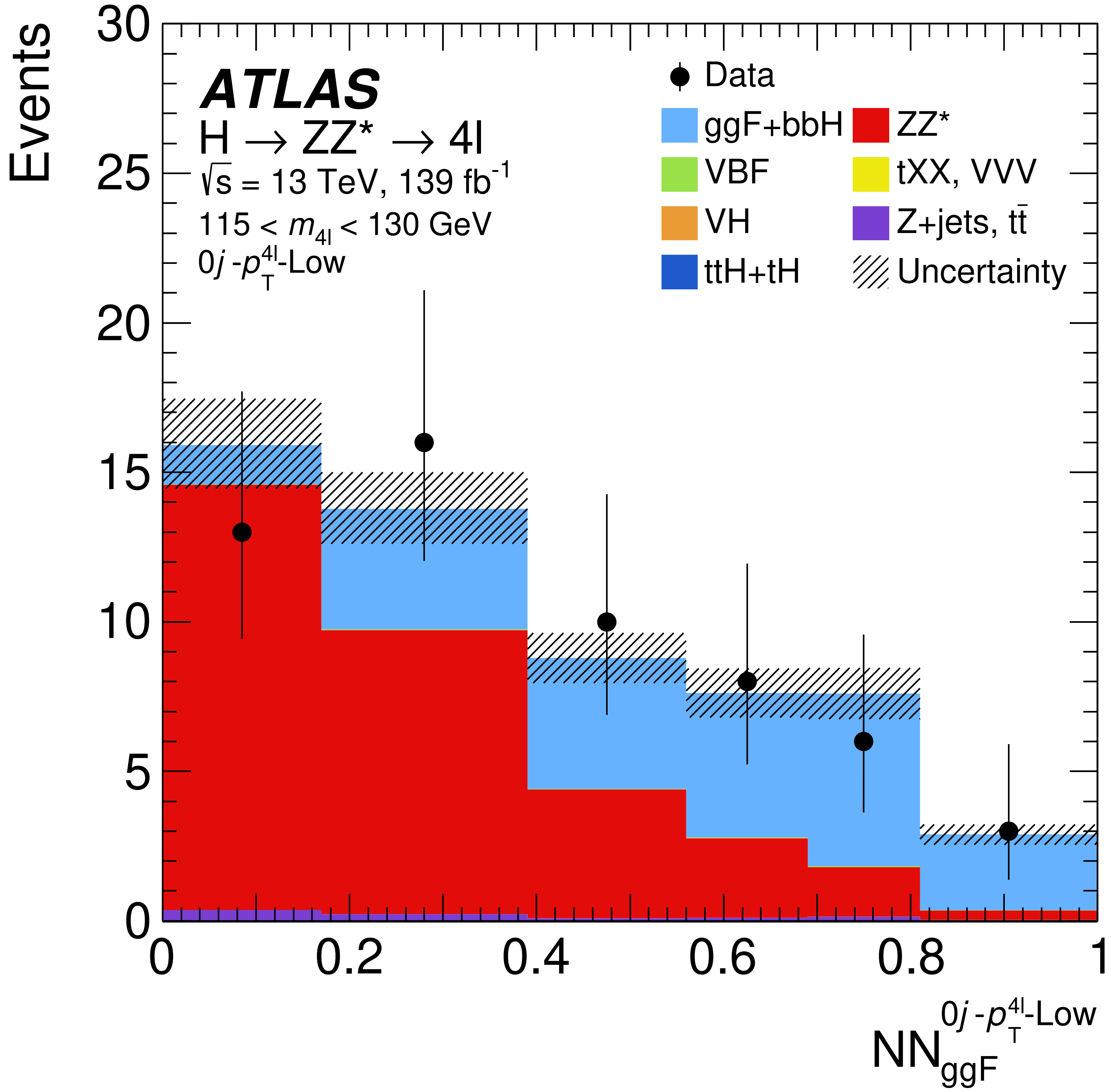


- Large background, but excellent sensitivity ensured by very good photon efficiency and resolution
- Analysis categories designed to isolate out events from different production modes
- Also explores different kinematic regions within production modes

ATLAS-CONF-2020-026

H→ZZ→4l (l=e, μ) (139 fb^{-1})



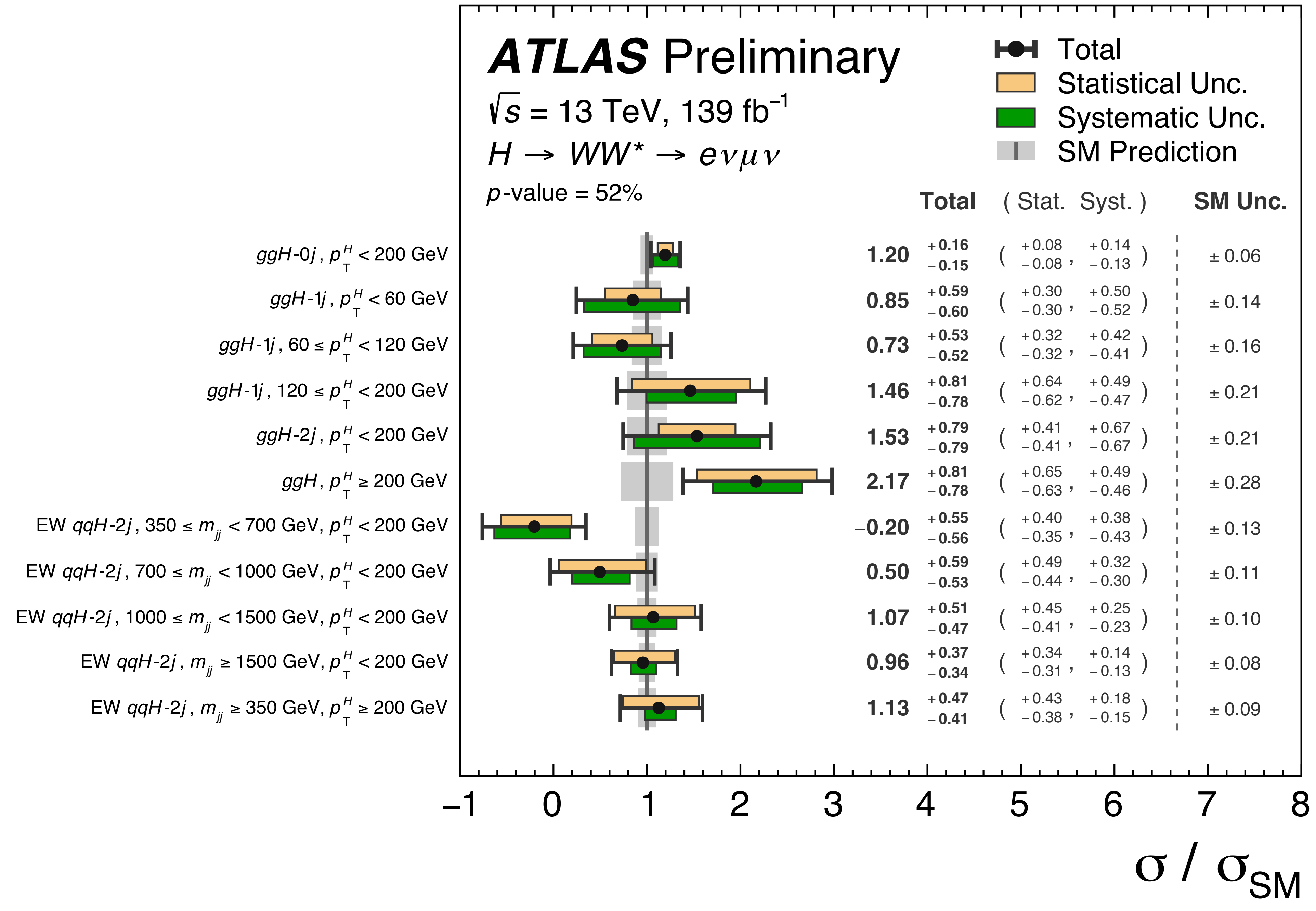


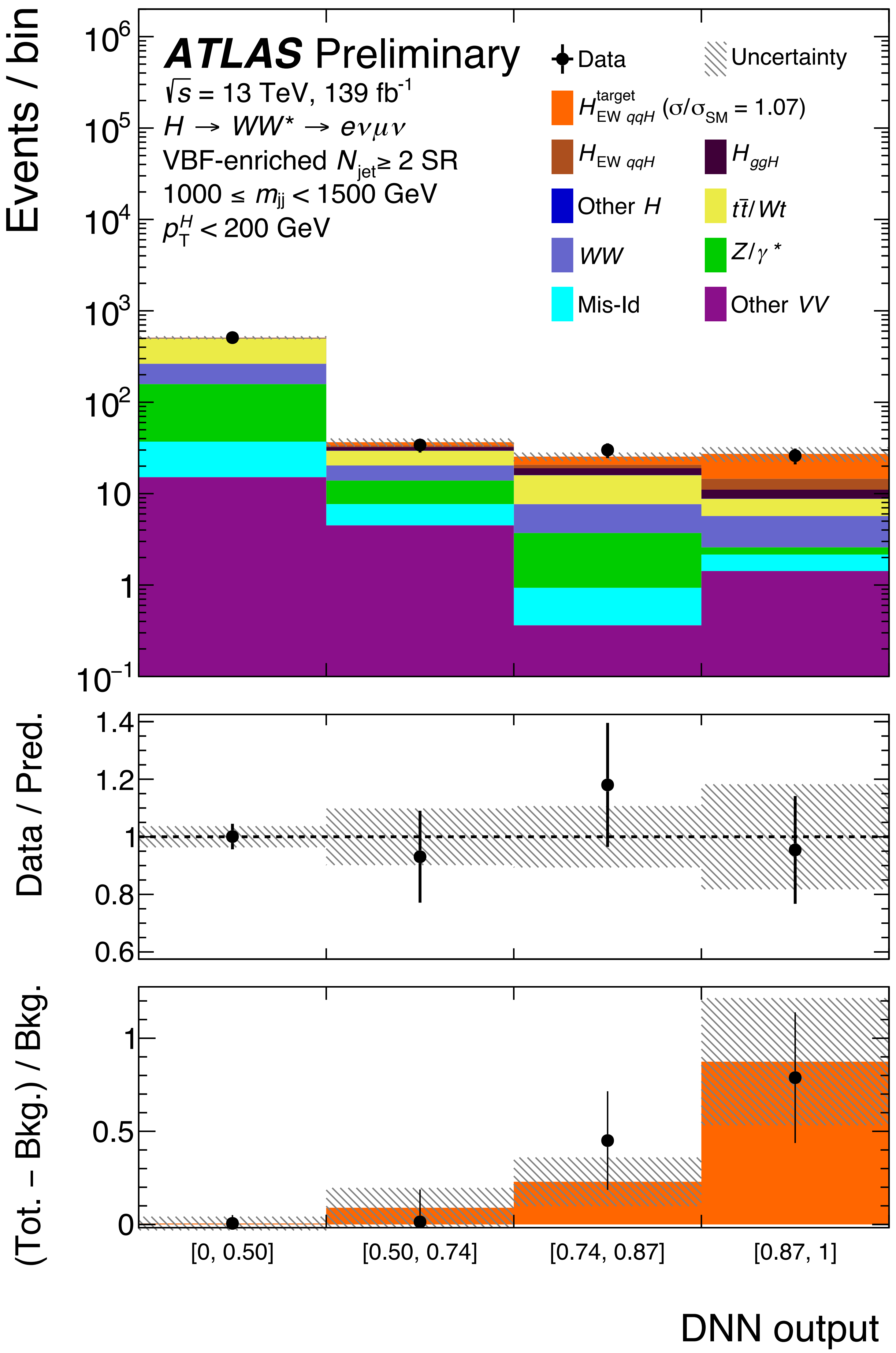
- Very clean channel with high S/B
- Neural networks (NN) used to further suppress bkg. and increase sensitivity to different production modes

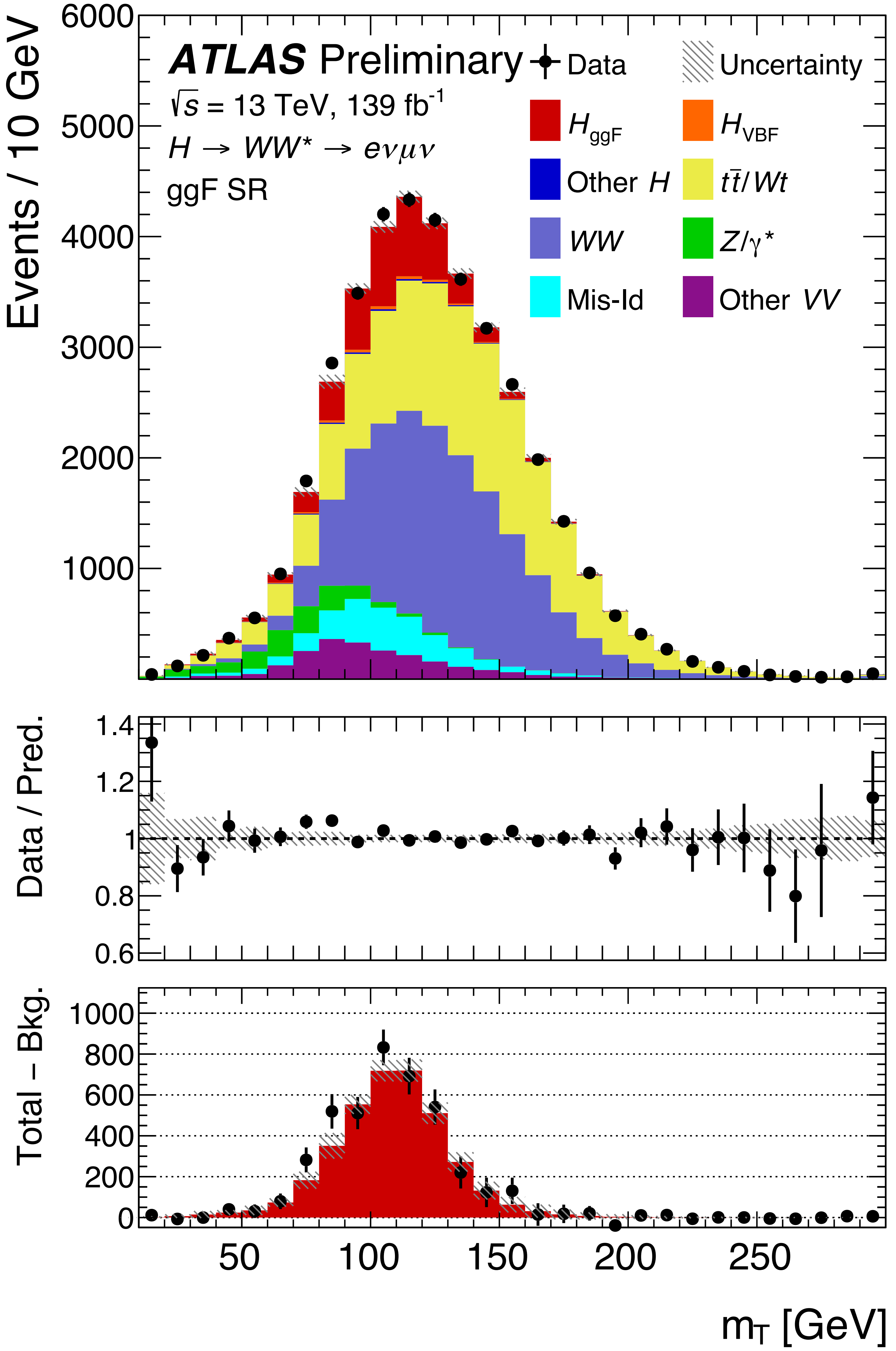
Eur. Phys. J. C 80 (2020) 957

H→WW→eνμν (139 fb^{-1})

- Vetoing events with jets tagged as from b-quark in signal region (suppress ttbar bkg.)
- Dedicated control regions for main background: WW, top quark, $Z/\gamma^{*}\to\tau\ \tau$
- Train DNN to separate VBF from ggF and other bkg in VBF enriched region







