High-p_T experimental results on QCD

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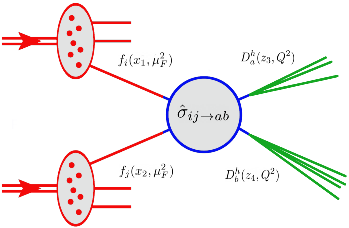
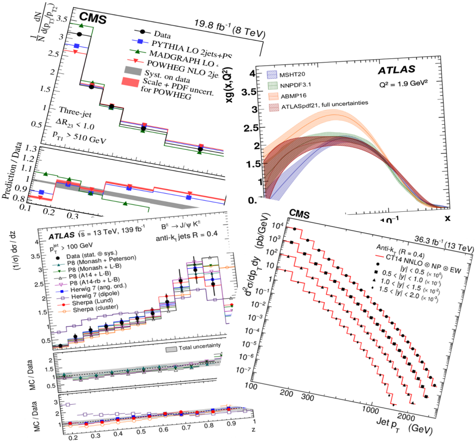
Introduction

- The QCD cross section can be factorised in three parts: IS, HS, FS.
- ATLAS and CMS have presented important QCD results recently.
- Measurements are exploited to understand these three parts separately.

- Initial State $\Rightarrow$ Parton Density $f_i(x, \mu_F)$
- Hard Scattering $\Rightarrow$ Matrix Element $\hat{\sigma} \propto |\mathcal{M}|^2$
- Final State $\Rightarrow$ Fragm. Functions $D_a^h(z, \mu_f)$

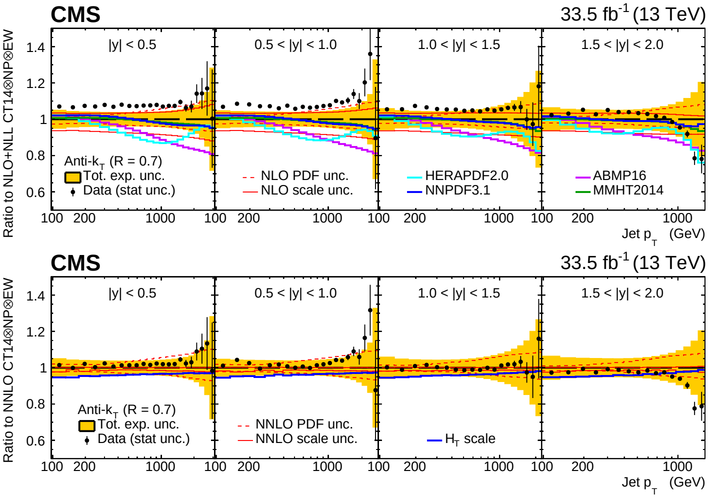




$$d\sigma = \sum_{i,j,a,b} \int_\Omega d^2\vec{x}\, d^2\vec{z}\; f_i(x_1, \mu_F^2) f_j(x_2, \mu_F^2) \times d\hat{\sigma}_{ij\to ab}(\vec{x}, \mu_R^2) \times D_a^h(z_3, \mu_f^2) D_b^h(z_4, \mu_f^2)$$

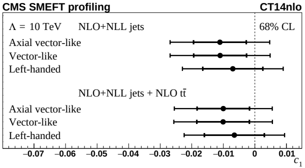
CMS inclusive jet cross section at $\sqrt{s} = 13$ TeV [JHEP 02, 142 (2022)]

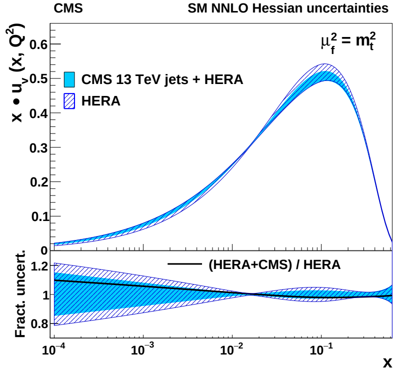
- Differential cross section as a function of (p_T, y) for $R = 0.4$ and $R = 0.7$.
- Comparison to NLO+NLL and NNLO pQCD $\otimes$ NP and EW effects.
- Description is well improved at NNLO with respect to NLO.

