Measurements of **Higgs boson couplings** to **bottom quarks, charm quarks** and **τ leptons** with the **ATLAS** detector

Brian Moser
on behalf of the ATLAS Collaboration

EPS HEP 2025 - Marseille

07/07/2025

ATLAS EXPERIMENT

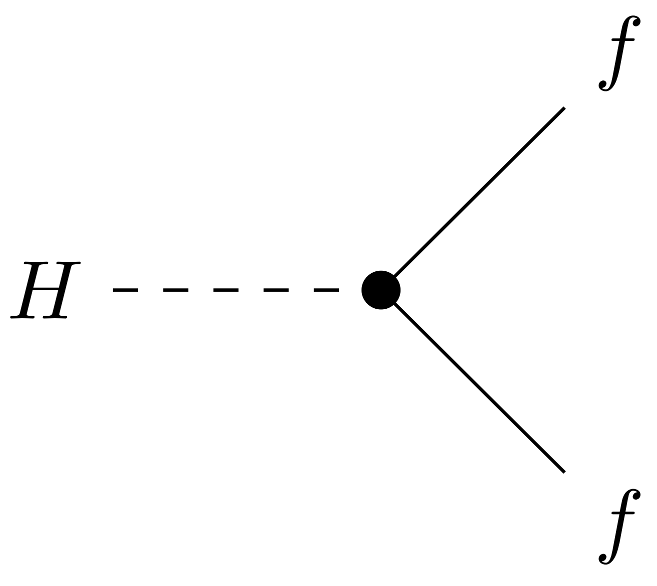
universität freiburg

Setting the stage: Yukawa couplings in the SM

The **Higgs sector** of the SM highlights our success with description but lack of understanding

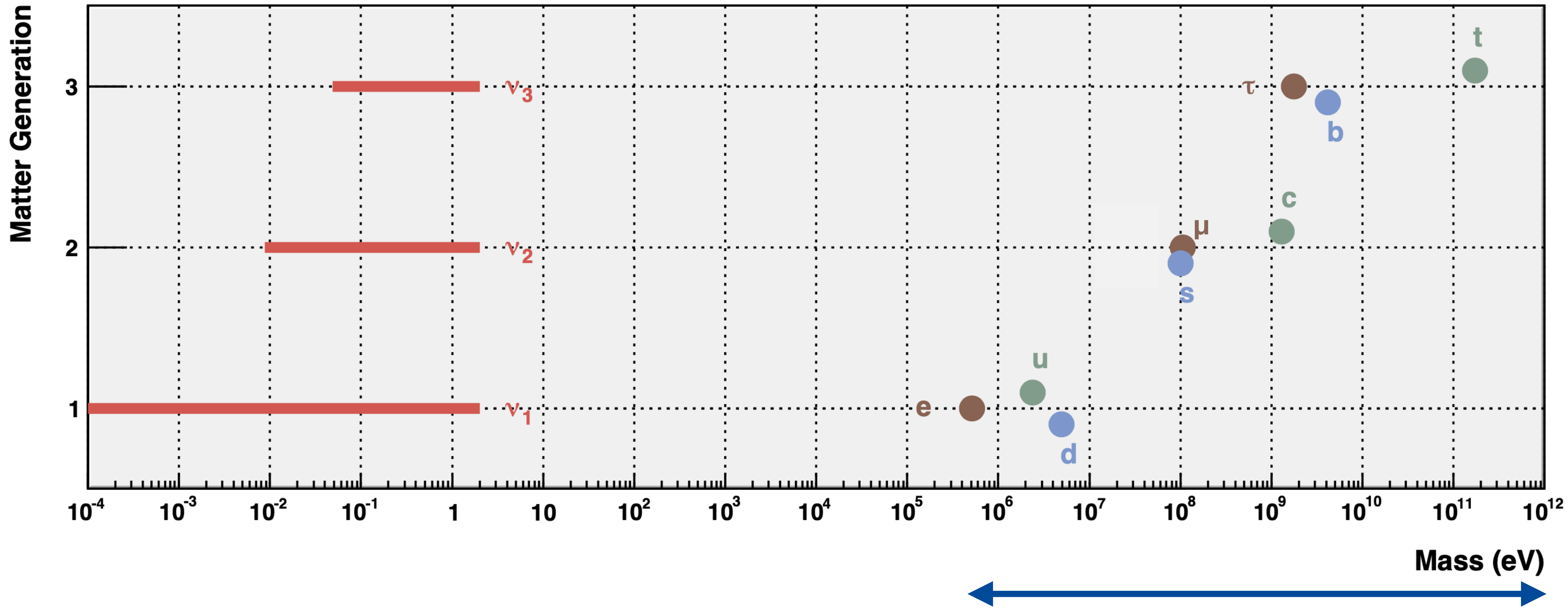
Yukawa terms: $\mathcal{L}_{\mathrm{SM}} \subset y_{ij}\ \psi_i\ \phi\ \psi_j + \mathrm{h.c.}$

Higgs boson coupling to fermions
proportional to their mass



$$Y_f = \sqrt{2}\,\frac{m_f}{\mathrm{vev}}$$

[arXiv:1109.5515v1]



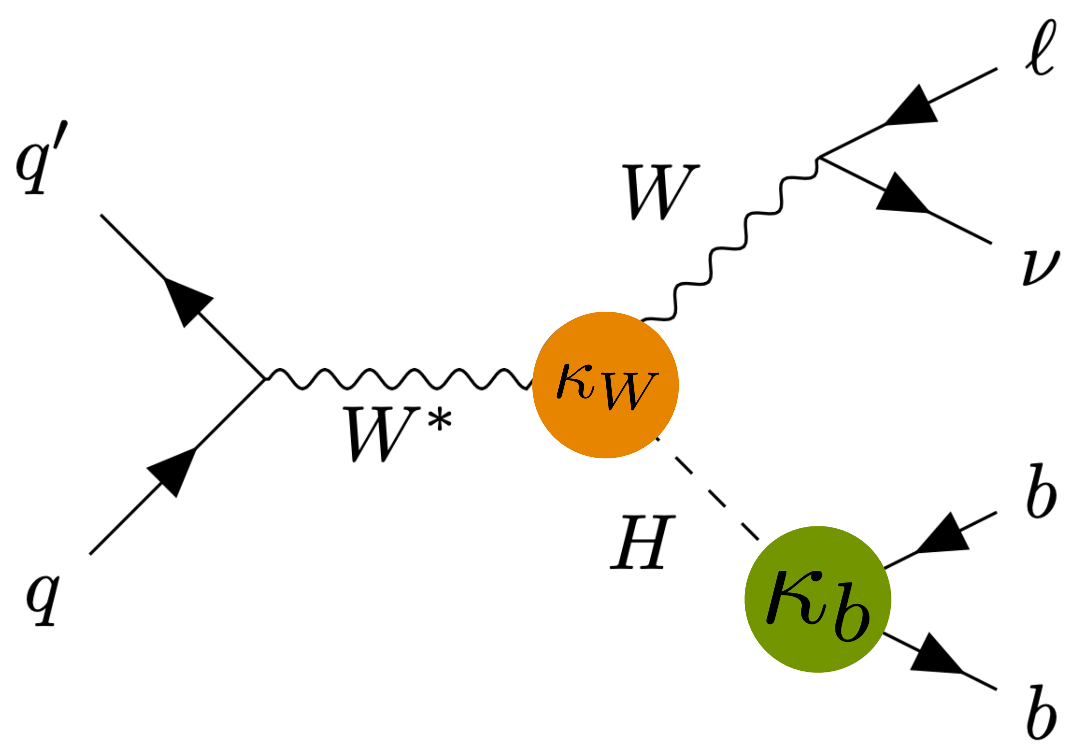
- Yukawa coupling values span > 5 orders of magnitude
  → this hierarchy is not understood
- Experimentalist:
  Is it really true?
  Measure them!

Measuring **coupling properties**

Couplings are not directly observable → need to extract them from observables [rates, distributions, …]
→ requires a theoretical framework (and often assumptions)

κ-framework

- Leading order coupling modifiers tailored for rates



$$(\sigma \times \mathrm{BR})(pp \to WH \to \ell\nu b\bar{b}) =$$

$$\sigma_{\mathrm{SM}}(pp \to WH) \times \mathrm{BR}_{\mathrm{SM}}(H \to b\bar{b})$$

$$\times \frac{\kappa_W^2 \kappa_b^2}{\kappa_H^2}$$

Higgs width → all couplings enter → combinations needed [and/or assumptions]

(SM)EFT

- Systematic expansion of the SM Lagrangian in terms of higher order operators and associated Wilson coefficients

$$\mathcal{L}_{\mathrm{SMEFT}} = \mathcal{L}_{\mathrm{SM}} + \sum_i \frac{c_i^{(5)}}{\Lambda} \mathcal{Q}_i^{(5)} + \sum_i \frac{c_i^{(6)}}{\Lambda^2} \mathcal{Q}_i^{(6)} + \dots$$

Wilson coefficients
[= the free parameters]

scale of new physics

higher dim. operators

Measuring **coupling properties**

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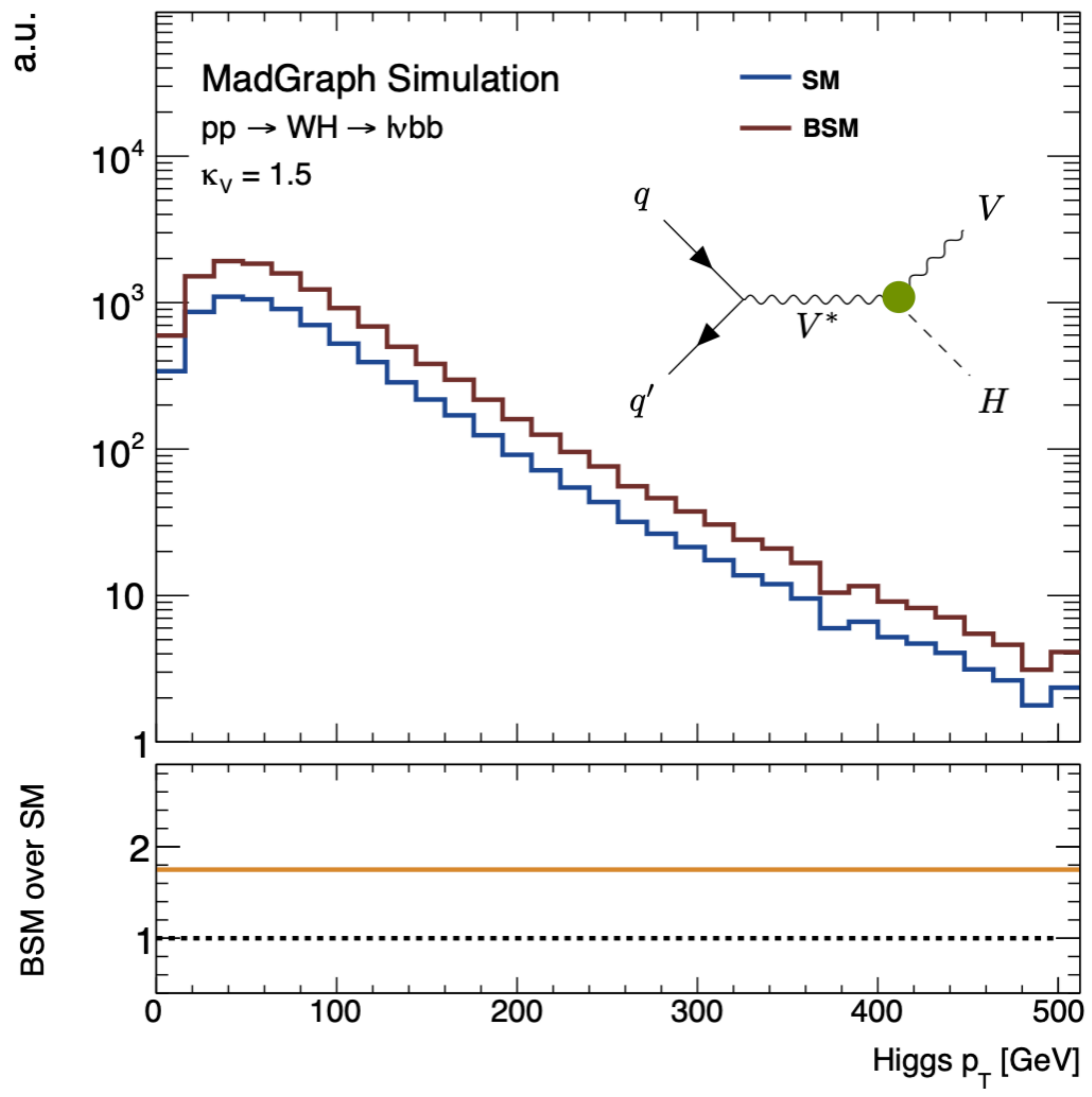

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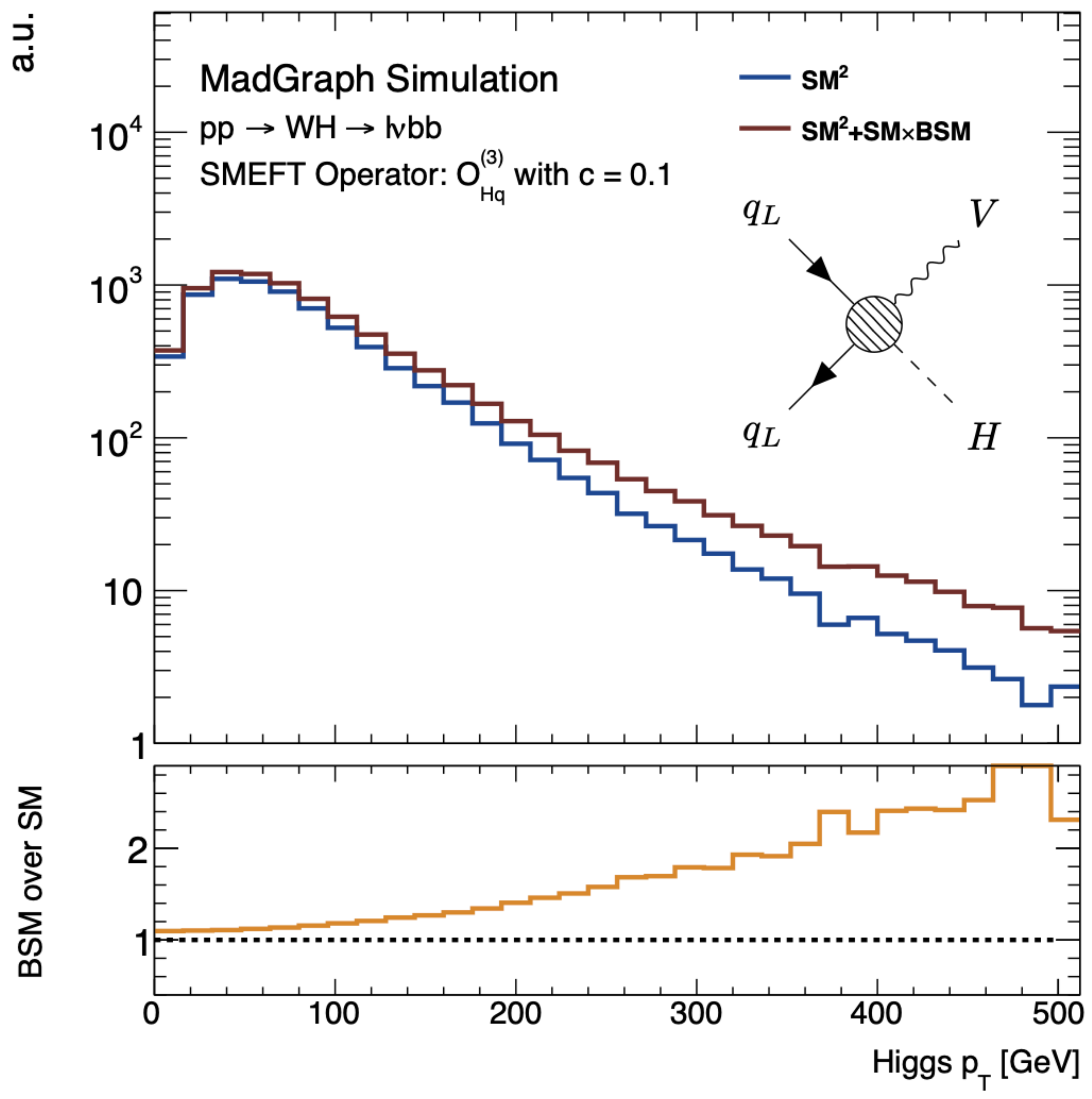


Thursday session

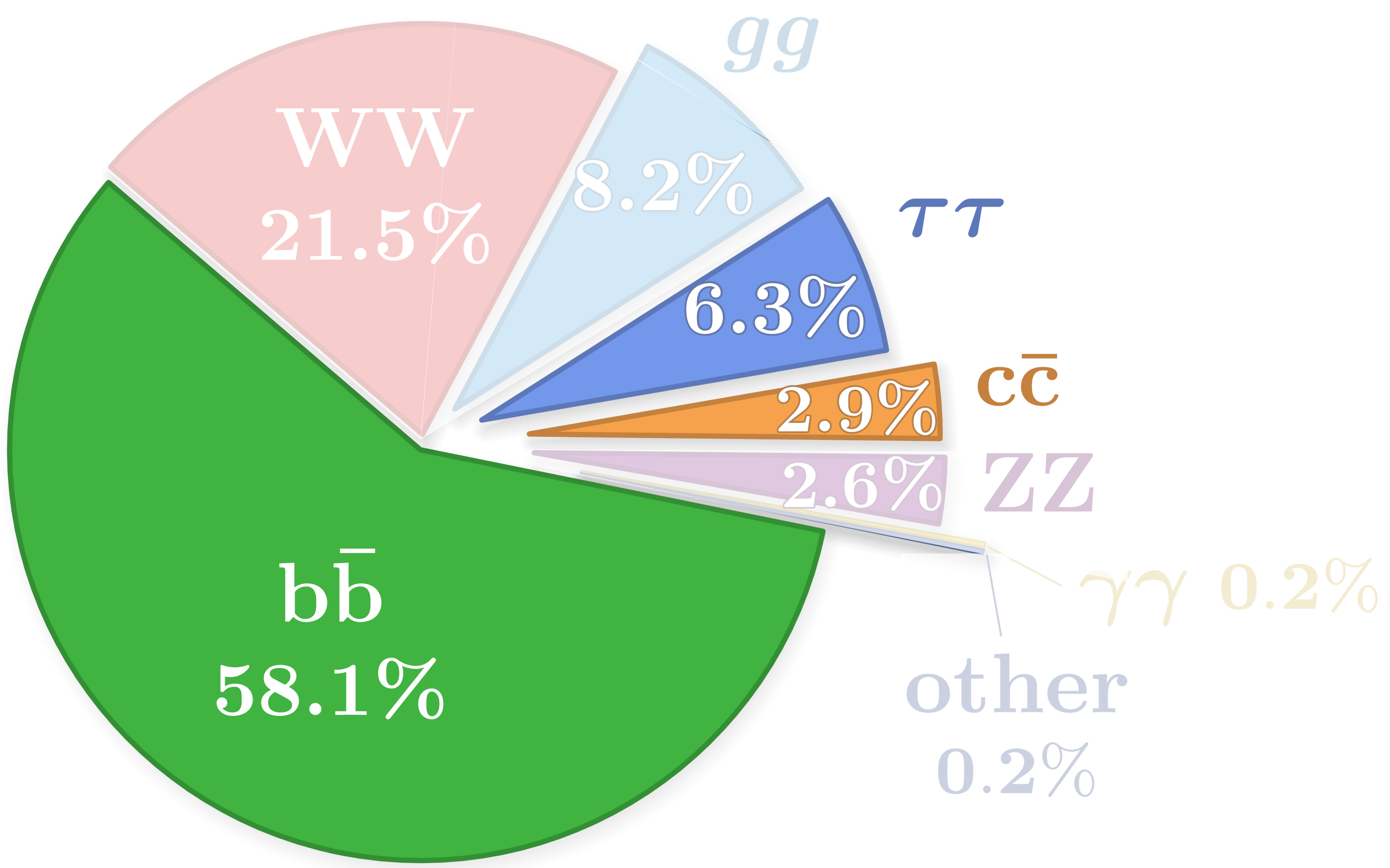
We are interested in: coupling strength and tensor structure [CP violating effects?]

