Heavy Ions Physics at ATLAS

Highlights

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ATLAS EXPERIMENT
CERN

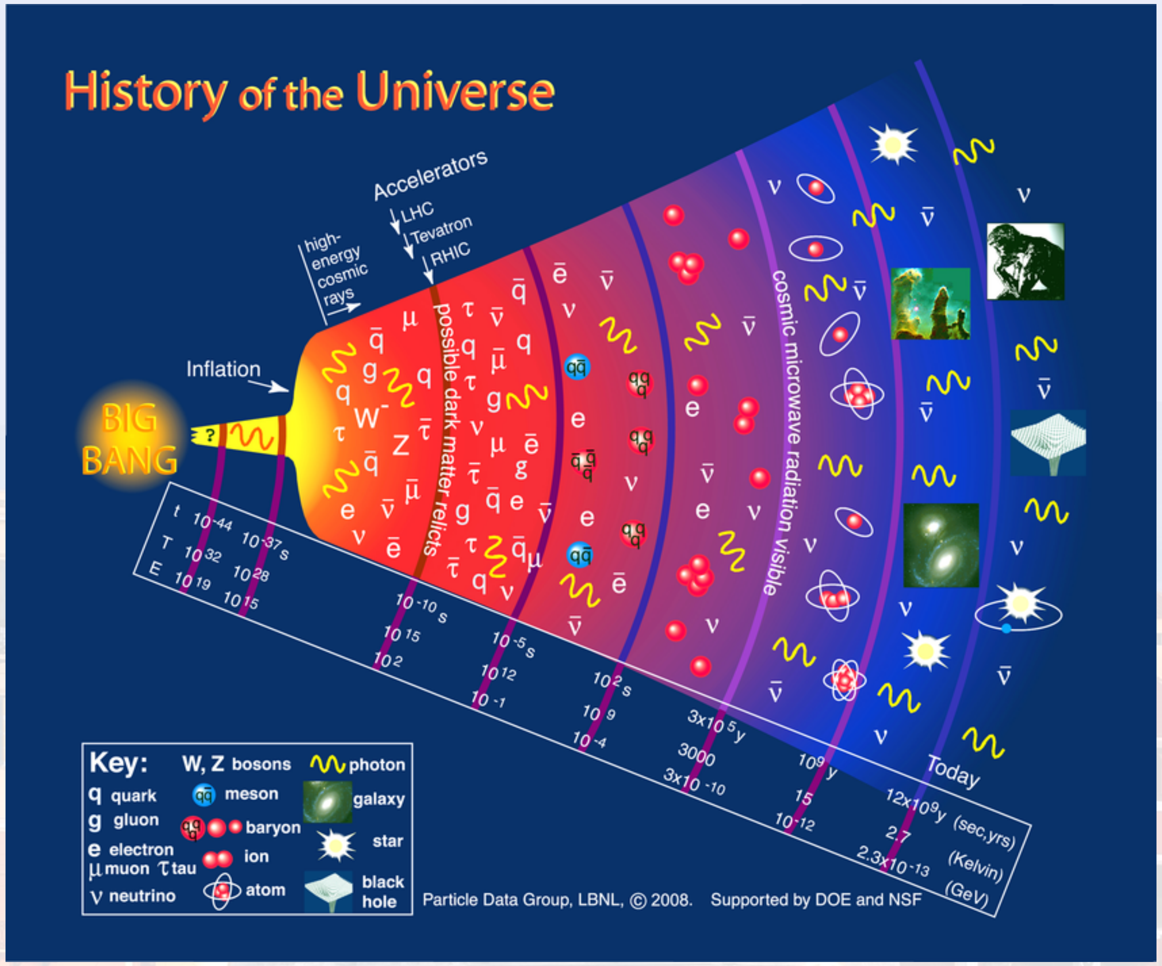
QCD and strong nuclear force

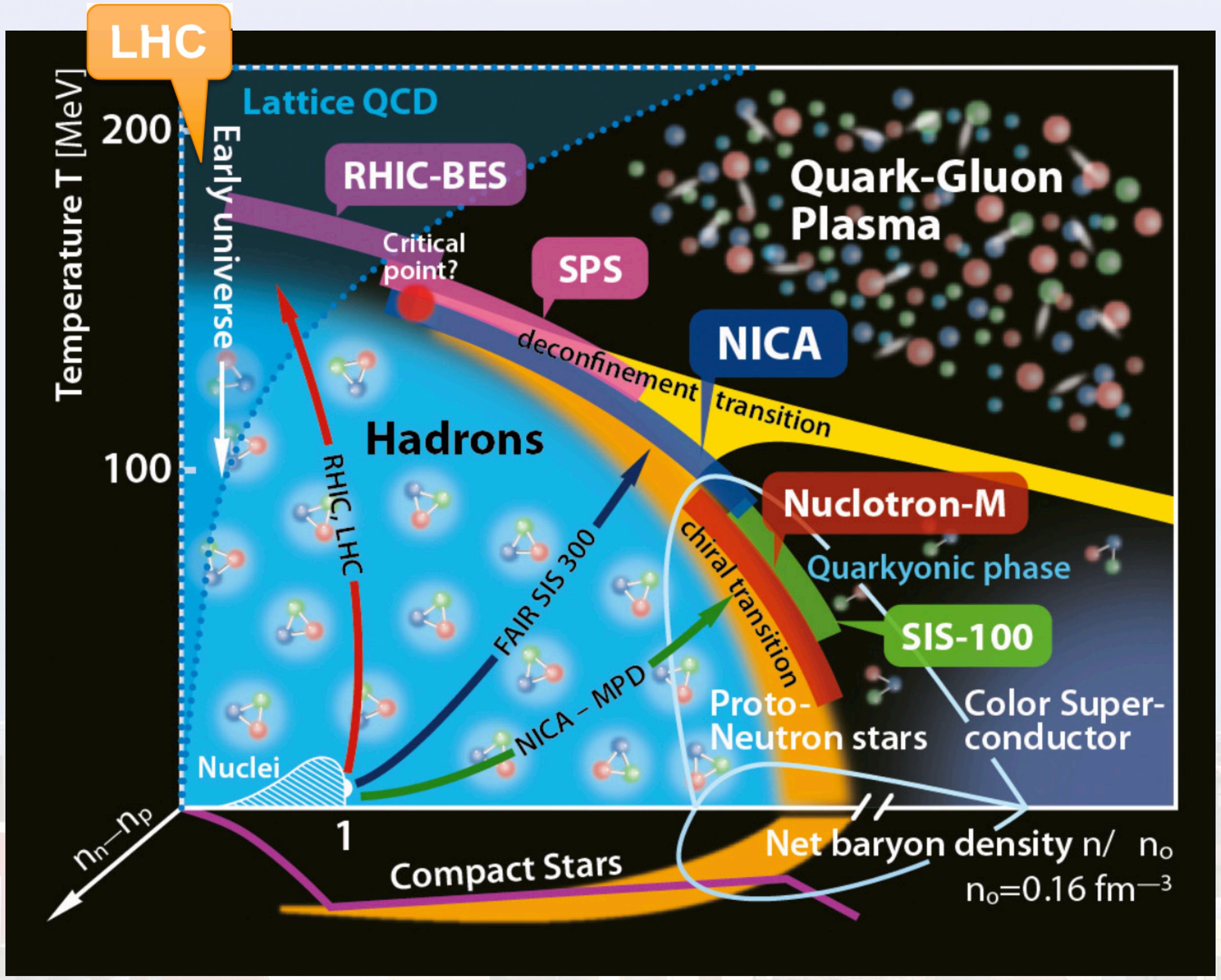
$$\mathscr{L}_{\text{QCD}} = -\frac{1}{4}F^{a}_{\mu\nu}F^{\mu\nu}_{a} + \sum_{f=1}^{N_f} \bar{\psi}_f \left(i\gamma^{\mu}D_{\mu} - m_f\right)\psi_f$$

$$F^{a}_{\mu\nu} = \partial_{\mu}A^{a}_{\nu} - \partial_{\nu}A^{a}_{\mu} + g_s f^{abc}A^{b}_{\mu}A^{c}_{\nu}$$

- Well-established theory in compact form as shown in the Lagrangian.
- Some aspects are not fully understood, like:
    - Confinement mechanism.
    - Hadron masses.
    - Types of bound quark-gluon state in Nature.

