Higgs boson measurements at the High Luminosity LHC with CMS

Pallabi Das
Tata Institute of Fundamental Research, Mumbai
on behalf of the CMS collaboration

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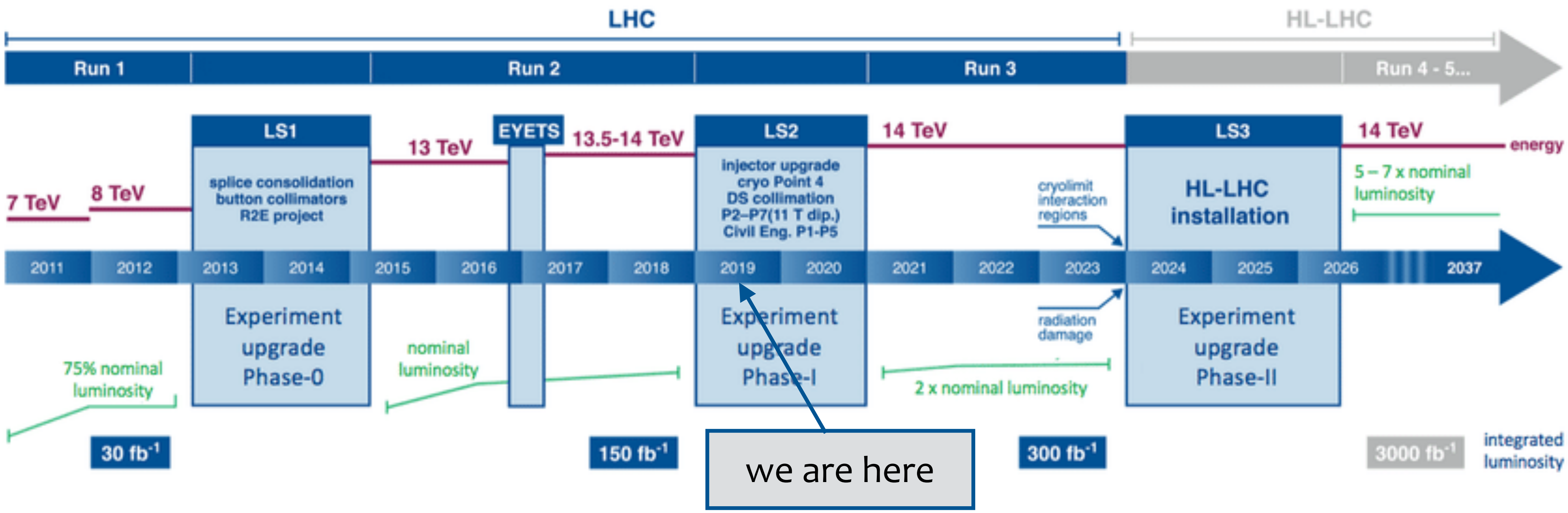
Future of Higgs physics

- After Higgs discovery, mandate of the LHC experiments is to characterize the resonance by measuring its properties precisely
- Coupling of this scalar to other particles determines if it belongs to standard model (SM) or corresponds to *New Physics*
- Status of relevant measurements performed by the LHC experiments:
  - ➡ couplings to Vector bosons: largely constrained to SM values with Run 1+Run 2 data
  - ➡ couplings to fermions: only to third gen particles measured with large uncertainty
  - ➡ self-coupling: not accessible till now
- 2026 onward LHC will operate in the high luminosity mode (HL-LHC)
  - ➡ Instantaneous luminosity ~ 5-7.5 x 10^{34} $cm^{-2}s^{-1}$
  - ➡ ~300 fb^{-1}/year → 3000 fb^{-1} by 2036
  - ➡ Access to rare processes, like di-Higgs production
  - ➡ Higgs factory: HL-LHC will produce ~150M Higgs
  - ➡ Average pileup anticipated 150-200, harsh experimental condition

Preparations for HL-LHC



- Very busy environment, radiation damage of the detectors
- Phase II upgrade ongoing to maintain physics performance
  - ➡ Pixel and strips system granularity to be increased, acceptance increase to $|\eta| < 4$
  - ➡ ECAL and HCAL endcaps to be replaced by High Granularity Calotimeter (HGC)
  - ➡ Increase in muon acceptance; GEM detectors already being installed
  - ➡ Addition of MIP Timing Detector for pileup suppression
  - ➡ Improved L1T, HLT, DAQ…
  - ➡ Detector upgrades described in detail in dedicated TDRs
- Physics potential with Phase II improved detectors has been estimated (YR2018)

Projection studies

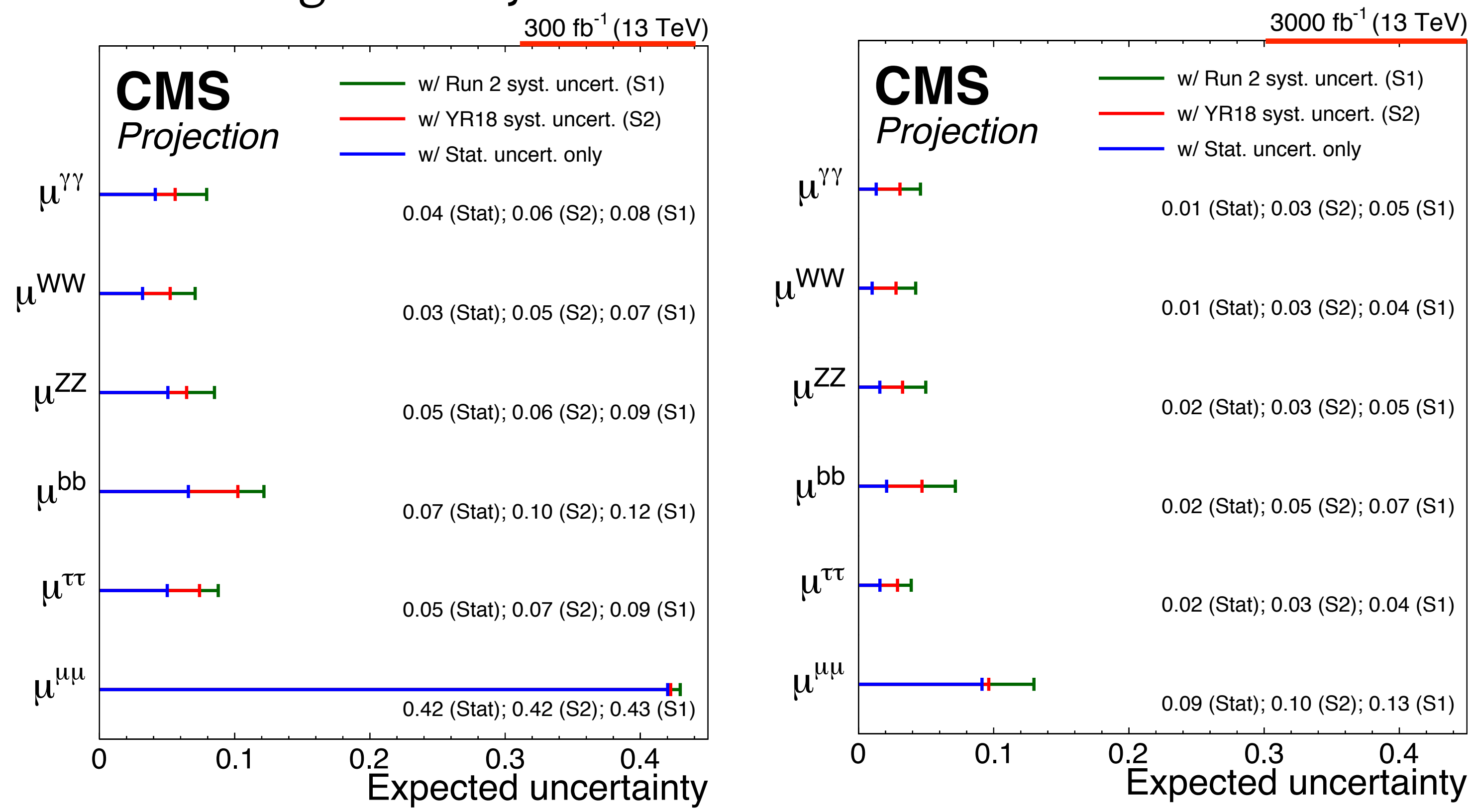
- Based on results or analysis strategies for 2016 data
- Most of the time at HL-LHC statistical uncertainty is not an issue, evolution of systematic uncertainties studied with time
- Consider two different integrated lumi (L): 300 fb^{-1} and 3000 fb^{-1}
- Uncertainty scenarios following YR recommendation:
  - ➡ **Run 2 systematic uncertainties (S1)**: event yields scale with luminosity, systematics uncertainties remain unchanged w.r.t. Run 2
  - ➡ **YR2018 systematic uncertainties (S2)**: event yields scale with luminosity, theoretical uncertainties reduce by factor 1/2, experimental uncertainties reduce by $1/\sqrt{L}$ until they reach a lower threshold
- Uncertainty determination methods:
  - ➡ Simple projection: scale Run 2 analysis to Phase II statistics, assume detector conditions are unchanged, incorporating the above uncertainty scenarios
  - ➡ Analyses using samples with HL-LHC detector simulation (Delphes): re-evaluate Run 2 analysis strategies using upgraded detector conditions and pileup effects, S2 uncertainty values

