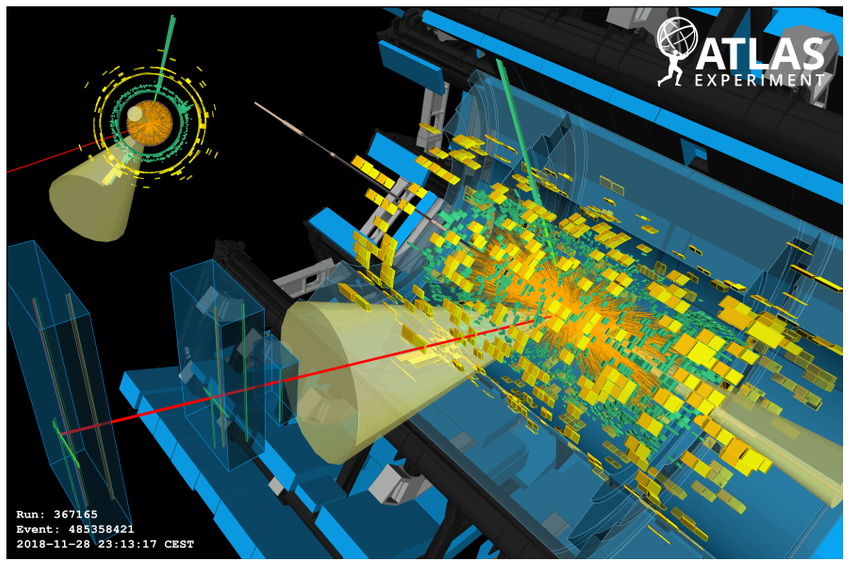
Heavy-ion physics highlights from ATLAS

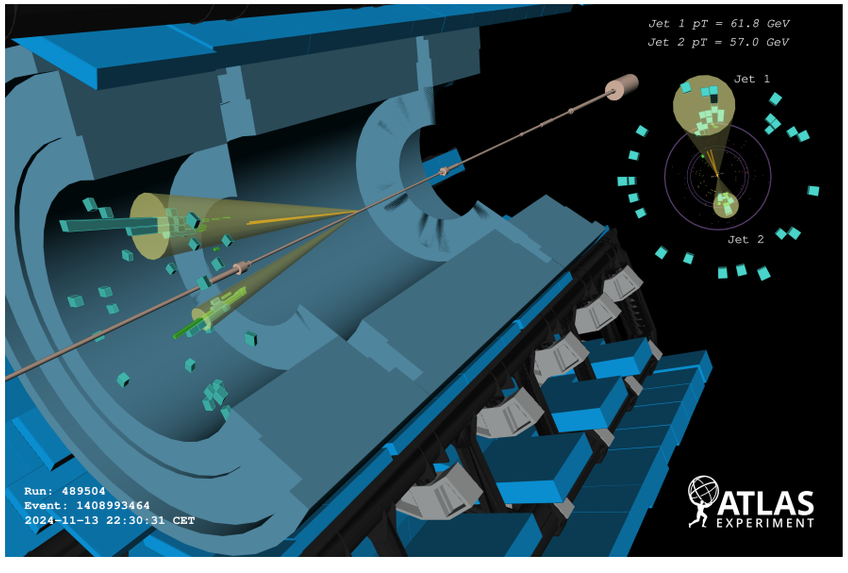
Iwona Grabowska-Bołd for the ATLAS Collaboration
(AGH University of Kraków)
XXXI Cracow Epiphany Conference on the recent LHC Results
Kraków, January 14th, 2025

INTRODUCTION

ttbar event candidate



dijet event candidate

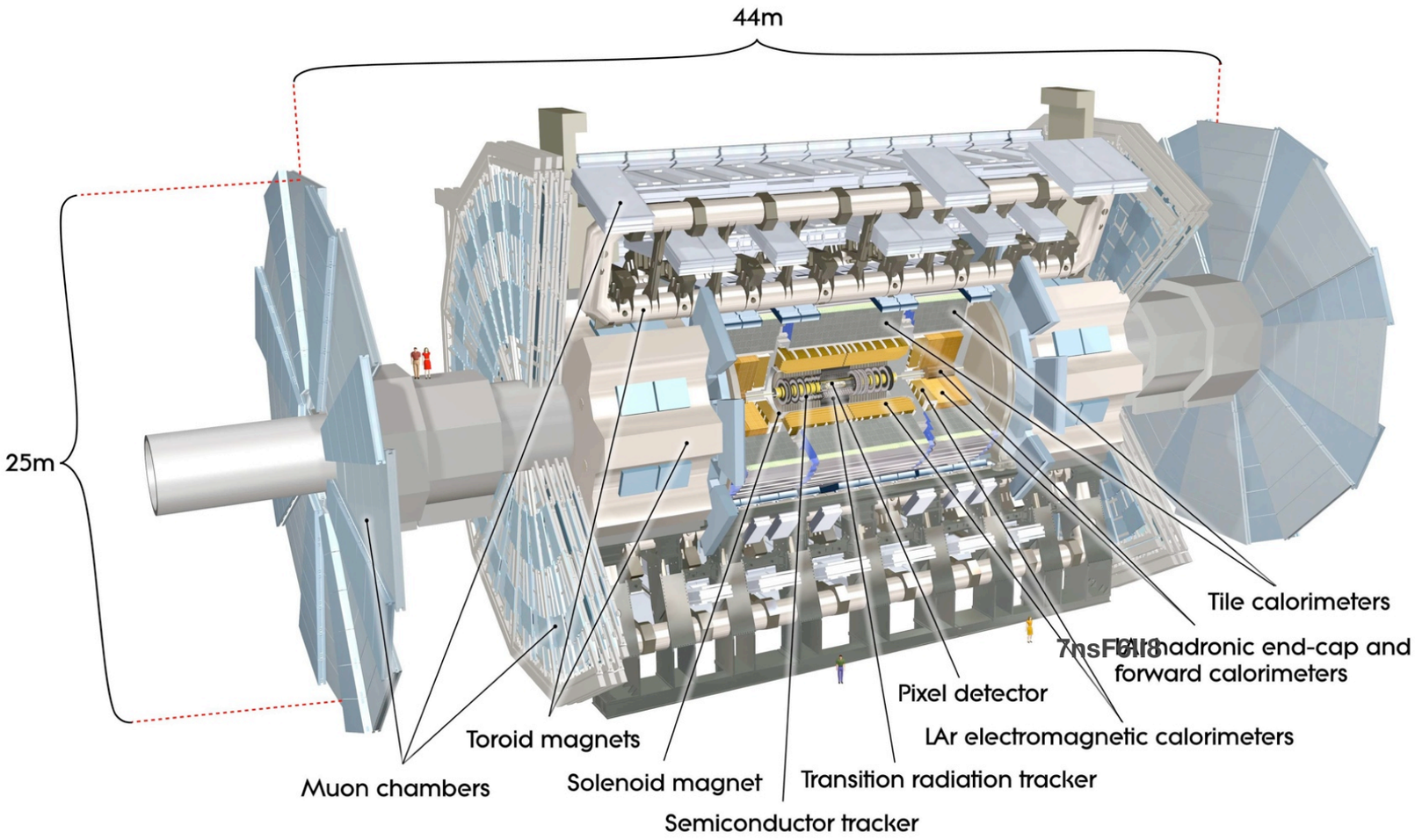


New final results released in 2024

- Investigation of properties of **Quark-Gluon Plasma** (QGP) produced in heavy-ion collisions (HIC)
  - Jet-radius dependence of dijet asymmetry
  - High-p_T flow
  - p_T fluctuations in Pb+Pb and Xe+Xe
  - Search for diffusion wake
  - Observation of top-quarks in p+Pb and Pb+Pb

- Insight into physics of **ultra-peripheral collisions** (**UPC**)
  - Photonuclear dijet production
  - Magnetic monopole search

ATLAS DETECTOR



Three main components: inner tracker, electromagnetic (EM) and hadronic (HAD) calorimeters, and muon system

Participation in the **HI program since 2010**

Electrons: inner tracker, EM calo

$$p_{\mathrm{T}}^{e} > 15\ (2)\ \mathrm{GeV} \text{ for } Z, W^{\pm}, t\bar{t} \text{ (UPC)}$$

Muons: inner tracker, muon system

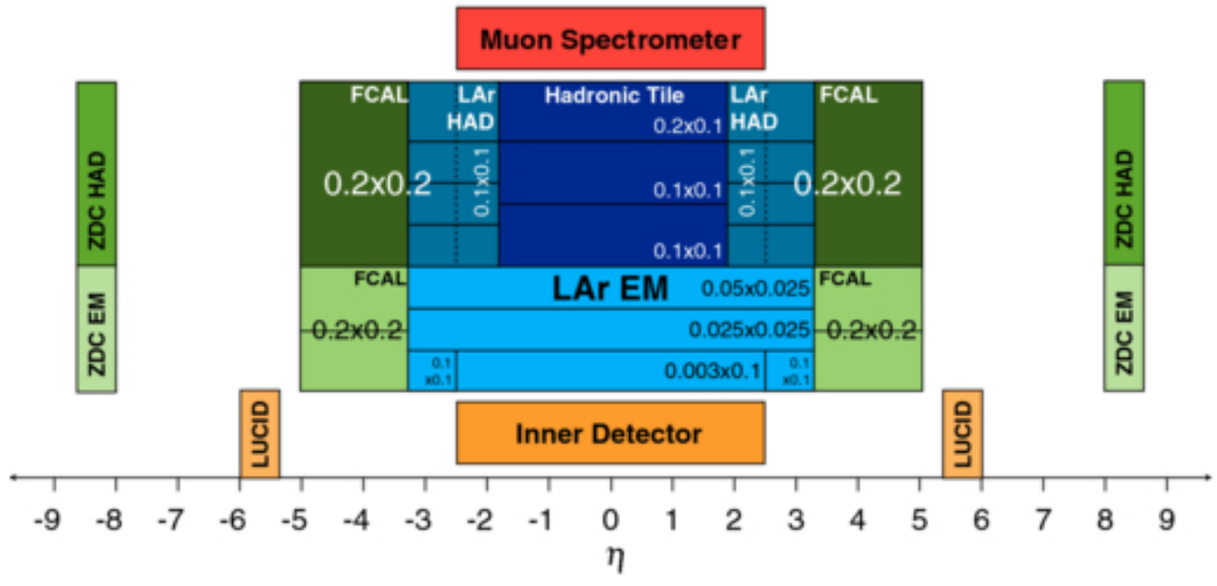
$$p_{\mathrm{T}}^{\mu} > 15\ (4)\ \mathrm{GeV} \text{ for } Z, W^{\pm}, t\bar{t} \text{ (UPC)}$$

Charged particles: inner tracker

$$p_{\mathrm{T}}^{\mathrm{ch}} > 500\ (100)\ \mathrm{MeV} \text{ for hadronic (UPC)}$$

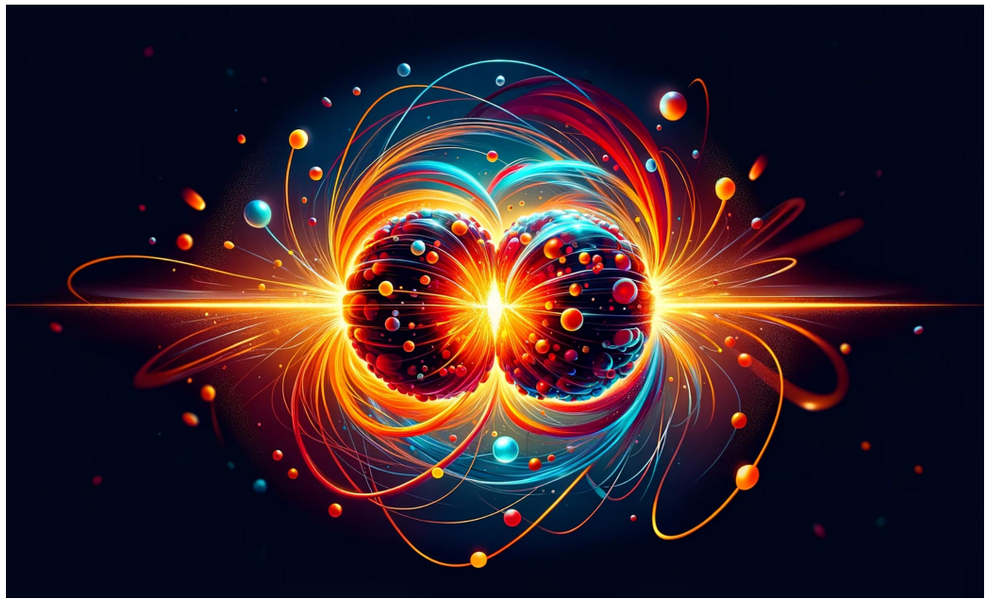
Neutrons: Zero Degree Calorimeter

$$|\eta| > 8$$



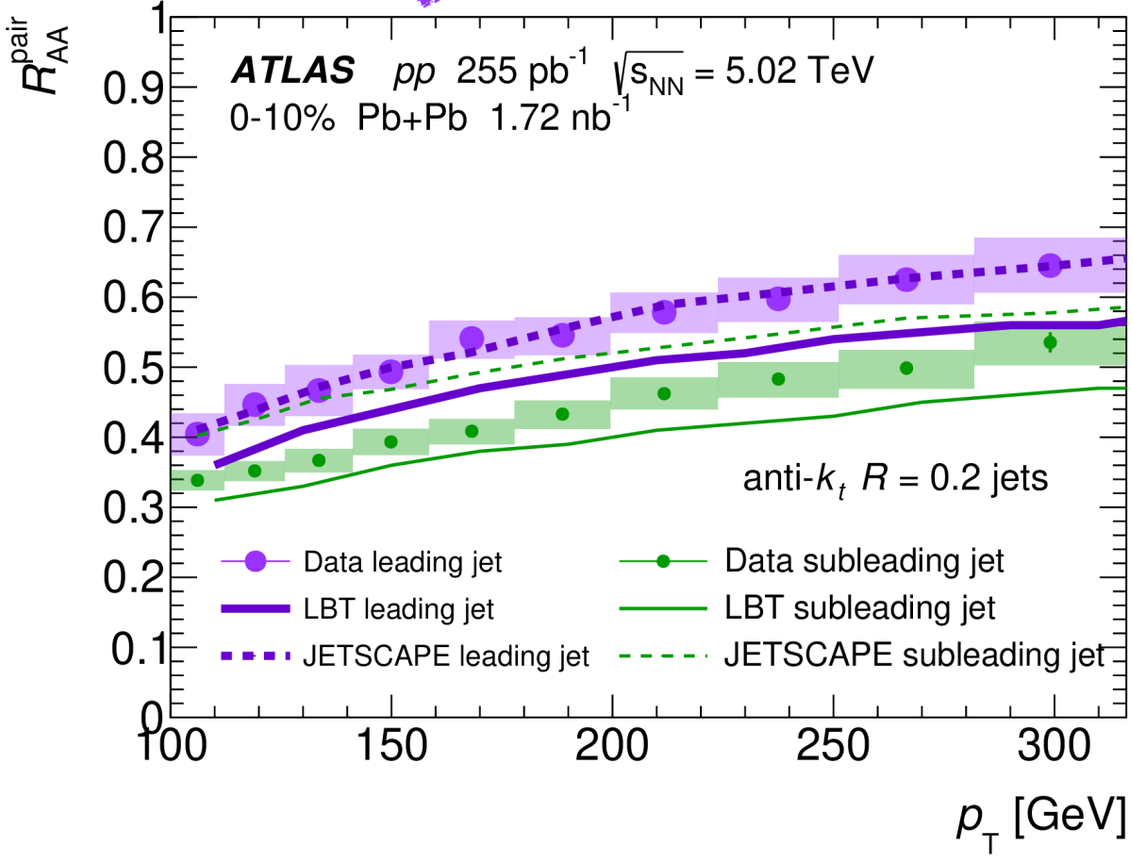
$$|\eta^{\ell,\mathrm{ch}}| \lesssim 2.5$$

