Enhanced Background Modelling and Signal Extraction for Electroweak Zjj Measurements with ATLAS

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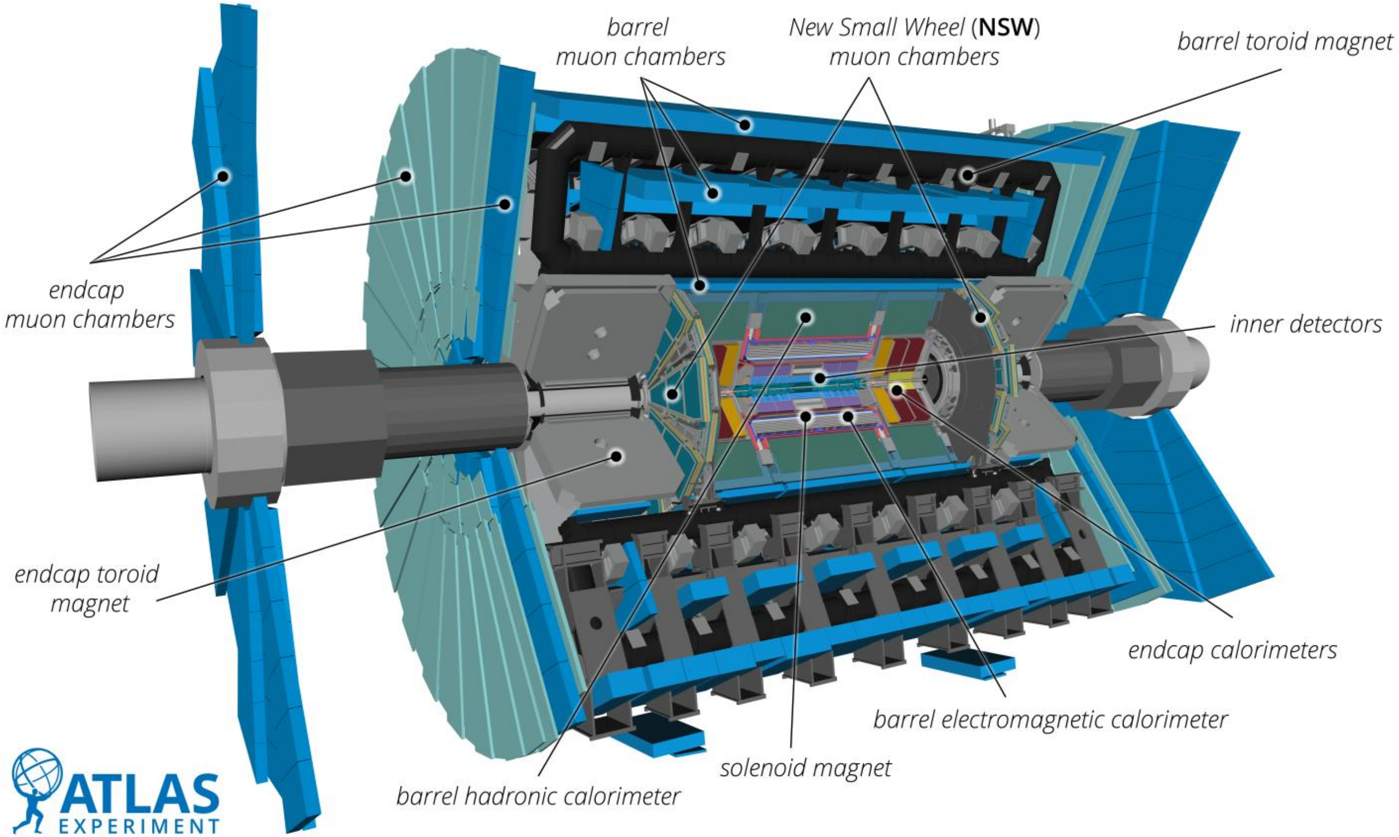
ATLAS EXPERIMENT

Carleton University

Large Hadron Collider

- ★ The Large Hadron Collider (LHC) is located at CERN near Geneva, spanning the France–Switzerland border.
- ★ It is a 27 km circular proton–proton collider.
- ★ The LHC hosts four major detectors, including ATLAS.

