ATLAS EXPERIMENT

Brookhaven National Laboratory

Brookhaven Science Associates

U.S. DEPARTMENT OF ENERGY

Higgs coupling measurements at the ATLAS experiment

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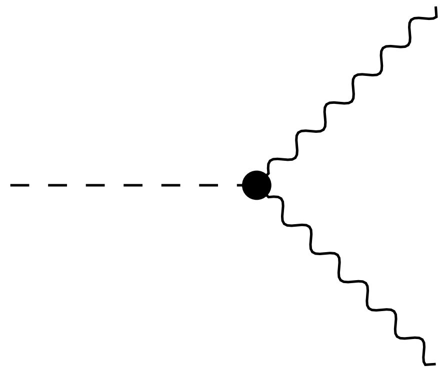
on behalf of the ATLAS Collaboration

Higgs Hunting

Sept. 2024

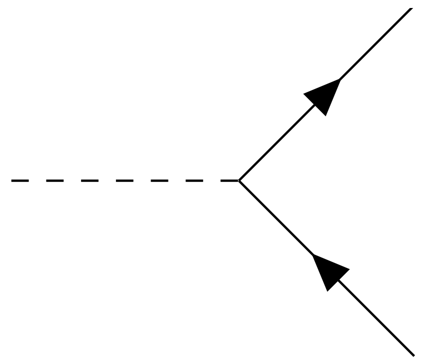
Higgs - 12 years since the discovery!

- Higgs is **essential** in the Standard Model
  - ➡ Discovery during Run-1 by ATLAS (PLB, V716, P1-29) and CMS (PLB, V716, P30-61)
  - ➡ Since the discovery, priority from the experiments to **measure its properties**
- **Couplings** of Higgs boson and massive particles split in the following main **categories**:
  - ➡ **Gauge** couplings to **vector bosons**



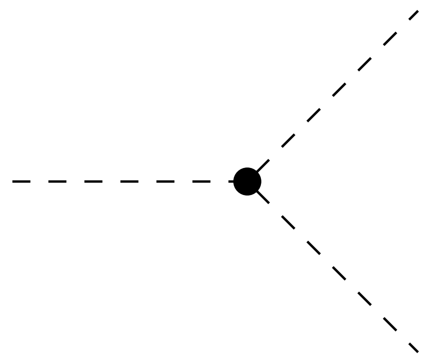
$$g_V = \frac{2m_V^2}{\text{vev}}$$

  - ➡ **Yukawa** couplings to **fermions**

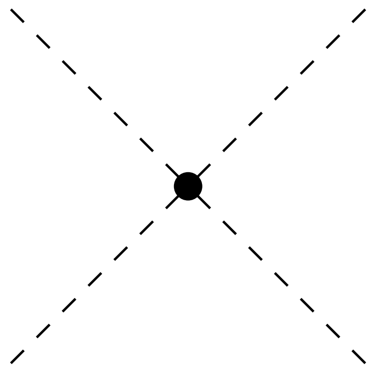


$$g_{Hf\bar{f}} = \frac{m_f}{\text{vev}}$$

  - ➡ **Self-coupling** of the Higgs field



$$g_{3H} = \frac{3m_H^2}{\text{vev}}$$



$$g_{4H} = \frac{3m_H^2}{\text{vev}^2}$$

→ **Dedicated talk by Zhijun Liang this afternoon**

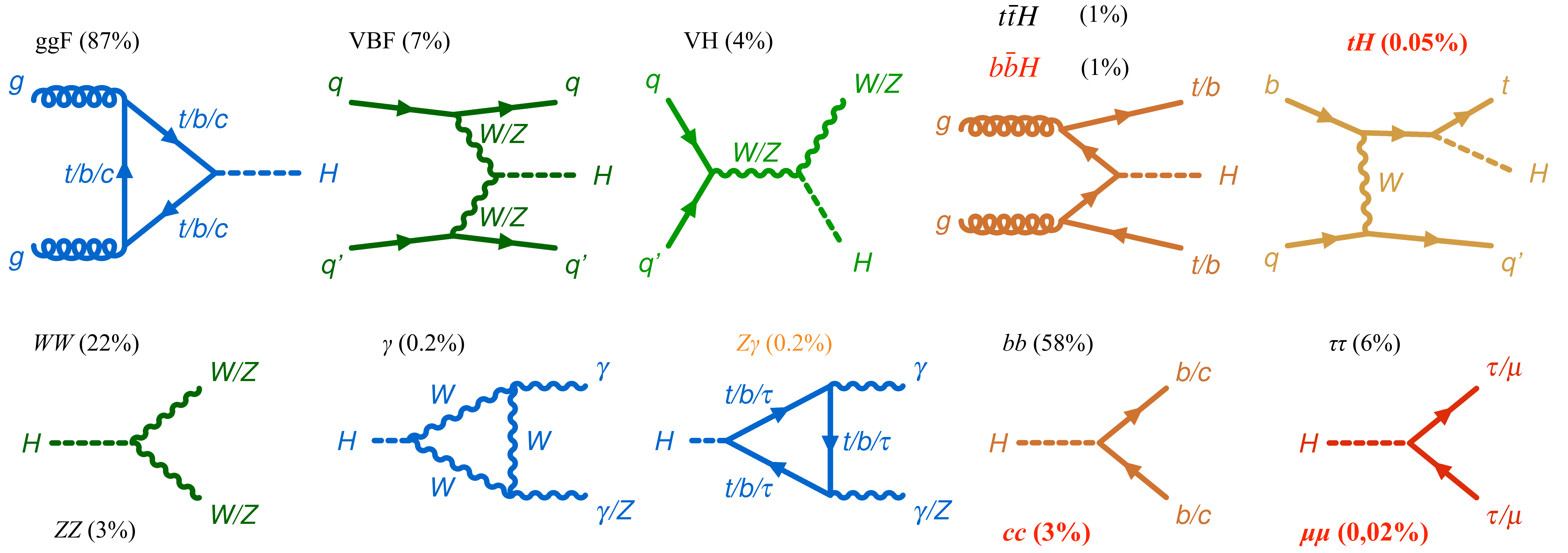
- **Coupling** measurements at best possible precision, **crucial for the physics program (incl. BSM)** (symmetry breaking, Standard Model prediction testing)

Outline

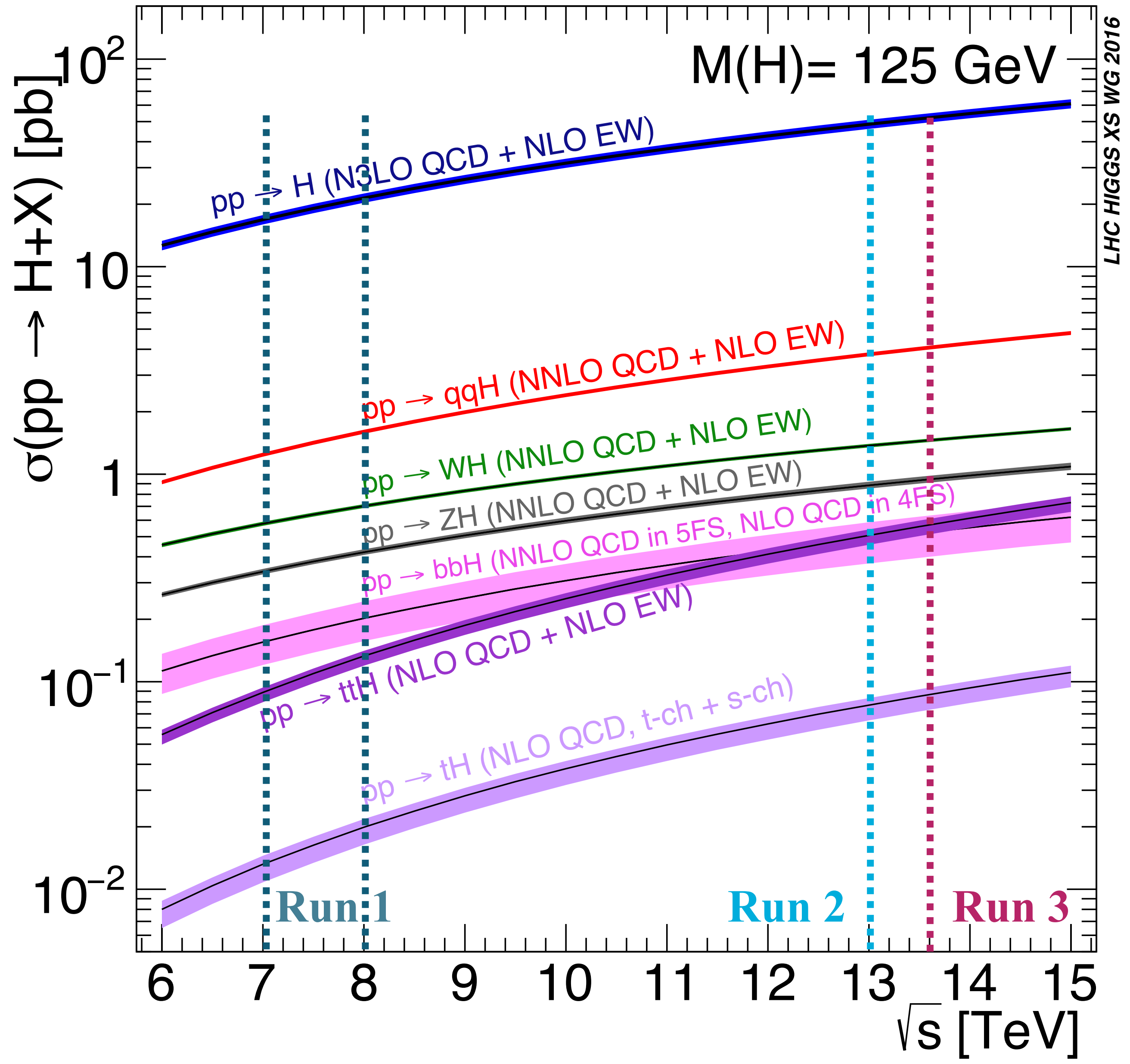
- Recap the Couplings from 2022 (Nature 607, 52–59 (2022))
  - Higgs production and decay modes
  - Global signal strength and Couplings to individual particles
  - κ-framework, STXS and SMEFT interpretations
- Updated results
  - Relative sign of W, Z couplings
  - Update on the $H \rightarrow \tau\tau$ including results in STXS
  - Latest results from the $V(\rightarrow \text{lep})H(\rightarrow b\bar{b}/c\bar{c})$ analysis
  - Highly boosted VH production in fully hadronic decay modes

Higgs Production & Decay modes

- During Run 2, ATLAS recorded ~140 fb^{-1} luminosity in *pp* collisions
  - ~9 millions of Higgs bosons are produced (SM prediction) → 0.3% experimentally accessible



arXiv:1610.07922



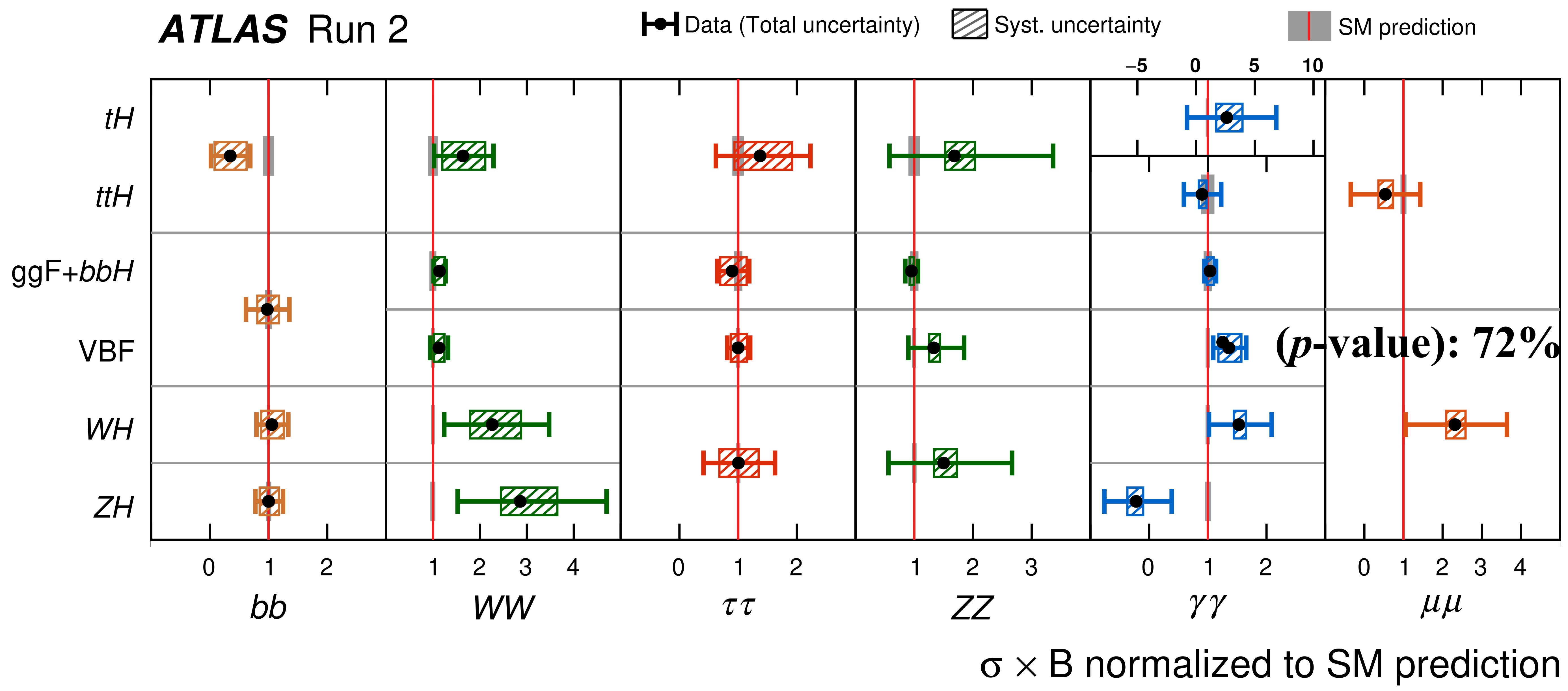
- Major production/decay **processes** observed at the LHC
- All available channels are combined to yield the most precise couplings measurements
- Rare/difficult decay modes are pursued (second generation couplings, $Z\gamma$)
  - **Important** for beyond the SM scenarios