The **menu** for today

Higgs boson couplings to

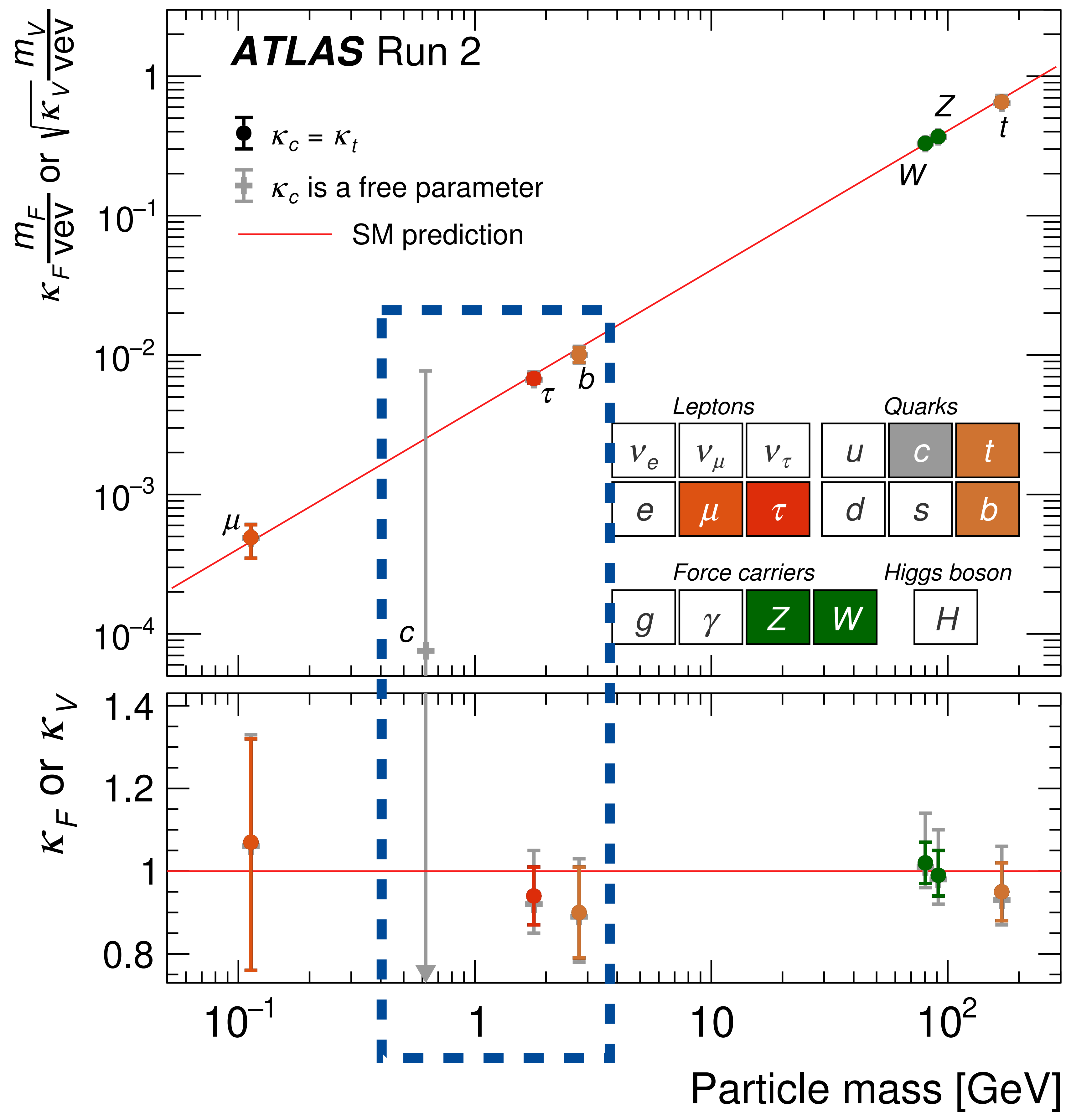
bottom quarks | charm quarks | τ leptons

Higgs boson **branching fractions**:



[Izaak Neutelings, TikZ.net]

[Nature 607 52 (2022)]

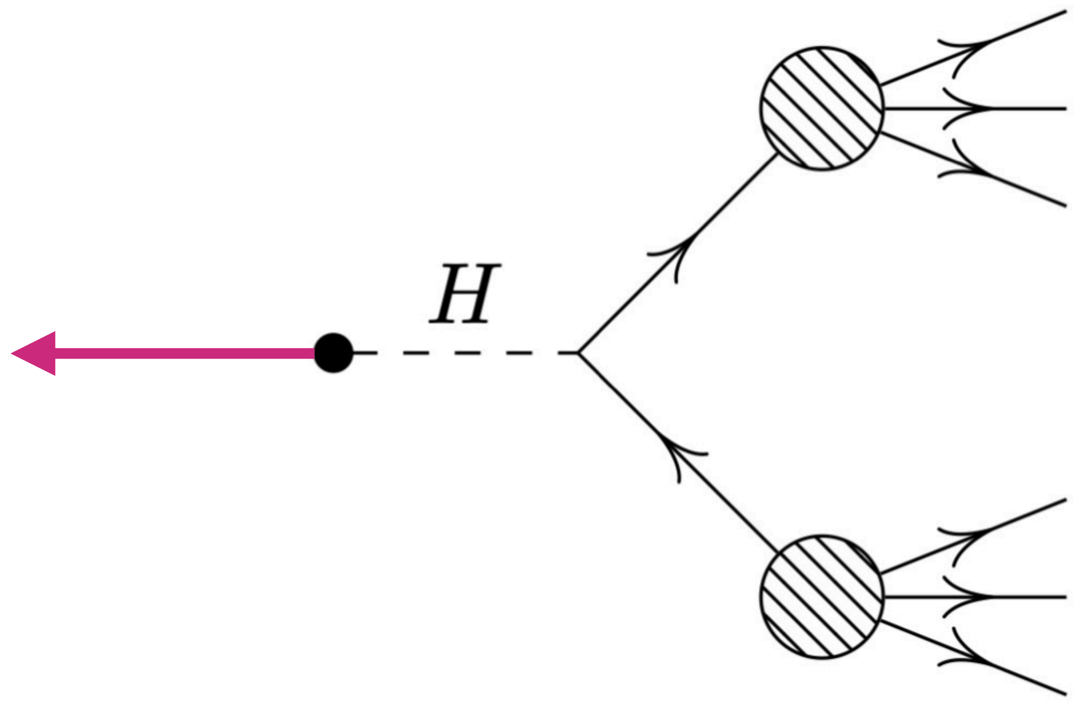


H→bb/cc: Overview

Hadronic signature at a hadron collider → need additional objects (X) to trigger on and increase the signal to background ratio

e.g. Vector bosons
high p_T jets
VBF jets
top-quark pairs
...

X



b-jet or c-jet

b-jet or c-jet

$$\left[\text{e.g.}\quad \frac{\sigma(bb)}{\sigma(H)} \sim 10^7\right]$$

ATLAS analyses:

- V(→leptons)H(→bb/cc) [JHEP 04 (2025) 075]
- ttH(→bb) [EPJC 85 (2025) 210]
- V(→hadronic)H(→bb) [PRL 132 (2024) 131802]
- boosted H(→bb) + high p_T jet [PRD 105 (2022) 092003]

- CP properties from WH(→bb) [ATL-PHYS-PUB-2025-022]
- VBF H(→bb) [EPJC 81 (2021) 537]
- VBF H(→bb) + photon [JHEP 03 (2021) 268]
- VBF WH(→bb) [PRL 133 (2024) 141801]
- H→meson + photon [PLB 786 (2018) 134]

[sensitivity to the charm Yukawa coupling also probed in H(→γγ)+c production [JHEP 02 (2025) 045] and in differential $d\sigma/dp_T^H$ measurements in H→ZZ* and H→γγ [JHEP 05 (2023) 028]]

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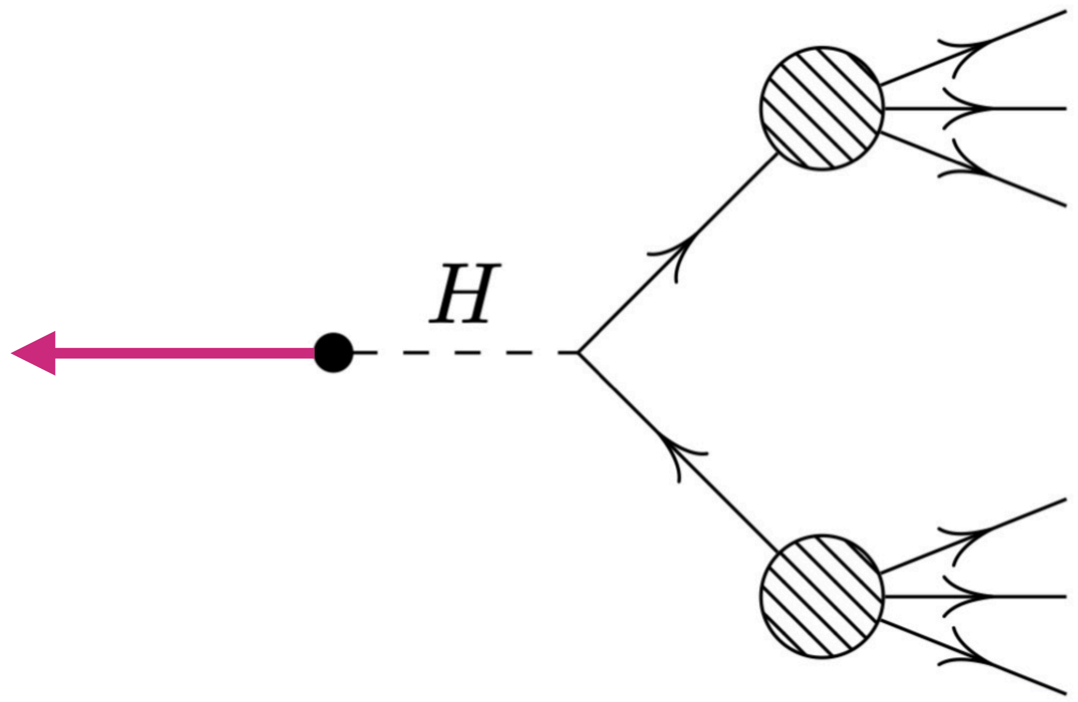

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Today!

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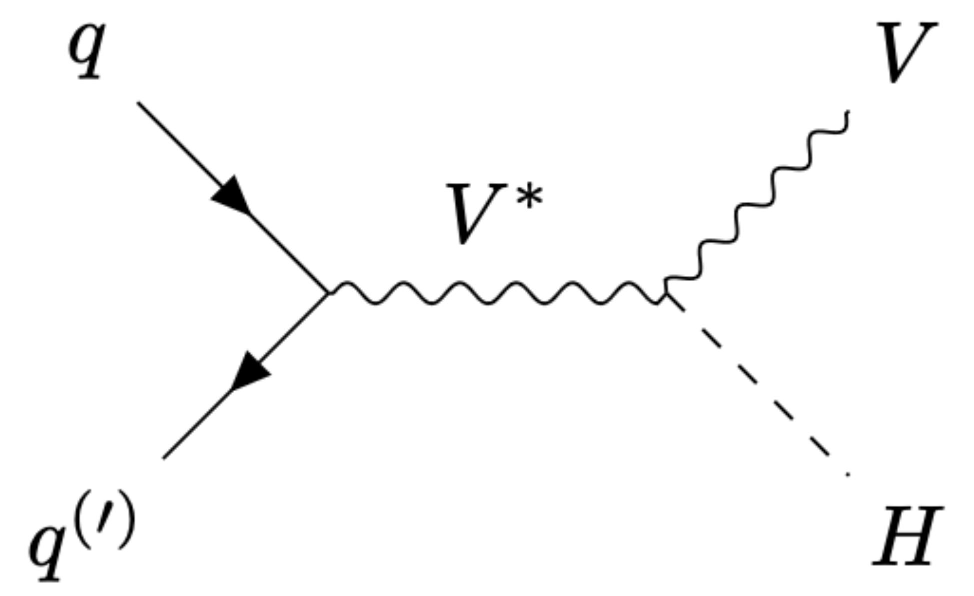
talk by Marina Kholodenko on Thursday

[sensitivity to the charm Yukawa coupling also probed in H(→γγ)+c production [JHEP 02 (2025) 045] and in differential $d\sigma/dp_T^H$ measurements in H→ZZ* and H→γγ [JHEP 05 (2023) 028]]

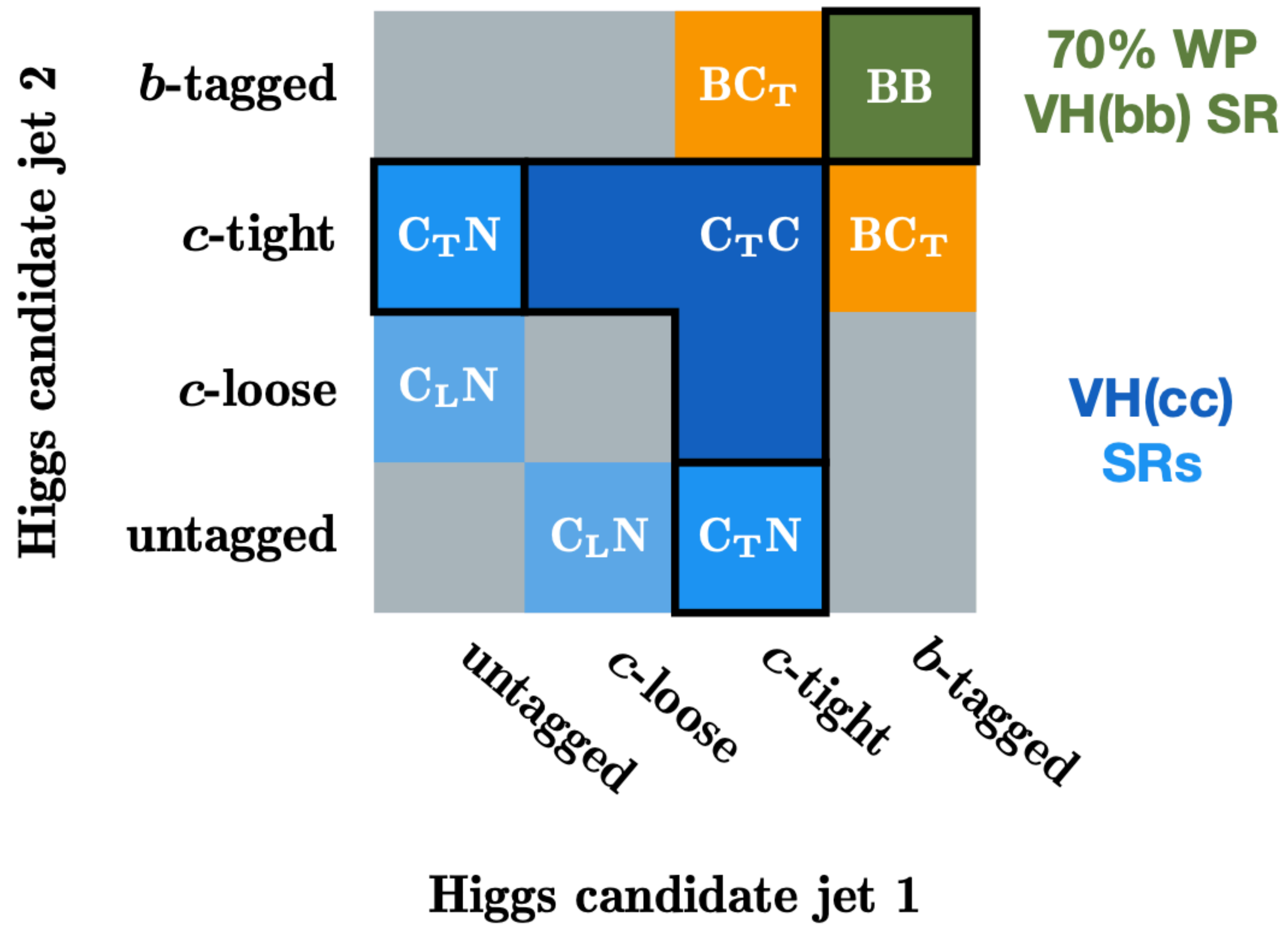
Resolved + Boosted VH, H→bb/cc [Run 2]

JHEP 04 (2025) 075

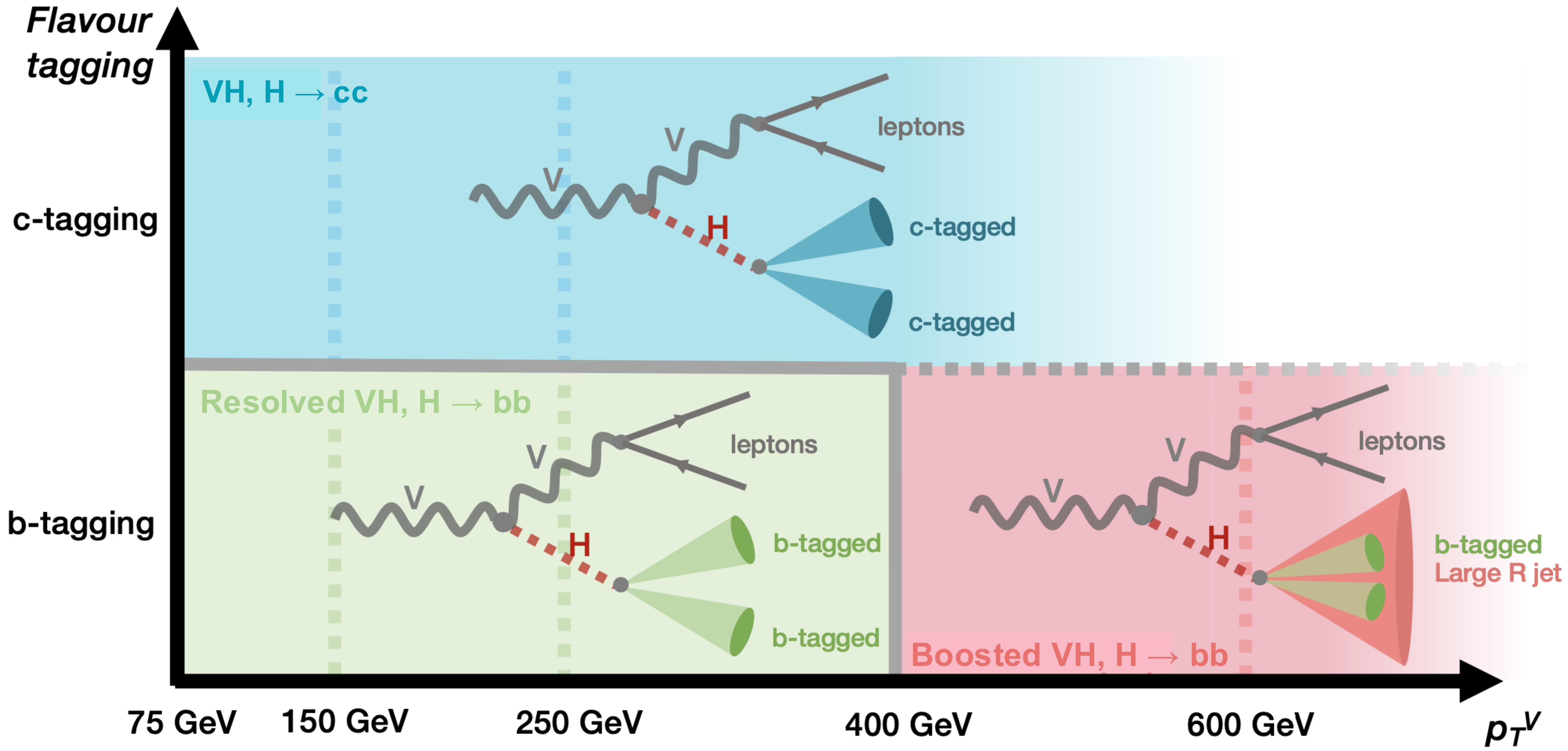
- Analysis categorized by charged lepton final state multiplicity
  Z(→νν): **0-lepton** W(→ℓν): **1-lepton** Z(→ee/μμ): **2-lepton**



- **Resolved** (= 2 R=0.4 jets) H→bb reconstruction at low + intermediate V p_T, **boosted** (=1 R=1.0 jet) H→bb reconstruction for p_T^V > 400 GeV
- Resolved reconstruction for H→cc
- **Pseudo-continuous flavor tagging** scheme used [exclusive b- and c-tagging]
- Multiple signal and control regions:



+ ΔR_{jj}-based control regions



- **Boosted Decision Trees** to separate the signal from the plethora of backgrounds [and as a fit discriminant]

Resolved + Boosted VH, H→bb/cc [Run 2]

JHEP 04 (2025) 075

Results:

- Di-boson cross-check (Z→bb/cc instead of H→bb/cc):

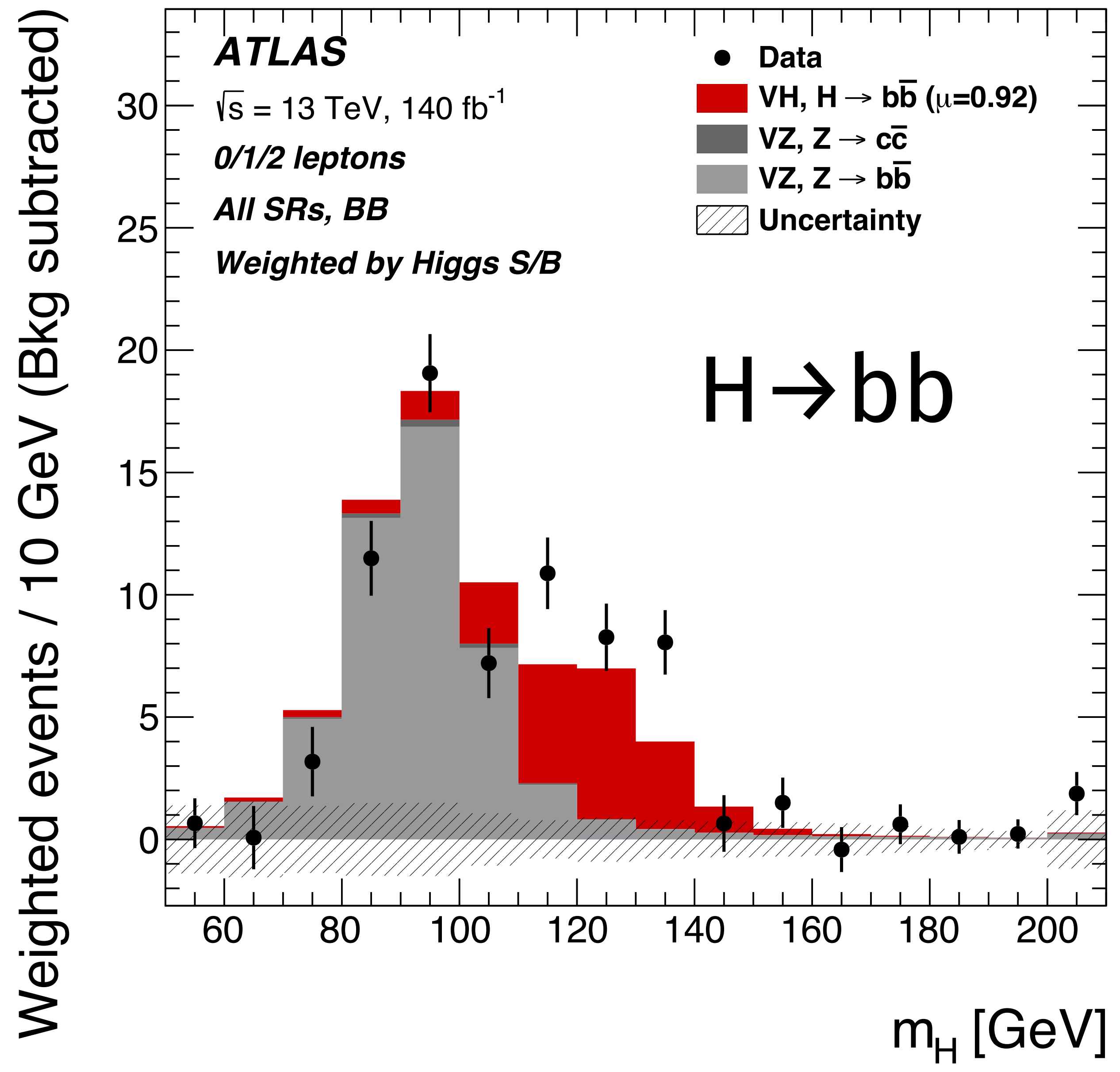
$$\mu^{bb}_{VZ} = 0.92^{+0.13}_{-0.11} = 0.92 \pm 0.05\ (\text{Stat.})^{+0.12}_{-0.10}\ (\text{Syst.})$$
$$\mu^{cc}_{VZ} = 0.98^{+0.25}_{-0.22} = 0.98 \pm 0.13\ (\text{Stat.})^{+0.22}_{-0.18}\ (\text{Syst.})$$

