Higgs Properties at HL-LHC with ATLAS

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Introductory Remarks

- Unless stated, results presented are for SM Higgs boson with m_H=125 GeV.
- At 2014 ECFA, ATLAS presented a comprehensive results for Higgs boson couplings at HL-LHC.
  - ➡ More recent analyses focused on understanding the impact of the detector design and on rarer processes.
- Pile-up: 140 and/or 200, depending on analysis.

Main Analysis Technique for HL-LHC

Truth+Smear Technique

- Generate truth-only 14 TeV events
- Overlay the truth information with jets from the ***pile-up library***:
  - ➡ Pile-up library consists of pile-up jets generated with full simulation (i.e. with detector response simulated)
  - ➡ $<\mu>$ = 140 or 200
- Reconstruct electron, muons, jets and missing-E_T from truth+overlay
- Smear the p_T and energy of reconstructed electrons, muons, jets and missing-E_T using appropriate ***smearing functions***
- Apply trigger efficiencies
- Apply efficiencies for electron, muon and jet reconstruction

Smearing and efficiency functions

- dependent on p_T and η
- Functions are based on fully simulated samples samples using upgrade ATLAS detector geometry and high pile-up

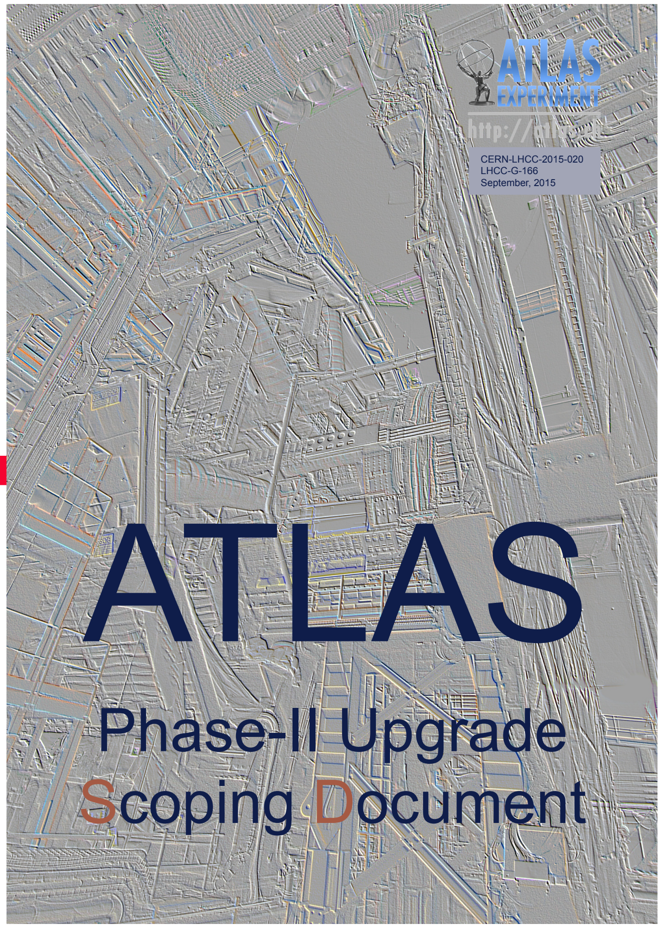
- Approach has been validated by studies on limited number of physics studies comparing full sim and truth+smearing approach

Jet techniques: pile-up reduction & flavour tagging

- At $<\mu> = 200$, 4.8 pileup jets ($p_T > 30$ GeV, $|\eta| < 2.5$) per event
- To reduce sensitivity to pile-up in jets we apply a ***track-confirmation*** requirement:
  - ➡ Jets with $p_T < 100$ GeV and $|\eta| < 3.8$ (not *b*-jets) must have a jet that matches with a track that comes from the primary vertex.
- Reduces pile-up by factor ~50

- Parametrised *b*-tagging, based on Run 1 `MV1` tagger, run on *truth-jets*
  - ➡ Provides a 70% working point for b-tagging
  - ➡ mistag rates for light and charm jets
  - ➡ dependent on p_T and η
  - This can very likely be improved … (less mistags)

ATLAS Phase II Scoping Document



- Two VBF production analysis: each evaluated in the context of three different detector scenario
- Only **Reference** results presented in this talk.

Detector System	Scoping Scenarios Reference (275 MCHF)	Middle (235 MCHF)	Low (200 MCHF)
Inner Tracker			
Pixel Detector	$\|\eta\| \leq 4.0$	$\|\eta\| \leq 3.2$	$\|\eta\| \leq 2.7$
Barrel Strip Detector	✓	✓ [No stub layer]	✓ [No stereo in layers #2,#4] [Remove layer #3] [No stub layer]
Endcap Strip Detector	✓	✓ [Remove 1 disk/side]	✓ [Remove 1 disk/side]
Calorimeters			
LAr Calorimeter Electronics	✓	✓	✓
Tile Calorimeter Electronics	✓	✓	✓
Forward Calorimeter	✓	✗	✗
High Granularity Precision Timing Detector	✓	✗	✗

