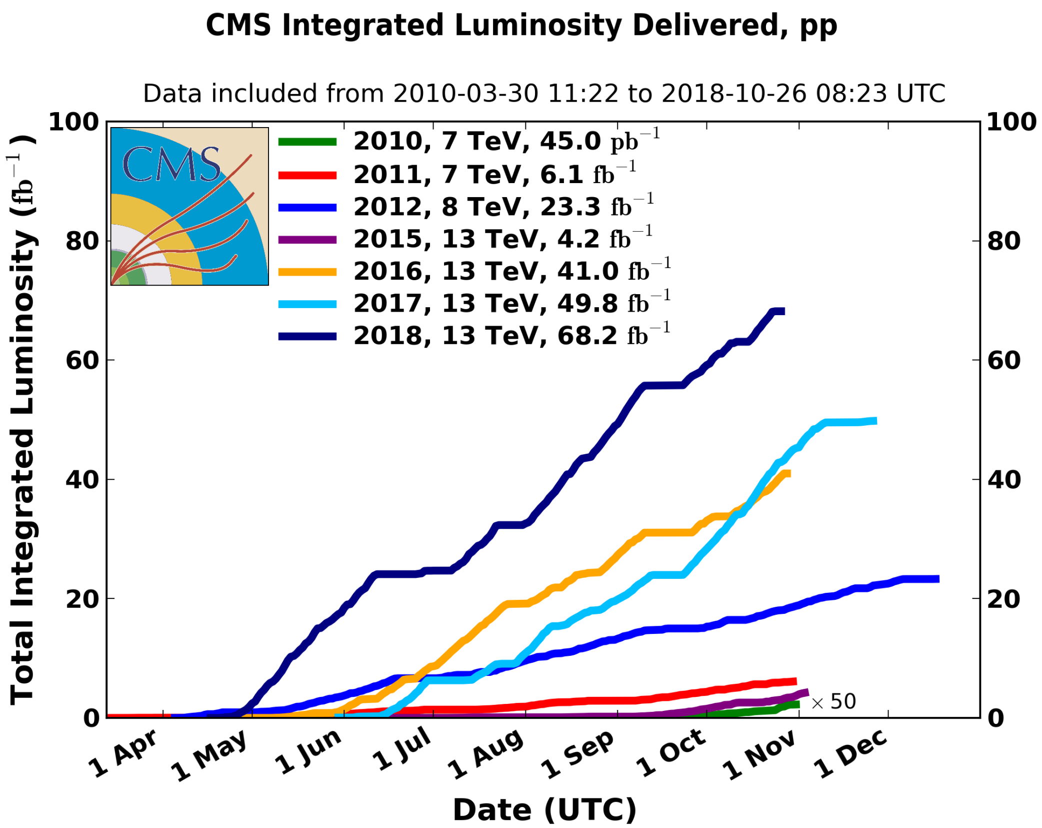
HIGGS AND EWK PHYSICS AT HIGH-LUMINOSITY LHC

ESPPU, MAY 13 2019, GRANADA

Patrizia Azzi, INFN-PD

STATUS OF LHC



- Run 2 proton physics run 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)
- Enormous success of the LHC program in the amount and quality of measurements performed way beyond expectations
- Standard Model working impeccably, but we know many questions still anaswered

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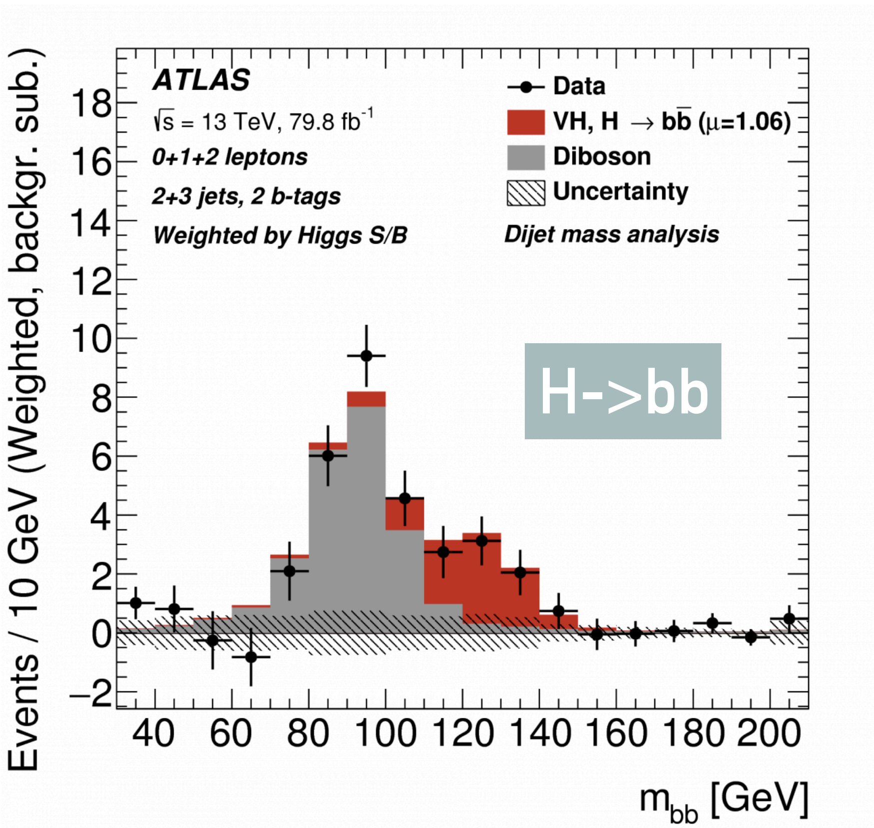
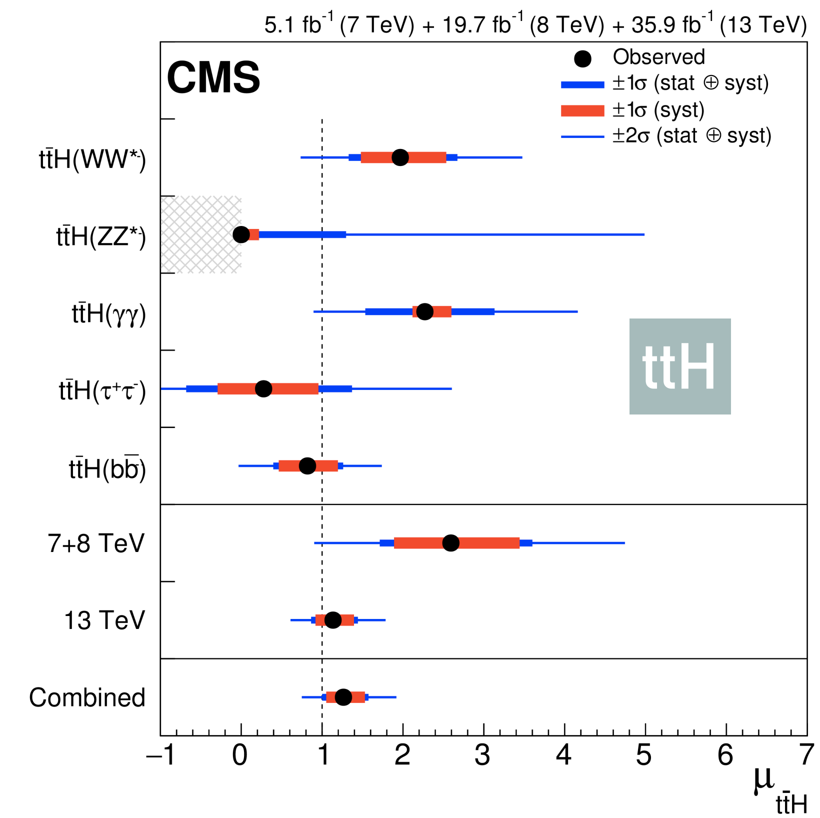


Latest big results of 2018: Observation of Higgs coupling to third generation quarks



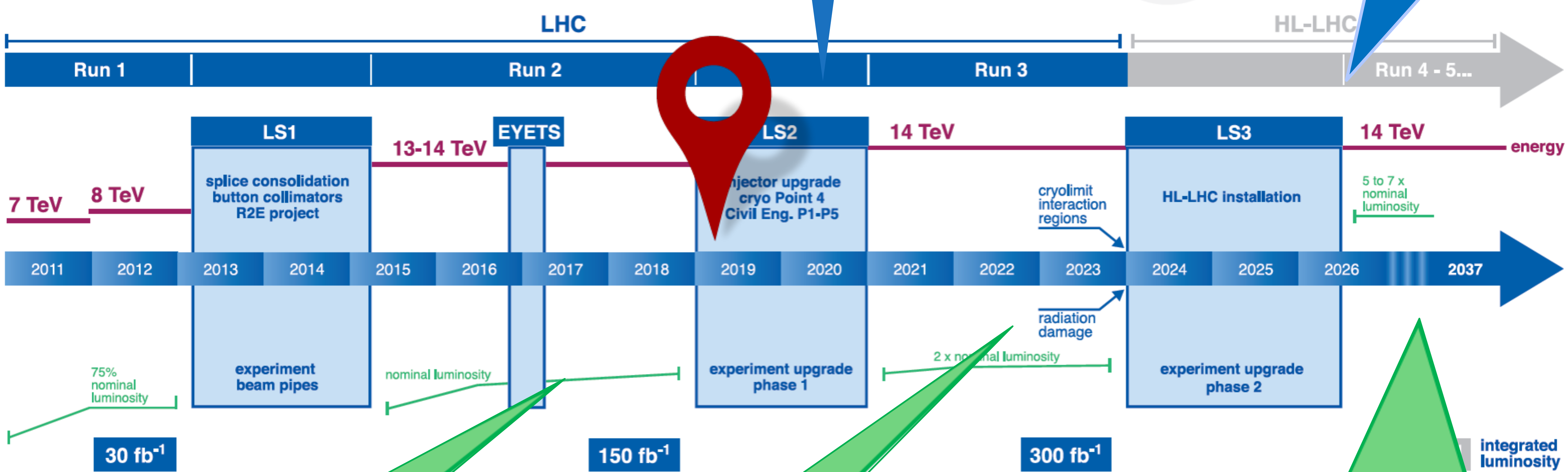
HL-LHC PLAN

upgrade of injector chain to deliver brighter bunches

new interaction region layout and crab cavity

LHC

HL-LHC



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

Run 3:
$\mathcal{L} = 2\times10^{34}/cm^2/s$
for 300/fb

HL-LHC: Peak $\mathcal{L} = 2\times10^{35}/cm^2/s$
level luminosity to
Nominal scenario: $\mathcal{L} = 5\times10^{34}/cm^2/s$
for 3000/fb; Pile-up $<\mu>$ = 140
Ultimate Scenario: $\mathcal{L} = 7.5\times10^{34}/cm^2/s$
for 4000/fb; Pile-up $<\mu>$ = 200
⇒25% increase in integrated lum.

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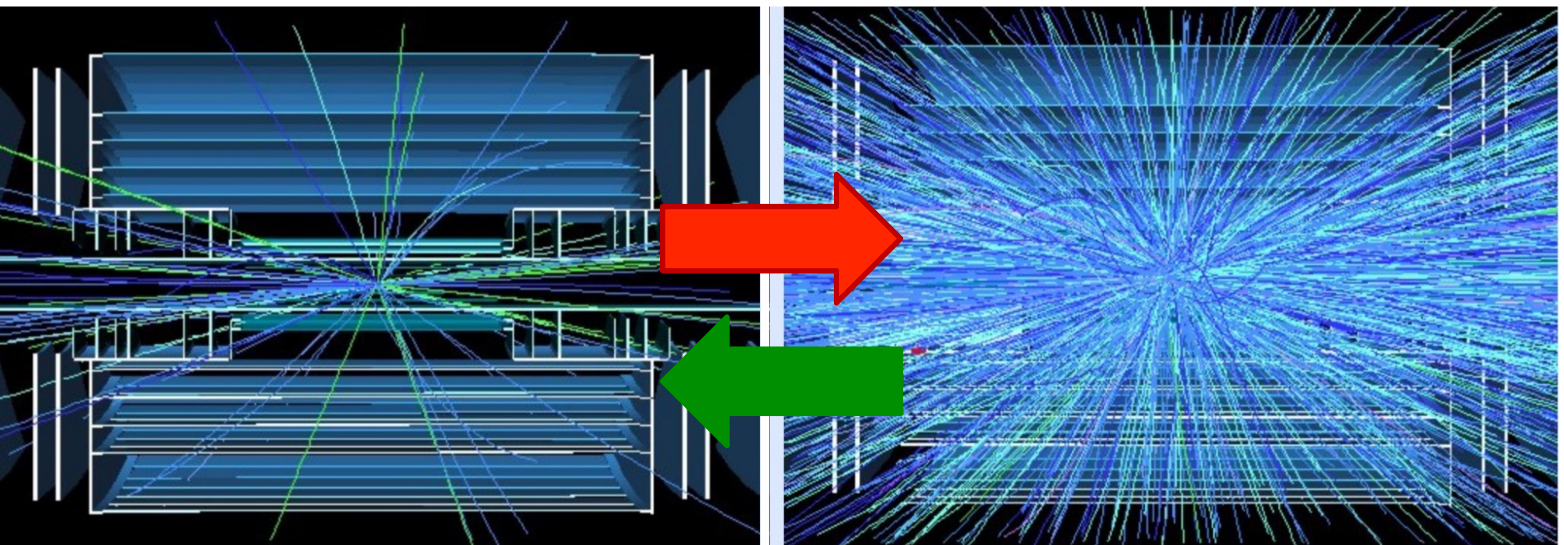
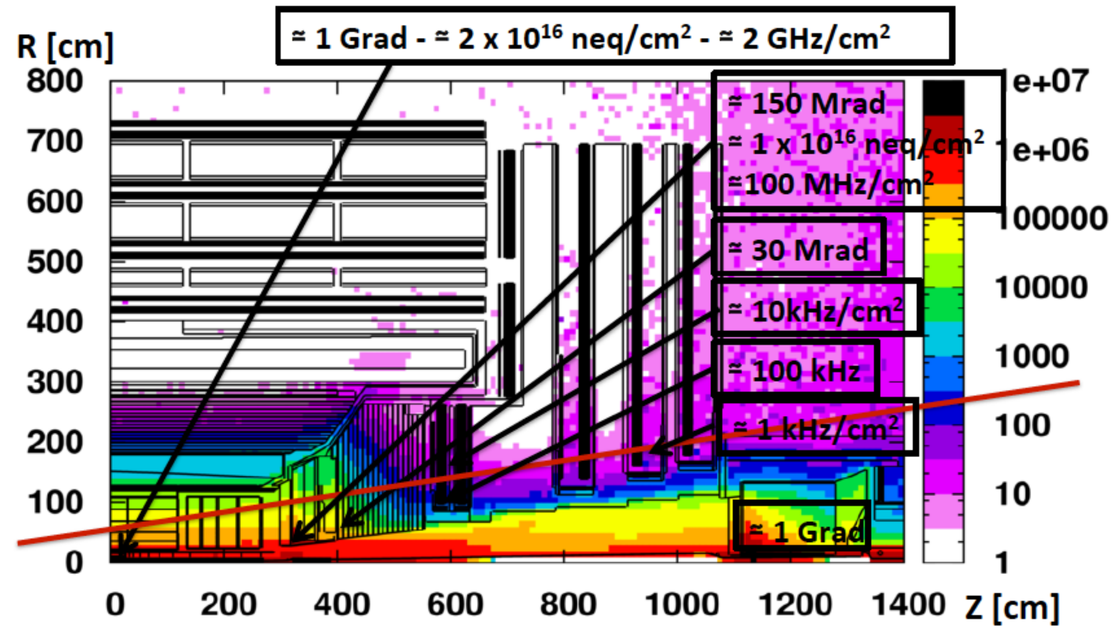
4 SWARMS OF PARTICLES AND HIGH RADIATION

- High luminosity ➔ 200 soft pp interactions per crossing
  - Increased combinatorial complexity, rate of fake tracks, spurious energy in calorimeters, increased data volume to be read out in each event
- Detector elements and electronics are exposed to high radiation dose
  - Requires new tracker, endcap calorimeters, forward muons, replacing readout systems

25 pileup 200 pileup





Roughly reaching limits of current techniques in several systems

- Goal of ATLAS and CMS detector upgrades
  - to achieve same performance at 200PU as in Run2 with ~40PU (or better)
  - For precision measurements and observations of very rare processes, we need to at least maintain current performance for all physics objects. Requires excellence in every corner
  - associating particles with primary hard scatter collision with high efficiency
  - increase detector acceptance
  - Increased spatial granularity to resolve signals from individual particles
  - Precise timing measurements to provide an additional dimension for discrimination

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. J. 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.

References

1. P. Azzi, S. Farry, P. Nason, A. Tricoli, and D. Zeppenfeld, (conveners), et al, *Standard Model Physics at the HL-LHC and HE-LHC* , CERN-LPCC-2018-03, CERN, Geneva, 2018. https://cds.cern.ch/record/2650160.
2. M. Cepeda, S. Gori, P. J. Ilten, M. Kado, and F. Riva, (conveners), et al, *Higgs Physics at the HL-LHC and HE-LHC*, CERN-LPCC-2018-04, CERN, Geneva, 2018. https://cds.cern.ch/record/2650162.
3. X. Cid-Vidal, M. D'Onofrio, P. J. Fox, R. Torre, and K. Ulmer, (conveners), et al, *Beyond the Standard Model Physics at the HL-LHC and HE-LHC*, CERN-LPCC-2018-05, CERN, Geneva, 2018. https://cds.cern.ch/record/2650173.
4. A. Cerri, V. V. Gligorov, S. Malvezzi, J. Martin Camalich, and J. Zupan, (conveners), et al, *Flavour Physics at the HL-LHC and HE-LHC*, CERN-LPCC-2018-06, CERN, Geneva, 2018. https://cds.cern.ch/record/2650175.
5. Z. Citron, A. Dainese, J. F. Grosse-Oetringhaus, J. M. Jowett, Y.-J. Lee, U. Wiedemann, and M. A. Winn, (conveners), et al, *Future physics opportunities for high-density QCD at the LHC with heavy-ion and proton beams*, CERN-LPCC-2018-07, CERN, Geneva, 2018. arXiv:1812.06772 [hep-ph]. https://cds.cern.ch/record/2650176.
6. The ATLAS and CMS Collaborations, *Report on the Physics at the HL-LHC and Perspectives for the HE-LHC*, CERN-LPCC-2019-01, CERN, Geneva, 2019. https://cds.cern.ch/record/2651134.
7. LHCb Collaboration, R. Aaij et al., *Physics case for an LHCb Upgrade II - Opportunities in flavour physics, and beyond, in the HL-LHC era*, arXiv:1808.08865.

The physics potential of HE-LHC

Editors:
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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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1. M. Benedikt, J. Gutleber, and F. Zimmermann, (editors), *Future Circular Collider Study. Volume 4: The High Energy LHC (HE-LHC) Conceptual Design Report*, CERN-ACC-2018-0059, CERN, Geneva, Dec, 2018. Submitted to Eur. Phys. J. ST. http://cern.ch/go/S9Gq.
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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

HOW TO APPROACH SYSTEMATICS

- The large HL-LHC dataset will enable accurate measurements and unprecedented sensitivity to very rare phenomena
- In several analyses **systematic uncertainties will become a limiting factor**
- Several sources of systematics to consider:

Detector driven

Data statistics in control regions

Theory normalization and modeling

Luminosity

Method uncertainties

MC statistics

- Synergy of ATLAS and CMS in many physics projections and complexity of the problem required development of a **common set of guidelines**
  - Focus on experimental systematics that are most important for the projection studies we need (can't be comprehensive!)
    - Jet Energy Scale/Resolution, MET, B-tagging, Tau-ID, and many more…
  - Evaluation of theory uncertainties improvement

7 COMMON GUIDING PRINCIPLES FOR YR18

- Statistics-driven sources: data → $\sqrt{L}$, simulation → 0
  - account for larger data sample statistics available
  - to better understand full potential of HL-LHC
- Theory uncertainties typically halved
  - applies to both normalization (x-sec) and modeling
  - due to higher-order calculation and PDF improvements
- Uncertainties on methods kept as latest published results
  - Trigger thresholds same or better(lower) than current
  - assumption that pile-up effects are compensated by detector upgrades improvement and algorithmic developments
- Intrinsic detector limitations stay ~constant
  - usage of full simulation tools for detailed analysis of expected performance, thanks to the large effort for TDRs preparation
  - detector understanding and operational experience may compensate for e.g. detector aging
  - harmonized definition of « floor » values for experimantal systematics
- Luminosity uncertainty 1%

MORE DETAILS ON PROCEDURE

* Whenever feasible present results as

value ± stat ± syst_exp ± syst_theory [± syst_lumi]

* Baseline scenario defined as:
  * **YR18(S2):** based on synchronised estimates of ultimate performance for experimental and theory uncertainties, and applying guidelines as in previous slide

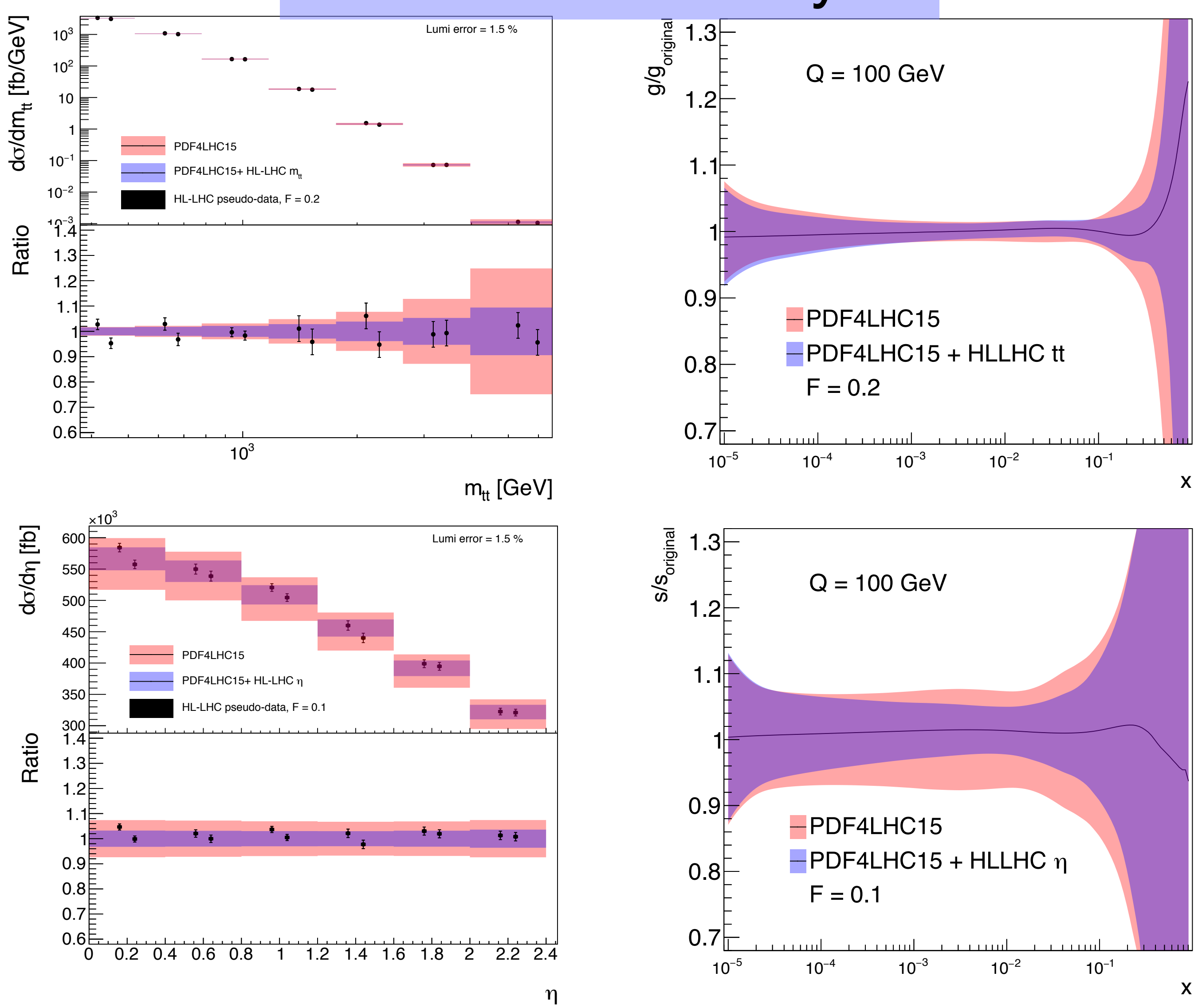
Summary (simplified) table of some values of experimental systematics harmonized between ATLAS & CMS

