Vector Boson Scattering at the HL-LHC

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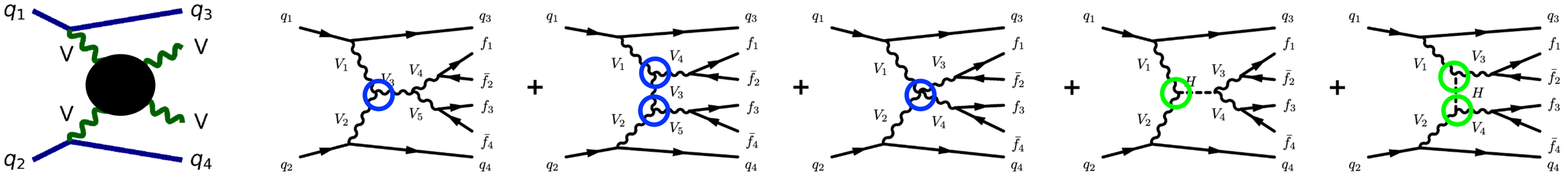
on behalf of the ATLAS and CMS collaborations

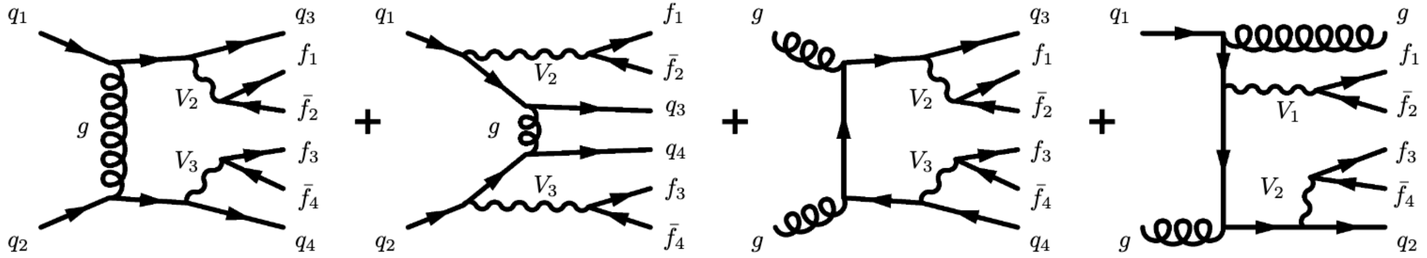
Introduction

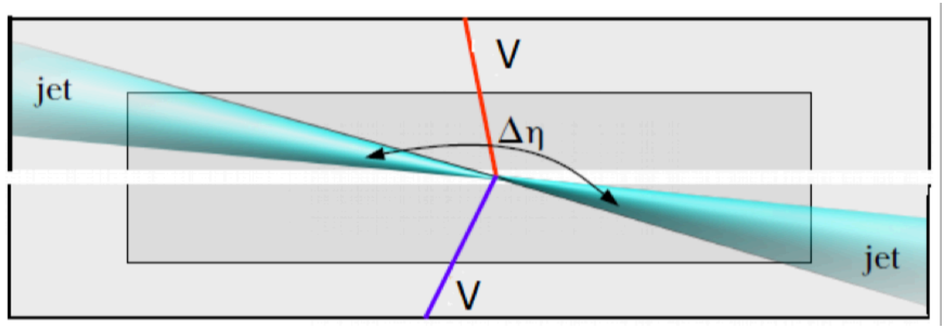
- Vector boson scattering (VBS) is the production of VV (V= W/Z/γ) involving EWK triple and quartic gauge couplings, and Higgs boson exchange at tree level. Provides a test of EWK Symmetry Breaking - still to be proven that presence of discovered Higgs boson preserves the unitarity of the longitudinal polarised VV scattering.



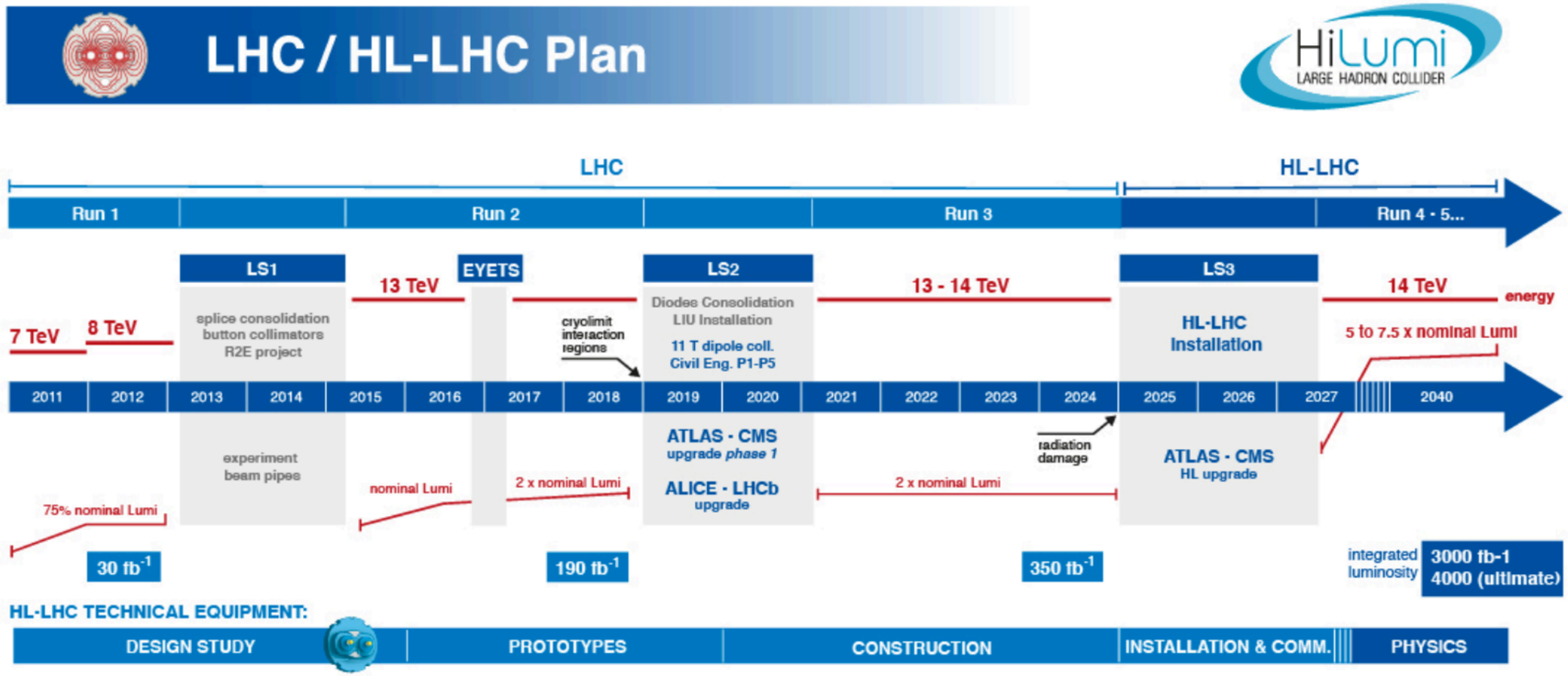
- Clean signature with two forward jets with large dijet invariant mass and |Δη| gap

