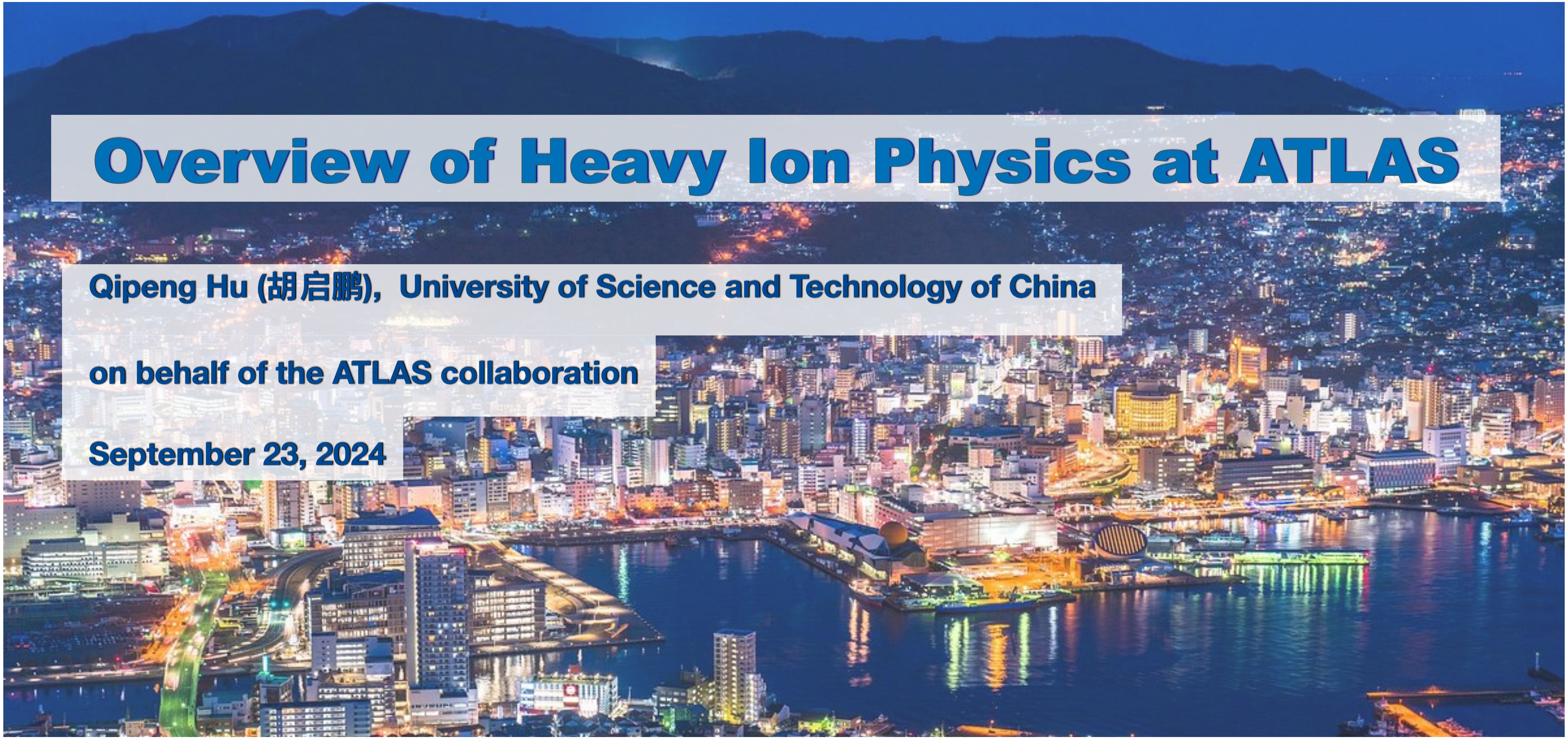


Overview of Heavy Ion Physics at ATLAS

Qipeng Hu (胡启鹏)，University of Science and Technology of China

on behalf of the ATLAS collaboration

September 23, 2024

HP2024
N A G A S A K I

ATLAS EXPERIMENT

1958
University of Science and Technology of China

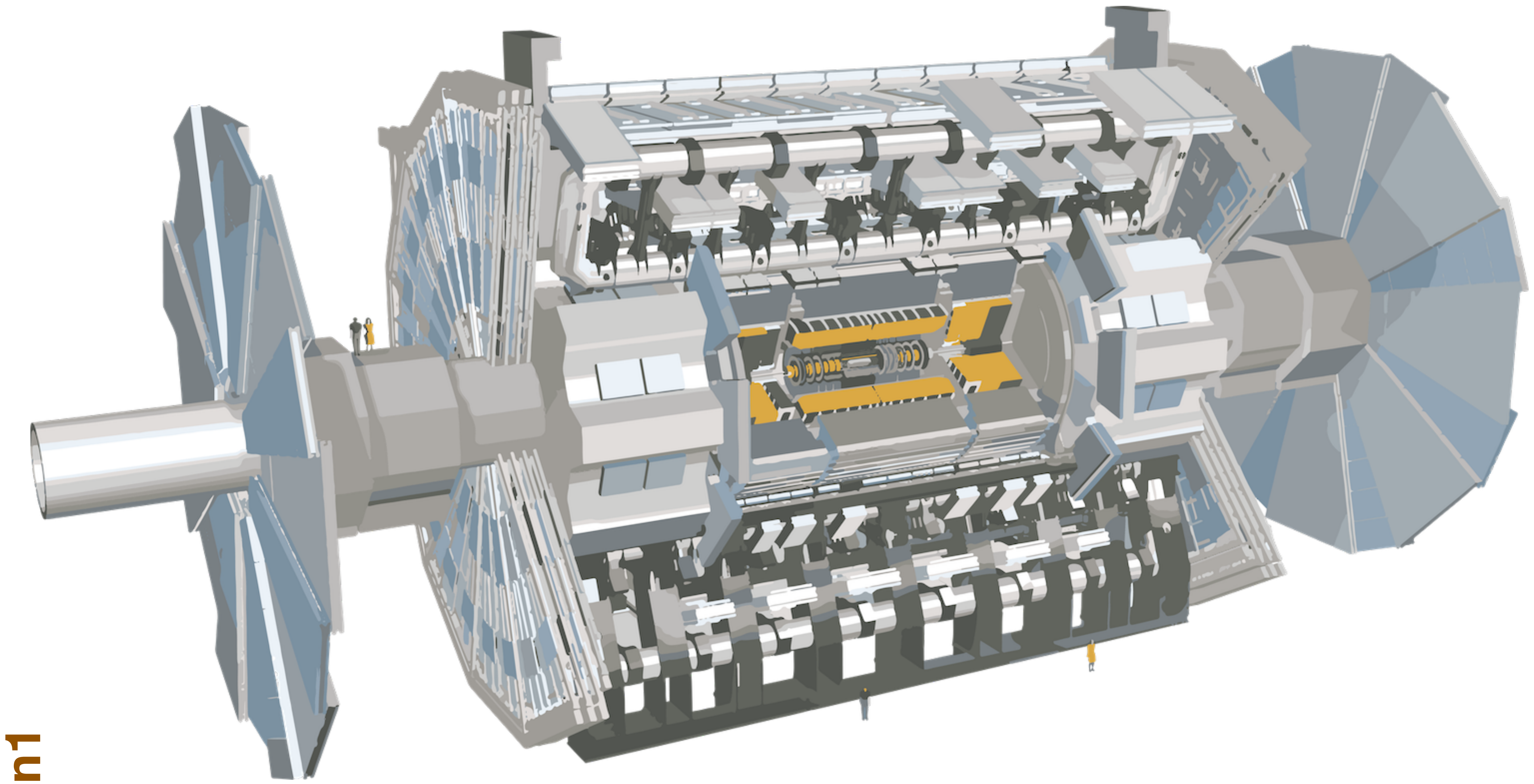
ATLAS Heavy Ion Data Summary

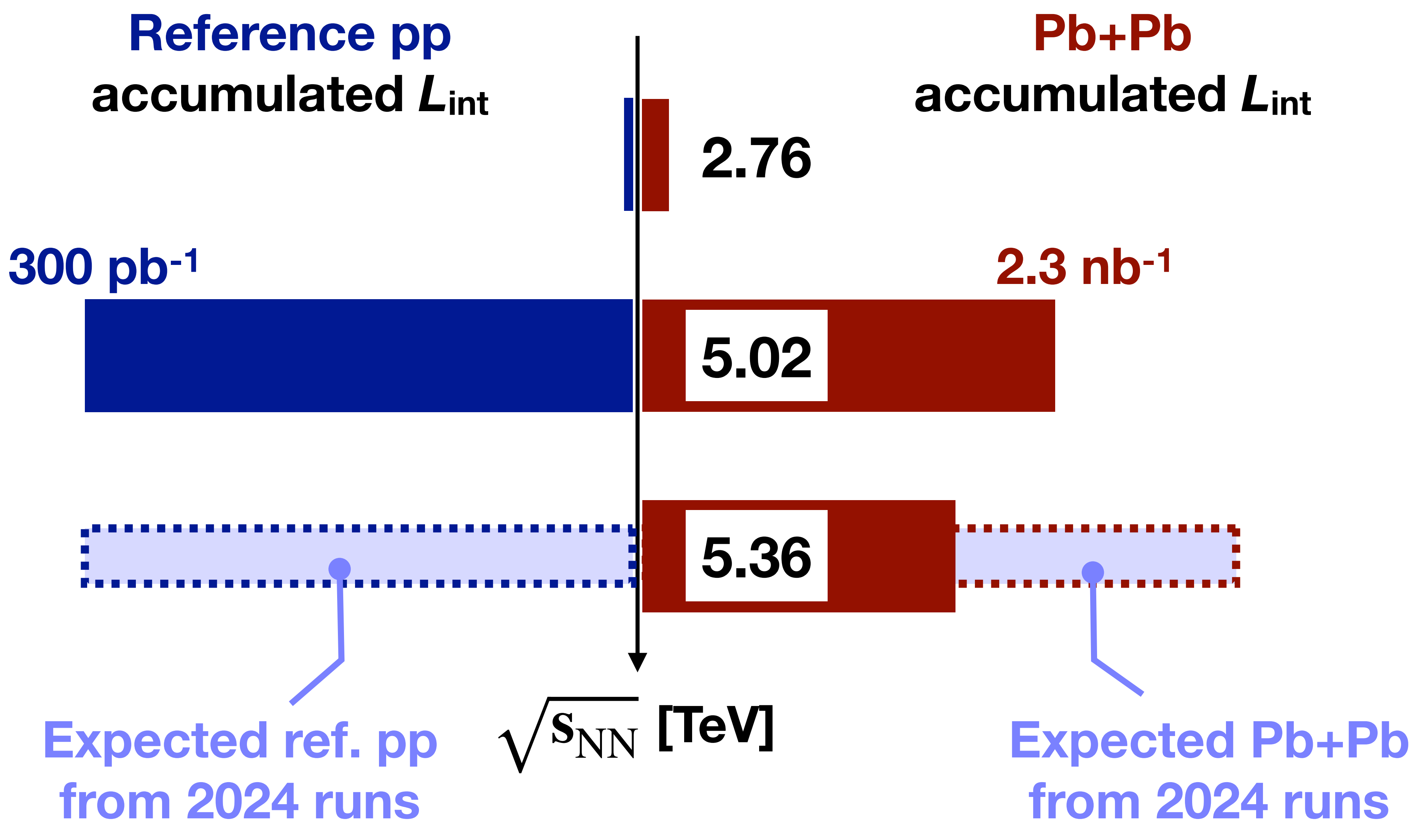
System	Year	$\sqrt{s_{NN}}$ [TeV]	L_{int}
Pb+Pb	2010	2.76	7 μb^{-1}
Pb+Pb	2011	2.76	0.14 nb^{-1}
pp	2013	2.76	4 pb^{-1}
p+Pb	2013	5.02	29 nb^{-1}
pp	2015	5.02	28 pb^{-1}
Pb+Pb	2015	5.02	0.49 nb^{-1}
p+Pb	2016	5.02	0.5 nb^{-1}
p+Pb	2016	8.16	0.16 pb^{-1}
Xe+Xe	2017	5.44	3 μb^{-1}
pp	2017	5.02	270 pb^{-1}
Pb+Pb	2018	5.02	1.76 nb^{-1}
Pb+Pb	2023	5.36	1.71 nb^{-1}

Run1

Run2

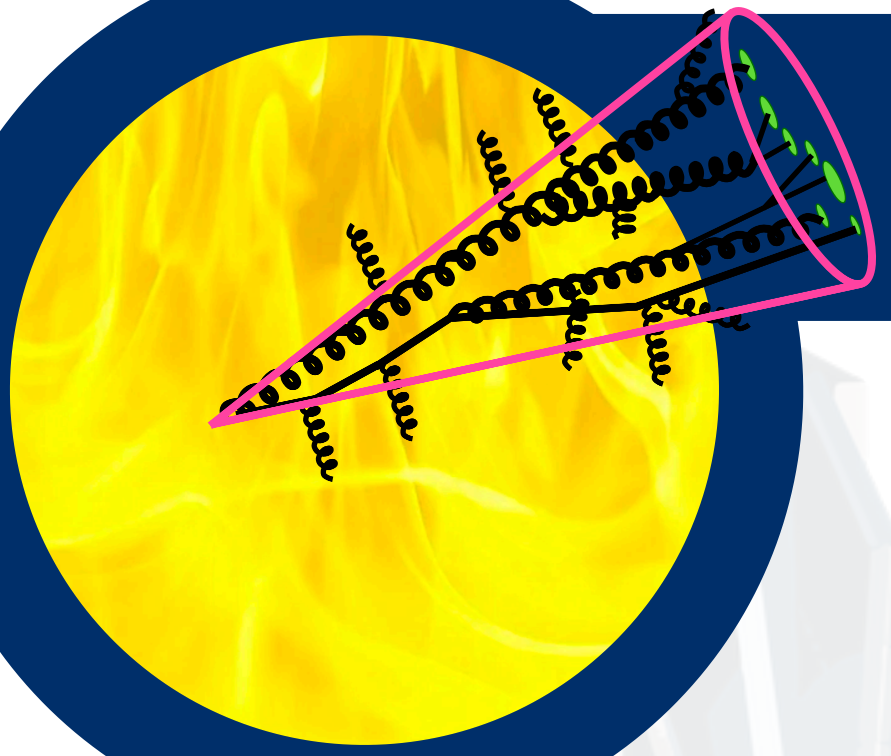
Run3





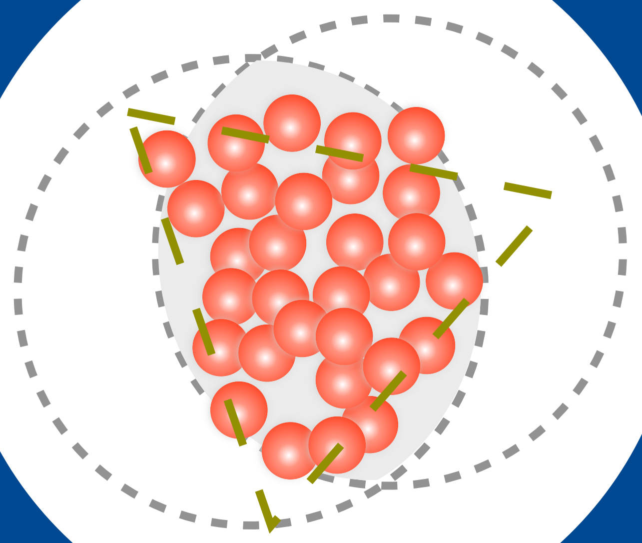
Focus since last Hard Probes

Probing QGP with penetrating particles



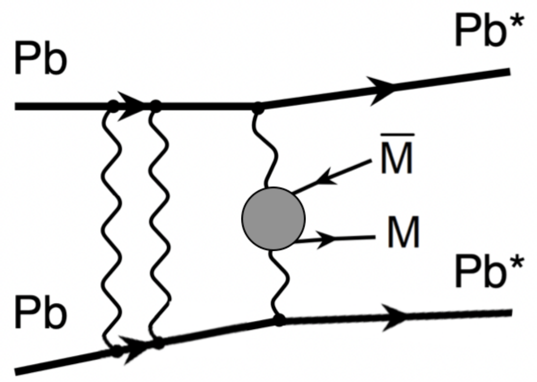
- Jet modification and medium response
- Heavy flavors
- Hard-soft correlation

Understand the initial state

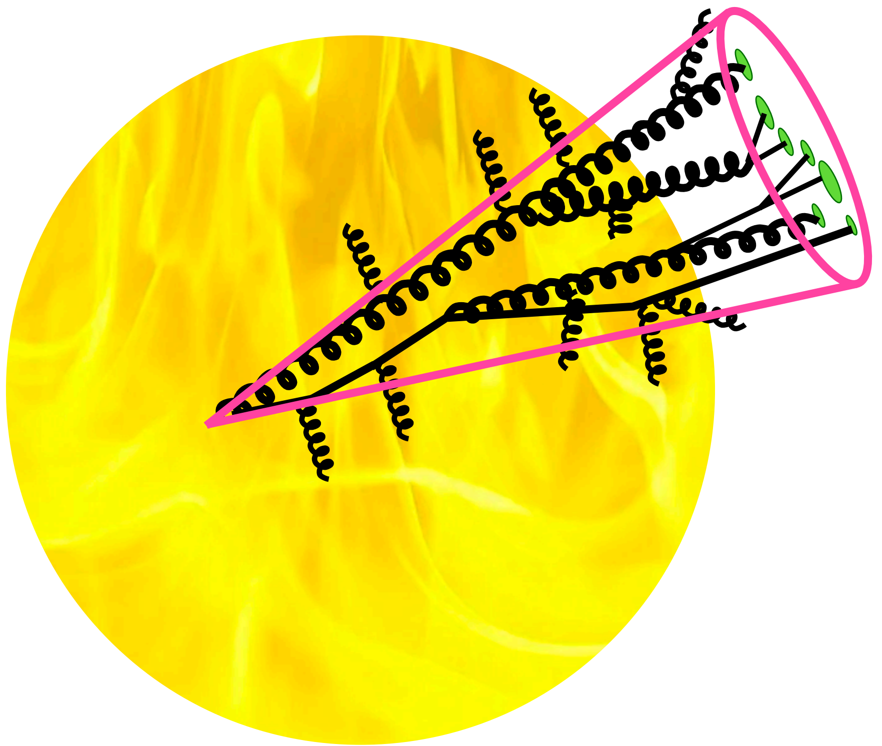


- Role of fluctuating geometry
- Color fluctuation in nucleons
- Nuclear modification of PDF

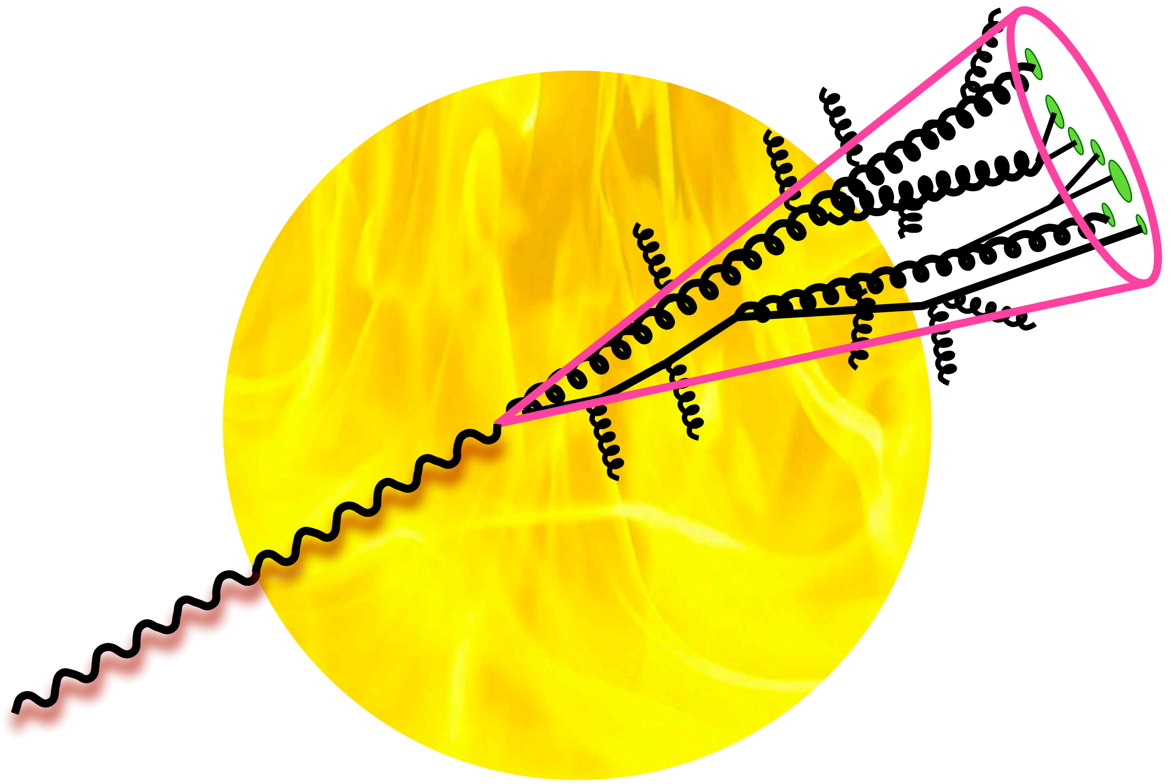
Exploring novel physics in UPCs



- Collectivity in UPC
- Tau g-2
- Magnetic Monopole



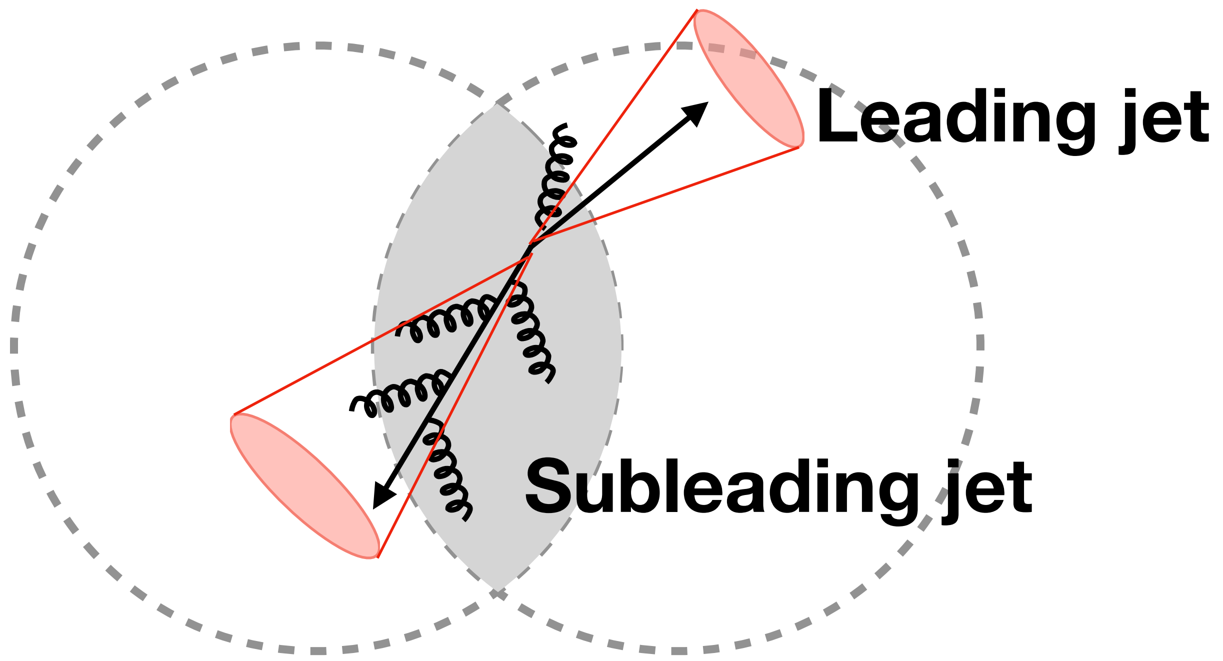
Penetrating probes of QGP



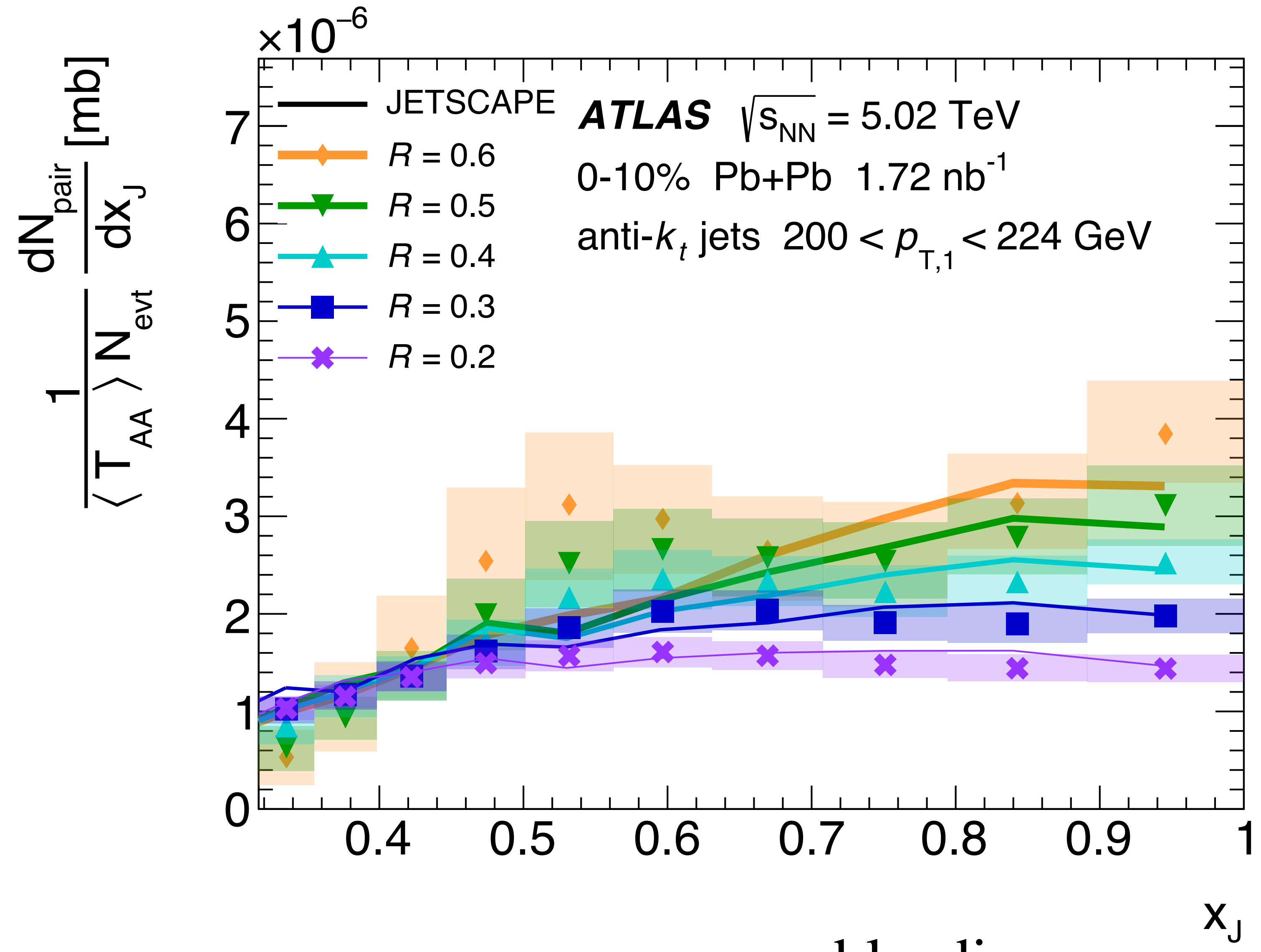
R-dependence of dijet asymmetry

arXiv:2407.18796

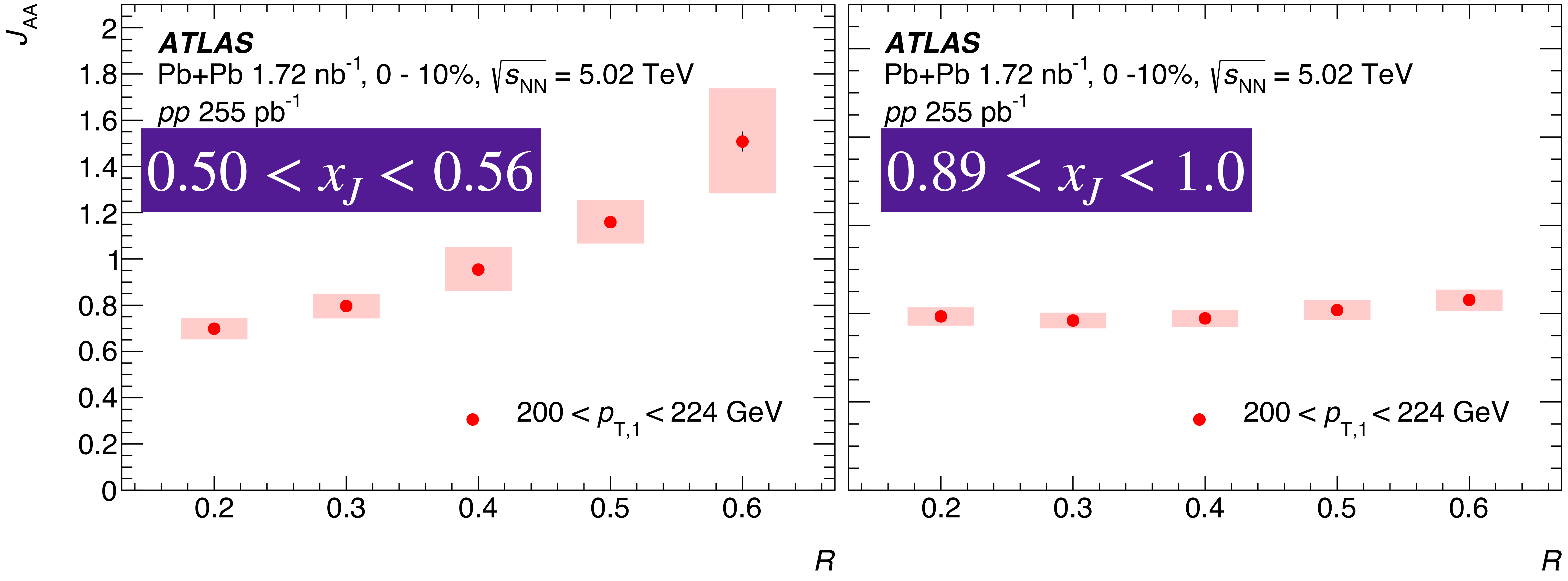
Final for HP2024



$$J_{AA} = \frac{1}{\langle T_{AA}\rangle N_{evt}^{AA}} \frac{dN_{pair}^{AA}}{dx_J} \Big/ \frac{dN_{pair}^{pp}}{L_{pp} dx_J}$$



$$x_J = \frac{p_T^{subleading}}{p_T^{leading}}$$

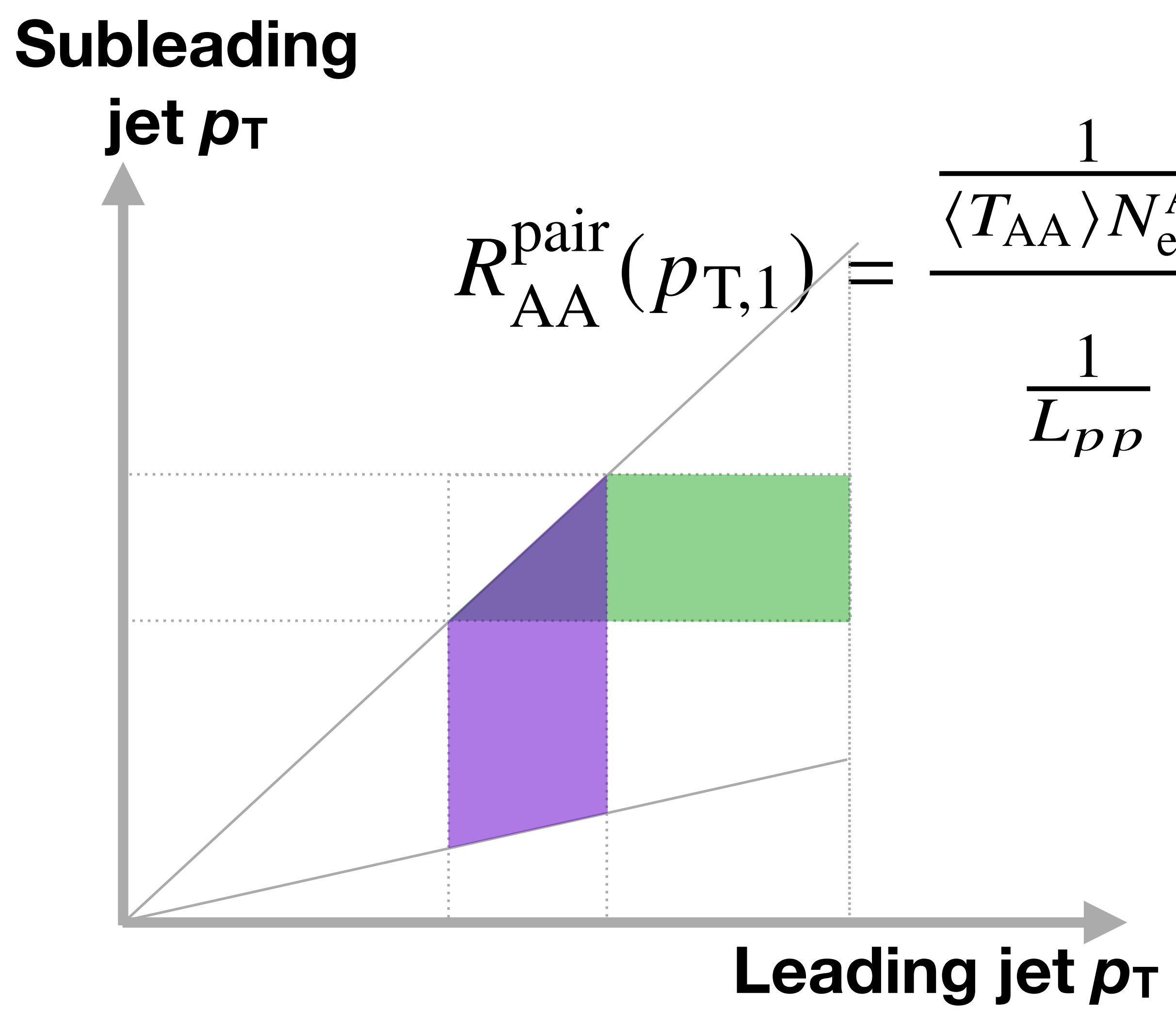


- Strong *R*-dependence for imbalanced dijets
- Smaller-*R* dijets are more suppressed