QCD matter in strong conditions

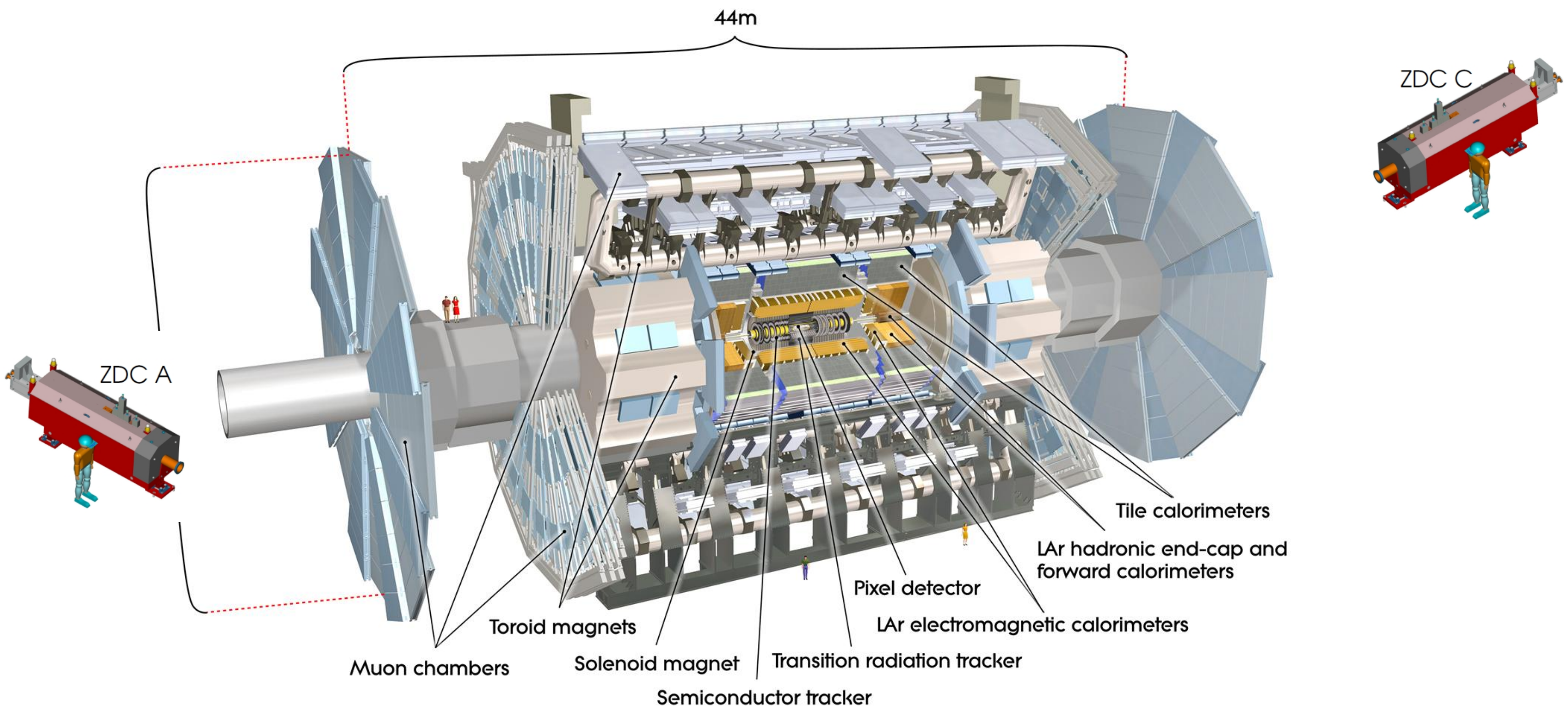


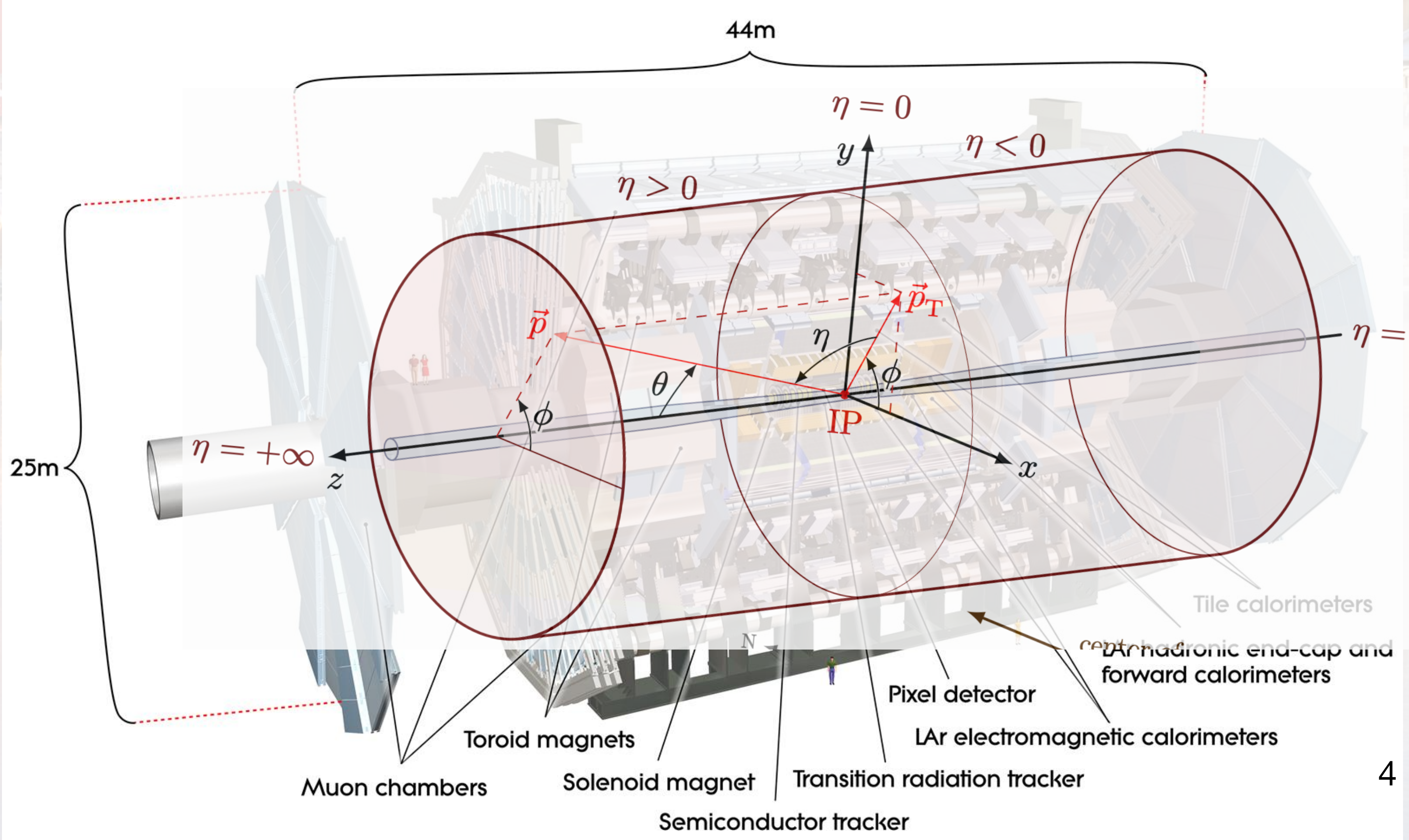


- Under extreme conditions of temperature and densities:
  - **Quark Gluon Plasma** (QGP) takes place as a state of matter.
  - Quarks and Gluons are deconfined from the nucleus.
  - No longer in vacuum (as in pp collisions).
- At particle colliders, it is possible to reproduce such extreme conditions, especially at the Large Hadron Collider (LHC) with the ATLAS experiment, to produce QGP.

The ATLAS experiment

- Multipurpose particle detector at the LHC.
- Main components:
  - Transition Radiation Tracker (TRT)
  - EM and Hadronic Calorimeters
  - Forward calorimeters
  - Muon Spectrometer (MS)
  - Zero Degree Calorimeter (ZDC)

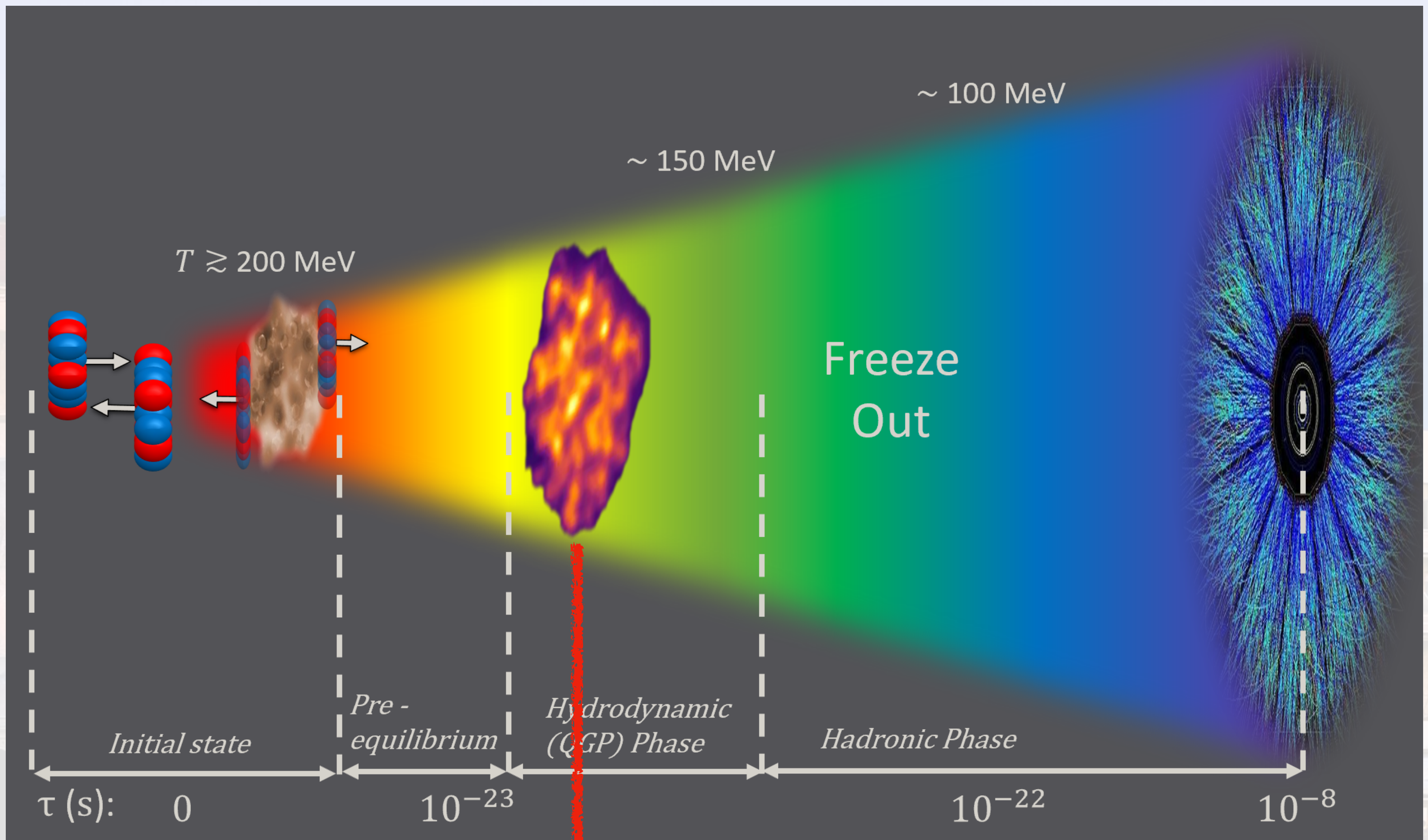




QGP at the ATLAS detector with Heavy Ions collisions

- One month per year at LHC, Pb-Pb collisions are performed to generate extreme conditions to obtain QGP.

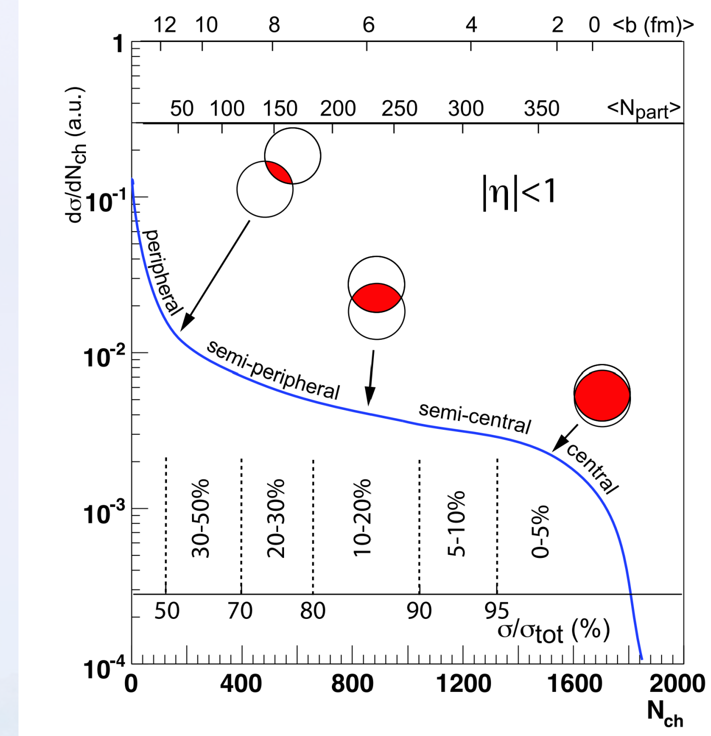
$\sqrt{s_{NN}}$ = 5.36 TeV



- QGP behaves almost as a perfect fluid; its expansion is governed by relativistic hydrodynamics.

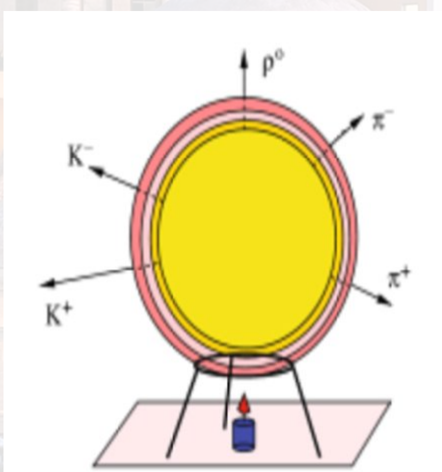
Parameters at ATLAS experiment for Heavy Ions collisions