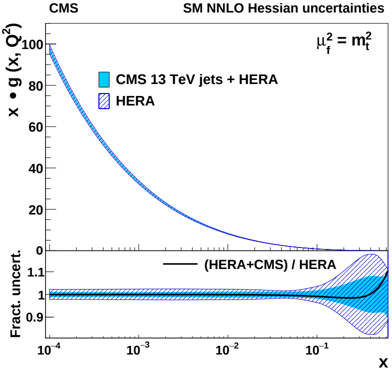


CMS inclusive jet cross section at $\sqrt{s} = 13$ TeV [JHEP 02, 142 (2022)]

- Full QCD analysis includes HERA DIS and CMS $t\bar{t}$ data.
- PDFs as $xf(x) = A_f x^{B_f}(1-x)^{C_f}(1 + D_f x + E_f x^2)$.
- Improved uncertainties on PDF by including jet data.
- Wilson coefficient for 4-quark CI obtained for different Λ.
- Limits on CI are set to $\Lambda > 24$ TeV @ 95% CL.







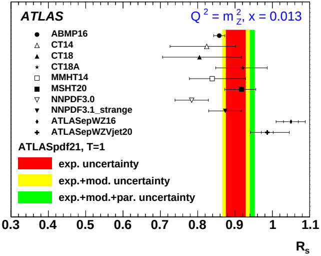
$$\alpha_s(m_Z) = 0.1170 \pm 0.0014\ (\text{fit}) \pm 0.0007\ (\text{model}) \pm 0.0008\ (\text{scale}) \pm 0.0001\ (\text{param.})$$

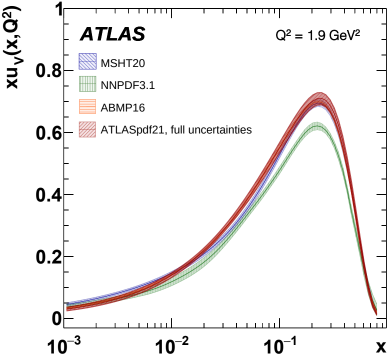
- Determination of PDFs from HERA + ATLAS data at different $\sqrt{s}$.
- PDF parameterisation follows the generic formulation:
  - Quarks: $xq_i(x) = A_i x^{B_i} (1-x)^{C_i} P_i(x)$
  - Gluons: $xg(x) = A_g x^{B_g} (1-x)^{C_g} P_g(x) - A'_g x^{B'_g} (1-x)^{C'_g}$
- For all PDFs $P_i(x) = 1 + D_i x + E_i x^2 + F_i x^3$.
- D, E, F are non-zero only if χ^2 decreases significantly $\Rightarrow$ 21 parameters in total.
- χ^2 fit includes full correlation between uncertainties.

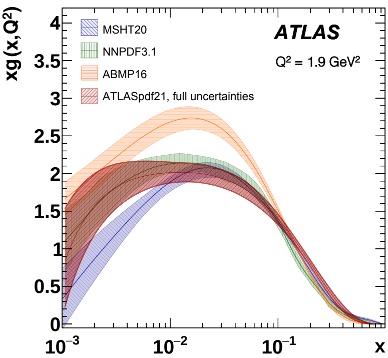
Data set	$\sqrt{s}$ [TeV]	Luminosity [fb^{-1}]	Decay channel	Observables entering the fit
Inclusive $W, Z/\gamma^*$	7	4.6	e, μ combined	η_ℓ (W), y_Z (Z)
Inclusive Z/γ^*	8	20.2	e, μ combined	$\cos\theta^*$ in bins of $y_{\ell\ell}$, $m_{\ell\ell}$
Inclusive W	8	20.2	μ	η_μ
$W^\pm$ + jets	8	20.2	e	p_{T}^{W}
Z + jets	8	20.2	e	$p_{\mathrm{T}}^{\mathrm{jet}}$ in bins of $\lvert y^{\mathrm{jet}}\rvert$
$t\bar{t}$	8	20.2	lepton + jets, dilepton	$m_{t\bar{t}}$, p_{T}^{t}, $y_{t\bar{t}}$
$t\bar{t}$	13	36	lepton + jets	$m_{t\bar{t}}$, p_{T}^{t}, y_t, $y_{t\bar{t}}^{\mathrm{b}}$
Inclusive isolated γ	8, 13	20.2, 3.2	-	E_{T}^{γ} in bins of η^γ
Inclusive jets	7, 8, 13	4.5, 20.2, 3.2	-	$p_{\mathrm{T}}^{\mathrm{jet}}$ in bins of $\lvert y^{\mathrm{jet}}\rvert$

