ATLAS EXPERIMENT

Prospects for Single- and Di-Higgs Measurements at the HL-LHC with ATLAS

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On behalf of the ATLAS experiment

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High Luminosity LHC (HL-LHC)

Higgs Discovery

HL-LHC:
$3000\ fb^{-1}$ at $\sqrt{s}=14$ TeV
expected

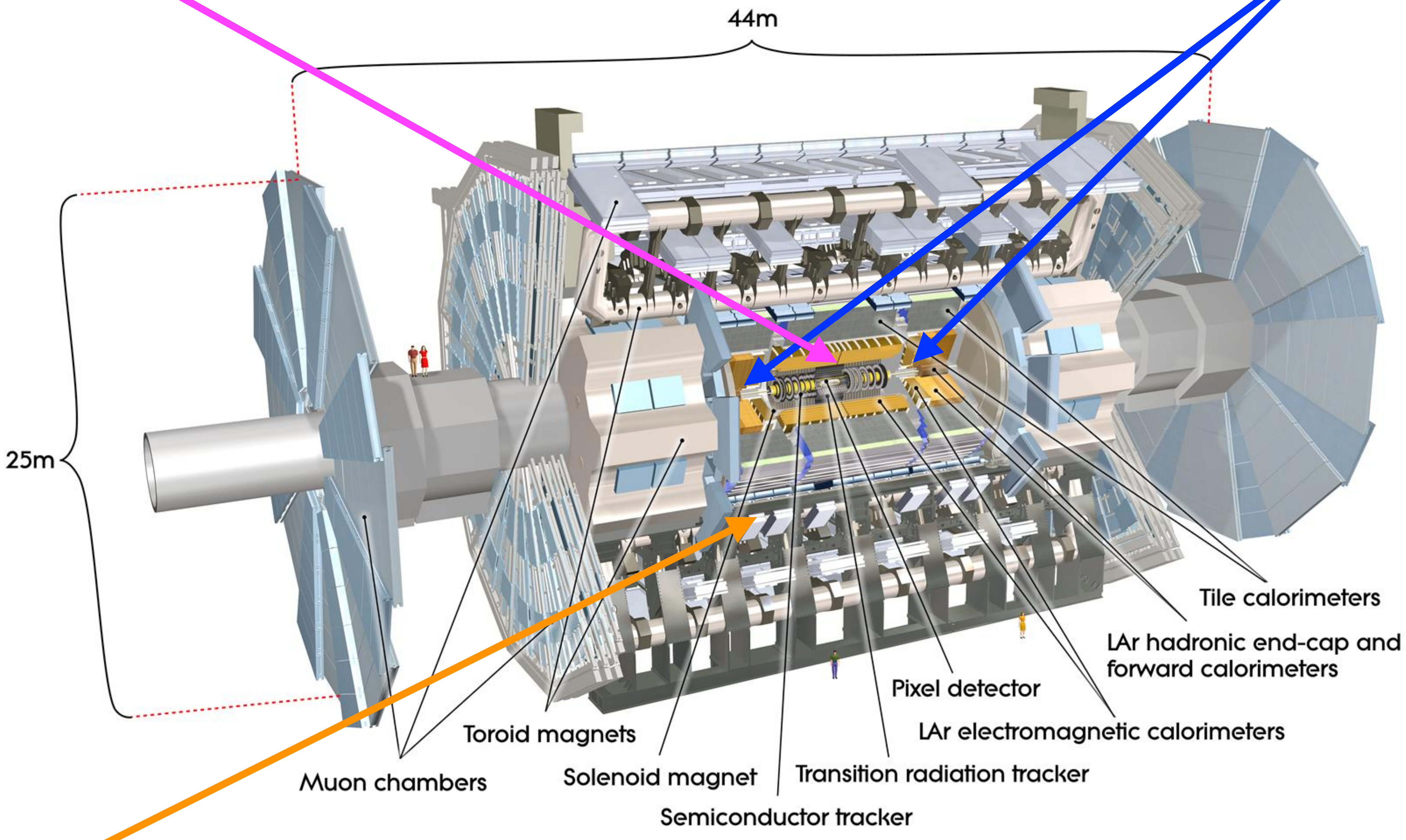
- HL-LHC will provide 20 times the dataset delivered so far!
  - But a more challenging environment, with up to 200 additional interactions per bunch crossing, up to an order of magnitude larger radiation dose
- Upgrades to the LHC and detectors needed for efficient data taking and event reconstruction at increased luminosity, and in a challenging environment

High Luminosity LHC web page

ATLAS Upgrades for HL-LHC

New all-silicon inner tracker (ITK) with coverage up to $|\eta|=4$

New High Granularity Timing Detector (HGTD) in forward region



Front-end to be replaced for calorimeters and muon detectors

New TDAQ off-detector electronics

- `L0` hardware trigger
  - with an output rate of 1 MHz
- Event Filter
  - with an output rate of 10 kHz

New muon chambers in barrel inner region

[General overview of ATLAS Upgrades projects for HL-LHC]

ATLAS HL-LHC Projection Strategies

CERN Yellow Report from European Strategy for Particle Physics (2019):

Yellow Report

- Report on the Physics at the HL-LHC and Perspectives for the HE-LHC

Snowmass White Paper (2022):

Snow mass

- Physics with the Phase-2 ATLAS and CMS Detectors

Two main strategies for ATLAS projections:

- Extrapolations based on Run-2 results
  - Benefit from well-studied systematics models developed for the Run-2 analyses
    - A baseline scenario: "*YR18 Systematic Uncertainties*"
- Parametric simulations based on detailed simulations of the upgraded detectors under HL-LHC conditions

For the extrapolations, a HL-LHC scenario corresponding to a dataset of 3000 fb^{-1} of pp collisions at $\sqrt{s}$ = 14 TeV is considered

Higgs Boson Mass and Width

Yellow Report

ATL-PHYS-PUB-2018-054
CERN-2019-007

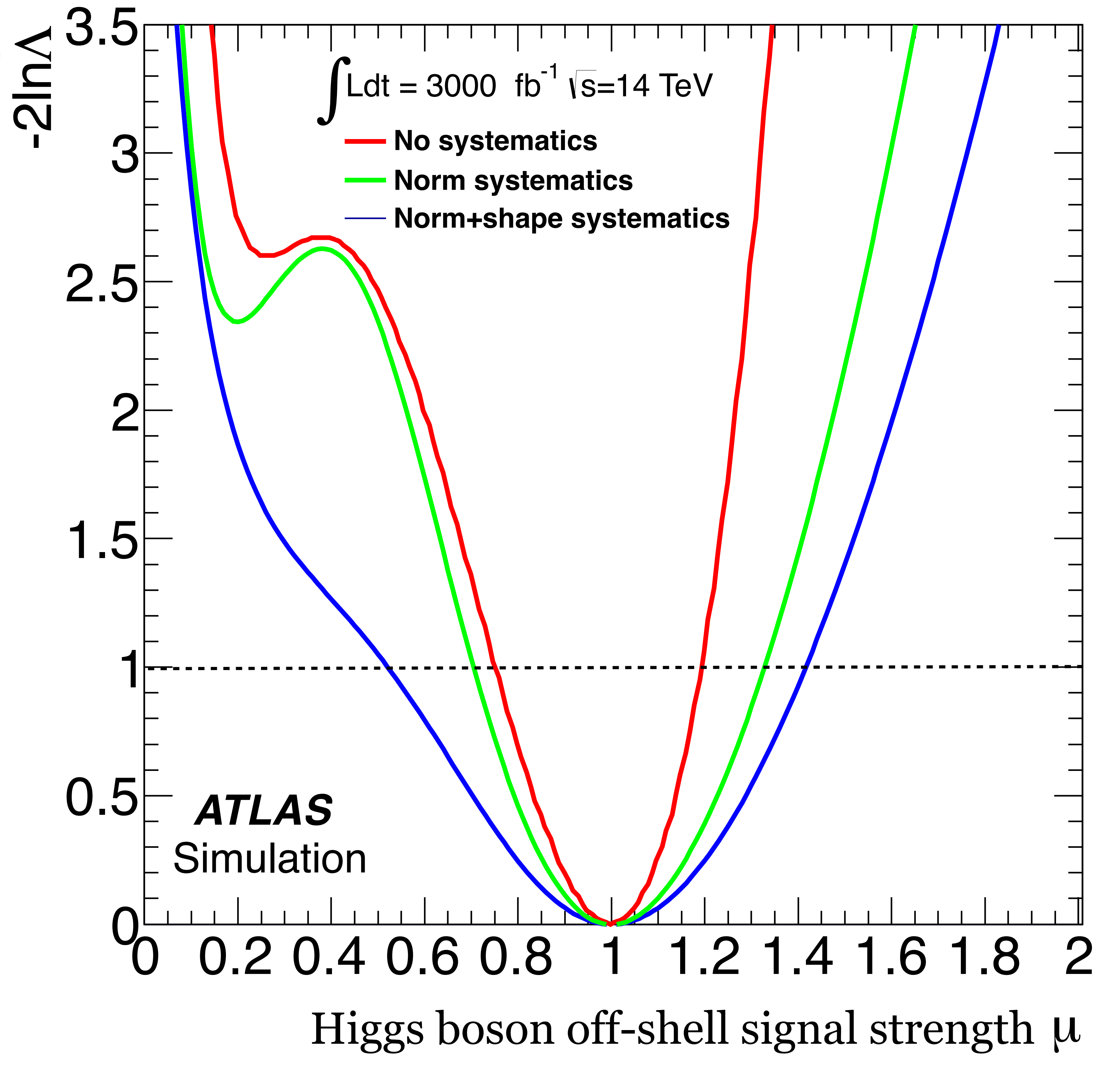
Higgs boson mass measurement projections

- Based on the H→Z Z*→ 4ℓ channel results
  - The least sensitive to systematic uncertainties

	Δ_{tot} (MeV)	Δ_{stat} (MeV)	Δ_{syst} (MeV)
Current Detector	52	39	35
μ momentum resolution improvement by 30% or similar	47	30	37
μ momentum resolution/scale improvement of 30% / 50%	38	30	24
μ momentum resolution/scale improvement 30% / 80%	33	30	14

Higgs boson width projections

- Based on Run-1 Analysis
- Only H→Z Z*→ 4ℓ final state used
- Only theoretical uncertainties considered, systematics uncertainties are negligible
- The expected precision on Γ_H at 3000 fb^{-1}
  - 4.2 MeV + 1.5 MeV - 2.1 MeV

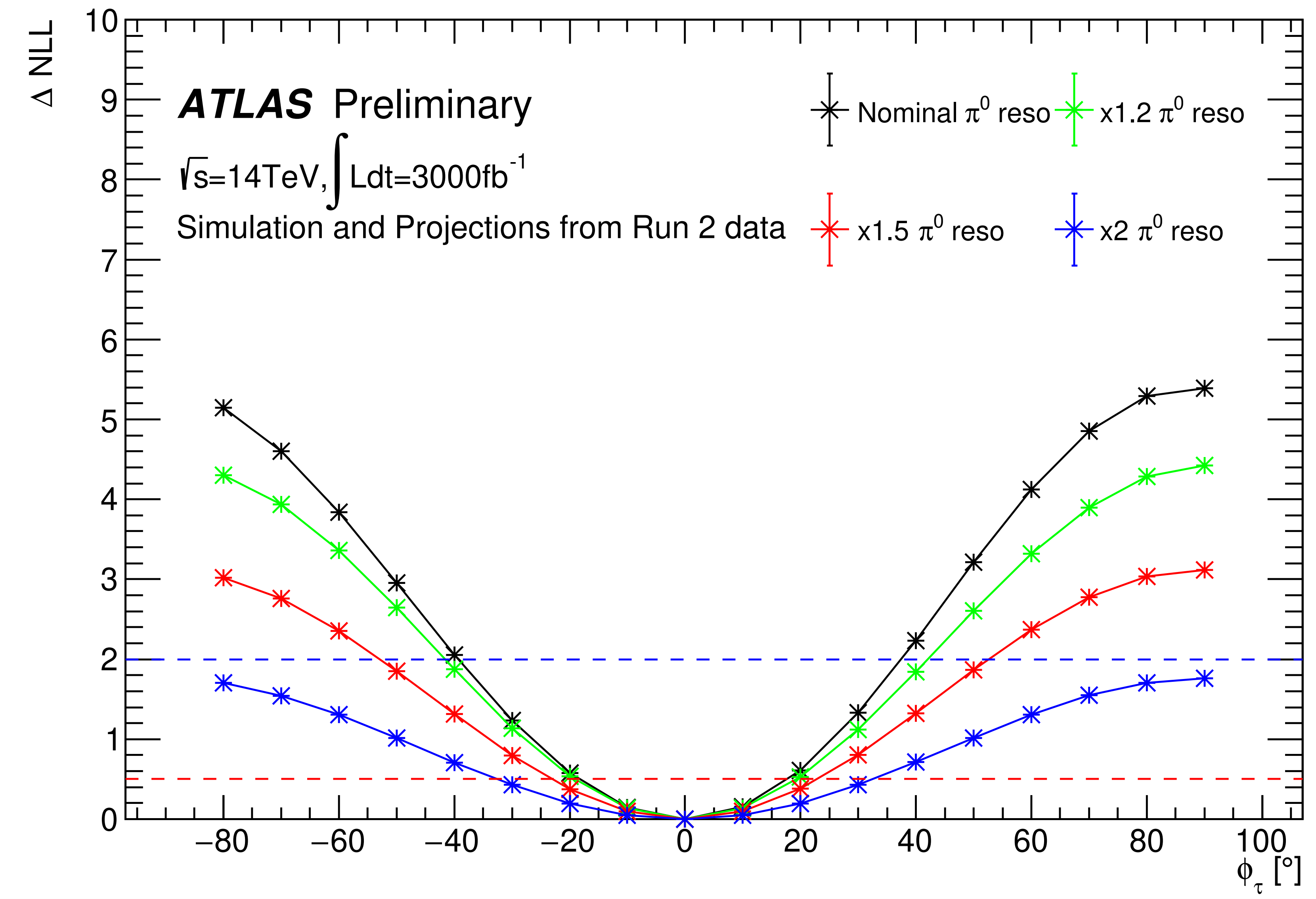


Higgs Boson Spin/CP

Yellow Report

ATL-PHYS-PUB-2019-008

- Measurement of the *CP* quantum number of the Higgs boson coupling to τ leptons
  - Based on estimates from the measurement of the $H \to \tau\tau$ cross section with 36.1 fb^{-1} of $\sqrt{s}$=13 TeV data
- Contributions from *CP*-violating interactions between the Higgs boson and τ leptons are described by a single mixing angle parameter φ_τ
  - $\varphi_\tau = 0$ for the SM (pure scalar)
  - $\varphi_\tau = \pi/2$ for maximally CP-odd coupling (pure pseudoscalar)
- Only $\tau^\pm \to \rho^\pm \nu_\tau \to \pi^\pm \pi^0 \nu_\tau$ decays considered
  - The direction of the pions retain a strong correlations to the τ spin direction