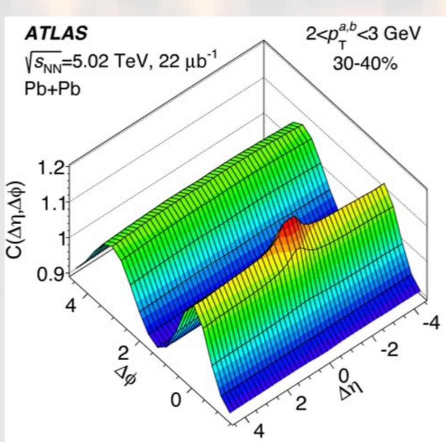
- Centrality



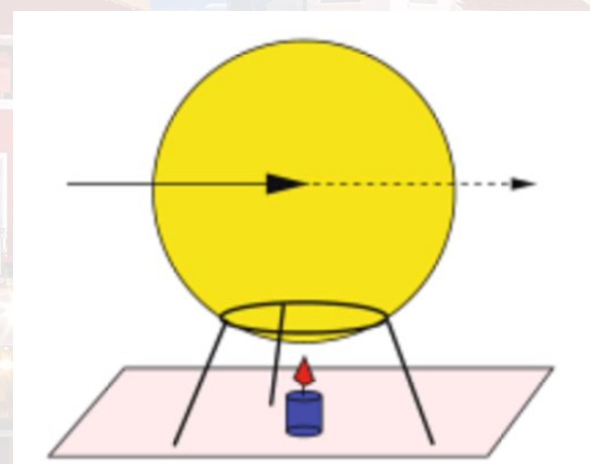
- Existence of QGP

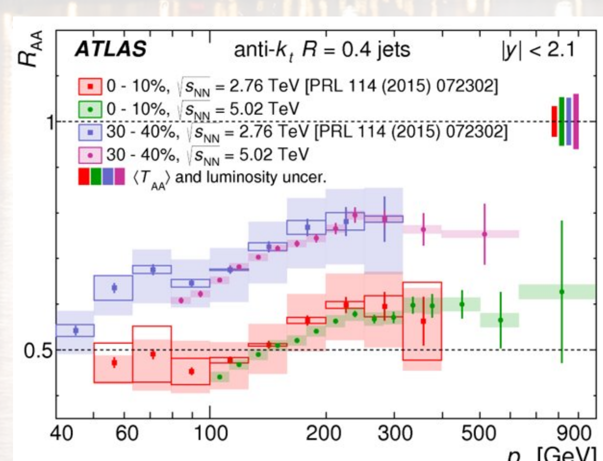
Collectivity



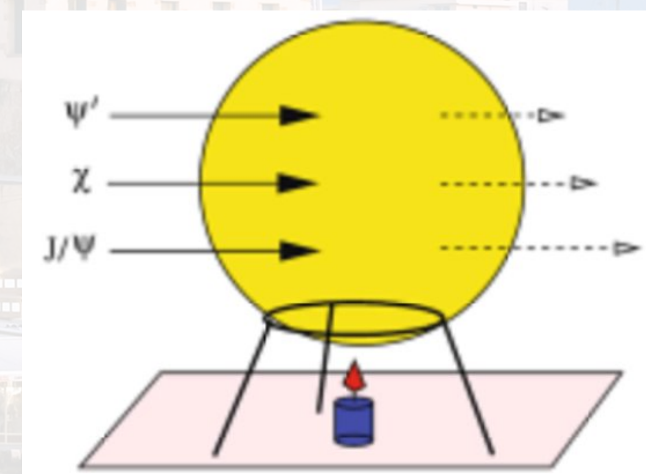


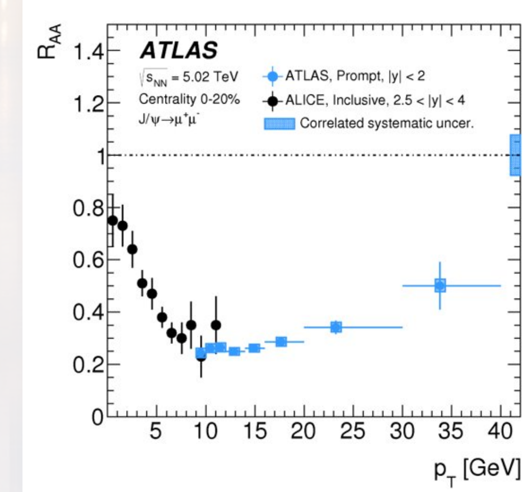
Jet Quenching





Quarkonia Supression



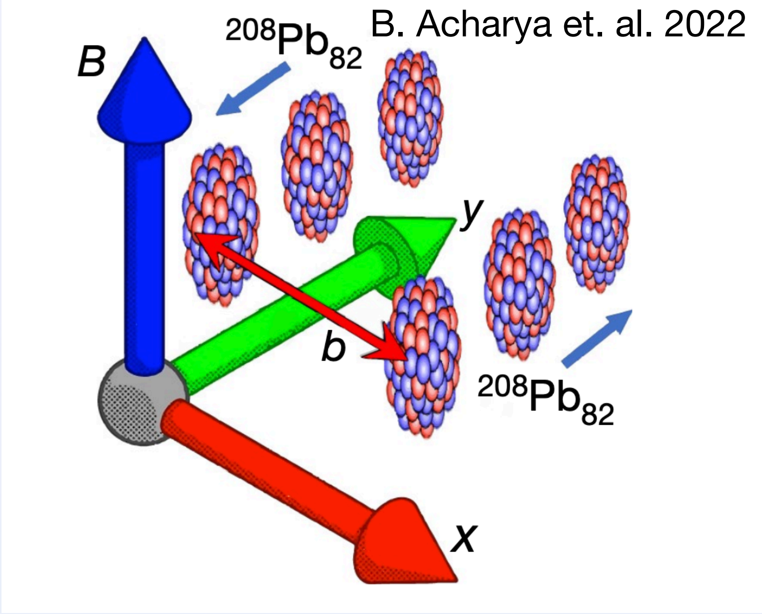


Heavy Ions Physics at the ATLAS detector

Highlights for today

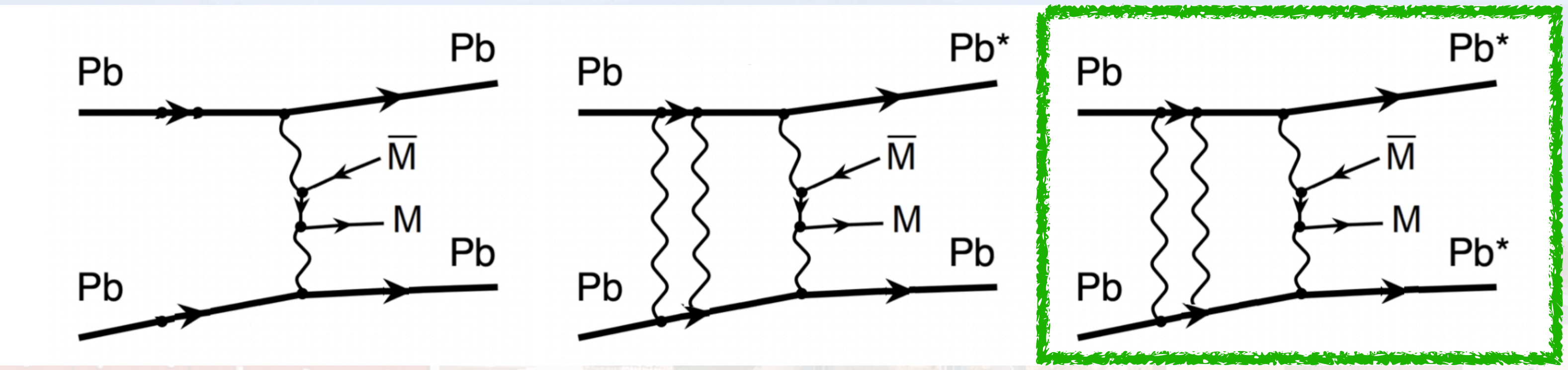
- Search for magnetic monopole pair production in ultraperipheral Pb+Pb collisions at $\sqrt{s_{NN}}$ = 5.36 TeV with the ATLAS detector at the LHC.
- Search for jet-induced diffusion wake in the quark-gluon-plasma via measurements of jet-track correlations in photon-jet events in Pb+Pb collisions at $\sqrt{s_{NN}}$ = 5.36 TeV with the ATLAS detector.
- Disentangling sources of momentum fluctuations in Xe+Xe and Pb+Pb collisions with the ATLAS detector.

Magnetic monopole pair production in Pb+Pb UPC @ ATLAS detector



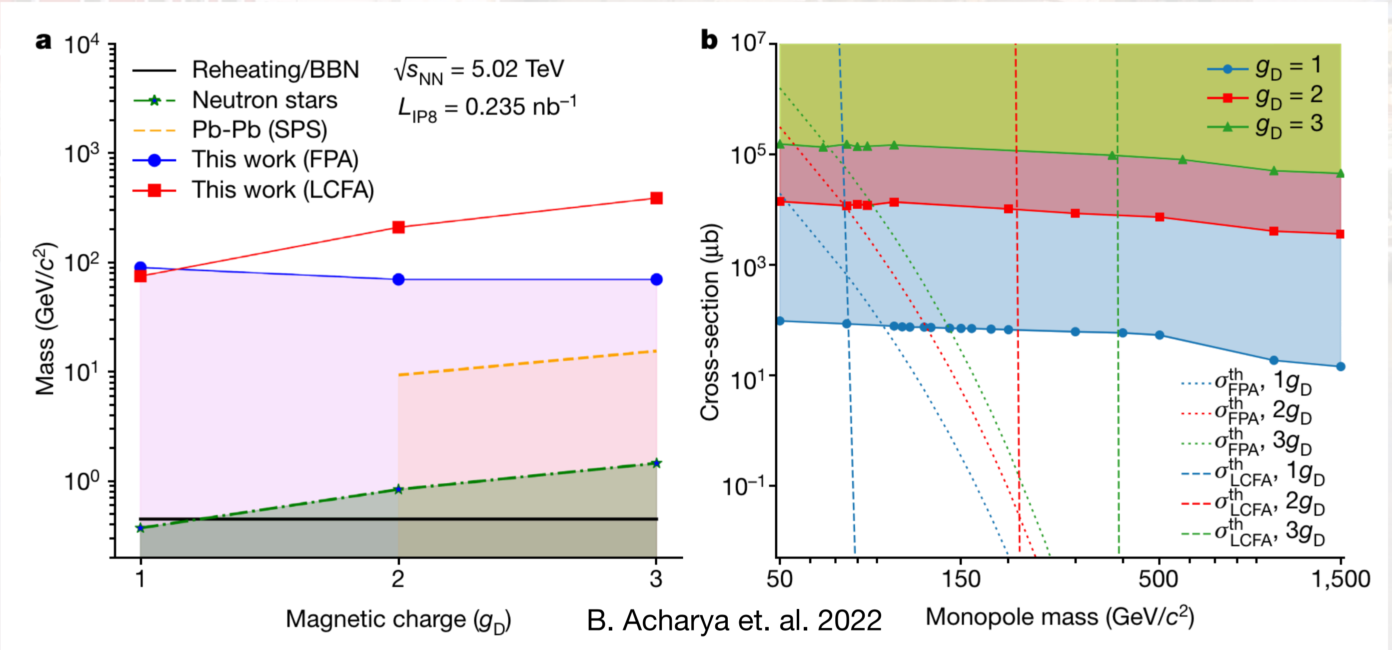
- Due to the Schwinger effect, a magnetic monopole-antimonopole pair can be produced with a strong magnetic field:

$$P \sim \exp\left(-\frac{\pi m^2}{gB} + \frac{g^2}{4}\right)$$ Gould, Ho, Rajantie 2021



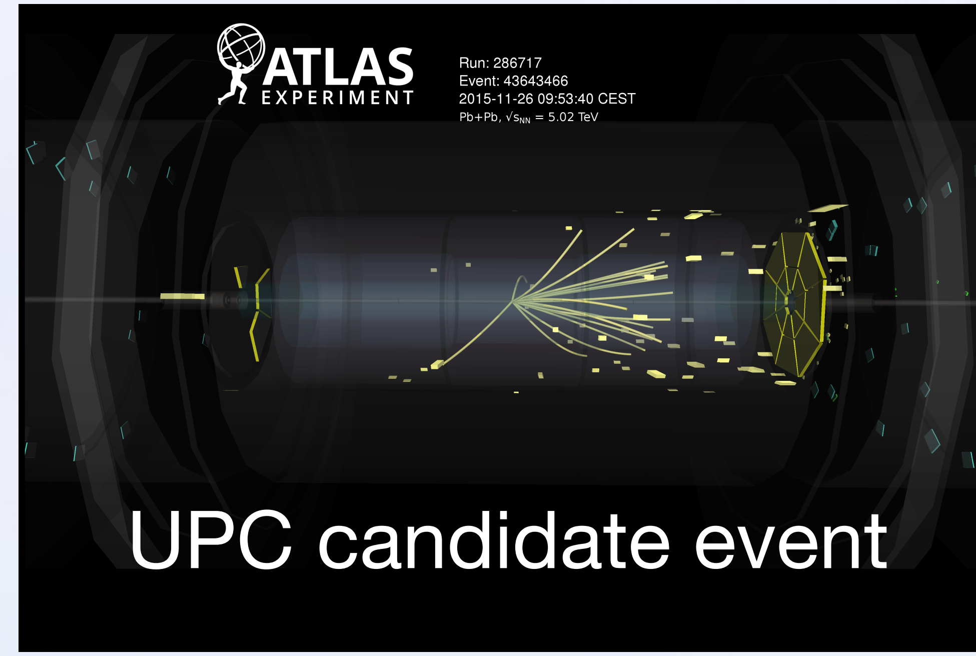
- Today, the strongest known magnetic fields on Earth are in heavy-ion collisions. It's a good place to look at it!