ATLAS global PDF fit at $\sqrt{s} = 7, 8, 13$ TeV [arXiv:2112.11266 (hep-ex)]

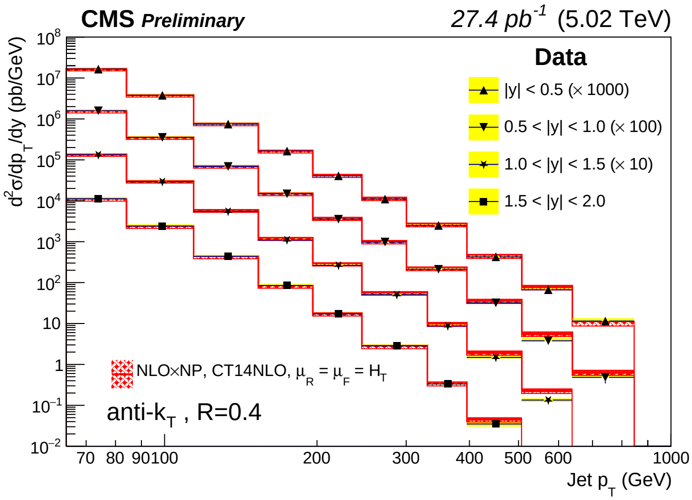
- Inclusion of ATLAS data brings ATLAS PDF close MSHT20 than HERAPDF.
- Comparison to CT18, NNPDF, MSHT20, ...
- Measurement of $R_s(x, Q^2) = x(s + \bar{s})/x(\bar{u} + \bar{d})$.
- Uncertainties estimated using different tolerances $\chi^2 = T^2;\ T = 1, 3$.





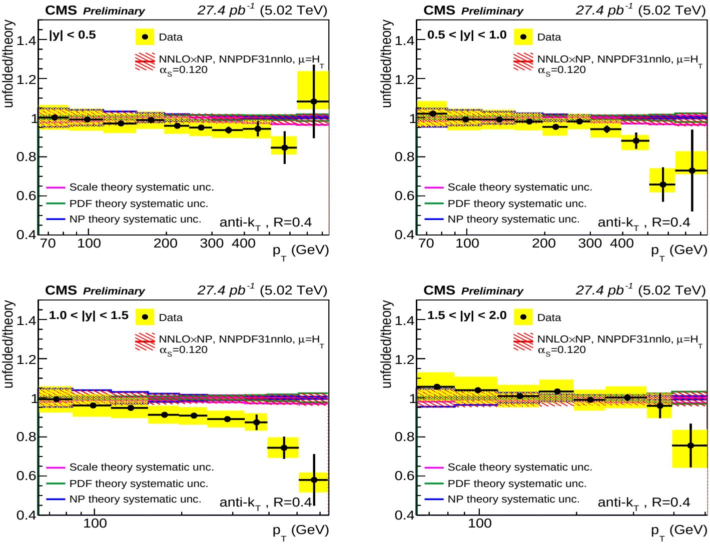


- Double-differential inclusive jet cross section as a function of (p_T, y).
- Comparison to theoretical pQCD predictions at NLO and NNLO.