- Strong + EWK interactions (EWK QCD) result in irreducible background





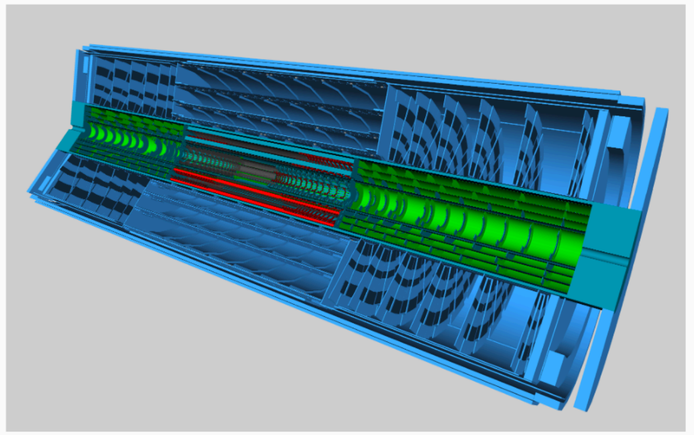
HL-LHC prospects for VBS measurements

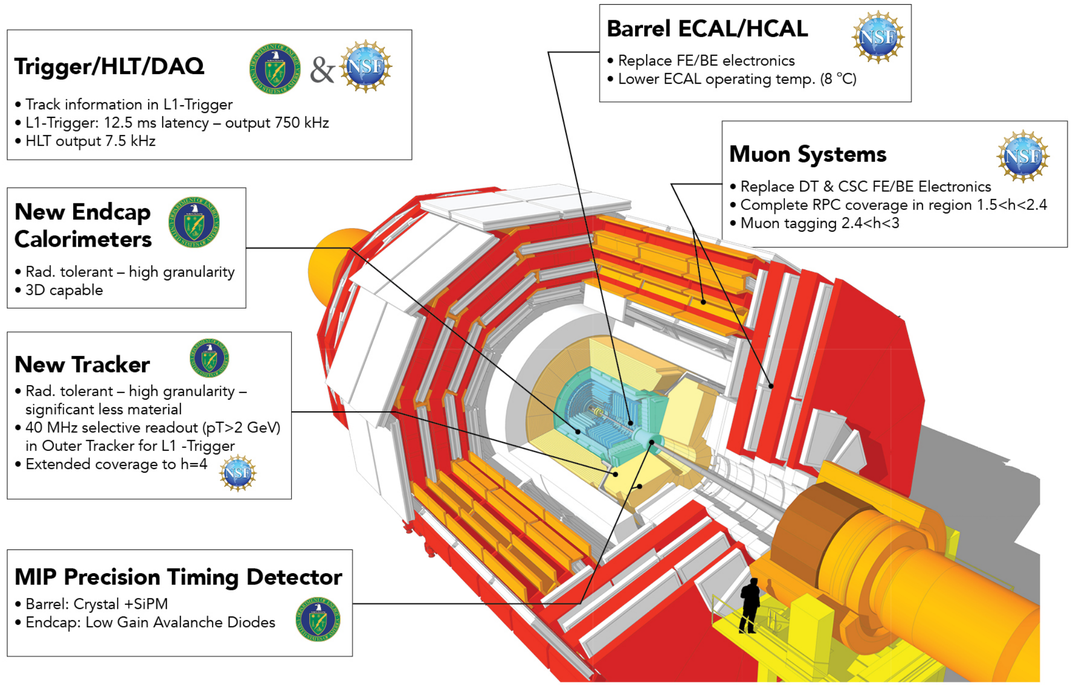


- ATLAS and CMS projections of VBS at HL-LHC
  - Assume 200 pile-up, CM energy of 14 TeV
  - Inst. lumi 5 - 7.5 x 10^{-34} (gain of ~ 5 - 7.5 compared to Run II) - Integrated lumi up to 3 ab^{-1}
- To cope with the increased lumi, radiation and pile-up challenges, both ATLAS and CMS need upgrades.

Overview of CMS and ATLAS upgrades

ATLAS all-silicon Inner Tracker (ITk)





- New silicon tracker/inner detector with extended η (upto | η| < 4) coverage for both ATLAS and CMS detectors
- New FE electronics in calorimeters for both ATLAS and CMS allowing higher trigger rate
- New timing detector for both ATLAS and CMS
- Upgraded muon system and coverage for ATLAS
- New Highly granular forward calorimeter for CMS

Overview of VBS measurements at the HL-LHC

Experiment	ssWWjj	WZjj	ZZjj	VV semileptonic	$Z\gamma$	$W\gamma$
ATLAS	ATL-PHYS-PUB-2018-052	ATL-PHYS-PUB-2018-023	ATL-PHYS-PUB-2018-029	ATL-PHYS-PUB-2018-022	-	-
CMS	CMS-PAS-FTR-18-005	CMS-PAS-FTR-18-038	CMS-PAS-FTR-18-014	-	-	-

Most of the results have been extrapolated from the 13 TeV analysis with corrections for cross sections and parameterised efficiencies using fast simulation or full-detector simulation.

