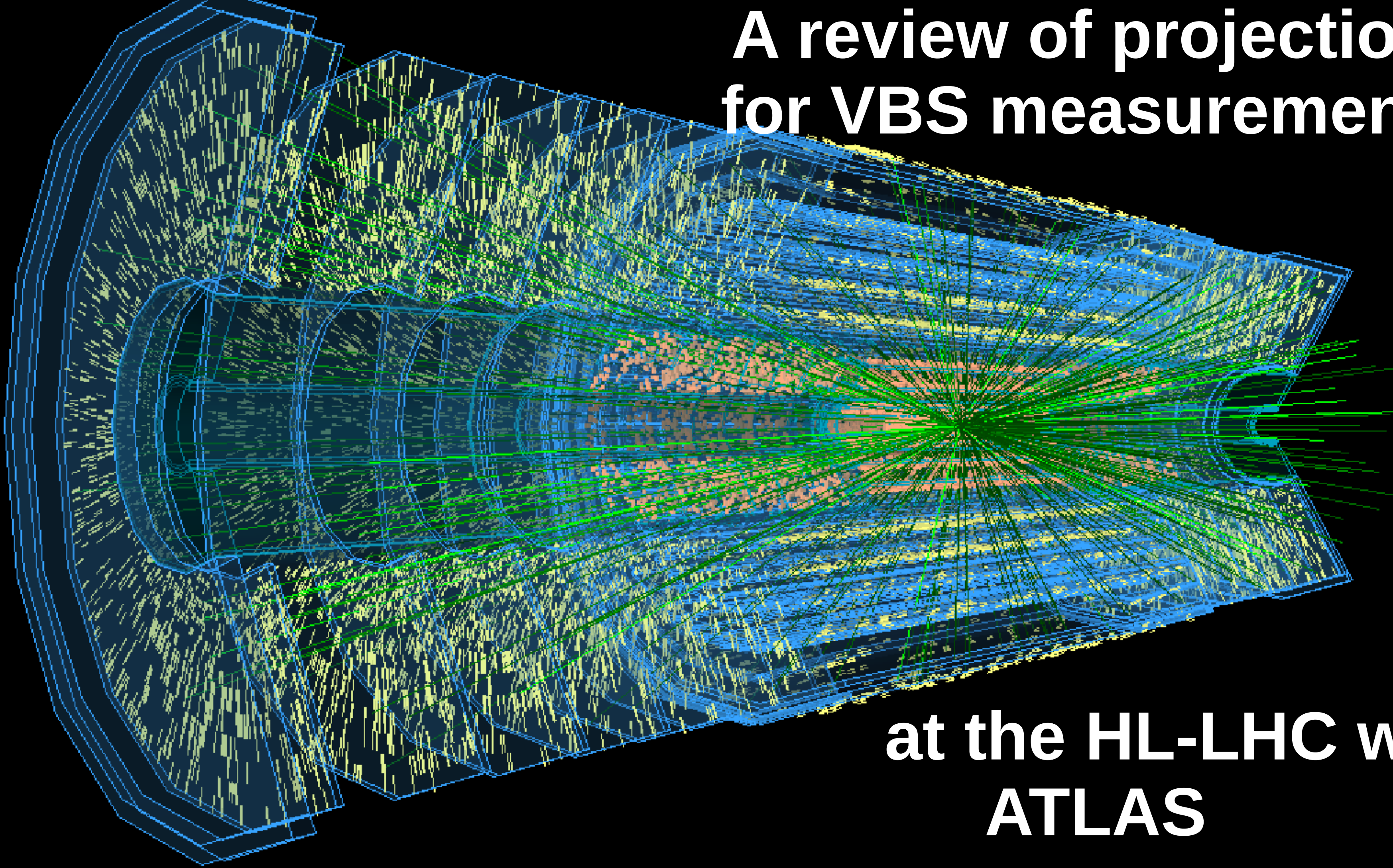
A review of projections for VBS measurements at the HL-LHC with ATLAS



Kristin Lohwasser on behalf of the ATLAS collaboration
University of Sheffield

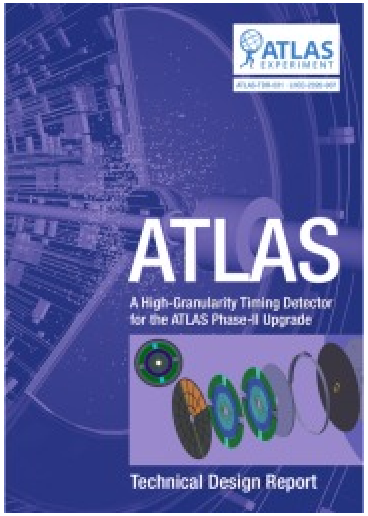
European Research Council
Established by the European Commission

The University Of Sheffield.

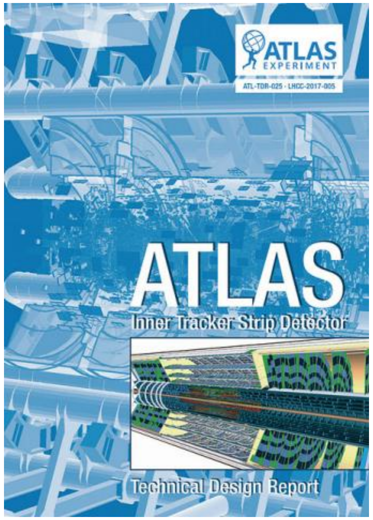
VBS at Snowmass, January 25th 2021

ATLAS at the HL-LHC: What to expect?

- Upgrade during Long Shutdown 3 to prepare for HL-Lumi:
  - → prepare for increased pile-up and radiation
  - → maintain detector performance
  - → **unlock physics potential**

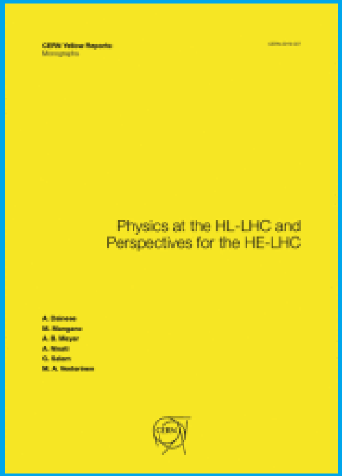


- Prospects updated (European Strategy for Particle Physics)
- Expected integrated luminosity: 3000 fb^{-1}
- **Substantial detector upgrades (see talk K. Potamianos, Tuesday 14.50):**
  - → trigger: 10 kHz bandwidth:
  - → all-silicon tracker extends up to $|\eta| = 4.0$
  - → high granularity timing ($2.4<|\eta|<4.0$, 30 ps)



→ extended coverage
→ decreased trigger p_T thresholds
→ suppression of pile-up

- **Collection of ATLAS+CMS prospects in HL-LHC Yellow report: https://cds.cern.ch/record/2651134 (2019)**
  - [1] The W+W- scattering cross section (ATL-PHYS-PUB-2018-052)
  - [2] VBS in WZ (fully leptonic) (ATL-PHYS-PUB-2018-023)
  - [3] Electroweak vector boson scattering in the WW/WZ $\rightarrow \ell\nu qq$ final state (ATL-PHYS-PUB-2018-022)