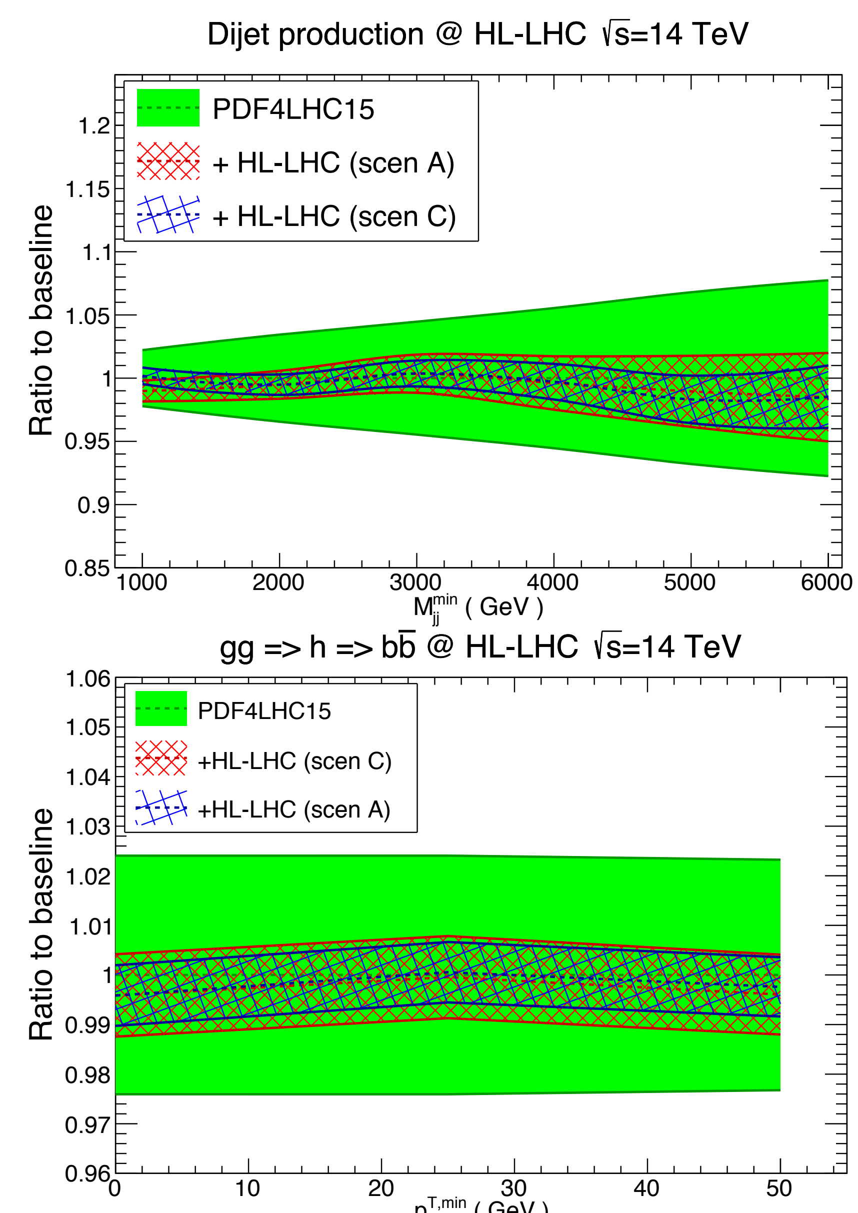
Object	WP	Value
Muons	reco+ID(+ISO)	0.1%(0.5%)
Electrons	reco+ID+ISO	0,5%
Taus	reco+ID+ISO	5%(as in Run2)
B-jet tag	30<pt<300GeV (pt>300GeV)	~1%(2-6%)
c-jet tag		~2%
Light jets	L/M/T WP	5/10/15%
JES	abs/rel scale	0.1-0.2%(0.1-0.5%)
JEC	Pile-Up	0-2%
JEC	Flavor	0,75%
Integrated Luminosity		1%

PDF UNCERTAINTIES

- exercise trying to quantify the precision of the PDF at the end of the HL-LHC running and use them in the systematic estimate of the experimental extrapolations
- pseudo-data generated for various inputs: top Drell-Yan, iso photons, W+charm, W and Z in the forward region, inclusive jets…
  - Scenario A(C) corresponds to factor 2(5) reduction of uncertainties on exp. inputs.
  - LHeC could provide improvement of a factor 5 on PDF uncertainties
- Tested effect on some SM and BSM processes. Justifies assumptions used for YR18 scenario

tt differential analysis

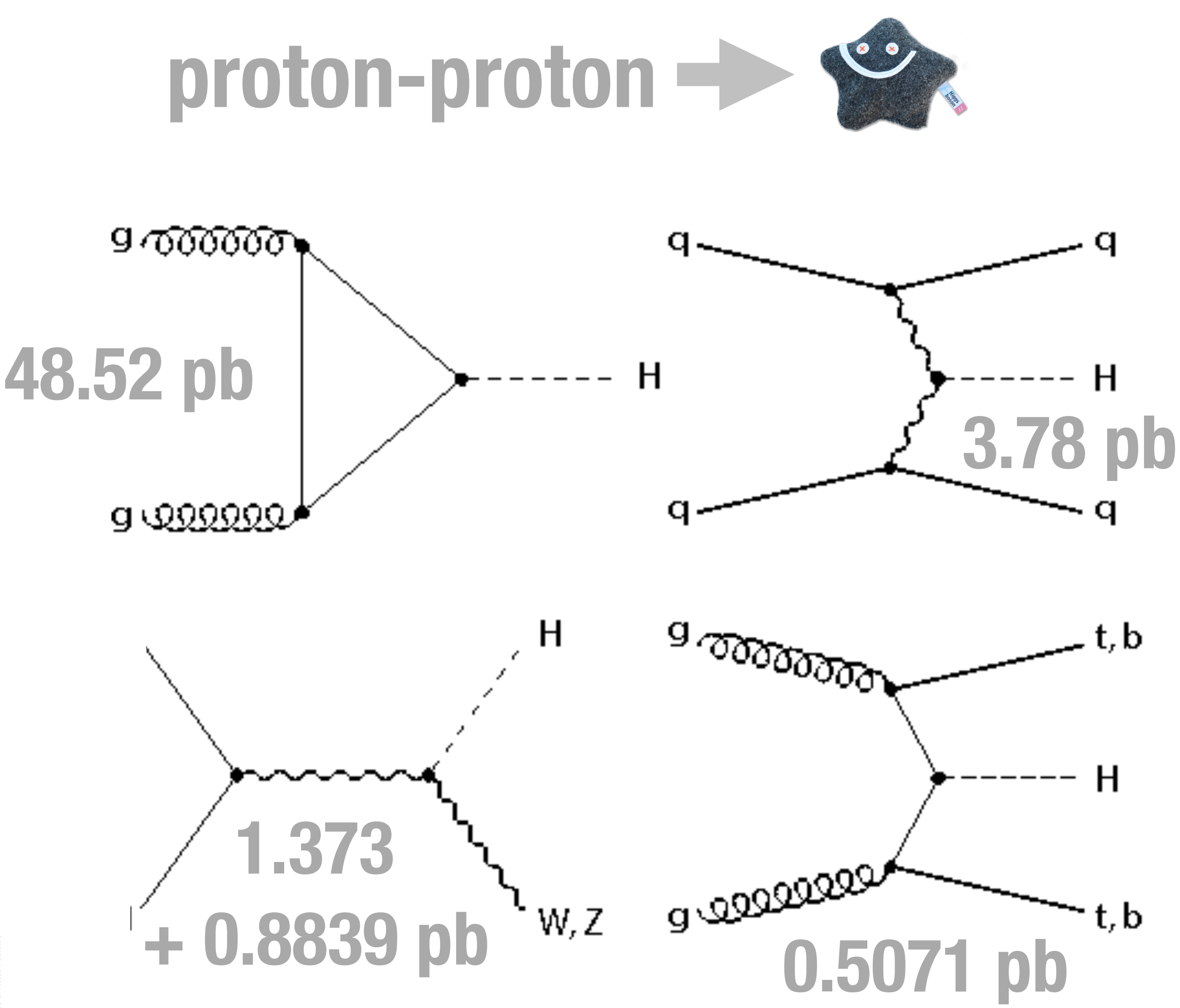


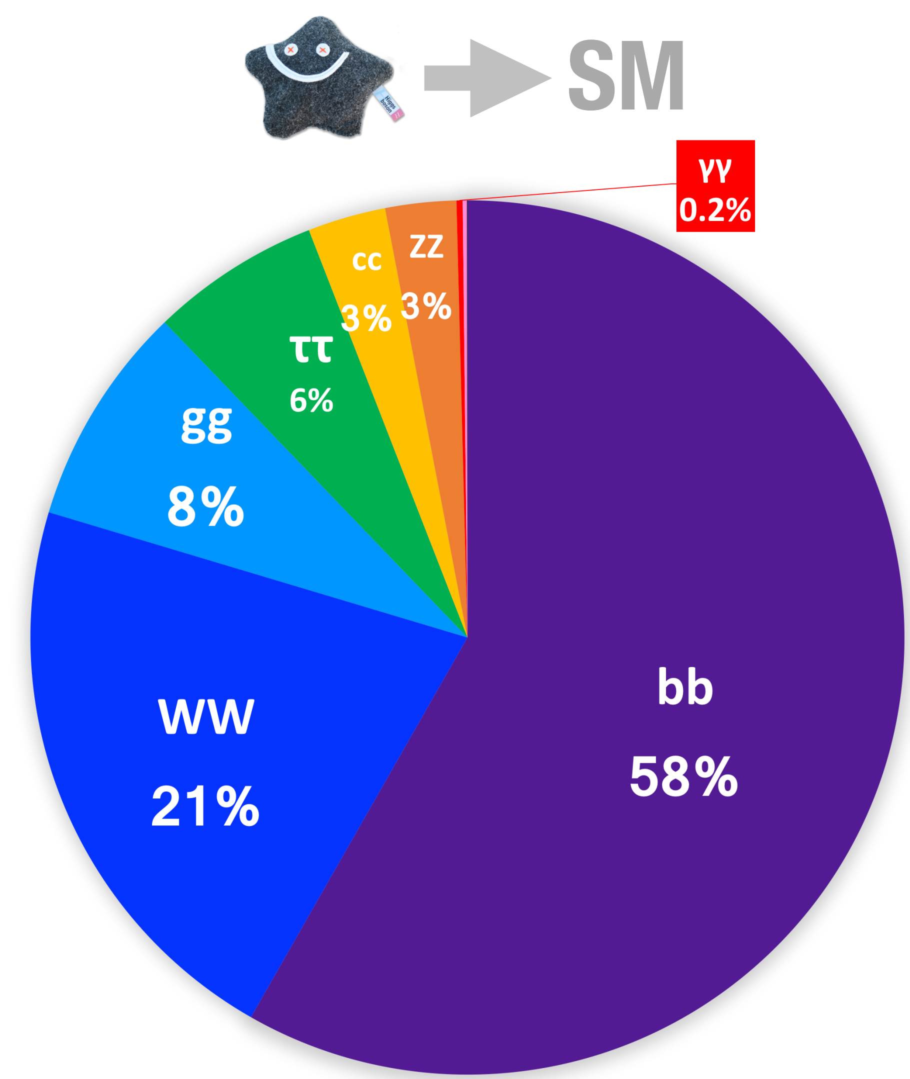


THE HIGGS SECTOR

HIGGS PHYSICS AT THE LHC

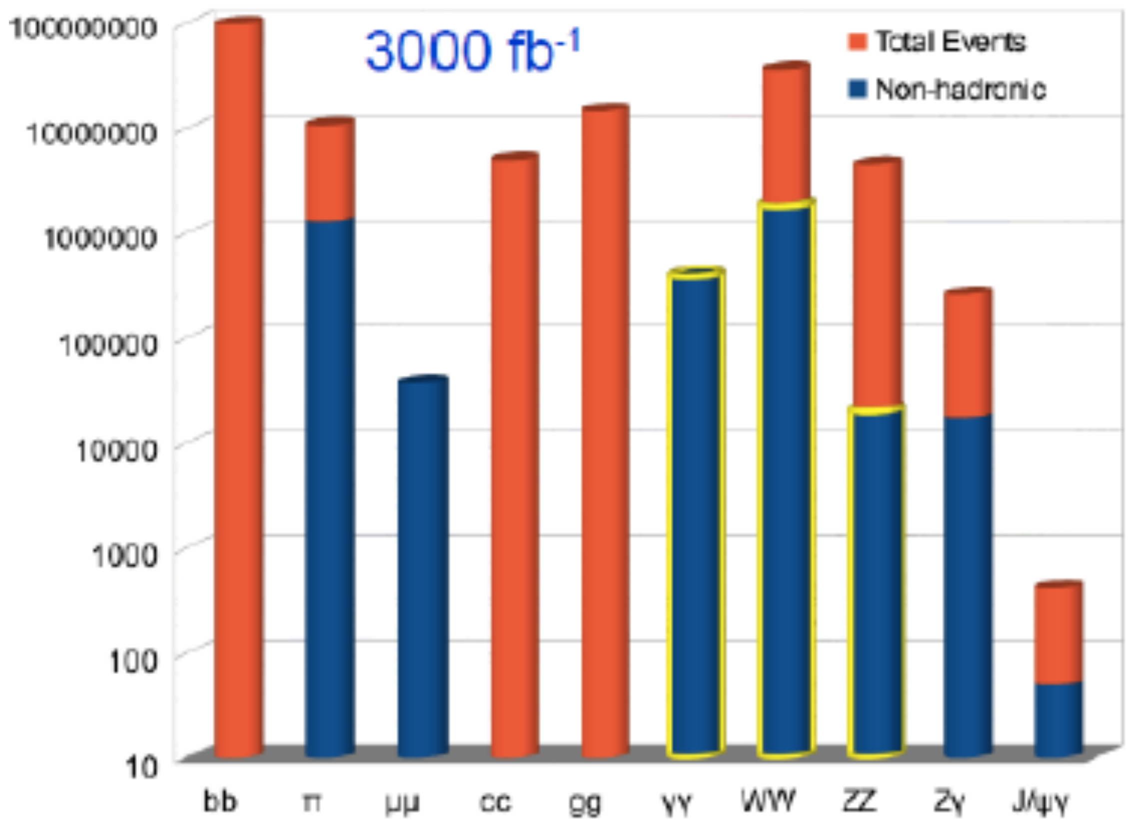
- We have come a long way since the Higgs discovery in 2012
  - The available LHC Run1 (7,8 TeV~25fb-1) & Run2 (13 TeV ~150fb-1) datasets have pushed Higgs physics from search mode to measurement mode, probing the nature of the boson and its agreement with the SM
- All the main production and decay modes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

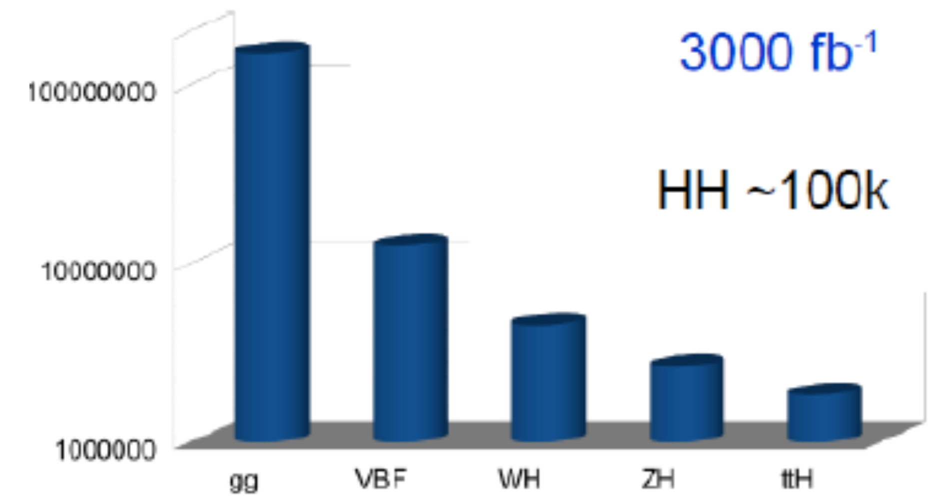


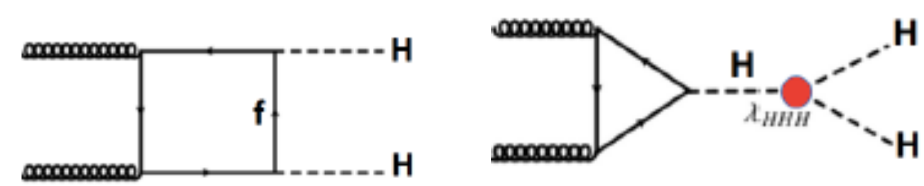


HL-LHC IS A HIGGS FACTORY

- At HL-LHC, we expect to produce ~170M Higgs Bosons, including ~120k of HH pair produced events
- Over 1Million for each of the main production mechanisms, spread over many decay modes







- Enables a broad program:
  - Precision O(few%) measurements of couplings across broad kinematics
  - Exploration of Higgs potential (hh production)
  - Sensitivity to rare decays involving new physics
  - extend BSM Higgs searches (extra scalars, BSM Higgs resonances, exotic decays…)

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

- **Precision Measurements:** Couplings to ~5%, Cross Sections, Differential Distributions, Width

- **Rare decays**

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

☞ **See presentation by E. Petit**

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

☞ **BSM group of EPPSU**

SM HIGGS PRECISION MEASUREMENTS

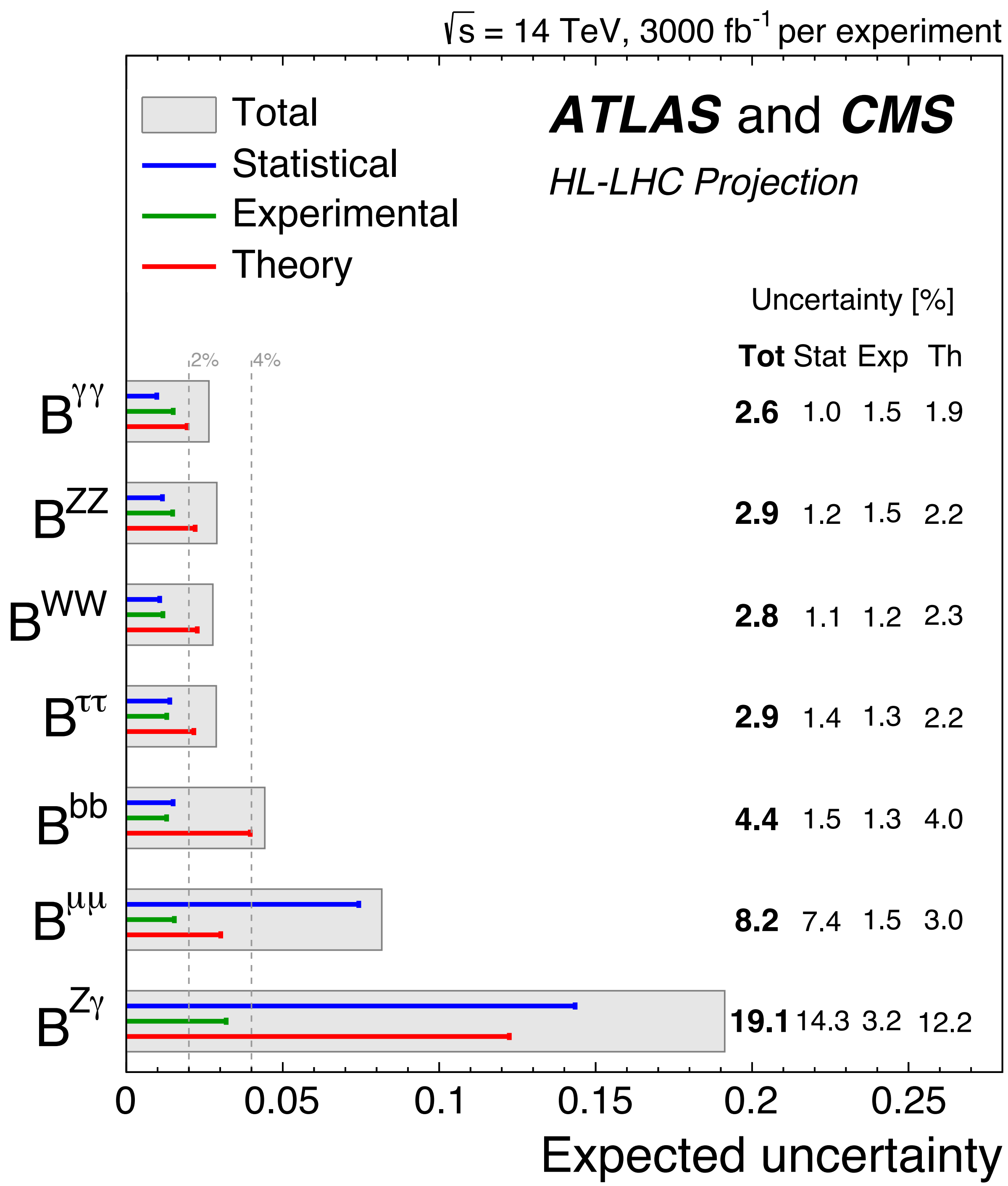
- Old studies (before YR) comprehensive, BUT
  - mostly based on extrapolations of Run1/early Run2 results
    - plus specific analyses with parametrised full simulation.
  - Not harmonized uncertainty assumptions
  - Single experiment only!

