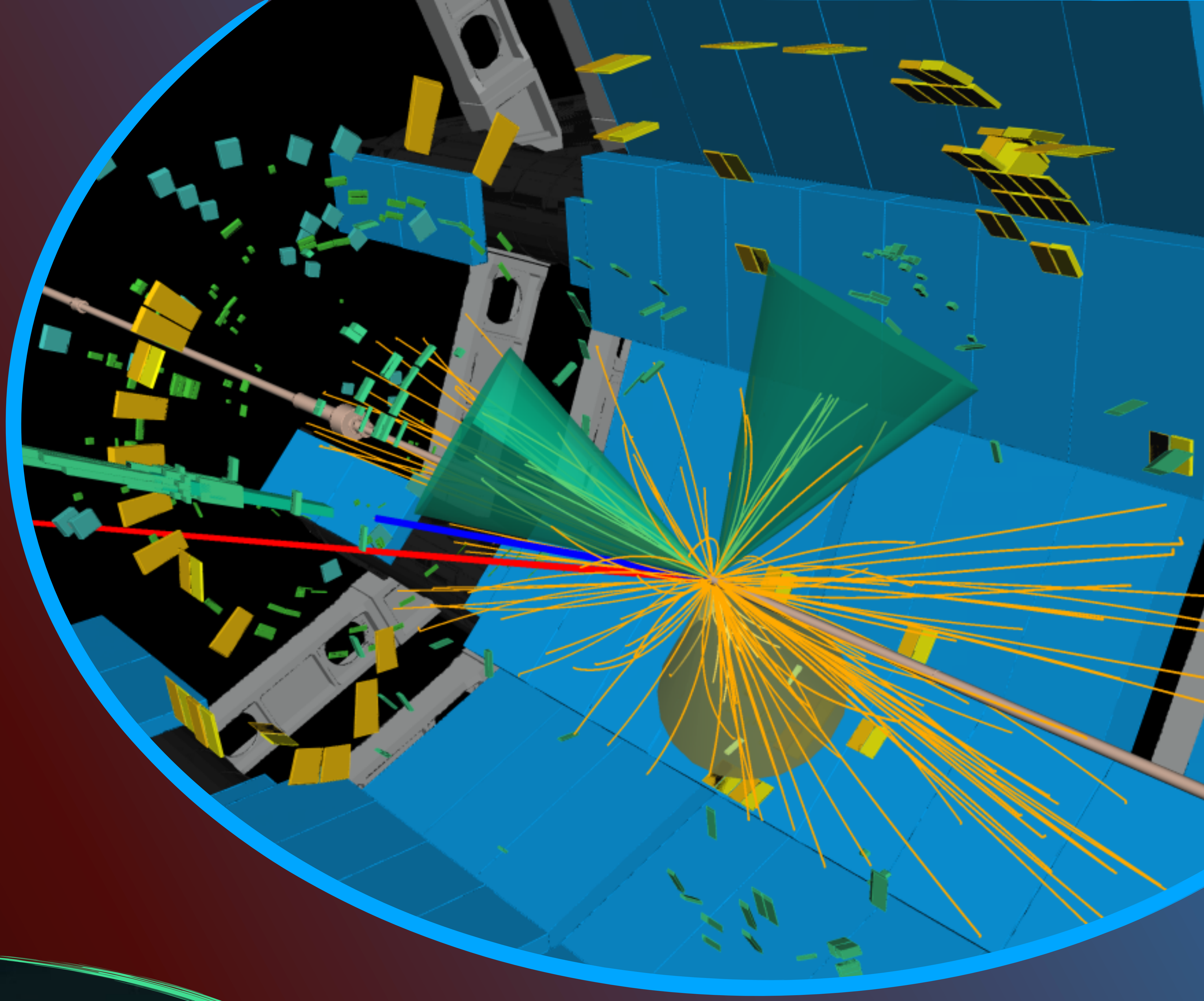
PHYSICS SYNERGIES BETWEEN THE ATLAS HEAVY ION PROGRAM AND THE EIC

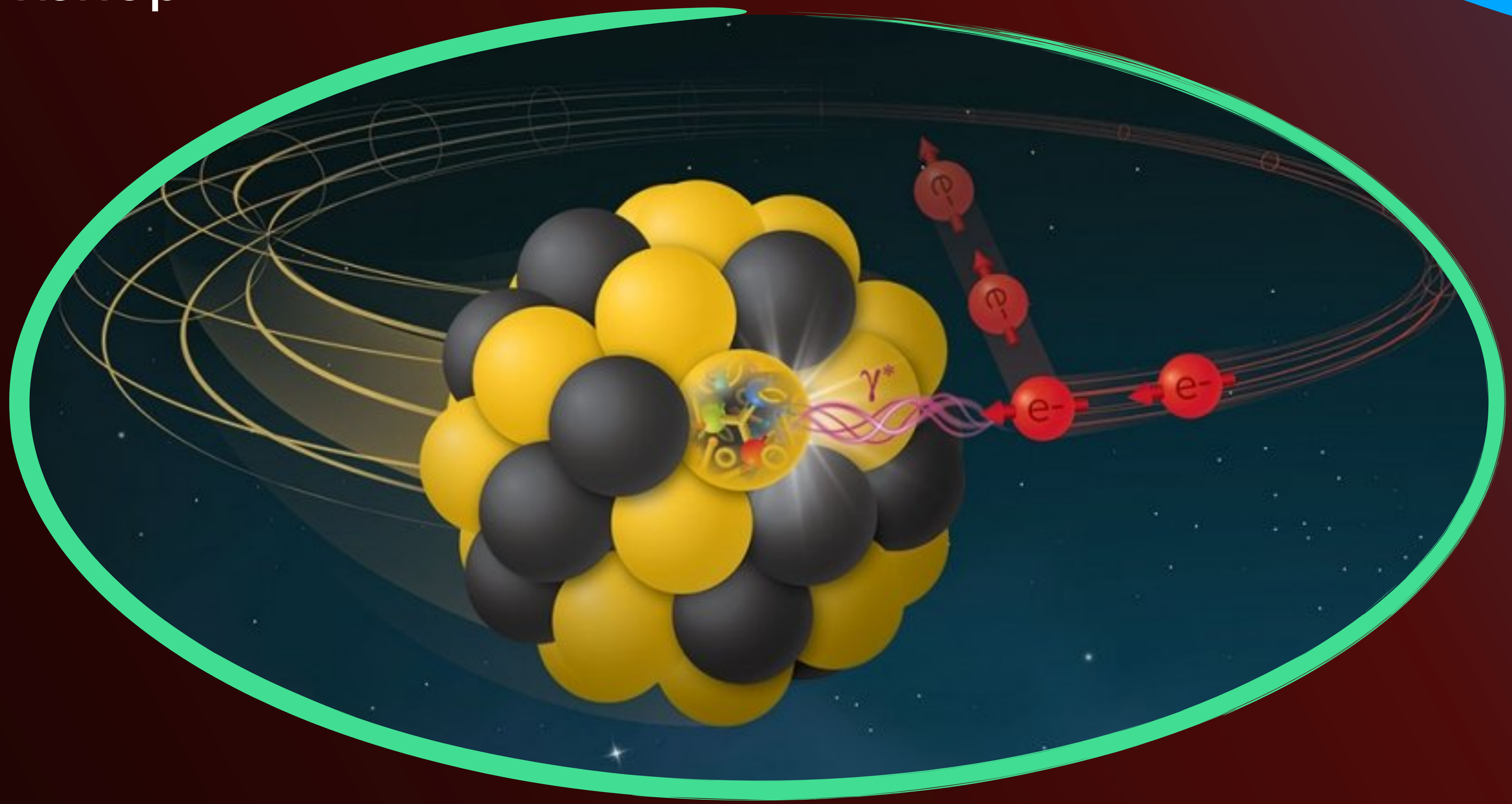


Riccardo Longo

On behalf of the ATLAS Collaboration

August 19th 2024

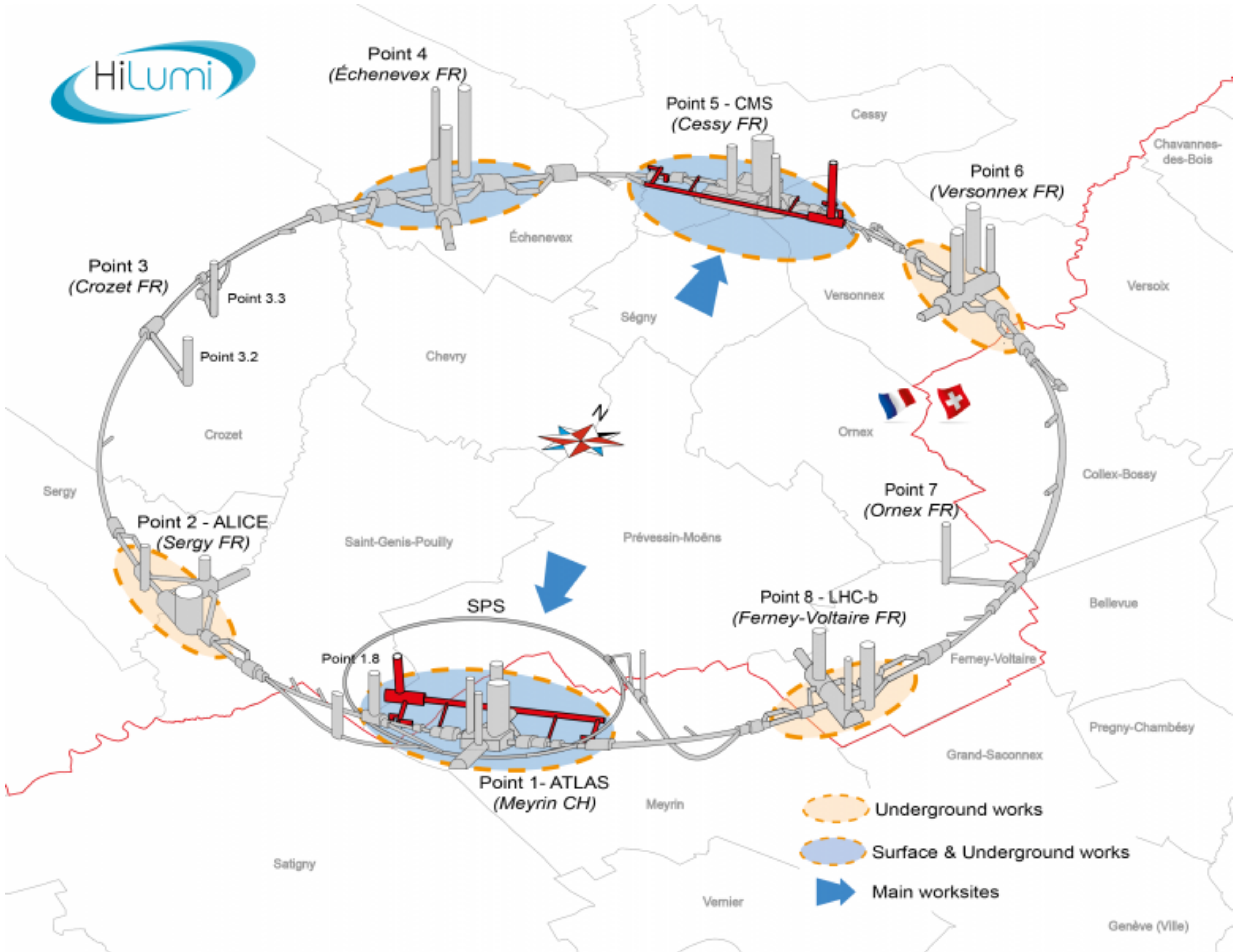
INT Heavy Ion physics in the LHC era workshop



UNIVERSITY OF ILLINOIS URBANA-CHAMPAIGN

ATLAS EXPERIMENT

FACILITIES: (HL-) LHC



LHC: until 2025 (or 2026)

First Pb+Pb run in 2023. More to come this year and the next (+ Oxygen pilot run)

Possible extension to 2026 under discussion

HL-LHC: starting 2029++

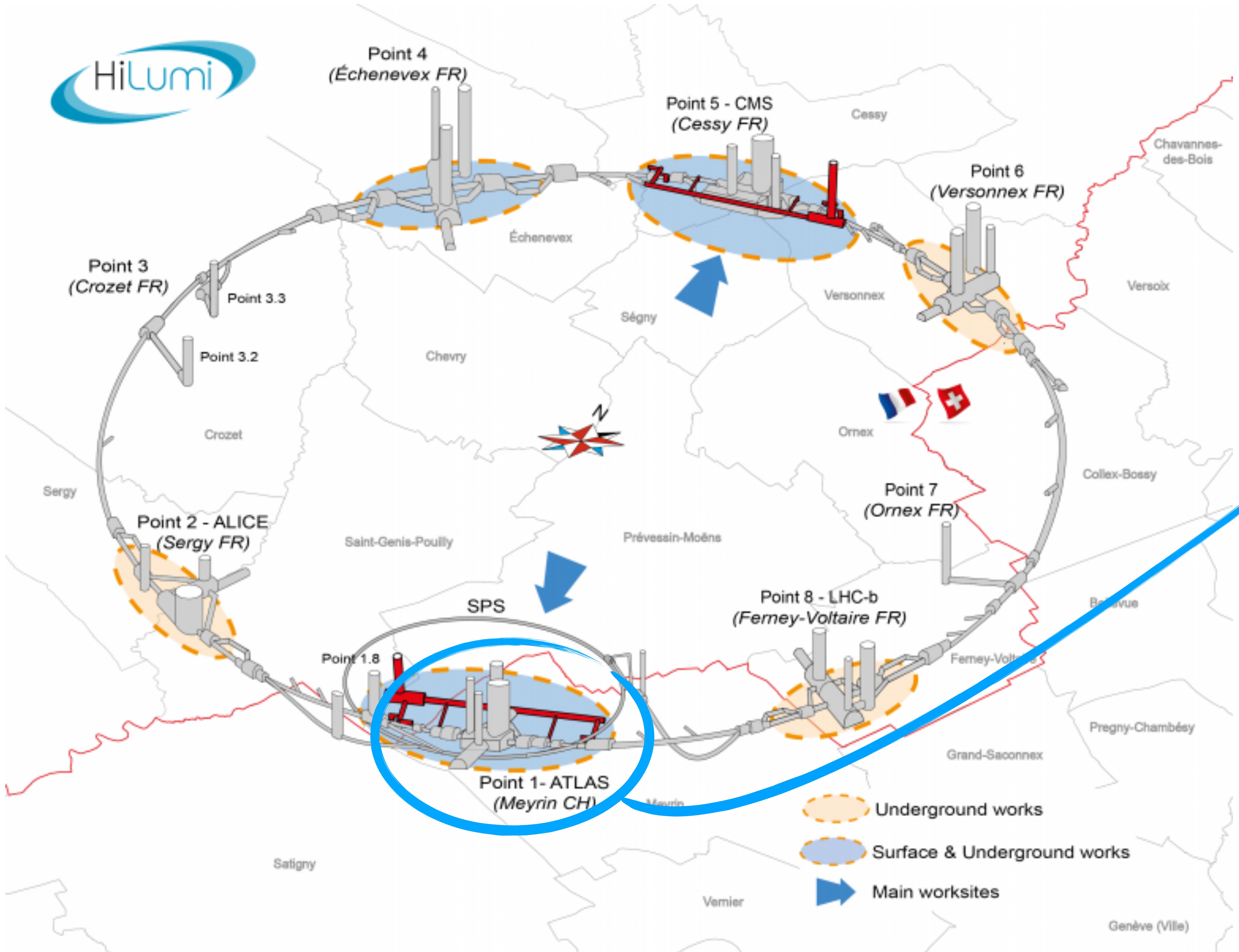
Will be the **only high-energy p+A/A+A collider after RHIC shutdown** and transition to the EIC.

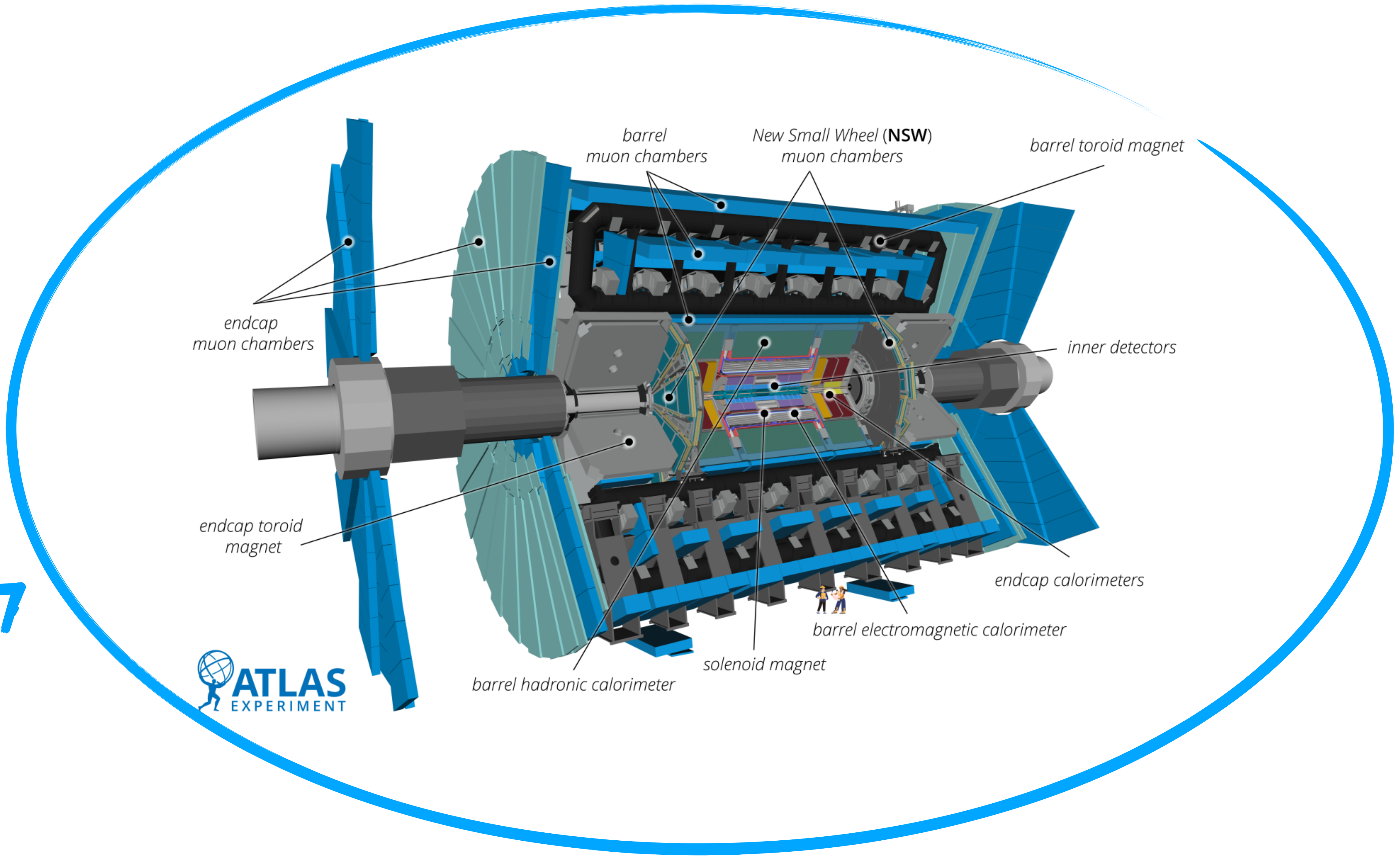
HI program officially in the schedule

No substantial changes expected foreseen for HI luminosity on LHC side

Discussion about HI in Run 5 and beyond to ramp up soon

FACILITIES: ATLAS

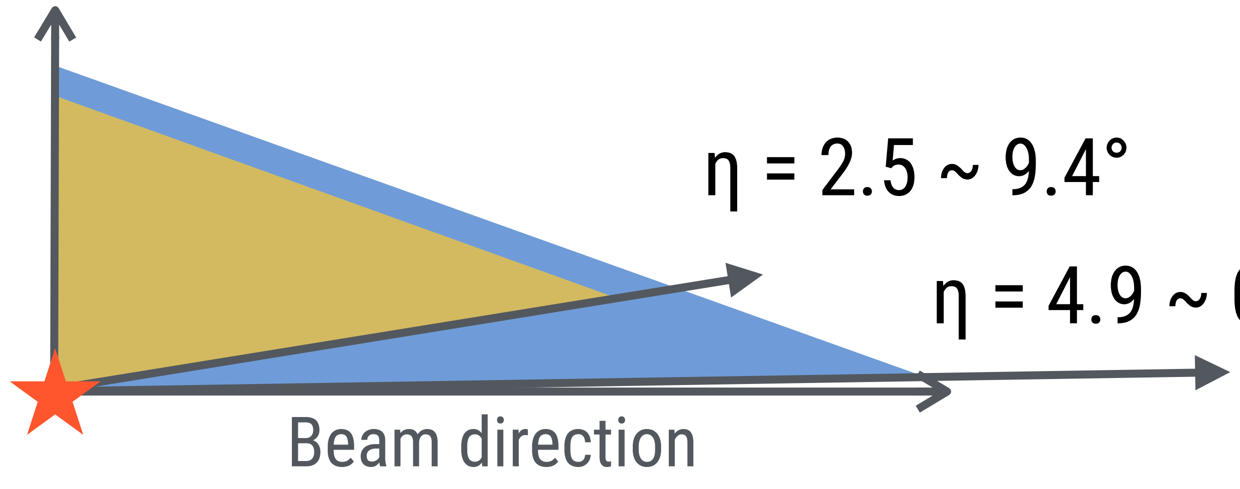




Hermetic detector

Tracker acceptance:
$|\eta| < 2.5$

Calorimeter acceptance:
$|\eta| < 4.9$

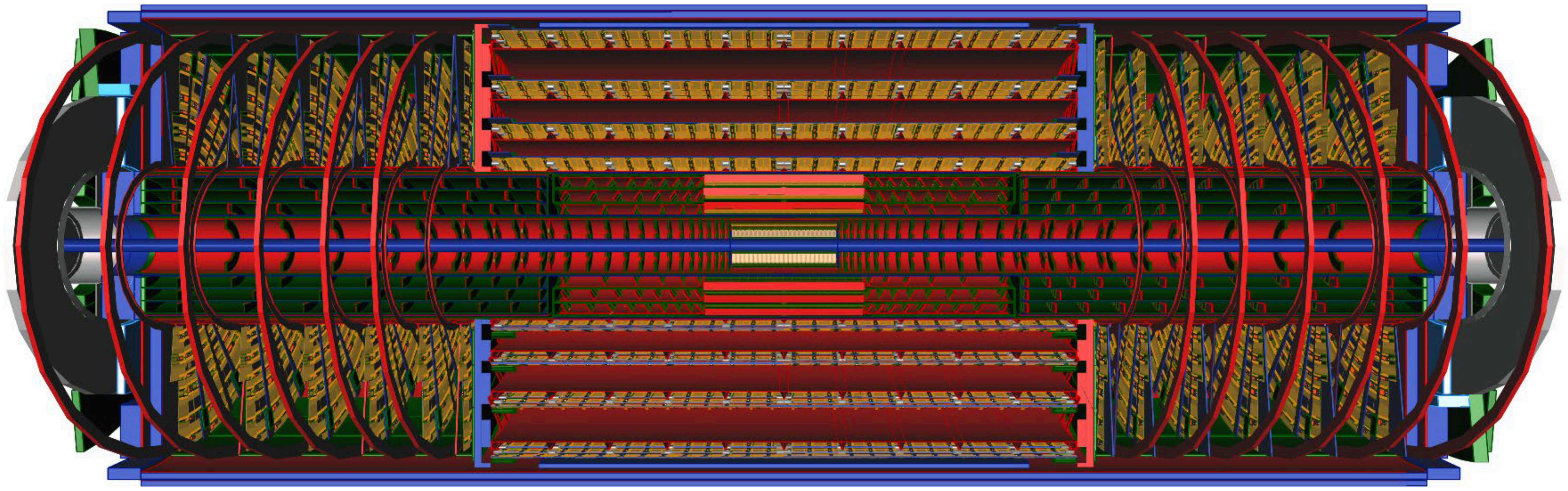


High-performance multi-purpose detector: can detect with high efficiency both p+p and heayv-ion collisions

FACILITIES: ATLAS PHASE-II UPGRADE FOR HL-LHC

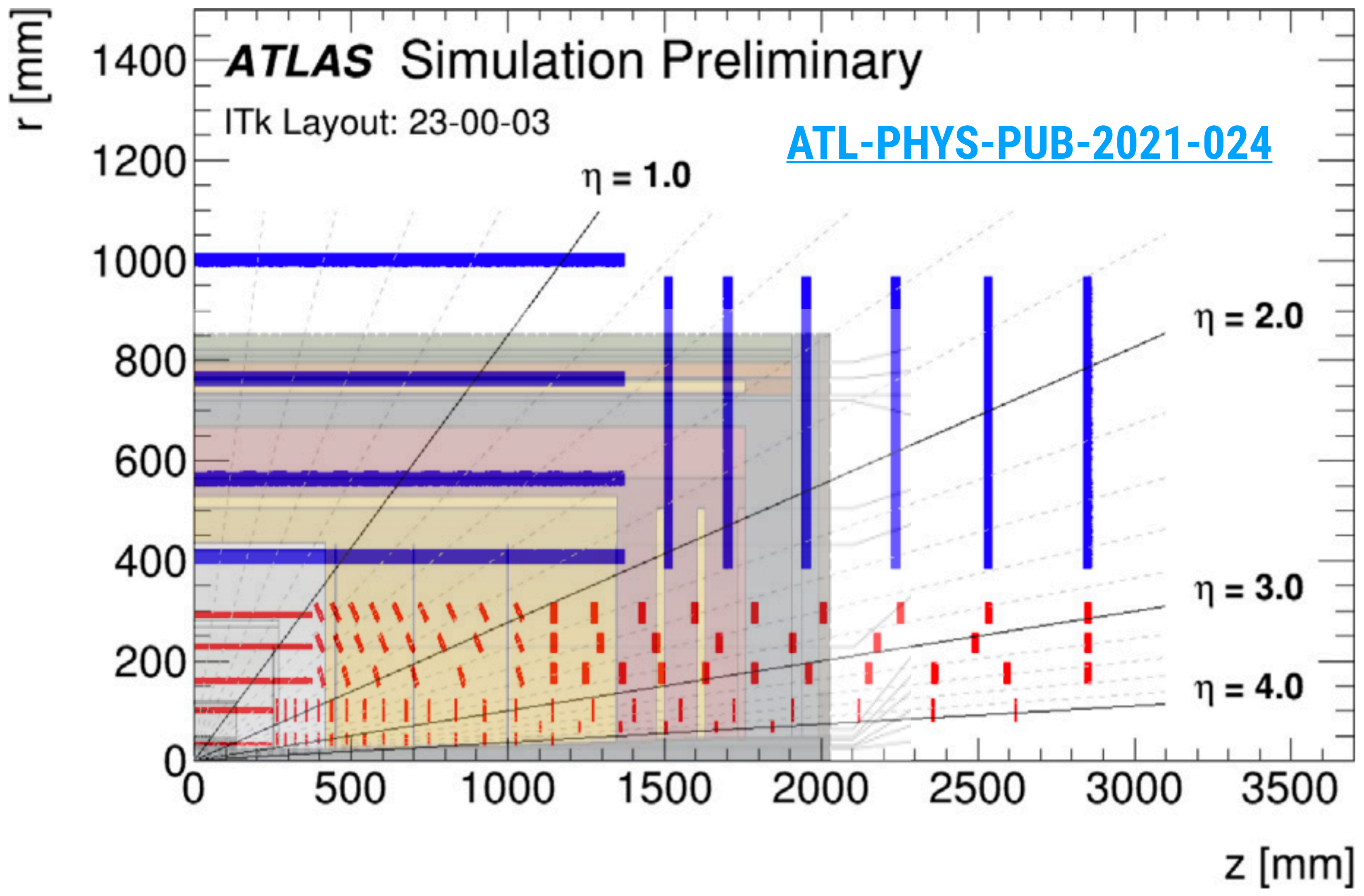
Several Upgrades to get ATLAS ready for the HL era

- **Upgrade of Trigger and DAQ**
- **New Inner Tracking System**
- New HL-ZDC & RPD (Heavy Ion only)
- Upgrade of Muon System
- Upgrade of LUCID (Luminosity)
- New High Granularity Timing Detector
- Upgrade of Calorimeter



Rates	Phase I	Phase II
Trigger input	40 MHz	
L0/L1 trigger	100 kHz	1 MHz
Event Farm	1 kHz	10 kHz

ATLAS ITK upgrade setup (overlaid w/ ePIC tracker, sketch courtesy of P.Steinberg)



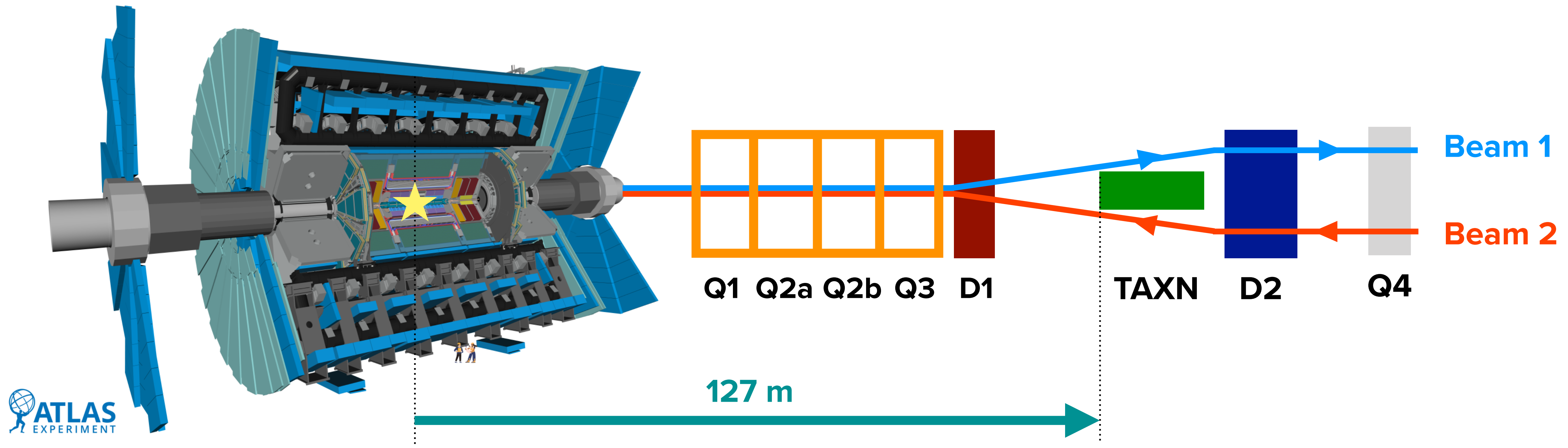
New outstanding tracking coverage (|η| < 4) and trigger capabilities will further boost ATLAS capabilities in detecting and analyzing HI events!

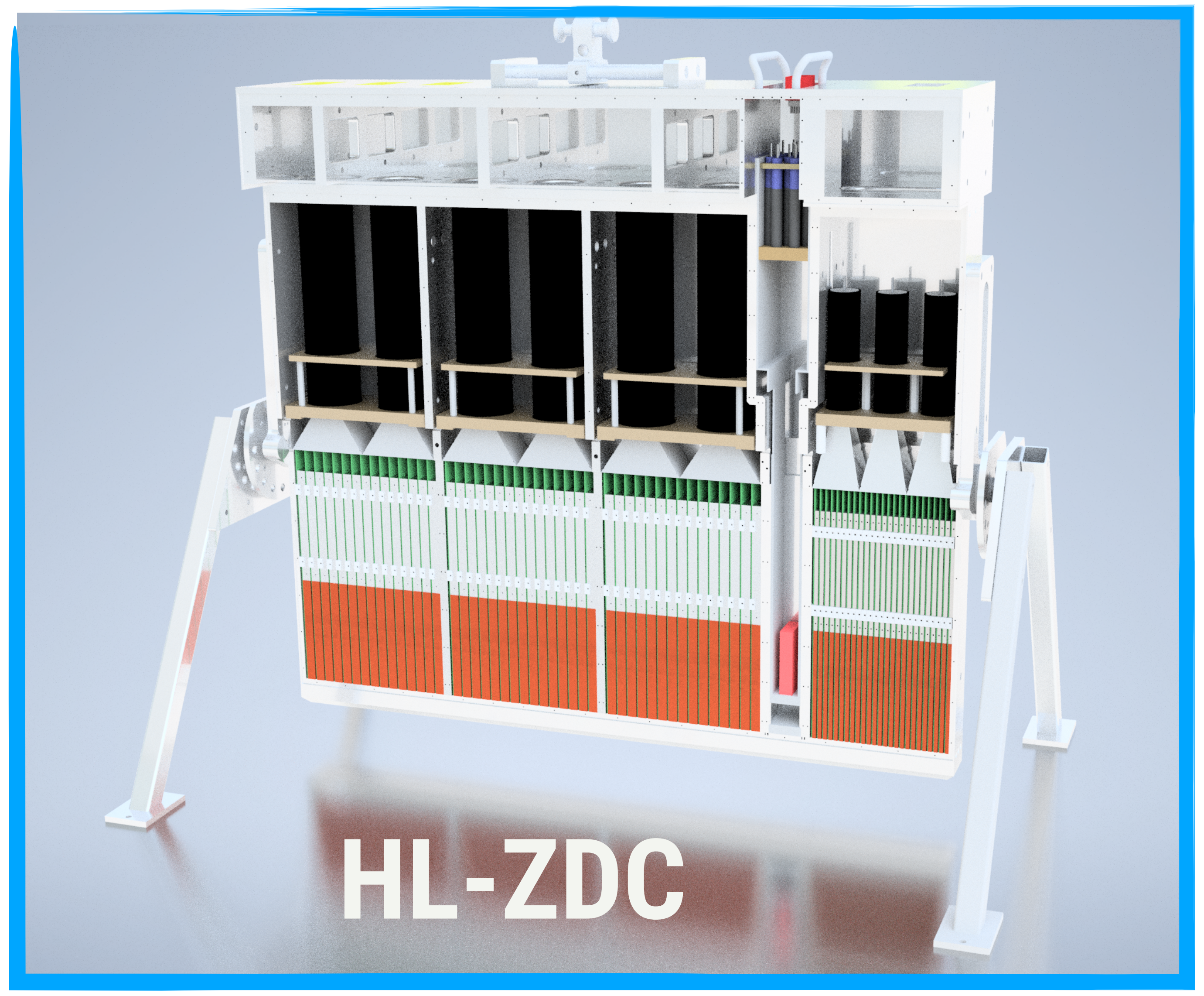
FACILITIES: ATLAS PHASE-II UPGRADE FOR HL-LHC

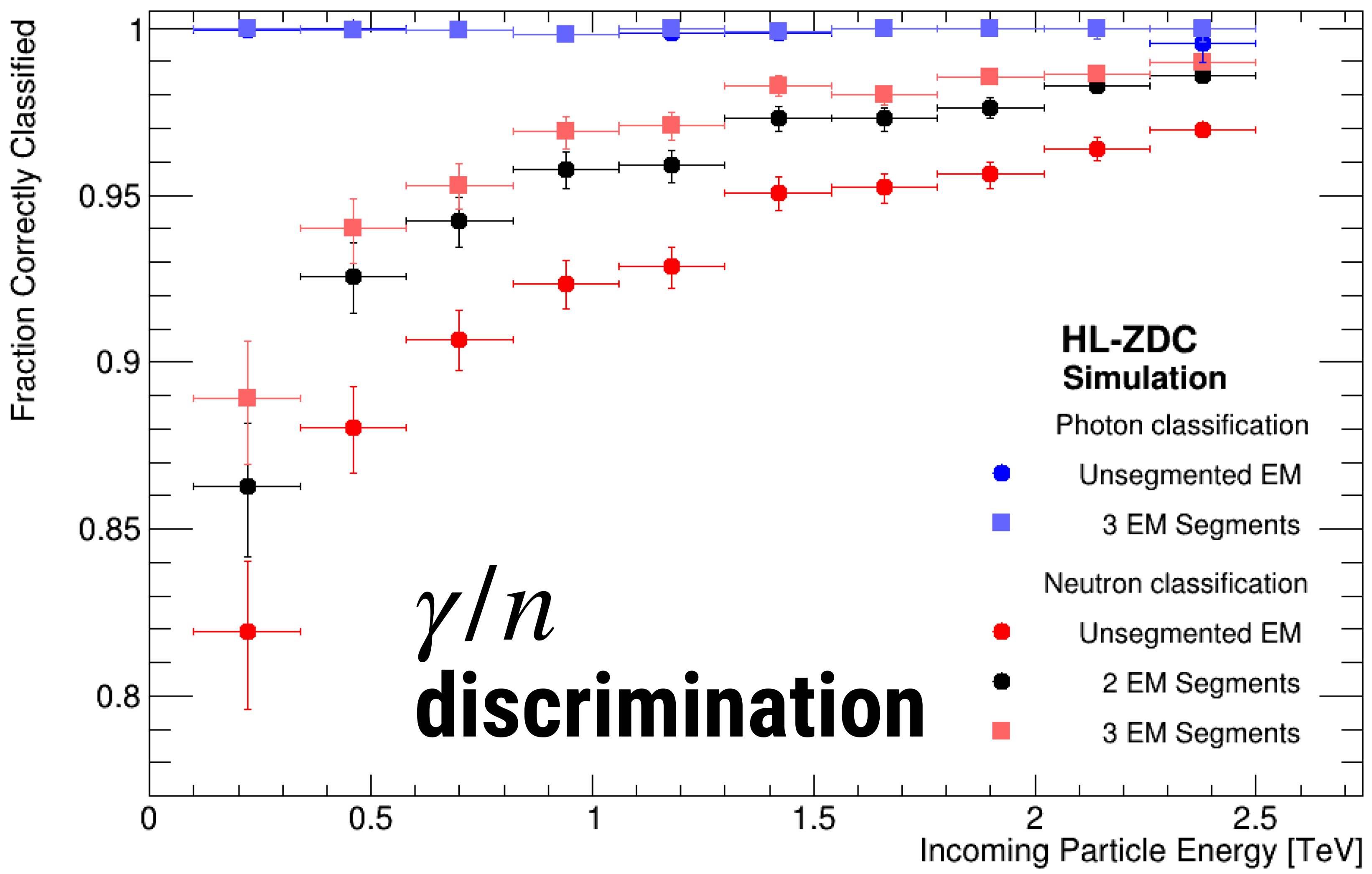
Several Upgrades to get ATLAS ready for the HL era

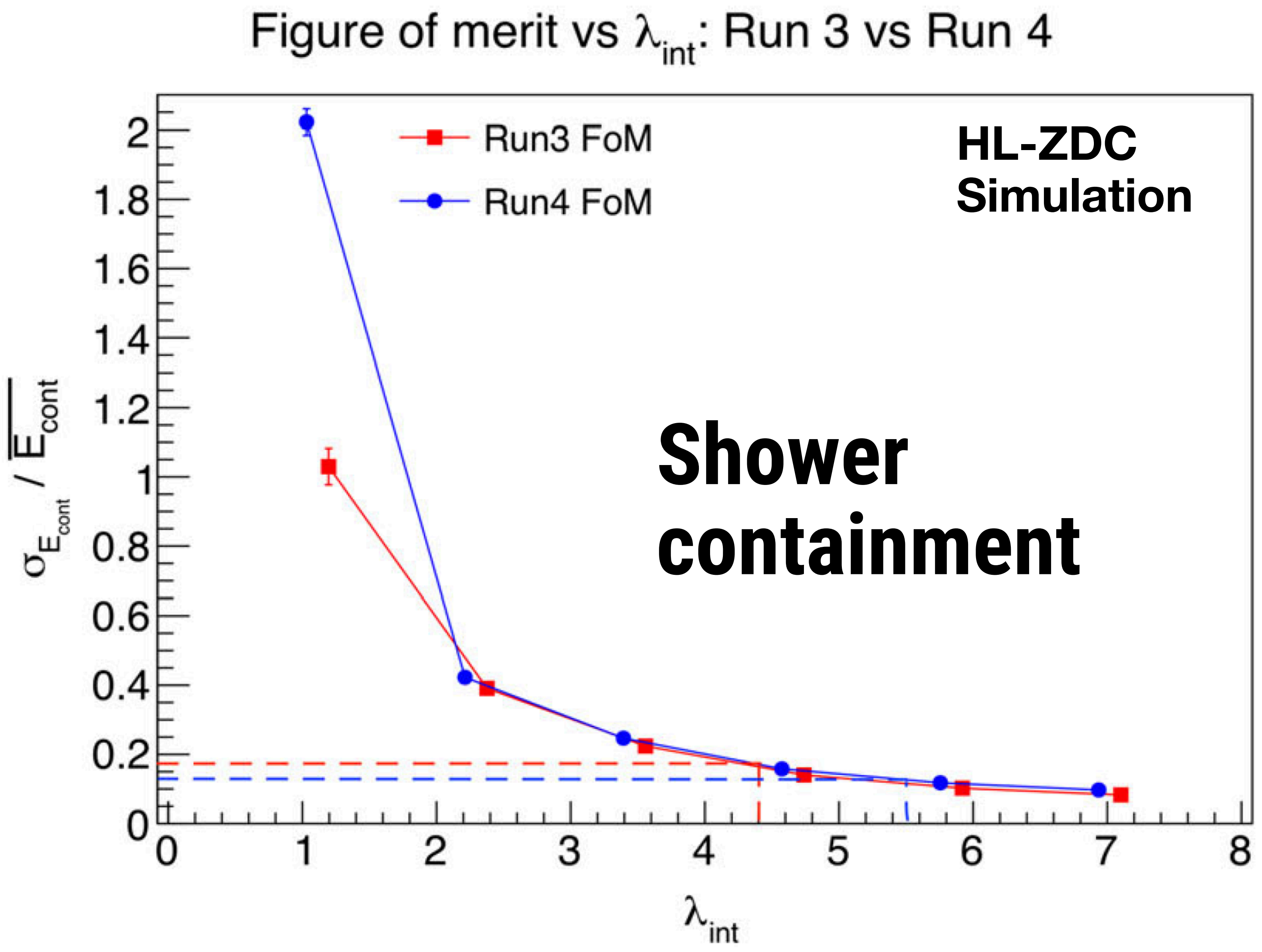
- Upgrade of Trigger and DAQ
- New Inner Tracking System
- **New HL-ZDC & RPD (Heavy Ion only)**
- Upgrade of Muon System
- Upgrade of LUCID (Luminosity)
- New High Granularity Timing Detector
- Upgrade of Calorimeter