Signal strength measurement

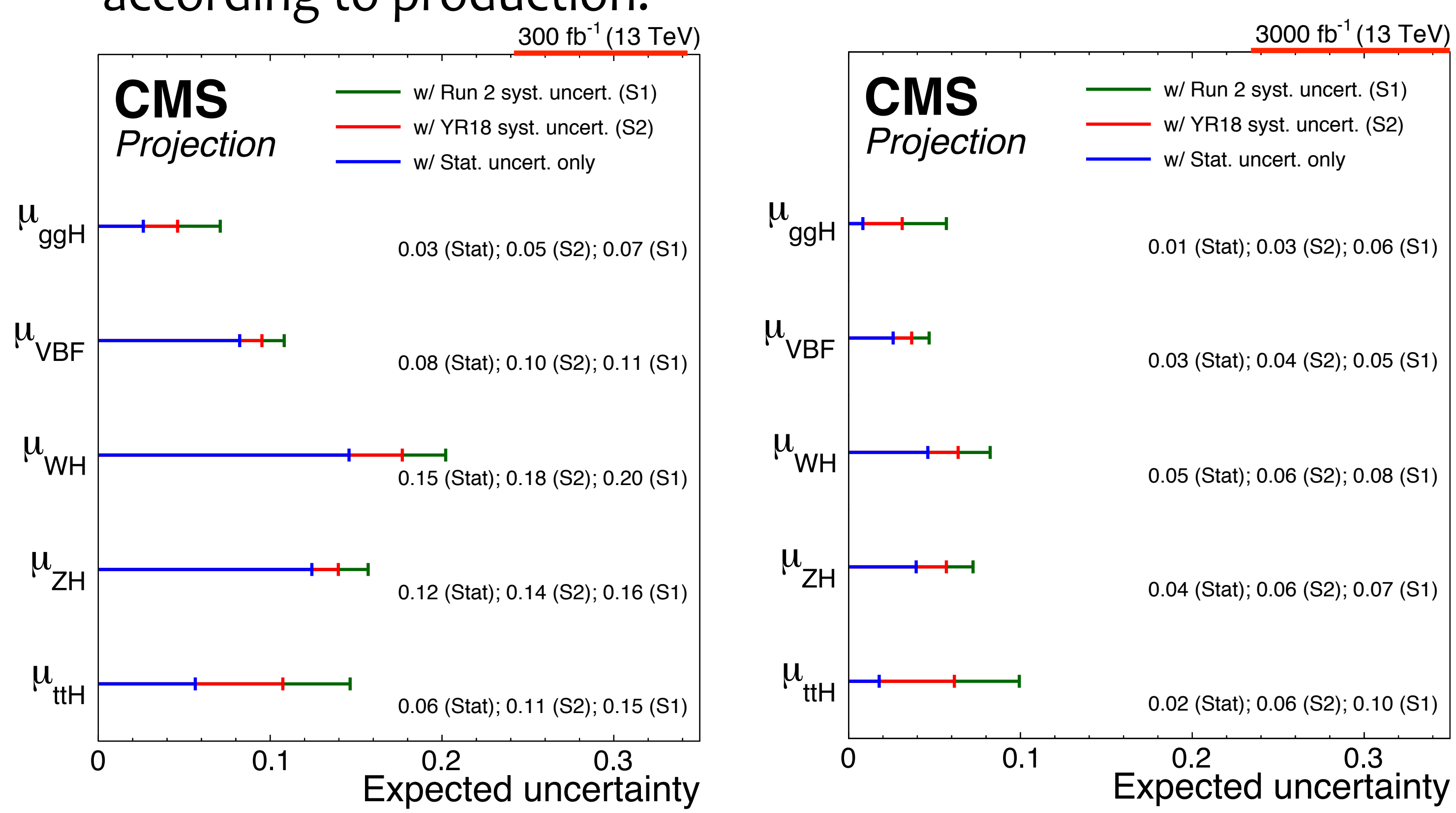
- Signal strength parameters defined to scale cross section (production) and branching ratio (decay):

$$\mu_i^f = \mu_i \times \mu^f = \frac{\sigma_i}{\sigma_i^{SM}} \times \frac{BR_f}{BR_f^{SM}}$$

according to decay:



according to production:



Precision reaches upto 3-10%, main uncertainty due to signal theory systematics

To be compared with Run 2 achievement of 10-50%

Probing coupling strengths

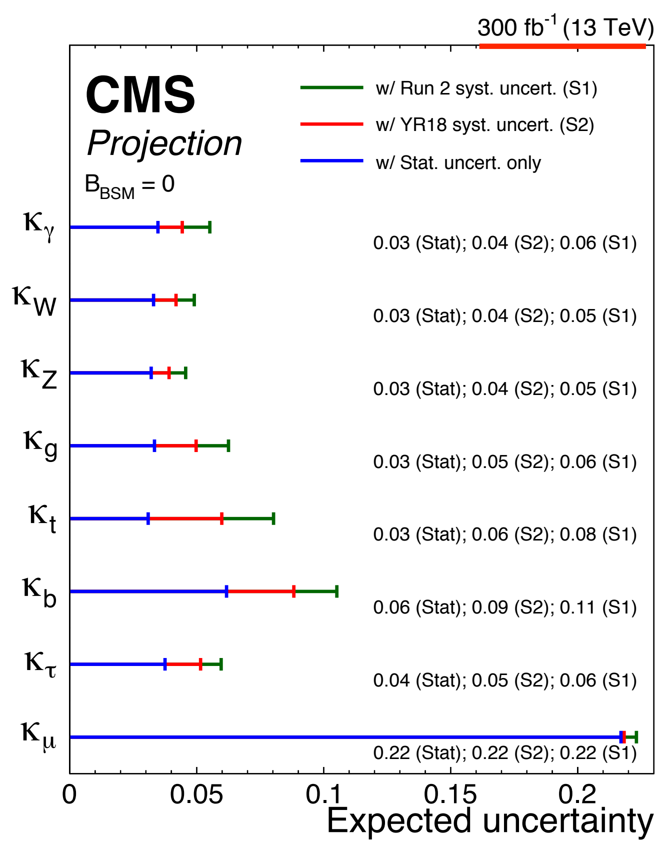
- Coupling strength modifier or kappa model: scale factors used to determine deviation from standard model (SM) couplings:

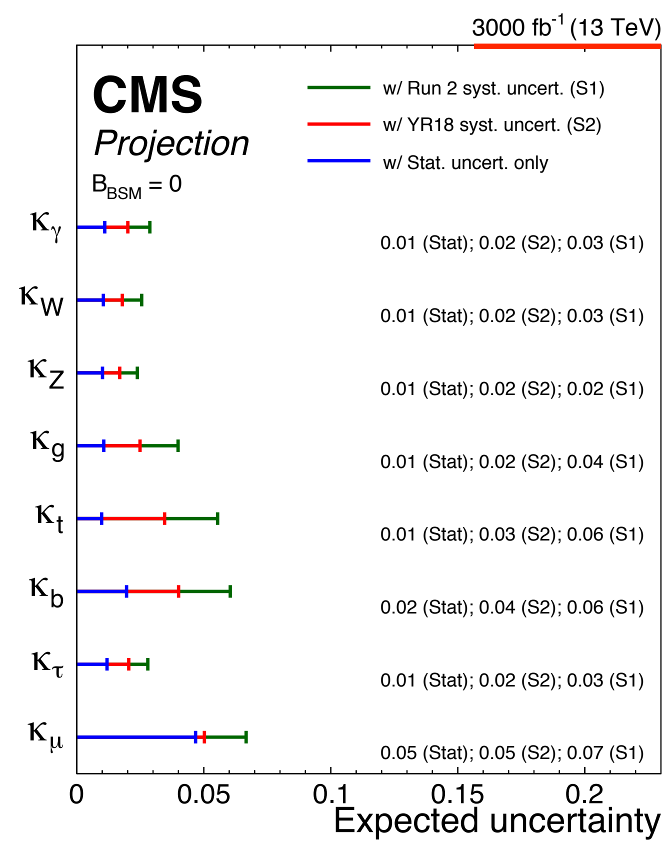
$$\kappa_{\mathrm{i}}^2 = \frac{\sigma_{\mathrm{i}}}{\sigma_{\mathrm{i}}^{\mathrm{SM}}} \qquad \kappa_{\mathrm{i}}^2 = \frac{\Gamma_{\mathrm{i}}}{\Gamma_{\mathrm{i}}^{\mathrm{SM}}}$$

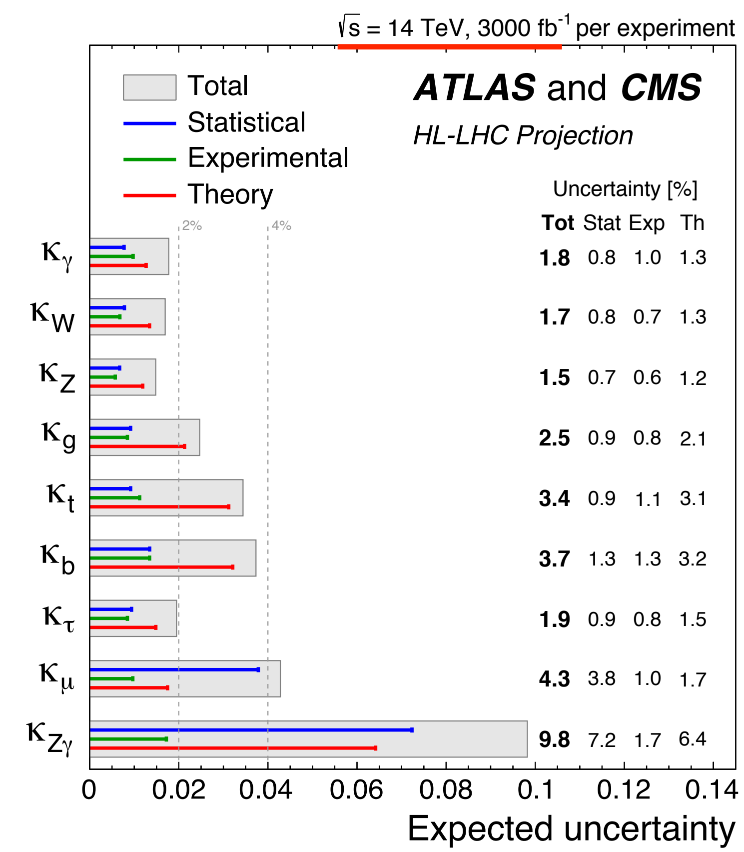
- Total width determined as:

$$\Gamma_{\mathrm{H}} = \frac{\kappa_{\mathrm{H}}^2 . \Gamma_{\mathrm{H}}^{\mathrm{SM}}}{1 - \mathrm{B}_{\mathrm{BSM}}} \qquad \kappa_{\mathrm{H}}^2 = \sum_{\mathrm{j}} \mathrm{B}_{\mathrm{SM}}^{\mathrm{j}} \kappa_{\mathrm{j}}^2$$