These projections are done with upgraded detector configurations.

Summarised in Yellow Report

Summary of RunII results in backup. For detailed update on Run2, please see Christian Gütschow's talk on Thursday

Systematics assumptions for HL-LHC

Run-2 scenario:

- no change in systematics, propagated as it is.

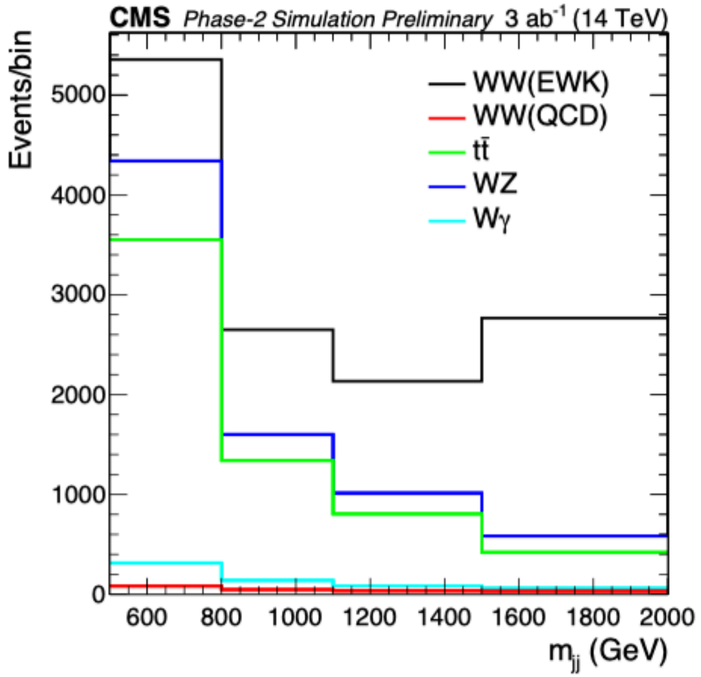
YR18 scenario :

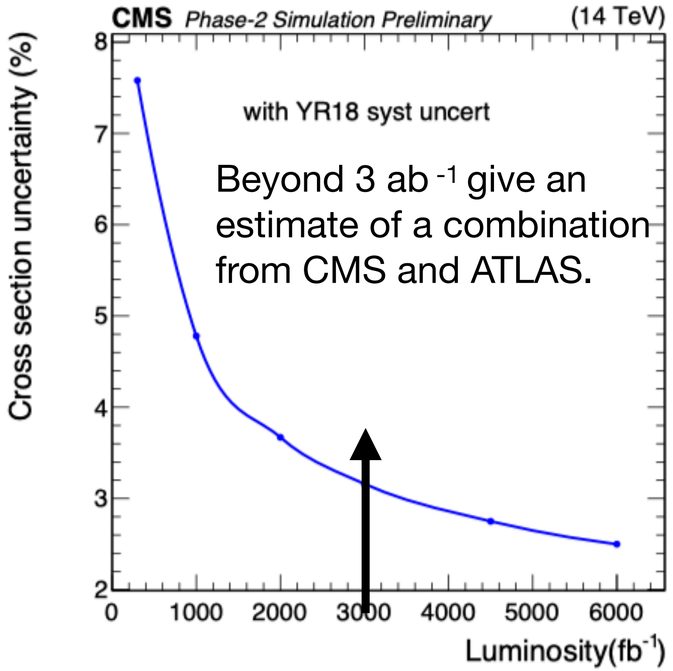
- Theoretical uncertainties are reduced by a factor of two compared to the current situation,
- Experimental ones go as ~ $1/\sqrt{L}$ until they hit the detector capabilities [Yellow Report]

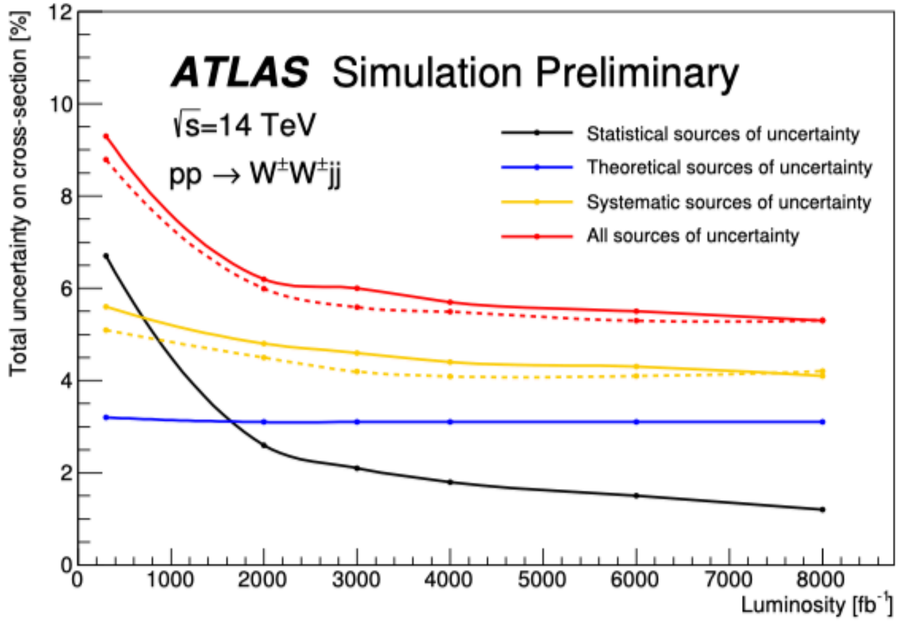
ssWWjj - Extraction of the cross section uncertainty

- 1D binned maximum likelihood fit to the invariant mass distribution of jets (m_{jj}) is used to measure the uncertainty of the WW EWK cross section measurement.

