Recent observation and measurements of vector-boson fusion and scattering with ATLAS

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XXVIII International Workshop on Deep-Inelastic Scattering and Related Subjects

Stony Brook University / The Virtual World

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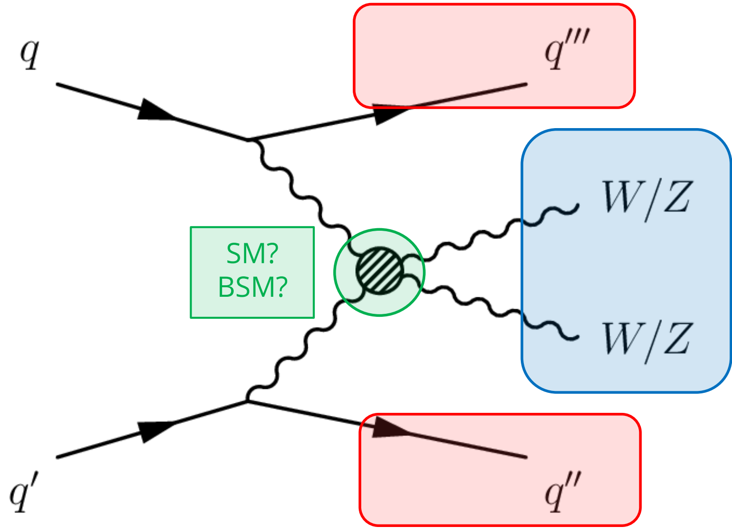
Brandeis University

ATLAS EXPERIMENT

VBF and VBS at the LHC

One of the main physics goals of the LHC: Study **nature of EW symmetry breaking**

- One avenue: Direct interaction of gauge fields with the Higgs field
- In addition: Self-interaction of gauge bosons at high energy scales
  - ➢ **VBF** and **VBS** processes



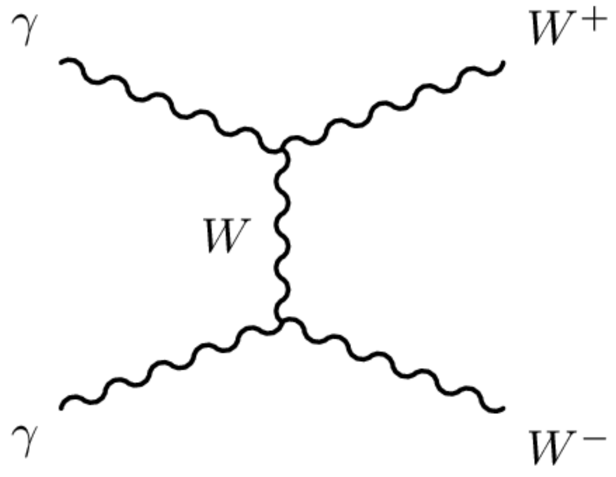
At the LHC:

"Classical" search topology involves vector bosons radiated off **initial state partons**

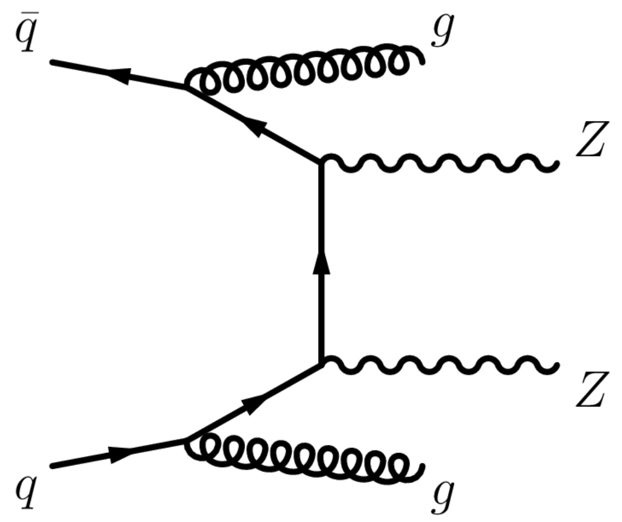
- ➢ Signature: Two high-energy (forward) jets and product of gauge boson self interaction

Interesting special case:

Photon-Photon scattering – can leave initial state protons (or ions) **intact**



Experimental challenges

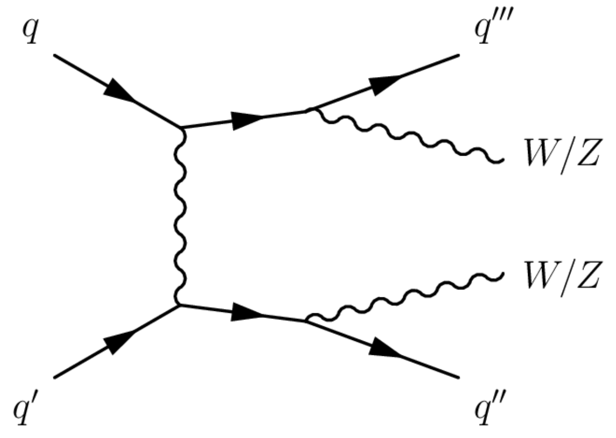


Even at LHC luminosities, VBF/VBS is a **rare process**

- Typically, O($\alpha_{EW}^{3\text{-}4}$) x decay BR

Measurement requires enrichment against other **SM processes** (backgrounds)

- Vast multijet background: Prefer **leptonic** or **semileptonic** final states
- Competition with **strong (di)boson** production associated with jets
  - ➢ Jets either from higher-order QCD in hard scatter, or from **pileup** activity
- For dedicated VBS/VBF measurements: Embedded with **other EW production modes**
- Typically constrain backgrounds using **collision data** to reduce modelling uncertainties



Both low rates and enrichment against background require **large dataset**

➢ Major progress with **full run-2 dataset**

This talk: Walk through select recent highlights in ATLAS VBF/VBS results + glimpse at **photon-scattering.**

Electroweak Z+jj production in ATLAS

Eur. Phys. J. C 81 (2021) 163

Differential measurement of Z+jj production with Z->ee/μμ

- Sensitive to **vector boson fusion** in VV->Z
- Measure both **inclusive** and **electroweak** cross-sections

Both strong and electroweak components **challenging** to model in simulation

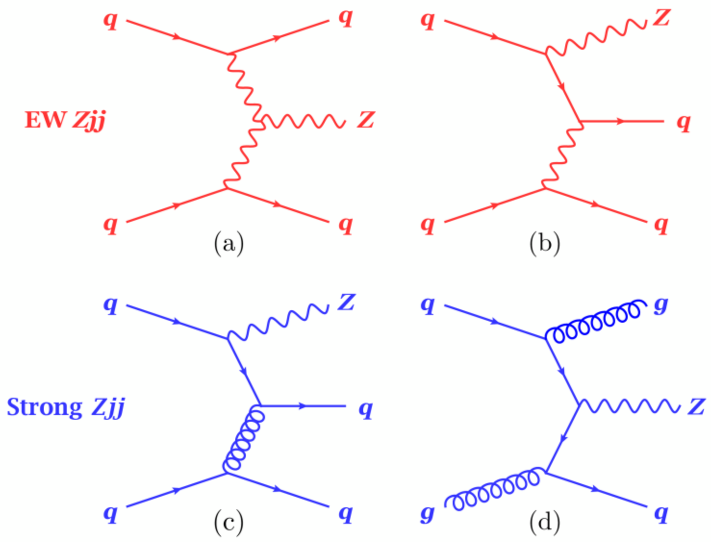
- Differential measurements can act as guideline for future improvements

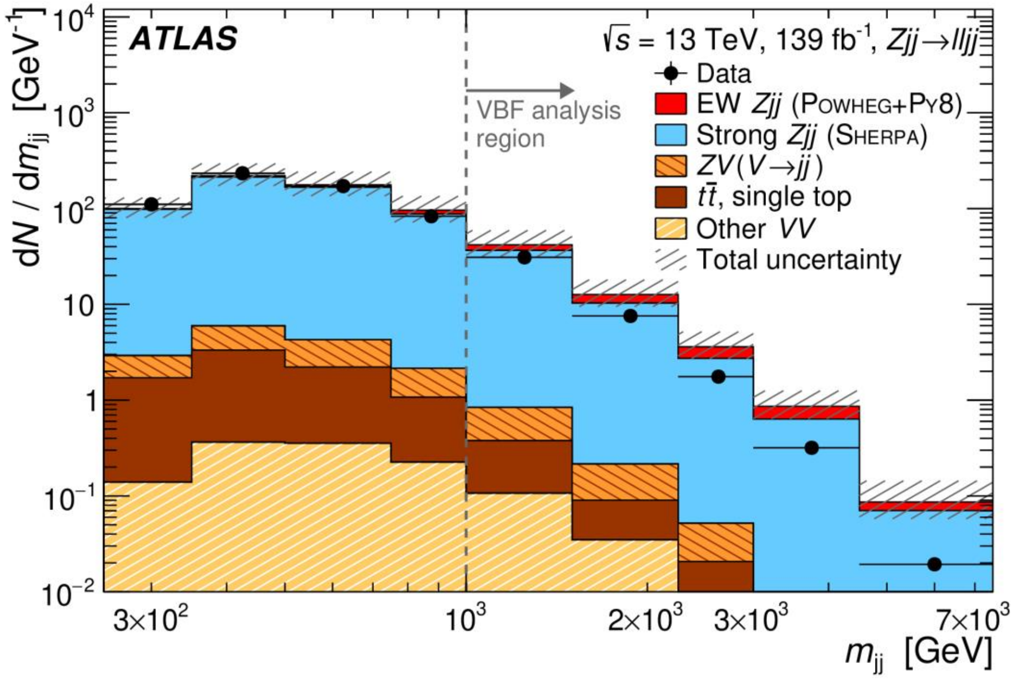
Measurement performed in **EW-enriched phase-space**

- Presence of **Z->ll** signature – very effective background suppression
- Requirement of two high-Et **jets** with large **rapidity gap** and **high dijet mass**
- Z system required to be **central** relative to dijets
- Rejection of pileup activity by requiring transverse **momentum balance** between dijet and Z systems

Resulting data sample:

Highly **pure** in signal, dominant residual background from **diboson** processes with V->jj and **top pair** production