1st joint hardware project ATLAS/CMS

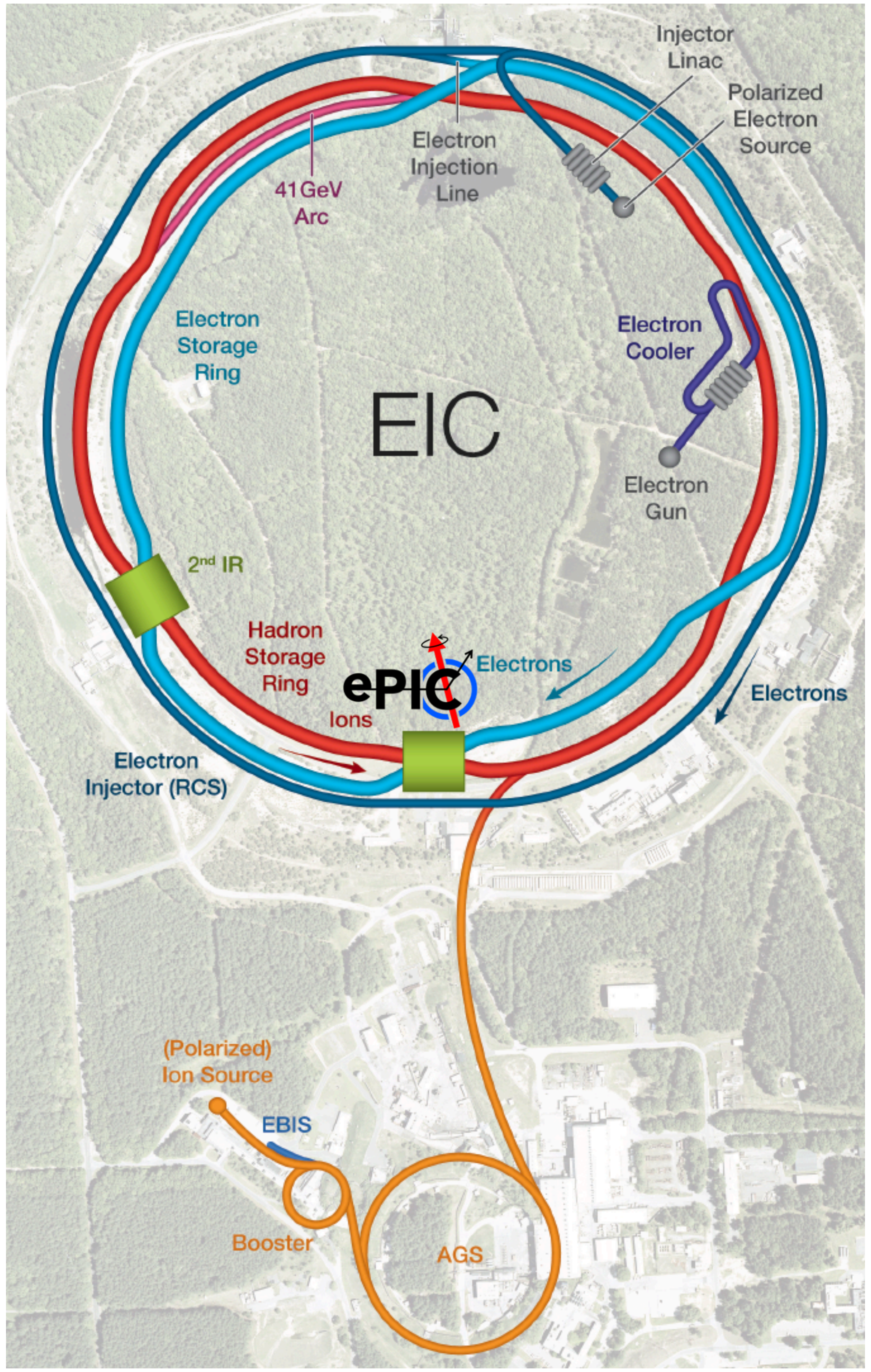








FACILITIES: EIC



EIC: from RHIC to the next generation experiments

- Use existing hadron stage ring energy: 41 - 275 GeV
- Add e- storage ring in RHIC tunnel energy: 5 - 18 GeV

$\sqrt{s} = 29 - 141\ \text{GeV}$

Beam versatility, polarization, high luminisity

- Electron beam combined with different (un)polarized beams
  - $e^- + (p^\uparrow, d^\uparrow, \text{He}^\uparrow,$ unpolarized ions with different $A)$
  - ~70% polarization for polarizable hadron/ion beams
- High luminosity machine:
  - $e^- + p$: $\mathscr{L} = 10^{33-34}\text{cm}^{-2}\text{s}^{-1}, \ L = 10 - 100\,\text{fb}^{-1}/\text{year}$
  - $e^- + A$: $\mathscr{L} = 10^{32}\text{cm}^{-2}\text{s}^{-1}, \ L = 1\,\text{fb}^{-1}/\text{year}$

HL-LHC & EIC: TIMELINES

LHC Long term schedule

YOU ARE HERE

Very dynamic picture.
Don't mark your calendars (yet!)

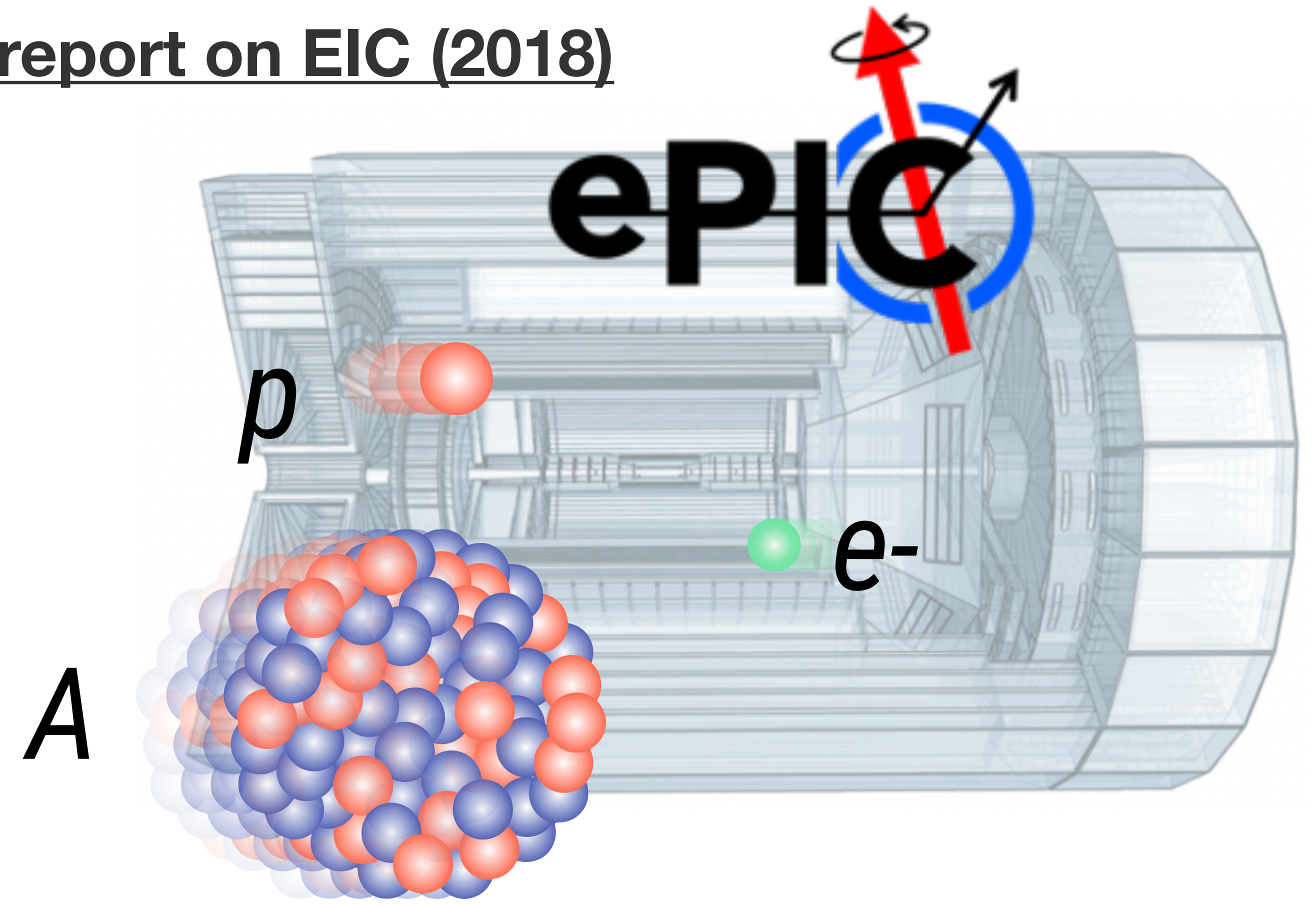
Facility/Year	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034
LHC	LS2		Run 3				HL-LHC Upgrade			Run 4				LS4	
EIC	R&D and Design Phase									Construction & Installation				Commissioning & start of Operations	

Currently, great alternation between EIC and HL-LHC schedule

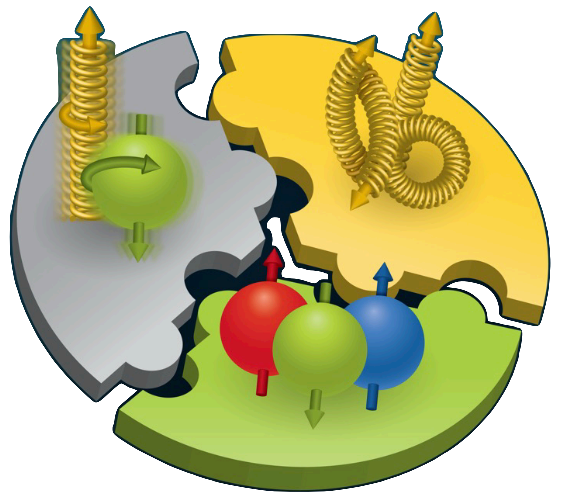
Allows for parallel deployment of scientific effort on both sides to enhance the understanding of the strong force and QCD

EIC MAIN PHYSICS GOALS

NAS report on EIC (2018)

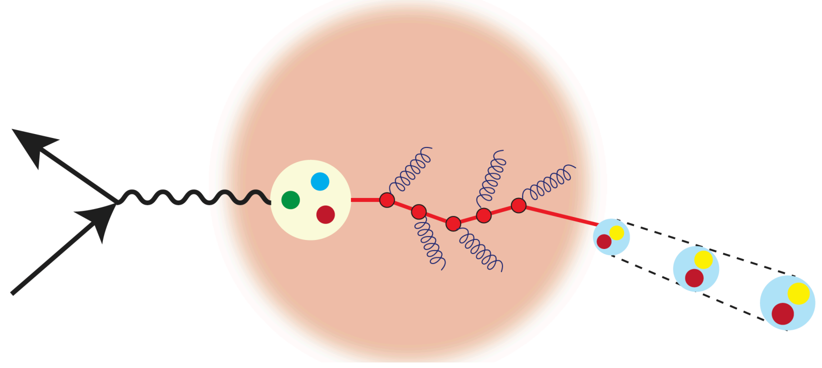


Origin of nucleon spin

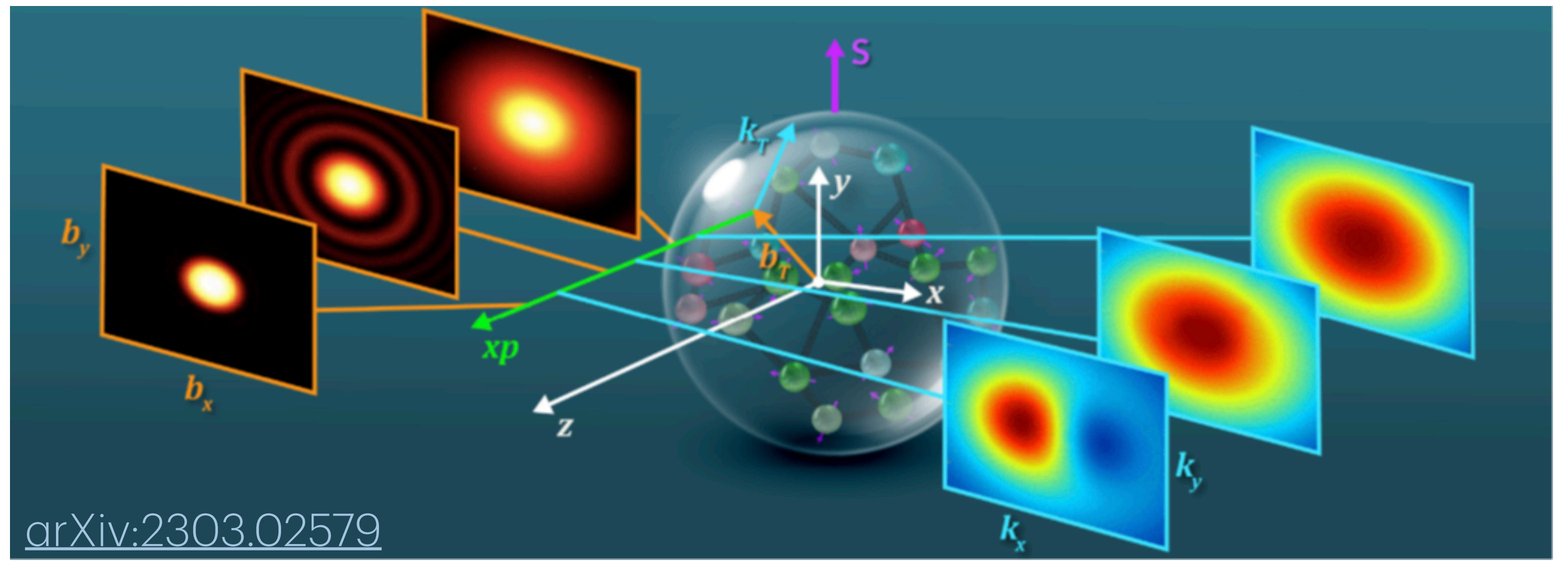


Origin of nucleon mass

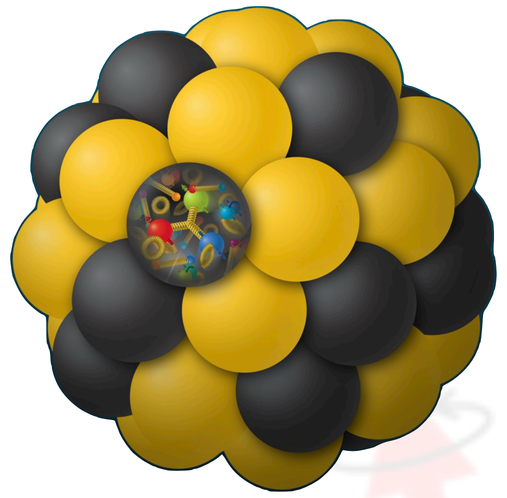
Passage of color charge through cold nuclear matter



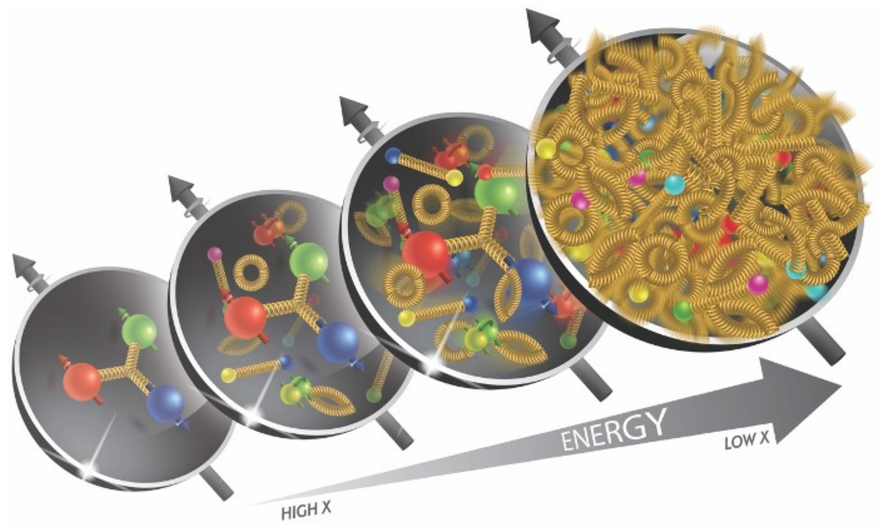
Multi-dimensional imaging of the nucleon in momentum and impact parameter space



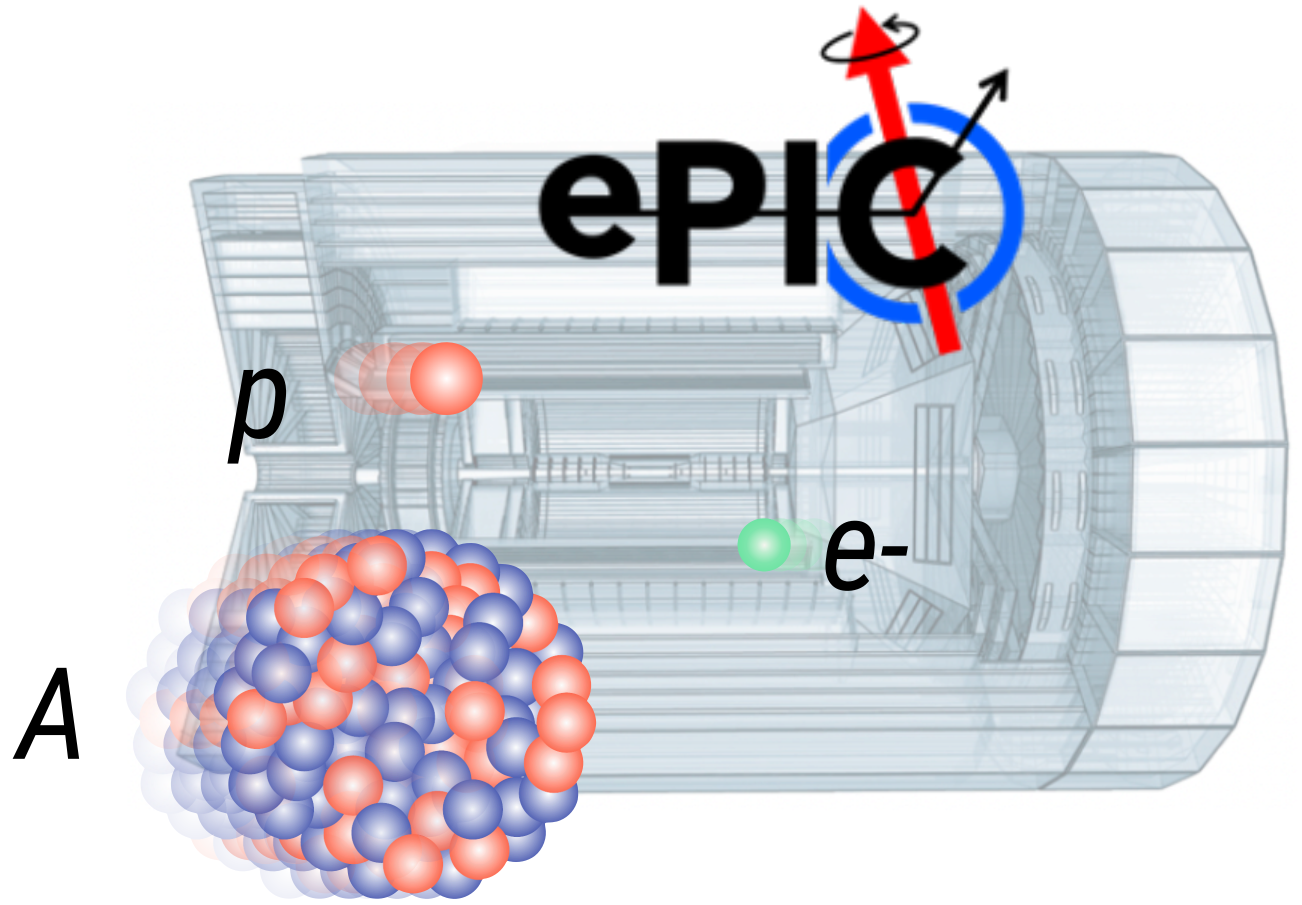
Nuclear modification of parton distribution functions

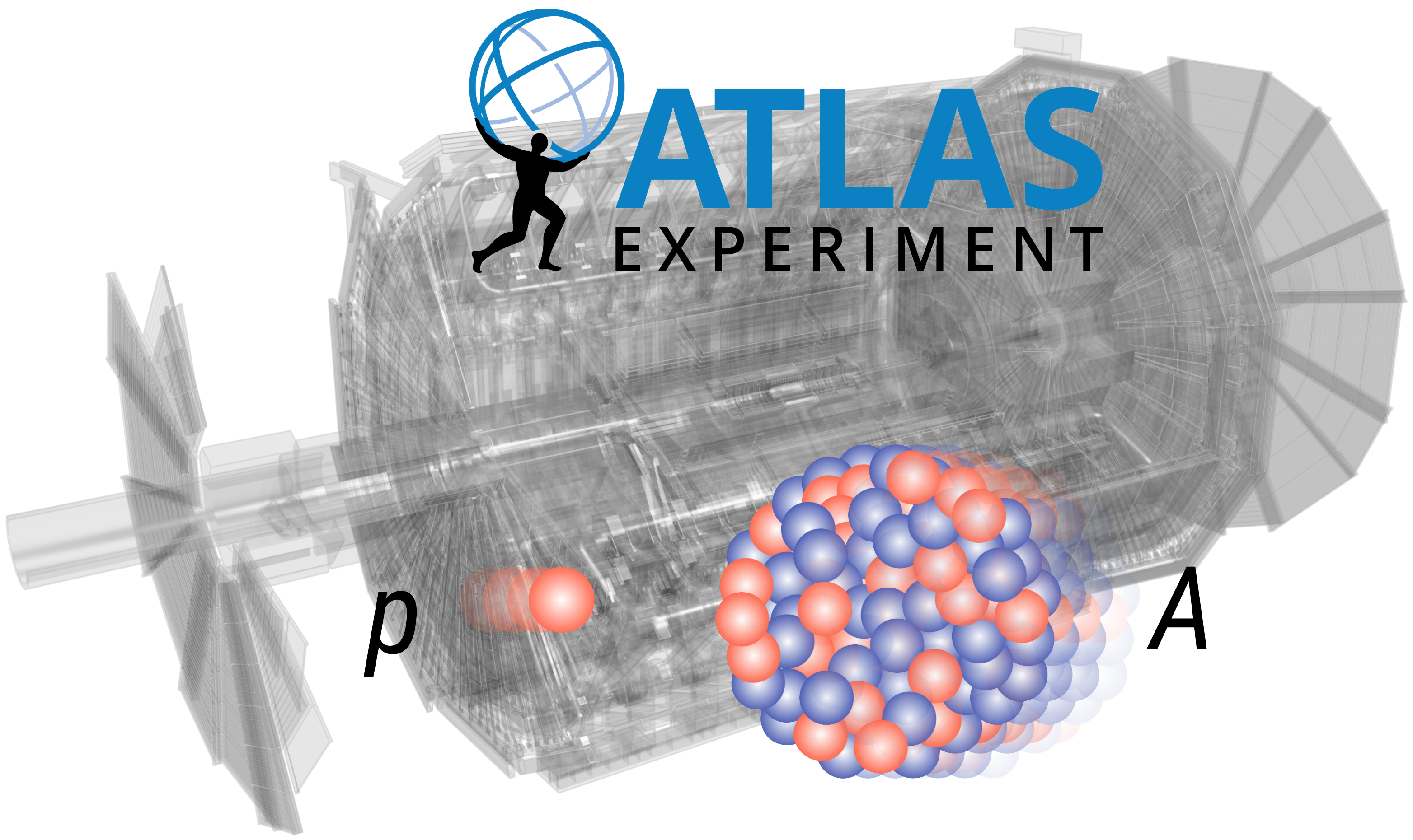


Search for saturation onset

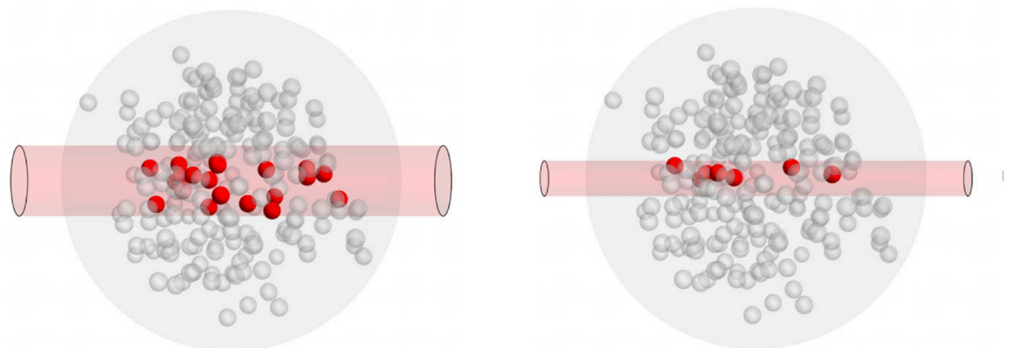


ATLAS & EPIC: PHYSICS SYNERGIES

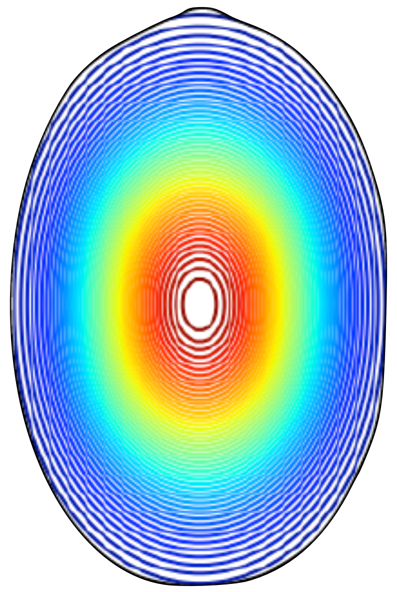




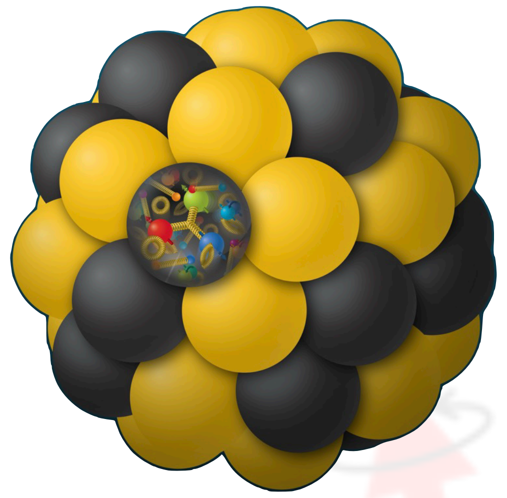
Passage of color charge through cold nuclear matter & color fluctuations



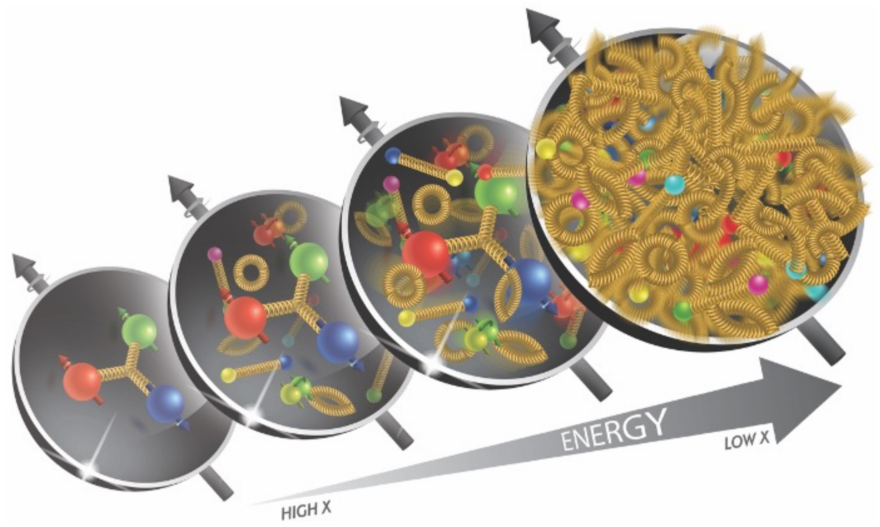
Study of collectivity in small system



Nuclear modification of parton distribution functions

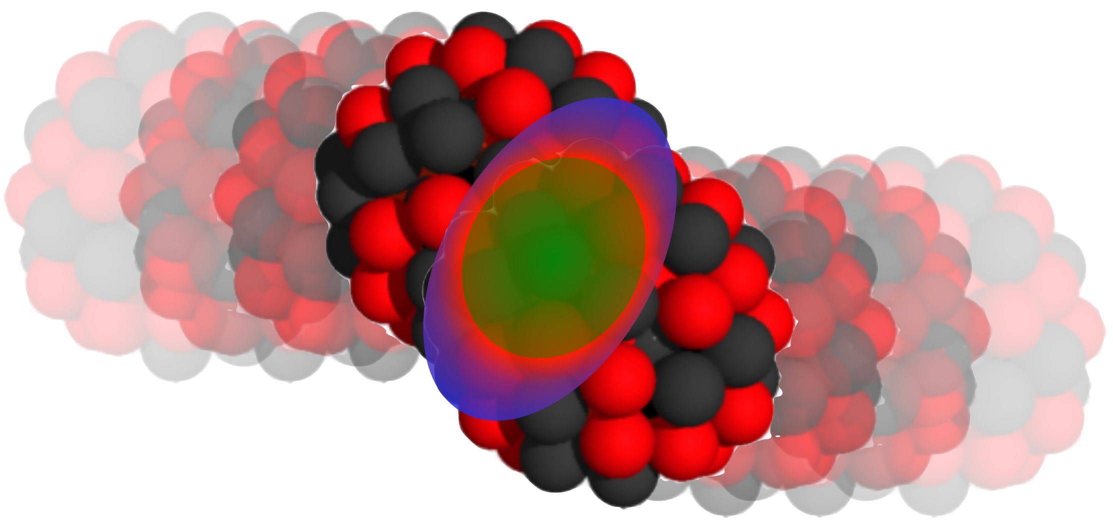


Search for saturation onset



Discoveries in Hot QCD from the LHC

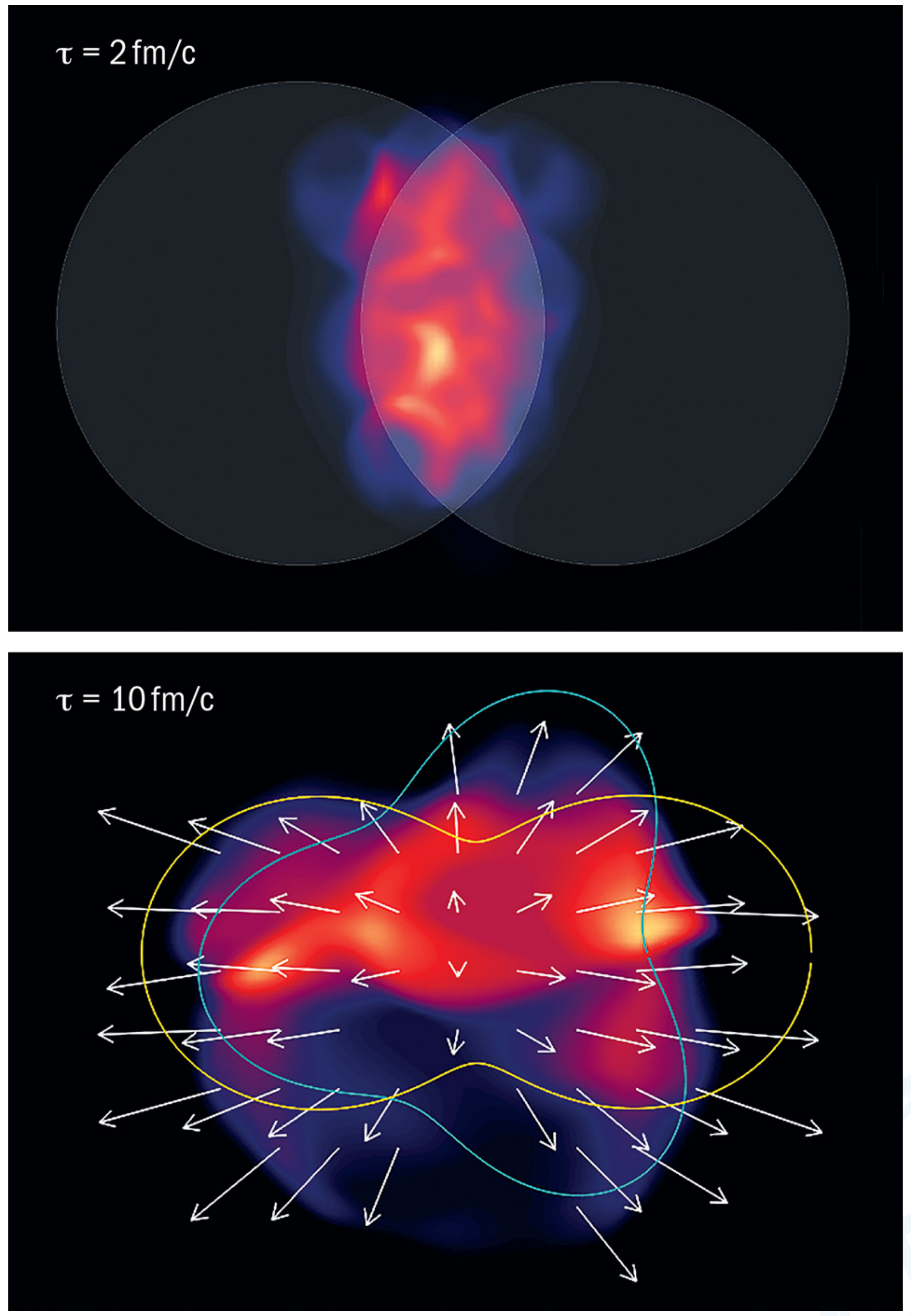
HOT QCD @ ATLAS: QGP SIGNATURES IN A+A



Heavy Ion collisions at multi-TeV scale

- Creation of QGP droplets, observed via different signatures:
  - **Collectivity**
  - Energy Loss

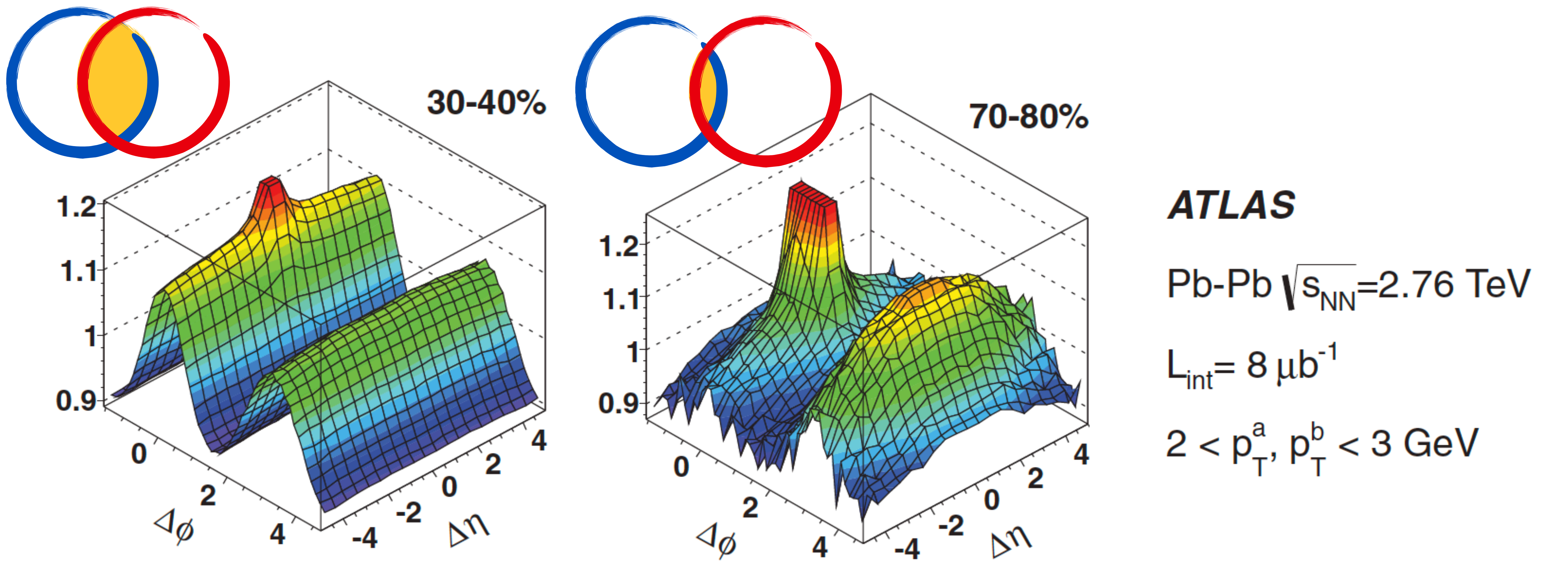
QGP: nearly perfect fluid following hydrodynamic expansion