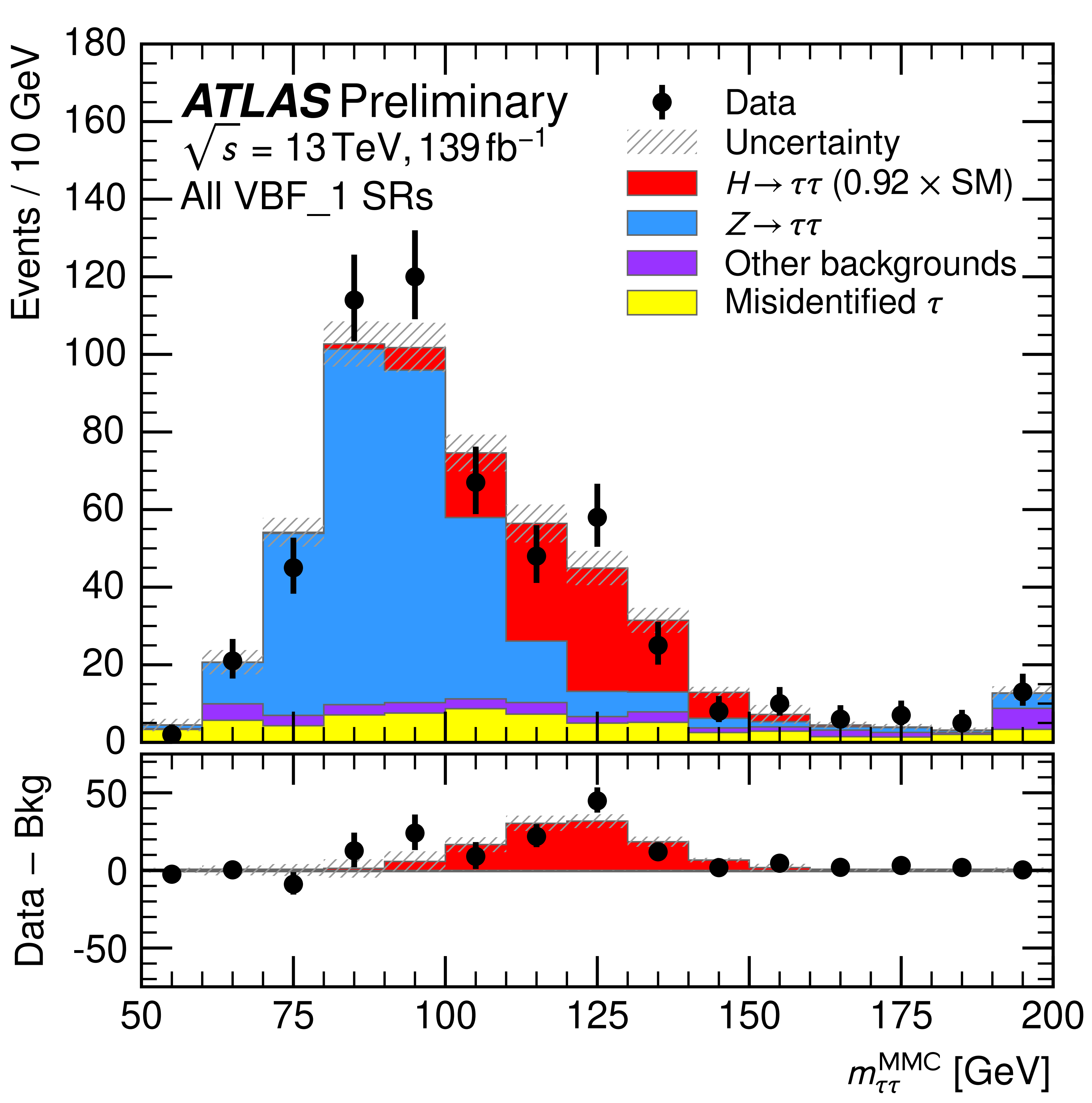
ATLAS-CONF-2021-014

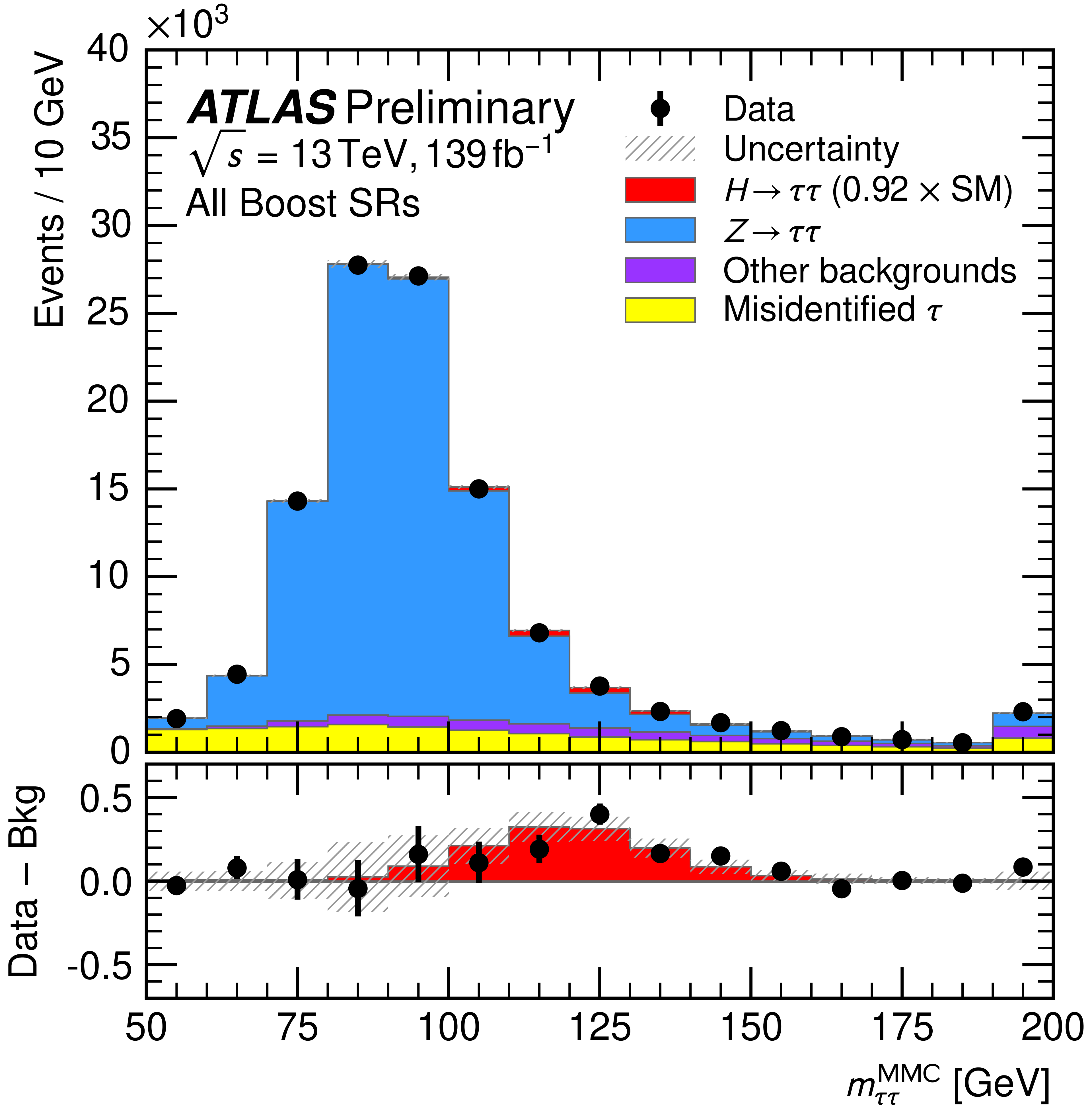
H→ττ (139 fb^{-1})

- Exploit three di-τ decay channels ($\tau_e\tau_\mu$, $\tau_{lep}\tau_{had}$, $\tau_{had}\tau_{had}$)

ATLAS-CONF-2021-044

- Analysis targeting VBF and boosted ggF signal events to suppress the Z→ττ backgrounds

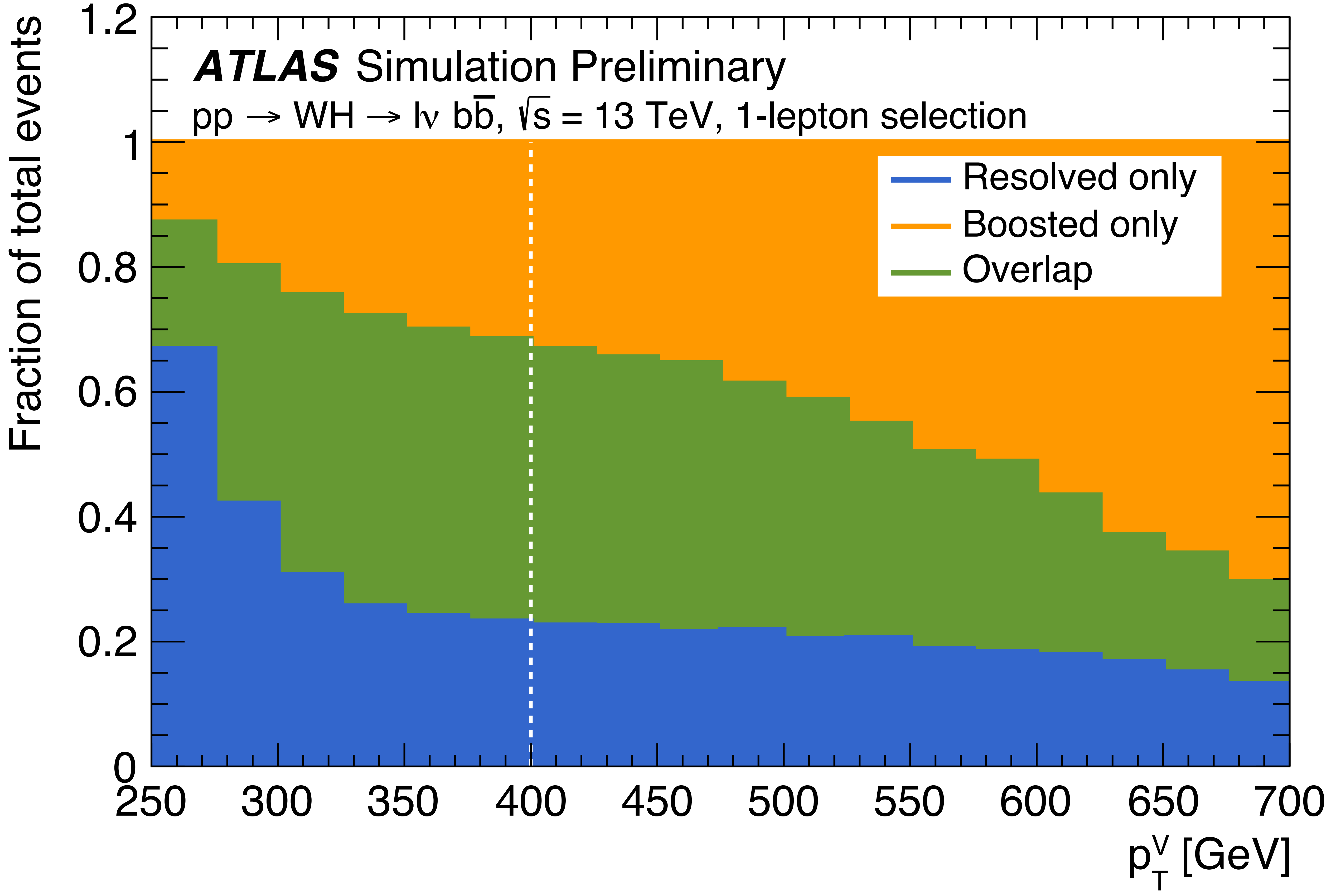


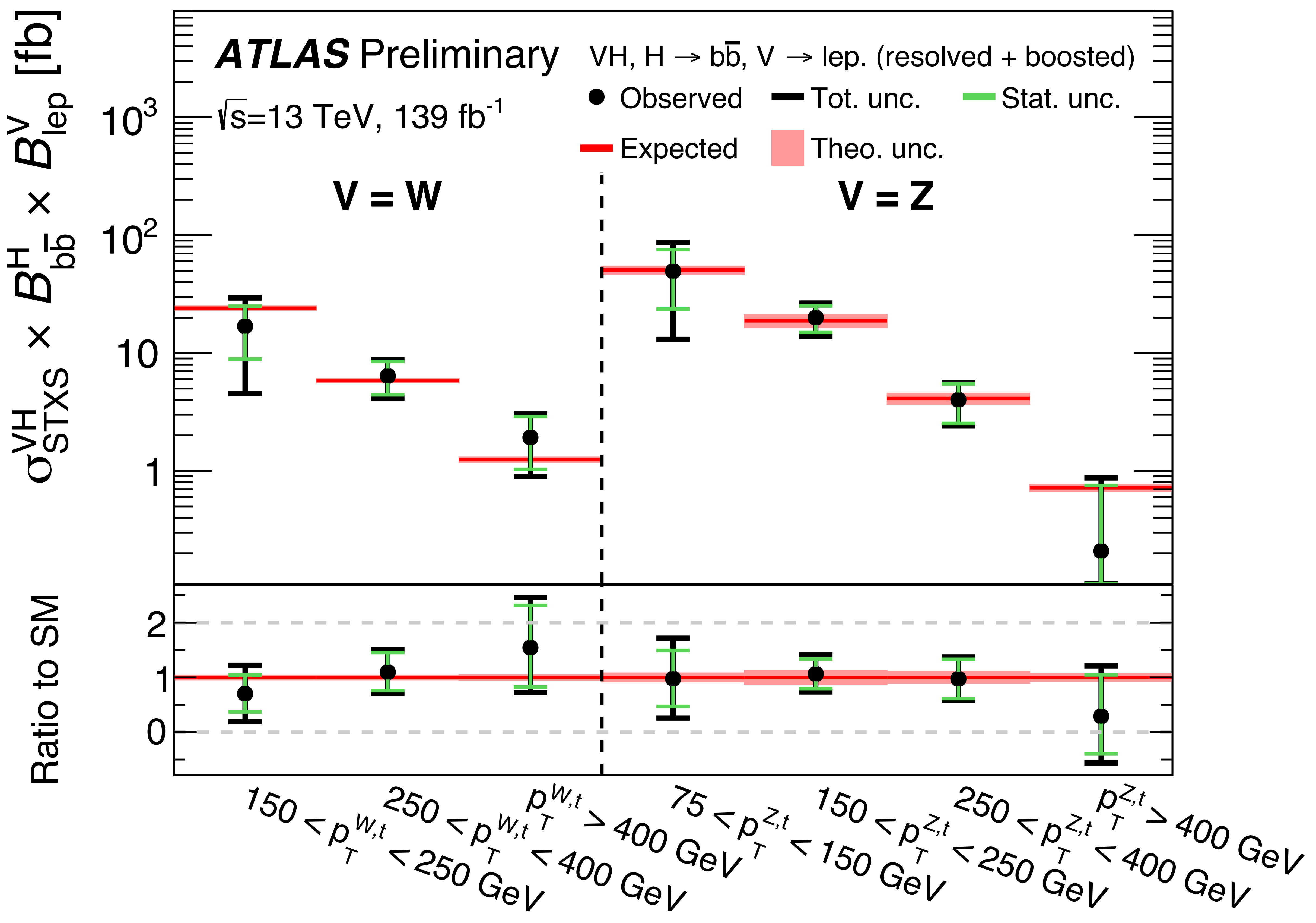


VH, H→bb (139 fb^{-1})

ATLAS-CONF-2021-051

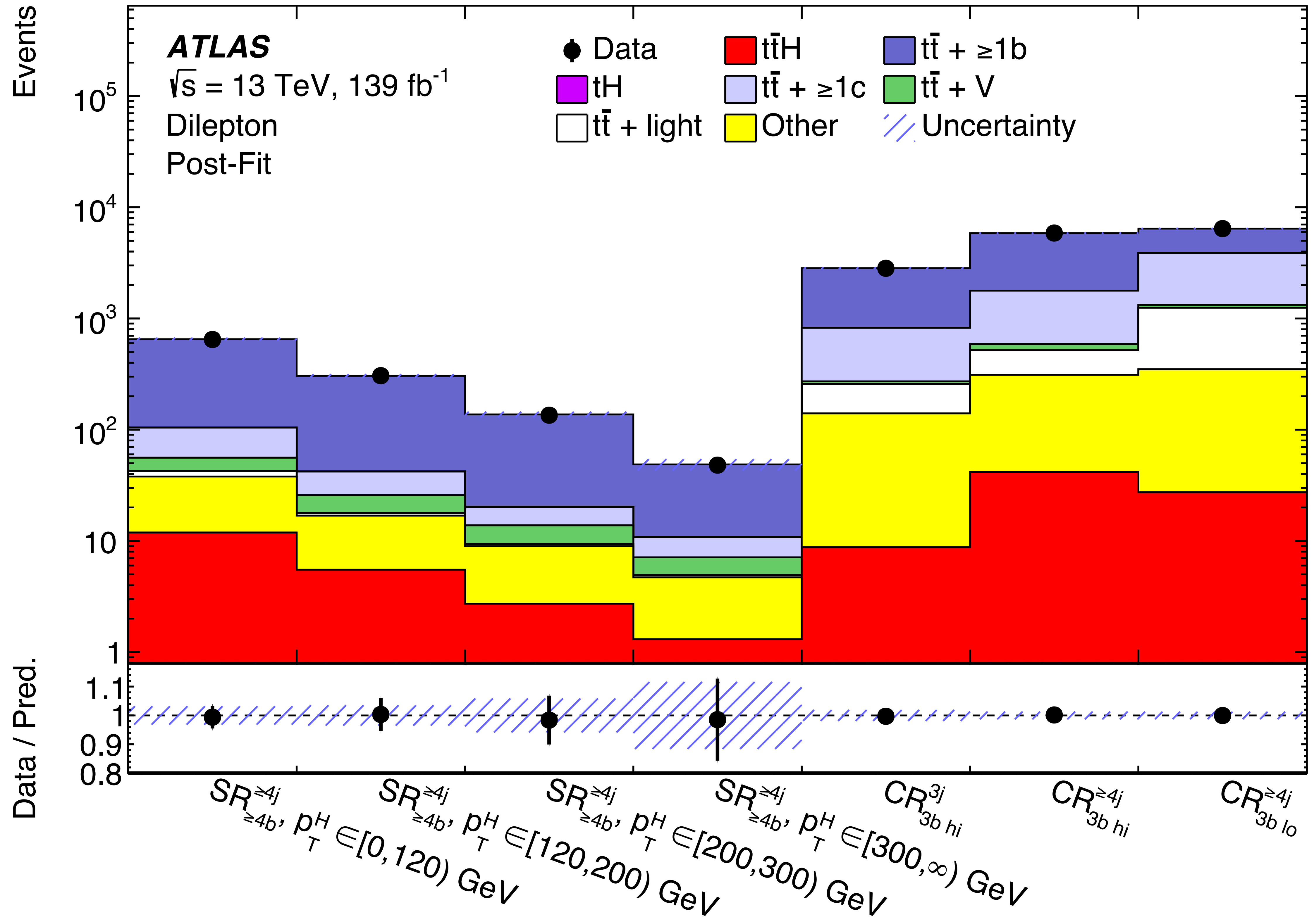
- Leading analysis for observation of H→bb and VH at LHC
- Exploit Resolved (pTV< 400 GeV) and the Merged regimes (pTV> 400 GeV)





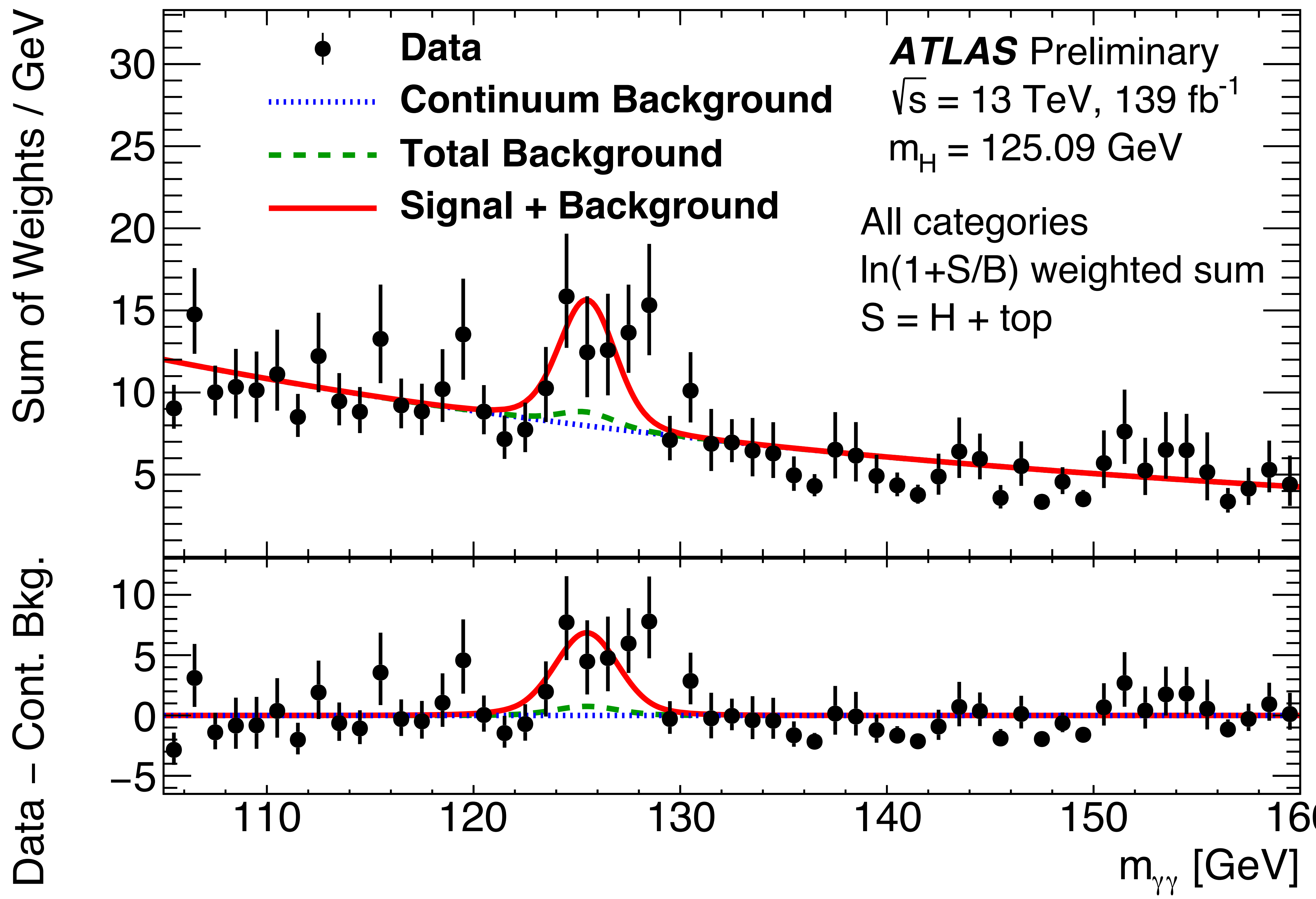
ttH channels (36.1 - 139 fb^{-1})