- First search at MoEDAL experiment (at the LHC) in 2022. No candidates were observed, and constraints were placed on g,m, and σ.



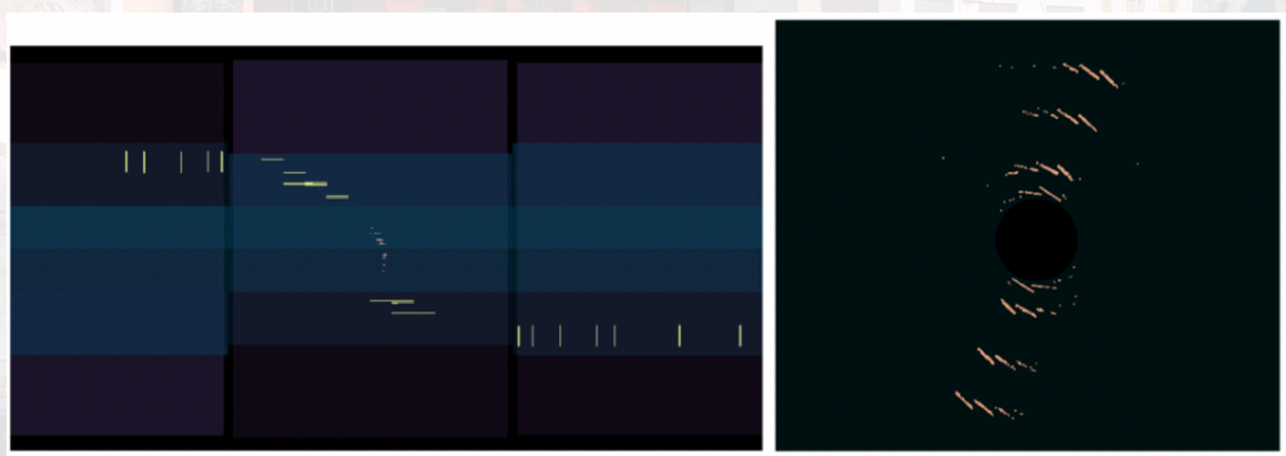
Magnetic monopole pair production in Pb+Pb UPC

@ ATLAS detector



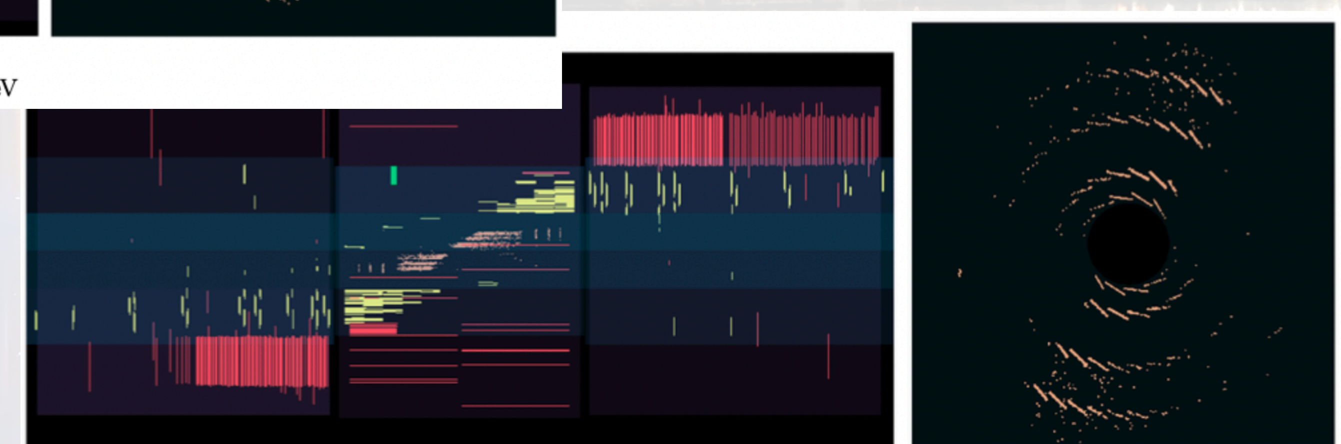
(a) $p_T = 20$ GeV

$> p_T$



(b) $p_T = 50$ GeV

- Monopole simulation through ATLAS detector.
- $m_M = 50$ GeV
- Different trajectories, depending on which plane we are looking at and the value on p_T .

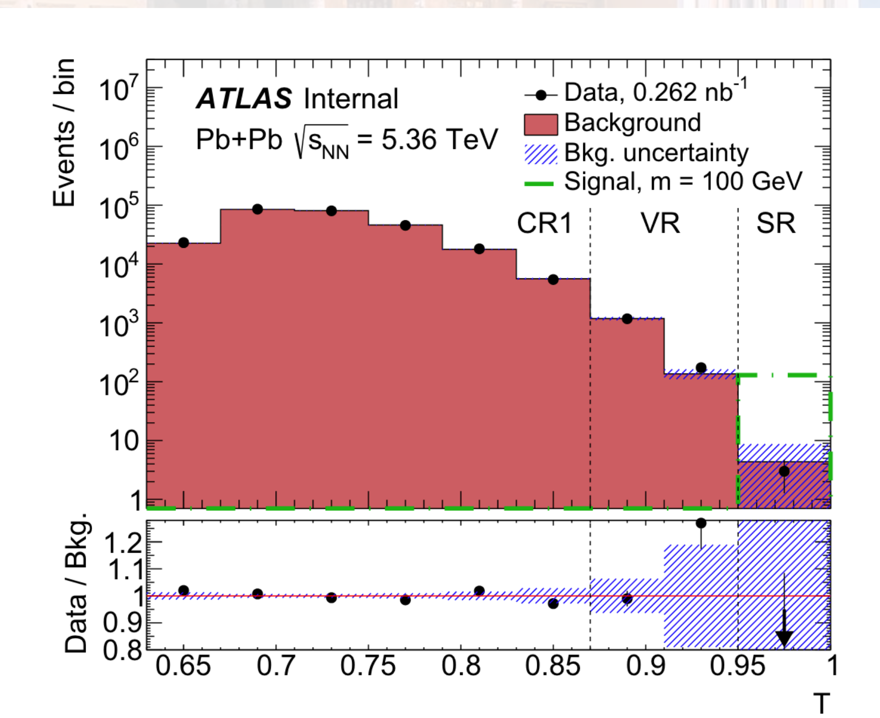


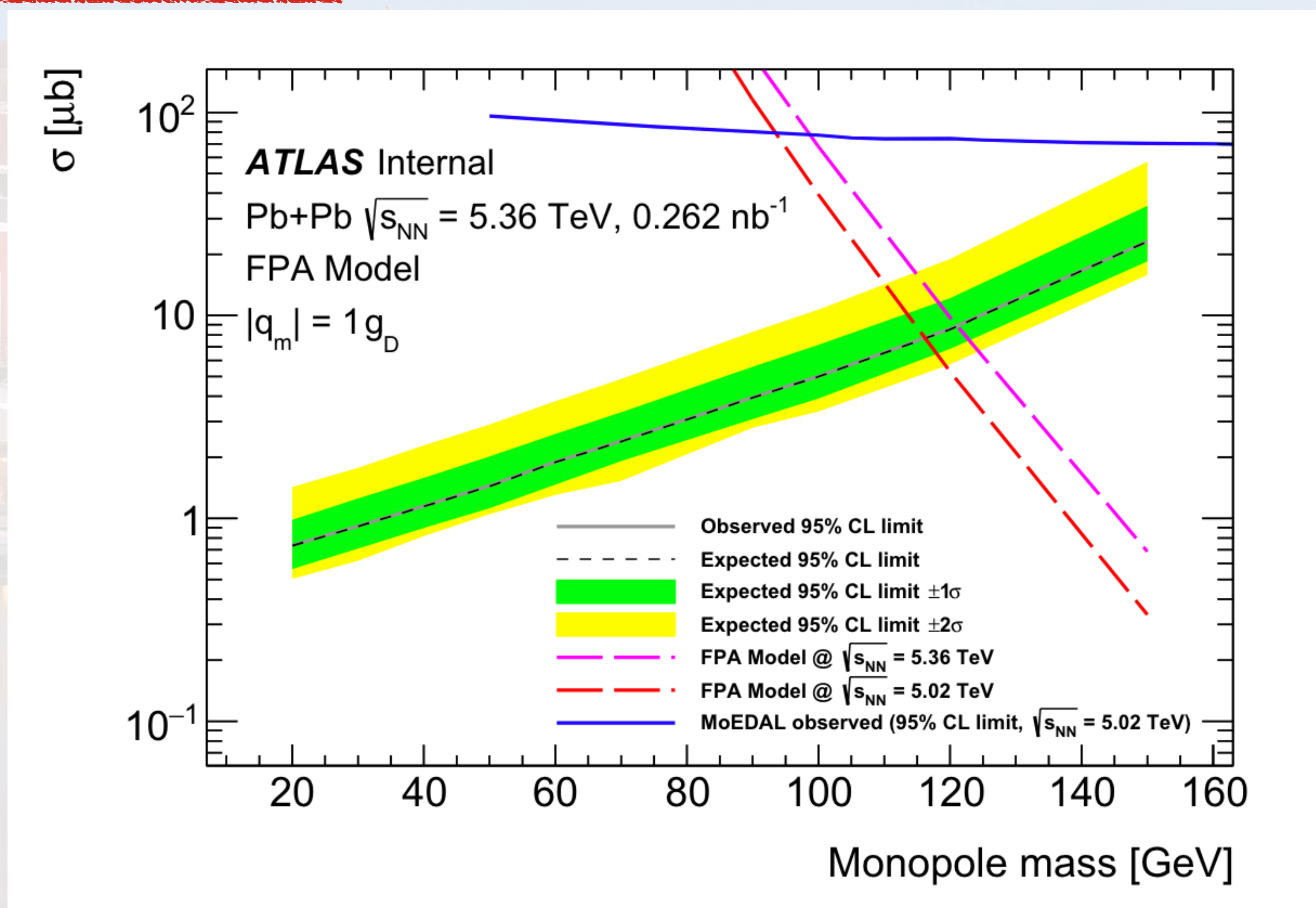
(c) $p_T = 280$ GeV

Magnetic monopole pair production in Pb+Pb UPC

- Transverse Thrust:
  - A key observable, particularly in the study of jet production and event shapes in collisions.
  - Used to quantify the collimation of transverse momentum flow in an event

$$T = 1/n_{\mathrm{PixCl}} \sum_{i=1}^{n_{\mathrm{PixCl}}} |\hat{r}_i \cdot \hat{n}|$$