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

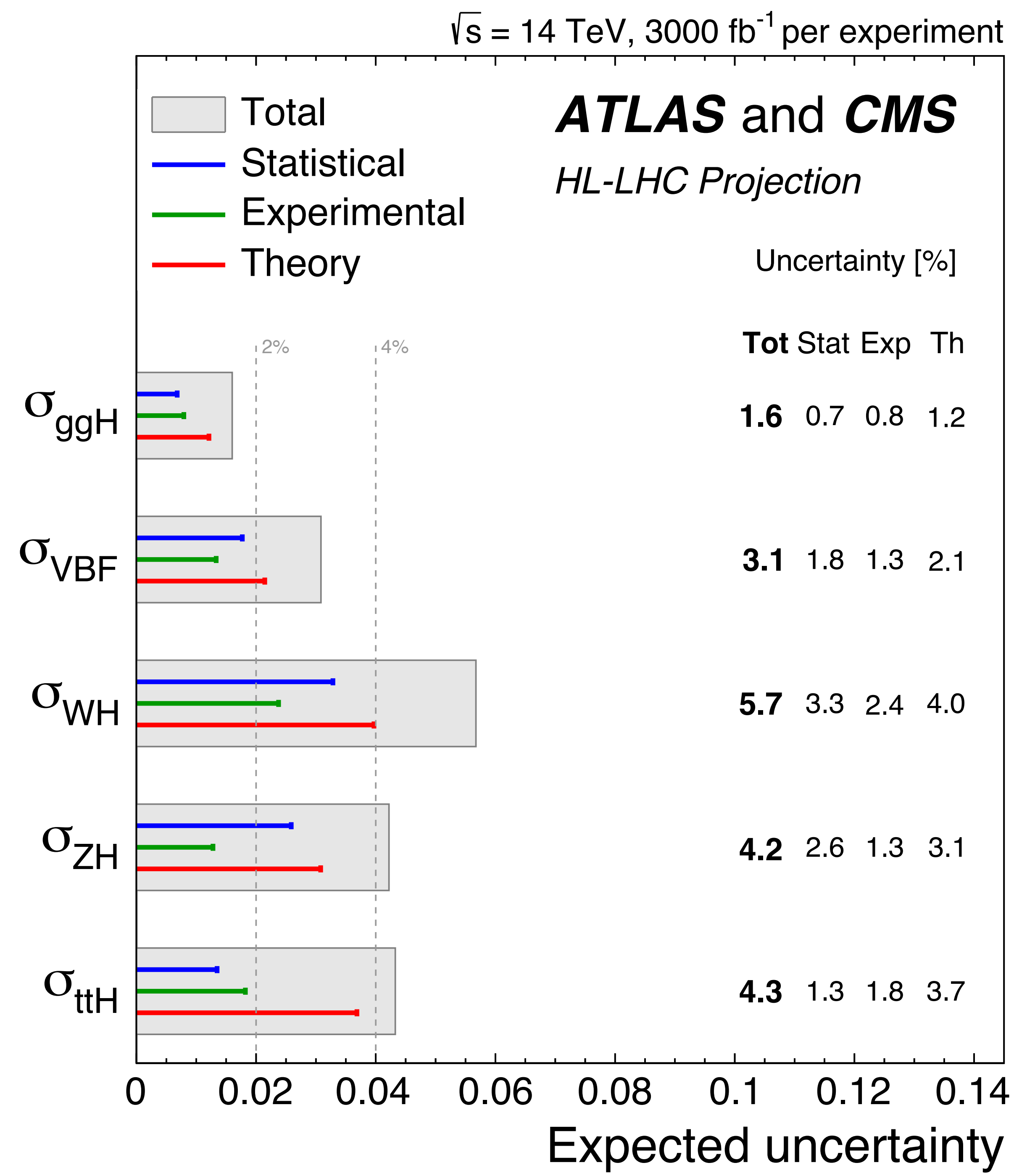
Couplings can be measured at the few % level

- **Complete revamp of the SM Higgs projections, starting from Run2 results and incorporating the current understanding of the future ATLAS&CMS performance.**
  - Profit of the lesson learned in the Run1 combination
- All main decays x production modes incorporated into the study ($\gamma\gamma$, WW, ZZ, $\tau\tau$, bb, $\mu\mu$, Zγ x ggF, VBF, WH, ZH, ttH)
- COMBINATION of the individual results of the ATLAS and CMS, for a definition of the overall HL-LHC reach
  - Theoretical systematics assumed fully correlated, experimental uncertainties uncorrelated

COUPLINGS - RESULTS OF COMBINATION



By decay mode



By production mode

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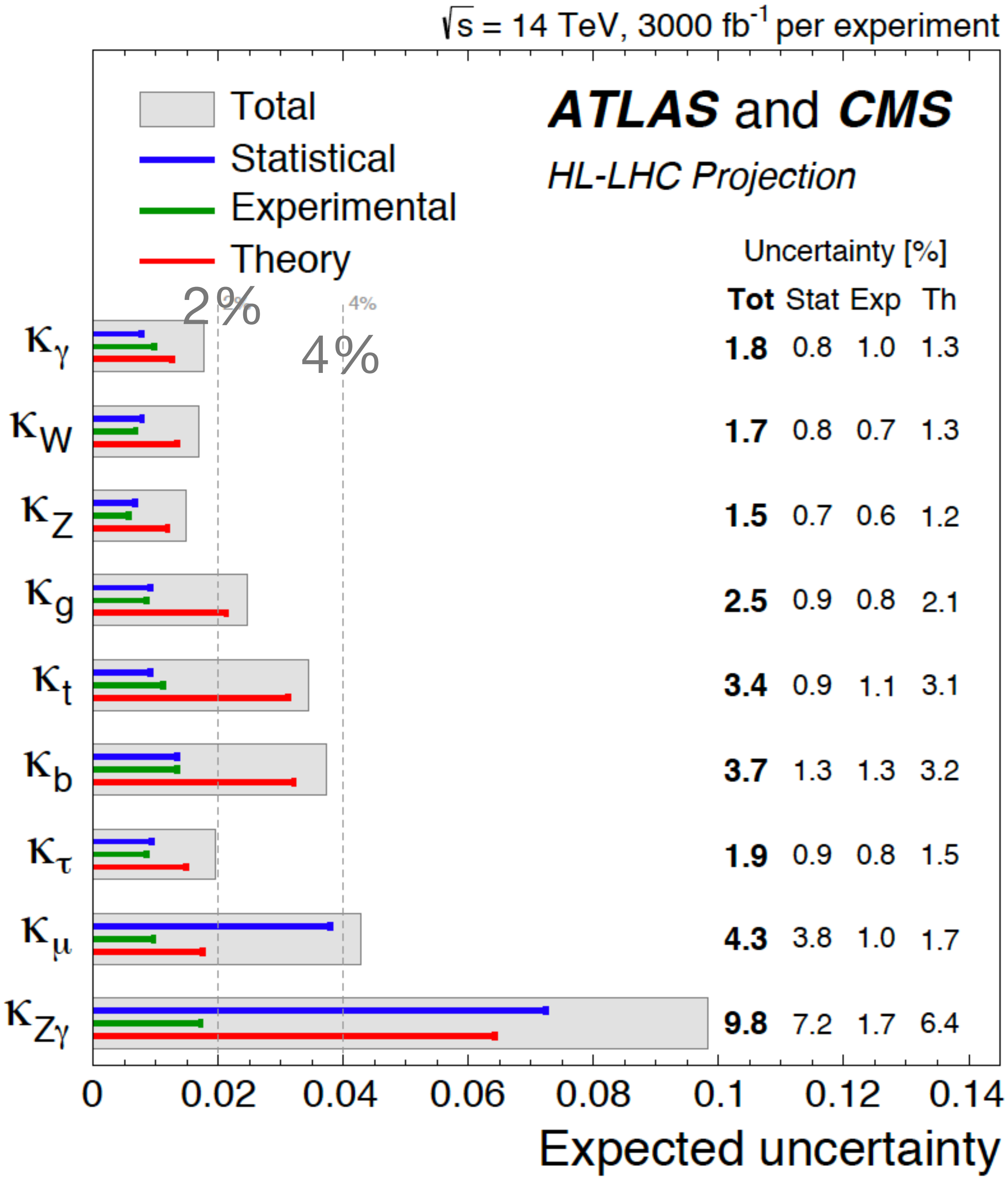
K-FRAMEWORK INTERPRETATION

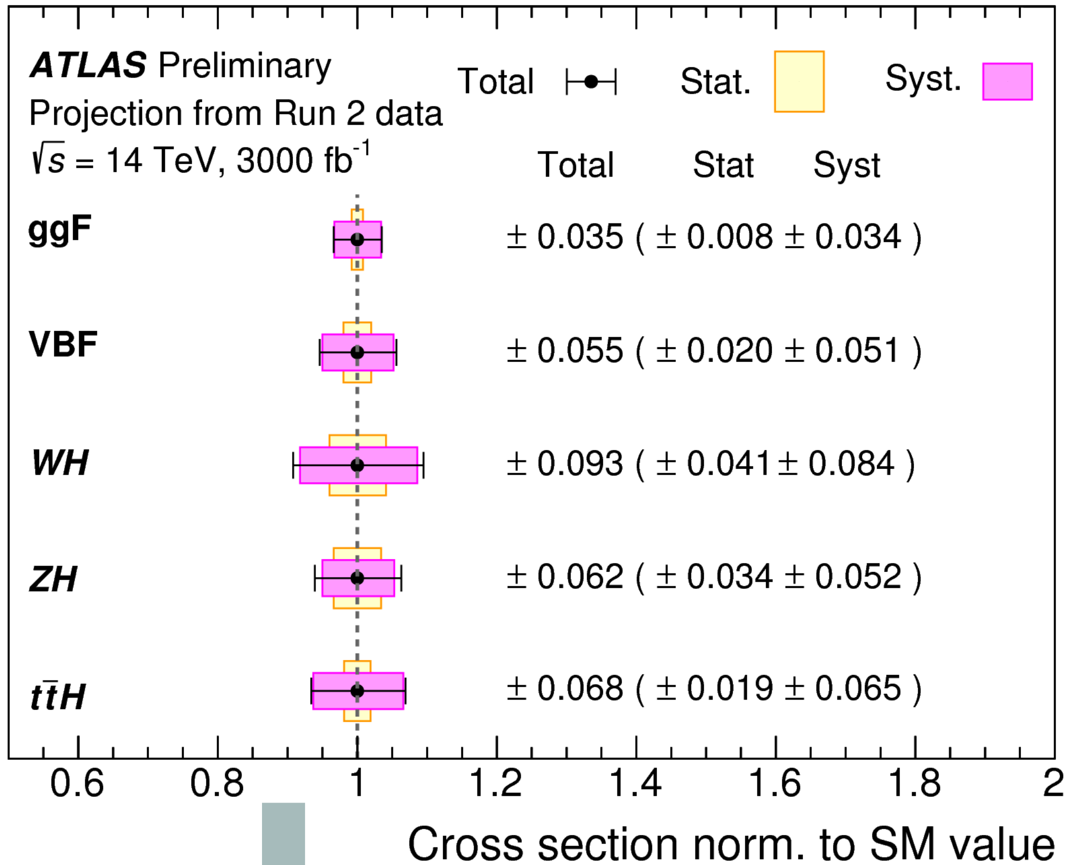
☞See presentation by M. Cepeda

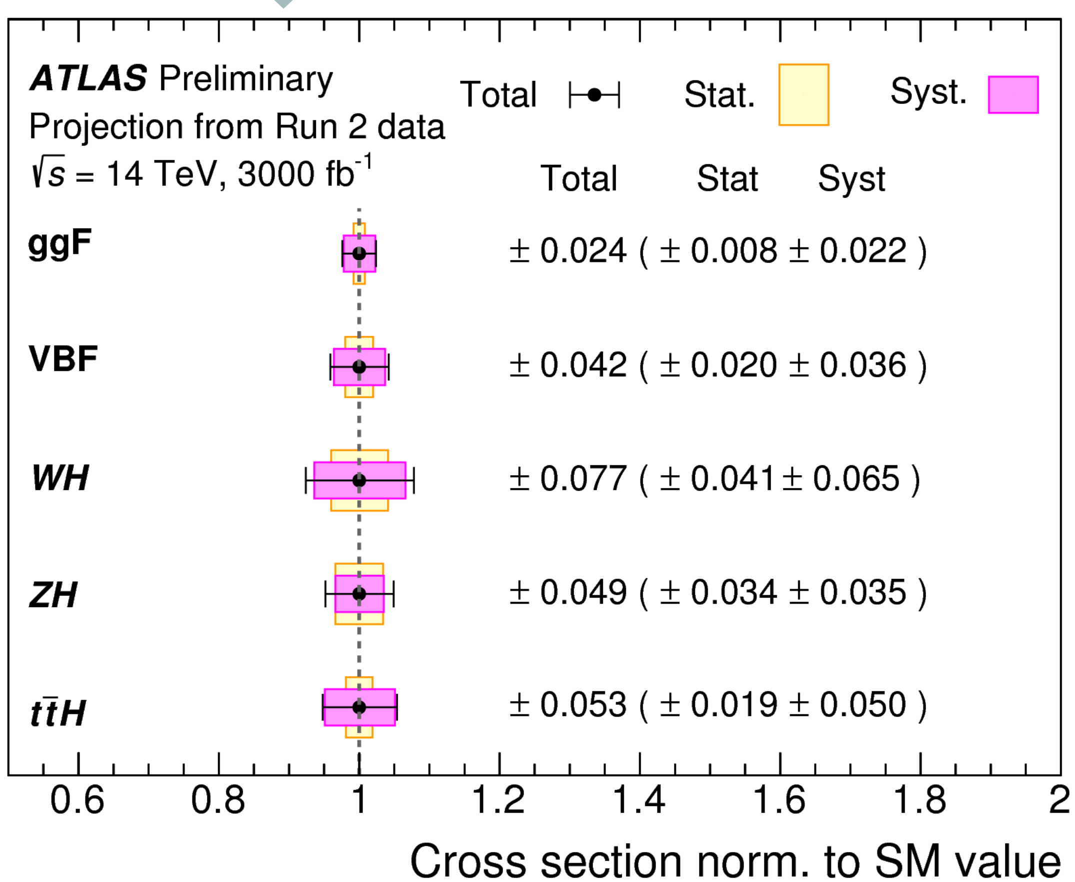


Precision on kappas of 2-4% can be reached with $3ab^{-1}$ for the non-statistically dominated modes

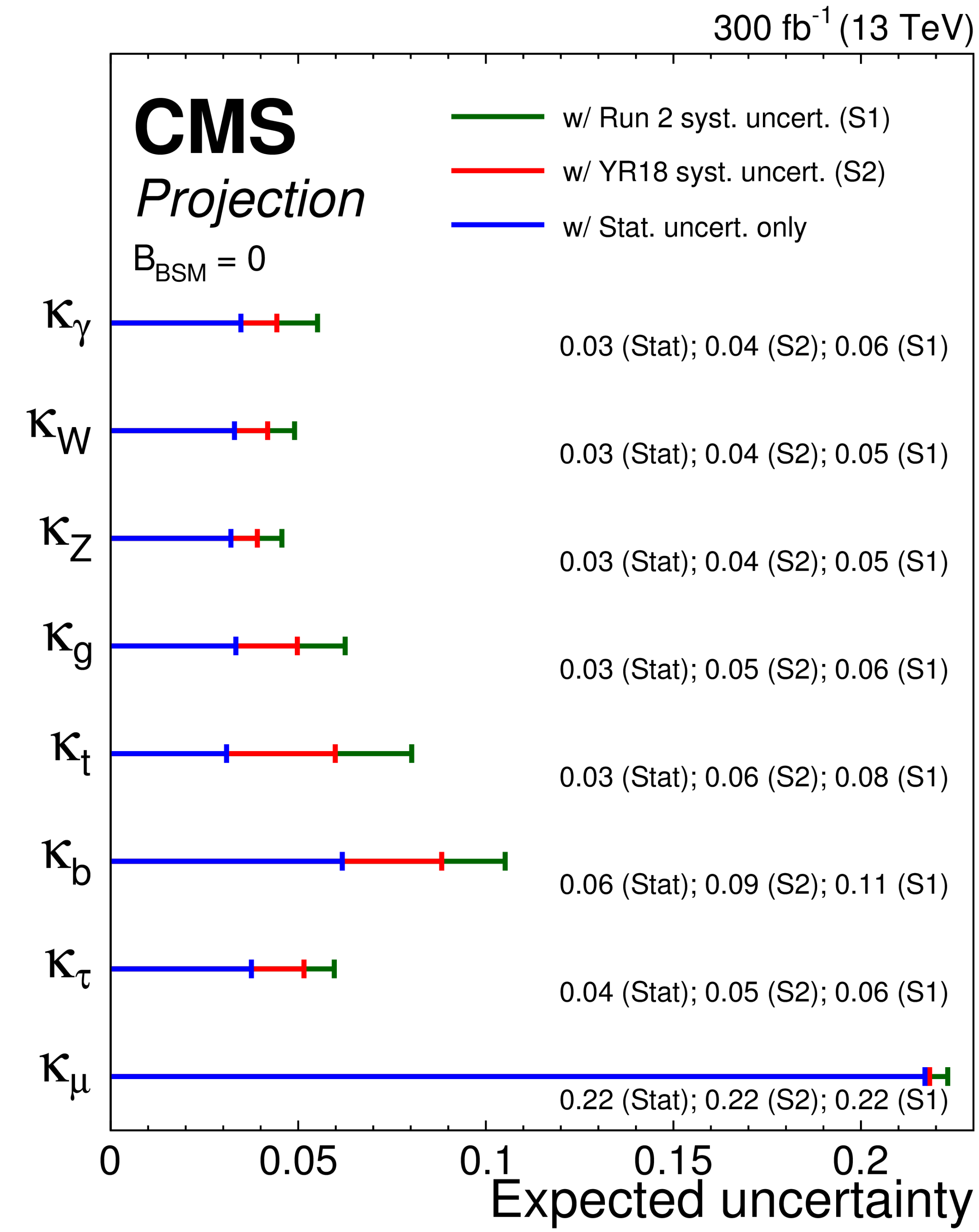
Measurements become systematically limited rather quickly -> challenge

