Global status of Higgs boson coupling projections in ATLAS

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on behalf of the ATLAS Collaborations

Workshop on the physics of HL-LHC and perspectives at HE-LHC, June 20th 2018

Outline of the talk

✓ Introduction

- The High-Luminosity LHC program and the ATLAS detector upgrade
- A quick look at the object reconstruction and identification performance
- Higgs physics at HL-LHC, production modes, couplings and signal strengths
- Strategy and methodology for the extrapolation studies at HL-LHC

✓ Coupling to bosons

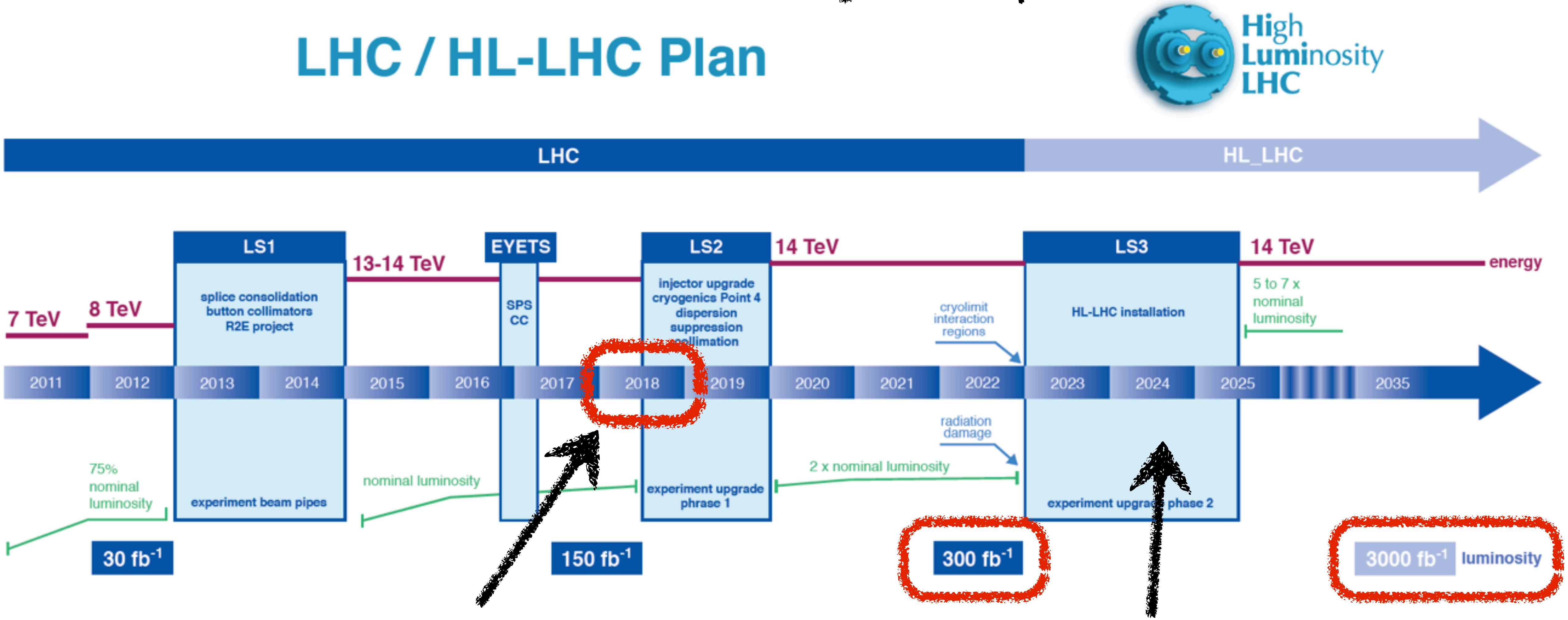
- $H\to\gamma\gamma$, $H\to ZZ\to 4l$, $H\to WW$

✓ Yukawa couplings

- $H\to\tau\tau$, $H\to\mu\mu$. top-Yukawa couplings ($ttH\to bb$, $ttH\to ZZ/WW/\tau\tau$, $ttH\to\gamma\gamma$)

✓ Wrapping-up and conclusions

The High-Luminosity LHC program



Now (√s=13 TeV), <μ>~38 (2017 data-taking)

Phase-II Atlas and CMS Upgrade

	Peak luminosity (cm^{-2} s^{-1})	μ (pile-up)
Current	$1.3 \cdot 10^{34}$	~40
HL-LHC baseline	$5 \cdot 10^{34}$	140
HL-LHC ultimate	$7.5 \cdot 10^{34}$	200

- Increased instantaneous luminosity and mean number of interactions per bunch-crossing (pile-up)
- Integrated luminosity collected during HL-LHC ~ 3000 fb^{-1}
- Precision measurements on the Higgs sector (couplings, self-couplings, VBF production), rare-decays

HL-LHC environment and object performance

✓ Very challenging environment at HL-LHC → detector requirements to maximize benefits from high luminosity

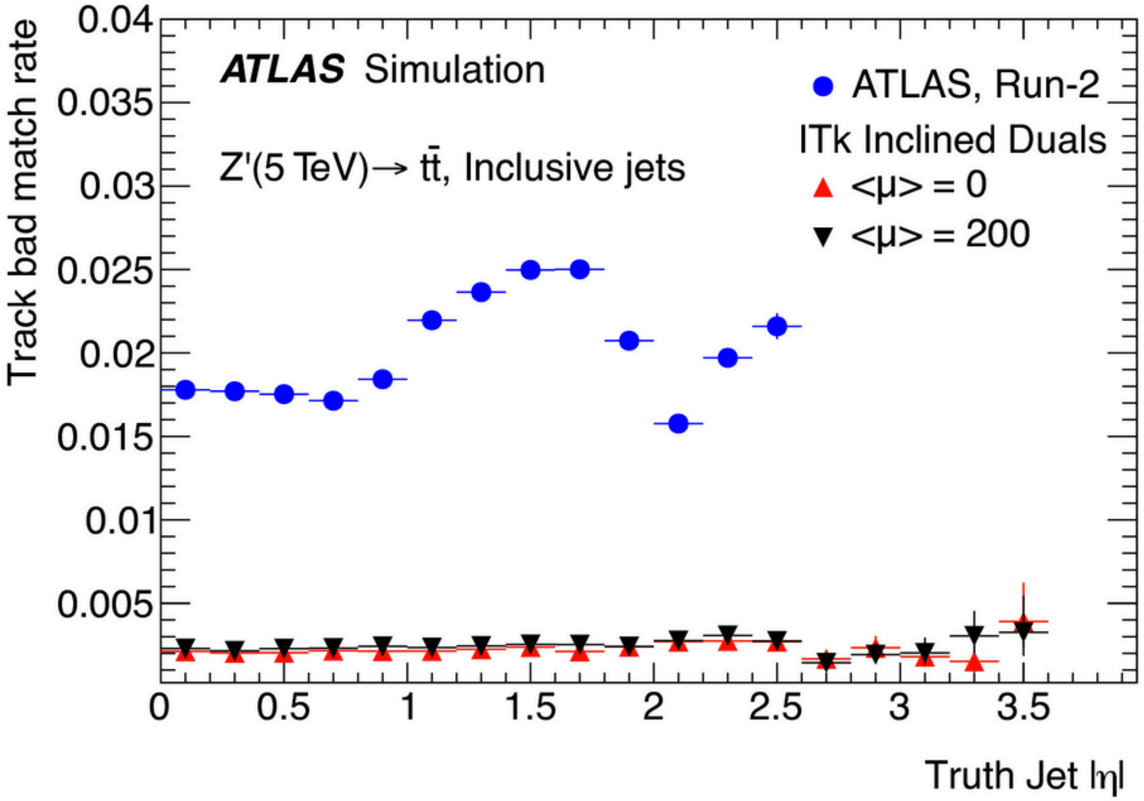
ATLAS-TDR-030 (Pixel TDR)

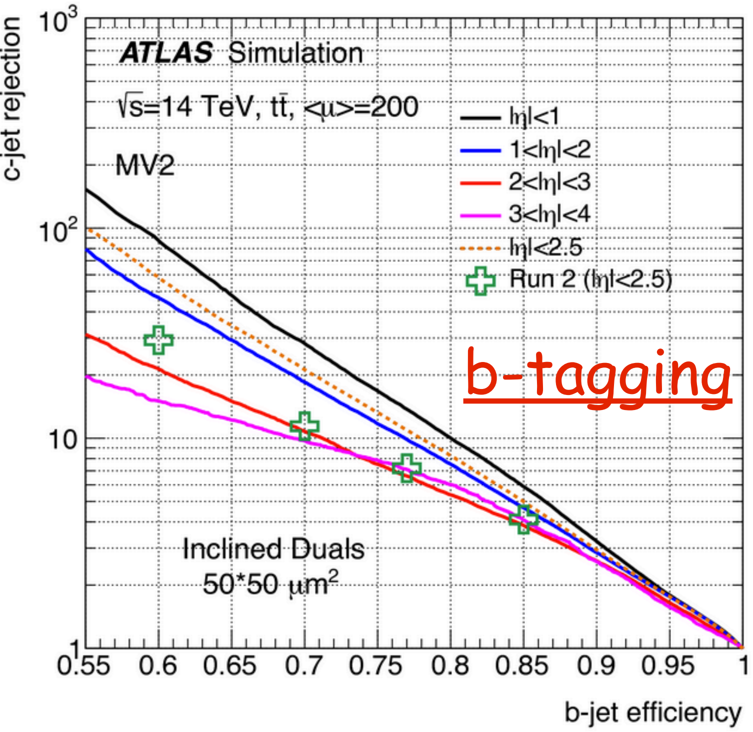
- large integrated radiation dose
- mitigation of pile-up effects
- sustain large event rate with more sophisticated trigger and data acquisition systems

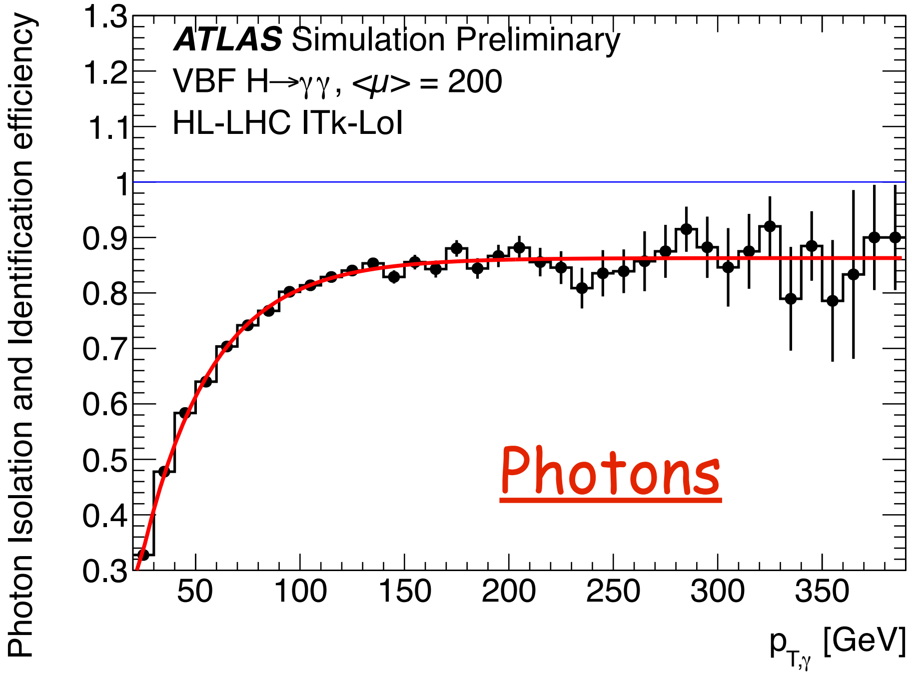
✓ Important to keep good control over performance of physics objects (identification and reconstruction, background rejection)

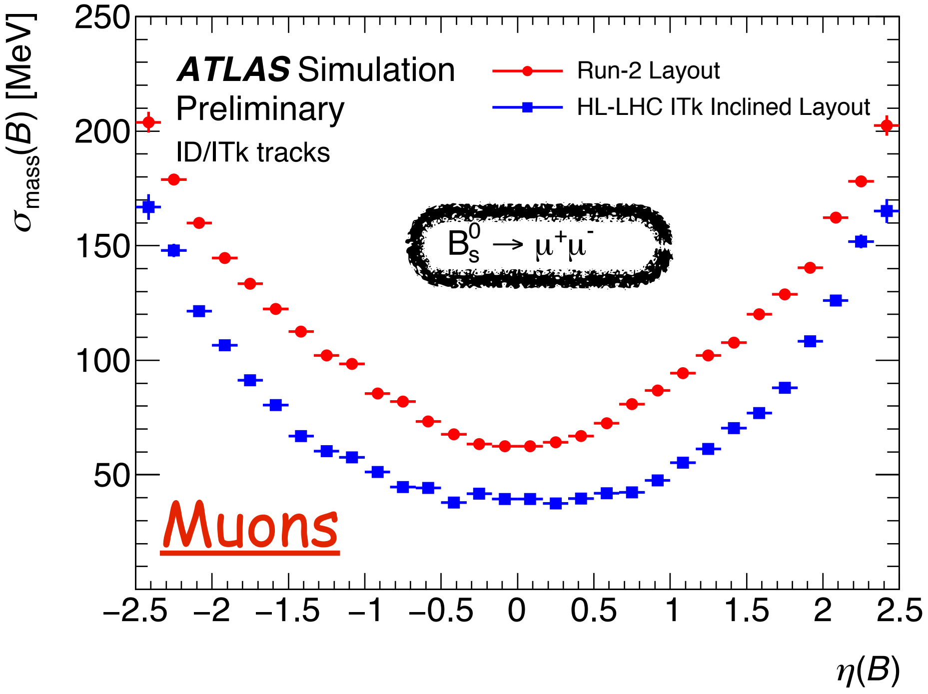
- track resolution, pile-up jet rejection, background rejection for b-tagging, identifications of electrons and photons

Tracking









Higgs precision measurements at HL-LHC

✓ Higgs boson studies are a major target for the physics program at HL-LHC

- large statistics collected (3000 fb^{-1}) will be very useful to test the Higgs properties and to have a global picture of its couplings to initial and final state particles
  - achieve high-precision measurements on coupling strengths and access to sensitivity for possible deviations to SM values revealing New Physics
  - sensitivity to rare decays ($H \to J/\psi\gamma$, $H \to Z\gamma$), couplings with 2nd generations ($H \to \mu\mu$) and shape of the Higgs potential (HH)
- significant increase in production cross section from $\sqrt{s}=13$ TeV to $\sqrt{s}=14$ TeV
- for many channels, the foreseen sensitivity extracted from past extrapolation studies is already by far superseded
- studies on Higgs properties will be included in YR2018
  - extrapolation on current Run 2 analyses with scaling of luminosity and signal/background yields to account for the new conditions. Systematics model kept the same as in Run 2 analyses
  - additional scaling of systematic uncertainties currently being discussed in ATLAS and CMS to reach a common procedure for the two experiments and to prepare floor for combination
  - additional studies based on the smearing function approach that will be also discussed later in this talk