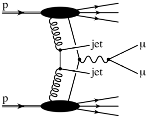


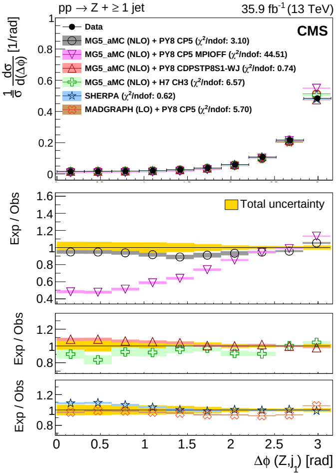
CMS Inclusive jet cross section at $\sqrt{s} = 5.02$ TeV [CMS-PAS-SMP-21-009]

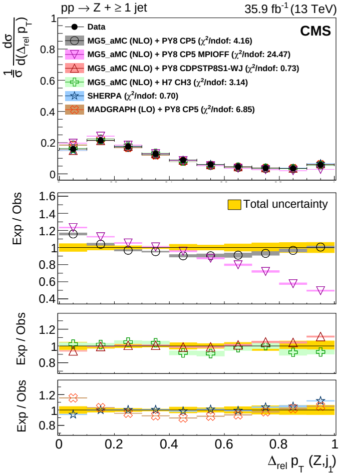
- NNLO scale uncertainties reduced with respect to NLO. $\mu_R = \mu_F = \hat{H}_T$.
- Best agreement is observed for NNPDF31 with $\alpha_s(m_Z) = 0.120$.



- Measurement of $Z+\geq 1$ jet and $Z+\geq 2$ jets in $\mu\mu$ channel.
- Azimuthal separation $\Delta\phi(Z, j_1)$ and $\Delta\phi(Z, \text{dijet})$.
- p_T-balance $\Delta_{\text{rel}} p_T(Z, j_1) = \dfrac{|\vec{p}_T(Z) + \vec{p}_T(j_1)|}{|\vec{p}_T(Z)| + |\vec{p}_T(j_1)|}$ and $\Delta_{\text{rel}} p_T(Z, \text{dijet})$.

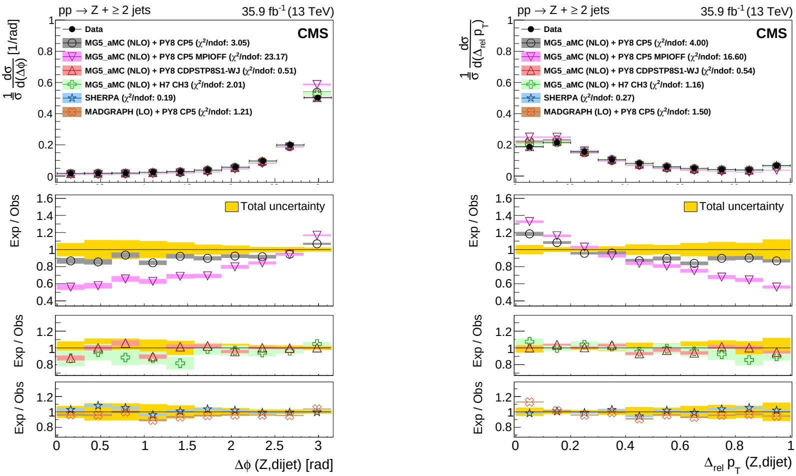




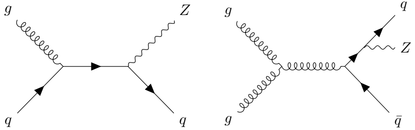


CMS Z+jets sensitivity to DPS at $\sqrt{s} = 13$ TeV [JHEP 10, 176 (2021)]

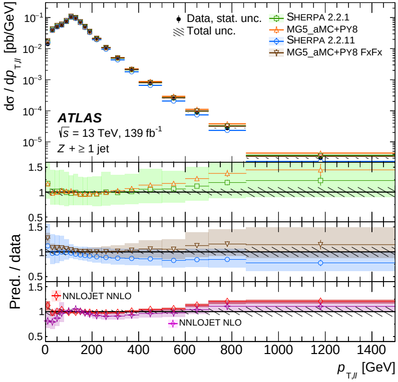
- Measurements are compared to different predictions at different orders.
- MG5_aMC with different MPI and fragmentation tunes (and without MPI!).
- Sherpa merged NLO samples with up to 2 partons in final state.
- The effect of DPS is clearly seen when setting MPI off.

