Higgs and High Energy Probes: Main couplings
Experimental vision

Andrew Gilbert
on behalf of the ATLAS & CMS Collaborations

Ultimate precision at hadron colliders | 2 December 2019

Introduction

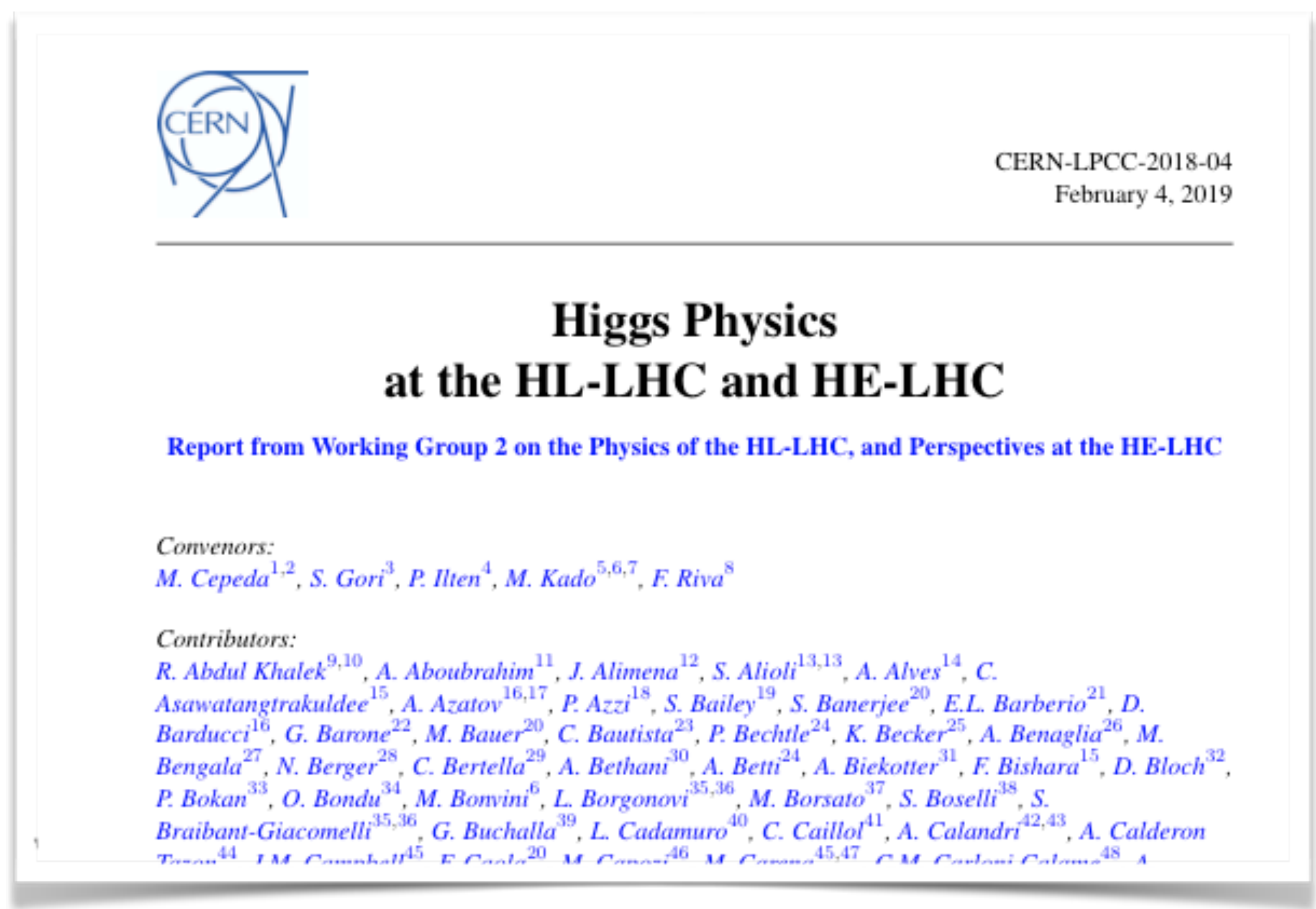
- Precision Higgs coupling measurements are a key pillar of the HL-LHC physics programme

- BSM physics can manifest as percent-level deviations

- **HL/HE-LHC Physics Workshop:**
  - Extensive studies of the HL-LHC physics potential based on latest understanding of the upgraded detectors, experimental techniques and theoretical developments
  - Higgs WG: ultimate precision for SM Higgs properties, sensitivity to rare channels & indirect NP

Model	κ_V	κ_b	κ_γ
Singlet Mixing	$\sim 6\%$	$\sim 6\%$	$\sim 6\%$
2HDM	$\sim 1\%$	$\sim 10\%$	$\sim 1\%$
Decoupling MSSM	$\sim -0.0013\%$	$\sim 1.6\%$	$\sim -.4\%$
Composite	$\sim -3\%$	$\sim -(3-9)\%$	$\sim -9\%$
Top Partner	$\sim -2\%$	$\sim -2\%$	$\sim +1\%$

arXiv:1310.8361



CERN

CERN-LPCC-2018-04
February 4, 2019

Higgs Physics
at the HL-LHC and HE-LHC

Report from Working Group 2 on the Physics of the HL-LHC, and Perspectives at the HE-LHC

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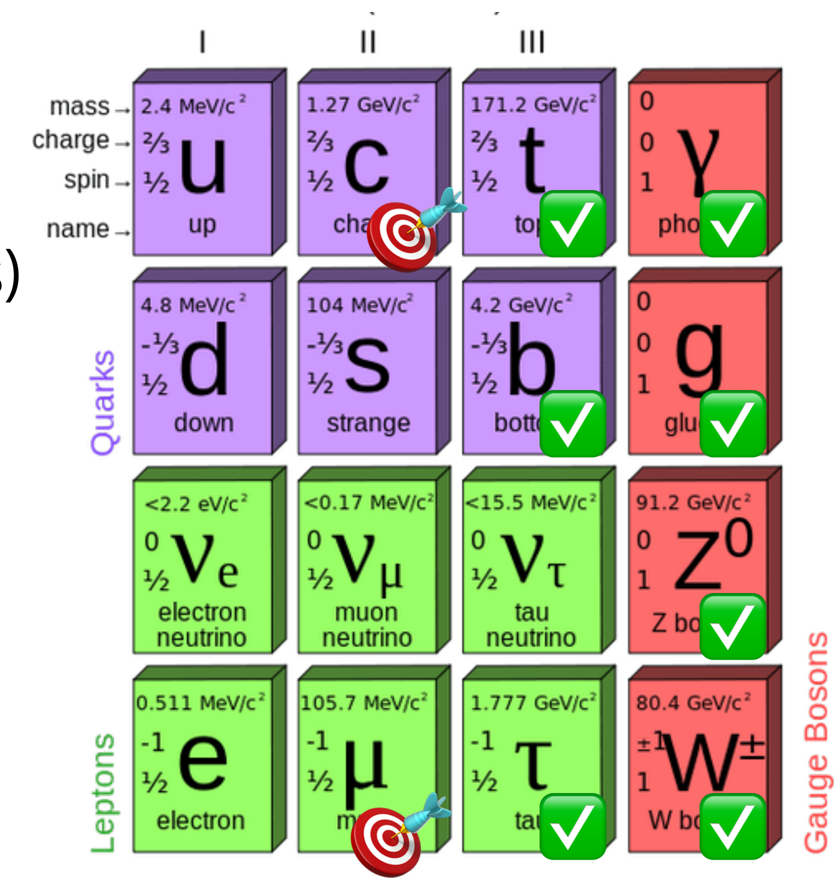
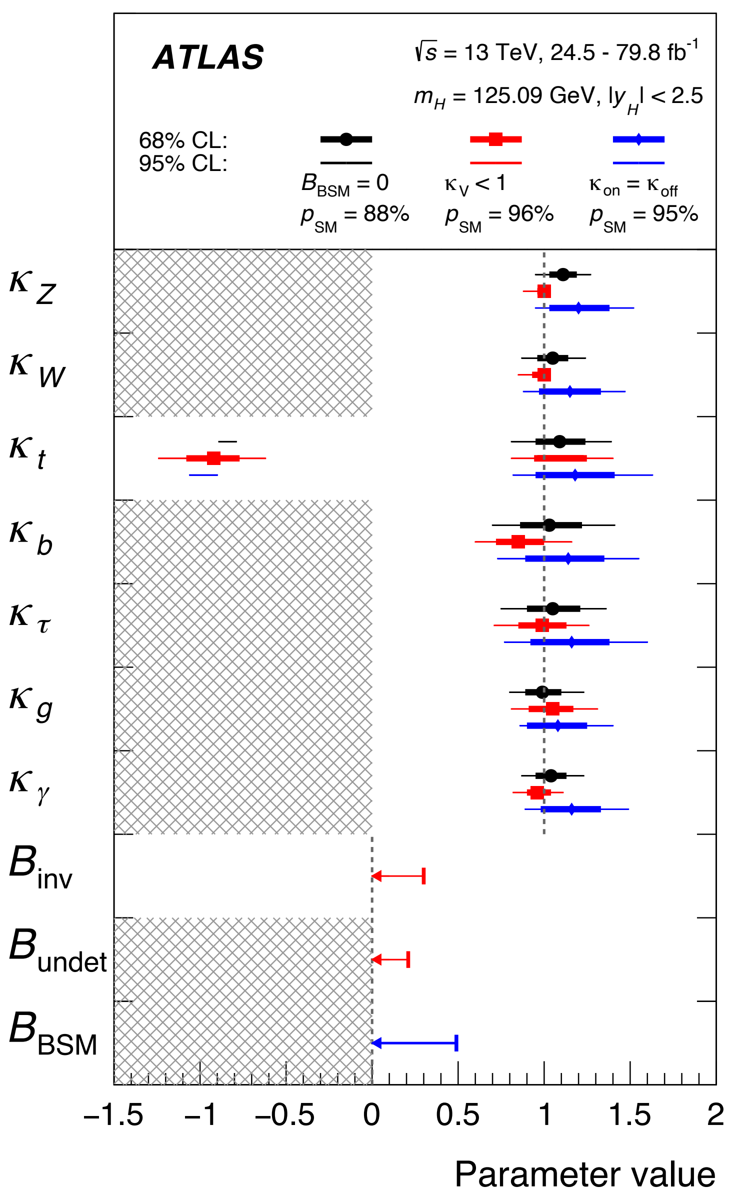
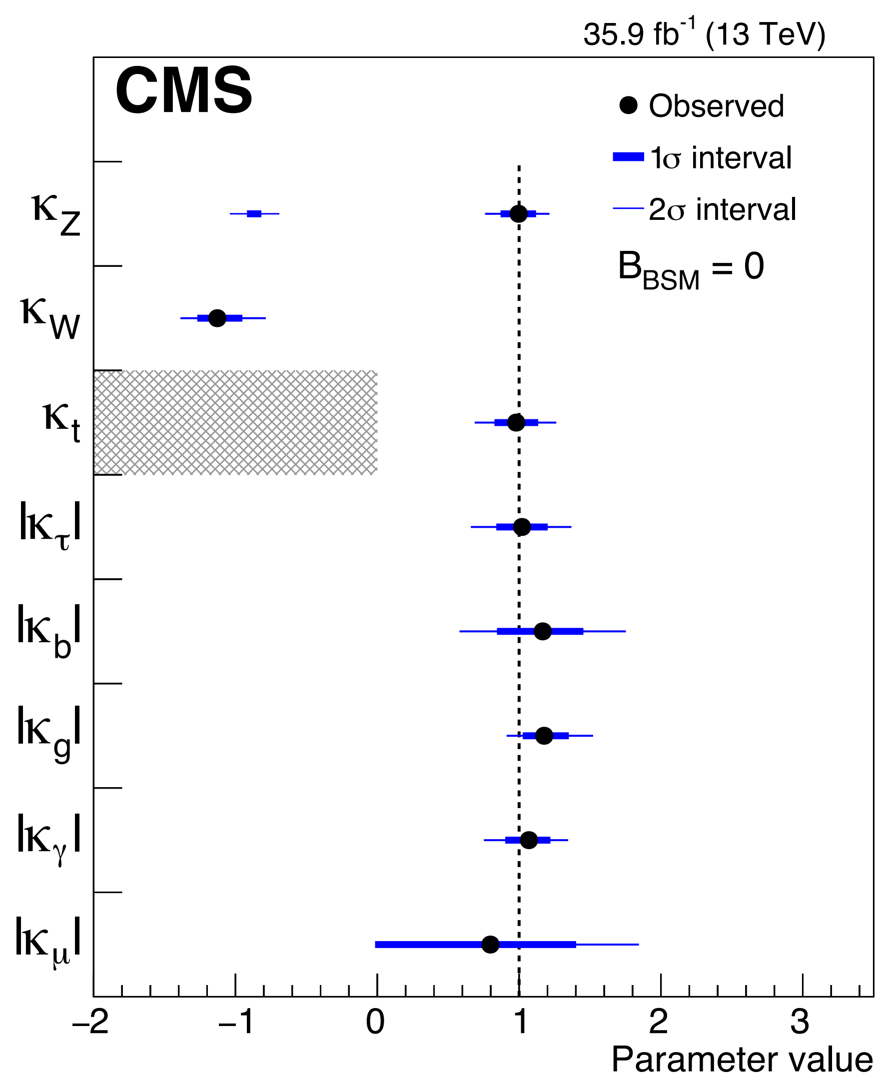
Progress with Run 2 data

- Higgs couplings to 3rd generation fermions established
- All main production & decay modes targeted
- Couplings measured with 10-15% precision (w/ partial datasets)