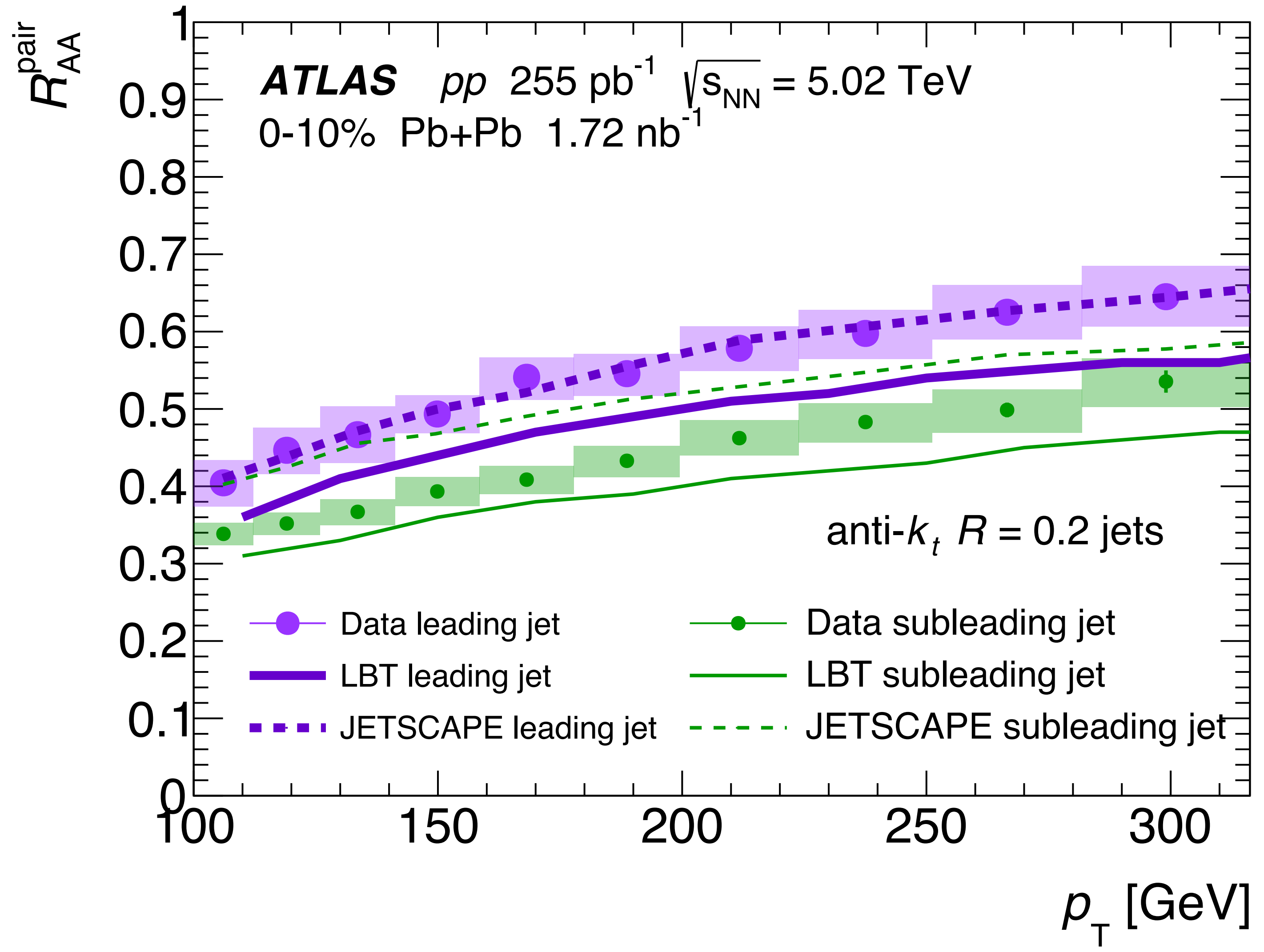
R-dependence of dijet quenching

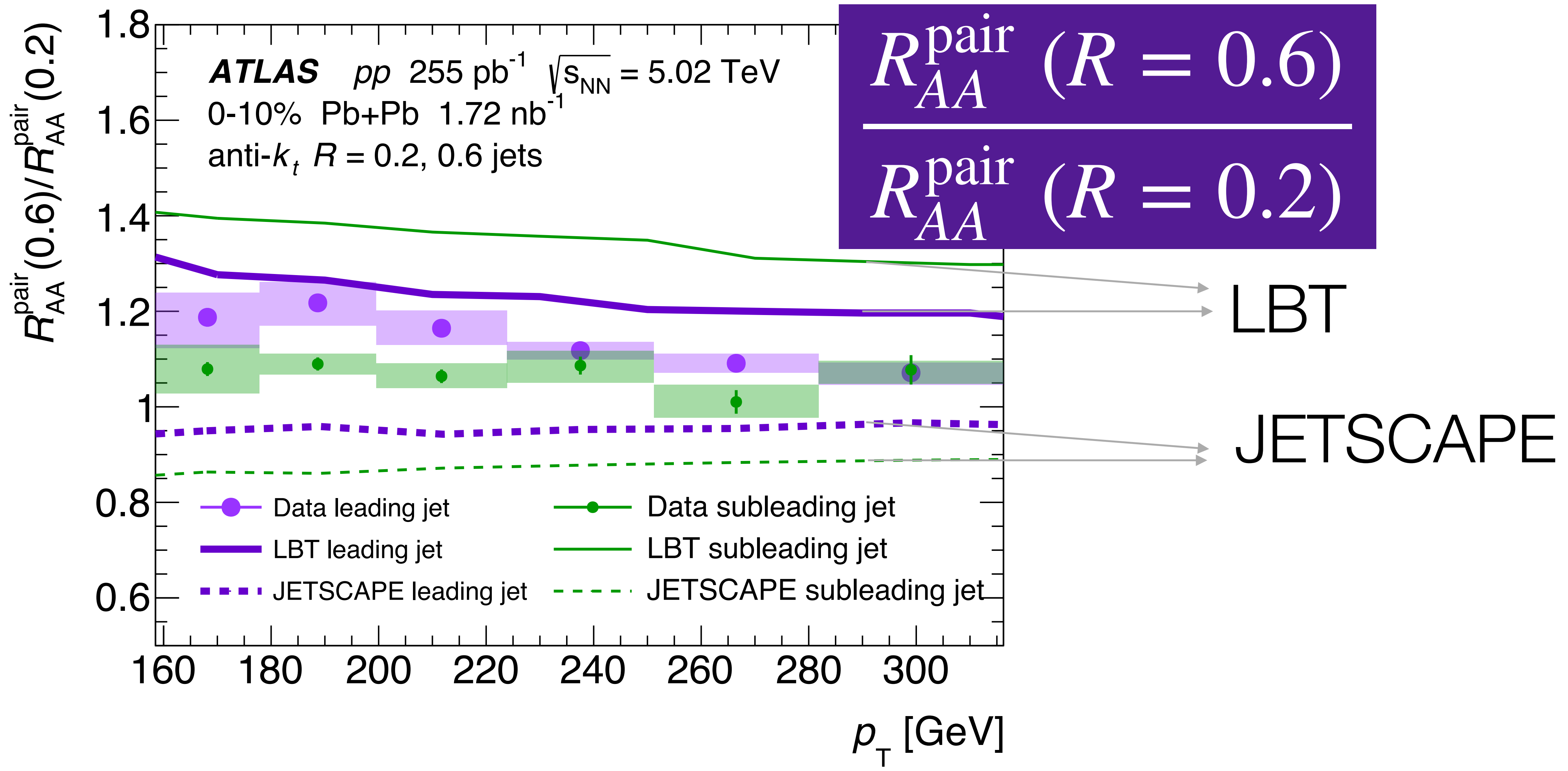
arXiv:2407.18796

Final for HP2024



$$R_{AA}^{\text{pair}}(p_{T,1}) = \frac{\frac{1}{\langle T_{AA}\rangle N_{\text{evt}}^{AA}} \int_{0.32\times p_{T,1}}^{p_{T,1}} \frac{d^2 N_{\text{pair}}^{AA}}{dp_{T,1}dp_{T,2}} dp_{T,2}}{\frac{1}{L_{pp}} \int_{0.32\times p_{T,1}}^{p_{T,1}} \frac{d^2 N_{\text{pair}}^{pp}}{dp_{T,1}dp_{T,2}} dp_{T,2}}$$

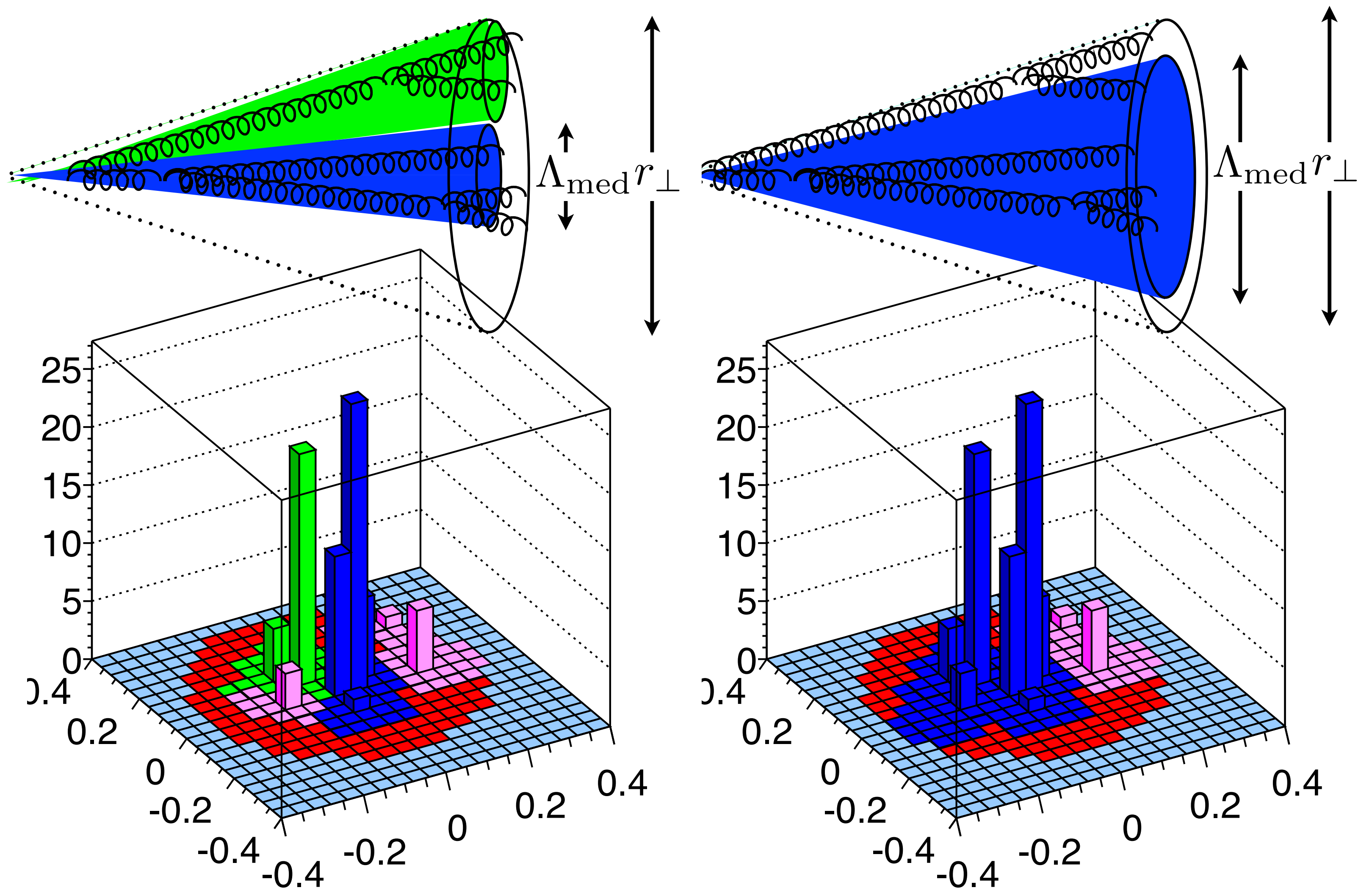




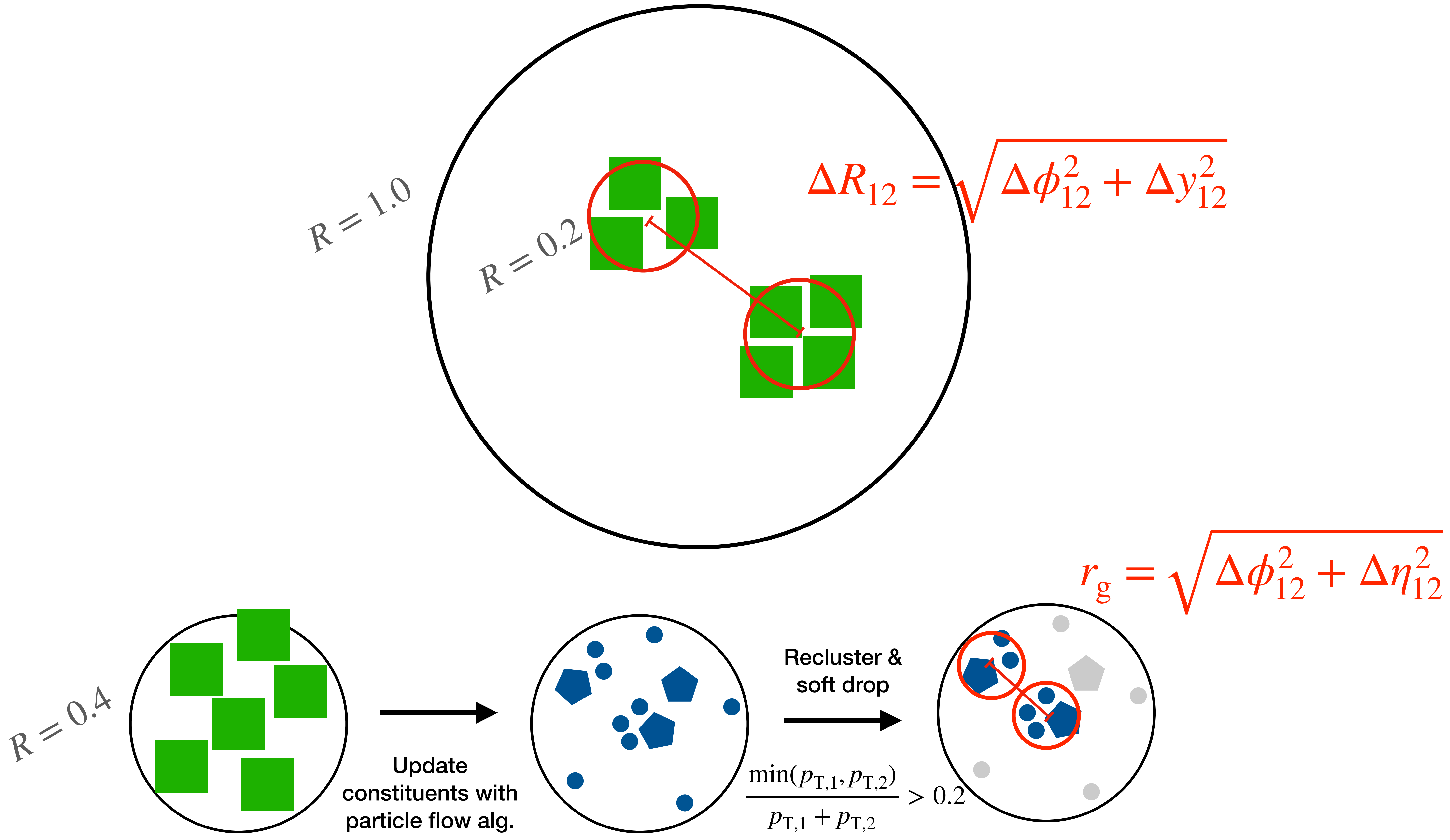
- Leading and subleading jet R_{AA}^{pair} are probing different population of dijet events, useful differential information to improve modeling
- Smaller-R dijets are more suppressed

Jet substructure

PRL 131 (2023) 172301
PRC 107 (2023) 054909



Casalderrey-Solana et al.
PLB 725 (2013) 357

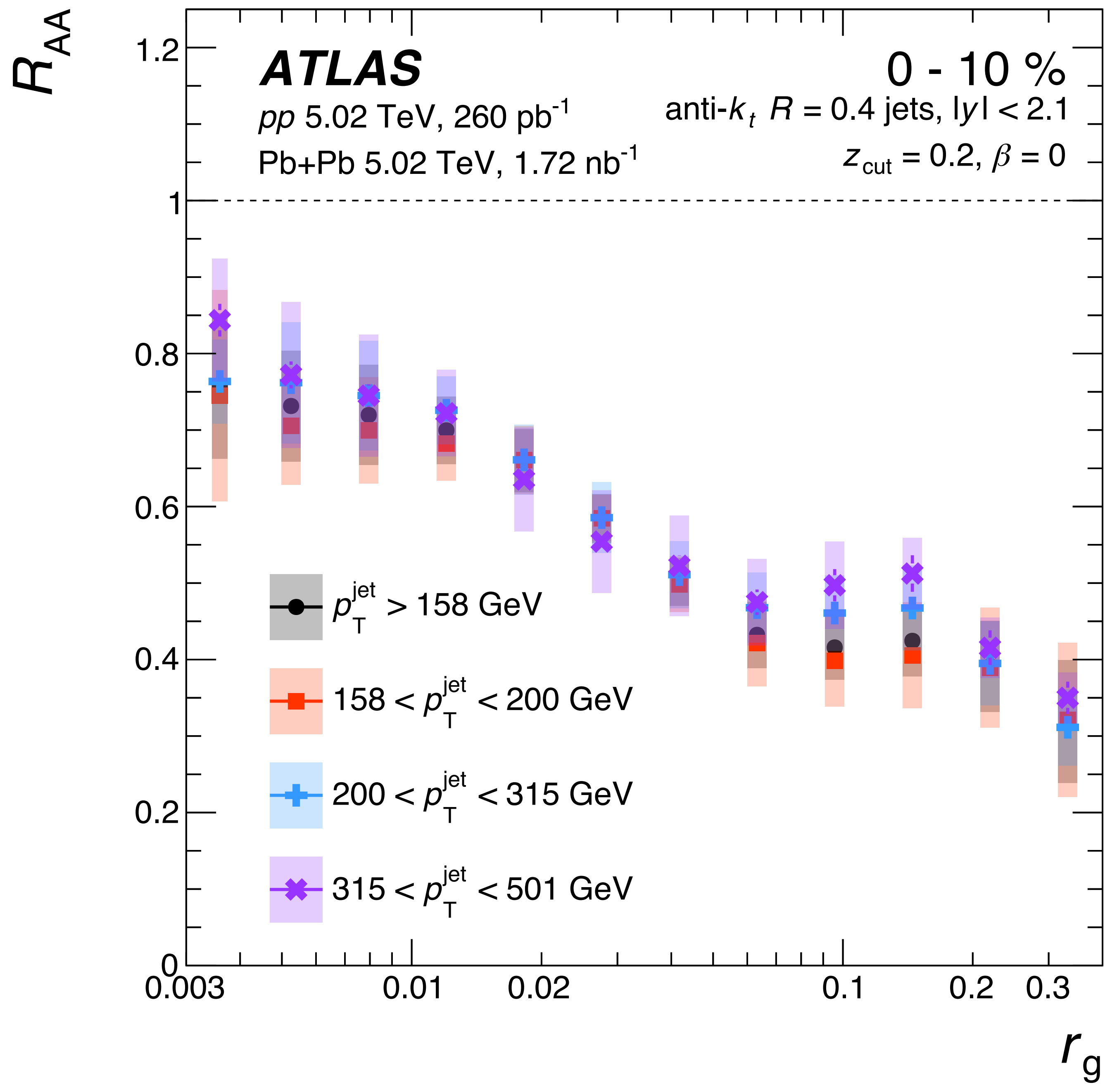


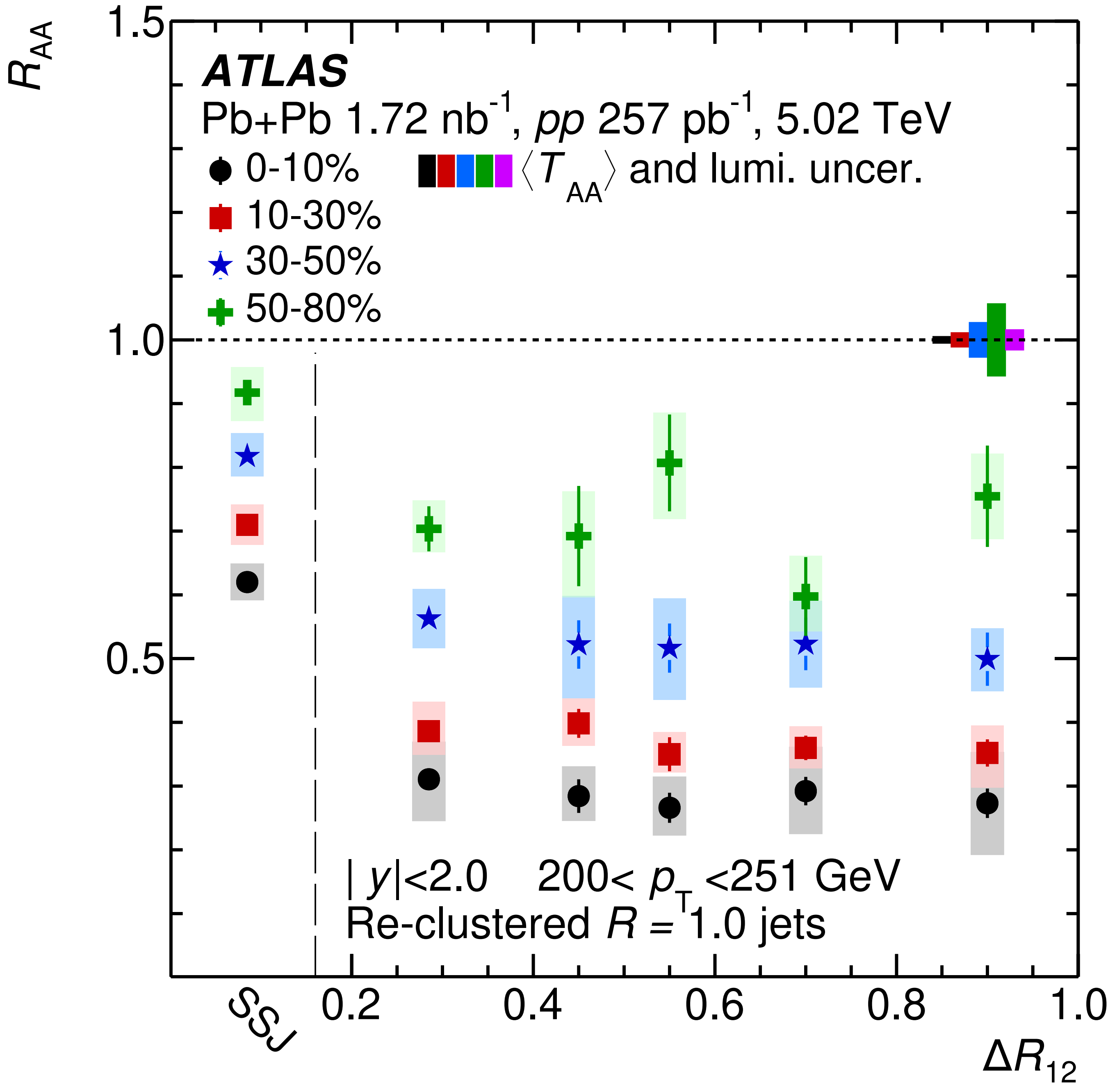
- Color decoherence can be study via hard splitting angle dependence of jet quenching
- Two measurements extracting opening angles between hard splittings in jets at complementing values

Jet substructure — cont.

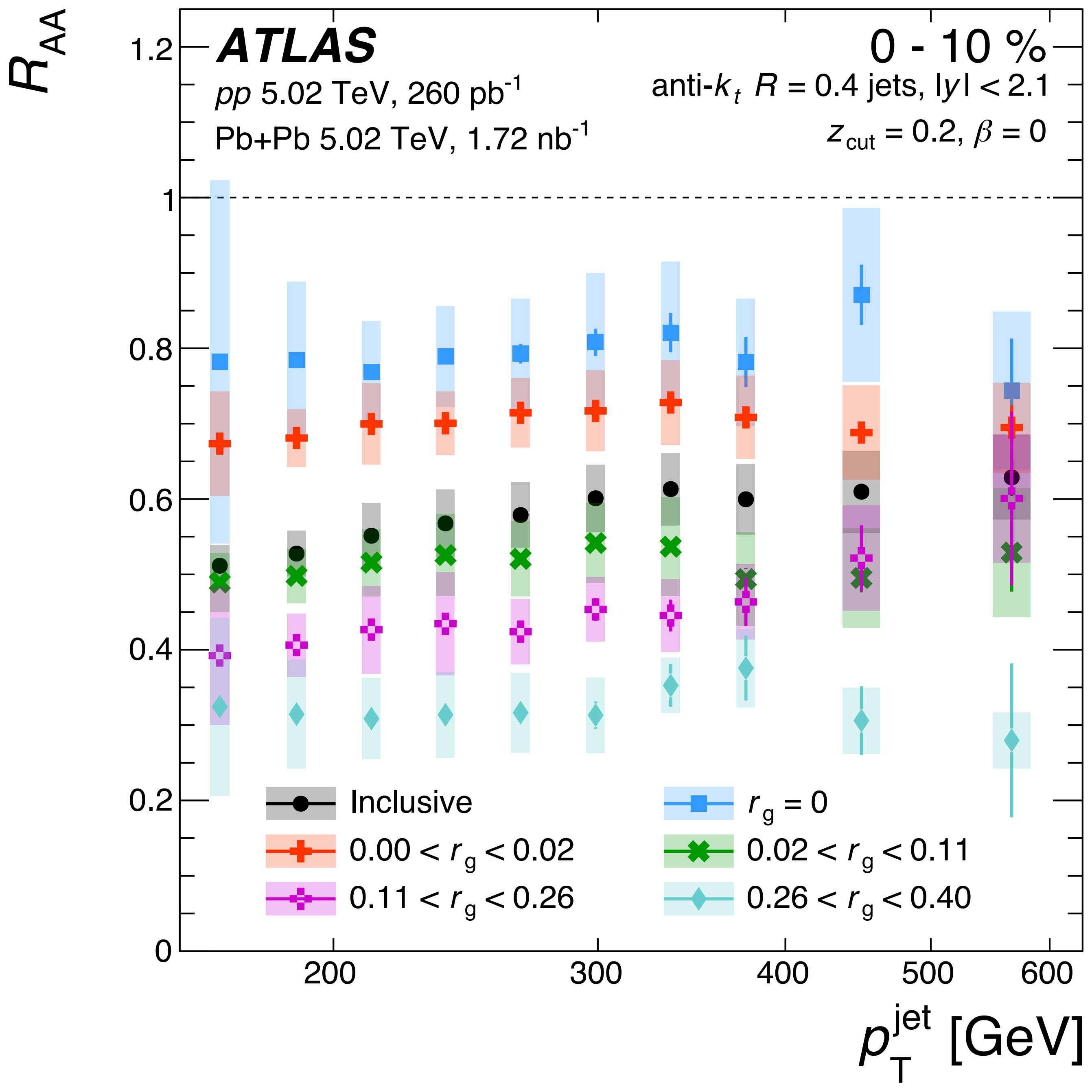
PRL 131 (2023) 172301
PRC 107 (2023) 054909

substructure opening angle dependence





Jet p_T dependence

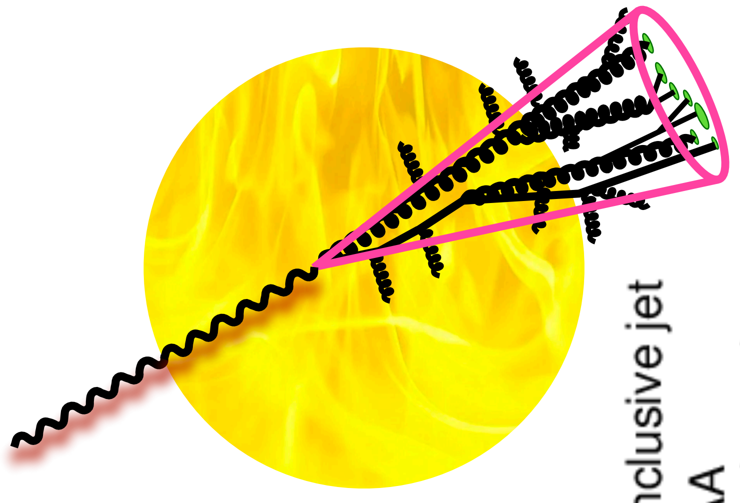


- Decoherence angular scale (**0.1 ~ 0.2**) observed in both large-*R* jets and groomed *R*=0.4 jets: significant larger energy loss above the scale
- Jet energy loss is most directly correlated with the jet substructure not jet p_T