Higgs Properties Overview

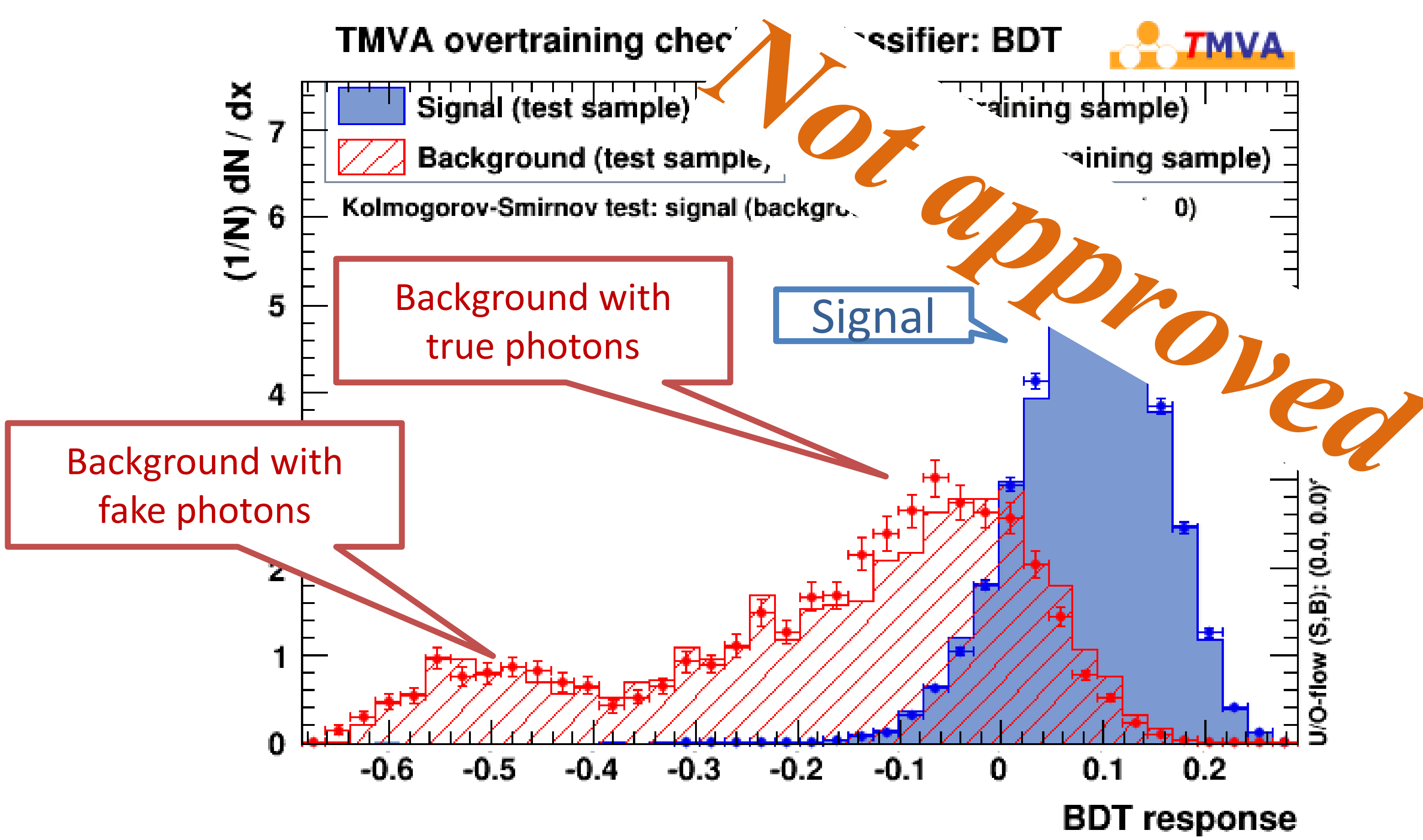
- New analyses since ECFA 2014 workshop

Analysis	Status / Publication
$bbH,\ H\rightarrow\gamma\gamma$	In preparation
$H\rightarrow J/\psi\ \gamma$	ATL-PHYS-PUB-2015-043
VBF $H\rightarrow W^+W^-$	ATL-PHYS-PUB-2016-018
VBF $H\rightarrow ZZ\rightarrow 4\ell$	ATL-PHYS-PUB-2016-008
Γ(H) from off-shell couplings (WW, ZZ)	ATL-PHYS-PUB-2015-024
$H\rightarrow ZZ\rightarrow\mu^+\mu^-\mu^+\mu^-$ (for acceptance studies)	In ATLAS Phase-II ScopingDocument
$H\rightarrow\mu^+\mu^-$	In preparation (might not make it to ECFA2016)

bbH, H→γγ

- Backgrounds: ZH, ttH, ttγ, tt, 4 jets, 3 jets+γ, 2 jets+γγ
- Jets faking photons is considered
- Cut-based and multivariate analysis

Photons	Jets	Isolated leptons
❑ ≥ 2 isolated photons ❑ P_T>30 GeV ❑ 1.52<|η|<2.4, 0 <|η|< 1.37	❑ ≥ 2 b-matched jets ❑ jet P_T>30 GeV ❑ |η|< 3.8	❑ No isolated μ, e ✓ with P_T>25 GeV ✓ e^-:|η|< 2.5 ✓ μ :|η|< 4.0



- No m(γγ) in BDT ; m(γγ) cut applied after BDT cut

bbH, $H \to \gamma\gamma$ signal & background

Stream	120GeV < $m_{di\text{-}photon}$ < [illegible]	
	Expected events	% of total backg[illegible]
$b\bar{b}\gamma\gamma$	110 ± 5	(7,72 ± 4,31)%
3 $b\bar{b}j\gamma$	211 ± 105	(14,73 ± 8,16)%
$H(\to b\bar{b})H(\to \gamma\gamma)$	9,07 ± 0,10	(0,63 ± 0,41)%
2 $jj\gamma\gamma$	366 ± 23	(25,61 ± 14,15)%
$t\bar{t}\gamma$	2,7 ± 1,4	(0,19 ± 0,16)%
$t\bar{t}H(\to \gamma\gamma)$	31,2 ± 1,0	(2,19 ± 1,26)%
$t\bar{t}l$	0 ± 0	(0 ± 0)%
$Z(\to b\bar{b})H(\to \gamma\gamma)$	10,31 ± 0,10	(0,72 ± 0,46)%
4 $c\bar{c}\gamma\gamma$	95 ± 5	(6,70 ± 3,75)%
1 $c\bar{c}j\gamma$	593 ± 419	([illegible]50 ± 22,88)%

Not approved

Final analysis results after $m_{\gamma\gamma}$

Significance (σ)	0,184 ± 0,028
Signal events	6,96 ± 0,07
Background events	1429 ± 433

