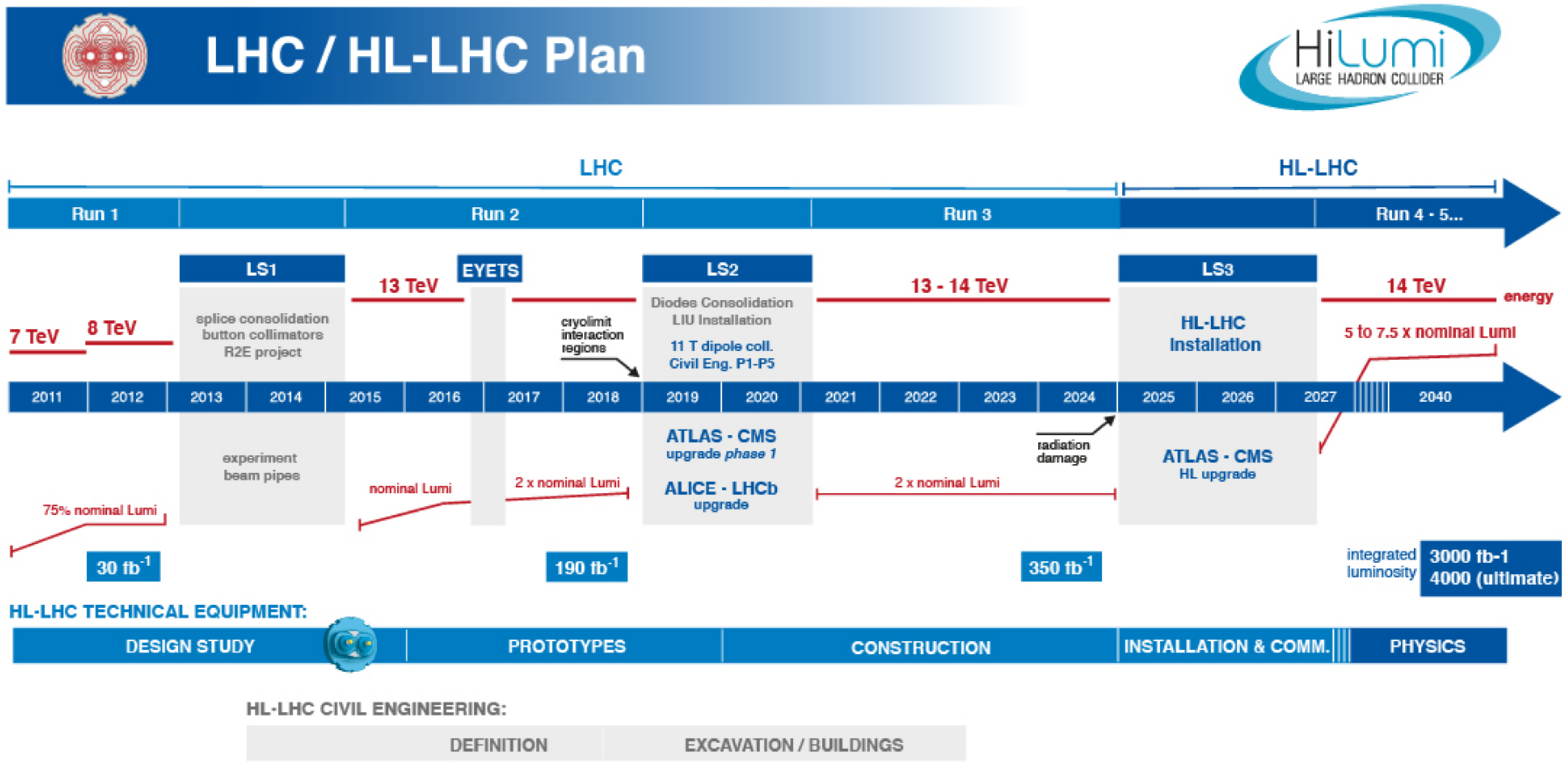
Higgs Boson Measurements and HH production at the High-Luminosity LHC with the CMS detector

Sandhya Jain, IP2I
on behalf of the CMS collaboration

Why HL-LHC?

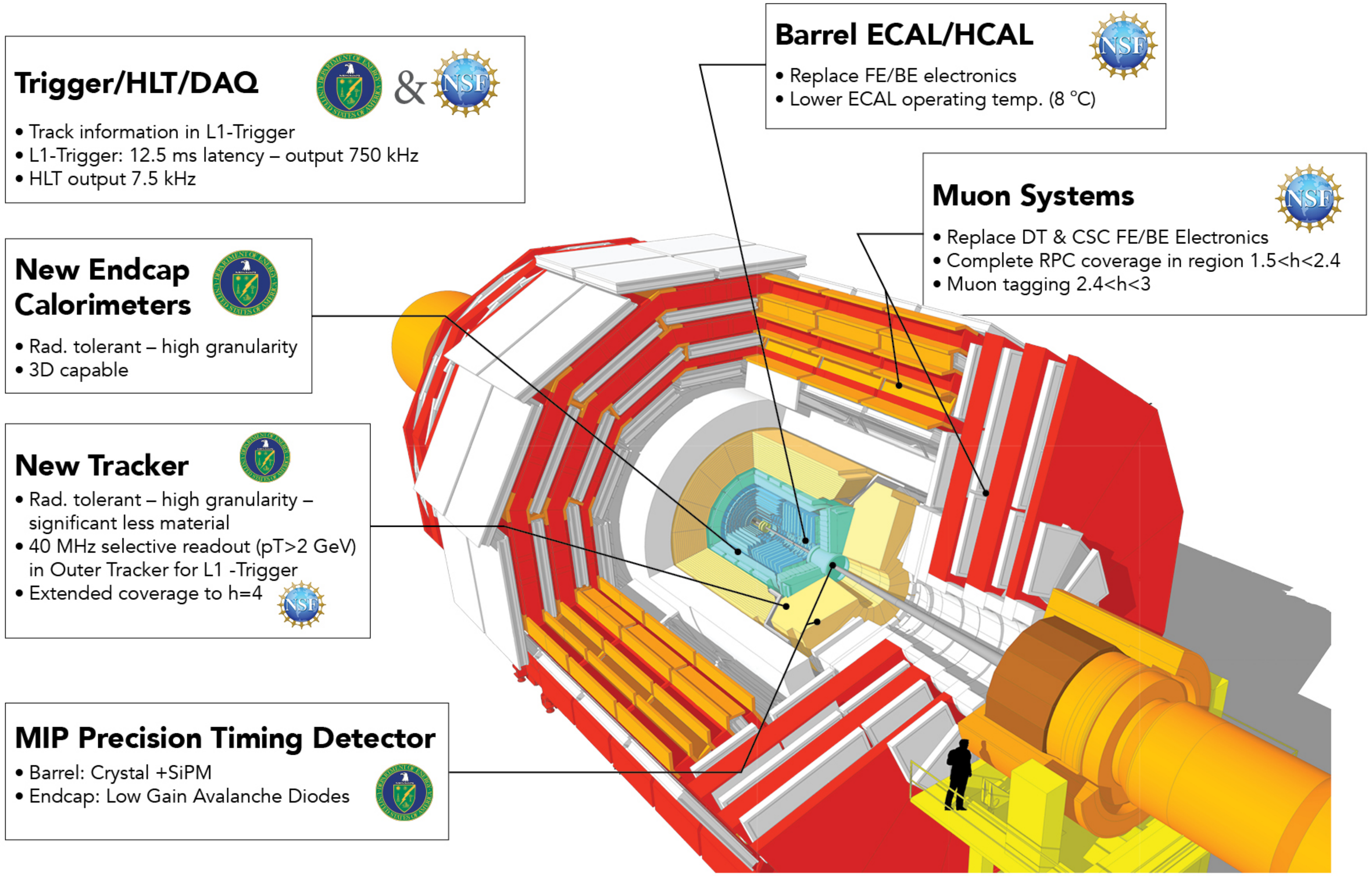
- **What have we learnt so far?**
  - LHC experiments confirm that the **SM is robust!**
  - **No direct evidence of new physics at the LHC.**
    - Many key questions still remain unanswered:
      - Hierarchy problem
      - Unknown “dark” part (96% !) of the universe
      - Origin of matter-antimatter asymmetry
      - why is gravity so weak ?



- **Answers may lie at the TeV scale, providing a strong motivation to look for new physics.**
- **What can the HL-LHC do?**
  - It provides access to new particles indirectly [deviations from SM expectations, indirect loop contributions and very rare processes]
  - With the HL-LHC, it will deliver 3/ab (x20 today’s data sample) @ 14 TeV.
  - Precise study of “SM-like” Higgs properties (discussed in next slides in details).

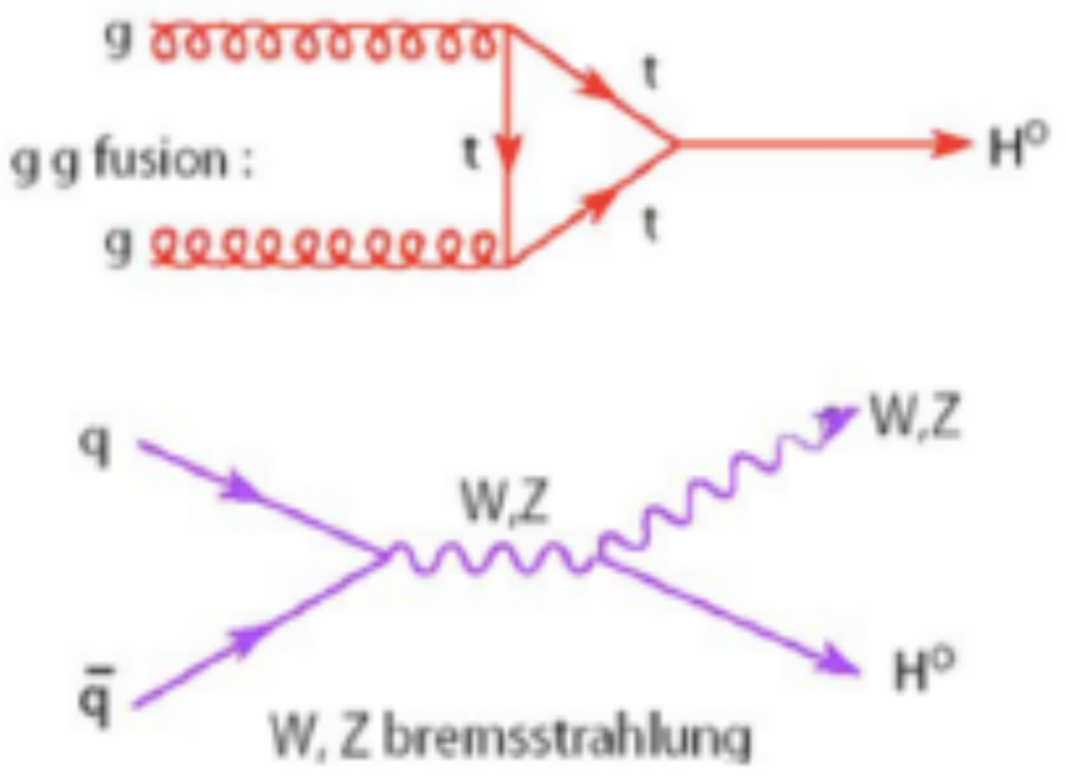
Challenges and detector upgrades

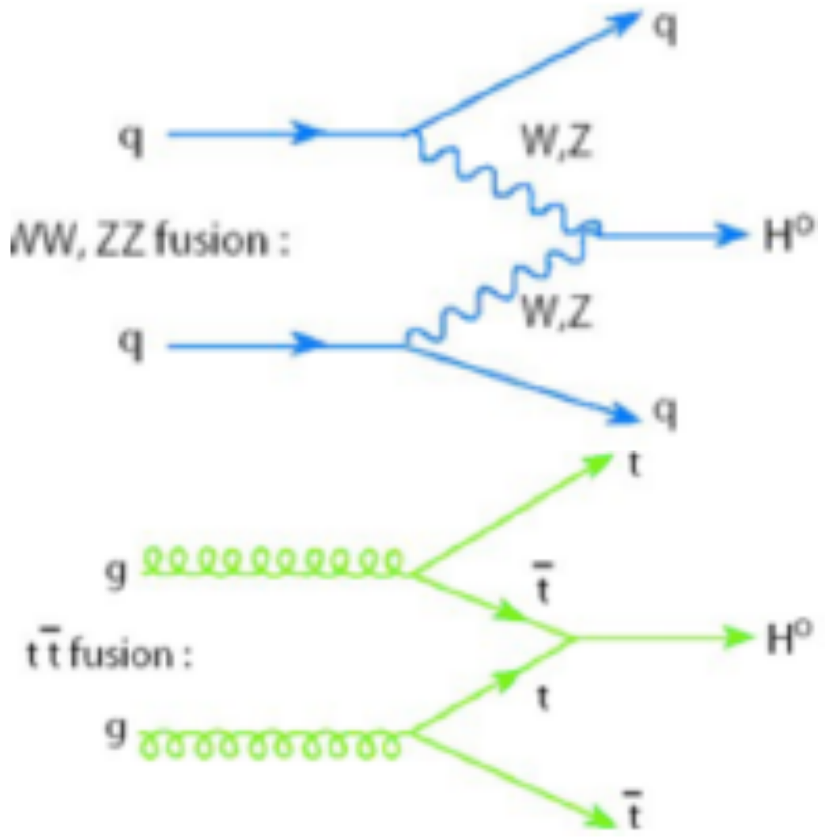
- As pile-up increases, as does event complexity (increased rate of fake tracks, spurious energy in calorimeters, increased data volume to be read out in each event)
- Detector elements and electronics are exposed to high radiation dose (reaching limits for several systems) → Detector upgrades
- To meet the machine performance, CMS have major phase-2 upgrade as involving **new tracker, new EC, new readout for barrel calorimeters, extended muon capabilities, new trigger, new DAQ**

