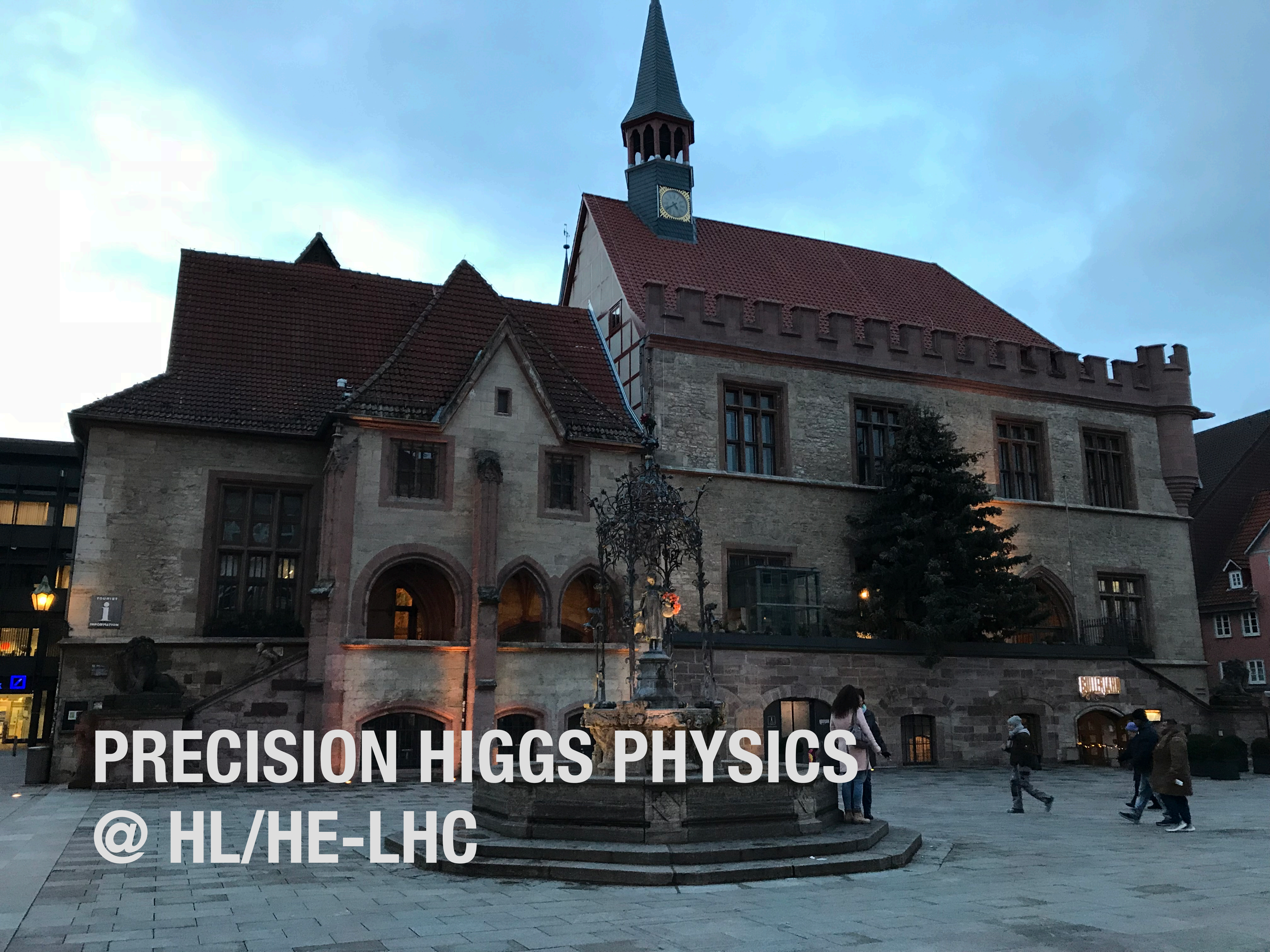
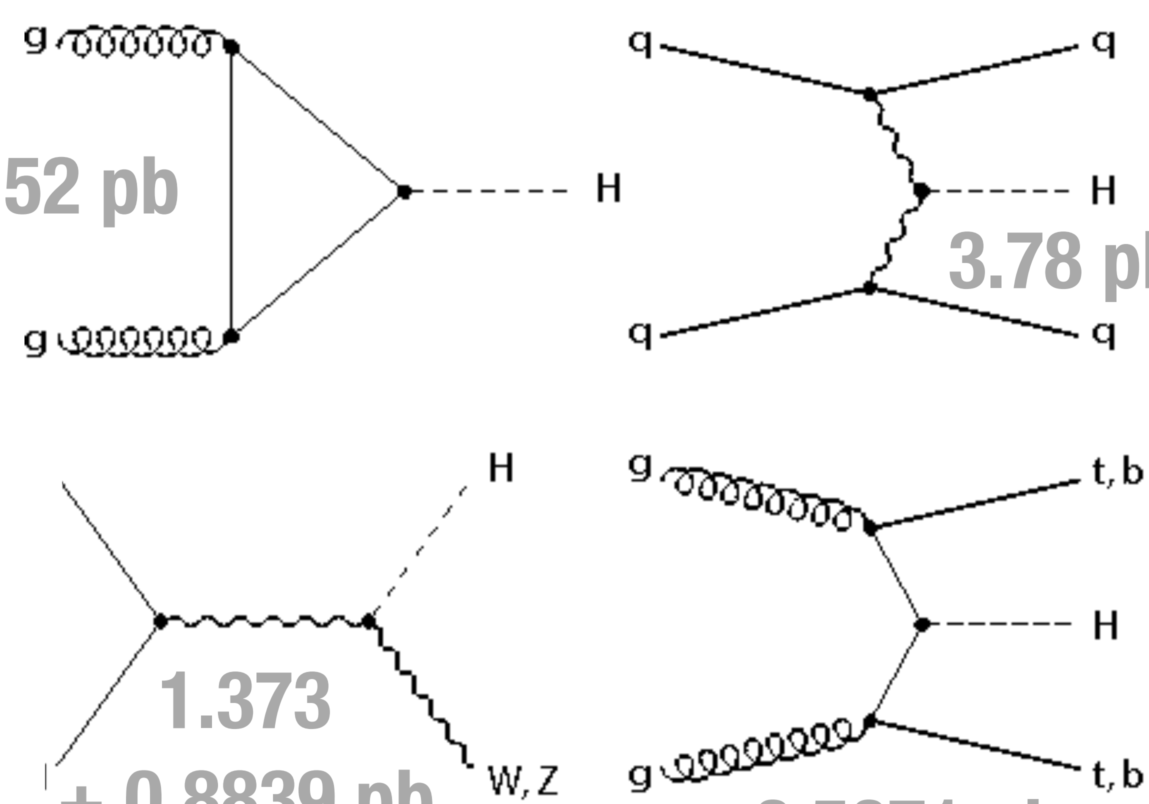

PRECISION HIGGS PHYSICS
@ HL/HE-LHC

Higgs Physics at the LHC

- We have come a long way since the Higgs discovery in 2012
- The available LHC Run1 (7,8 TeV~25fb^{-1}) & Run2 (13 TeV ~150fb^{-1}) datasets have pushed Higgs physics from search mode to measurement mode, probing the nature of the boson and its agreement with the SM
- All the main production and decay modes under scrutiny by ATLAS and CMS

proton-proton → 



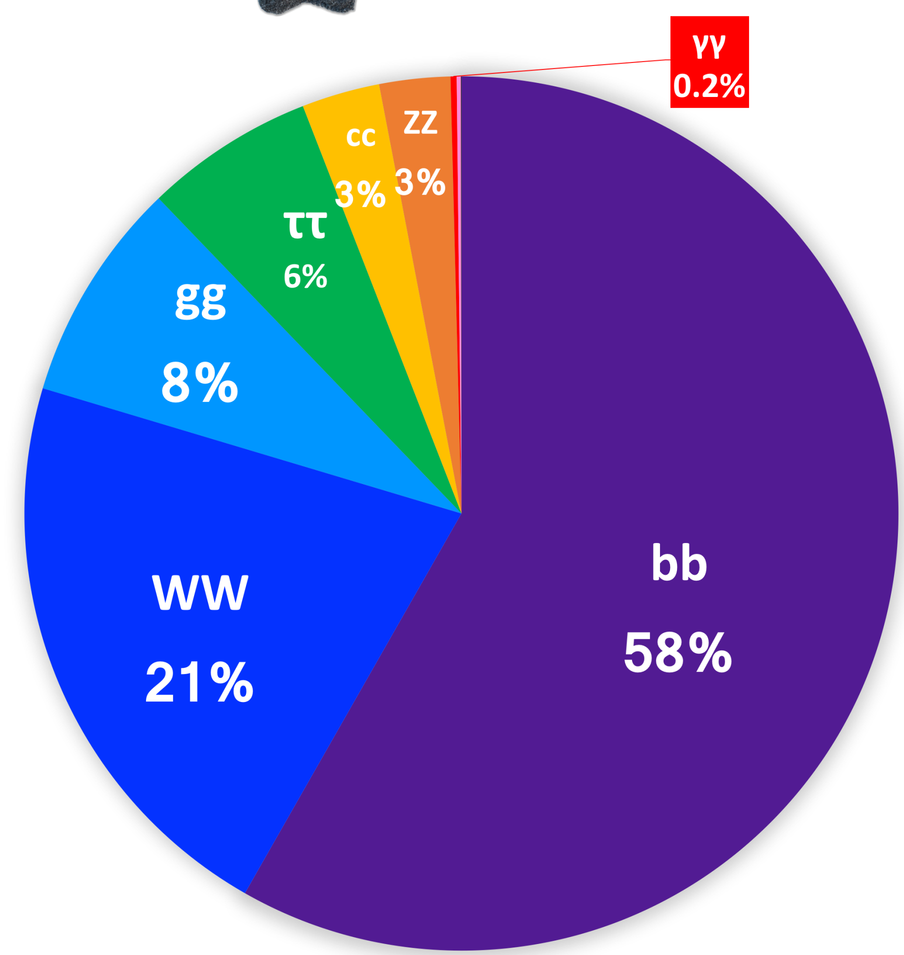
48.52 pb

3.78 pb

1.373 + 0.8839 pb

0.5071 pb

 **→ SM**



What to ask the boson?

- Is its production rate, where we measure it, at the correct SM level?
- How do we caracterize it? (mass, width, spin)
- How well can we model its behaviour?
- Does it couple to SM particles at the appropriate level?
- Does it couple to itself?
- Does it decay unusually?
- Are there more Higgses?
- Higgs as a tool for discovery

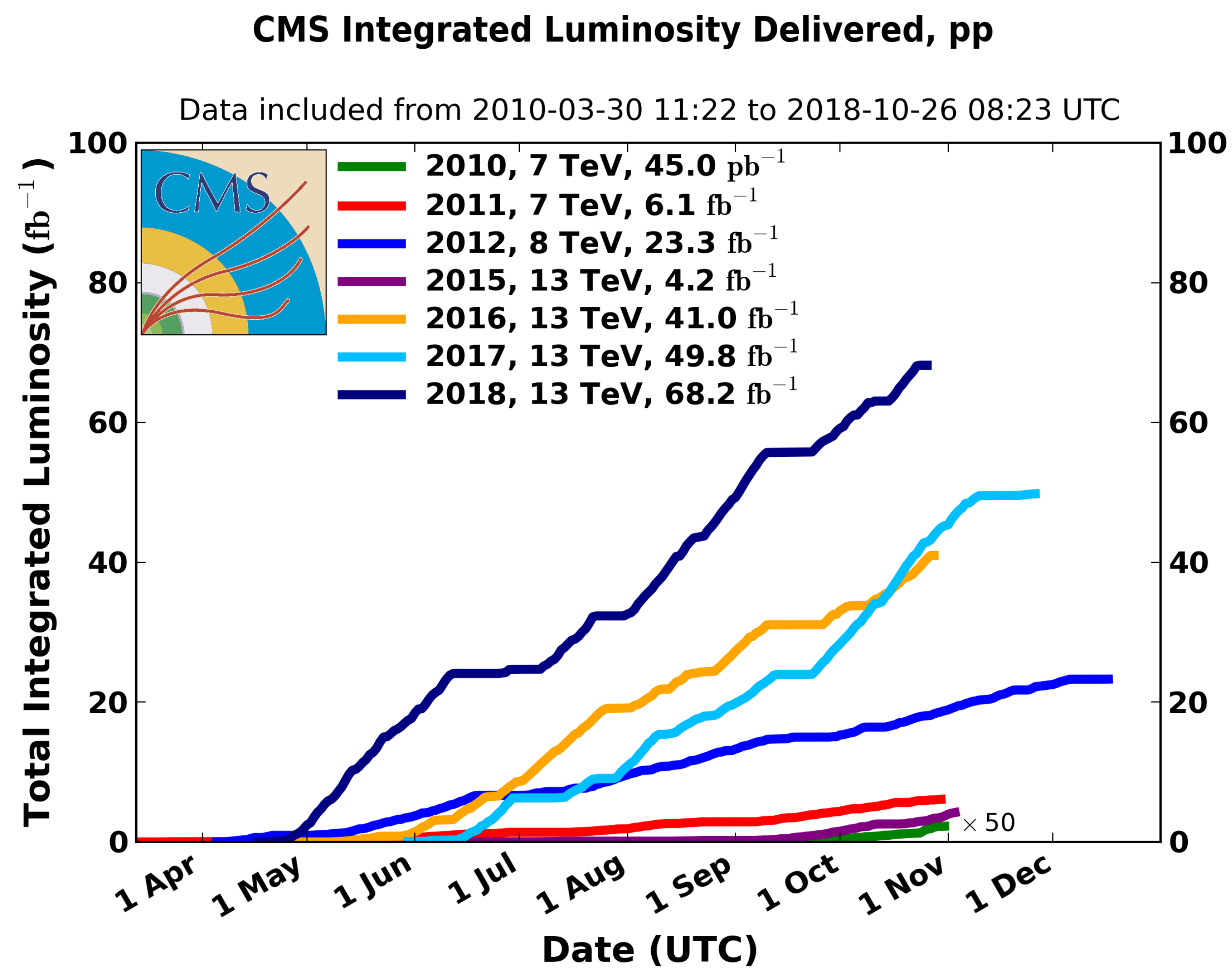
Larger datasets → rarer / more complex production and decay modes become accessible
Precise differential measurements possible

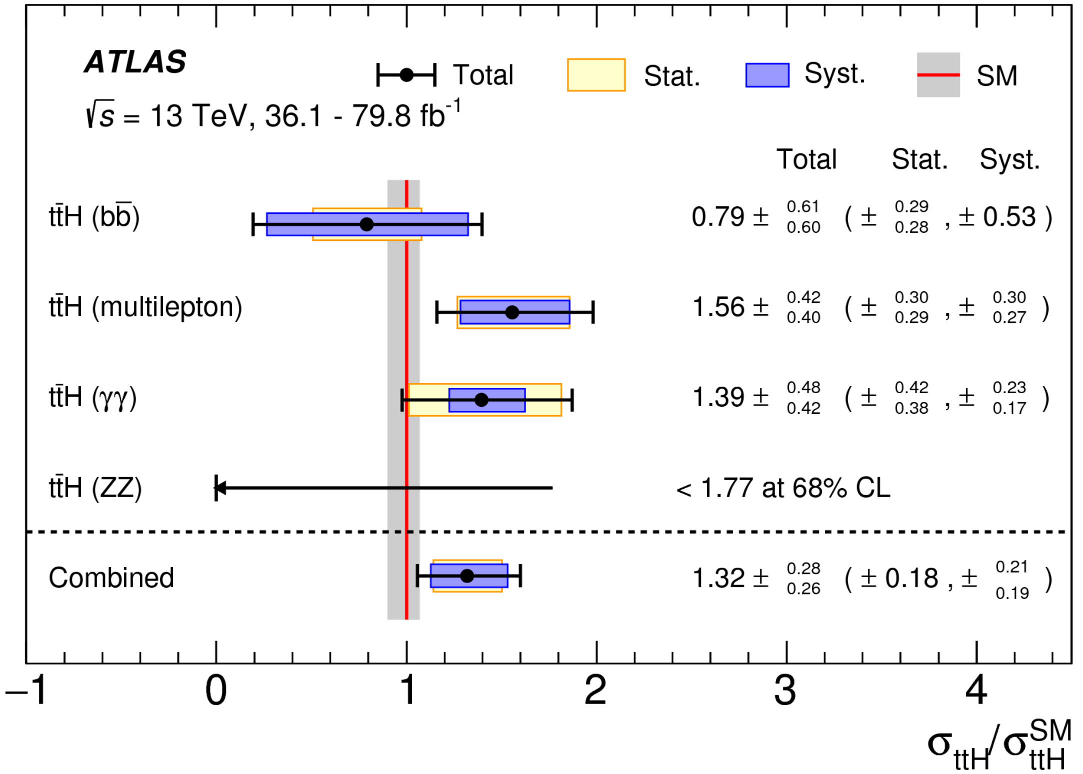
HL/HE LHC ?

So long Run2…

- The 2nd run of the LHC has just ended marking the conclusion of an extremely successful data taking period.

- Over 150 fb^{-1} of 13TeV pp collisions recorded for analysis (36fb^{-1}/80fb^{-1} analysed so far)





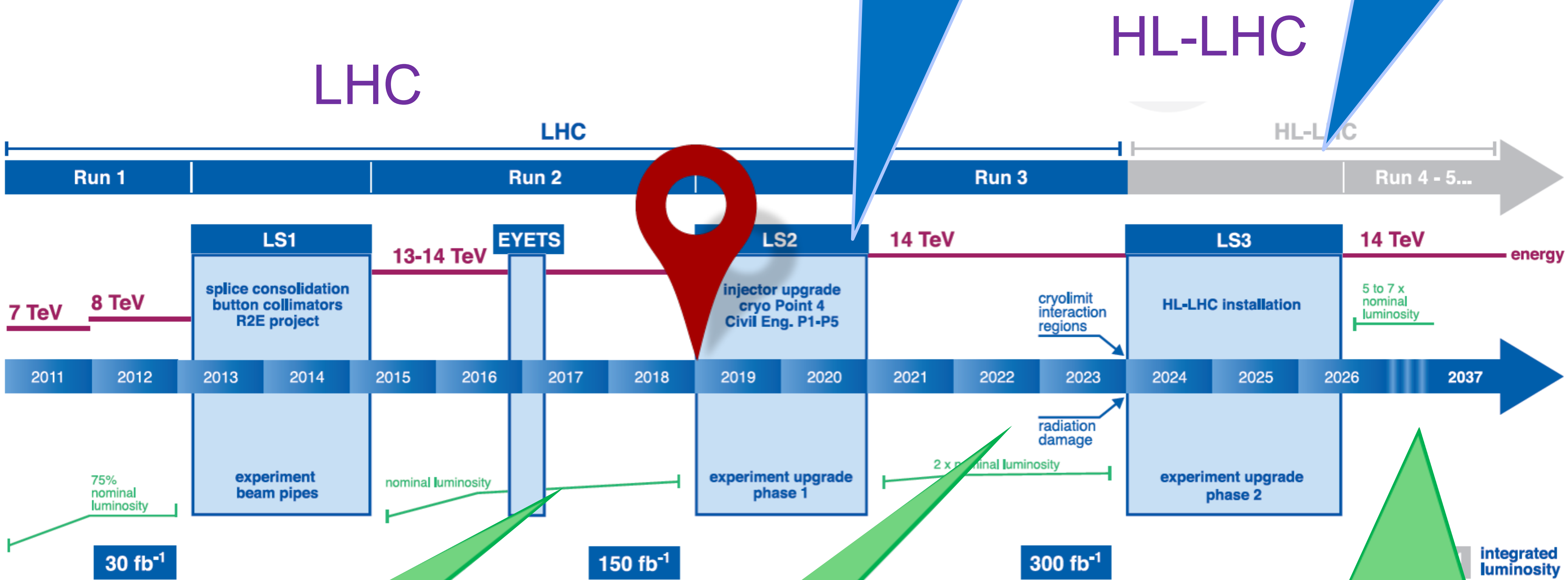
- Standard Model works beautifully/ stubbornly at the LHC: no direct evidence of new physics yet

- Lastest highlights of Run2 again in the Higgs realm: Observation of Higgs coupling to third generation quarks

So what next?

upgrade of injector chain to deliver brighter bunches

new interaction region layout and crab cavity



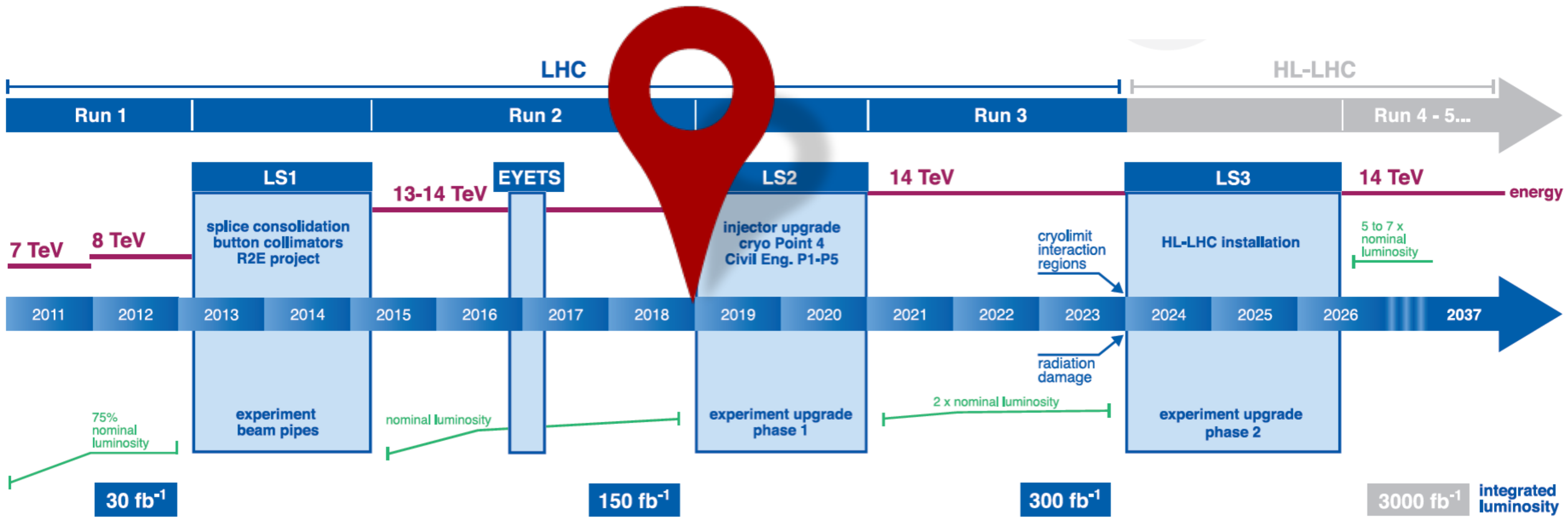
Run 2:
Design $\mathcal{L} = 10^{34}/\mathrm{cm}^2/\mathrm{s}$

Run 3:
$\mathcal{L} = 2{\times}10^{34}/\mathrm{cm}^2/\mathrm{s}$
for 300/fb

HL-LHC: Peak $\mathcal{L} = 2 \times 10^{35}/\mathrm{cm}^2/\mathrm{s}$
level luminosity to
Nominal scenario: $\mathcal{L} = 5 \times 10^{34}/\mathrm{cm}^2/\mathrm{s}$
for 3000/fb; Pile-up $\langle\mu\rangle$ = 140
Ultimate Scenario: $\mathcal{L} = 7.5 \times 10^{34}/\mathrm{cm}^2/\mathrm{s}$
for 4000/fb; Pile-up $\langle\mu\rangle$ = 200
⇒25% increase in integrated lum.

(* slide stolen from P. Azzi)

So what next?



HE-LHC

Recent proposal: LHC tunnel, 16T magnets ➡ 27 TeV pp collisions

Target Luminosity: 15 ab-1 (20 years)

~800 PU

Earliest possible start of physics: 2040

Technical challenge: magnet schedule

Precision physics at the HL-LHC?

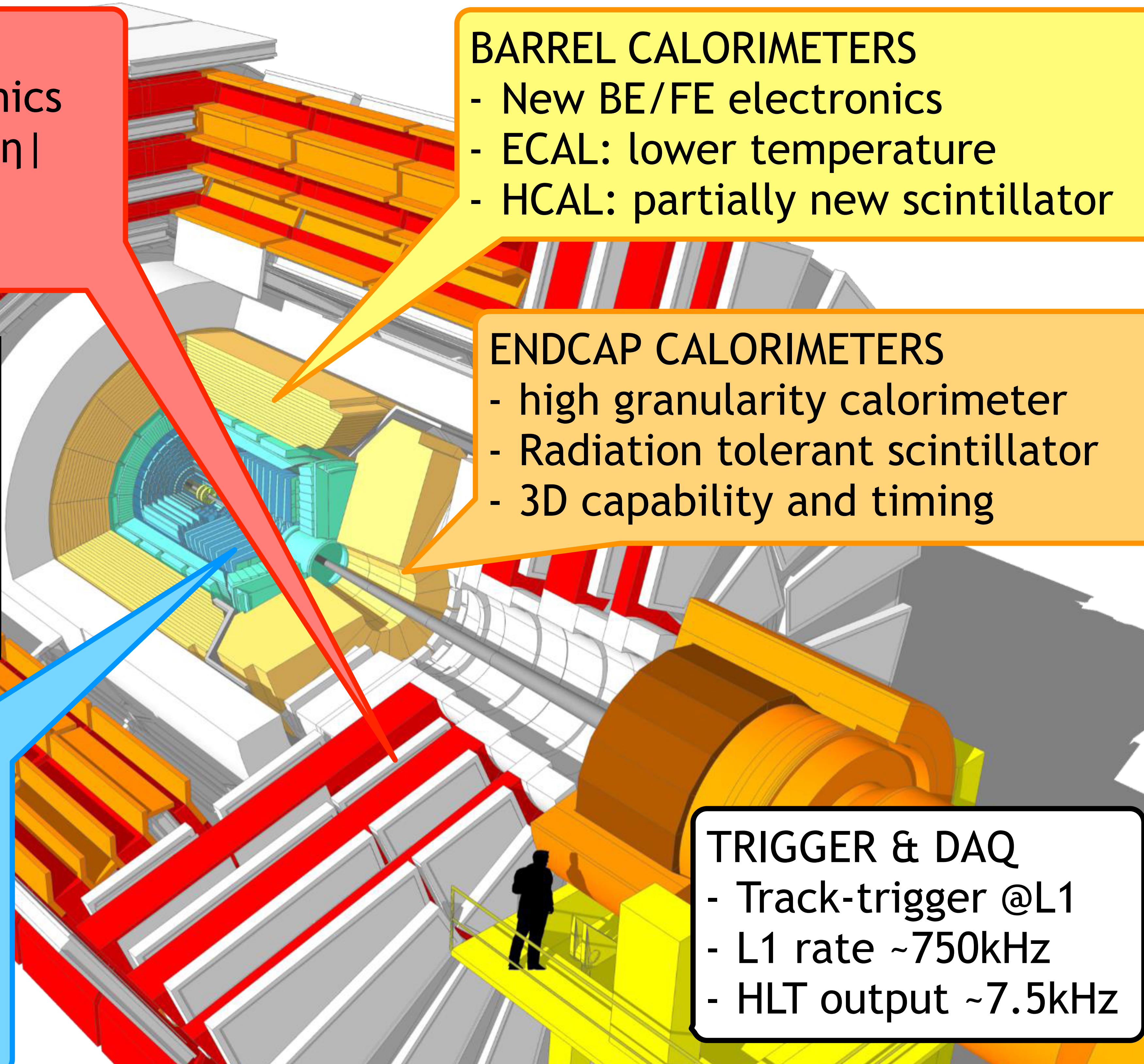
- **High statistics does not come for free: extremely challenging conditions**
  - High luminosity ➔ 200 soft pp interactions per crossing
  - Detector elements and electronics are exposed to high radiation dose

- Extensive upgrade program by ATLAS and CMS underway, with the goal of at least maintaining the current performance despite the hard conditions
  - Effective pileup mitigation & extended capabilities with new algorithms
  - Increased detector acceptance
  - Increased spatial granularity to resolve signals from individual particles
  - Precise timing measurements to provide an additional dimension for discrimination

MUON SYSTEMS
- New DT/CSC BE/FE electronics
- GEM/RPC coverage in 1.5<|η|<2.4
- Muon-tagging in 2.4|η|<3.0

BARREL CALORIMETERS
- New BE/FE electronics
- ECAL: lower temperature
- HCAL: partially new scintillator

ENDCAP CALORIMETERS
- high granularity calorimeter
- Radiation tolerant scintillator
- 3D capability and timing