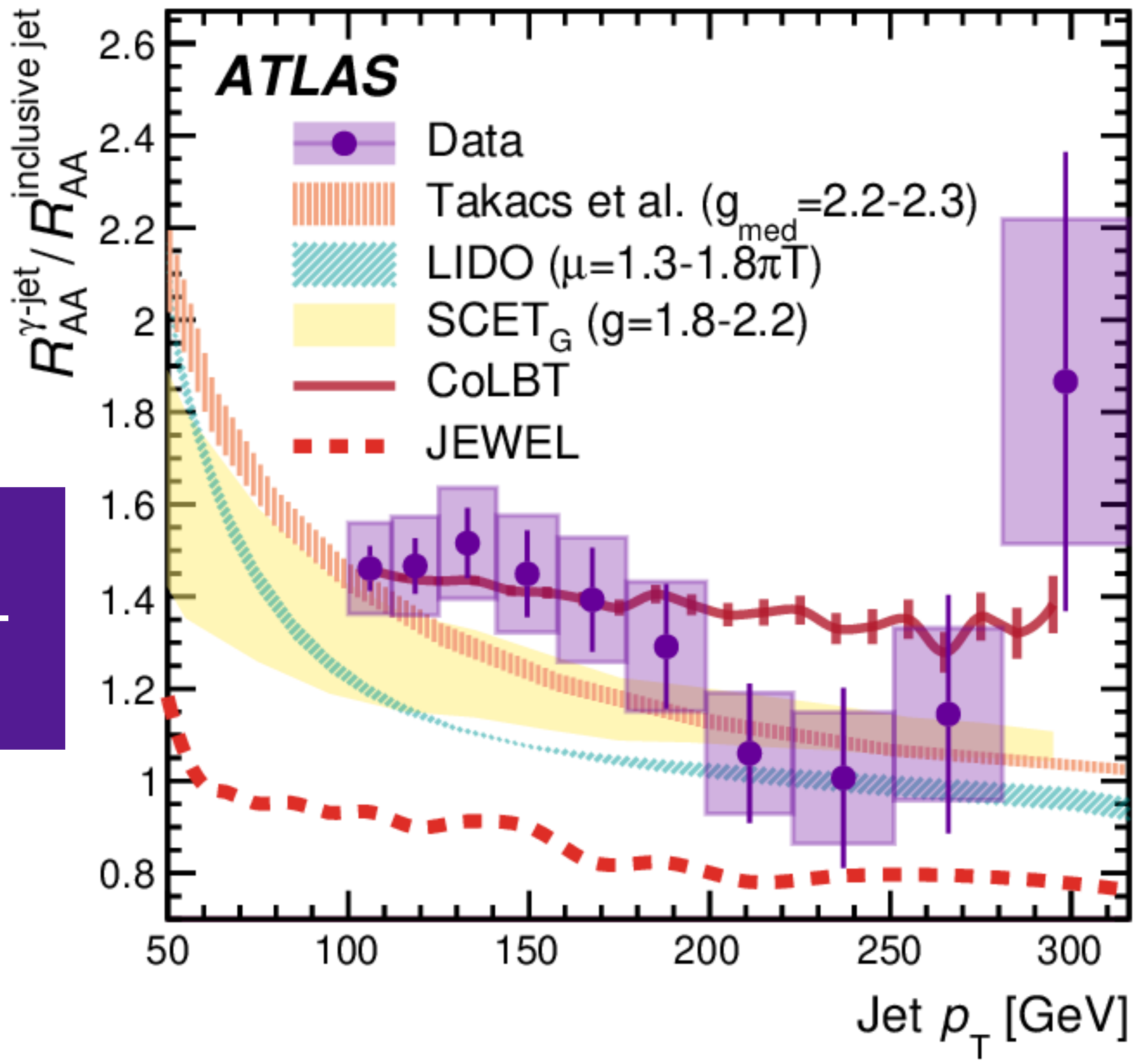
Monday 2:20 PM
Martin Rybar

Photon-tagged jet

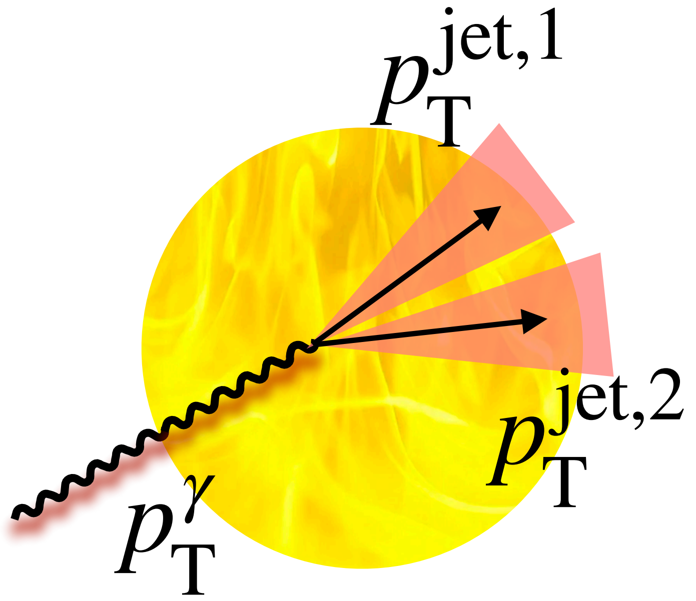
PLB 846 (2023) 138154
ATLAS-CONF-2023-008

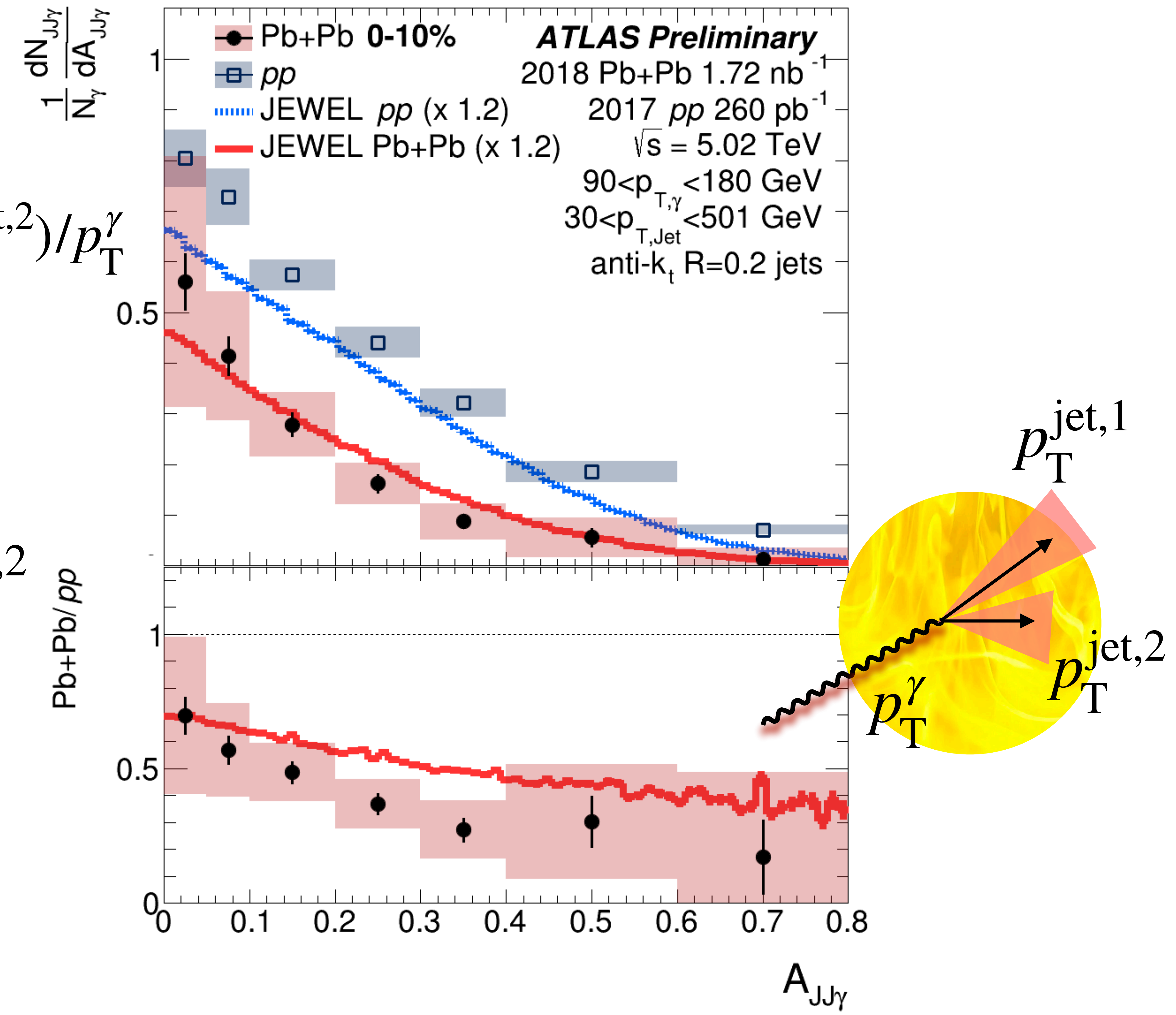


$$\frac{R_{AA}^{\gamma-\mathrm{jet}}}{R_{AA}^{\mathrm{inclusive\ jet}}}$$



$$A_{JJ\gamma} = (p_T^{\mathrm{jet},1} - p_T^{\mathrm{jet},2})/p_T^{\gamma}$$





- Photon-tagged jets: avoiding jet selection bias and enhancing quark jet fraction; $R_{AA}^{\gamma-\mathrm{jet}}/R_{AA}^{\mathrm{inclusive\ jet}}$ provides an important constraint for various models
- Photon-tagged multi-jet: complementing the previously shown dijet and jet substructure studies

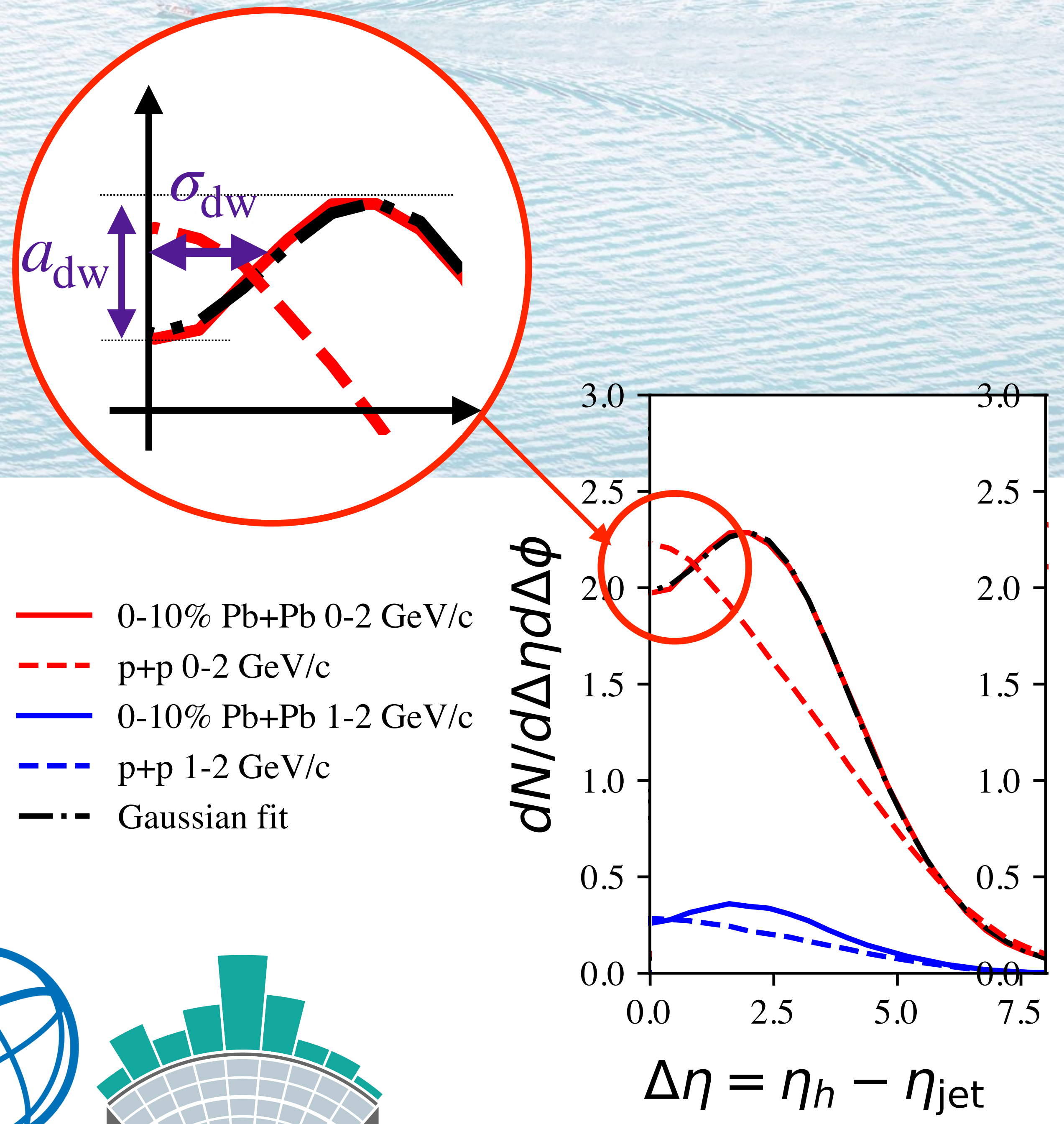
Jet-induced diffusion wake

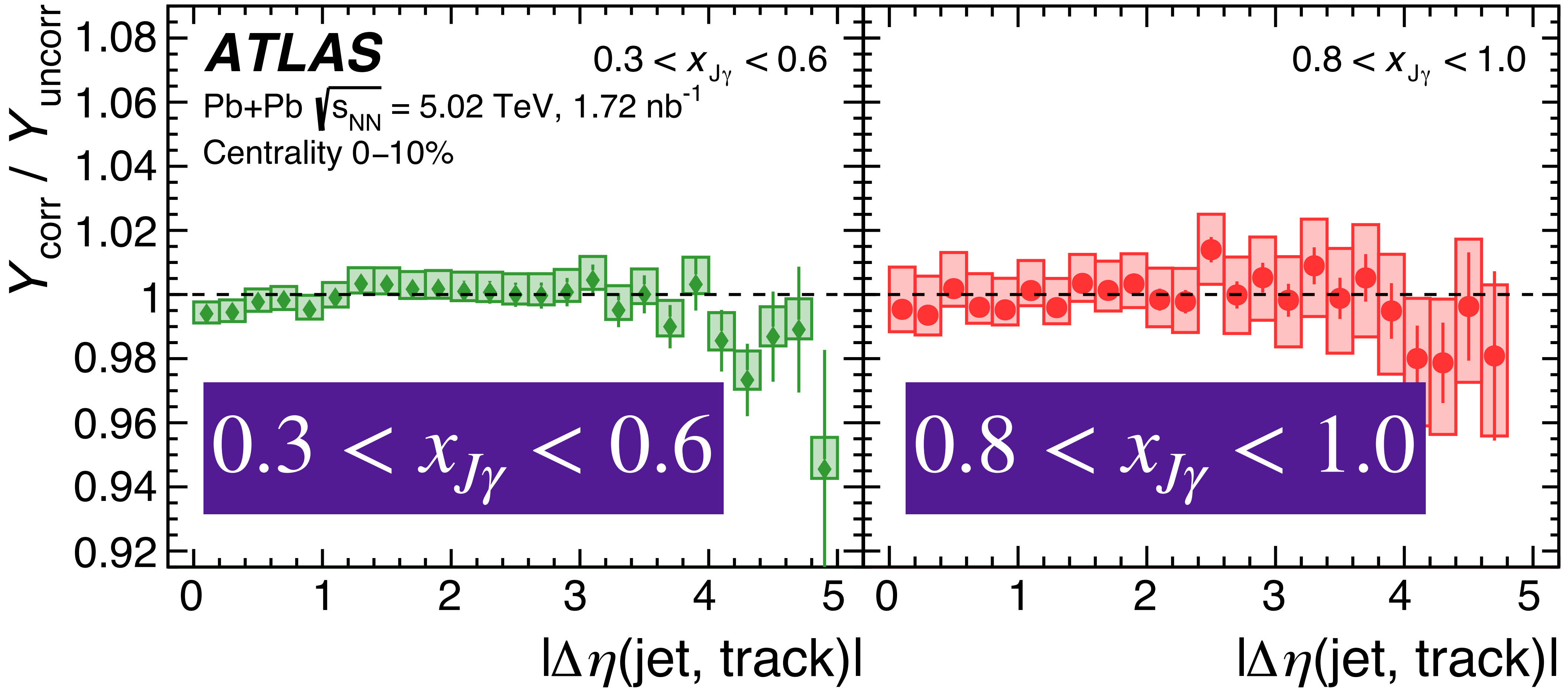
arXiv:2408.08599

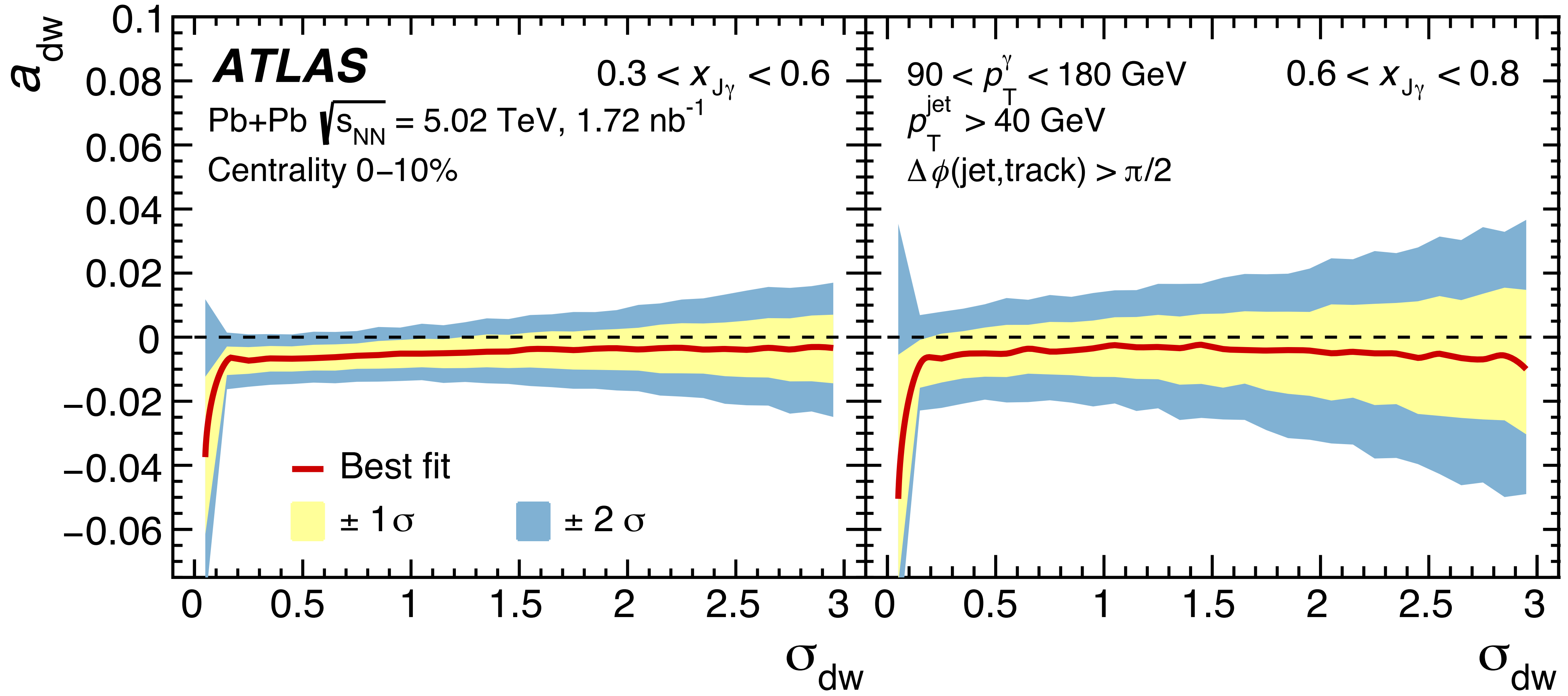
Final for HP2024

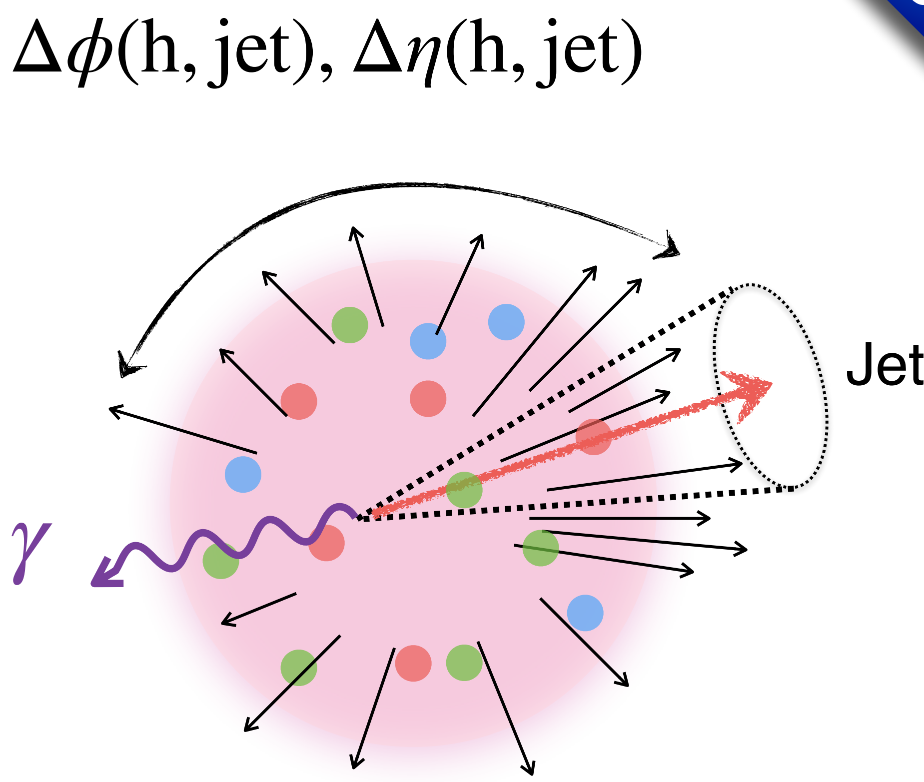
Lost energy → hydrodynamic evolution diffusion wake

Follow proposal of **CoLBT** PRL 130 (2023) 052301 look at photon-jet: depletion in charged particle production perpendicular to the jet







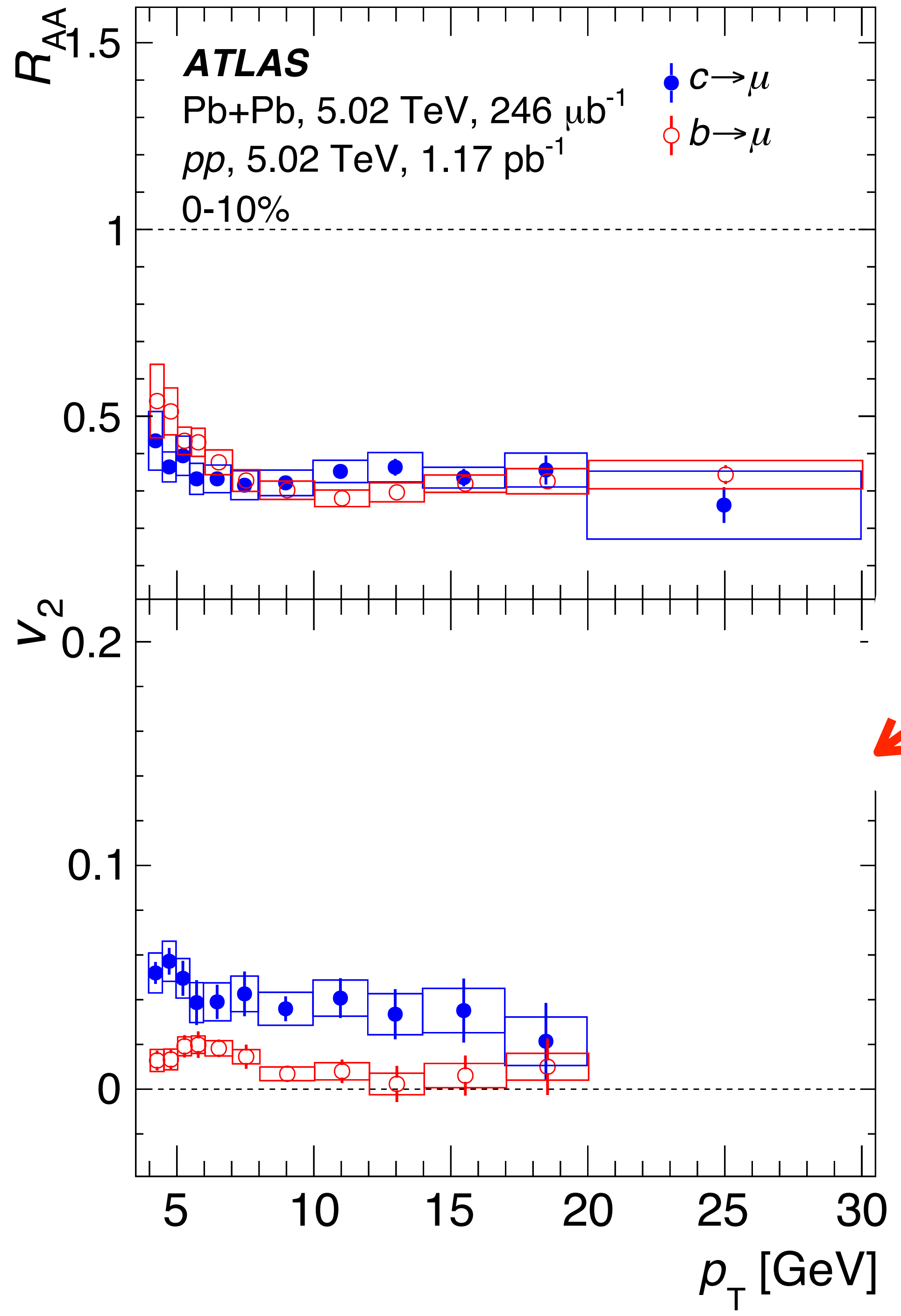


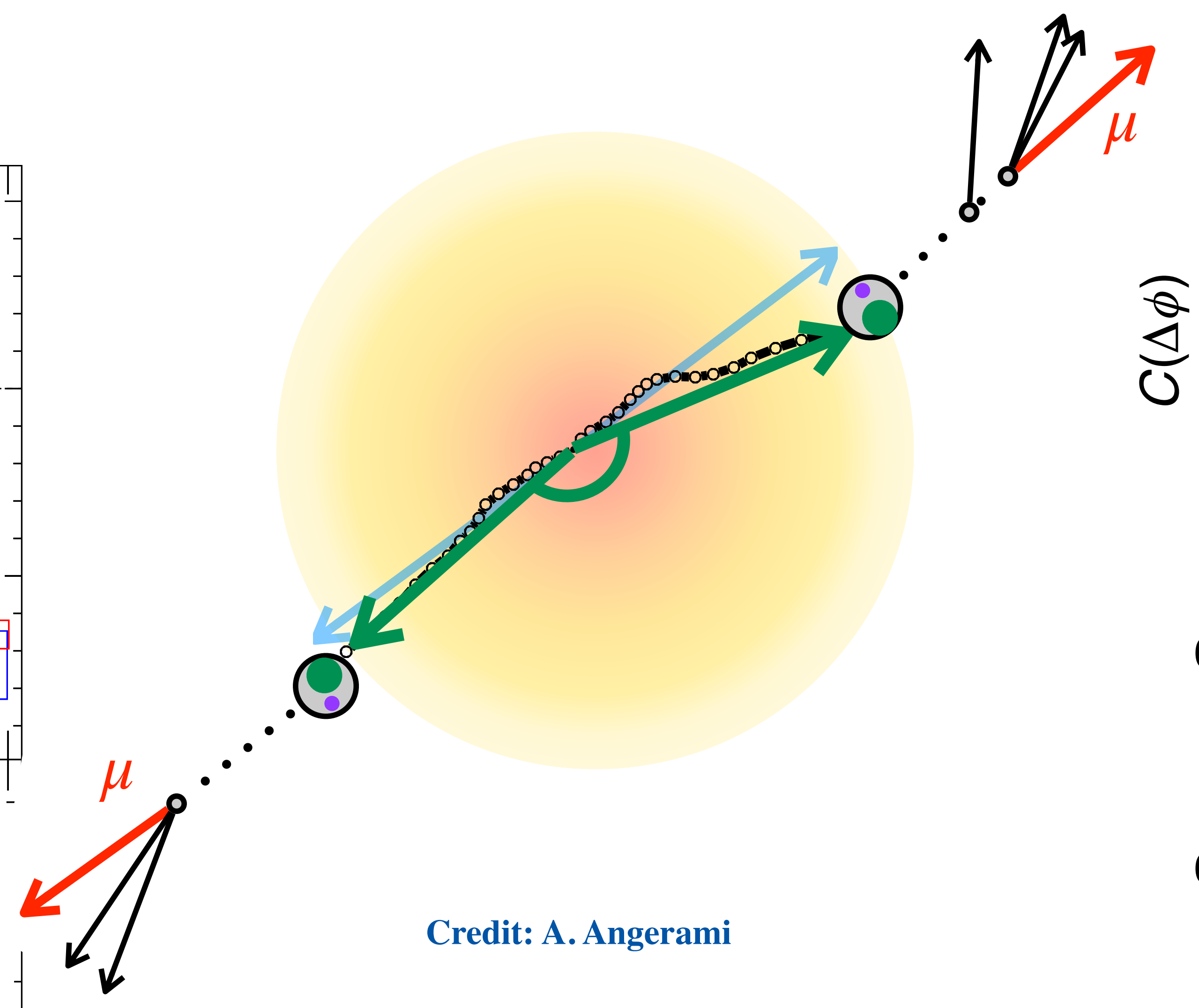
- No significant diffusion wake within the present uncertainties.
- Difference between different $x_{J\gamma}$ are consistent with CoLBT

Wednesday 9:20AM
Yeonju Go

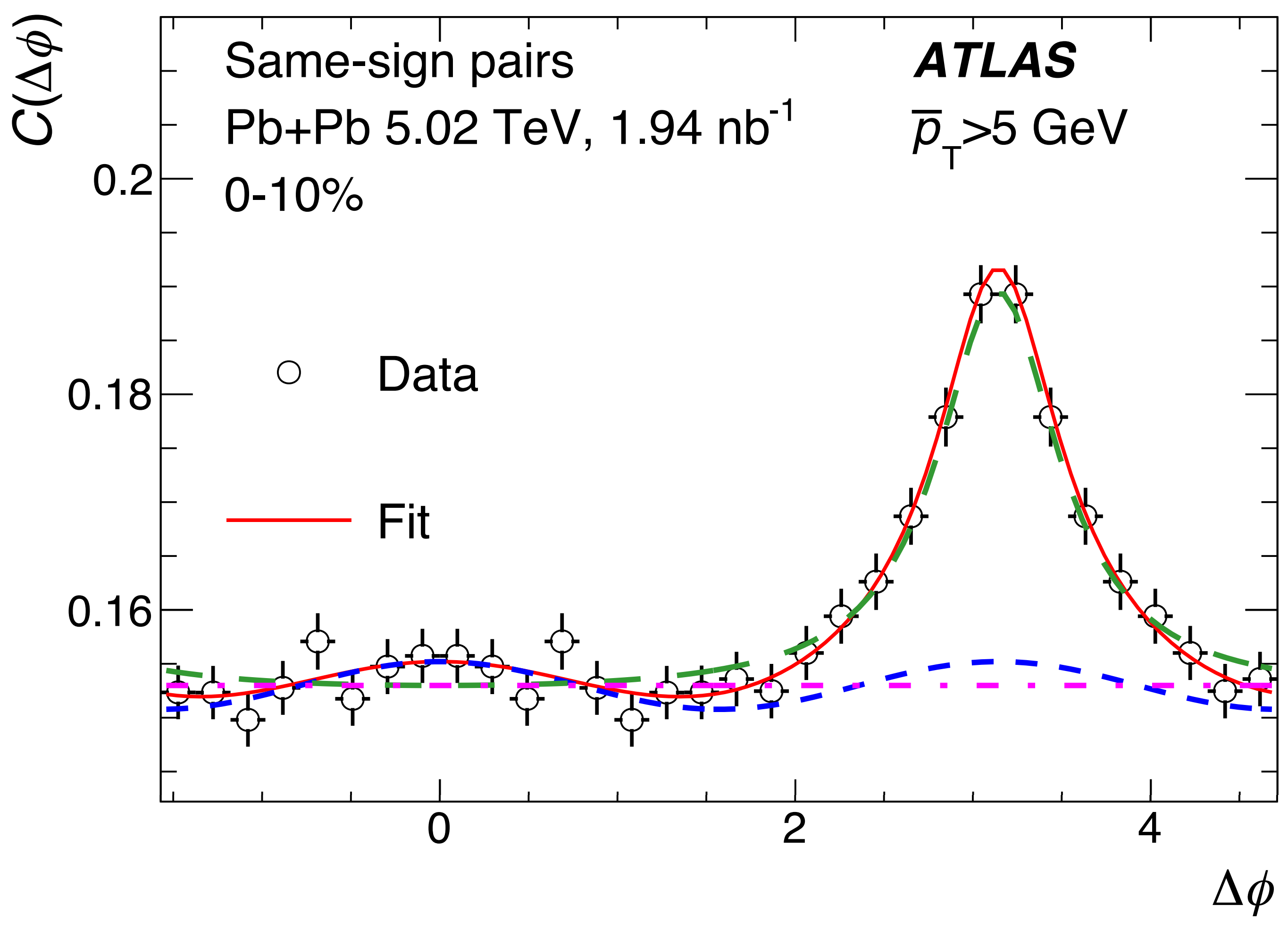
Heavy flavor probe of QGP

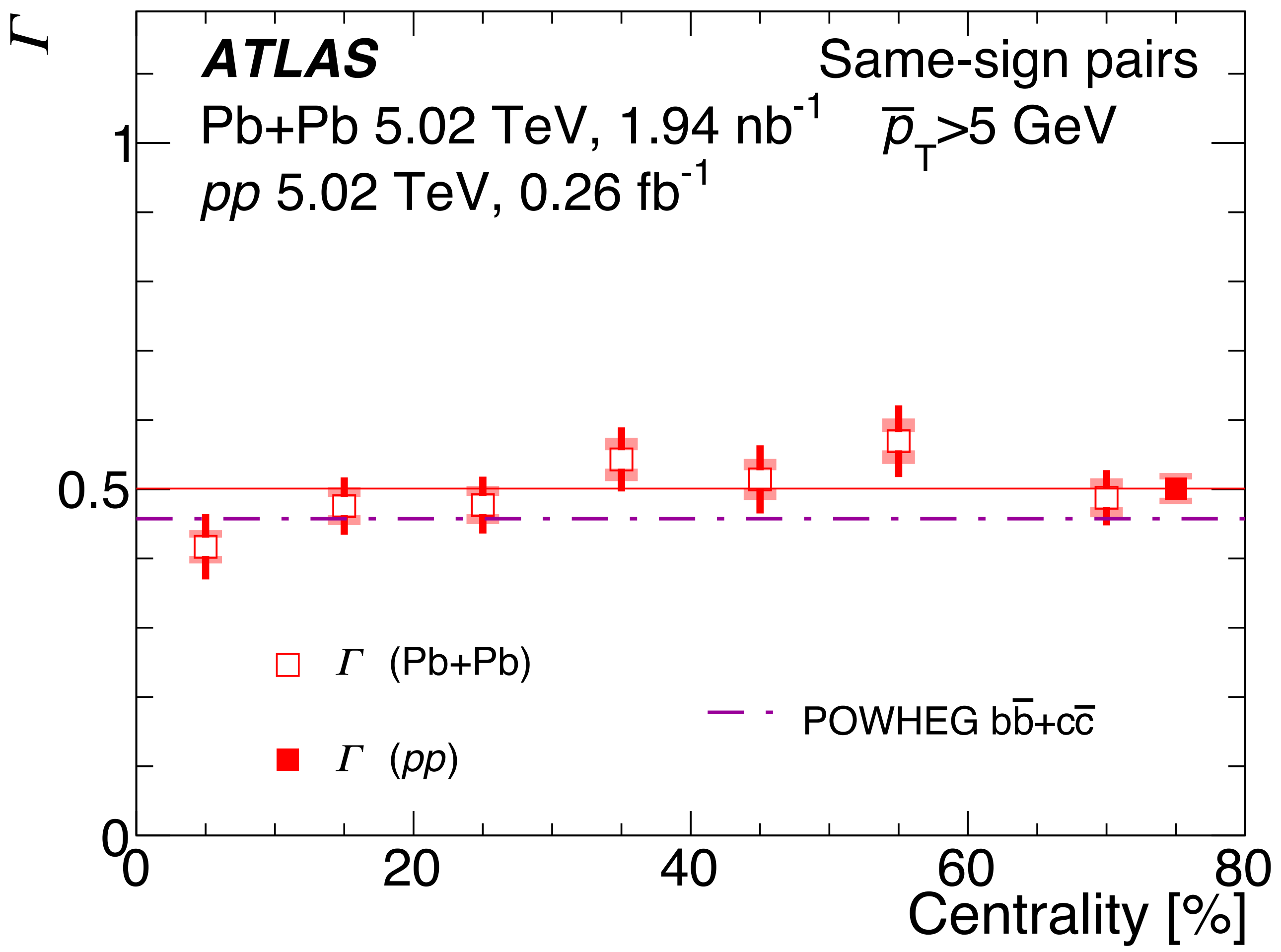
PLB 807 (2020) 135595
PLB 829 (2022) 137077
PRL 132 (2024) 202301