INSIGHT INTO THE QGP

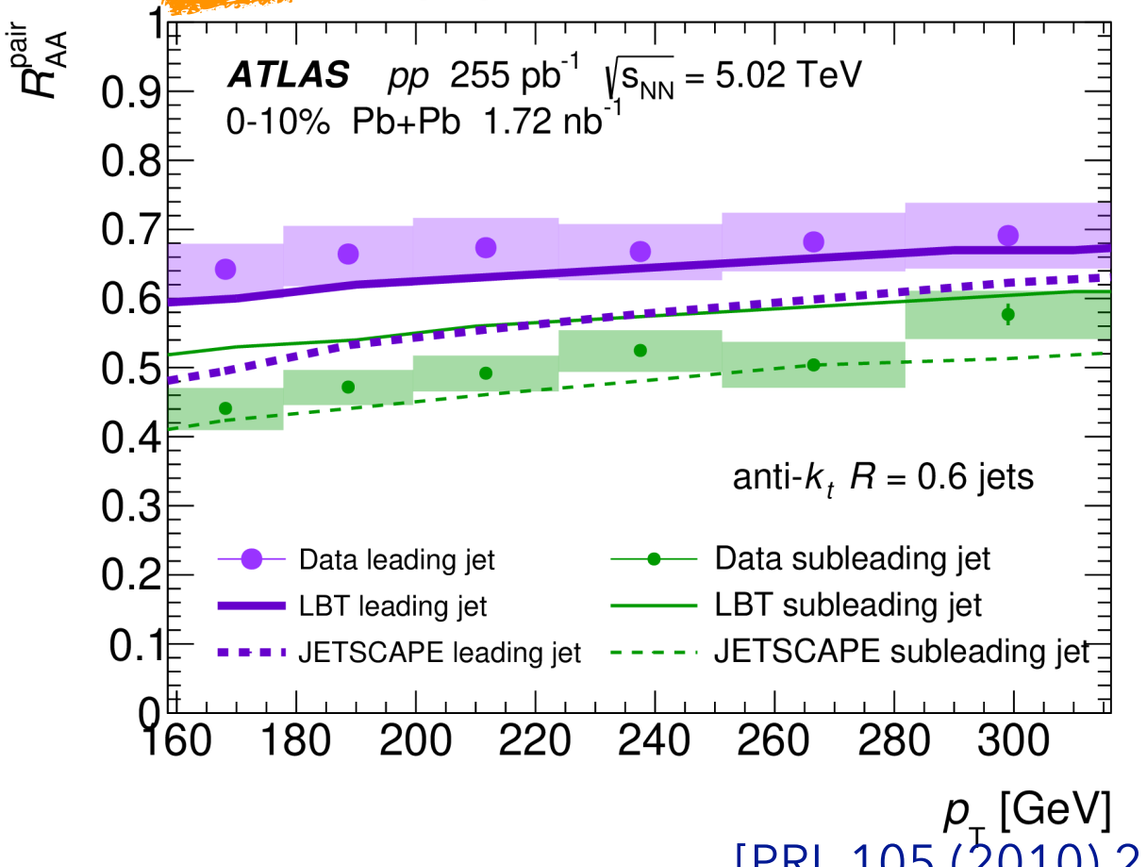


DIJET ASYMMETRY VERSUS JET RADIUS

R=0.2

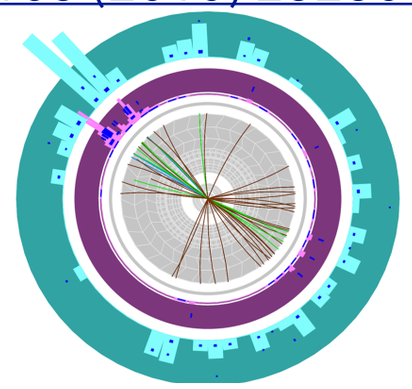


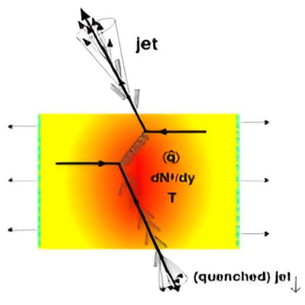
R=0.6 [PRC 110 (2024) 054912]



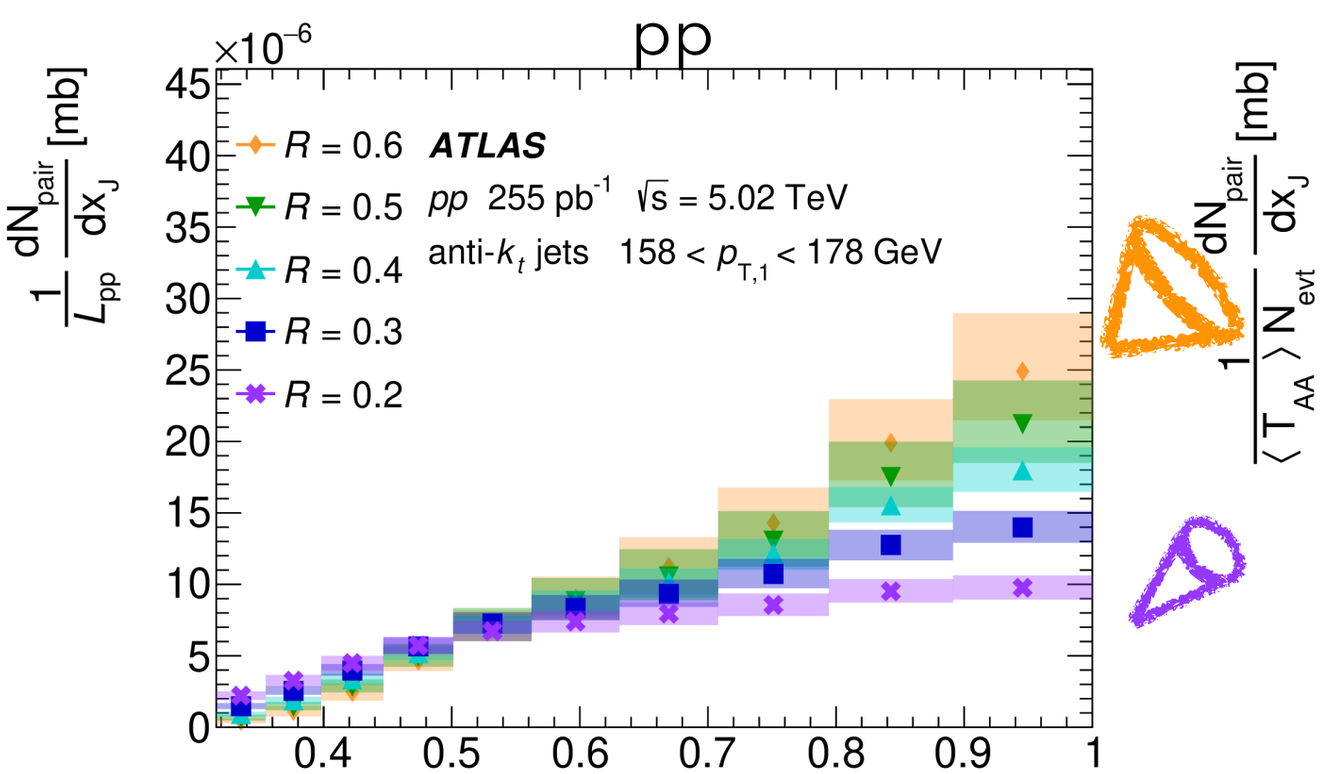
- **Dijet momentum balance** between leading back-to-back jets in Pb+Pb (pp) data at $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV with an int lumi of 1.72 nb^{-1} (255 pb^{-1})
- Jets reconstructed using the anti-kt algorithm with jet radius parameters R= 0.2, 0.3, 0.4, 0.5, 0.6
- In **0-10% centralities**, $R_{\mathrm{AA}}^{\mathrm{pair}}(\mathrm{leading}) > R_{\mathrm{AA}}^{\mathrm{pair}}(\mathrm{subleading})$ for all p_{T} considered here
- $R_{\mathrm{AA}}^{\mathrm{pair}}$ generally increases with increasing p_{T}, except $R_{\mathrm{AA}}^{\mathrm{pair}}$ for the leading in R=0.6, which is flatter
  - Models **LBT** and **JETSCAPE** reproduce the trend with varying degrees of success in describing $R_{\mathrm{AA}}^{\mathrm{pair}}$ values

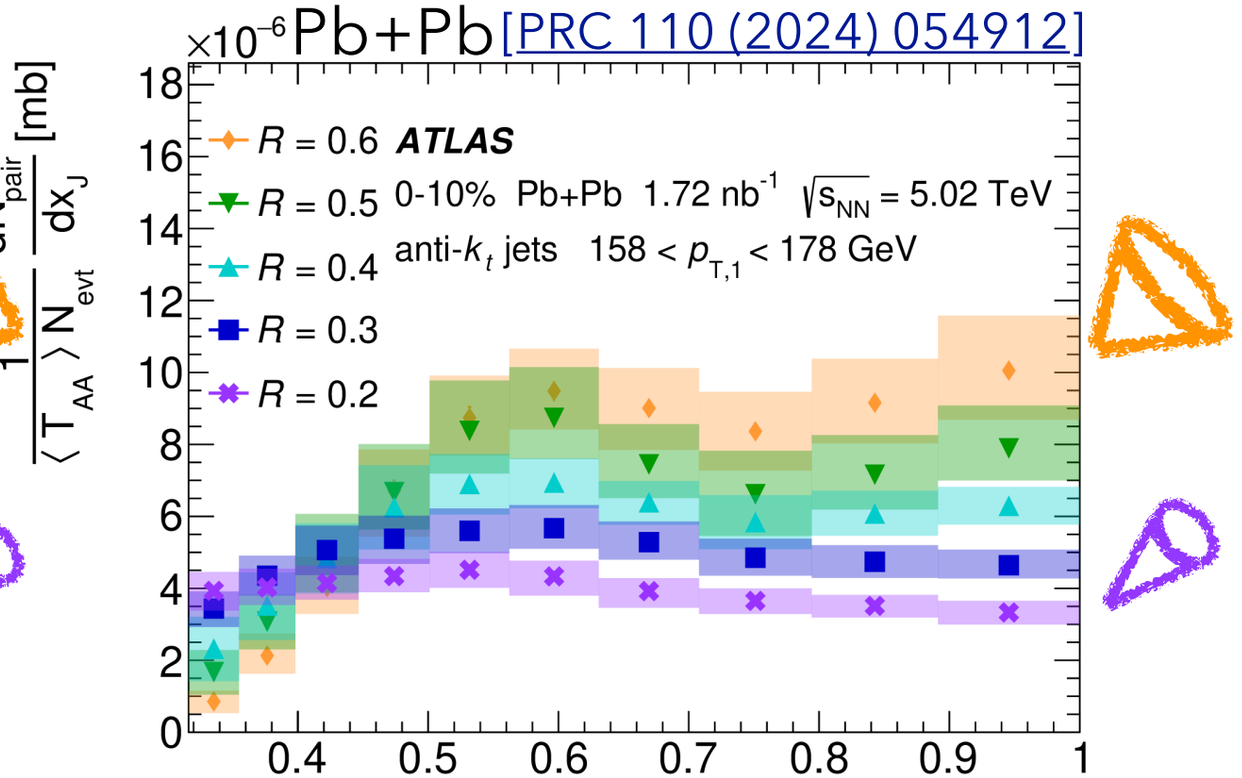
[PRL 105 (2010) 252303]





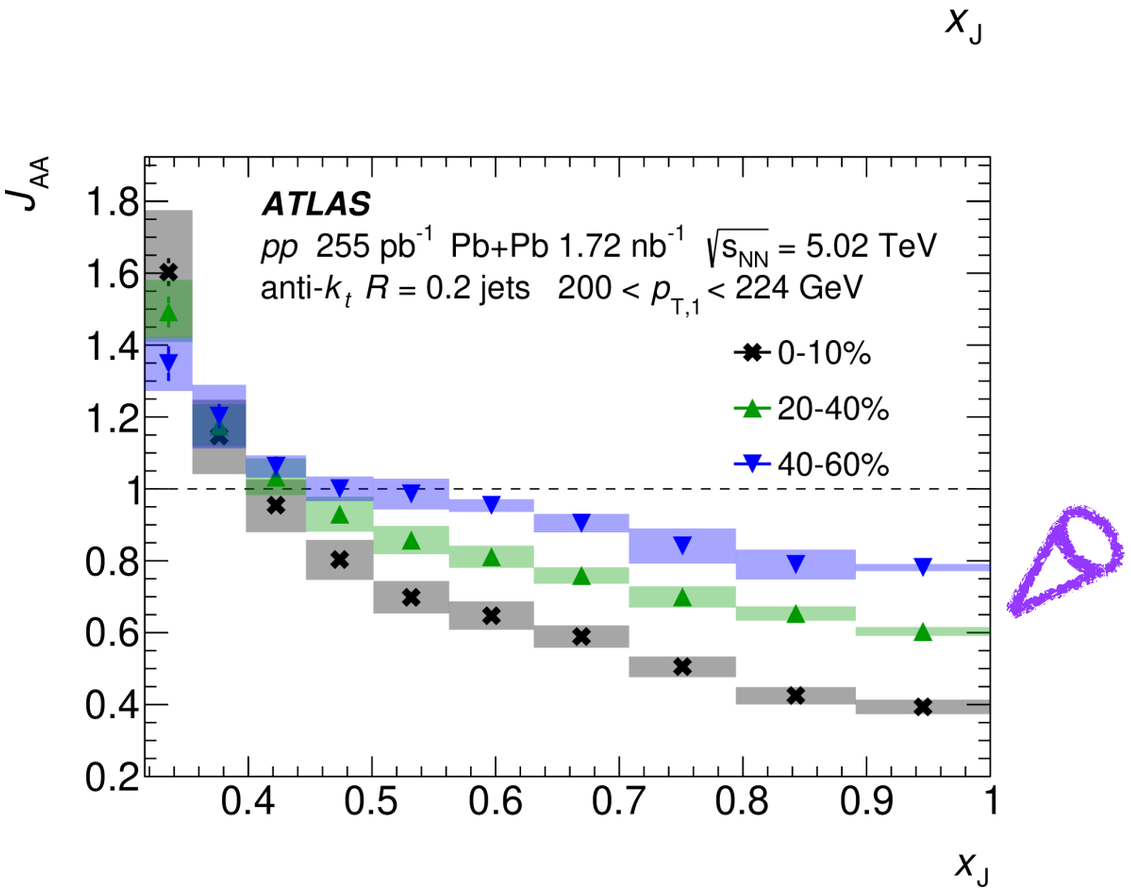
DIJET ASYMMETRY VERSUS JET RADIUS





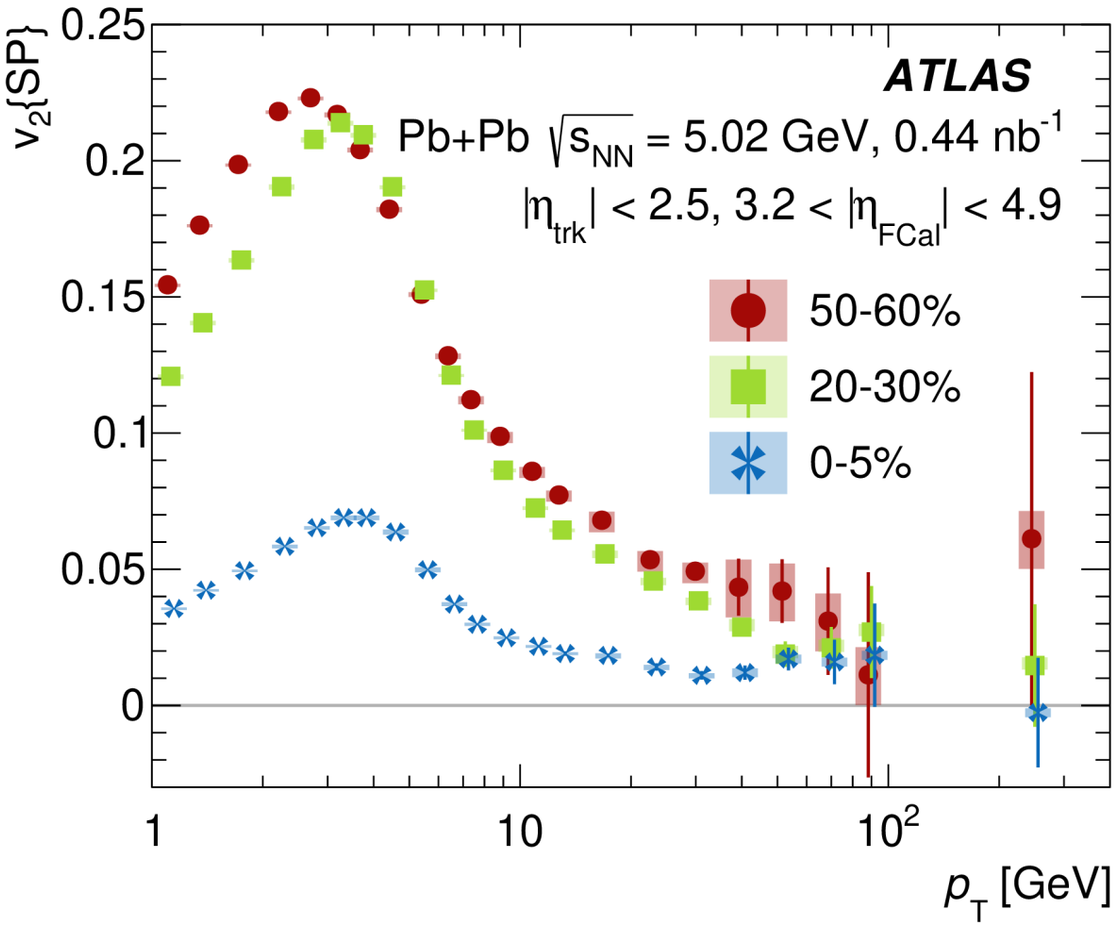
$$x_J = \frac{p_{T,2}}{p_{T,1}} \qquad J_{AA} = \frac{\text{Yields in Pb + Pb}}{\text{Yields in } pp}$$