- ttH multi-lepton (36 fb^{-1}): targeting WW, $\tau\tau$, and ZZ decay modes + ttbar with ⩾1 leptonic W decay
- ttH, H→bb (139 fb^{-1}): targeting ttbar with ⩾1 leptonic W decay. Divide into single lepton and dilepton regions
- ttH, H→$\gamma\gamma$ and ttH, H→ZZ→4l analyses included as part of full H→$\gamma\gamma$ and H→ZZ→4l analyses introduced before



ttH→bb dilepton channel

CERN-EP-2021-202

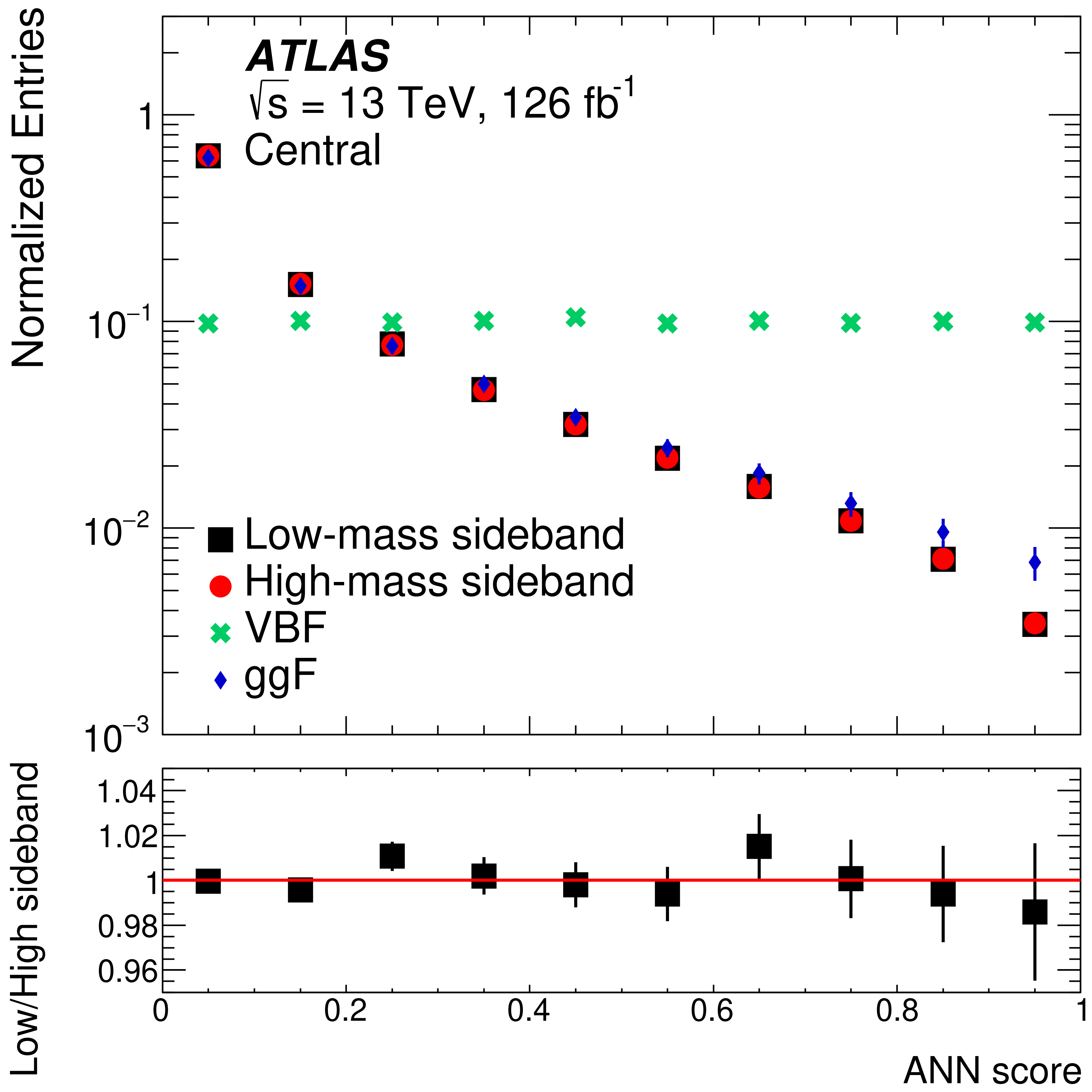


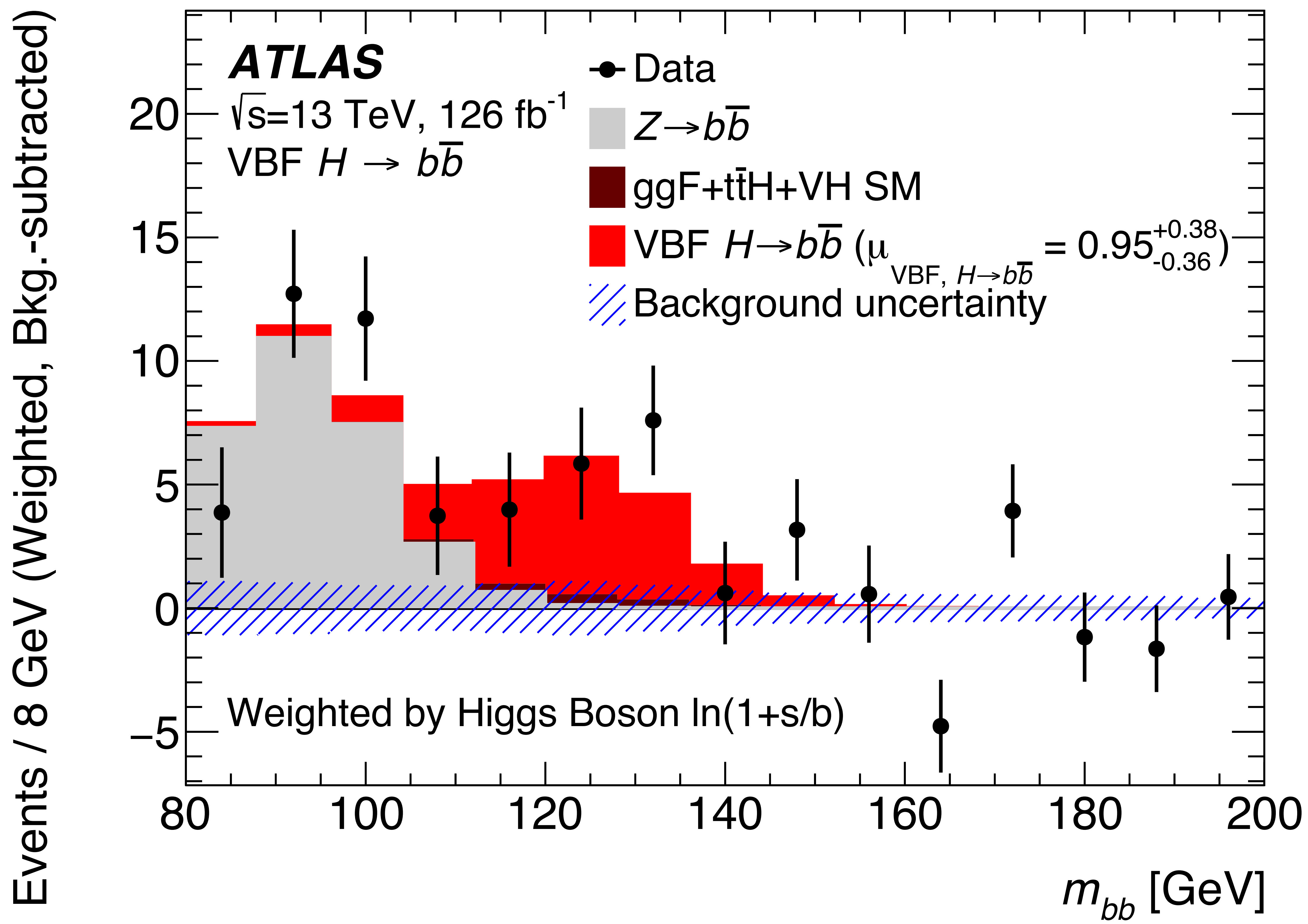
ttH, H→$\gamma\gamma$ included as part of full H→$\gamma\gamma$

ATLAS-CONF-2020-026

VBF, H→bb (126 fb^{-1})

- VBF, H→bb: exploit VBF topology for trigger
- Forward and central channels: presence or absence of a high pT forward (3.2<| η |<4.5) jet in the event (VBF vs ggF)
- ANN used to enhance the signal background separation

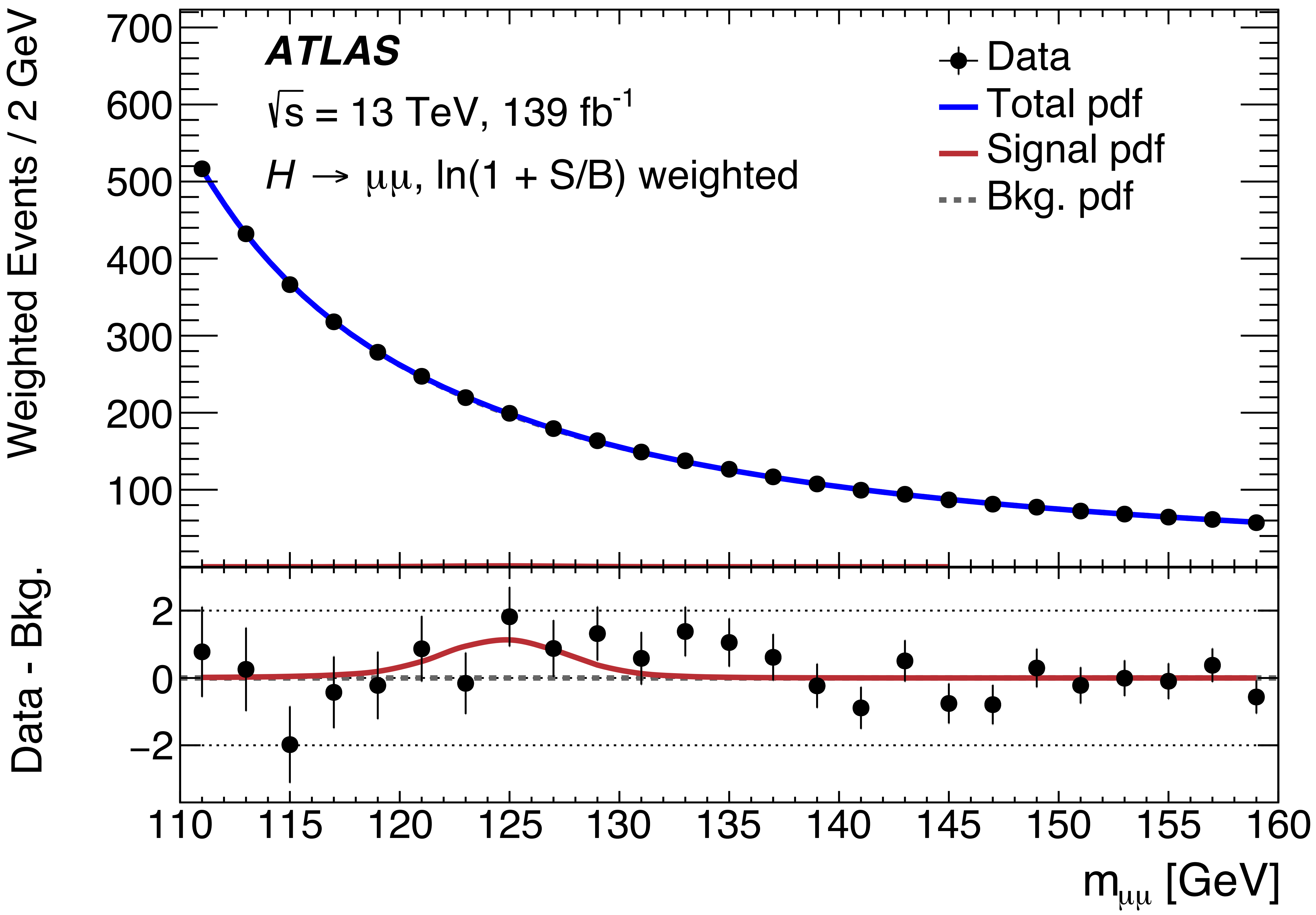


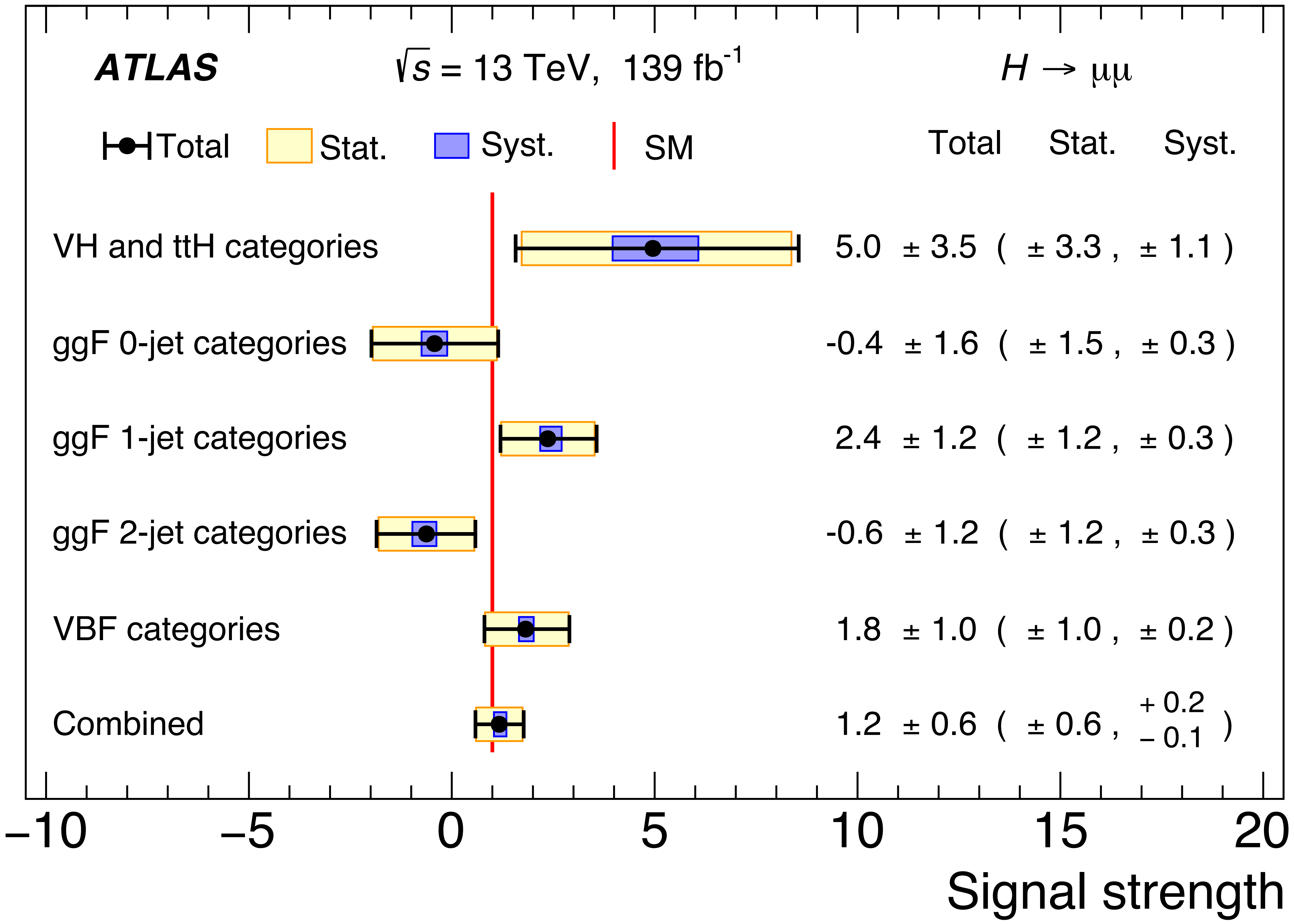


Eur. Phys. J. C. 81 (2021) 537

H→μμ (139 fb^{-1})

- H→$\mu\mu$: bump hunting on the large tail of Drell-Yan bkg.
- Current observed (expected) significance: 2.0σ (1.7σ) and Signal strength: μ = 1.2 ± 0.6 [N_{signal}(obs.)/N_{signal}(exp.)]