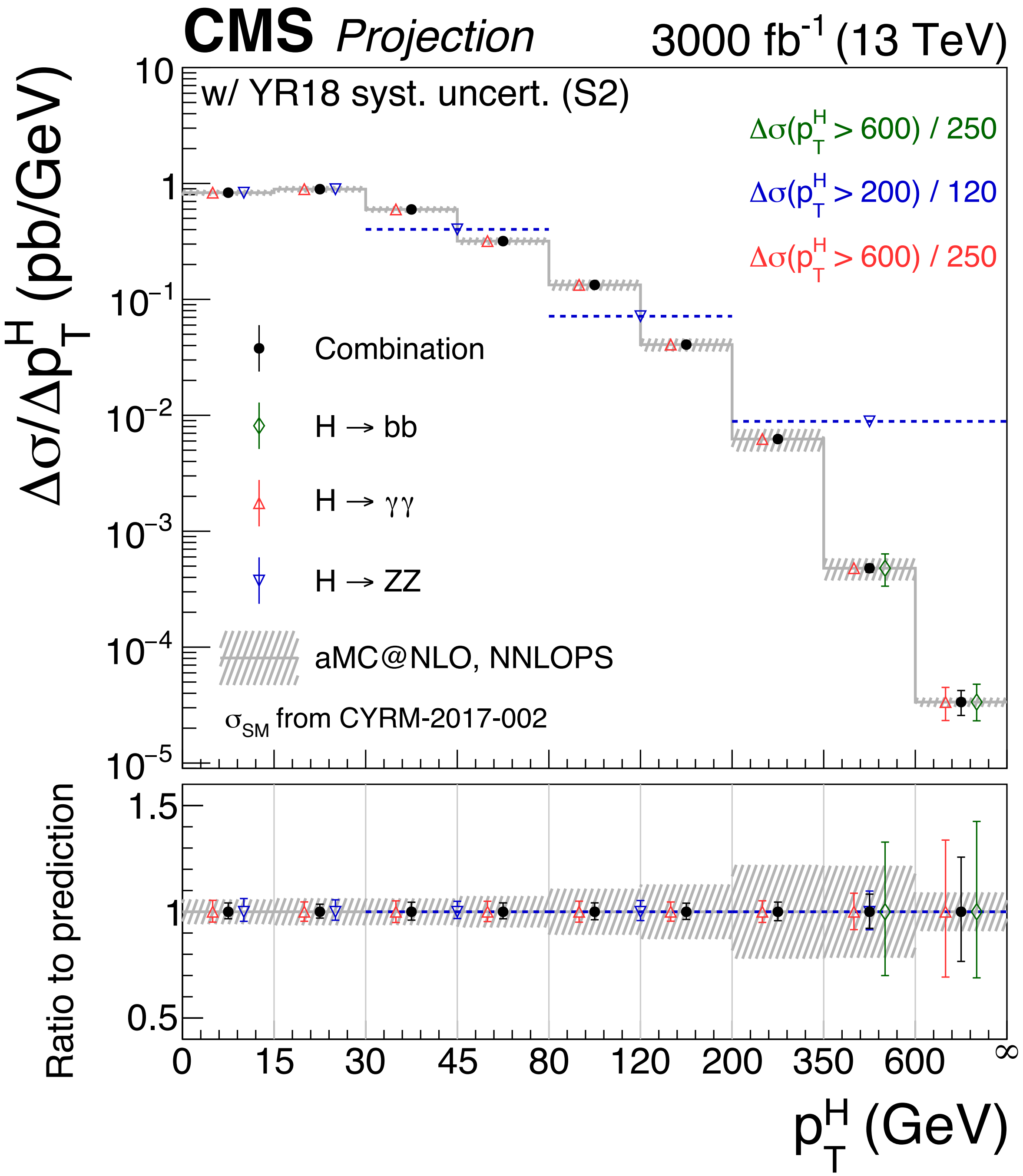
EFFECT OF UNCERTAINTY SCENARIOS

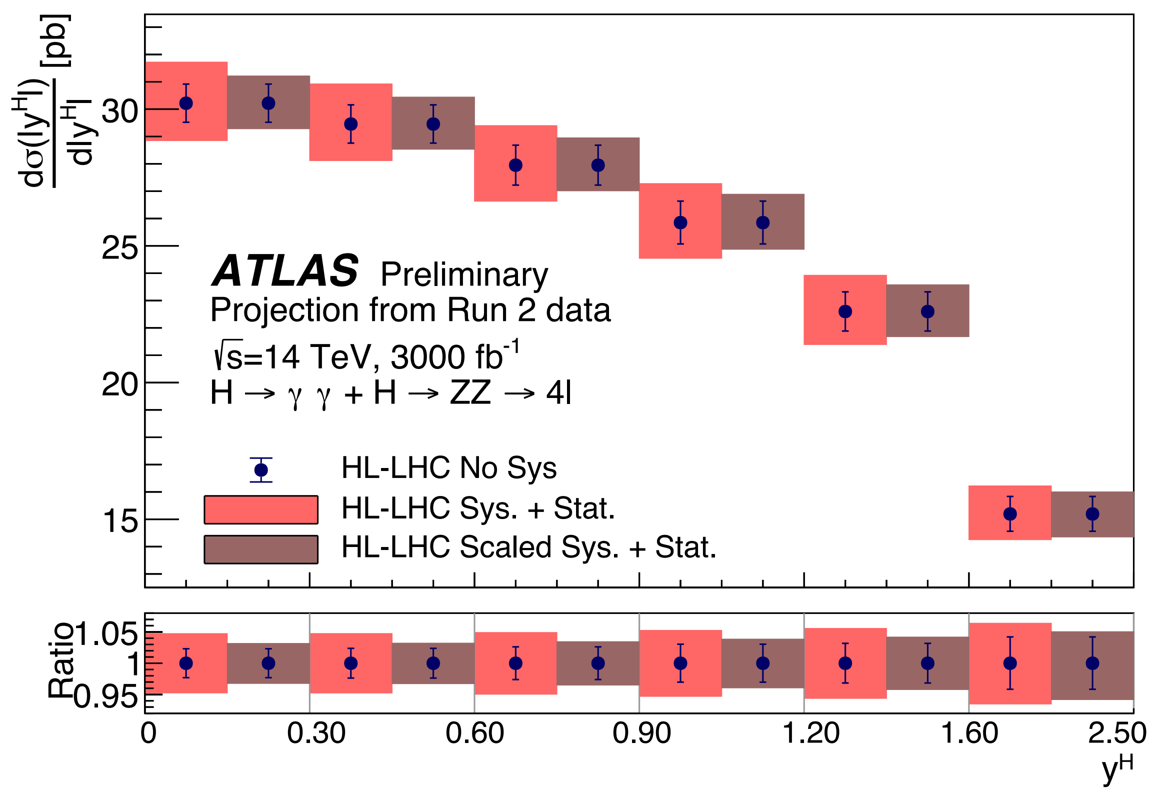


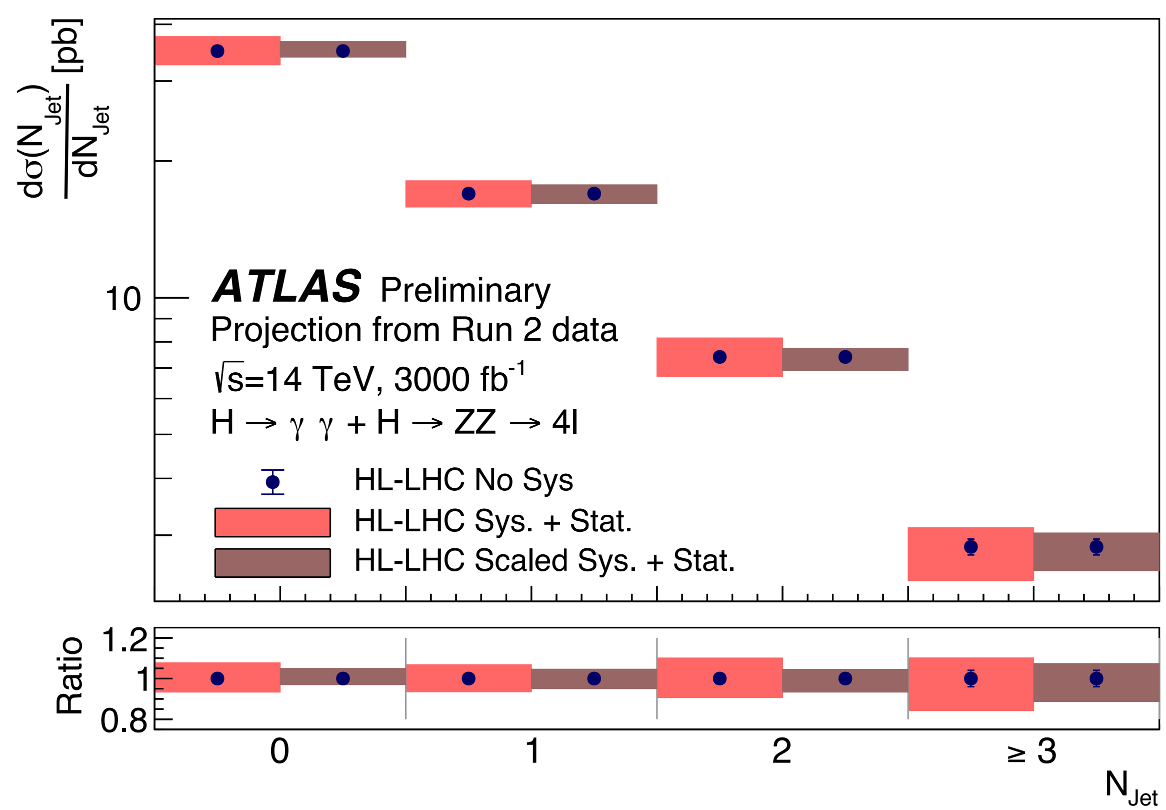


- Comparing Run2(S1) with YR18(S2) scenarios







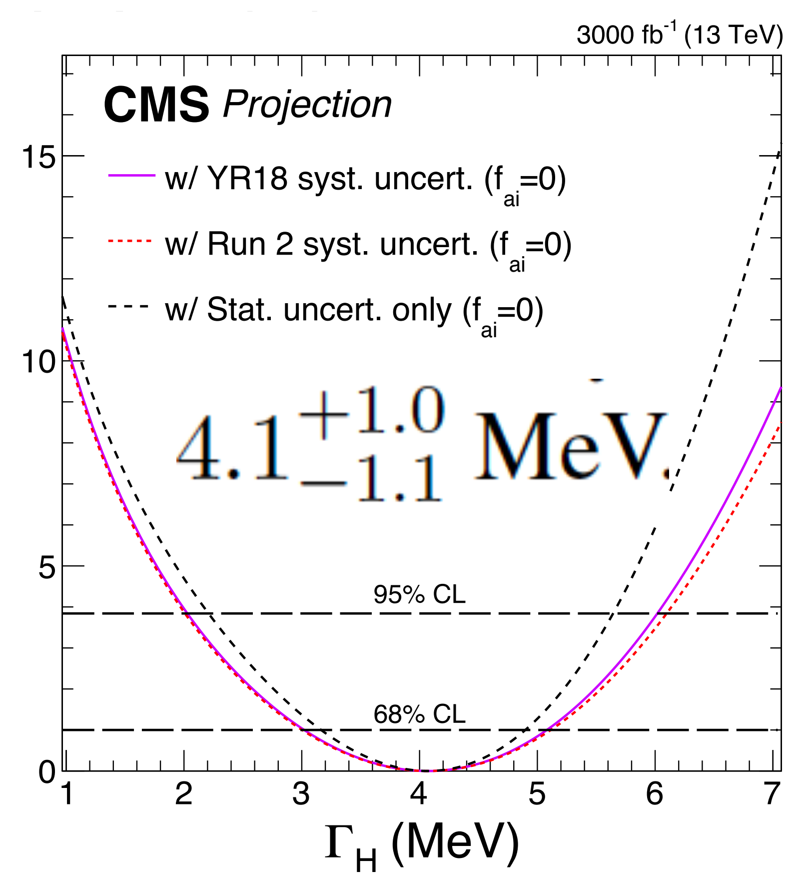


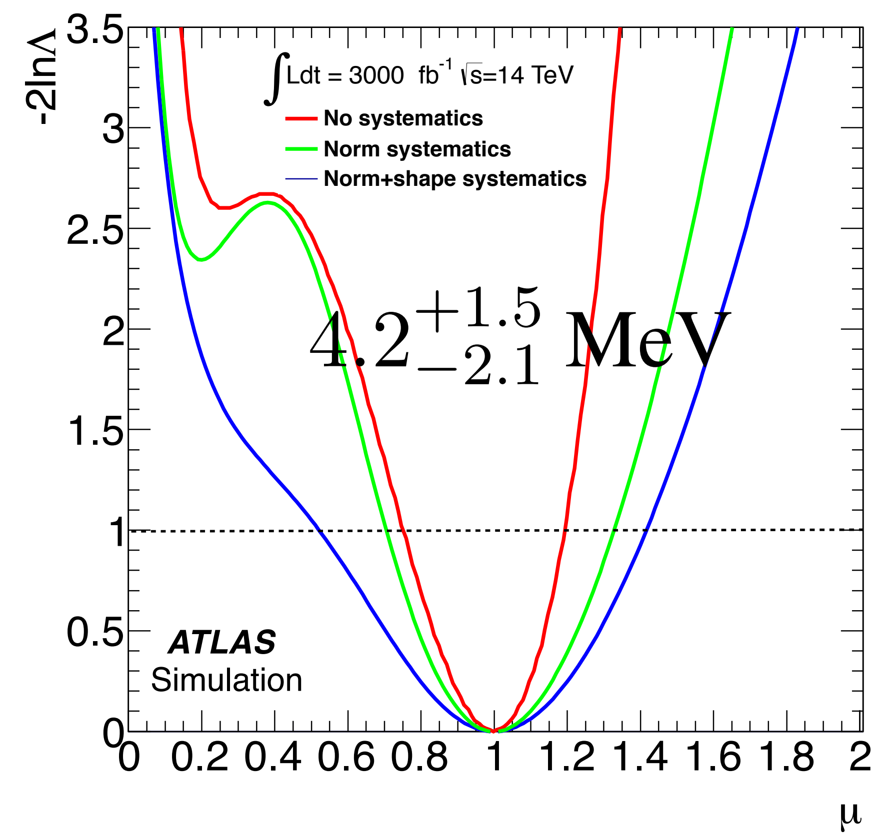
- Sensitive to k_b/k_c at low pt and k_t/BSM at high pt
- Expected precision of ~ 10% for $p_T(H)$ > 350 GeV, statistically limited

MASS & WIDTH

☞See presentation by M. Cepeda

* **Mass:** most precise measurement using H->ZZ->4μ, 2e2μ events. Reach of 10-20 MeV precision plausible goal dependent on future improvements on muon momentum measurements.





Width: Direct measurement will be challenging also with HL-LHC statistics. Probe New Physics in the Higgs domain at large momenta

* **4L Onshell and Offshell:** 20% precision at 68% CL combining CMS+ATLAS
* **From couplings:** Γ_H 5% precision at 95% CL, but model dependent (kV<1 and B_{unt}=0)
* **Diphoton** interference study, only weaker constraints

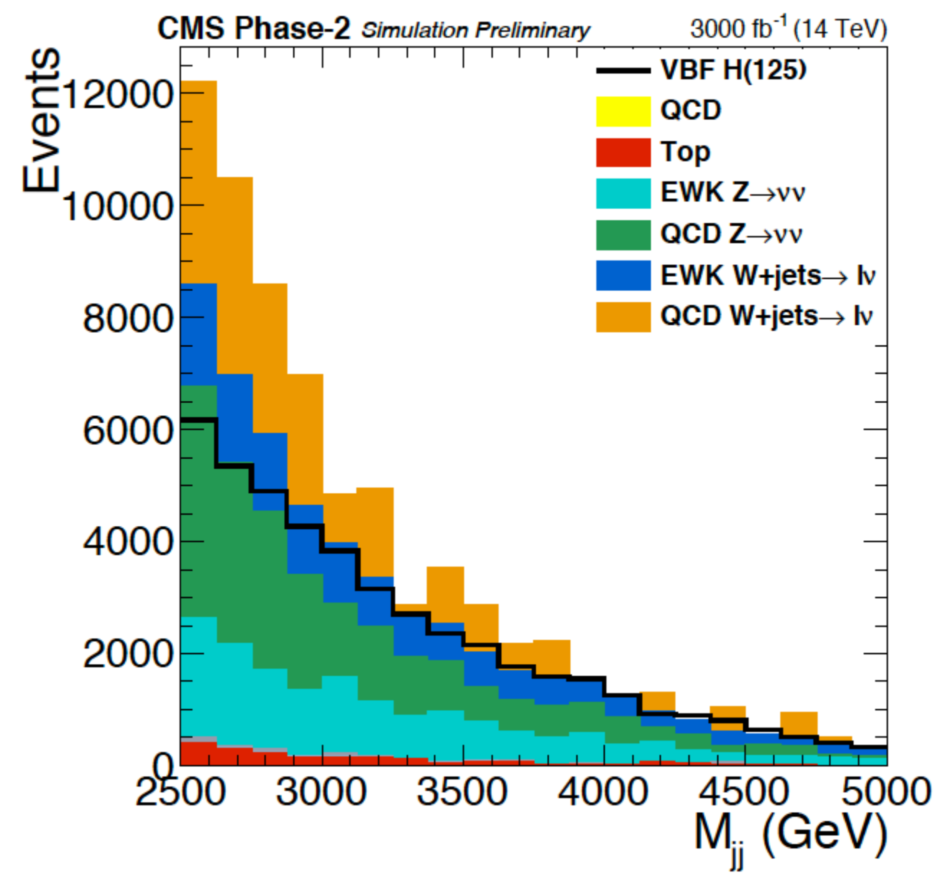
HIGGS INVISIBLE WIDTH

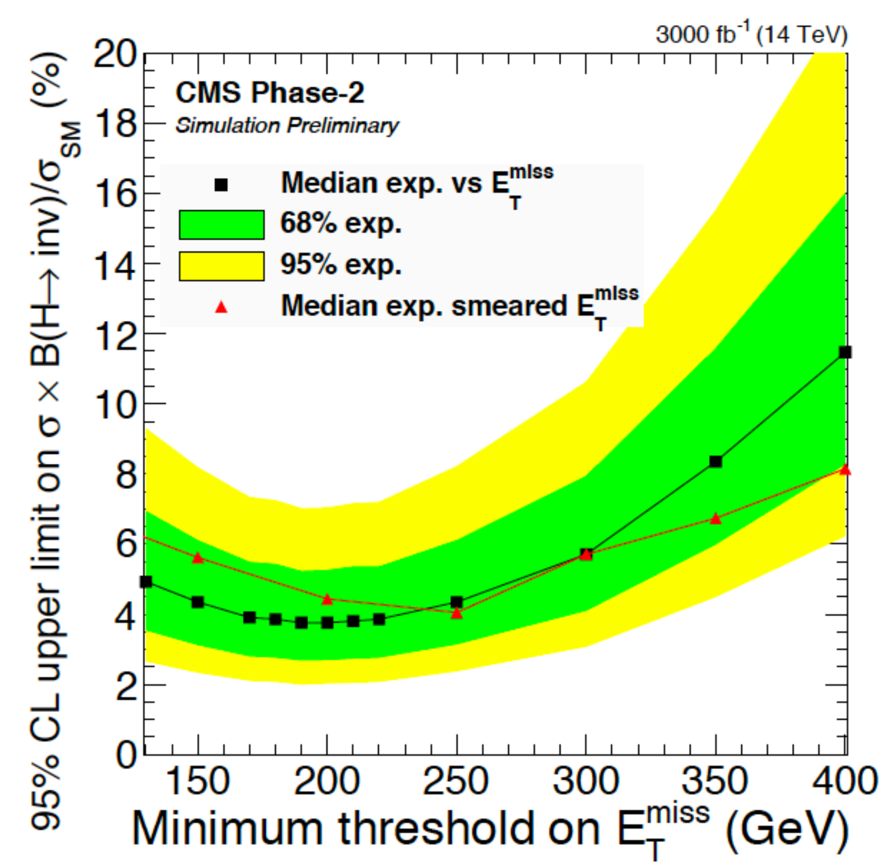
* Connection between Higgs & Dark Matter
  * Run2 Limit ~20% @ 95%CL (in both experiments sensitivity dominated by the VBF channel)
* From the global coupling fit B_{BSM} < 2.5% @ 95% CL if $B_{BSM} \geq 0$ (any invisible or undetected states):
* Prospects of direct searches @14TeV:

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 study how to handle the impact of PU in MET





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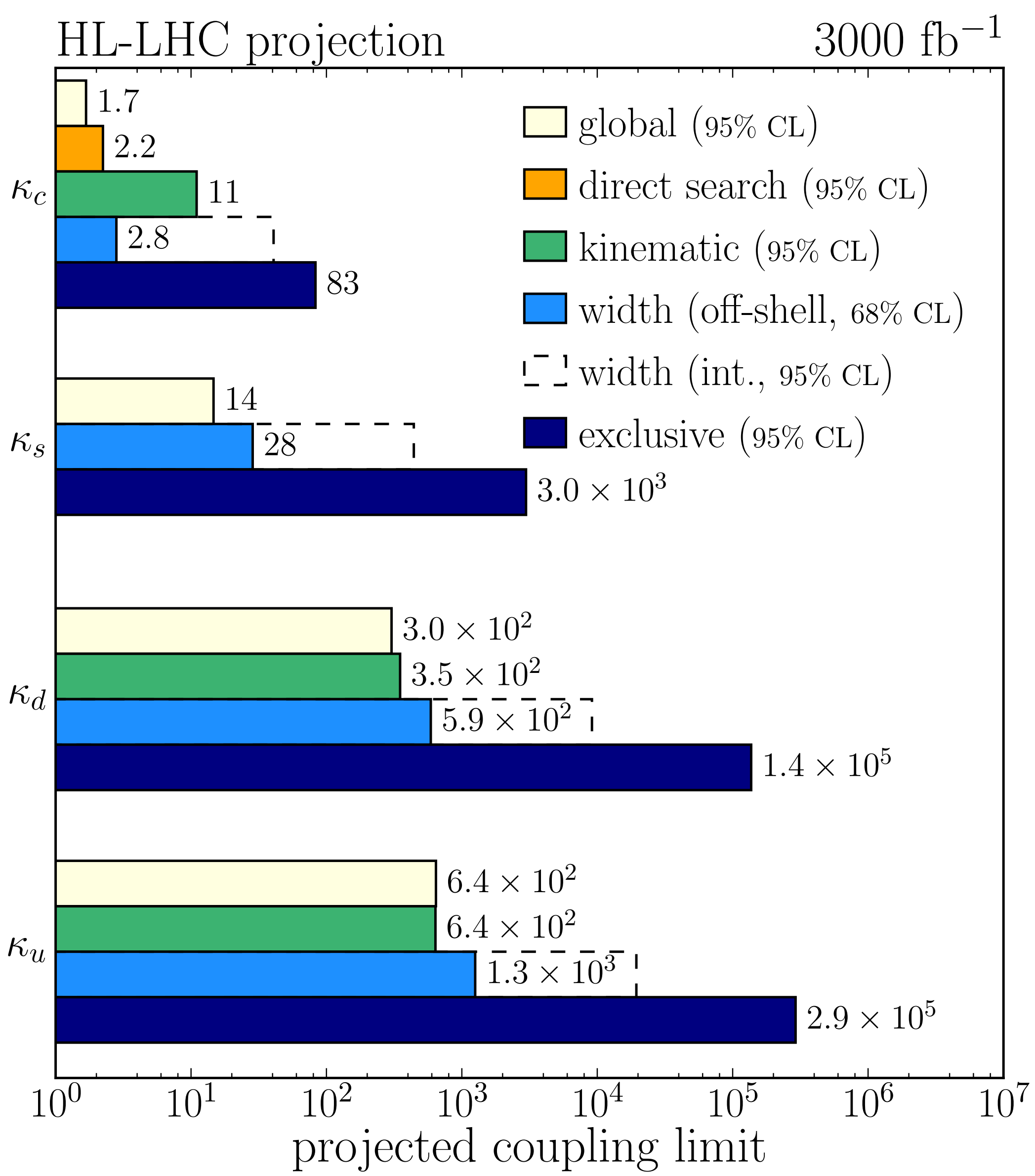
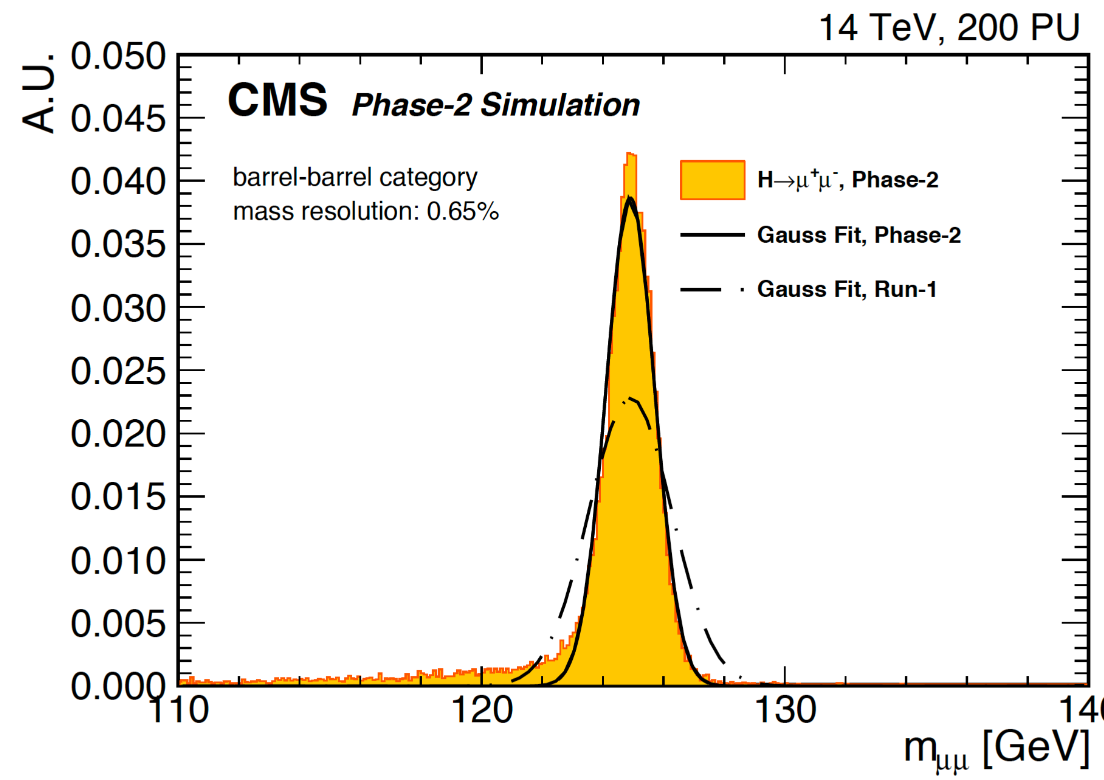
- **Hμμ:** Probe coupling to 2nd generation —> prospects for cross section and coupling measurement → 8% & 5% uncertainty@3000fb^{-1} respectively





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

- Indirect constraints will complement the direct searches (eg from differential distributions, off-shell couplings, or from the global coupling fits)
- The combined LHC (ATLAS+CMS+LHCb) reach for kappa_c could reach the 1% level

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DI-HIGGS@HL-LHC

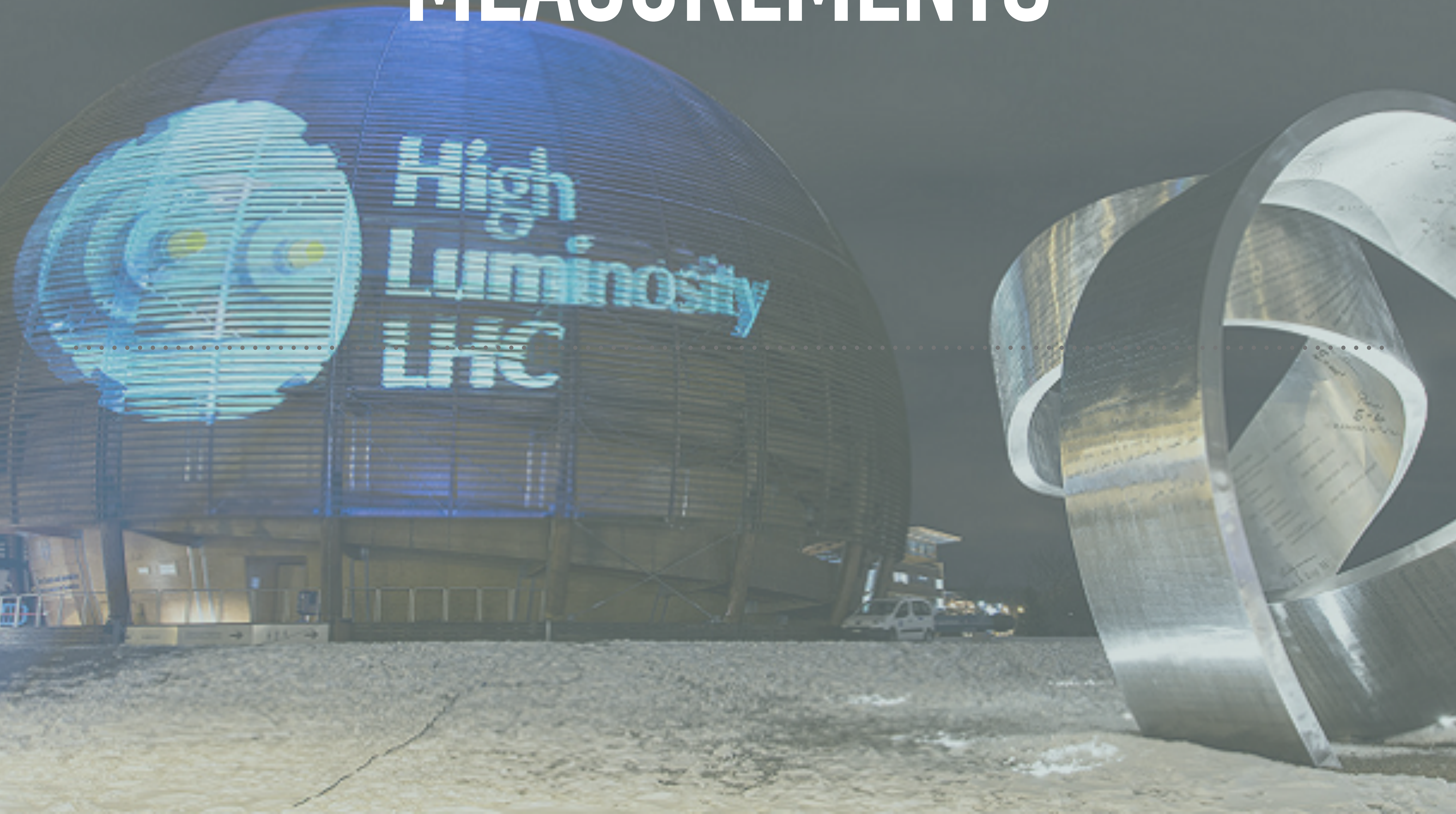
☞ **See presentation by E. Petit**

- σ~ 39.5 fb@14TeV → HL-LHC benchmark
  - Access the H self-coupling λ
  - Low cross section: destructive interference
- Expanding list of final states w. Run2 & extrapolated to HL-LHC

