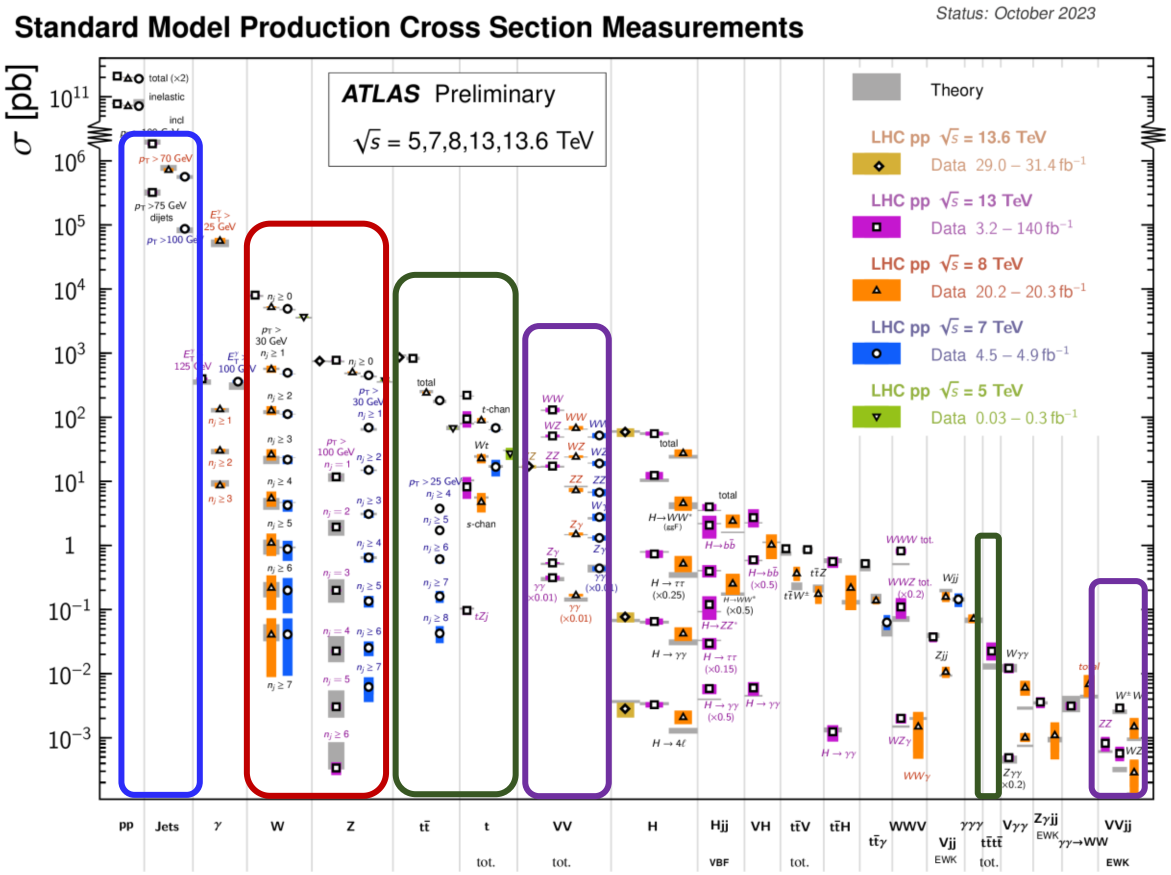
Precision measurements of the Standard Model with the ATLAS Experiment

Yi Yu
On behalf of the ATLAS Collaboration

8th Jan 2024, Cracow Epiphany Conference

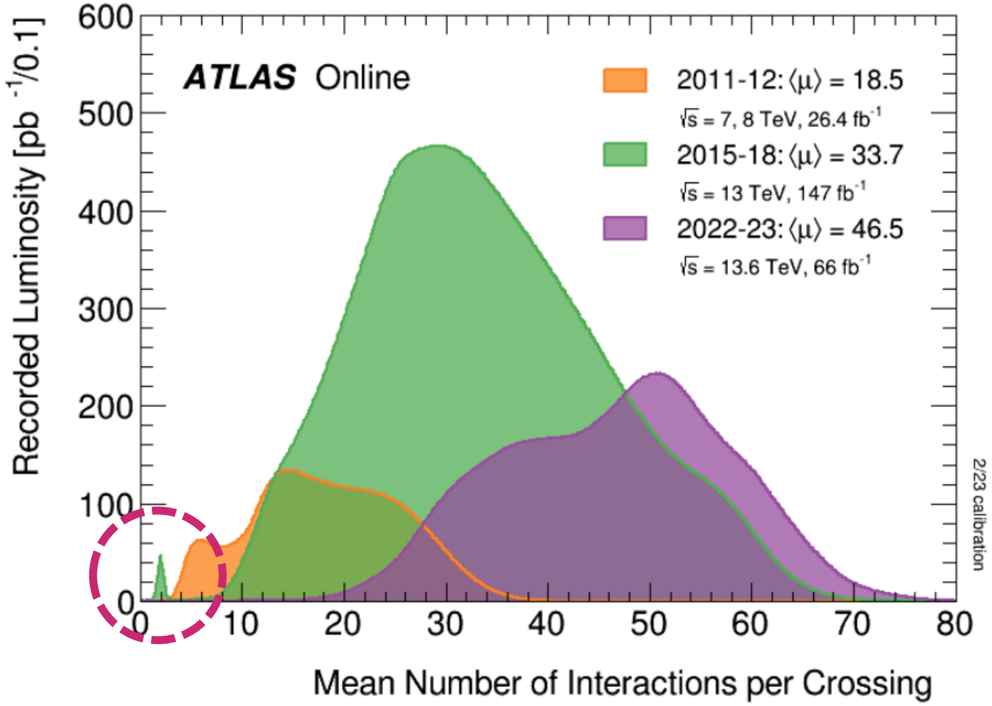
Introduction

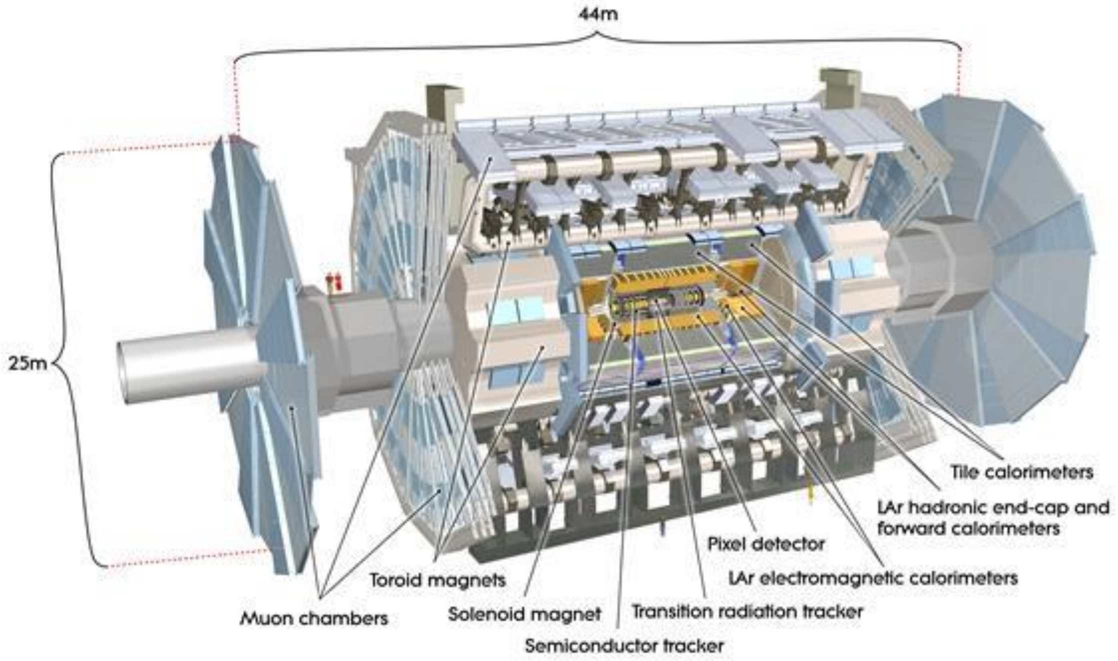
- Precision measurements with the ATLAS experiment at the LHC
  - Determine fundamental parameters of the Standard Model
  - Provide stringent tests of the electroweak theory and perturbative QCD
- Talk content
  - **Drell-Yan** measurements of $m_W, p_T^V, \alpha_s, \Gamma_V$
  - **Diboson** production at 13/13.6 TeV
  - Determination of α_s with **multi-jets**
  - **Single top, $t\bar{t}$, four-top** observations
- Selection from the most recent results



ATLAS Detector and Data Taking

- Detector components
  - Inner detector, Calorimeters, Muon Spectrometer
- Successful start of the Run-3 in 2022 July with new pp energy at 13.6 TeV





- **<μ>~2 taken during 2017 – 2018: 255 pb^{-1} at 5.02 TeV, 338 pb^{-1} at 13 TeV**

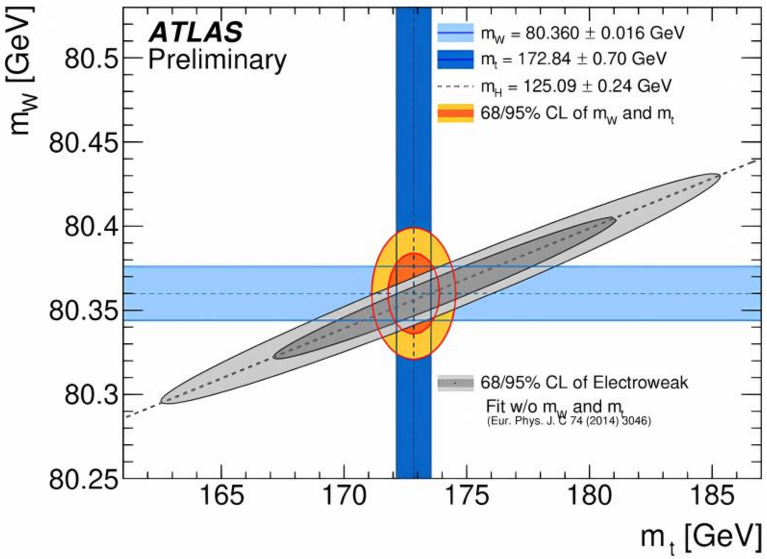
Drell-Yan W/Z Production

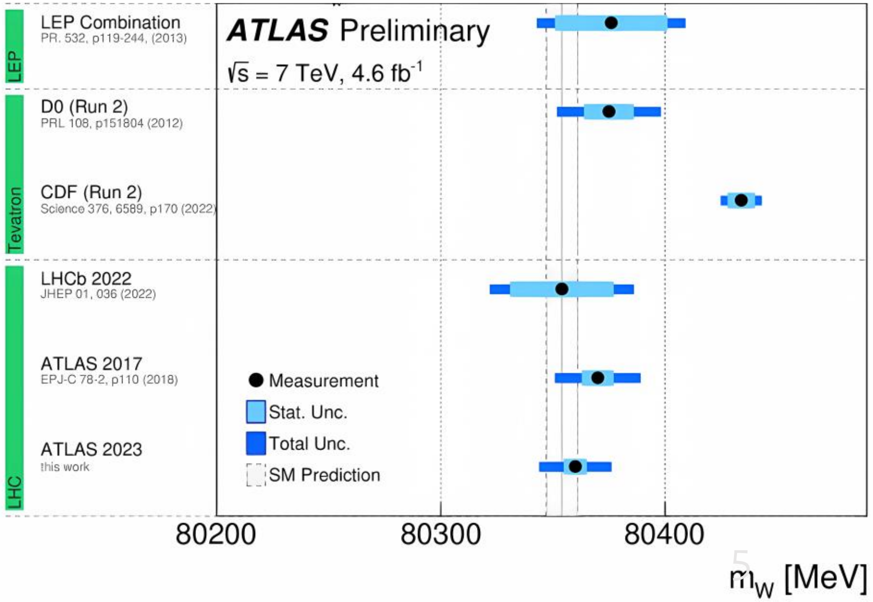
- Probe the SM Electroweak sector: m_W, weak mixing angle, lepton universality
- Probe PDF, (non) perturbative QCD predictions
- Standard candle for precision measurements and theory at LHC

m_W re-analysis at 7TeV

ATLAS-CONF-2023-004

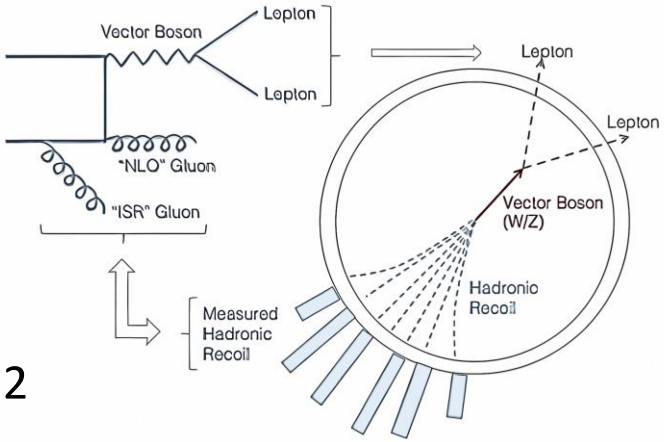
- Importance of m_W measurement
  - Dependence on m_Z, α, G_μ, m_t, m_H, gauge couplings in EWK theory
  - Loop-corrections can receive contributions from BSM particles
- m_W determined from templates fits to p_T^l and m_T^W
  - $\vec{p}_T^{\,miss} = -(\vec{p}_T^{\,l} + \vec{u}_T)$
  - $m_T^W = \sqrt{2 p_T{}^l p_T{}^{miss}\left(1 - \cos\left(\phi_l - \phi_{E_T{}^{miss}}\right)\right)}$
- Strategy update
  - Update PDF set: CT10NNLO ⇨ CT18NNLO
  - χ^2 offset method ⇨ profile likelihood fit
- New results
  - m_W = 80360 ± 5 (stat.) ± 15 (syst.) = 80360 ± 16 MeV
  - Uncertainty reduced by 15%, dominant by l calibration and PDF
  - Central value shifted closely to the SM prediction by 10 MeV
  - More details can be found in backup





p_T^W and p_T^Z with low pile-up data

ATLAS-CONF-2023-028



Motivation

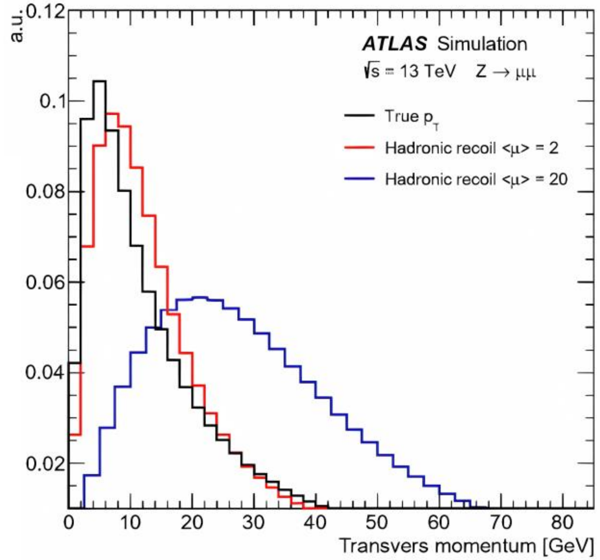
- Non-zero p_T^V arises from higher order corrections and non-perturbative effects
- Spectrum of $p_T^V < 30$ GeV is of particular interest for the measurement of m_W

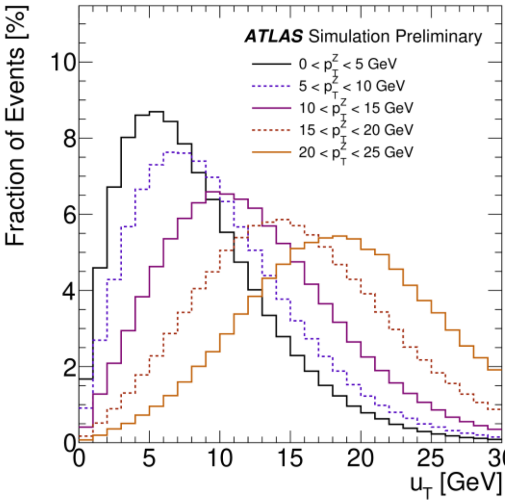
Data collected with reduced instantaneous luminosity

