Prospects for Higgs physics at High-Luminosity LHC

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on behalf of the ATLAS and the CMS collaborations

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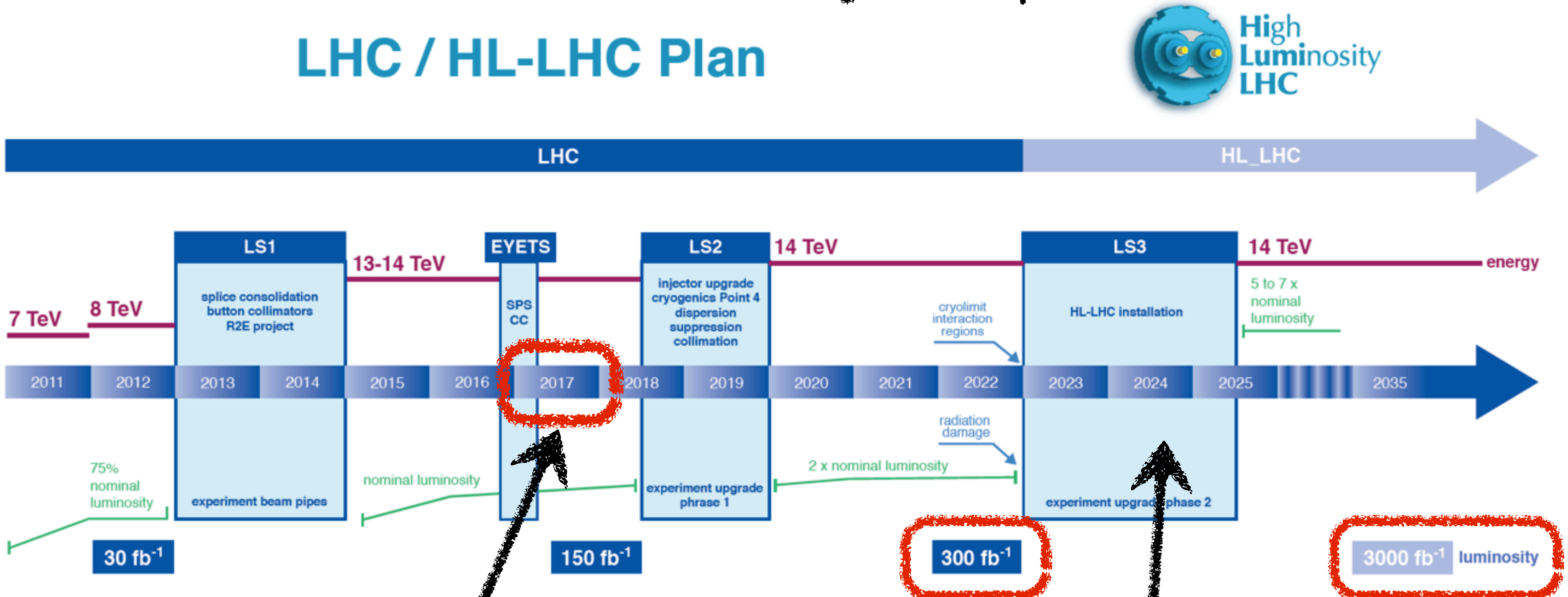
Outline of the talk

- The High-Luminosity LHC (HL-LHC) program
- The ATLAS and CMS upgrade programs
  - HL-LHC environment and object performance
- The analysis procedure and treatment of the systematic uncertainties for studies on Higgs measurements
- Higgs analysis prospects
  - Higgs boson couplings, differential measurements, spin and parity
  - Anomalous couplings and searches for additional Higgs states
  - Rare decays ($H \to J/\Psi\ \gamma$, $H \to \mu\mu$)
  - Studies on vector boson fusion Higgs production in ZZ and WW channel
  - Extraction of the Higgs boson width
- Wrapping-up and conclusions

The High-Luminosity LHC program



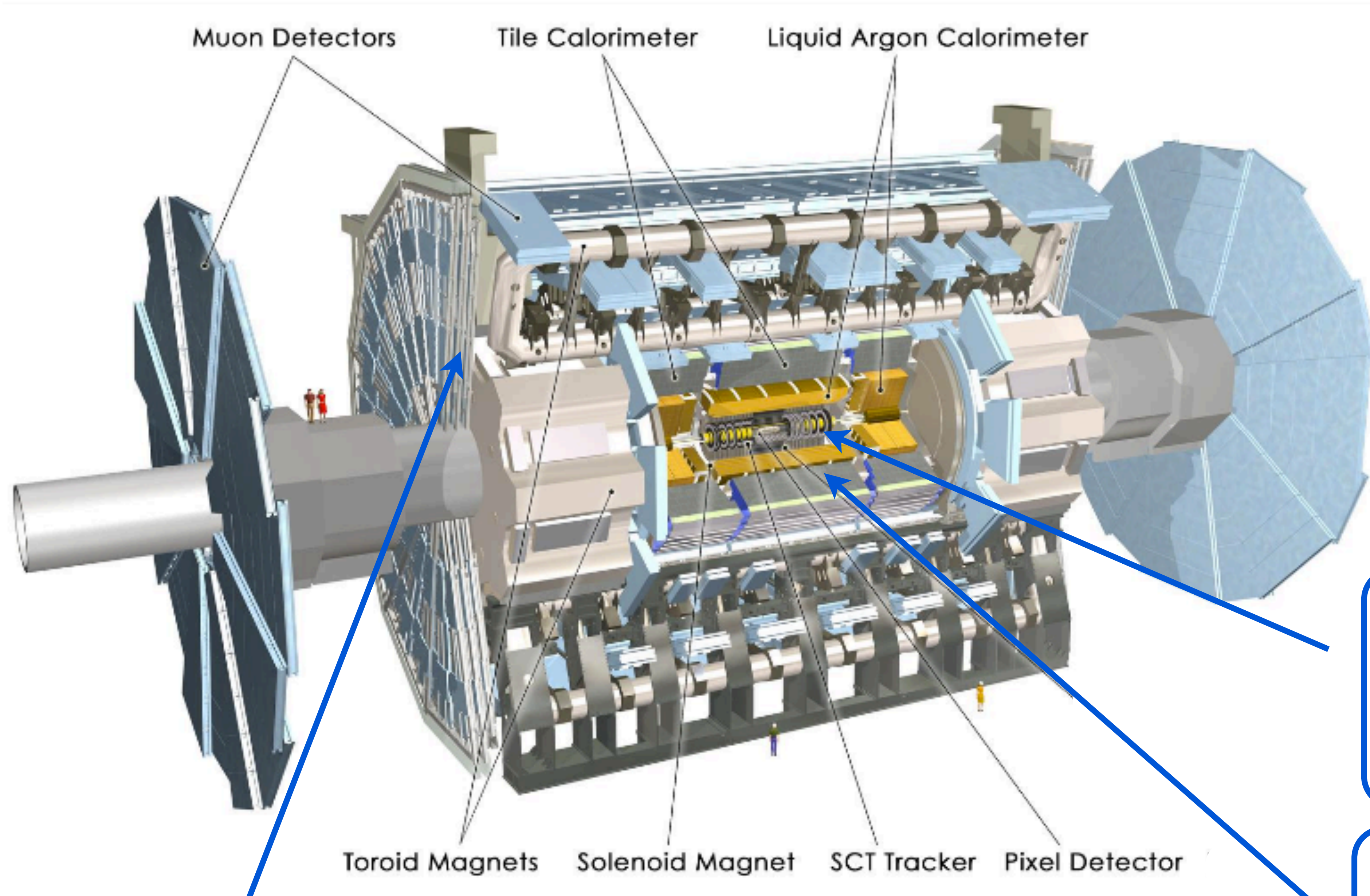
Now ($\sqrt{s}$=13 TeV), $\langle\mu\rangle$~38 (2017 data-taking)

Phase-II Atlas and CMS Upgrade

	Peak luminosity ($cm^{-2}\ s^{-1}$)	μ (pile-up)
Current	$1.3 \cdot 10^{34}$	25
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

A sketch of the ATLAS Phase-II Upgrade



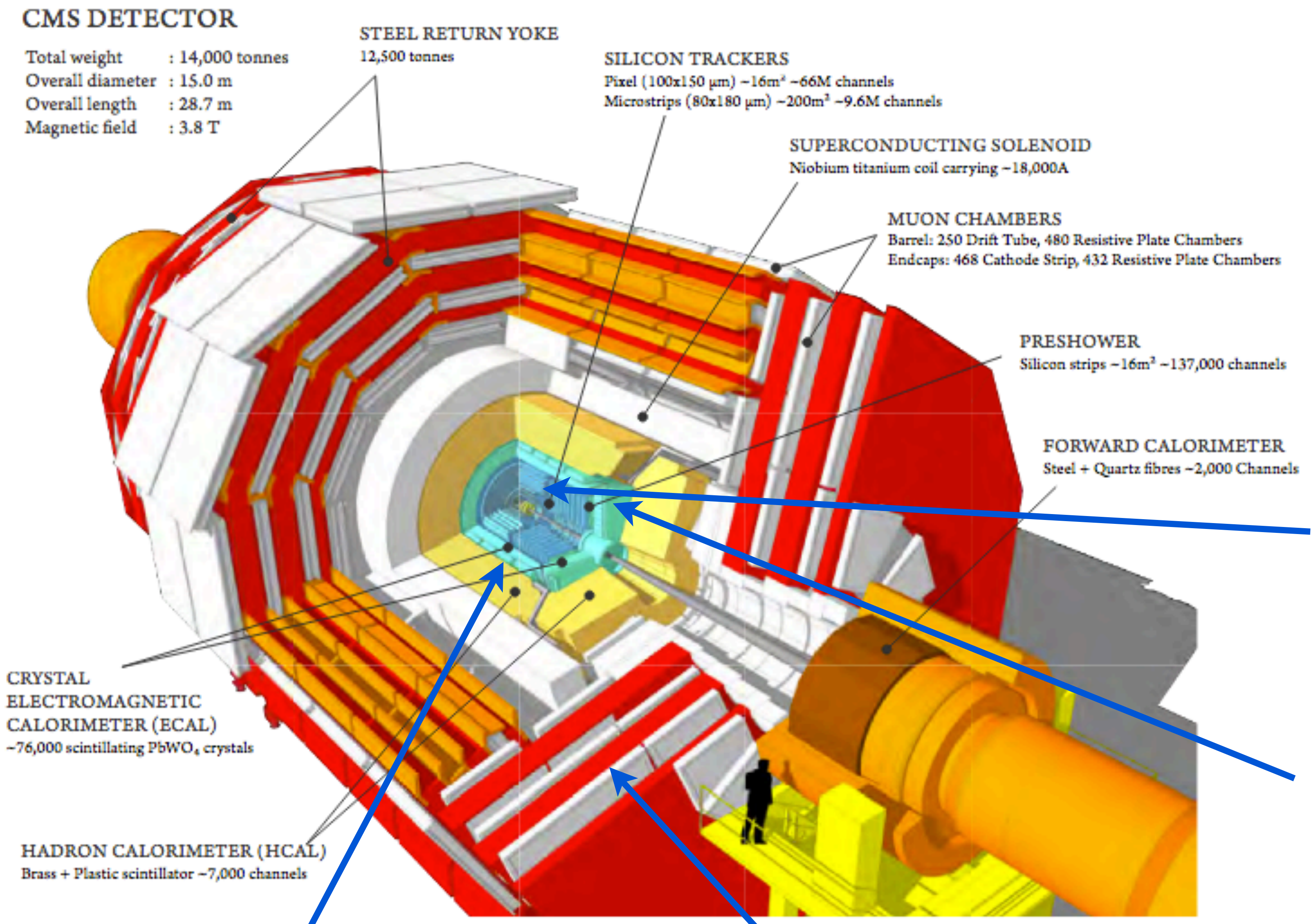
- Upgrade trigger system
  - track trigger
  - modification of the data acquisition system to deal with the high rate at HL-LHC
- Inner tracker (all-silicon, pixel and strip sensors) extended to $|\eta|=4$
- Upgrade electronics for Liquid-Argon electromagnetic and for Tile hadronic calorimeter
- New 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 EXPERIMENT

A sketch of the CMS Phase-II Upgrade



- Upgrade trigger system
  - L1 track trigger, improved rate capability and extension of the L1 latency

- Silicon inner tracker with extended coverage to $|\eta|=4$

- High granularity calorimeters using silicon technology

- Upgrade barrel calorimeter
  - electronics and photodetectors

- Muon system coverage in $1.5<|\eta|<2.5$ improved and extension to $|\eta|=3.0$

