Recent hard and soft QCD measurements in ATLAS

Zdenek Hubacek, Czech Technical University in Prague
On behalf of the ATLAS Collaboration

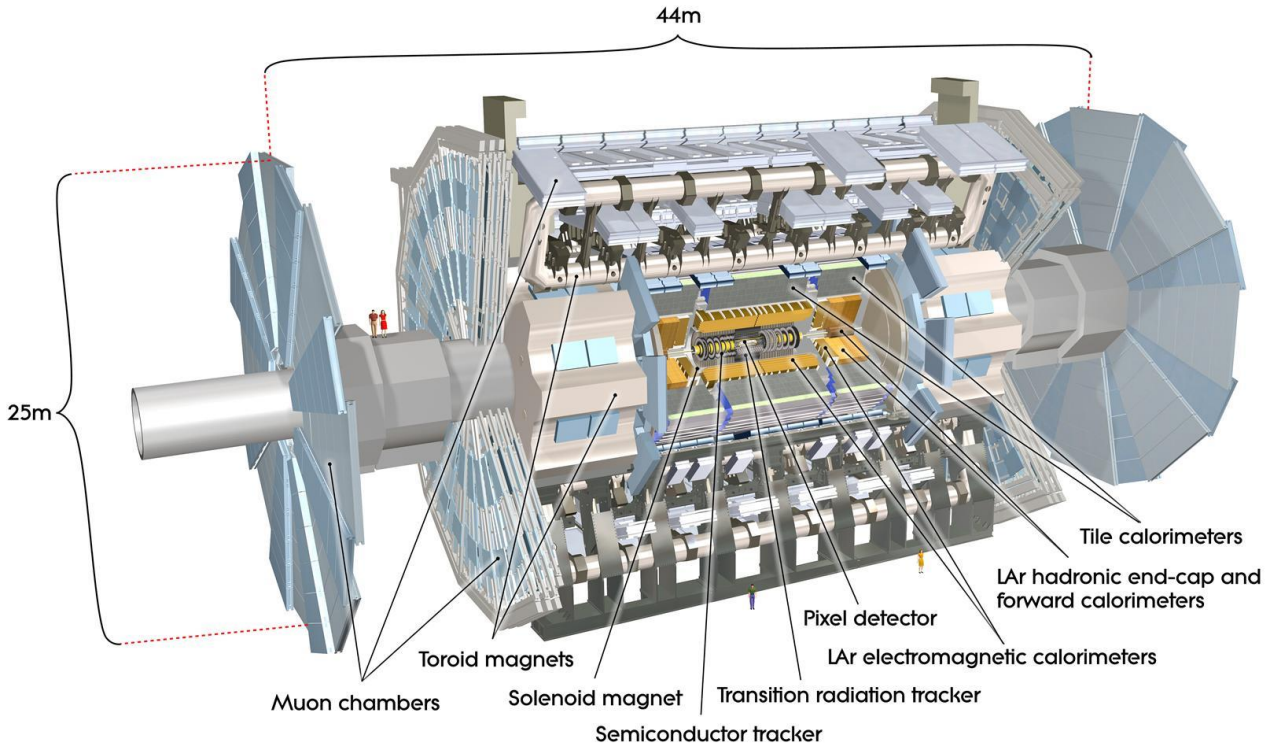
DIS 2026, Bologna

Co-funded by the European Union

Ministry of Education, Youth and Sports of the Czech Republic

Outline

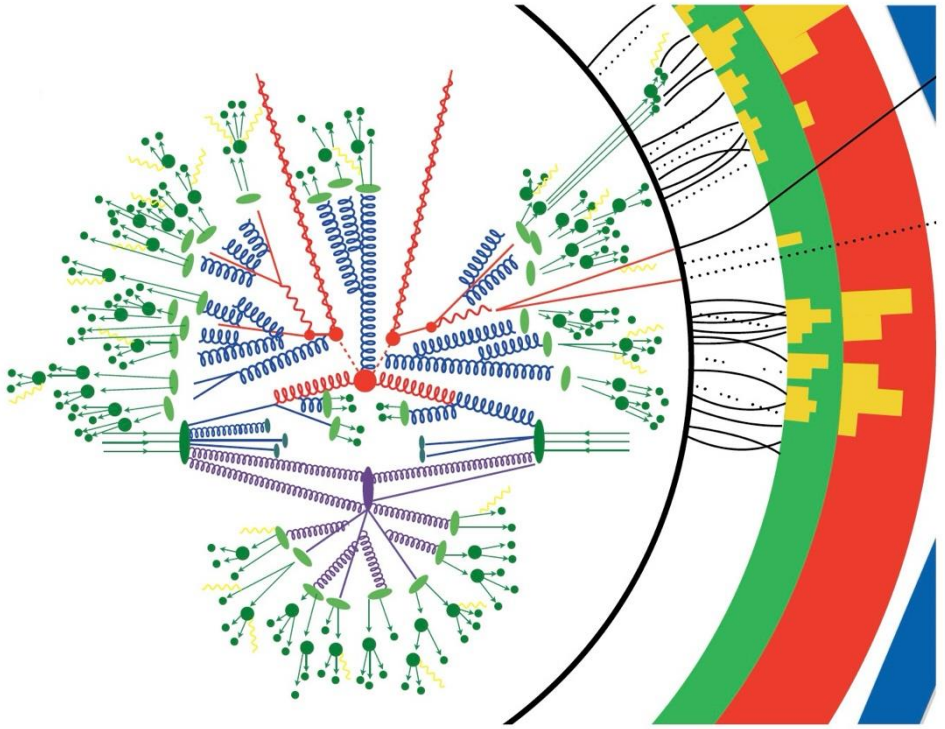
- An uneasy task – navigating recent ATLAS QCD results in 17min



CTU CZECH TECHNICAL UNIVERSITY IN PRAGUE

Outline – the story of proton

- How many different ways can we destroy the proton and what does it tell us

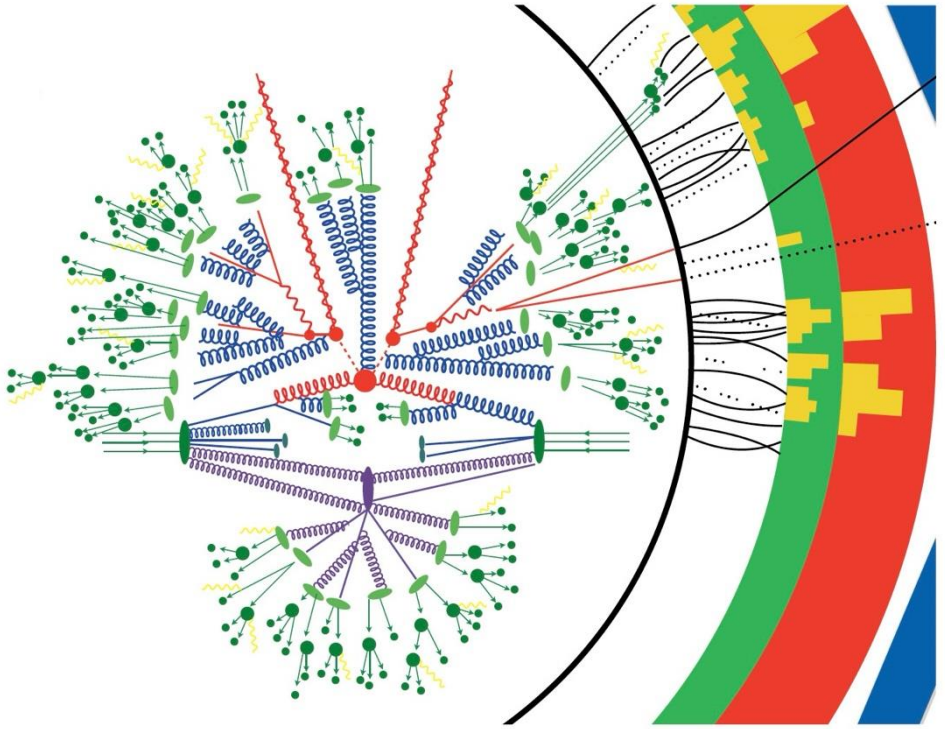


Credit: Benjamin Nachman

CTU CZECH TECHNICAL UNIVERSITY IN PRAGUE

Outline – the story of proton – the story of scales

- How many different ways can we destroy the proton and what does it tell us
- Charged-particle production in pO

