Search for Higgs-pair production in ATLAS experiment

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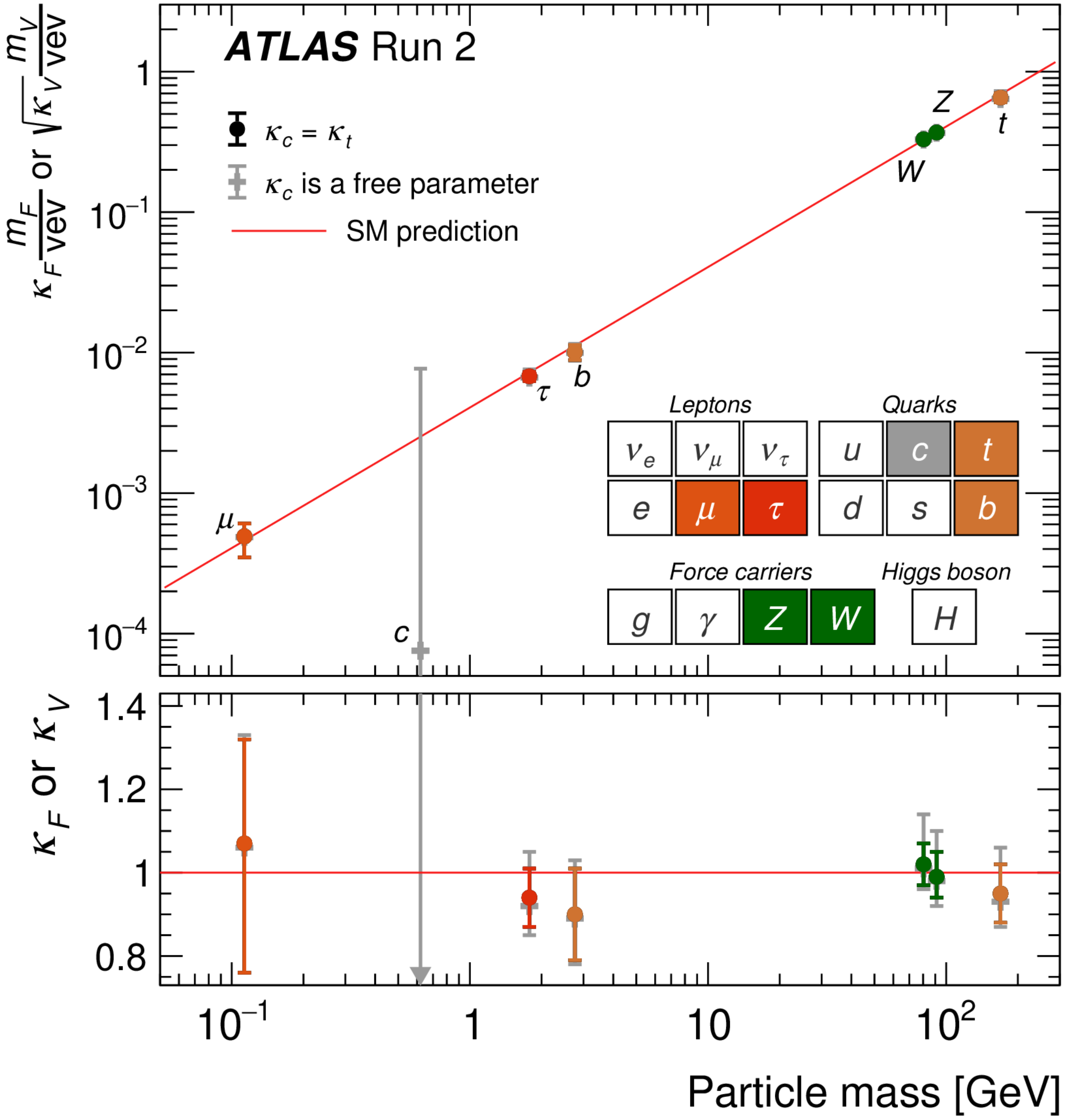
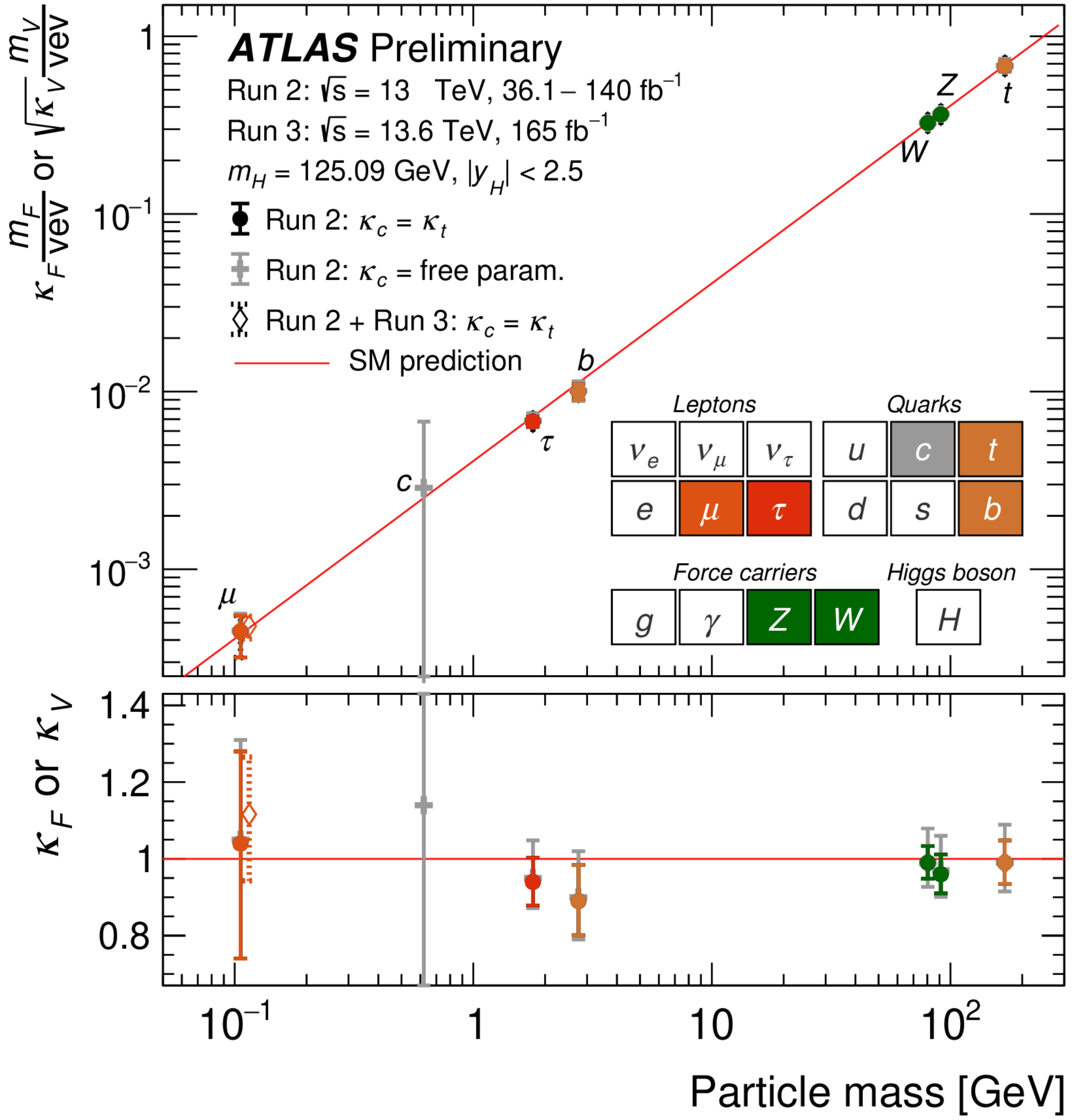
BPCS 2025, 25—29 September 2025

Higgs coupling measurement updates

Nature 607 (2022) 52



ATLAS-CONF-2025-006



All the measurements are in good agreement with the Standard Model prediction!

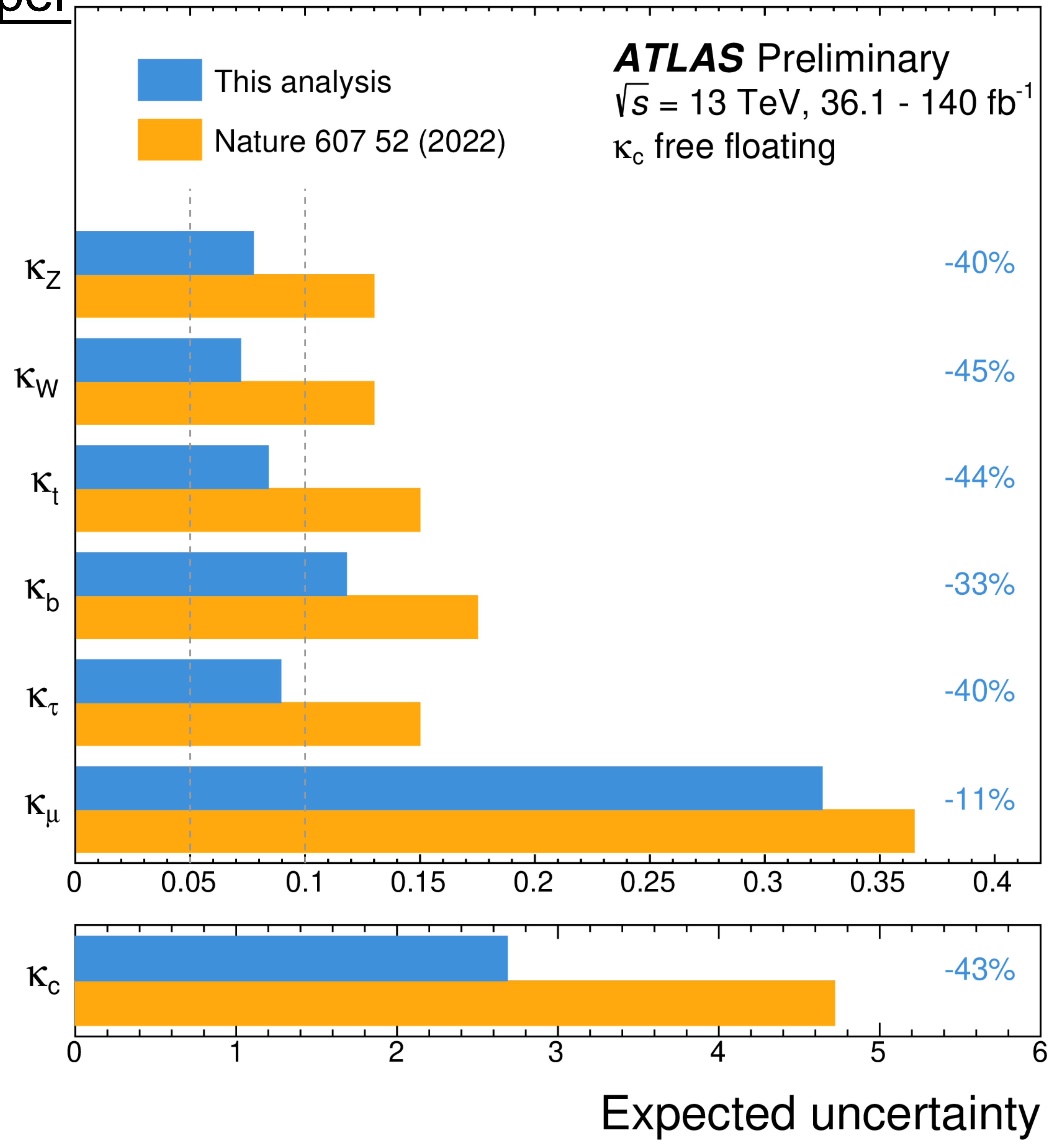
Higgs coupling measurement updates

ATLAS-CONF-2025-006

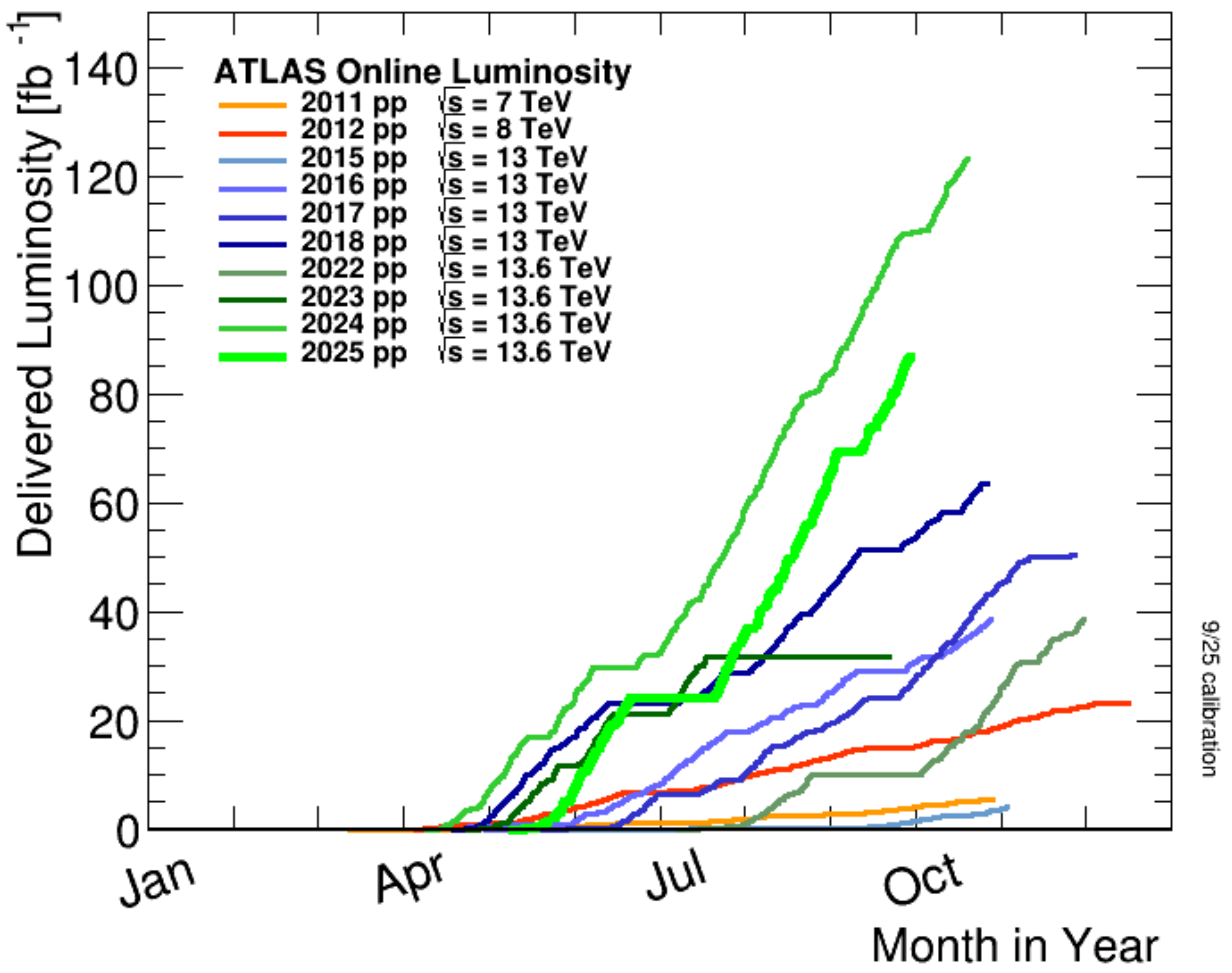
- **Precision improved inclusively 10%** from Nature 607 (2022) 52 paper
  - Added new measurements: ttHbb, VH(bb,cc), $H\tau\tau$,
- **Main improvements:**
  - WH/ZH precision improved by 30/20% (new VHbb)
  - ttH+tH precision improved by 25% (new ttHbb)
- **Higgs inclusive signal strength** $\mu = 1.023^{+0.056}_{-0.053}$, uncertainty:

$$0.028\ (\text{stat.})\ {}^{+0.026}_{-0.025}\ (\text{exp.})\ {}^{+0.039}_{-0.036}\ (\text{sig. theo.})\ \pm 0.012\ (\text{bkg. theo.})$$

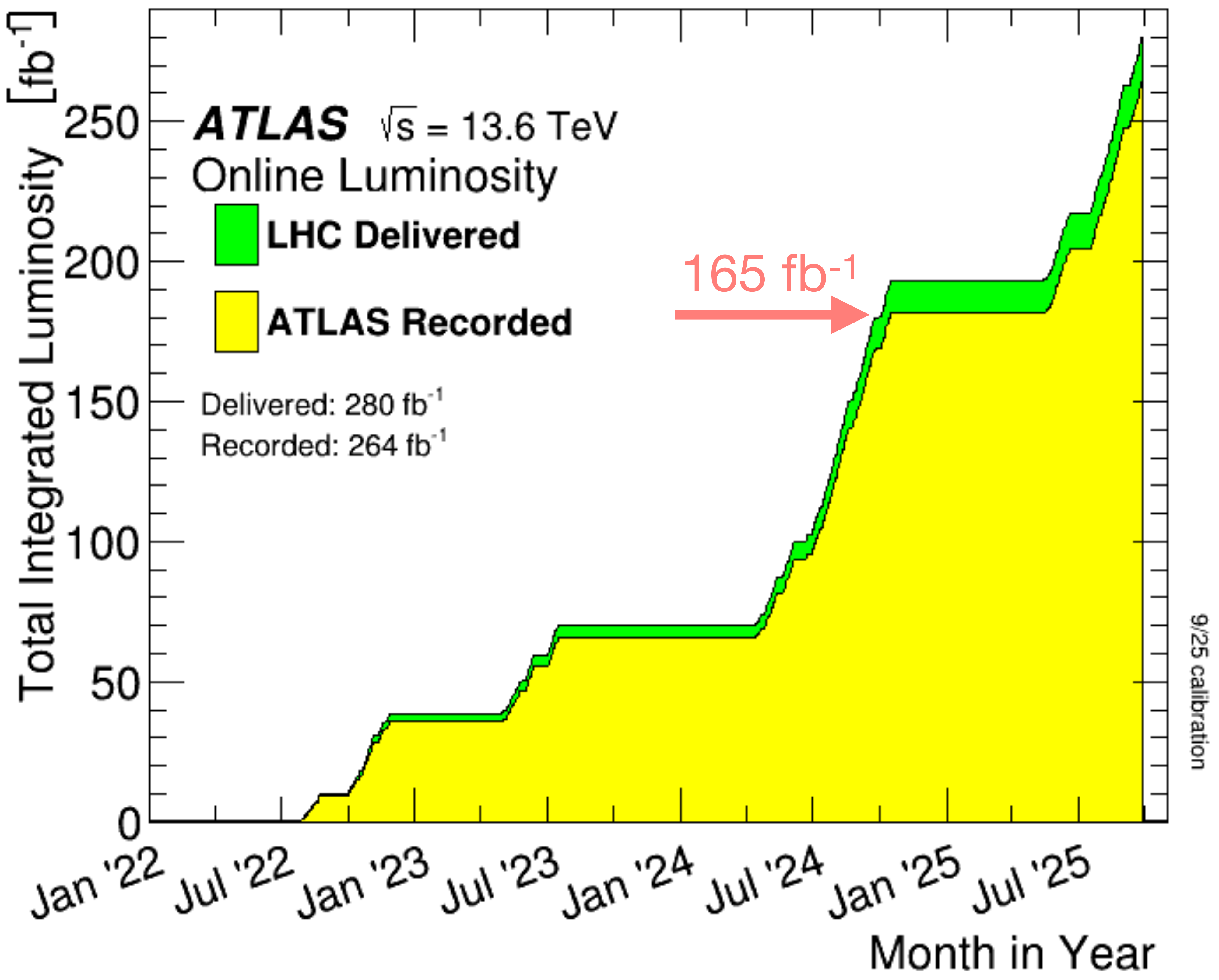
- **Improvement on charm coupling modifier (κ_c) by 43%.**



ATLAS Run 2 and Run 3 datasets



Run 3 integrated luminosity

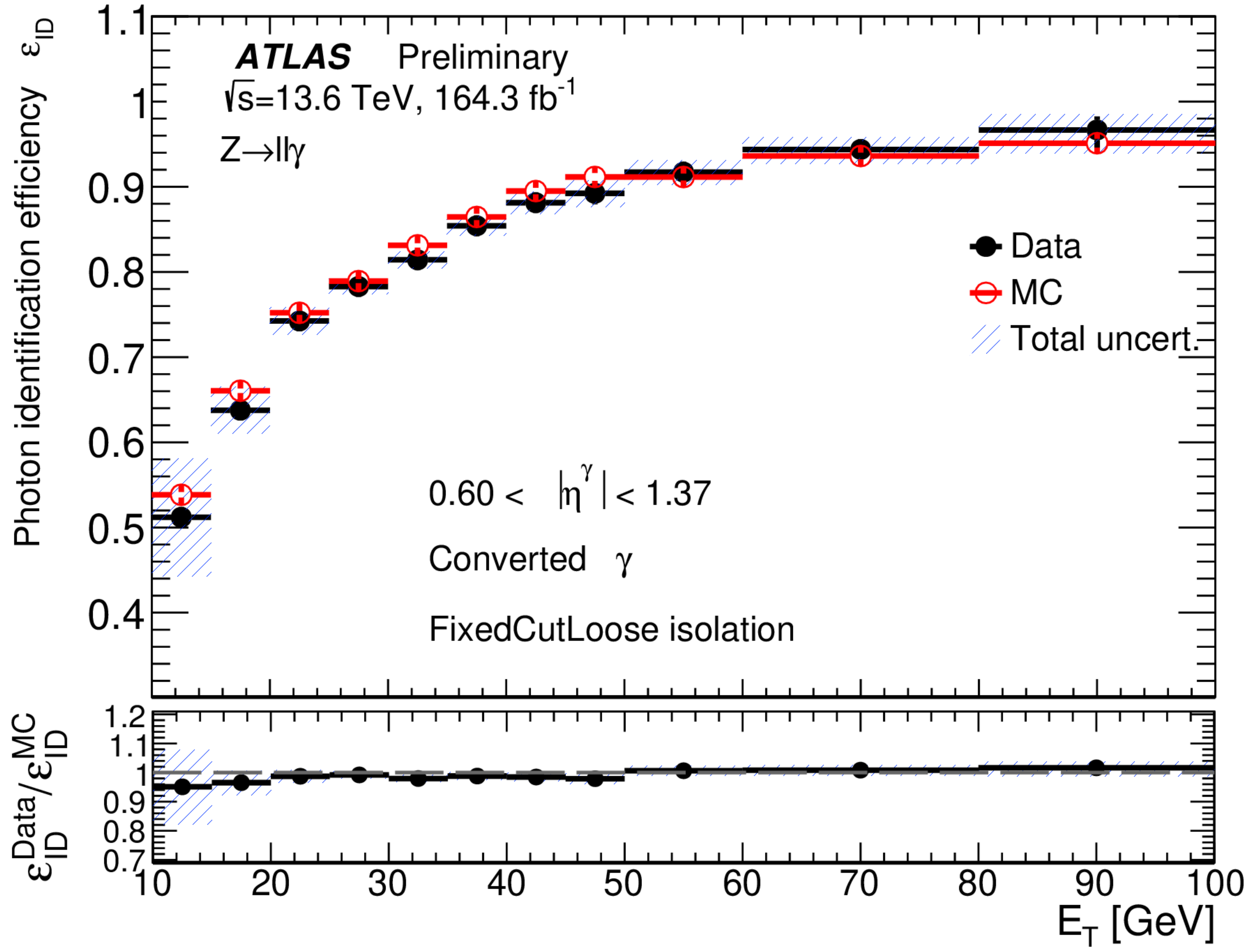


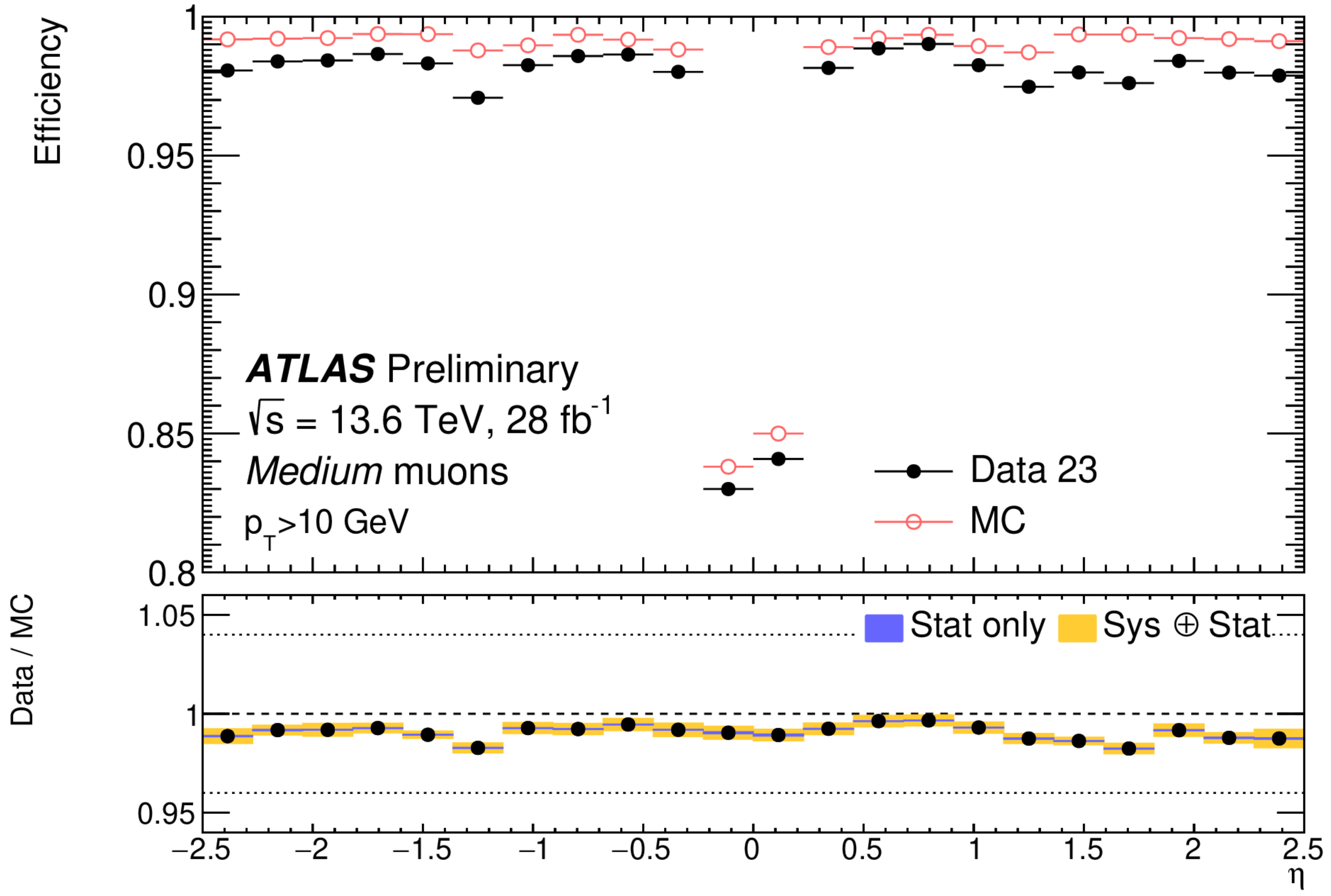
- **Recent results update with totaling up ~ 305 fb^{-1} integrated luminosity**
  - 140 fb^{-1} of Run 2 data and up to 165 fb^{-1} (by end of 2024) of Run 3 data

➔ Thanks to the accelerator and technical teams for excellent LHC operation!

