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

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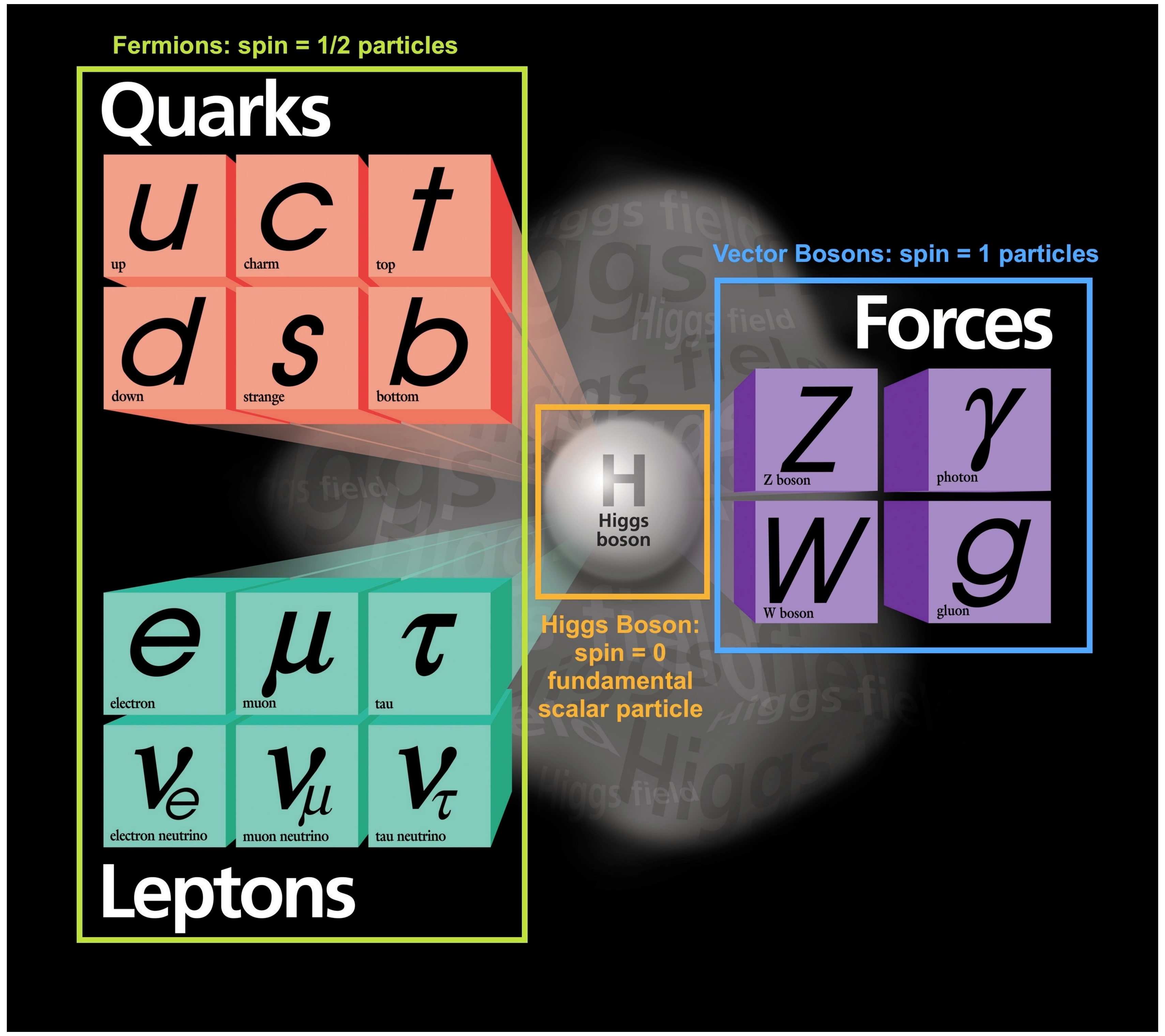
What have we learnt so far?

- 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 ?

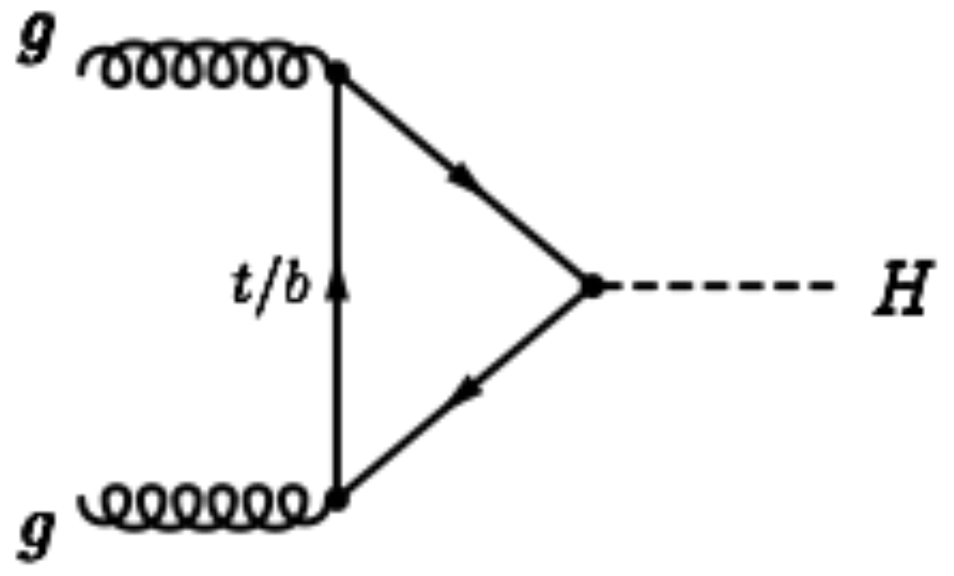


- **Answers may lie at the TeV scale, providing a strong motivation to look for new physics.**

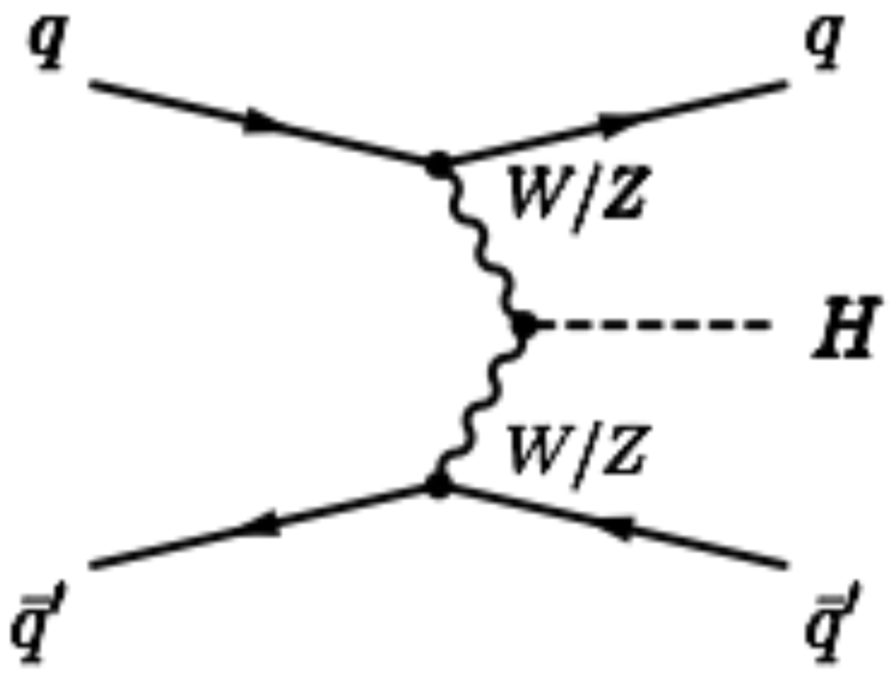
Higgs boson main production mechanism at the LHC