(YR2018)







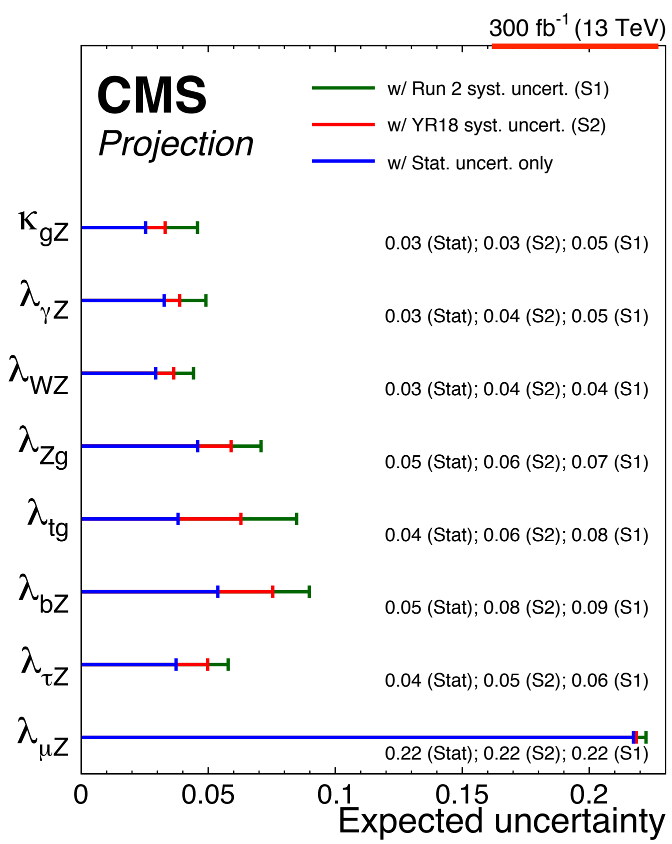
Most of the uncertainties reach the range 2-5% from 10-100% at Run 2

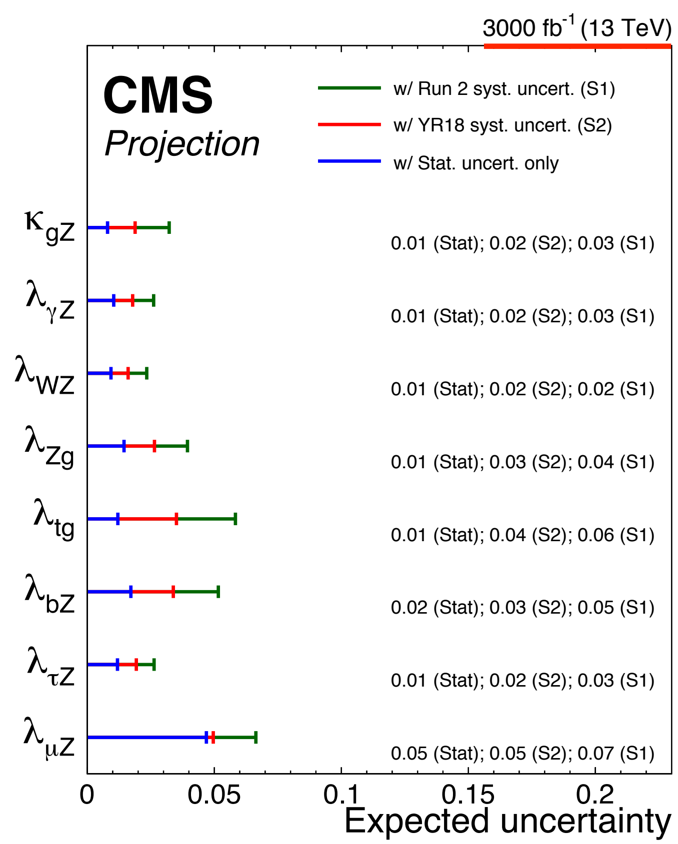
Uncertainty on κ_{μ} statistically dominated

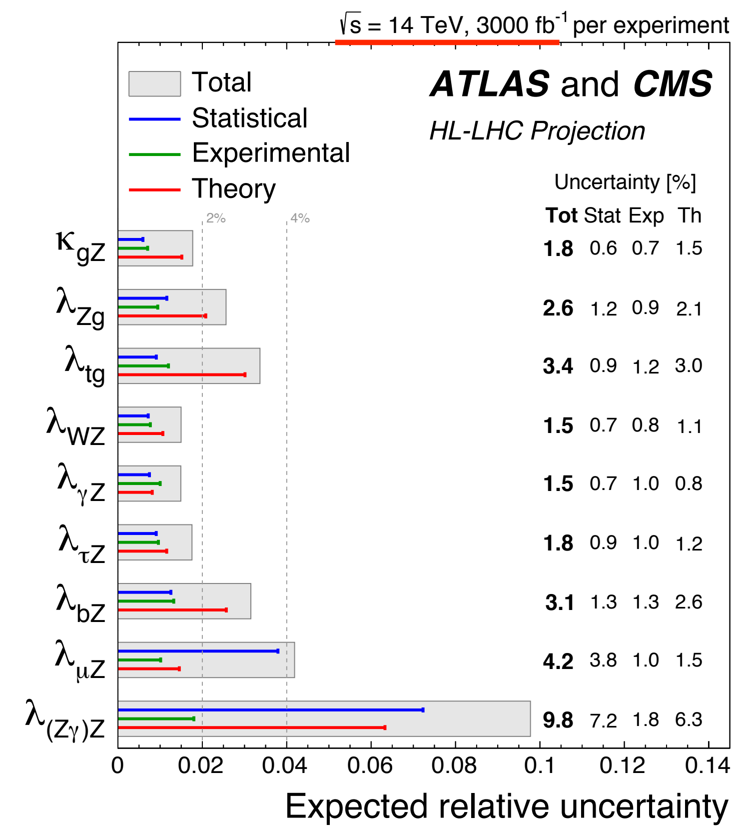
Fermion coupling ratios

- Ratios of coupling modifiers: $\lambda_{ij} = \kappa_i/\kappa_j$, assumptions in Γ_H not needed
- Given the reference ratio: $\kappa_{gZ} = \kappa_g . \kappa_Z/\kappa_H$
- Common uncertainties also cancel out in the ratio

(YR2018)



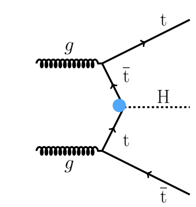


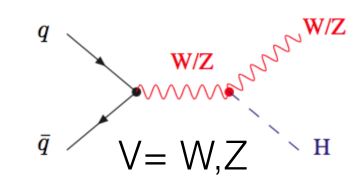


Precision improves to 2-5% from 10-100% at Run 2

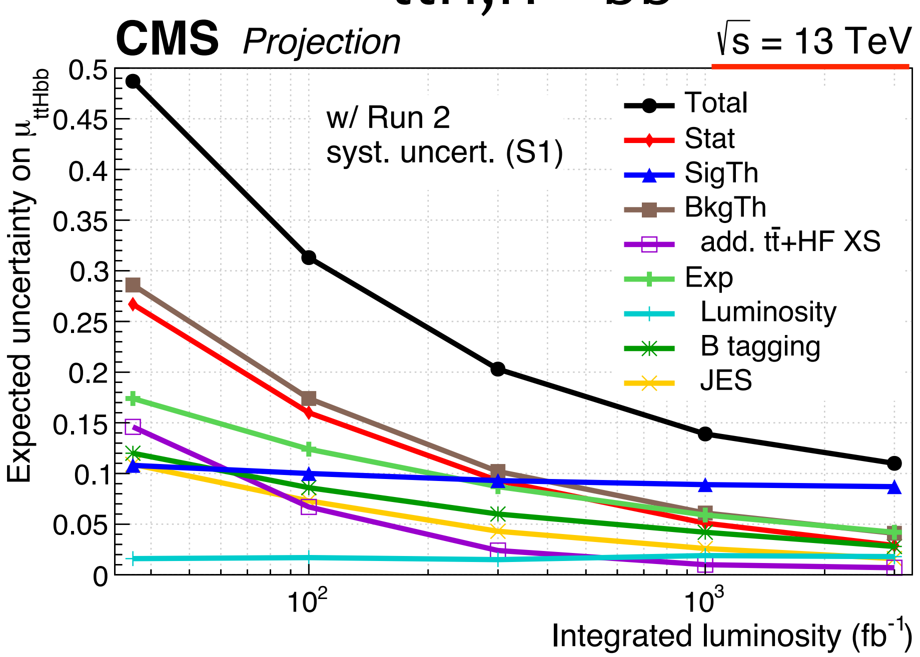
Uncertainty evolution examples: ttH, VH

- BR(H→bb) is largest ~58%, useful to study rare Higgs production modes
- ttH provides direct probe of top-Higgs Yukawa coupling observed in Run 2
- VH production is most sensitive to study, H→bb decay observed in Run 2