Physics object performance updated with Run 3 dataset

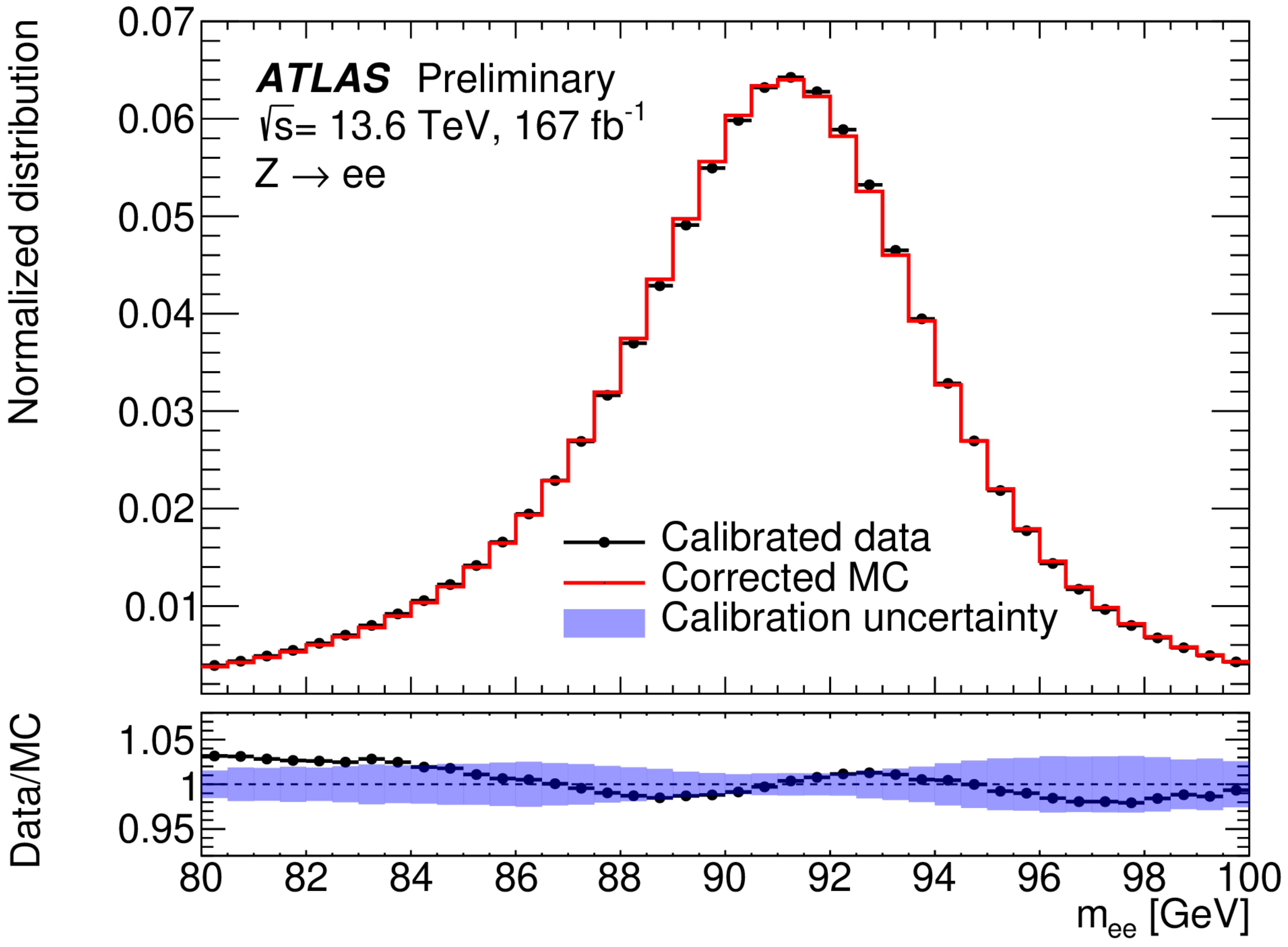
- **The high-quality physics results rely on excellent performance of physics objects**
  - γ identification: 50% – 95% efficiency measured with photons from radiative $Z\rightarrow ll\gamma$ decays
  - μ identification: > 95% efficiency measured with muons from $Z\rightarrow\mu\mu$ with 28 fb^{-1}

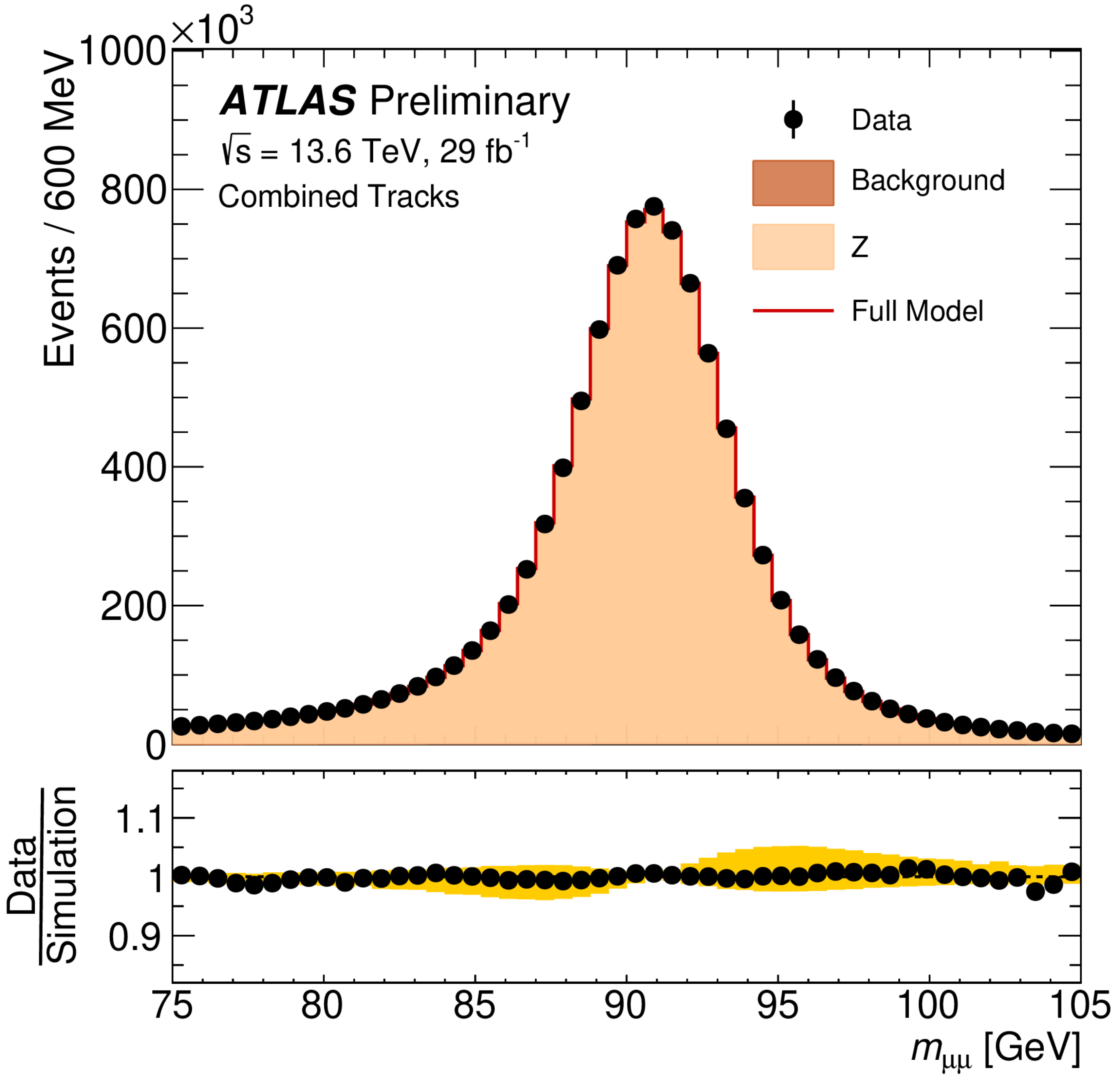




Physics object performance updated with Run 3 dataset

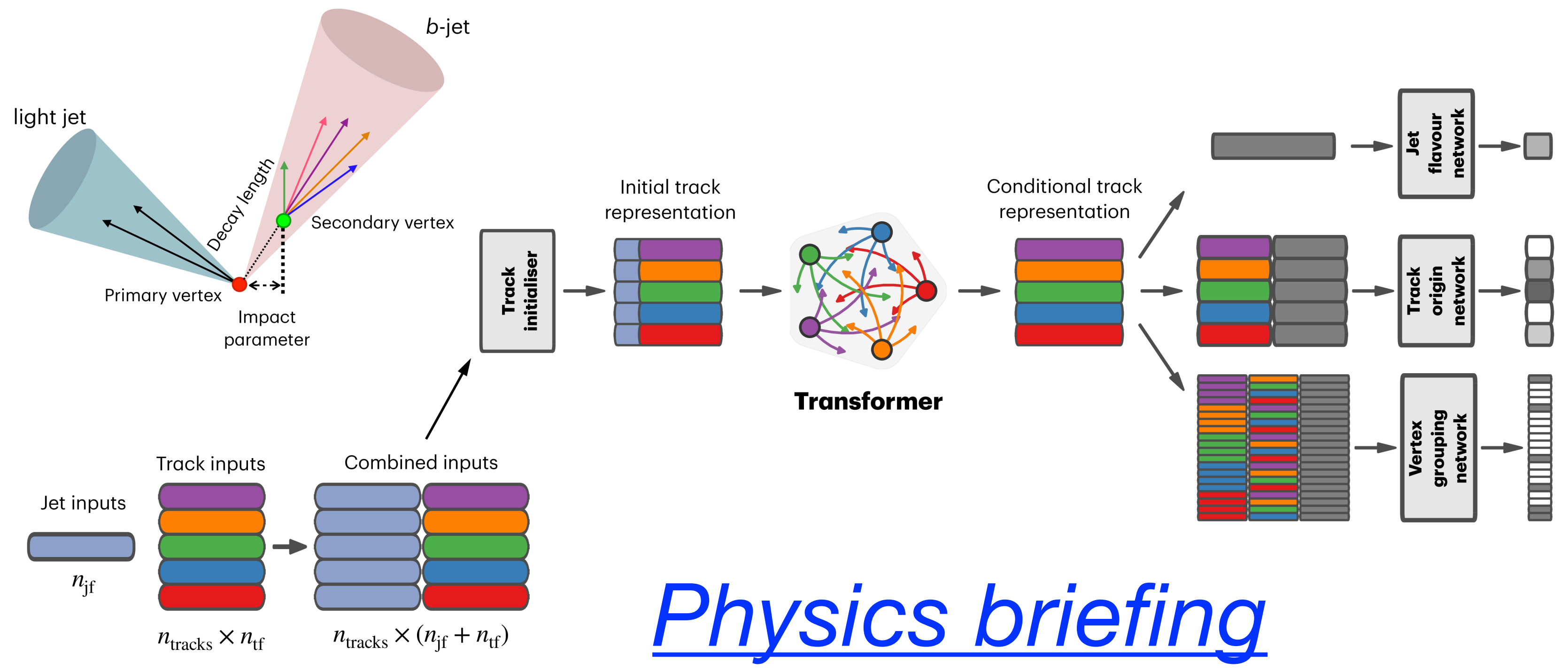
- **The high-quality physics results rely on excellent performance of physics objects**
  - e/γ energy calibration: calibration uncertainty < 3% vs m_{ee}, updated with 167 fb^{-1}
  - μ energy calibration: calibration uncertainty < 5% vs $m_{\mu\mu}$, updated with 29 fb^{-1}



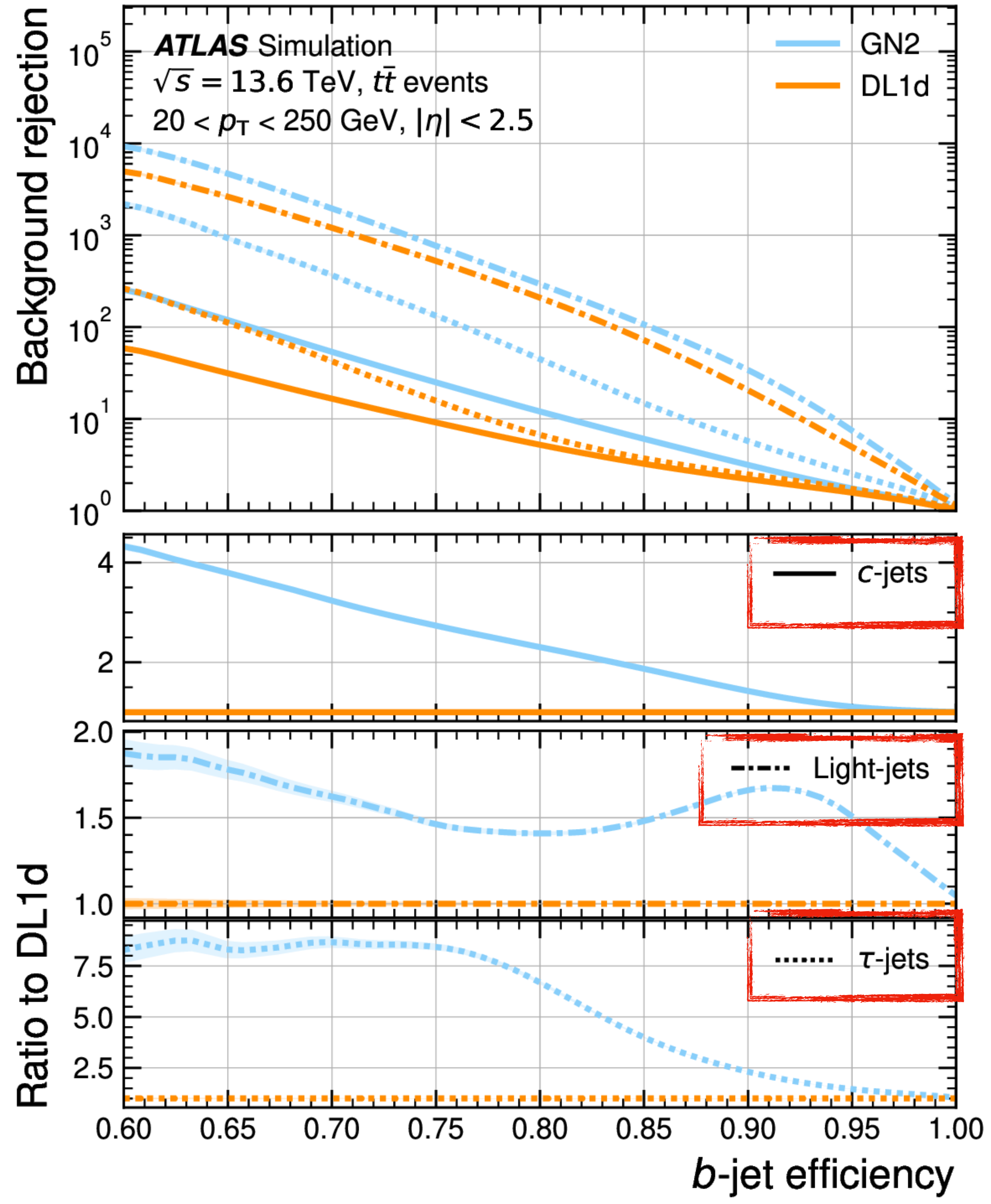


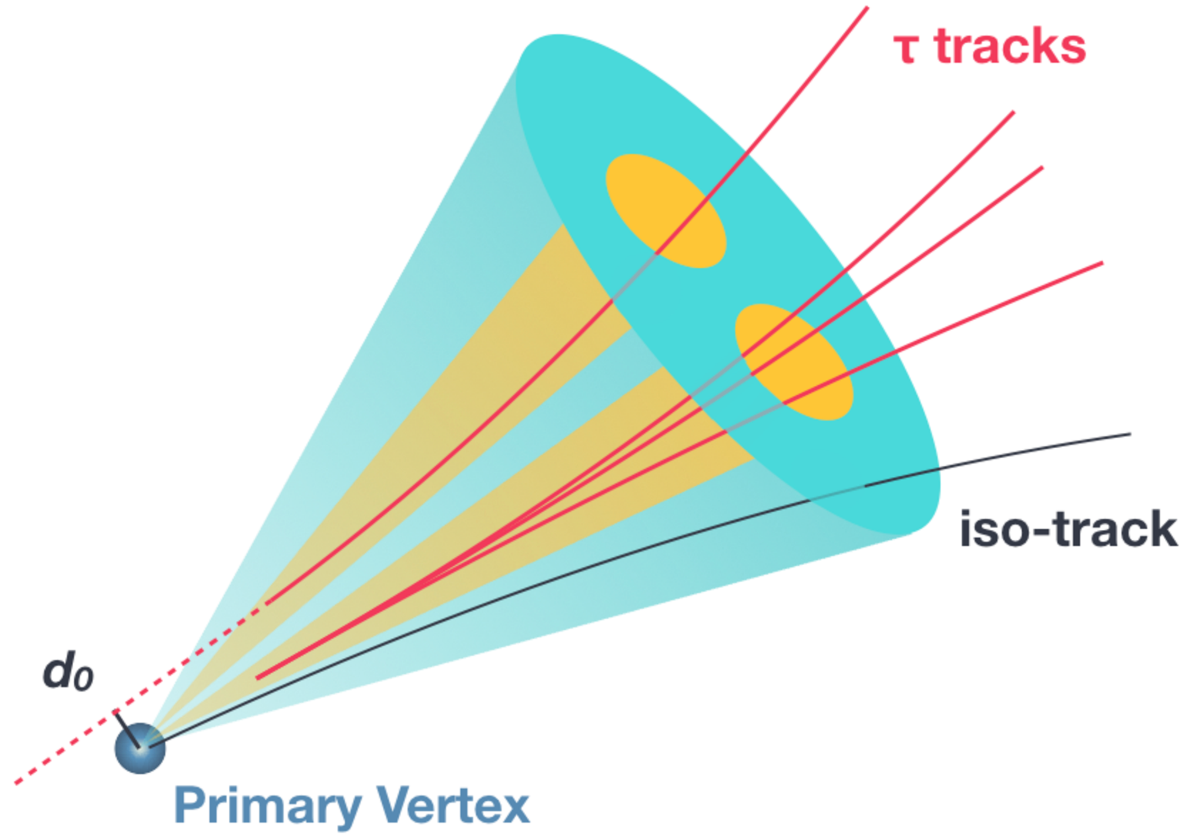
Improvements in Flavor Tagging and Collimated τ-pair in Run 3

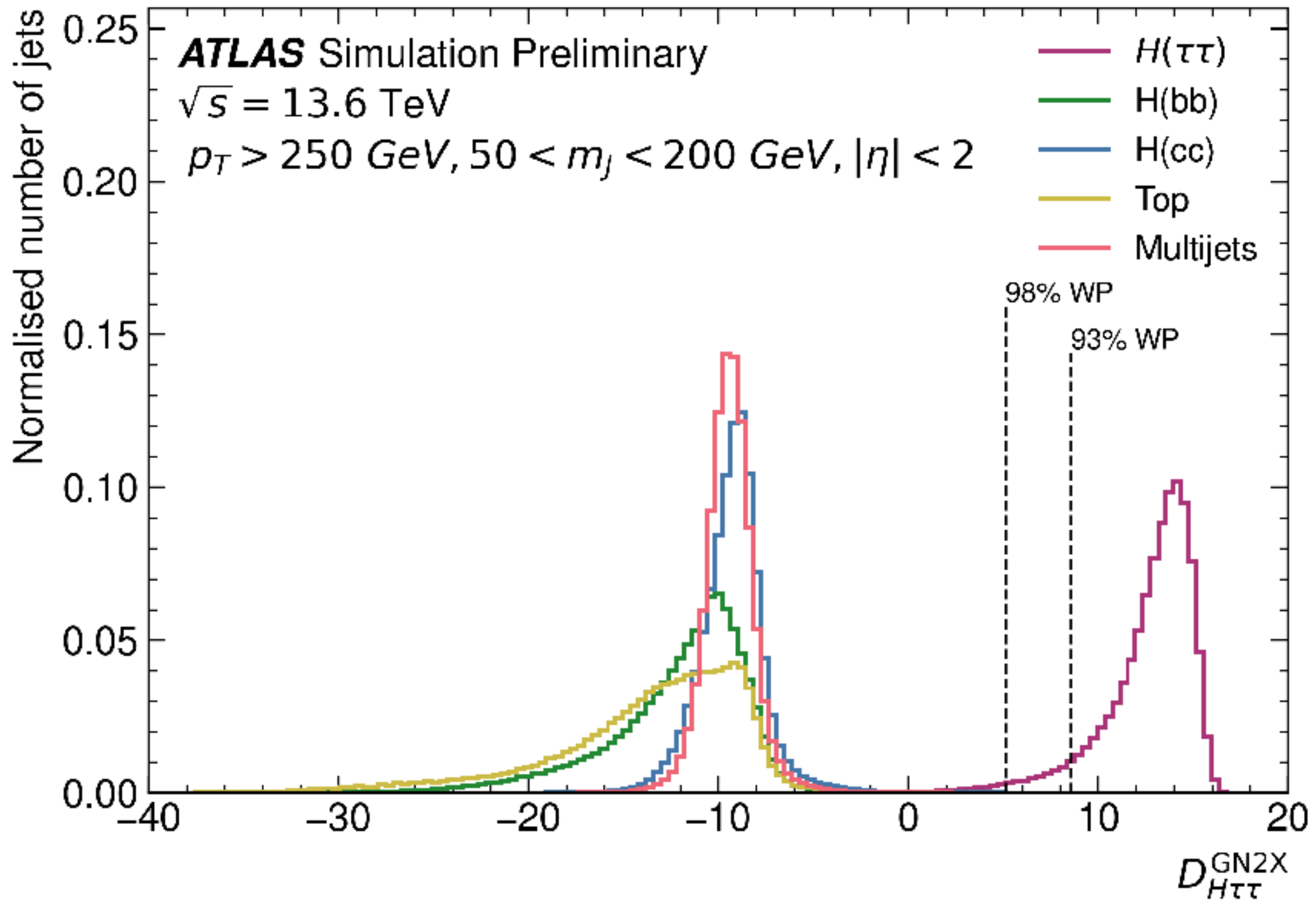
- **Traditional approach (DL1r)**: low-level quantities based on tracks followed by high-level multivariate classifiers
- **New approach (GN2)**: directly process track and jet information. In addition to the primary training target (jet flavor prediction) auxiliary training objectives are introduced to reconstruct the internal structure of a jet by grouping tracks originating from a common vertex
- **Transformer Neural Networks** improves boosted Higgs to collimated hadronic τ-leptons: 98% efficiency for $H\tau\tau$ identification, 10^4 of bkg. rejections



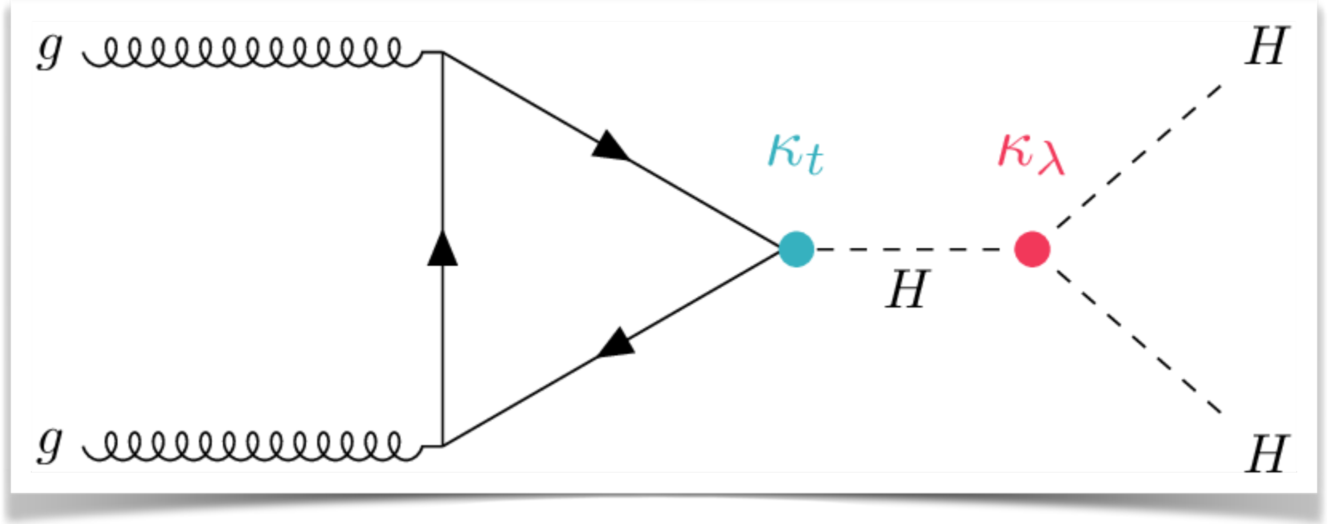
Physics briefing

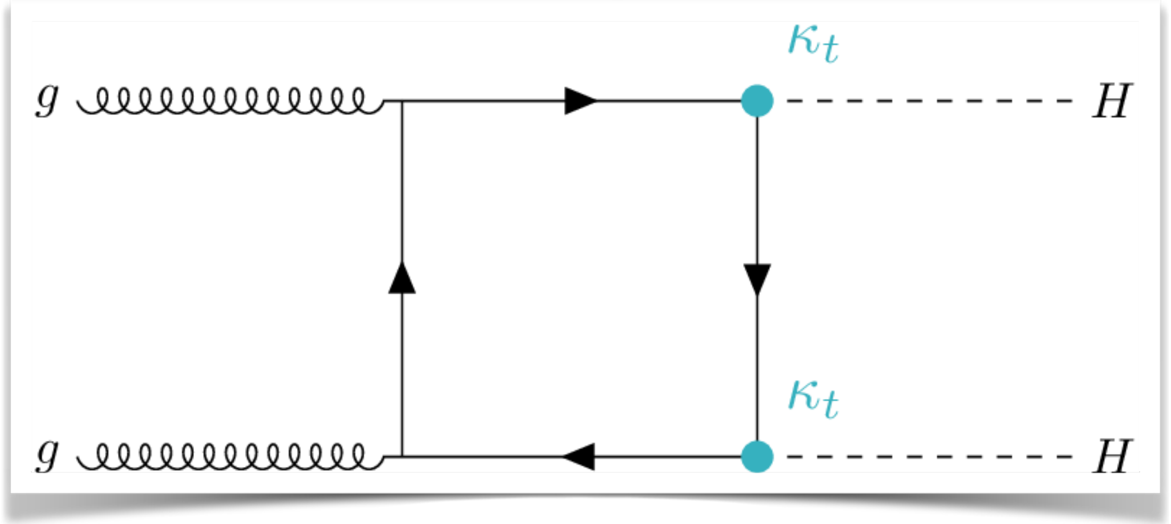




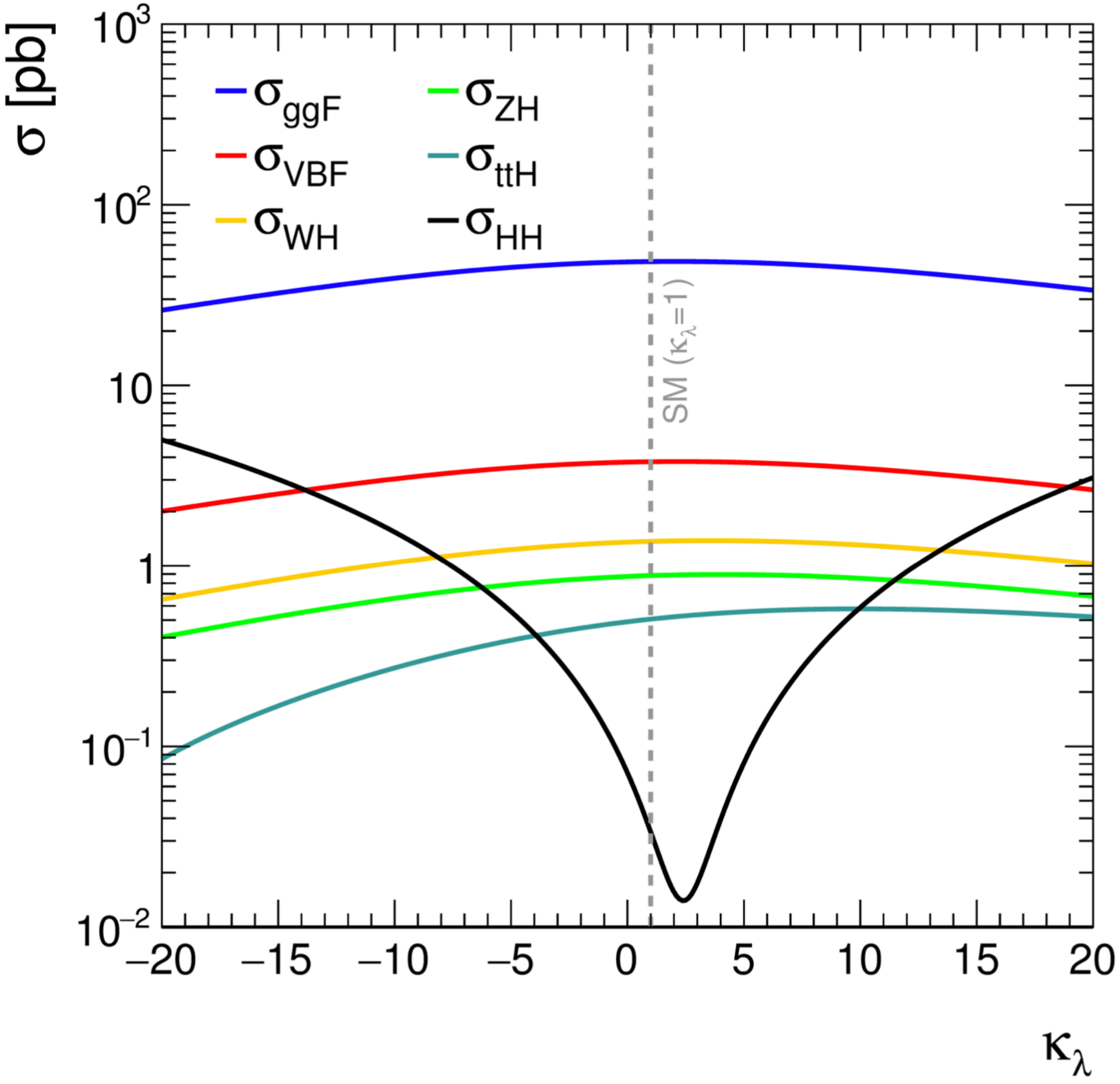


Motivation for the Higgs pair production





- **Higgs pair (HH) production is a rare process**
  - Direct access of the Higgs self-coupling (κ_λ)
  - 32.8 fb @ NNLO at 13 TeV ➔ not observed yet
- **Many BSM models enhance HH production rate**
  - 2HDMs, hMSSM, xSM-singlet, EWK-singlet etc.
- **LHC + HL-LHC is unique factory for HH search**
  - Energy frontier: $\sqrt{s} = 7/8/13/13.6\ TeV$
  - Expected luminosity in Run 3 and HL-LHC: 350fb^{-1} / 3ab^{-1}