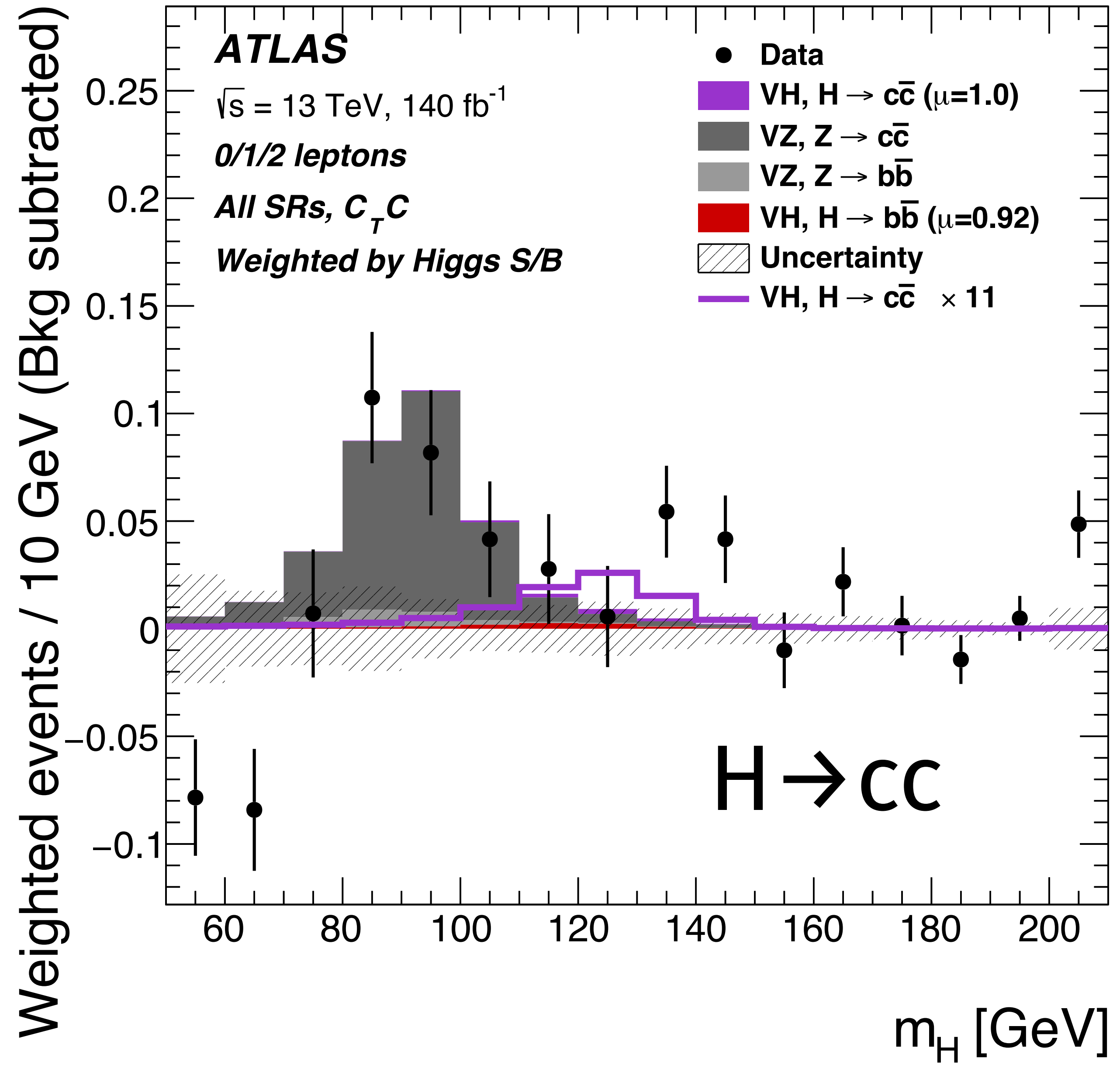
  - Signal strengths in good agreement with SM
  - First ATLAS observation of VZ(→cc)

- Higgs boson results:

$$\mu^{bb}_{VH} = 0.92^{+0.16}_{-0.15} = 0.92 \pm 0.10\ (\text{Stat.})^{+0.13}_{-0.11}\ (\text{Syst.})$$
$$\mu^{cc}_{VH} = 1.0^{+5.4}_{-5.2} = 1.0^{+4.0}_{-3.9}\ (\text{Stat.})^{+3.7}_{-3.5}\ (\text{Syst.})$$

  - Signal strengths in good agreement with SM
  - VH, H→cc limit of 11 x SM prediction at 95% CL [best ATLAS limit to date]

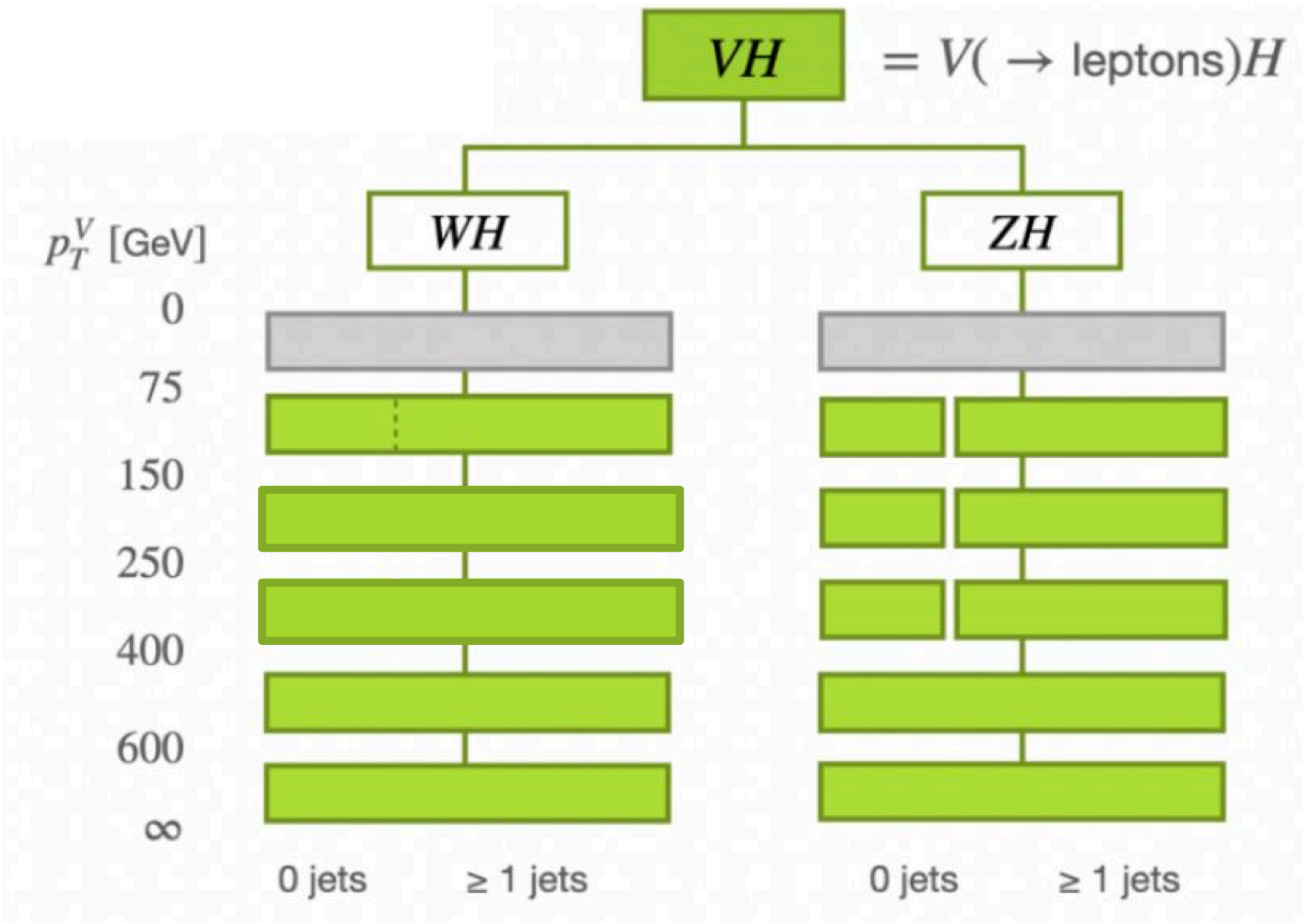




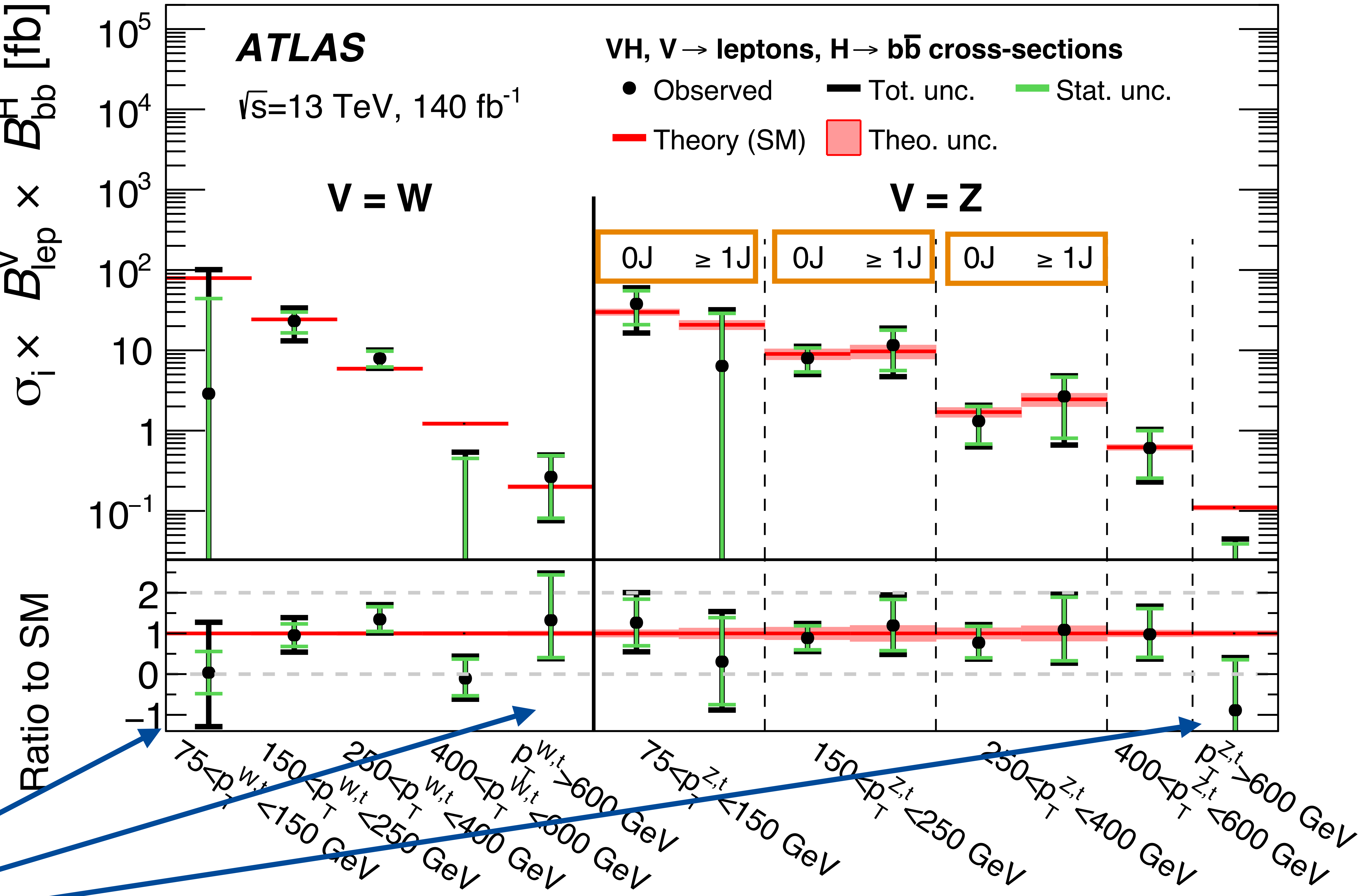
Resolved + Boosted VH, H→bb/cc [Run 2]

JHEP 04 (2025) 075

- Pseudo-differential cross-section measurement with an extended **STXS** stage 1.2 scheme



SM compatibility: p-value = 90%

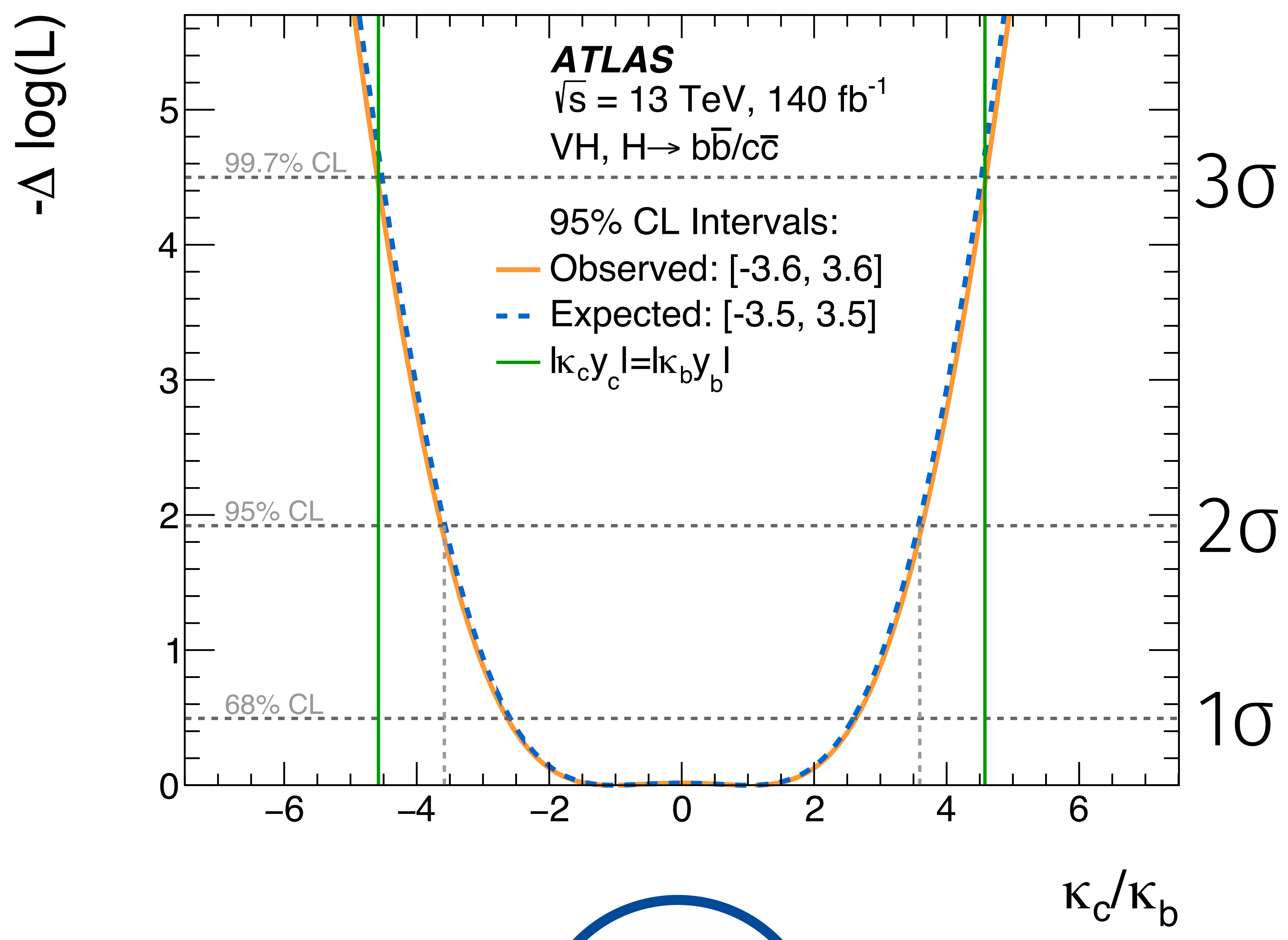


- Extended granularity/reach [both at low and high p_T^V]
- n_{Jets} binning in ZH

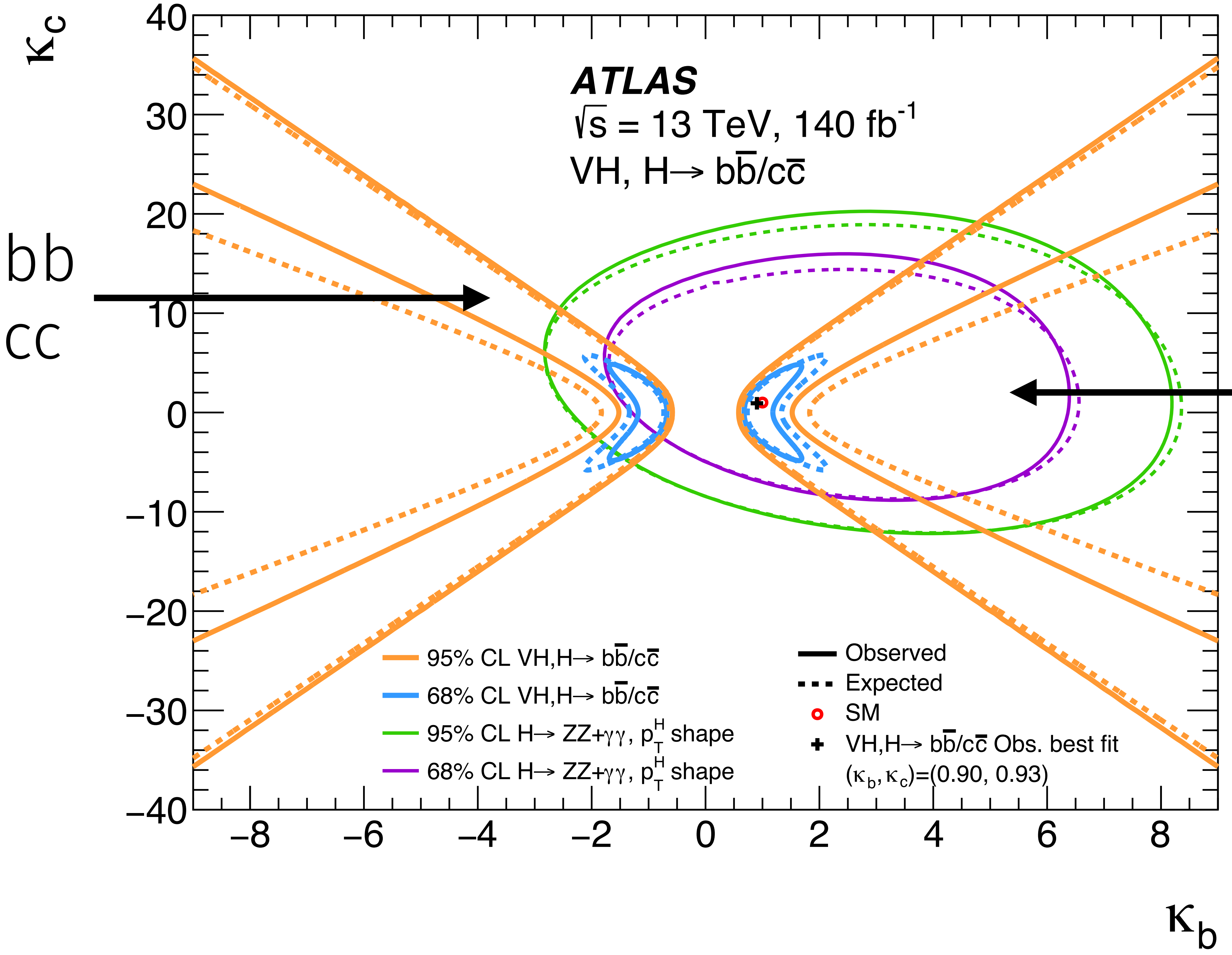
Leading input to constrain $c_{Hq}^{(3)}$ (effect $\sim (p_T^V)^2$) in the SMEFT interpretation of the ATLAS Higgs combination

[see e.g. JHEP 11 (2024) 097]

Resolved + Boosted VH, H→bb/cc [Run 2]



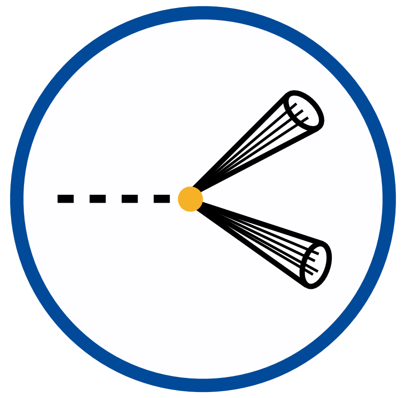
VH, H→bb
VH, H→cc



$\frac{d\sigma}{dp_{\mathrm{T}}^{H}}$

H→ZZ*,
H→γγ

$\mathrm{BR}(H \to \color{darkred}{b\bar{b}}) \sim \frac{{\kappa_b}^2}{{\kappa_H}^2}$



$\mathrm{BR}(H \to c\bar{c}) \sim \frac{{\kappa_c}^2}{{\kappa_H}^2}$

[assuming all κ but κ_b and κ_c are SM-like]

→ the ratio of κ_c/κ_b can be constrained without having to make assumptions on κ_H