The pseudoscalar hypothesis excluded at 95% CL even with 1.5x nominal π^0 resolution

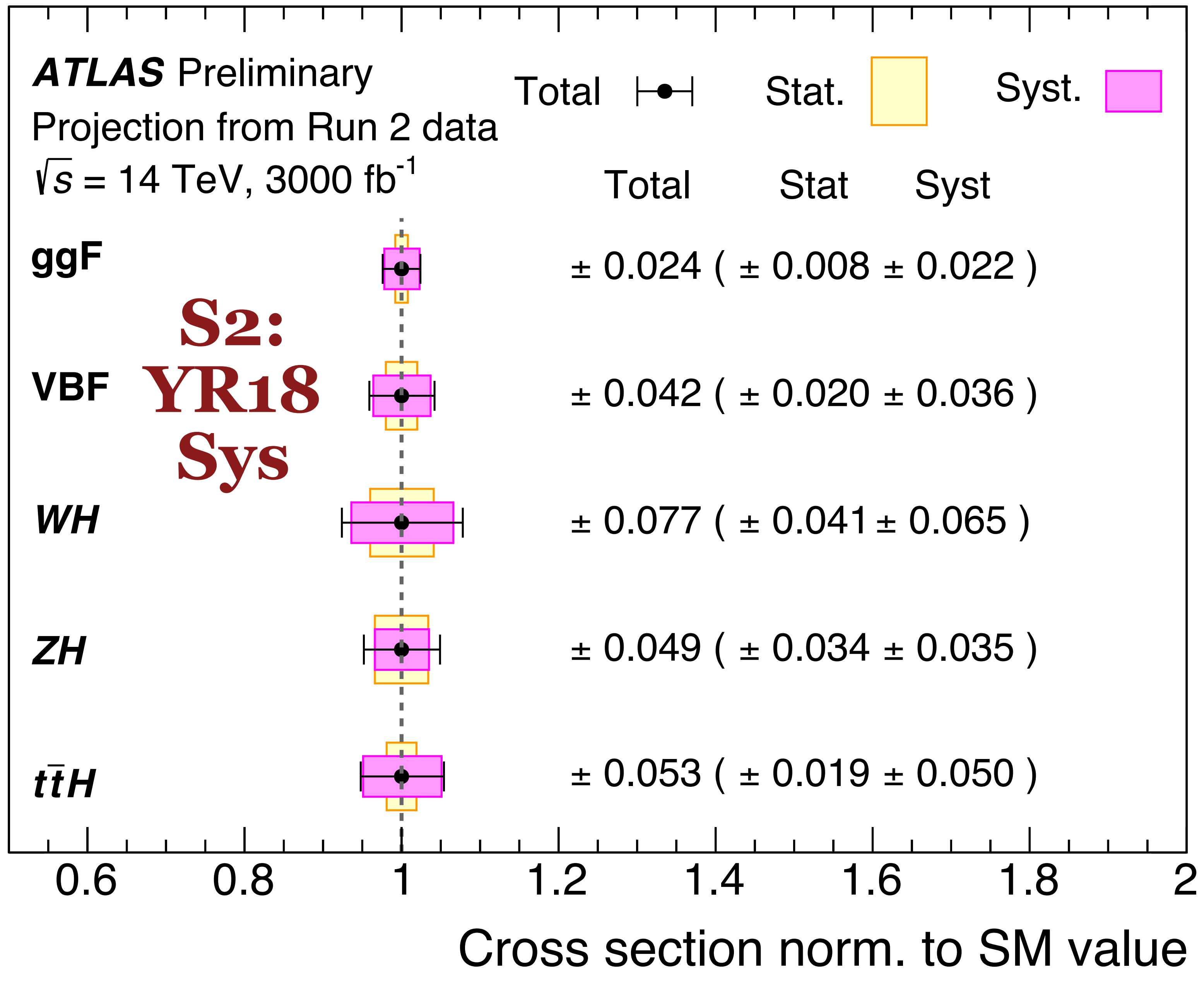
A statistical precision of approximately ±18° and ±33° assuming the nominal or 2x π^0 resolution at 68% CL

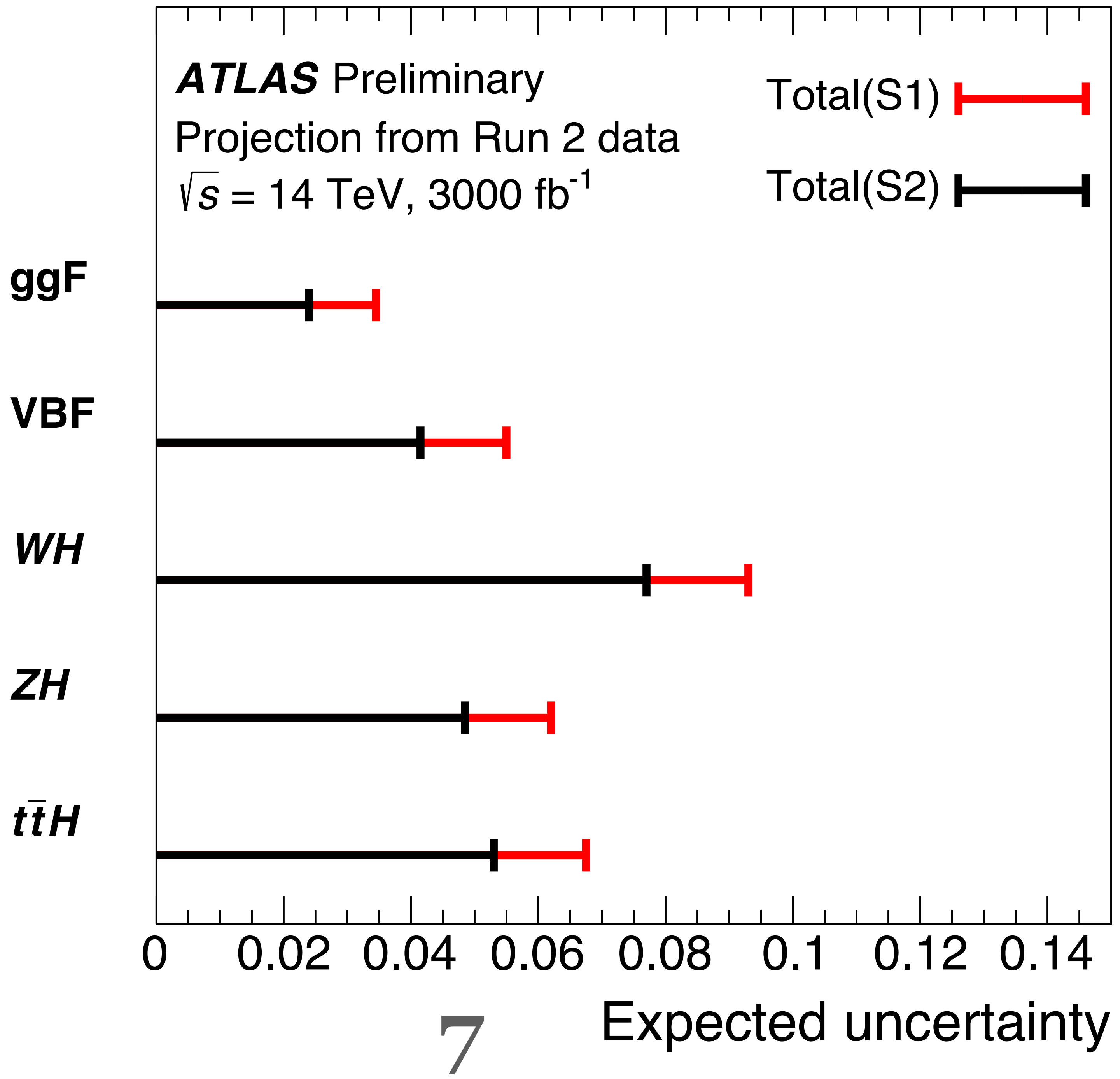
Higgs Boson Cross-Section

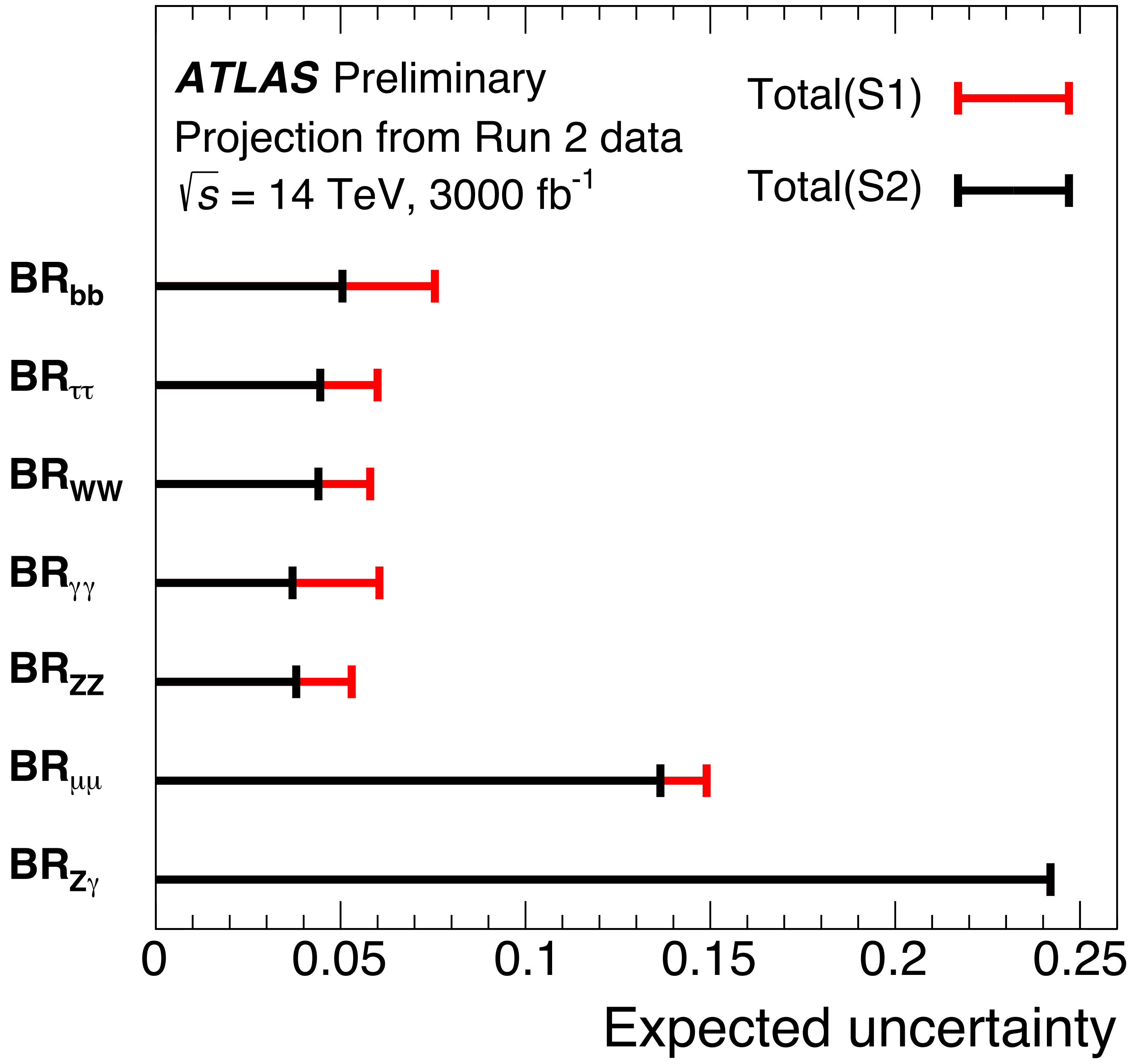
Yellow Report

ATL-PHYS-PUB-2018-054

- Extrapolated from the Run-2 results using datasets of 36 fb^{-1} and 80 fb^{-1} collected at 13 TeV
- All the extrapolated single-channel results are combined to compute the cross sections per production mode and the branching ratios
- ggF, VBF, VH, ttH+tH production modes are studied
- Decays of the Higgs boson to γγ, Z Z, WW, ττ, bb considered







