



XVIII Polish Workshop on Relativistic Heavy-Ion Collisions Strange and Heavy Flavour Physics

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13-14 Dec 2025

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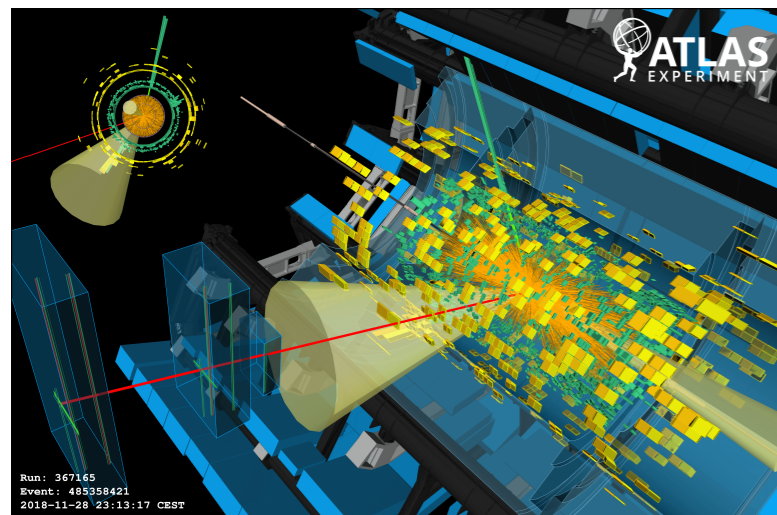
Highlights in heavy-ion physics including strangeness and heavy-flavour production from ATLAS

Iwona Grabowska-Bołd (AGH University of Kraków)

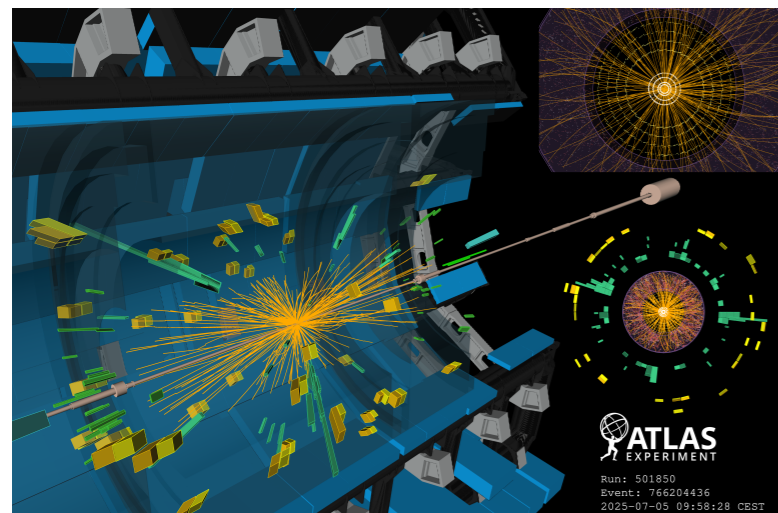
Kraków, December 13th, 2025



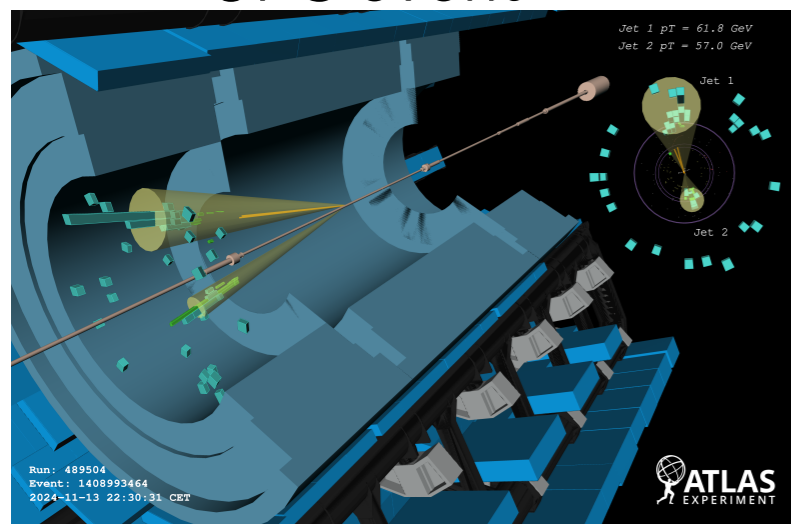
Pb+Pb event



O+O event



UPC event

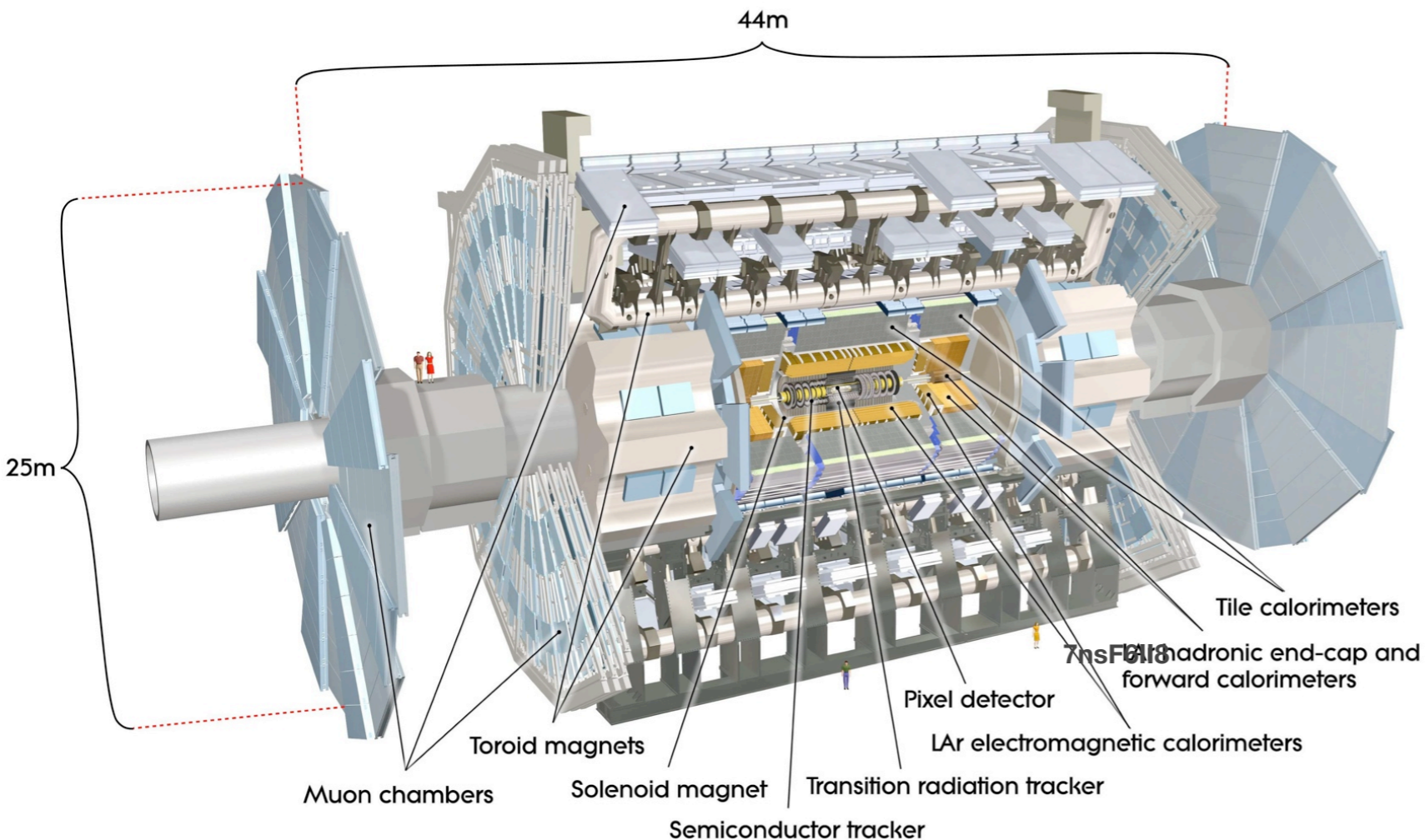


Mostly new results from 2025

- Properties of **Quark-Gluon Plasma (QGP)** produced in **heavy-ion** collisions (HIC)
 - Dijet asymmetry
 - Substructure of large-R jets
 - Observation of top-quarks in p+Pb and Pb+Pb

- Onset of the QGP formation in **light-ion** collisions
 - Dijet asymmetry
 - Flow in oxygen and neon

- Insight into physics of **ultra-peripheral collisions (UPC)**
 - Exclusive ditau production
 - Coherent J/ψ
 - Coincident UPC processes
 - Charged particles in photonuclear collisions



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

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

Muons: inner tracker, muon system

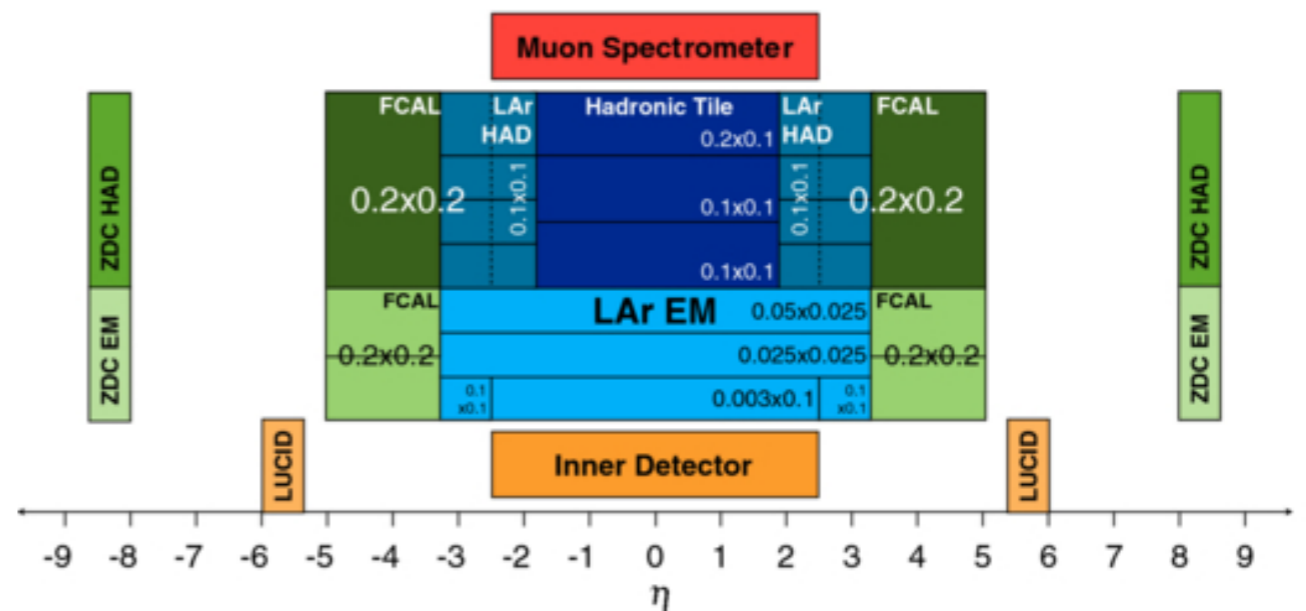
$$p_T^\mu > 15 \text{ (4) GeV for } Z, W^\pm, t\bar{t} \text{ (UPC)}$$

Charged particles: inner tracker

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

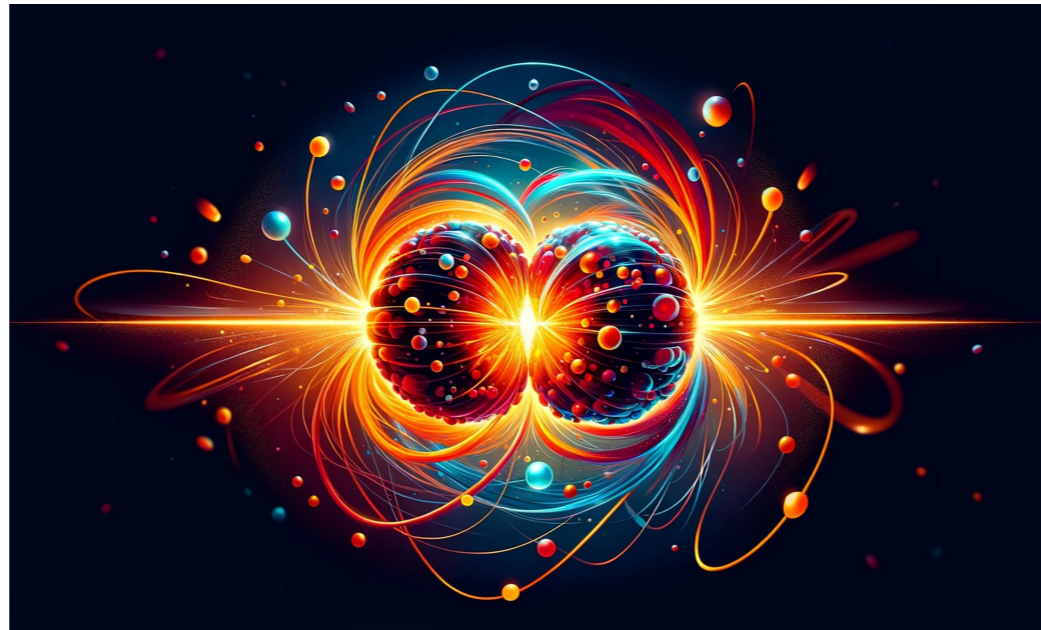
Neutrons: Zero Degree Calorimeter

$$|\eta| > 8$$



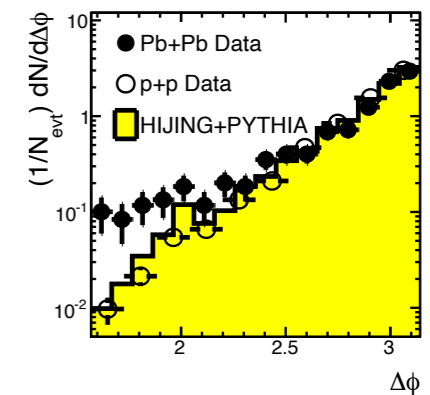
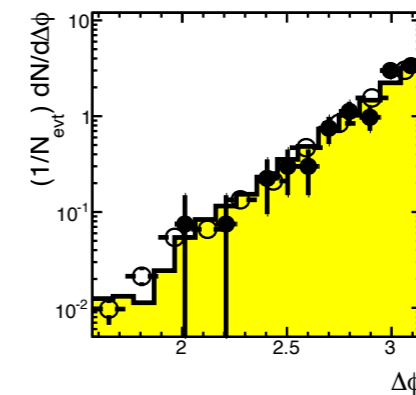
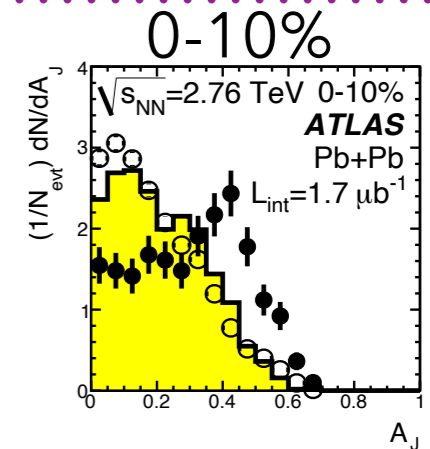
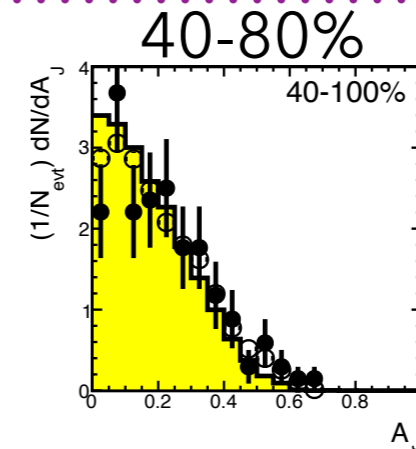
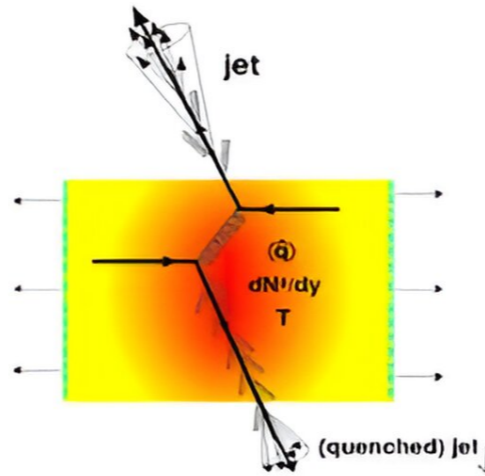
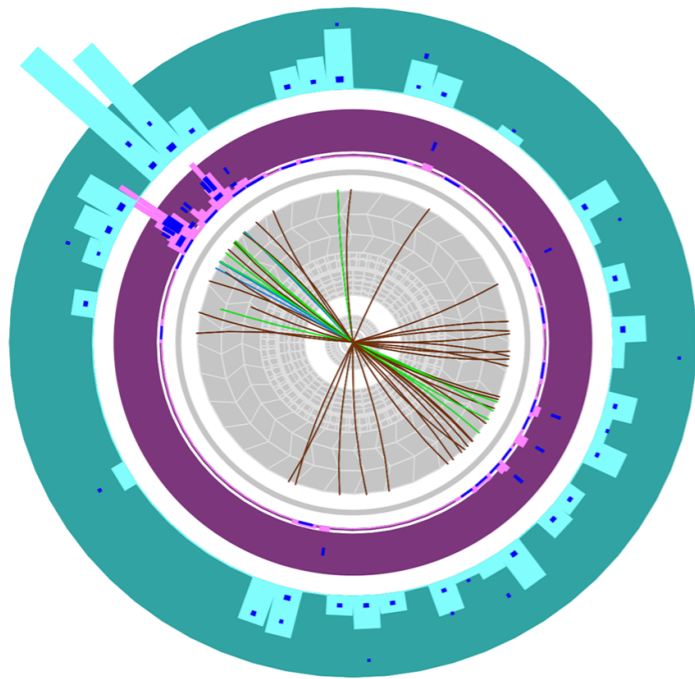
$$|\eta^{\ell, \text{ch}}| \lesssim 2.5$$