Dedicated ATLAS BSM and rare H(125) decays talk by Huacheng Cai on Tuesday

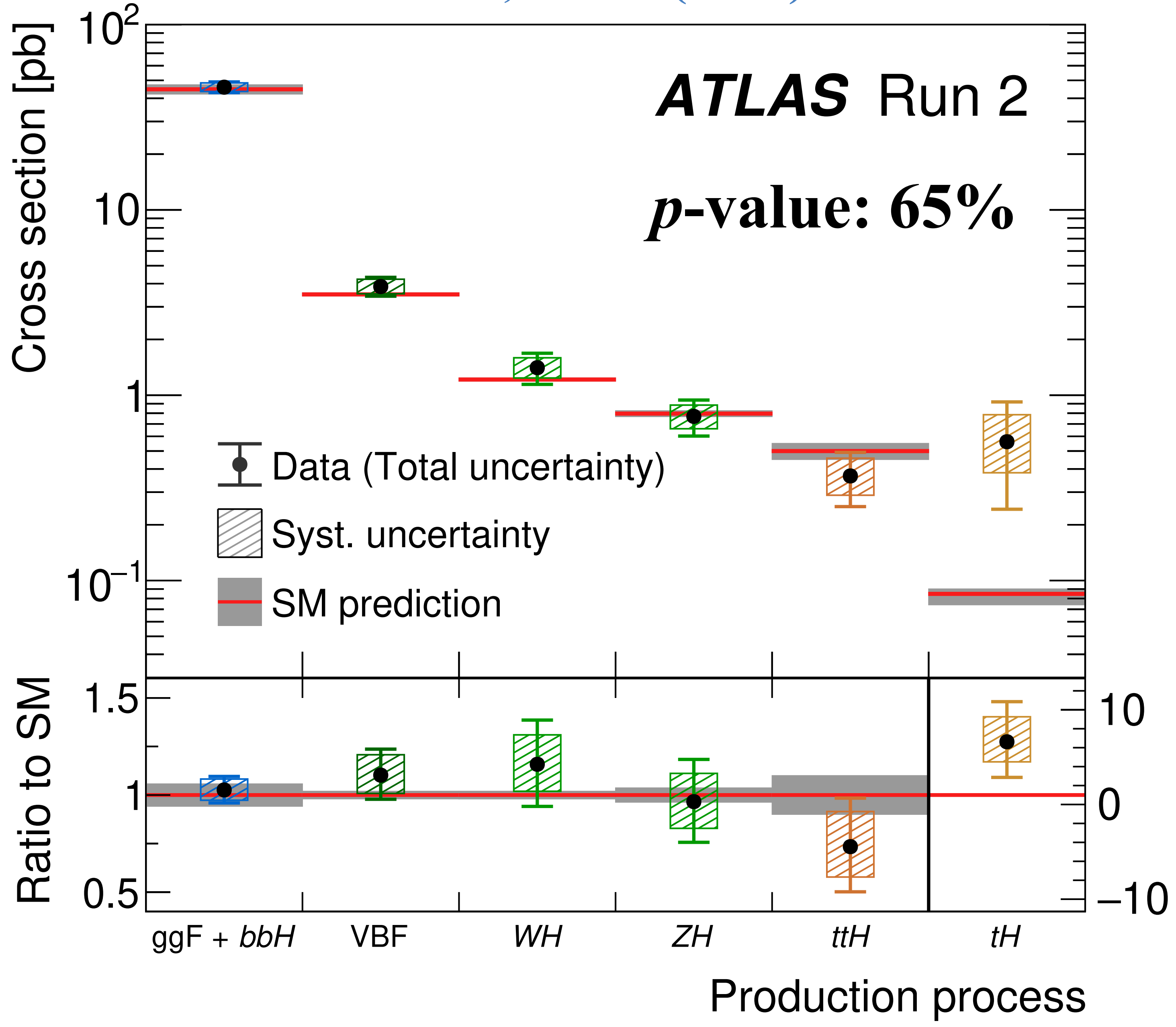
ATLAS measurements @ Run2

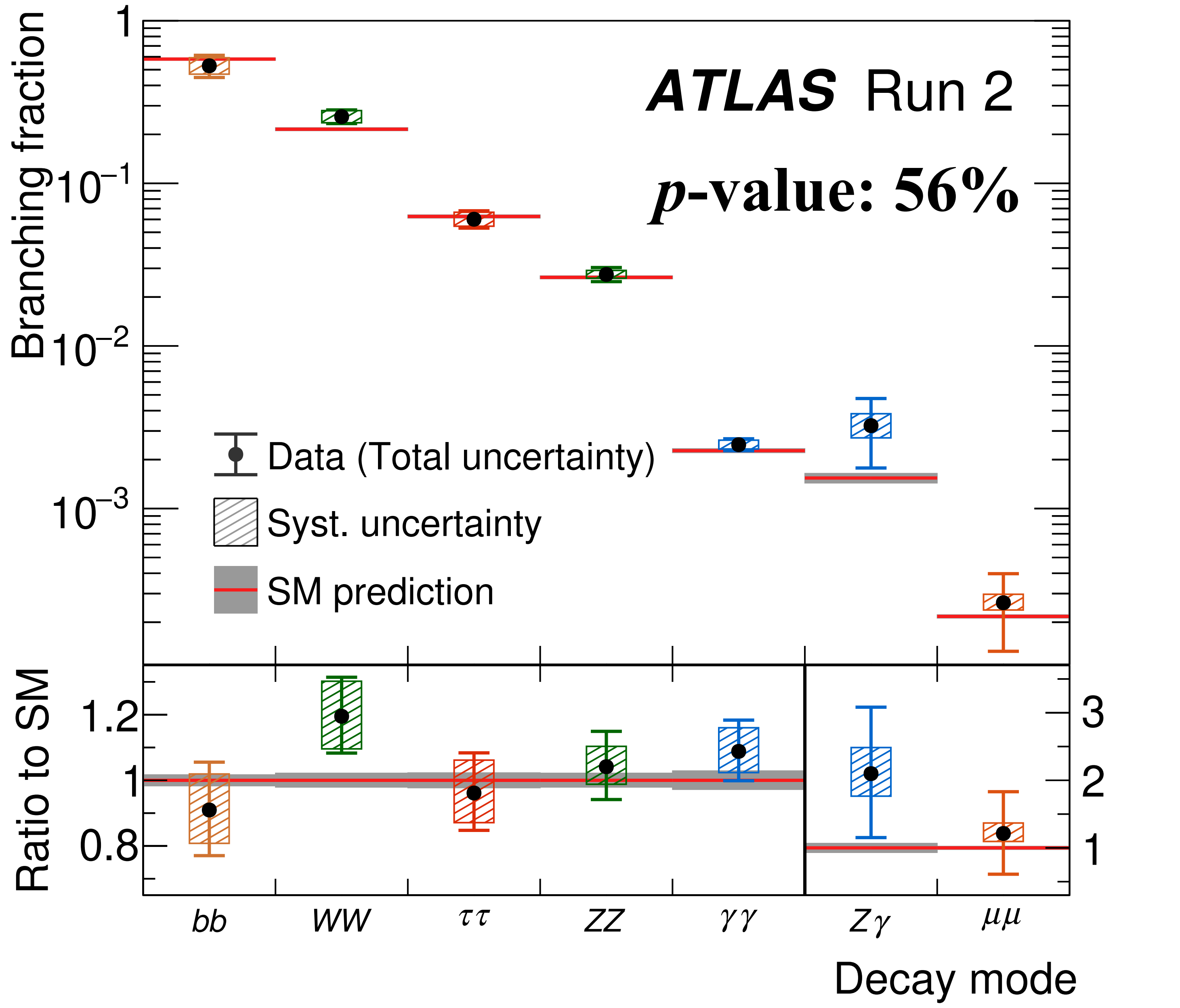
- Global signal strength measured for all production processes and decays together

$$\mu = \frac{\sigma \times \mathrm{B}}{(\sigma \times \mathrm{B})_{\mathrm{SM}}} = 1.05 \pm 0.06^{\,(*)}$$



Nature 607, 52–59 (2022)





- **Ratio** of observed to predicted SM event rate
- Already **better than 10%** precision in *ggF* measured in a number of decay channels
  - Still several channels **dominated** by the statistical **uncertainty**

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(*) $\mu = 1.05 \pm 0.03(\mathrm{stat.}) \pm 0.03(\mathrm{exp.}) \pm 0.04(\mathrm{sig.th.}) \pm 0.02(\mathrm{bkg.th.})$

κ-Framework @ Run 2

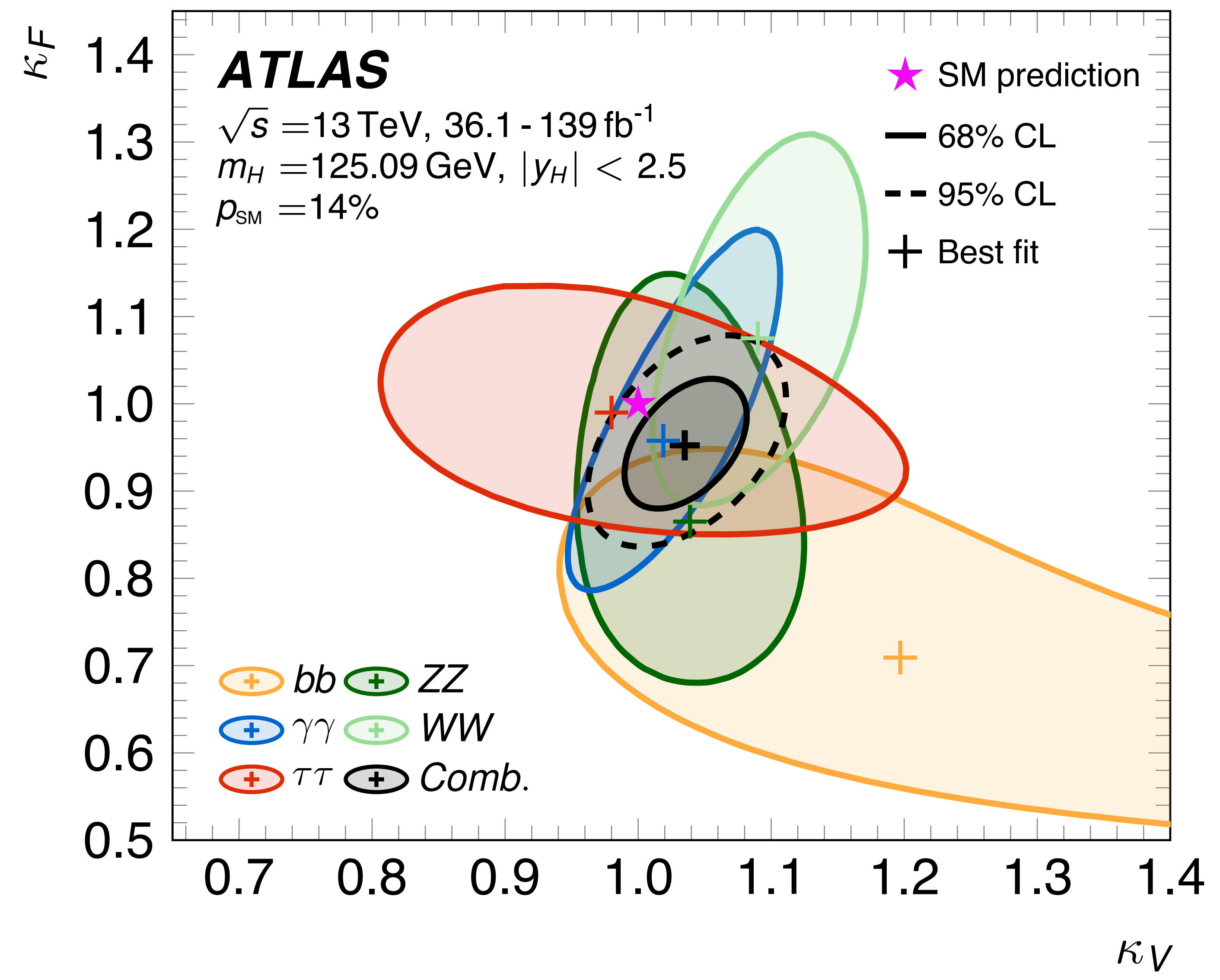
Nature 607, 52–59 (2022)

- **Event rates** for Higgs **production** and **decay** processes can be expressed in terms of **coupling modifiers (κ)** multiplying the SM Higgs coupling **strengths** to other particles.

$$\sigma(i \to H \to f) = \sigma_i B_f = \frac{\sigma_i^{SM}\kappa_i^2 \cdot \Gamma_f^{SM}\kappa_f^2}{\Gamma_H^{SM}\kappa_H^2} \to \mu_i^f = \frac{\kappa_i^2\kappa_f^2}{\kappa_H^2}$$

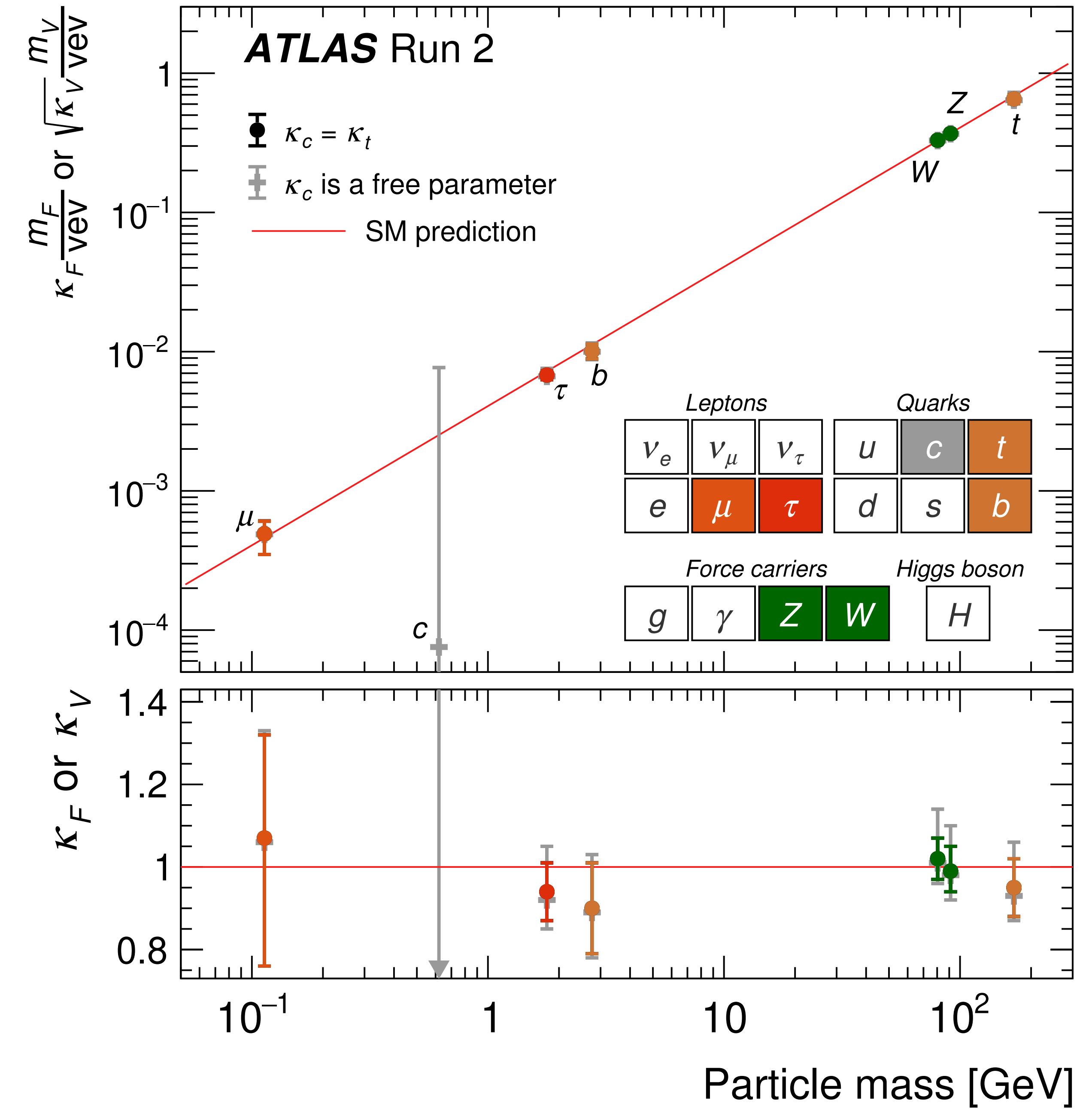
- **Three** classes of models with **progressively fewer assumptions**

Single modifier for vector **bosons** $\kappa_V (= \kappa_W = \kappa_Z)$ and single modifier for **fermion** couplings κ_F

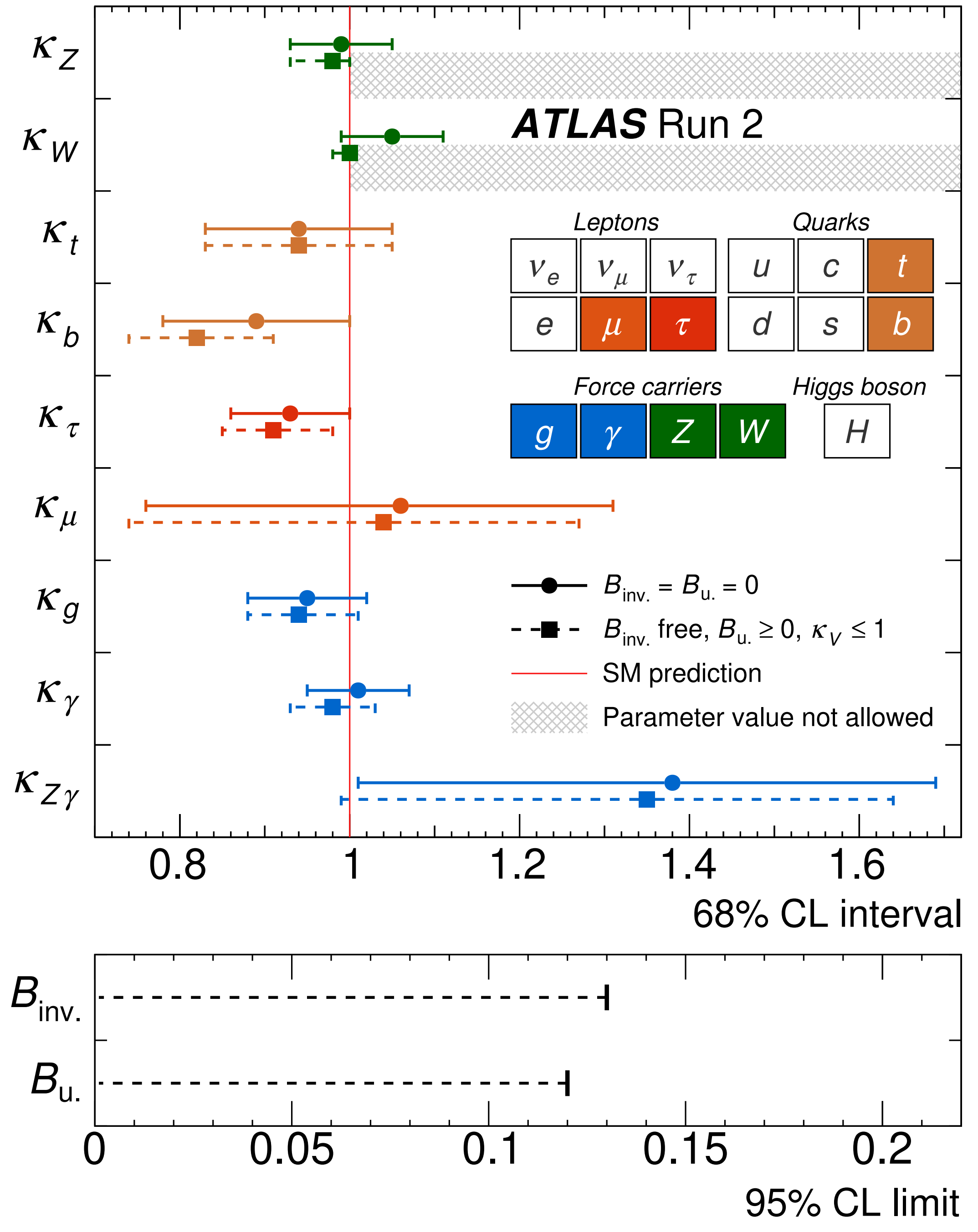


$\kappa_V = 1.035 \pm 0.031,\ \kappa_F = 0.95 \pm 0.05$

Coupling strength modifiers for W, Z, t, b, c, τ and μ (only SM particles assumed, loop processes resolved)