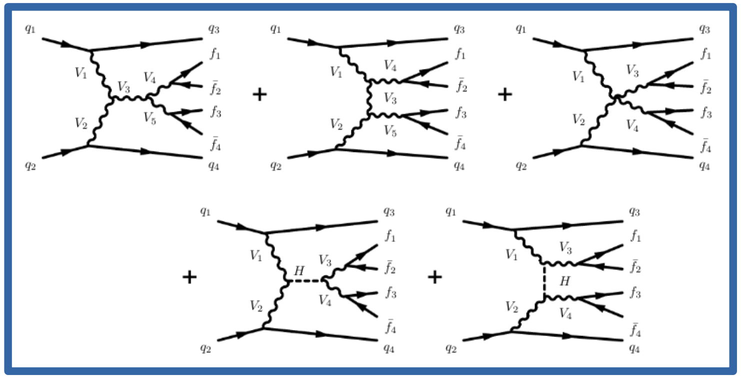


- **ECFA HL-LHC (2016/17)**
  - [4] Studies on the impact of an extended Inner Detector tracker and a forward muon tagger on W±W± scattering in pp collisions (ATL-PHYS-PUB-2017-023)
  - [5] Measurement prospects for VBF $H \rightarrow WW^{(*)} \rightarrow e\nu\mu\nu$ (ATL-PHYS-PUB-2016-018)
  - [6] Prospective results for vector-boson fusion-mediated Higgs-boson searches in the four lepton final state at the High Luminosity Large Hadron Collider (ATL-PHYS-PUB-2016-008)
- **Snowmass on the Mississippi (2013)**
  - [7] Studies of Vector Boson Scattering And Triboson Production with an Upgraded ATLAS Detector at a High-Luminosity LHC (ATL-PHYS-PUB-2013-006)
- **European Strategy for Particle Physics (2012)**
  - [8] Studies of Vector Boson Scattering with an Upgraded ATLAS Detector (ATL-PHYS-PUB-2012-005)

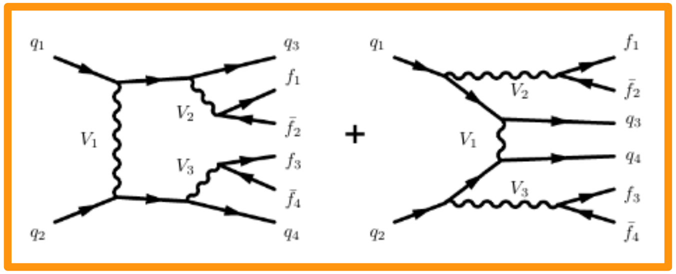
WW production (dilepton channel) [1,4,7,8]

- **Same-sign WW is one of the most studied process for HL-LHC** because of its sensitivity to longitudinal scattering amplitude of VV

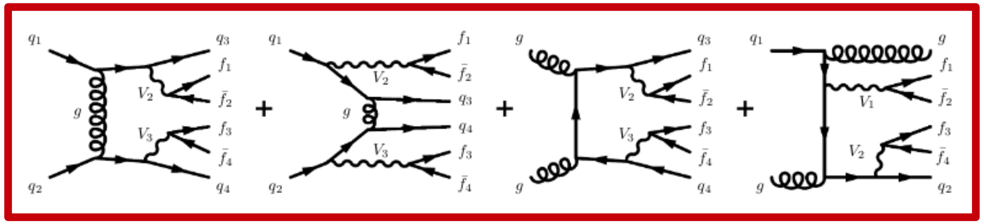
WWjj EWK with scattering topology
→ small signal with large backgrounds
(relevant for all VVjj processes)



WWjj EWK without scattering topology



WWjj QCD



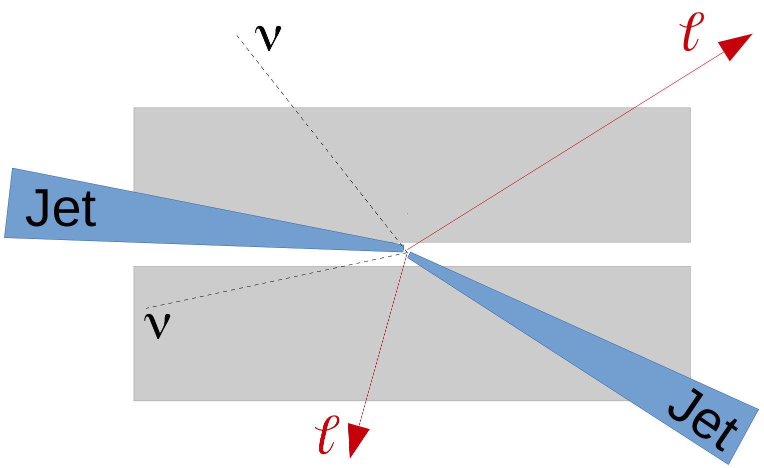
- Two recent results ($\sqrt{s}$ = 14 TeV) with focus on:
  - → **comparison of detector scenarios**
  - → **extraction of longitudinal compoment**

WW: Detector study (dilepton channel) [4]

- **Scenarios considering improvements from new ITK tracking detector):**

	Applied range for jet vertex requirement	Lepton η range
No forward tracking	$\|\eta_{\text{jet}}\| \leq 2.5$	$\|\eta_{e,\mu}\| \leq 2.7$
Forward tracking for jets only	$\|\eta_{\text{jet}}\| \leq 3.8$	$\|\eta_{e,\mu}\| \leq 2.7$
Forward tracking for jets and electrons	$\|\eta_{\text{jet}}\| \leq 3.8$	$\|\eta_{e}\| \leq 4.0$, $\|\eta_{\mu}\| \leq 2.7$
Forward tracking for jets, electrons and muons	$\|\eta_{\text{jet}}\| \leq 3.8$	$\|\eta_{e,\mu}\| \leq 4.0$

- **Selection** (based on 8 TeV)
  - → 2 leptons (p_T>25 GeV)
  - → $m(\ell\ell)$>20 GeV, $\Delta(m_{ee},m_Z)$>10 GeV
  - → E_T^{miss} > 40 GeV
  - → jet separation $\Delta\eta(j,j)$ > 2.4
  - → jet p_T > 30 GeV (70 GeV w/o vtx tag)
  - → m_{jj} > 500 GeV
  - → no additional low-p_T leptons
  - → lepton centrality ζ >0



Leptons within the rapidity range spanned by the jets

$$\zeta = \min[\min(\eta_{\ell 1},\eta_{\ell 2}) - \min(\eta_{j1},\eta_{j2}), \max(\eta_{j1},\eta_{j2}) - \max(\eta_{\ell 1},\eta_{\ell 2})]$$

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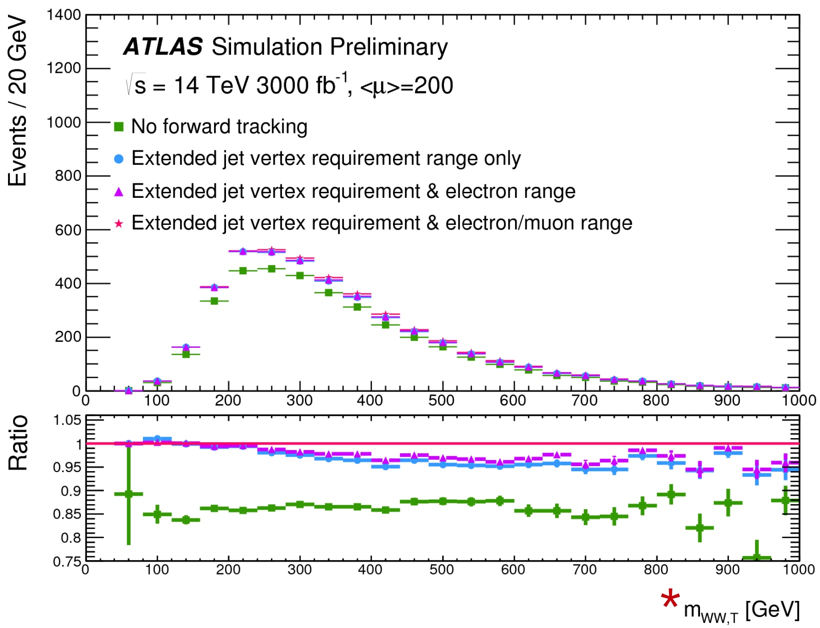
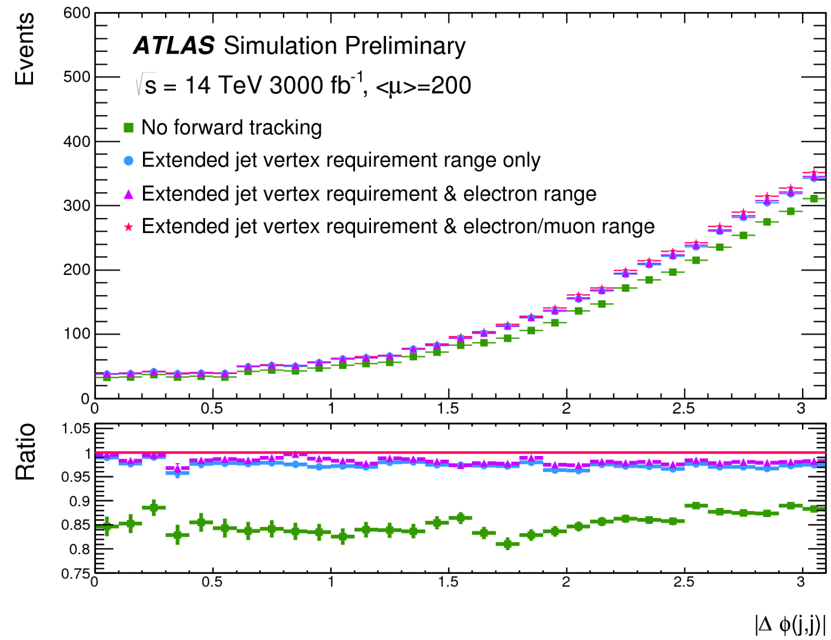
Simplifications:

- → Simulation of only WW and WZ (QCD+EWK)
- → non-dominant backgrounds estimated (8 TeV result)
- → Particle-level objects smeared based on full-GEANT4
- → 15% systematics (8 TeV result)

WW: Detector study (dilepton channel) [4]





- Larger acceptance with extended detectors
- Estimated significance of Z_0=17 - 19

$$\frac{\Delta\mu}{\mu} = \frac{\sqrt{N_{\rm sig} + N_{\rm bkg} + \sum_{i=0}^{\rm bkg}\left(N_i \sigma_i\right)^2}}{N_{\rm sig}}$$

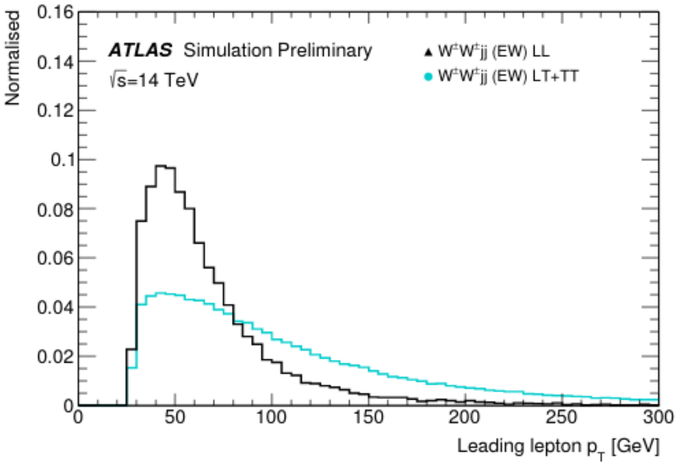
	$\frac{\Delta\mu}{\mu}$ ee	$e\mu$	μe	$\mu\mu$	$\frac{\Delta\mu}{\mu}$ Combined
No forward tracking	18%	11%	9.8%	6.1%	4.5%
Forward tracking for jets only	19%	11%	10%	6.2%	4.6%
Forward tracking for jets and electrons	18%	11%	9.8%	6.2%	4.6%
Forward tracking for jets, electrons and muons	18%	10%	8.9%	5.1%	4.0%

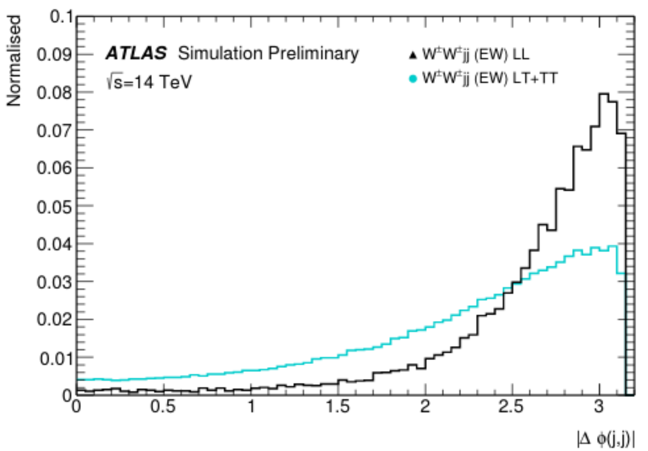
* $m_{WW,T} = \sqrt{\left(E_T^{\ell\ell} + E_T^{\rm miss}\right)^2 - \left|p_T^{\ell\ell} + E_T^{\rm miss}\right|^2}$, where $E_T^{\ell\ell} = \sqrt{\left|p_T^{\ell\ell}\right|^2 + m_{\ell\ell}^2}$

WW Update: Optimized selection [1]

- Added full suite of backgrounds (VV,VVjj, V+jets, top)

- Optimized selection using longitudinal component as signal (though mostly serves to reject more QCD)





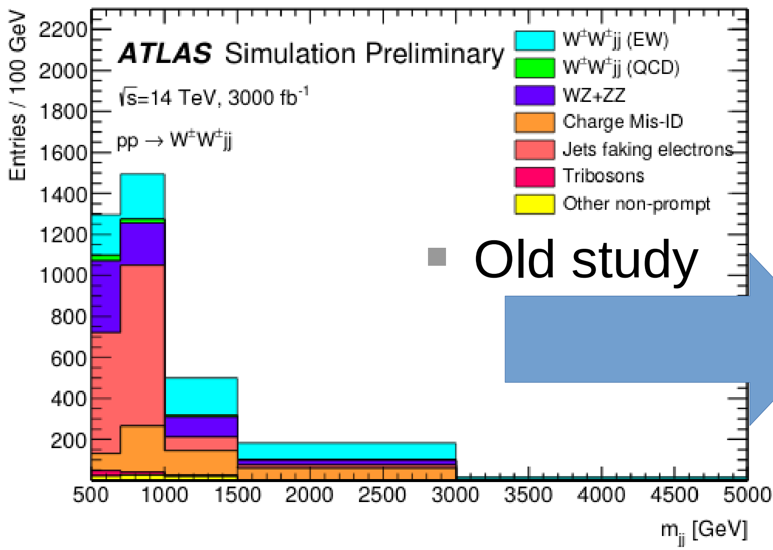
Selection requirement	Selection value
Signal lepton kinematics	**p_T > 28 GeV (leading lepton)**
	p_T > 25 GeV (subleading lepton)
Tag jet kinematics	**p_T > 90 GeV (leading jet)**
	p_T > 45 GeV (subleading jet)
Dilepton separation and charge	Exactly two signal leptons with $\Delta R_{\ell,\ell} \geq 0.3$, $q_{\ell_1} \times q_{\ell_2} > 0$
Dilepton mass	**$m_{\ell\ell}$ > 28 GeV**
Z_{ee} veto	$\lvert m_{ee} - m_Z \rvert > 10$ GeV
E_T^{miss}	$E_T^{miss} > 40$ GeV
Jet selection and separation	at least two jets with $\Delta R_{\ell,j} > 0.3$
Number of b-tagged jets	0
Dijet rapidity separation	$\Delta\eta_{j,j} > 2.5$
Number of additional preselected leptons	0
Dijet mass	**m_{jj} > 520 GeV**
Lepton centrality	**ζ > -0.5**