ATLAS Detector

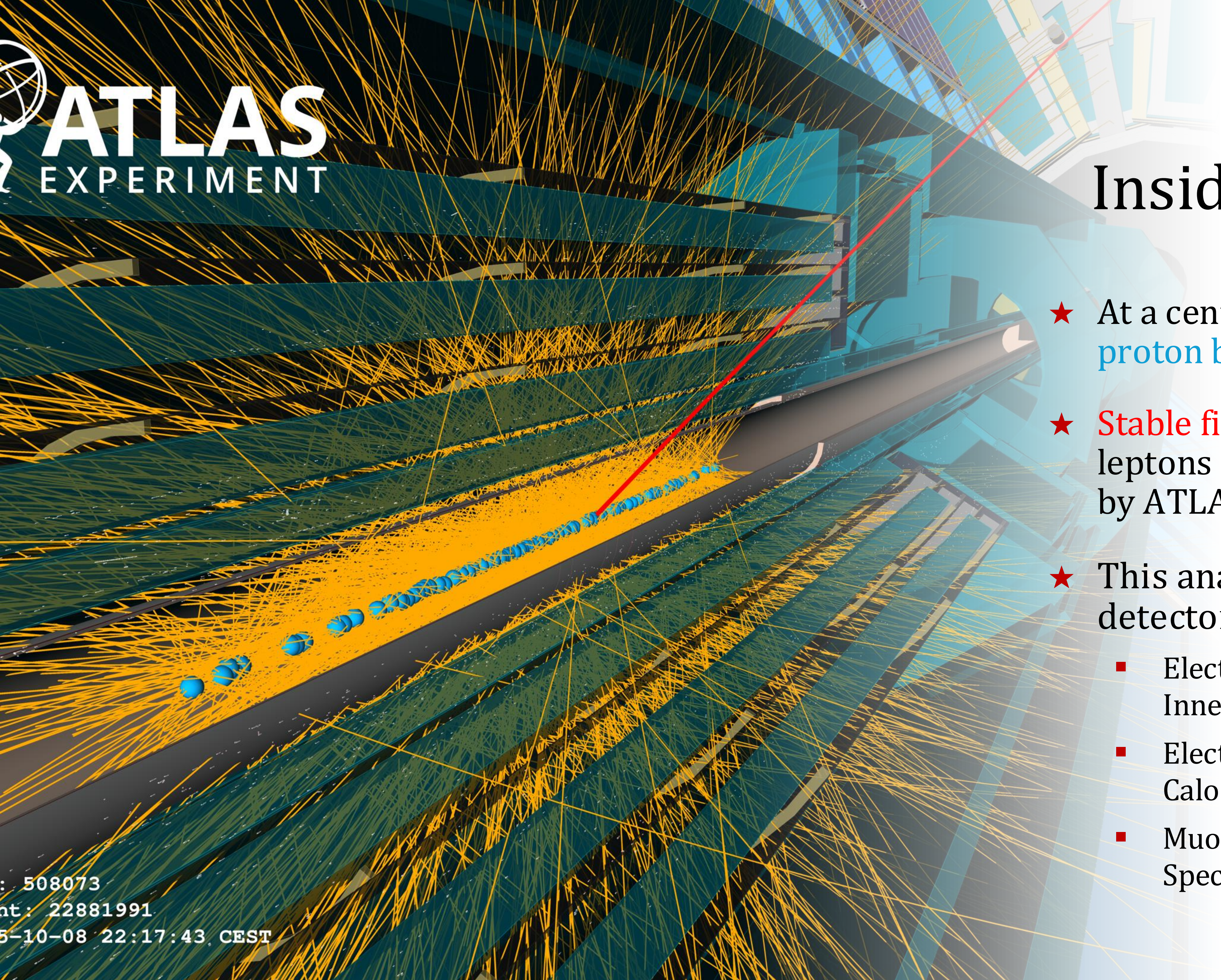


★ ATLAS is a multi-layer detector built around one of the LHC interaction points.

★ The inner detector tracks particles close to the collision point.

★ A set of calorimeters measure the energy of the particles.

★ The muon spectrometer is optimized for precise muon detection.



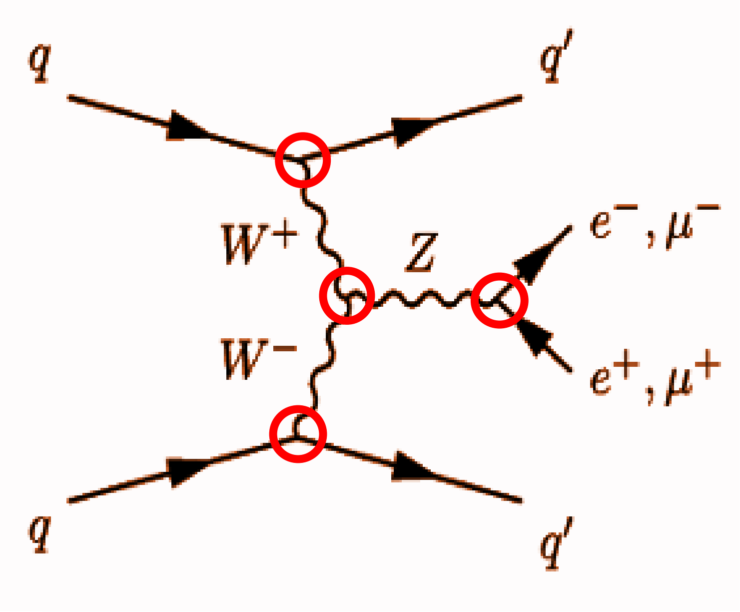
Inside ATLAS

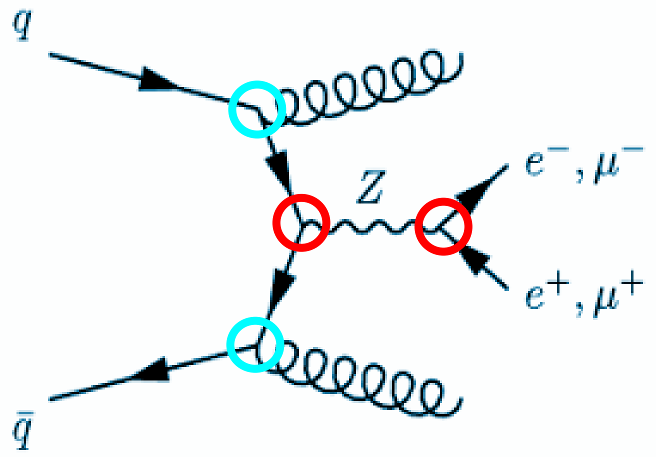
- ★ At a center-of-mass energy of 13.6 TeV, proton bunches collide every 25 ns.
- ★ Stable final-state particles such as leptons and hadronic jets are detected by ATLAS.
- ★ This analysis uses the full ATLAS detector
  - Electrons and muons are tracked in the Inner Detector.
  - Electron and jet energies reconstructed in Calorimeters.
  - Muons are tracked by Muon Spectrometer.

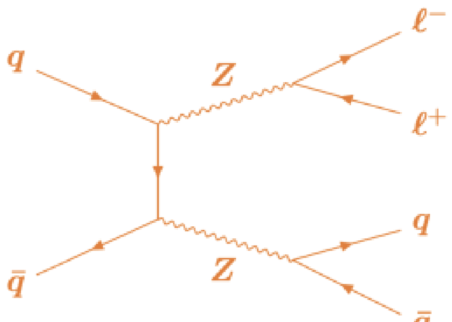
Zjj Production Mechanisms

Z boson, in association with two jets at LHC occurs via:

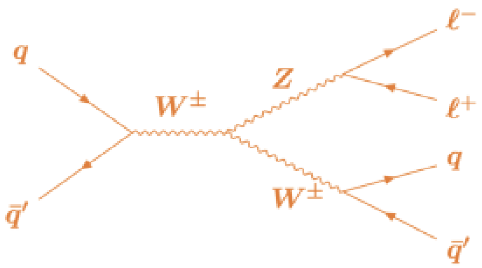
- ★ Electroweak Zjj:
  - Quark–quark scattering via t-channel electroweak exchange
  - $O(\alpha^4_{EW})$
- ★ Strong Zjj:
  - No t-channel exchange of a weak boson (e.g. Drell Yan process)
  - $O(\alpha^2_{EW}\,\alpha^2_S)$
  - Dominant process
- ★ Other Processes: Diboson, Top-associated Z production, etc.