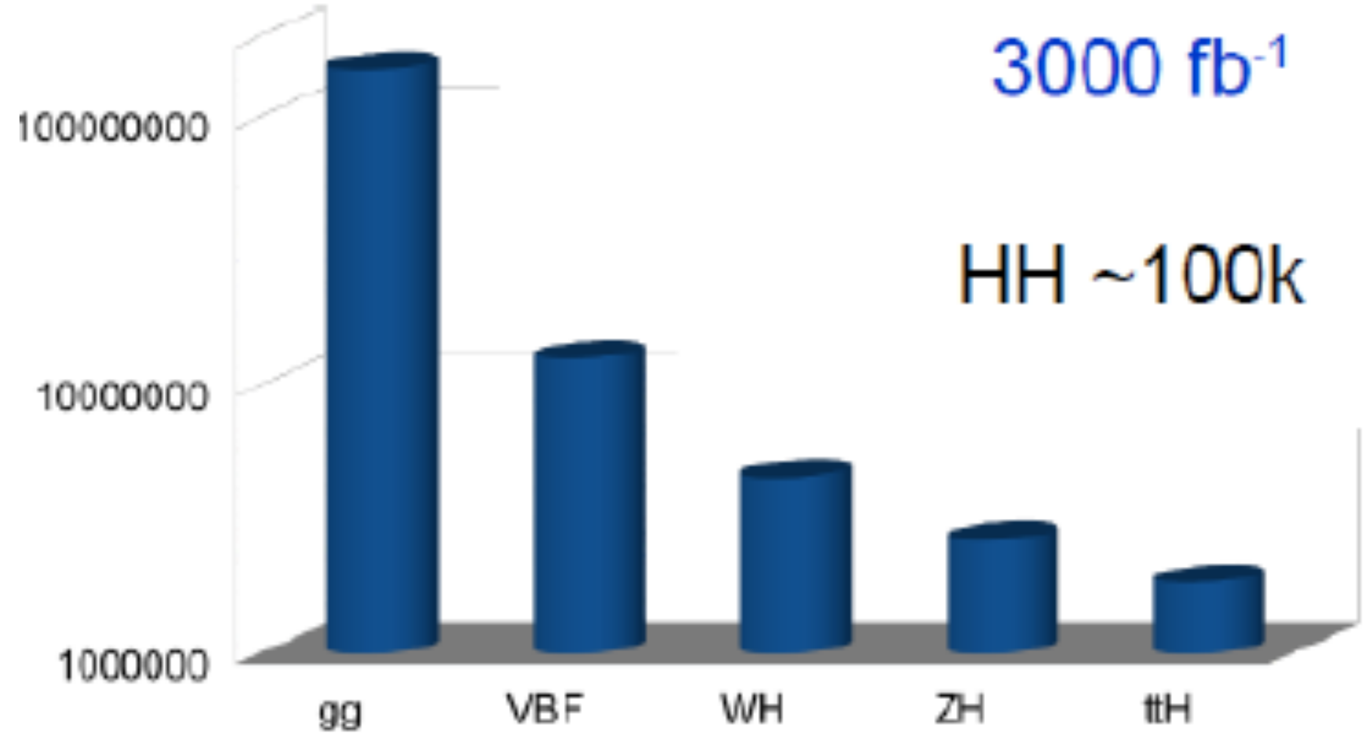


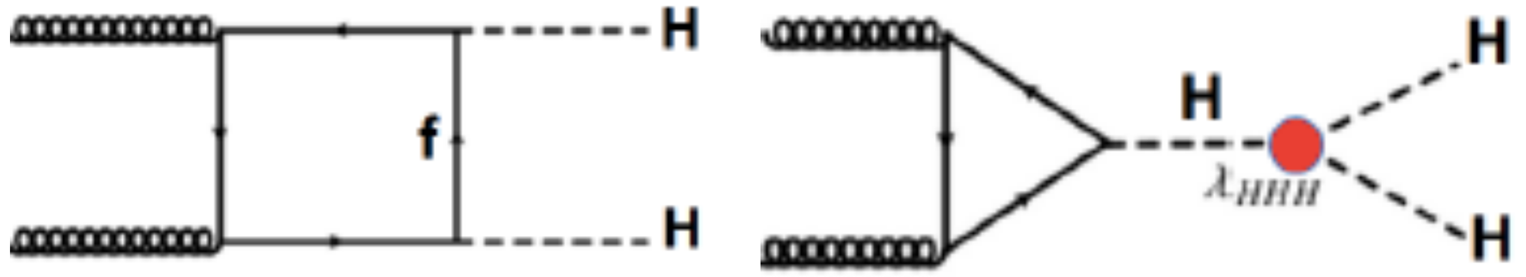
Expected Physics potential at HL-LHC in Higgs sector

- Higgs physics is a major component of HL-LHC physics program. HL-LHC (Higgs factory), we expect to produce >150M Higgs Bosons (over 1Million for each of the main production mechanisms, spread over many decay modes)









- Enables a broad physics program:
  - Higgs **Precision O(1-10%) Measurements** of couplings, x-sections, mass → looking for deviations from the SM
  - Di-Higgs production → **Higgs self coupling**
  - Sensitivity to **Rare decays and couplings**: H→$\mu\mu$, H→ee, H→cc, H→Zg
  - **BSM Higgs direct searches**: extra scalars, BSM Higgs resonances, exotic decays, anomalous couplings

Analysis approach in HL-LHC

Various analysis approaches to assess the sensitivity in searching for new physics at the HL-LHC at CMS.

Full simulation: use most updated phase-2 geometry, algorithms and tuning along with the PU simulation

Fast simulation: perform full analysis with parameterised detector performance. Use DELPHES with up-to-date phase-2 detector performance

Projections: Existing signal and background samples extrapolated from the 13 TeV analysis to higher lumi and corrected efficiencies using fast-sim and full-simulation.

Uncertainties assumptions

Run-2 scenario (S1):

- no change in systematics, propagated as it is wrt current analyses.

YR18 scenario (S2):

- Theoretical uncertainties are reduced by a factor of two compared to the current analyses
- Experimental ones go as ~ $1/\sqrt{L}$ until they hit the detector capabilities [Yellow Report]

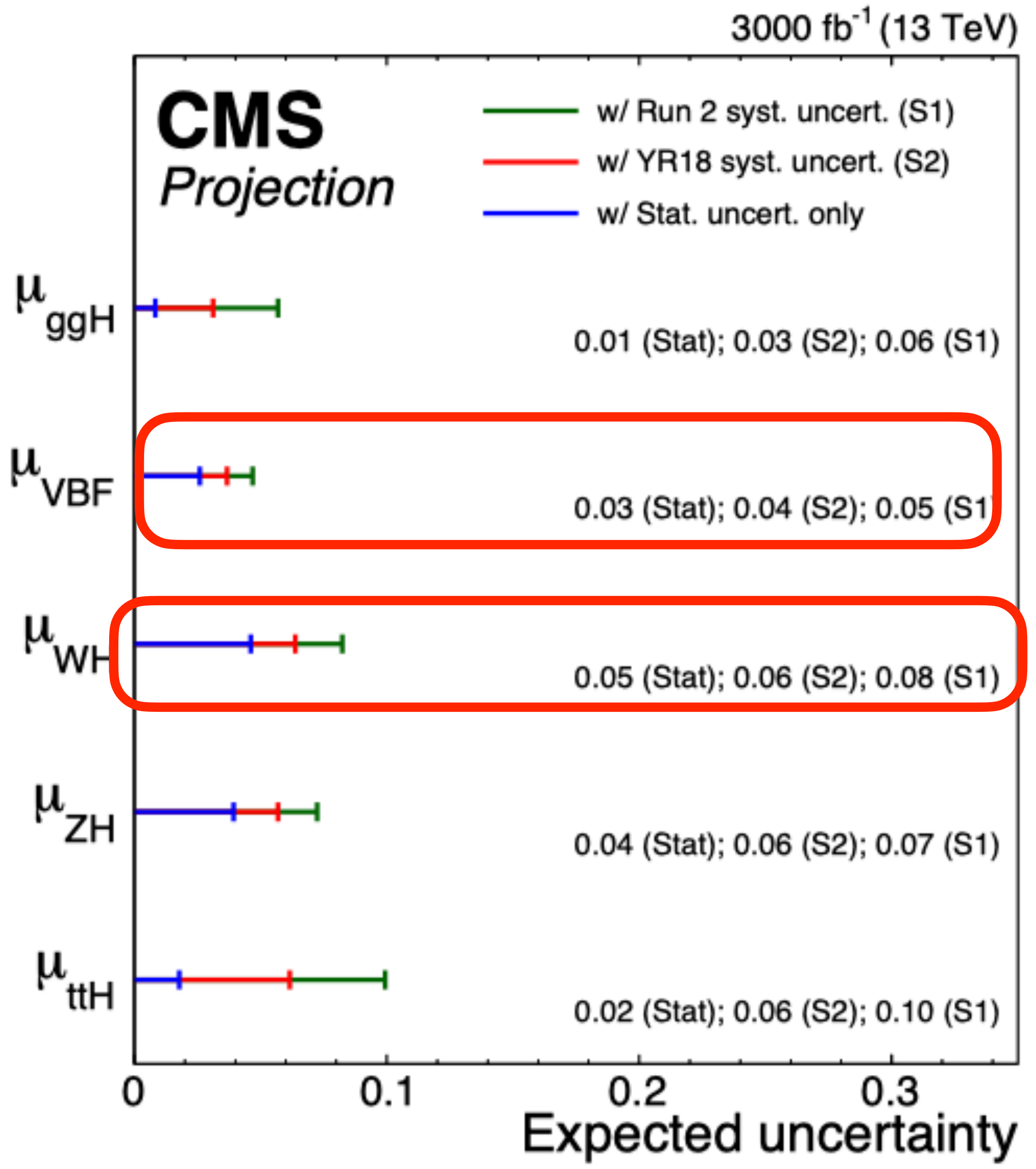
Higgs production and decay rate signal strengths, cross-sections and coupling measurements

- Performed from results obtained with the 2015-2016 datasets corresponding to 36 fb^{-1} of data.

- Size O(1%) of the expected HL-LHC integrated luminosity. Thus, projections very limited with respect to the potential reach of the real HL-LHC analyses

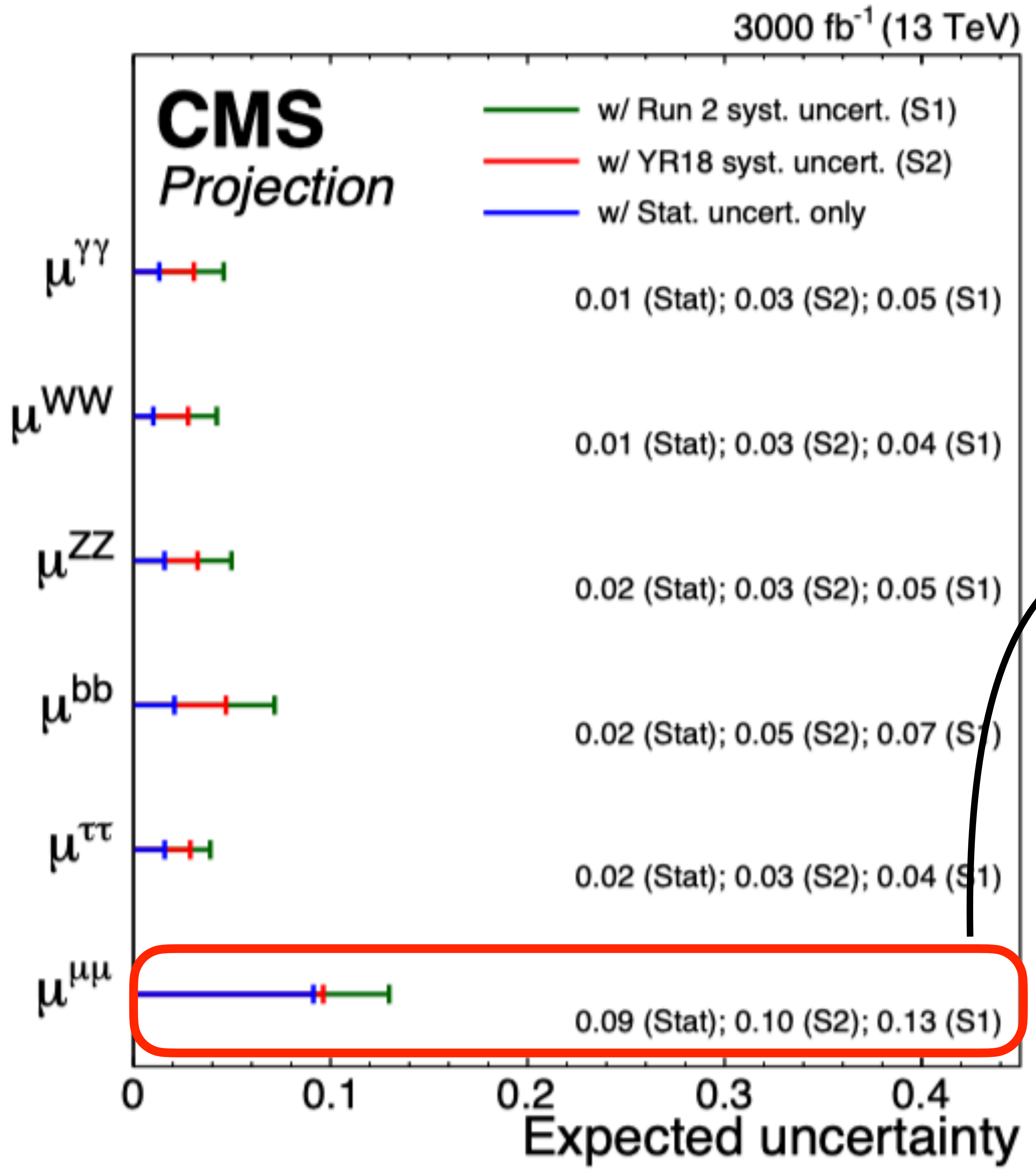
Combined signal strength per production and decay mode