CERN-LHCC-2015-019

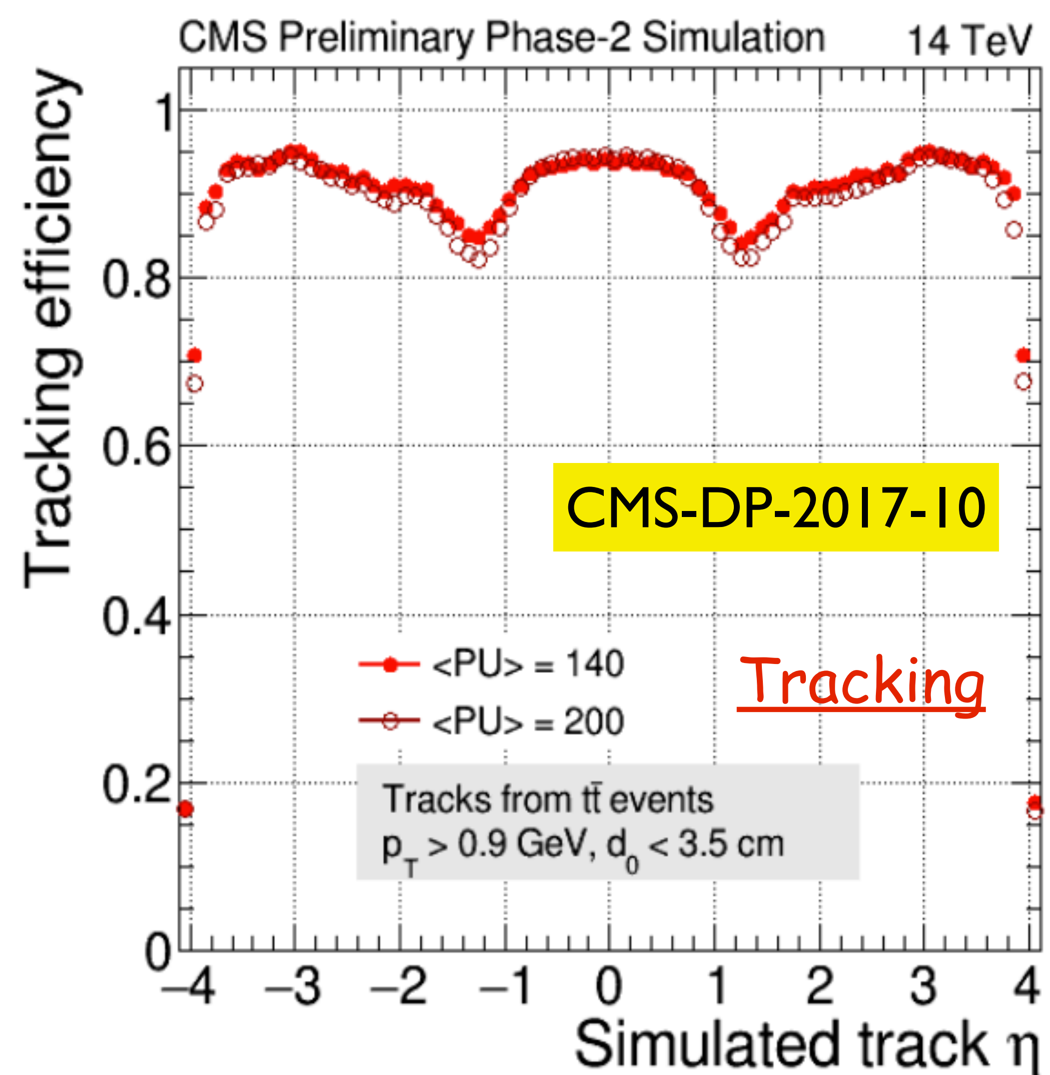
HL-LHC environment and object performance

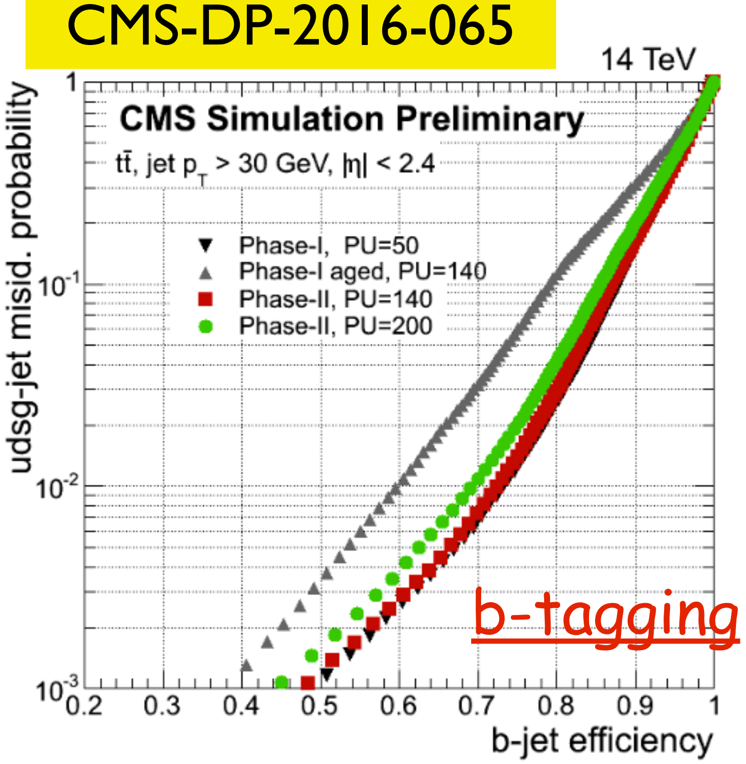
✓ Very challenging environment at HL-LHC → detector requirements to maximize benefits from high luminosity

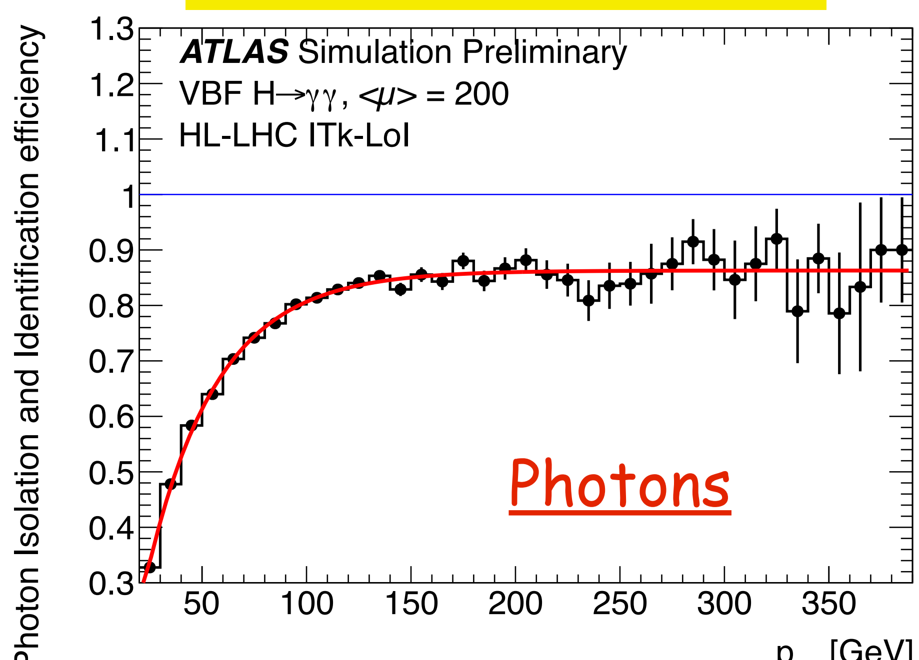
- large integrated radiation dose
- mitigation of pile-up effects
- sustain large event rate with more sophisticated trigger and data acquisition systems

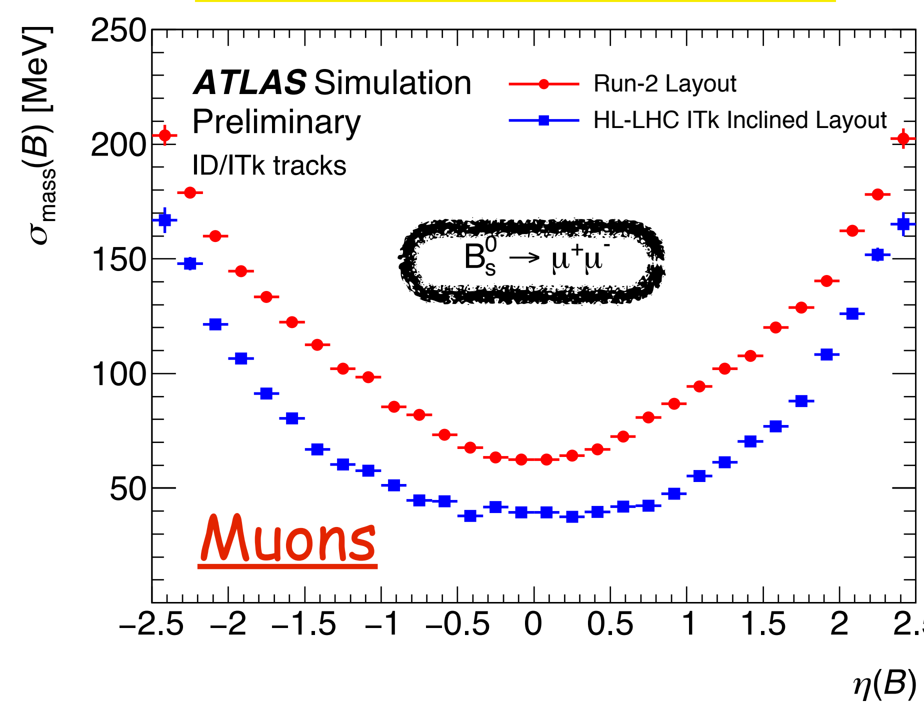
✓ Important to keep good control over performance of physics objects (identification and reconstruction, background rejection)

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









Analysis strategy and treatment of the uncertainties

CMS

✓ CMS uses extrapolation of current analyses accomplished with 2015 or 2016 dataset at 13 TeV

✓ Several scenarios for systematic uncertainties (results also provided for statistics-only scenario)

- ➡ S1: systematic uncertainties kept constant with (S1+) or without (S1) presence of high pile-up and detector improvements
- ➡ S2: systematic uncertainties are scaled wrt Run 2 analyses (theory→×1/2, experimental→ $\propto$ 1/L

ATLAS EXPERIMENT

✓ 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

✓ Some results rely on Run1/Run 2 results being extrapolated to HL-LHC and same detector performance and analysis strategy

✓ Pile-up included in the simulation ($\langle\mu\rangle$=140 and $\langle\mu\rangle$=200)

➡ Theoretical systematic uncertainties: same as Run 1/ Run 2 analysis, reduced by 1/2 or absent

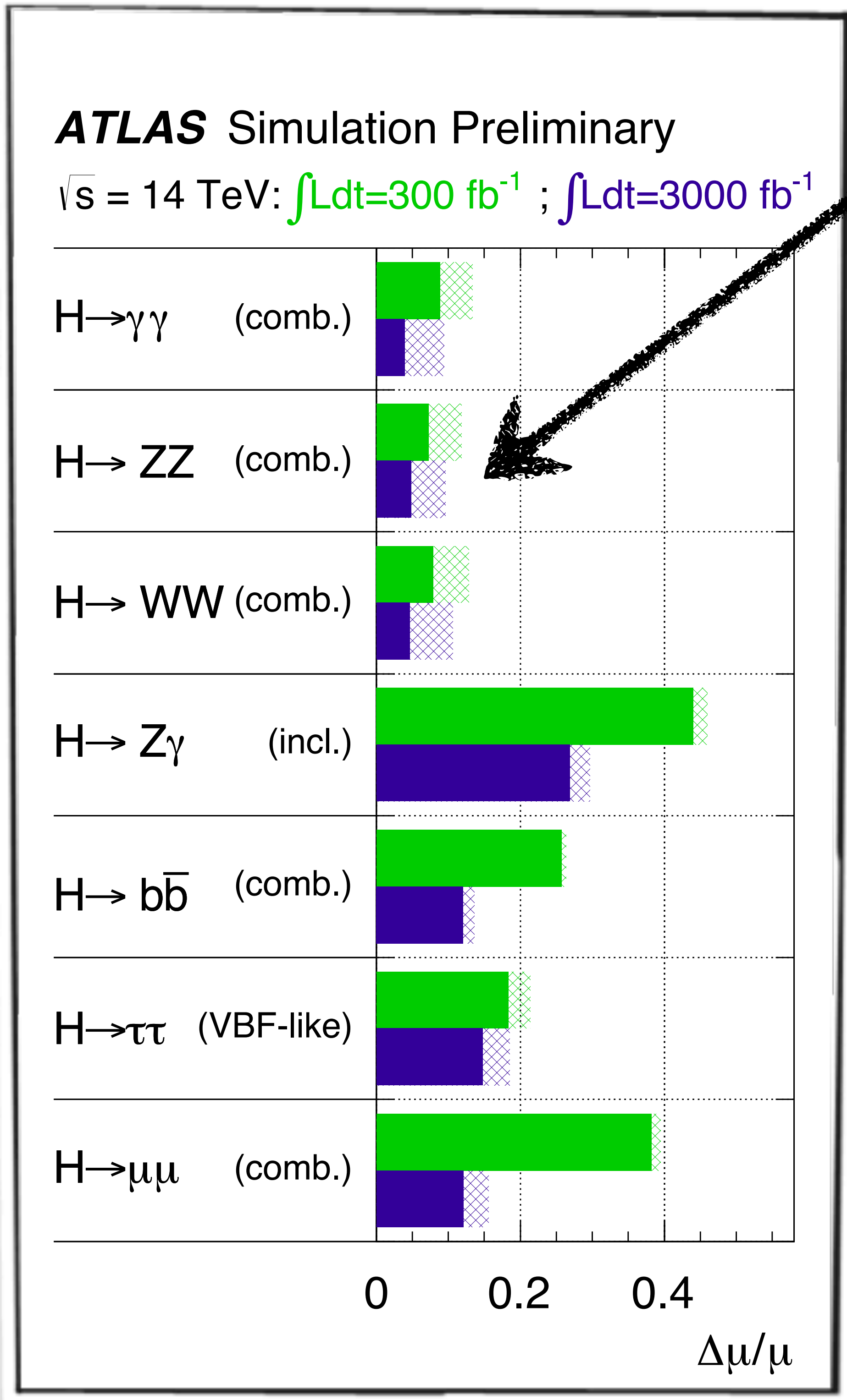
➡ Experimental uncertainties: scaled wrt current analyses in Run 1/Run 2

