Prospects for Higgs physics at High-Luminosity LHC in ATLAS

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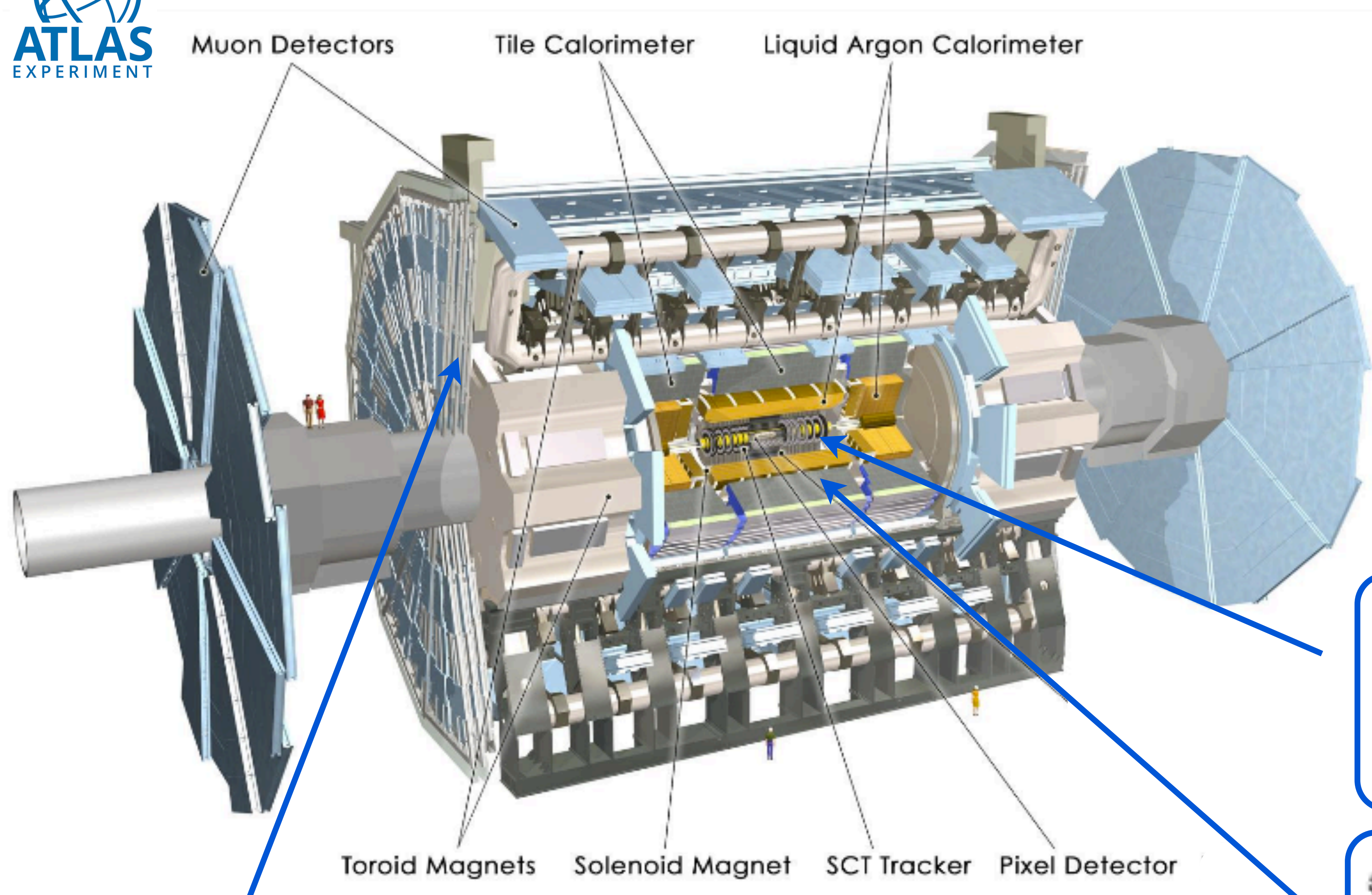
on behalf of the ATLAS Collaboration

Higgs Hunting 2018, July 25th 2018 @ Paris

Outline of the talk

- A quick look at the ATLAS upgrade program and the object performance for HL-LHC
- The analysis procedure and treatment of the systematic uncertainties for studies on Higgs measurements
- Higgs analysis prospects
  - Higgs boson couplings, differential measurements
  - Studies on vector boson fusion (in the ZZ and WW decay channels)
  - Rare decays ($H \to J/\Psi\, \gamma$, $H \to \mu\mu$)
  - Yukawa and top-Yukawa couplings ($VH \to cc$, $ttH \to ZZ/WW/\tau\tau$, $ttH \to \gamma\gamma$)
  - Extraction of the Higgs boson width
  - Search for additional Higgs states
- Wrapping-up and conclusions

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 $|\eta|=4$

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

ITK-2018-001 (Pixel TDR plots)

ATLAS-TDR-025 (Strip TDR)

- New muon trigger chambers in the barrel

CERN-LHCC-2015-020 (Scoping Document)

- High-granularity timing detector

CERN-LHCC-2017-028 (Expression of Interest HGTD)

HL-LHC environment and object performance

ITK-2018-001 (Pixel TDR plots)

ATLAS-TDR-026 (Muon TDR)

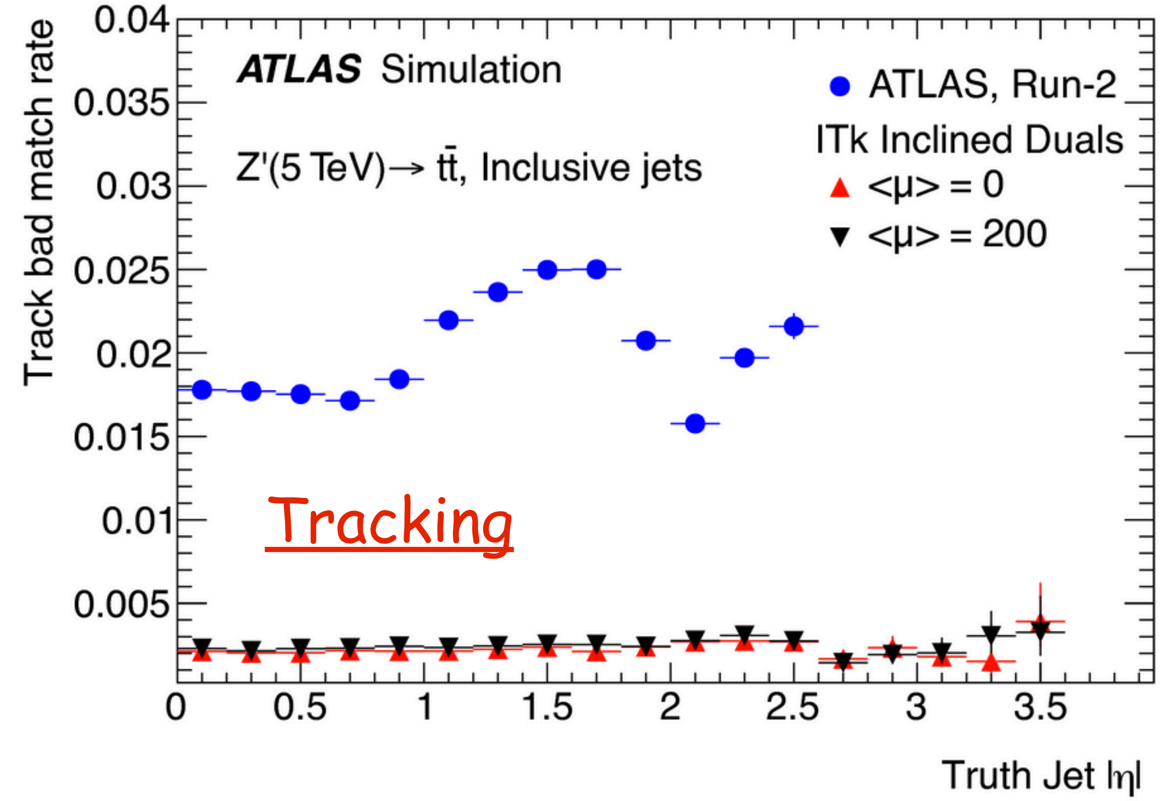
ATLAS-TDR-022 (LAr TDR)

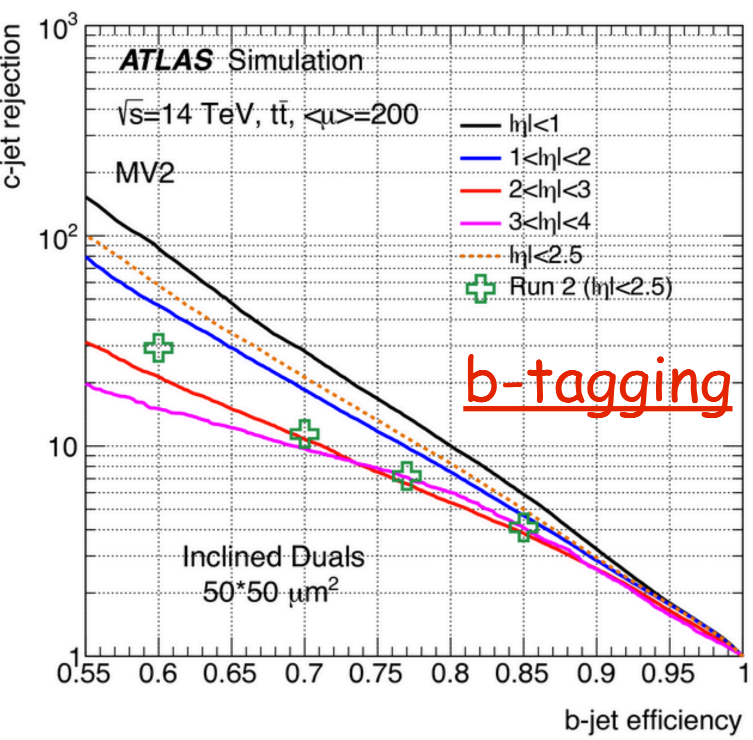
✓ Very challenging environment at HL-LHC → detector requirements to maximize benefits from high luminosity

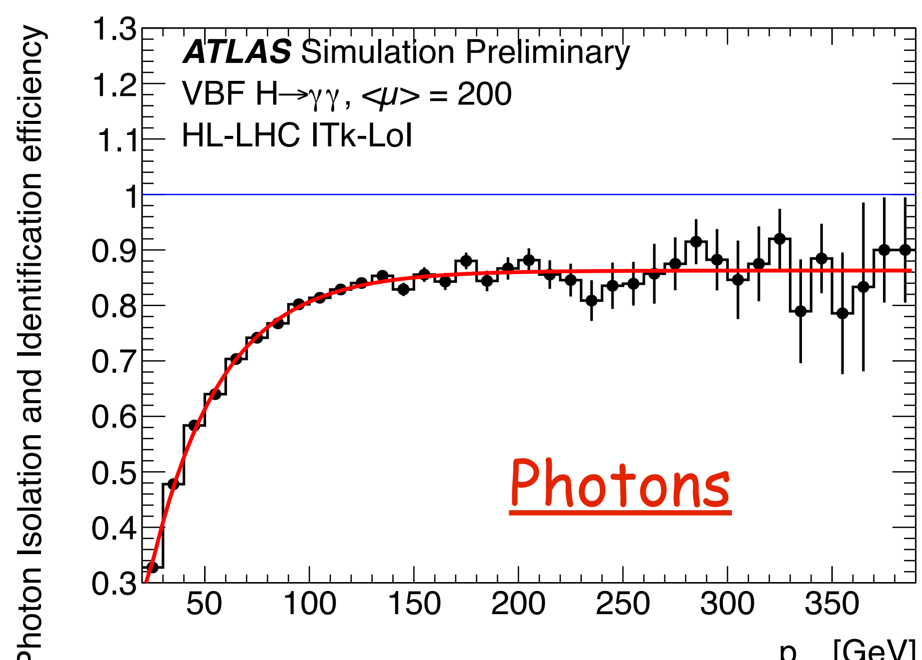
- sustain large integrated radiation dose
- mitigation of pile-up effects
- sustain large event rate with more sophisticated trigger and data acquisition systems