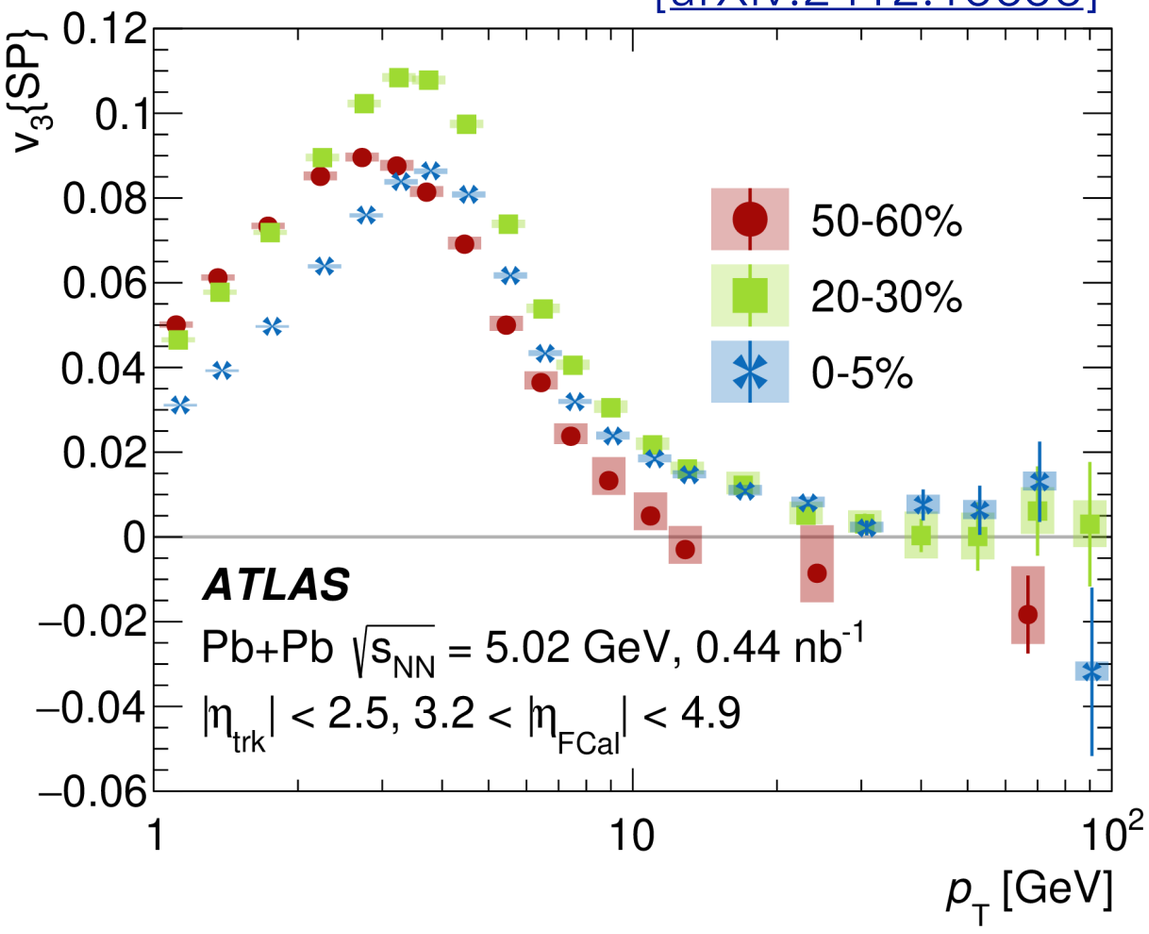
- x_J distributions in Pb+Pb collisions are **broadened** compared to those in pp
- **Peak** at intermediate x_J emerges in Pb+Pb in 0-10% but becomes weaker as the jet radius decreases
- In J_{AA} there is a **suppression** of balanced (high x_J) dijets and an **enhancement** of imbalanced (low x_J) dijets, with the modifications being larger towards more central collisions



HIGH-PT FLOW

[arXiv:2412.15658]

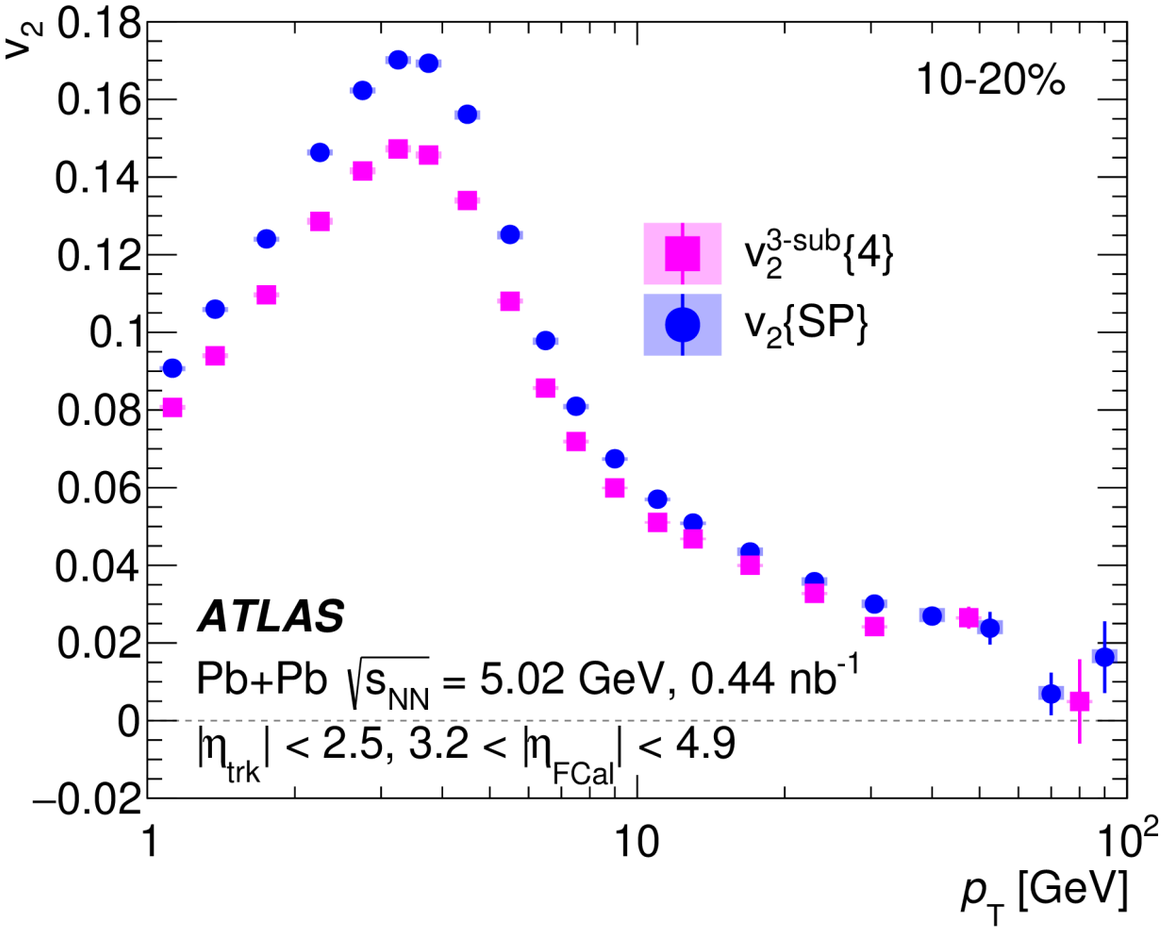


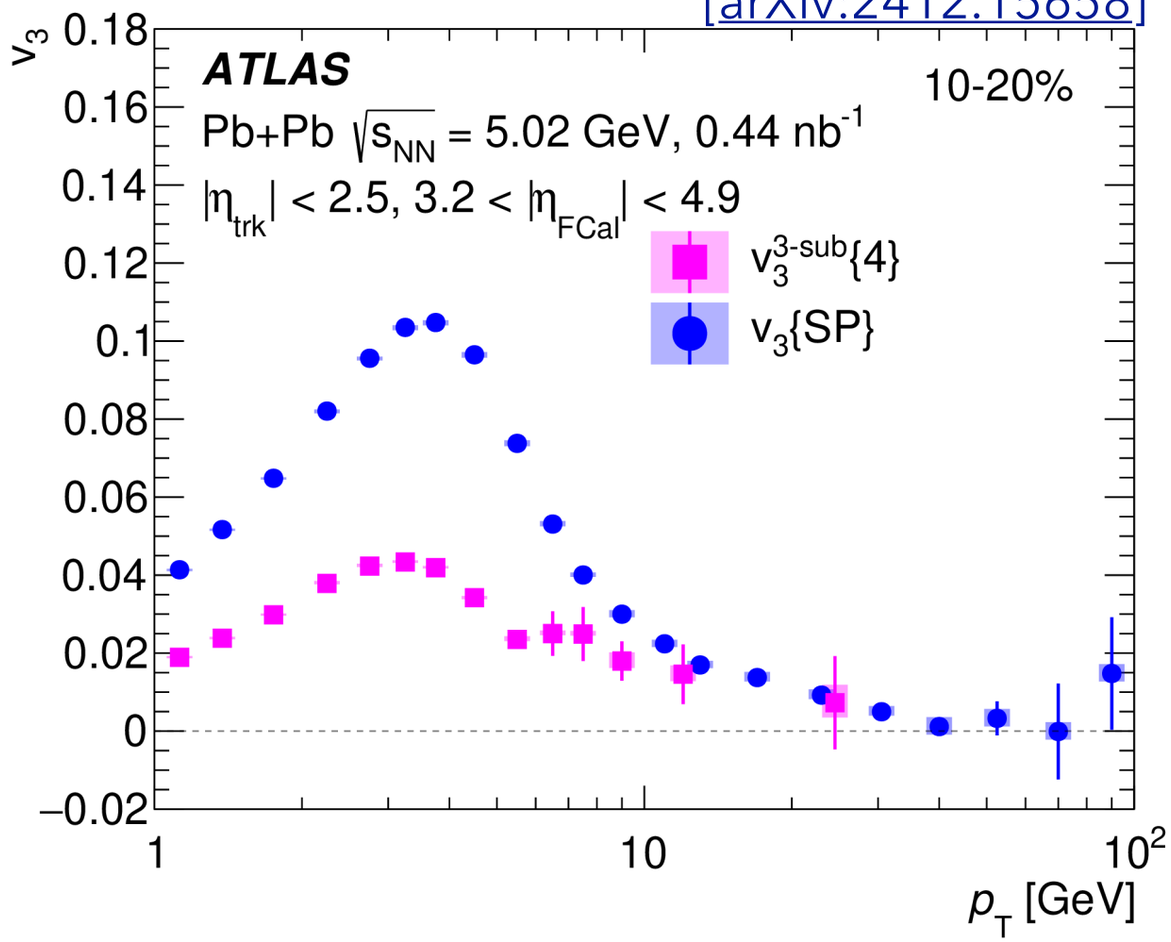


- **Precision** measurement of **elliptic** (v_2) and **triangular** (v_3) azimuthal correlation coefficients for charged particles in Pb+Pb at $\sqrt{s_{\mathrm{NN}}} = 5.02\ \mathrm{TeV}$ with an int lumi of 0.44 nb^{-1} for **0-60%** centralities and p_T values of **1-400 GeV**
- Scalar product (SP) and multi-particle cumulant methods are utilised
- $v_2(\mathrm{SP})$ values are positive for the selected centrality intervals up to a p_T of 100 GeV, become approximately constant with p_T for $p_T > 50$ GeV
- $v_3\{\mathrm{SP}\} > 0$ up to approximately 25 GeV

HIGH-PT FLOW

[arXiv:2412.15658]



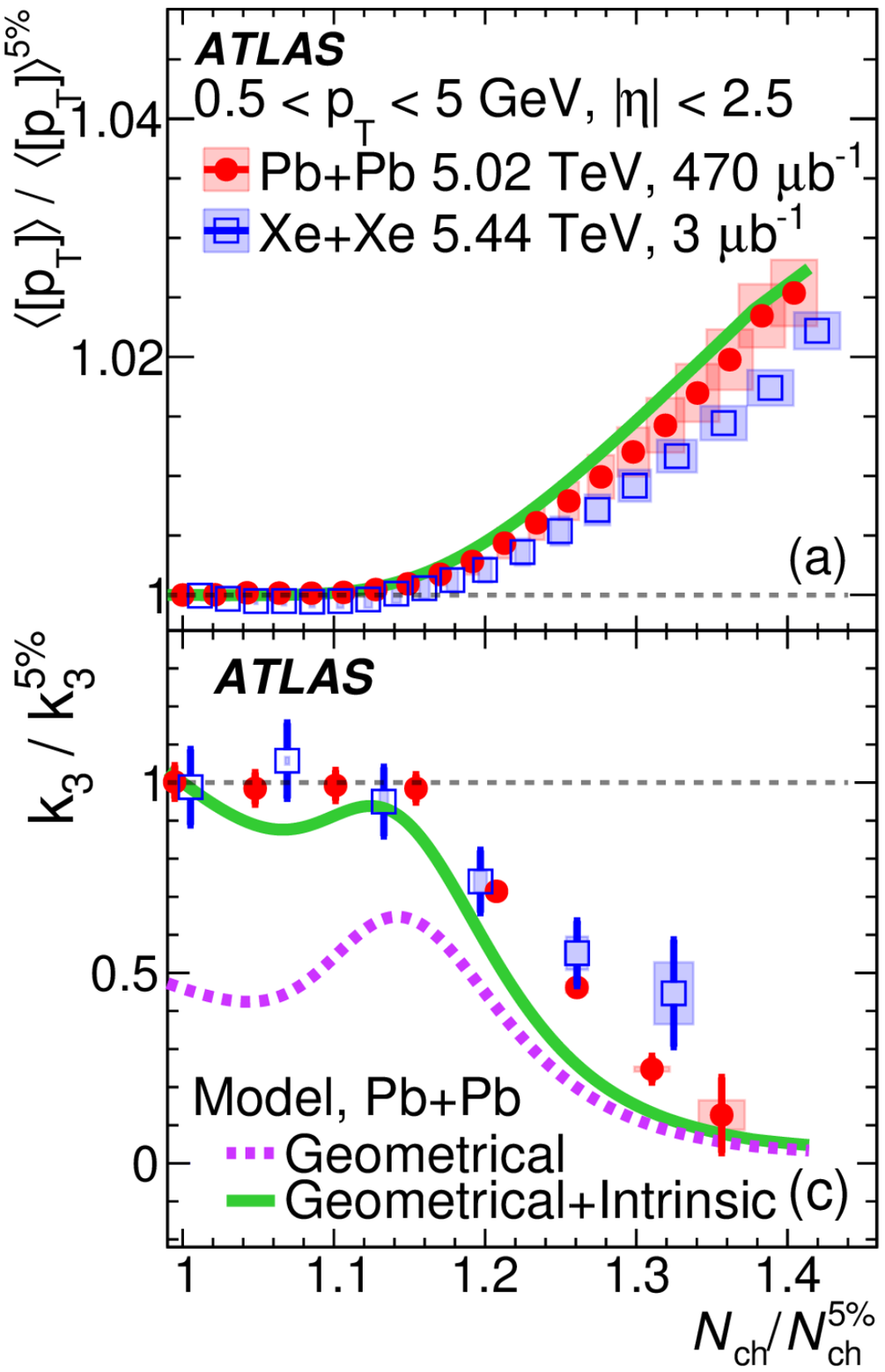


- Comparison between the **SP** and the **3-subevent Q-cumulant** multi-particle methods
- For p_T > 10 GeV, the comparison between the two methods contains information about how hard scattered partons respond to the event-by-event distribution of the initial-state QGP geometry
- In 10-20% centralities, values of $v_n\{\mathrm{SP}\} > v_n^{3-\mathrm{sub}}\{4\}$ at lower p_T and both methods converge at hight p_T (less non-flow)