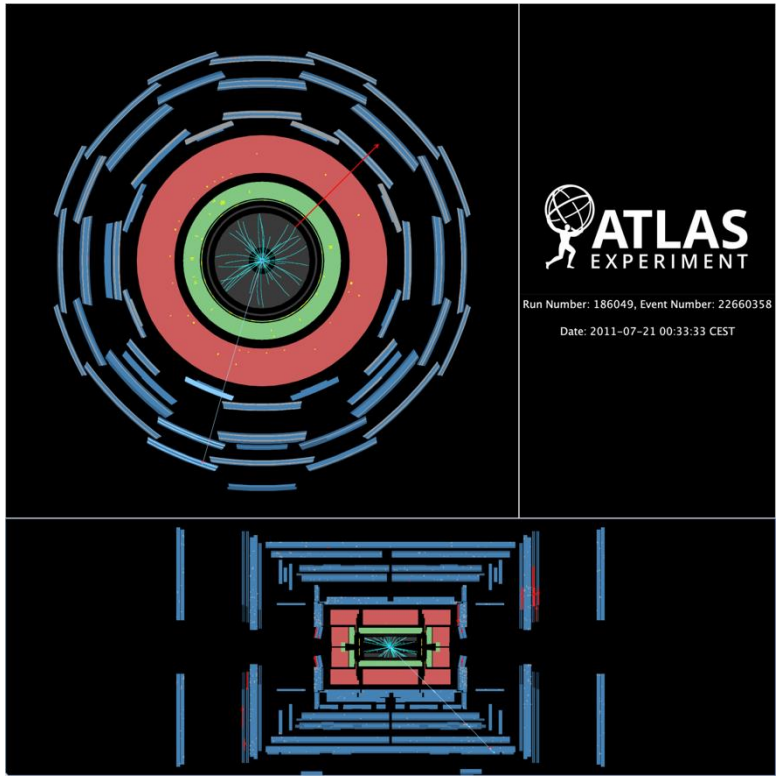


Credit: Benjamin Nachman

CTU CZECH TECHNICAL UNIVERSITY IN PRAGUE

Outline – the story of proton – the story of scales

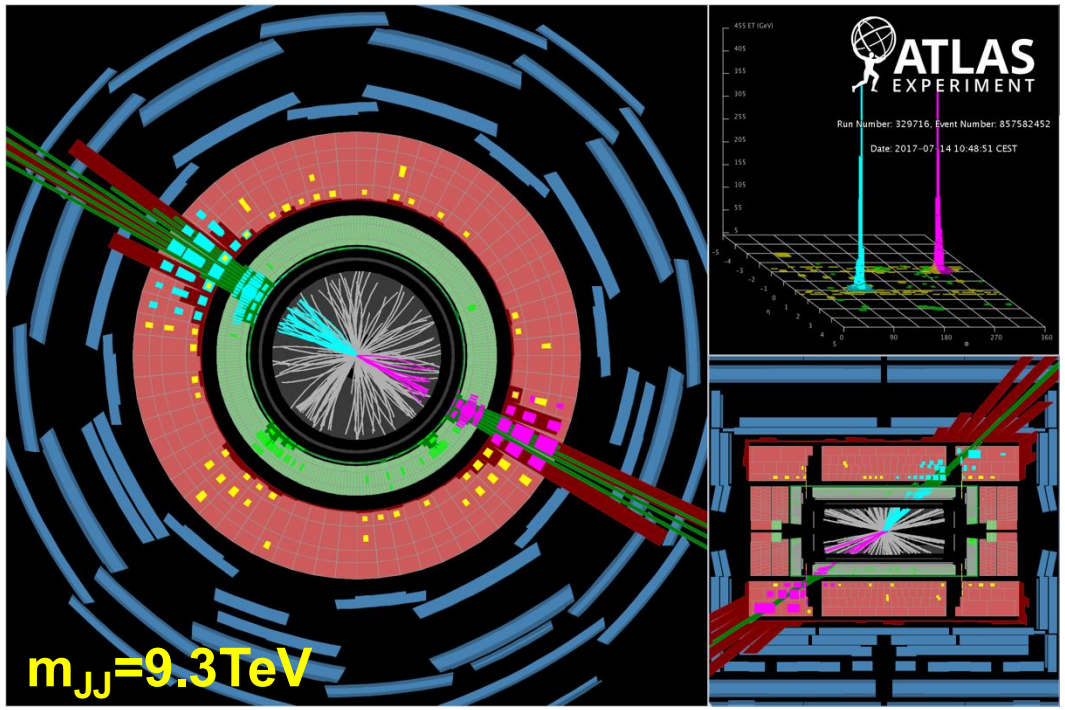
- How many different ways can we destroy the proton and what does it tell us
- Charged-particle production in pO
- W-boson angular coefficients



CTU
CZECH TECHNICAL UNIVERSITY IN PRAGUE

Outline – the story of proton – the story of scales

- How many different ways can we destroy the proton and what does it tell us
- Charged-particle production in pO
- W-boson angular coefficients
- Dijet invariant mass

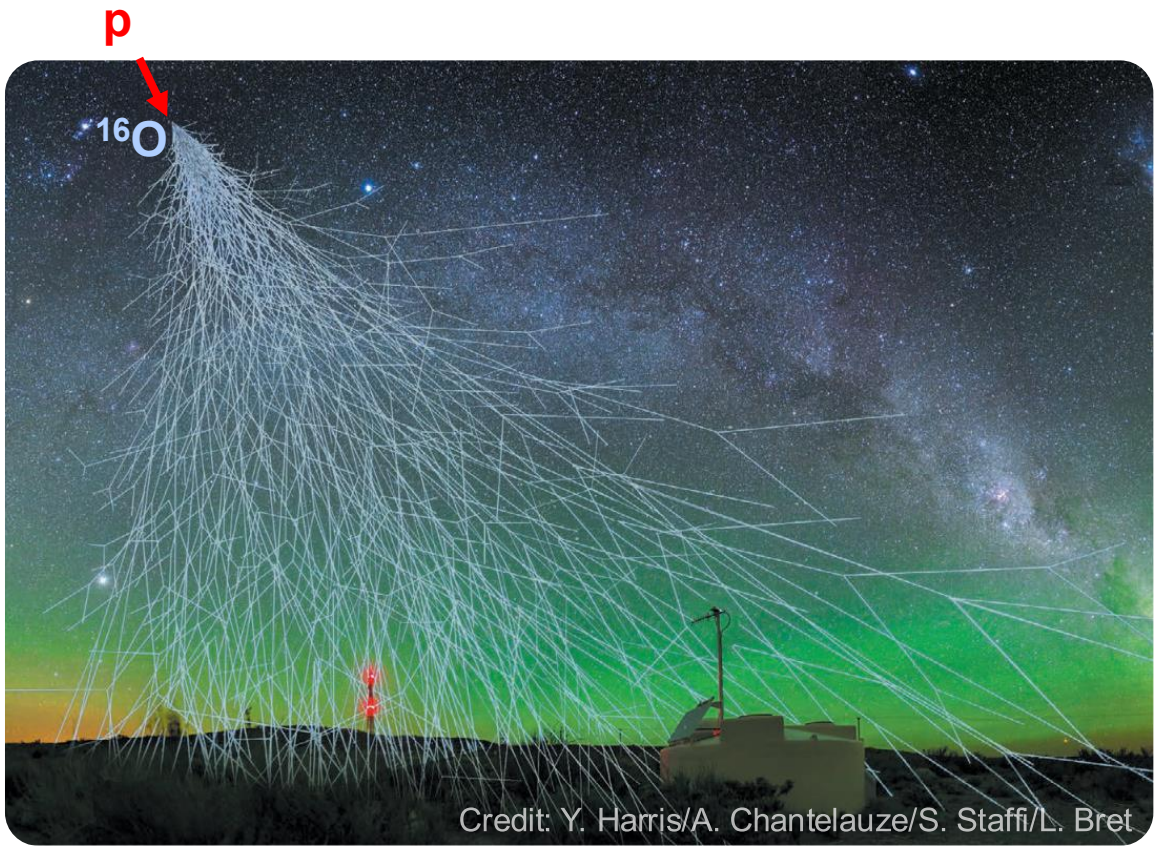


CTU
CZECH TECHNICAL UNIVERSITY IN PRAGUE

arXiv:2604.05512

Charged-particle production in proton-oxygen collision: ATLAS cosmic ray laboratory

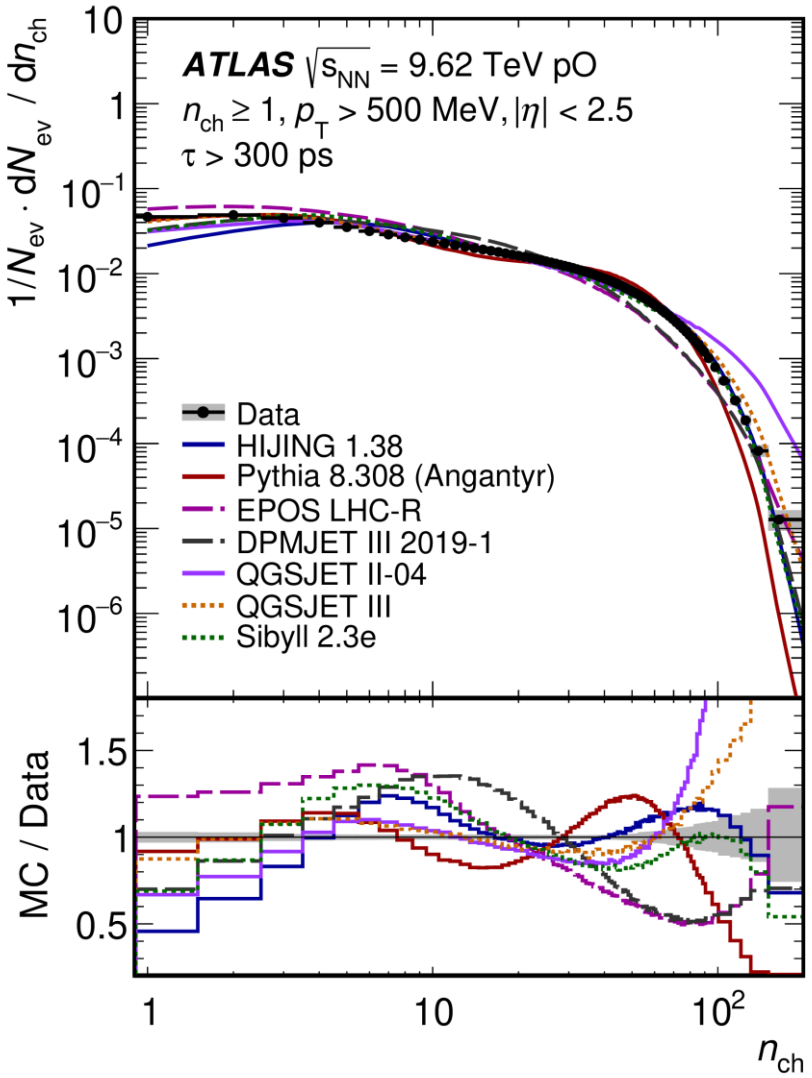
- Astrophysics - origin, energy spectrum and mass composition of cosmic rays
- Above PeV energies rare
- In 2025 **first** LHC pO run, $\sqrt{s_{NN}}$ = 9.62 TeV ~ 49 PeV fixed-target energy
- $\mathcal{L}$ = 634 μb^{-1} (2.3% uncertainty)
- $\langle \mu \rangle \simeq 0.025$, 246 million events, 5.11 billion selected tracks