CMS-PAS-FTR-16-002

Higgs boson couplings

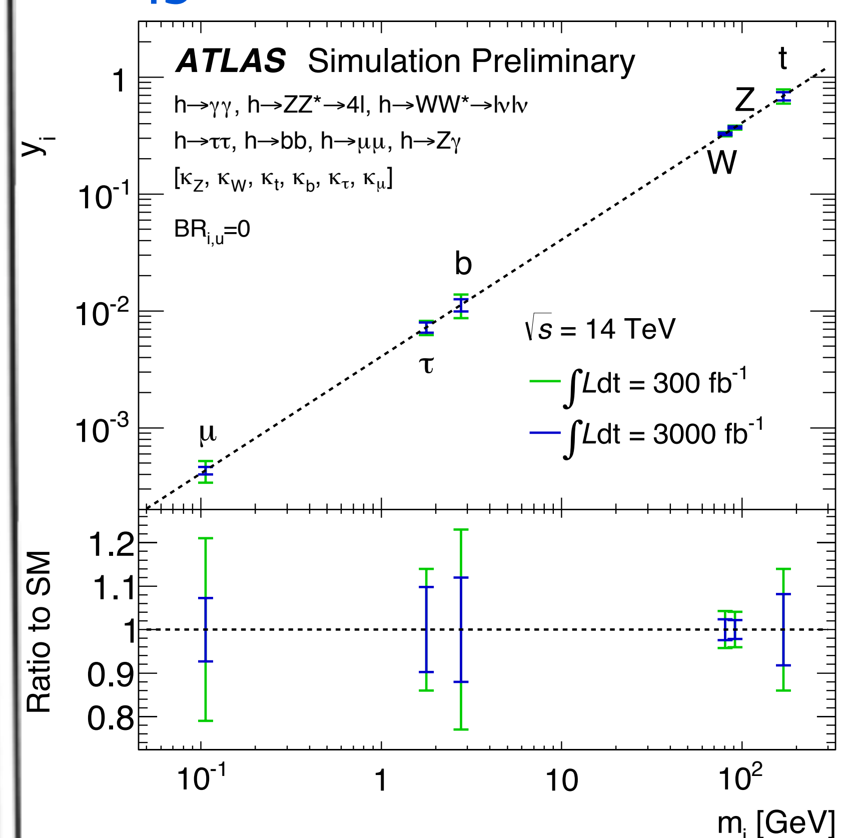
ATL-PHYS-PUB-2014-016

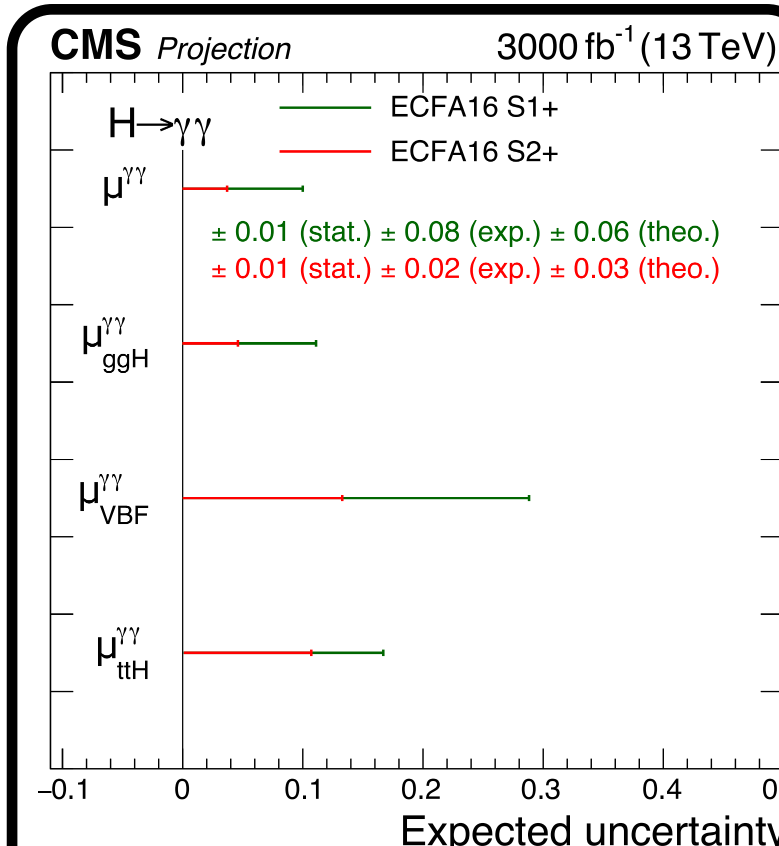
- ✓ ATLAS performs an extrapolation from Run 1 analysis using $\langle\mu\rangle=140$
- ✓ CMS makes projections for different Higgs couplings in production using the $H\rightarrow\gamma\gamma$ and $H\rightarrow ZZ\rightarrow 4l$ decay channels



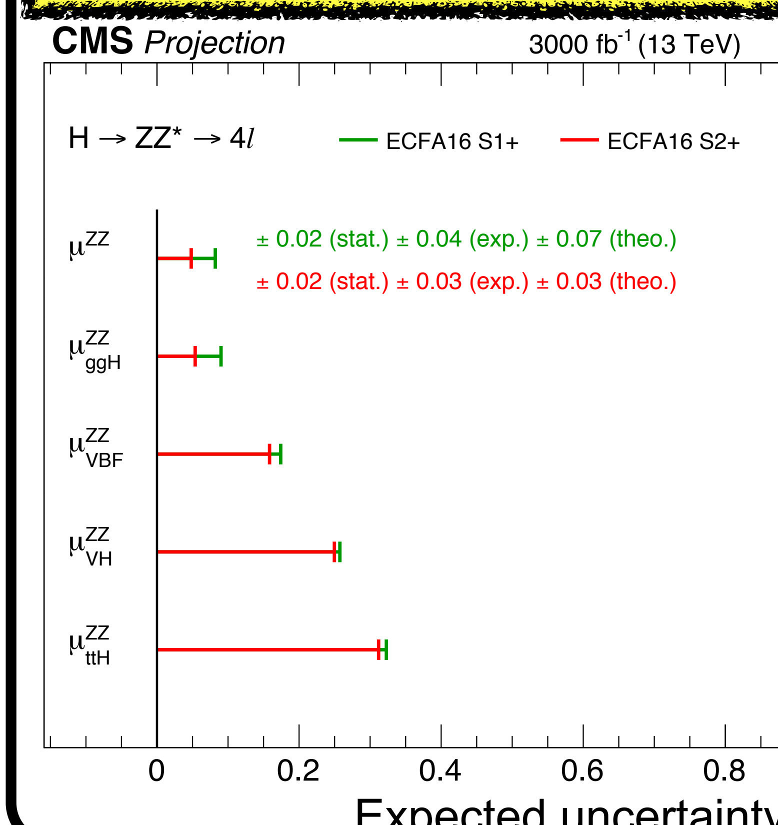
Run 1: $\Delta\mu/\mu$ ($H\rightarrow\gamma\gamma$)=23%, $\Delta\mu/\mu$ ($H\rightarrow ZZ$)=24%, $\Delta\mu/\mu$ ($H\rightarrow WW$)=33%

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



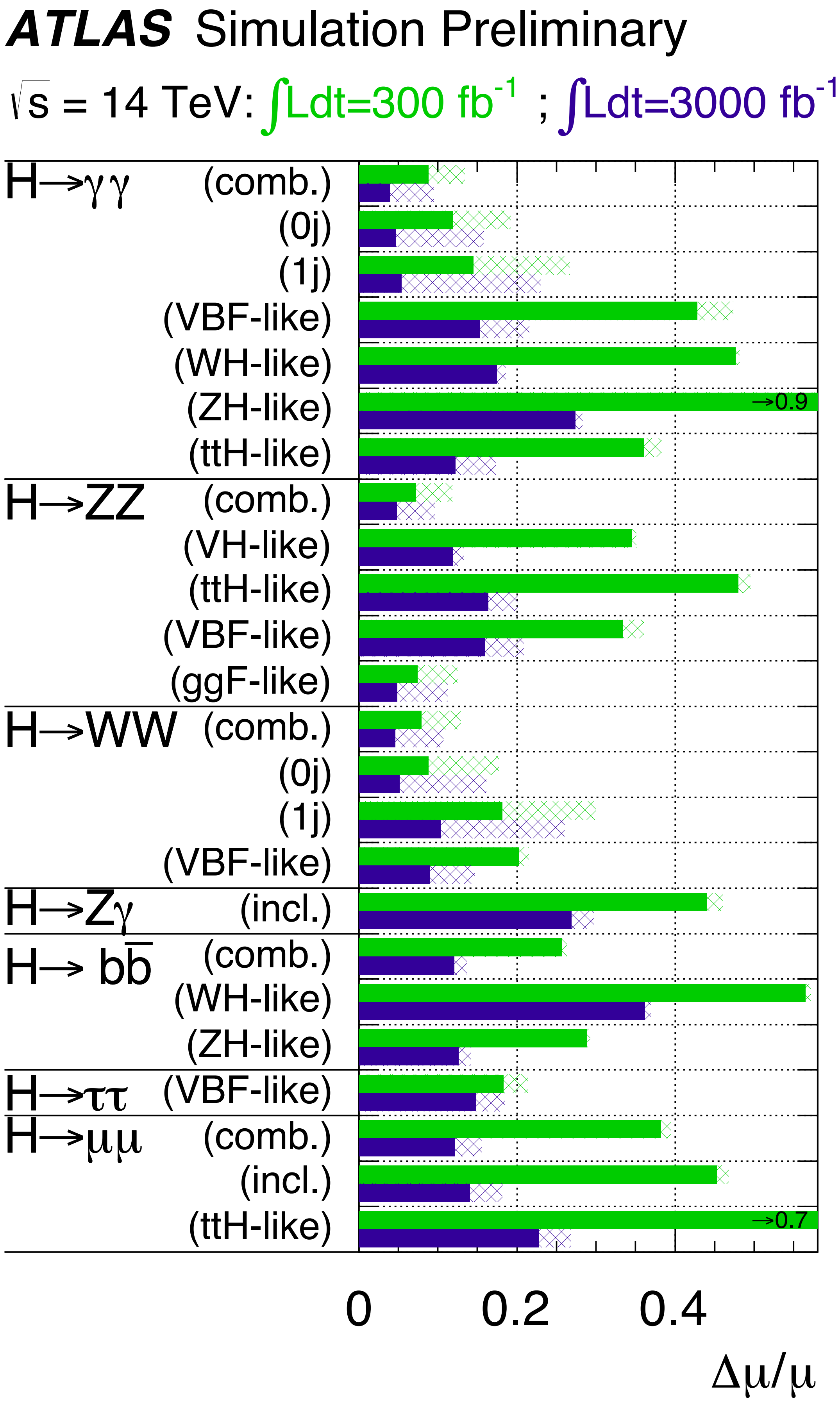


Systematic uncertainties in the present and in the HL-LHC conditions

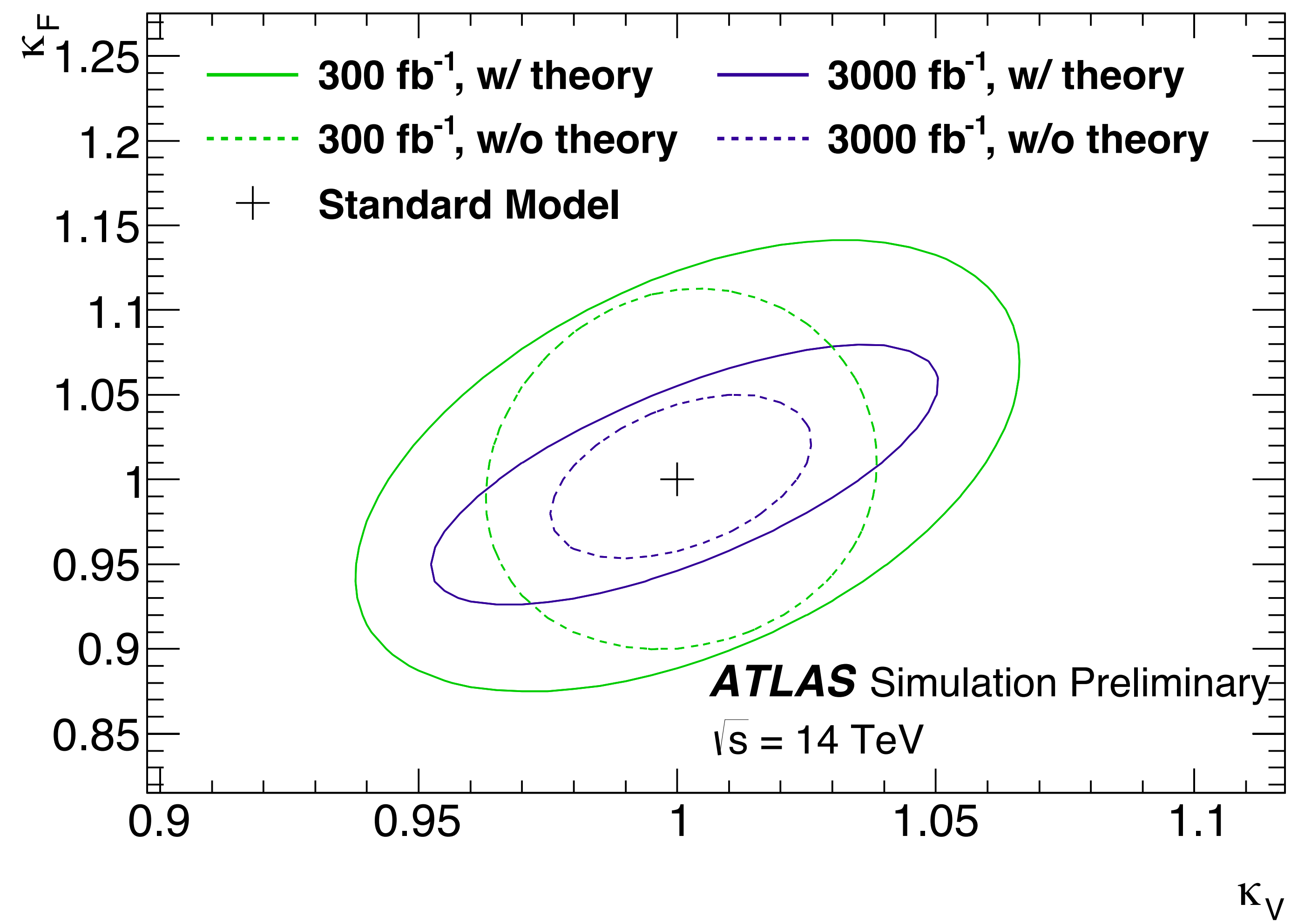


Higgs boson couplings (2)