PT FLUCTUATIONS IN PB+PB AND XE+XE

[PRL 133 (2024) 252301]

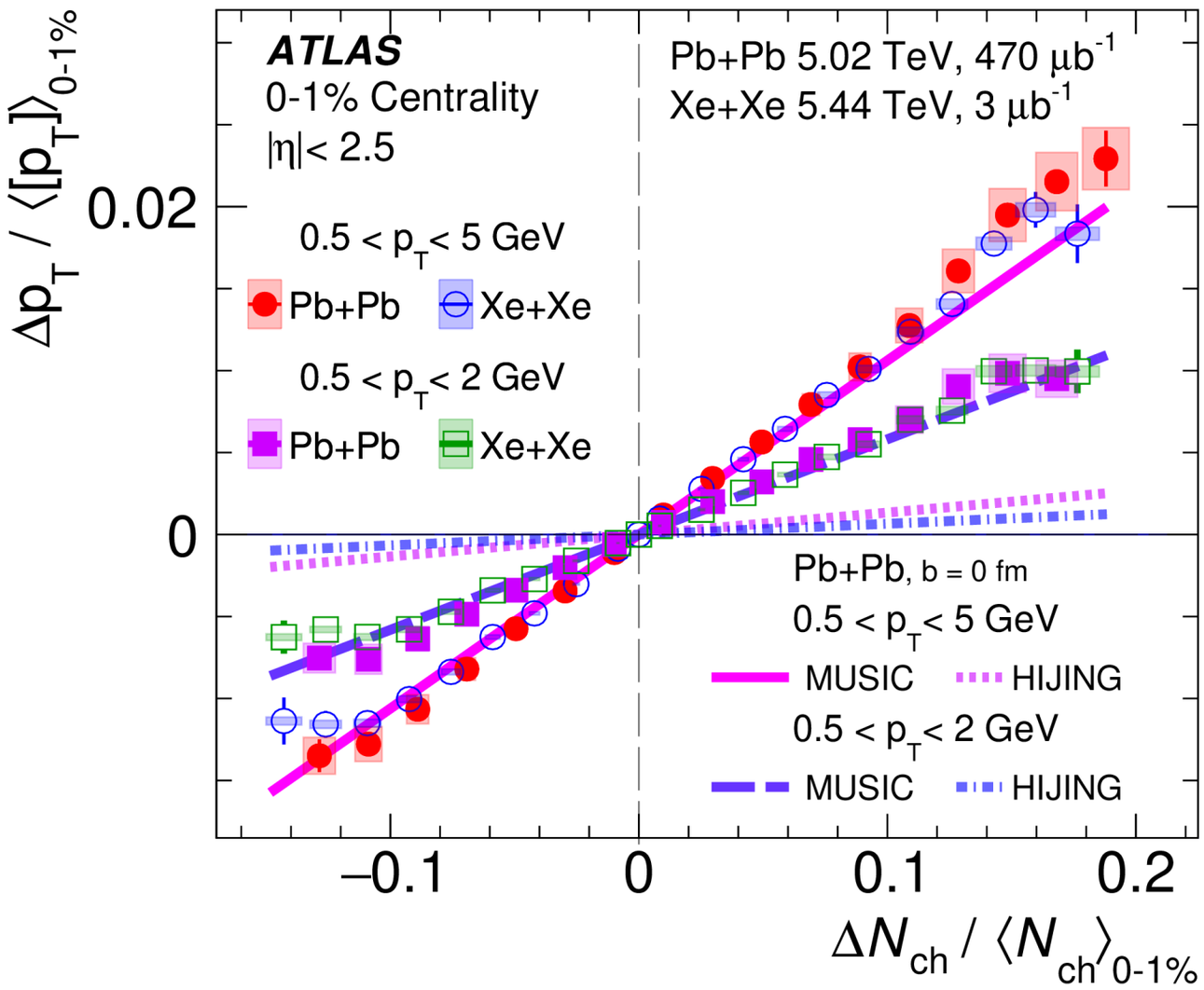
- Measurement in $^{208}\mathrm{Pb} + ^{208}\mathrm{Pb}$ and $^{129}\mathrm{Xe} + ^{129}\mathrm{Xe}$ at $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV and $\sqrt{s_{\mathrm{NN}}} = 5.44$ TeV, respectively, sensitive to initial conditions of HIC
- Contributions from fluctuations in the size of the nuclear overlap area (**geometrical component**) and other sources at fixed size (**intrinsic component**)
- Two components are distinguished by measuring **mean** ($\langle[p_{\mathrm{T}}]\rangle$), **variance** ($k_2$), and **skewness** ($k_3$) of event-wise transverse momentum $P([p_{\mathrm{T}}])$
- In **ultra-central collisions** (UCC) all observables show distinct changes in behaviour
- Phenomenological **model** by R. Samanta et al. PRC 108 (2023) 024908 of 2D Gaussian fluctuations works well
- Variations in k_3 can be described by the sum of geometrical and intrinsic components



PT FLUCTUATIONS IN PB+PB AND XE+XE

[PRL 133 (2024) 252301]

- A detailed analysis of **0-1% of UCC** events performed
- $\langle [x] \rangle_{0-1\%}$ quantity averaged over 1% of UCC, and $\Delta x = \langle [x] \rangle - \langle [x] \rangle_{0-1\%}$
- Correlation in 0−1% for Pb+Pb and Xe+Xe collisions in two p_{T} ranges measured
  - It is observed to be **positive** and nearly **linear**, and with similar slopes in both systems
- Slope varies with the p_{T} selection
- **HIJING** (no final-state interactions) model grossly underpredicts the slope, while **MUSIC** (full hydrodynamic response of the QGP) quantitatively captures the slope



Model study relates the increase of $[p_{\mathrm{T}}]$ in UCC to the speed of sound of the QGP, $c_S^2(T_{\mathrm{eff}}) \sim \dfrac{d \ln(\langle [p_{\mathrm{T}}] \rangle)}{d \ln(N_{\mathrm{ch}})}$

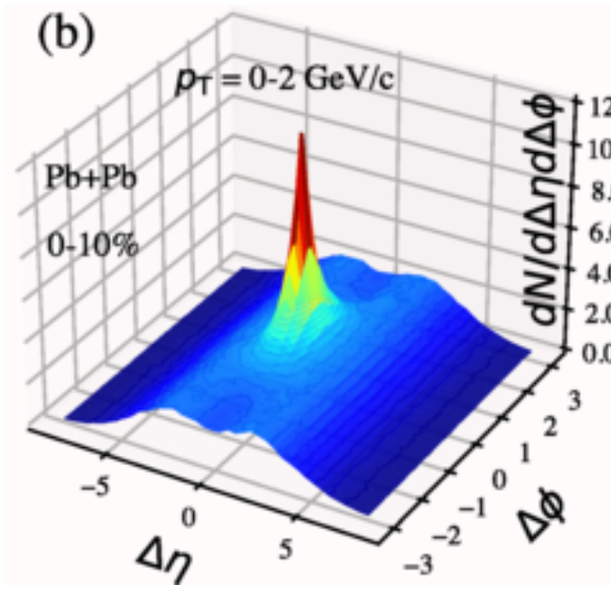
ATLAS measures:

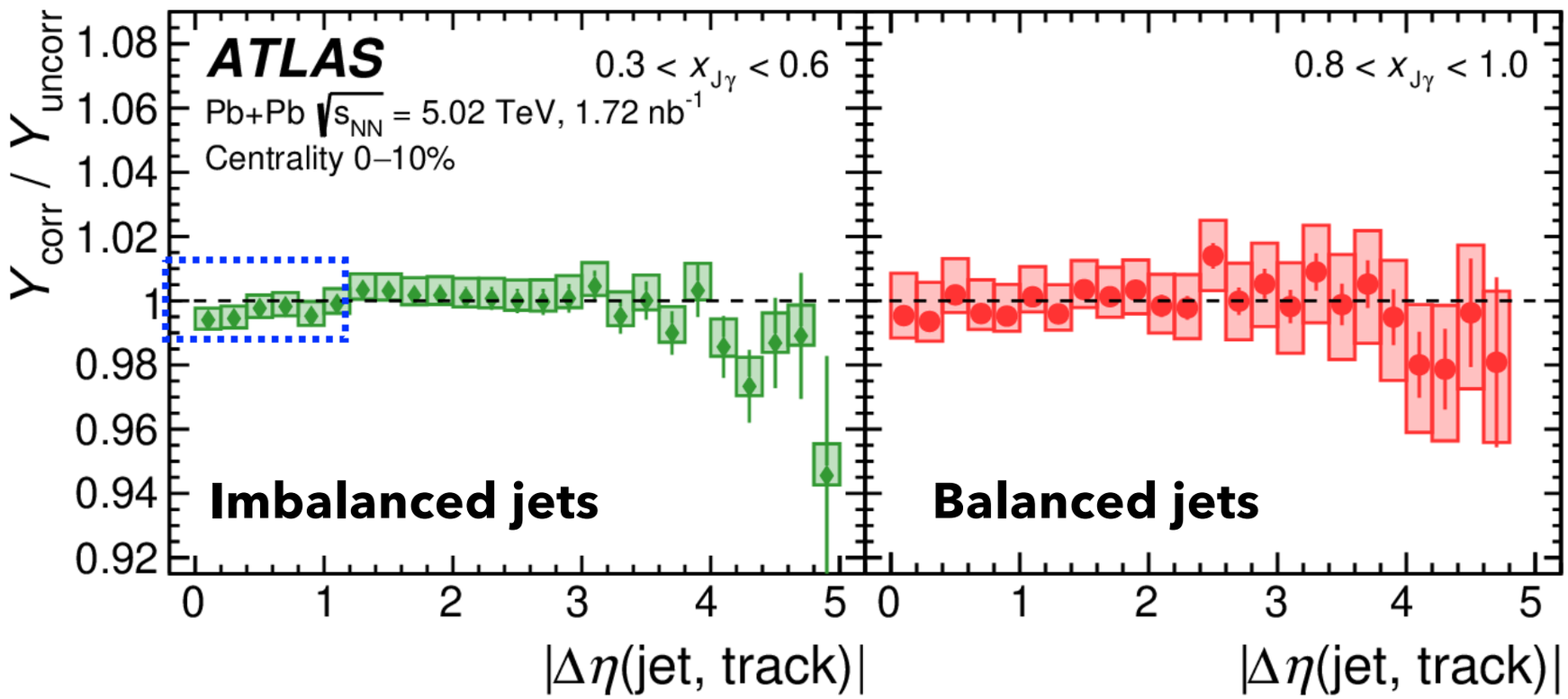
$c_S^2(T_{\mathrm{eff}}) \approx 0.23$ with $T_{\mathrm{eff}} \approx 222$ MeV

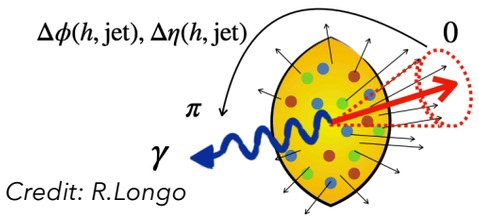
SEARCH FOR DIFFUSION WAKE

[PRL 130 (2023) 052301]

[arXiv:2408.08599]







$$Y_{\text{corr}} = \frac{1}{N^{\gamma-\text{jet}}} \frac{d^2 N^{\text{jet}-\text{track}}}{d\Delta\eta d\Delta\phi}$$

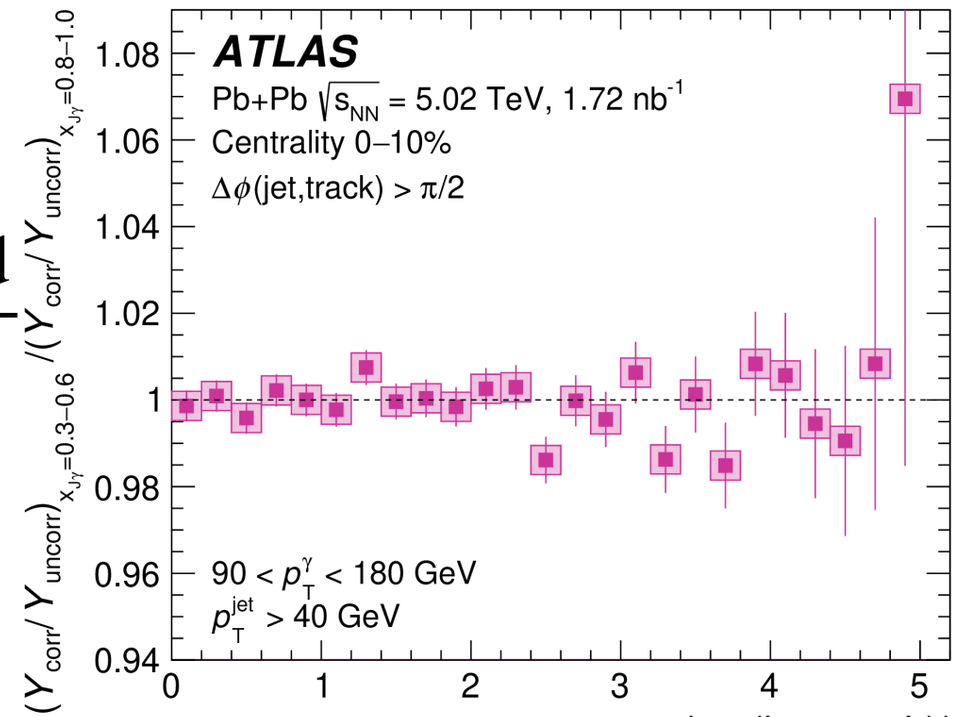
$$x_{\text{J}\gamma} = \frac{p_{\text{T}}^{\text{jet}}}{p_{\text{T}}^{\gamma}}$$

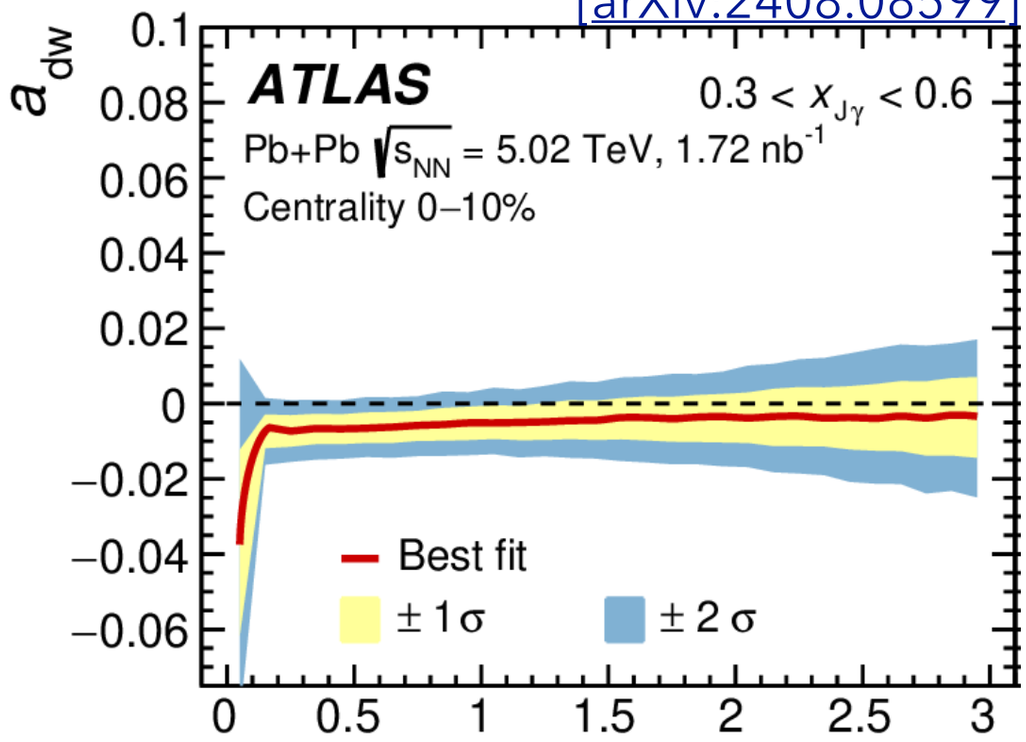
- Predictions of a **diffusion wake** accompanying the jet-induced Mach cone as a **unique probe** of the QGP
- **Jet-track correlations** in Pb+Pb at $\sqrt{s_{\text{NN}}} = 5.02$ TeV with an int lumi of 1.72 nb^{-1}
- Events with energetic γ**-jet pairs** are selected in back-to-back configuration in azimuth
- Angular correlations between a jet and tracks with $0.5<p_T<2$ GeV in the opposite hemisphere to the jet are measured as a function of $|\Delta\eta(\text{jet, track})|$ in three $x_{\text{J}\gamma}$ intervals
- A zoom into $|\Delta\eta(\text{jet, track})| \sim 0$ reveals a **depletion** of about 0.5% which is also consistent with unity