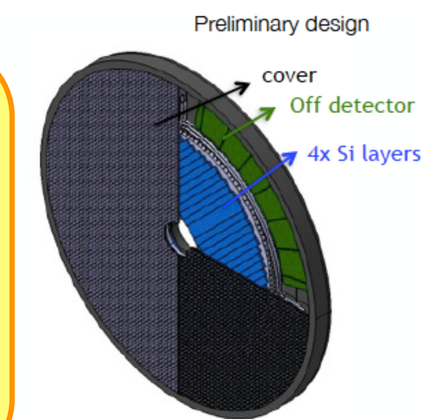
TRACKER
- radiation tolerant, high granularity, low material budget
- coverage up to |η|=3.8
- track trigger at l1

TRIGGER & DAQ
- Track-trigger @L1
- L1 rate ~750kHz
- HLT output ~7.5kHz

(* slide stolen from P. Azzi)

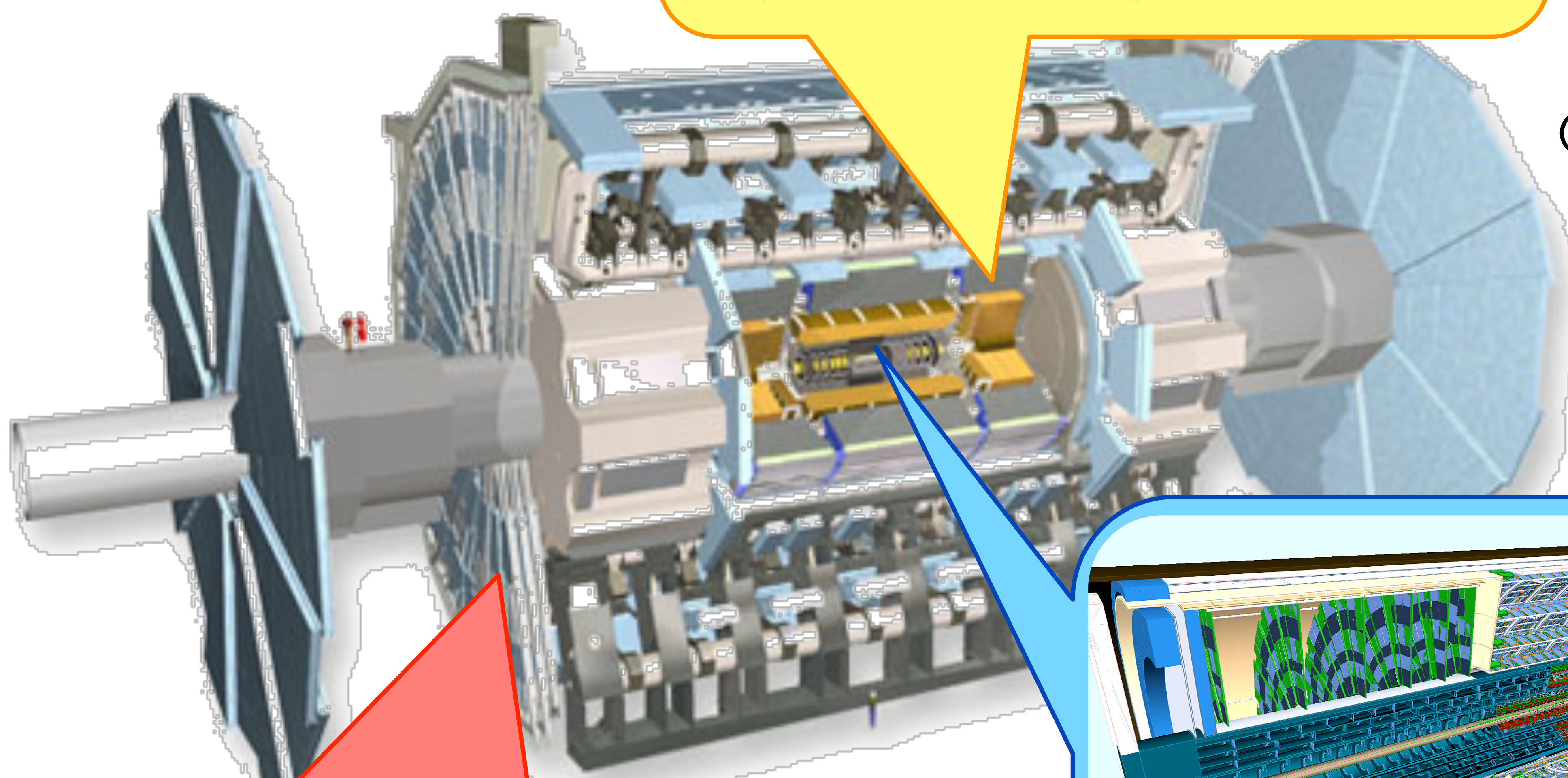
Trigger and DAQ
- L0 (Calo+μ): 1 MHz
- L1 (Calo+μ+Itk): 400 kHz
- HLT: 10 kHz

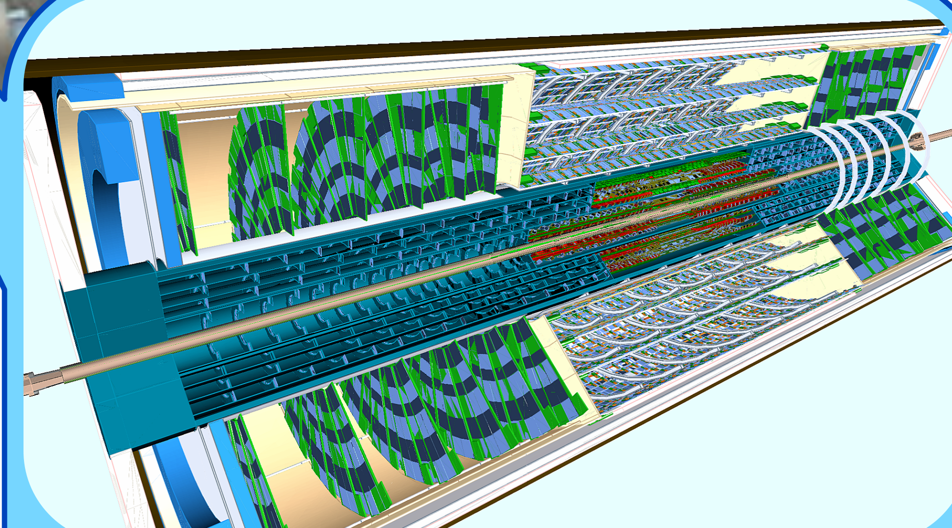
Calorimeters
- New readout electronics compatible with L0 1 MHz rate
- High granularity timing detector (under discussion)



HGTD

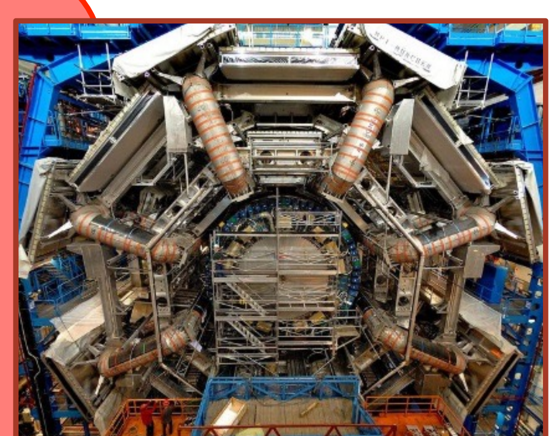
@z~3500mm





All-silicon tracking detector
5 pixel+4 strip layers to $|\eta|<4$

Muon systems
- New readout and trigger electronics
- Additional chambers for inner barrel layer improves acceptance
- Muon tagger for $2.7<|\eta|<4.0$

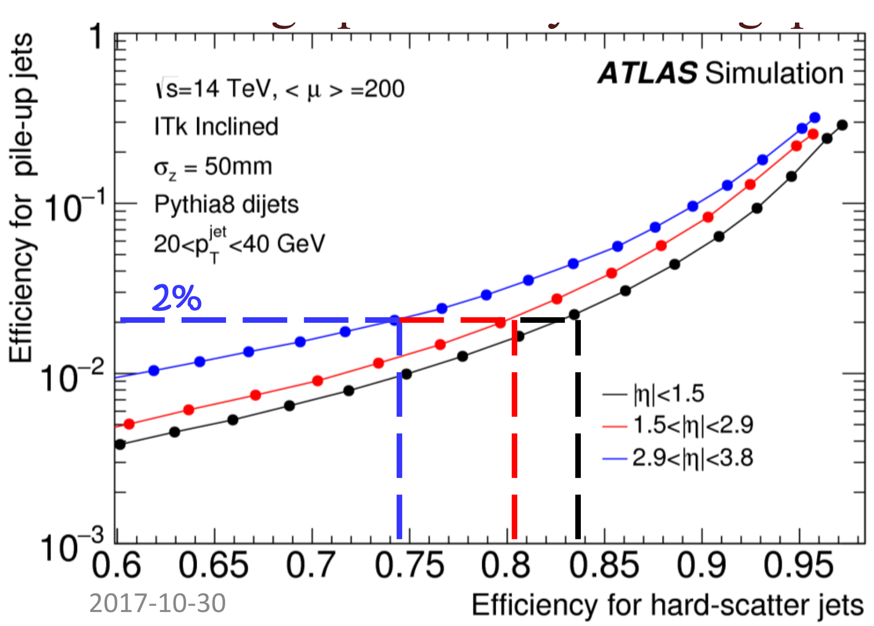


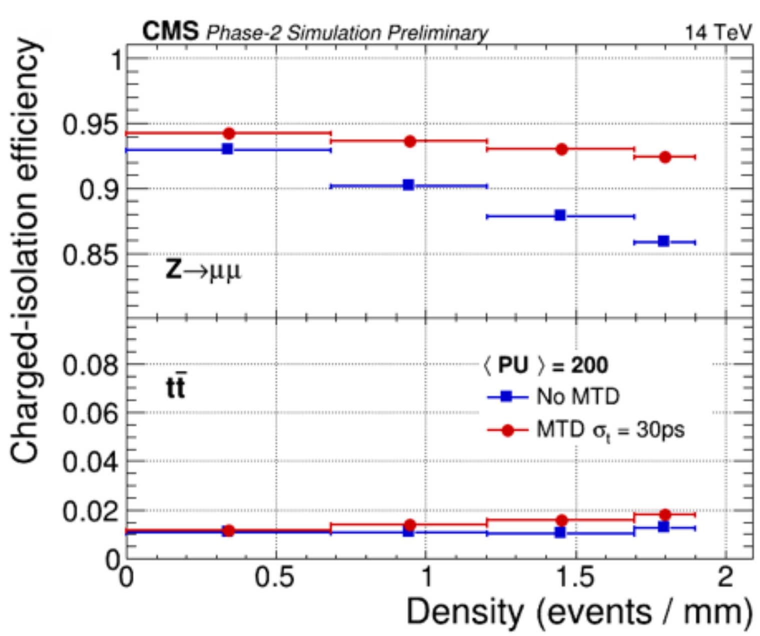
(* slide stolen from P. Azzi)

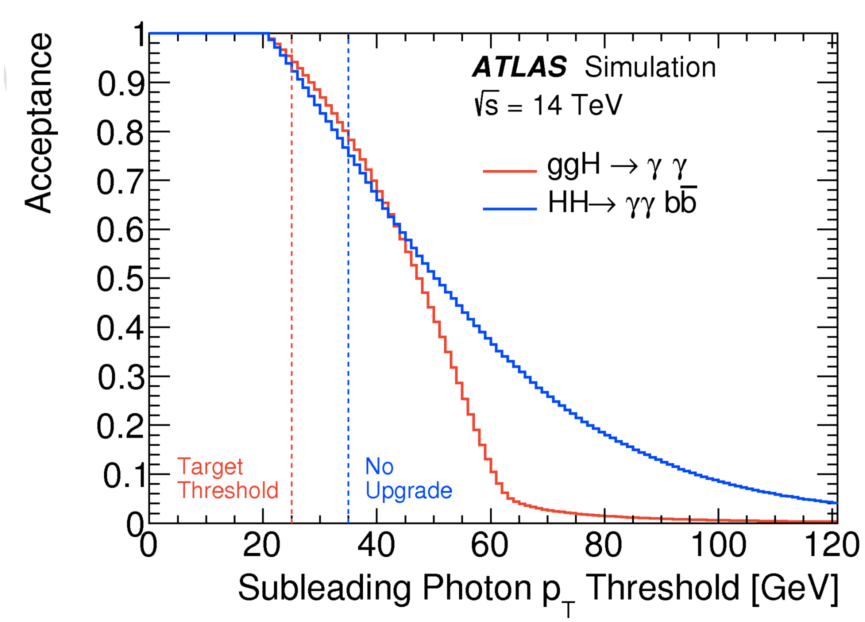
Precision physics at the HL-LHC?

- Studies of detector performance with fully simulated Monte Carlo samples in HL-LHC conditions allow us to have an understanding of the expected future performance of the detectors.

- These studies, performed extensively in 2017 for the ATLAS&CMS Technical Design Reports, are critical to support our updated physics prospects (both those based on projections of Run2 analysis and those directly using fast/ parameterized simulations of the HL-LHC performance)



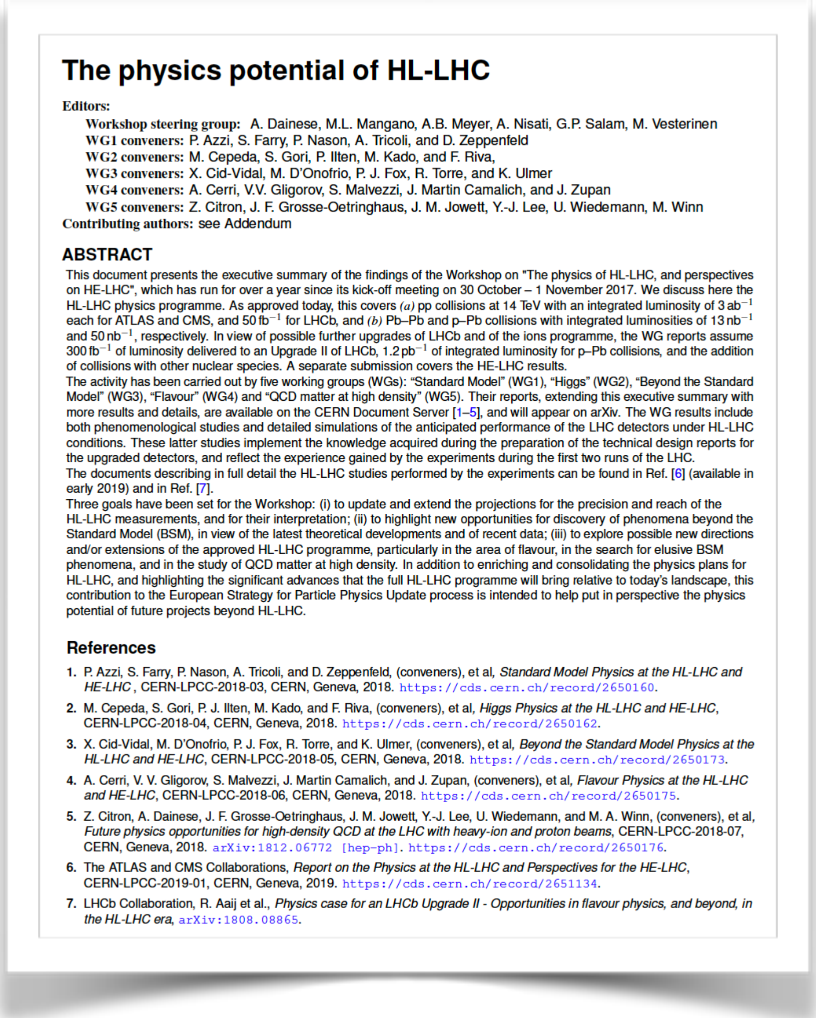




The HL-LHC/HE-LHC Workshop: 2018 Yellow Reports

- Objectives of the workshop:
  - Prepare a **synthesis** of current status of the HL-LHC physics program. Reappraise past projections, perform new analyses, complete partial analyses and combine to provide **the most complete picture**.
  - Begin a systematic study of the physics **potential of the HE-LHC** (27 TeV)
  - **Coherence**: Harmonize results between LHC experiments and projections from the TH community.
  - Gather and discuss **new ideas** from the community and revisit prospects in the light of increased precision in SM measurements with the much larger data sample.
- The results of the workshop were summarised in Yellow Reports that were submitted to the European Strategy group on 18/December/2018

The HL-LHC/HE-LHC Workshop: 2018 Yellow Reports



The physics potential of HL-LHC

Editors:

Workshop steering group: A. Dainese, M.L. Mangano, A.B. Meyer, A. Nisati, G.P. Salam, M. Vesterinen
WG1 conveners: P. Azzi, S. Farry, P. Nason, A. Tricoli, and D. Zeppenfeld
WG2 conveners: M. Cepeda, S. Gori, P. Ilten, M. Kado, and F. Riva,
WG3 conveners: X. Cid-Vidal, M. D'Onofrio, P. J. Fox, R. Torre, and K. Ulmer
WG4 conveners: A. Cerri, V.V. Gligorov, S. Malvezzi, J. Martin Camalich, and J. Zupan
WG5 conveners: Z. Citron, J. F. Grosse-Oetringhaus, J. M. Jowett, Y.-J. Lee, U. Wiedemann, M. Winn
Contributing authors: see Addendum

ABSTRACT

This document presents the executive summary of the findings of the Workshop on "The physics of HL-LHC, and perspectives on HE-LHC", which has run for over a year since its kick-off meeting on 30 October – 1 November 2017. We discuss here the HL-LHC physics programme. As approved today, this covers *(a)* pp collisions at 14 TeV with an integrated luminosity of 3 ab^{-1} each for ATLAS and CMS, and 50 fb^{-1} for LHCb, and *(b)* Pb–Pb and p–Pb collisions with integrated luminosities of 13 nb^{-1} and 50 nb^{-1}, respectively. In view of possible further upgrades of LHCb and of the ions programme, the WG reports assume 300 fb^{-1} of luminosity delivered to an Upgrade II of LHCb, 1.2 pb^{-1} of integrated luminosity for p–Pb collisions, and the addition of collisions with other nuclear species. A separate submission covers the HE-LHC results.
The activity has been carried out by five working groups (WGs): "Standard Model" (WG1), "Higgs" (WG2), "Beyond the Standard Model" (WG3), "Flavour" (WG4) and "QCD matter at high density" (WG5). Their reports, extending this executive summary with more results and details, are available on the CERN Document Server [1–5], and will appear on arXiv. The WG results include both phenomenological studies and detailed simulations of the anticipated performance of the LHC detectors under HL-LHC conditions. These latter studies implement the knowledge acquired during the preparation of the technical design reports for the upgraded detectors, and reflect the experience gained by the experiments during the first two runs of the LHC.
The documents describing in full detail the HL-LHC studies performed by the experiments can be found in Ref. [6] (available in early 2019) and in Ref. [7].
Three goals have been set for the Workshop: (i) to update and extend the projections for the precision and reach of the HL-LHC measurements, and for their interpretation; (ii) to highlight new opportunities for discovery of phenomena beyond the Standard Model (BSM), in view of the latest theoretical developments and of recent data; (iii) to explore possible new directions and/or extensions of the approved HL-LHC programme, particularly in the area of flavour, in the search for elusive BSM phenomena, and in the study of QCD matter at high density. In addition to enriching and consolidating the physics plans for HL-LHC, and highlighting the significant advances that the full HL-LHC programme will bring relative to today's landscape, this contribution to the European Strategy for Particle Physics Update process is intended to help put in perspective the physics potential of future projects beyond HL-LHC.

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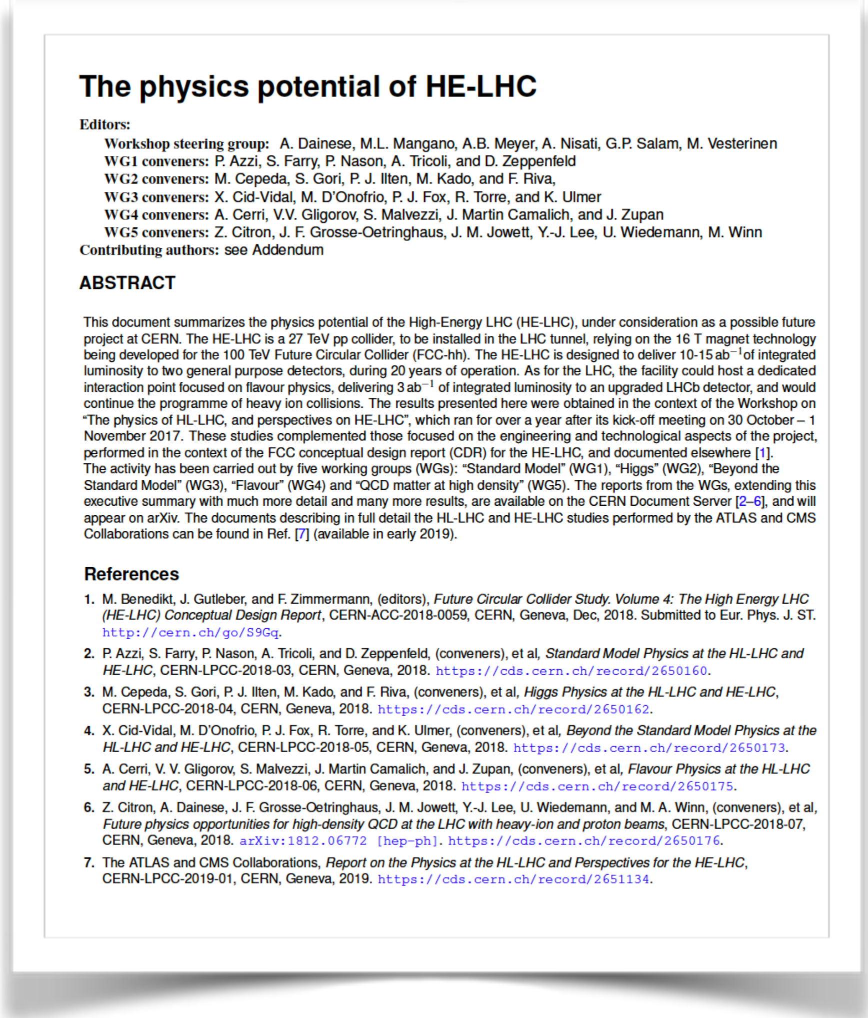

The physics potential of HE-LHC

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Contributing authors: see Addendum

ABSTRACT

This document summarizes the physics potential of the High-Energy LHC (HE-LHC), under consideration as a possible future project at CERN. The HE-LHC is a 27 TeV pp collider, to be installed in the LHC tunnel, relying on the 16 T magnet technology being developed for the 100 TeV Future Circular Collider (FCC-hh). The HE-LHC is designed to deliver 10-15 ab^{-1} of integrated luminosity to two general purpose detectors, during 20 years of operation. As for the LHC, the facility could host a dedicated interaction point focused on flavour physics, delivering 3 ab^{-1} of integrated luminosity to an upgraded LHCb detector, and would continue the programme of heavy ion collisions. The results presented here were obtained in the context of the Workshop on "The physics of HL-LHC, and perspectives on HE-LHC", which ran for over a year after its kick-off meeting on 30 October – 1 November 2017. These studies complemented those focused on the engineering and technological aspects of the project, performed in the context of the FCC conceptual design report (CDR) for the HE-LHC, and documented elsewhere [1].
The activity has been carried out by five working groups (WGs): "Standard Model" (WG1), "Higgs" (WG2), "Beyond the Standard Model" (WG3), "Flavour" (WG4) and "QCD matter at high density" (WG5). The reports from the WGs, extending this executive summary with much more detail and many more results, are available on the CERN Document Server [2–6], and will appear on arXiv. The documents describing in full detail the HL-LHC and HE-LHC studies performed by the ATLAS and CMS Collaborations can be found in Ref. [7] (available in early 2019).

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SM & TOP - CERN-LPCC-2018-03

Higgs - CERN-LPCC-2018-04

BSM - CERN-LPCC-2018-05

Flavor - CERN-LPCC-2018-06

Heavy Ions - CERN-LPCC-2018-07

WG2: Higgs

Higgs - CERN-LPCC-2018-04

- Huge collaborative effort, joining forces across the LHC ring and with the theoretical community
- The bar for the Higgs studies was really high:
    - Stress on combinations (LHC potential, ATLAS+CMS)
    - Stress on theo+experimental cross-feed: revision of future theoretical uncertainties (theo->exp) and experimental updates feed to theoretical teams to be able to attack the full HL phase-space (exp->theo)
- 400 authors
- 343 pages (x2 the original goal…)

- I will focus on the experimental updates presented in the Higgs chapter, and mostly on HL-LHC

CERN

CERN-LPCC-2018-04
January 7, 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

Convenors:
M. Cepeda[1,2], *S. Gori*[3], *P. Ilten*[4], *M. Kado*[5,6,7], *F. Riva*[8],

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Uncertainty Scenarios

- Main experimental uncertainties synchronised between CMS and ATLAS
- In most cases, two complementary scenarios given for each of the updated projections:
  - S1 - Conservative, based on the current Run2 systematic uncertainties (including theory)
  - S2 - Ultimate, based on synchronised estimates of ultimate performance for experimental uncertainties, and applying a factor of 1/2 for theoretical uncertainties

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%

Uncertainty Scenarios

- Main experimental uncertainties synchronised between CMS and ATLAS
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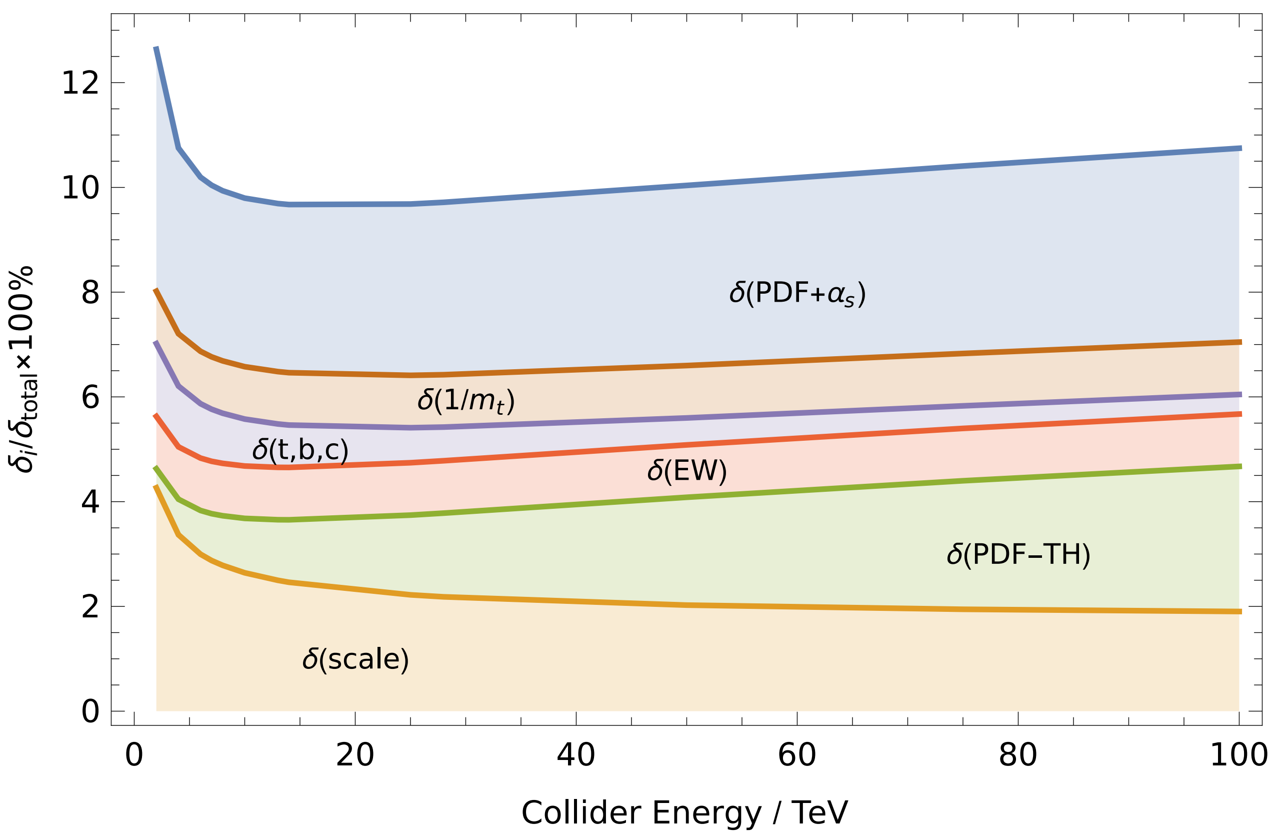
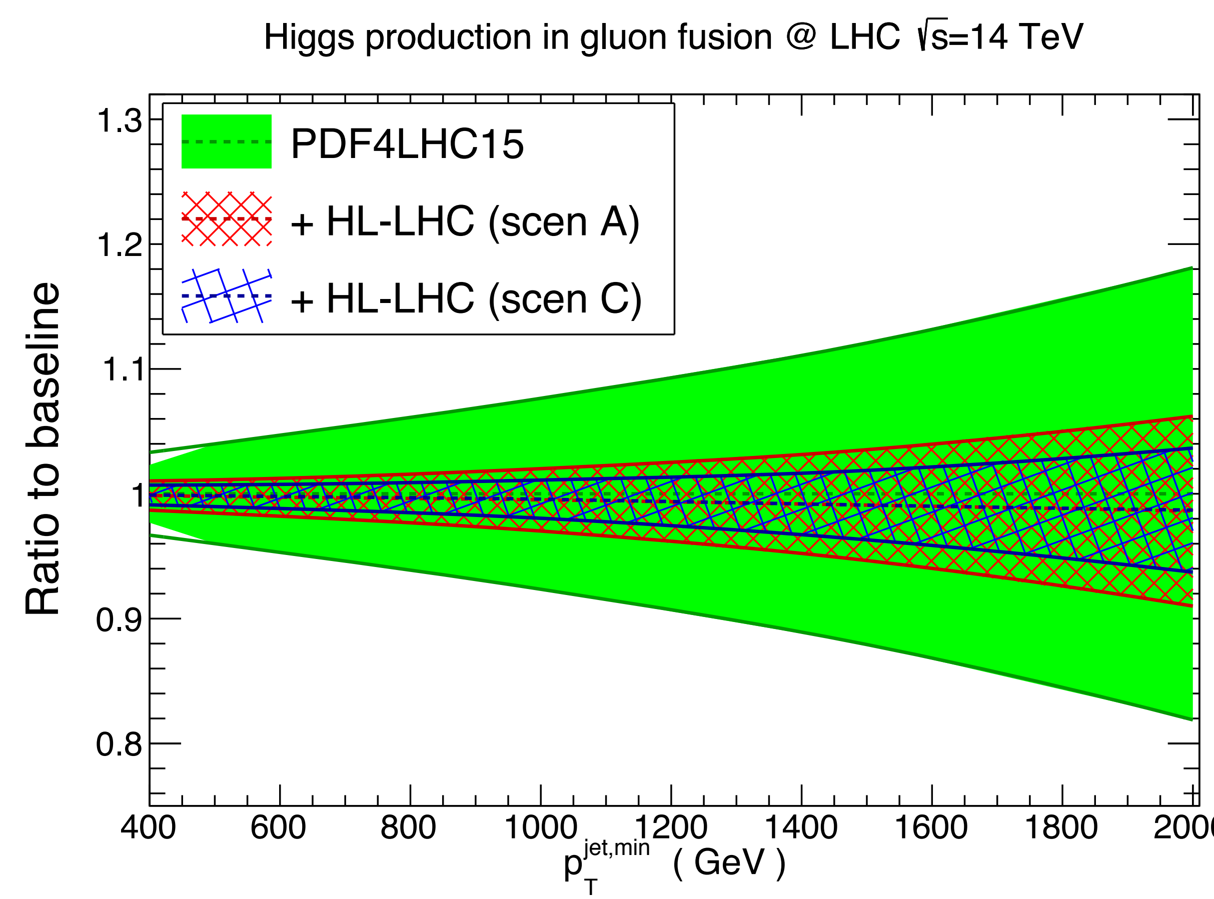




HIGGS PHYSICS @ HL-LHC

The HL-LHC: A Higgs Factory

What do we need to know? Where will the HL-LHC impact?