125 GeV Higgs boson production cross section @13 TeV

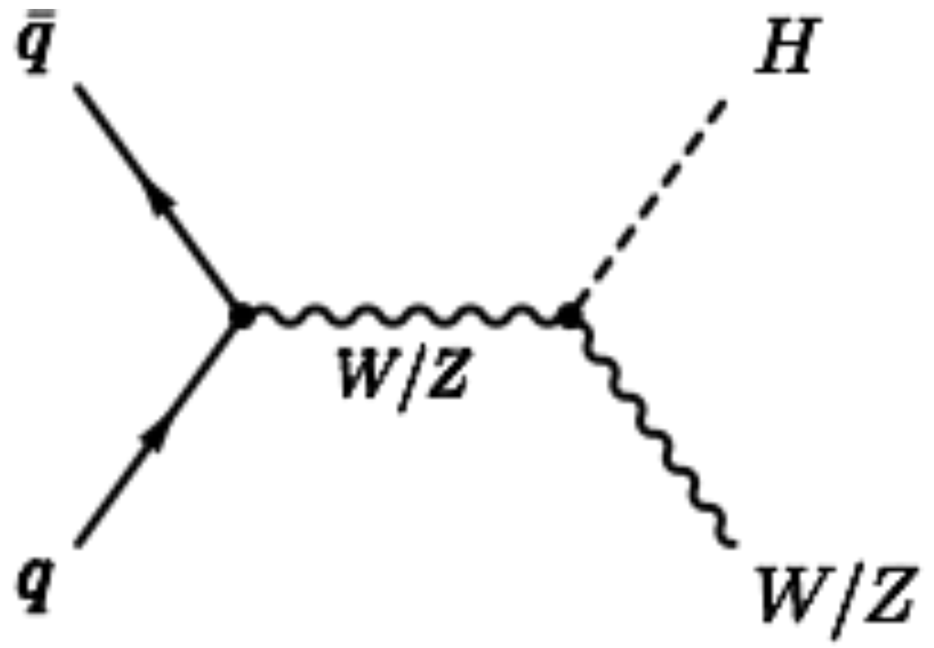
Gluon-fusion (ggH)
48.5 pb ~87%



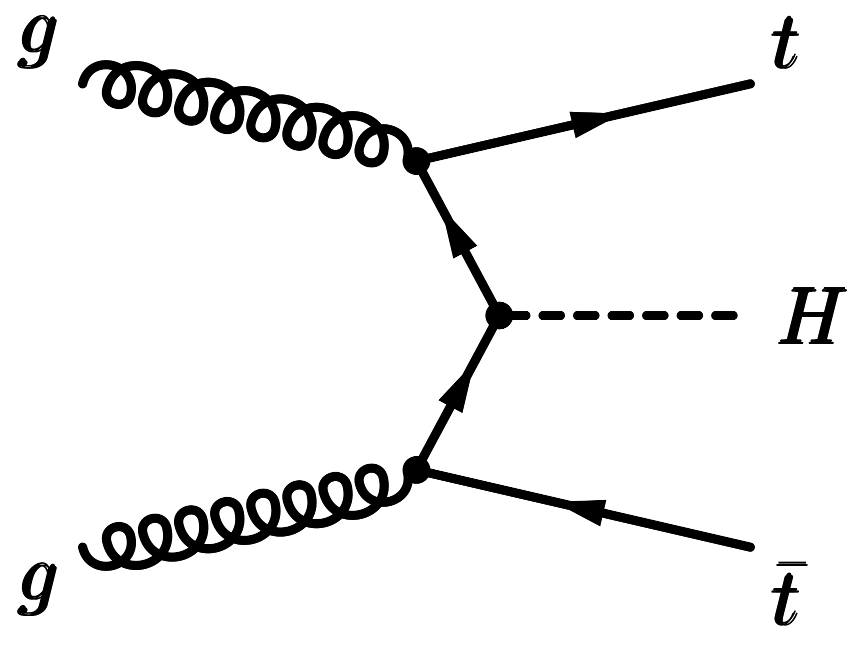
Vector boson fusion (VBF)
3.8 pb ~7%



Associated Higgs production with a W or Z boson (VH): 2.3 pb ~ 4%

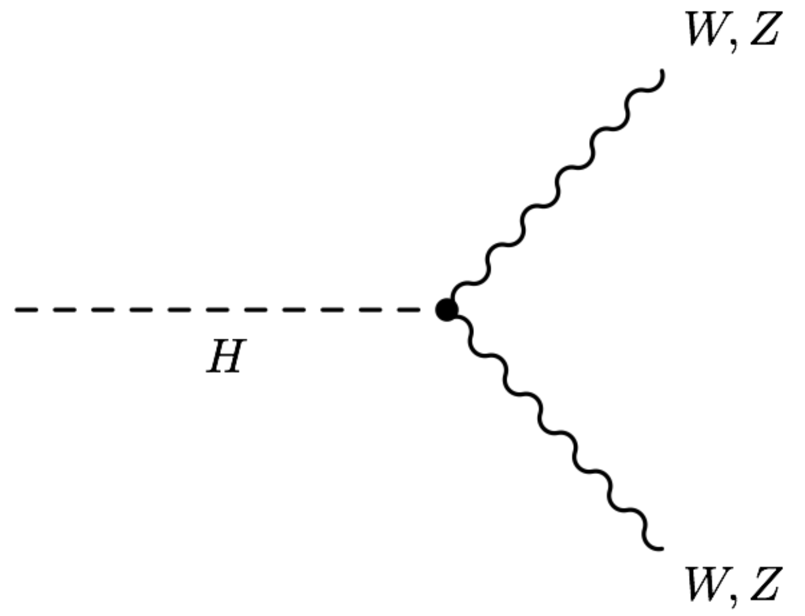


Associated Higgs production with a top quark pair (ttH): 0.5 pb ~1%

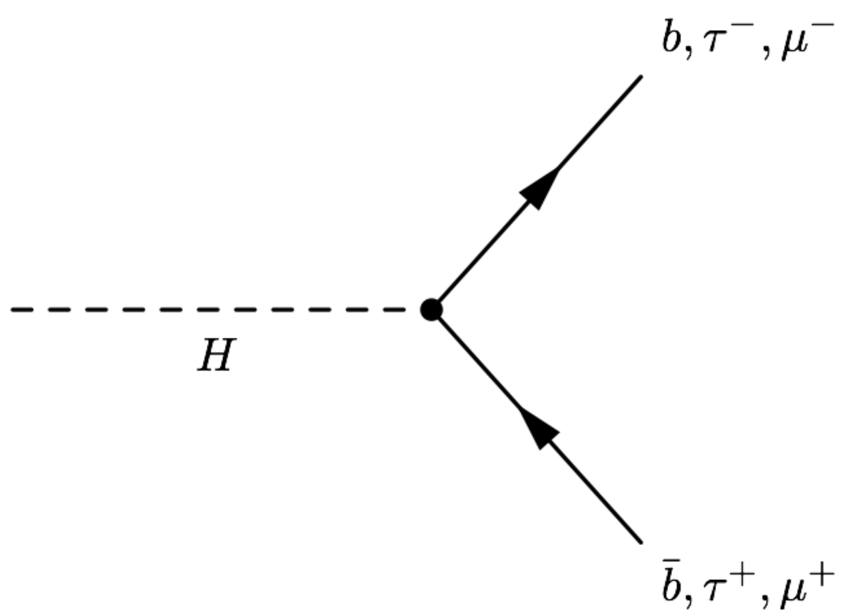


Higgs boson main decay channels

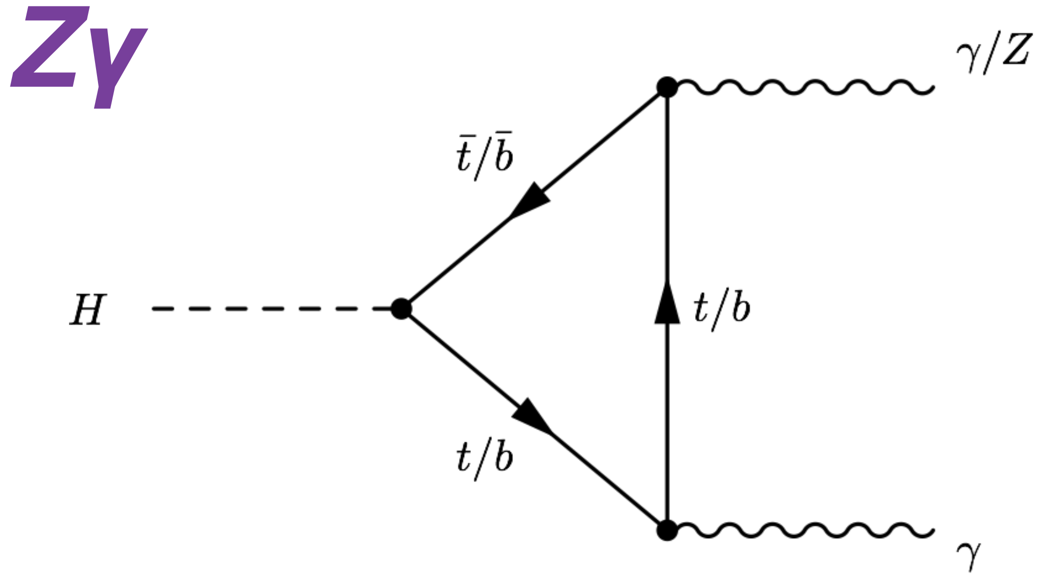
ZZ, WW

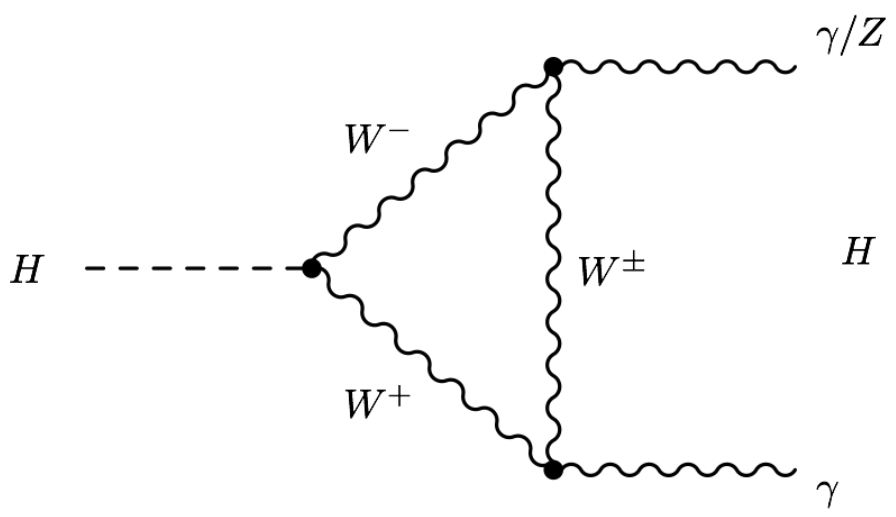


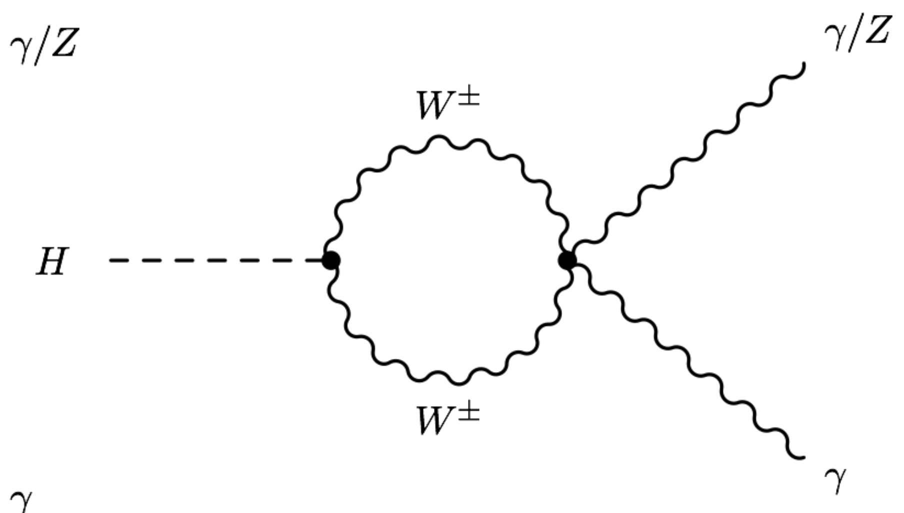
bb, ττ, μμ



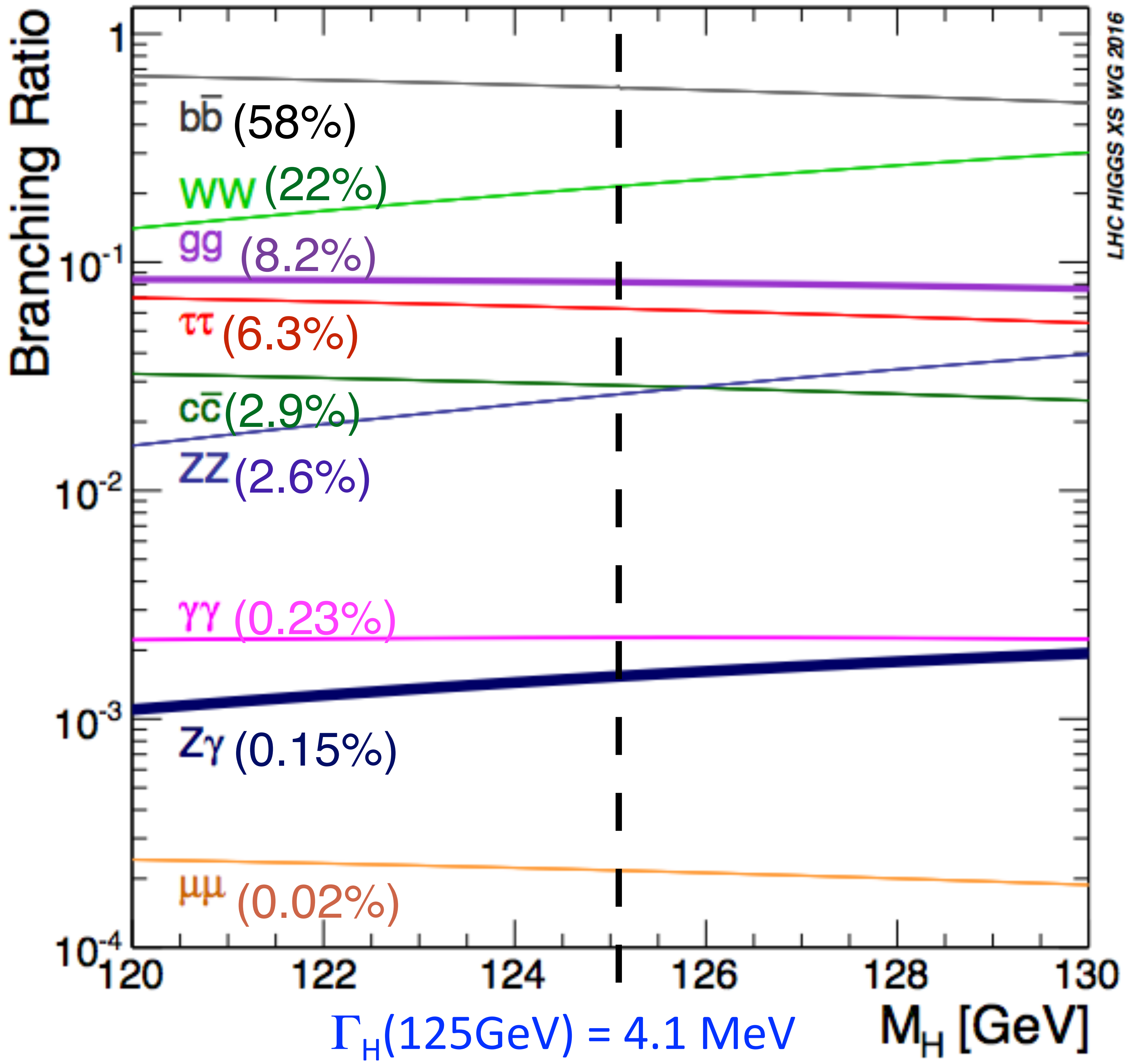
γγ, Zγ







- *bosonic decays in precision measurement stage: γγ, ZZ*→4l, WW**
- *fermionic decays: bb, ττ observed*
- *channels not yet observed: cc, μμ, Zγ, …*

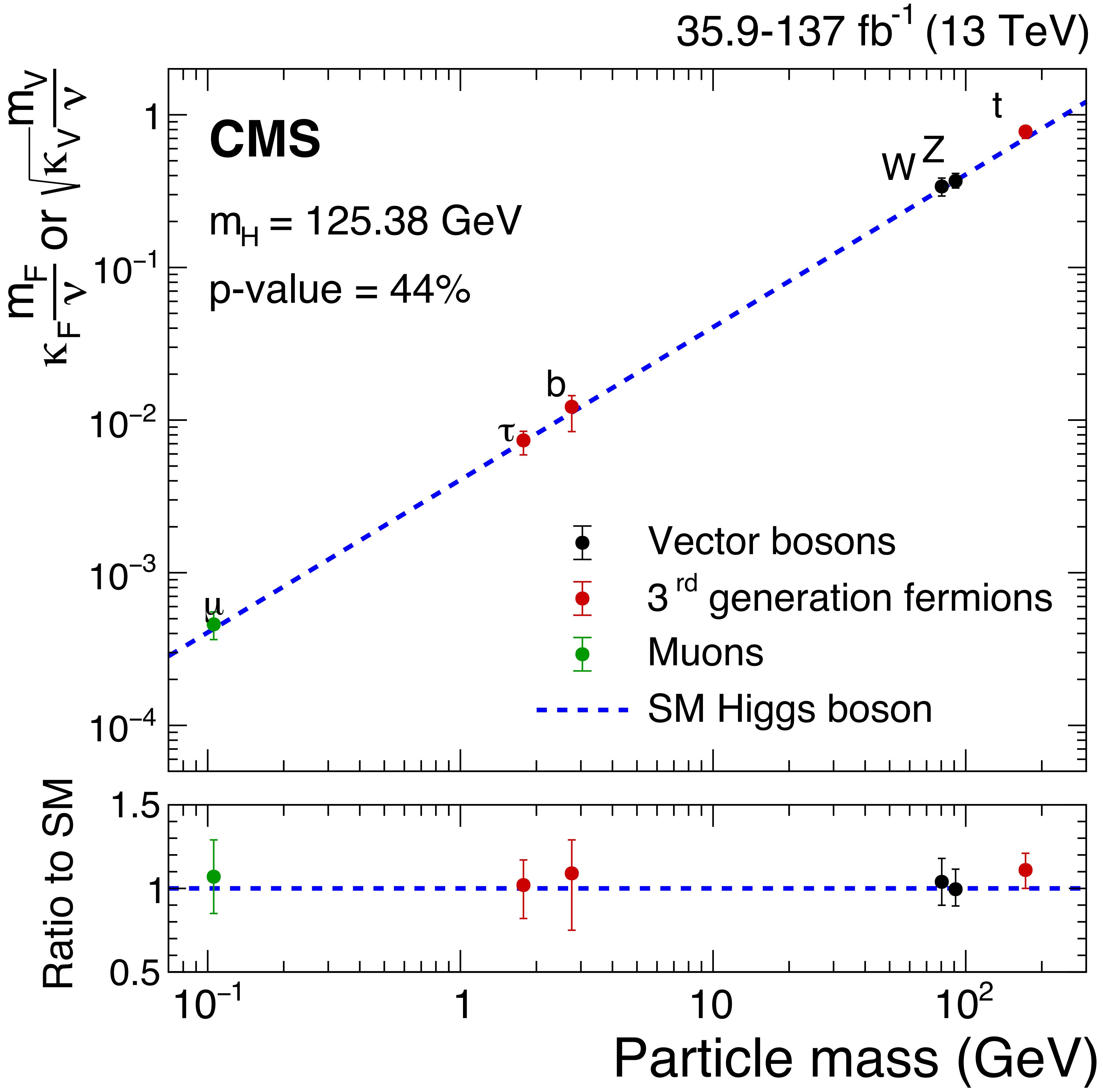


$\Gamma_H(125\text{GeV}) = 4.1$ MeV

Higgs boson physics: where we are now

- Higgs boson mass measured down to 0.1%
- Higgs boson couplings to W and Z boson measured down to ~5% precision, consistent with SM prediction
- Higgs boson couplings to fermions:
  - 3rd generation fermions t, b, τ have been established
  - 2rd generation fermions: 3σ evidence for H→μμ by CMS