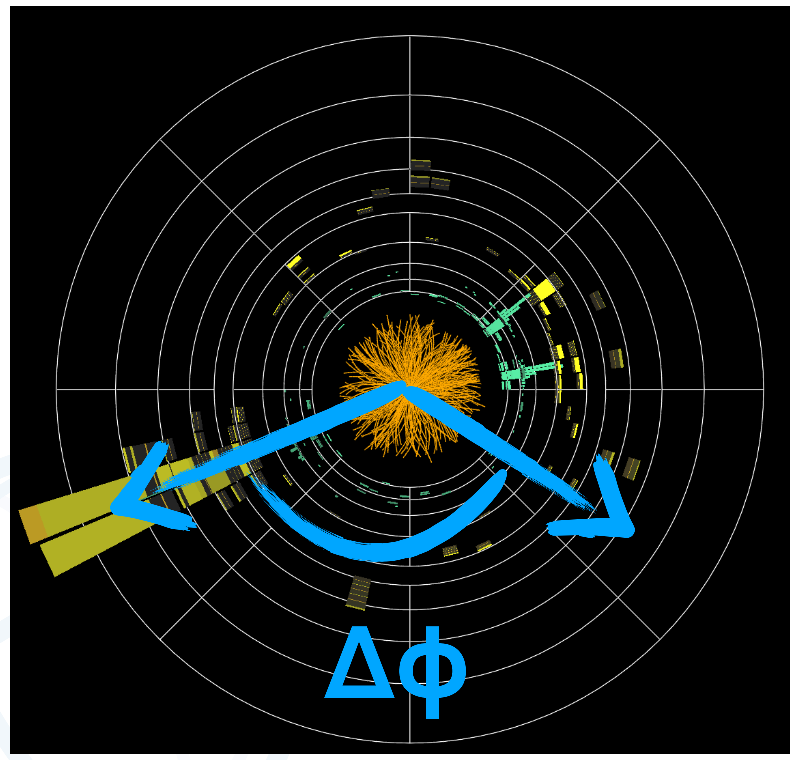


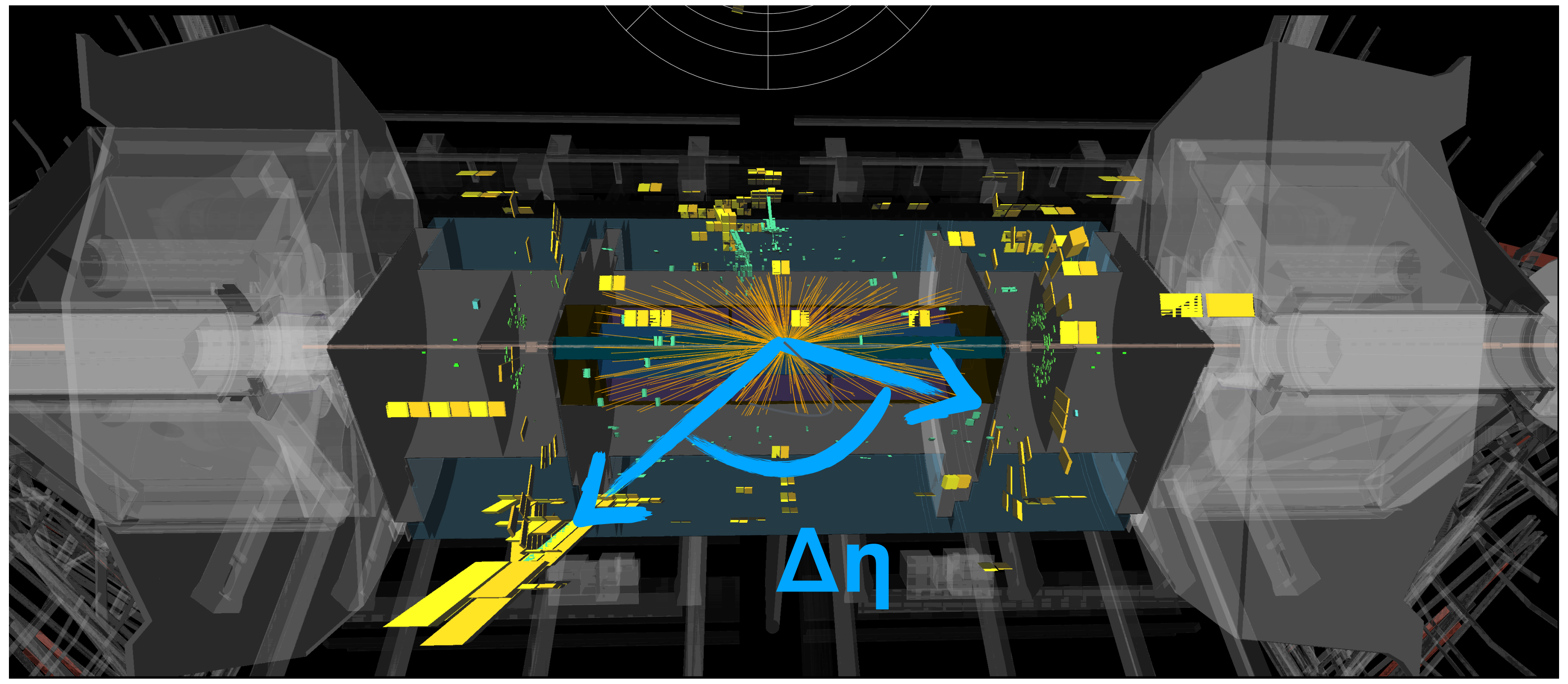
PRL 110, 012302

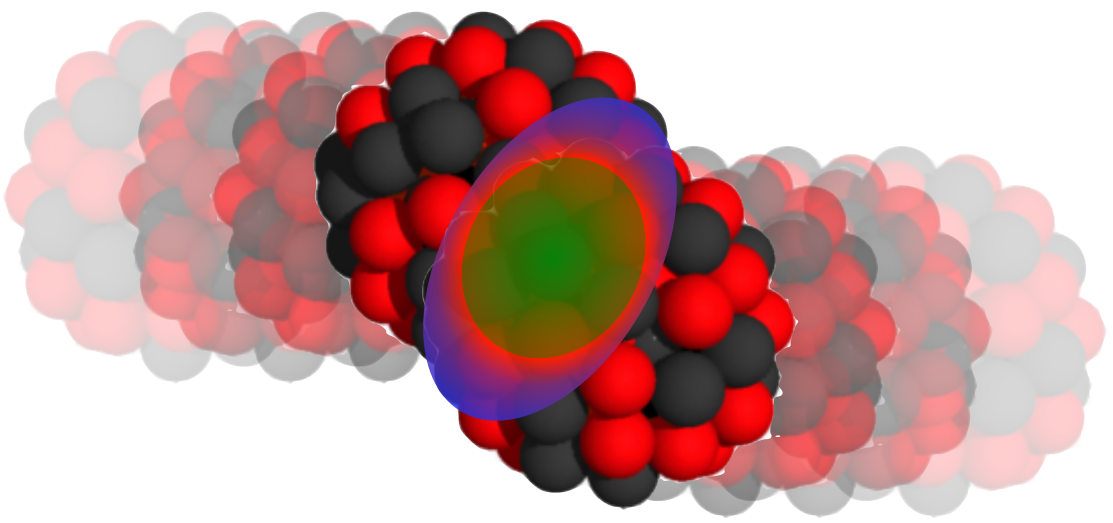
2-particle correlations

To study azimuthal (Δϕ) and longitudinal (Δη) correlations between pairs of particles





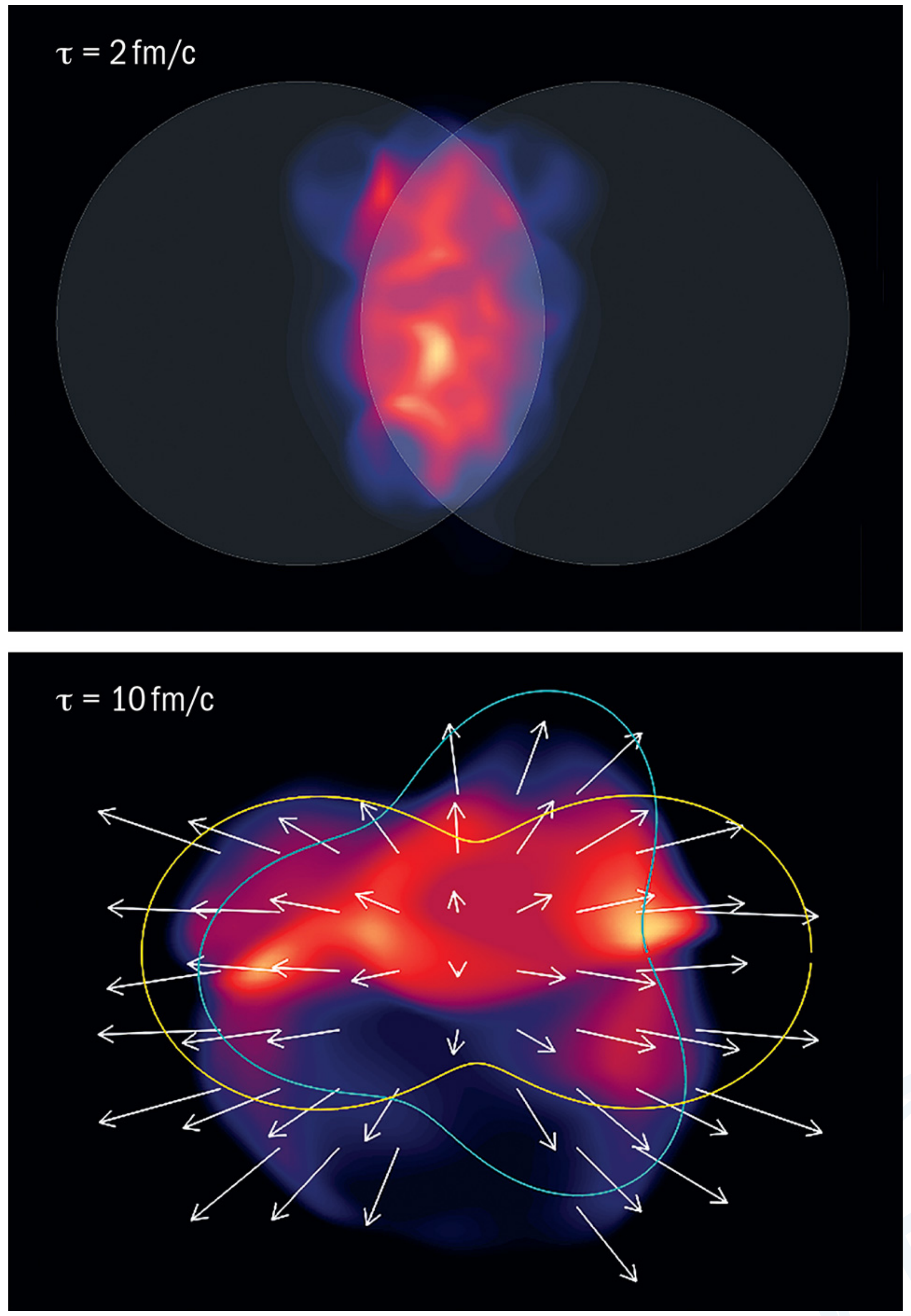




Heavy Ion collisions at multi-TeV scale

- Creation of QGP droplets, observed via different signatures:
  - **Collectivity**
  - Energy Loss

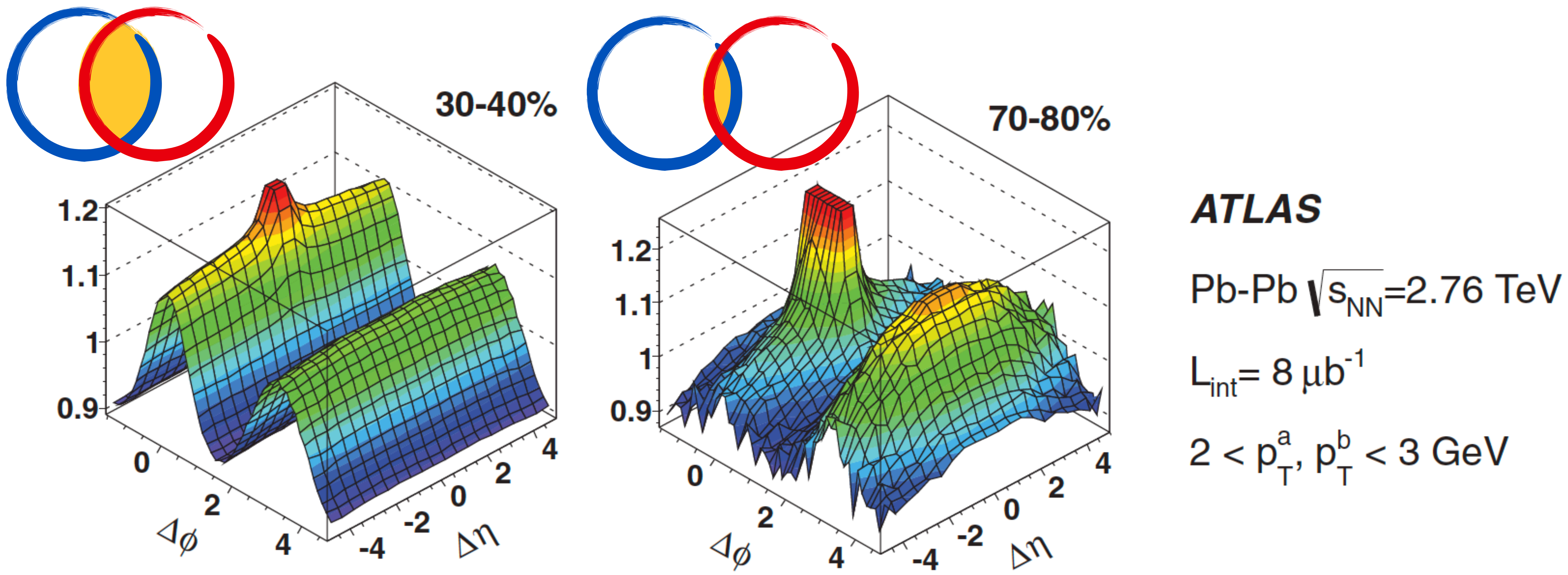
QGP: nearly perfect fluid following hydrodynamic expansion

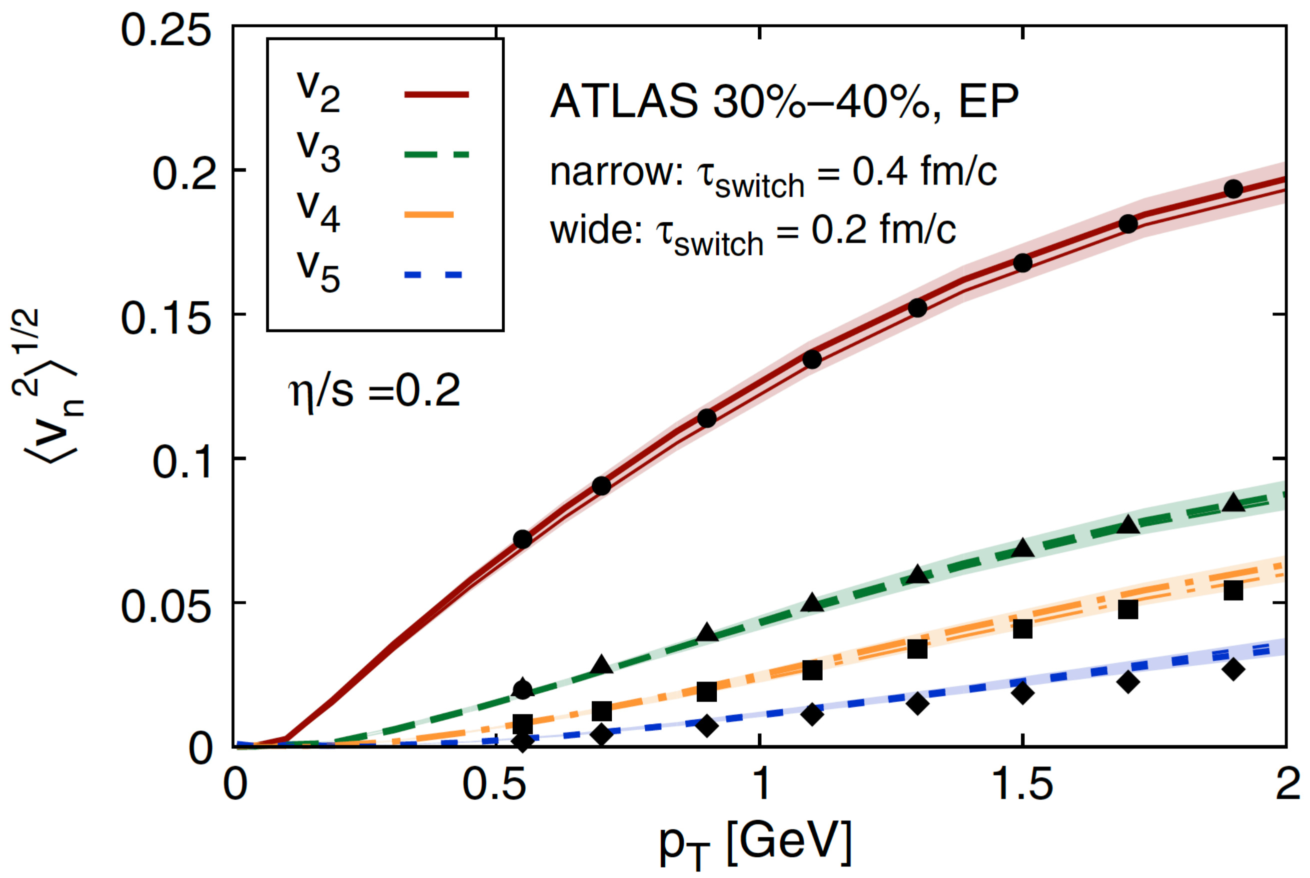


PRL 110, 012302

2-particle correlations

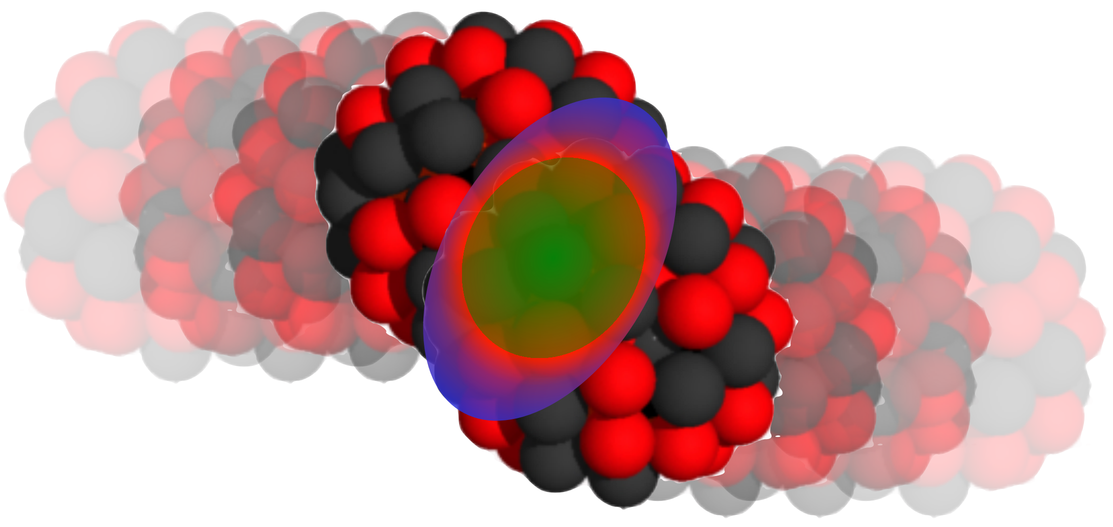
To study azimuthal (Δϕ) and longitudinal (Δη) correlations between pairs of particles





Hydrodynamic calculations well capture the physics observed
PRL 110, 012302 (2013)

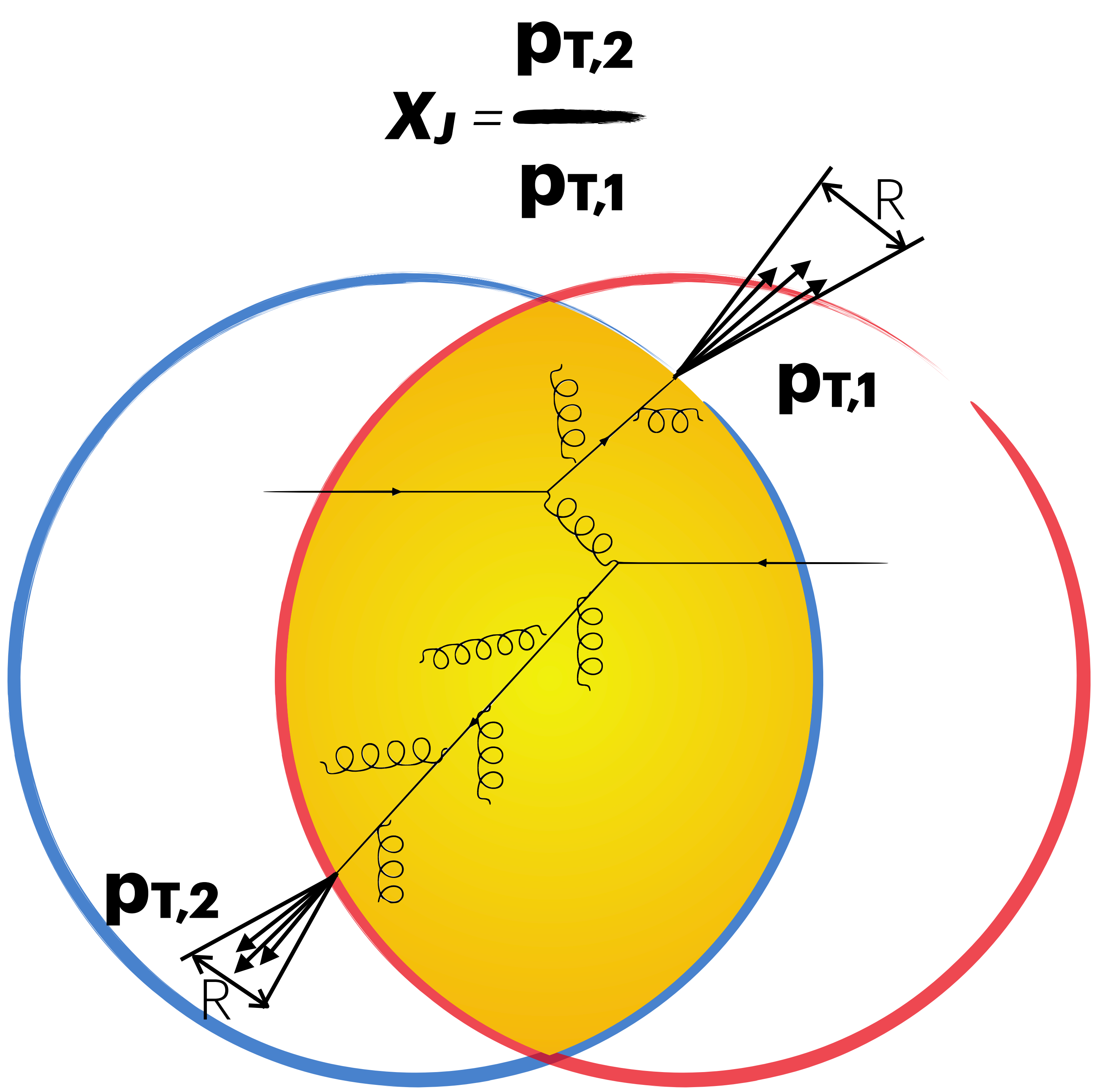
HOT QCD @ ATLAS: QGP SIGNATURES IN A+A

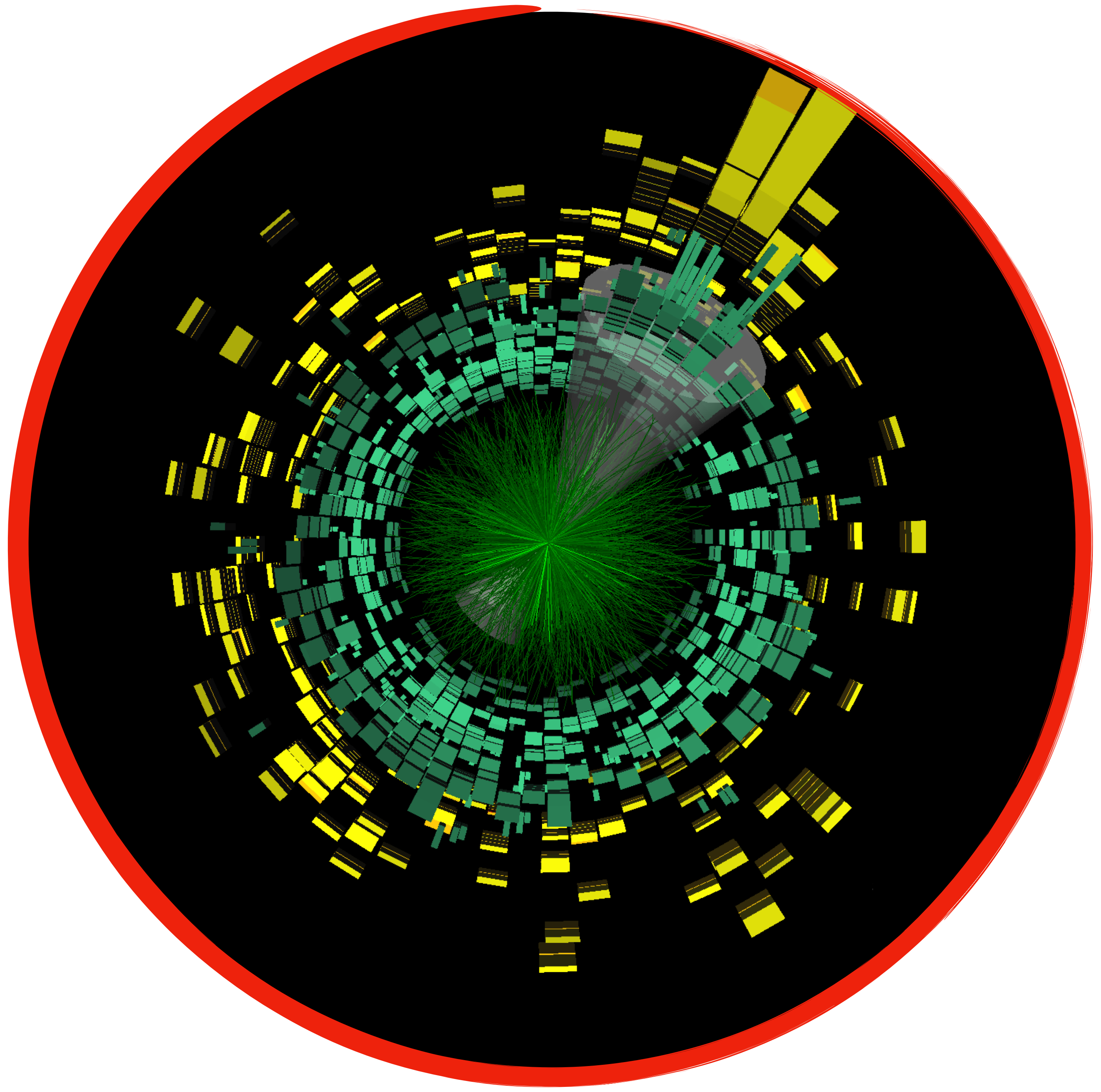


Heavy Ion collisions at multi-TeV scale

- Creation of QGP droplets, observed via different signatures:
  - Collectivity
  - **Energy Loss**

Energy loss of hard scattered partons in the QGP before hadronization





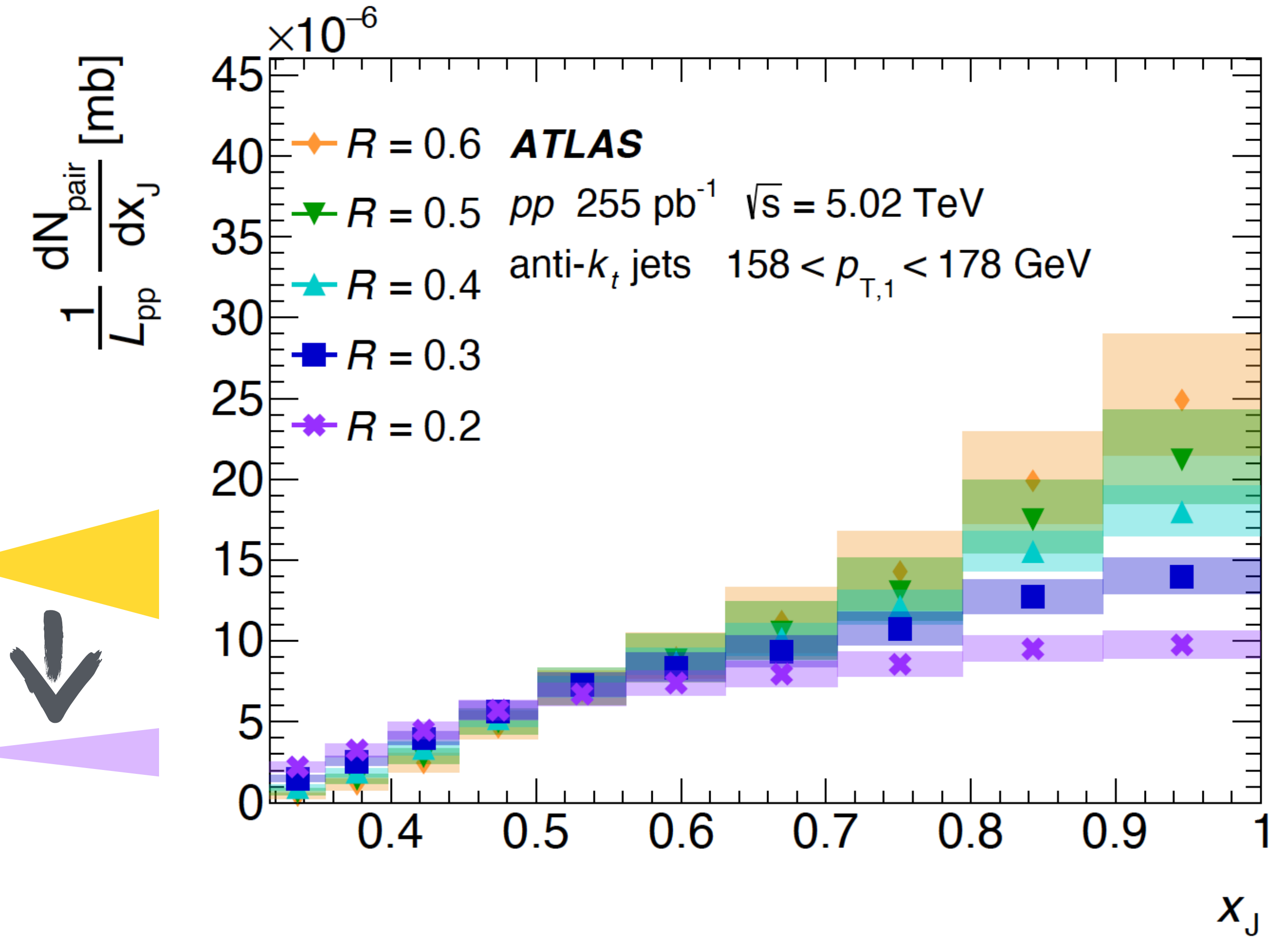
Dijets are ideal probes to experimentally access the path-length dependence of the energy loss

HOT QCD @ ATLAS: QGP SIGNATURES IN A+A

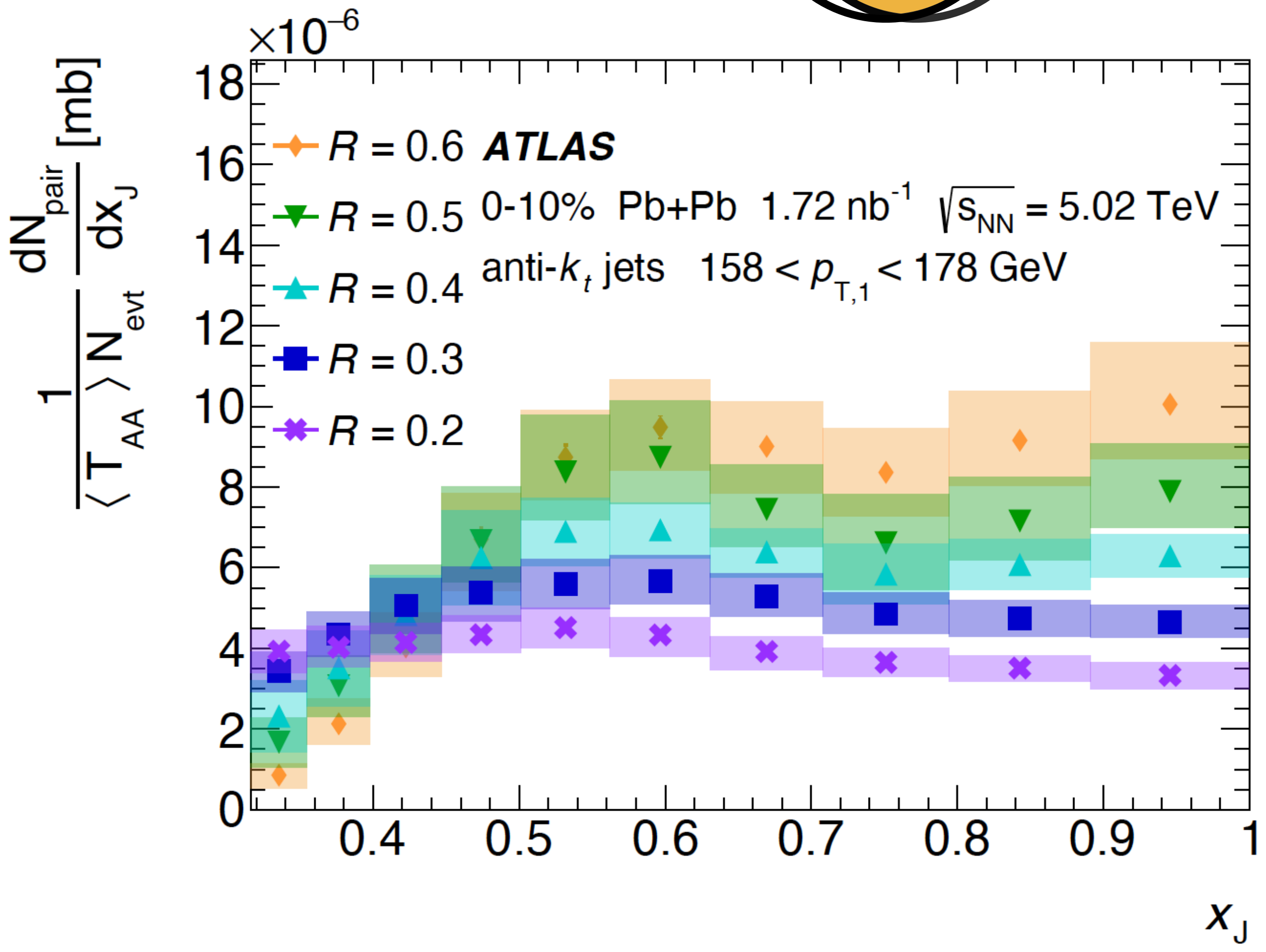
New! arXiv:2407.18796
Extensive characterization of QGP microscopic properties via measurement of dijet asymmetry using jets of different radii

- Creation of QGP droplets, observed via different signatures:
  - Collectivity
  - **Energy Loss**

pp



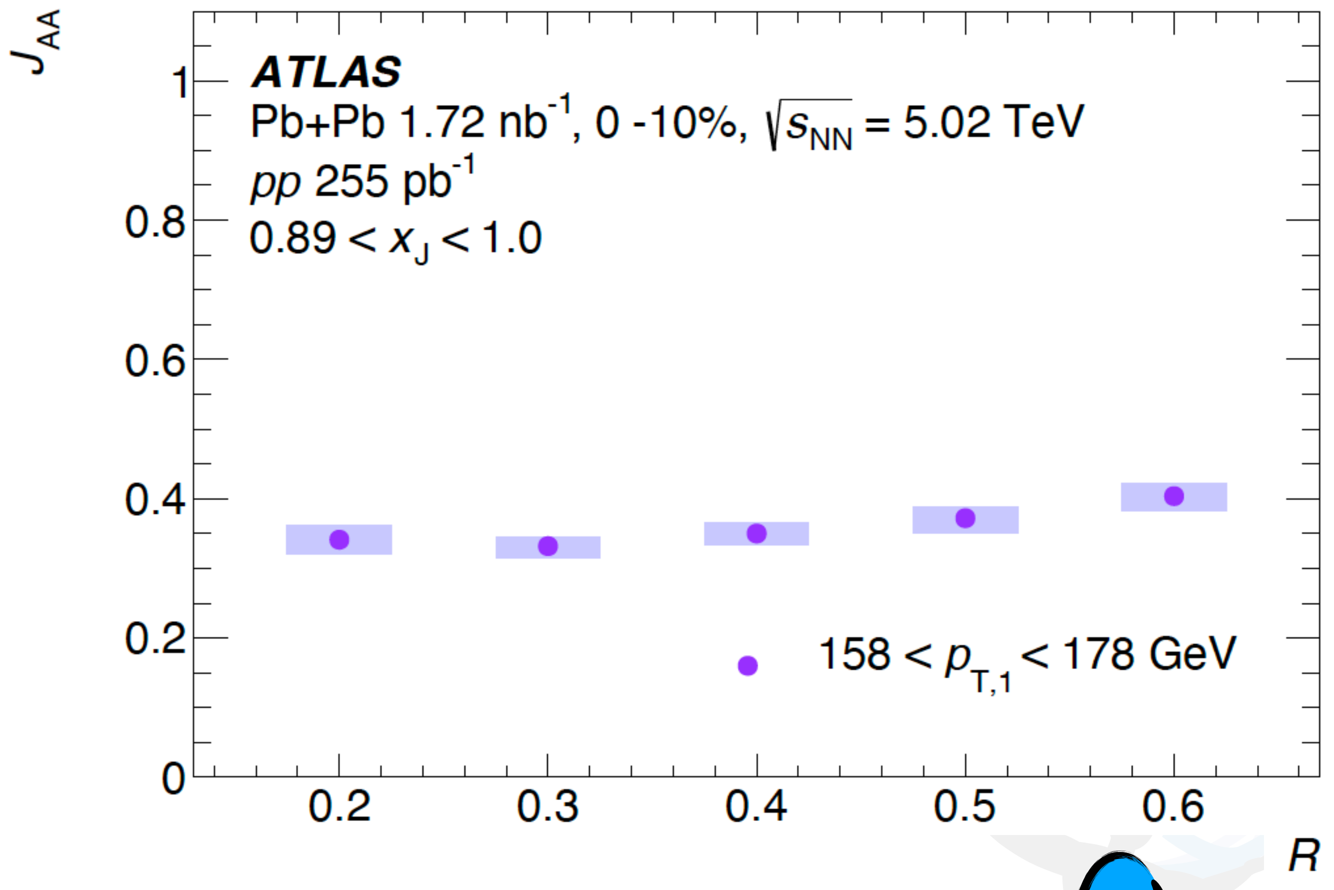
Pb+Pb
0-10%

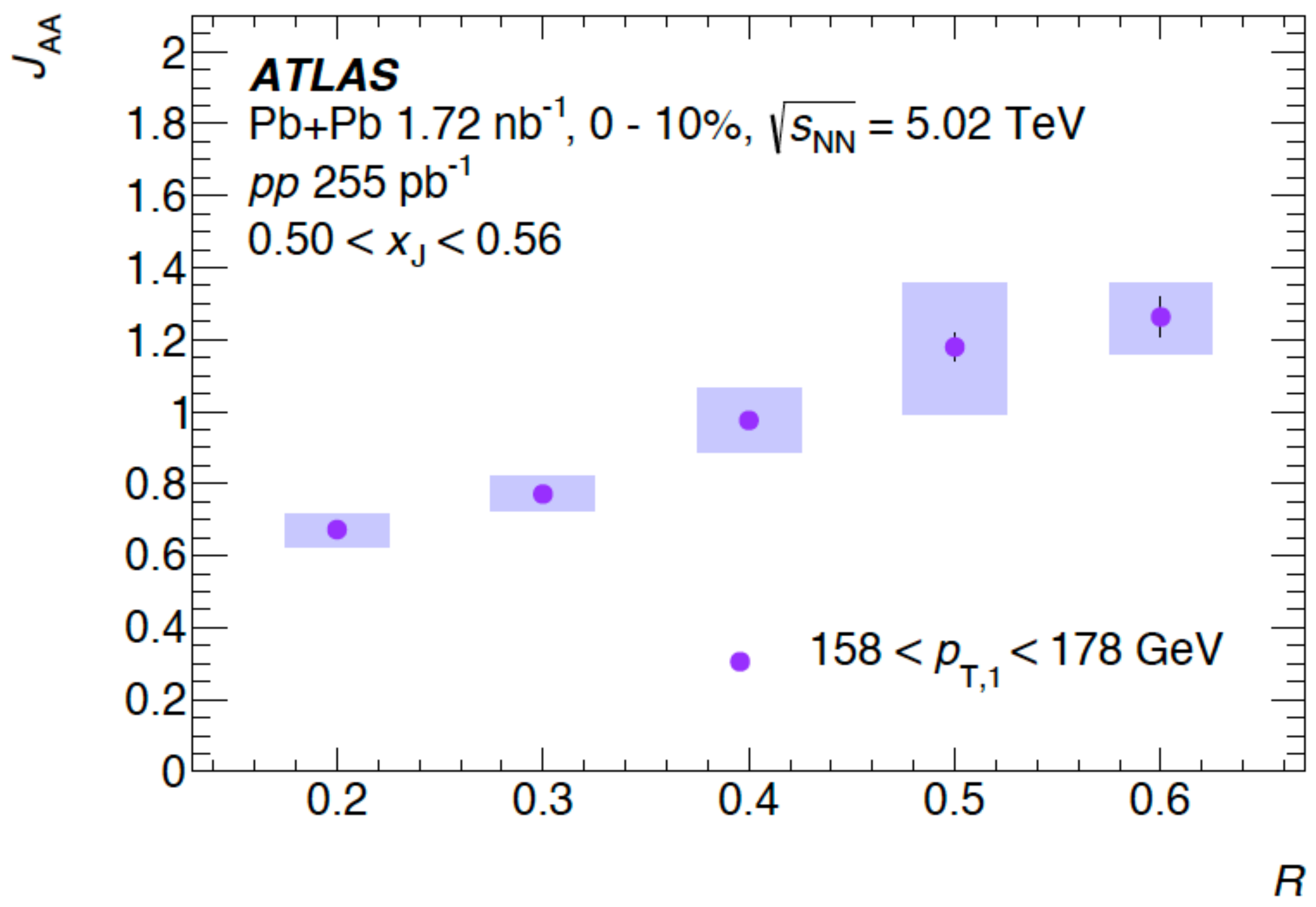


J_{AA} = *Pb+Pb 0-10%* / *pp*

Balanced jets

Unbalanced jets





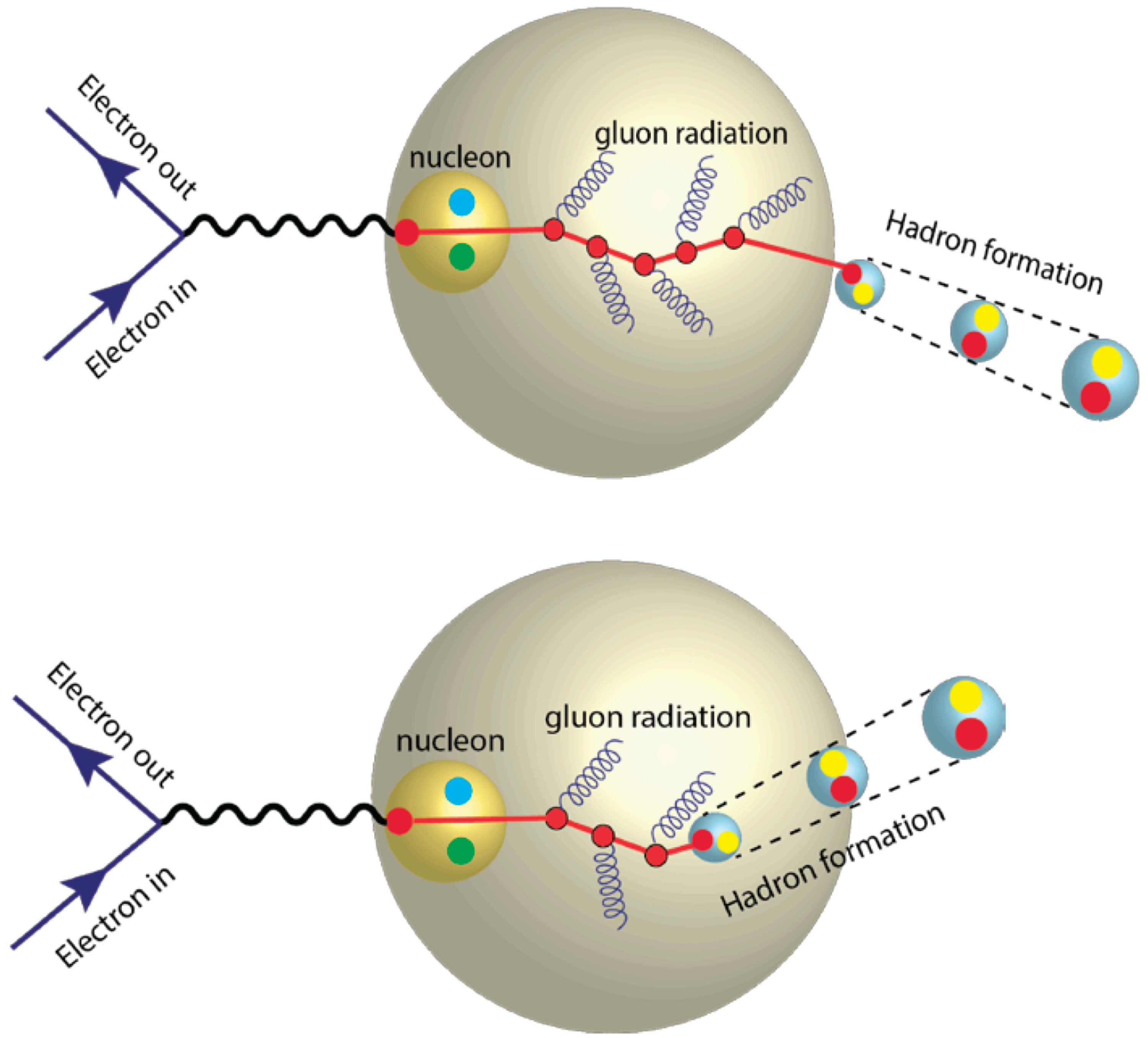
Imbalanced jets are less suppressed for larger radius