Allows for the presence of **non-SM** particles in the loop-induced processes with **effective coupling modifiers $\kappa_g, \kappa_\gamma, \kappa_{Z\gamma}$**



All measured coupling strength **modifiers are compatible** with their SM **predictions**

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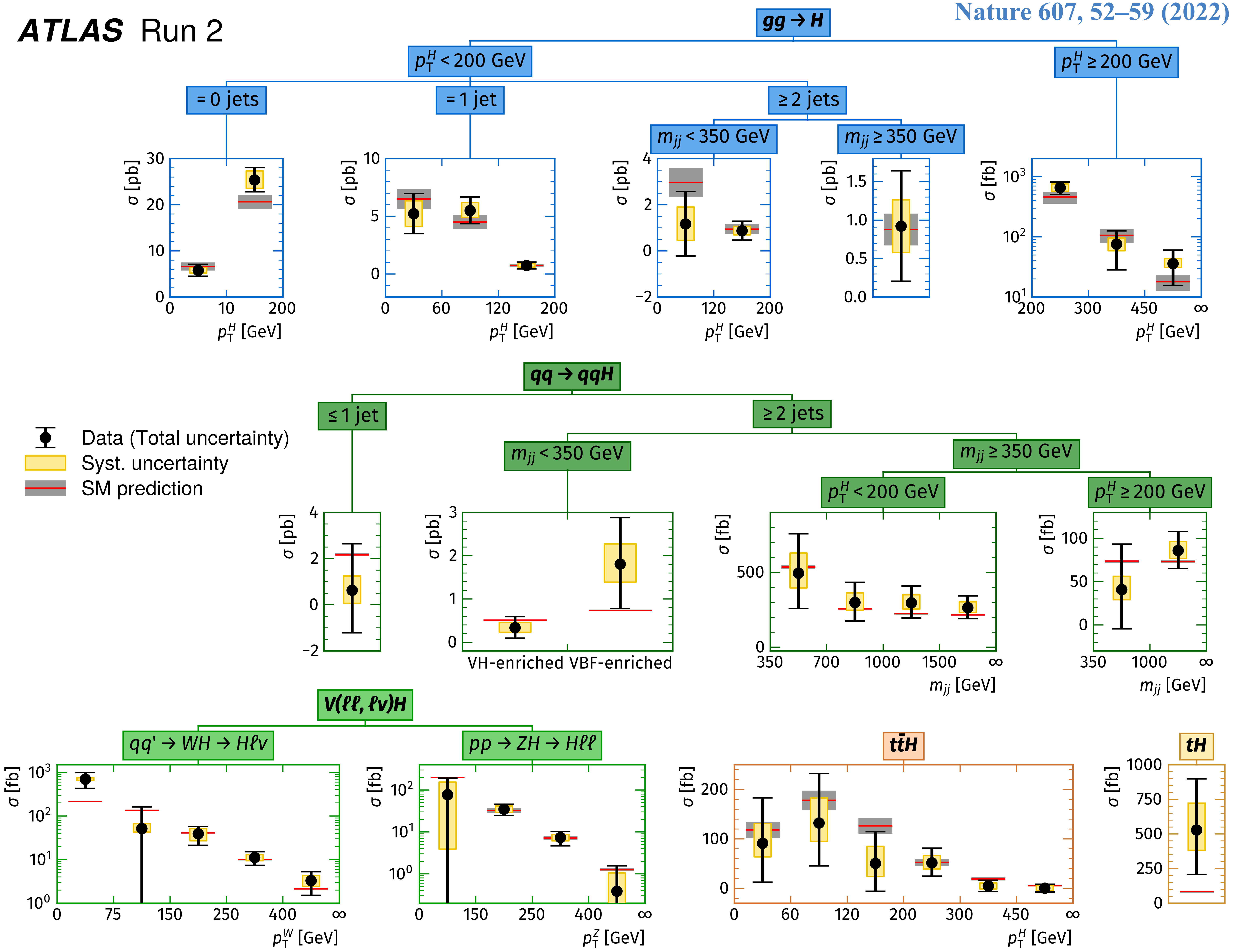
Simplified template cross section (STXS)

- **STXS framework** partitions the Higgs **cross section** measurements **separately in production modes and** in several bins of **kinematic** regions in an optimized way
  - Split phase space of Higgs production processes into **36 kinematic regions**
  - **Optimise** signal and BSM sensitivity
  - **Reduce** theoretical uncertainties that are directly folded into the measurements.
  - **Allowing** the combination of measurements in different decay channels and eventually between experiments.
  - The ***p*-value** for compatibility of the combined measurement and the **SM** prediction is **94%**

Nature 607, 52–59 (2022)



All measurements are consistent with the SM predictions

Interpretations in SMEFT

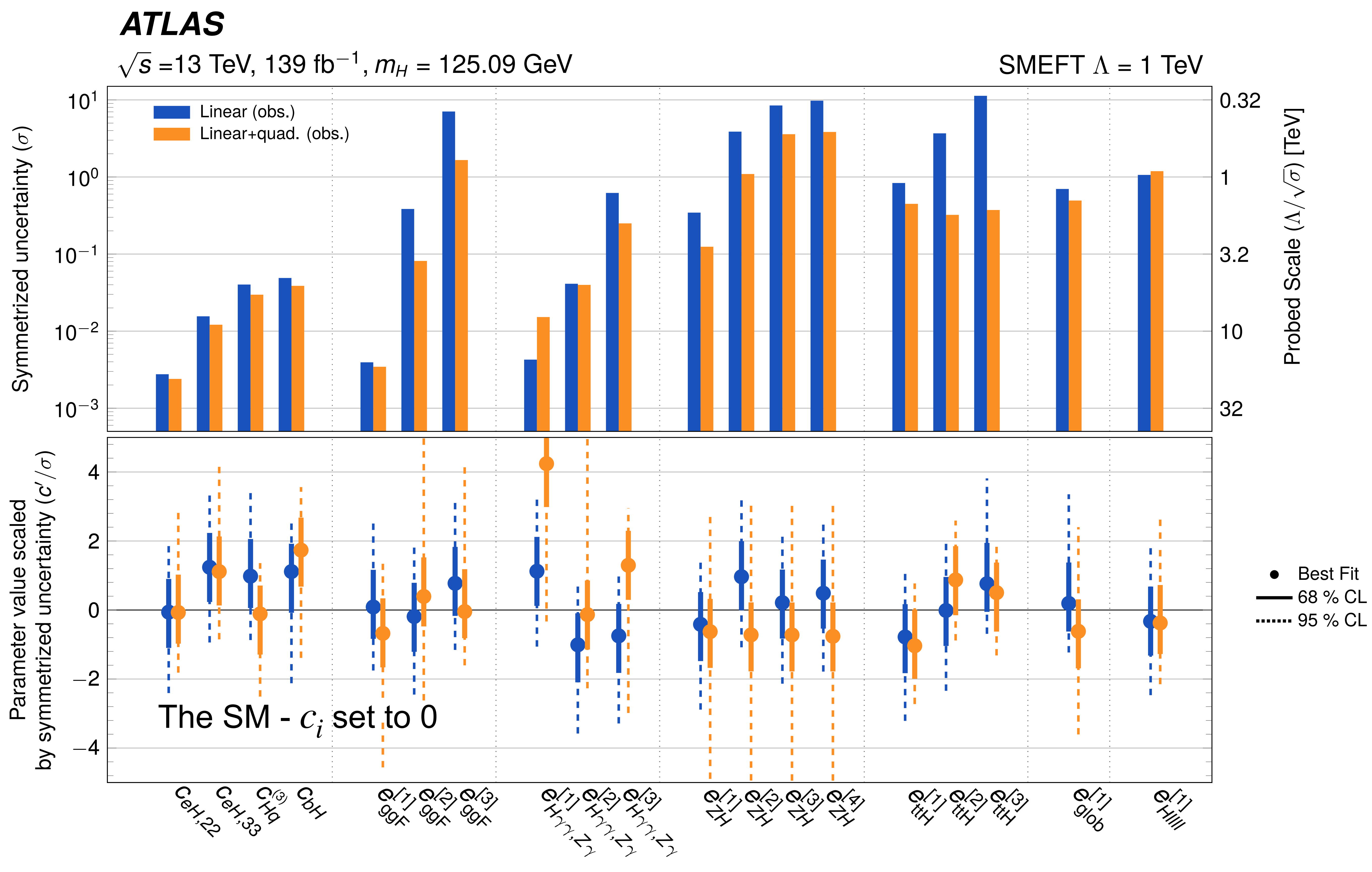
Dedicated talk by Yicong Huang on Tuesday

arXiv:2402.05742

- Standard Model Effective Field Theory (**SMEFT**) provides a **model-independent** setting to **describe deviations from SM**
- Effective **Lagrangian** :

$$\mathscr{L}_{\text{SMEFT}} = \mathscr{L}_{\text{SM}} + \sum_i^{N_{d=6}} \frac{c_i}{\Lambda^2}\mathcal{O}_i^{(6)} + \sum_j^{N_{d=8}} \frac{b_j}{\Lambda^4}\mathcal{O}_j^{(8)} + \ldots,$$

- c_i, b_j- **Wilson** coefficients operators are expressed in the **Warsaw** basis
  - Up to dimension 6 is considered
- **Simultaneous** measurement of SMEFT parameters by computing eigenvectors **EVn** with PDF approx. **Gaussian**: $V_{\text{SMEFT}}^{-1} = P^T V_{\text{STXS}}^{-1} P$
- Stronger constraints with quadratic model



p-value: 98.2%

no significant deviation from SM

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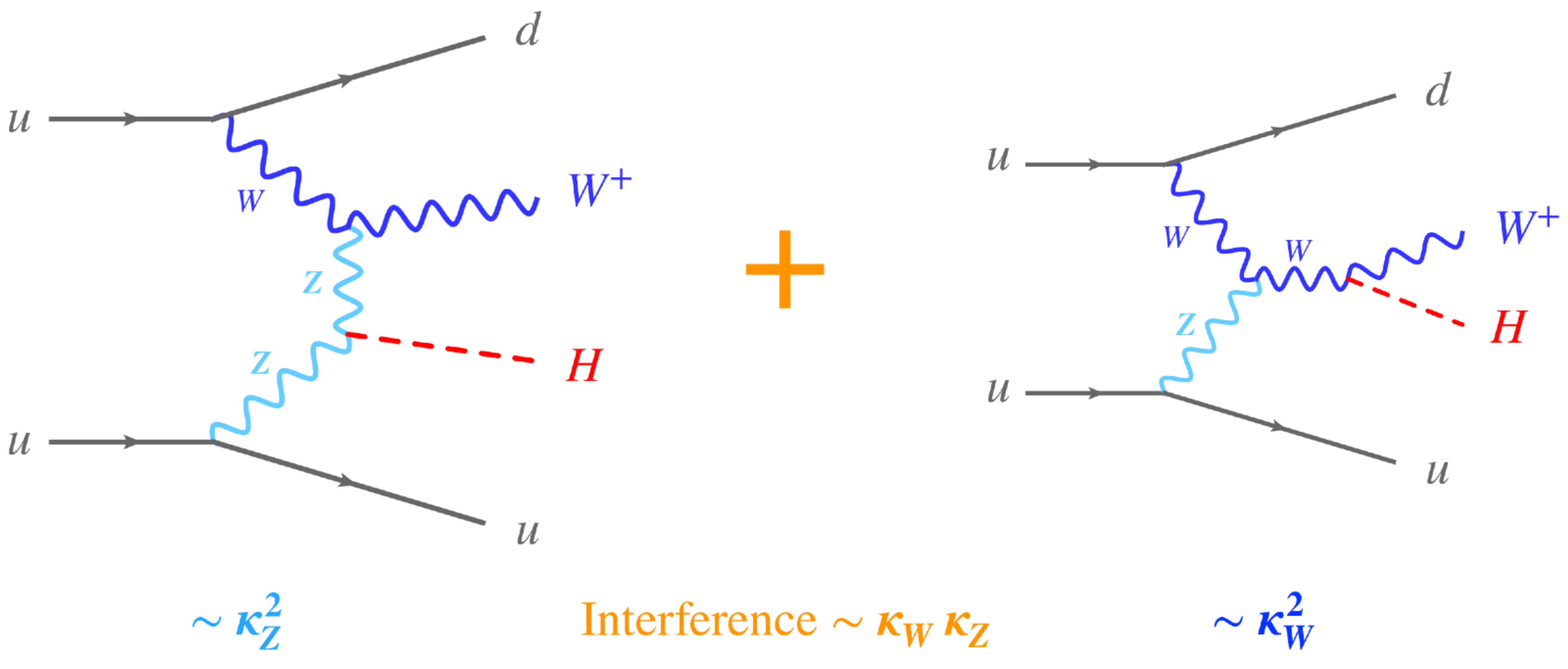
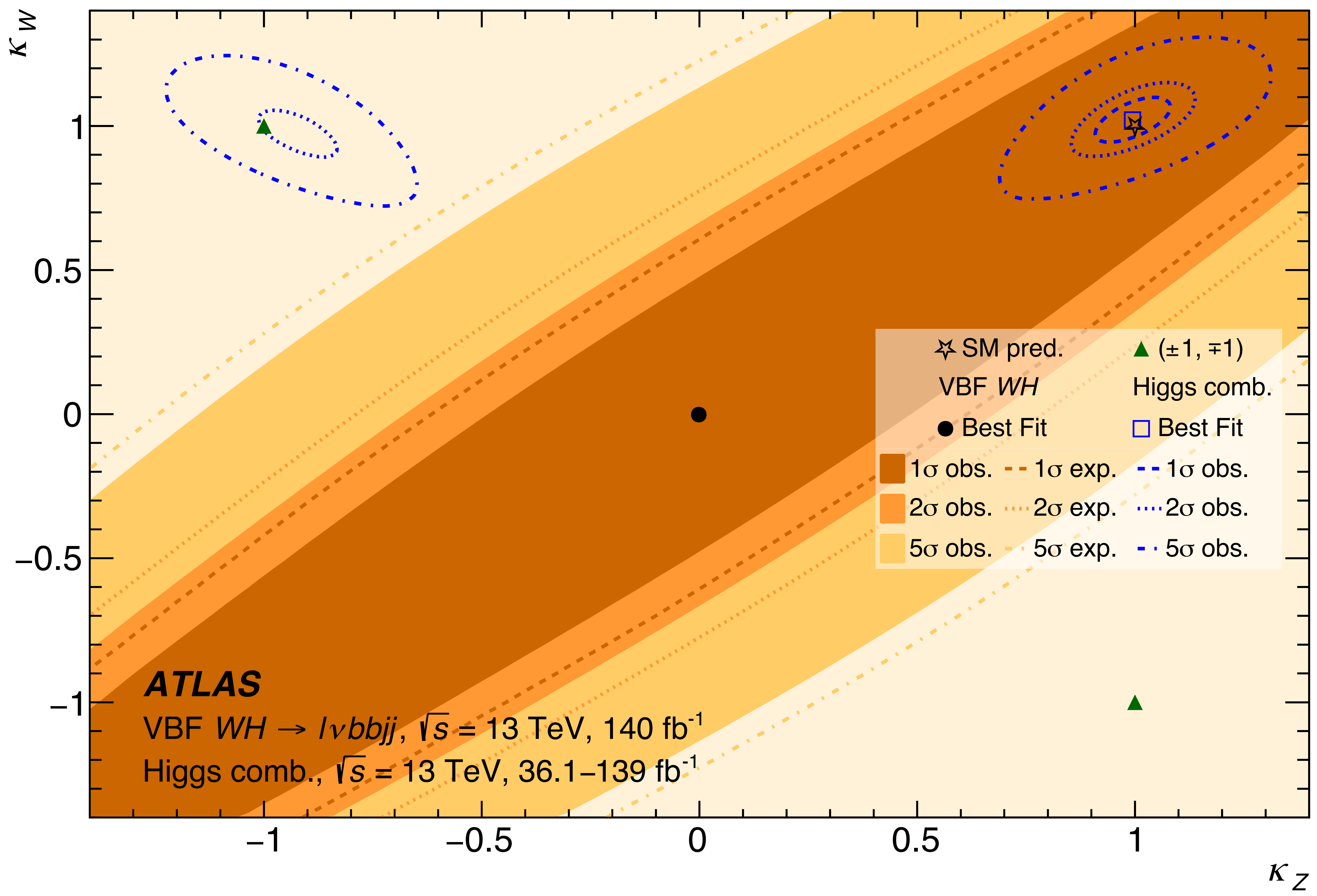
Relative sign of the *W* and *Z* couplings with VBF *WH* production