Credit: A. Angerami



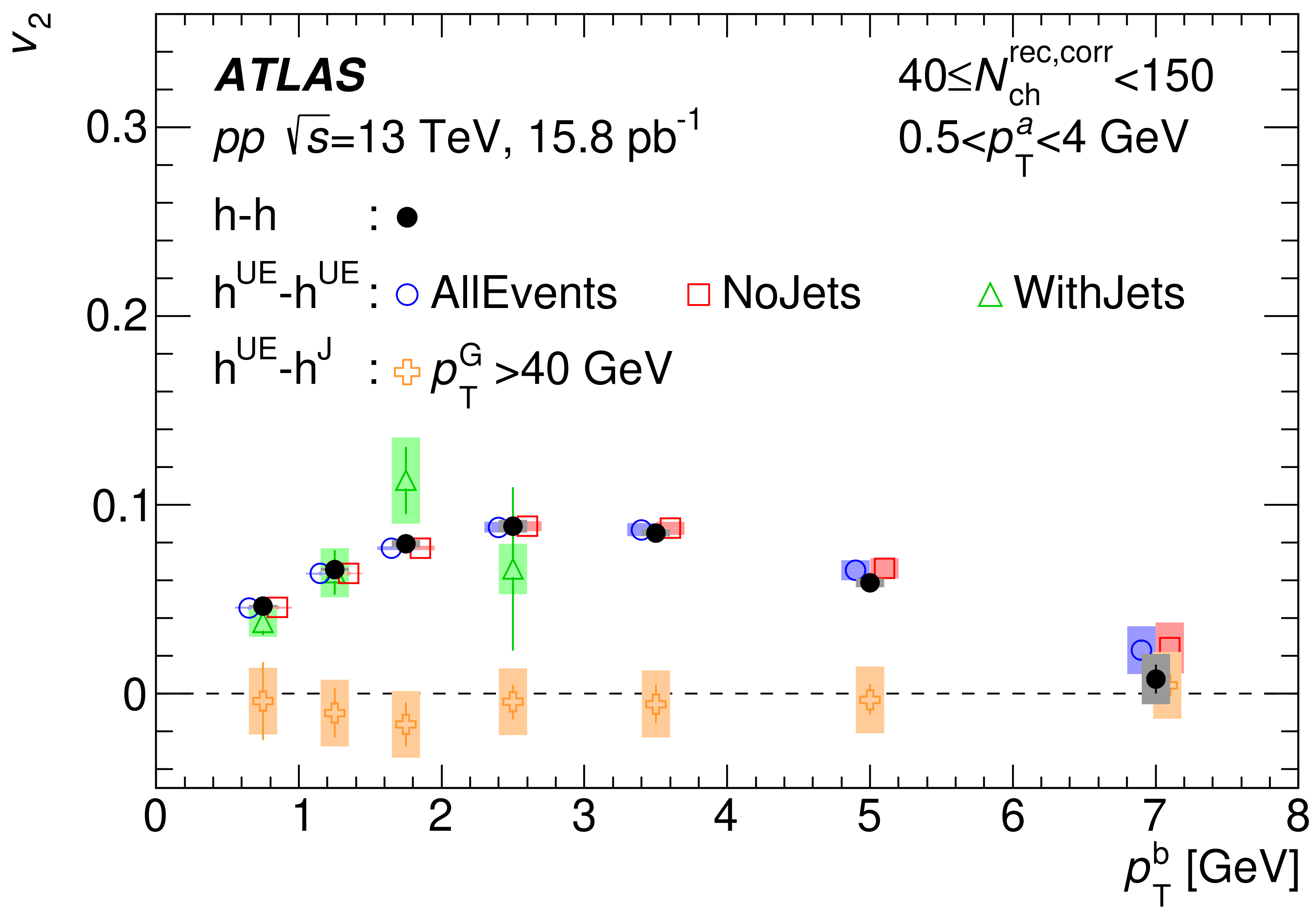


- Single heavy flavor production is strongly modified
- Azimuthal correlation of heavy flavor **pairs** may be distorted by scatterings in the medium, characterized by centrality dependence of away-side width
- No significant broadening compared to pp collisions and NLO generator without QGP

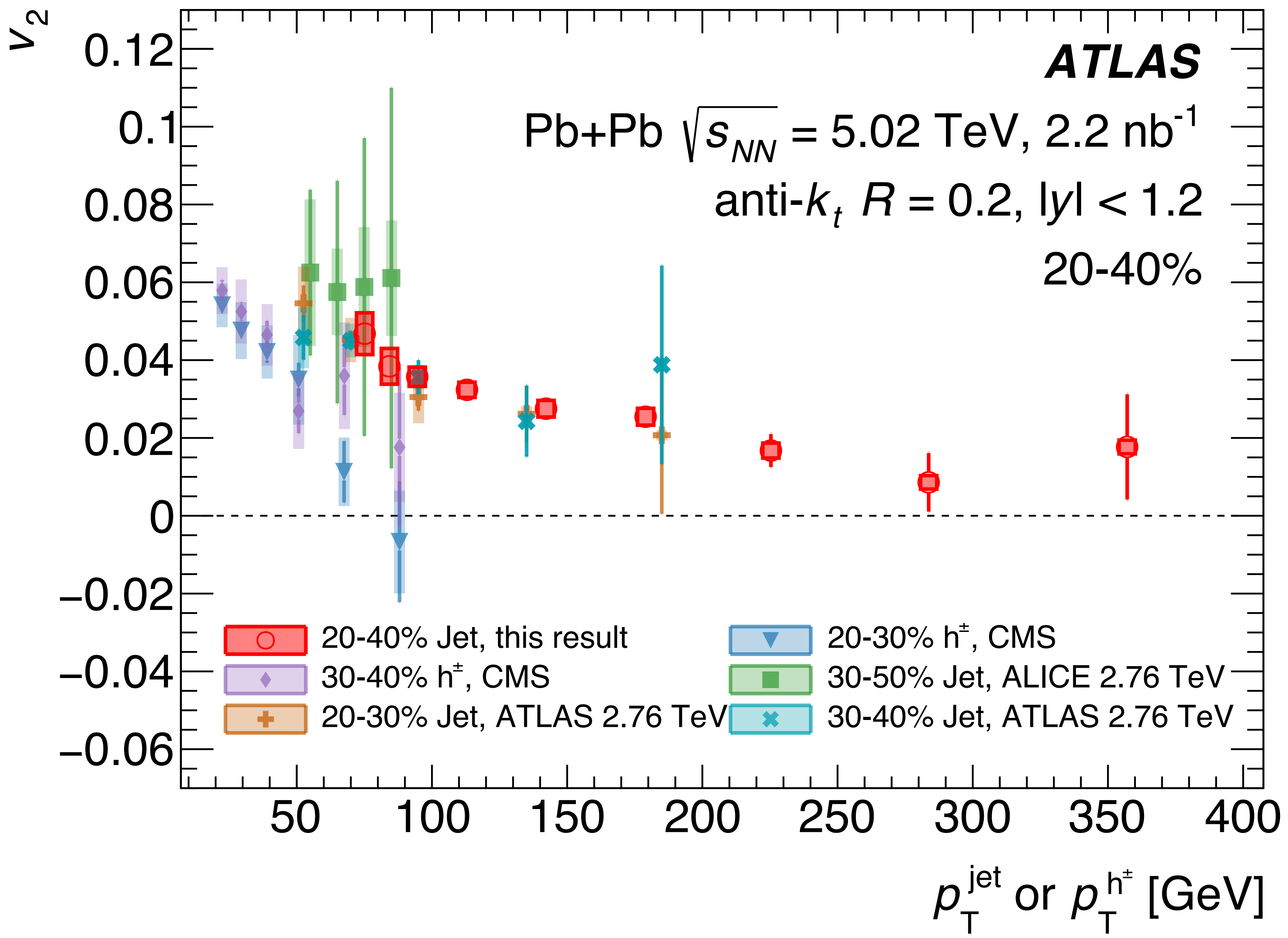
Jet-UE correlation

PRL 131 (2023) 162301
PRC 105 (2022) 064903

pp



Pb+Pb



In pp collisions:

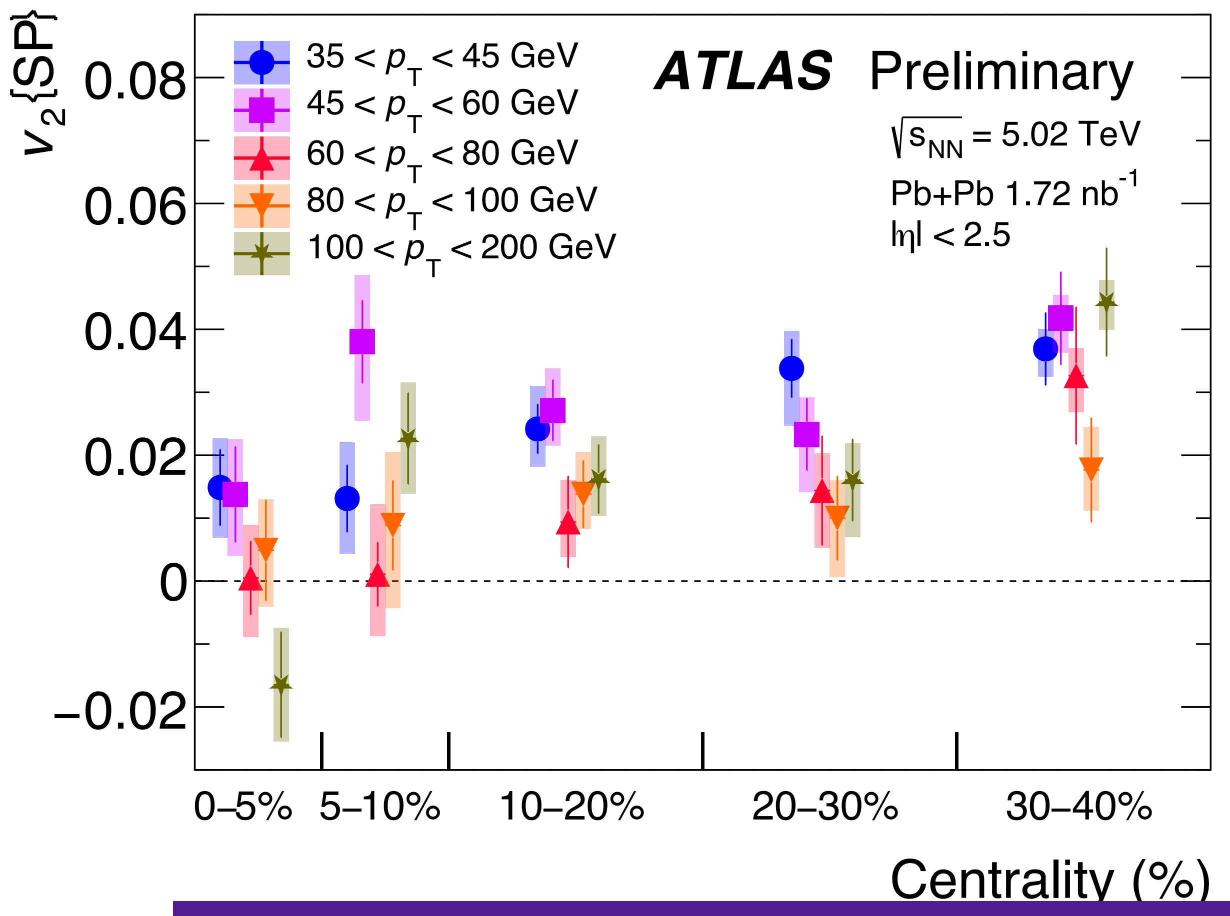
- Jets do not affect UE collectivity
- Jet-fragment particles do not exhibit collective behavior

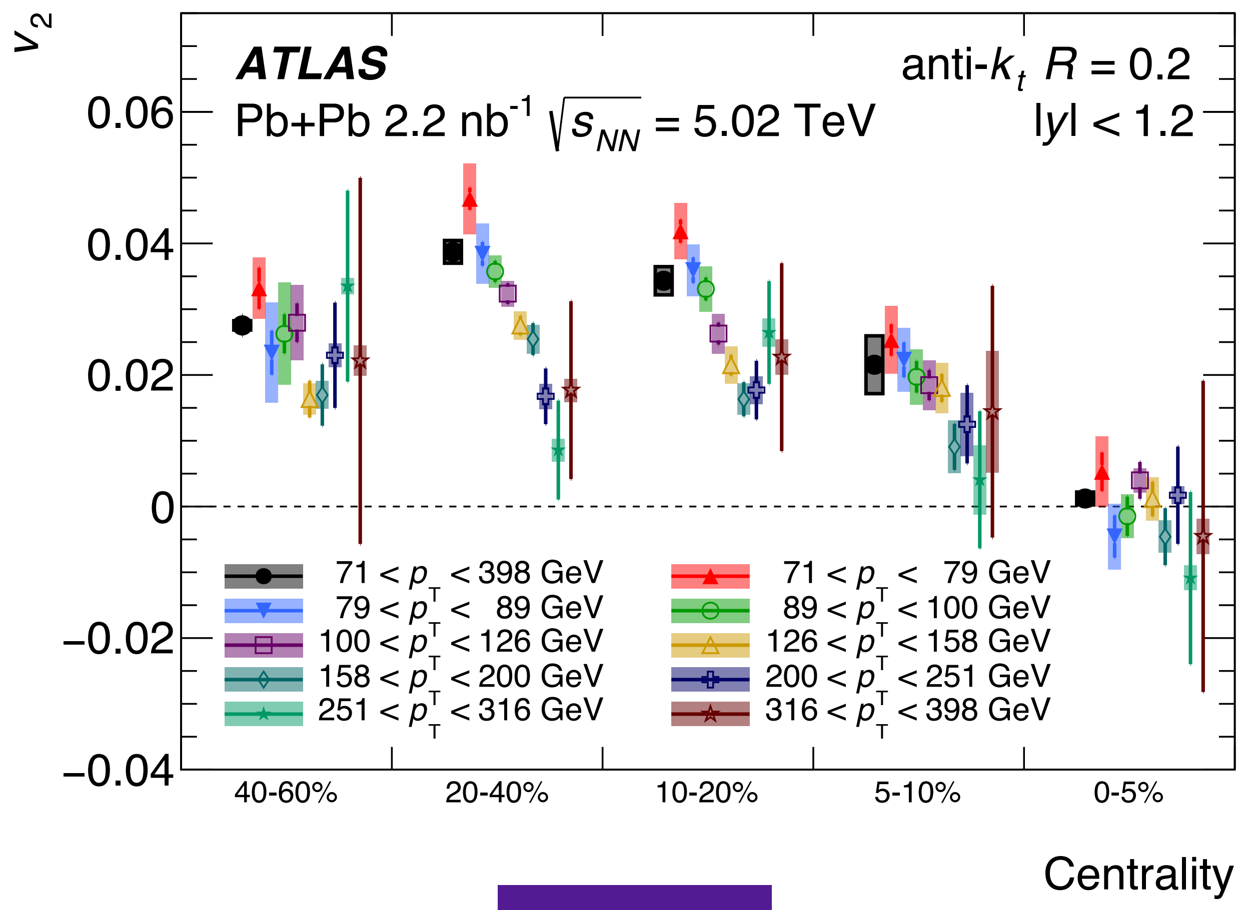
In Pb+Pb collisions: jets have significant elliptic flow from path-length dependence of energy loss

Jet and Jet-particle v_n in Pb+Pb

PRC 105 (2022) 064903
ATLAS-CONF-2023-007

v_2

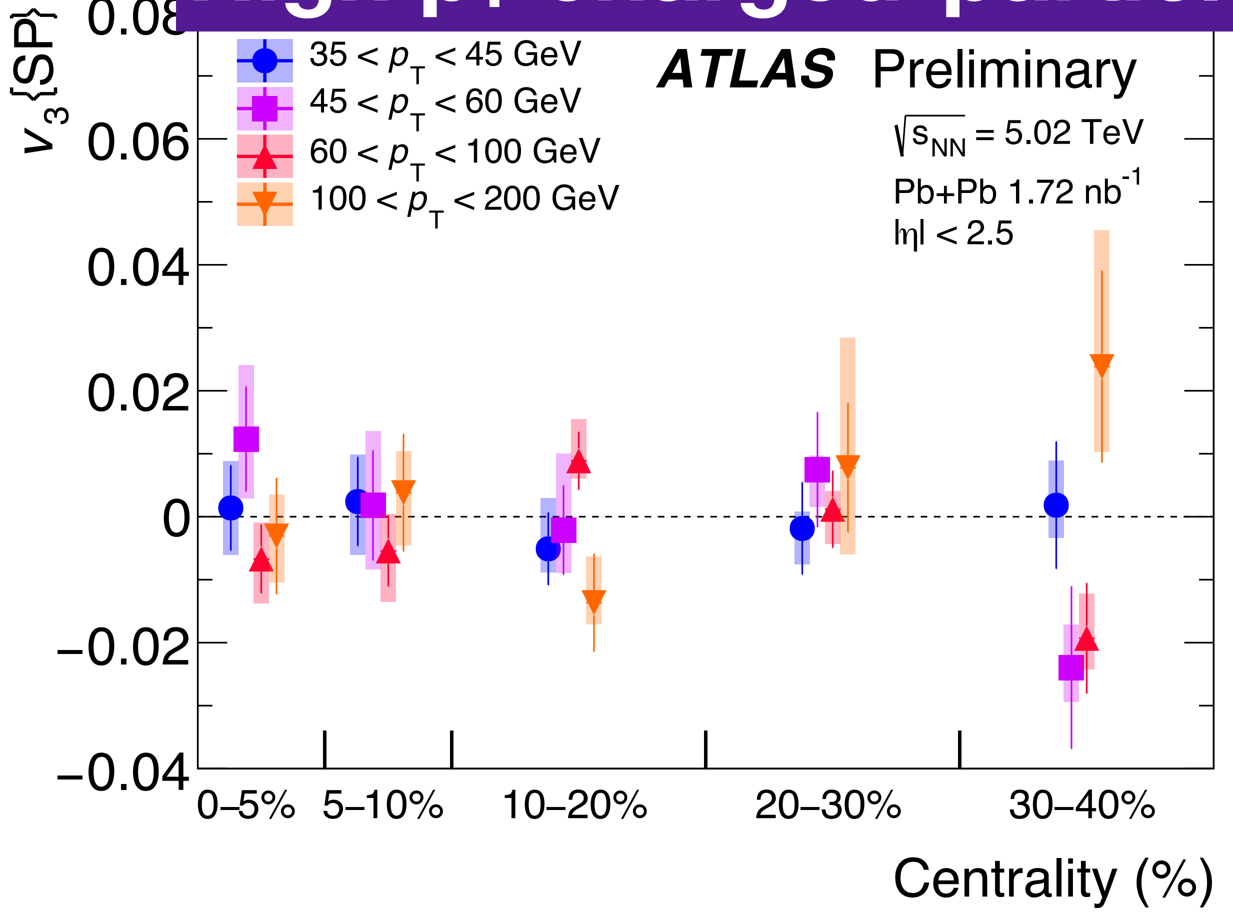


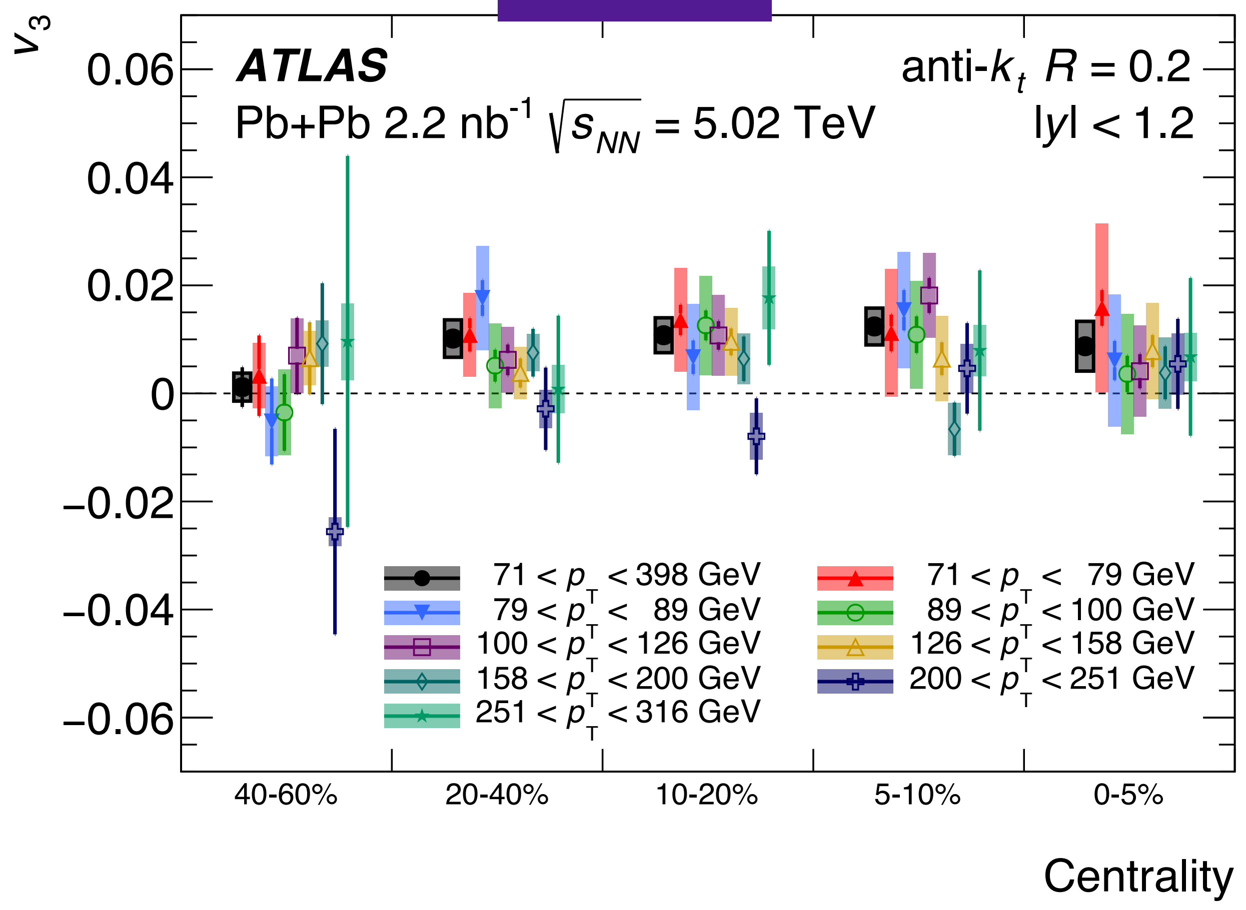


High p_T charged-particle v_n

Jet v_n

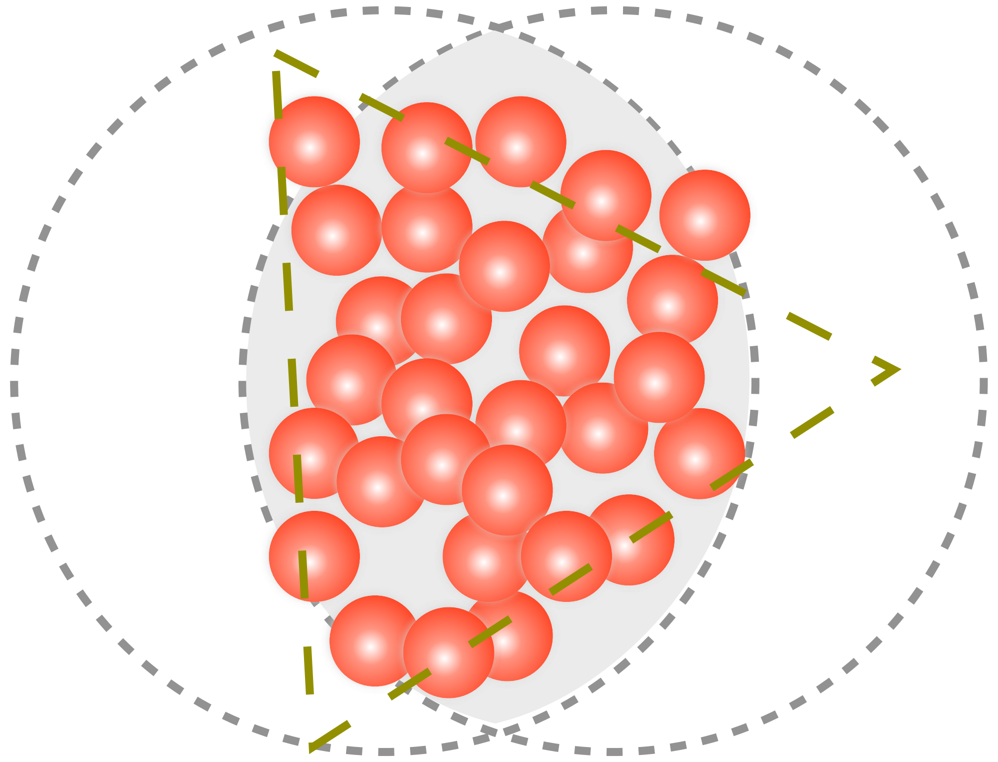
v_3



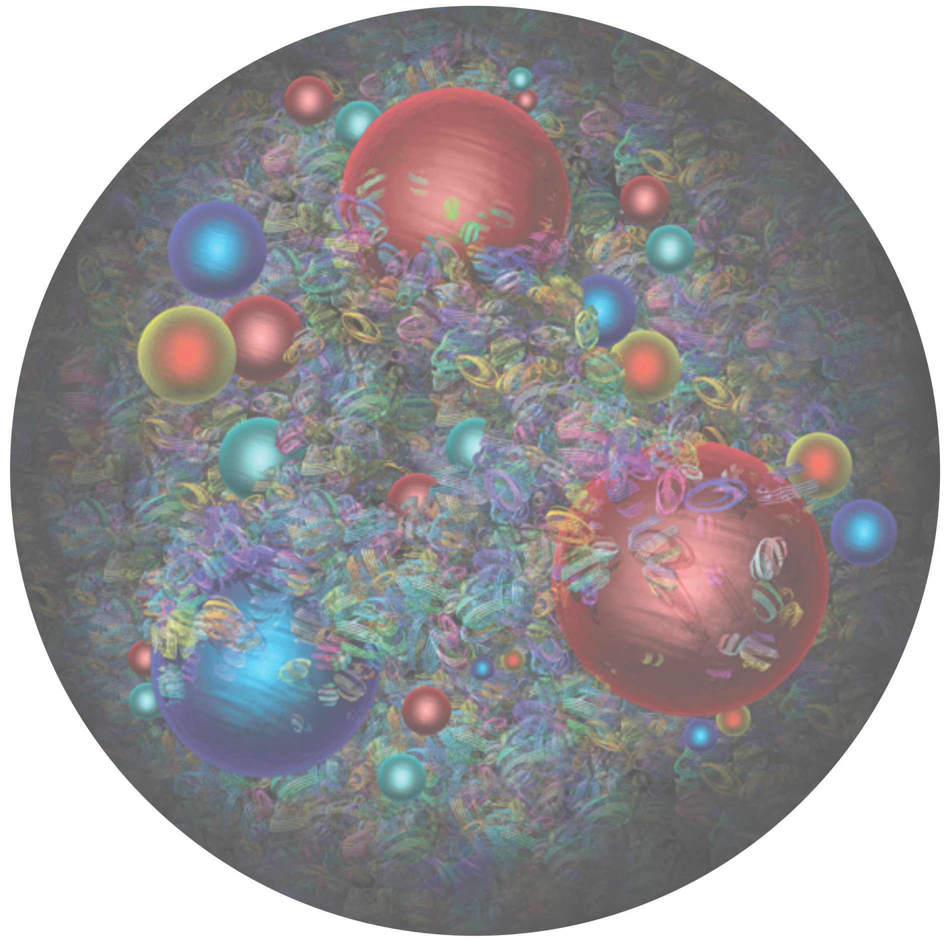


- Similar p_T and centrality dependence of jet and charged-particle v_2
- Jet $v_3 > 0$, while high p_T charged-particle $v_3 \sim 0$

Monday 5:10 PM
Xiaoning Wang



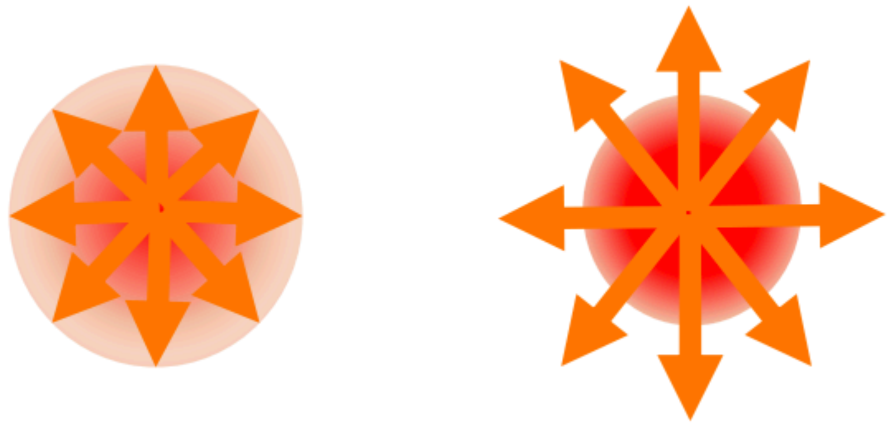
Understand the initial state



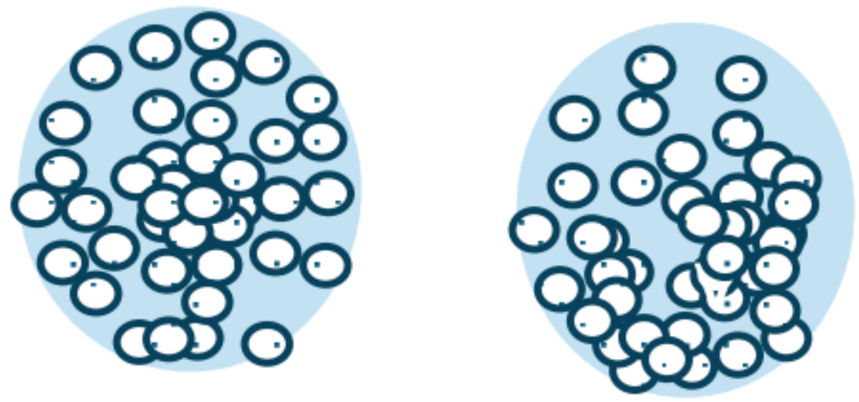
Credit: D. Dominguez/CERN

Disentangling sources of initial fluctuations

arXiv:2407.06413



“Geometric Component”



“Intrinsic Component”