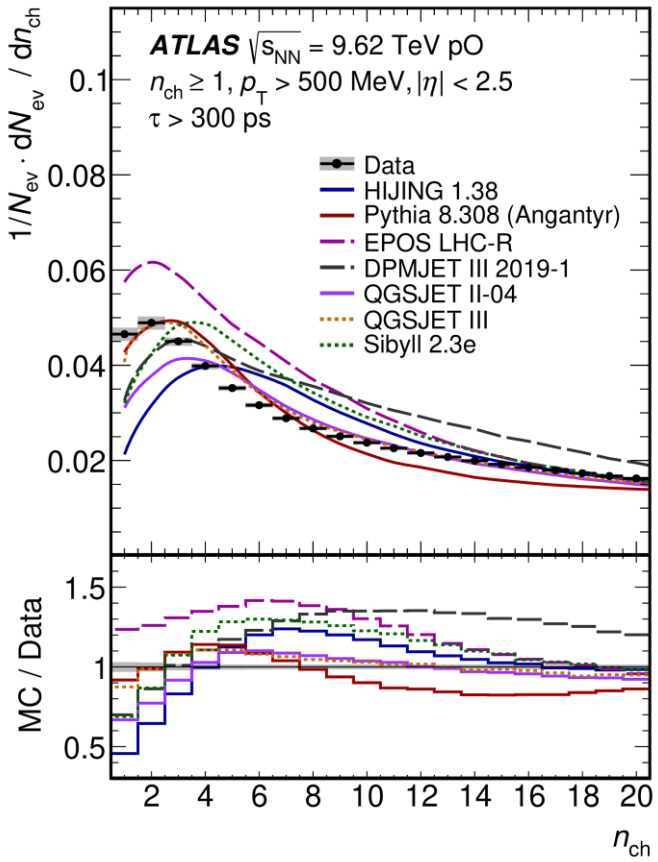
CTU CZECH TECHNICAL UNIVERSITY IN PRAGUE

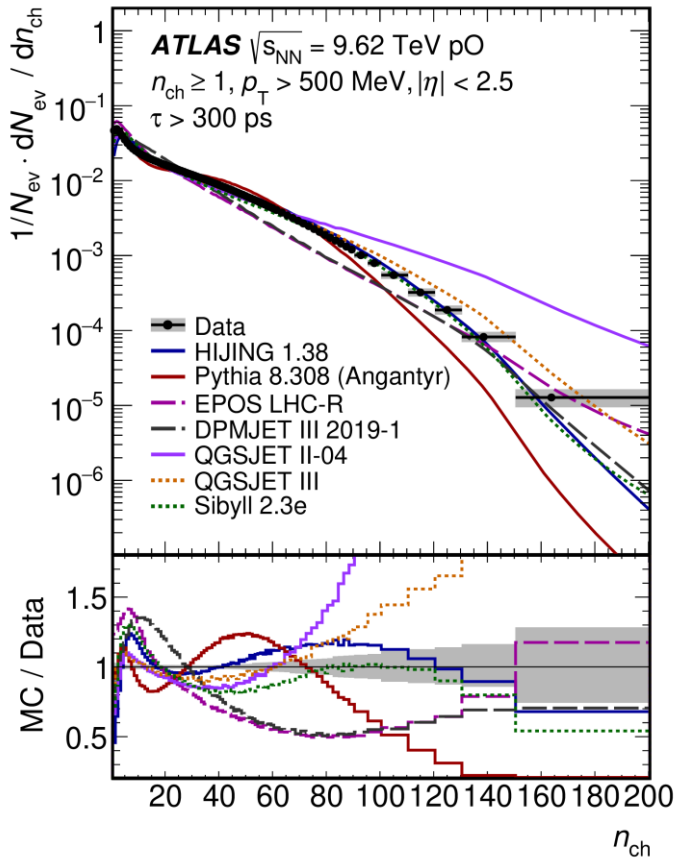
Charged particle multiplicity in pO collisions

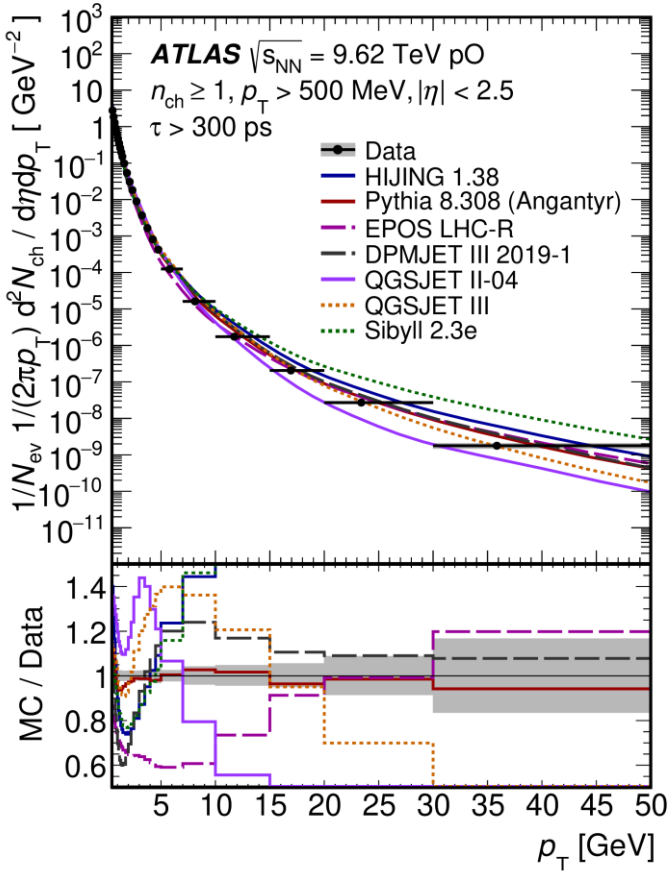
- Charged particle track multiplicity and properties
- tracks with p_T>500MeV and |η|<2.5
- Significant model disagreement



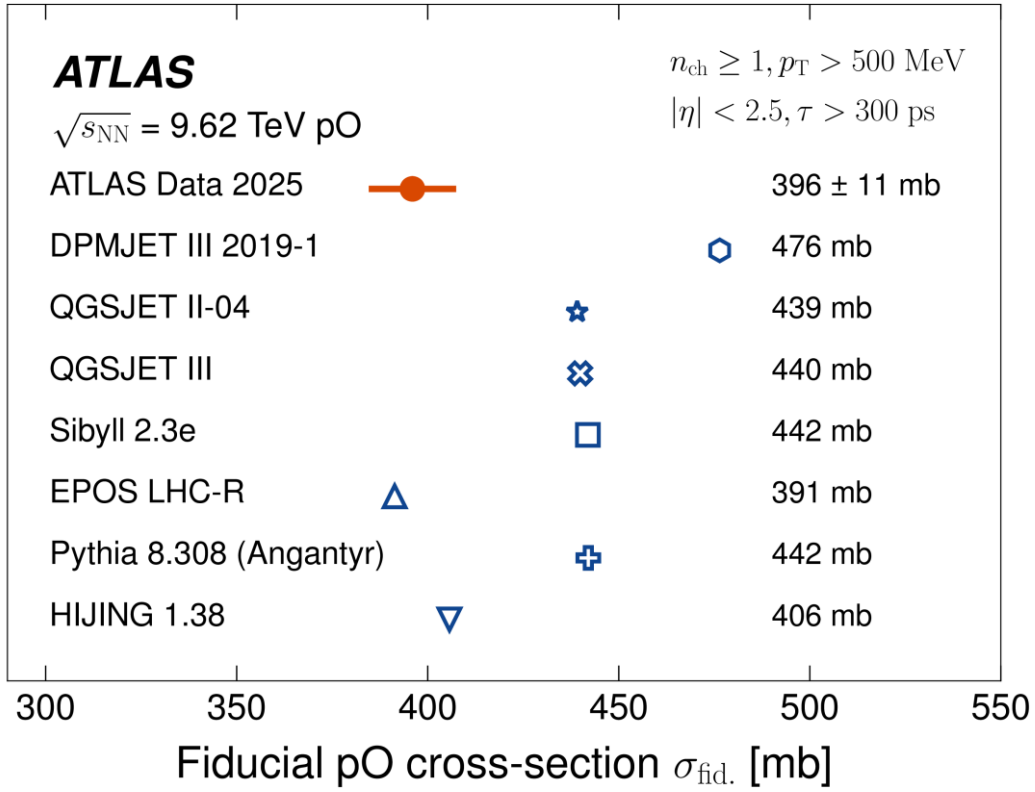
Models disagree by ~40% at low n_{ch}, rising to >100% in the high-n_{ch} tail
Measurement order of magnitude more precise than differences between hadronic-interaction models

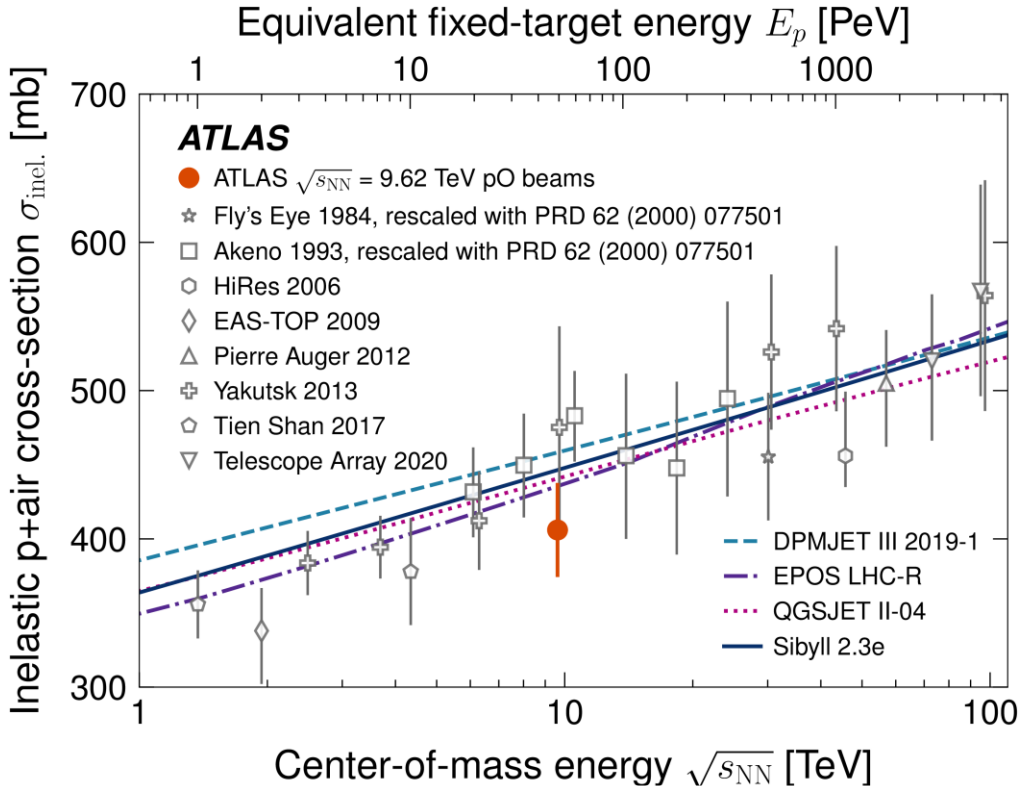






pO cross section measurement





Extrapolated to total inelastic cross-section using mean acceptance from the generators, A = (90 ± 6) %

$$\sigma_{\mathrm{fid.}}^{p\mathrm{O}} = 396 \pm 6\ (\mathrm{exp.}) \pm 9\ (\mathrm{lumi.})\ \mathrm{mb.} \Rightarrow \sigma_{\mathrm{inel.}}^{p\mathrm{O}} = 438 \pm 6\ (\mathrm{exp.}) \pm 10\ (\mathrm{lumi.}) \pm 30\ (\mathrm{th.})\ \mathrm{mb.}$$