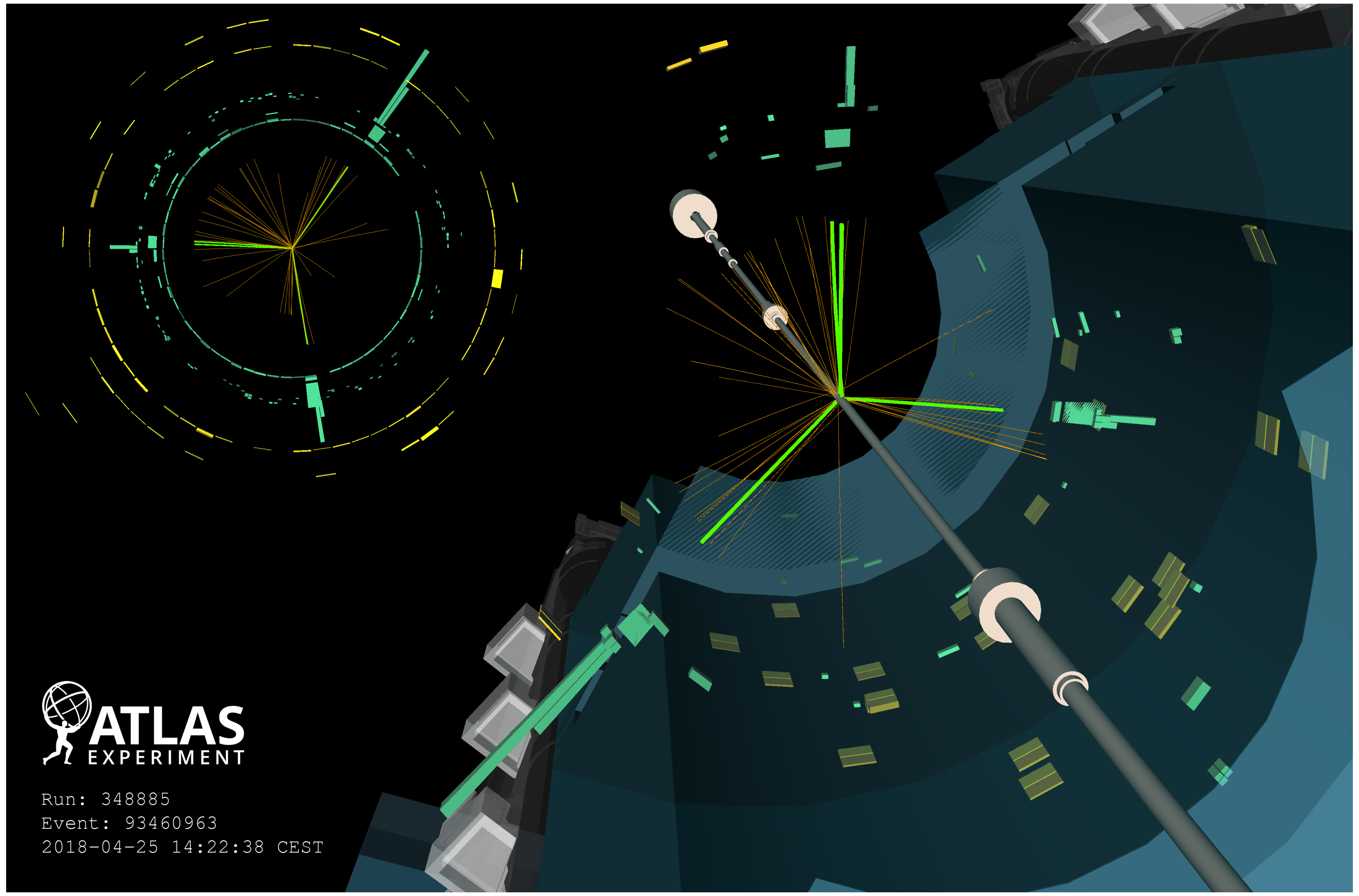
Phys. Lett. B 812 (2021) 135980

$H \to \mu\mu$ (139 fb^{-1})

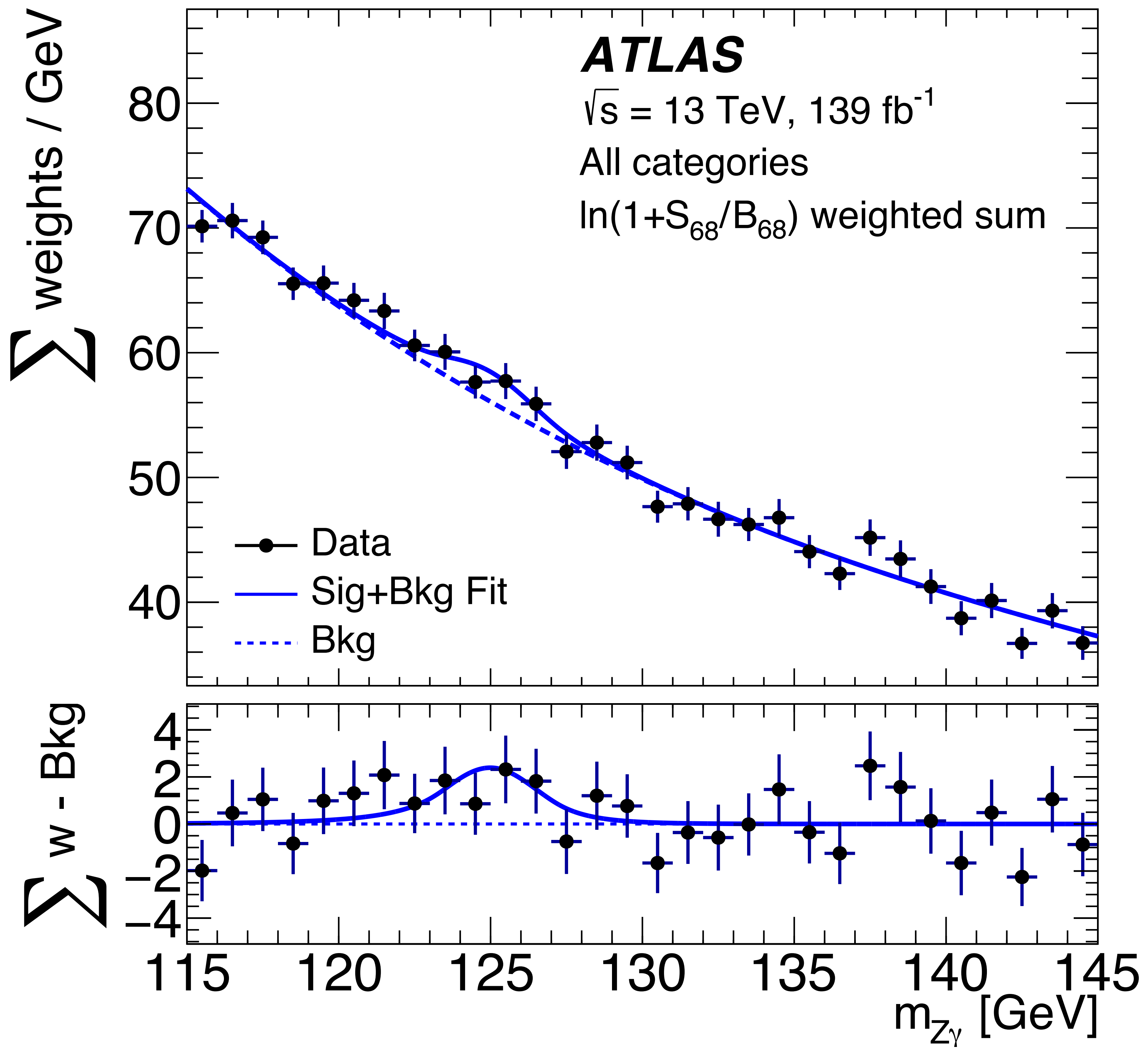
- ttH: dileptonic or semileptonic decay of the ttbar
  - $\geqslant$ 1 lepton in addition to the opposite sign muon pair and at least one b-tagged jet
- VH:
  - Not selected in ttH
  - $\geqslant$ 1 isolated lepton in addition to the opposite sign muon pair
  - no b-tagged jet
- ggF and VBF:
  - Not selected in the VH and ttH
  - Classified into 0-, 1-, 2-jet categories
  - 2-jet: O_{VBF} BDT classifier used to define 4 regions
  - The remaining classified into 4 regions based on 0- / 1- / 2- O_{ggF} BDT respectively

$H \rightarrow Z\gamma$ (139 fb^{-1})

- Very rare decay
- The observed data are consistent with the expected background with a p-value of 1.3%
- An upper limit @ 95% C.L. on the production cross-section times the branching ratio is set at 3.6 (2.6 exp.) times SM
- First time included into the Run2 combination



A candidate $H \rightarrow Z\gamma$ event with the $Z \rightarrow e^+e^-$

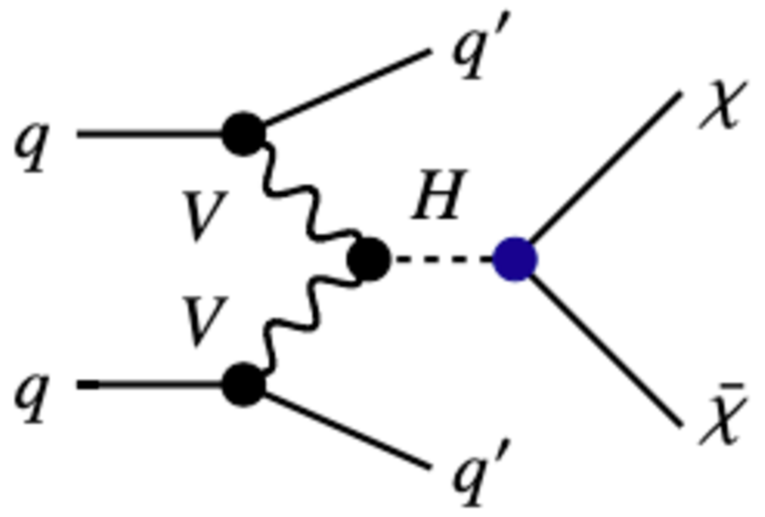


Phys. Lett. B 809 (2020) 135754

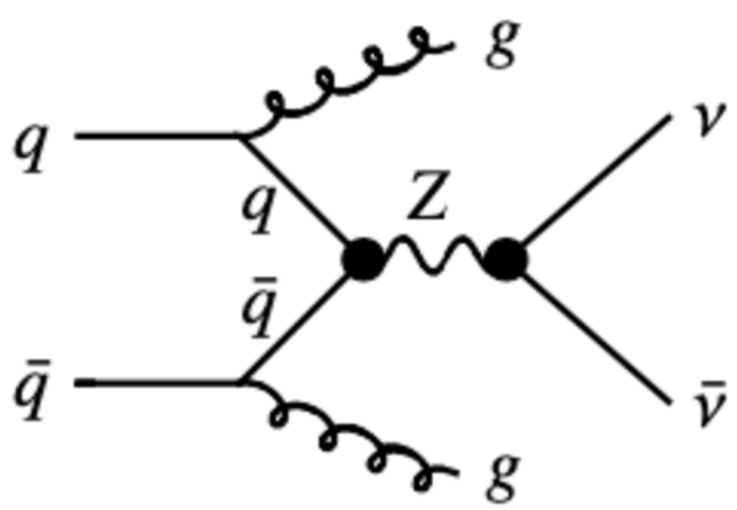
H→invisible searches

- The SM expectation for H→inv. BR is tiny (0.1% from H→ZZ→4ν), but the BR can be enhanced with BSM physics (e.g. H→dark matter)
- Search for missing transverse momentum signature in VBF topology, small contribution form ggF and VH after selection