→ Increase momentum thresholds

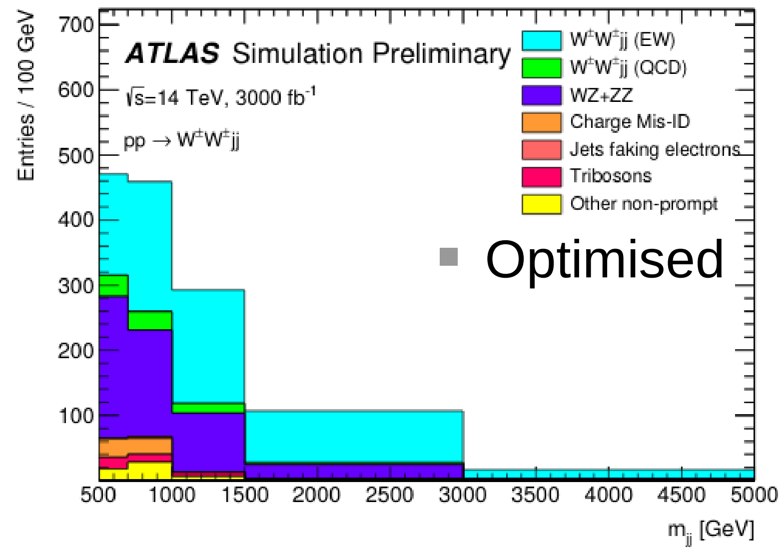
→ increase invariant jet mass requirement

→ relax centrality critrium

WW Update: Opimized selection [1]



- Old study

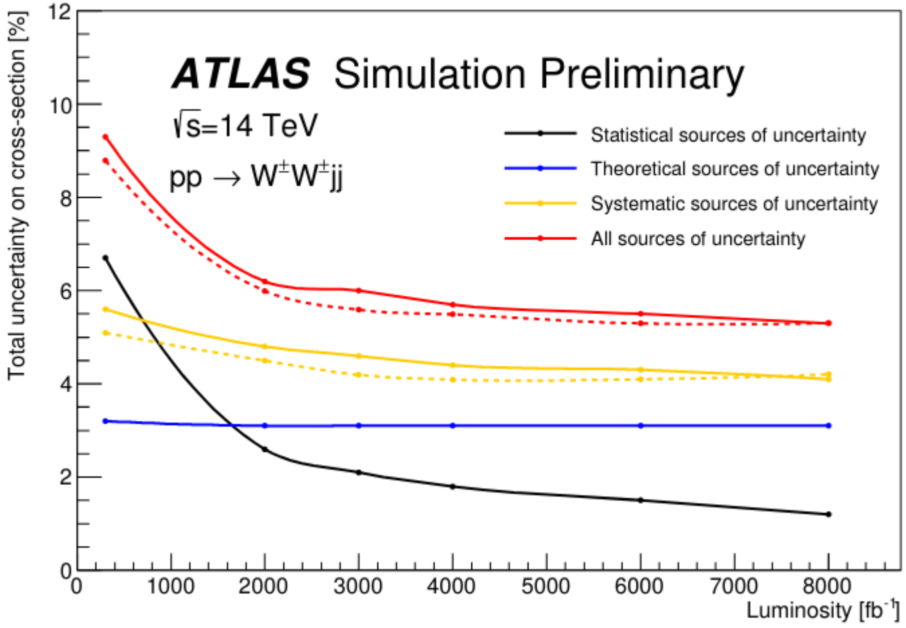


- Optimised

Source	Uncertainty (%) Baseline	Uncertainty (%) Optimistic
$W^{\pm}W^{\pm}jj$ (EW)	3	
Luminosity	1	
Trigger efficiency	0.5	
Lepton reconstruction and identification	1.8	
Jets	2.3	
Flavour tagging	1.8	
Jets faking electrons	20	
Charge mis-ID	25	
$W^{\pm}W^{\pm}jj$ (QCD)	20	5
Top	15	10
Diboson	10	5
Triboson	15	10

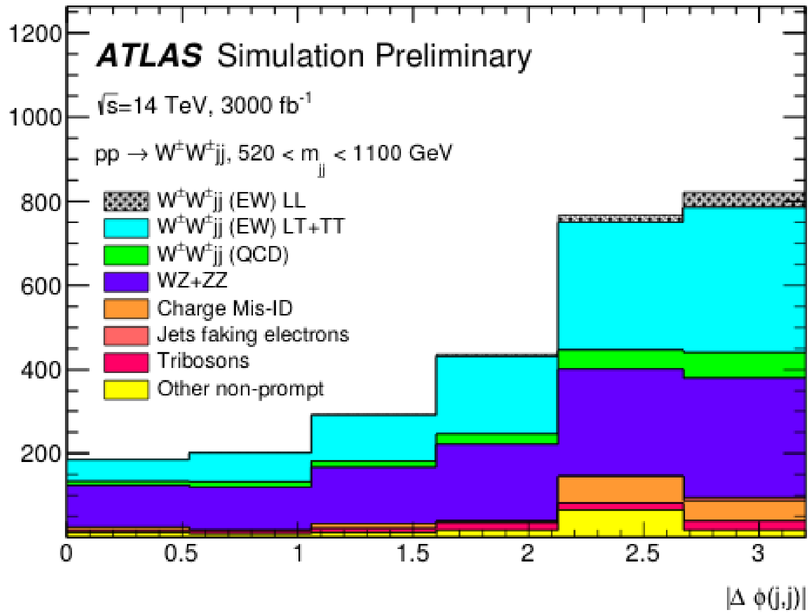
- Experimental systematics taken from the 13 TeV analysis (baseline)
- "Optimistic" scenario reduces uncertainties on-data-driven backgrounds
(mainly from modelling)

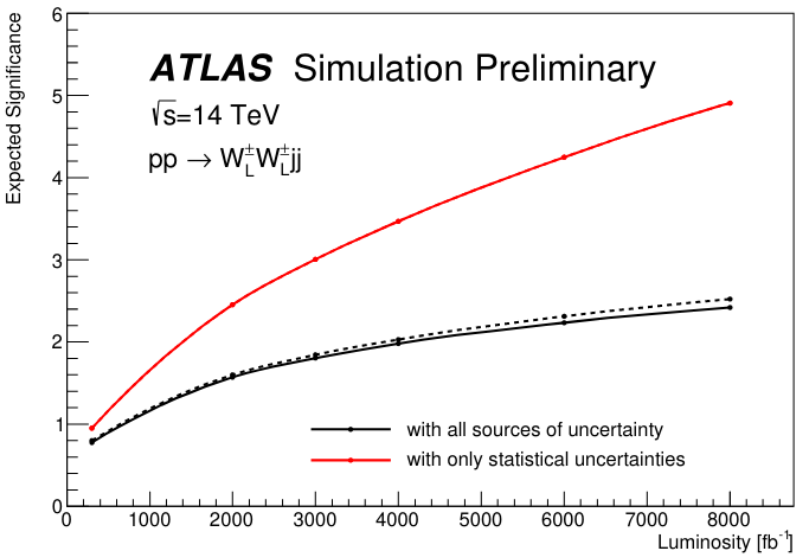
WW Update: Extraction of cross-section [1]

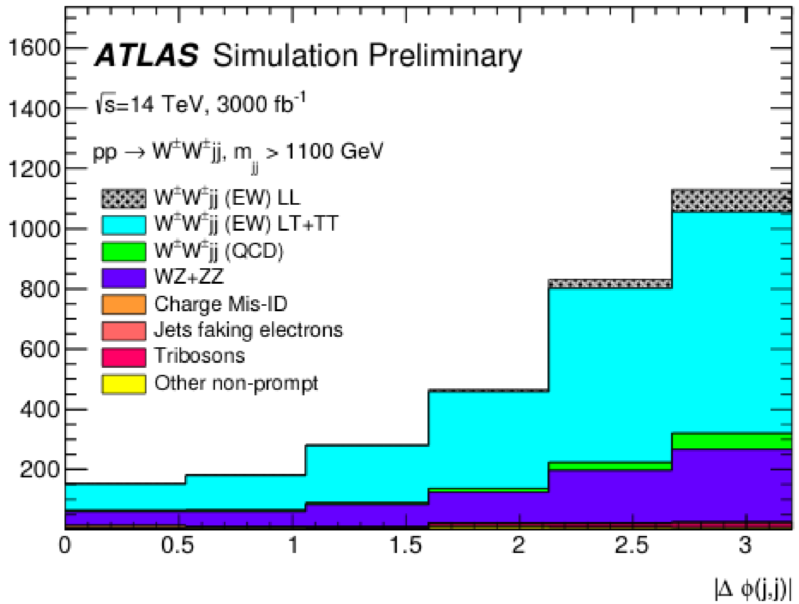


- Statistical uncertainty on expected cross-section improves dramatically with luminosity
- Only weak dependence of systematic uncertainty on the luminosity
- Total uncertainty of 6% is expected → compatible with earlier study