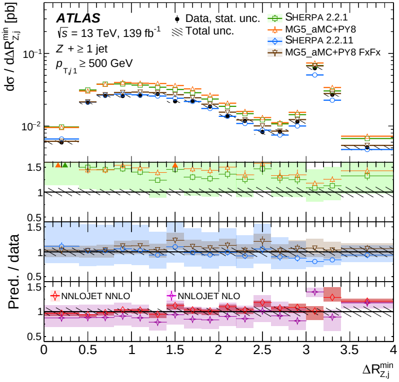


- $Z \to ee$ ($\mu\mu$) with additional jets ($p_T > 100$ GeV).
- High-p_T region is selected with $p_T^{\text{jet}} > 500$ GeV.
- Z-boson radiation $\propto \alpha_s \ln^2(p_{T,j_1}/m_Z)$.

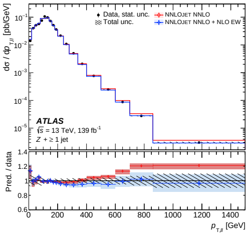


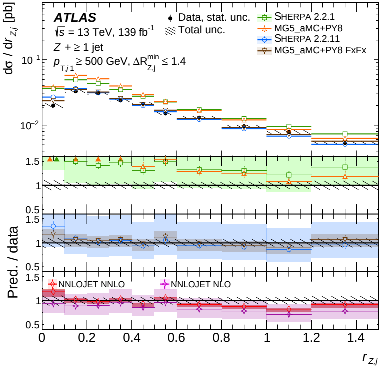
- Characterized in different topologies (collinear, back-to-back) using ΔR_{Zj}.
- Comparison to different ME+PS and fixed-order predictions.

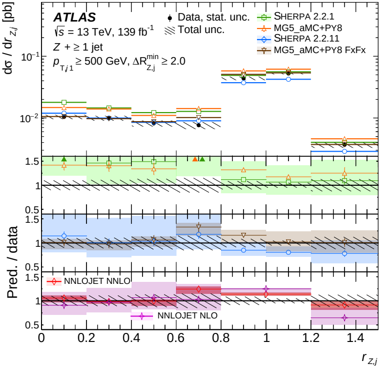




- Measurement of $r_{Zj} = \dfrac{p_{T,\ell\ell}}{p_T(\text{closest jet})}$ in ΔR bins.
- Excellent description by NNLO QCD + NLO EW.
- Sherpa 2.2.1 and MG5_aMC+Py8 overestimate the cross section at high p_T.
- Sherpa 2.2.11 and FxFx merging for MG5_aMC+Py8 provide an improved description.

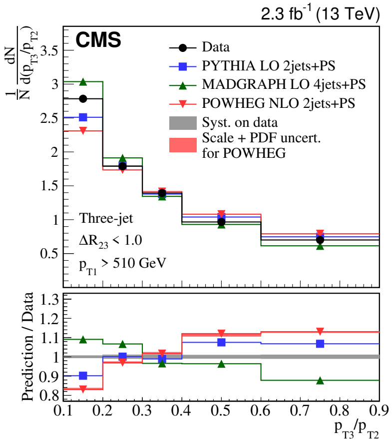


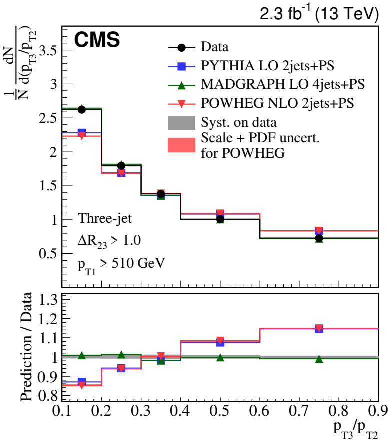




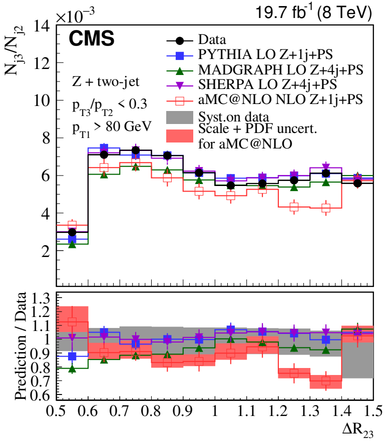
CMS ΔR-distance and p_T-ratios at $\sqrt{s} = 8$, 13 TeV [EPJC 81, 852 (2021)]