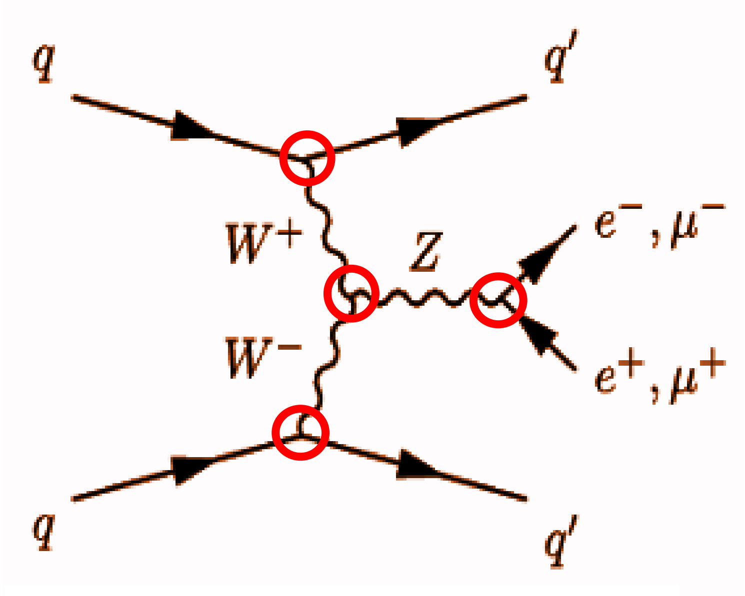
A) T-CHANNEL ZZ

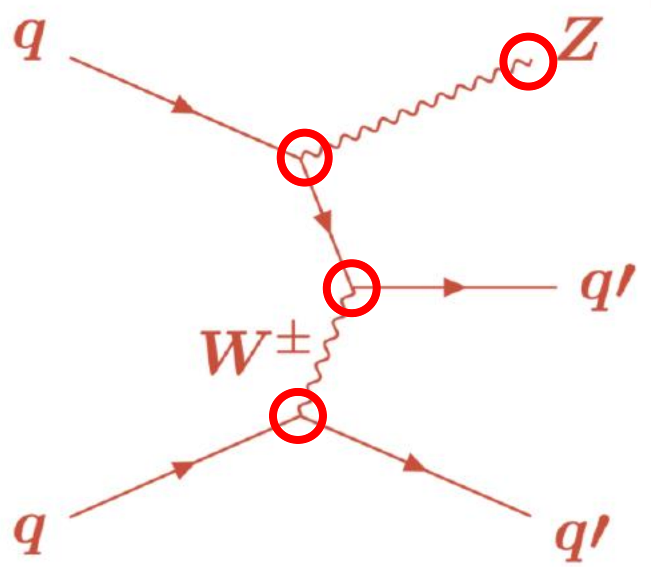


B) S-CHANNEL WZ

Electroweak Production of Zjj

- ★ **EW Zjj production is ~10^4 times rarer than strong Zjj production.**
- ★ We focus on $Z \rightarrow e^+e^-$ and $Z \rightarrow \mu^+\mu^-$, which together occur **only 6.7% of the time**.
- ★ Although statistically limited, this channel is very clean:
  - Minimal extra QCD radiation
  - Excellent lepton reconstruction

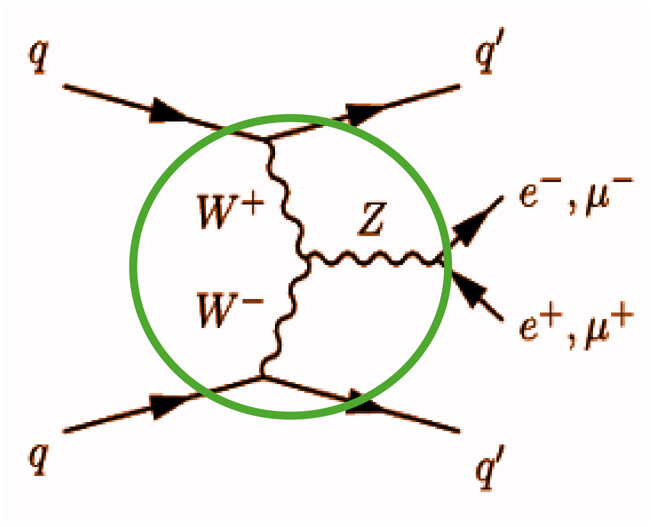




Physics Scope and VBF Event Topology

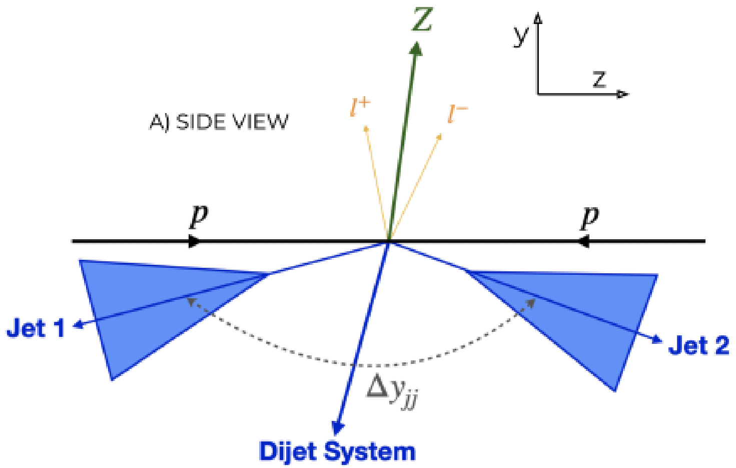
★ We are interested in the Vector Boson Fusion (VBF) process:

- Part of EW Zjj measurement.
- Two energetic forward jets with large rapidity separation - Δy_{jj}
- Reduced hadronic activity between the jets
- Z boson produced centrally to the dijet system.