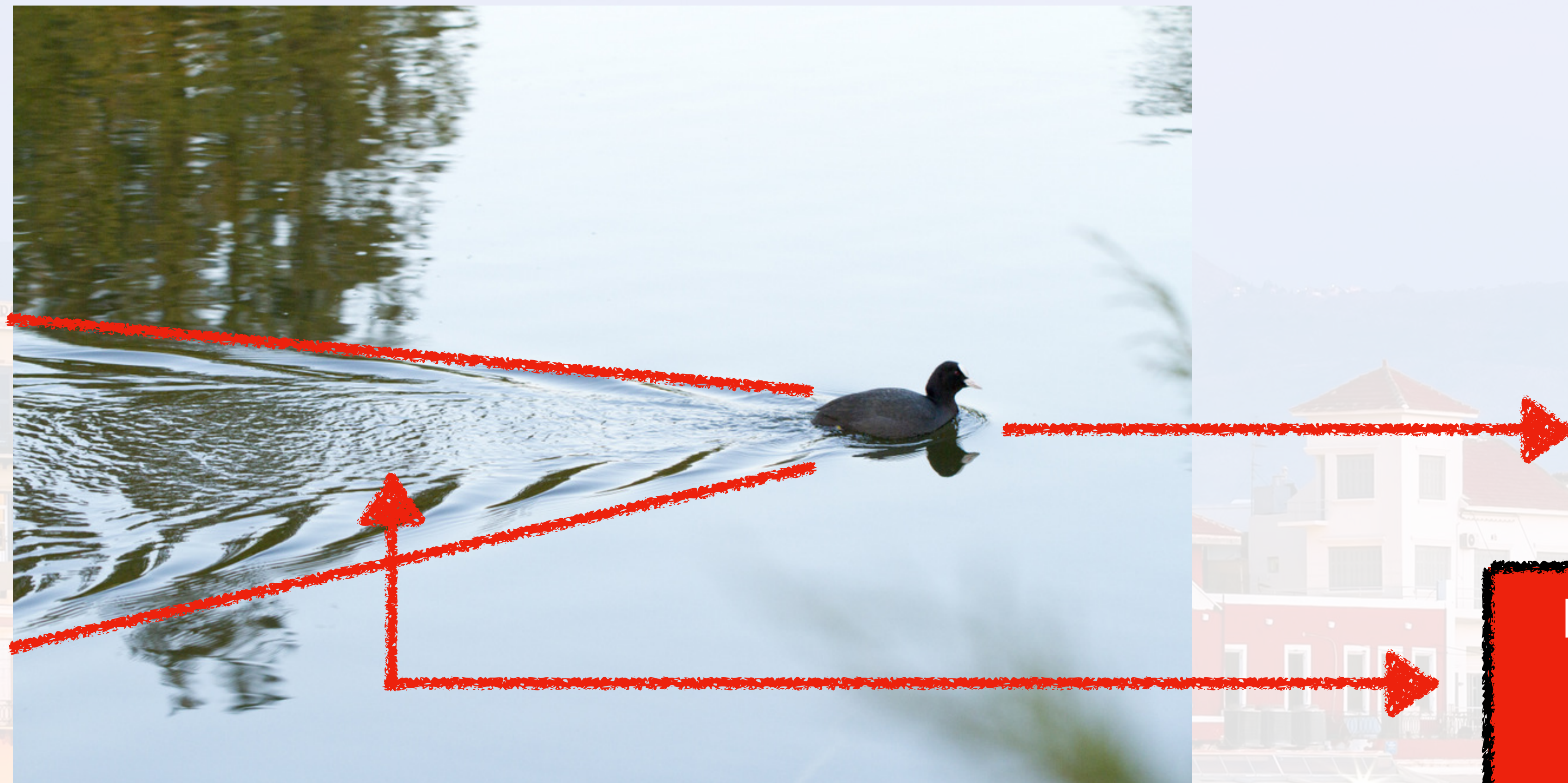


3 events were observed, consistent with the backgraund estimate of 4±4 events

Jet-induced wake via Photon-Jet events in QGP in Pb+Pb

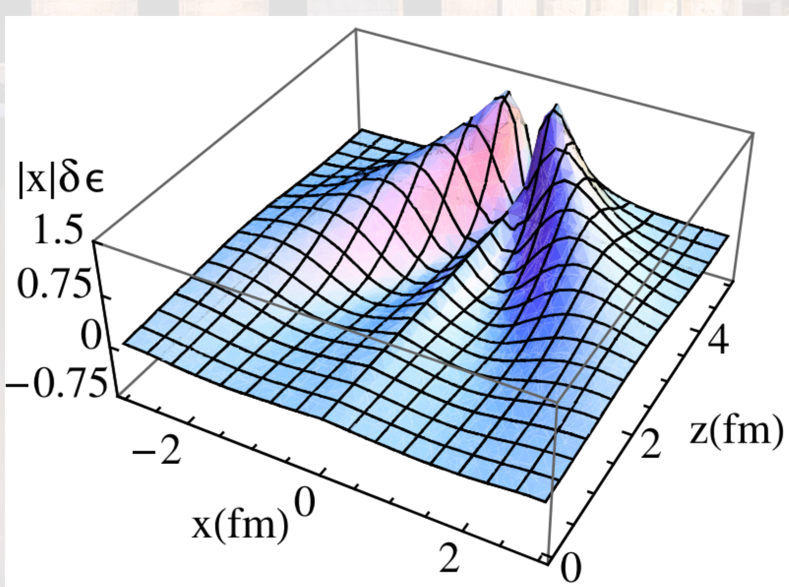
@ ATLAS detector

- As QGP modifies an object that interacts with it, this object also modify the QGP.



Jets

Mach Cones, Di-Jet Asymmetry, soft particle enhancment, wake diffusion

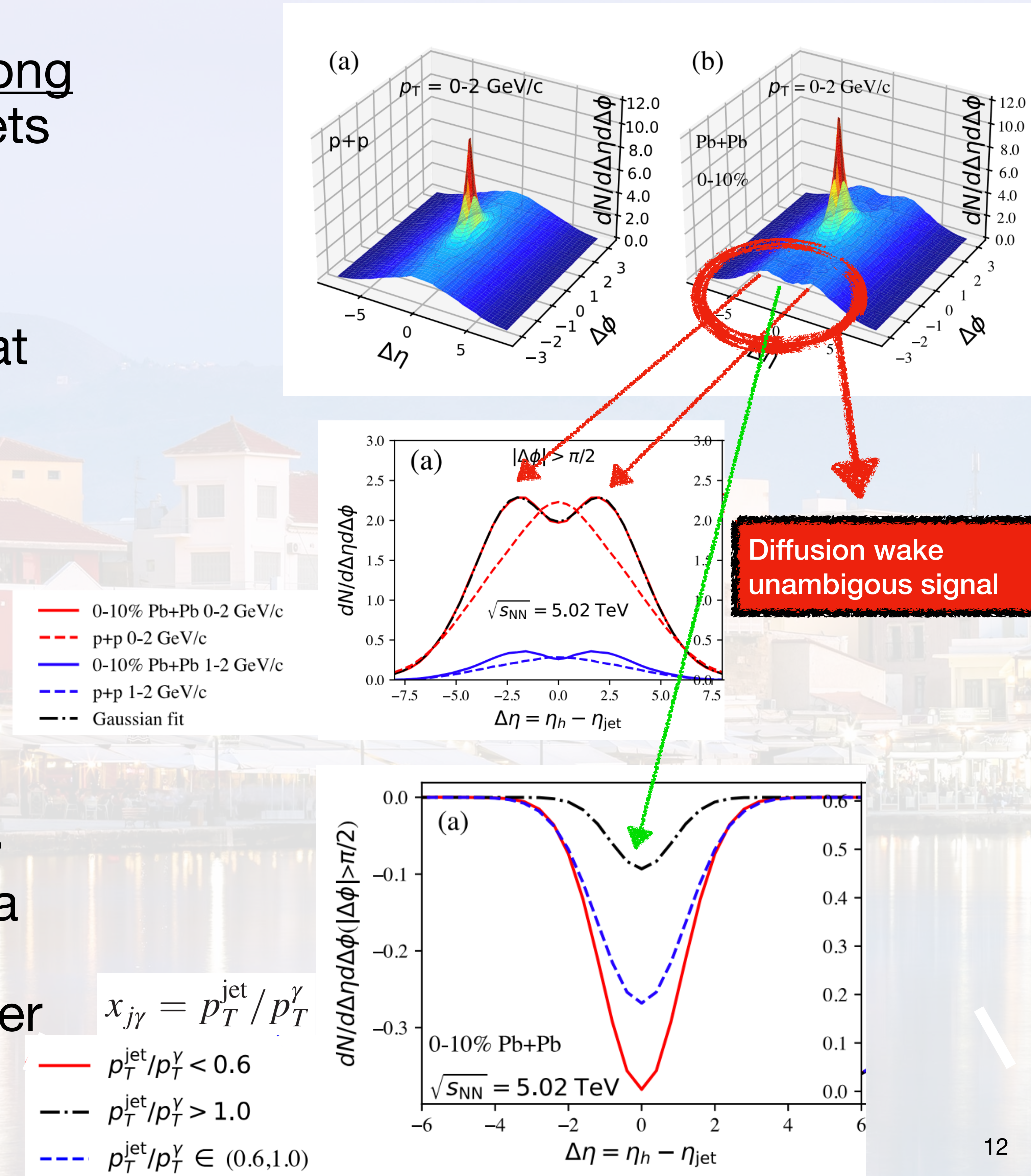


G.-Y. Qin et. al. 2009

- Understanding the medium is important for knowing its parameters, such as the shear viscosity, sound velocity, jet transport coefficient, etc.

Jet-induced wake via Photon-Jet events in QGP in Pb+Pb @ ATLAS detector

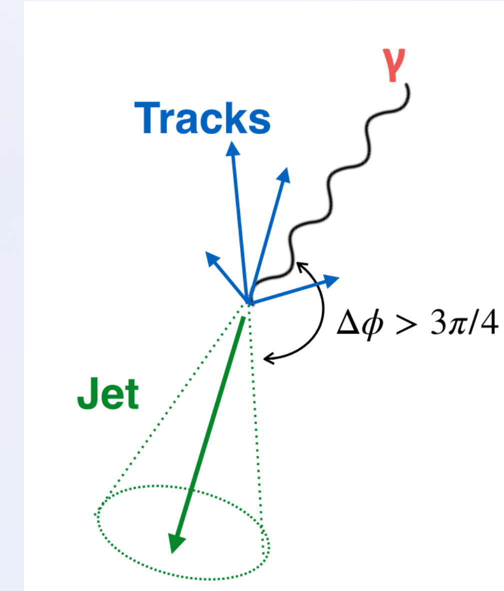
- From CoLBT-hydro results (Zhong Yang et al. 2023), γ-triggered jets in Pb+Pb collisions:
    - Enhancement from Multi Parton Interactions (MPI) at $\Delta\phi \sim \pi$.
    - Diffusion wake signal.
    - The MPI signal is not correlated with $x_{J\gamma}$.
    - A decrement in $x_{J\gamma}$ implies larger jet energy loss and a longer path through the medium and, hence a larger medium response, i.e., diffusion wake.