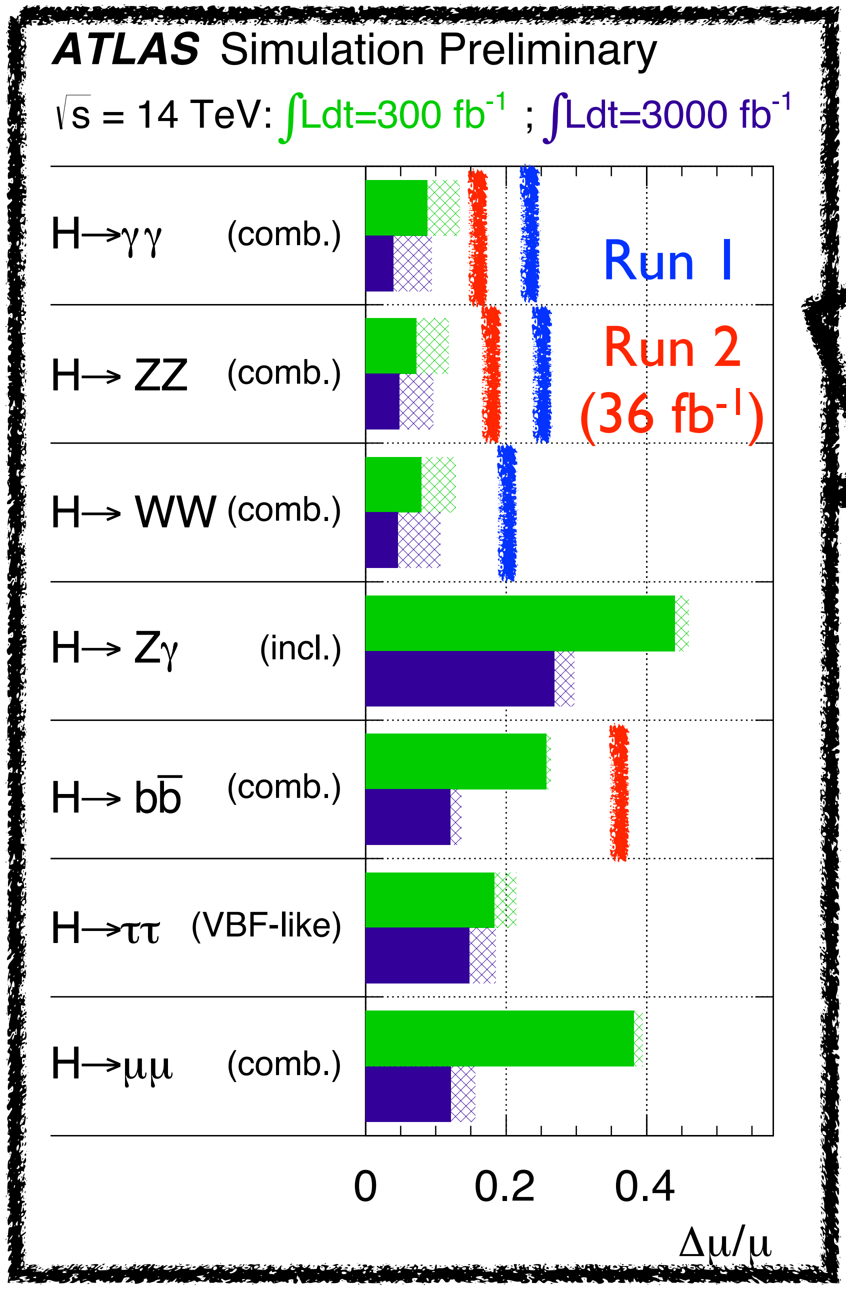
Signal strength and couplings - results for HL-LHC

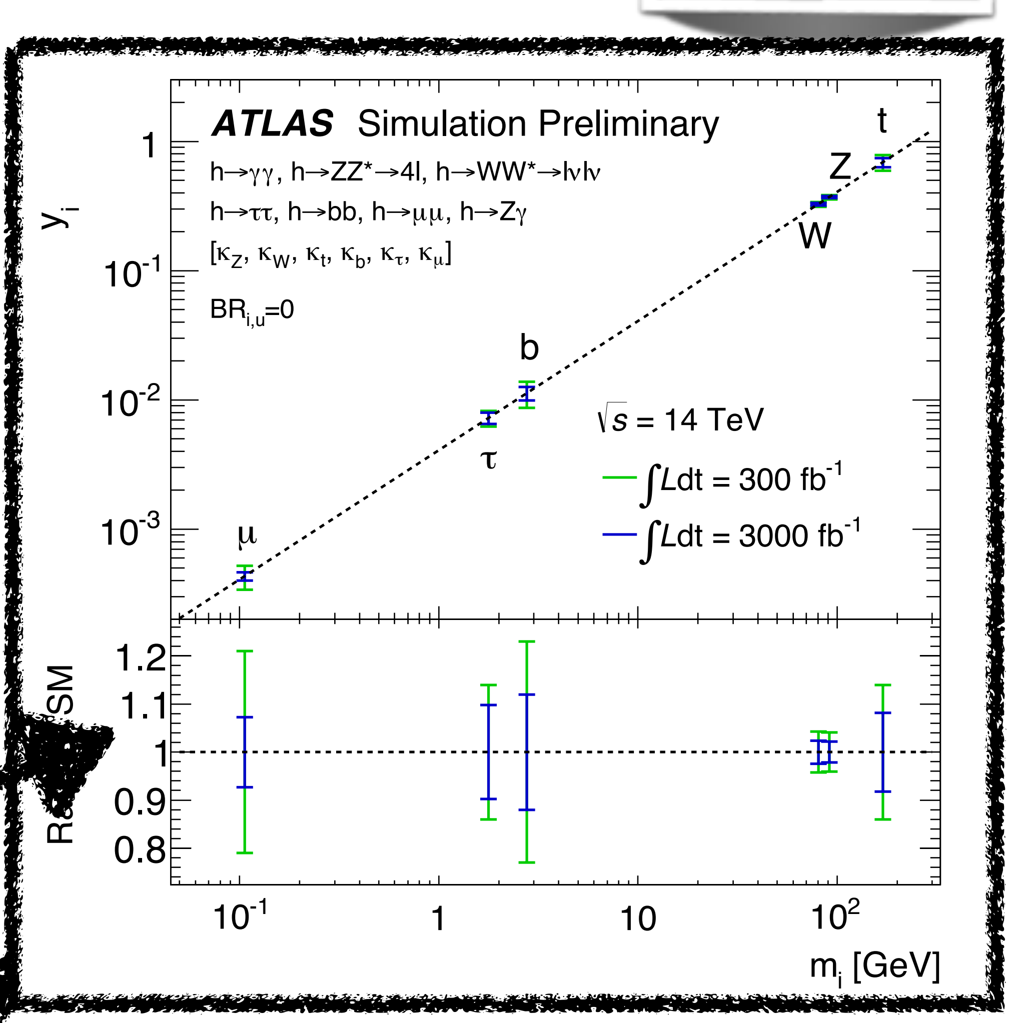
HL-LHC

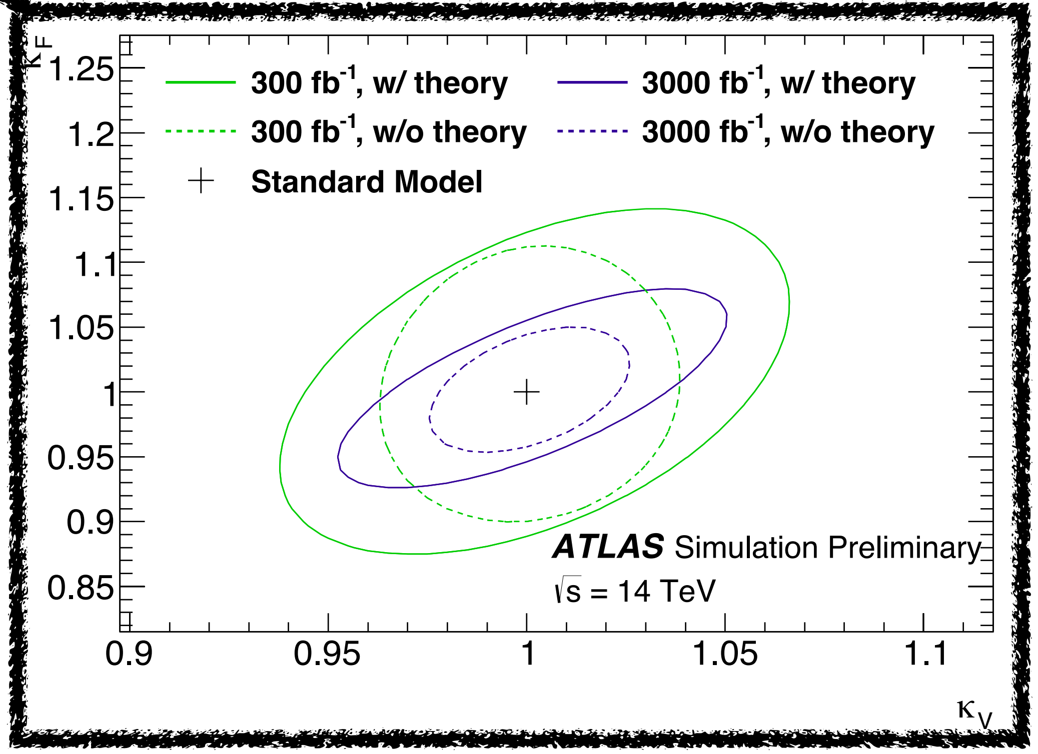
ATL-PHYS-PUB-2014-016

- ✓ ATLAS public results on couplings at HL-LHC → extrapolation from Run 1 using <μ>=140
  - Run 1: Δμ/μ (H→γγ)=23%, Δμ/μ (H→ZZ)=24%, Δμ/μ (H→WW)=33%
  - ➡ Expected precision on couplings to W/Z around 3%, to muons ~7%, to τ, b, t approximately 10% @ 3000 fb^{-1}

- ✓ Coupling combination with Run 2 inputs currently being performed by ATLAS
  - will supersede results based on Run 1 extrapolation presented here
  - various ingredients and channels for coupling combination will be presented in what follows







Strategy and methodology for extrapolation studies

Smearing functions

- ✓ ATLAS uses generator-level 14 TeV samples
- ✓ Particles (e, μ, τ, missing energy, jets) at event-generator level are smeared in pT and energy according to functions that take into account the upgraded detector layout
  - ▶ Smearing functions extracted from fully-simulated samples in HL-LHC configuration
  - ▶ gauge impact of upgraded detector and optimized object performance
  - ▶ requires a full re-analysis
- ✓ Pile-up included in the simulation (<μ>=140 and <μ>=200)
- ➡ <u>Theoretical systematic uncertainties</u>: same as Run 1/ Run 2 analysis, reduced by 1/2 or absent (same approach for the Run 2 extrapolation treatment)

Run 2 extrapolation

YR

- ✓ Kept analysis strategy as in Run 2
- ✓ Scale luminosity and signal/background cross section yields to match HL-LHC conditions (3000 fb^{-1} and 14 TeV)
- ✓ At a later stage, apply HL-LHC detector performance

Systematics uncertainties

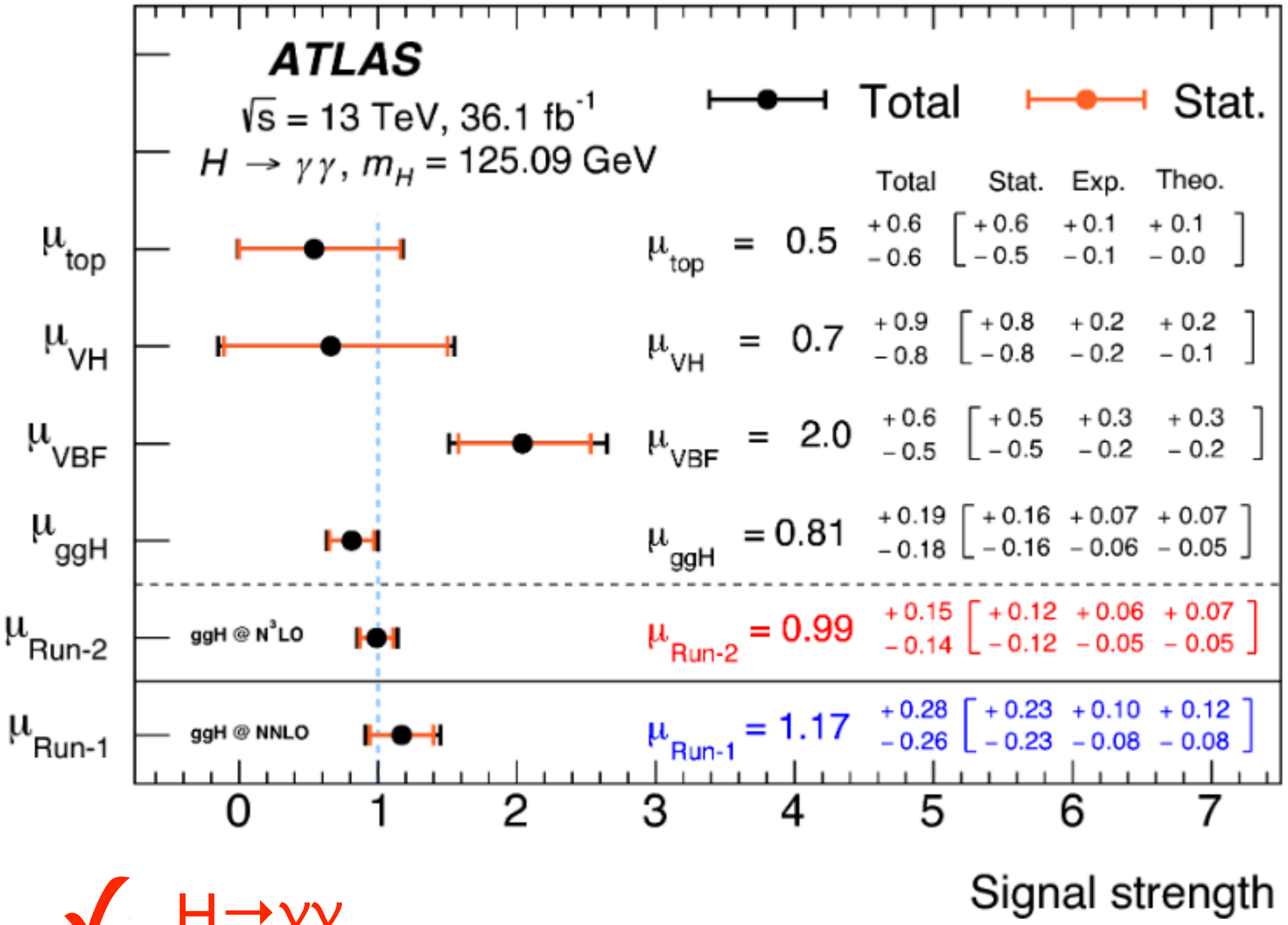
- ✓ Agree on scenarios for experimental (optimistic, pessimistic) systematic uncertainties
  - ▶ talk by S. Pagan Griso and M. Narain at the plenary session yesterday
  - ▶ difficult to predict evolution vs luminosity of systematic uncertainties which do not have statistical component (modeling, ...)
  - ➡ main topic of this talk is review of main systematic uncertainties of various Higgs channels with a special focus on theory uncertainties