★ Measure 1D differential cross sections of key VBF observables using Run 2 (2015-2018) and Run 3 (2022-2026) data:

- Dijet Invariant mass - m_{jj}
- Rapidity Separation - $|\Delta y_{\mathrm{jj}}|$
- Z boson transverse momentum - p_{T}^{Z}
- Signed Azimuthal angle - $\Delta\phi_{\mathrm{jj}}^{\mathrm{signed}}$



★ Explore 1D & 2D-distribution for increased sensitivity to SMEFT.

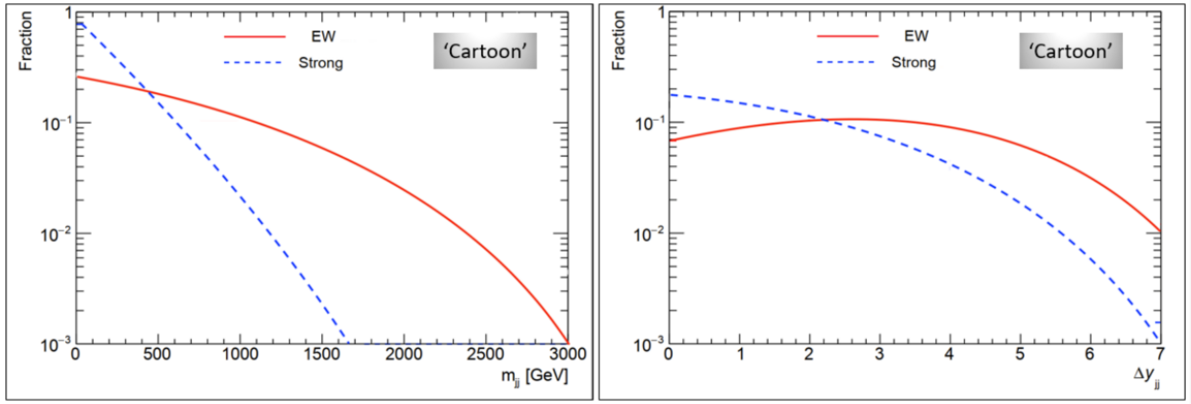
- Set limits on anomalous Triple Gauge Couplings (aTGCs).

S. Weber, Zjj measurements with ATLAS Run-II, PhD thesis (2020).

VBF-rich Phase space

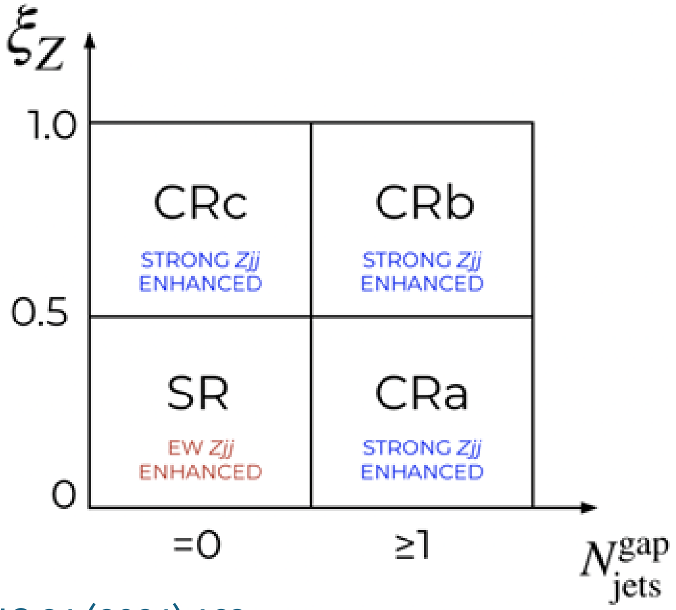
- ★ Kinematic cuts are applied to enhance VBF search.[1]
- ★ VBF-enriched region is dominated by EW Zjj and strong Zjj contributions.
- ★ Phase space is further categorized using:
  - Z-centrality $\xi_Z = \frac{|y_{ll} - y_{jj}|}{\Delta y_{jj}}$
  - $N_{\text{jets}}^{\text{gap}}$ – Jets reconstructed in the rapidity gap between leading jets
  - Split into three background-rich control regions and one signal region.

Illustrations of how kinematic selections enhance VBF-enriched phase space.



Centrally produced MC samples

Process	Run-2	Run-3
EW Z+jj	SHERPA 2.2.11	SHERPA 2.2.14
Z+jets QCD	SHERPA 2.2.11	SHERPA 2.2.14
Z+jets QCD	MG+PY8 FxFx	MG+PY8 FxFx
Z($\tau\tau$)+jets	SHERPA 2.2.14	SHERPA 2.2.14
Diboson EW	SHERPA 2.2.12	SHERPA 2.2.14
Diboson QCD	SHERPA 2.2.12	SHERPA 2.2.16
$t\bar{t}$	SHERPA 2.2.12	SHERPA 2.2.14
t	Pow+Py8	Pow+Py8 EG
W+jets QCD	SHERPA 2.2.11	SHERPA 2.2.14
W+jets EW	SHERPA 2.2.14	SHERPA 2.2.14