Expected ±1σ uncertainties per production mode



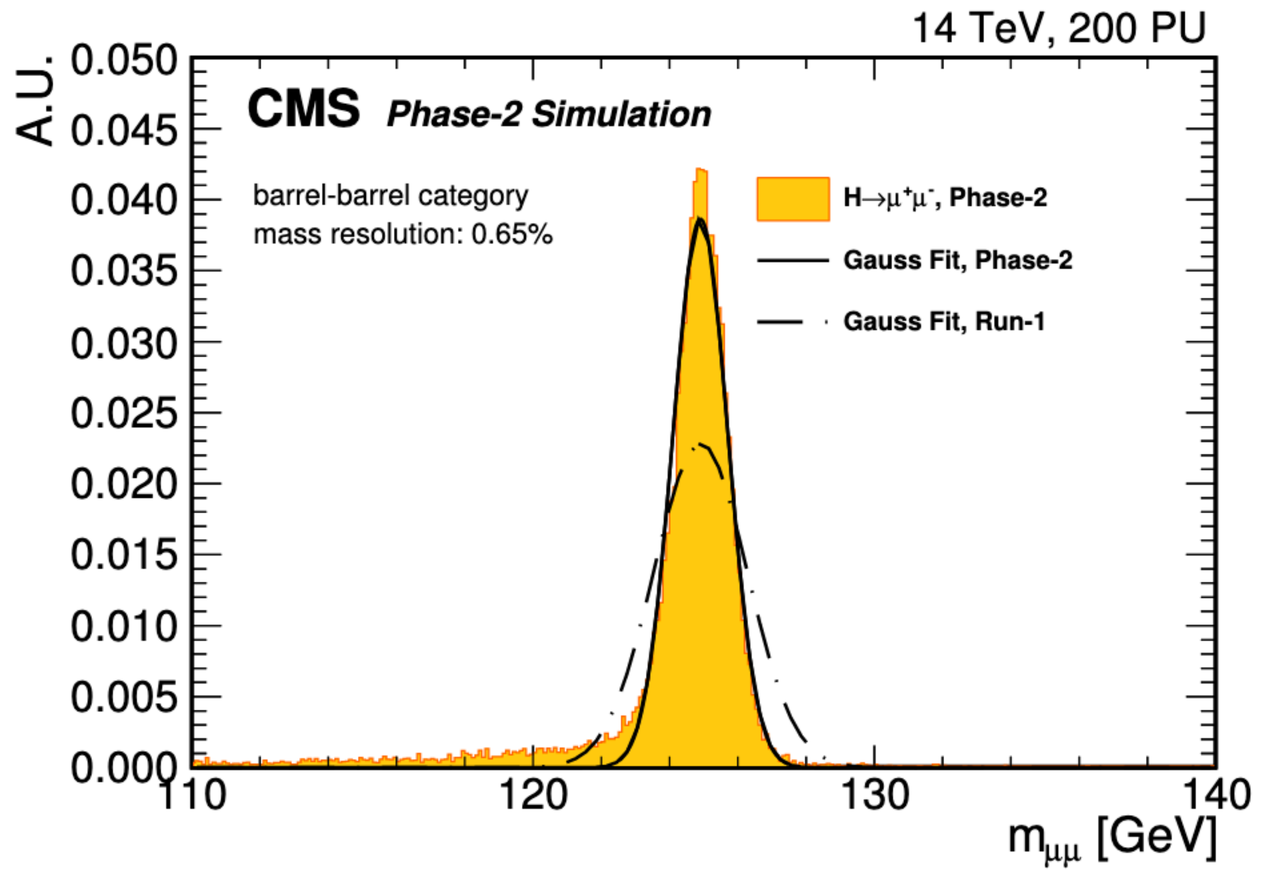
In S1, the signal theory unc. is the main contribution for all modes except WH (stat. limited). In S2, μ^{VBF} and μ^{WH} both are stat. limited

Expected ±1σ uncertainties per decay mode



signal theory unc. is the largest component for all parameters except $\mu^{\mu\mu}$, which remains stat. limited.

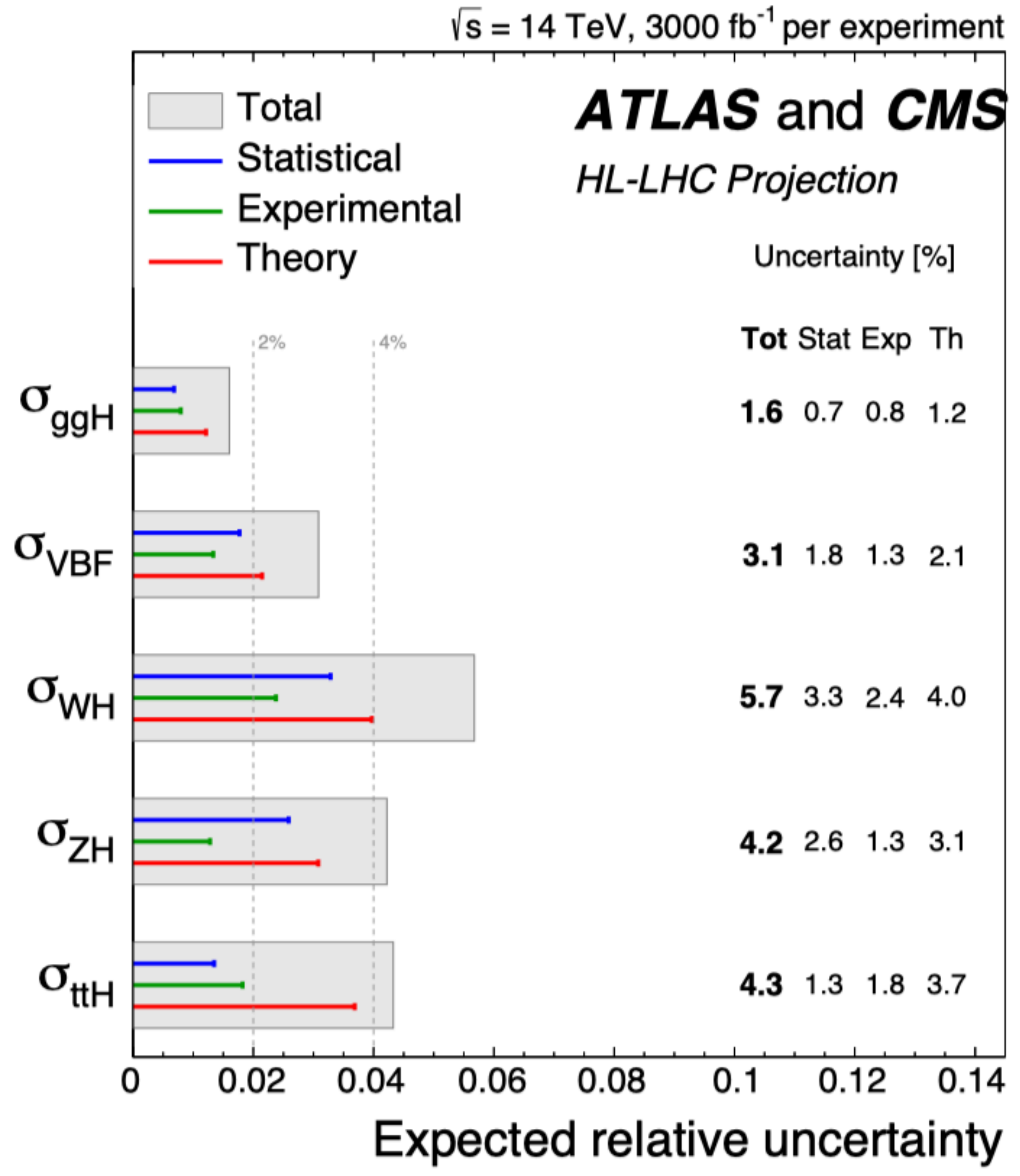
This analysis depends critically on dimuon mass resolution. Thanks to New tracker - Dimuon invariant mass width is reduced in order to match the increase in performances [40% improvement in the dimuon mass resolution]



A precision of 3-6% is reachable per production mode and 3-5% per decay mode except for $\mu^{\mu\mu}$ (10%) in S2 scenario

Higgs Cross-section and branching-fraction measurement

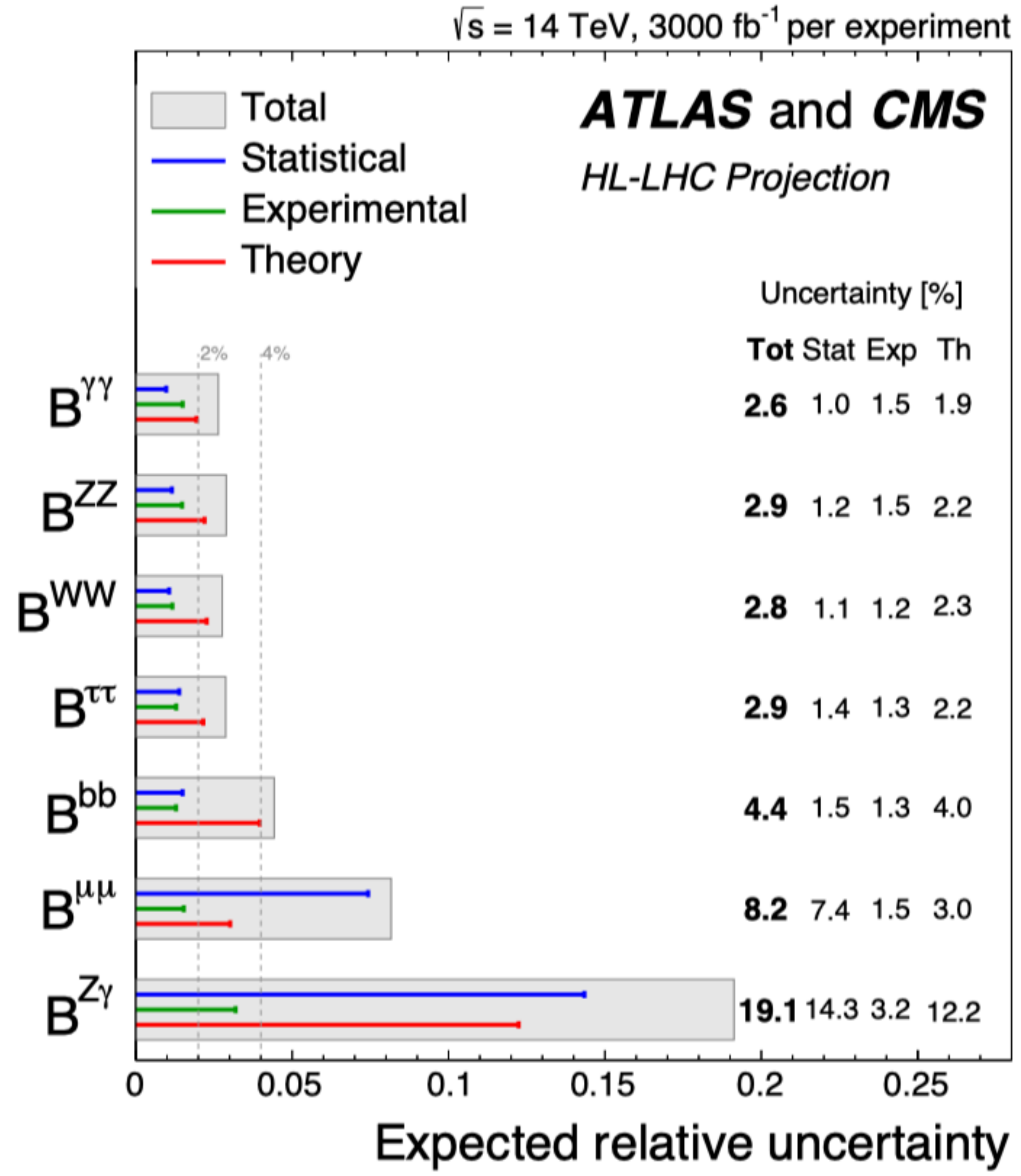
Expected ±1σ uncertainties on cross-section measurement per production mode



ggH, VBF : contribution from the stat., exp. and theor. unc to the total error are similar.
WH and ZH : the stat. and theor. unc. are the dominant one.
ttH: dominated by the theor. unc. (~ factor two larger wrt other components)

Uncertainty range from 1 – 6%

Expected ±1σ uncertainties on branching fraction measurement per decay mode



In S2, the signal theory uncertainty is the largest

Range from 2 – 4%, except $B^{\mu\mu}$ at 8% and $B^{Z\gamma}$ at 19%

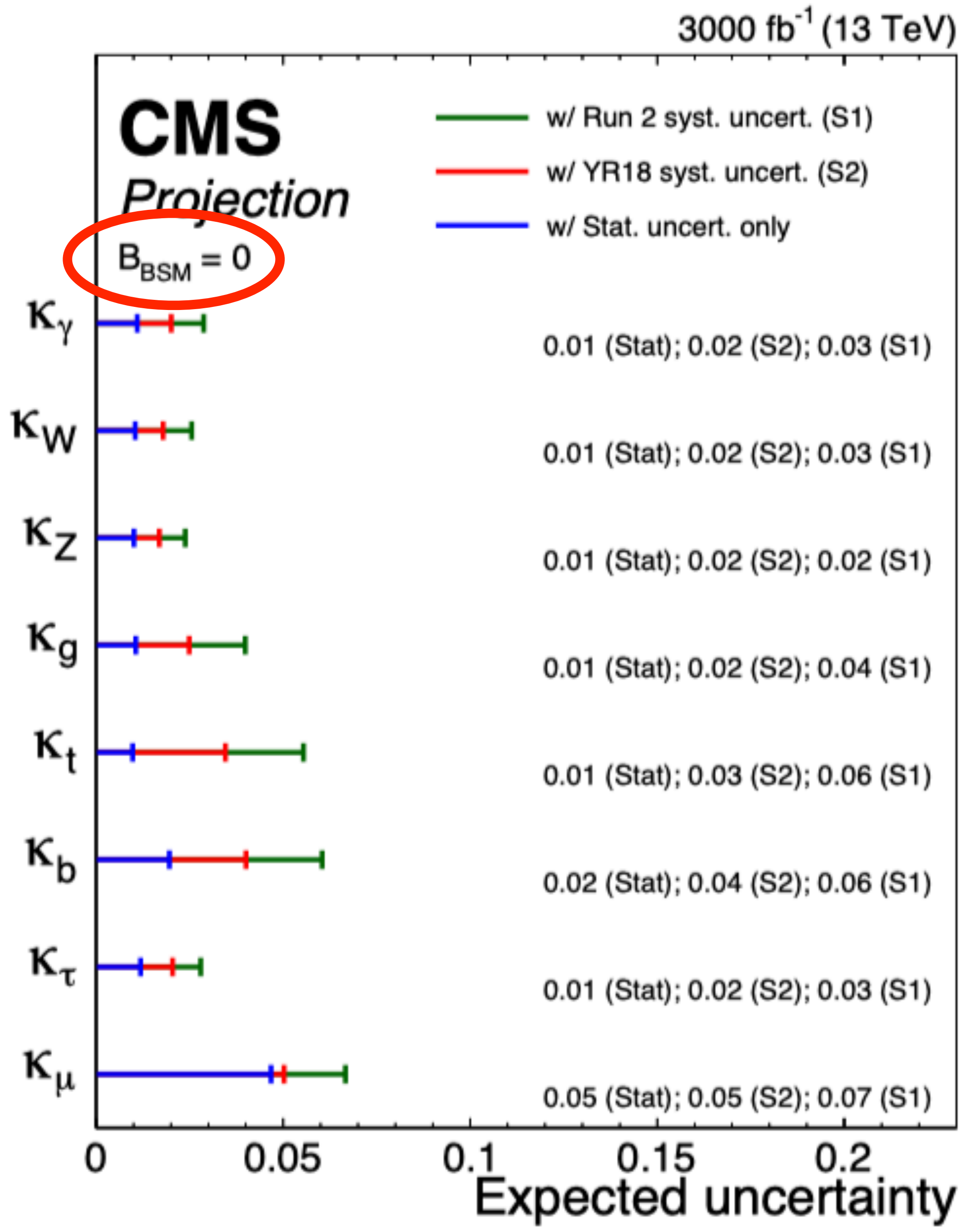
Coupling modifiers, κ

Parametrise deviations from the SM Higgs boson couplings to SM bosons and fermions