ATL-PHYS-PUB-2014-016



- Precision on the signal strength parameter for the different Higgs production modes
- 68% CL expected likelihood contours for couplings to fermions and bosons at 14 TeV for an assumed integrated luminosity of 300 fb^{-1} and 3000 fb^{-1}



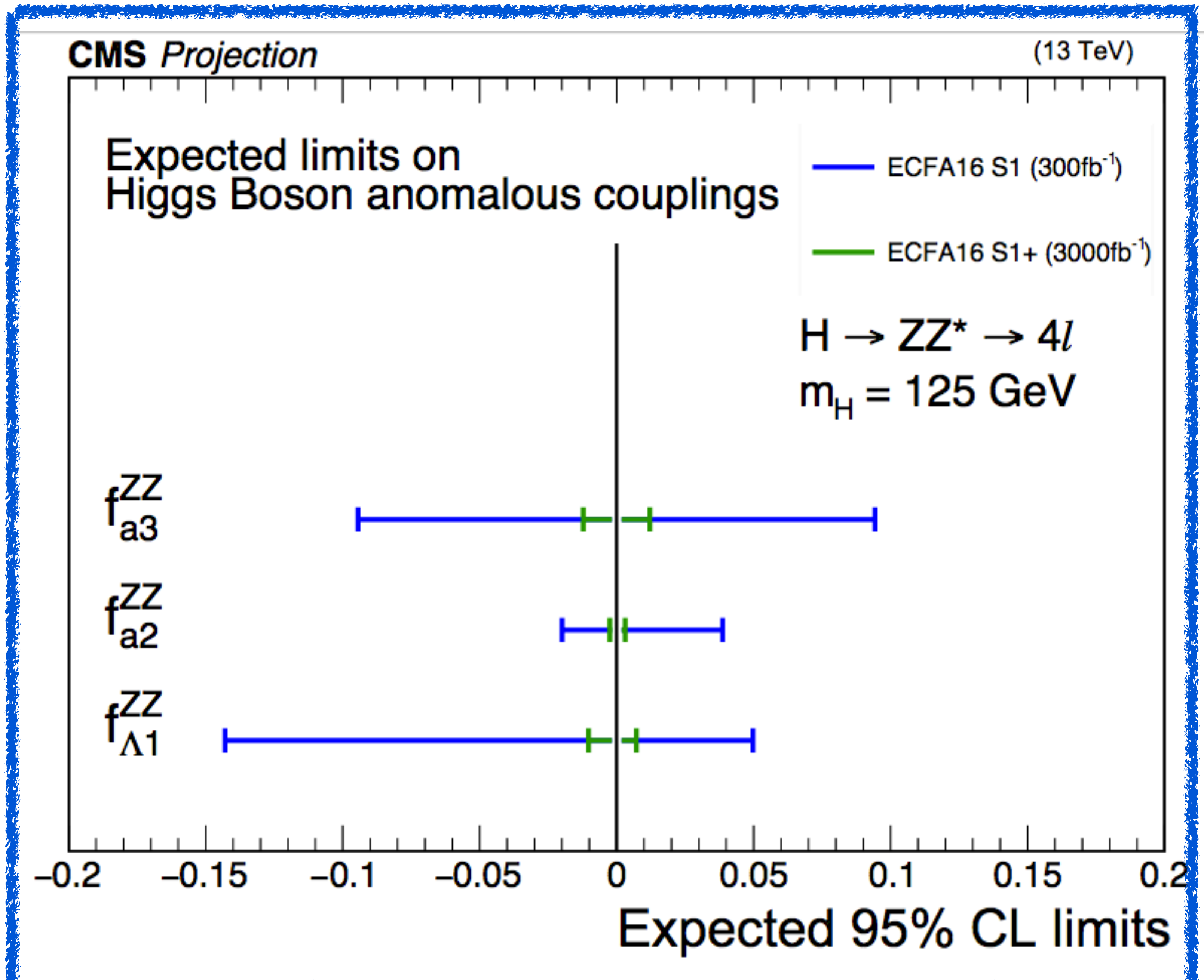
Higgs boson anomalous couplings

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

SM

CMS-PAS-FTR-16-002

- Test for anomalous couplings also useful in the context of HL-LHC
  - still statistically limited
  - results shown as 95% CL limits for 300 fb^{-1} and 3000 fb^{-1}

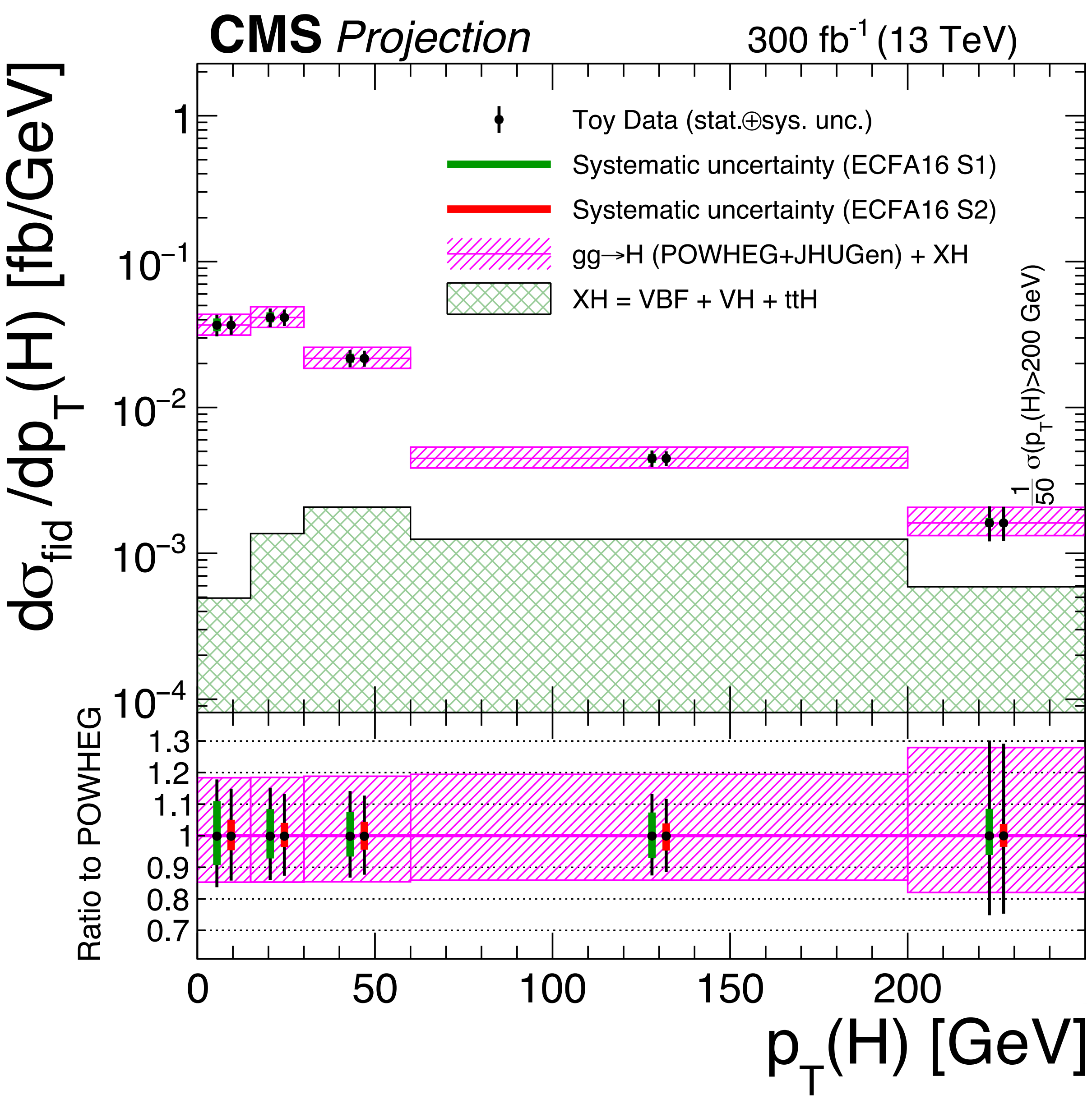


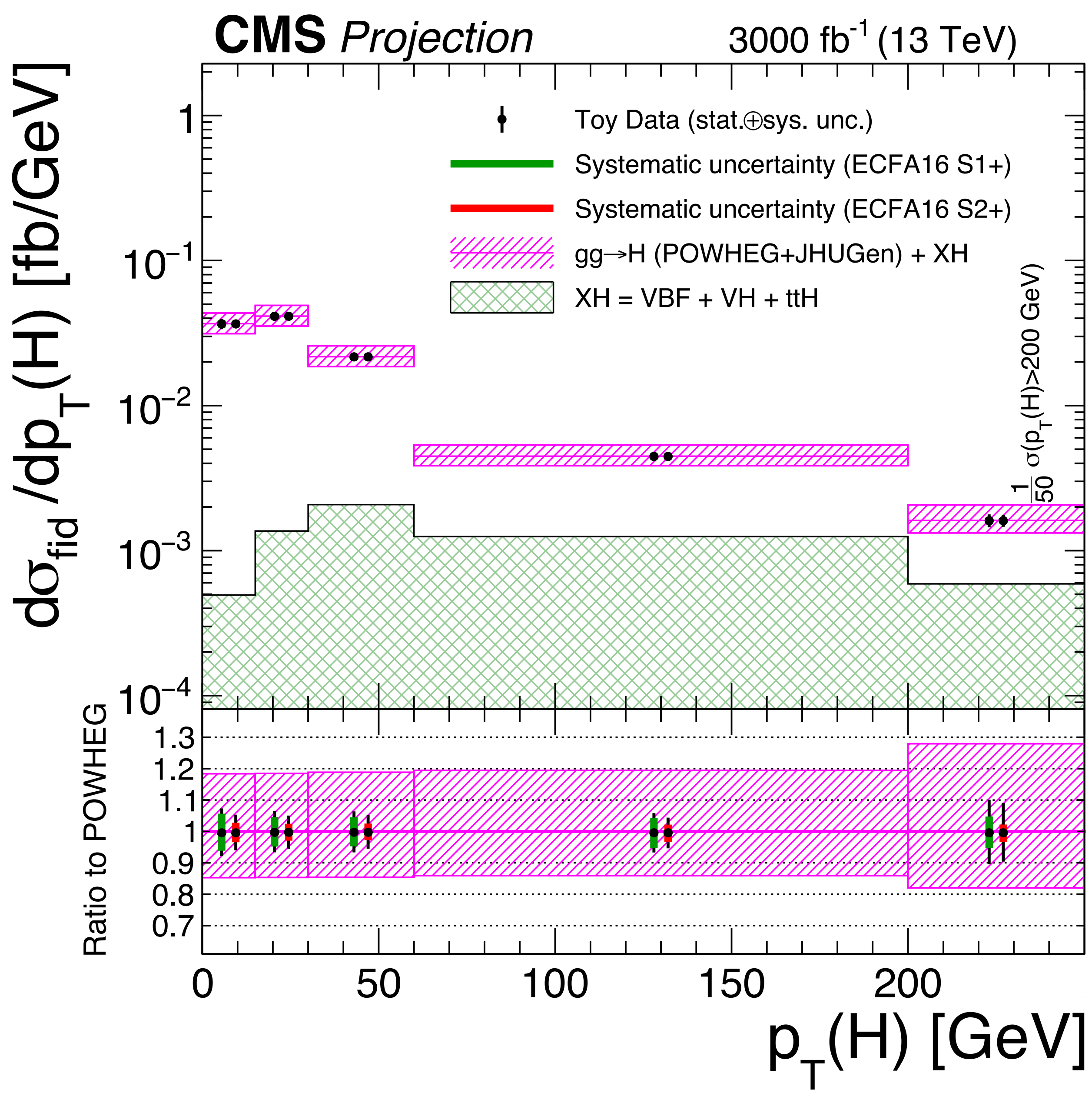
CMS-PAS-FTR-16-002

H->ZZ*->4l (differential)

✓ Measurements of differential cross section as a function of the Higgs transverse momentum allow to probe the high pT phase space and be sensitive to possible deviations from Standard Model expectations

- fiducial region matching the expected experimental acceptance for HL-LHC
- statistical component in the measurement of the high pT spectrum is still large at HL-LHC