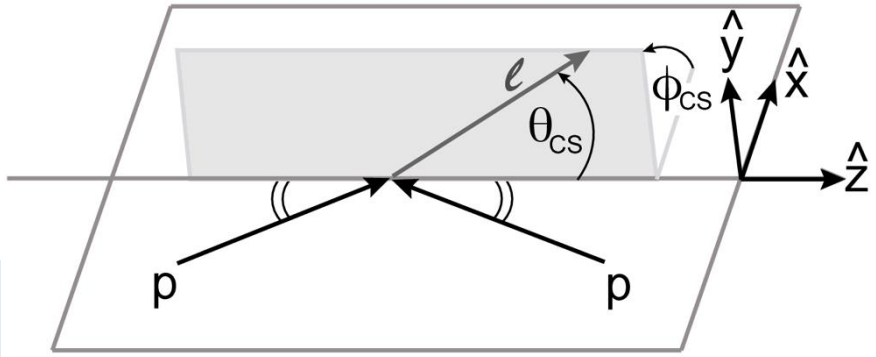
CTU CZECH TECHNICAL UNIVERSITY IN PRAGUE

W-boson angular coefficients

- W->*l*ν production can be factorized to production dynamics and decay kinematic properties of the dilepton system

$$\frac{d\sigma}{d\cos\theta d\phi} \propto (1+\cos^2\theta) + \sum_{i=0}^{7} A_i P_i(\cos\theta,\phi)$$

- For spin-1 boson – 8 coefficients A_i and spherical harmonics P_i
- Angles defined in Collins-Soper frame



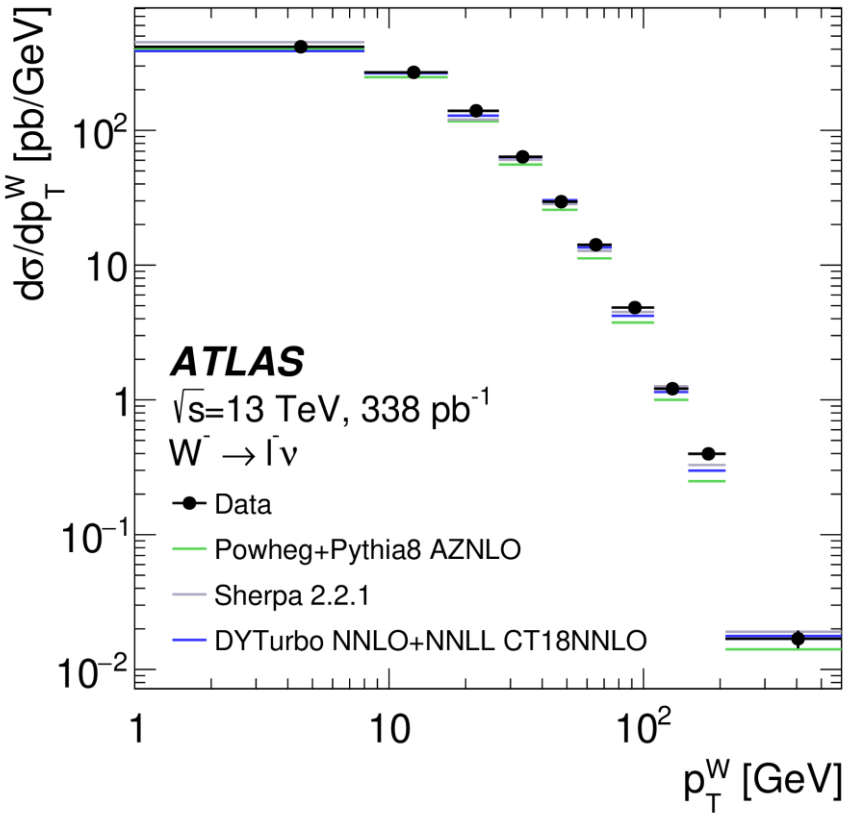
$$\begin{aligned}
P_0(\cos\theta,\phi) &= \frac{1}{2}(1-3\cos^2\theta)\\
P_1(\cos\theta,\phi) &= \sin 2\theta\cos\phi\\
P_2(\cos\theta,\phi) &= \frac{1}{2}\sin^2\theta\cos 2\phi\\
P_3(\cos\theta,\phi) &= \sin\theta\cos\phi\\
P_4(\cos\theta,\phi) &= \cos\theta\\
P_5(\cos\theta,\phi) &= \sin^2\theta\sin 2\phi\\
P_6(\cos\theta,\phi) &= \sin 2\theta\sin\phi\\
P_7(\cos\theta,\phi) &= \sin\theta\sin\phi
\end{aligned}$$

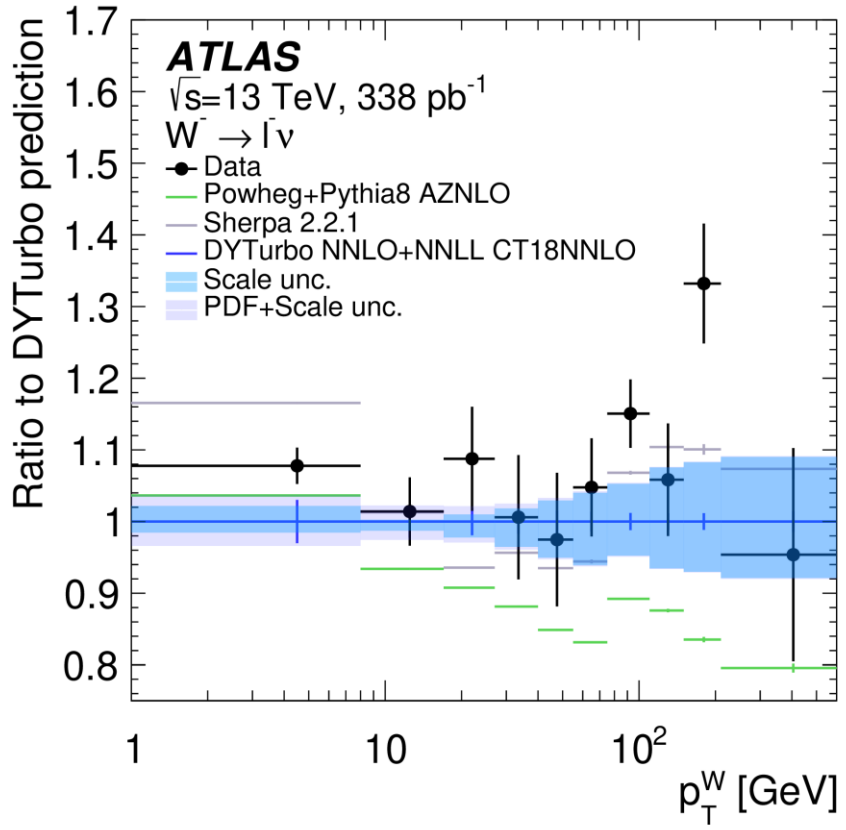
- Coefficients:
  - A_0 – fraction of longitudinally polarized W bosons
  - A_2 – transverse spin anisotropy, Lam-Tung relation $A_0 \sim A_2$ at LO
  - A_4 – induces FB asymmetry ($\cos\theta^*$<,>0)
    - directly related to $\sin^2\theta_{eff}$ => indirect measurement of m_W
  - $A_{1,3,5\text{-}7}$ typically small, BUT non-zero values could be hints of new physics