The Higgs pair decay signatures

Di-Higgs decay branching ratios

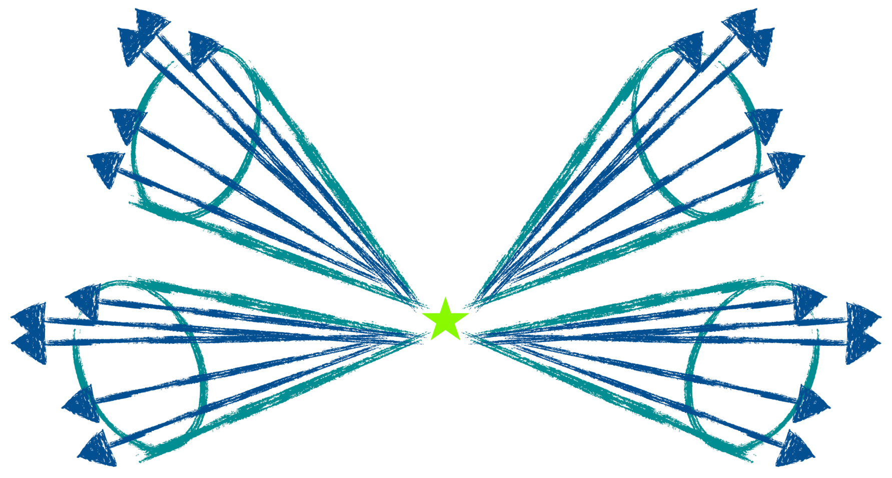
rarer →

↓ rarer

	bb	WW	gg	ττ	cc	ZZ	γγ	Zγ	μμ
bb	33%								
WW	25%	4.6%							
gg									
ττ	7.4%								
cc									
ZZ	3.1%								
γγ	0.26%	0.1%							
Zγ									
μμ									

There are also bb$\ell\ell$+E_T^{miss}, multilepton channels

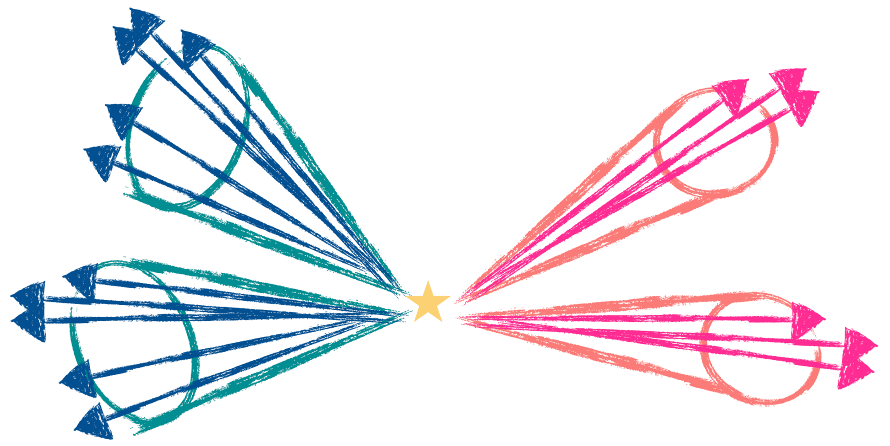
- Relatively large branching ratios
- Complexity in the final states



Picture from E. Brost

HH→4b

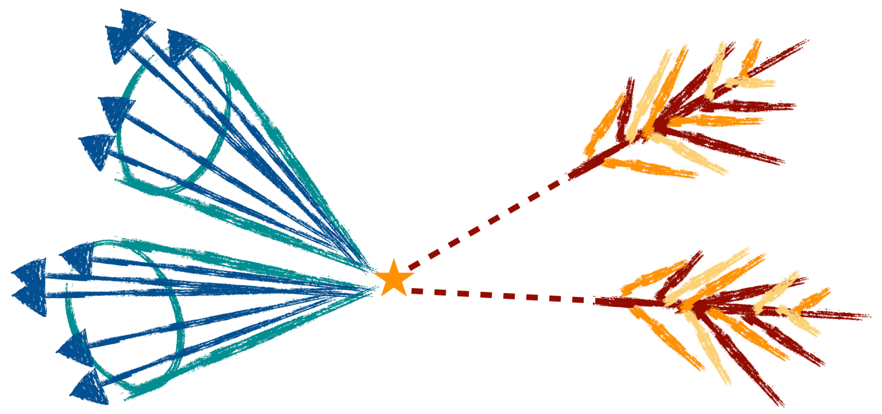
- The highest branching ratio
- Huge QCD multi-jet background



Picture from E. Brost

HH→bb$\tau\tau$

- Relatively large BR
- Cleaner final state



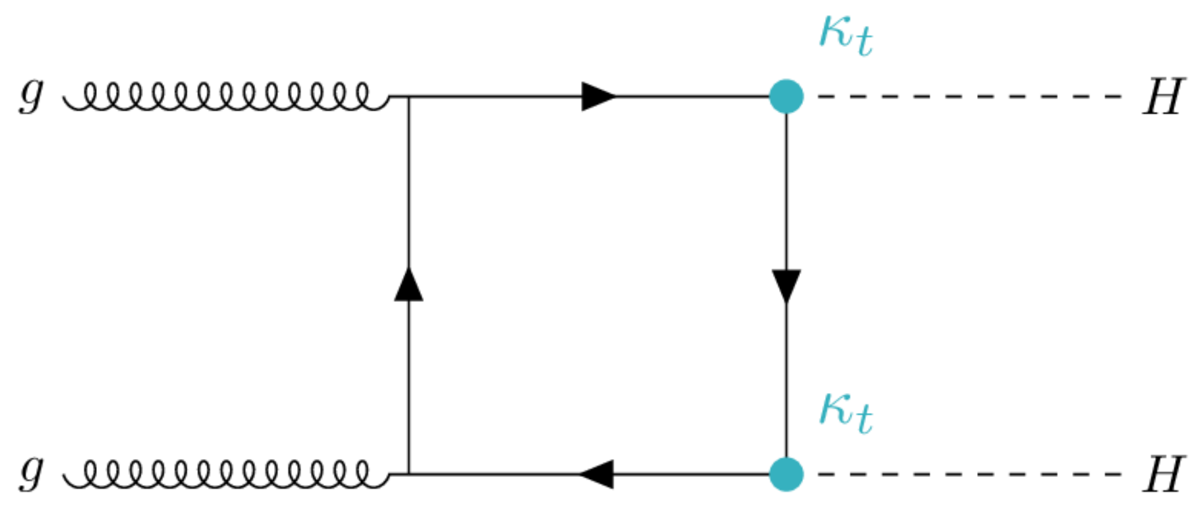
Picture from E. Brost

HH→bb$\gamma\gamma$

- Small branching ratio
- Narrow H→$\gamma\gamma$ peak atop continuum background

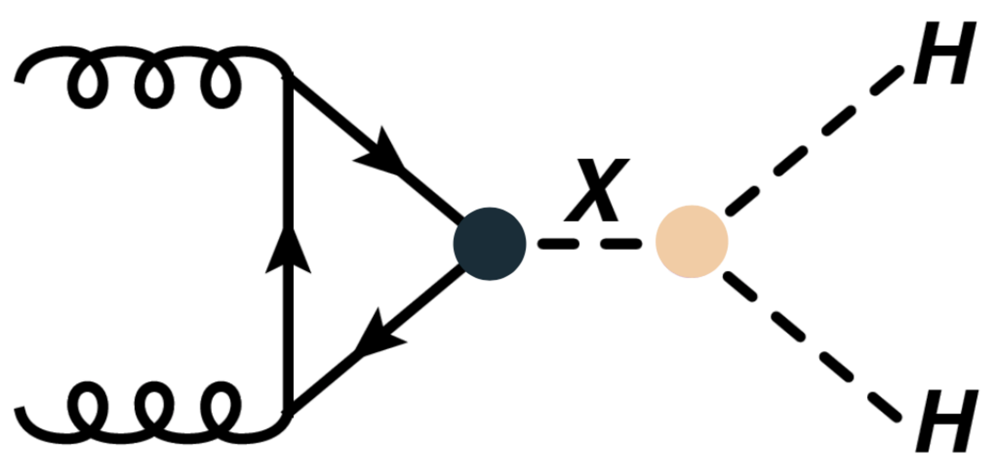
The Higgs pair event reconstruction

Non-resonant HH production

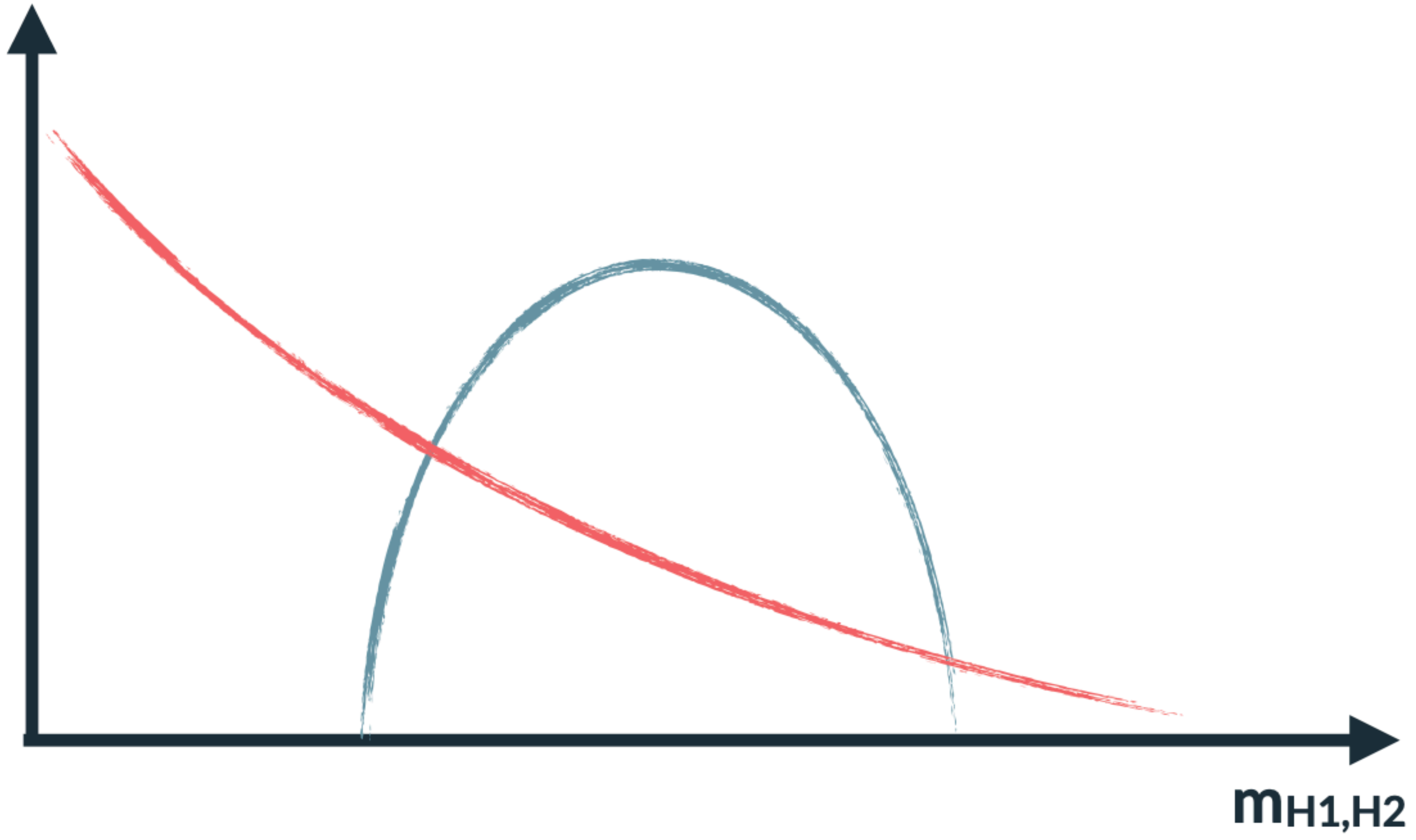


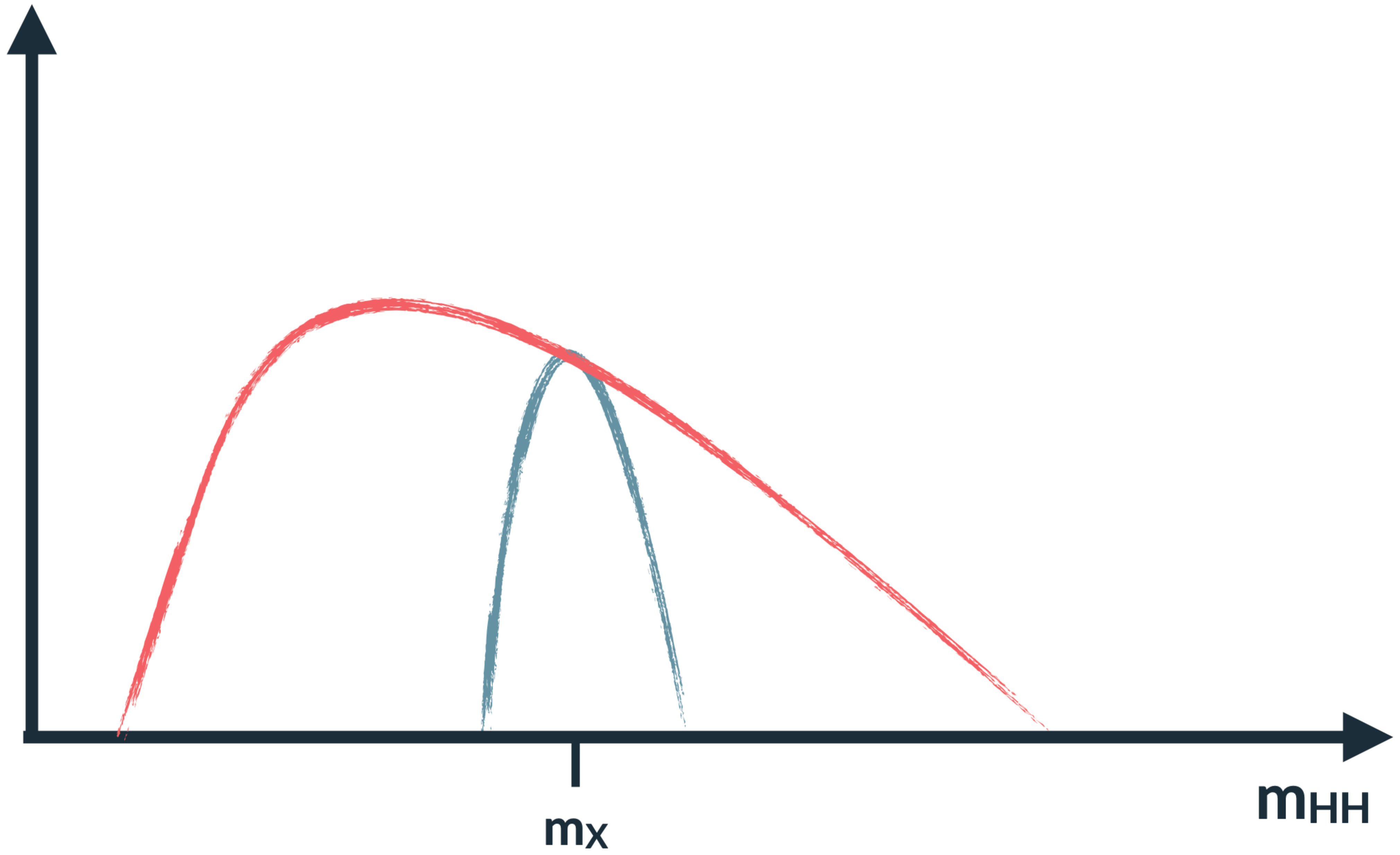
Single Higgs can be reconstructed, from $\gamma\gamma$, $\tau\tau$ or bb

Resonant HH production



Di-Higgs invariant mass m_{HH} reconstruction from 4-body decay products



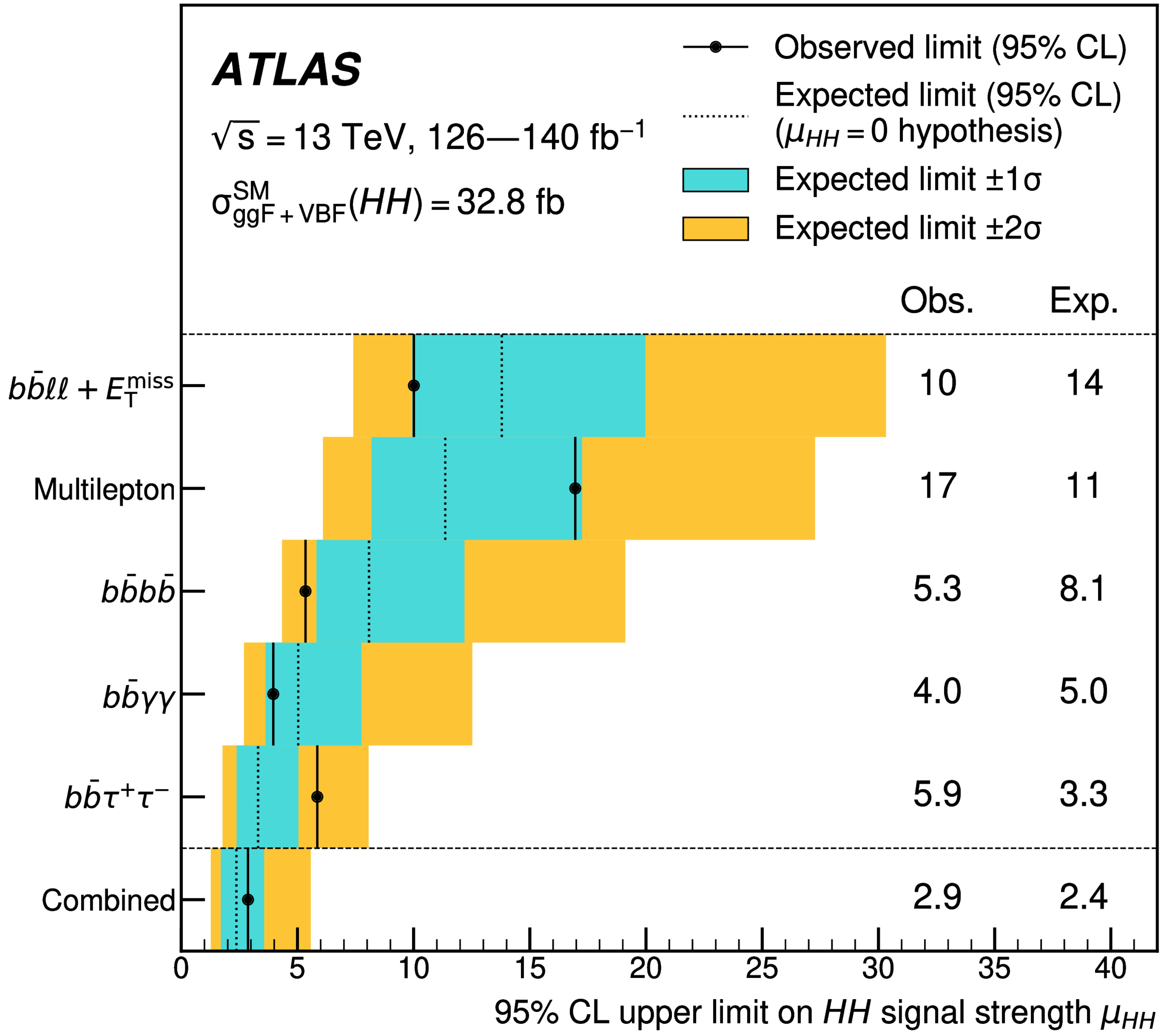


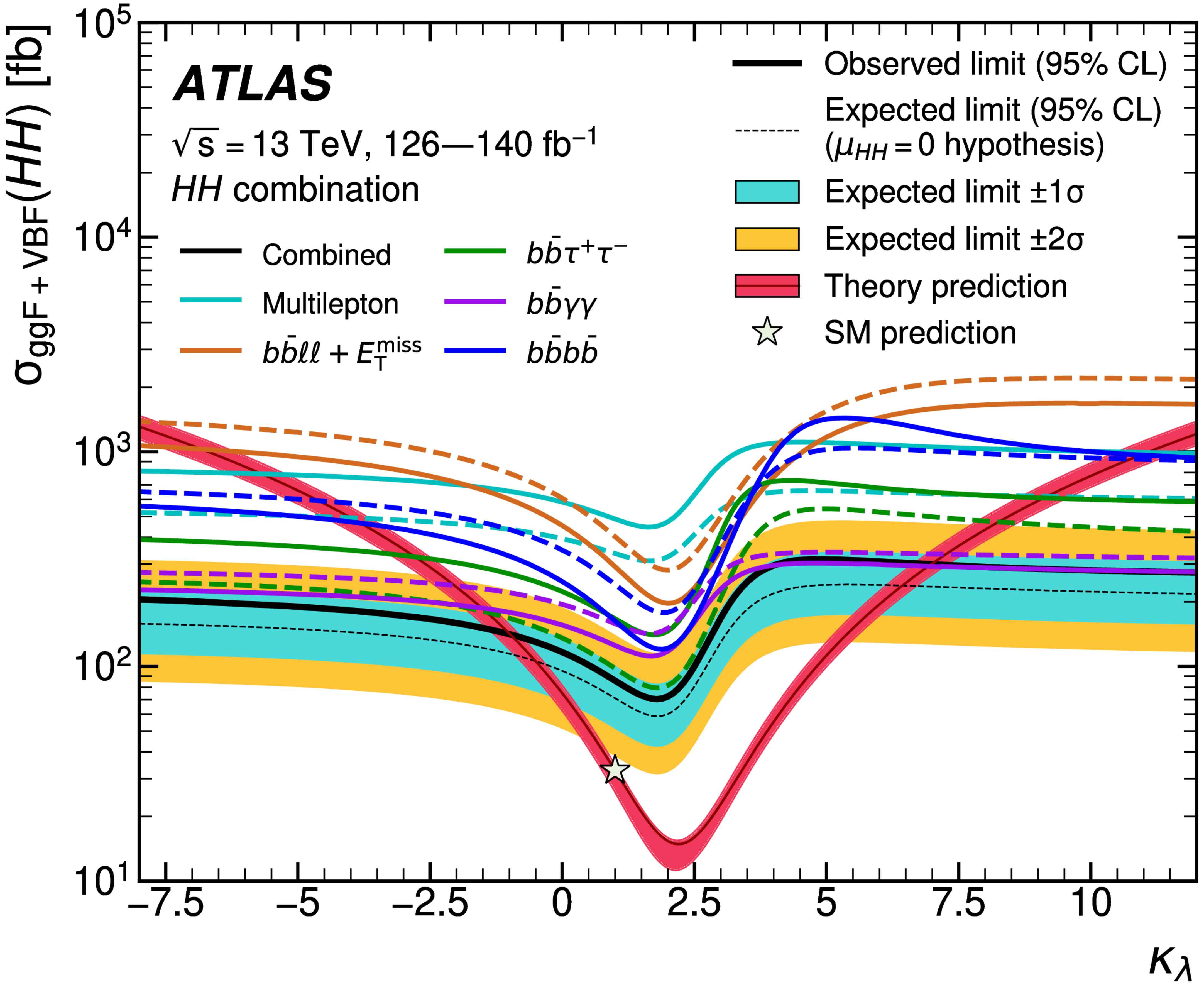
Then, multi-variate discriminator is employed to enhance analysis sensitivity!