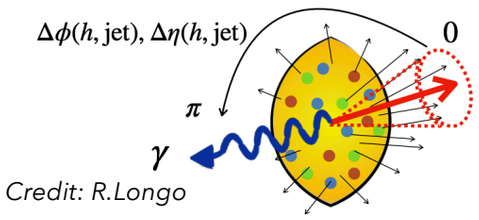
SEARCH FOR DIFFUSION WAKE

[arXiv:2408.08599]

$$\frac{\text{imbalanced}}{\text{balanced}}$$







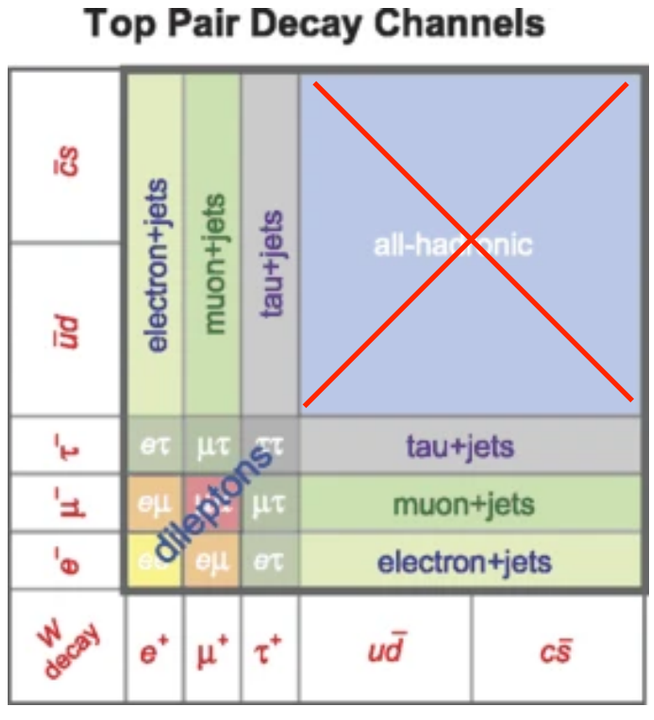
$$a + a_{\text{dw}} \cdot e^{-|\Delta\eta(\text{jet,track})|/(2\sigma_{\text{dw}}^2)}$$

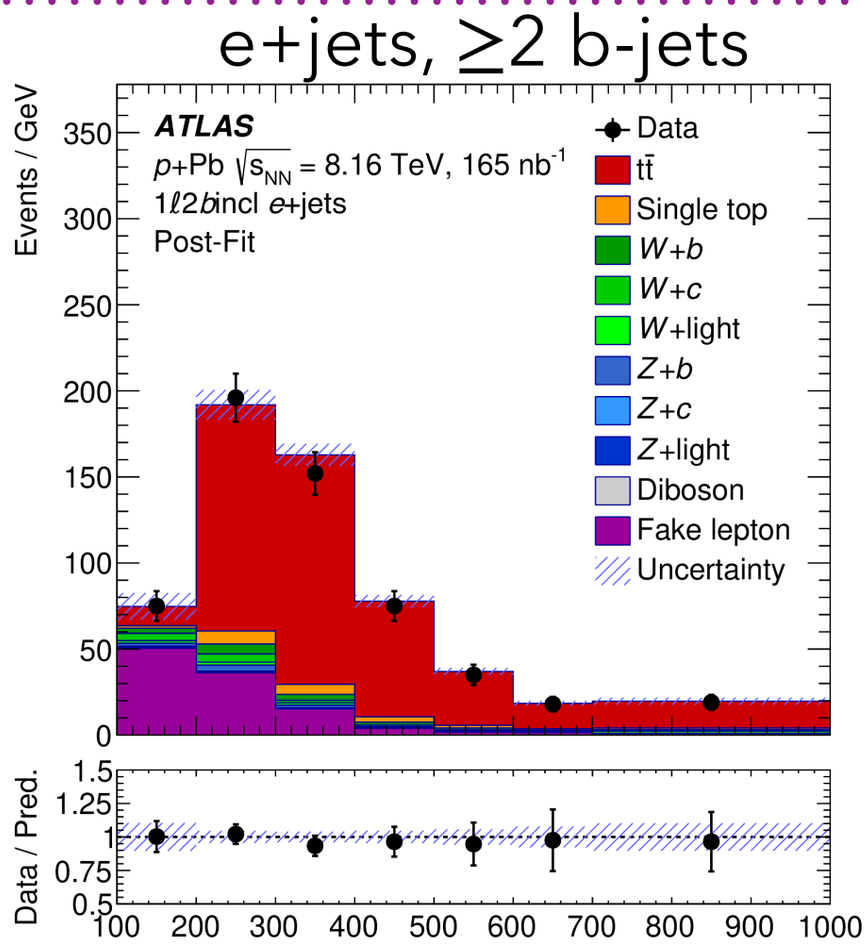
a_{dw}: diffusion wake amplitude

σ_{dw}: diffusion wake width

- **Double ratio**, in particular sensitive to whether a larger diffusion wake is present when the parton loses more energy in the QGP, also **consistent with unity**
- All results are consistent with **no signal** $a_{\text{dw}} = 0$

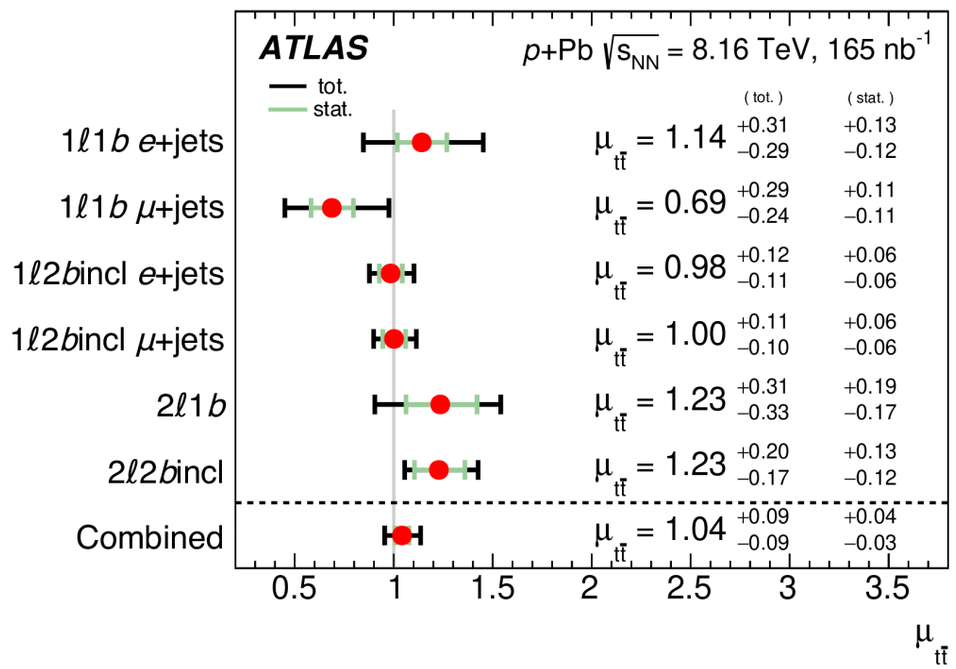
OBSERVATION OF TOP-QUARKS IN P+PB



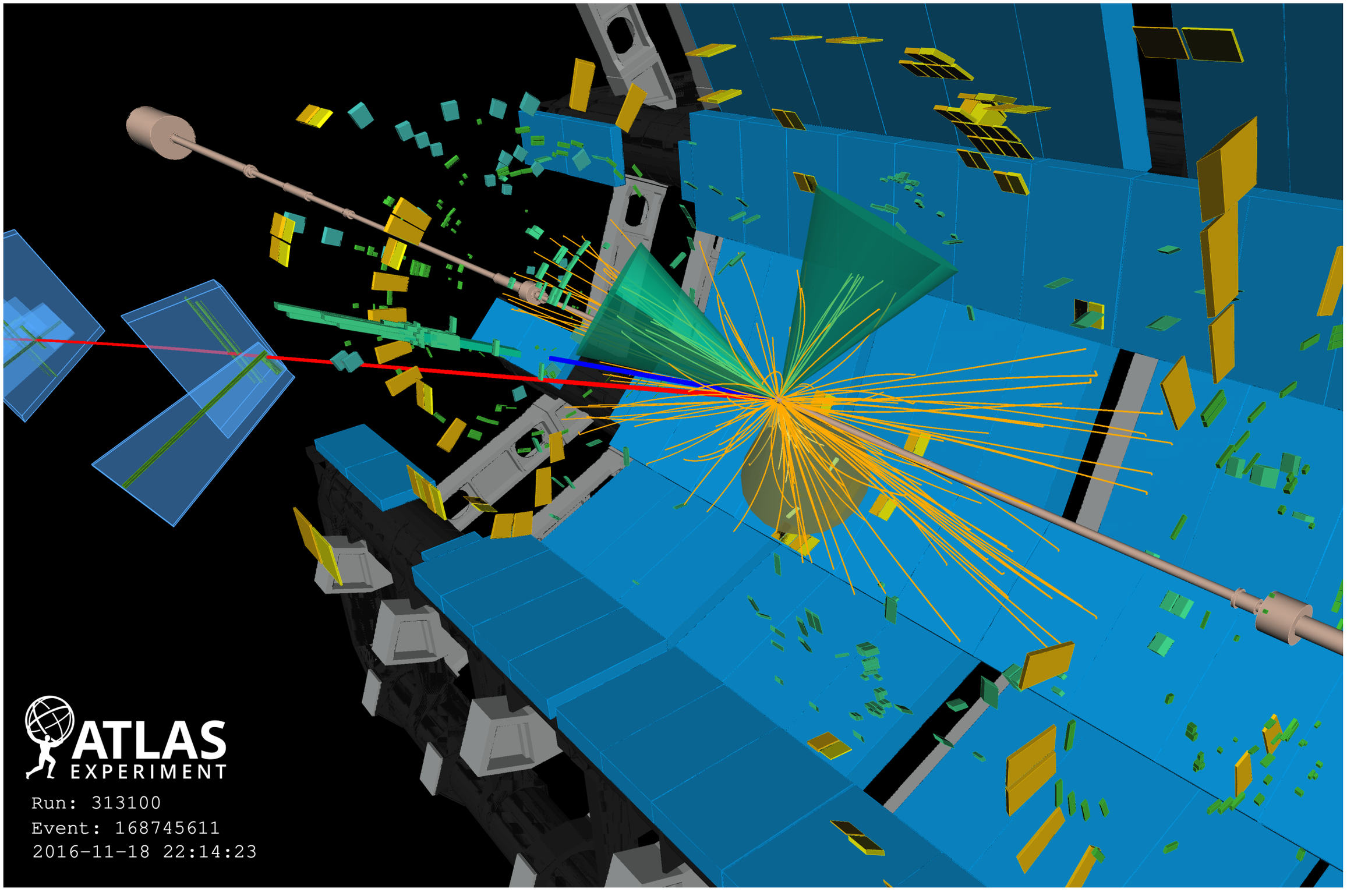


[JHEP 11 (2024) 101]

- Top-quark pair production $t\bar{t}$ in p+Pb collisions at $\sqrt{s_{\mathrm{NN}}} = 8.16$ TeV with int lumi of 165 nb^{-1}
- **Lepton+jet** and **dilepton** channels (BR=~50%) investigated
- Profile-likelihood fit to a $H_{\mathrm{T}}^{\ell j}$ distribution with $\ell = e, \mu$
- **Signal strength** $\mu_{t\bar{t}} = \dfrac{\sigma_{t\bar{t}}^{\mathrm{meas}}}{\sigma_{t\bar{t}}^{\mathrm{SM}}}$ extracted
- $\mu_{t\bar{t}}$ consistent with unity in the individual channels



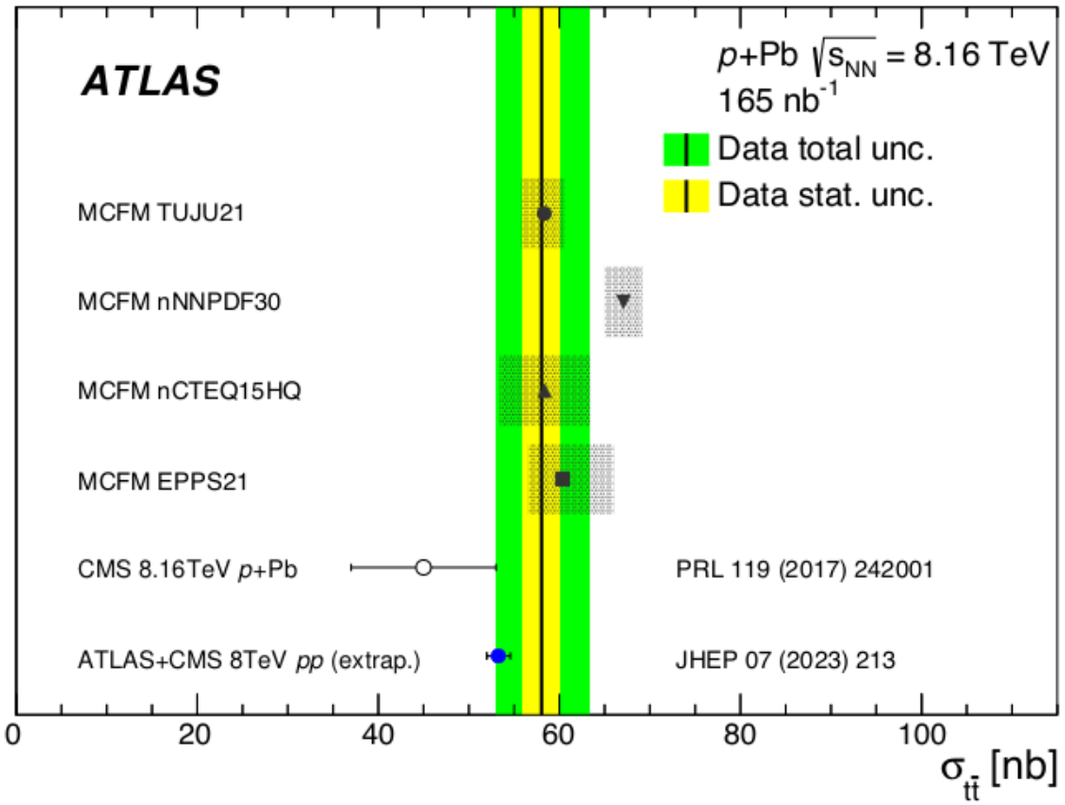
TTBAR EVENT CANDIDATE

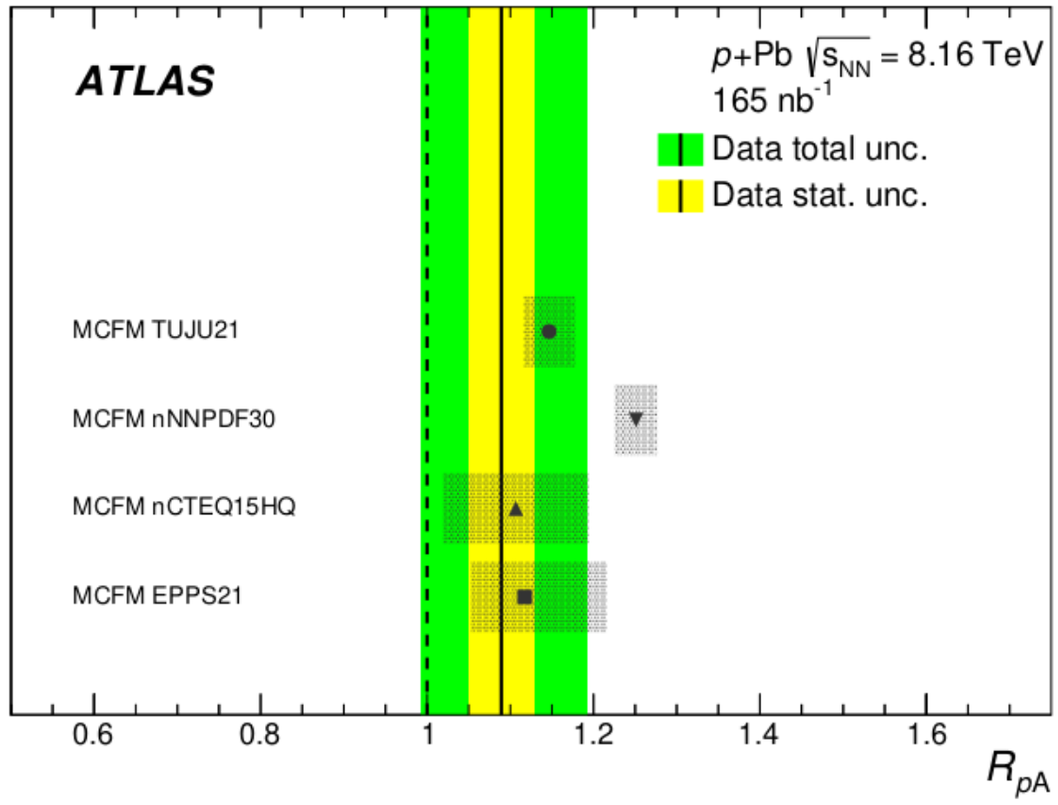


- Event candidate from the dilepton channel with an electron (blue track) and muon (red track), one b-jet (yellow cone) and two jets (green cones)