- ATLAS uses different systematics assumptions compared to CMS

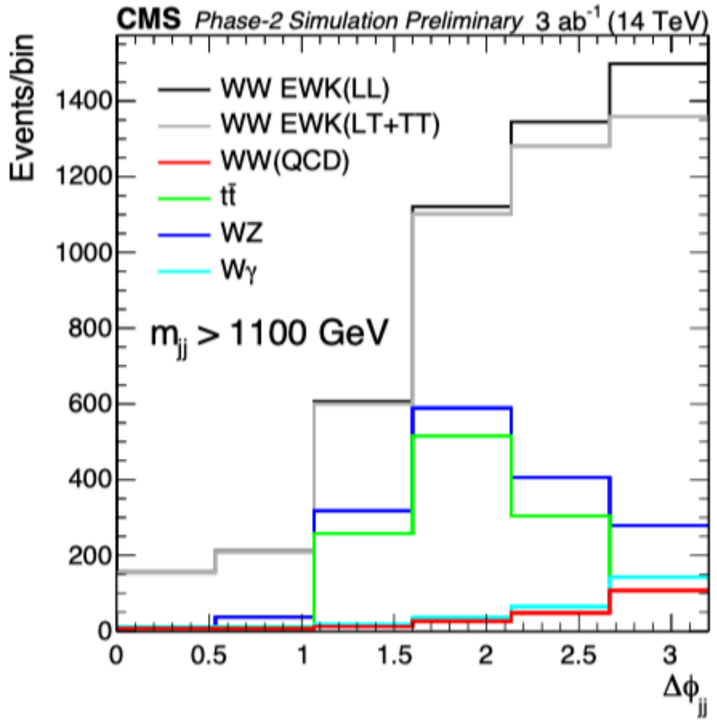


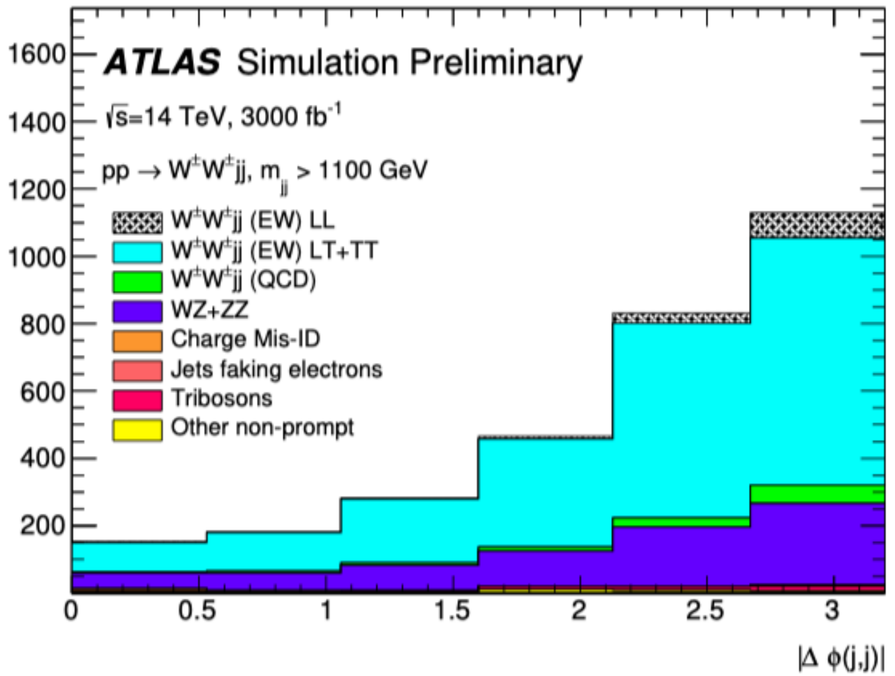




ssWWjj - Longitudinal scattering measurement

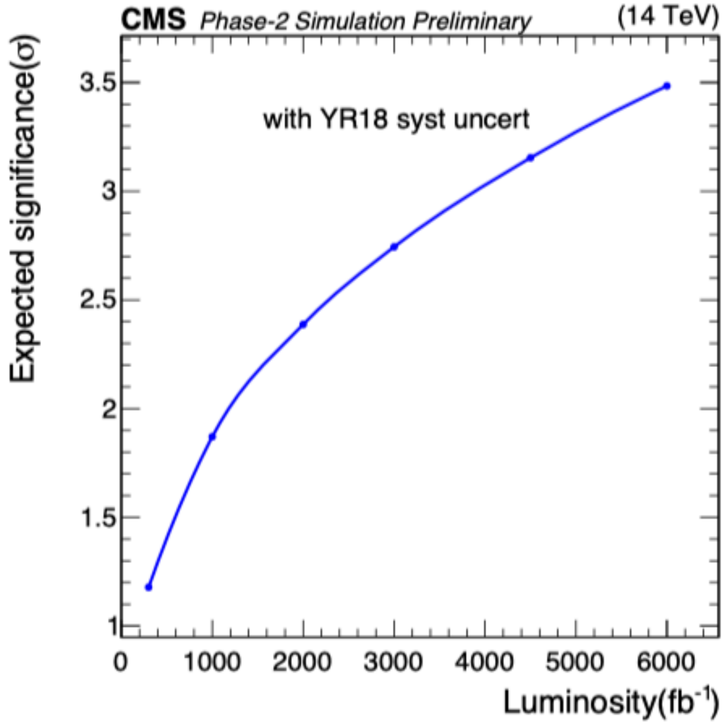
- The total VBS scattering cross section can be decomposed in the polarised components based on the W decays, when both W bosons are longitudinally (LL) or transversely (TT) polarised, as well as for the mixture (LT).
- LL component is ~ 6-7% of the total VBS cross section with Pt jet > 50 GeV.
- $\Delta\varphi_{jj}$ distribution used to discriminate LL from LT+TT.