Electroweak Z+jj production in ATLAS

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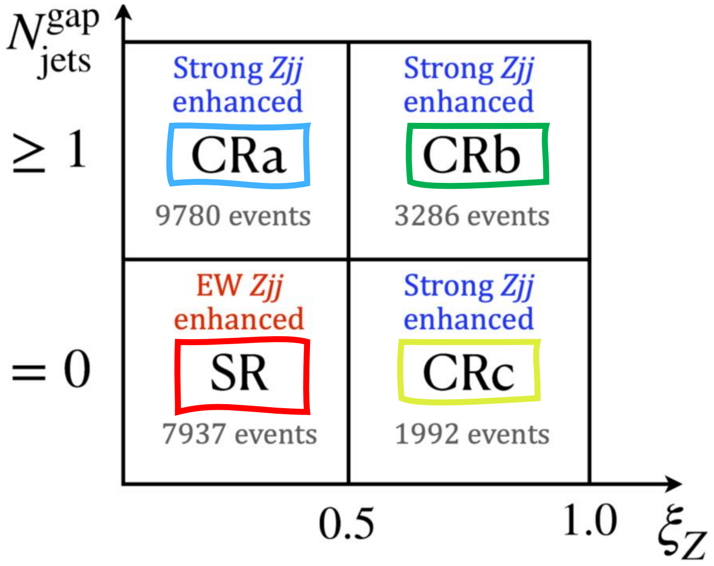
Measure **four observables** differentially**:**

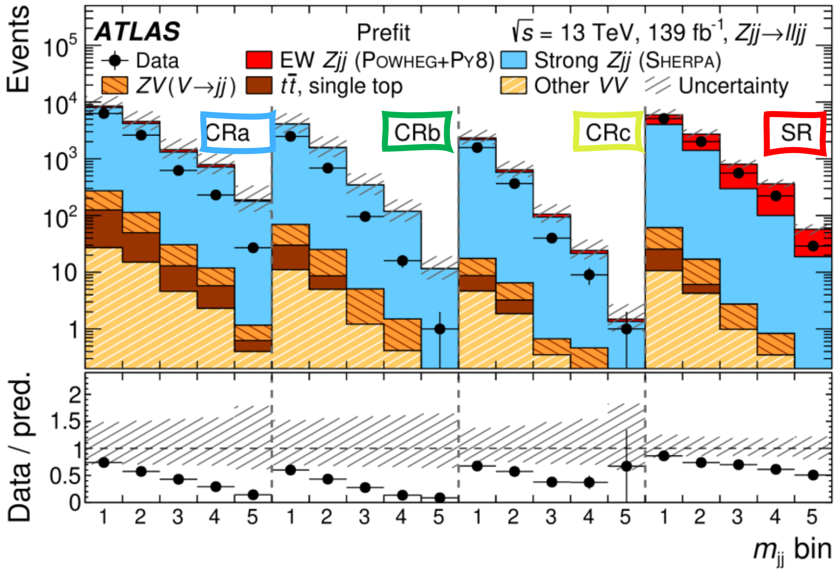
- Dijet mass m_{jj}
- Dijet rapidity gap $|\Delta y_{jj}|$
- Z system p_T $p_{T,ll}$
- Signed dijet azimuthal angle $\Delta\varphi_{jj}$



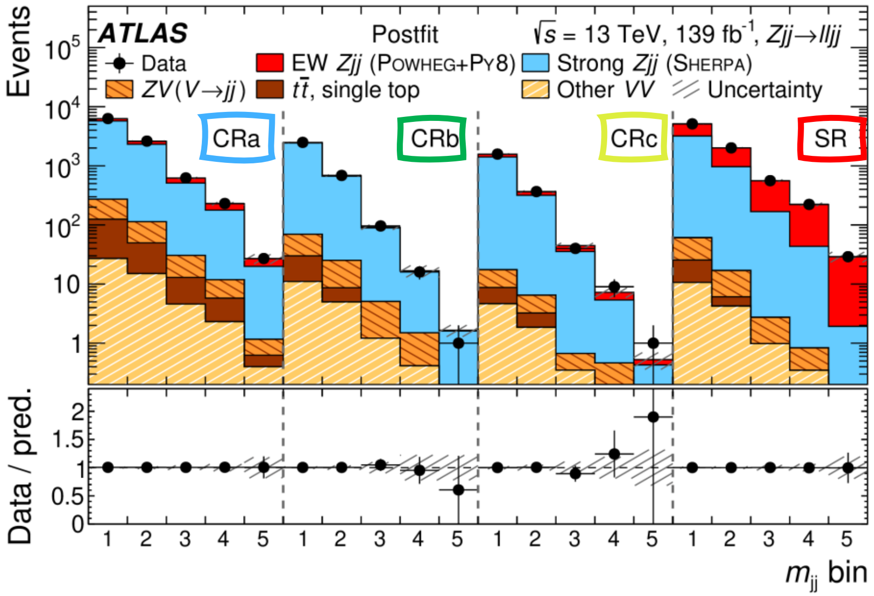
Extraction of **inclusive** signal yield by (MC) by **subtraction** of remaining backgrounds

Extraction of **electroweak** signal yield: **Data-driven** subtraction of strong component using **simultaneous fit** across SR and four control regions

In both cases: **Cross-section** measurement by **unfolding** measured yield to particle level



Fit



Electroweak Z+jj production in ATLAS

[Eur. Phys. J. C 81 (2021) 163]

Uncertainties in cross-section driven by

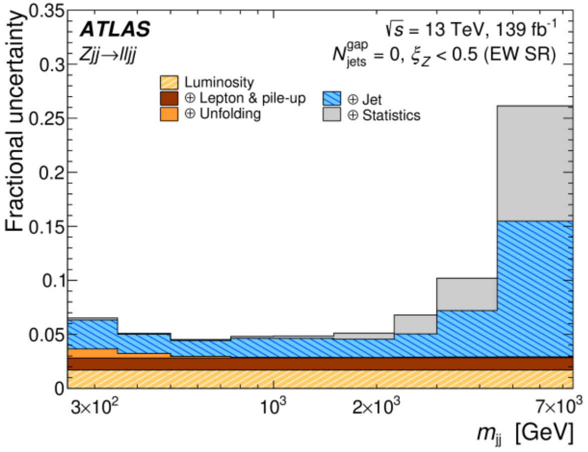
- data **statistics**
- Strong ZZjj **signal modelling** (even with data-driven subtraction)
- Experimental **jet uncertainties**

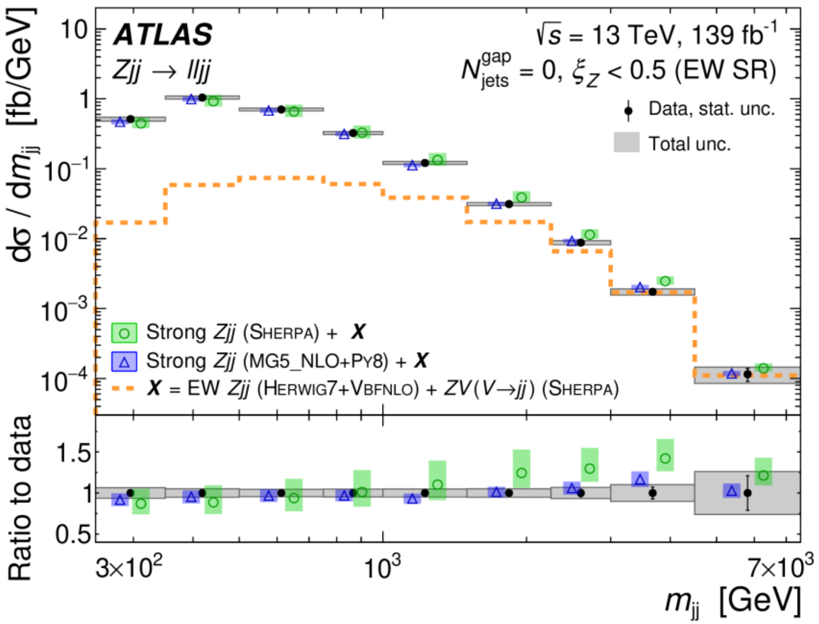
Resulting cross-sections **challenge theory precision**

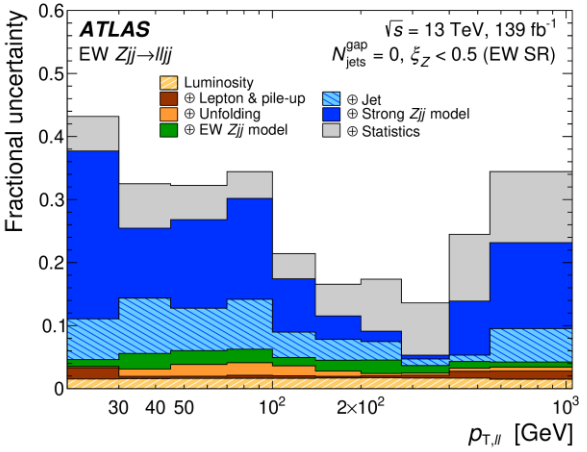
- Can be linked to choices in generator settings used for predictions

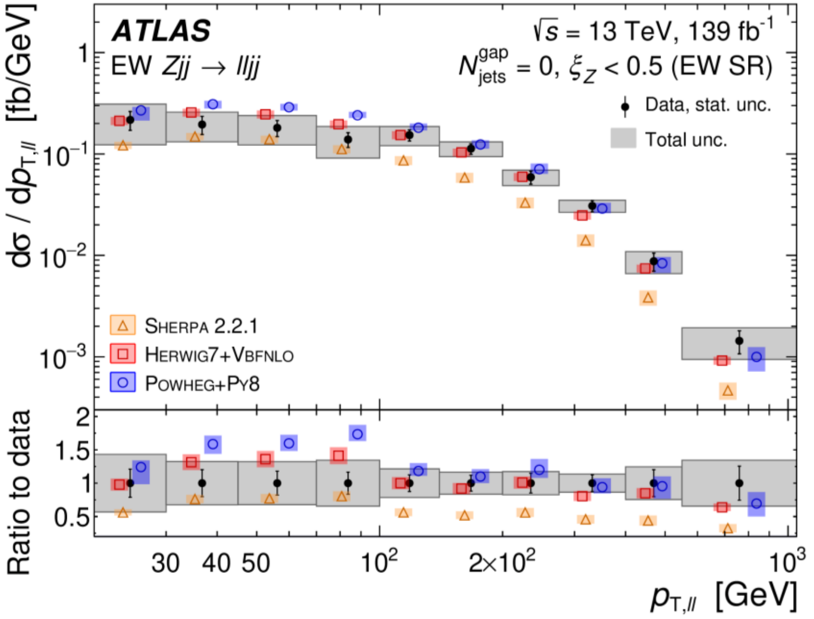
➢ Allow refinement of future predictions