OBSERVATION OF TOP-QUARKS IN P+PB

[JHEP 11 (2024) 101]



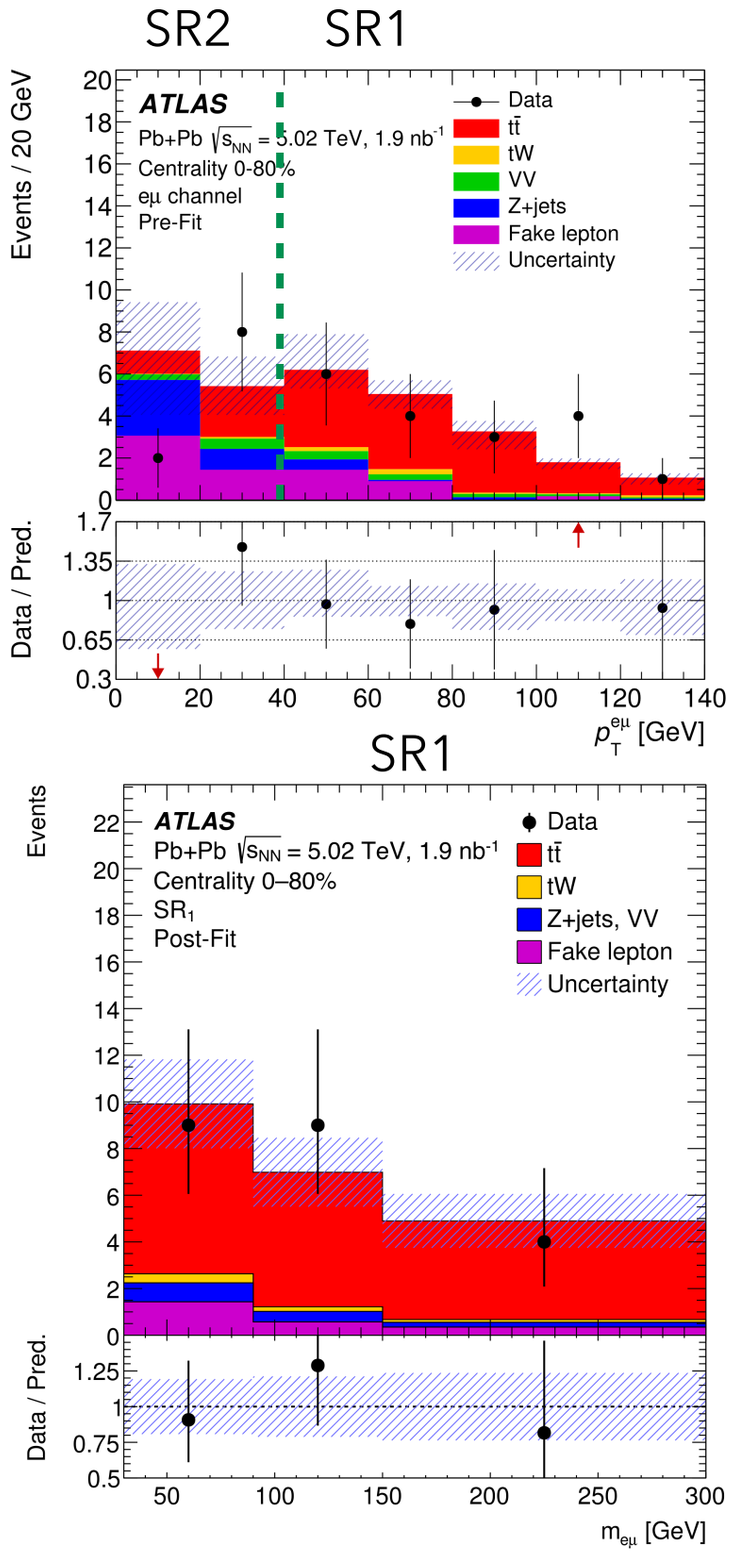


- $t\bar{t}$ production **cross-section** is measured in p+Pb collisions at $\sqrt{s_{\mathrm{NN}}} = 8.16$ TeV
  - $\sigma_{t\bar{t}} = 58.1 \pm 2.0\ (\mathrm{stat.}) \pm^{4.8}_{4.4}\ (\mathrm{syst.})$ nb
  - Dominated by systematics (jet energy scale and ttbar modelling)
  - Most precise measurement at the LHC
  - Consistent with the previous measurements and nPDF predictions
- **Nuclear modification factor** for $t\bar{t}$ production measured for the first time
  - $R_{p\mathrm{A}} = 1.090 \pm 0.039\ (\mathrm{stat.}) \pm^{0.094}_{0.087}\ (\mathrm{syst.})$
  - Hint of nuclear modifications to PDF

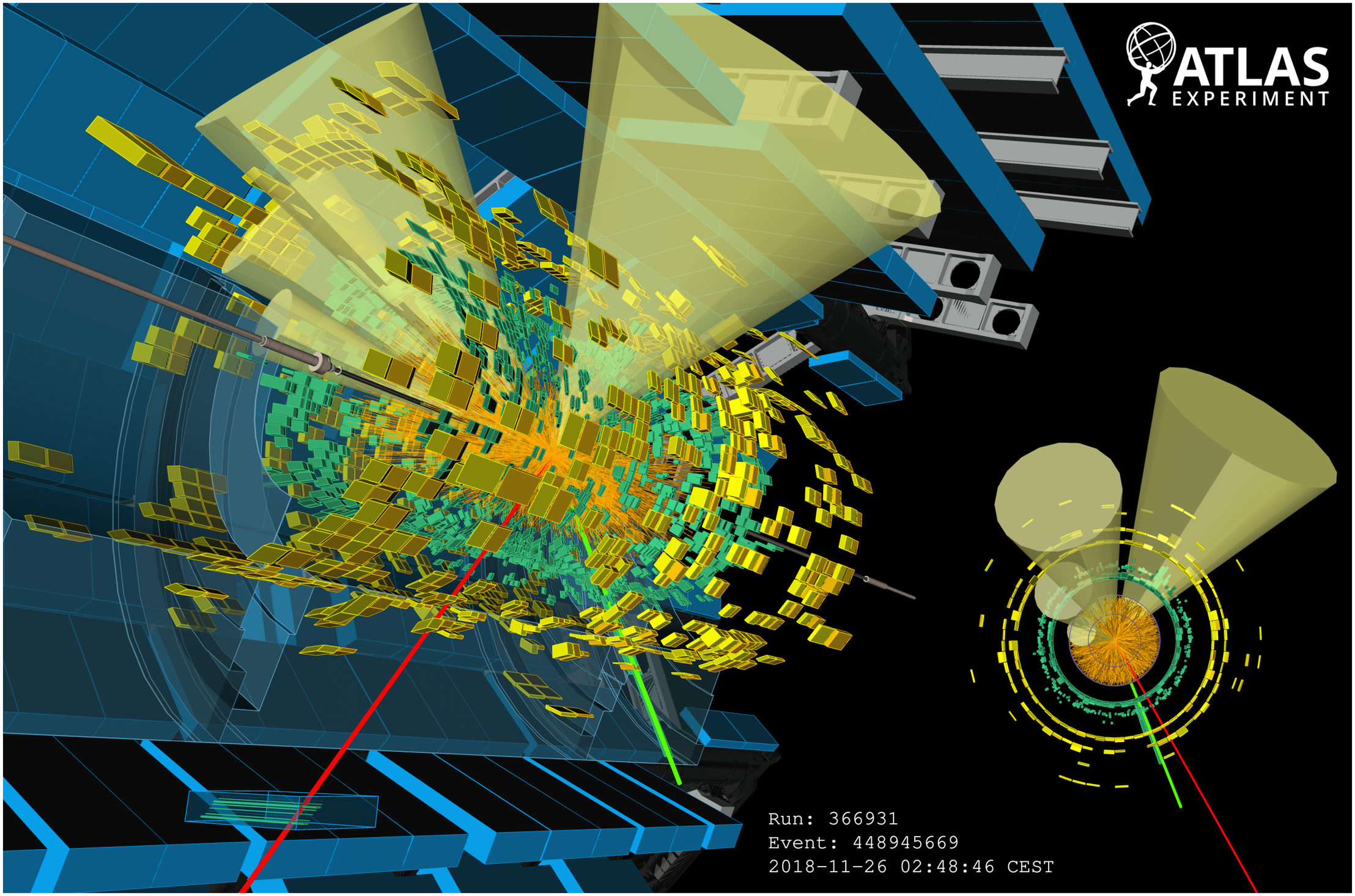
OBSERVATION OF TOP-QUARKS IN PB+PB

[arXiv:2411.10186]

- $t\bar{t}$ production is measured in Pb+Pb collisions from 2015 and 2018 at $\sqrt{s_{\mathrm{NN}}} = 5.02\ \mathrm{TeV}$ in 0-80% centralities
- **Dilepton** channel (BR=~2%) investigated
- Profile-likelihood fit to a $m_{e\mu}$ distribution in two signal regions SR1 and SR2
- Signal strength $\mu_{t\bar{t}} = \dfrac{\sigma_{t\bar{t}}^{\mathrm{meas}}}{\sigma_{t\bar{t}}^{\mathrm{SM}}}$ extracted
- Distributions predicted by the fit and the observed distributions are **in good agreement**
- Observed (expected) significance of 5.0 (4.1) standard deviations
- **First observation** of $t\bar{t}$ in Pb+Pb collisions at the LHC



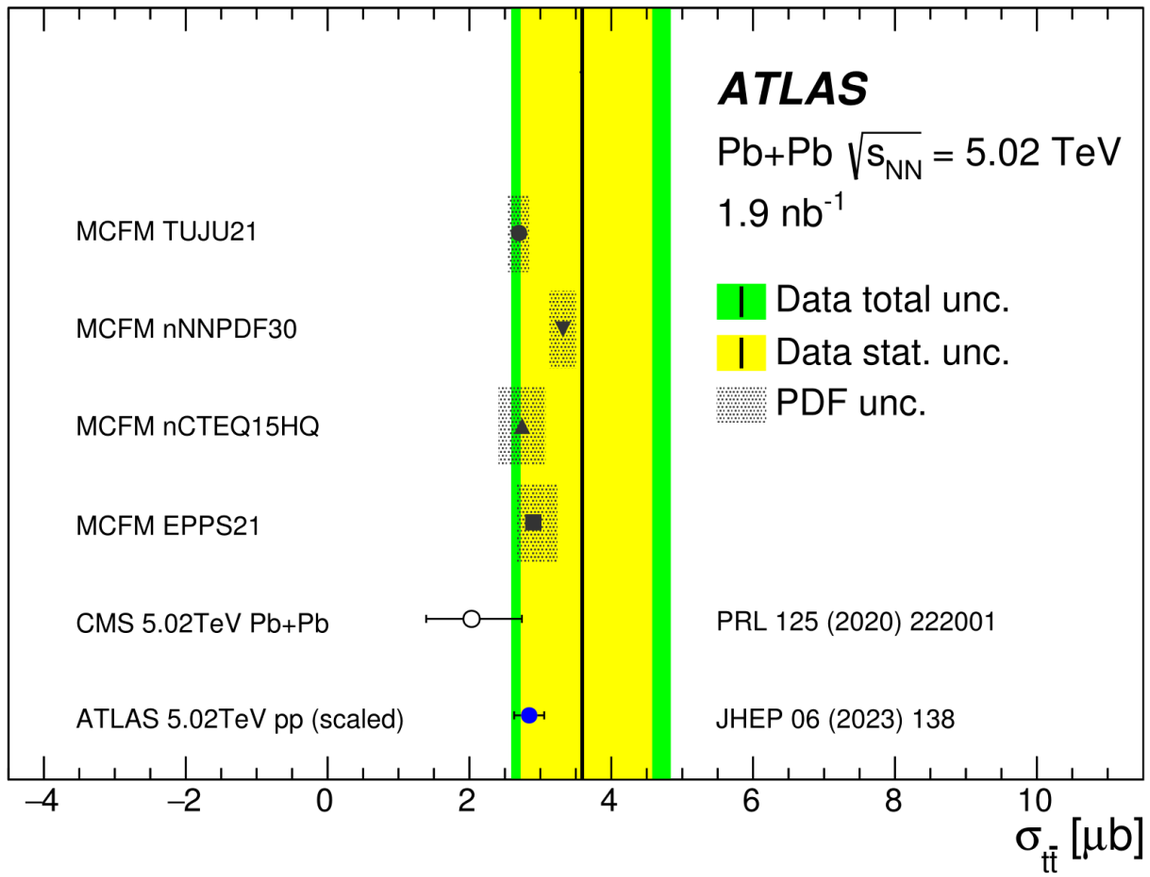
TTBAR EVENT CANDIDATE



- $t\bar{t}$ event candidate from the $e\mu$ channel with an electron (green track) and muon (red track), and four jets (yellow cones)

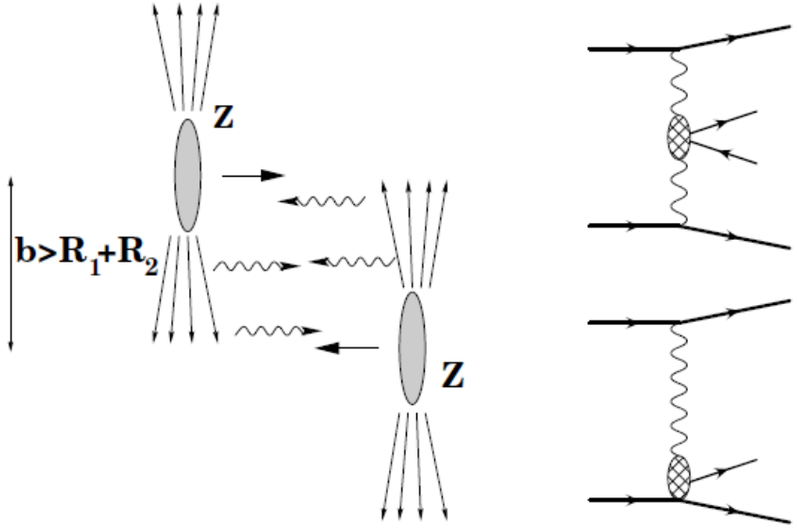
OBSERVATION OF TOP-QUARKS IN PB+PB

[arXiv:2411.10186]