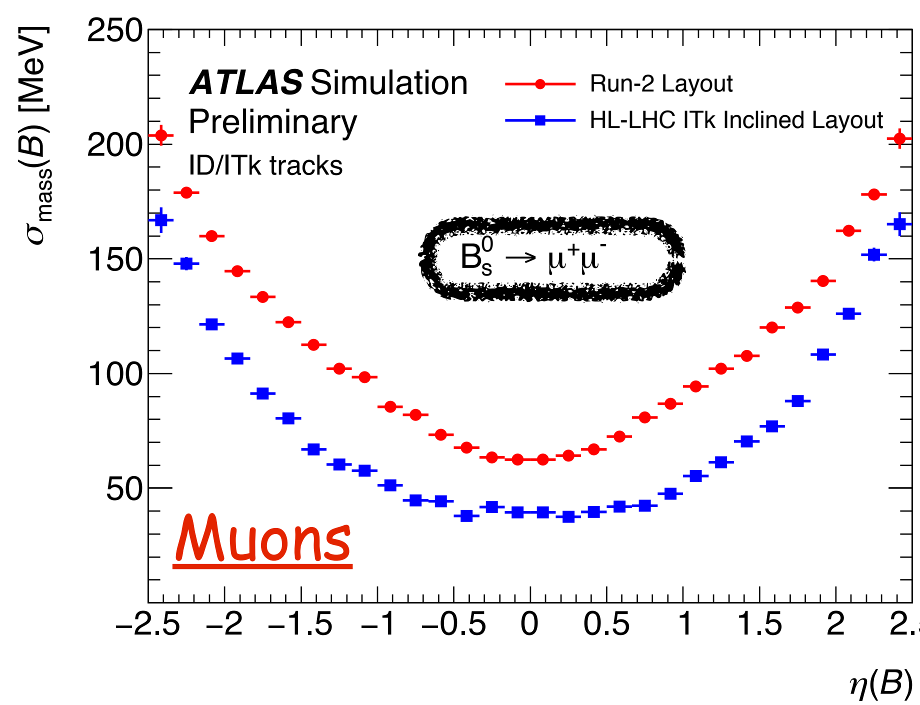
✓ Important to keep good control over performance of physics objects (identification and reconstruction, background rejection)

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









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) [HH production discussed in J. Qian's talk on Tuesday]
  - Higgs BSM searches at HL-LHC (backup material)
- increase (~10%) 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 ATLAS+CMS Yellow Report 2018 project
  - 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

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)

Run 2 extrapolation

- ✓ Benefit from elaborated Run 2 analysis
- ✓ Scale luminosity and signal/background cross section yields to match HL-LHC conditions (3000 fb^{-1} and 14 TeV)

Systematic uncertainties

- ✓ <u>Theoretical systematic uncertainties</u>: same as Run 1/ Run 2 analysis, reduced by 1/2 or absent
- ✓ Reduction of <u>experimental systematics</u> for HL-LHC studies also being discussed in ATLAS and CMS to ensure harmonization of treatments across experiments

Signal strength and couplings at HL-LHC

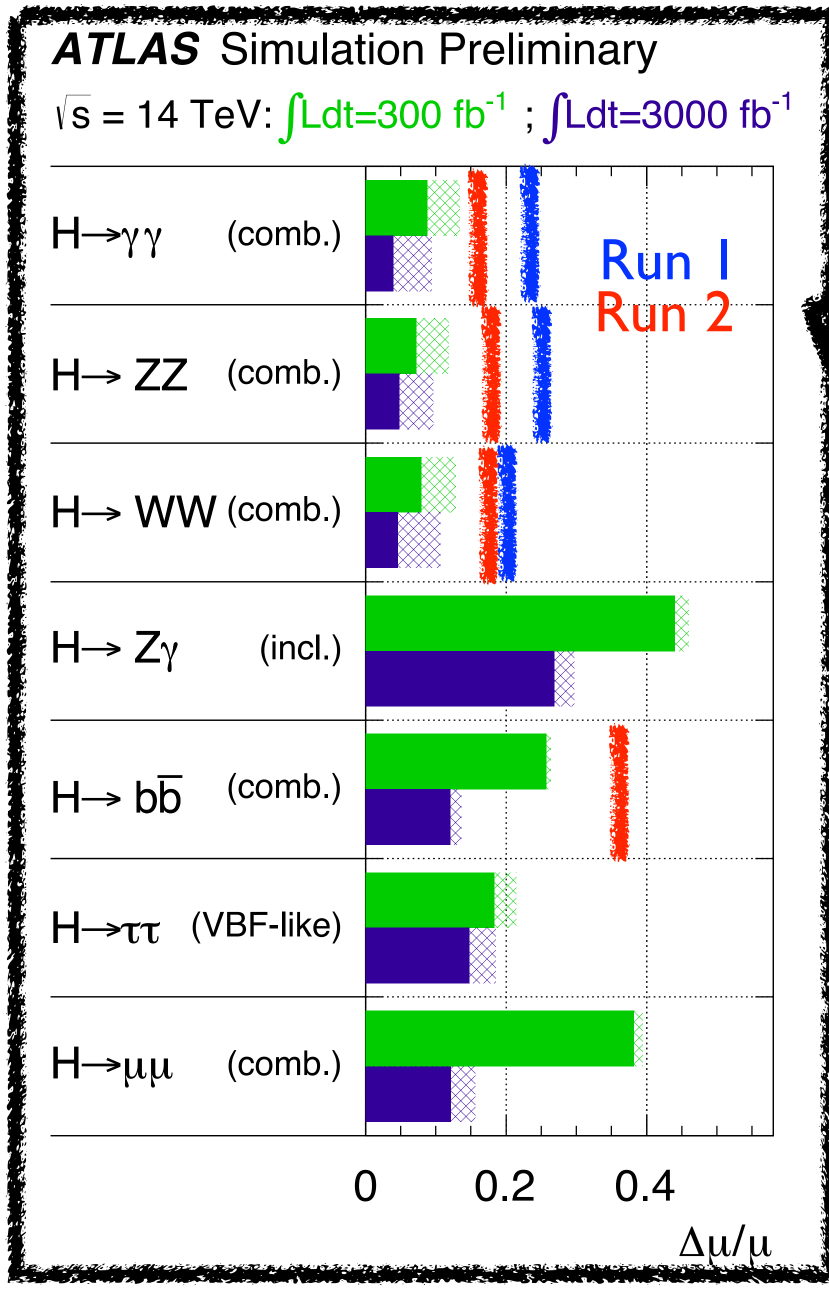
ATL-PHYS-PUB-2014-016

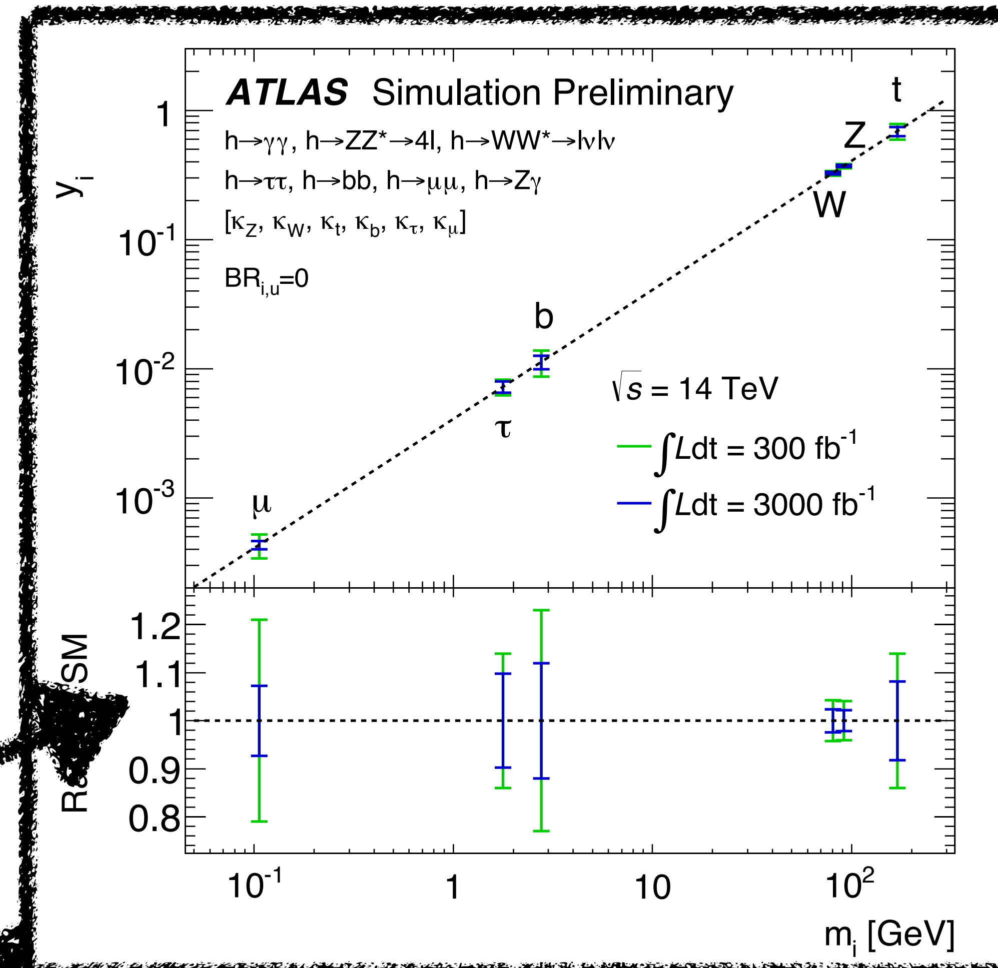
✓ ATLAS public results on couplings at HL-LHC → extrapolation from Run 1 using <μ>=140

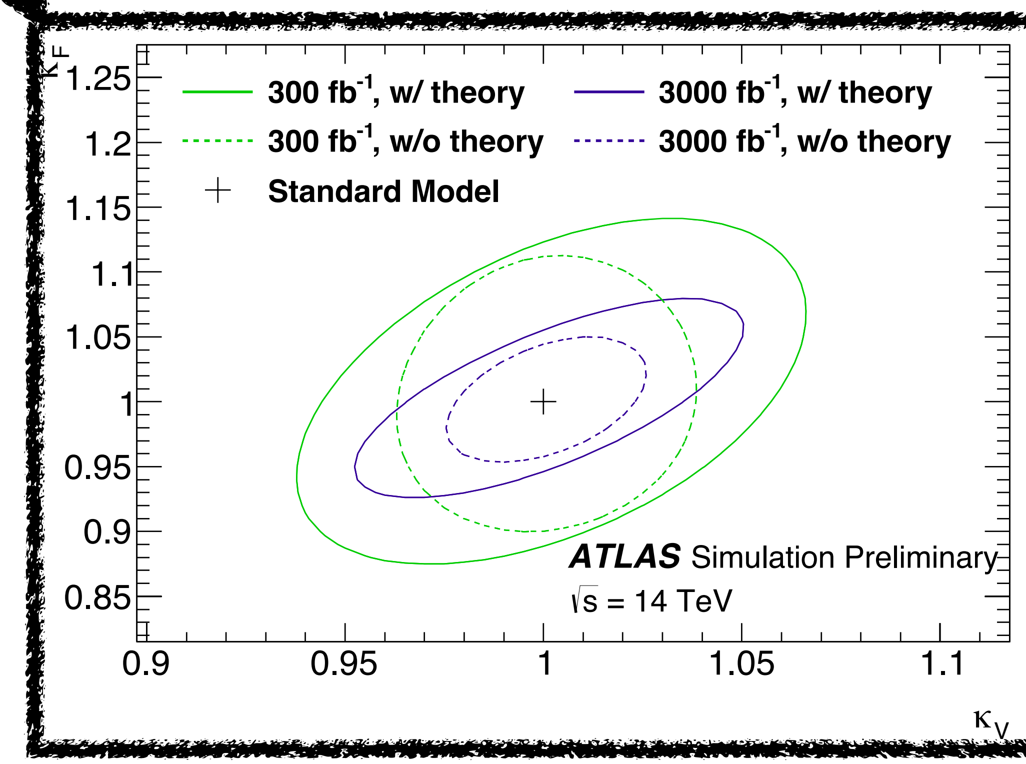
➡ Expected precision on couplings to W/Z around 3%, to muons ~7%, to τ, b, t approximately 10% @ 3000 fb^{-1}