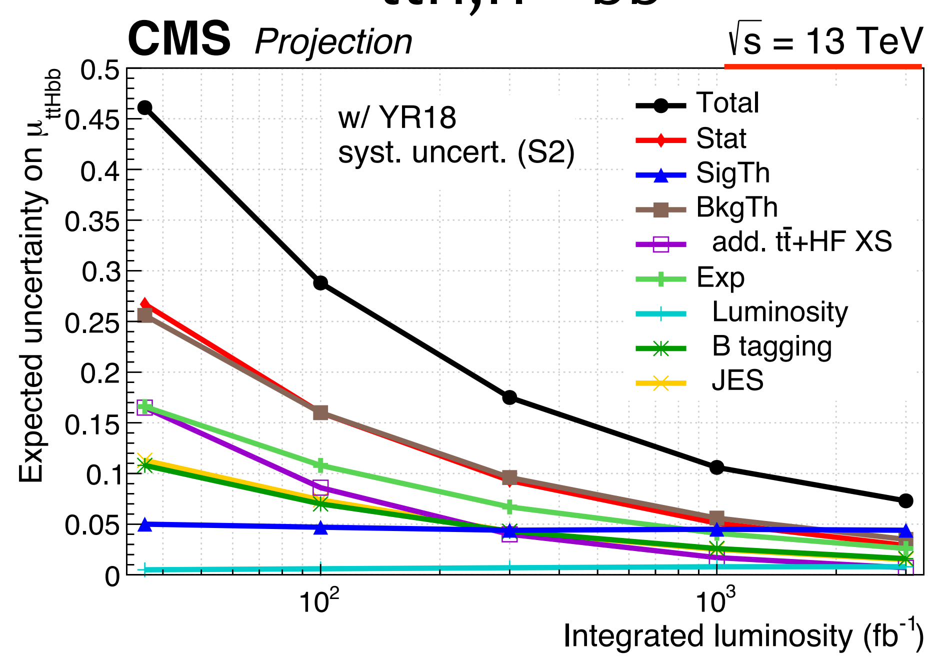




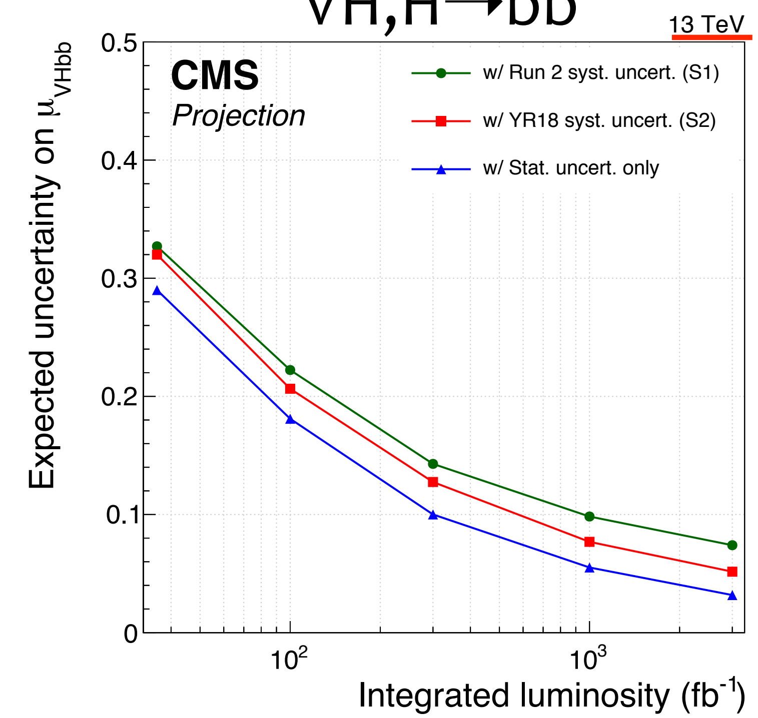
ttH,H→bb



ttH,H→bb



VH,H→bb

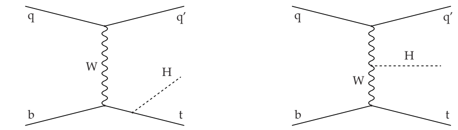


ttH analysis will gain from better background estimation from control region, e.g. tt+HF process cross section uncertainties

VH signal strength will improve with better knowledge of QCD scale uncertainties of signal (ggZH production) and backgrounds (V+jets)

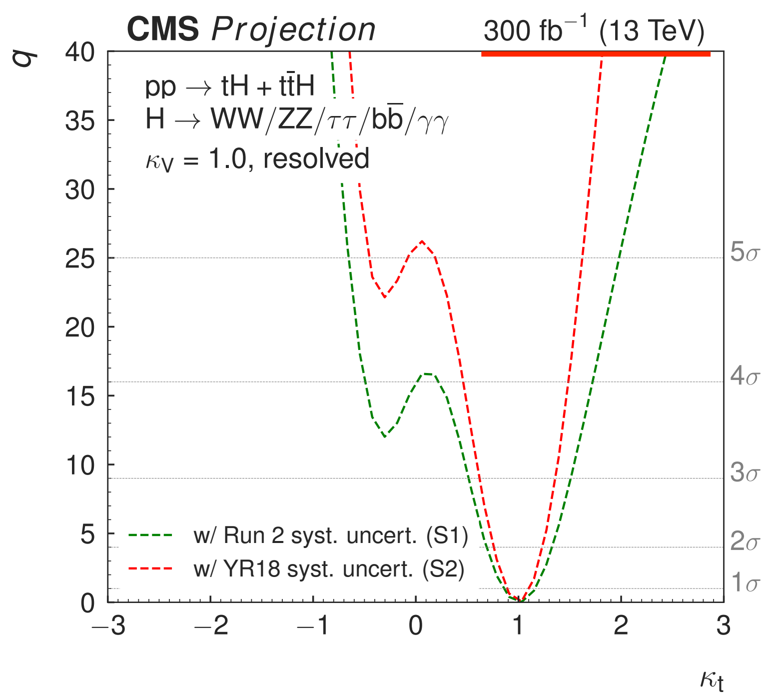
tH production process

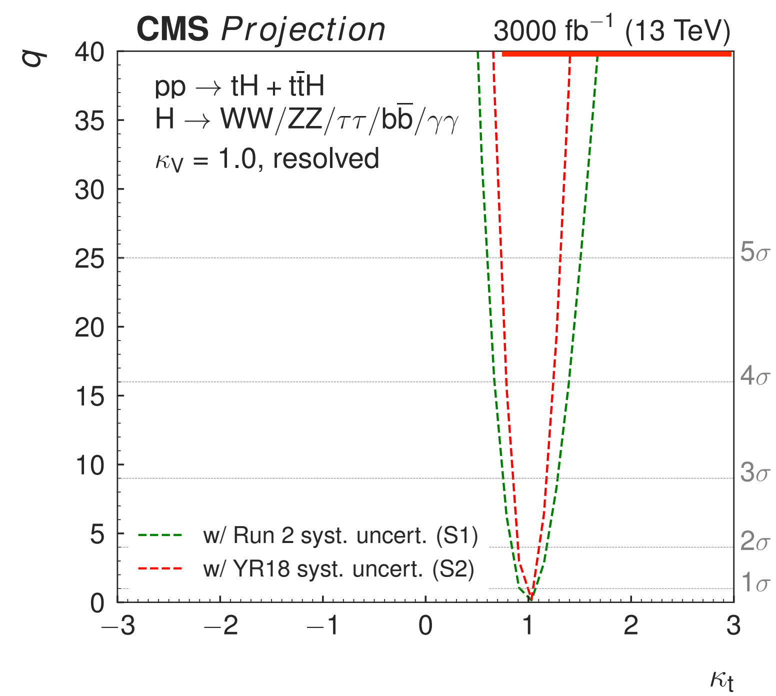
- tH (tHq+tHW) production sensitive to relative sign of κ_t and κ_V



- SM production rate very small due to interference, Run 2 sensitivity limited
- Higgs decay modes considered: H→bb, multilepton, $\gamma\gamma$