CTU CZECH TECHNICAL UNIVERSITY IN PRAGUE

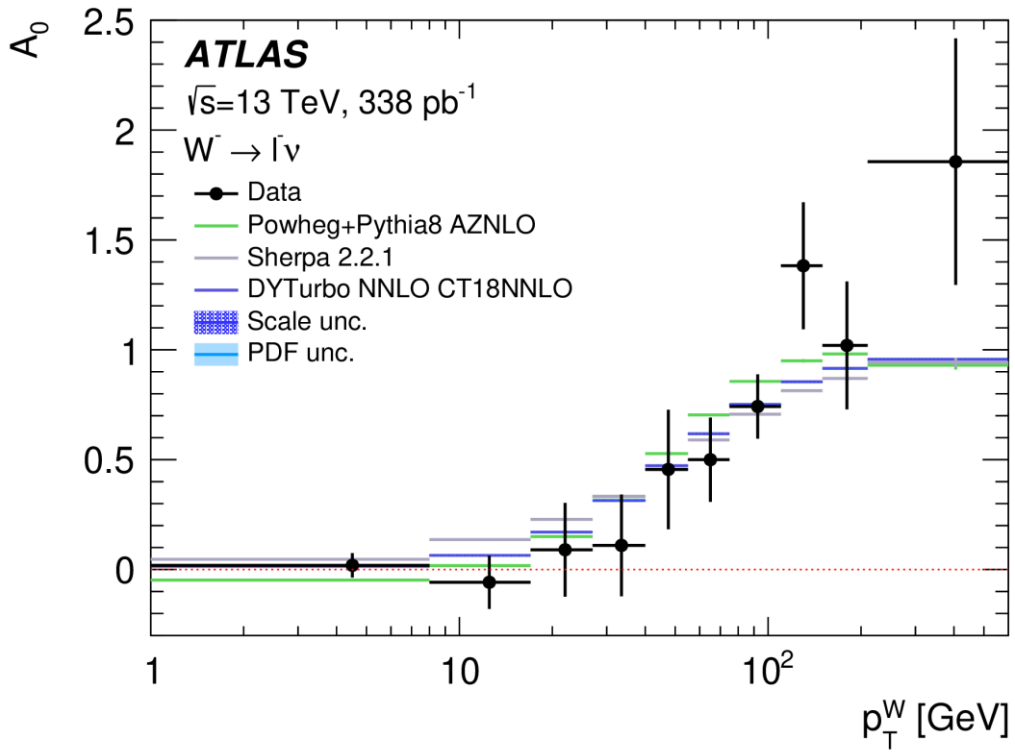
W-boson differential cross-section

- 2017-2018 low pile-up run, $\mathcal{L}$=338pb^{-1}
- W->$l\nu$, with l=e,μ; W^+, W^- separately
- Measurement of differential cross-sections and angular coefficients as a function of p_T^W

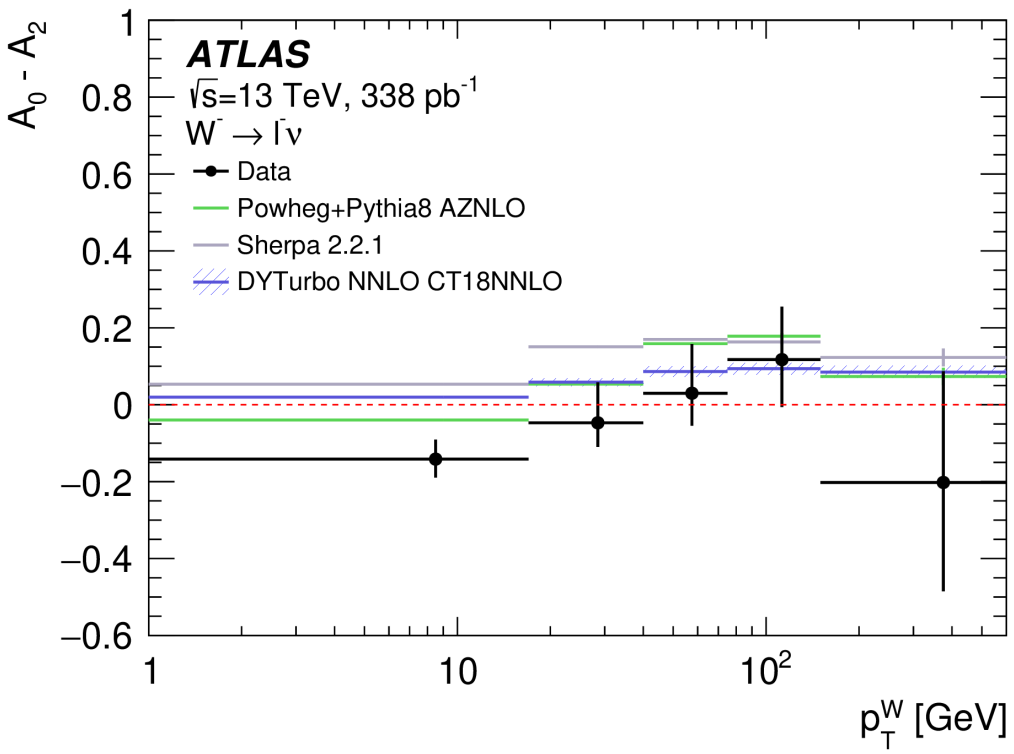




W-boson angular coefficients measurement



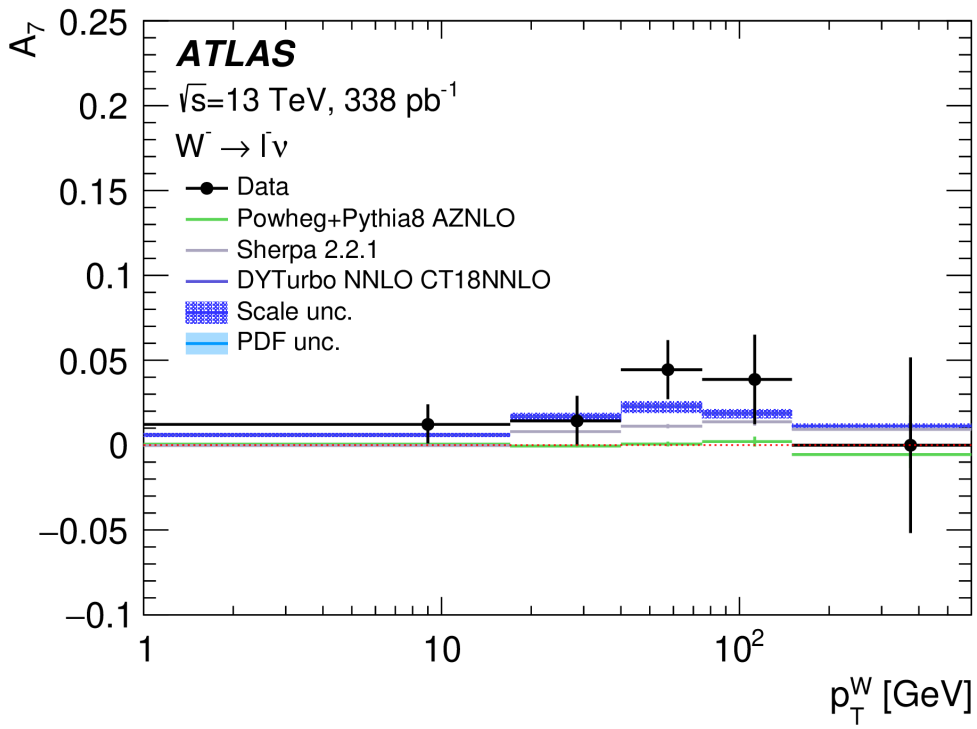
A_0 in a good agreement with theory prediction



No significant deviation from Lam-Tung relation observed

W-boson angular coefficients – a probe for BSM

- $A_{5,6,7}$ are naïve T-odd
- ~0 at LO/NLO
- Could be used to probe dim-8 SMEFT (see for example arXiv:2511.19617)

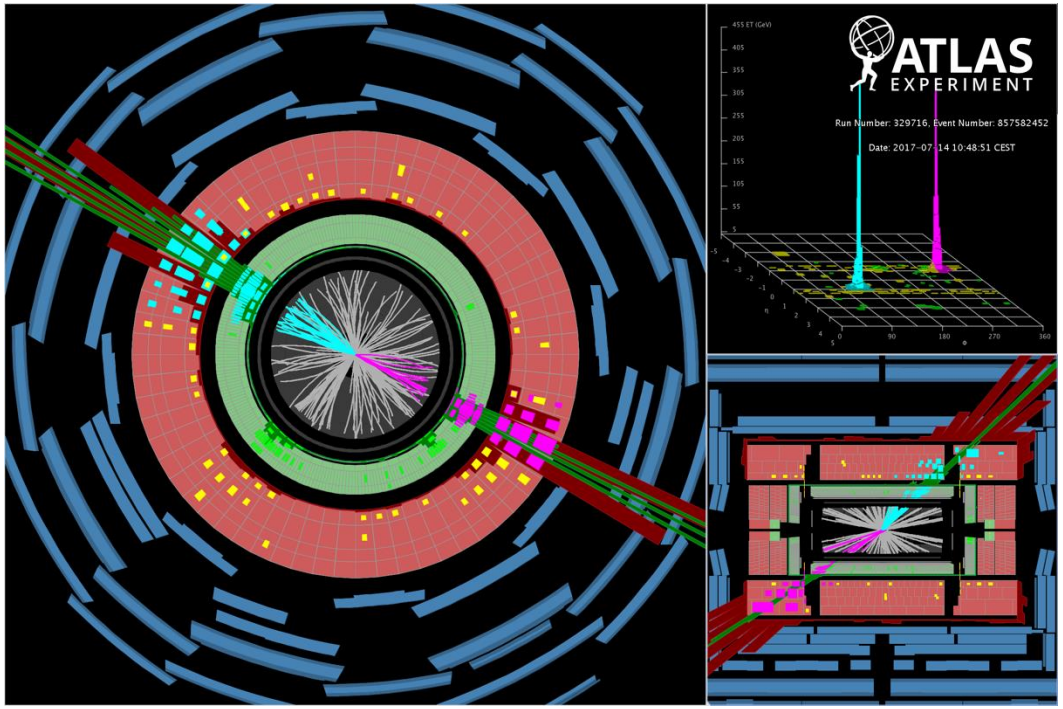


CTU CZECH TECHNICAL UNIVERSITY IN PRAGUE

arXiv:2512.19073

Inclusive dijet cross-section

- $\sqrt{s}$=13TeV, $\mathcal{L}$=140fb^{-1}
- anti-k_T R=0.4
- Fundamental QCD test, PDFs
- NNLO QCD predictions corrected for non-perturbative and electroweak effects