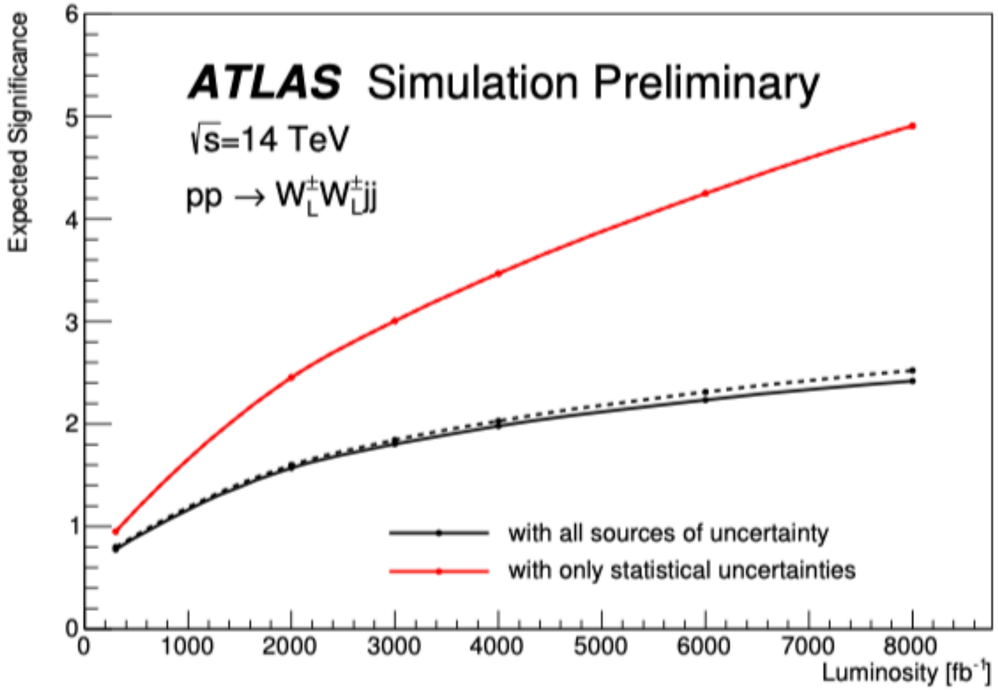




ssWWjj - Longitudinal scattering measurement results

- Using a simultaneous fit to $\Delta\varphi_{jj}$ and two mass regions of m_{jj}, significance from CMS is found to be up to 2.7σ for L = 3 ab $^{-1}$
- Expected to go above 3σ if both experiments combine their results beyond 2 ab $^{-1}$



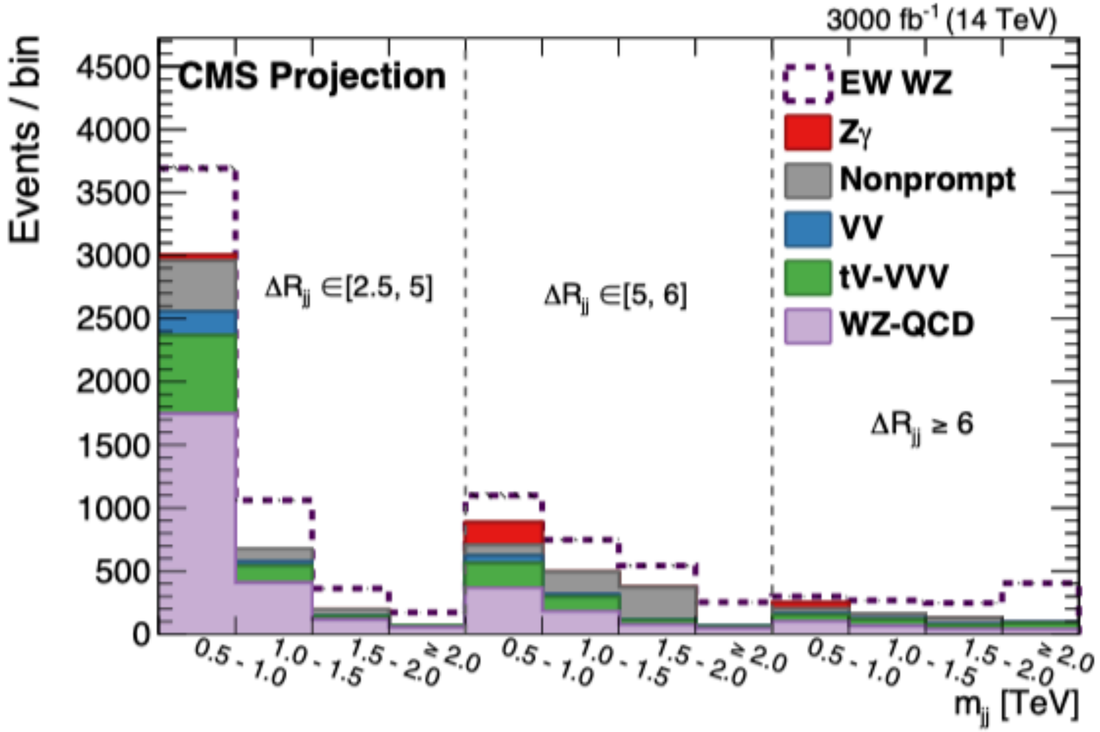


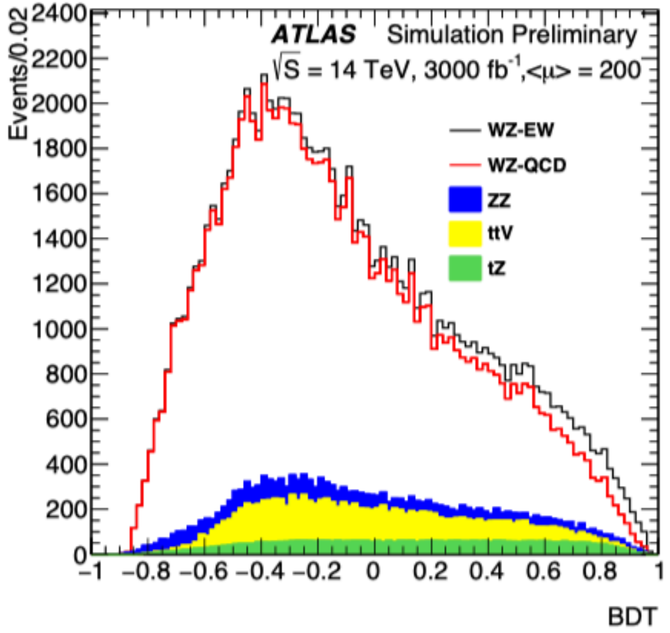
Here multivariate based analysis could possibly improve the results.