CMS-HIG-19-006

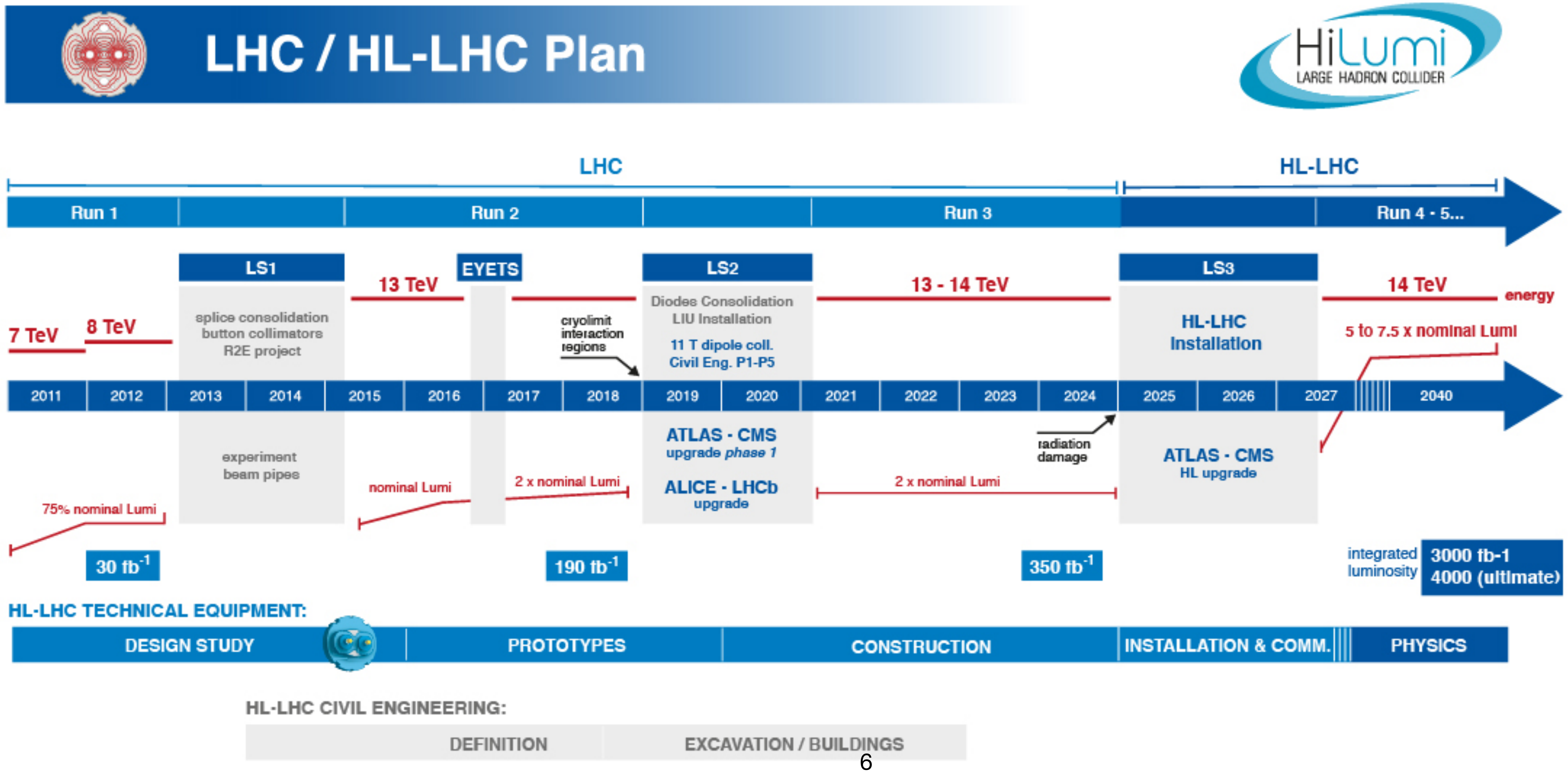


What can the HL-LHC do?

- 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.

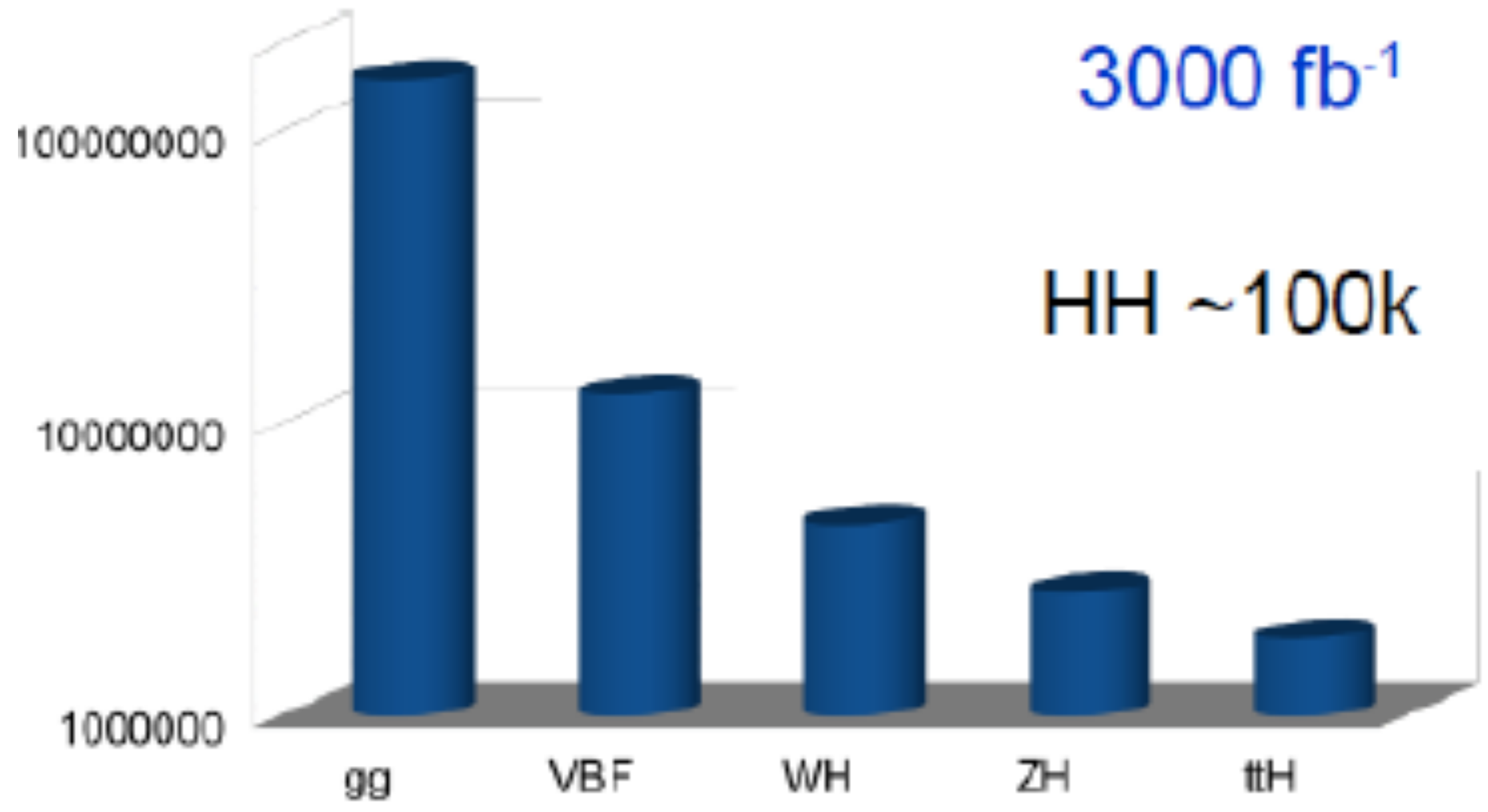
- Precise study of "SM-like" Higgs properties (discussed in next slides in details).



Expected Physics potential at HL-LHC in Higgs sector

Higgs physics is a major component of HL-LHC physics program.

At HL-LHC (Higgs factory), we expect to produce >150M Higgs Bosons (over 1M for each of the main production mechanisms, spread over various 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

Phase-2 detector upgrades

Phase-2 detector upgrade is crucial to meet the machine challenge of the HL-LHC

- **high pileup**: 140-200 interactions per bunch crossing. 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)

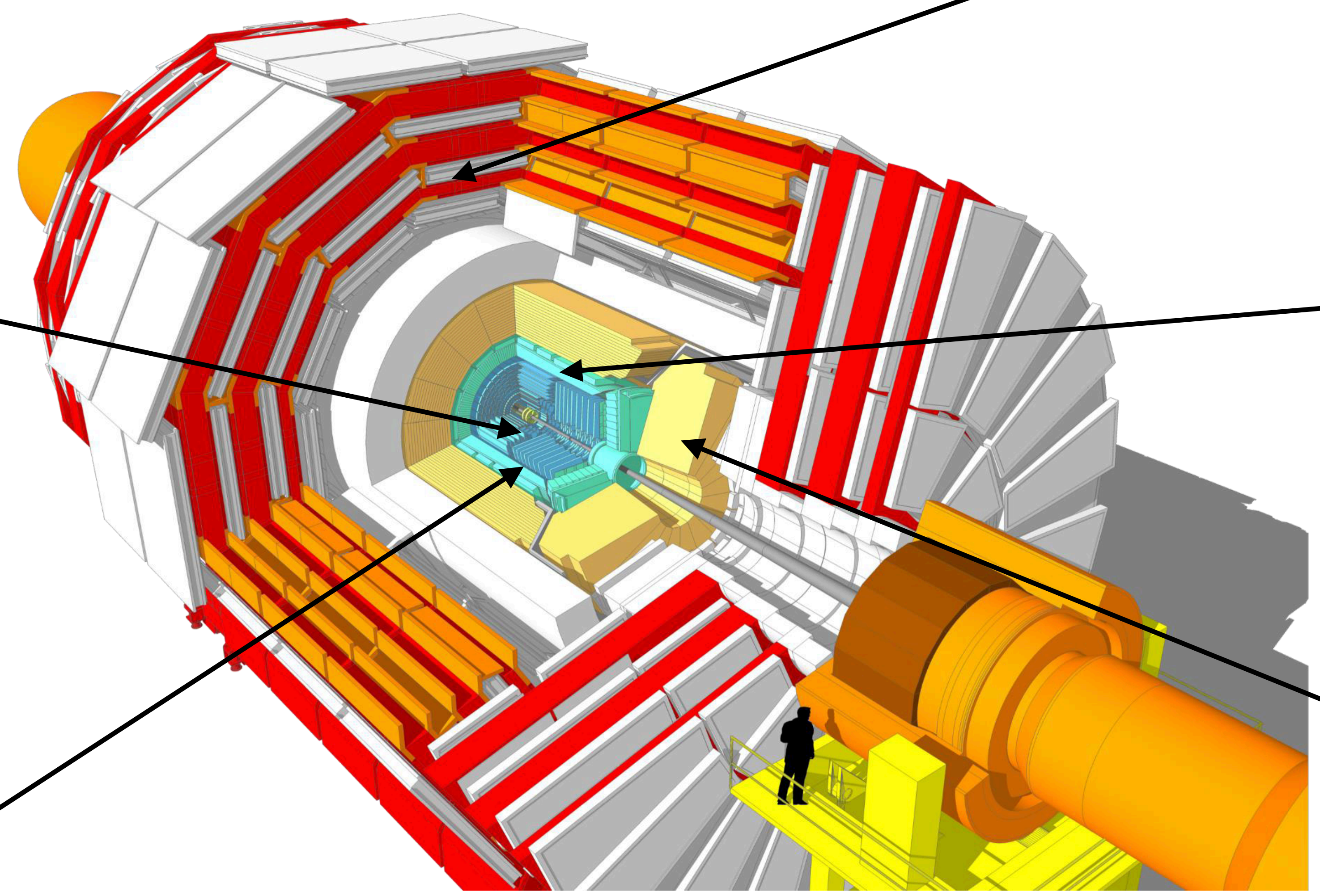
- **severe radiation environment** : Detector elements and electronics are exposed to high radiation dose (reaching limits for several systems) → Detector upgrades

.

L1-Trigger/HLT/DAQ:
Tracks, particle flow like selection, and machine learning in L1/HLT/DAQ
HLT output 7.5 kHz

Muon system:
DT&CSC new FE/BE readout, new GEM/RPC
Extended coverage to η~ 2.8

Tracker:
All silicon Pixel and strip detectors with increased granularity
extended coverage to η~3.8
P_T module design for tracking in Level1-Trigger



Calorimeter Barrel:
ECAL precision timing for high energy photon/electron > 30 GeV
ECAL/HCAL new back-end boards.

Calorimeter Endcap:
3D showering topology
Precision timing for high energy showers
Si, Scint+SiPM in Pb/W-SS

MIP Timing detector :
30-40 ps time resolution for charged particles up to η~ 3 between tracker and ECAL/CE

CMS have major phase-2 upgrade as involving **new tracker, new EC, new readout for barrel calorimeters, extended muon capabilities, new trigger, new DAQ**

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.

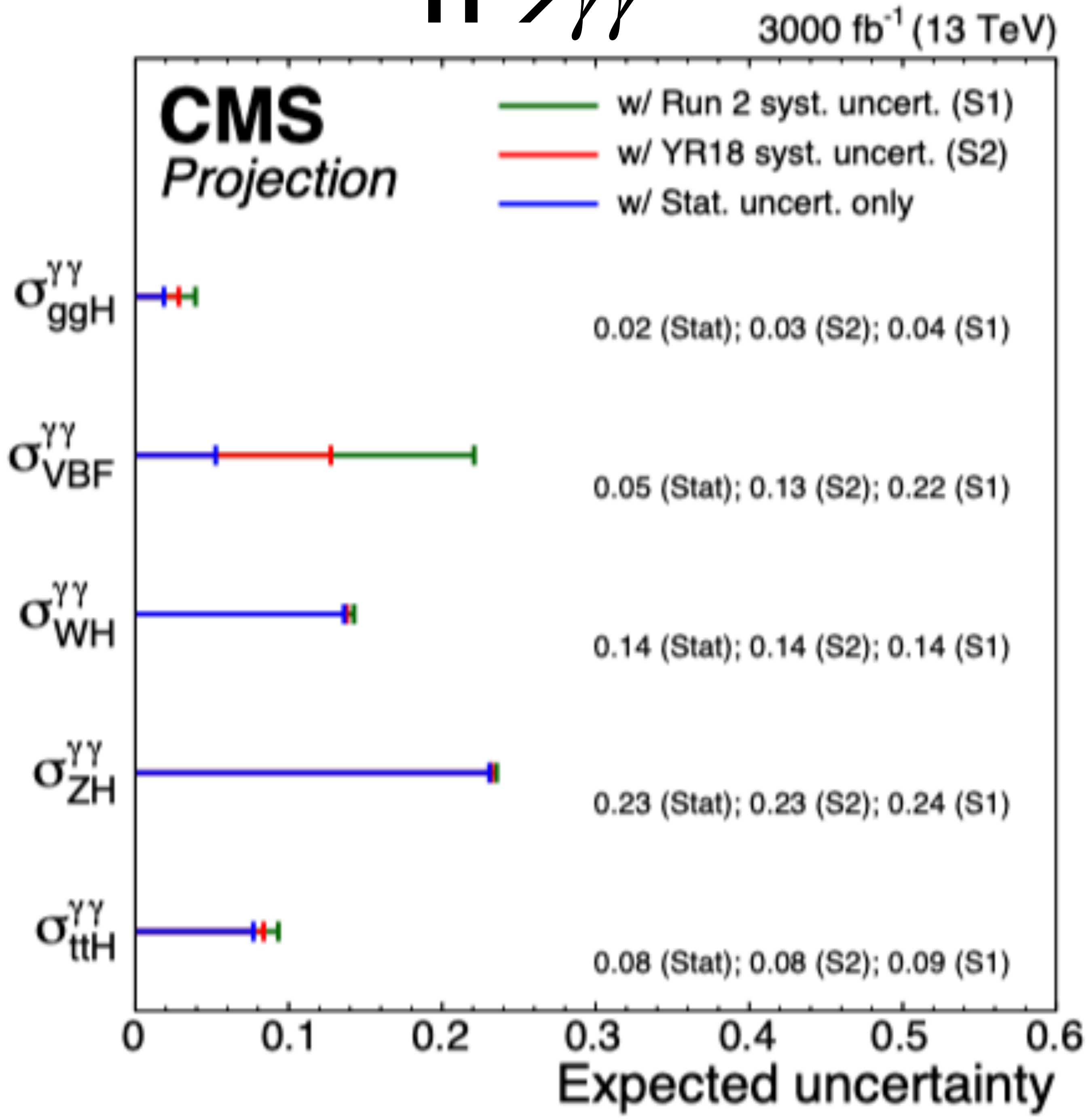
- Size O(1%) of the expected HL-LHC integrated luminosity. Thus, projections very limited with respect to the potential reach of the real HL-LHC analyses