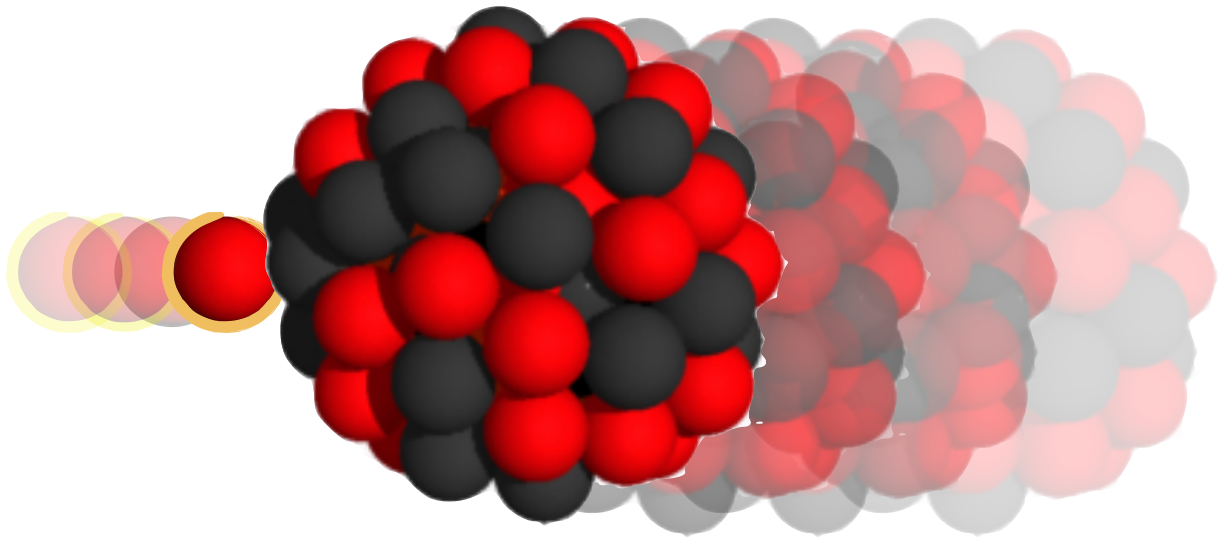
COLD QCD AND NUCLEAR MODIFICATION

COLD NUCLEAR MATTER MODIFICATION IN $p/e^{-} + A$

To understand the microscopic behavior of the QGP requires also a comprehensive understanding of the initial state

NAS report on EIC (2018)





The EIC will have the unique opportunity to study hadronization by varying the virtual photon energy and selecting different hadronization regimes (in or out nucleus)

p+A collisions @ LHC provide experimental access to study nuclear matter effects

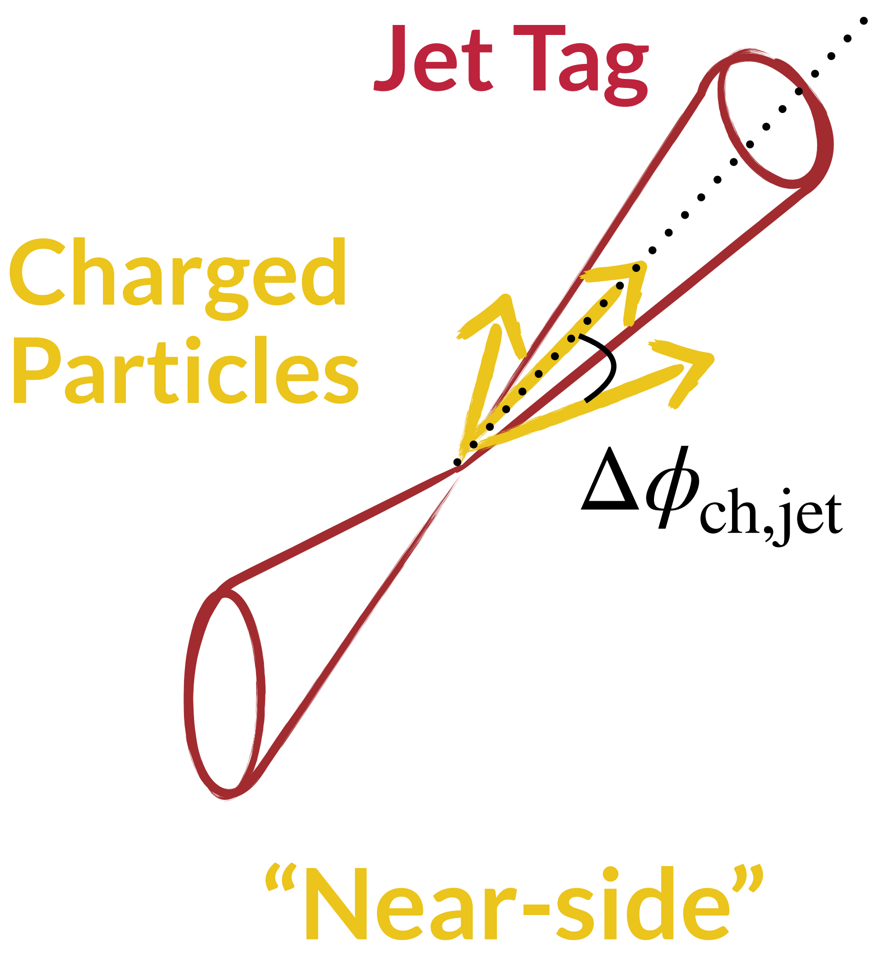
➡ Search for QGP-signatures (**Hot**)

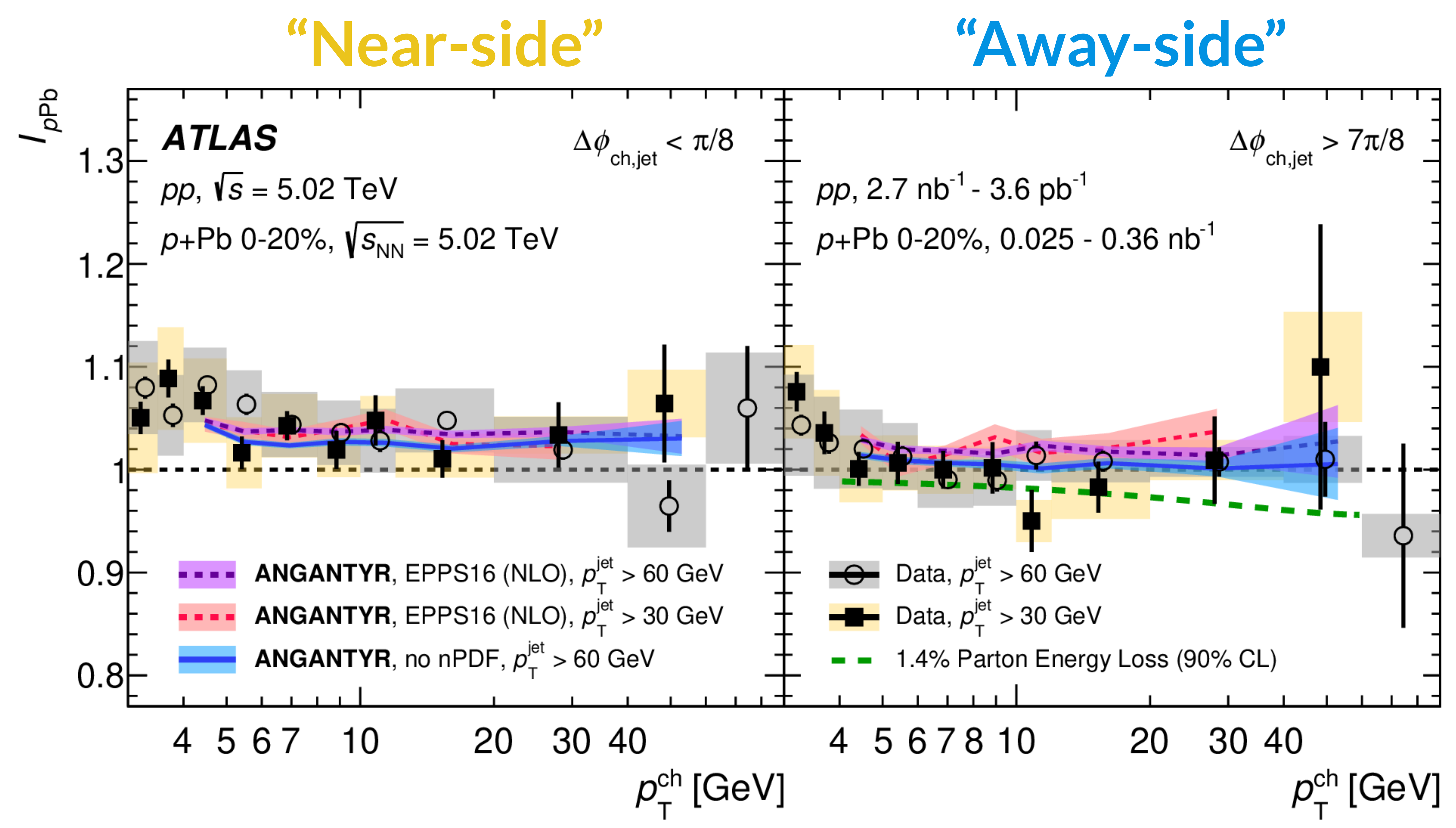
➡ Investigation of **Cold** nuclear matter effects

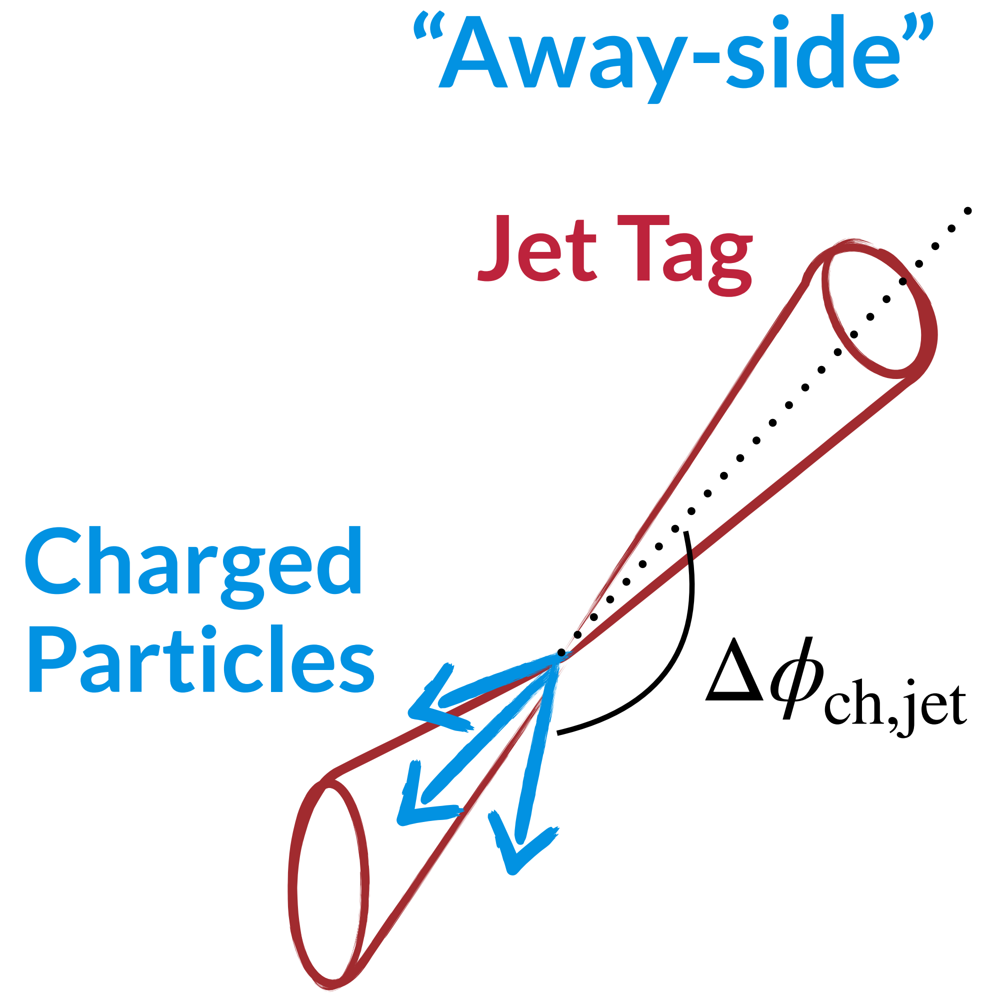
QGP-LIKE SIGNATURE: ENERGY LOSS ?

Phys. Rev. Lett. 131 (2023) 072301

$$I_{p\mathrm{Pb}} = \left(\frac{1}{N_{\mathrm{jet}}}\frac{dN_{\mathrm{ch}}}{dp_{\mathrm{T}}^{\mathrm{Ch}}}\right)_{p+Pb} \Big/ \left(\frac{1}{N_{\mathrm{jet}}}\frac{dN_{\mathrm{ch}}}{dp_{\mathrm{T}}^{\mathrm{Ch}}}\right)_{p+p}$$







Comparison to Angantyr:

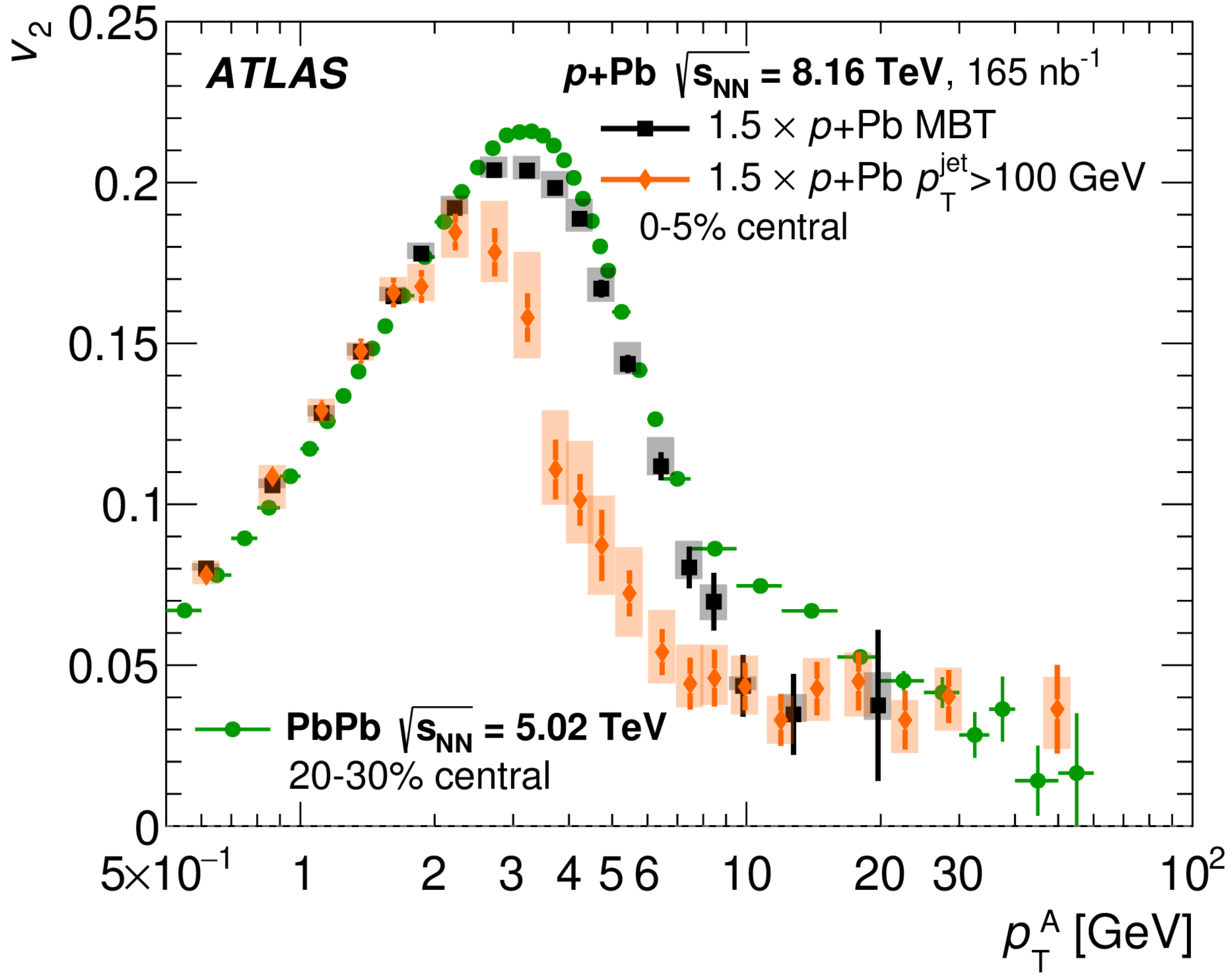
- No final state interactions - e.g. no jet quenching
- Consistent with data on both sides - no large effect from nPDFs

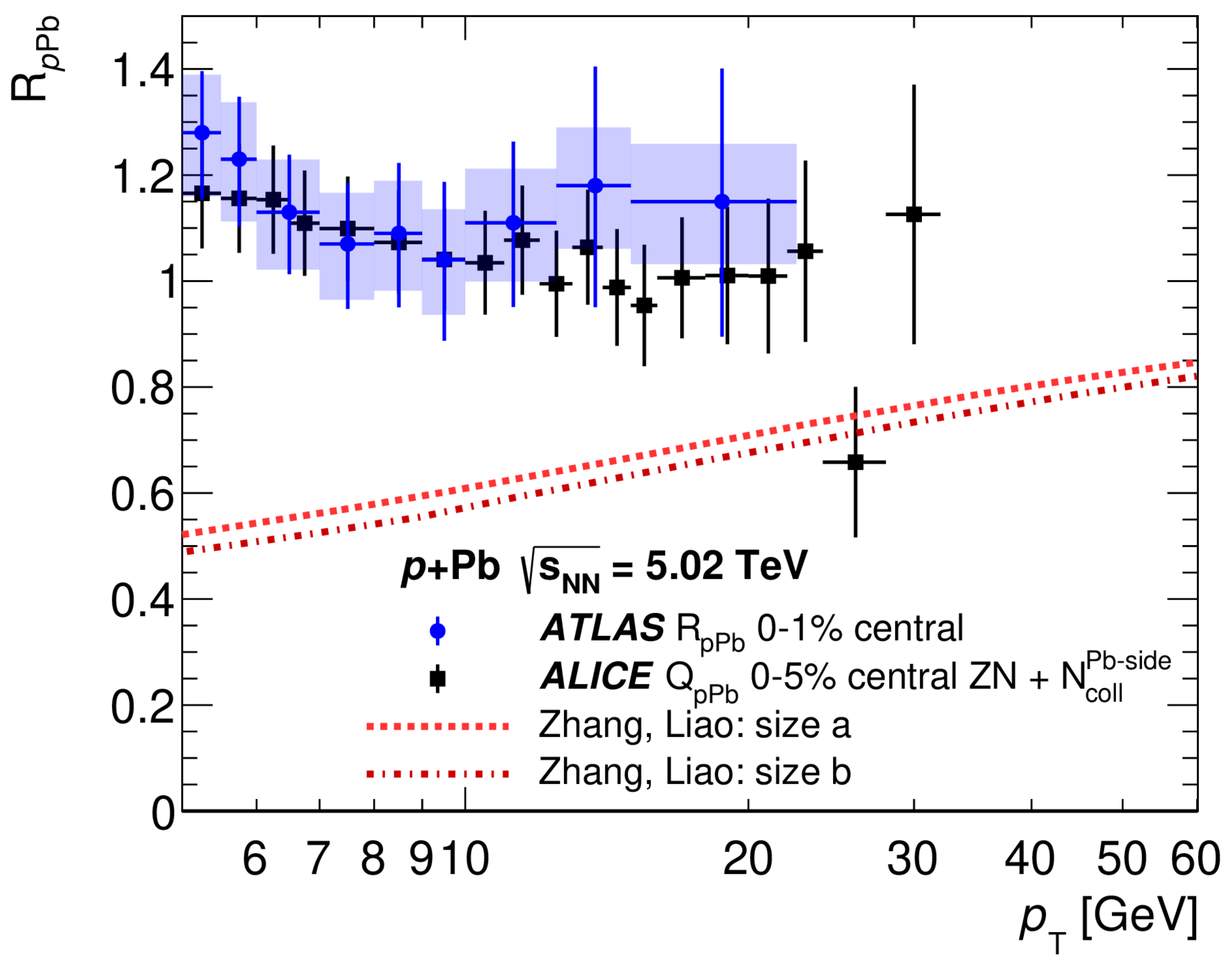
No evidence of **Jet quenching** in $I_{p\mathrm{Pb}}$ observable

Parton energy loss constraint: 0.2 ± 0.5% and < 1.4% at 90% confidence level

HIGH PT PUZZLE: NO ENERGY LOSS BUT COLLECTIVITY

Eur. Phys. J. C 80 (2020) 73

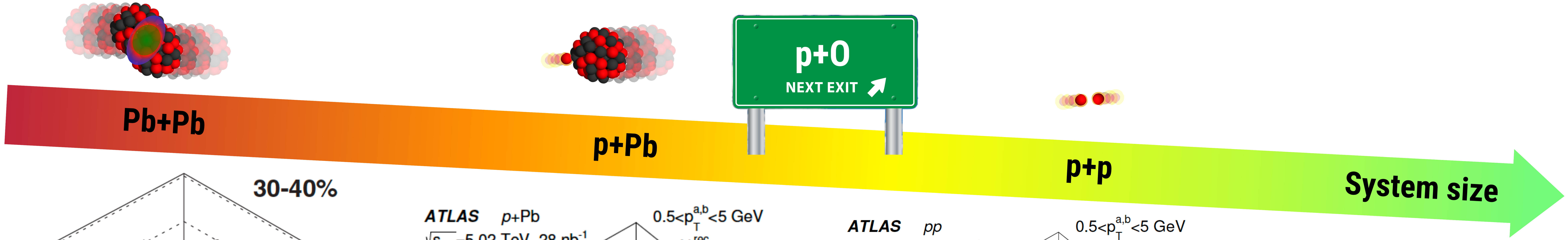


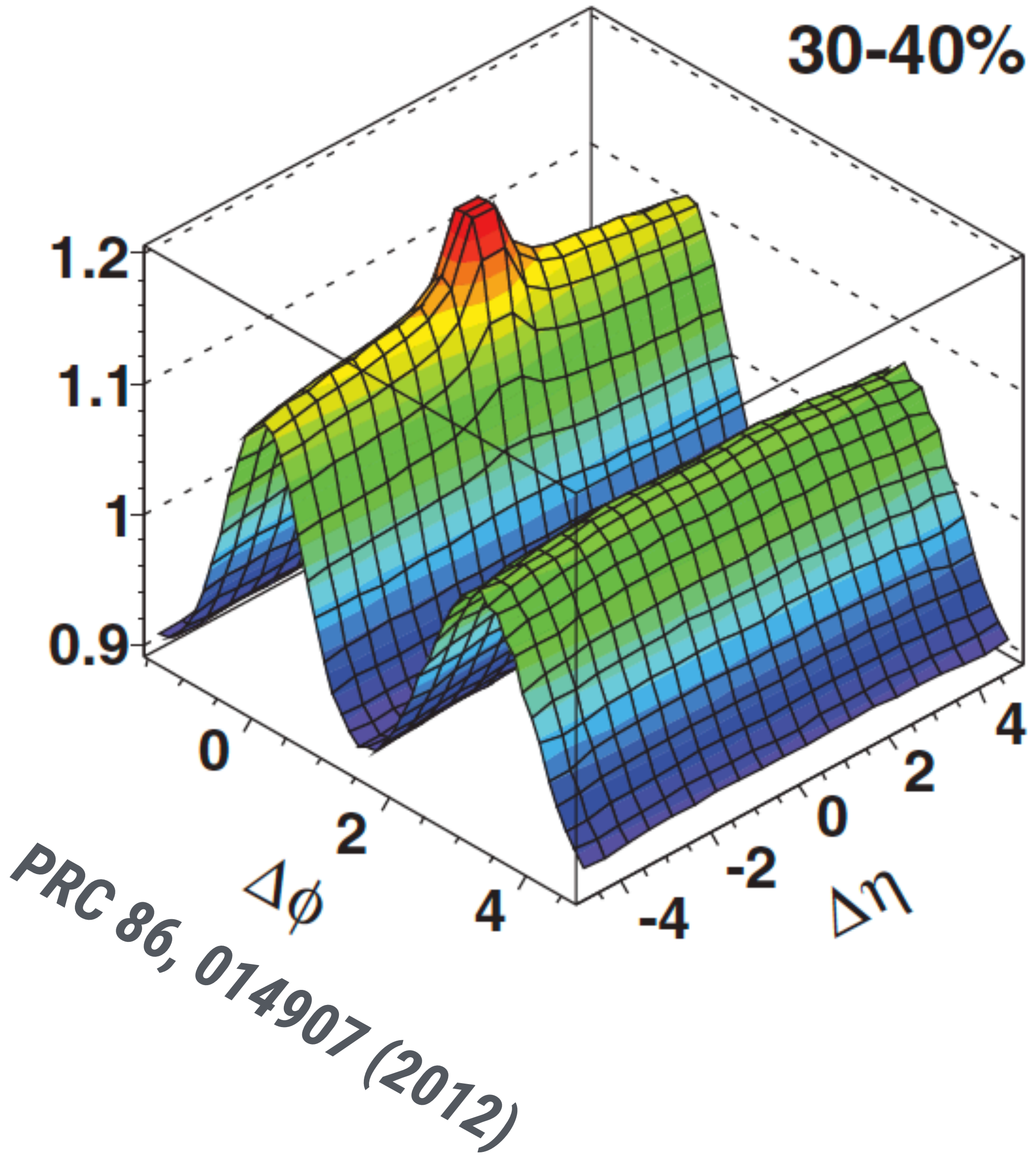


High p_T puzzle in small-systems

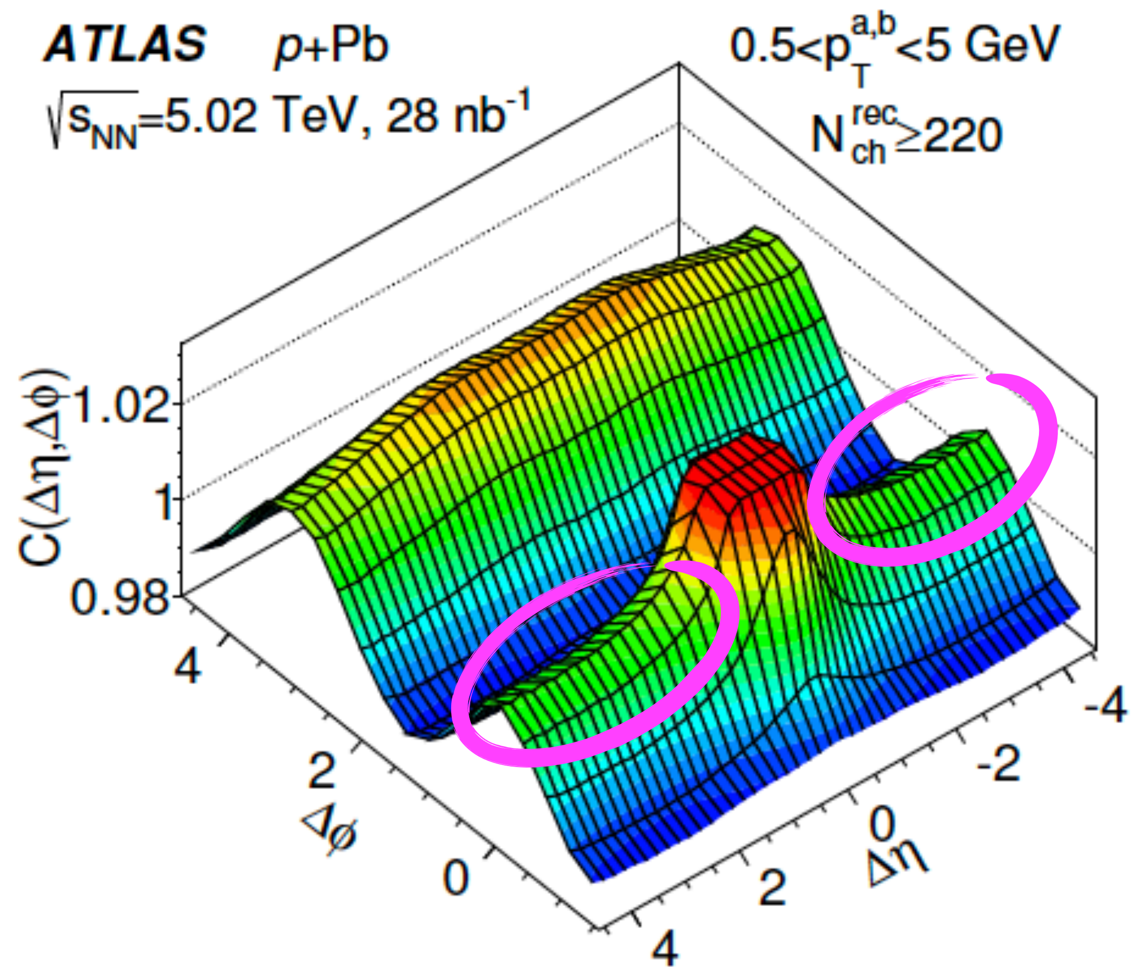
- No jet quenching
- Clear v_2 signal - similar to mid-central Pb-Pb
- Models that predict collective behavior largely overestimate R_{pPb} suppression

TURNING OFF THE COLLECTIVITY?

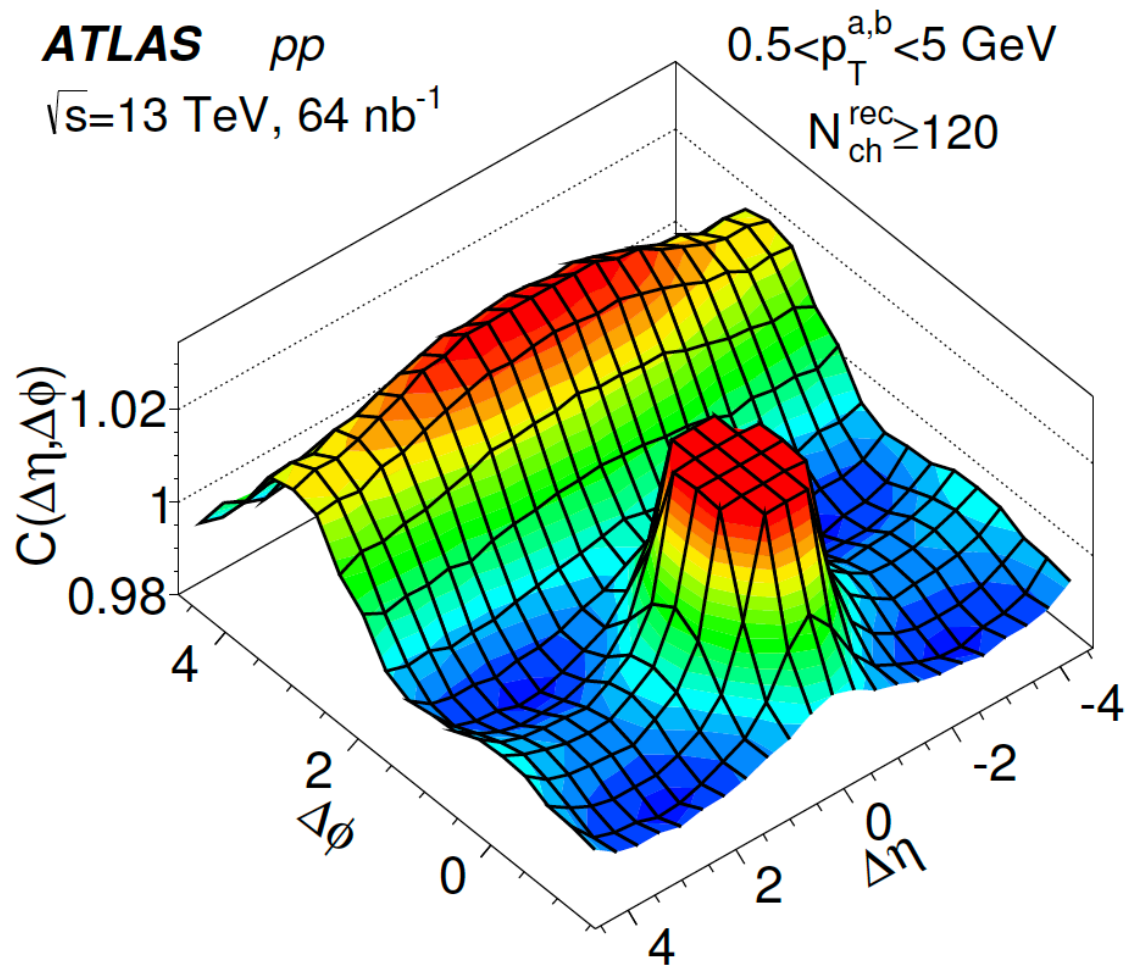




Pb+Pb: collective, strongly-coupled long-distance behavior

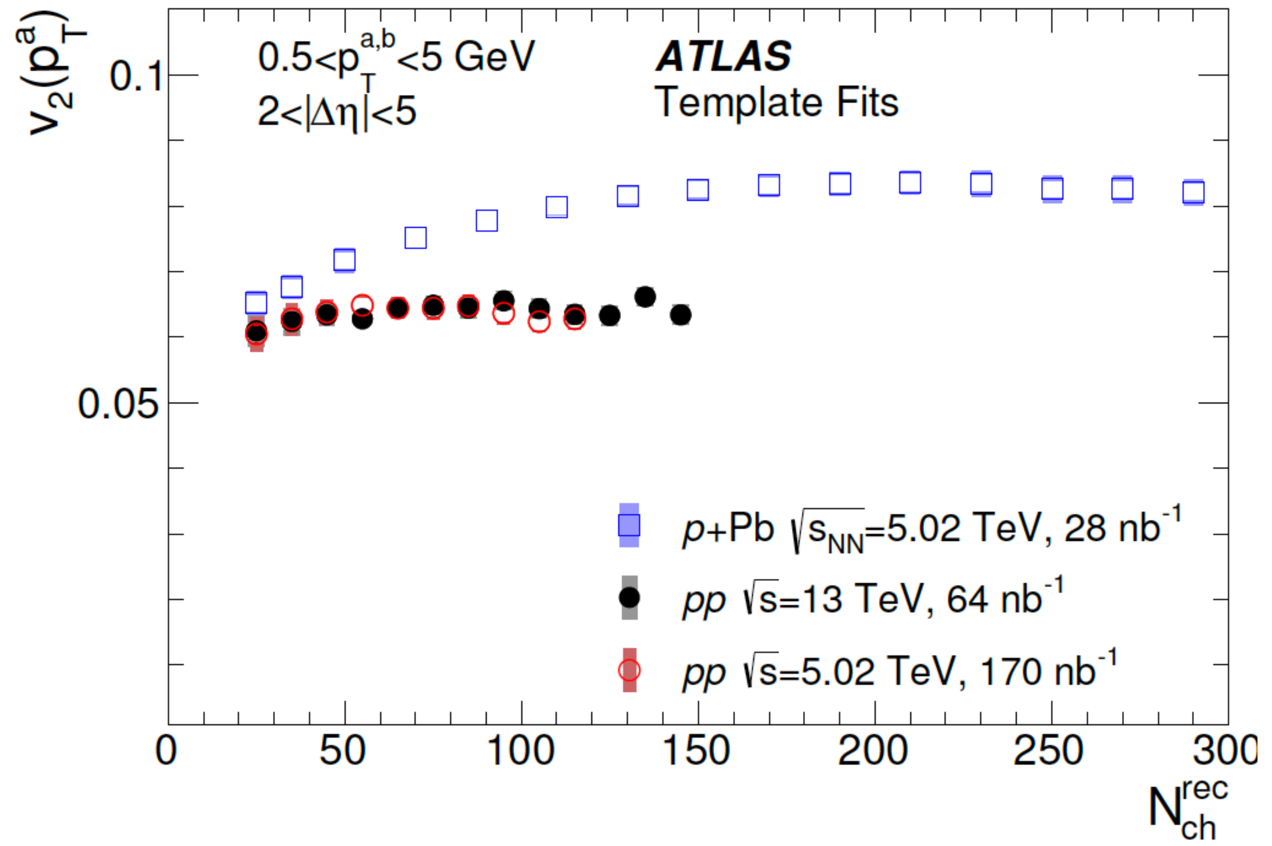


p+Pb: unexpected near-side ridge. QGP still on?