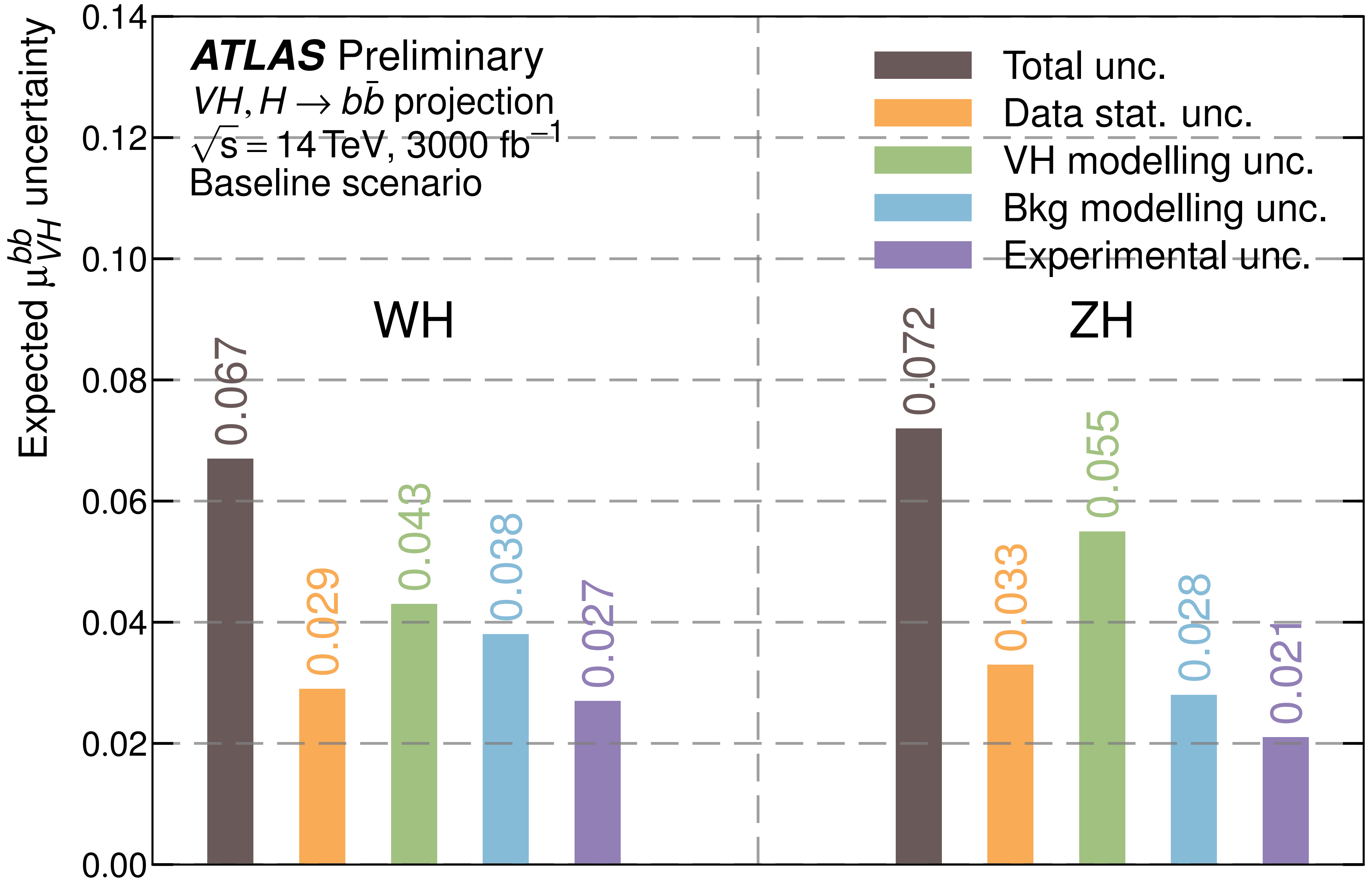
The Higgs boson couples weaker to charm quarks than it couples to bottom quarks

Constraints from direct measurements are complementary to indirect constraints

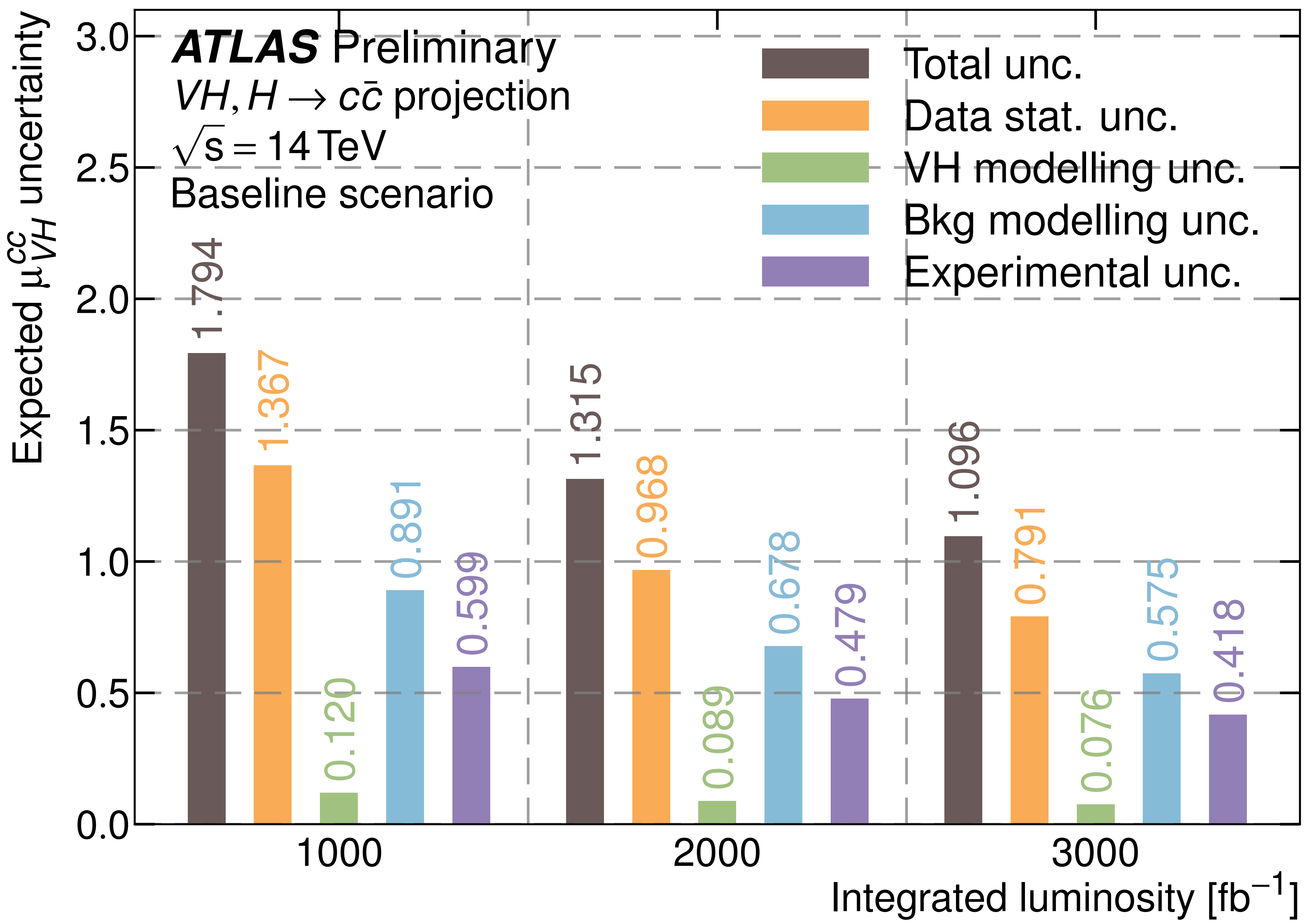
Quo-vadis: HL-LHC prospects for VH, H→bb/cc

Uncertainty contribution at 3000/fb for:

H→bb



H→cc



Rate measurements with 6-7% seem possible
→ can afford many more bins differentially
[e.g. μ for W/Z p_T > 600 GeV with < 30% unc.]

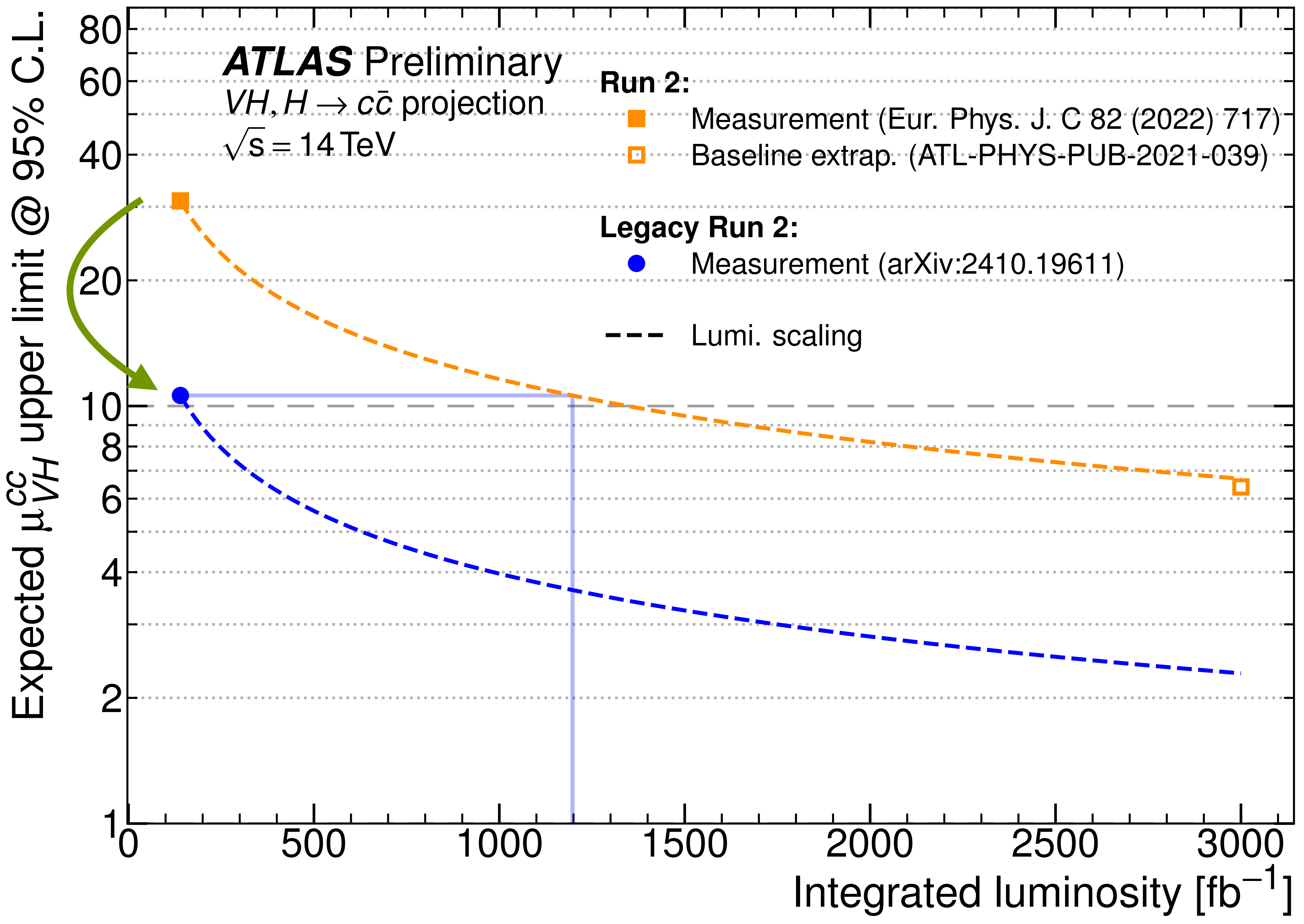
Inclusive μ eventually limited by theory unc. on VH production [currently MiNLO+PS]

Signal strength limit < 2.2 x SM @ 95% confidence level expected

But: e.g. improvements in charm tagging will further lower this number

Quo-vadis: HL-LHC prospects for VH, H→bb/cc

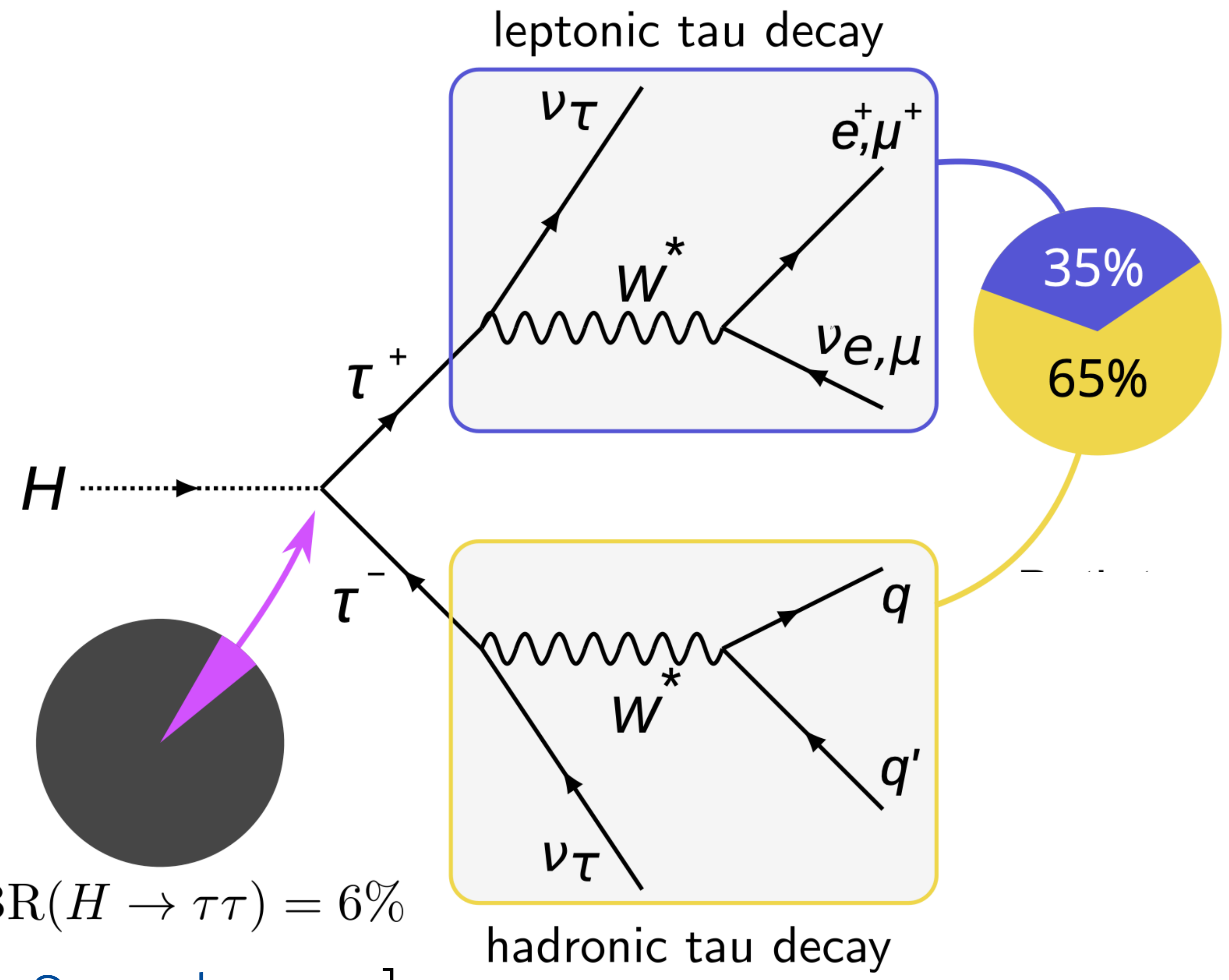
~ factor 3 improvement



Caution with projections: Reanalysis of Run 2 with better techniques equivalent improvement to adding 1000 fb^{-1} to the data set!

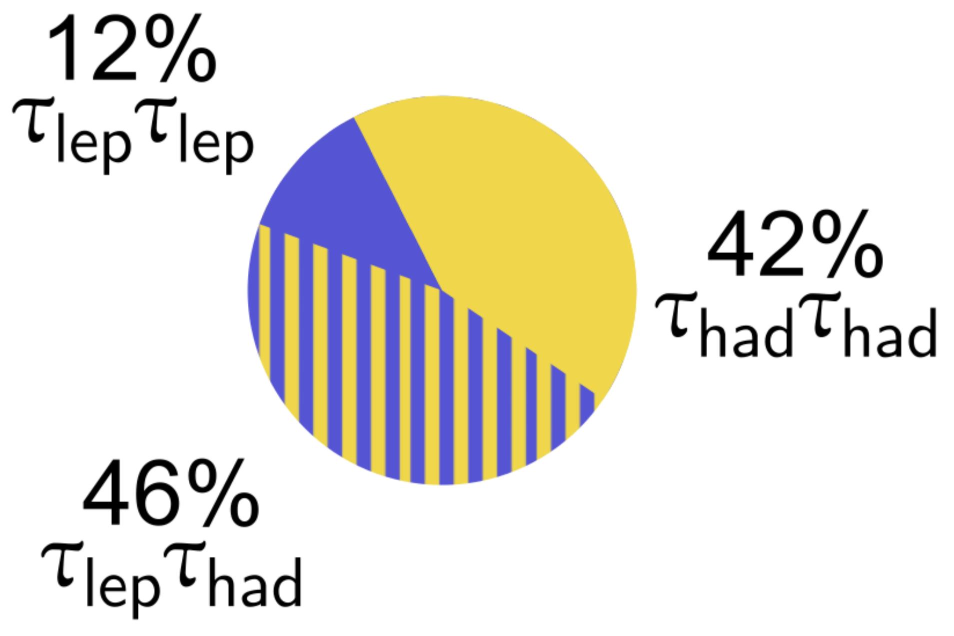
For example, with the latest GN2 tagger we expect a significance of **1.2σ** for the VH, H→cc signal at 3000 fb^{-1}

H→$\tau\tau$: Overview

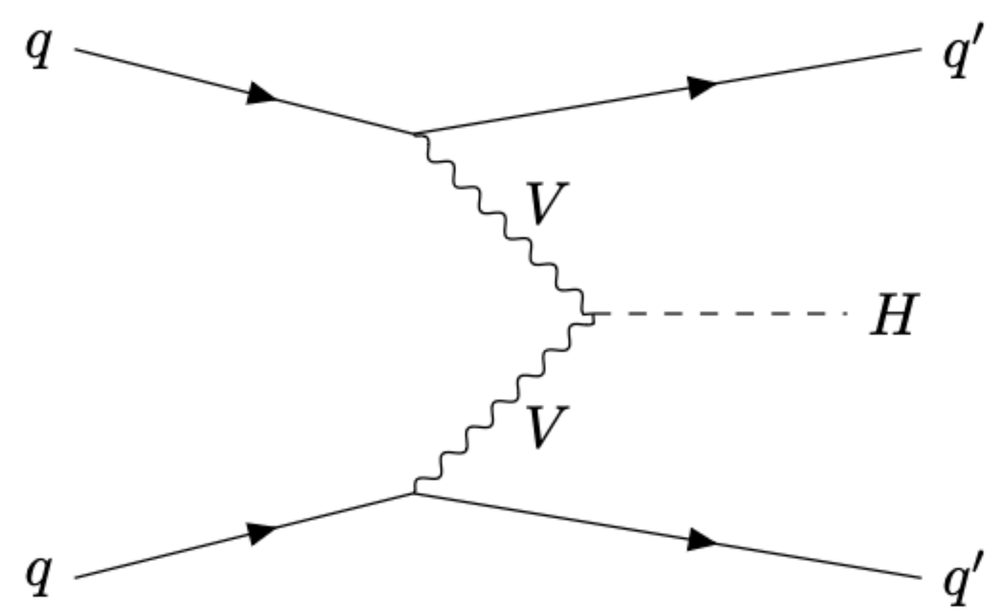


[Frank Sauerburger]

Both τ leptons decay
→ 3 analysis channels



Large background, e.g. from Z/γ*→ℓℓ
→ **VBF production** has typically the best sensitivity



ATLAS analyses:

- CP properties in VBF H→$\tau\tau$ [arXiv:2506.19395]
- H→$\tau\tau$ cross-sections and couplings (mostly VBF, but also ggF, VH and ttH) [JHEP 03 (2025) 010]
- V(→leptons) H→$\tau\tau$ [PLB 855 (2024) 138817]
- CP properties in VBF and ggF H→$\tau\tau$ [Eur. Phys. J. C 83 (2023) 563]

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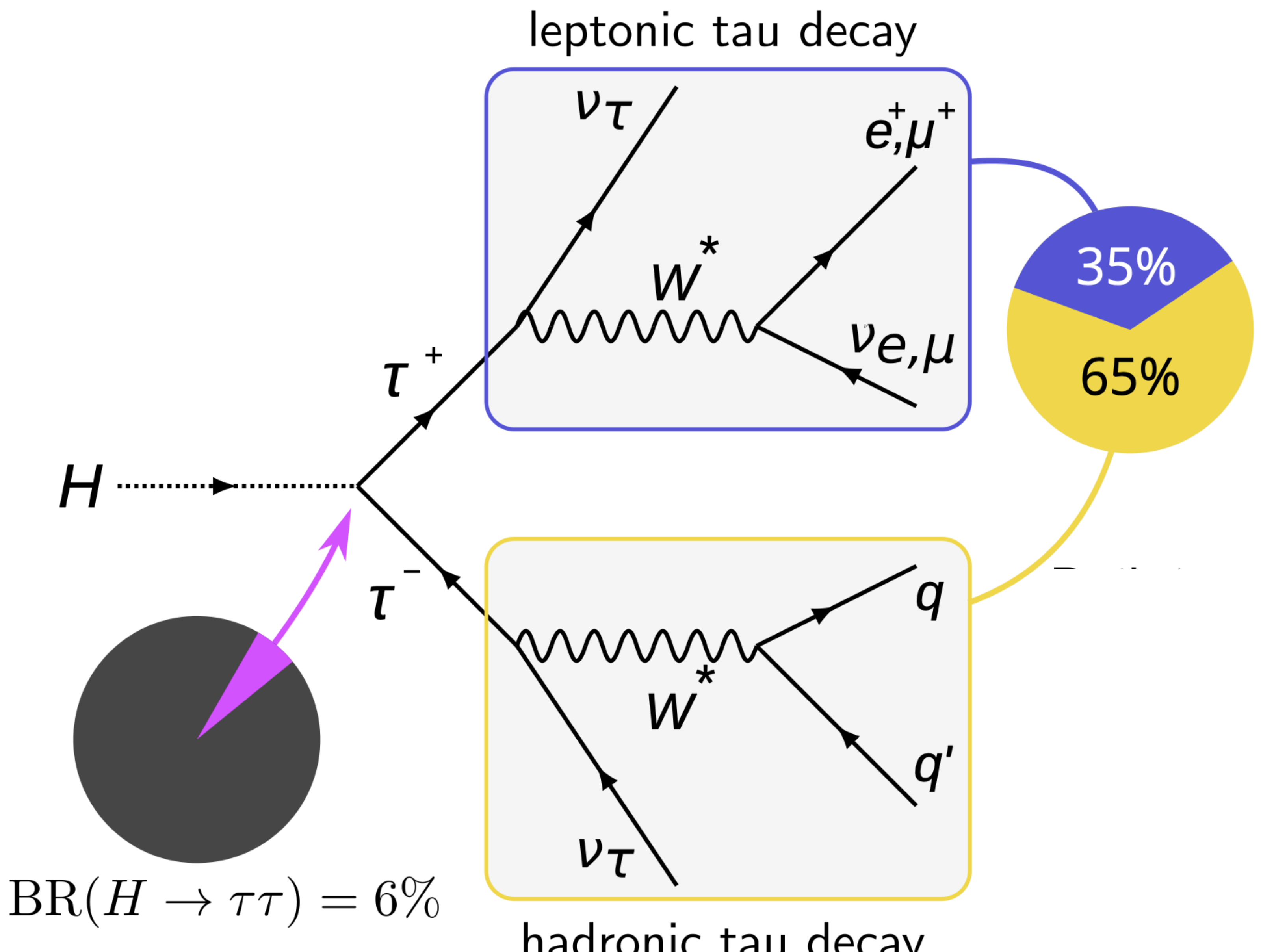