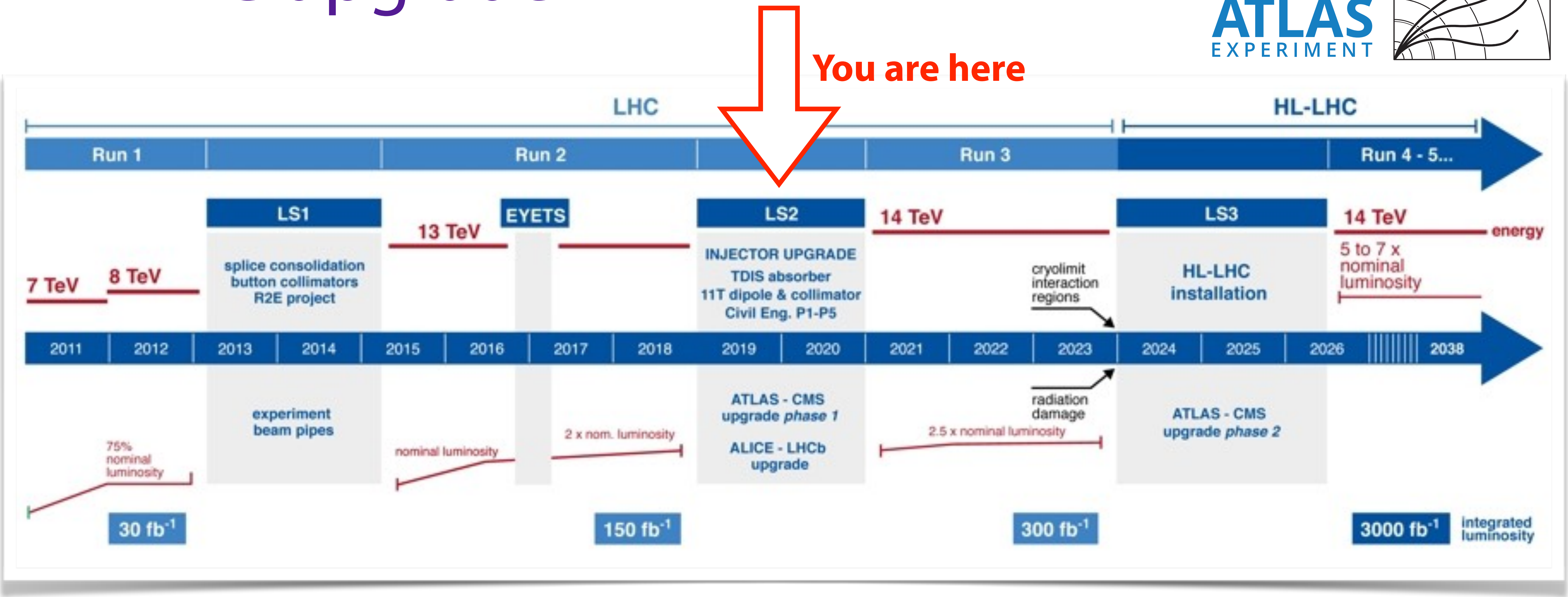






- 2nd generation couplings remain challenging...
- ...but sensitivity approaching SM level for $H \to \mu\mu$

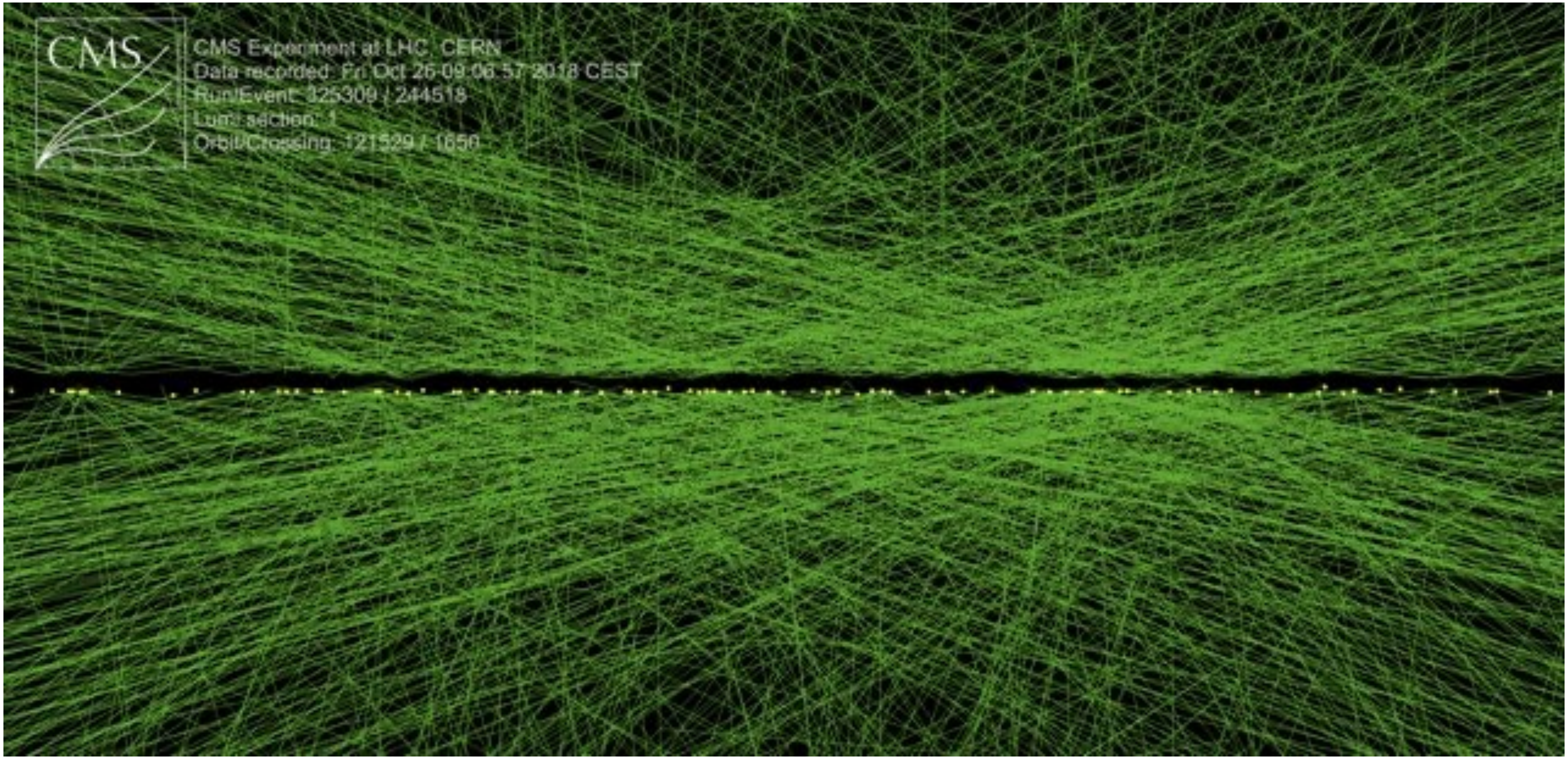
HL-LHC upgrade



- Nominal HL-LHC scenario:
  - L = 5 x 10^{34} $cm^{-2}s^{-1}$ ⇒ 300 fb^{-1} / year ⇒ 3000 fb^{-1} total, <PU> = 140
- Ultimate scenario:
  - L = 7.5 x 10^{34} $cm^{-2}s^{-1}$ ⇒ 400 fb^{-1} / year ⇒ 4000 fb^{-1} total, <PU> = 200
- **HL-LHC is a Higgs factory:**
  - **170M Higgs bosons**
  - **120k HH pairs** (⇒ Talk by E. Petit this afternoon)

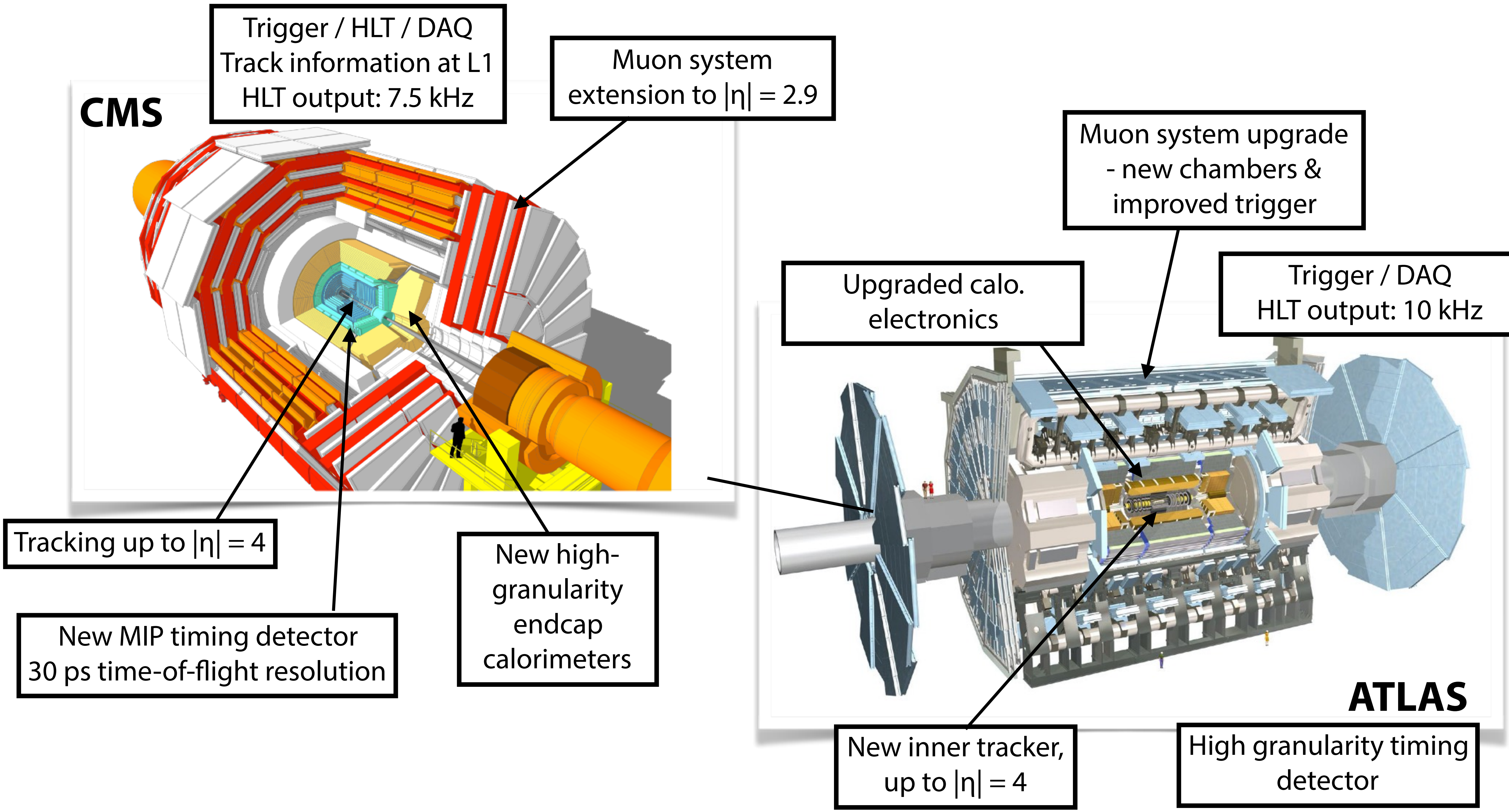
Challenges for the experiments

- 140-200 pileup interactions per bunch crossing
  - Major challenge in terms of irradiation and triggering for the experiments
- Real data event with136 simultaneous collisions from October 2018:



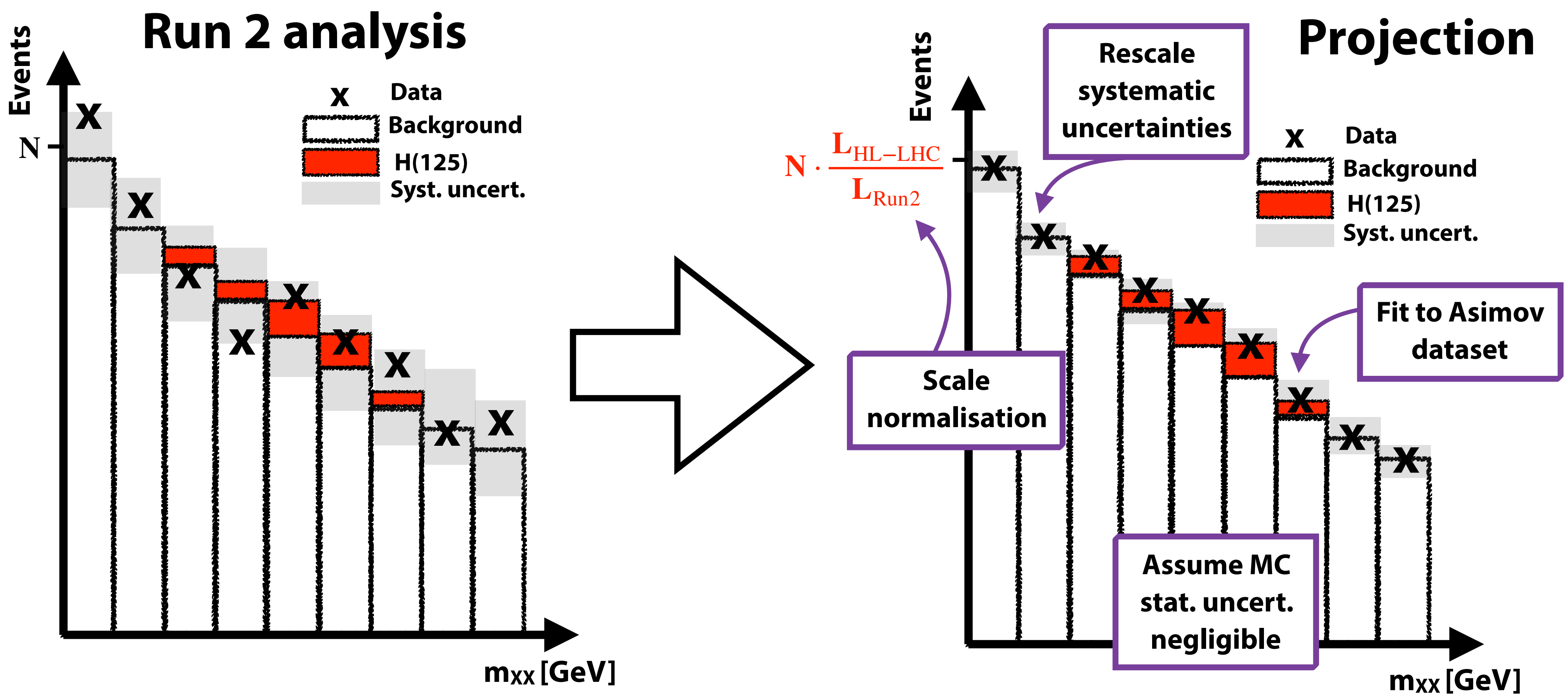
Detector upgrades

- Comprehensive upgrade programme to prepare for HL-LHC conditions:



Physics studies for HL-LHC

- Many measurements will be **systematics limited,** approaches used**:**
- **(1) Projection of existing analyses** - based on the Run 2 analysis statistical model
  - Used for the majority of the following results



  - Generally assumes Run 2 performance (efficiencies, resolutions...) maintained
- **(2) Analysis based on new simulation** - often with fast techniques, e.g. Delphes

Projection scenarios

- Results given under two assumptions
  - **S1** : Current uncertainties remain unchanged
  - **S2** : Theoretical uncertainties scaled down by a factor 1/2, experimental uncertainties reduced with integrated luminosity until **expected minimum uncertainty** reached