- **Precision Measurements** (Couplings to ~5%, Cross Sections, Differential Distributions, Width, assessment of the top Yukawa)

- **Rare decays**

- **Di-Higgs production ➜** self coupling

- **BSM Higgs searches** (extra scalars, BSM Higgs resonances, anomalous couplings)

SM Higgs Precision Measurements

- Old studies (before 2018): comprehensive, but mostly based on extrapolations of Run1/early Run2 results, plus specific analyses with parametrised full simulation. Varying uncertainty assumptions. Single experiment only!

Rates can be measured at the few % level (10-20% for rarer modes)

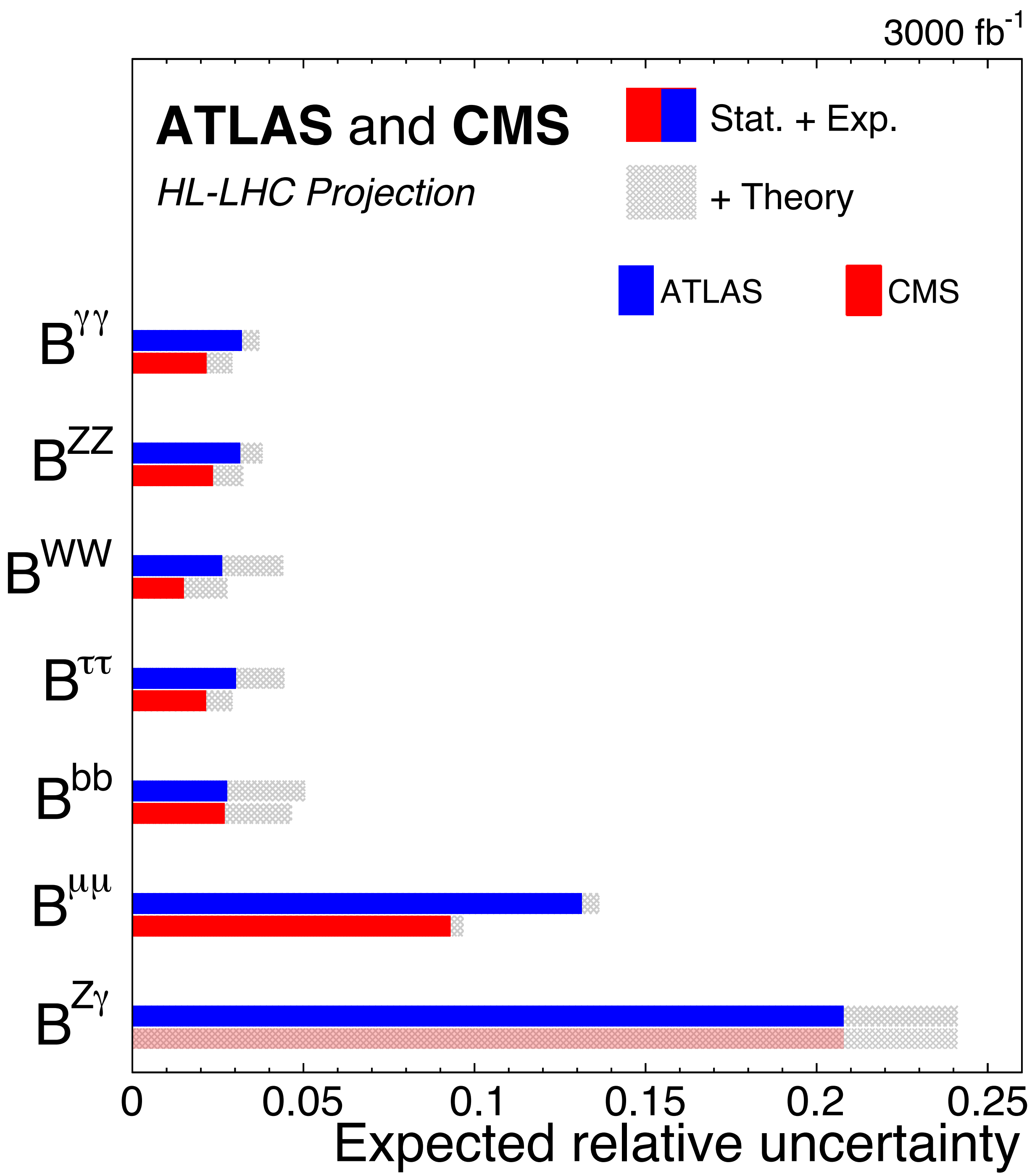
Coupling can be measured at the few % level

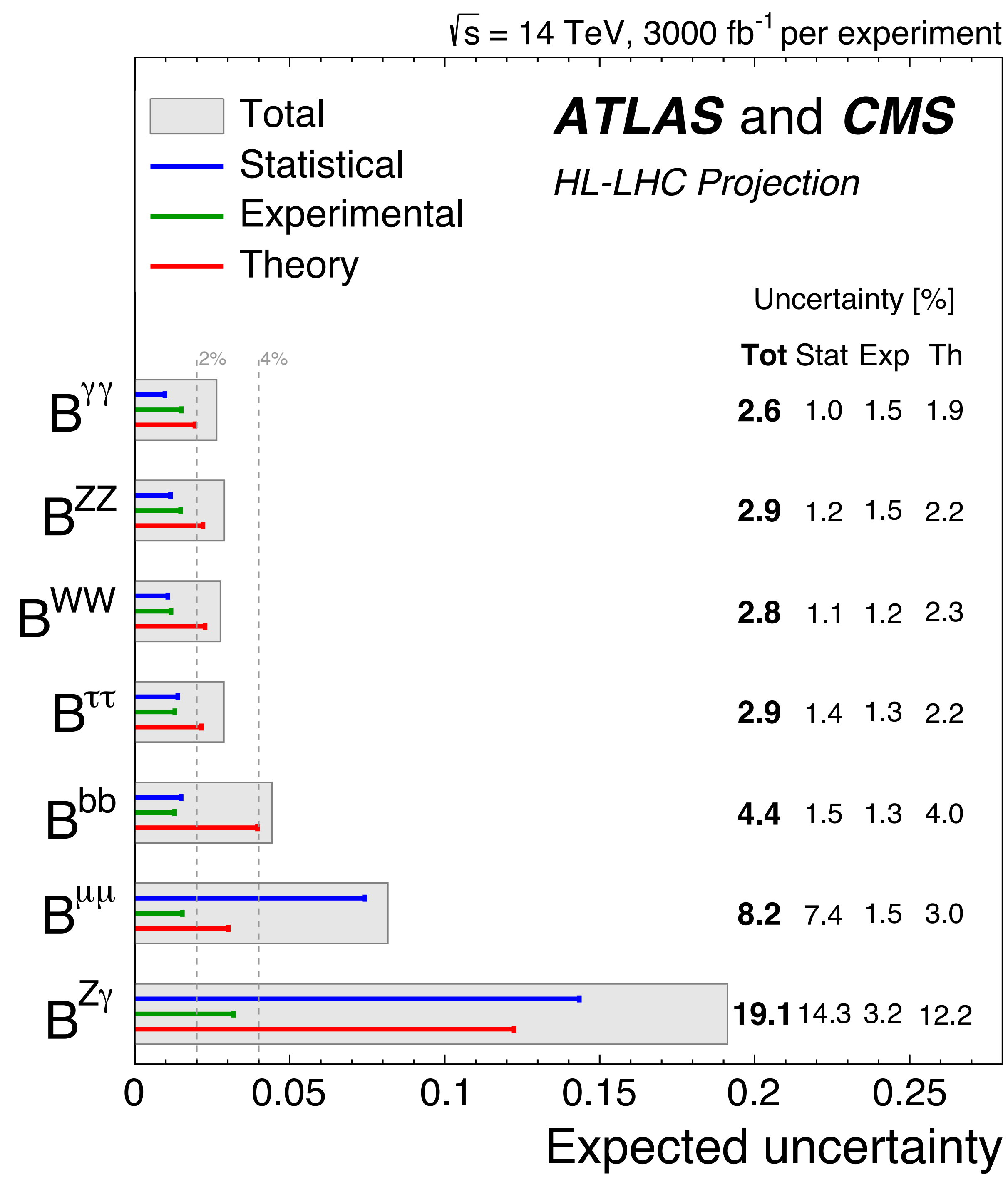
- Complete revamp of the SM Higgs projections, starting from Run2 results and incorporating the current understanding of the future ATLAS&CMS performance

- **All main decay x production modes incorporated to the study (γγ, WW, ZZ, ττ, bb, μμ, Zγ x ggF, VBF, WH, ZH, ttH)**

- Individual experiment results, leading to a combination of the ATLAS and CMS sensitivity (LHC reach)
  - Theoretical systematics assumed fully correlated, experimental uncertainties uncorrelated

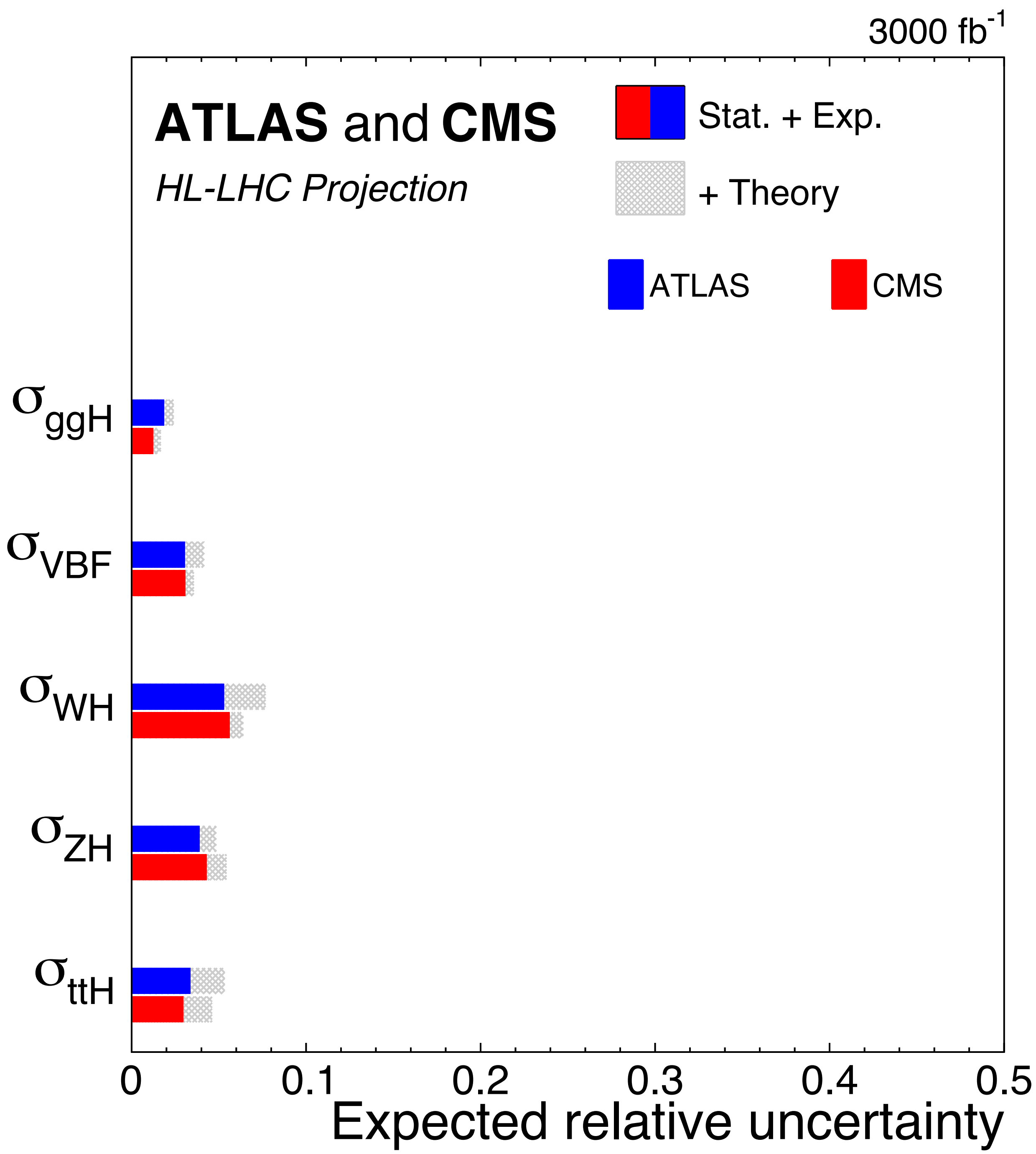
Results Per Decay Mode

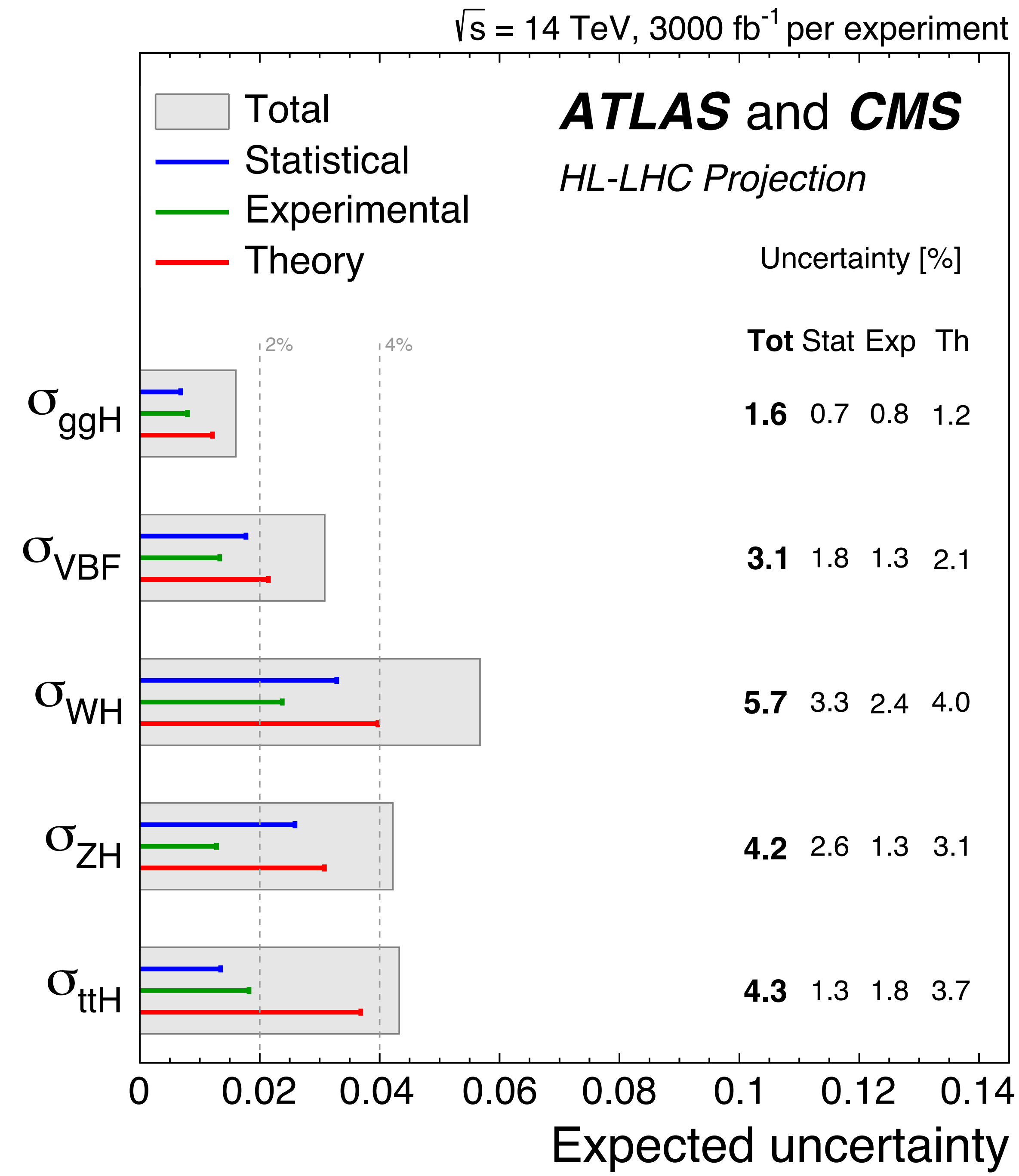




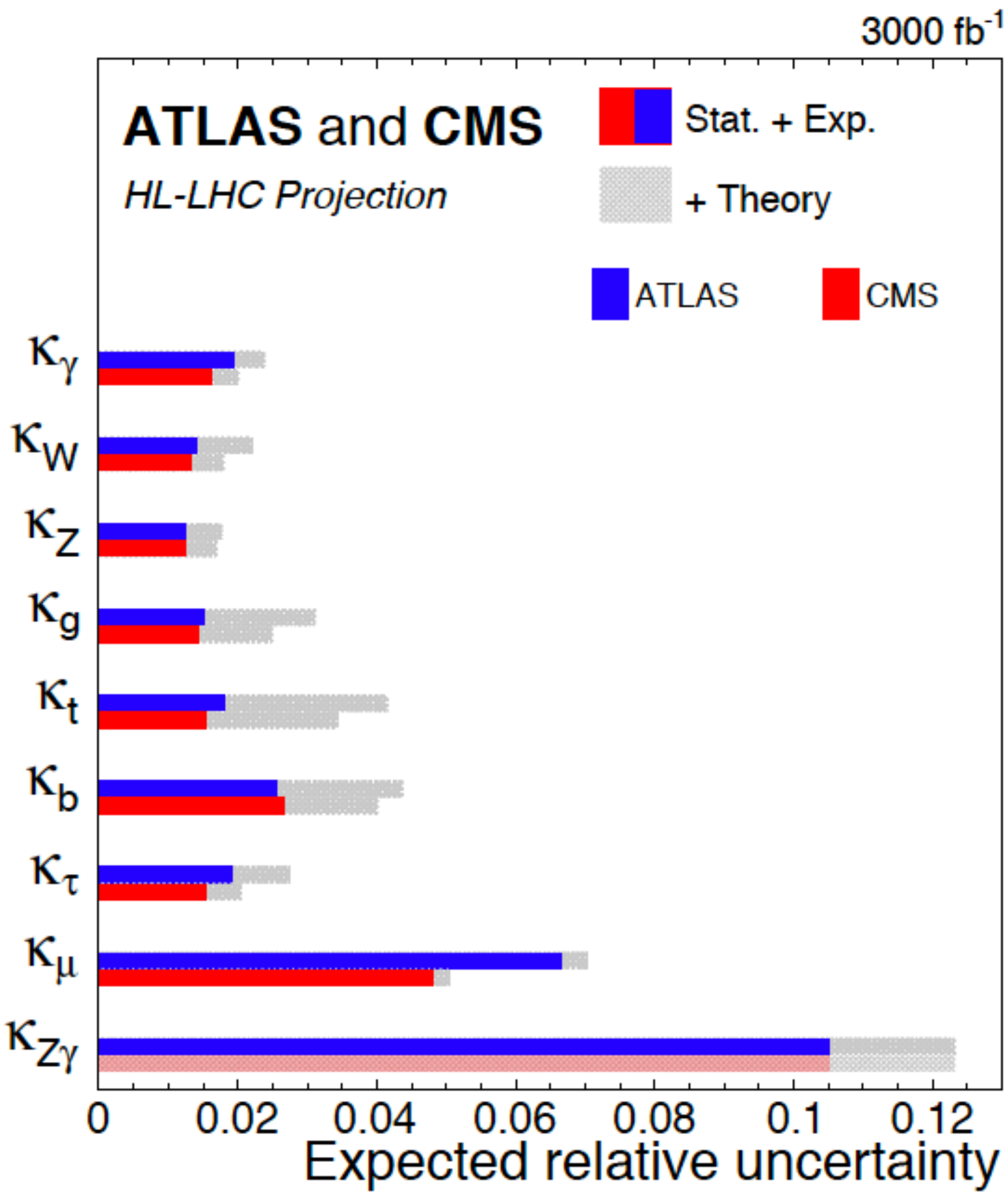
- Importance of Theory / MC understanding: specially important for background modelling