Non-resonant HH search updates

Combination of non-resonant HH in Run2 (140fb^{-1})

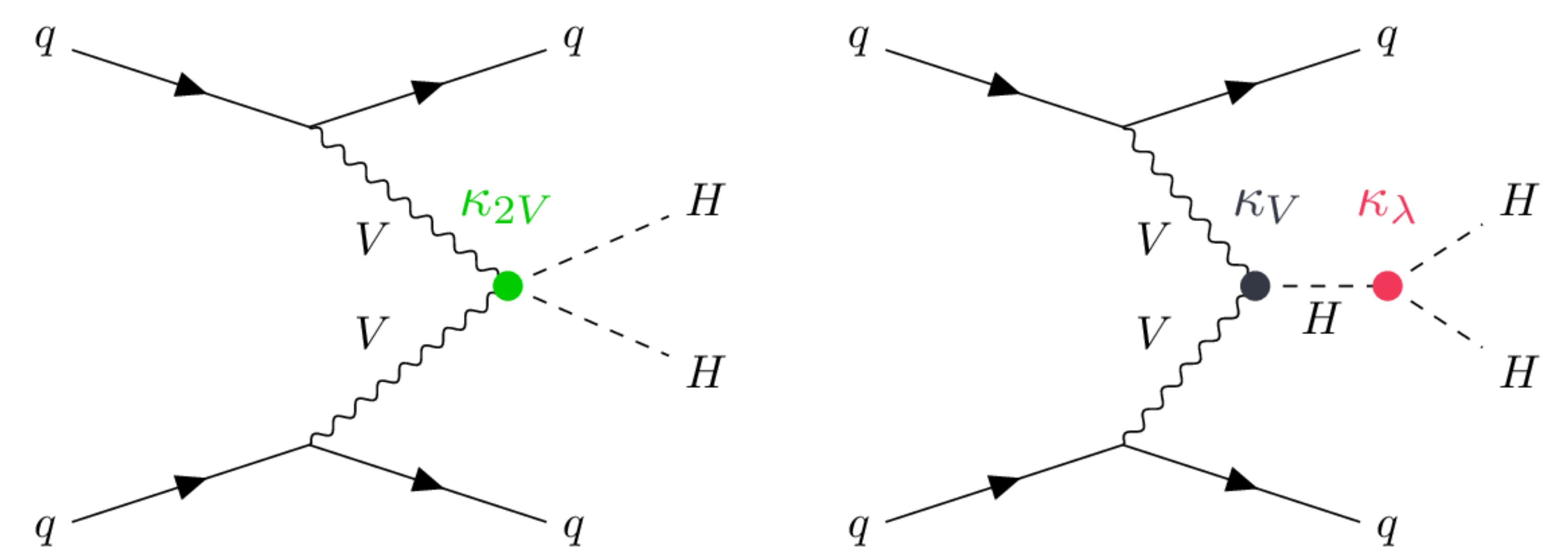
- **95% CL upper limit on μ_{HH} is 2.9, and 2.4 (3.4) if expected SM HH exist (absent)!**
- **The measured HH production signal strength:** $\mu_{HH} = 0.5^{+1.2}_{-1.0} = 0.5^{+0.9}_{-0.8}(\text{stat})^{+0.7}_{-0.6}(\text{syst})$
- **The best fit value of $\kappa_\lambda = 3.8^{+2.1}_{-3.6}$, compatible with the SM prediction**

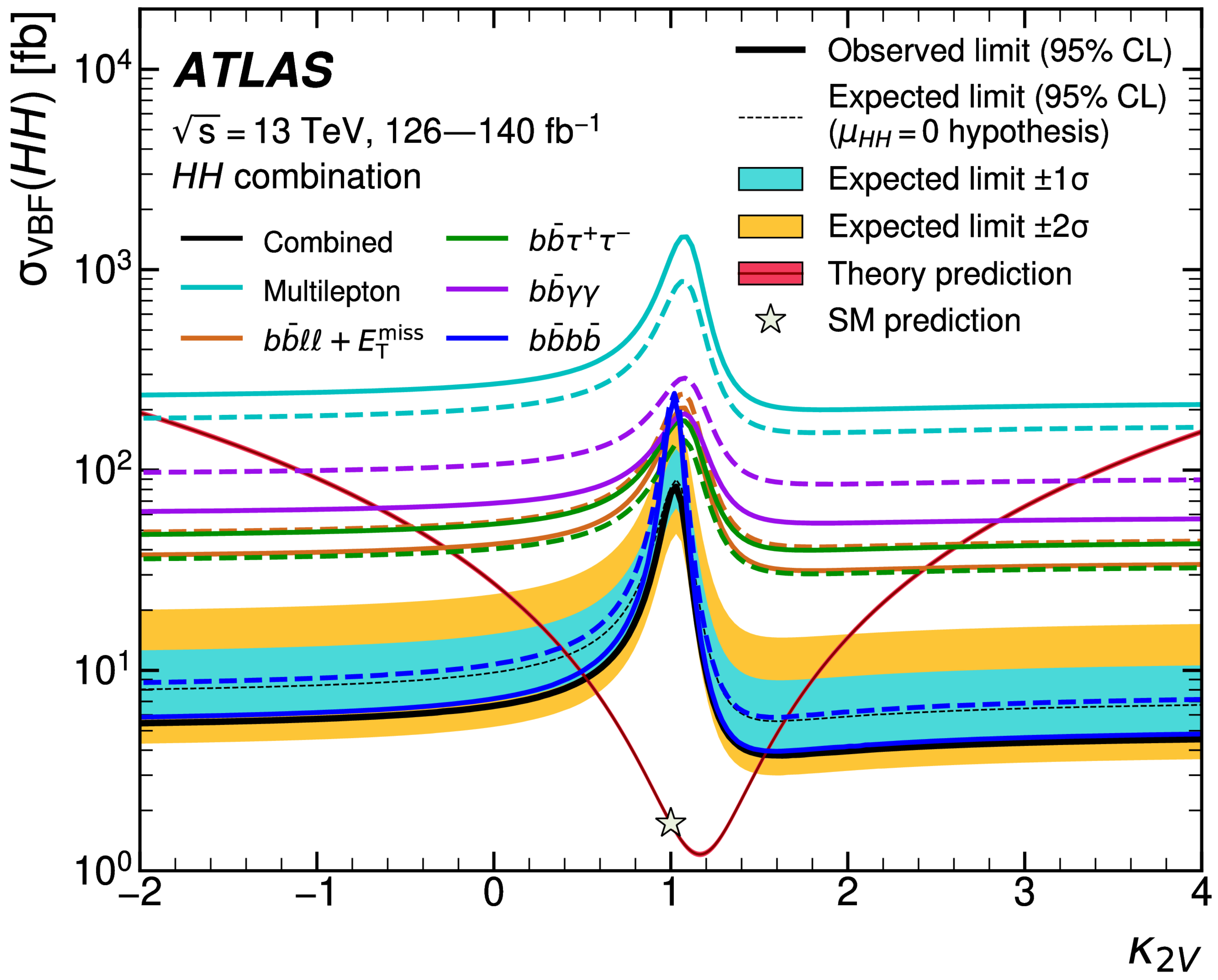


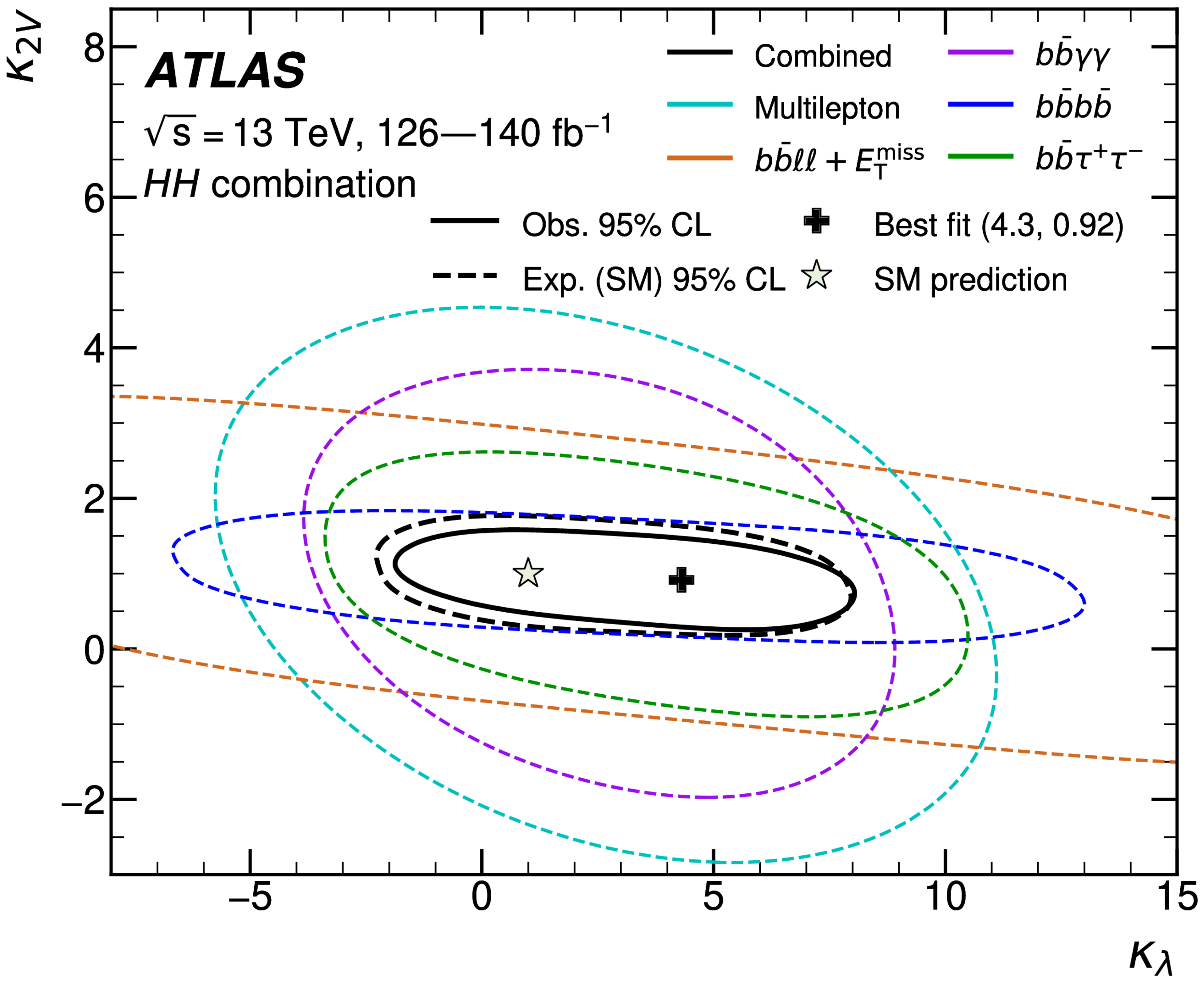


Combination of non-resonant HH in Run2 (140fb-1)

- **VBF HH production is also sensitive to HHVV coupling strength κ_{2V}**
- **95% CL upper limit on κ_{2V}: $0.6 < \kappa_{\lambda} < 1.5$.**
- **The observed best-fitted value is $\kappa_{2V} = 1.02^{+0.22}_{-0.23}$**

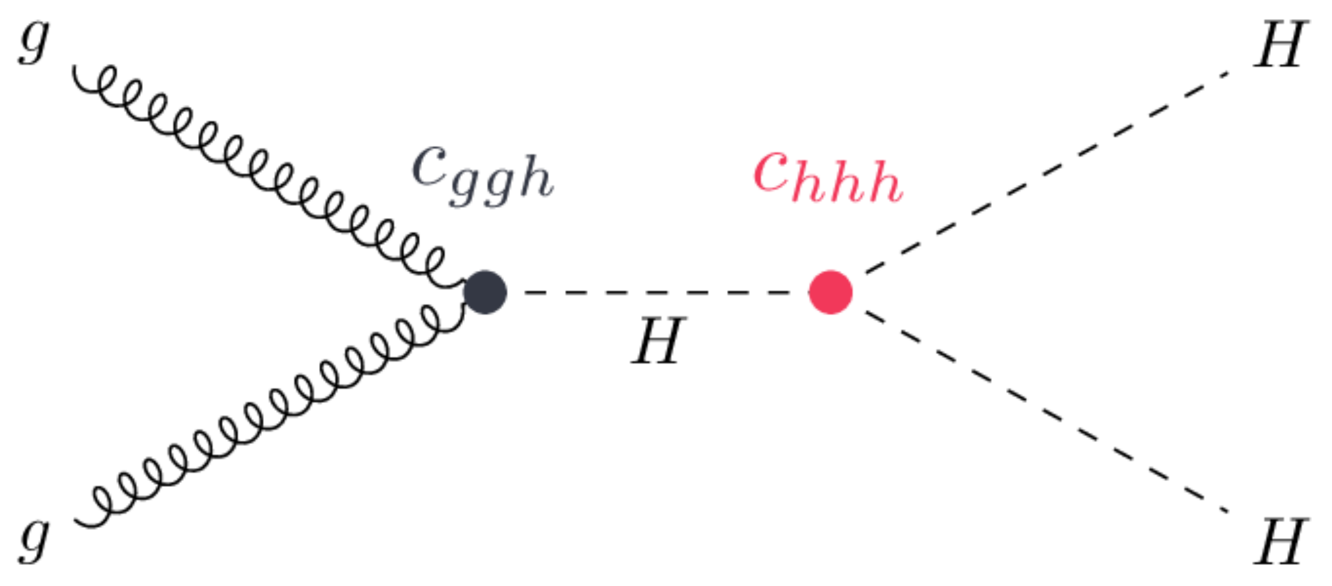


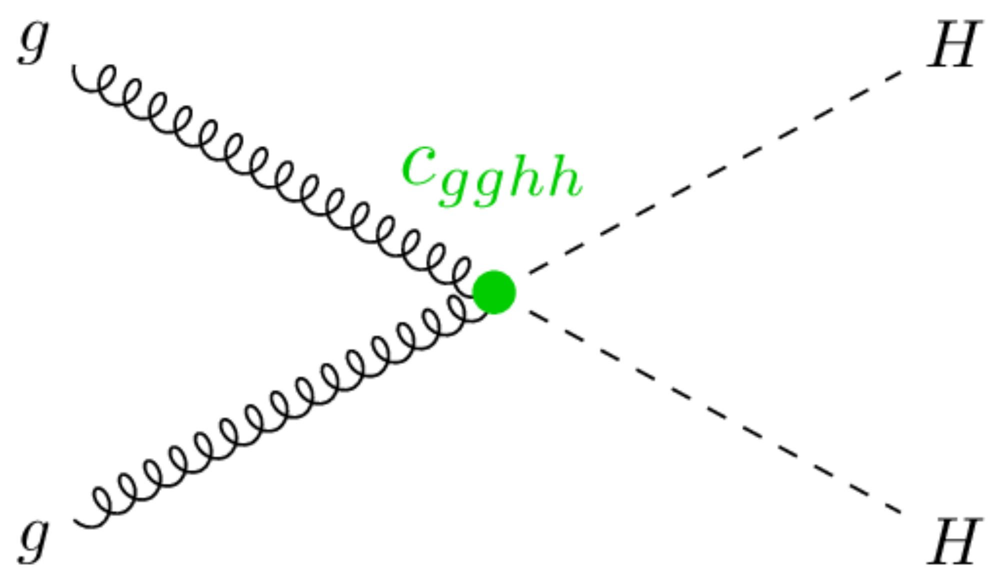


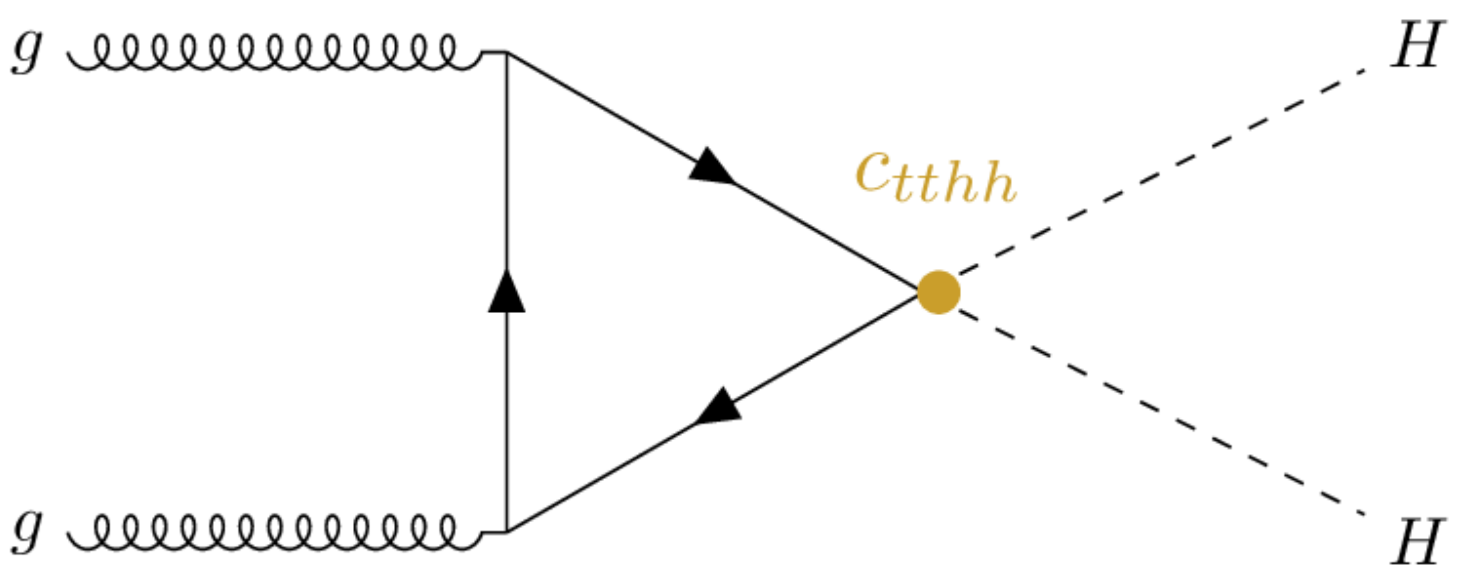


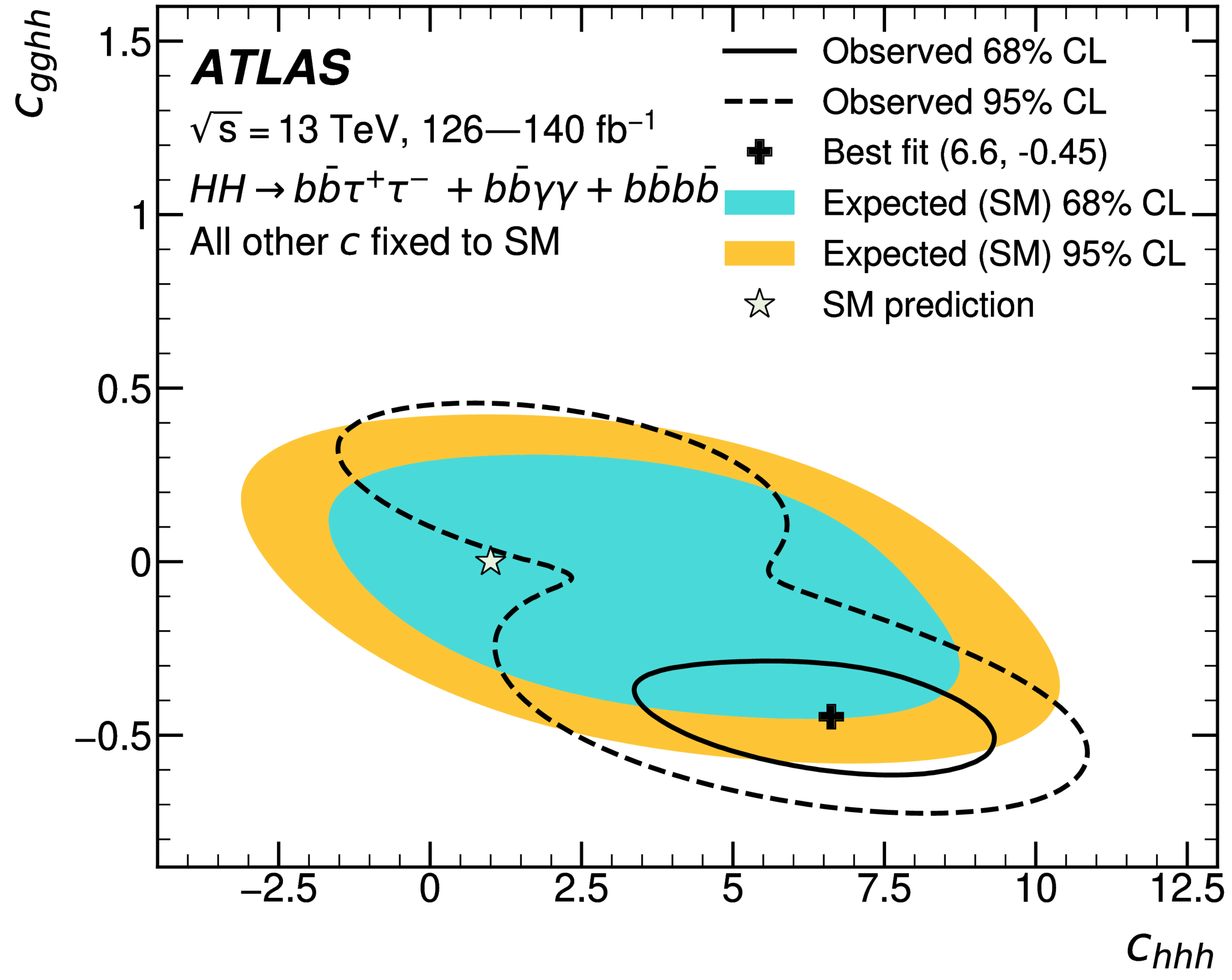
Combination of non-resonant HH in Run2 ($140 fb^{-1}$)

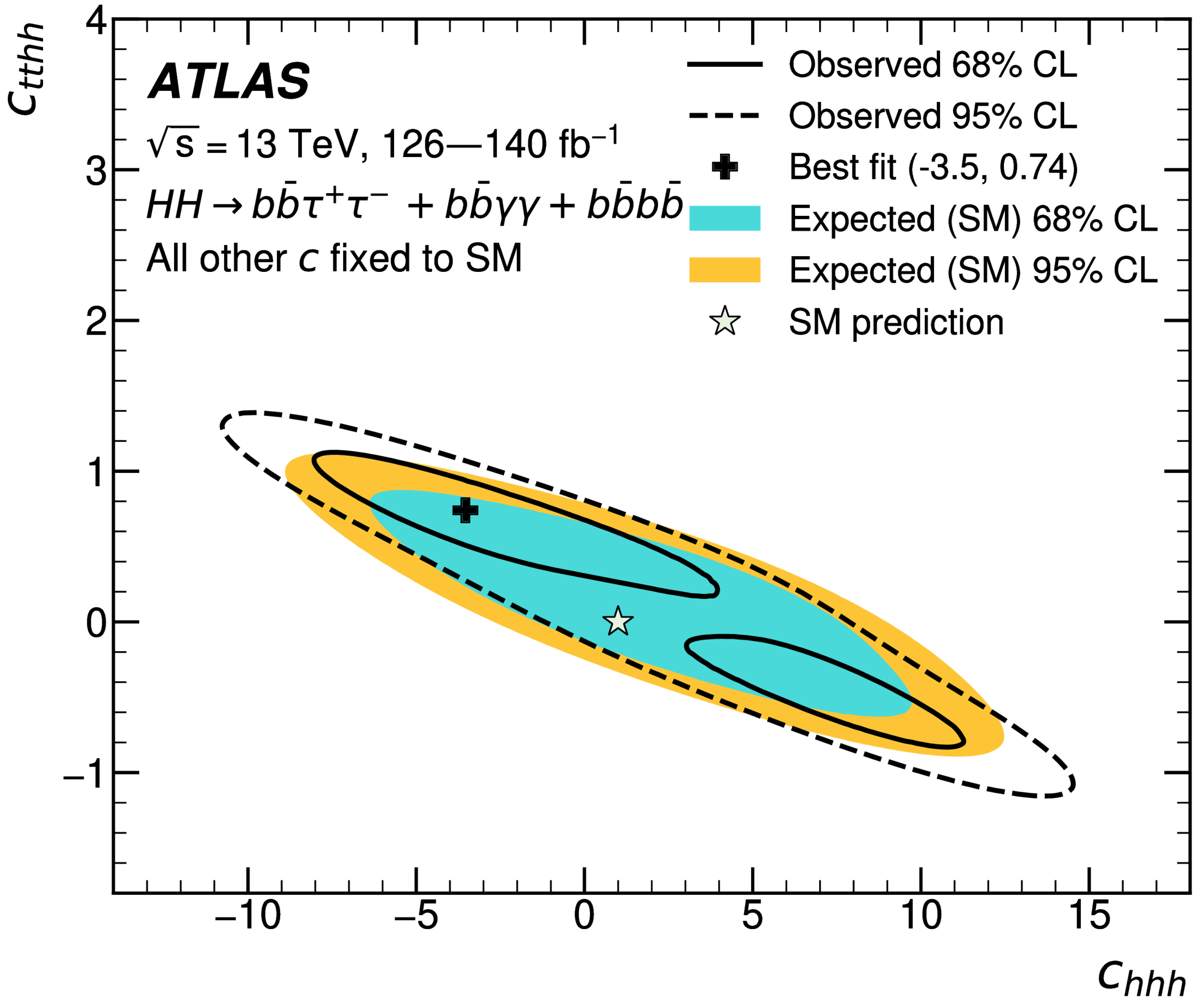
- **The p-values for compatibility of $c_{gghh} - c_{hhh}$, $c_{tthh} - c_{hhh}$, $c_{gghh} - c_{tthh}$ to SM are 0.044, 0.21 and 0.031.**