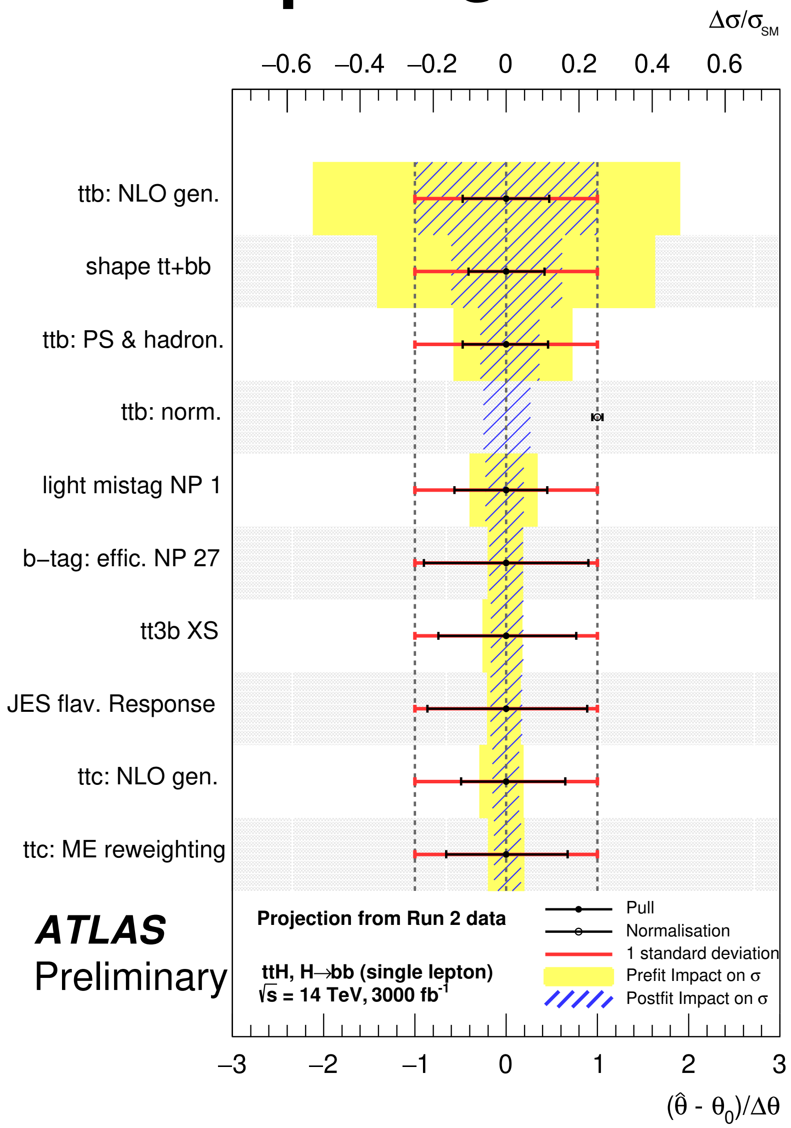
- Common treatment for ATLAS & CMS:

Source	Component	Run 2 uncertainty	Projection minimum uncertainty
Muon ID		1–2%	0.5%
Electron ID		1–2%	0.5%
Photon ID		0.5–2%	0.25–1%
Hadronic tau ID		6%	2.5%
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
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
Integrated lumi.		2.5%	1%

Example: ttH(→bb)

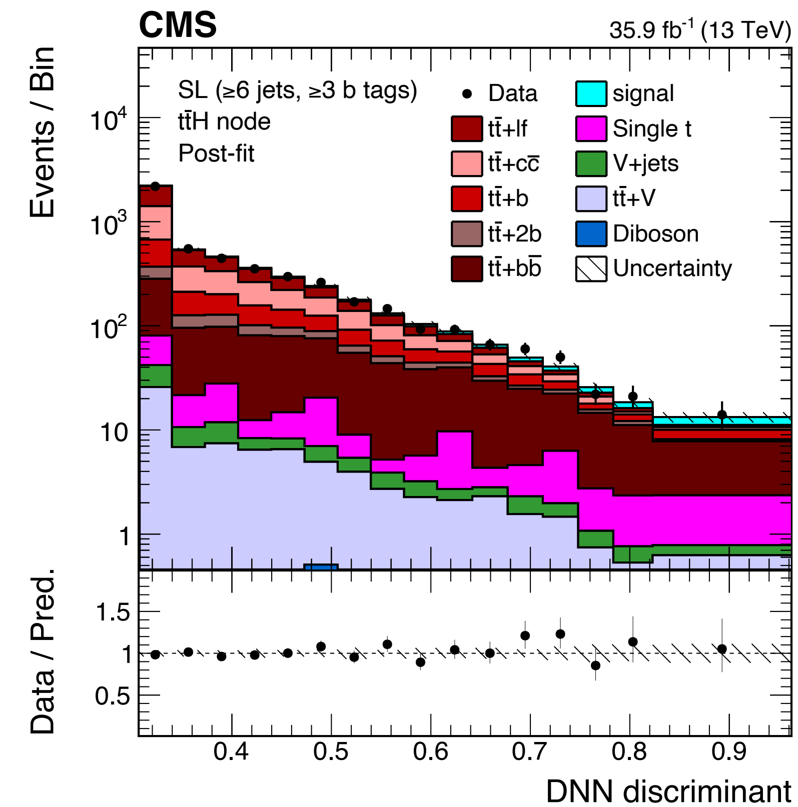
- Important channel for **top Yukawa** coupling, but challenging:
  - Good b-jet energy resolution required
  - High jet & b-jet multiplicity ⇒ categorisation improves S/B
  - Main systematics from modelling of **tt+HF** with simulation
- High-level analysis techniques (BDT, DNN, MEM) exploited

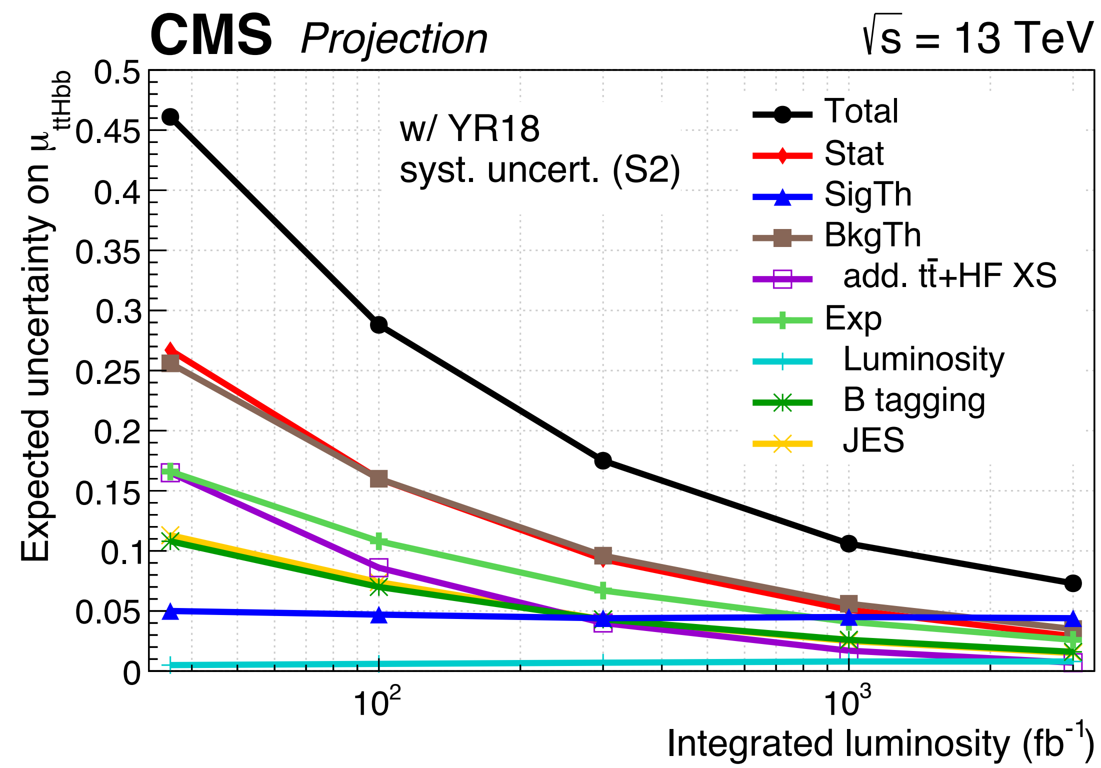
ATLAS impacts @ 3000 fb^{-1}



- tt+HF cross section uncertainties expected to reduce by factor 2-3

10-20% precision on σ(ttH→bb) achievable in each experiment





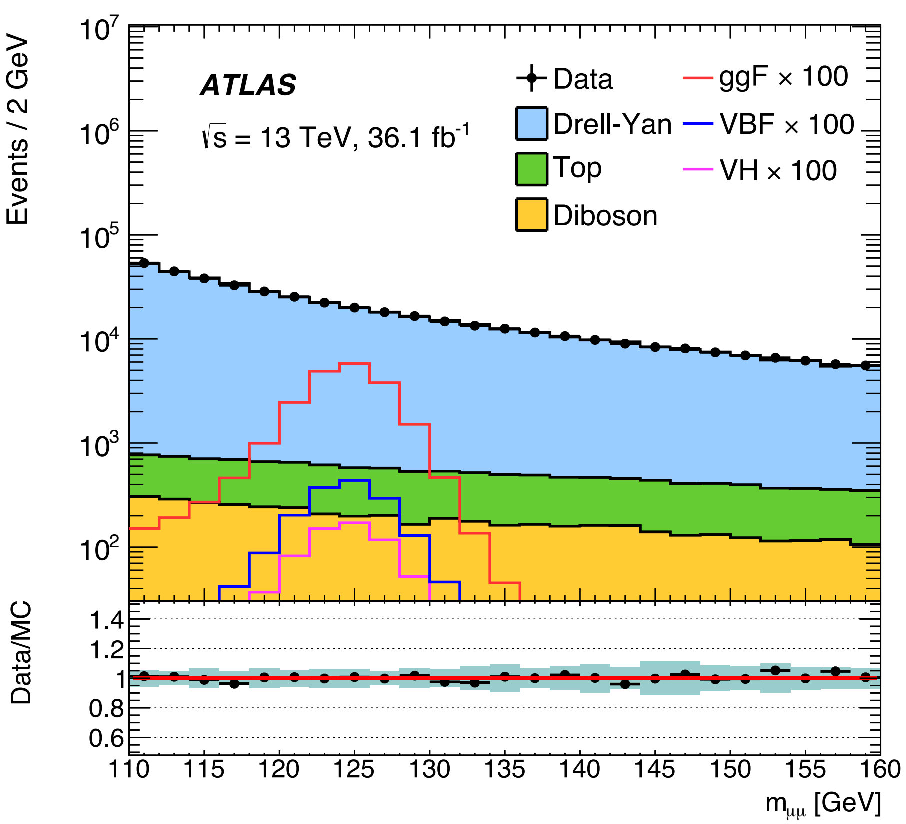
CMS uncertainty evolution

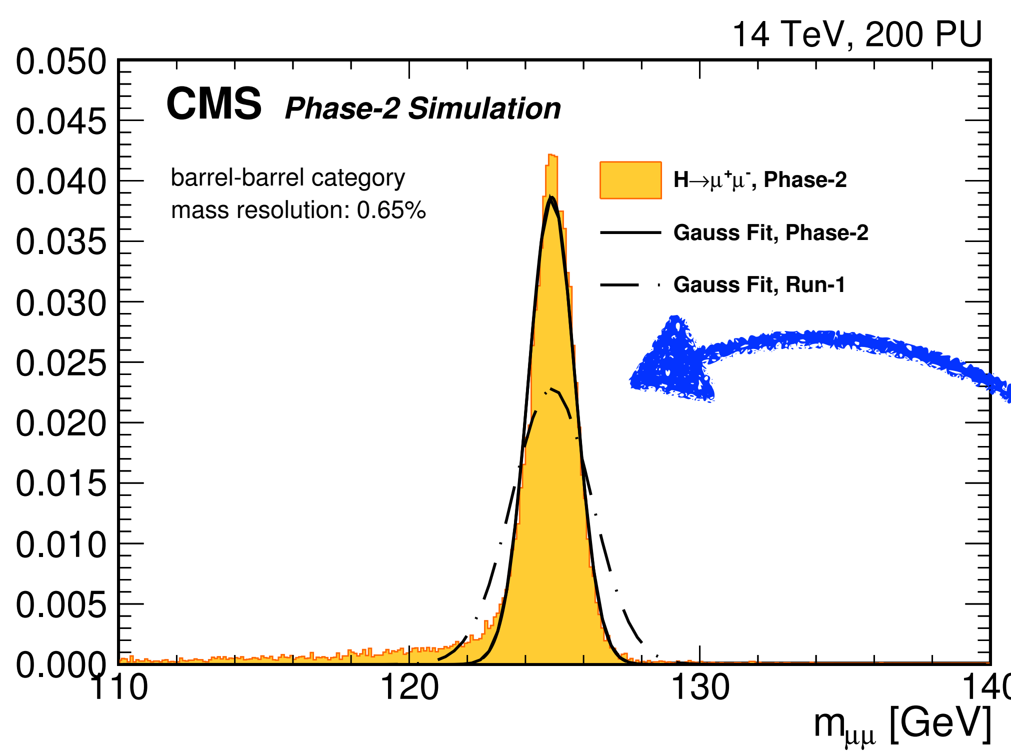
Example: H→μμ

- Search for narrow peak on smoothly falling Z/γ*→μμ background
- Measurement sensitive to di-muon mass resolution
- ATLAS upgraded Inner Tracker improves resolution by 15-30%
- CMS upgraded tracker expected to give 40% improvement

Experiment	ATLAS	
Process	Combination	
Scenario	S1	S2
Total uncertainty	$^{+15\%}_{-14\%}$	$^{+13\%}_{-13\%}$
Statistical uncert.	$^{+12\%}_{-13\%}$	$^{+12\%}_{-13\%}$
Experimental uncert.	$^{+3\%}_{-3\%}$	$^{+2\%}_{-2\%}$
Theory uncer.	$^{+8\%}_{-5\%}$	$^{+5\%}_{-4\%}$

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





Reduction from 1.1% to 0.65% for muons in the barrel region

Combination: production & decay rates

- ATLAS+CMS combination assumes experimental uncertainties uncorrelated, theory uncertainties 100% correlated