- In **VBF** *WH* process, the Higgs boson interacts with either a *W* or *Z* boson
  - **Analysis selects VBF** $WH \rightarrow l\nu b\bar{b}jj$ **events**
  - Couplings parametrized with κ_W, κ_Z modifiers
- $\lambda_{WZ} = \kappa_W/\kappa_Z$, SM prediction $\lambda_{WZ} = 1$
- Probing λ_{WZ} sign (previously unconstrained)
  - $\mu = 0.9^{+4.0}_{-4.3}$ and upper limit 9.0x (obs.) SM (8.7 exp.)
    - largest systematics due to W+jets and $t\bar{t}$ modeling and jet energy resolution
  - The *W* **and** *Z* **boson couplings** to the Higgs boson are determined to have the **same sign**
  - **Opposite-sign hypotheses** now excluded with **significance** $> 5\sigma$



$$\sigma_{\mathrm{VBF},WH} \propto \kappa_Z^2 |\mathcal{M}_Z|^2 + \kappa_W^2 |\mathcal{M}_W|^2 - 2\,\kappa_Z\,\kappa_W\,\Re[\mathcal{M}_Z^\dagger \mathcal{M}_W]$$
$$= \kappa_Z^2 |\mathcal{M}_Z|^2 + \kappa_W^2 |\mathcal{M}_W|^2 - 2\,\kappa_Z^2\,\lambda_{WZ}\,\Re[\mathcal{M}_Z^\dagger \mathcal{M}_W]$$

arXiv:2402.00426



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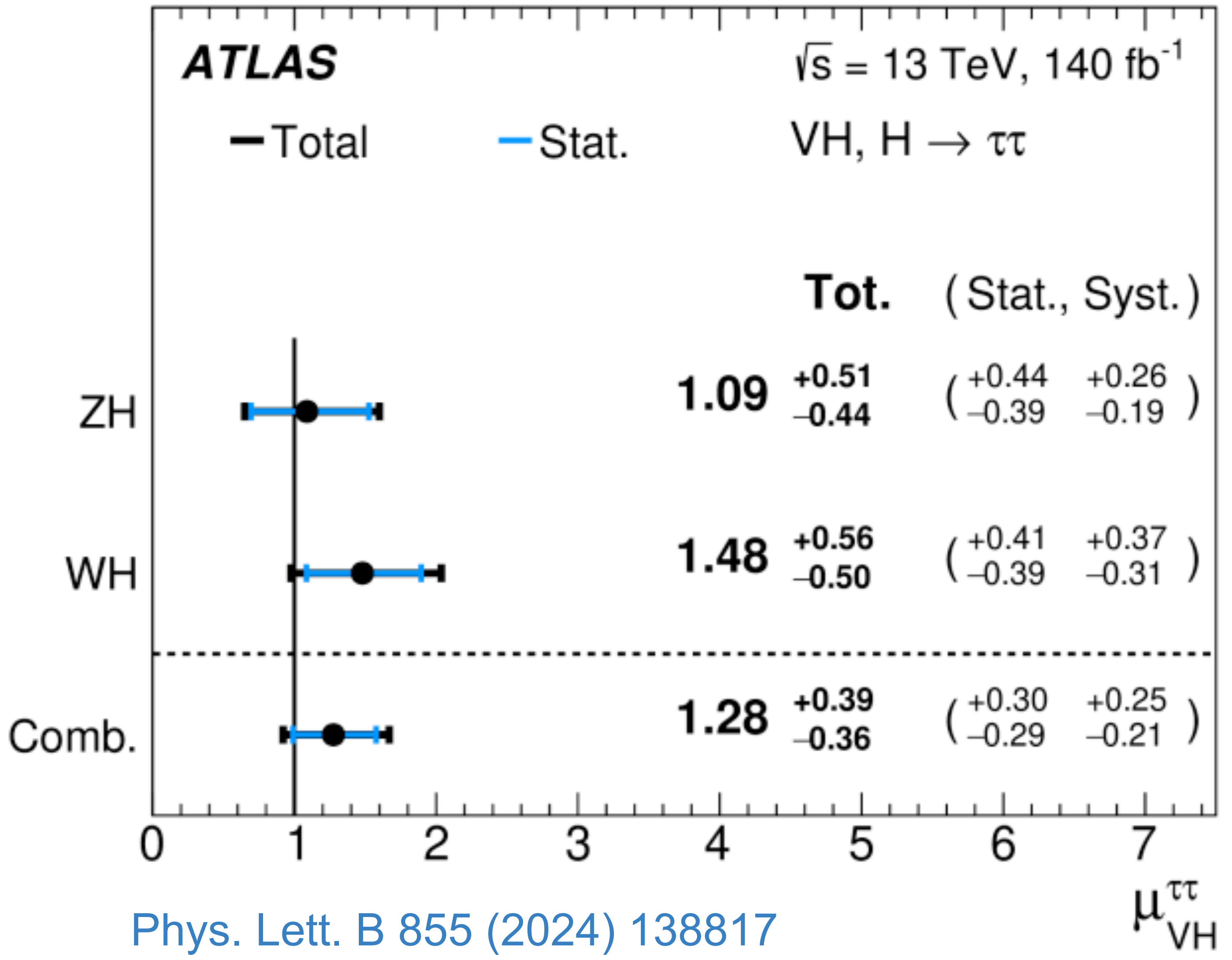
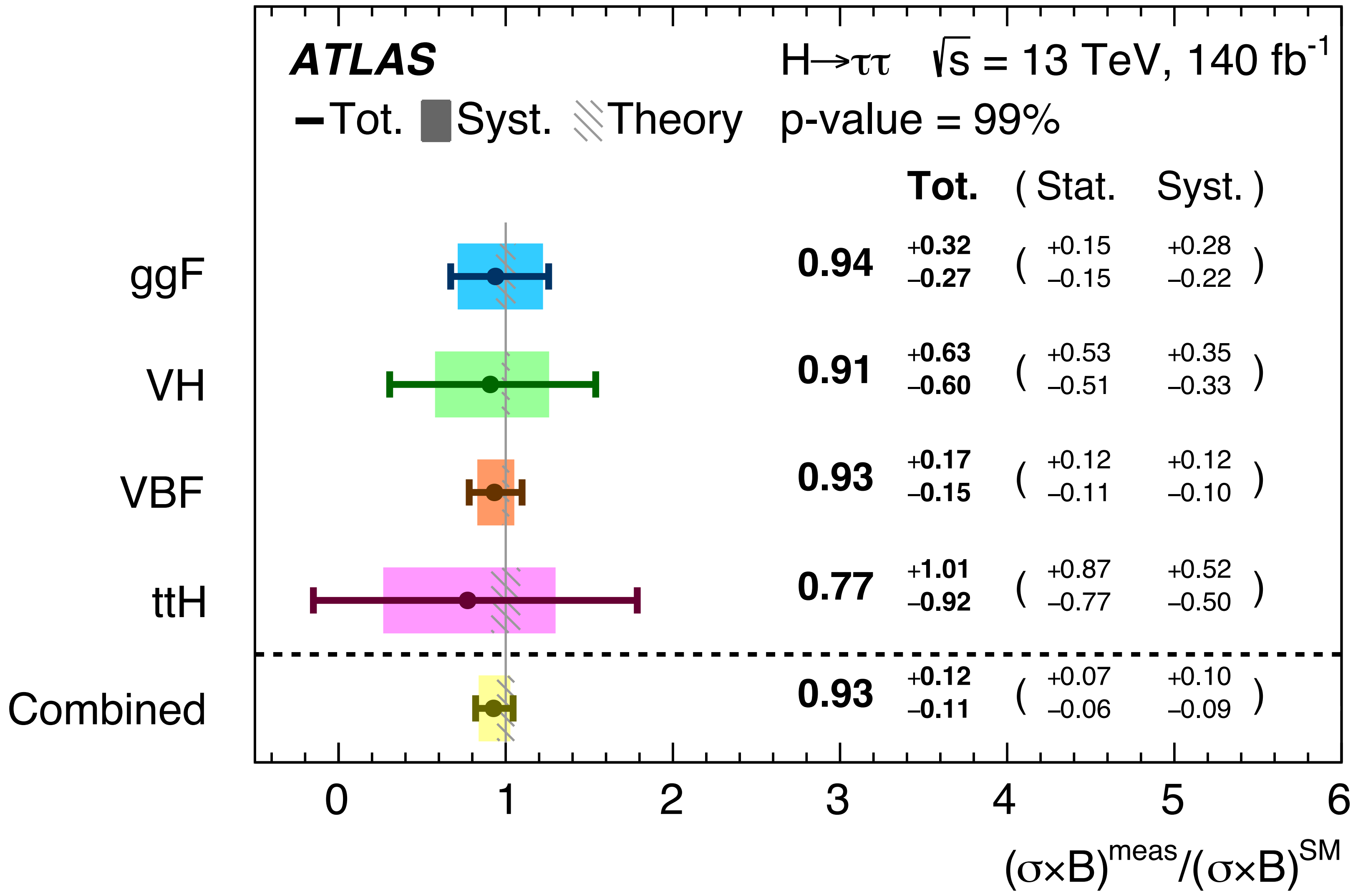
$H \to \tau\tau$ channel (incl. STXS)

- The τ-lepton is the heaviest lepton and therefore has the largest coupling to the Higgs boson, BR($H \to \tau\tau$) 6%
- First analysis considers **only leptonic W, Z decays** and **H** final states with **at least one τ-lepton decaying hadronically**
  - NN analysis is used to separate signal and background
- Signal strength: $\mu = 1.28 \pm 0.3(\text{stat}) \pm 0.2(\text{sys})$ with overall significance ~4.2σ



Phys. Lett. B 855 (2024) 138817

- The fit is also performed for the four production modes (**STXS**)
  - **Good agreement** with the SM predictions.
- **Improvements** over the previous analysis splitting VBF in more **kinematic** regions and **enhancing** the $t\bar{t}H$ measurement using ML
  - 8% **improvement** in the global signal strength and a ~ 25% improvement in the $t\bar{t}H$ signal strength (statistically limited)



arXiv:2407.16320

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Legacy $V(\to \text{lep})H(\to b\bar{b}/c\bar{c})$ (1/2)

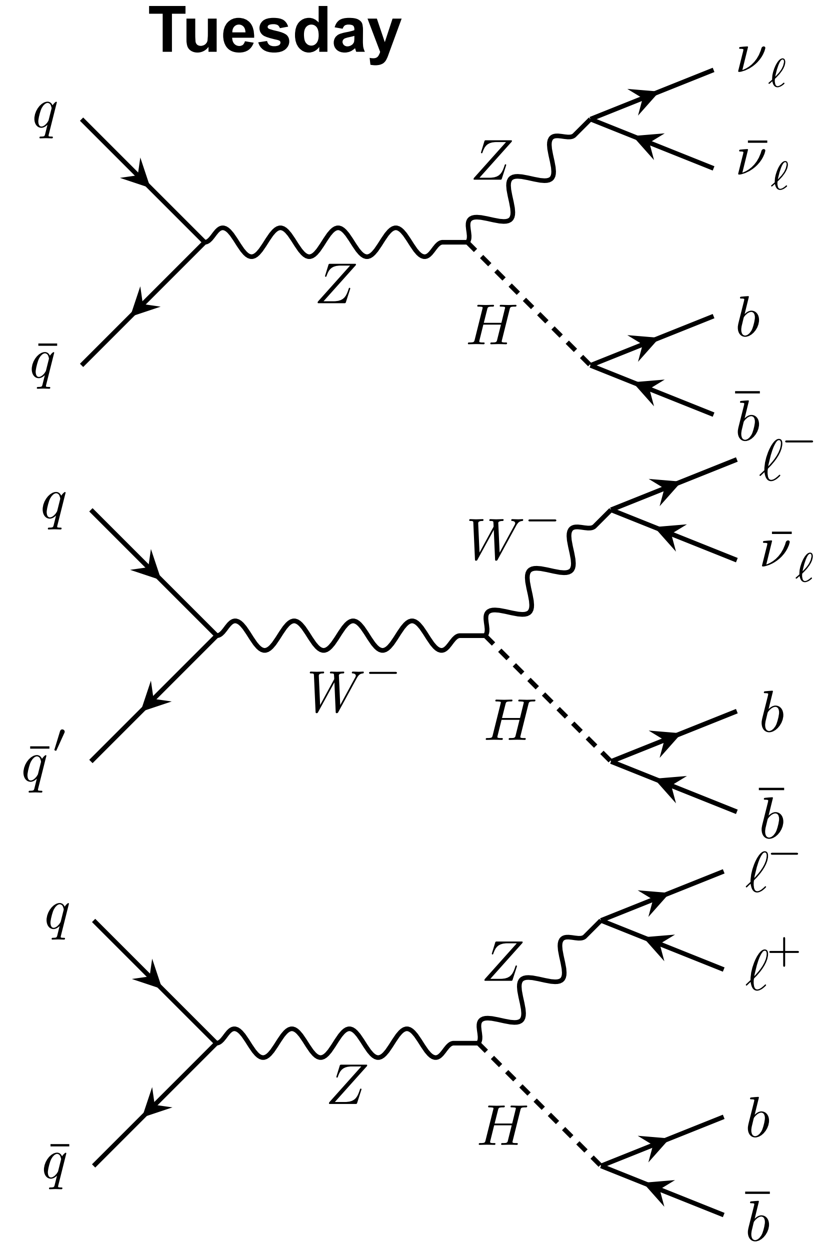
Dedicated talk by Marion Miissio on Tuesday

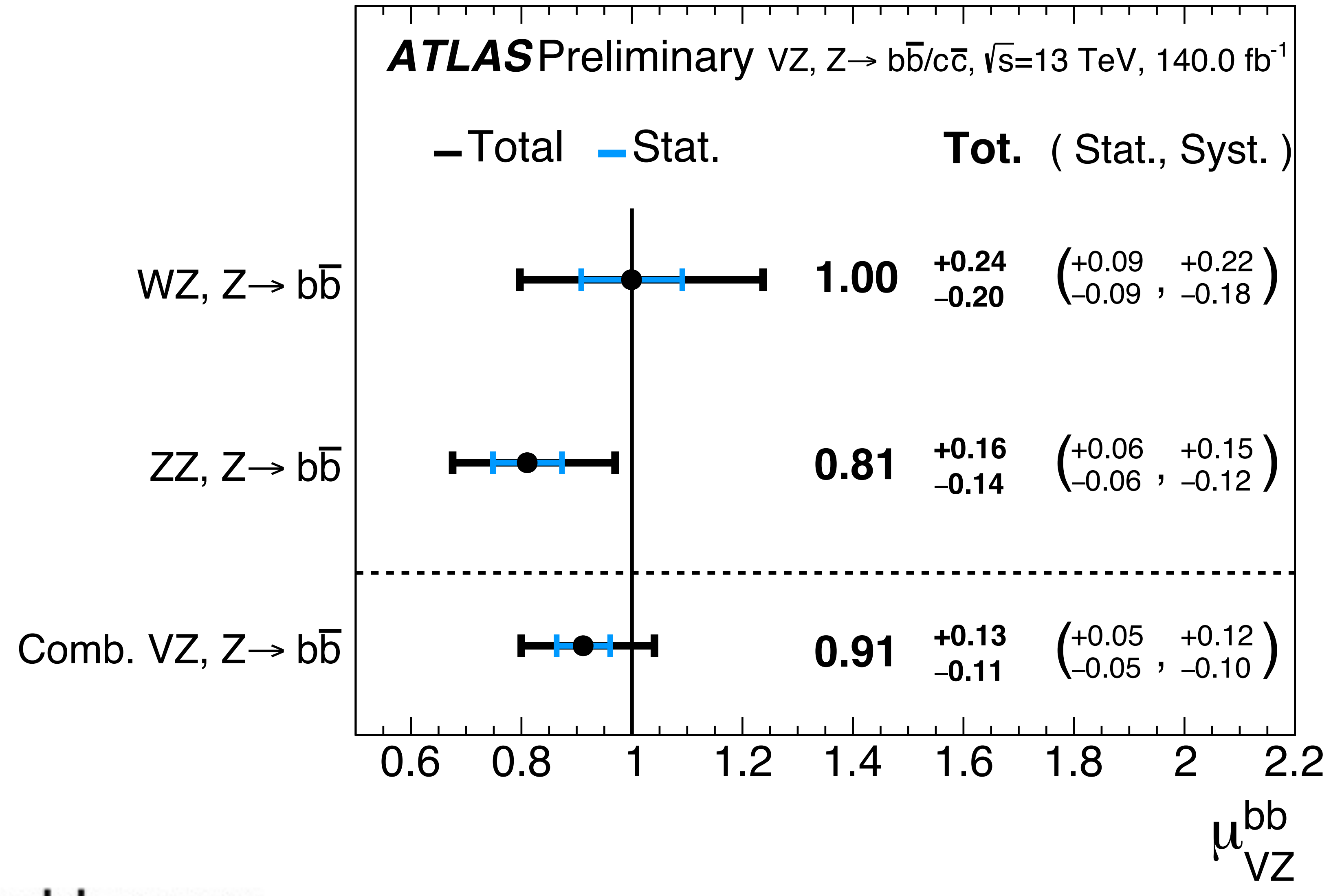
- $V(\to \text{lep})H(\to b\bar{b})$ is the most sensitive process to study some of the rarer Higgs production mechanisms such as the associated production with a W or Z boson (VH)
  - Higgs decays to $b\bar{b}, c\bar{c}$ pairs
  - Simultaneous extraction of both signals
  - Analysis strategy **validated** searching diboson WZ and ZZ signal