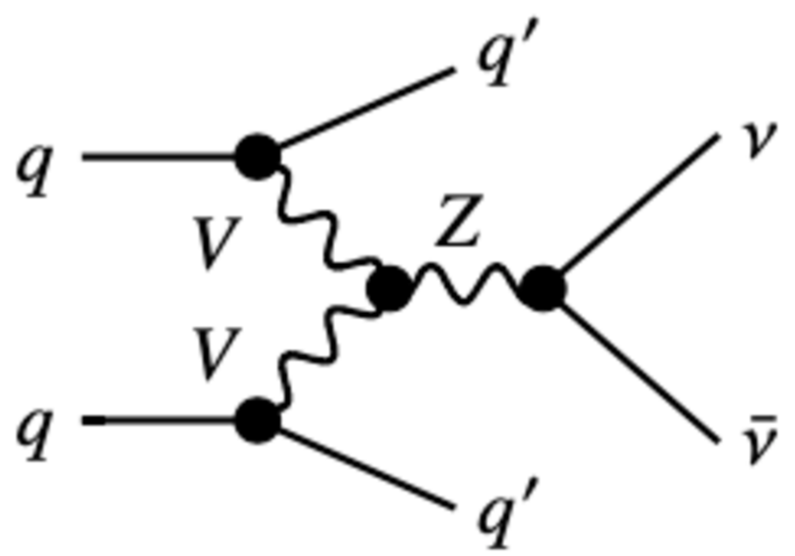
Signal



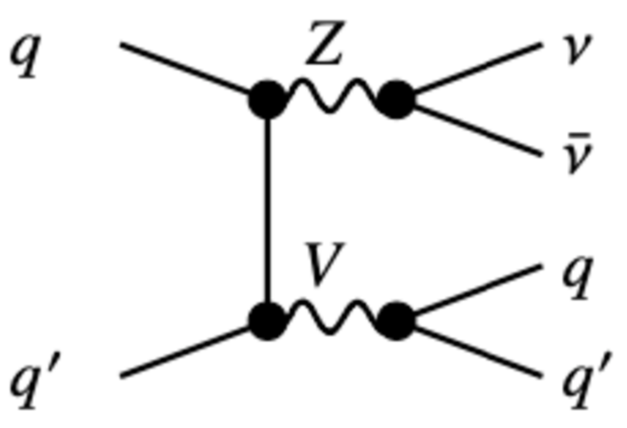
Strong Z+jets background

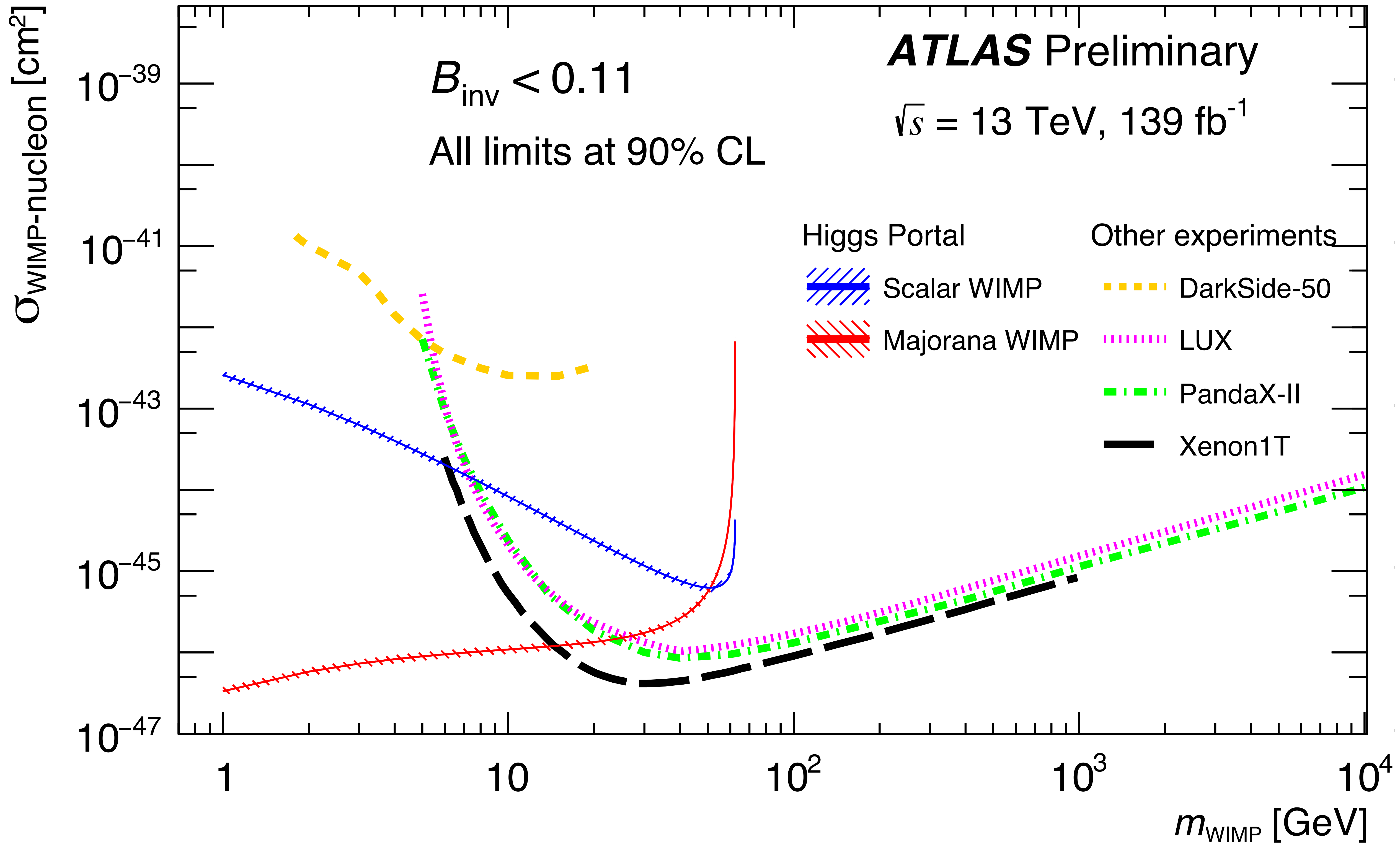


electroweak VBF Z+jet background



electroweak diboson background





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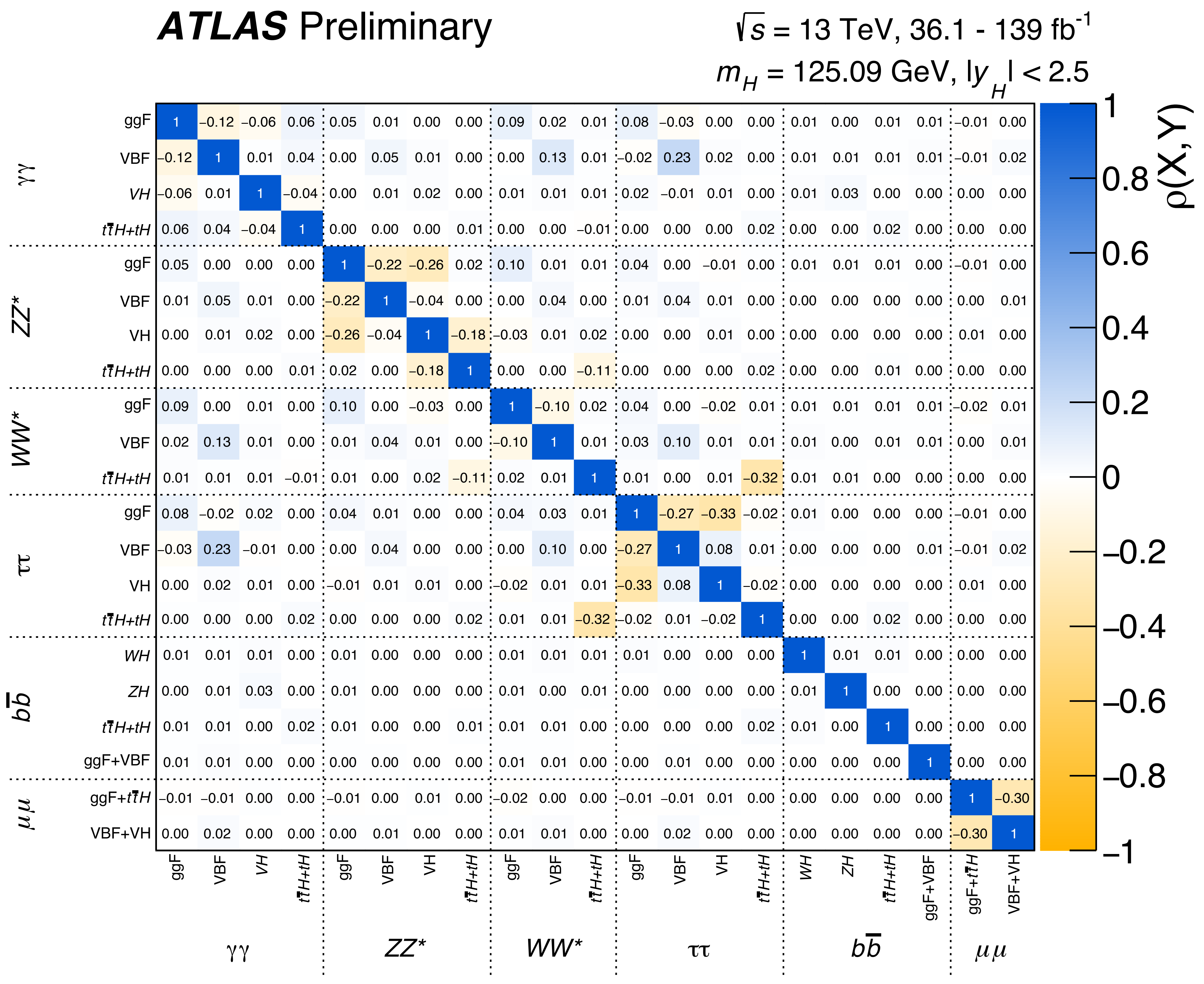
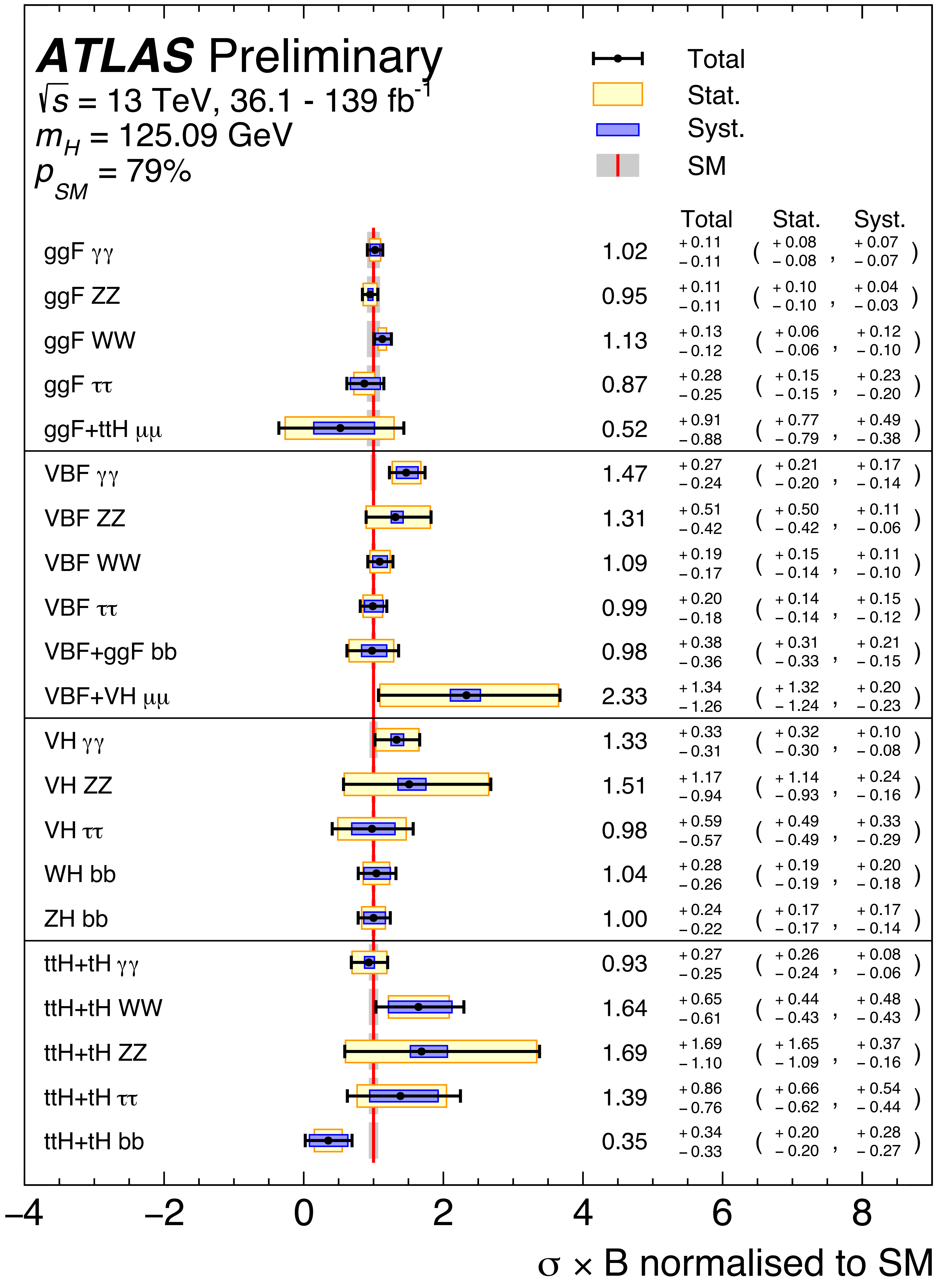
Production cross-section in each decay channel

- Good compatibility among production modes and also with the SM
- Anti-correlation most notable for ggF vs. VBF, and VV vs. $\tau\tau$ in ttH multi-lepton analysis





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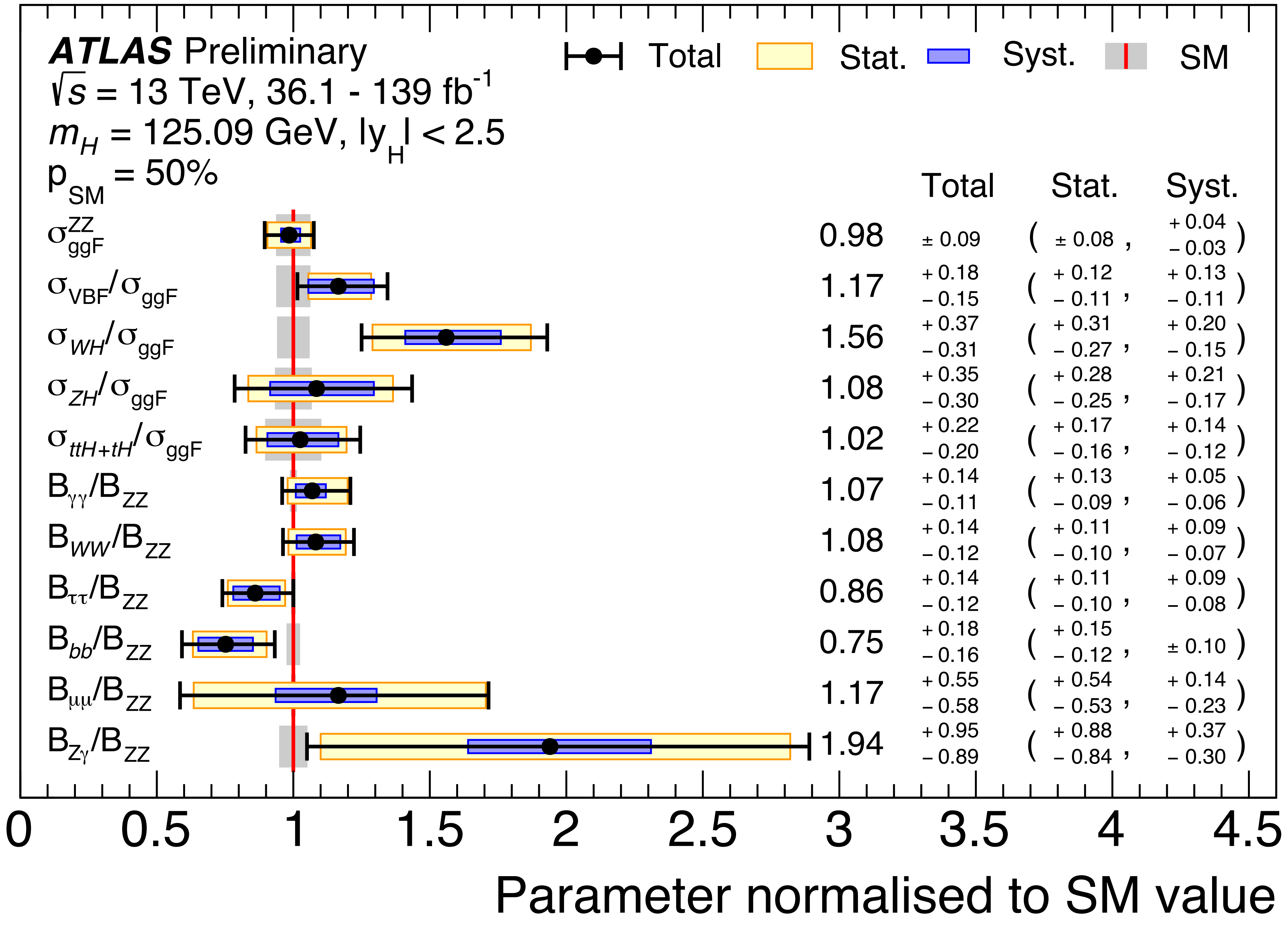
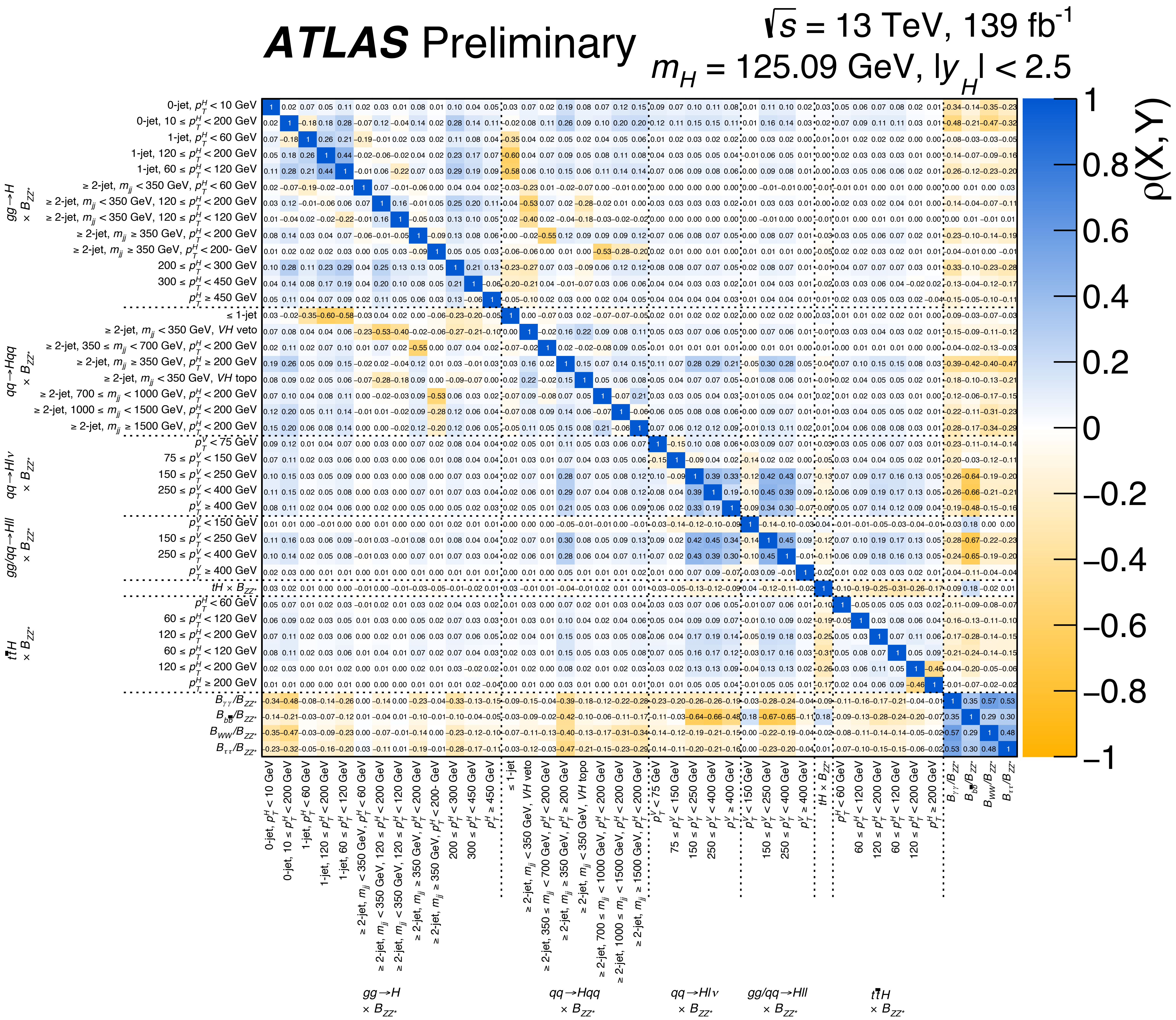
Production and decays ratios



Process ($\|y_H\| < 2.5$)		Observed	Uncertainty Total	Stat.	Syst.	SM prediction
σ^{ZZ}_{ggF}	[pb]	1.16	± 0.11	± 0.10	± 0.04	1.18 ± 0.07
$\sigma_{VBF}/\sigma_{ggF}$		0.091	$^{+0.012}_{-0.014}$	± 0.009	$^{+0.009}_{-0.010}$	0.079 ± 0.005
σ_{WH}/σ_{ggF}		0.042	$^{+0.008}_{-0.010}$	$^{+0.007}_{-0.008}$	$^{+0.004}_{-0.005}$	0.0269 ± 0.0016
σ_{ZH}/σ_{ggF}		0.019	$^{+0.005}_{-0.006}$	$^{+0.004}_{-0.005}$	$^{+0.003}_{-0.004}$	0.0178 ± 0.0012
$\sigma_{ttH+tH}/\sigma_{ggF}$		0.0134	$^{+0.0027}_{-0.0029}$	$^{+0.0021}_{-0.0022}$	$^{+0.0016}_{-0.0018}$	0.0131 ± 0.0013
$B_{\gamma\gamma}/B_{ZZ}$		0.092	$^{+0.010}_{-0.012}$	$^{+0.008}_{-0.011}$	$^{+0.005}_{-0.004}$	0.086 ± 0.001
B_{WW}/B_{ZZ}		8.8	$^{+1.0}_{-1.2}$	$^{+0.8}_{-0.9}$	$^{+0.6}_{-0.7}$	$8.15 \pm < 0.01$
$B_{\tau\tau}/B_{ZZ}$		2.04	$^{+0.29}_{-0.34}$	$^{+0.23}_{-0.25}$	$^{+0.19}_{-0.21}$	2.369 ± 0.017
B_{bb}/B_{ZZ}		16.5	$^{+3.5}_{-4.0}$	$^{+2.7}_{-3.4}$	± 2.2	22.0 ± 0.5
$B_{\mu\mu}/B_{ZZ}$		0.009	± 0.005	± 0.004	$^{+0.001}_{-0.002}$	$0.0082 \pm < 0.0001$
$B_{Z\gamma}/B_{ZZ}$		0.11	$^{+0.05}_{-0.06}$	± 0.05	± 0.02	0.0584 ± 0.0029

STXS correlation matrix

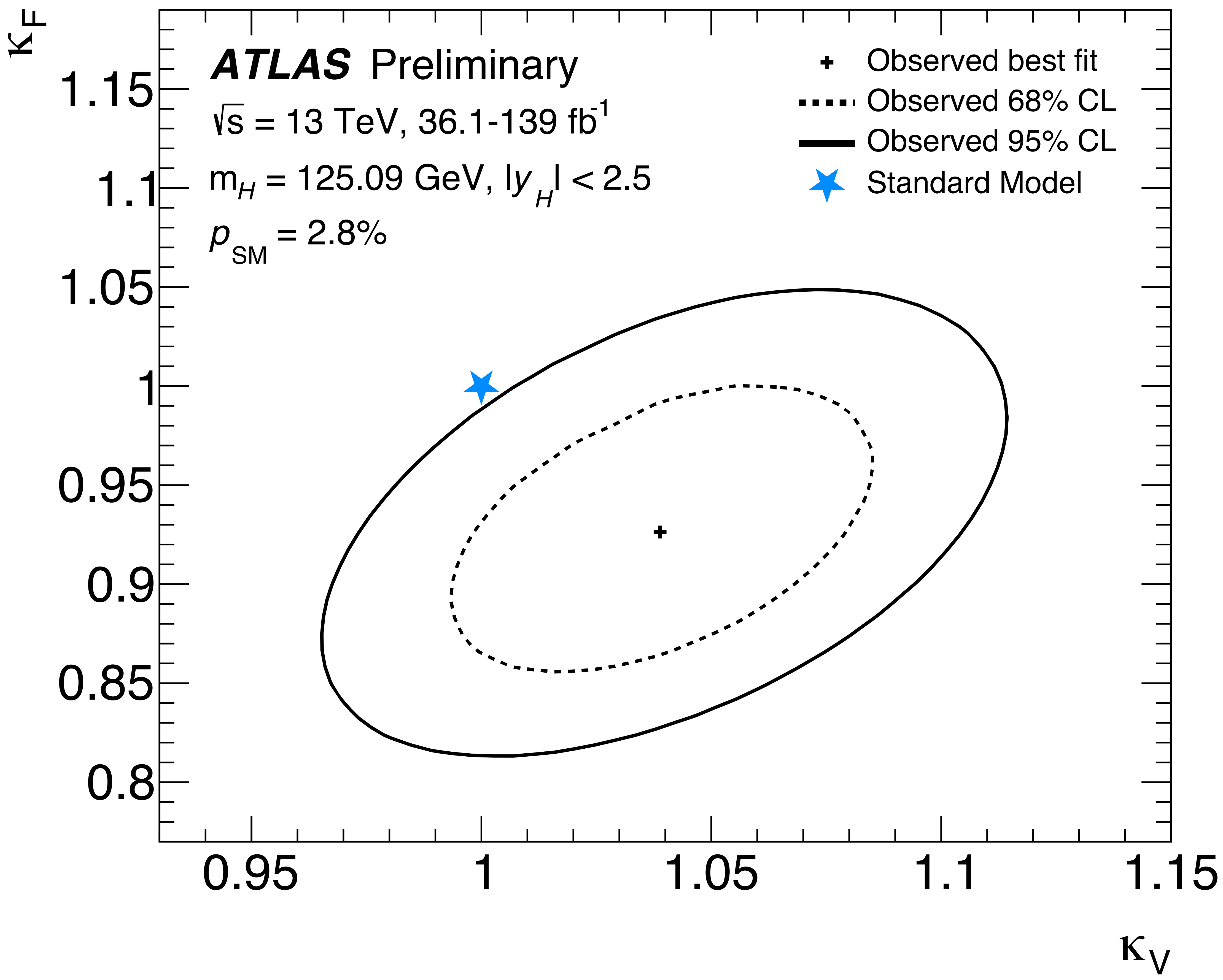


kappa parametrization

Production cross section	Loops	Main interference	Effective modifier	Resolved modifier
$\sigma(\text{ggF})$	✓	t–b	κ_g^2	$1.040\,\kappa_t^2 + 0.002\,\kappa_b^2 - 0.038\,\kappa_t\kappa_b - 0.005\,\kappa_t\kappa_c$
$\sigma(\text{VBF})$	-	-	-	$0.733\,\kappa_W^2 + 0.267\,\kappa_Z^2$
$\sigma(qq/qg \to ZH)$	-	-	-	κ_Z^2
$\sigma(gg \to ZH)$	✓	t–Z	$\kappa_{(ggZH)}$	$2.456\,\kappa_Z^2 + 0.456\,\kappa_t^2 - 1.903\,\kappa_Z\kappa_t$ $- 0.011\,\kappa_Z\kappa_b + 0.003\,\kappa_t\kappa_b$
$\sigma(WH)$	-	-	-	κ_W^2
$\sigma(H)$	-	-	-	κ_t^2
$\sigma(tHW)$	-	t–W	-	$2.909\,\kappa_t^2 + 2.310\,\kappa_W^2 - 4.220\,\kappa_t\kappa_W$
$\sigma(tHq)$	-	t–W	-	$2.633\,\kappa_t^2 + 3.578\,\kappa_W^2 - 5.211\,\kappa_t\kappa_W$
$\sigma(H)$	-	-	-	κ_b^2
Partial decay width				
Γ^{bb}	-	-	-	κ_b^2
Γ^{WW}	-	-	-	κ_W^2
Γ^{gg}	✓	t–b	κ_g^2	$1.111\,\kappa_t^2 + 0.012\,\kappa_b^2 - 0.123\,\kappa_t\kappa_b$
$\Gamma^{\tau\tau}$	-	-	-	κ_τ^2
Γ^{ZZ}	-	-	-	κ_Z^2
Γ^{cc}	-	-	-	$\kappa_c^2\ (= \kappa_t^2)$
$\Gamma^{\gamma\gamma}$	✓	t–W	κ_γ^2	$1.589\,\kappa_W^2 + 0.072\,\kappa_t^2 - 0.674\,\kappa_W\kappa_t$ $+0.009\,\kappa_W\kappa_\tau + 0.008\,\kappa_W\kappa_b$ $-0.002\,\kappa_t\kappa_b - 0.002\,\kappa_t\kappa_\tau$
$\Gamma^{Z\gamma}$	✓	t–W	$\kappa_{(Z\gamma)}^2$	$1.118\,\kappa_W^2 - 0.125\,\kappa_W\kappa_t + 0.004\,\kappa_t^2 + 0.003\,\kappa_W\kappa_b$
Γ^{ss}	-	-	-	$\kappa_s^2\ (= \kappa_b^2)$
$\Gamma^{\mu\mu}$	-	-	-	κ_μ^2
Total width ($B_{\text{i.}} = B_{\text{u.}} = 0$)				
Γ_H	✓	-	κ_H^2	$0.581\,\kappa_b^2 + 0.215\,\kappa_W^2 + 0.082\,\kappa_g^2$ $+0.063\,\kappa_\tau^2 + 0.026\,\kappa_Z^2 + 0.029\,\kappa_c^2$ $+0.0023\,\kappa_\gamma^2 + 0.0015\,\kappa_{(Z\gamma)}^2$ $+0.0004\,\kappa_s^2 + 0.00022\,\kappa_\mu^2$