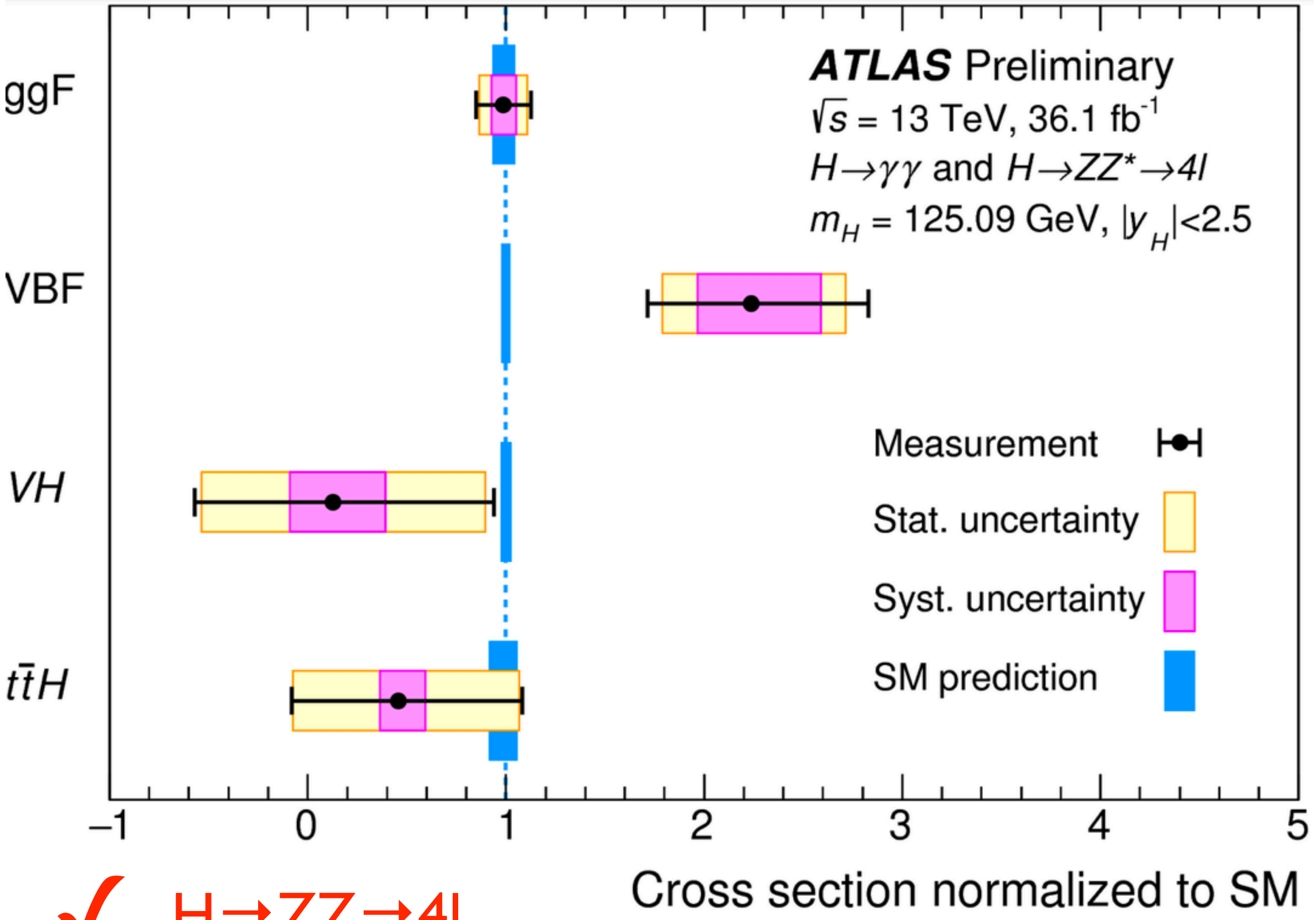
Higgs couplings to bosons

State-of-the art: H->γγ & H-ZZ*->4L

Run 2

ATLAS-CONF-2017-047





✓ H→γγ

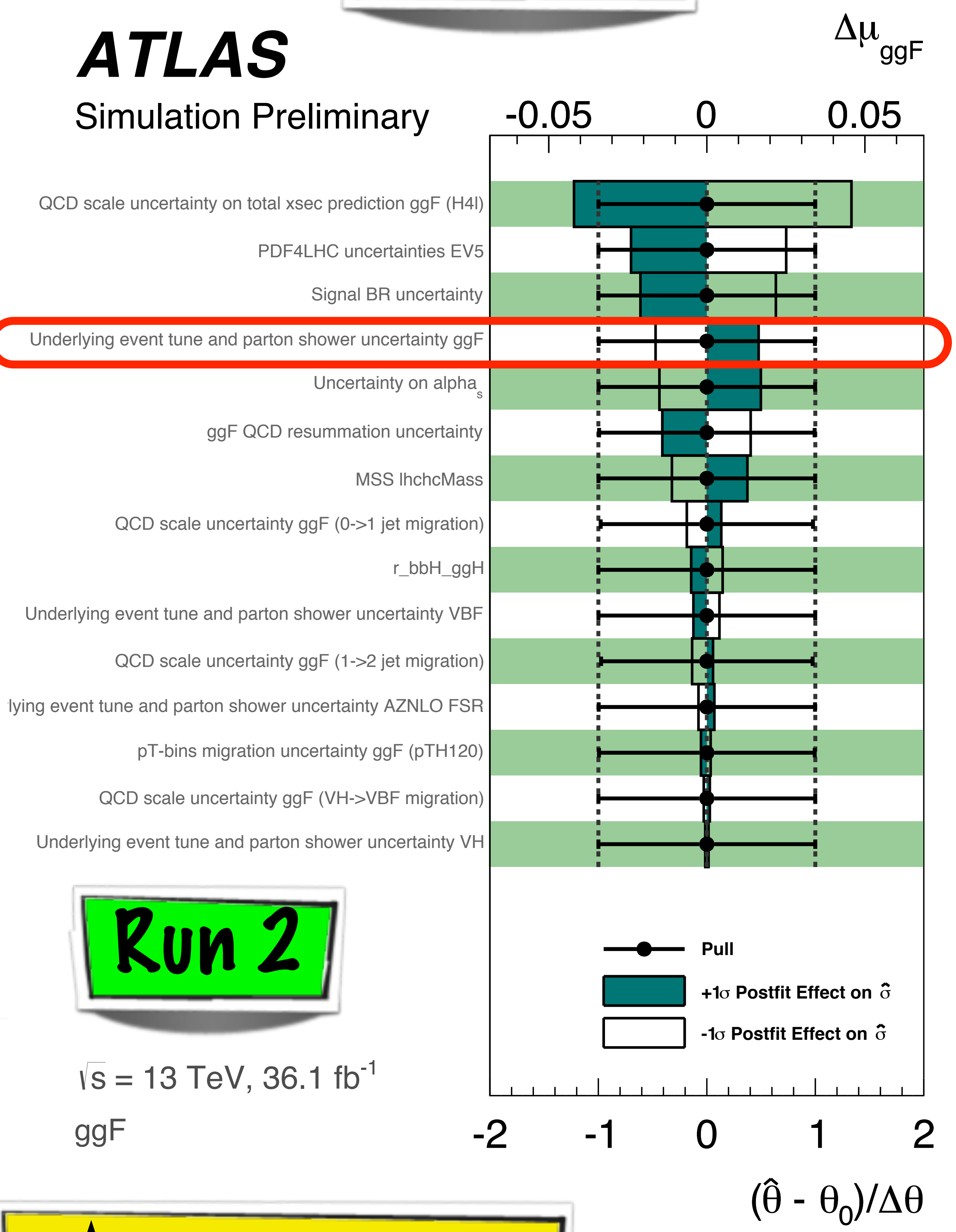
- expected uncertainty on μ at HL-LHC: 2% (ggF), 5% (VBF), 10% (VH)
- limited by photon resolution uncertainties and background modeling uncertainties
- going from NNLO to N3LO description reduces theory uncertainties significantly
- more on ttHγγ extrapolation in this talk

✓ H→ZZ→4l

- expected statistical uncertainty on μ at HL-LHC: 2% (ggF) and 9% (VBF), 17% (VH)
- dominant uncertainties in Run 2: QCD scales (ggF) and jet-bin migration (VBF and VH)
- dedicated discussion later in the talk on systematic uncertainties affecting extrapolation

H->ZZ*->4l

Gluon fusion



Run 2

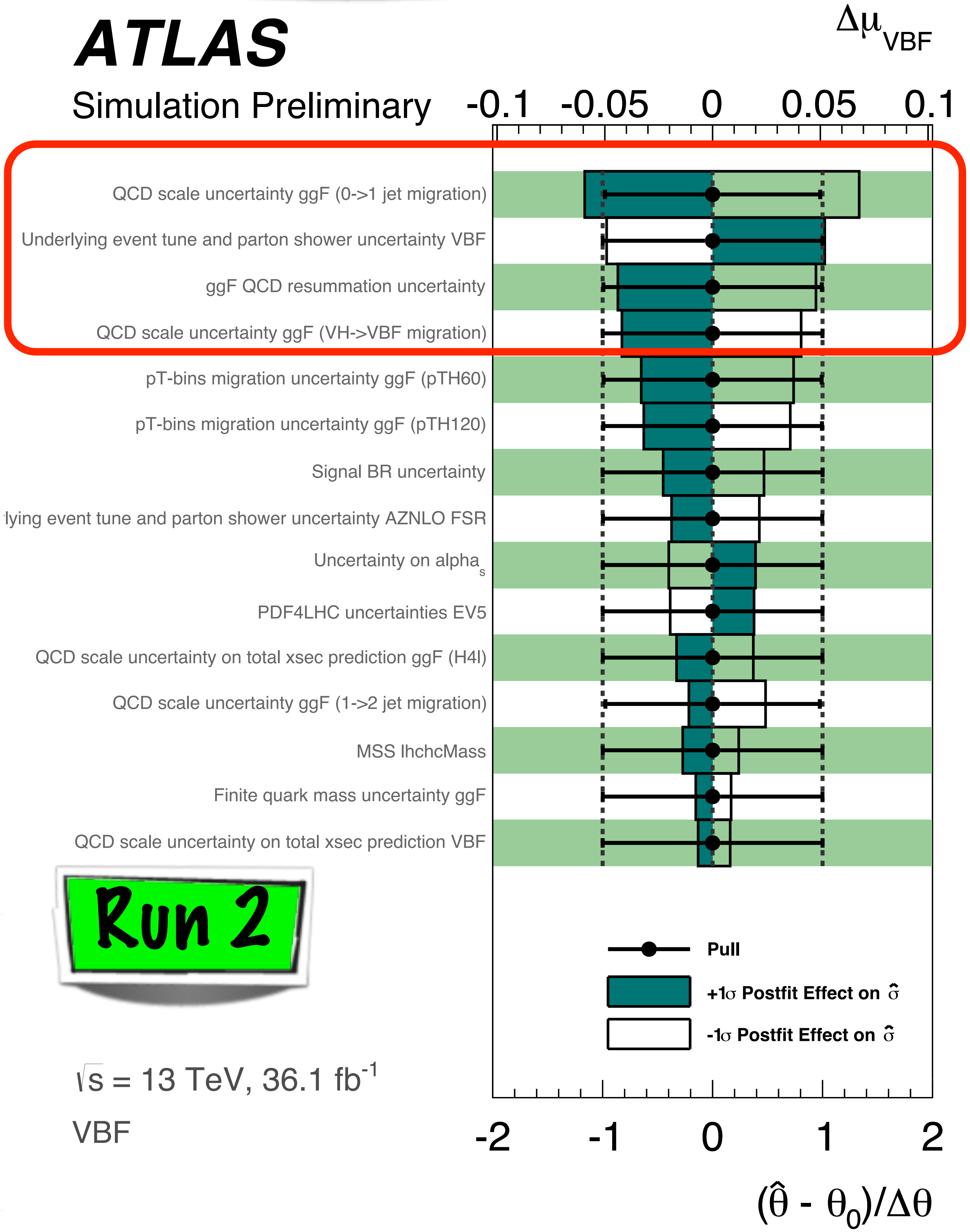
★ Exp. stat error on μ at HL-LHC: 2% (ggF)

- Ranking plot reported with Run 2 statistics (36 fb^{-1}) - amplitude of uncertainties not significantly reduced at HL-LHC
  - H→ZZ using 80 fb^{-1} data is public (ATLAS-CONF-2018-018) - results will be re-discussed with updated analysis
- Ranking for theory uncertainties-only, all uncertainties included in the fit results
- Impact of experimental uncertainties on μ smaller than that of signal theory uncertainties (accuracy on cross-section dominated by luminosity determination)
- Second largest source of theory uncertainty related to PDF
  - they mostly impact signal normalization and have negligible impact on ggF cross section measurement
- Main source of signal theory uncertainty for cross section (UE and PS uncertainty)

H->ZZ*->4l

ATLAS-PHYS-PUB-AAA

Vector boson fusion



Run 2

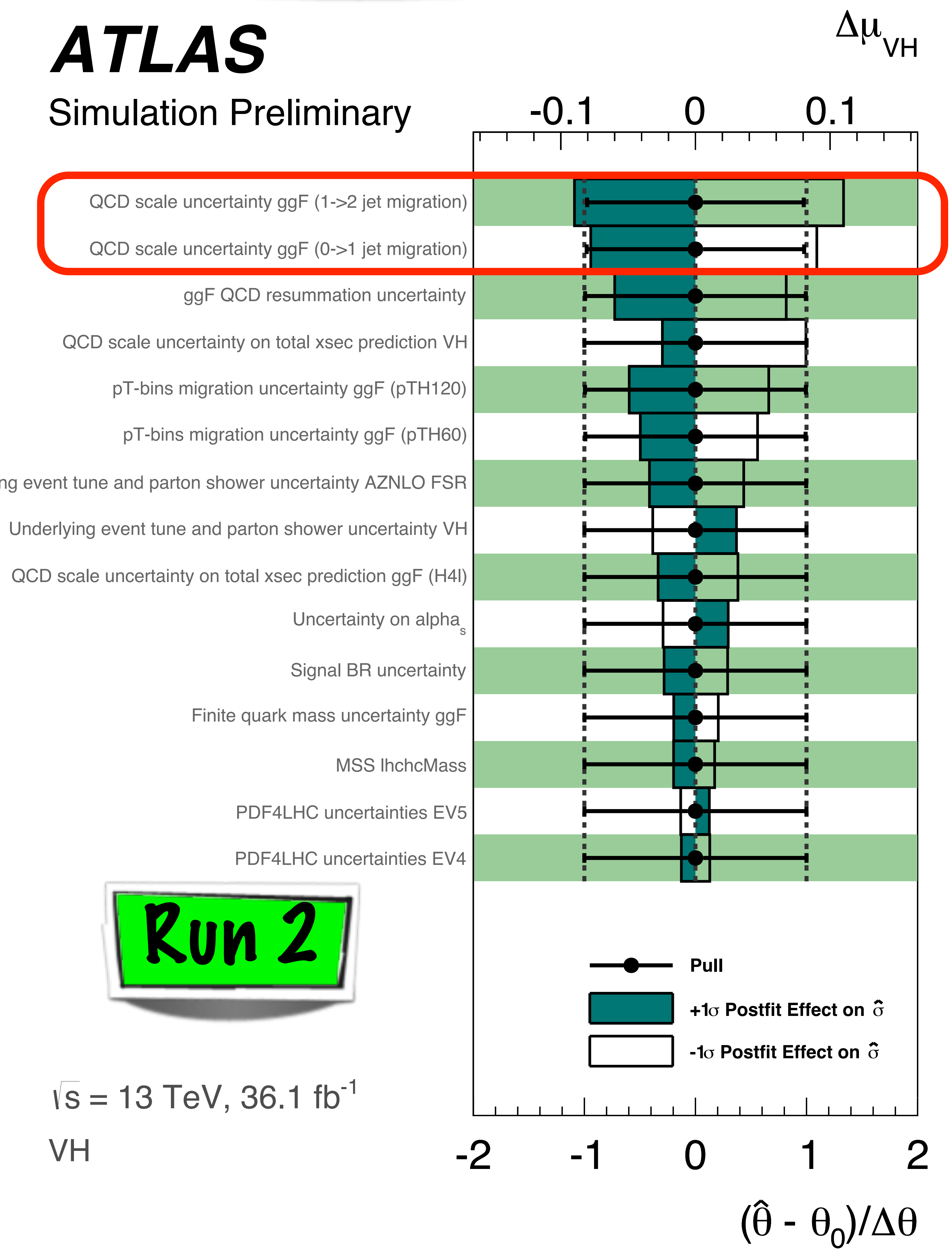
- Ranking for theory uncertainties-only, all uncertainties included in the fit results
- QCD uncertainties with 0-1 jet bin migration has the largest impact at Run 2
  - migration realized when ggF events with one or more jets enter in the background in the VBF category
  - this uncertainty affects the signal strength and the cross section measurement precision
- Second important uncertainty due to modeling of UE and PS
  - uncertainty on the acceptance (affect signal strength and cross section)

★ Exp. stat error on μ at HL-LHC: 9% (VBF)

Associated production

H->ZZ*->4L

ATLAS-PHYS-PUB-AAA



Run 2

- Ranking for theory uncertainties-only, all uncertainties included in the fit results
- QCD uncertainties with 1-2 jet bin migration has the largest impact at Run 2
  - affect signal strength and cross section measurement

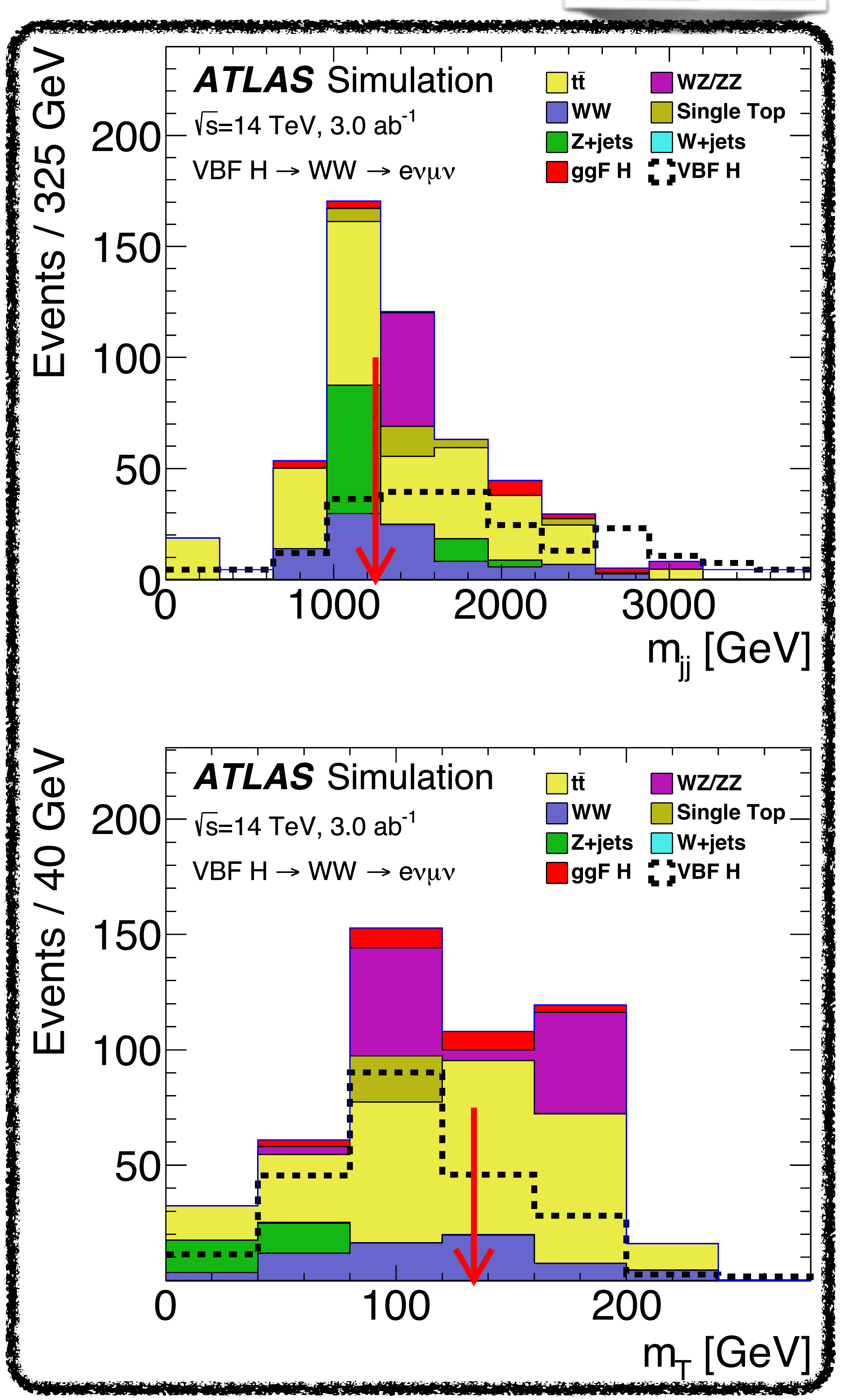
★ Exp. stat error on μ at HL-LHC: 17% (VH)