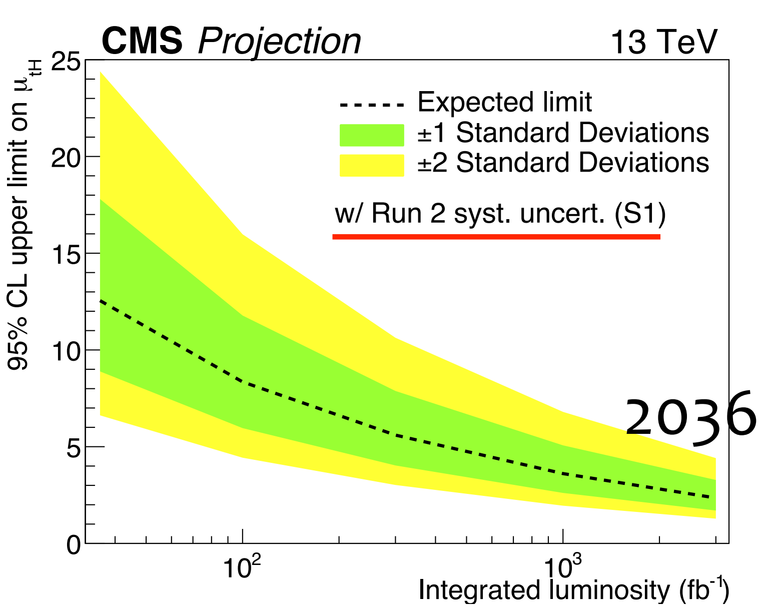
$$q(\vec{\alpha}) = -2\ln\left(\frac{L(\vec{\alpha},\hat{\hat{\vec{\theta}}}_\alpha)}{L(\hat{\vec{\alpha}},\hat{\vec{\theta}})}\right)$$



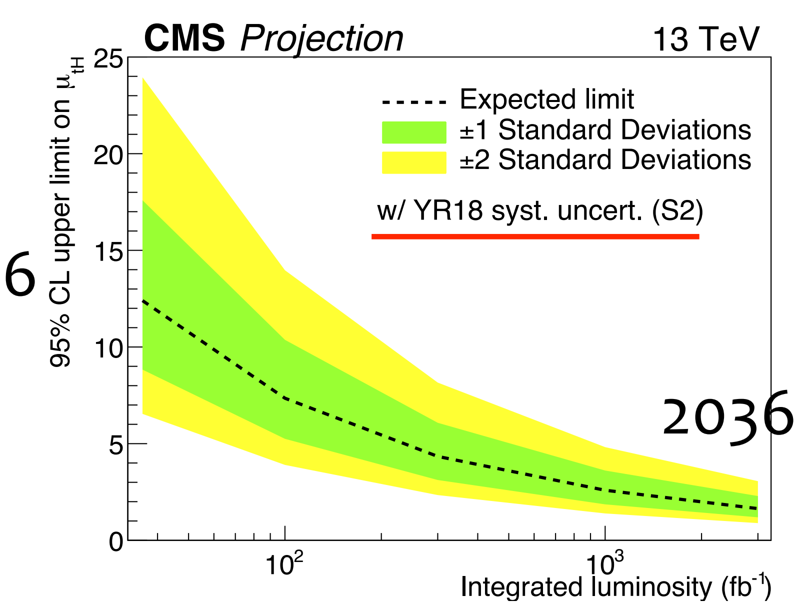


More data→-ve κ_t values more constrained

2016



2016

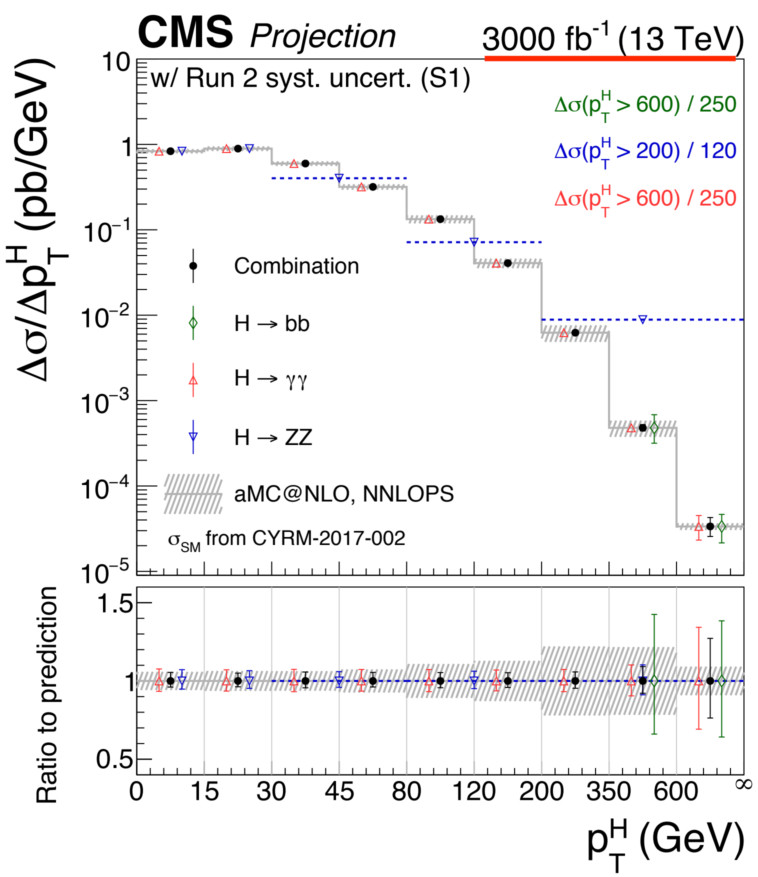


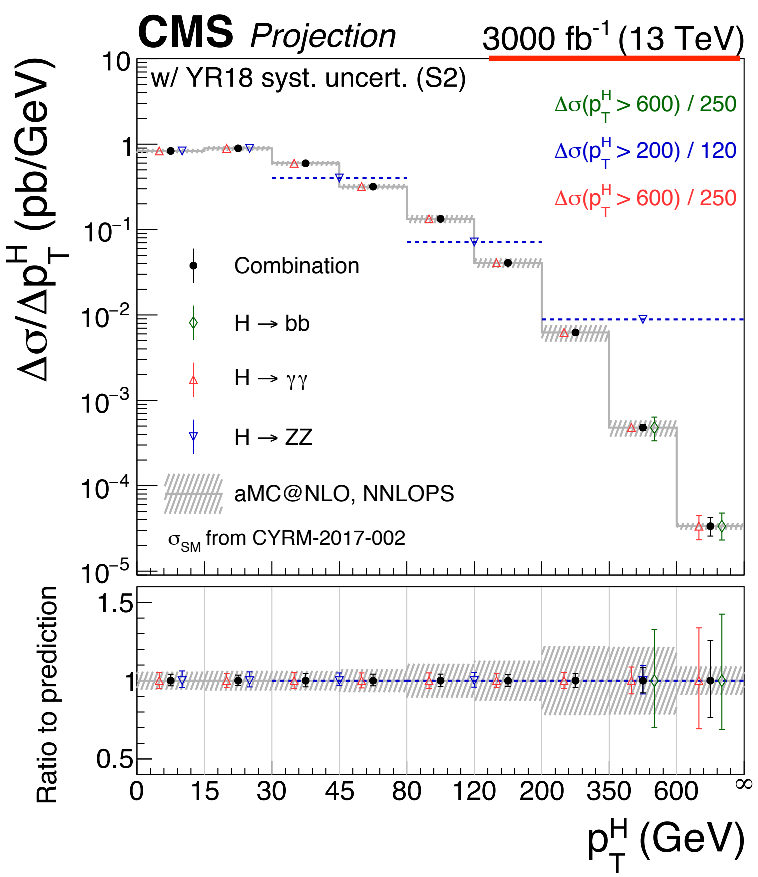
Factor of 8 improvement on μ_{tH} at HL-LHC,

sensitive to SM production

Differential distribution of p_T(Higgs)

- Higgs p_T is moderate in SM, but beyond SM (BSM) affects higher values
- Differential distribution only possible with large statistics
- Constrain coupling modifiers using p_T (Higgs) spectrum
- New physics at high energies can modify event kinematics

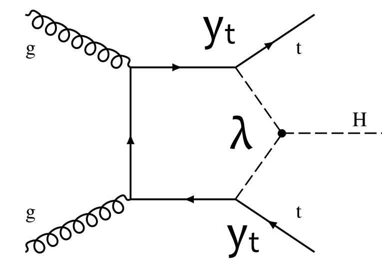




Uncertainty in high p_T bins statistically dominated → factor of 10 improvement possible with S1 alone at 3000 fb^{-1}, additional 25% at S2

p_T(Higgs) measurement with ttH & tH

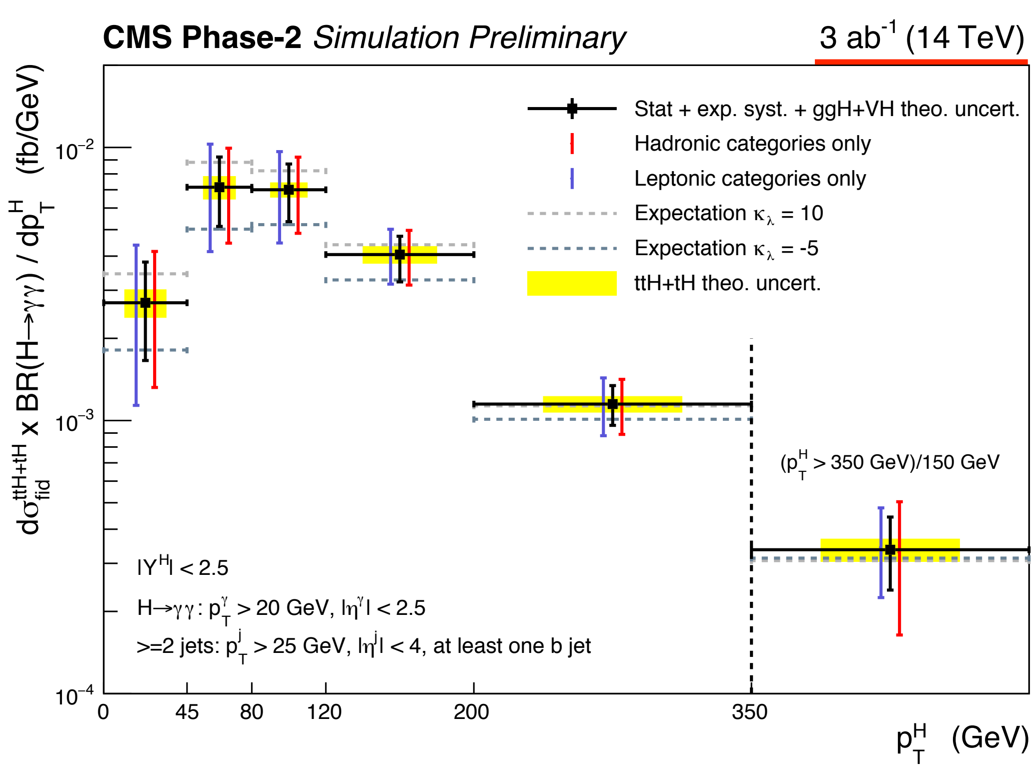
- Differential cross section measurement using p_T(Higgs) can disentangle self-coupling (λ) effects from anomalous top-Higgs coupling