Yellow Report - P256

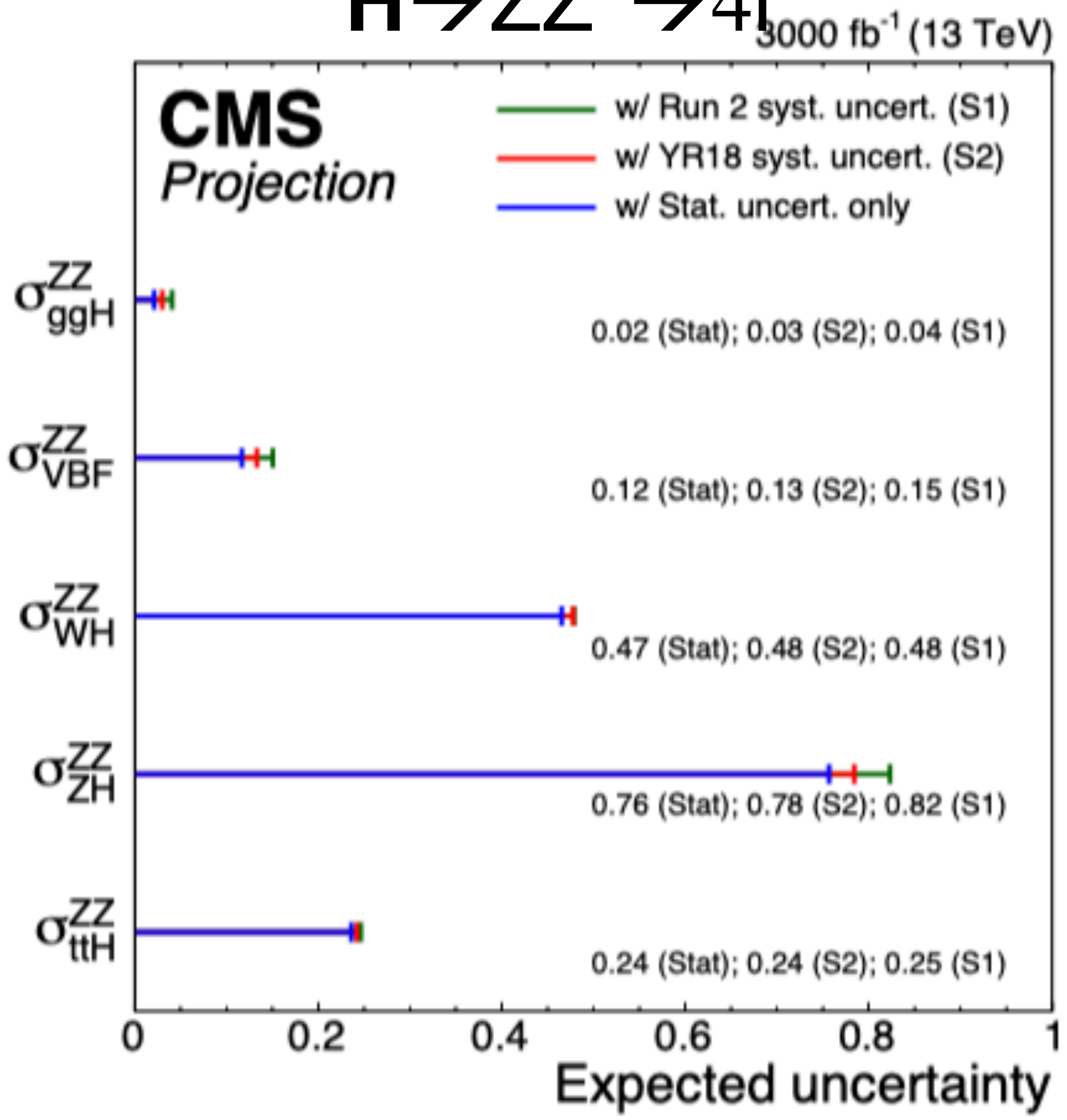
Signal Strengths

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.

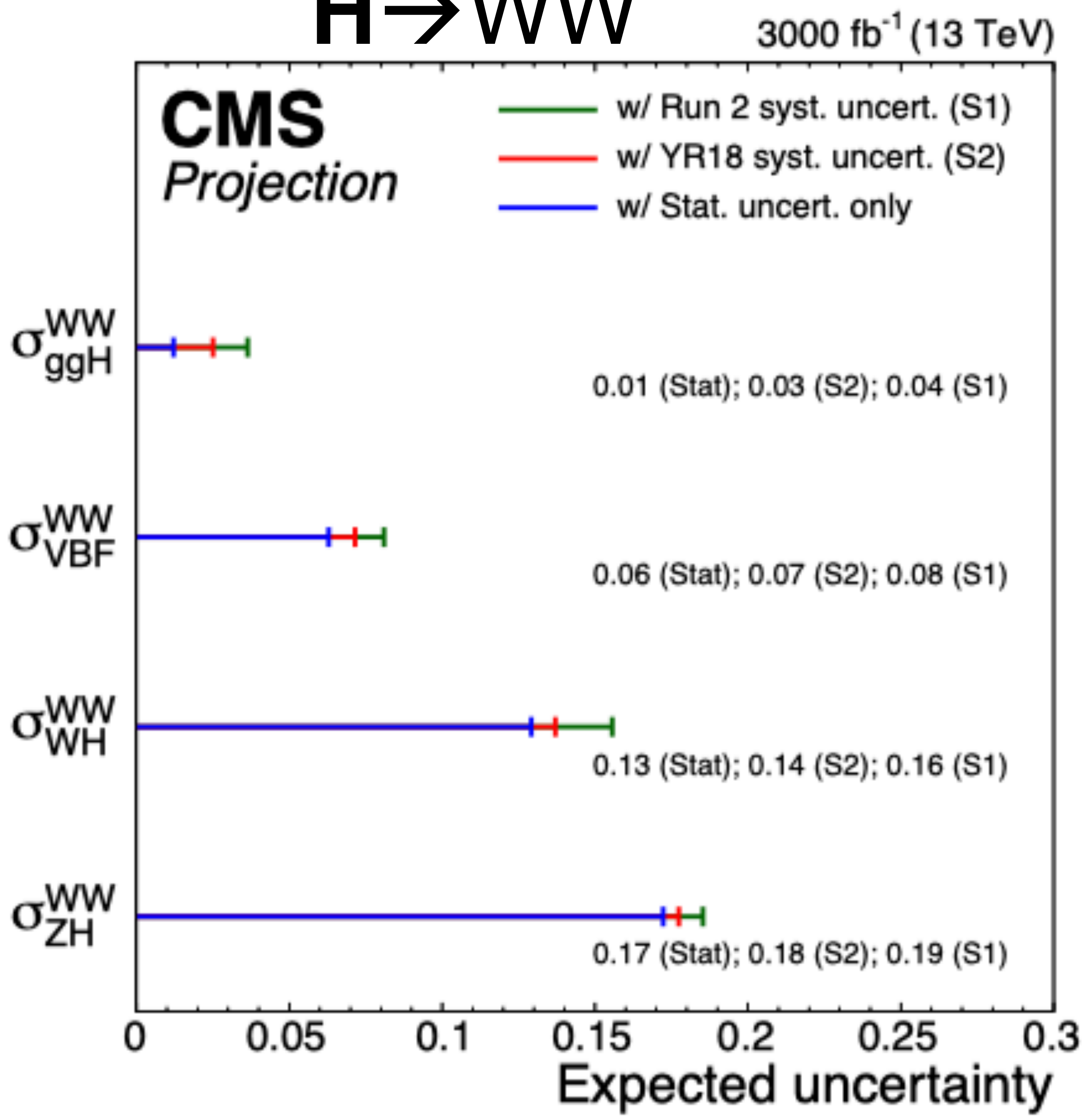
- For ggH : Dominant unc. are due to lepton reconstruction and identification efficiencies and pile-up modelling unc.
- For VBF and VH: Main unc. are due to jet energy scale and resolution,
- For ttH : missing higher order unc. + Parton shower modelling

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

Signal Strengths

Expected ±1σ uncertainties per production mode

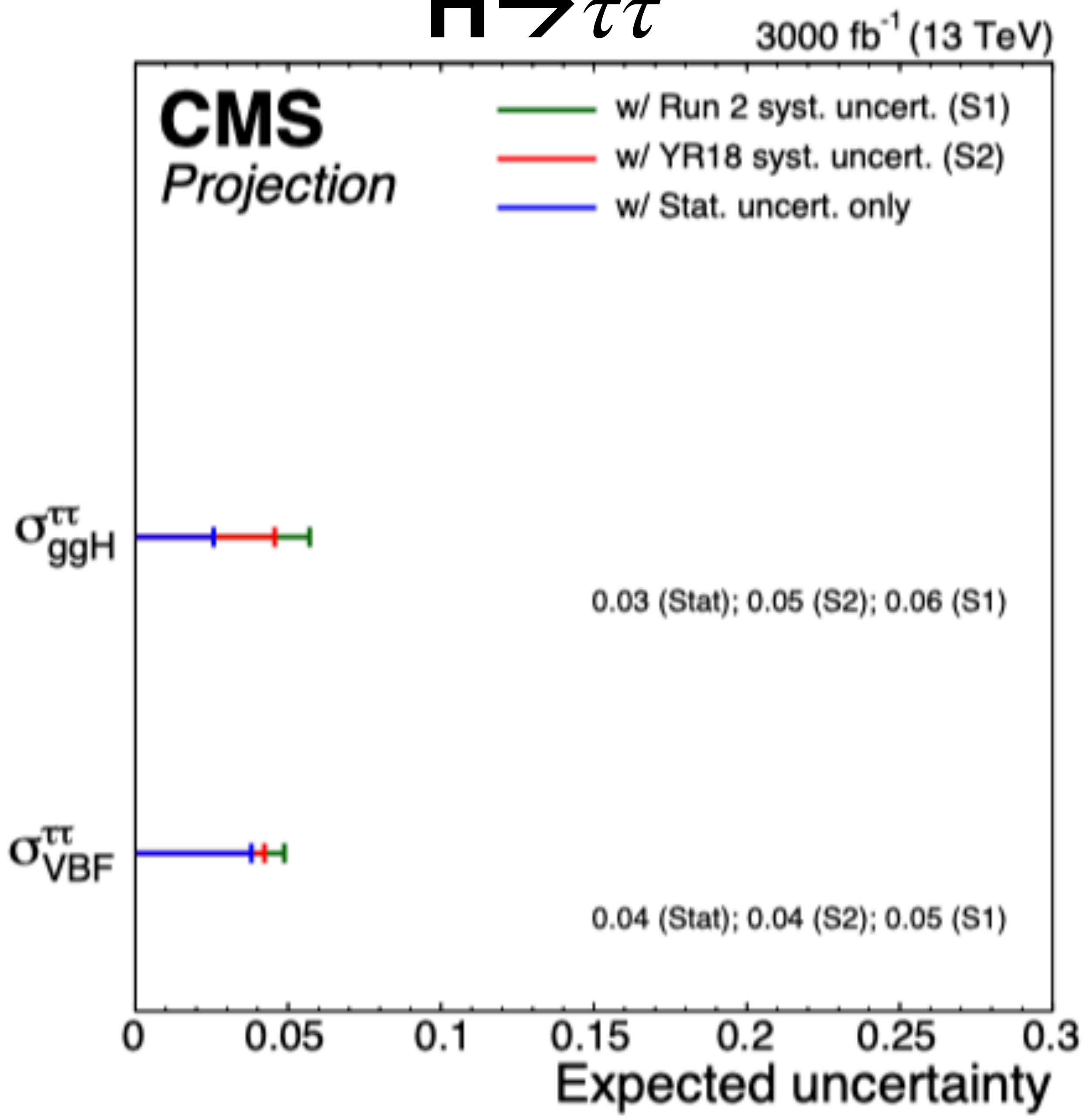
H→WW



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→$\tau\tau$

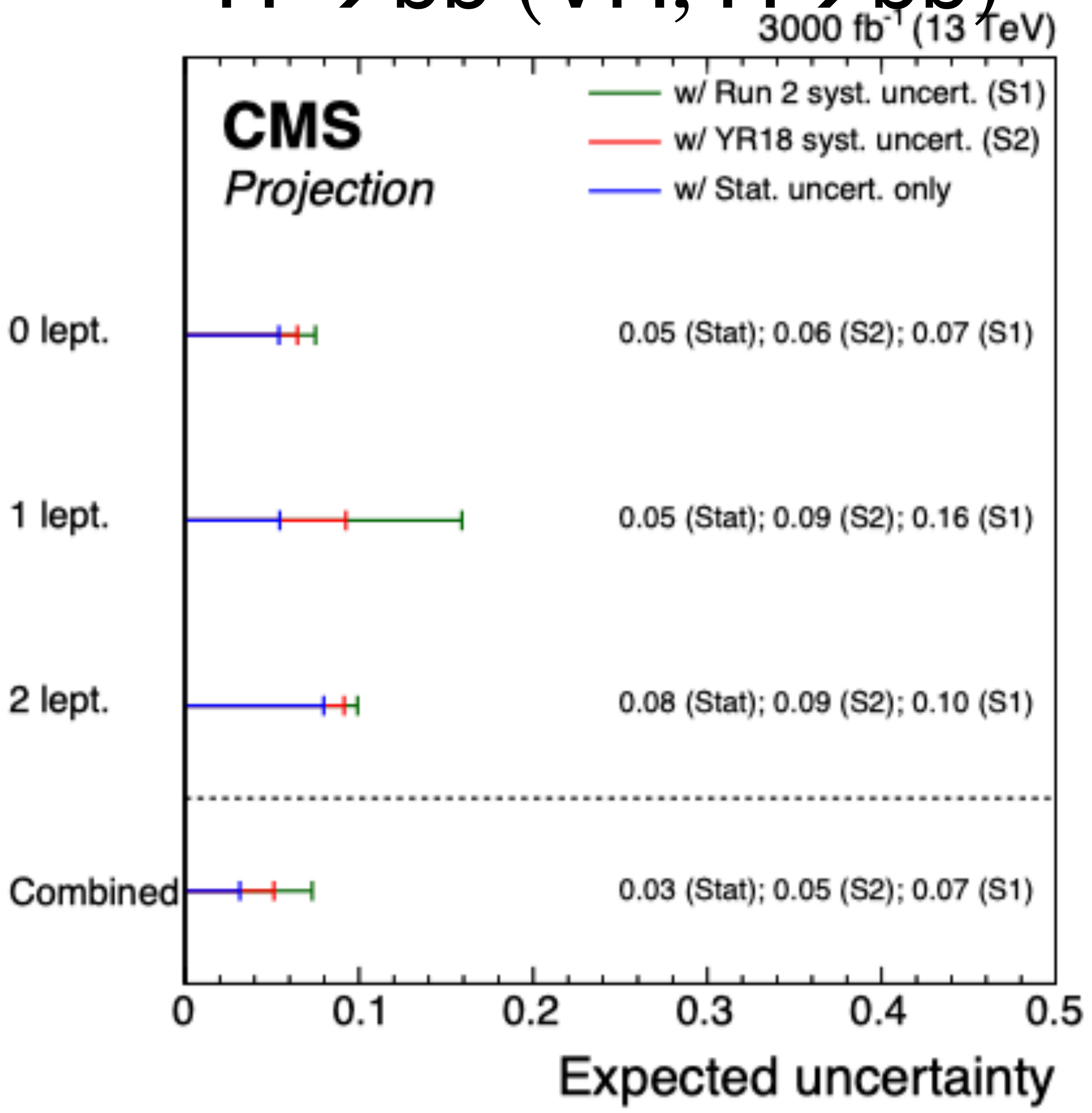


Here, main contributions come from :