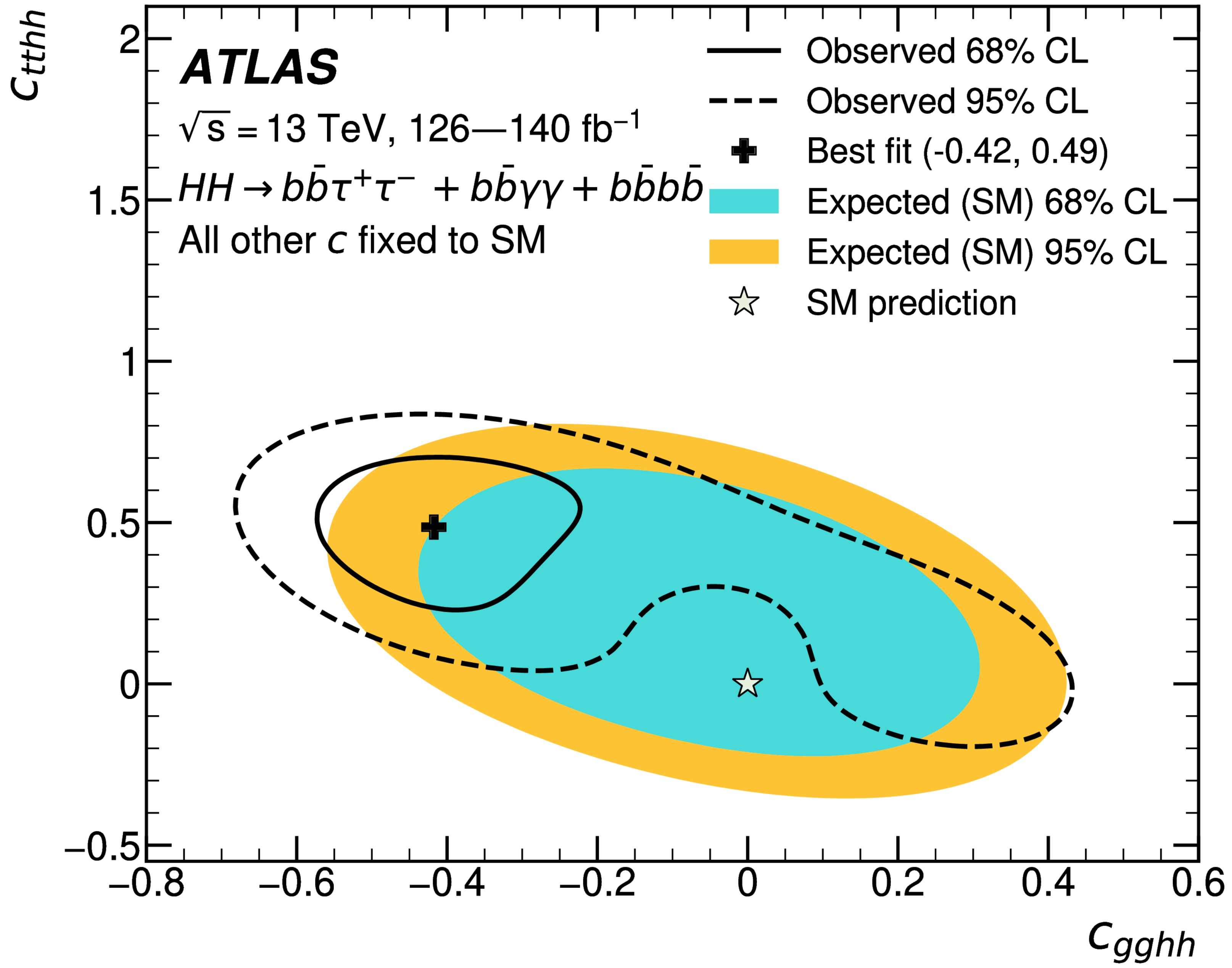






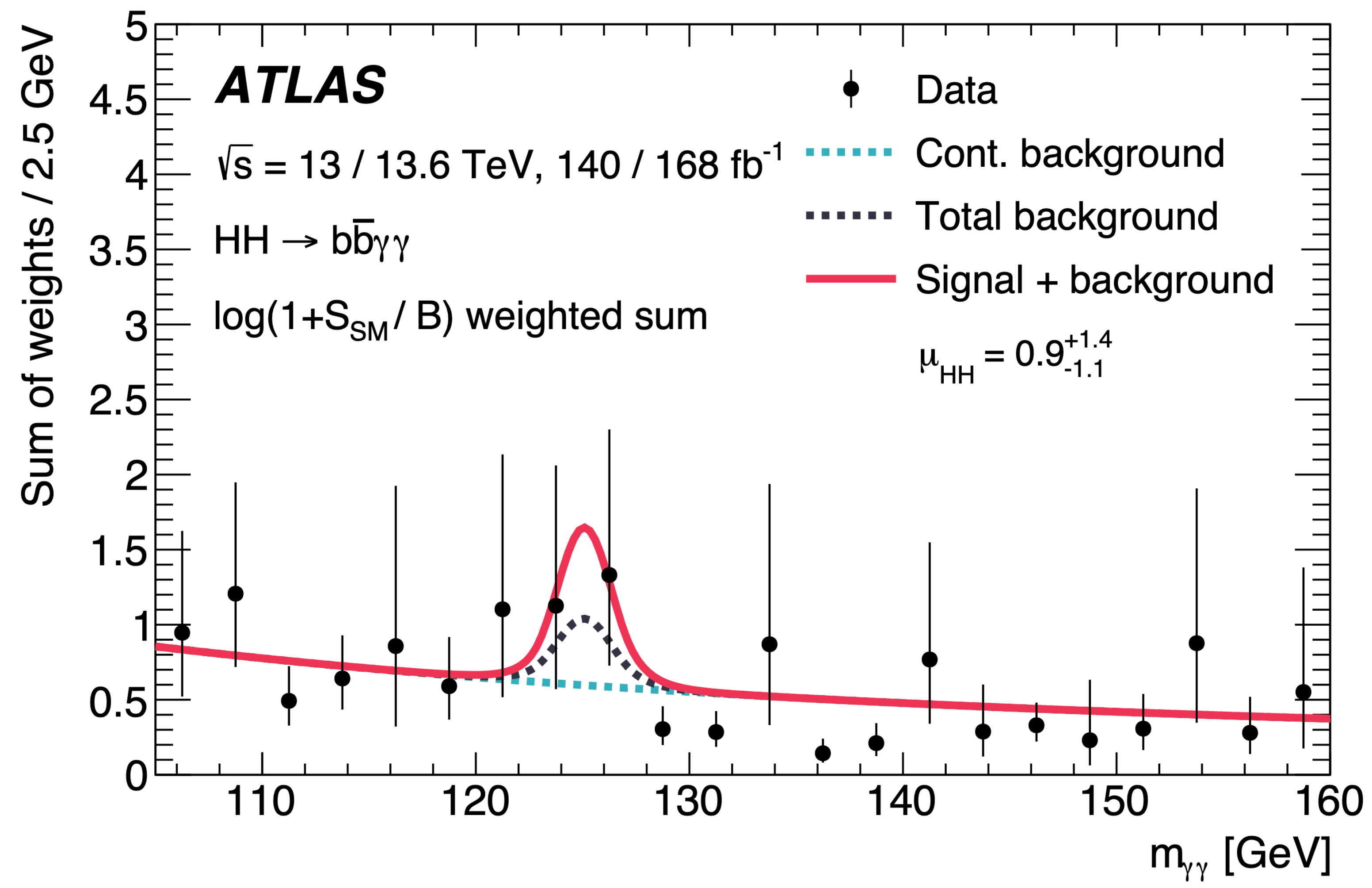


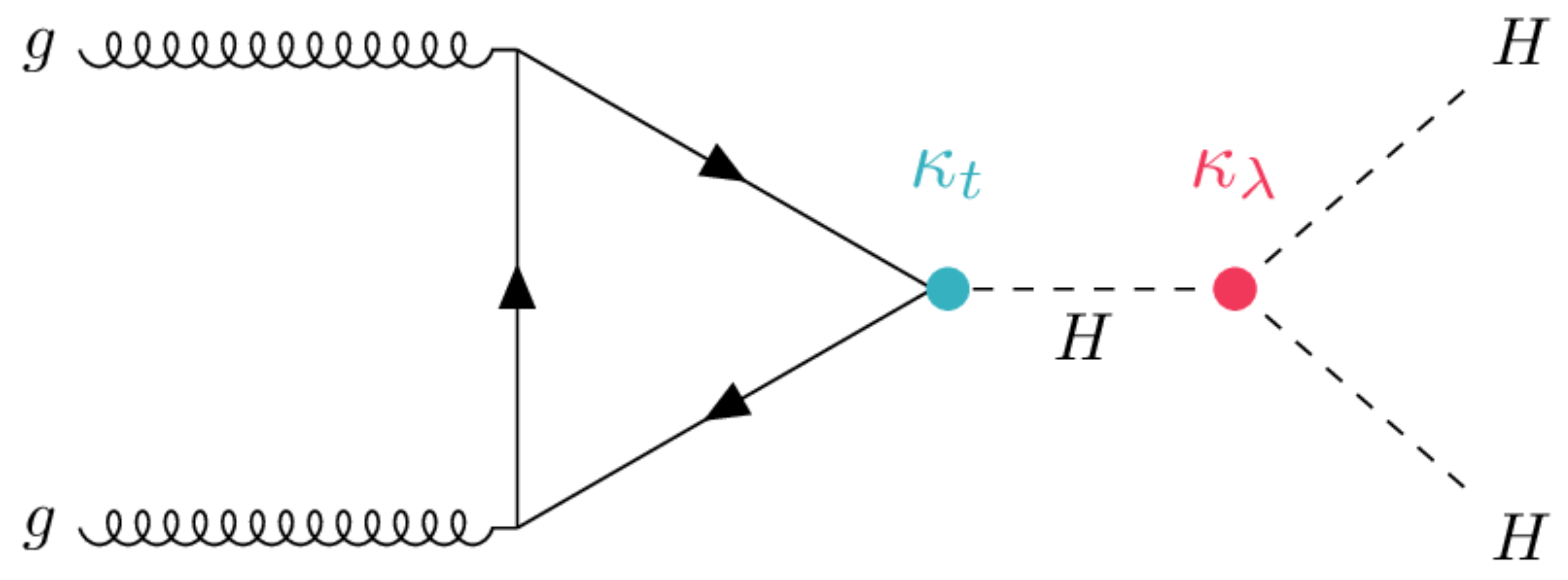


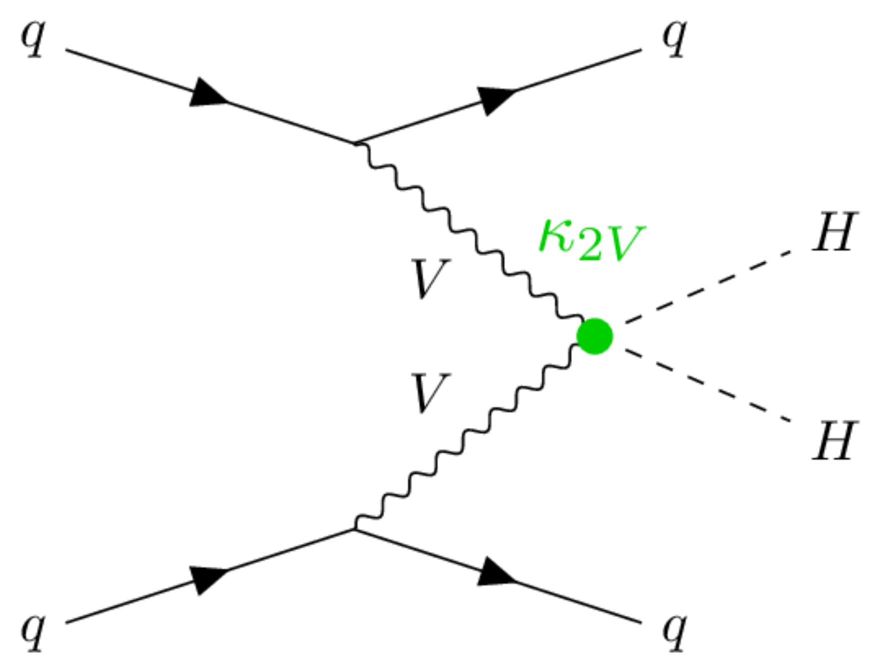


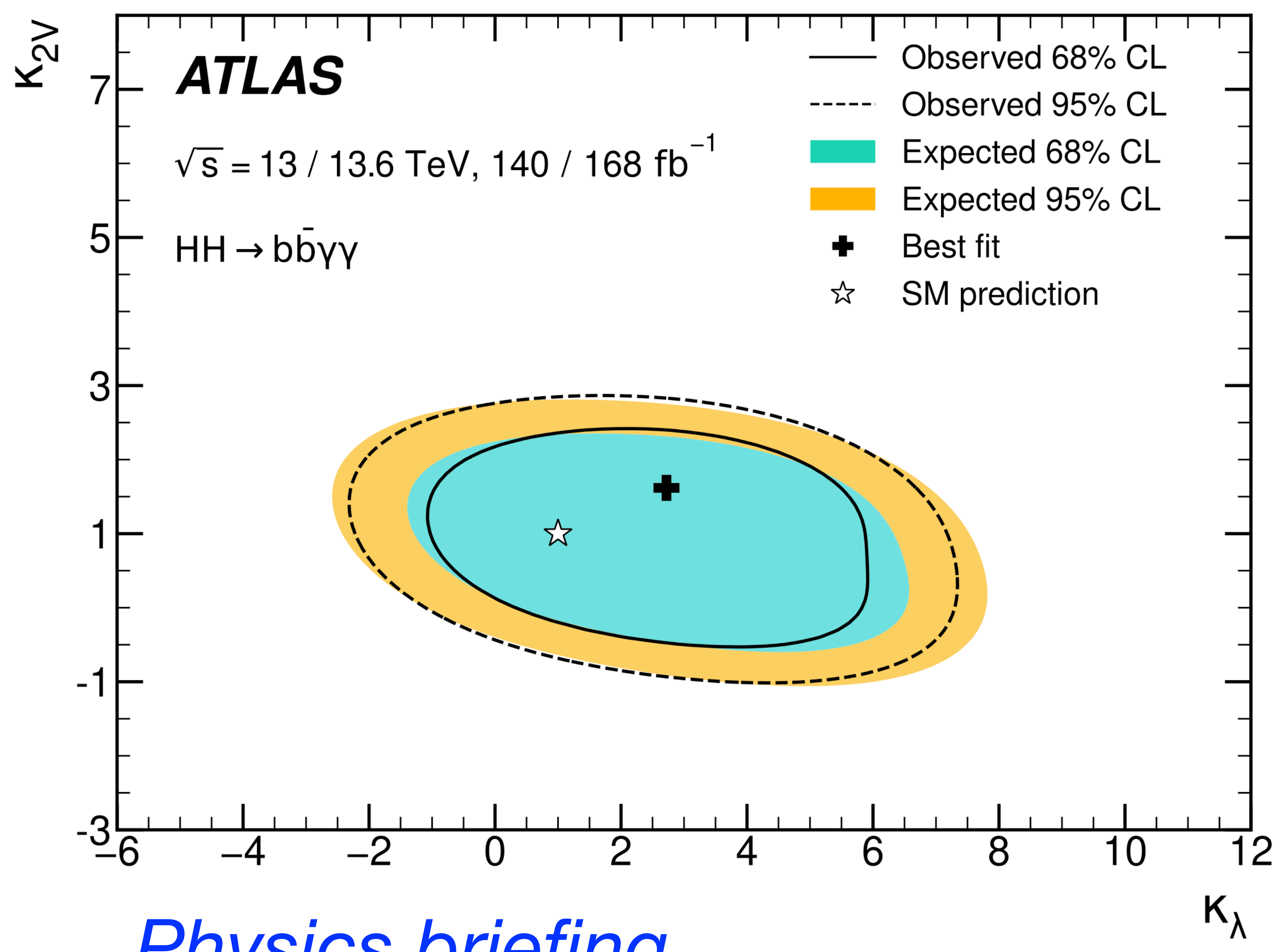
Non-resonant HH→bb$\gamma\gamma$ updates with Run3 dataset

- **Improvements to the Run 2 analysis**
  - Improved m_{bb}, $m^{*}_{bb\gamma\gamma}$ resolution, new kinematics fit
  - GN2 b-tagging algorithm (77%→85% WPs)
  - $N_{b\text{-jets}}$ from = 2 to ≥2 with new GN2 b-jet tagger
- **Run2+Run3 result: 95% CL upper limit on $\mu_{HH} < 3.8$ (exp. SM 3.7)**
  - Close to Run2 all channels combination!
- **Measured coupling modifiers ($\kappa_{\lambda}, \kappa_{2V}$) are in good agreement with SM**







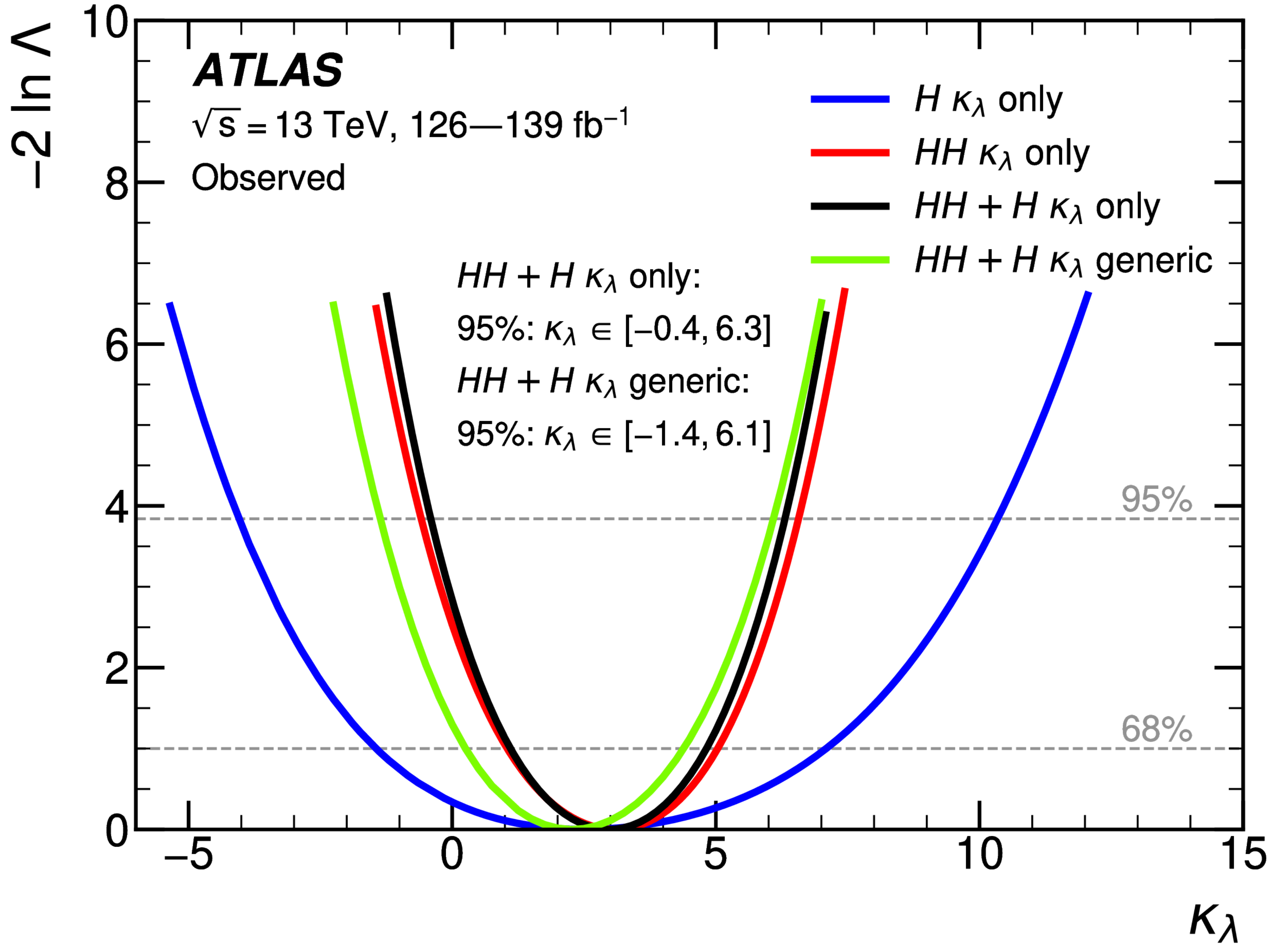


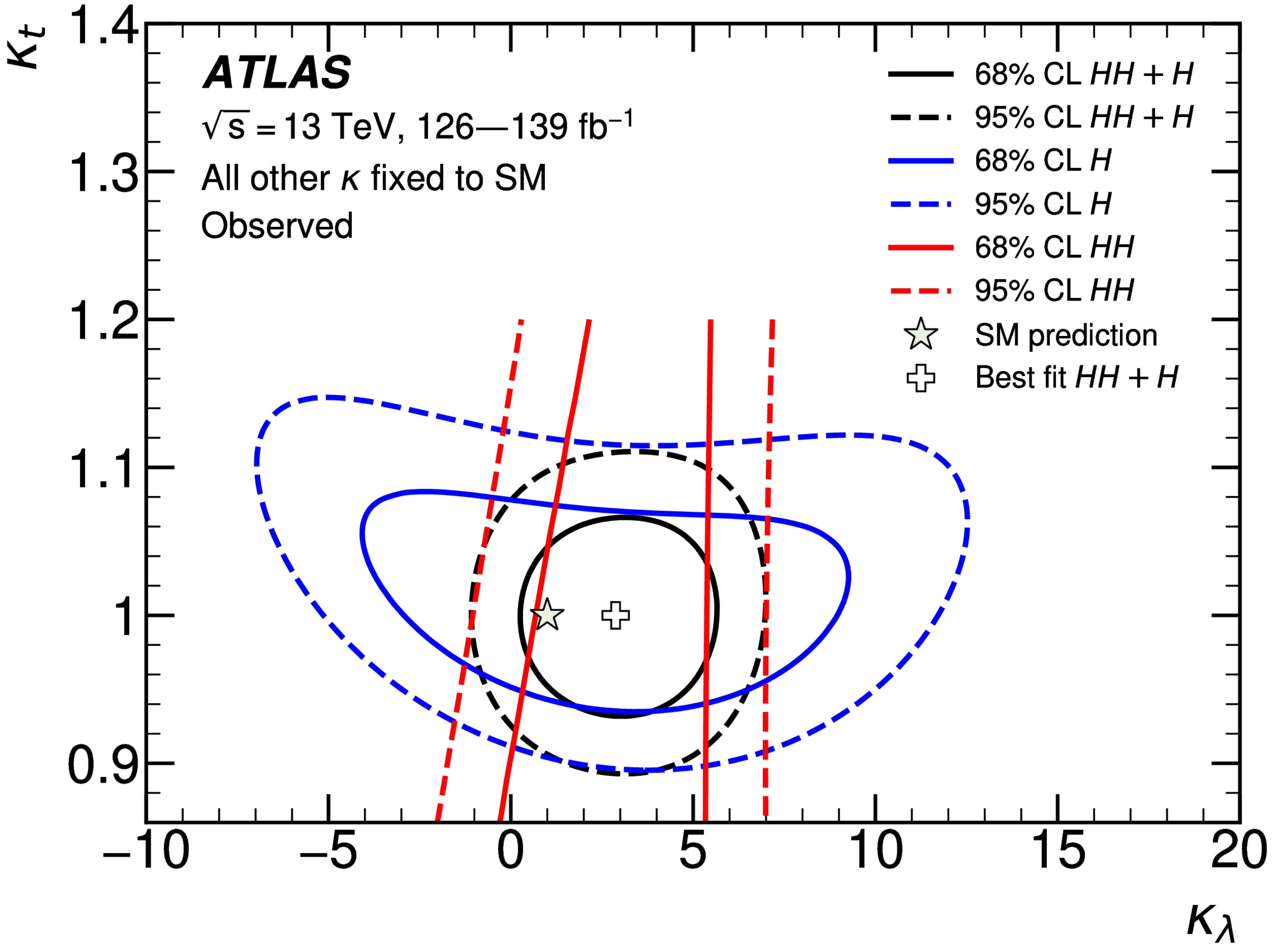
Physics briefing

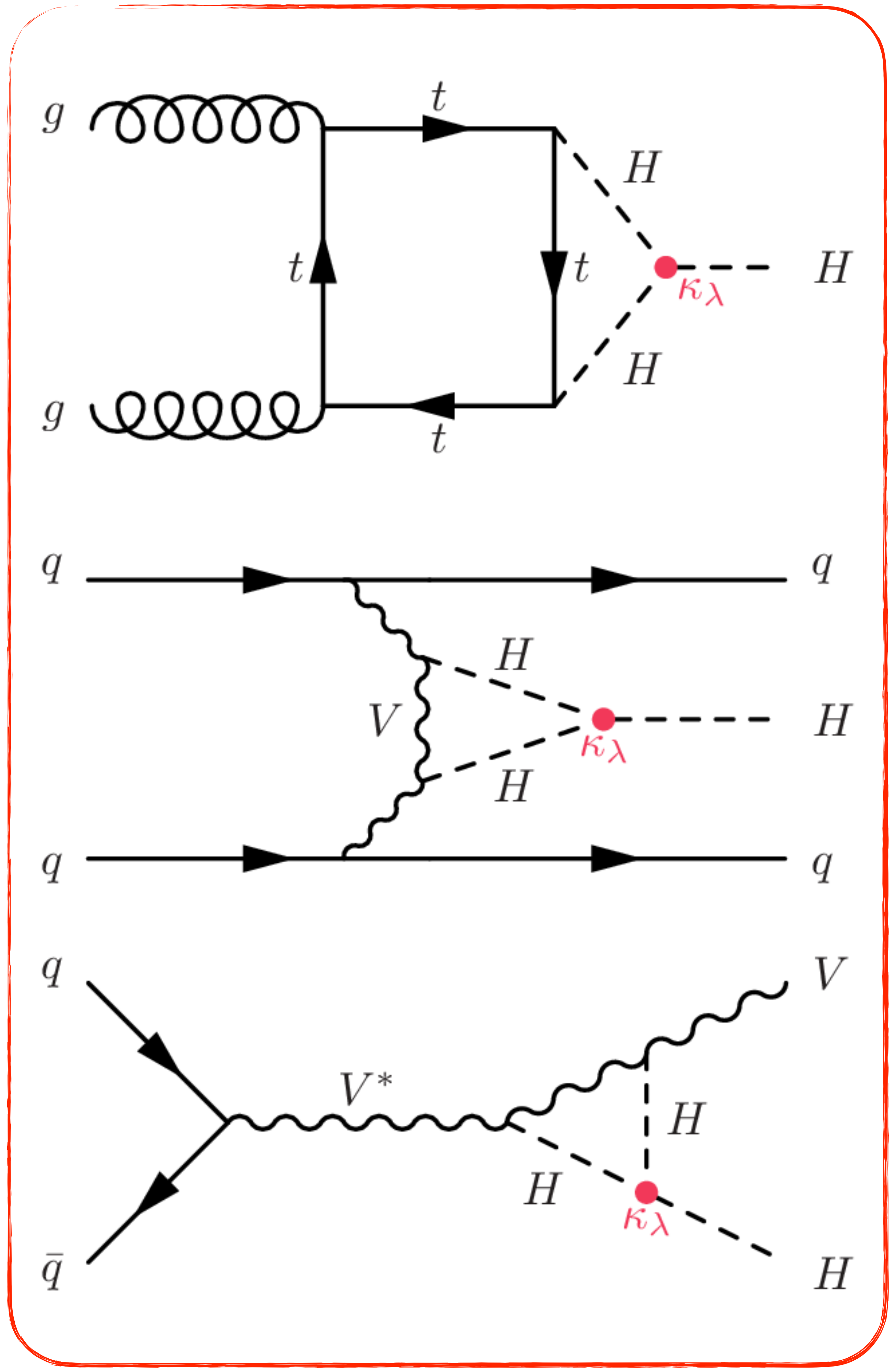
Higgs self-coupling constraints from H and HH production

- **Combination of HH→bbbb, bbττ and bbγγ with single H→γγ, WW, ZZ, ττ and bb**
- **HH only:** assuming new physics affects only on Higgs self-coupling value
- **H+HH:** can adding in the fit more coupling modifiers, e.g. Higgs-top coupling κ_t
- **Di-Higgs production dominant the Higgs self-coupling measurement**

Phys. Lett. B 843 (2023) 137745





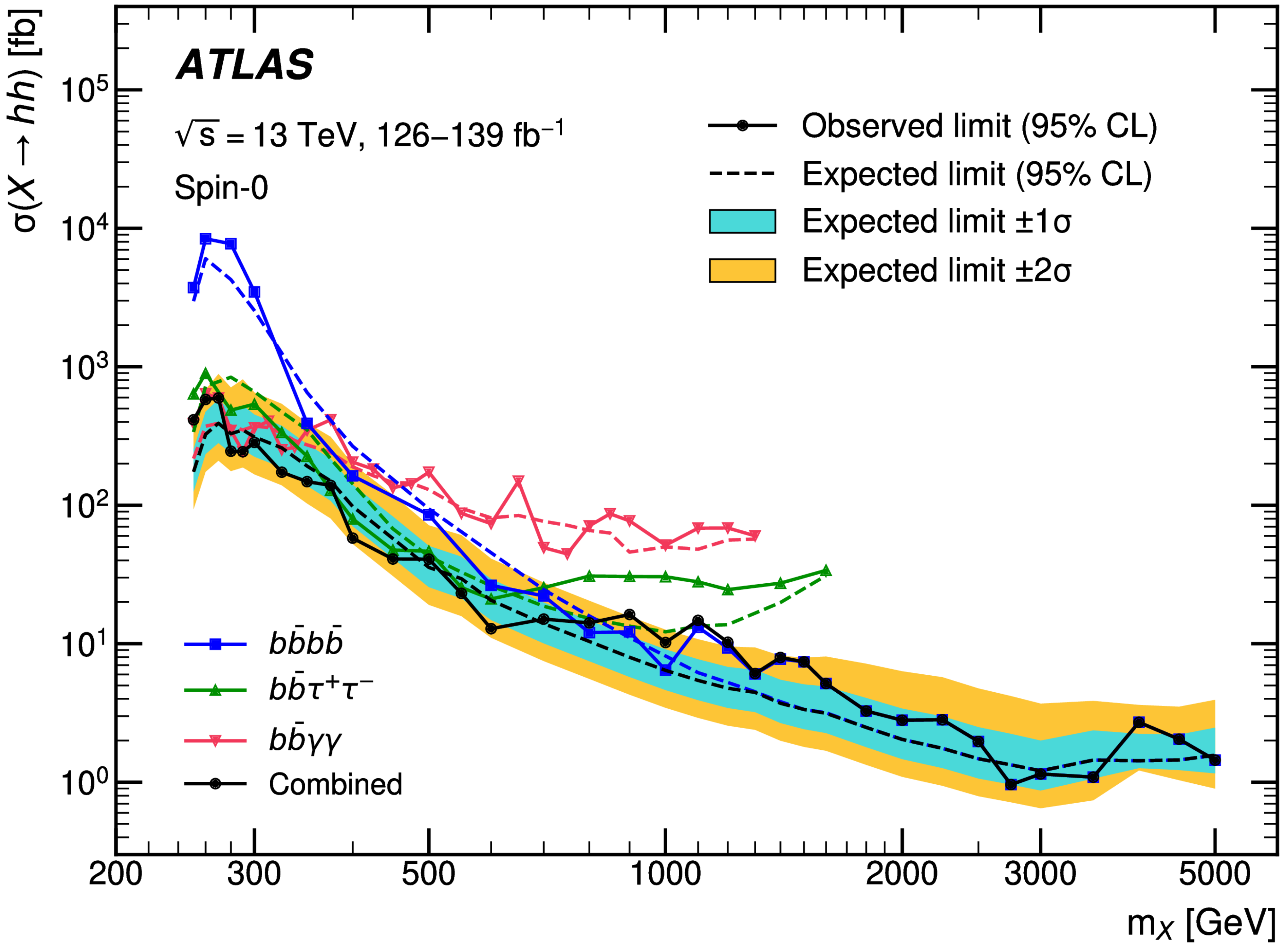


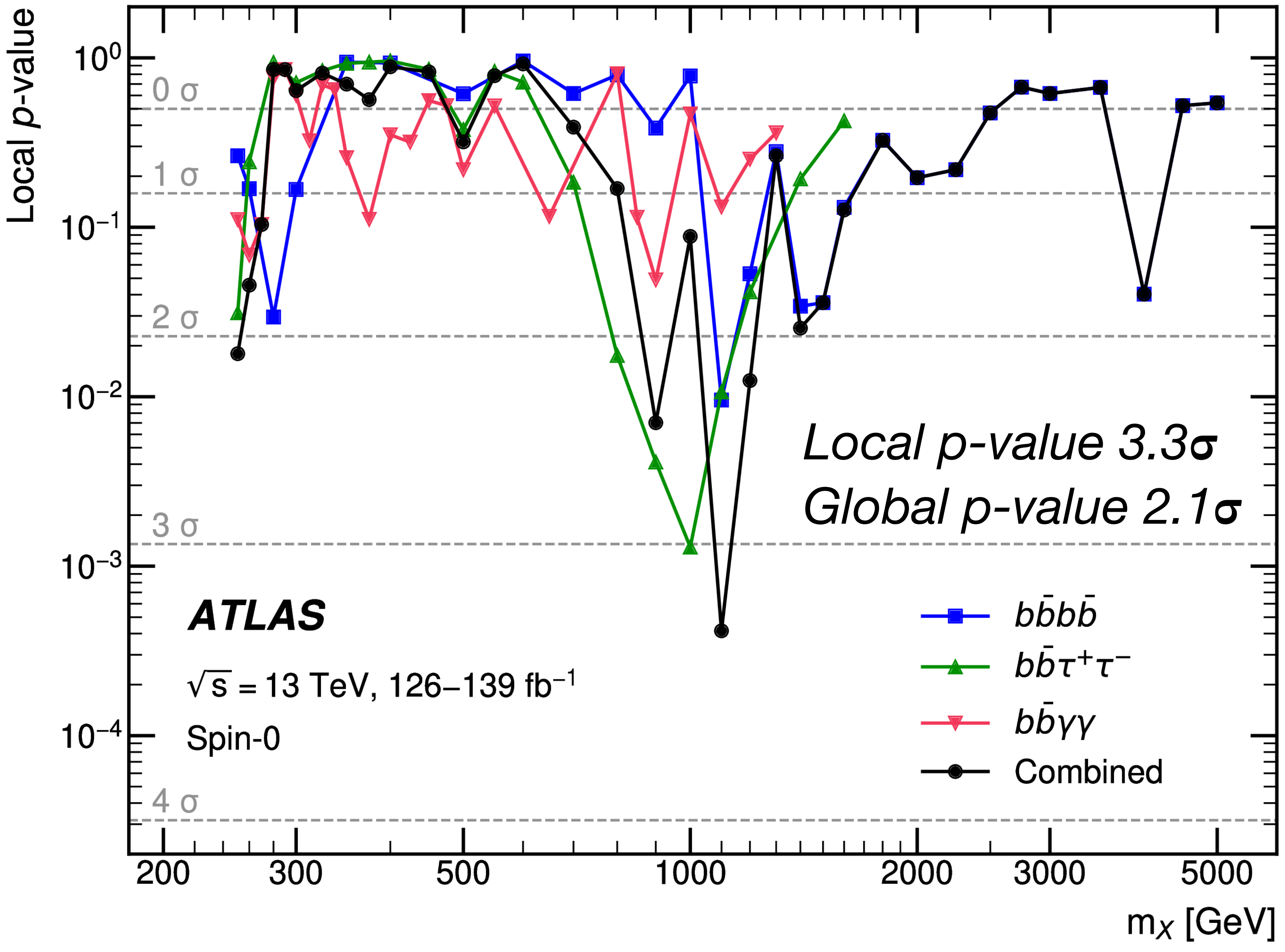
Resonant HH search updates

Resonant HH Run2 combination

- **Search for a narrow resonance *X* (251 GeV - 5 TeV) decays to Higgs pair *X➔HH➔bbγγ, bbττ or bbbb*.**
- **Sensitive channels from low ➔ high mass: *X➔HH➔bbγγ, bbττ* and *bbbb*.**
- **The observed (expected) 95% CL limits are in the range 0.96 - 600 fb (1.2 - 390 fb).**