Results allow to set limits on **BSM** contributions in the framework of **Effective field theory** (EFT)









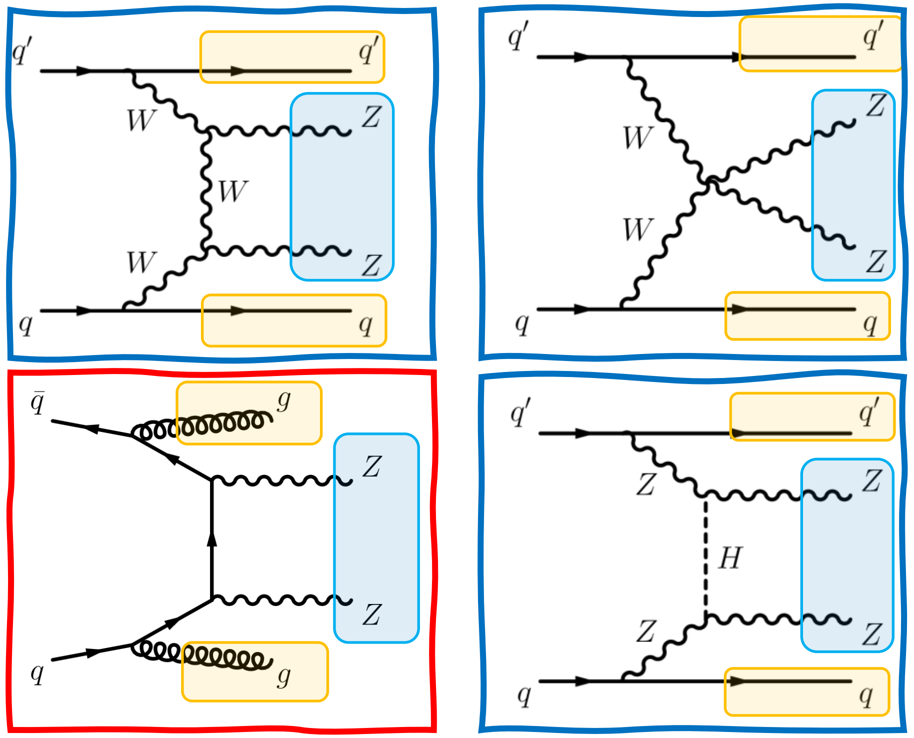
Observation of electroweak ZZ+jj

arXiv:2004.10612, submitted to Nature Physics

One of the **rarest** channels to observe vector boson **scattering**:

Electroweak ZZ production
- Unique sensitivity to anomalous quartic 4-Z coupling
- Challenging: Separation from **strong production** mode

Combine 4l and 2l2v decay channels to **establish initial observation**



Measurement phase-space designed to maximize sensitivity while maintaining acceptable yield
- 4l or 2l+MET system consistent with **ZZ topology**
- **Dijet** system to select EW topology – opposite rapidity and high dijet mass

Process	$\ell\ell\ell\ell jj$	$\ell\ell\nu\nu jj$
EW $ZZjj$	20.6 ± 2.5	12.3 ± 0.7
QCD $ZZjj$	77 ± 25	17.2 ± 3.5
QCD $ggZZjj$	13.1 ± 4.4	3.5 ± 1.1
Non-resonant-$\ell\ell$	–	21.4 ± 4.8
WZ	–	22.8 ± 1.1
Others	3.2 ± 2.1	1.2 ± 0.9
Total	114 ± 26	78.4 ± 6.2
Data	127	82

Resulting region **highly pure** in ZZjj for 4l
- Remaining task: Enrichment of **EW** component against strong

For llvv, two main non-ZZjj background sources:
- **WZ+jj**, with one lepton outside detector acceptance
- **top pair** production and **WWjj** – non-resonant pairs entering Z window in selection
- both **normalized to data** in dedicated **control regions** (DF pairs and 3l)

Observation of electroweak ZZ+jj

arXiv:2004.10612, submitted to Nature Physics

Final enrichment of signal against backgrounds: **multivariate discriminants (MD)**

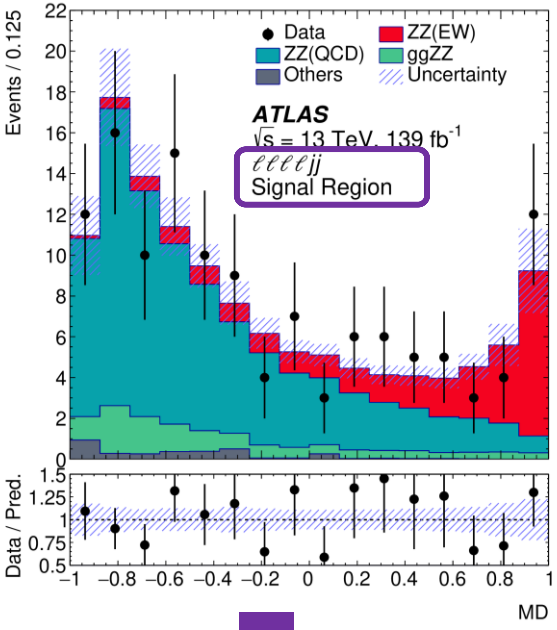
- ➢ Exploit lepton and jet kinematics

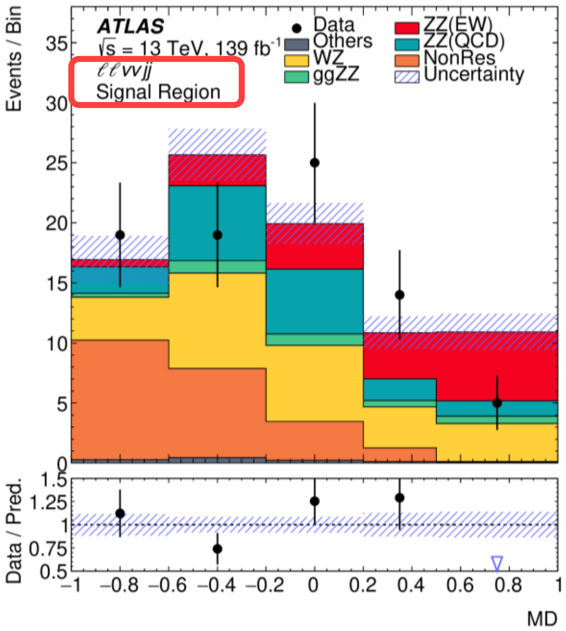
Uncertainties driven by

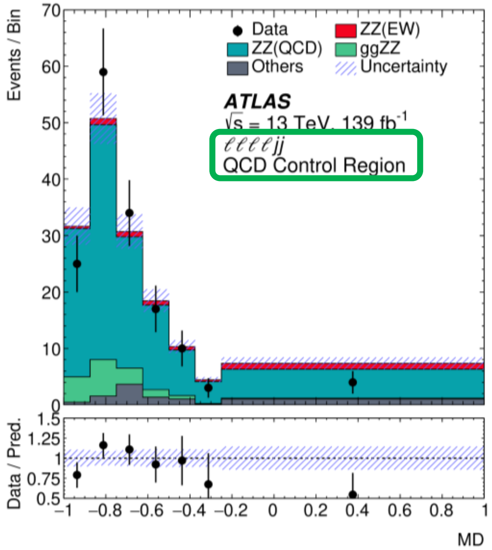
- **Statistics -** dominant
- Lepton efficiencies, signal and background modelling

Final **signal yield** extracted using **combined fit**

- 4l SR, 4l QCD CR and 2l2v SR – using the **MD** as observable
  - ➢ Result in a total signal strength **compatible** with the **SM prediction**
  - ➢ Rejection of the no-EW hypothesis at 5.5σ – first **observation** of this process







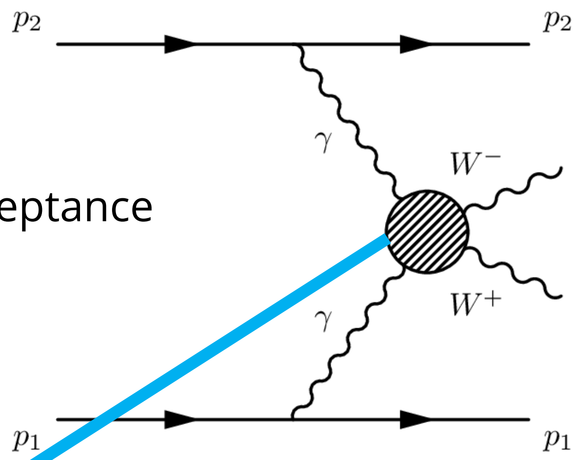
	μ_{EW}	$\mu_{\text{QCD}}^{\ell\ell\ell\ell jj}$	Significance Obs. (Exp.)
$\ell\ell\ell\ell jj$	1.5 ± 0.4	0.95 ± 0.22	$5.5\ (3.9)\ \sigma$
$\ell\ell\nu\nu jj$	0.7 ± 0.7	–	$1.2\ (1.8)\ \sigma$
Combined	1.35 ± 0.34	0.96 ± 0.22	$5.5\ (4.3)\ \sigma$