✓ 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 presented







H->ZZ*->4l and H->γγ (differential)

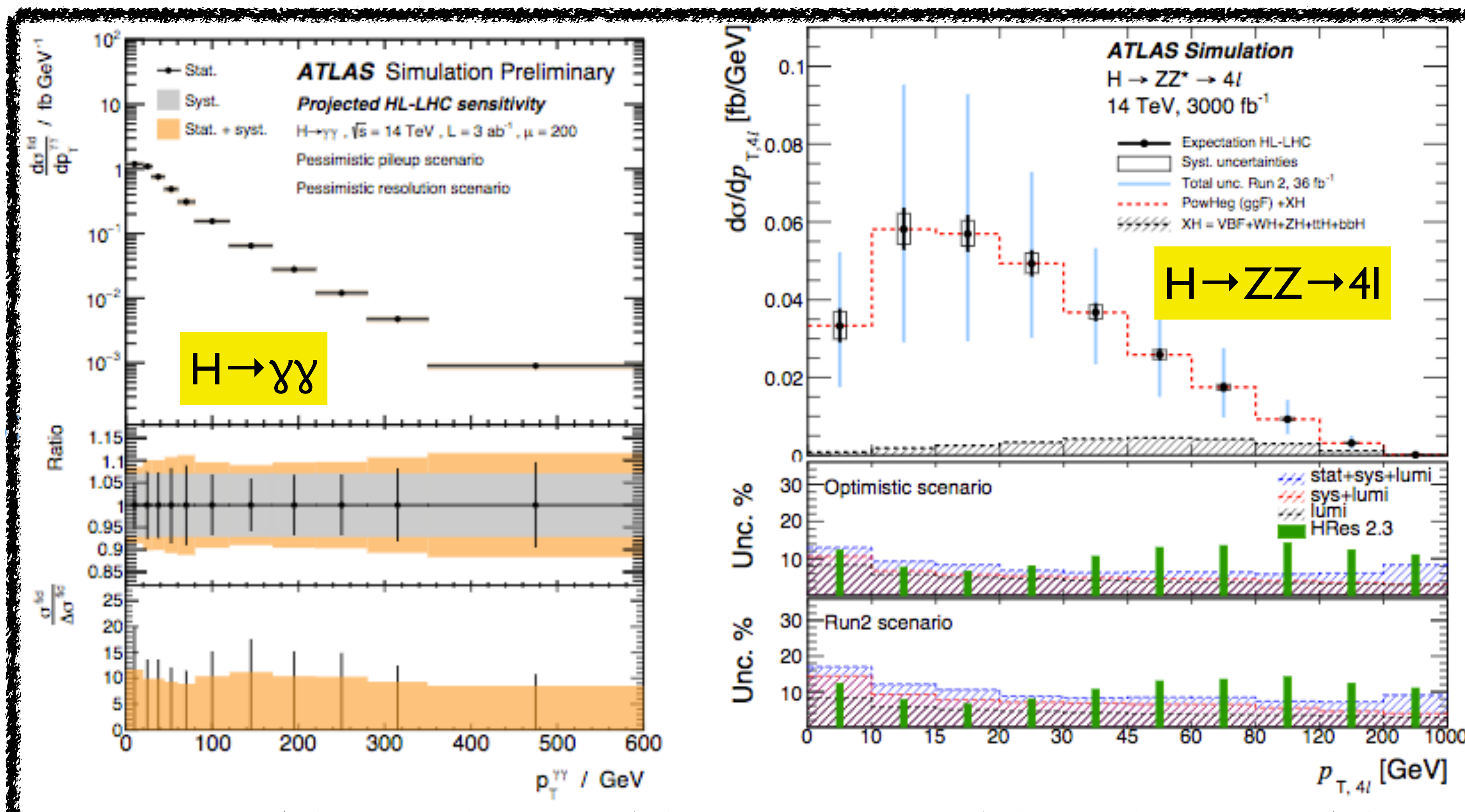
ATLAS-TDR-027, ATLAS- TDR-026

✓ 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

- H→ZZ→4l - lepton efficiency, unfolding method, modeling of qq→ZZ
- 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 available for various treatments of systematic uncertainties

- experimental uncertainties (halved or kept as in Run 2)
- differential cross section measured at ~ 10/15% level

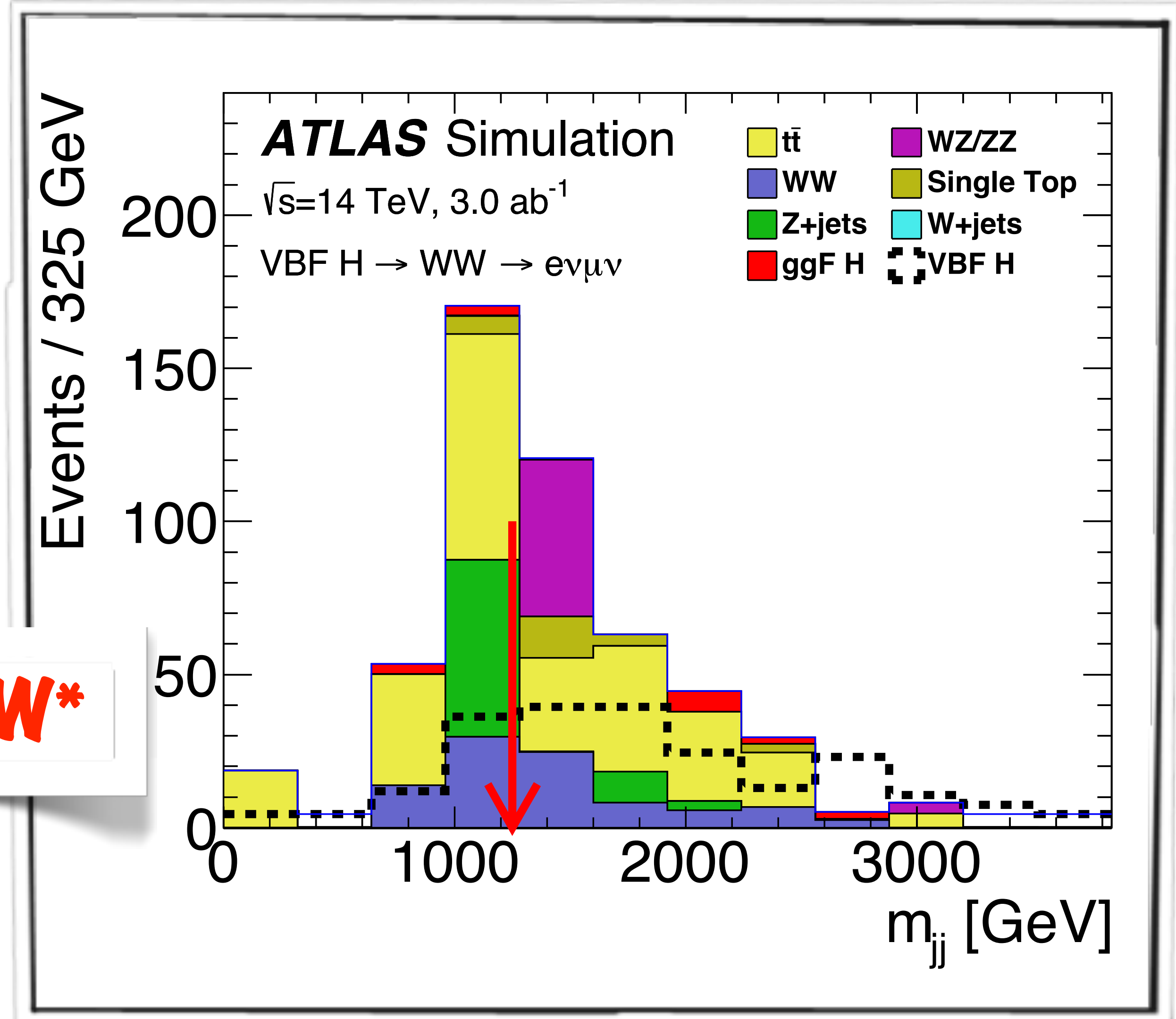


Vector boson fusion ($H\to ZZ^*\to 4l$ && $H\to WW^*\to e\nu\mu\nu$)

ATL-PHYS-PUB-2016-018 ATL-PHYS-PUB-2016-008

- ✓ VBF is kinematically distinctive - two energetic final state quark jets at very high rapidity gap
- ▶ VBF $H\to WW^*$ production very useful to test detector layouts
- ✓ Assuming Run 1 detector performance for e/μ - results for <μ>=200
- ✓ QCD scale on the VBF jets dominates the systematic uncertainties - theoretical computation will improve with time
- ➡ Available results (15% on Δμ/μ) will be superseded by Run 2 extrapolated - 6% stat-only on Δμ/μ from Run 2 extrapolation

$H\to WW^*$



- ✓ Assuming Run 1 detector performance for e/μ - results for <μ>=200
- ▶ Multivariate approach employed to separate VBF from gluon-fusion + 2 jets Higgs production and $qq\to ZZ$
- ➡ Extrapolation from Run 2 analysis VBF $H\to ZZ$ gives 9% uncertainty on Δμ/μ (stat-only)

$H\to ZZ^*$

<μ>=200, stat+sys ($H\to ZZ$)	Stat+sys ($H\to ZZ$)
Significance	7.2
Δμ/μ	18% (15% stat-only)

Impact of increasing jet tracking coverage in the forward region (η=2.4→4) improves the expected precision on Δμ/μ from 22% to 15%

VH->cc

ATL-PHYS-PUB-2018-BBB

✓ Expected limit calculated using pre-fit Asimov dataset and stat-only fit from Run 2

- main background as in Run 2 analysis dominated by Z +jets, smaller contributions from ZZ, ZW and ttbar
- focus on $Z(\to ll)H\to cc$ - similar to Run 2 cut-based 2-leptons VHbb
- simultaneous maximum likelihood fit in categorized defined using pT^Z (above or below 150 GeV) for 1- and 2 c-tagged jets using m_{cc} as kinematic discriminant

✓ Pioneer use of novel ATLAS c-tagging algorithm in Run 2

- BDT using low-level information and trained to separate b- from c-jets and c- from light-flavour jets
- rectangular cut in 2D (c/b separation bs c/l separation) to define analysis regions
- tight c-tagging working point for HL-LHC extrapolation (improves expected limit by 6%)