Higgs Boson Coupling Modifiers

Yellow Report

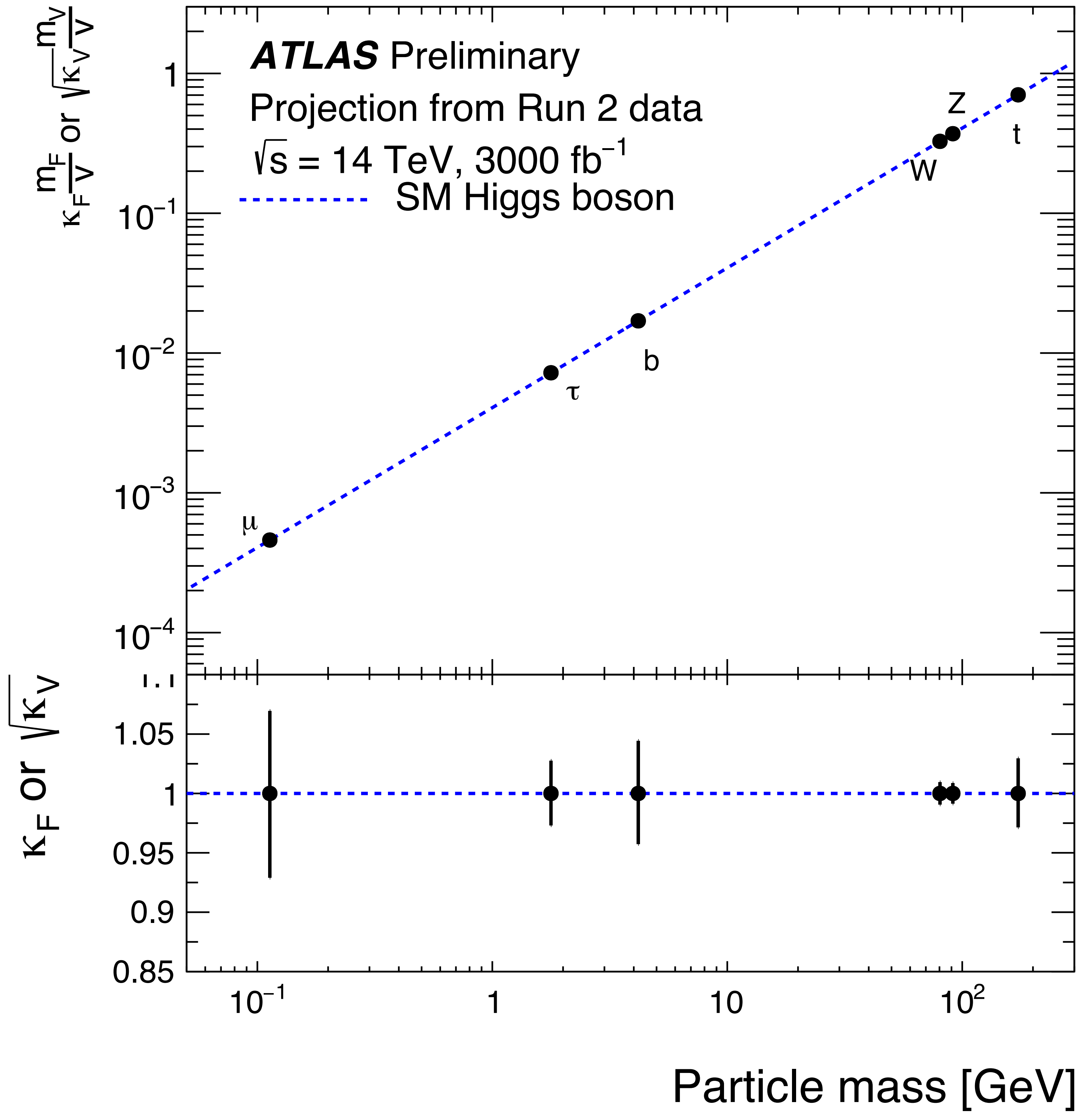
ATL-PHYS-PUB-2018-054

- Results are interpreted for Higgs boson coupling modifiers κ
- No BSM contribution to the Higgs boson total width

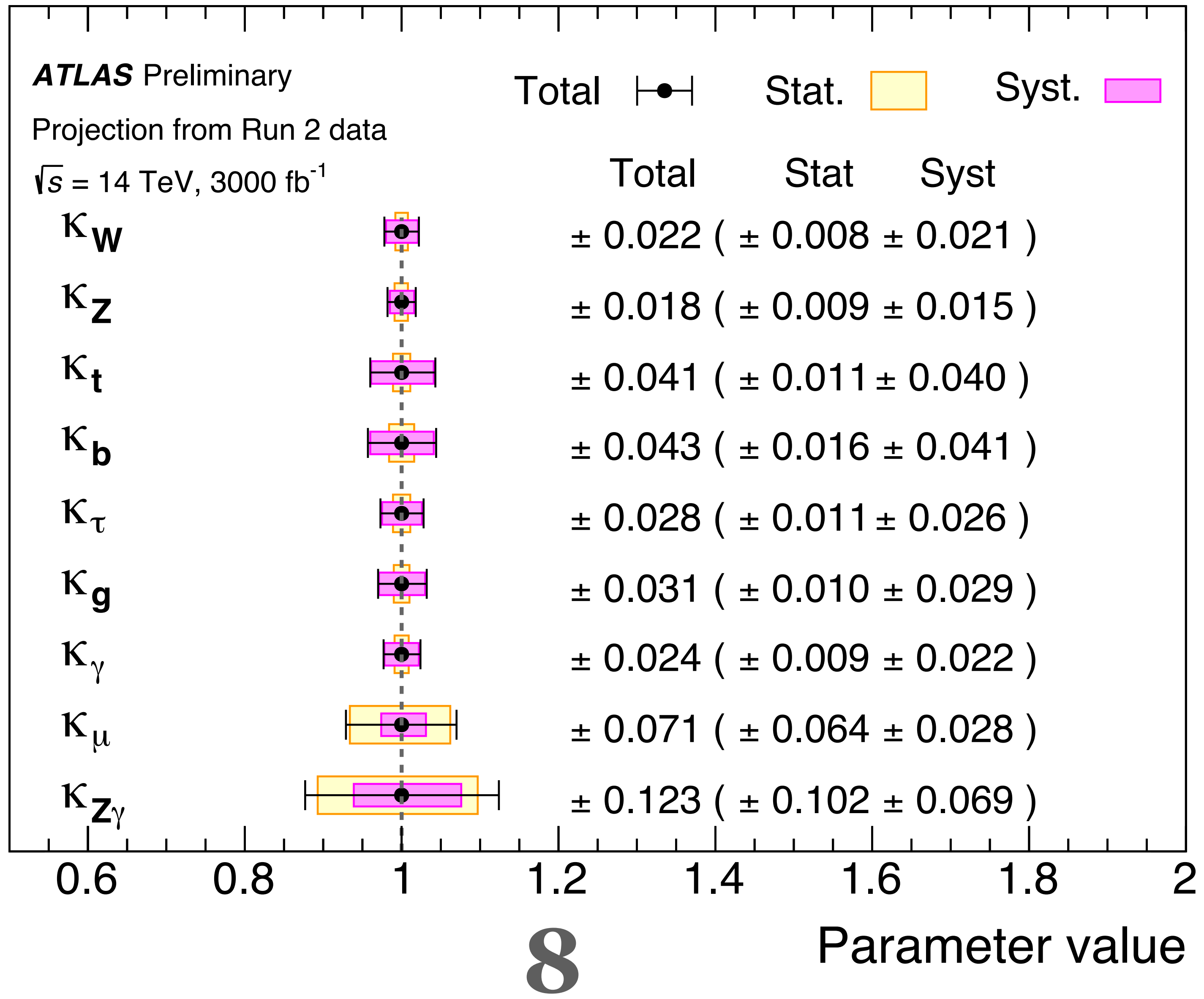
$$\sigma_i \times \mathrm{B}(H \to f) = \frac{\sigma_i \times \Gamma_f}{\Gamma_H}$$
$$= \frac{\kappa_i^2 \kappa_f^2}{\kappa_H^2} \sigma_i^{\mathrm{SM}} \times \mathrm{B}^{\mathrm{SM}}(H \to f)$$

$$\kappa_H^2 = \frac{\sum_f \kappa_f^2 \mathrm{B}^{\mathrm{SM}}(H \to f)}{1 - \mathrm{B}_{\mathrm{BSM}}}$$