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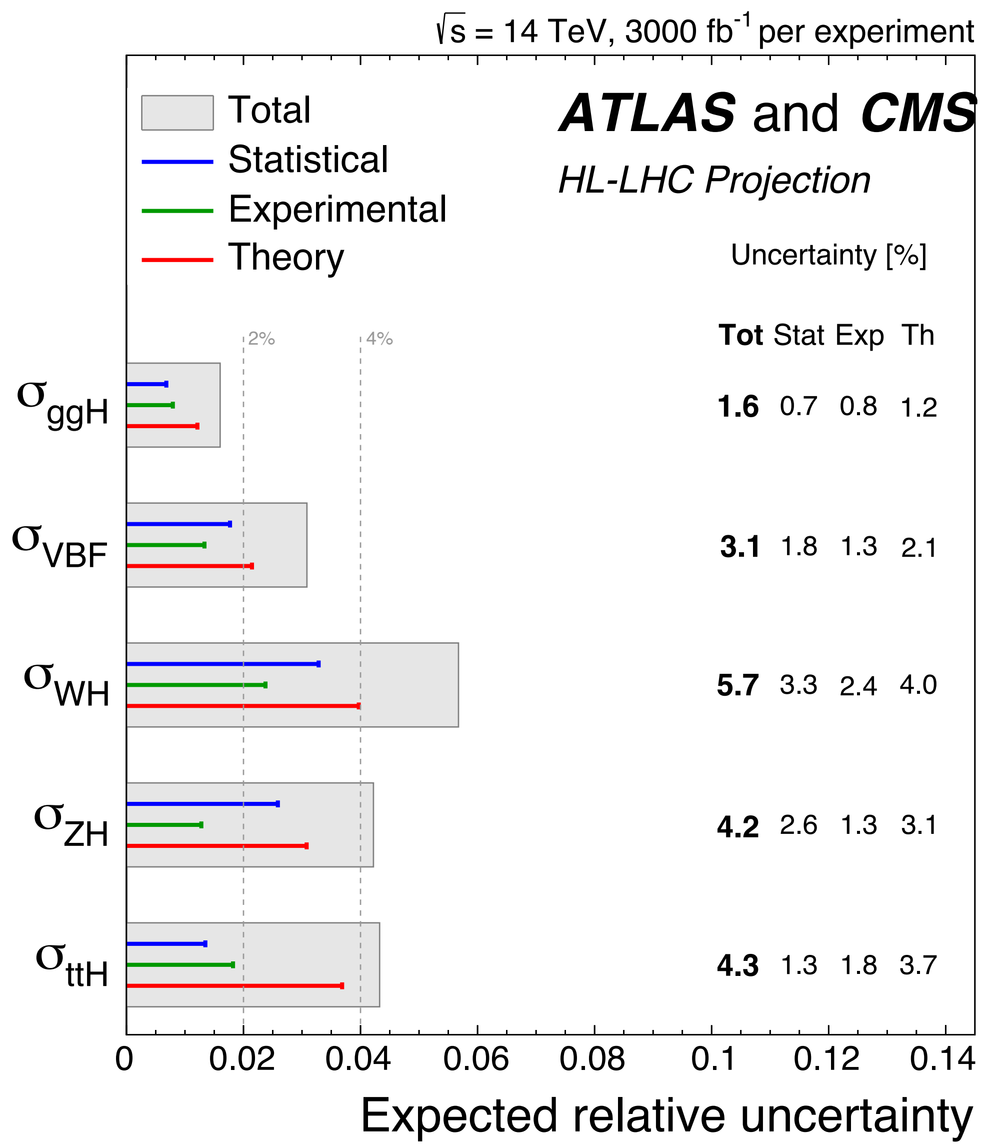
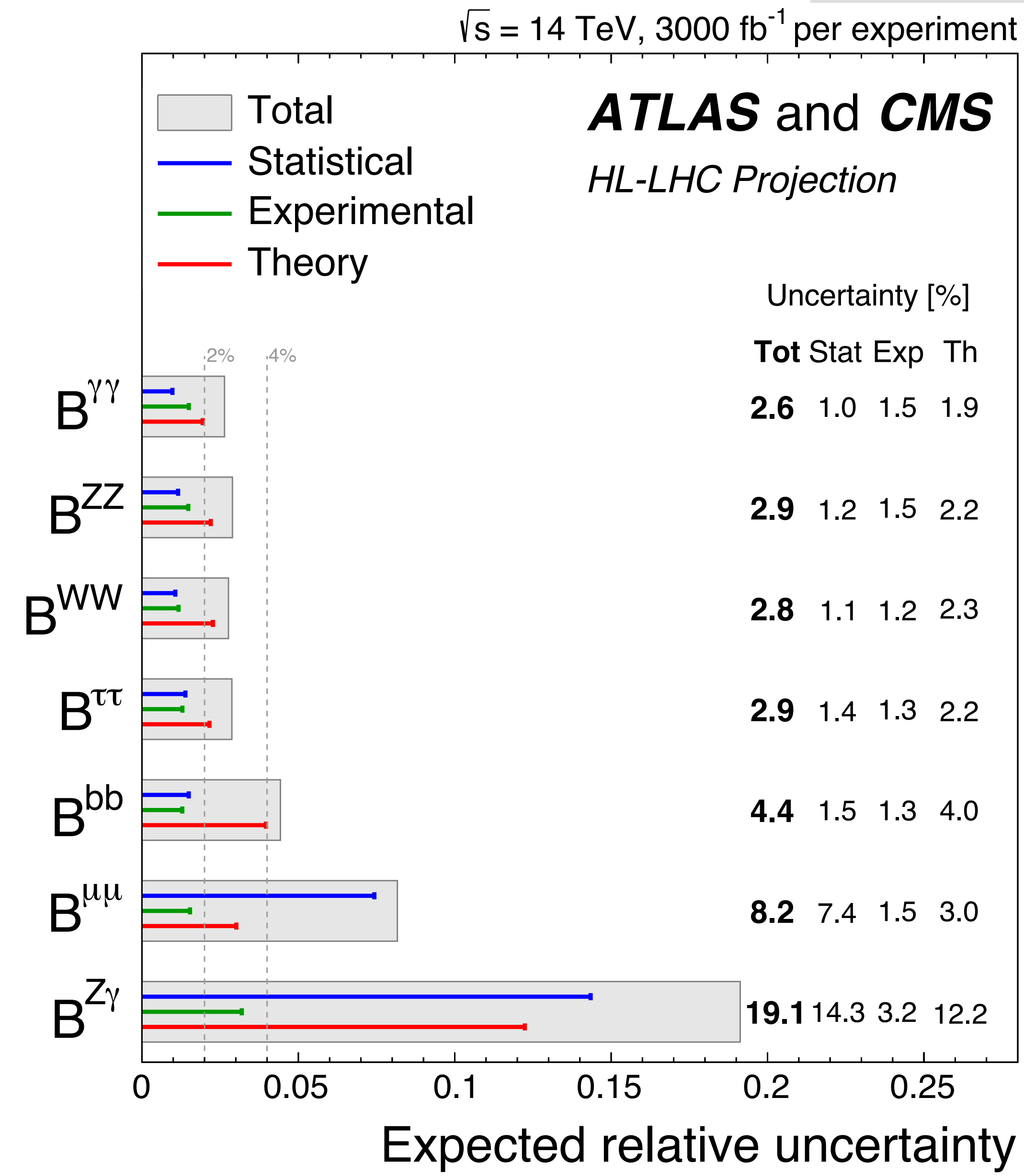




- NB: in these projections the inclusive SM theory uncertainties are not included
  - **"Theory"** = signal acceptance + all background theory

Higgs couplings

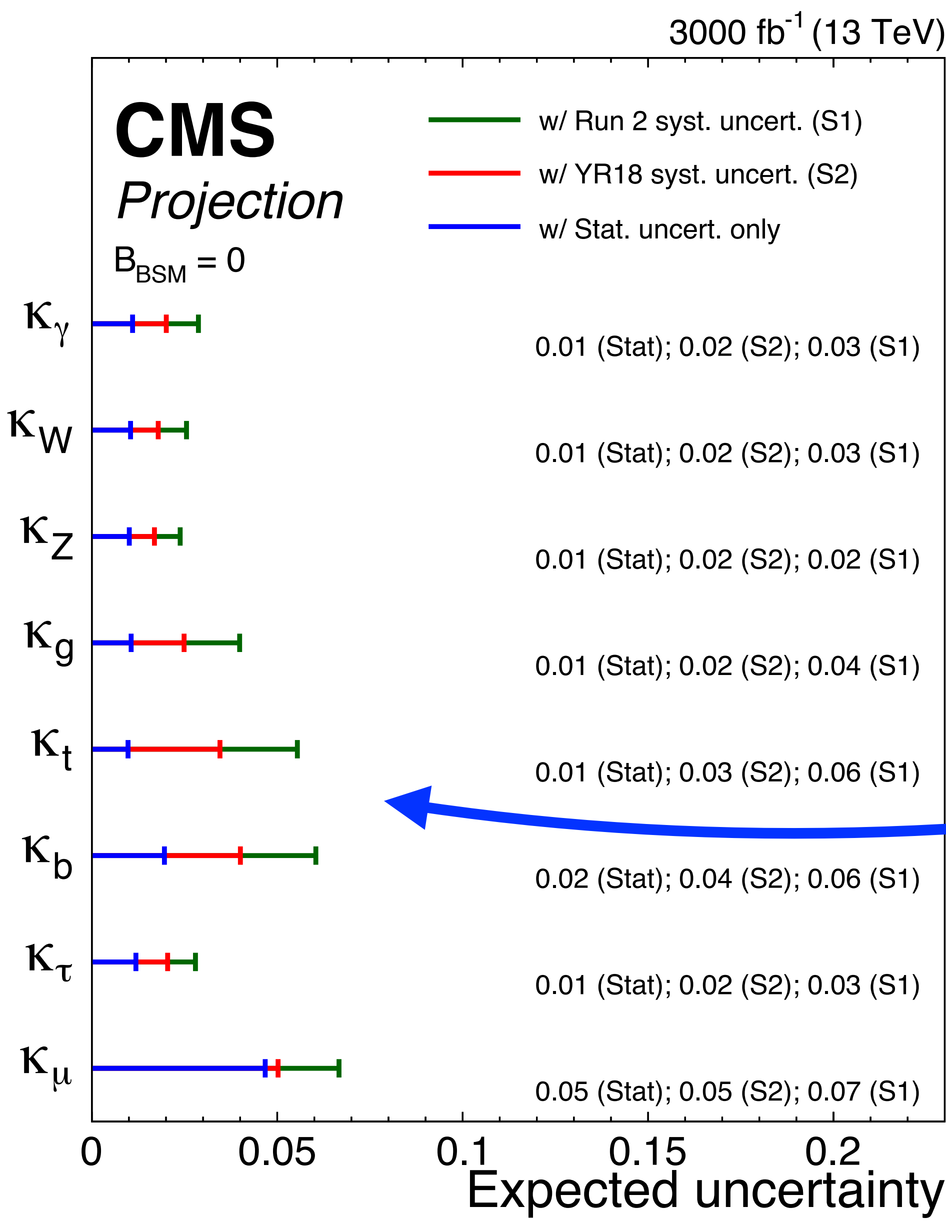
- Coupling modifier projections in the κ-framework
- ggH and H→γγ loops treated with effective modifiers κ_g and κ_γ

$$\kappa_j^2 = \sigma_j/\sigma_j^{\mathrm{SM}} \qquad \kappa_j^2 = \Gamma_j/\Gamma_j^{\mathrm{SM}}$$

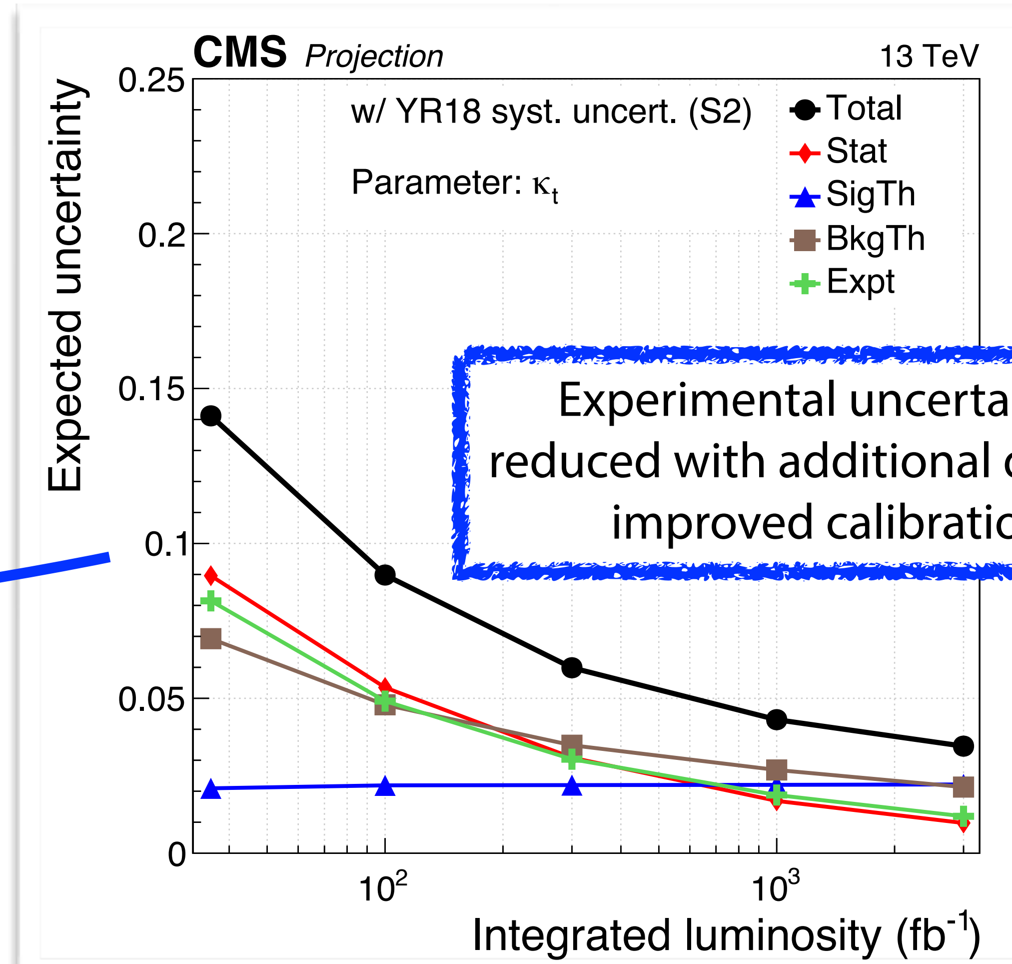
$$\Rightarrow \sigma_i \cdot \mathrm{BR}^f = \frac{\sigma_i(\vec{\kappa}) \cdot \Gamma^f(\vec{\kappa})}{\Gamma_{\mathrm{H}}}$$

where $\dfrac{\Gamma_{\mathrm{H}}}{\Gamma_{\mathrm{H}}^{\mathrm{SM}}} = \dfrac{\kappa_{\mathrm{H}}^2}{1 - (\mathrm{BR}_{\mathrm{undet.}} + \mathrm{BR}_{\mathrm{inv.}})}$