INSIGHT INTO THE QGP



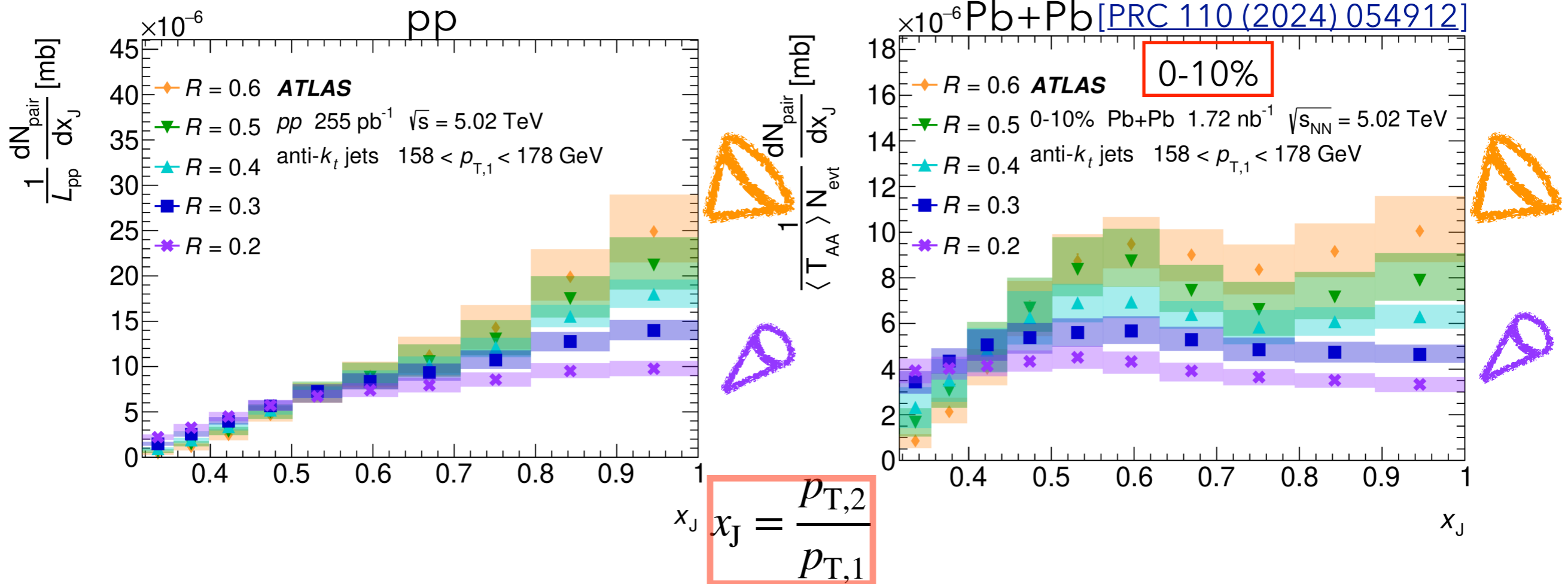
JET QUENCHING WITH DIJET ASYMMETRY

[PRL 105 (2010) 252303]



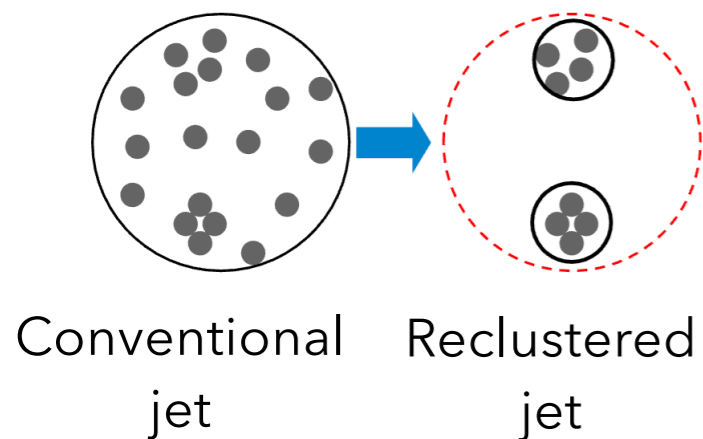
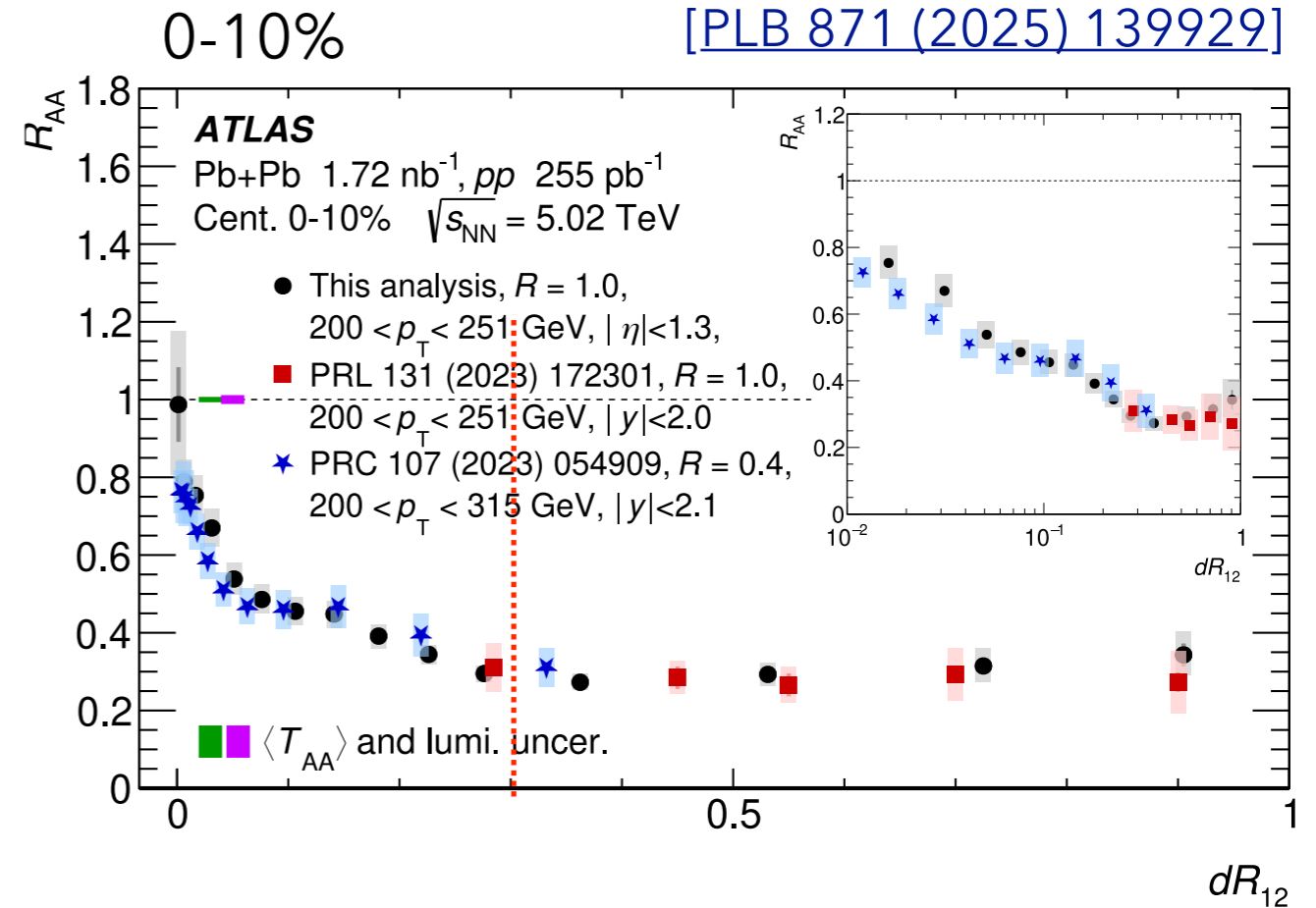
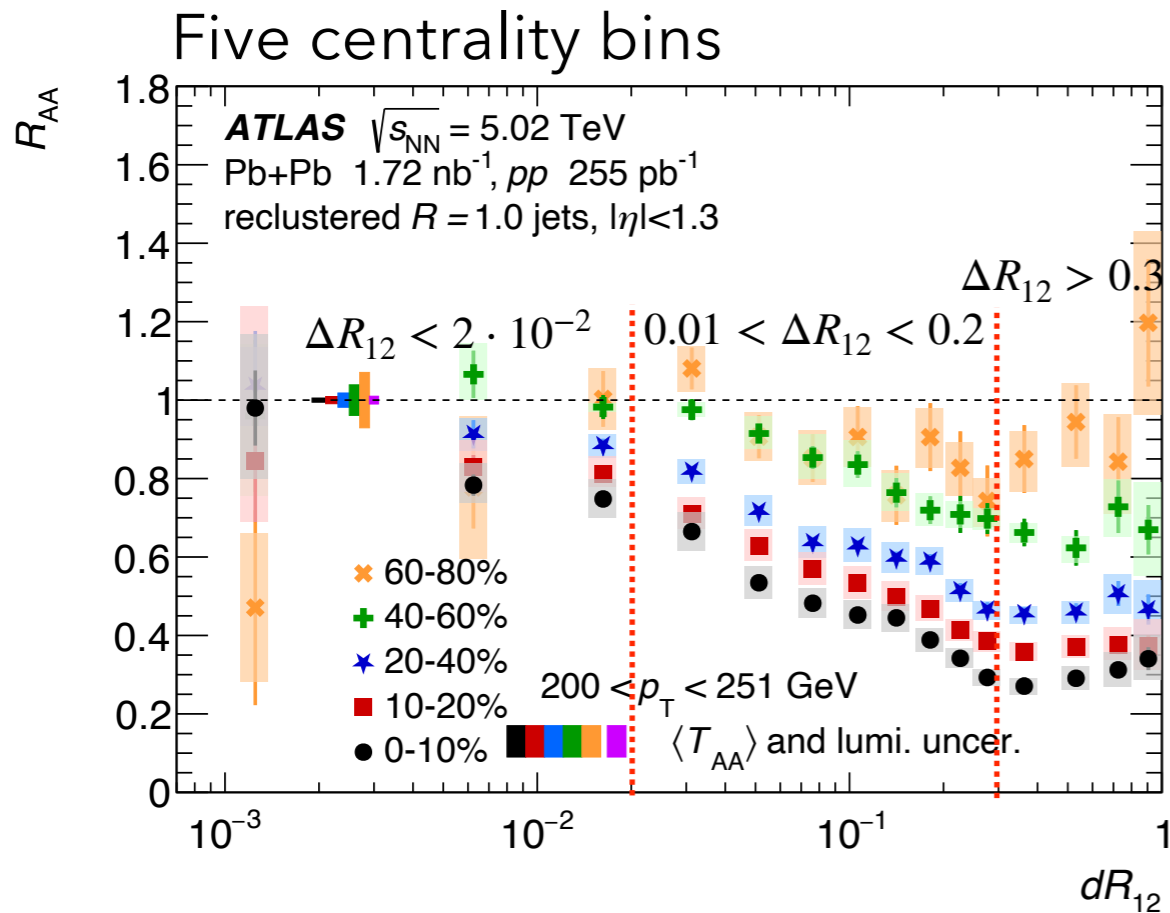
- In **2025** we celebrate the **15th anniversary** of the first HI run
- First Pb+Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV collected in **November 2010**
 - An order of magnitude higher energy comparing to RHIC
 - Larger jet production cross sections comparing to RHIC
- Looking at event displays one could see **jet suppression** by eye
- First direct observation of **jet-quenching** quantified with **dijet asymmetry** $A_J = \frac{E_{T,1} - E_{T,2}}{E_{T,1} + E_{T,2}}$
 - First HI publication in **December 2010** [PRL 105 (2010) 252303]
 - The **4th most cited** ATLAS paper

STATUS OF DIJET ASYMMETRY NOW



- In Run 2, fully **unfolded** measurements, study of **jet-radius** dependance, comparisons to **reference pp** data, **updated observable** x_J (momentum imbalance), also **Xe+Xe** system
- x_J peaked at unity 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

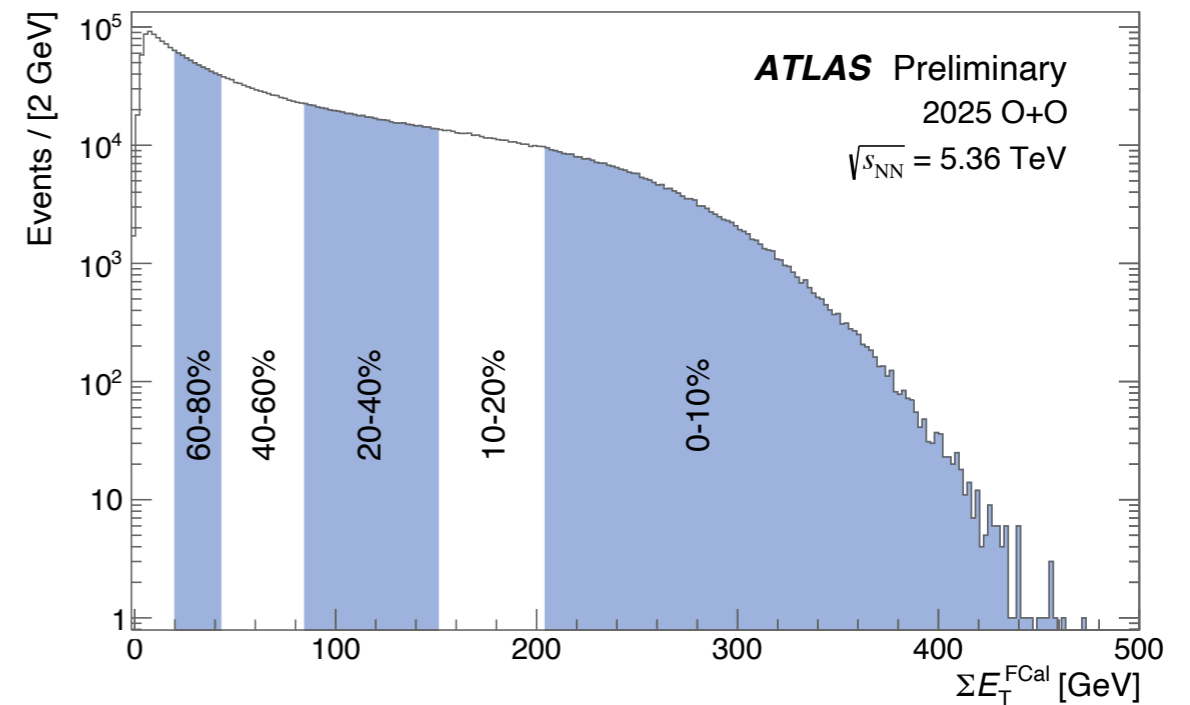
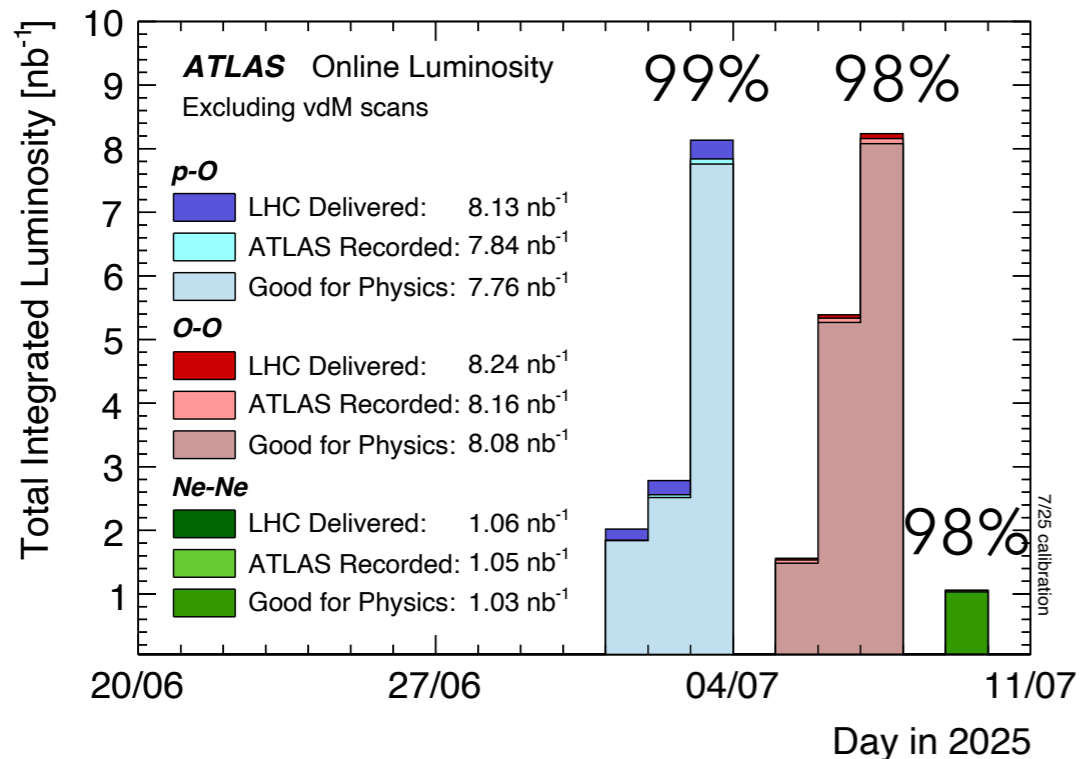
JET SUBSTRUCTURE WITH TRACKS



- **Large-radius jets** with radius $R = 1.0$ with $p_T > 200 \text{ GeV}$ and $|\eta| < 1.3$
- Jet substructure evaluated with **charged-particle tracks** with $p_T > 4 \text{ GeV}$
- R_{AA} is measured as a function of **angular separation**

$$\Delta R_{12} = \sqrt{(\Delta y_{12})^2 + (\Delta \phi_{12})^2}$$
- R_{AA} **decreases** for $0.01 < \Delta R_{12} < 0.2$, while for $\Delta R_{12} > 0.3$ R_{AA} values tend to be **constant** for all centralities, this change of behaviour might be connected with the **onset of coherent radiation**
- Measurement **consistent** with the previous published results from ATLAS

[ATLAS-CONF-2025-010]