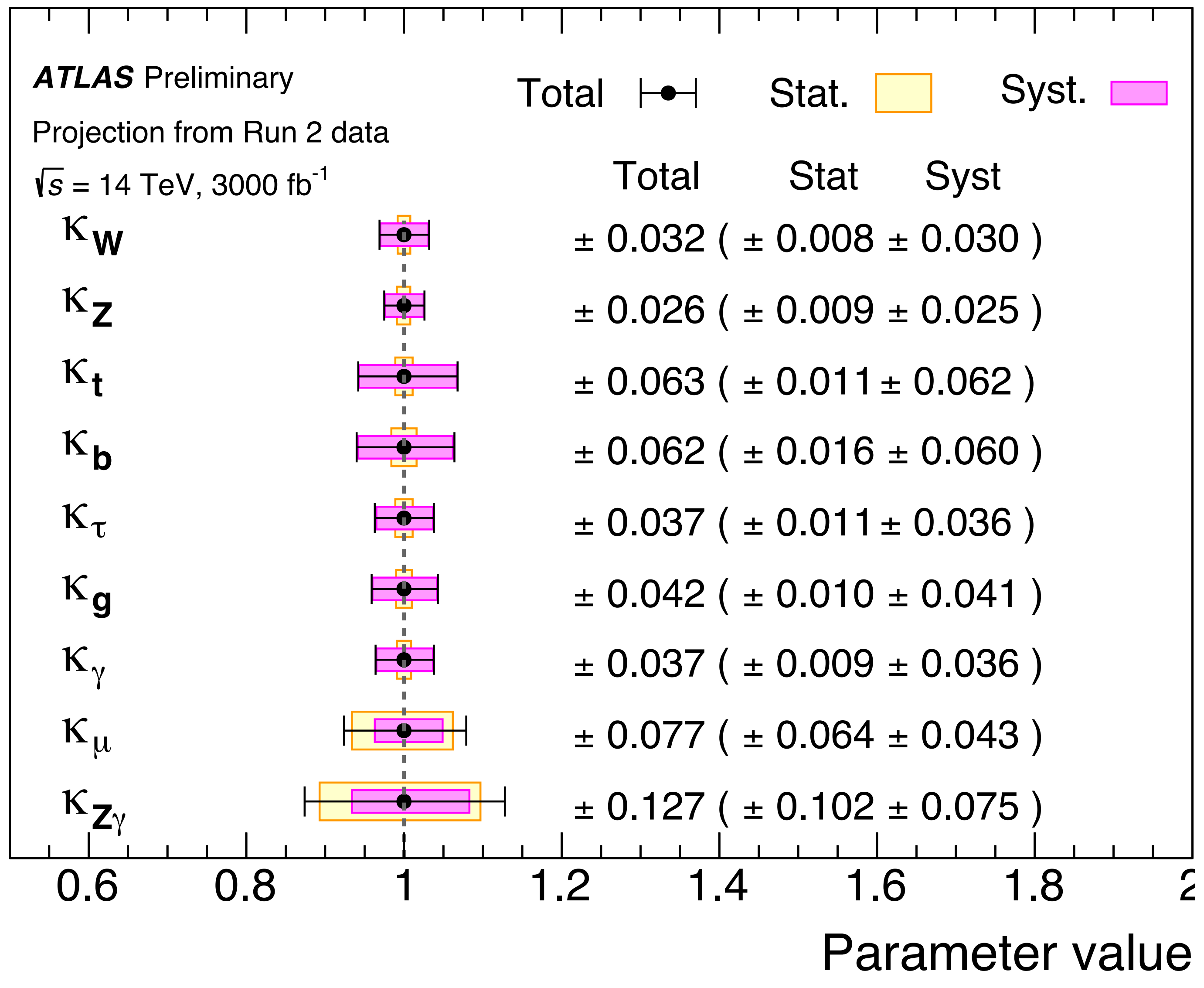
YR18 Systematics



YR18 Systematics



Run 2 Systematics

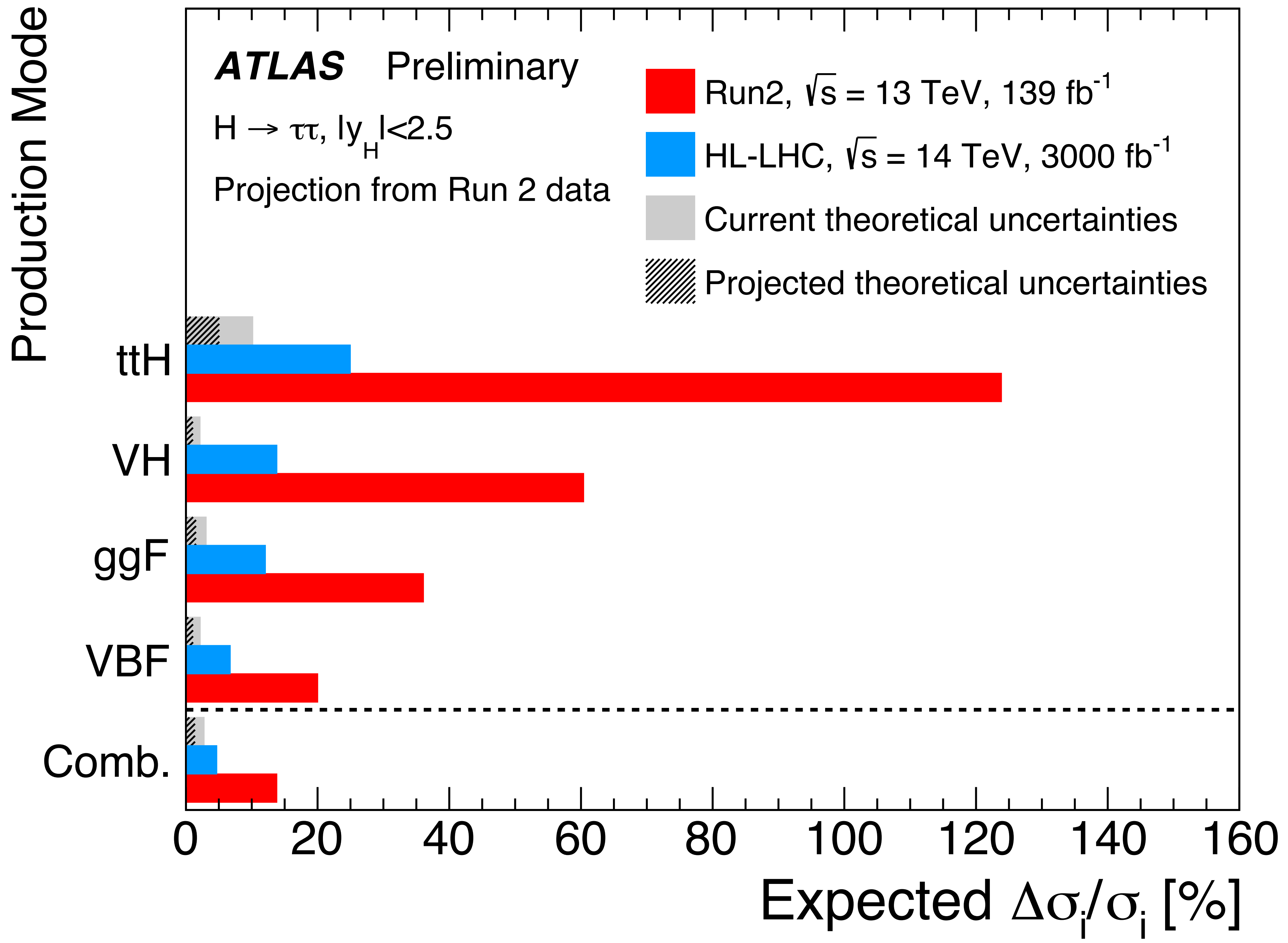


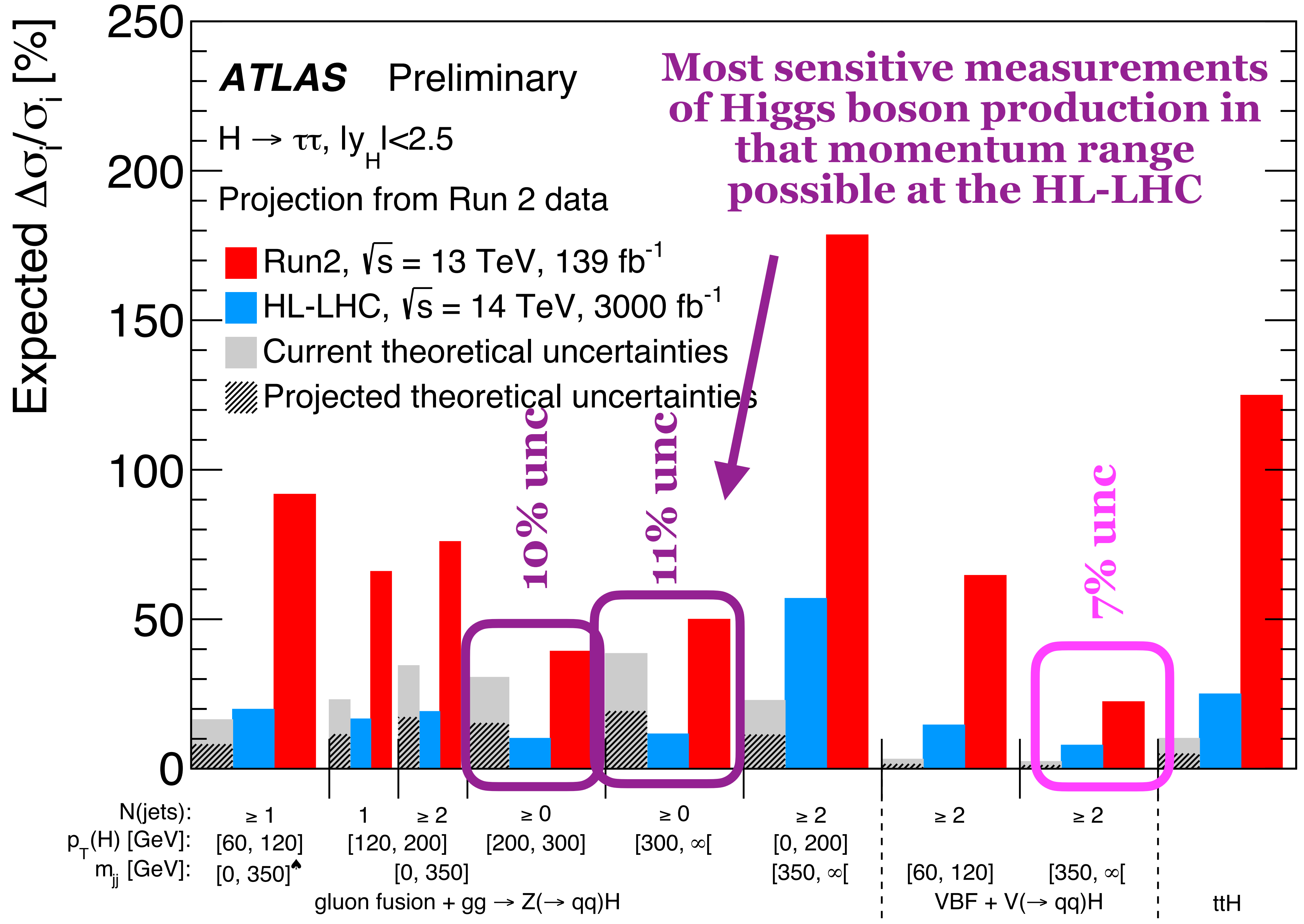
H→ττ Cross-Section

Snow mass

ATL-PHYS-PUB-2022-003

- The inclusive $pp \rightarrow H \rightarrow \tau^+\tau^-$ cross-section measurement is projected to have a precision of 5%
  - $\sigma(pp \rightarrow H \rightarrow \tau^+\tau^-)_{exp} / \sigma(pp \rightarrow H \rightarrow \tau^+\tau^-)_{SM} = 1.00 \pm 0.05 = 1.00 \pm 0.01\ (\text{stat.}) \pm 0.04\ (\text{sig. th.}) \pm 0.02\ (\text{syst})$
- The projected precisions are 11%, 7%, 14%, 24% for ggF, VBF, VH, and ttH production mode measurements, respectively



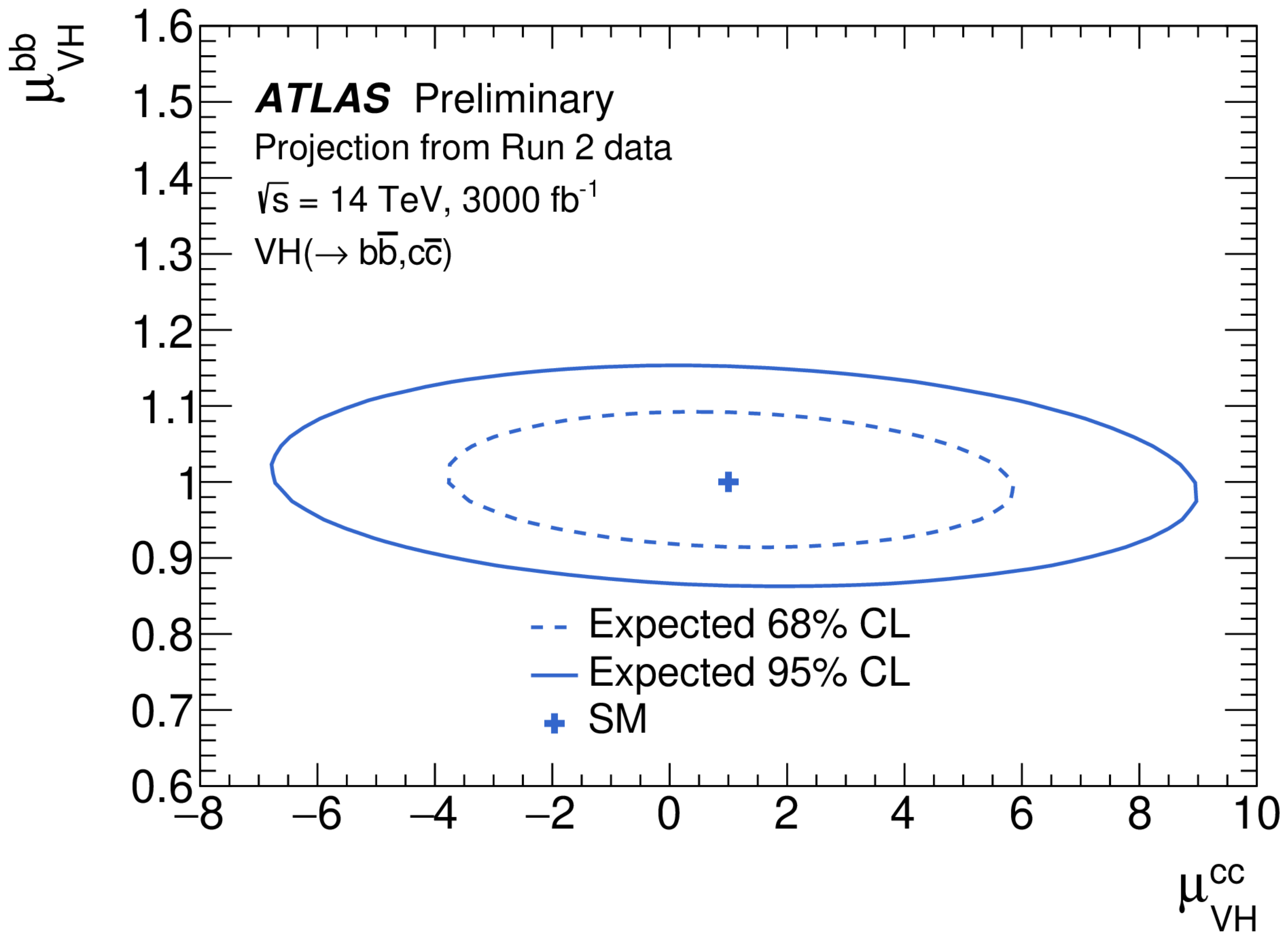


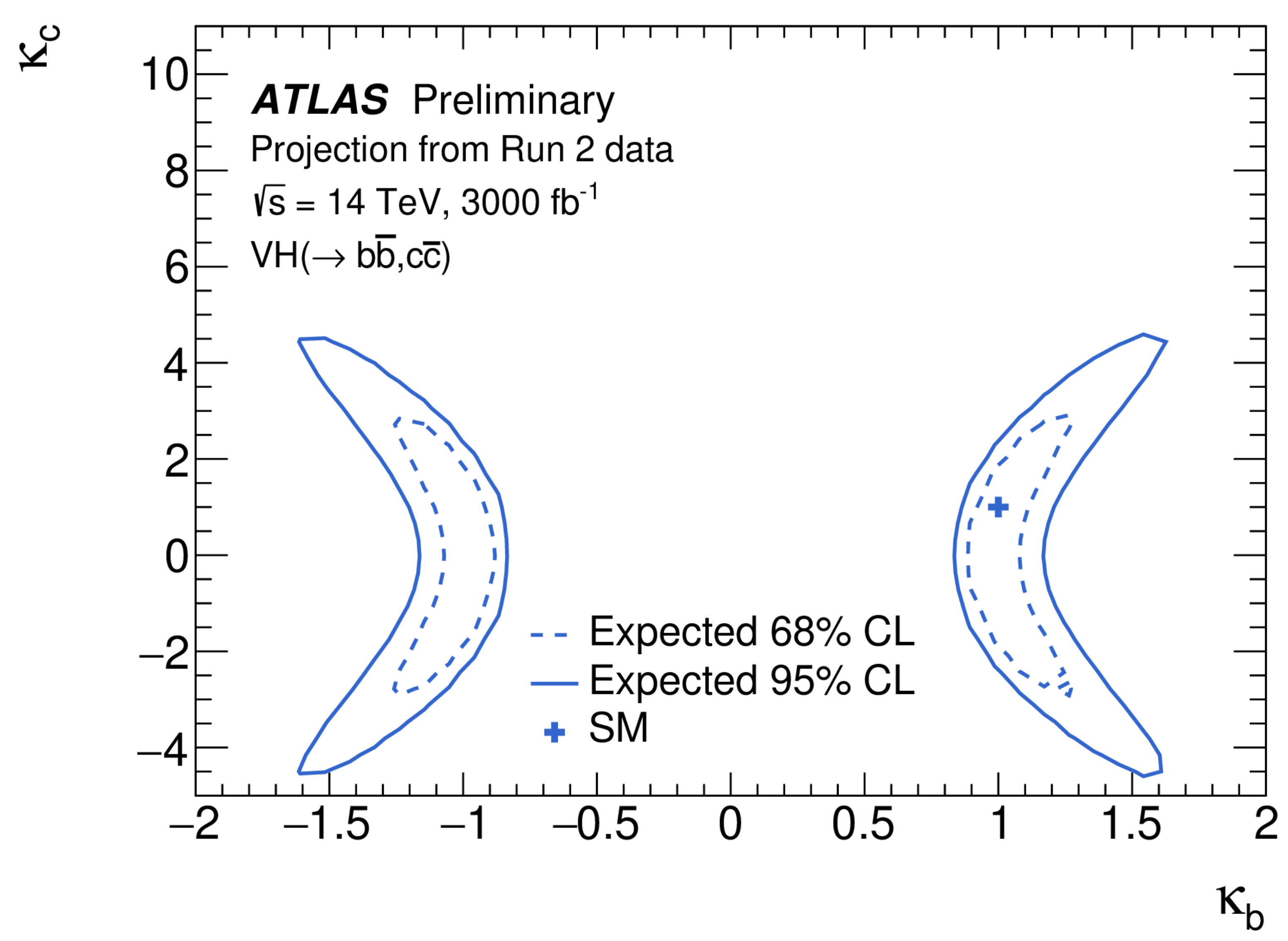
VH, H→bb and VH, H→cc

Snow mass

ATL-PHYS-PUB-2022-018
ATL-PHYS-PUB-2021-039

- The extrapolation from the Run-2 VH, H→bb and VH, H→cc analyses
- Performed a fit to the signal strengths as well as to the coupling modifiers