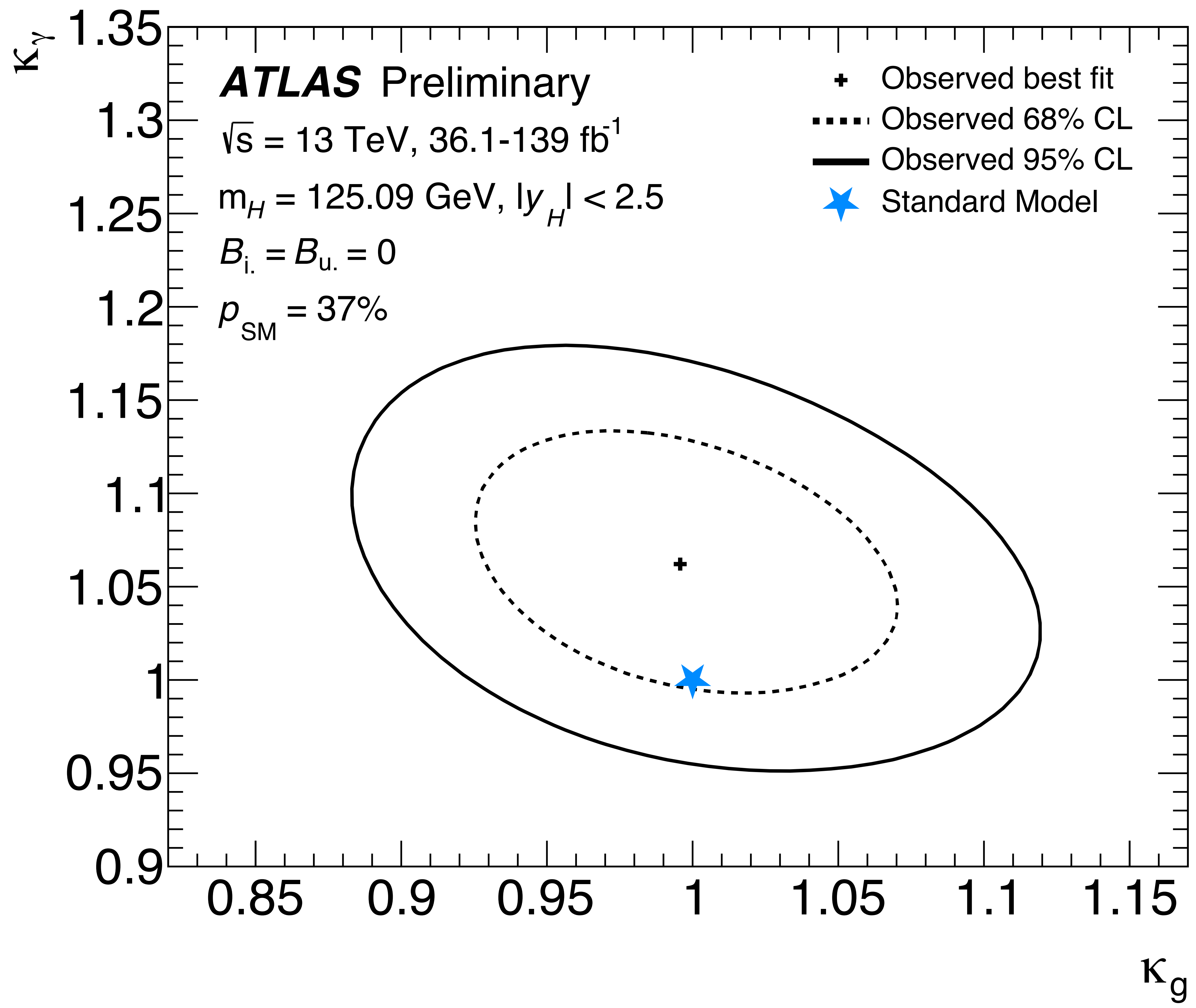
κ_V vs. κ_F

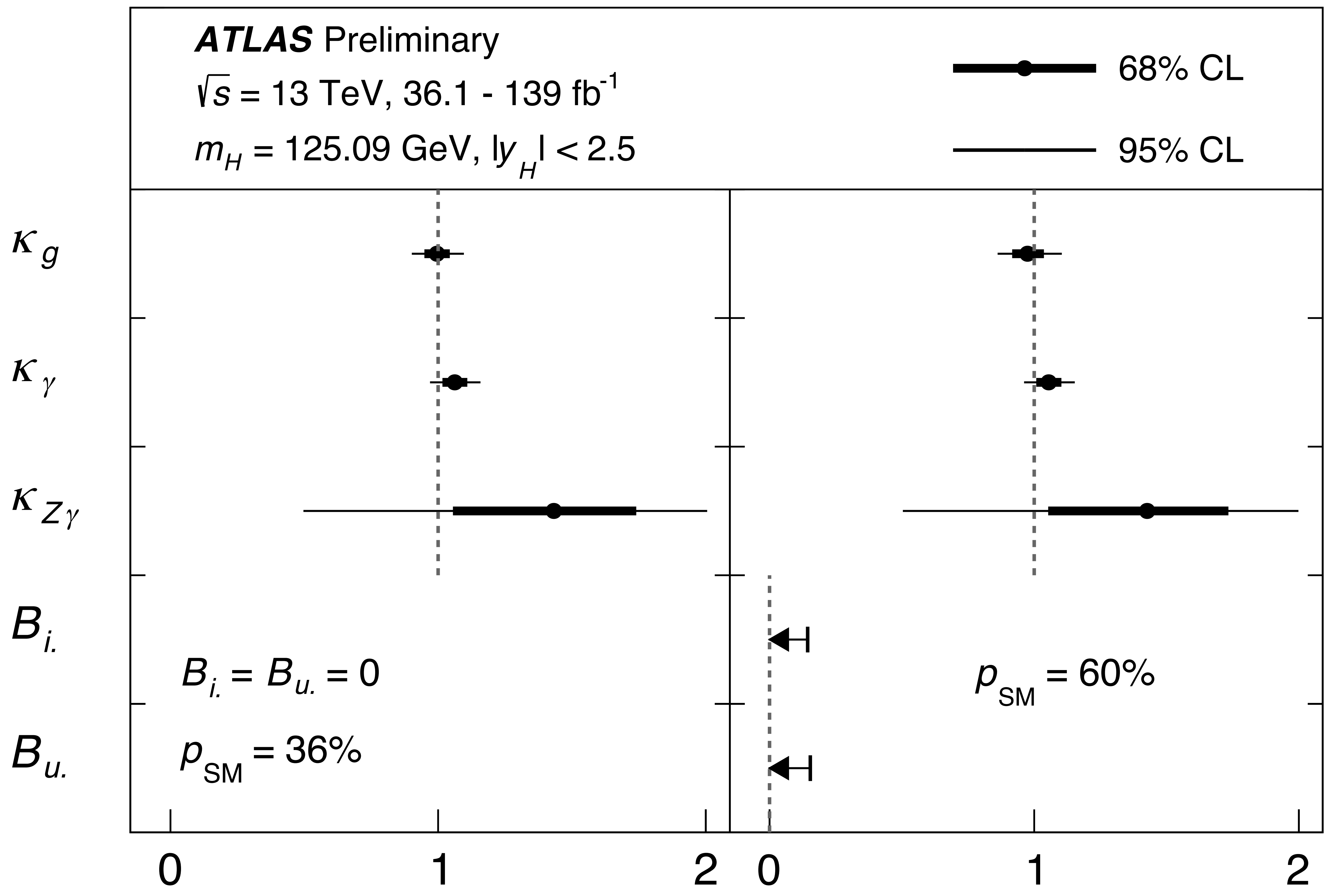
- Unify coupling for all the fermions and vector-bosons.
- Assume no BSM physics in loop-induced processes or total width
- Best fit values:



κ_g VS. κ_γ

- Focus on ggF and $H\gamma\gamma$ interactions, with other coupling strengths fixed to the SM
- Loop-induced in the SM, sensitive to new physics
- Can also determine $B_{inv.}$ and $B_{undet.}$ contributions at the same time by including H→inv. searches





Generic parameterization

Parameter	(a) $B_{\text{i.}} = B_{\text{u.}} = 0$	(b) $B_{\text{i.}}$ free, $B_{\text{u.}} \geq 0$, $\kappa_{W,Z} \leq 1$
κ_Z	0.99 ± 0.06	$0.96\ ^{+\ 0.04}_{-\ 0.05}$
κ_W	1.06 ± 0.06	$1.00\ ^{+\ 0.00}_{-\ 0.03}$
κ_b	0.87 ± 0.11	0.81 ± 0.08
κ_t	0.92 ± 0.10	0.90 ± 0.10
κ_μ	$1.07\ ^{+\ 0.25}_{-\ 0.30}$	$1.03\ ^{+\ 0.23}_{-\ 0.29}$
κ_τ	0.92 ± 0.07	0.88 ± 0.06
κ_γ	1.04 ± 0.06	1.00 ± 0.05
$\kappa_{Z\gamma}$	$1.37\ ^{+\ 0.31}_{-\ 0.37}$	$1.33\ ^{+\ 0.29}_{-\ 0.35}$
κ_g	$0.92\ ^{+\ 0.07}_{-\ 0.06}$	$0.89\ ^{+\ 0.07}_{-\ 0.06}$
$B_{\text{i.}}$	-	< 0.09 at 95% CL
$B_{\text{u.}}$	-	< 0.16 at 95% CL

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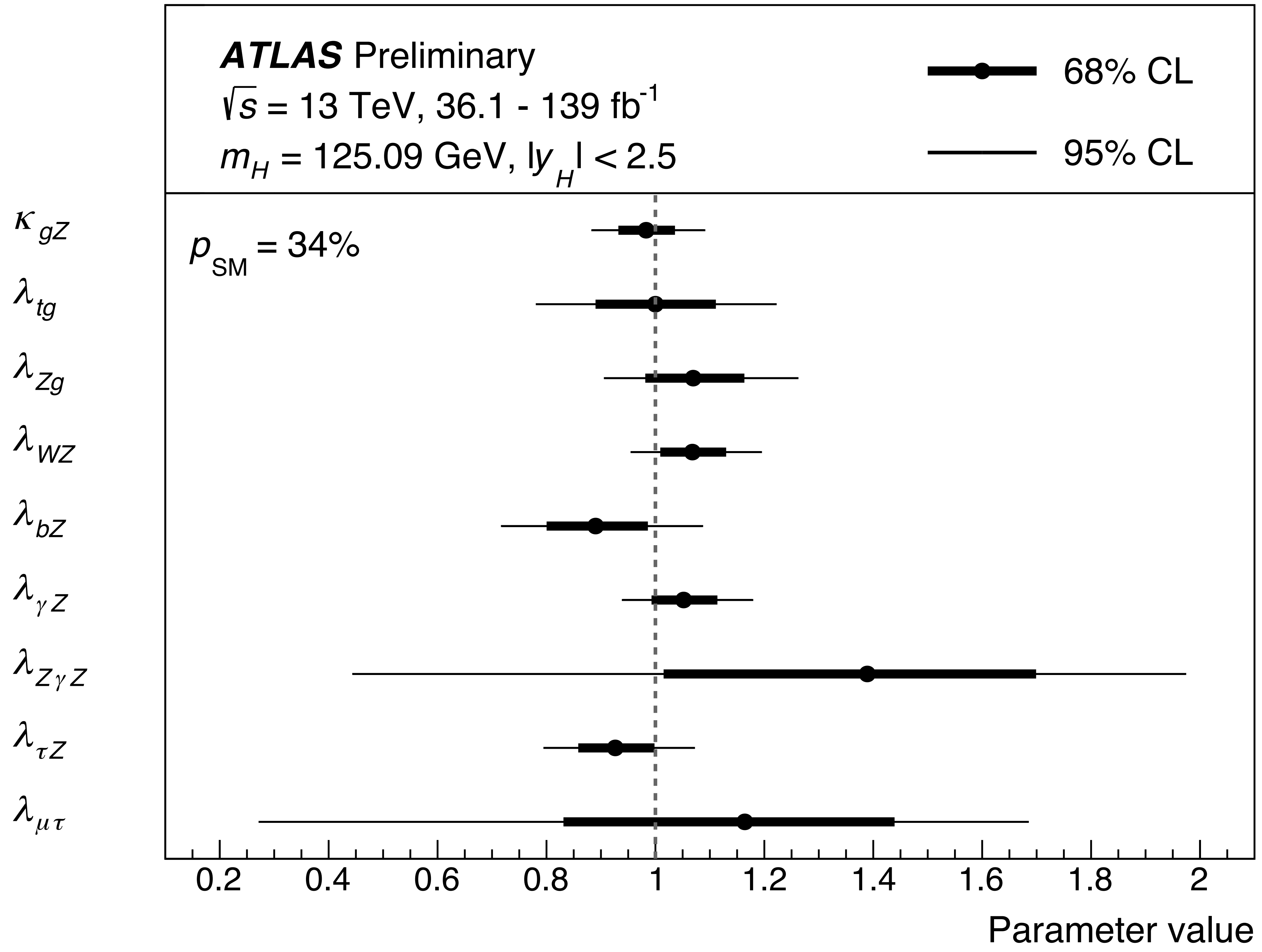
Expressed as ratios of scale factors

No need for the assumption on the total decay width modification



Parameter	Definition in terms of κ modifiers	Result
κ_{gZ}	$\kappa_g \kappa_Z / \kappa_H$	0.98 ± 0.05
λ_{tg}	κ_t / κ_g	1.00 ± 0.11
λ_{Zg}	κ_Z / κ_g	1.07 ± 0.09
λ_{WZ}	κ_W / κ_Z	1.07 ± 0.06
$\lambda_{\gamma Z}$	κ_γ / κ_Z	1.05 ± 0.06
$\lambda_{Z\gamma Z}$	$\kappa_{Z\gamma} / \kappa_Z$	$1.39^{+0.31}_{-0.37}$
$\lambda_{\tau Z}$	κ_τ / κ_Z	0.93 ± 0.07
λ_{bZ}	κ_b / κ_Z	$0.89^{+0.10}_{-0.09}$
$\lambda_{\mu\tau}$	κ_μ / κ_τ	$1.16^{+0.28}_{-0.33}$

- $\lambda_{tg} = \kappa_t / \kappa_g$: κ_t direct determination through ttH compared with indirect determination in the ggF loop (κ_g). Probe new physics in ggF process
- $\lambda_{\gamma Z} = \kappa_\gamma / \kappa_Z$ or $\lambda_{Z\gamma Z}$: new particle contribute to $H \to \gamma\gamma$ / $Z\gamma$ loop (κ_γ) unlike H→ZZ. Probe new physics in $H \to \gamma\gamma$ / $Z\gamma$
- $\lambda_{\mu\tau} = \kappa_\mu / \kappa_\tau$: deviation of Higgs Yukawa couplings to the second/third generation fermions