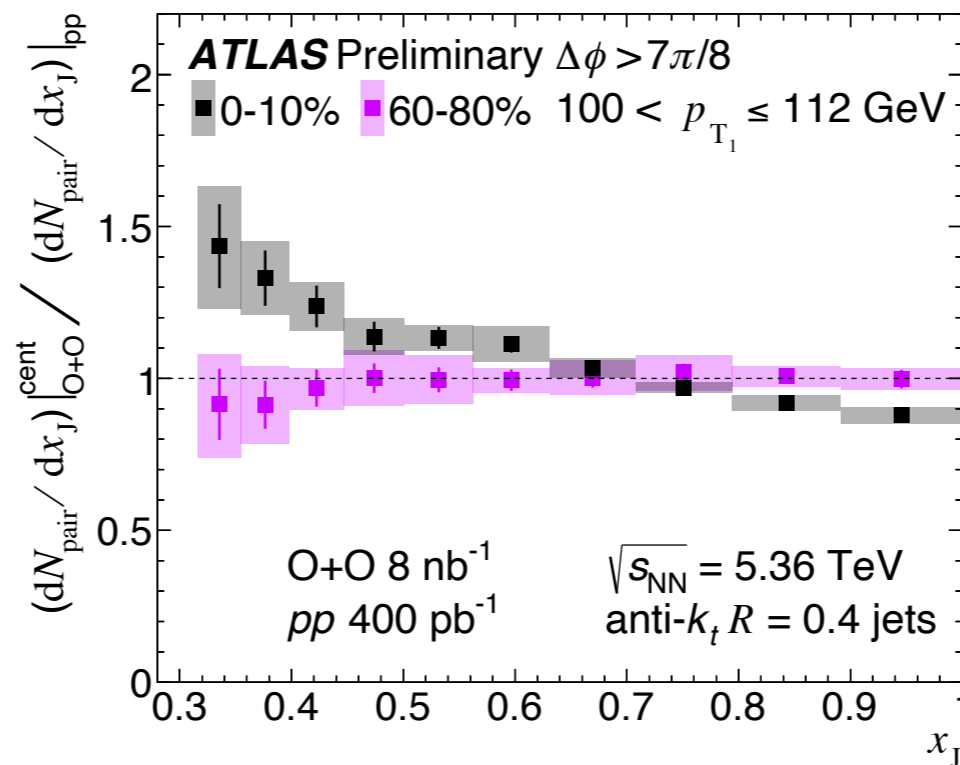
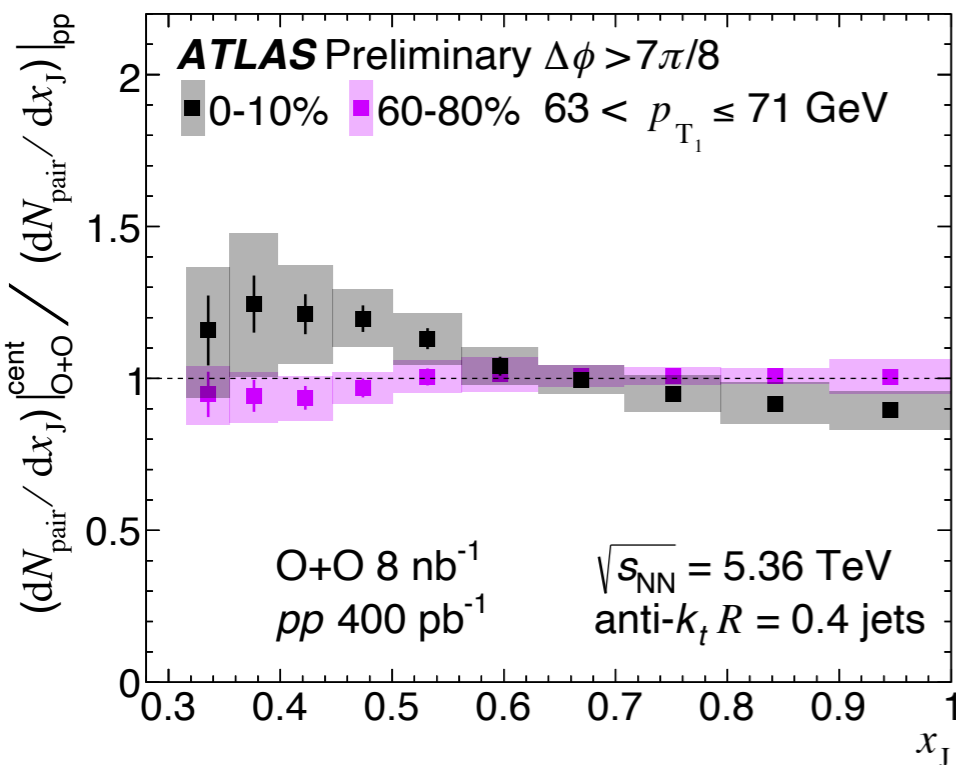
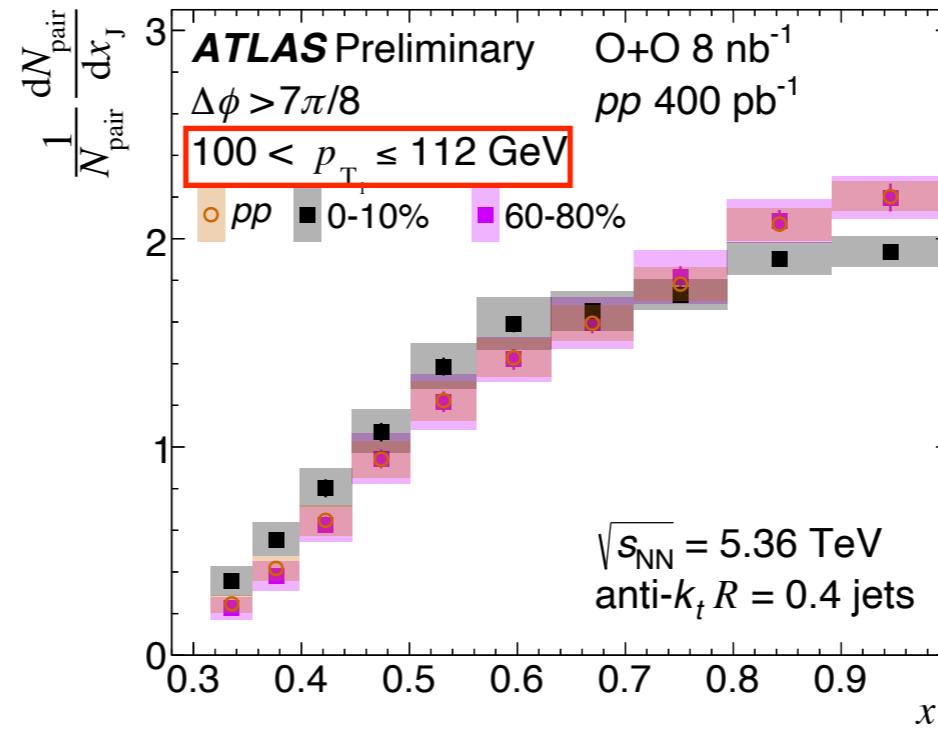
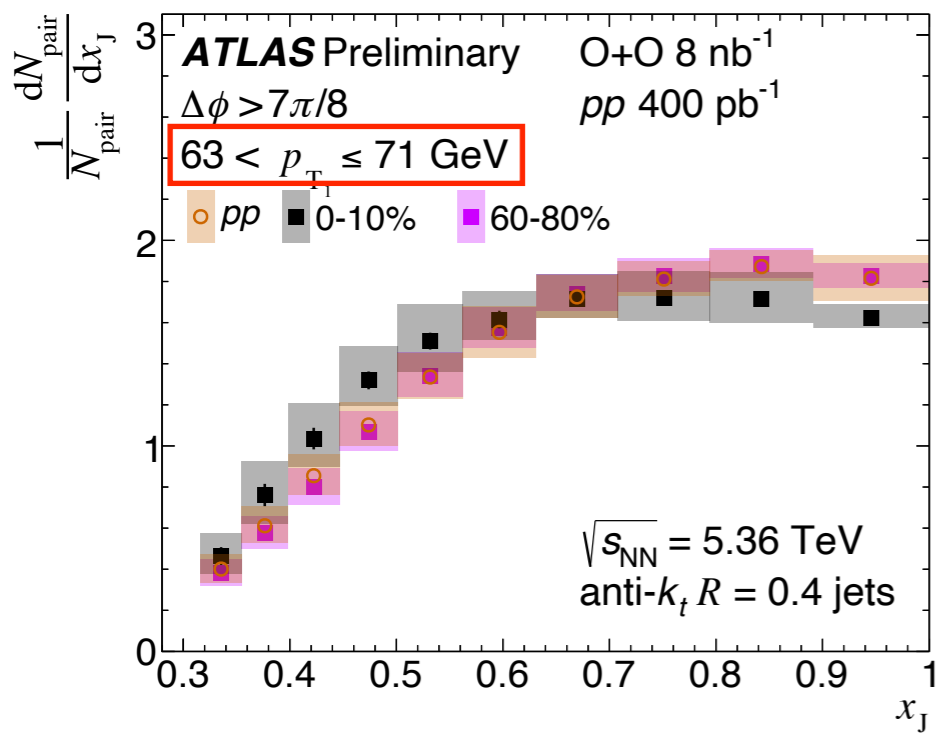
- In **July 2025**, **proton-oxygen (p+O)**, **oxygen-oxygen (O+O)** and **neon-neon (Ne+Ne)** collisions at the LHC
 - **O+O collisions** at $\sqrt{s_{NN}} = 5.36$ TeV with $L_{int} = 8$ nb⁻¹
 - Exceptional performance of the LHC, **98%** good for physics
 - Small system with FCal sum $E_T < 500$ GeV
 - Unique opportunity to search for an **onset of energy-loss effects**
 - Centrality calibration available

DIJET ASYMMETRY IN LIGHT IONS

[ATLAS-CONF-2025-010]

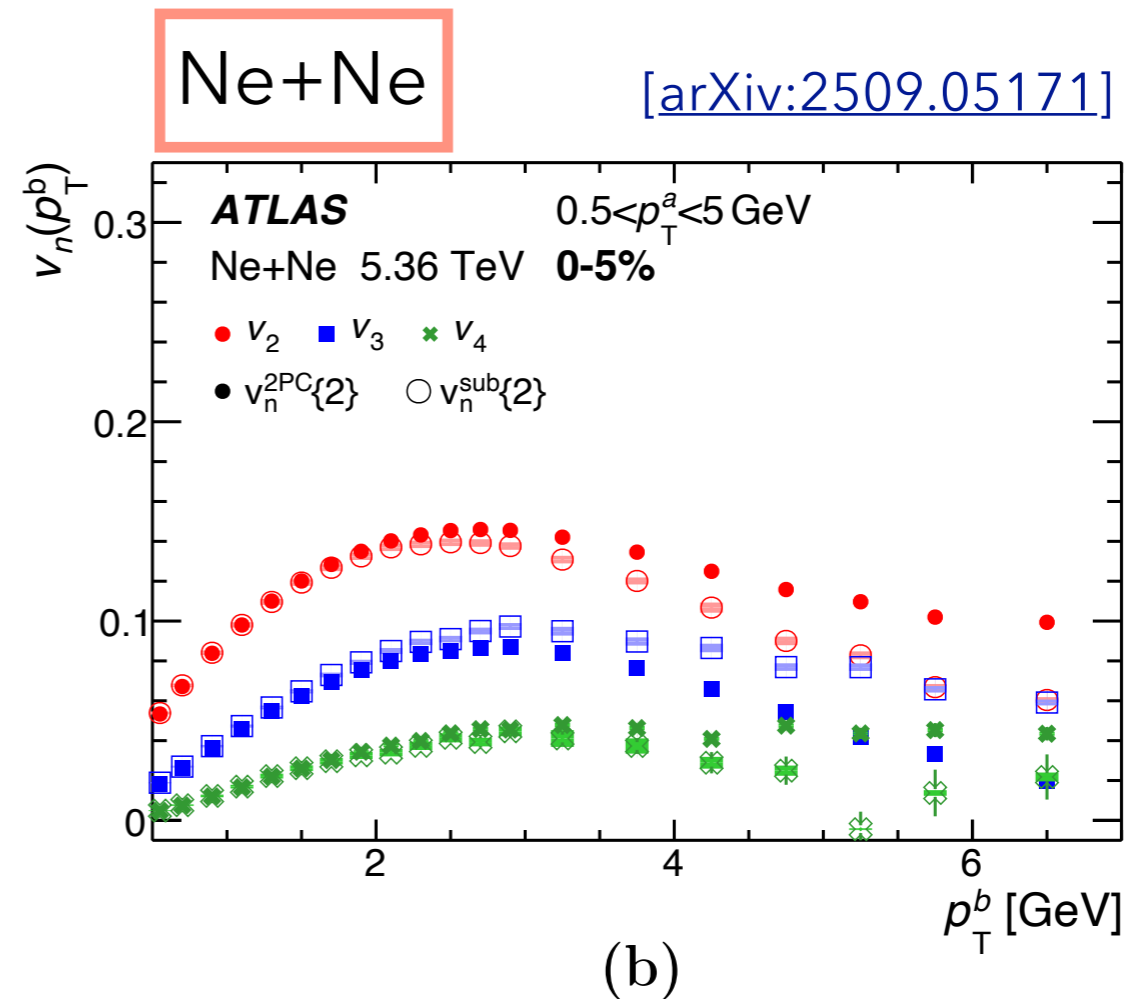
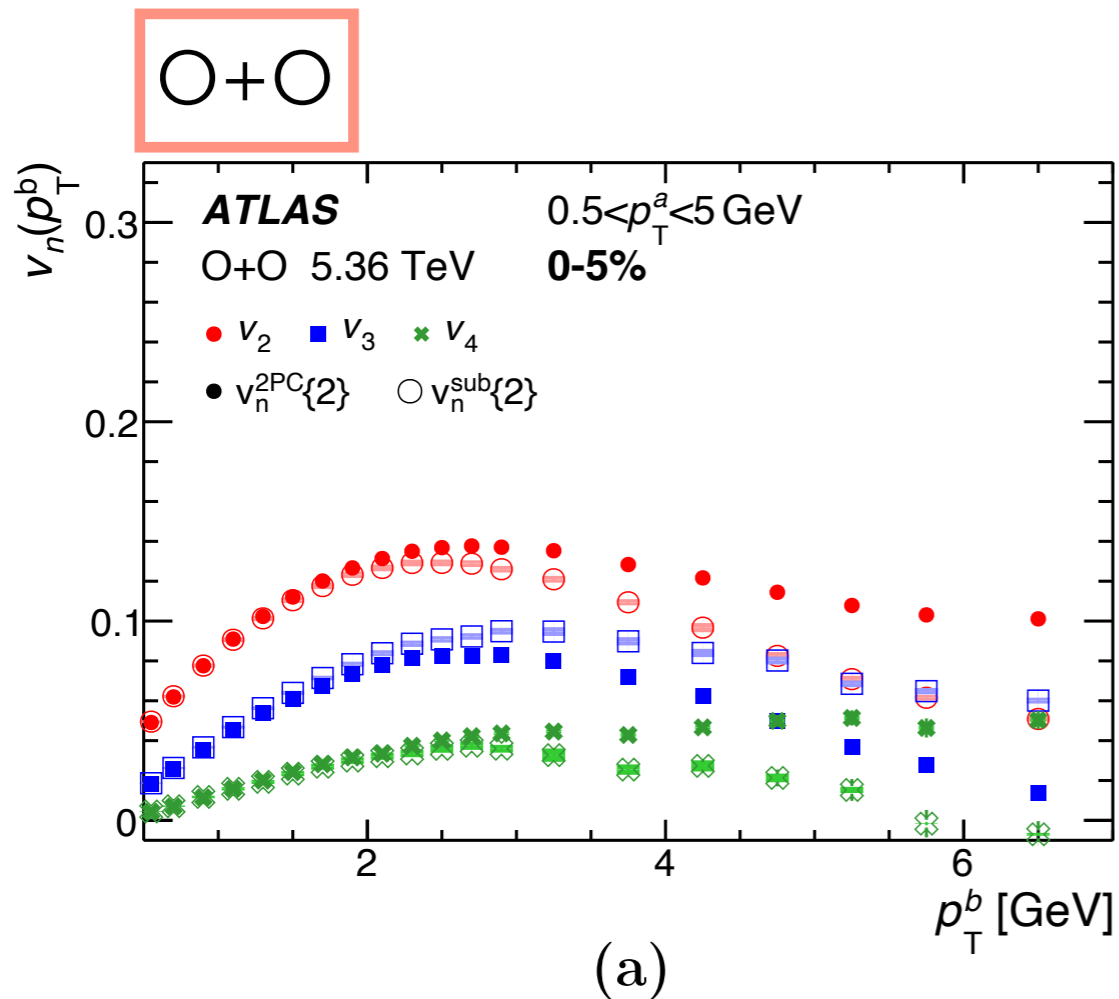
$63 < p_{T,1} < 71$ GeV

$100 < p_{T,1} < 112$ GeV

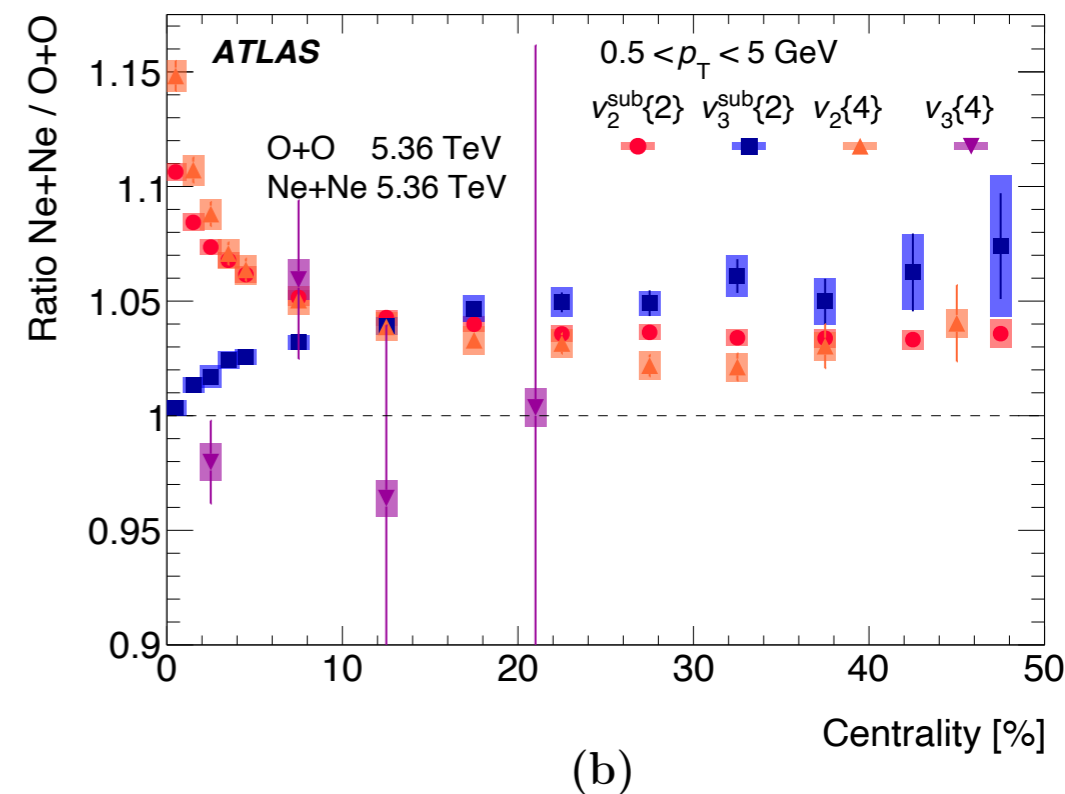
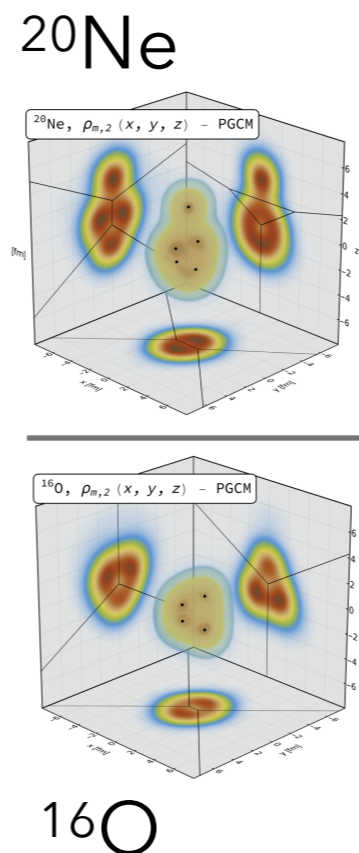
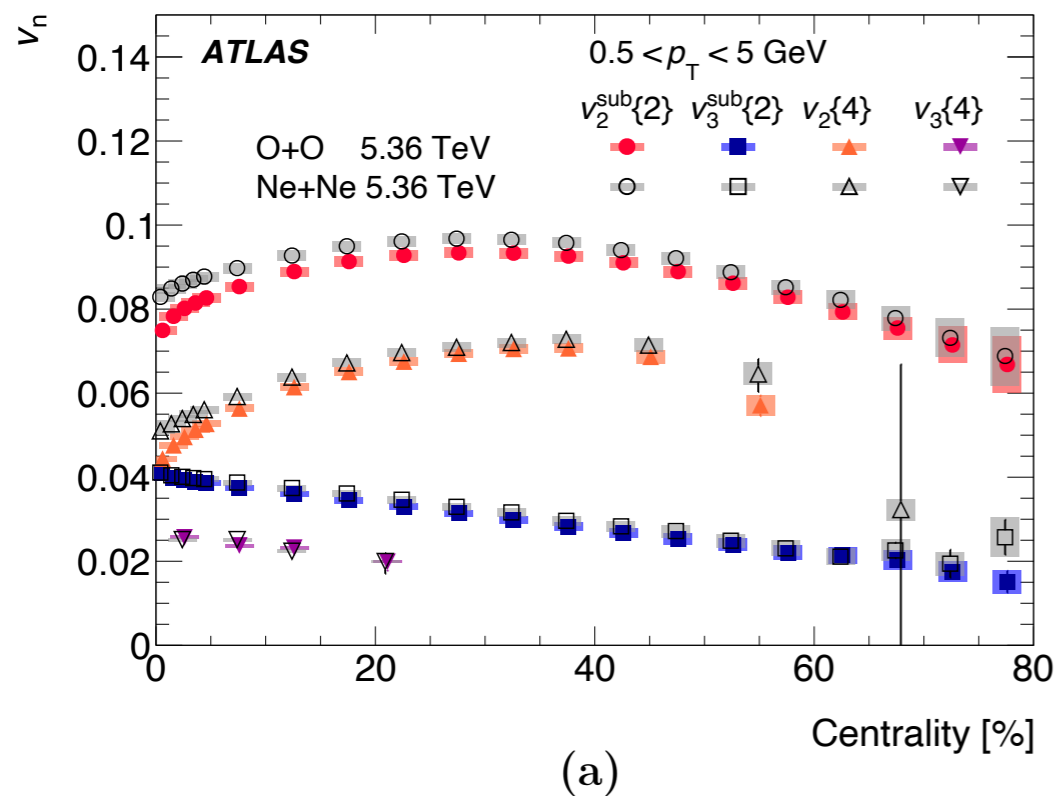