- the uncertainties on background modelling errors, 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% (dominated by systematic uncertainties)

H →bb (VH, H→bb)

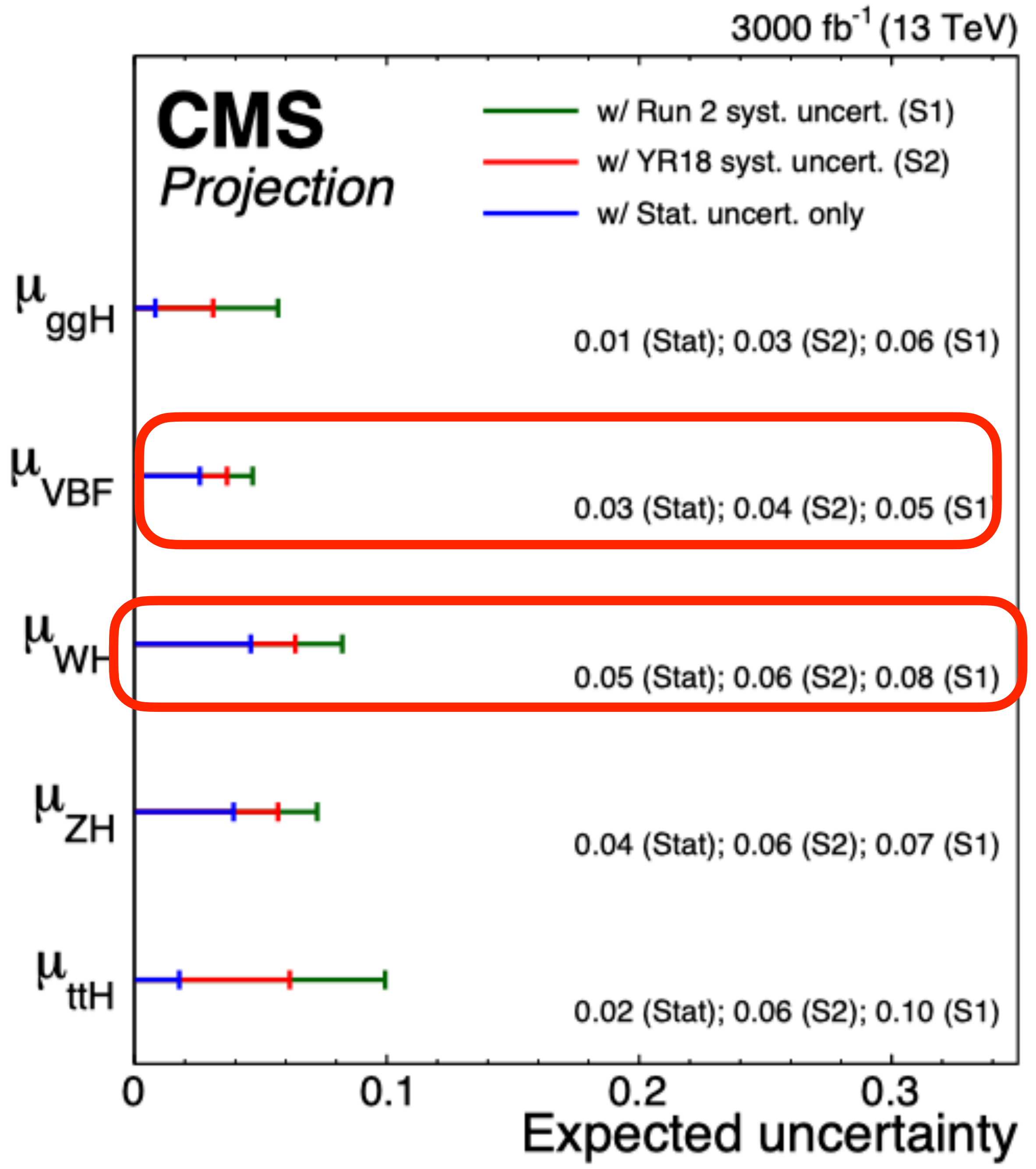


The largest component of the systematic uncertainty is theoretical coming from uncertainty in the gluon-induced ZH (gg→ZH) production cross section due to QCD scale variations

Expected precision: ~ 5%

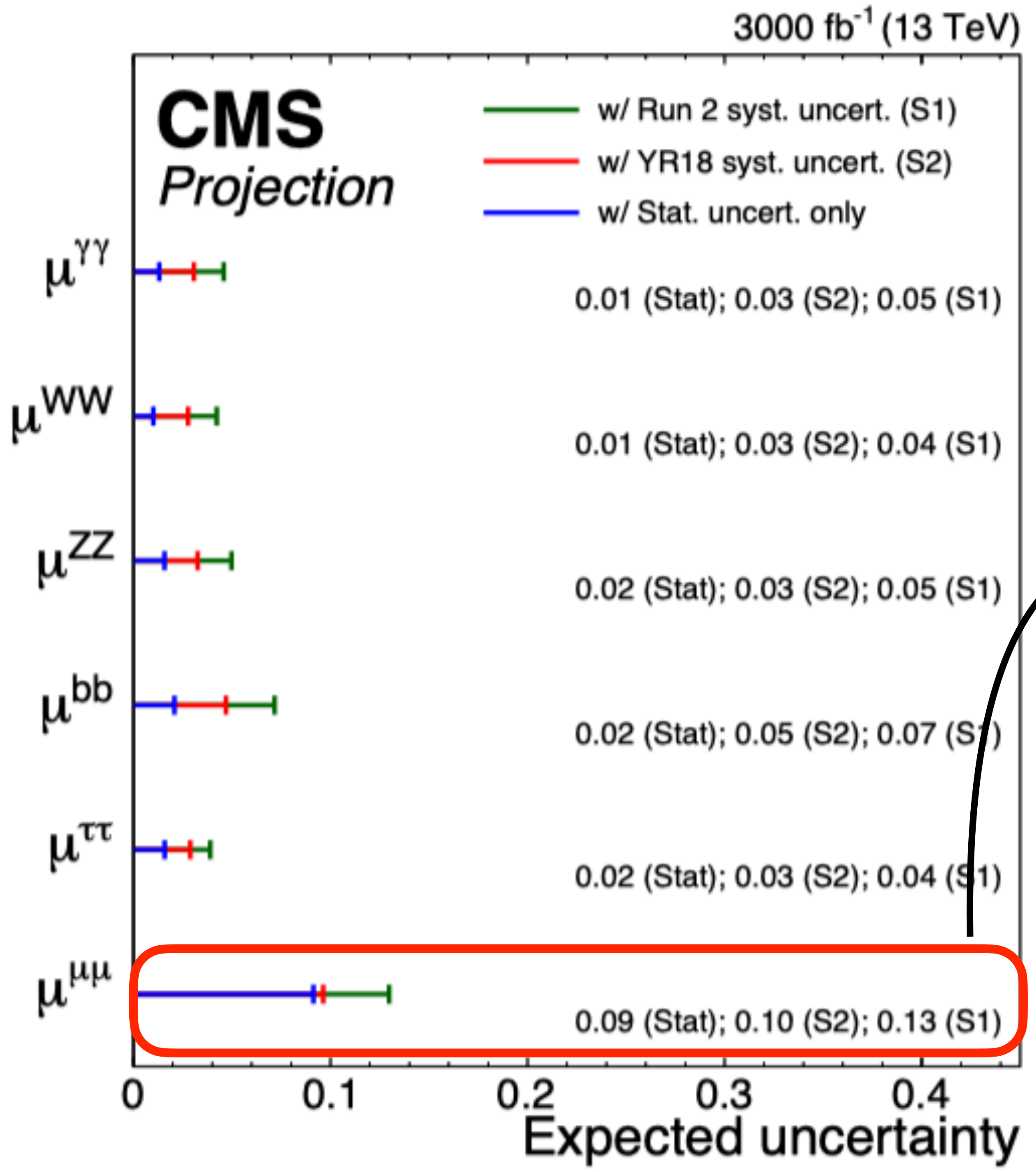
Combined signal strength per production and decay mode

Expected ±1σ uncertainties per production mode



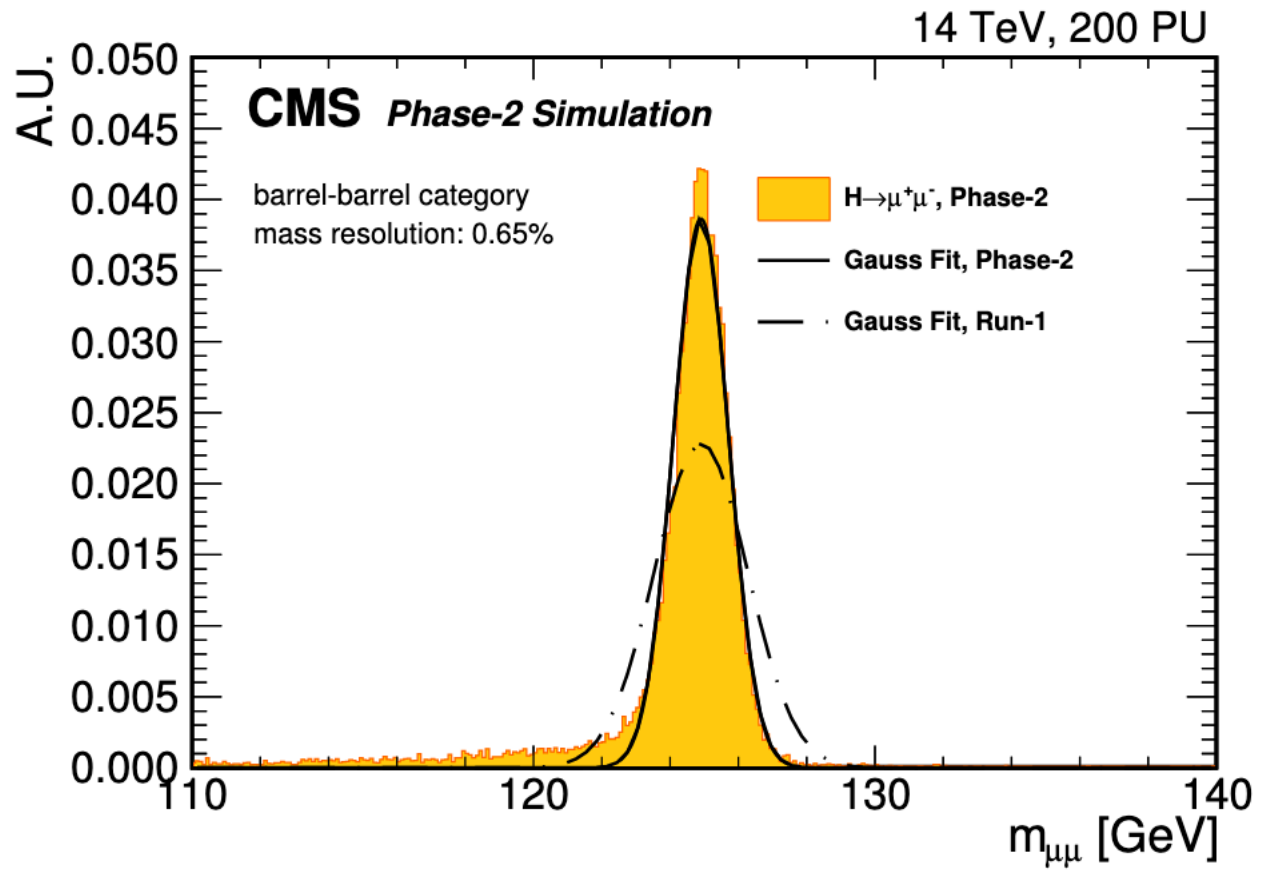
In S1, the signal theory unc. is the main contribution for all modes except WH (stat. limited). In S2, μ^{VBF} and μ^{WH} both are stat. limited