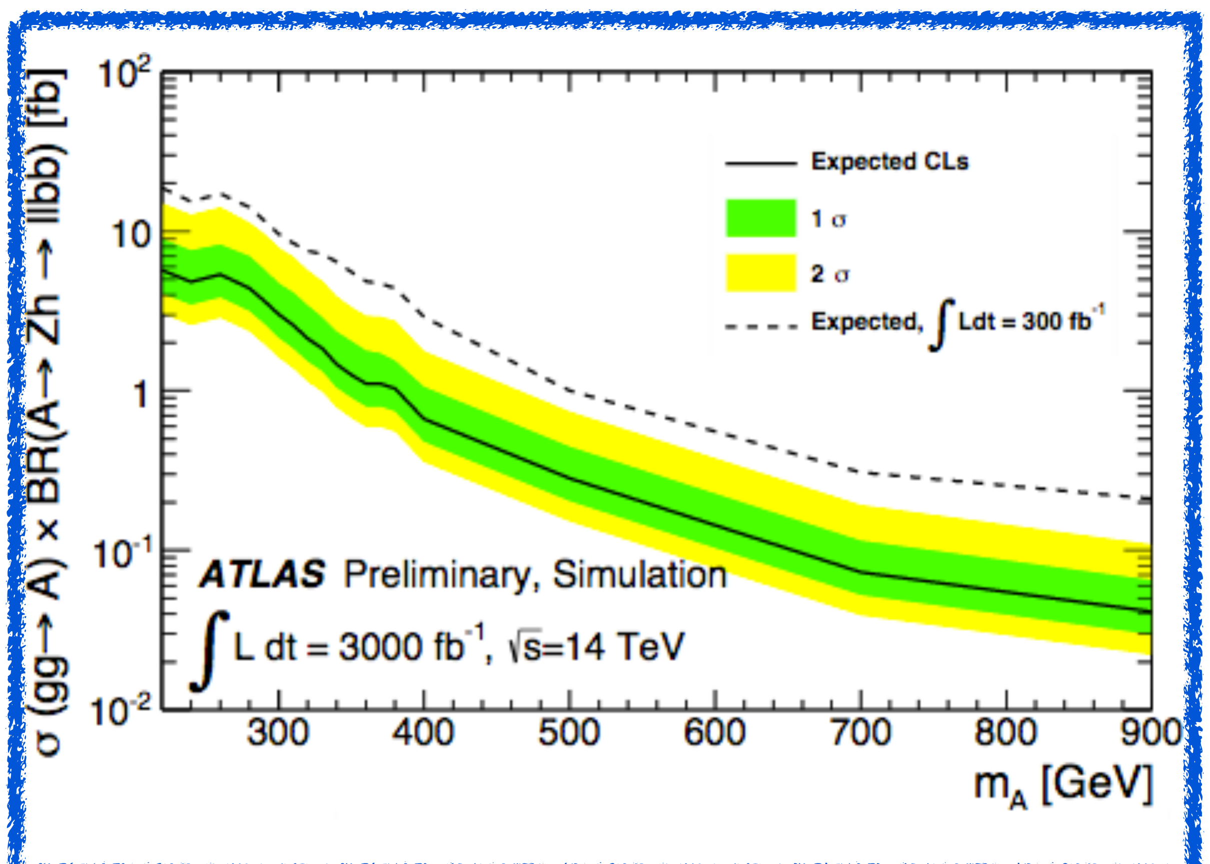


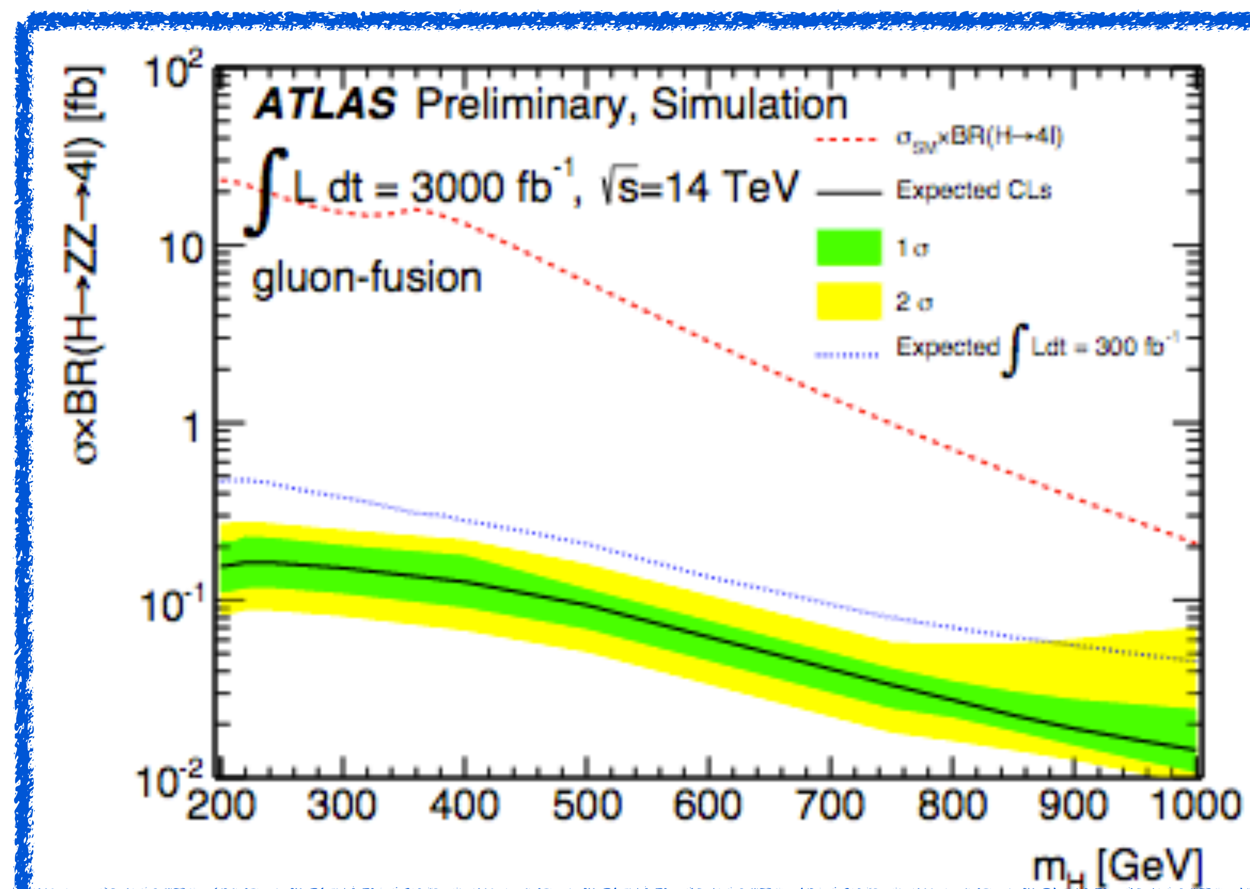
Search for additional Higgs states

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

ATL-PHYS-PUB-2014-016

- $A \rightarrow Zh$
  - $Zh \rightarrow llbb$ 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 $\tan\beta$
- $H, A \rightarrow \mu\mu$
  - only statistical uncertainties included in the projection
- Heavy $H \rightarrow ZZ \rightarrow 4l$
  - analysis uses extrapolation wrt Run 2 results - large improvement at HL-LHC wrt SM Higgs boson production





ATLAS-TDR-025

Higgs rare decays

ATL-PHYS-PUB-2015-043

✓ $H \to J/\Psi\ (\to \mu\mu)\ \gamma$ - using Run 1 detector performance and $\langle\mu\rangle=140$

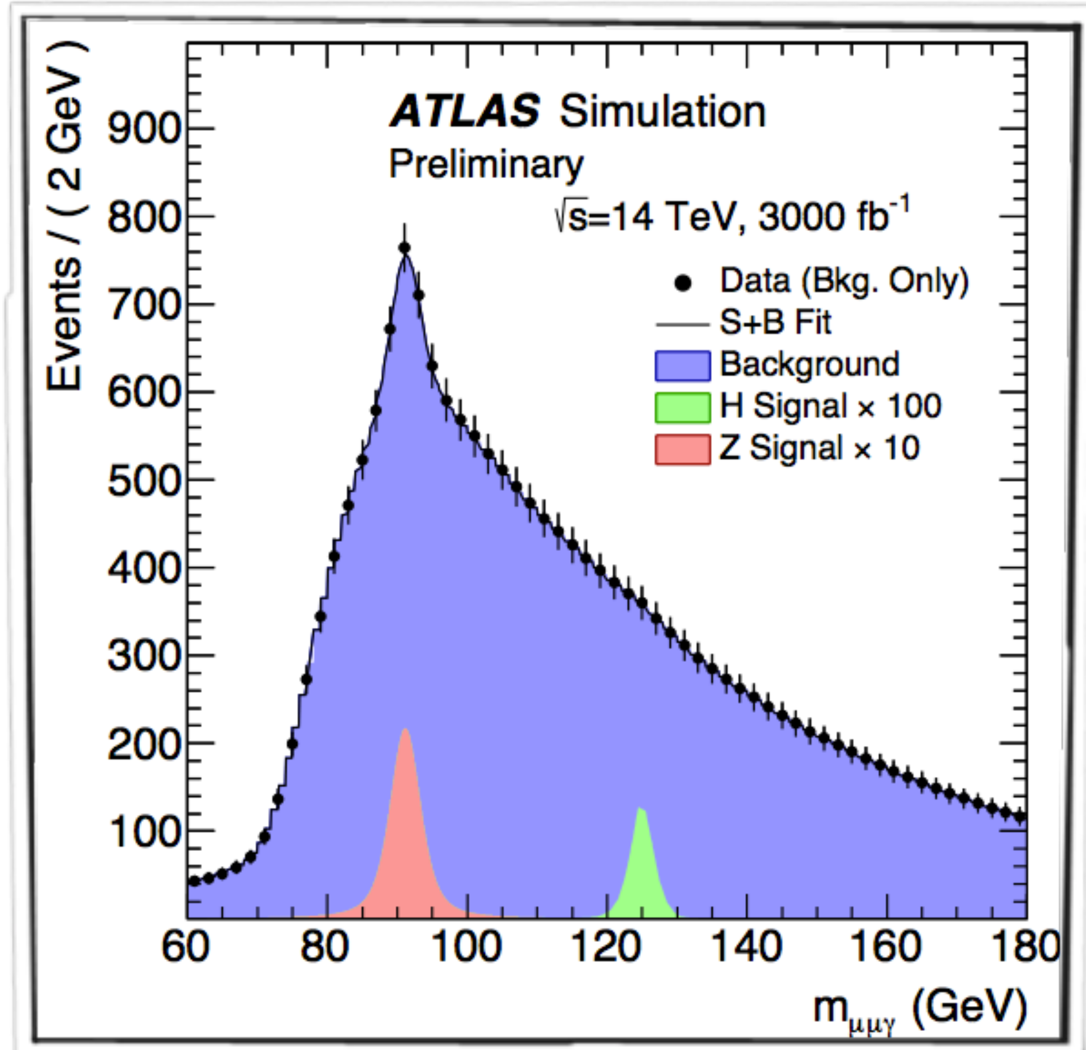
- sensitivity to the magnitude c and b quark couplings

✓ $J/\Psi \to \mu\mu$ 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 ($\mu\mu$), pT (γ) and μ/γ isolation

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

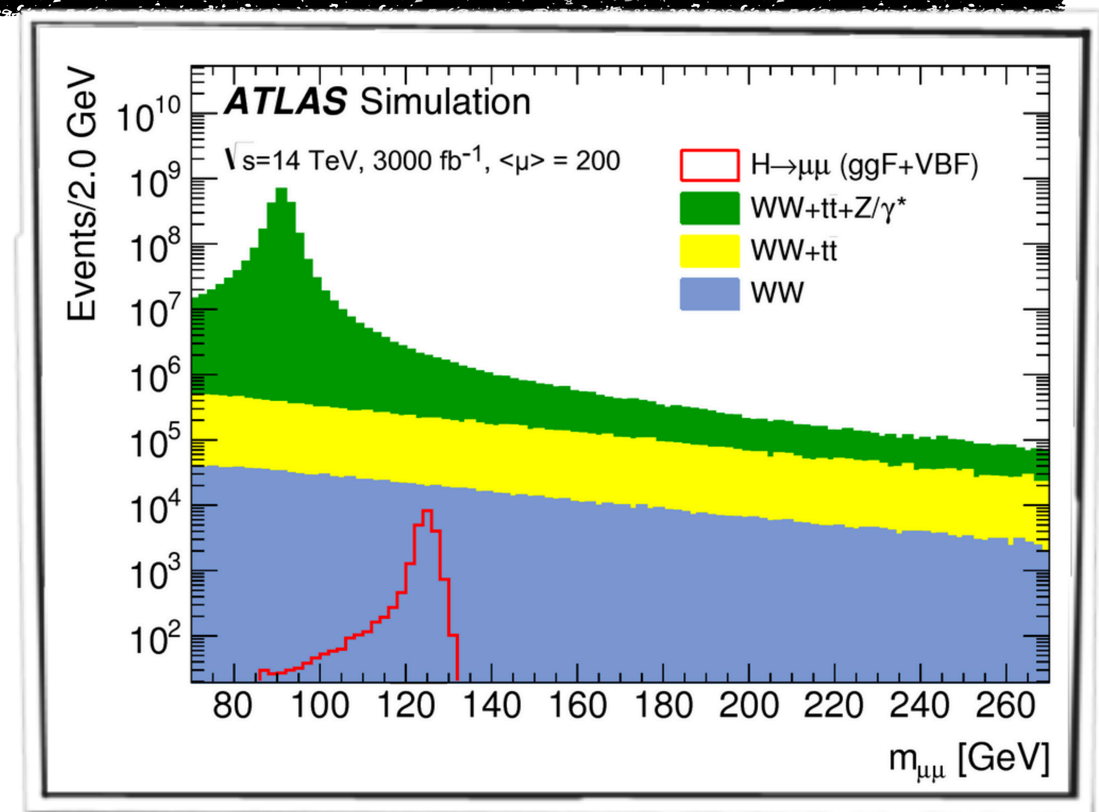


✓ $H \to \mu\mu$ - using Run 1 detector performance and $\langle\mu\rangle=200$

- very high mass resolution and low BR with very large irreducible background from Z/γ^*