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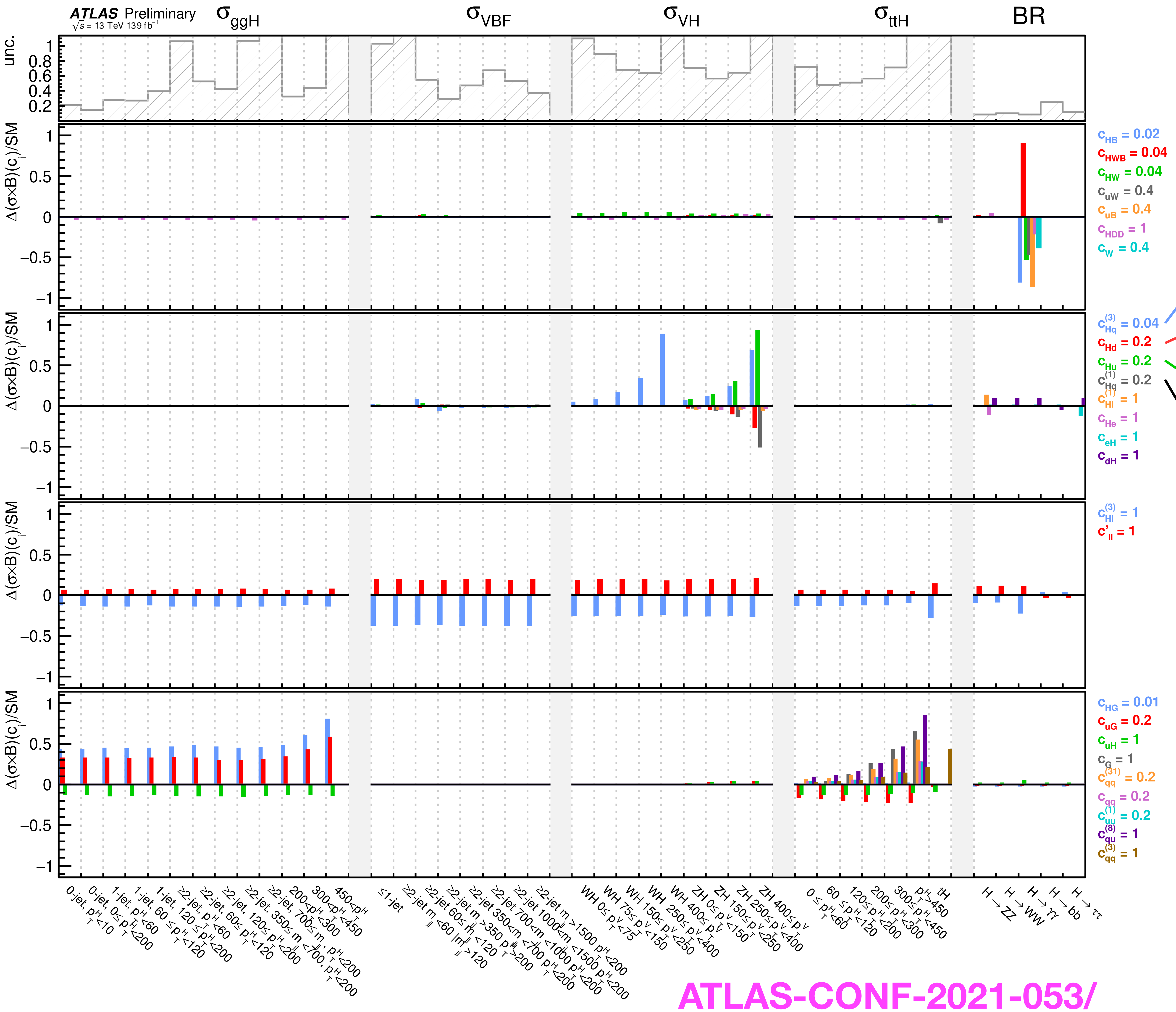
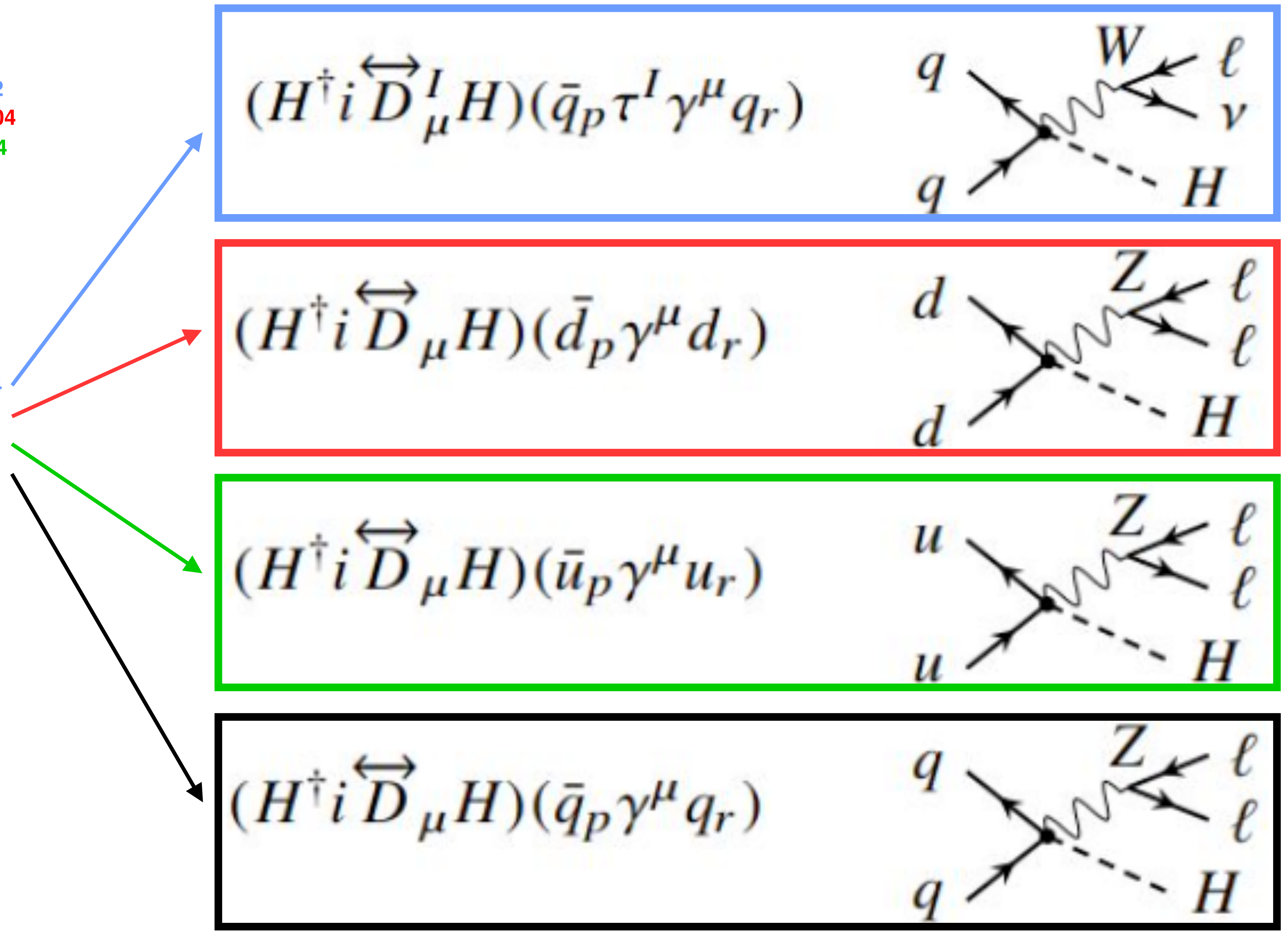
SMEFT: impacts

- Parametrized their impact on the signal yields in each STXS bin x 5 BR





Many parameters: for illustration, focus on a set that largely affects VH

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Model-dependent interpretation: 2HDM

The two-Higgs-doublet model (**2HDM**):

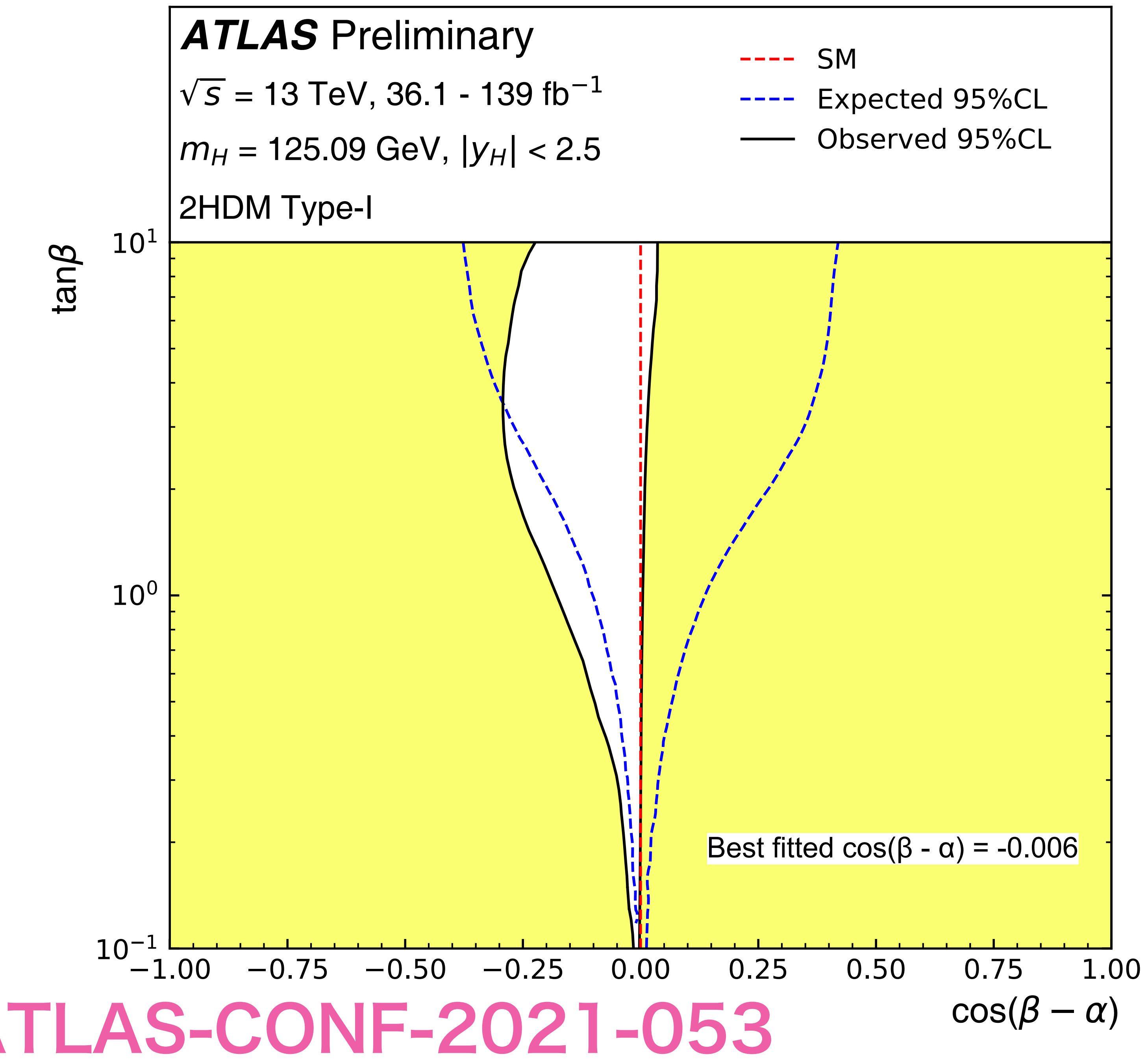
- Extended Higgs sector (2nd SU(2) doublet)→ 5 Higgs boson:
  - Two neutral CP-even: h,H
  - One neutral CP-odd: A
  - Two charged Higgs boson $H^{\pm}$
- α: mixing angle between two CP-even Higgs bosons (h, H)
- $\tan\beta$: ratio of the vacuum expectation values of the two SU(2) doublets
- $H_{SM} = h\cdot\sin(\beta-\alpha) + H\cdot\cos(\beta-\alpha)$
- $\cos(\beta-\alpha) = 0$ (**alignment limit**) ⇒ h indistinguishable from H_{SM}

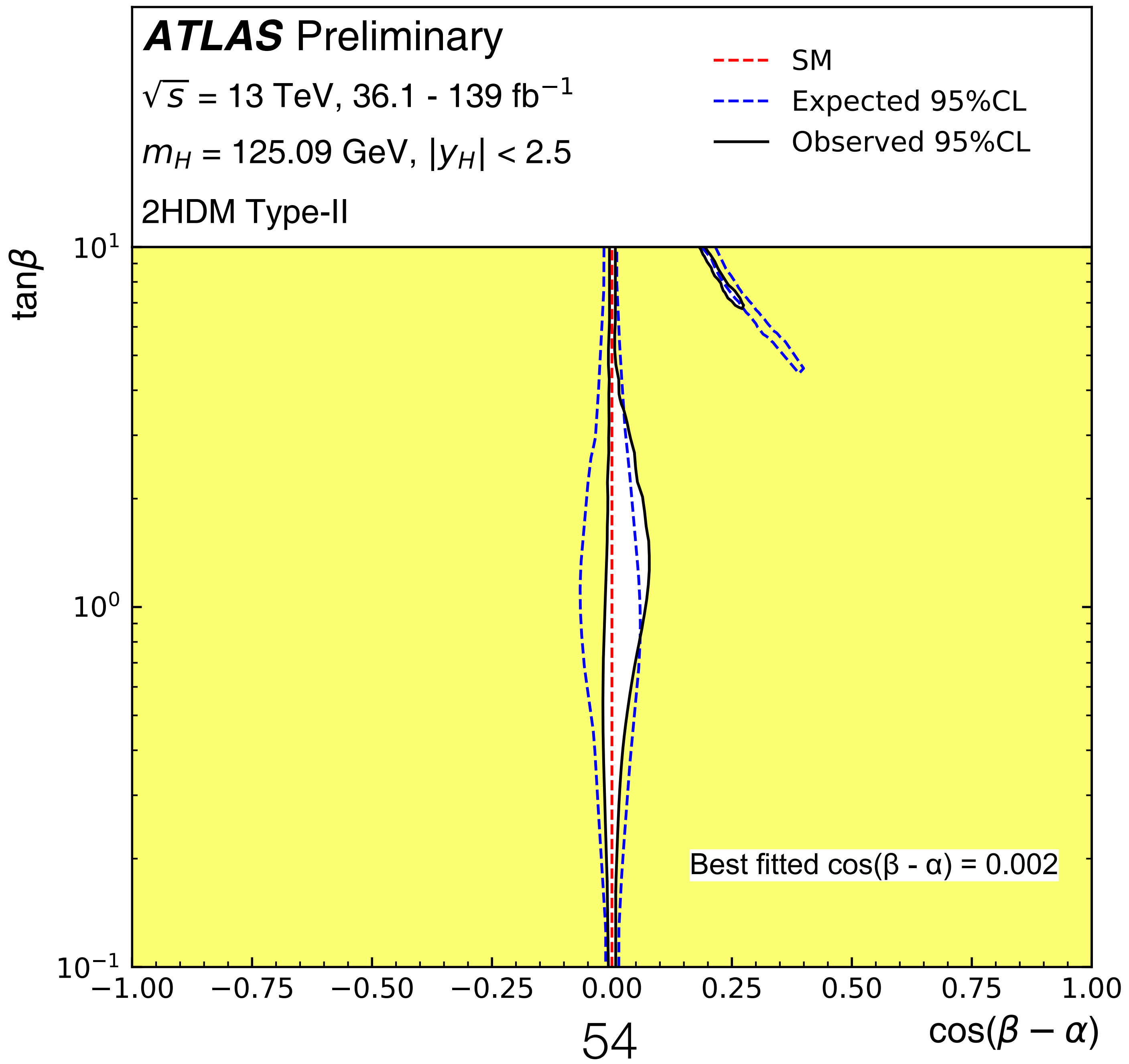
4 2HDM types can be defined w/o tree-level flavour-changing neutral currents

- Variation over allowed couplings to SM particles

Coupling scale factor	Type I	Type II	Lepton-specific	Flipped
κ_V	$\sin(\beta-\alpha)$			
κ_u	$\cos(\alpha)/\sin(\beta)$			
κ_d	$\cos(\alpha)/\sin(\beta)$	$-\sin(\alpha)/\cos(\beta)$	$\cos(\alpha)/\sin(\beta)$	$-\sin(\alpha)/\cos(\beta)$
κ_ℓ	$\cos(\alpha)/\sin(\beta)$	$-\sin(\alpha)/\cos(\beta)$	$-\sin(\alpha)/\cos(\beta)$	$\cos(\alpha)/\sin(\beta)$

Limits on $\cos(\beta-\alpha)$ vs $\tan\beta$ (Type I and II shown here, Lepton-specific and Flipped in backup)





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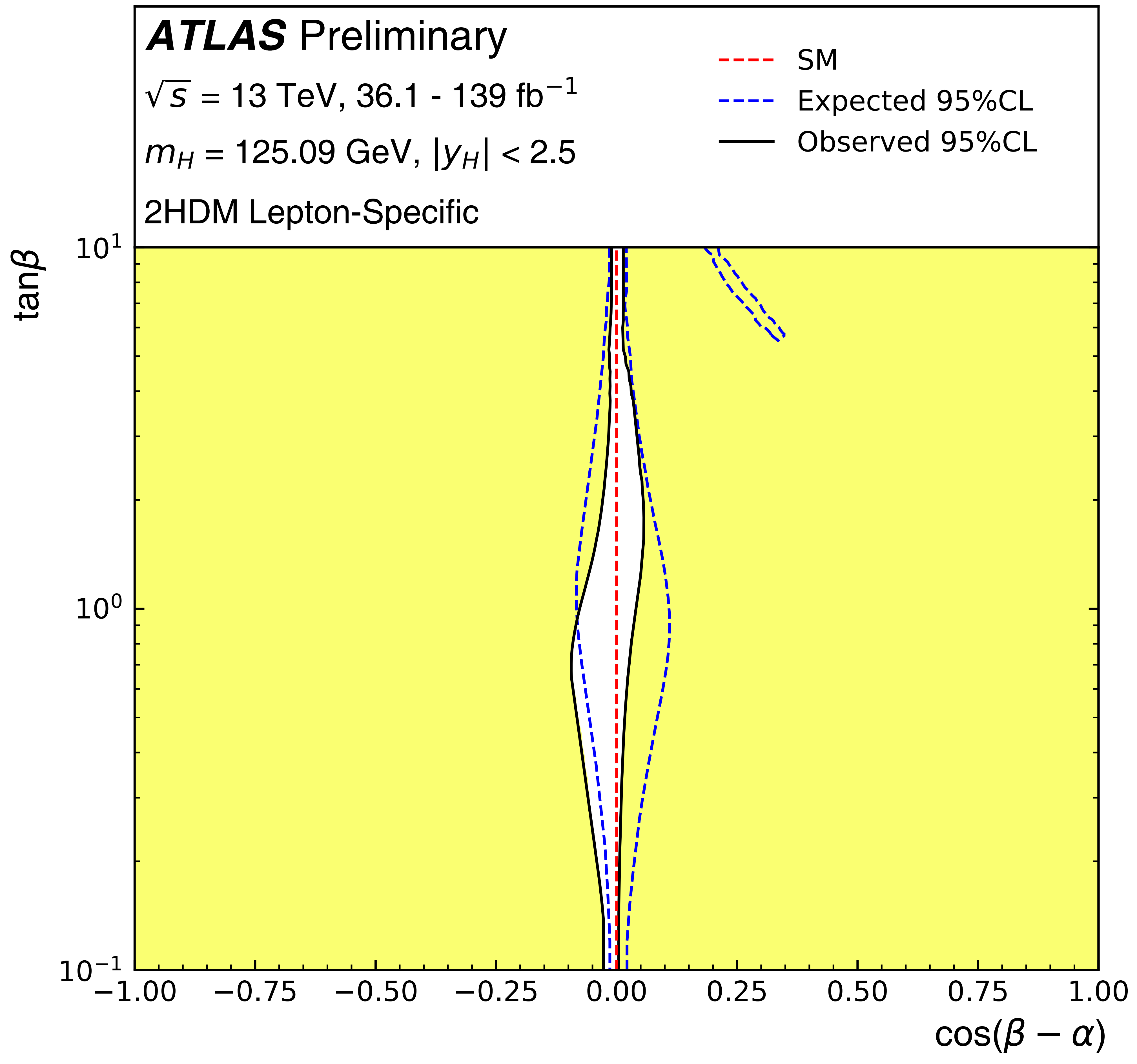
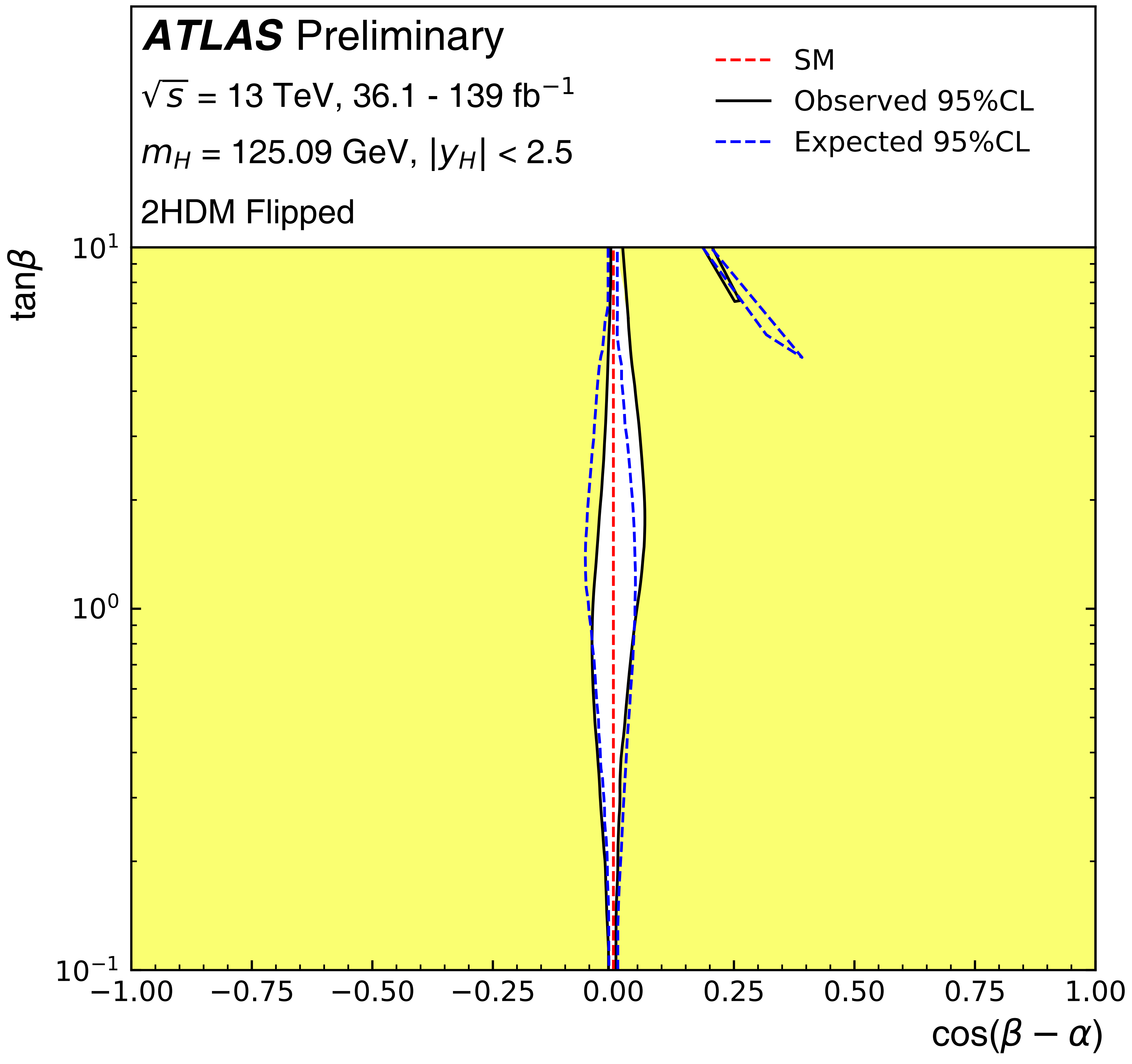
The data is consistent with the alignment limit within 1 σ or even better