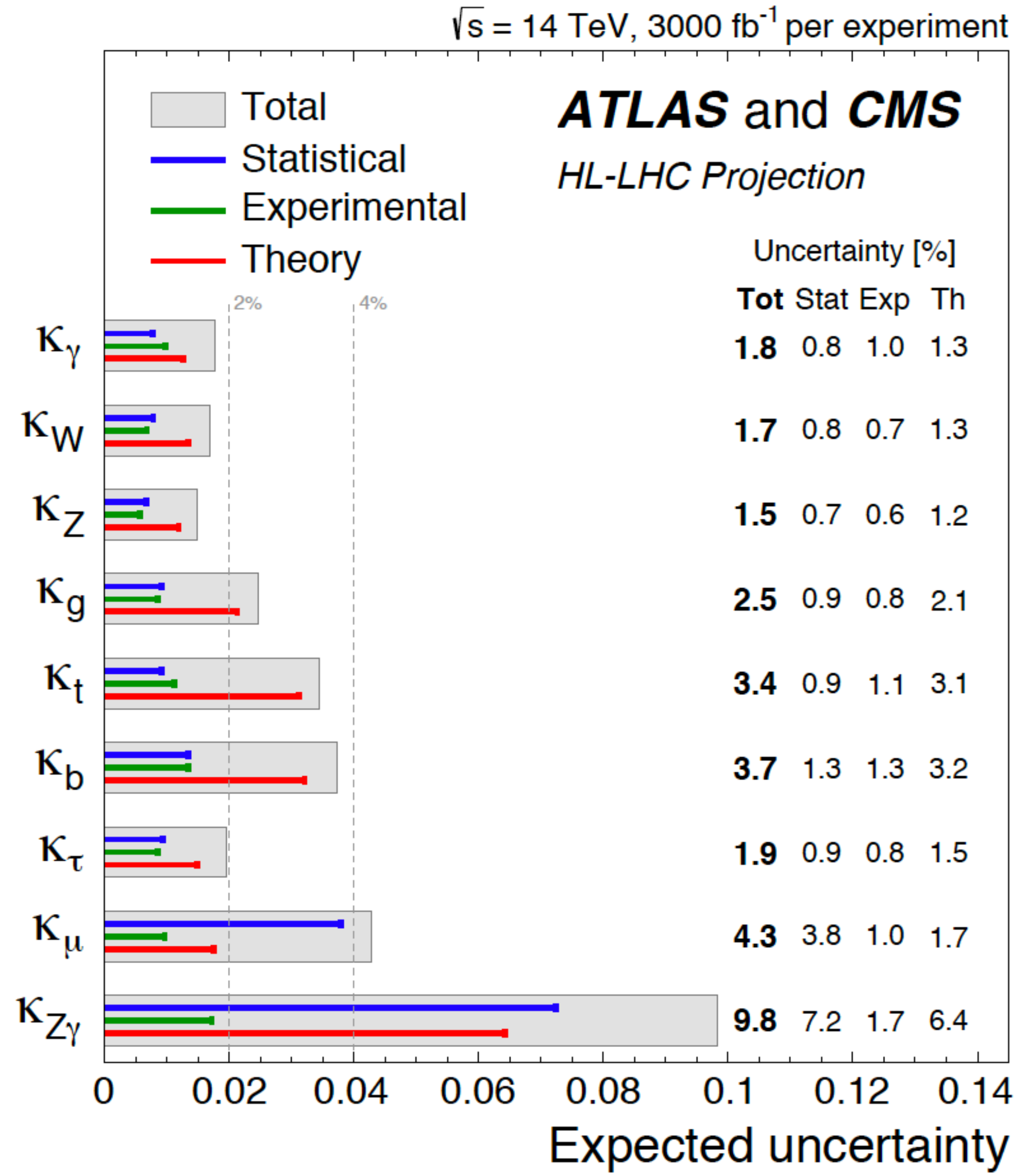
Results Per Production Mode





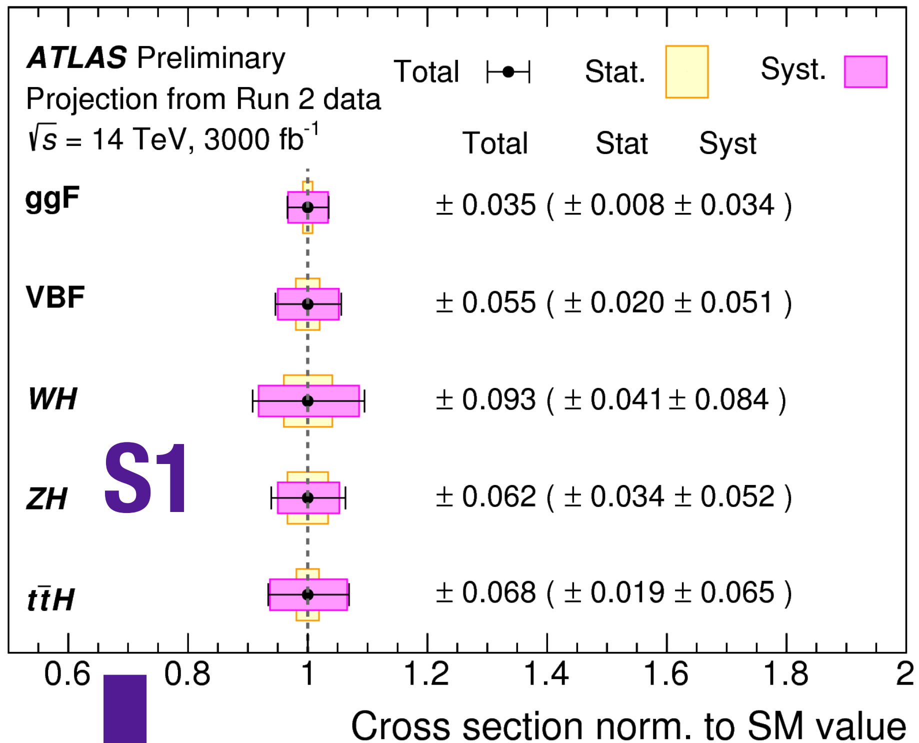
Couplings @ HL-LHC

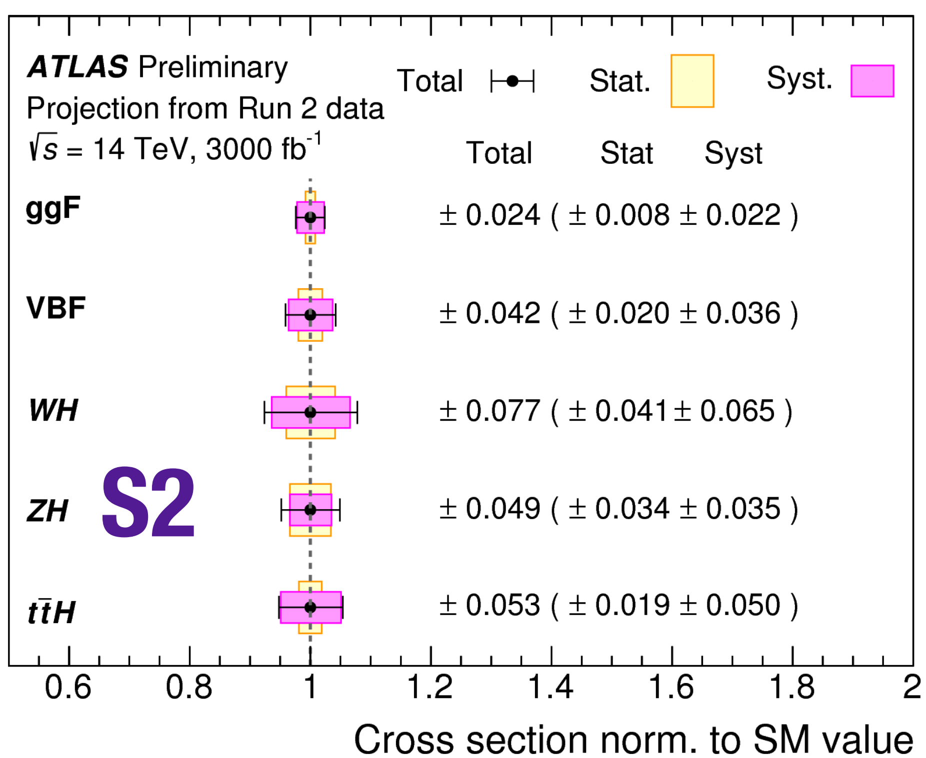


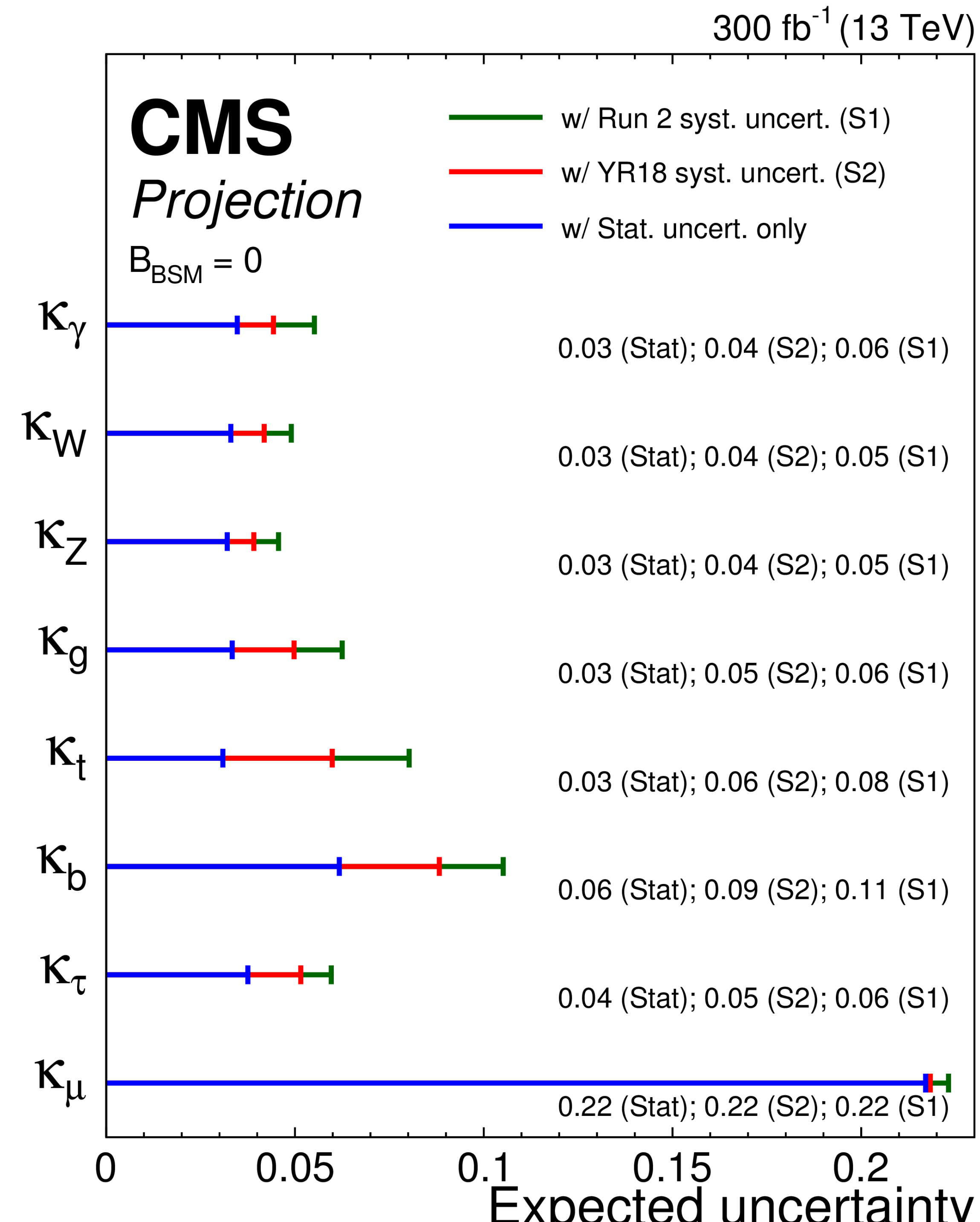


- Precision of 2-4% can be reached for the non-statistically dominated modes

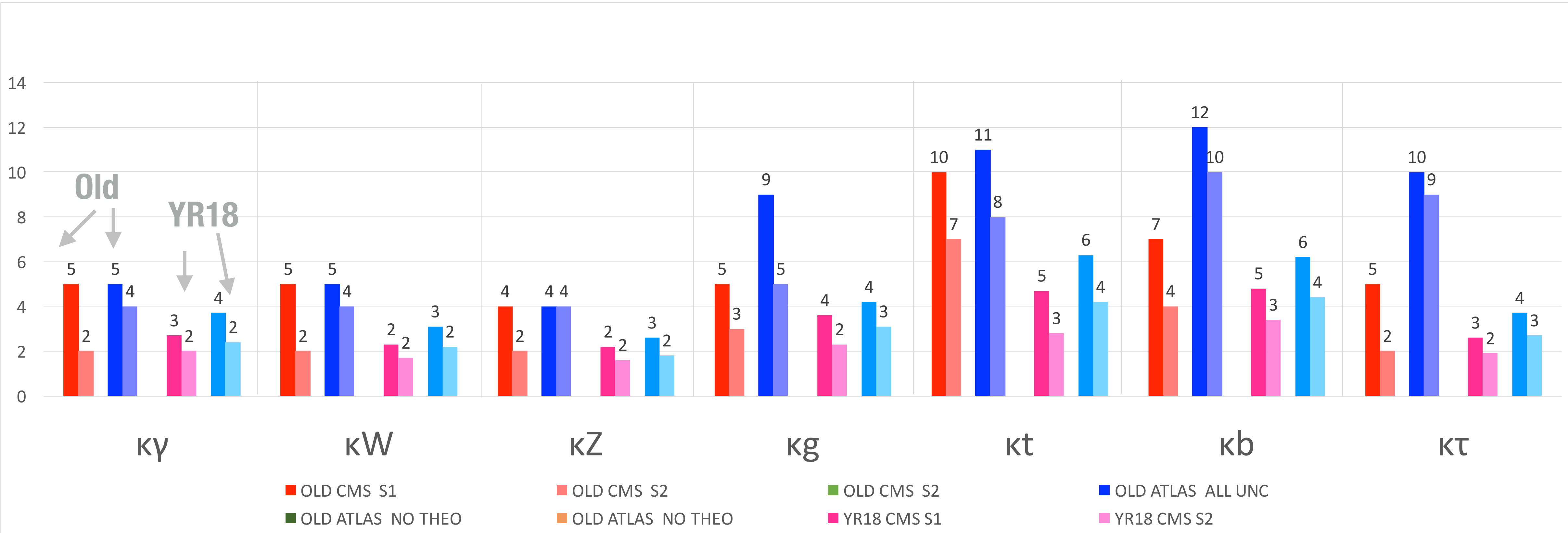
Uncertainty Scenario Comparison





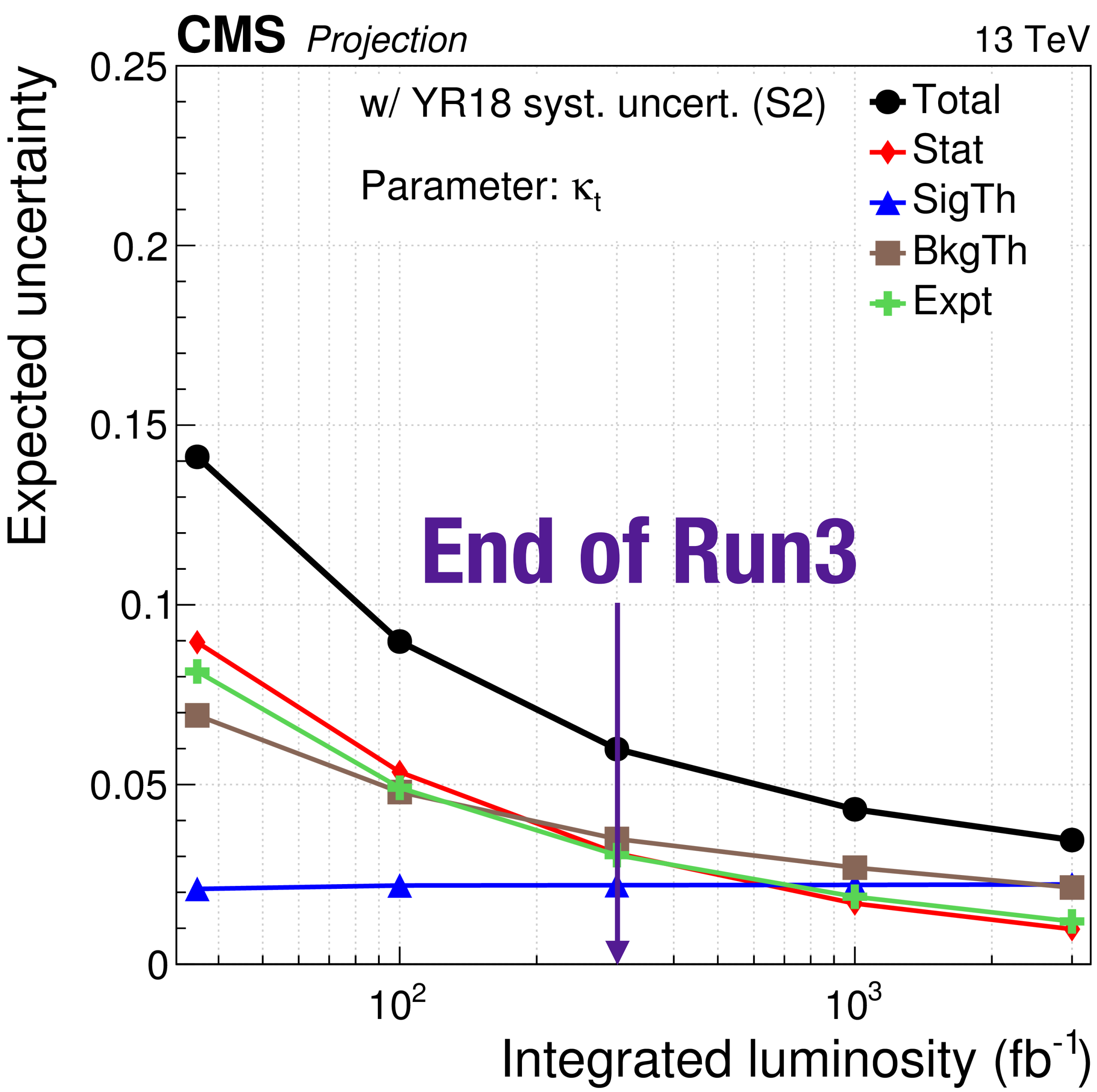


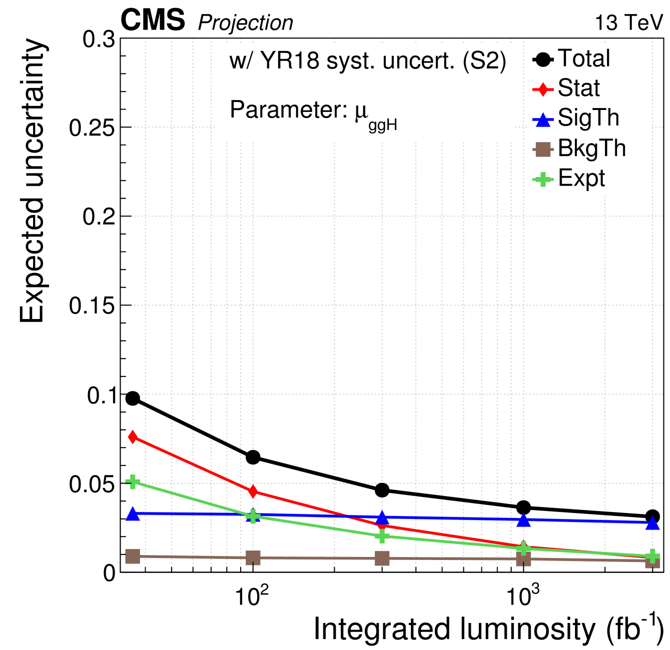
Comparison to older projections

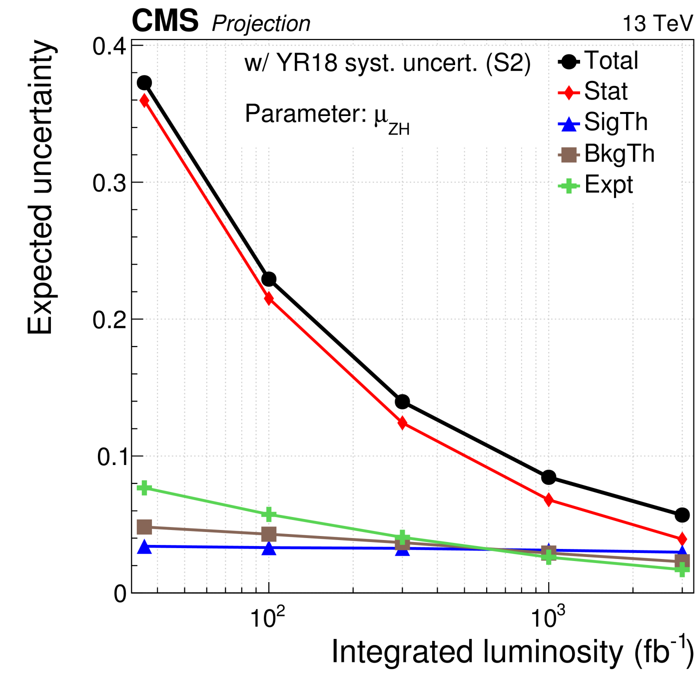


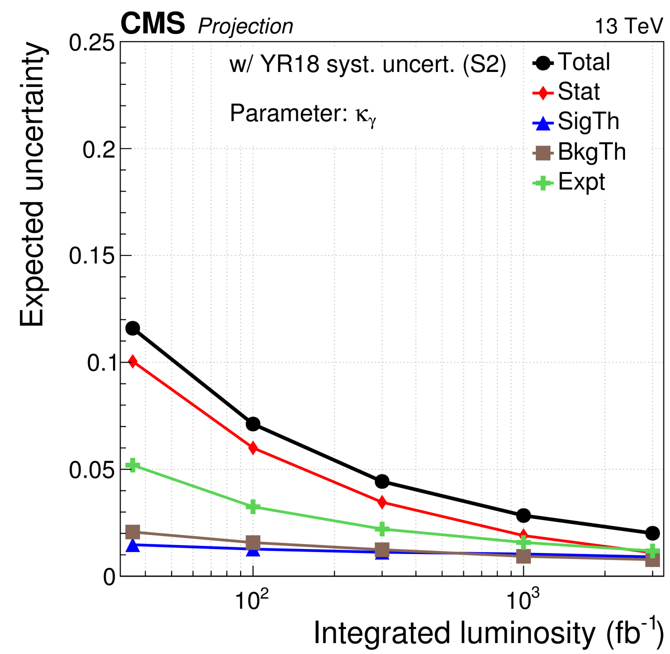
- Rather good agreement between the new ATLAS and CMS projections - while they differed clearly in the past
- Improvements wrt to old projections due to:
  - Theoretical uncertainties (now YR4, old YR3 - this is a factor of 2!)
  - Improvements in analysis going from Run1 to Run2 (eg: ttH)
  - Global fit / coherent study of all decay modes
  - Better understanding of performance at HL-LHC

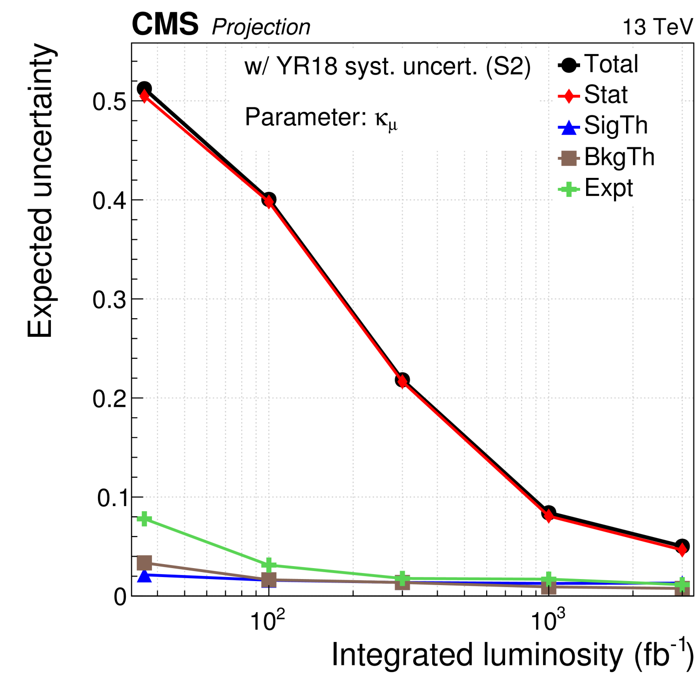
Time evolution





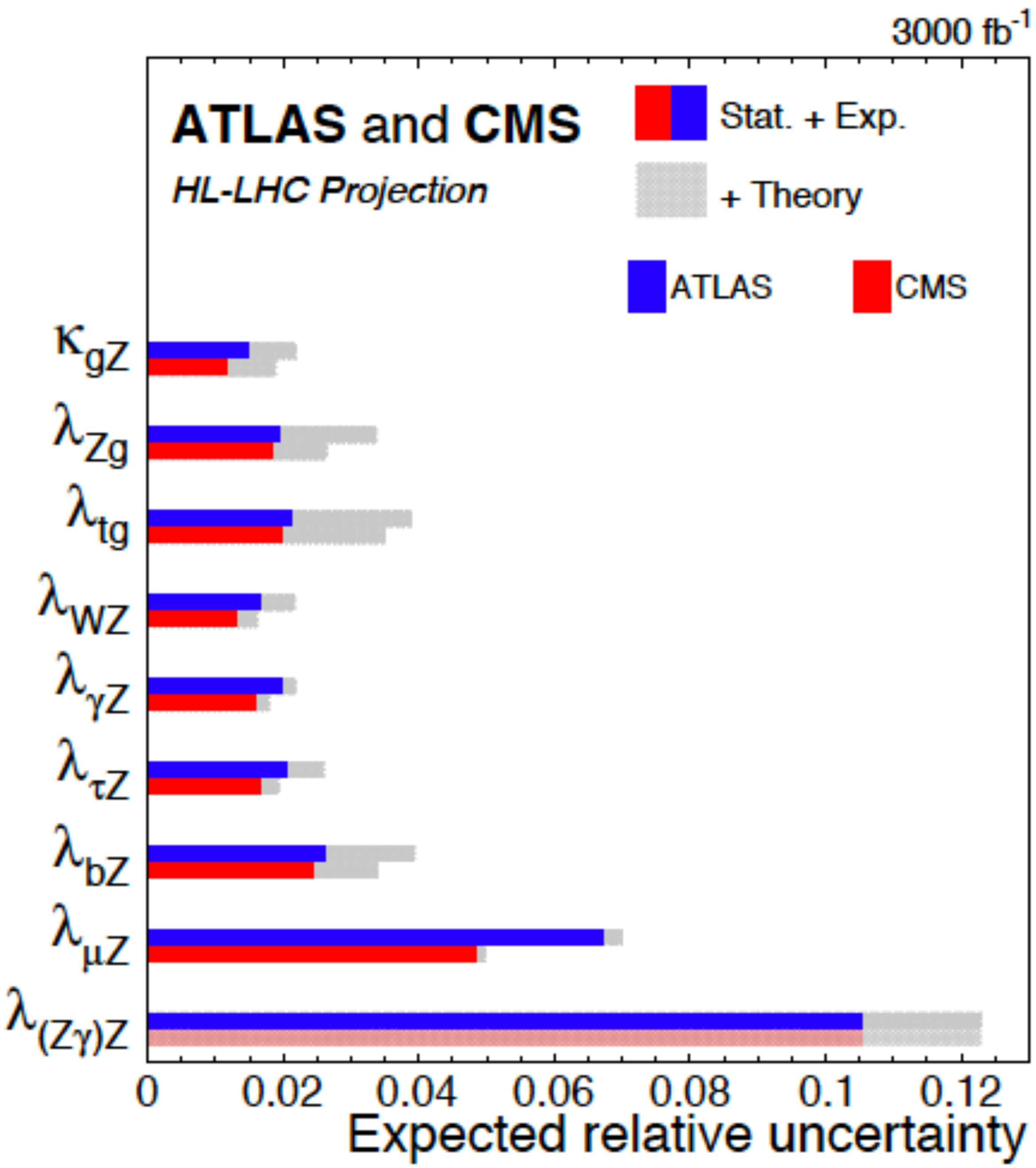


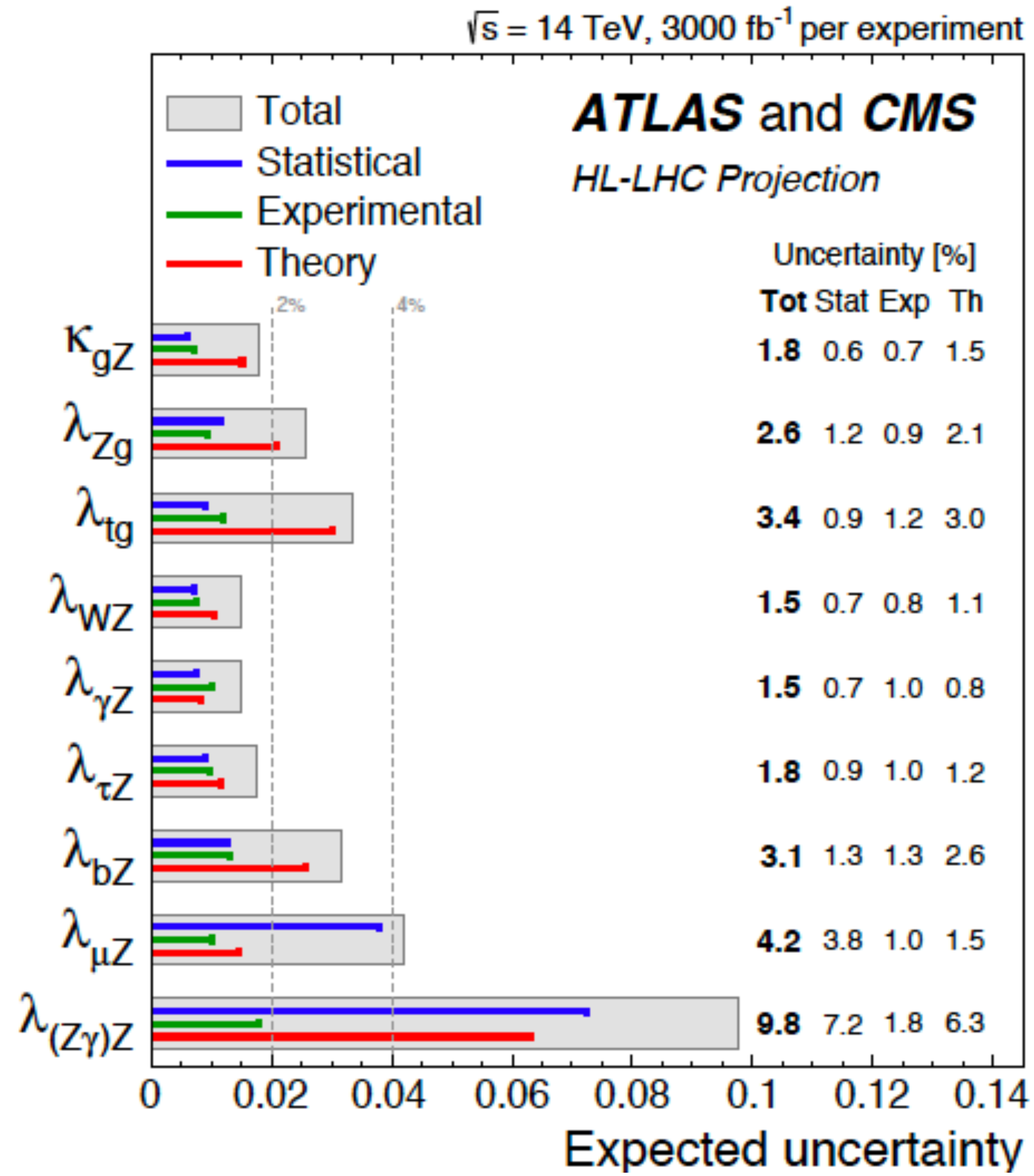




- Measurements became systematically limited rather fast in almost all cases -> challenge
- Most Coupling modifier uncertainties projected to reach ~4-6% precision by the end of Run 3, and 2-4% after 3000 fb^{-1} at HL-LHC