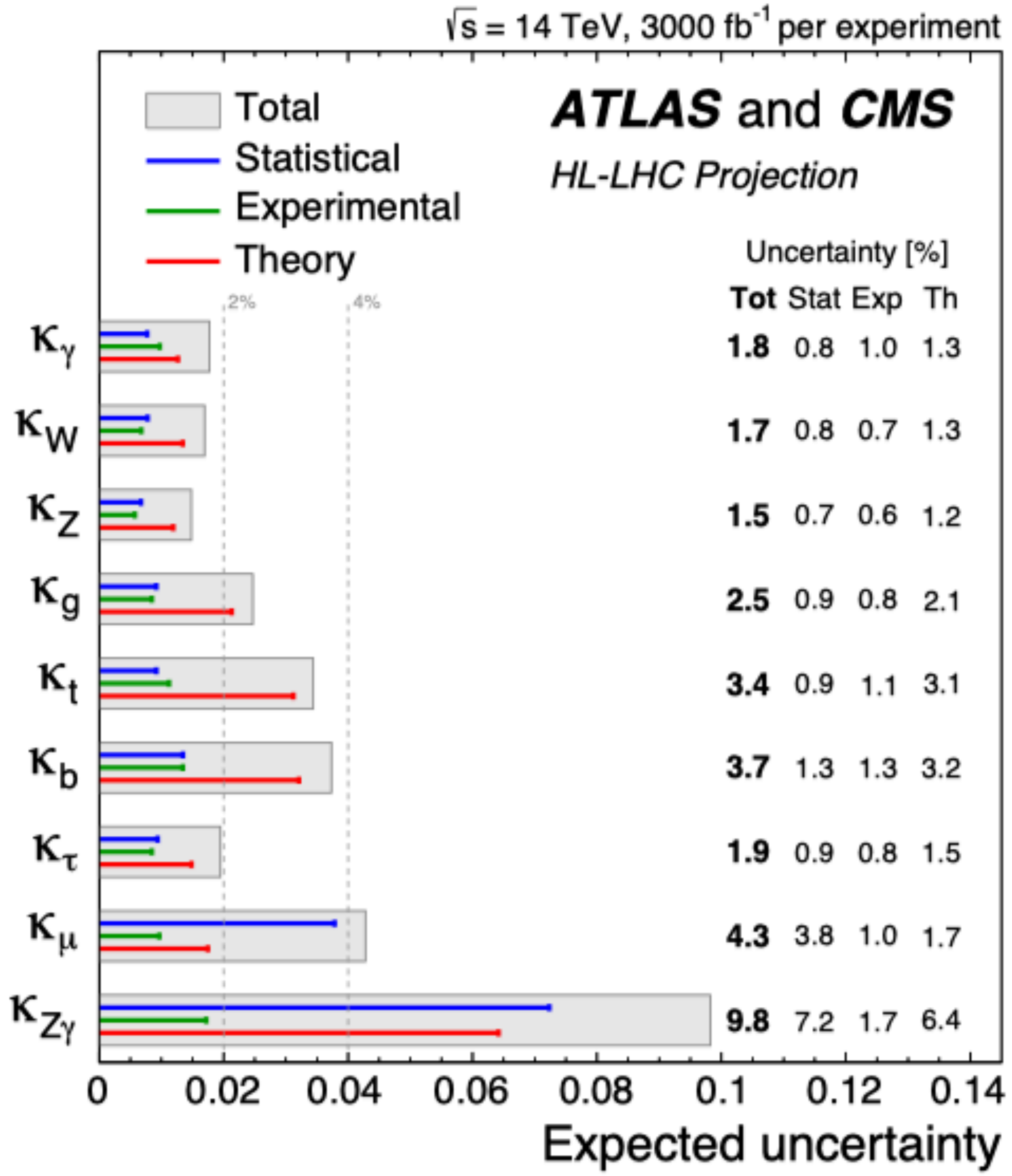
$$\kappa_j^2 = \sigma_j/\sigma_j^{\rm SM} \quad \text{or} \quad \kappa_j^2 = \Gamma^j/\Gamma^j_{\rm SM}.$$

Expected ±1σ uncertainties on coupling modifiers

Uncertainty components contribute at a similar level for κ_γ, κ_W, κ_Z and κ_τ . signal theory main component for κ_t and κ_g (κ_μ and $\kappa_{Z\gamma}$ stat. limited)



A precision of 1-4% reachable except for statistical limited cases of κ_μ and $\kappa_{Z\gamma}$



Differential Higgs Cross-section measurement

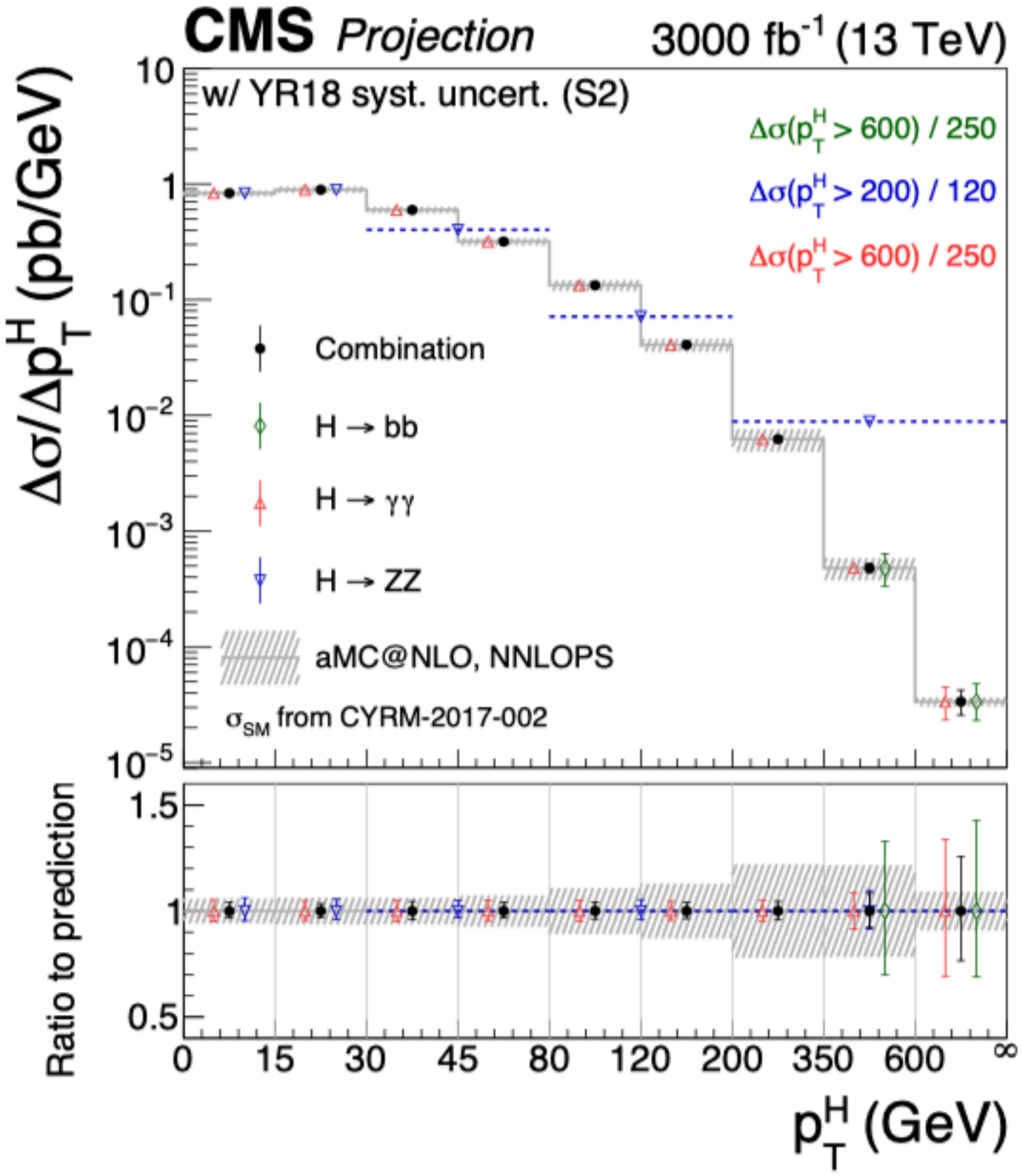
New physics may reside in the high scale tails of differential distributions. p_T^H differential distribution is of particular interest.

Combined distribution with $H \rightarrow \gamma\gamma$, H→ZZ→4l and boosted H→bb

Uncertainties in the higher p_t^H region are about a factor of ten smaller compared to RunII (stats. dominated region).
Lower p_t^H region are however no longer statistically dominated, where the reduced systematic uncertainties in S2 yield a reduction in the total uncertainty of up to 25% compared to S1

Relative uncertainties on the projected p_t^H spectrum measurements under S2 at 3000 fb −1

p_T^H [GeV]	0-15	15-30	30-45	45-80	80-120	120-200	200-350	350-600	600-∞
Combination	3.7%	3.3%	4.2%	3.7%	4.0%	3.8%	4.4%	8.0%	24.5%



Higgs pair production and Self coupling

- Performed with the DELPHES fast parametric simulation software to simulate the response of the upgraded CMS detector and account for the pileup contributions by overlaying an average of 200 minimum bias interaction events simulated with PYTHIA 8

- Explored 5 different decay channels: bbbb, bbτ τ , bbWW (WW → lνl'ν with l,l' = e, μ), bb γγ , and bbZZ (ZZ → lll'l' with l,l' = e, μ)

HH production : Benchmark channel for HL-LHC

Triple Higgs coupling :

Standard Model:

$$\lambda_{hhh} = \frac{m_h^2}{2v^2}$$

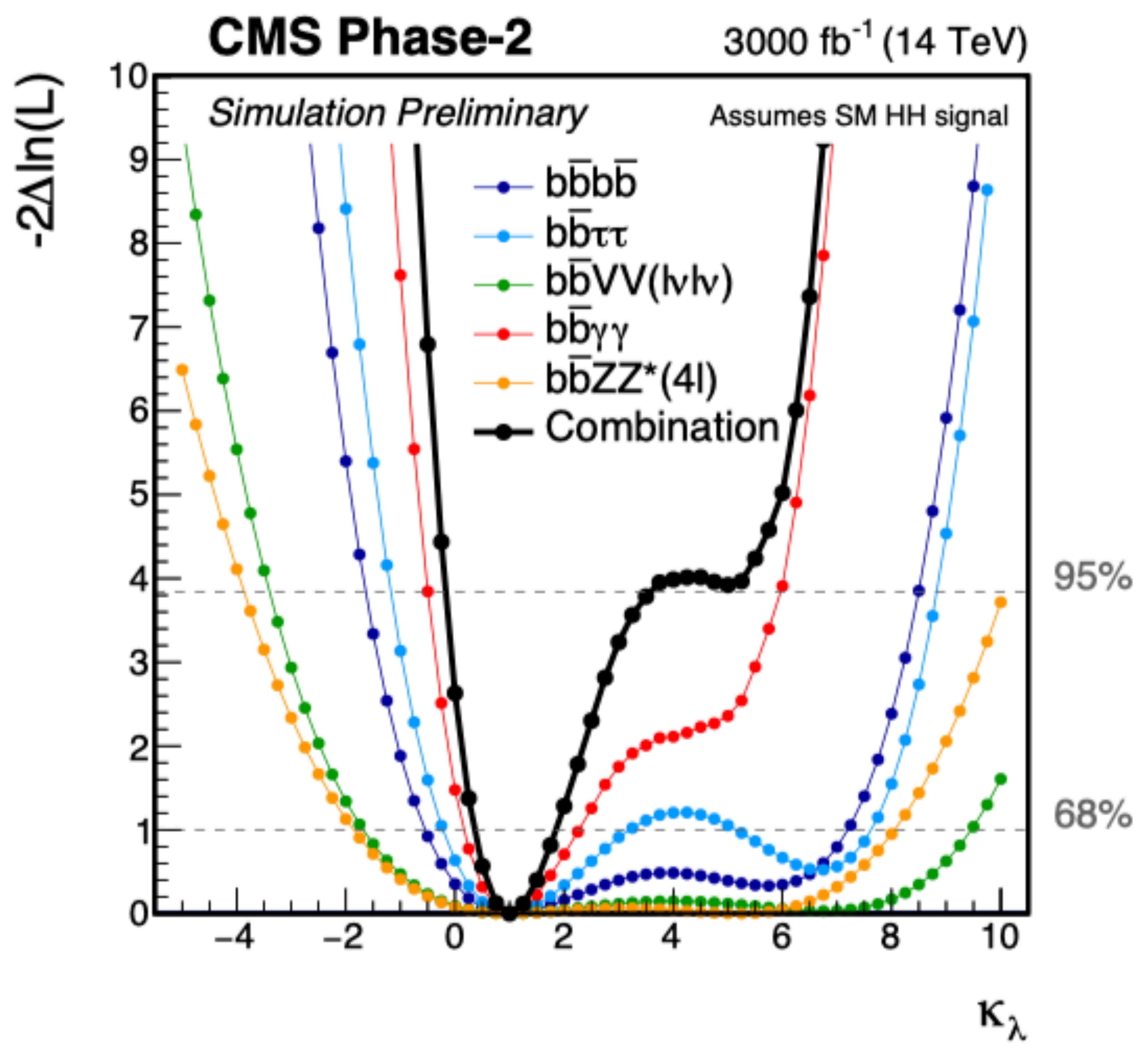
Coupling modifier: $\kappa_\lambda = \lambda_{hhh} / \lambda_{hhh}^{SM}$

Upper limit at the 95% confidence level (CL) and the significance for the SM HH signal at 68% CL.