(0 lep)

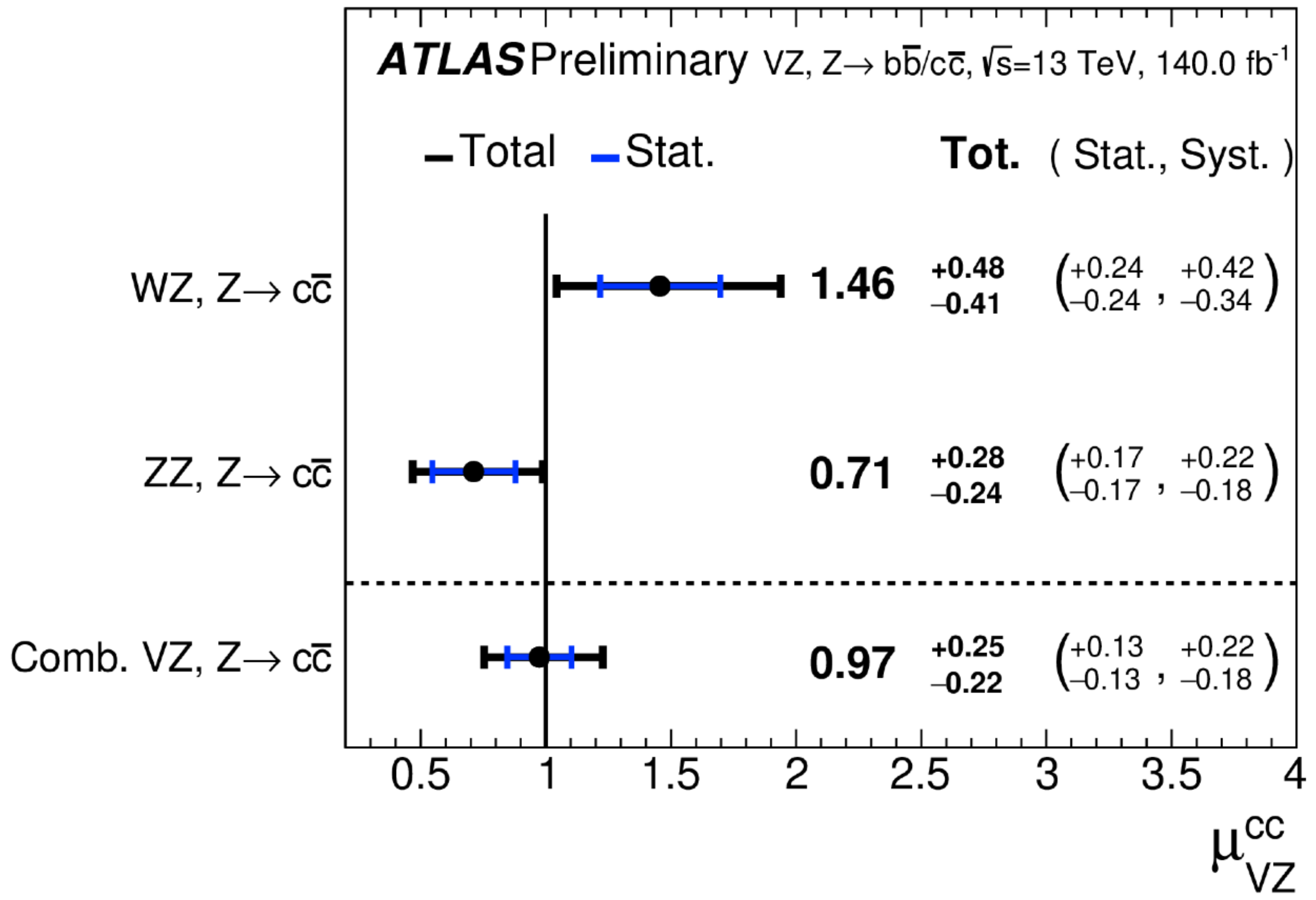
(1 lep)

(2 lep)





Obs. Significance
6.4σ
$>10\sigma$



Obs. Significance
3.9σ
3.1σ
$>5\sigma$

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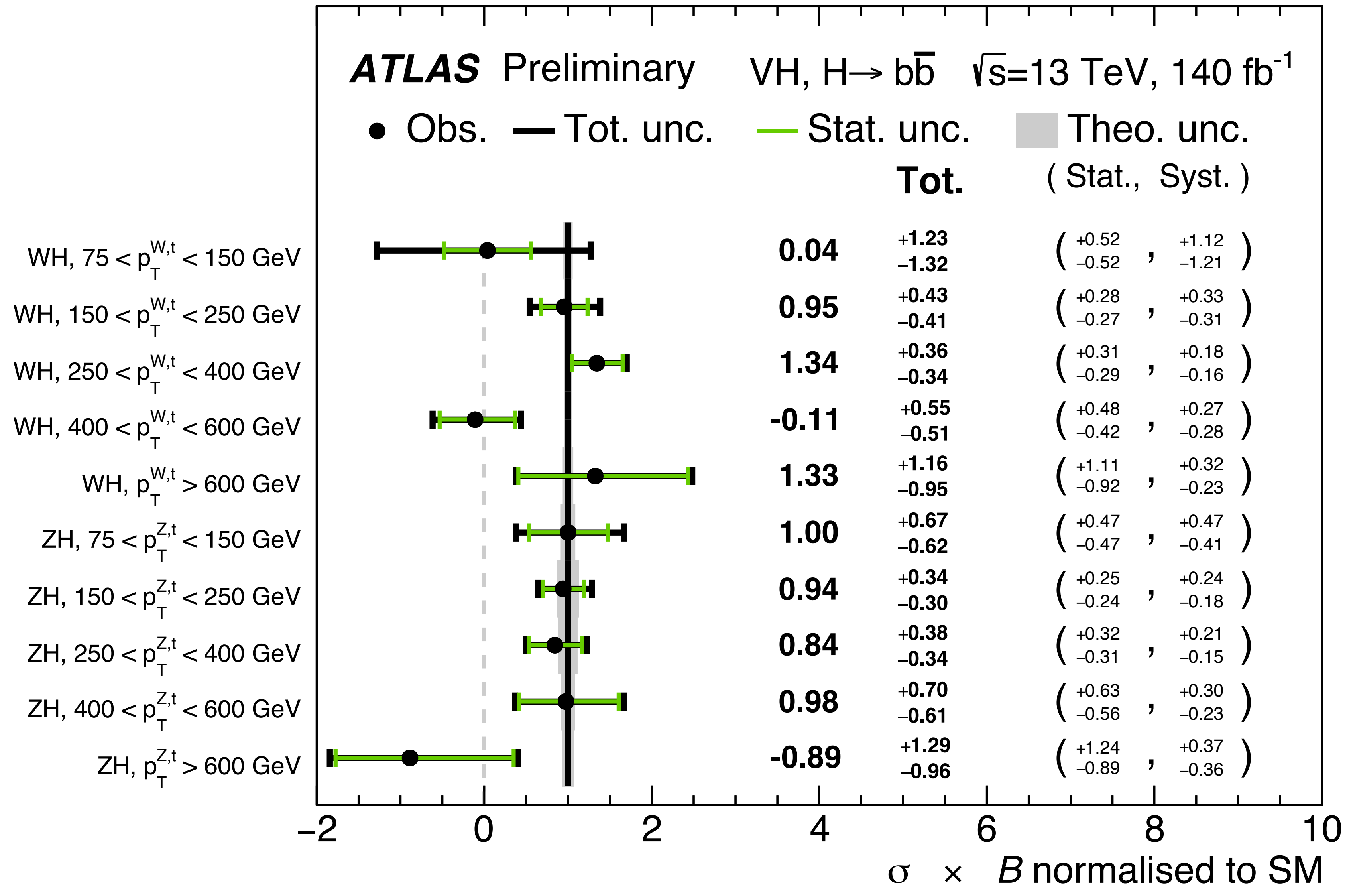
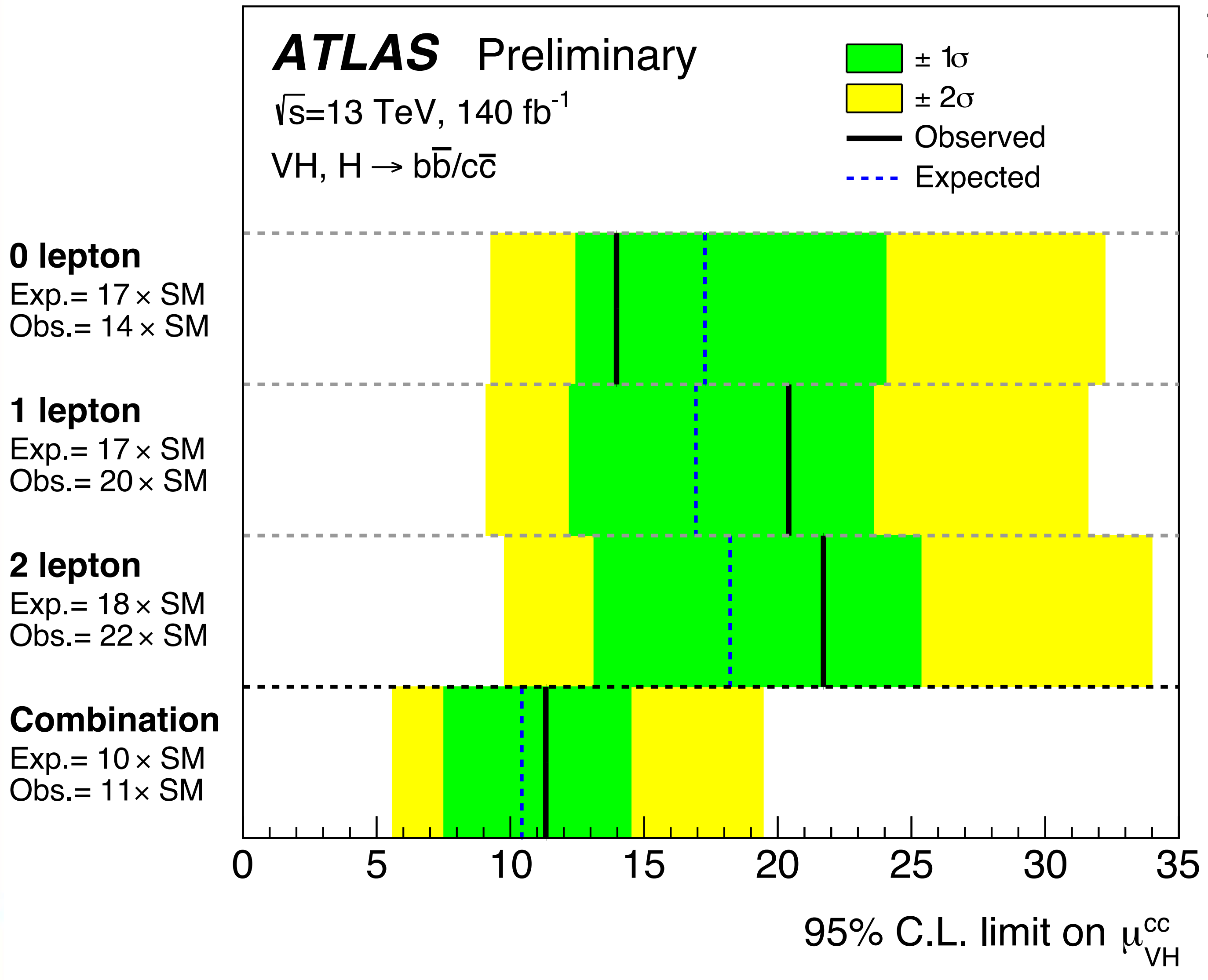
Legacy $V(\rightarrow \text{lep})H(\rightarrow b\bar{b}/c\bar{c})$ (2/2)

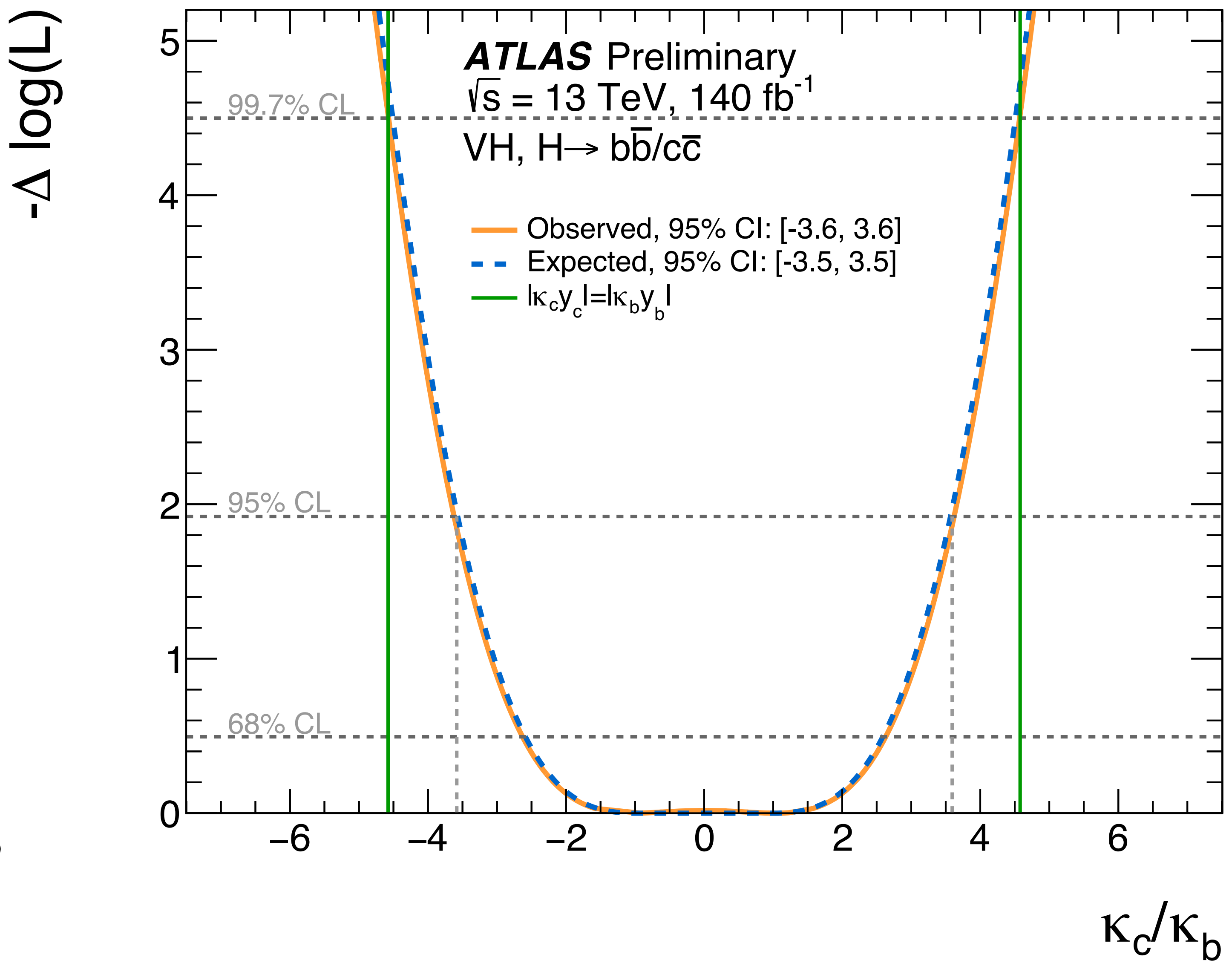
ATLAS-CONF-2024-010

Dedicated talk by Marion Miissio on Tuesday

- Analysis shows 15% **improvement** in precision of $\mu_{VH}^{b\bar{b}}$ (resolved, boosted) compared to previous analysis
  - Better object reconstructions/calibrations, improved analysis strategies
  - $\mu_{VH}^{bb} = 0.91^{+0.16}_{-0.14}$, with obs. (exp.) significance $7.4\,\sigma\,(8.0\,\sigma)$