WW Update: Extraction of longitudinal scattering [1]





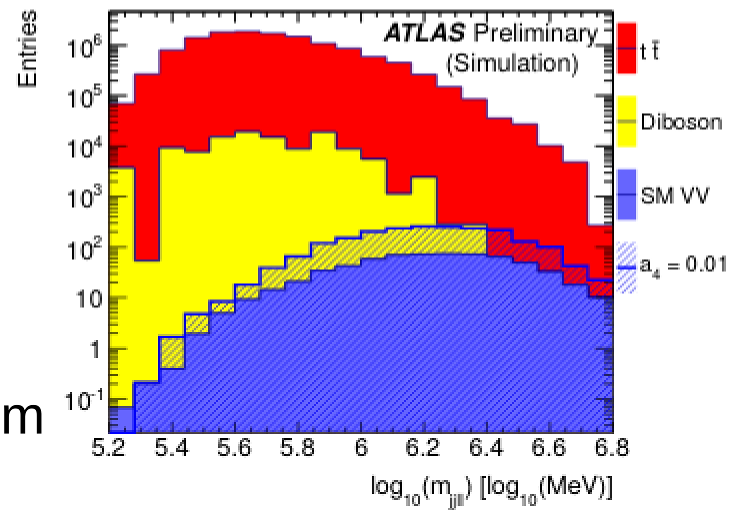


Two-bin likelihood fit to extract **longitudinal scattering signal**

- The expected significance is 1.8 σ, with an expected precision of 47% on the measurement
- Considerable improvements achievable using MVA techniques

WW: earlier studies (dilepton channel) [7,8]

- Investigating BSM models:
  - → **a4** (EW chiral Lagrangian, weak isospin conserving)
  - → **fs0** (Dim-8 operator) (f_{s0} related to a4)



- Main backgrounds either ttbar (constaints from low mass spectrum) or WZ (newer analysis)

- Systematics not discussed (for [7] lepton charge mis-ID from 8 TeV data study used to scale opposite sign WW bkg)

Parameter	dimension	channel	Λ_{UV} [TeV]	300 fb^{-1} 5σ	300 fb^{-1} 95% CL	3000 fb^{-1} 5σ	3000 fb^{-1} 95% CL
$c_{\phi W}/\Lambda^2$	6	ZZ	1.9	34 TeV^{-2}	20 TeV^{-2}	16 TeV^{-2}	9.3 TeV^{-2}
f_{S0}/Λ^4	8	$W^\pm W^\pm$	2.0	10 TeV^{-4}	6.8 TeV^{-4}	4.5 TeV^{-4}	0.8 TeV^{-4}
f_{T1}/Λ^4	8	WZ	3.7	1.3 TeV^{-4}	0.7 TeV^{-4}	0.6 TeV^{-4}	0.3 TeV^{-4}
f_{T8}/Λ^4	8	$Z\gamma\gamma$	12	0.9 TeV^{-4}	0.5 TeV^{-4}	0.4 TeV^{-4}	0.2 TeV^{-4}
f_{T9}/Λ^4	8	$Z\gamma\gamma$	13	2.0 TeV^{-4}	0.9 TeV^{-4}	0.7 TeV^{-4}	0.3 TeV^{-4}

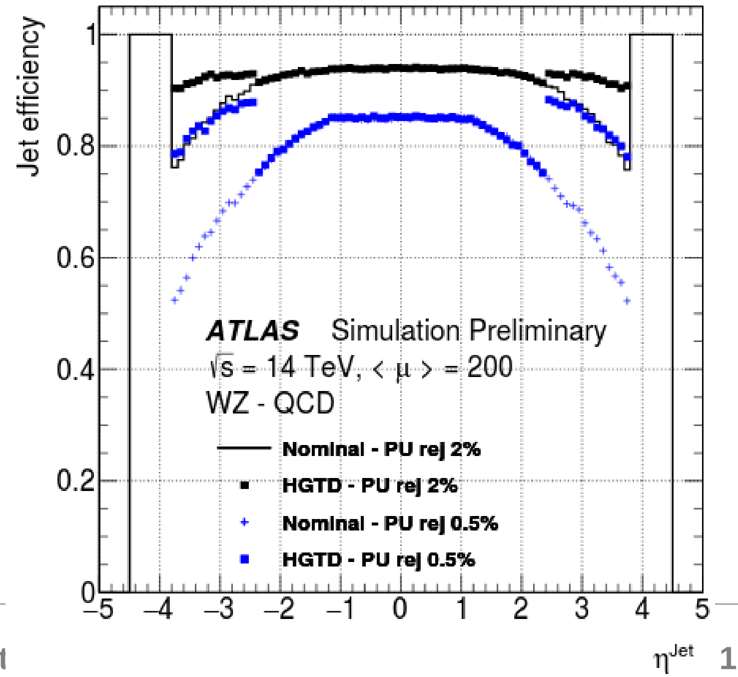
WZ: (fully leptonic channel) [2,7]

- **Includes High Granularity Timing detector and detailed studies on pile-up rejections (0.5% vs 2% nominal)**

- All major detector effects are included (mostly parametrized):
  - → Energy resolution, ID and trigger efficiencies for leptons and jets
  - → Pile-up added with $<\mu>=200$
  - → “fake” probability for jets to be reconstructed as electrons
  - → jets below 100 GeV and $|\eta|<3.8$ associated with hard scatter using track-confirmation
  - → Smearing of missing energy

- Expected integrated luminosity: 3000 fb^{-1} with $\sqrt{s}$ = 14 TeV

- **Main objectives:**
  - → Study selections (run-2 benchmark)
  - → Polarization studies
  - → aQGC studies



WZ: Selection studies (fully leptonic channel) [2]

- Different selections:
  → **Run-2 optimised**
  (only central leptons, |η|<2.5, forward jet p_T>70 GeV)

  → **ATLAS HL-LHC setting**
  (increased acceptance for central jets (lower pT threshold))