Channel	Significance		95% CL limit on $\sigma_{HH}/\sigma_{HH}^{SM}$	
	Stat. + syst.	Stat. only	Stat. + syst.	Stat. only
bbbb	0.95	1.2	2.1	1.6
$bb\tau\tau$	1.4	1.6	1.4	1.3
$bbWW(\ell\nu\ell\nu)$	0.56	0.59	3.5	3.3
$bb\gamma\gamma$	1.8	1.8	1.1	1.1
$bbZZ(\ell\ell\ell\ell)$	0.37	0.37	6.6	6.5
Combination	2.6	2.8	0.77	0.71

κ_λ measurement with significance of the signal of 2.6σ.

Expected Likelihood scan as a function of κ_λ



Results on the combination from ATLAS and CMS shown in the next talk by Stephane

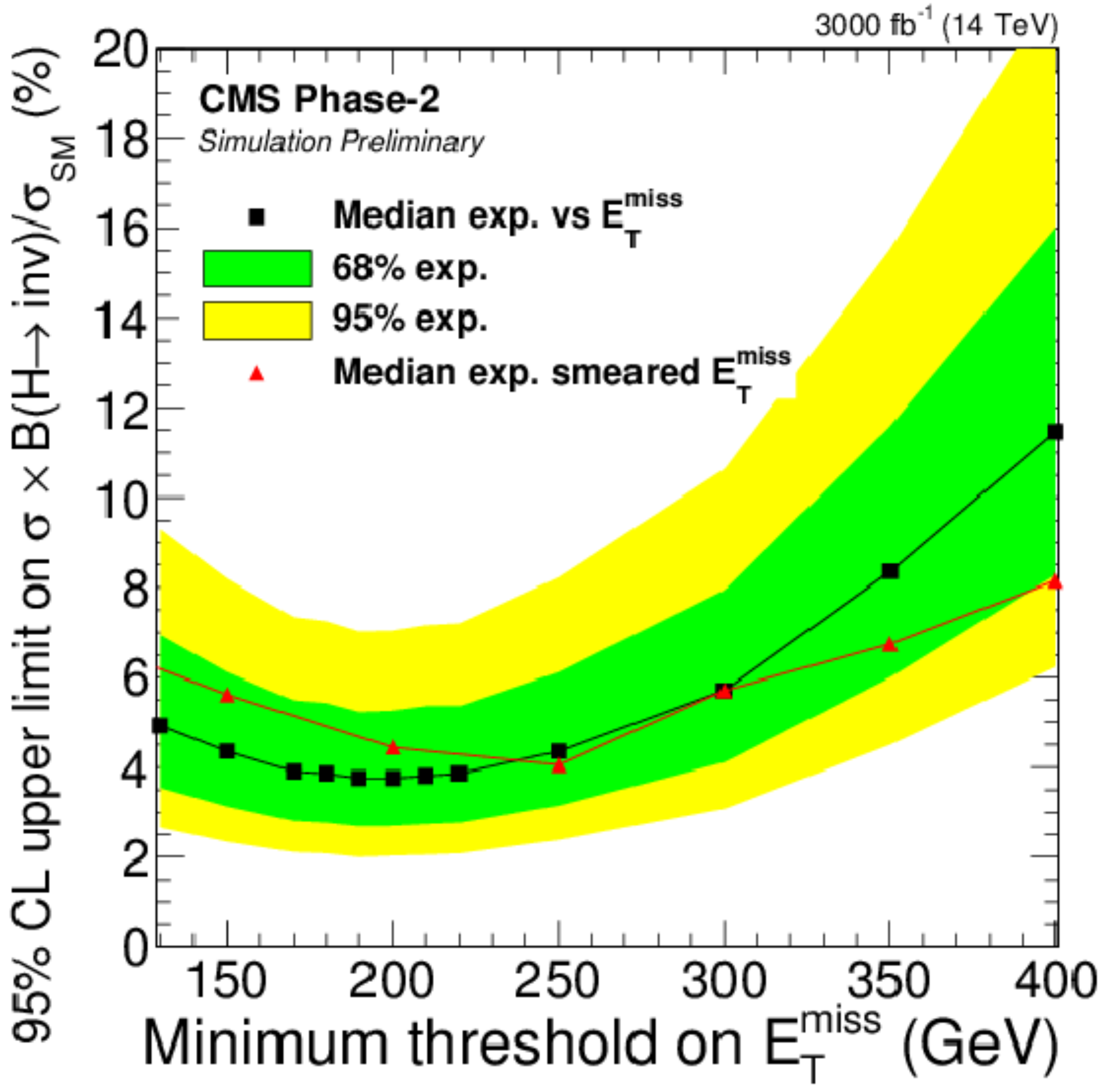
Sensitivity to BSM effects in Higgs Physics

Sensitivity to BSM effects in Higgs Physics

Several studies on probing the BSM effects in the Higgs physics :

- Probe for anomalous interactions & rare/exotic decays:
  - H→invisible [FTR-18-016]
    - **B_{INV} < 3.8%** (compare to 24% combination of full Run1 and Run2 at 36 fb^{-1})
  - Exotic/rare/forbidden decays and signatures [FTR-18-011]
    - **B_{BSM} < 6%** from couplings combination (compare to 22% for B_{inv} and 38% for B_{undet} @Run2 with 36 fb^{-1})
  - Anomalous couplings and width [FTR-18-011]
    - significant improvement in limits on anom. coupl. Width: **$\Gamma_H \subset$ [2,6] MeV** @ 95%CL
  - L1T TrackJet for BSM Higgs signatures [FTR-18-018]
    - signatures with displaced jets
- Search for additional Higgs bosons and/or scalars :
  - MSSM H→$\tau\tau$ search [FTR-18-017]
  - High mass search X→ZZ→2l2q [FTR-18-040]

95% CL limits on σ/σ_{SM}*B(H → inv.) as a function of the minimum threshold on Missing transverse energy



Summary

HL-LHC : First Higgs factory! Provides potential for precision measurements and new physics discoveries in the Higgs sector

- Most Higgs cross-sections and couplings at few percent level precision
- Many measurements limited by systematic uncertainties ➔ work needed from theoretical and experimental side
- Significance of 2.6 σ (4σ with ATLAS+CMS combined) on triple Higgs coupling for HH production.
- Sensitivity to BSM physics enhanced
- Higgs width measurement possible within 1MeV. [backup slide]

Exciting times ahead!

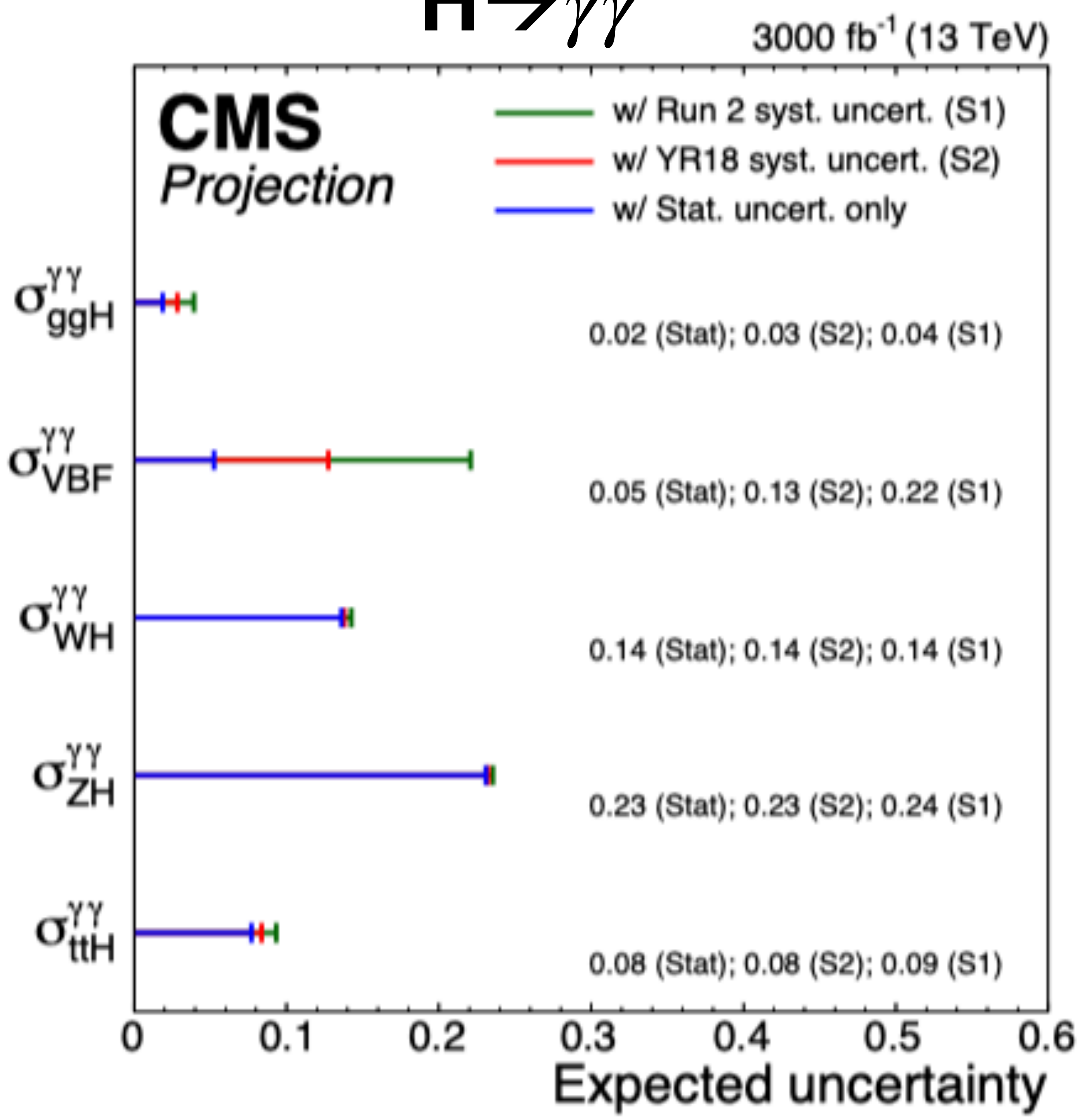
Backup

[Yellow Report - P256]

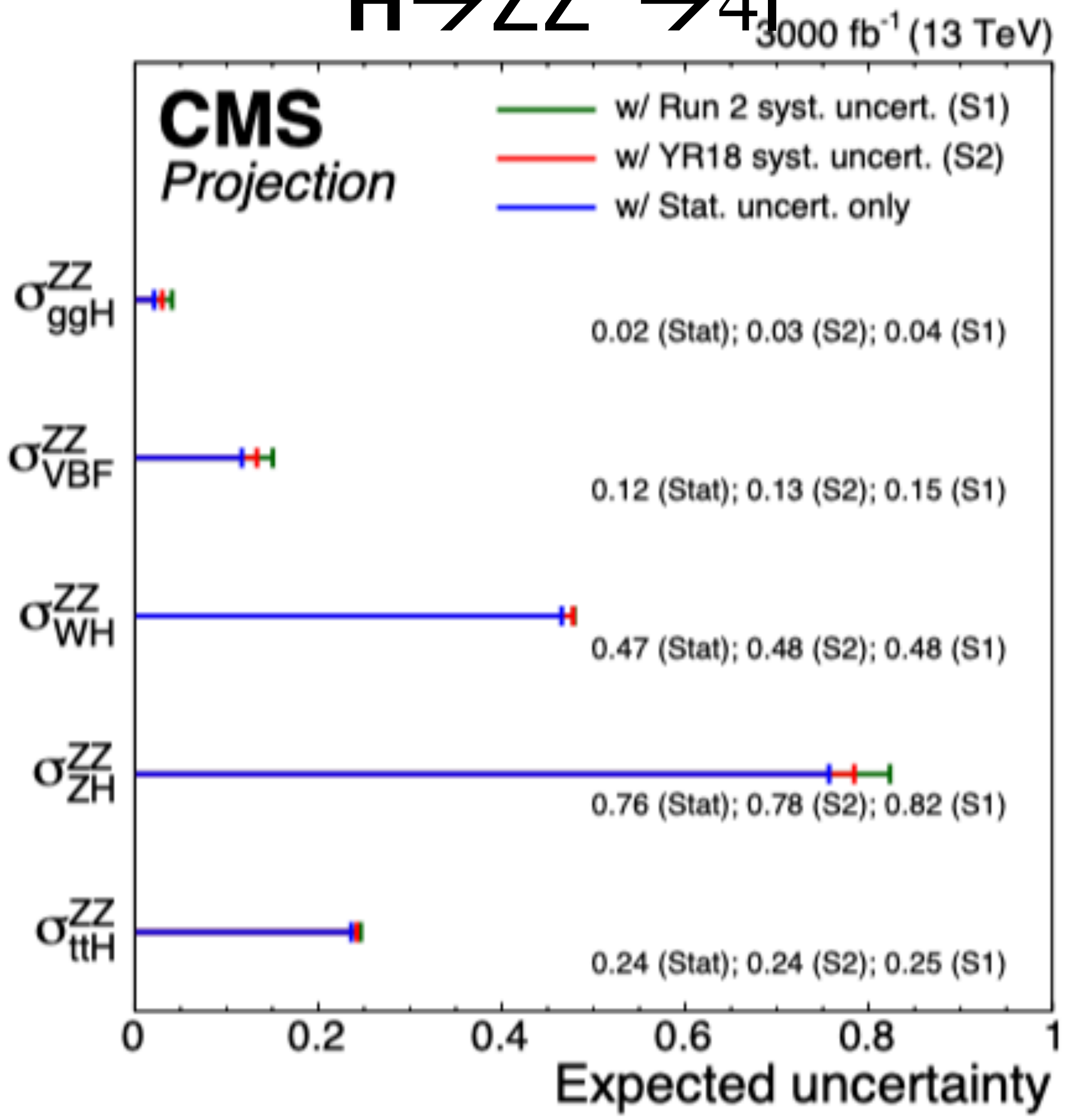
Signal Strengths

Expected ±1σ uncertainties per production mode

H→$\gamma\gamma$



H→ZZ*→4l



The main systematic uncertainties are the background modeling uncertainty, missing higher order uncertainties causing event migrations between the bins, photon isolation efficiencies and jet uncertainties

Expected precision: < 25% (VH dominated by stat unc.) in S2 scenario.