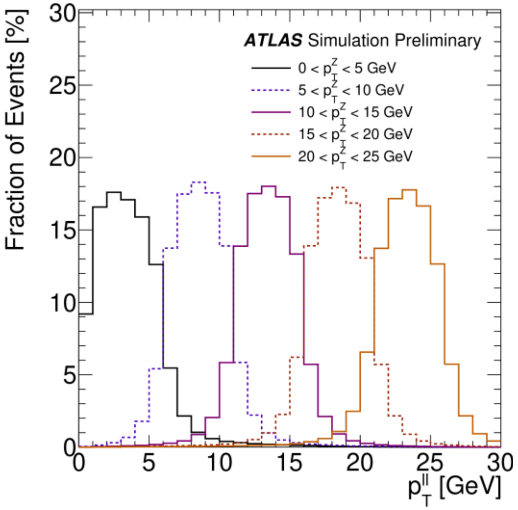
- L_{int} as 254 and 338 pb^{-1} at $\sqrt{s} = 5.02$ TeV and 13 TeV respectively with <μ> ≈ 2
- Clean experimental conditions optimize the resolution on the hadronic recoil

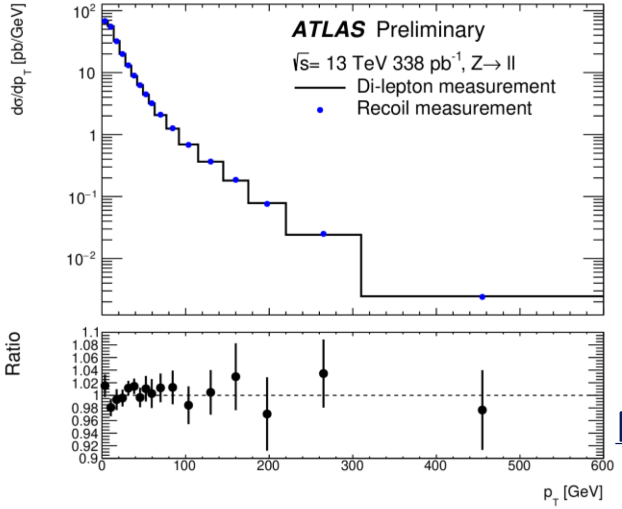
Iterative Bayesian Unfolding are used to correct detector effect

- $u_T \rightarrow p_T^W, u_T$ or $p_T^{ll} \rightarrow p_T^Z$









More details can be found in backup

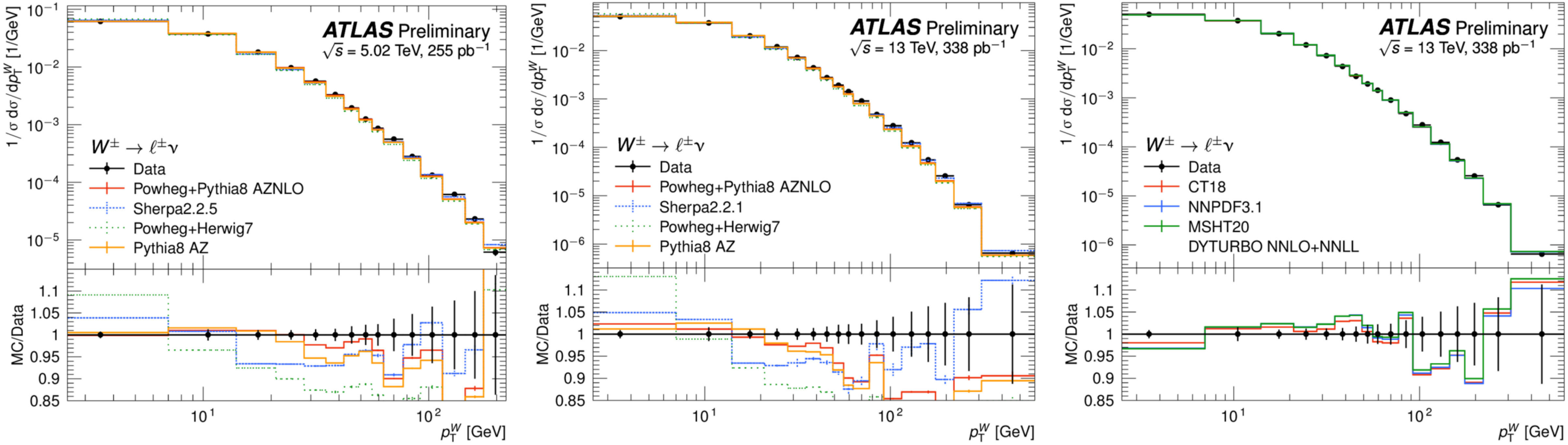
p_T^W and p_T^Z with low pile-up data

ATLAS-CONF-2023-028

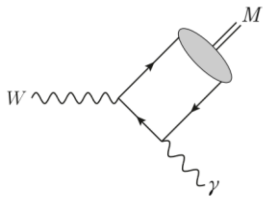
Normalized differential cross sections

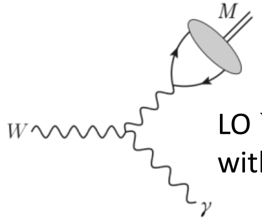
- Parton shower MC predictions show significant differences largely common to W^-, W^+ and Z production
  - Better agreement at $\sqrt{s} = 5.02$ TeV, especially for predictions tuned to Z production data at $\sqrt{s} = 7$ TeV
- Higher-order, resummed predictions from DYTURBO (NNLO+NNLL) match the data best across the spectra
- Ratios give a better agreement resulting from the similarity in the processes

Integrated cross sections see back up



W rare decays at 13TeV





LO $W \to M\gamma$
with $M = \{\pi, K, \rho, D, D_s, \text{B}\}$

[Submit to PRL:](#)

arXiv:2309.15887

Motivation

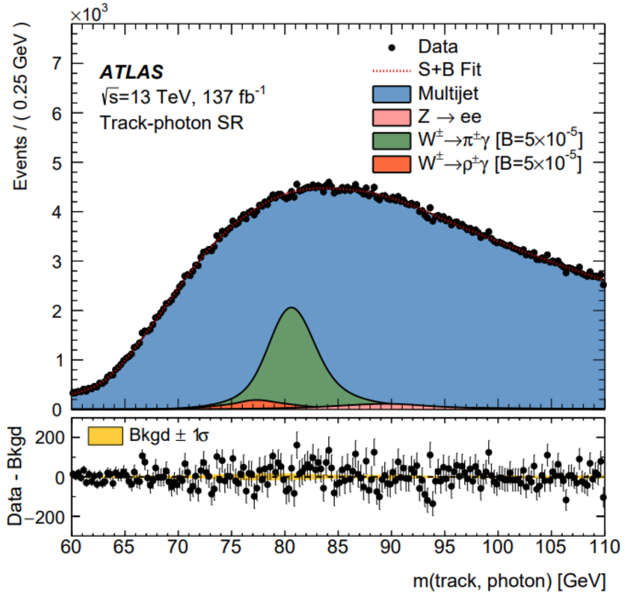
- Provide a probe of the W boson coupling to different generations of quarks
- New direct channels for the measurement of the W boson mass
- Sensitivity to both the weakly and strongly coupled regimes of quantum chromodynamics (QCD)
- Radiative decays are a test bench for the QCD factorization framework

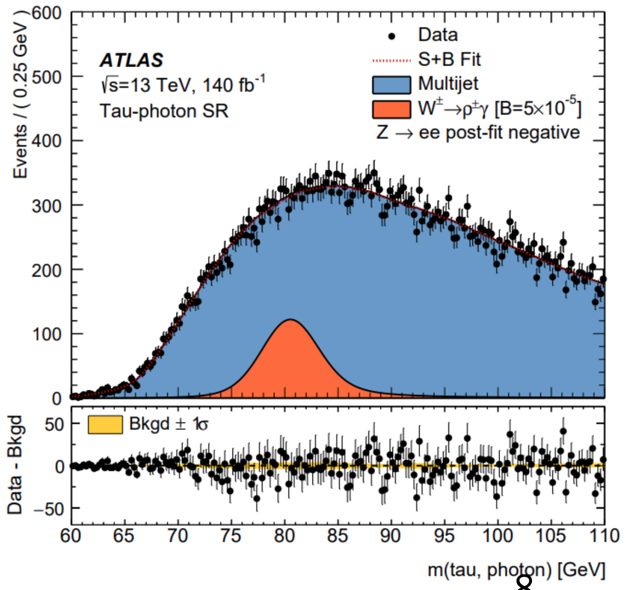
Strategy

- utilizes a dedicated trigger for $W^\pm \to \pi^\pm\gamma$ and $W^\pm \to \text{K}^\pm\gamma$ events
- τ reconstruction algorithms for $W^\pm \to \rho^\pm\gamma$

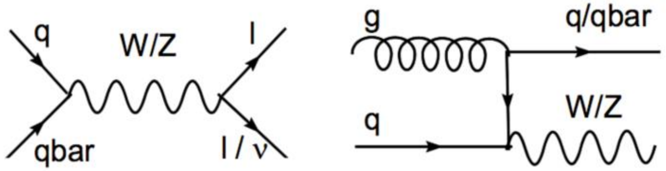
Most stringent upper limit to date

	95% CL upper limits	
Branching fraction	Expected $\times 10^{-6}$	Observed $\times 10^{-6}$
$\mathcal{B}(W^\pm \to \pi^\pm\gamma)$	$1.2^{+0.5}_{-0.3}$	1.9
$\mathcal{B}(W^\pm \to K^\pm\gamma)$	$1.1^{+0.4}_{-0.3}$	1.7
$\mathcal{B}(W^\pm \to \rho^\pm\gamma)$	$6.0^{+2.3}_{-1.7}$	5.2





Z pT and rapidity at 8 TeV



Submit to EPJC:

arXiv:2309.09318

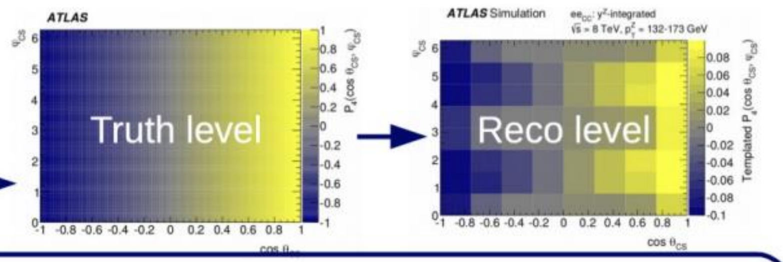
Motivation

- First time measurement of production properties of Z boson in the full-lepton phase space
- Practice a 4D measurement of the DY process in p_T, y, $\cos\theta$, ϕ

Profile likelihood fit

- simultaneously extracts 8 angular coefficients and unpolarized cross-section in each bin in $(p_T, |y|)$ space

$$\frac{d\sigma}{dp_T^Z\, dy^Z\, dm^Z\, d\cos\theta\, d\phi} = \frac{3}{16\pi}\frac{d\sigma^{U+L}}{dp_T^Z\, dy^Z\, dm^Z}\Big\{(1+\cos^2\theta)+\frac{1}{2}A_0(1-3\cos^2\theta)+A_1\sin 2\theta\cos\phi + \frac{1}{2}A_2\sin^2\theta\cos 2\phi + A_3\sin\theta\cos\phi + A_4\cos\theta + A_5\sin^2\theta\sin 2\phi + A_6\sin 2\theta\sin\phi + A_7\sin\theta\sin\phi\Big\}$$



Expected Yield

Reco (p_T^Z, y^Z, m^Z, cosθ, ϕ) bin

Cross section

Background template

$$N^n_{\text{exp}}(A,\sigma,\theta) = \left\{\sum_{j=1}^{N^{ana}_{\text{bins}}} \mathcal{L}\sigma_j\left[t^n_{8j}(\beta) + \sum_{i=0}^{7} A_{ij}\, t^n_{ij}(\beta)\right]\right\}\gamma^n + \sum_{B}^{\text{bkgs}} T^n_B(\beta)$$

Truth (p_T^Z, y^Z, m^Z) bin

Angular coefficient

Templated polynomial

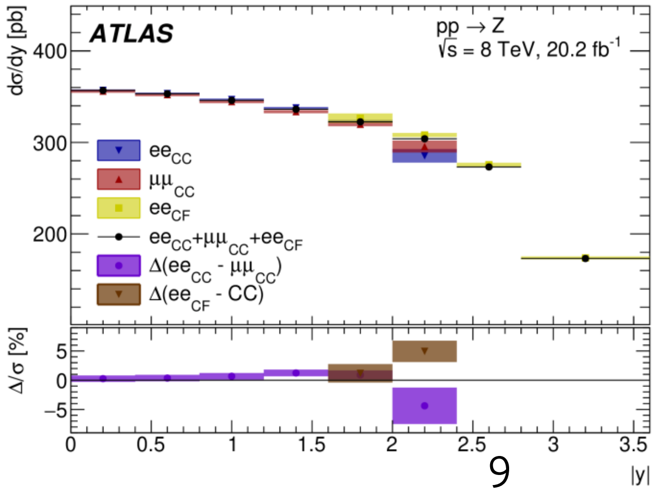
Likelihood

$$\mathcal{L}(A,\sigma,\theta|N_{\text{obs}}) = \prod_{n}^{N_{bins}}\left\{P(N^n_{\text{obs}}|N^n_{\text{exp}}(A,\sigma,\theta))P(N^n_{\text{eff}}|\gamma^n N^n_{\text{eff}})\right\}\prod_{m}^{M} G(0|\beta^m, 1)$$

2

Forward $e^{\pm}$ calibration

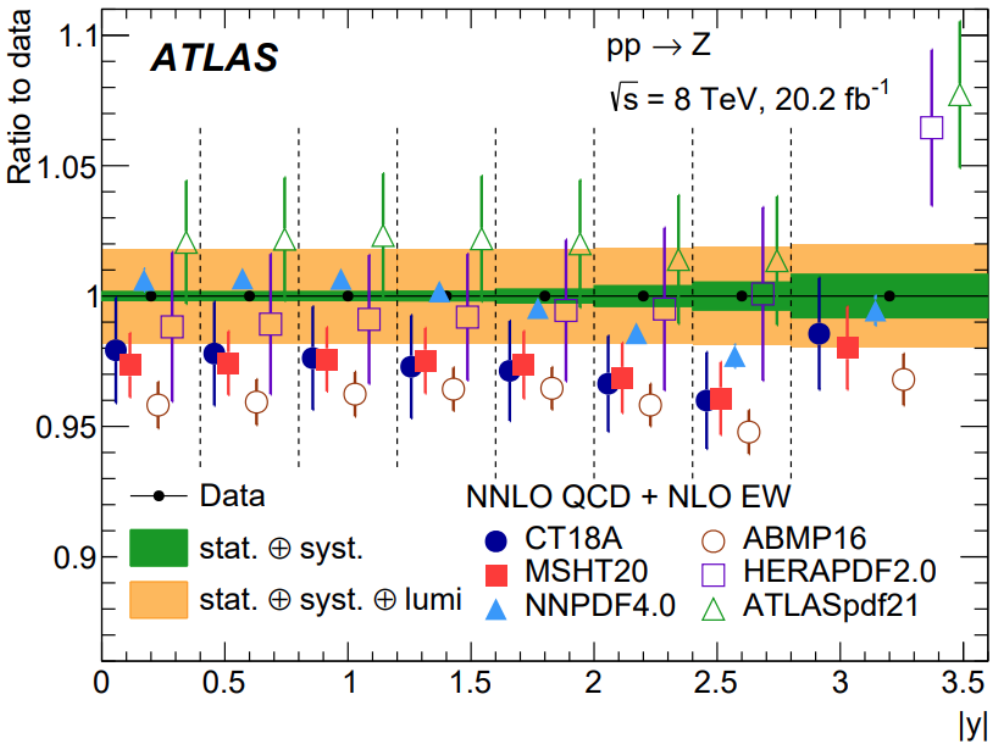
- improved allows better probe of large Y region