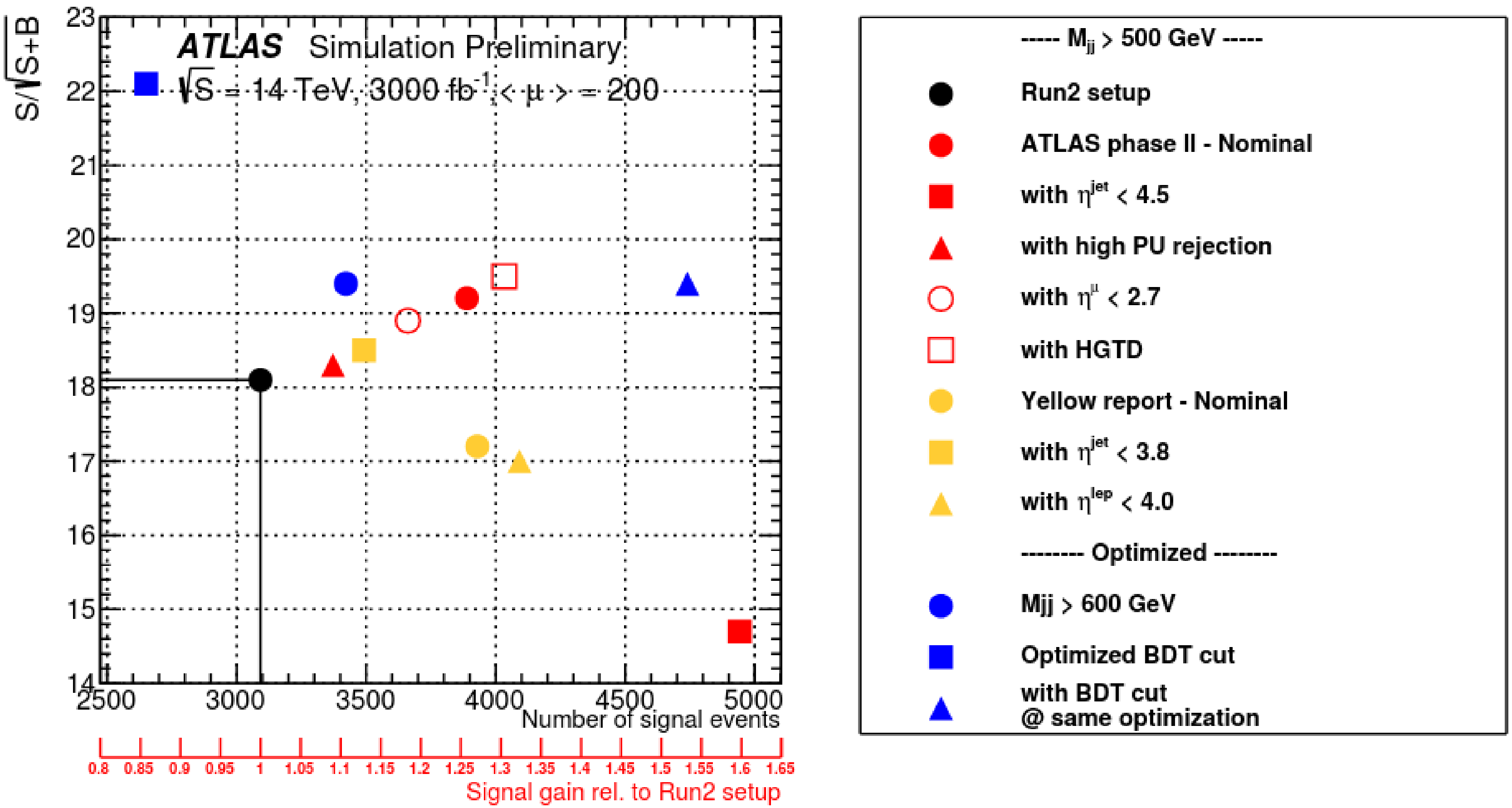
  → **Yellow Report settings**
  (baseline to compare within HL-LHC YR to other channels)

	ATLAS	YR
Leptons	3 leptons	
p_T^{lep}	> 15 GeV	
$\|\eta^{lep}\|$	< 4.0	< 3.0
	At least one lepton with p_T^{lep} > 25 GeV	
ZZ Veto	No extra leptons with p_T^{lep} > 7 GeV	
Z boson	SFOC lepton pair $\|m_{ll} - M_Z\|$ < 10 GeV	
W boson	p_T^{lW} > 20 GeV m_T^W > 30 GeV	
Jets	2 jets	
	p_T^{jet} > 30 GeV $\|\eta^{jet}\|$ < 3.8 (see text) opp. hemisphere M_{jj} > 200 GeV	p_T^{jet} > 30 GeV for $\|\eta^{jet}\|$ < 3.8 p_T^{jet} > 50 GeV for 3.8 < $\|\eta^{jet}\|$ < 4.5 $\|\delta_{jj}\|$ > 2.5 M_{jj} > 200 GeV
Final selection		
Benchmark	M_{jj} > 500 GeV	
Optimised	M_{jj} > 600 GeV or BDT	

  → **Different detector settings**
  (same cuts, different efficiencies, either using HGTD or high PU rejection)

  → **Optimized BDT selection** (25 variables to get best possible results)

WZ: Selection studies (fully leptonic channel) [2]



→ **Uncertainty dominated by jet-related syst and WZ QCD background**
→ better control through further control regions in data

WZ: Polarization studies (fully leptonic channel) [2]

Express differential cross sections as function of polarization states (L-eft / R-ight and longitudinal 0)

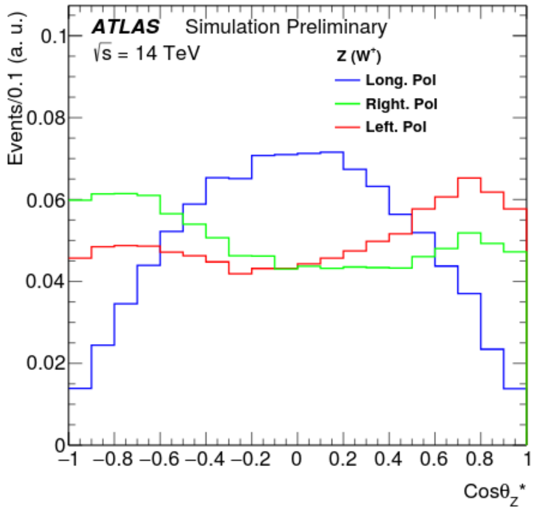
$$\frac{1}{\sigma}\frac{d\sigma}{d\cos\theta^*_{W^\pm}} = \frac{3}{8}FL(1 \mp \cos\theta^*_W)^2 + \frac{3}{8}FR(1 \pm \cos\theta^*_W)^2 + \frac{3}{4}F0(1 - \cos\theta^{*\,2}_W),$$

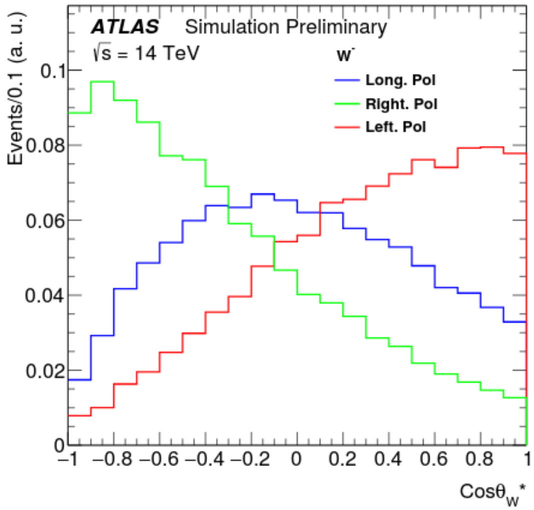
$$\frac{1}{\sigma}\frac{d\sigma}{d\cos\theta^*_Z} = \frac{3}{8}FL(1 + 2A\cos\theta^*_Z + \cos\theta^{*\,2}_Z) + \frac{3}{8}FR(1 - 2A\cos\theta^*_Z + \cos\theta^{*\,2}_Z) + \frac{3}{4}F0(1 - \cos\theta^{*\,2}_Z),$$

cosθ* refers to decay angle of the lepton (or anti-lepton forW+) w/r to the boson direction in the WZ rest-frame

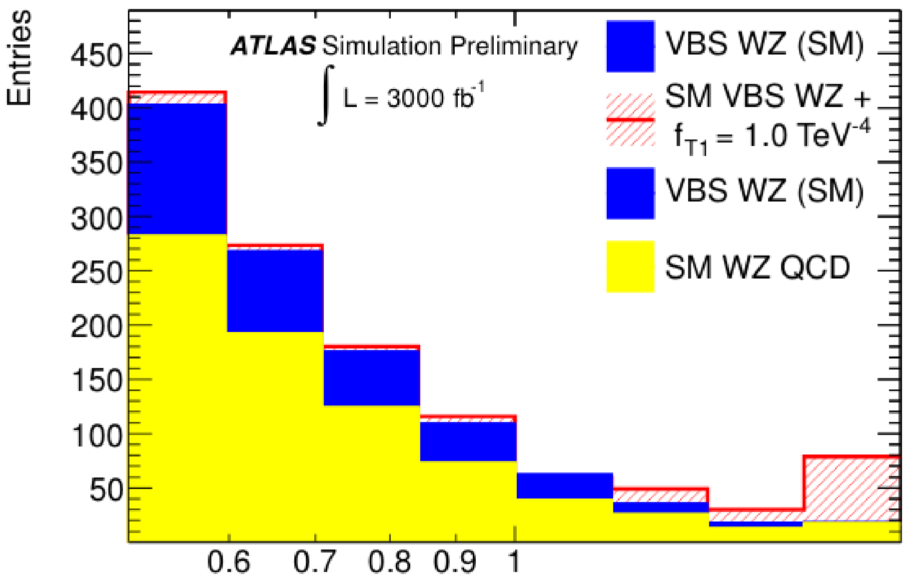
- Extracted using templates
- Exp. Sig. of F0 for *single boson*: 0.5-3.5 (different selections + ATLAS/CMS combination)
- Double polarization < 1 σ