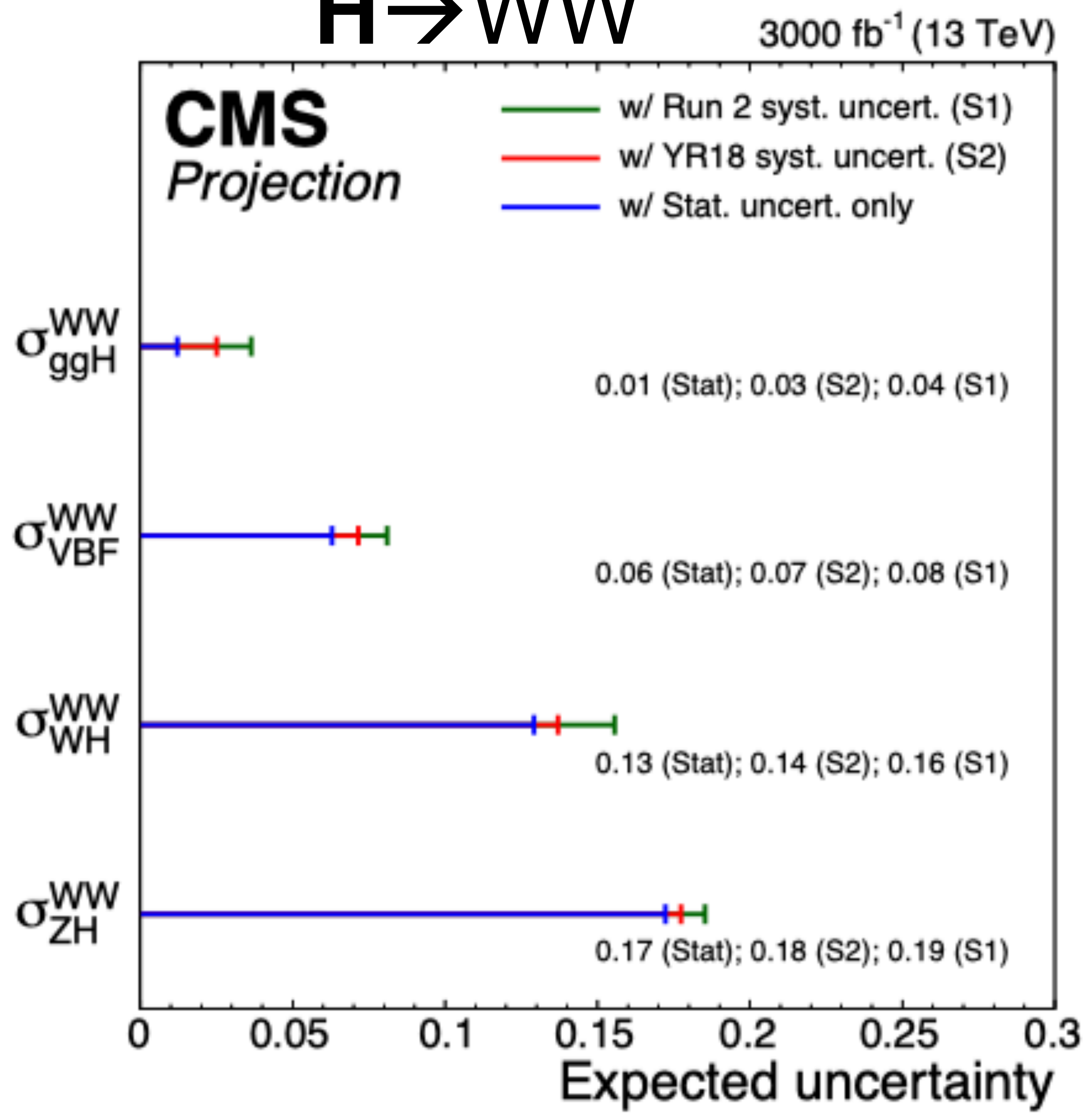
- For ggH : Dominant unc. are due to lepton reconstruction and identification efficiencies and pile-up modelling unc.
- For VBF and VH: Main unc. are due to jet energy scale and resolution,
- For ttH : missing higher order unc. + Parton shower modelling

Expected precision: < 78% (VH, ttH dominated by stat unc.) in S2 Scenario

Signal Strengths

Expected ±1σ uncertainties per production mode

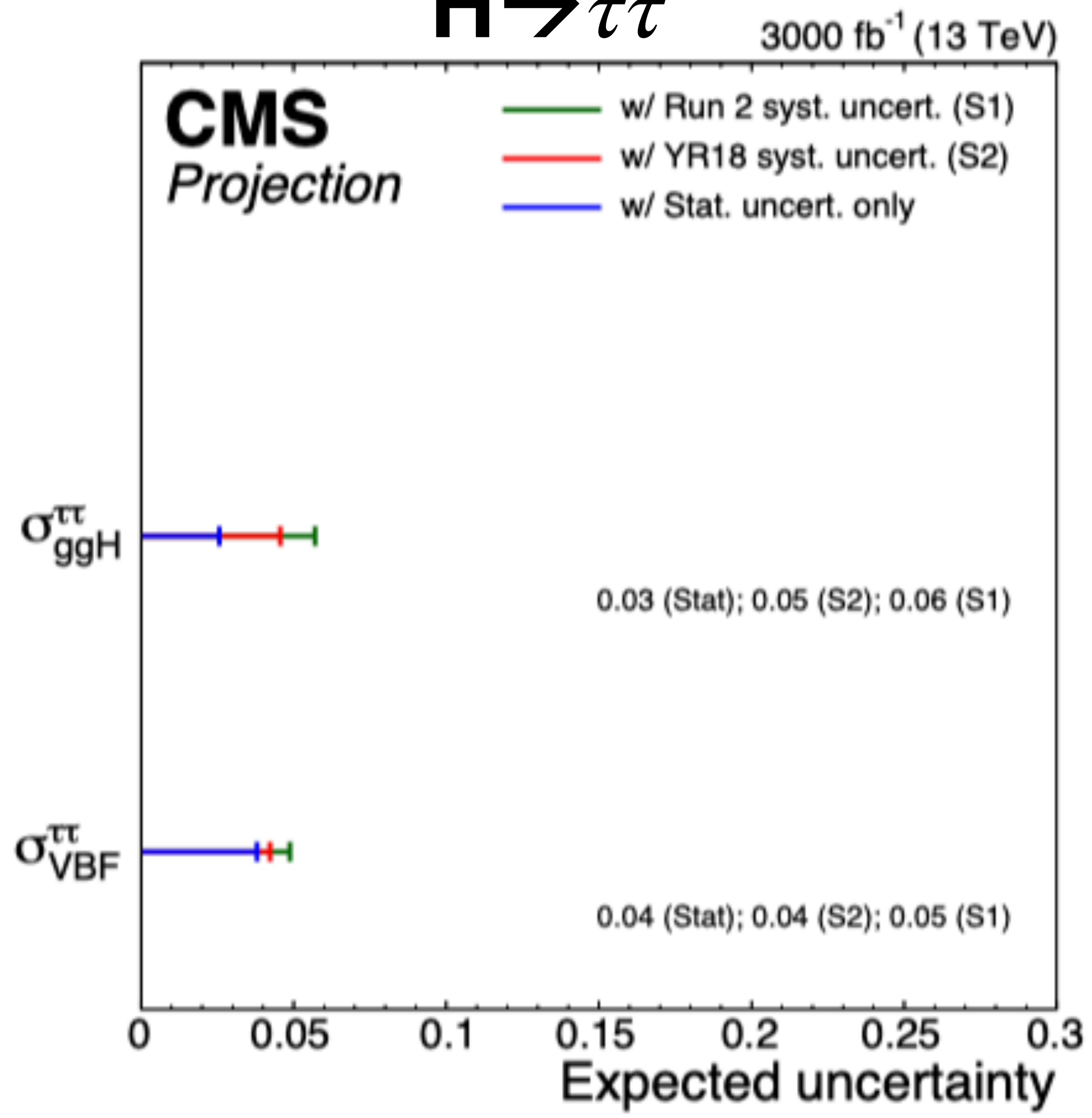
H→WW



Unc. in ggH is dominated by theoretical PDF uncertainty followed by experimental uncertainties affecting the signal acceptance, including uncertainties on the jet energy scale and flavour composition, and lepton mis-identification.

Expected precision: < 20%
(VH dominated by stat unc.)
in S2 scenario.

H→$\tau\tau$

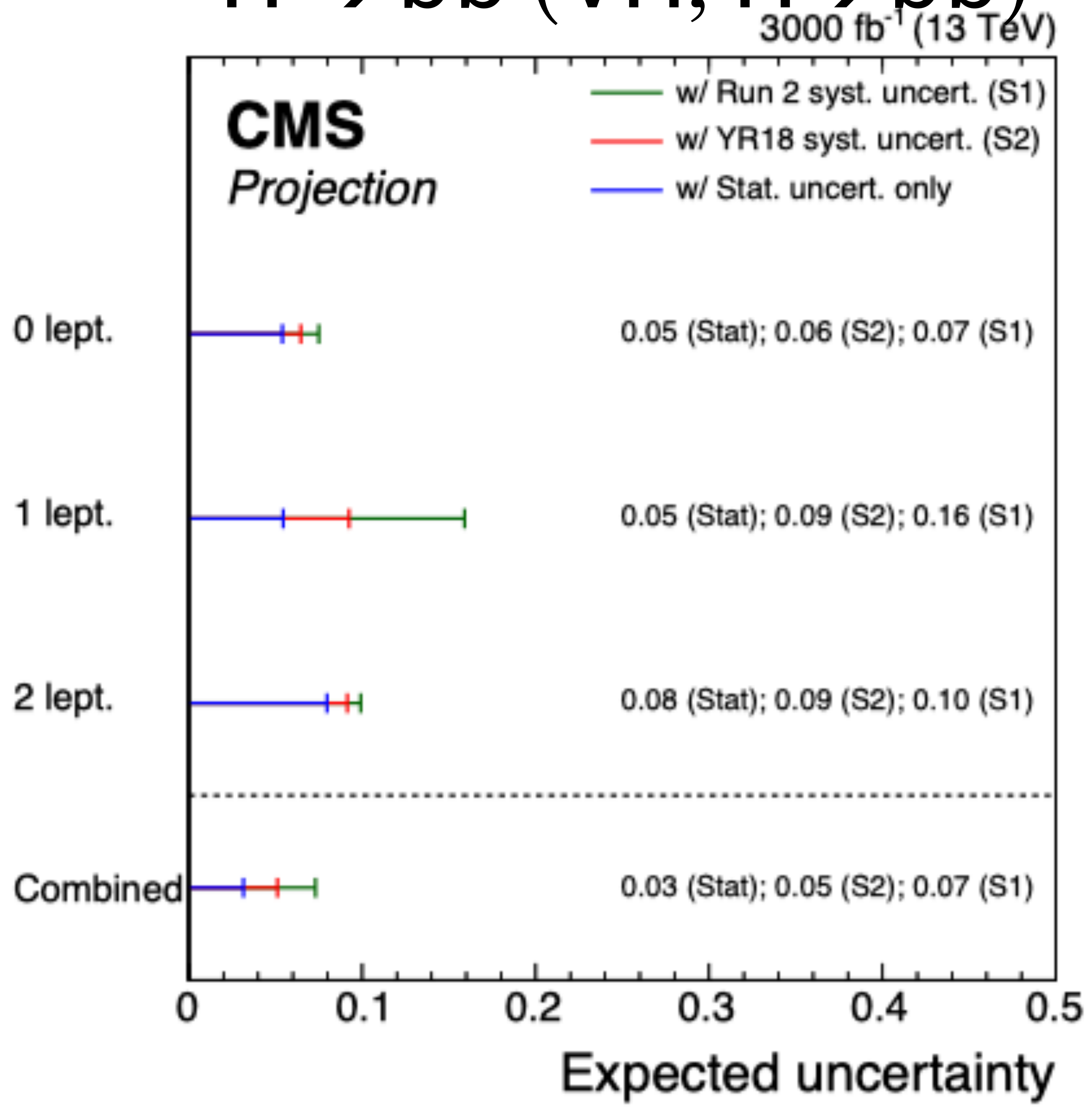


Here, main contributions come from :

- the uncertainties on jet calibration and resolution, on the reconstruction of the missing transverse energy.
- Determination of the background normalization from signal and control regions

Expected precision: ~ 5%

H →bb (VH, H→bb)