Not approved

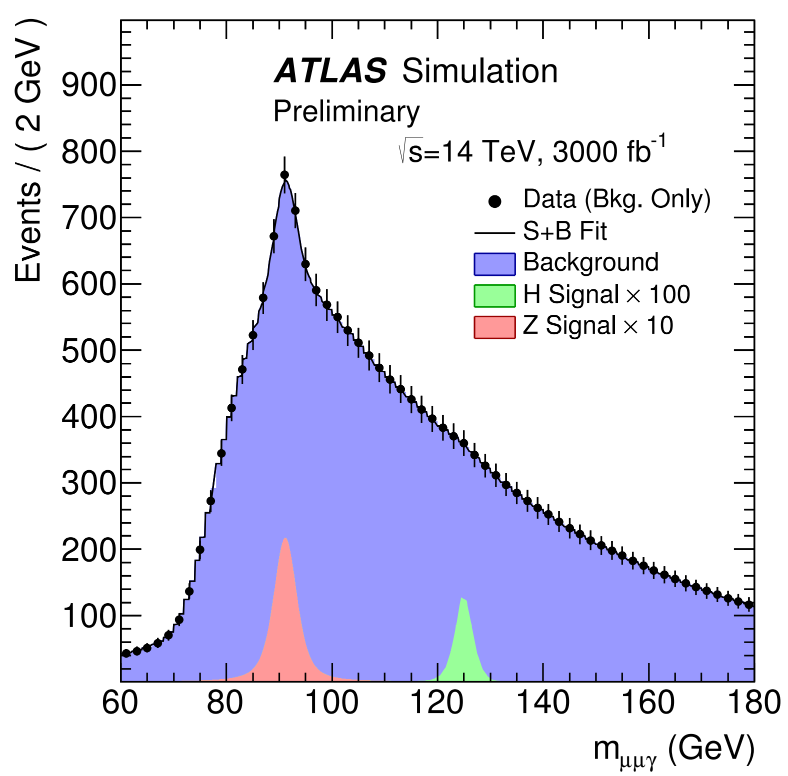
$H \rightarrow J/\psi\ \gamma$

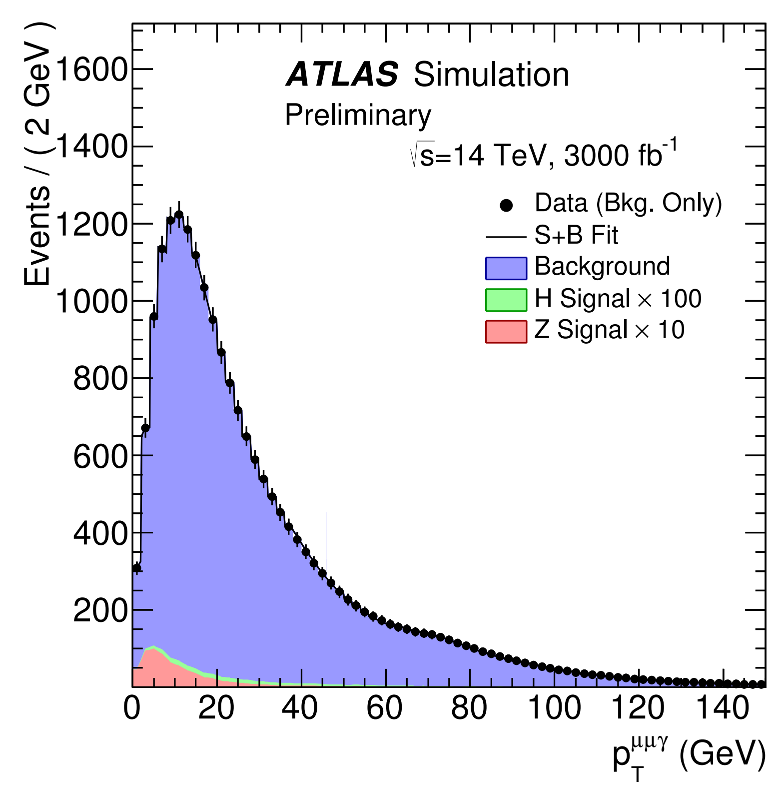
3000 fb^{-1}
<μ> = 140

ATL-PHYS-PUB-2015-043

- SM expected **BR($H \rightarrow J/\psi\ \gamma$): (2.9 ± 0.2) × 10^{-6}**
- Cut-based and Multivariate analysis
- Multivariate results: ~3 signal events, 1700 background

	Expected Background				Signal	
	Inclusive QCD Mass Range [GeV]		Other Backgrounds			
	80-100	115-135	$Z \rightarrow \mu^+\mu^-\gamma$	$H_{\gamma^*\gamma} \rightarrow \mu^+\mu^-\gamma$	Z	H
Cut Based Analysis	7800±500	3500±400	780 ±100	15.1 ±1.4	50±3	3.2±0.1
Multivariate Analysis		1700±200		13.7 ±1.3		2.9±0.1





$H \rightarrow J/\psi\ \gamma$ Results

3000 fb^{-1}
<μ> = 140

ATL-PHYS-PUB-2015-043

- No background systematics considered

	Expected branching ratio limit at 95% CL		
	$\mathcal{B}(H \rightarrow J/\psi\gamma)$ [10^{-6}]		$\mathcal{B}(Z \rightarrow J/\psi\gamma)$ [10^{-7}]
	Cut Based	Multivariate Analysis	Cut Based
300 fb^{-1}	185^{+81}_{-52}	153^{+69}_{-43}	$7.0^{+2.7}_{-2.0}$
3000 fb^{-1}	55^{+24}_{-15}	44^{+19}_{-12}	$4.4^{+1.9}_{-1.1}$

	Standard Model expectation	
	$\mathcal{B}(H \rightarrow J/\psi\gamma)$ [10^{-6}]	$\mathcal{B}(Z \rightarrow J/\psi\gamma)$ [10^{-7}]
	2.9 ± 0.2	0.80 ± 0.05

	Expected $\sigma \times \mathcal{B}$ limit at 95% CL $\sigma(pp \rightarrow H) \times \mathcal{B}(H \rightarrow J/\psi\gamma)$ [fb]	
	Cut Based	Multivariate Analysis
300 fb^{-1}	$10.4^{+2.9}_{-4.5}$	$8.6^{+2.4}_{-3.7}$
3000 fb^{-1}	$3.1^{+0.9}_{-1.3}$	$2.5^{+0.7}_{-1.0}$

VBF $H \to WW^* \to e\nu\mu\nu$

3000 fb^{-1}
<μ> = 200

ATL-PHYS-PUB-2016-018

- Selections:

Category	$N_{\text{jet}} \geq 2$
Pre-selection	Two isolated leptons (one e and one μ) with opposite charge Leptons with $p_{\text{T}}^{\text{lead}} > 25$–$28$ GeV and $p_{\text{T}}^{\text{sublead}} > 15$ GeV $m_{\ell\ell} > 10$ GeV
Jet-corrected-track-$E_{\text{T}}^{\text{miss}}$	$E_{\text{T}}^{\text{miss}} > 20$ GeV
General selection	$p_T^{\text{jet}} > 70$ (60) GeV lead (sublead) $N_{\text{b-jet}} = 0$ (before pile-up jet removal) $p_{\text{T}}^{\text{tot}} < 20$ GeV $Z/\gamma^* \to \tau\tau$ veto (Collinear approx. $m_{\tau\tau} < 50$ GeV)
VBF topology	$m_{\text{jj}} > 1250$ GeV and $\lvert\eta_j\rvert > 2.0$, opposite hemisphere No jets ($p_{\text{T}} > 30$ GeV) in rapidity gap (CJV) Require both ℓ in rapidity gap
$H \to WW^* \to e\nu\mu\nu$ topology	$m_{\ell\ell} < 60$ GeV $\Delta\phi_{\ell\ell} < 1.8$ $m_{\text{T}} < 1.07 \times m_H$

- 200 signal events and 410 background events

Scoping scenario	N_{VBF}	N_{bkg}	N_{ggF}	N_{WW}	N_{VV}	$N_{t\bar{t}}$	N_t	N_{Z/γ^*+jets}	N_{W+jets}
Reference	200	410	57	48	55	146	20	27	0

- Three different background uncertainties considered: same as Run 1 (**Full**), 1/2 of Run 1, and **None**

<μ> = 200

Scoping scenario / Signal unc.	Δ_μ Full	Δ_μ 1/2	Δ_μ None	Significance (σ) Full	Significance (σ) 1/2	Significance (σ) None
Reference	0.20	0.16	0.14	5.7	7.1	8.0

<μ> = 140

Scoping scenario / Signal unc.	Δ_μ 1/2	Significance (σ) 1/2
Reference	0.13	9.0

VBF $H \rightarrow WW^* \rightarrow e\nu\mu\nu$ Plots

3000 fb^{-1}
<μ> = 200

ATL-PHYS-PUB-2016-018

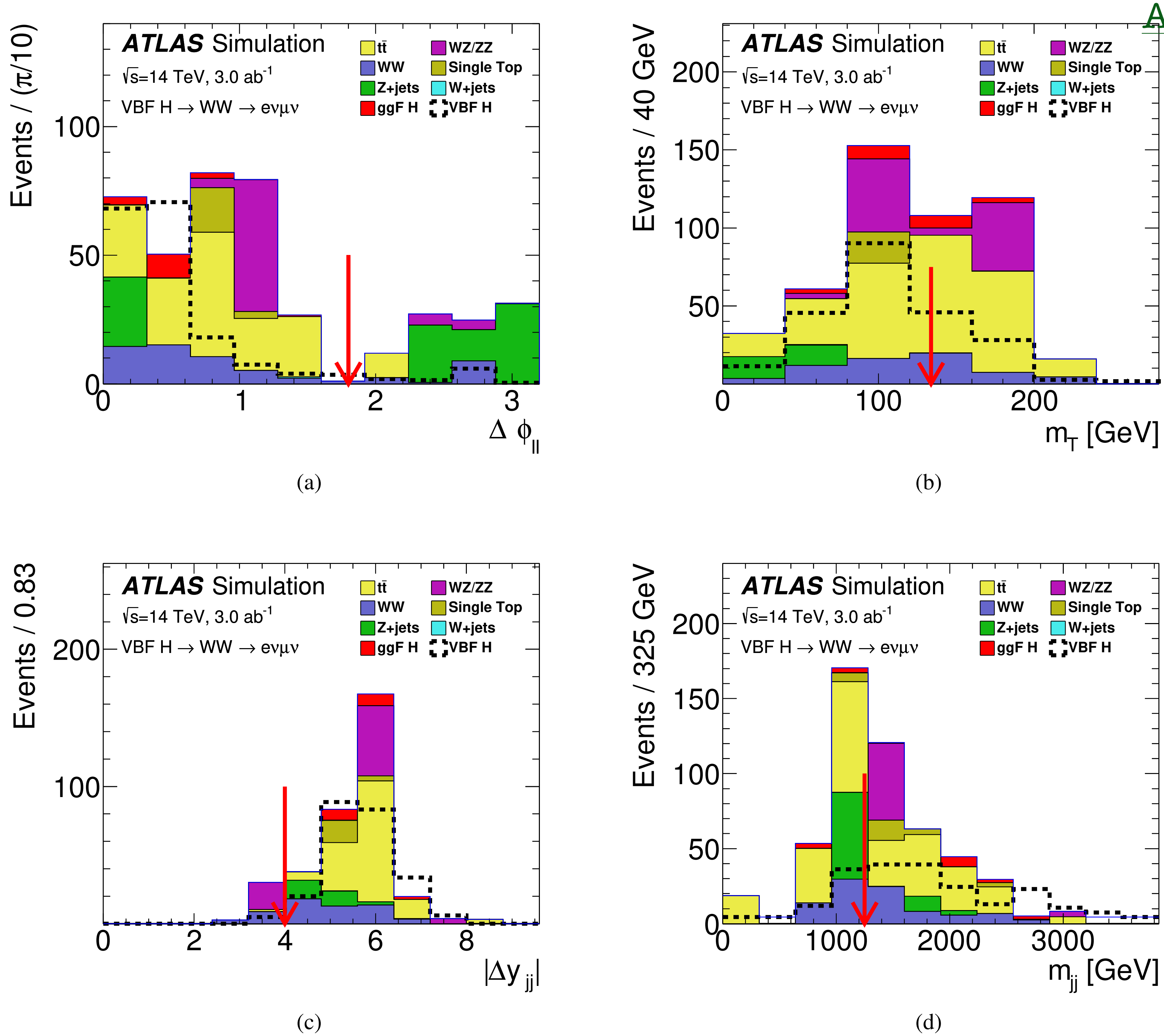


Figure 2: The (a) $\Delta\phi_{\ell\ell}$, (b) m_{T}, (c) $|\Delta y_{jj}|$, and (d) m_{jj} distributions are shown with all signal region selections applied except for the one on the kinematic variable shown, and an arrow indicates the selection threshold. For $|\Delta y_{jj}|$, the arrow indicates a minimum threshold from the $|\eta_j| > 2$ and opposite-hemisphere jet requirements. All distributions assume the Reference scenario detector performance.