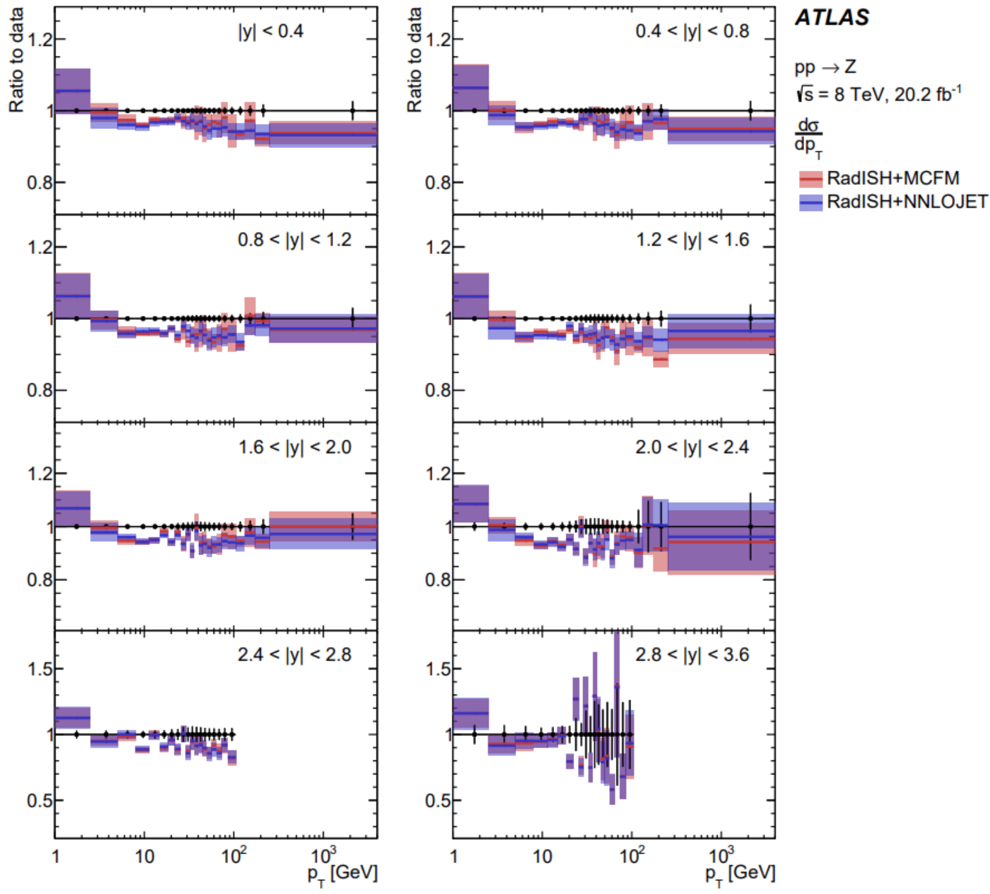
Z pT and rapidity at 8 TeV

[Submit to EPJC:](#)
arXiv:2309.09318

- Stringent test of the state-of-art QCD predictions
  - σ_{Z/γ^*} = 1055.3 ± 0.7 (stat.) ± 2.2 (syst.) ± 19.0 (lumi.) pb
  - Agree with the state-of-art predictions at N3LO in QCD

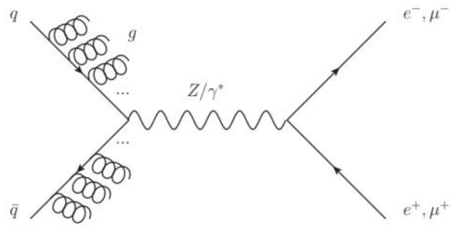


Predictions with different PDF sets, displaying a varying degree of agreement with the data



Predictions based on qT-resummation at approximate N4LL accuracy matched to fixed-order O(α_s^3) calculations at high pT

Extraction of αs from p_T^Z at 8 TeV



Submit to NPHYS: arXiv:2309.12986

- Z recoil coming from QCD initial-state radiations
  - Sudakov peak of p_T^Z is linearly sensitive to α_s

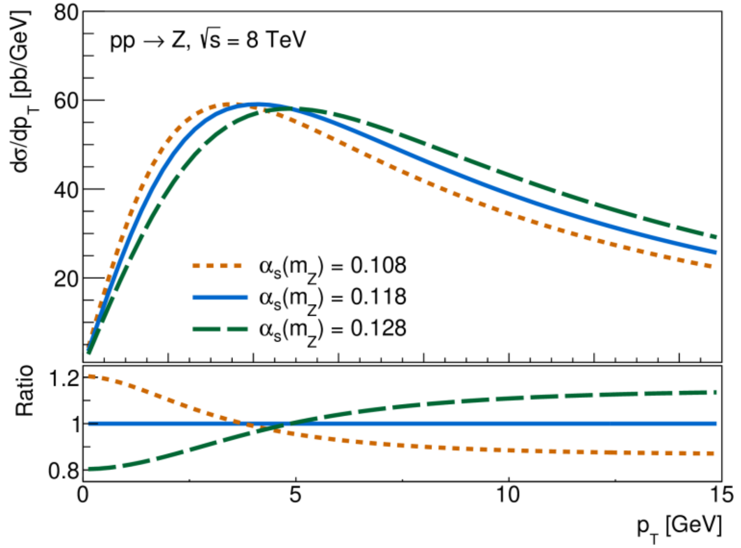
$$\frac{d\hat{\sigma}_V^{(\mathrm{res.})}}{dq_T^2}(q_T, M) = \frac{M^2}{\hat{s}} \int_0^\infty db\, \frac{b}{2}\, J_0(bq_T)\, \mathcal{W}^V(b, M)$$

$$\mathcal{W}_N^V(b, M) = \mathcal{H}_N^V(\alpha_S) \times \exp\{\mathcal{G}(\alpha_S, L)_N\},\ L = log(M^2 b^2)$$

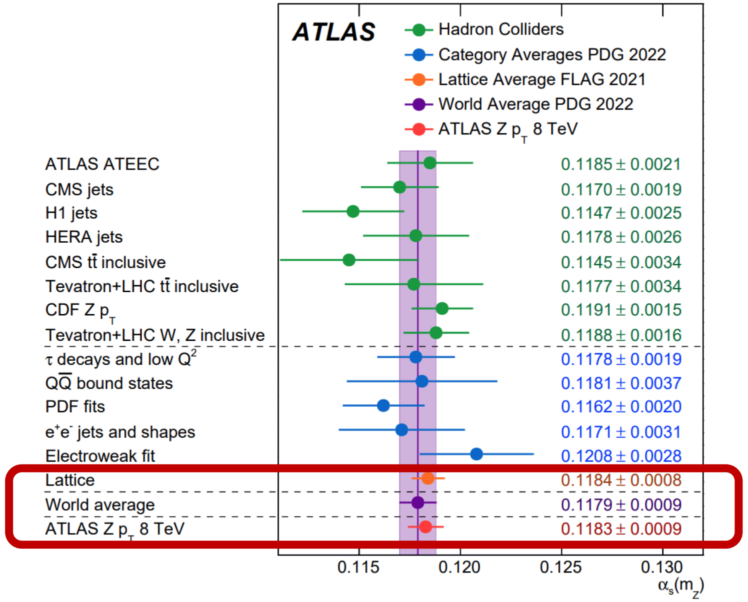
perturbative Sudakov form factor

Sensitivity to α_s

- Extraction performed by χ^2 fit
  - $\chi^2(\beta_{\mathrm{exp}}, \beta_{\mathrm{th}}) = \sum_{i=1}^{N_{data}} \frac{\left(\sigma_i^{\mathrm{exp}} + \sum_j \Gamma_{ij}^{\mathrm{exp}} \beta_{j,\mathrm{exp}} - \sigma_i^{\mathrm{th}} - \sum_k \Gamma_{ik}^{\mathrm{th}} \beta_{k,\mathrm{th}}\right)^2}{\Delta_i^2} + \sum_j \beta_{j,\mathrm{exp}}^2 + \sum_k \beta_{k,\mathrm{th}}^2$
  - With inputs of double-differential Z-boson pT and y distributions

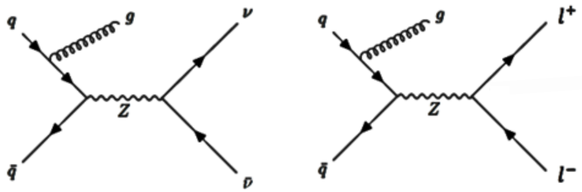


- The most precise measurement to date
  - $\alpha_s(m_Z)$ = 0.1183 ± 0.0009
  - Fist time based on N^4LLa+N^3LO resumed QCD predictions
  - PDF uncertainty as the dominant one (aN^3LO MSHT20 as the baseline)



More details can be found in backup

Z invisible width at 13 TeV



ATLAS EXPERIMENT

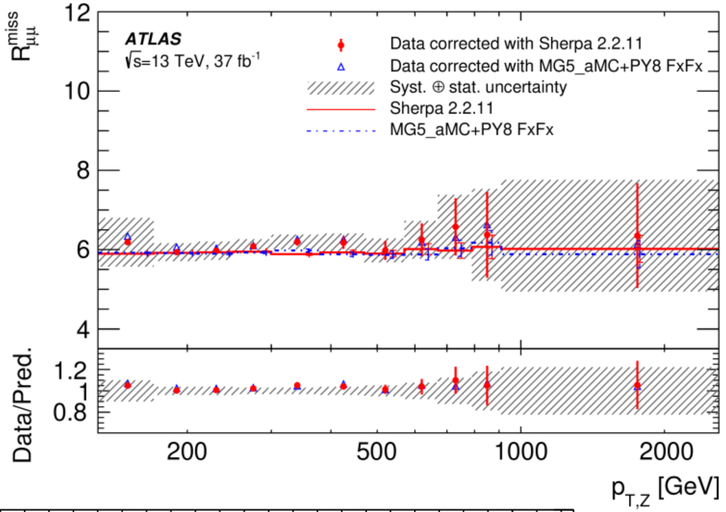
Submit to PLB: arXiv:2312.02789

Motivation

- Reveals the number of light ν that couple to the Z boson and potential BSM contributions
- Different strategies are an important consistency test of SM

Determination

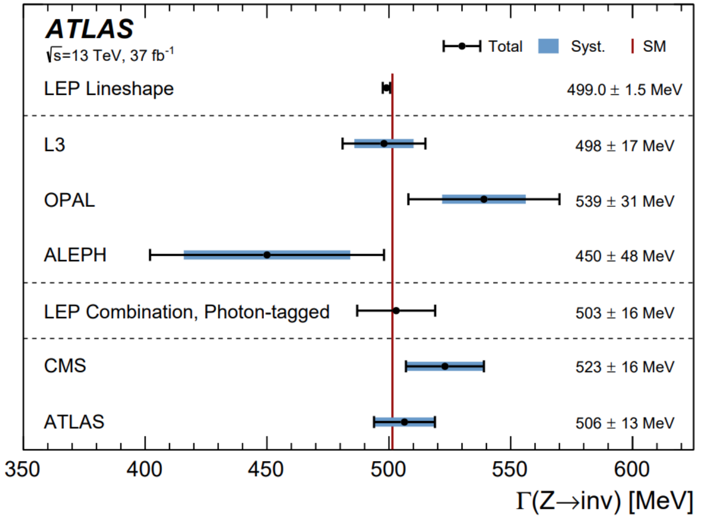
- $$\boldsymbol{R} \equiv \frac{\frac{d\sigma(Z(\to inv)+jets)}{dp_T^Z}}{\frac{d\sigma(Z(\to ll)+jets)}{dp_T^Z}} = \frac{\frac{d\sigma(Z+jets)\times BR(Z\to inv)}{dp_T^Z}}{\frac{d\sigma(Z+jets)\times BR(Z\to ll)}{dp_T^Z}} = \frac{\boldsymbol{\Gamma(Z\to inv)}}{\Gamma(Z\to \ell\ell)}$$
- Bin-wise correction used for detector effects, FSR, γ^* contributions
- Determined by a constant χ^2 fit to reduce the uncertainties further
  - $\chi^2 = \left(y_{\text{data, i}} - \bar{y}\right)^T V_{ij}^{-1}\left(y_{\text{data, }j} - \bar{y}\right)$



The single most precise recoil-based measurement

- $\Gamma(Z \to inv) = 506 \pm 2\text{ (stat.)} \pm 12\text{ (syst.) MeV}$
- SM prediction with 3 ν generations: 501.445 ± 0.047 MeV

More details can be found in backup



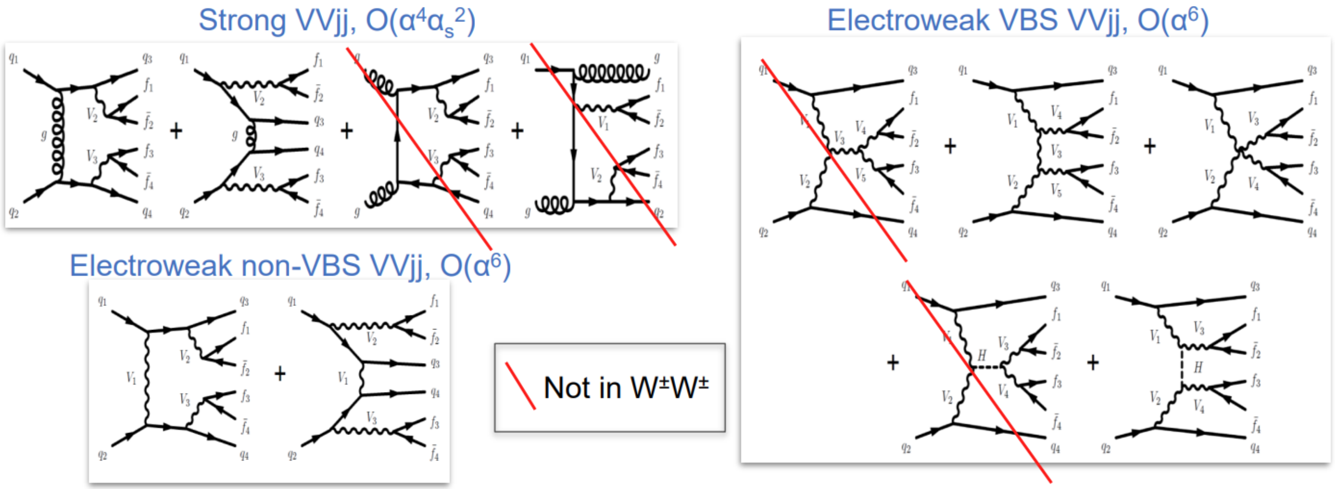
Di-boson Production

- Probe the electroweak gauge structure
- Search BSM physics via anomalous couplings
- Test QCD corrections for better modelling of EW processes + jets

$W^{\pm}W^{\pm}jj$ production at 13TeV

Submit to JHEP: arXiv:2312.00420

- Vector Boson Scattering is a key process to test EW sector of SM
  - Delicate cancellation of divergencies in the $V_L V_L \rightarrow V_L V_L$ amplitude from Higgs contributions
  - Sensitive to the abnormal triple and quartic gauge couplings
- Unique feature of VBS same-sign WW



- Suppression of QCD-induced background
- Sensitive to H^{++}

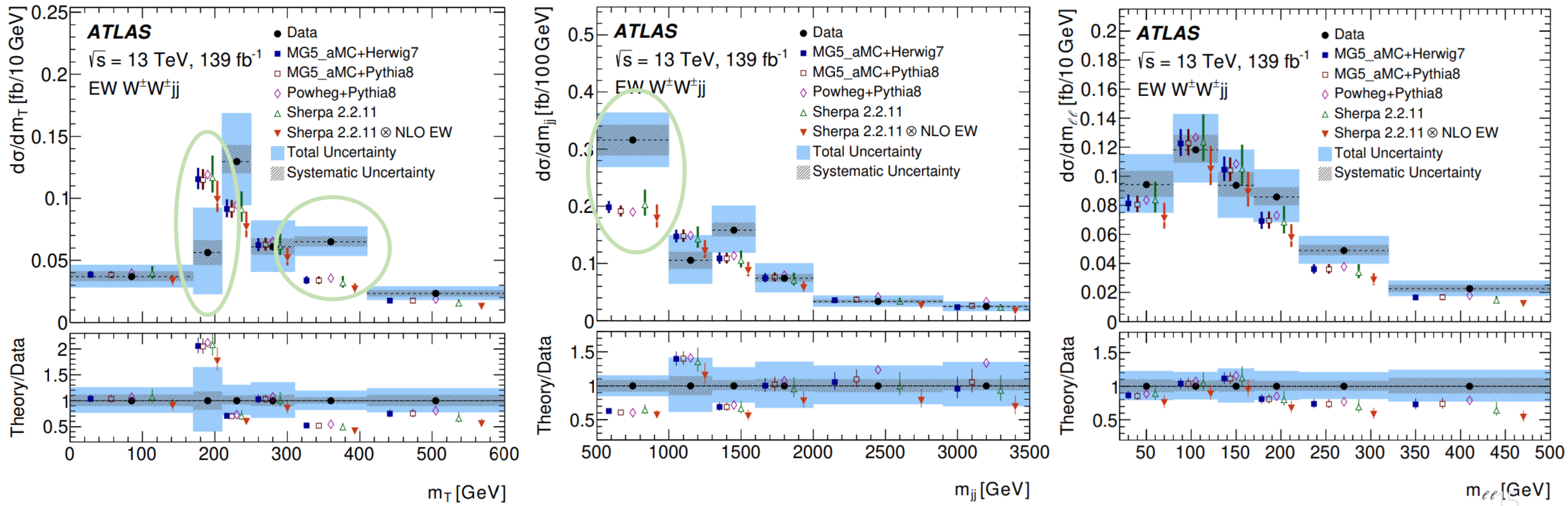
The interference term of QCD and EW diagrams producing contributions at O($\alpha^5\alpha_s$) at LO