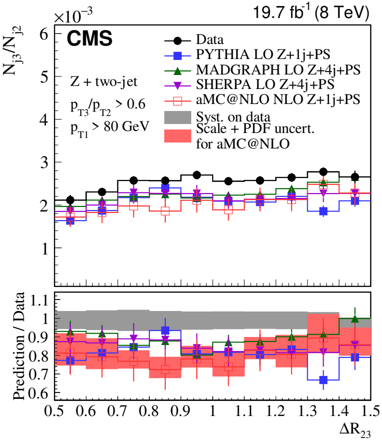
- Collinear/large-angle and soft/hard radiation in different final states.
- Measurement of ΔR_{23} and p_{T3}/p_{T2} in three-jet and Z+2-jet events.
- Z+2-jet measurement at $\sqrt{s} = 8$ TeV, 3-jets at $\sqrt{s} = 8$ and 13 TeV.
- Multi-let MG5_aMC describes better the wide-angle region.





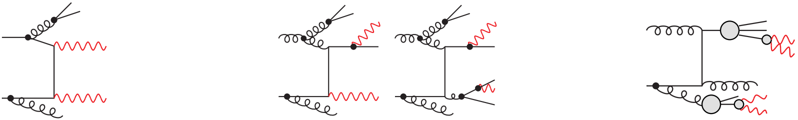
- Measurement of ΔR_{23} for soft and hard emissions.
- In general, ME+PS describe the data better for soft regions.
- Hard-emission regions underestimated by theoretical predictions.



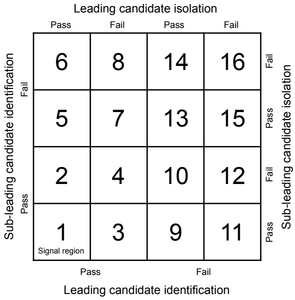


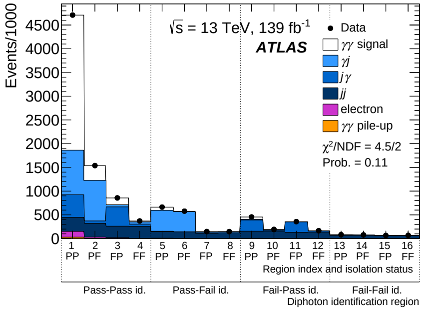
ATLAS diphoton cross section at $\sqrt{s} = 13$ TeV [JHEP 11, 169 (2021)]

- Measurement of $\gamma\gamma$ production for $p_T(\gamma_1) > 40$ GeV, $p_T(\gamma_2) > 30$ GeV.
- Background estimated from (ID, iso) sidebands for 2 photons (16 regions).
- Signal includes direct and fragmented γ, against non-prompt background.
- Poisson likelihood fit performed separately on each bin of each observable.



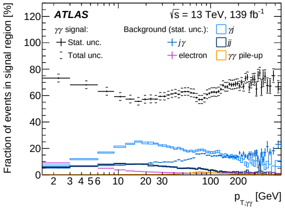
Direct photons | Fragmented photons | Non-prompt photons

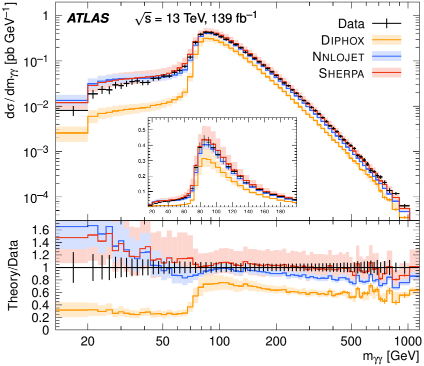


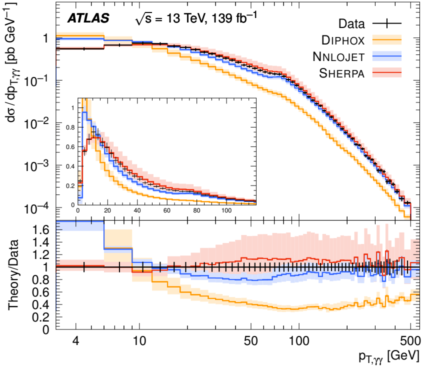


ATLAS diphoton cross section at $\sqrt{s} = 13$ TeV [JHEP 11, 169 (2021)]

- Comparison to ME+PS and fixed-order pQCD predictions.
- Sherpa (NLO) and NNLOJet give a good description.
- NNLOJet provides improved scale precision wrt NLO.
- DiPhox (NLO) fails to describe the data.