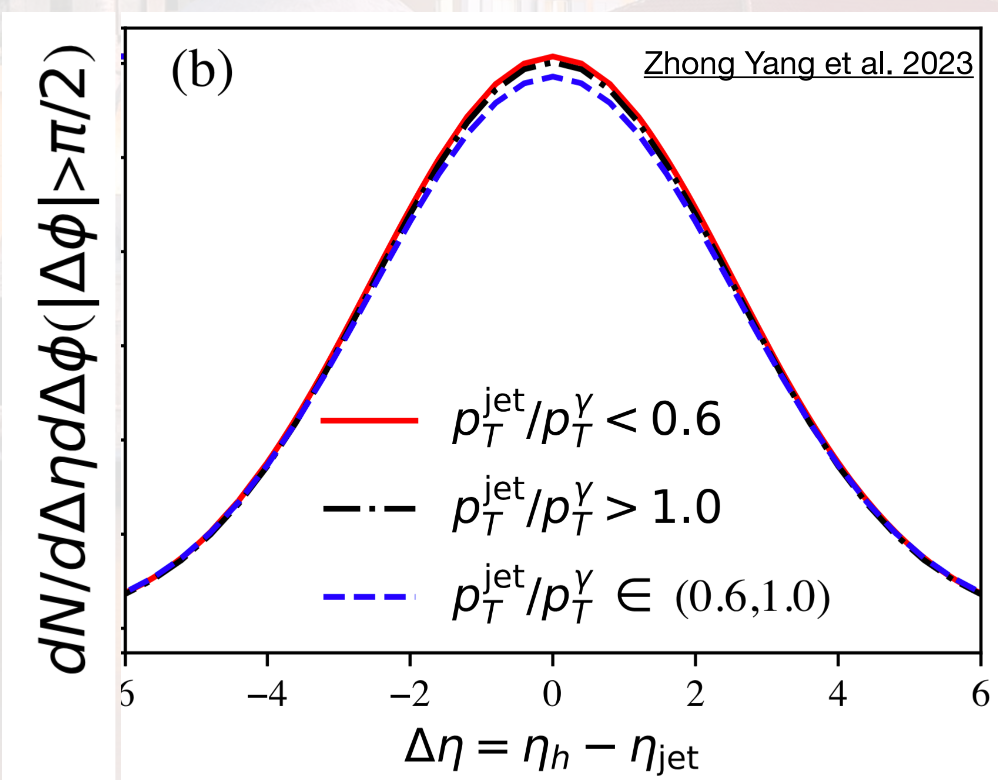


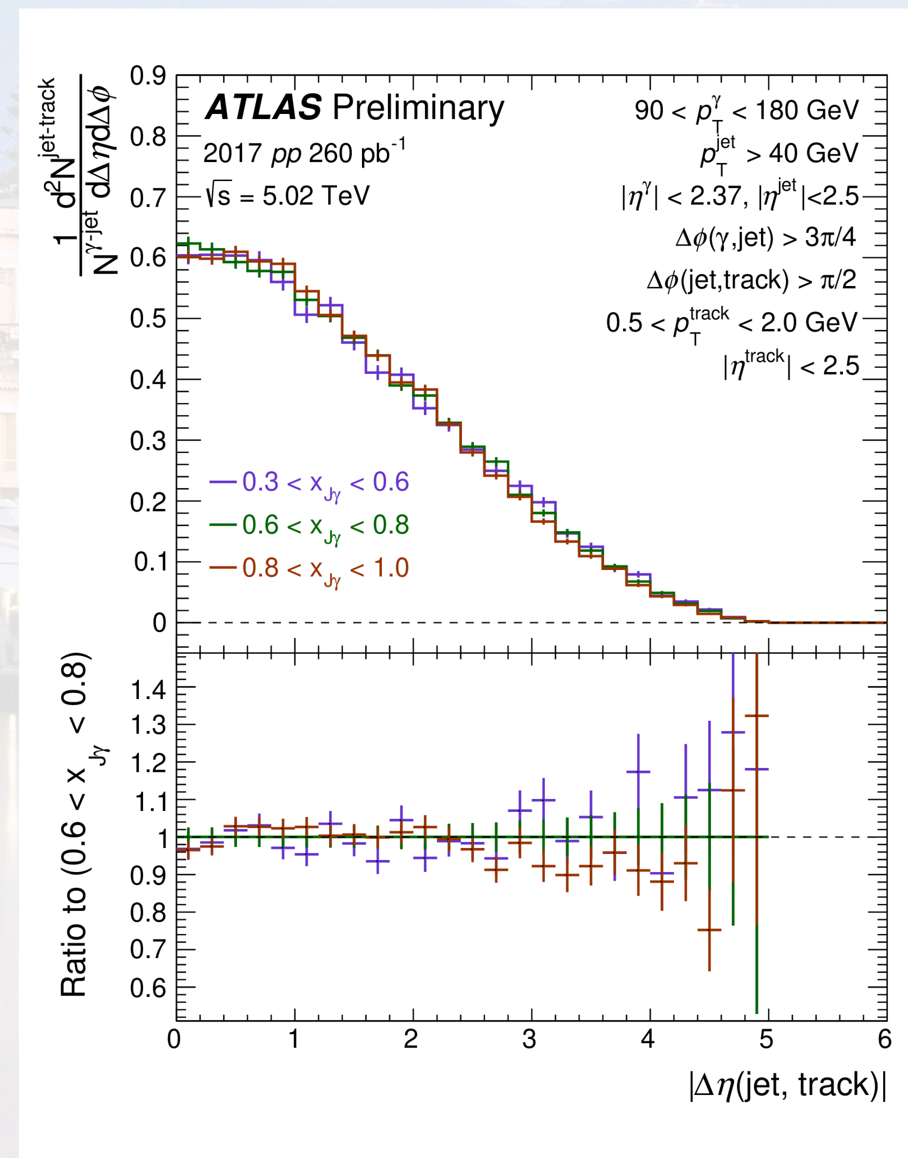
Jet-induced wake via Photon-Jet events in QGP in Pb+Pb

@ ATLAS detector

- ATLAS search for Jet+γ+Tracks events.
- MPI signal is not correlated with $x_{J\gamma}$ as is studied in the theoretical framework.

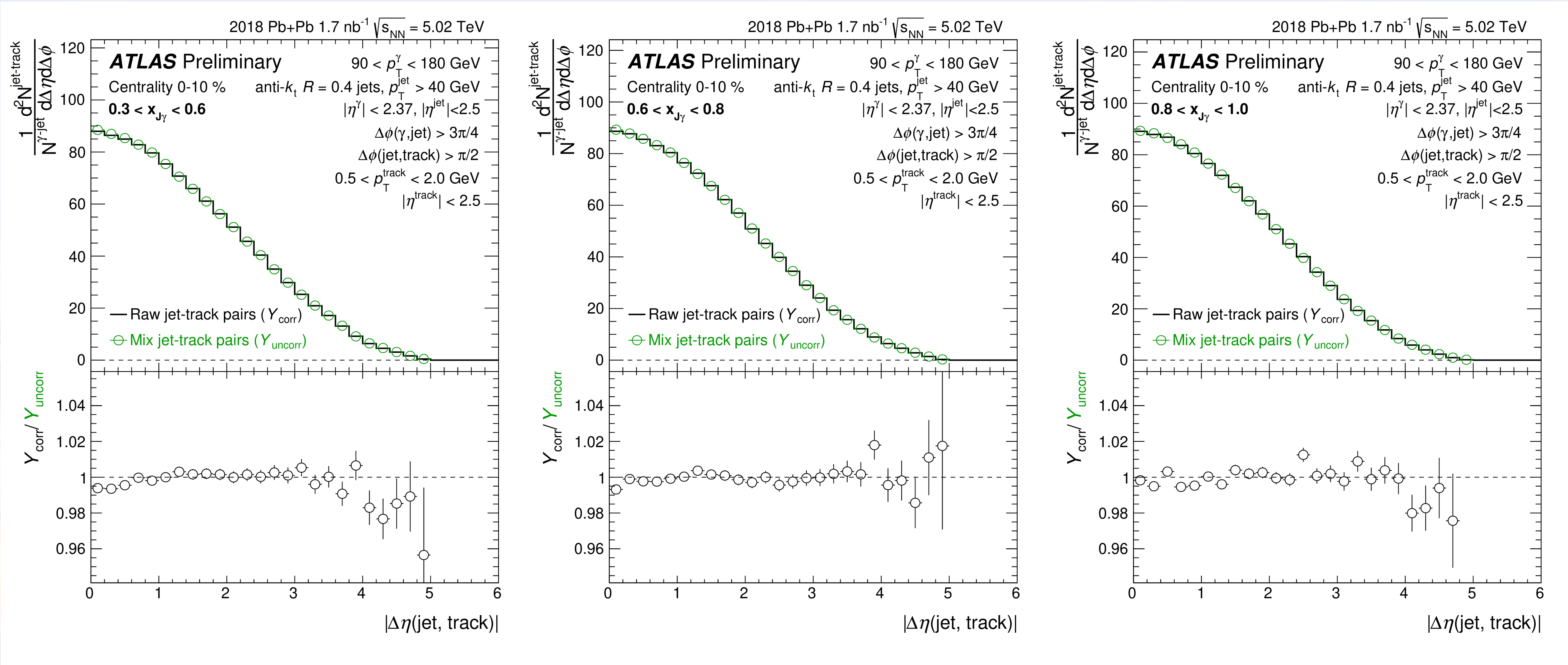






Jet-induced wake via Photon-Jet events in QGP in Pb+Pb @ ATLAS detector

$0.3 < x_{J\gamma} < 0.6$ $0.6 < x_{J\gamma} < 0.8$ $0.8 < x_{J\gamma} < 1.0$



- Y_{corr} : jet-track pairs from the signal (photon-jets) events.
- Y_{uncorr} : jets from signal events and tracks from Mini Bias events.
- $Y_{\text{corr}}/Y_{\text{uncorr}}$: Relative yield ratio between signal and mixed events

Jet-induced wake via Photon-Jet events in QGP in Pb+Pb @ ATLAS detector

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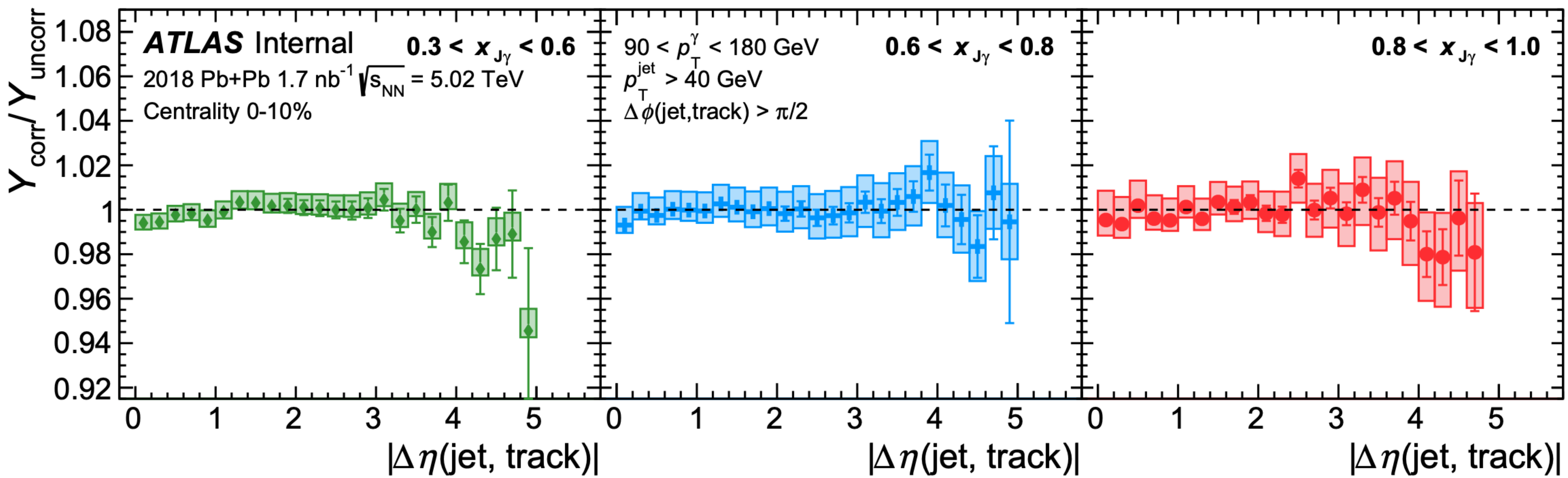

- Y_{corr} : jet-track pairs from the signal (photon-jets) events.
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- $Y_{\text{corr}}/Y_{\text{uncorr}}$: Relative yield ratio between signal and mixed events

No clear diffusion wake signal is found for the three $x_{J\gamma}$ regions

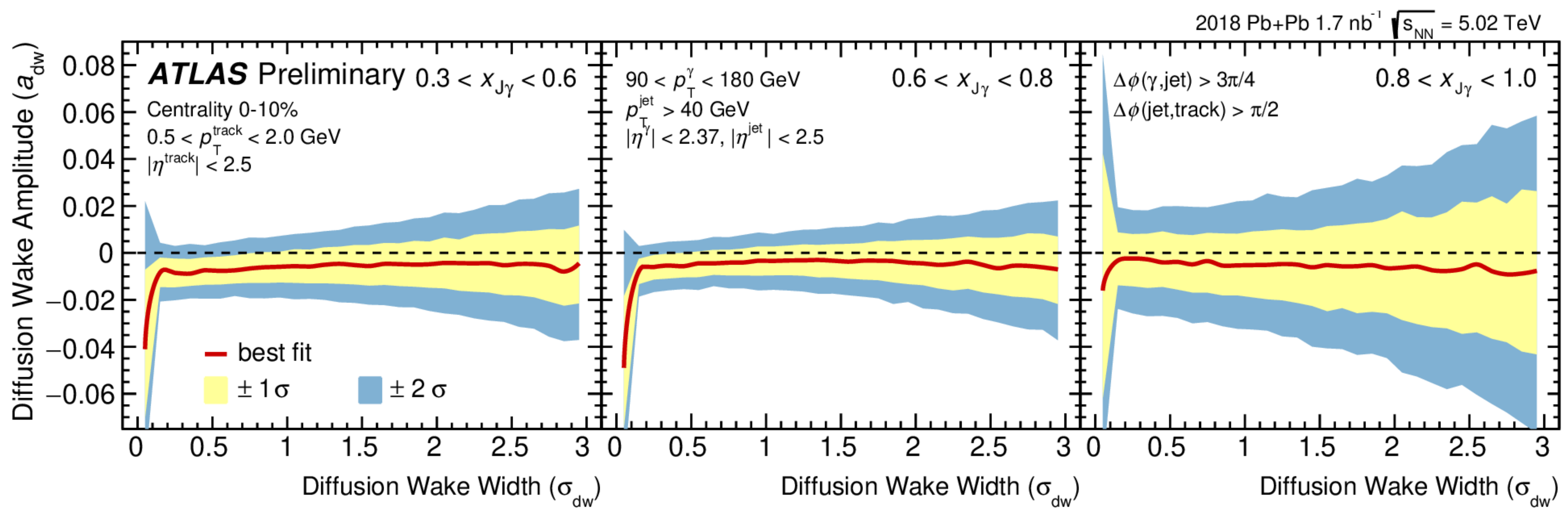
Jet-induced wake via Photon-Jet events in QGP in Pb+Pb @ ATLAS detector

- The $Y_{\text{corr}}/Y_{\text{uncorr}}$ distributions are fitted with:

$$a_0 + a_{dw}e^{-\Delta\eta(jet,track)|^2/(2\sigma_{dw}^2)}$$

to quantify those observations.