► Identical method and jet selection as in Pb+Pb and Xe+Xe analysis

- Leading jets from 63 - 251 GeV
- In Pb+Pb collisions leading jets are > 100 GeV
- However, smaller UE in O+O allow to push to lower jet p_T
- No significant difference between **pp** and **peripheral O+O**
- No significant $p_{T,1}$ dependence
- Increase in x_J between **pp** and **central O+O** collisions



- Probe of **initial state** using momentum anisotropy
- Azimuthal anisotropy coefficients v_n with $n=2-4$ in $\sqrt{s_{NN}} = 5.36$ TeV $^{16}\text{O}+^{16}\text{O}$ and $^{20}\text{Ne}+^{20}\text{Ne}$ collisions
- Clear **hierarchy** between flow harmonics: $v_2 > v_3 > v_4$
- Strong influence of **non-flow** beyond 3 GeV
- Qualitatively **similar** to observations from **large systems**

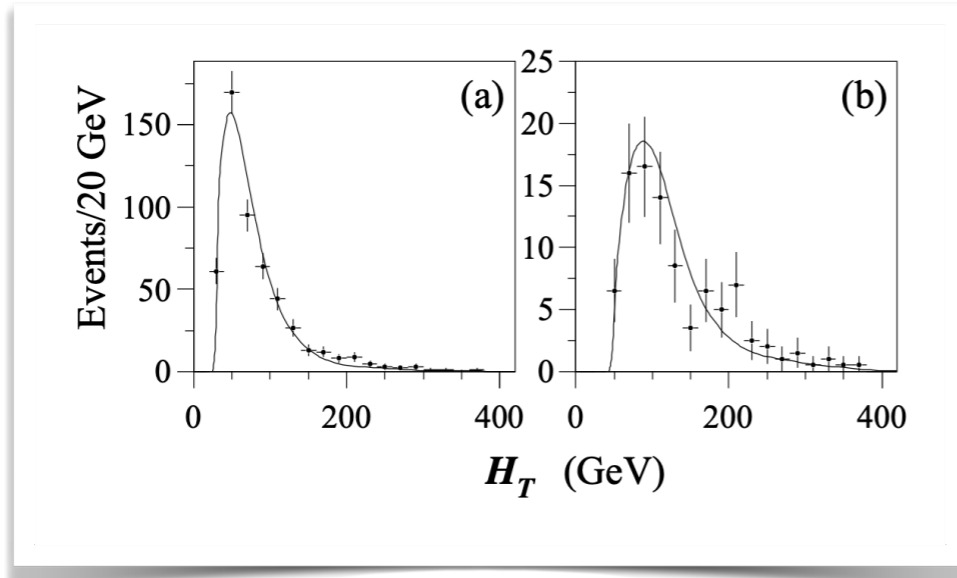


- Azimuthal anisotropy coefficients v_n with $n=2-4$ in $\sqrt{s_{\text{NN}}} = 5.36$ TeV $^{16}\text{O}+^{16}\text{O}$ and $^{20}\text{Ne}+^{20}\text{Ne}$ collisions
 - Test similar-size systems with drastically different geometry
- $v_2\{2\}$ **larger** for Ne+Ne than O+O
- $v_3\{2\}$ is also **larger** at fixed centrality
- $v_n\{4\}$ **lower** than $v_n\{2\}$ due to large fluctuation component in $v_n\{2\}$
- $v_2\{k\}$ **enhancement** in Ne+Ne **up to 15%** → **evidence** of the **elongated shape** of Ne

OBSERVATION OF TOP QUARKS IN P+PB

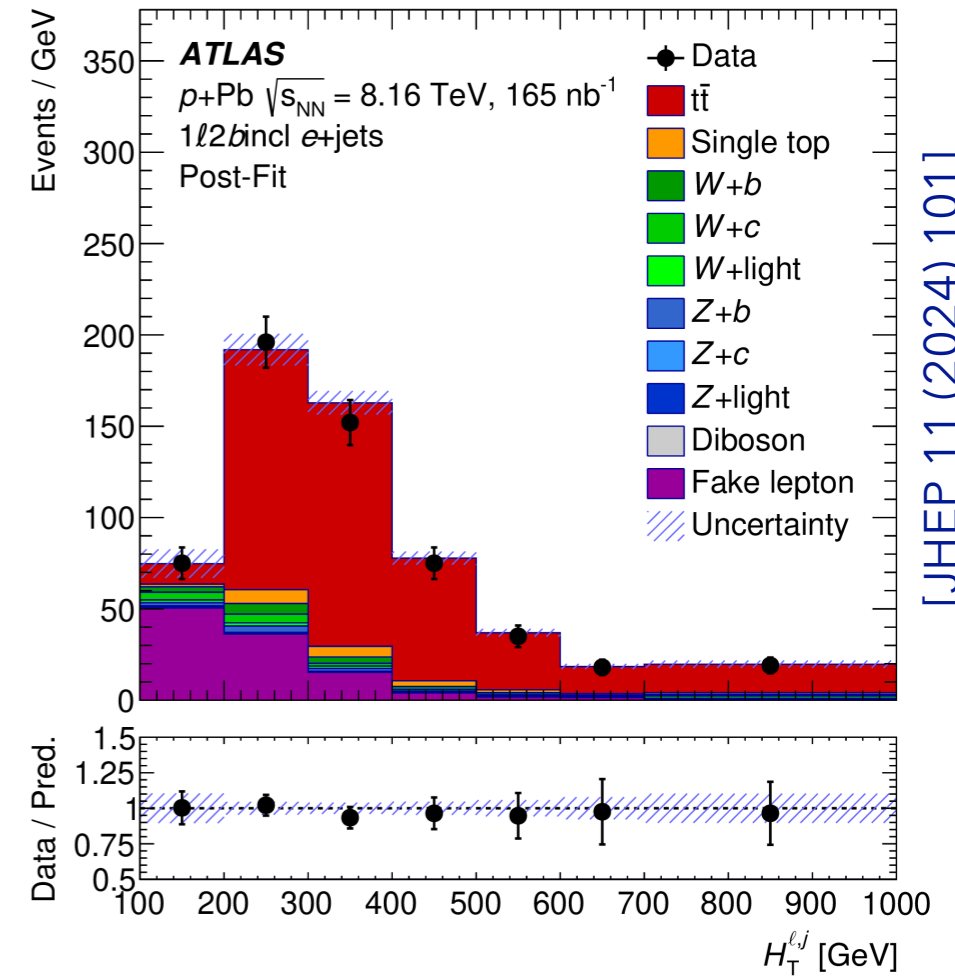
➤ In 2025: **30th anniversary** of the top-quark **discovery** at **Tevatron** [[PRL 74 \(1995\) 2632](#)]

- **Dilepton** and **lepton+jets** channels investigated
- **17 observed** event candidates with 3.8 ± 0.6 backgrounds

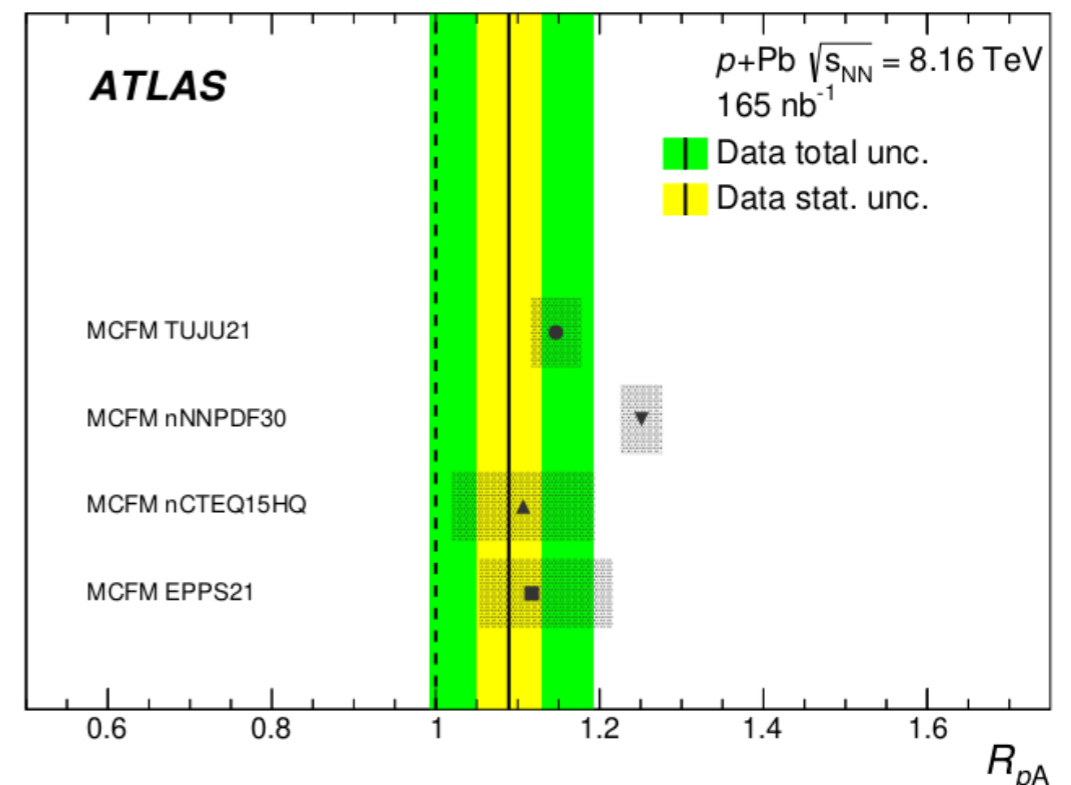


➤ Top quarks **observed** in **p+Pb** collisions at $\sqrt{s_{NN}} = 8.16$ TeV with $L_{int} = 165$ nb⁻¹

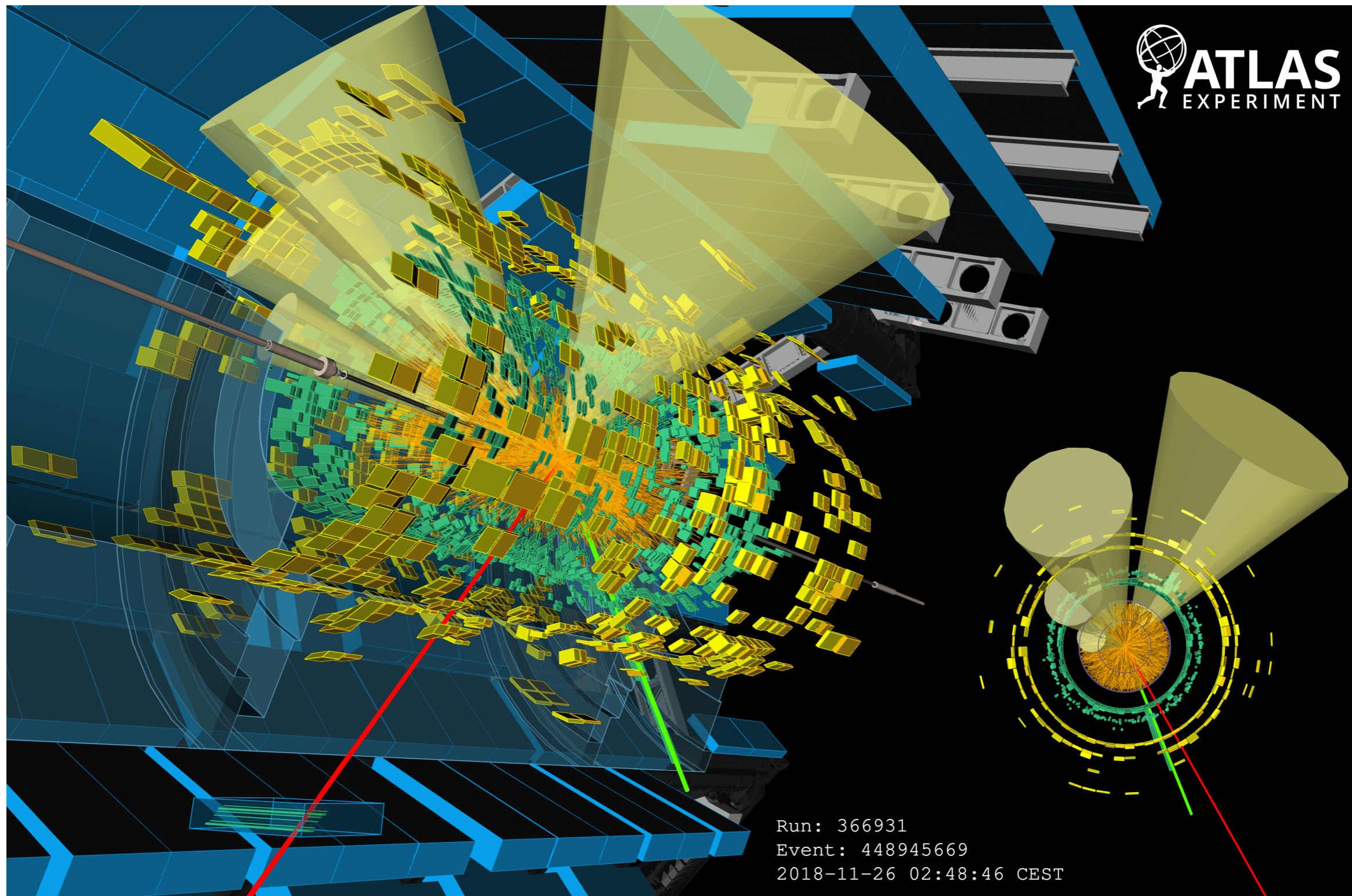
- **Lepton+jet** and **dilepton** channels (BR= \sim 50%) investigated
- Use $H_T^{\ell j}$ distribution with $\ell = e, \mu$ to extract signal
- $R_{pA} = 1.090 \pm 0.039$ (stat.) $\pm_{0.087}^{0.094}$ (syst.) with a hint of nuclear modifications to PDF



[JHEP 11 (2024) 101]



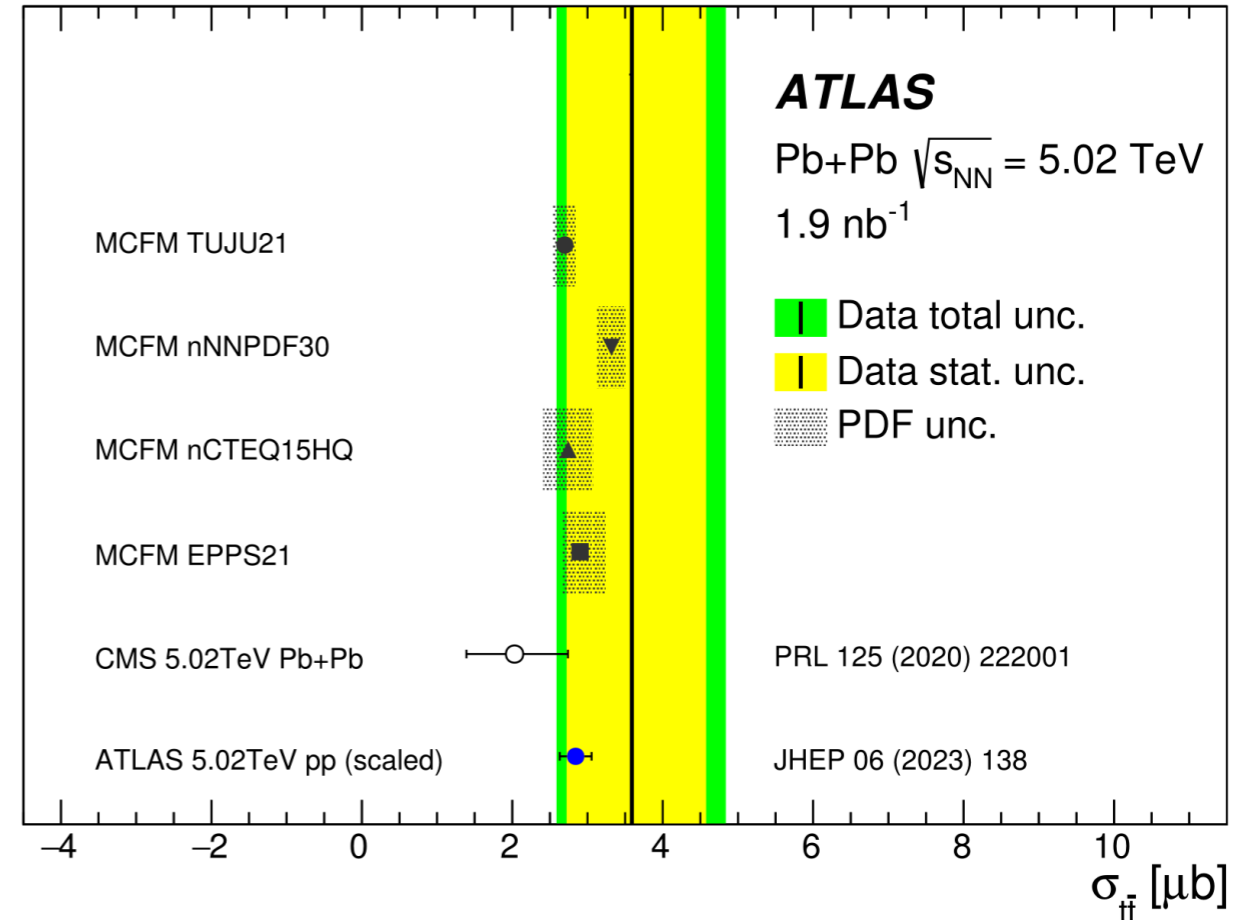
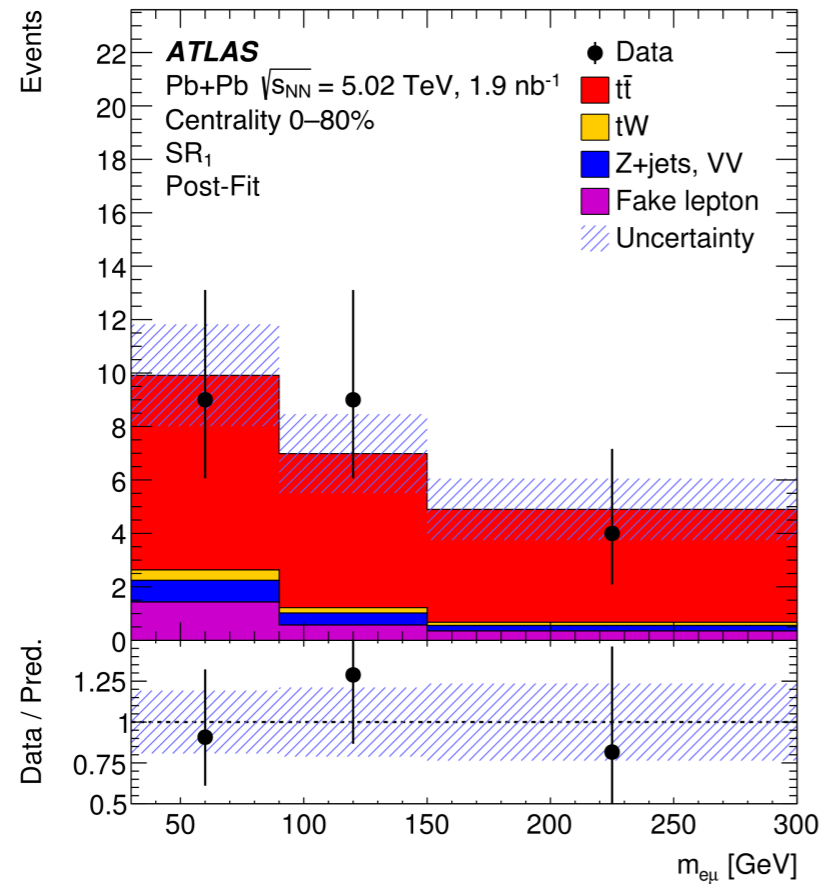
$t\bar{t}$ EVENT CANDIDATE IN $PB+PB$