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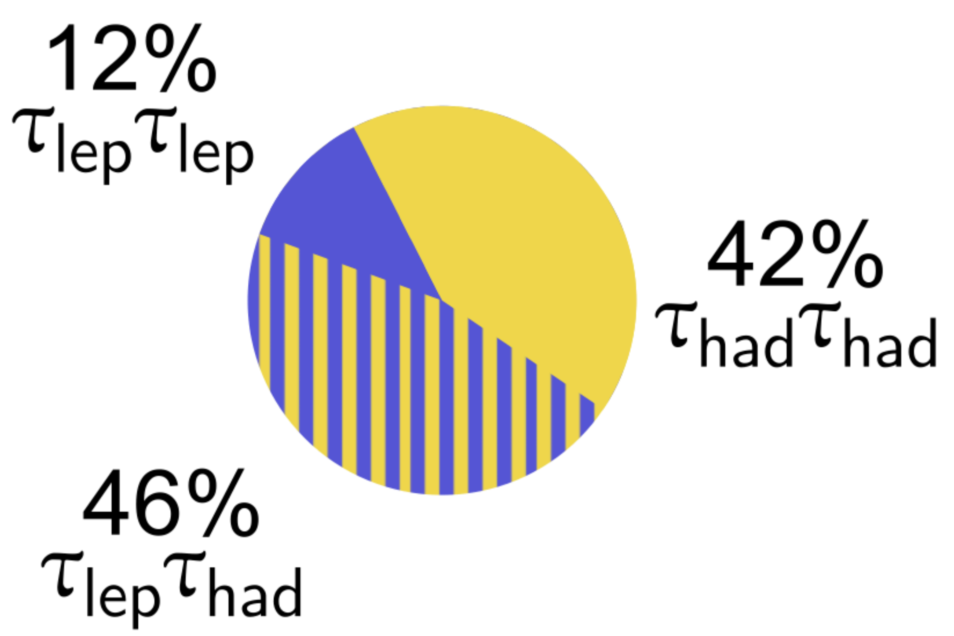

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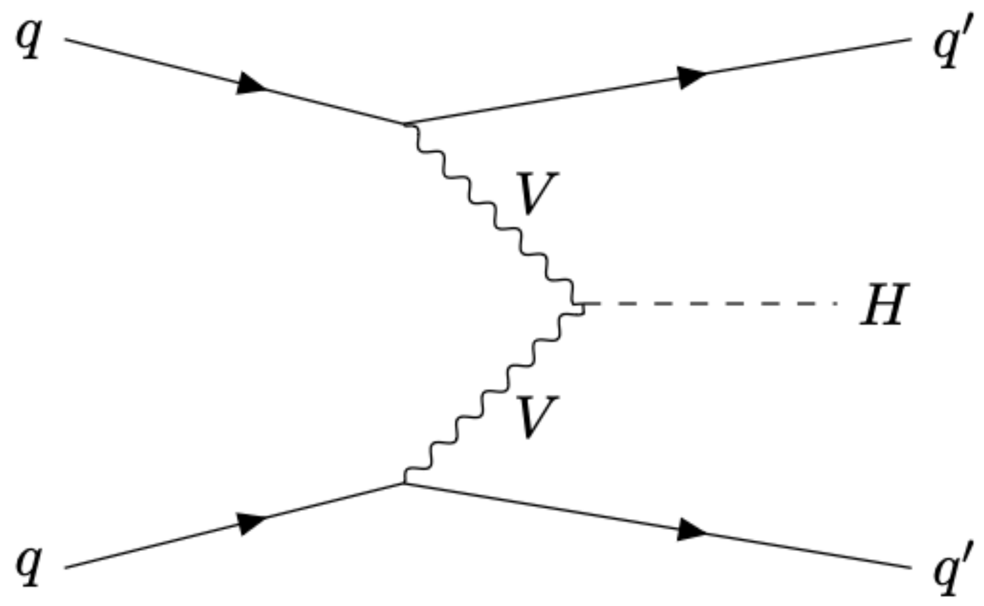

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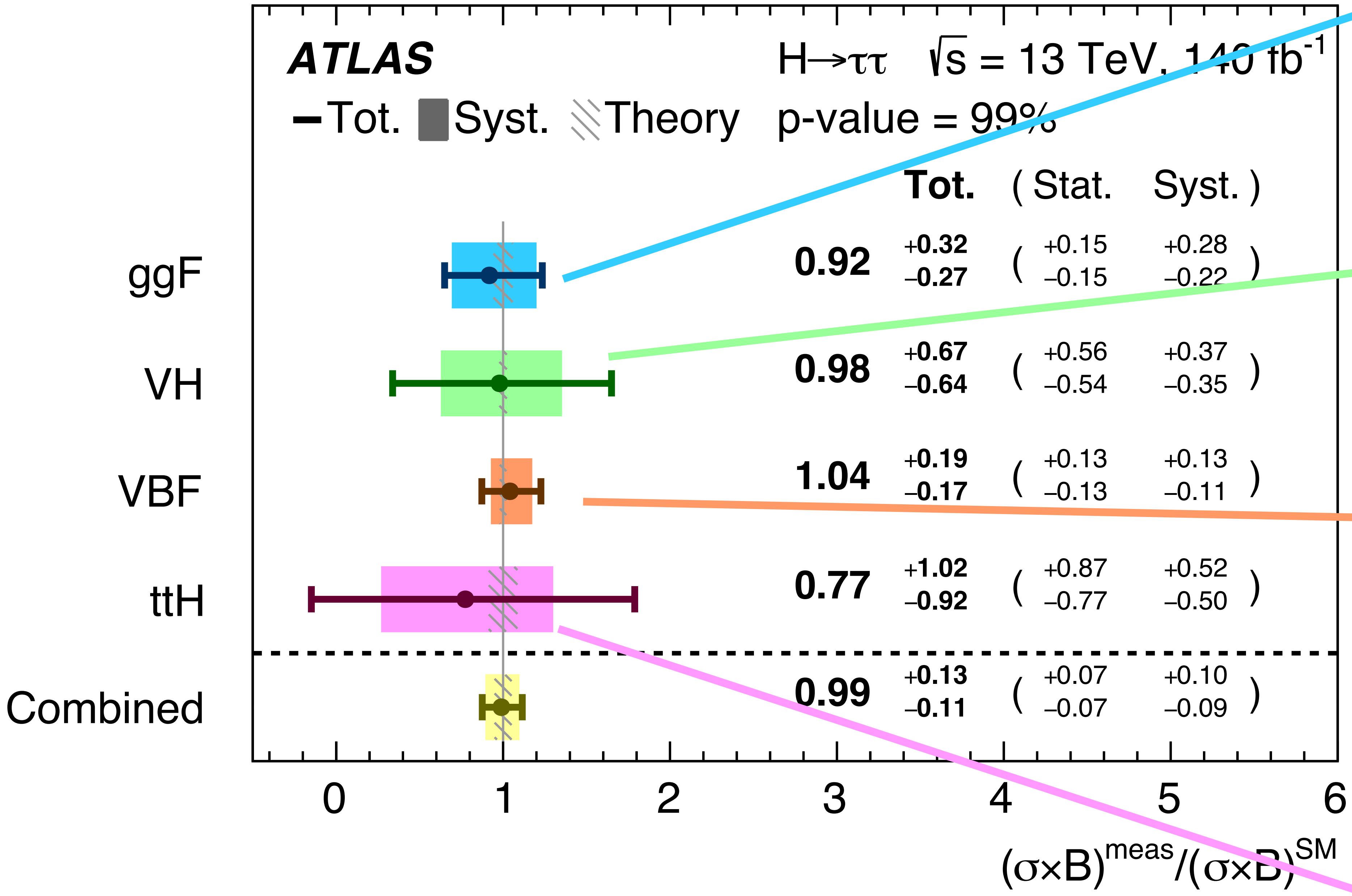
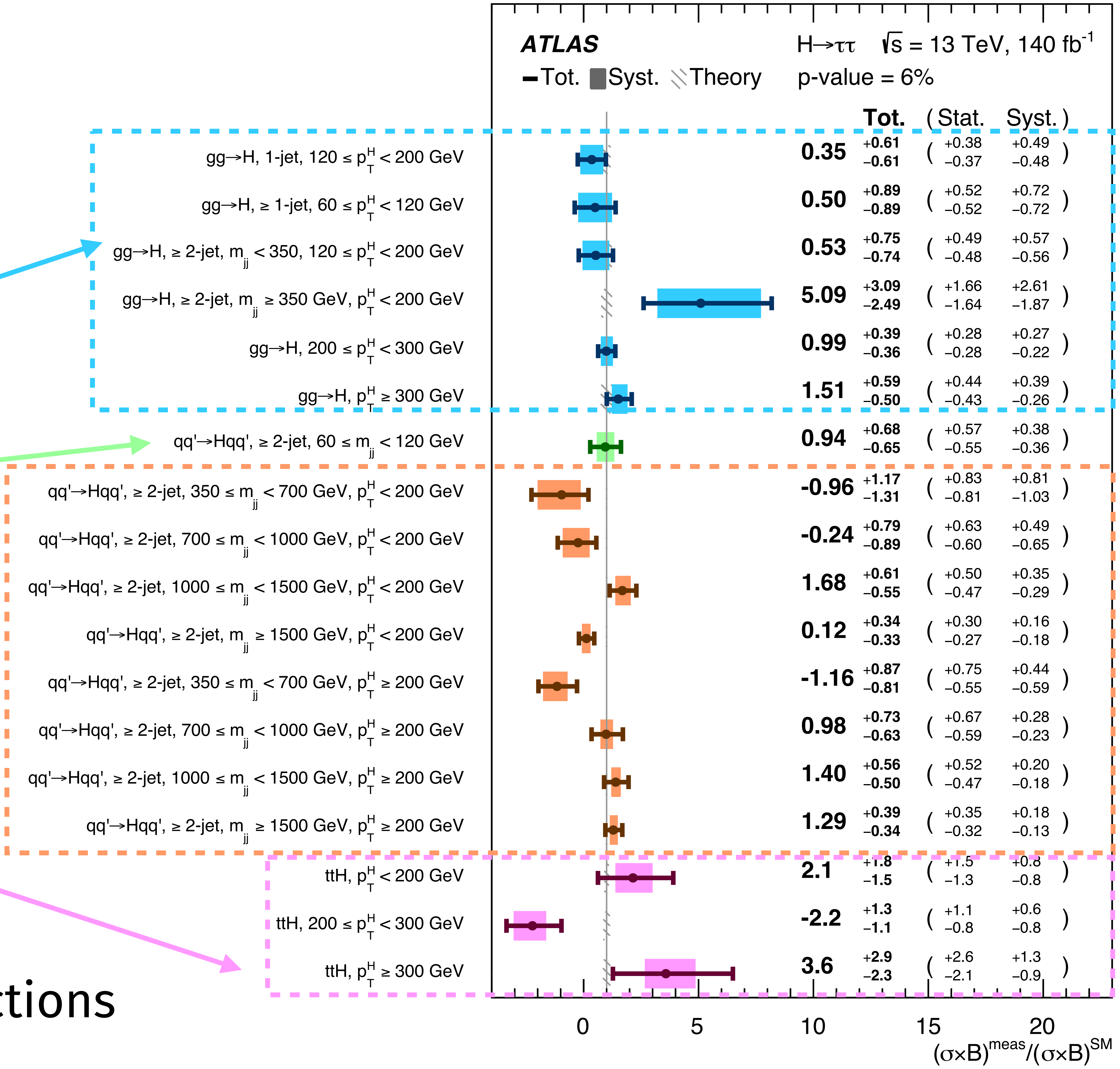
Measurements of $H \to \tau\tau$

[JHEP 03 (2025) 010]

- Measurement targeting **ggF, VH, VBF** and **ttH production** in **all 3 decay modes**
  → VBF channel contributes most to the inclusive rate measurement



SM compatibility: p-value = 6%



- Differential measurement in **STXS bins** as well as **unfolded differential cross-sections** in various kinematic variables

Measurements of H→$\tau\tau$

[JHEP 03 (2025) 010]

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  → VBF channel contribu
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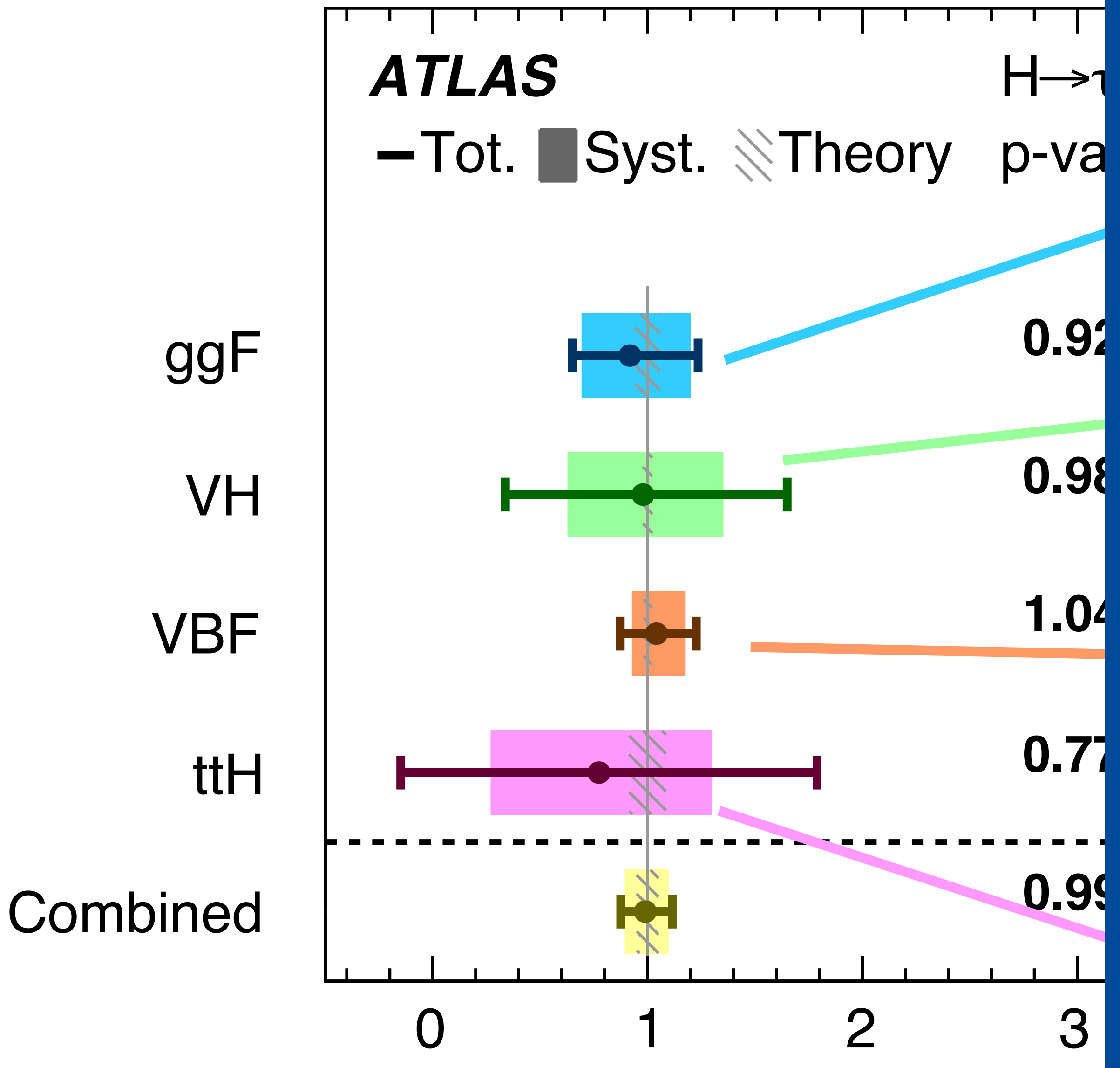

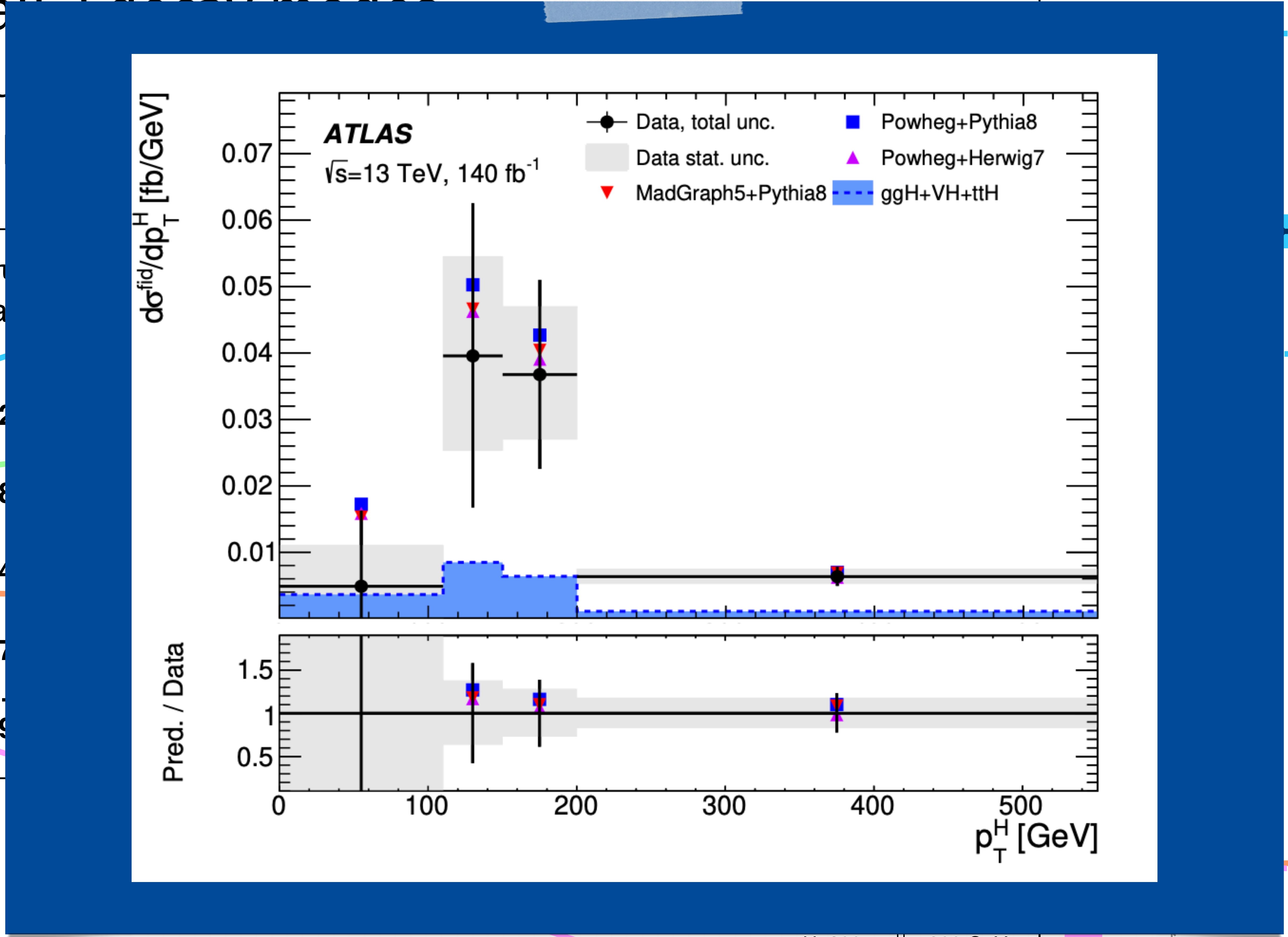

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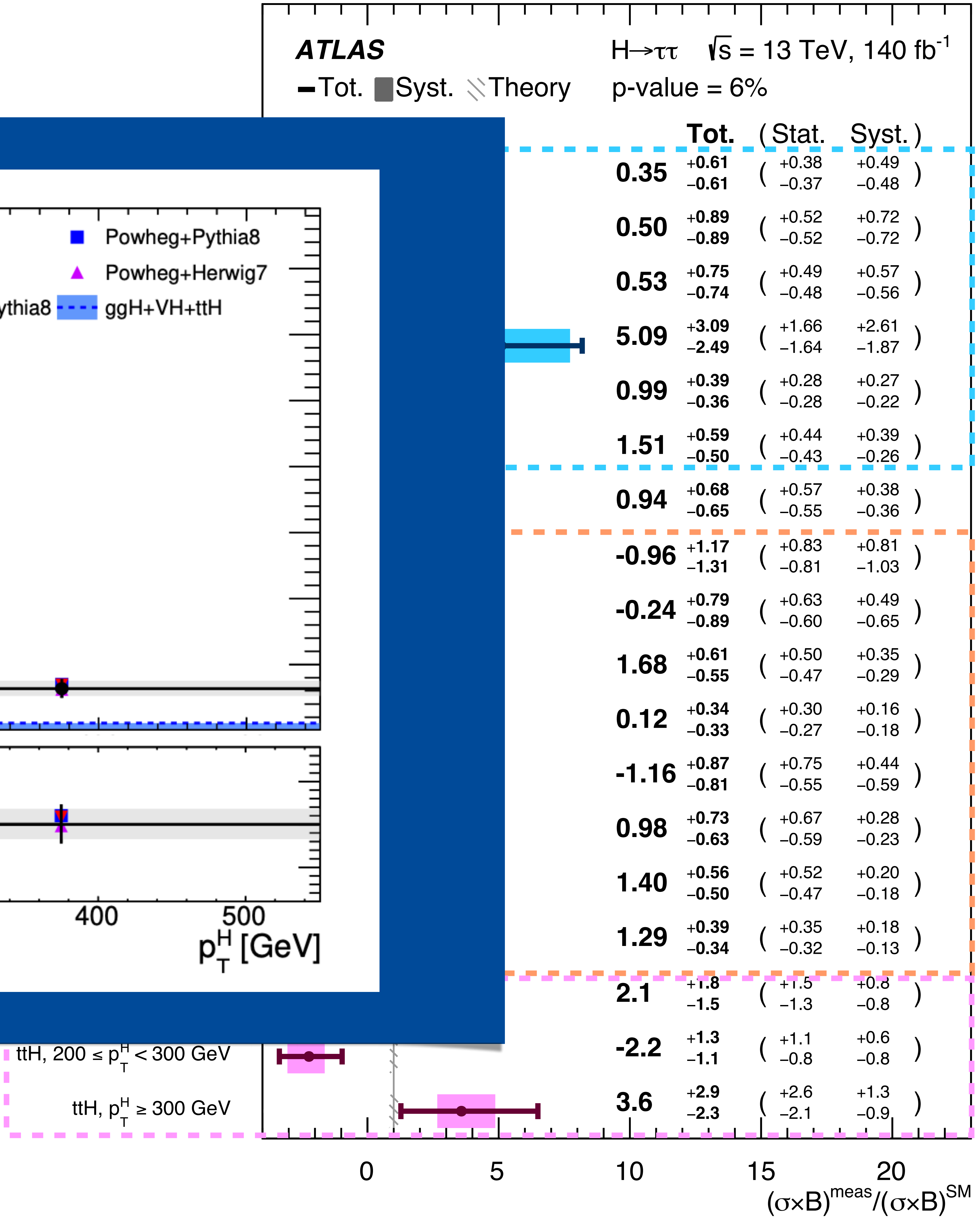