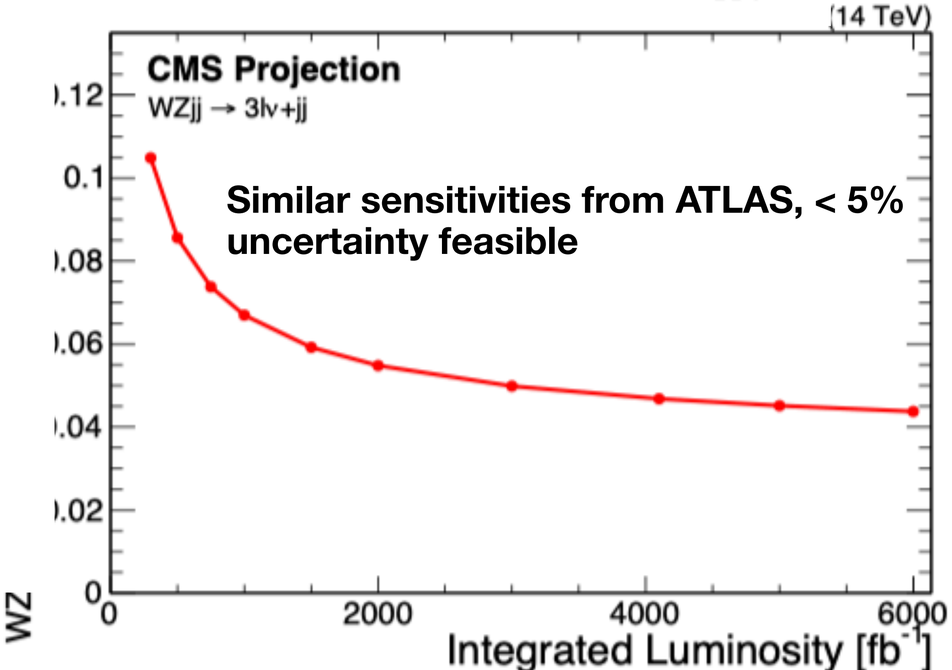
WZjj - Extraction of the cross section uncertainty

- ATLAS uses a final m_{jj} cut at 600 GeV or a multivariate analysis (BDT)

- CMS uses a 2D distribution of dijet invariant mass in bins of dijet angular separation.