$\mathrm{BR}_{\mathrm{undet}} = \mathrm{BR}_{\mathrm{inv}} = 0$ here



CMS-PAS-FTR-18-011

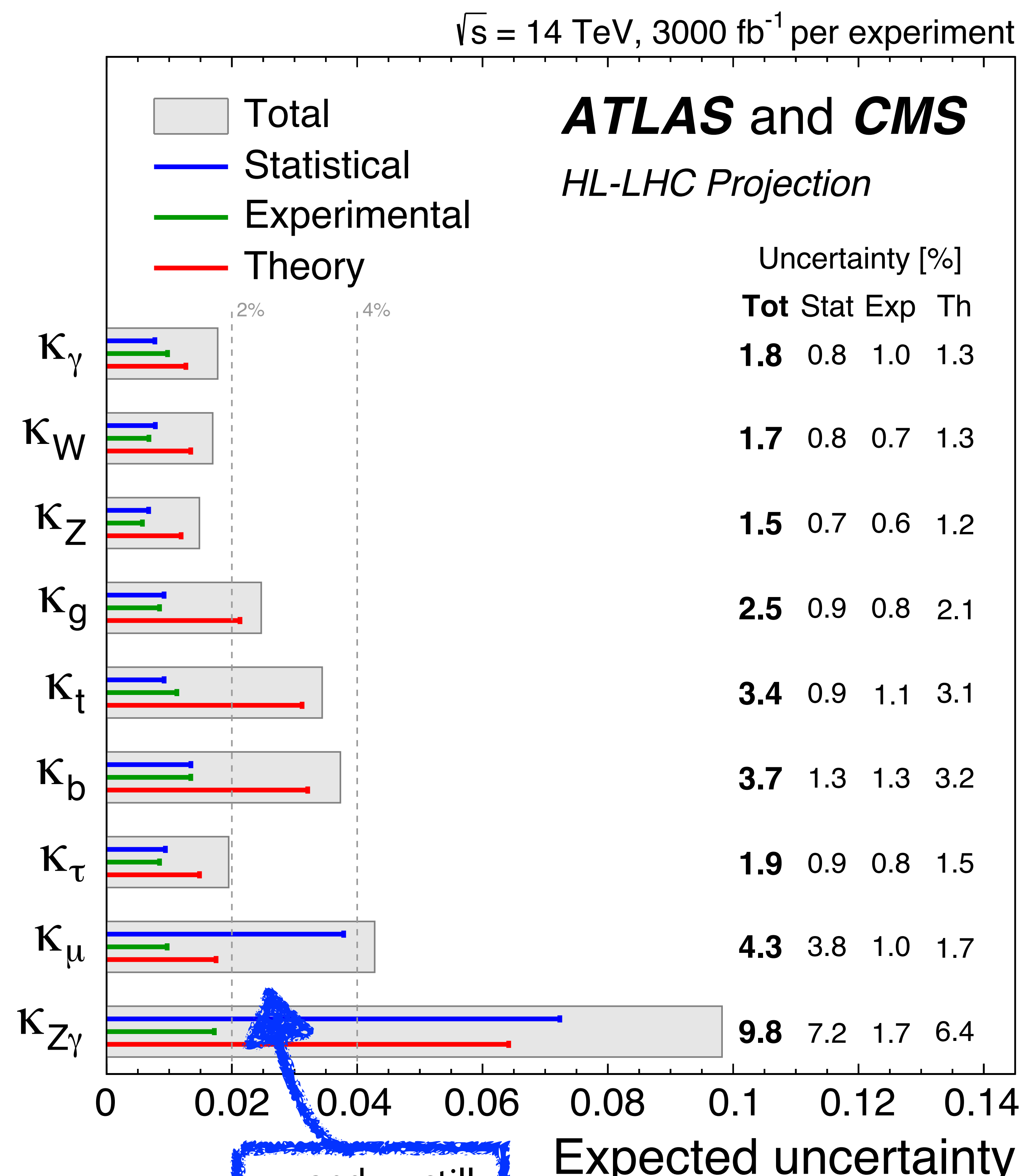


Experimental uncertainties reduced with additional data and improved calibrations

Evolution of uncertainties vs. L_{int}

Higgs couplings

- CMS + ATLAS combination: most couplings measured with 2-4% precision for scenario 2
- NB: unlike σ and BR projections the inclusive signal uncertainties are included here and tend to dominate
- Impact of some uncertainties can be reduced by measuring ratios of couplings: $\lambda_{xy} = \kappa_x/\kappa_y$ where uncertainties cancel (see backup)



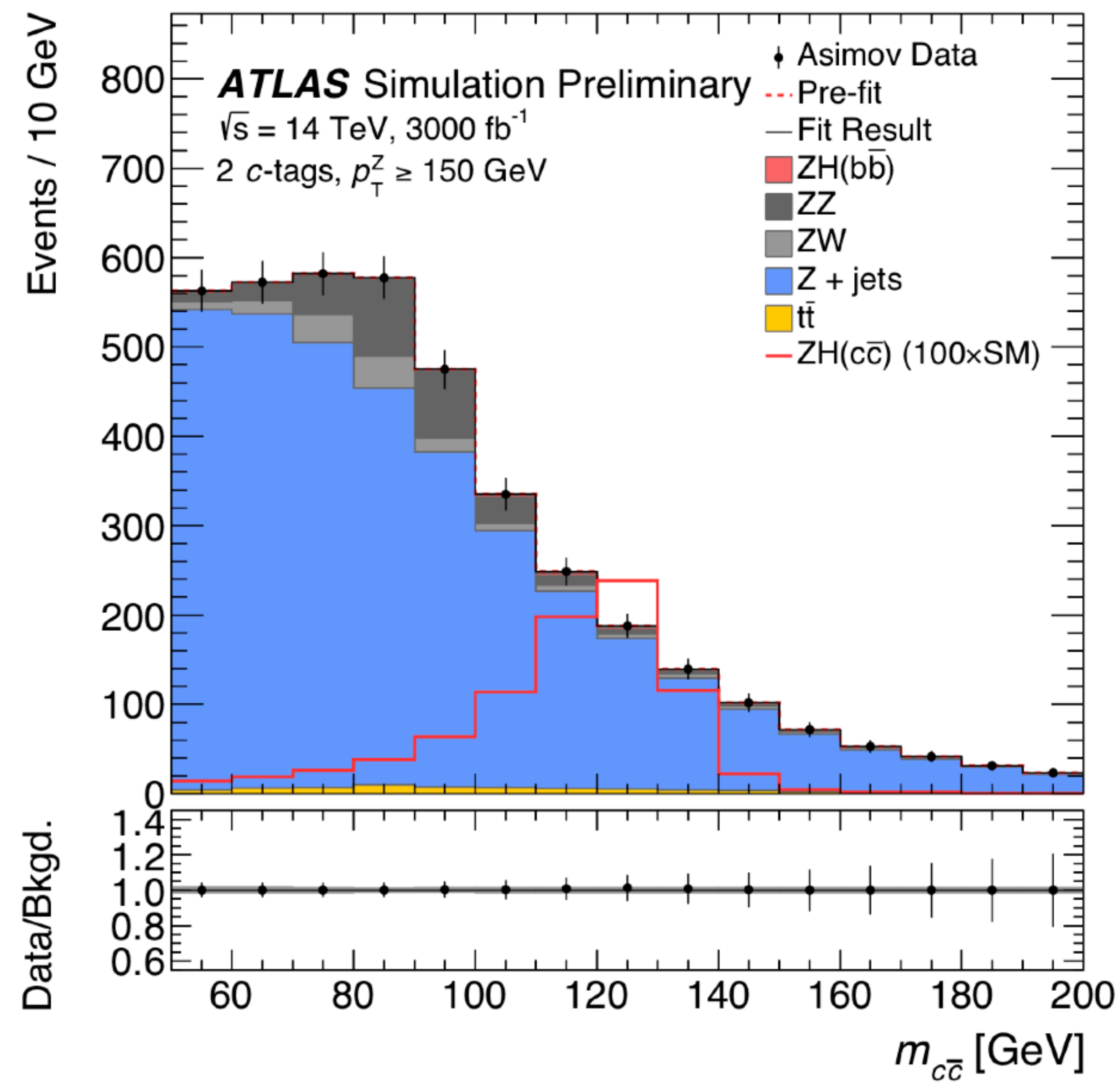
κ_μ and $\kappa_{Z\gamma}$ still statistically limited

Charm Yukawa coupling

- BR(H→cc) ~ 2.9%, but suffers from large background
- Direct searches from ATLAS & CMS:
  - ATLAS: $\mu_{ZH(cc)}$ < 110 x SM @ 95% CL
  - CMS: $\mu_{VH(cc)}$ < 70 x SM @ 95% CL
- Projection of ATLAS result to 3000 fb^{-1} gives expected limit: $\mu_{ZH(cc)}$ < 6.3 x SM @ 95% (stat. only)
  - Systematics expected to increase limit by 36%
- Will benefit from future improvement in c-tagging techniques
- VH(bb/cc) also studied in LHCb, projection [*] gives μ_{cc} limit of ~ 50 x SM, but with detector upgrades can reach 5-10 x SM level

arXiv:1802.04329, ATL-PHYS-PUB-2018-016

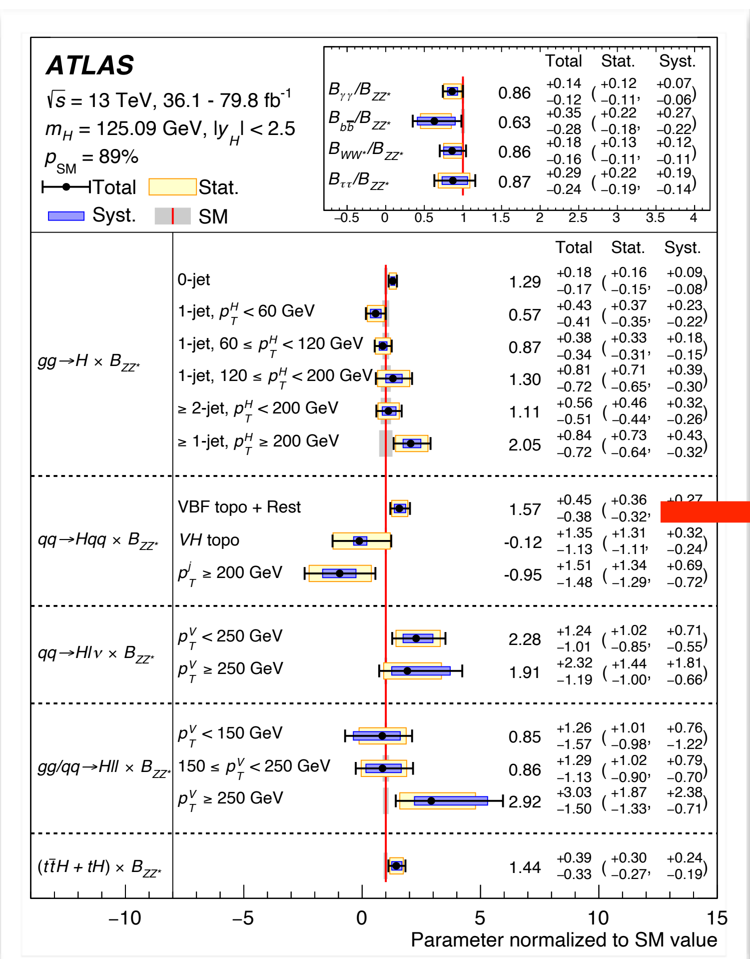
CMS-PAS-HIG-18-031



[*] LHCb-CONF-2016-006

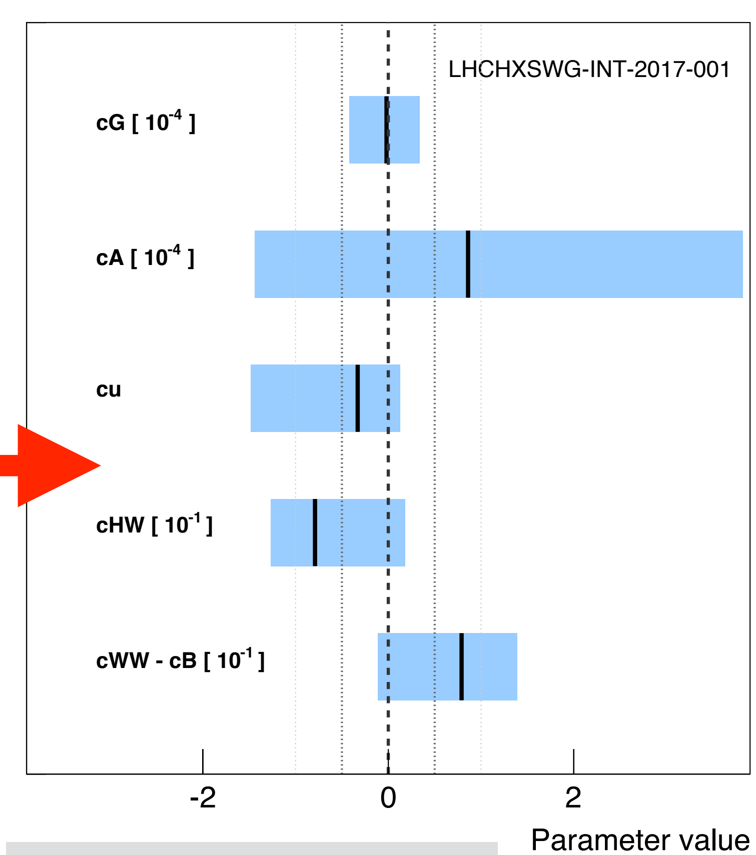
A note of caution

- These projections are predictions of future improvement to measurements we have **already made**, but **new measurements** will go beyond this
- ⇒ Current projections are not the final word on HL-LHC physics reach
- For example, in going from inclusive σ x BR measurement to simplified template cross sections can use distributions to constrain EFT coefficients