- $\mu_{VH}^{cc} = 1.0^{+5.4}_{-5.2}$, obs. (exp.) **upper limit** 11.3 (10.4) x SM @ 95% CL
  - Uncertainties improved by x3 wrt previous results
- **Constrain** on $|\kappa_c| < 4.2$ at 95% CL
- **Constrain** on ratio $(\kappa_c/\kappa_b) < 3.6$ at 95% CL
  - Total coupling strength **smaller** for charm than the bottom

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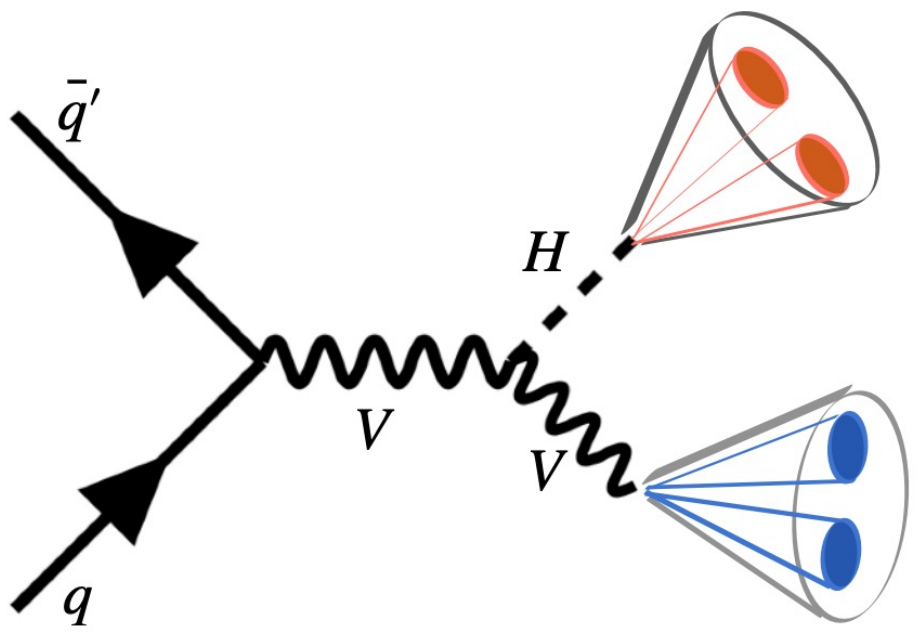
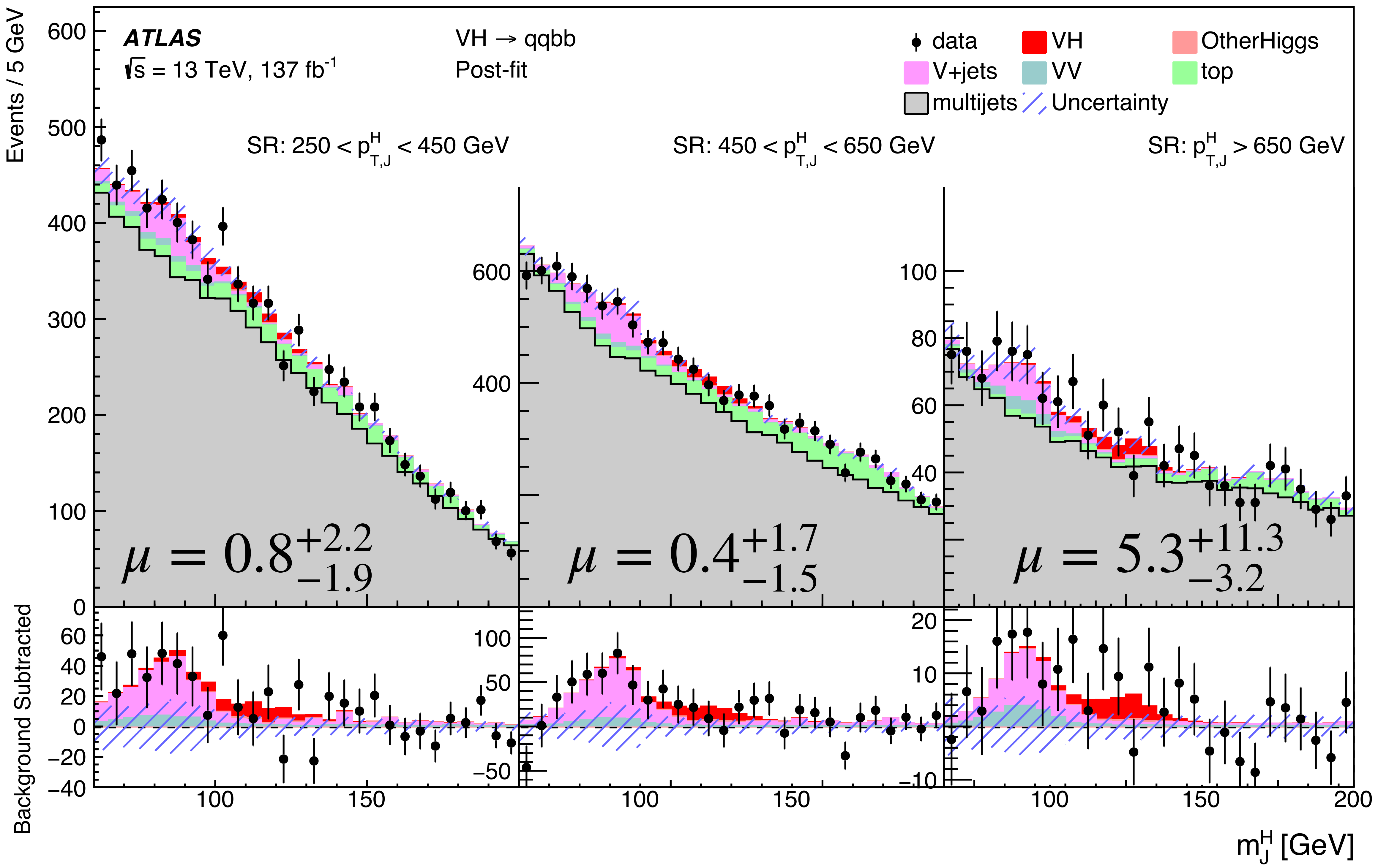
All results agree with SM

Boosted VH production in fully hadronic $qqb\bar{b}$

- **Highly boosted** topology using fully hadronic final state: $V(\rightarrow qq')H(\rightarrow b\bar{b})$
- NN algorithms employed to tag boosted $H \rightarrow b\bar{b}$
  - Larger BR than $V(\rightarrow \text{lep})H(\rightarrow b\bar{b})$,
  - Fully hadronic decays large irreducible multijet contribution though
- **Signal** strength $\mu = 1.4^{+1.0}_{-0.9}$ in agreement with SM
- **Significance** at 1.7σ observed (1.2σ exp.)





PhysRevLett.132.131802

Conclusions

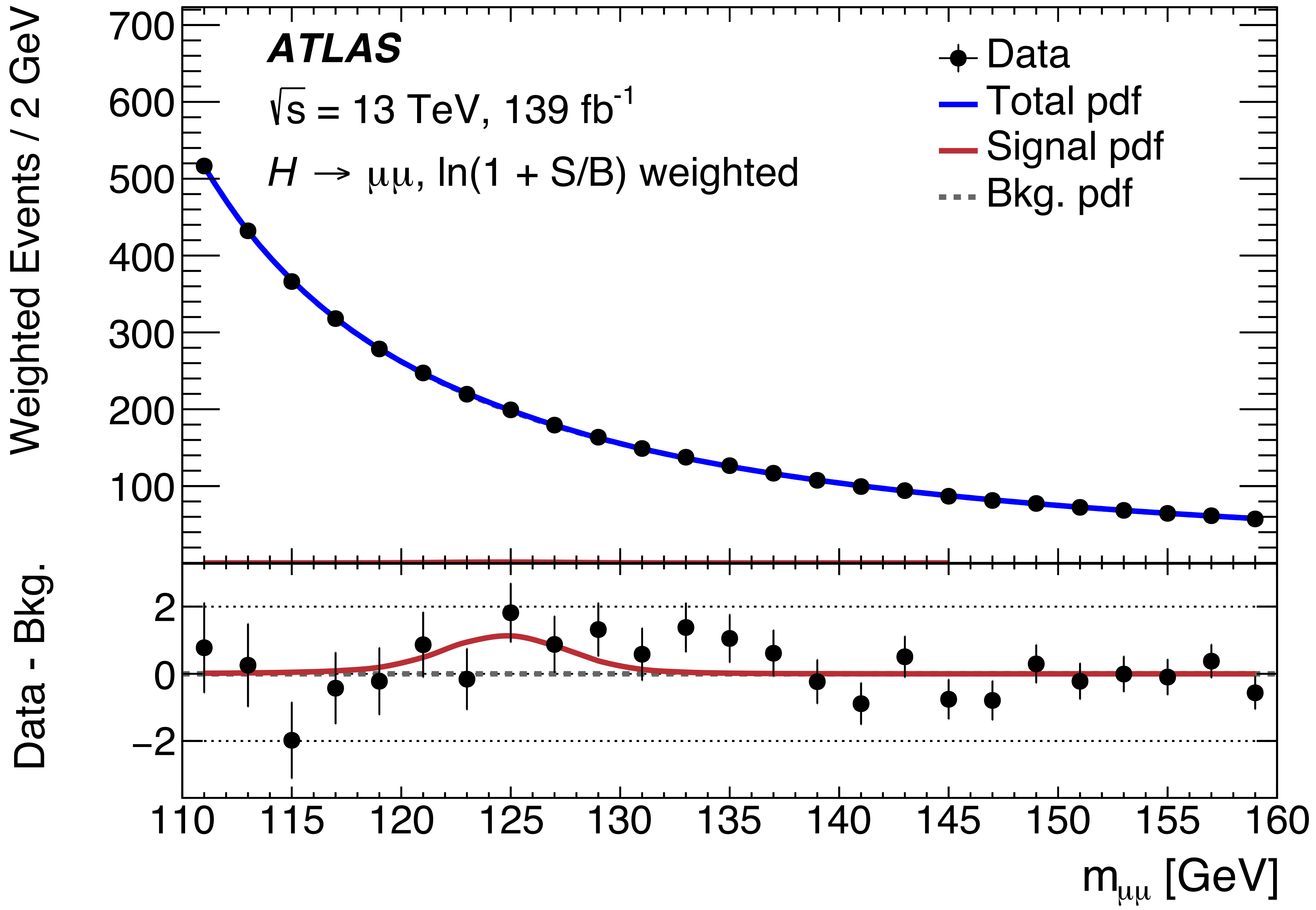
- Higgs couplings measured up to date are **compatible with SM**, no significant deviation is observed
  - **Crucial** for constraining Higgs-fermion and Higgs-boson couplings
    - Going to **precision** era of <10% in some, other still suffer from **statistical** uncertainties
- **Extend** coupling measurements to second-generation fermions
- New **advanced techniques** have been adopted along with **increased statistics** allow more and more channels to be exploited but also **improve** the existing ones
  - STXS interpretations to extensively test the **validity of the SM** in different regions of phase space
- **Looking forward to Run 3 results** with improved statistics and analysis methods

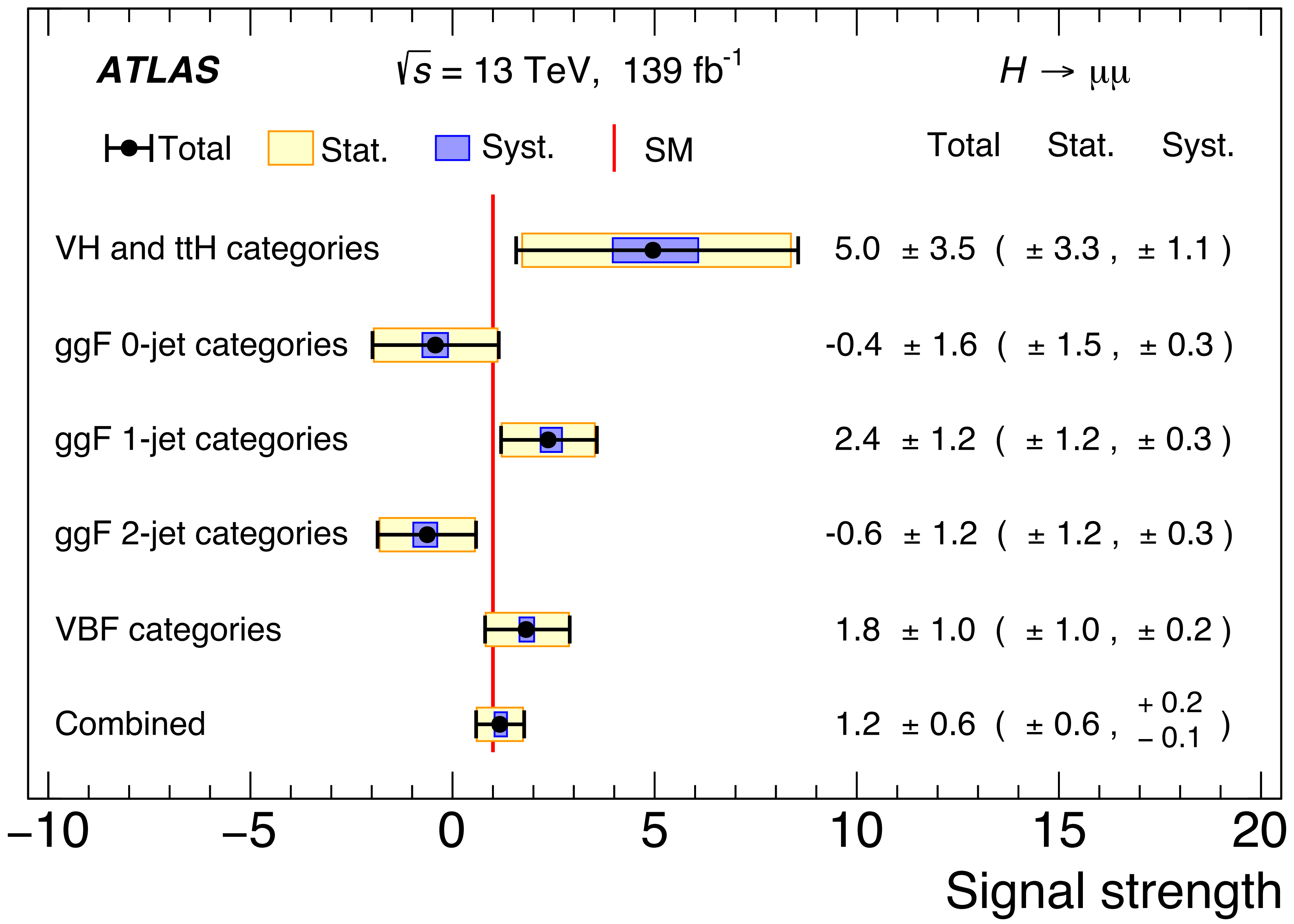
backup

$H \to \mu\mu$

[Phys. Lett. B 812 (2021) 135980]

- Large Drell-Yan background.
- Events sorted targeting different production modes (ggF, VBF, VH, $t\bar{t}H$)
- Observed (expected) significance over background-only hypothesis is $2.0\,\sigma$ $(1.7\,\sigma)$ for $m_H = 125.09\,\mathrm{GeV}$
- Upper limit of $pp \to H \to \mu\mu$ is 2.2x SM @ 95% CL
- Best fit for signal strength $\mu = 1.2 \pm 0.6$





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Global *H* Signal strength

- The Higgs boson production rates are probed by the likelihood fit to observed signal yields
- Global signal strength measured for all production processes and decays together
- Expressed in terms of a single **signal-strength modifier** μ:

$$\mu = \frac{\sigma \times \mathrm{B}}{(\sigma \times \mathrm{B})_{\mathrm{SM}}} = 1.05 \pm 0.06$$

- Systematic uncertainty **reduced** by factor of 2 since the discovery
- Total measurement **uncertainty decreased** by ~30%
- SM **compatibility** (p-value): 39%