λ_{SM} = 0.13 for m_H = 125 GeV

- Delphes simulated samples for Phase II geometry used

- ttH and tH events with $H \rightarrow \gamma\gamma$ decay selected in hadronic or leptonic final states depending on top decay



Analysis results on κ_λ in Sylvie's talk

Uncertainties on differential cross section 20-40% at 3000 fb^{-1}

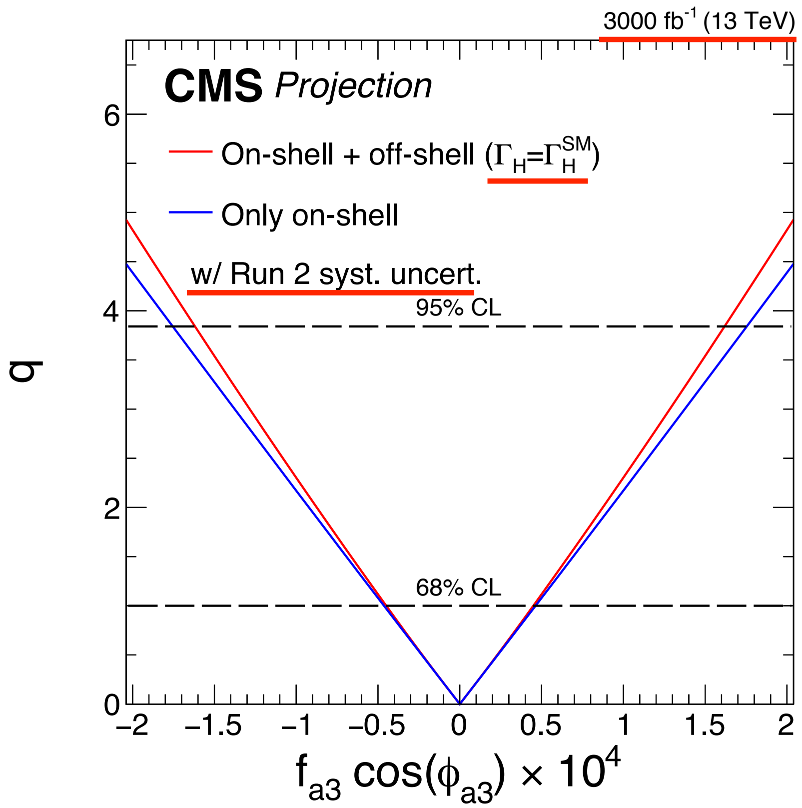
Higgs width

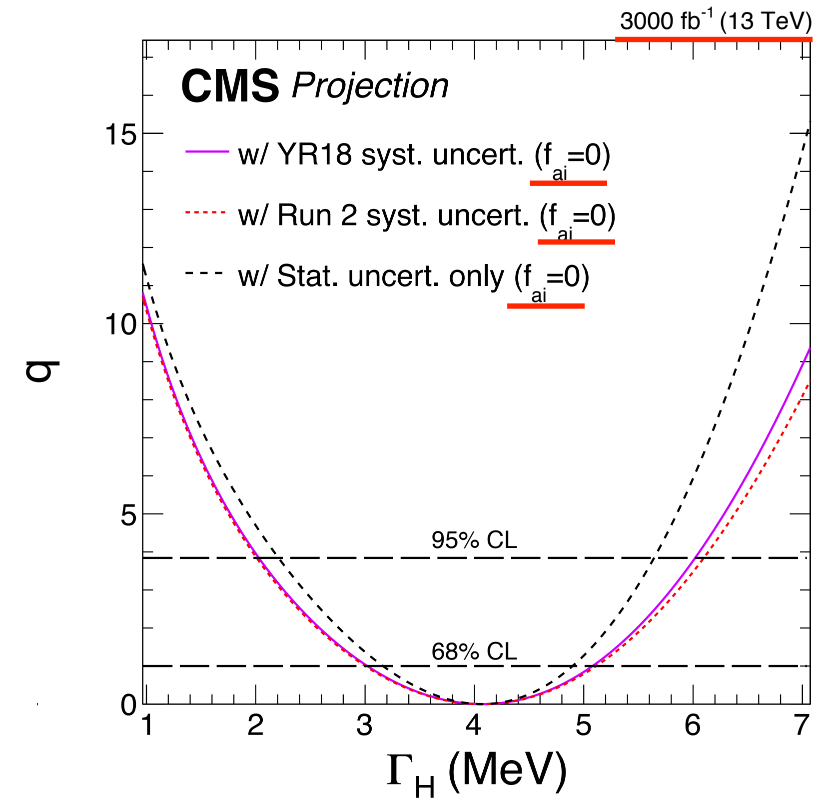
- Physical Higgs width (~4 MeV) much smaller than experimental resolution (~100 MeV)
- Width can be constrained comparing H→ZZ→4ℓ on-shell and off-shell contributions
- Off-shell contributions can be enhanced due to:
  - ➡ larger width
  - ➡ anomalous HVV coupling
  - ➡ new resonances

$$\sigma^{\mathrm{on-shell}}_{\mathrm{H\to VV\to 4\ell}} \propto \mu_{\mathrm{VVH}}$$

$$\sigma^{\mathrm{off-shell}}_{\mathrm{H\to VV\to 4\ell}} \propto \mu_{\mathrm{VVH}}.\Gamma_{\mathrm{H}}$$

tensor structure of HVV coupling can be probed using anomalous coupling a_3, corresponding phase φ_3



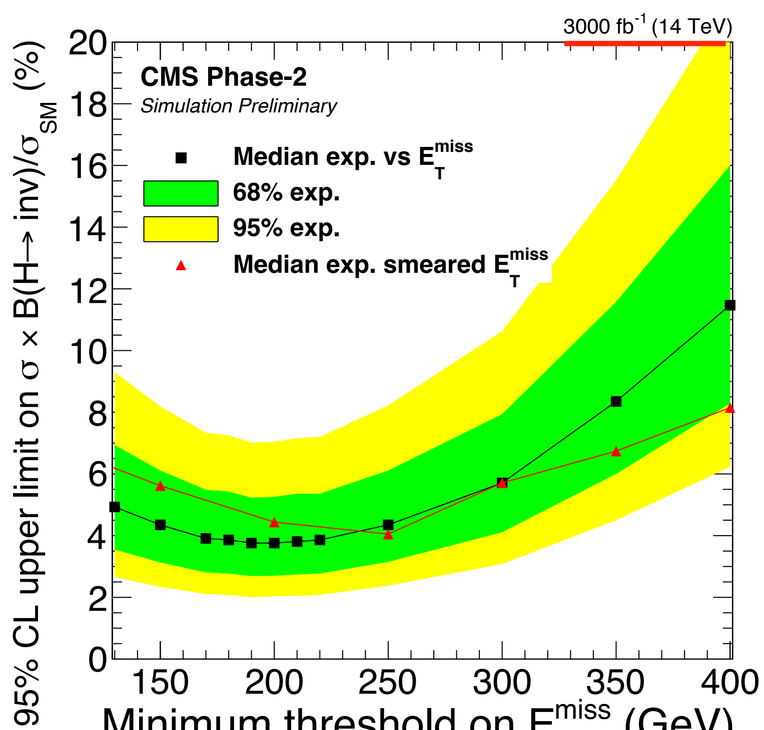


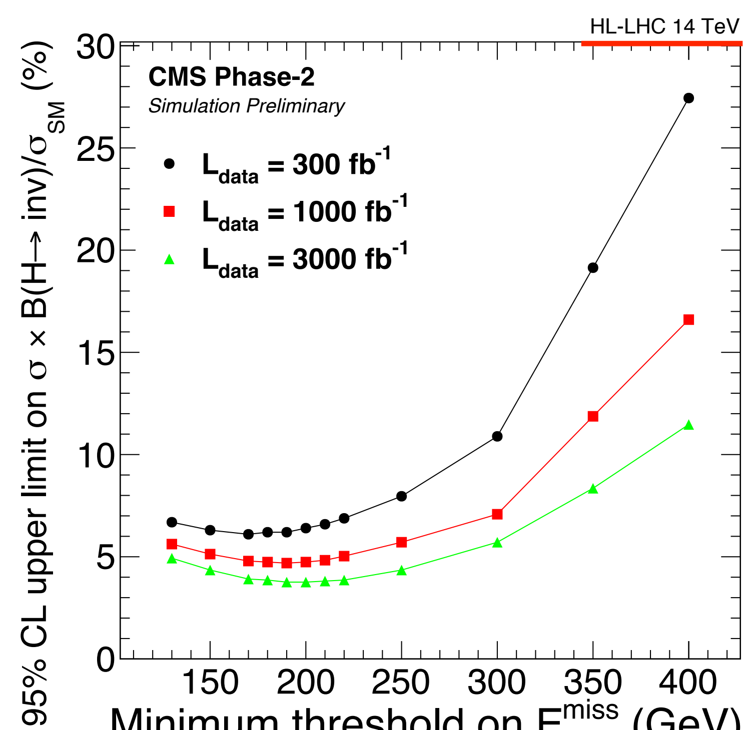
95% CL exclusion outside (-0.00016, 0.00016) at S1, Run 2 measurement (-0.0076, 0.0050)