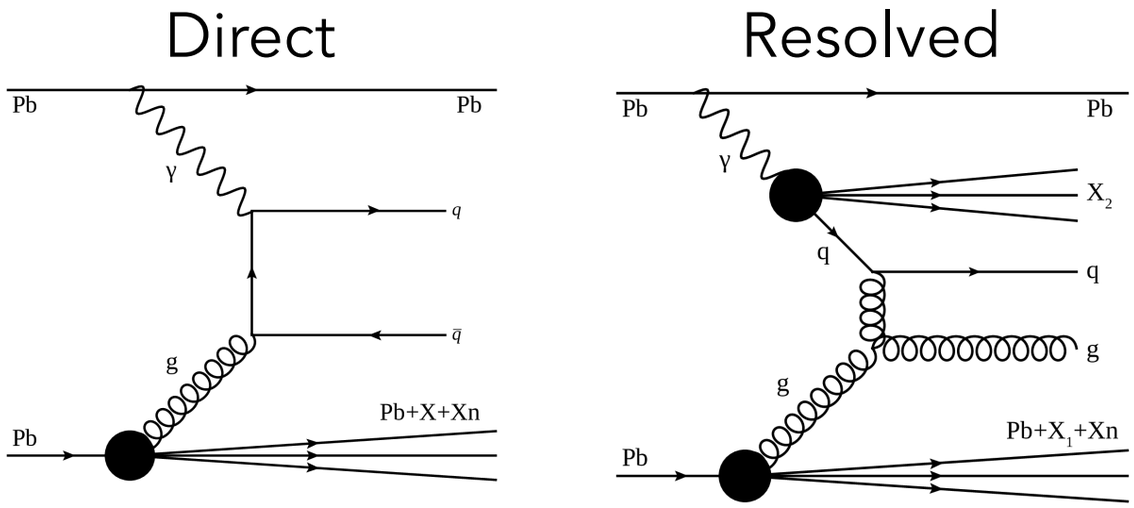
- $t\bar{t}$ production **cross-section** is measured in Pb+Pb collisions at $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV with an int. luminosity of 1.9 nb^{-1}
  - $\sigma_{t\bar{t}} = 3.6 \pm^{1.0}_{0.9}\ (\mathrm{stat.}) \pm^{0.8}_{0.5}\ (\mathrm{syst.})\ \mu\mathrm{b}$
  - Total relative uncertainty of 31% dominated by event statistics
  - Consistent with the previous measurements and nPDF predictions
  - **New probe** of the QGP established at the LHC

UPC PHYSICS

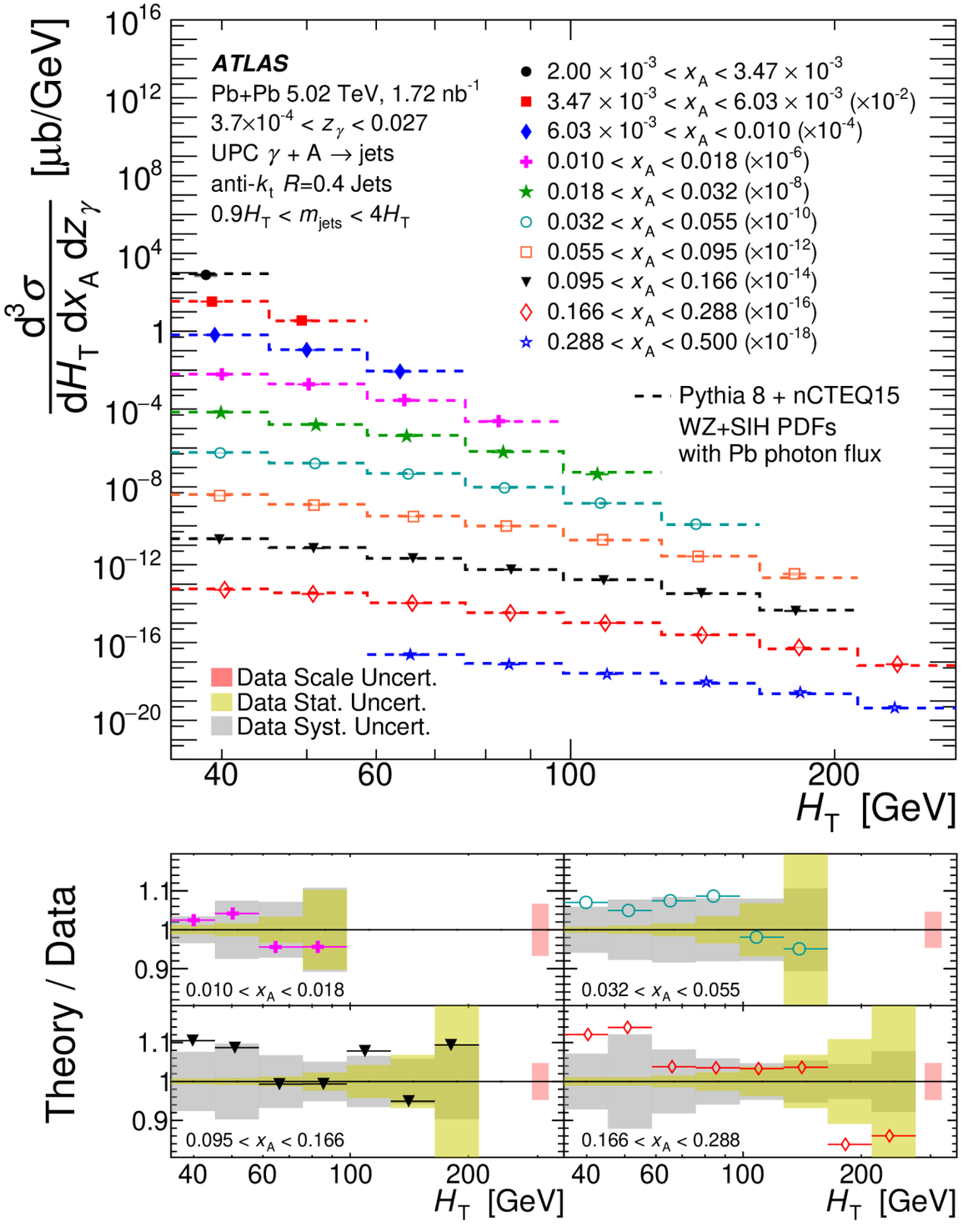


PHOTONUCLEAR JETS IN PB+PB

[arXiv:2409.11060]

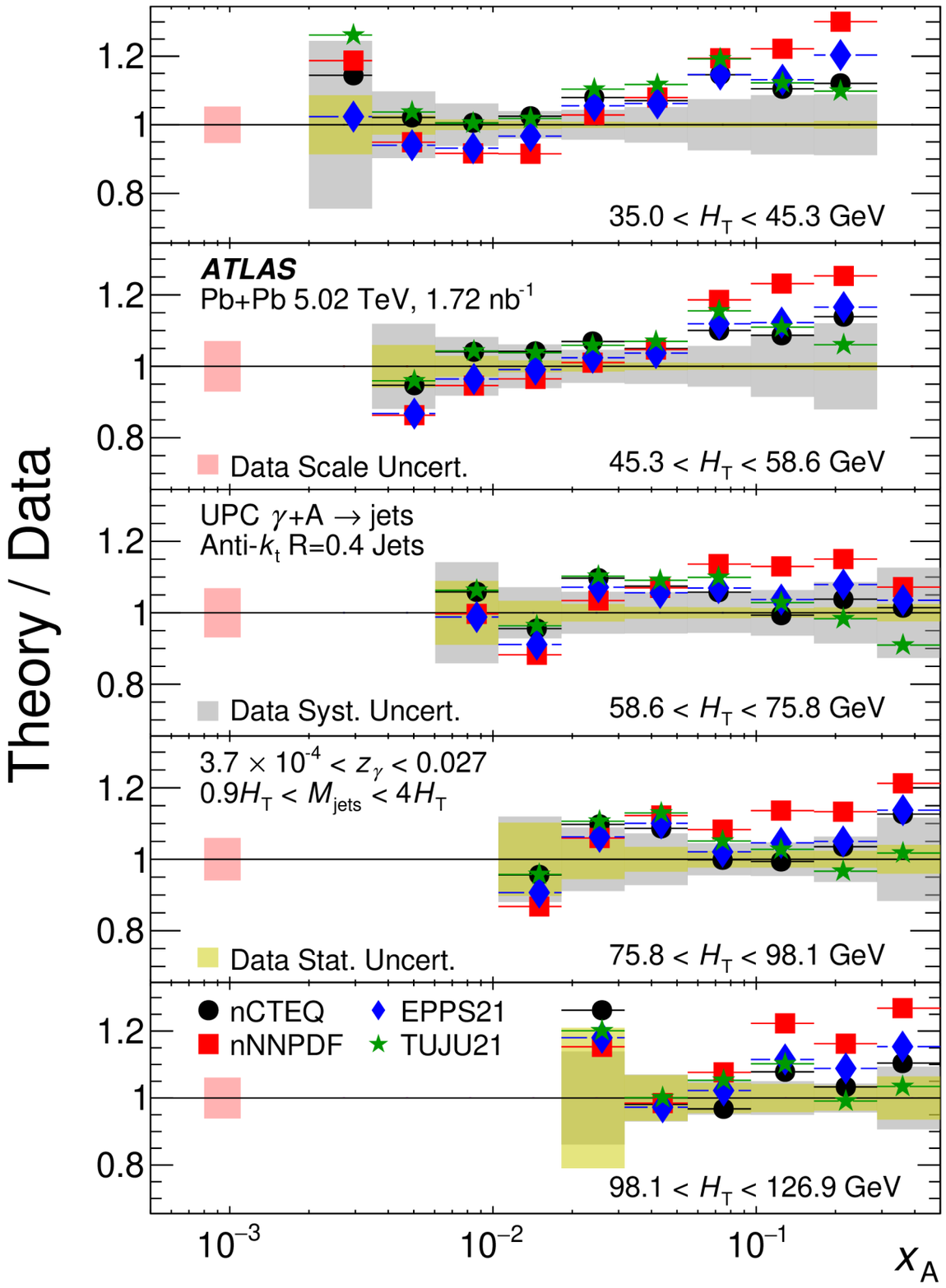


- **Photonuclear** production of **dijet** in UPC of Pb+Pb at $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV with an int lumi of 1.72 nb^{-1}
- Complementary way to constraint **nuclear modifications of PDFs** in the colliding nuclei
- **Triple-differential cross-sections** measured for two sets of kinematic variables (H_{T}, rapidity, mass) and (H_{T}, x_A, z_γ)
  - H_{T}: total transverse momentum of jet system
  - nuclear x_A
  - z_γ: photon parton momentum fractions
- Comparison to **LO Pythia8** with **photon fluxes** (recent development)
- Data suggests that the nPDF in nCTEQ15 are too large at lower H_{T}, but that the agreement improves at higher H_{T}



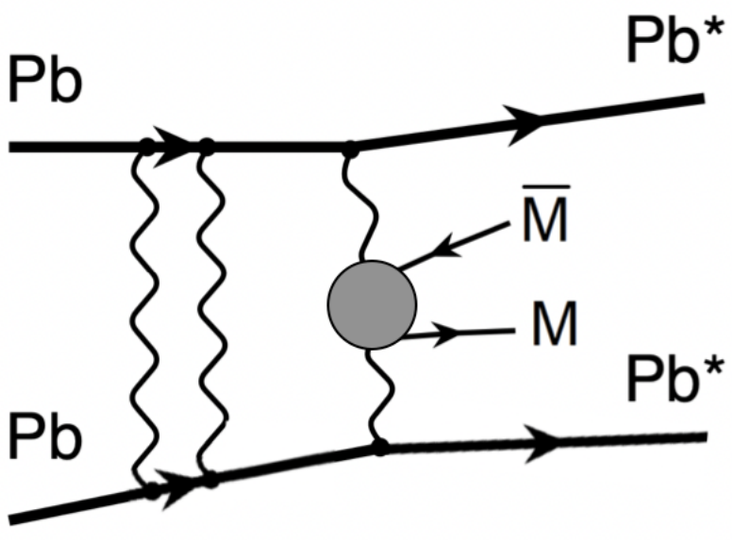
PHOTONUCLEAR JETS IN PB+PB

[arXiv:2409.11060]



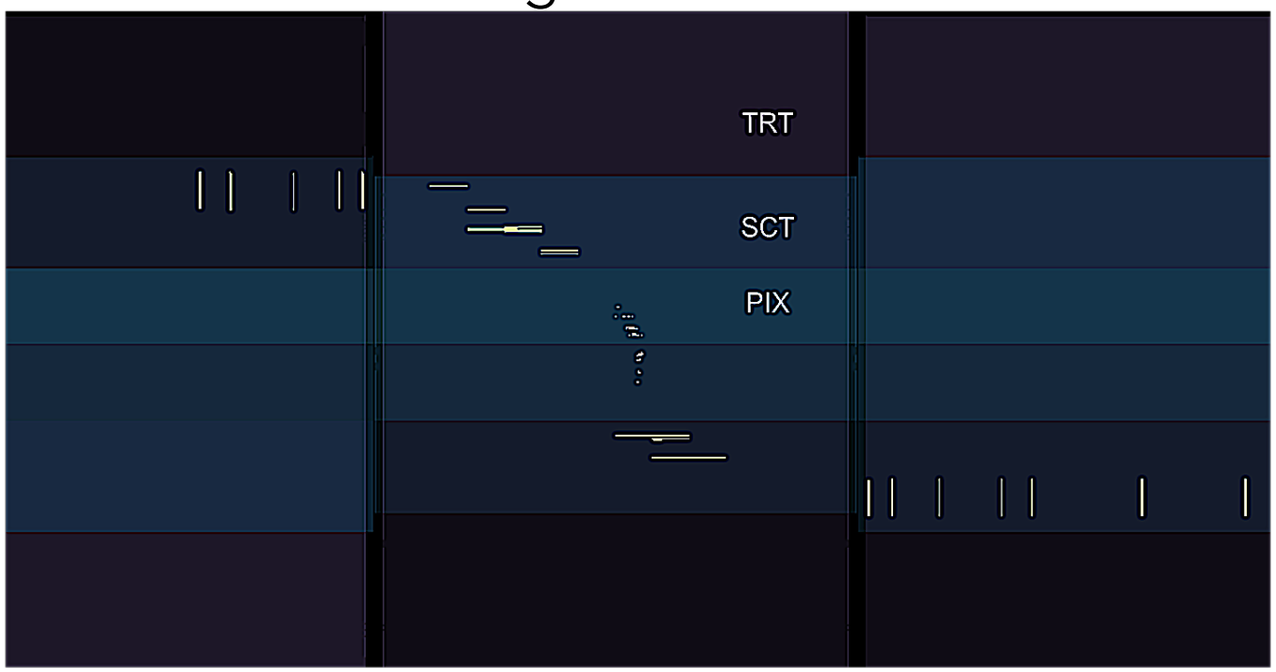
- Measured cross-sections in 5 H_T intervals compared with predictions using **Pythia 8 LO** calculations with a simulated parton shower for a variety of **nPDF sets** (nCTEQ15 WZ+SIH, nNNPDF 3.0, EPPS21, and TUJU21)
  - **nCTEQ results** typically agree best due to their weaker (anti-)shadowing effects
- At higher H_T, the data typically agrees well with **nCTEQ** and **TUJU21**, while the other models typically over-predict the cross-section in the anti-shadowing region
- These observations may be modified when NLO corrections become available, or when theoretical uncertainties on the modelling of the photon flux are included

SEARCH FOR MAGNETIC MONOPOLES

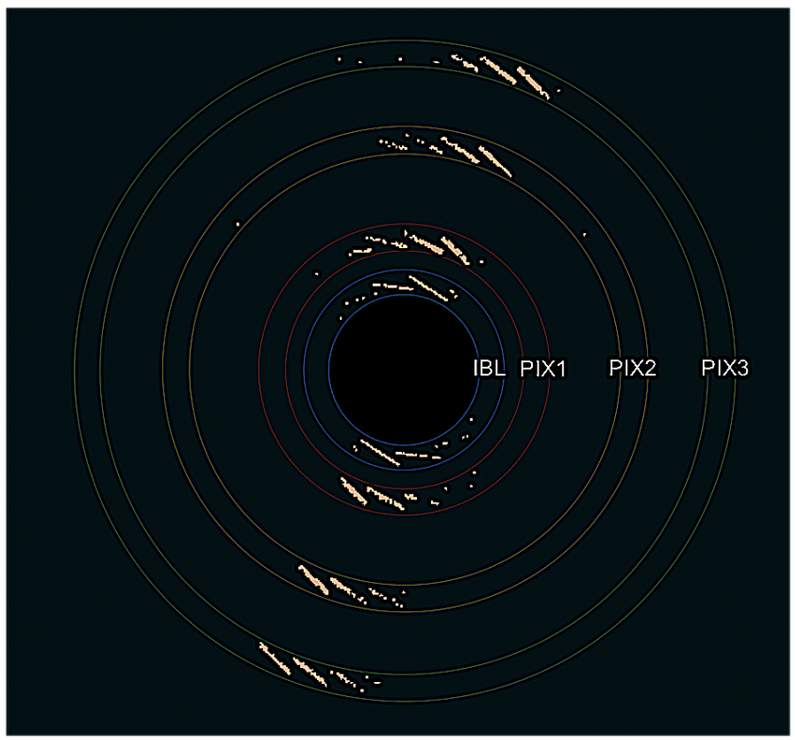


- Search for highly-ionising magnetic monopoles in 262 μb^{-1} in **UPC** of Pb+Pb at $\sqrt{s_{NN}} = 5.36$ TeV
- **First ATLAS result** based on **2023 Pb+Pb** collisions
- Monopole pairs $M\bar{M}$ produced using Schwinger mechanism
- Pioneering analysis exploiting hits in the Pixel detector
- Data-driven estimate of beam-induced background events