(i.e. $W_0Z_T + W_TZ_0 + W_TZ_T + W_0Z_0$)





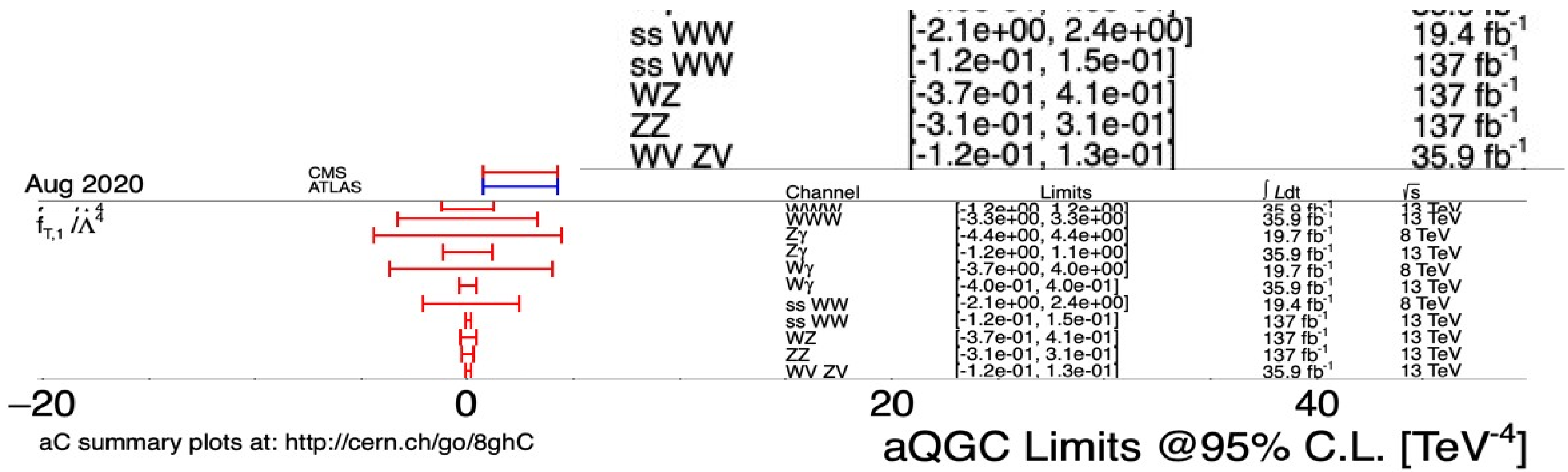
WZ: quartic coulings (fully leptonic channel) [7]



- Older study with basic selection and considering only WZ QCD background without systematic [7] gives projection on aQGC limits

	$300\,\mathrm{fb}^{-1}$	$3000\,\mathrm{fb}^{-1}$
f_{T1}/Λ^4	$1.3\ \mathrm{TeV}^{-4}$	$0.6\ \mathrm{TeV}^{-4}$

Close to current limits



H→WW(*): projections (dilepton channel) [5]

- Investigation of three detector scenarios with $\sqrt{s}$ = 14 TeV – <μ>=200

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

- Using 8 TeV MC samples scaled to 14 TeV cross-section
- Performance for leptons from 8 TeV full detector simulation
- Missing ET and jet performance (PU rejection) from parametrization studies
- Background uncertainties assumed to be reduced w/r to Run-2
  Signal: size is varied

Syst. unc.	ggF (%)	VBF (%)
QCD N_{jet} cross-section	43	1
QCD acceptance	4	4
PDF	8	3
UE/PS	9	3
Total	44	6

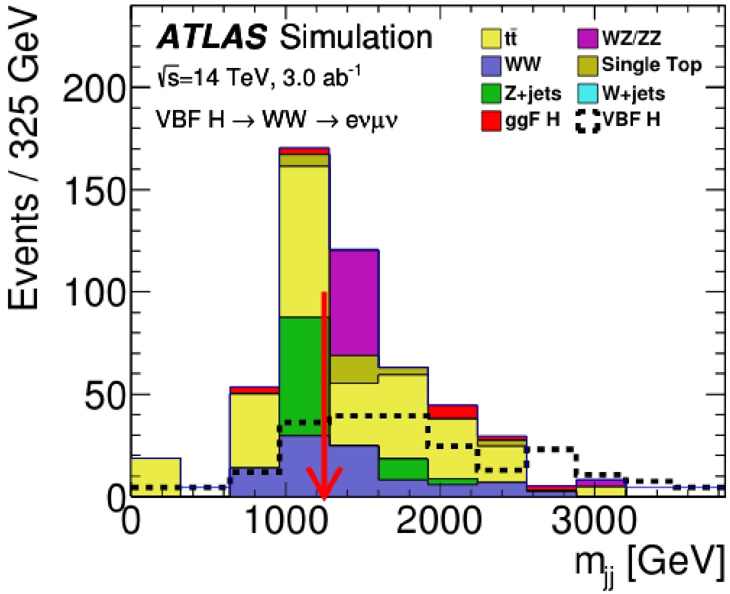
Bkg. process	$N_{\text{jet}} \geq 2$ 14 TeV (%)	$N_{\text{jet}} \geq 2$ Run-1 (%)
WW	10	30
VV	10	20
$t\bar{t}$	10	33
$tW/tb/tqb$	10	33
Z+jets	10	20
W+jets	20	30

$H\rightarrow WW(*)$: projections (dilepton channel) [5]

- Restriction to cut-based analysis

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 $Z/\gamma^* \rightarrow \tau\tau$ 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
$H \rightarrow WW^* \rightarrow e\nu\mu\nu$ topology	$m_{\ell\ell} < 60$ GeV $\Delta\phi_{\ell\ell} < 1.8$ $m_{\text{T}} < 1.07 \times m_H$

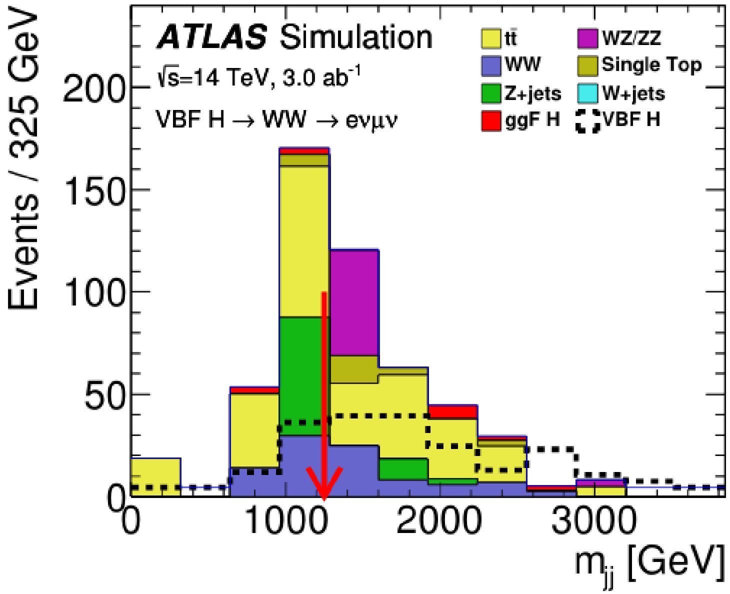
H→WW(*): projections (dilepton channel) [5]