The expected best fit signal strengths at HL-LHC

- $\mu_{VH}(bb) = 1.00 \pm 0.06$
- $\mu_{VH}(cc) = 1.00 \pm 3.20$

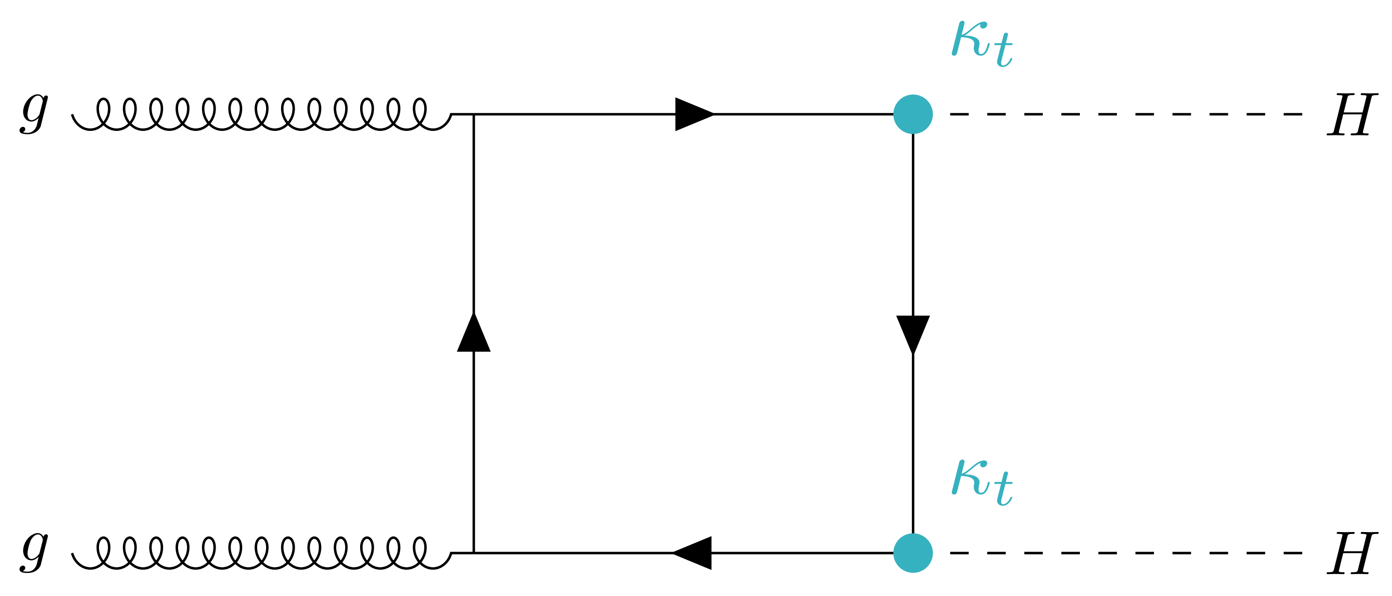
The expected constraint of $|K_c/K_b|$

- $|K_c/K_b| < 2.7$ at 95% CL

Higgs Self-Coupling

- One of the major goals of the HL-LHC is to measure the Higgs boson self-coupling (λ_{HHH})
- Higgs self-coupling is accessible at tree level in HH production and at loop level in single-H production
- SM HH production cross-section (σ_{HH}) is ~1000 times smaller than σ_H
- Various BSM theories predict enhancements in the HH production rate

ggF production - 36.69 fb at √s=14 TeV at NNLO



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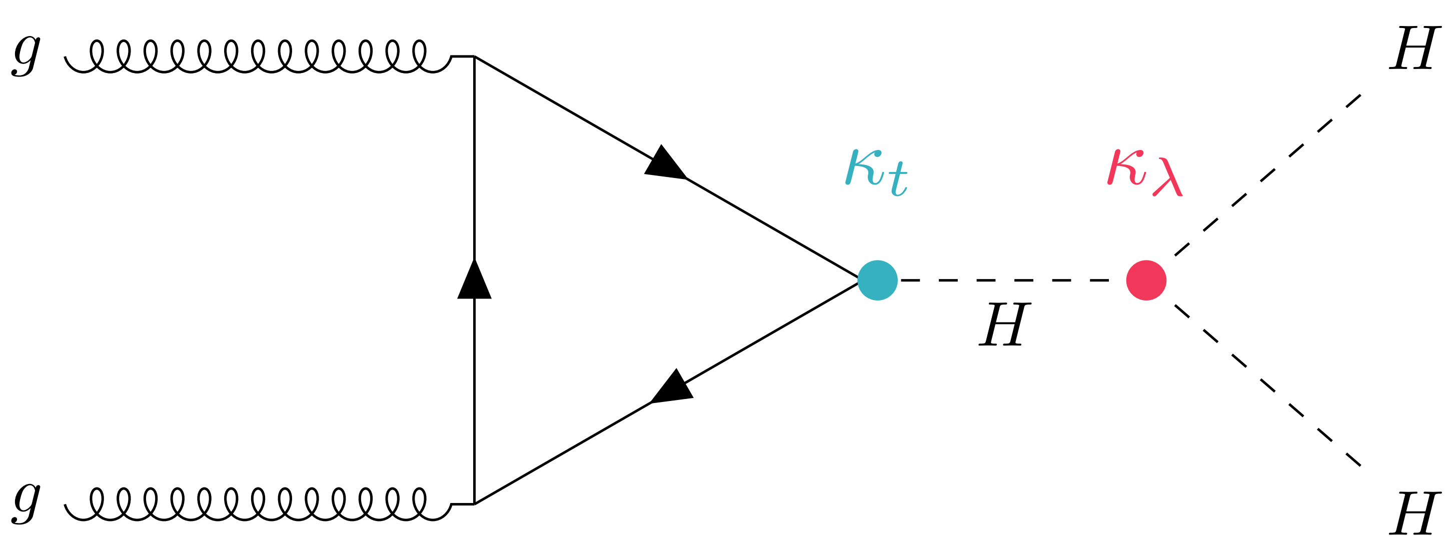


Destructive interference between box and triangle diagrams

Higgs Self-Coupling

Snow mass

bbγγ: ATL-PHYS-PUB-2022-001
bbττ: ATL-PHYS-PUB-2021-044

The projections for the non-resonant HH production in bbγγ and bbττ final states updated

- Results contain substantial improvements (in analysis methods, τ reconstruction identification, b-tagging) with respect to the previous projections
- A statistical combination of these updated projections performed
- Effects of κ_λ on VBF processes were also introduced in the updated results

ATL-PHYS-PUB-2018-053 combination results updated with more realistic b-tagging performance in ATL-PHYS-PUB-2020-005

Channel	Statistical-only	Statistical + Systematic
$HH \to b\bar{b}b\bar{b}$	1.2	0.5
$HH \to b\bar{b}\tau^+\tau^-$	2.3	2.0
$HH \to b\bar{b}\gamma\gamma$	2.1	2.0
Combined	3.3	2.9

Previous results: Combination of bbbb, bbγγ, bbττ

ATL-PHYS-PUB-2022-005

Uncertainty scenario	Significance [σ] $b\bar{b}\gamma\gamma$	$b\bar{b}\tau^+\tau^-$	Combination	Combined signal strength precision [%]
No syst. unc.	2.3	4.0	4.6	$-23/+23$
Baseline	2.2	2.8	3.2	$-31/+34$
Theoretical unc. halved	1.1	1.7	2.0	$-49/+51$
Run 2 syst. unc.	1.1	1.5	1.7	$-57/+68$

Updated results: Combination of bbγγ, bbττ

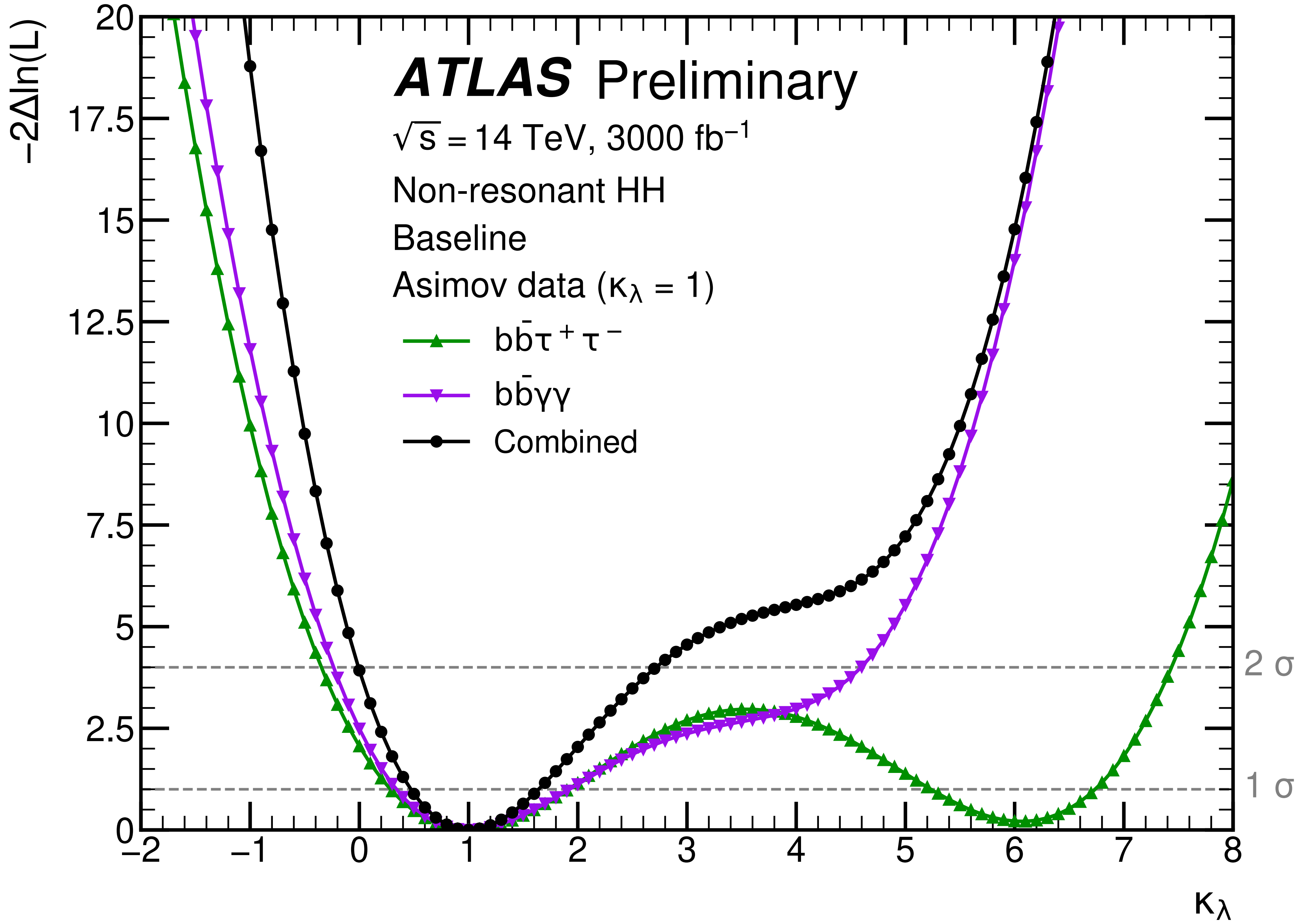
Higgs Self-Coupling

Snow mass

bbγγ: ATL-PHYS-PUB-2021-044
bbττ: ATL-PHYS-PUB-2022-001

The projections for the non-resonant HH production in bbγγ and bbττ final states updated

- Results contain substantial improvements (in analysis methods, τ reconstruction identification, b-tagging) with respect to the previous projections
- A statistical combination of these updated projections performed
- Effects of κ_λ on VBF processes were also introduced in the updated results



Likelihood scan 1σ CI on κ_λ

- Baseline: [0.5,1.6]
  - Previously: [0.25,1.9]
- Without systematics: [0.6,1.5]
  - Previously: [0.4,1.7]

Conclusion

- Impressive progress since the discovery of the Higgs boson
- Major upgrades to ATLAS for the HL-LHC are foreseen
- The HL-LHC projections are performed for the single- and di-Higgs measurements with ATLAS
  - Mostly extrapolated from the Run-2 results
  - Based on predictions on the performance of the upgraded ATLAS detector
- Some of the projections already updated using the latest Run-2 results
- Higgs self-couplings could be measured with expected significance of 3.2σ (baseline scenario)

Stay tuned for more data, more results…

BACK UP

YR18 Systematic Uncertainties

Yellow Report

- Most of the experimental uncertainties scaled down with $\sqrt{\mathcal{L}_{int}}$
- Statistical uncertainty reduced by a factor of $1/\sqrt{(\mathcal{L}_{int\ (HL\text{-}LHC)}/\ \mathcal{L}_{int\ (reference\ Run2)})}$
- Uncertainties related to the limited number of simulated events are neglected
- Theoretical uncertainties are halved
- 1% luminosity uncertainty
- Systematics driven by intrinsic detector limitations are left unchanged
- Uncertainties on methods left unchanged

Rare Higgs Boson Decays

Yellow Report

ATL-PHYS-PUB-2018-054

$H \rightarrow \mu\mu$

- Based on the analysis using 79.8 fb^{-1} of data collected at $\sqrt{s}$ = 13 TeV
- Limited by the statistical uncertainty
- Expected precision of the measurement of the signal strength 13% for the baseline scenario