- Consideration
  - VBS and non-VBS diagrams are not separable in a gauge invariant way ⇨ EW ssWW measurement
  - Separation into pure QCD, pure EW, and interference is only possible at LO ⇨ Total ssWW measurement

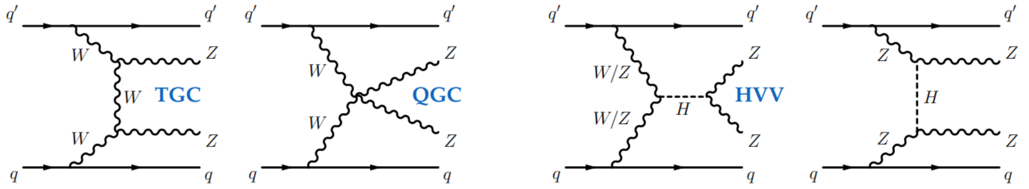
$W^{\pm}W^{\pm}jj$ production at 13TeV

[Submit to JHEP:](#) arXiv:2312.00420

- The most precise fiducial cross section measurement to date
  - σ_{fid}^{EW} = 2.92 ± 0.22 (stat.) ± 0.13 (mod. syst.) ± 0.12 (exp. syst.) ± 0.06 (lumi.) fb
  - $\sigma_{fid}^{EW+Int+QCD}$ = 3.38±0.22 (stat.)±0.11 (mod. syst.) ±0.14 (exp. syst.)±0.06 (lumi.) fb
- Mis-modelling are found in some regions of m_T and m_{jj}



VBS ZZjj at 13TeV



Submit to JHEP:

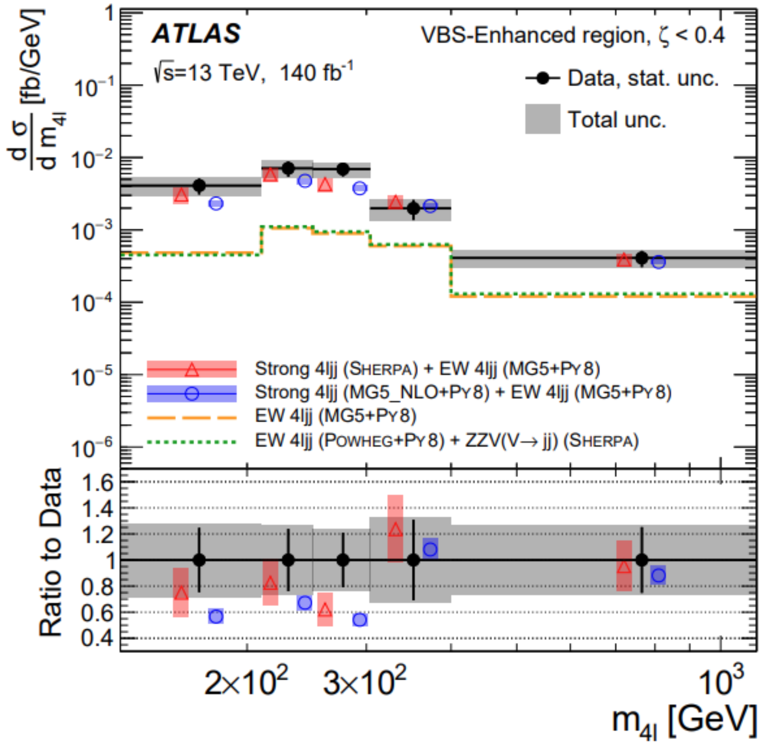
arXiv:2308.12324

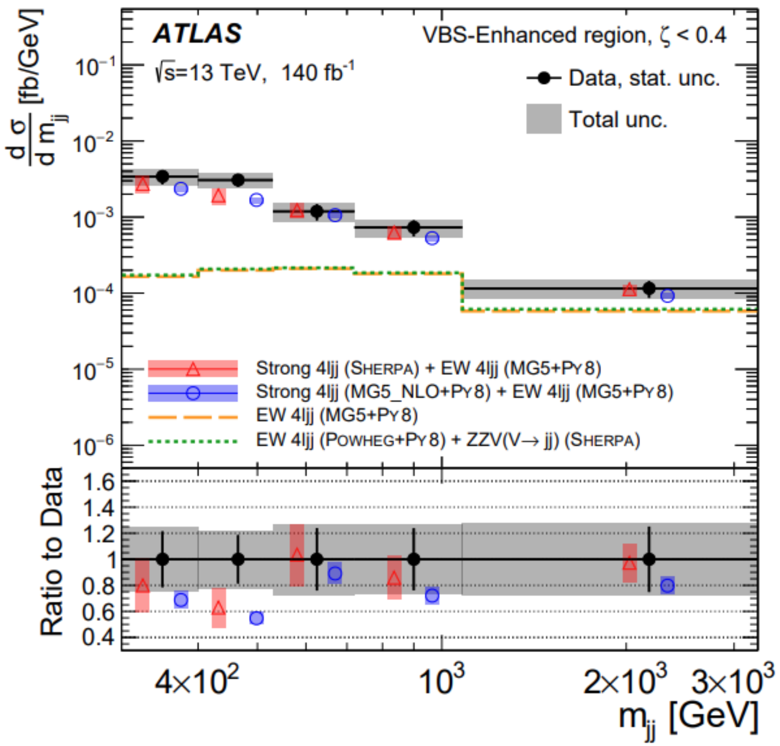
Motivation

- Probe high energy behavior of VBS differentially
- Search for anomalous couplings

Unfolded results

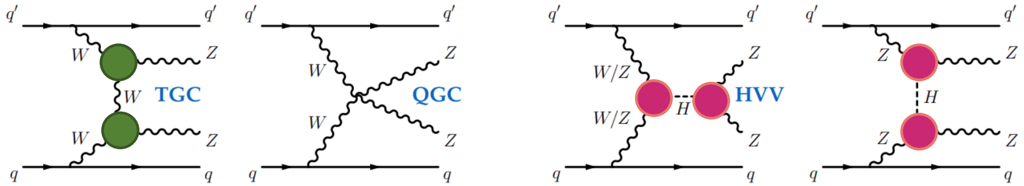
More interesting observables are also explored:
[characterize VBS] $p_{T,4l}$, $p_{T,jj}$, $|\Delta y_{jj}|$
[probe polarization, CP structure] $\cos\theta^*_{12}$, $\cos\theta^*_{34}$, $\Delta\phi_{jj}$
[probe real emissions of quarks and gluons] $p_{T,4ljj}$, $S_{T,4ljj}$





- MG5+Py8 underestimate data, especially noticeable at low m_{jj}, m_{4l} and $|\Delta\phi_{jj}|$
- Sherpa is in satisfactory agreement, with simulating additional jet activity at LO in QCD
- EWK contribution is much larger in high m_{jj} region accounting for 50%

VBS ZZjj at 13TeV



Submit to JHEP:
arXiv:2308.12324

Motivation

- Probe high energy behavior of VBS differentially
- Search for anomalous couplings induced by new phenomena

EFT fit results

- $\mathcal{L}(c) = \frac{1}{\sqrt{(2\pi)^k |C|}} \exp\left[-\frac{1}{2}\left\{\sigma_{data} - \sigma_{pred}(c,\vec{\theta})\right\}^T C^{-1} \left\{\sigma_{data} - \sigma_{pred}(c,\vec{\theta})\right\}\right] \times \prod_i \mathcal{G}(\theta_i)$

Wilson coefficient	$\lvert\mathcal{M}_{d6}\rvert^2$ Included	95% confidence interval [TeV^{-2}] Expected	Observed
c_W/Λ^2	yes	[-1.3, 1.3]	[-1.2, 1.2]
	no	[-32, 32]	[-37, 28]
$c_{\widetilde{W}}/\Lambda^2$	yes	[-1.3, 1.3]	[-1.2, 1.2]
	no	[-17, 17]*	[0, 30]*
c_{HWB}/Λ^2	yes	[-16, 7]	[-16, 6]
	no	[-12, 12]	[-15, 10]
$c_{H\widetilde{W}B}/\Lambda^2$	yes	[-1.3, 1.3]	[-1.2, 1.2]
	no	[-67, 67]*	[-25, 130]*
c_{HB}/Λ^2	yes	[-13, 13]	[-12, 12]
	no	[-38, 38]	[-38, 38]
$c_{H\widetilde{B}}/\Lambda^2$	yes	[-13, 13]	[-12, 12]
	no	[-420, 420]*	[-200, 790]*

Wilson coefficient	$\lvert\mathcal{M}_{d8}\rvert^2$ Included	95% confidence interval [TeV^{-4}] Expected	Observed
$f_{T,0}/\Lambda^4$	yes	[-1.00, 0.97]	[-0.98, 0.93]
	no	[-19, 19]	[-23, 17]
$f_{T,1}/\Lambda^4$	yes	[-1.3, 1.3]	[-1.2, 1.2]
	no	[-140, 140]	[-160, 120]
$f_{T,2}/\Lambda^4$	yes	[-2.6, 2.5]	[-2.5, 2.4]
	no	[-63, 62]	[-74, 56]
$f_{T,5}/\Lambda^4$	yes	[-2.6, 2.5]	[-2.5, 2.4]
	no	[-68, 67]	[-79, 60]
$f_{T,6}/\Lambda^4$	yes	[-4.1, 4.1]	[-3.9, 3.9]
	no	[-550, 540]	[-640, 480]
$f_{T,7}/\Lambda^4$	yes	[-8.8, 8.4]	[-8.5, 8.1]
	no	[-220, 220]	[-260, 200]
$f_{T,8}/\Lambda^4$	yes	[-2.2, 2.2]	[-2.1, 2.1]
	no	[-3.9, 3.8]×10^4	[-4.6, 3.1]×10^4
$f_{T,9}/\Lambda^4$	yes	[-4.7, 4.7]	[-4.5, 4.5]
	no	[-6.4, 6.3]×10^4	[-7.5, 5.5]×10^4

The impact of quadratic terms is significant!

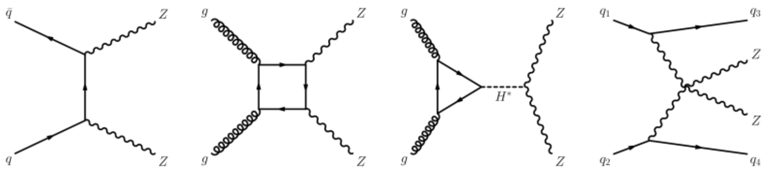
$$L_{SMEFT} = L_{SM} + \sum_i \frac{c_i}{\Lambda^{d-4}} O_i$$

$$\sigma = \sigma_{SM} + c \cdot \sigma_{int} + c^2 \cdot \sigma_{int}$$

Dim-6 operators affecting VBS ZZ:
- CP odd: $c_{\widetilde{W}}$, $c_{H\widetilde{B}}$, $c_{H\widetilde{W}B}$
- CP even: c_W, c_{HB}, c_{HWB}

Dim-8 (Eboli Model)
- Provides aQGC operators w/o TGC

ZZ Production at 13.6 TeV



[Submit to PLB:](#)
arXiv:2311.09715

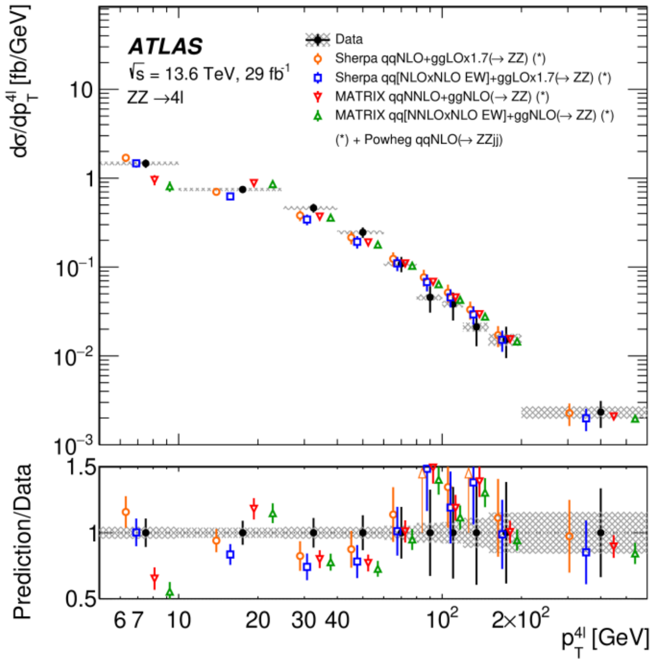
- First step of VV measurements at the new energy of 13.6 TeV
  - Based on 29 fb^{-1} of data collected by the ATLAS detector in 2022

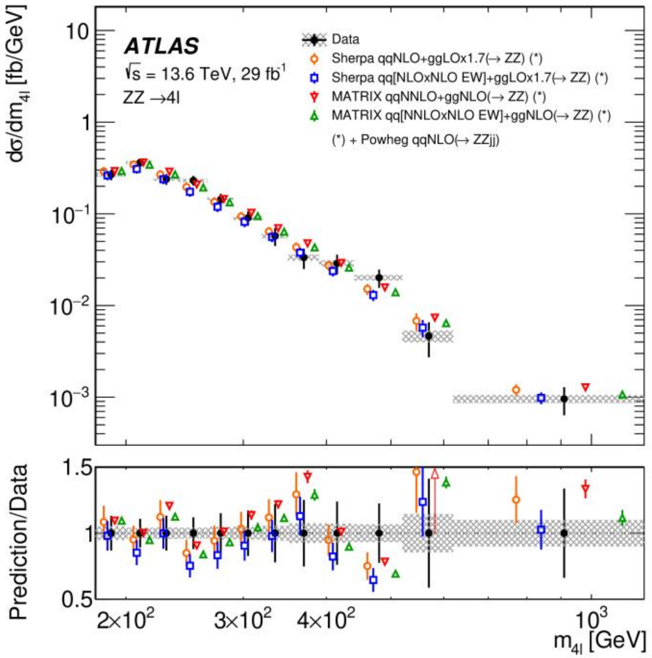
	Measurement	MC prediction	MATRIX prediction
Fiducial	36.7 ± 1.6(stat) ± 1.5(syst) ± 0.8(lumi) fb	$36.8\ ^{+4.3}_{-3.5}$ fb	36.5 ± 0.7 fb
Total	16.8 ± 0.7(stat) ± 0.7(syst) ± 0.4(lumi) pb	$17.0\ ^{+1.9}_{-1.4}$ pb	16.7 ± 0.5 pb

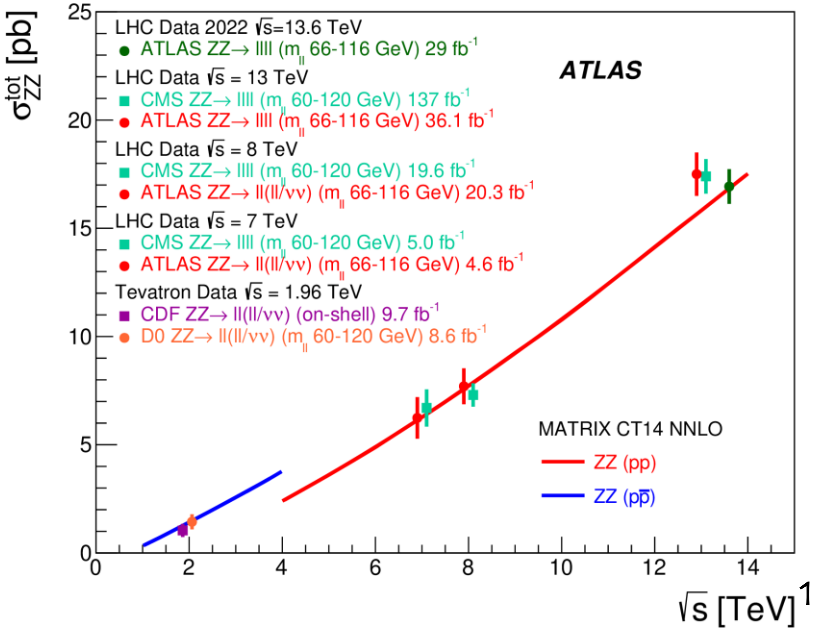
$$\sigma^{fid} = \frac{N_{sig}^{reco}}{C \cdot L_{int}}$$ C corrects detector effects

$$\sigma^{tot} = \frac{\sigma^{fid}}{A}$$ A corrects FSR effects

- Results are well described by predictions with accuracy up to NNLO QCD + NLO EW