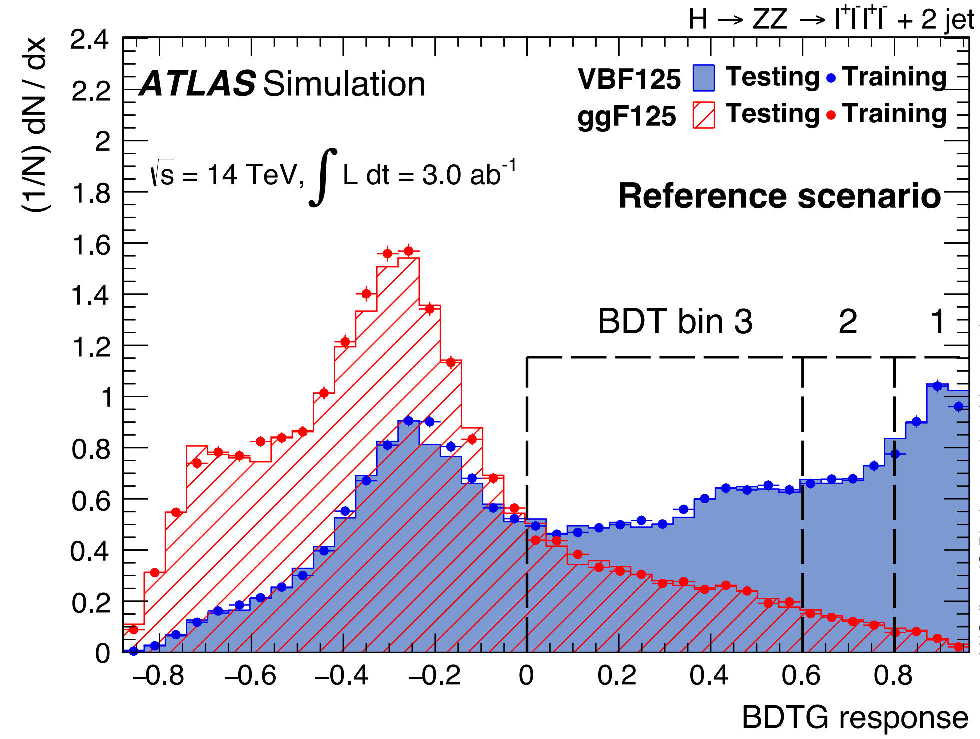
VBF $H\to ZZ\to 4\ell$

ATL-PHYS-PUB-2016-008

3000 fb^{-1}
<μ> = 200

- Selections:

Event pre-selection	
Lepton selection	Require all truth electrons to have $E_T > 7$ GeV, $\lvert\eta\rvert < 2.47$ Require all truth muons to have $p_T > 6$ GeV $\lvert\eta\rvert < 2.7$
Event selection	
$H \to 4l$ kinematic selection	Require at least one quadruplet of leptons consisting of two pairs of same-flavour opposite-charge leptons fulfilling the following requirements p_T thresholds for three leading leptons in the quadruplet 20, 15, and 10 GeV Select best quadruplet to be that with the leading, subleading dilepton masses closest to the Z mass Leading dilepton mass requirement 50 GeV $< m_{12} <$ 106 GeV Subleading dilepton mass requirement $m_{\mathrm{Threshold}} < m_{34} <$ 115 GeV Remove quadruplet if alternative same-flavour opposite-charge dilepton gives $m_{ll} <$ 5 GeV or $\Delta R(l,l') < 0.10$ (0.20) for same (different) flavour leptons in the quadruplet
Dijet selection	Require $p_T > 30$ GeV, $\lvert\eta\rvert < 4.5$ for each jet Remove jets overlapping leptons within $\Delta R < 0.2$ Dijet mass $m_{jj} > 130$ GeV



(d) Reference layout

- Use BDT and **m(4ℓ)** as discriminating variables.

- 192 signal events and 326 background events (**ggF**, ***qqZZ***)

- Results for statistical uncertainty only and stat+signal QCD scale

$$Z_0 \approx n_{\mathrm{VBF}}/\sqrt{n_{\mathrm{VBF}} + n_{\mathrm{ggF}}}.$$

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

<μ> = 200

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

<μ> = 200

VBF $H \to ZZ \to 4\ell$

ATL-PHYS-PUB-2016-008

3000 fb^{-1}
<μ> = 140

- Also results for pileup of 140

<μ> = 140

Statistical uncertainty only					
Scoping scenario	VBF + 2j events	ggF + 2j events	$qqZZ$ + 2j events	Z_0	$\Delta\mu/\mu$
Reference	185 (173)	192 (121)	23 (12)	11.1	0.144