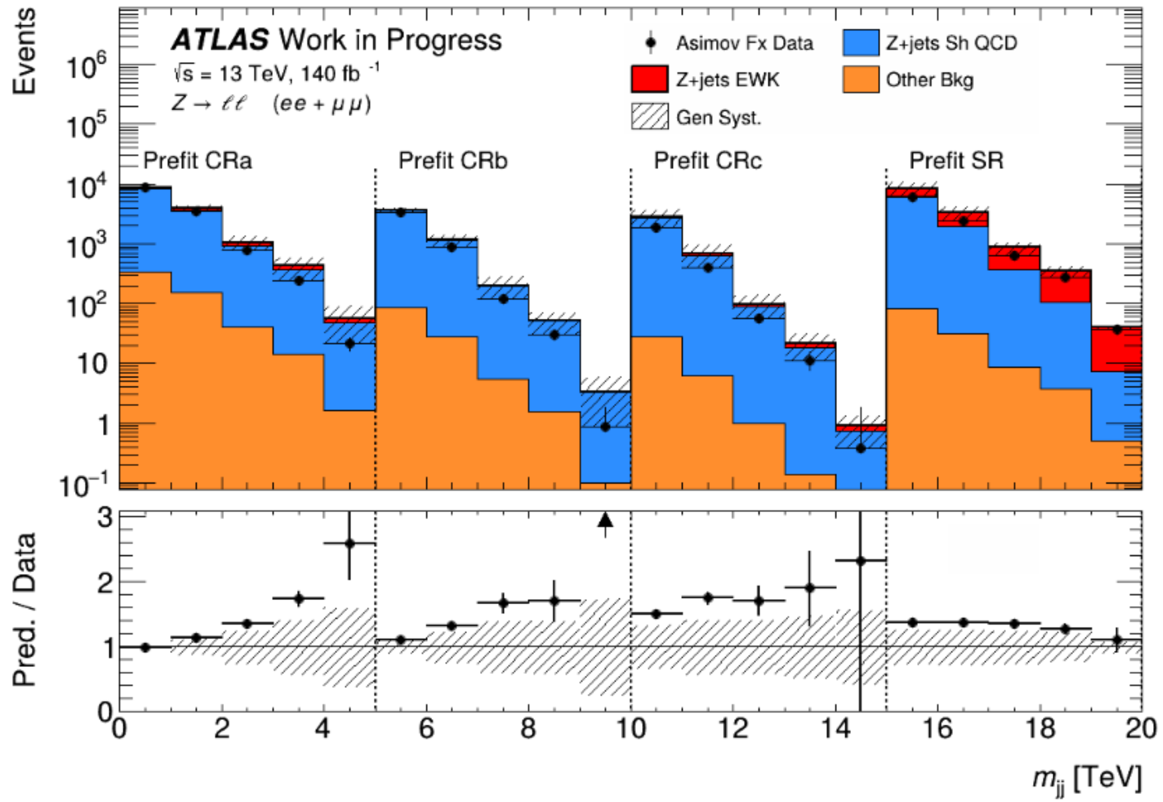
[1] STDM-2017-27 EPJC 81 (2021) 163

QCD Generator Systematics

- ★ Strong Zjj contribution now comparable to the signal in Signal Region.
- ★ Sherpa and MadGraph shows varying strong Zjj predictions.
- ★ Sherpa predictions are compared to Asimov Fx data.
    - Asimov Fx = **MadGraph QCD Zjj** + EW Zjj + Others
- ★ The difference between the QCD predictions is the generator choice systematic – a dominant uncertainty in previous Zjj analysis.

We aim to develop a background estimation strategy that reduces sensitivity to the choice of QCD generator.

Asimov Data – MC agreement



Background Estimation Strategy

$$\mathcal{L}_{joint} = \prod_i \left[\left(\lambda_i^{CRa}\right)^{D_i^{CRa}} e^{-\lambda_i^{CRa}}\right]\left[\left(\lambda_i^{CRb}\right)^{D_i^{CRb}} e^{-\lambda_i^{CRb}}\right]\left[\left(\lambda_i^{CRc}\right)^{D_i^{CRc}} e^{-\lambda_i^{CRc}}\right]\left[\left(\lambda_i^{SR}\right)^{D_i^{SR}} e^{-\lambda_i^{SR}}\right]$$

- $\lambda_i^{CRb} = b_i\, Q_i^{CRb}$
- $\lambda_i^{CRa} = \mu_i E_i^{CRa} + a_i\, Q_i^{CRa}$
- $\lambda_i^{CRc} = \mu_i E_i^{CRc} + t_i\, b_i\, Q_i^{CRc}$
- $\lambda_i^{SR} = \mu_i E_i^{SR} + t_i\, b_i\, Q_i^{SR}$
- $t_i = c\left[\frac{b_i}{a_i}\right]$

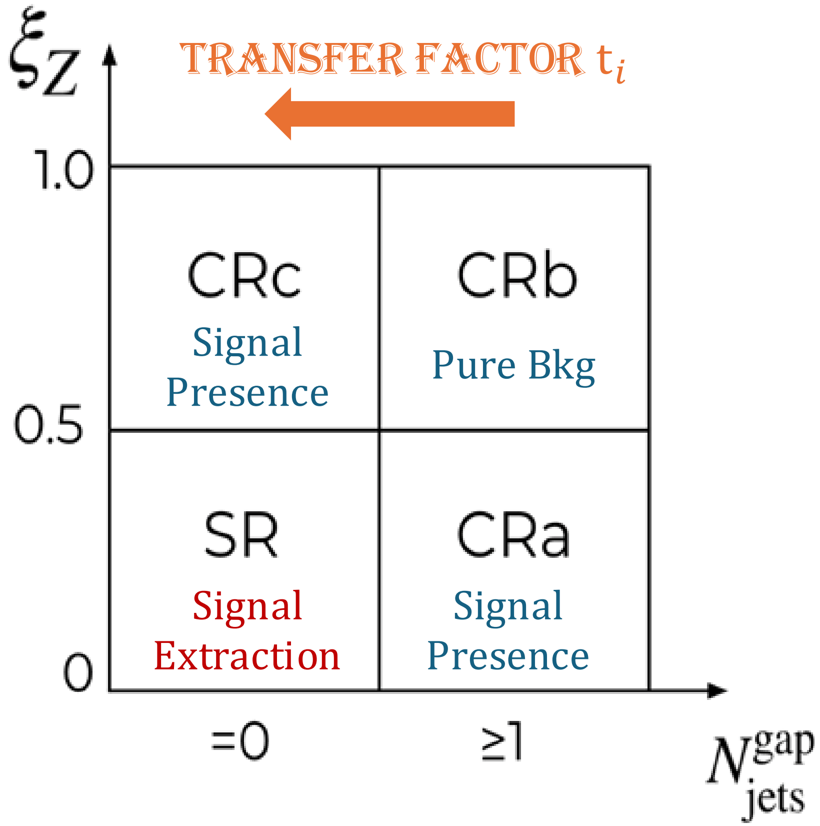
★ Binned maximum likelihood fit across four regions where, λ_i denotes expected yield and D_i are observed data in bin *i*.

★ Background normalization and shape are constrained using CRa and CRb.

★ The strategy minimizes reliance on prior QCD modeling through a pure background control region (CRb).

★ A transfer factor derived from these regions is applied across the $N_{jets}^{gap} = 1$ boundary into CRc and SR.