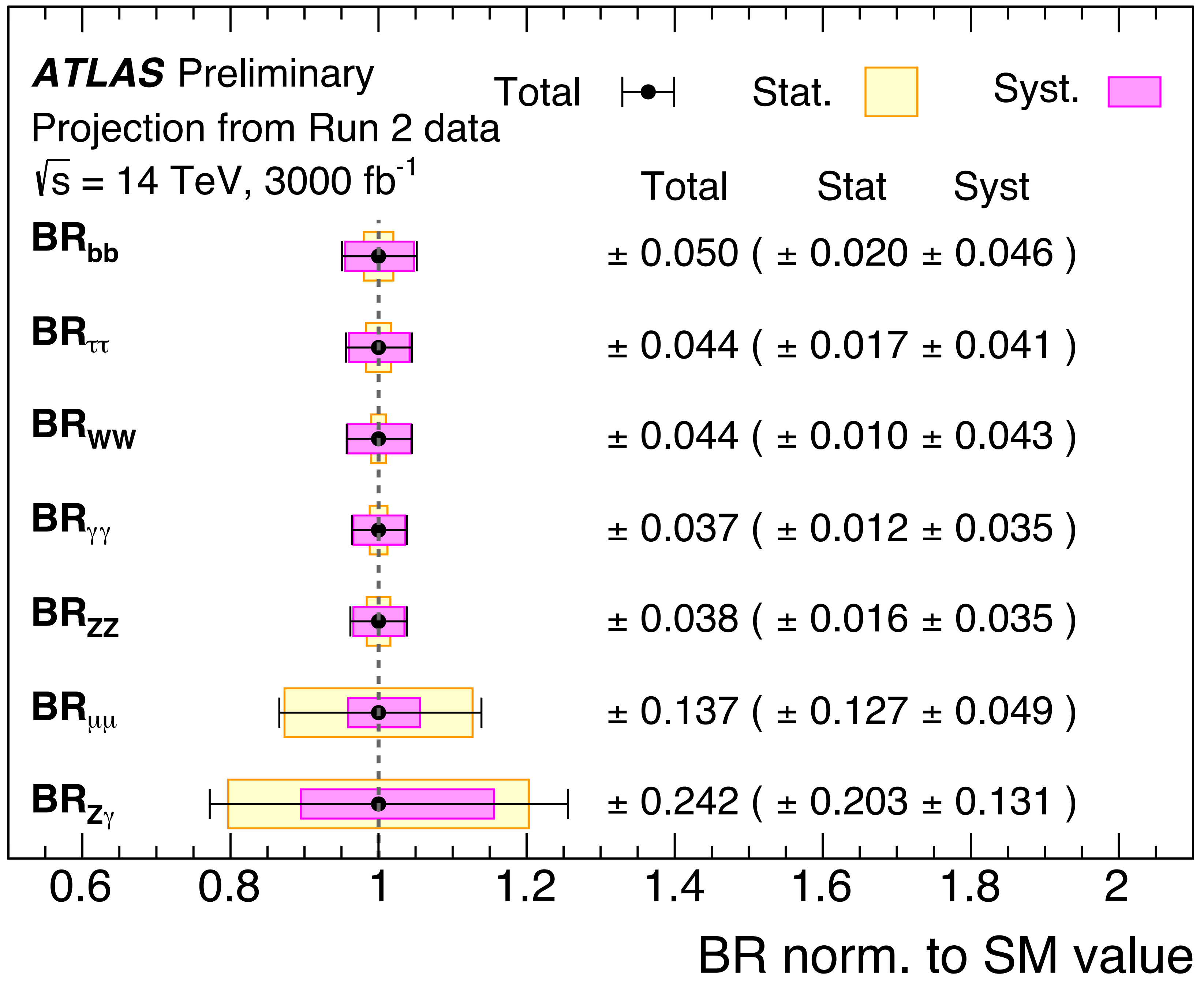
$H \rightarrow Z\gamma$

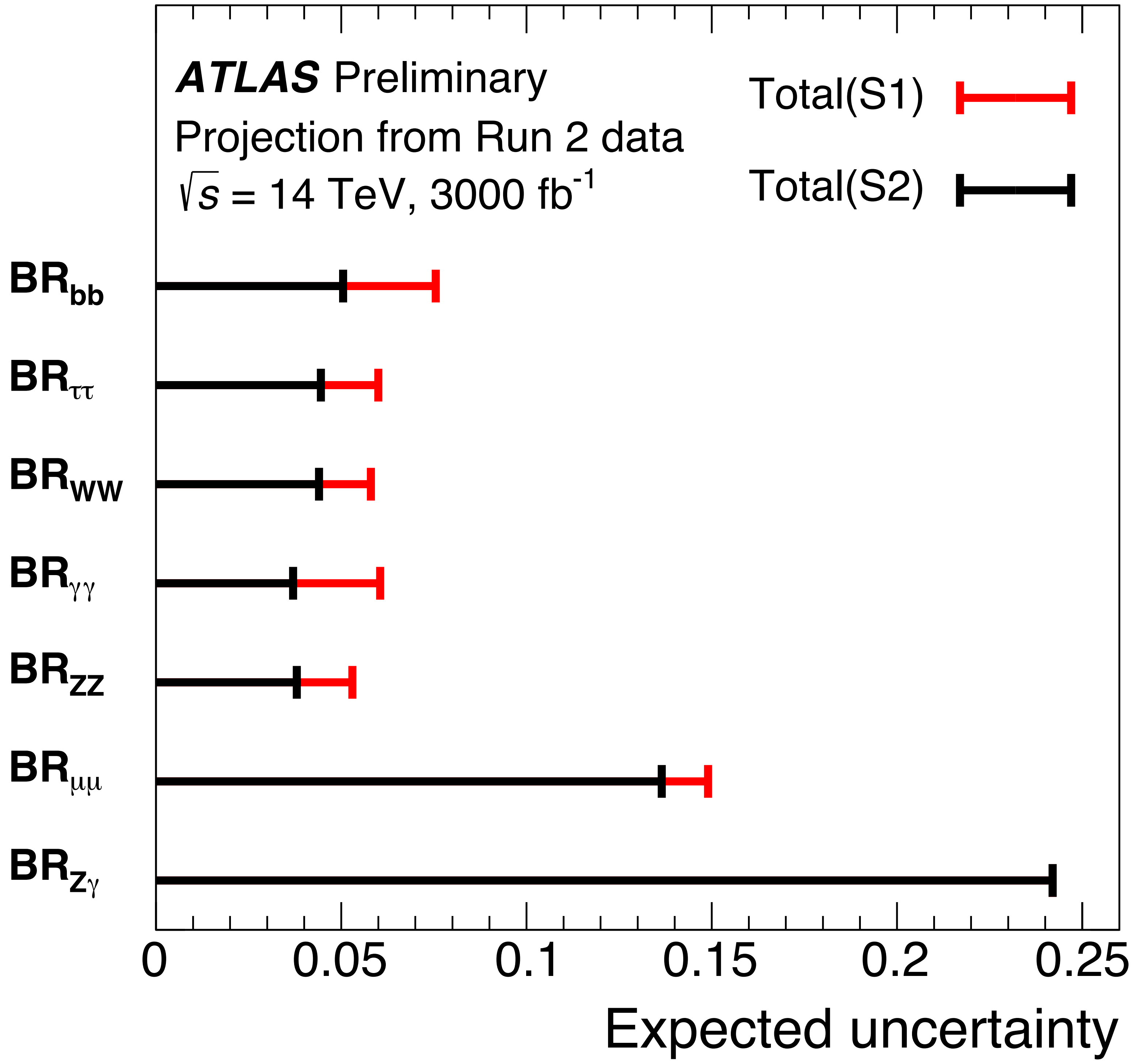
- Based on 36.1 fb^{-1} data collected at $\sqrt{s}$ = 13 TeV
- All the experimental and systematic uncertainties are the same as before
- The expected significance of the SM Higgs boson is 4.9 σ with 3000 fb^{-1}
- The precision for the cross section times branching ratio measurement is expected to be 0.23 times the SM prediction

Higgs Boson Branching Ratios

Yellow Report

- Extrapolated from the Run 2 results using datasets of 36 fb^{-1} and 80 fb^{-1} collected at $\sqrt{s}$=13 TeV
- All the extrapolated single-channel results are combined to compute the cross sections per production mode and the branching ratios
- ggF, VBF, VH, ttH and tH production modes are studied
- Decays of the Higgs boson to γγ, Z Z, WW, ττ, bb considered





H→ττ Cross-Section

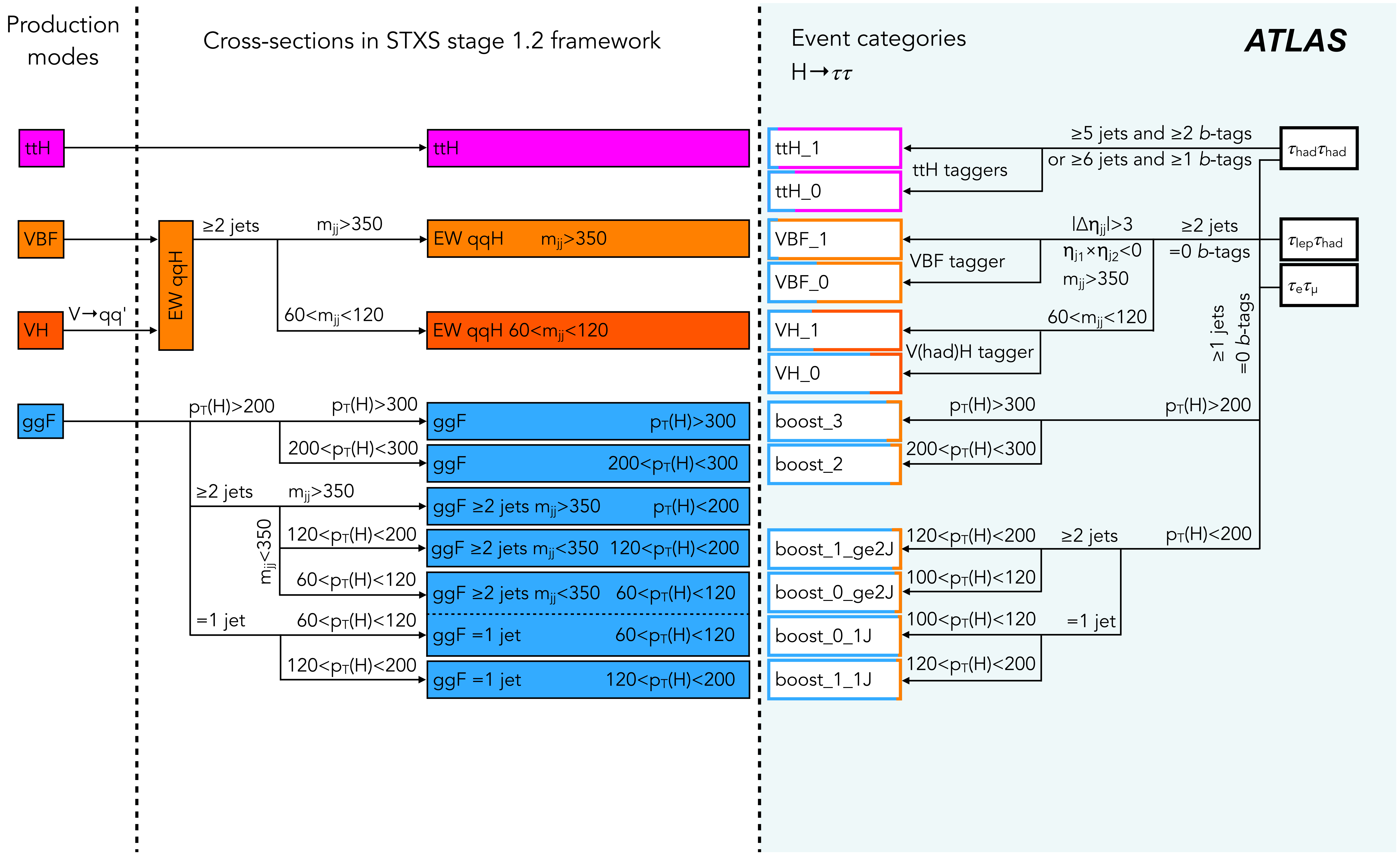
ATL-PHYS-PUB-2022-003

Based on the H→ττ cross-section measurement

- Using the full Run-2 dataset, consisting of 139 fb^{-1} of pp collisions at $\sqrt{s}$=13 TeV

Measurements presented within the Simplified Template Cross-Section (STXS) framework

- Measurements per production mode, in different region of phase space
- Minimize the dependence on theory
- Maximize the experimental sensitivity
- Isolate possible BSM effects



H→ττ Cross-Section

Snow mass

ATL-PHYS-PUB-2022-003

Source of uncertainty	Impact on $\Delta\sigma / \sigma(pp \to H \to \tau\tau)$ [%] Run 2	HL-LHC	HL-LHC*
Theoretical uncertainty on the signal	8.5	3.8	3.7
Jet and $E_{\mathrm{T}}^{\mathrm{miss}}$	4.2	1.7	1.7
Background sample size	3.7	1.3	0.9
Hadronic τ decays	2.1	0.9	0.9
Misidentified τ	2.0	0.7	0.7
Luminosity	1.8	0.7	0.7
Theoretical uncertainty in $Z+$jets processes	1.2	0.7	0.7
Theoretical uncertainty in Top processes	1.1	0.3	0.3
Flavour tagging	0.5	0.2	0.3
Electrons and muons	0.4	0.3	0.3
Total systematic uncertainty	11.4	4.4	4.3
Data sample size	6.7	1.3	1.3
Total	13.2	4.6	4.5

Table 3: Summary of the different sources of uncertainty in decreasing order of their impact on $\sigma(pp \to H \to \tau\tau)$ for the Run 2 analysis and the HL-LHC extrapolation. A scenario in which the Monte Carlo background sample size is sufficiently large that its contribution as a systematic uncertaity is negligible is also included and labelled as HL-LHC*. The expected fractional impacts of the various sources of uncertainty, computed by the fit, are given, relative to the $\sigma(pp \to H \to \tau\tau)$ value. Experimental uncertainties in reconstructed objects combine efficiency and energy/momentum scale and resolution uncertainties. Background sample size includes the bin-by-bin statistical uncertainties in the simulated backgrounds as well as statistical uncertainties in misidentified τ backgrounds, which are estimated using data.