CTU CZECH TECHNICAL UNIVERSITY IN PRAGUE

Dijet system

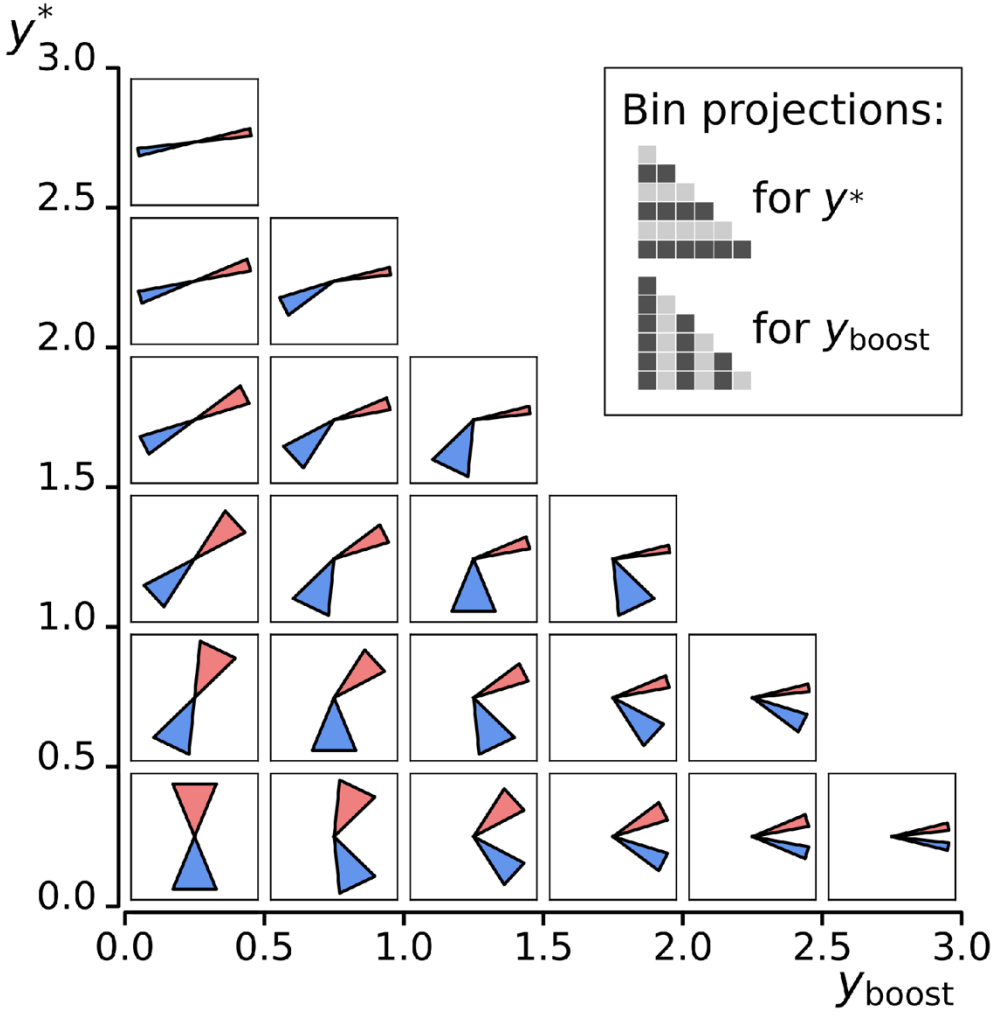
$$m_{jj} = \sqrt{(p_1 + p_2)^2}, \quad y^* = \frac{1}{2}|y_1 - y_2|, \quad y_{boost} = \frac{1}{2}|y_1 + y_2|,$$

$$\frac{d^2\sigma}{dm_{jj}dy^*} = \frac{1}{\mathcal{L}_{int}} \frac{N^{part}}{\Delta m_{jj} \Delta y^*},$$

$$\frac{d^2\sigma}{dm_{jj}dy_{boost}} = \frac{1}{\mathcal{L}_{int}} \frac{N^{part}}{\Delta m_{jj} \Delta y_{boost}}.$$

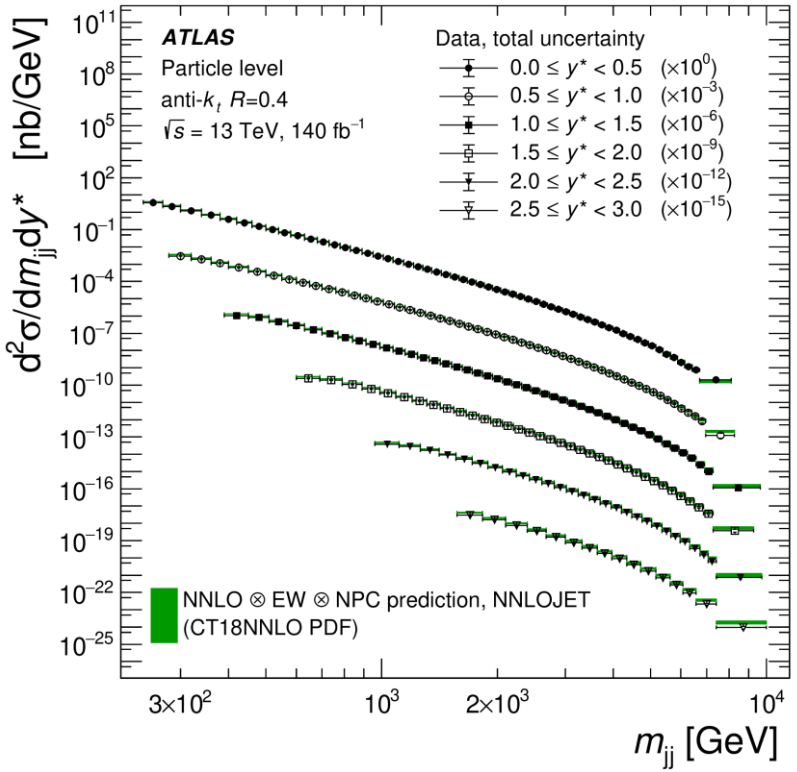
$$\tanh(y^*) = \cos(\theta^*)$$

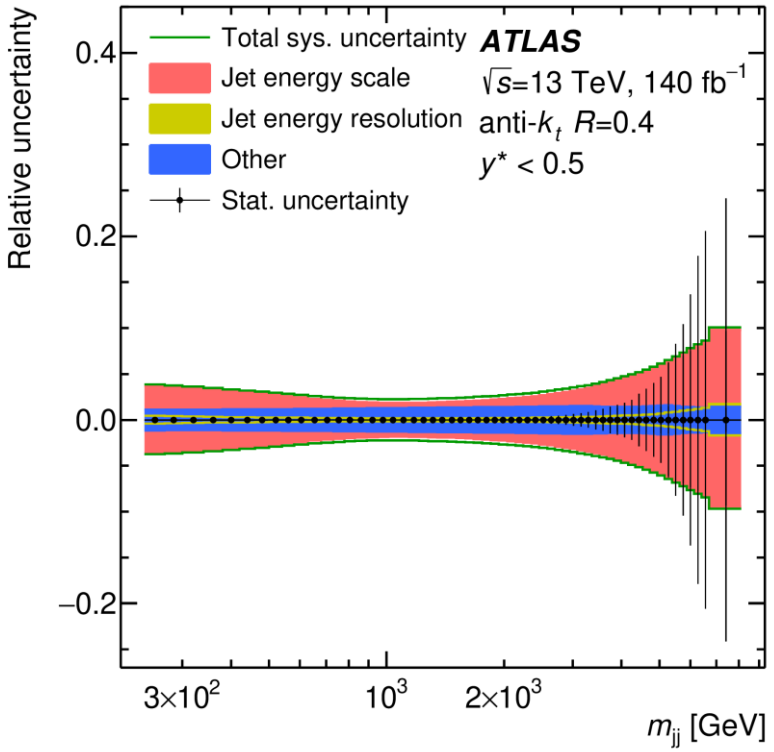
$$x_{1,2} = \frac{m_{jj}}{\sqrt{s}} e^{\pm y_{boost}}$$

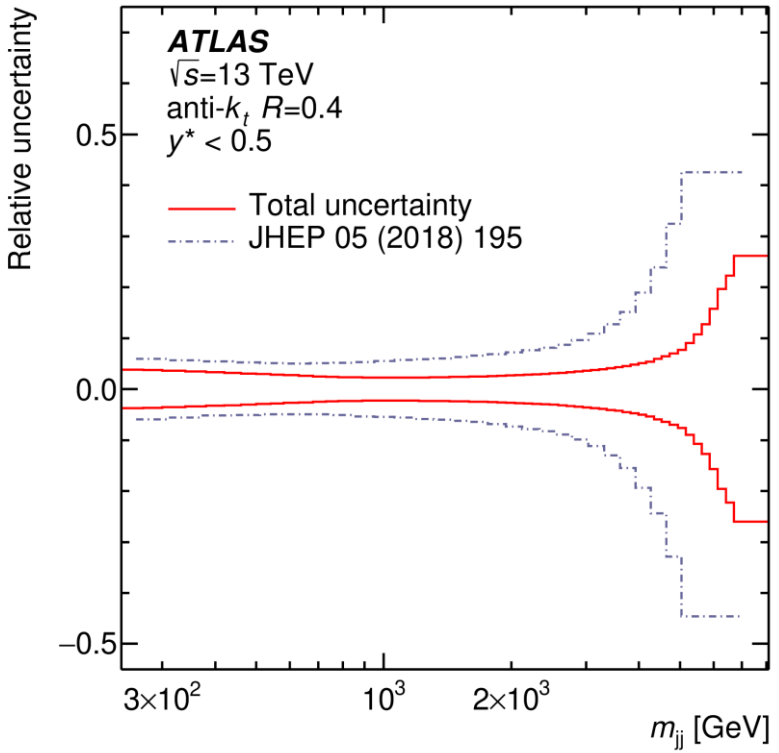


CTU CZECH TECHNICAL UNIVERSITY IN PRAGUE

Dijet cross-section as a function (m_{jj}, y^*)