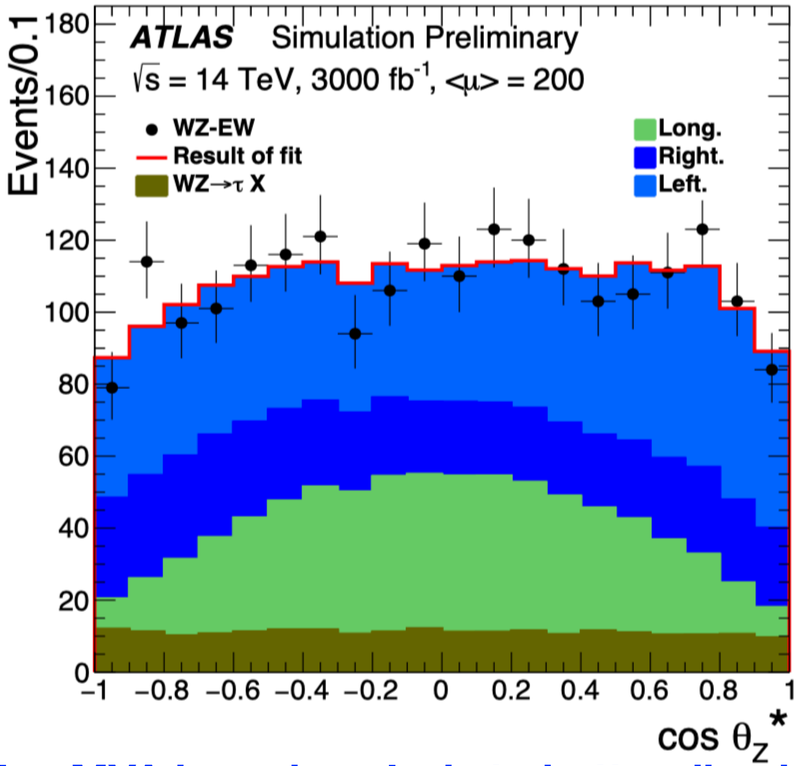


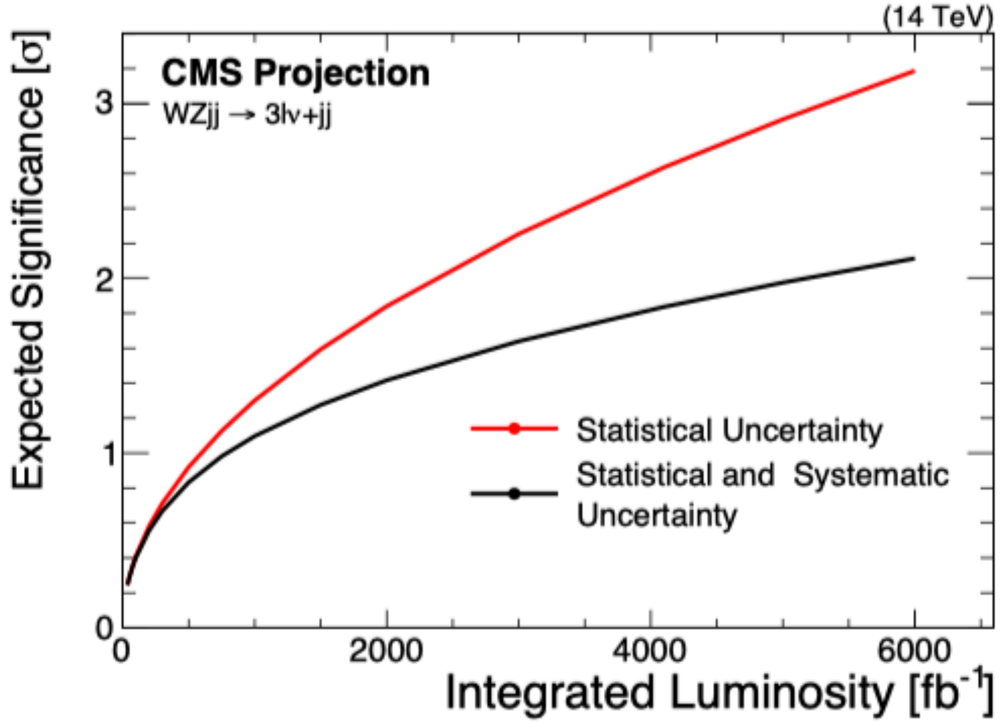




WZjj - Longitudinal scattering measurement

- ATLAS explored cosθ* as discriminating variable for polarised fraction of Z/W.
- Exp. significance for single longitudinal polarisation fraction of the Z bosons ~ 2 to 3σ
- CMS used jet based kinematics very similar to the distribution in last slide to extract the LL fraction significance and is found to be 1.6σ for L = 3 ab $^{-1}$

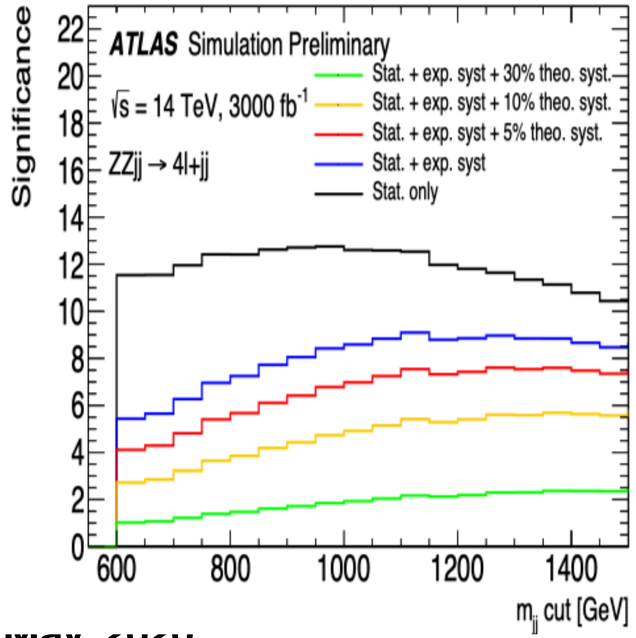


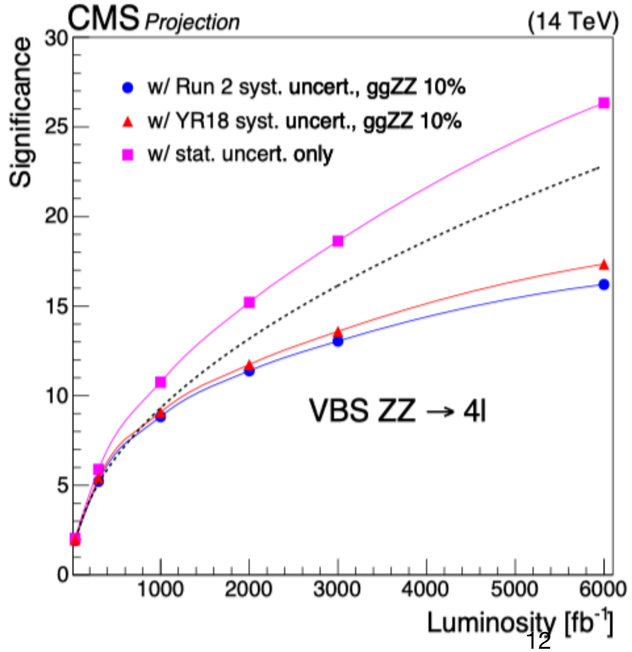


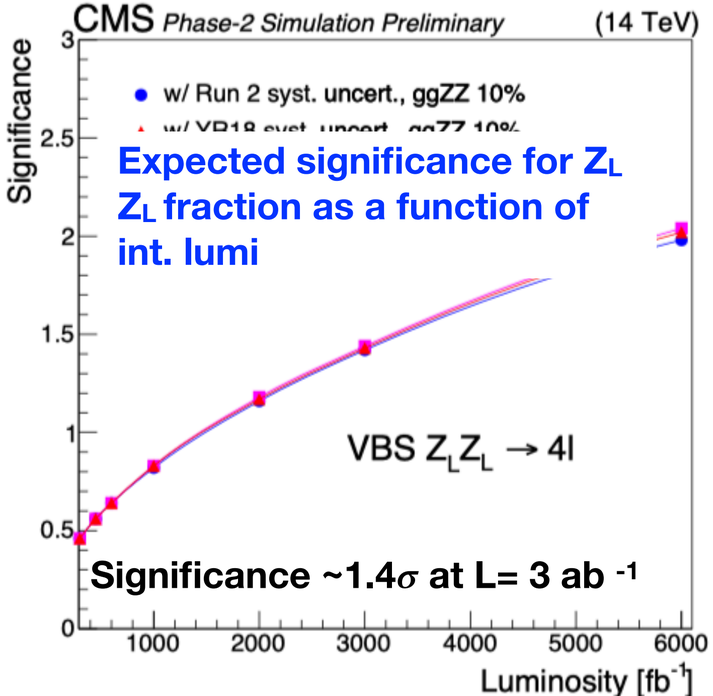
Here also MVA based analysis to better discriminate against background could possibly improve the results.

ZZjj - Extraction of the cross section uncertainty and Longitudinal scattering measurement

- Most challenging (high theoretical uncertainty on QCD-ZZjj process)
- ALTAS uses 3 different assumptions on QCD ZZ systematics while CMS uses both Run-2/YR-18 scenarios with 10% unc. on ggZZ background yield.
- ATLAS use mjj while CMS uses BDT to differentiate EWK and QCD ZZjj processes. Can be observed with significance ~ 13.0σ for both Run-2/YR-18 scenarios at L = 3 ab $^{-1}$
- The precision ~ 20% (with 5% thr. unc.) for ATLAS and ~8.5% for YR-18 scenario at CMS.