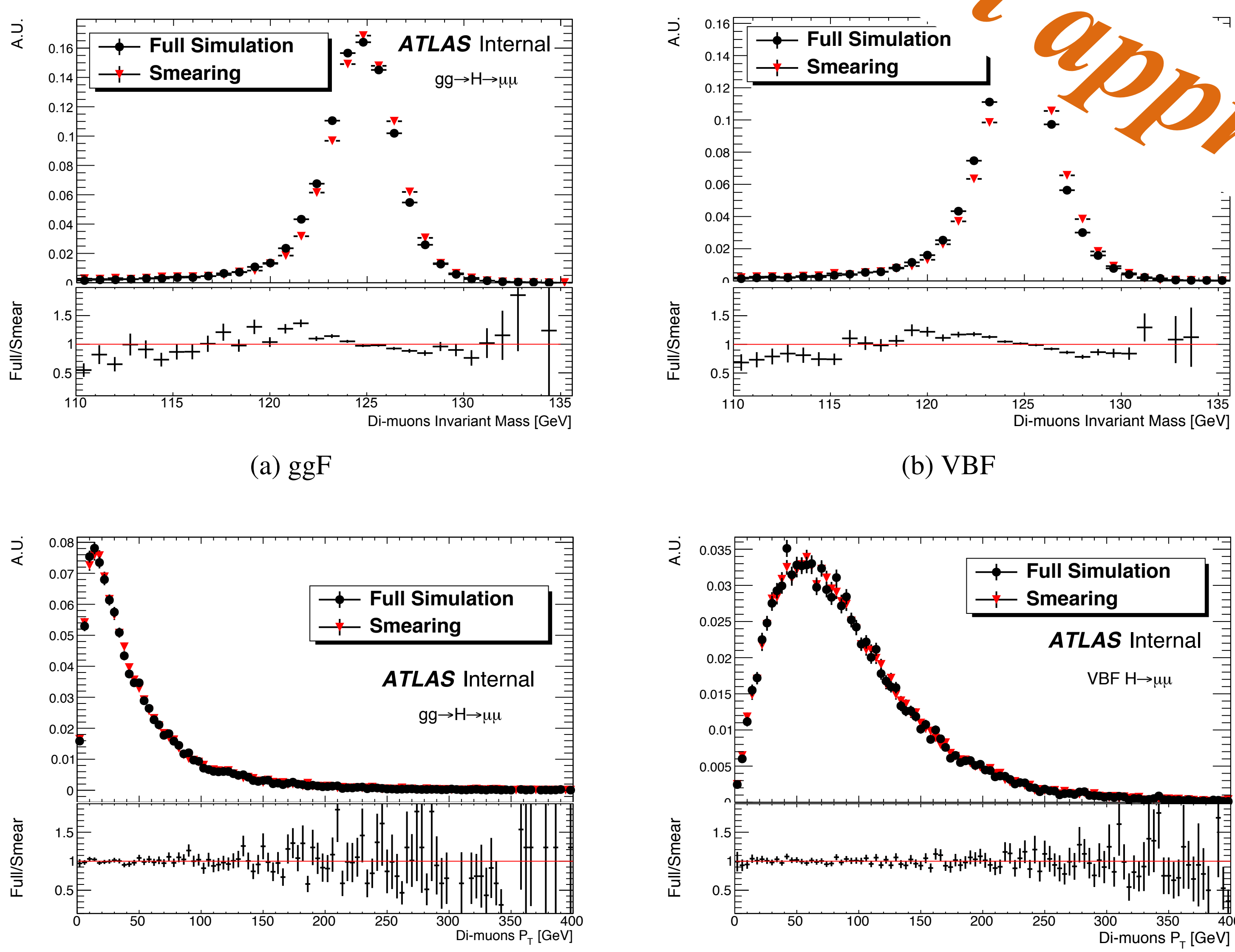
<μ> = 140

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	185	192	23	7.7	0.170

Table 10: Expected signal and background event counts for different jet tracking coverage scenarios at $\mathcal{I} = 3000\,\text{fb}^{-1}$ and $\langle\mu\rangle = 140$ in the region (BDT score) > 0 and $120 < m_{4l} < 130$ GeV. Shown also is the VBF signal significance and signal strength precision for each scenario. Background is composed of both ggF and $qqZZ$ events, and scenarios are shown where only the statistical uncertainty (top), and also Stewart-Tackmann uncertainties (bottom) are considered in the fit. Bracketed terms represent the number of events in the signal region with two selected jets from the primary vertex.

$H \to \mu\mu$ (not approved)

- Full simulation used to cross check truth+smearing approach



(a) ggF (b) VBF

(c) ggF (d) VBF

Figure 11: Di-muons System. (a) shows the di-muons invariant mass for the ggF sample and (b) shows the di-muons invariant mass for the VBF sample (c) shows the di-muons p_T for the ggF sample and (d) shows the di-muons p_T for the VBF sample

$H \rightarrow \mu\mu$ (not yet approved)

3000 fb^{-1}
$\langle\mu\rangle = 200$

Process	-	2 rec. muons	$p_T(\mu_1) > 25$ GeV	muon triggers	$m_{\mu\mu} > 70$ GeV	$110 < m_{\mu\mu} < 160$ GeV
ggF	3.25e+04	2.01e+04	[illegible]	1.98e+04	1.97e+04	1.91e+04
VBF	2.46e+03	1.60e+03	[illegible]	1.58e+03	1.58e+03	1.53e+03
ggF+VBF	3.50e+04	2.17e+04	[illegible]	2.14e+04	2.13e+04	2.06e+04
Z+0p	4.55e+09	1.69e+09	[illegible]	[illegible]	1.55e+09	2.34e+07
Z+1p	1.17e+09	4.85e+08	4.79e+08	[illegible]	4.61e+08	8.39e+06
Z+2p	4.21e+08	1.81e+08	1.79e+08	[illegible]	1.73e+08	3.36e+06
Z+3p	1.42e+08	6.21e+07	6.17e+07	[illegible]	[illegible]	1.23e+06
Z+4p	4.52e+07	1.95e+07	1.94e+07	[illegible]	[illegible]	4.32e+05
Z+5p	1.75e+07	7.35e+06	7.32e+06	7.19e+06	[illegible]	1.58e+05
Z+np	6.34e+09	2.45e+09	2.36e+09	2.33e+09	[illegible]	3.70e+07
top	1.46e+09	2.63e+07	2.50e+07	2.46e+07	1.48e+07	4.23e+06
WW	3.84e+07	2.39e+06	2.29e+06	2.25e+06	1.48e+06	4.25e+05
Total bkg	7.84e+09	2.48e+09	2.39e+09	2.36e+09	2.29e+09	4.16e+07