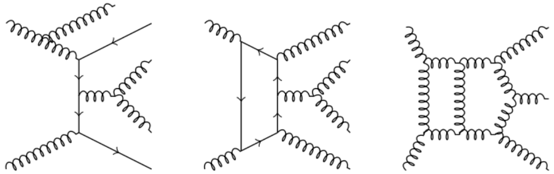




Multi-jets Production

- Large momentum transfer provides an ideal testing ground for pQCD
- Event shapes characterize the hadronic energy flow in a collision

TEEC at 13 TeV

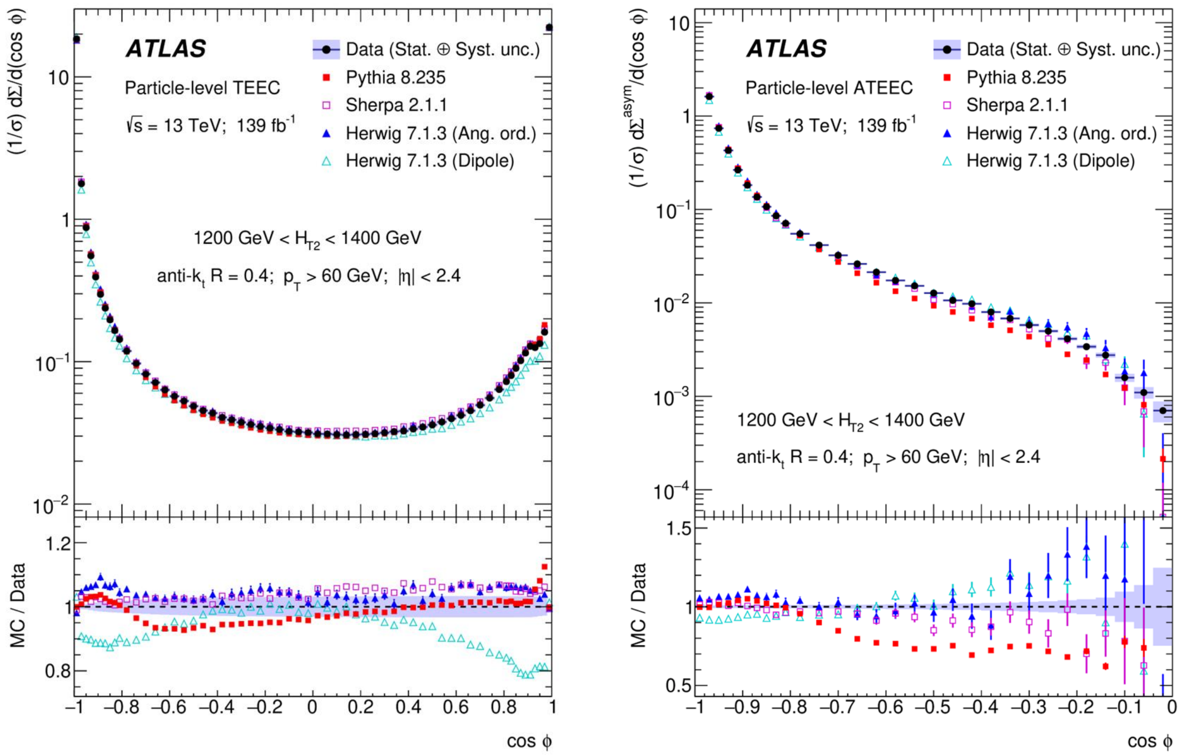


$gg \rightarrow jjj$ at NNLO

JHEP 07 (2023) 85

- **TEEC - Transverse Energy-Energy Correlations**
  - $\frac{1}{\sigma}\frac{d\Sigma}{d\cos\phi} = \frac{1}{\sigma}\sum_{i,j}^{jets}\int d\sigma_{pp\rightarrow \text{jets}}\frac{E_{Ti}E_{Tj}}{E_T^2}\delta(\cos\Delta\varphi_{ij} - \cos\phi)$
- **ATEEC - forward-backward azimuthal angular asymmetry**
  - $\frac{1}{\sigma}\frac{d\Sigma^{asym}}{d\cos\phi} = \frac{1}{\sigma}\frac{d\Sigma}{d\cos\phi}\Big|_{\phi} - \frac{1}{\sigma}\frac{d\Sigma}{d\cos\phi}\Big|_{\pi-\phi}$

☞ **Both of the TEEC and ATEEC are sensitive to gluon radiation and show a clear dependence on the strong coupling**

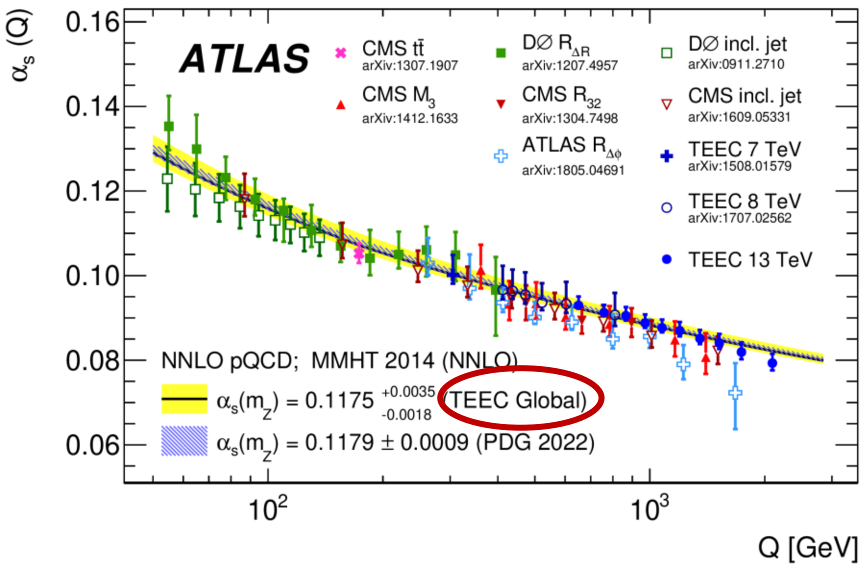


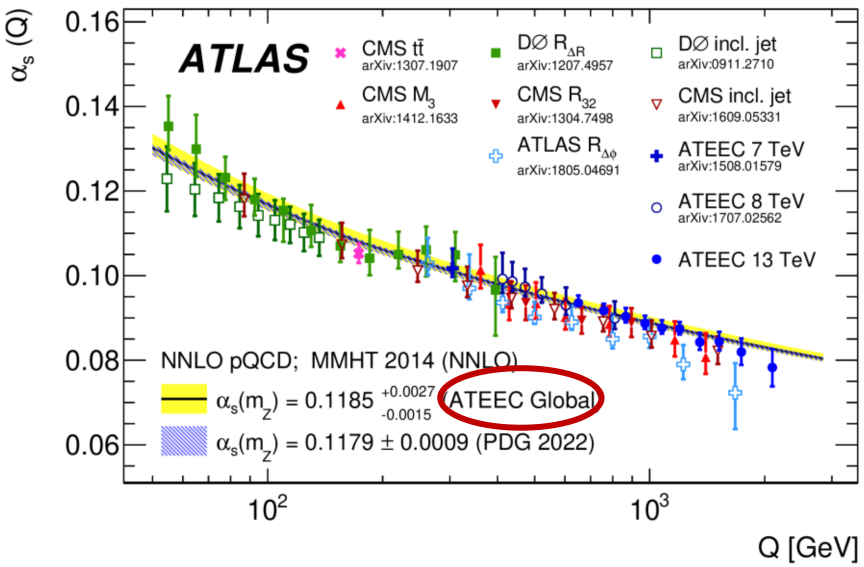
- TEEC
  - ✓ shows two peaks arising from back-to-back ($\cos\phi = -1$) and collinear($\cos\phi = 1$), with a central plateau arising from the wide-angle radiation
  - ✓ The effect of the jet radius R is seen as a kink in the TEEC distributions at $\cos\phi \cong 0.92$
- ATEEC
  - ✓ exhibits a steep fall-off of several orders of magnitude between $\cos\phi = -1$ and $\cos\phi = 0$

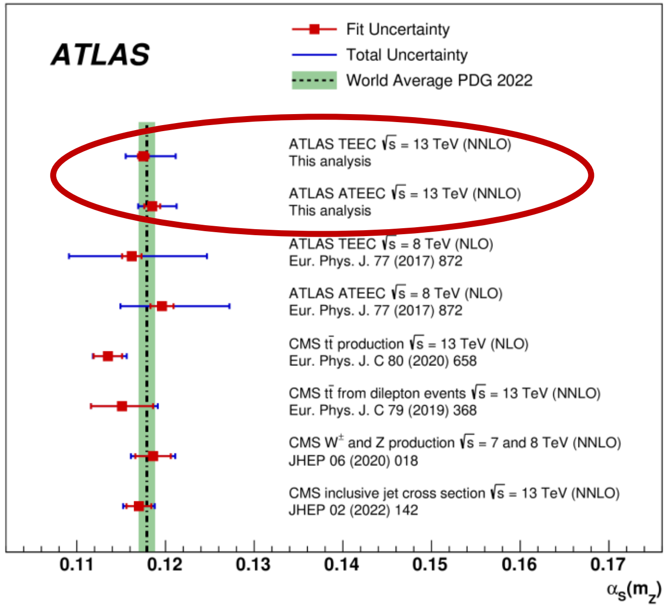
TEEC and Its Asymmetry at 13 TeV

JHEP 07 (2023) 85

- Determination of α_s by minimizing χ^2
  - $\chi^2\left(\alpha_s,\vec{\lambda}\right) = \sum_i \frac{\left(x_i - F_i\left(\alpha_s,\vec{\lambda}\right)\right)^2}{\Delta x_i^2 + \Delta \xi_i^2} + \sum_k \lambda_k^2$, with $F_i\left(\alpha_s,\vec{\lambda}\right) = \psi_i(\alpha_s)\left(1 + \sum_k \lambda_k \sigma_k^{(i)}\right)$
- Test asymptotic freedom beyond TeV scale at NNLO







$\boldsymbol{\alpha_s(m_Z) = 0.1175 \pm 0.0006\ (\mathrm{exp.})^{+0.0034}_{-0.0017}\ (\mathrm{theo.})}$ from TEEC

$\boldsymbol{\alpha_s(m_Z) = 0.1185 \pm 0.0009\ (\mathrm{exp.})^{+0.0025}_{-0.0012}\ (\mathrm{theo.})}$ from ATEEC

Pearson correlation coefficient as 0.86 ± 0.02 (exp.) for central values

Top(s) Production

- Sensitive to EW, QCD and PDFs
- Strong connection to Higgs and New physics as the heaviest SM particles
- Rare top processes predicted by SM are enhanced in multiple BSM models

$t\bar{t}$ Production at 13.6TeV

Phys. Let. B 848 (2024) 138376

Motivation

- Provide an independent test of QCD and PDFs
- $\mathrm{R}_{t\bar{t}/Z}$ has a significant sensitivity to the gluon-to-quark PDF ratio

Profile-likelihood fit

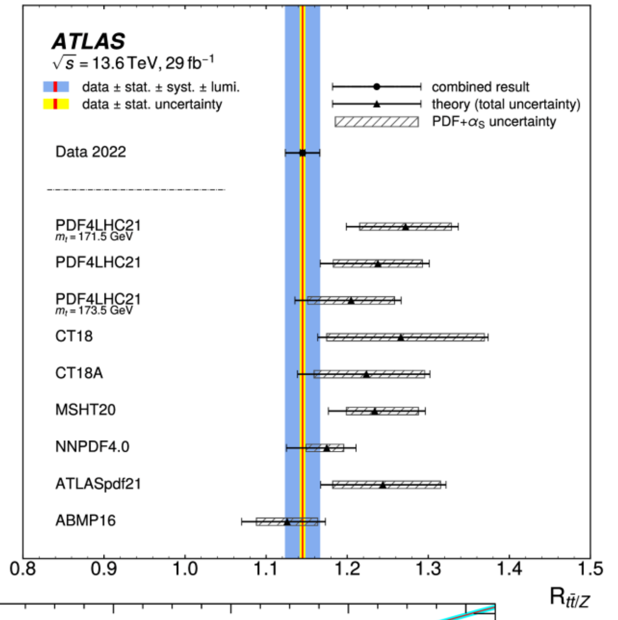
- Used to extract $\sigma_{t\bar{t}}$ and $R_{t\bar{t}/Z}$ together with the b-tagging efficiency ϵ_b

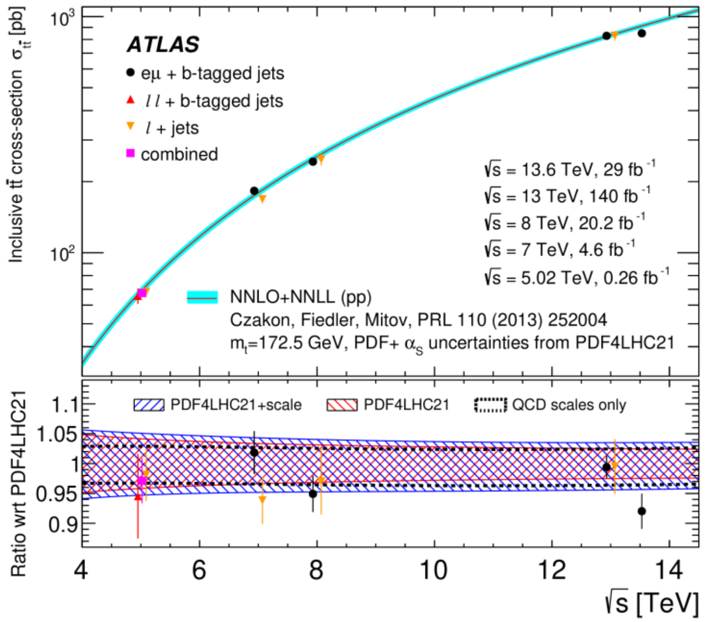
Results already limited by systematic uncertainties

- $\sigma_{t\bar{t}} = 850 \pm 3\ (\mathrm{stat.}) \pm 18\ (\mathrm{syst.}) \pm 20\ (\mathrm{lumi.})\ \mathrm{pb}$
- $\sigma_{Z\to ll} = 744 \pm 11\ (\mathrm{stat.} + \mathrm{syst.}) \pm 16\ (\mathrm{lumi.})\ \mathrm{pb}$
- $R_{t\bar{t}/Z} = 1.145 \pm 0.003\ (\mathrm{stat.}) \pm 0.021\ (\mathrm{syst.}) \pm 0.002\ (\mathrm{lumi.})$
- Dominated by luminosity and lepton uncertainties

⇨ Cancel out largely for $R_{t\bar{t}/Z}$ resulting in the total uncertainty of 1.9%