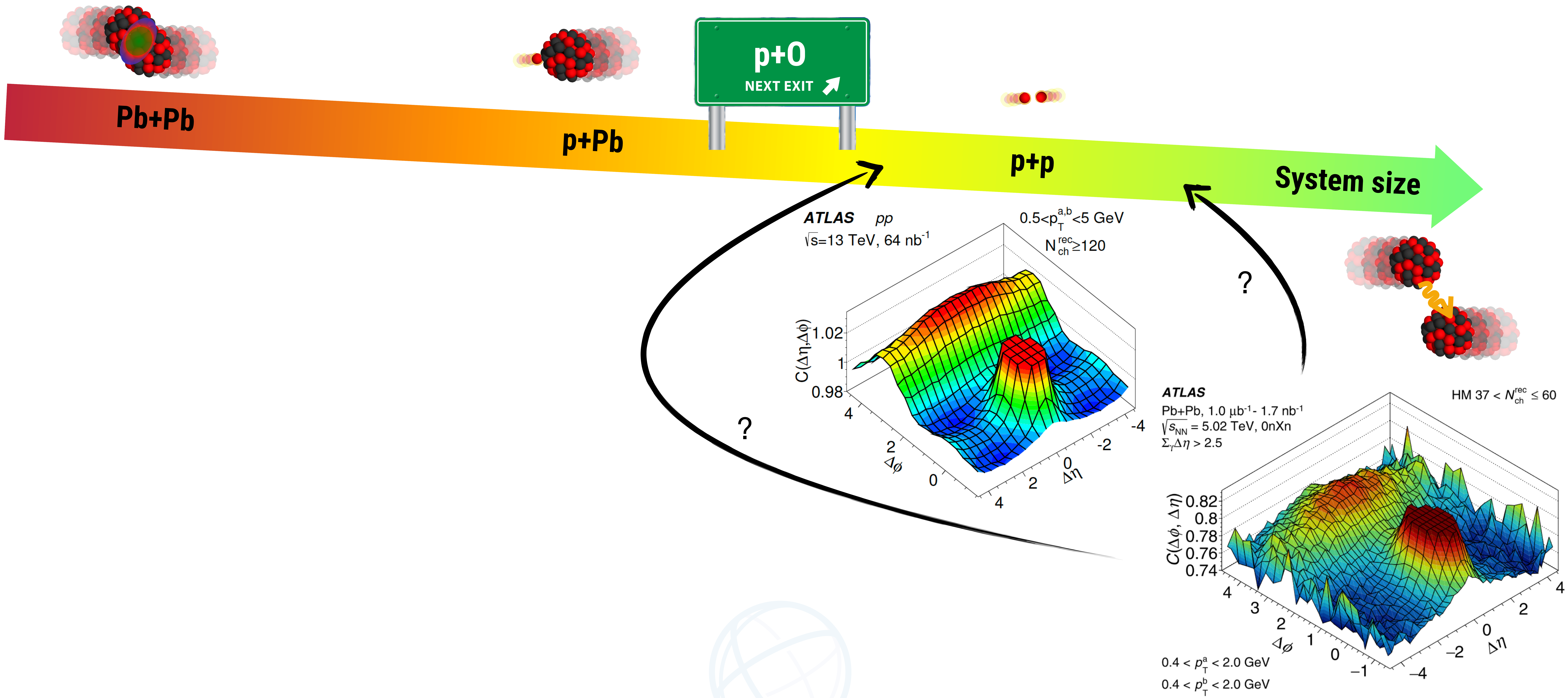


p+p: near-side ridge still present. Effect independent from collision energy

Phys. Rev. C 96 (2017) 024908

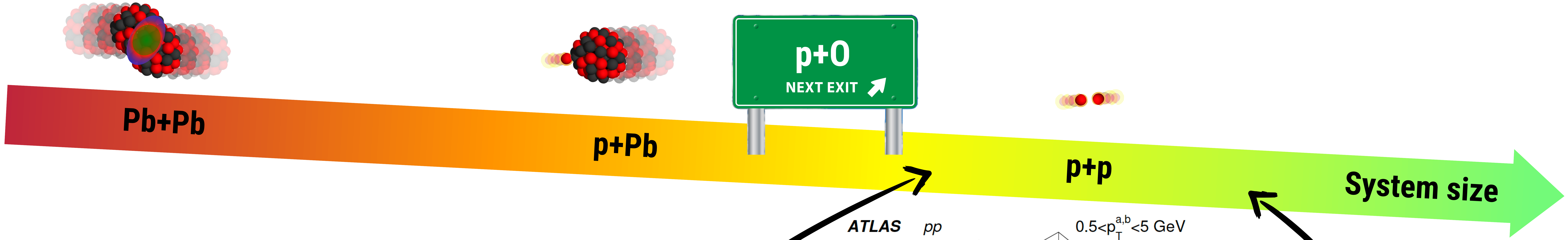


WHAT ABOUT $\gamma + \mathrm{Pb}$?



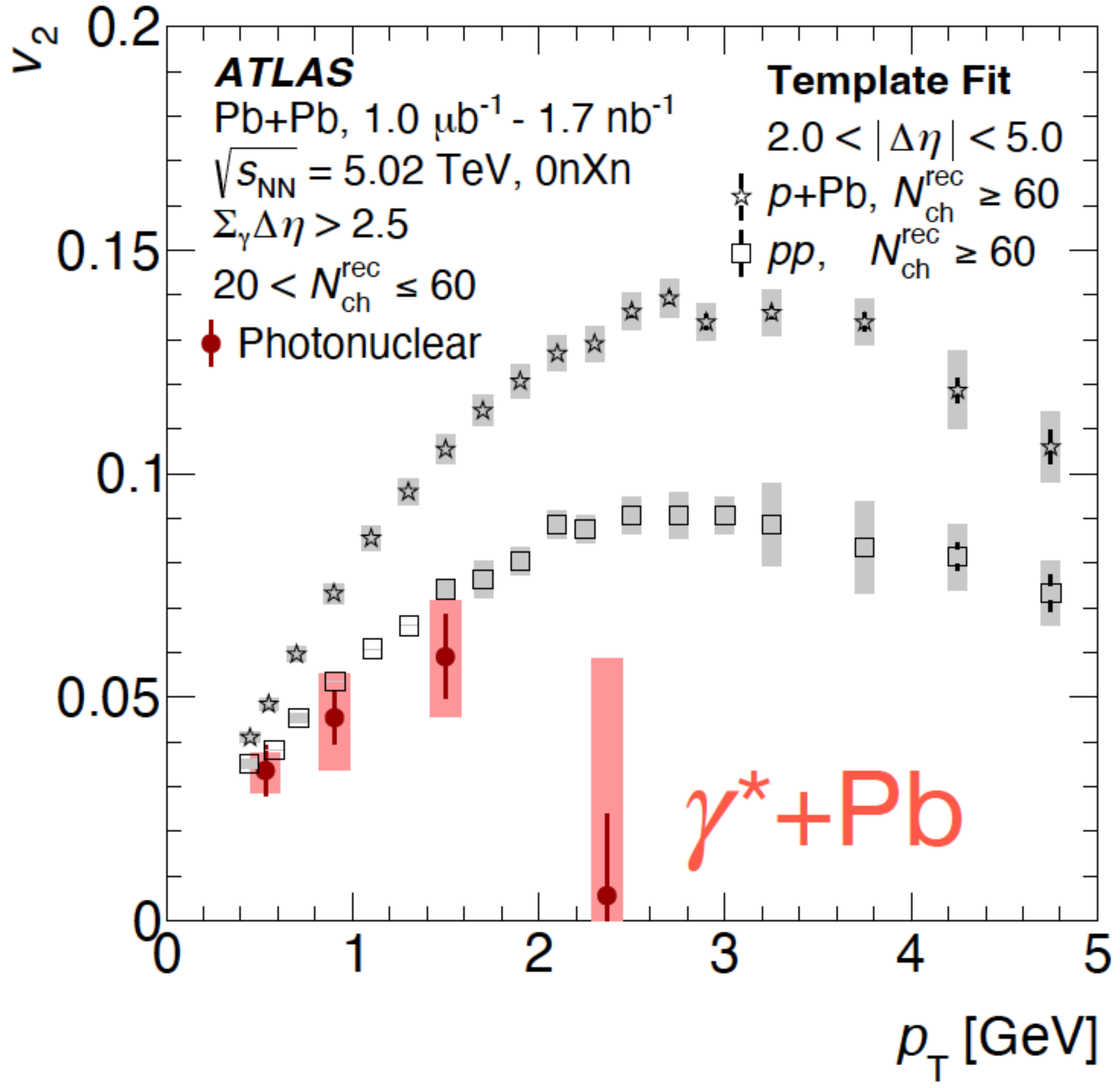
PRC 104, 014903 (2021)

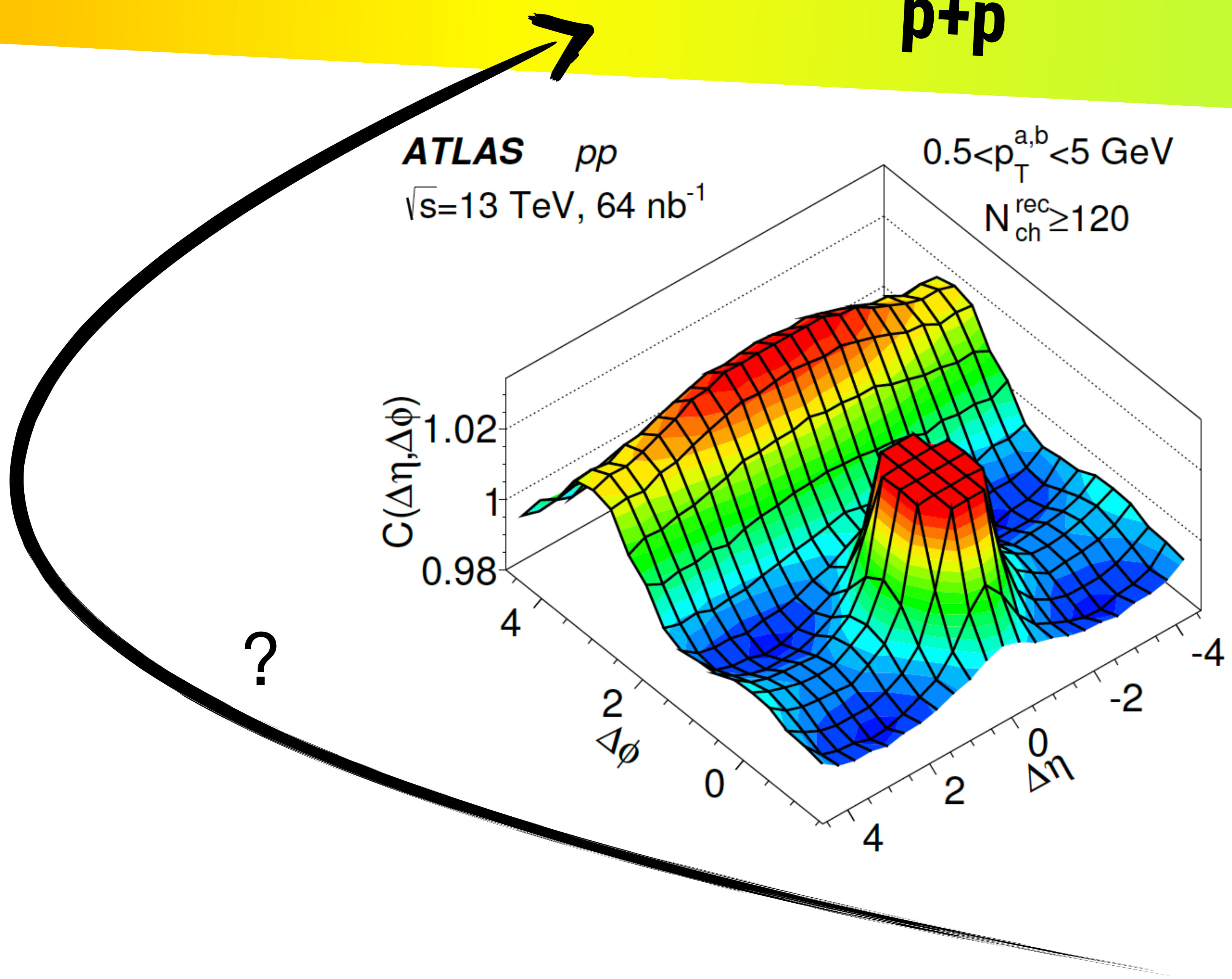
WHAT ABOUT $\gamma + \mathrm{Pb}$?

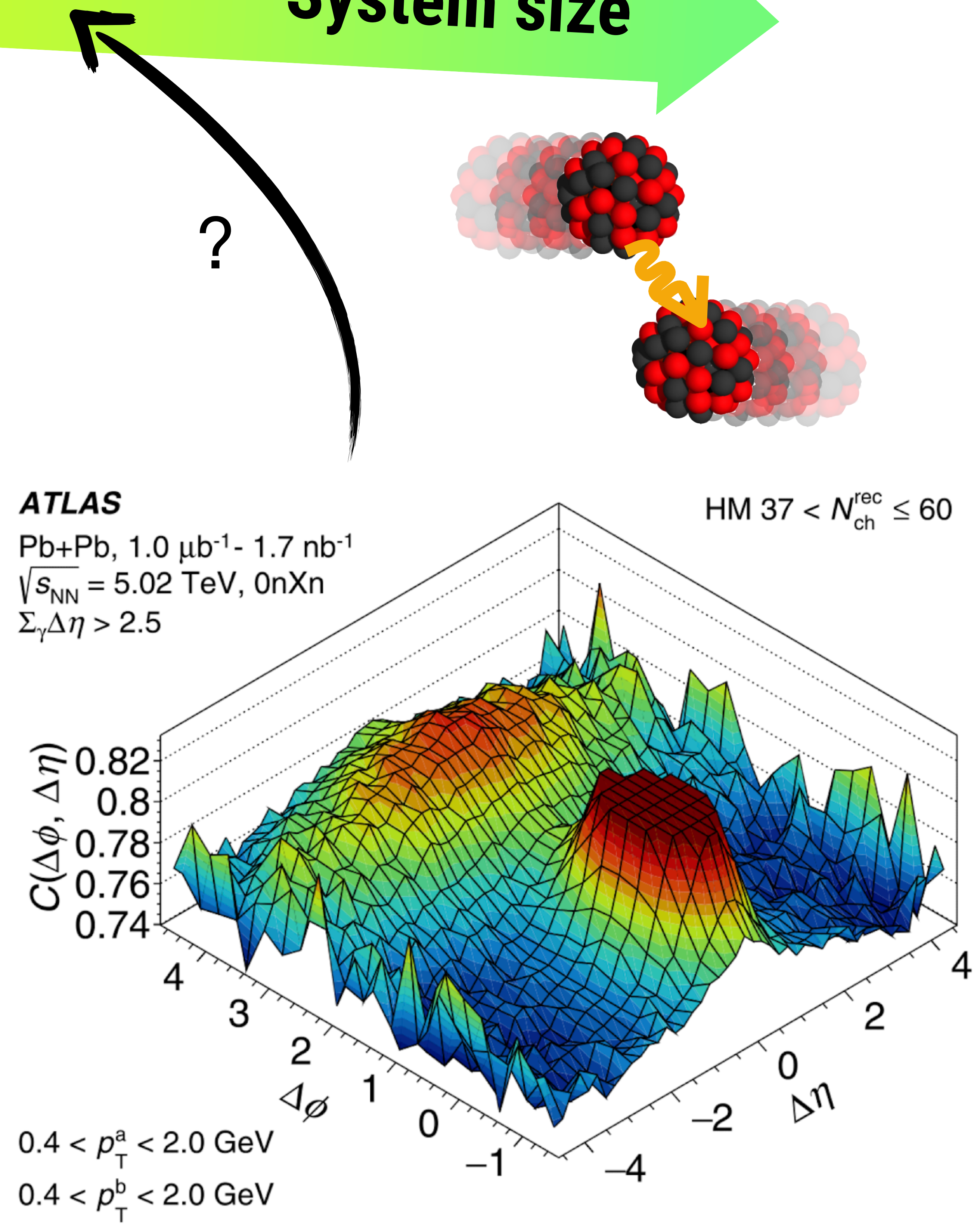


QGP-like signature found by ATLAS in UPCs via resolved photons

Hierarchy?







Two-dimensional correlation functions in $\gamma + \mathrm{Pb}$ have features similar to those observed in pp collision

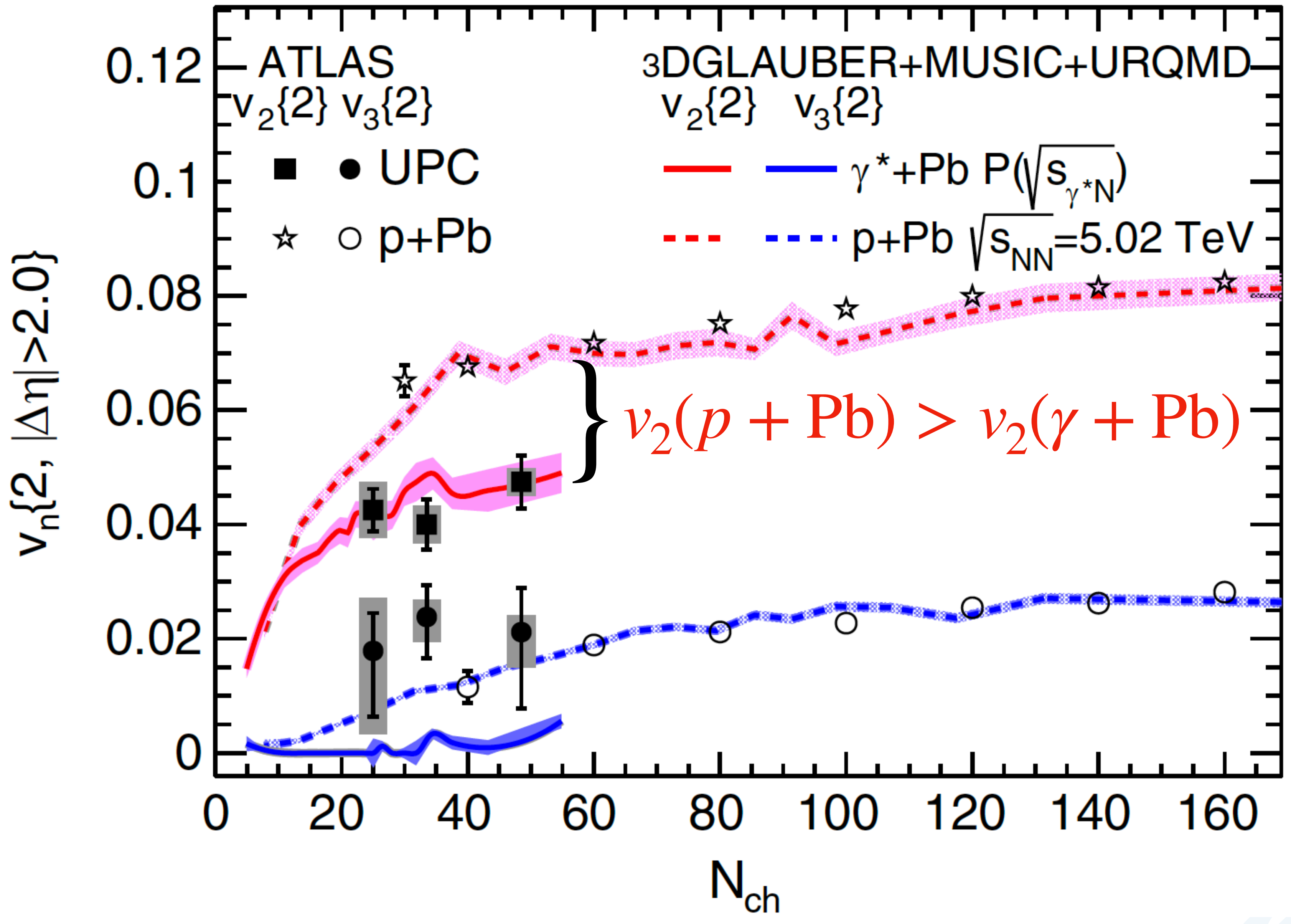
PRC 104, 014903 (2021)

HOW $\gamma + \mathrm{Pb}$ AND $p + \mathrm{Pb}$ COMPARE?

QGP-like signature found by ATLAS in UPCs via resolved photons

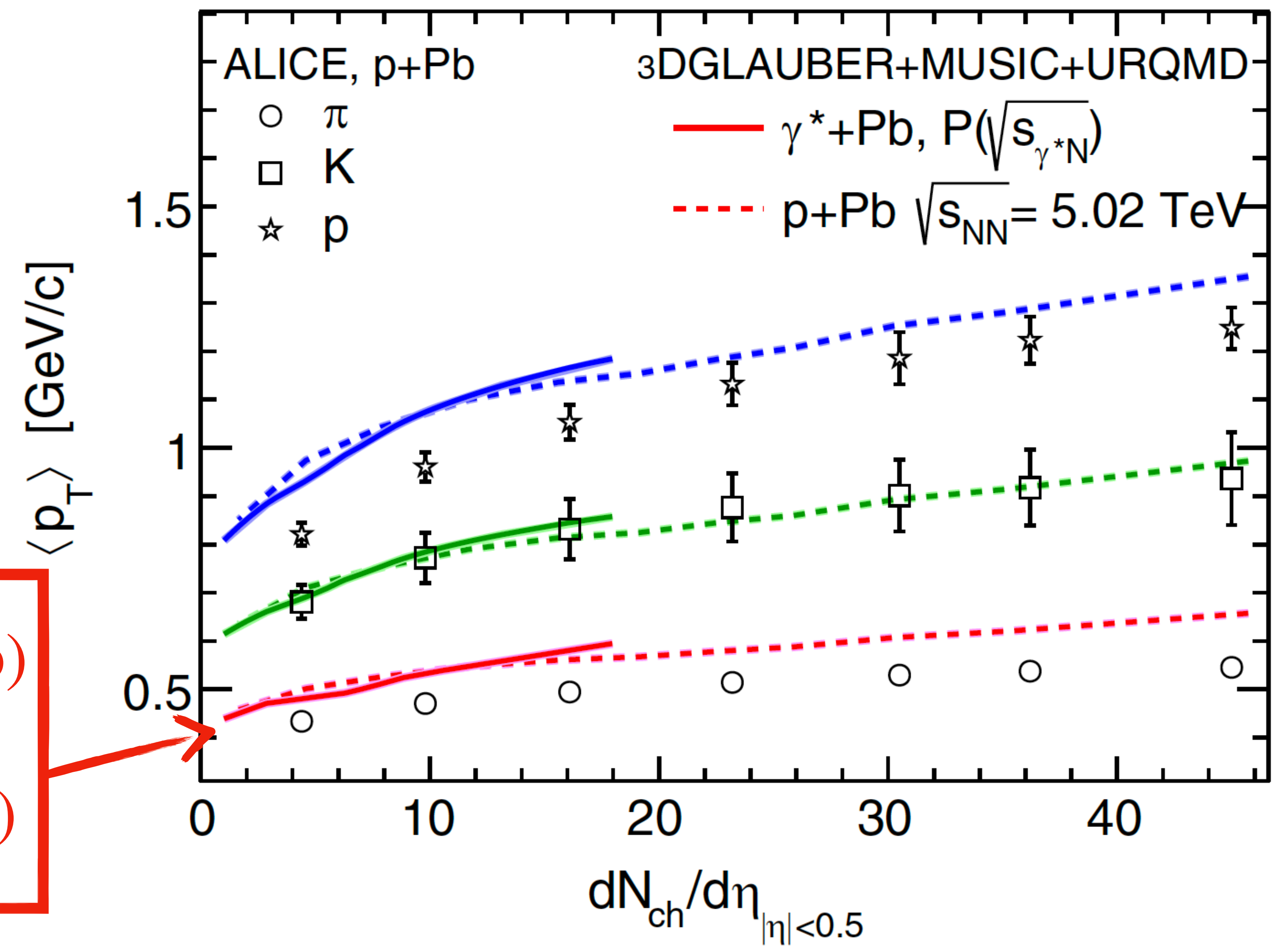
Hierarchy?

W.Zhao, C.Shen, B.Schenke,
PRL 129, 252302



3+1D hydrodynamics suggests v_2 hierarchy between p+Pb and γ+Pb driven by flow decorrelations

$\langle p_T \rangle(p + \mathrm{Pb})$
$\sim$
$\langle p_T \rangle(\gamma + \mathrm{Pb})$

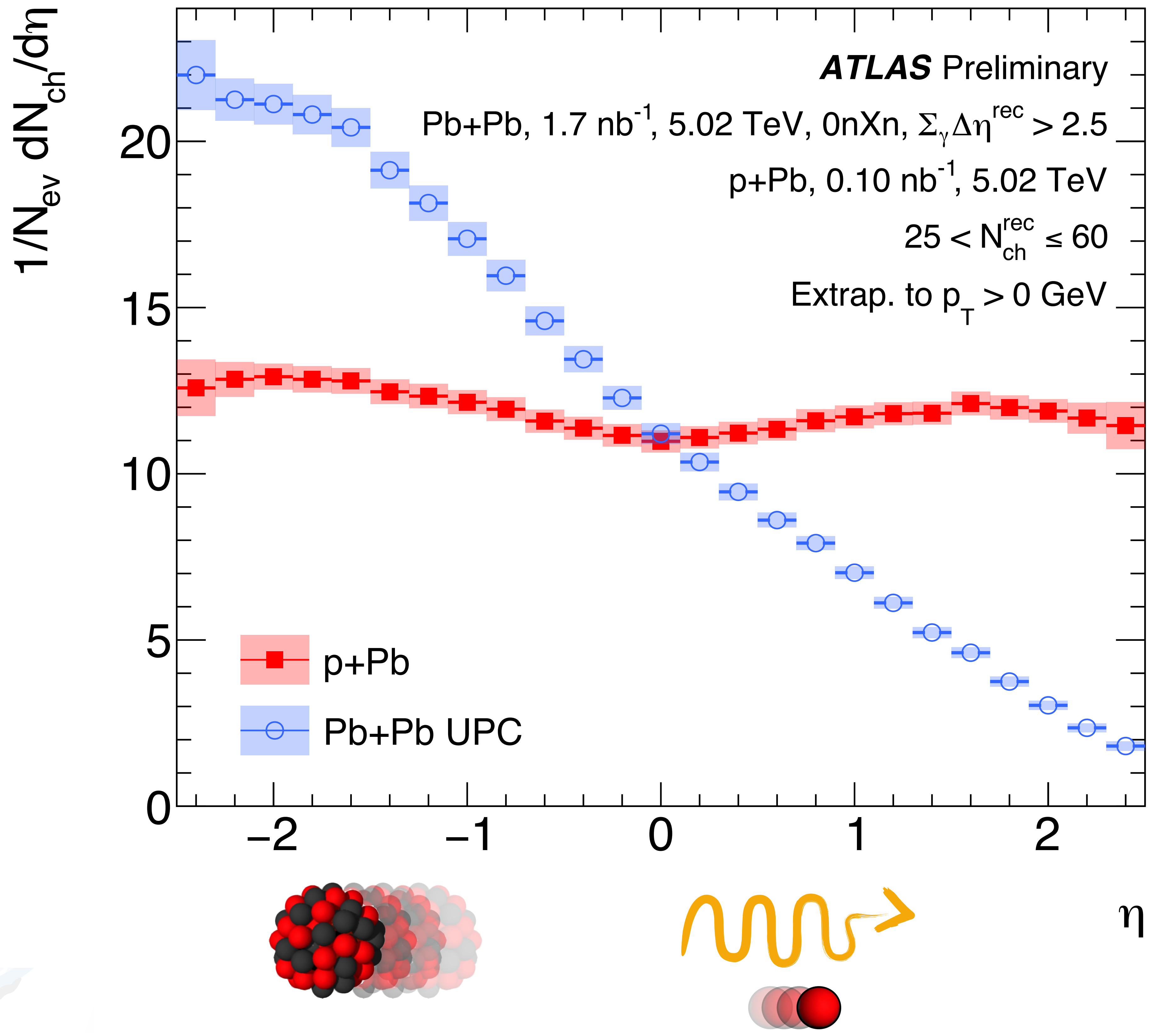


Same model predicts ~same radial flow for both systems $\rightarrow$ same $\langle p_T \rangle$

HOW $\gamma + \text{Pb}$ AND $p + \text{Pb}$ COMPARE?

- Analysis in the same multiplicity region for both γ+Pb and p+Pb
- γ+Pb distribution highly asymmetric (E_γ << energy per nucleon in the Pb)
- p+Pb distribution nearly simmetric

ATLAS-CONF-2023-059

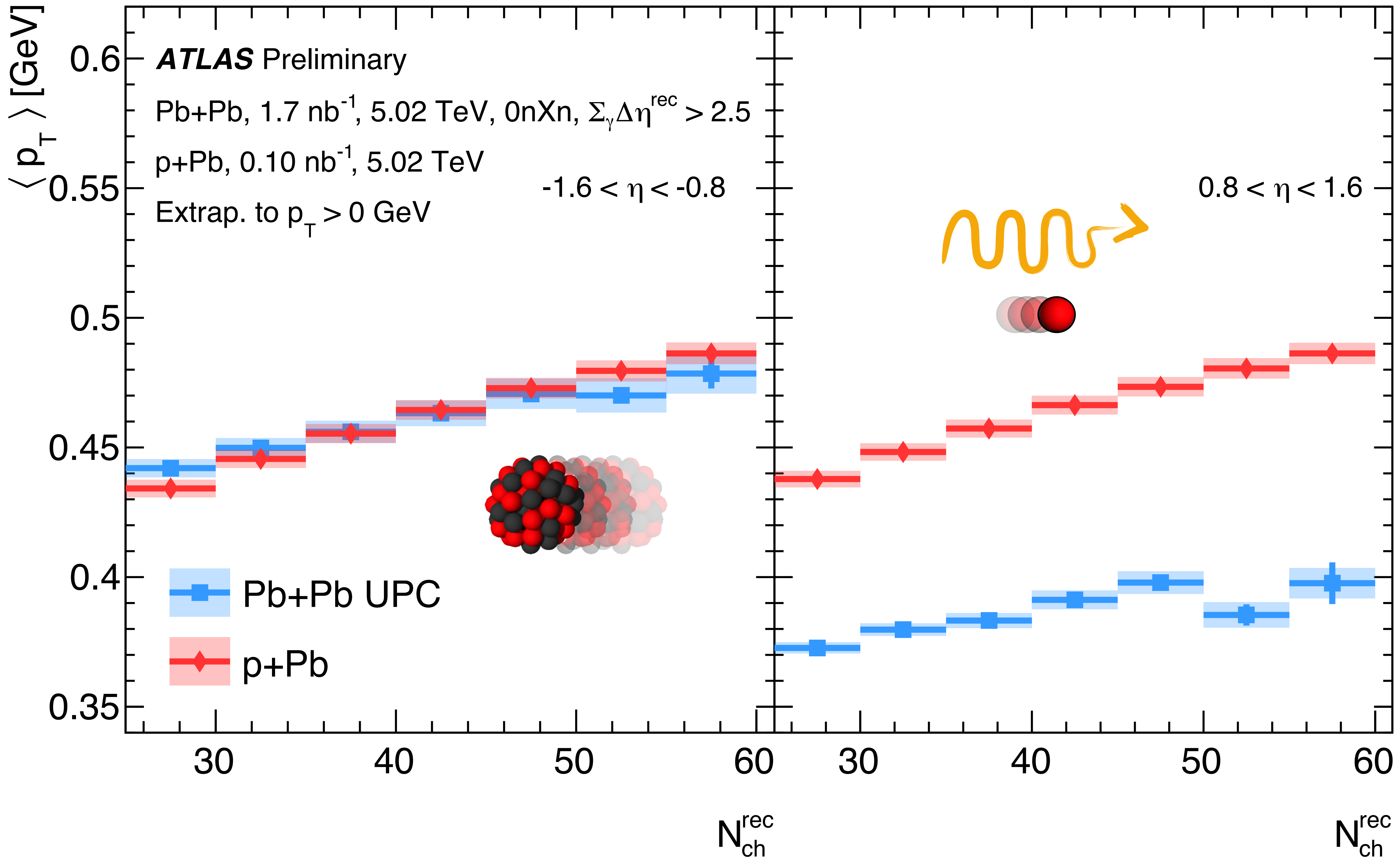


HOW $\gamma + \mathrm{Pb}$ AND $p + \mathrm{Pb}$ COMPARE?

See talk by S.Mohapatra on Wednesday

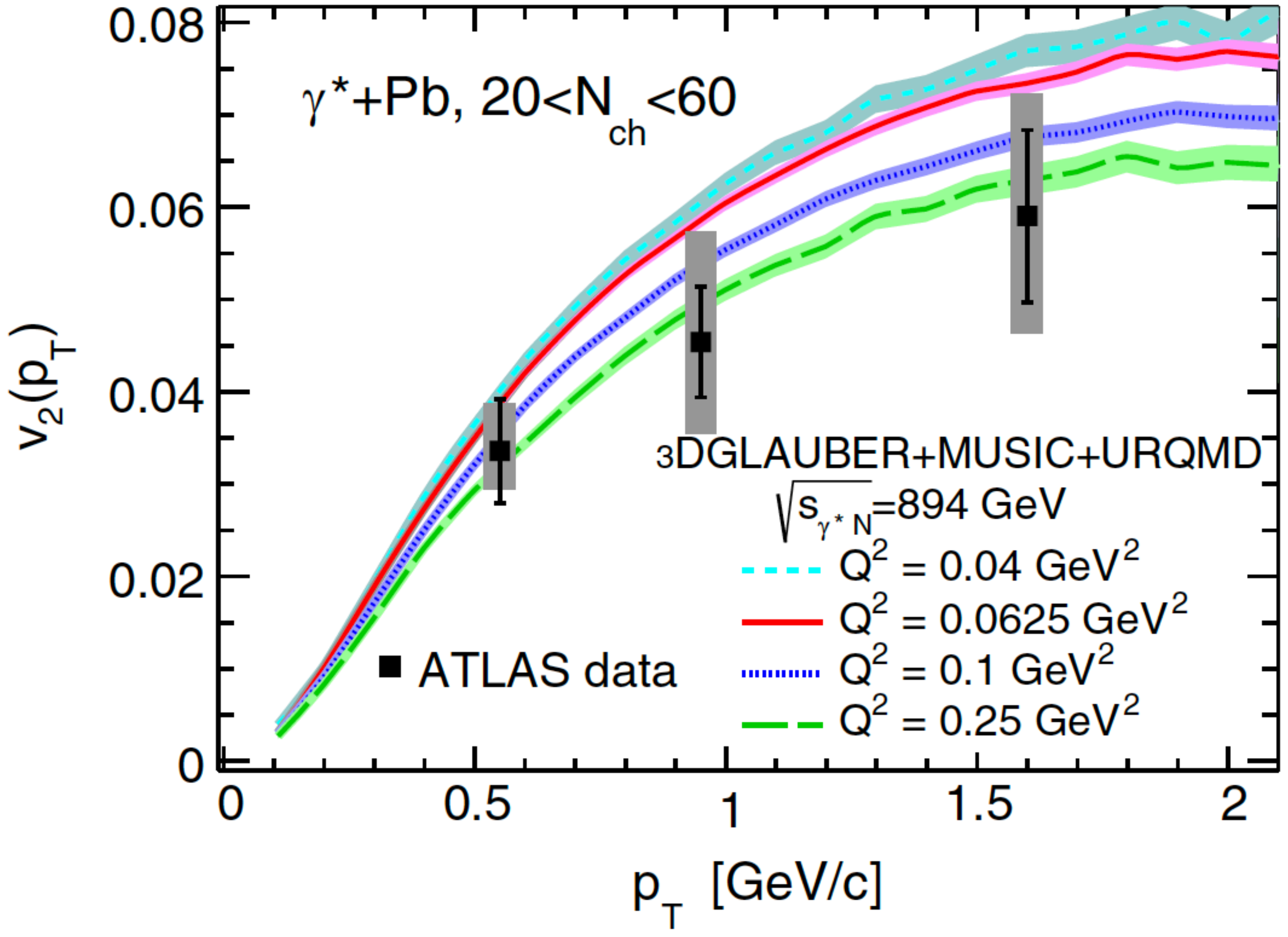
- $\langle p_{\mathrm{T}} \rangle$ similar in γ+Pb and p+Pb in the Pb going direction (as predicted by theory)
- Currently working on K_S^0, Λ and Ξ^- to enhance sensitivity to radial flow

ATLAS-CONF-2023-059



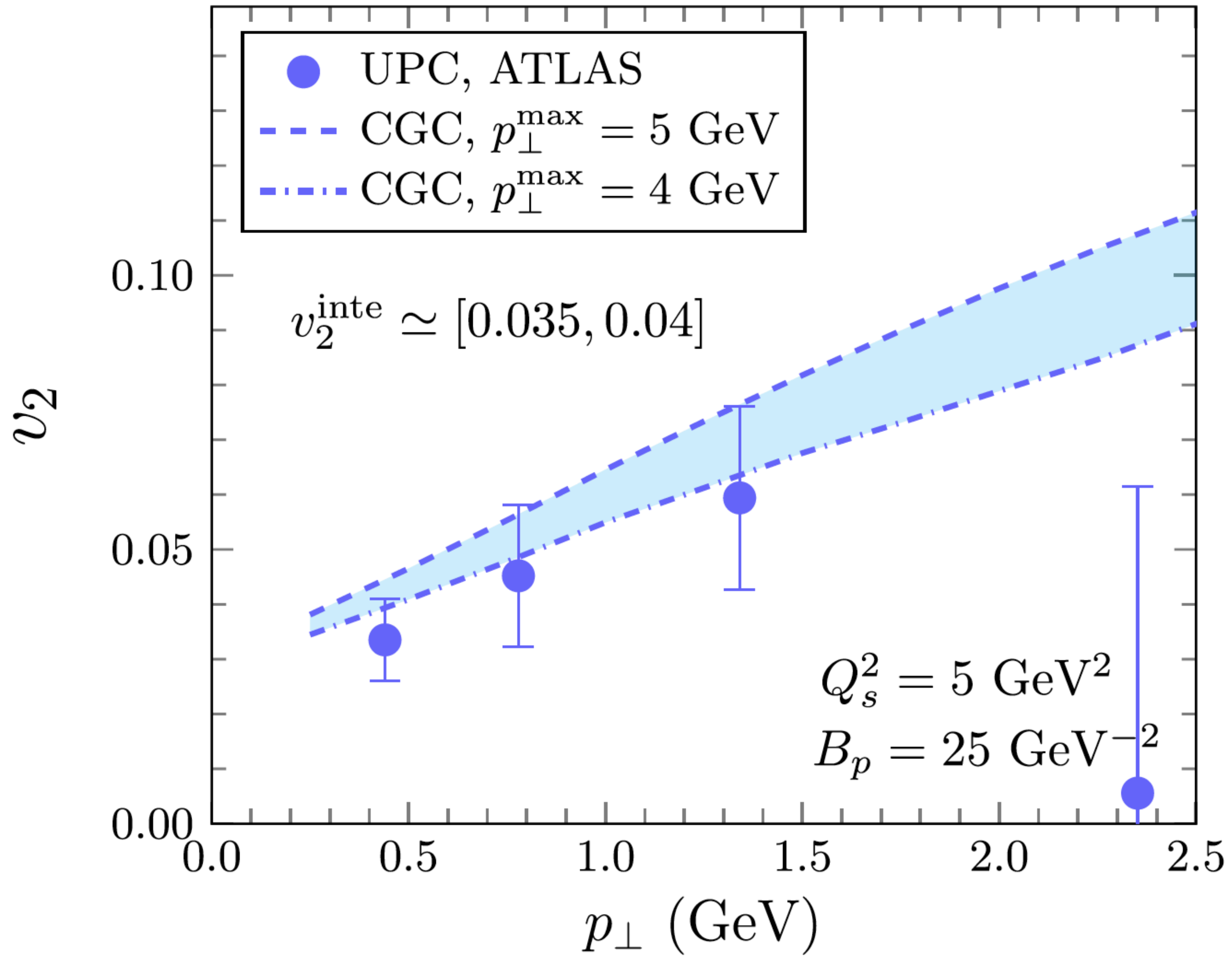
MODELING $\gamma + \mathrm{Pb}$ FLOW

See talk by S.Mohapatra on Wednesday



W.Zhao, C.Shen, B.Schenke,
PRL 129, 252302:
final-state effect from hydrodynamic

The model predicts larger v_2 signal in γ+Pb at smaller virtuality of the resolved photon

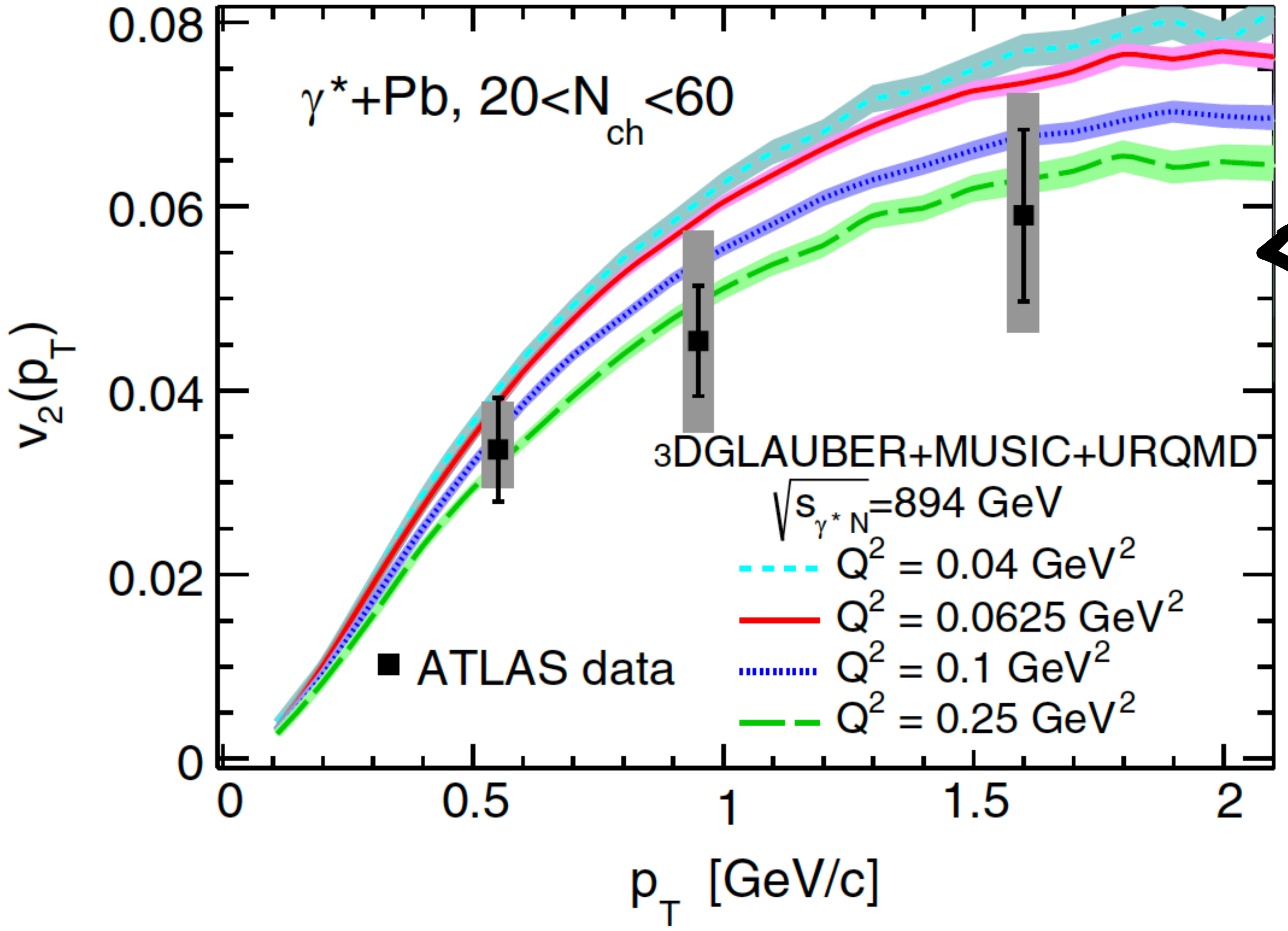


Y.Shi, L.Wang, S.Wei, B.Xiao, L.Zheng
PRD 103 (2021) 054017:
initial-state effect from CGC

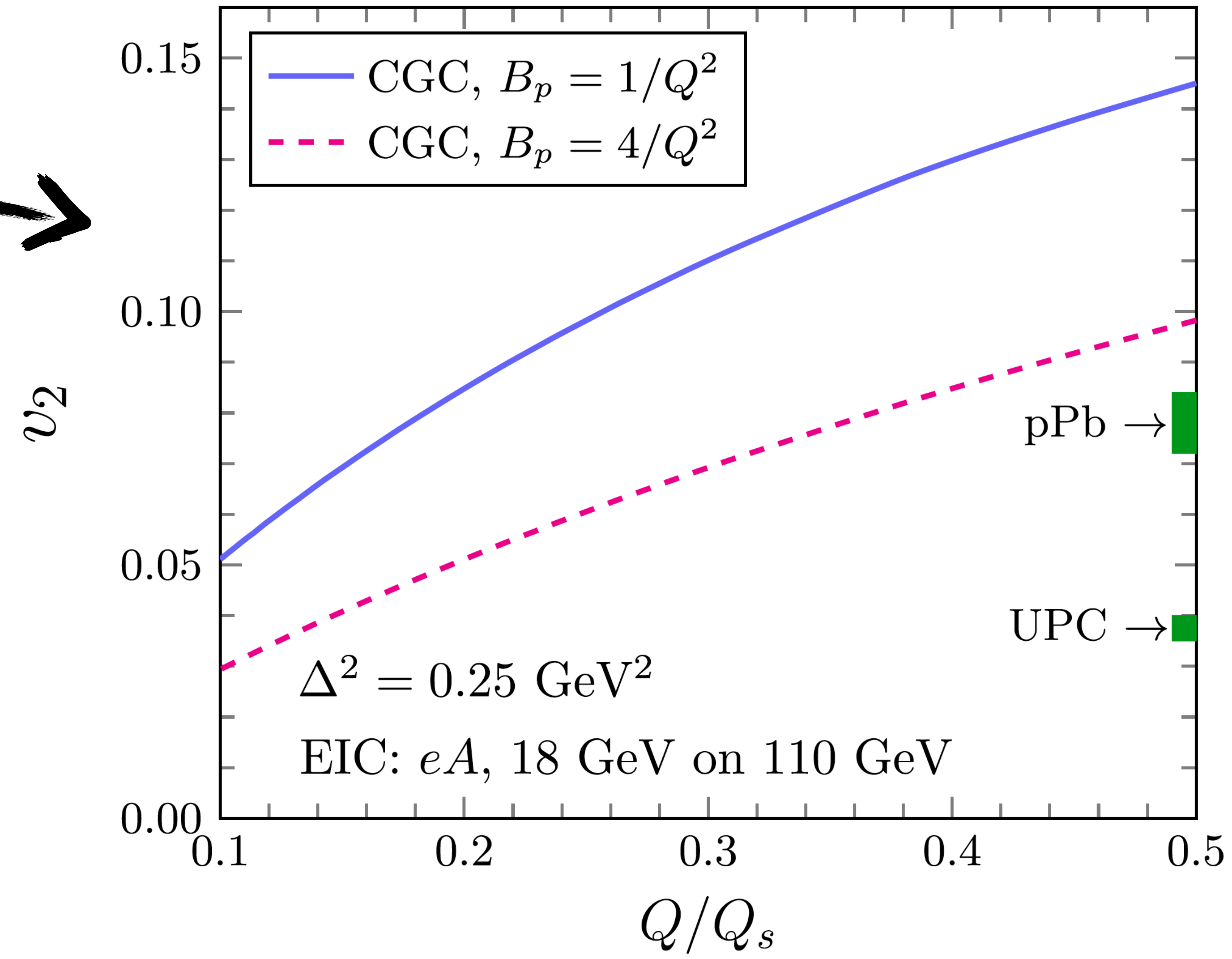
The model predicts larger v_2 signal in γ+Pb at larger virtuality of the resolved photon

MODELING $\gamma + \mathrm{Pb}$ FLOW

See talk by S.Mohapatra on Wednesday



Hydro vs CGC: predictions have opposite virtuality dependences



EIC CAN BE THE TIE-BREAKER BETWEEN IS AND FS MODELS!