Cross-section region	$\sum_i A_i c_i$
$gg \to H$ (0-jet)	
$gg \to H$ (1-jet, $p_T^H < 60$ GeV)	$56c'_g$
$gg \to H$ (1-jet, $60 \leq p_T^H < 120$ GeV)	
$gg \to H$ (1-jet, $120 \leq p_T^H < 200$ GeV)	$56c'_g + 18c3G + 11c2G$
$gg \to H$ (1-jet, $p_T^H \geq 200$ GeV)	$56c'_g + 52c3G + 34c2G$
$gg \to H$ ($\geq$ 2-jet, $p_T^H < 60$ GeV)	$56c'_g$
$gg \to H$ ($\geq$ 2-jet, $60 \leq p_T^H < 120$ GeV)	$56c'_g + 8c3G + 7c2G$
$gg \to H$ ($\geq$ 2-jet, $120 \leq p_T^H < 200$ GeV)	$56c'_g + 23c3G + 18c2G$
$gg \to H$ ($\geq$ 2-jet, $p_T^H \geq 200$ GeV)	$56c'_g + 90c3G + 68c2G$
$gg \to H$ ($\geq$ 2-jet VBF-like, $p_T^{j3} < 25$ GeV)	$56c'_g$
$gg \to H$ ($\geq$ 2-jet VBF-like, $p_T^{j3} \geq 25$ GeV)	$56c'_g + 9c3G + 8c2G$

Fit to ATLAS STXS measurements (ATLAS-CONF-2017-047)

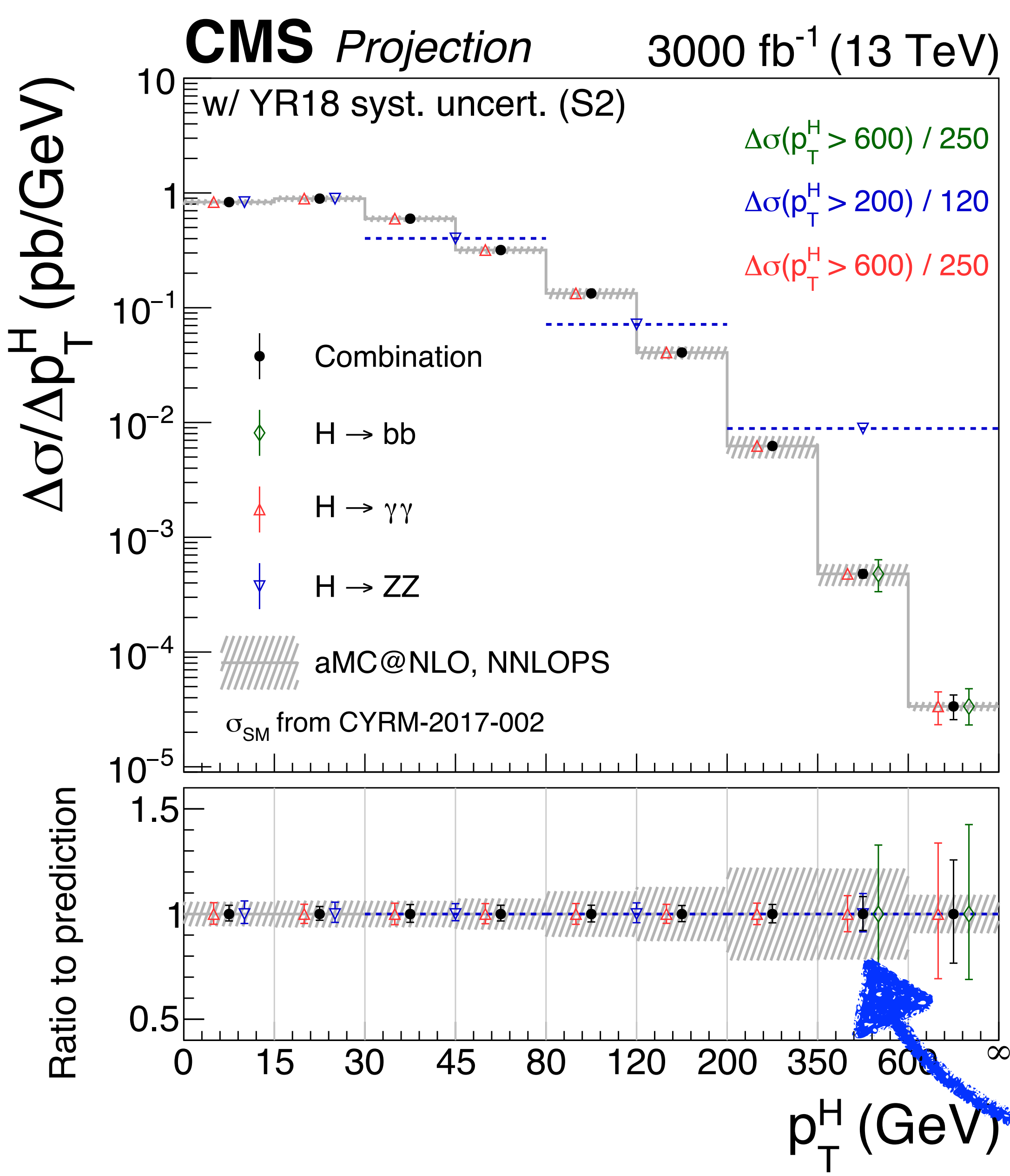


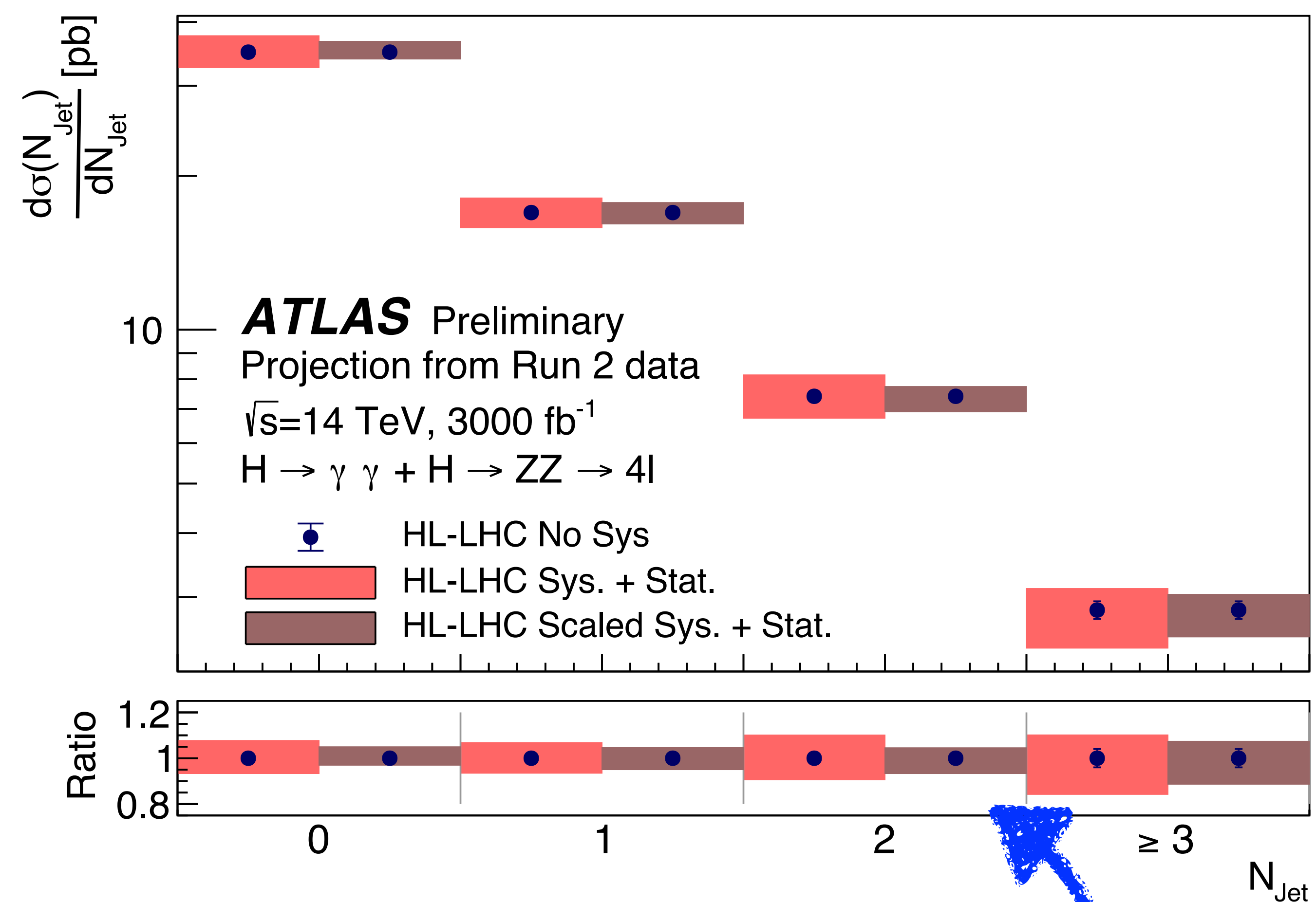
Hays, Sanz, Zemaityte

arXiv:1909.02845

Differential cross sections

- Projection of H→γγ + H→ZZ→4l differential cross section for $p_T(H)$



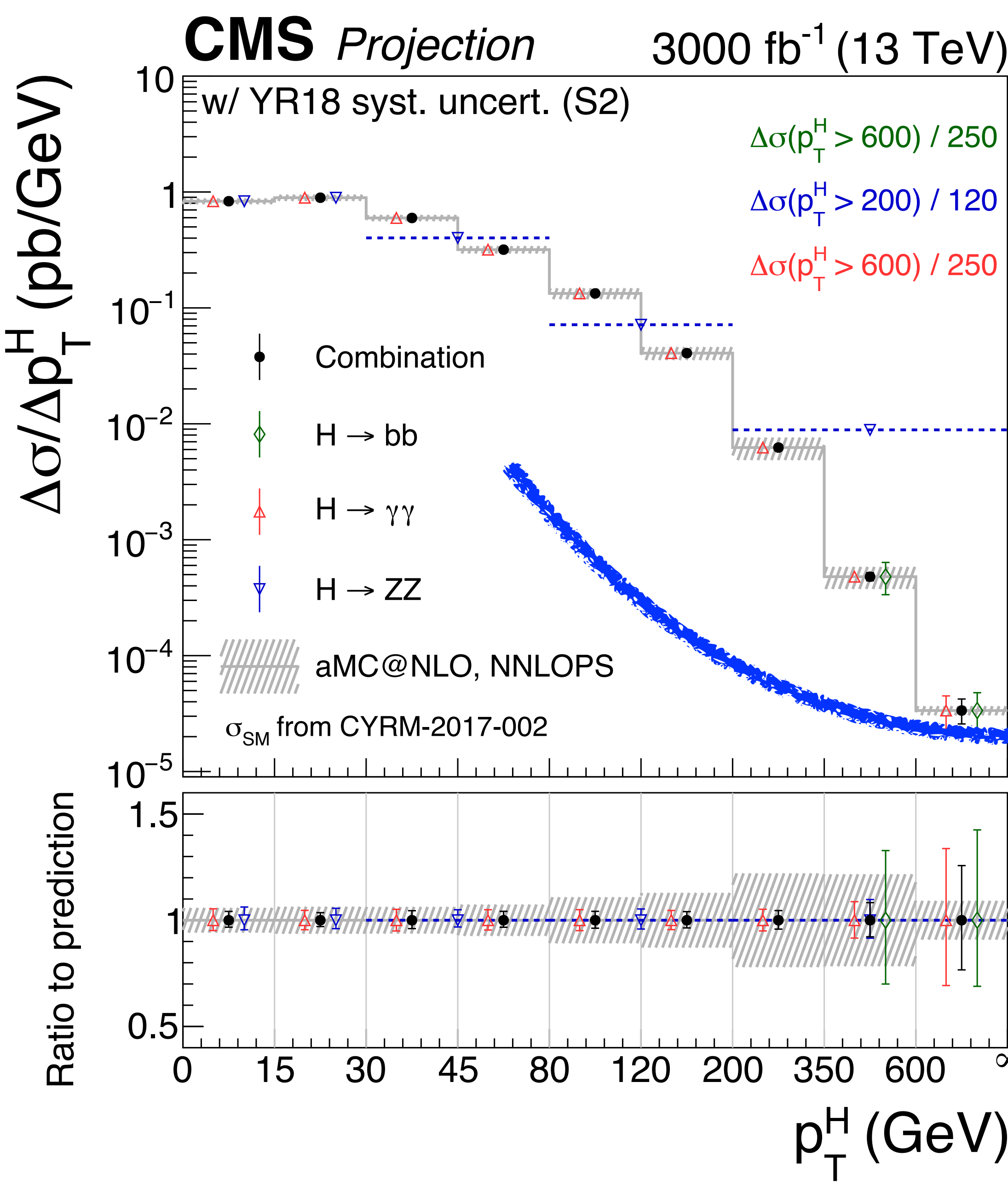


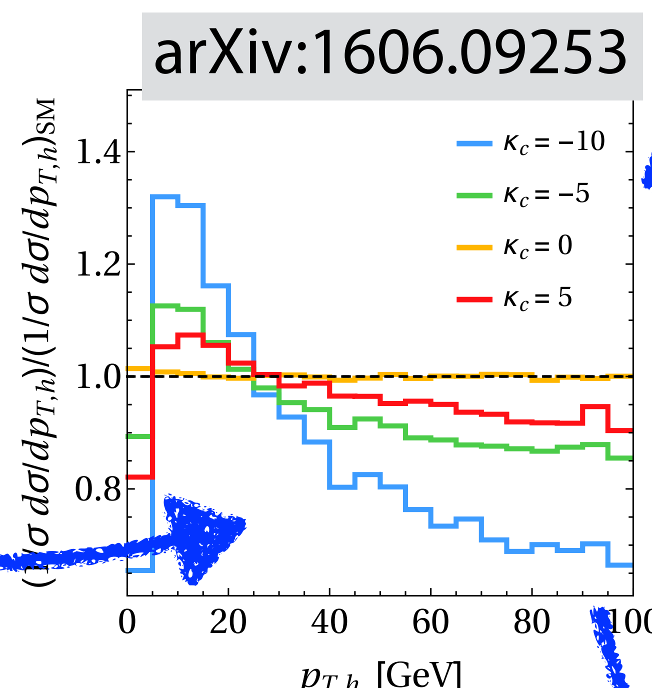
Expected precision of ~10% for $p_T(H)$ > 350 GeV, statistically limited