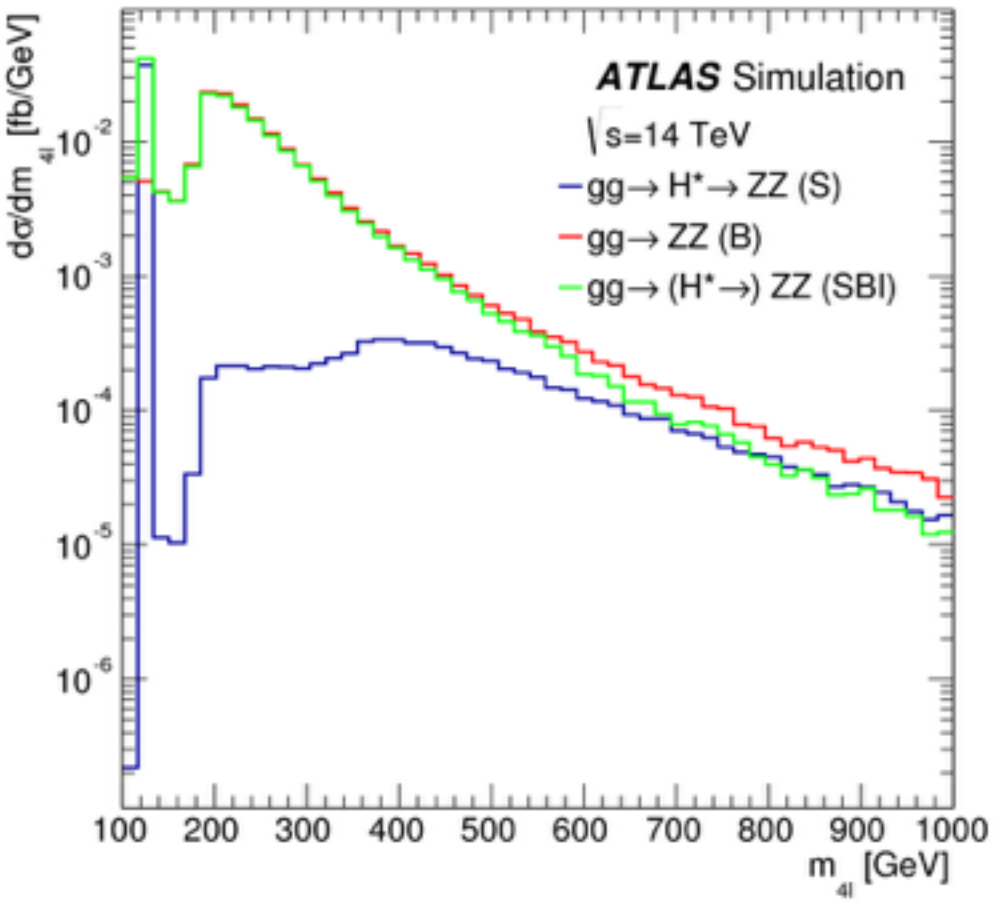
- In large mass window: 19,000 ggF signal events, 1500 VBF signal events, 40M background events
- Fit $m(\mu\mu)$ shape

Scoping Scenario	$\langle\mu\rangle$	Overall significance	$\Delta\mu$ w/ syst. errors	$\Delta\mu$ w/o syst. errors
275M-Reference	200	8.6	$^{+0.18}_{-0.16}$	$^{+0.13}_{-0.13}$

Scoping Scenario	$\langle\mu\rangle$	VBF significance	$\Delta\mu_{\text{VBF}}$ w/ syst. errors	$\Delta\mu_{\text{VBF}}$ w/o syst. errors
275M-Reference	200	1.4	$^{+0.99}_{-0.99}$	$^{+0.98}_{-0.99}$

Γ_H from Off Shell Couplings

ATL-PHYS-PUB-2015-024



- $H \to ZZ \to 4\ell$: Use the interference between off-shell and on-shell production in ***WW*** and ***ZZ*** final state to measure $\Gamma(H)$
- Depends on the knowledge of the k-factor between signal and background, $R_{H^*}{}^{B}$
- Also considered 10 % systematic uncertainty due to $qq \to ZZ$ normalisation
  - For **3000 fb^{-1}** and $\sigma(R_{H^*}{}^{B}) = 10\%$:
    - Stat uncertainties only: $\mu_{\text{off-shell}} = 1.00^{+0.23}_{-0.27}$
    - Stat+syst uncertainties: $\mu_{\text{off-shell}} = 1.00^{+0.43}_{-0.50}$

➡ Combined with on-shell measurement, assuming off-shell measurement dominates, for $\Gamma = \Gamma_{SM}$ gives
$\Gamma_H = 4.2^{+1.5}_{-2.1}$ **MeV (stat+sys)**