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

- Combined significance of a single experiment ~3 standard deviations
- **Combining the ATLAS and CMS results a significance of 4 standard deviation can be achieved (including systematic uncertainties).**

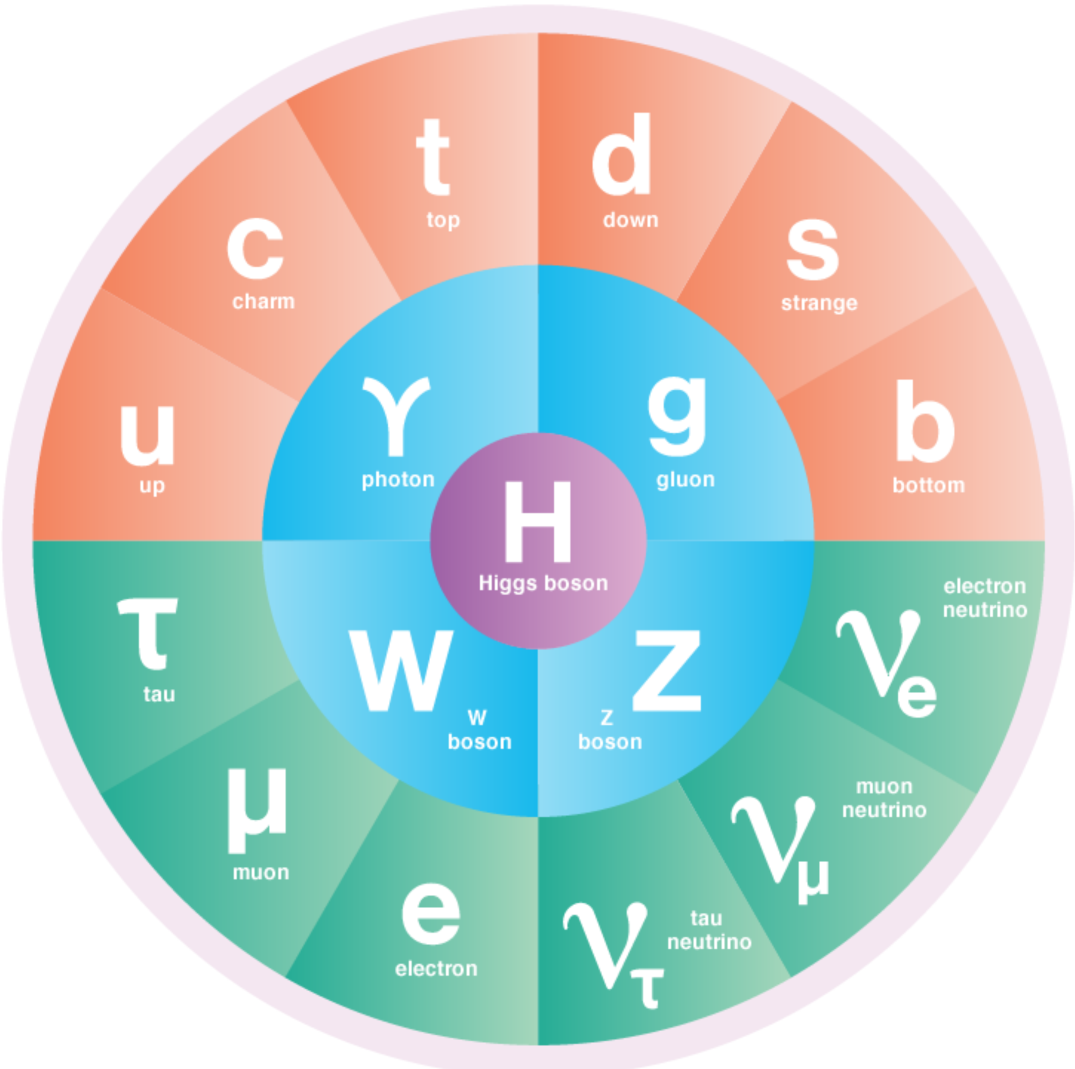
ELECTROWEAK PRECISION MEASUREMENTS



PRECISION SM PHYSICS FOR THE HL-LHC

- Only moderate increase in energy …but incredibly large statistics: many bosons, many tops!

  - Need to improve our understanding of systematic uncertainties and their interplay
  - Improve techniques for uncertainty mitigation
  - High precision differential measurements
  - Era of ‘dark’ corners of phase space (BSM sensitivity in the tails!)



- Renewed recognition of importance of Standard model measurements for their contribution to EWPO fits
- Engagement of theory community to match experimental precision

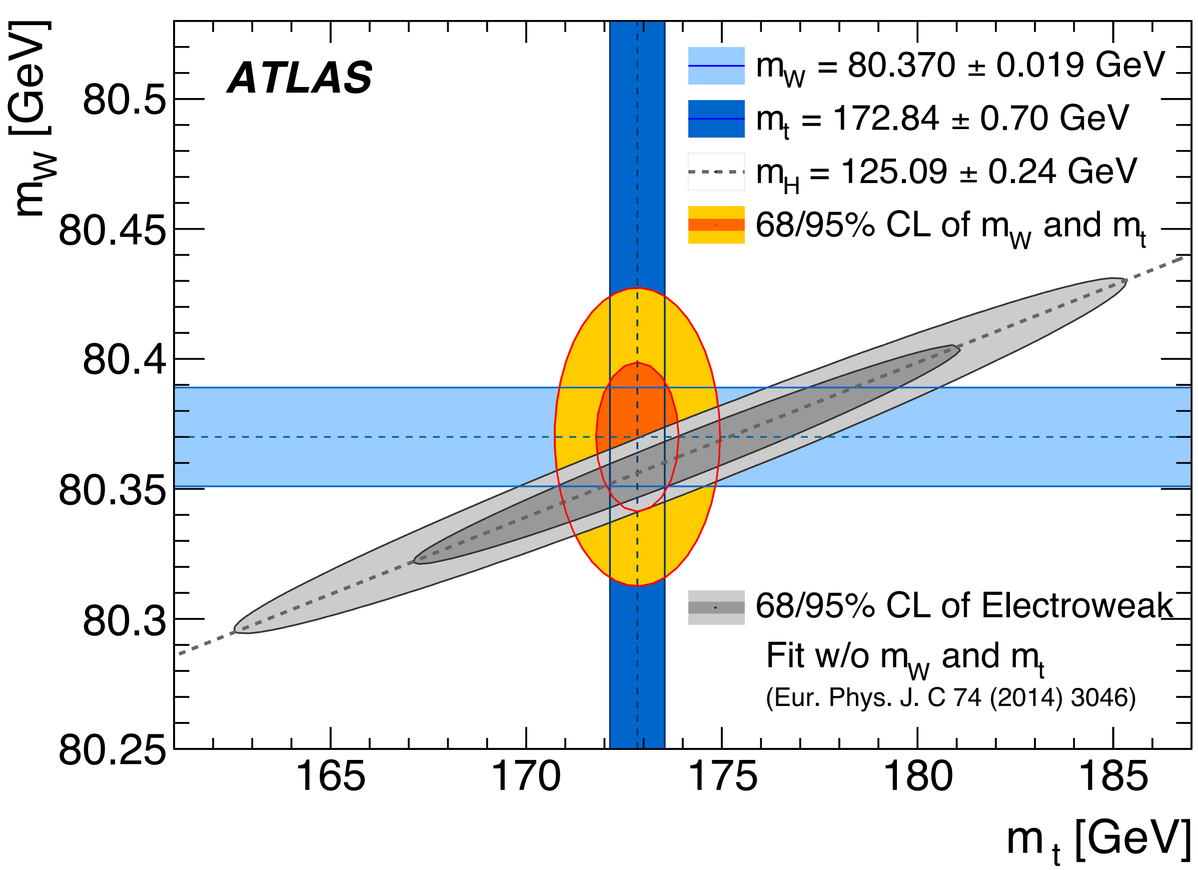
VECTOR BOSON PROCESSES

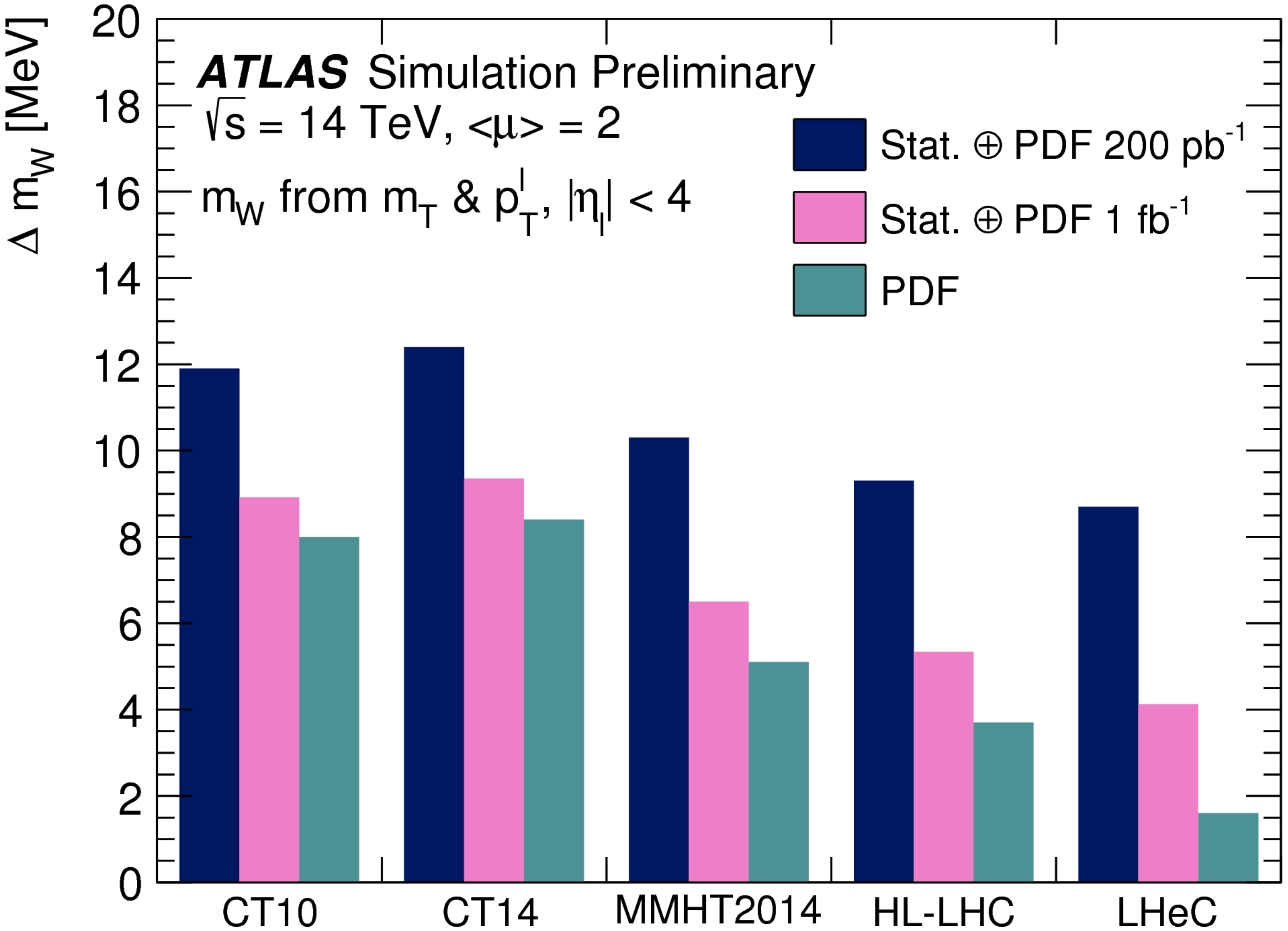
Process	$W^\pm W^\pm$	WZ	WV	ZZ	WWW	WWZ	WZZ
Final state	$\ell^\pm\ell^\pm jj$	$3\ell jj$	$\ell jjjj$	$4\ell jj$	$3\ell 3\nu$	$4\ell 2\nu$	$5\ell\nu$
Precision	6%	6%	6.5%	10–40%	11%	27%	36%
Significance	$> 5\sigma$	$> 5\sigma$	$> 5\sigma$	$> 5\sigma$	$> 5\sigma$	3.0σ	3.0σ

- **Vector boson scattering**
- Sensitive to anomalous EWK couplings and effects from new physics at higher scales
  - dim-8 EFT operators interpretation
- Distinct signature in the detector allows to mitigate effects from large PU, large statistics allows a comprehensive study in every channel
- 3σ Evidence for longitudinal polarization component $V_L V_L$ can be achieved combining channels and experiments

EWK PRECISION MEASUREMENTS - W MASS

- **W and top mass are key parameters of the SM**
- Motivation for low PileUp run: 200 pb-1 of Low PU data (μ~2) at 14 TeV
  - 5-10 weeks of running —> ~3MeV (stat only)
  - Exp syst assumed to be at same level of Stat uncertainty
  - PDF unc ~4MeV with ultimate PDF)
- **Goal Δm(W)~6MeV (extended coverage+combination+ultimate PDF)**
  - PDF syst can go down to ~2MeV with LHeC PDF set





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EWK PRECISION MEASUREMENTS - TOP MASS

- The methods that can be employed for the top mass reconstruction are characterized by different experimental and theoretical issues and uncertainties.
- High statistics allows new methods to become competitive
  - different systematics effects
- Theoretical advances in the contribution to the uncertainties have a major role in the ability to reach the ultimate precision at a hadron collider

Method:	$t\bar{t}$ lepton+jets	t-channel single top	$m_{SV\ell}$	J/ψ	$\sigma_{t\bar{t}}$
Δm_{top} (GeV):	0.17	0.45	0.62	0.50	1.2

Standard → ℓ+jets measurement

Statistically dominated

Limited by theory uncertainty and luminosity measurement

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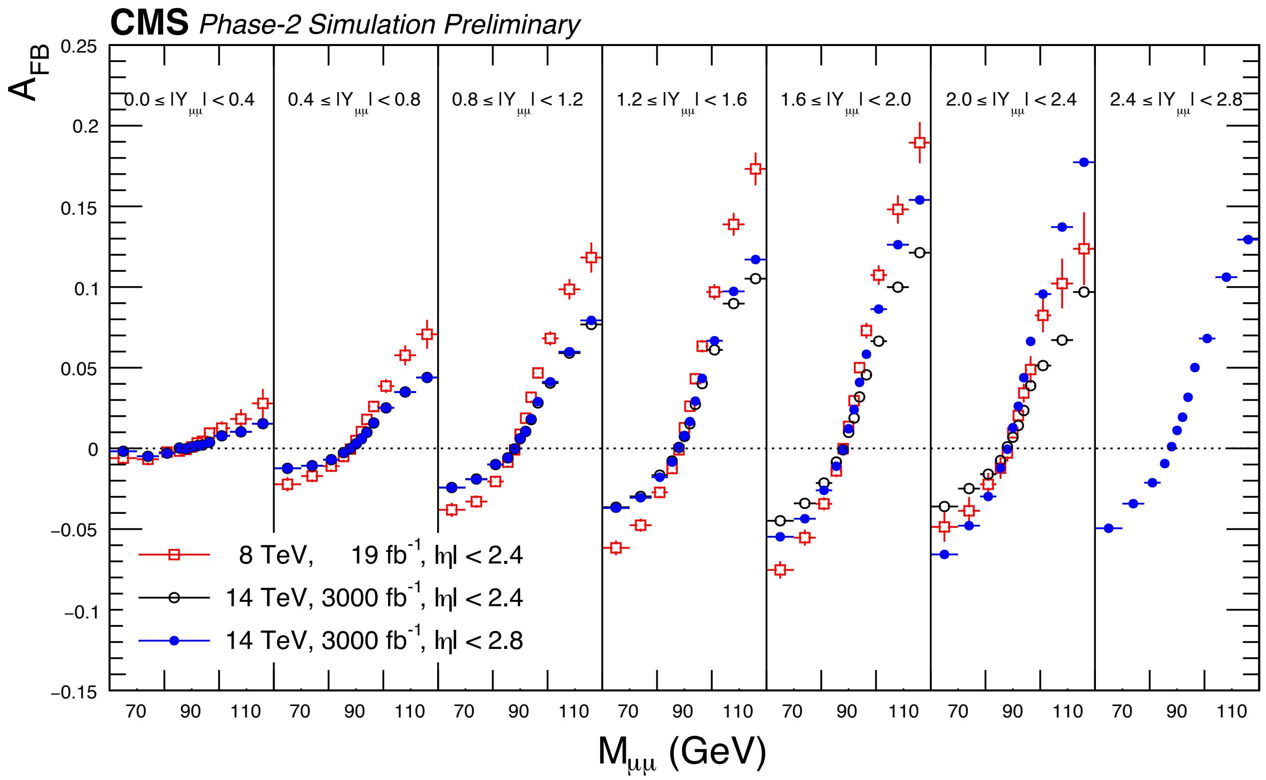
INFN Istituto Nazionale di Fisica Nucleare

EWK PRECISION MEASUREMENTS - $SIN^2\Theta_W$

Indirect determination of Mw and $\sin^2\theta^{eff}$ more precise then the experimental measurement:

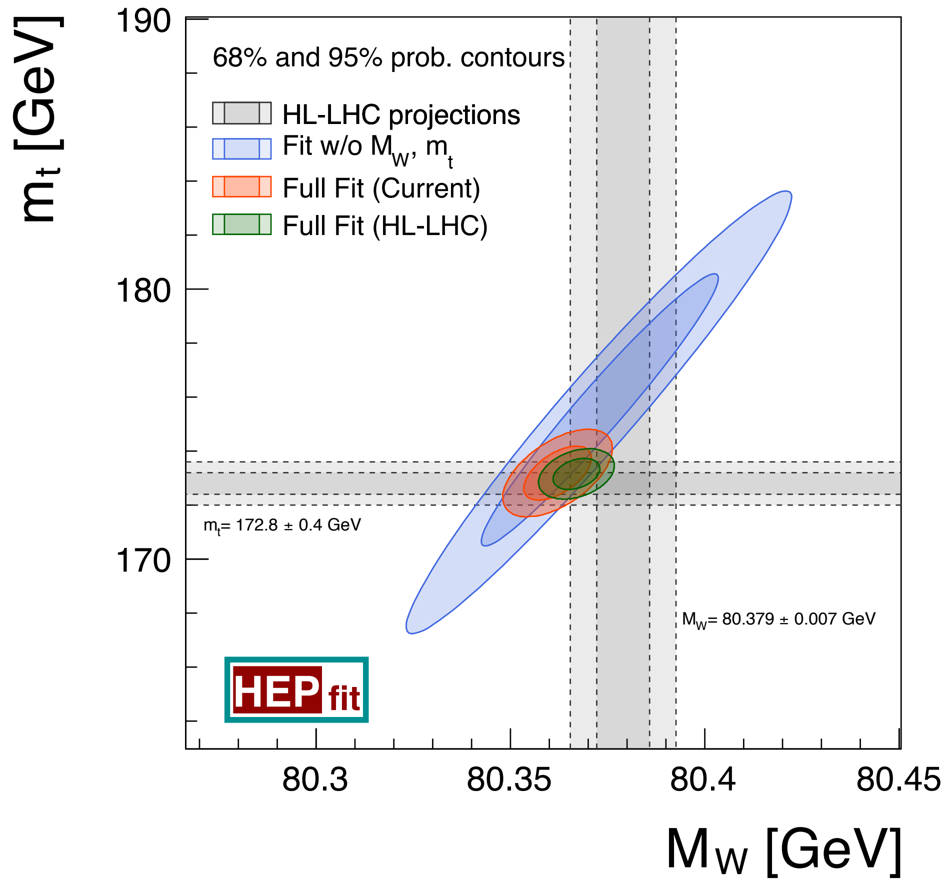
- This call for a precise direct Measurement
- Stringent test of the self consistency of the SM

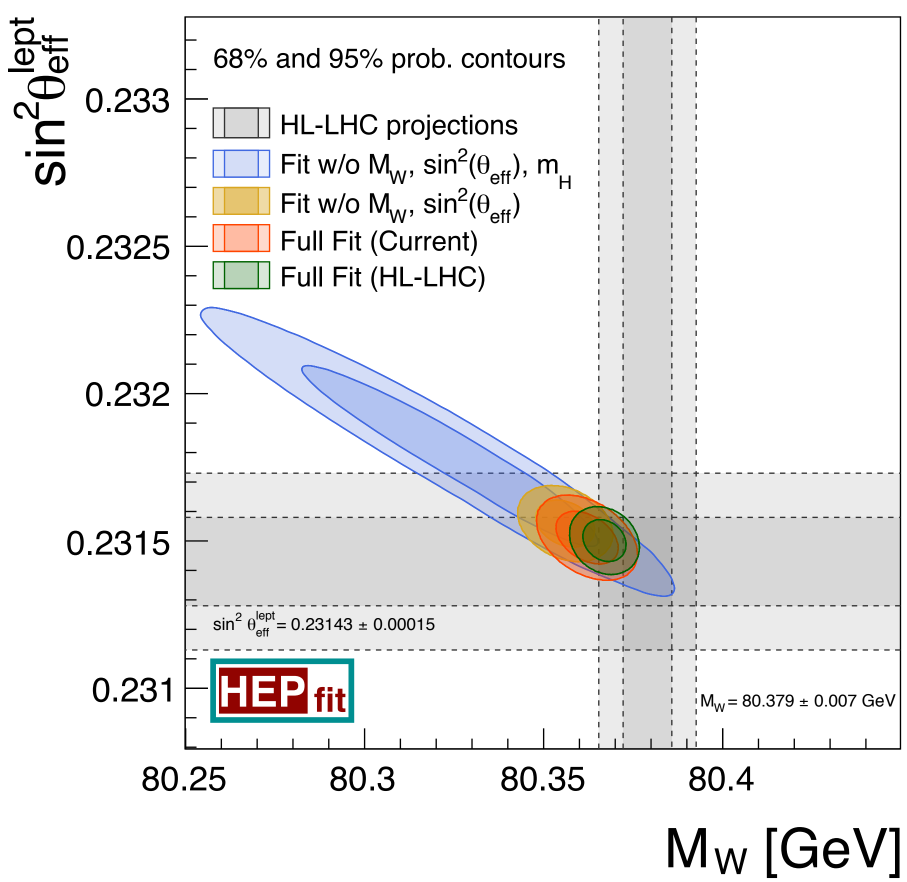


- Statistical uncertainty of single experiment better than $5*10^{-5}$
- Strong benefit from extended eta coverage of upgraded detectors

	ATLAS $\sqrt{s} = 8$ TeV	ATLAS $\sqrt{s} = 14$ TeV	ATLAS $\sqrt{s} = 14$ TeV
$\mathcal{L}$ [fb^{-1}]	20	3000	3000
PDF set	MMHT14	CT14	$PDF4LHC15_{HL-LHC}$
$\sin^2\theta^{lept}_{eff}$ [$\times 10^{-5}$]	23140	23153	23153
Stat.	± 21	± 4	± 4
PDFs	± 24	± 16	± 13
Experimental Syst.	± 9	± 8	± 6
Other Syst.	± 13	-	-
Total	± 36	± 18	± 15

- with LHeC reduction of PDF syst of additional x5





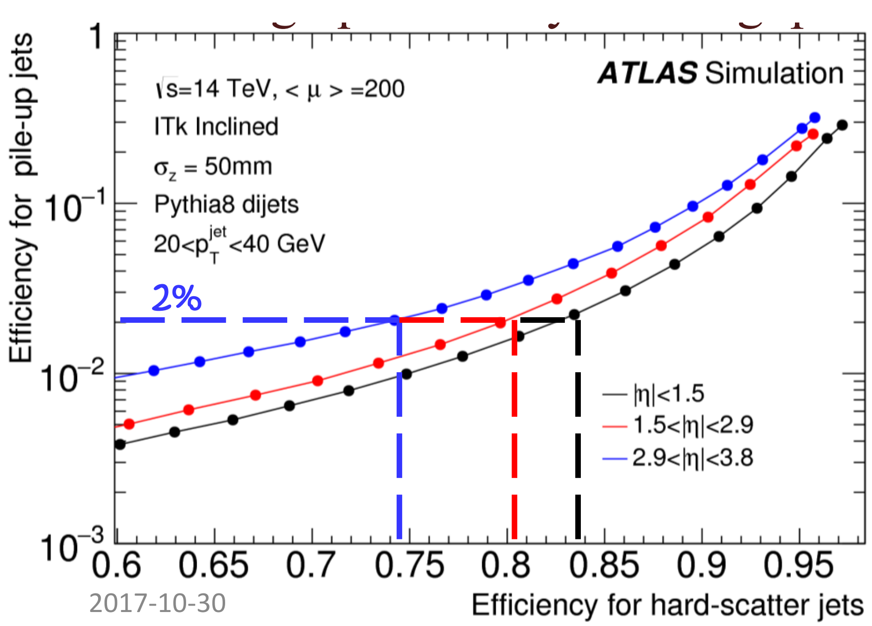
- Careful studies and projections for the physics at the HL-LHC we have shown:
  - we have designed amazing detectors that will be able to fully mitigate the 200PU conditions
  - we can expand the knowledge of the SM with improved precision and the observation of new processes that become accessible
  - we can expand the search for BSM physics with tools that allow to probe new and unusual processes
- We believe the extrapolations have been made on solid assumptions, and we are ready to see even bigger improvement once the data comes!