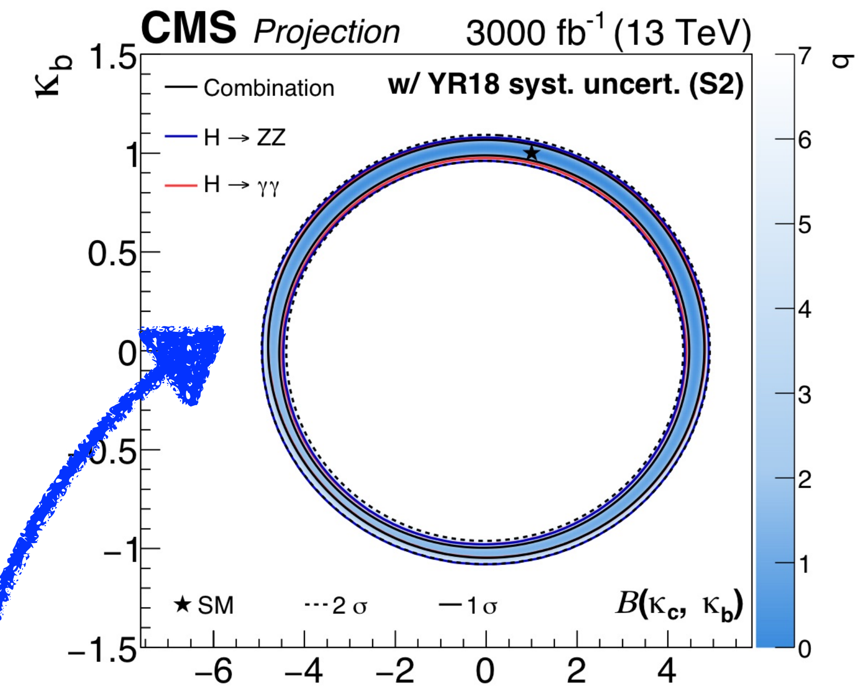
Njet precision of 5-10%, systematically limited

Differential cross sections

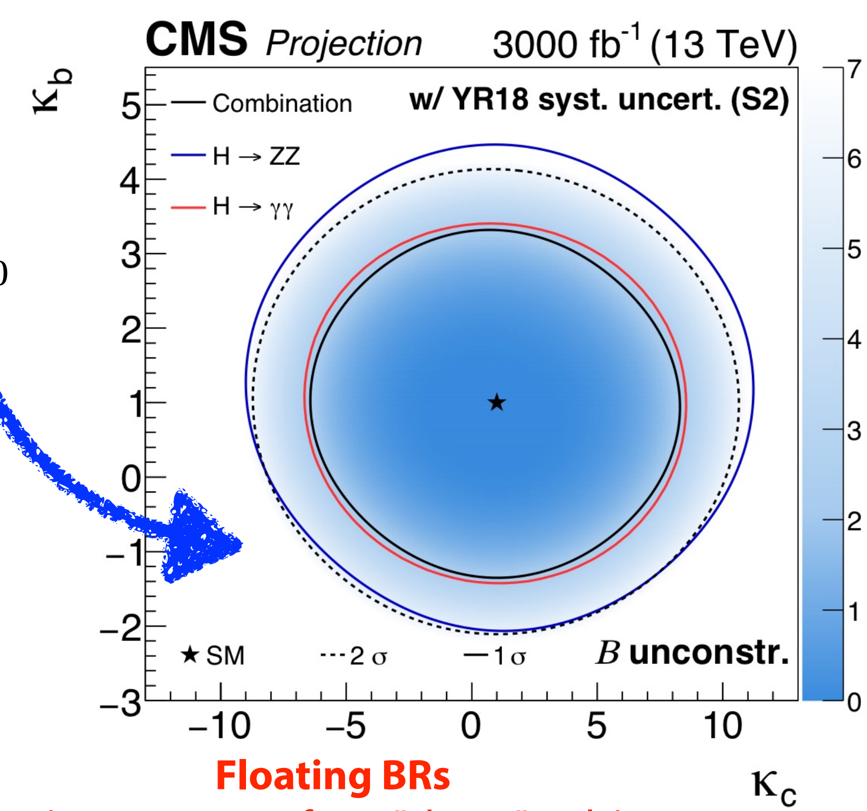
- Parameterise differential cross section in terms of coupling modifiers - low $p_T(H)$ region gives access to $\boldsymbol{\kappa_c}$







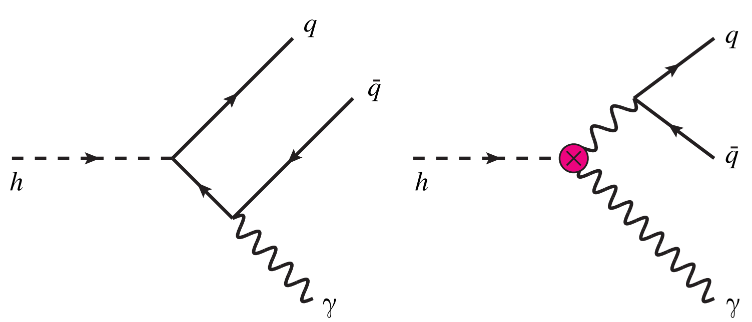
Coupling-dependent BRs
(assumes no B_{inv}, resolved loops)



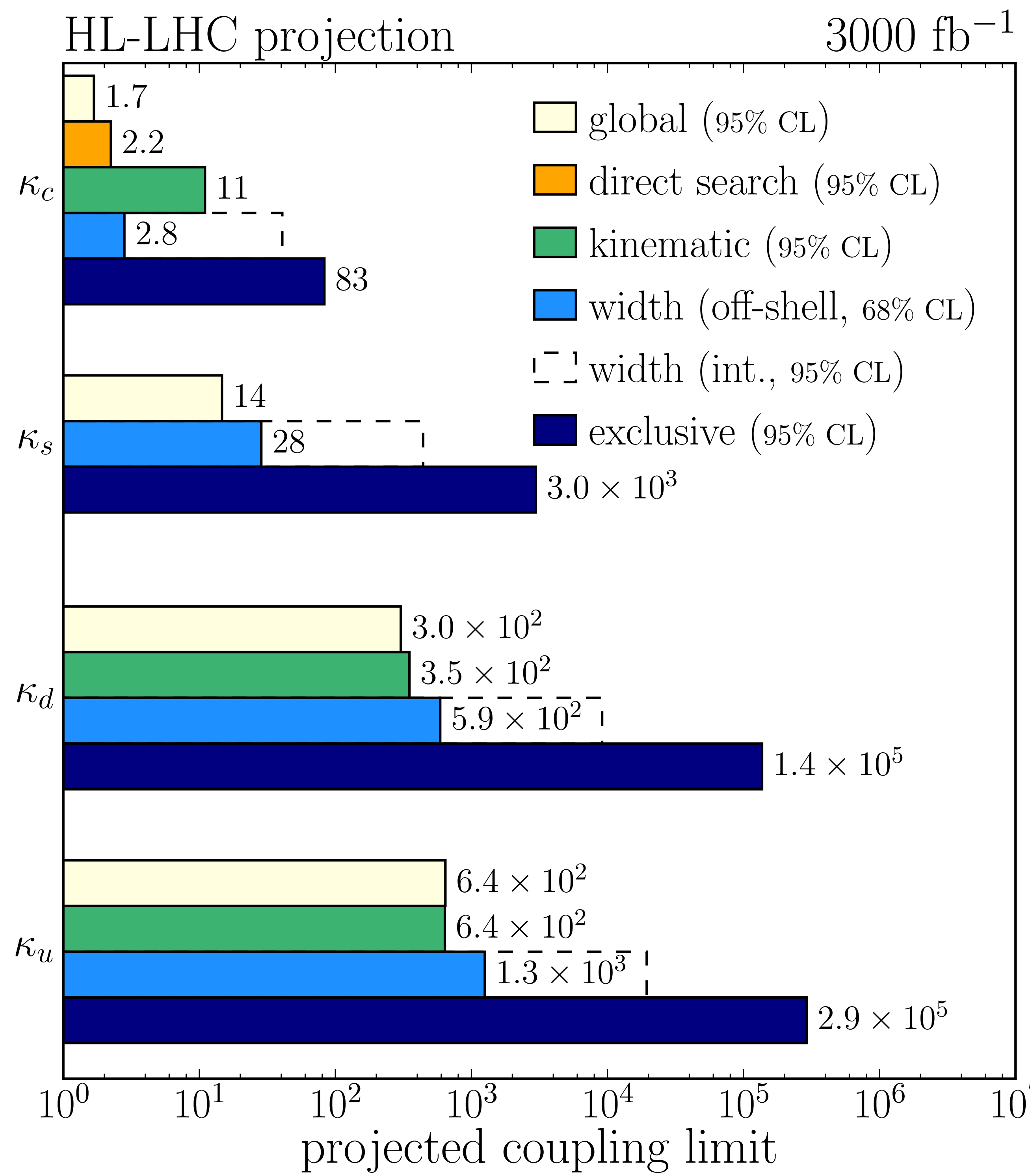
Floating BRs
(i.e. constraint from "shape" only)

Prospects for light quark couplings

- **Exclusive decays** to γ+meson include contributions from light quark Yukawa couplings

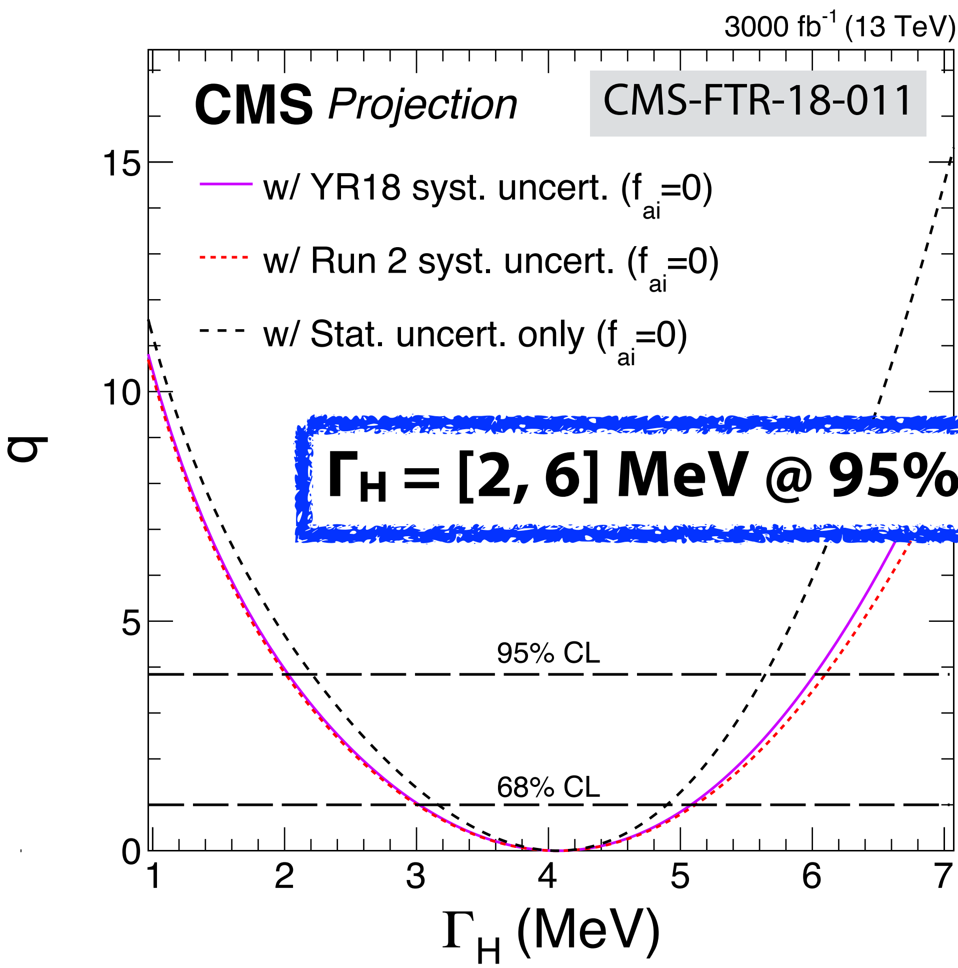


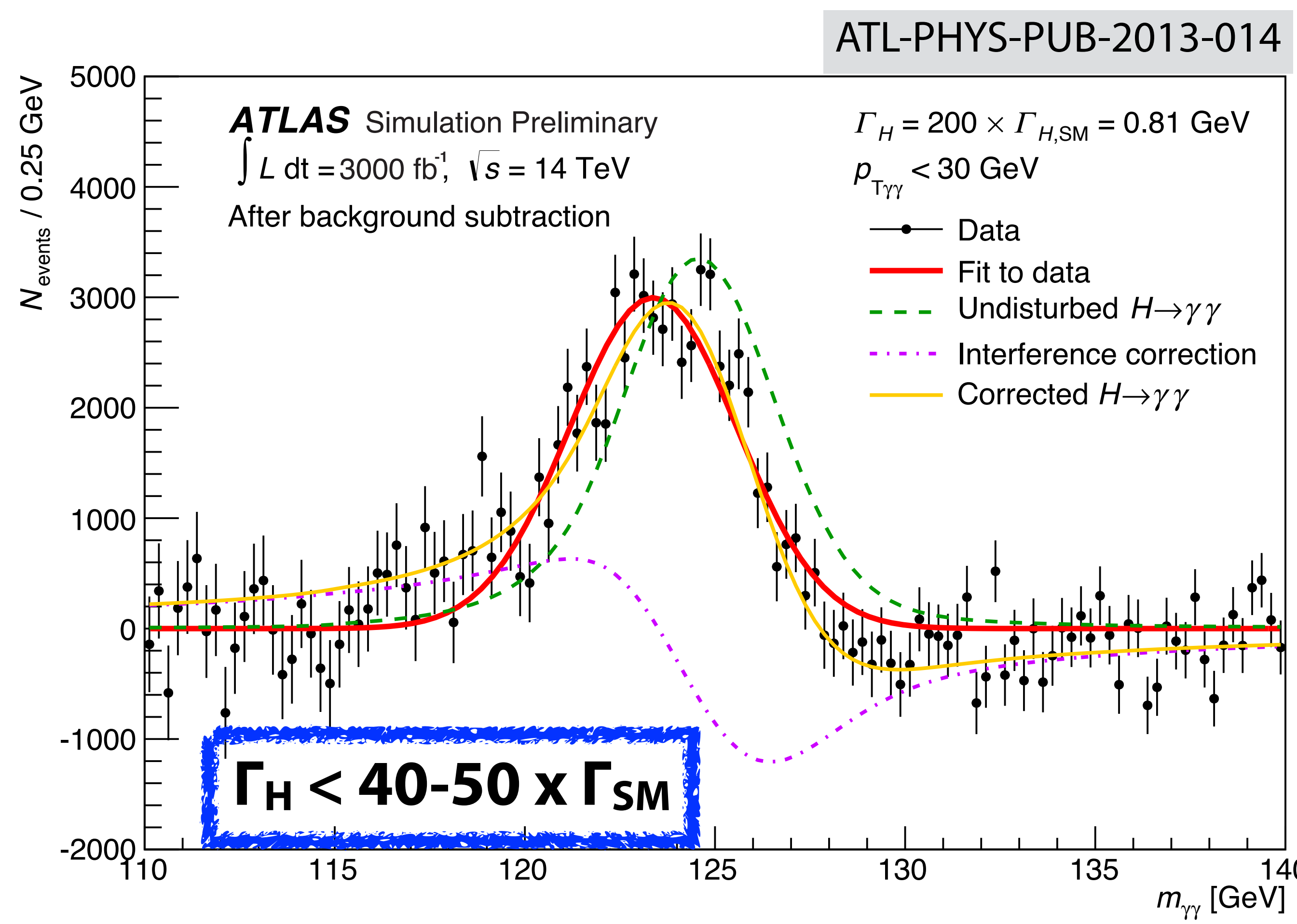
- Interpretation of **Higgs width constraint** (from direct measurement or via off-shell)
- Interpretation of **kinematic distributions**
- **Direct search** for H→cc
- **Global fit** of all Higgs couplings (assuming no other BSM decays)