- with 3000 fb^{-1}, expected sensitivity of 7σ

➡ Key aspect is the reconstruction of the di-muon final state - upgraded layout improves the di-muon invariant mass resolution by 25%



Vector boson fusion - H→ZZ→4l

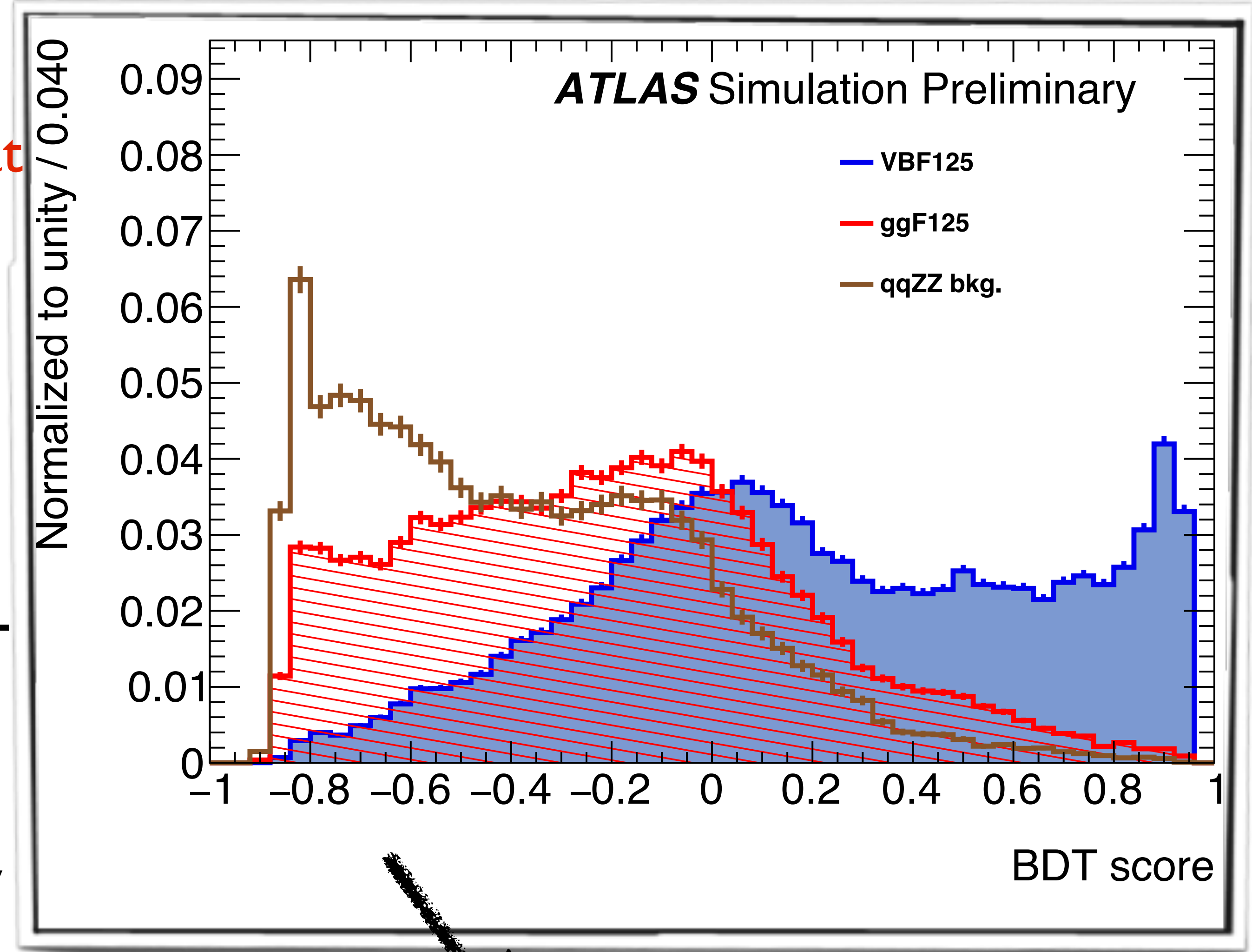
ATL-PHYS-PUB-2016-008

- 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%

Vector boson fusion - H→WW→eνμν

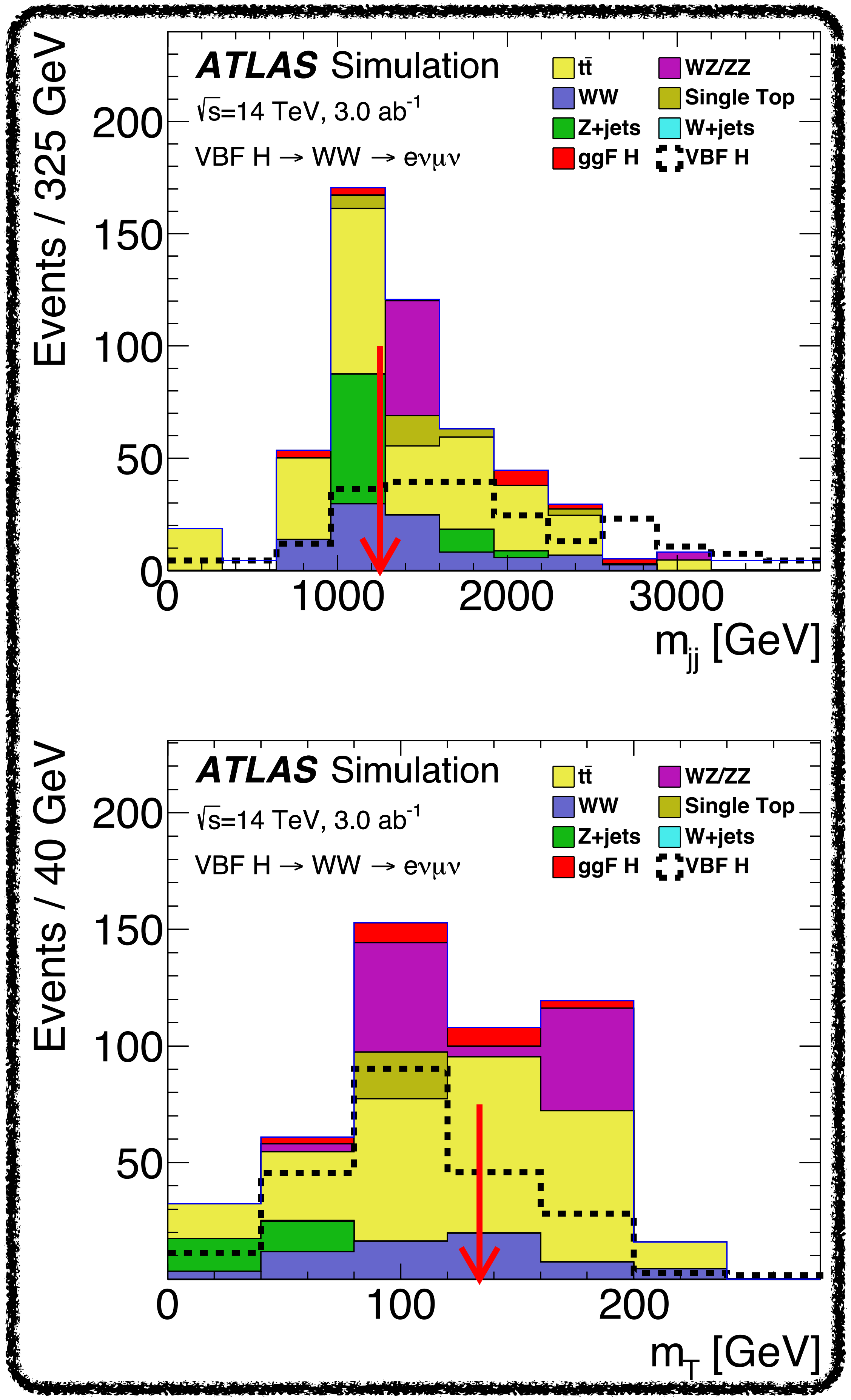
ATL-PHYS-PUB-2016-018

- 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 1 detector performance for e/μ - results for <μ>=200
  - events with two opposite-sign and different flavour leptons (e/μ) passing quality selection criteria
  - no other jets present between the VBF jets (events are removed if jet with pT> 30 GeV within the rapidity range of 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



Higgs boson total width

ATL-PHYS-PUB-2015-024

✓ Off-shell Higgs production used to indirectly constrain the Higgs boson width, Γ_H

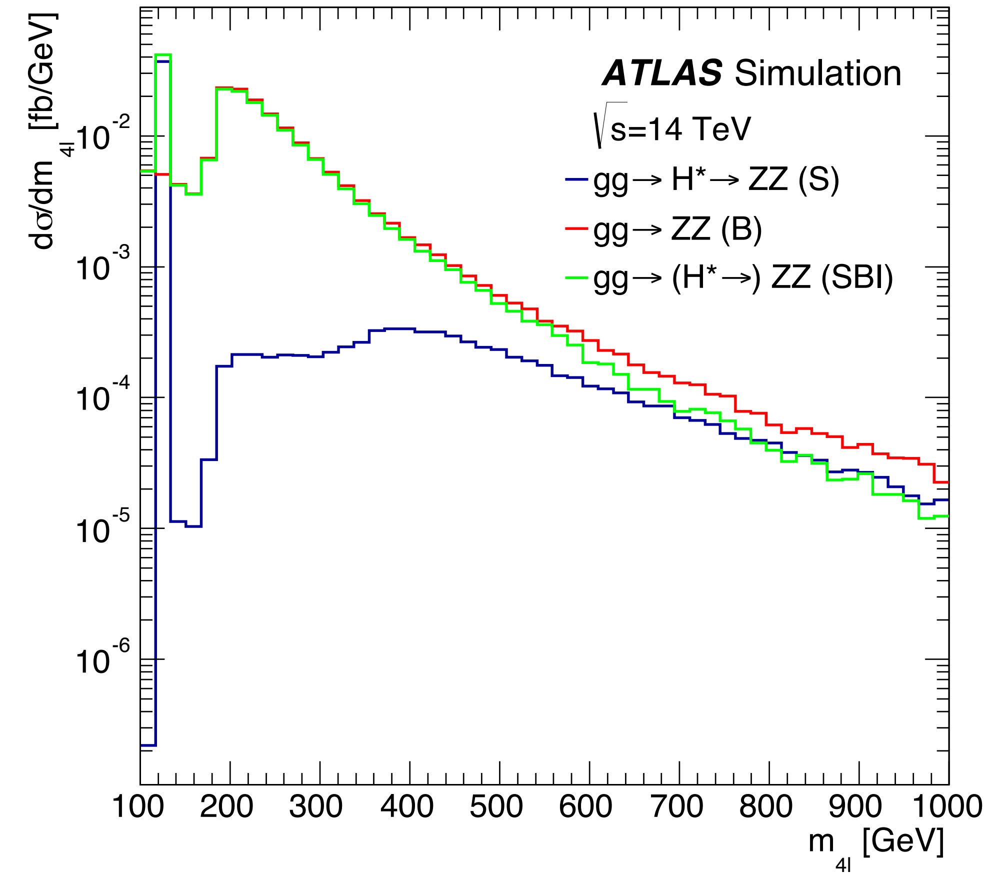
✓ Using $H \rightarrow ZZ^* \rightarrow 4l$ final state with m(4l)>220 GeV to select the high-mass region

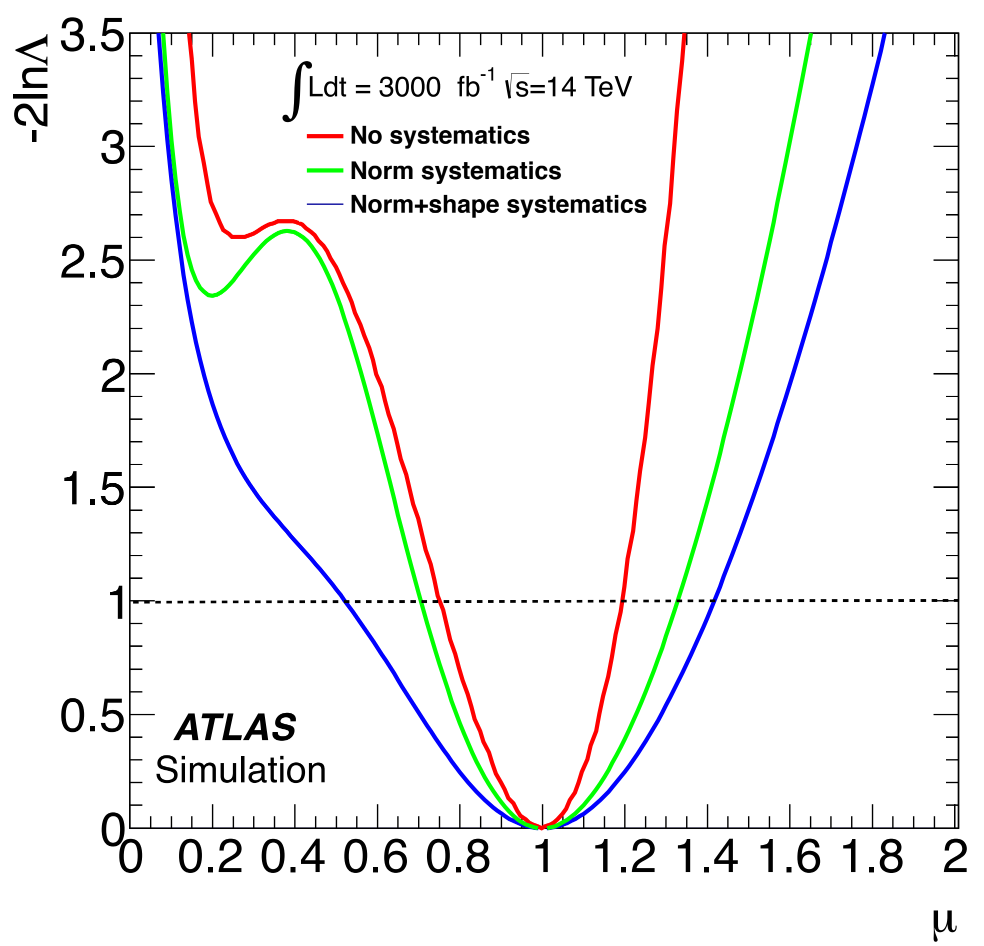
- m(4l) shape and matrix-element method to discriminate between the Higgs signal and the $qq \rightarrow ZZ$ and $gg \rightarrow ZZ$ backgrounds
- signal-to-background interference from same gg-initiated initial states ($gg \rightarrow H \rightarrow ZZ \rightarrow 4l$ and non-resonant $gg \rightarrow ZZ$) taken into account in the simulation
- same treatment of systematic uncertainties as in Run-1 analysis (theory uncertainty on $gg \rightarrow ZZ$ 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