$0.3 < x_{J\gamma} < 0.6$ $0.6 < x_{J\gamma} < 0.8$ $0.8 < x_{J\gamma} < 1.0$

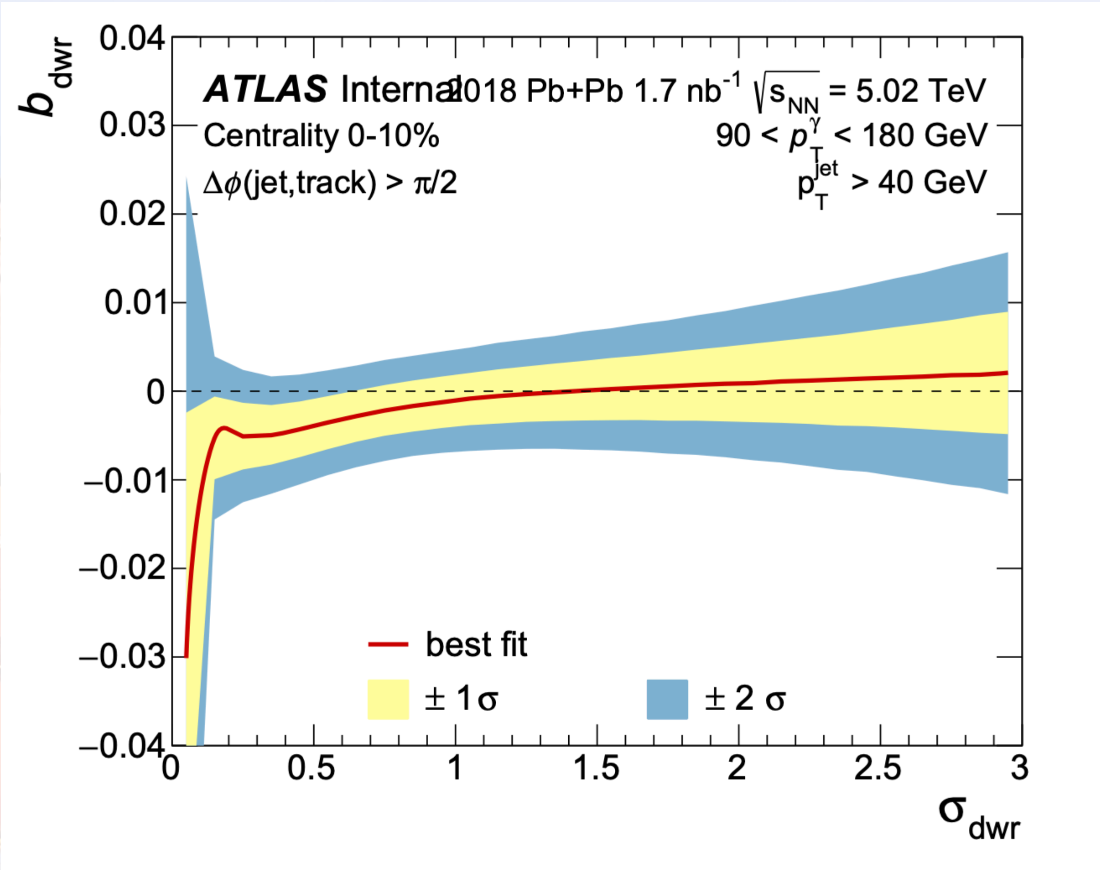


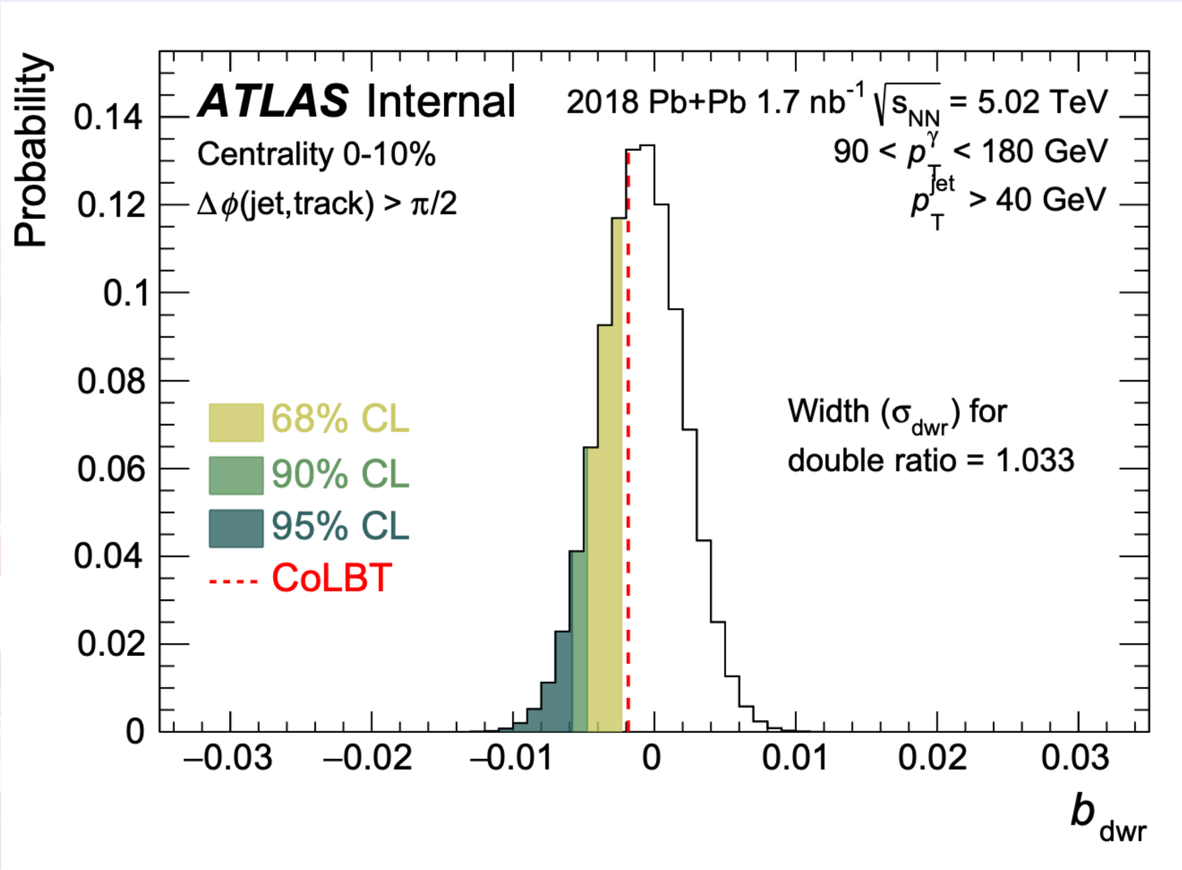
Results are consistent with $a_{dw} = 0$ at 1σ

Jet-induced wake via Photon-Jet events in QGP in Pb+Pb @ ATLAS detector

- Double ratio amplitude $\left(\frac{Y_{\text{corr}}}{Y_{\text{uncorr}}}\right)_{x_{J\gamma}=0.3-0.6} / \left(\frac{Y_{\text{corr}}}{Y_{\text{uncorr}}}\right)_{x_{J\gamma}=0.8-1.0}$, also analyzed, fitted with:

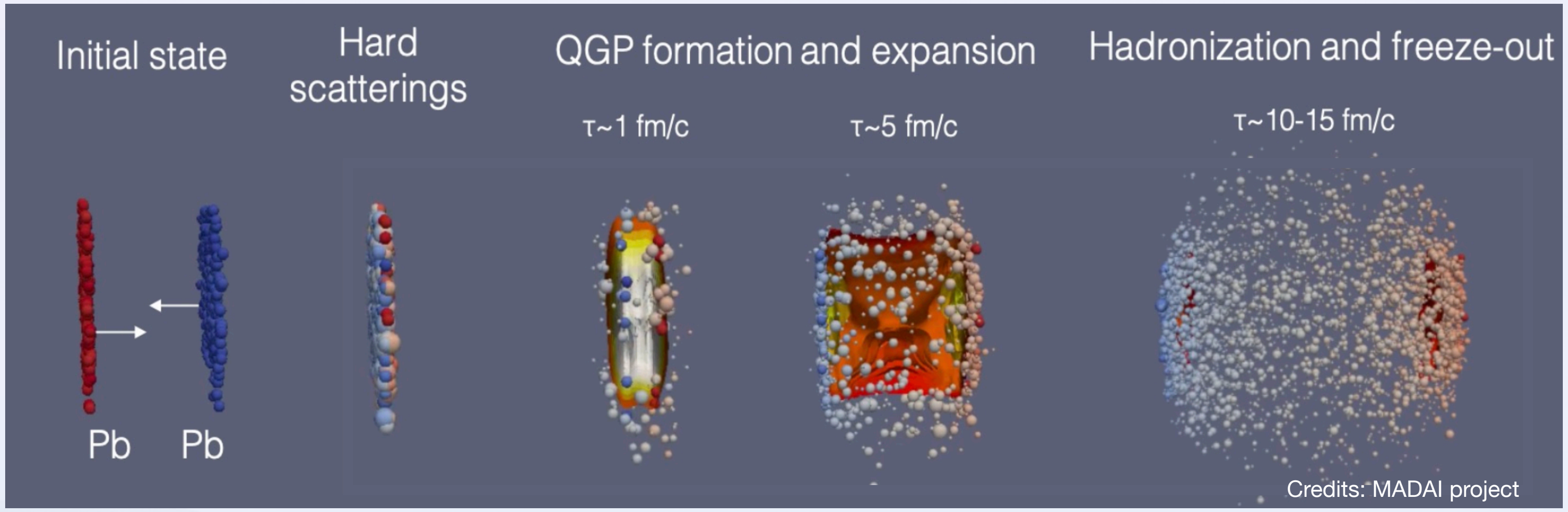
$$b_0 + b_{dwr} e^{-\Delta\eta(jet,track)|^2/2(\sigma_{dwr}^2)}$$



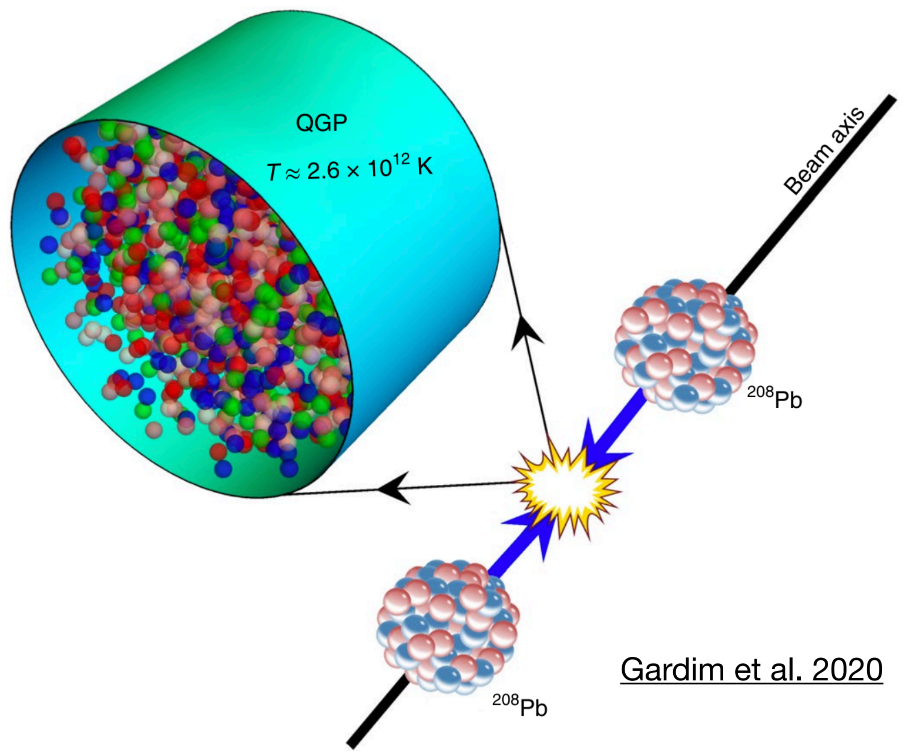


- Theory predicts $b_{dwr} = -0.00185$ and $\sigma_{dwr} = 1.033$.
- $b_{dwr} < -0.0058$ can be ruled out at the 95% CL.
- The CoLBT-hydro theory prediction is consistent with data within 68% of upper CL.