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

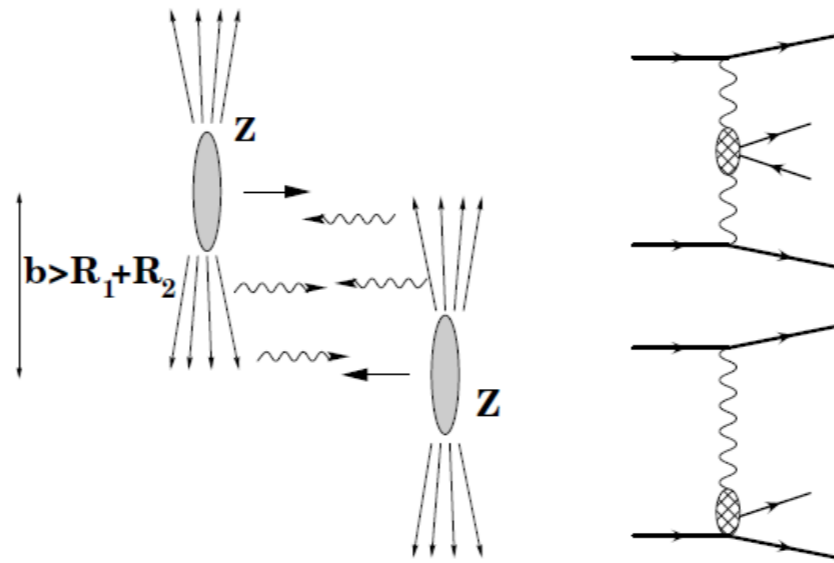
OBSERVATION OF TOP QUARKS IN Pb+Pb

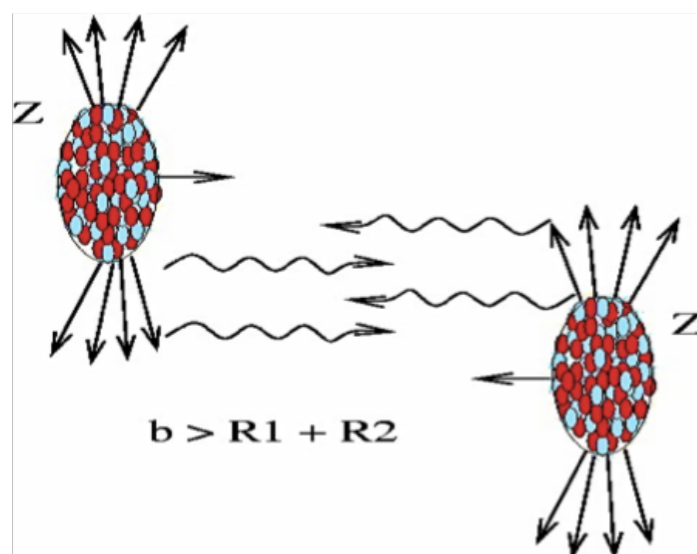
[PRL 134 (2025) 142301]



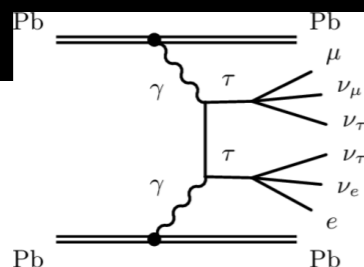
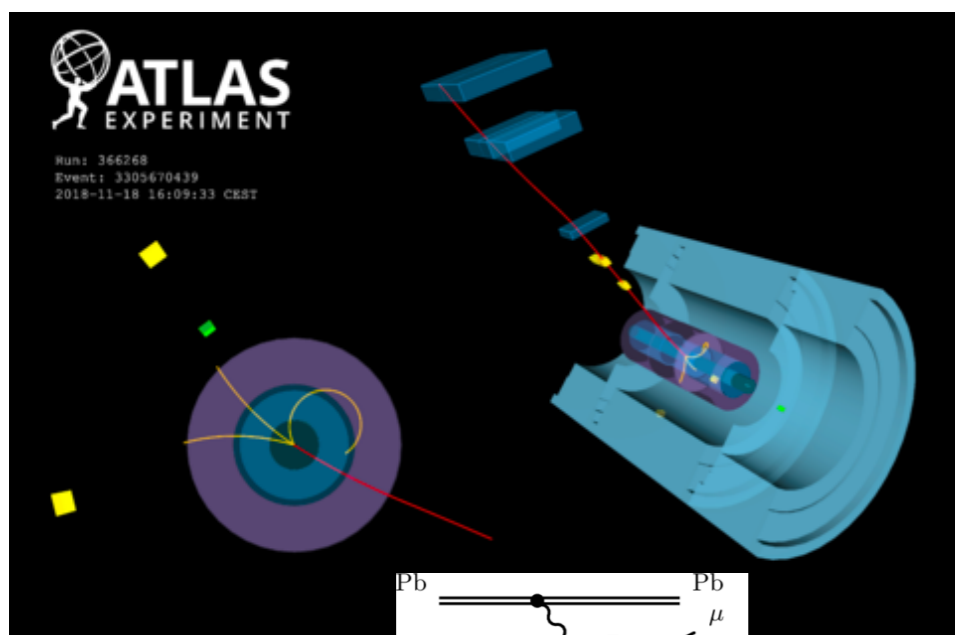
- 30 years after the discovery, $t\bar{t}$ production **observed** with significance of 5.0 standard deviations in Pb+Pb collisions at $\sqrt{s_{\text{NN}}} = 5.02 \text{ TeV}$ with $L_{\text{int}} = 1.9 \text{ nb}^{-1}$
 - **First observation** of $t\bar{t}$ in HIC collisions at the LHC
 - Cross section: $\sigma_{t\bar{t}} = 3.6 \pm_{0.9}^{1.0} \text{ (stat.)} \pm_{0.5}^{0.8} \text{ (syst.)} \mu\text{b}$
 - 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



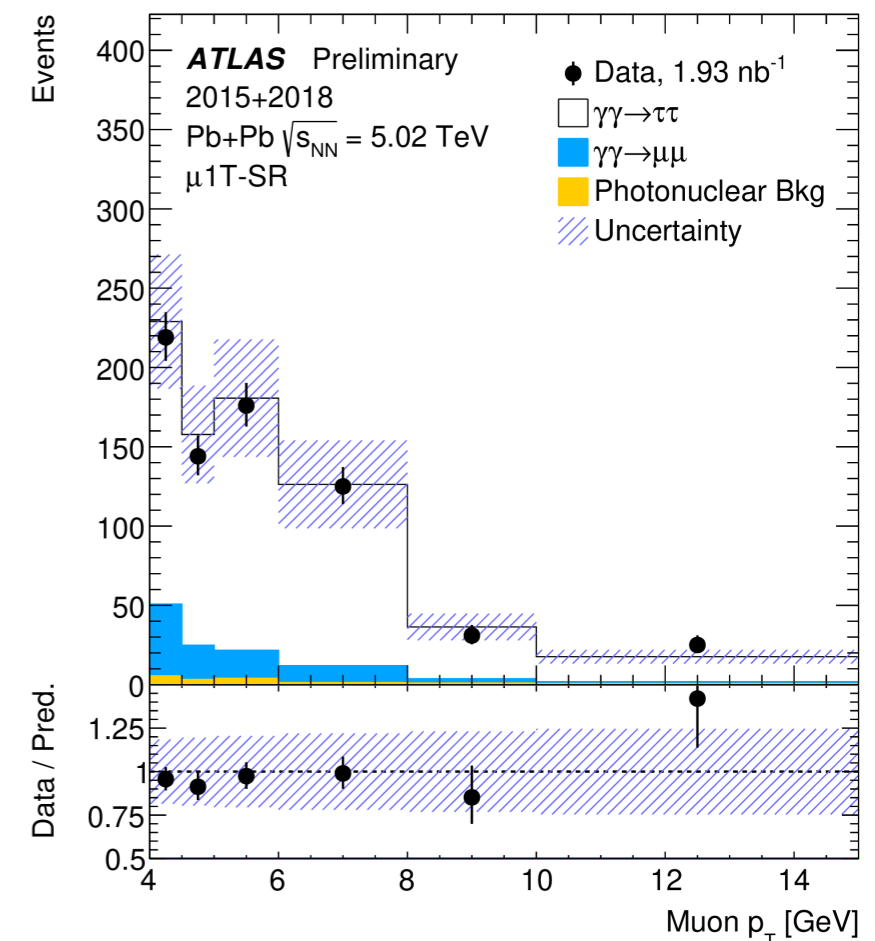
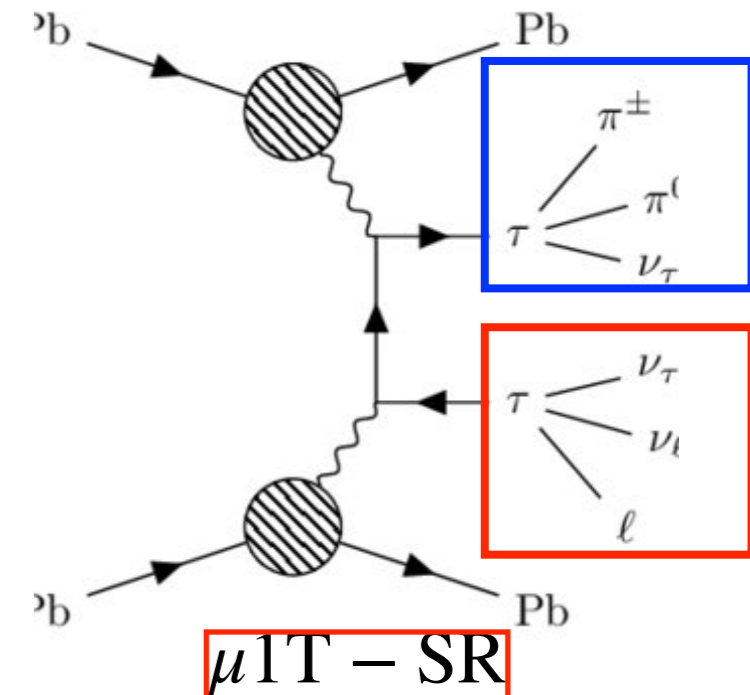


- **Ultra-peripheral collisions (UPC)** of lead-lead (Pb+Pb) have attracted a lot of attention in the heavy-ion community
 - **Photon fluxes** in the Equivalent Photon Approximation (EPA) framework
 - Photon-induced processes: $\gamma\gamma$ or γA (photonuclear)
 - For $\gamma\gamma$, Z^4 ($\approx 4.5 \times 10^7$) **enhancement** of cross sections in Pb+Pb wrt pp collisions
 - $\gamma\gamma$ collisions prove to be a competitive tool for **searches for beyond Standard Model (BSM) physics**
 - **Zero Degree Calorimeters (ZDC)** offer control over backgrounds and impact-parameter dependence
 - UPC events feature very **low detector activity**



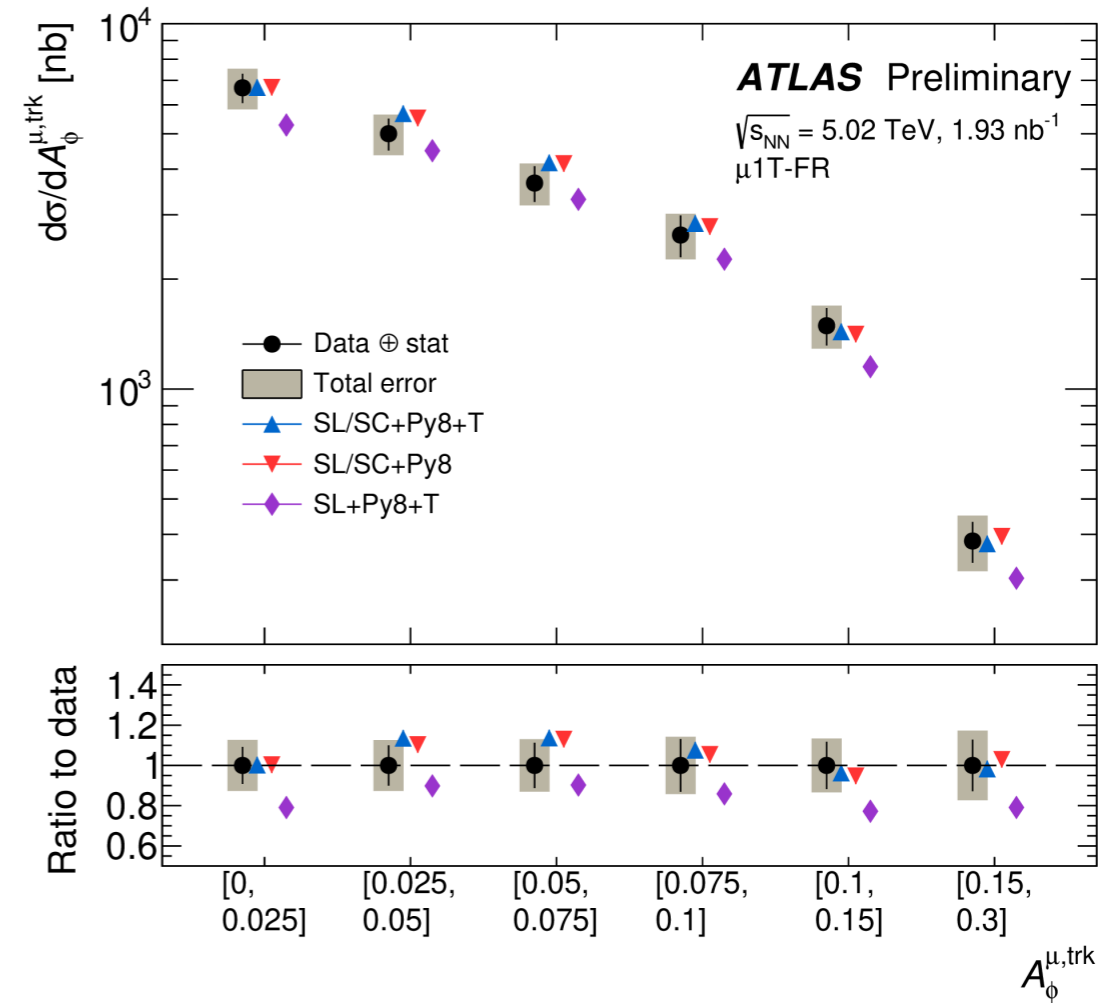
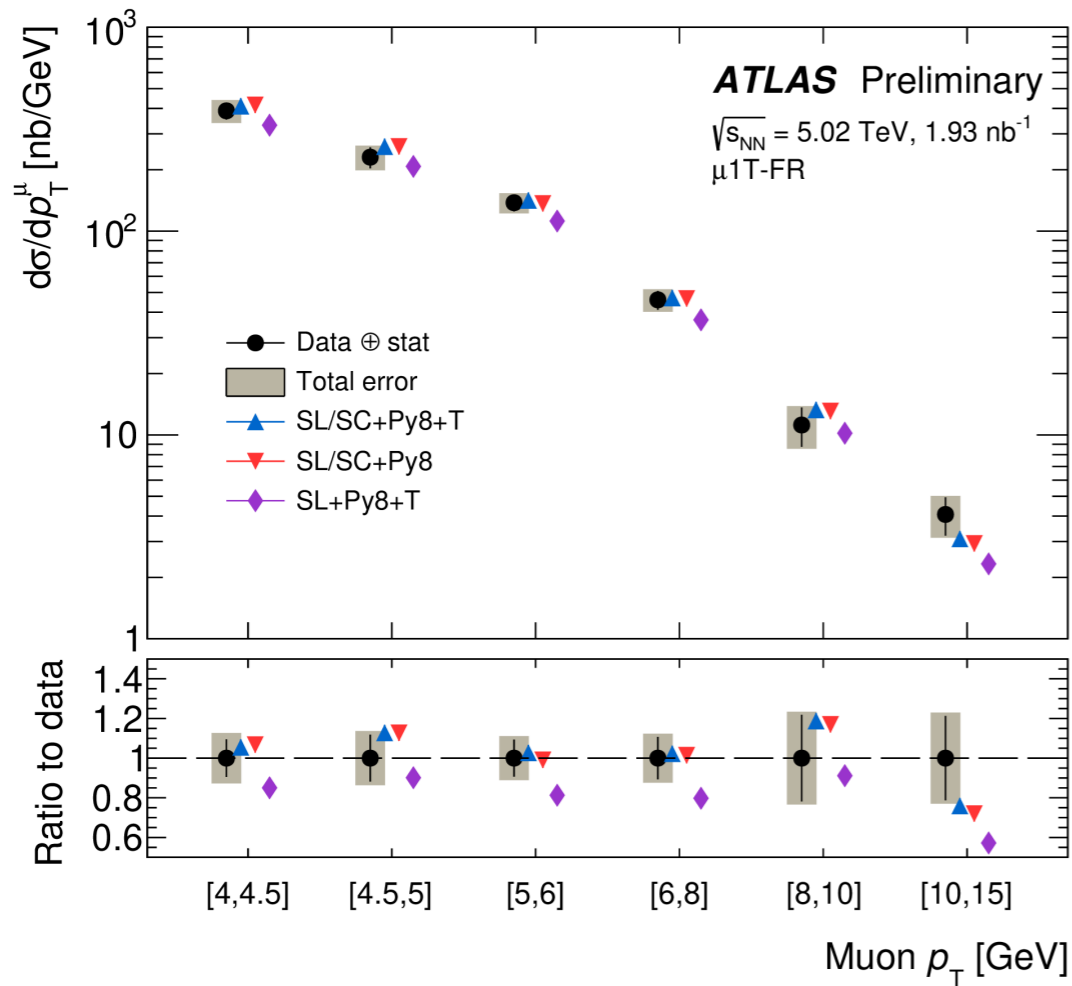
- **First observation** of $\gamma\gamma \rightarrow \tau^+\tau^-$ in Pb+Pb collisions in **2018**
UPC Pb+Pb collisions of 1.44 nb^{-1} [[PRL 131 \(2023\) 151802](#)]
 - **2nd analysis** uses the same methodology, new features:
 - **2015 data** with 0.49 nb^{-1} added
 - Differential cross sections measured
 - Exclusive ditau production $\gamma\gamma \rightarrow \tau^+\tau^-$ with **(semi)leptonic decay** modes
 - $\mu 1T\text{-SR}$: muon + 1 track (e/ μ /hadron)
 - $\mu 3T\text{-SR}$: muon + 3 tracks (3 hadrons)
 - $\mu e\text{-SR}$: muon + electron
- with $p_T^\mu > 4 \text{ GeV}$, $p_T^e > 4 \text{ GeV}$, $p_T^{\text{trk}} > 100 \text{ MeV}$
 $p_T^{\text{clus}} > 1 \text{ GeV}$ ($|\eta| < 2.5$)
 $p_T^{\text{clus}} > 100 \text{ MeV}$ ($2.5 < |\eta| < 4.5$)
- Exclusivity: veto additional clusters ($\mu 1T\text{-SR}$ and $\mu 3T\text{-SR}$ only) and tracks
 - **Data** w/o forward neutron emission (**0n0n**) used to suppress photonuclear/hadronic backgrounds
 - **Backgrounds:** $\gamma\gamma \rightarrow \mu^+\mu^-(\gamma)$ and photonuclear (<15%)