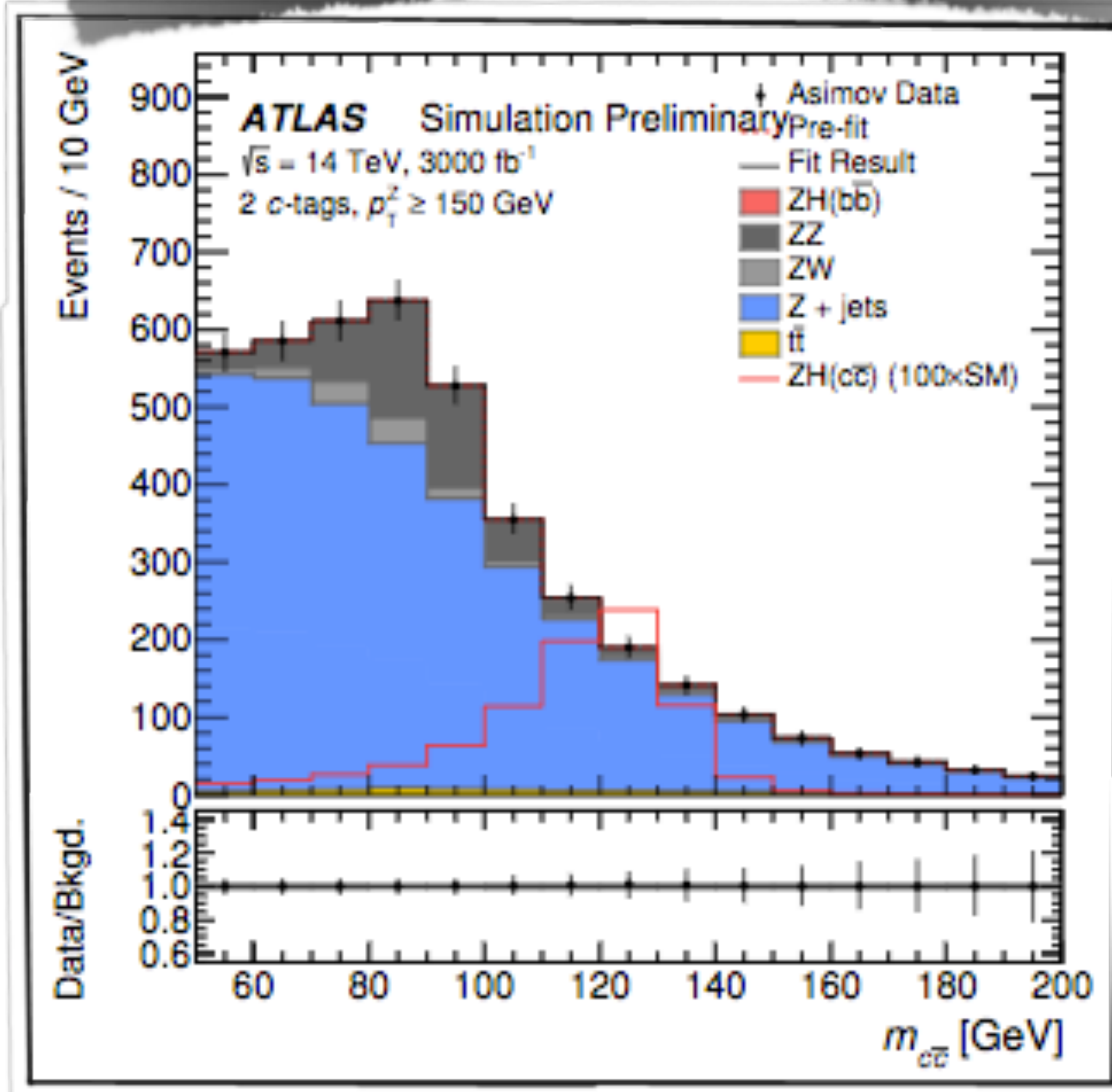
➡ Expected stat-only upper limit: $\mu_{ZH(cc)} < 6.3^{+2.5}_{-1.8}$ (Run 2 upper limit ~ 150)

➡ Charm couplings at HL-LHC in $H\to J/\psi\gamma$ in the backup

Run 2 - Impact of systematic uncertainties

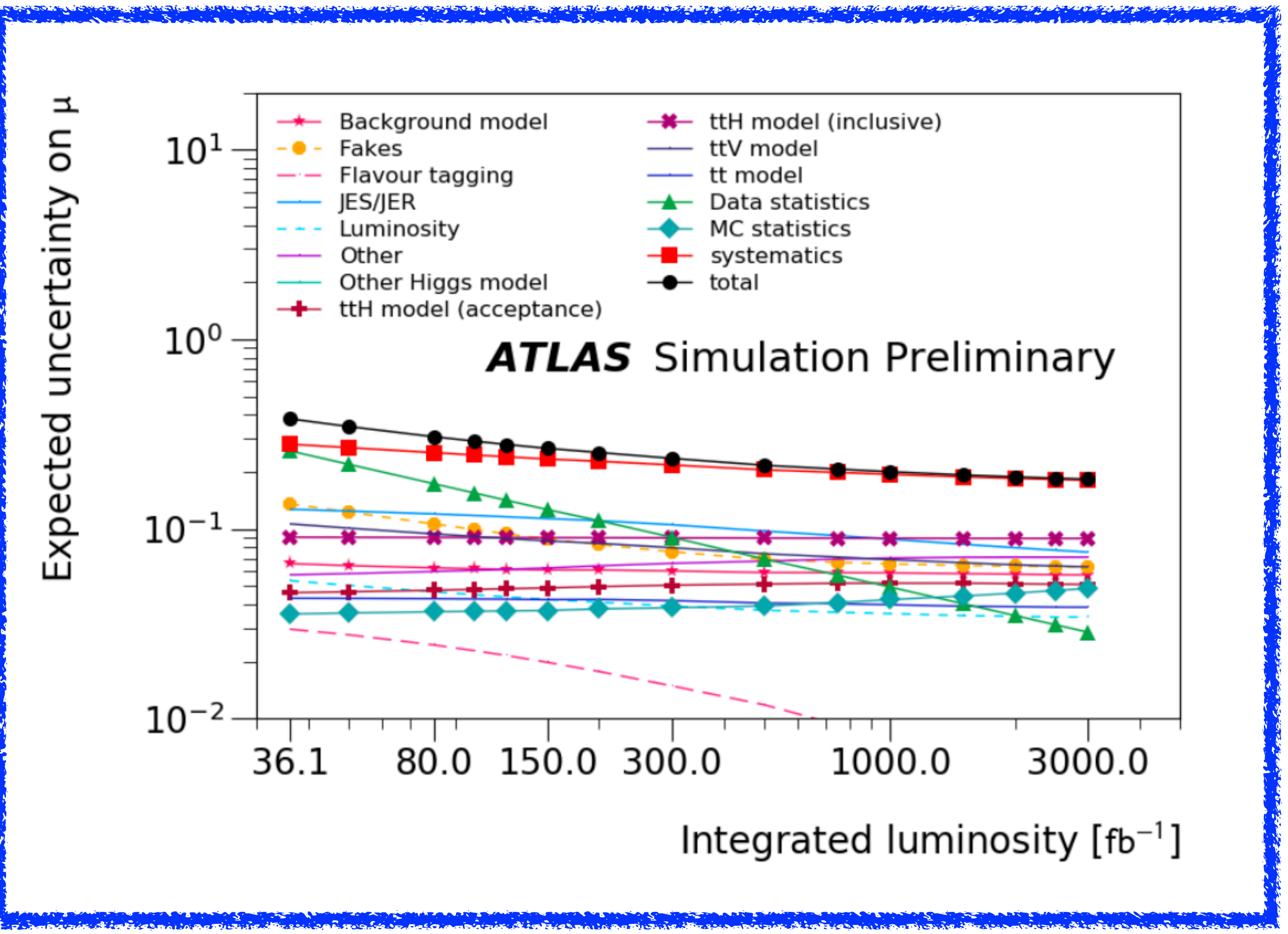
PRL 120, 211802 (2018)

Source	σ/σ_{tot}
Statistical	**49%**
Floating Z + jets normalization	31%
Systematic	**87%**
Flavor tagging	73%
Background modeling	47%
Lepton, jet and luminosity	28%
Signal modeling	28%
MC statistical	6%



$t\bar{t}(H\to ZZ/WW/\tau\tau)$

ATLAS-PHYS-PUB-2018-010

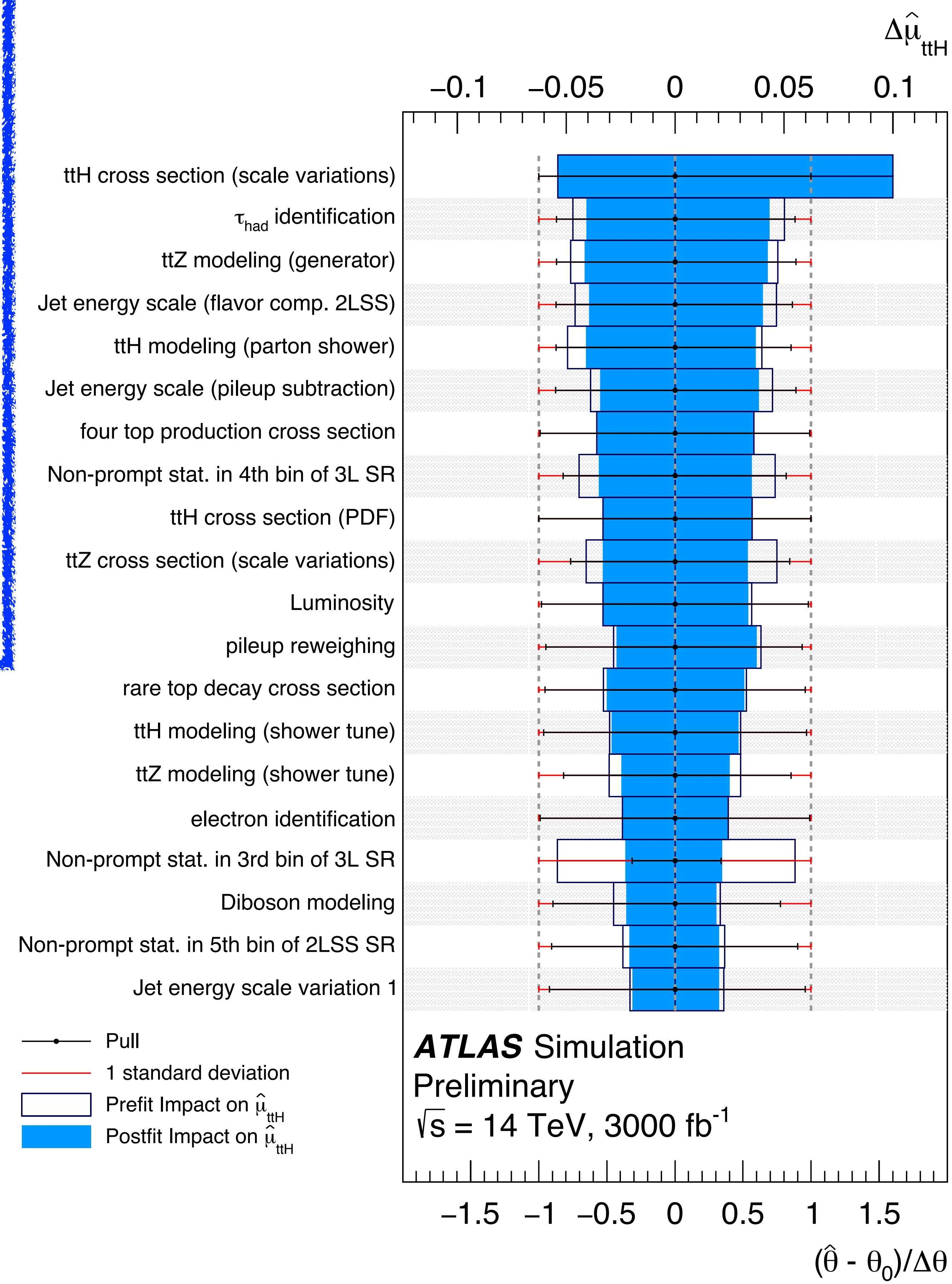


➡ Results extrapolated from Run 2 (36 fb^{-1}) analysis

✓ Largest signal theory uncertainty (QCD/PDF scales) for $\mu=\sigma/\sigma^{SM}$ related to assumed σ^{SM}

✓ Contributions also from signal acceptance (PS modeling) affecting σ in the numerator of μ (dominant for "ttH model acceptance")

✓ Some systematic components specific of the ttH→ML channel (fakes); some others correlated with ttH→γγ (JES, JER + signal systematics)



Higgs rare decays ($H \to \mu\mu$)