95% CL exclusion outside (2, 6) at S2, Run 2 measurement (0.08, 9.16)

Higgs to invisible search

- Higgs decays to massive invisible particles is sensitive probe of DM coupling
- Limited sensitivity to Higgs to invisible decays with Run 2 data
- VBF topology has the best sensitivity
- 95% CL upper limit on H→invisible BR is 3.8% assuming SM production at 3000 fb^{-1}, SM prediction of higgs BR to invisible ~10^{-3}
- Run 2 measurement in VBF channel yields an upper limit of 33%





HL-LHC will put more stringent constraint on new physics in Higgs→invisible sector

Conclusions

- Run 2 saw plethora of Higgs measurements → reaching precision frontier, some still statistics dominated
- Analyses are well established, fine-grained measurements will be possible at HL-LHC
- More data will provide access to rare production and decay modes, e.g., H →μμ, Zγ
- To reach the goal, need improvement in theoretical and experimental uncertainties
- Roadmap of LHC essentially includes building new detector to tackle pileup, radiation damage

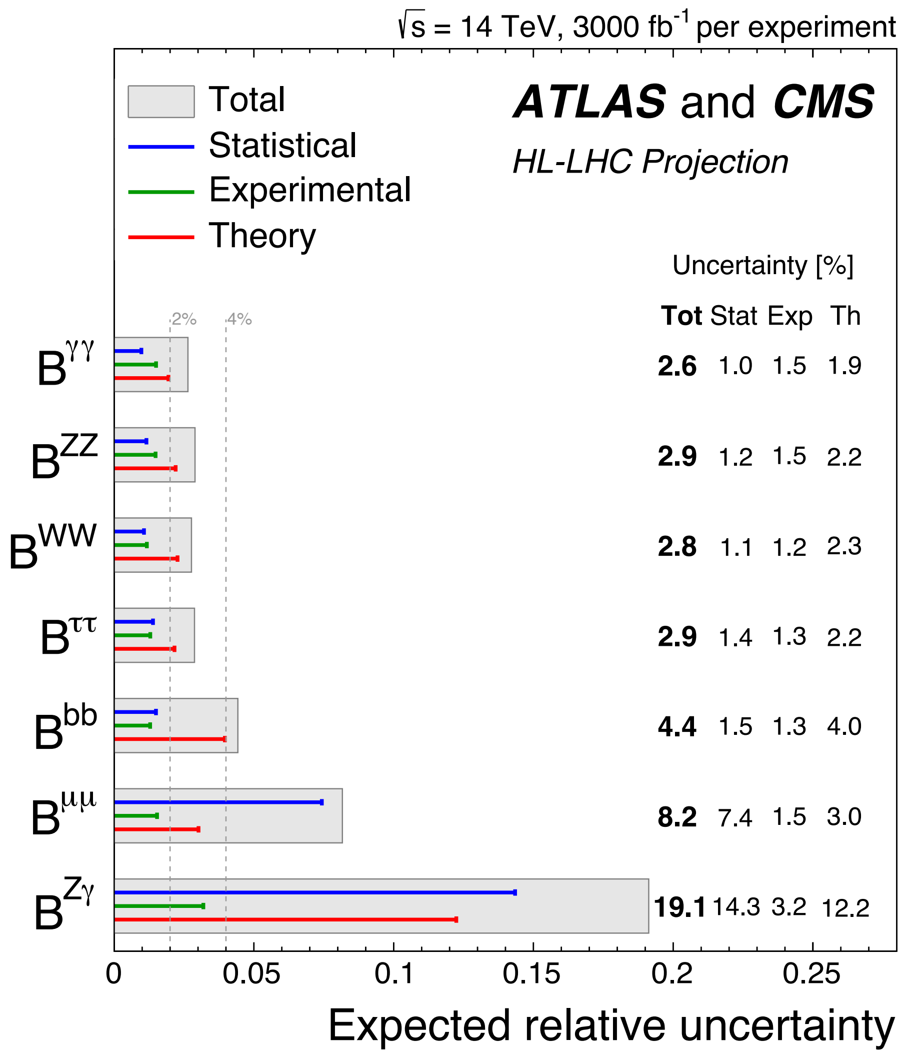
Thank You.

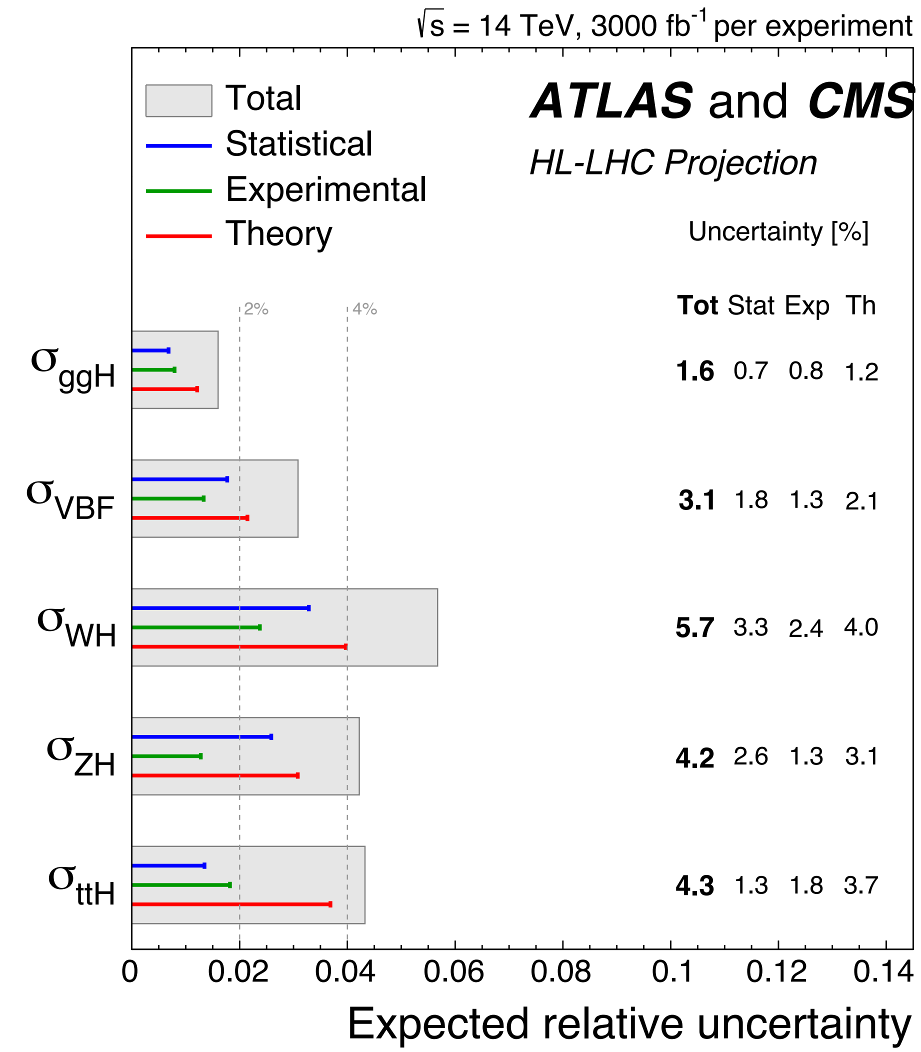
Back up

Table 1: The sources of systematic uncertainty for which limiting values are applied in scenario S2.

Source	Component	Run 2 uncertainty	Projection minimum uncertainty
b-Tagging	b-/c-jets (syst.)	Varies with p_T and η	Same as Run 2
	light mis-tag (syst.)	Varies with p_T and η	Same as Run 2
	b-/c-jets (stat.)	Varies with p_T and η	No limit
	light mis-tag (stat.)	Varies with p_T and η	No limit
Muon ID		1–2%	0.5%
Electron ID		1–2%	0.5%
Photon ID		0.5–2%	0.25–1%
Hadronic tau ID		6%	Same as Run 2
Jet energy scale	Absolute	0.5%	0.1–0.2%
	Relative	0.1–3%	0.1–0.5%
	Pileup	0–2%	Same as Run 2
	Method and sample	0.5–5%	No limit
	Jet flavour	1.5%	0.75%
	Time stability	0.2%	No limit
Jet energy res.		Varies with p_T and η	Half of Run 2
MET scale		Varies with analysis selection	Half of Run 2
Integrated lumi.		2.5%	1%