[ATLAS-CONF-2025-004]



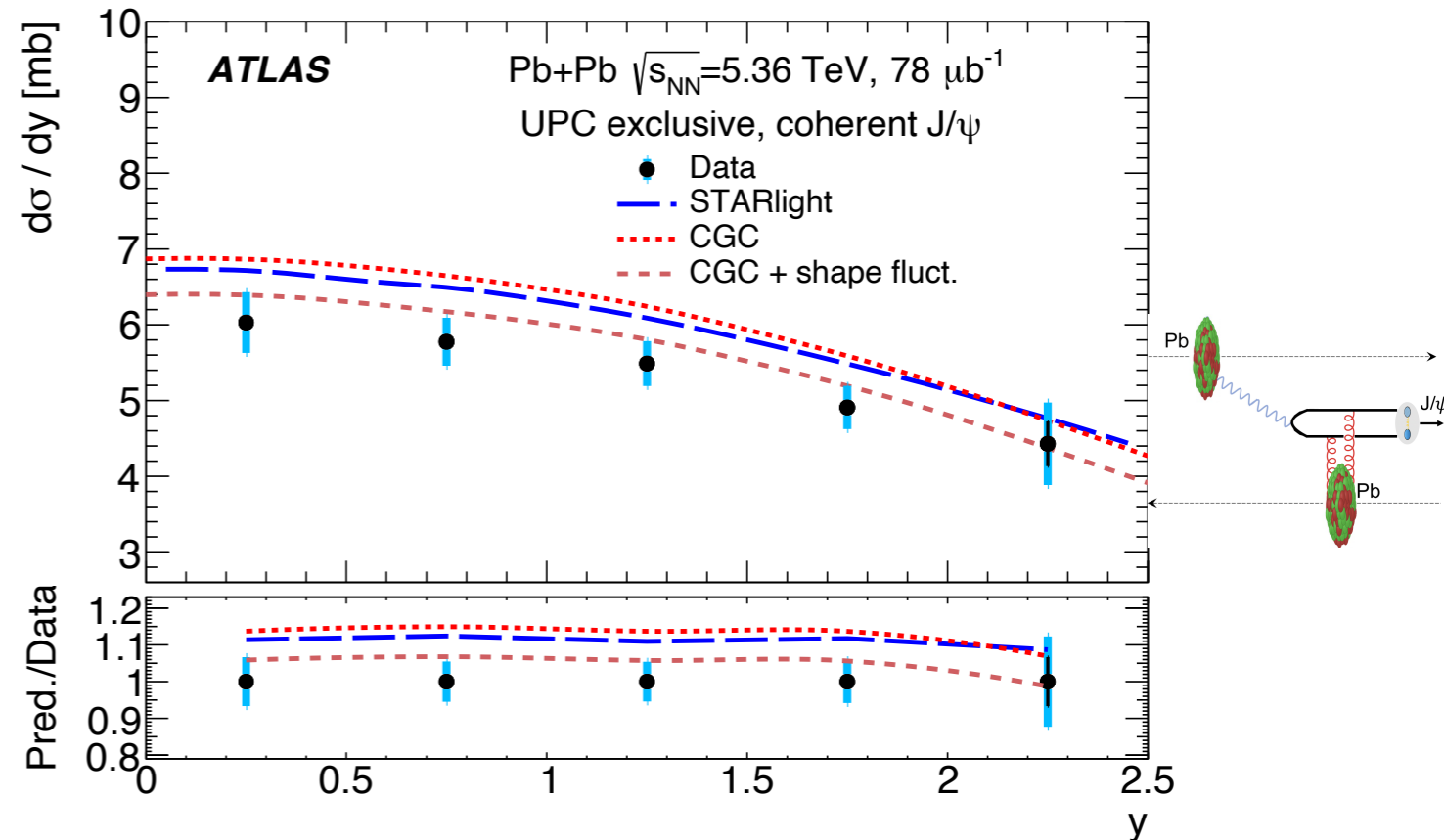
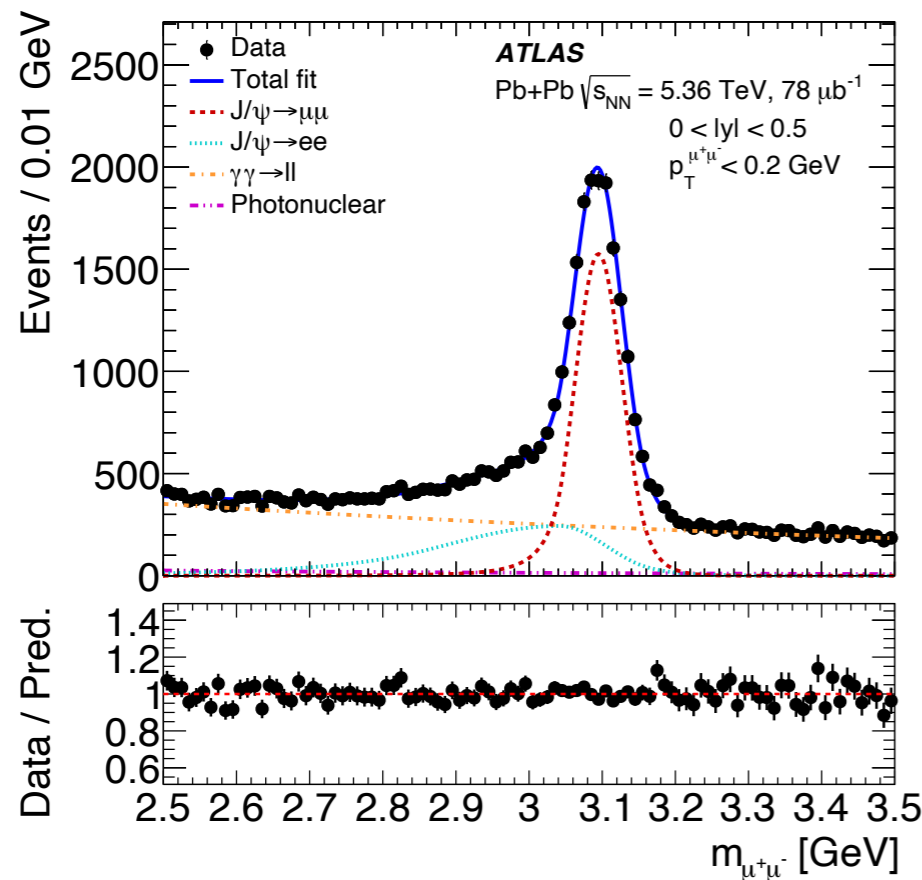
[ATLAS-CONF-2025-004]

$\mu 1T - SR$



- Data corrected for detector effects through an iterative Bayesian unfolding procedure
- **Differential fiducial cross sections** measured for **seven kinematic variables** representing τ decay products
 - Precision limited by statistical uncertainty
- Cross sections are largely **compatible** with **the theoretical predictions** within measurement uncertainties
 - StarLight is 10-30% below the data (SL+Py8+T)
- In the future cross sections can also be used to extract a_τ and d_τ

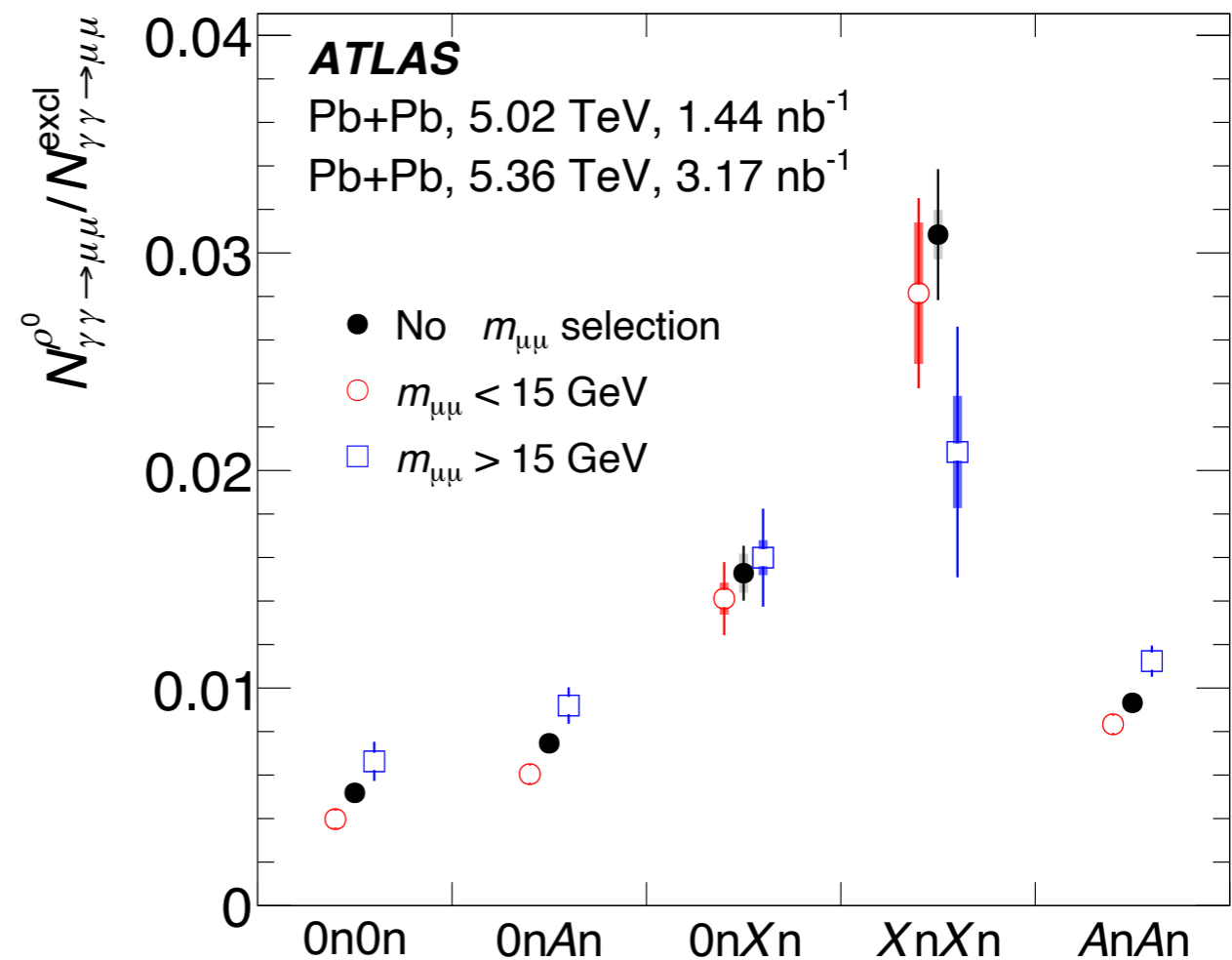
[arXiv:2509.04135]



- Dedicated **L1 TRT trigger** to collect low p_T muons in Run 3 in ATLAS
- Differential cross section for **exclusive coherent J/ψ** is measured as a function of J/ψ rapidity in UPC Pb+Pb at $\sqrt{s_{NN}} = 5.36$ TeV with $L_{int} = 78 \mu\text{b}^{-1}$
 - Measured values compared with predictions from **STARlight** and two calculations based on **colour glass condensate (CGC)** approach, one with **nucleon shape fluctuations**
 - **CGC+shape fluctuations** provide the **best description**
 - See a talk by Paweł Rybczyński

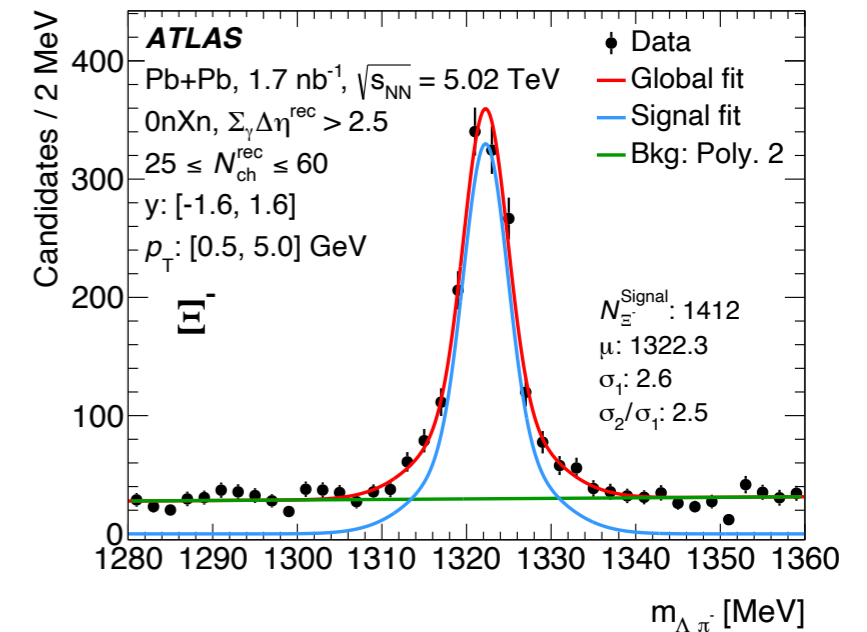
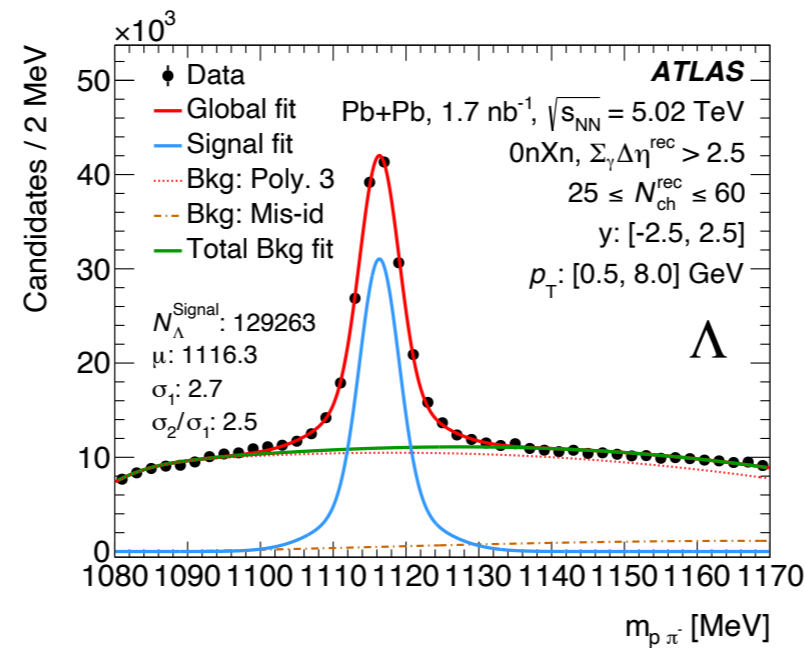
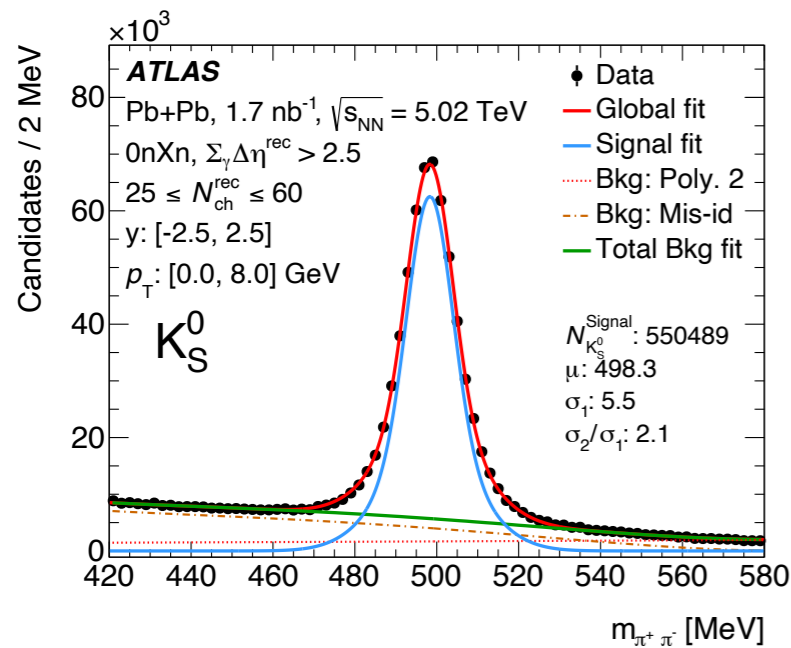
[arXiv:2504.0779]

- **Intense photon fluxes** at the LHC may lead to electromagnetic pile-up so-called **coincident UPC processes**
- ATLAS measures rates of coincident UPC processes using $\gamma\gamma \rightarrow \mu^+\mu^-$ and $\gamma A \rightarrow \rho^0(\pi^+\pi^-)A$ from the same Pb+Pb interaction at **5.02** and **5.36 TeV**
- Relative rate is $\sim 5 \cdot 10^{-3}$ in **0n0n** and **increases** 0n0n \rightarrow 0nXn \rightarrow XnXn to $\sim 30 \cdot 10^{-3}$ as a function of $m_{\mu\mu}$, $y_{\mu\mu}$ and E_γ^{lead}
- Relative rate **increases** with $m_{\mu\mu}$ where **higher** $m_{\mu\mu}$ reflects **smaller** b
- Measurement can provide new insights into b dependence of γ -induced vector meson production
- Important in case of **exclusivity conditions**



- Event classes:
 - 0n0n** - no activity in ZDC
 - 0nXn** - activity in ZDC on one side
 - XnXn** - activity in both ZDC
 - 0nAn** - no activity in one ZDC, no requirement on another
 - AnAn** - no requirement on ZDC activity
- Increasing b values

[PRC 111 (2025) 064908]