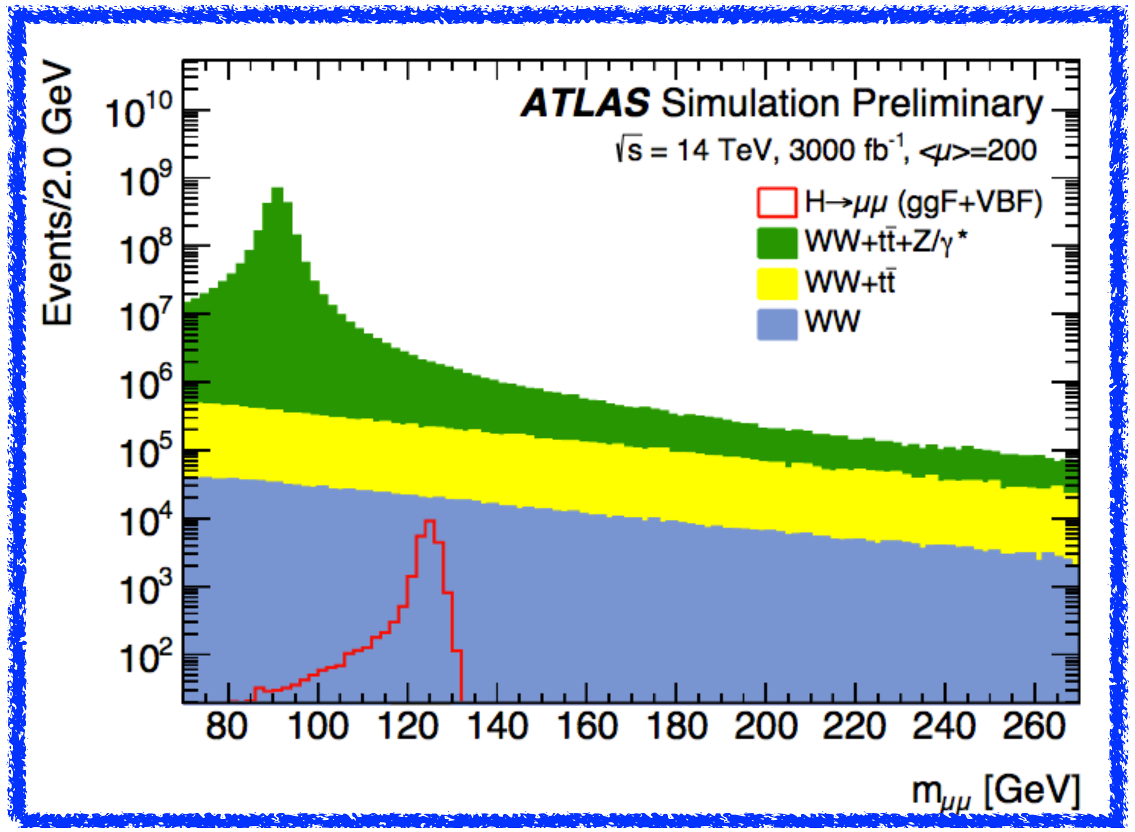
ATL-PHYS-PUB-2018-006

✓ Low BR (0.02%) and significant irreducible background from $Z/\gamma \to \mu\mu$ - high statistics needed

- fundamental to achieve excellent mass resolution in HL-LHC environment
- analysis is carried out with smearing function approach at 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 $m(\mu\mu)$ to estimate signal yields
- smearing function approach validated against full simulation MC



➡ $H \to \mu\mu$ 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

Higgs boson total width

ATL-PHYS-PUB-2015-024

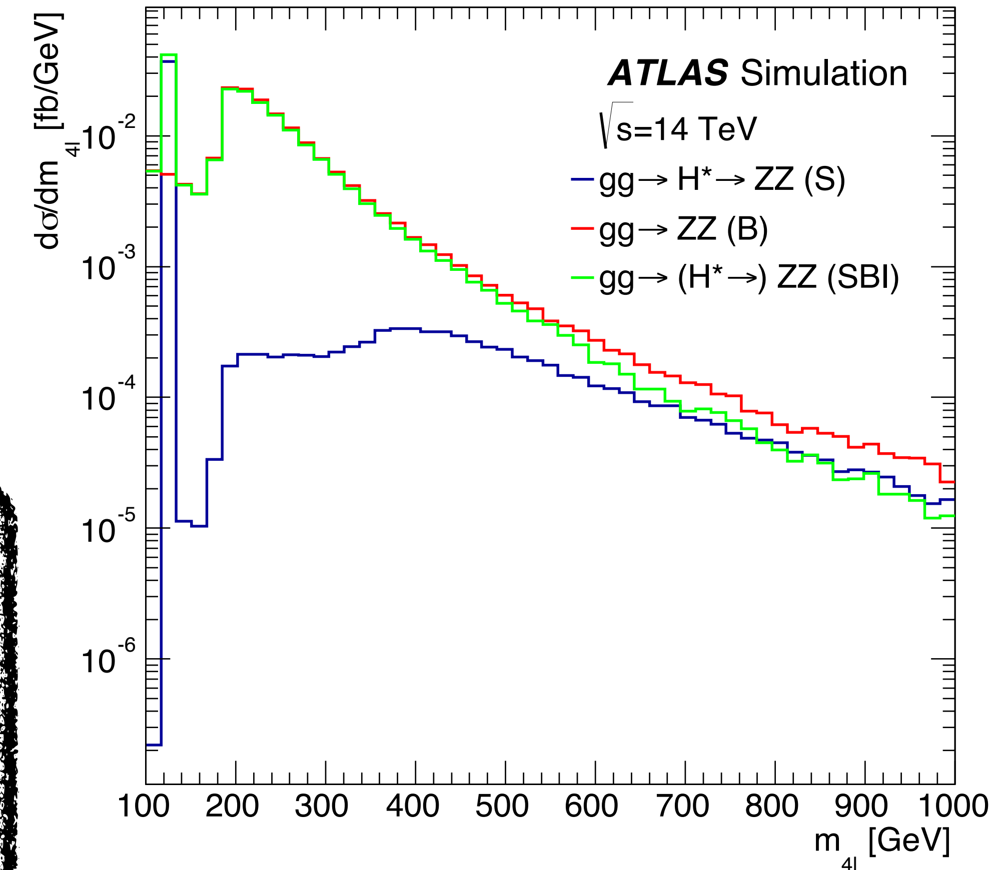
- ✓ Off-shell Higgs production used to indirectly constrain the Higgs boson width, Γ_H
- ✓ Using $H \to ZZ^* \to 4l$ final state with m(4l)>220 GeV to select the high-mass region

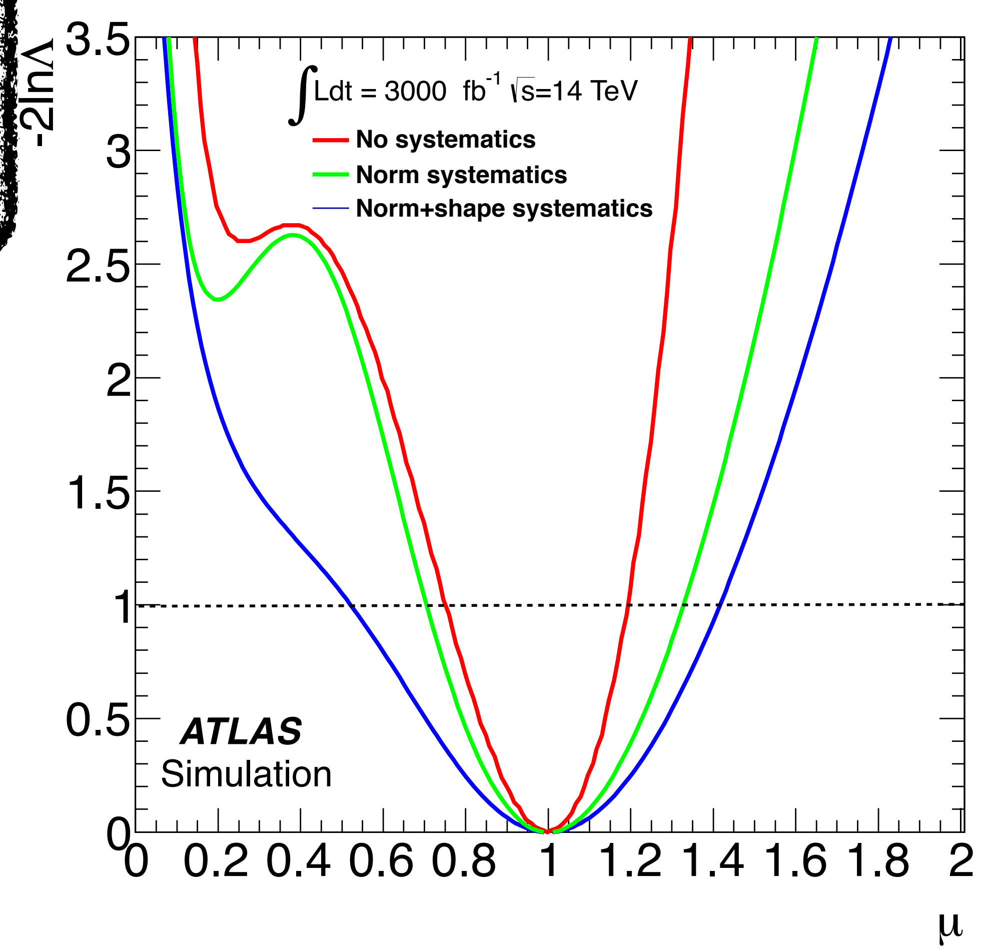
  - m(4l) shape and matrix-element method to discriminate between the Higgs signal and $qq \to ZZ$ / $gg \to ZZ$
  - signal-to-background interference from same gg-initiated initial states
  - same treatment of systematic uncertainties as in Run-1 analysis (theory uncertainty on $gg \to ZZ$ will reduce at HL-LHC)

➡ Off-shell signal strength - μ(off-shell)= $1.00^{+0.43}_{-0.50}$

➡ Combining with the on-shell measurement in the on-peak Higgs region and assuming that the error on the combination is dominated by off-shell - $\Gamma_H = 4.2^{+1.5}_{-2.1}$ MeV

- Run-1 (ATLAS) limit on Γ_H at 22 MeV (ZZ and WW) at 95% CL





Wrapping-up and conclusions

- High-Luminosity LHC will represent an important challenge for the physics program within the Higgs sector of ATLAS and CMS

- Object and particle performances will have to be re-optimized due to the large pile-up contamination and the upgrades of the two experiments

- The Higgs program will largely benefit for the high statistics provided during HL-LHC - a lot of studies from ATLAS and CMS covering several topics

  - ☑ precision measurements on Higgs boson couplings
  - ☑ Higgs width and rare-decays
  - ☑ can extend the present sensitivity and explore Higgs-self couplings with good precision

- ATLAS/CMS Yellow Report project covering Higgs analyses in preparation - expected completion end of the year