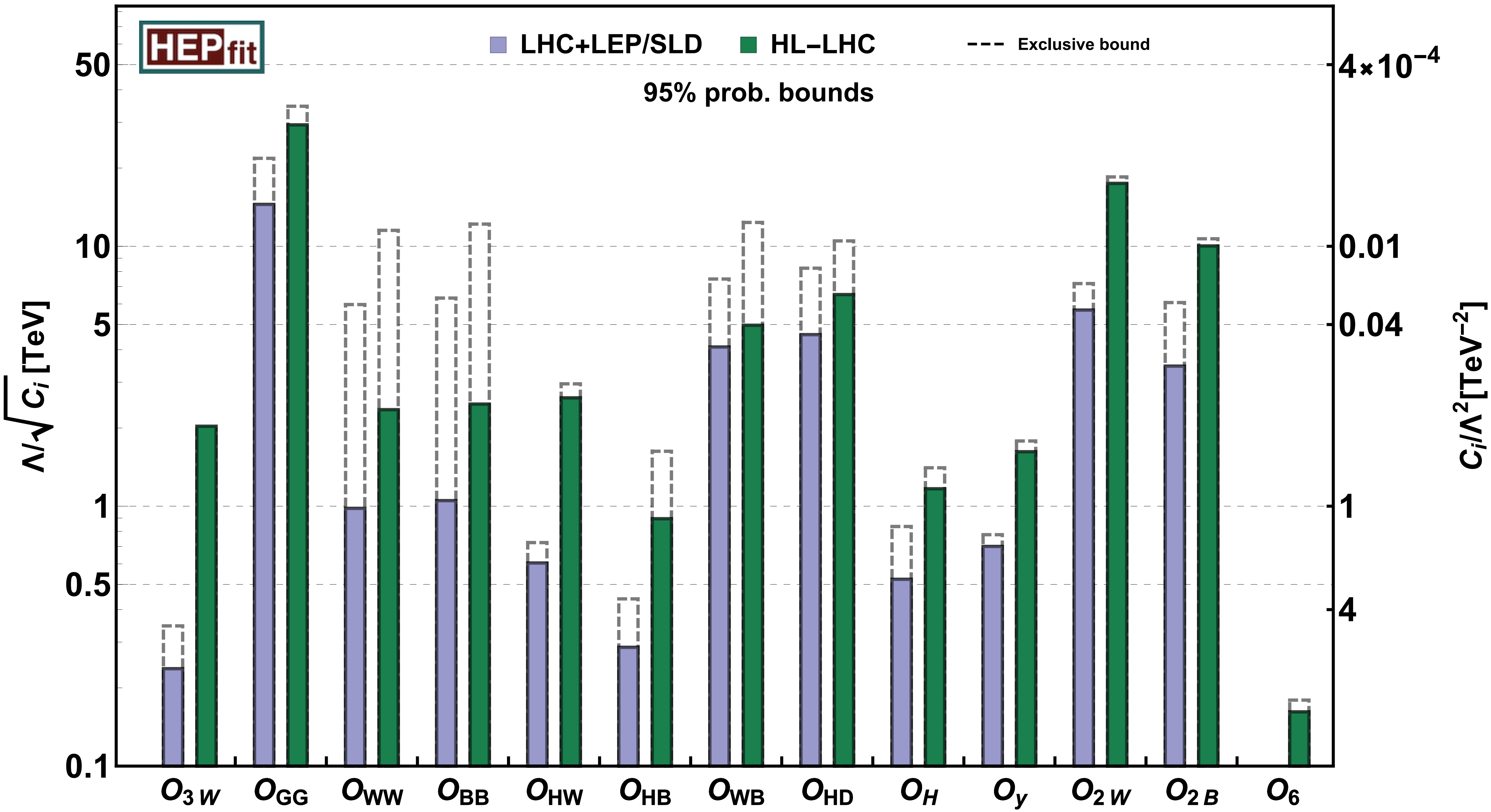
Ratios: Cancelation of uncertainties





Global Fits: EFT

Higgs couplings + DY + Diboson observables

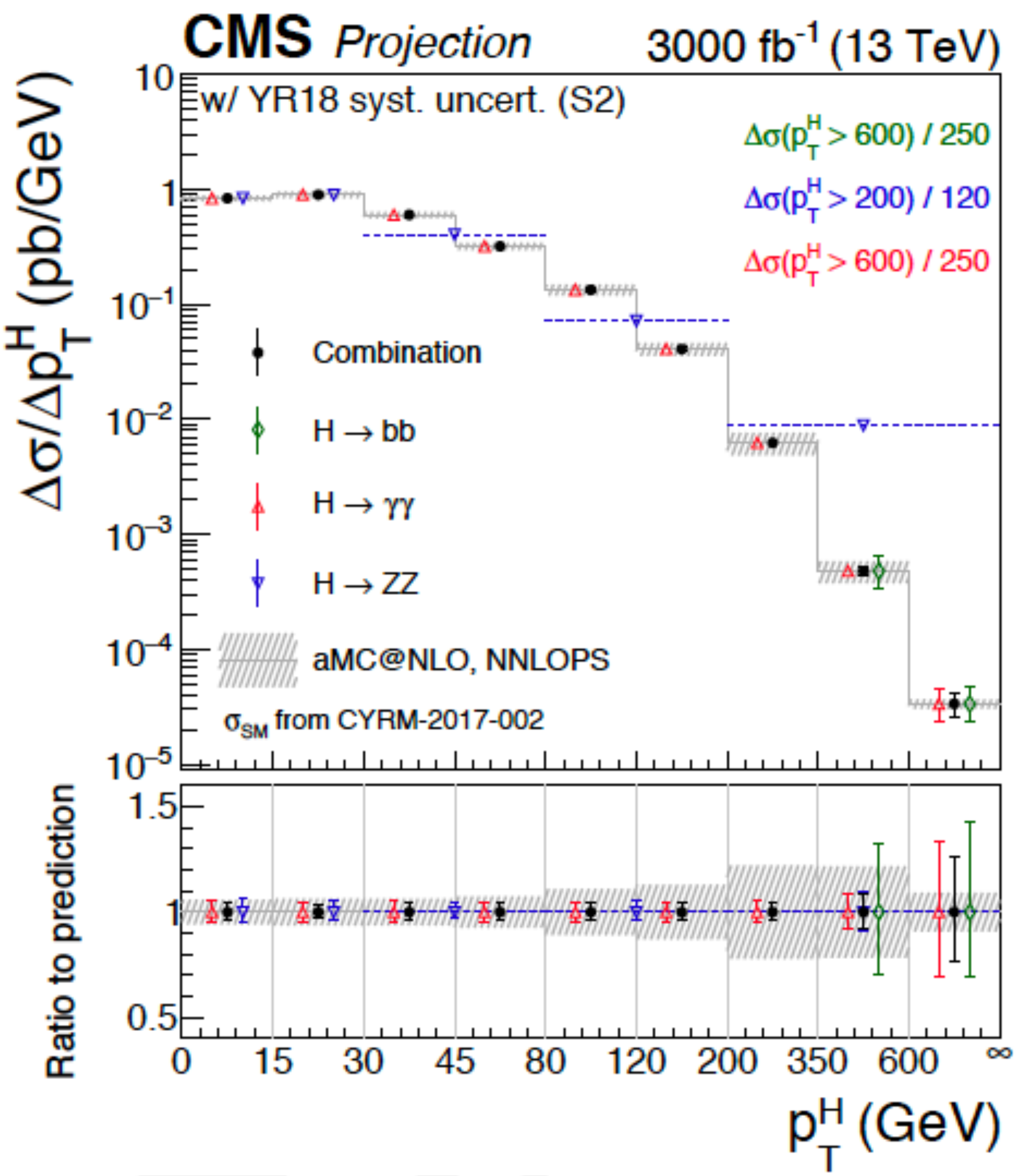


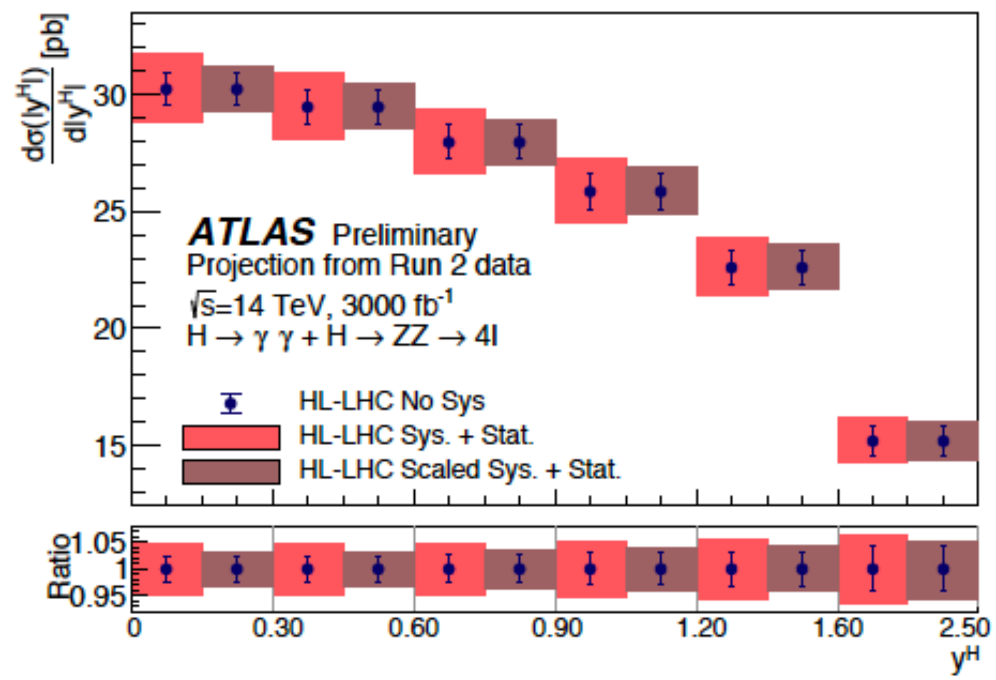
Fit by J. De Blas et al using CMS/ATLAS projections

eg: compositeness f>1.6 TeV, mass scale 20TeV

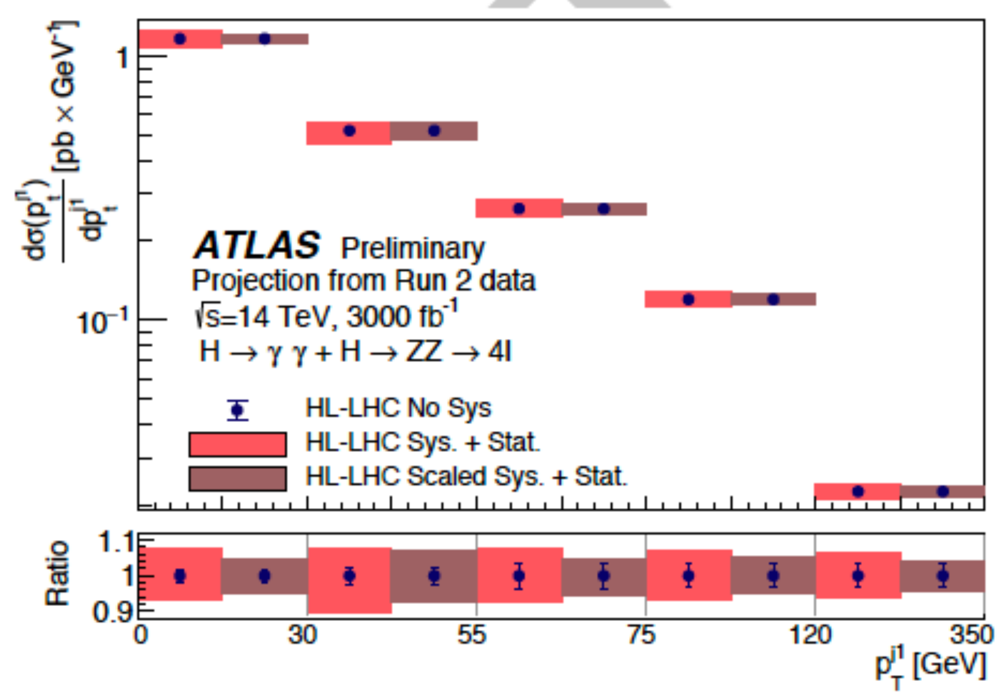
Differential Cross Sections

- Exploit the large dataset and go beyond inclusive measurements





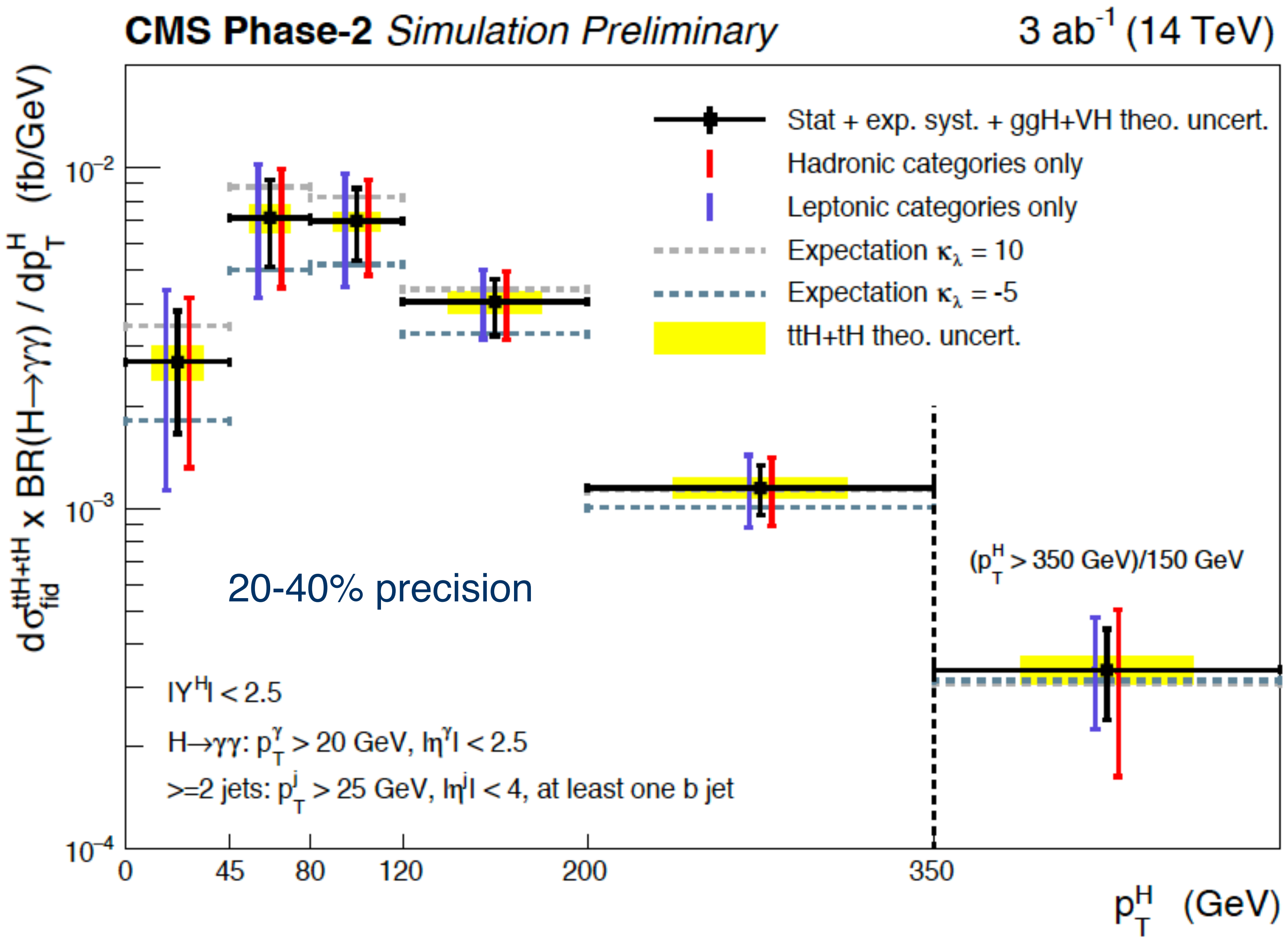
(b)



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

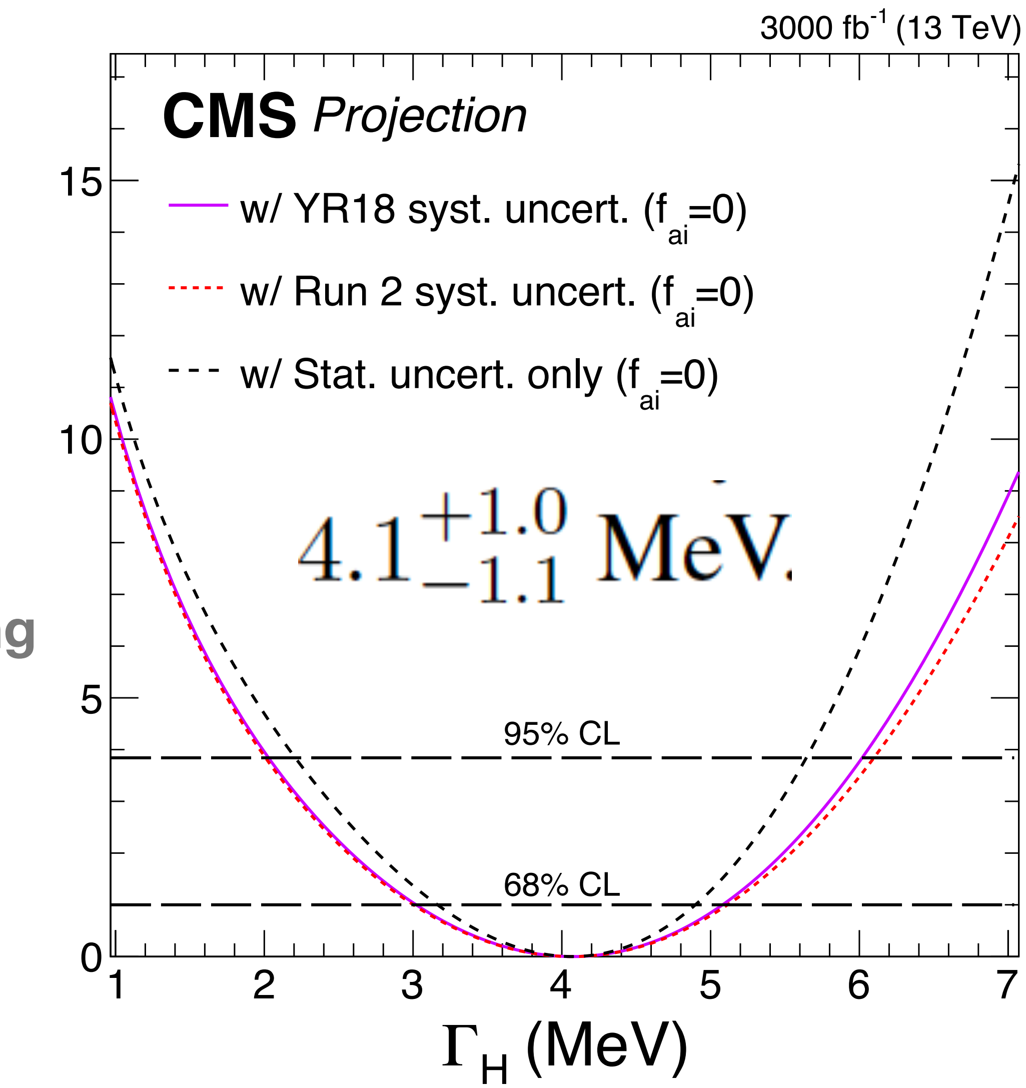
Differential Cross Sections

- Further characterisation of the kinematics of the boson: rarer production modes (tth) x differential measurements provide further insight
- Example: can be used to constrain the Higgs self coupling in an alternative way to the traditional HH analysis



Mass&Width

- **Width**:
  - Probe New Physics in the Higgs domain at large momenta
  - Direct measurement will be challenging also with HL-LHC statistics
  - **From couplings: Γ_H if kV≤1 —> 5% precision at 95% CL**
  - **4L Offshell: 25% precision at 68% CL (20% assuming CMS+ATLAS)**
  - gammagamma interference study: <40-50 Γ_{SM} (ATLAS)



- **Mass**: Exploit H->ZZ->4μ events. Reach dependent on future improvements on muon momentum measurements

ATLAS	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 Invisible

Connection between Higgs & Dark Matter

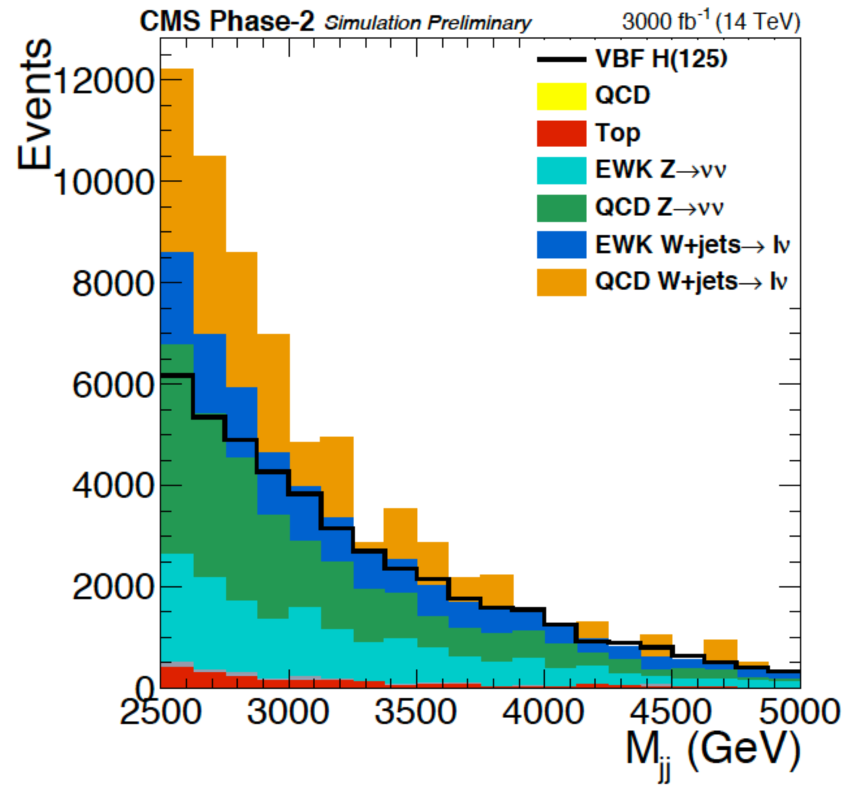
Run2 Limit ~20% @ 95%CL (in both experiments sensitivity dominated by the VBF channel)

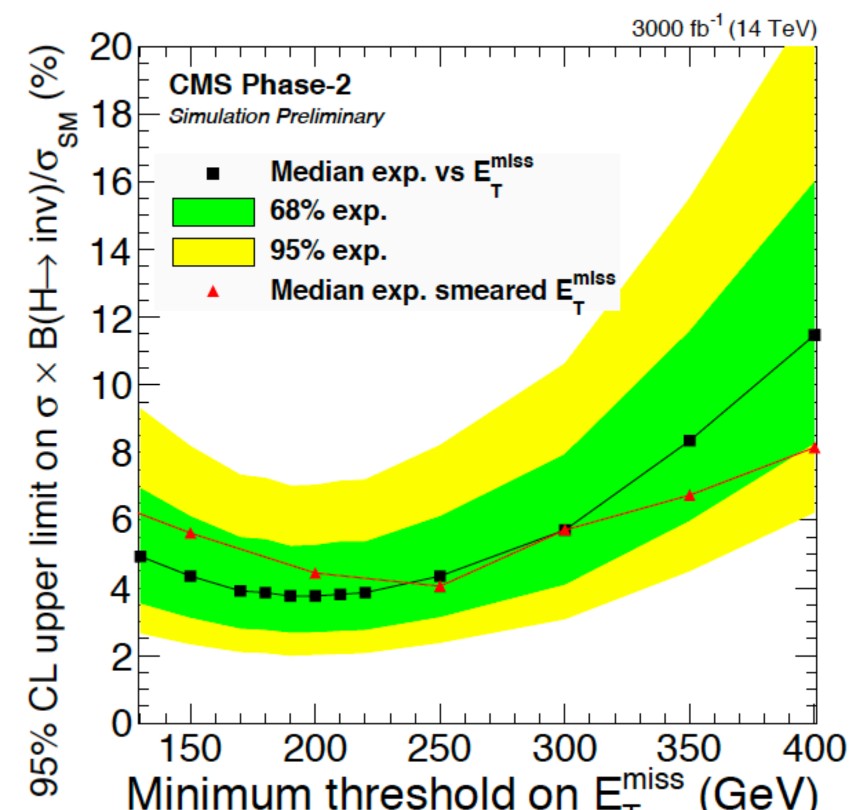
From the global coupling fit, if $B_{BSM} \geq 0$ (any invisible or undetected states): $B_{BSM} < 2.5\%$ @ 95% CL

Prospects of direct searches @ 14TeV:

VH: ATLAS, 2013: <8% @ 95%CL
VBF: CMS, 2018: <3.8% @ 95%CL

In the VBF case: full reoptimization of the analysis at 200PU to handle the impact of PU in MET



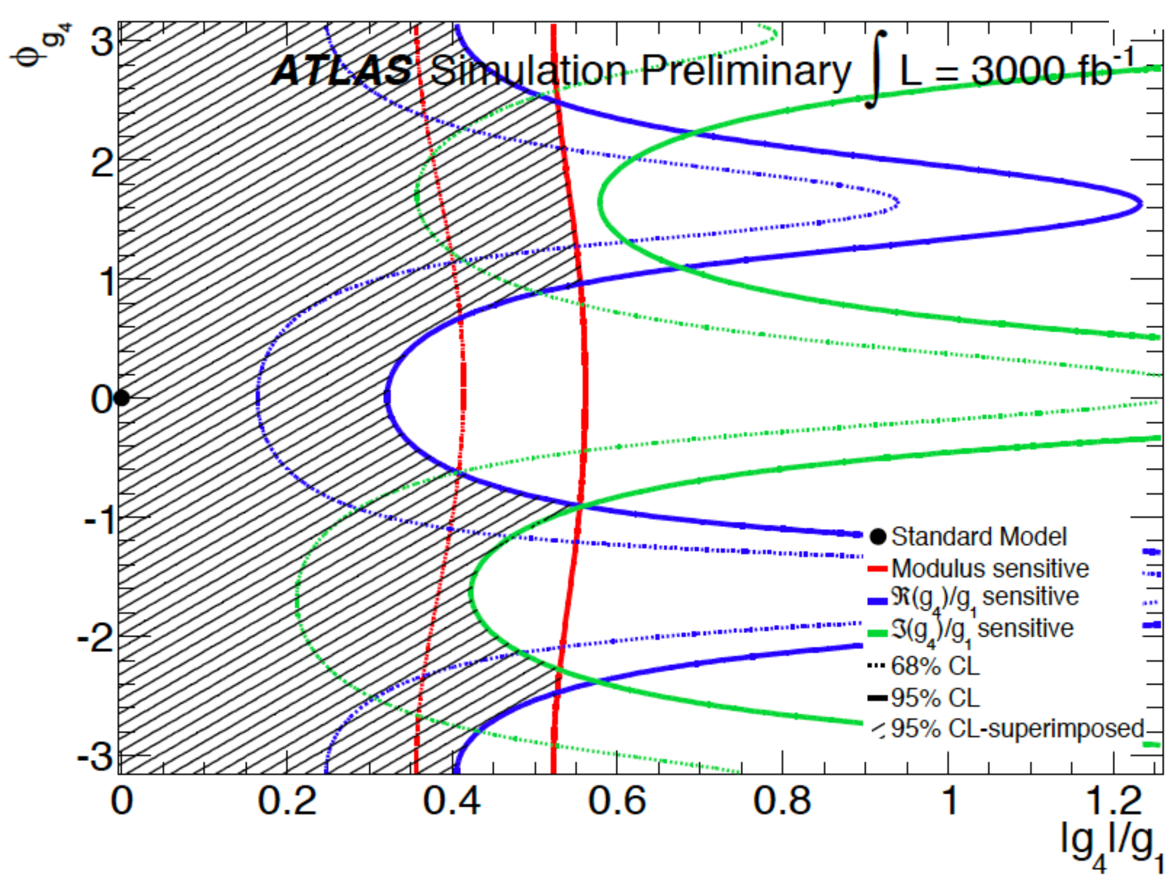


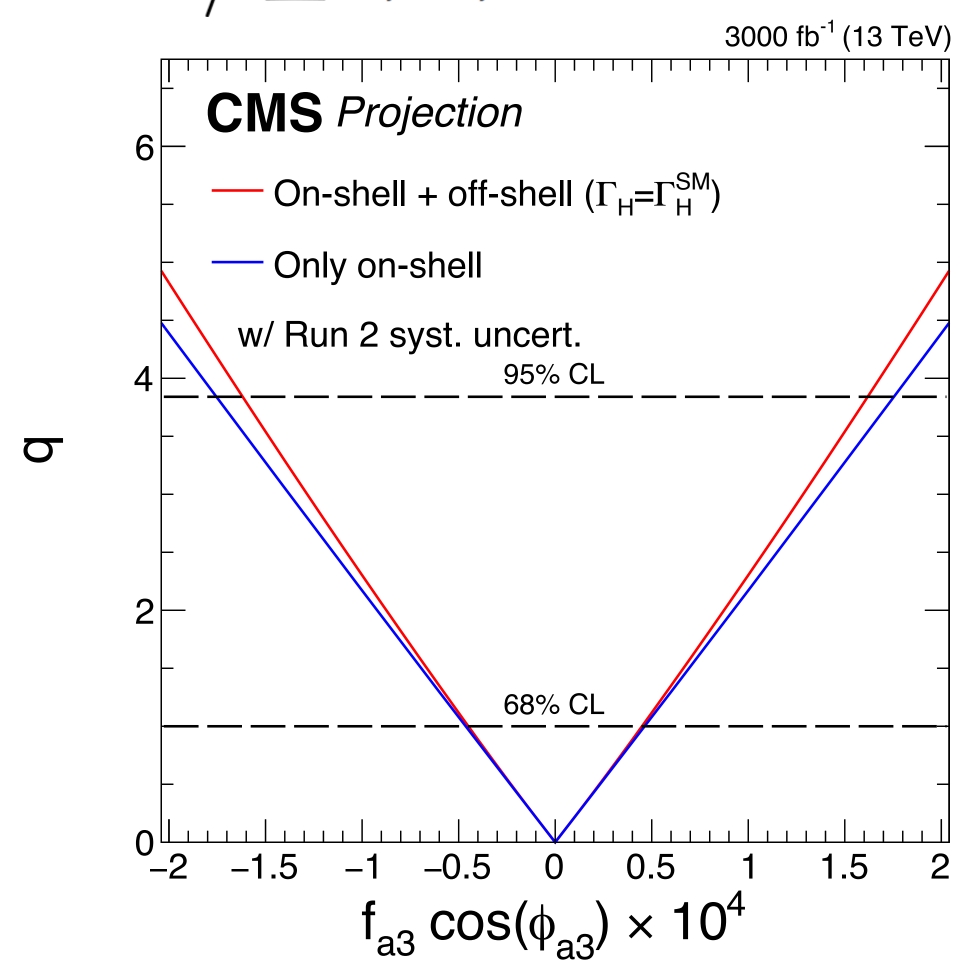
Anomalous Couplings

$$A(\mathrm{HVV}) \sim \left[a_1^{\mathrm{VV}} + \frac{\kappa_1^{\mathrm{VV}} q_1^2 + \kappa_2^{\mathrm{VV}} q_2^2}{\left(\Lambda_1^{\mathrm{VV}}\right)^2} \right] m_{\mathrm{V1}}^2 \epsilon_{\mathrm{V1}}^* \epsilon_{\mathrm{V2}}^* + a_2^{\mathrm{VV}} f_{\mu\nu}^{*(1)} f^{*(2),\mu\nu} + a_3^{\mathrm{VV}} f_{\mu\nu}^{*(1)} \tilde{f}^{*(2),\mu\nu}$$

SM

- Test for anomalous couplings: $f_{ai} = |a_i|^2 \sigma_i \Big/ \sum |a_j|^2 \sigma_j \quad \phi_{ai} = \arg\left(a_i / a_1\right)$





- Interference contribution becomes more dominant at smaller values of f_{ai} cos (f_{ai})

Rare decays

- **High statistics: rare decays become accessible**

- **Hμμ:** Probe coupling to 2nd generation —> prospects for **cross section and coupling measurement** → **8% & 5% uncertainty@3000fb^{-1}** respectively

- **Hcc**: how close can we get?