CTU CZECH TECHNICAL UNIVERSITY IN PRAGUE

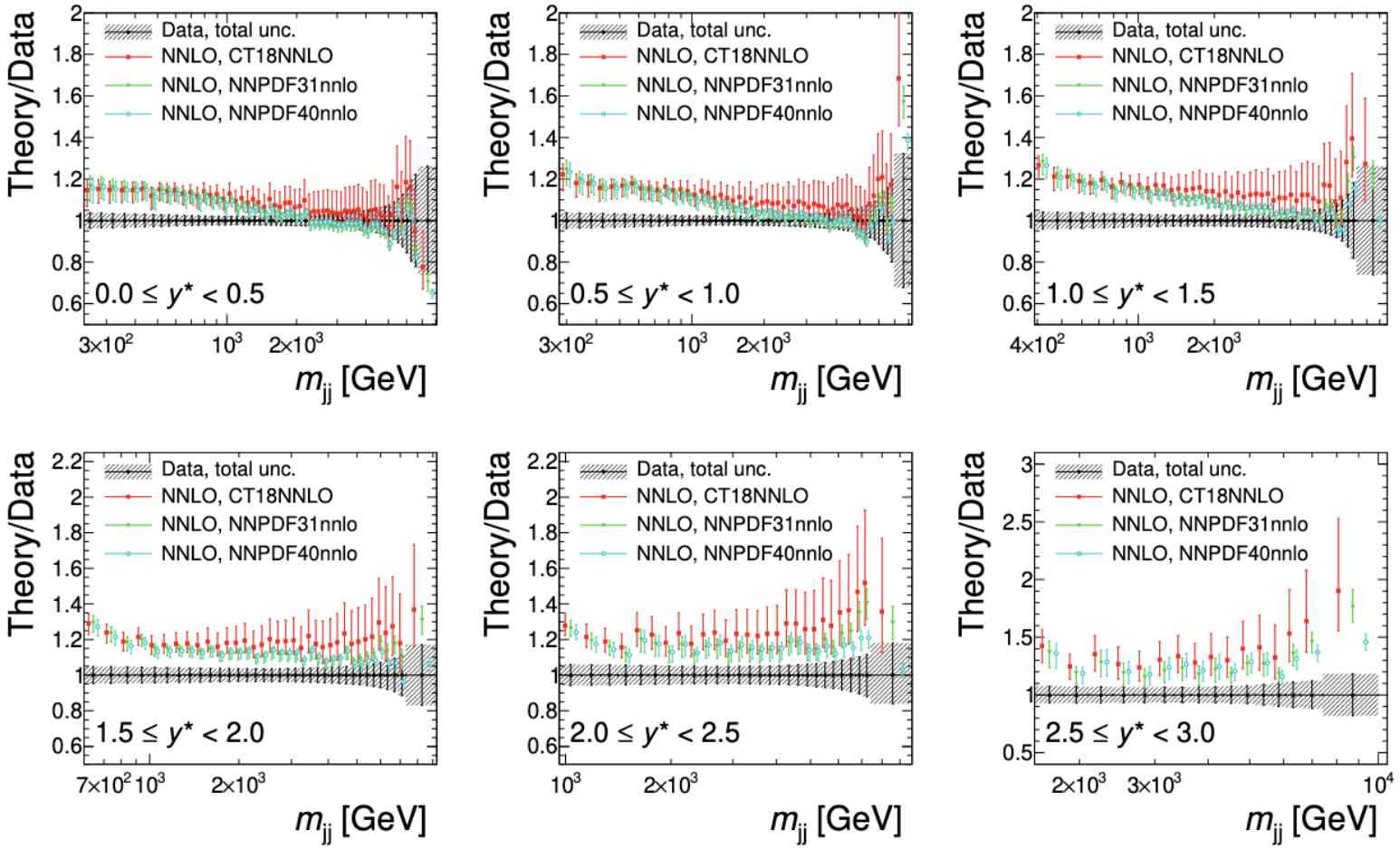
Theory comparison NNLO pQCD

- NNLOJET, full colour NNLO pQCD
- Corrected for NPC, EW effects
- CT18, NNPDF, MSHT20, ATLASpdf21 PDF sets

- Quantitative assessment (χ^2 test)

	χ^2/ndf		
	CT18NNLO	NNPDF3.1NNLO	NNPDF4.0NNLO
$y^* < 0.5$	58/58	68/58	59/58
$0.5 \le y^* < 1.0$	62/54	70/54	63/54
$1.0 \le y^* < 1.5$	56/45	67/45	63/45
$1.5 \le y^* < 2.0$	51/36	59/36	57/36
$2.0 \le y^* < 2.5$	30/28	41/28	36/28
$2.5 \le y^* < 3.0$	17/16	21/16	17/16
$0.0 \le y^* < 3.0$	329/237	343/237	342/237

	MSHT2020NNLO	ATLASPDF21T3
$y^* < 0.5$	61/58	58/58
$0.5 \le y^* < 1.0$	67/54	59/54
$1.0 \le y^* < 1.5$	65/45	58/45
$1.5 \le y^* < 2.0$	54/36	63/36
$2.0 \le y^* < 2.5$	34/28	39/28
$2.5 \le y^* < 3.0$	21/16	19/16
$0.0 \le y^* < 3.0$	347/237	288/237



ATLAS precision QCD – synergy of scales

- pO charged particle multiplicity – “The Environment”
  - hadronic interaction model tuning
- W angular coefficients – “The Dynamics”
  - first simultaneous measurement of all 8 coefficients
- Dijet invariant mass – ”The Ingredients”
  - probing the high-energy frontier to constrain PDFs at high x

CTU CZECH TECHNICAL UNIVERSITY IN PRAGUE

Thank you for attention

Zdenek Hubacek
zdenek.hubacek@cvut.cz

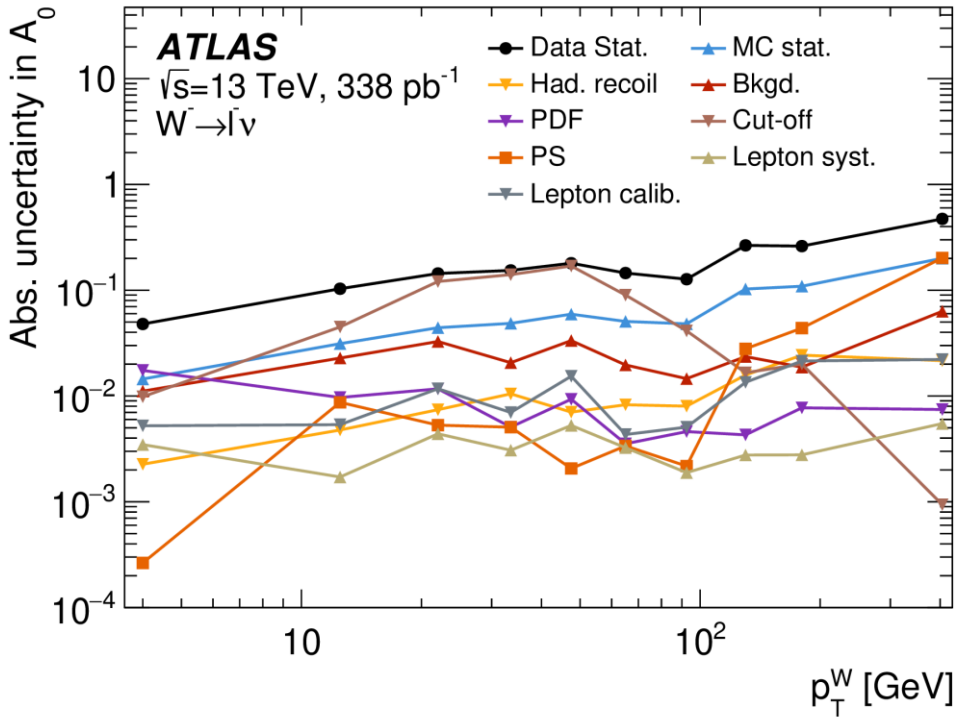
Fundamental constituents of matter through frontier technologies (FORTE)
CZ.02.01.01/00/22_008/0004632

Co-funded by the European Union

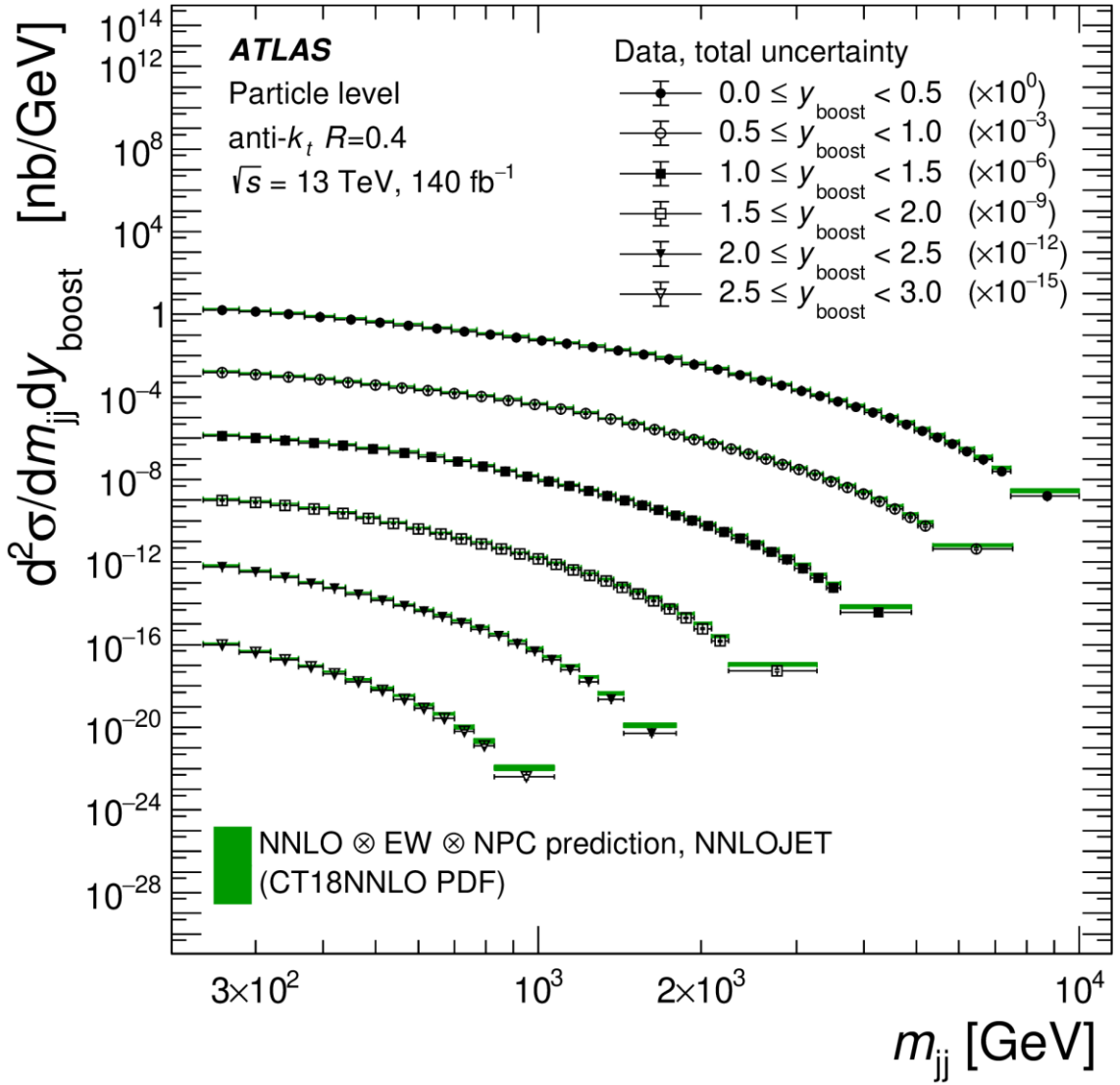
Ministry of Education, Youth and Sports of the Czech Republic