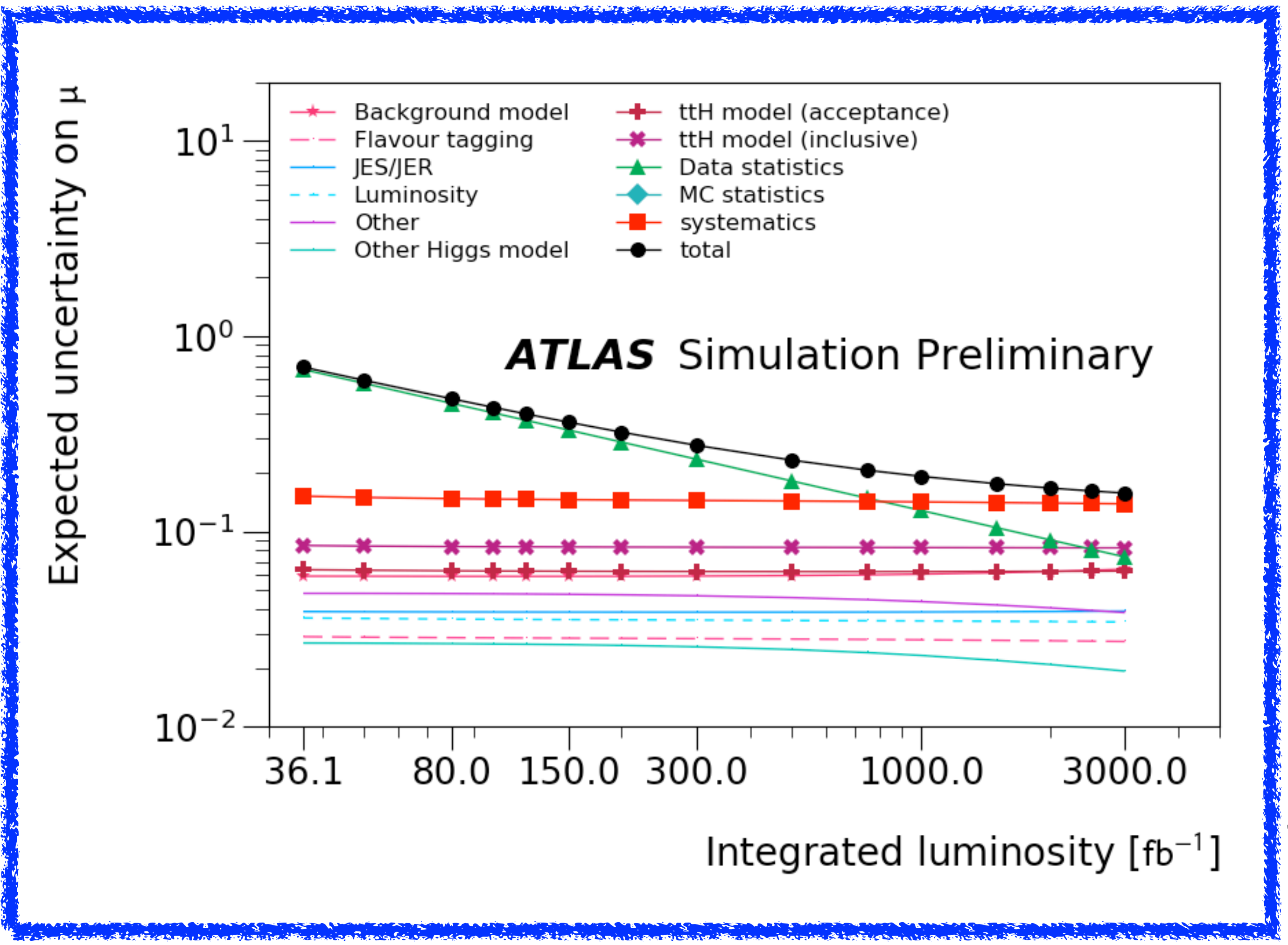
- A lot of activities and ongoing discussions aiming at converging on the YR2018 publication

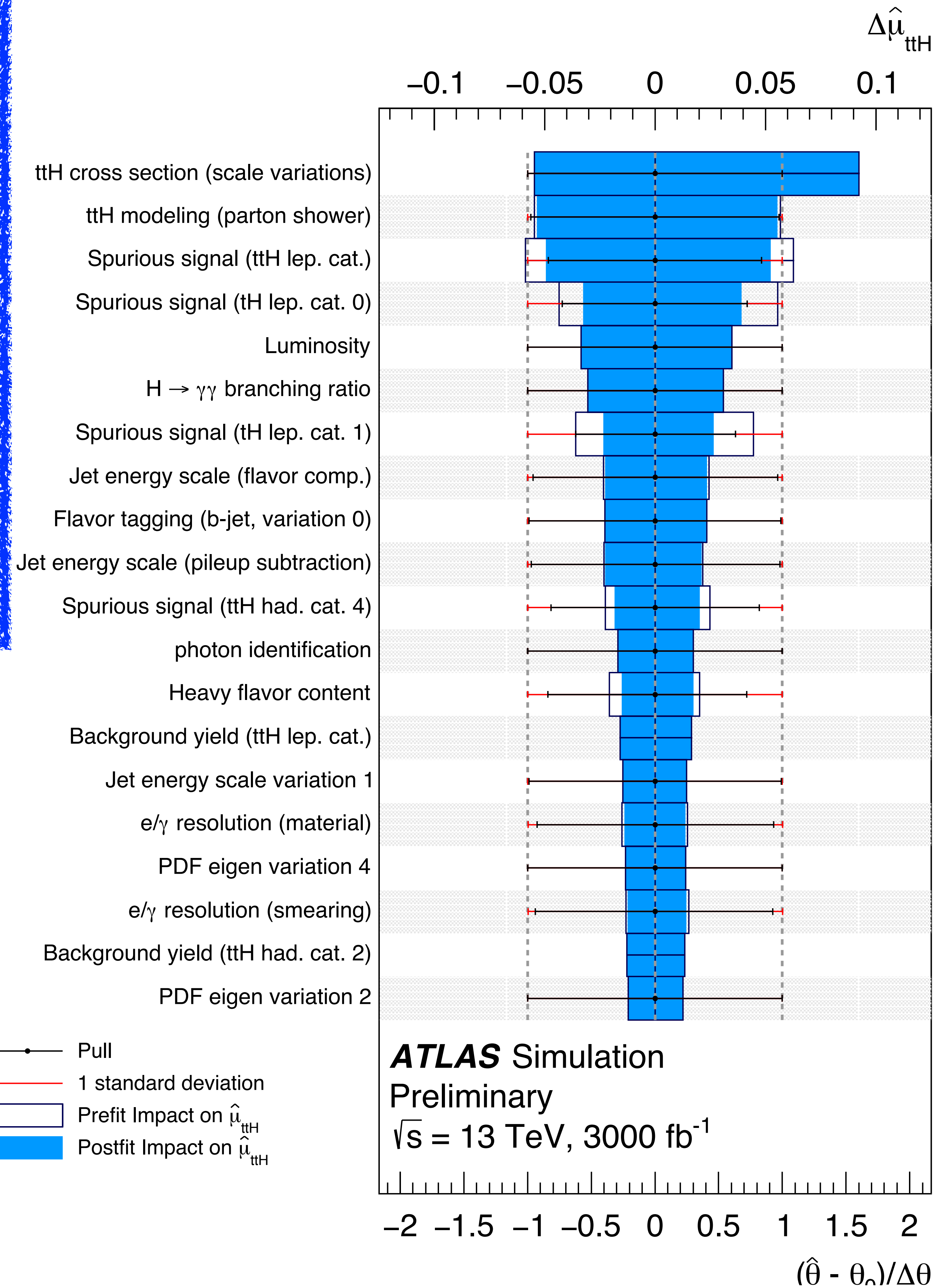
  - ☑ HL-LHC Higgs working group established (https://twiki.cern.ch/twiki/bin/view/LHCPhysics/HLHEWG2)
  - ☑ workshop at CERN in June on the Higgs physics at HL-LHC (https://indico.cern.ch/event/686494/)

Additional slides

$t\bar{t}(H \to \gamma\gamma)$

ATLAS-PHYS-PUB-2018-010





➡ Results extrapolated from Run 2 (36 fb^{-1}) analysis

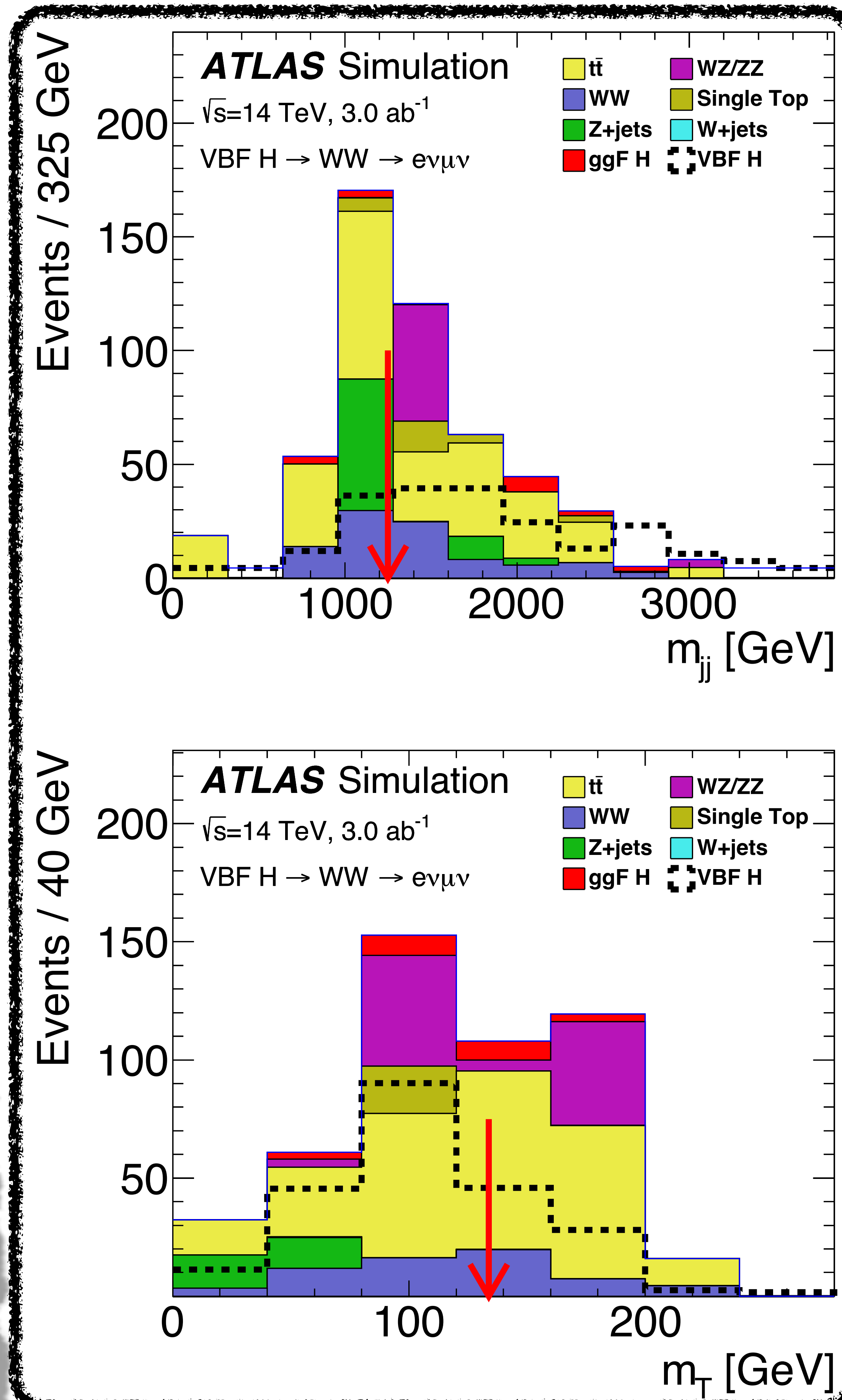
✔ Similar conclusions can be drawn for $ttH \to \gamma\gamma$

- $ttH \to \gamma\gamma$ 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

H→WW→e ν μ ν (VBF production) ATL-PHYS-PUB-2016-018

- ✓ VBF signature is kinematically distinctive - presence of two energetic final state quark jets at very high rapidity gap
- VBF H→WW* production mode very useful to test detector layouts - several objects in the final state
- ✓ Assuming Run I detector performance for e/μ - results for <μ>=200
  - no other jets present between the VBF jets
- ✓ QCD scale on the VBF jets dominates the systematic uncertainties - theoretical computation will improve with time
- ➡ Results will be superseded by Run 2 extrapolated - 6% stat-only on Δμ/μ from Run 2 extrapolation

Scoping scenario	Δ_μ			Significance (σ)		
Signal unc.	Full	1/2	None	Full	1/2	None
Reference	0.20	0.16	0.14	5.7	7.1	8.0
Middle	0.25	0.21	0.20	4.4	5.2	5.4
Low	0.39	0.32	0.30	2.7	3.3	3.5