  μ(ZH, Hcc, ATLAS)<6.3 @ 95% CL, 3000fb^{-1}, 14 TeV (Best fit: Δμ=3.2)

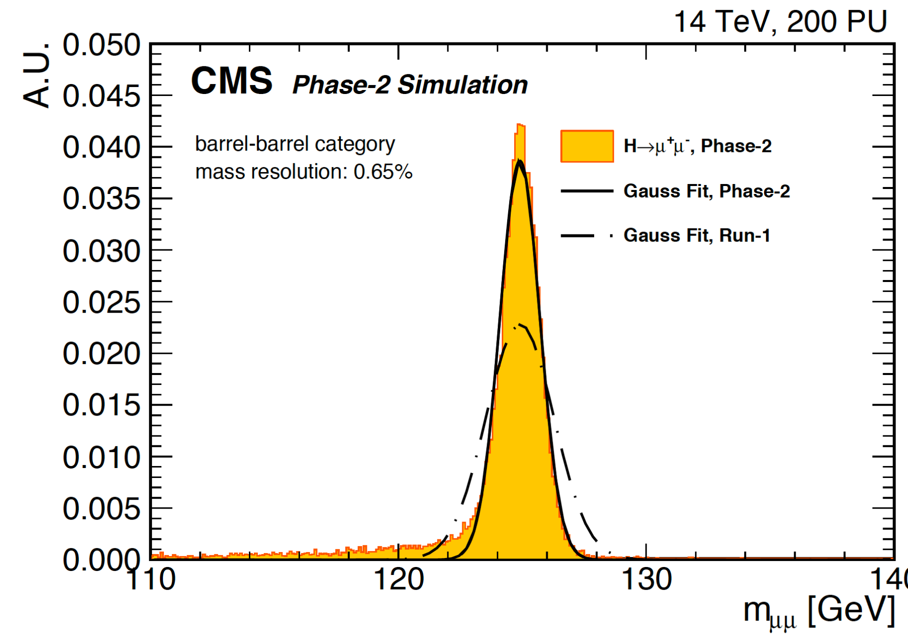
  LHCb: 50xSM projected, but factoring in detector upgrades 5-10XSM could be achieved, LHCb-CONF-2016-006

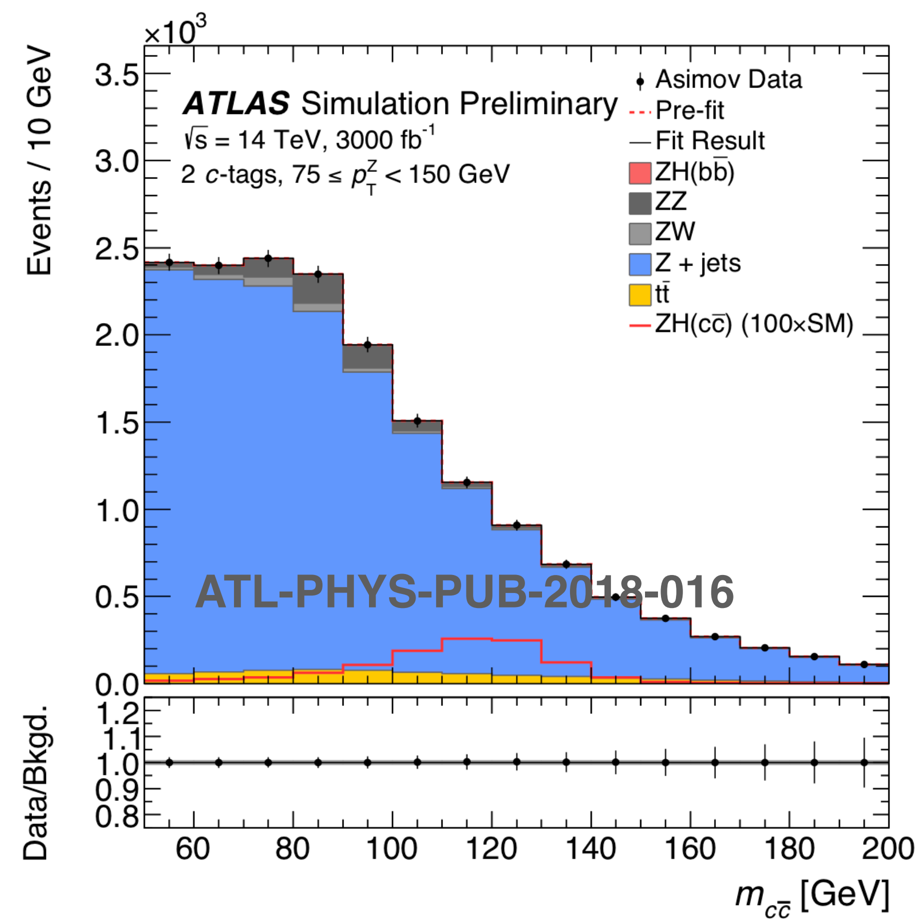
- **Also:**
  - H->J/ψ γ (ATLAS) -> probe c coupling (~x15 SM)

    Run2: B ($H \rightarrow \phi\gamma$)< 4.8×10^{-4}, exp SM $(2.31 \pm 0.11) \times 10^{-6}$

    B ($H \rightarrow \rho\gamma$) <8.8×10^{-4}, exp SM$(1.68 \pm 0.08) \times 10^{-5}$
  - H->Φγ / ργ (ATLAS) -> probe light-quark couplings. ργ already close to expectation.

BR (H→J/Ψ γ) < ($44^{+19}_{-22} \times 10^{-6}$) @ 95% CL

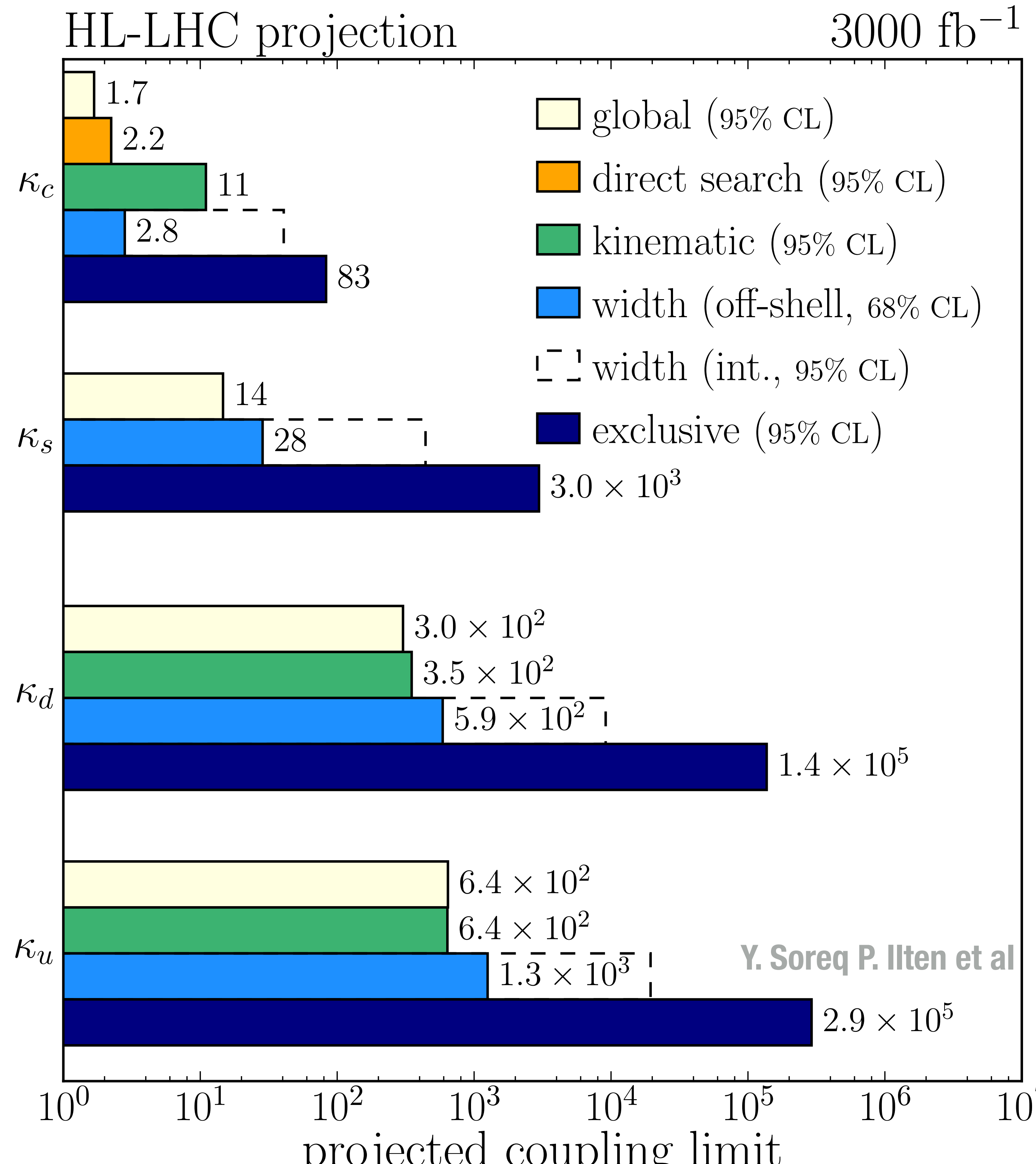




Summary of rare Yukawa Couplings

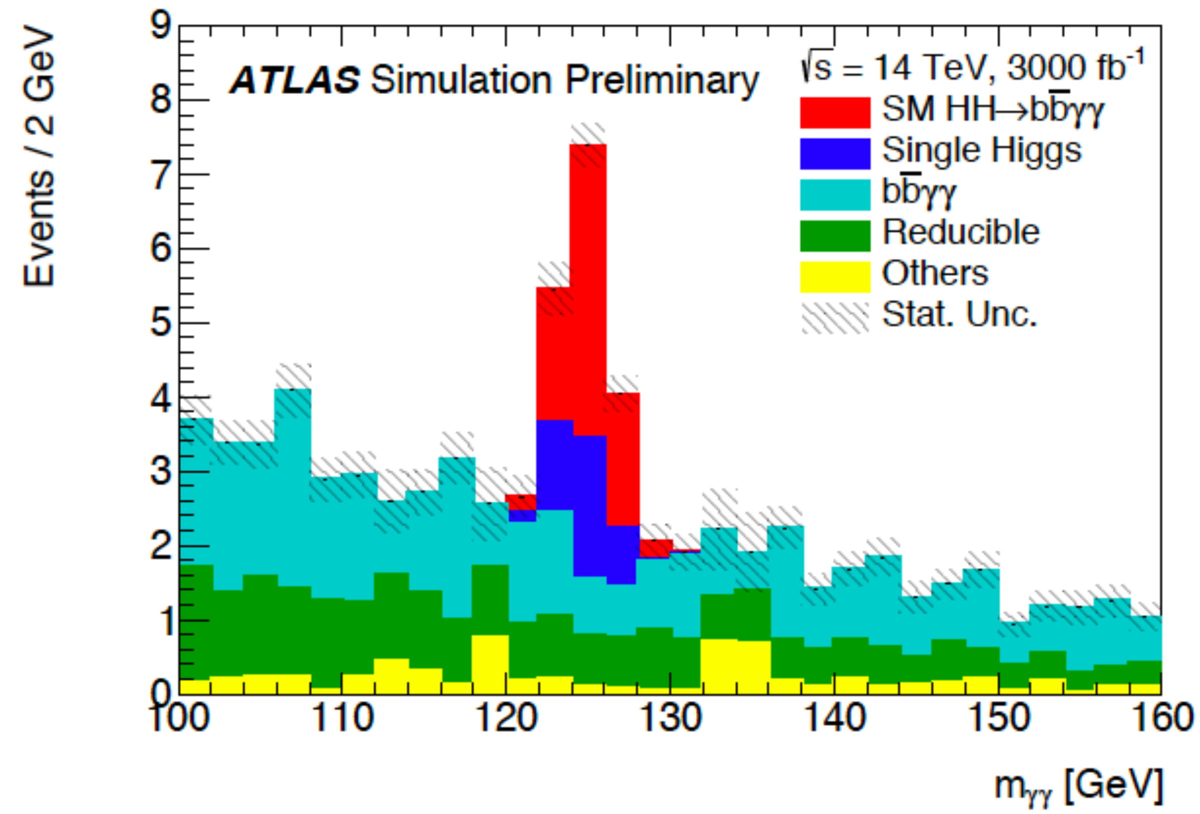
- Indirect constraints (eg from differential distributions, off-shell couplings, or from the global coupling fits) complement the direct searches

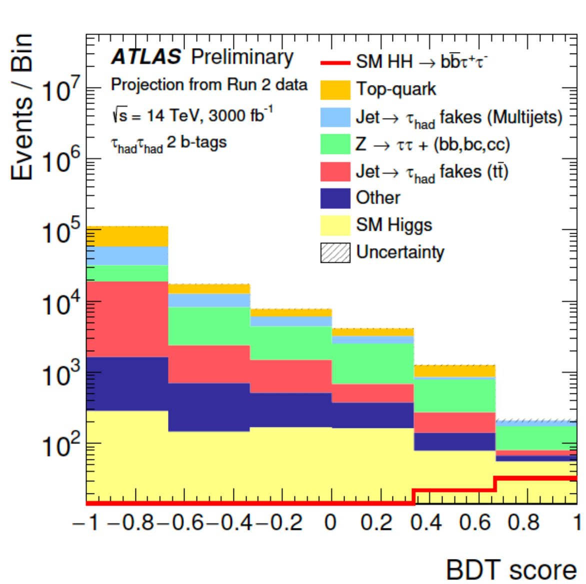
- The combined LHC (ATLAS+CMS+LHCb) reach for kappa_c could reach the 1% level

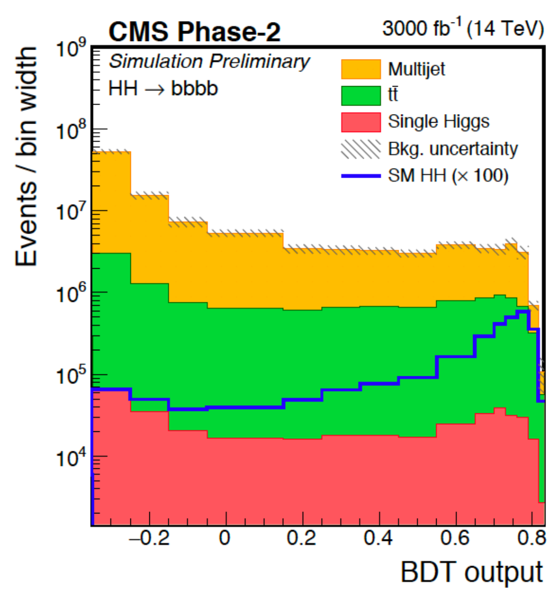


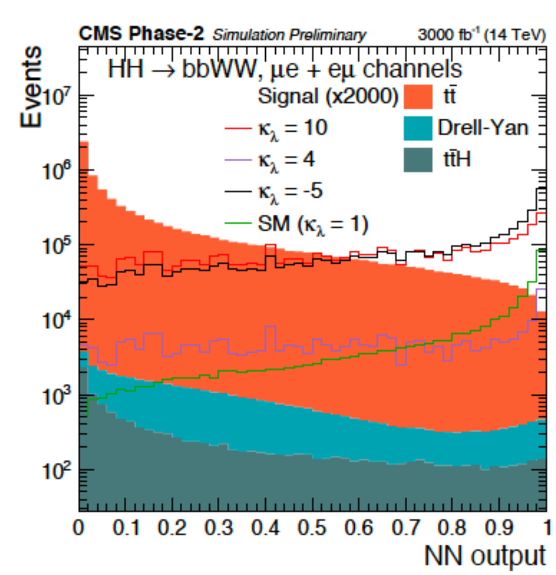
DiHiggs Production

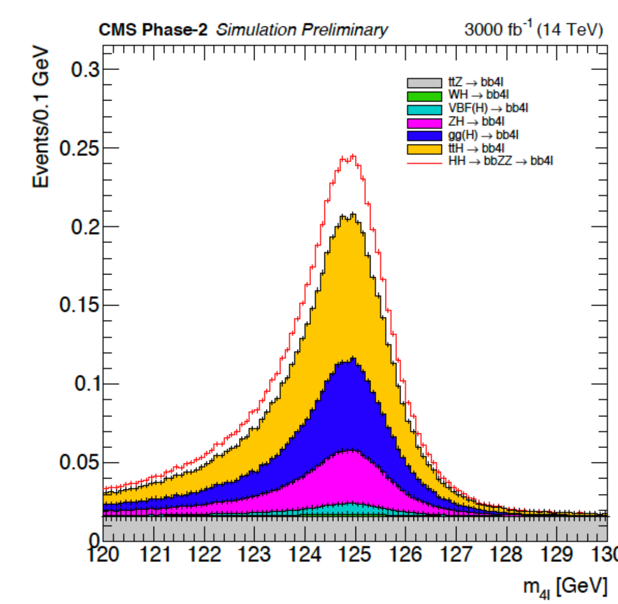
- **σ~ 39.5 fb@14TeV → HL-LHC benchmark**
  - Can we access the Higgs self-coupling λ?
  - Low cross section: destructive interference
- Expanding list of final states w. Run2 & extrapolated to HL-LHC : from the classical 2b2gamma to rarer modes like bbZZ
- Fully fledged MonteCarlo analyses



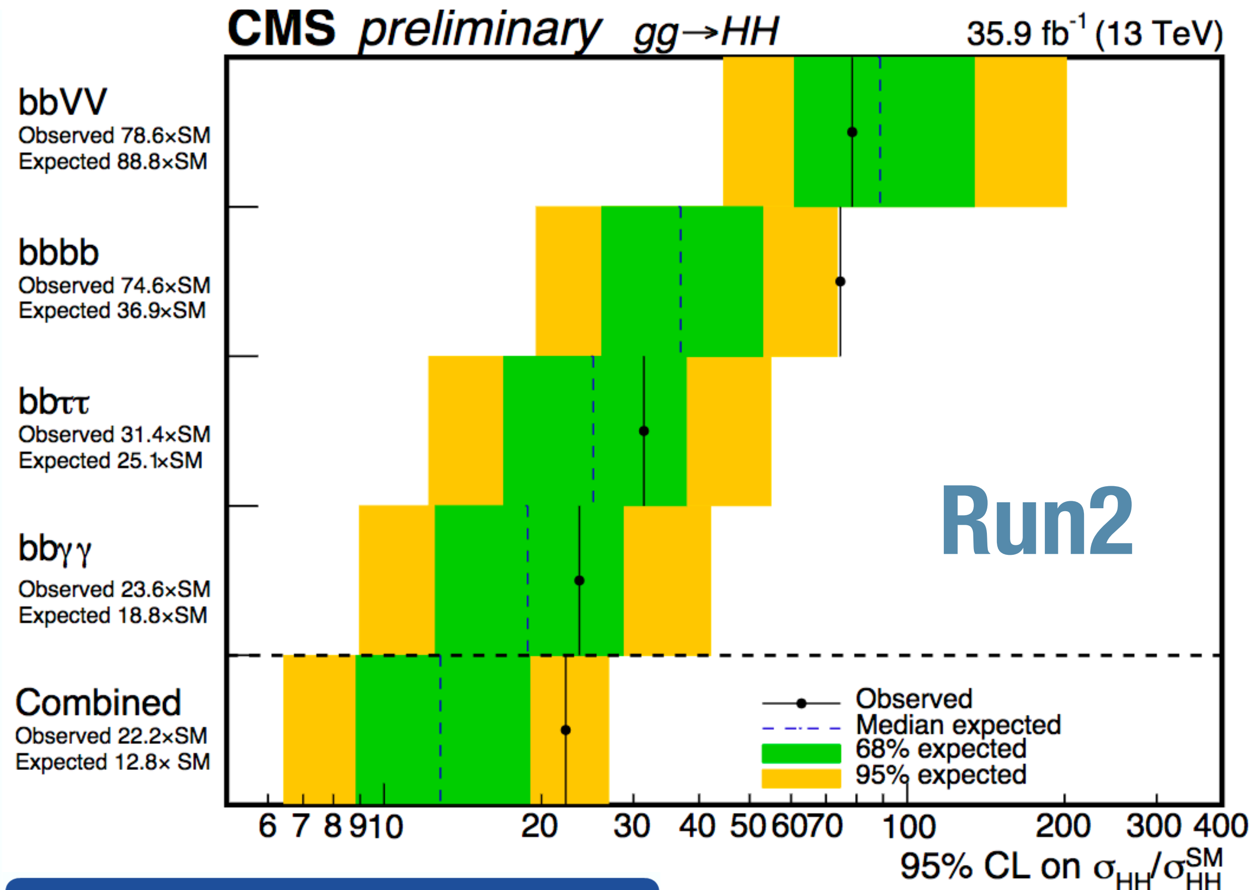




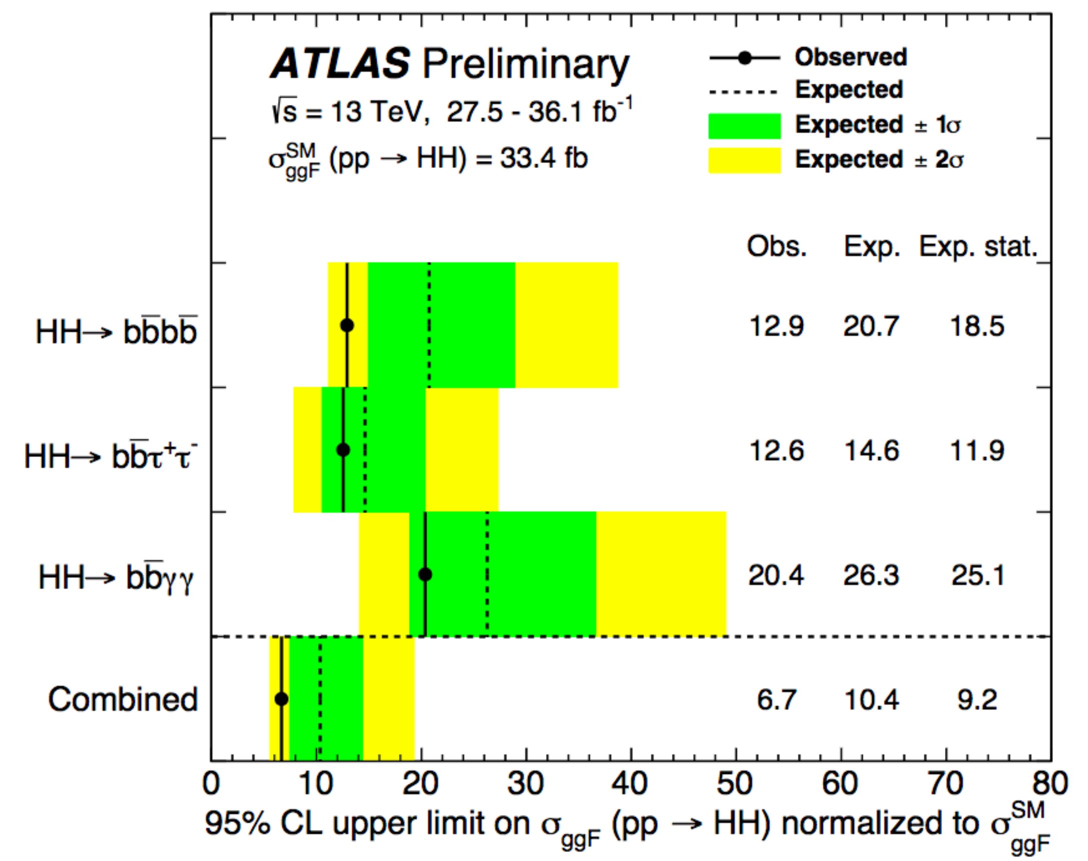




DiHiggs: Today



Constraint on $k_\lambda = \lambda_{HHH} / \lambda_{HHH}^{SM}$
Observed : $-11.8 < k_\lambda < 18.8$
Expected : $-7.1 < k_\lambda < 13.6$



$$-5.0 < \kappa_\lambda < 12.1 \; (-5.8 < \kappa_\lambda < 12.0)$$

~10 times the SM cross section (expected)