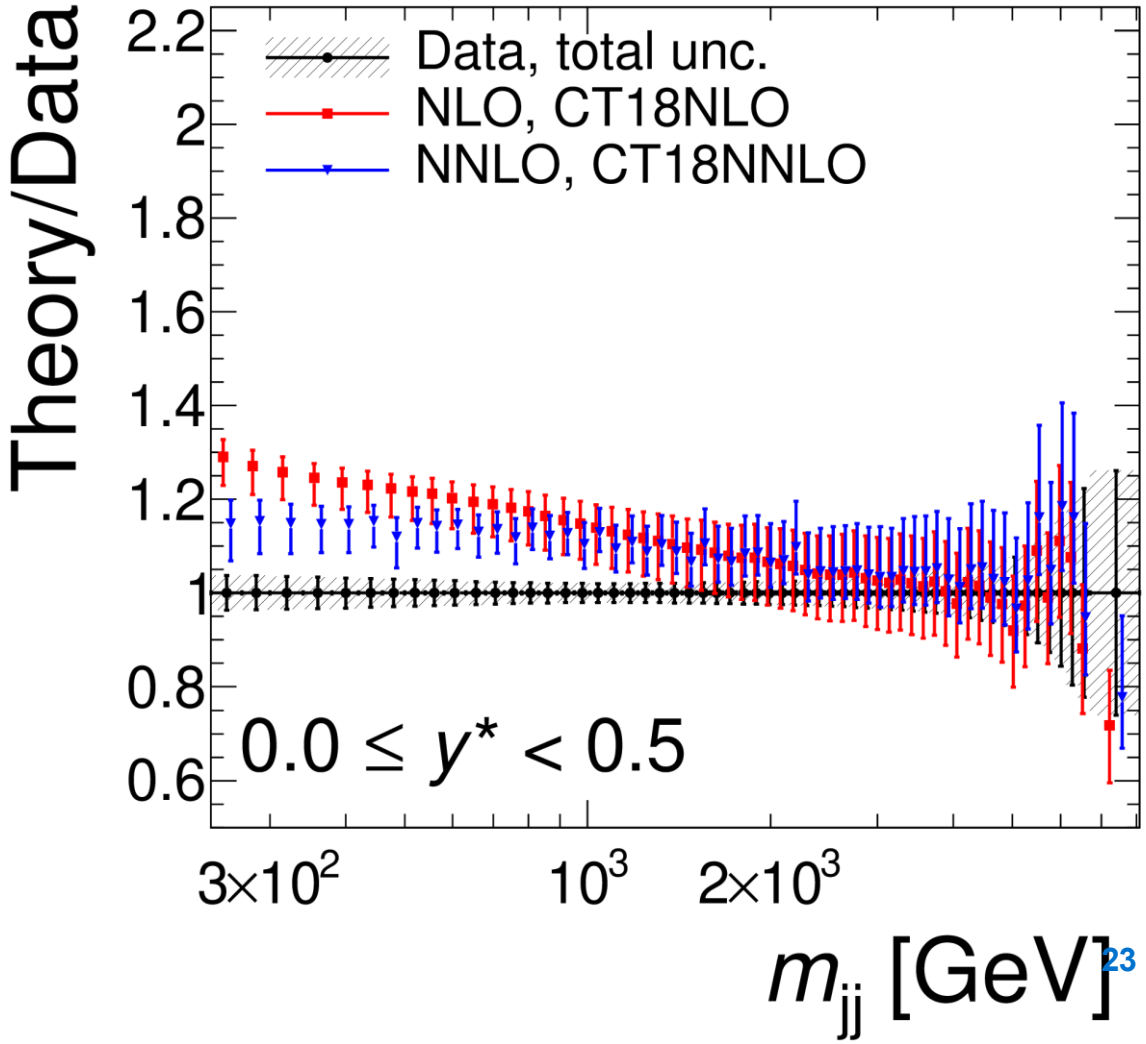
Backup

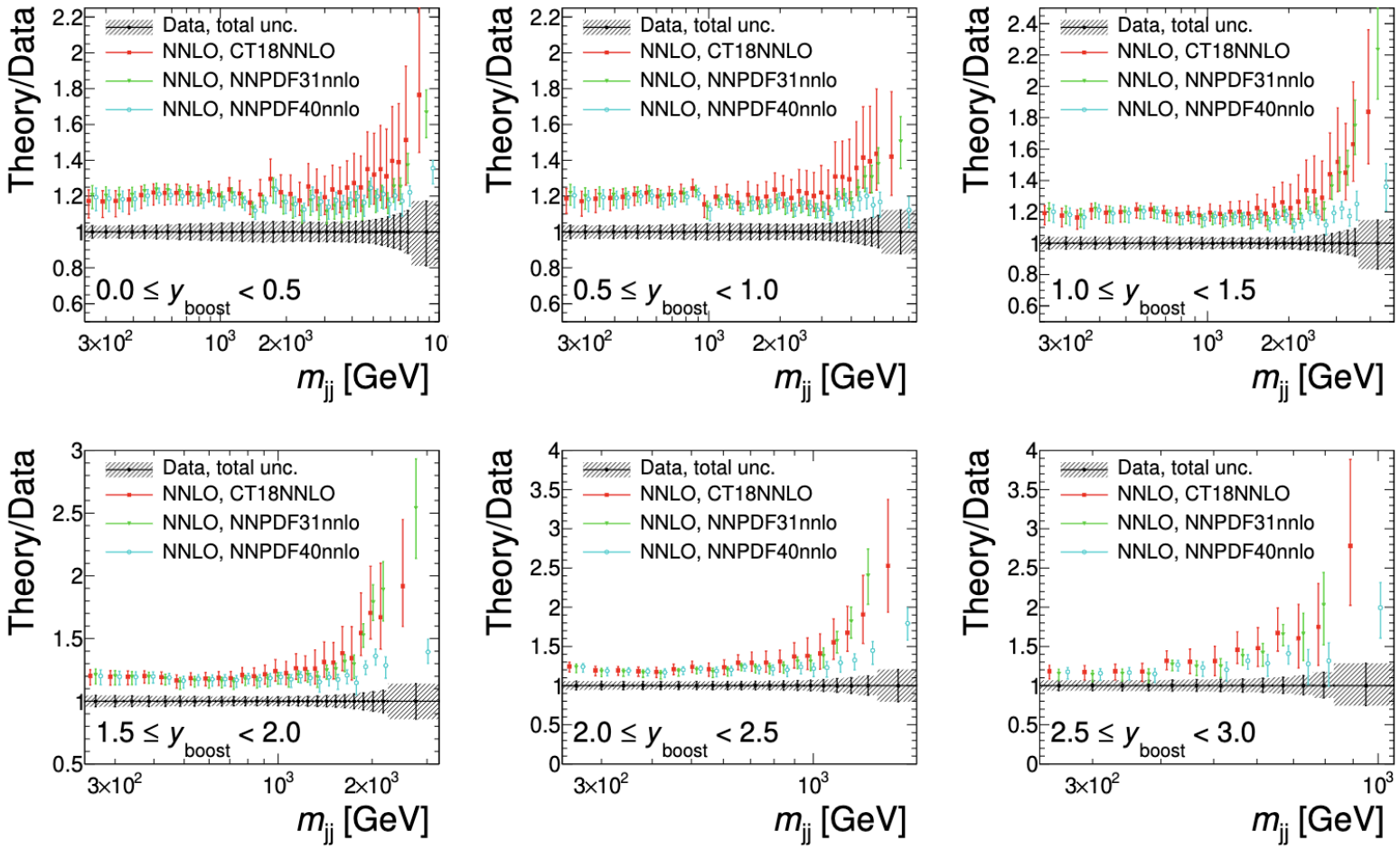
W angular coefficients systematics



Dijet (m_{jj}, y_{boost}) + QCD NLO







ATLAS Particle level

$\sqrt{s}$ = 13 TeV, 140 fb^{-1}
anti-k_t R=0.4

$\mu_R = \mu_F = m_{jj}$
$\alpha_s(m_Z)$ = 0.118

pQCD ⊗ EW ⊗ NPC

Dijet (m_{jj},y_{boost}), χ^2 test values

	χ^2/ndf				
	CT18NNLO	NNPDF3.1NNLO	NNPDF4.0NNLO	MSHT2020NNLO	ATLASPDF21T3
$y_{boost} < 0.5$	33/36	48/36	37/36	43/36	44/36
$0.5 \leq y_{boost} < 1.0$	51/34	55/34	53/34	55/34	54/34
$1.0 \leq y_{boost} < 1.5$	41/31	40/31	39/31	47/31	47/31
$1.5 \leq y_{boost} < 2.0$	26/26	27/26	26/26	31/26	35/26
$2.0 \leq y_{boost} < 2.5$	24/20	24/20	21/20	28/20	31/20
$2.5 \leq y_{boost} < 3.0$	15/13	15/13	14/13	20/13	16/13
$0.0 \leq y_{boost} < 3.0$	183/160	178/160	185/160	195/160	166/160

CTU CZECH TECHNICAL UNIVERSITY IN PRAGUE