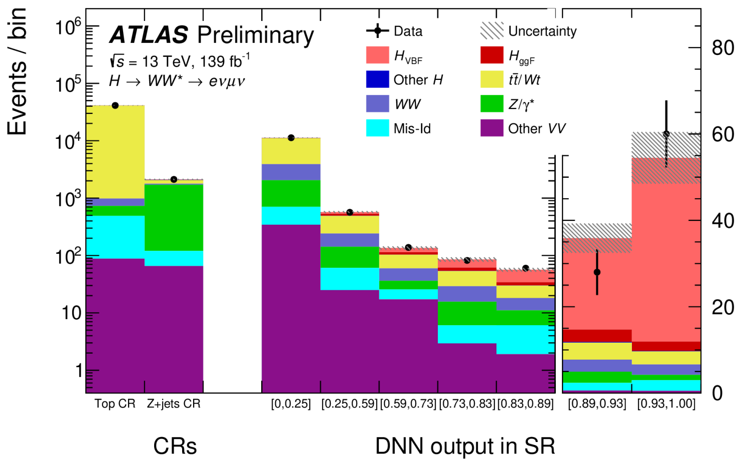
Scoping scenario	Δ_μ			Significance (σ)		
Signal unc.	Full	1/2	None	Full	1/2	None
Reference	0.20	0.16	0.14	5.7	7.1	8.0
Middle	0.25	0.21	0.20	4.4	5.2	5.4
Low	0.39	0.32	0.30	2.7	3.3	3.5

Full, ½, None → size of signal theory uncertainty

H→WW(*): projections (dilepton channel) [5]



- Comparison with Run-2 results:
  $\Delta\mu/\mu = 0.22$
  https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CONFNOTES/ATLAS-CONF-2020-045/

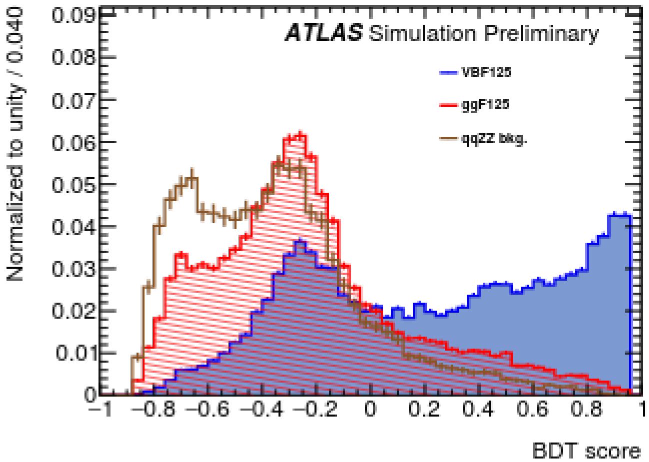


Scoping scenario Signal unc.	Full	Δ_μ 1/2	None	Full	Significance (σ) 1/2	None
Reference	0.20	0.16	0.14	5.7	7.1	8.0
Middle	0.25	0.21	0.20	4.4	5.2	5.4
Low	0.39	0.32	0.30	2.7	3.3	3.5

Full, ½, None → size of signal theory uncertainty

H → 4ℓ: projections [6]

- Same Reference / Middle / Low scenarios investigated as for H → WW$^{(*)}$
- Results obtained using a BDT to target VBF final state
- **More realistic (and promising) channel for HL-LHC**



(a) Reference layout

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

H→4ℓ: projections [6]

- Same Reference / Middle / Low scenarios investigated as for H→ WW(*)
- Results obtained using a BDT to target VBF final state
- **More realistic (and promising) channel for HL-LHC as it is still stats dominated**

Production bin	$(\sigma \cdot \mathcal{B})/(\sigma \cdot \mathcal{B})_{SM}$ Observed
	$1.01 \pm 0.08 \pm 0.03 \pm 0.02$
ggF	$0.96 \pm 0.10 \pm 0.03 \pm 0.03$
VBF	$1.21 \pm 0.44\ ^{+0.13}_{-0.08}\ ^{+0.07}_{-0.05}$
VH	$1.44^{+1.13}_{-0.90}\ ^{+0.21}_{-0.14}\ ^{+0.24}_{-0.17}$
ttH	$1.7^{+1.7}_{-1.2} \pm 0.2 \pm 0.2$

(stat.)+(exp.)+(th.)

Scoping scenario	VBF + $2j$ events	ggF + $2j$ events	$qqZZ + 2j$ events	Z_0	$\Delta\mu/\mu$
Statistical uncertainty only					
Reference	192 (168)	287 (140)	39 (16)	10.2	0.152
Middle	218 (167)	454 (155)	69 (15)	9.5	0.157
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Statistical uncertainty + QCD scale var. uncertainty (S-T method)					
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How well have the historical projections aged?

- "Historical" = anything we can test / something we have by now measured
  → mainly predicted before LHC data taking

https://cds.cern.ch/record/391177
ATLAS detector and physics performance : Technical Design Report, 2
best possible parameters using Wy / WZ

- ATLAS technical design report
  → only studies in there on dibosons
  → nothing on VBS
  → additional difficulty from 7,8 TeV runs

Table 16-2 The envisaged statistical precision from single parameter fits for a given coupling, assuming an integrated luminosity of 30 fb^{-1}. The limits are presented for the different sets of variables and the ideal case denote fits at generator level using all available information.

Coupling	95% C.L. $(m_{W\gamma}, \lvert\eta^*\rvert)$	95%C.L. (p_T^{γ}, θ^*)	95%C.L. Ideal case
$\Delta\kappa_\gamma$	0.035	0.046	0.028
λ_γ	0.0025	0.0027	0.0023
Δg_1^Z	0.0078	0.0089	0.0053
$\Delta\kappa_Z$	0.069	0.100	0.058
λ_Z	0.0058	0.0071	0.0055

- Agree within a factor of ~2 (sqrt(3)=1.7) → quite on point

https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CONFNOTES/ATLAS-CONF-2016-043/
(13/fb at 13 TeV, 20/fb at 8 TeV) WZ

Dataset	Coupling	Expected	Observed
13 TeV	Δg_1^Z	[-0.017; 0.032]	[-0.016; 0.036]
	$\Delta\kappa_1^Z$	[-0.18; 0.24]	[-0.15; 0.26]
	λ^Z	[-0.015; 0.014]	[-0.016; 0.015]
8 and 13 TeV	Δg_1^Z	[-0.014; 0.029]	[-0.015; 0.030]
	$\Delta\kappa_1^Z$	[-0.15; 0.21]	[-0.13; 0.24]
	λ^Z	[-0.013; 0.012]	[-0.014; 0.013]

- Systematic uncertainty from PDF/scale

Conclusions

- Have reviewed current HL-LHC projections
- Quite sophisticated: reconstruction level, full backgrounds
- Where comparisons are possible:
  → Projections probably rather on the pessimistic side!
  e.g. because no BDT was used
- Few historical comparisons possible → again looks rather good in terms of how they have aged

Backup slides.

WZ BDT

	ranking
mjj	
PT sublead jet	
Transv. Mass of leading jets	
sum(pT, lep) / (Ej1 + Ej2)	
PT leading jet	
centrality	
[Sum(pT(lep)) / Sum(E(lep)] / [Sum(pT(j) / Sum(E(jet))]	
Largest invariant with an extra jet	
Delta R (angle in space between leading jets)	
1st eigenvalue of leading jets spericity tensor	
Transverse mass of WZ system	
Mass of WZ system	
$\mid \eta j1 - \eta j2 \mid$	
Angle in WZ restframe of the leading jet with the Z axis	
$\phi j1 - \phi j2$	
[Sum(pT(j) / Sum(E(jet))]	
η of the leading jet	

1st eigenvalue of the 3-leading-jet sphericity tensor
$\mid\eta\mid$ of Z boson
$\mid\eta\mid$ of the third lepton
1st eigenvalue of the lepton sphericity tensor
PT leading lepton
$\mid\eta\mid$ of the leading lepton