H→WW→eν μν (VBF production)

ATL-PHYS-PUB-2016-018

HL-LHC

- ✓ VBF signature is kinematically distinctive - presence of two energetic final state quark jets at very high rapidity gap - corresponding H boson centrally produced
- ▶ VBF H→WW* production mode very useful to test detector layouts because of the several objects in the final state which are affected by pile-up
- ✓ Assuming Run I detector performance for e/μ - results for <μ>=200
  - no other jets present between the VBF jets
  - Drell-Yan and multi-jet background suppressed by requiring E_T^{miss}>20 GeV
- ✓ QCD scale on the VBF jets dominates the systematic uncertainties - theoretical computation will improve with time and will reduce the uncertainty
- ➡ Results will be extrapolated - very important to account for background systematics (WW modeling for 0-jet category)

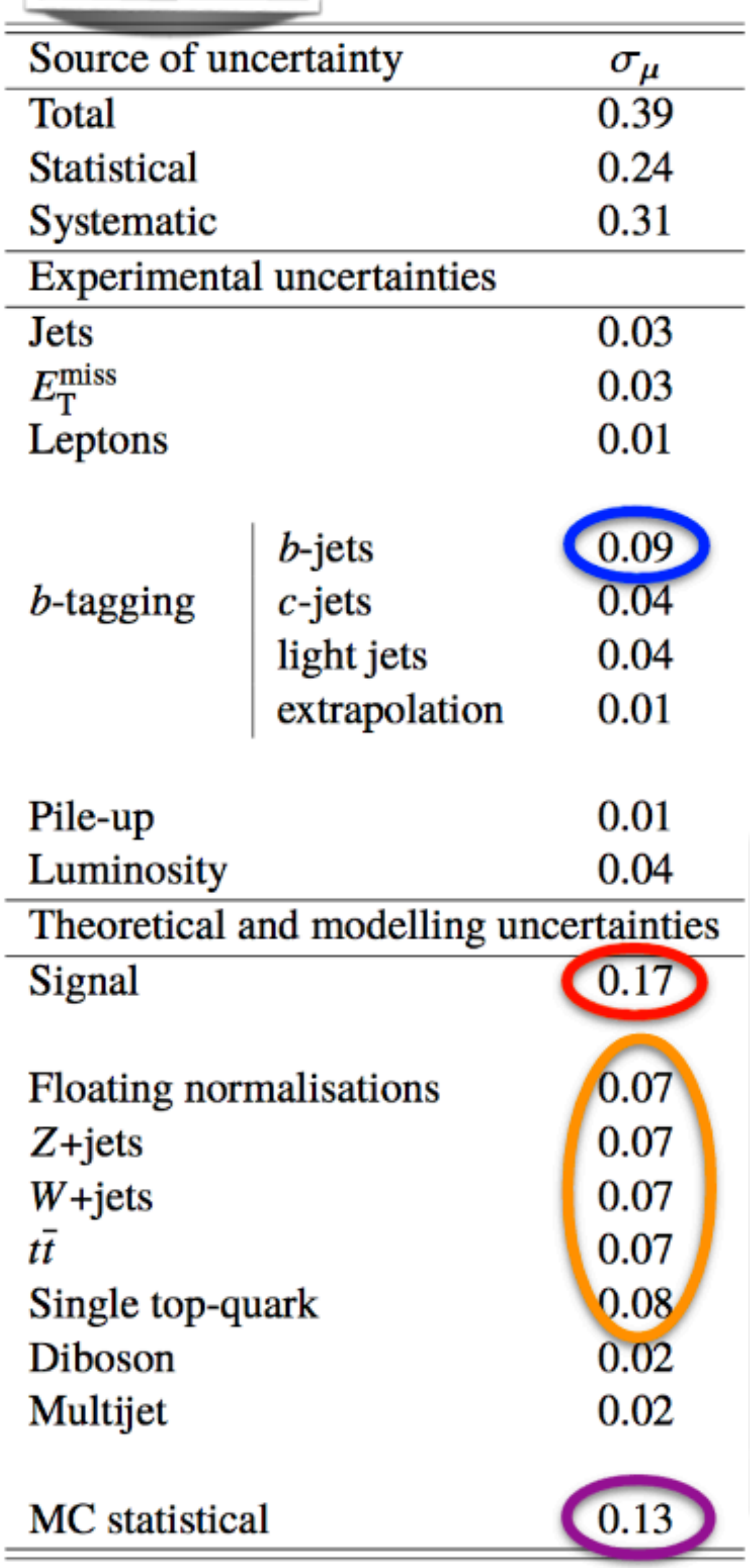


Yukawa couplings

Run 2

VH->bb

JHEP 12 - 2017 (024)



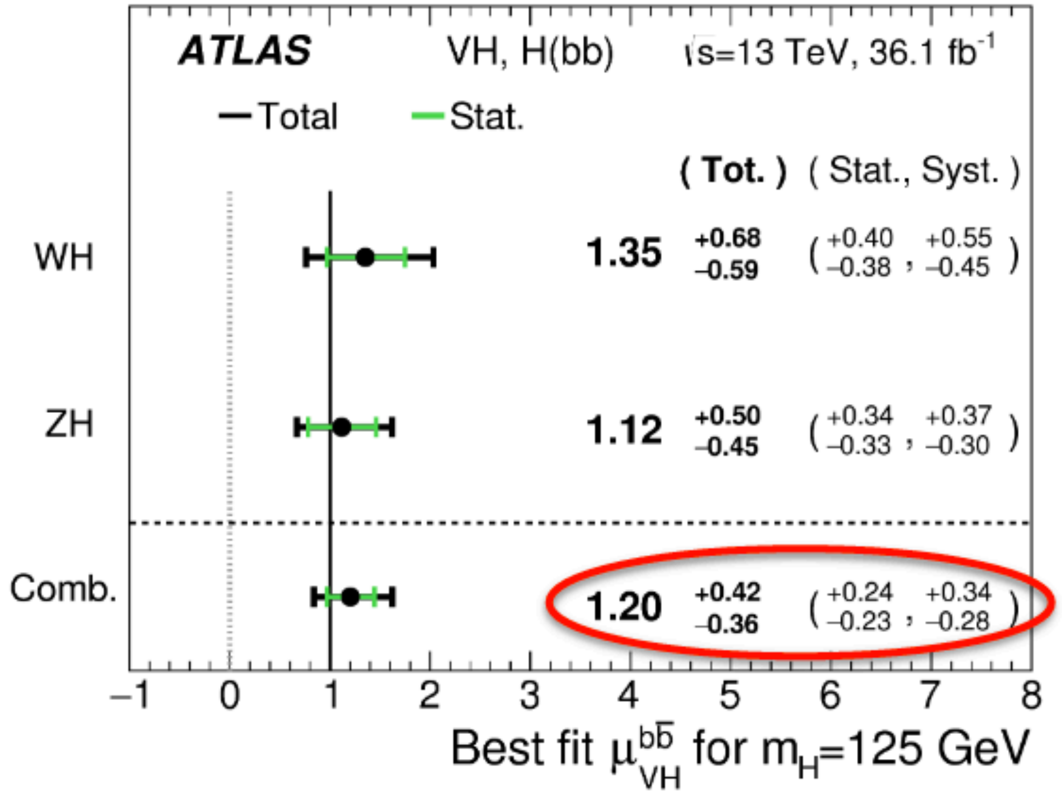
Source of uncertainty		σ_μ
Total		0.39
Statistical		0.24
Systematic		0.31
Experimental uncertainties		
Jets		0.03
E_T^{miss}		0.03
Leptons		0.01
b-tagging	*b*-jets	0.09
	c-jets	0.04
	light jets	0.04
	extrapolation	0.01
Pile-up		0.01
Luminosity		0.04
Theoretical and modelling uncertainties		
Signal		0.17
Floating normalisations		0.07
Z+jets		0.07
W+jets		0.07
$t\bar{t}$		0.07
Single top-quark		0.08
Diboson		0.02
Multijet		0.02
MC statistical		0.13

✓ Systematic uncertainties are dominant in Run 2 analysis

- signal modeling uncertainties (dominated by extrapolation uncertainties from high pt(V) to inclusive phase-space and parton shower/modeling for the signal)
- background modeling (statistical component from floating normalization will reduce with large data statistics provided by HL-LHC)
- b-tagging calibration experimental uncertainties
- limited size of simulation statistics

✓ Larger statistics will have more power to constrain nuisance parameters

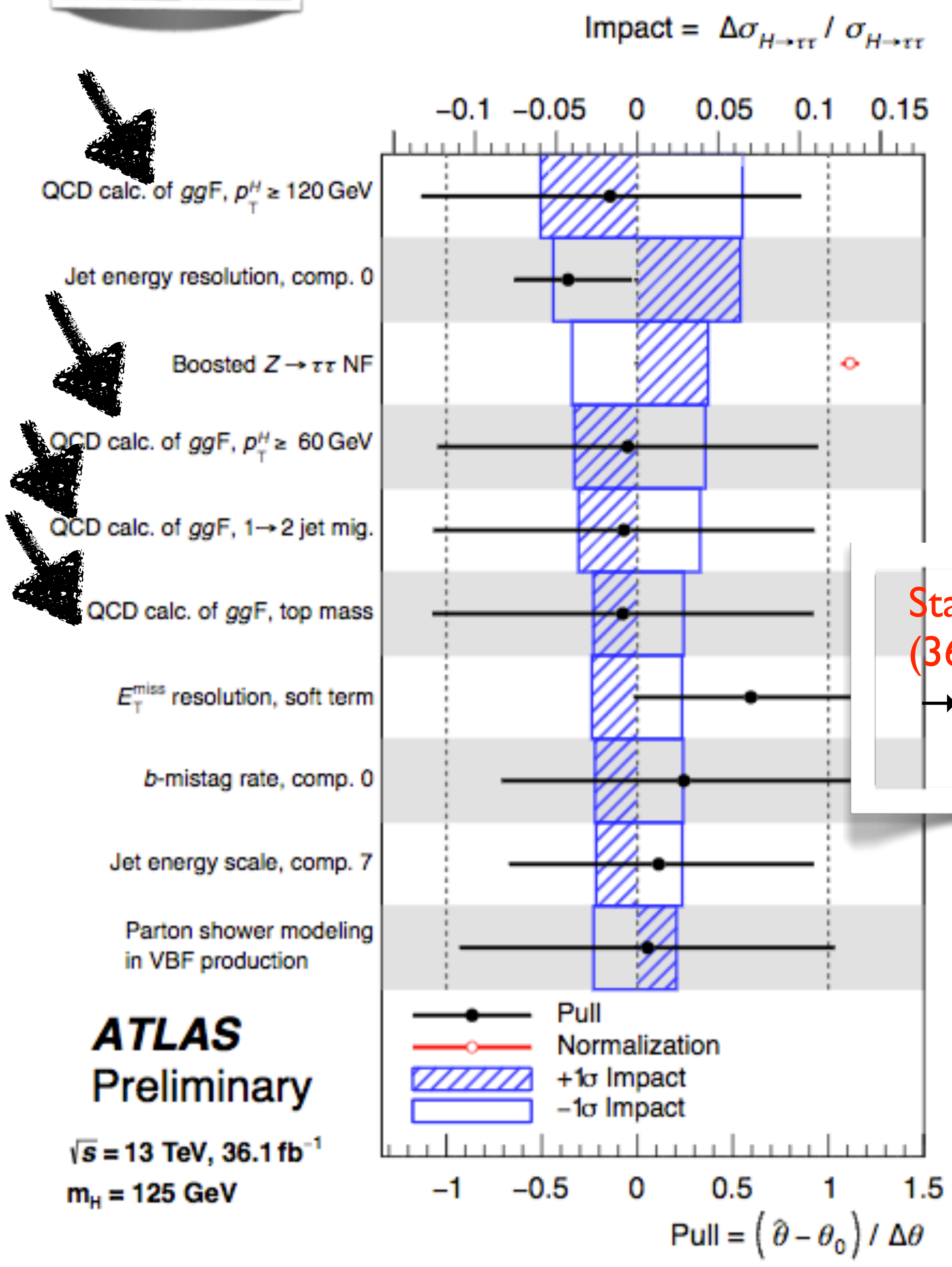
✓ Stat-only increase on the uncertainty on µ:0.24 (36 fb^{-1}) → 0.03 (HL-LHC)



Run 2

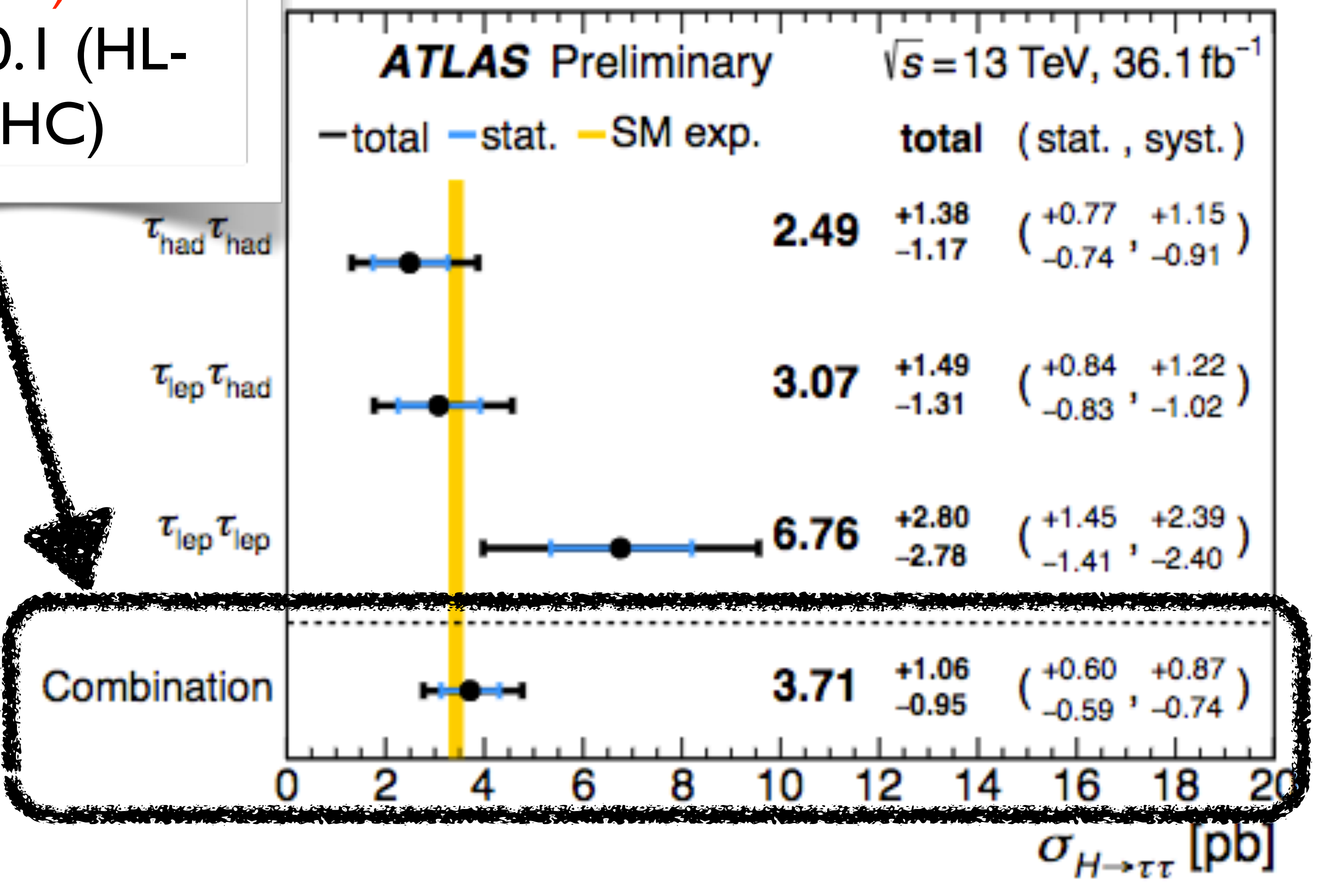
H-> τ τ

ATLAS-CONF-2018-021



- ✓ Several channels with taus + VBF and boosted signatures, 36 fb^{-1} : 4,1σ (with 36 fb^{-1})
- ✓ Error on cross-section dominated by
  - modeling on Higgs pt
  - experimental uncertainties on jet energy resolution, missing energy and light-flavour jet mistag rate (moderately constrained, will get worse with larger data statistics)

Stat.err on σ (36 fb^{-1}): 0.60 →~0.1 (HL-LHC)



H->μ μ

New for YR!