Extract **fiducial cross-sections** by correcting for detector effects

	Measured fiducial σ [fb]	Predicted fiducial σ [fb]
$\ell\ell\ell\ell jj$	$1.27 \pm 0.12(\text{stat}) \pm 0.02(\text{theo}) \pm 0.07(\text{exp}) \pm 0.01(\text{bkg}) \pm 0.03(\text{lumi})$	$1.14 \pm 0.04(\text{stat}) \pm 0.20(\text{theo})$
$\ell\ell\nu\nu jj$	$1.22 \pm 0.30(\text{stat}) \pm 0.04(\text{theo}) \pm 0.06(\text{exp}) \pm 0.16(\text{bkg}) \pm 0.03(\text{lumi})$	$1.07 \pm 0.01(\text{stat}) \pm 0.12(\text{theo})$

Observation of photon-induced W pair production

[Phys. Lett. B 816 (2021) 136190]



Photon-Photon scattering: Can leave **initial protons intact**

Unique topology: Initial protons either escape intact or fragment outside tracking detector acceptance

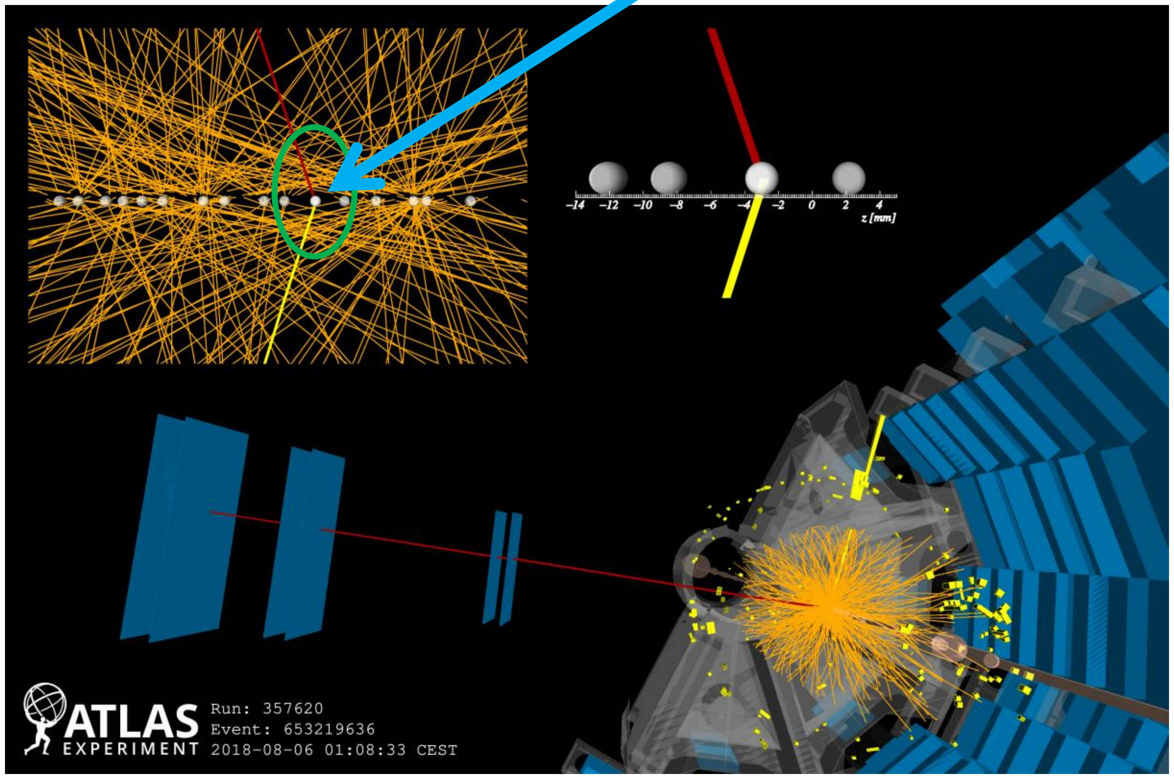
- ➢ Signature of W decay products in **isolation of other charged-particle activity**

Measurement exploits **leptonic WW** topology – two opposite-charge leptons

Strategy based on **track counting**:

Count **additional charged tracks n_{trk}** within **1mm** of the lepton pair vertex

- ➢ Select **signal** by **vetoing** additional tracks (n_{trk} =0)



Not used here, but interesting: *Proton-tagging* in ATLAS
See Talk by Jesse Liu yesterday *Small-x, Diffraction and Vector Mesons track*
Also: Talk by Maciej Trzebinski later today

And of course: Discussion in previous talk by Christophe Royon!

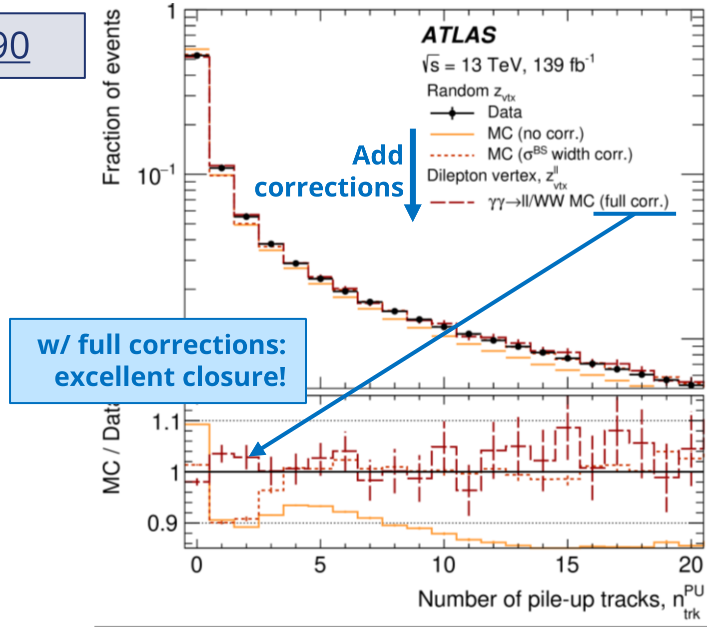
Observation of photon-induced W pair production

Phys. Lett. B 816 (2021) 136190

Analysis relies on **accurate modelling of track density** around dilepton vertex

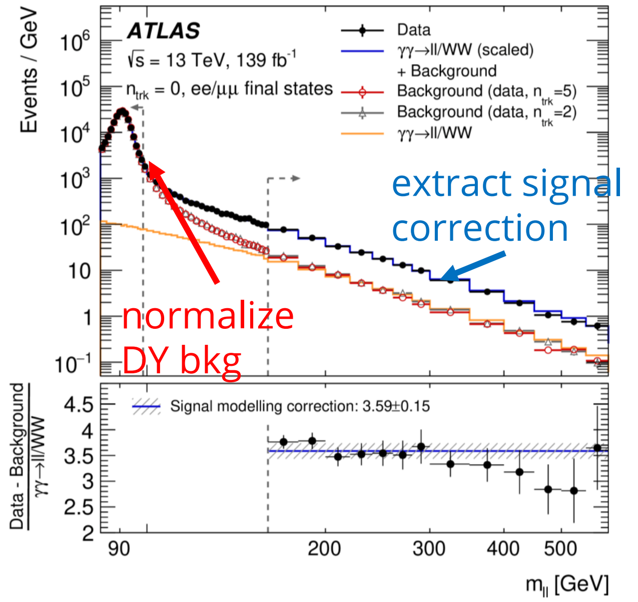
→Requires **careful calibration** of predicted track multiplicity
- In **pileup** interactions – affects **signal** efficiency
- In the **underlying event** – affects **background** prediction

Correct MC using **collision data**



Additional data-driven correction to **signal prediction**: Account for **rescattering** and **single/double diffractive** events (simulate only fully elastic)
- Exploit **exclusive γγ→ll** events to extract correction factor

- Additional, data-driven estimate of W+jets events with non-prompt leptons (background)



Main uncertainties:
- Track reconstruction efficiency: Negligible for signal, 5-6% for background
- Non-prompt leptons: Driven by statistics in control region → **dominant source**
- Signal and background (in particular WW) modelling

Observation of photon-induced W pair production

- Final **signal extraction** using different-flavour **eμ** events**: Simultaneous fit**

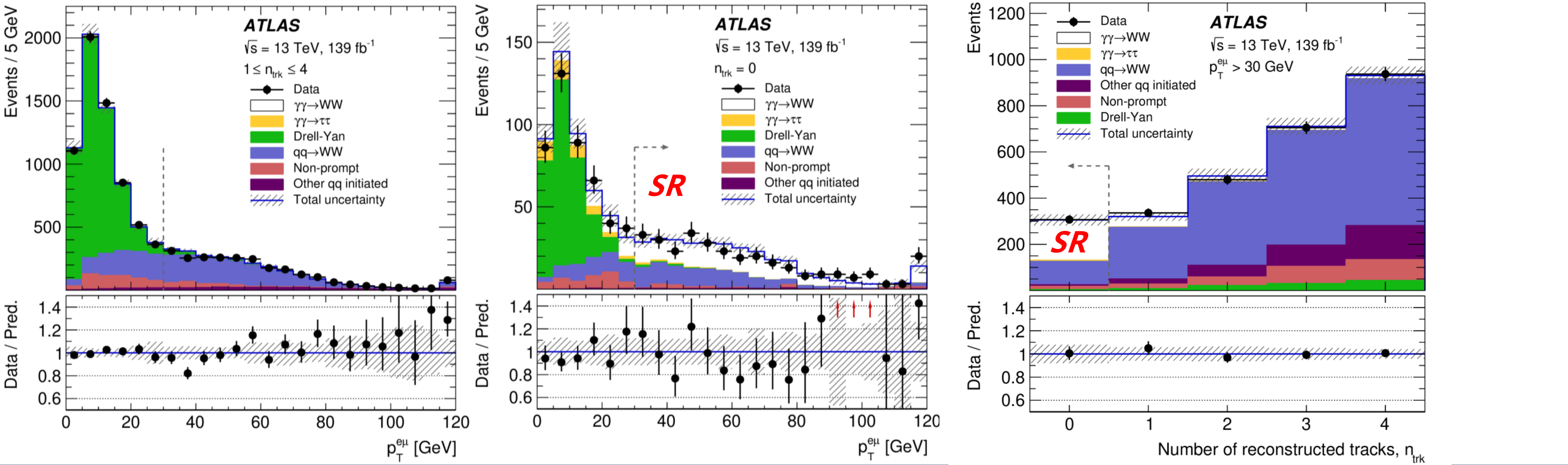
[Phys. Lett. B 816 (2021) 136190]