- **Charged- and identified hadron** $K_S^0(\pi^+\pi^-)$, $\Lambda(p\pi^-)$, $\Xi^-(\Lambda\pi^-)$ yields are measured in photonuclear Pb+Pb and p+Pb at 5.02 TeV, channels with $\text{BR} > 63\%$
- Tracks with $p_{\text{T}} > 0.4 \text{ GeV}$ and $|\eta| < 2.5$ define a range of $15 < N_{\text{ch}}^{\text{rec}} < 60$ reconstructed charged-particle multiplicity
- Yields reported down to $p_{\text{T}} = 0 \text{ GeV}$
- Measurement limited by **systematic uncertainties** (extrapolation and material in the ID)

CHARGED- AND IDENTIFIED HADRONS

Pb+Pb

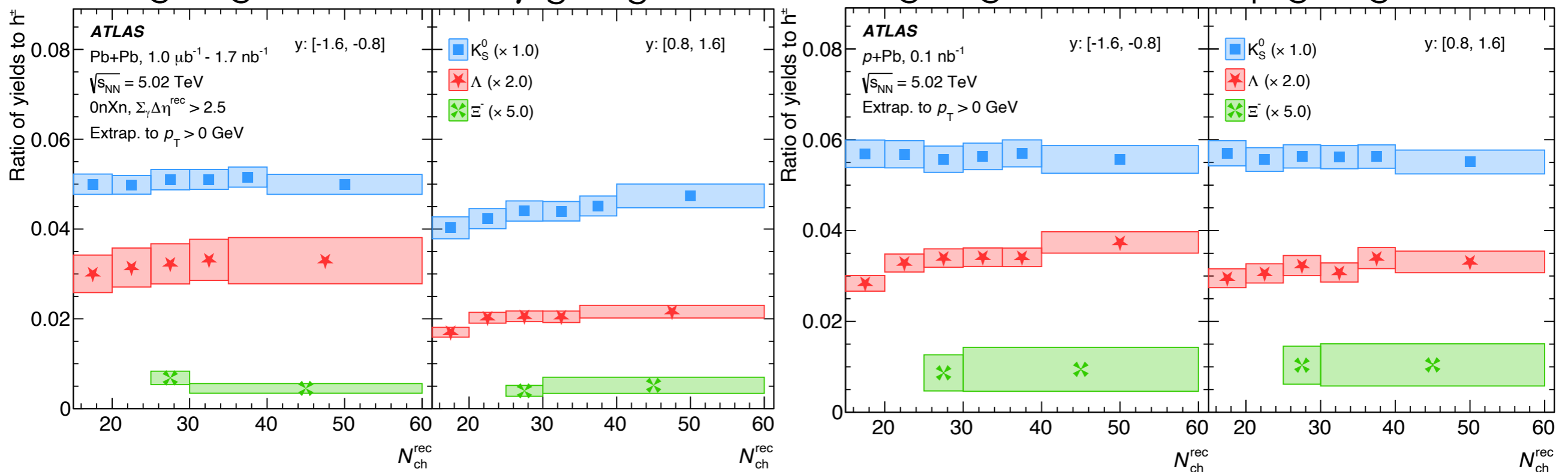
p+Pb [[PRC 111 \(2025\) 064908](#)]

Pb-going side

γ -going side

Pb-going side

p-going side

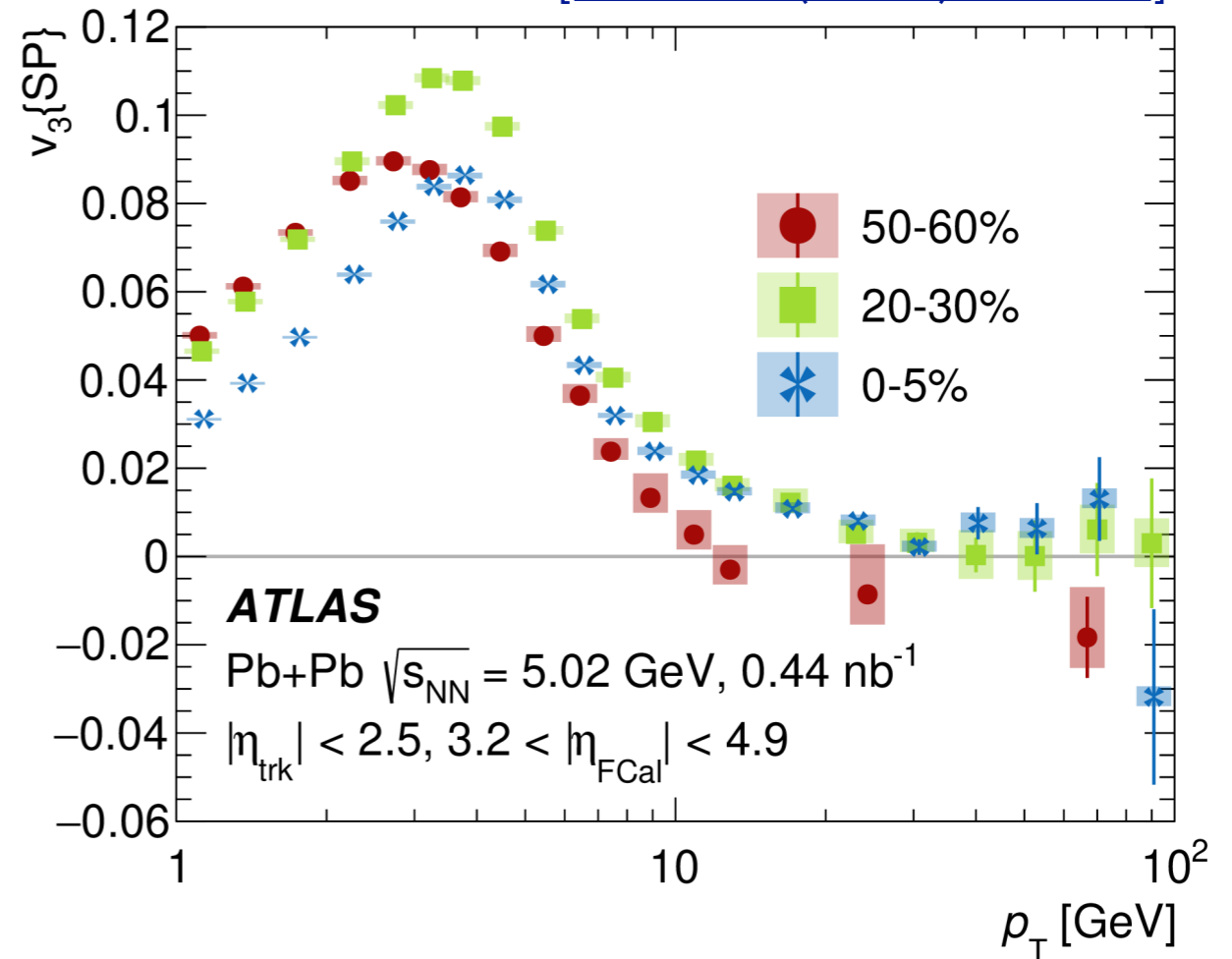
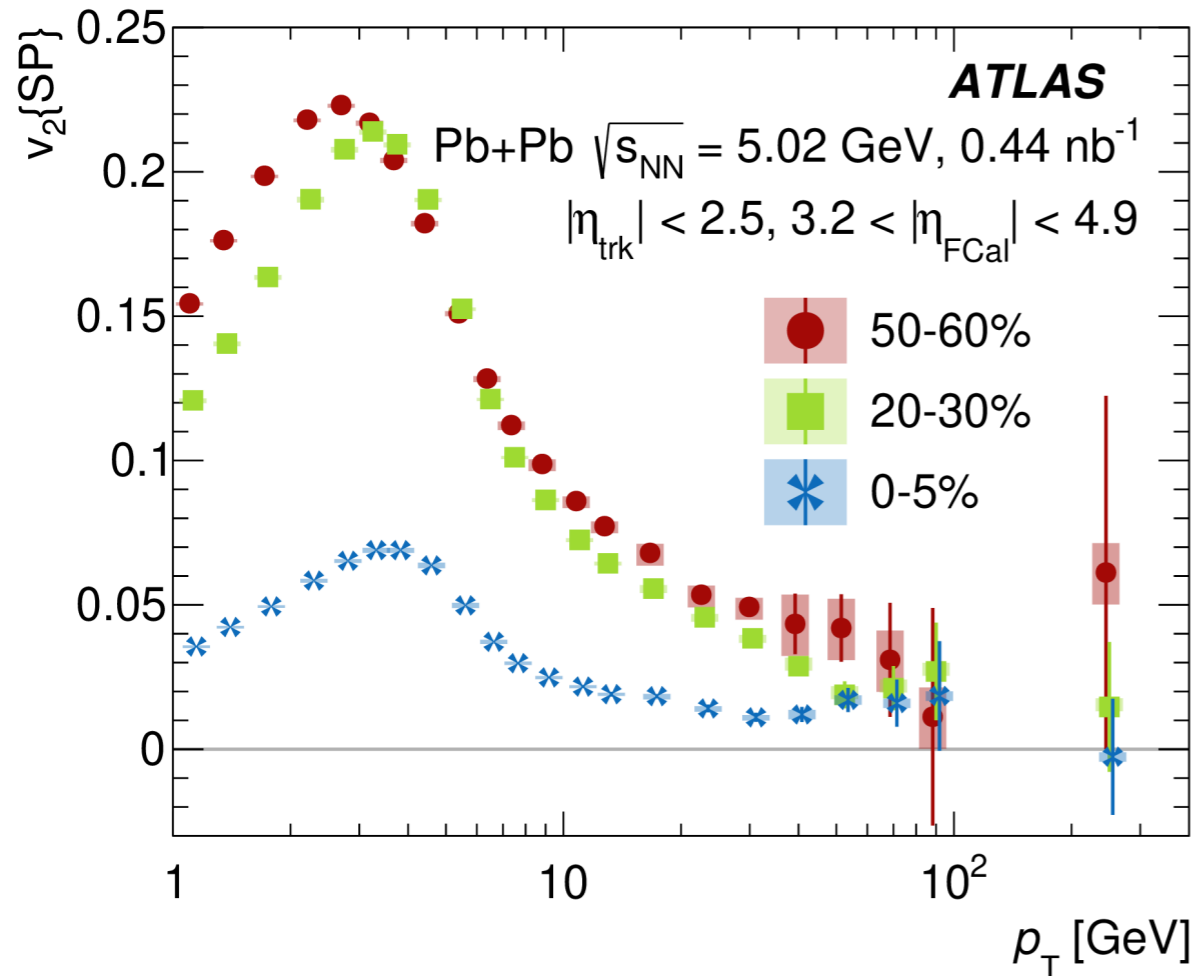


- Ratios of **identified-to-charged-hadron yields** in photonuclear Pb+Pb and p+Pb collisions as a function of $N_{\text{ch}}^{\text{rec}}$ reconstructed charged-particle multiplicity
- Clear **increase** in **strange-hadron yields** relative to charged hadrons between backward and forward rapidity
- In general, ratios are flat with $N_{\text{ch}}^{\text{rec}}$ with a hint of increase for Λ -to-hadron ratios
- Picture **consistent** with **strangeness enhancement** by ALICE [[NP 13 \(2017\) 35-539](#)]

- ATLAS has been contributing to the HI programme based on **Run 2 Pb+Pb** data at $\sqrt{s_{\text{NN}}} = 5.02 \text{ TeV}$
 - With $L_{\text{int}} < 2 \text{ nb}^{-1}$
- First new results from **Run 3 2023 Pb+Pb** at $\sqrt{s_{\text{NN}}} = 5.36 \text{ TeV}$ available
 - With $L_{\text{int}} < 1.7 \text{ nb}^{-1}$
- ATLAS had very successful data taking for **Pb+Pb** in Run 3
 - About $L_{\text{int}} \approx 6 \text{ nb}^{-1}$ available data at $\sqrt{s_{\text{NN}}} = 5.36 \text{ TeV}$
 - More new results to come soon
- The **light-ion program** is complementary to the study in Pb+Pb collisions
- Also the **UPC Pb+Pb programme** is in full swing
 - New capabilities available in Run 3 data
- All results from ATLAS available at <https://twiki.cern.ch/twiki/bin/view/AtlasPublic/HeavyIonsPublicResults>

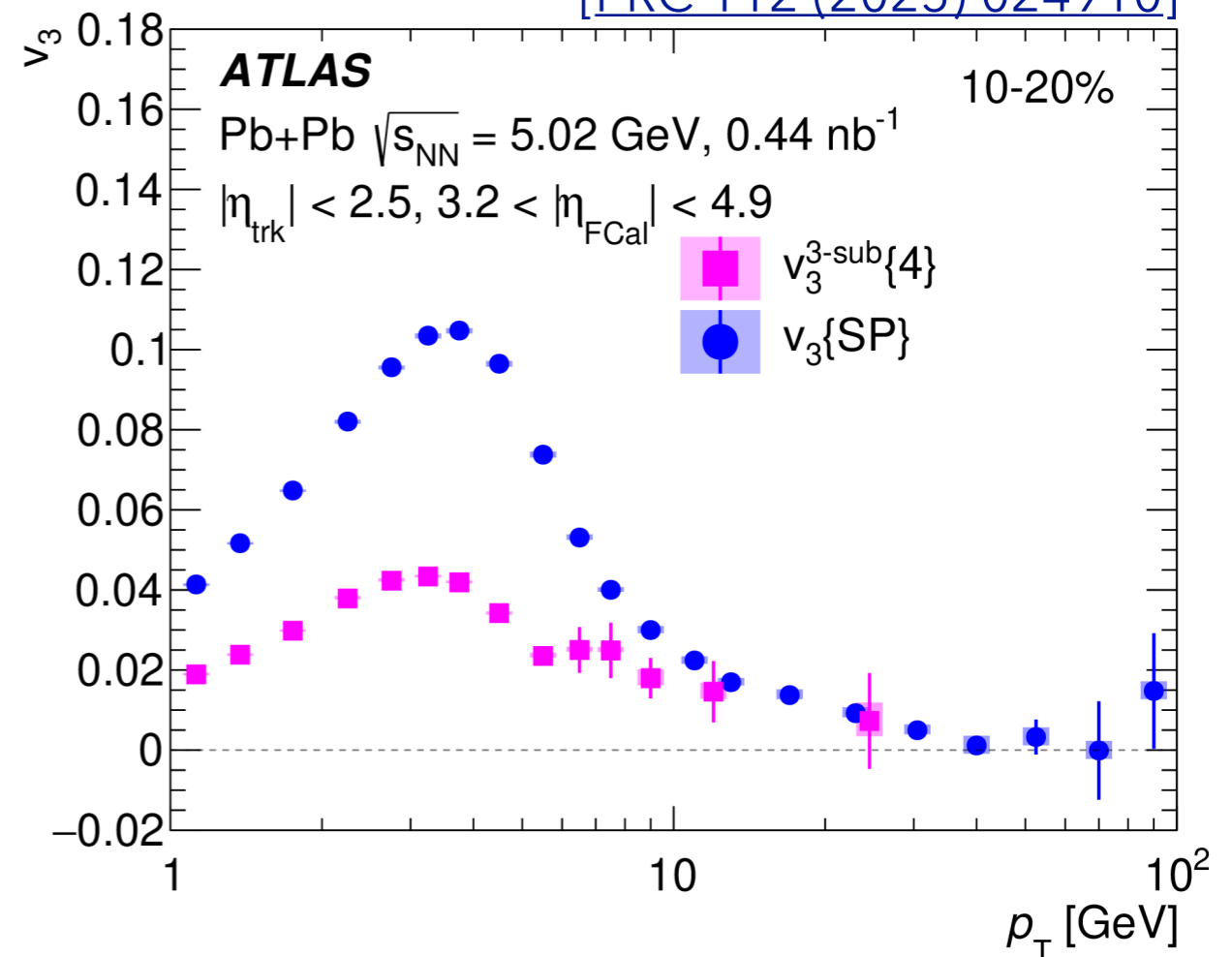
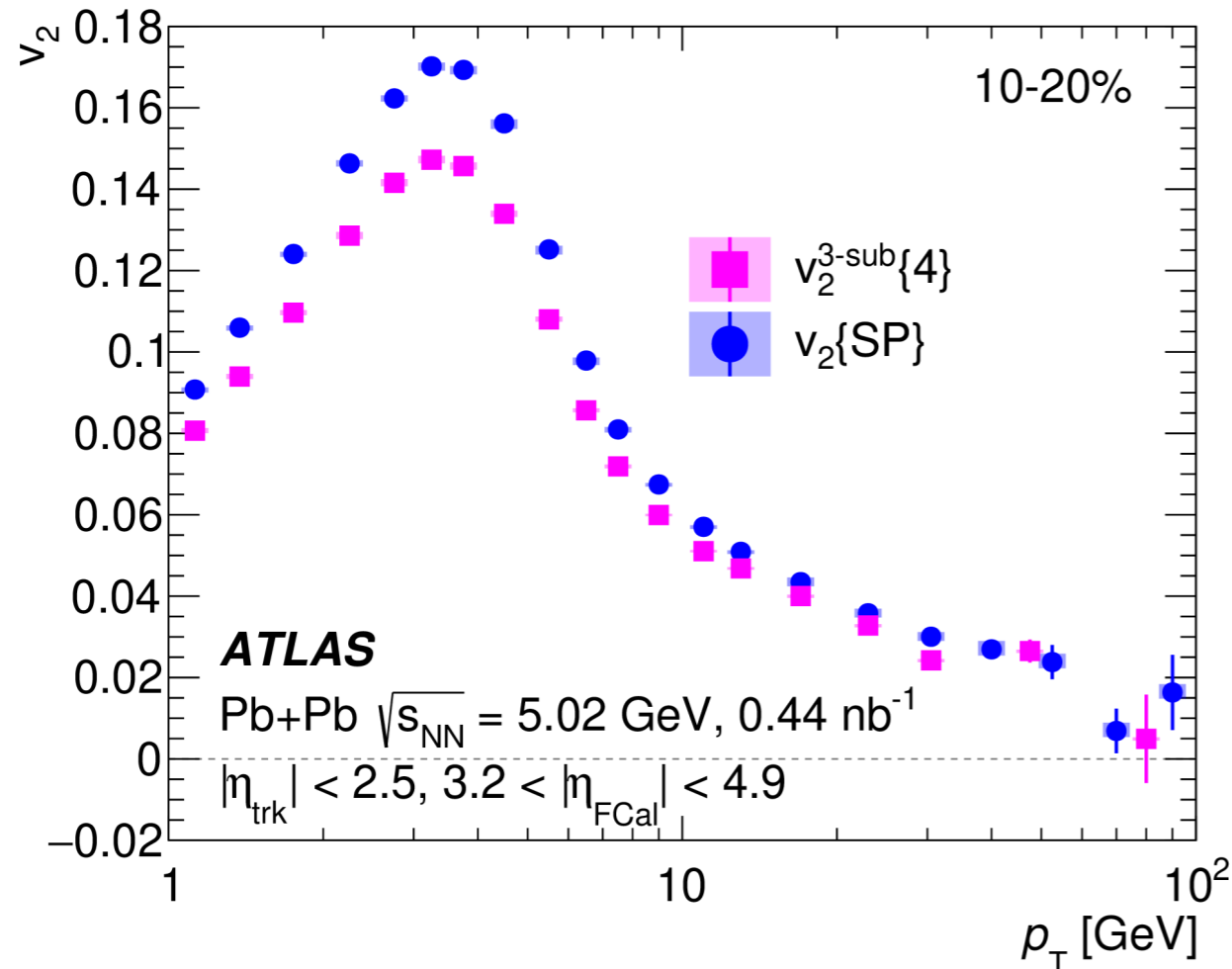
BACK-UP SLIDES