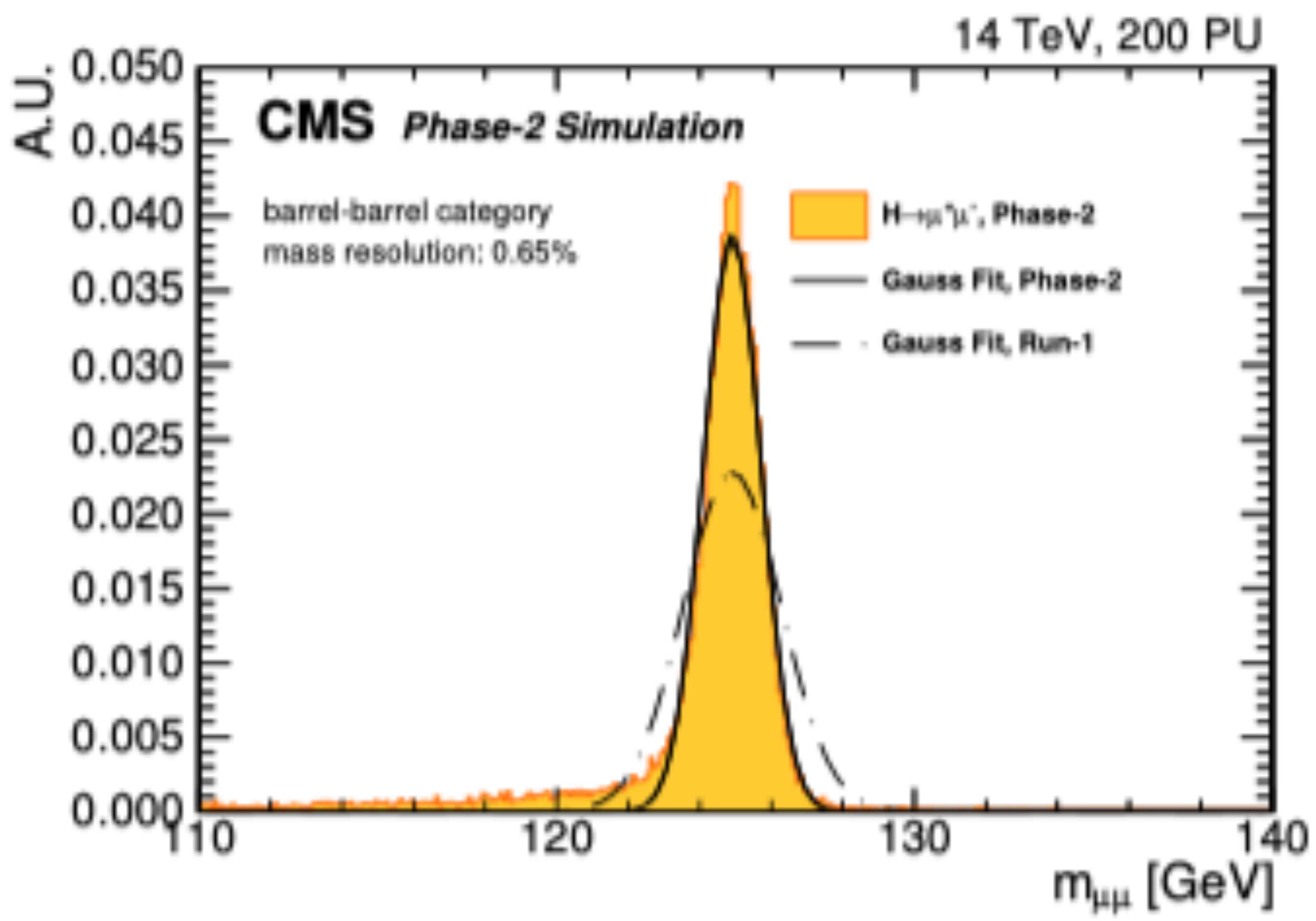


The largest component of the systematic uncertainty is theoretical coming from uncertainty in the gluon-induced ZH (gg→ZH) production cross section due to QCD scale variations

Expected precision: ~ 5%

Rare Decays : H→$\mu\mu$

- This analysis depends critically on dimuon mass resolution.
- New tracker achieves a much better mass resolution (low material budget, better measurement)
- Dimuon invariant mass width is reduced in order to match the increase in performances [40% improvement in the dimuon mass resolution]



Expected precision on the signal strength measurement

Experiment	CMS	
Process	Combination	
Scenario	S1	S2
Total uncertainty	13%	10%
Statistical uncert.	9%	9%
Experimental uncert.	8%	2%
Theory uncer.	5%	3%

Limited by the stat. unc., while the leading systematic uncertainty is the bias introduced by the choice of the function describing the background (spurious signal uncertainty), and the uncertainties on the modelling of the signal (their reduction in S2 contributes to an overall improvement of 10% on the precision of the measurement).

Constraints on couplings from Higgs diff. Cross section

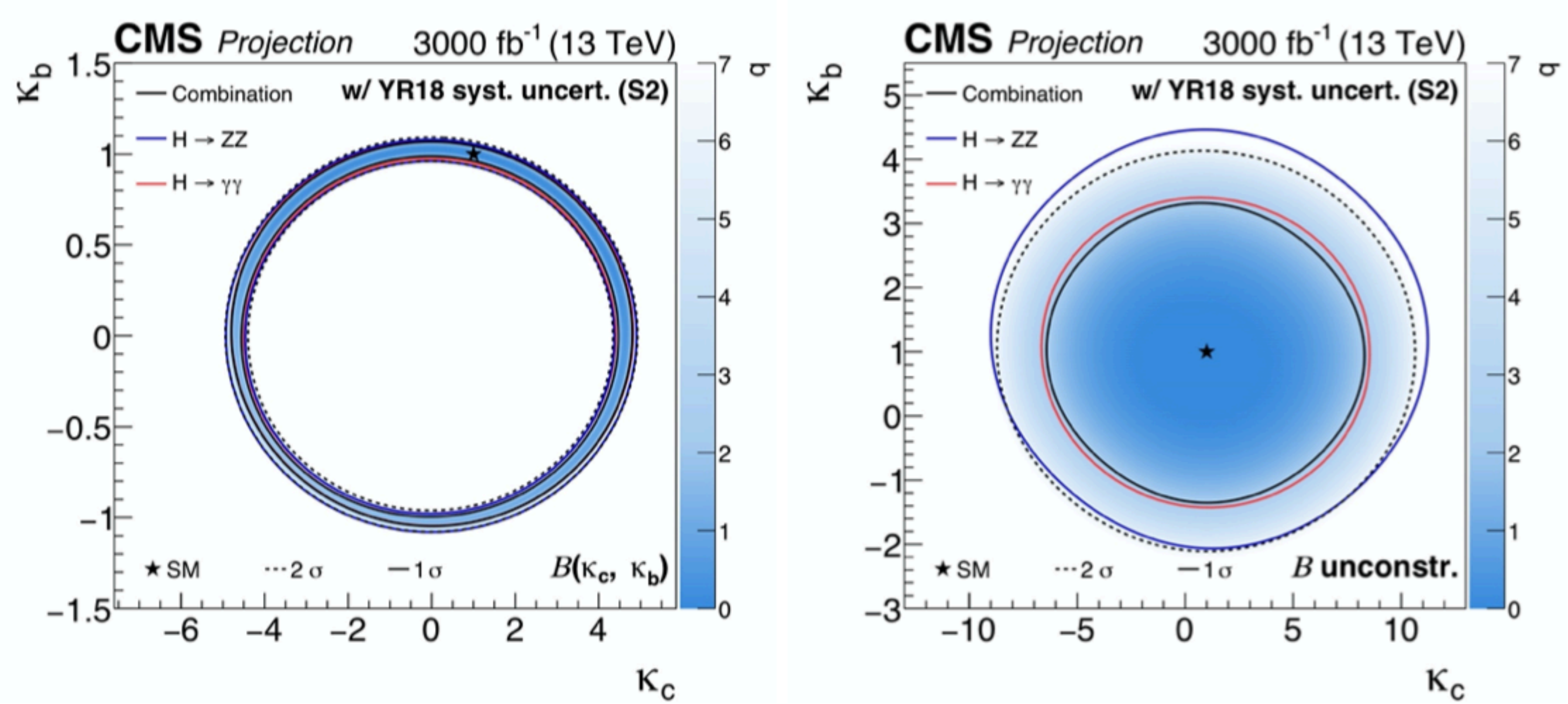
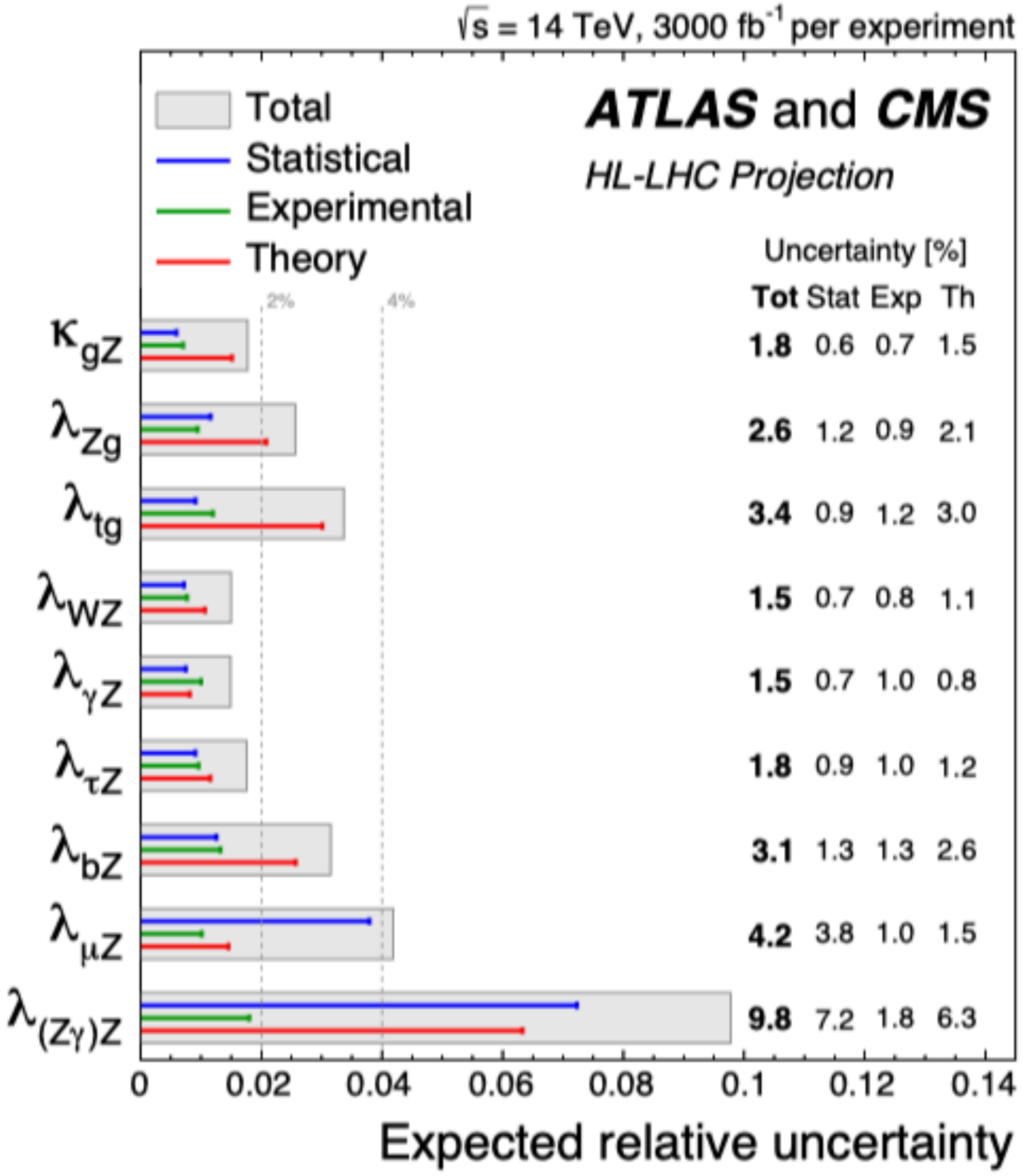


Figure 15: Projected simultaneous fit for κ_b and κ_c, assuming the branching fractions to be determined by the couplings (left) and the branching fractions implemented as nuisance parameters with no prior constraint (right), under S1 (top) and S2 (bottom). The one standard deviation contour is drawn for the combination ($H \to \gamma\gamma$ and $H \to ZZ$), the $H \to \gamma\gamma$ channel, and the $H \to ZZ$ channel in black, red, and blue, respectively. For the combination the two standard deviation contour is drawn as a black dashed line, and the shading indicates the negative log-likelihood, with the scale shown on the right hand side of the plots.

Ratio of coupling modifiers

Expected ±1σ uncertainties on the ratios of coupling modifiers

- Parametrisation based on ratios of the coupling modifiers ($\lambda_{ij} = \kappa_i / \kappa_j$) together with a reference ratio of coupling modifiers $\kappa_{gZ} = \kappa_g * \kappa_Z / \kappa_H$.
- No assumption on the Higgs total width as its effective modifier κ_H has been absorbed into the ratio κ_{gZ}.