  - **Signal Region:** ntrk =0, $p_{T,e\mu}$ > 30 GeV
  - **Sidebands** in ntrk and $p_{T,e\mu}$: Constrain background

Result:

Reject background-only hypothesis at **8.4σ**, signal strength (1.33) **compatible** with **SM** prediction

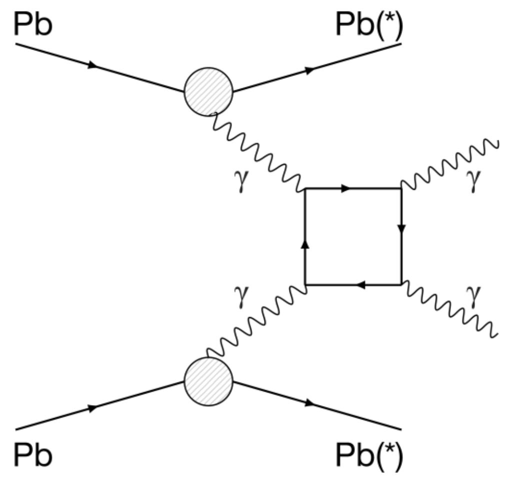
Resulting **fiducial cross-section** of 3.13 ± 0.31 (stat.) ± 0.28 (syst.) fb agrees with predictions after accounting for dissociative contributions and survival factor



Measurement of light-by-light scattering in Pb+Pb collisions

JHEP 03 (2021) 243

Strong electromagnetic fields in **heavy ion** collisions allow to probe **light-by-light** scattering



Striking signature: **Two soft photons**, **no other activity**

- In particular, no charged tracks!

Challenging to **trigger** – dedicated trigger chain requiring low calorimetric deposits while vetoing activity in remaining detector

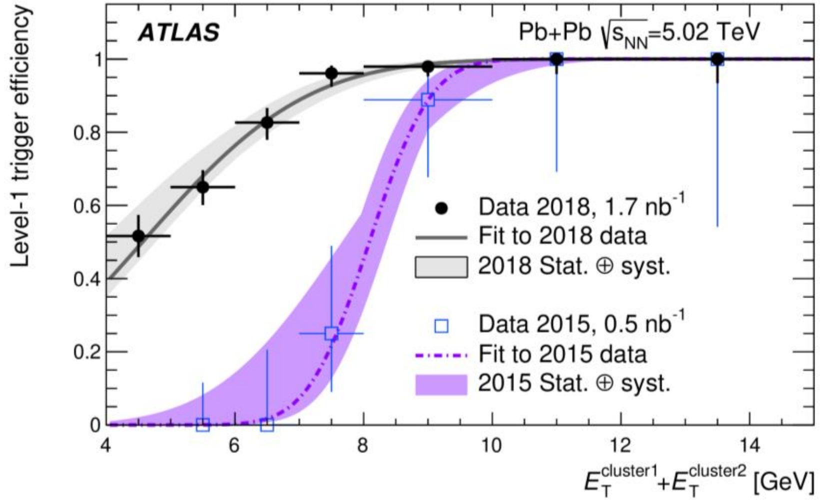
Phase-space defined on top of dedicated trigger:

Look for **two soft photons** (system close to rest), **no charged tracks**

Main **backgrounds:**

- exclusive ee production, with e misidentified as photons (missed tracks)
  - estimated using **data**, extrapolated from **control region** with 1 or 2 **pixel tracklets**
- central exclusive production (CEP) – gg→γγ
  - estimated using **MC simulation**, normalized using **data** in a high-acoplanarity sideband

Both **trigger** and **soft photon** reconstruction require **careful calibration**



Measurement of light-by-light scattering in Pb+Pb collisions

[JHEP 03 (2021) 243](#)

Uncertainties dominated by **statistics,** also **background** and **trigger/photon calibration**

Extract **fiducial cross-section** as 120 ±17(stat.) ±13(syst.) ±4 (lumi) nb

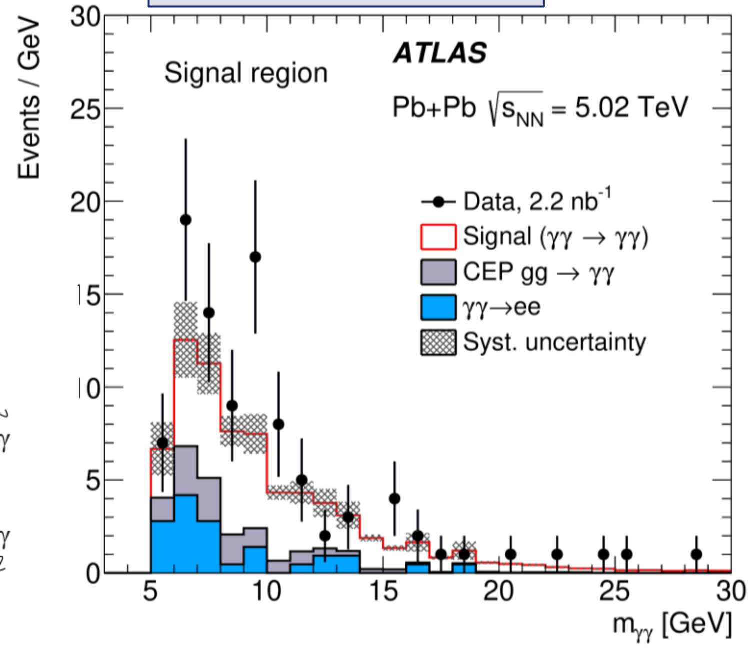
- factor 1.5 ±0.3 above current predictions

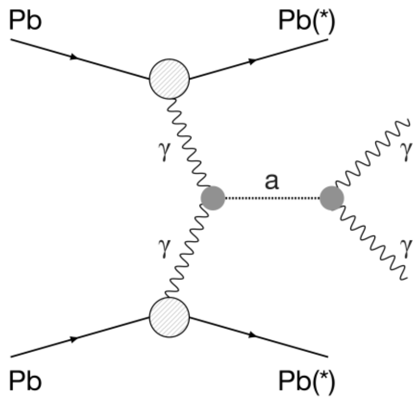
Also measure **differential cross-sections**

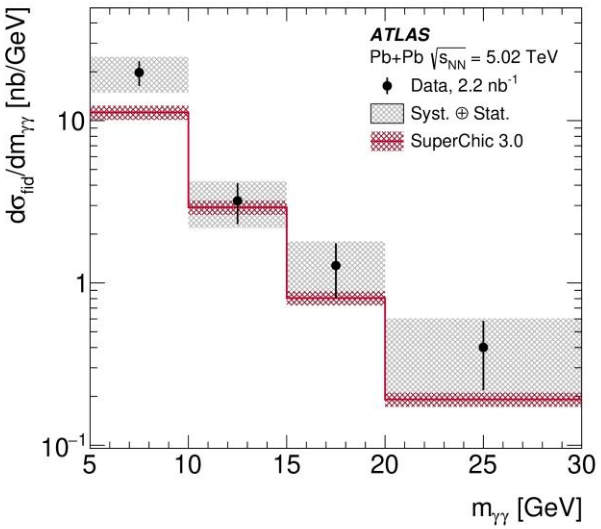
- via **Bayesian iterative unfolding** with one iteration
- All measurements still statistically limited

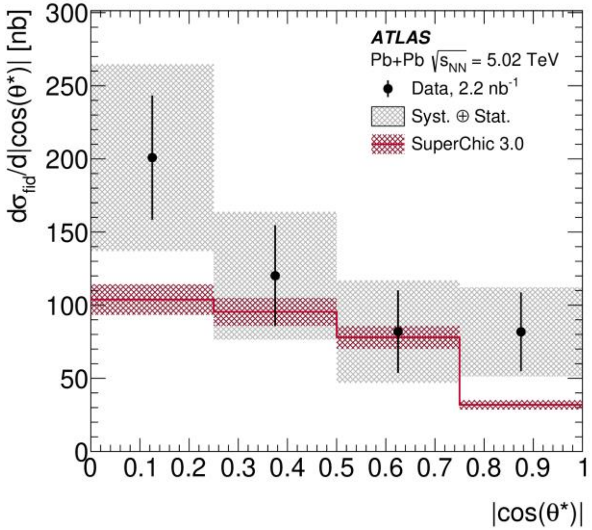
Use results to place limit on **axion-like particle** production

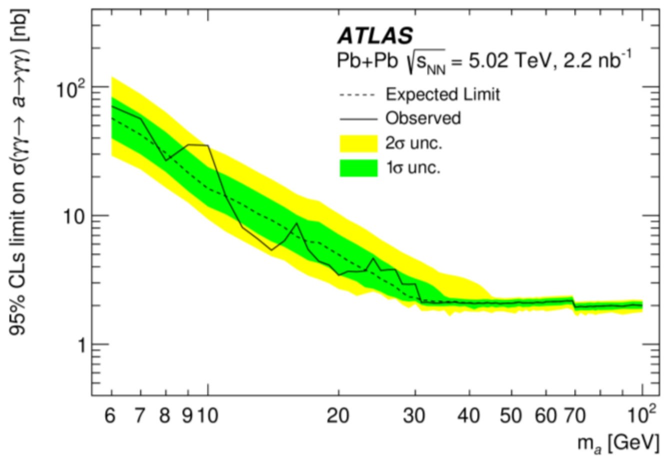
- Competitive with strongest-existing bounds in 6-100 GeV region

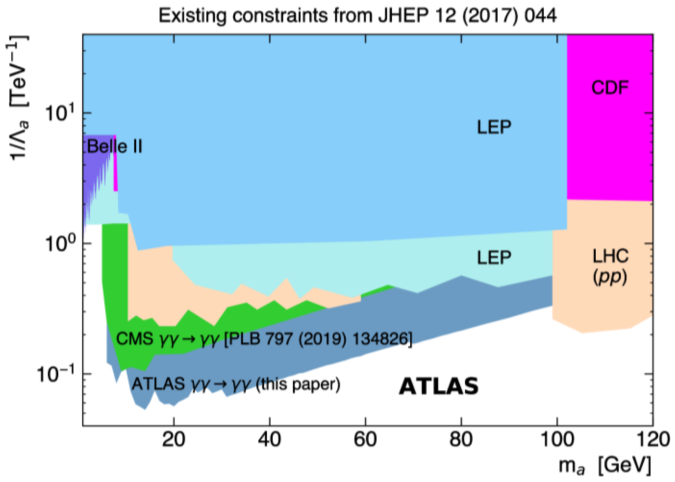












Summary

The full LHC Run-2 dataset has unlocked **unprecedented potential** for precise probes of vector boson self-interaction