p_T fluctuations components, Xe+Xe, Pb+Pb @ ATLAS detector



- Due to the hydrodynamical expansion of QGP, the final state particles are boosted.
- Once QGP forms, initial anisotropies exist, translated into variations in the average for each event $[p_T]$.
- The moments serve as a probe of QGP properties, like: EOS, c_s^2, etc.
- The $[p_T]$ fluctuations can be separated in:
    - Geometrical
    - Intrinsic



$$c_s^2(T_{\text{eff}}) \propto \frac{d\ln(\langle[p_{\text{T}}]\rangle)}{d\ln(N_{\text{ch}})} \approx \frac{\Delta p_{\text{T}}/\langle[p_{\text{T}}]\rangle}{\Delta N_{\text{ch}}/\langle N_{\text{ch}}\rangle}$$

(Sound speed in QGP)

p_T fluctuations components, Xe+Xe, Pb+Pb @ ATLAS detector

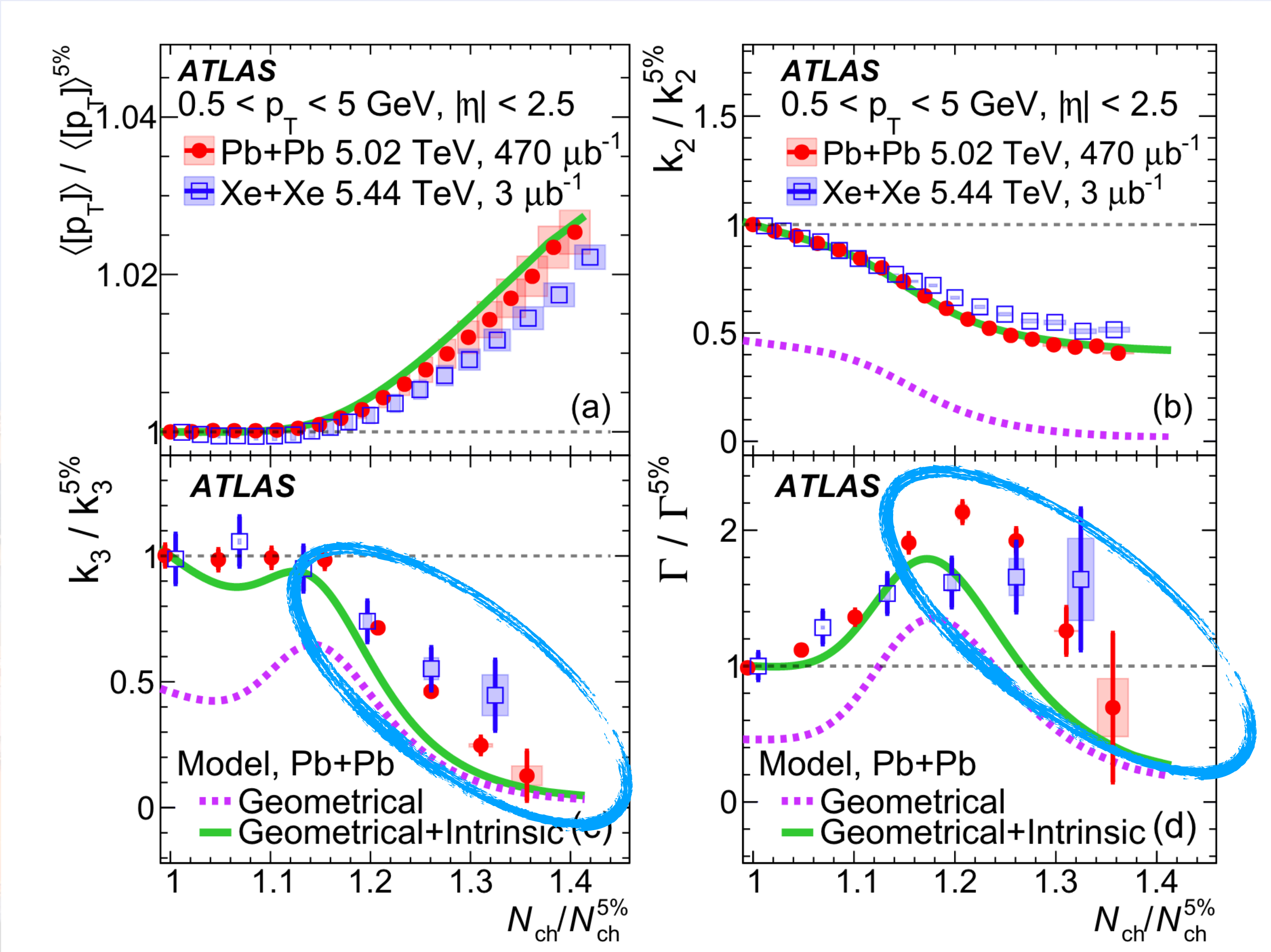
- Oservables to look at:

$$[p_T] = \frac{\sum_{i_1} w_{i_1} p_{T,i_1}}{\sum_{i_1} w_{i_1}} \qquad c_n = \frac{\sum_{i_1 \neq \ldots \neq i_n} w_{i_1} \cdots w_{i_n} (p_{T,i_1} - \langle [p_T] \rangle) \cdots (p_{T,i_n} - \langle [p_T] \rangle)}{\sum_{i_1 \neq \ldots \neq i_n} w_{i_1} \cdots w_{i_n}}$$

$$k_2 = \frac{\langle c_2 \rangle}{\langle [p_T] \rangle^2}, \quad k_3 = \frac{\langle c_3 \rangle}{\langle [p_T] \rangle^3}, \quad \gamma = \frac{\langle c_3 \rangle}{\langle c_2 \rangle^{3/2}}, \quad \Gamma = \frac{\langle c_3 \rangle \langle [p_T] \rangle}{\langle c_2 \rangle^2}$$

- $\langle c_2 \rangle$ It is the variance and $\langle c_3 \rangle$ the skewness, k_2 and k_3 are normalized into dimensionless quantities.
- $\langle [p_T] \rangle$ It is the average over an ensemble of events.

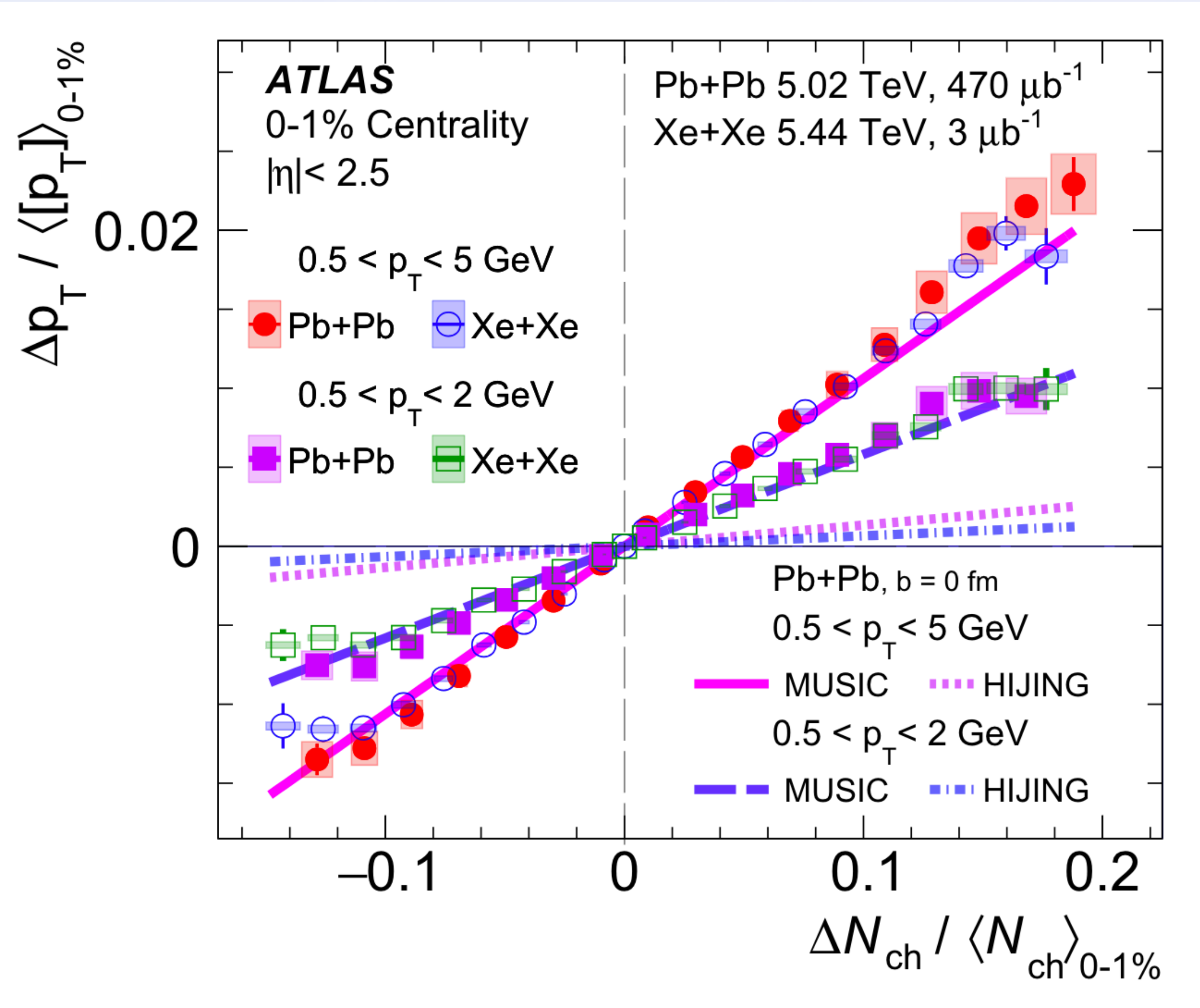
p_T fluctuations components, Xe+Xe, Pb+Pb @ ATLAS detector



- The $\langle[p_T]\rangle$ fluctuations can be disentangled with geometrical and intrinsical components.

- A 2D Gaussian was used to describe the increment $\langle[p_T]\rangle$ and decrement in k_2 (Rupam S. et al. 2023).

p_T fluctuations components, Xe+Xe, Pb+Pb @ ATLAS detector



$$\Delta p_T = \langle [p_T] \rangle - \langle [p_T] \rangle_{0-1\%}$$

$$\Delta N_{\text{ch}} = N_{\text{ch}} - \langle N_{\text{ch}} \rangle_{0-1\%}$$

$c_s^2 \approx 0.23$ (Similar to CMS collaboration)

$T_{eff} \approx 222[MeV]$ (Gardim et al. 2020)

- The slope depends on the track selection and centrality.
- HIJING model (no final-state interactions) underpredicts the slope.
- MUSIC model (include full hydrodynamics response of QGP to its initial-stage geometry).

Conclusions

- First ATLAS search for magnetic monopoles in Pb+Pb collisions.
- Best cross-sections upper limits for $M\overline{M}$ between 20 and 150 GeV mass ranges set.
- Jet-hadron correlations provide an unambiguous signal of medium response:
    - No diffusion wake signal was found.
    - Limits on diffusion wake amplitude.
- p_T fluctuations as a tool for QGP key properties.
- Agreement for different slopes with MUSIC model.
- It is possible to extract $c_s^2 \approx 0.23$ with an effective temperature, similar results obtained in CMS.