Back up

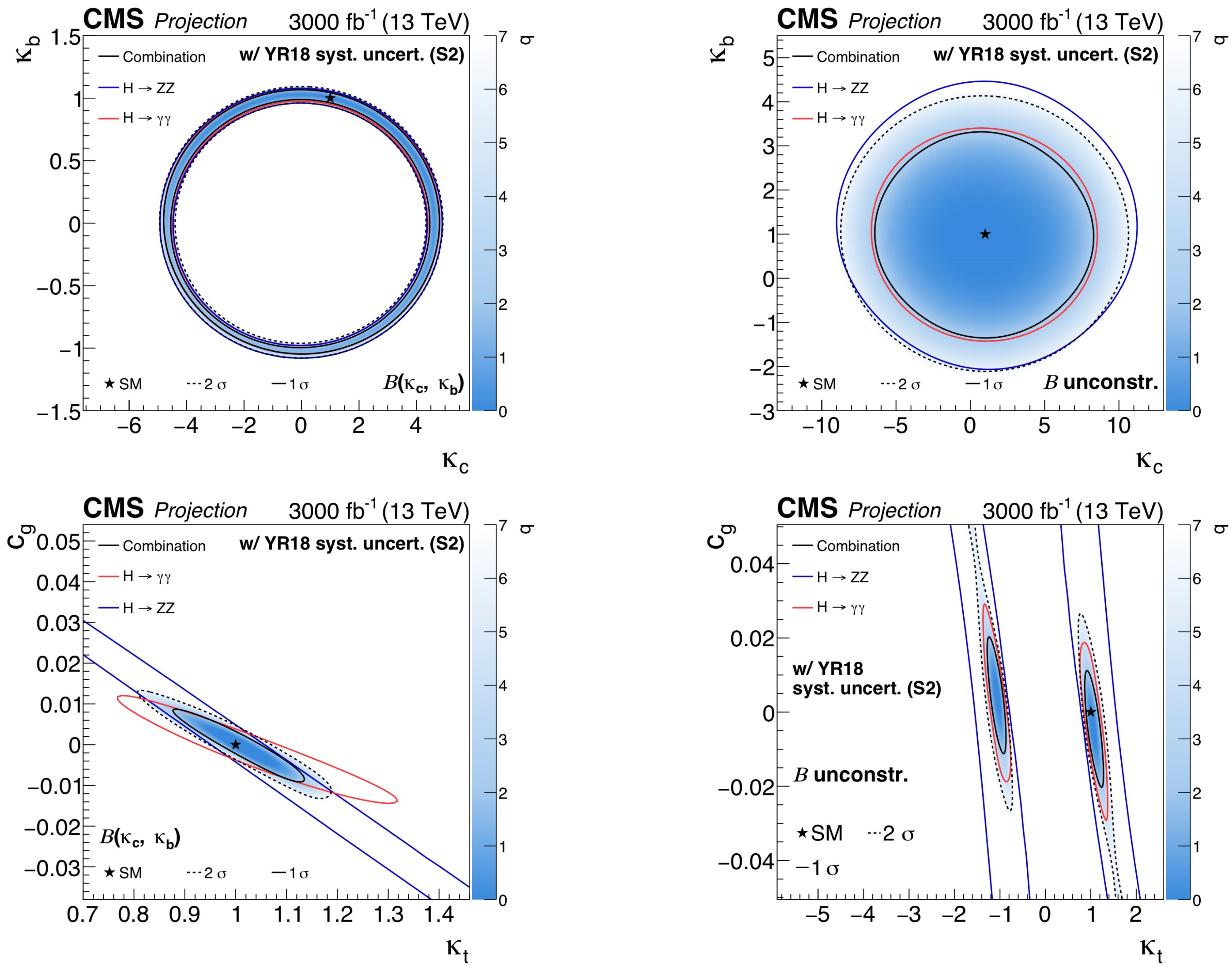




- Combined total expected ±1σ uncertainties in S2 on per-decay-mode BR and per-production-mode cross section normalized to SM prediction

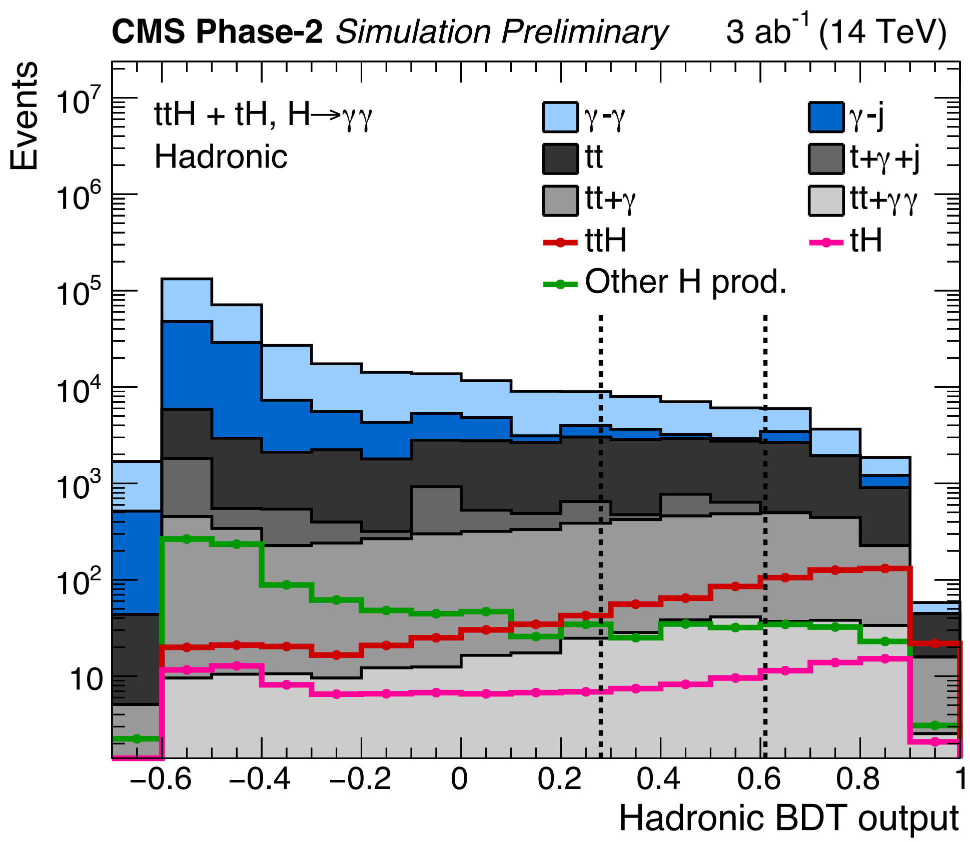
Back up

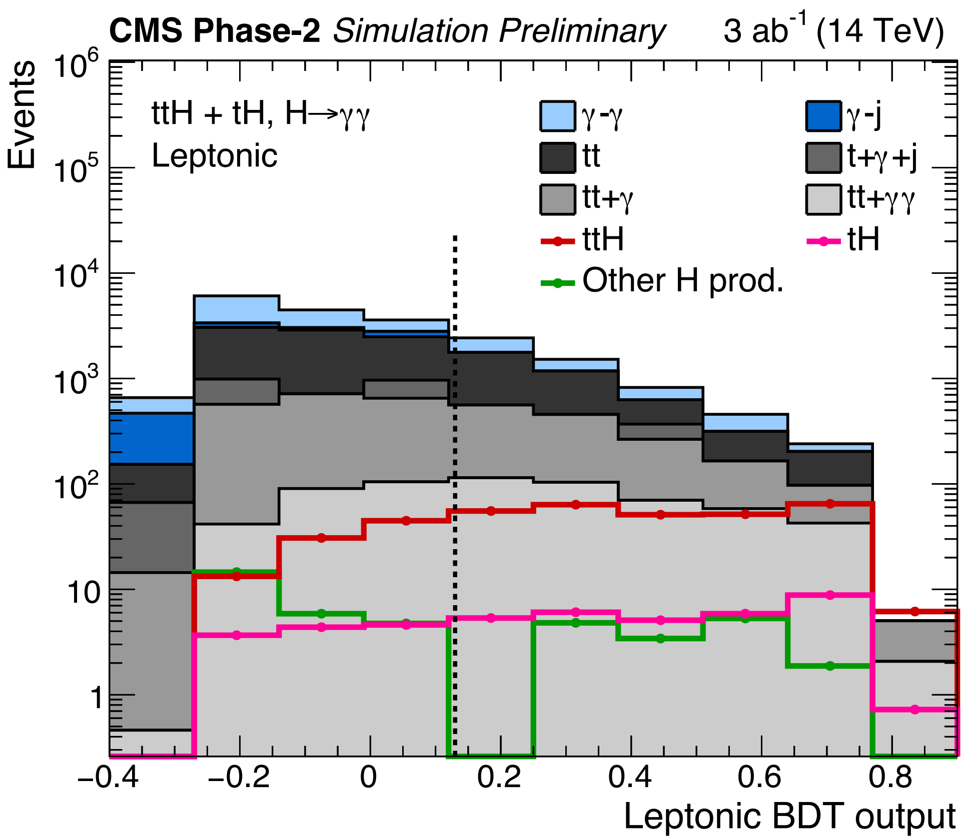
- Theoretical prediction for the p_T (Higgs) fit to data can be used to constrain Higgs couplings
- Use parametrisation dependent on κ_b, κ_t and κ_b, c_g



Back up

- In the ttH+tH, H→$\gamma\gamma$ analysis, BDT classifiers are trained with variables such as event kinematics and photon quality
- Variables that may distort p_T(Higgs) spectrum are avoided, such as di-photon rapidity





Back up

- Difference in Delphes and FullSim distributions adjusted accordingly
- Final state contains two jets with high rapidity gap, high dijet mass (M_{jj}), small angle in transverse plane, missing transverse momentum (MET)
- Reject events with identified electrons, muons, photons, taus, b jets
- Four control regions dominated with $W \to e\nu$, $W \to \mu\nu$, $Z \to ee$, $Z \to \mu\mu$ events