- Precision tests of the electroweak symmetry breaking mechanism
- Sensitivity to signs of BSM physics
- Typically rare processes, profit from enormous dataset available

Wide set of **measurements** in ATLAS, stretching across pp and HI programs

- “Classical” measurements exploiting the VBF/VBS dijet signature, but also...
- ... creative ideas making the most of the detector!
  - Track vetoes, forward proton tagging, dedicated trigger chains, soft object reconstruction, ...
- Experimentally challenging, but invaluable results

Most measurements still **statistically limited**

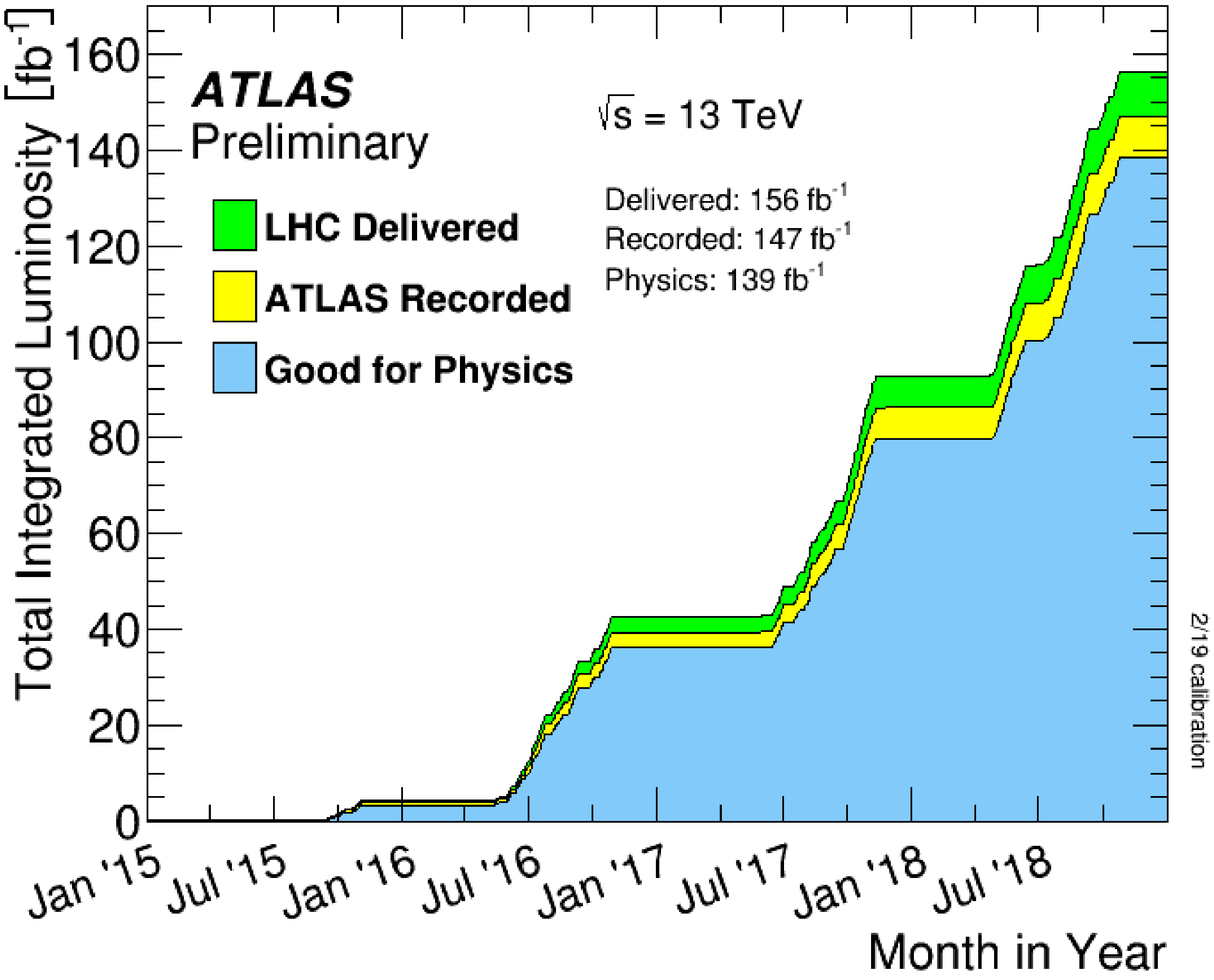
- ➢ Potential for further improvement during Runs 3, 4 and beyond
- ➢ High-precision VBF/VBS measurements are one of the main targets of the HL-LHC programme!

Thank you for your attention!

Backup

Run-2 ATLAS dataset

ATLAS Public Luminosity results



EW Z+jj measurement – phase-space and event selection

Dressed muons	$p_{\mathrm{T}} > 25$ GeV and $\lvert\eta\rvert < 2.4$
Dressed electrons	$p_{\mathrm{T}} > 25$ GeV and $\lvert\eta\rvert < 2.37$ (excluding $1.37 < \lvert\eta\rvert < 1.52$)
Jets	$p_{\mathrm{T}} > 25$ GeV and $\lvert y\rvert < 4.4$
VBF topology	$N_{\ell} = 2$ (same flavour, opposite charge), $m_{\ell\ell} \in (81, 101)$ GeV $\Delta R_{\mathrm{min}}(\ell_1, j) > 0.4$, $\Delta R_{\mathrm{min}}(\ell_2, j) > 0.4$ $N_{\mathrm{jets}} \geq 2$, $p_{\mathrm{T}}^{j1} > 85$ GeV, $p_{\mathrm{T}}^{j2} > 80$ GeV $p_{\mathrm{T},\ell\ell} > 20$ GeV, $p_{\mathrm{T}}^{\mathrm{bal}} < 0.15$ $m_{jj} > 1000$ GeV, $\lvert\Delta y_{jj}\rvert > 2$, $\xi_Z < 1$
CRa	VBF topology $\oplus$ $N_{\mathrm{jets}}^{\mathrm{gap}} \geq 1$ and $\xi_Z < 0.5$
CRb	VBF topology $\oplus$ $N_{\mathrm{jets}}^{\mathrm{gap}} \geq 1$ and $\xi_Z > 0.5$
CRc	VBF topology $\oplus$ $N_{\mathrm{jets}}^{\mathrm{gap}} = 0$ and $\xi_Z > 0.5$
SR	VBF topology $\oplus$ $N_{\mathrm{jets}}^{\mathrm{gap}} = 0$ and $\xi_Z < 0.5$

EW Z+jj measurement – signal modelling

Two main samples for QCD Z+jj:

- Sherpa 2.2.1, NLO (0-2 partons) / LO (3,4 partons), normalized to NNLO Z XS
- MG5_aMC@NLO NLO (0-2p), FxFx merging, normalized to (same) NNLO Z XS

Three main samples for EW Z+jj:

- POWHEG-BOX v1 + Pythia8, NLO QCD
- HERWIG 7.1.5 + VBFNLO, NLO QCD
- Sherpa 2.2.1 – LO QCD for 0-2 add. partons

VBF approximation – enforce t-chan color singlet exchange (first two samples)

Process	Generator	ME accuracy	PDF	Shower and hadronisation	Parameter set
EW Zjj	Powheg-Box v1	NLO	CT10nlo	Pythia8 + EvtGen	AZNLO
	Herwig7 + Vbfnlo	NLO	MMHT2014lo	Herwig7 + EvtGen	default
	Sherpa 2.2.1	LO (2–4j)	NNPDF3.0nnlo	Sherpa	default
Strong Zjj	Sherpa 2.2.1	NLO (0–2j), LO (3–4j)	NNPDF3.0nnlo	Sherpa	default
	MadGraph5_aMC@NLO	NLO (0–2j), LO (3–4j)	NNPDF2.3nlo	Pythia8 + EvtGen	A14
	MadGraph5	LO (0–4j)	NNPDF3.0lo	Pythia8 + EvtGen	A14
VV	Sherpa	NLO (0–1j), LO (2–3j)	NNPDF3.0nnlo	Sherpa	default
$t\bar{t}$	Powheg-Box v2 hvq	NLO	NNPDF3.0nnlo	Pythia8 + EvtGen	A14
VVV	Sherpa	LO (0–1j)	NNPDF3.0nnlo	Sherpa	default
W+jets	Sherpa	NLO (0–2j), LO (3–4j)	NNPDF3.0nnlo	Sherpa	default