"petal" allowed regions: correspond to regions with $\cos(\beta+\alpha) \approx 0$, some fermion couplings have the same magnitude as in the SM, but the opposite sign

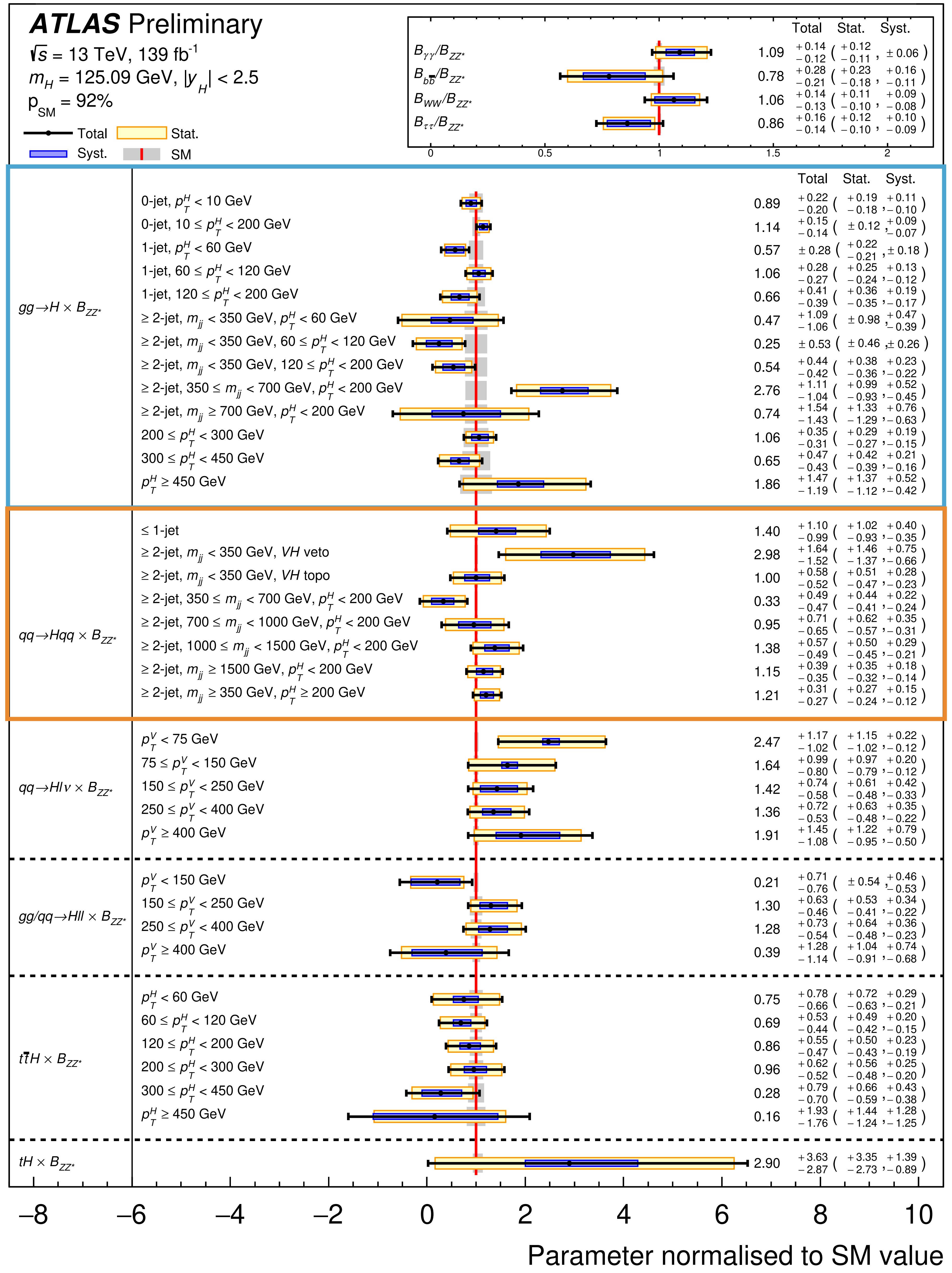
Constraints on new phenomena

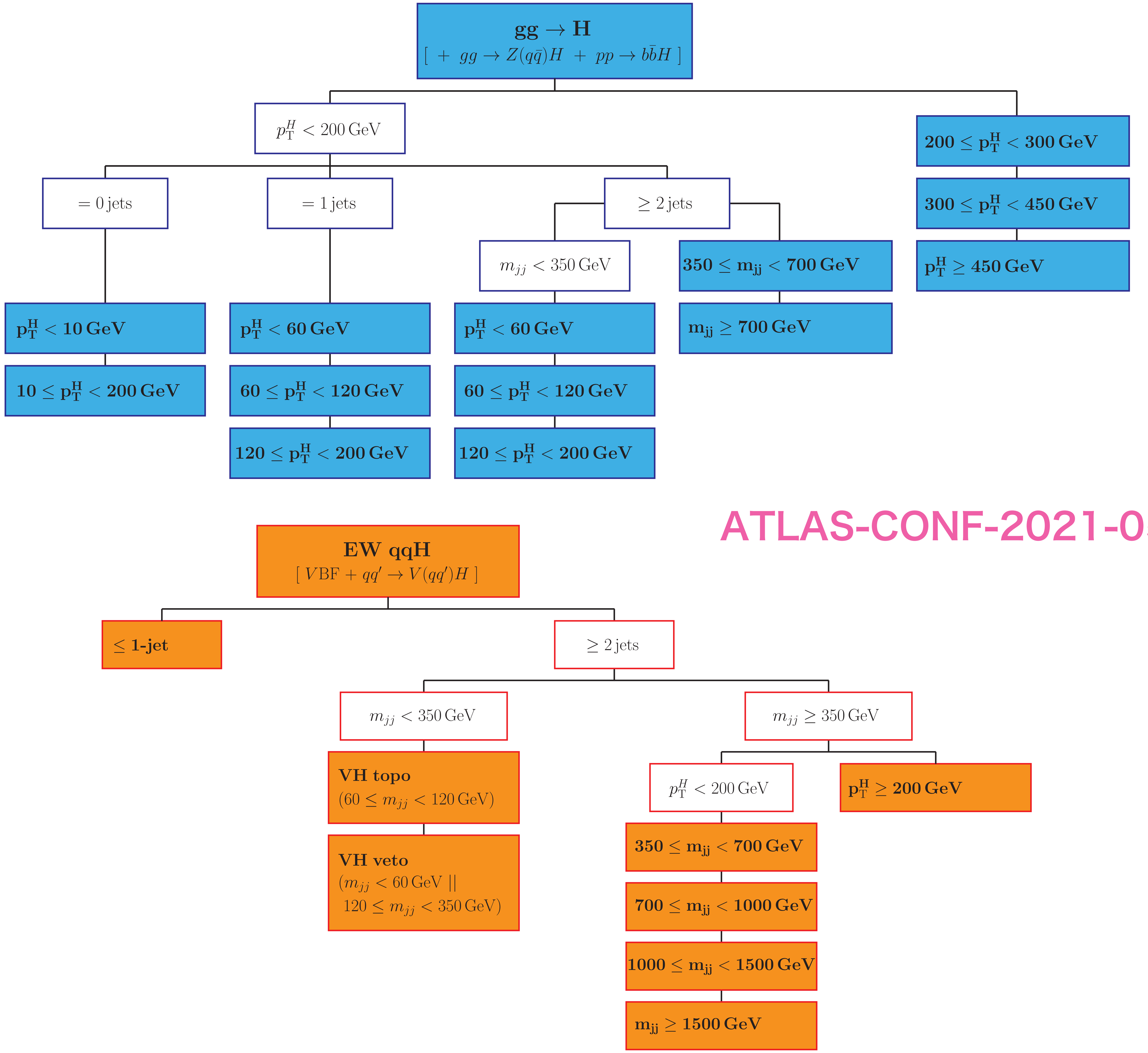
- Alternative models





STXS results





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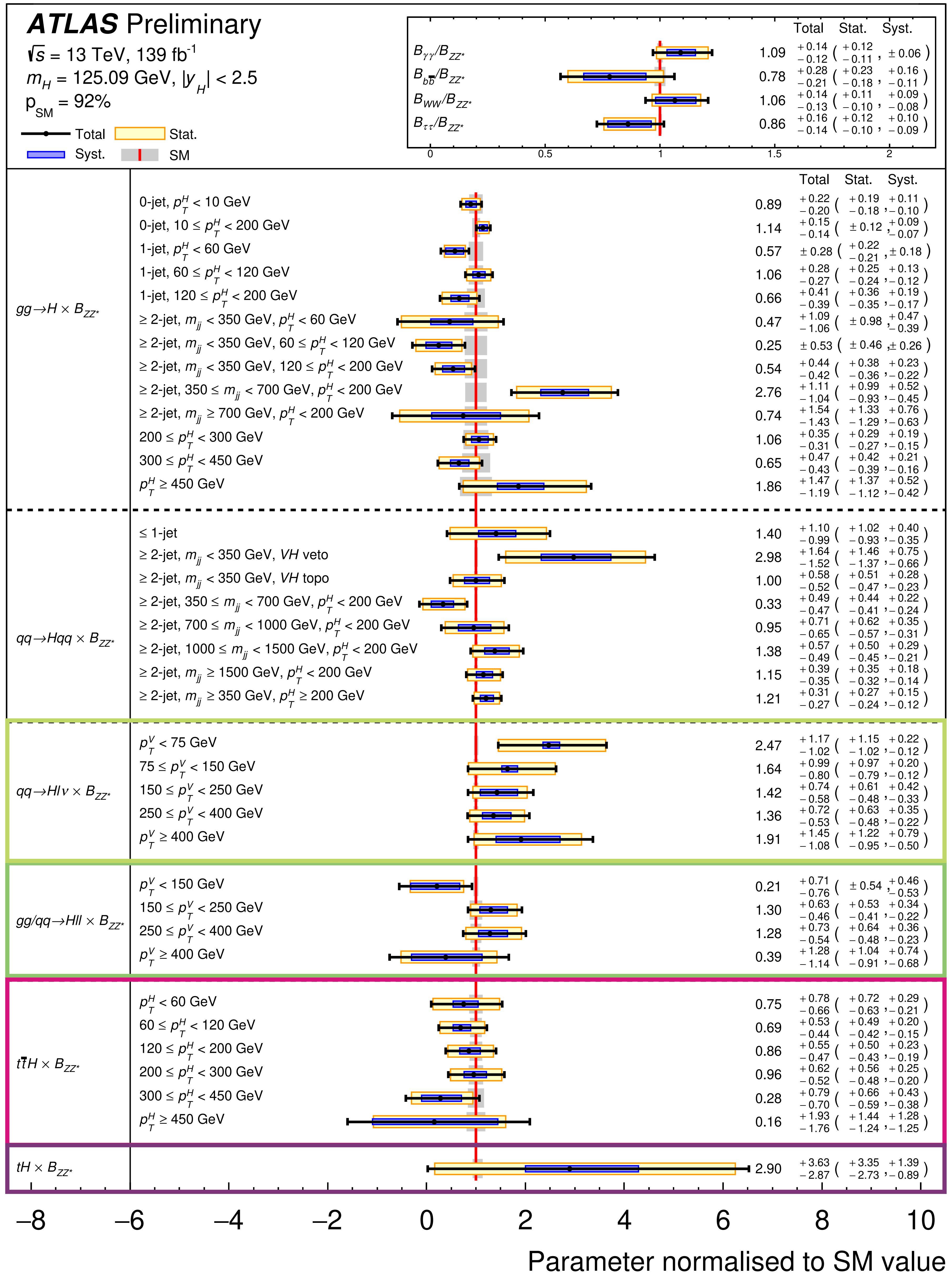
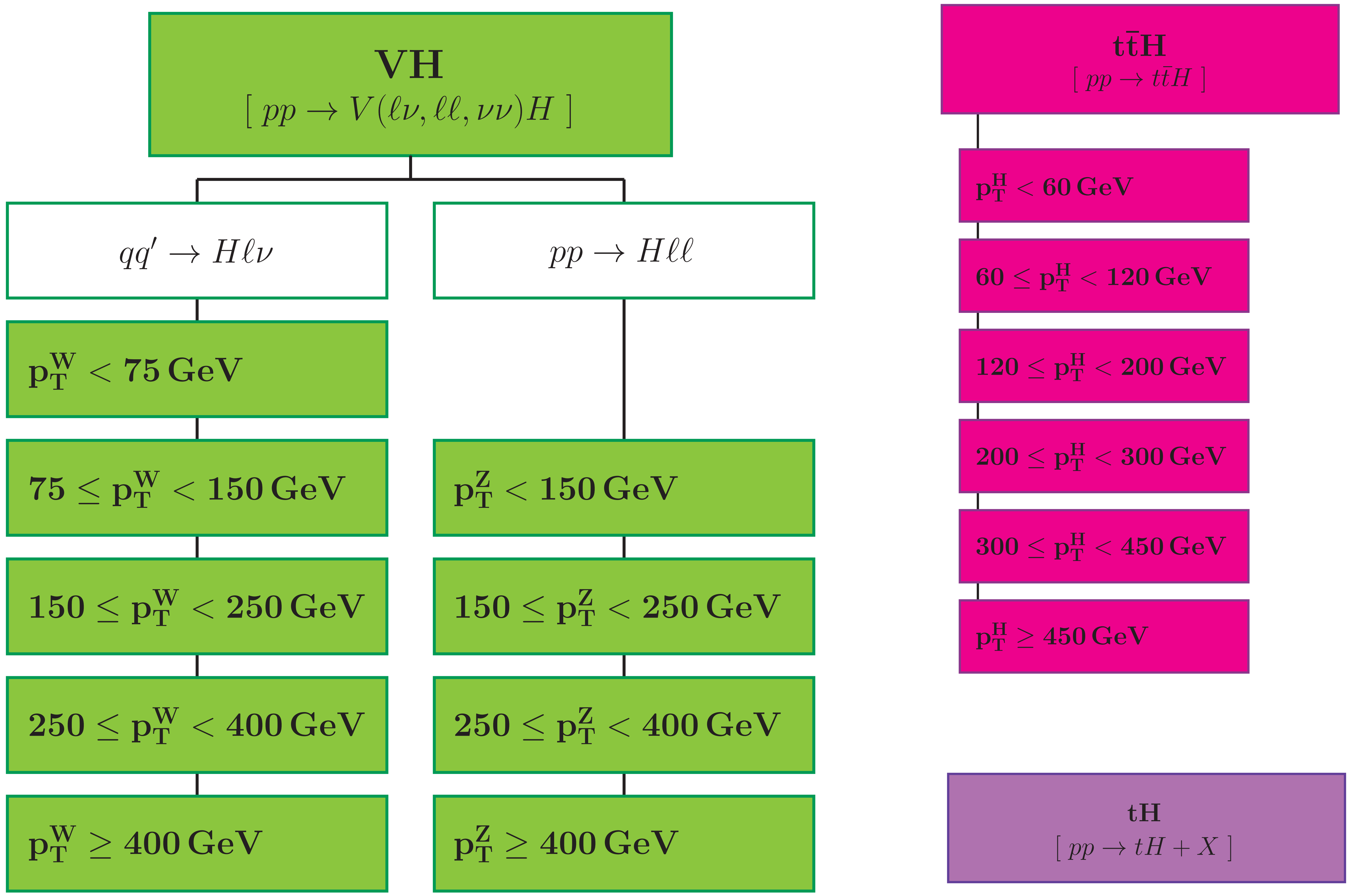
STXS results





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HH→bbγγ

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