Higgs width & mass

- Indirect constraint from H→ZZ off-shell & direct constraint using gg→γγ interference

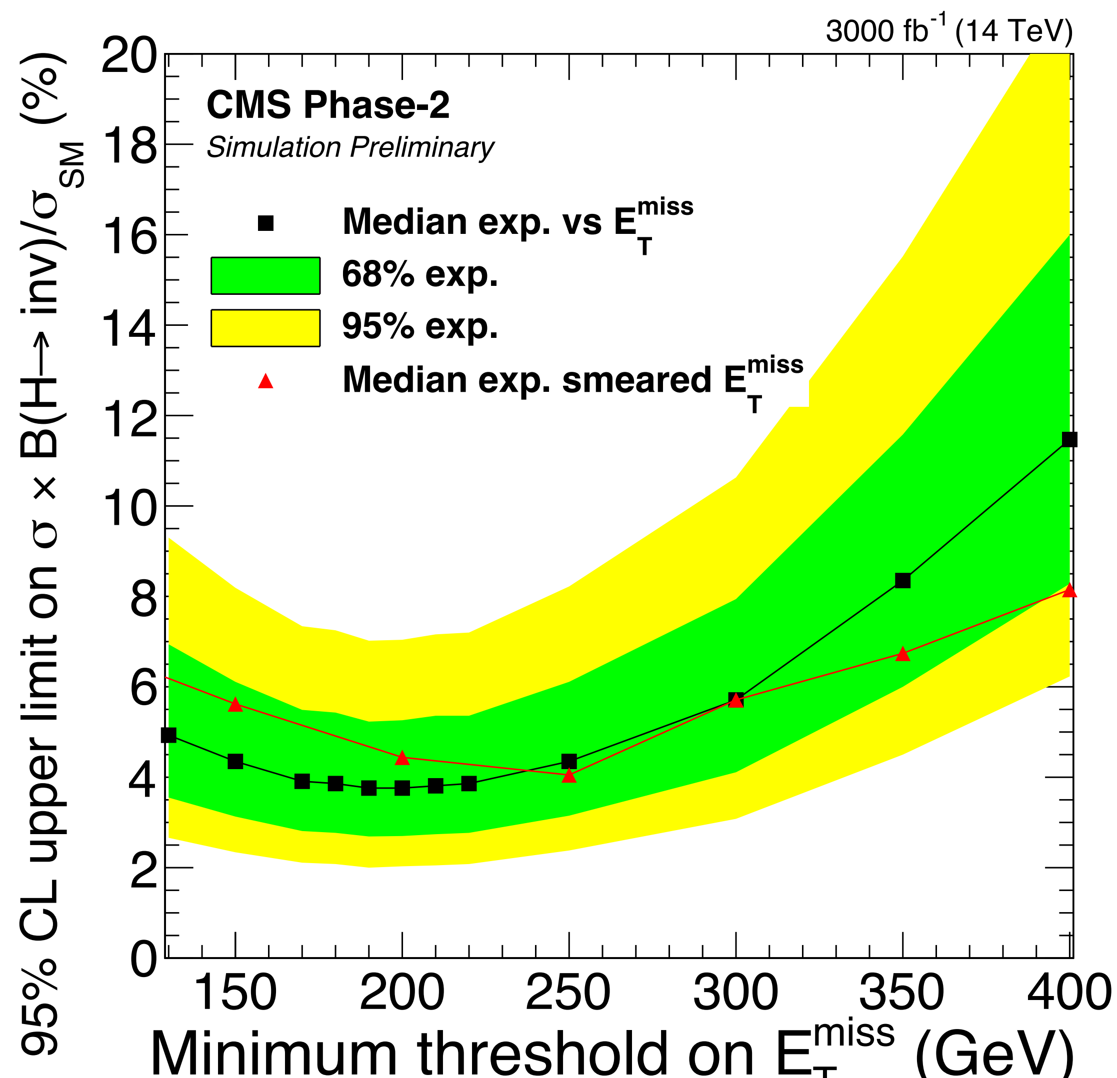




- **Higgs mass:** ultimate precision will depend strongly on the calibration of muons, electrons & photons, but 10-20 MeV considered possible
  - cf. CMS+ATLAS Run 1: $m_H = 125.09 \pm 0.21(\text{stat.}) \pm 0.11(\text{syst.})$ GeV

Invisible decays

- Current 95% observed (expected) upper limits on B_{inv}: PRL 122 (2019) 231801 EPJC 79 (2019) 421
  - 26% (17%) - ATLAS combination of direct H→inv channels in Run 1 + Run 2
  - 22% (17%) - CMS combination of direct H→inv channels + all visible channels in Run 2
- In both experiments sensitivity dominated by the VBF channel



CMS-FTR-18-016

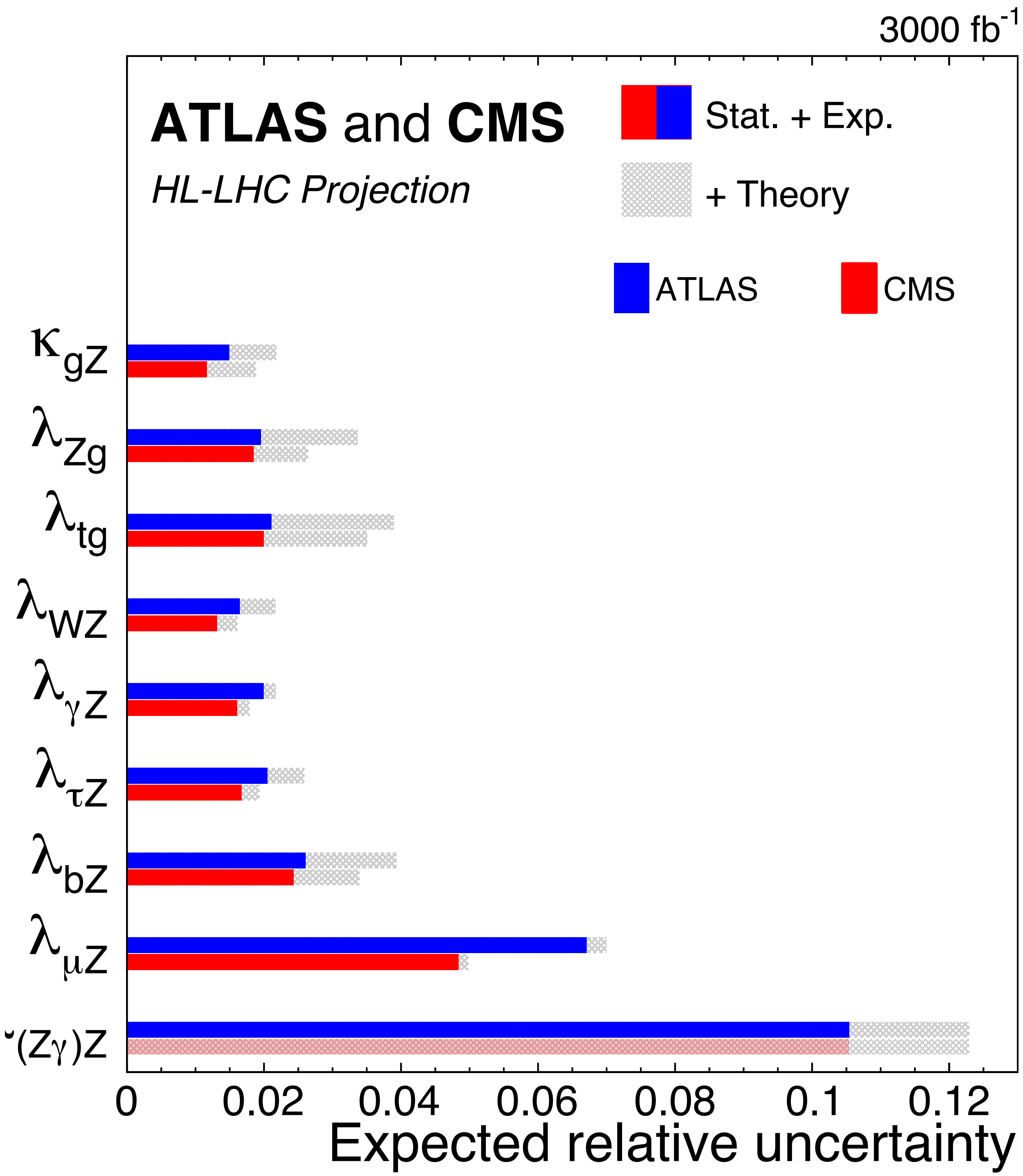
- Delphes-based study of CMS sensitivity in HL-LHC
- Optimal selections: m_{jj} > 2500 GeV, E_T^{miss} > 190 GeV ⇒ **B_{inv} < 3.8% @ 95% CL**
- Theoretical uncertainty on W/Z ratio important now (~12.5%), but less so with larger control regions in ≥ 300 fb^{-1}
- Sensitivity not impacted too much if E_T^{miss} resolution degrades in high pileup

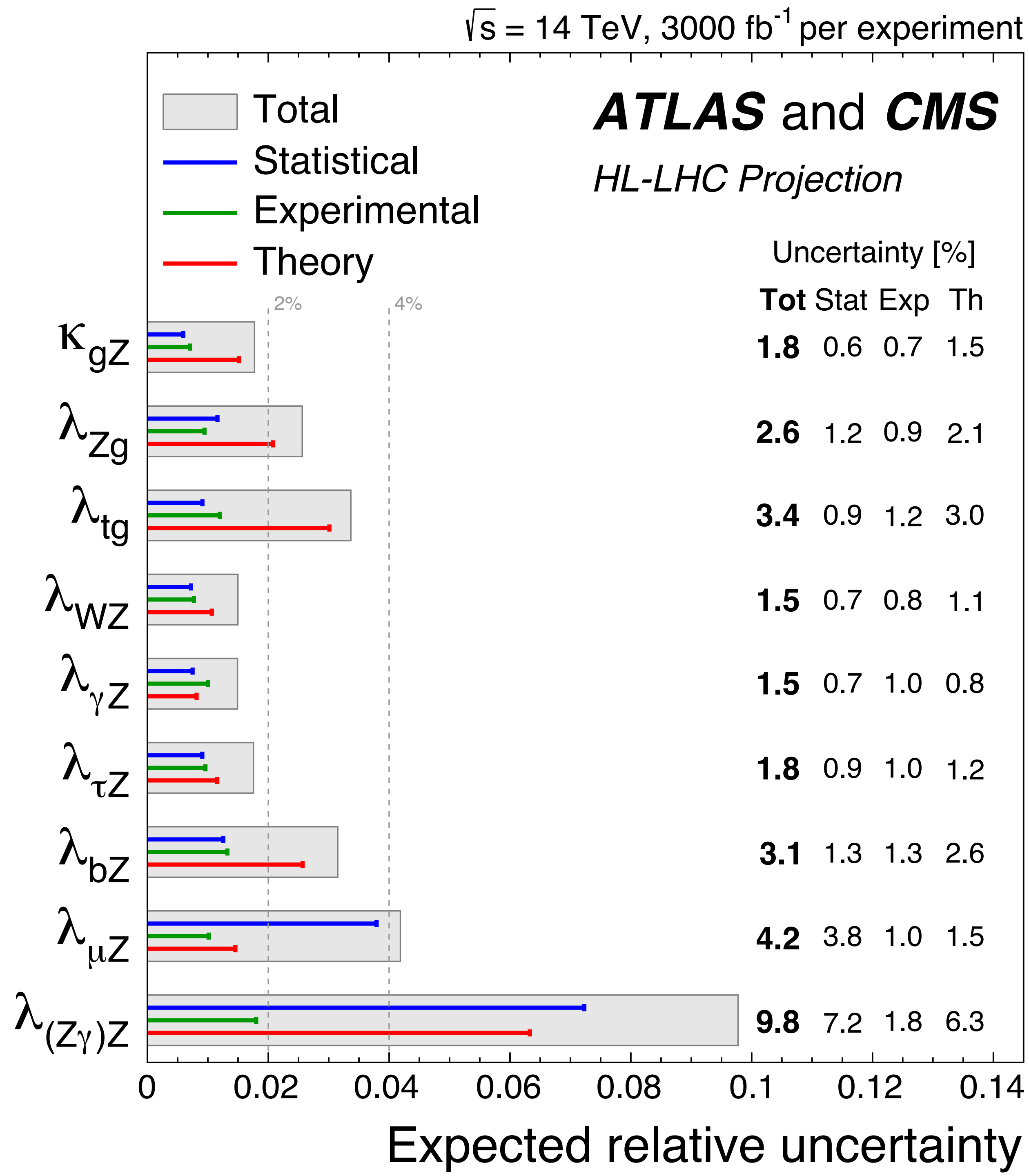
Summary

- HL-LHC will dramatically expand the physics reach for Higgs physics:
  - 2-4% precision on Higgs couplings
  - Access to 2nd generation Yukawa couplings, with direct & indirect approaches for probing the charm Yukawa
  - Limit on B_{inv} < 2.5% @ 95% CL, combining CMS+ATLAS
- Many inclusive measurements will be systematically limited ⇒ important work ahead on both theory and experimental sides
- Prospects for HE-LHC Higgs couplings not directly studied by the experiments, but see studies by the Higgs@Future colliders group

Backup

Projections of coupling ratios





Correlations