Higgs-self couplings - wrapping-up

	ATLAS EXPERIMENT	CMS
$HH \to bbbb$	$-3.5 < \lambda_{HHH}/\lambda_{SM} < 11$ @ 95% C.L.	uncertainty on $\mu \sim 2.4$ (with systematic uncertainties included)
$HH \to bb\gamma\gamma$	$-8.0 < \lambda_{HHH}/\lambda_{SM} < 7.7$ @ 95% C.L.	uncertainty on $\mu \sim 3.0$ (with systematic uncertainties included)
$HH \to bb\tau\tau$	$-4.0 < \lambda_{HHH}/\lambda_{SM} < 12.0$ @ 95% C.L.	uncertainty on $\mu \sim 3.2$ (with systematic uncertainties included)

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 performance 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

- LHCb will complement the searches ($H \rightarrow cc$ and $H \rightarrow bb$) with forward coverage exploiting particle ID and vertex identification capabilities

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

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- Results for prospects on Higgs measurements at HL-LHC from ATLAS and CMS are preliminary

  - ☑ detectors are still in the development/optimization phase
  - ☑ more advanced analysis techniques and better characterization of the systematics uncertainties will give a more precise picture
  - ☑ coherent review of the expected HL-LHC performance and physics results for the CERN Yellow Report (end of 2018)

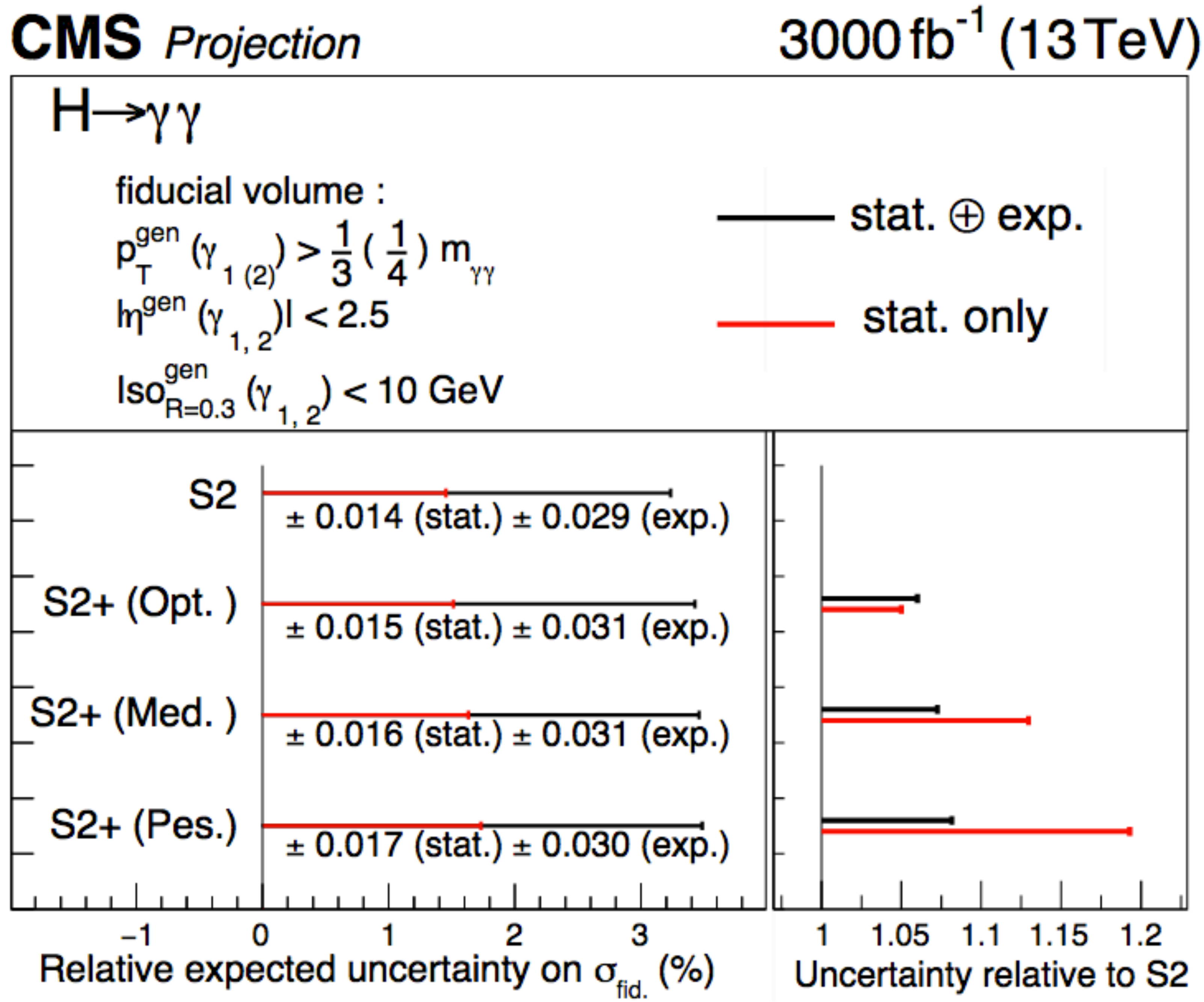
Very exciting times ahead!

Additional slides

CMS-PAS-FTR-16-002

H->γγ (fiducial)

- ✓ More results from CMS on H→γγ for cross section in fiducial volume
  - Improvement in mass resolution thanks to timing O (30 ps) for photons and charged particles



Higgs spin and parity

ATL-PHYS-PUB-2013-013

$$A(X_{J=0} \to VV) = v^{-1}\left(g_1 m_V^2 \epsilon_1^* \epsilon_2^* + g_2 f_{\mu\nu}^{*(1)} f^{*(2),\mu\nu} + g_3 f^{*(1),\mu\nu} f_{\mu\alpha}^{*(2)} \frac{q_\nu q^\alpha}{\Lambda^2} + g_4 f_{\mu\nu}^{*(1)} \tilde{f}^{*(2),\mu\nu}\right)$$

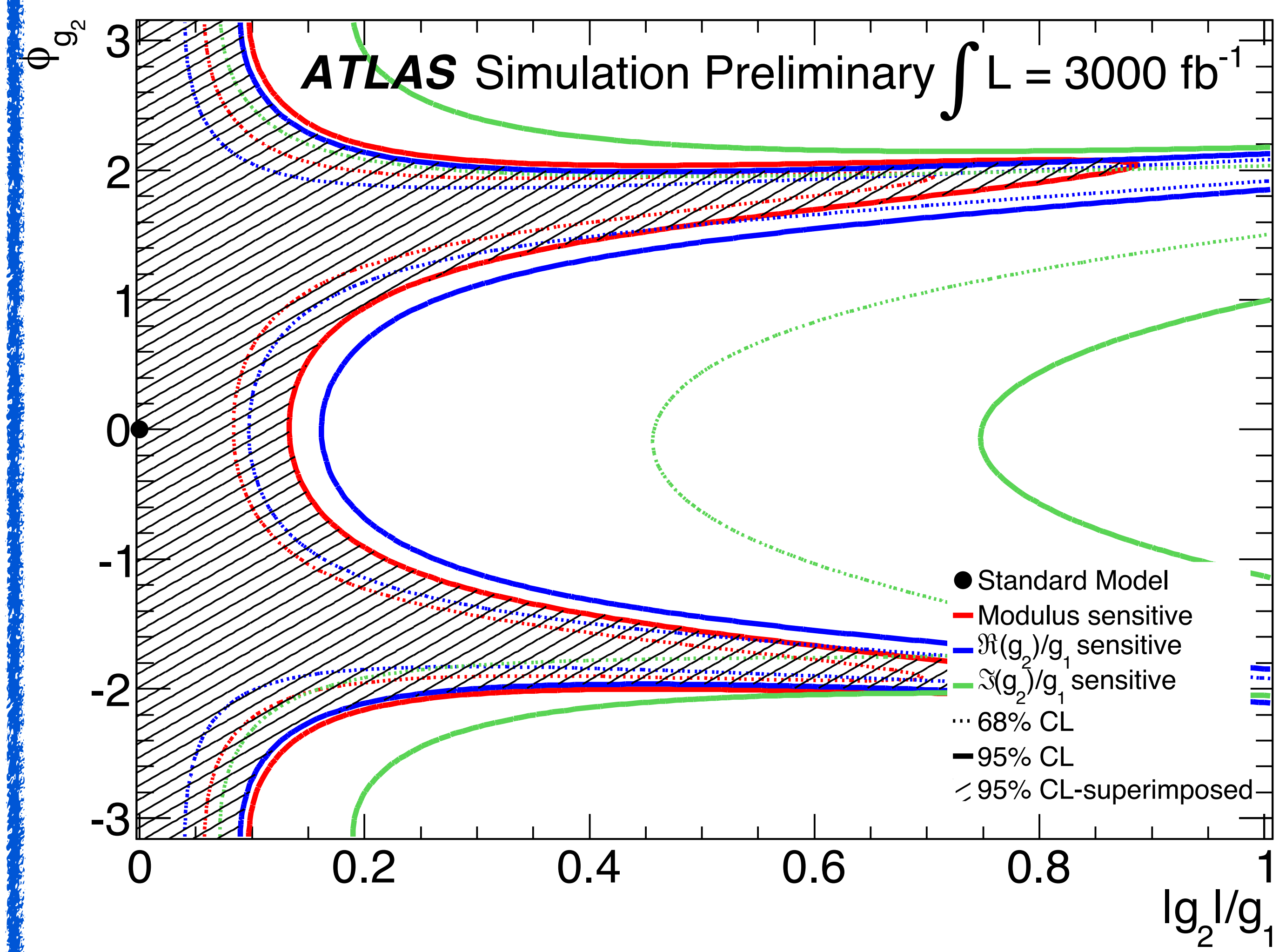
✓ General formula to describe the amplitude of a spin-0 particle and two spin-1 gauge bosons

- g1 (g2) describe the tree-level (loop-induced) interaction for a CP-even scalar - g3 coupling can be absorbed into g2
- g4 describes the interaction of a CP-odd scalar

➡ SM predictions - CP-conserving tree-level interaction: g1>0, g2, g3, g4=0

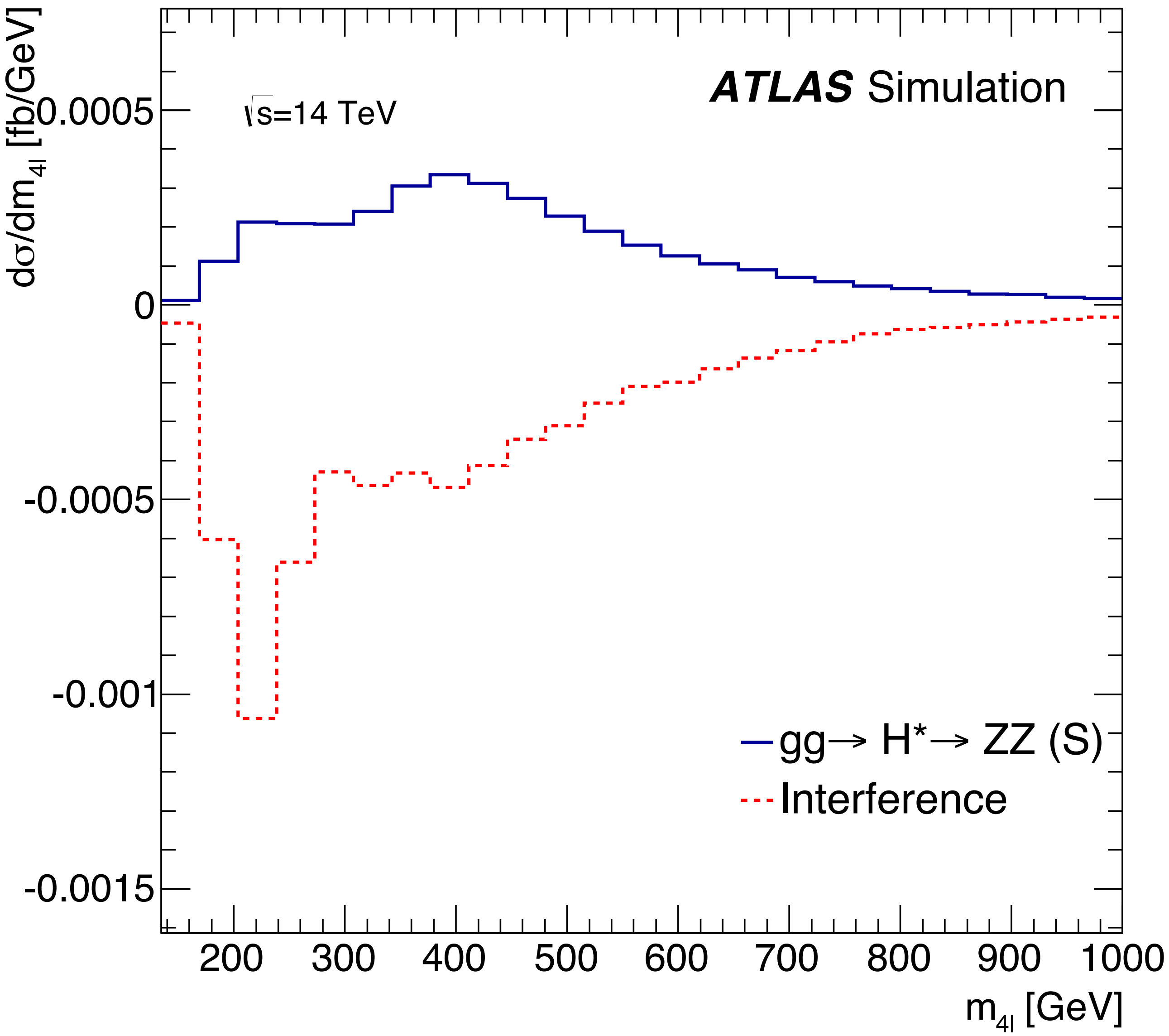
- sensitive test of the tensor structure of the Higgs boson