Expected ±1σ uncertainties per decay mode



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

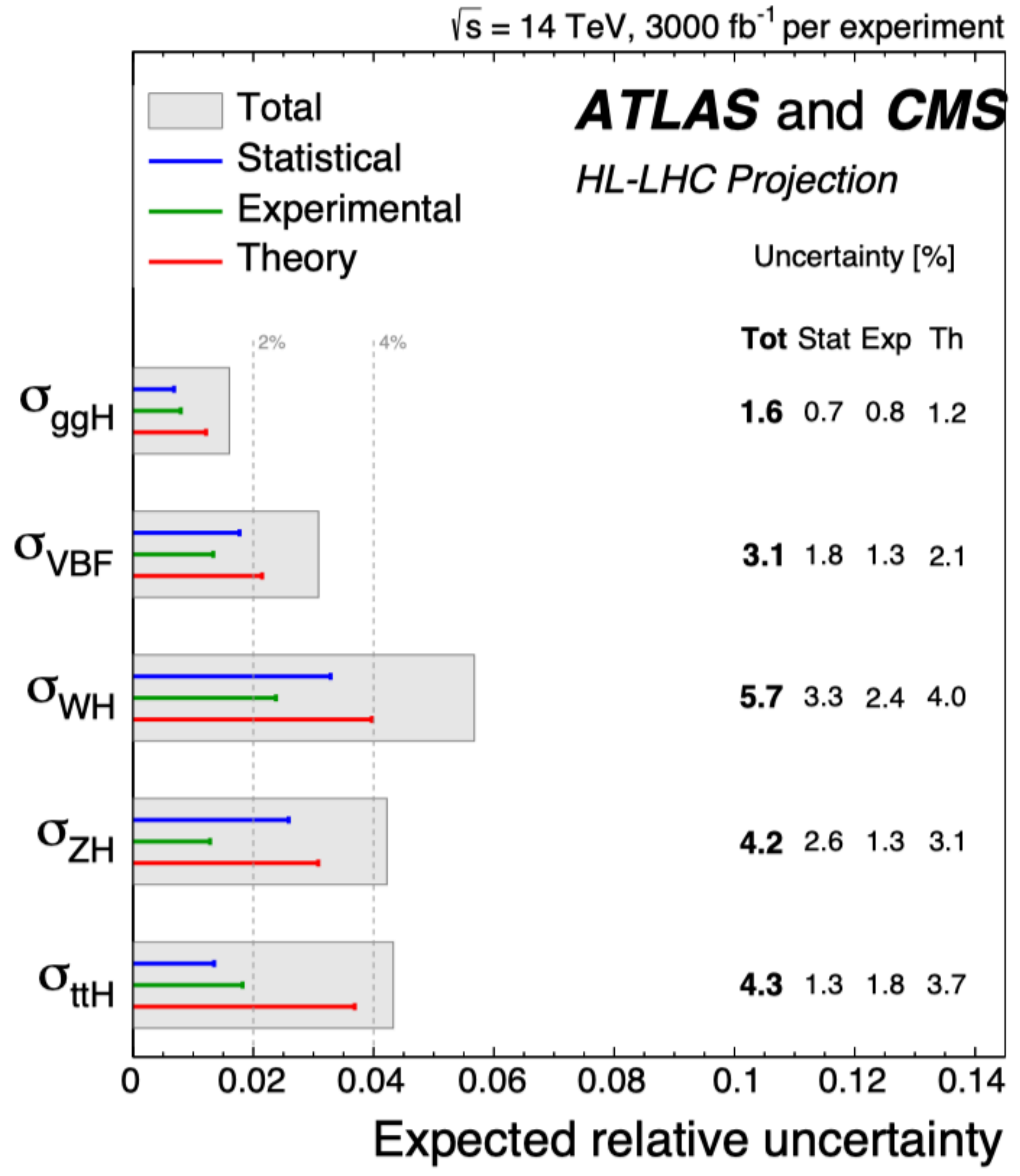
This analysis depends critically on dimuon mass resolution. Thanks to New tracker - Dimuon invariant mass width is reduced in order to match the increase in performances [40% improvement in the dimuon mass resolution]



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

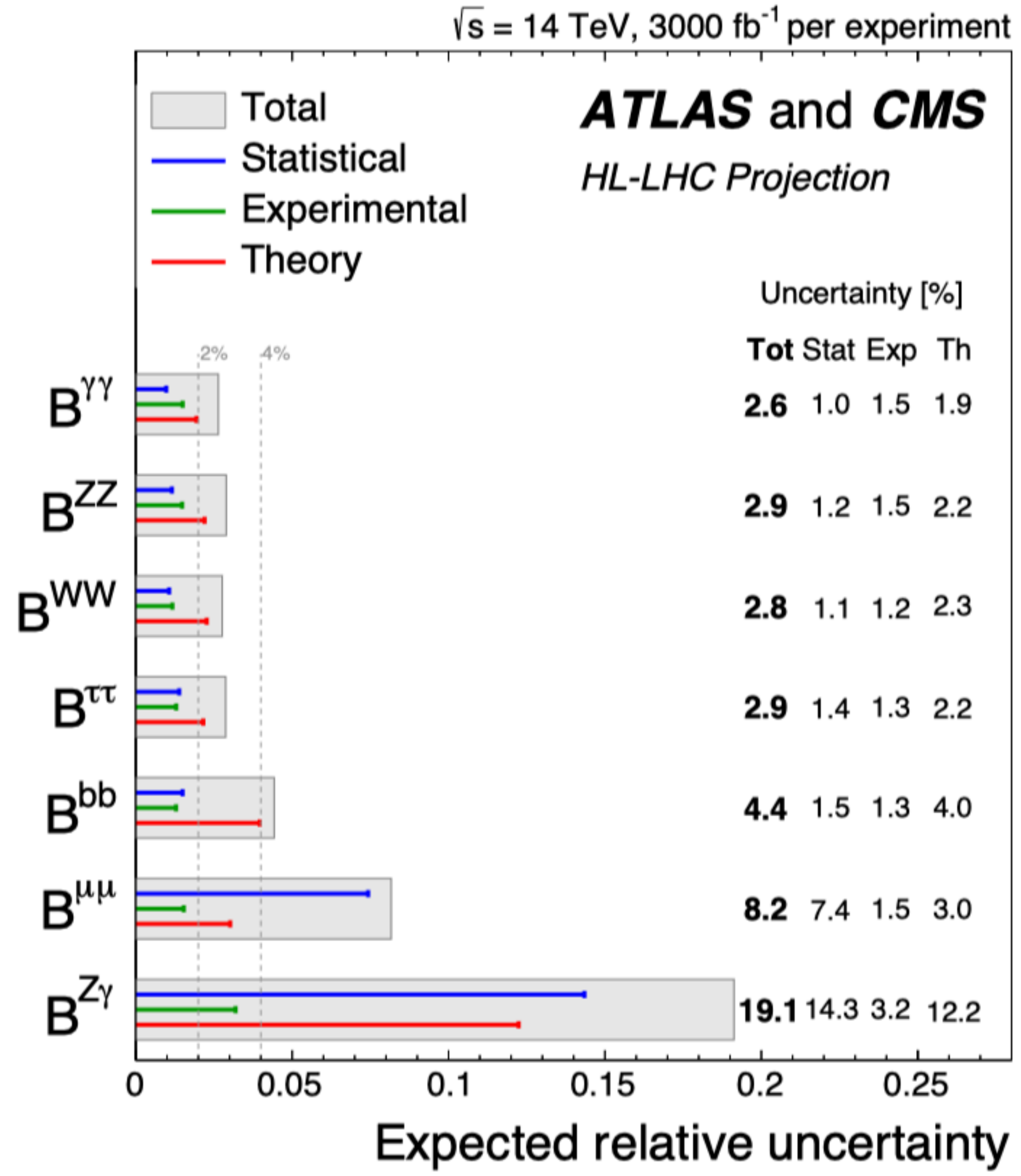
Expected ±1σ uncertainties on cross-section measurement per production mode



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%

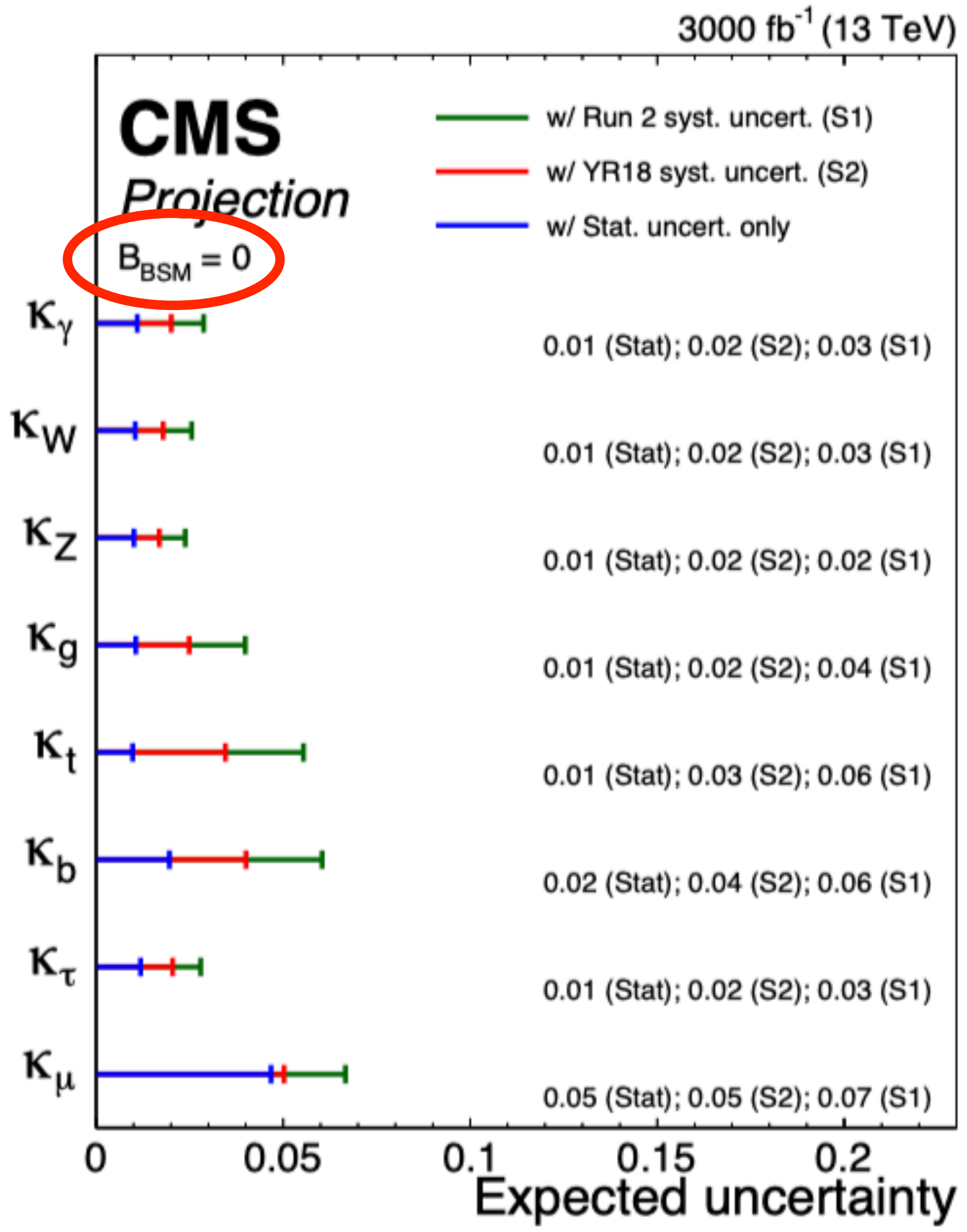
Coupling modifiers, κ

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

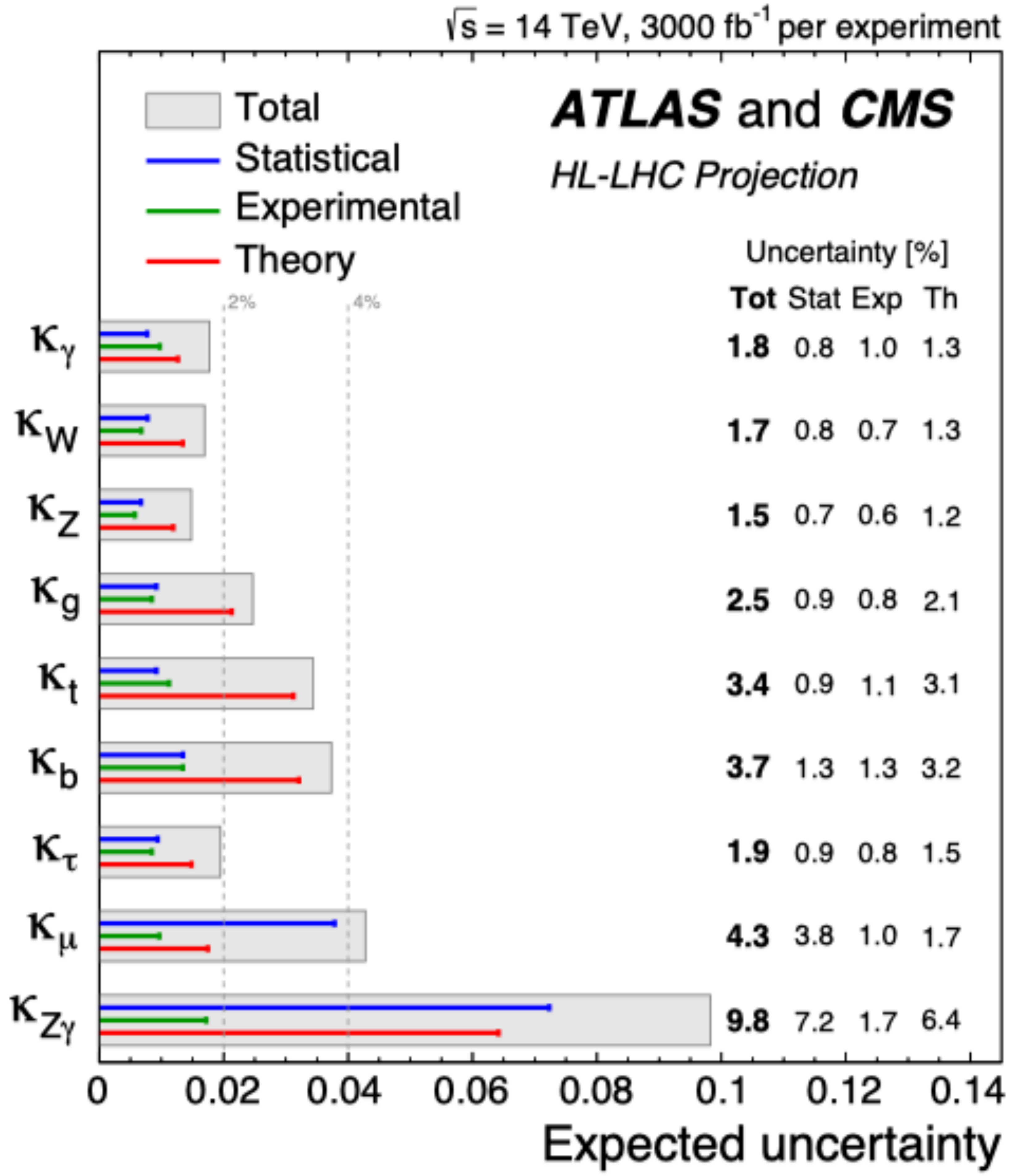
$$\kappa_j^2 = \sigma_j/\sigma_j^{\text{SM}} \quad \text{or} \quad \kappa_j^2 = \Gamma^j/\Gamma^j_{\text{SM}}.$$