With compared to the total uncertainty of $\sigma_{t\bar{t}}$ as 3.2%

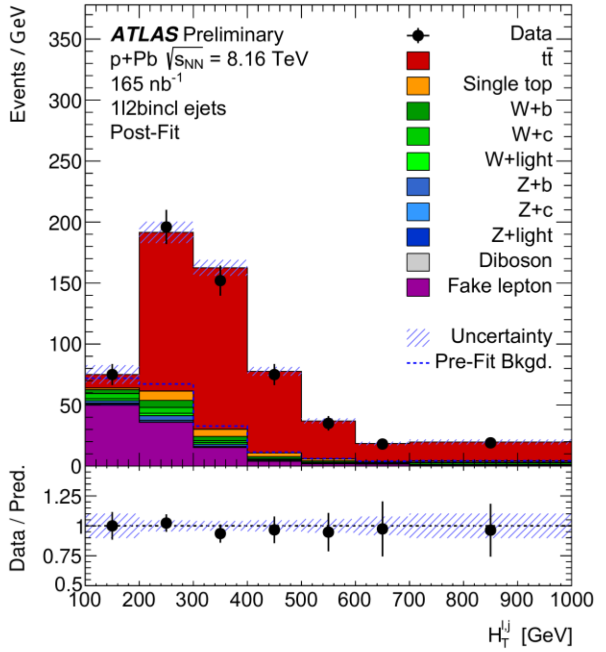


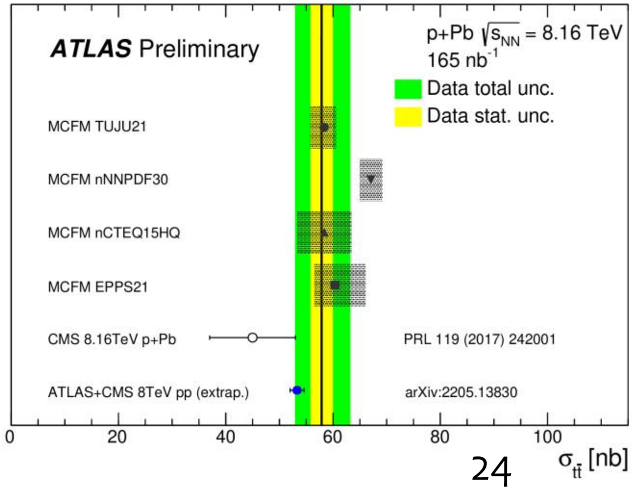


$t\bar{t}$ Production in p+Pb Collisions at 8 TeV

ATLAS-CONF-2023-063

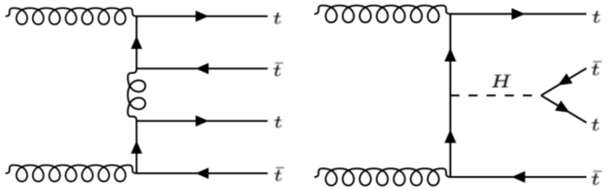
- **Heavy-ion collisions provided at the TeV-scale energies at LHC**
  - Possibility to measure elementary particles in Pb+Pb and p+Pb for the first time
  - Expected to provide unique information on the properties of quark-gluon plasma
- **Data recorded with an integrated luminosity of 165 $\mathrm{n}b^{-1}$ in 2016**
  - $\mu_{t\bar{t}}$ is determined by the fit to the $H_{\mathrm{T}}^{\ell\mathrm{jet}}$ data distributions in the six SRs
  - $\sigma_{t\bar{t}} = \mu_{t\bar{t}} \cdot A_{\mathrm{Pb}} \cdot \sigma_{t\bar{t}}^{\mathrm{th}}$
- **Results**
  - $\sigma_{t\bar{t}} = 57.9 \pm 2.0\ (\mathrm{stat.})\ {}^{+4.9}_{-4.5}\ (\mathrm{syst.})\ \mathrm{nb}$
  - Observation of $t\bar{t}$ production in the individual ℓ+jets and dilepton channels
  - Precision paves a new way to constrain nPDFs in the high-x region



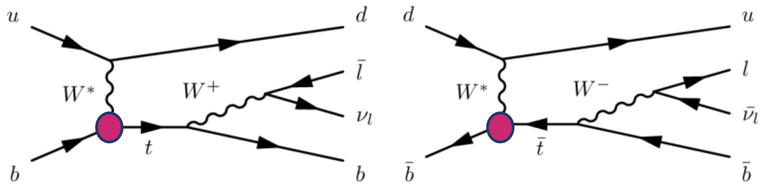


Observations for Top Processes

- 4-Top Observation at 13TeV: 6.1 (4.3) σ [EPJC 83 (2023) 496]
  - $\sigma_{t\bar{t}t\bar{t}} = 22.5^{+4.7}_{-4.3}(\text{stat})^{+4.6}_{-3.4}(\text{syst})\text{fb} = 22.5^{+6.6}_{-5.5}\text{fb}$
  - Interpretations on EFT operators ($O^1_{QQ}, O^1_{Qt}, O^1_{tt}, O^8_{Qt}$) and Higgs oblique parameter



- EW t-channel Single-Top Observation at 5TeV: 6.1 (6.4) σ [Submit to PLB]
  - $\sigma(tq) = 19.8^{+3.9}_{-3.1}$ (stat.) $^{+2.9}_{-2.2}$ (syst.) pb
  - $\sigma(\bar{t}q) = 7.3^{+3.2}_{-2.1}$ (stat.) $^{+2.8}_{-1.5}$ (syst.) pb
  - $f_{\text{LV}} \cdot |V_{tb}| = 0.94^{+0.11}_{-0.10}$



- Observation of quantum entanglement in ttbar events [Submit to Nature]

Summary

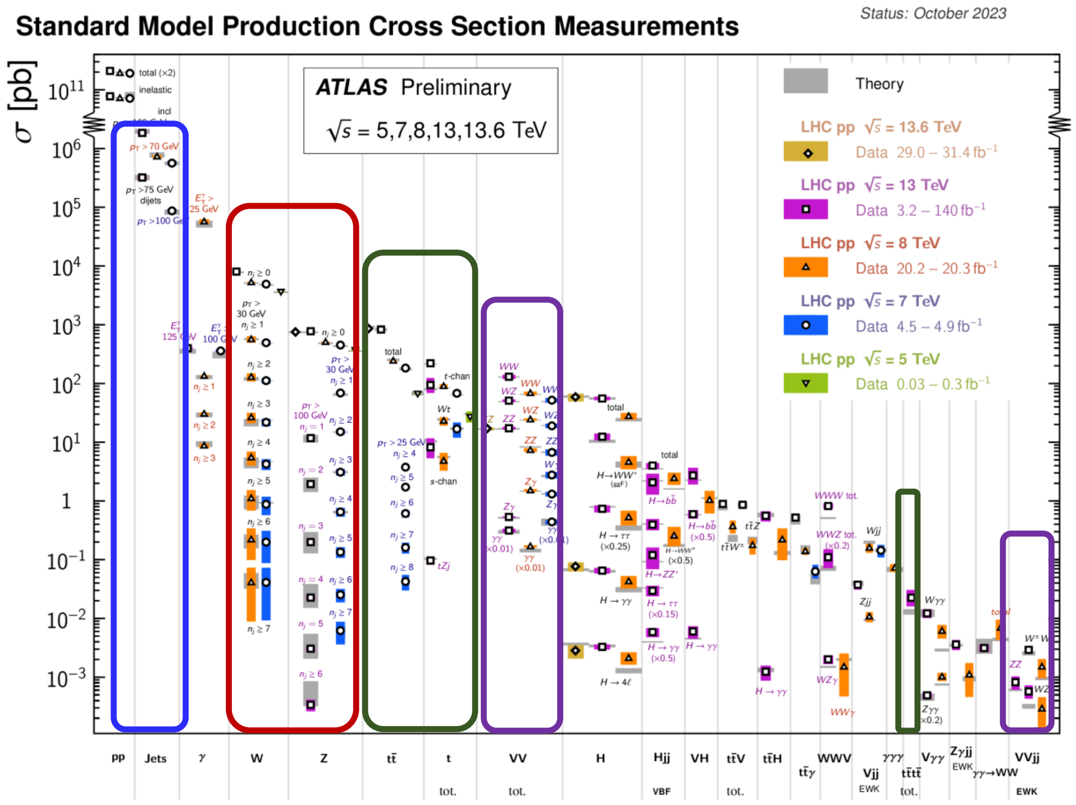
- Precision measurements of fundamental parameters of the Standard Model
  - Crucial probes of the Standard Model and may provide hints of new physics
  - Reduces the modeling uncertainties (QCD, PDF) for amounts of processes in the future
  - Knowledge of the nPDFs in heavy nuclei expected for extracting QGP properties with precision from data
- Extensive precise measurements presented, with highlights of
  - The most precise experimental determination of α_s has been achieved by ATLAS
  - Multiple measurements reach the percent (permille)-level precision with NN(N)LO QCD predictions
  - Several observations and the most stringent limits on BSM effects are reported
- **Looking forward to improved precison and new ideas in the Run2+Run3!**

Thank you for your attention

Backup

Outline

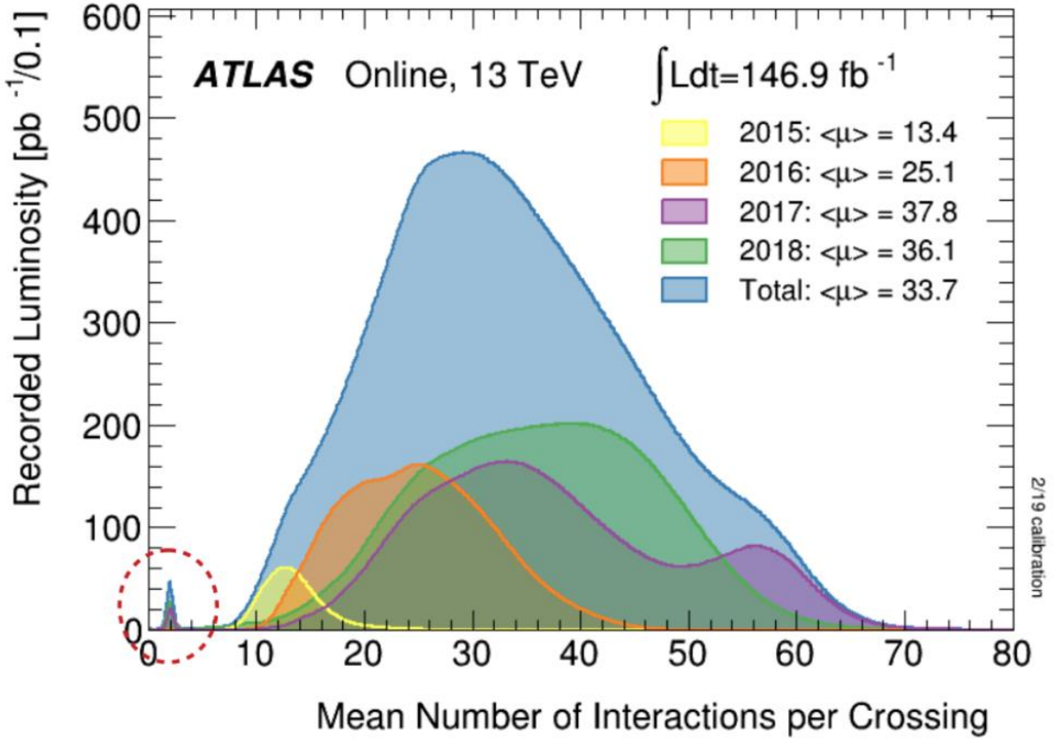
- Precision measurements with the ATLAS experiment at the LHC
  - Determine fundamental parameters of the Standard Model
  - Provide stringent tests of the electroweak theory and perturbative QCD
- Talk content
  - m_W re-analysis at 7TeV
  - Precise double-differential measurement of p_T^Z and Y_Z
  - Determination of α_s from the recoils of Z-boson
  - Measurements of p_T^W and p_T^Z with low pile-up data
  - Measurements of $\Gamma(Z \rightarrow inv)$ with Z+jets
  - Search for the exclusive W boson hadronic decays
  - Measurements of WW, Same-sign WWjj
  - Measurements of ZZ production at 13/13.6 TeV
  - Determination of α_s from multi-jet energy flow
  - Measurements of t-channel single top, $t\bar{t}$, four-top



ATLAS Detector and Data Taking

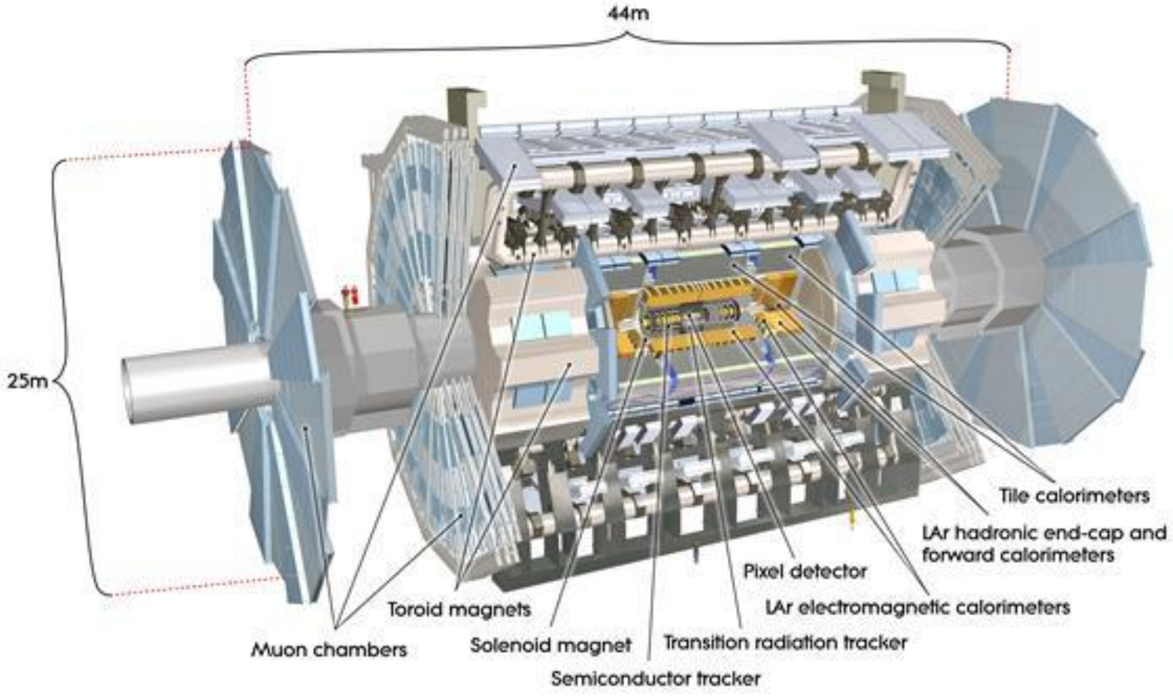
Low pile-up data

- <μ>~2 taken during 2017 - 2018
- 255 pb^{-1} at 5.02 TeV, 338 pb^{-1} at 13 TeV



Consist of

- Inner Detector
- Calorimeters
- Muon Spectrometer
- Magnet System



Cross Section Derivation

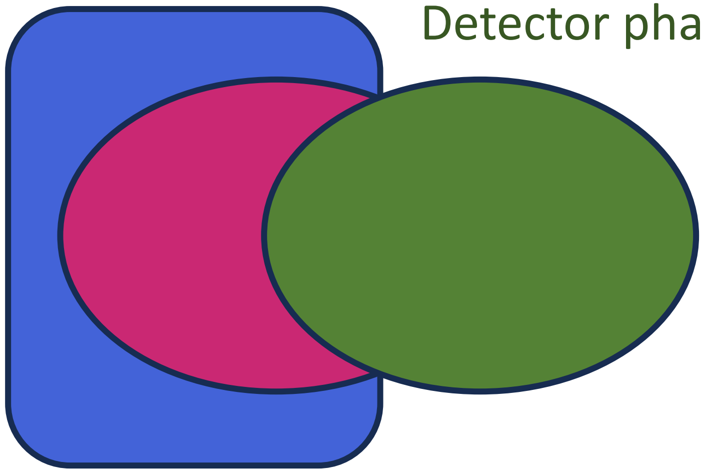
Fiducial production cross-section

- $\sigma^{fid} = \frac{N_{sig}^{reco}}{\mathrm{C} \cdot L_{int}}$
- C-factor used to correct mis-selections resulting from the limited resolution and inefficiency of detectors

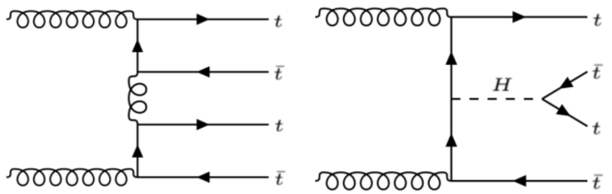
Total production cross-section

- $\sigma^{tot} = \frac{N_{sig}^{reco}}{\mathrm{A} \cdot \mathrm{C} \cdot L_{int}}$
- Acceptance used to correct the FSR effects for quick comparison with broad theory predictions in the future

Selections for
enhancement of the signal significance
reduction of modelling and exp. uncertainty