★ f (g4)<0.0037, f (g2)<0.12 at 95% CL at 3000 fb^{-1}

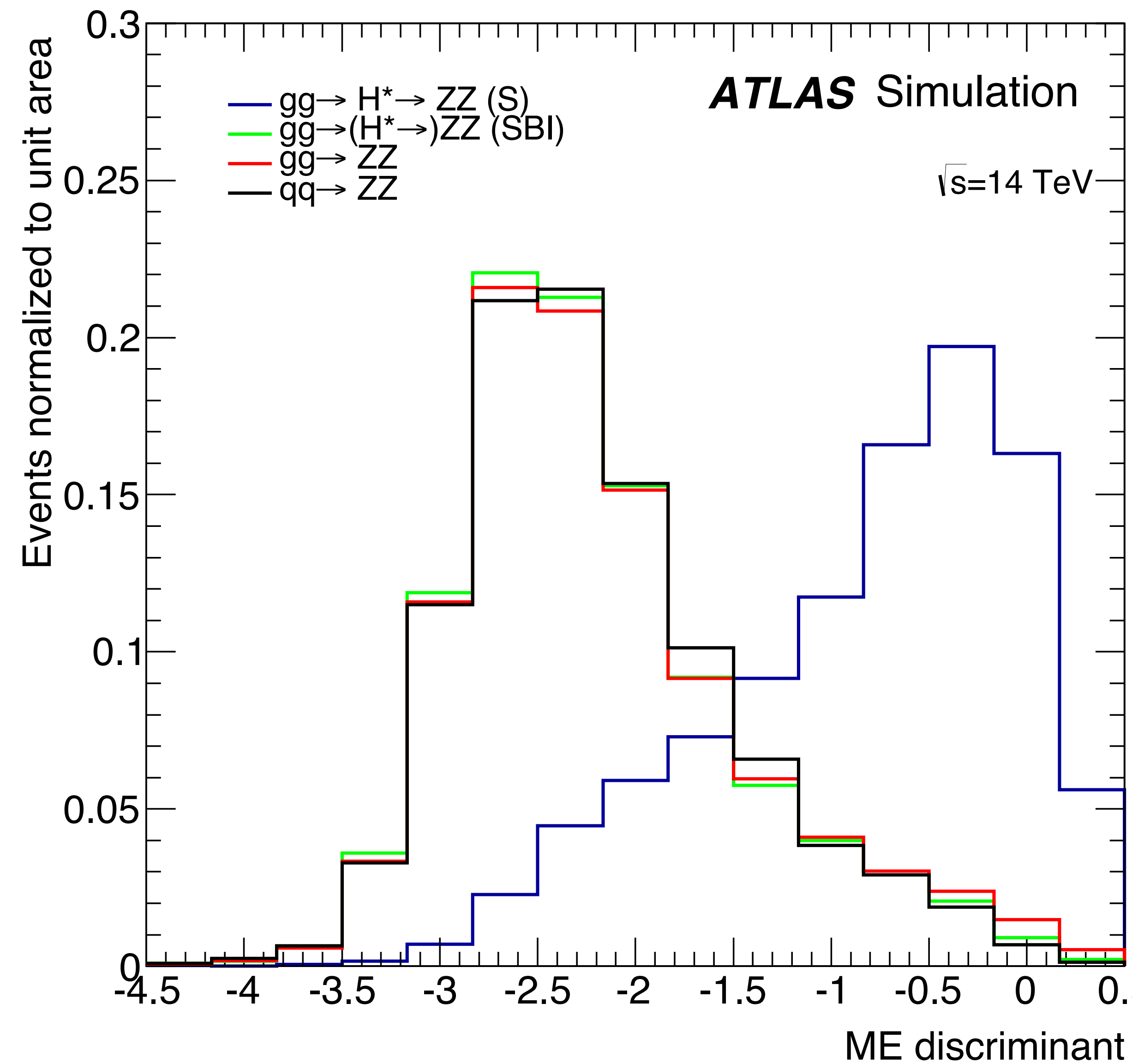


Higgs boson total width

ATL-PHYS-PUB-2015-024



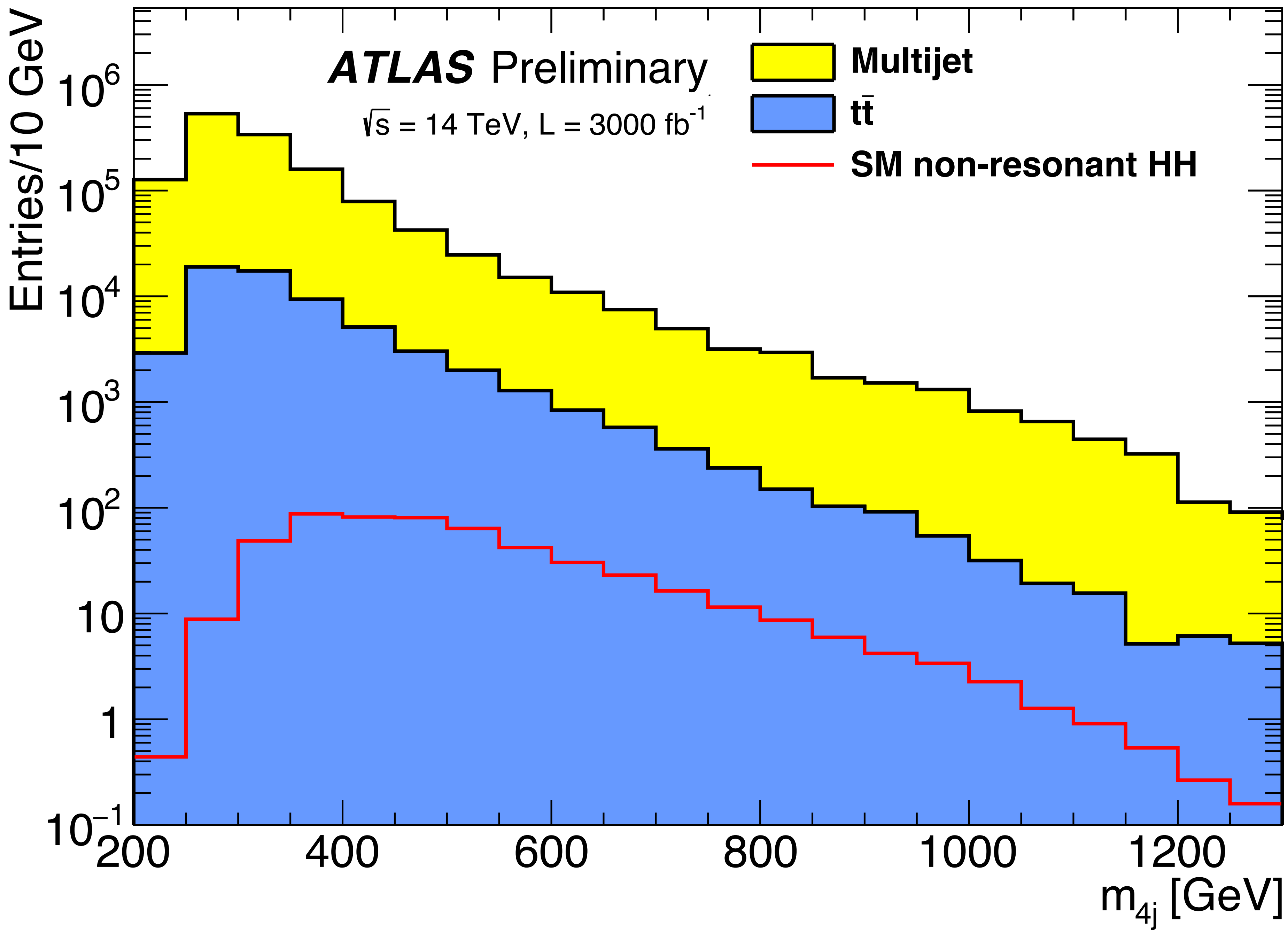
Signal component and signal-to-background interference



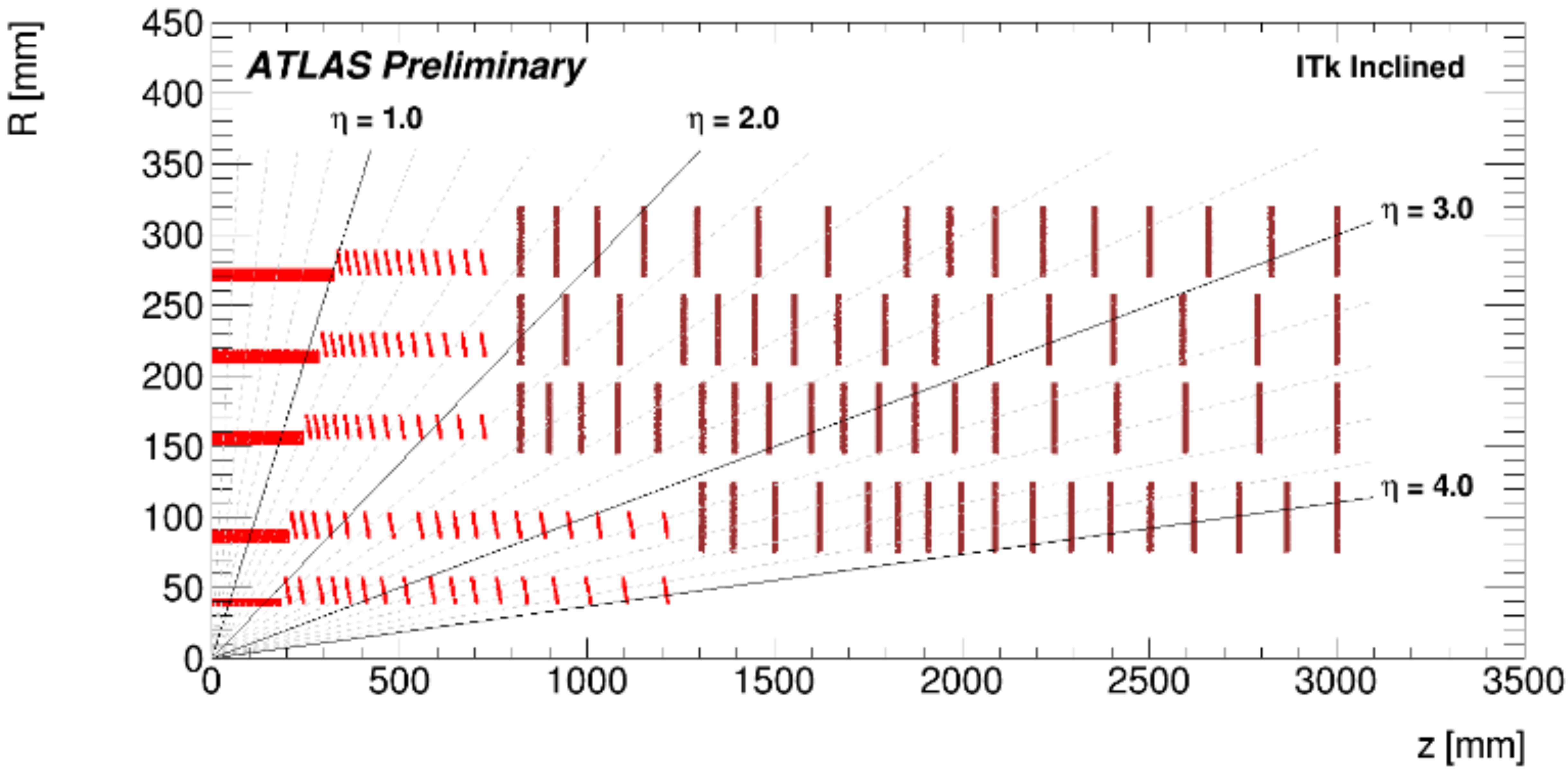
Matrix element-based discriminant for gg→H→ZZ (signal), qq→ZZ and gg→ZZ (backgrounds). The signal-to-background interference is also included

Higgs self-couplings - HH→bbbb (ATLAS)

ATL-PHYS-PUB-2016-024



ATLAS inner tracker



Higgs rare decays - H->μμ