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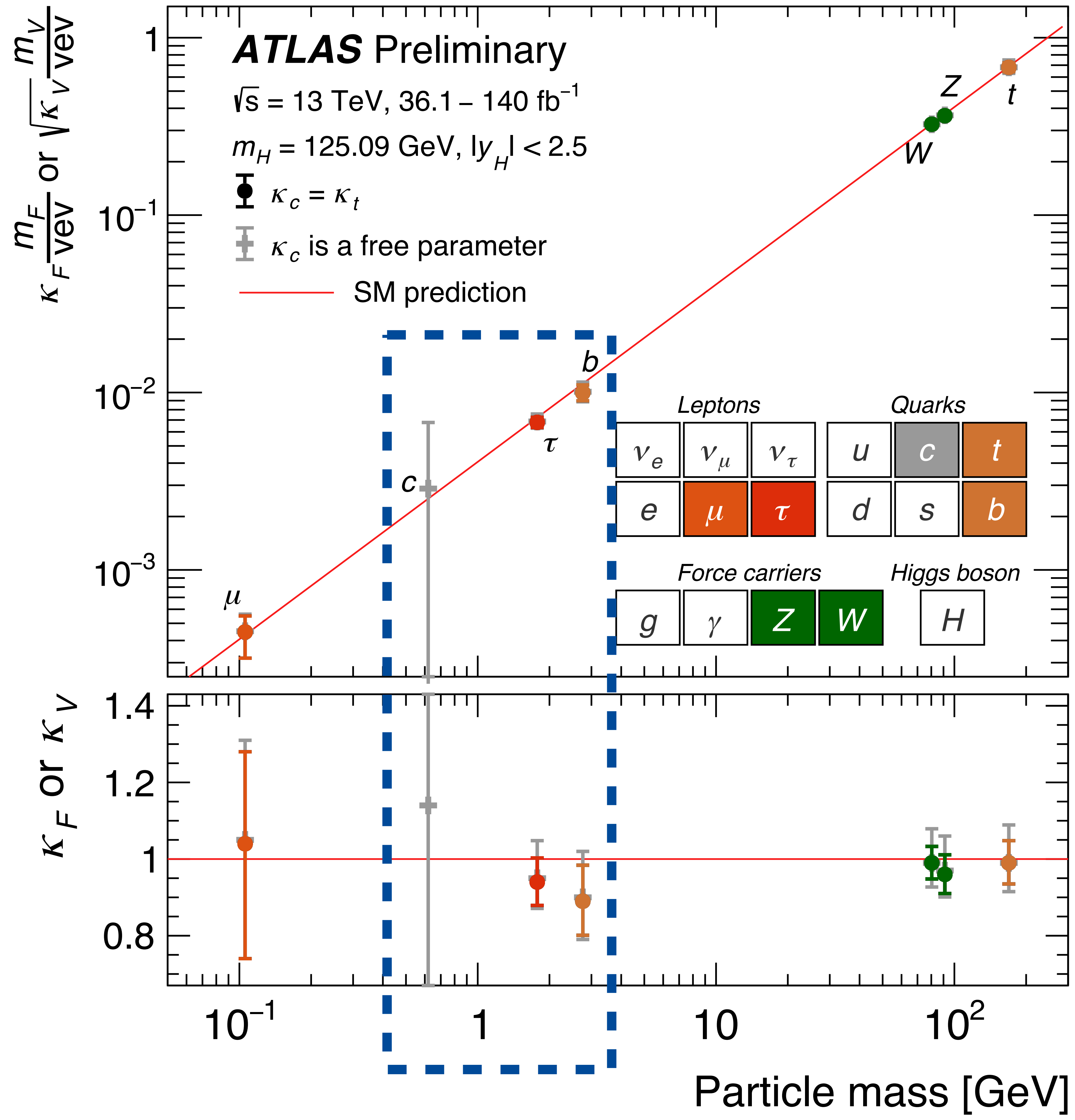
Concluding remarks

- Presented a selected overview of **Higgs boson** measurements probing its **couplings to bottom-** and **charm-quarks** as well as to τ **leptons**
- Impressive progress to extract as much Physics as possible from the Run 2 data set, reanalyzing it where large gains were expected
- The Run 3 data set is growing with > 200 fb^{-1} already recorded

NEW [ATLAS-CONF-2025-006]

Updated combination of ATLAS Higgs boson measurements



See talk by Zef Wolffs on Wednesday for more details!

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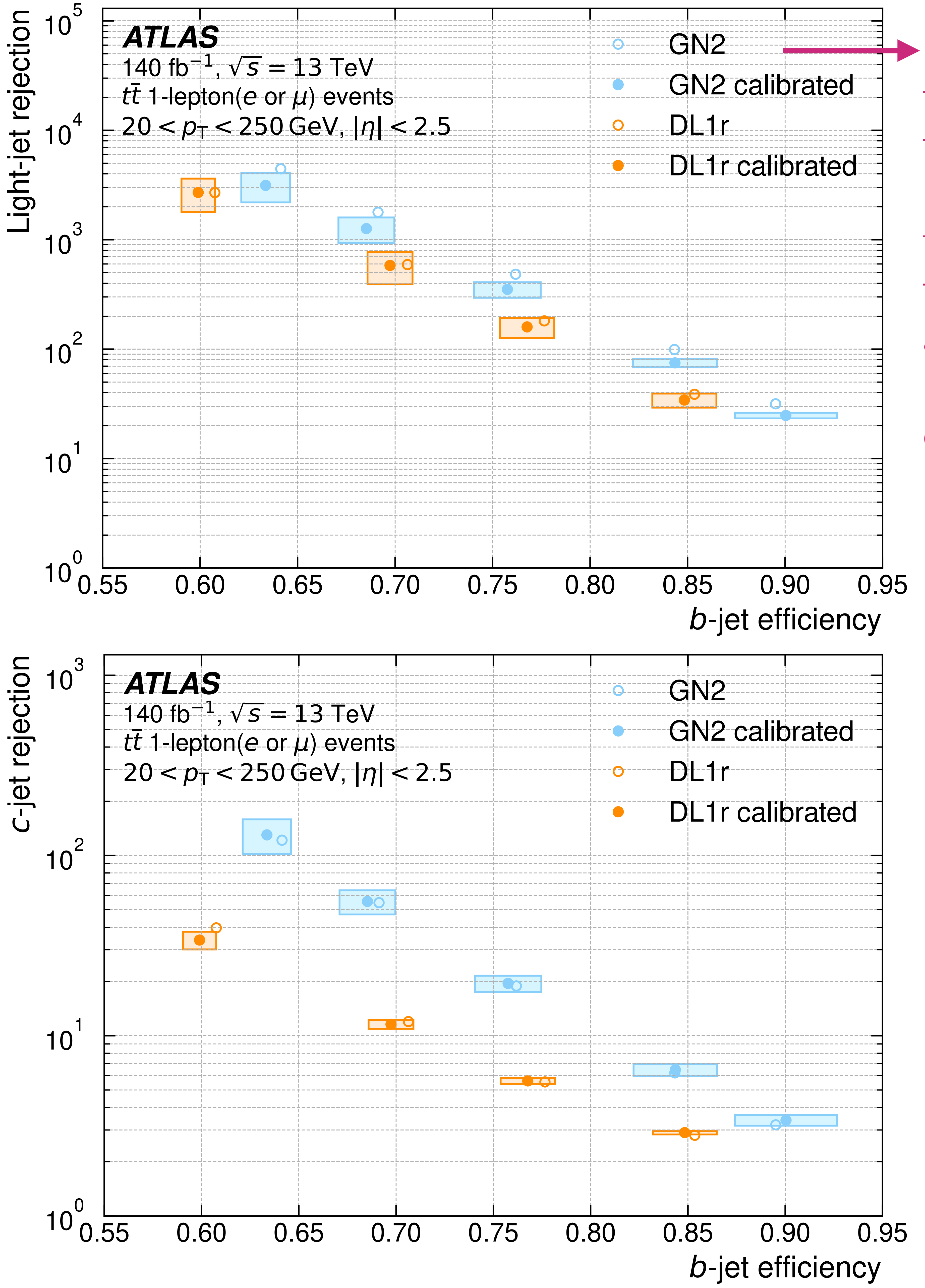
- Impressive progress to extract as much Physics as possible from the Run 2 data set, reanalyzing it where large gains were expected
- The Run 3 data set is growing with > 200 fb^{-1} already recorded
- In addition, further **algorithmic improvements**, e.g. on the identification of hadronic signatures [transformers for flavour-tagging], suggest additional gains on top of the larger collision data set

Exciting times ahead!

[arXiv:2505.19689]

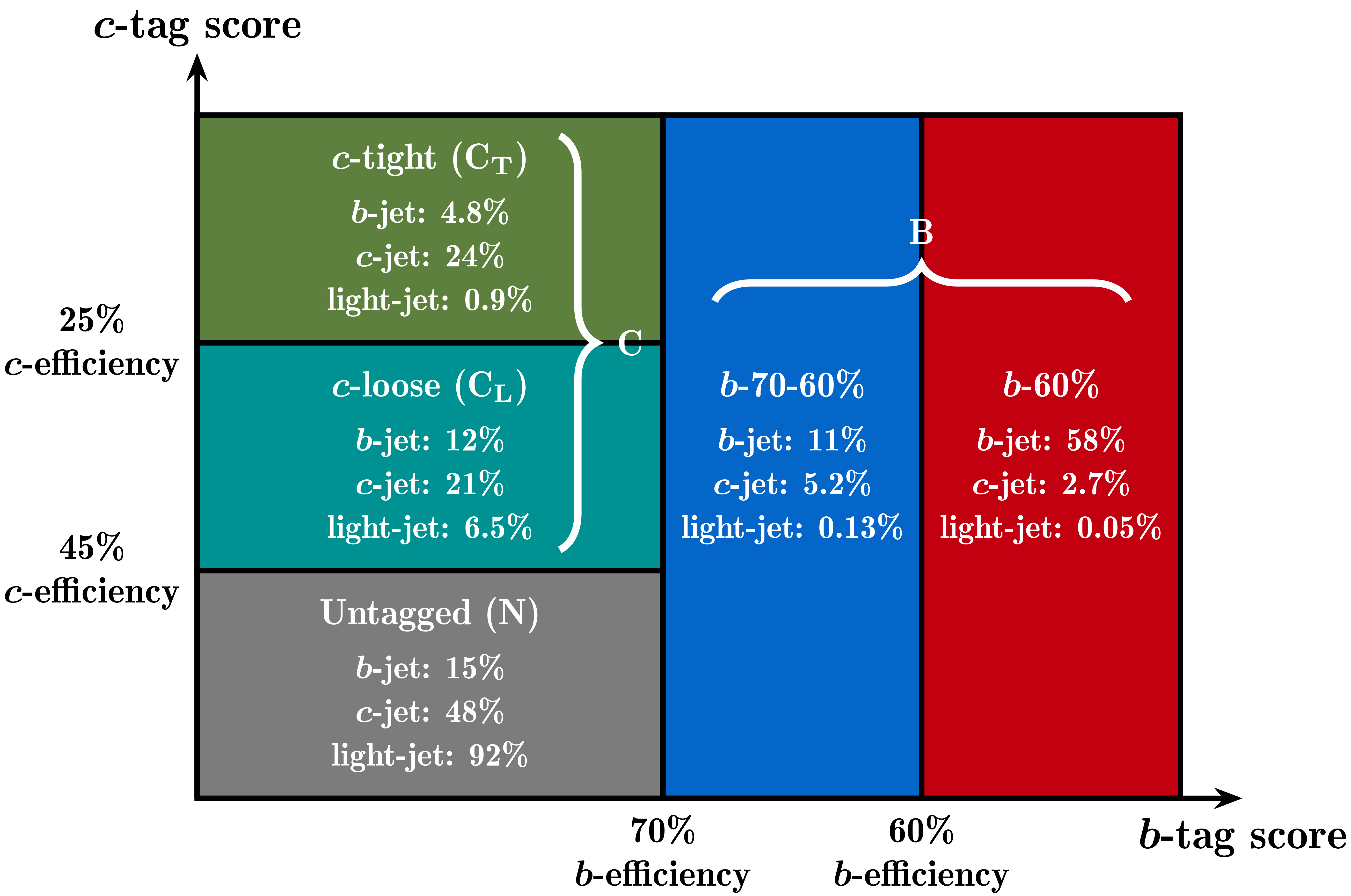
NEW



new, transformer-based flavour tagging algorithm [now calibrated]

Backup

Additional material: **VH, H→bb/cc**



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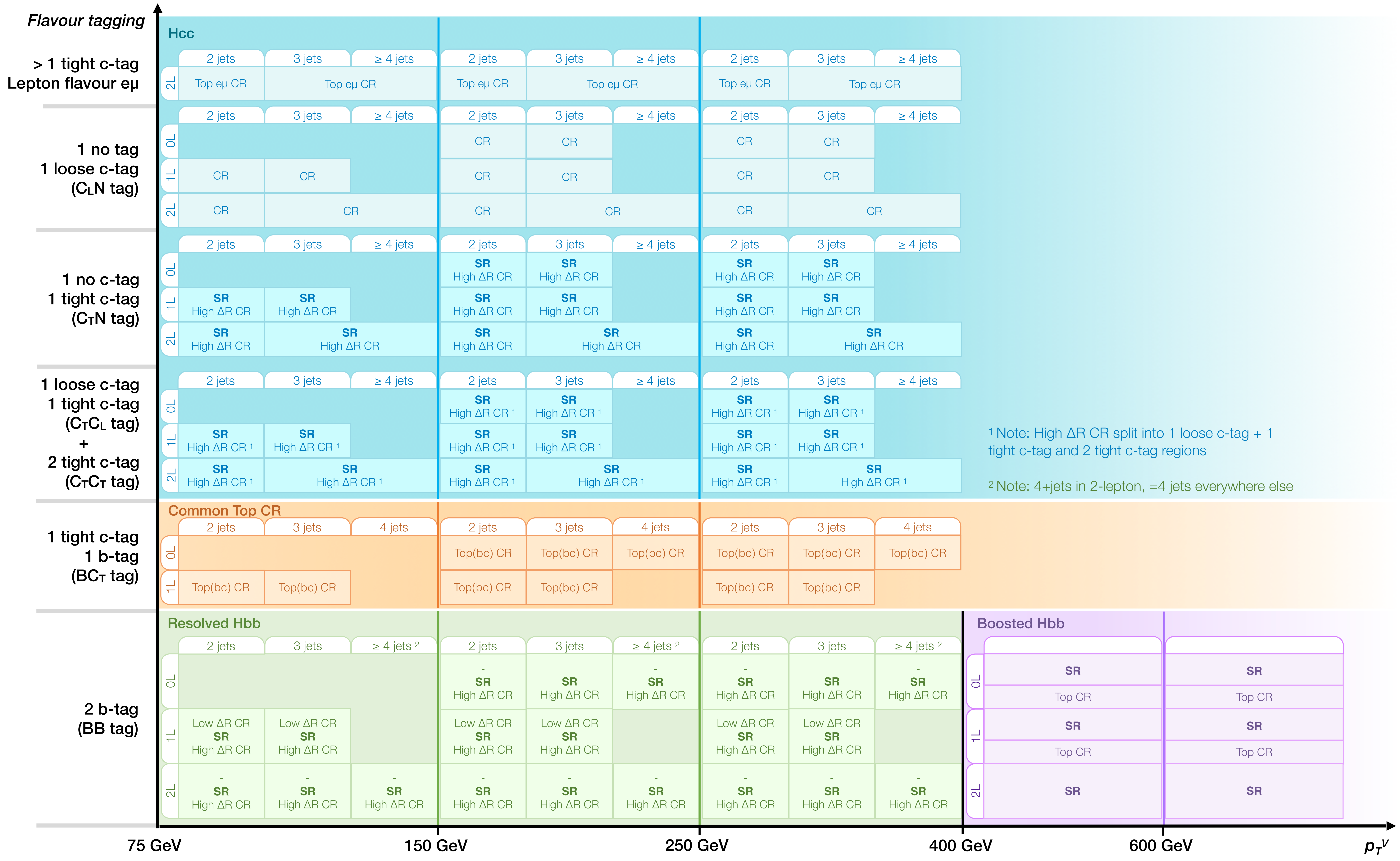

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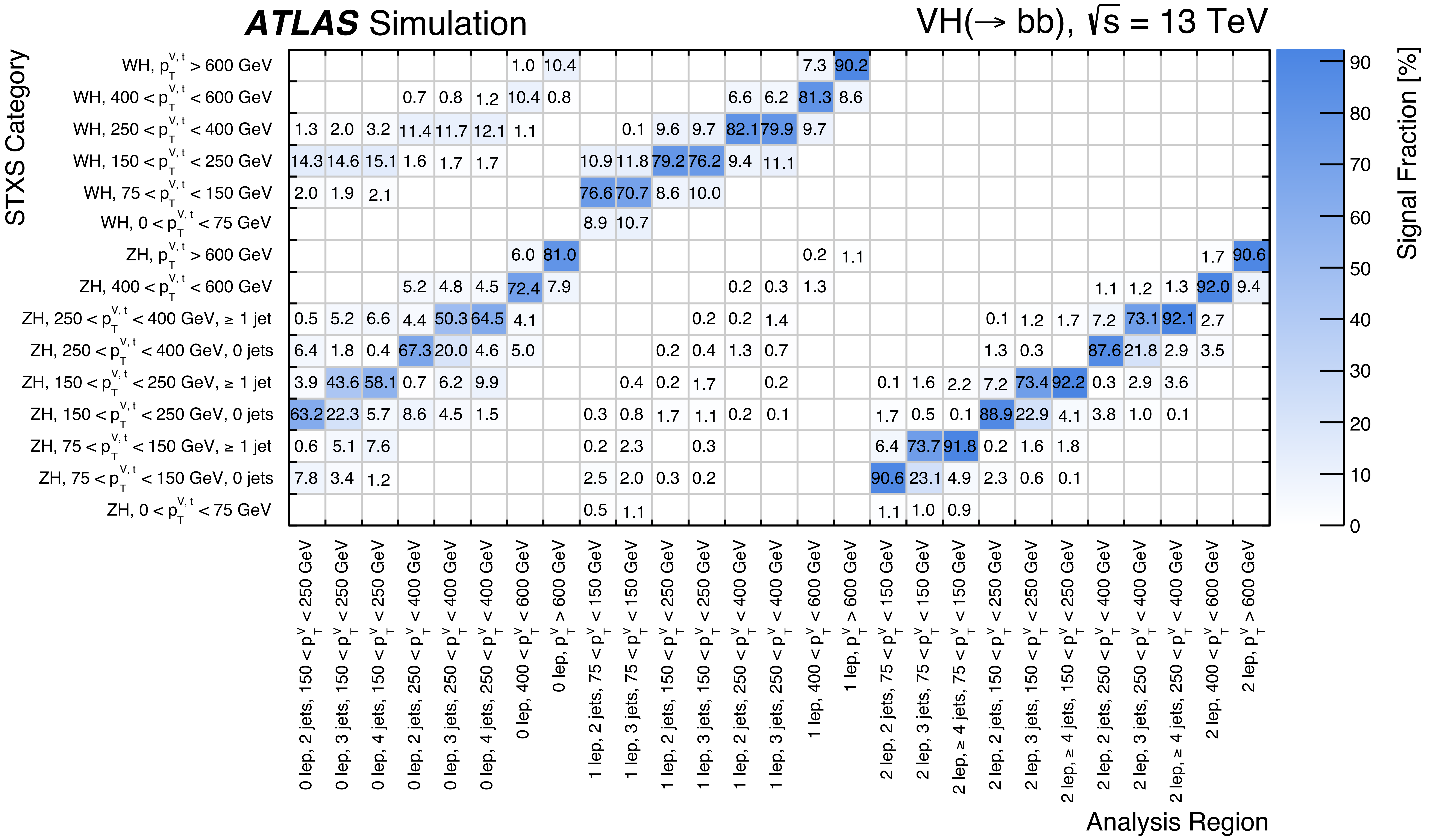