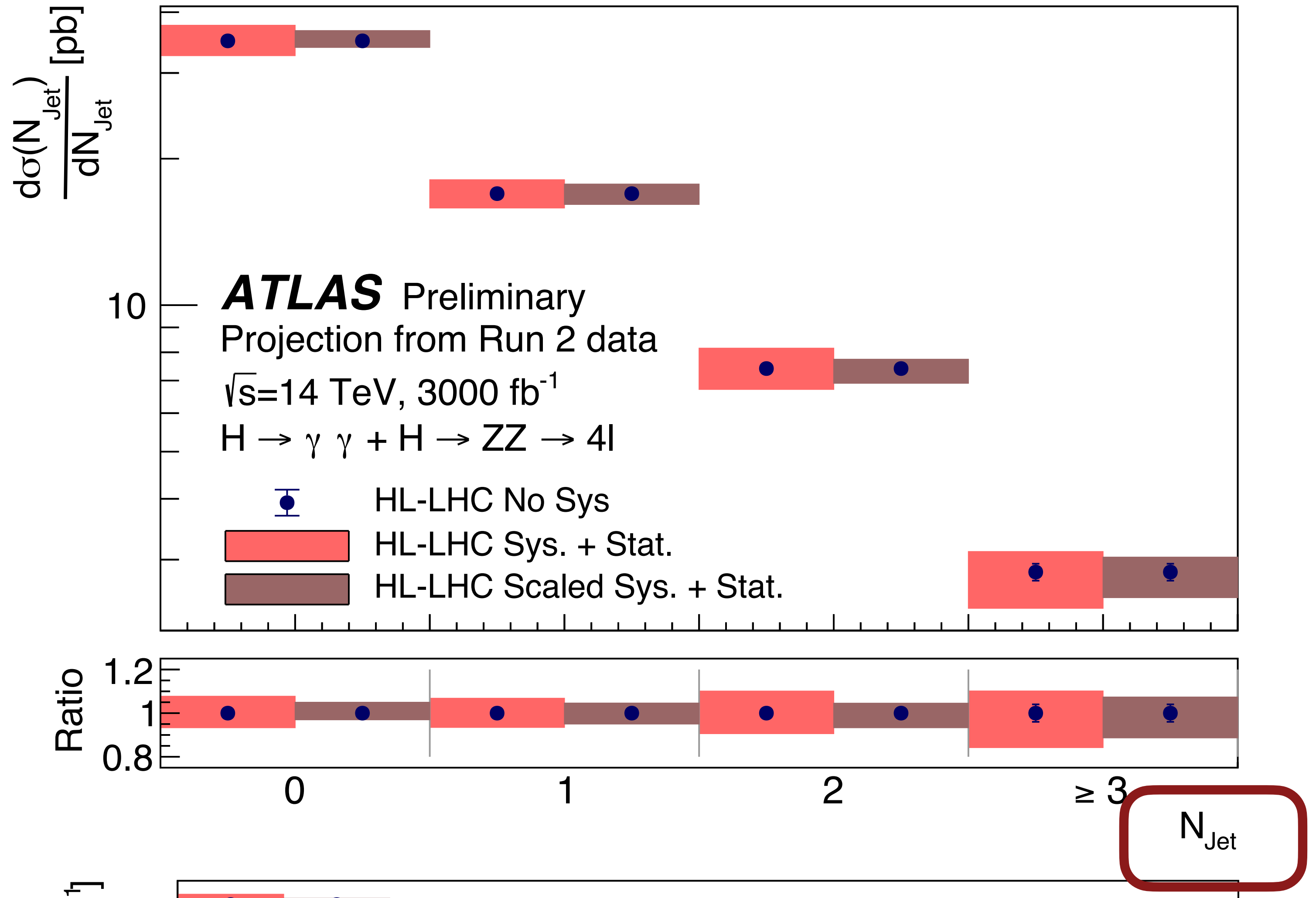
Theoretical uncertainties include

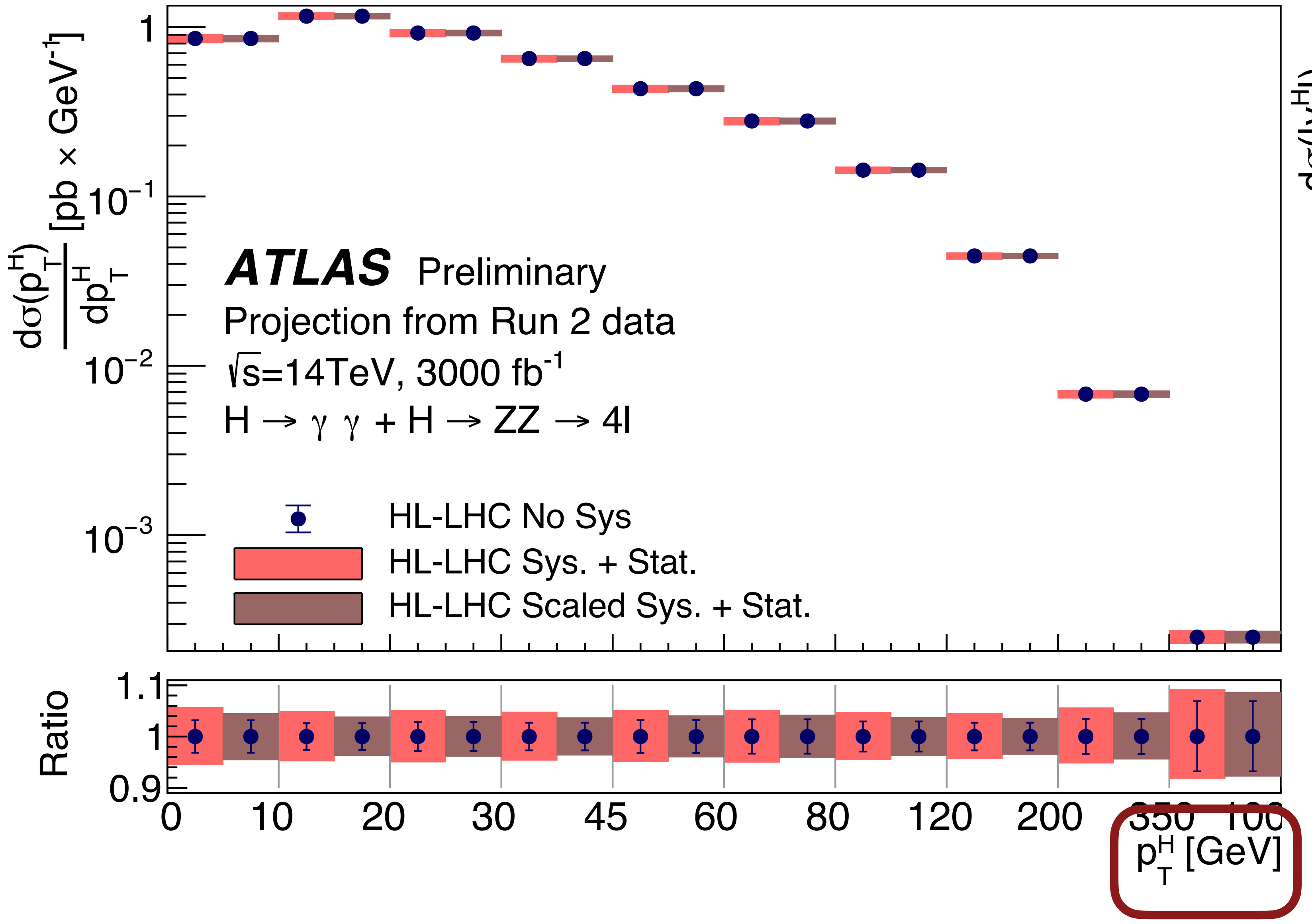
- Uncertainties on the cross-sections of the processes of interest,
- on the value of α_S,
- on the factorization, renormalization and resummation scales,
- on the parton distribution function and shower models,
- on the chosen merging scheme,
- and on the description of the initial and final state radiation

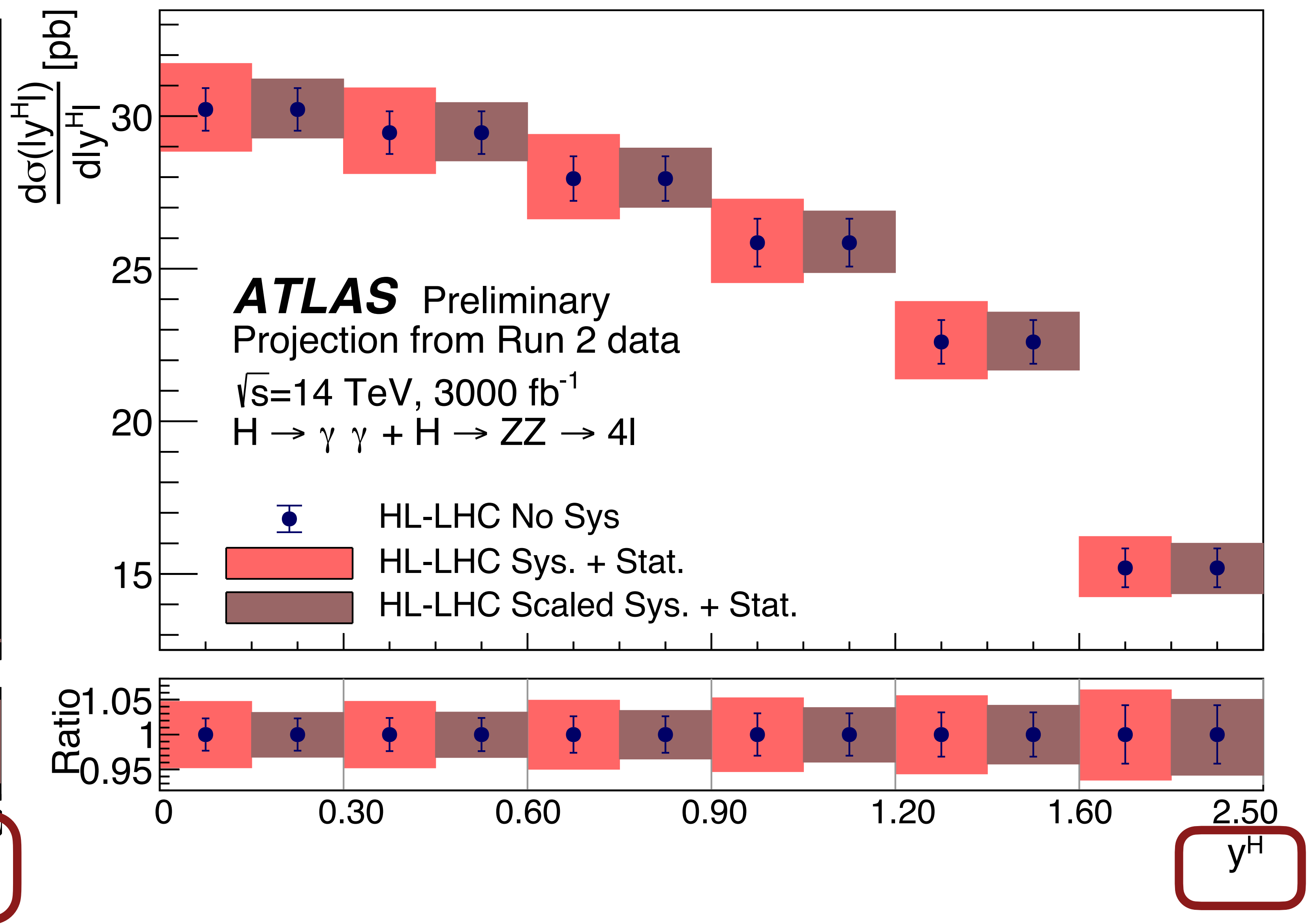
Differential Cross-Section Measurements

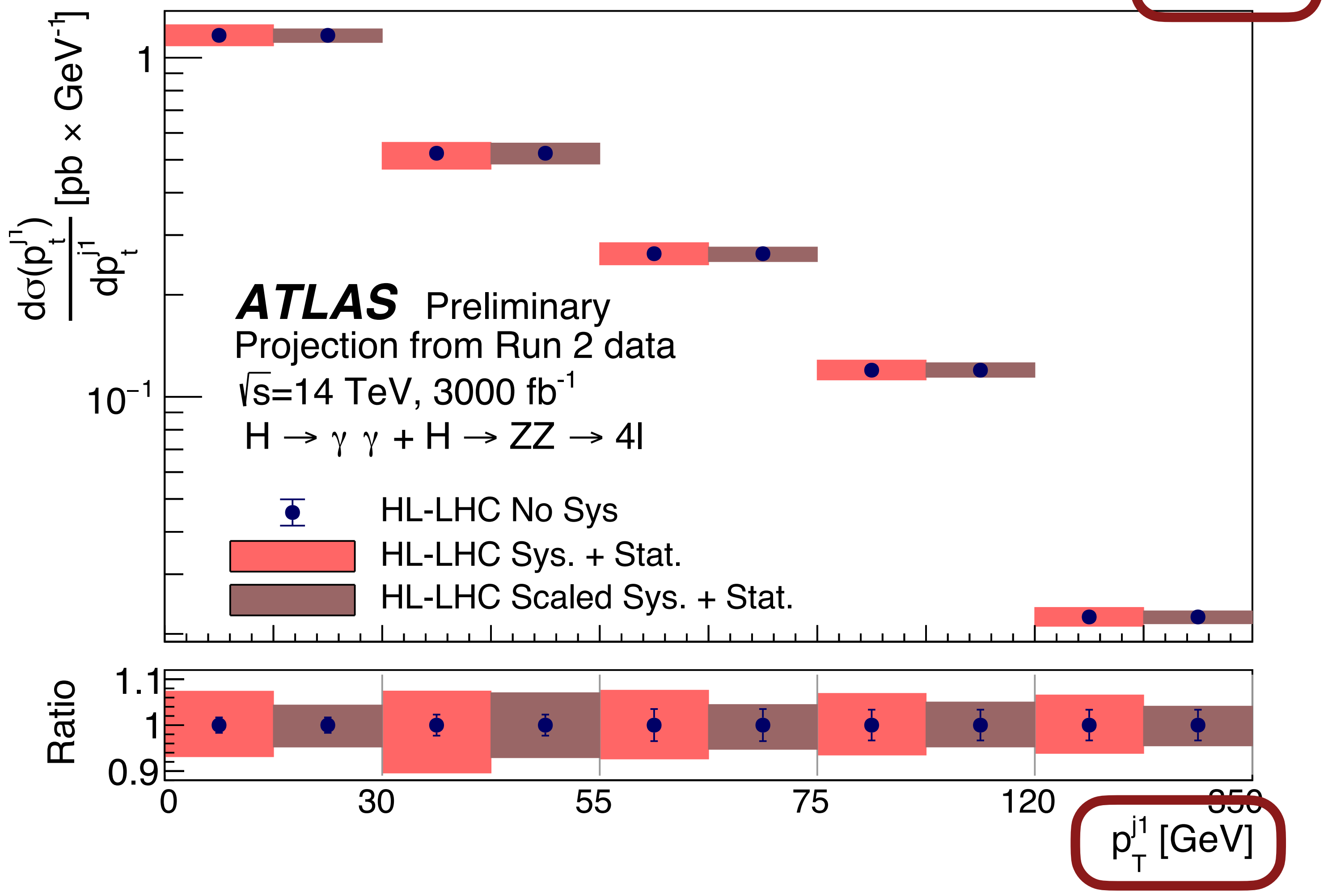
ATL-PHYS-PUB-2018-040

- Measured in $H \rightarrow \gamma\gamma$, $H \rightarrow ZZ^* \rightarrow 4\ell$ decay channels, in total phase space, and their combination performed
- The extrapolations are based on the Run-2 analyses using the datasets with an integrated luminosity of 36 fb^{-1} and 80 fb^{-1}
- Presented for p_T^H, $|y^H|$, N_{jets}, with p_T > 30 GeV, p_T^{jlead}
- The uncertainties are expected to range between 3% and 20%
- With the increase statistical precision, the systematics will play an important role