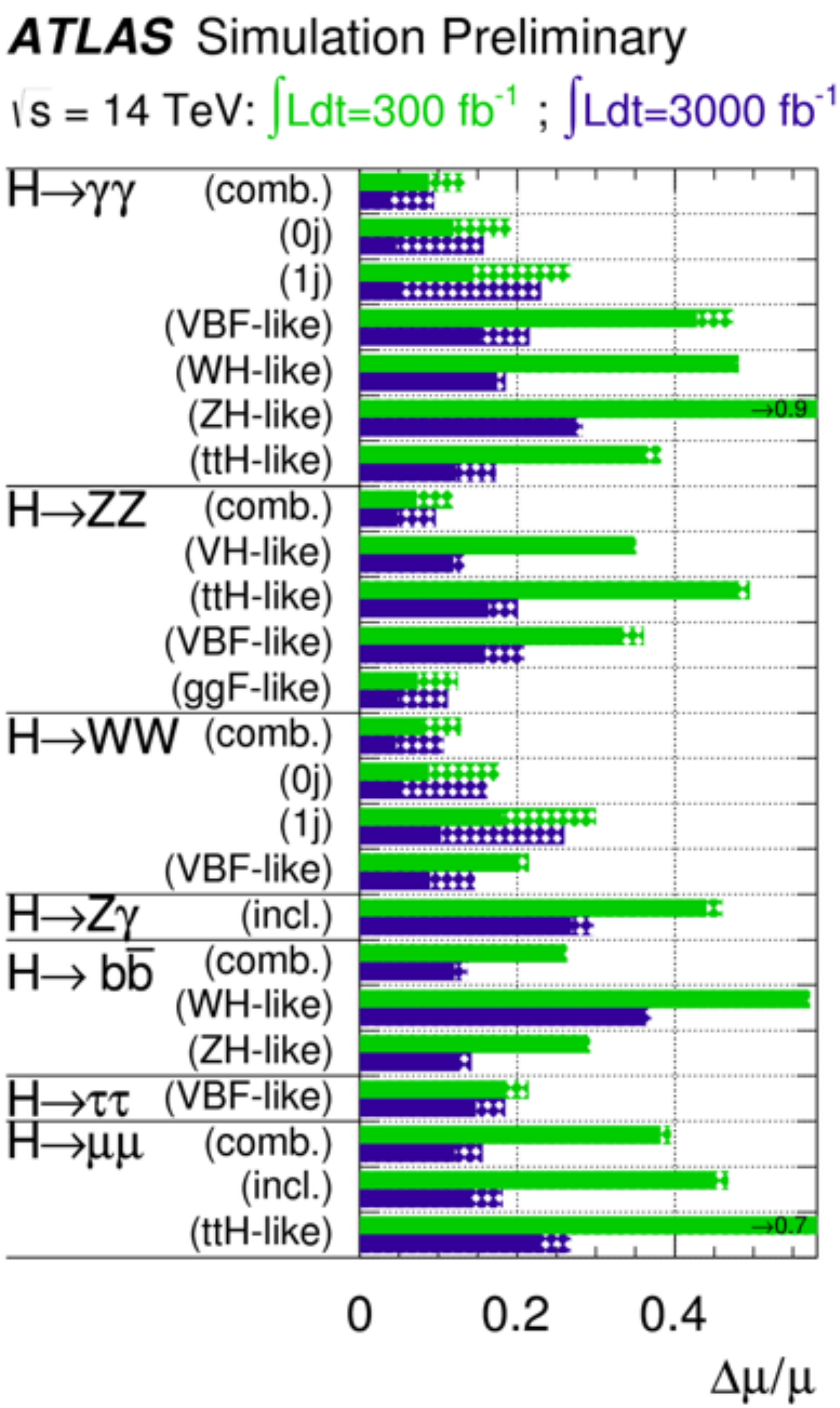
Higgs Properties Summary

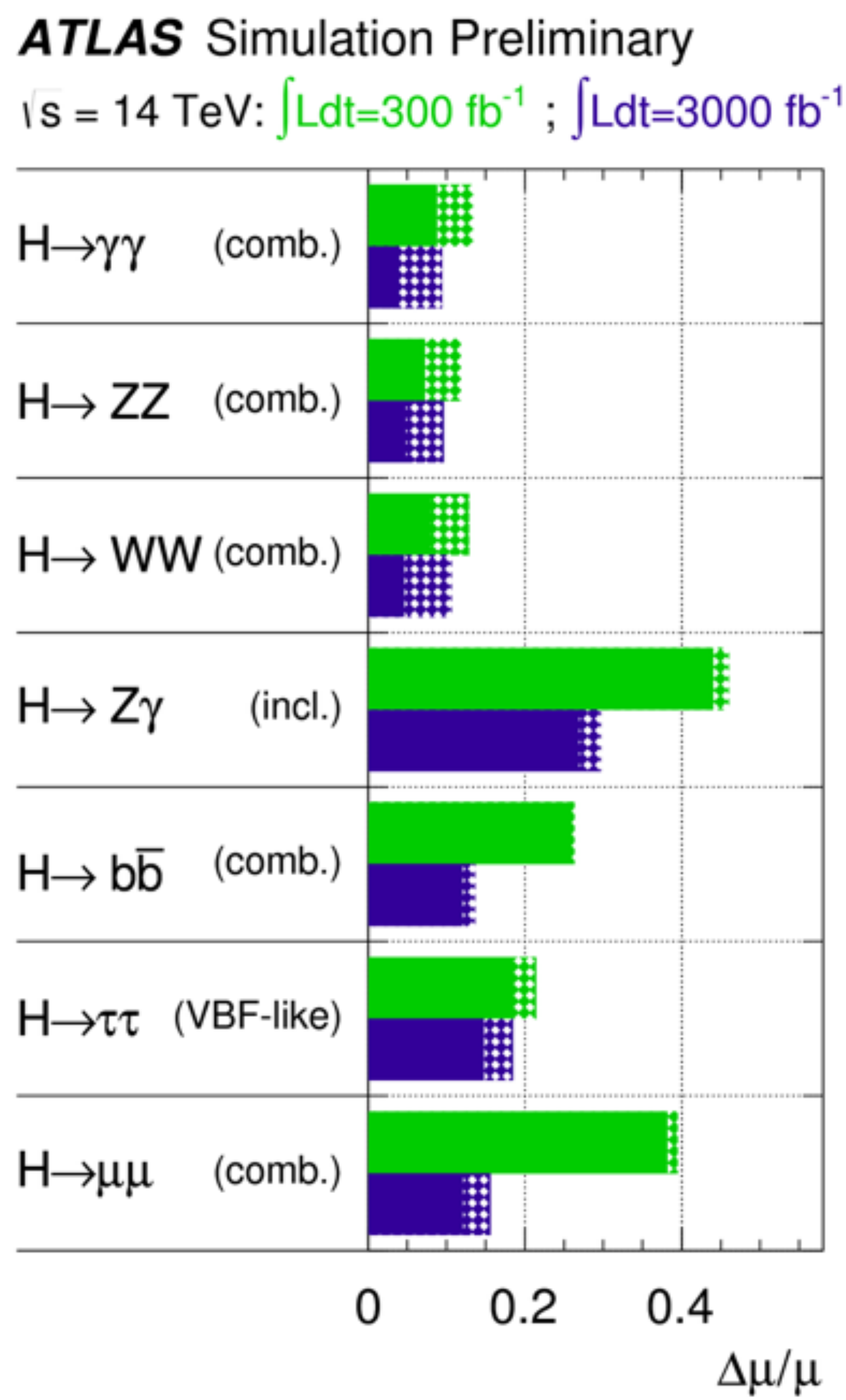
- New analyses since ECFA 2014 workshop

Analysis	Results
$H \to J/\psi\ \gamma$	BR < 44 × 10^{-6} @95%
bbH, $H \to \gamma\gamma$ (not approved)	0.2 σ
VBF $H \to W^+W^-$ (<μ> = 200)	Δμ/μ ≃ 14 to 20%
VBF $H \to ZZ \to 4\ell$ (<μ> = 200)	Δμ/μ ≃ 15 to 18%
ggF: $H \to \mu^+\mu^-$ (not approved)	Δμ/μ ≃ 13 to 18%
VBF: $H \to \mu^+\mu^-$ (not approved)	Δμ/μ ≃ 100%

Backup

Backup: ECFA 2014 Couplings





Backup: ECFA 2014 Couplings