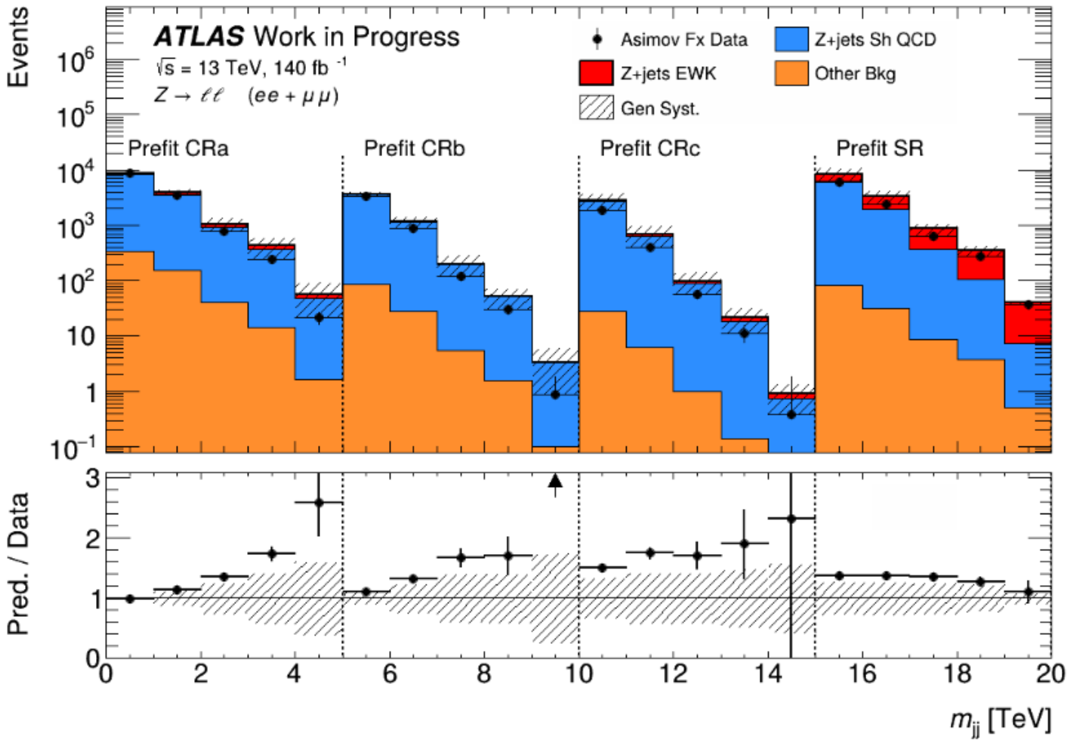
★ Zjj EW is extracted simultaneously across three regions.



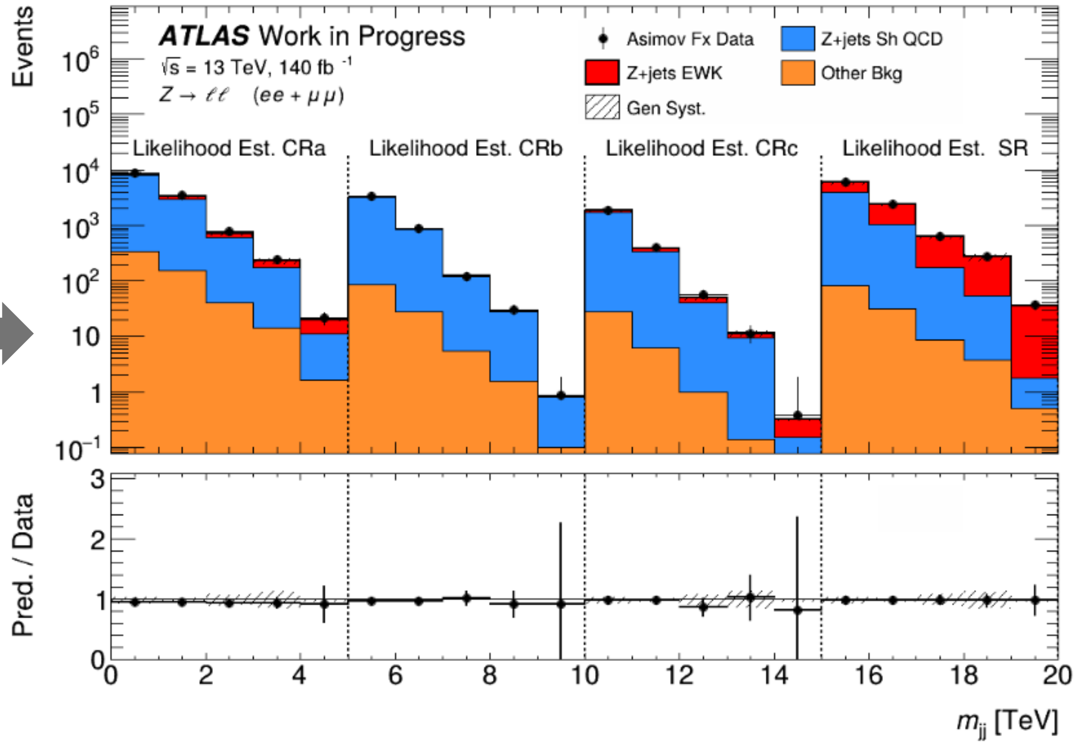
Fit Results (Plots)

- ★ Dijet Mass (m_{jj}) is used as an example to show the fit performance.
- ★ Post-fit results show:
  - Improved agreement to Asimov MadGraph dataset.
  - Significantly reduced error on the estimation.

Pre-fit Predictions



Post-fit Predictions



EW Yield in Signal Region

- ★ Preliminary study suggests a significant reduction in the generator choice systematic uncertainty across all bins of m_{jj}.
- ★ Results compared to the published Run 2 results.