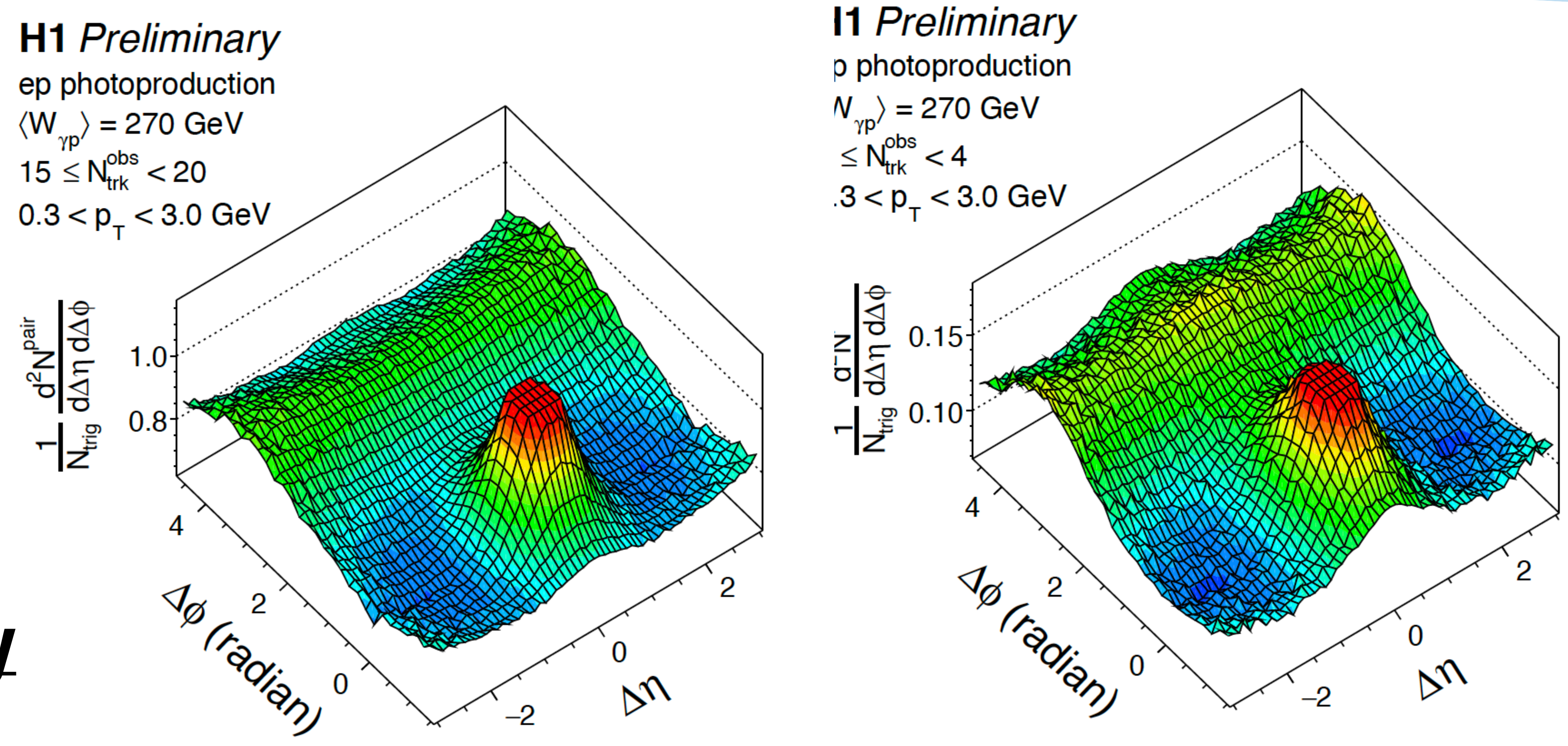
W.Zhao, C.Shen, B.Schenke,
PRL 129, 252302:
final-state effect from hydrodynamic
The model predicts larger v_2 signal in γ+Pb at smaller virtuality of the resolved photon

Y.Shi, L.Wang, S.Wei, B.Xiao, L.Zheng
PRD 103 (2021) 054017:
initial-state effect from CGC
The model predicts larger v_2 signal in γ+Pb at larger virtuality of the resolved photon

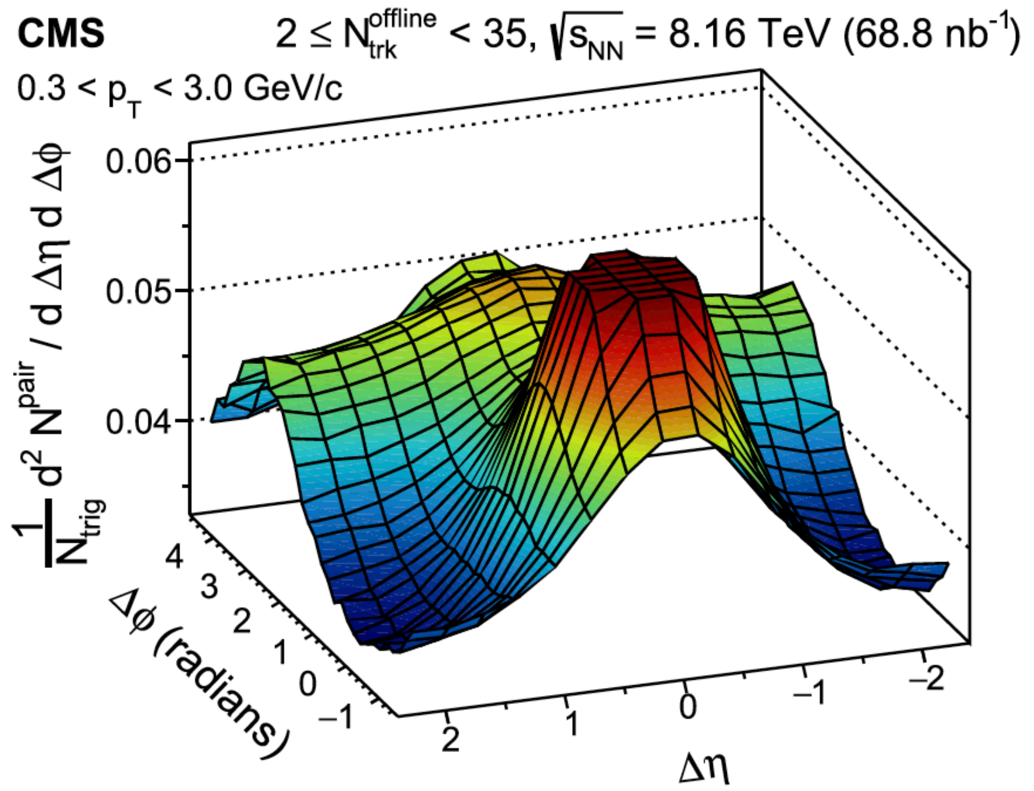
COLLECTIVITY ONSET - THE EIC ROLE

Lately, several searches in smaller systems were carried out

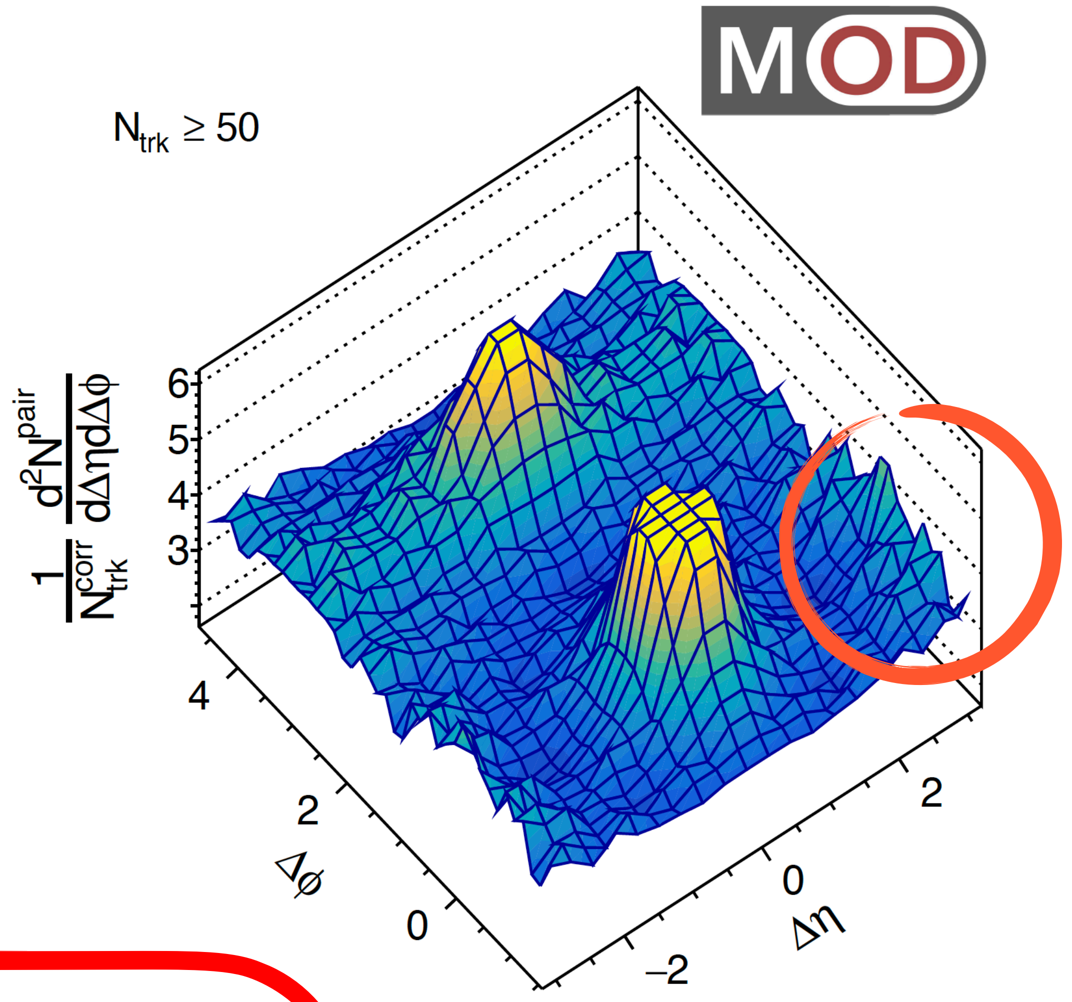
... p+p, γ+Pb → $e^-(\gamma^*)$+p → γ+p → e^-+e^+



H1 Preliminary

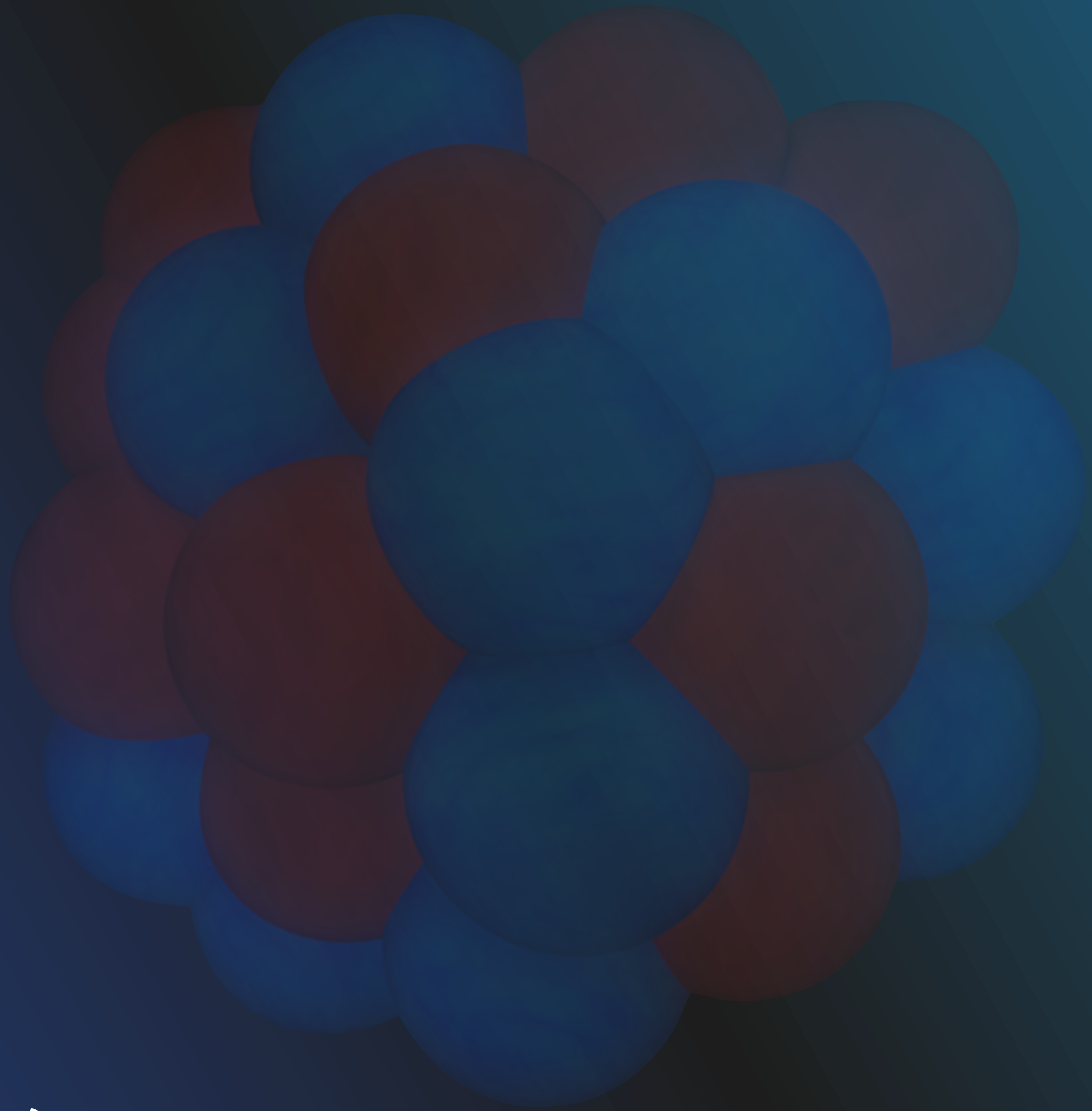


CMS, PLB 844 (2023) 137905



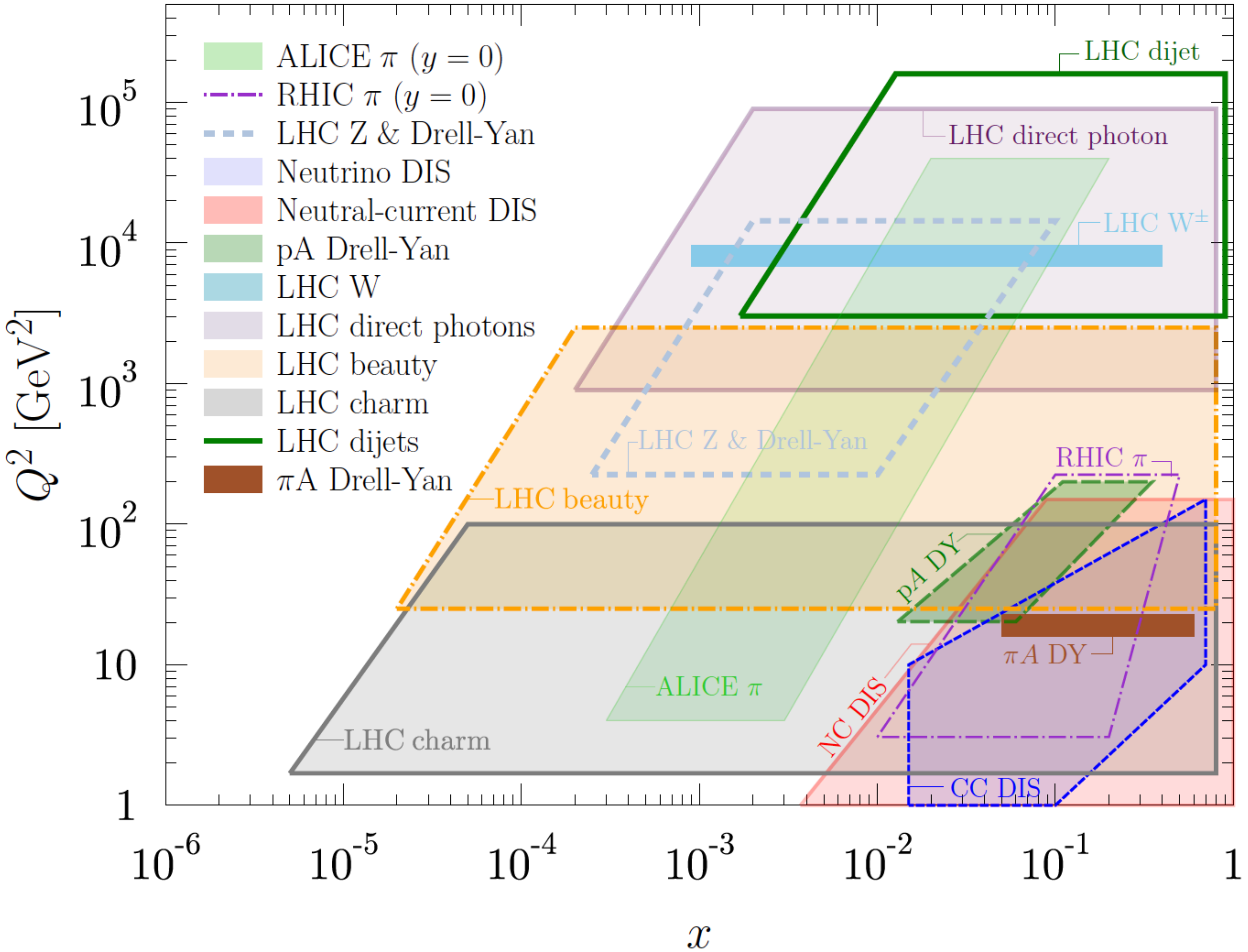
arXiv:2312.05084

What we will find in $e^- + p/A$ at ePIC ?
Another piece to complete the puzzle
(or expand it...)



Nuclear PDFs

NPDF - CURRENT PICTURE



(x,Q²) Phase space coverage of data currently available on the market

Taken from Klasen & Paukkunen

Ann. Rev. Nucl. Part. Sci. 2024. 74:1–41

Large variety of data from different experiments, spanning over a wide (x,Q²) range, down to x ~ 10^{-5}

Different combinations of these data included in different nPDF parametrizations:

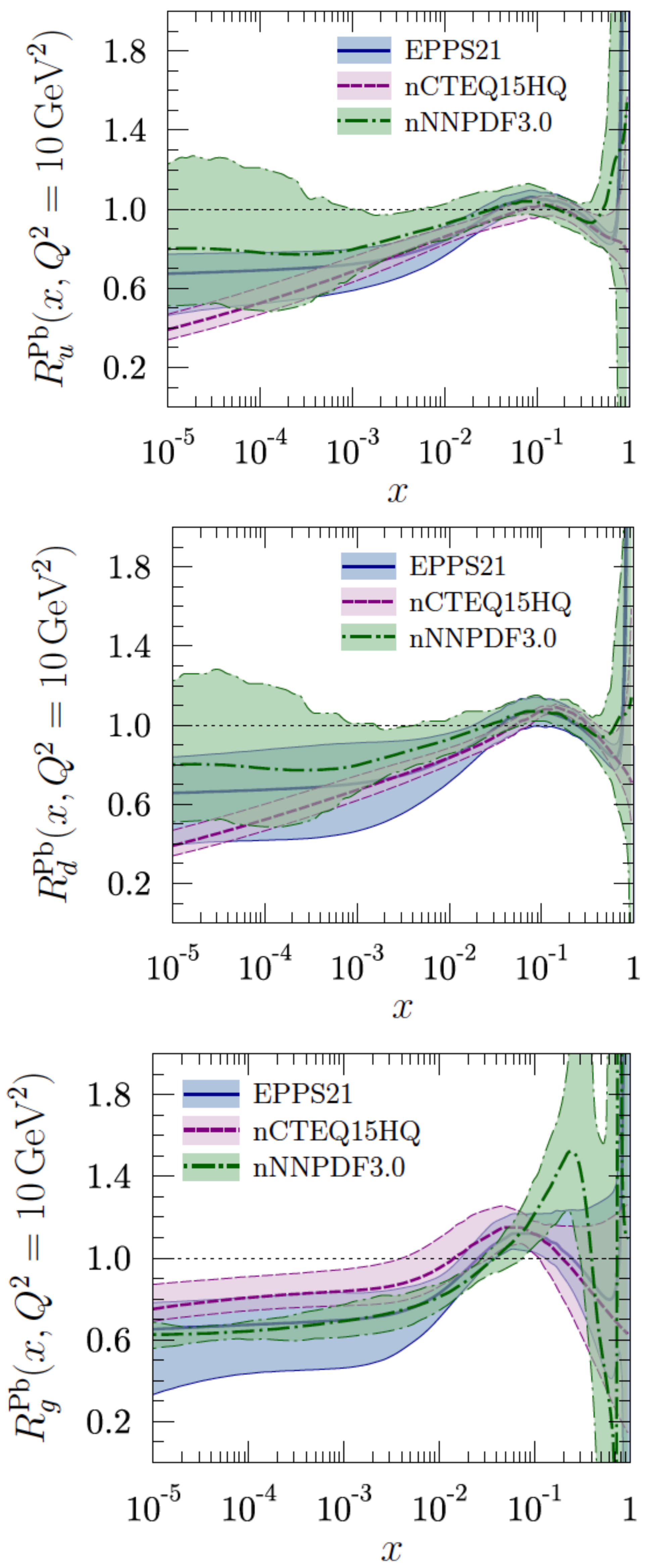
EPPS21

TUJU21

nCTEQ15HQ

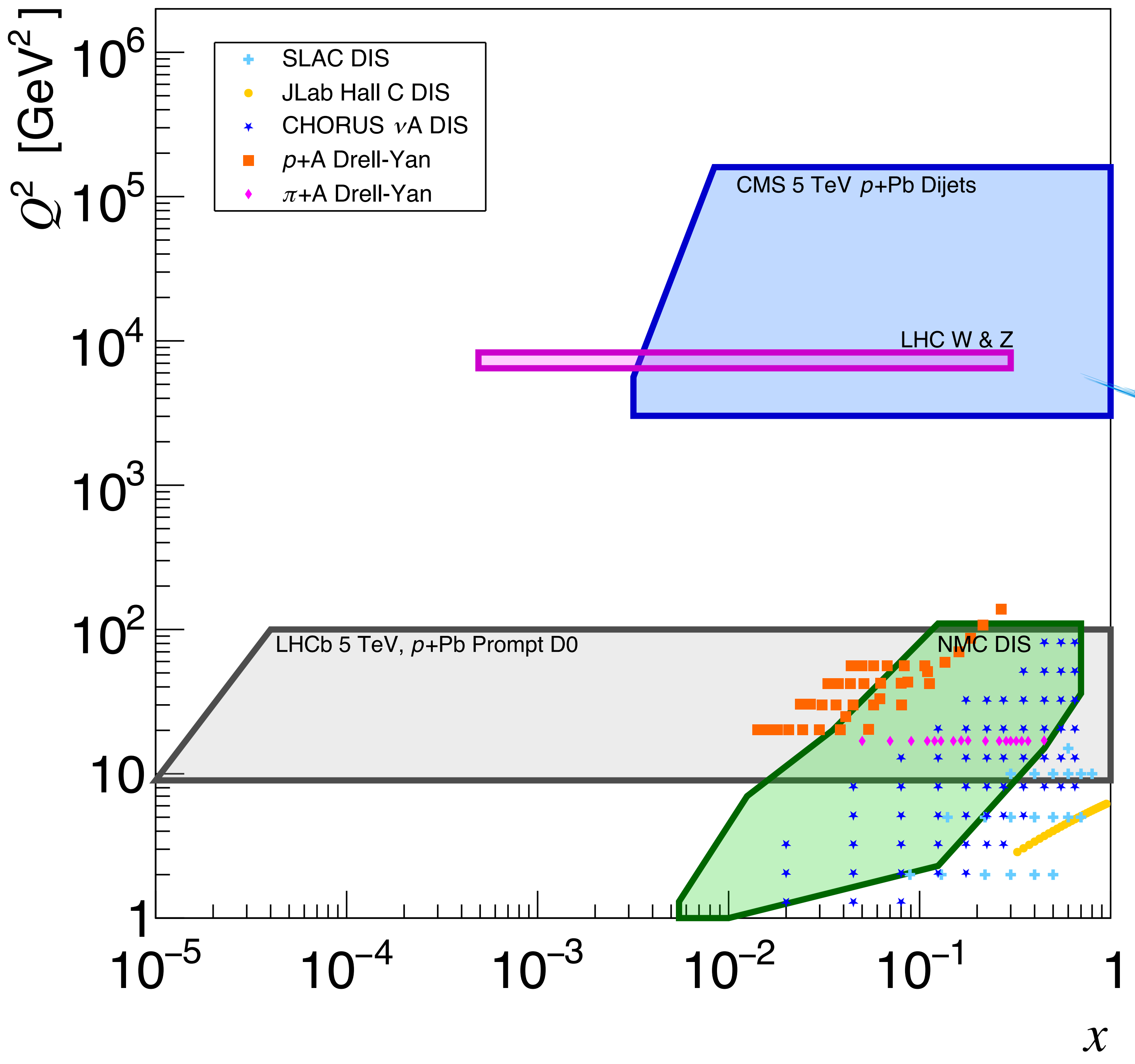
nNNPDF3.0

KSAG20



DIJETS IN P+PB FOR NPDF CONSTRAINTS: EPPS21 EXAMPLE

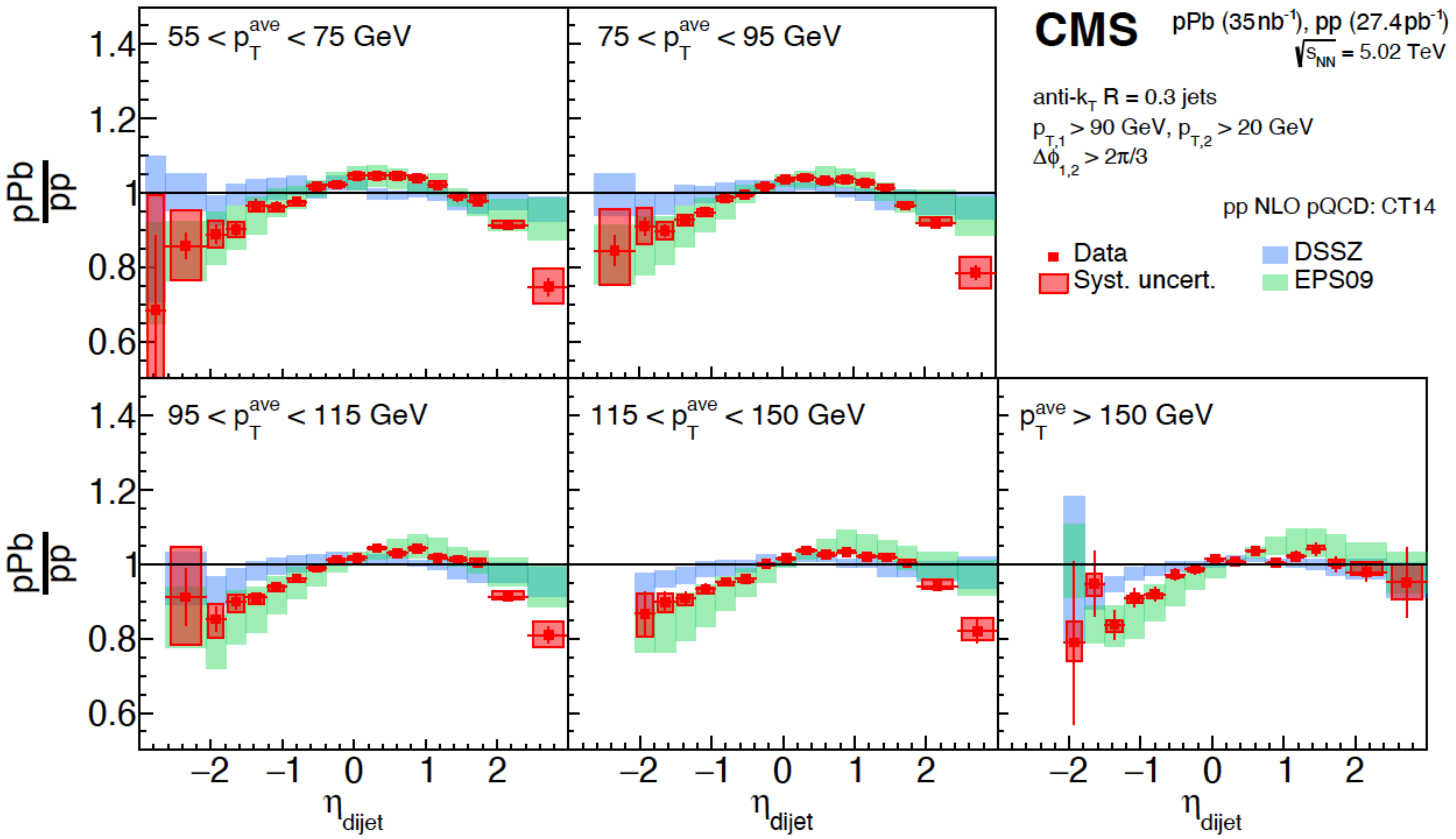
Adapted from **Eur. Phys. J. C (2022) 82:413**



Wide (x, Q^2) phase space region could be explored using dijets in p+Pb @ LHC

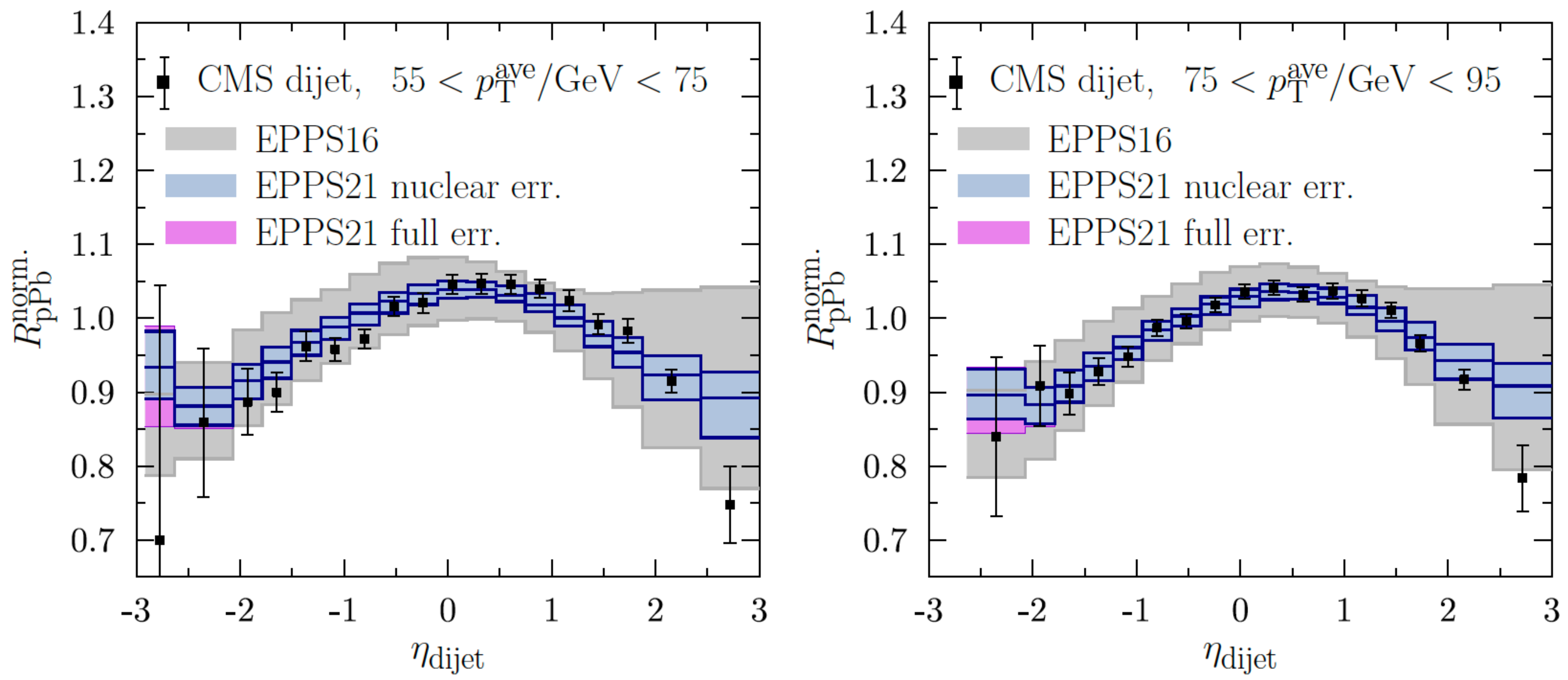
CMS dijet data @ 5.02 TeV only one published so far

PRL 121, 062002 (2018)

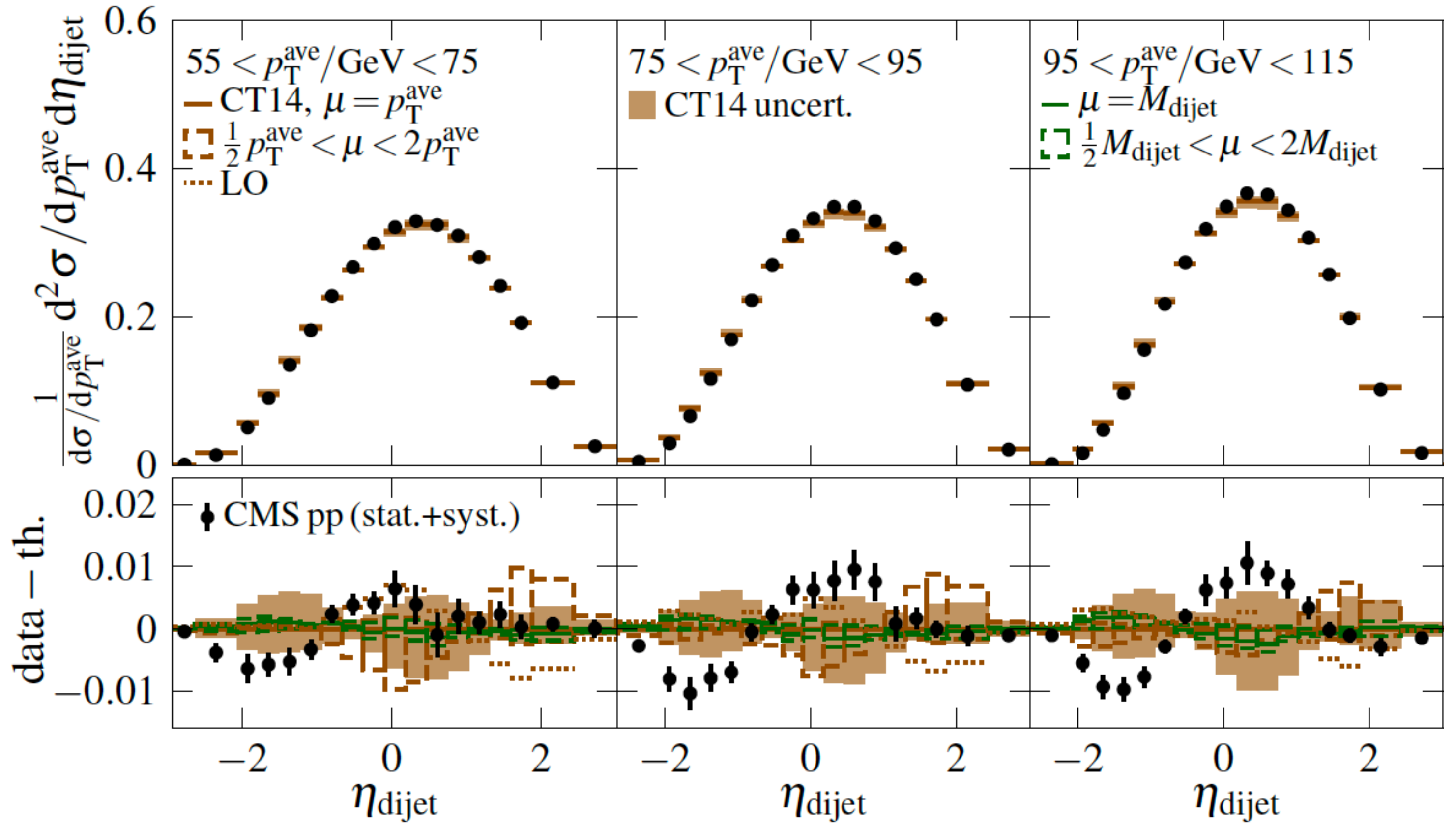


Ratios are well described!