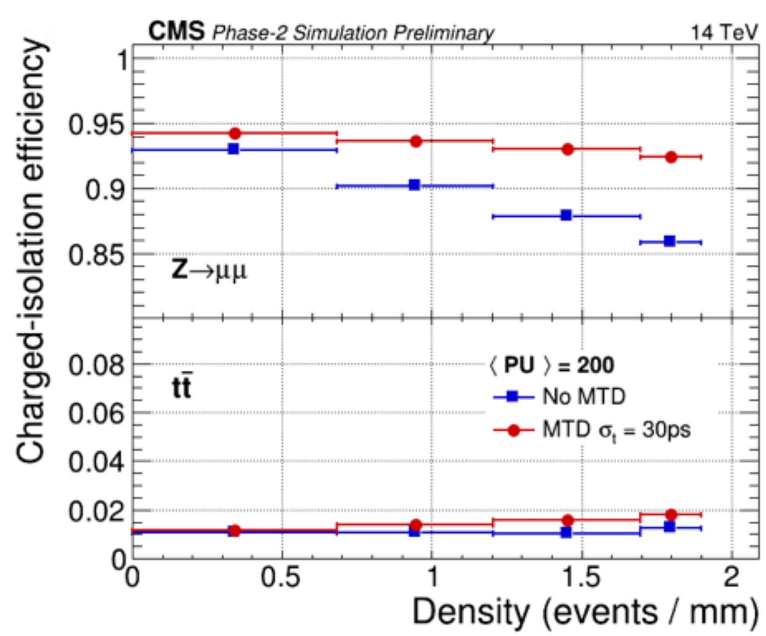
BACKUP

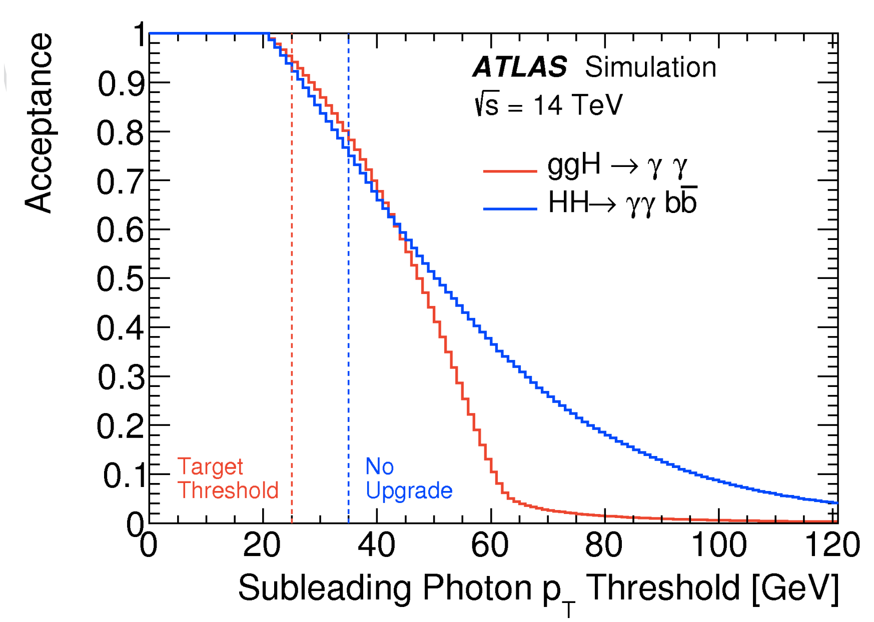
Precision physics at the HL-LHC?

- 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.

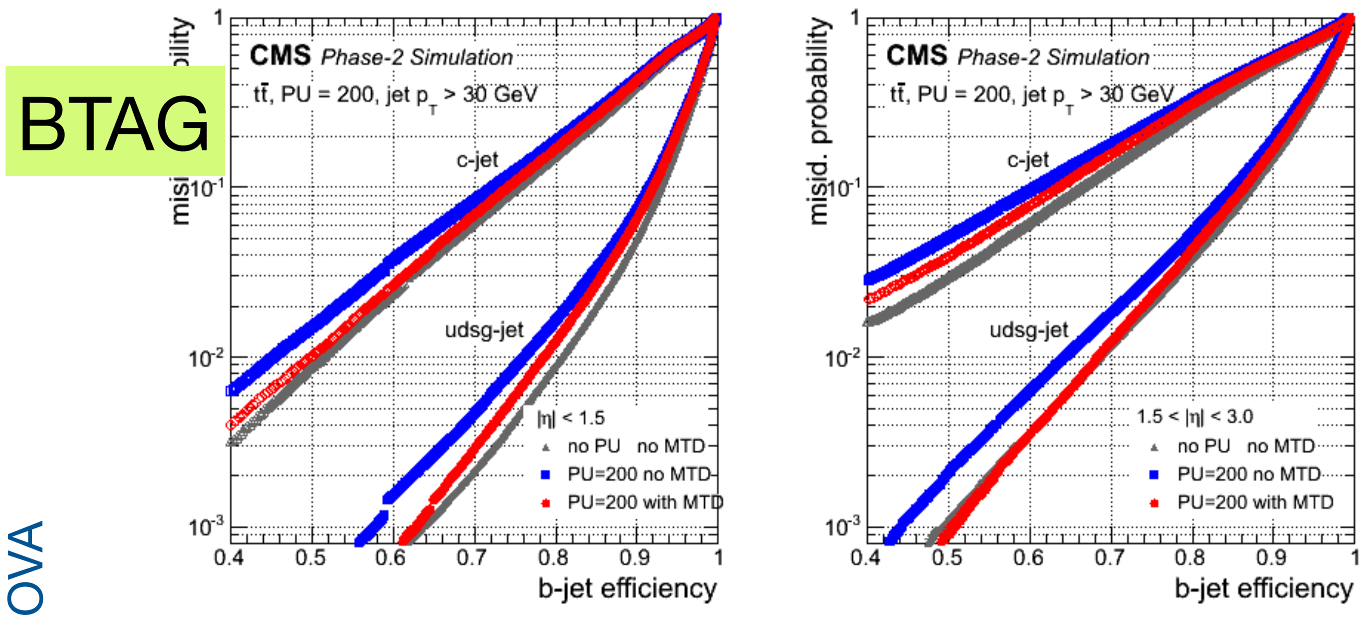
- These studies, performed extensively in 2017 for the ATLAS&CMS Technical Design Reports, are critical to support our updated physics prospects (both those based on projections of Run2 analysis and those directly using fast/parameterized simulations of the HL-LHC performance)

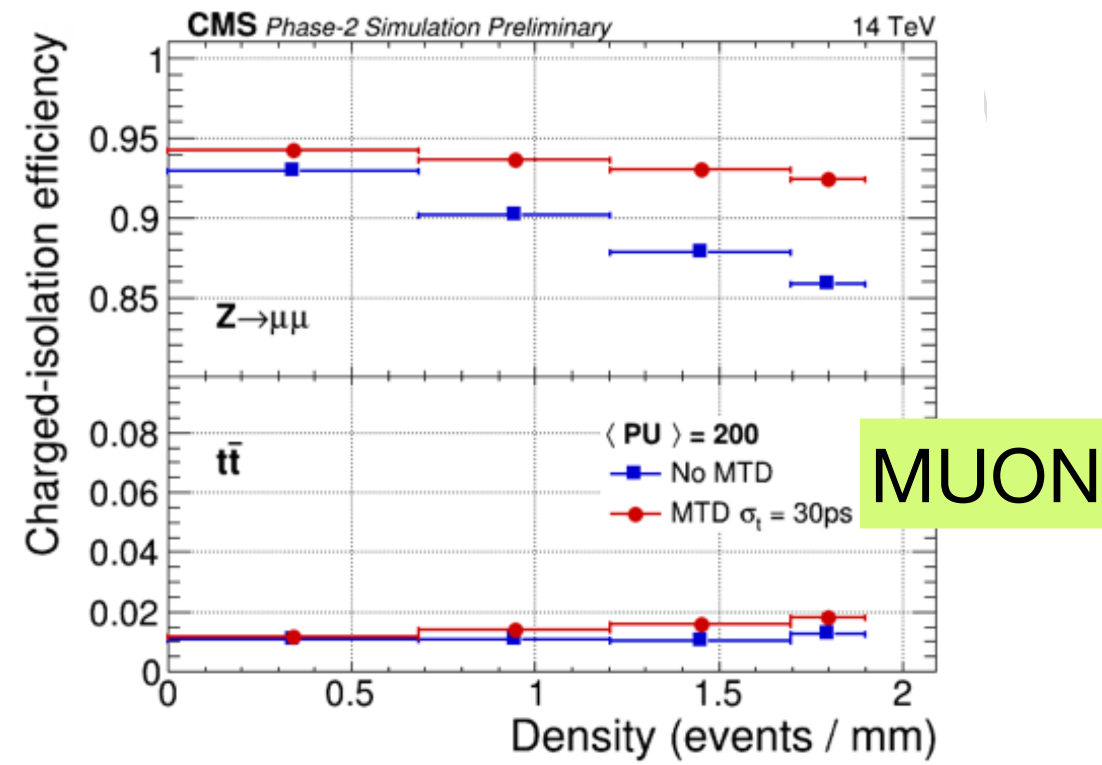


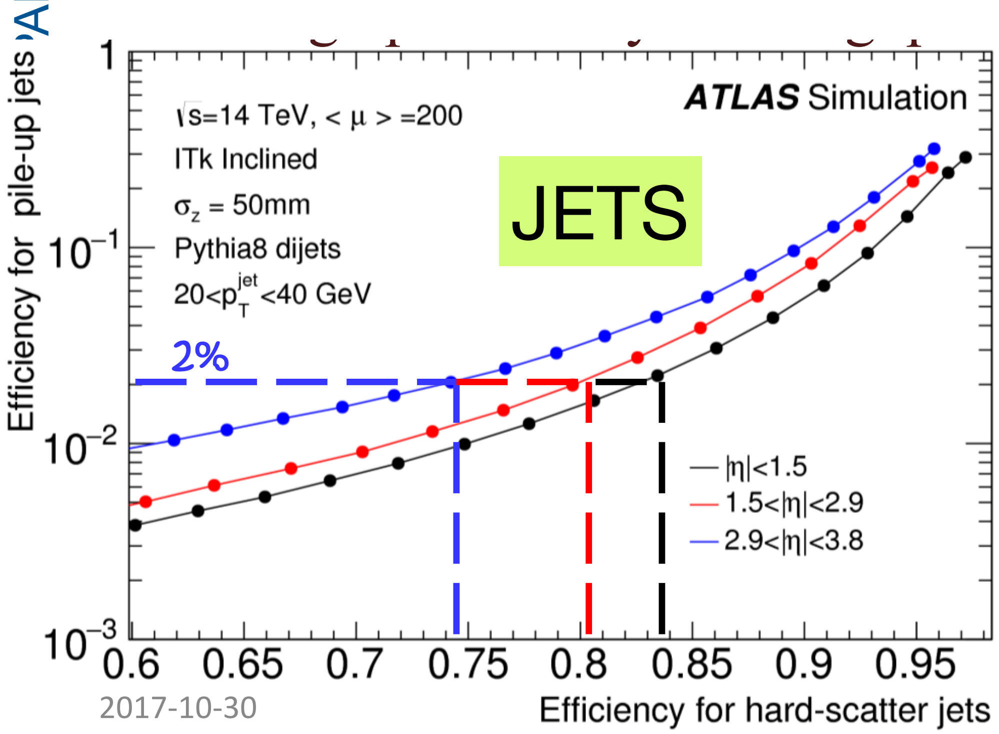


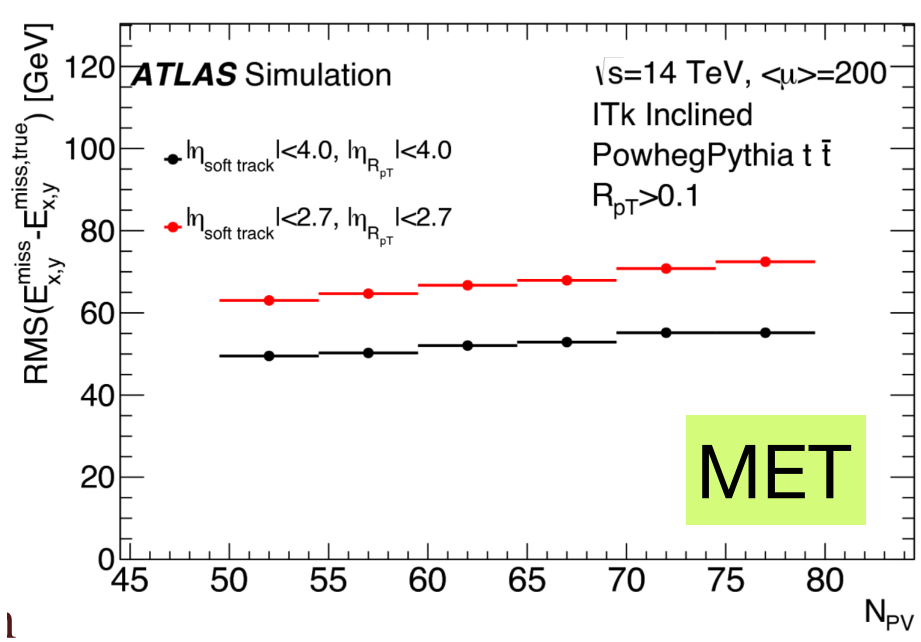


- Maintain performance similar or better than Run 2
- Effective pileup mitigation & extended capabilities with new algorithms









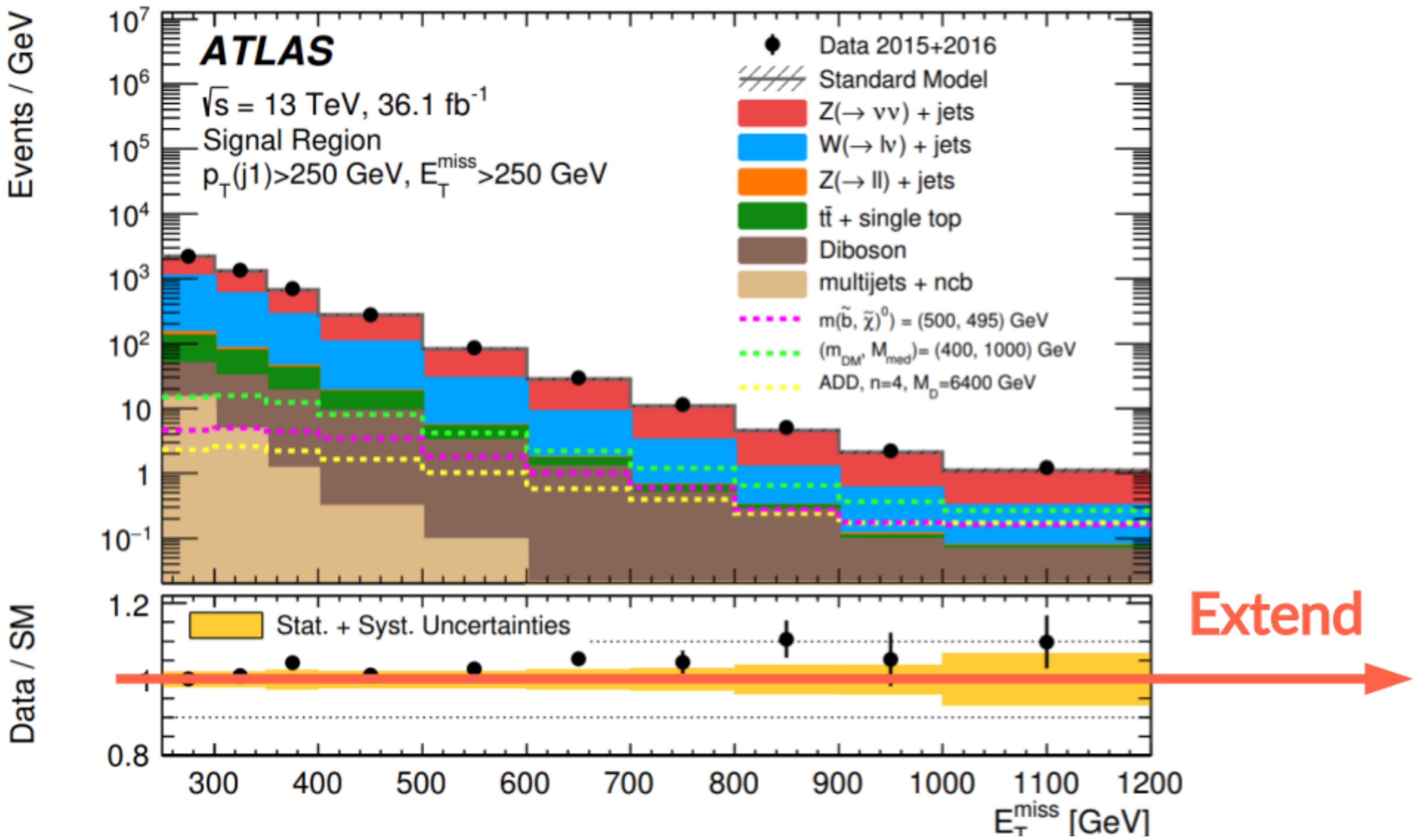
…just selected plots, more available in the TDRs

Systematics in "truth-based" projections

- Parametrized detector performance or delphes "reconstruction"
  - more rarely full-simulation samples too
  - allows re-optimization of selections and direct usage of parametrized performance of upgraded detector

- Consider leading systematic uncertainties if dominant over stat.
  - Applied shifting "reconstructed" quantities and assessing impact

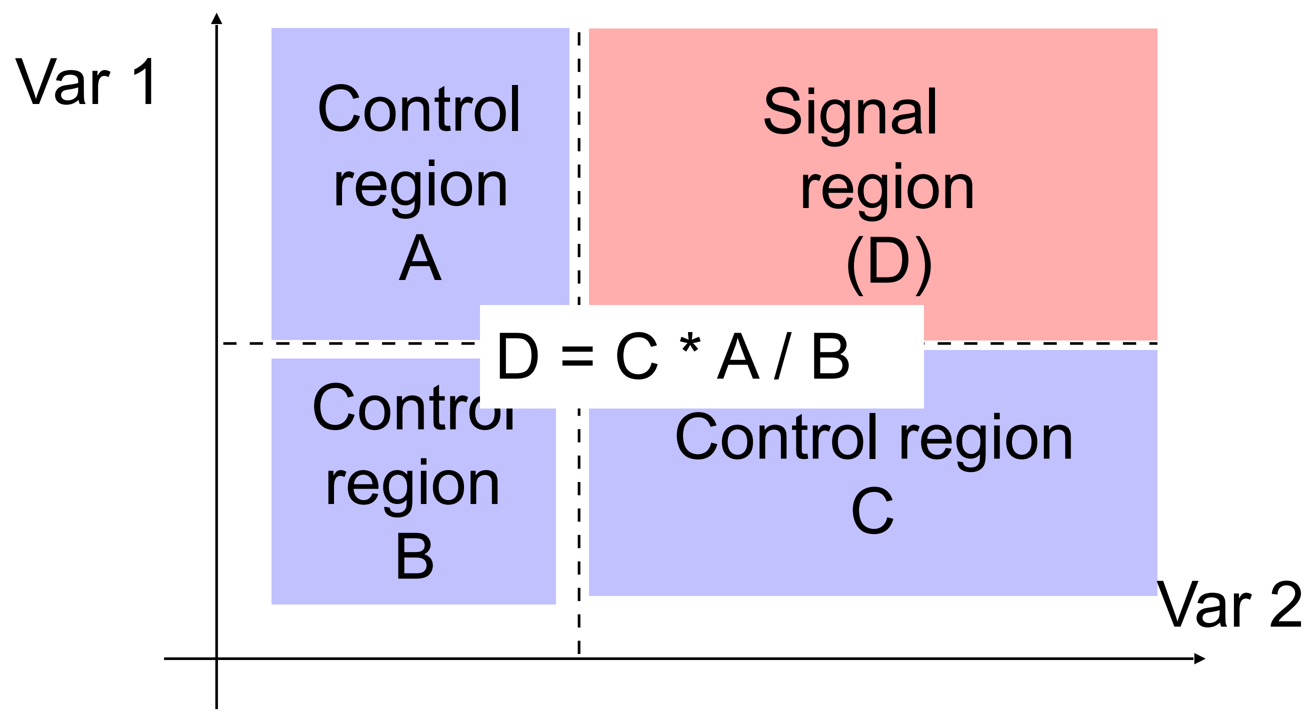
- Non-trivial extrapolation to run-2 "inaccessible" regions/features
  - detector capabilities (timing, ...)
  - kinematics (large h tracking, high p_{T},...)