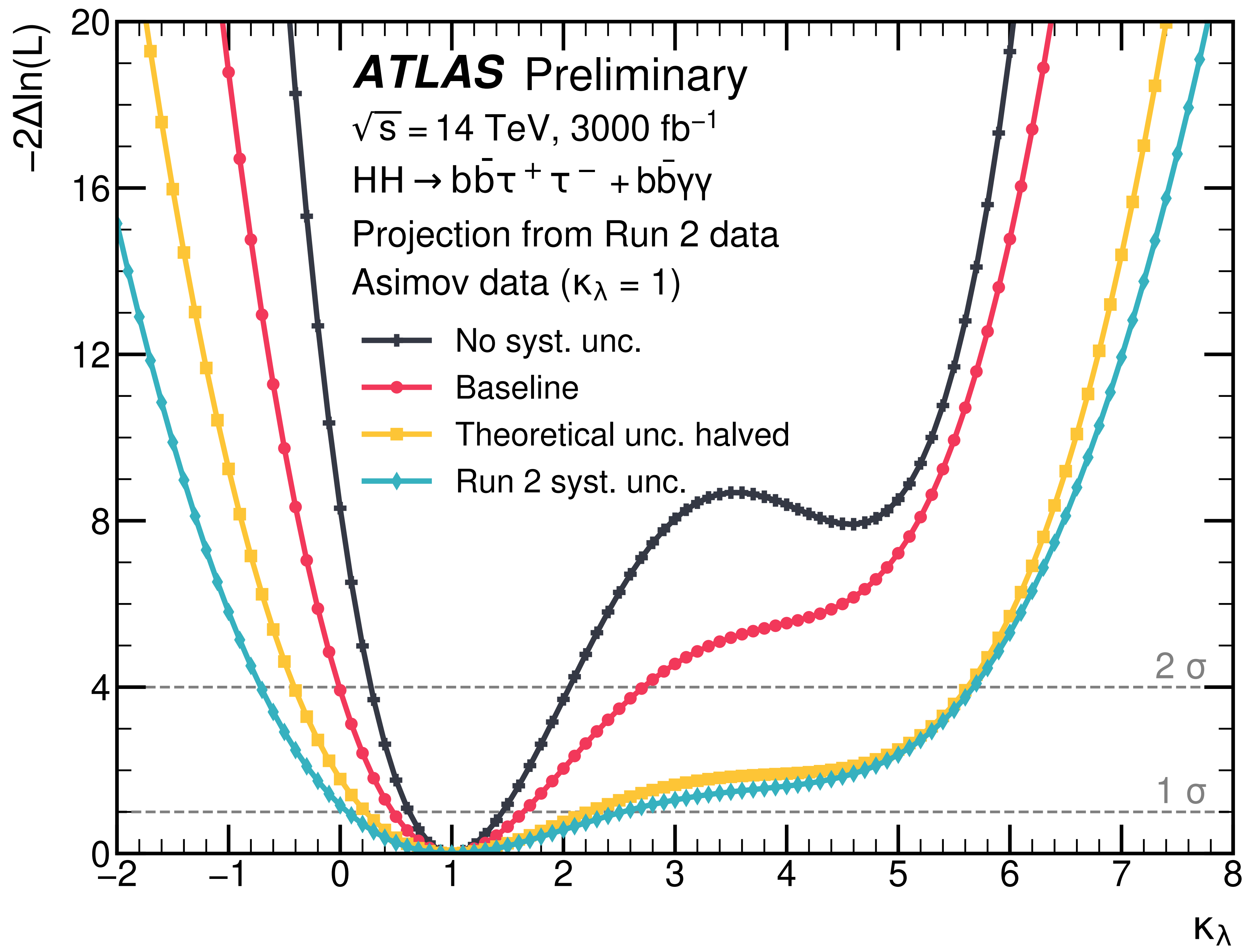


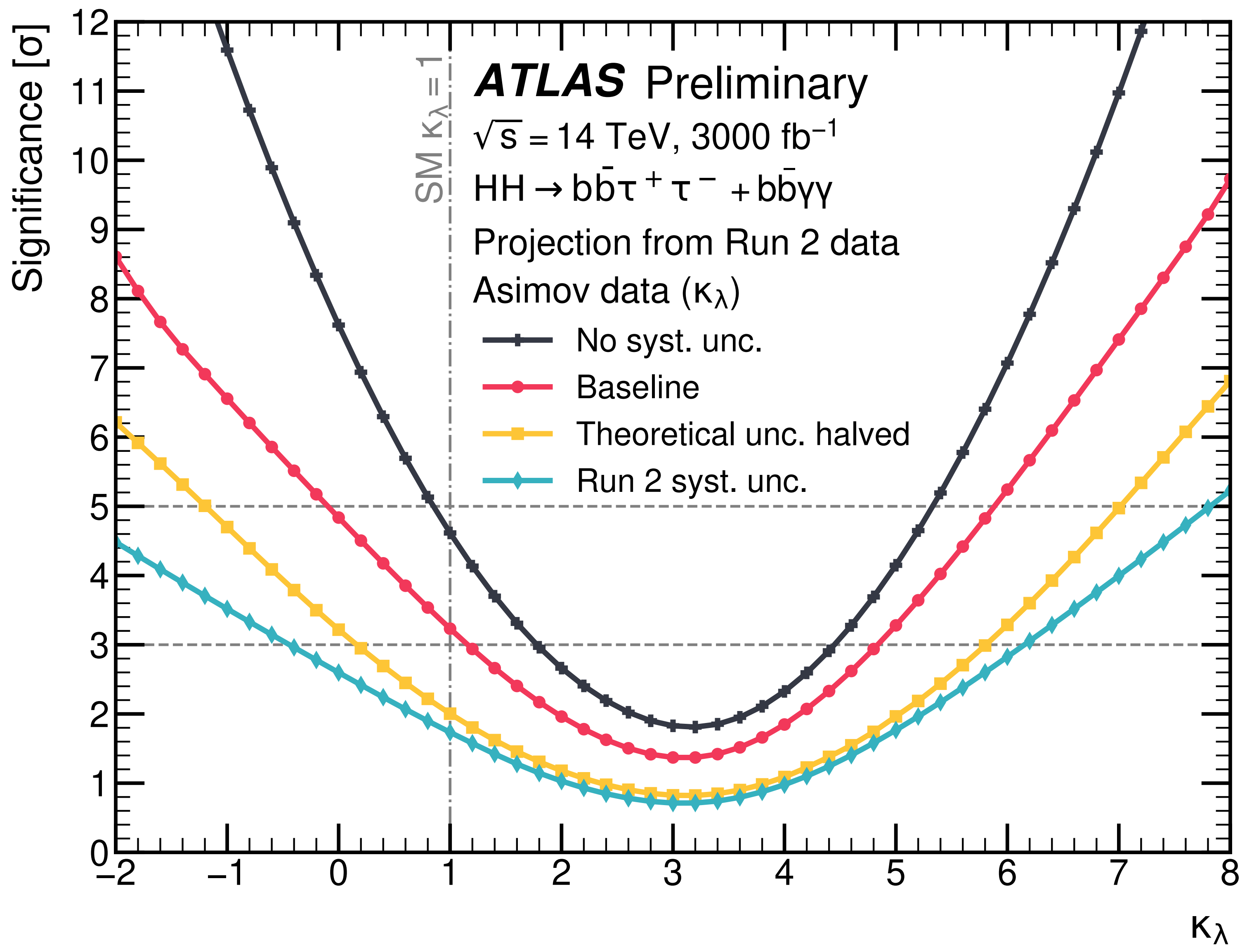




Higgs Self-Coupling

Snow mass

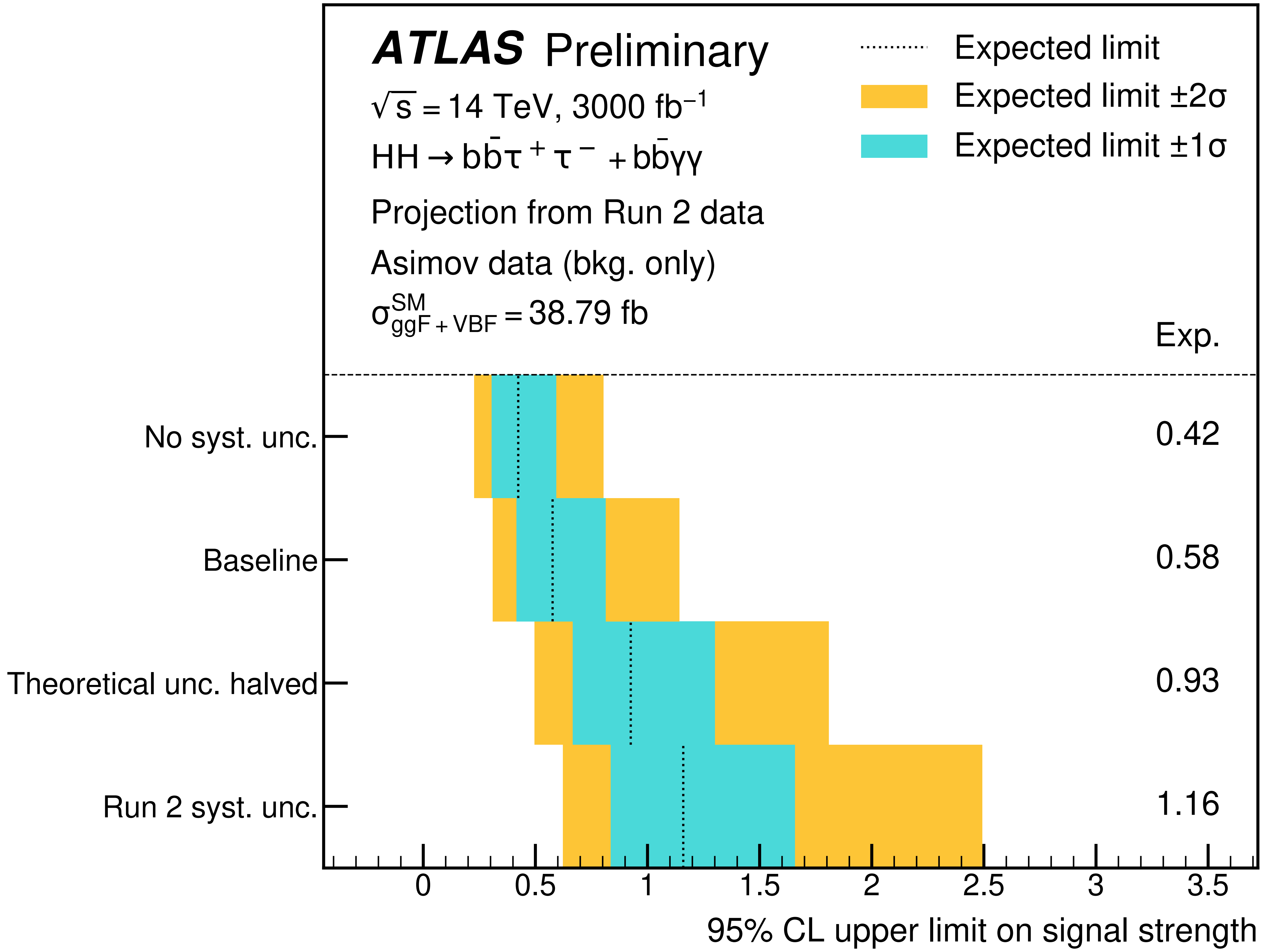




Uncertainty scenario	Likelihood scan 1 σ CI	Likelihood scan 2 σ CI
No syst. unc.	[0.6, 1.5]	[0.3, 2.1]
Baseline	[0.5, 1.6]	[0.0, 2.7]
Theoretical unc. halved	[0.2, 2.2]	[−0.4, 5.6]
Run 2 syst. unc.	[0.1, 2.5]	[−0.7, 5.7]

Higgs Self-Coupling

Snow mass



	95% CL upper limit		
Uncertainty scenario	$b\bar{b}\gamma\gamma$	$b\bar{b}\tau^+\tau^-$	Combination
No syst. unc.	0.86	0.49	0.42
Baseline	0.93	0.71	0.58
Theoretical unc. halved	1.7	1.07	0.93
Run 2 syst. unc.	1.9	1.37	1.16

Higgs Self-Coupling

Snow mass

- The dominant source of uncertainties on the combined projection result:
  - Theoretical uncertainty on the ggF, VBF, WH production modes due to the imperfect modelling of additional heavy flavour jet radiation in these processes
  - Theoretical uncertainty on the HH cross-section

In the future, the reduction of systematic uncertainties from the theory community will represent an essential ingredient to measure HH production at the HL-LHC