More issues when trying to describe separately p+p and p+Pb data



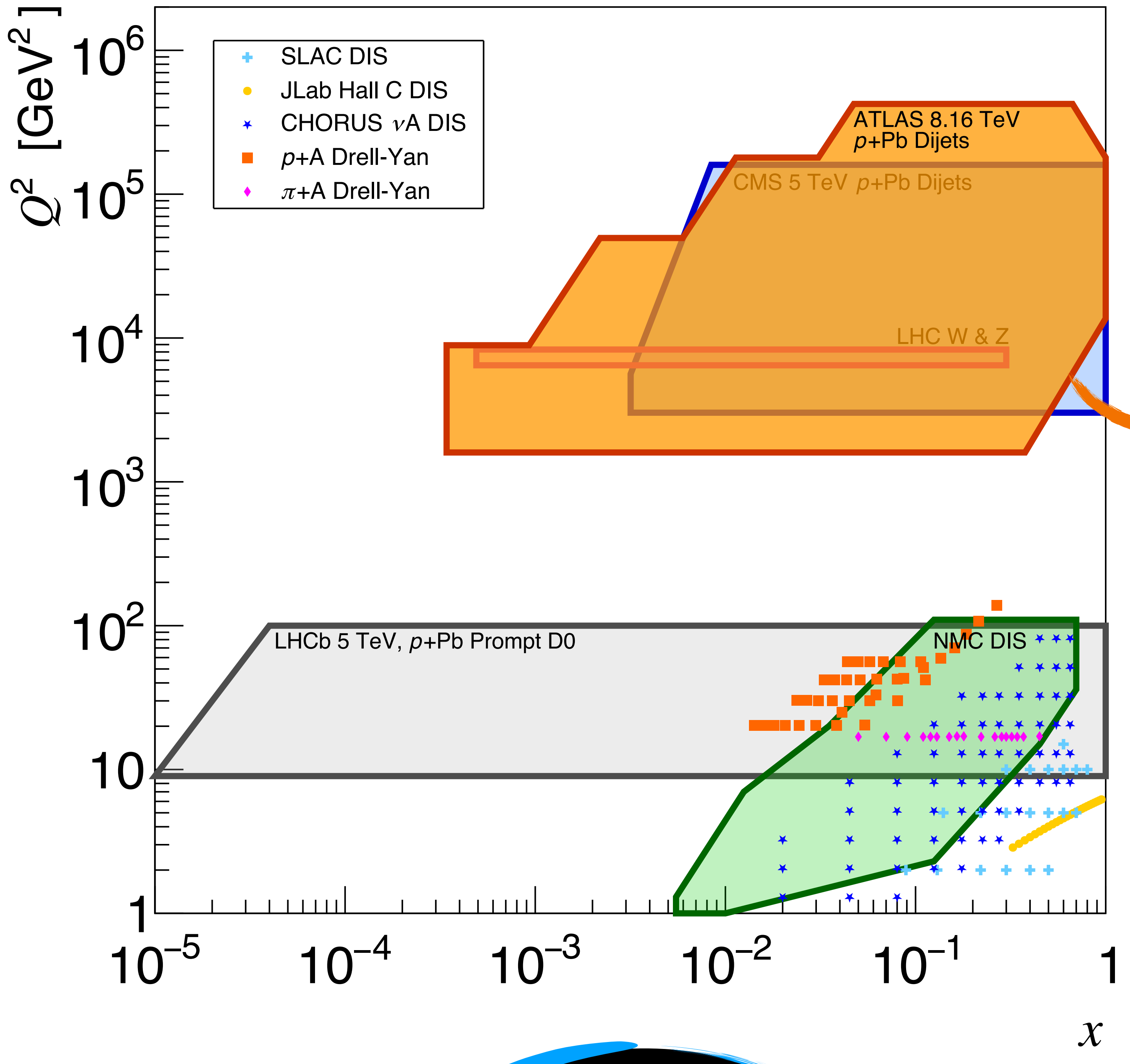
Eskola et al.,
Eur.Phys.J.C 82 (2022) 5, 413



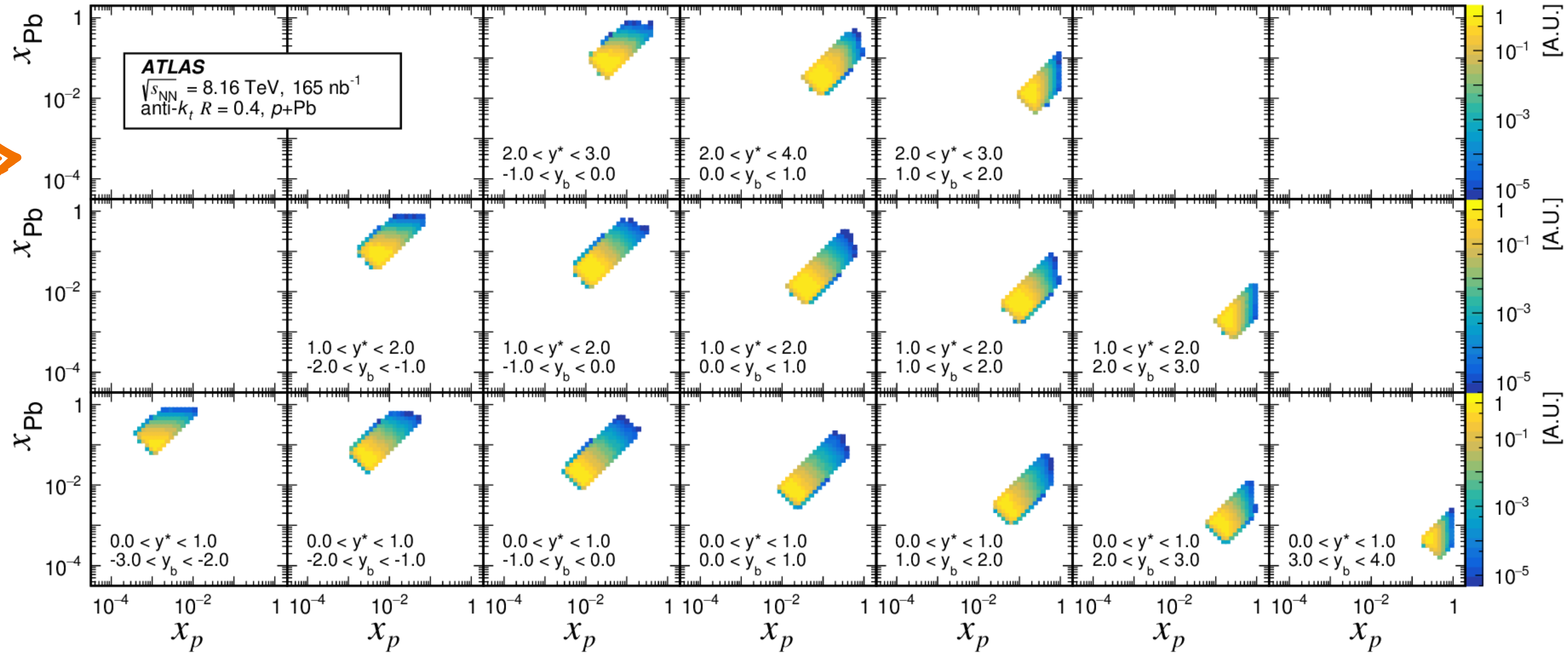
Eskola et al.,
Eur.Phys.J. C79 (2019) no.6, 511

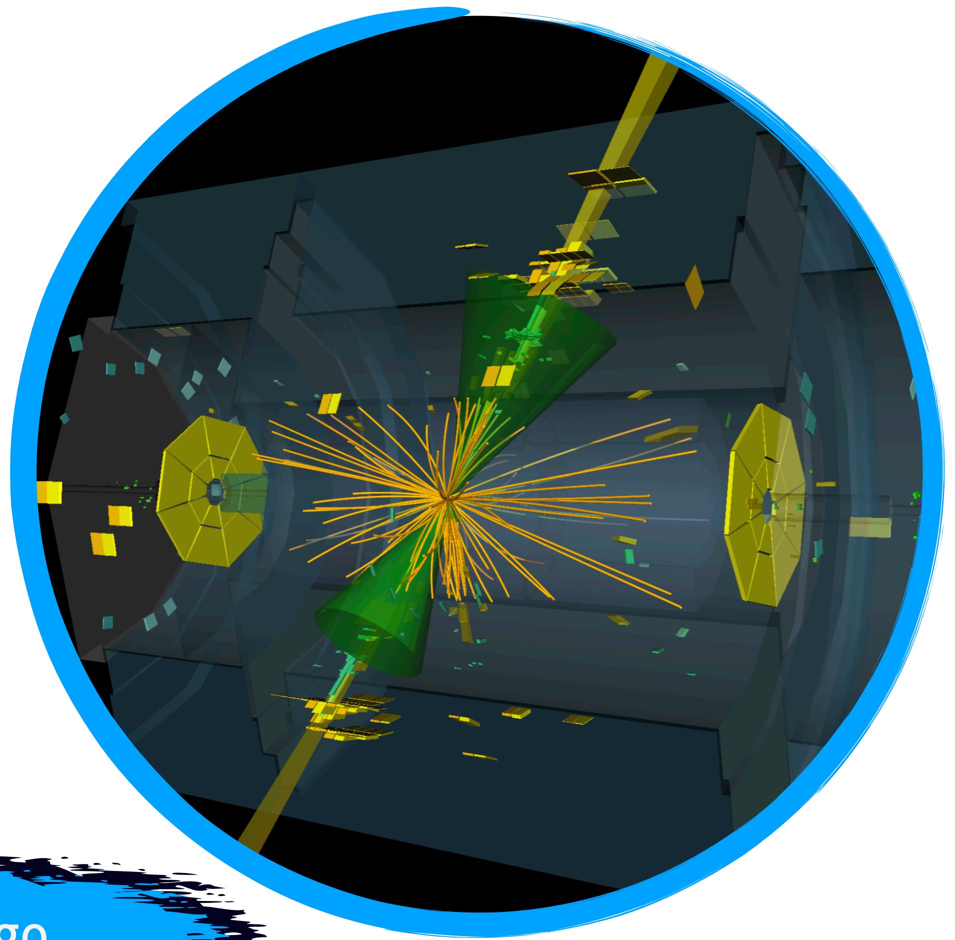
DIJETS IN P+PB FOR NPDF CONSTRAINTS: ATLAS INPUT

Adapted from **Eur. Phys. J. C (2022) 82:413**



Dijet in p+Pb @ 8.16 TeV measured by ATLAS using the full acceptance of the calorimeter explore a wide kinematic range

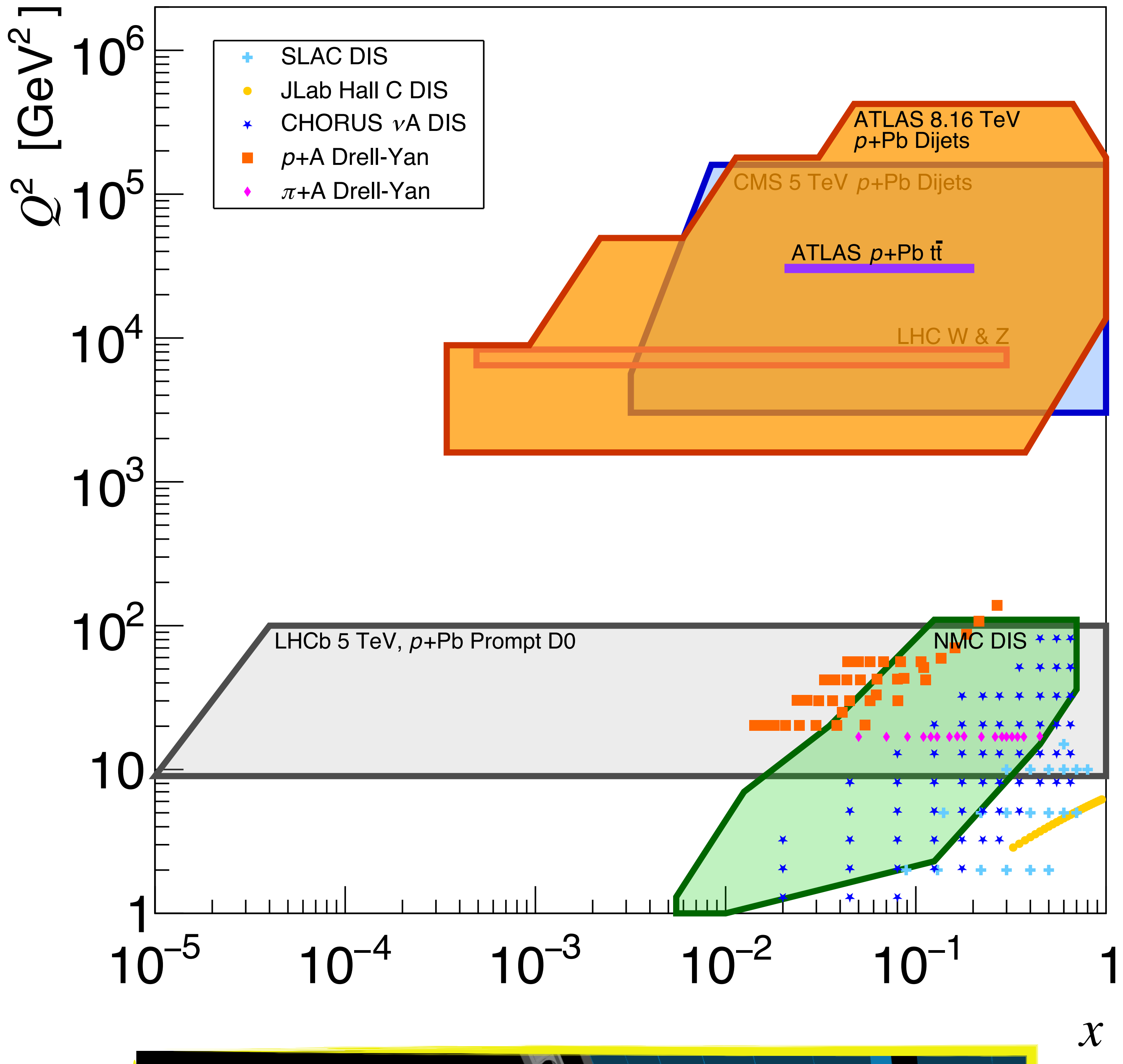


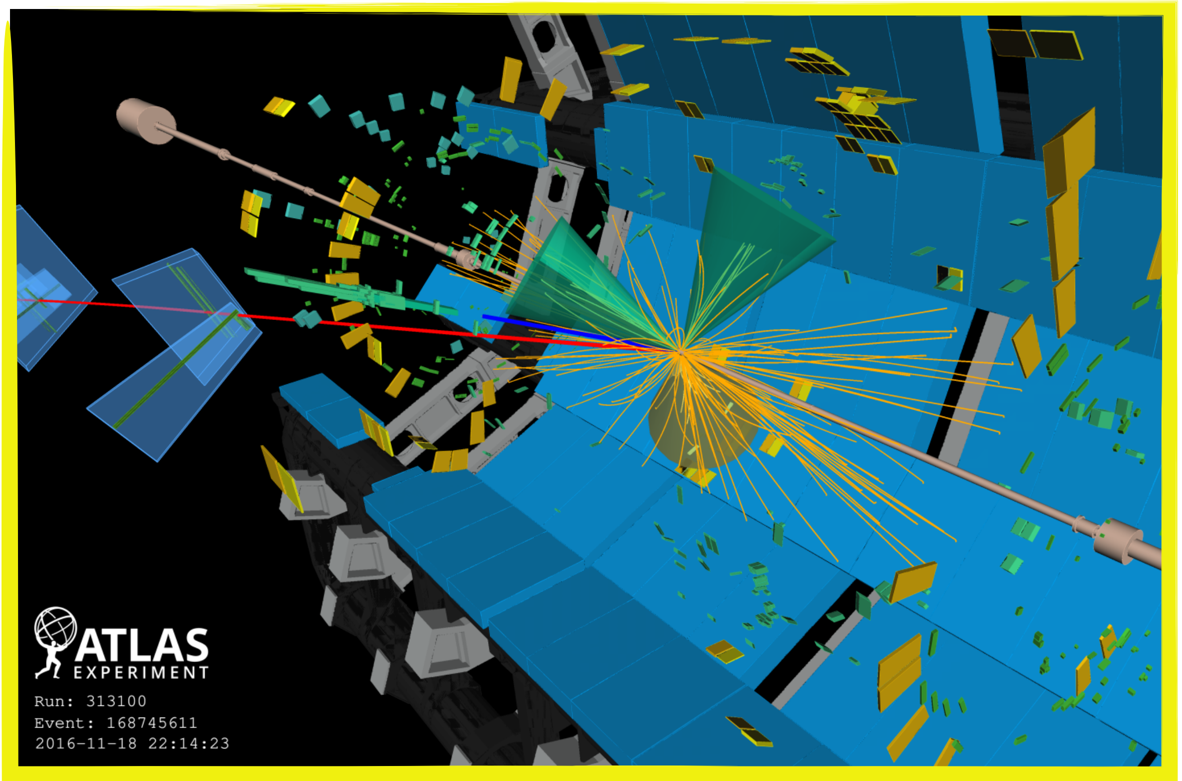


ONGOING MEASUREMENT OF DIJET PRODUCTION OVER ~4 ORDERS OF MAGNITUDE IN x_p, x_{Pb} !

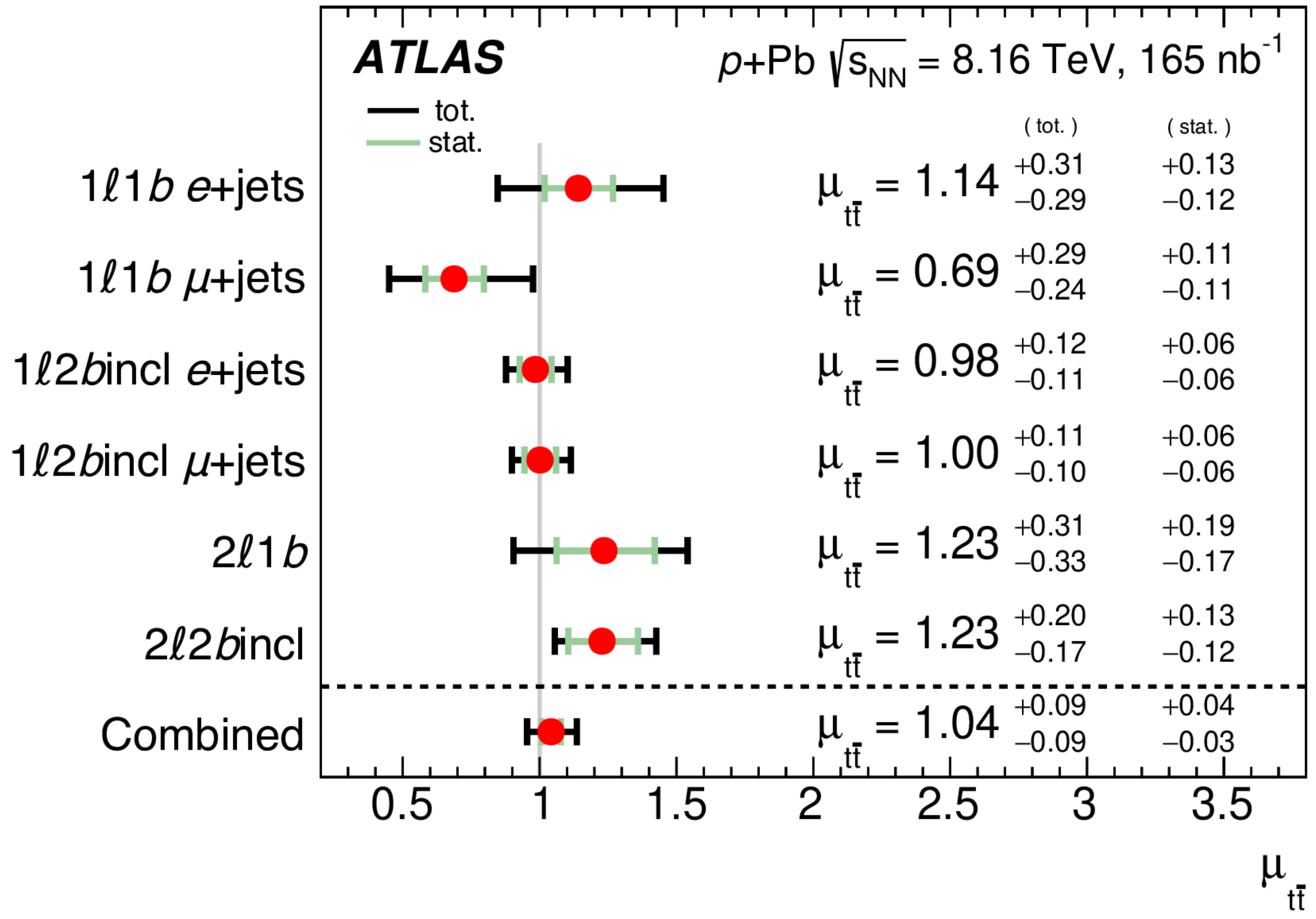
NPDF STUDIES VIA $t\bar{t}$ PRODUCTION IN P+PB

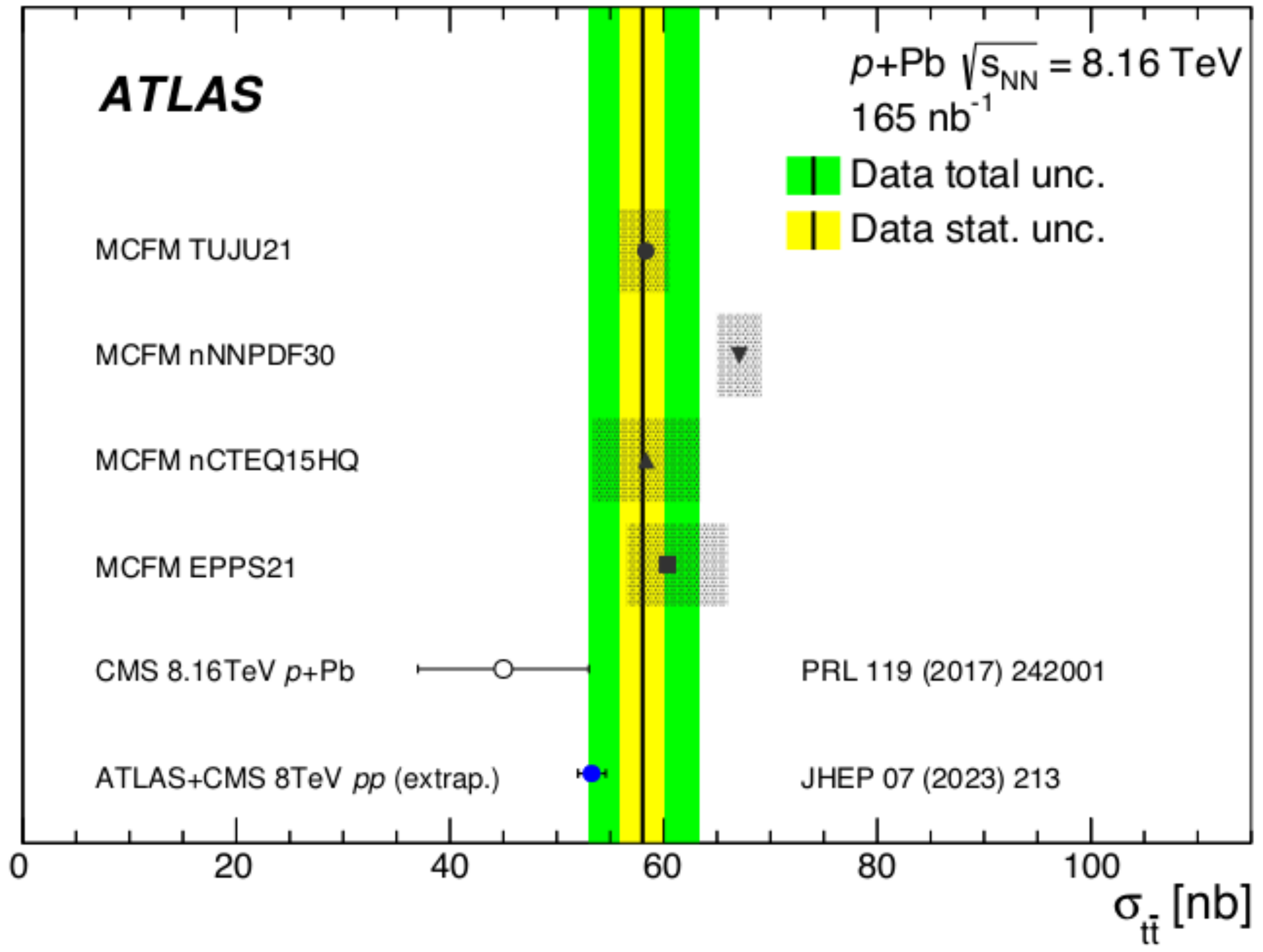
Adapted from **Eur. Phys. J. C (2022) 82:413**





- Top quarks provide novel probes of nuclear modifications of parton distribution functions (nPDF) [**H.Khanpour et al., PRD 93, 014026 (2016)**].
- $t\bar{t}$ cross-section measured in p+Pb in the combined ℓ+jets and dilepton channels
  - ➡First measurement including the dilepton channels
  - ➡Most precise $t\bar{t}$ cross-section measurement in nuclear collisions to date
- Good agreement with NNLO calculation based on several nPDF sets

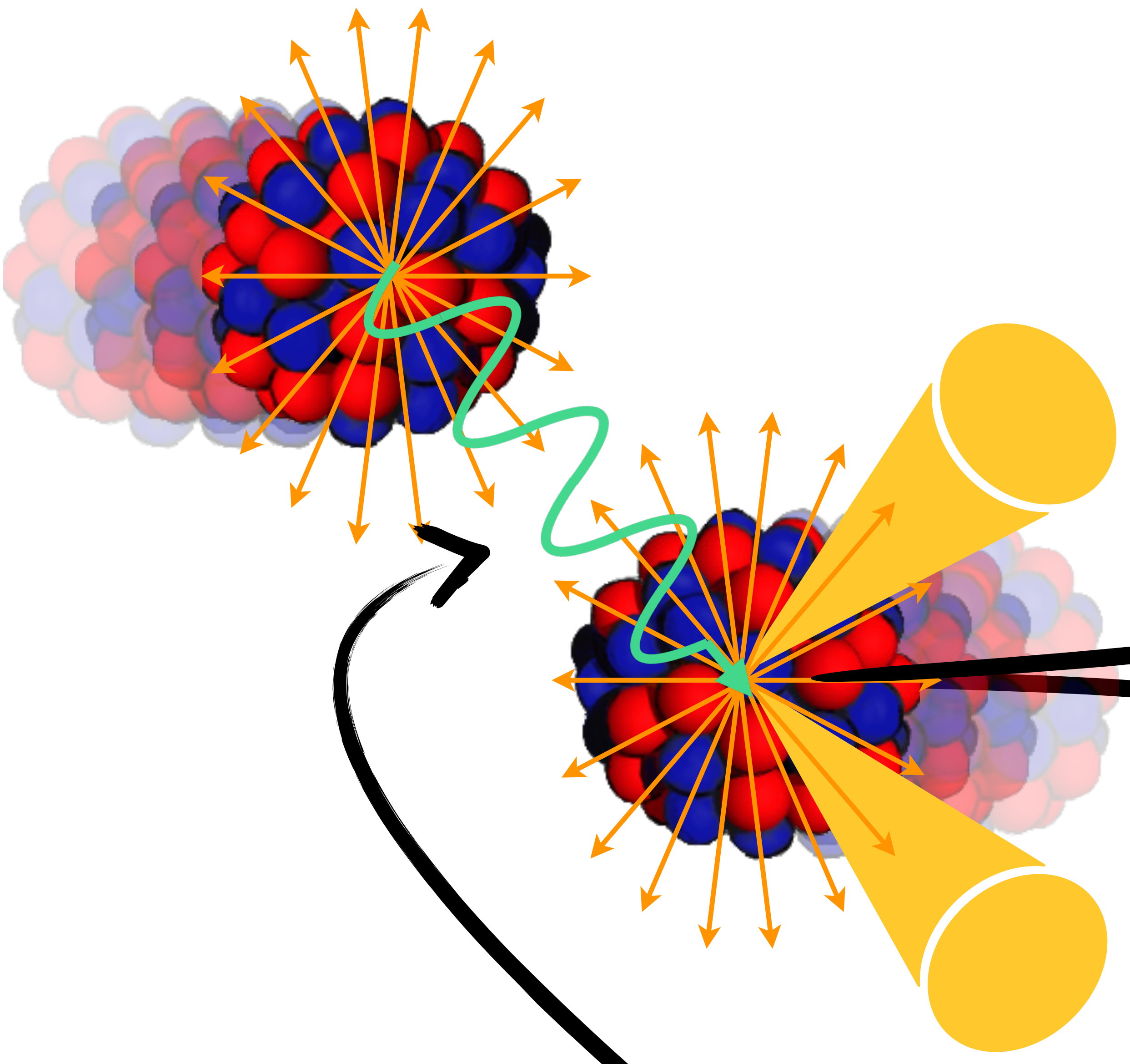




$$\sigma_{t\bar{t}} = 58.1 \pm 2.0\,(\text{stat.})\,^{+4.8}_{-4.4}(\text{syst.})\,\text{nb}$$

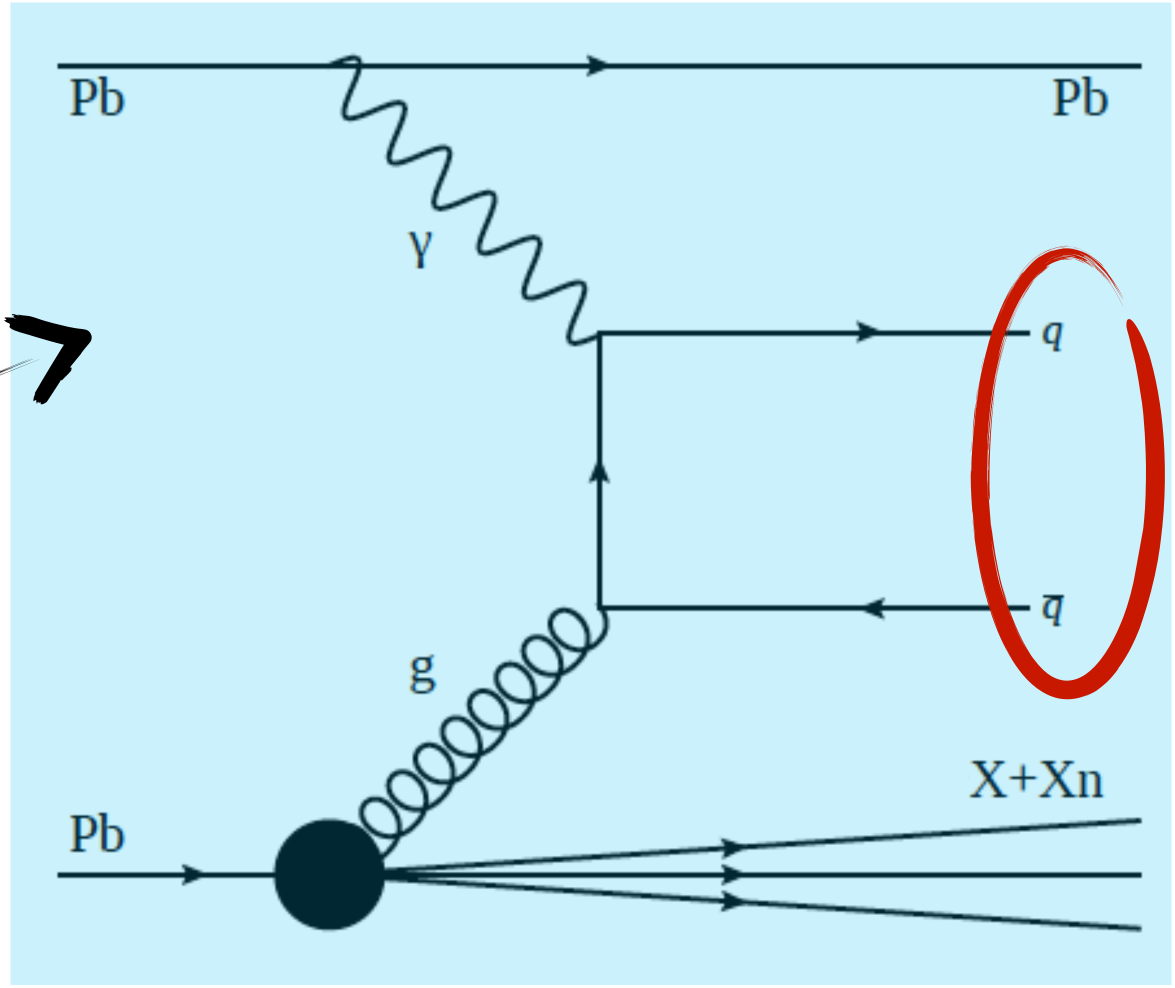
arXiv 2405.05078 - sub. JHEP

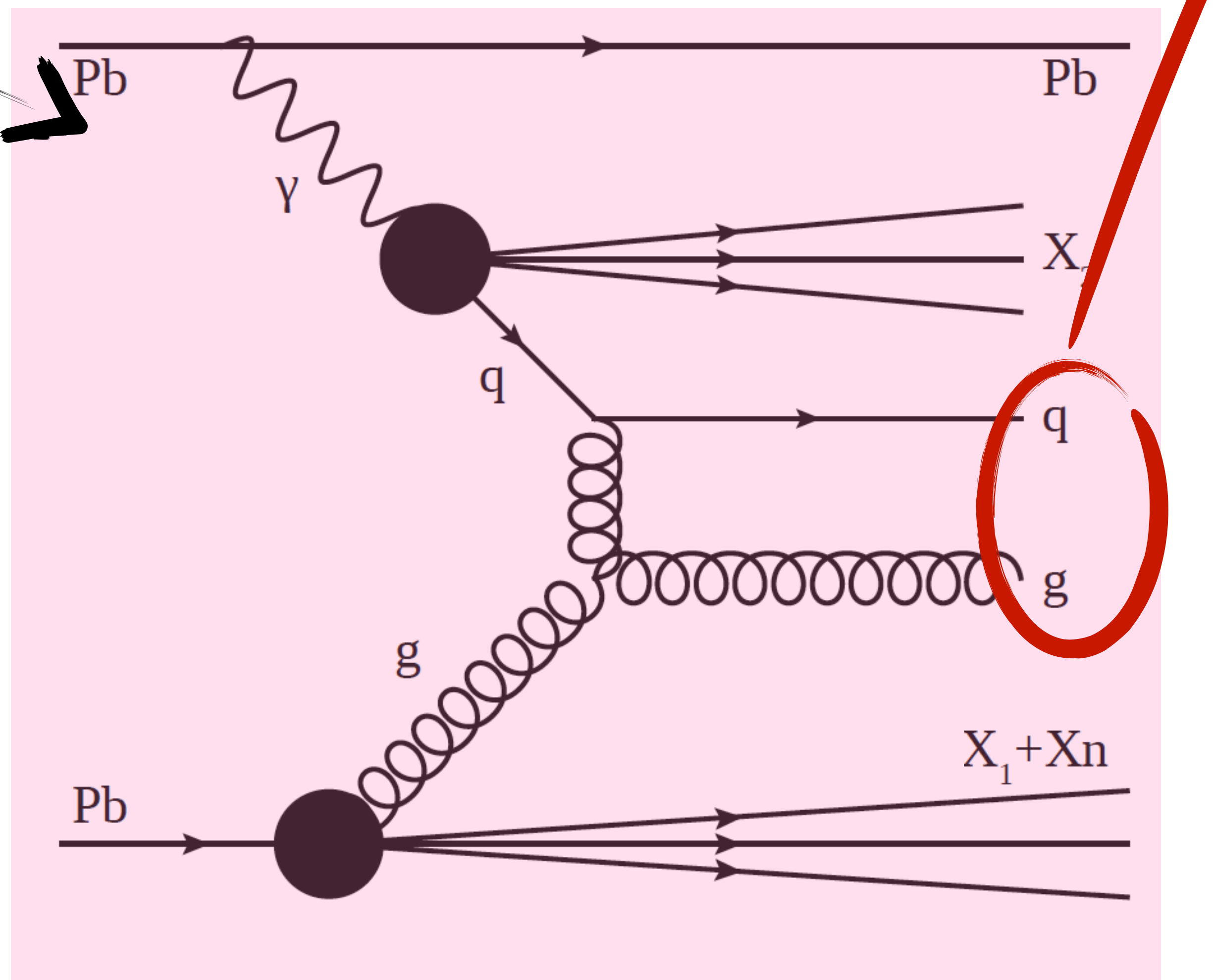
ATLAS UPC DIJETS



"**Direct**" photons scatter off the nucleus

"**Resolved**" photons scatter through a virtual hadronic excitation of the photon



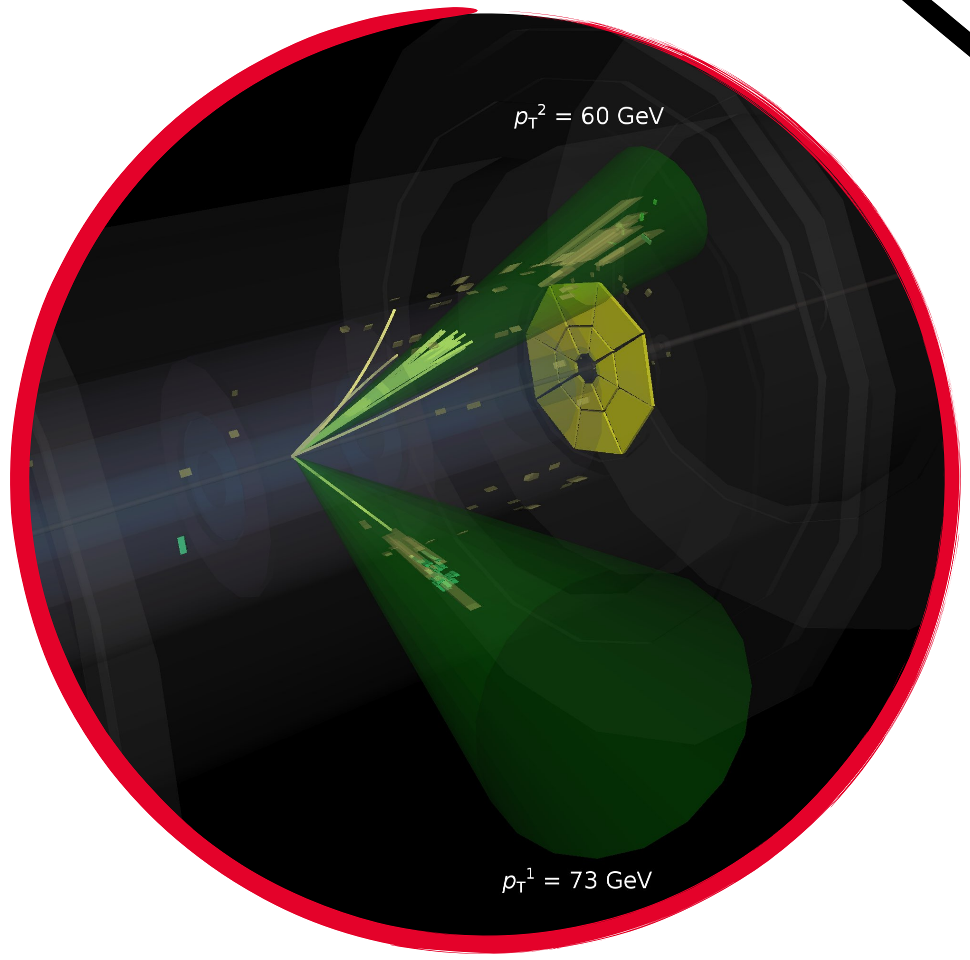


Jet kinematics are proxy to hard-scattering kinematics

$$H_{\mathrm{T}} = \sum_i p_{\mathrm{T}}^i$$

$$x_{\mathrm{A}} = \frac{M_{\mathrm{jets}} e^{-y_{\mathrm{jets}}}}{\sqrt{S_{\mathrm{NN}}}}$$