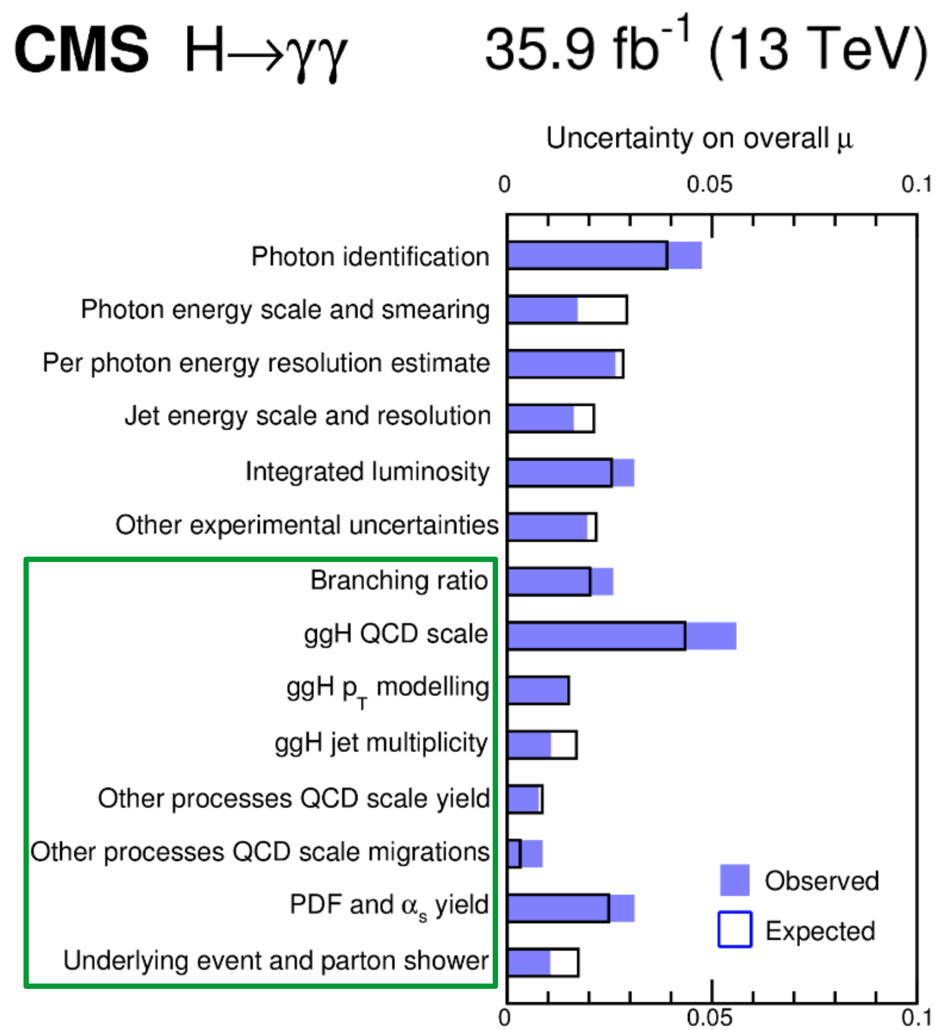


JHEP01 (2018) 126

Method/Modeling uncertainties

- Expected background often constrained in dedicated control regions
- Extrapolation from control to signal region:
  - MC prediction → modeling uncertainty
  - entirely data-driven methods → check assumptions often in MC
- In both cases expect:
  - closure of method → harder to predict, **keep same**
  - statistics in control region → **~sqrt(L)**
  - theory uncertainty critical → **halved**
  -





- Theorists' input crucial on a case by case

SYSTEMATIC UNCERTAINTIES (II)

Object Efficiency	uncertainty	Recommendation
Muons	muon reco+ID (all WP)	0.1%
	muon reco+ID+isolation (all WP)	0.5%
Electrons/photons	electron reco=ID (incl. isolation), all WP (pt > 20 GeV)	0.5%
	photon reco+ID+incl. isolation)	~2% (?)
tau	tau reco+ID+isolation (all WP)	5% as in Run2
		recommend 2.5% for analyses where tau efficiency is one of the diominant uncertainties
flavor tagging	b-jets (all working points) c-jets (all working points)	~ 1% for 30<pt<300 GeV, 2--6% for pt>300 GeV ~2%
	light jets (loose WP)	5%
	light jets (medium WP)	10%
	light jets (tight WP)	15%
	subjet b-tagging	
	double b tag	

See https://twiki.cern.ch/twiki/bin/view/LHCPhysics/HLHELHCCommonSystematics for more details

SYSTEMATIC UNCERTAINTIES (III)

JME	JES for **Delphes based analysis**	Total			for recommendations see slides 1 and 2 of JEC-CommonWithATLAS
					TOTAL_DIJET_AntiKt4EMTopo_: to be applied only to light-jets or generic jets
					TOTAL_BJES_AntiKt4EMTopo_: to be applied only to b-jets
	JES **reduction factors for Run2 projection - eta independent**				for eta **dependent** reduction factor see slide 1 of JEC-CommonWithATLAS. Below are eta independent reduction factors
		TOTAL	0.5%	N/A	1/2
		abs. scale	0.5%	N/A	1/5
		rel. scale	0.1-3%	N/A	1
		Pile up	0-2%	N/A	1/2
		Method and Sample	0.5-5%	N/A	0%
		Jet Flavour	1.5%	N/A	1/2
		Time Stability	0.2%	N/A	0%
	JER			N/A	3-5% as a fcuntion of eta
	MET		propagate JEC uncs.		propagate JEC uncs. (must)
					propagate JER uncs. (recommended)
					vary unclustered energy by 10% (recommended)

Integrated luminosity uncertainty already dominant in some SM measurements

Dominant for HL-LHC SM analyses. Sub-leading only if at the ~1% level

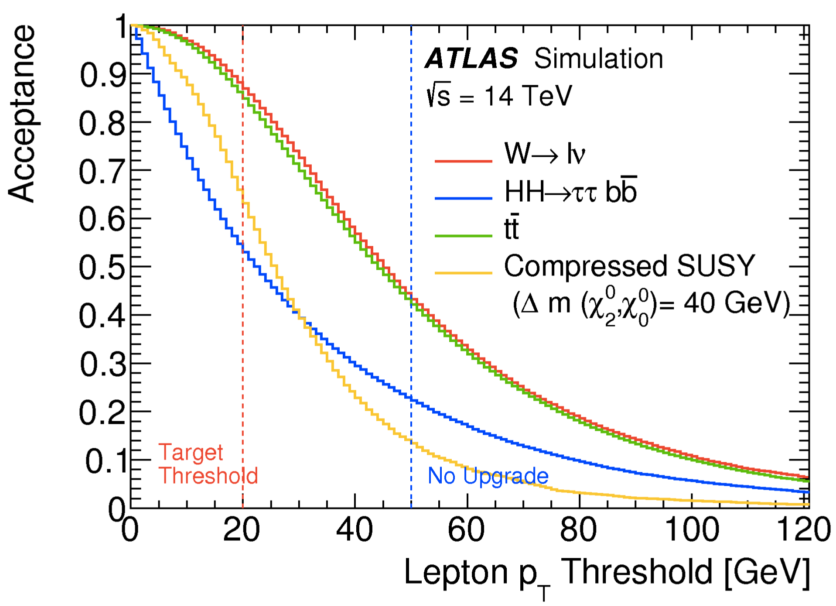
LHC-wide integrated luminosity uncertainty target agreed upon

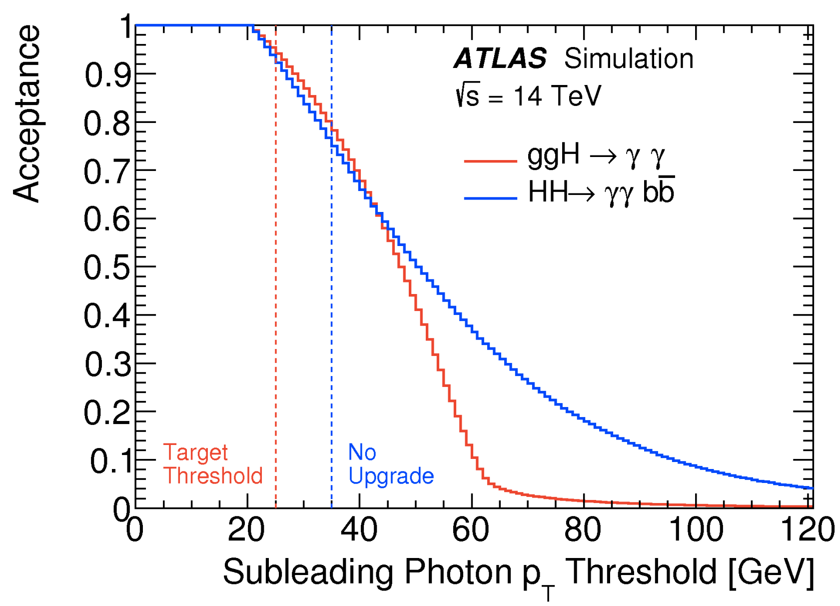
Luminosity: 1.0% precision (and no worse than 1.5%) to fully exploit HL-LHC potential

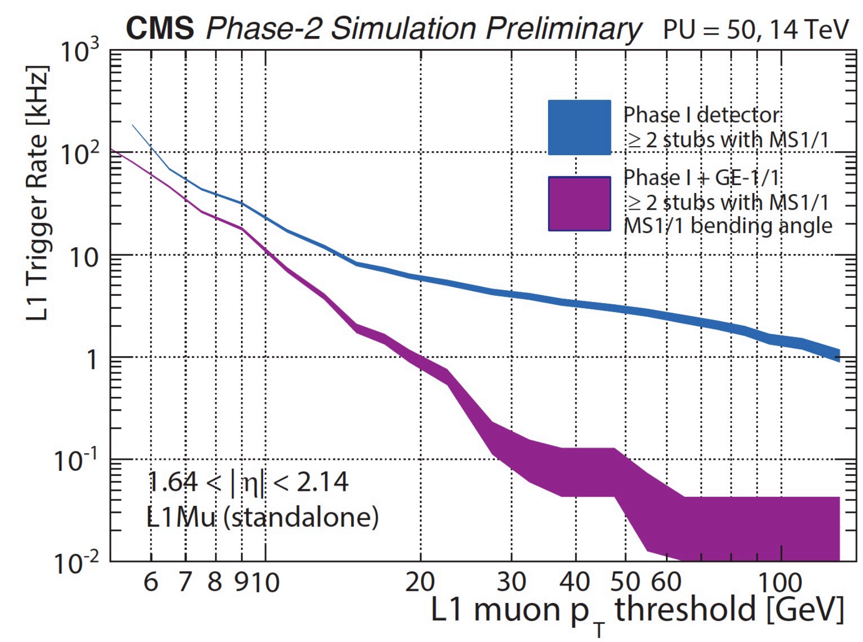
TRIGGER PERFORMANCE

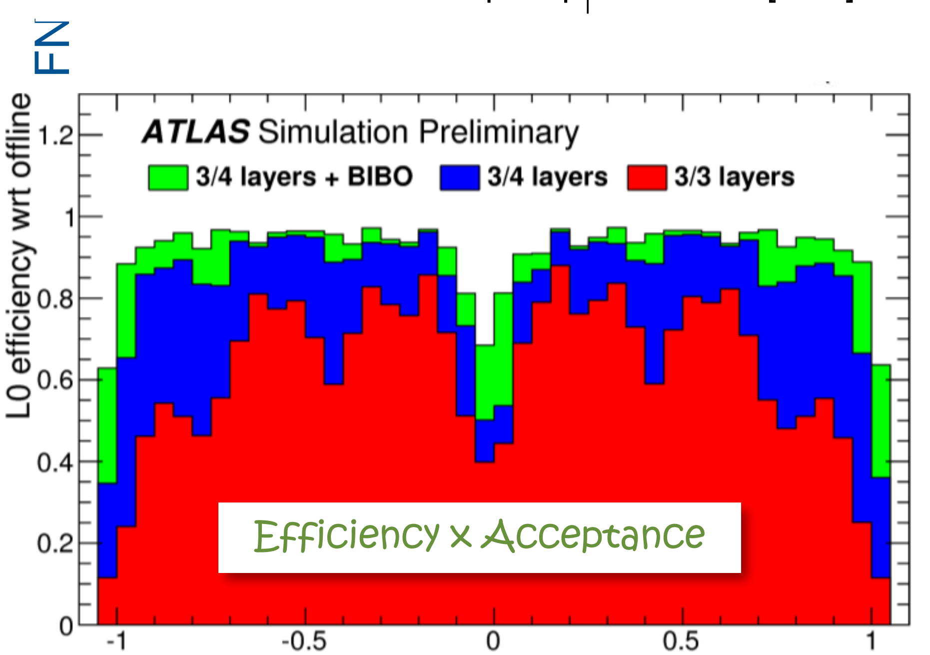
- Requirements for Trigger and DAQ for CMS-ATLAS:
  - L1 latency increase to ~10-12.5μs (~2.5-3.2μs today)
  - Readout rate increase to 750-1000kHz (100 kHz today)
  - Overall throughput to ~50 Tb/s (~2Tb/s today)
  - Rate to permament storage to ~7.5-10kHz (~1kHz today)

L1 tracking helps reducing rates, keeping thresholds low, improving efficiency









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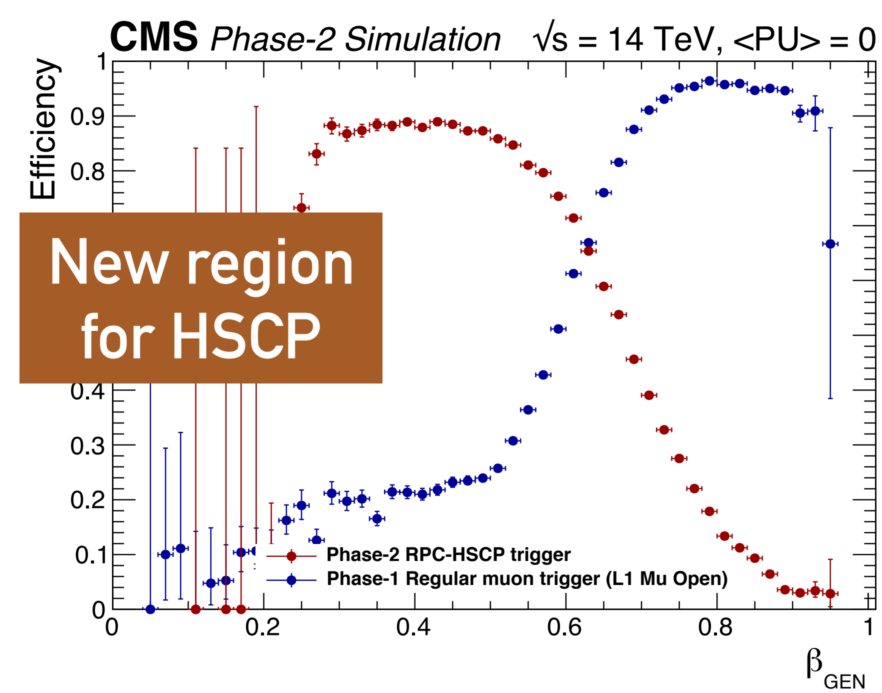
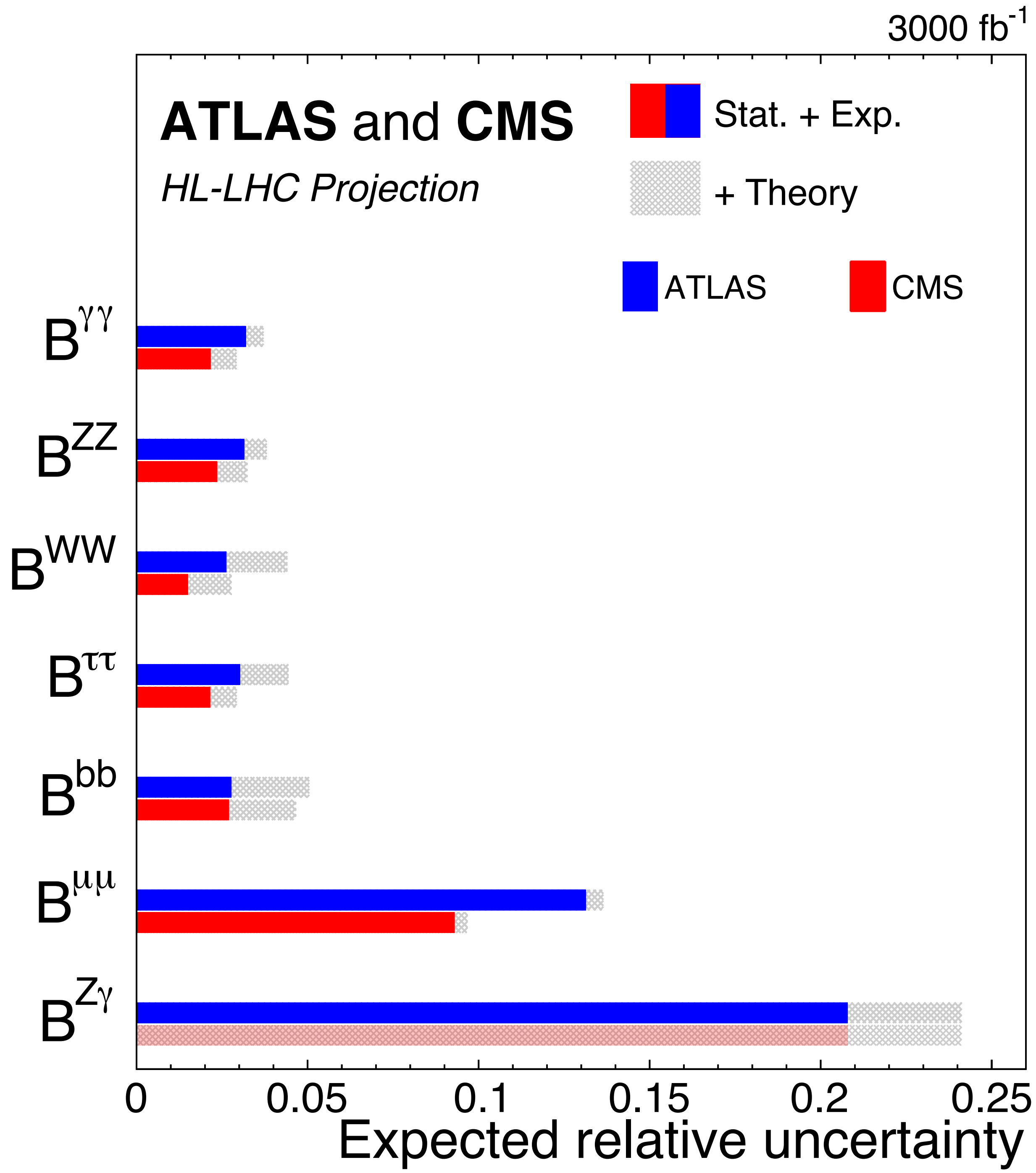
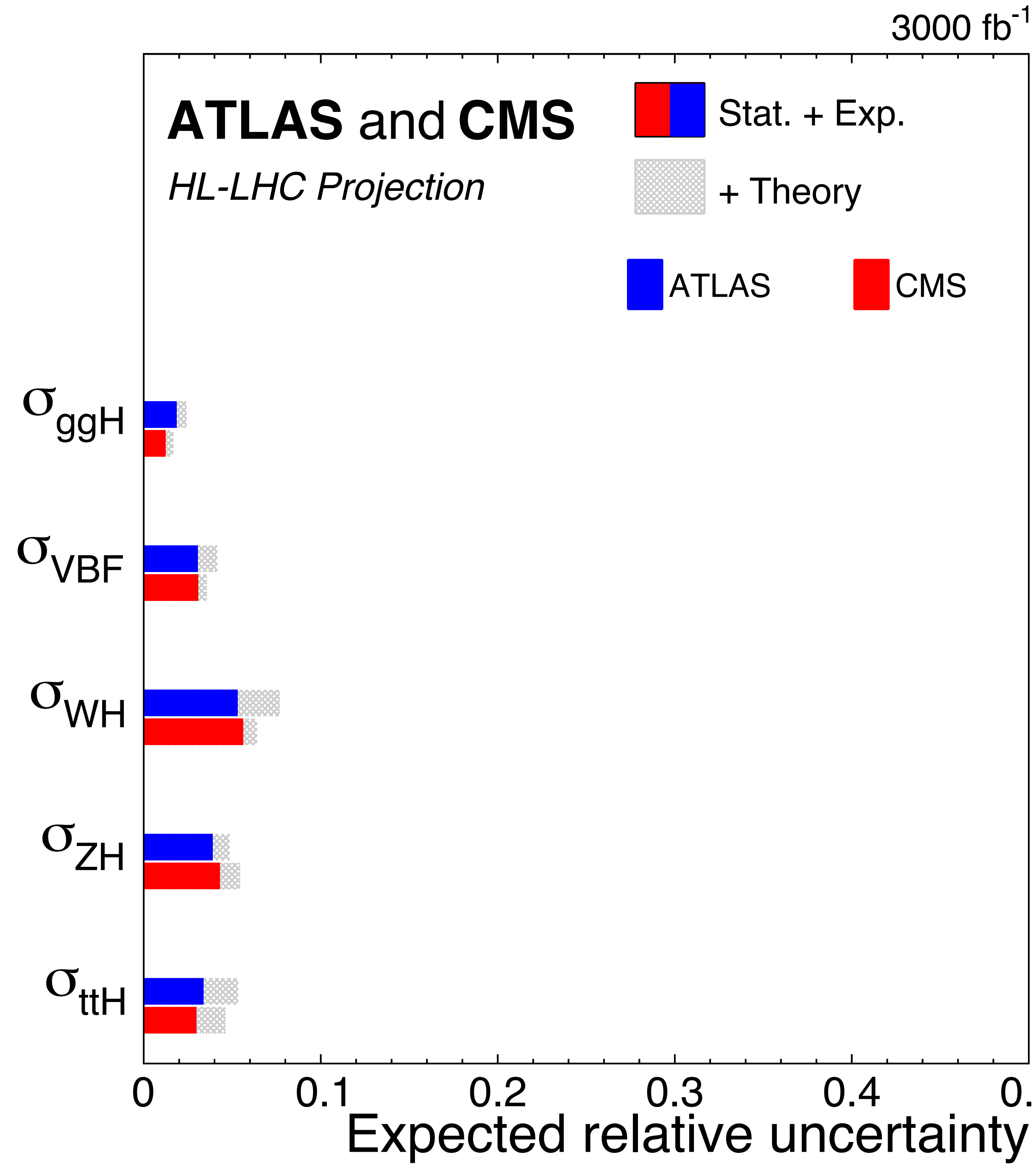
Improve: with redundancy and new features!