Electroweak Z+jj – EFT interpretation

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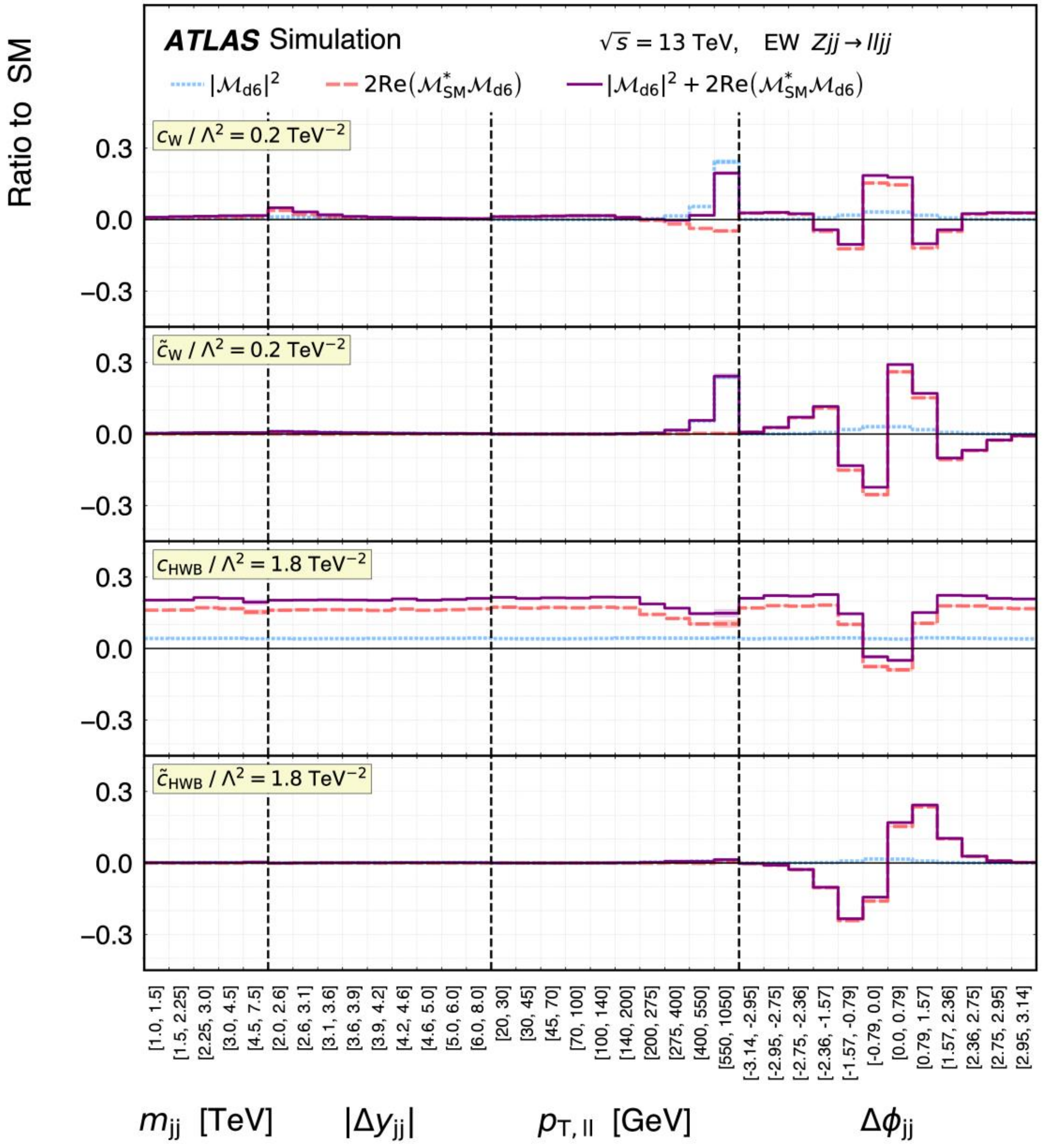
Beyond SM cross-section measurement:

Results allow to constrain **BSM physics**

Interpret in the formalism of **effective field theory** – dimension 6 operators known to affect the WWZ coupling

- Parity-odd **$\Delta\varphi_{jj}$** observable provides strong sensitivity to **CP-violating** couplings
- Dominated by **interference** between dimension-6 and SM – hint of low dependence on (potentially ignored) dimension-8 contributions
- Resulting bounds on Wilson coefficients: Competitive with existing bounds from WW at ATLAS or WZ/EW Zjj at CMS

Wilson coefficient	Includes $\lvert\mathcal{M}_{d6}\rvert^2$	95% confidence interval [TeV^{-2}] Expected	Observed	p-value (SM)
c_W/Λ^2	no	[−0.30, 0.30]	[−0.19, 0.41]	45.9%
	yes	[−0.31, 0.29]	[−0.19, 0.41]	43.2%
$\tilde{c}_W/\Lambda^2$	no	[−0.12, 0.12]	[−0.11, 0.14]	82.0%
	yes	[−0.12, 0.12]	[−0.11, 0.14]	81.8%
c_{HWB}/Λ^2	no	[−2.45, 2.45]	[−3.78, 1.13]	29.0%
	yes	[−3.11, 2.10]	[−6.31, 1.01]	25.0%
$\tilde{c}_{HWB}/\Lambda^2$	no	[−1.06, 1.06]	[0.23, 2.34]	1.7%
	yes	[−1.06, 1.06]	[0.23, 2.35]	1.6%



EW ZZ+jj measurement – detailed selection

<table>
<tr><th></th><th>$\ell\ell\ell\ell jj$</th><th>$\ell\ell\nu\nu jj$</th></tr>
<tr><td>Electrons</td><td colspan="2">$p_{\mathrm{T}} > 7$ GeV, $|\eta| < 2.47$
$|d_0/\sigma_{d_0}| < 5$ and $|z_0 \times \sin\theta| < 0.5$ mm</td></tr>
<tr><td rowspan="2">Muons</td><td>$p_{\mathrm{T}} > 7$ GeV, $|\eta| < 2.7$</td><td>$p_{\mathrm{T}} > 7$ GeV, $|\eta| < 2.5$</td></tr>
<tr><td colspan="2">$|d_0/\sigma_{d_0}| < 3$ and $|z_0 \times \sin\theta| < 0.5$ mm</td></tr>
<tr><td>Jets</td><td>$p_{\mathrm{T}} > 30$ (40) GeV for $|\eta| < 2.4$ ($2.4 < |\eta| < 4.5$)</td><td>$p_{\mathrm{T}} > 60$ (40) GeV for the leading (sub-leading) jet</td></tr>
<tr><td>ZZ selection</td><td>$p_{\mathrm{T}} > 20, 20, 10$ GeV for the leading, sub-leading and third leptons
Two OSSF lepton pairs with smallest $|m_{\ell^+\ell^-} - m_Z| + |m_{\ell'^+\ell'^-} - m_Z|$
$m_{\ell^+\ell^-} > 10$ GeV for lepton pairs
$\Delta R(\ell, \ell') > 0.2$
$66 < m_{\ell^+\ell^-} < 116$ GeV</td><td>$p_{\mathrm{T}} > 30$ (20) GeV for the leading (sub-leading) lepton
One OSSF lepton pair and no third leptons
$80 < m_{\ell^+\ell^-} < 100$ GeV
No b-tagged jets
$E_{\mathrm{T}}^{\mathrm{miss}}$-significance > 12</td></tr>
<tr><td rowspan="2">Dijet selection</td><td colspan="2">Two most energetic jets with $y_{j_1} \times y_{j_2} < 0$</td></tr>
<tr><td>$m_{jj} > 300$ GeV and $\Delta y(jj) > 2$</td><td>$m_{jj} > 400$ GeV and $\Delta y(jj) > 2$</td></tr>
</table>

Observation of electroweak ZZ+jj - backgrounds

arXiv:2004.10612, submitted to Nature Physics

Backgrounds constrained using **collision data**:

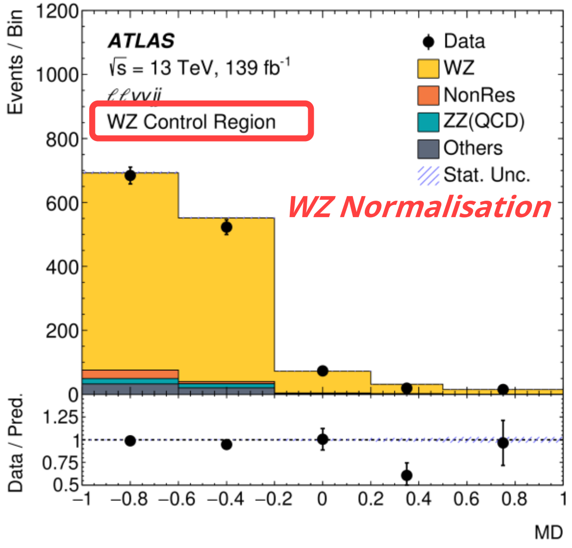
4l:

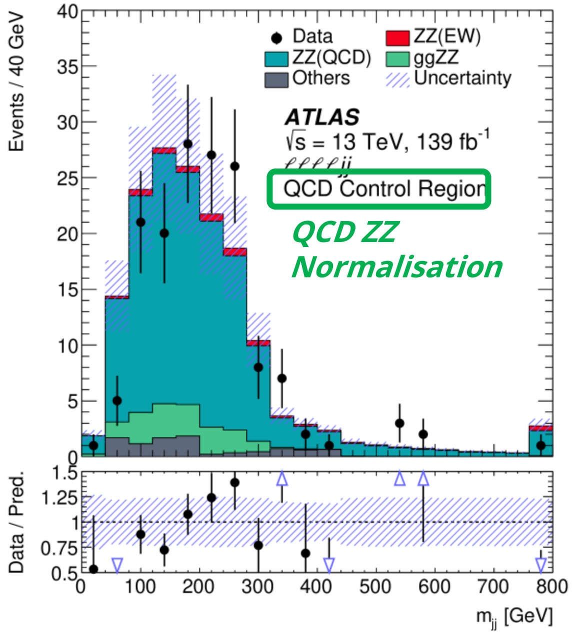
Normalise **strong** ZZjj in dedicated **QCD control region**
- invert requirement on **dijet mass** or **rapidity gap** between jets
- Validate in region with large Z boson centrality value

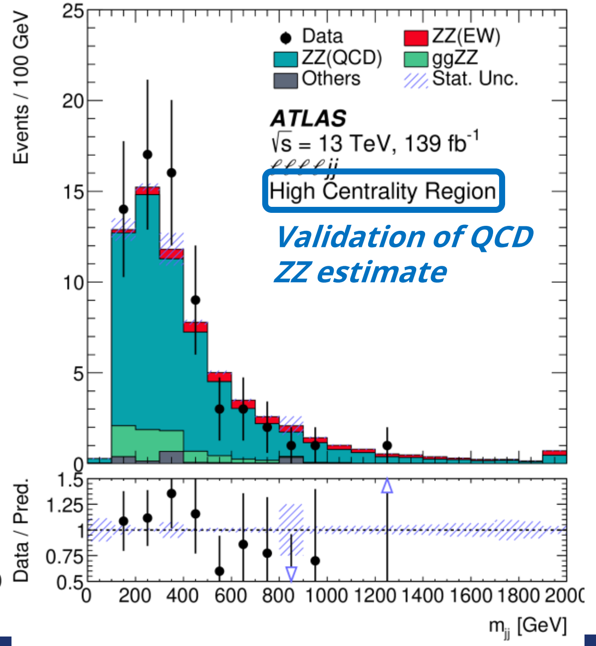
- Minor background from non-prompt lepton estimated using data-driven 'fake factor' method