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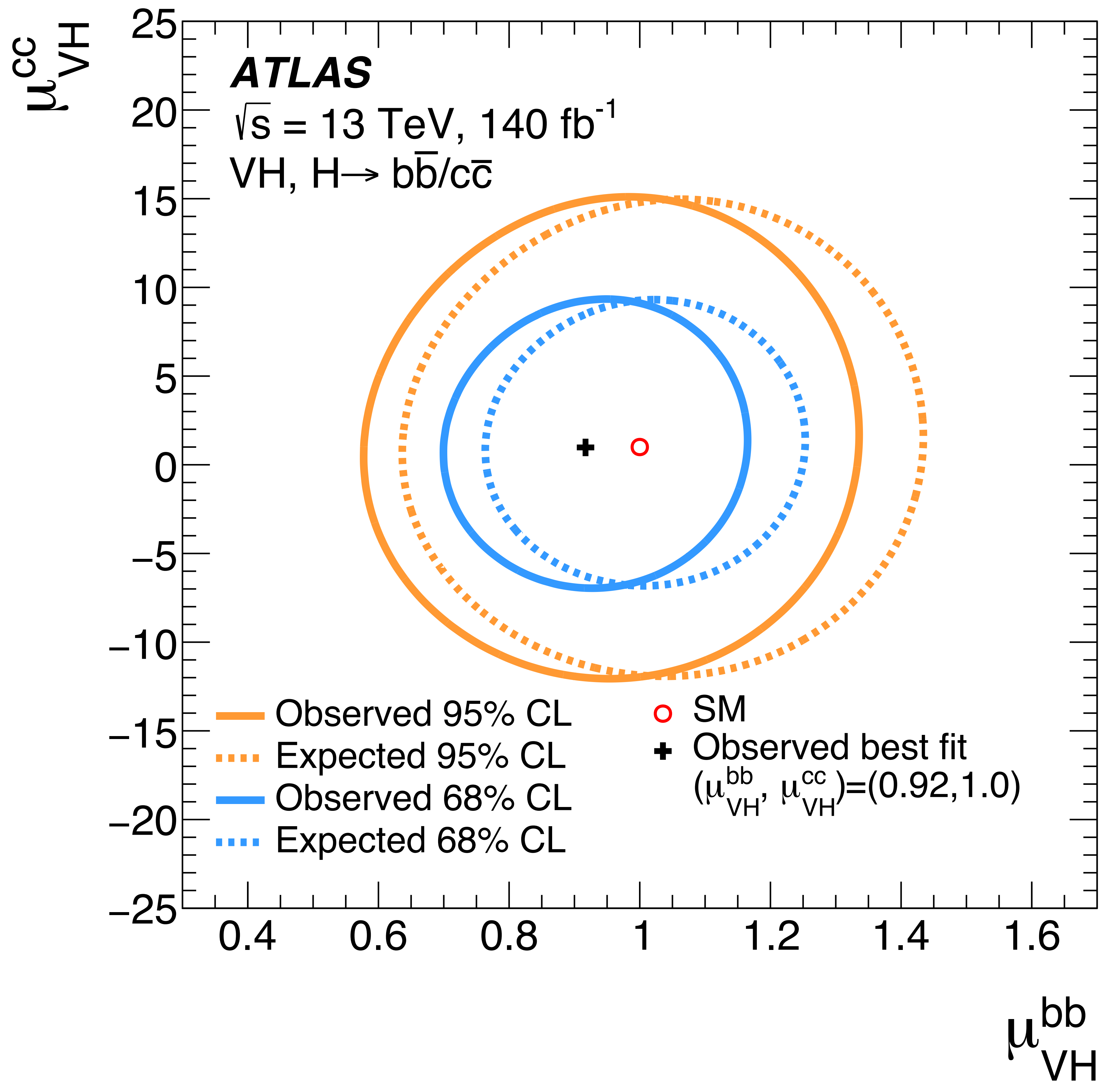

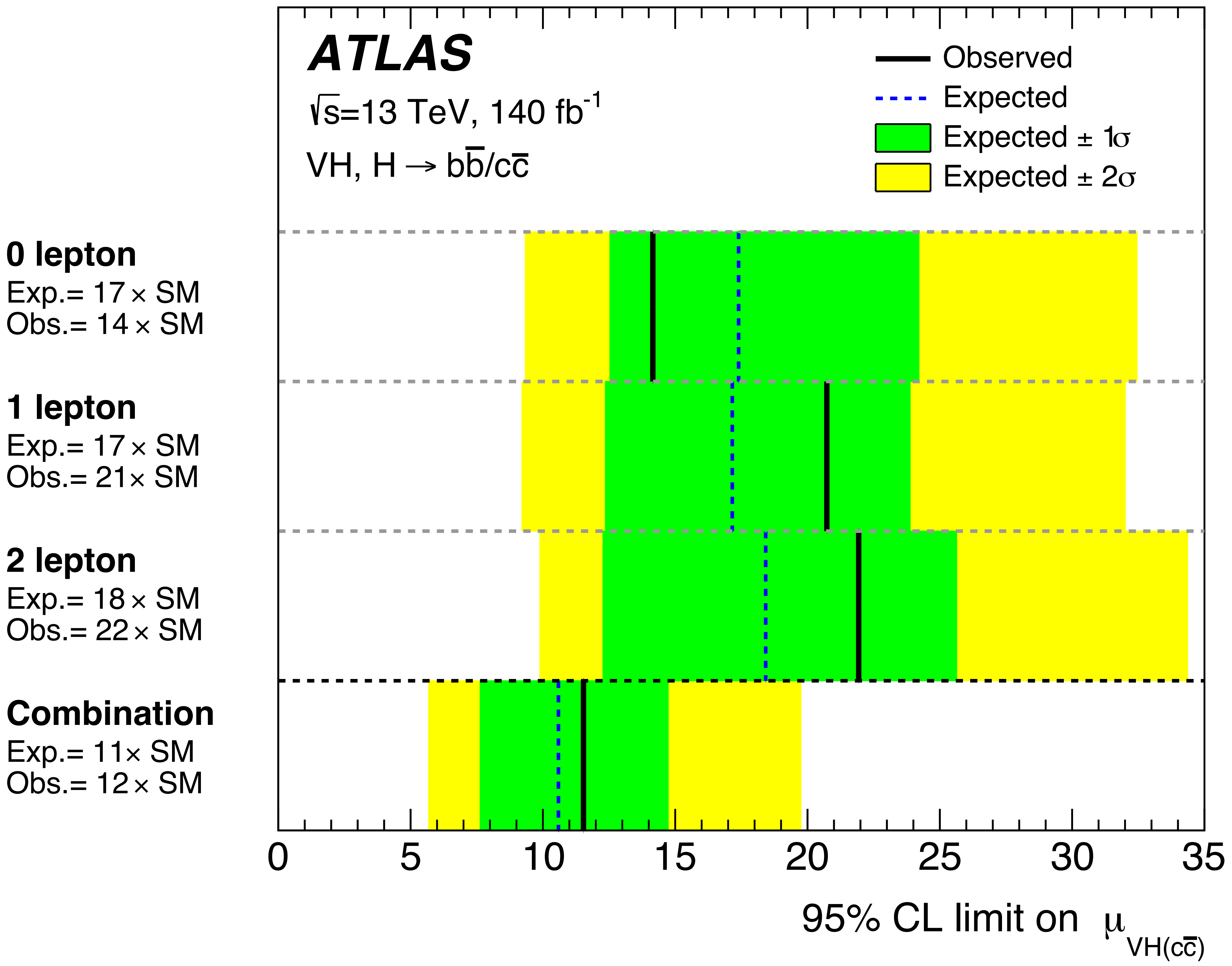

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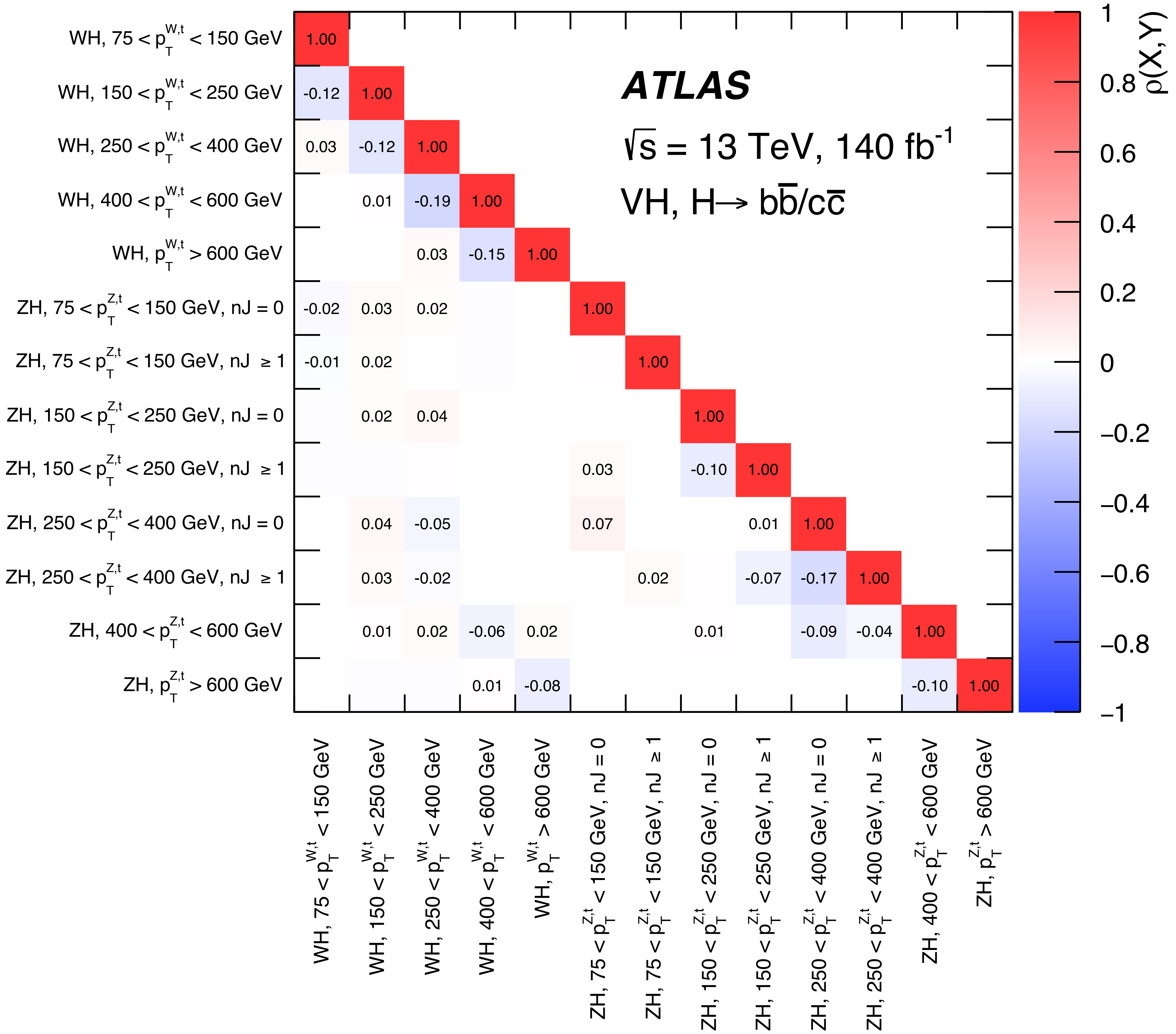
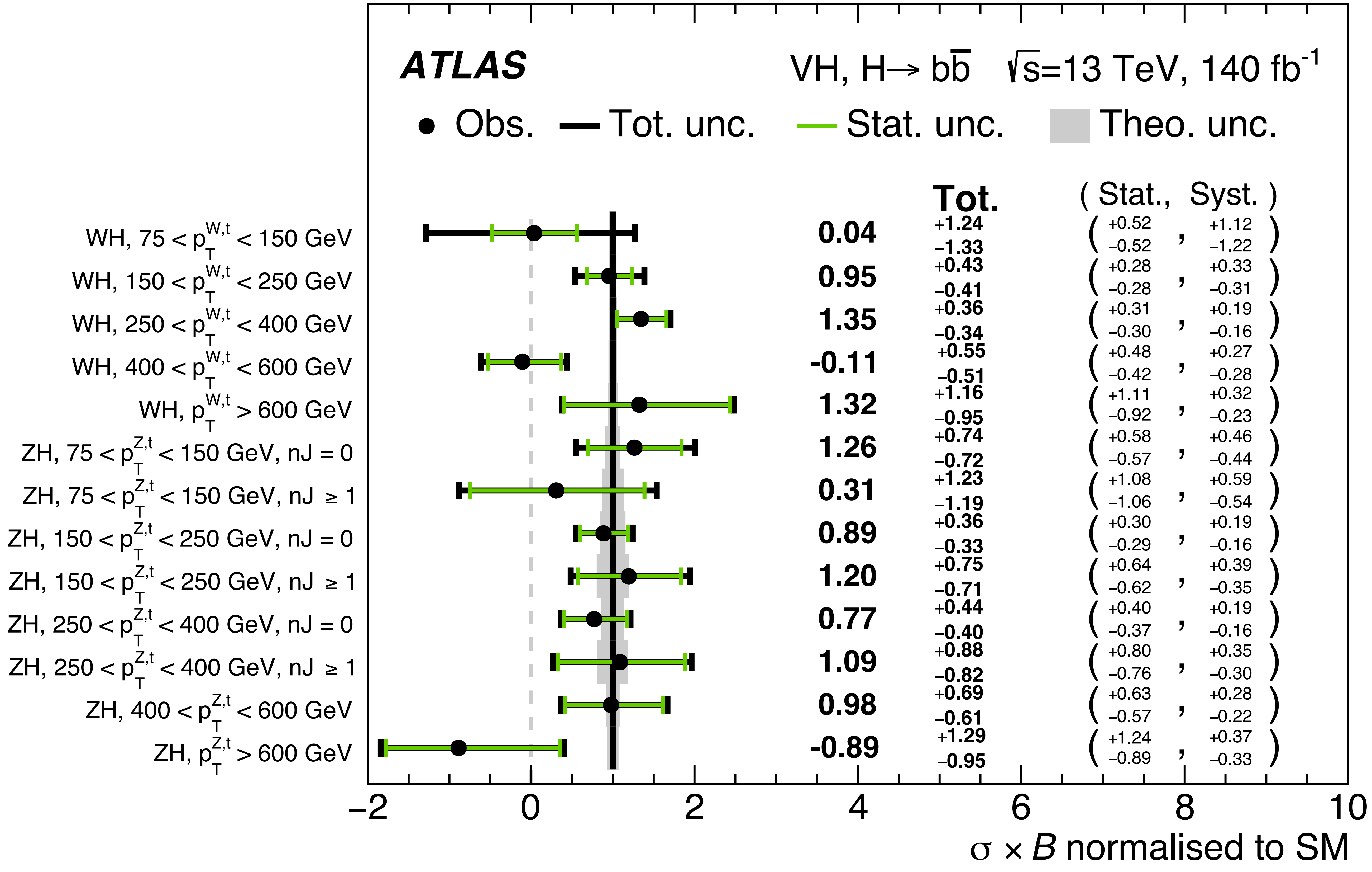
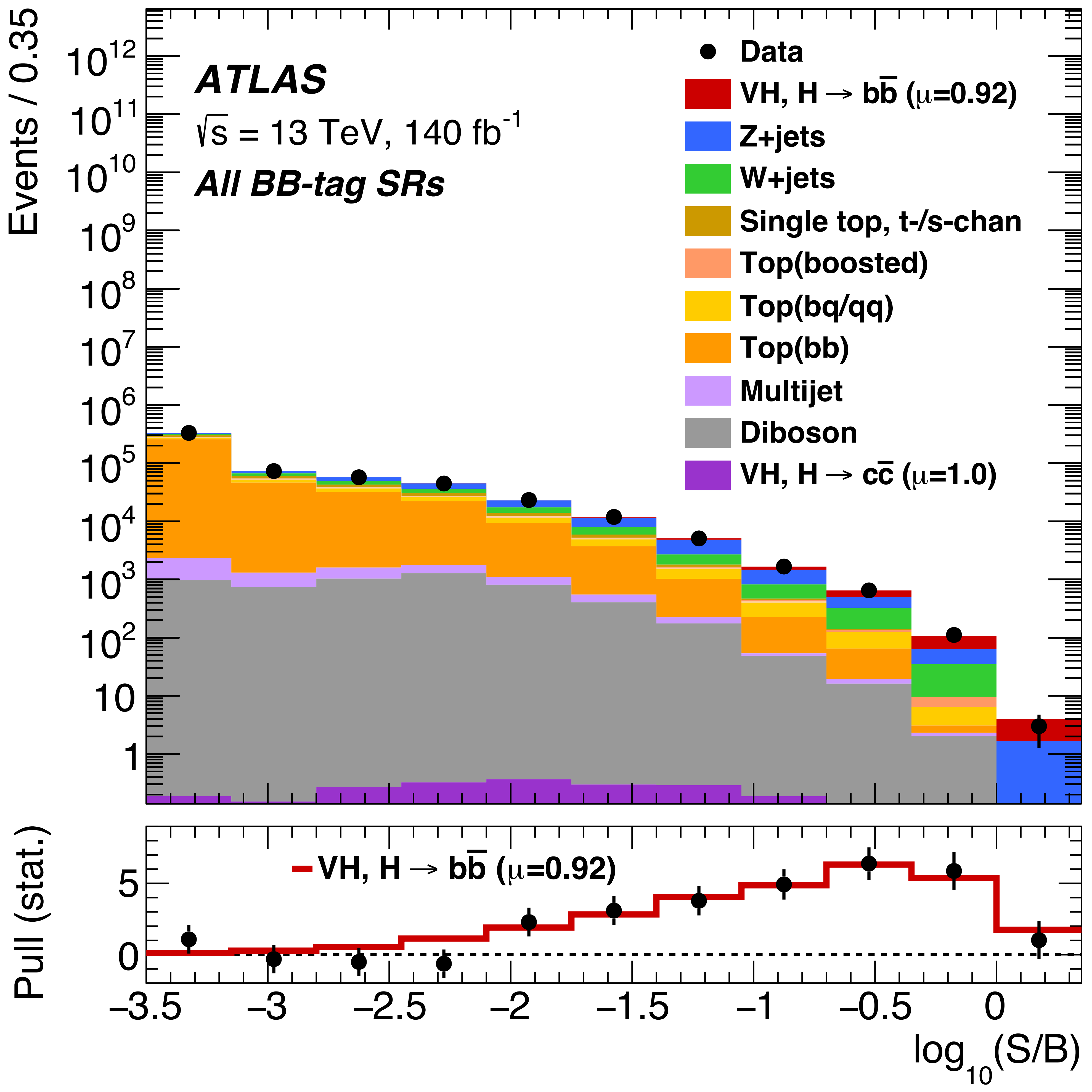
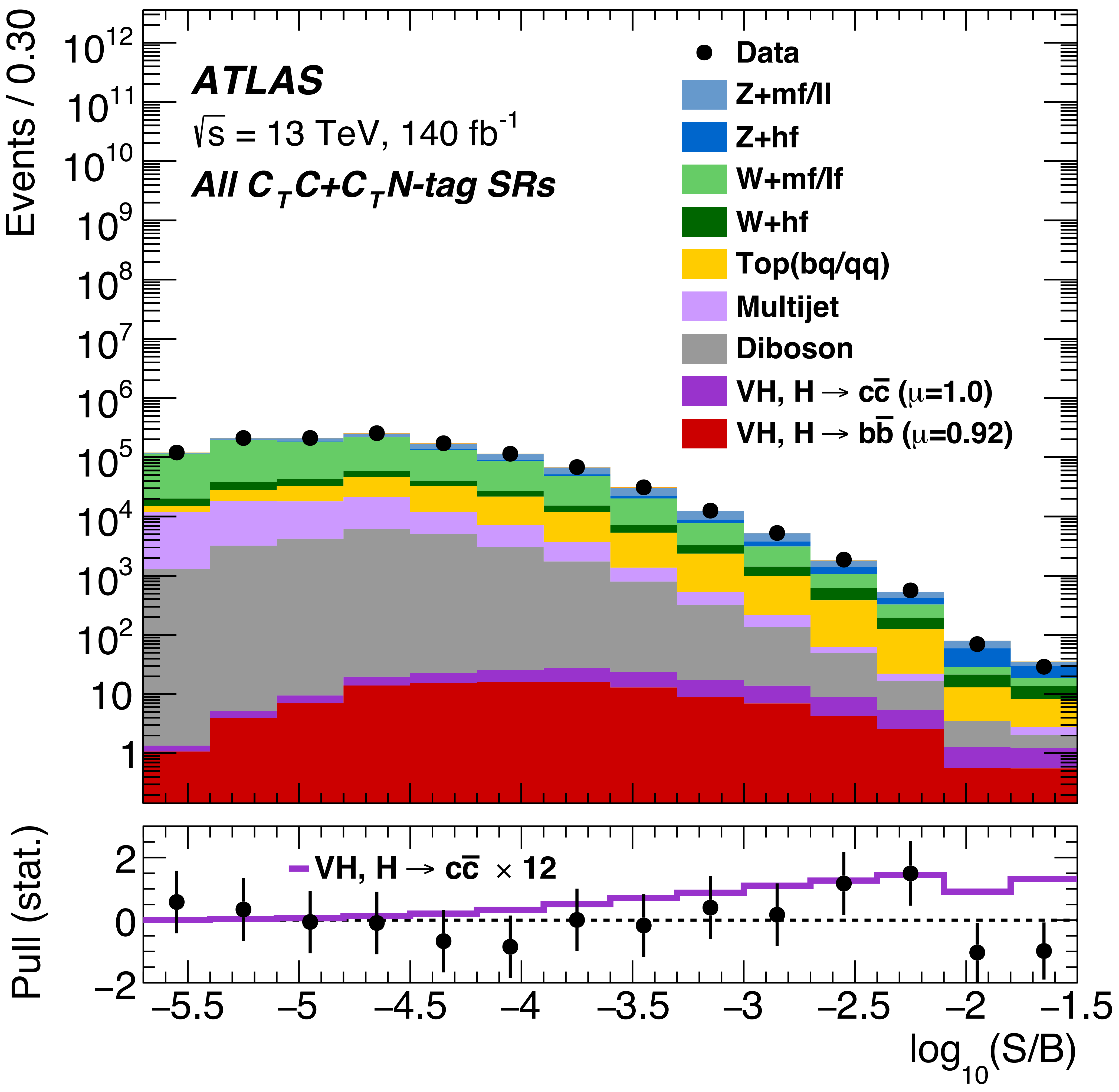