✓ Low BR (0.02) and significant irreducible background from Z/γ→μμ - high statistics needed

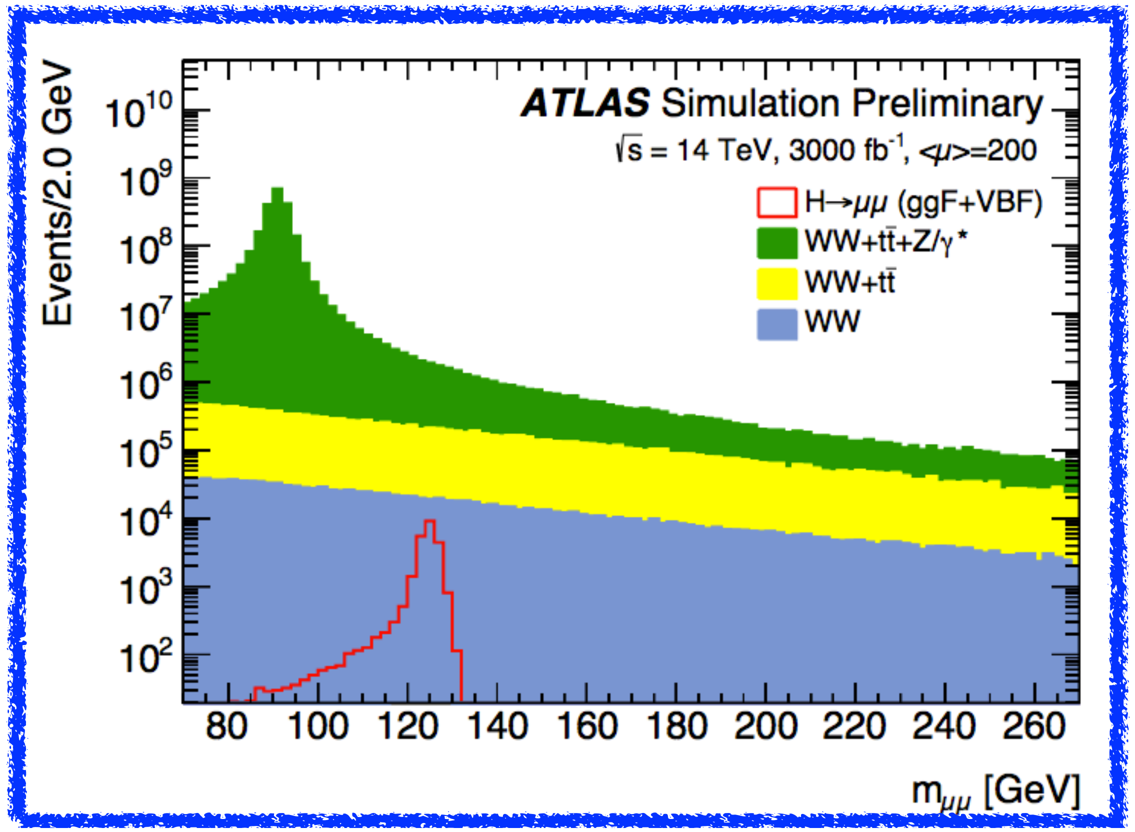
- fundamental to achieve excellent mass resolution in HL-LHC environment
- analysis is carried out with smearing function approach at HL-LHC

HL-LHC

✓ Analysis strategy optimized wrt results documented in ATLAS scoping document

- upgraded smearing functions and detector performance with state-of-the-art parametrizations
- event classification splitting the sample in different S/B regions and ML fit to m(μμ) to estimate signal yields
- smearing function approach validated against full simulation MC

ATL-PHYS-PUB-2018-006



➡ H→μμ signal signal from gluon-fusion and vector boson fusion is expected to be observed with >9 σ

➡ Total uncertainty on signal strength μ at 3000 fb^{-1} expected to be around 13% (dominant uncertainties: muon reco/id efficiency, muon momentum scale/resolution)

➡ Theory uncertainties dominated by scales and PDF for various production modes

Top-Yukawa couplings

Top-Yukawa observation has recently been published by ATLAS and CMS way before this was foreseen by their corresponding projections!

Run 2

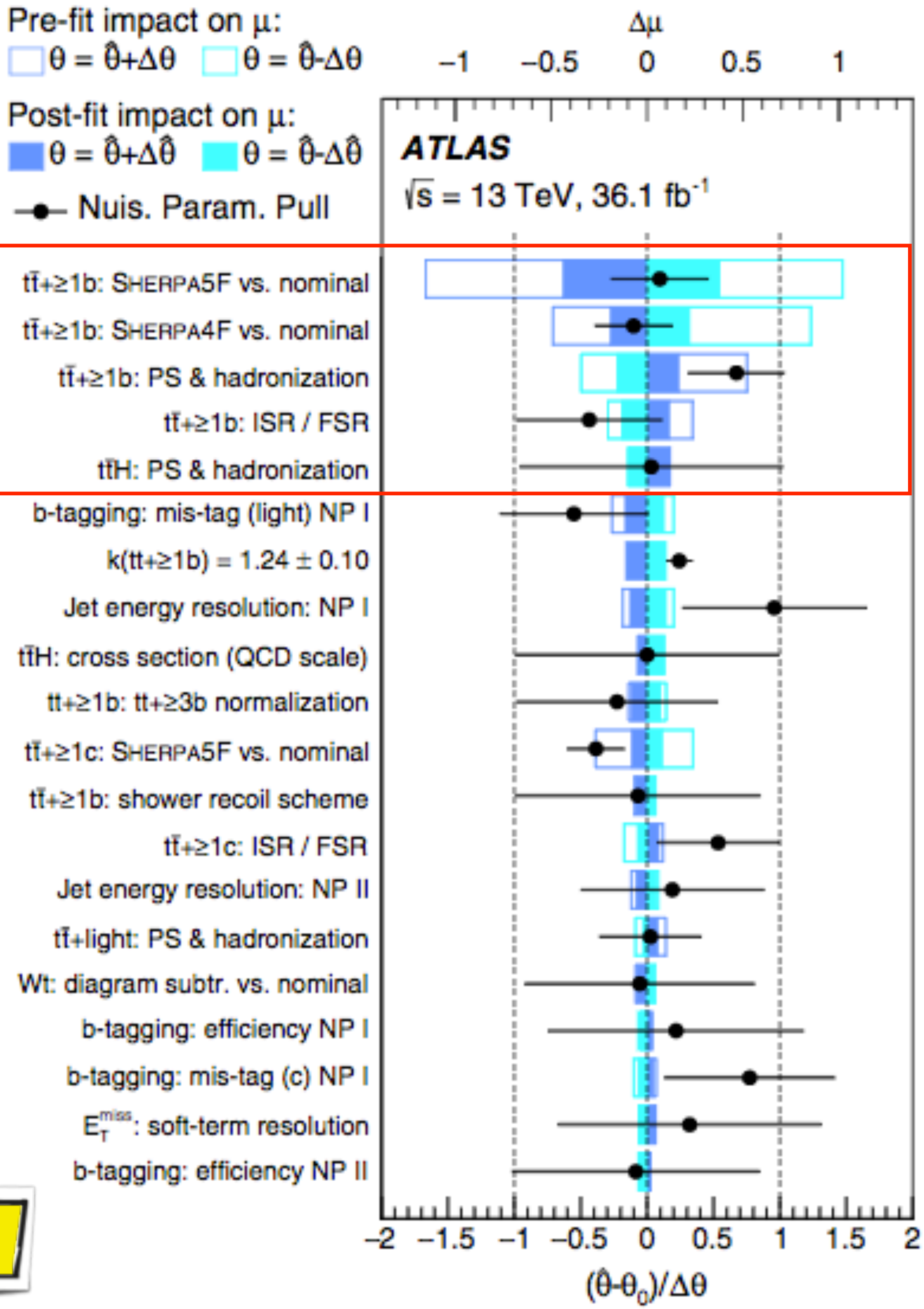
ttH->bb

PRD 97, 07, 2016 (2018)

✓ Current analysis is already limited by large tt +HF (mostly tt+≥1b) and ttH modeling systematics

- two-point systematics extracted from comparison of MC predictions with different matrix-element and parton shower schemes
- constraints of modeling uncertainties observed in Run 2 analysis
- current model will result in even large constraints of nuisance parameters when Asimov data statistics reaches HL-LHC level

➡ Current analysis cannot be extrapolated to such a high luminosity as the systematics scheme (2-point systematics) breaks

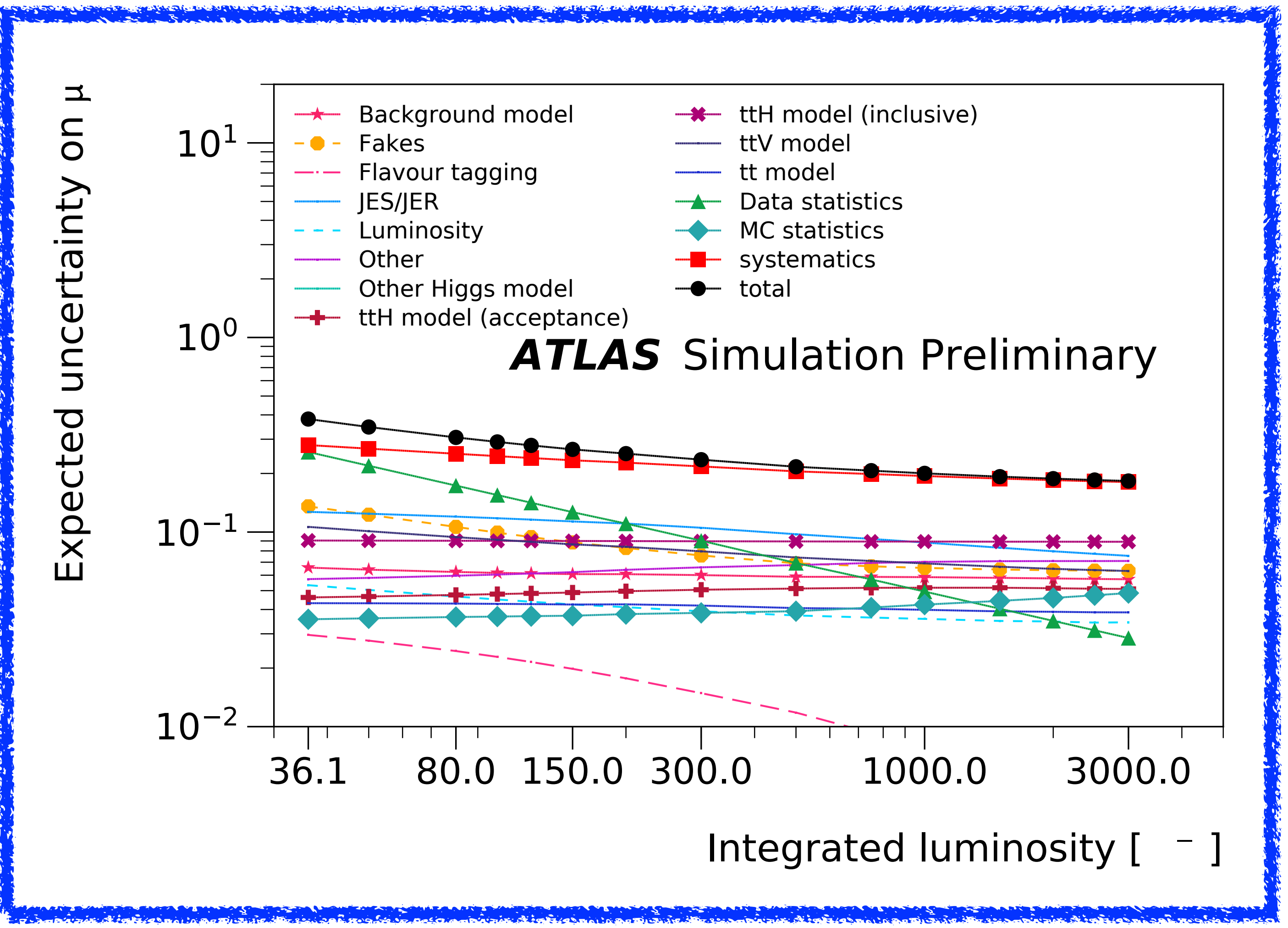


★ **Run 2 results:** $\mu=0.84\pm0.29(\mathrm{stat})\pm0.56\ (\mathrm{sys})$

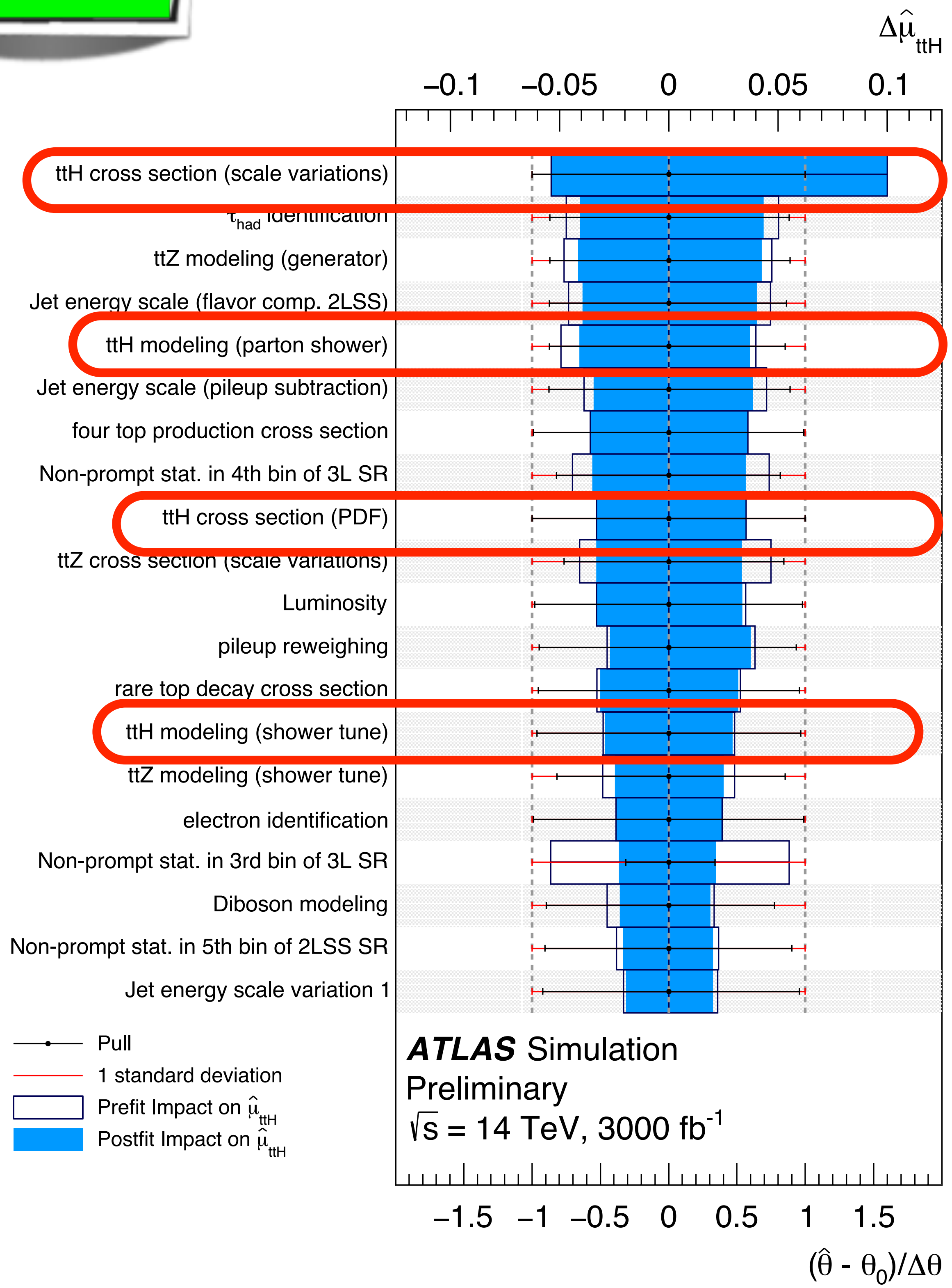
ttH->ML at Run 2 and extrapolation at HL-LHC