[PRC 112 (2025) 024910]



- **Precision** measurement of **elliptic** (v_2) and **triangular** (v_3) azimuthal correlation coefficients for charged particles in Pb+Pb at $\sqrt{s_{NN}} = 5.02 \text{ TeV}$ 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
- $v_2(\text{SP})$ values are positive for the selected centrality intervals up to a p_T of 100 GeV, become approximately constant with p_T for $p_T > 50 \text{ GeV}$
- $v_3\{\text{SP}\} > 0$ up to approximately 25 GeV

[PRC 112 (2025) 024910]

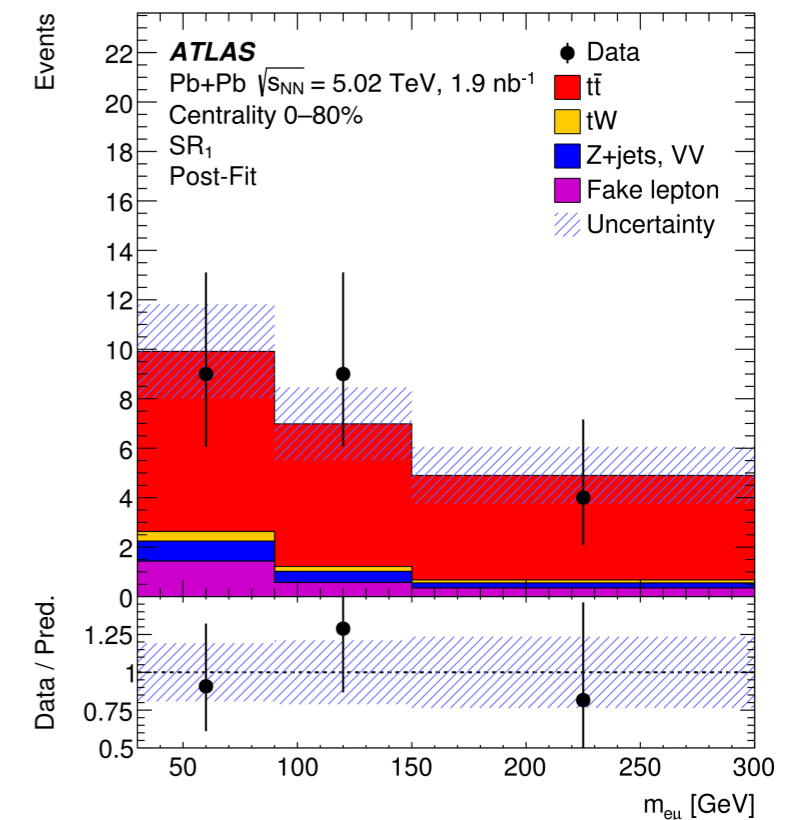
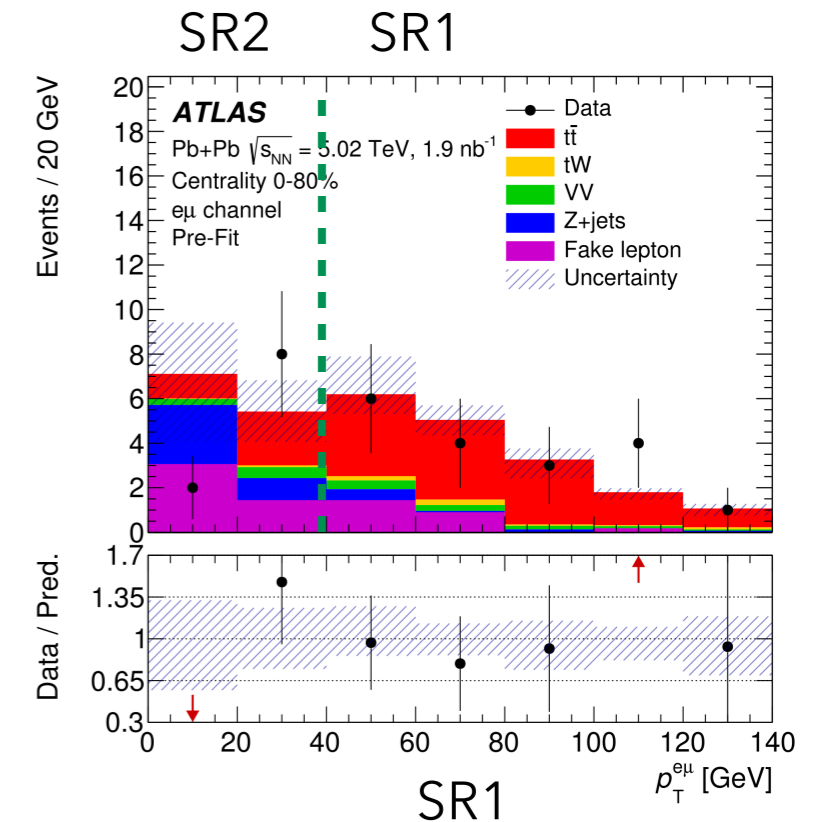


- Comparison between the **SP** and the **3-subevent Q-cumulant** multi-particle methods
- For $p_T > 10$ GeV, the comparison between the two methods contains information about how hard scattered partons respond to the event-by-event distribution of the initial-state QGP geometry
- In 10-20% centralities,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

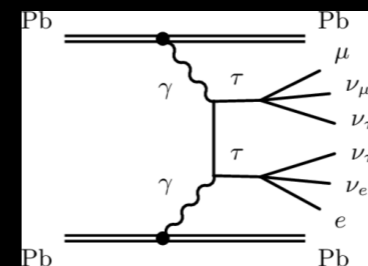
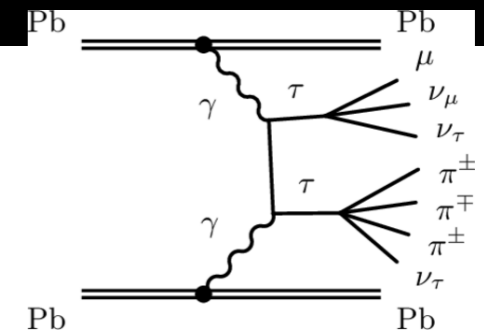
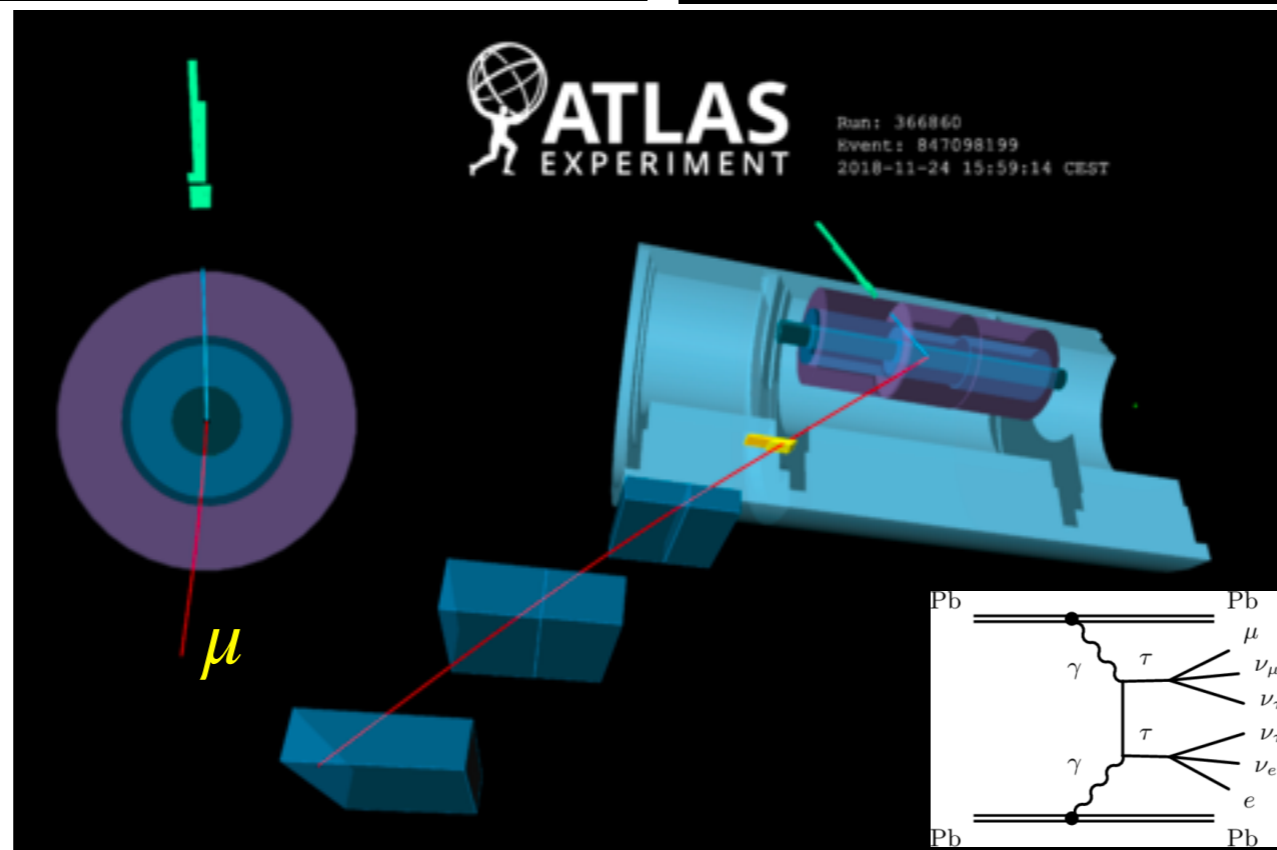
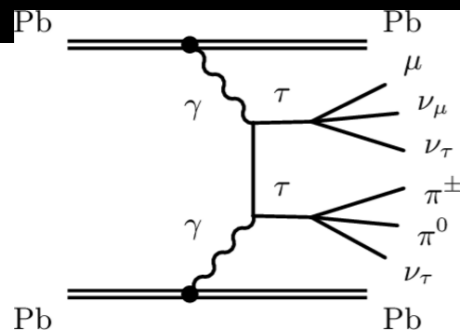
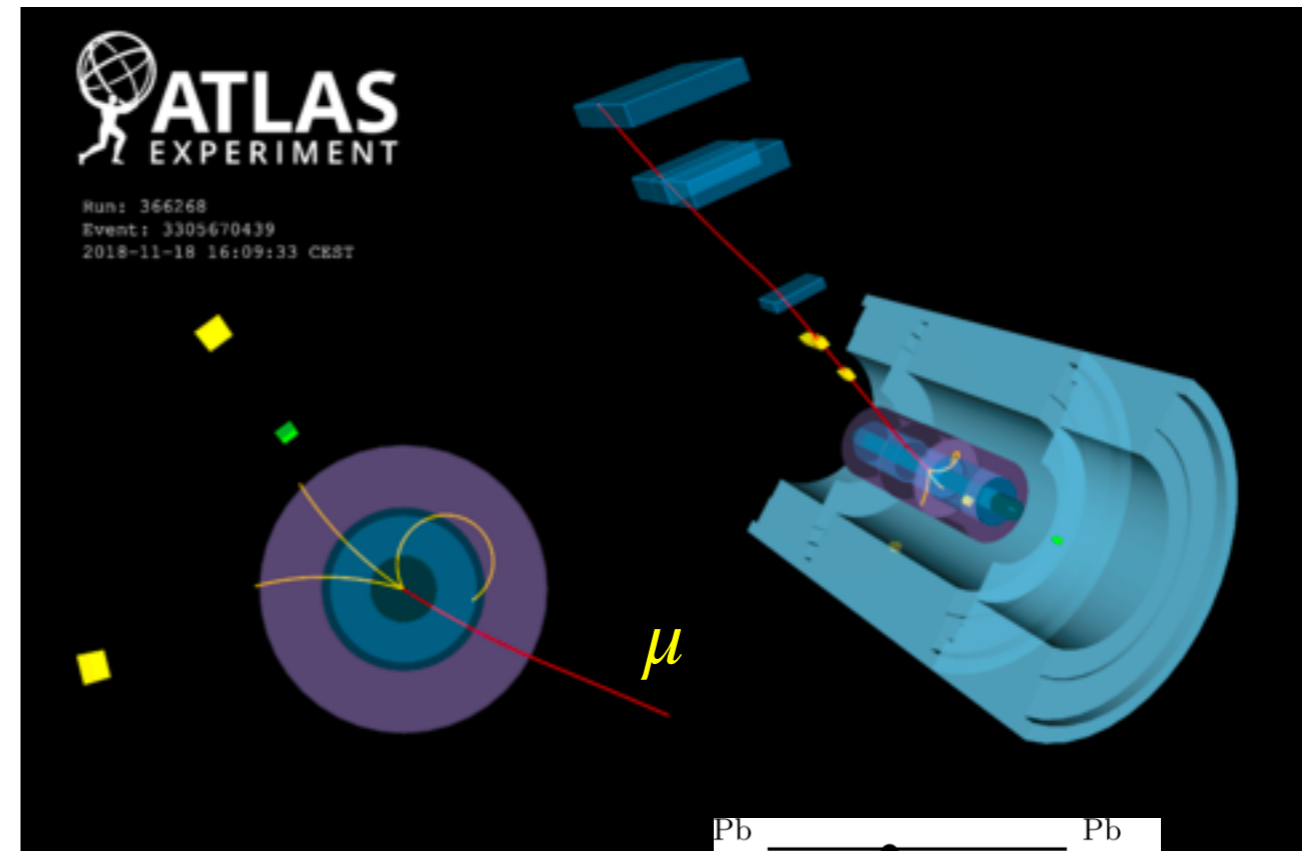
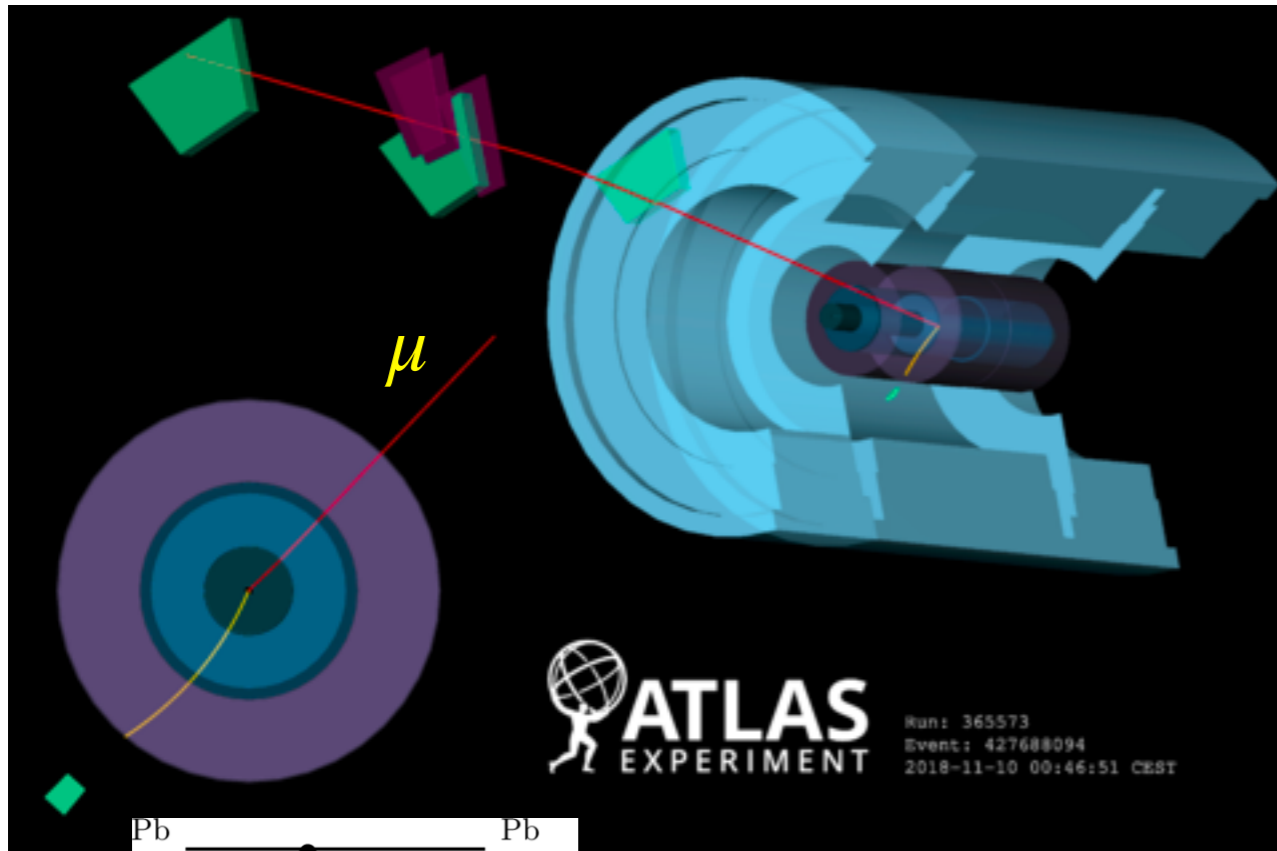
OBSERVATION OF TOP-QUARKS IN Pb+Pb

[PRL 134 (2025) 142301]

- $t\bar{t}$ production is measured in Pb+Pb collisions from 2015 and 2018 at $\sqrt{s_{NN}} = 5.02$ TeV in 0-80% centralities
- **Dilepton** channel (BR= \sim 2%) investigated
- Profile-likelihood fit to a $m_{e\mu}$ distribution in two signal regions SR1 and SR2
- Signal strength $\mu_{t\bar{t}} = \frac{\sigma_{t\bar{t}}^{\text{meas}}}{\sigma_{t\bar{t}}^{\text{SM}}}$ 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



EXCLUSIVE DITAU



- Event candidates for $\gamma\gamma \rightarrow \tau^+\tau^- \rightarrow \mu^\pm\nu_\mu\nu_\tau$ track(s) or $\gamma\gamma \rightarrow \tau^+\tau^- \rightarrow \mu^\pm\nu_\mu\nu_\tau e^\pm\nu_e\nu_\tau$

[ATLAS-CONF-2025-004]

- **First observation** of τ leptons in Pb+Pb collisions in **2018** UPC
Pb+Pb collisions of 1.44 nb^{-1} [[PRL 131 \(2023\) 151802](#)]
 - 2nd analysis uses the same methodology, new features:
 - **2015 data** 0.49 nb^{-1} added
 - Differential cross sections measured
 - Exclusive ditau production $\gamma\gamma \rightarrow \tau^+\tau^-$ with **(semi)leptonic decay** modes
 - μ 1T-SR: muon + 1 track (e/ μ /hadron)
 - μ 3T-SR: muon + 3 tracks (3 hadrons)
 - μ e-SR: muon + electron
- with $p_T^\mu > 4 \text{ GeV}$, $p_T^e > 4 \text{ GeV}$, $p_T^{\text{trk}} > 100 \text{ MeV}$
 $p_T^{\text{clus}} > 1 \text{ GeV}$ ($|\eta| < 2.5$)
 $p_T^{\text{clus}} > 100 \text{ MeV}$ ($2.5 < |\eta| < 4.5$)
- Exclusivity: veto additional clusters (μ 1T-SR and μ 3T-SR only) and tracks
 - Total of ~ **650 events** across all SRs
 - Only **data** in the **0n0n category** used to suppress photonuclear/hadronic backgrounds
 - Simulation (**STARlight+Tauola**) reweighted to 0n0n with data-driven weights