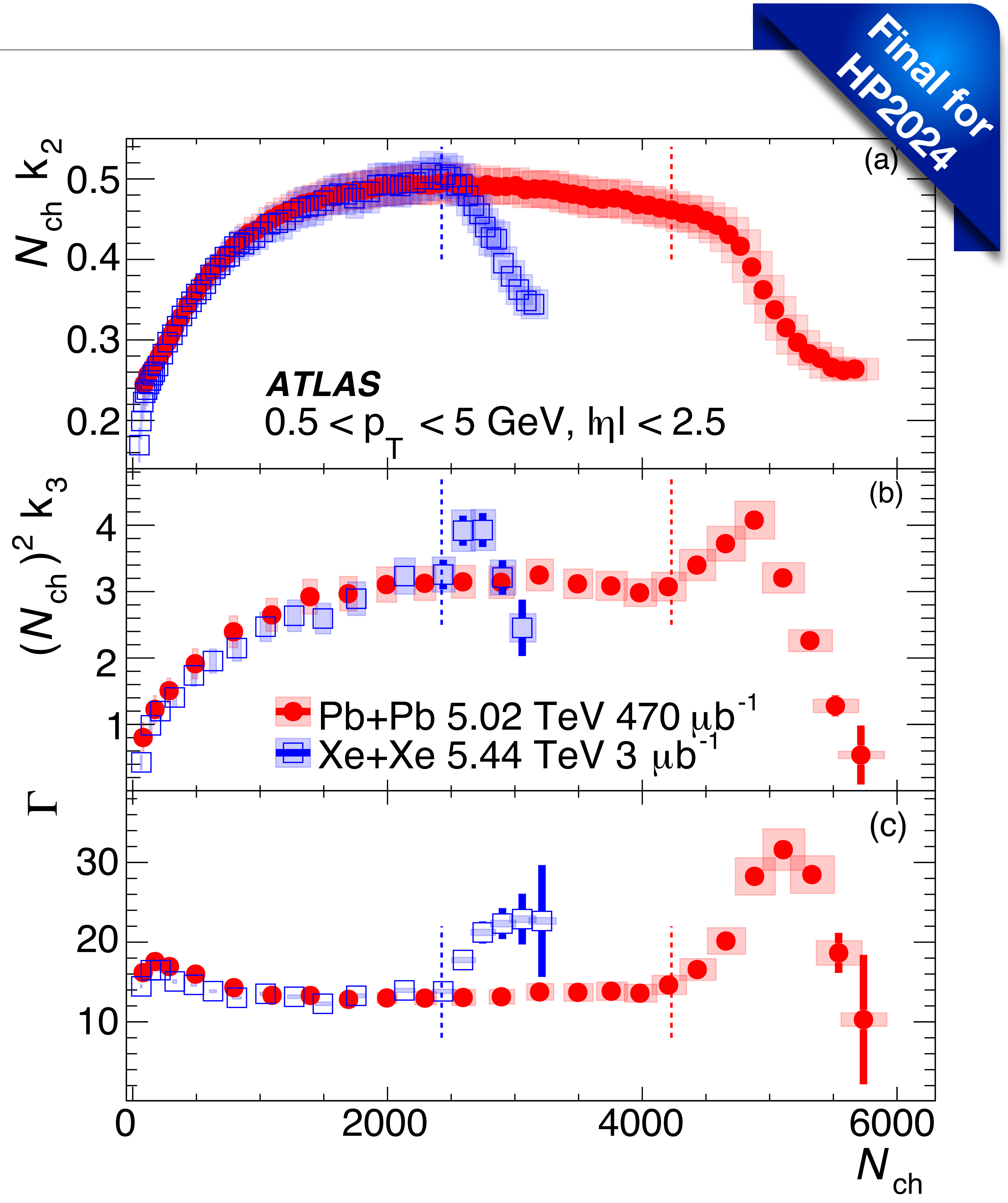
Understand roles of fluctuations in initial conditions:

- Geometric fluctuations
- Intrinsic fluctuations

Moments of event-wise average p_T distribution in **ultra-central** Pb+Pb and Xe+Xe via n-particle momentum correlators:

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

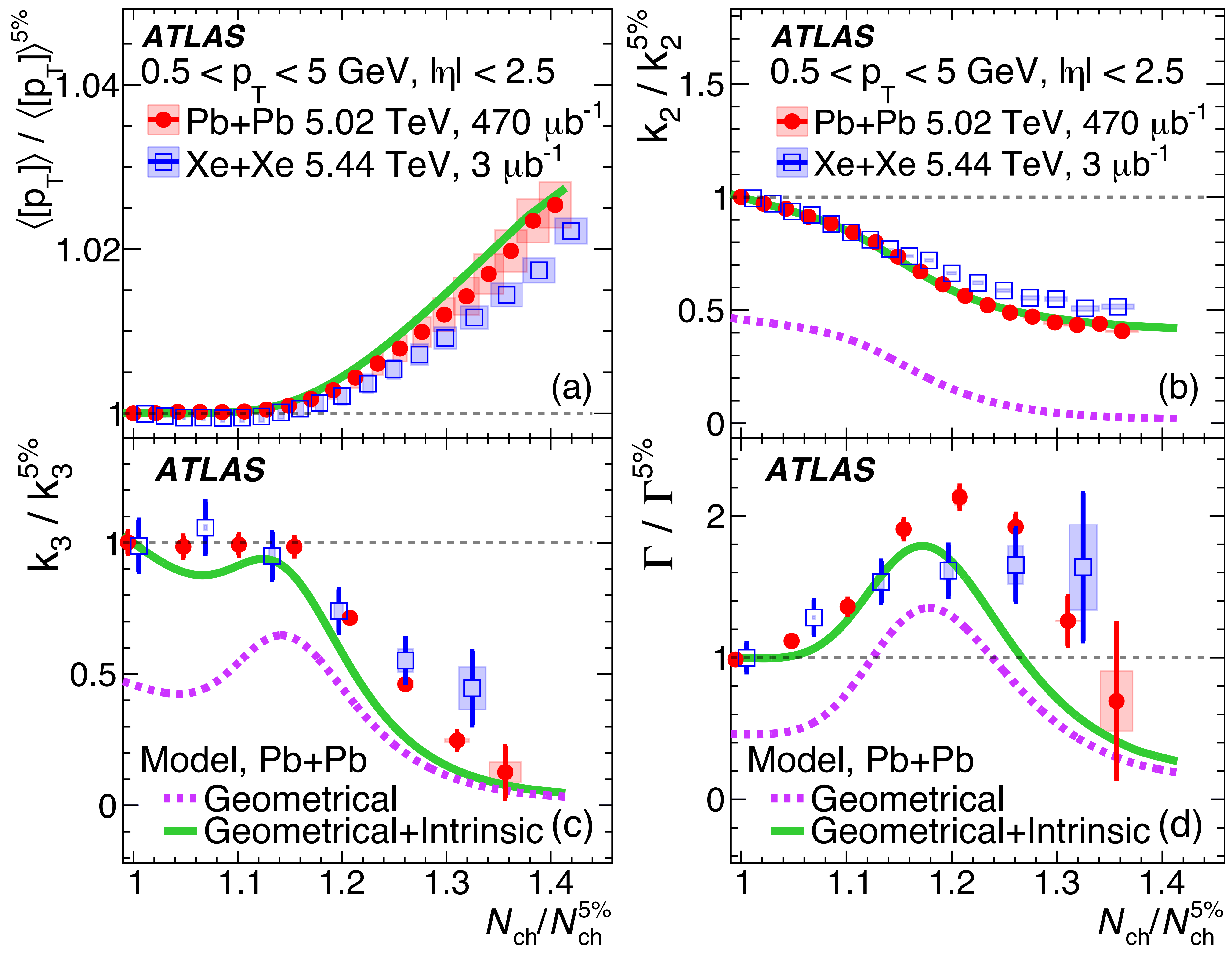
$$k_2 = \frac{\langle c_2 \rangle}{\langle [p_T] \rangle^2}, \quad k_3 = \frac{\langle c_3 \rangle}{\langle [p_T] \rangle^3}, \quad \gamma = \frac{\langle c_3 \rangle}{\langle c_2 \rangle^{3/2}}, \quad \Gamma = \frac{\langle c_3 \rangle \langle [p_T] \rangle}{\langle c_2 \rangle^2}.$$



Monday 4:50 PM
Tomasz Bold

Disentangling sources of initial fluctuations — cont.

arXiv:2407.06413

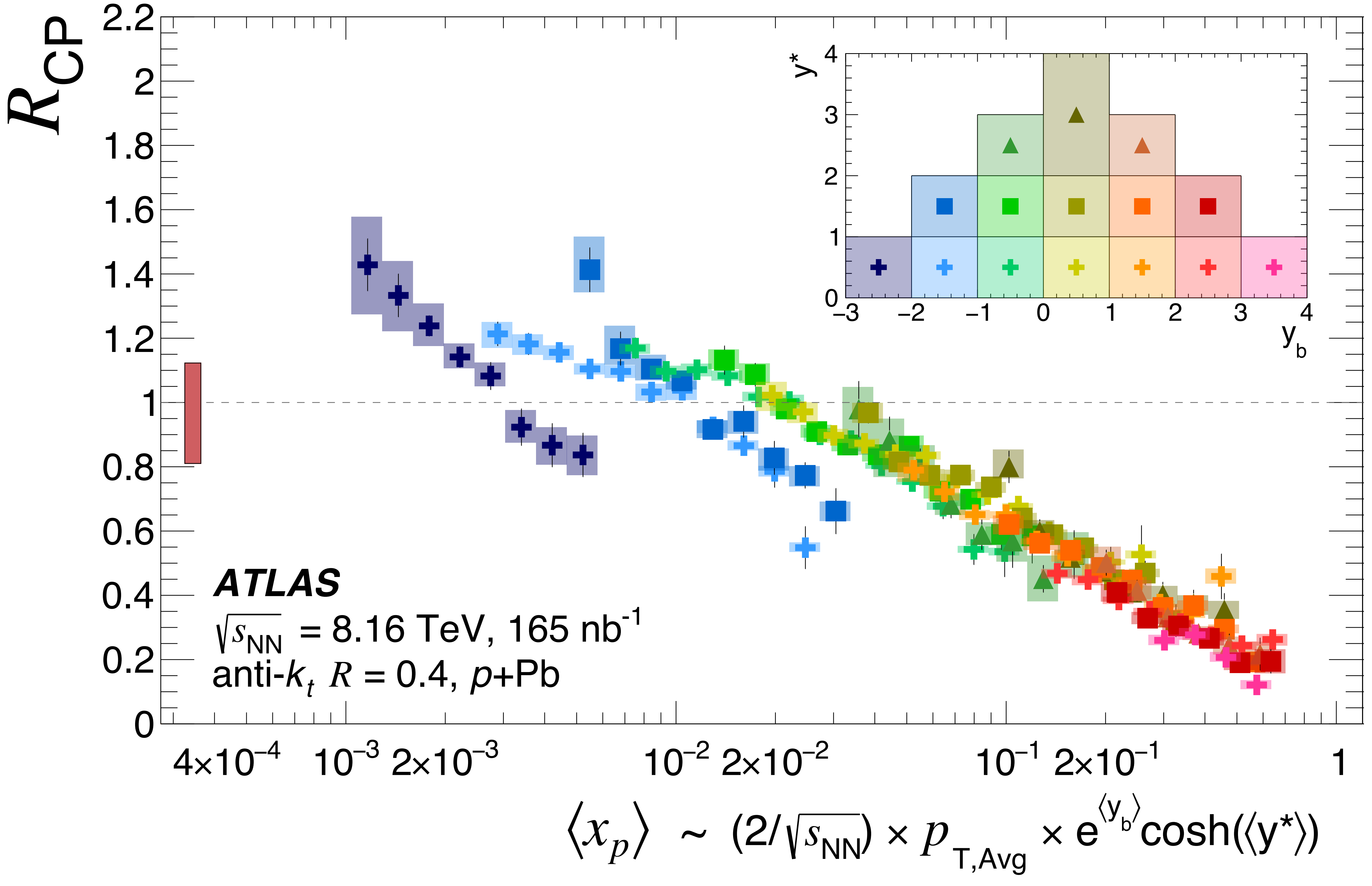


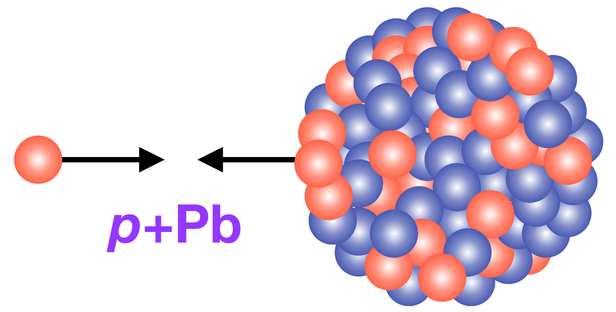
- A phenomenological 2D Gaussian fluctuations predicts the trends well (R. Samanta et al. Phys. Rev. C 109 (2024) L051902)

Final for HP2024

Monday 4:50 PM
Tomasz Bold

Dijet in p+Pb





Dijet events in 8.16 TeV p+Pb data

$$p_{T,Avg} = \frac{p_{T,1} + p_{T,2}}{2}, \quad y_b = \frac{y_1^{c.m.} + y_2^{c.m.}}{2}, \quad \text{and} \quad y^* = \frac{|y_1^{c.m.} - y_2^{c.m.}|}{2}$$

- $R_{CP}(x_p)$ is qualitatively described by the color fluctuations: smaller than average interaction strength at large x_p
- Centrality dependences of jet p_T- and rapidity-yields in p+Pb collisions were observed in Run1 are directly correlated with x_p biases

Poster
Matthew Hoppesch

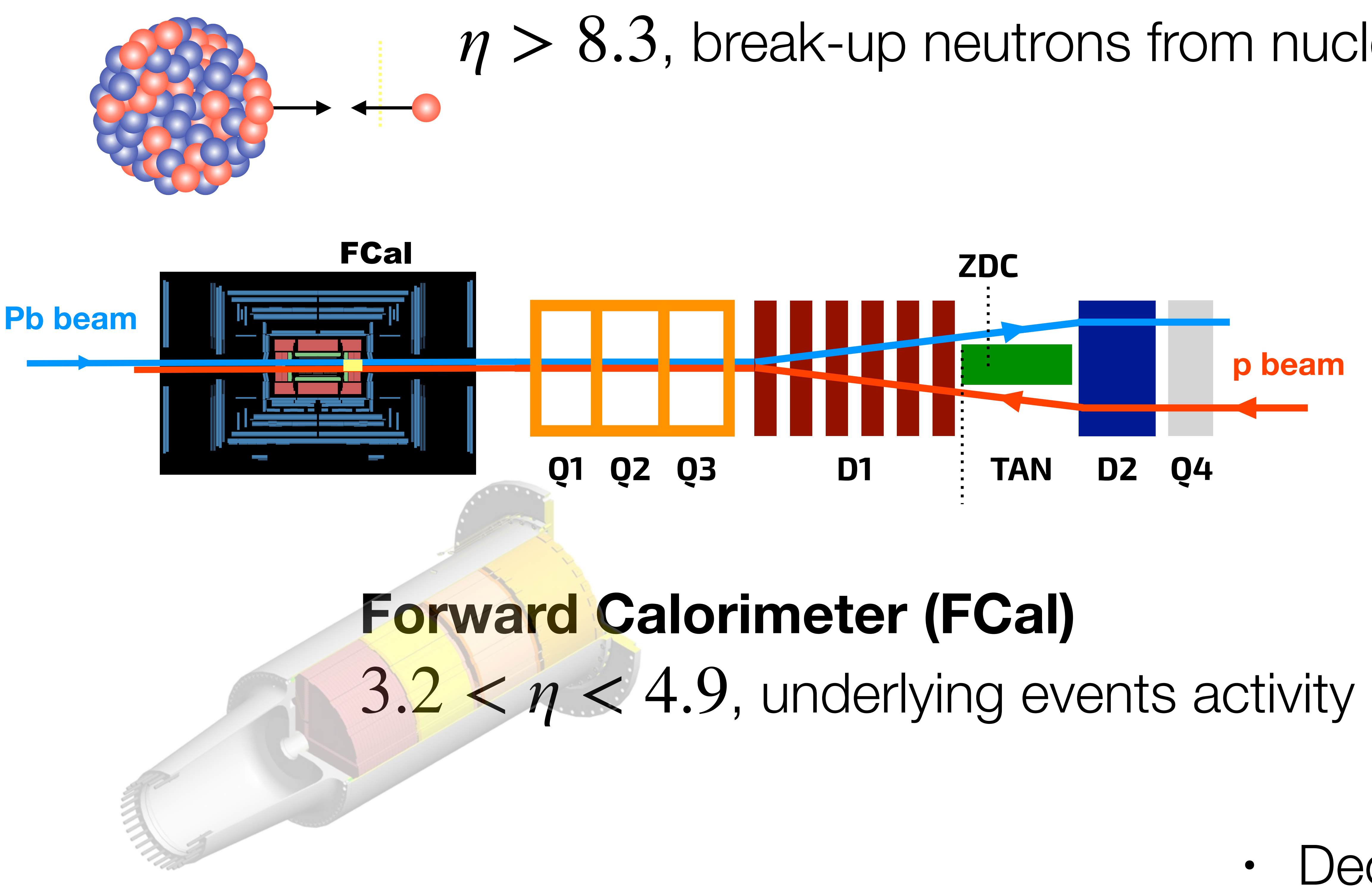
UE vs. nuclear break-ups in p+Pb

ATLAS-CONF-2024-013

New for HP2024

Zero-Degree Calorimeter (ZDC)

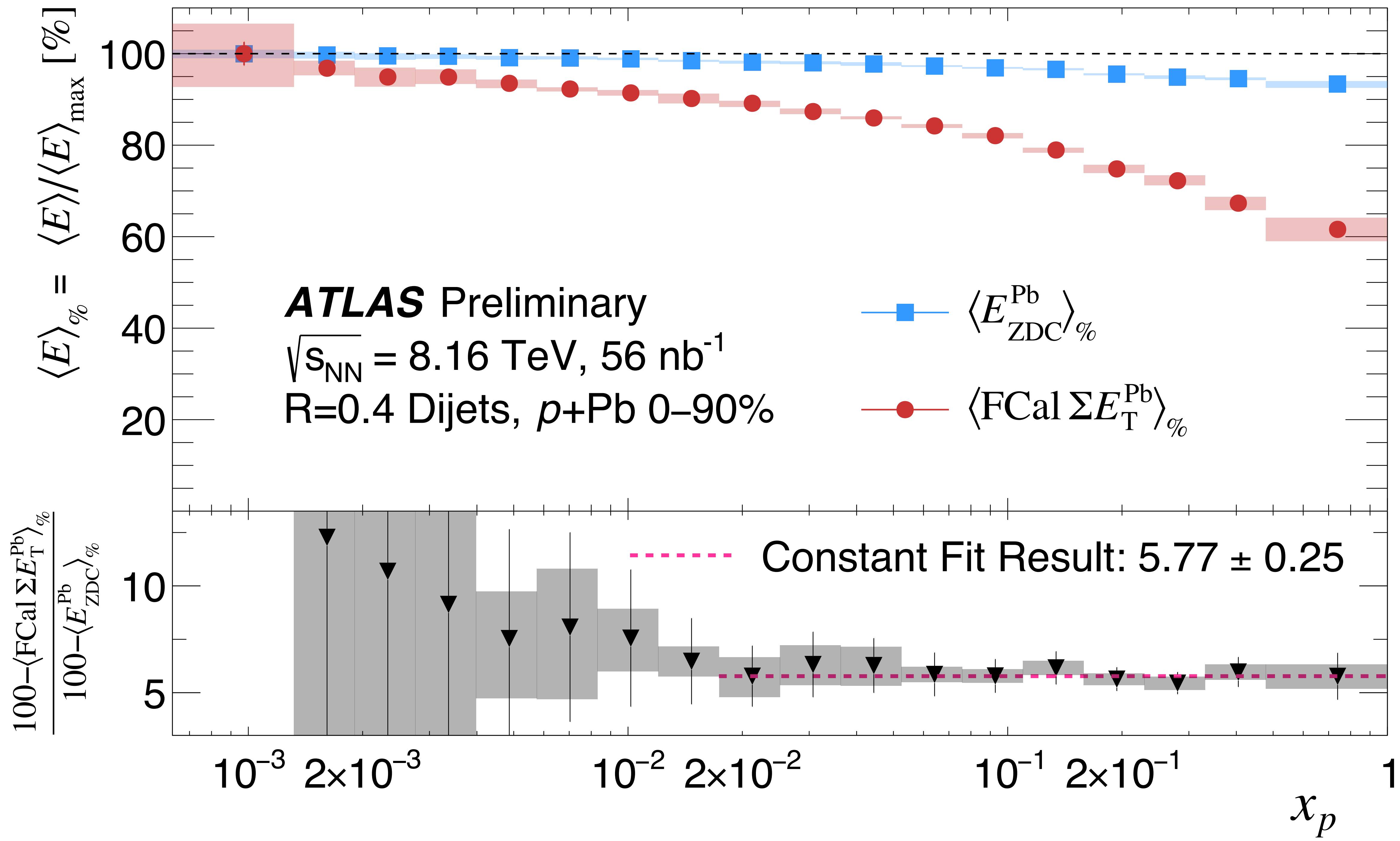
$\eta > 8.3$, break-up neutrons from nucleus



Forward Calorimeter (FCal)

$3.2 < \eta < 4.9$, underlying events activity

$$x_p = \frac{p_{\mathrm{T},1} e^{y_1^{\mathrm{c.m.}}} + p_{\mathrm{T},2} e^{y_2^{\mathrm{c.m.}}}}{\sqrt{s_{\mathrm{NN}}}} \simeq \frac{2 p_{\mathrm{T,Avg}}}{\sqrt{s_{\mathrm{NN}}}} e^{y_b} \cosh(y^*)$$

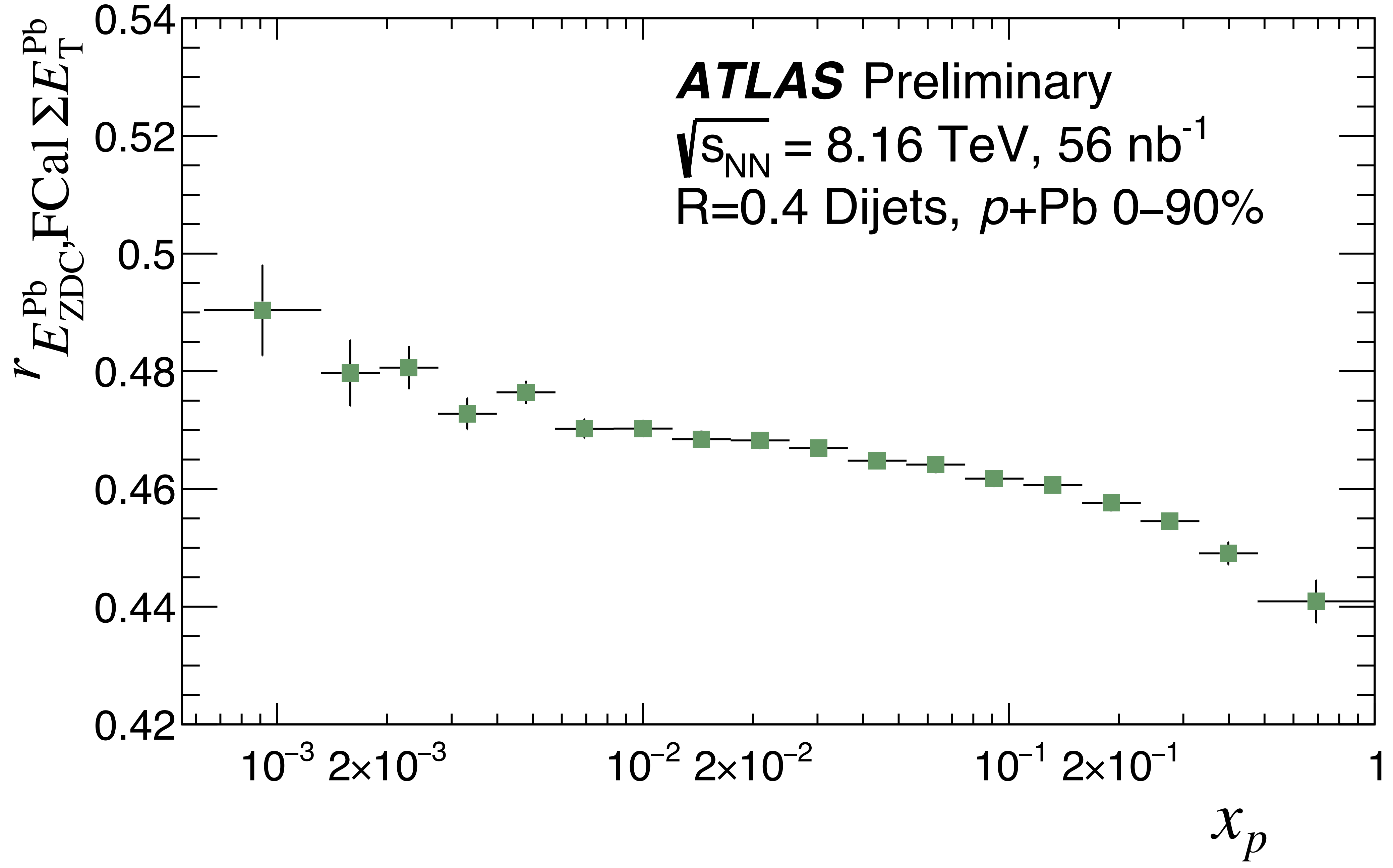


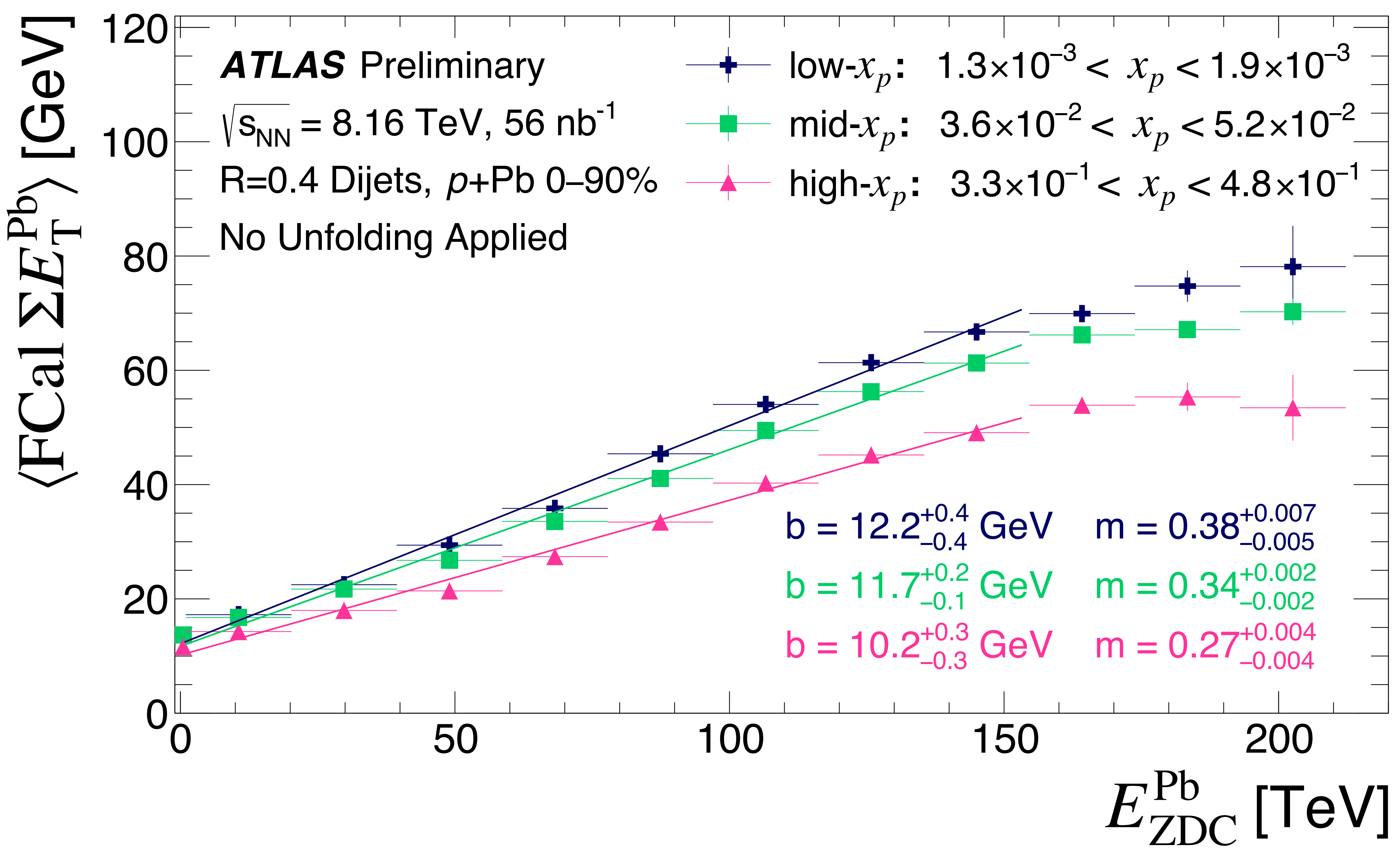
- Decreasing UE energy and break-up neutrons with increasing x_p
- UE is more sensitive to the change in x_p

UE vs. nuclear break-ups in p+Pb — Cont.