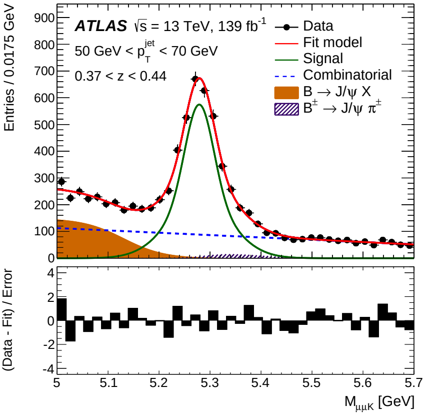


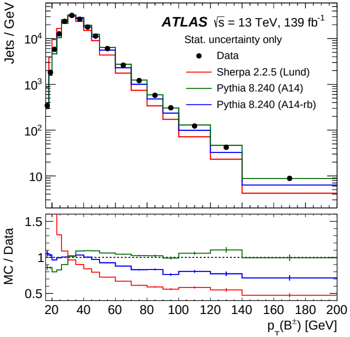
ATLAS b-fragmentation to $B^{\pm}$ at $\sqrt{s} = 13$ TeV [JHEP 12, 131 (2021)]

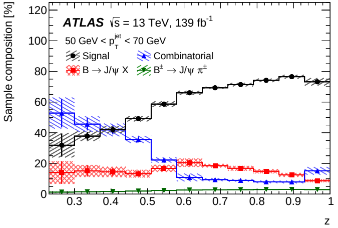
- Fragmentation observables for jets containing $B^{\pm} \to J/\psi K^{\pm}$ at $\Delta R < 0.4$
- Fully reconstructed decay from $\mu\mu K$ tracks.
- Longitudinal and transverse profiles of $B^{\pm}$:

$$z = \frac{\vec{p}_J \cdot \vec{p}_B}{|\vec{p}_J|^2}; \qquad p_T^{\mathrm{rel}} = \frac{|\vec{p}_J \times \vec{p}_B|}{|\vec{p}_J|}$$

- Background estimated using $M_{\mu\mu K}$ likelihood fits.

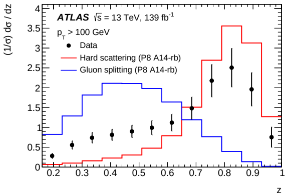


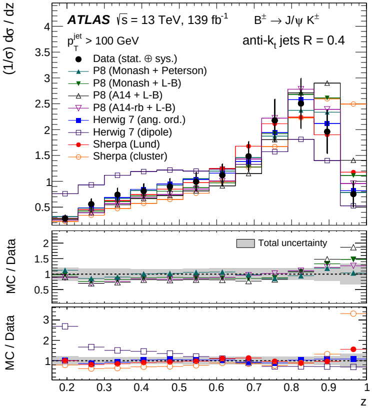


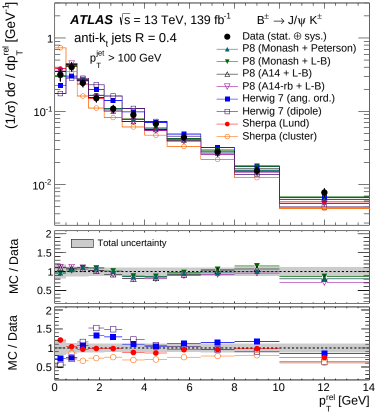


ATLAS b-fragmentation to $B^{\pm}$ at $\sqrt{s} = 13$ TeV [JHEP 12, 131 (2021)]

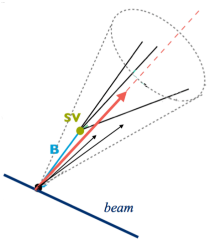
- Comparison to different ME+PS+fragmentation models.
- Pythia, Sherpa, H7 with different fragmentation/PS.
- Sensitivity to $g \to b\bar{b}$ splitting is investigated.
- Discrepancies observed with H7 dipole shower ($g \to b\bar{b}$).
- Sherpa cluster model shows discrepancies at high z.