Phys. Rev. Lett. 132 (2024) 231801

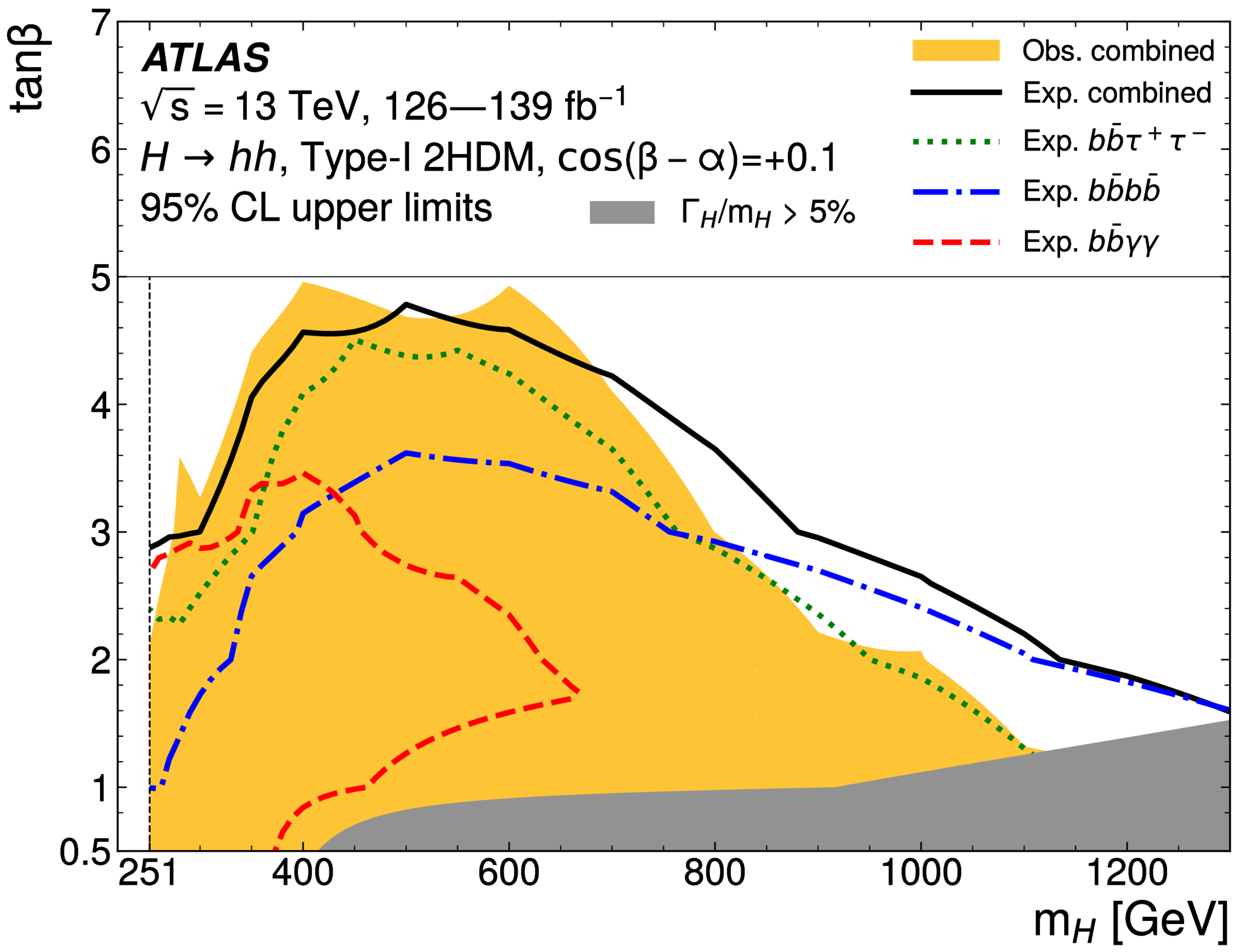


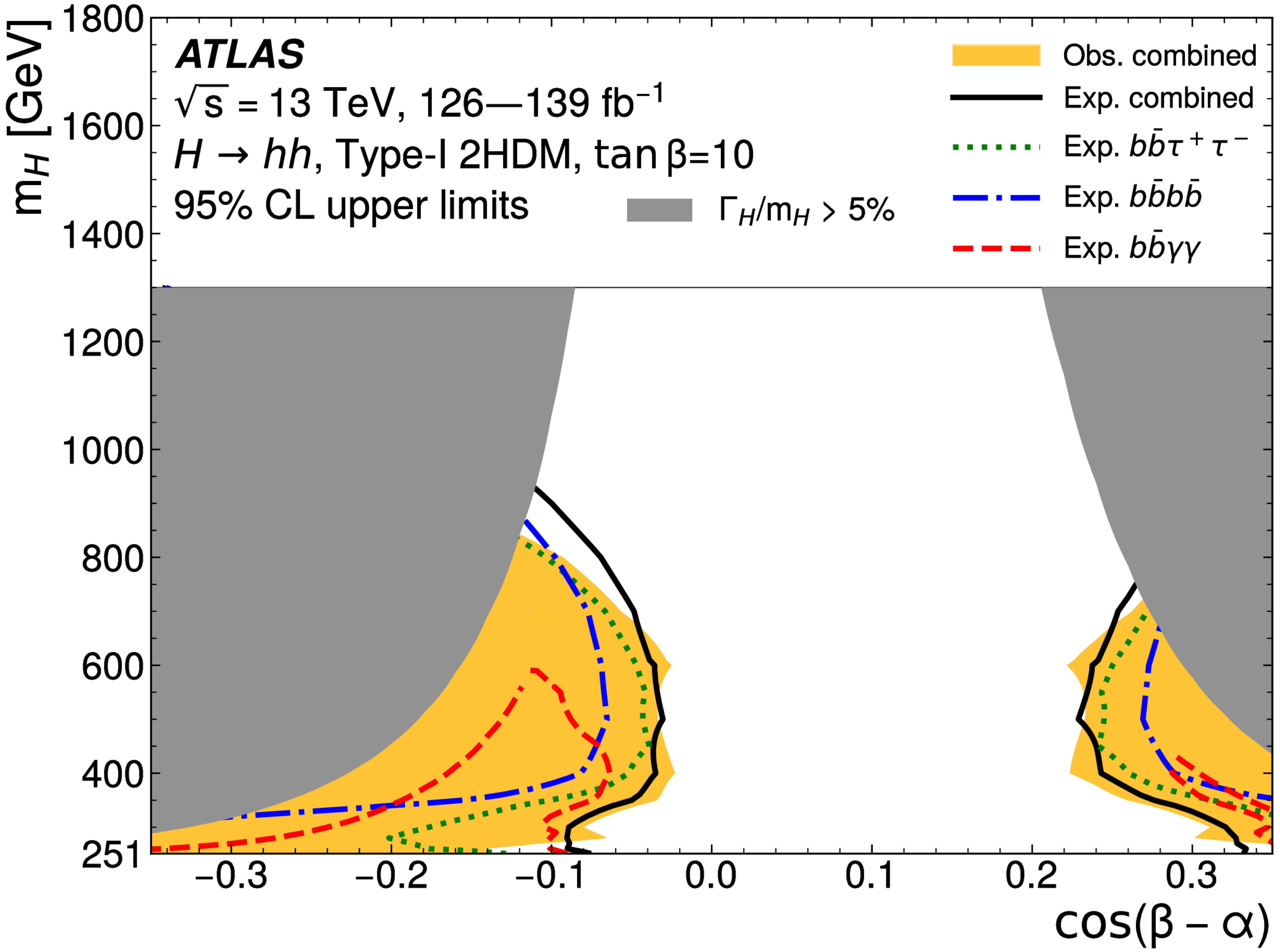


Resonant HH Run2 combination

- **The limits are interpreted in the Type-I 2HDM and the MSSM model.**
- **Exclusion limits at the 95% CL on the type-I 2HDM parameter space:**

Phys. Rev. Lett. 132 (2024) 231801



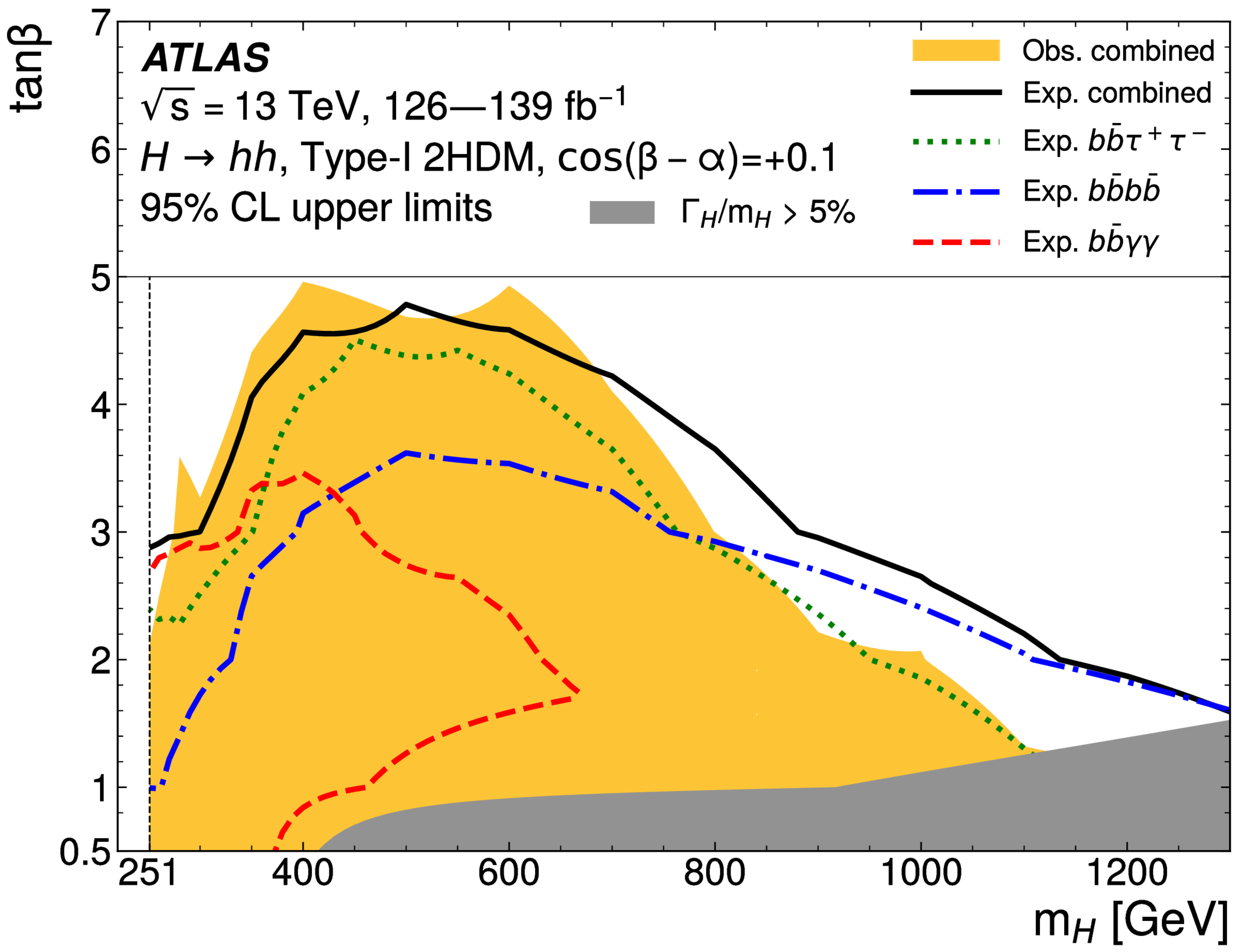


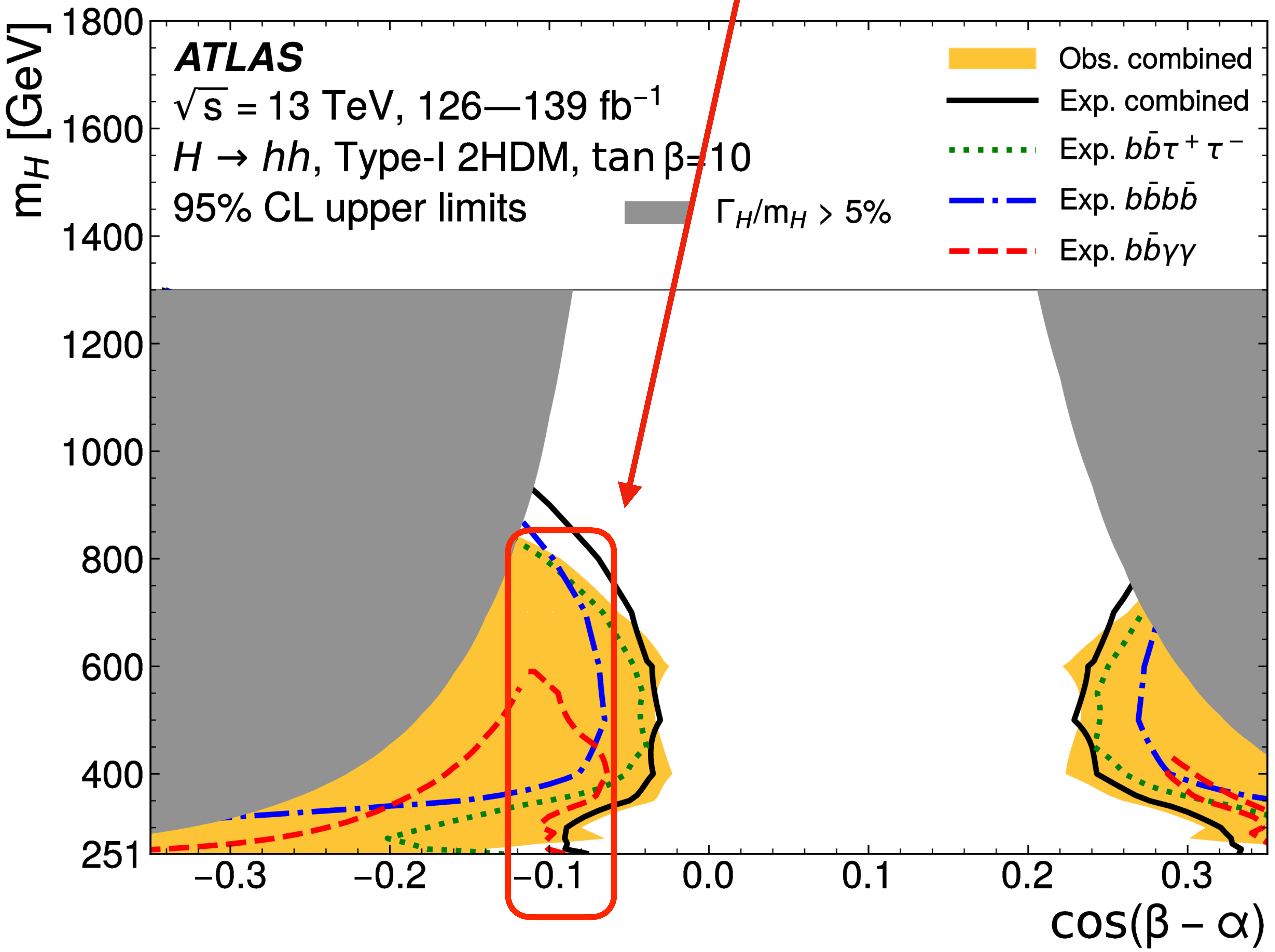
Resonant HH Run2 combination

- **The limits are interpreted in the Type-I 2HDM and the MSSM model.**
- **Exclusion limits at the 95% CL on the type-I 2HDM parameter space:**

A region allowed by the Higgs boson coupling measurement

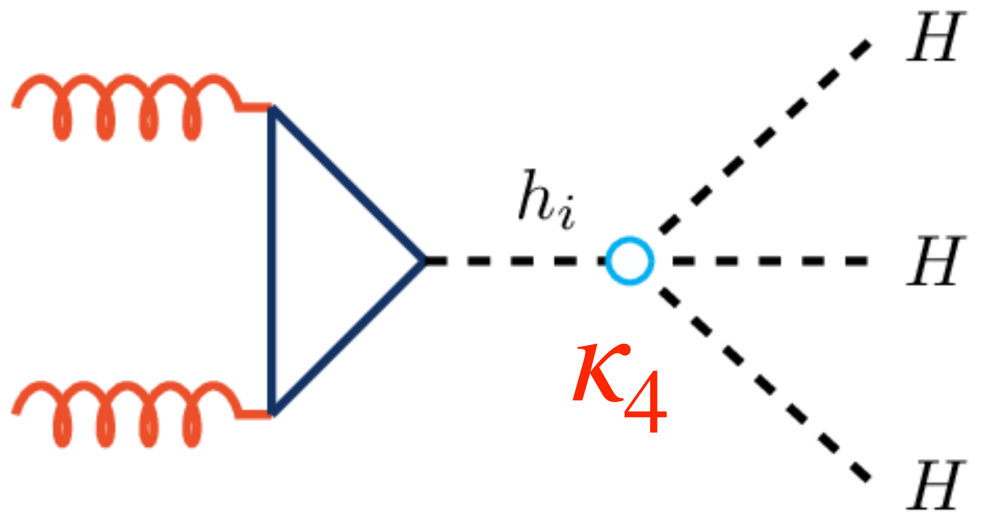
Phys. Rev. Lett. 132 (2024) 231801

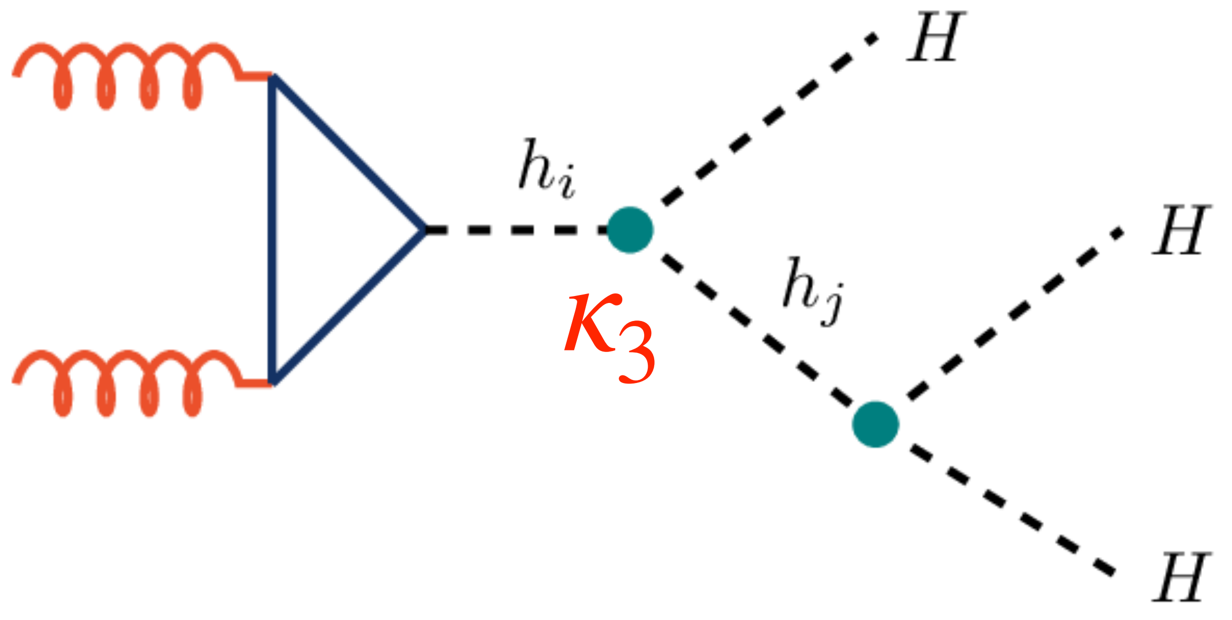




Search for triple Higgs in 6b final states: X➔SH➔*HHH*➔*6b*

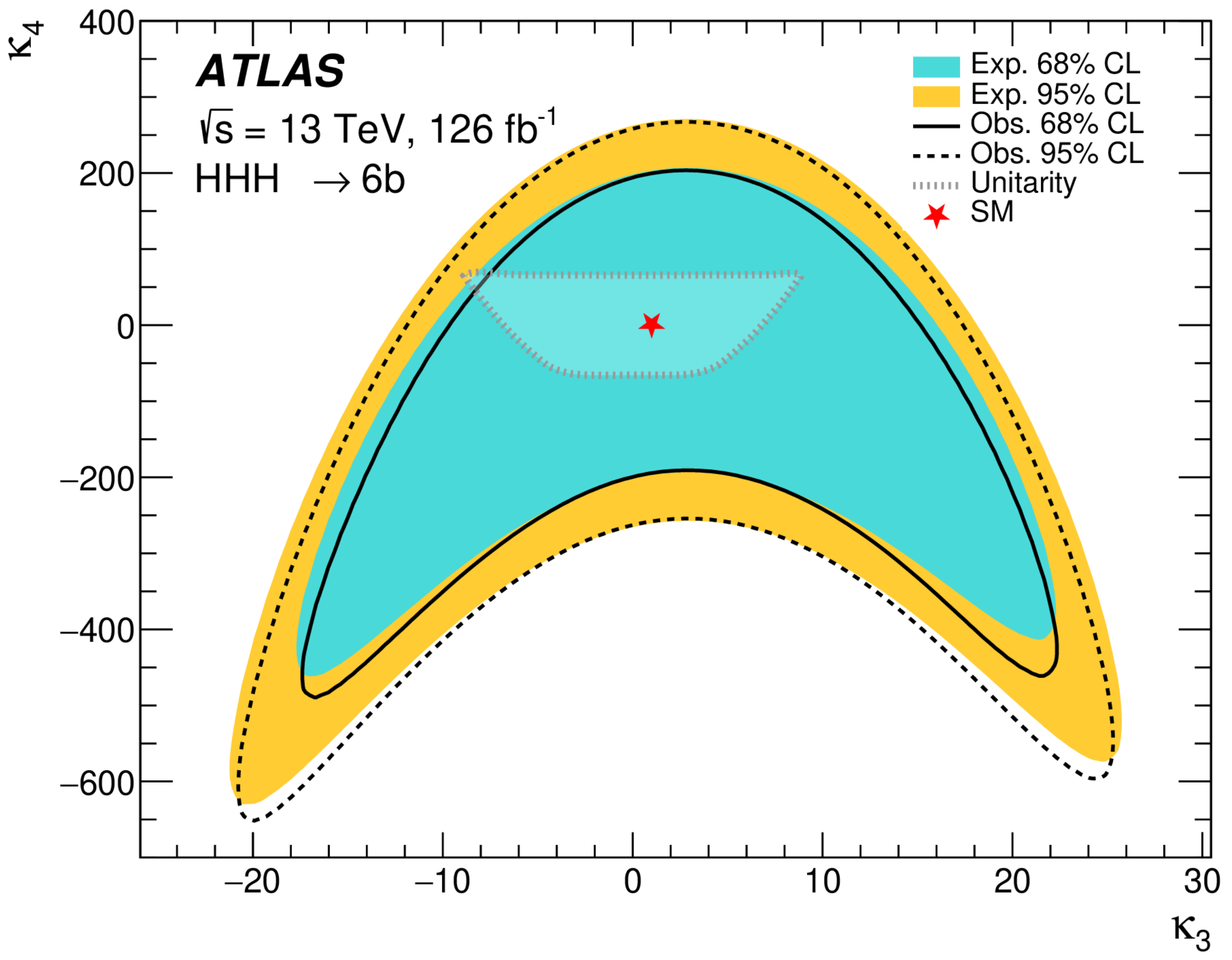
- **Observed (expected) limit on non-resonance *HHH*: $\mu_{\sigma_{HHH}/\sigma^{SM}_{HHH}}$ = 760 (750) ➔ constraints on κ_3 and κ_4**
- **Interpretation of *X➔SH➔HHH* resonance cascade decay, limits range between 48 — 310 fb.**



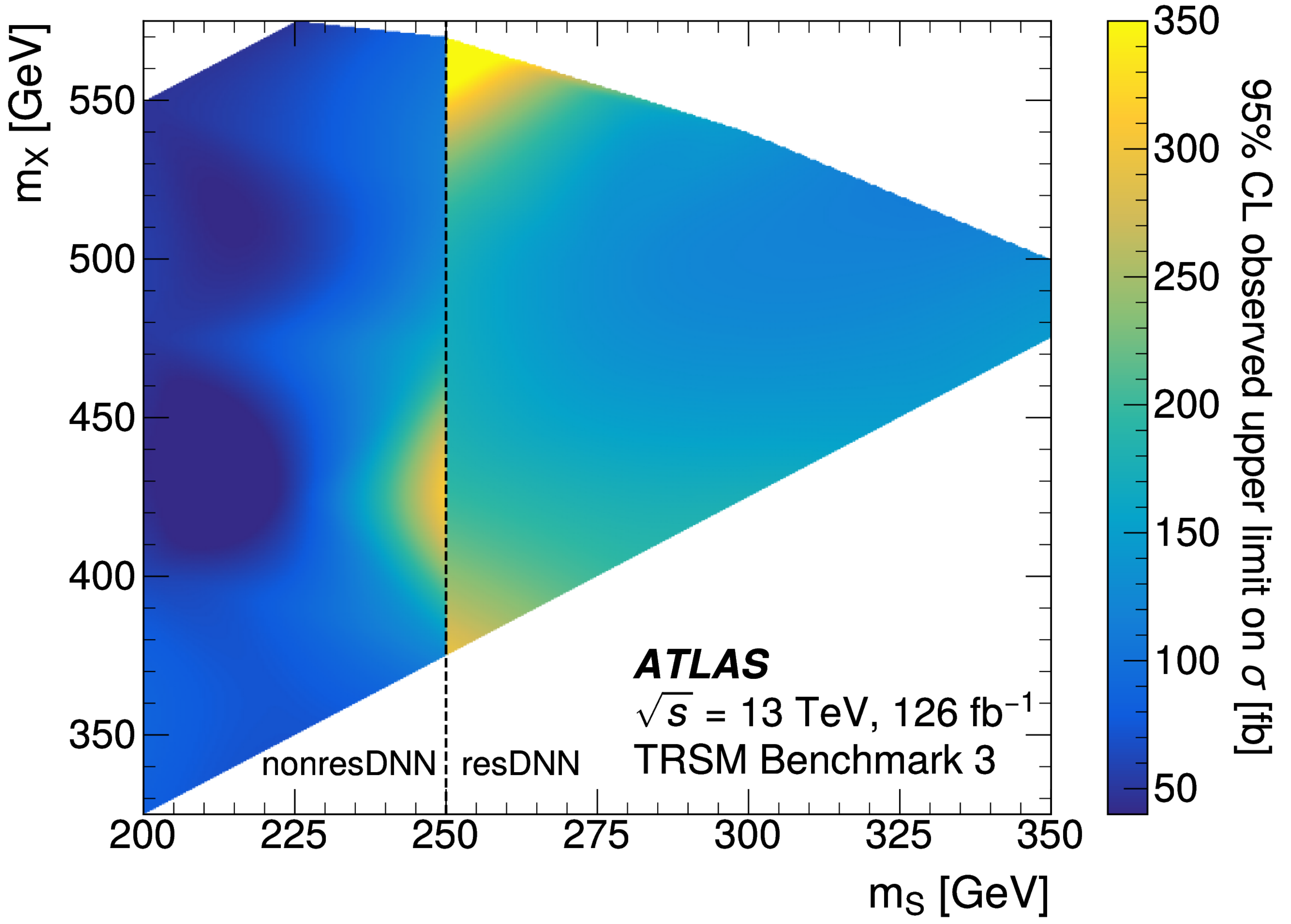


Why stop at two? (Physics Briefing)