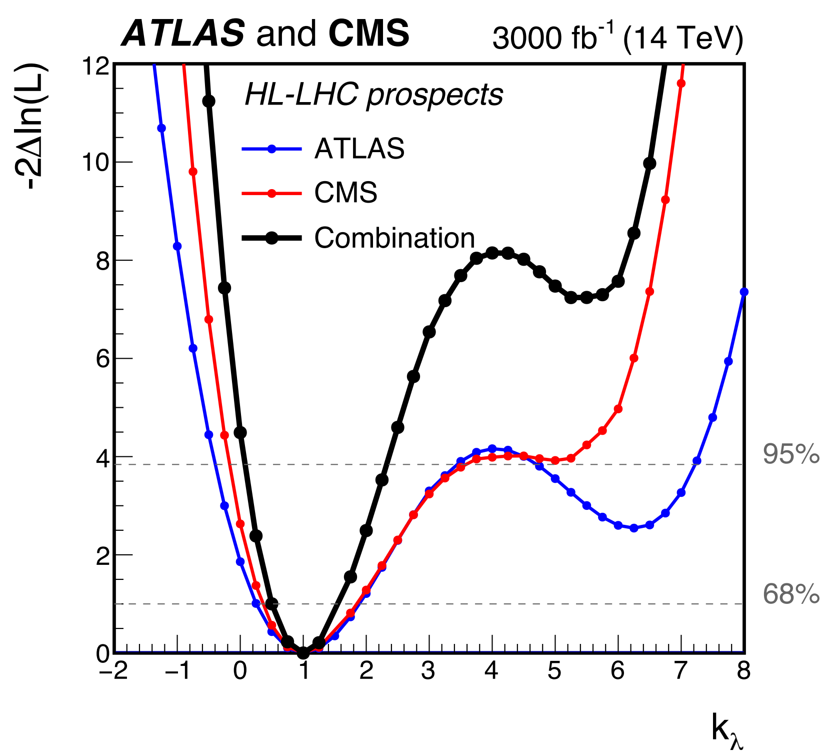
DiHiggs: 3000fb-1

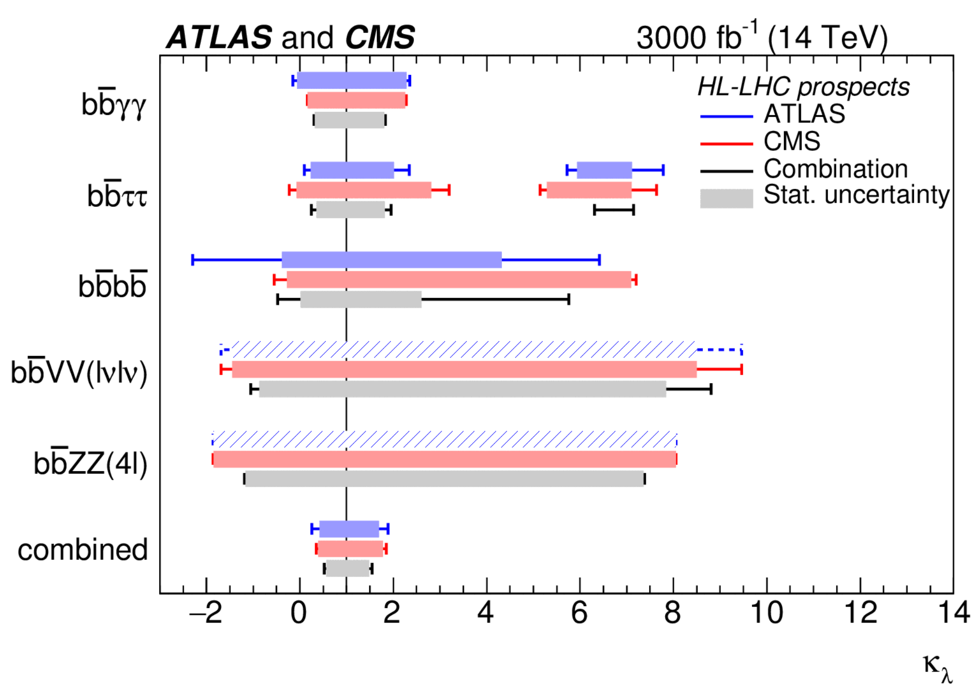
Combined significance of a single experiment: roughly 3 standard deviations

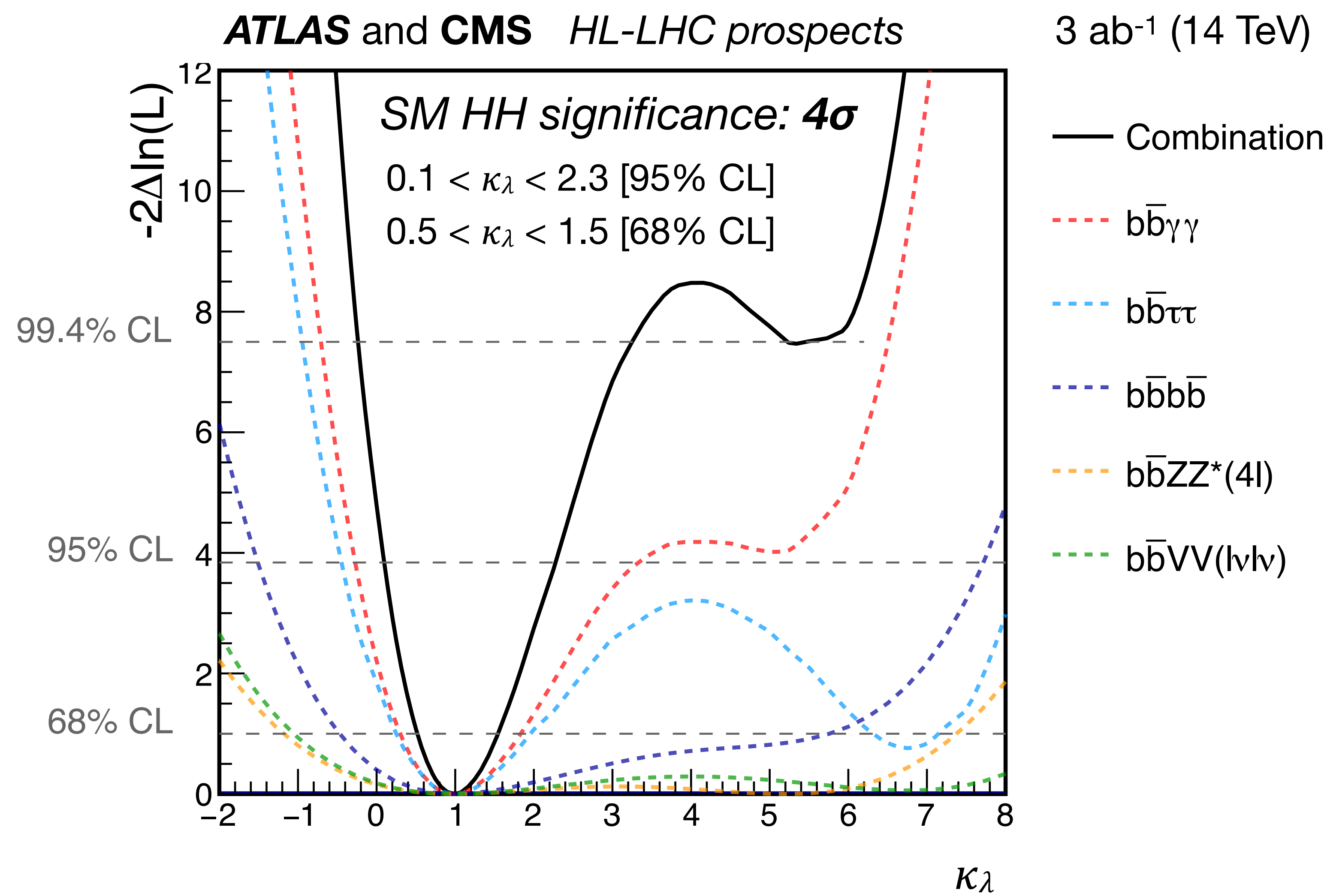
Combining the ATLAS and CMS results a significance of 4 standard deviation can be achieved (including systematic uncertainties).

	Statistical-only		Statistical + Systematic	
	ATLAS	CMS	ATLAS	CMS
$HH \rightarrow b\bar{b}b\bar{b}$	1.4	1.2	0.61	0.95
$HH \rightarrow b\bar{b}\tau\tau$	2.5	1.6	2.1	1.4
$HH \rightarrow b\bar{b}\gamma\gamma$	2.1	1.8	2.0	1.8
$HH \rightarrow b\bar{b}VV(ll\nu\nu)$	-	0.59	-	0.56
$HH \rightarrow b\bar{b}ZZ(4l)$	-	0.37	-	0.37
combined	3.5	2.8	3.0	2.6
	Combined 4.5		Combined 4.0	

DiHiggs: 3000fb-1



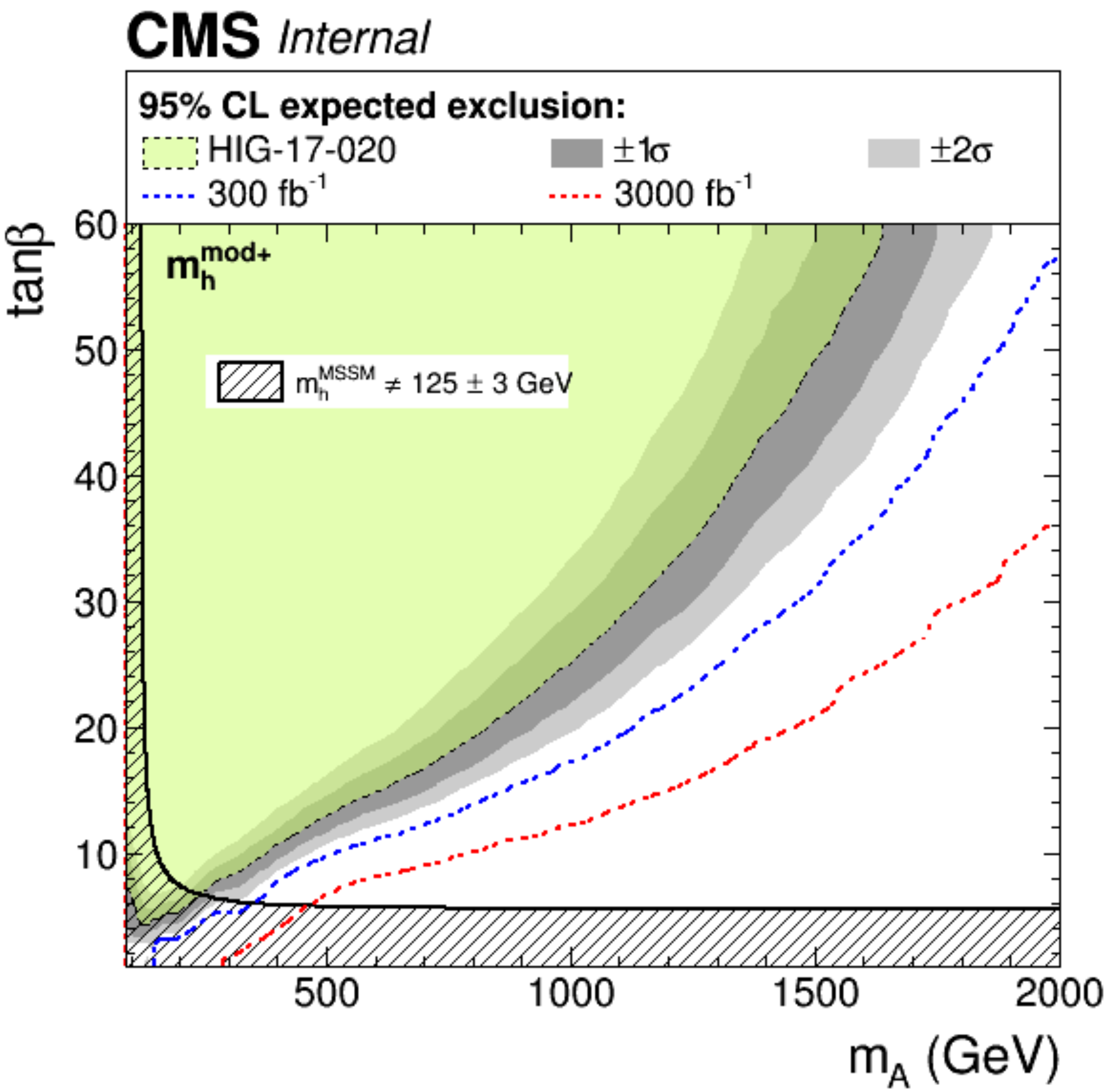


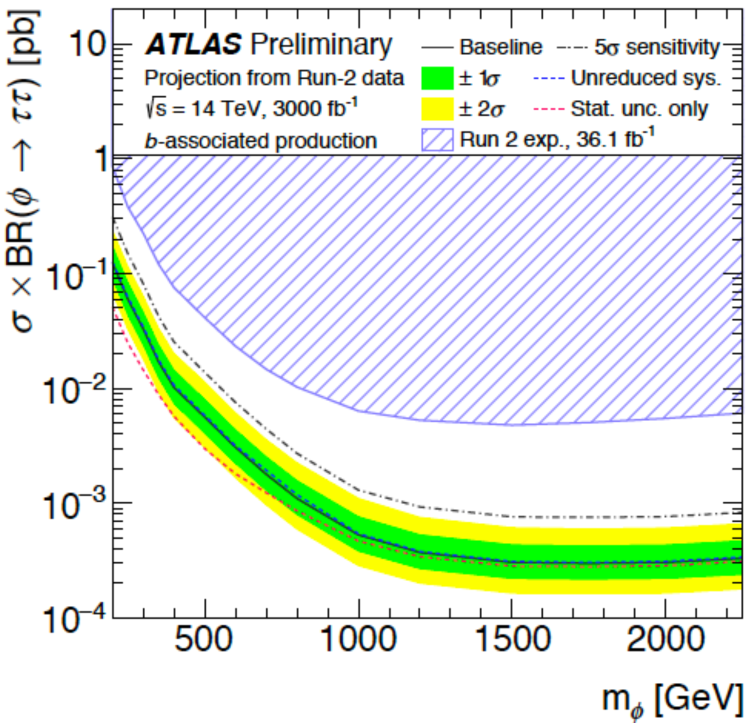


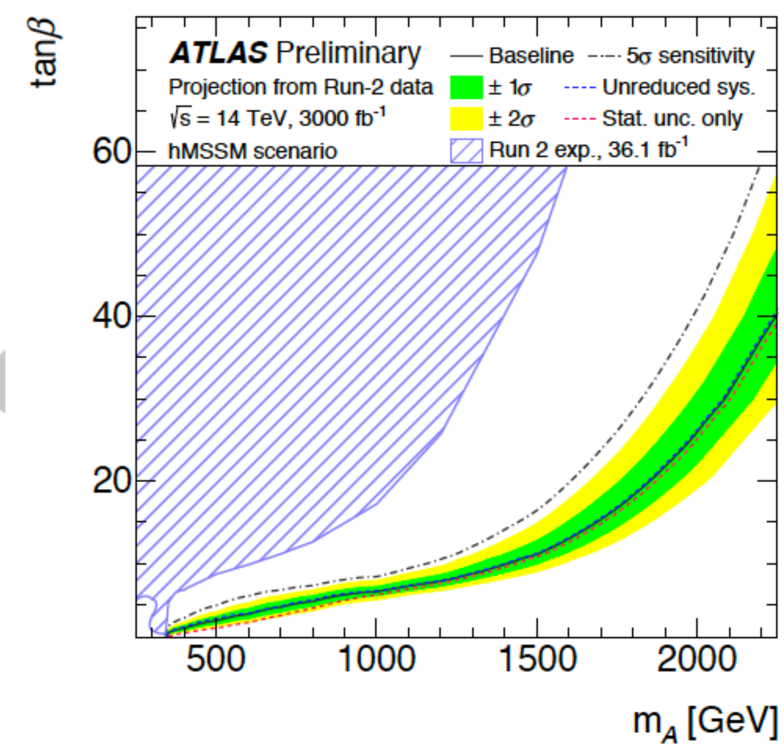
Second minimum of the negative log-likelihood excluded at 99.4% CL.

Extended Higgs Sector

Are there more Higgs bosons? Can we find them at the HL-LHC?
Benchmark channel: Htautau

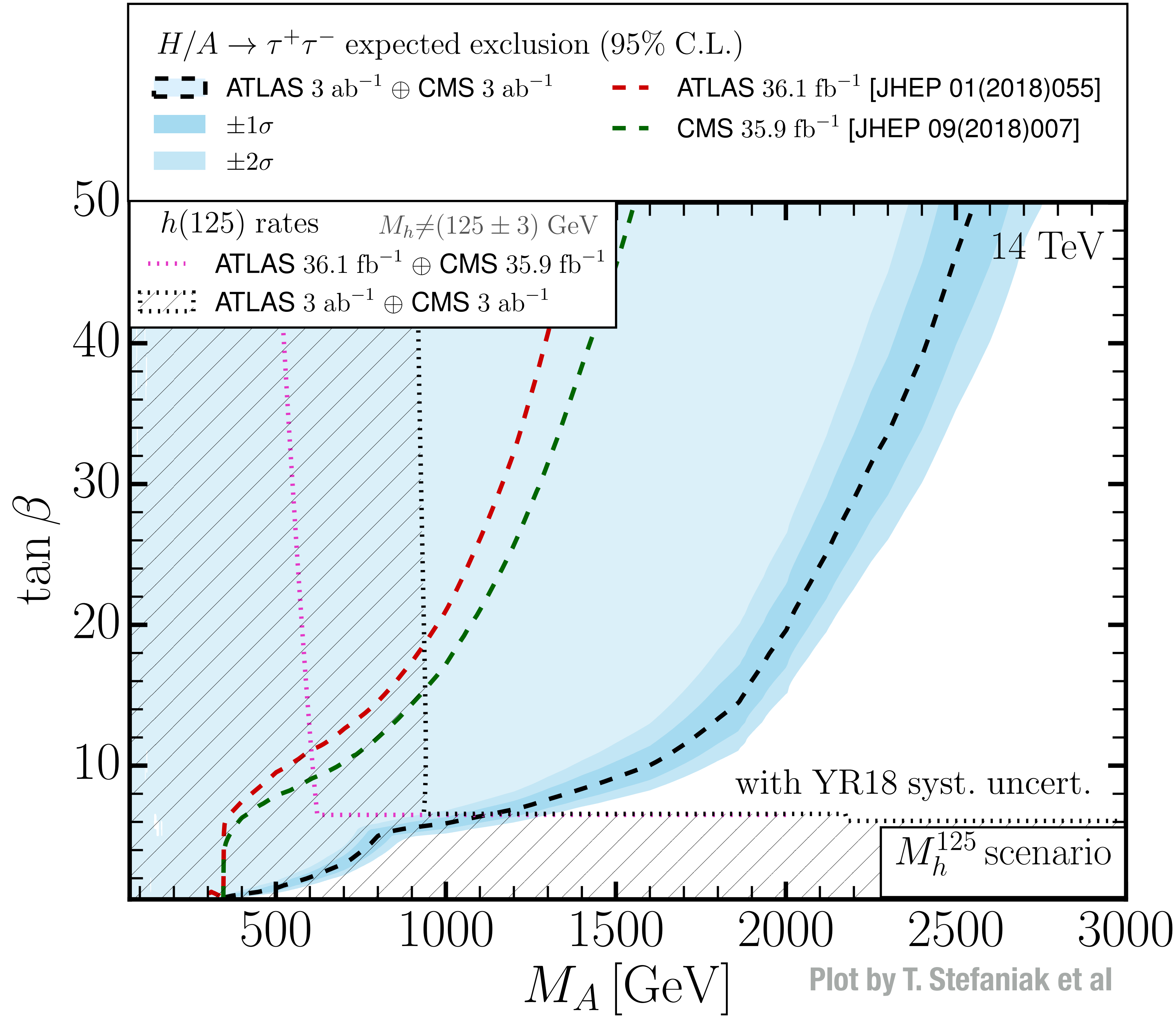






MSSM: Benchmarks update

Update of the traditional MSSM scenarios: comparison of direct Htautau limits and indirect constraints from the couplings extrapolations



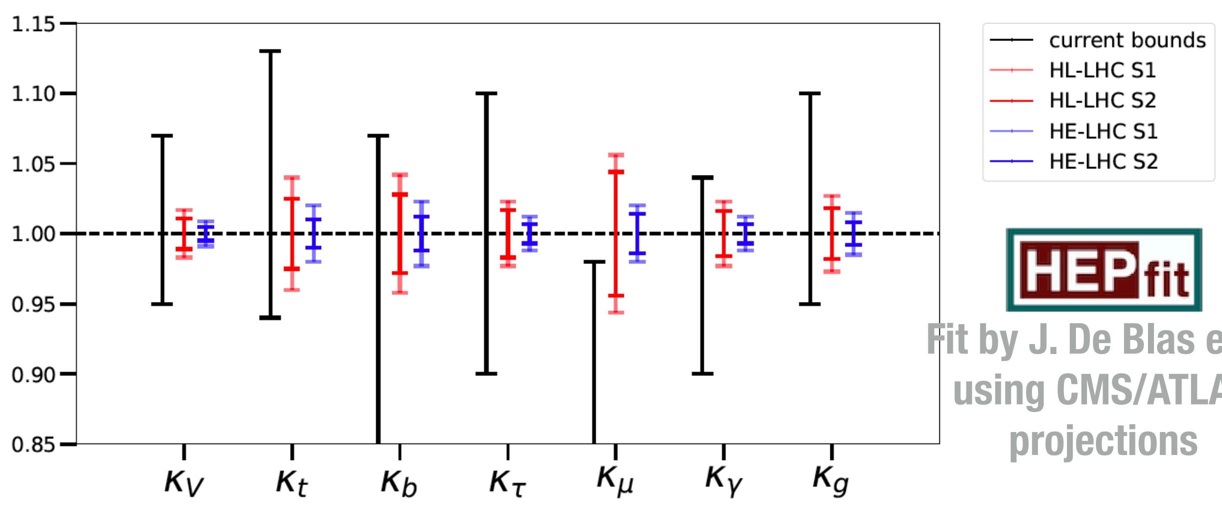
Higgs@HL-LHC: How much have we covered?

	CMS	ATLAS	LHCb
Couplings Studies	✔✔★	✔✔★	
Differential CrossSections	✔★	✔★	
Width	★	✔	
Anomalous couplings	✔★	✔	
Rare Decays	Zγ,μμ	Zγ,J/ψγ,FCNC μμ,ργ,cc	**Hcc/Hbb**
Exotic Decays	**VBF H Invisible, 4jets**	**Invisible (ZH)**	**DarkSusy**
DiHiggs & self coupling	✔✔★	✔✔★	
Additional Scalars	A->Zh, high mass ττ	μμ, ZZ, A->Zh, ττ	

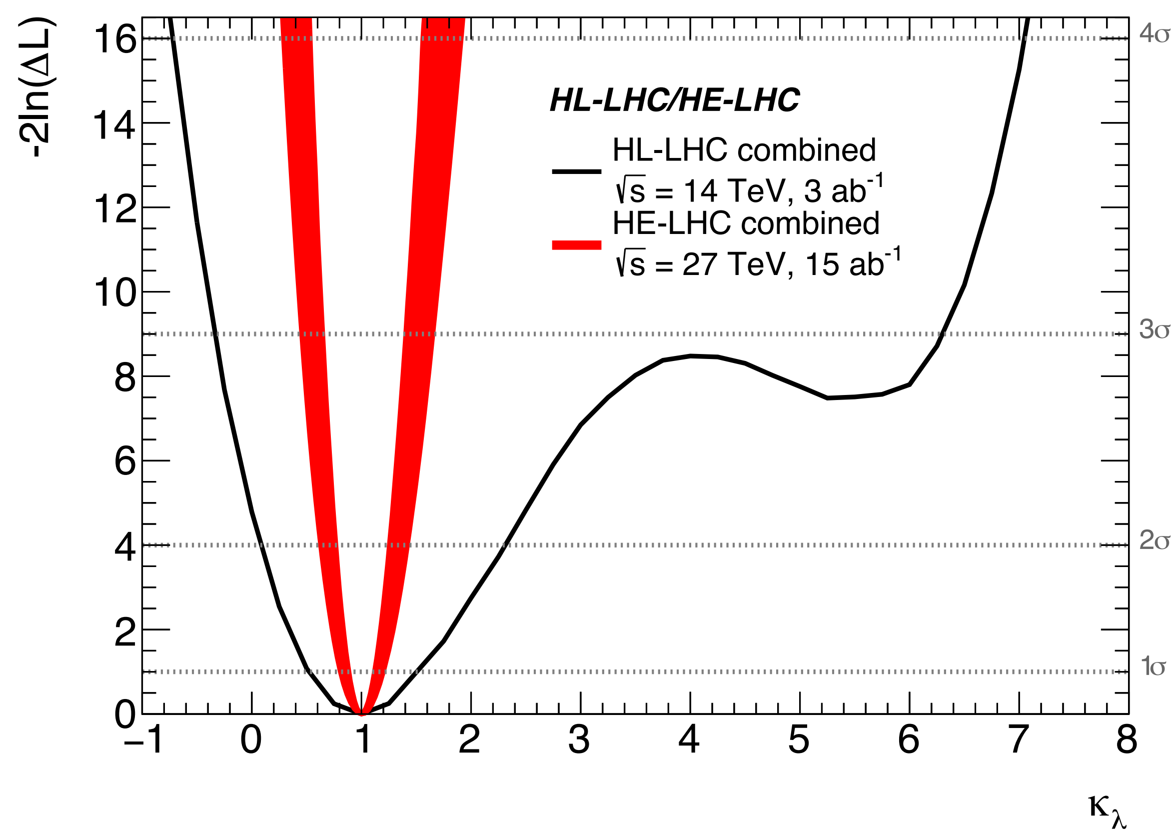
Legend: Past Studies, 2017 TDRs, 2New in 2018

What about the HE-LHC?

- The HE-LHC will extend the HL-LHC reach in direct searches for new particles, approximately doubling the reach in mass —> high impact on BSM Higgs studies
- In terms of SM Higgs, it will enhance statistically limited processes and enable the access to very large transverse momenta.



Fit by J. De Blas et al using CMS/ATLAS projections



- As an hyphotesis, assuming an additional factor of 1/2 reduction of theoretical uncertainties plus the increase in cross section yields clear improvements in the global fit results
- Once again, special focus on HH reach: precision of 10% to 20% on κ_λ could be achieved from just the combination of the two main decay modes (bbtautau and bbgammagamma)

How well will we know the Higgs by the end of the LHC program?

- Is its production rate, where we measure it, at the correct SM level?
- How do we caracterize it? (mass, width, spin)
- How well can we model its behaviour?
- Does it couple to SM particles at the appropriate level?
- Does it couple to itself?
- Does it decay unusually?
- Are there more Higgses?
- Higgs as a tool for discovery

The HL/HE-LHC datasets will allow us to fully characterise the Higgs boson
Will new physics be able to still hide after the scrutiny?