HL-LHC

ATLAS-PHYS-PUB-AAA



- Largest signal theory uncertainty (QCD/PDF scale variations) for $\mu=\sigma/\sigma^{SM}$ related to assumed σ^{SM}
- Large contributions also from signal acceptance (PS modeling) which affects σ in the numerator of the signal strength (main component of "ttH model acceptance")
- Some systematic components are specific of the ttH→ML channel (fake estimation) and some others are correlated with ttH→γγ (JES, JER + signal systematics)

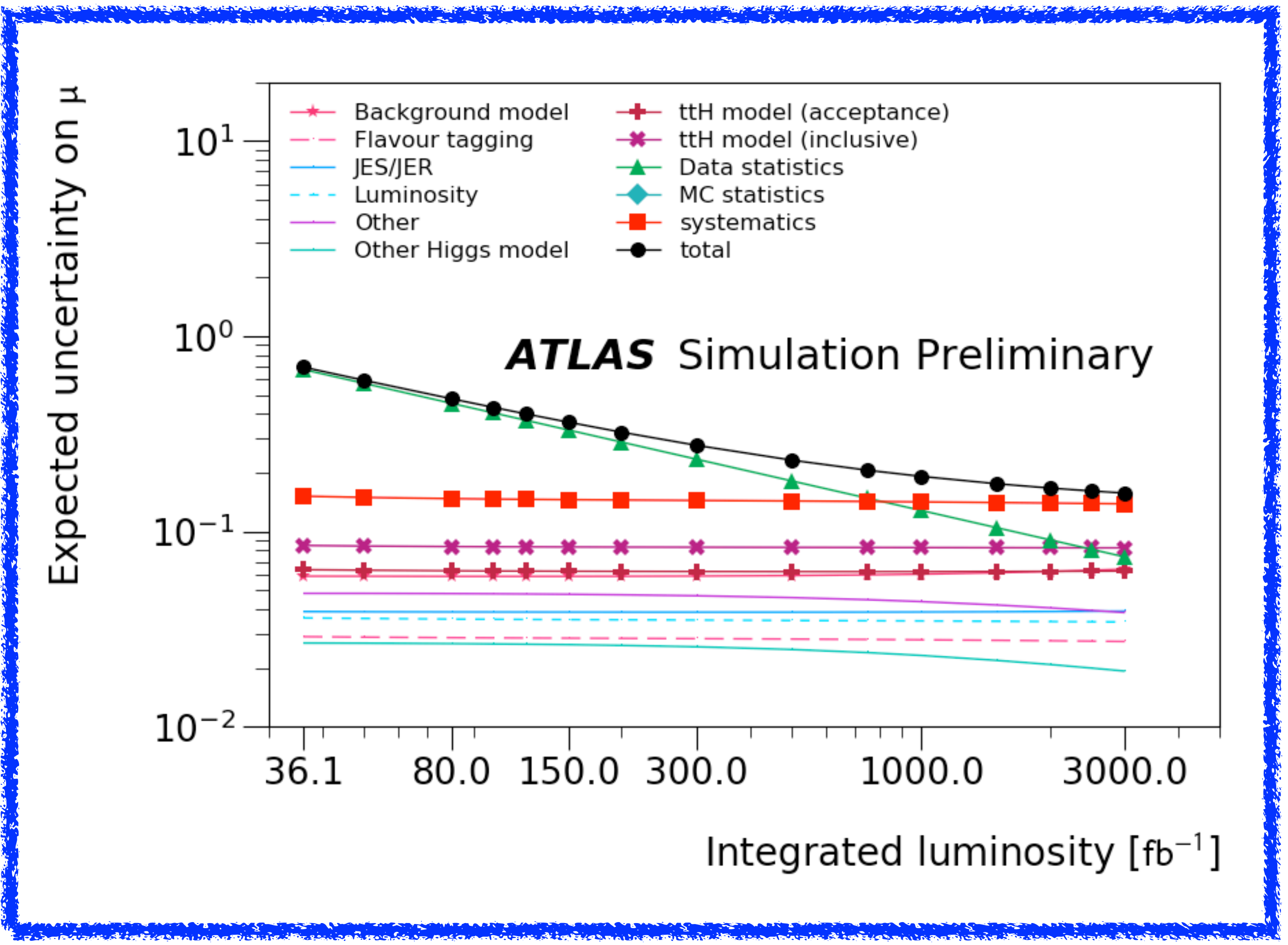


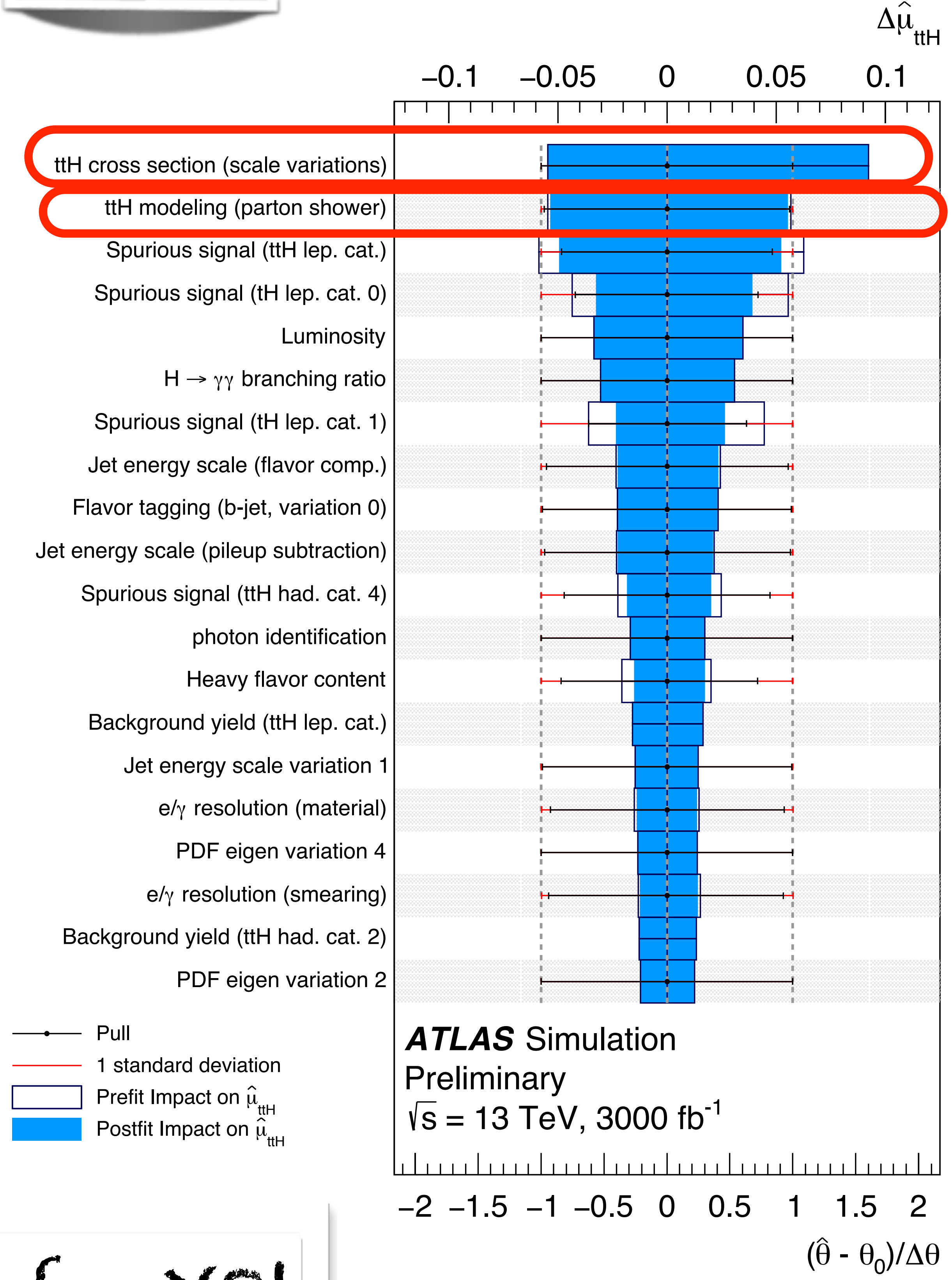
New for YR!

ttH->γγ at Run 2 and extrapolation at HL-LHC

HL-LHC

ATLAS-PHYS-PUB-AAA





✓ Similar conclusions can be drawn for ttH→γγ

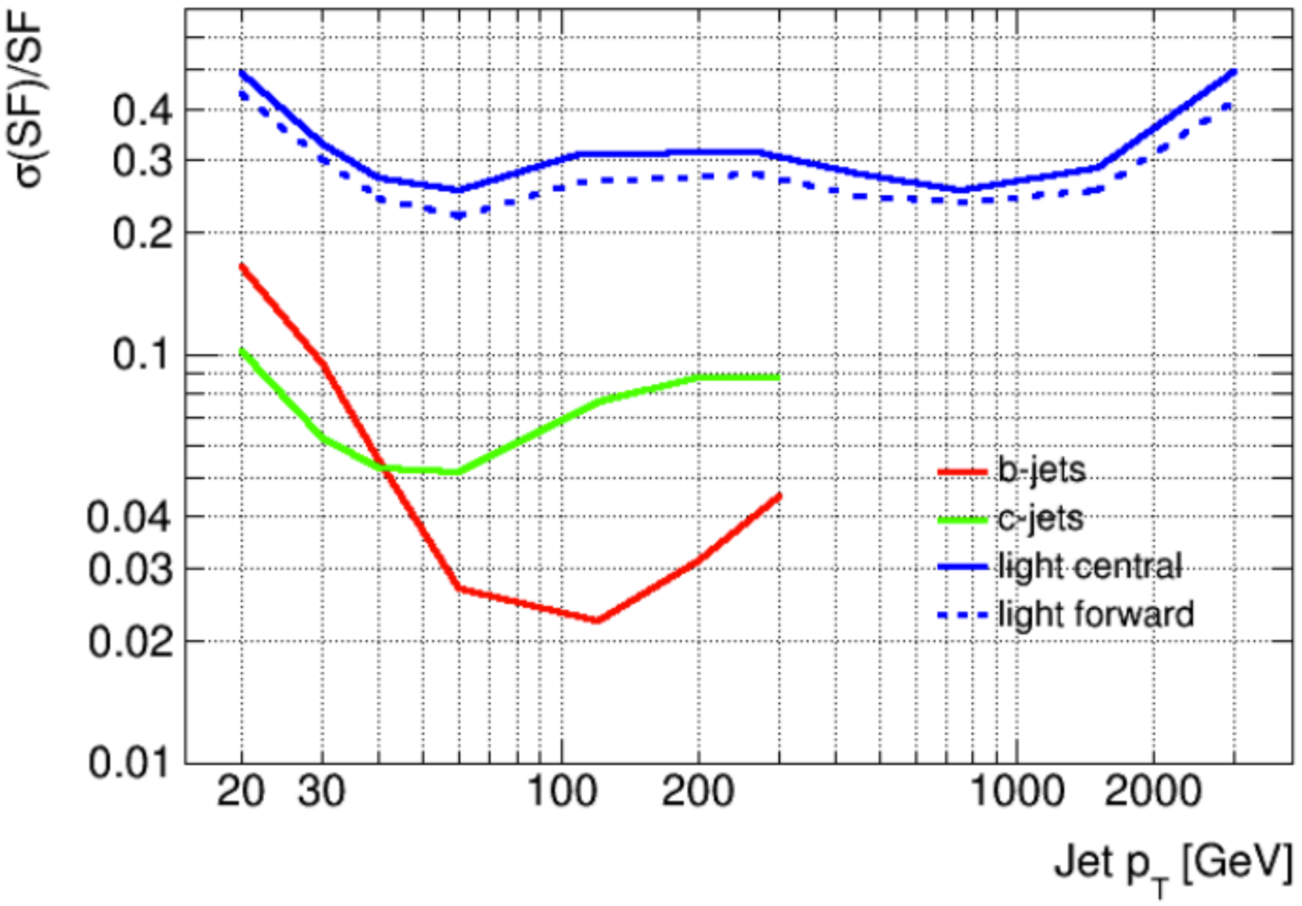
- ttH→γγ guides the precision among all ttH-initiated states
- dominated by theory uncertainties on ttH cross section prediction
- large contribution also from parton shower modeling on the ttH signal

New for YR!

Role of the systematics uncertainties in the extrapolation

- ✓ The current approach assumes same (experimental) systematics as in Run 2
- ✓ Need to project current systematic uncertainty schemes from Run 2 to HL-LHC
  - statistical component of systematics scales with luminosity → negligible at HL-LHC
  - hard to predict theory/MC advancements for modeling (e.g. ttH→bb, VH→bb)
  - new methods may reduce systematics components
  - impact of larger pile-up at HL-LHC also to be accounted for
- ✓ Ongoing discussion between ATLAS and CMS experts to define a common treatment of uncertainties (S. Pagan Griso and M. Narain's talks in yesterday's plenary)
  - systematics will be discussed on a case-by-case basis - if needed, prefit projections will be taken into account

- ✓ Let's use b-tagging as an example...
  - relatively different approaches in ATLAS and CMS to evaluate b-, c- and light-flavour jet systematic uncertainties on efficiencies and scale factors
  - e.g. for b-jets ATLAS is dominated by ttbar modeling systematics (comparison of MC generators) while CMS uses comparison of calibration methods (ttbar vs dijet)
  - need to converge on common approach/value of the uncertainty to ensure coherence of results



Wrapping-up and conclusions

➡ Very rich physics program at HL-LHC profits from the upgraded ATLAS detector

✓ Higgs physics is fundamental for the HL-LHC program

- potential to improve precision on Higgs couplings and have sensitivity to possible New Physics contributions
- rare processes (rare decays, couplings to 2nd generation, double Higgs production) getting accessible

✓ ATLAS and CMS are currently working on YR2018 project

- extrapolation of Run 2 analysis to HL-LHC conditions
- definition of conservative and optimistic scenarios for systematics uncertainties underway
- common treatment of systematic uncertainties in ATLAS and CMS being defined - strong need to harmonize approaches to exercise the coupling combination
- opportunity for fruitful and enriching discussion within and across experiments!

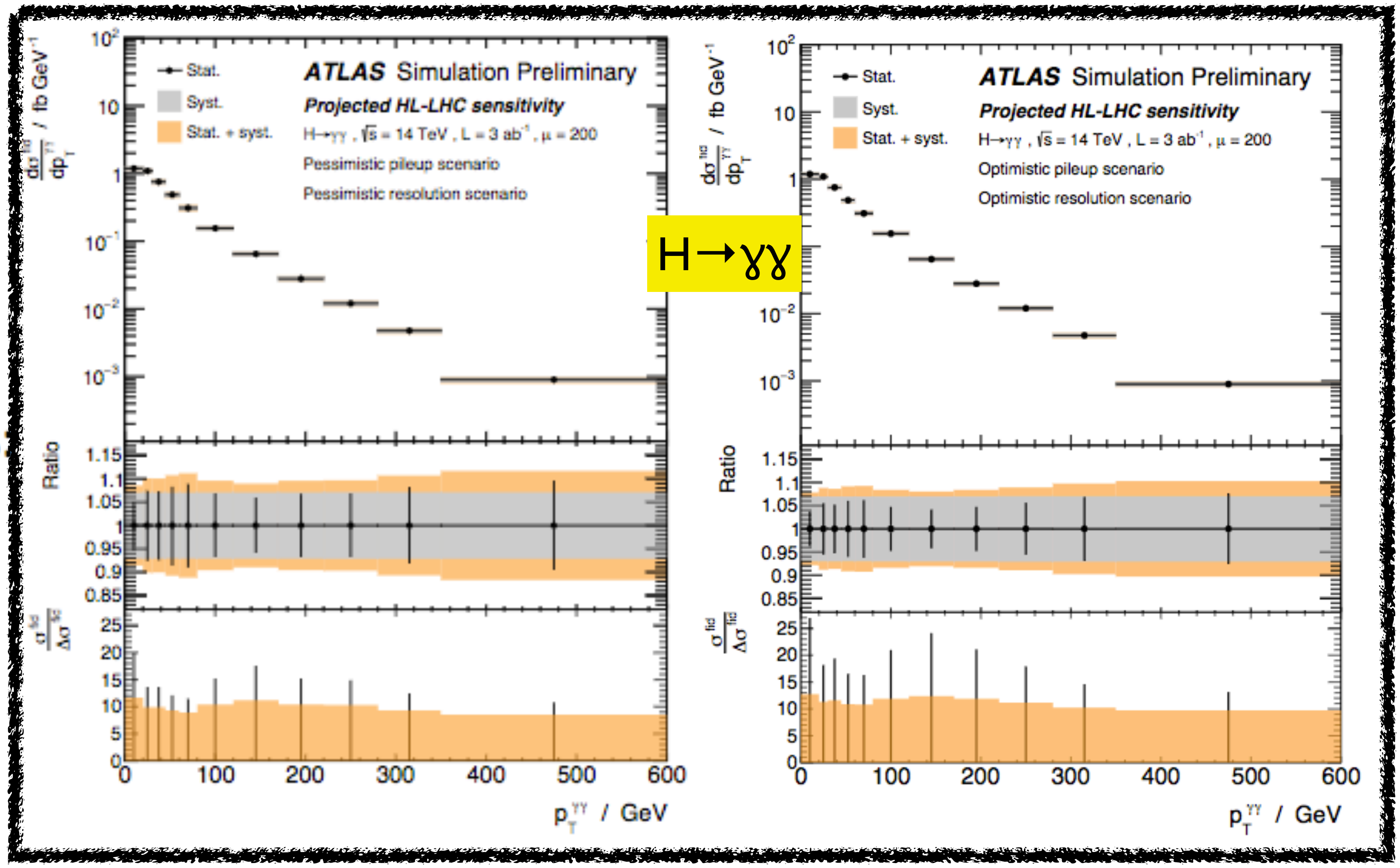
Additional slides

H->ZZ*->4l and H->γγ (differential)