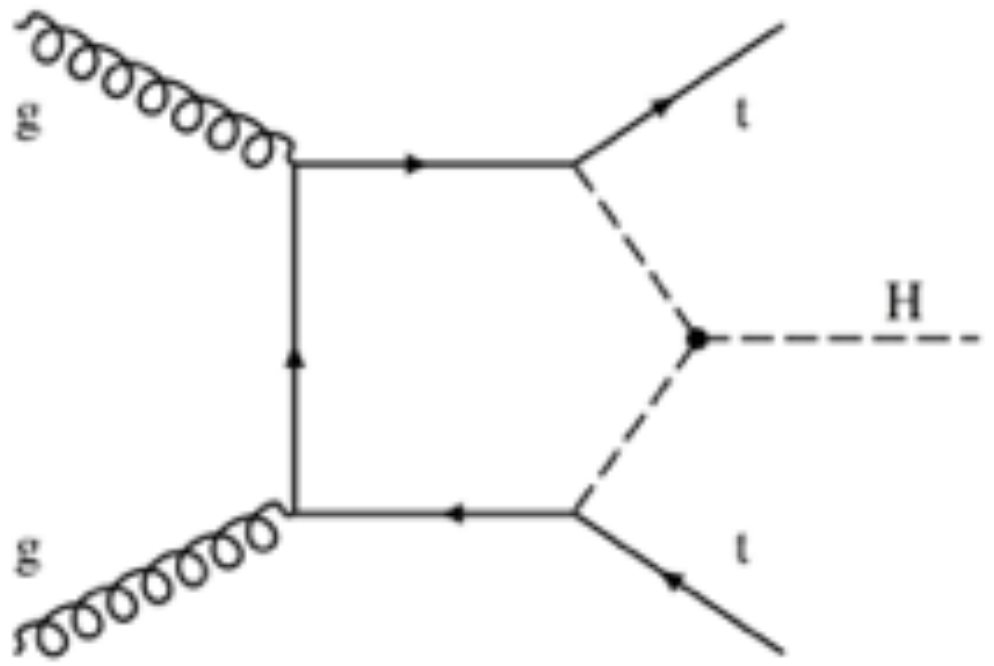


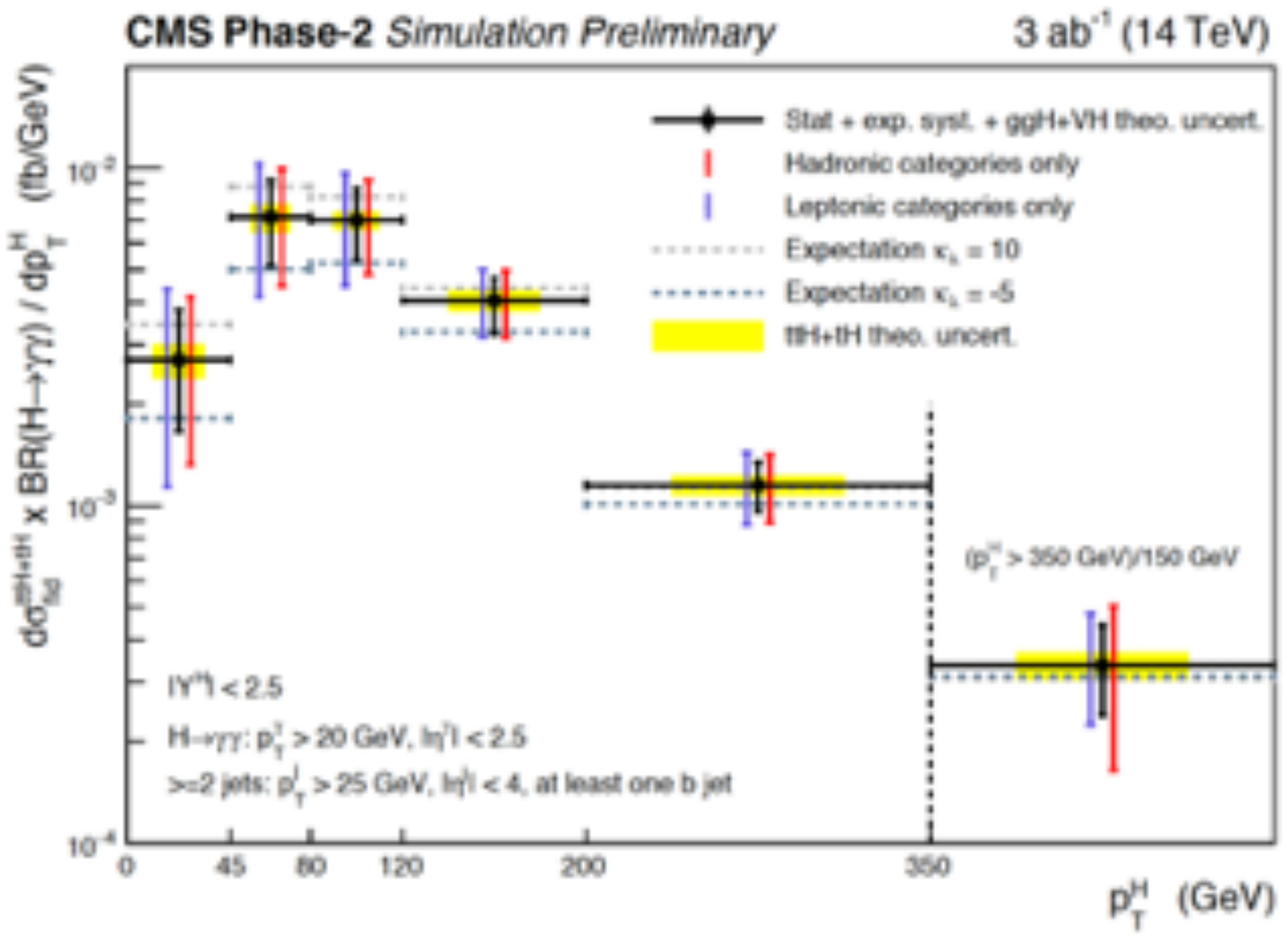
Differential cross-section and self-coupling

Alternative approach: exploiting radiative corrections to inclusive and differential Higgs boson production rates → at NLO single Higgs boson production modes include contributions involving the λ_3 → sizeable contribution from ttH, tH, VH

Focus in ttH (+tH), $H\rightarrow\gamma\gamma$ using Delphes simulation and a strategy similar to the Run2

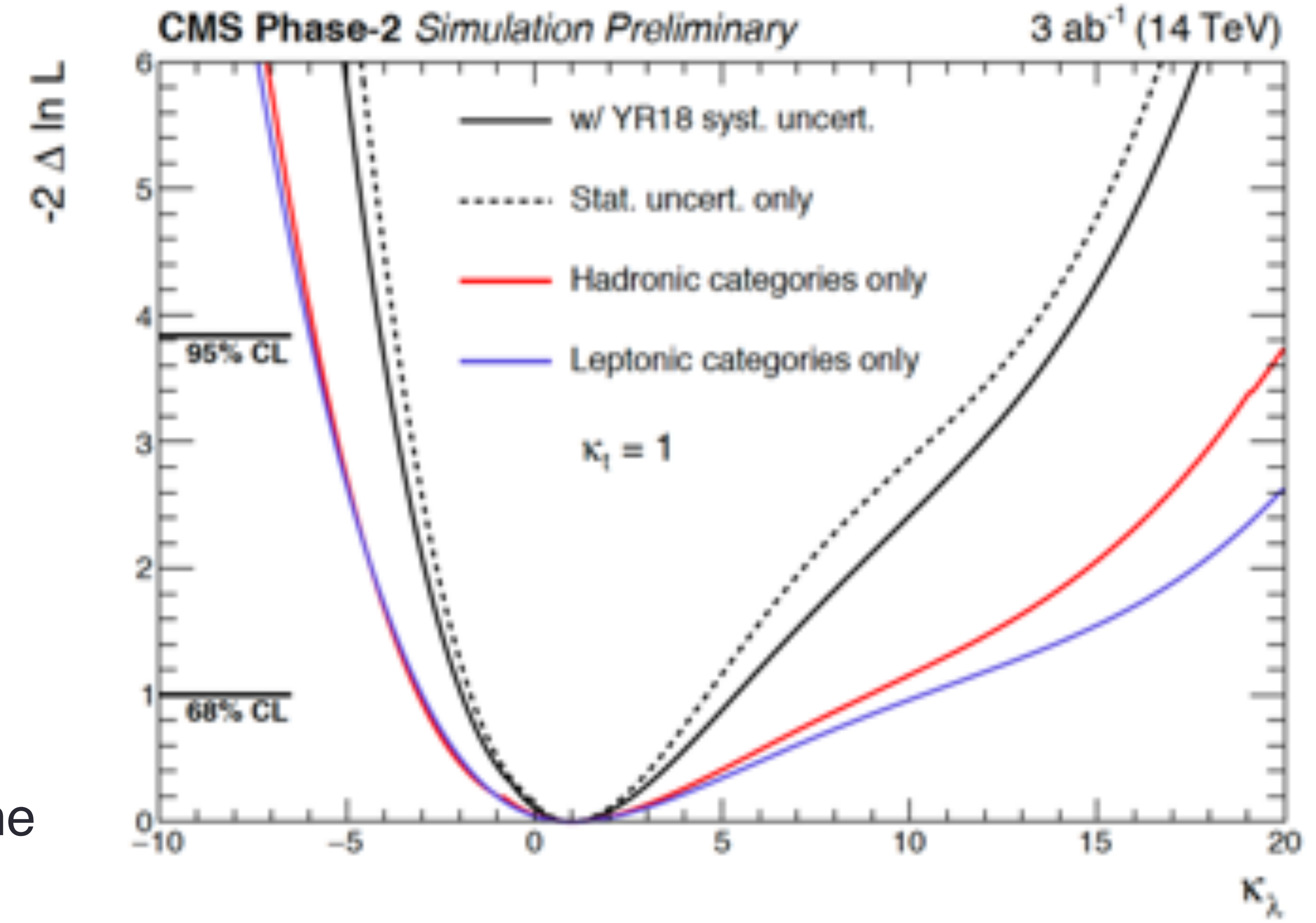
At 68% C.L.: $-1.9<k_\lambda<5.3$ → complementary to the stronger constraints from direct Higgs production





p_T^H allows to disentangle the effects of modified Higgs boson self-coupling values from other effects such as the presence of anomalous top–Higgs couplings.

The dependence of the single-Higgs boson differential xs is parameterised as a function of k_λ



Limits on Higgs Width

Comparison of on-shell and off-shell rate in H→ZZ→4l constrain the Higgs boson width

• current constraint: Γ< 9.16 MeV @ 95% CL

Off-peak to on-peak ratio

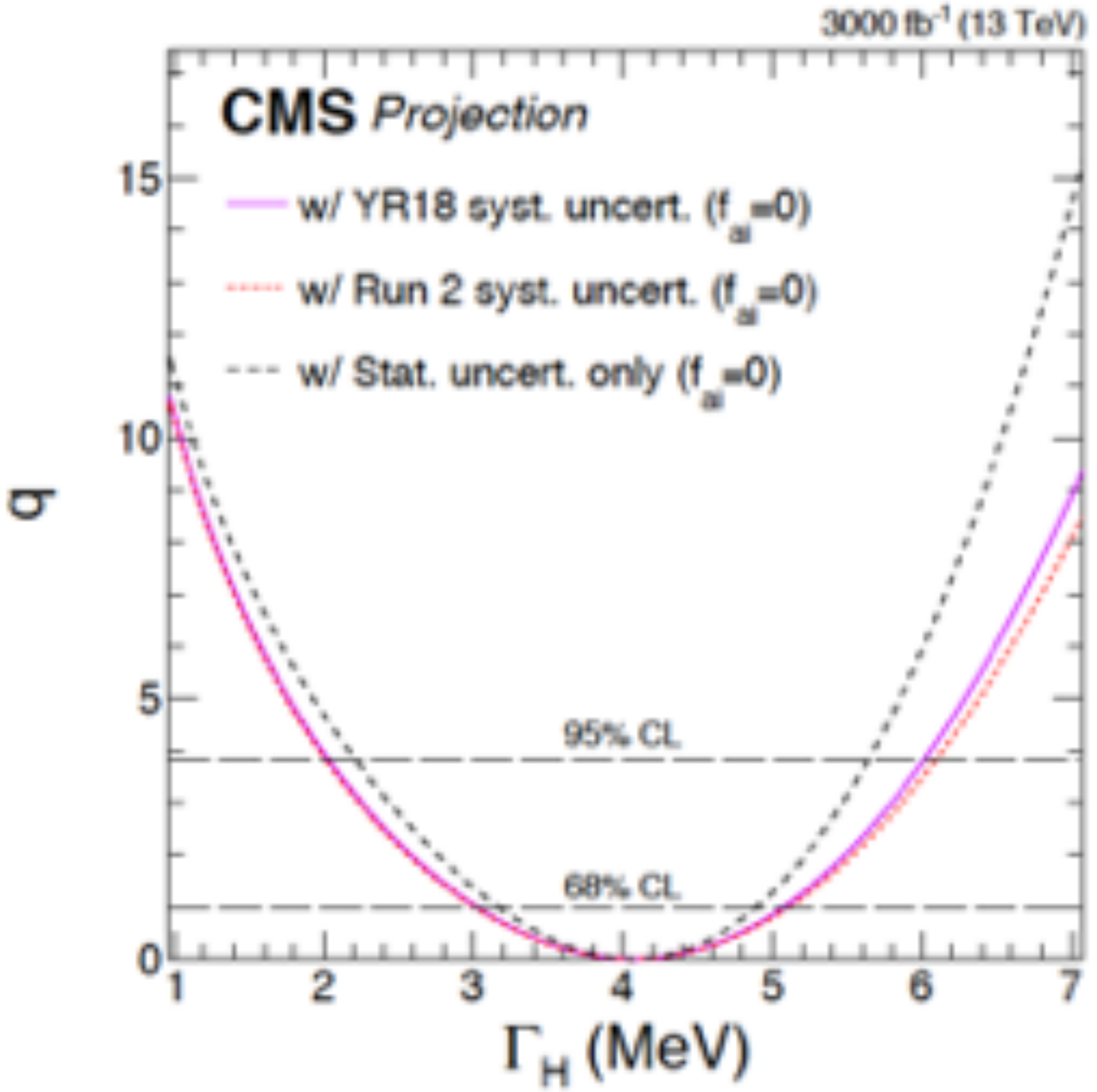
$$\frac{\sigma^{\mathrm{off-shell}}}{\sigma^{\mathrm{on-shell}}} \sim \Gamma_H$$

Systematic uncertainty:

• theoretical unc. dominant over exp. ones ←dominant effect comes from the uncertainty in the NLO EW correction on the qq→4l simulation above the 2m$_Z$ threshold

• approximate S2 in which the experimental uncertainties not reduced, while the theoretical uncertainties halved w.r.t S1

• 10% additional uncertainty applied on the QCD NNLO K factor on the gg



Precision (CMS + ATLAS) : $4.1^{+0.7}_{-0.8}$ MeV @68% C.L.