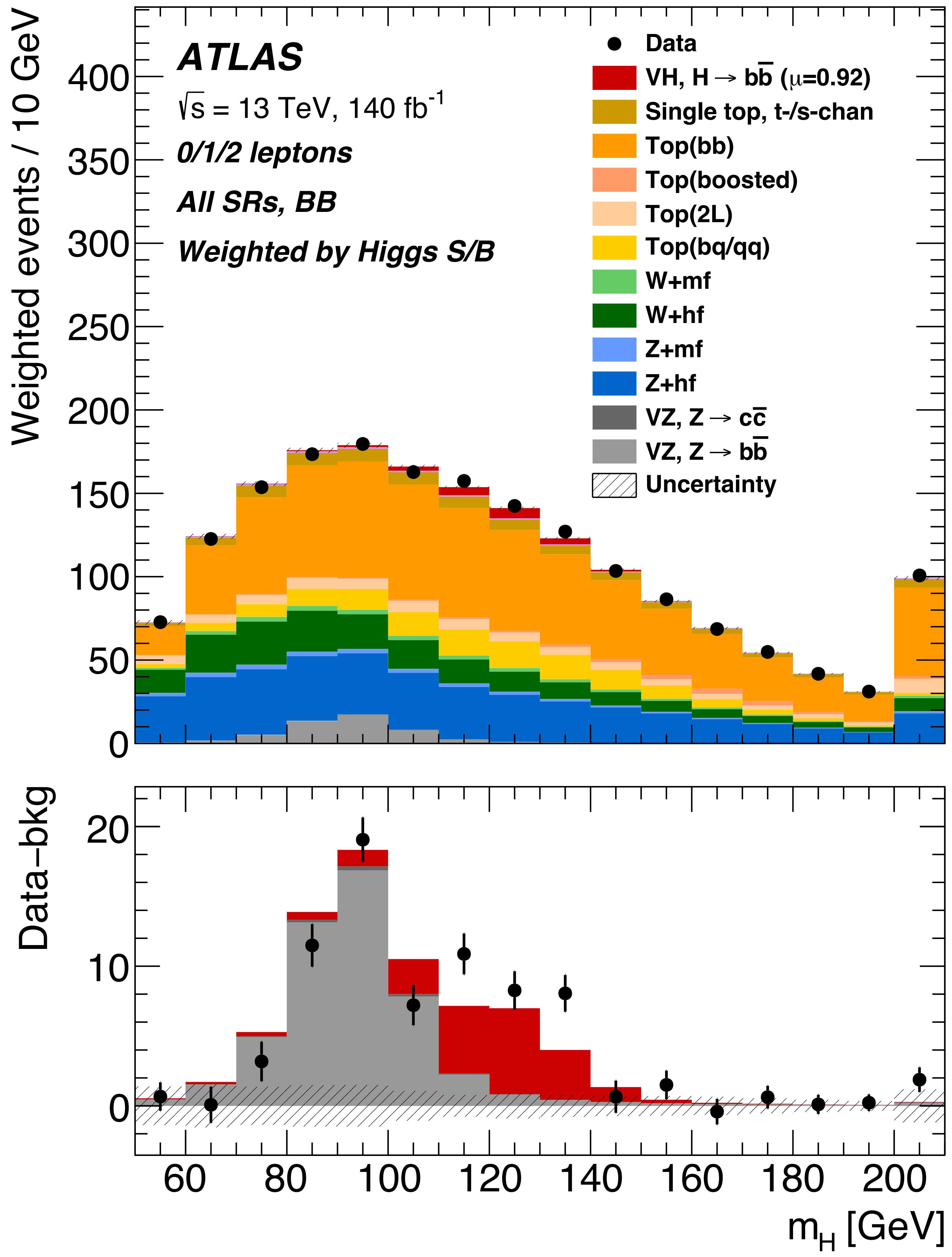


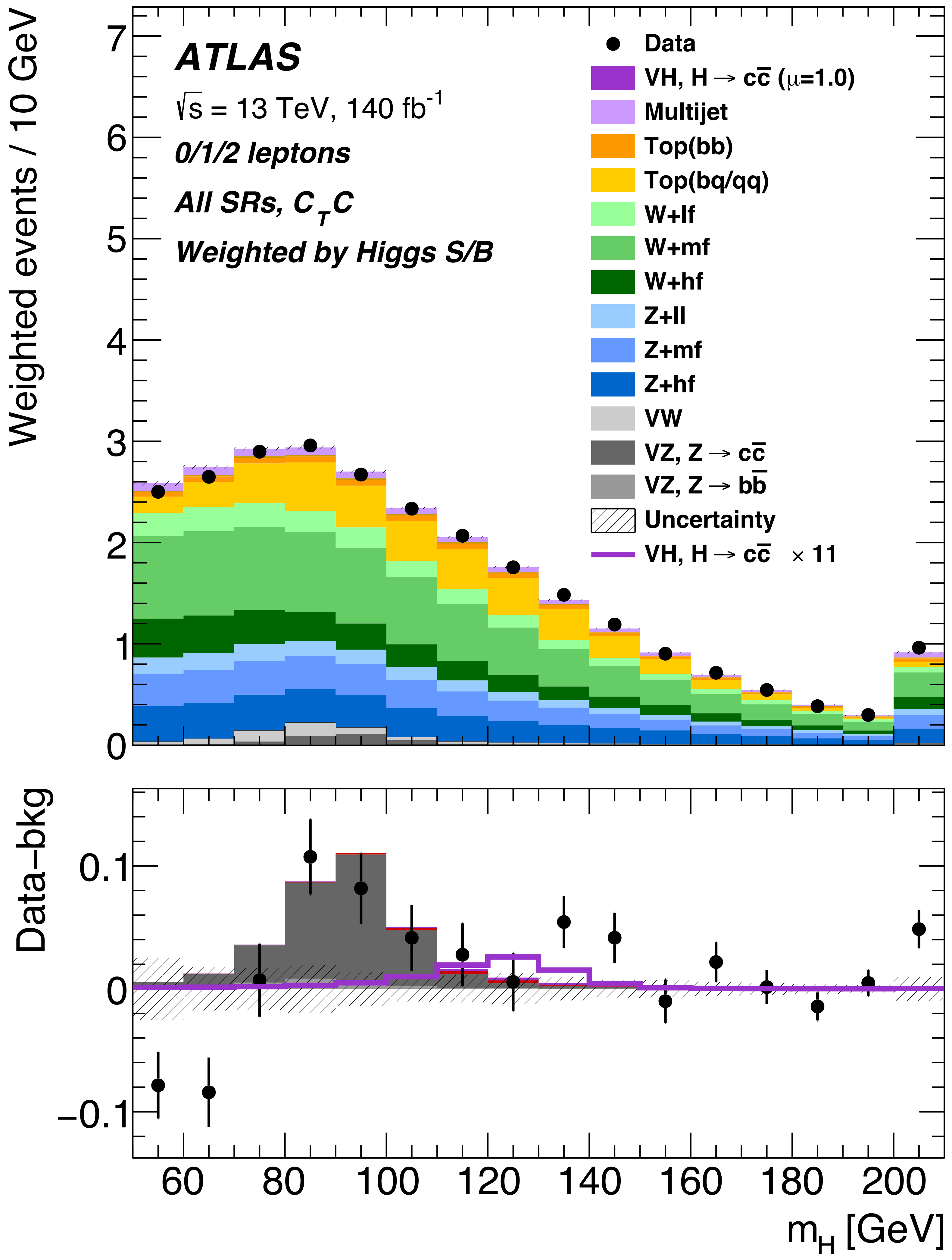
Additional material: **VH, H→bb/cc**



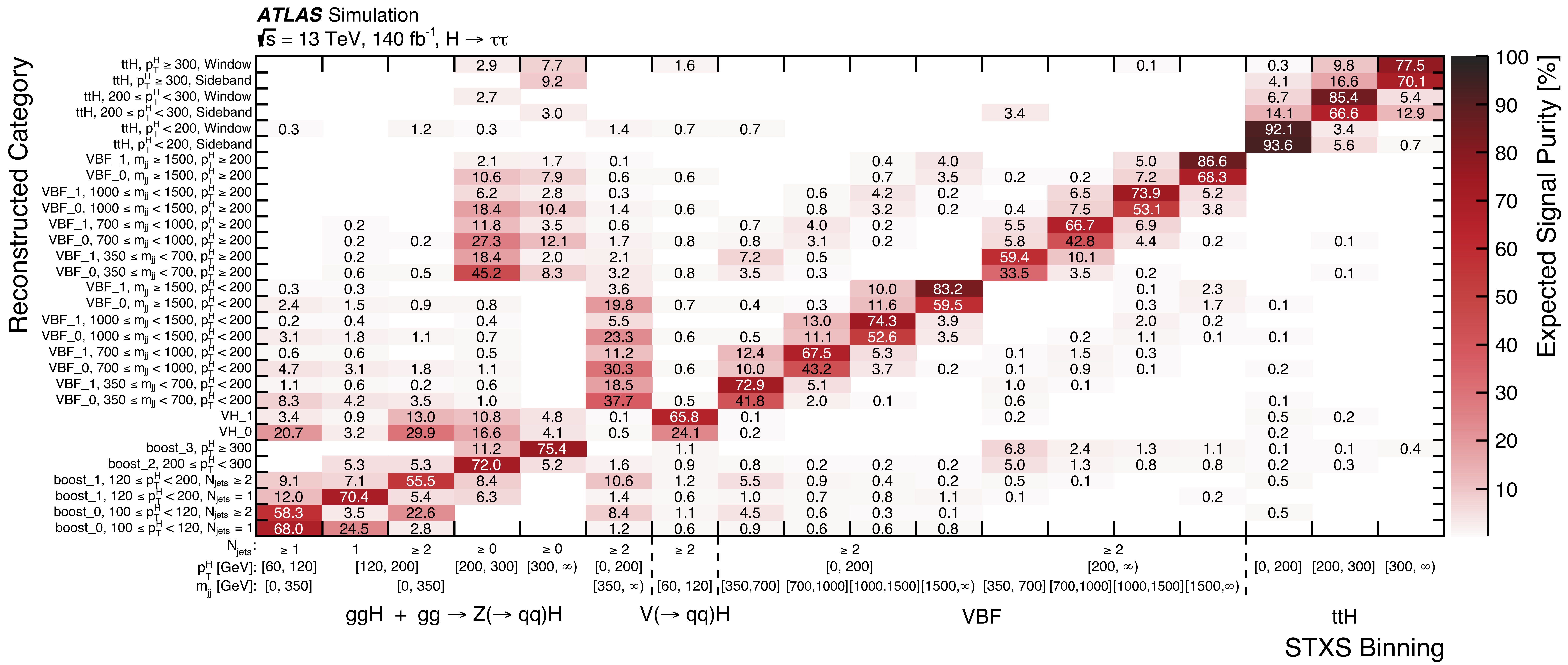


Additional material: **VH, H→bb/cc**

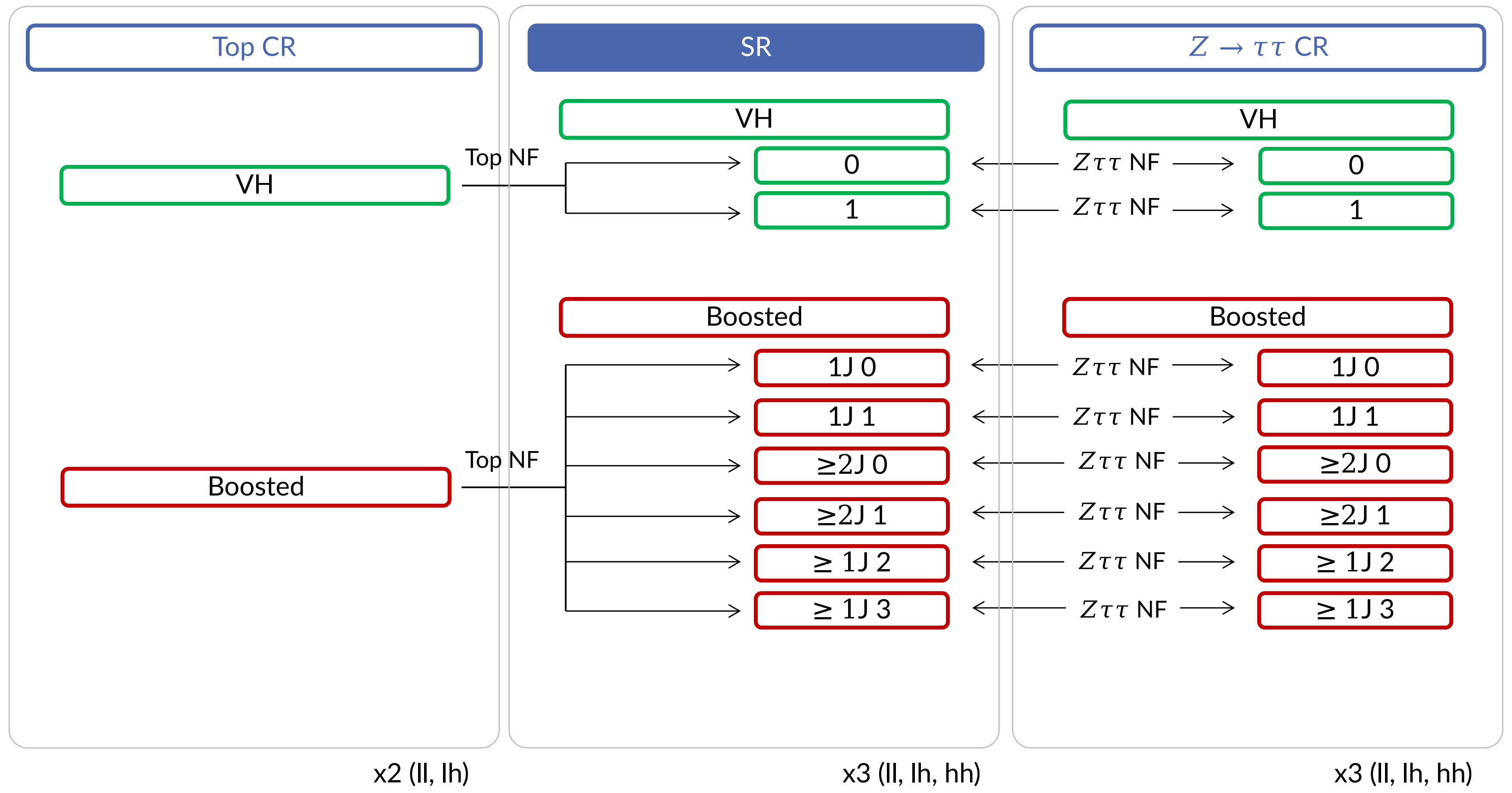


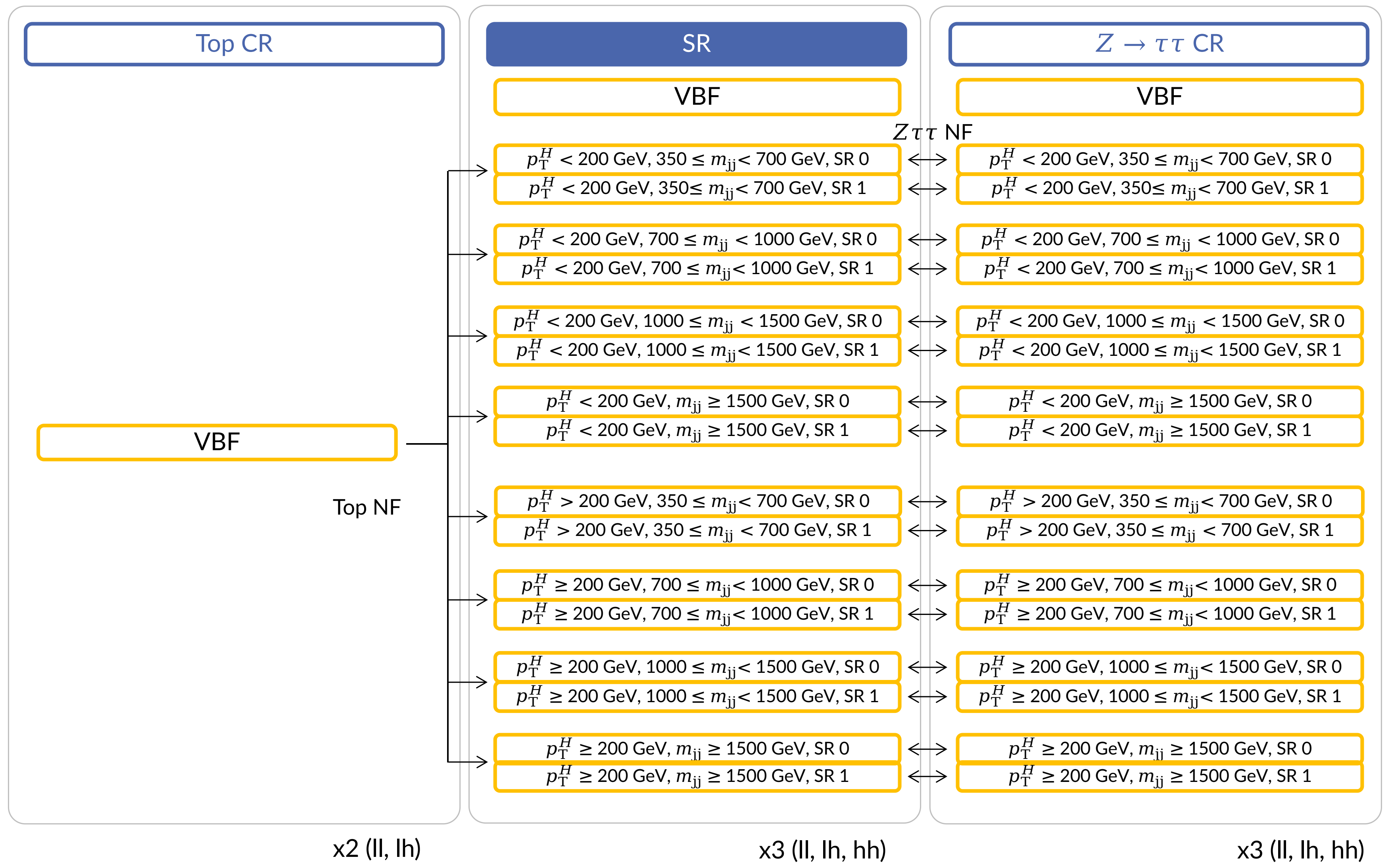


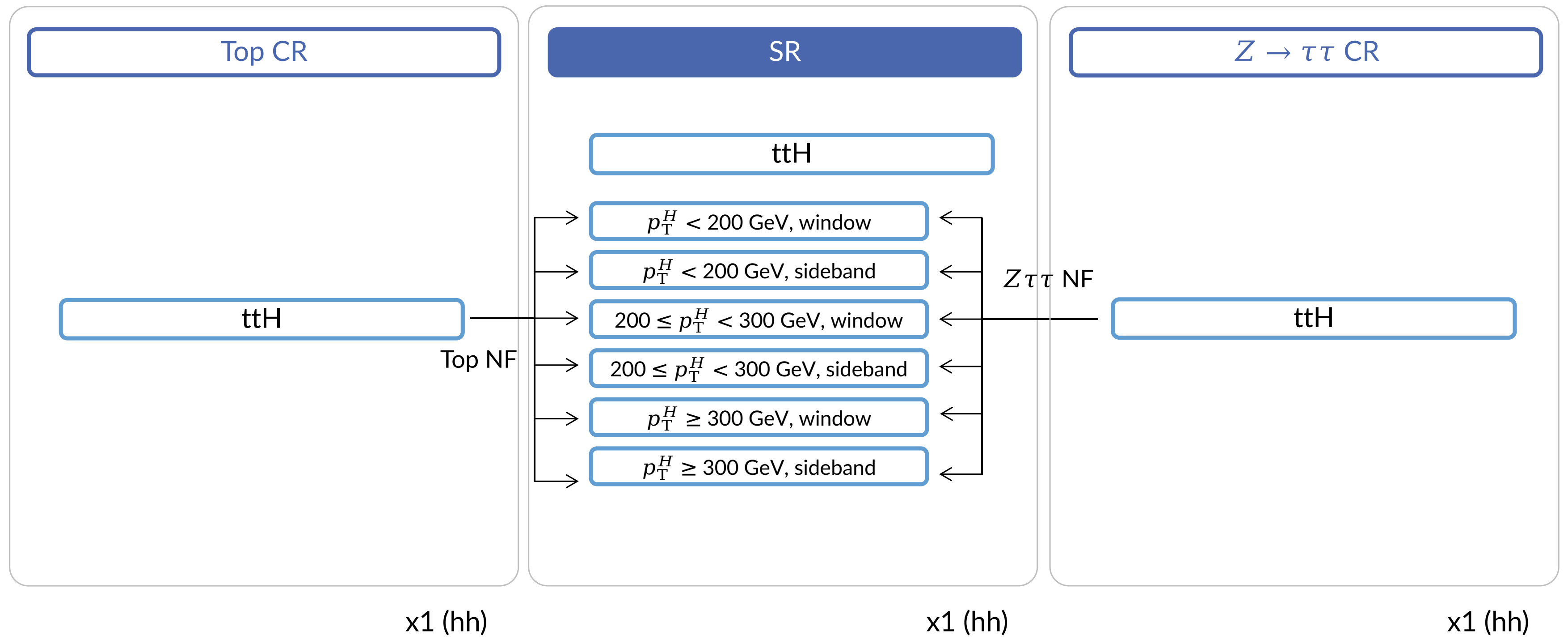
Additional material: H→ττ



Additional material: **H→$\tau\tau$**







Additional material: H→$\tau\tau$