✓ Differential cross section allows to probe the high pT phase space (pQCD) and to be sensitive to possible deviations from SM - treatment of systematics uncertainties in H→ZZ→4l and H→γγ

HL-LHC

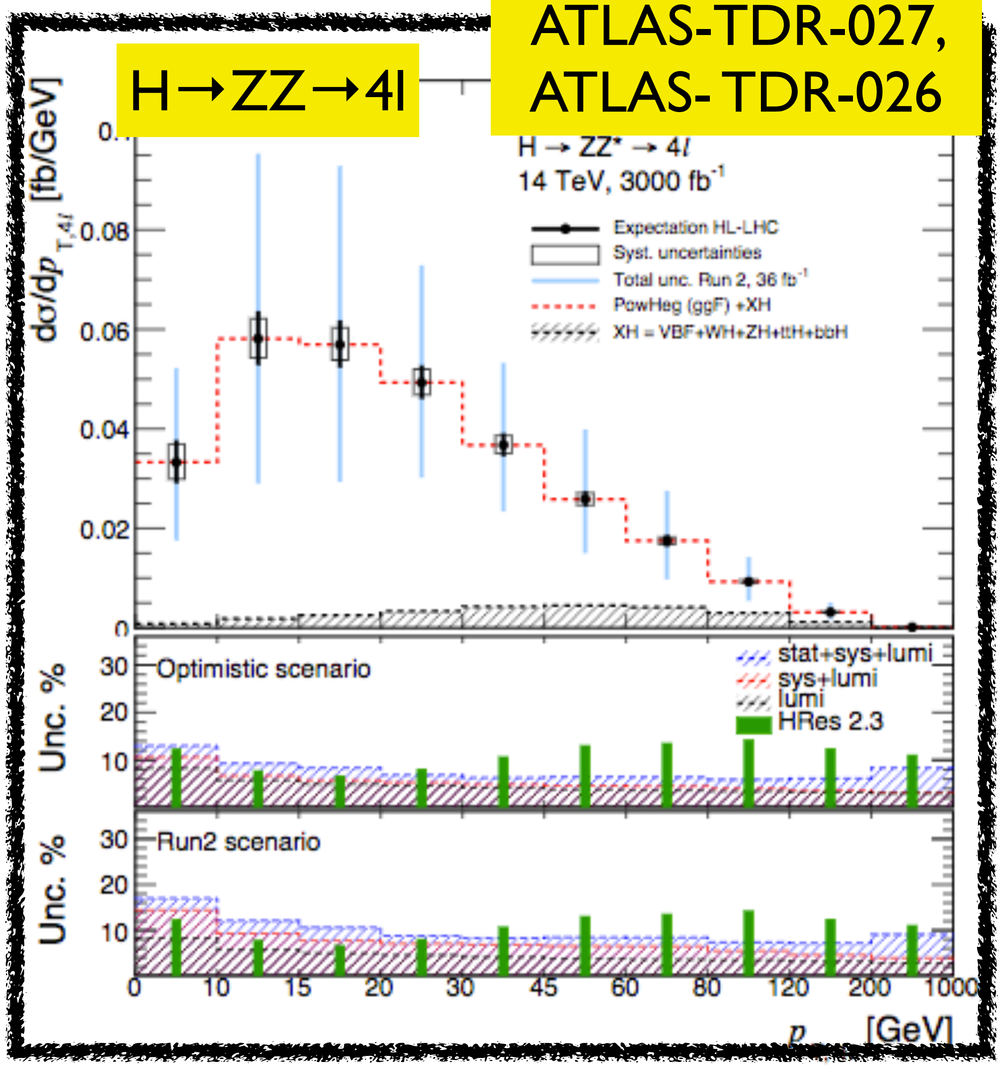
- lepton efficiency, unfolding method, modeling of qq→ZZ (H→ZZ→4l)
- optimistic scenario: Run 2 experimental uncertainties are halved (H→ZZ→4l)
- H→γγ - sys uncertainties from Run 2: bkg modeling and γ energy resolution
- background modeling (H→γγ), will reduce with larger data stats at HL-LHC
- results for pessimistic/optimistic scenarios (pile-up jets faking γ for γ energy resolution)

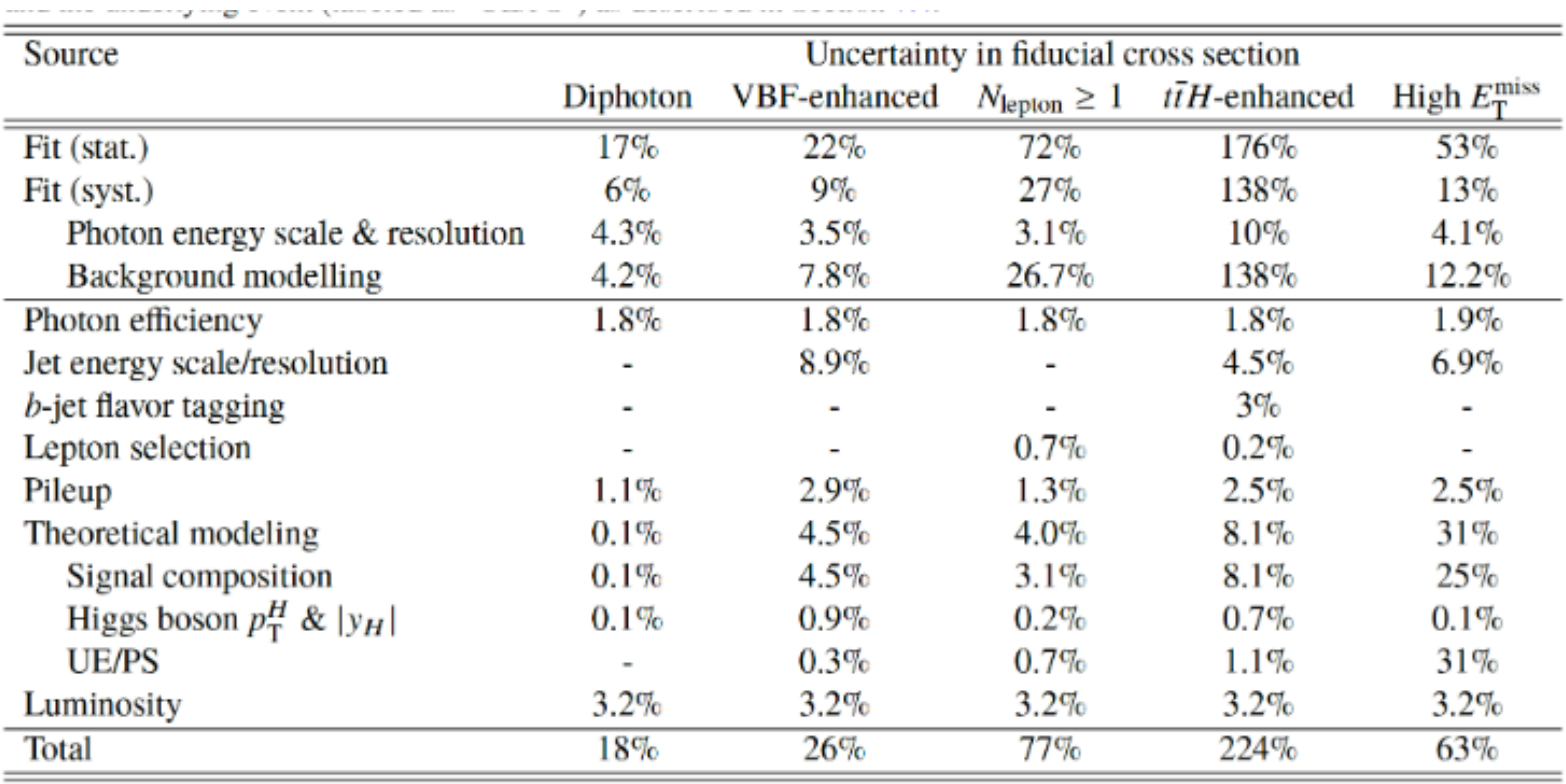


H→γγ

ATLAS-TDR-027,
ATLAS- TDR-026

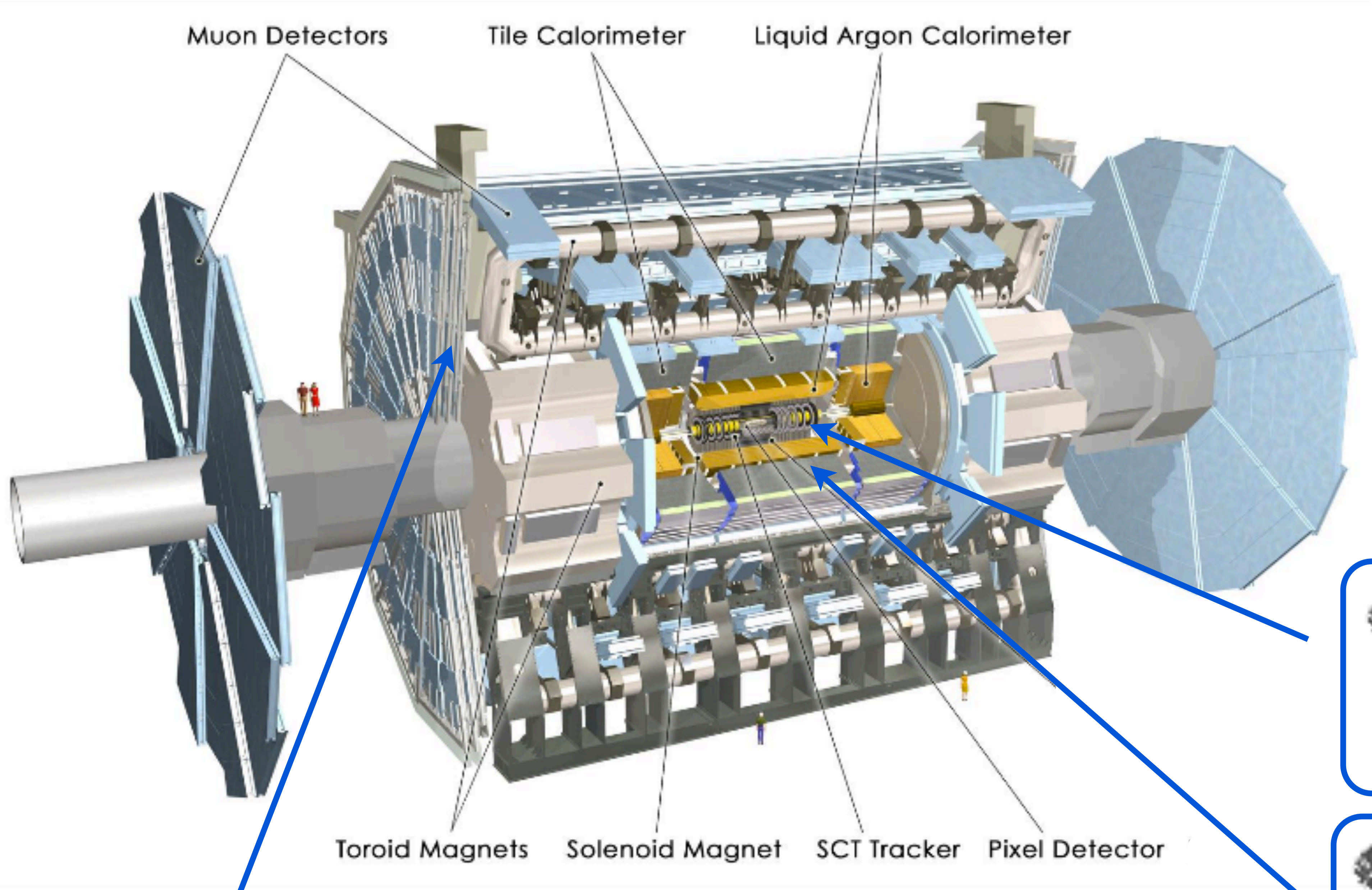
H→ZZ→4l





Source	Uncertainty in fiducial cross section				
	Diphoton	VBF-enhanced	$N_{\text{lepton}} \geq 1$	$t\bar{t}H$-enhanced	High $E_{\text{T}}^{\text{miss}}$
Fit (stat.)	17%	22%	72%	176%	53%
Fit (syst.)	6%	9%	27%	138%	13%
Photon energy scale & resolution	4.3%	3.5%	3.1%	10%	4.1%
Background modelling	4.2%	7.8%	26.7%	138%	12.2%
Photon efficiency	1.8%	1.8%	1.8%	1.8%	1.9%
Jet energy scale/resolution	-	8.9%	-	4.5%	6.9%
b-jet flavor tagging	-	-	-	3%	-
Lepton selection	-	-	0.7%	0.2%	-
Pileup	1.1%	2.9%	1.3%	2.5%	2.5%
Theoretical modeling	0.1%	4.5%	4.0%	8.1%	31%
Signal composition	0.1%	4.5%	3.1%	8.1%	25%
Higgs boson p_{T}^{H} & $\lvert y_H \rvert$	0.1%	0.9%	0.2%	0.7%	0.1%
UE/PS	-	0.3%	0.7%	1.1%	31%
Luminosity	3.2%	3.2%	3.2%	3.2%	3.2%
Total	18%	26%	77%	224%	63%

A sketch of the ATLAS Phase-II Upgrade



- Upgrade trigger system
  - track trigger
  - modification of the data acquisition system to deal with the high rate at HL-LHC

- Inner tracker (all-silicon, pixel and strip sensors) extended to |η|=4

- Upgrade electronics for Liquid-Argon electromagnetic and for Tile hadronic calorimeter

- New muon trigger chambers in the barrel

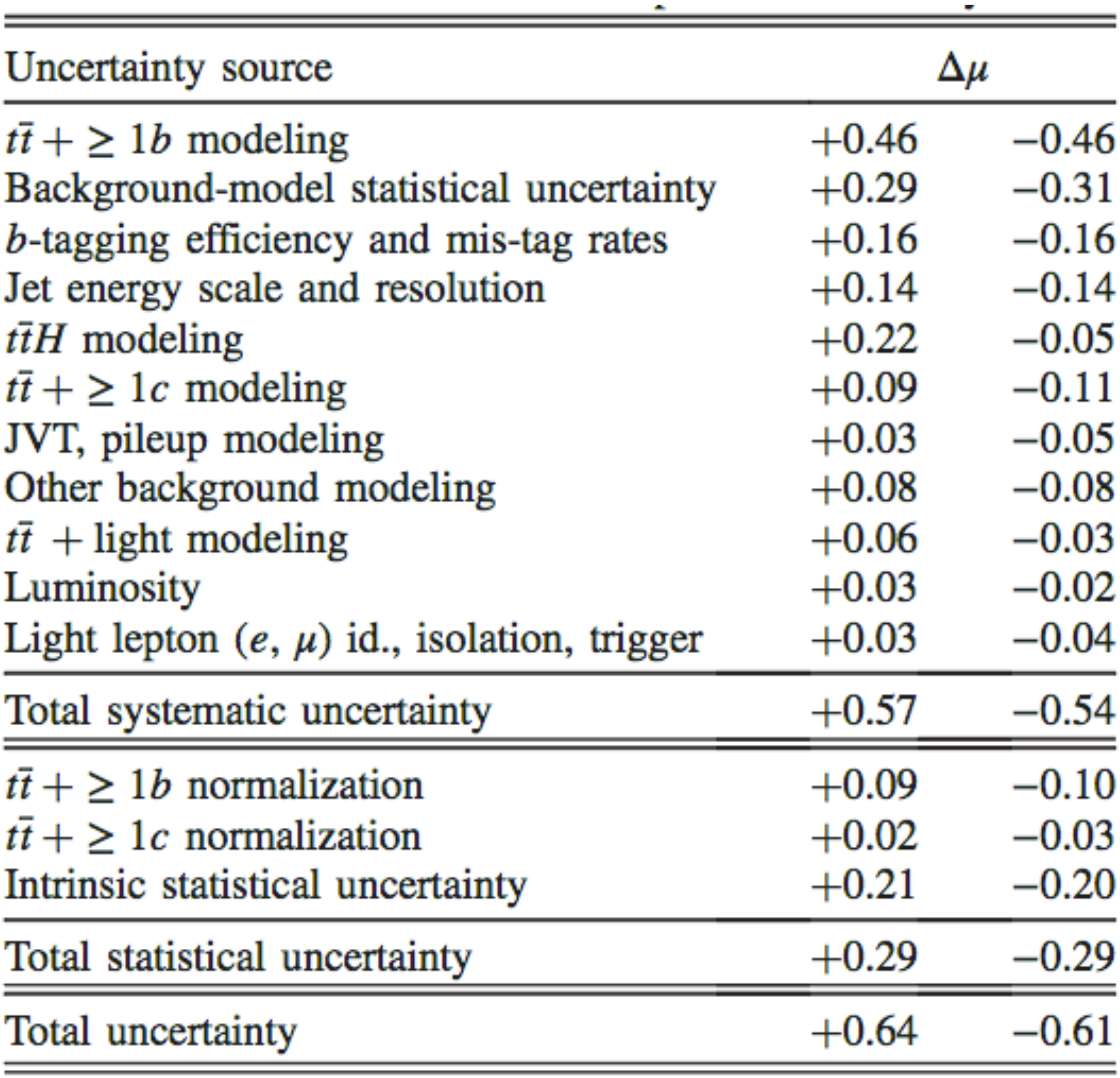
- High-granularity timing detector (still under discussion)