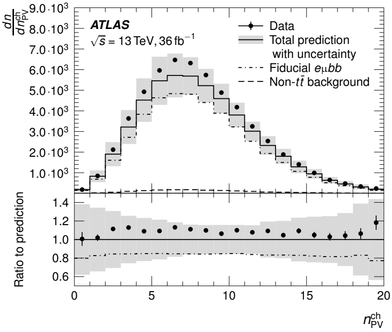


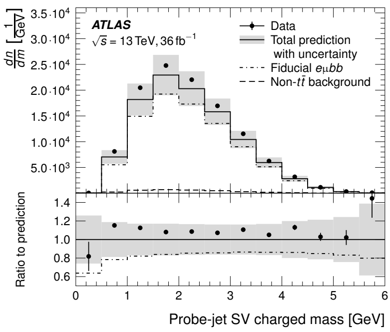




- Event selection in $t\bar{t} \to b\bar{b}e^{\pm}\mu^{\mp}$ dileptonic events.
- Exactly two jets: tag one jet, use the other as probe.
  - Probe jet should contain SV with at least 3 tracks.
  - If both jets are tagged, both jets are measured.
- Tracks from secondary vertex used to reconstruct $\vec{p}_b^{ch}$.
- All ghost-associated tracks used to reconstruct $\vec{p}_{jet}^{ch}$.

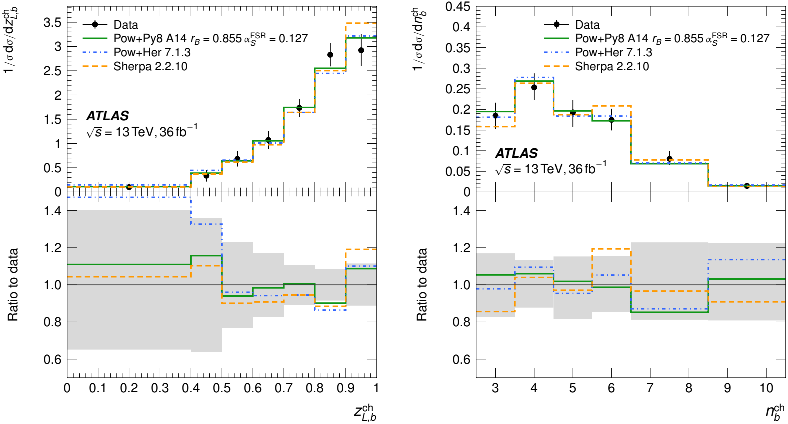






ATLAS b-fragmentation in $t\bar{t}$ at $\sqrt{s} = 13$ TeV [arXiv:2202.13901 (hep-ex)]

- Results are in reasonable agreement with MC expectations.
- Powheg + Pythia 8 gives a good description of the data.
- Powheg + Herwig 7.1.3 shows large differences at low z.
- Sherpa 2.2.10 provides the best overall description.



- Interesting dependence with α_s^{FSR}. No dependence with α_s^{ISR}.

Summary and conclusions

- Wide variety of QCD measurements recently released at the LHC.
- Different analyses sensitive to different aspects of the QCD modelling.
- PDF fits have been performed by ATLAS and CMS.
- Inclusive jet cross sections at different values of $\sqrt{s}$.
- Z+jets and multijet final states are thoroughly explored.
  - Z+jets measurement in different topologies.
  - Three-jet events in different angular and momentum phase spaces.
- Diphoton cross section compared to theoretical predictions up to NNLO.
- b-quark fragmentation explored by ATLAS in two different final states.
  - In dijets with $B^{\pm}$ production, with explicit sensitivity to $g \to b\bar{b}$.
  - In $t\bar{t}$ using charged momentum of B-hadrons.
- Stay tuned for more interesting results!