4-Top Observation at 13TeV



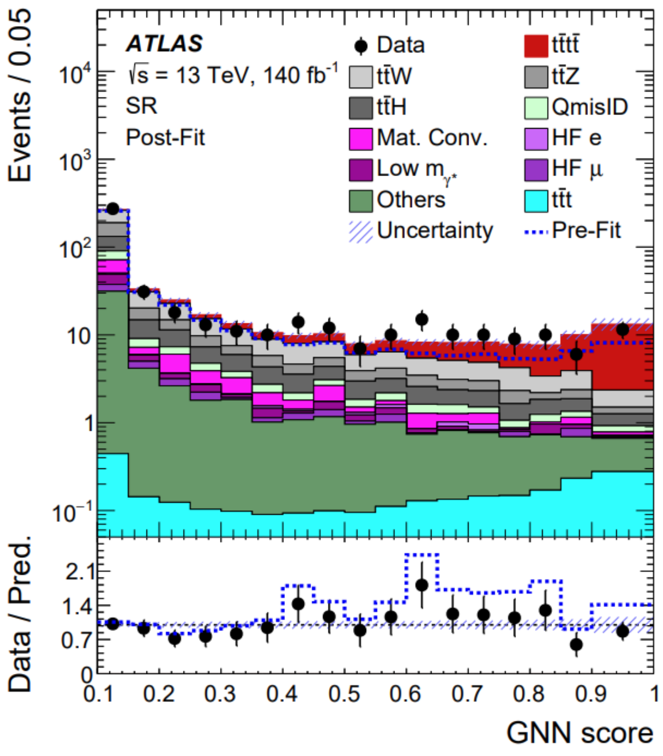
Eur. Phys. J. C 83 (2023) 496

Motivation

- $t\bar{t}t\bar{t}$ cross section sensitive to Top Yukawa coupling
- Sensitive probe for new physics such as EFT, 2HDM model

Improvement of the re-analysis

- Lower pt cuts on lepton and jets, better object definition
- Better modelling uncertainties, data-driven $t\bar{t}W$ estimation
- Maximum-likelihood fit performed to the GNN score



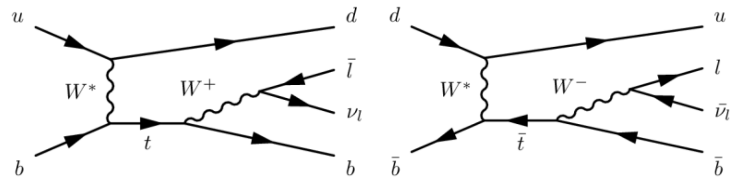
Results

- $\sigma_{t\bar{t}t\bar{t}} = 22.5^{+4.7}_{-4.3}(\text{stat})^{+4.6}_{-3.4}(\text{syst})\text{fb} = 22.5^{+6.6}_{-5.5}\text{fb}$
- Consistent within 1.8 σ with the SM prediction: 12.0 ± 2.4 fb
- Observed (expected) significance is 6.1 (4.3) σ

Almost limited by systematics even though the process is so rare

- Interpretations on EFT operators ($O^1_{QQ}, O^1_{Qt}, O^1_{tt}, O^8_{Qt}$) and Higgs oblique parameter already possible

EW Single-Top Observation at 5TeV



Submit to PLB:

arXiv:2310.01518

Motivation

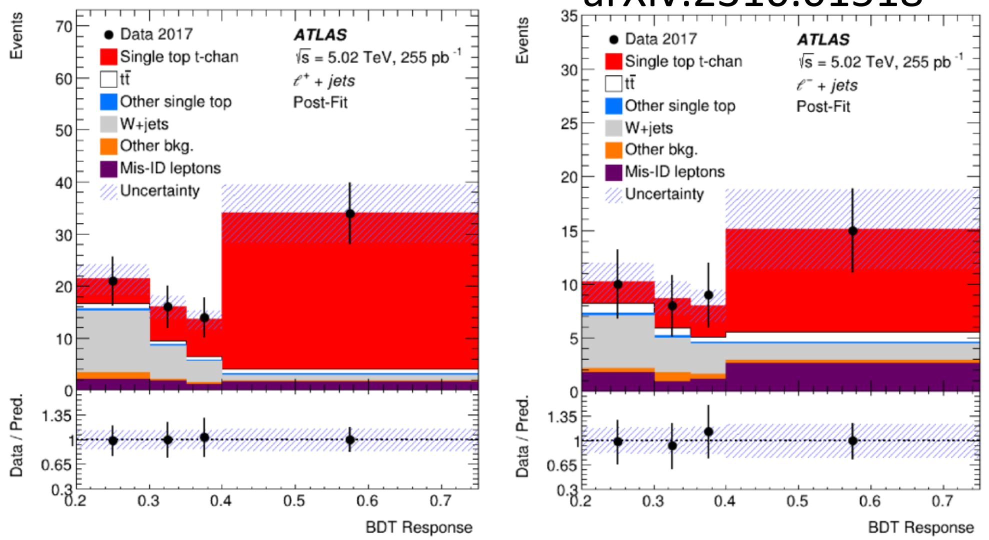
- Provide a window into the properties of the top quark itself
- Cross section depends on the CKM matrix element V_{tb}

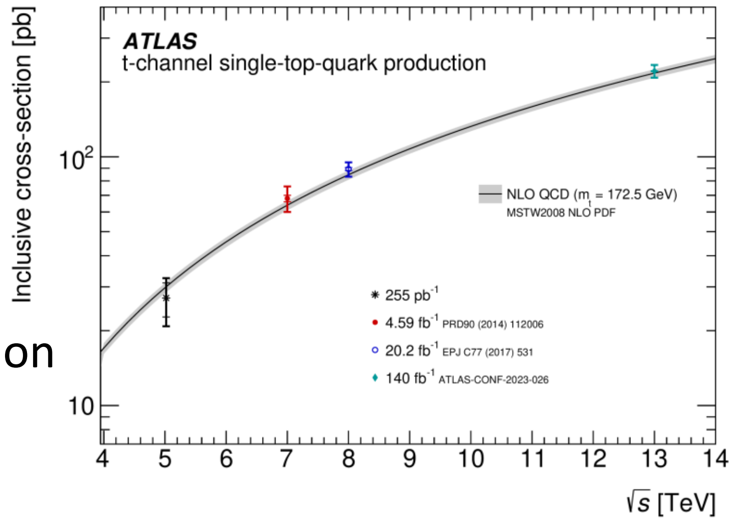
Data taken under low-pile-up conditions in 2017

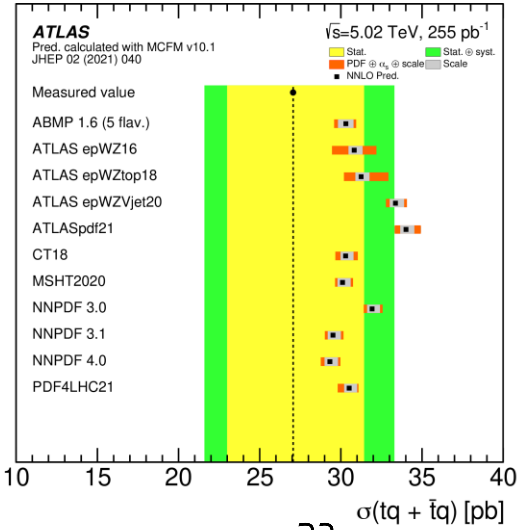
- <number of inelastic pp collisions> / bunch crossing ≈2

Results

- $\sigma(tq+\bar{t}q) = 27.1^{+4.4}_{-4.1}$ (stat.) $^{+4.4}_{-3.7}$ (syst.) pb
- $R_t = 2.73^{+1.43}_{-0.82}$ (stat.) $^{+1.01}_{-0.29}$ (syst.)
- $\sigma(tq) = 19.8^{+3.9}_{-3.1}$ (stat.) $^{+2.9}_{-2.2}$ (syst.) pb
- $\sigma(\bar{t}q) = 7.3^{+3.2}_{-2.1}$ (stat.) $^{+2.8}_{-1.5}$ (syst.) pb
- $f_{\mathrm{LV}} \cdot |V_{tb}| = 0.94^{+0.11}_{-0.10}$
- NLO predictions (MCFM) well describes the evolution
- Observed (expected) significance is 6.1 (6.4) σ





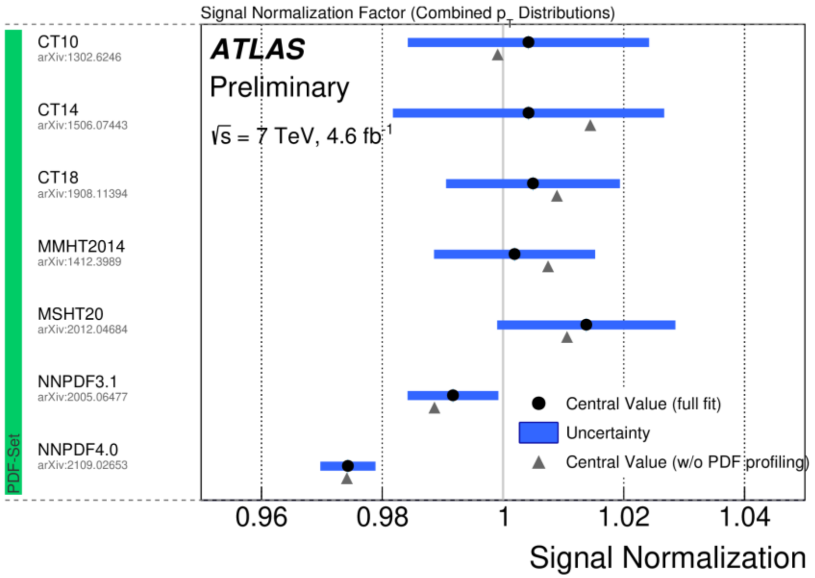


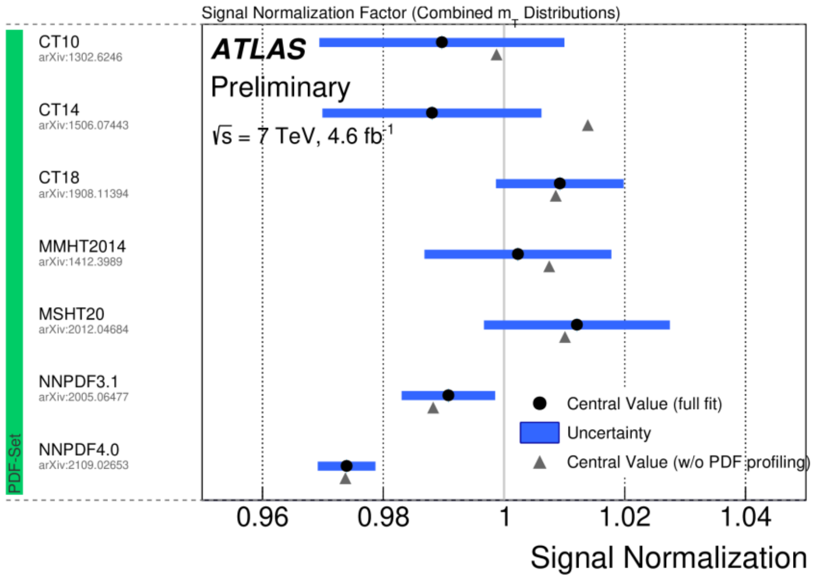
m_W re-analysis at 7TeV

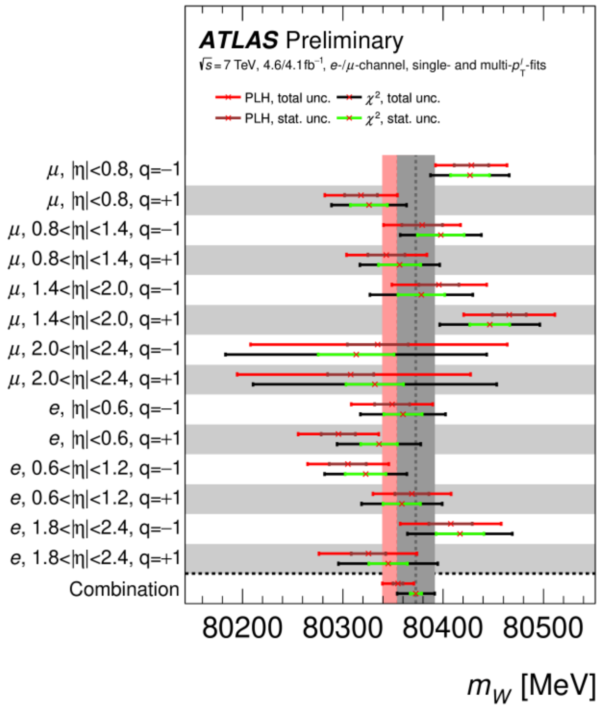
Decay channel	$W \to e\nu$	$W \to \mu\nu$
Kinematic distributions	p_T^ℓ, m_T	p_T^ℓ, m_T
Charge categories	W^+, W^-	W^+, W^-
$\lvert\eta_\ell\rvert$ categories	[0, 0.6], [0.6, 1.2], [1.8, 2.4]	[0, 0.8], [0.8, 1.4], [1.4, 2.0], [2.0, 2.4]

Profile likelihood fit

- $L(\mu, \vec{\theta} \mid \vec{n}) = \prod_i \text{Poisson}\left(n_{ji} \mid \nu_{ji}(\mu, \vec{\theta})\right) \cdot \text{Gauss}(\vec{\theta})$
- $$\nu_{\text{ji}}(\mu, \vec{\theta}) = \Phi \times \left[S_{\text{ji}}^{\text{nom}} + \mu \times \left(S_{\text{ji}}^{\mu} - S_{\text{ji}}^{\text{nom}}\right)\right] + \sum_s \theta_s \times \left(S_{\text{ji}}^{p} - S_{\text{ji}}^{\text{nom}}\right) + B_{\text{ji}}^{\text{nom}} + \sum_b \theta_b \times \left(B_{\text{ji}}^{p'} - B_{\text{ji}}^{\text{nom}}\right)$$







Obs.	Mean [MeV]	Elec. Unc.	PDF Unc.	Muon Unc.	EW Unc.	PS & A_i Unc.	Bkg. Unc.	Γ_W Unc.	MC stat. Unc.	Lumi Unc.	Recoil Unc.	Total sys.	Data stat.	Total Unc.
p_T^ℓ	80360.1	8.0	7.7	7.0	6.0	4.7	2.4	2.0	1.9	1.2	0.6	15.5	4.9	16.3
m_T	80382.2	9.2	14.6	9.8	5.9	10.3	6.0	7.0	2.4	1.8	11.7	24.4	6.7	25.3