[arXiv:2408.11035] longitudinal view



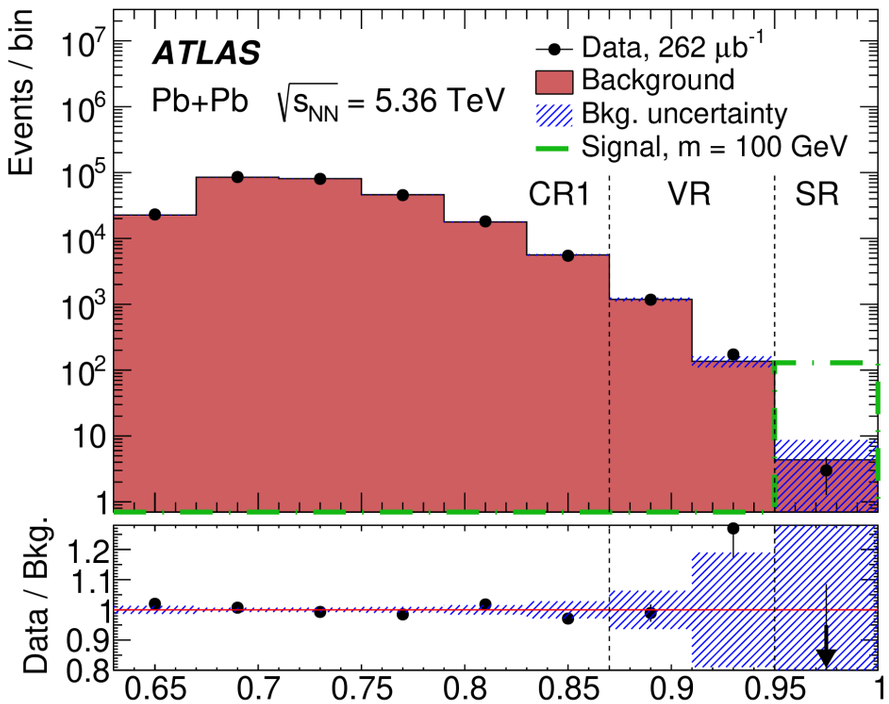
transverse view

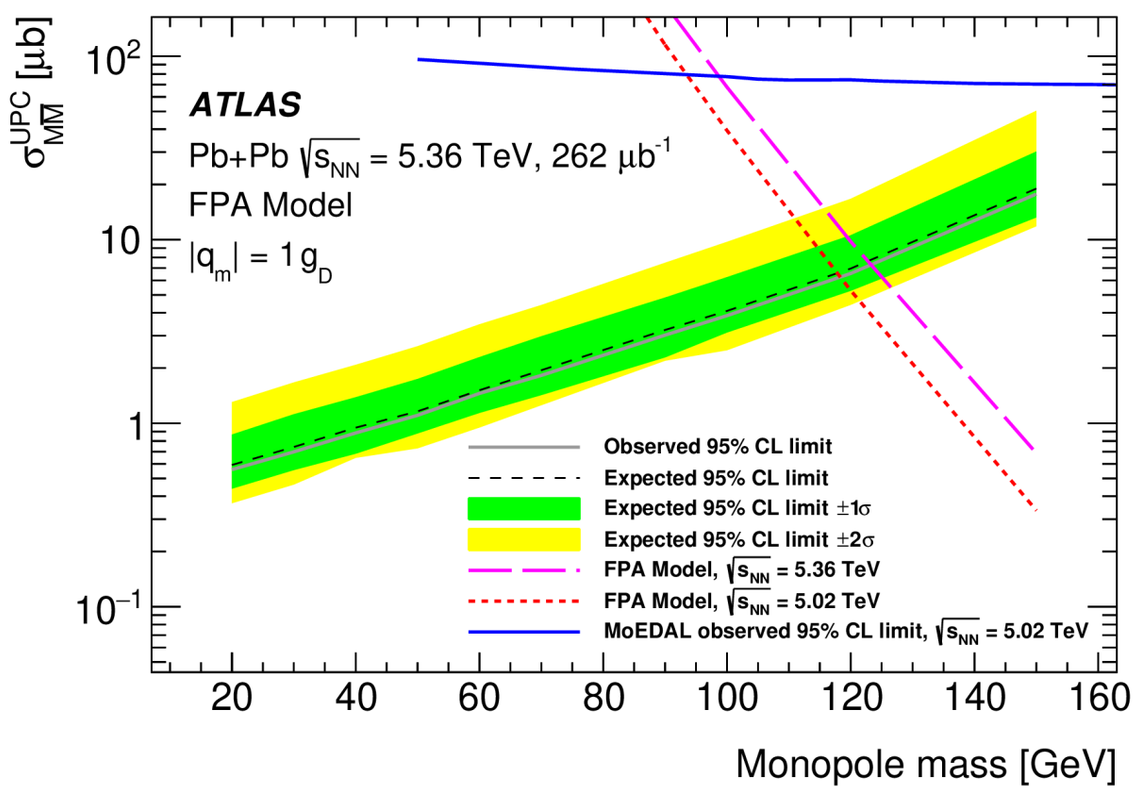


Simulated monopole event with mass of 20 GeV and $p_T = 50$ GeV

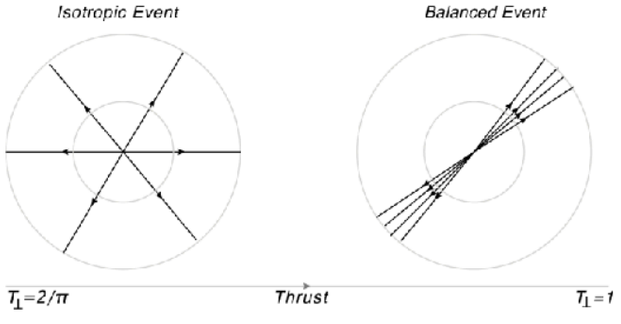
SEARCH FOR MAGNETIC MONOPOLES

[arXiv:2408.11035]





$$T = 1/N_{pix} \sum_{pix} |\hat{r}_{pix} \cdot \hat{n}_{max}|$$

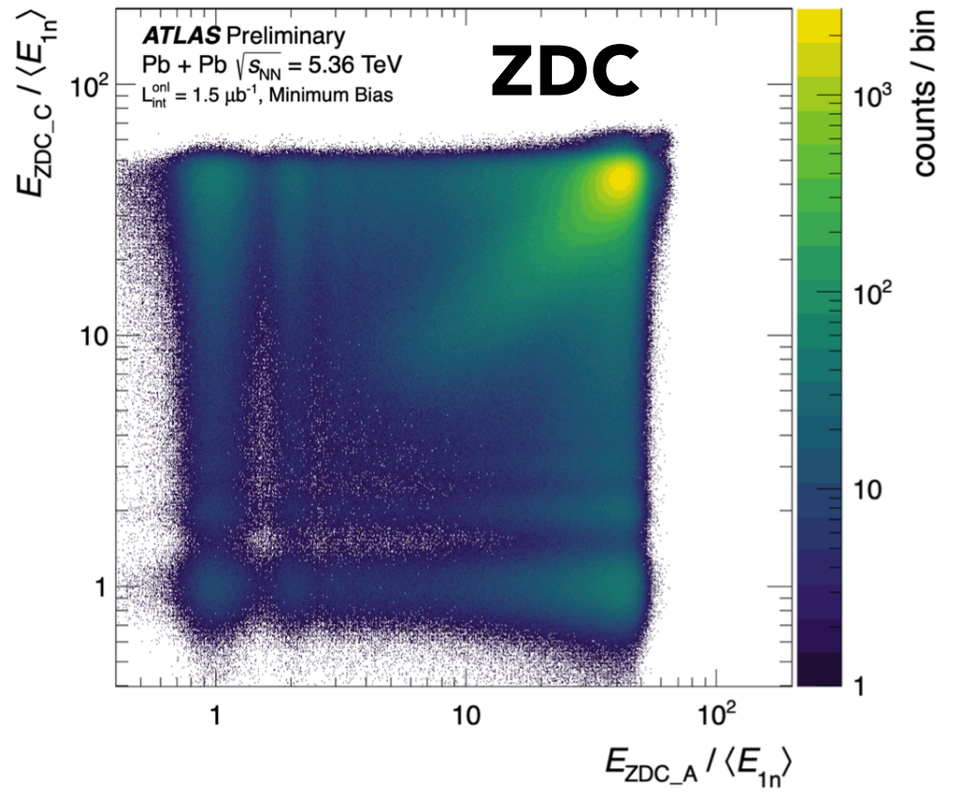


- Distribution of **transverse thrust** T is exploited
  - 3 data events found in the signal region (SR), consistent with the estimate of $4 \pm 4\ (\text{stat.}) \pm 1\ (\text{syst.})$ for backgrounds
  - Data consistent with the background-only hypothesis
- Non-perturbative semiclassical model FPA [PRD 100 (2019) 015041] used to set upper limits at 95% CL on the cross-section for $M\bar{M}$ production with a single Dirac magnetic charge for masses of 20-150 GeV
  - **Monopole masses** below 120 GeV are excluded
  - **Significant improvement** in the cross-section limits reported by MoEDAL
  - Power of UPC Pb+Pb data is demonstrated

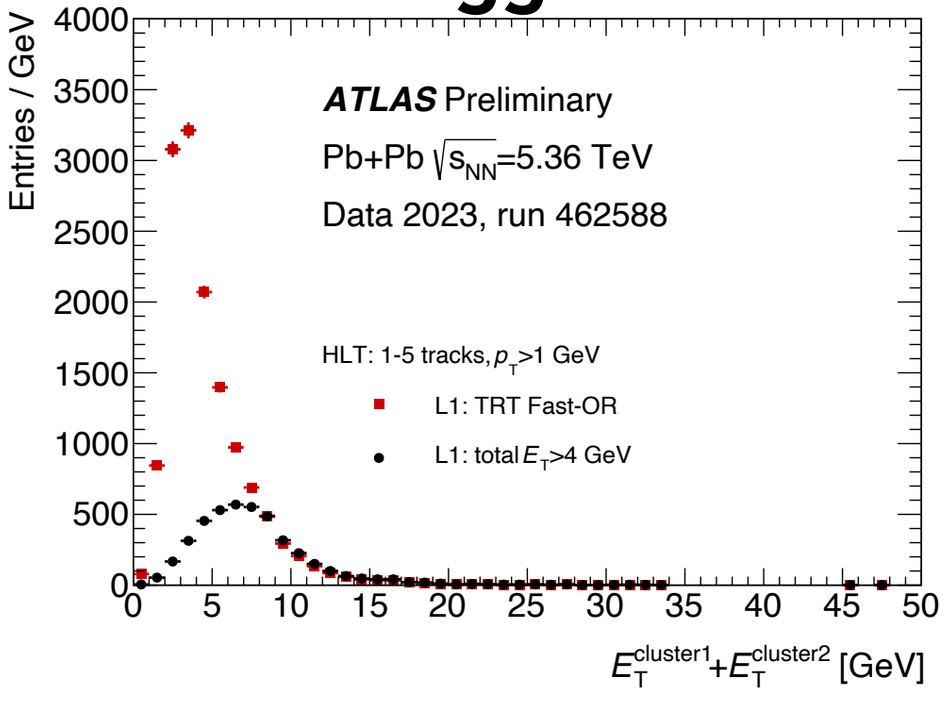
TOWARDS RUN-3 DATA ANALYSIS

- ATLAS experiment collected Pb+Pb collisions in 2023 and 2024
  - Run 2: 2.2 nb^{-1} at $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV
  - Run 3: 3.2 nb^{-1} at $\sqrt{s_{\mathrm{NN}}} = 5.36$ TeV
  - **Readout** and **trigger upgrade** of **ZDC**
  - Improved **trigger** strategies for low-p_T particles in UPC
  - Significant improvements in low-p_T **electron reconstruction** with access to electrons with $p_{\mathrm{T}} > 1$ GeV

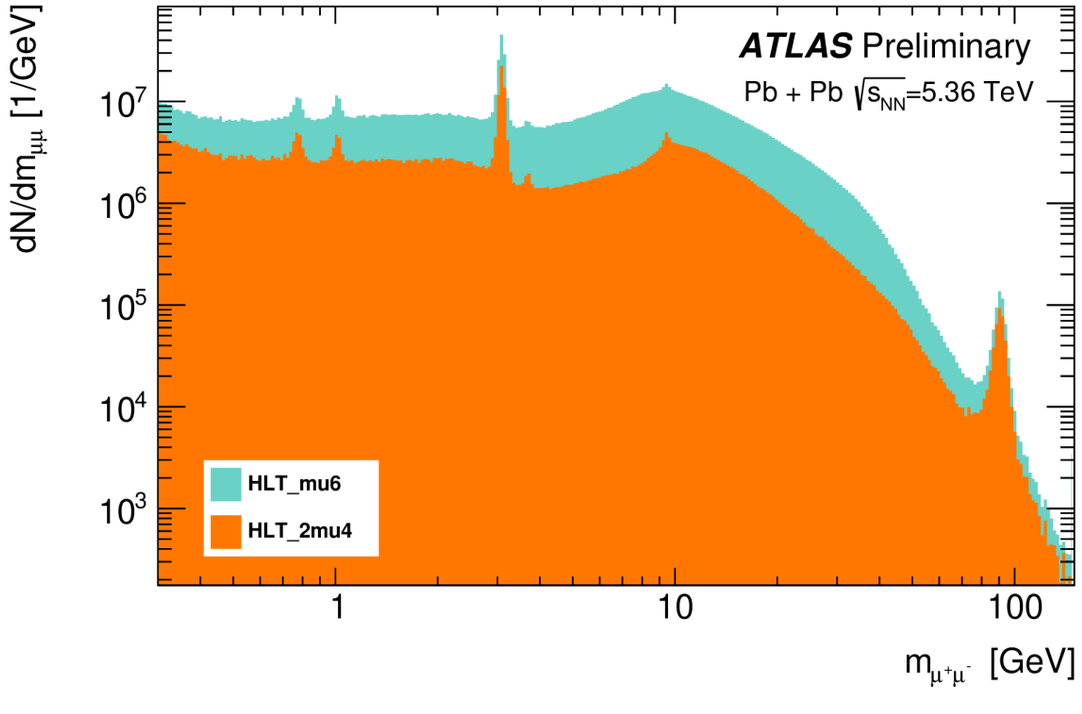
[HION-2023-001]



Trigger



Reconstruction



SUMMARY AND OUTLOOK

- ATLAS provides **precision measurements** based on Run-2 Pb+Pb data at $\sqrt{s_{\mathrm{NN}}} = 5.02\ \mathrm{TeV}$ to constraint initial-state and properties of the **Quark-Gluon Plasma**
- **First observation** of $t\bar{t}$ production is reported in p+Pb and Pb+Pb collisions
  - Analysis methodology established
  - New **unique probe** of the QGP
  - Opens a new avenue for future studies with other decay modes and more data
- Search for **diffusion wake** provides no signal with current sensitivity of the data
- ATLAS continues the physics programme based on **ultra-peripheral collisions**
  - Powerful data to constraint nPDFs
  - Pioneering search of magnetic monopoles with the most stringent limits to date
- **Run 3** is in progress, new 2023-2024 Pb+Pb data set collected at $\sqrt{s_{\mathrm{NN}}} = 5.36\ \mathrm{TeV}$ is on tape with an int lumi of 3.2 nb^{-1}
  - **Significant improvements** in instrumentation, trigger and reconstruction efficiency

- All results from ATLAS available at https://twiki.cern.ch/twiki/bin/view/AtlasPublic/HeavyIonsPublicResults