Vector boson fusion - H→ZZ→4l

ATL-PHYS-PUB-2016-008

✓ Vector boson fusion (VBF) signature is kinematically highly distinctive

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

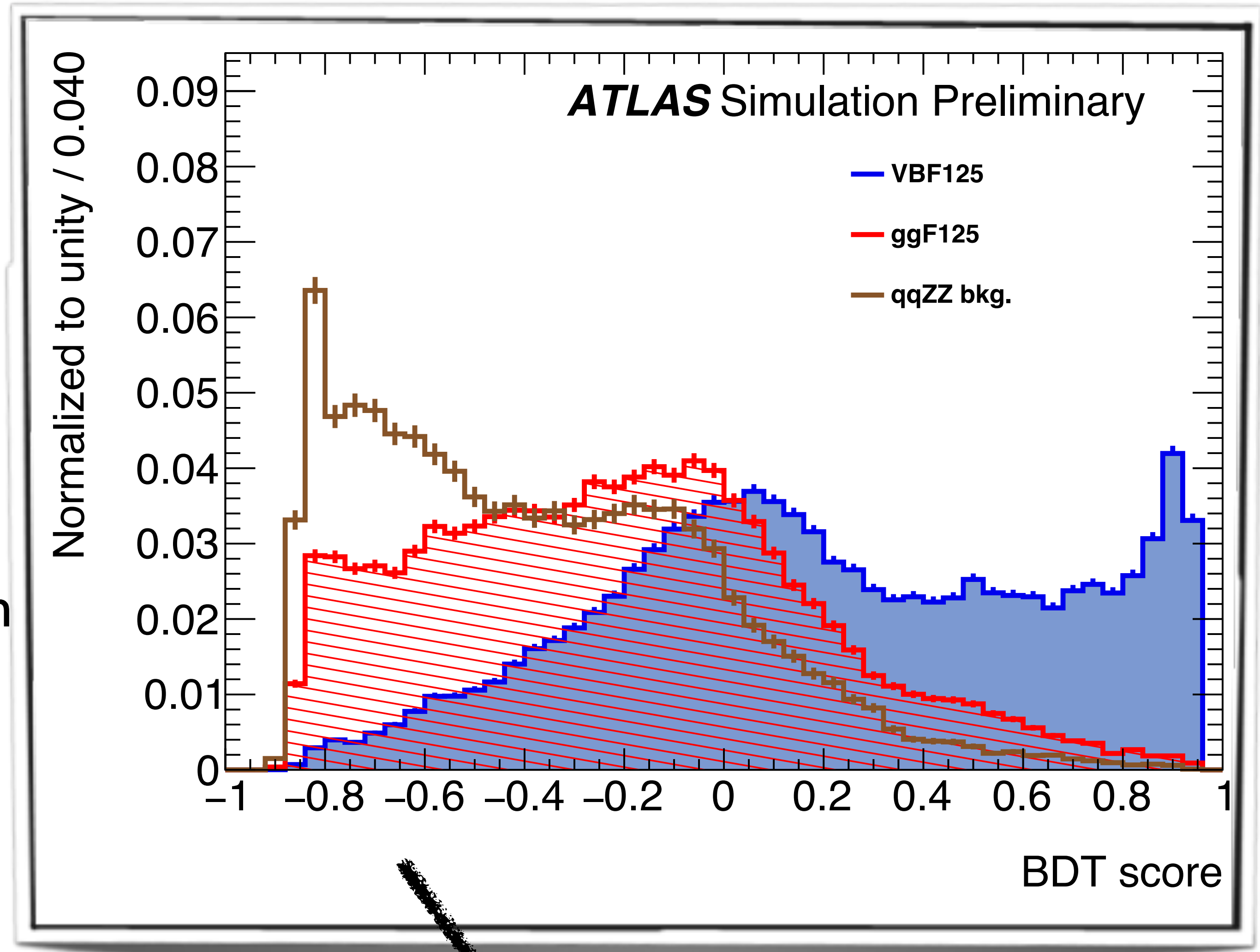
✓ Assuming Run 1 detector performance for e/μ - results for <μ>=200

- Selection requirements: same selection as in Run 1 VBF H→ZZ analysis + m(jj)>130 GeV

✓ Multivariate approach employed to separate VBF from gluon-fusion + 2 jets Higgs production and qq→ZZ

- definition of the signal region exploited by a cut on BDT
- QCD scale variation systematic uncertainty included

➡ Extrapolation from Run 2 analysis VBF H→ZZ gives 9% uncertainty on Δμ/μ (stat-only)



<μ>=200, stat+sys	Stat+sys
Significance	7.2
Δμ/μ	18% (15% stat-only)

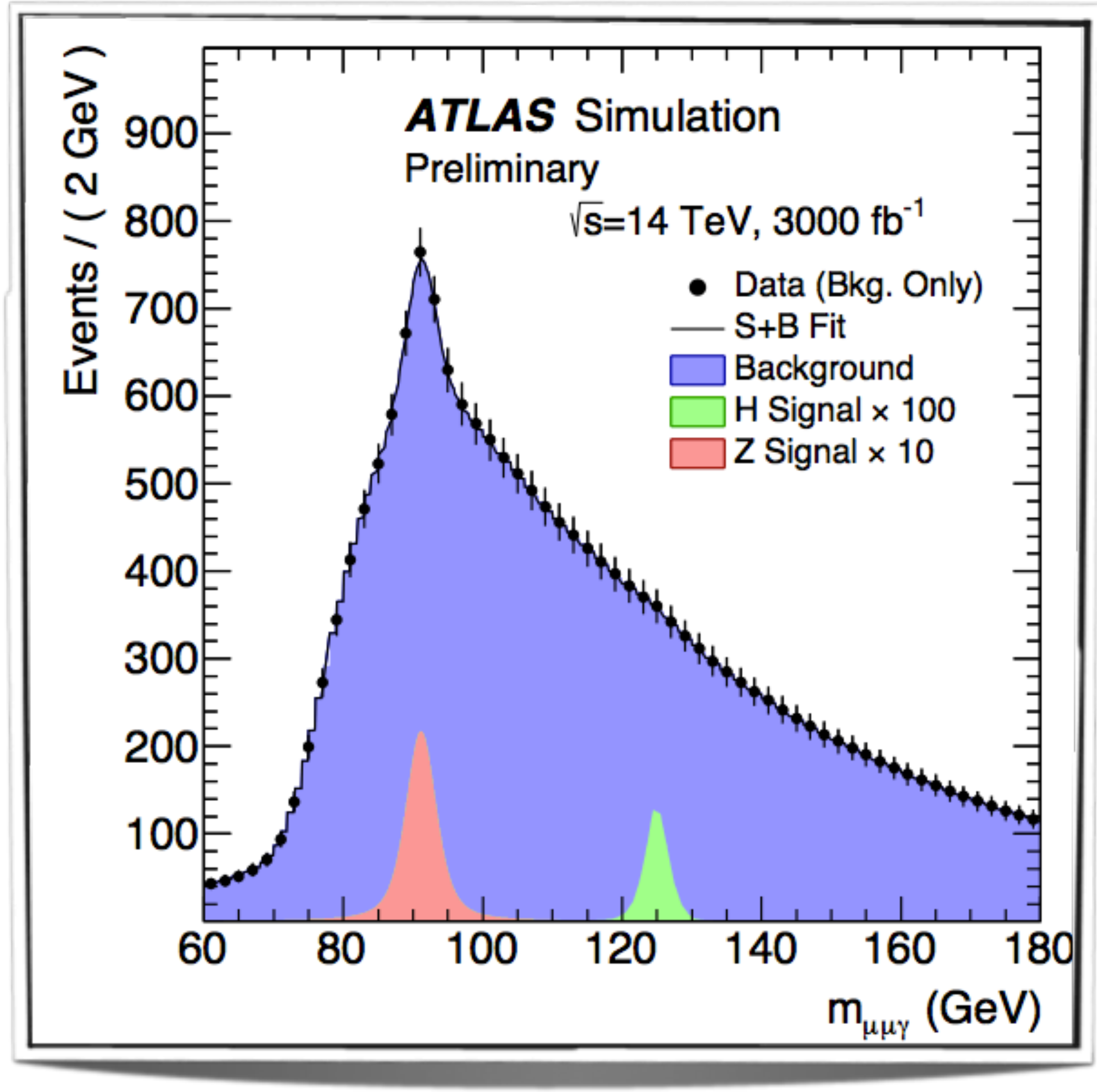
Impact of increasing jet tracking coverage in the forward region (η=2.4→4) improves the expected precision on Δμ/μ from 22% to 15%

Higgs rare decays (H->J/ψγ)

ATL-PHYS-PUB-2015-043

- ✓ $H\to J/\Psi\,(\to\mu\mu)\,\gamma$ - using Run I detector performance and <μ>=140
  - sensitivity to the magnitude c and b quark couplings
- ✓ $J/\Psi\to\mu\mu$ decays - opposite sign muons with pT>3 GeV $|\eta|<2.5$ consistent with common vertex
  - Dimuon invariant mass compatible with J/Ψ
- ✓ Multivariate analysis employed using pT (μμ), pT (γ) and μ/γ isolation
- ✓ Theory and detector uncertainties (lepton/photon reconstruction) kept as Run I analysis
- ✓ Uncertainties on the background shape (conservative 5%) expected to be reduced with large data stats at HL-LHC

➡ BR $(H\to J/\Psi\,\gamma) < (44^{+19}_{-22}\cdot 10^{-6})$ @ 95% CL where SM expectation $2.9\cdot 10^{-6}$



Vector boson fusion - H→ZZ→4l

ATL-PHYS-PUB-2016-008

Statistical uncertainty only					
Scoping scenario	VBF + $2j$ events	ggF + $2j$ events	$qqZZ + 2j$ events	Z_0	$\Delta\mu/\mu$
Reference	192 (168)	287 (140)	39 (16)	10.2	0.152
Middle	218 (167)	454 (155)	69 (15)	9.5	0.157
Low	259 (159)	803 (182)	124 (21)	8.6	0.165
Statistical uncertainty + QCD scale var. uncertainty (S-T method)					
Scoping scenario	VBF + $2j$ events	ggF + $2j$ events	$qqZZ + 2j$ events	Z_0	$\Delta\mu/\mu$
Reference	192	287	39	7.2	0.182
Middle	218	454	69	6.9	0.192
Low	259	803	124	6.2	0.208

Reference scenarios for scoping document

ATL-PHYS-PUB-2016-018

Table 1: Brief Description of the Detector Scenarios

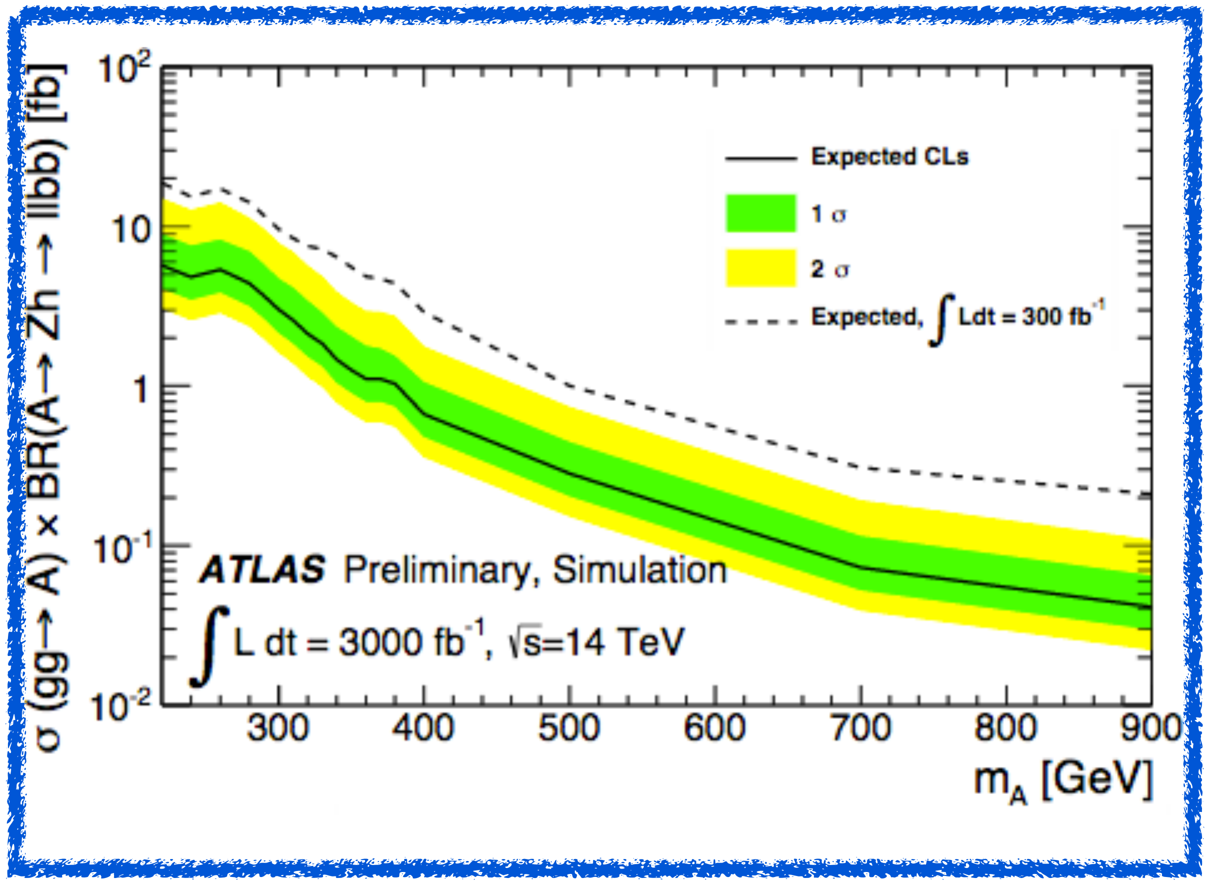
Name	Cost (MCHF)	Tracking η coverage	Quality of b-jet identif.
Reference	275	4.0	Excellent
Middle	230	3.2	Good
Low	200	2.7	Satisfactory