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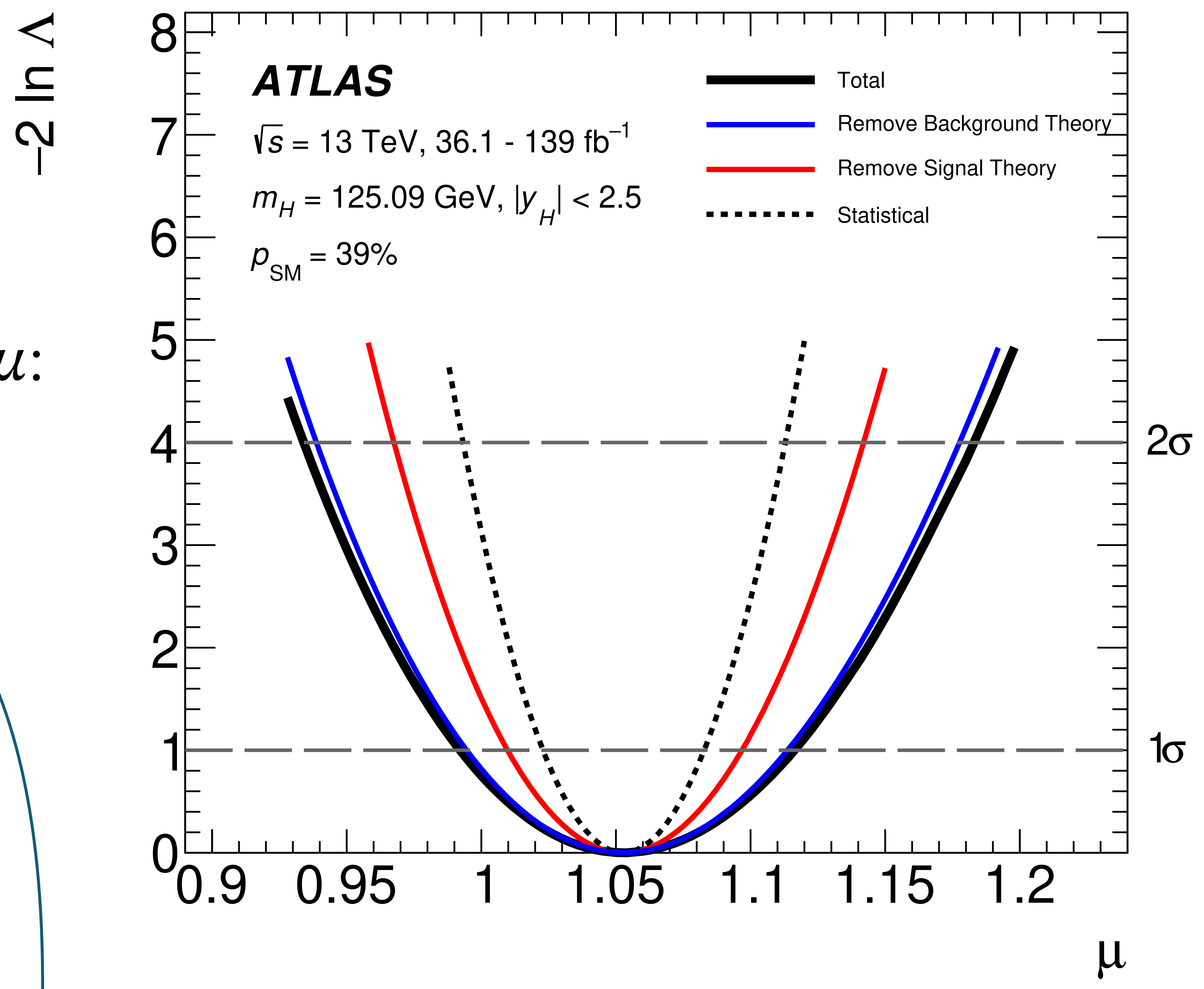


$$\mu = 1.05 \pm 0.03(\mathrm{stat.}) \pm 0.03(\mathrm{exp.}) \pm 0.04(\mathrm{sig.th.}) \pm 0.02(\mathrm{bkg.th.})$$

κ-Framework

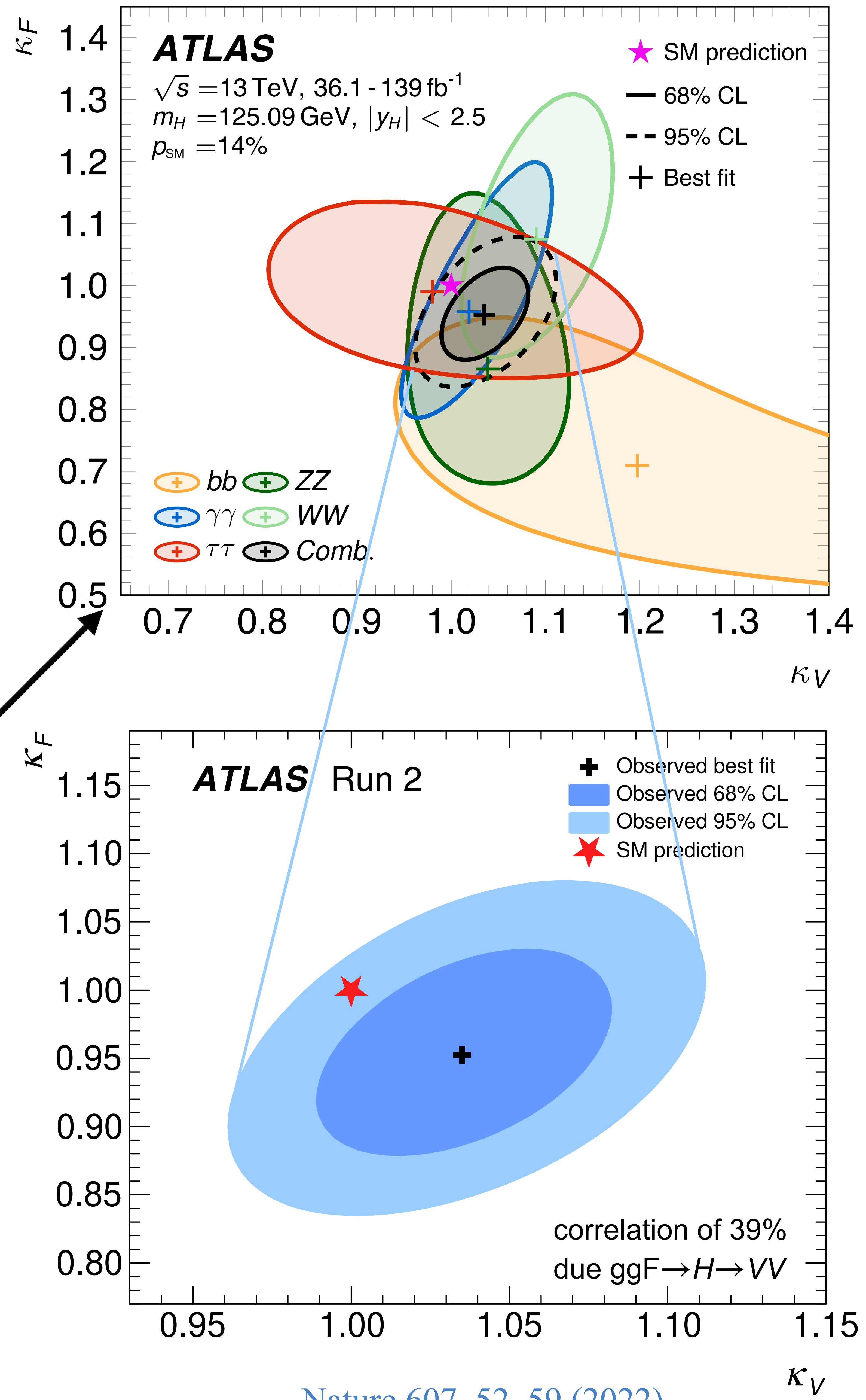
- **Event rates** for Higgs **production** and **decay** processes can be expressed in terms of **coupling modifiers (κ)** multiplying the SM Higgs coupling **strengths** to other particles.

$$\sigma(i \to H \to f) = \sigma_i B_f = \frac{\sigma_i^{\rm SM}\kappa_i^2 \cdot \Gamma_f^{\rm SM}\kappa_f^2}{\Gamma_H^{\rm SM}\kappa_H^2} \to \mu_i^f = \frac{\kappa_i^2\kappa_f^2}{\kappa_H^2}$$

- **Three** classes of models with **progressively fewer assumptions**:
  1. **Single** modifier for vector **bosons** $\kappa_V (= \kappa_W = \kappa_Z)$ and single modifier for **fermion** couplings κ_F :

     best-fit values: $\kappa_V = 1.035 \pm 0.031,\ \kappa_F = 0.95 \pm 0.05,\ p$-value: 14%

     ➡ **Compatible** with **SM** predictions ($\kappa_V = \kappa_F = 1$)
  2. Coupling strength **modifiers** for W, Z, t, b, c, τ and μ are **treated independently** (**only SM** particles assumed, loop processes resolved)
  3. **Same** as 2) but **allows** for the presence of **non-SM particles** in the loop-induced processes with coupling modifiers κ_g, κ_γ, $\kappa_{Z\gamma}$



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Couplings to individual particle

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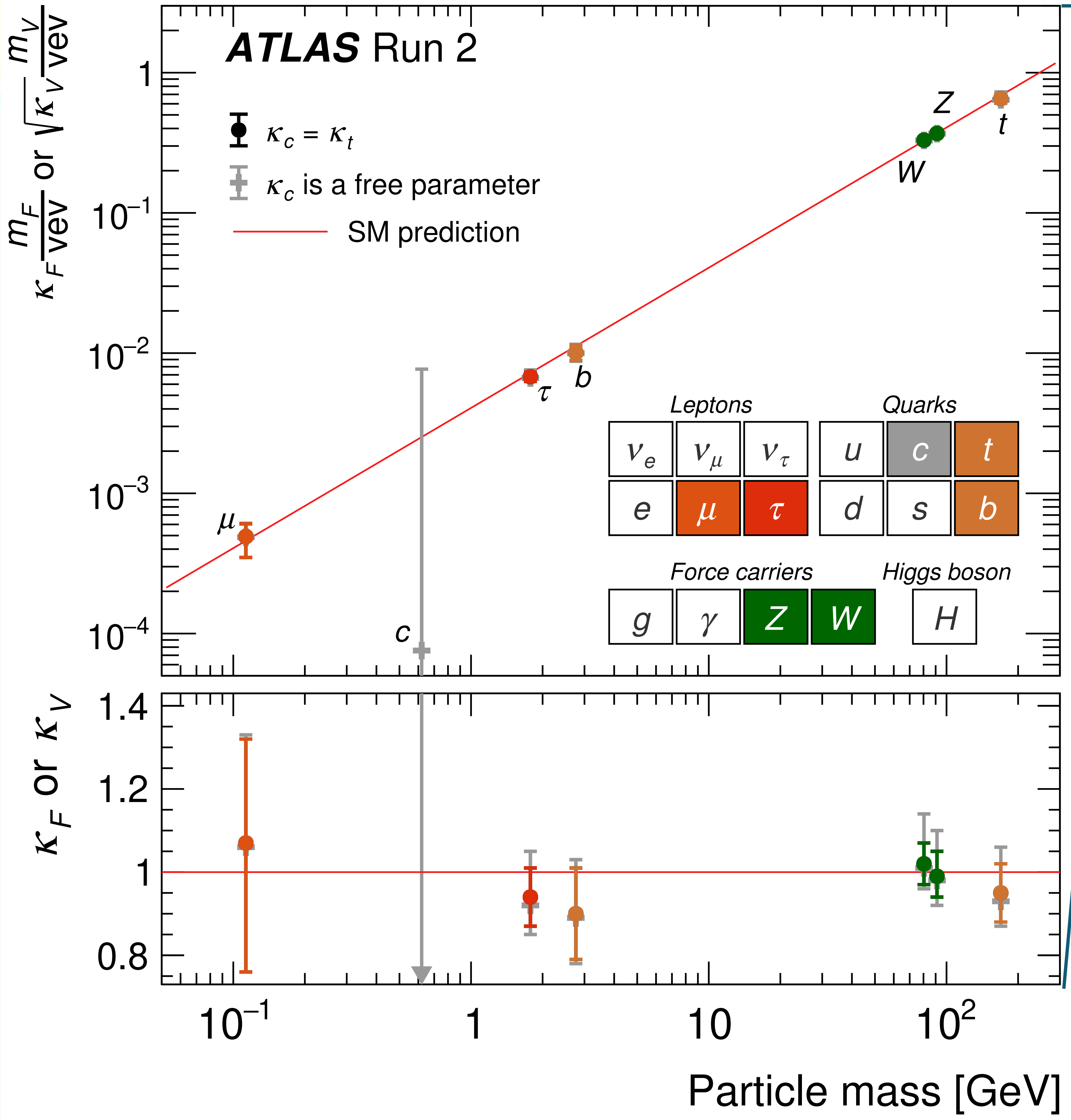
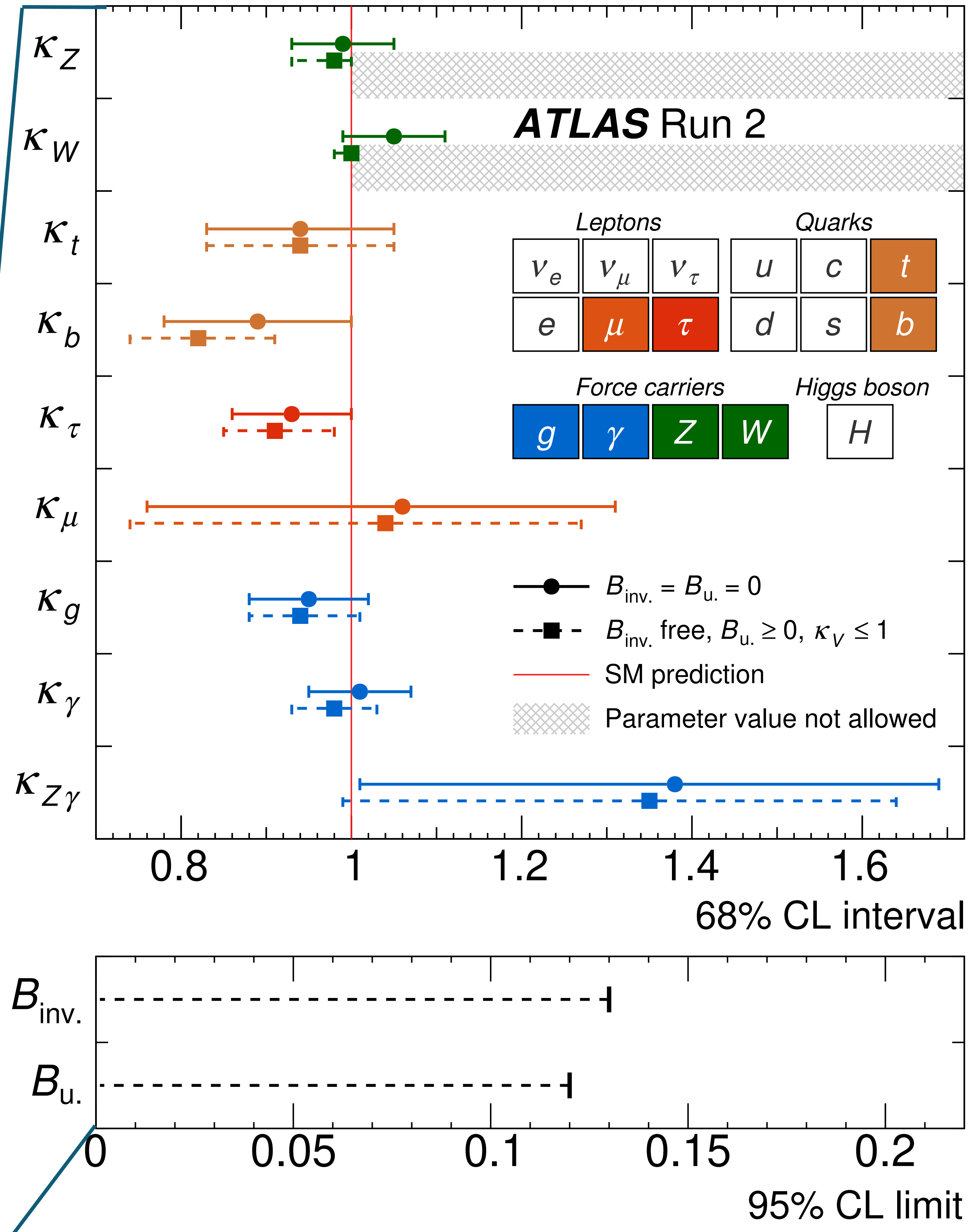


2nd Model

- *VH(cc)* data in the combination **allows** to have κ_c for the first time in this model (free param.)
- **Upper limit** (when left unconstrained) on κ_c is 5.7 (6.7) × SM obs. (exp.) at 95% CL (improve from Eur. Phys. J. C 82 (2022) 717)

3rd Model

- **Effective** photon, $Z\gamma$ and gluon couplings
- **Improves** the current best limit of $B_{\text{inv.}} < 0.145 \rightarrow B_{\text{inv.}} < 0.13$ limit from earlier search: arXiv:2202.07953
- Statistical and the systematic uncertainty contribute almost equally
  - exceptions are the κ_μ, $\kappa_{Z\gamma}$, κ_c and B_u where **statistical** uncertainty **dominates**



SM *p*-value (61%)

All measured coupling strength **modifiers are compatible** with their SM **predictions**

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SMEFT

- The strongest constraints can be found on coefficients which affect SM processes that are suppressed by small Yukawa couplings or include quantum loops.
- The operators corresponding to $c_{eH,22}, c_{eH,33}, c_{bH}$ are effectively modifiers for the Higgs Yukawa coupling to μ, τ, b quarks, respectively, while non-zero values of c_{Hq} would modify WH and ZH production.
- The eigenvectors $e^{[i]}_{\mathrm{ggF}}$ encapsulate changes to the ggF production and $e^{[i]}_{H\gamma\gamma,Z\gamma}$ could affect the $H \to \gamma\gamma$ and $H \to Z\gamma$ decays.