ATLAS-CONF-2024-013

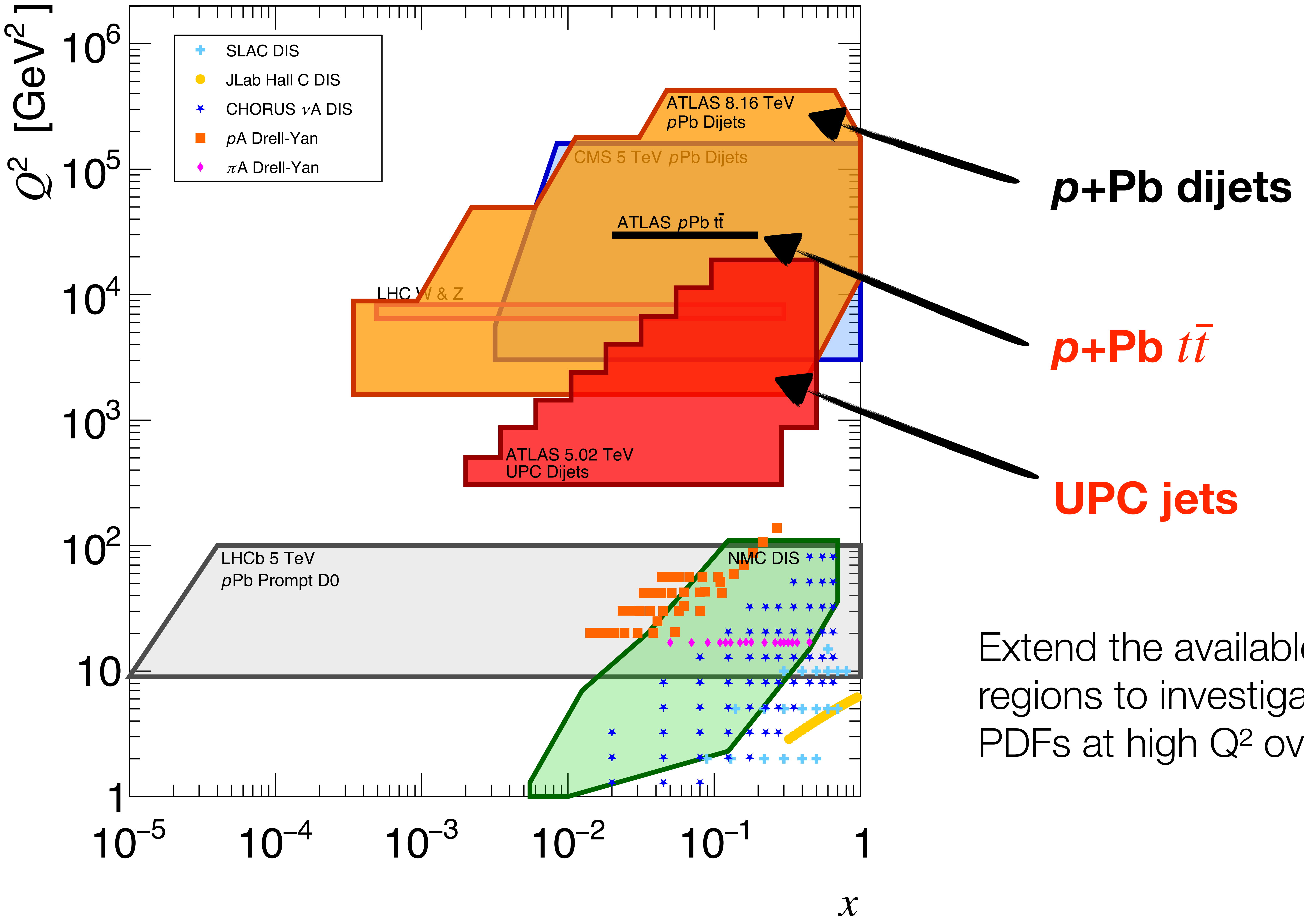
New for HP2024





- Correlation between UE energy and break-up neutrons becomes weaker with increasing x_p
- Scaling of UE energy and break-up neutrons at low ZDC energy, fluctuation of break-ups when UE energy saturated
- Offer a new approach to exploring hard-scattering biases in UE based centrality classifications and biases in modeling nuclear break-ups

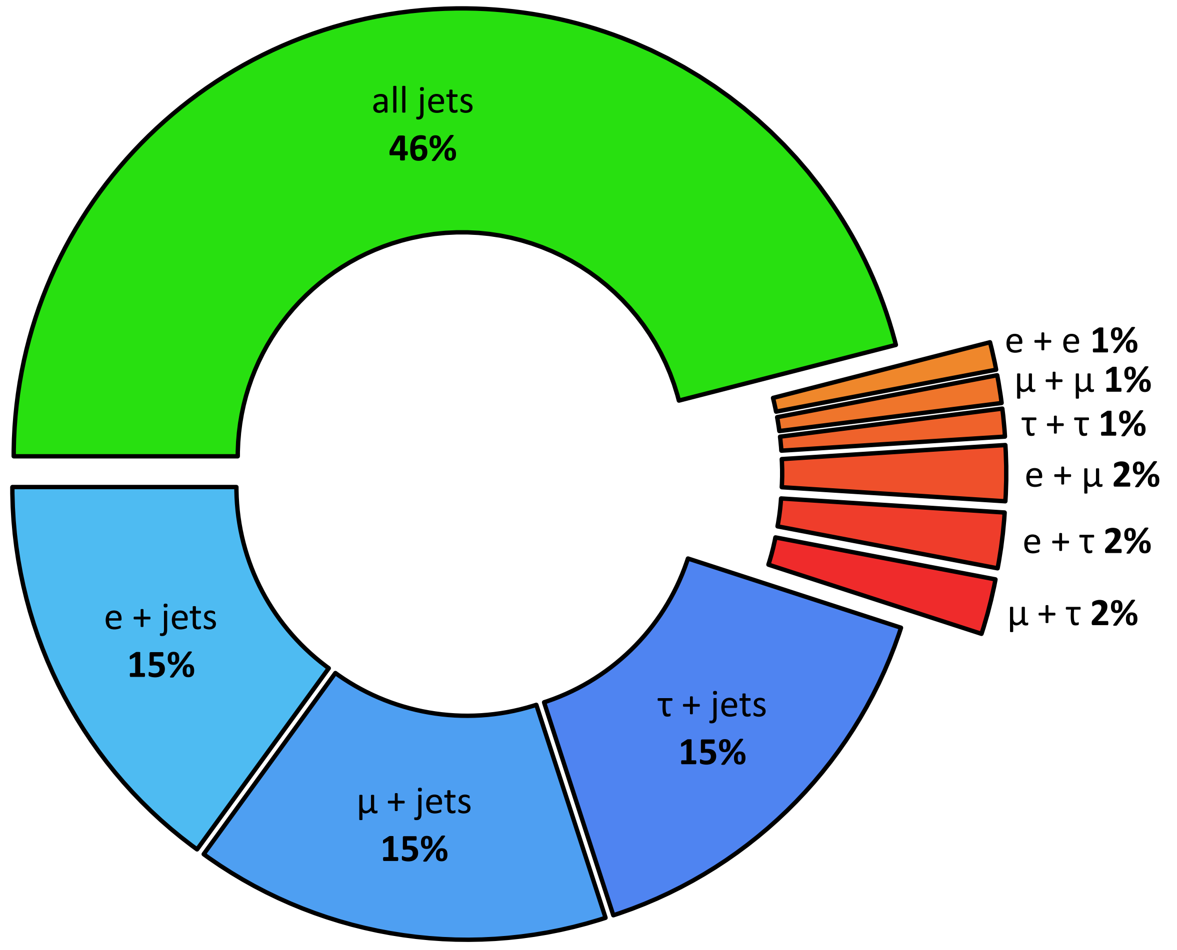
Nuclear modification of parton distribution function



Extend the available data into unexplored regions to investigate nuclear effects on PDFs at high Q^2 over wide x-range

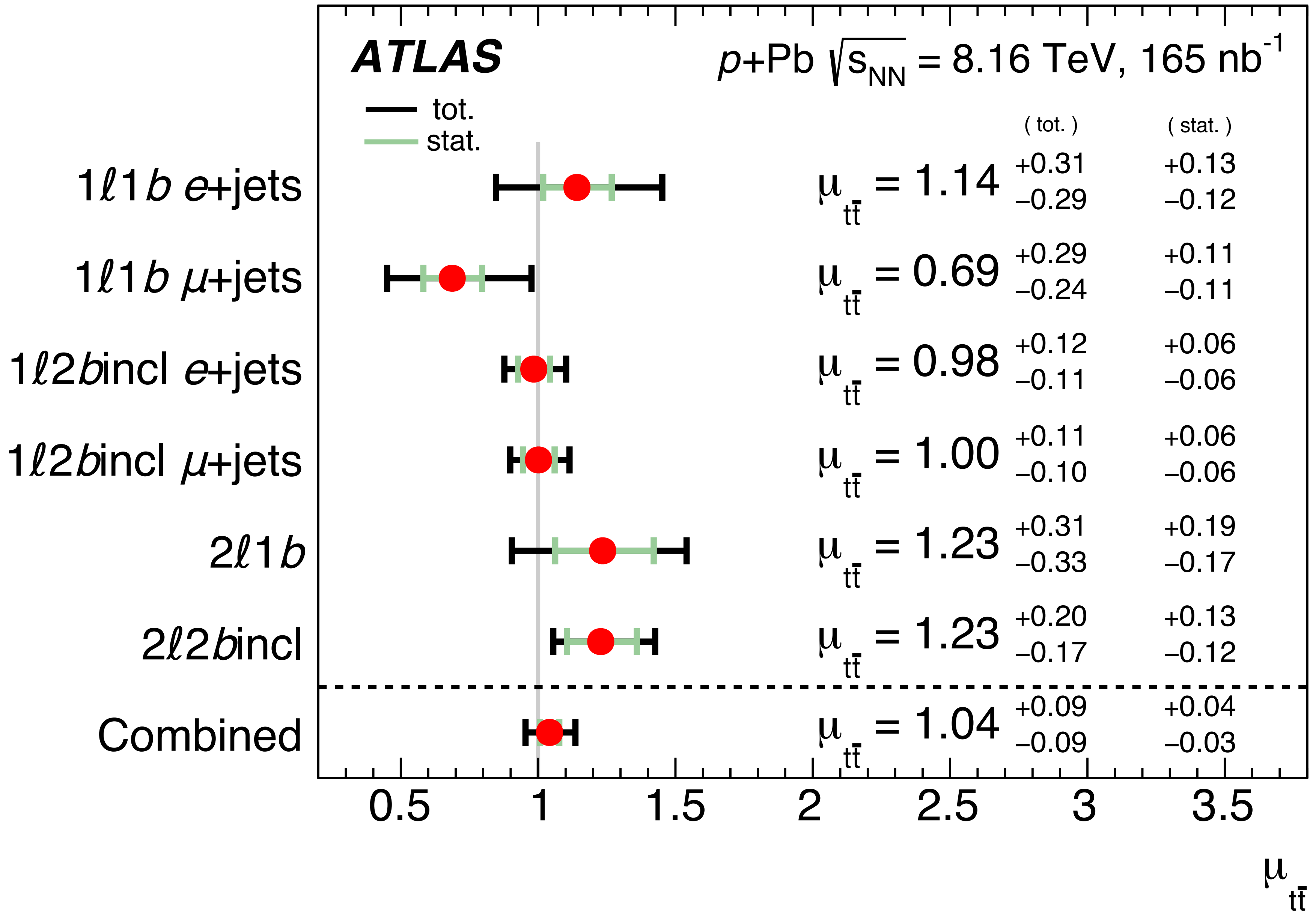
Top pair in p+Pb

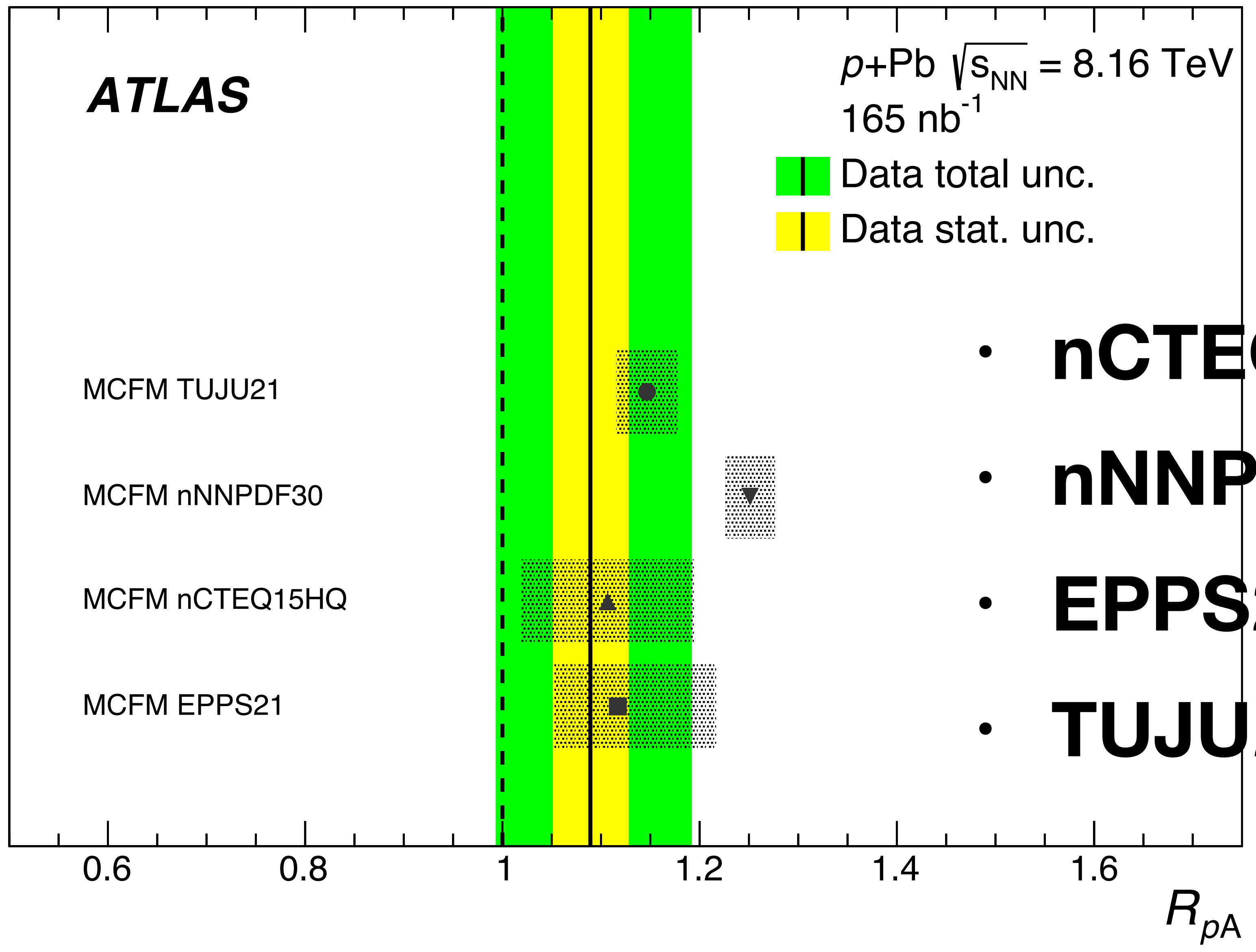
arXiv:2405.05078



$\ell + \textbf{jets}: \quad t\bar{t} \to WbW\bar{b} \to \ell\nu_\ell bq\bar{q}'\bar{b}$

$\textbf{dilepton}: \quad t\bar{t} \to WbW\bar{b} \to \ell\nu_\ell b\ell\bar{\nu}_\ell\bar{b}$





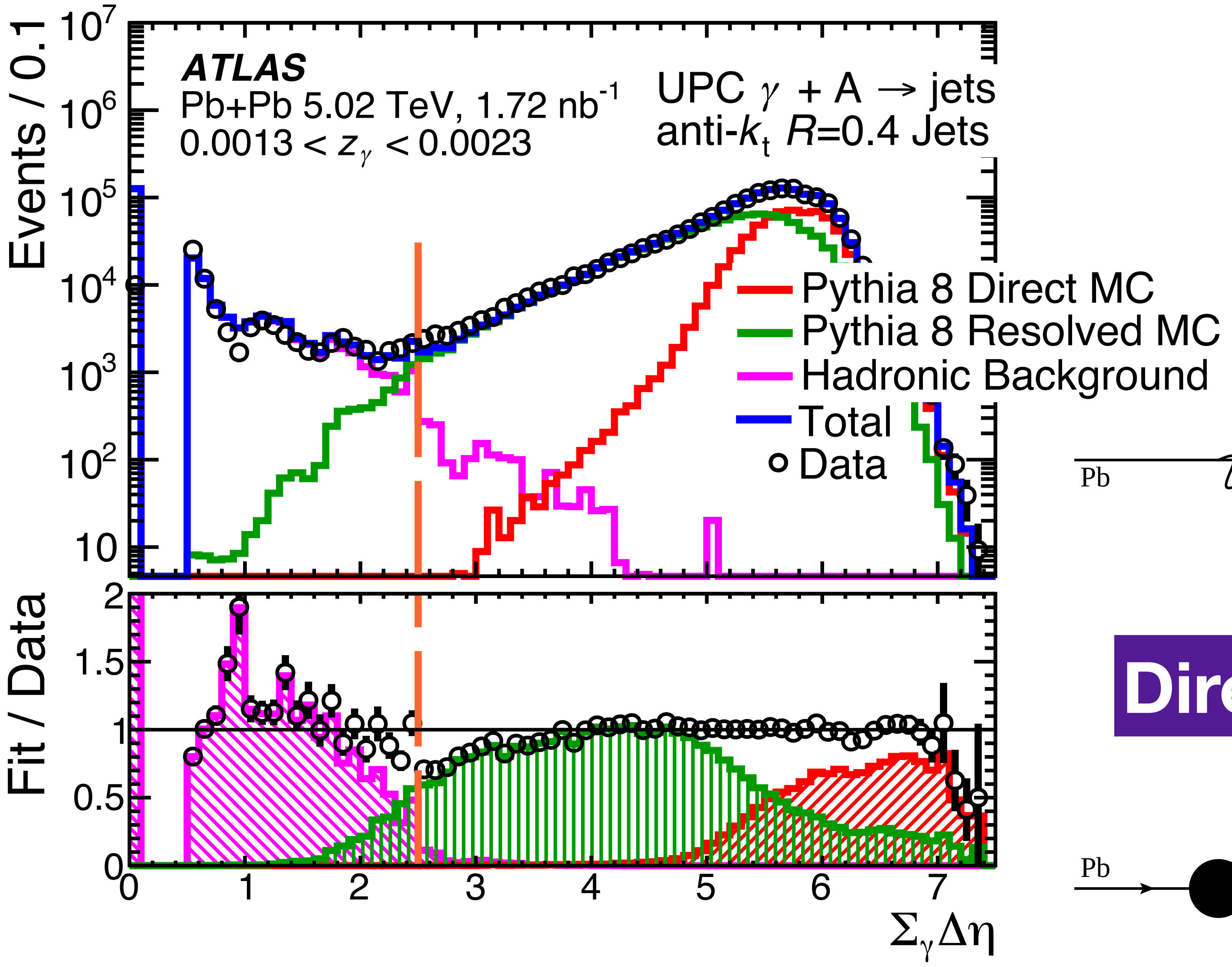
- **nCTEQ**15 HQ
- **nNNPDF** 3.0
- **EPPS**21
- **TUJU**21

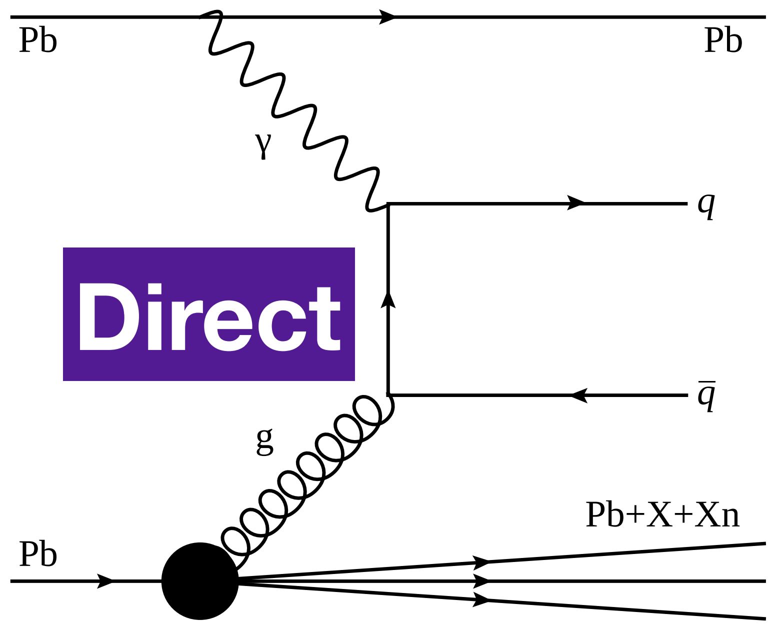
- The $t\bar{t}$ cross section is measured to be $\sigma_{t\bar{t}} = 58.1 \pm 2.0^{+4.8}_{-4.4}$ nb
- Extrapolated $R_{\text{p+Pb}}$ is consistent with unity; nNNPDF overestimates of $t\bar{t}$ $R_{\text{p+Pb}}$

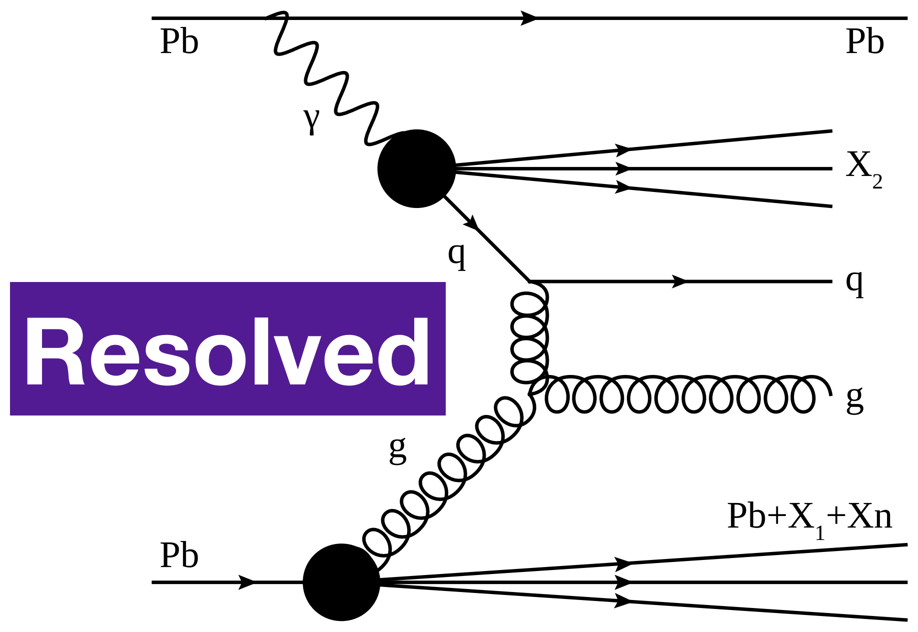
Jets in photonuclear UPC

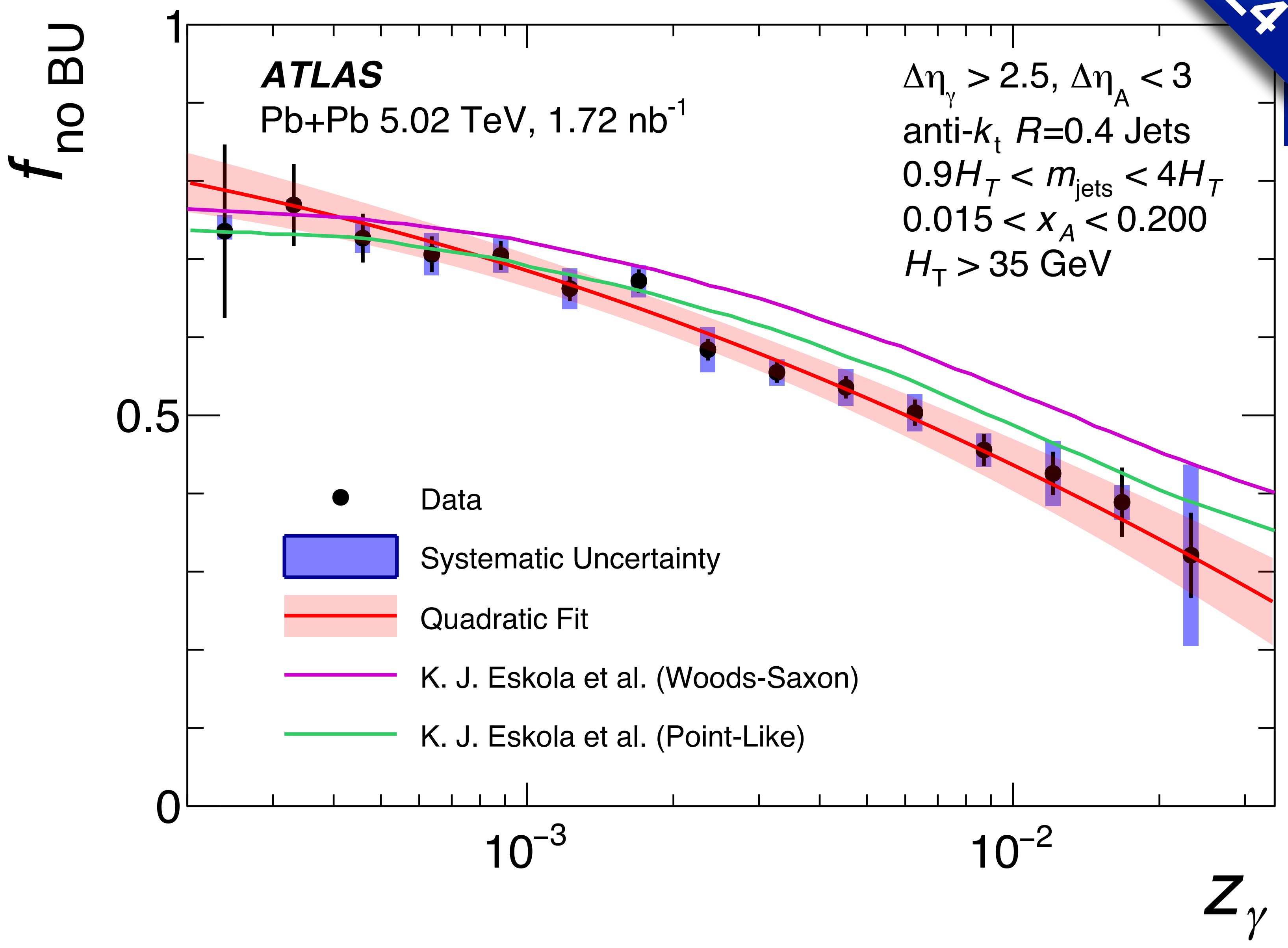
arXiv:2409.11060

Final for HP2024









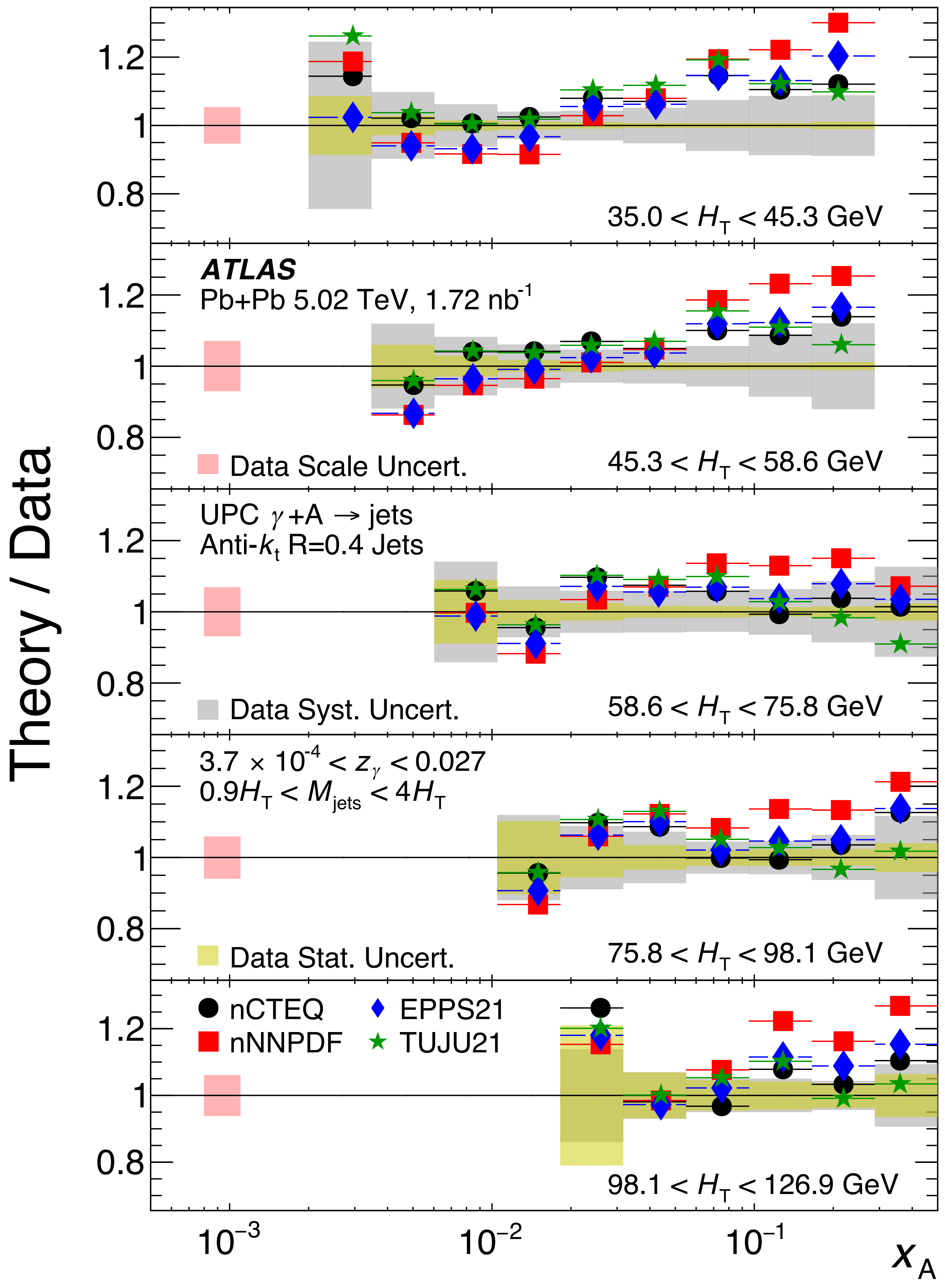
After years of detailed studies, we now confidently understand the basic properties of photonuclear UPCs with jets:

- Achieved well-modeled rapidity gaps that allows us to separate direct from resolved
- Measured break-up corrections to enable direct model comparison
- Extended jet p_T down to 15 GeV while keep control over systematic

Jets in photonuclear UPC — cont.

arXiv:2409.11060

Final for HP2024



$$H_T \equiv \sum_i p_{T\,i} \qquad x_A \equiv \frac{m_{jets}}{\sqrt{s_{NN}}} e^{-y_{jets}} \qquad z_\gamma \equiv \frac{m_{jets}}{\sqrt{s_{NN}}} e^{+y_{jets}}$$

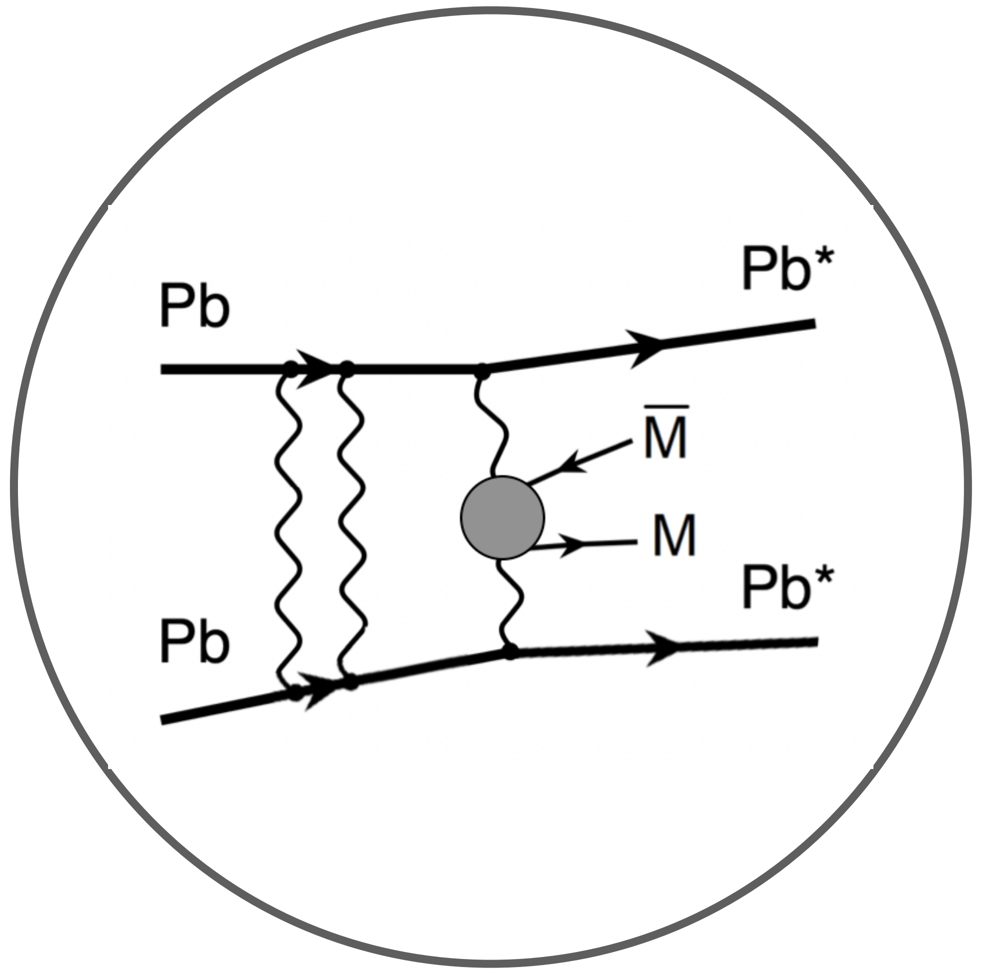
$$m_{jets} \equiv \left[\left(\sum_i E_i \right)^2 - \left| \sum_i \vec{p}_i \right|^2 \right]^{1/2}$$

$$y_{jets} \equiv \frac{1}{2} \ln \left(\frac{\sum_i E_i + \sum_i p^*_{z\,i}}{\sum_i E_i - \sum_i p^*_{z\,i}} \right)$$

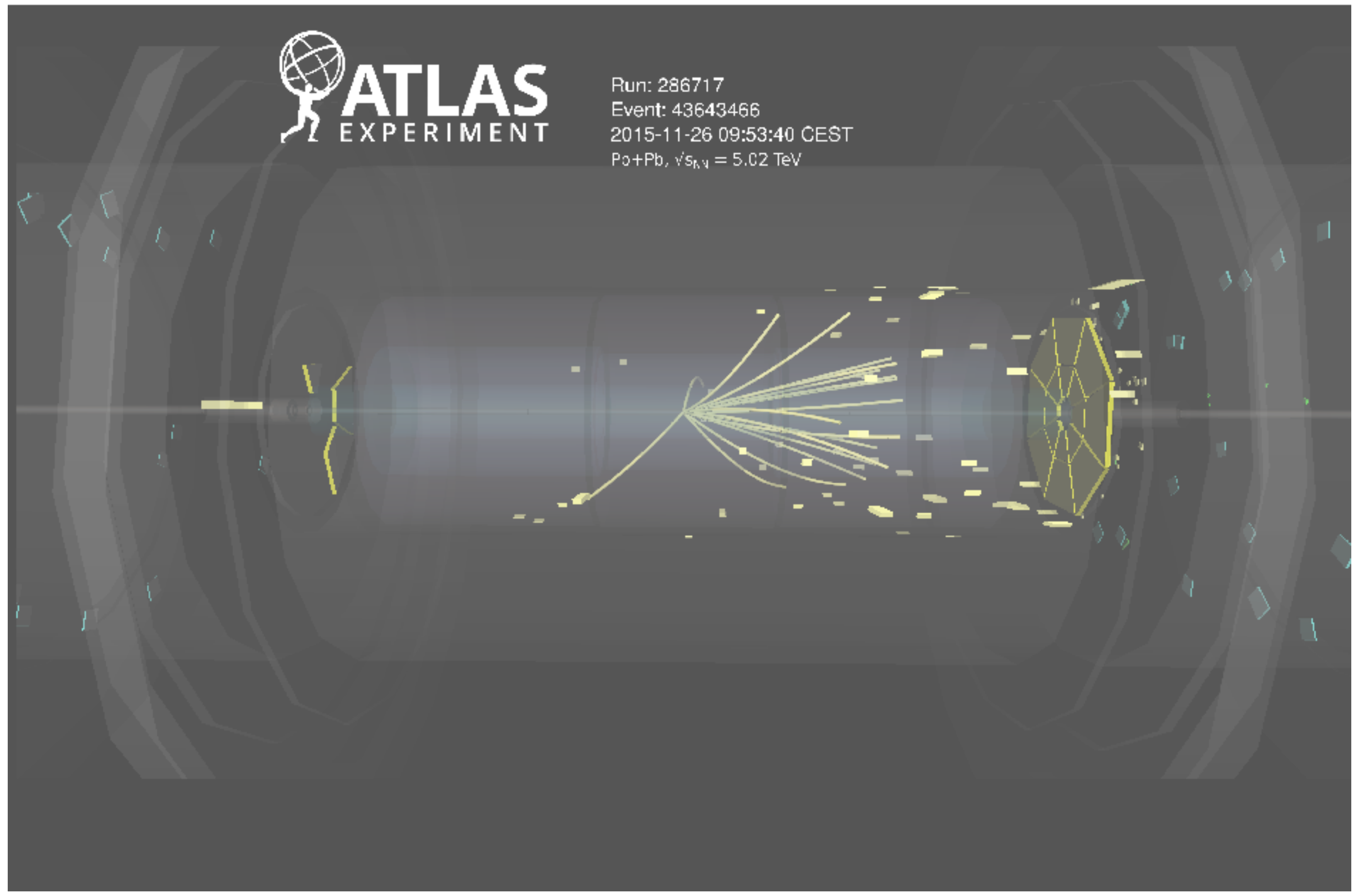
Ratio between measured precise 3D cross-sections and predictions with different nPDF fits, while uncertainties of the photon flux not included:

- **nCTEQ**15 WZ+SIH
- **nNNPDF**3.0
- **EPPS**21
- **TUJU**21

- nCTEQ results typically agree best. At higher H_T, the data typically agree well with TUJU
- nNNPDF overpredicts the cross sections at high H_T and x_A

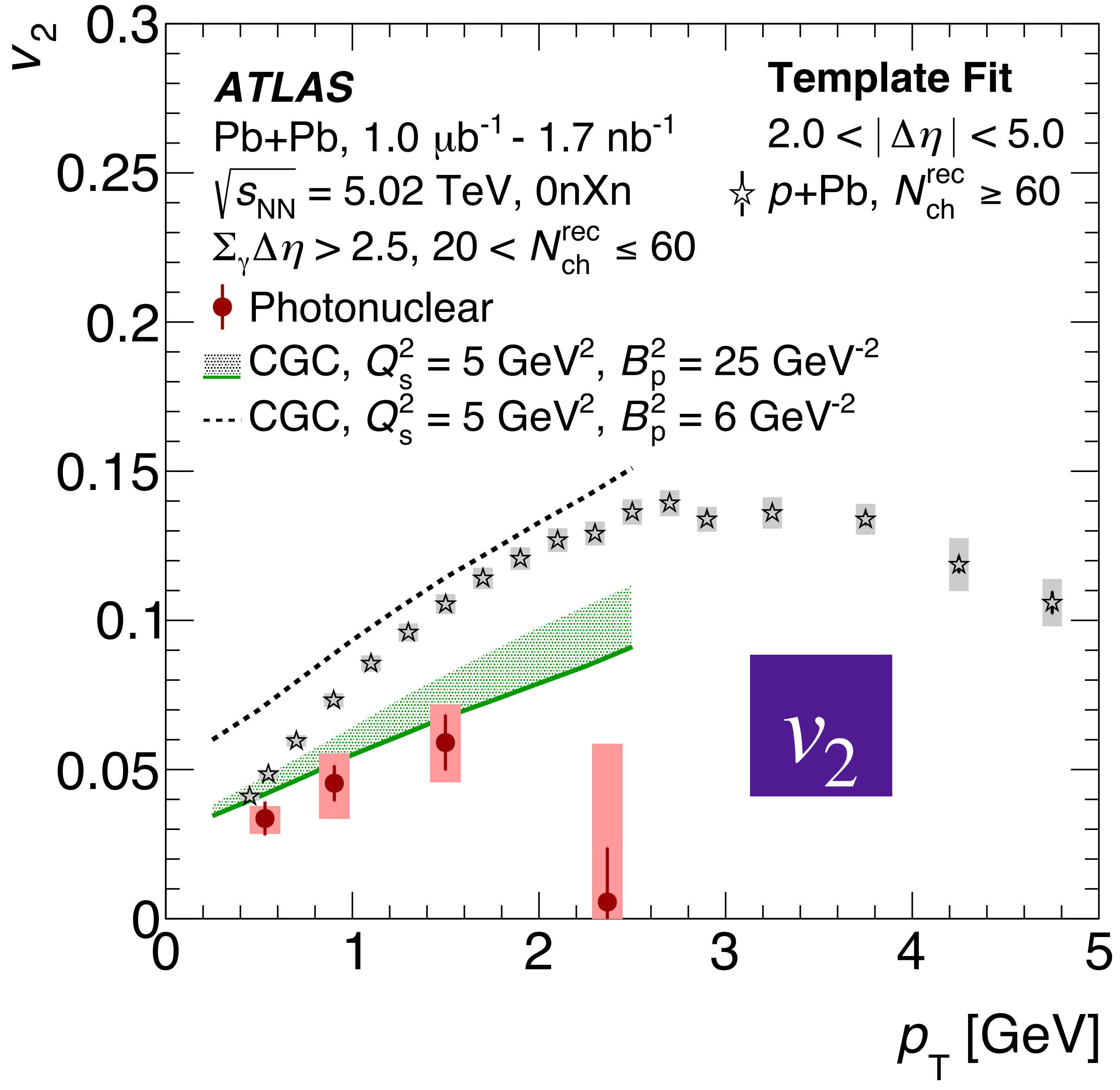


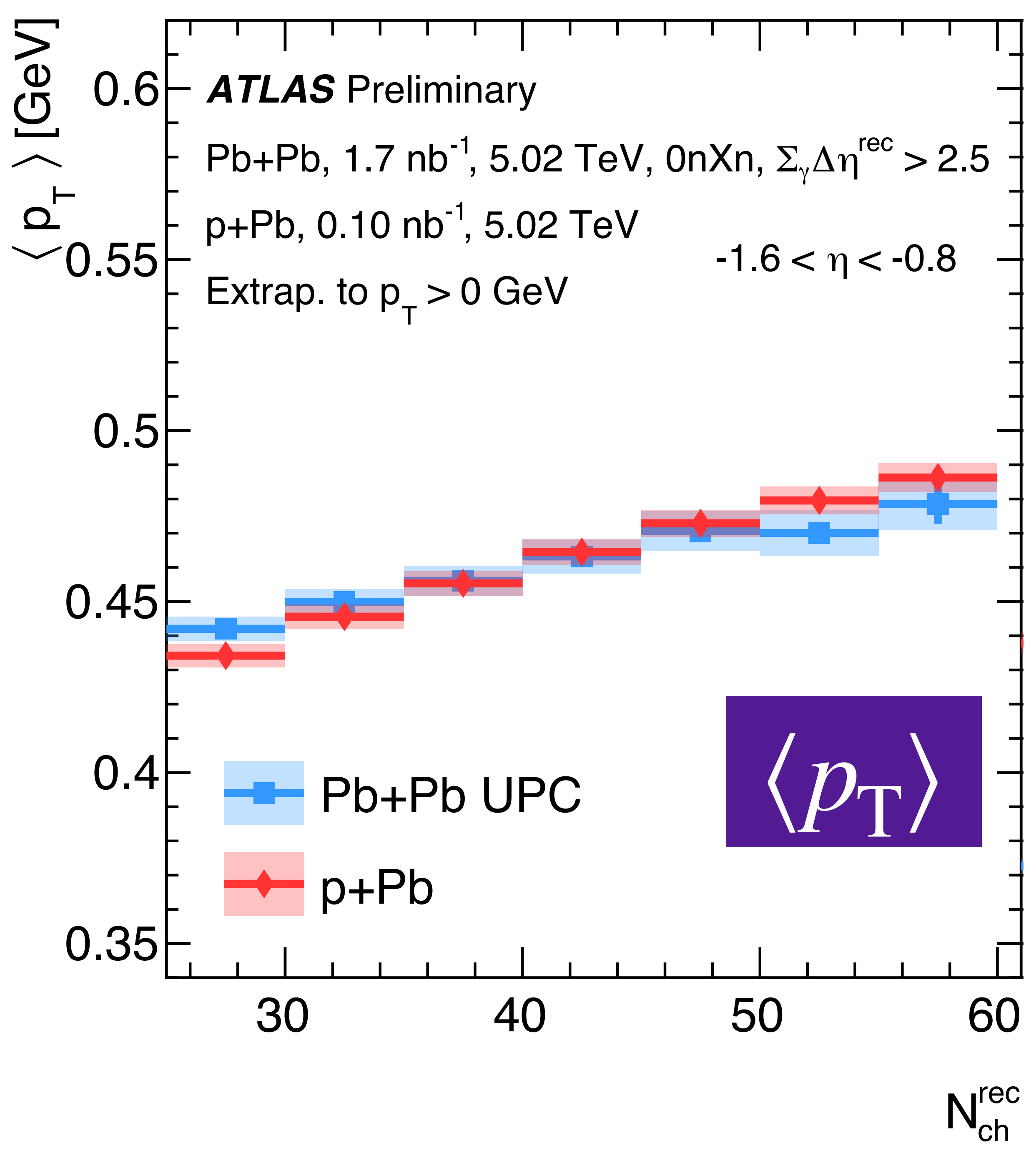
Exploring novel physics in UPCs

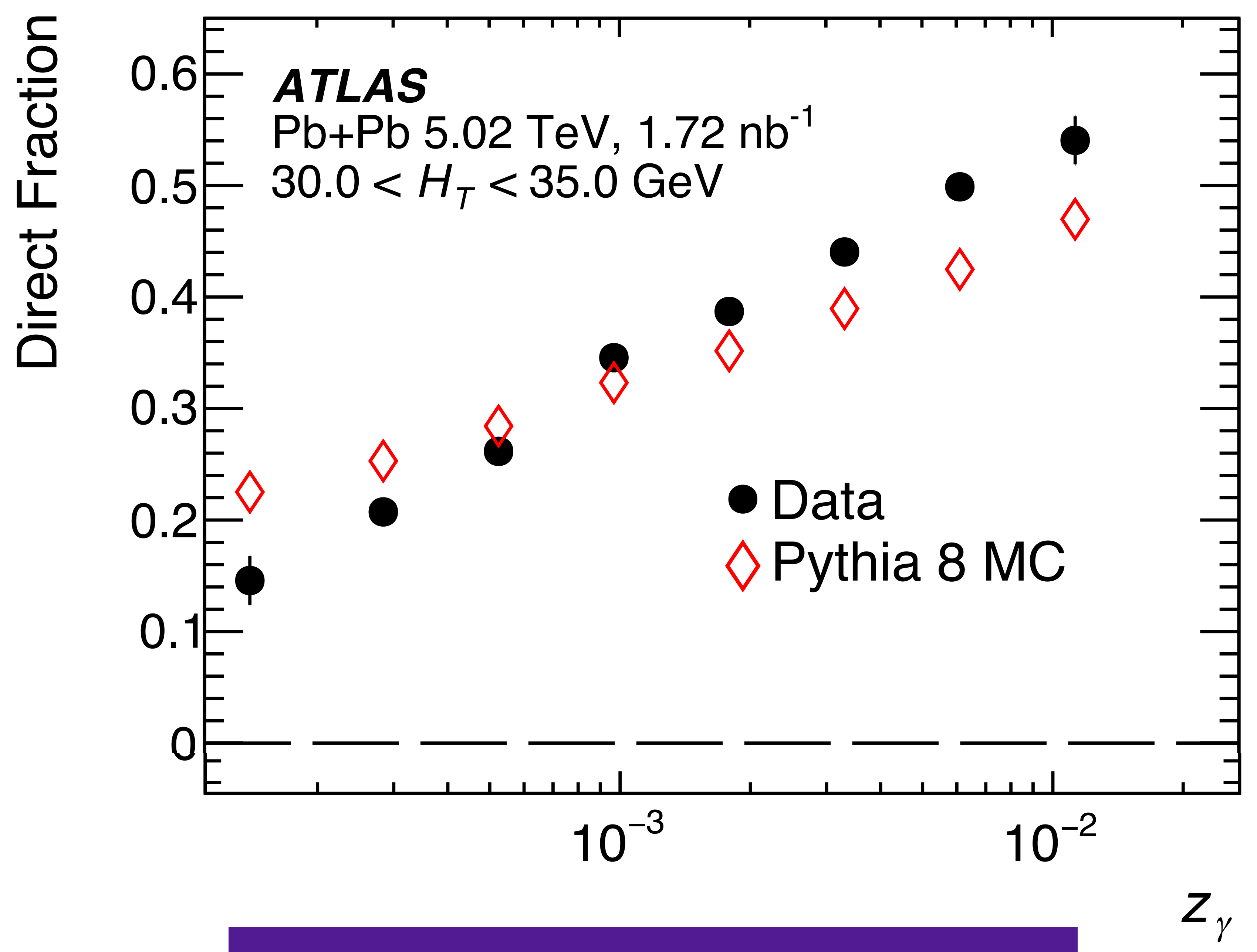


v_2 and $\langle p_T \rangle$ in photonuclear interactions

PRC 104 (2021) 014903
ATLAS-CONF-2023-059







$v_2\ (p + \text{Pb}) > v_2\ (\gamma + \text{Pb})$

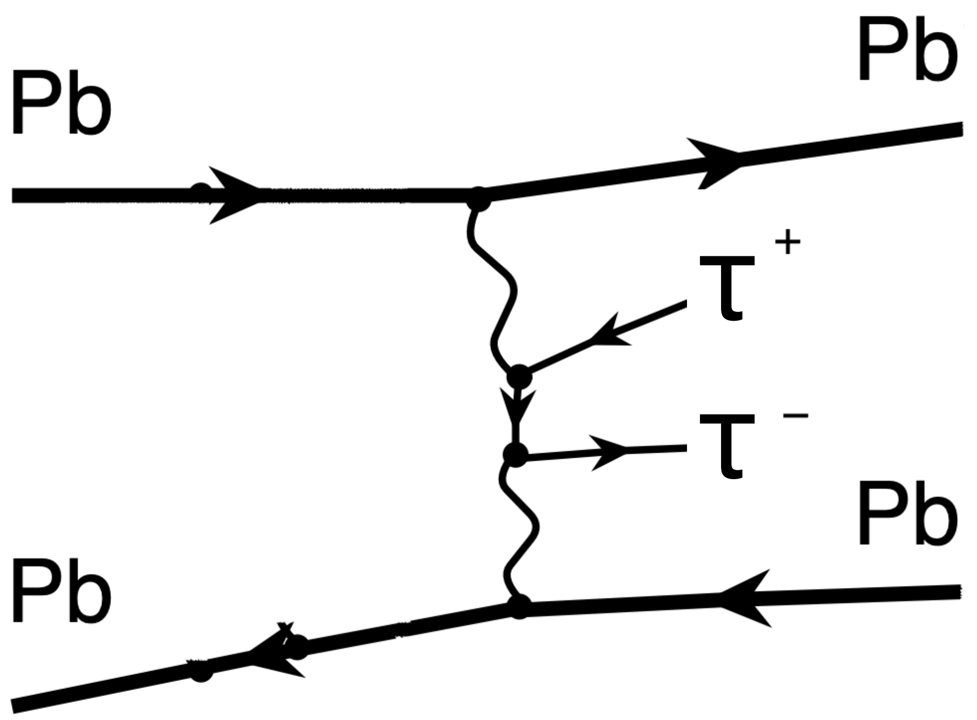
$\langle p_T \rangle\ (\gamma + \text{Pb}) \approx \langle p_T \rangle\ (p + \text{Pb})$

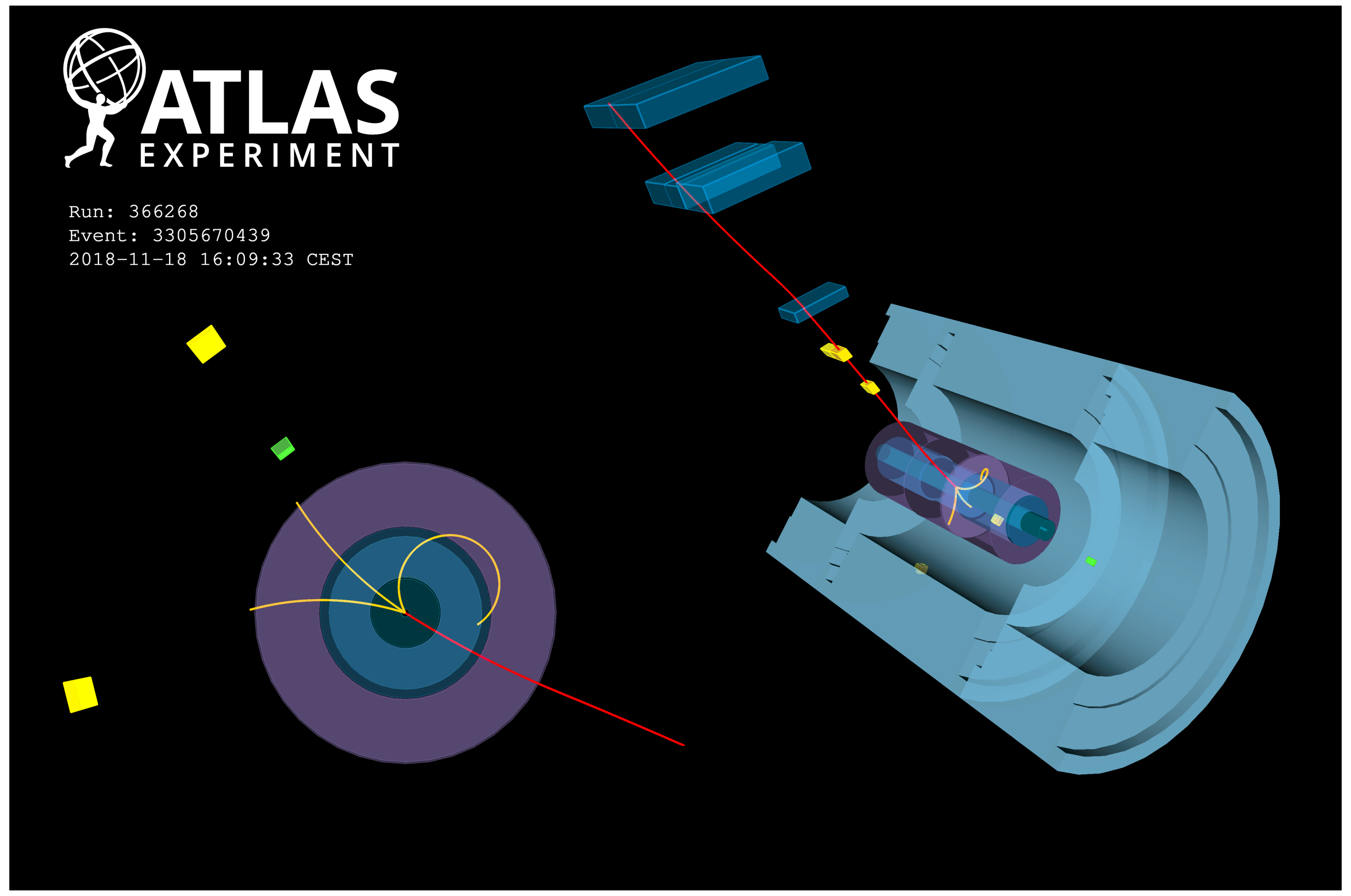
Direct fraction from the photonuclear jet analysis

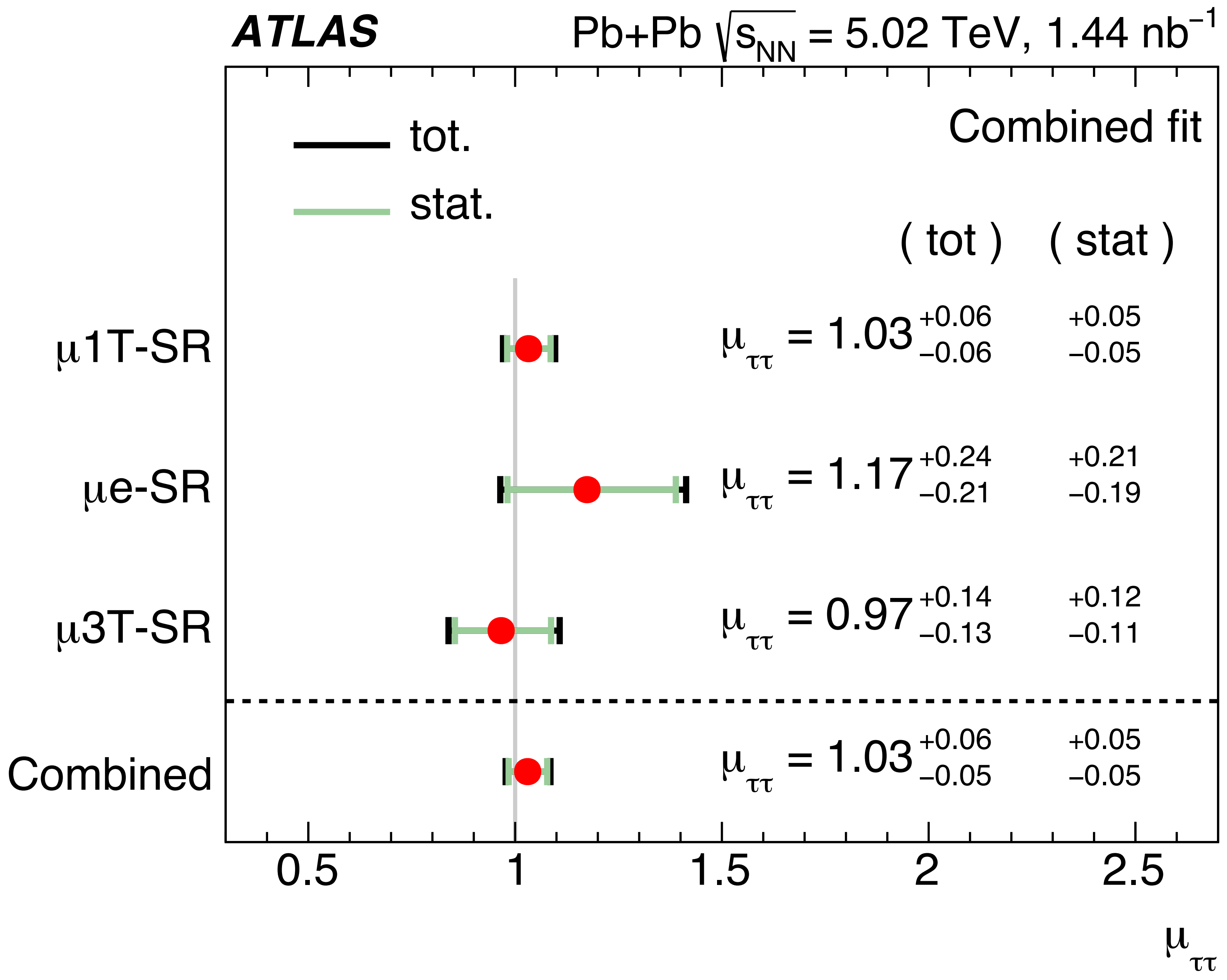
- Could be understood as different longitudinal decorrelation and similar radial flow in the hydro picture (Zhao et al PRL 129 (2022) 252302)
- However, direct and resolved processes should be studied separately and it becomes possible

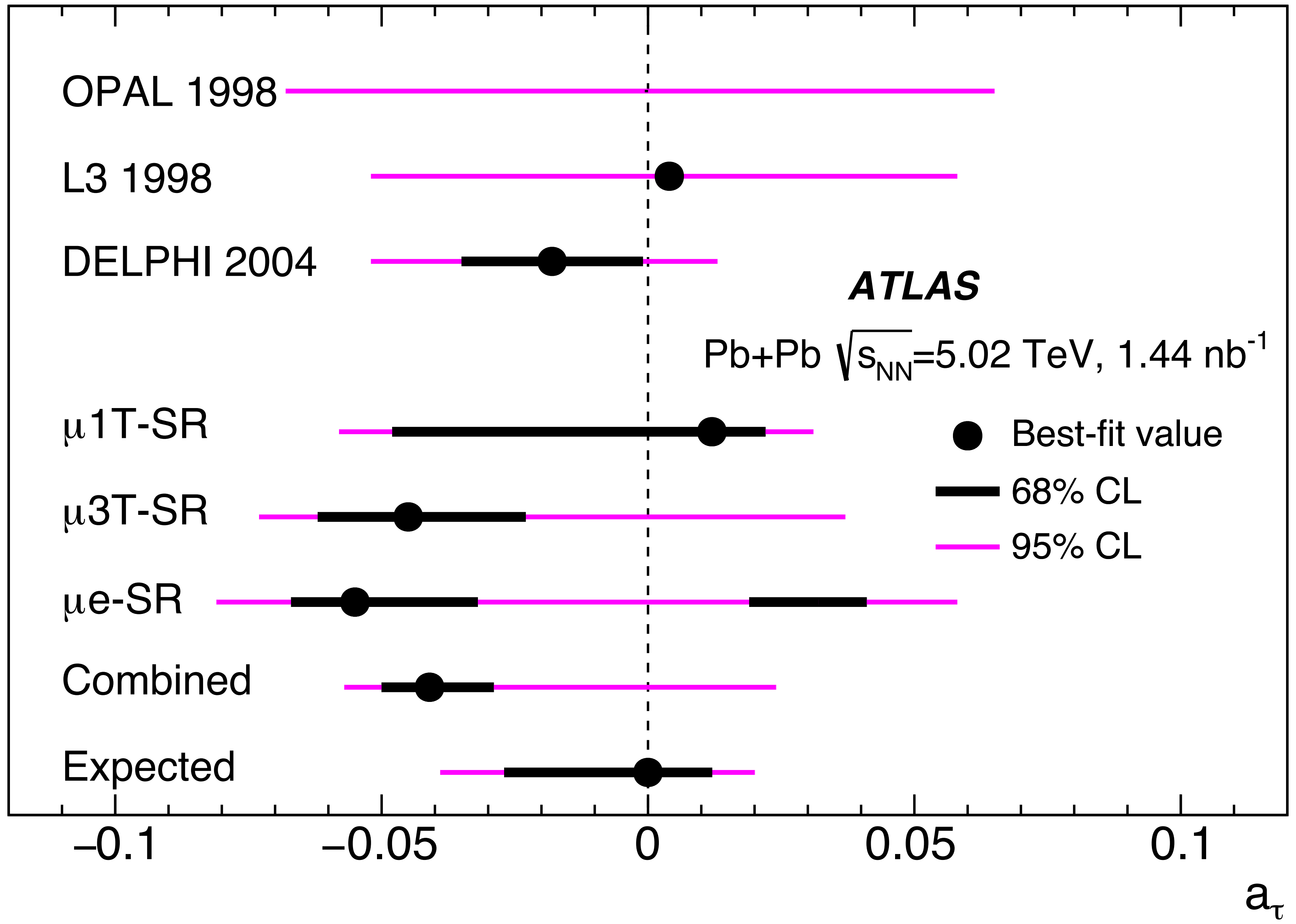
τ anomalous magnetic moment via $\gamma\gamma \rightarrow \tau\tau$

PRL 131 (2023) 151802







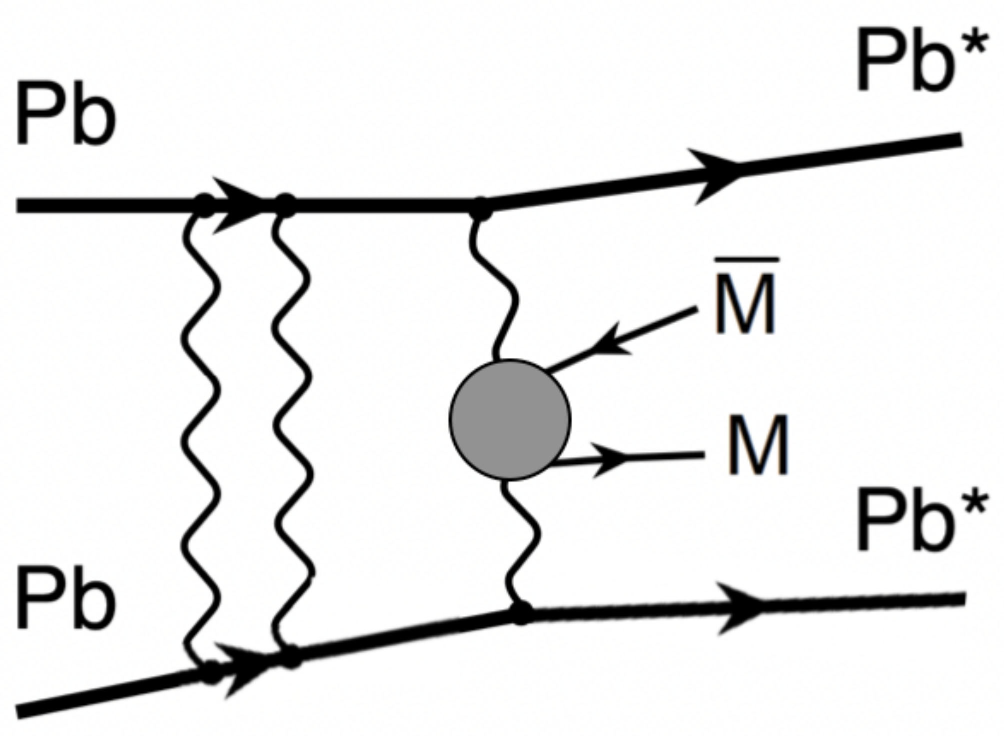


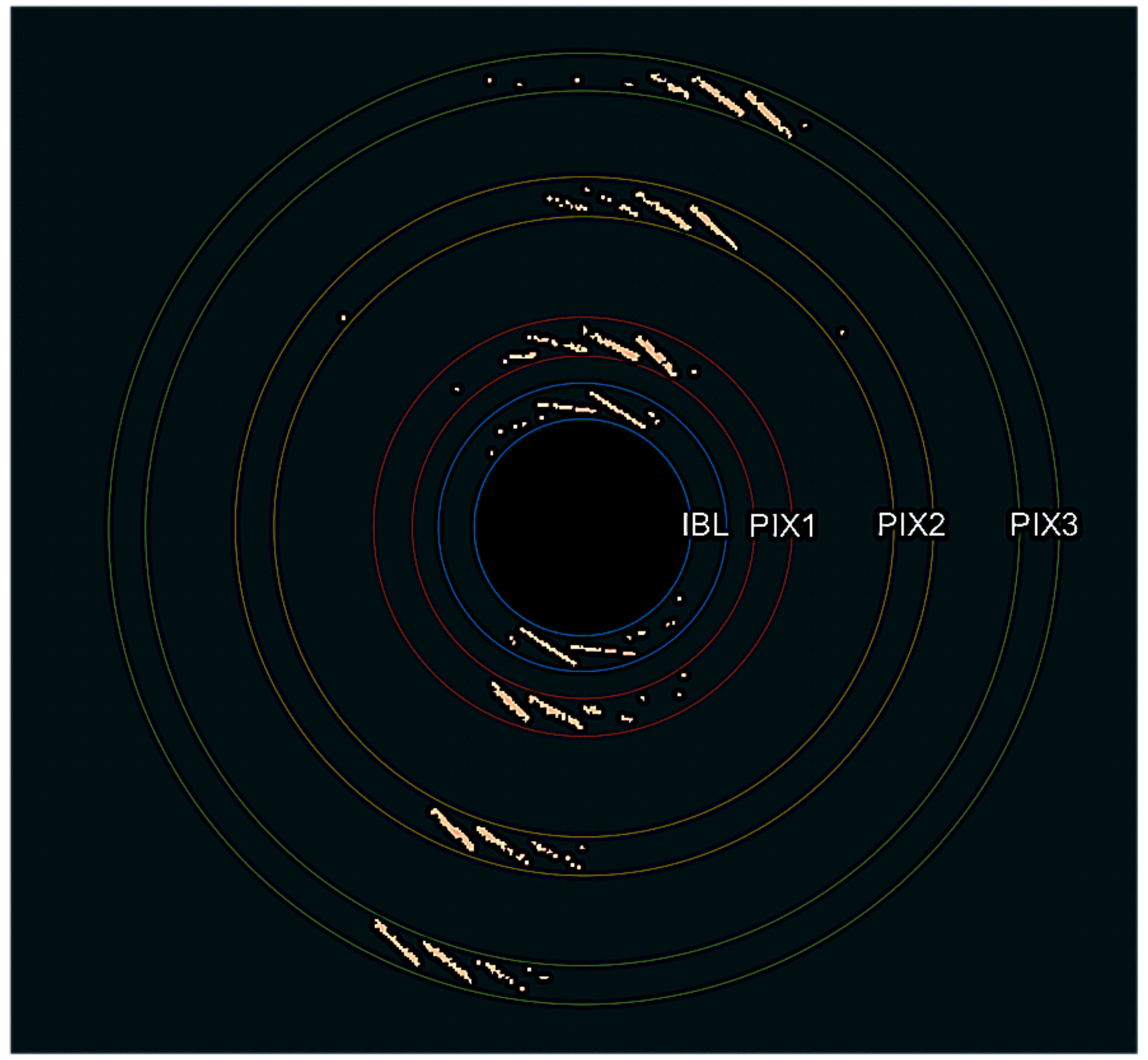
- Study (low-energy) taus for the first time in nuclear collisions
- No nuclear breakup required using ZDC to suppress hadronic background
- Constraints on a_τ extracted from the interaction strength is competitive with those observed at LEP (DELPHI)