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

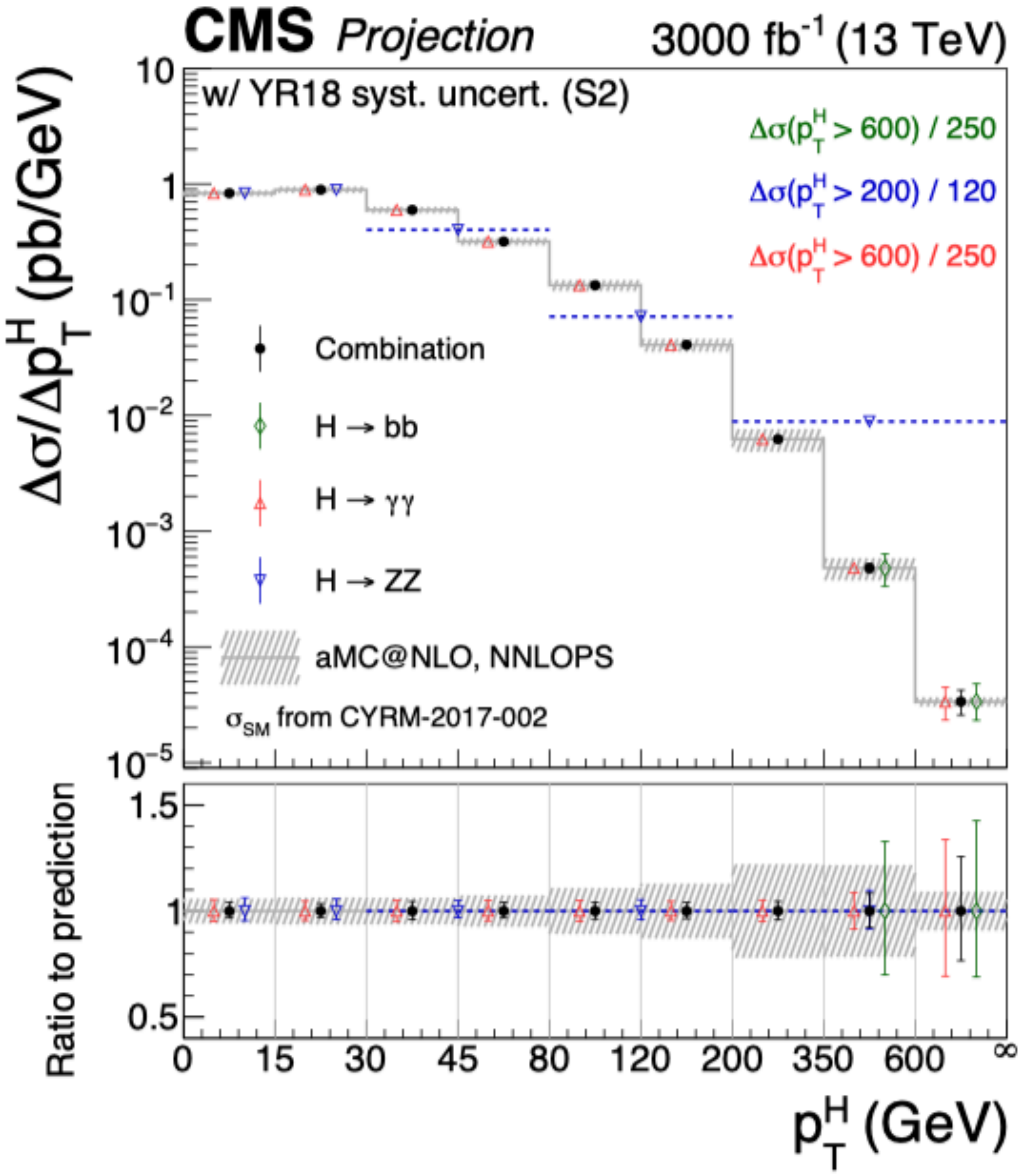
New physics may reside in the high scale tails of differential distributions. p_T^H differential distribution is of particular interest.

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

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

3000 fb^{-1} CMS									
p_T^H [GeV]	0-15	15-30	30-45	45-80	80-120	120-200	200-350	350-600	600-∞
$H \to \gamma\gamma$	5.1%	4.6%	5.1%	4.8%	4.9%	4.5%	5.1%	8.6%	32.2%
$H \to ZZ$	5.4%	4.8%	4.1%		4.7%		9.1%		
$H \to bb$	none							31.4%	36.8%
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, $bb\tau\tau$, bbWW ($WW \rightarrow l\nu l'\nu$ with $l,l' = e, \mu$), $bb\gamma\gamma$, and bbZZ ($ZZ \rightarrow lll'l'$ with $l,l' = e, \mu$)

HH production : Benchmark channel for HL-LHC

Triple Higgs coupling :

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

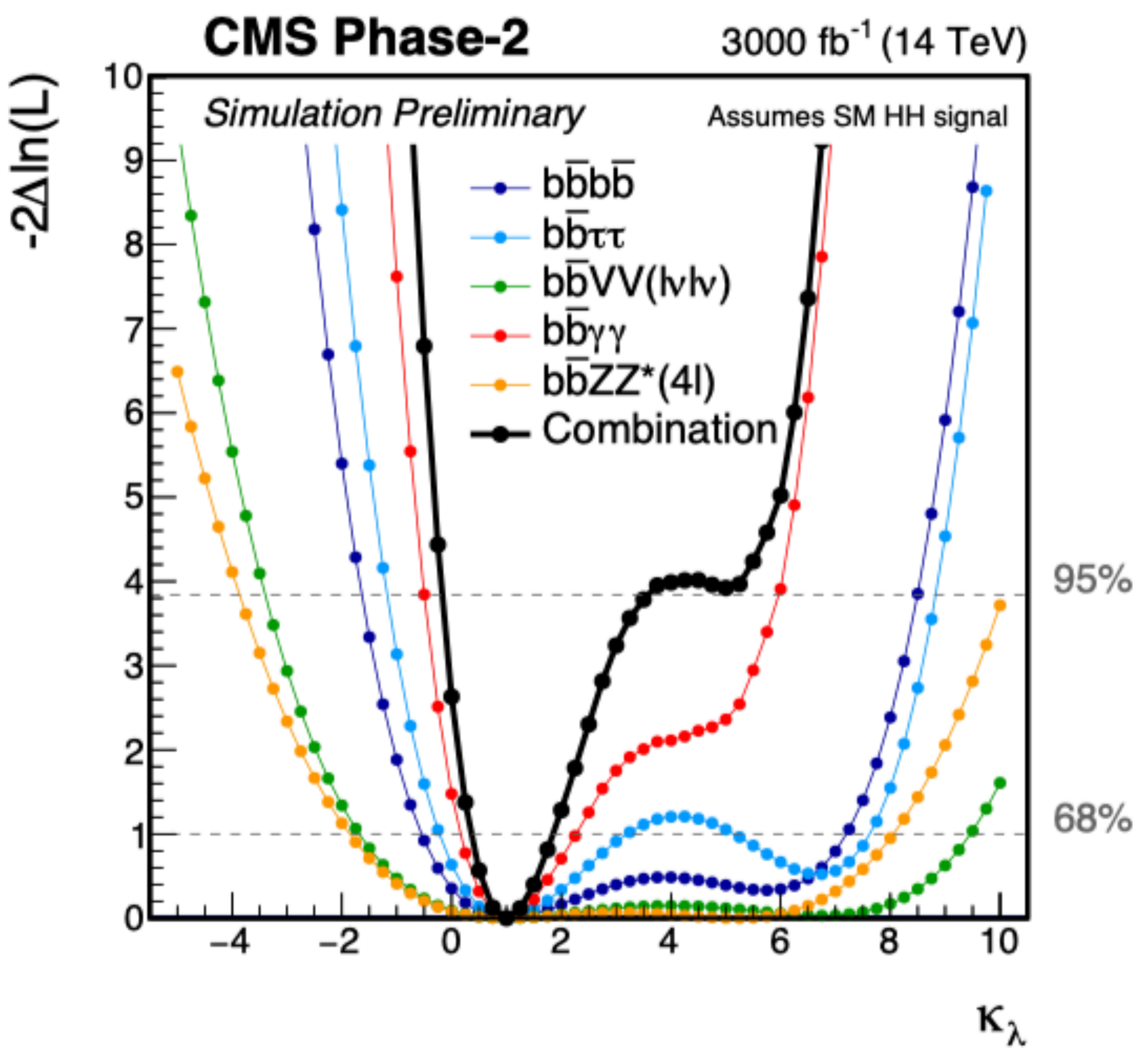
Coupling modifier: $\kappa_\lambda = \lambda_{hhh} / \lambda_{hhh}^{SM}$

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

Channel	Significance Stat. + syst.	Significance Stat. only	95% CL limit on $\sigma_{HH}/\sigma_{HH}^{SM}$ Stat. + syst.	95% CL limit on $\sigma_{HH}/\sigma_{HH}^{SM}$ 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



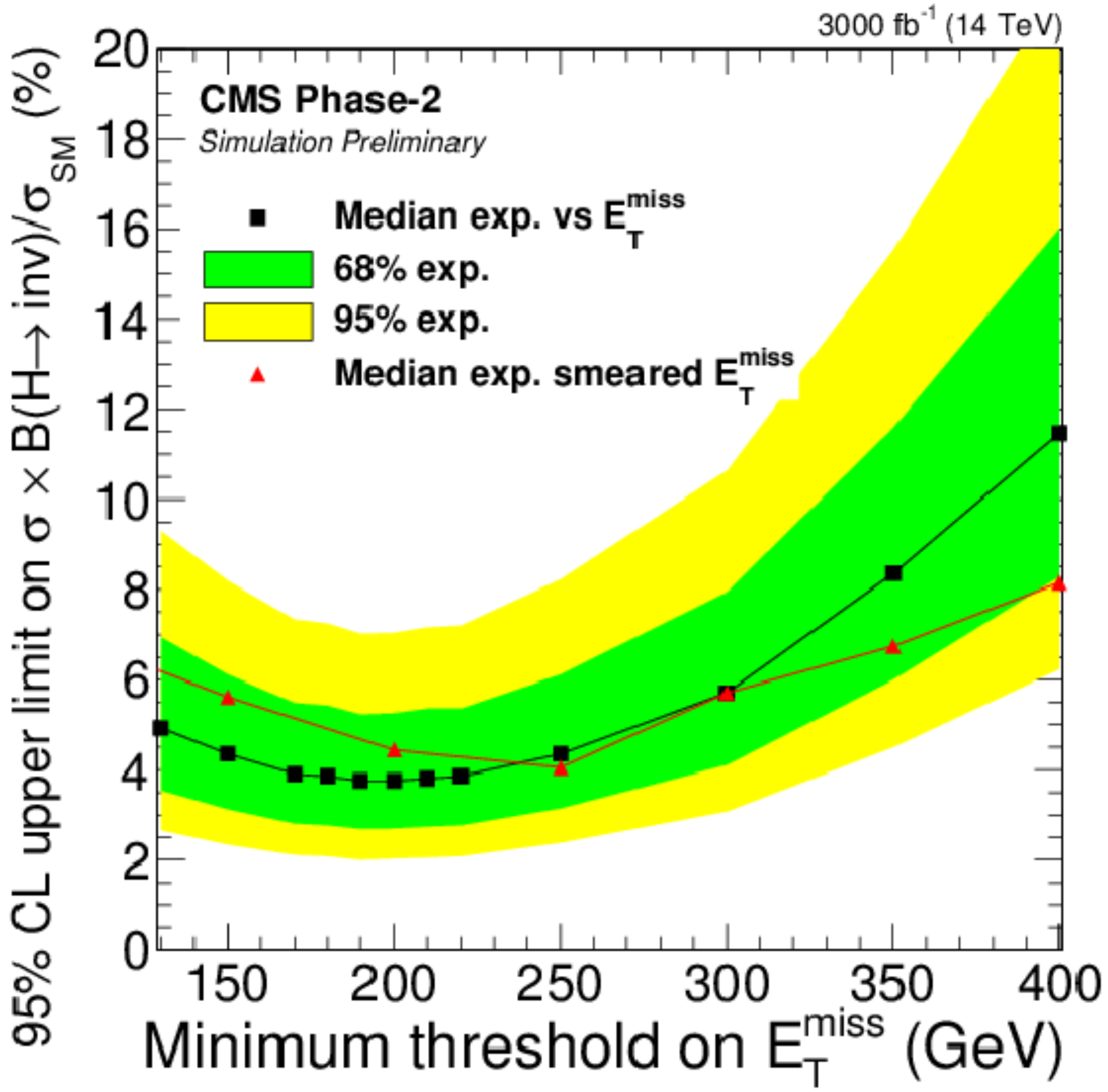
Sensitivity to BSM effects in Higgs Physics

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.
- Higgs width measurement possible within 1MeV. [Backup!]
- Sensitivity to BSM physics enhanced.

More results are expected for snowmass early next year.

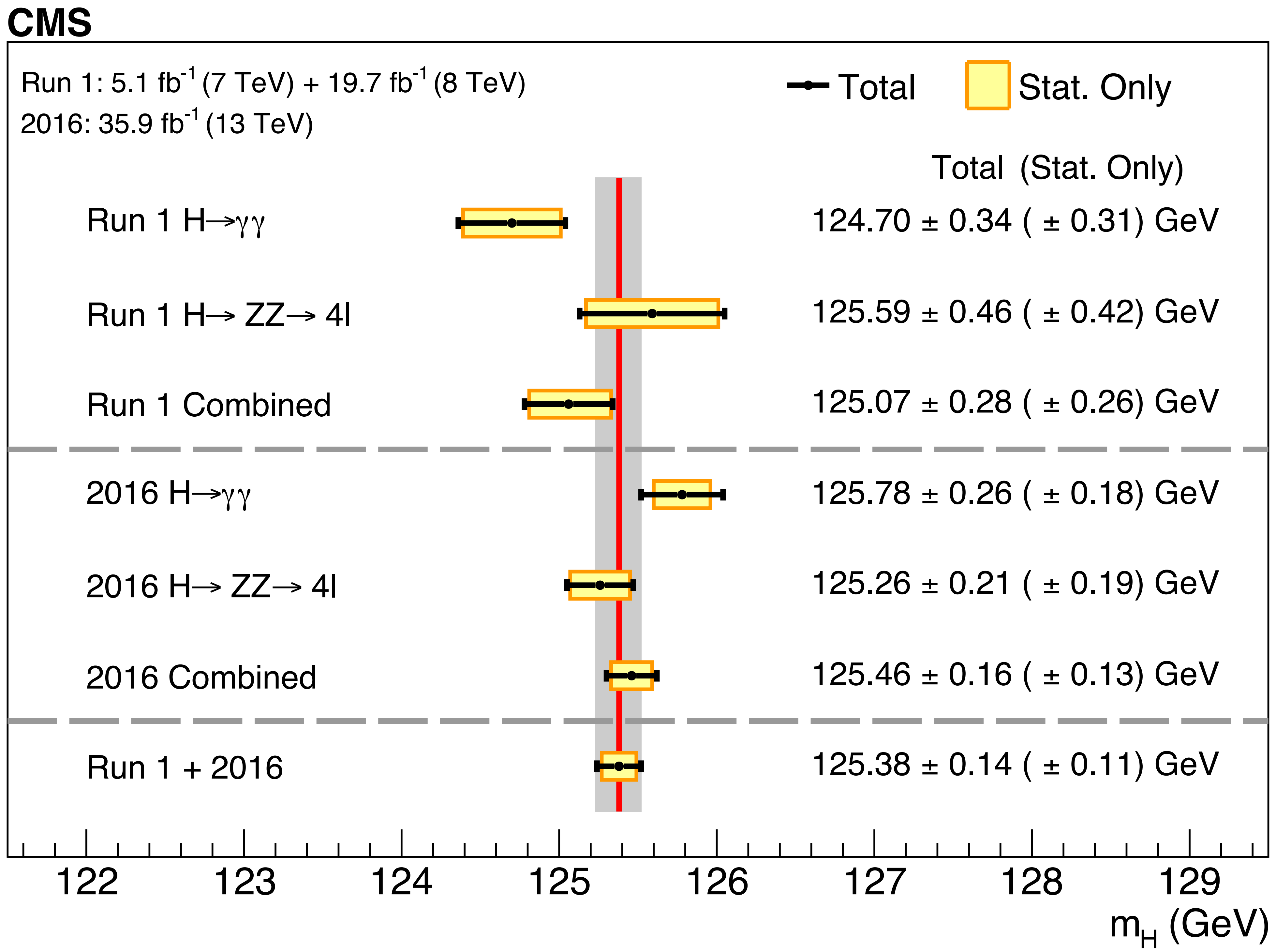
Exciting times ahead!