COUPLINGS - UNCERTAINTIES





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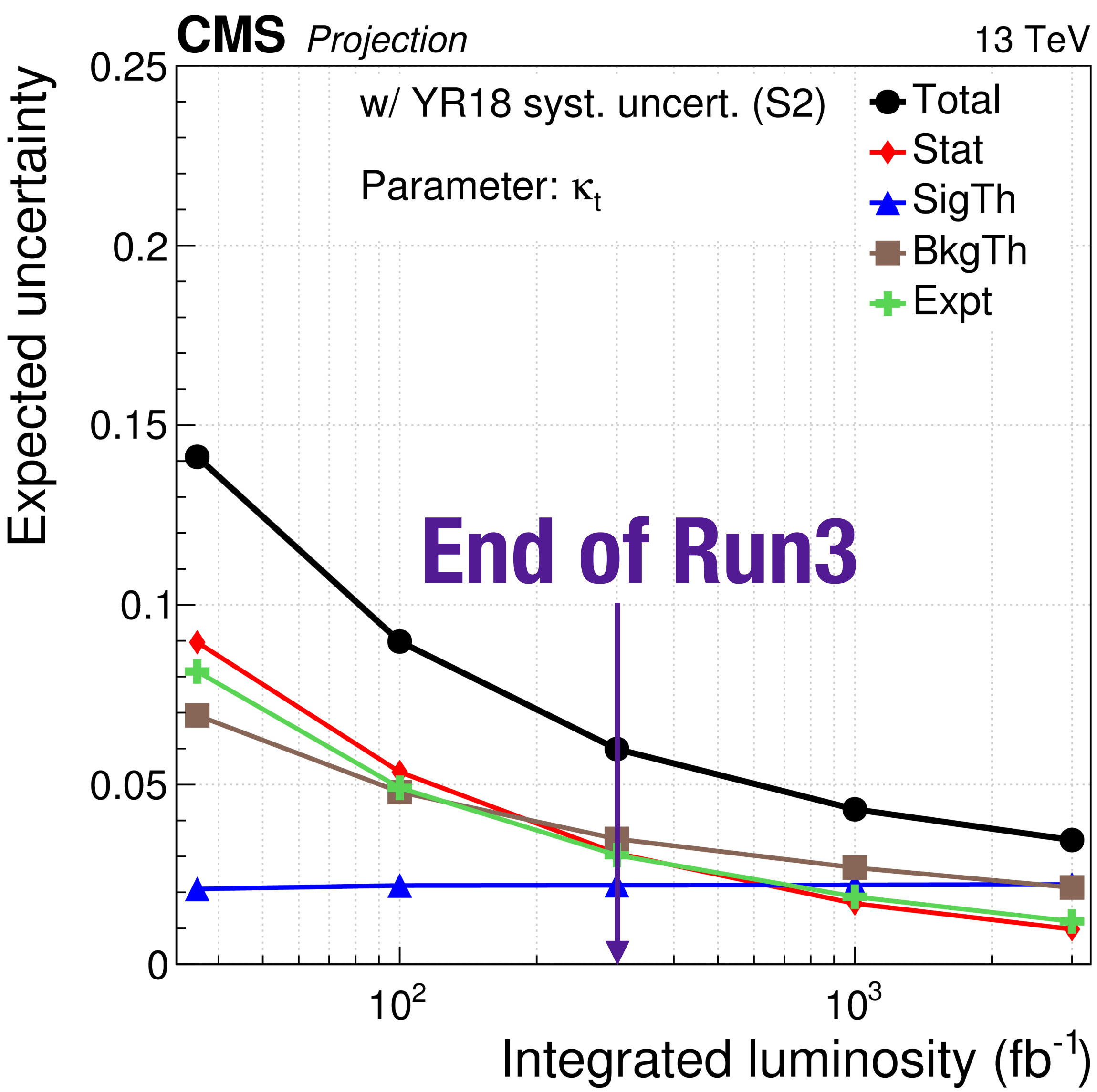
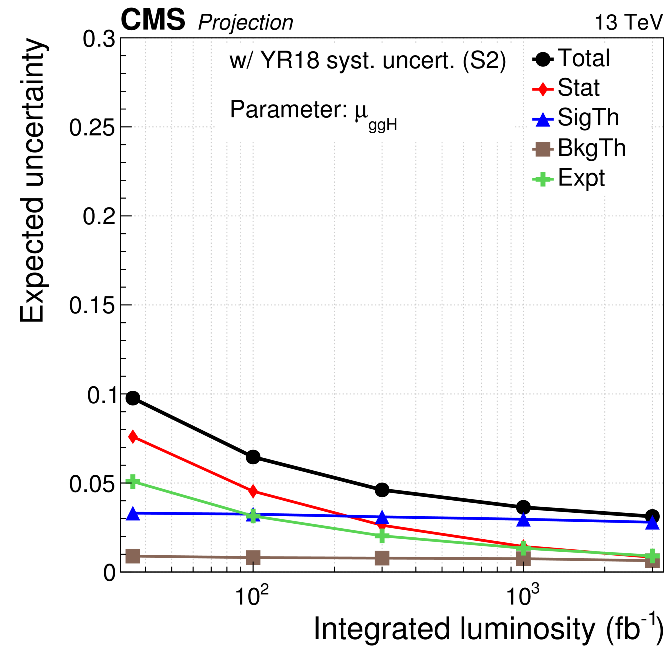
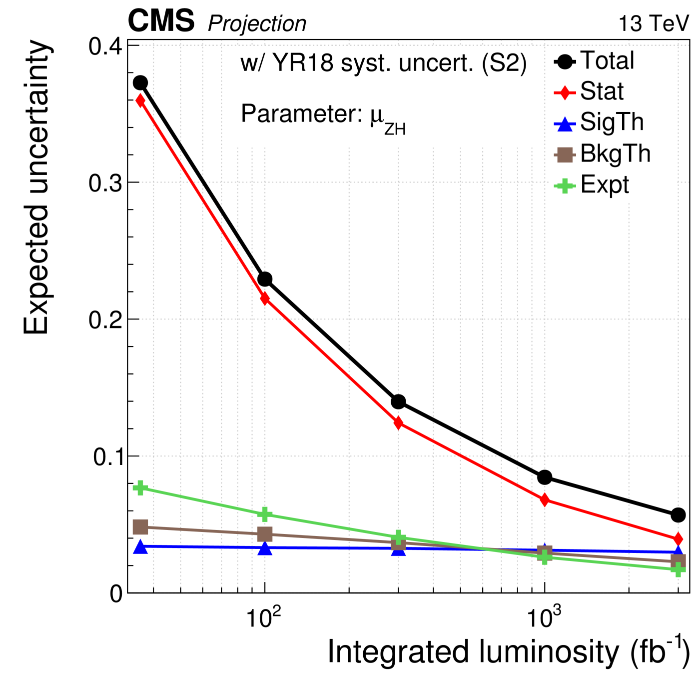
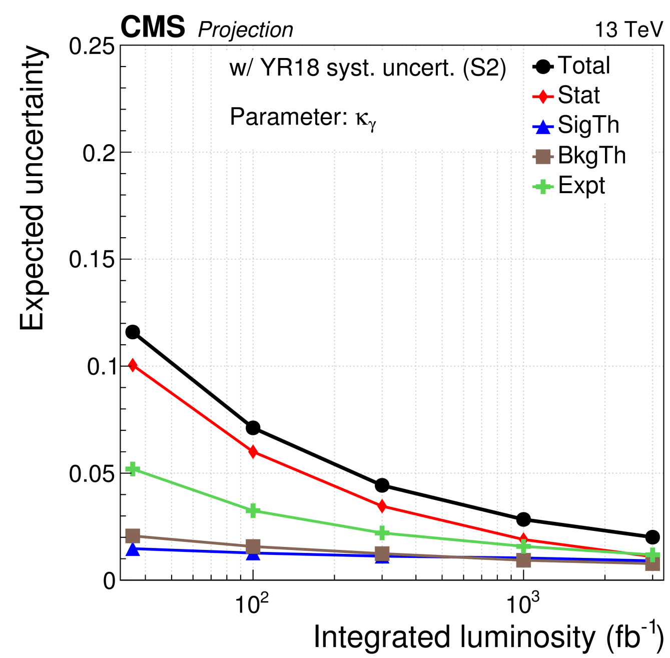
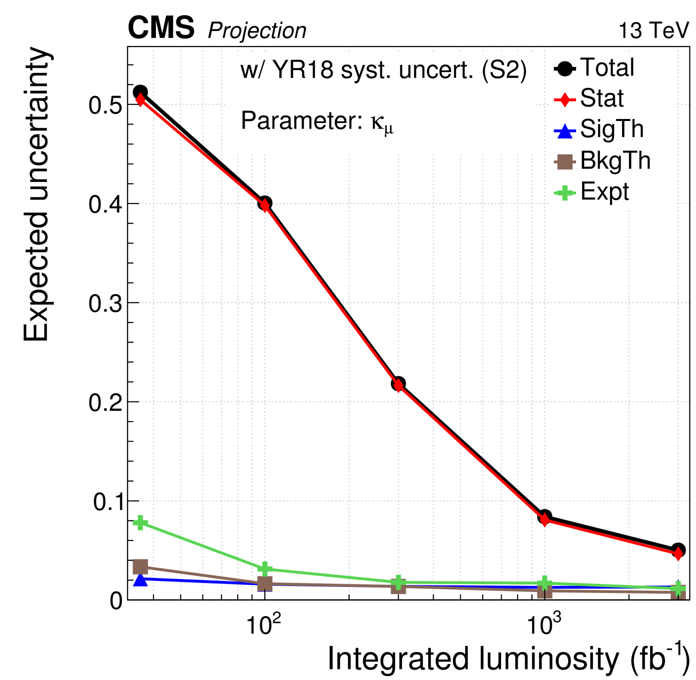
Time evolution





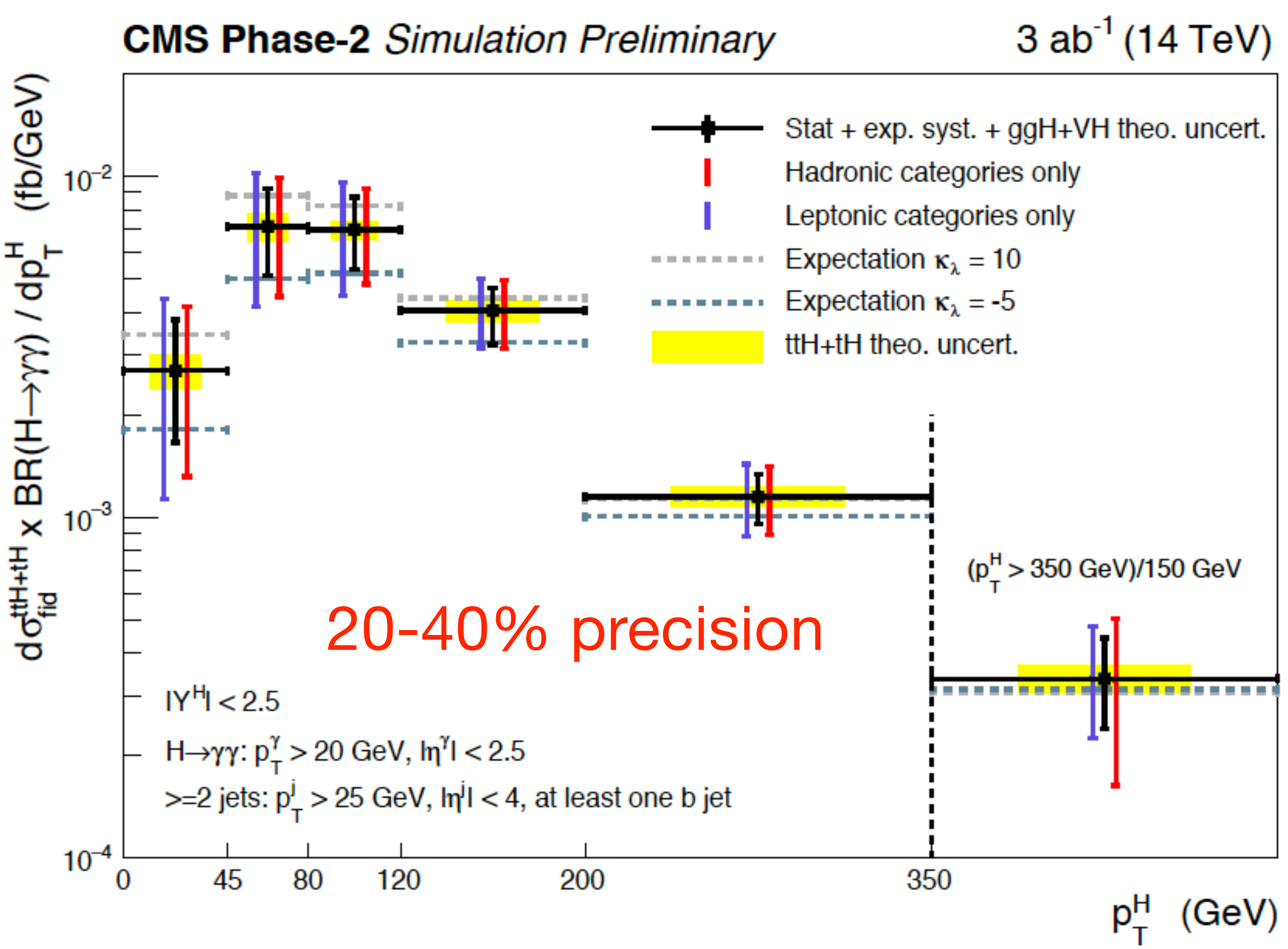






- Measurements became systematically limited rather fast in almost all cases -> challenge
- Most Coupling modifier uncertainties projected to reach ~4-6% precision by the end of Run 3, and 2-4% after 3000 fb^{-1} at HL-LHC

DIFFERENTIAL CROSS SECTIONS

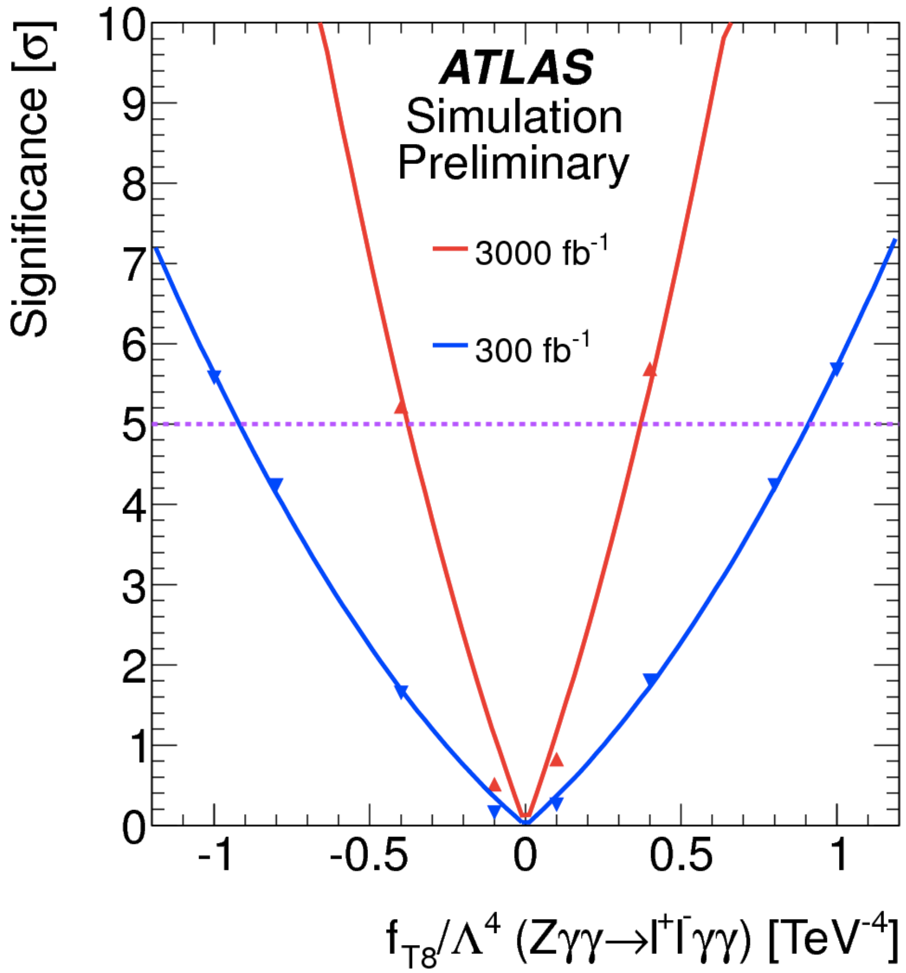


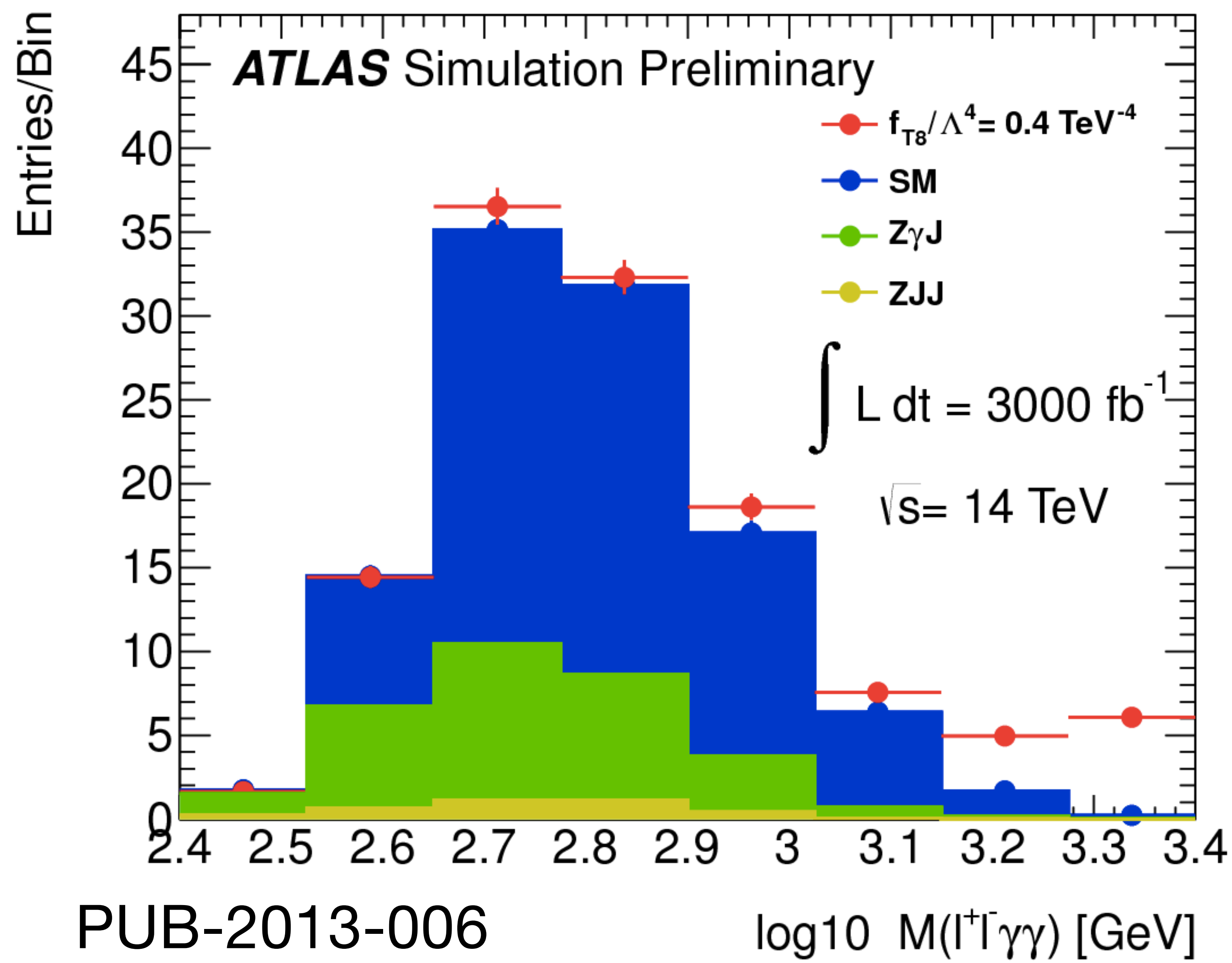
- Example: can be used to constrain the Higgs self coupling in an alternative way to the traditional HH analysis

- Additional characterisation of the kinematics of the H boson
- Rarer production modes (tth) x differential measurements provide further insight

TRI-BOSON PRODUCTION

- Complementary to QGC
- Study production of Z bosons in association with 2 photons
- Contributions from BSM (EFT) in tails





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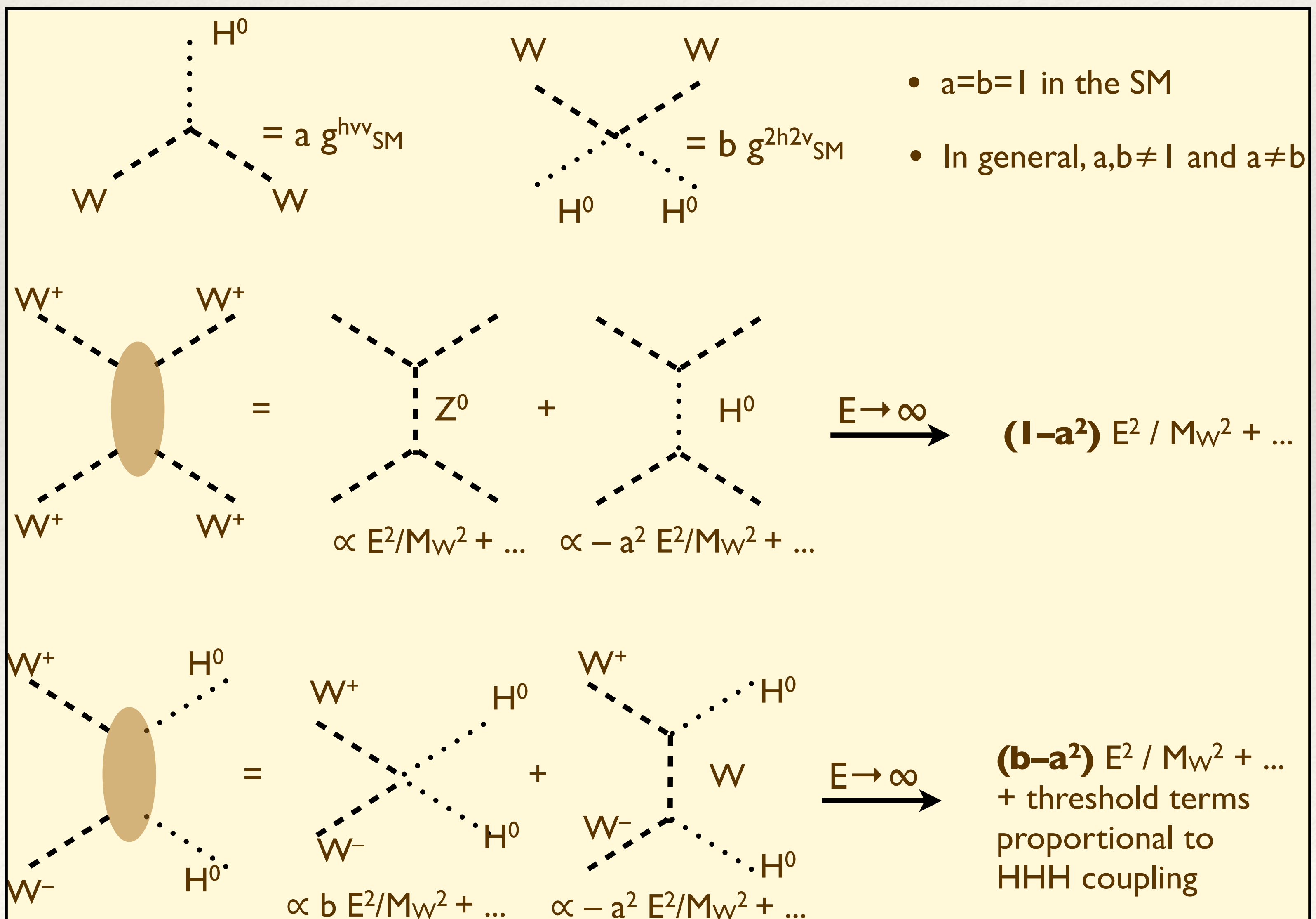
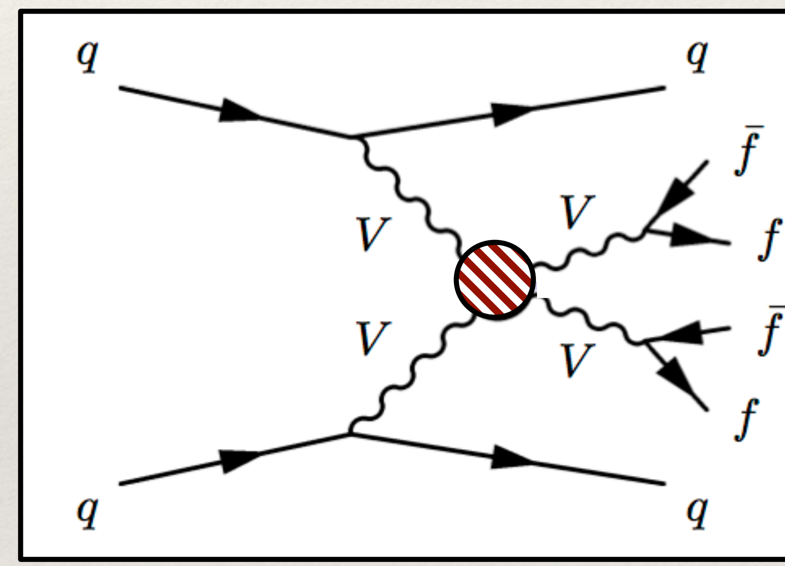
Sensitivities higher 3σ in WWW, WWZ, and WZZ - in progress!

WW scattering at high energy

- In the SM the Z and H exchange diagrams diverge but *exactly* cancel each other
  - anomalous couplings, as hints from New Physics, would have dramatic effects
  - the total WW scattering/Higgs pair cross section diverge with $\mathbf{m^4_{WW,HH}}$





Precision on **a** and **b**:
~30% at HL-LHC 14 TeV
~1% with FCC-hh 100 TeV

Precision on **a**:
~1% with ILC
~ 0.1% with FCC-ee