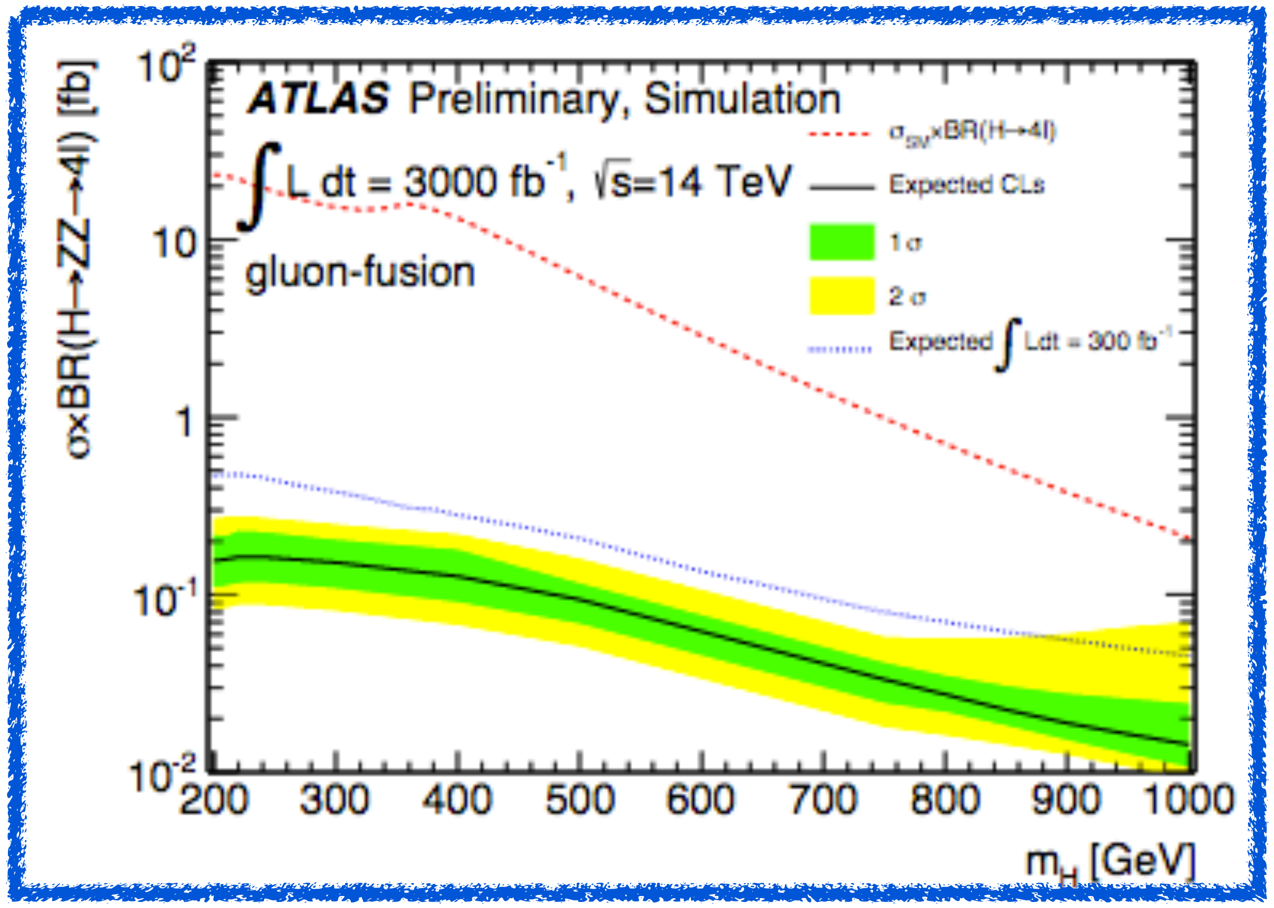
Search for additional Higgs states

✓ HL-LHC also beneficial for studies on two-Higgs-doublet models with 5 Higgs boson observables

ATL-PHYS-PUB-2014-016

- $A \to Zh$
  - $Zh \to llbb$ final state considered in the study (+30% systematic uncertainties included in the projection) - dominant decay mode for $m_Z+m_H<m_A<2m_{top}$ and for low $\tan\beta$
- $H,A \to \mu\mu$
  - only statistical uncertainties included in the projection
- Heavy $H \to ZZ \to 4l$
  - large improvement at HL-LHC wrt SM Higgs boson production



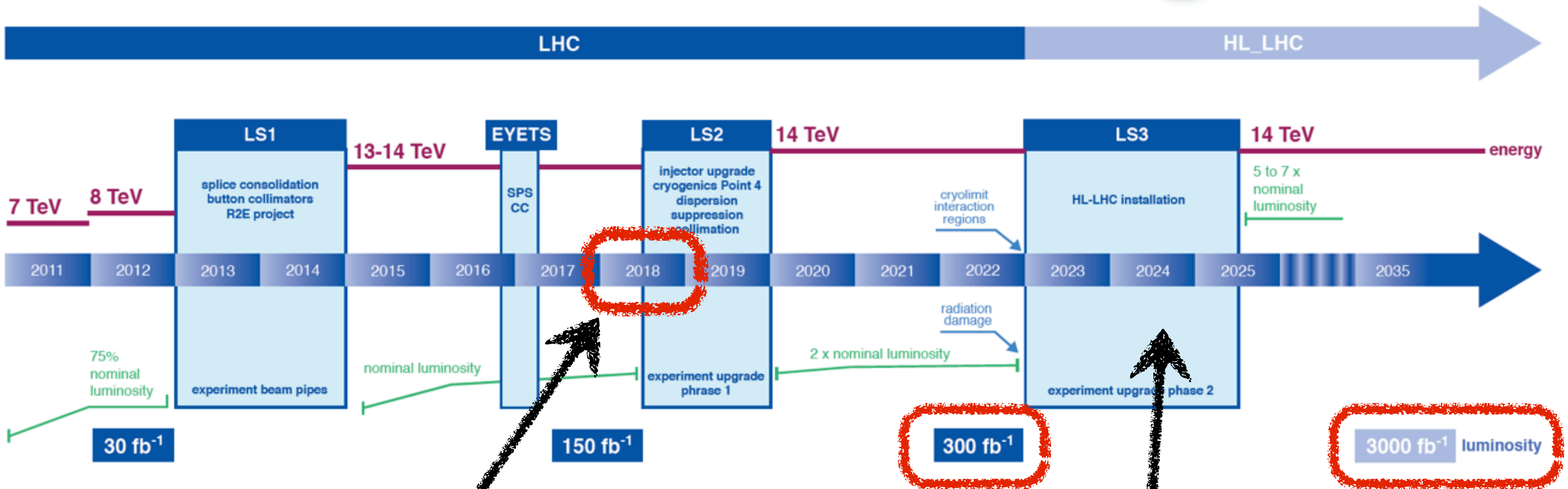


VH->cc (systematic uncertainties)

Source of uncertainty	Change in limit (%)
Background shape	+37%
c-tagging efficiency	+34%
Jet energy scale and resolution	+18%
Lepton reconstruction and identification	+12%

The High-Luminosity LHC program

LHC / HL-LHC Plan

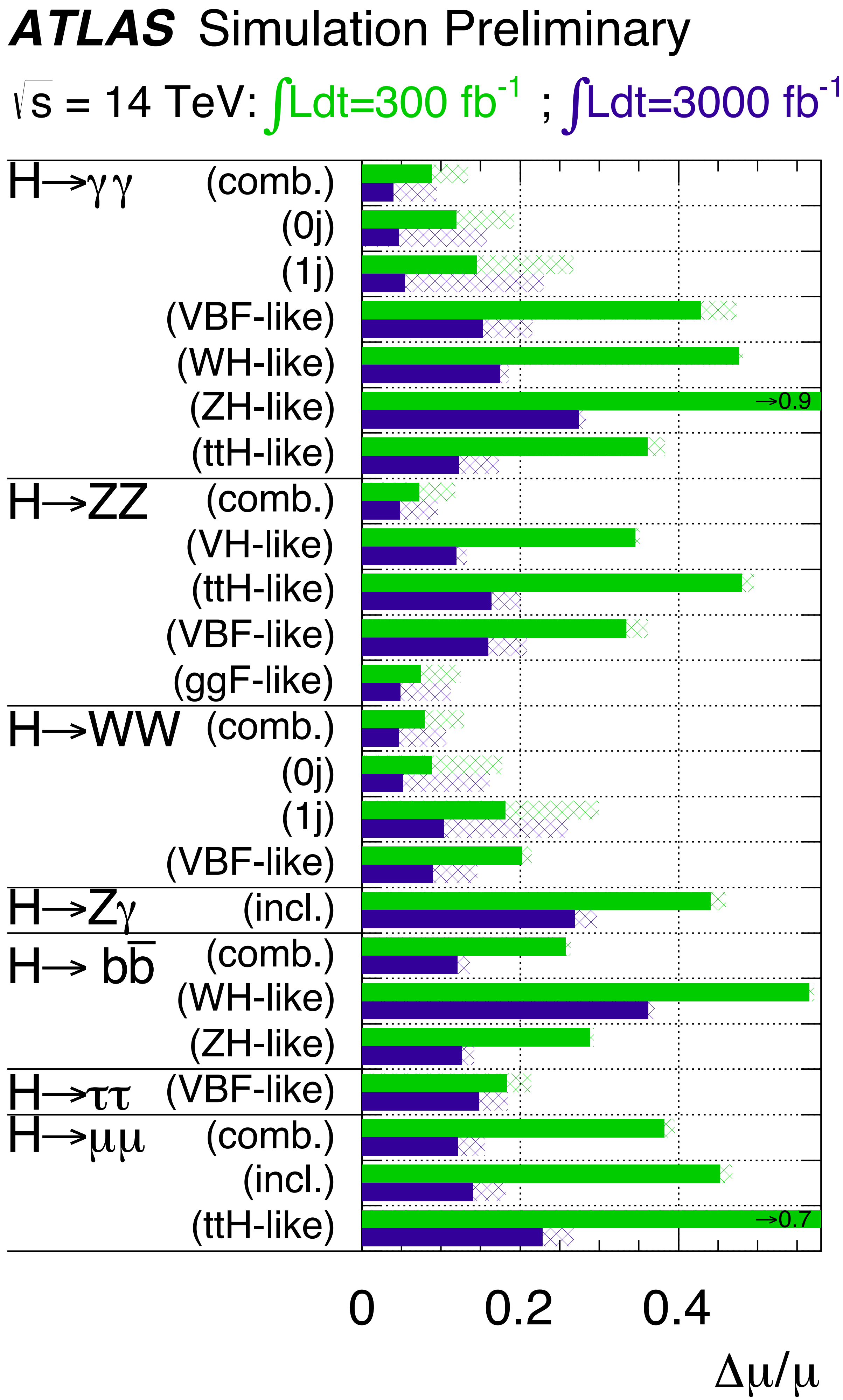


Now ($\sqrt{s}$=13 TeV), <μ>~38 (2017 data-taking)

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



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