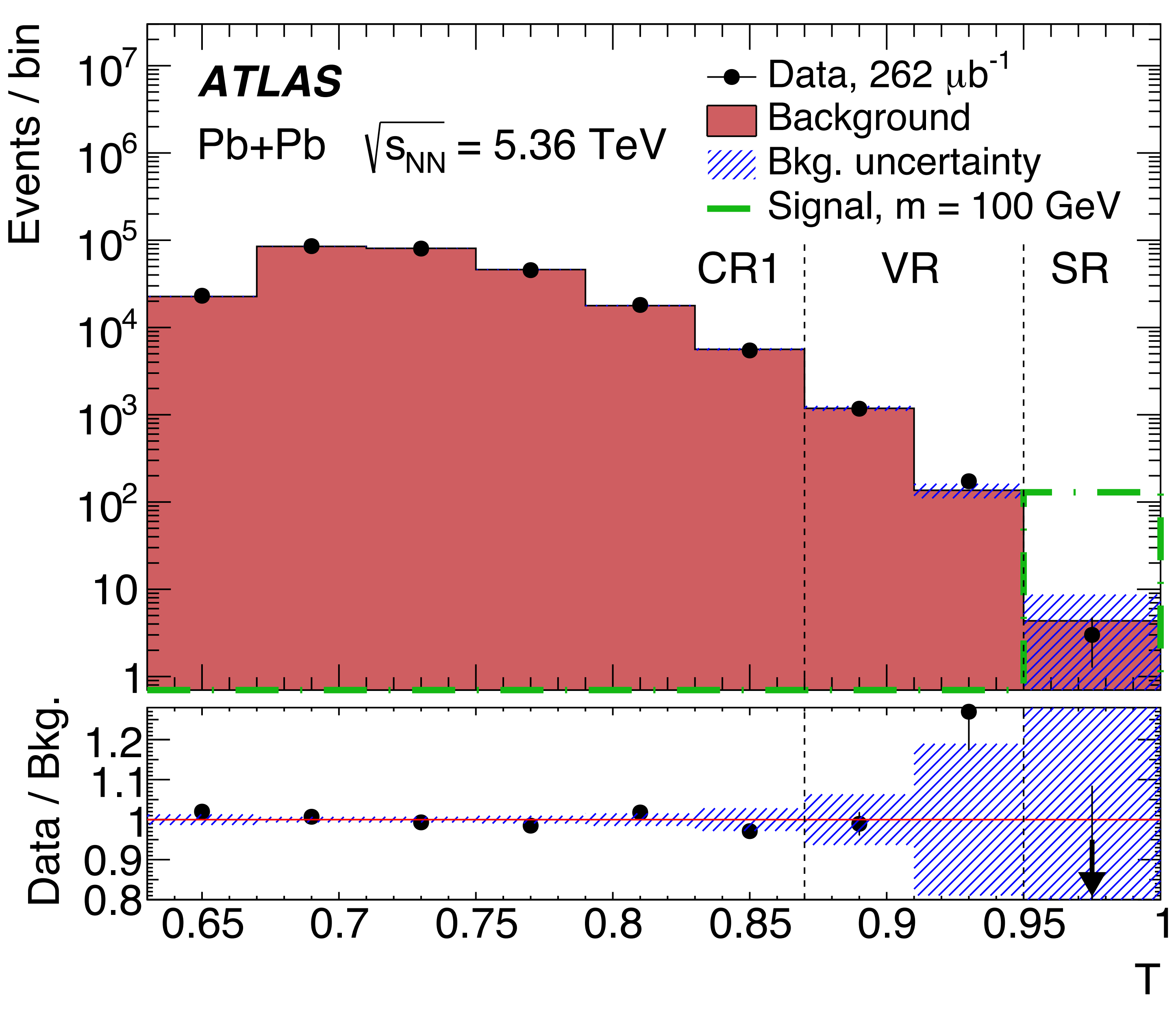
Magnetic monopoles via $\gamma\gamma \to M\bar{M}$

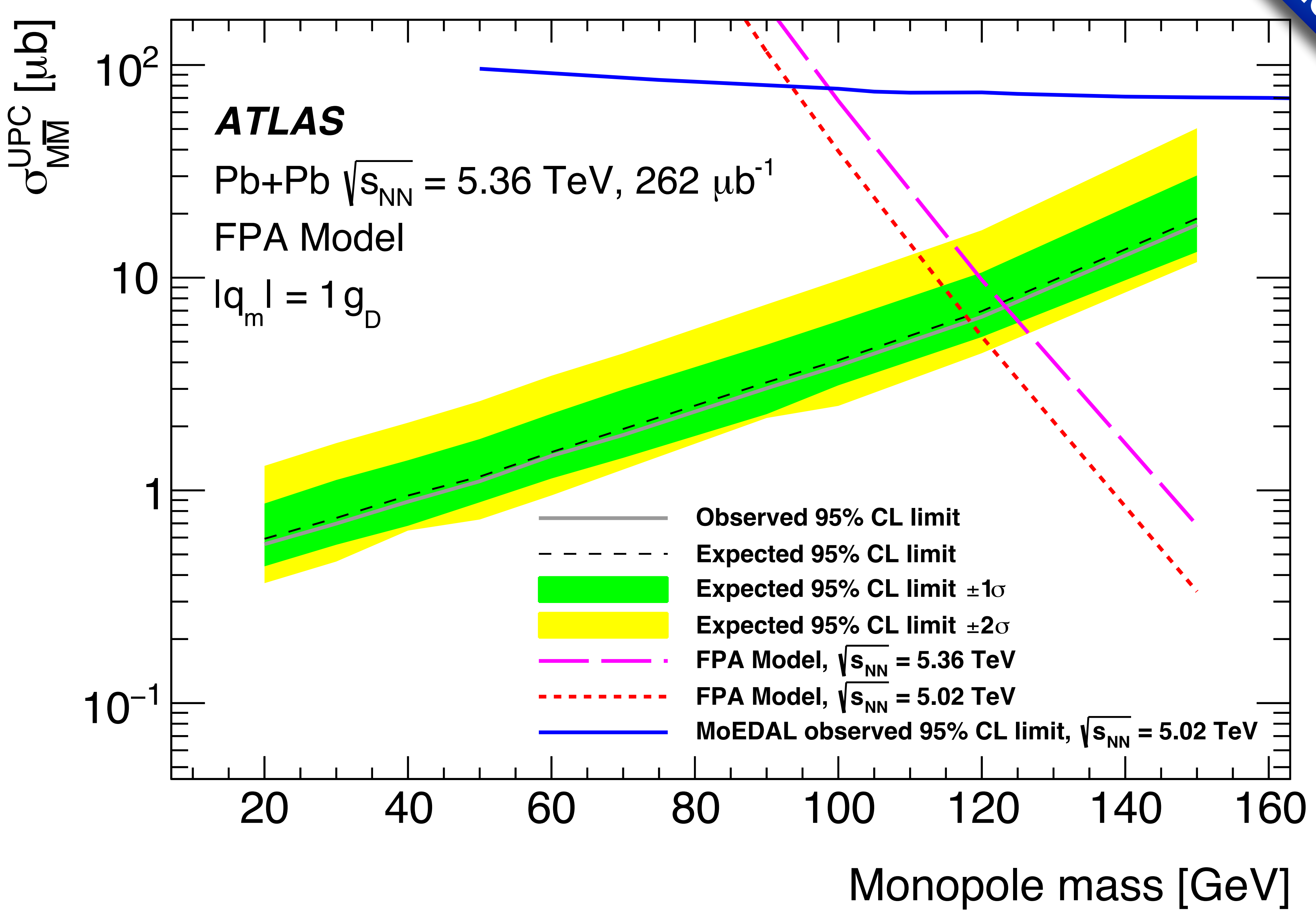
arXiv:2408.11035

Final for HP2024



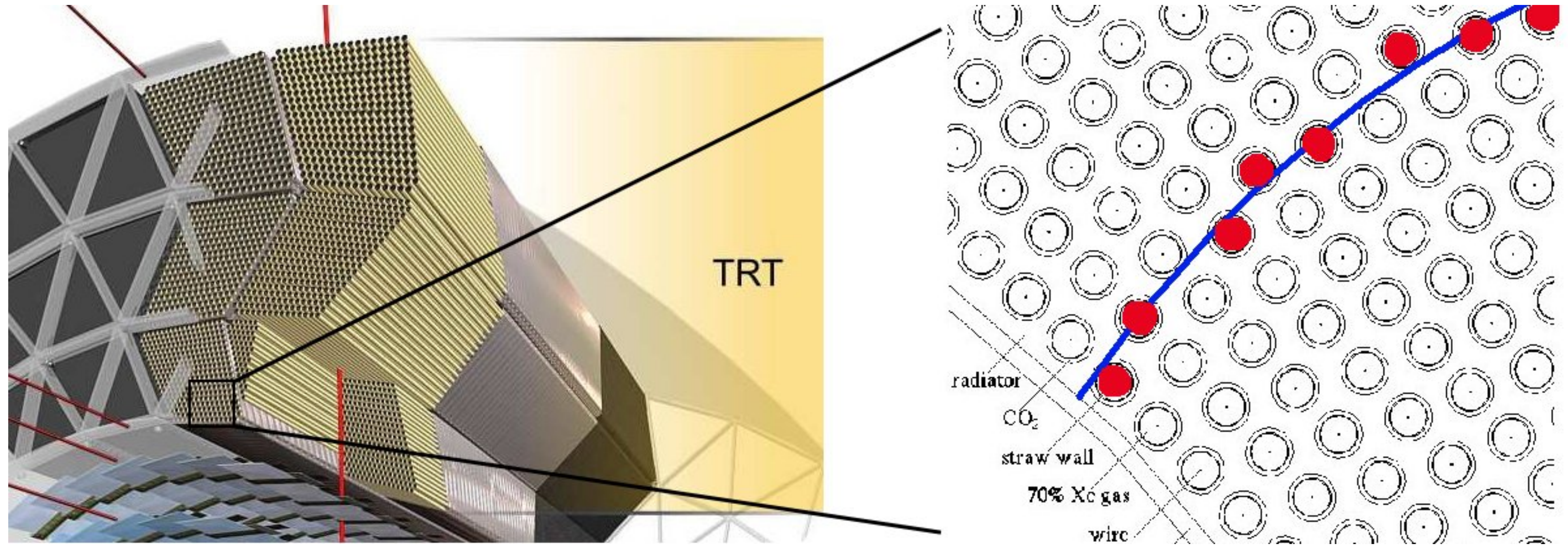


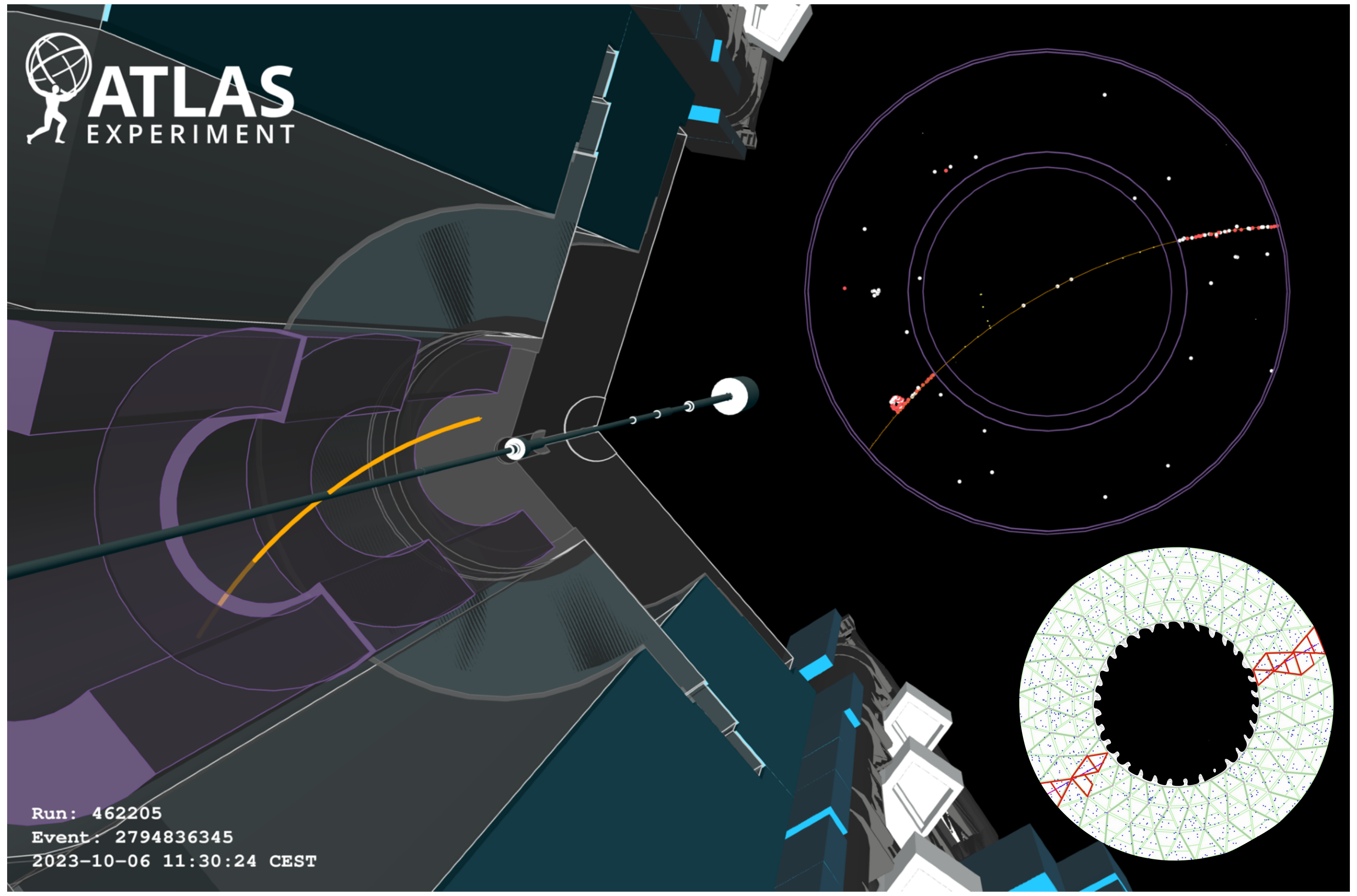




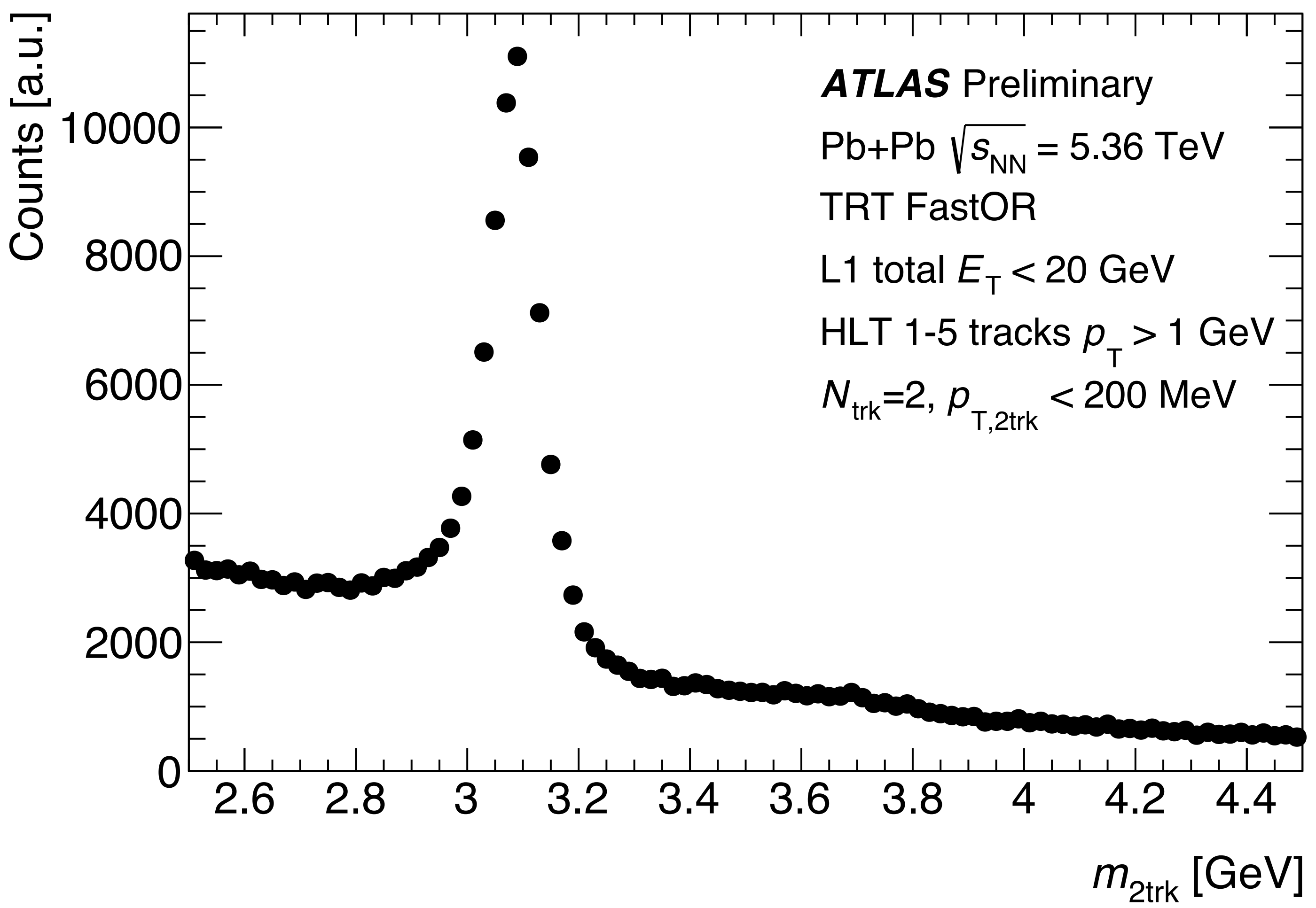
- Magnetic monopoles via the Schwinger mechanism in UPCs. First ATLAS analysis using Run3 heavy ion data
- 3 events in SR, consistent with background estimate (4 ± 4)
- Better limits compared to dedicated MoEDAL experiment (Nature 602 (2022) 63), achieve up to x8 improvement at masses below 120 GeV

Run3 new L1 track trigger

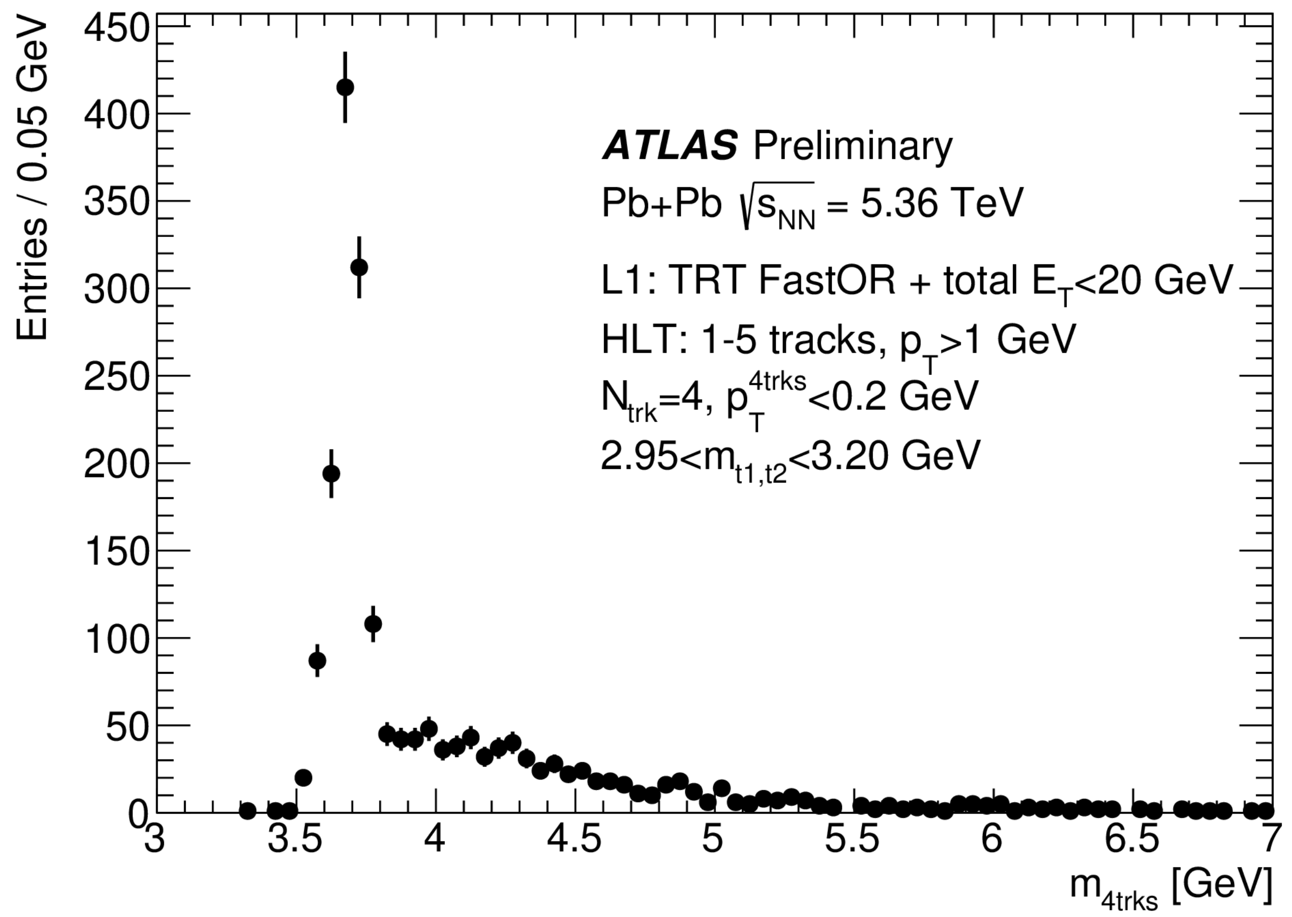




Two tracks

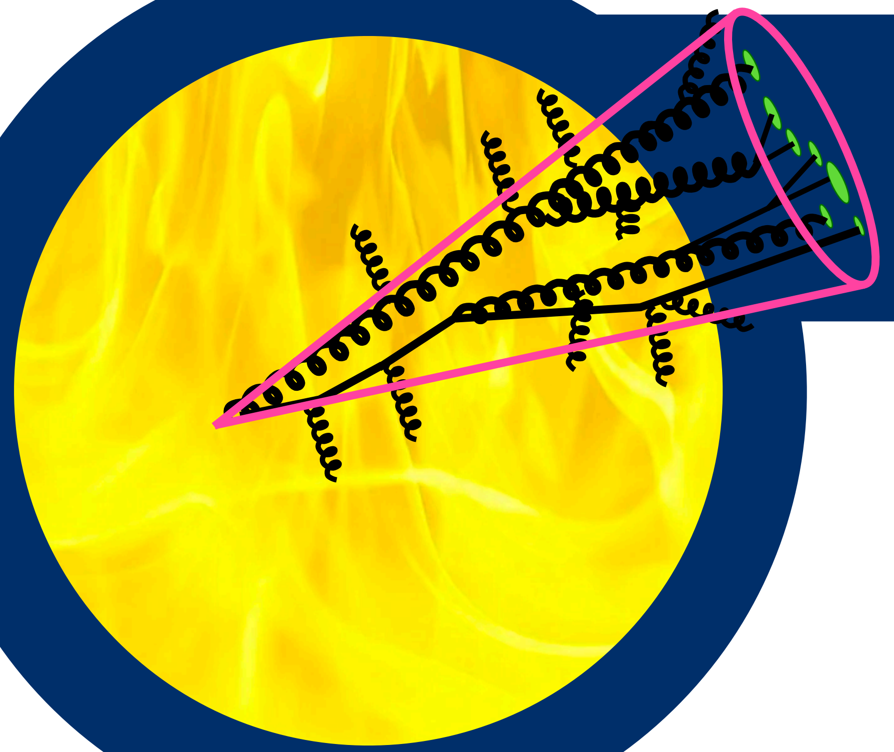


Four tracks



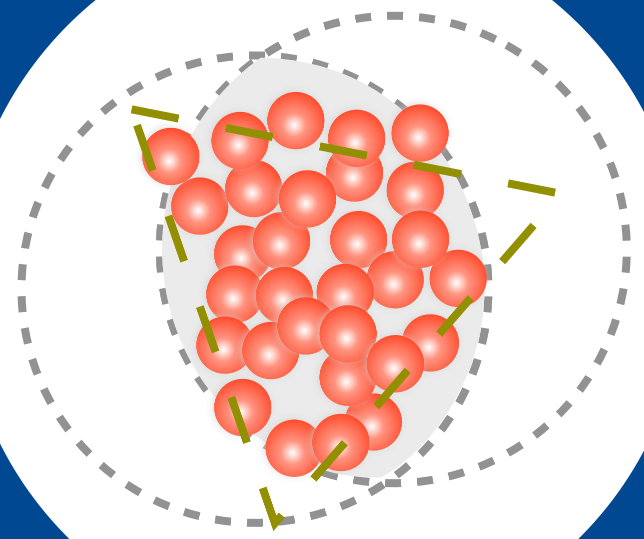
- Newly commissioned TRT trigger (L1 track trigger running at MHz level!)
- Let us accumulate large UPC sample with various track multiplicities for exclusive *J/ψ* and other hadron spectroscopy researches

Where we are heading



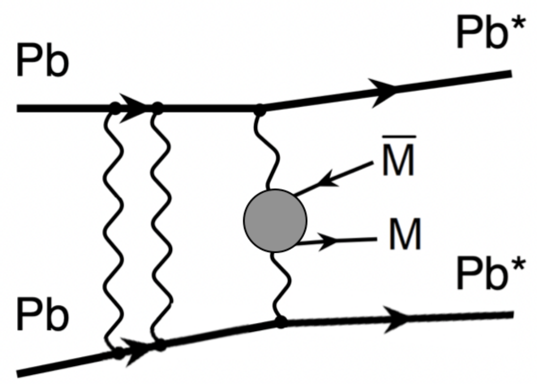
Probing QGP with penetrating particles

Precision and differential results to constrain model in order to extract underlying physics



Understand the initial state

New observables to test different effects/models



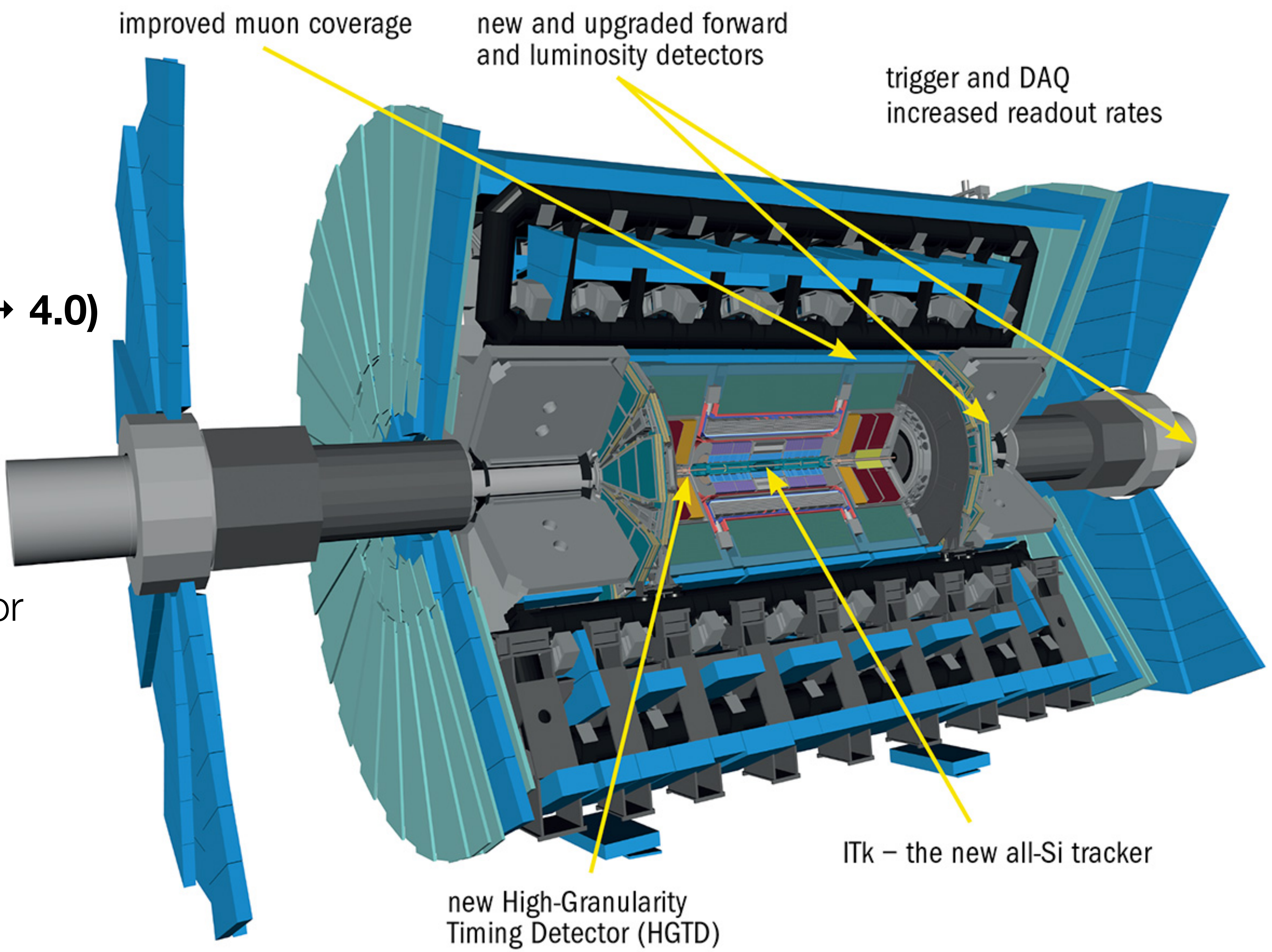
Exploring novel physics in UPCs

Expand the scope of the physics program and foster strong collaboration with the broader community

Phase-II ATLAS

An upgraded ATLAS (> 2030s)

- **High-granularity, high-coverage tracker (2.5 → 4.0)**
- **New ZDC (same as CMS Phase-II ZDC)**
- High-granularity timing detector
- Replaced muon chambers
- New and upgraded forward and luminosity detector
- Improved trigger, high-performance software & computing, deeply embedded machine learning



ATLAS contributions at HP 2024

Parallel Talks

Monday 2:00PM	*Radius dependent jet quenching measurements from ATLAS*	**Anne Sickles**
Monday 2:20PM	*ATLAS measurements of soft-hard correlations and anisotropy decorrelations in pp collisions*	**Blair Seidlitz**
Monday 2:20PM	*Jet substructure measurements with small and large radius jets with ATLAS*	**Martin Rybar**
Monday 2:20PM	*Top quark pair production in Heavy Ion Collisions with the ATLAS experiment*	**Patrycja Potepa**
Monday 4:50PM	*Investigating initial state of heavy-ion and pp collisions using [pT] fluctuations and vn – [pT] correlations in ATLAS*	**Tomasz Bold**
Monday 5:10PM	*Measurement of Azimuthal Anisotropy of High Transverse Momentum Charged Particles in Pb+Pb Collisions using Multi-particle Cumulants with the ATLAS Detector*	**Xiaoning Wang**
Tuesday 2:00PM	*Measurements of heavy-flavor azimuthal correlations and b-jet suppression in 5.02 TeV Pb+Pb collisions with ATLAS*	**Soumya Mohapatra**
Wednesday 9:00AM	*Jet quenching and medium response using photon+jet events in ATLAS*	**Dominik Derendarz**
Wednesday 9:20AM	*Searching for jet-induced diffusion wakes of quark gluon plasma via jet-track correlations in heavy ion collisions with the ATLAS detector*	**Yeonju Go**
Wednesday 11:10AM	*Results on photon-induced processes in ultra-peripheral Pb+Pb collisions with ATLAS*	**Mateusz Dyndal**
Wednesday 12:10PM	*Measurement of dijet production in ultraperipheral Pb+Pb collisions with ATLAS*	**Benjamin Gilbert**

Posters

Observation of top-quark pair production in heavy-ion collisions in the ATLAS experiment	**Patrycja Potepa**
Jet radius dependence of dijet momentum balance and pair nuclear modification factor in Pb+Pb and pp collisions with the ATLAS detector	**Anabel Romero**
Probing initial state effects in nuclear collisions via dijet and spectator neutron measurements with the ATLAS detector	**Matthew Hoppesch**

All ATLAS HI public results: https://twiki.cern.ch/twiki/bin/view/AtlasPublic/HeavyIonsPublicResults