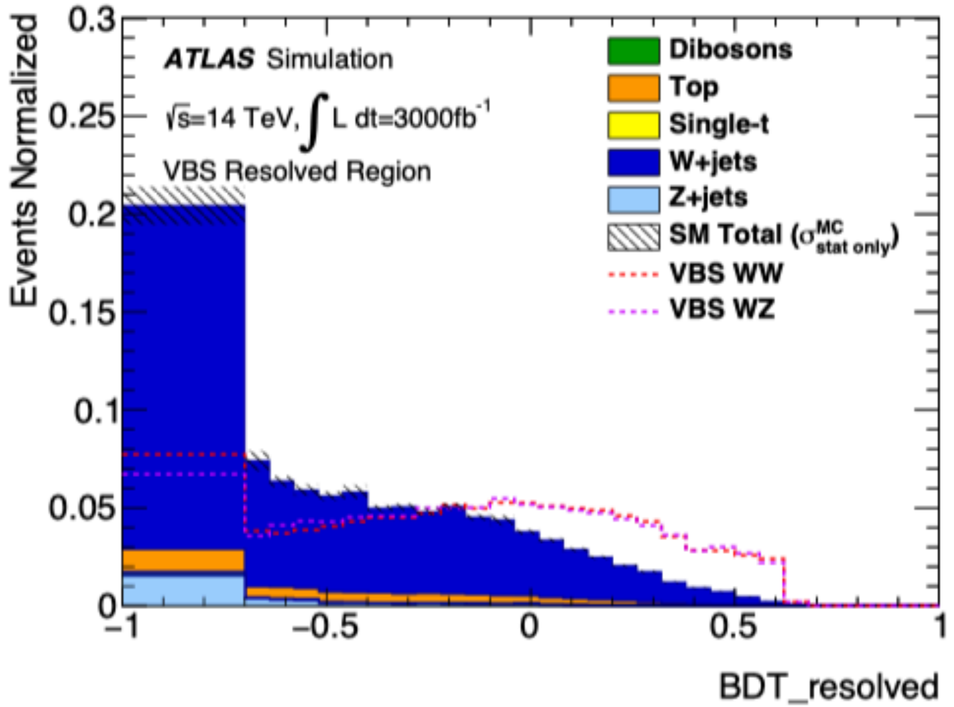


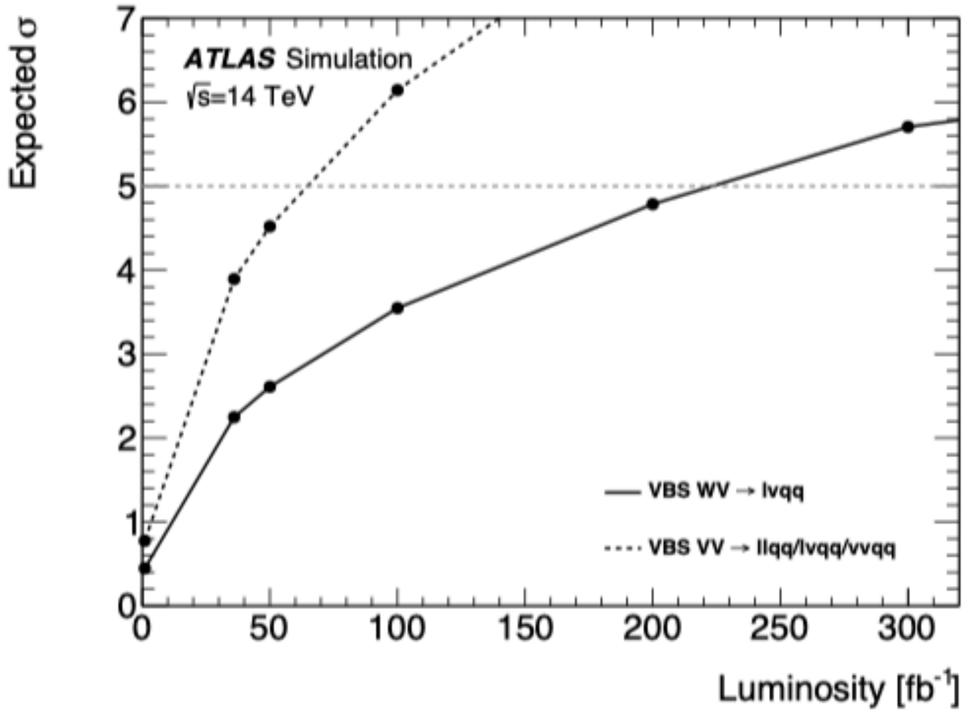




VV(qqll)jj

- Different analysis as deals with hadronic decays.
- BDT are chosen as the discriminants. BDT distributions in the signal regions and the W+jets and tt control regions are used to extract the results by simultaneous binned maximum-likelihood fit
- The expected significance for the SM VBS process is 5.7σ at 300 fb^{-1}. The expected cross section uncertainties are 18% at 300 fb^{-1} and 6.5% at 3000 fb^{-1}





Summary

- Measurement on VBS production are presented for phase-2 ATLAS and CMS detectors at the HL-LHC
- Expected cross-section uncertainties < 10% for integrated lumi of 3 ab $^{-1}$
- Potential for establishing longitudinal VV scattering is shown
  - Still challenging at HL-LHC even with combination of ATLAS and CMS.
  - More sophisticated analysis and techniques (like MVA) needed to do better

Backup

RunII results from VBS observation

Summary of observed significances at 13 TeV

Experiment	ssWWjj	WZjj	ZZjj	VV semileptonic	Zγ	Wγ
ATLAS (36 fb-1)	6.5σ arXiv:1906.03203	5.3σ arXiv:1812.09740	5.5σ ATLAS-CONF-2019-033	2.7σ arXiv:1905.07714	3.9σ arXiv:1910.09503	-
CMS (35.9 fb-1)	5.5σ arXiv:1709.05822	2.2σ arXiv:1901.04060	2.7σ arXiv:1708.02812	No SM measurement arXiv:1905.07445	3.9σ CMS-PAS-SMP-18-007	-

For detailed update on Run2, please see Christian Gütschow's talk on Thursday

WZjj - Longitudinal scattering measurement