Backup

Higgs boson mass

- m_H is a free parameter in the SM. Once m_H is known, all Higgs boson couplings to Standard Model particles are fixed.

- Most precise m_H measurement currently: **0.11%** precision by CMS experiment using 2016 and Run 1 data.
- Yellow Report : plausible to reach $\sigma(m_H)$ ~10-20 MeV at HL-LHC, no detailed study performed.
- Snowmass: HL-LHC prospect of m_H measurement, using 4l and γγ channels, improve upon the Run 2 analysis techniques

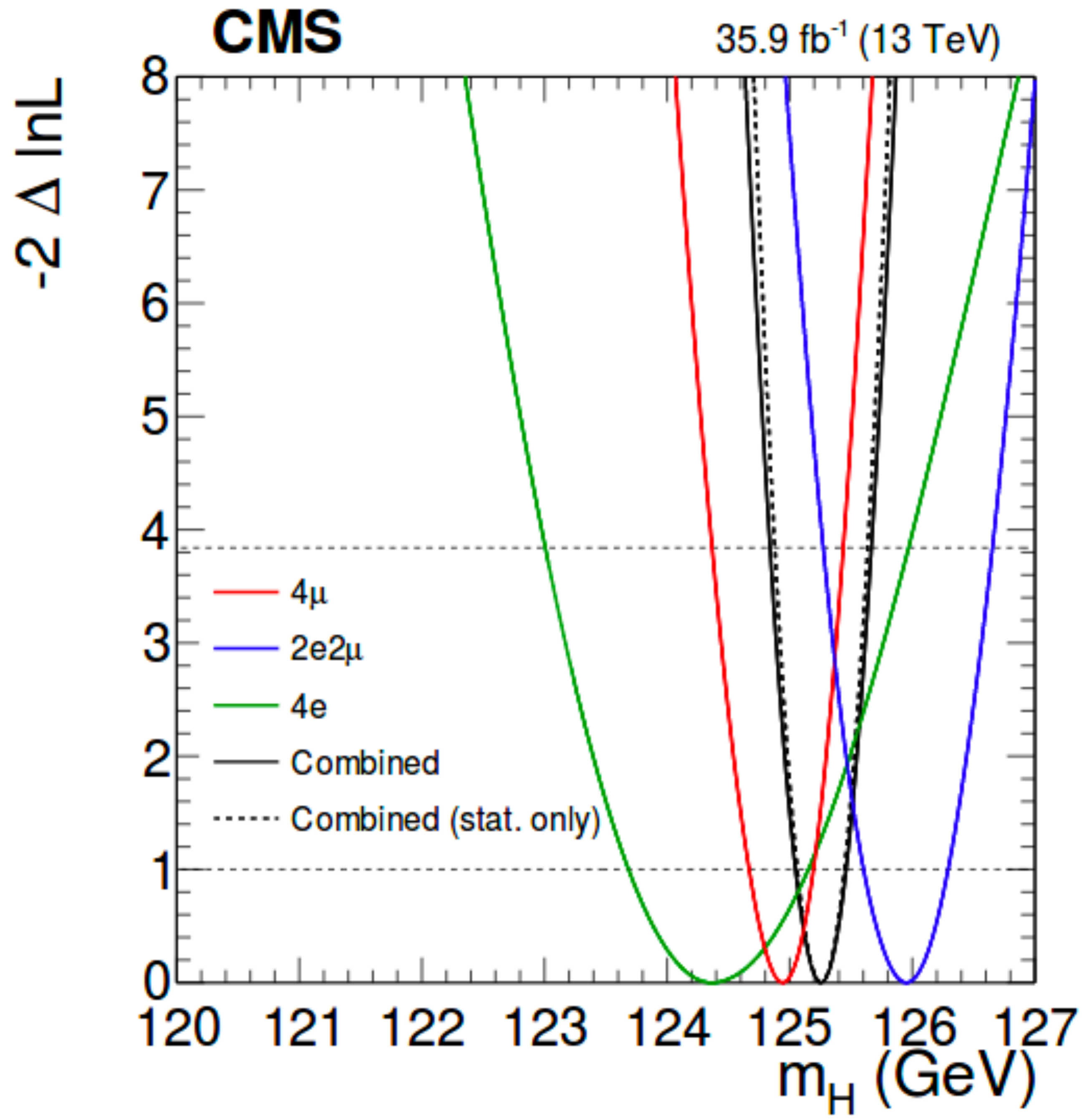


Rajdeep Chatterjee et. al., "The Ultimate Measurements of the Higgs Boson Mass and Width in Run 3, the HL-LHC, and Beyond" Snowmass EF01 WGM Aug 50, 2020

Higgs boson mass: experimental challenge

- Four-lepton channel:
  - Run 2 analysis statistical uncertainty dominated, main systematic uncertainty is lepton energy scale uncertainty: 0.04%, 0.3% and 0.1% for 4μ, 4e, and 2e2μ channels
  - 4μ channel drives the precision

arxiv:1706.09936



- Diphoton channel: aim for <100 MeV precision at HL-LHC
  - expected to be systematic uncertainties dominated: need to develop strategies to reduce them

arxiv:2002.06398

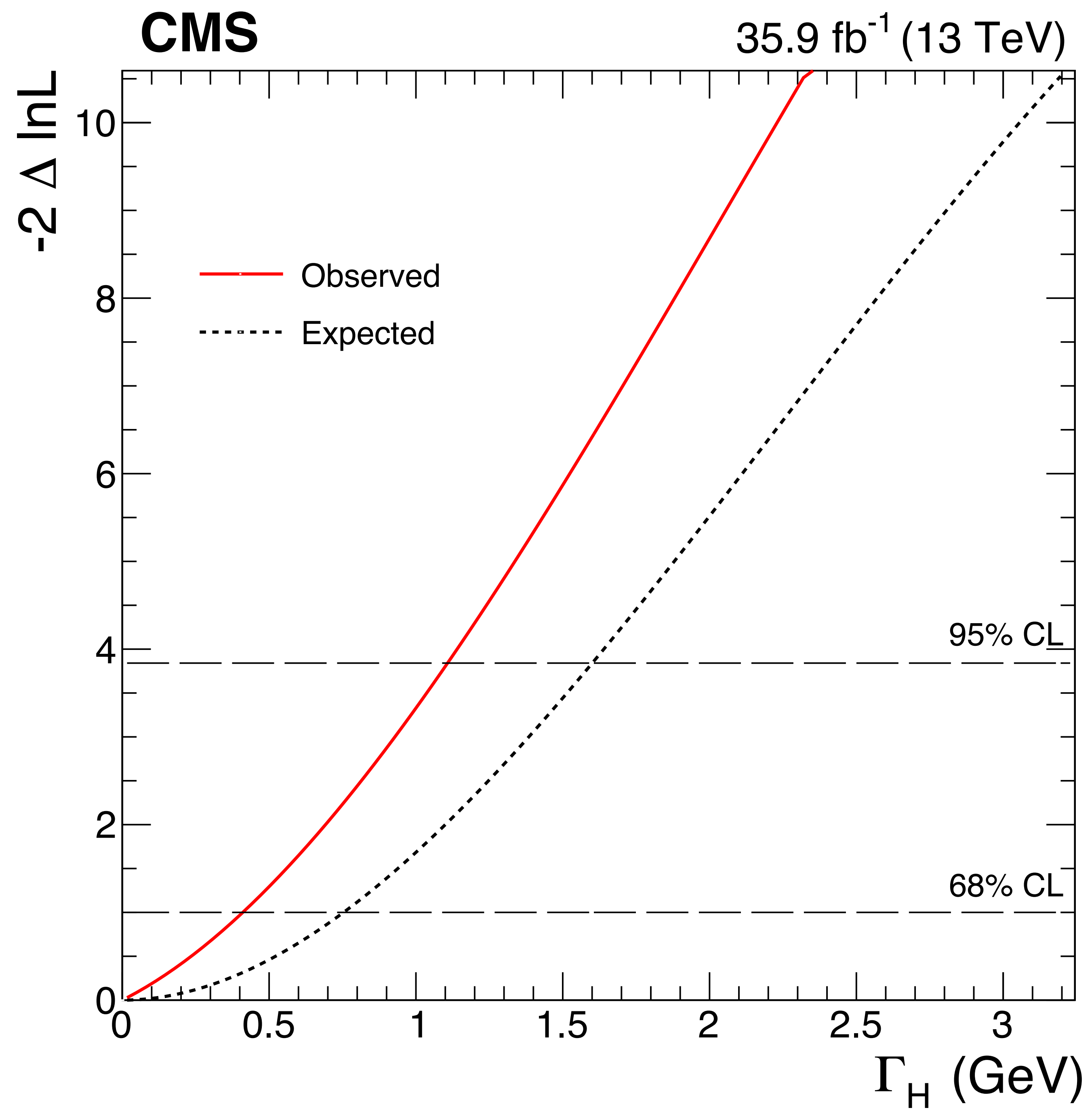
Source	Contribution (GeV)
Electron energy scale and resolution corrections	0.10
Residual p_T dependence of the photon energy scale	0.11
Modelling of the material budget	0.03
Nonuniformity of the light collection	0.11
Total systematic uncertainty	0.18
Statistical uncertainty	0.18
Total uncertainty	0.26

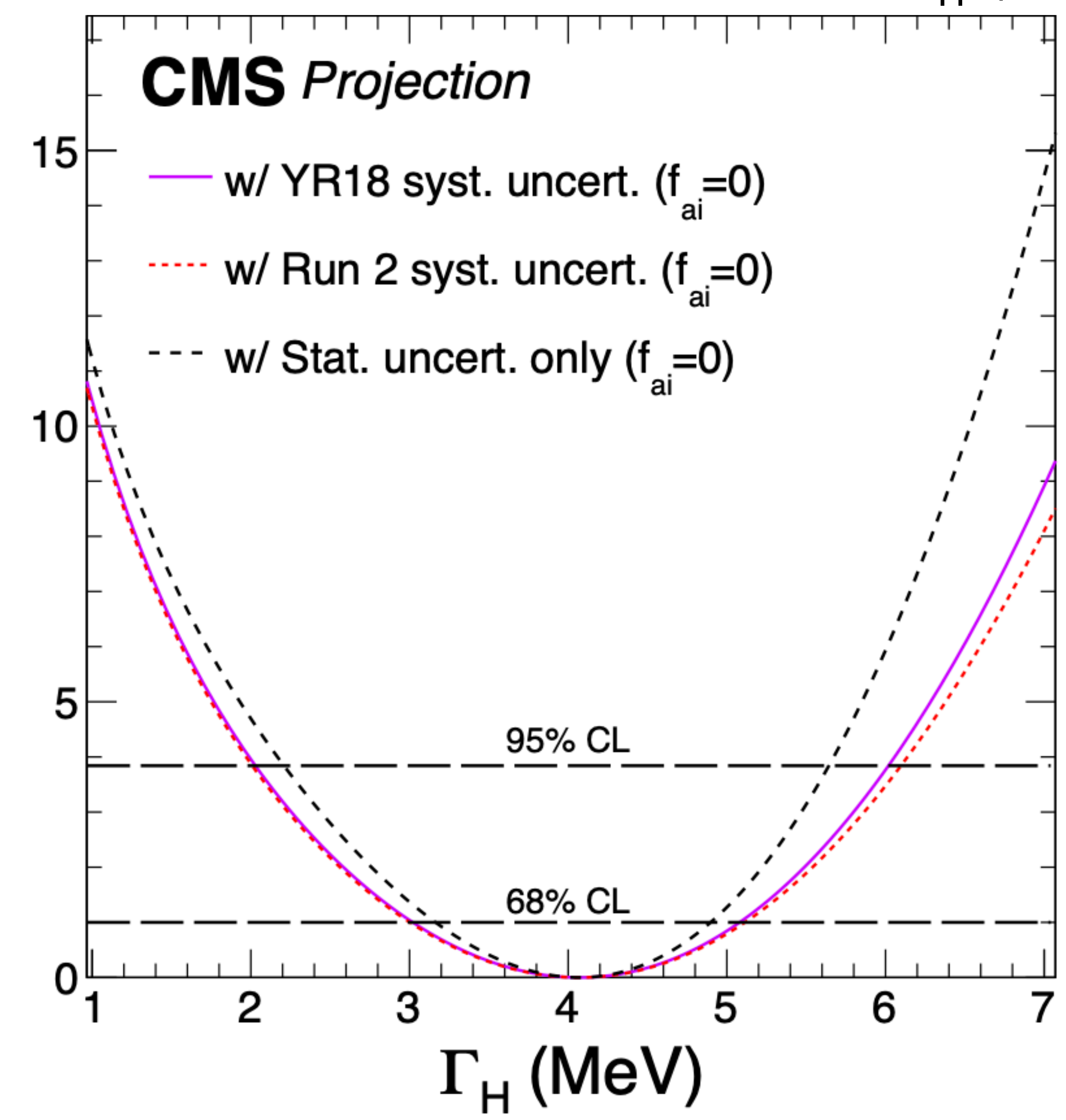
Higgs boson width

- Direct measurement of Higgs boson width limited by the detector resolution
  - observed (expected) limit $\Gamma_H < 1.1$ (1.6) GeV at 95% CL using 2016 data with H→ZZ→4l channel arxiv:1706.09936

- Indirect constraint: combining on-shell and off-shell Higgs measurements, assuming on-shell and off-shell couplings are the same, expected precision from CMS for HL-LHC: $\Gamma_H = 4.1^{+1.0}_{-1.1}\ MeV$

- Snowmass: aim to study constraint on the Γ_H using interference in the gg→H→γγ channel on-shell rate and Higgs mass shift





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}.