CERN-LHCC-2015-020 (Scoping Document, SD)

ATLAS-TDR-025 (Strip TDR)

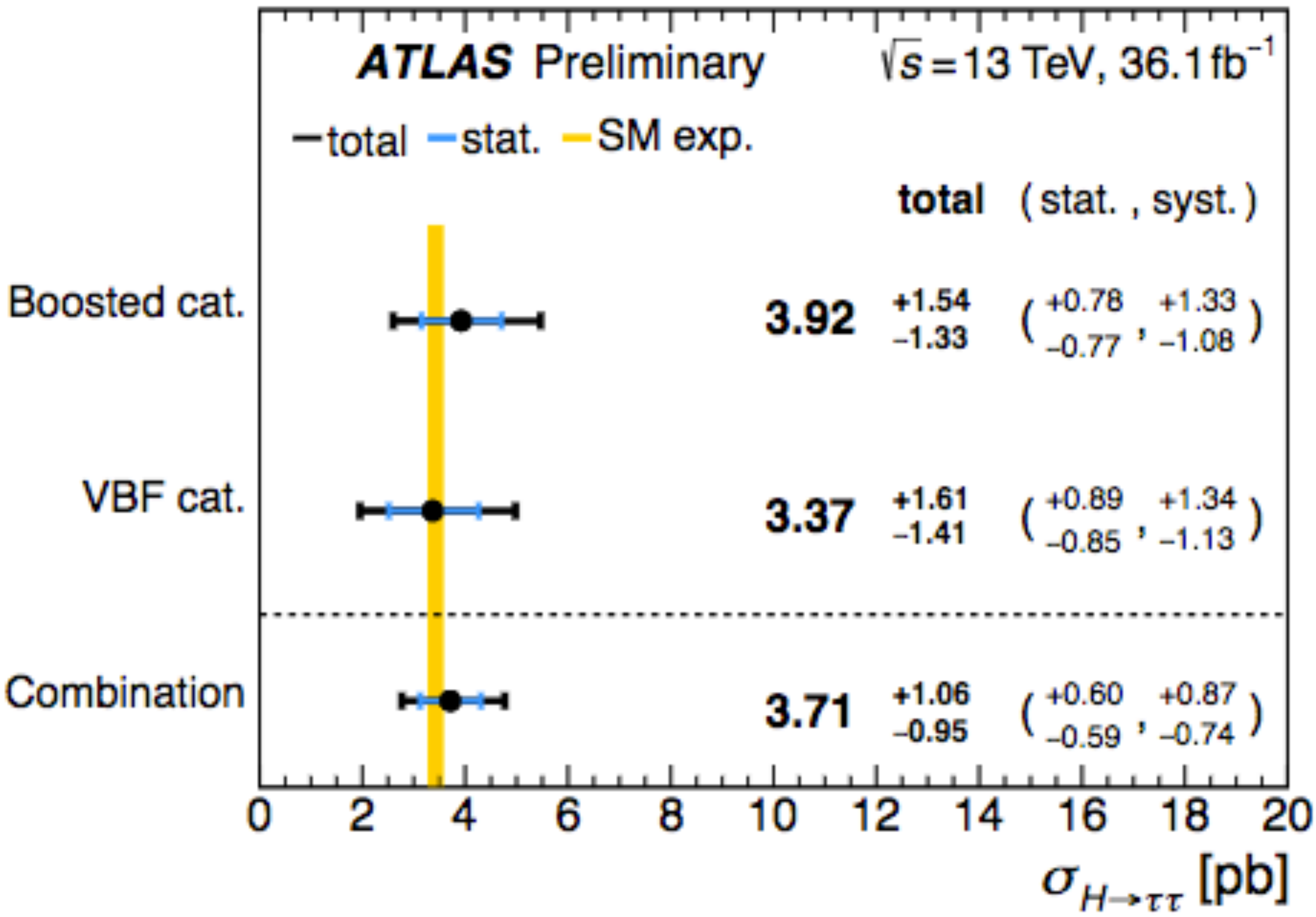
ATLAS-TDR-030 (Pixel TDR)

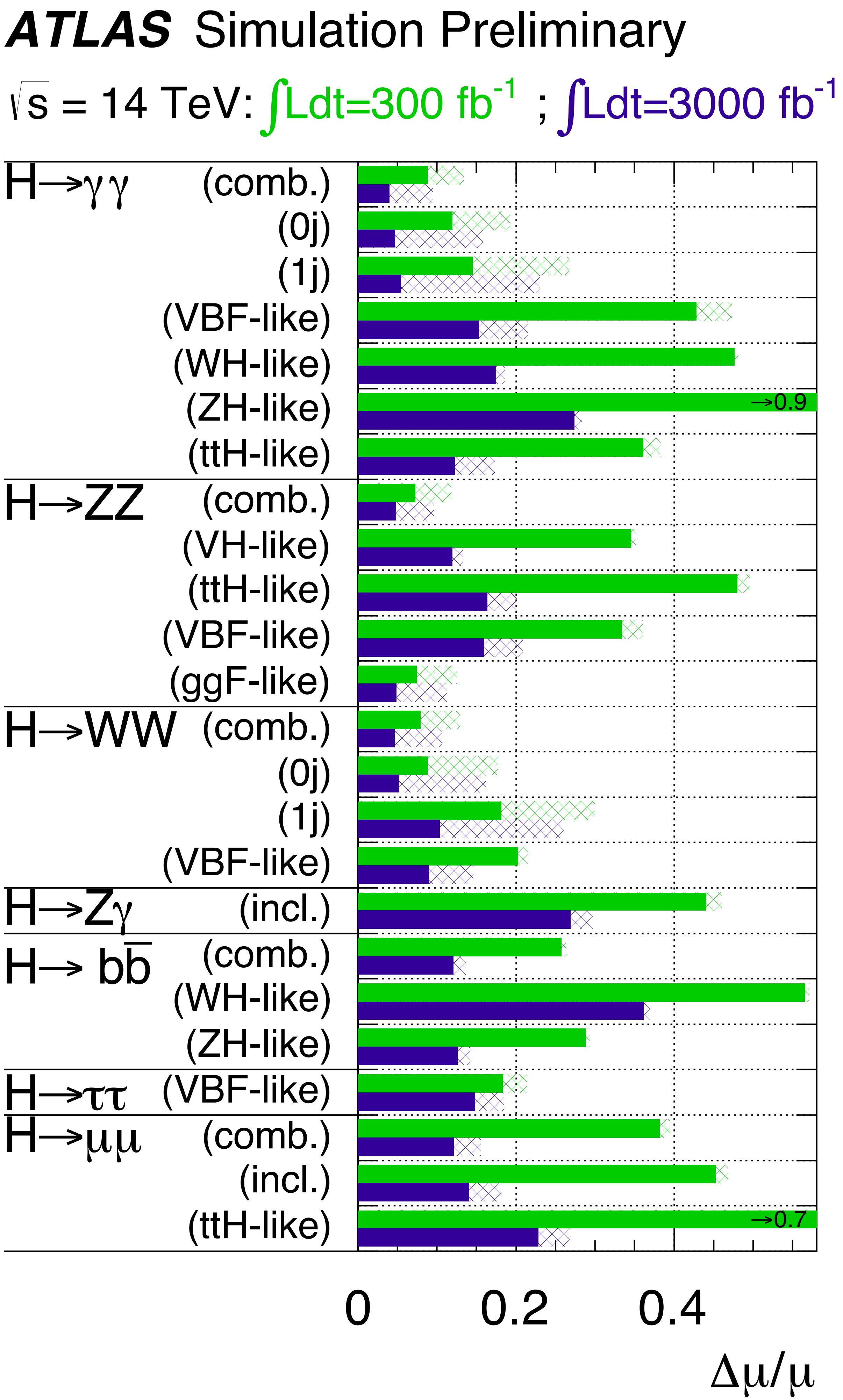
ttH->bb



Uncertainty source	$\Delta\mu$	
$t\bar{t} + \geq 1b$ modeling	+0.46	−0.46
Background-model statistical uncertainty	+0.29	−0.31
b-tagging efficiency and mis-tag rates	+0.16	−0.16
Jet energy scale and resolution	+0.14	−0.14
$t\bar{t}H$ modeling	+0.22	−0.05
$t\bar{t} + \geq 1c$ modeling	+0.09	−0.11
JVT, pileup modeling	+0.03	−0.05
Other background modeling	+0.08	−0.08
$t\bar{t}$ + light modeling	+0.06	−0.03
Luminosity	+0.03	−0.02
Light lepton (e, μ) id., isolation, trigger	+0.03	−0.04
Total systematic uncertainty	+0.57	−0.54
$t\bar{t} + \geq 1b$ normalization	+0.09	−0.10
$t\bar{t} + \geq 1c$ normalization	+0.02	−0.03
Intrinsic statistical uncertainty	+0.21	−0.20
Total statistical uncertainty	+0.29	−0.29
Total uncertainty	+0.64	−0.61

H-> τ τ


ATLAS Preliminary
$\sqrt{s}$ = 13 TeV, 36.1 fb^{-1}
total
stat.
SM exp.
total (stat. , syst.)
Boosted cat.
3.92 $^{+1.54}_{-1.33}$ ($^{+0.78}_{-0.77}$, $^{+1.33}_{-1.08}$)
VBF cat.
3.37 $^{+1.61}_{-1.41}$ ($^{+0.89}_{-0.85}$, $^{+1.34}_{-1.13}$)
Combination
3.71 $^{+1.06}_{-0.95}$ ($^{+0.60}_{-0.59}$, $^{+0.87}_{-0.74}$)
0
2
4
6
8
10
12
14
16
18
20
$\sigma_{H\rightarrow\tau\tau}$ [pb]


ATLAS Simulation Preliminary
$\sqrt{s}$ = 14 TeV: $\int$Ldt=300 fb^{-1} ; $\int$Ldt=3000 fb^{-1}
H→γγ (comb.)
(0j)
(1j)
(VBF-like)
(WH-like)
(ZH-like)
(ttH-like)
H→ZZ (comb.)
(VH-like)
(ttH-like)
(VBF-like)
(ggF-like)
H→WW (comb.)
(0j)
(1j)
(VBF-like)
H→Zγ (incl.)
H→ $b\bar{b}$ (comb.)
(WH-like)
(ZH-like)
H→ττ (VBF-like)
H→μμ (comb.)
(incl.)
(ttH-like)
→0.9
→0.7
0
0.2
0.4
Δμ/μ

Vector boson fusion - H→ZZ→4l

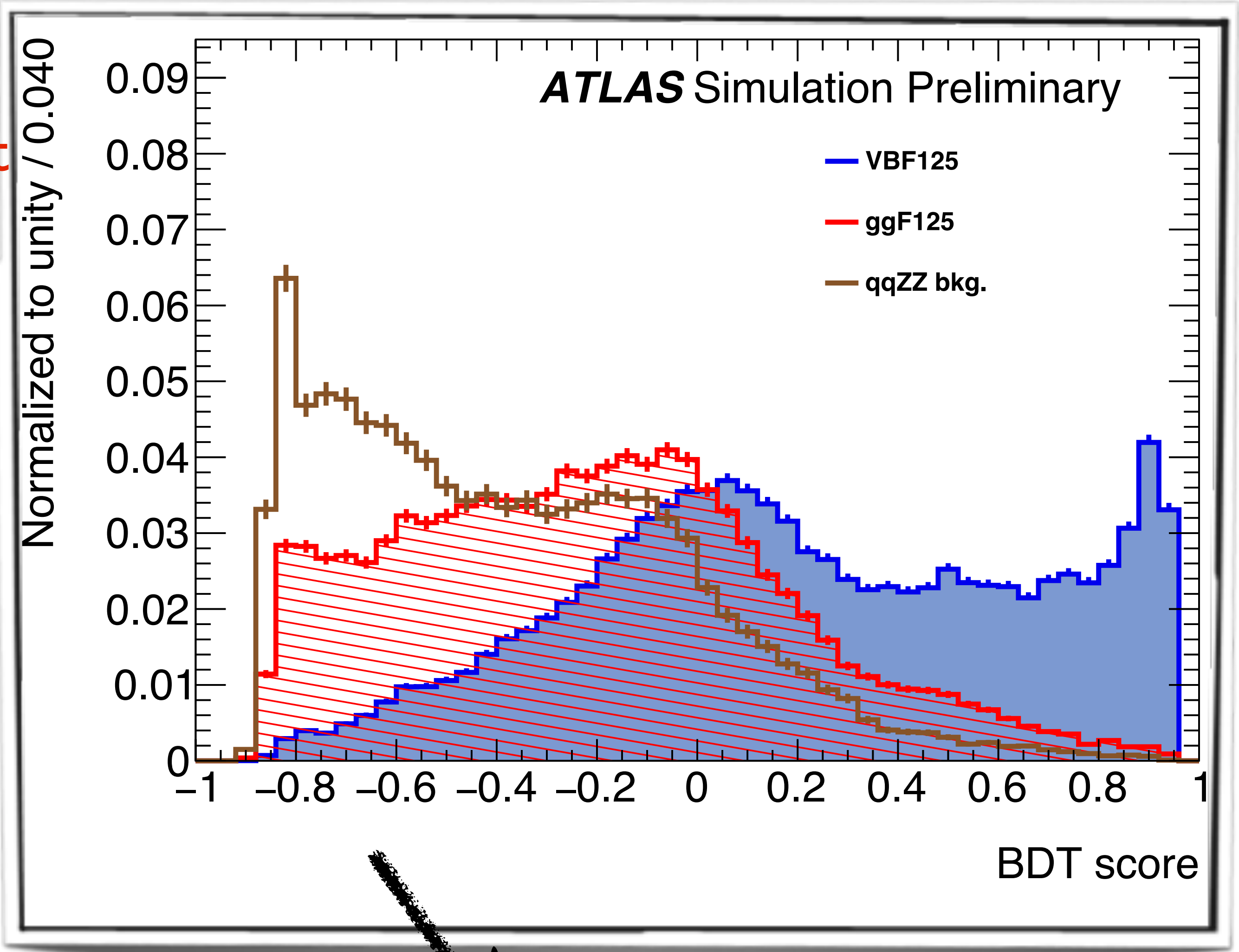
ATL-PHYS-PUB-2016-008

- ✓ Vector boson fusion (VBF) signature is kinematically highly distinctive, marked by the presence of two energetic final state quark jet at very high rapidity gap - corresponding H boson centrally produced

- ▸ Important role of pile-up jet suppression in the forward region

- ✓ Assuming Run I detector performance for e/μ - results for <μ>=200
    - Selection requirements: same selection as in Run I VBF H→ZZ analysis + m(jj)>130 GeV

- ✓ Multivariate approach employed to separate VBF from gluon-fusion + 2jets Higgs production and qq→ZZ
    - definition of the signal region exploited by a cut on BDT to improve resulting VBF H→4l significance
    - QCD scale variation systematic uncertainty included



<μ>=200, stat+sys	Stat+sys
Significance	7.2
Δμ/μ	0.18

Impact of increasing jet tracking coverage in the forward region (η=2.4→4) improves the expected precision on Δμ/μ from 22% to 14%