p_T^W and p_T^Z with low pile-up data

Reference

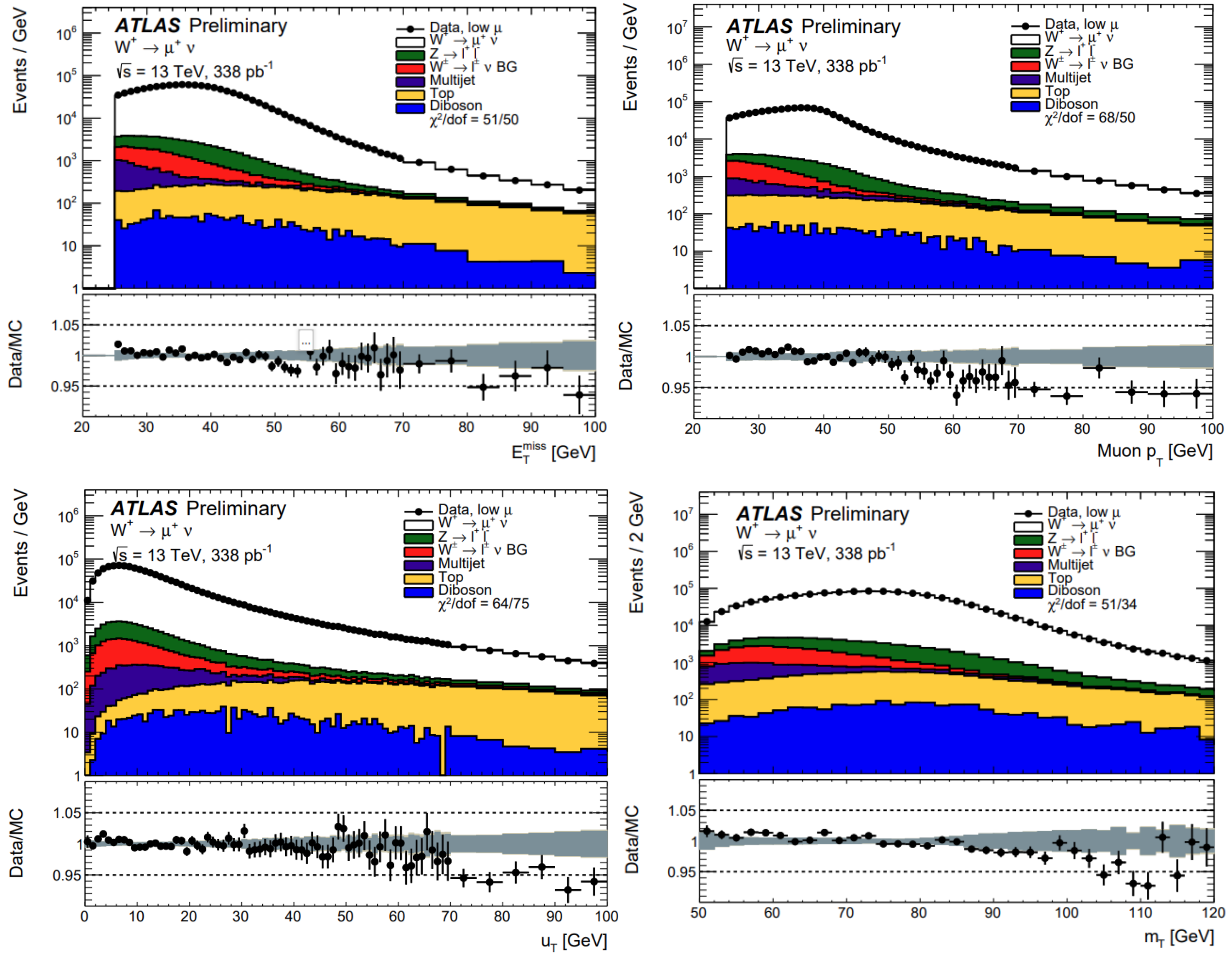
- Data
  - 2017: 258 pb^{-1} at $\sqrt{s}$ = 5.02 TeV, 147 pb^{-1} at $\sqrt{s}$ = 13 TeV
  - 2018: 193 pb^{-1} at $\sqrt{s}$ = 13 TeV
- Predictions
  - Powheg+Pythia8 AZNLO, Pythia8 AZ, Herwig7, Sherpa(v2.2.1), DYRes, DYTurbo (to NNLL+NNLO),
- Fiducial Volume
  - $Z \to \ell\ell$: $p_{\mathrm{T}}^{\ell} > 25\mathrm{GeV}, |\eta^{\ell}| < 2.5, 66\mathrm{GeV} < m_{\ell\ell} < 116\mathrm{GeV}$
  - $W \to \ell v$: $p_{\mathrm{T}}^{\ell} > 25\mathrm{GeV}, |\eta^{\ell}| < 2.5, p_{\mathrm{T}}^{v} > 25\mathrm{GeV}, m_T > 50\mathrm{GeV}$
- Dominant uncertainty
  - W: unfolding uncertainties at low p_T^W, statistical uncertainties at high p_T^W (0.5% ~ 6%)
  - Z: fully dominated by statistical uncertainties.
  - Generator dependence of the recoil calibration procedure is sizable at 13 TeV (0.6% ~ 3%)

p_T^W and p_T^Z with low pile-up data

Backgrounds

Channel	Observed	Signal	$W \to \ell\nu$ BG	$Z \to \ell\ell$	Top	Diboson	Multijet
			5.02 TeV $W \to \ell\nu$				
$W^- \to e^-\nu$	274375	264510 ± 170	7303 ± 29	1031 ± 6	862.7 ± 2.1	340.5 ± 2.9	2200 ± 700
$W^+ \to e^+\nu$	430662	417090 ± 210	9064 ± 32	1102 ± 7	951.4 ± 2.9	376.2 ± 2.3	2300 ± 900
$W^- \to \mu^-\nu$	288026	273900 ± 170	5160 ± 25	8517 ± 21	799.0 ± 2.0	339.1 ± 1.9	300 ± 340
$W^+ \to \mu^+\nu$	457223	438020 ± 210	7854 ± 30	9773 ± 22	890.6 ± 2.8	384.6 ± 2.3	500 ± 400
			13 TeV $W \to \ell\nu$				
$W^- \to e^-\nu$	949297	876490 ± 270	22360 ± 60	6546 ± 21	12780 ± 50	1720 ± 50	27000 ± 5000
$W^+ \to e^+\nu$	1207652	1116800 ± 300	24680 ± 60	6883 ± 21	13260 ± 50	1720 ± 50	29000 ± 5000
$W^- \to \mu^-\nu$	964514	897400 ± 270	14650 ± 50	33940 ± 40	11950 ± 50	1620 ± 40	6000 ± 2000
$W^+ \to \mu^+\nu$	1245755	1153400 ± 300	18390 ± 50	37690 ± 40	12520 ± 50	1720 ± 50	6000 ± 2000

Channel	Observed	Signal	$Z \to \tau\tau$	Top	Diboson	Multijet
			5.02 TeV $Z \to \ell\ell$			
$Z \to ee$	51772	51310 ± 40	23 ± 4	35.5 ± 0.4	109.1 ± 2.0	0 ± 100
$Z \to \mu\mu$	70447	69820 ± 60	39 ± 5	44.0 ± 0.4	144.9 ± 2.1	16 ± 8
			13 TeV $Z \to \ell\ell$			
$Z \to ee$	165027	158000 ± 100	80 ± 8	500 ± 10	324 ± 15	110 ± 70
$Z \to \mu\mu$	214035	207900 ± 100	80 ± 8	554 ± 9	414 ± 17	180 ± 40



p_T^W and p_T^Z with low pile-up data

ATLAS-CONF-2023-028

Integrated cross sections

- Improved by a factor of two or more profiting from the very precise luminosity measurement (0.9 – 1.0%)
- Compatible with DYTURBO predictions at order NNLO+NNLL
- CT18 tends to underestimate the cross sections of W, Z

Process	Cross section at $\sqrt{s}$ = 5.02 TeV [pb]	Cross section at $\sqrt{s}$ = 13 TeV [pb]
$W^- \to \ell\nu$	1385 ± 2 (stat.) ± 5 (sys.) ± 15 (lumi.)	3486 ± 3 (stat.) ± 18 (sys.) ± 34 (lumi.)
$W^+ \to \ell\nu$	2228 ± 3 (stat.) ± 8 (sys.) ± 23 (lumi.)	4571 ± 3 (stat.) ± 21 (sys.) ± 44 (lumi.)
$Z \to \ell\ell$	333.0 ± 1.2 (stat.) ± 2.2 (sys.) ± 3.3 (lumi.)	780.3 ± 2.6 (stat.) ± 7.1 (sys.) ± 7.1 (lumi.)

Process	Ratio $\sigma_{\text{fid}}(13\text{ TeV})/\sigma_{\text{fid}}(5.02\text{ TeV})$
$W^- \to \ell\nu$	2.517 ± 0.006 (stat.) ± 0.010 (sys.) ± 0.036 (lumi.)
$W^+ \to \ell\nu$	2.047 ± 0.004 (stat.) ± 0.009 (sys.) ± 0.029 (lumi.)
$Z \to \ell\ell$	2.340 ± 0.010 (stat.) ± 0.012 (sys.) ± 0.032 (lumi.)

Induced from different flavour and momentum fractions of initial quarks

Processes	Cross-section ratio at 5.02 TeV	Cross-section ratio at $\sqrt{s}$ = 13 TeV
W^+/W^-	1.611 ± 0.003 (stat.) ± 0.004 (sys.)	1.312 ± 0.001 (stat.) ± 0.003 (sys.)
W^-/Z	4.16 ± 0.01 (stat.) ± 0.05 (sys.)	4.46 ± 0.01 (stat.) ± 0.07 (sys.)
W^+/Z	6.69 ± 0.02 (stat.) ± 0.08 (sys.)	5.84 ± 0.01 (stat.) ± 0.09 (sys.)
$W^\pm/Z$	10.85 ± 0.04 (stat.) ± 0.11 (sys.)	10.31 ± 0.02 (stat.) ± 0.15 (sys.)

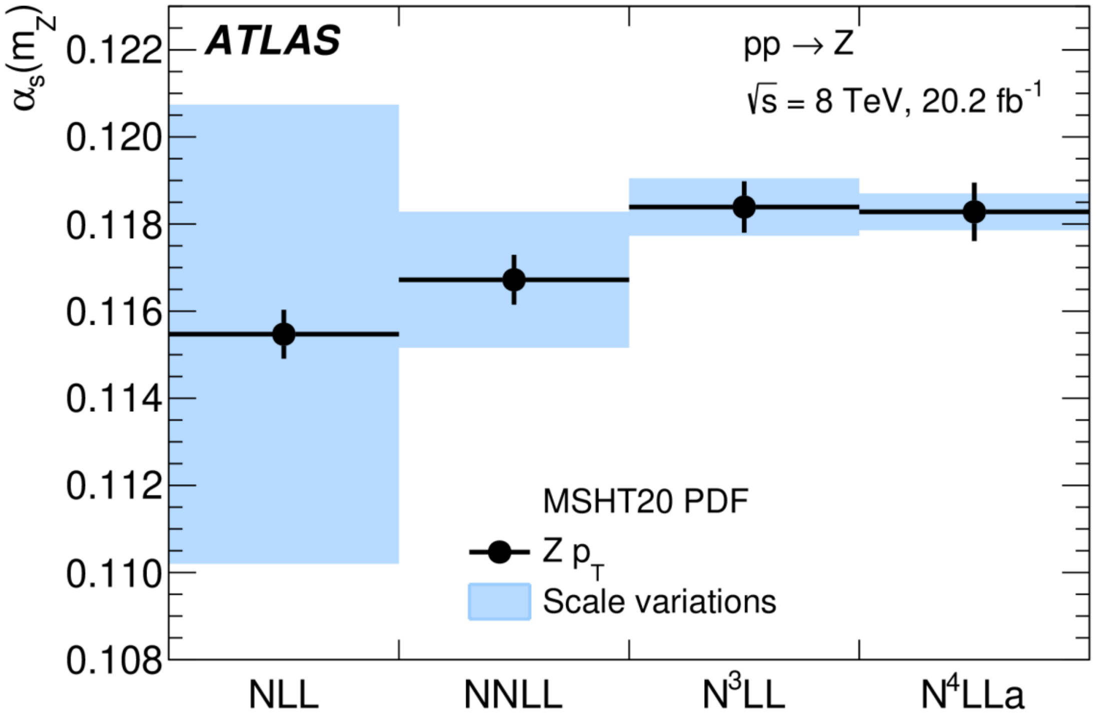
PDF set	$W^- \to \ell\nu$	$W^+ \to \ell\nu$	$Z \to \ell\ell$
Cross-section at 5.02 TeV [pb]			
CT18	1364	2199	320.9
MSHT20	1351	2185	324.3
NNPDF3.1	1381	2232	329.8
Data	1384 ± 16	2228 ± 25	333.0 ± 4.1
Cross-section at 13 TeV [pb]			
CT18	3410	4462	749.8
MSHT20	3397	4457	766.1
NNPDF3.1	3452	4513	771.4
Data	3486 ± 38	4571 ± 49	780.3 ± 10.4

DYTURBO predictions with NNLO PDF
Assess impact of PDF sets directly

Z pT and rapidity at 8 TeV

Extraction of αs from p_T^Z at 8 TeV

- Fit range: $p_T^Z < 29\ GeV$ of the double differential p_T^Z, Y^Z measurement
- The first α_s determination with N^4LLa+N^3LO prediction
  - Baseline PDF set: aN^3LO MSHT20



Vertical error bars include experimental and PDF uncertainties

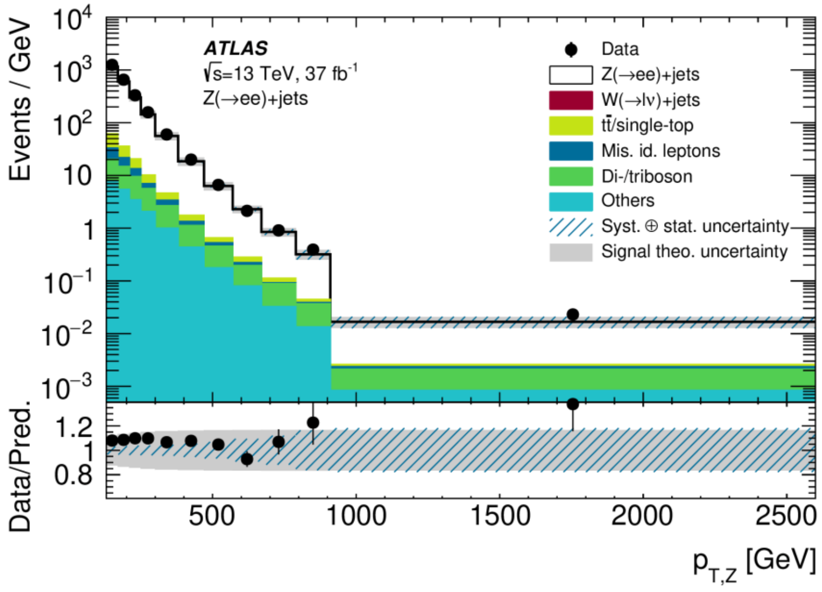
Experimental uncertainty	±0.44	
PDF uncertainty	±0.51	
Scale variation uncertainties	±0.42	
Matching to fixed order	0	−0.08
Non-perturbative model	+0.12	−0.20
Flavour model	+0.40	−0.29
QED ISR	±0.14	
N^4LL approximation	±0.04	
Total	+0.91	−0.88

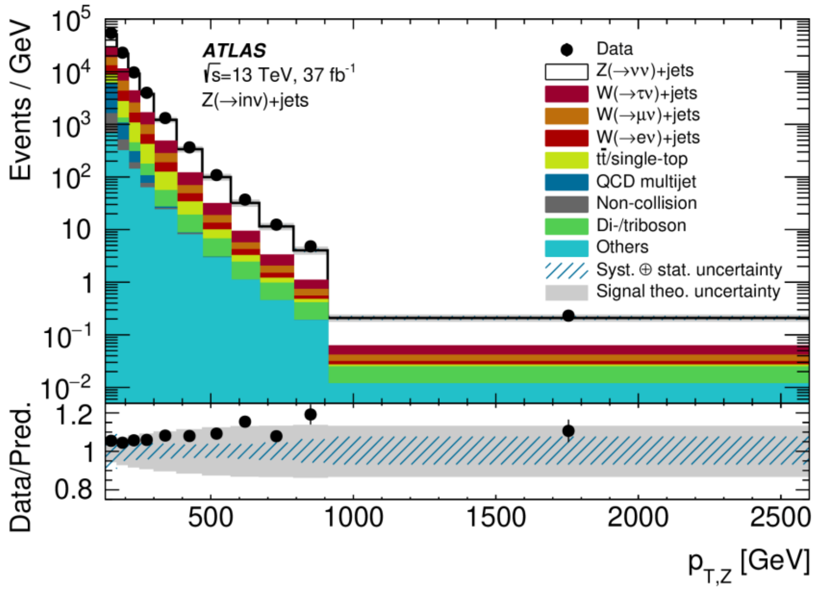
⇨ Good convergence of αs determination using different orders of resummation series

Z invisible width at 13 TeV

Reference

- Data
  - 2015+2016: 37 fb^{-1} at $\sqrt{s}$ = 13 TeV
- Fiducial Volume
  - at least one jet, where the leading jet must have pT ≥ 110 GeV and $|\eta|$ < 2.4
  - p_T^Z ≥ 130 GeV





Systematic Uncertainty	Impact on $\Gamma(Z \to \text{inv})$	in [MeV]	in [%]
Muon efficiency		7.4	1.5
Renormalisation & factorisation scales		5.9	1.2
Electron efficiency		4.9	1.0
Detector correction		4.4	0.9
QCD multijet		3.2	0.6
E_T^{miss}		2.4	0.5
$Z(\to \mu\mu)$+jets misid. lepton estimate		1.9	0.4
Jet energy resolution		1.6	0.3
$W(\to \ell\nu)$+jets normalisation		1.5	0.3
Pile-up reweighting		1.5	0.3
Non-collision background estimate		1.3	0.3
Jet energy scale		1.3	0.3
γ^*-correction		1.0	0.2
$Z(\to ee)$+jets misid. lepton estimate		1.0	0.2
Luminosity		1.0	0.2
Parton distribution functions + α_s		0.7	0.1
$\Gamma(Z \to \ell\ell)$		0.5	0.1
Tau energy scale		0.4	0.1
Muon momentum scale		0.3	0.1
$W(\to \ell\nu)$+jets misid. lepton estimate		0.3	0.1
(Forward) jet vertex tagging		0.2	< 0.1
Top subtraction scheme		0.2	< 0.1
Electron energy scale		0.1	< 0.1
Systematic		12	2.4
Statistical		2	0.4
Total		13	2.5