2l2v:

- **WZjj** normalized using **3-lepton control region**
- non-resonant contribution (WW, tt) estimated in **different-flavour** control region







EW ZZ+jj measurement – inputs to MD discriminant

- Gradient Boosted Decision Trees trained using TMVA Framework

4ljj: **12 variables –** m_{jj}, Δy_{jj}, p_T of two leading jets, $y_{j1} \times y_{j2}$, $p_{T,Z1}$, y_{Z1}, y_{Z2}, $p_{T,4l}$, m_{4l}, $p_{T,l3}$, S_T

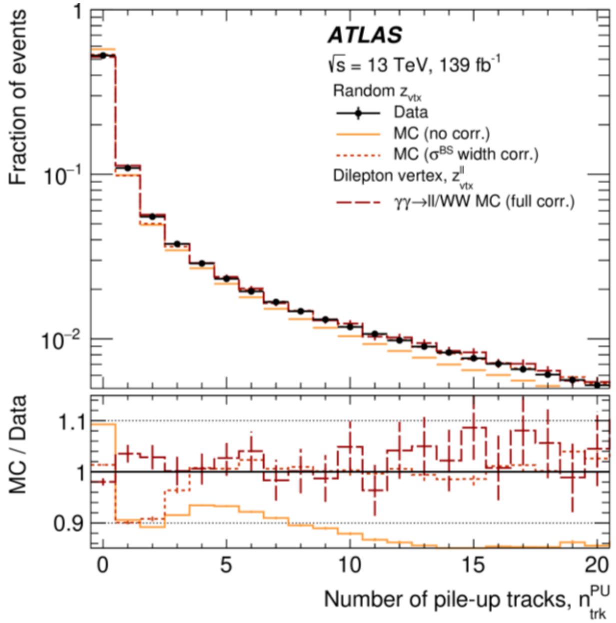
Jet variables drive sensitivity

2l2vjj: **13 variables -** m_{jj}, Δy_{jj}, $y_{j1} \times y_{j2}$, $p_{T,j2}$, $E_{T,Miss}$, $E_{T,Miss}$ significance, S_T, $\Delta\eta_{ll}$, $\Delta\varphi_{ll}$, ΔRll, m_{ll}, p_T of two leading jets

Both dilepton system and jets drive sensitivity

Photon-induced W pair production – nTrack calibration

Phys. Lett. B 816 (2021) 136190



Analysis relies on **accurate modelling of track density** around dilepton vertex

Two main sources of tracks to account for:

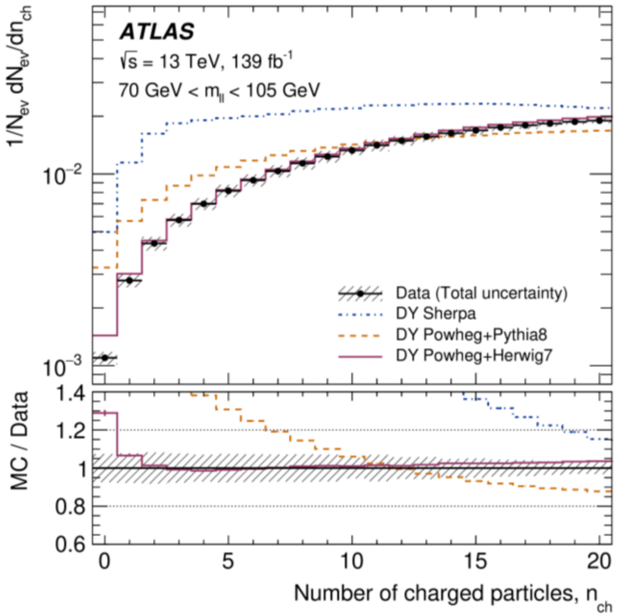
Pileup track contribution: Affects **signal** selection efficiency

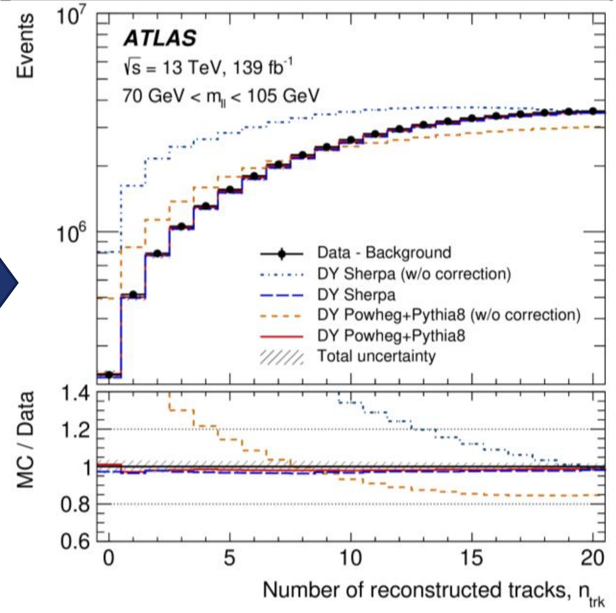
- Reweight MC to match average number of pp collisions per bunch in data
- Effective correction to emulate varying beam-spot width in data
- Additional correction based on **track density** around **random z** location in Z→ll events in data/MC

Underlying event track contribution: Affects rate of accepted **background** events

- Correct to data using **particle level n_{ch} distribution** measured in Z→ll in slices of $p_{T,ll}$
- Obtained using iterative Bayesian **unfolding** with 4 iterations, after subtracting γγ→ll events and pile-up tracks
- Reweight simulation using the measured data/MC ratio of particle-level n_{ch} as function of $p_{T,\text{final state}}$

After correction, charged particle production rates in simulation match data – both for pileup and UE tracks



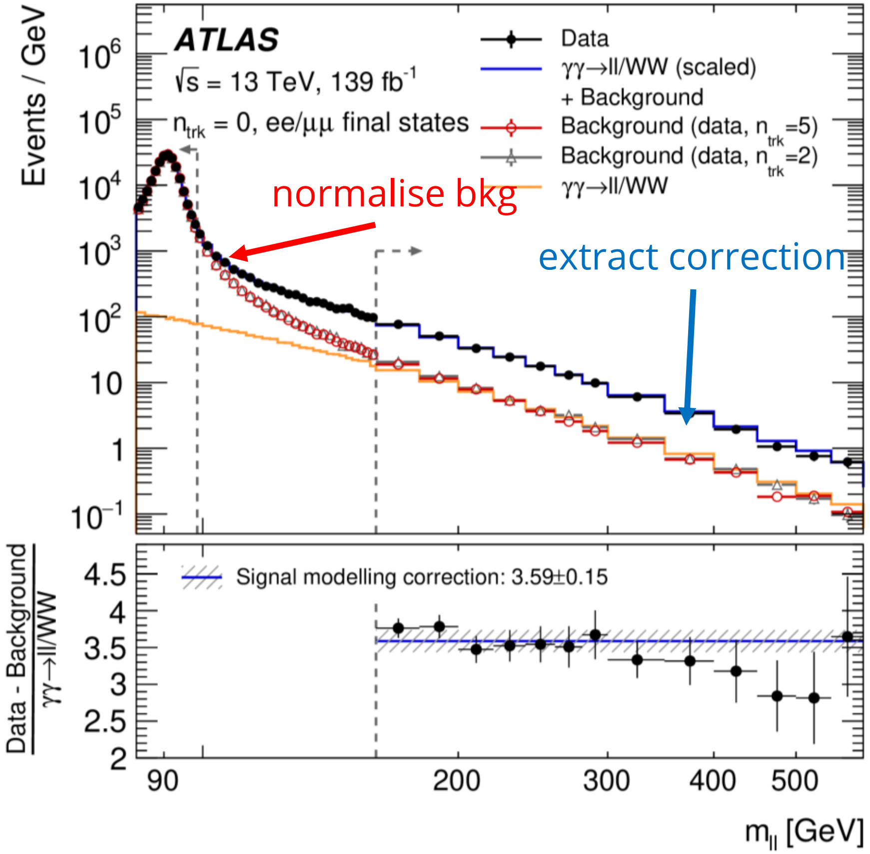


Photon-induced W pair production – signal calibration

Phys. Lett. B 816 (2021) 136190

Signal simulation only includes elastic modes and does **not** account for rescattering of escaping protons

- ➢ correct using **data** in $\gamma\gamma \to ll$ events
  - Use $n_{trk}=0$, m_{ll} > 160 GeV to extract rate, compare to elastic-only simulation
  - Subtract background (mainly DY) using $n_{trk}=5$ data, normalized in region around m_Z
- Significant correction factor 3.59±0.15 – compatible with expectation of 3.55 from simulation



Light-by-light scattering in Pb+Pb collisions - trigger

JHEP 03 (2021) 243

- 2015:
  - L1: ET after noise suppression: 5 – 200 GeV
  - HLT: Reject if >1 hits in the inner MBTS ring. Less than 10 Pixel hits in the event
- 2018:
  - L1:
    - at least one EM cluster with E_T > 1 GeV and total E_T in calorimeter 4 – 200 GeV
    - OR at least two EM clusters with E_T > 1 GeV and total E_T in calorimeter < 50 GeV
  - HLT: Require total E_T on each side of FCAL < 3 GeV. Less than 15 Pixel hits in the event

2018 trigger improves low photon-E_T sensitivity

Light-by-light scattering in Pb+Pb collisions – object calibration

[JHEP 03 (2021) 243]

Careful **detector calibration** required for custom trigger and low-E_T object reconstruction

- **Trigger** efficiencies measured using γγ→ee selected using supporting triggers
- Photon **reconstruction** efficiencies using γγ→eeγ, with hard bremsstrahlung emitted by electron
- Photon **identification** efficiencies using FSR in high-E_T γγ→ee
- Photon **energy scale and resolution** validated in γγ→ee based on **momentum balance**