Conclusions

- **Higgs studies are central to the HL(HE)-LHC program:**
  - Measurement of the Higgs couplings possible to few percent
  - Differential distributions and fiducial cross sections: probing interesting phase spaces and reducing dependence on theoretical uncertainties
  - High statistics: rare processes become accessible
  - Enhanced sensitivity to New Physics involving Higgs bosons
- **The 2018 Yellow Report presents a coherent view of the experimental and theoretical prospects for Higgs studies at the HL-LHC, and broach for the first time the HE-LHC reach**
- **Now the plan is set, next: making these prospects materialise in actual measurements!**

References

- The long report: CERN-LPCC-2018-04 - https://cds.cern.ch/record/2650162/
    - 10 pages summaries: https://twiki.cern.ch/twiki/pub/LHCPhysics/HLHELHCWorkshop/report.pdf https://twiki.cern.ch/twiki/pub/LHCPhysics/HLHELHCWorkshop/HEreport.pdf

- **ATLAS**: ATL-PHYS-PUB-2018-054 , ATL-PHYS-PUB-2018-053 , ATL-PHYS-PUB-2018-050, ATL-PHYS-PUB-2018-040, ATL-PHYS-PUB-2018-016, ATL-PHYS-PUB-2018-006 (plus older studies)

- **CMS**: CMS-PAS-FTR-18-011, CMS-PAS-FTR-18-016, CMS-PAS-FTR-18-017, CMS-PAS-FTR-18-018, CMS-PAS-FTR-18-019, CMS-PAS-FTR-18-020 (plus older studies)

ATLAS and CMS UPGRADE Documents

ATLAS

Letter of Intent CERN-LHCC-2012-022
https://cds.cern.ch/record/1502664
Scope Document CERN-LHCC-2015-020
https://cds.cern.ch/record/2055248
Itk Strip TDR
http://cdsweb.cern.ch/record/2257755
Muons TDR
http://cdsweb.cern.ch/record/2285580
Liquid Argon Calorimeter TDR
http://cdsweb.cern.ch/record/2285582
Tile Calorimeter TDR
http://cdsweb.cern.ch/record/2285583
Itk Pixel TDR
https://cds.cern.ch/record/2285585/
TDAQ TDR
https://cds.cern.ch/record/2285584/

PHYSICS STUDIES
https://twiki.cern.ch/twiki/bin/view/AtlasPublic/UpgradePhysicsStudies

CMS

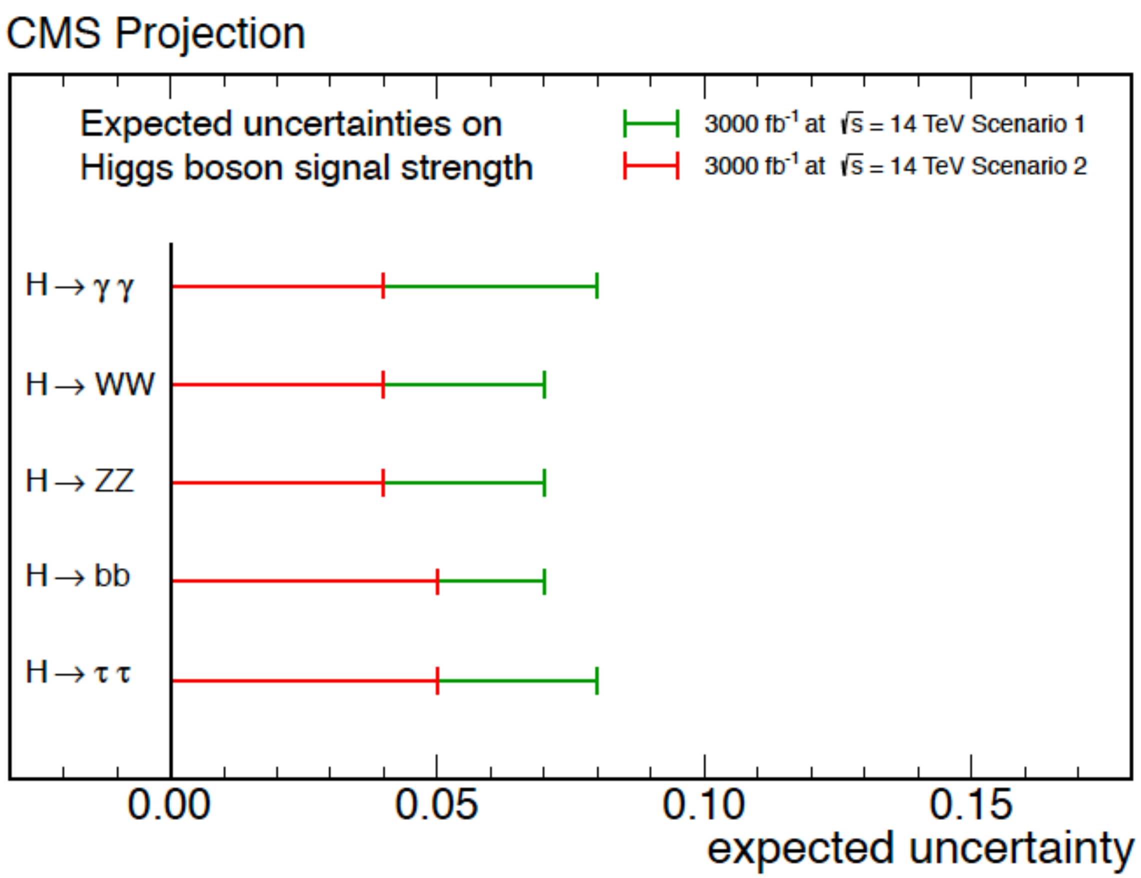
Technical Proposal: CERN-LHCC-2015-010
https://cds.cern.ch/record/2020886
Scope Document CERN-LHCC-2015-019
https://cds.cern.ch/record/2055167
Tracker TDR
https://cds.cern.ch/record/2272264
Barrel Calorimeter TDR
https://cds.cern.ch/record/2283187
Muon TDR
http://cds.cern.ch/record/2283189

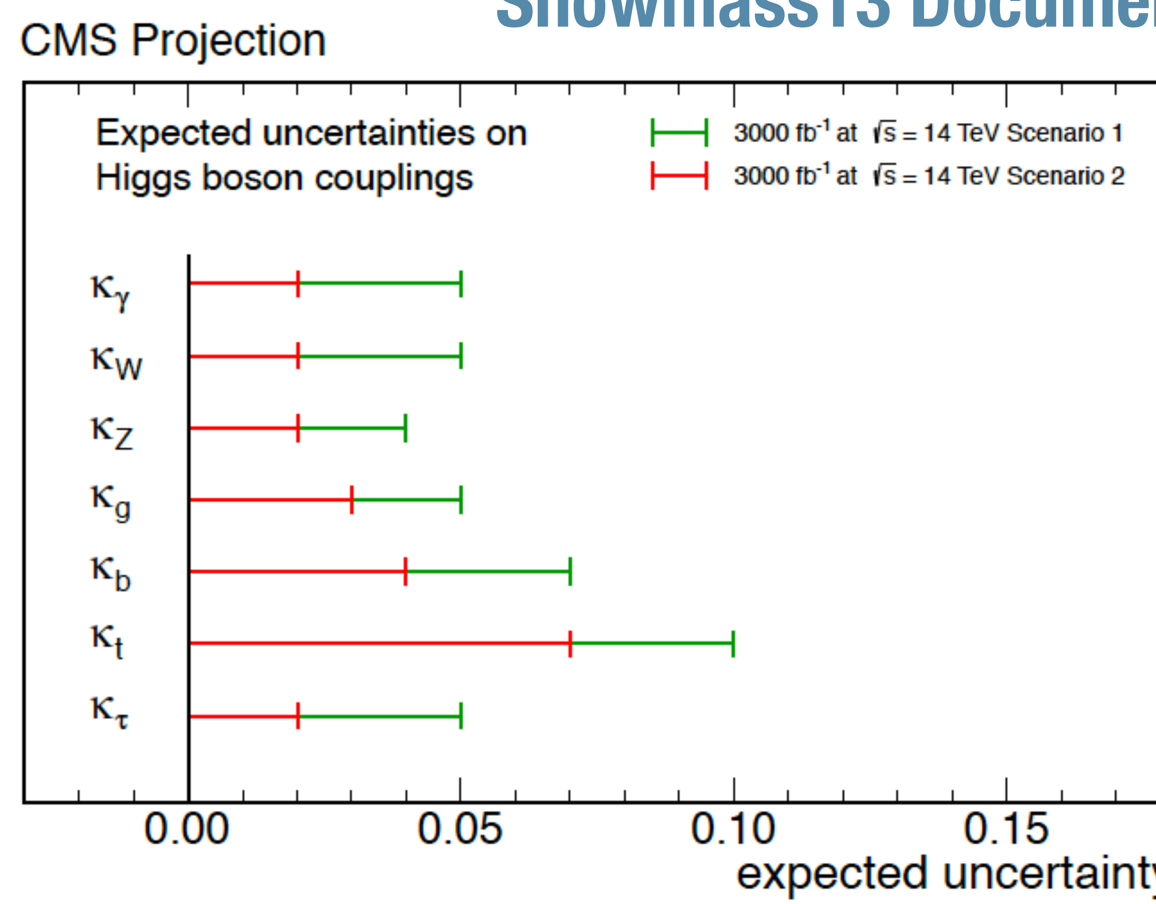
PHYSICS STUDIES
http://cms-results.web.cern.ch/cms-results/public-results/preliminary-results/FTR/index.html

Run1-based couplings study

- **Comprehensive study of Higgs couplings at HL-LHC**
- Run1 extrapolations for the main decay channels and production modes

Snowmass13 Document





L (fb^{-1})	$\gamma\gamma$	WW	ZZ	bb	$\tau\tau$	$Z\gamma$	$\mu\mu$	inv.
300	[6, 12]	[6, 11]	[7, 11]	[11, 14]	[8, 14]	[62, 62]	[40,42]	[17, 28]
3000	[4, 8]	[4, 7]	[4, 7]	[5, 7]	[5, 8]	[20, 24]	[16,16]	[6, 17]

(%)

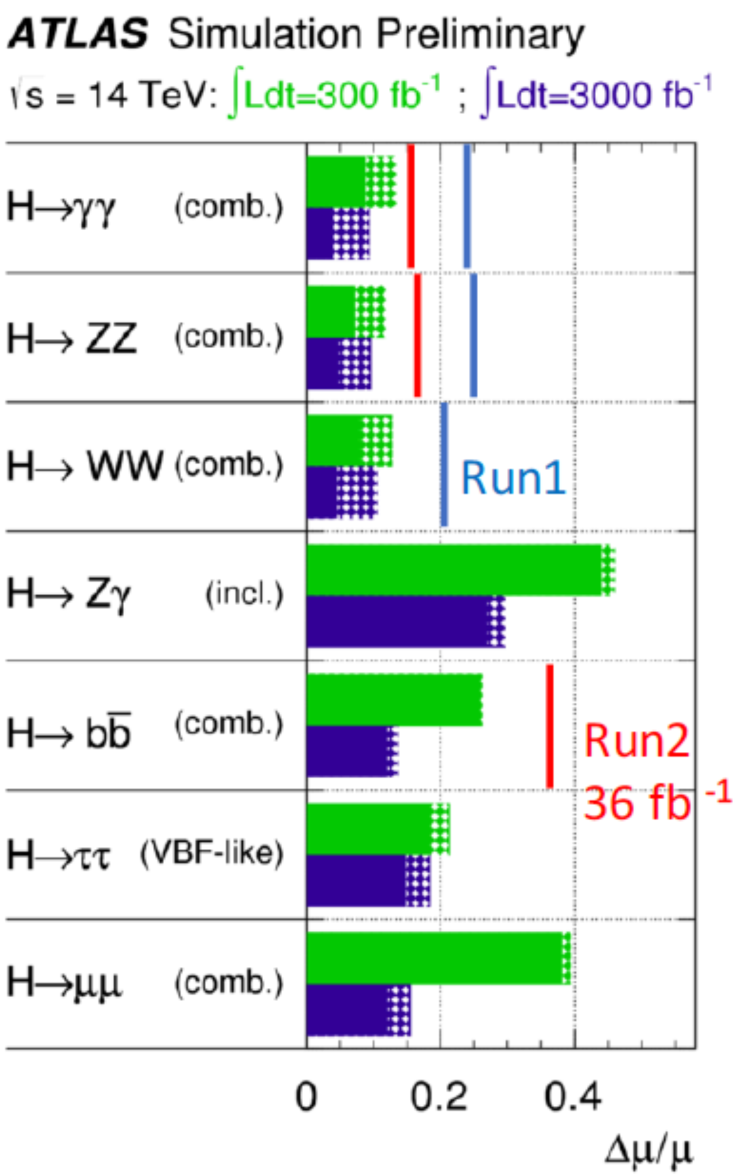
L (fb^{-1})	κ_γ	κ_W	κ_Z	κ_g	κ_b	κ_t	κ_τ	$\kappa_{Z\gamma}$	$\kappa_{\mu\mu}$	BR_{SM}
300	[5, 7]	[4, 6]	[4, 6]	[6, 8]	[10, 13]	[14, 15]	[6, 8]	[41, 41]	[23, 23]	[14, 18]
3000	[2, 5]	[2, 5]	[2, 4]	[3, 5]	[4, 7]	[7, 10]	[2, 5]	[10, 12]	[8, 8]	[7, 11]

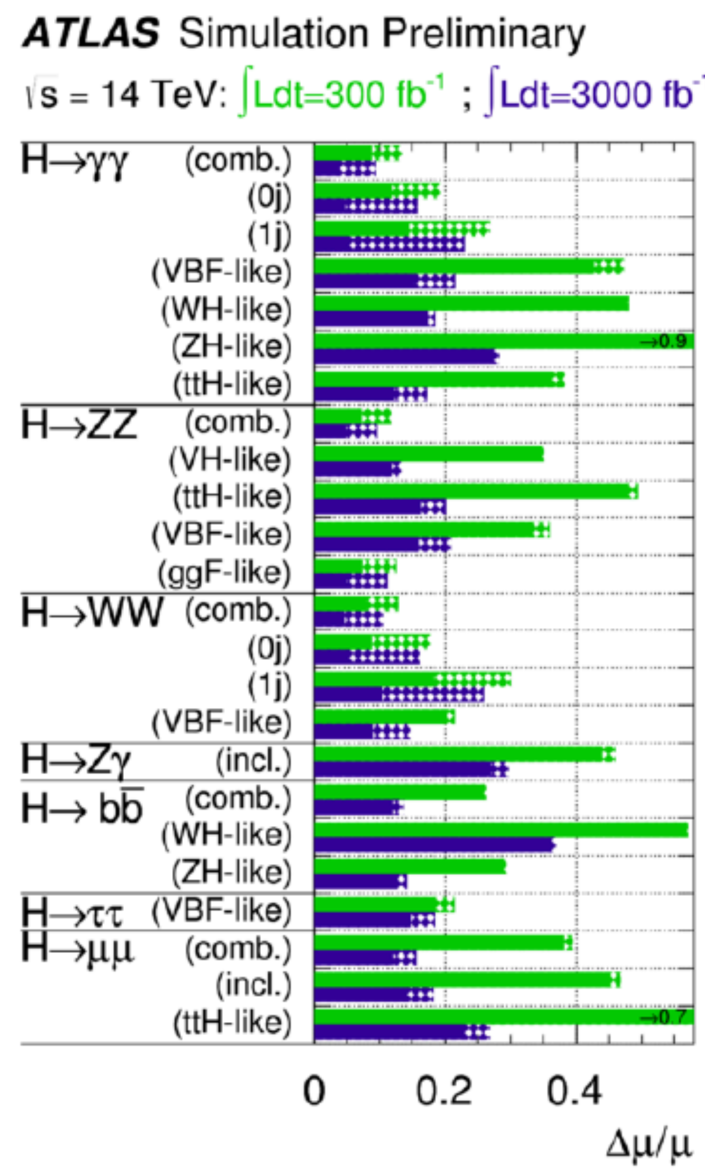
Coupling can be measured at the few % level

example: kt expected to improve substantially with the inclusion of latests channels

Run1-based couplings study

ATL-PHYS-PUB-2014-016





4-5% for main channels, 10~20% on rare modes

- Do not include improved detector designs or improvements in analysis techniques
- Impact of theoretical uncertainty (shadow band) not negligible for several channel
- Reduction of theoretical uncertainties needed

Run1-based couplings study

ATL-PHYS-PUB-2014-016

$\Delta\mu/\mu$	300 fb^{-1}		3000 fb^{-1}	
	All unc.	No theory unc.	All unc.	No theory unc.
$gg \to H$	0.12	0.06	0.11	0.04
VBF	0.18	0.15	0.15	0.09
WH	0.41	0.41	0.18	0.18
$qqZH$	0.80	0.79	0.28	0.27
$ggZH$	3.71	3.62	1.47	1.38
ttH	0.32	0.30	0.16	0.10

$\Delta\kappa/\kappa$ = [no theory uncert., full theory uncert.] Model allowing contributions from new physics in loop

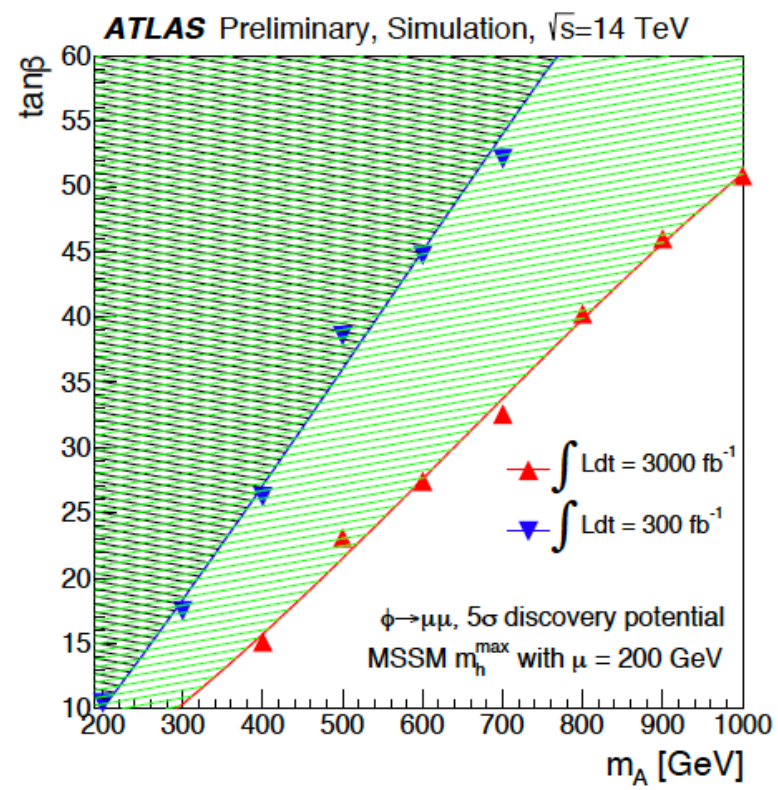
	$\kappa\gamma$	κW	κZ	κg	κb	κt	$\kappa\tau$	$\kappa Z\gamma$	$\kappa\mu$
300 fb^{-1}	[9,9]	[9,9]	[8,8]	[11,14]	[22,23]	[20,22]	[13,14]	[24,24]	[21,21]
3000 fb^{-1}	[4,5]	[4,5]	[4,4]	[5,9]	[10,12]	[8,11]	[9,10]	[14,14]	[8,8]

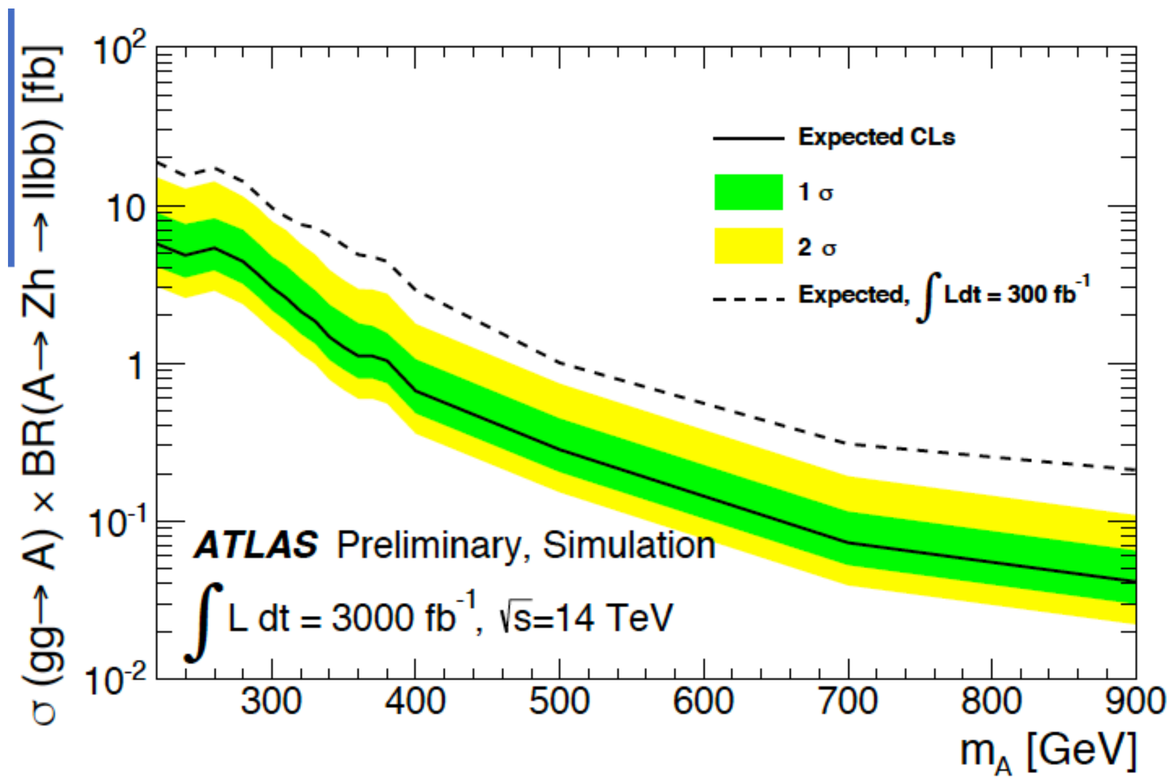
(%)

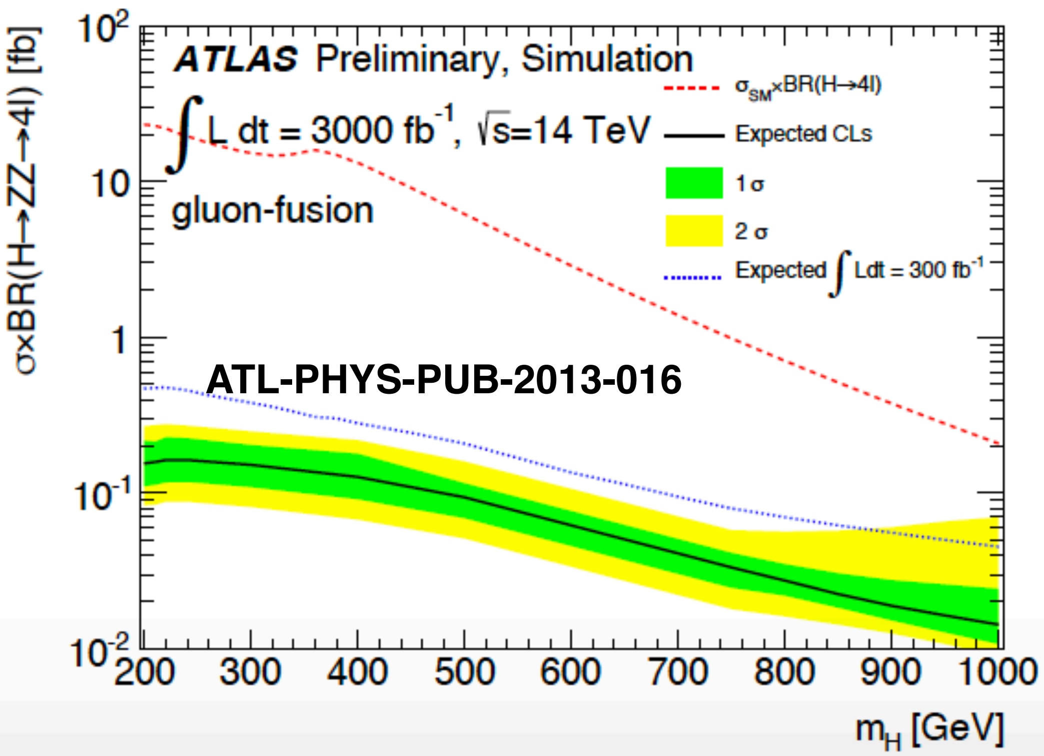
4-5% for main channels, 10~20% on rare modes

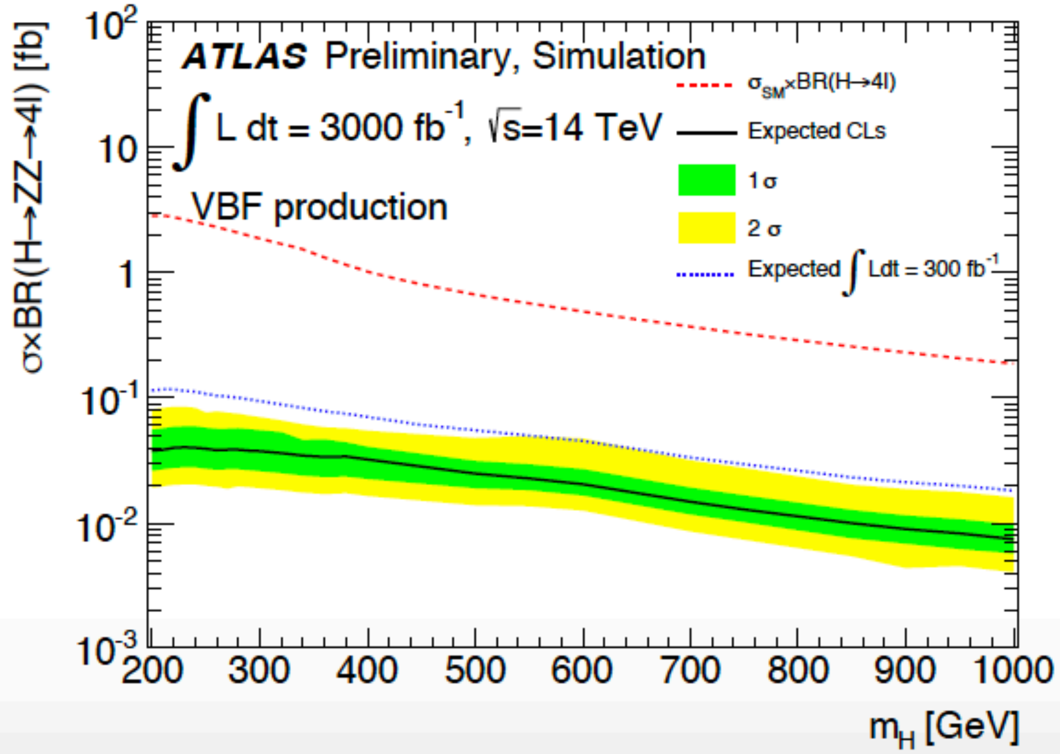
- Do not include improved detector designs or improvements in analysis techniques
- Impact of theoretical uncertainty (shadow band) not negligible for several channel
- Reduced theoretical uncertainties needed

Other (old) BSM Higgs Searches



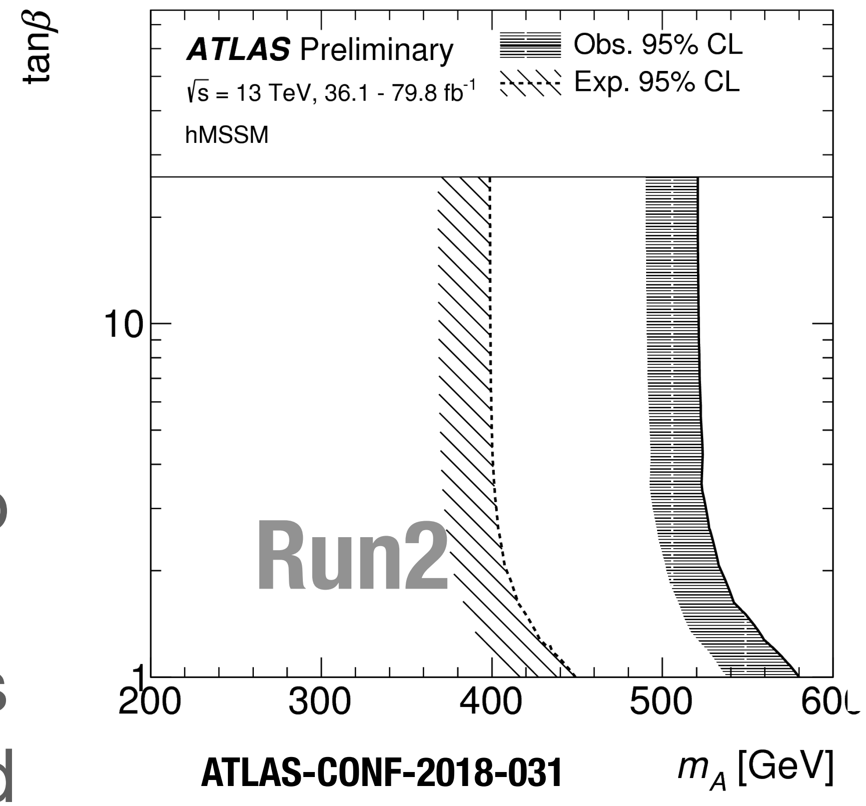




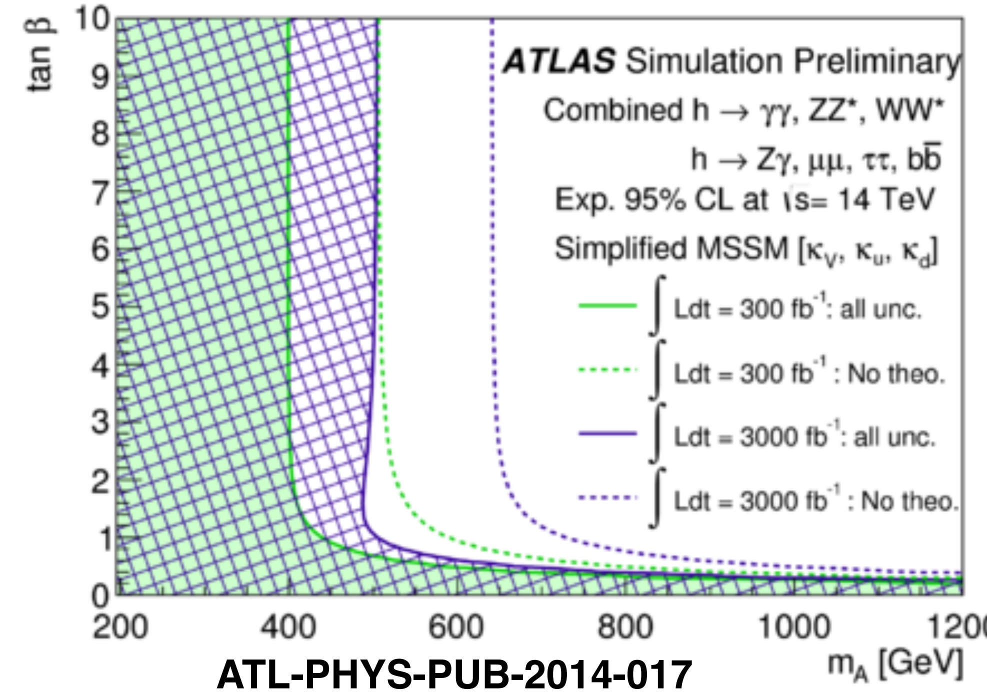


Couplings interpretations?

new couplings projections need to be interpreted in terms of constrains to BSM models (old projections are conservative)



ATLAS-CONF-2018-031



ATL-PHYS-PUB-2014-017