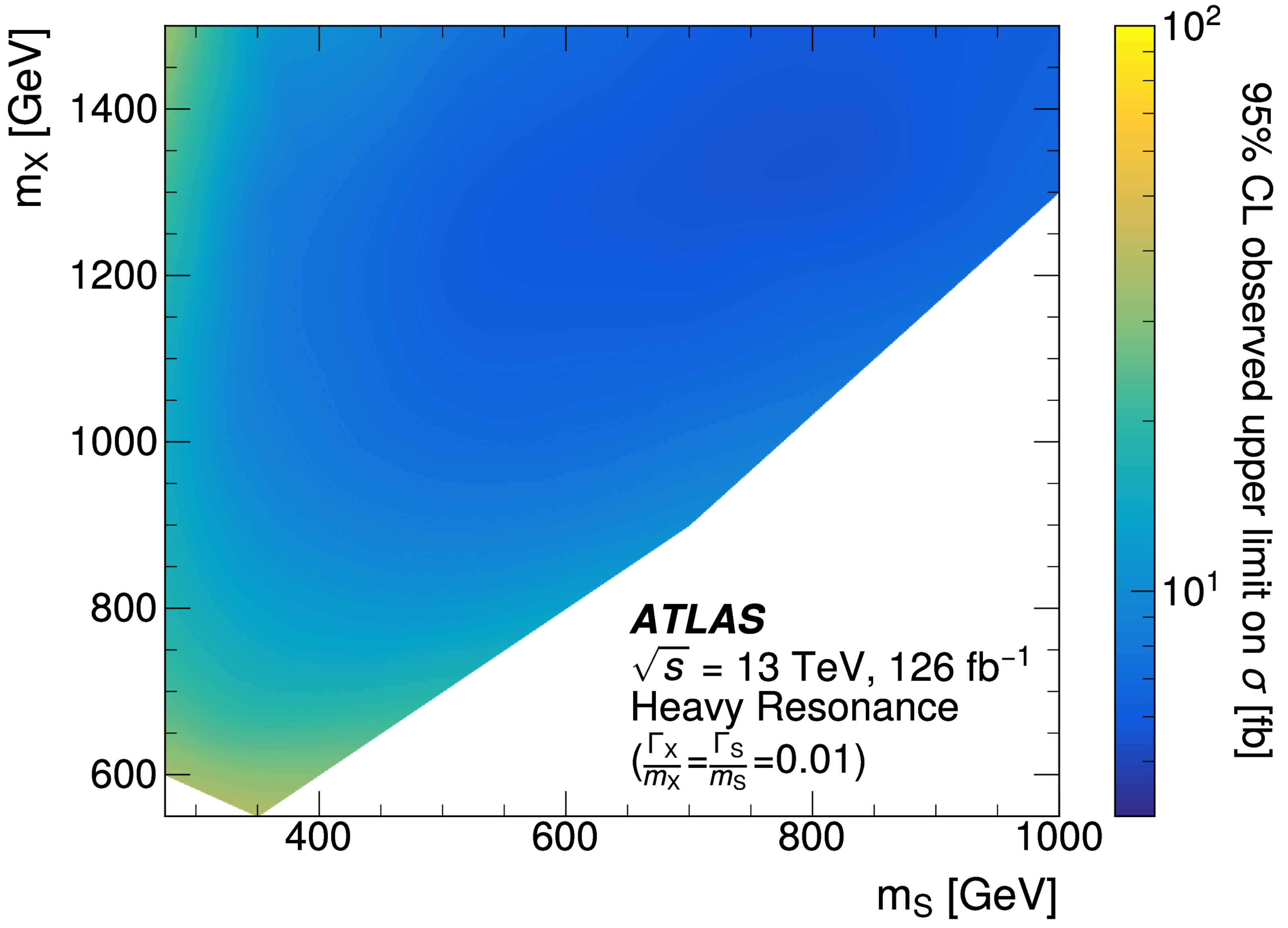
Phys. Rev. D 111 (2025) 032006



Two real scalars model (TRSM)

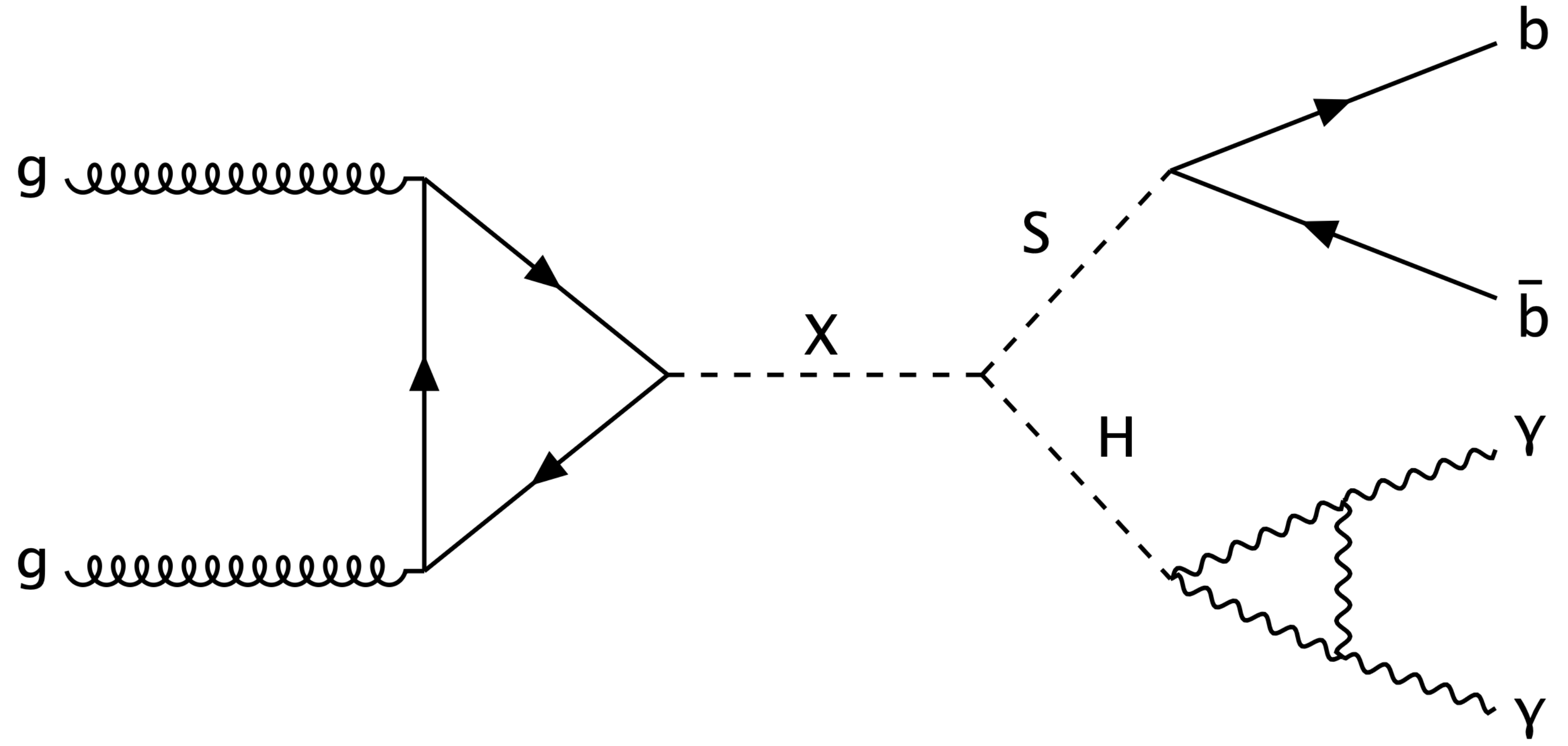


Heavy resonance model

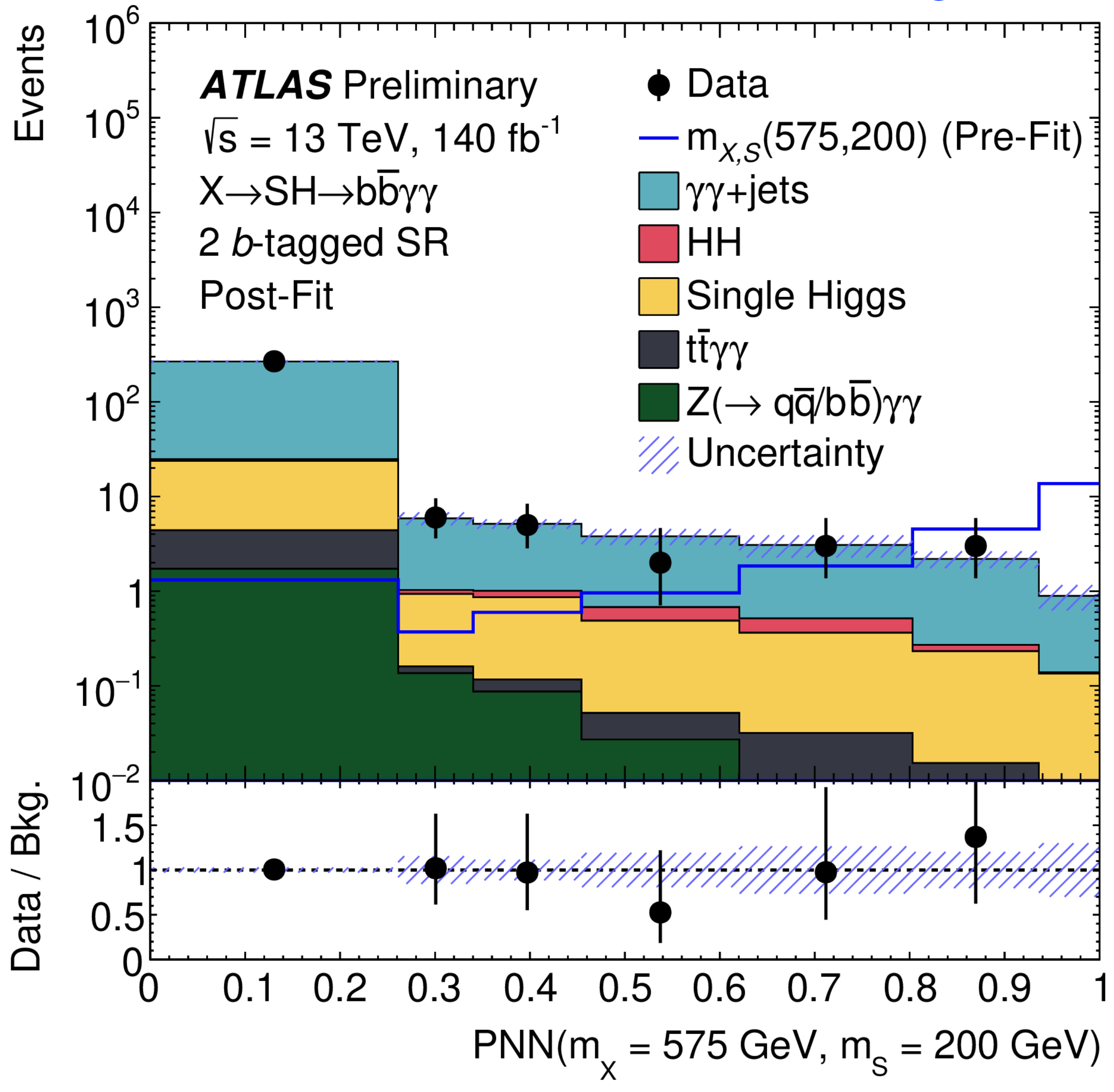


Search for resonant X→SH→bbγγ in Run 2+3 (2022-2023)

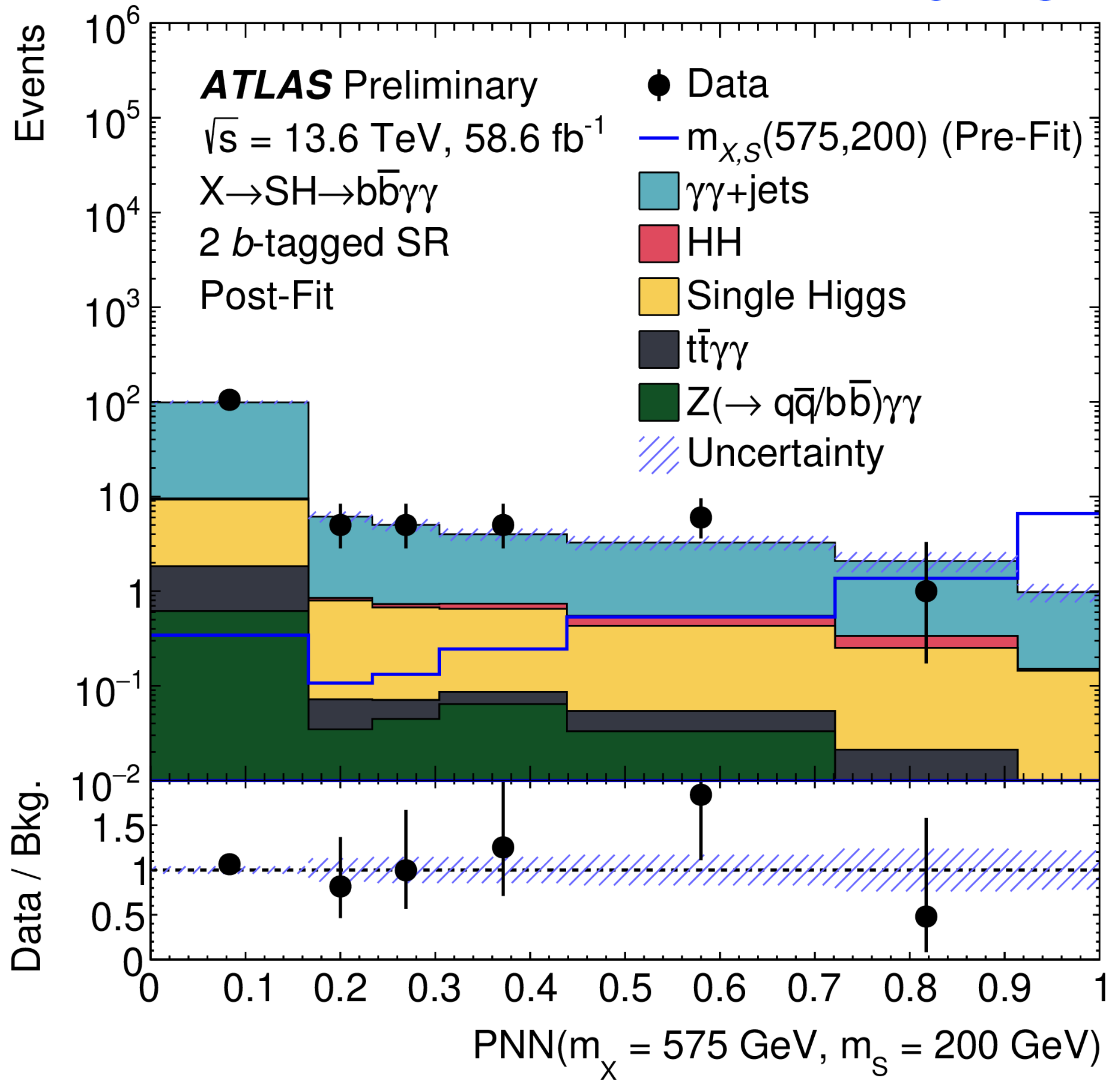
- **Updates w.r.t previous analysis** (**9-30% improvement** of early Run 3 analysis depending on mass point)
  - Substantial improvement of DL1r → GN2 b-tagger
  - Narrowing $m_{\gamma\gamma}$ window from 120-130 GeV to 122.5-127.5 GeV
- **No significant excess above the SM prediction is observed!**
  - No similar deviation as ATLAS Run 2: [3.5σ at (m_X, m_S) = (575, 200) GeV], neither as CMS Run 2: [3.8σ at (m_X, m_S) = (650, 90) GeV].

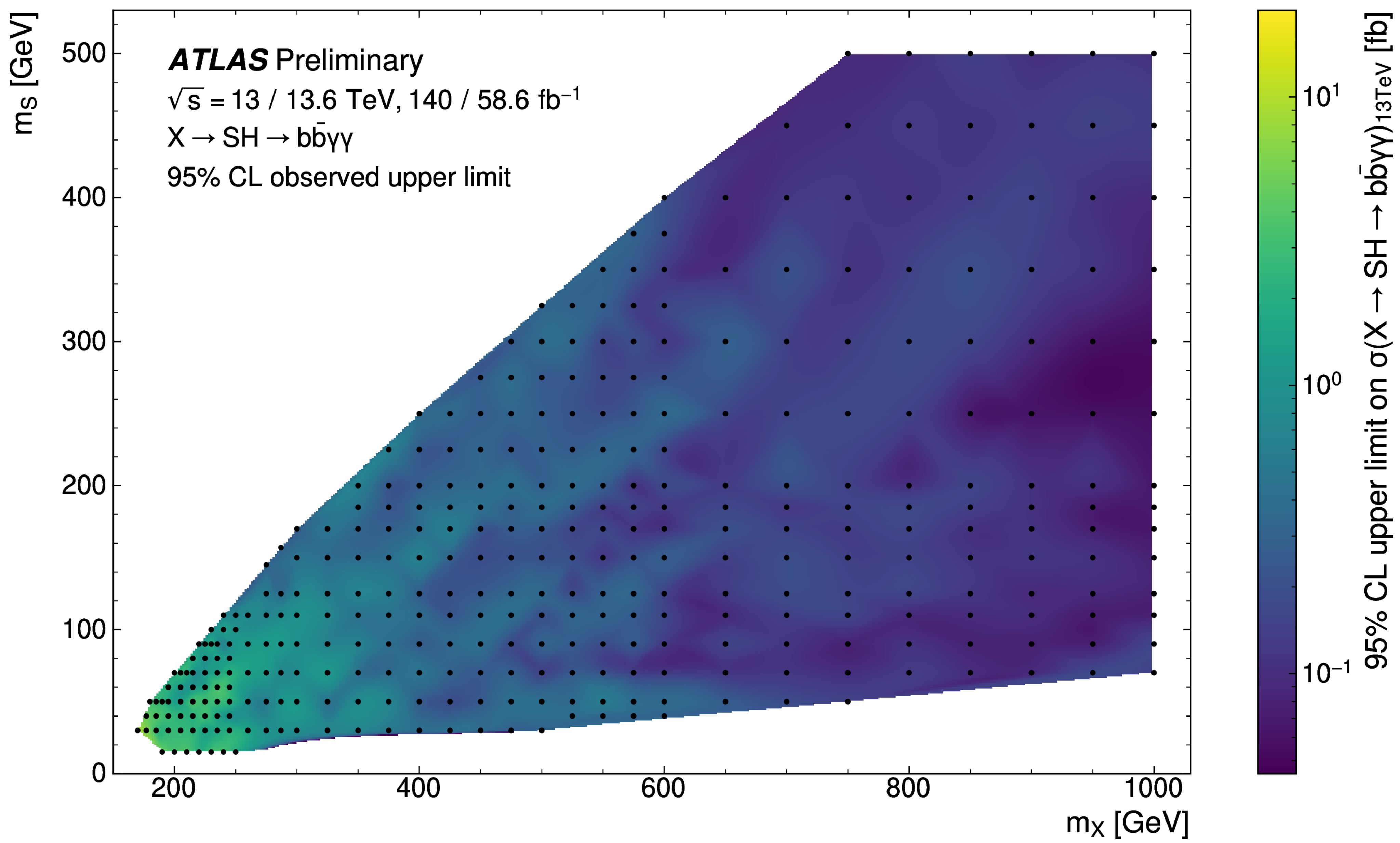


Run 2



Run 3



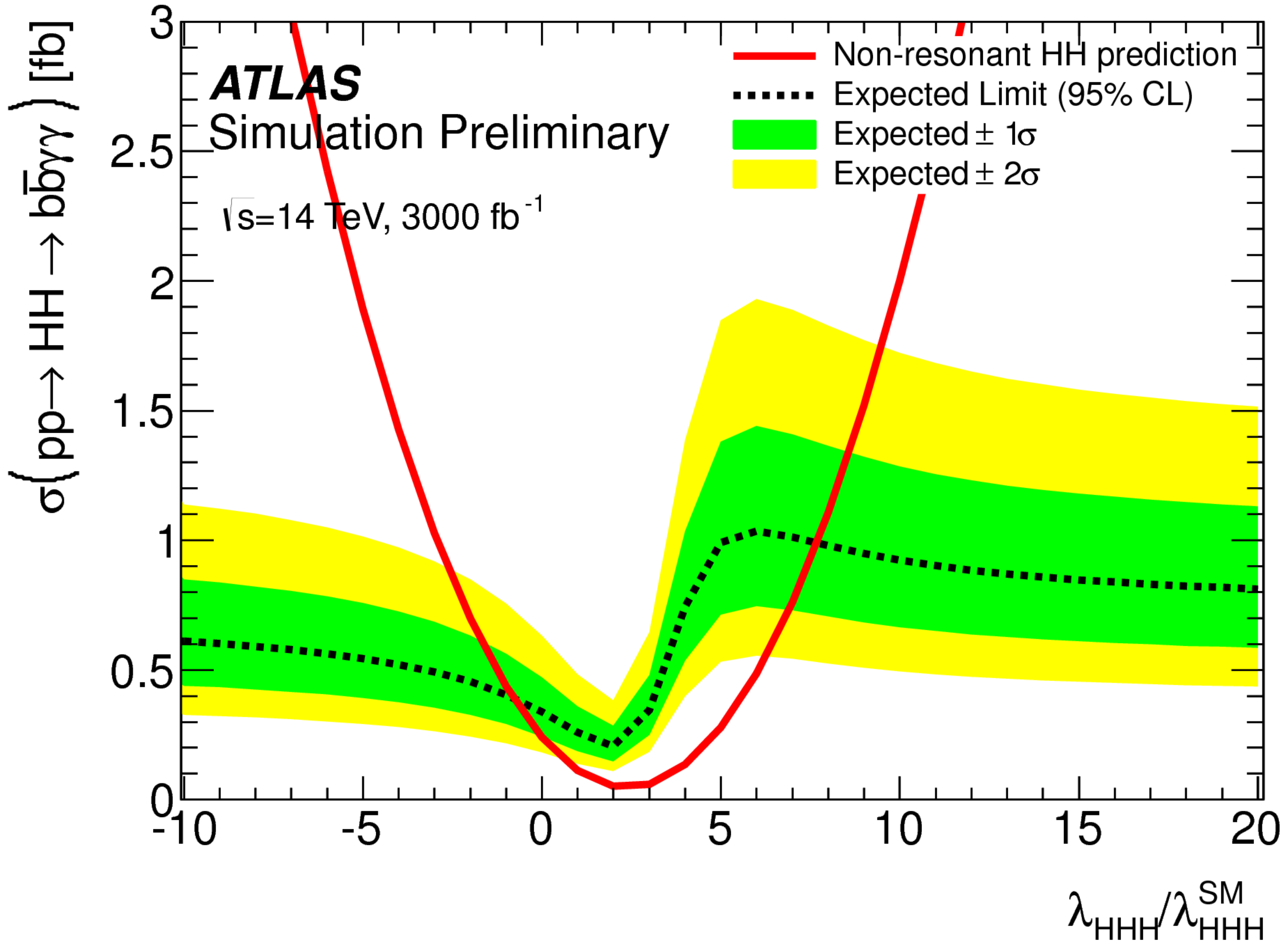


Prospects & conclusion

Prospects for the High-Luminosity LHC

Run 1

4.5/20.3 fb^{-1} at 7/8 TeV



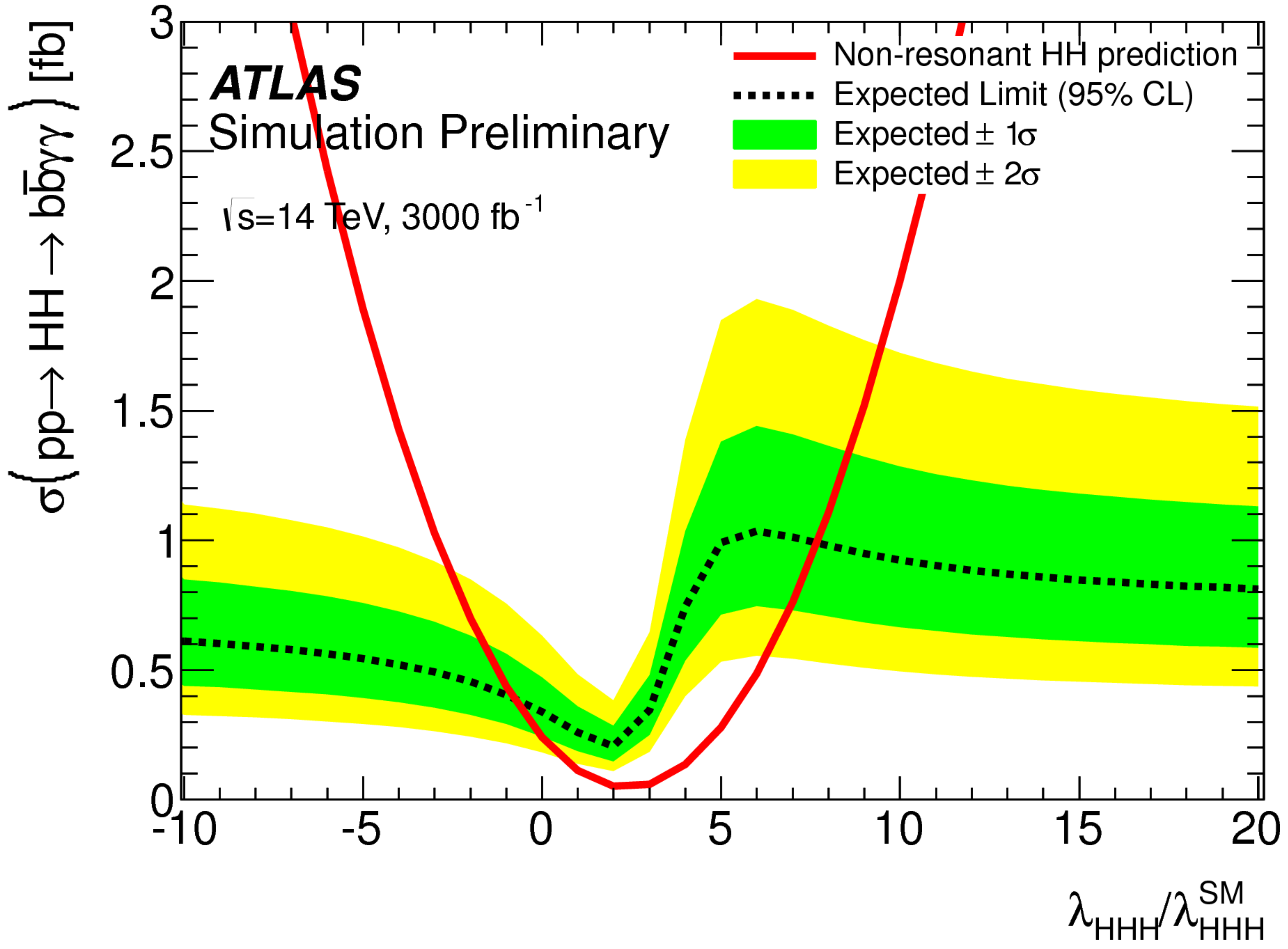
- ***Measurement:***
  70xSM limit on HH X-section
- ***Extrapolation to HL-LHC:***
  $-0.8 < \kappa_\lambda < 7.7$ *(no systematics)*