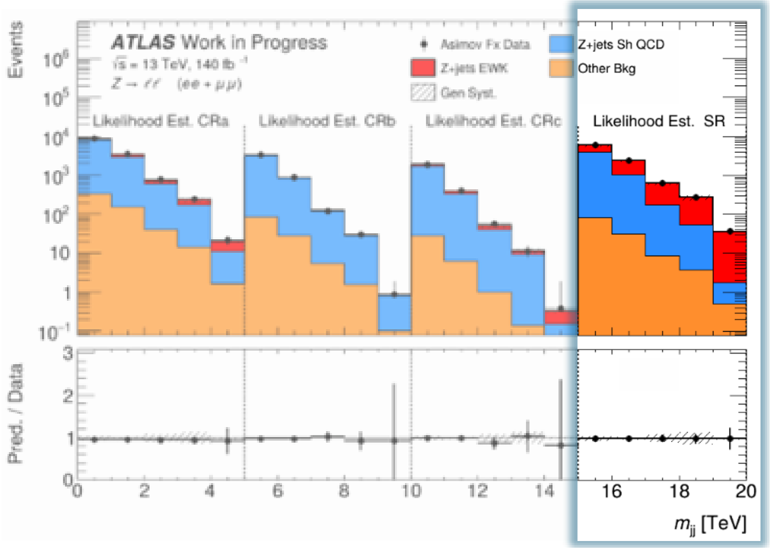
Fit to Asimov Fx

ATLAS Work in Progress

Table 1: EW yields with generator choice systematic errors for SR.

					Bin 1	Bin 2	Bin 3	Bin 4	Bin 5
EW in ToyData	-	-	-	-	2169.26	1403.92	500.64	246.54	33.34
PostFit EW	-	-	-	-	2047.26	1370.61	460.97	216.99	34.40
Gen. choice [%]	-	-	-	-	5.9	2.7	8.2	12.2	4.0

Post-fit Predictions



Run 2 Published Result

EW Zjj SR, m_{jj} cross-section measurements					Bin 1	Bin 2	Bin 3	Bin 4	Bin 5
$d\sigma$ / dm_{jj} [ab/GeV]	-	-	-	-	41	14	5.5	1.3	0.10
Stat. unc. [%]	-	-	-	-	13	13	13	17	26
Gen. choice [%]	-	-	-	-	11	11	9.4	14	7.6
Theory syst. [%]	-	-	-	-	8.1	6.6	4.3	3.1	1.2
Jet syst. [%]	-	-	-	-	8.4	6.9	6.3	9.4	14
Unfolding syst. [%]	-	-	-	-	2.3	1.1	0.7	0.6	0.6
Other syst. [%]	-	-	-	-	2.0	2.0	2.3	2.2	3.0

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Summary

- ★ We aim to measure EW Zjj differential cross sections of key VBF observables for Run 2(2015-2018) and Run 3 (2022-2026) ATLAS datasets.
- ★ QCD Gen. choice systematic uncertainty was the bottleneck in previous Zjj analysis.
- ★ Our novel likelihood-based background strategy, with a background only control region shows reduced sensitivity to the prior QCD modeling.
- ★ Future work will focus on incorporating detector-level systematic uncertainties, including those from jet reconstruction and lepton identification.

We are stress-testing EW theory in high-energy, high-momentum transfer regimes where new physics effects would most naturally appear.

Thank you

Backup Slides

Procedure for Ensemble test

Aim: **Check the fit bias and quantify the effect of modeling difference between Sherpa and MadGraph QCD generators.**

$$N_{r,i}^{\text{Nominal}} = N_{r,i}^{\text{EW,MC}} + N_{r,i}^{\text{MadGraph QCD, MC}} + N_{r,i}^{\text{Other,MC}}$$

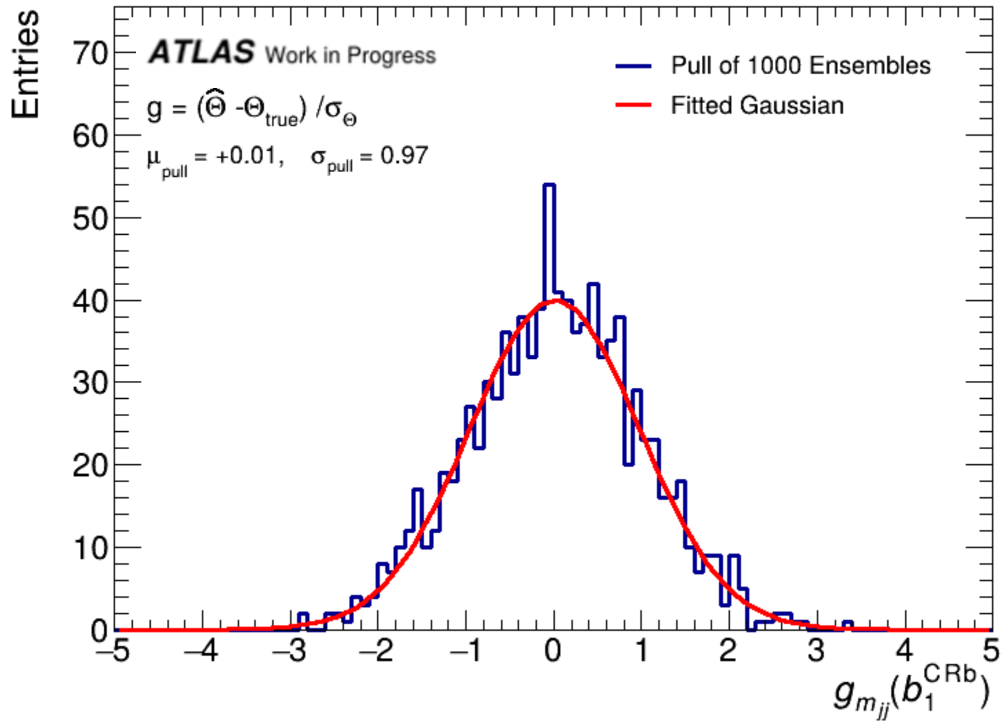
$$N_{r,i}^{\text{Ensemble}} = \text{Poisson}\left(N_{r,i}^{\text{Nominal}}\right)$$

$$\text{Pull } g = \frac{\hat{\theta} - \theta_{\text{Asimov}}}{\sigma_{\hat{\theta}}}$$

Procedure:

- Generate 1000 toy datasets adding per-bin Poisson variations of EW, QCD and other backgrounds.
- Perform likelihood fit using Sherpa QCD and EW samples on nominal and the toy datasets.
- Extract θ_{Asimov} from the nominal fit and $\hat{\theta}$ from toy fits.
- θ_{Asimov} gives information about the estimated QCD and EW yields .
- Plot the pull for $\hat{\theta}$ obtained from each of the toy fits.
- Fit a Gaussian and extract the mean and σ for each of the $\hat{\theta}$.
- Pull N(0,1) confirms that fit is bug free and toy datasets are indeed Poisson variated.