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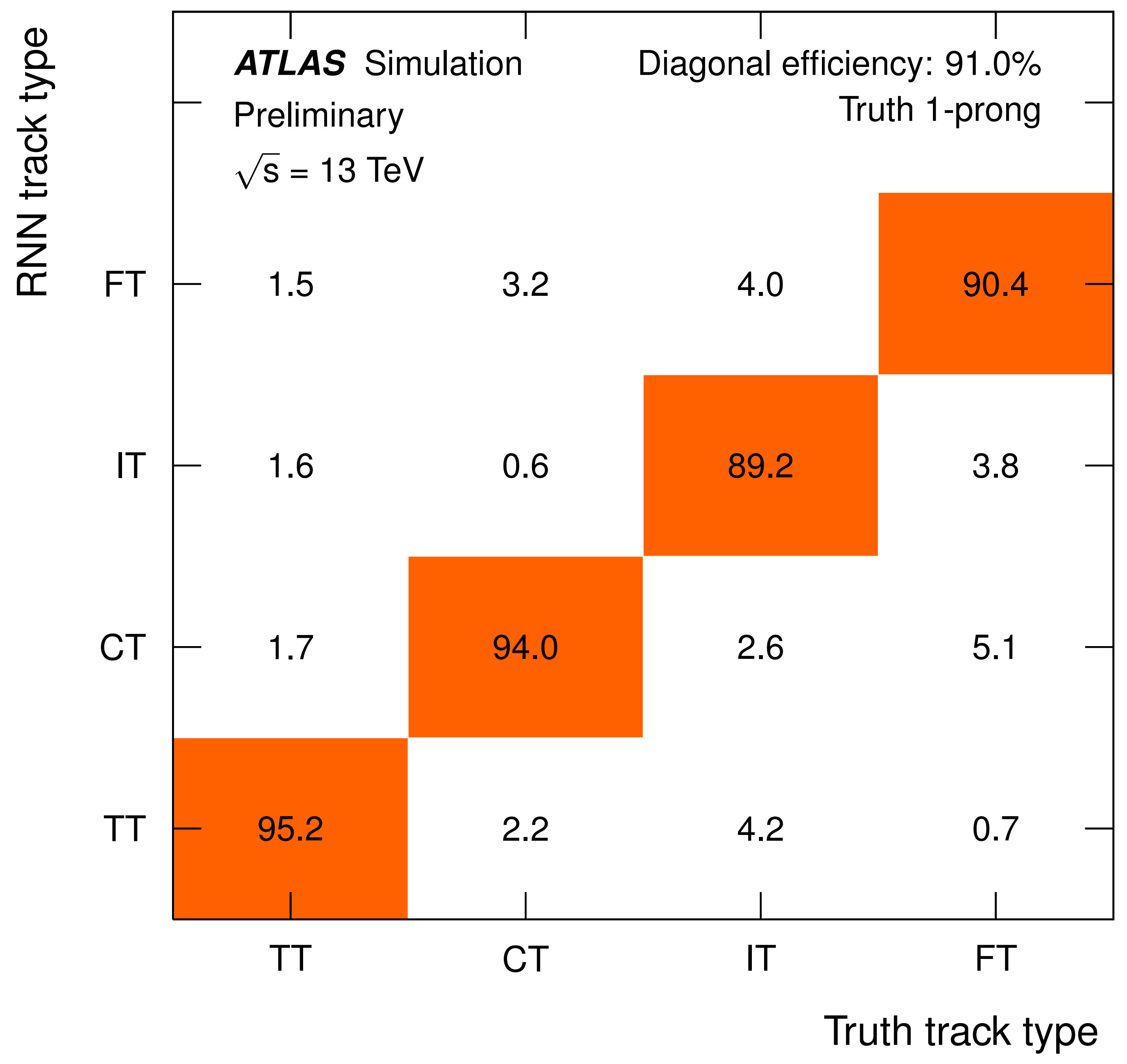
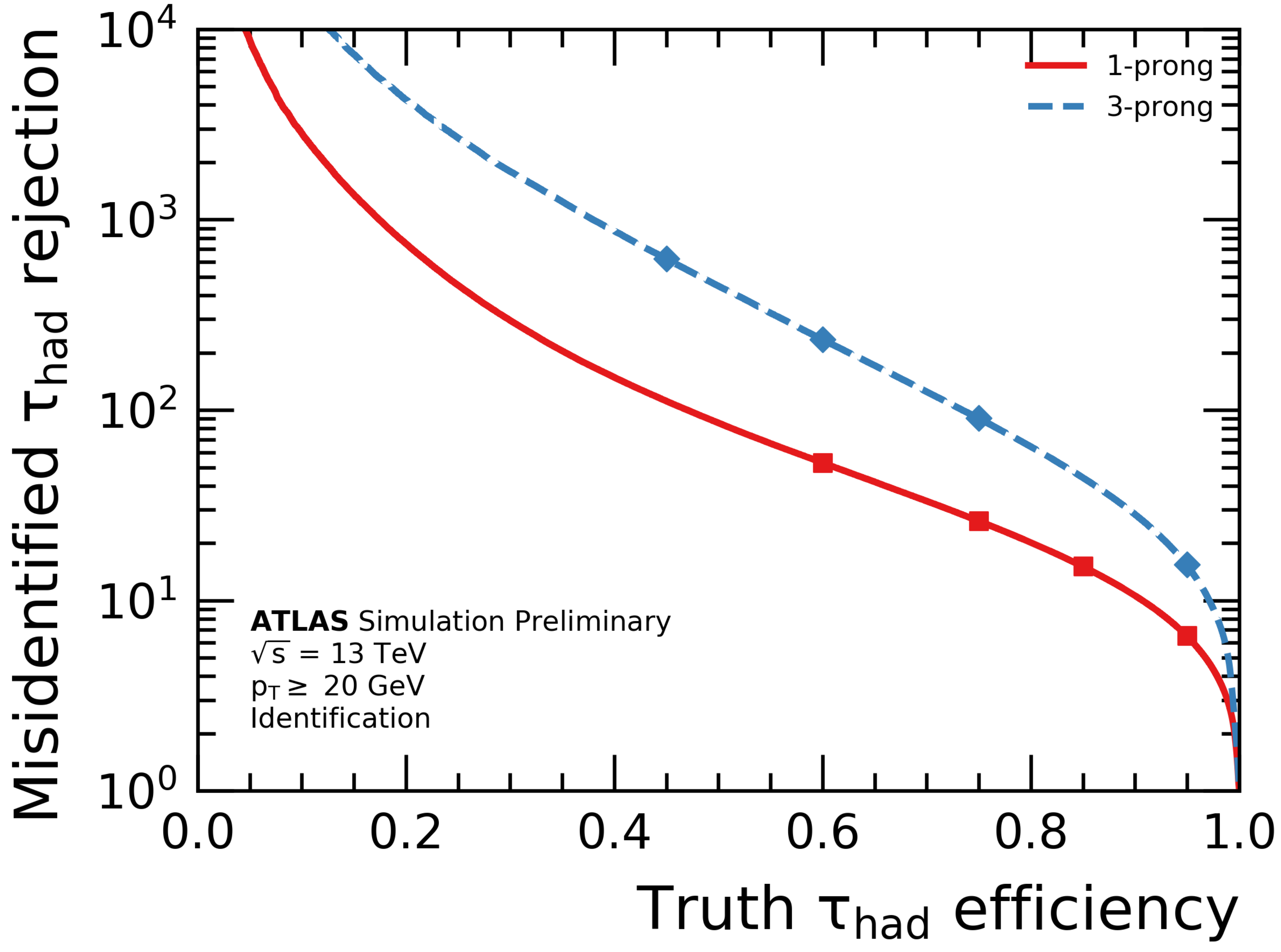
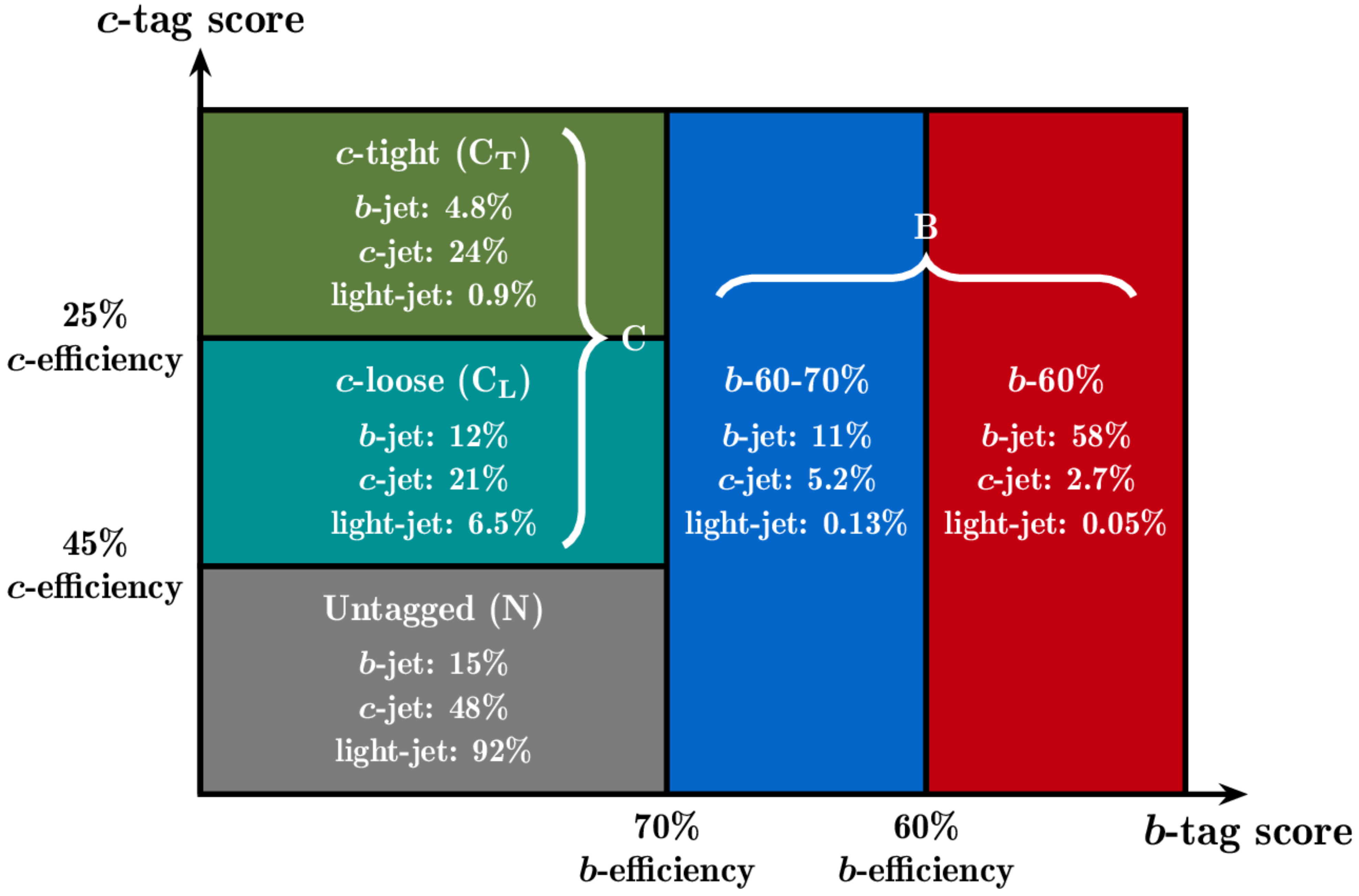
$H \to \tau\tau$ channel

- For Run 3 new algorithms have been developed to:
  - identify the τ production vertex
  - RNN to discriminate τ against jets and a separate one to veto electrons

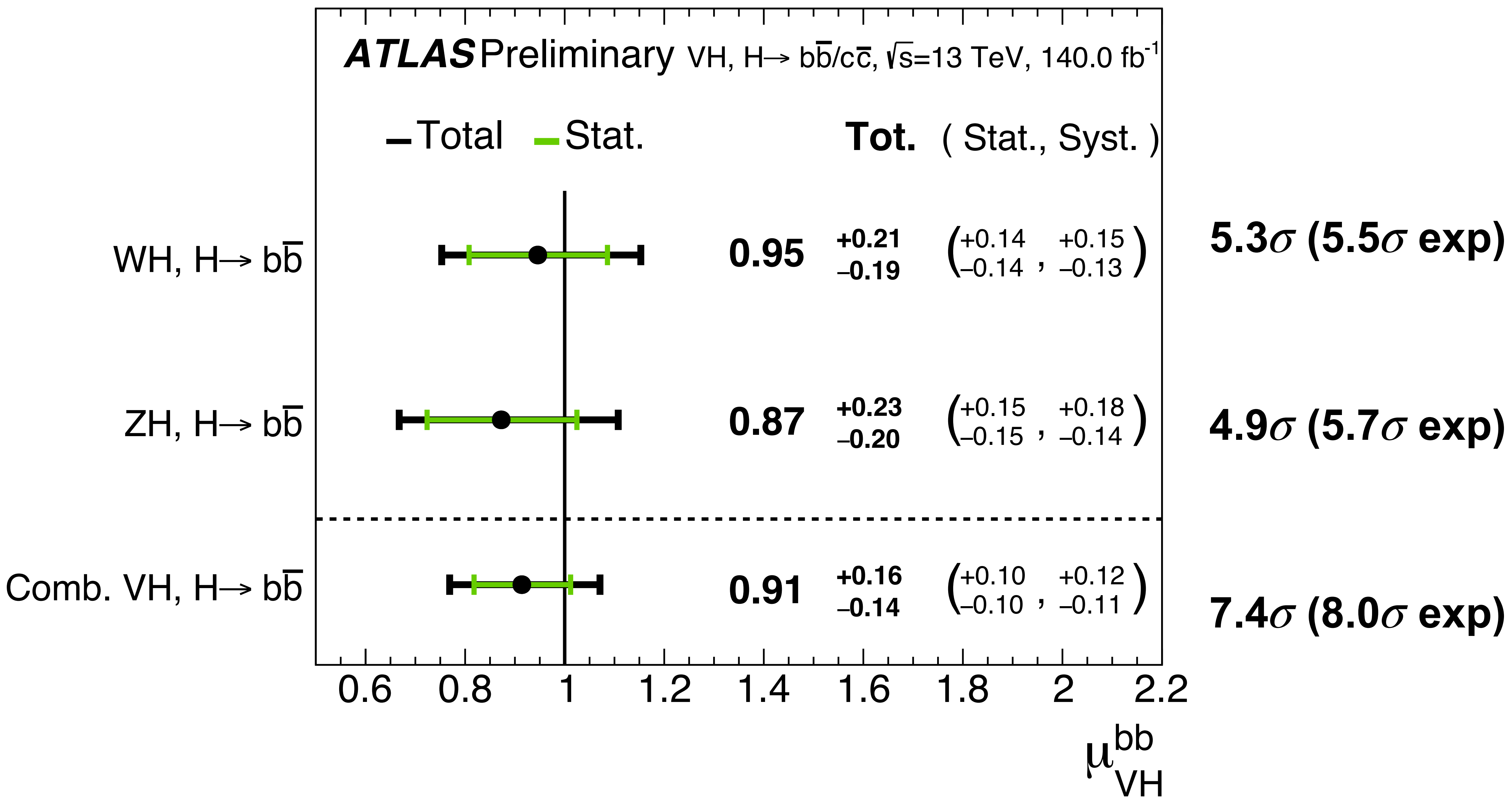




Legacy $V(\to \text{lep})H(\to b\bar{b}/c\bar{c})$



Schematic of the flavour tagging regions as used in the resolved regime. The efficiencies for the various jet flavours in the various regions are extracted from a simulated $t\bar{t}$ sample



The fitted values of the WH, $H \to b\bar{b}$ and ZH, $H \to b\bar{b}$ signal strengths, along with their combination along with the significance

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