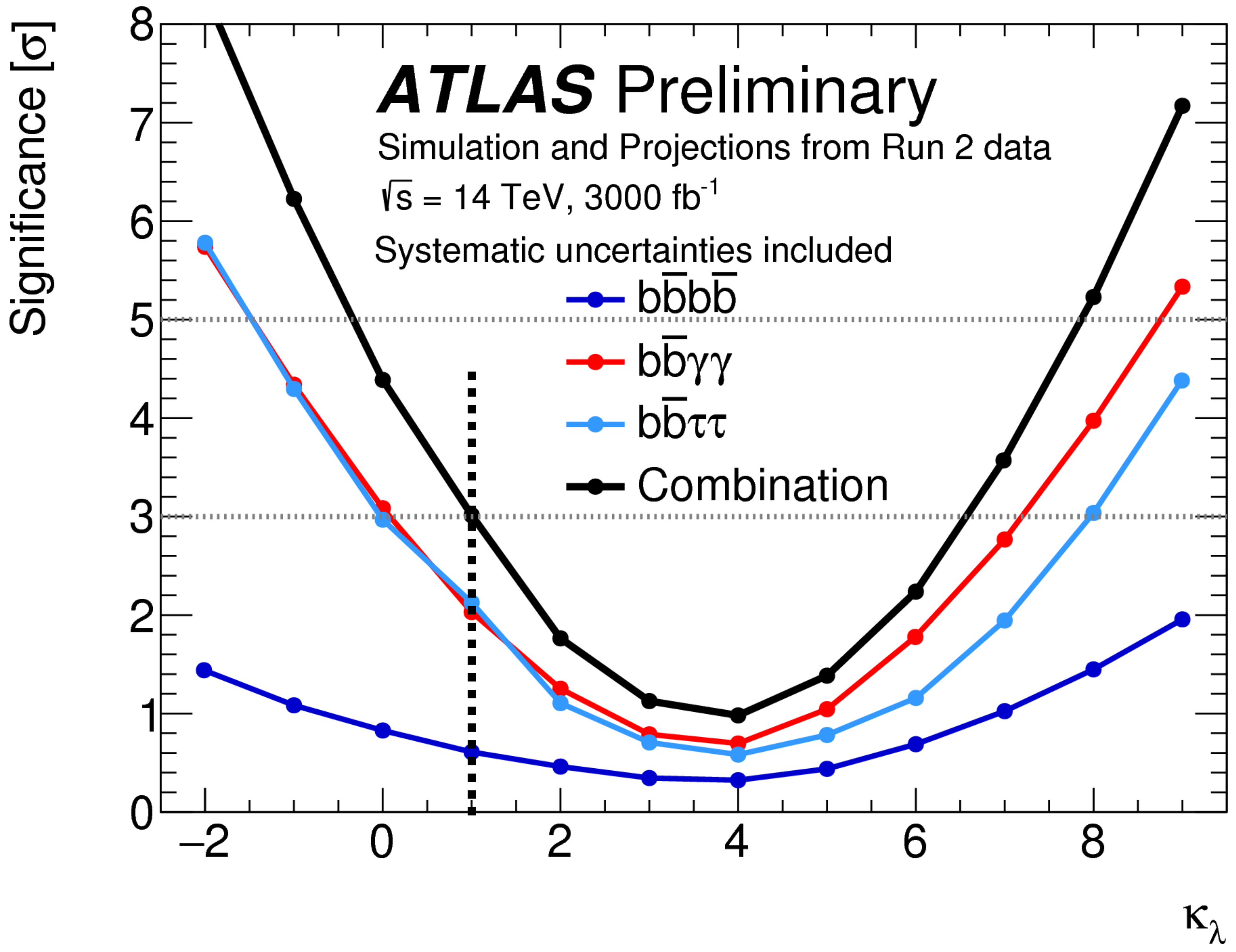
Prospects for the High-Luminosity LHC

Run 1 → First Run 2

4.5/20.3 fb^{-1} at 7/8 TeV

36 fb^{-1} at 13 TeV





- ***Measurement:***
  70xSM limit on HH X-section
- ***Extrapolation to HL-LHC:***
  $-0.8 < \kappa_\lambda < 7.7$ *(no systematics)*

- ***Measurement:***
  $-5 < \kappa_\lambda < 12$
- ***Extrapolation to HL-LHC:***
  $-0.4 < \kappa_\lambda < 7.3$

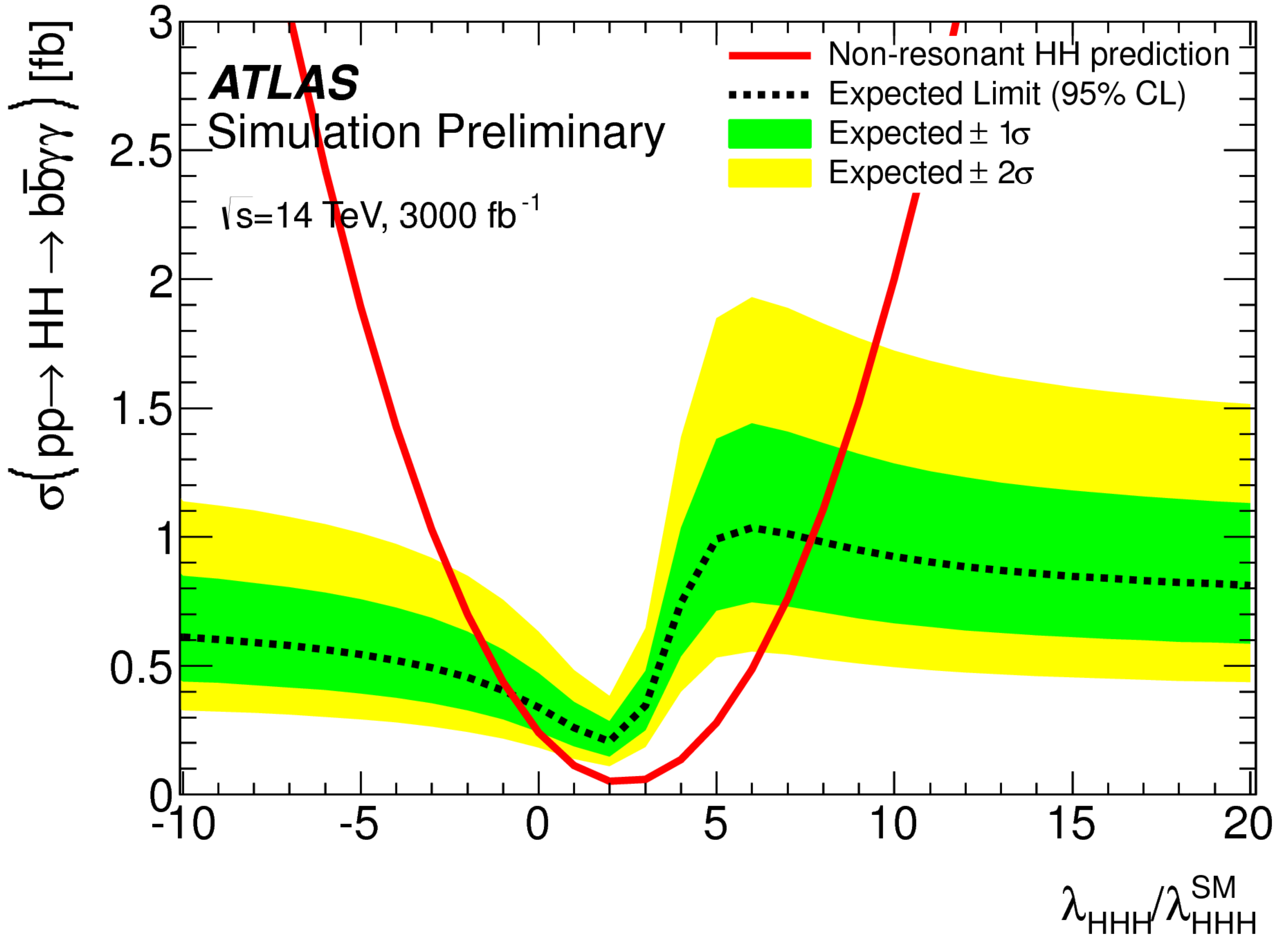
Prospects for the High-Luminosity LHC

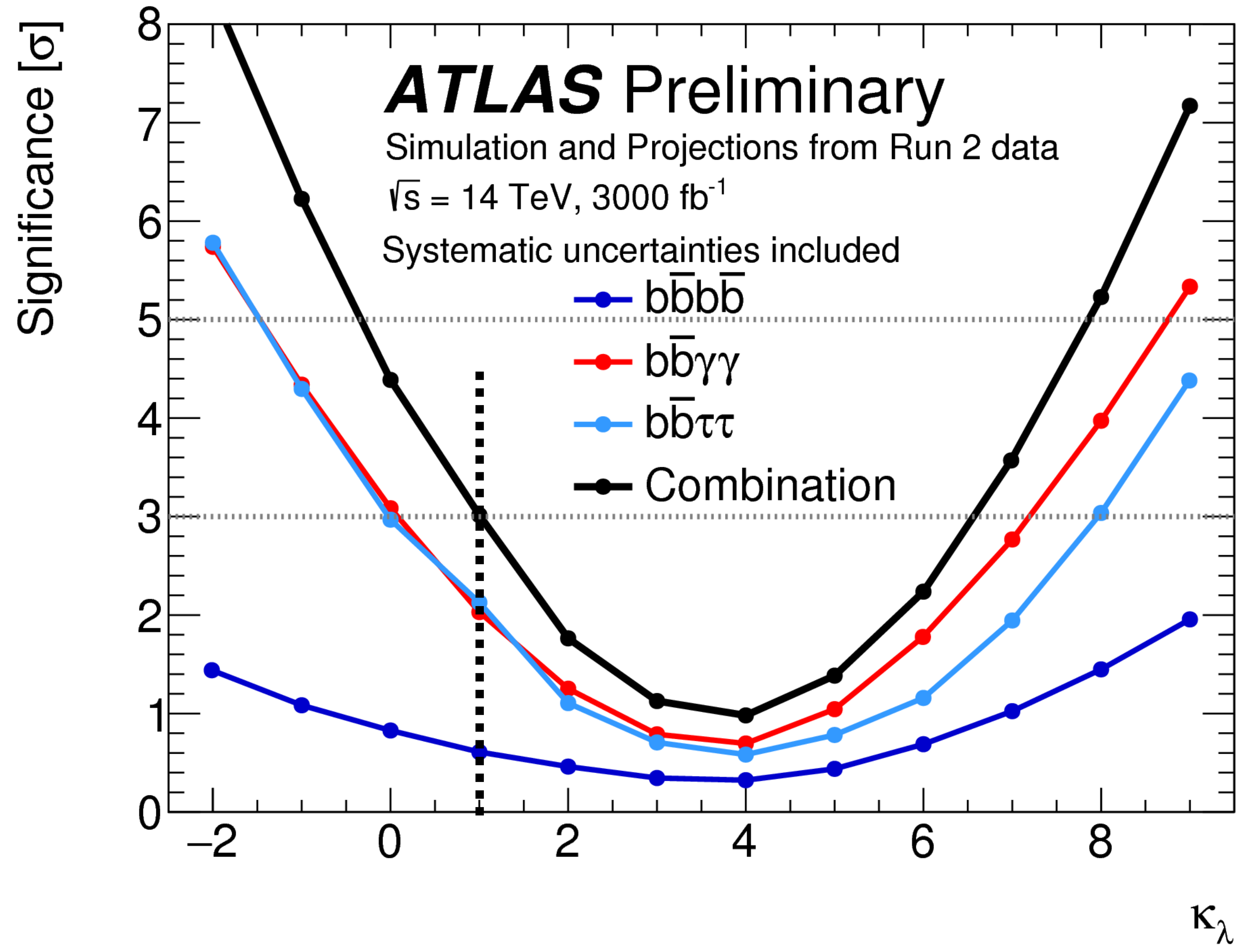
Run 1 → First Run 2 → Full Run 2

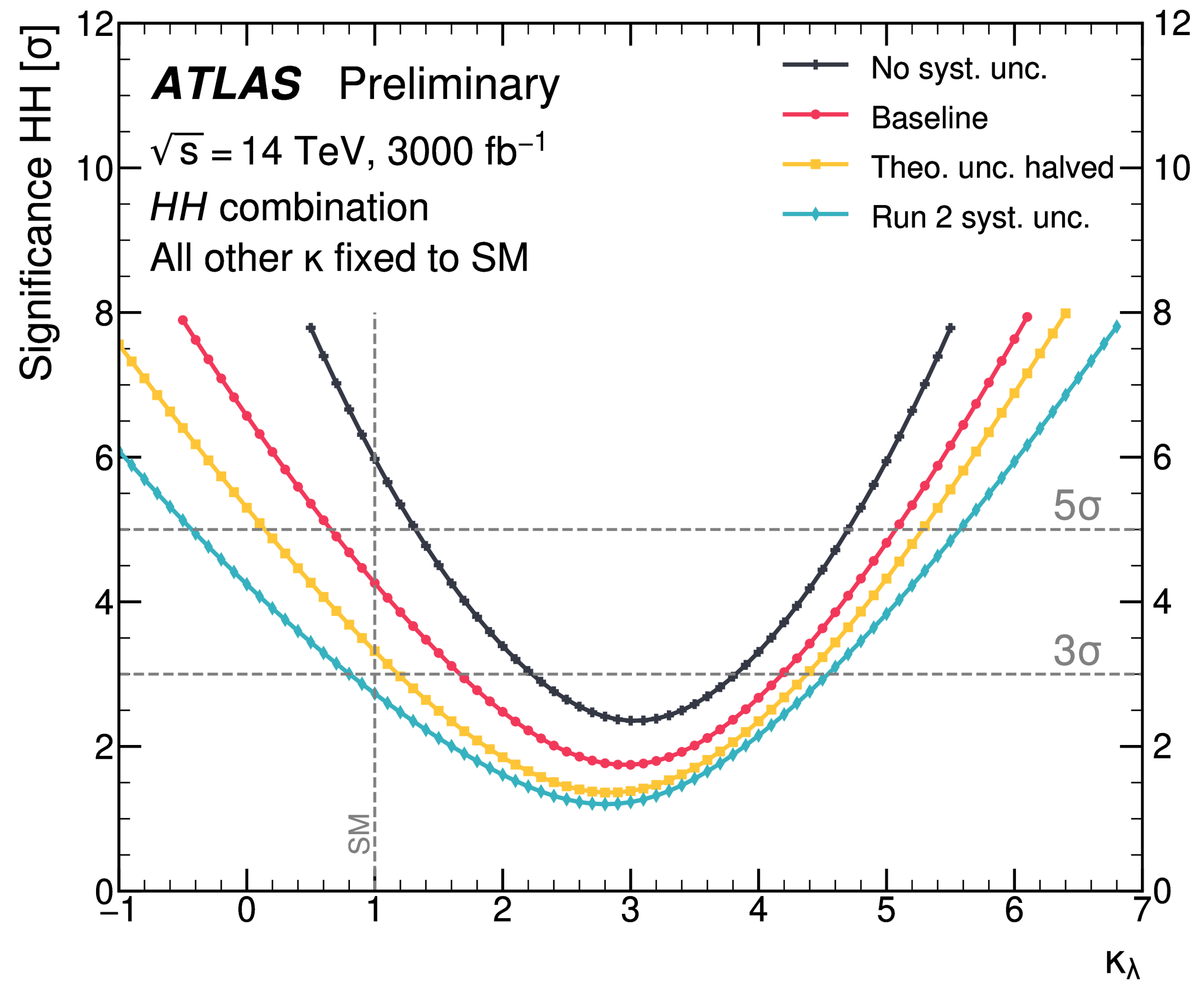
Run 1: $4.5/20.3\ fb^{-1}$ at 7/8 TeV

First Run 2: $36\ fb^{-1}$ at 13 TeV

Full Run 2: $140\ fb^{-1}$ at 13 TeV







- ***Measurement:***
  70xSM limit on HH X-section
- ***Extrapolation to HL-LHC:***
  $-0.8 < \kappa_\lambda < 7.7$ *(no systematics)*

- ***Measurement:***
  $-5 < \kappa_\lambda < 12$
- ***Extrapolation to HL-LHC:***
  $-0.4 < \kappa_\lambda < 7.3$

- ***Measurement:***
  $-1.2 < \kappa_\lambda < 7.2$
- ***Extrapolation to HL-LHC:***
  $0.58 < \kappa_\lambda < 1.48$

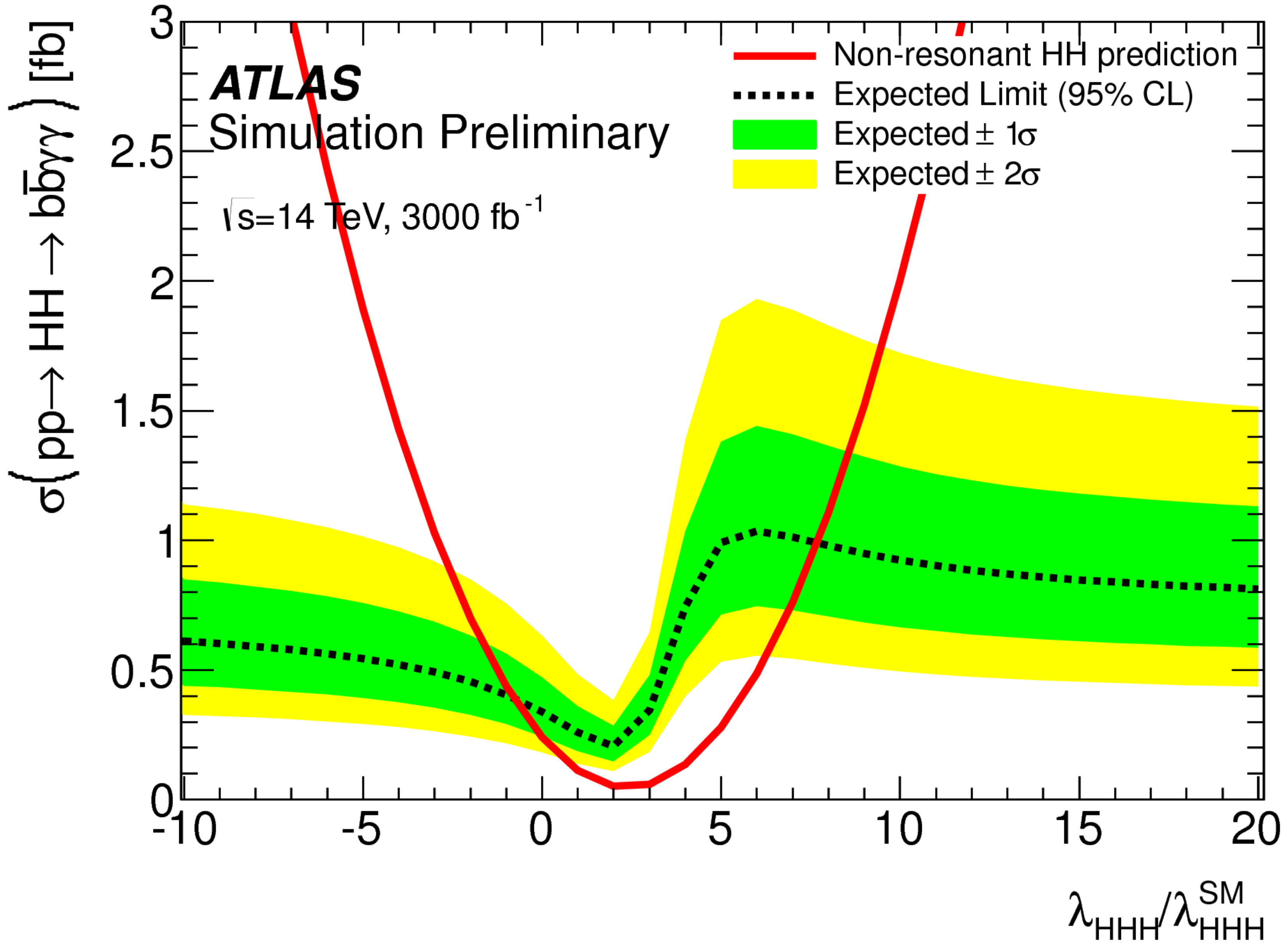
Prospects for the High-Luminosity LHC

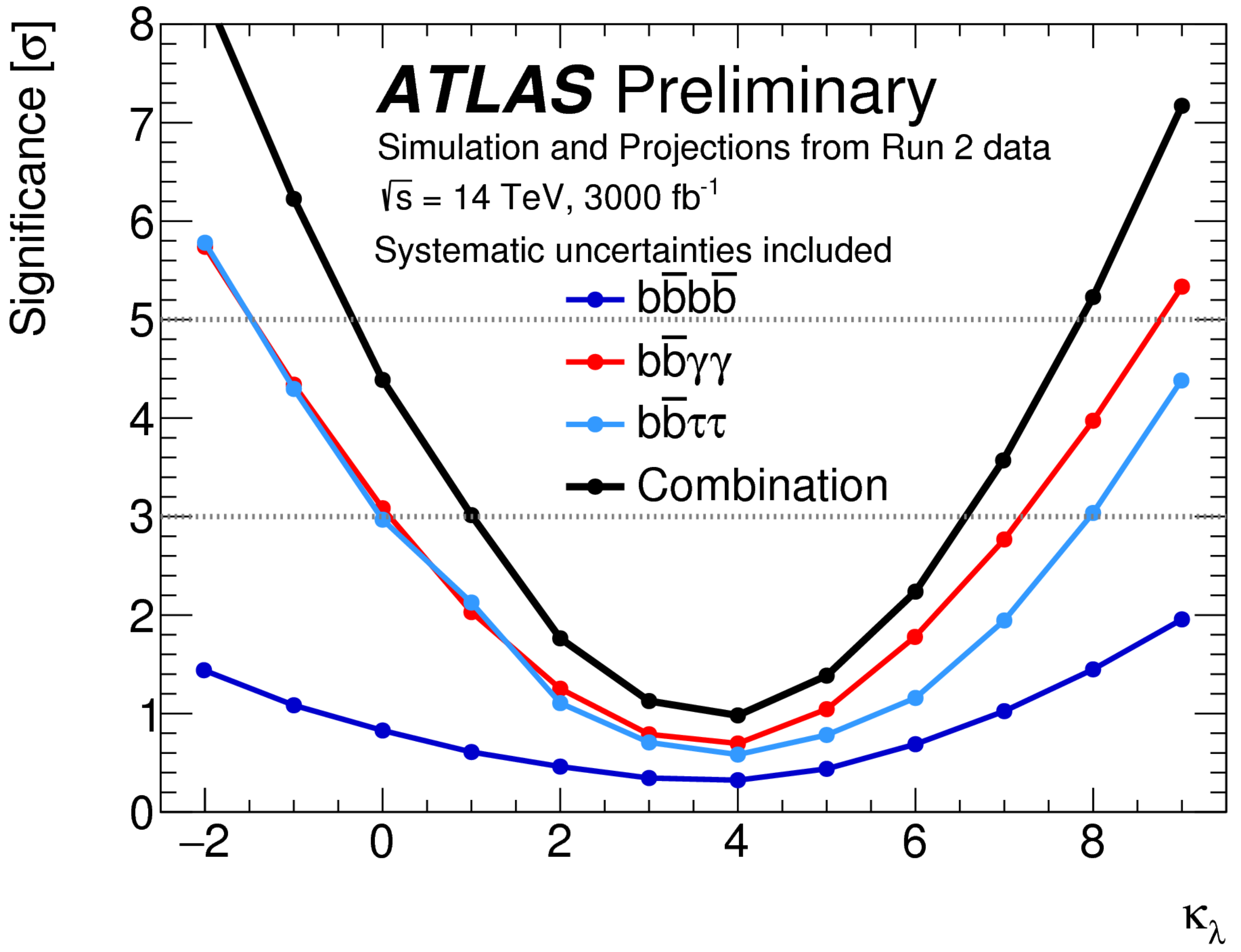
Run 1 → First Run 2 → Full Run 2

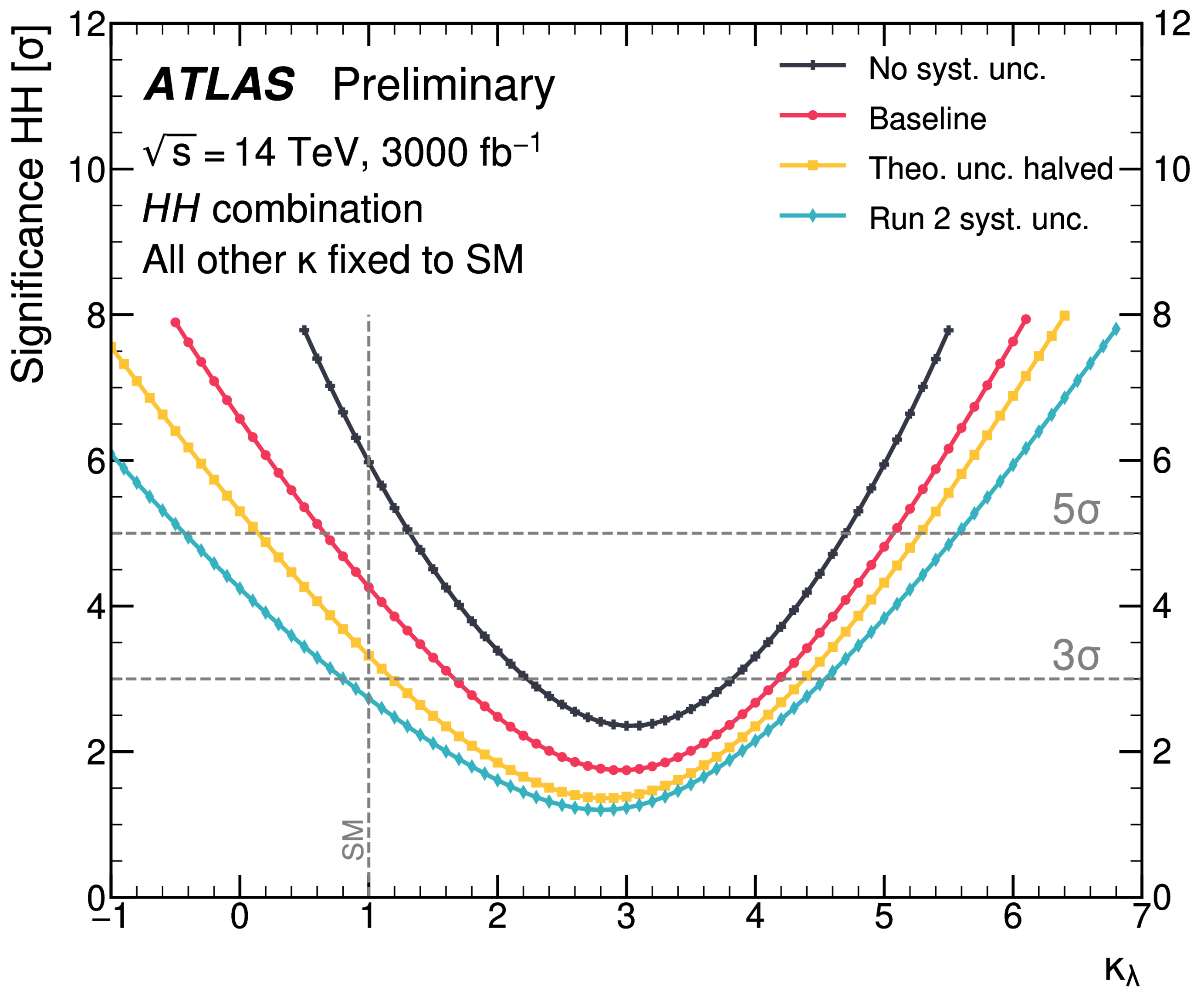
Run 1: $4.5/20.3\ fb^{-1}$ at 7/8 TeV

First Run 2: $36\ fb^{-1}$ at 13 TeV

Full Run 2: $140\ fb^{-1}$ at 13 TeV







- ***Measurement:***
  70xSM limit on HH X-section
- ***Extrapolation to HL-LHC:***
  $-0.8 < \kappa_\lambda < 7.7$ *(no systematics)*

- ***Measurement:***
  $-5 < \kappa_\lambda < 12$
- ***Extrapolation to HL-LHC:***
  $-0.4 < \kappa_\lambda < 7.3$

- ***Measurement:***
  $-1.2 < \kappa_\lambda < 7.2$
- ***Extrapolation to HL-LHC:***
  $0.58 < \kappa_\lambda < 1.48$

2015 → 2018 → 2025

Thank you very much!