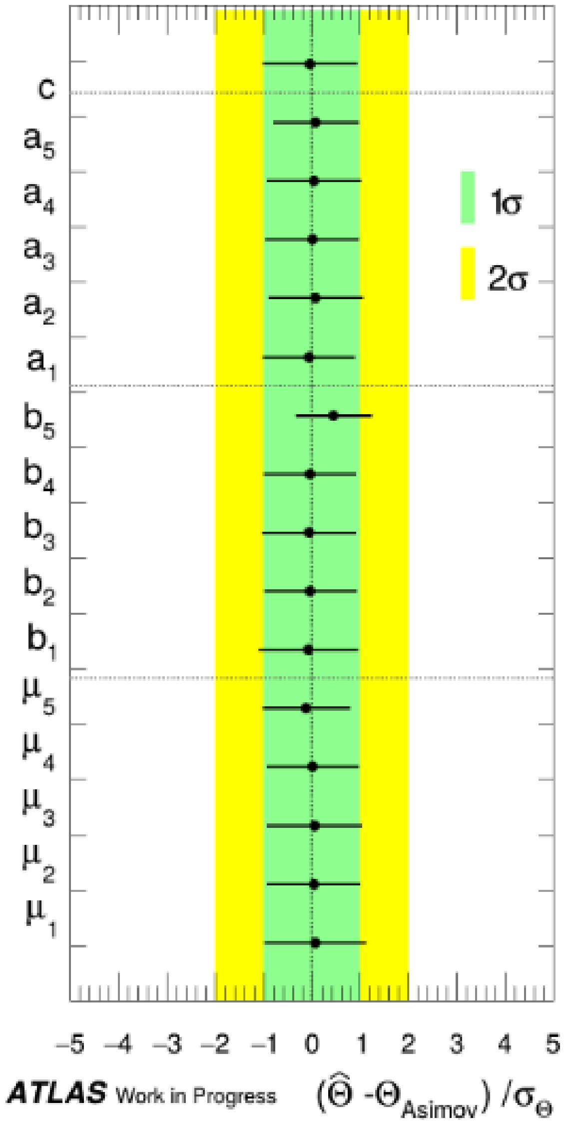
Example Pull



Pull from Ensemble Test: Fitting MadGraph to Itself

- **Pseudo Data:** Poisson (Sherpa EW + MadGraph FxFx QCD + Others)
- **Fitted MC:** Sherpa EW, MadGraph FxFx QCD and Others

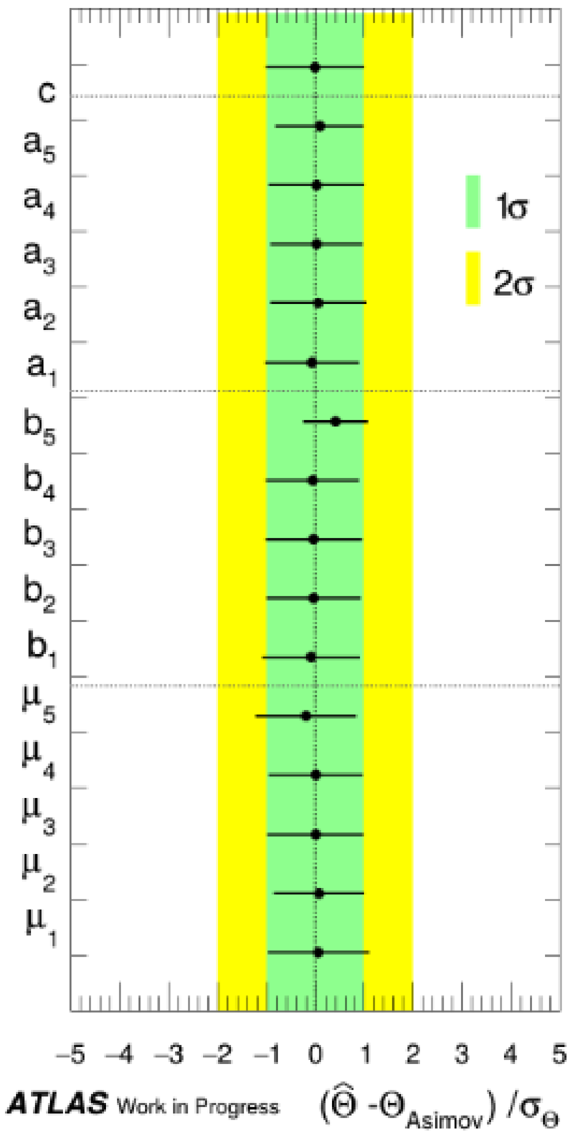
- The pull N(0, 1) VALIDATES the implementation of the likelihood fit.
- Fitting MadGraph to itself is a trivial check before performing Ensemble test using different predictions.



Pull from Ensemble Test: Fitting Sherpa to MadGraph

- **Pseudo Data:** Poisson (Sherpa EW + MadGraph FxFx QCD + Others)
- **Fitted MC:** Sherpa EW, Sherpa QCD and Others

- Summary of the Ensemble test conducted in fitting Sherpa QCD to the toy datasets.
- The pull N(0, 1) VALIDATES the implementation of the likelihood fit.
- This confirms that our toy datasets are indeed Poisson distributed.
- The slight deviations in the new fits are because of systematic error introduced by ignoring the EW component in CRb.
- This was independently confirmed by creating a separate dataset with no EW contribution in CRb, where the pulls lined up to N(0, 1).
- Later this error is added as a systematic uncertainty on the final EW and QCD yields.



Asimov Fit: Fitting Sherpa to MadGraph

- **Pseudo Data:** Sherpa EW + MadGraph FxFx QCD + Others
- **Fitted MC:** Sherpa EW, Sherpa QCD and Others

- Asimov fit tells us how biased the fit is.
- Sensitivity of the fits to prior QCD modelling, observed in the distribution of μ_i.
- Not expecting a_i, b_i to be 1, but I expect μ_i close 1.
- In the previous analysis, this shift in μ_i, was quoted as a modelling error.
- EW prediction is the insensitive to QCD modelling differences.