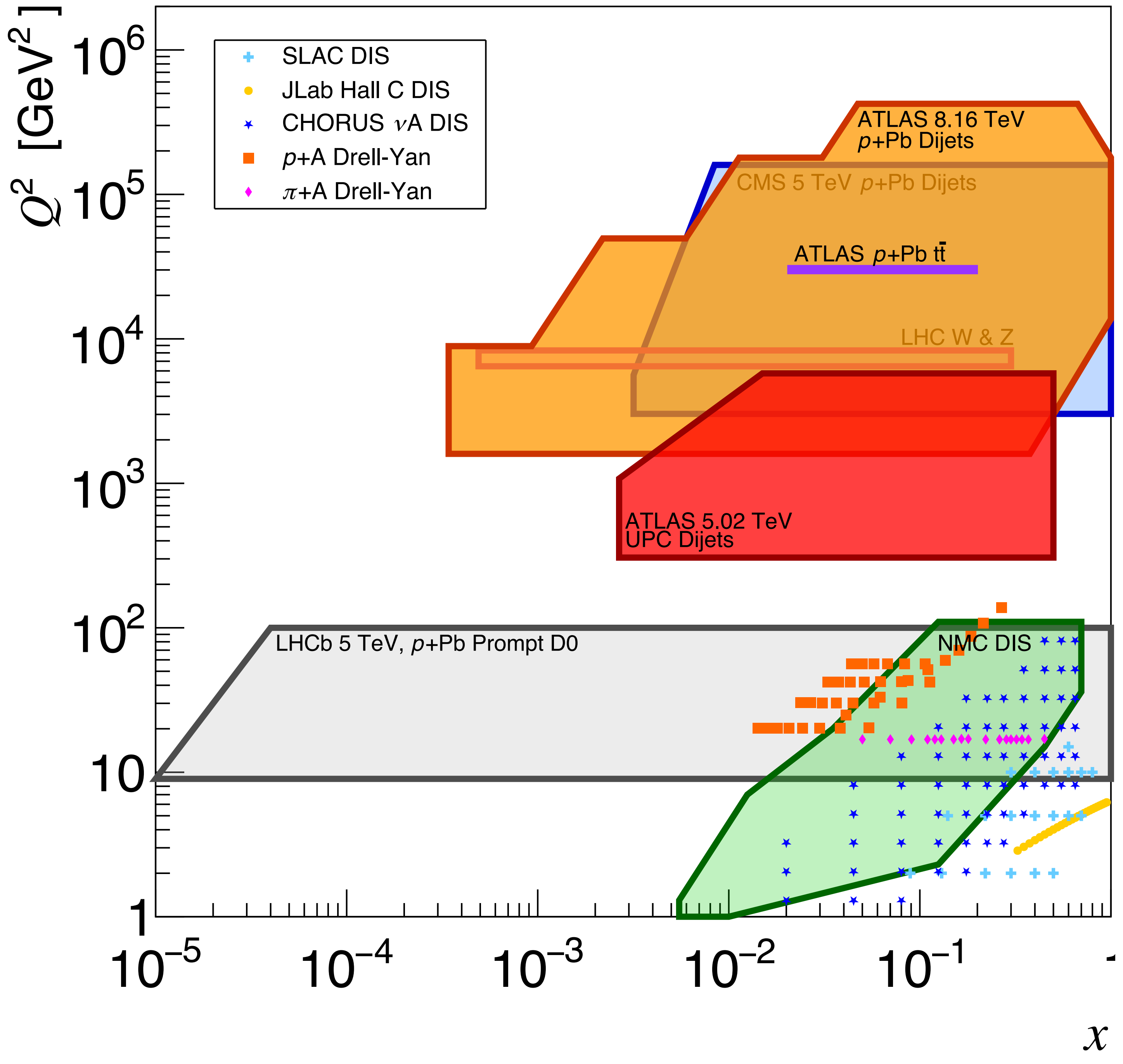
$$z_{\gamma} = \frac{M_{\mathrm{jets}} e^{+y_{\mathrm{jets}}}}{\sqrt{S_{\mathrm{NN}}}}$$

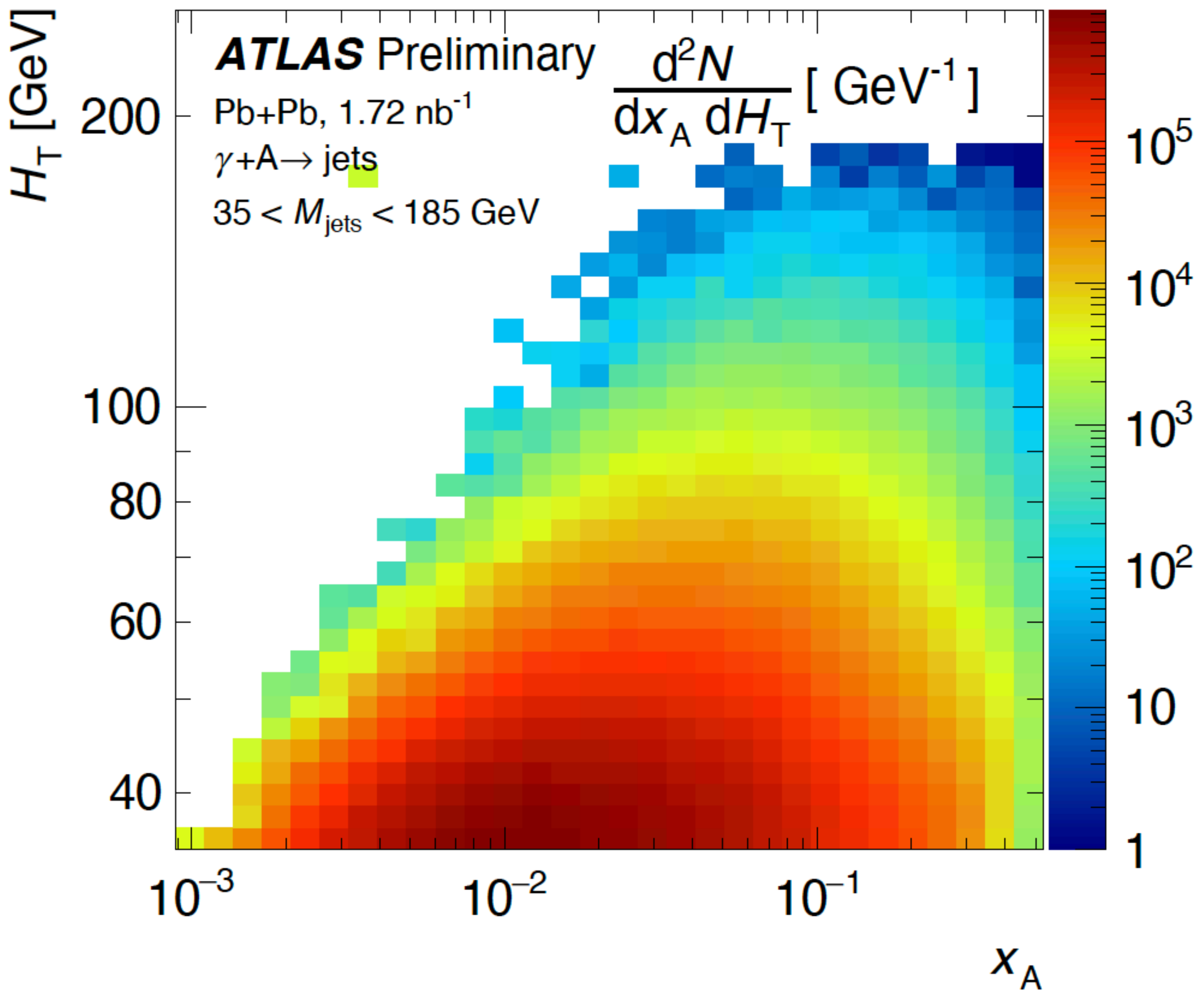


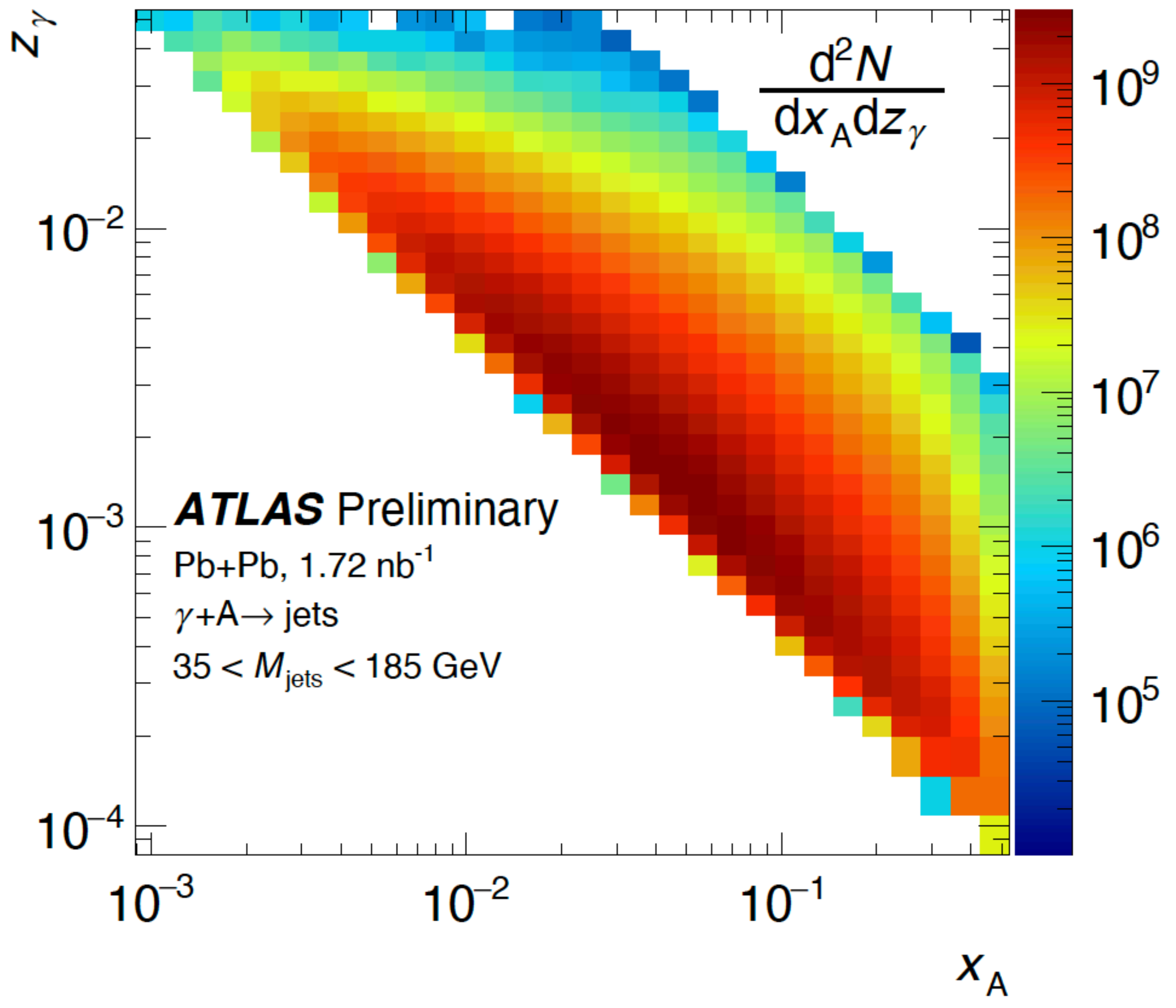
Photons emitted in UPCs can scatter off the nucleus and resolve nuclear partons!

ATLAS UPC DIJETS

Adapted from **Eur. Phys. J. C (2022) 82:413**







ATLAS-CONF-2022-021

Jet kinematics are proxy to hard-scattering kinematics

$$H_T = \sum_i p_T^i$$

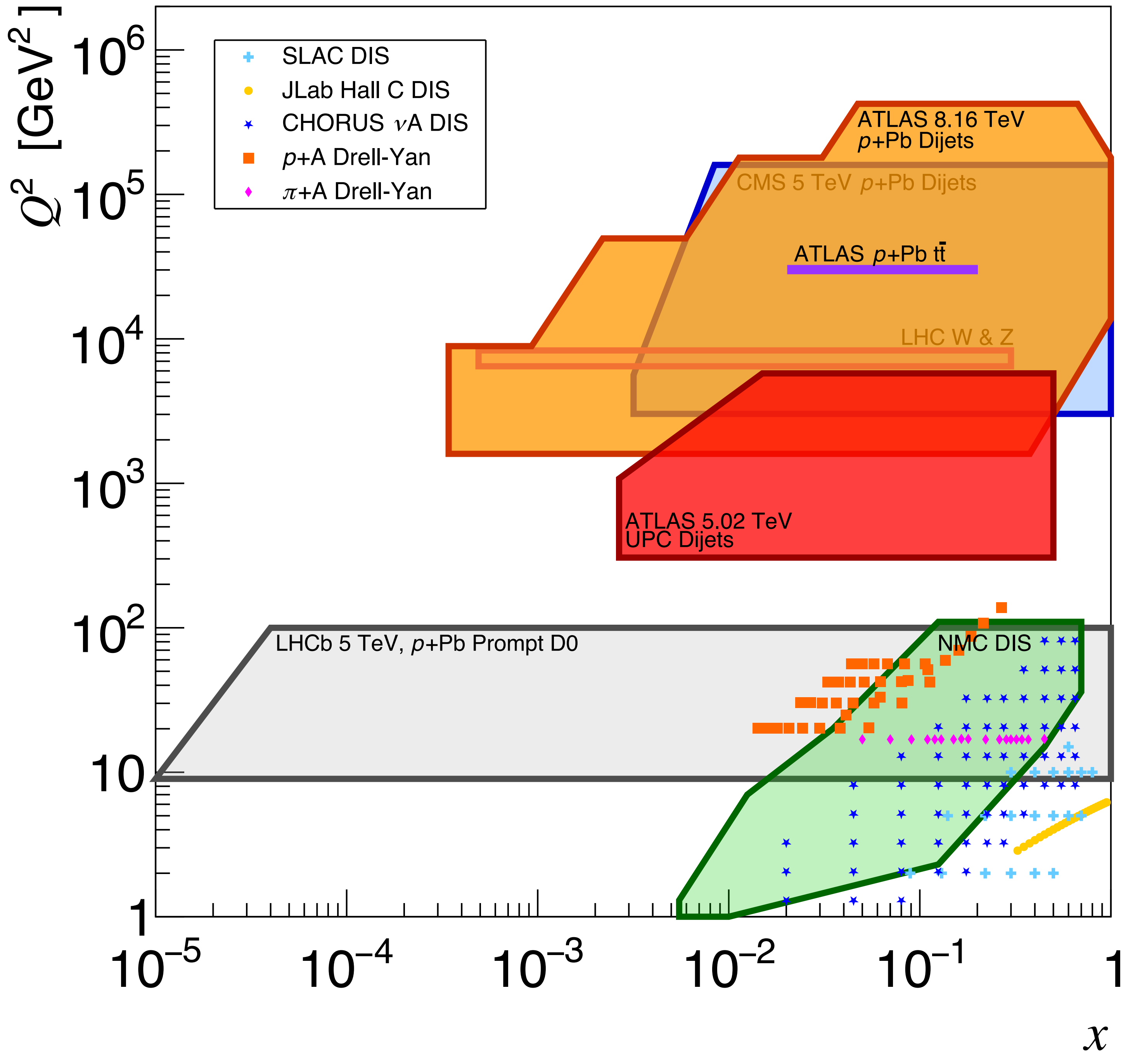
$$x_A = \frac{M_{jets} e^{-y_{jets}}}{\sqrt{S_{NN}}}$$

$$z_\gamma = \frac{M_{jets} e^{+y_{jets}}}{\sqrt{S_{NN}}}$$

- nPDF are **poorly constrained** at intermediate Q^2 and low-*x*
- Nuclear shadowing at low-x draws particular theoretical interest (see PoS HardProbes2018 (2018) 118)

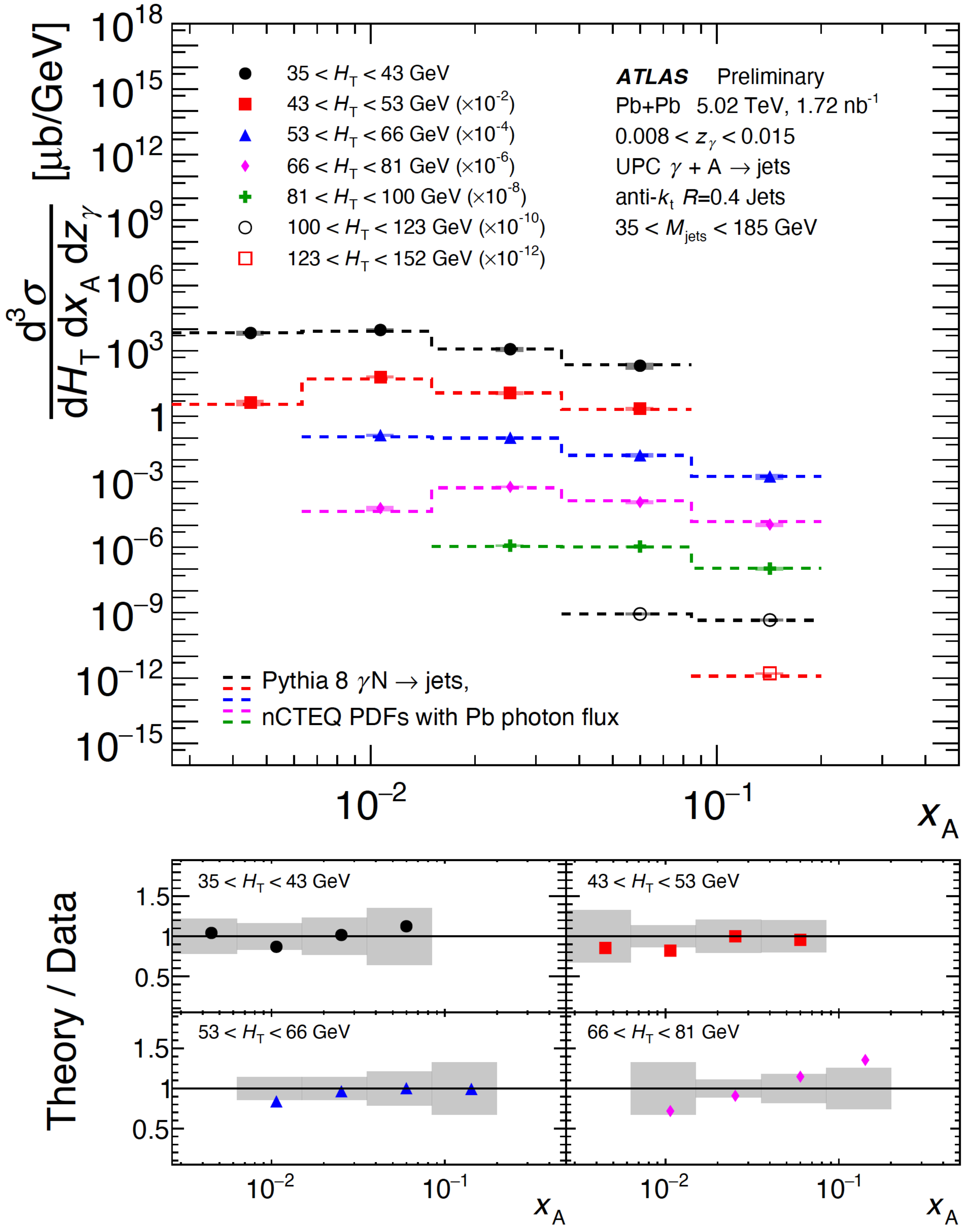
SCANNING THE NUCLEUS USING UPC PHOTONS

Adapted from **Eur. Phys. J. C (2022) 82:413**



The measured cross-sections are **unfolded in 3 dimensions** to correct for detector effects

ATLAS-CONF-2022-021



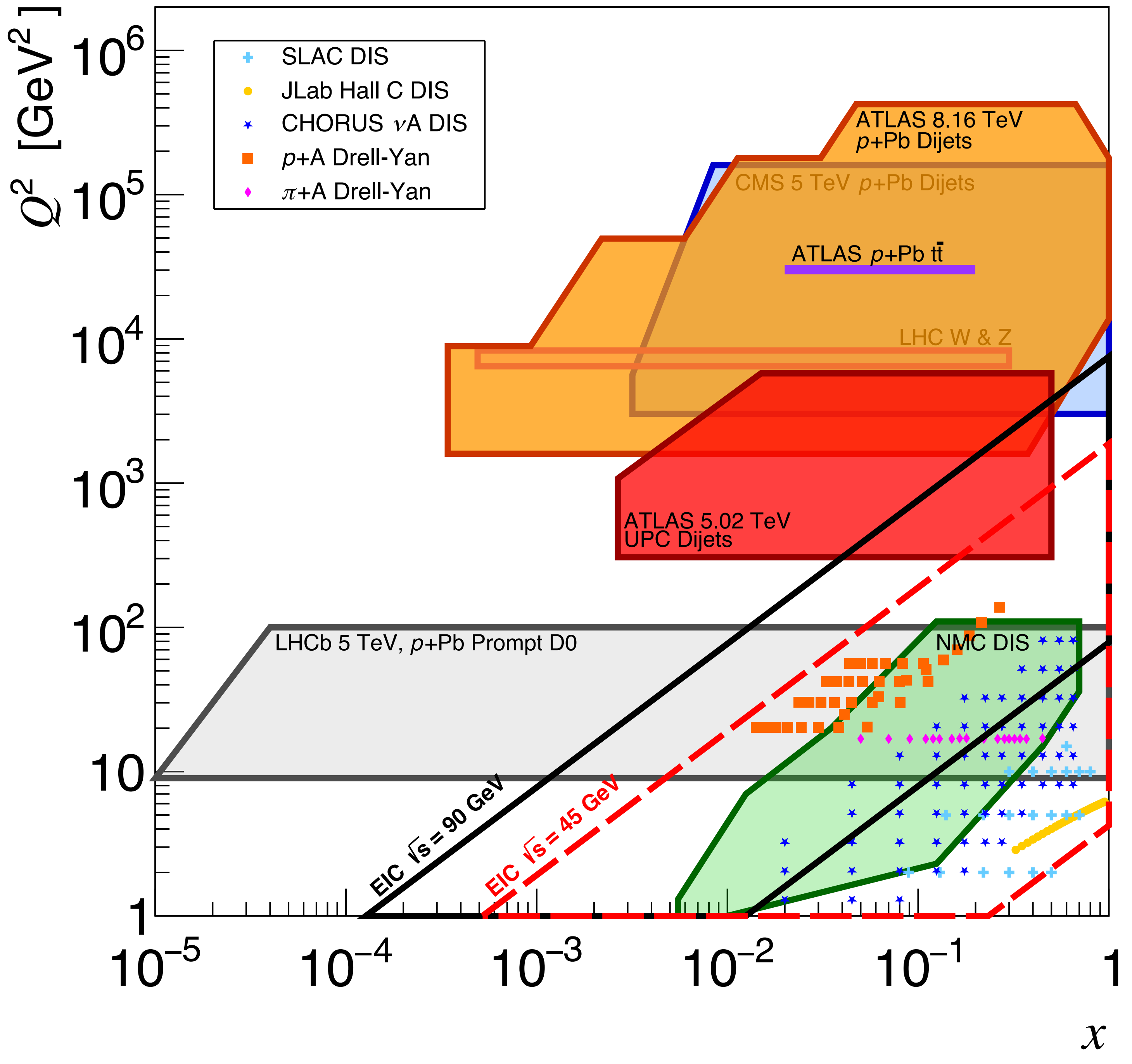
Comparison with Pythia8 with photon flux and nuclear breakup description

Final analysis with improved systematic uncertainties near completion

Final results will be coming soon!

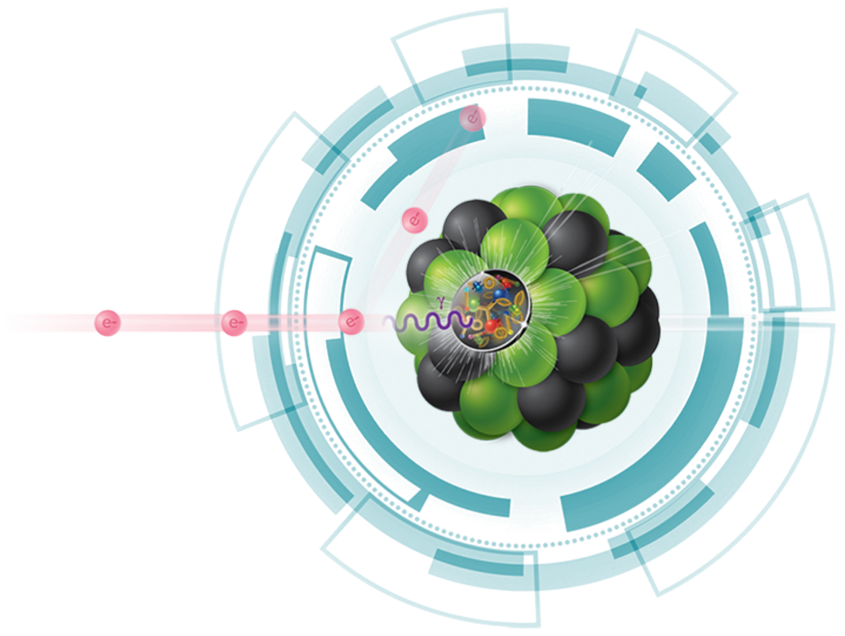
UPC DIJETS: AN LHC - EIC PHYSICS BRIDGE

Adapted from **Eur. Phys. J. C (2022) 82:413**



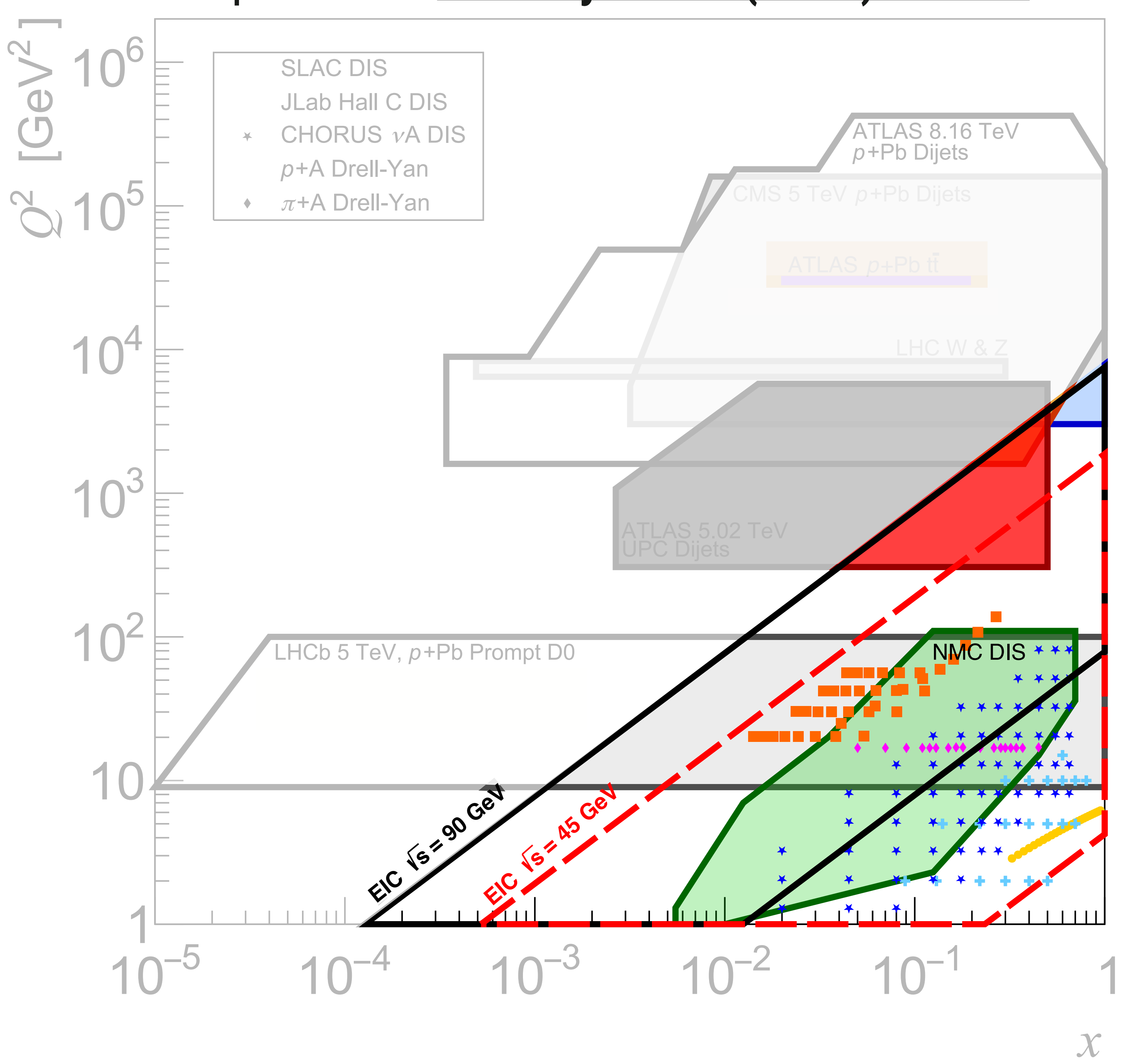
UPC dijets represent a natural **bridge** between the LHC and the EIC:

- Continuity in the (x,Q^2) phase space coverages
- Investigating the nucleus structure with photon probes in both cases

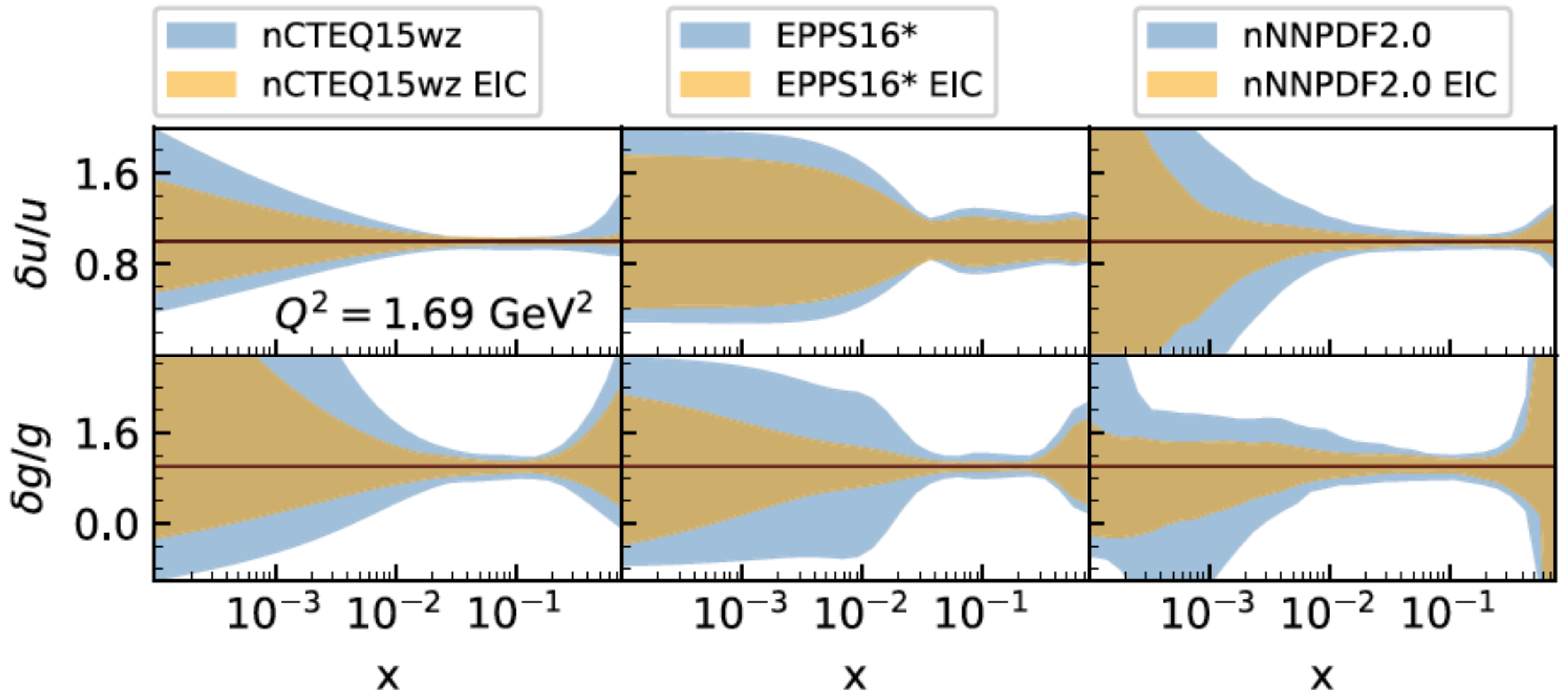


THE EIC CONTRIBUTION

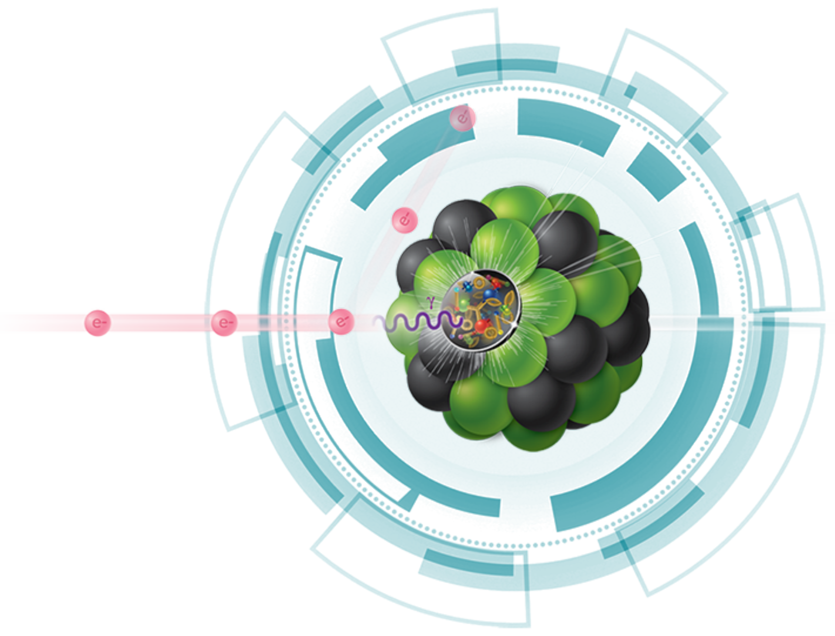
Adapted from **Eur. Phys. J. C (2022) 82:413**



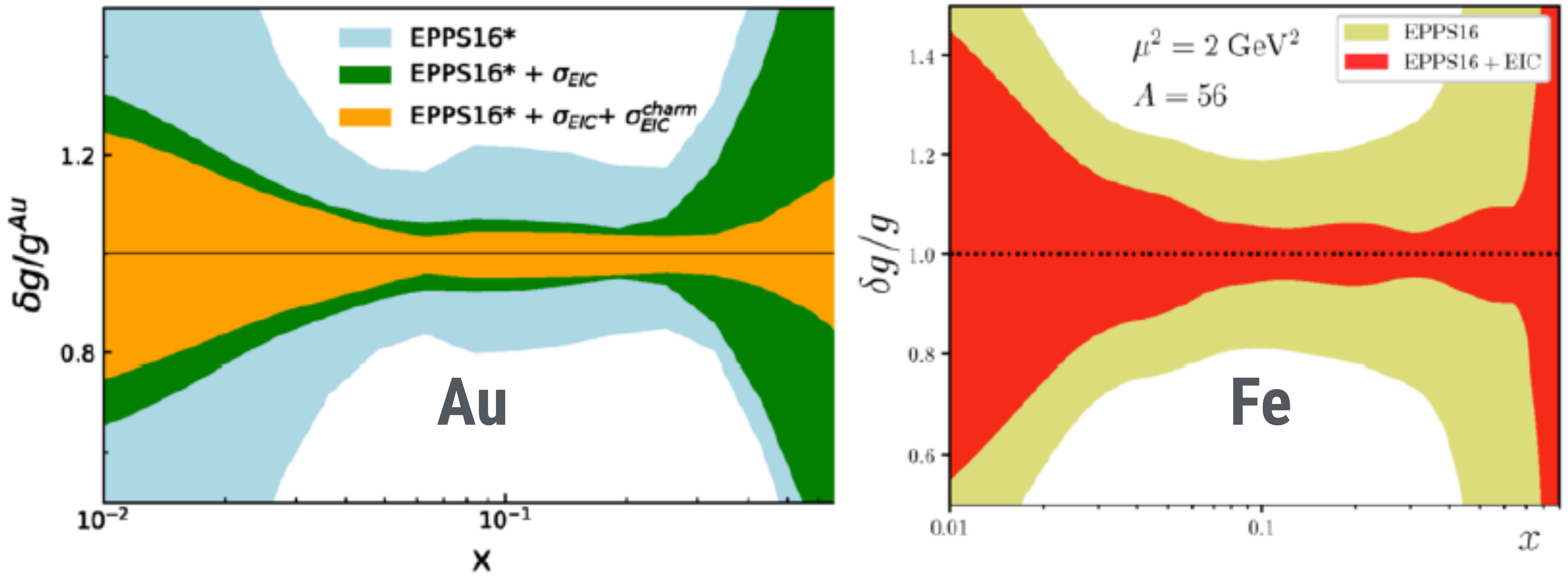
Nucl.Phys.A 1026 (2022) 122447



Precision measurements to constraint nPDF at low-x



e⁻+A: much cleaner compared to p+A; easier to disentangle cold nuclear matter effects from other higher twist effects

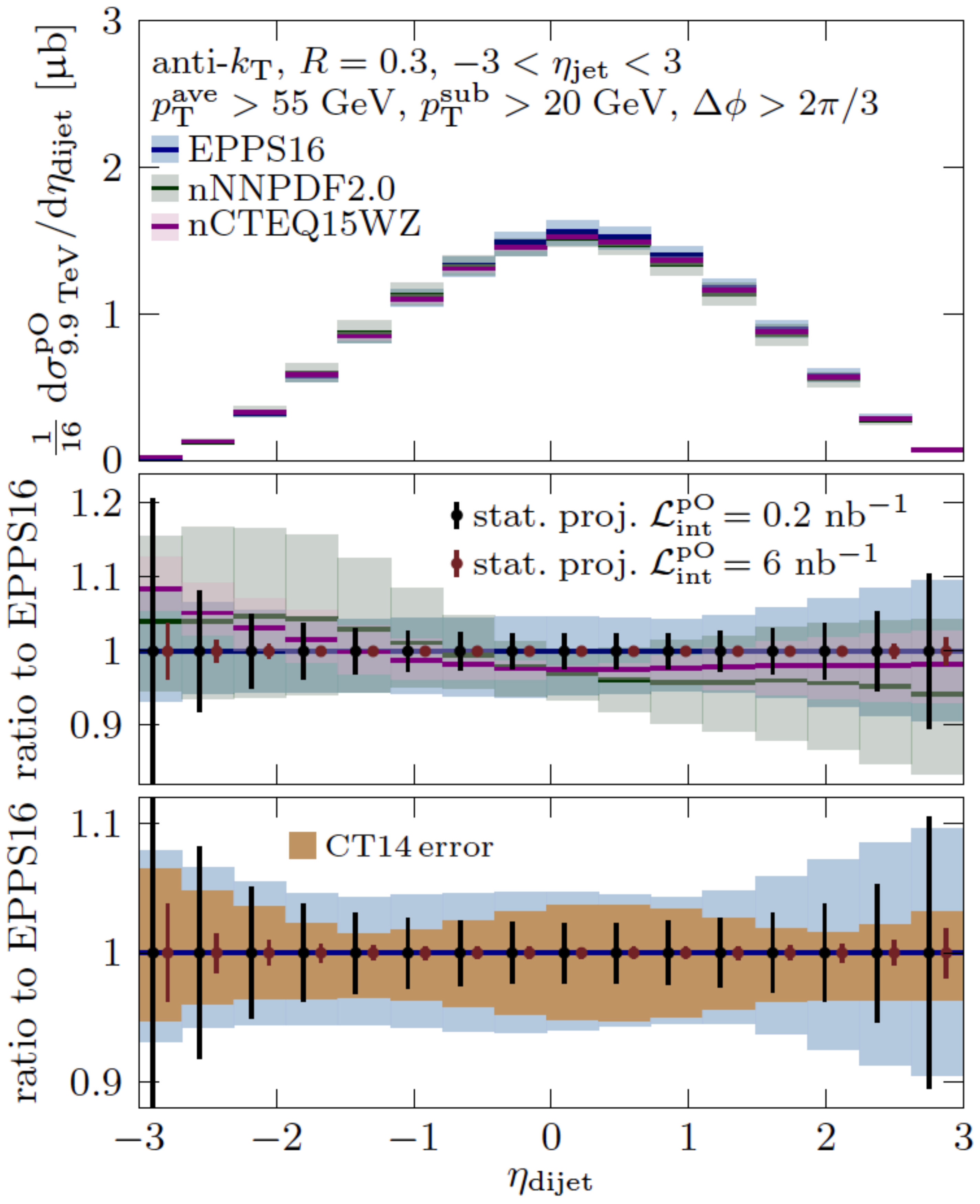


A-dependence of nPDFs

NPDF STUDIES AT ATLAS: NEAR FUTURE

- 1.5/2 nb^{-1} of **p+O data** taking (first ever @ LHC!) expected next year
  - Limited luminosity - officially an 'LHC pilot run'
  - Still - great physics potential - first opportunity to explore O nuclear structure
    - Also tied to understanding O+O collisions @ LHC (Run 3 novelty)!
- **Rest of Run 3 and beyond:** High statistic sample for UPC nPDF studies; no p+Pb run scheduled at the moment; outlook may change if Run 3 is extended by one full year
  - The community recently gathered at CERN (**Physics with high-luminosity proton-nucleus collisions at the LHC - Workshop**) to discuss possible scenarios on short and medium-term
  - p+A program at LHC will continue into Run 4 - upgraded ATLAS detector

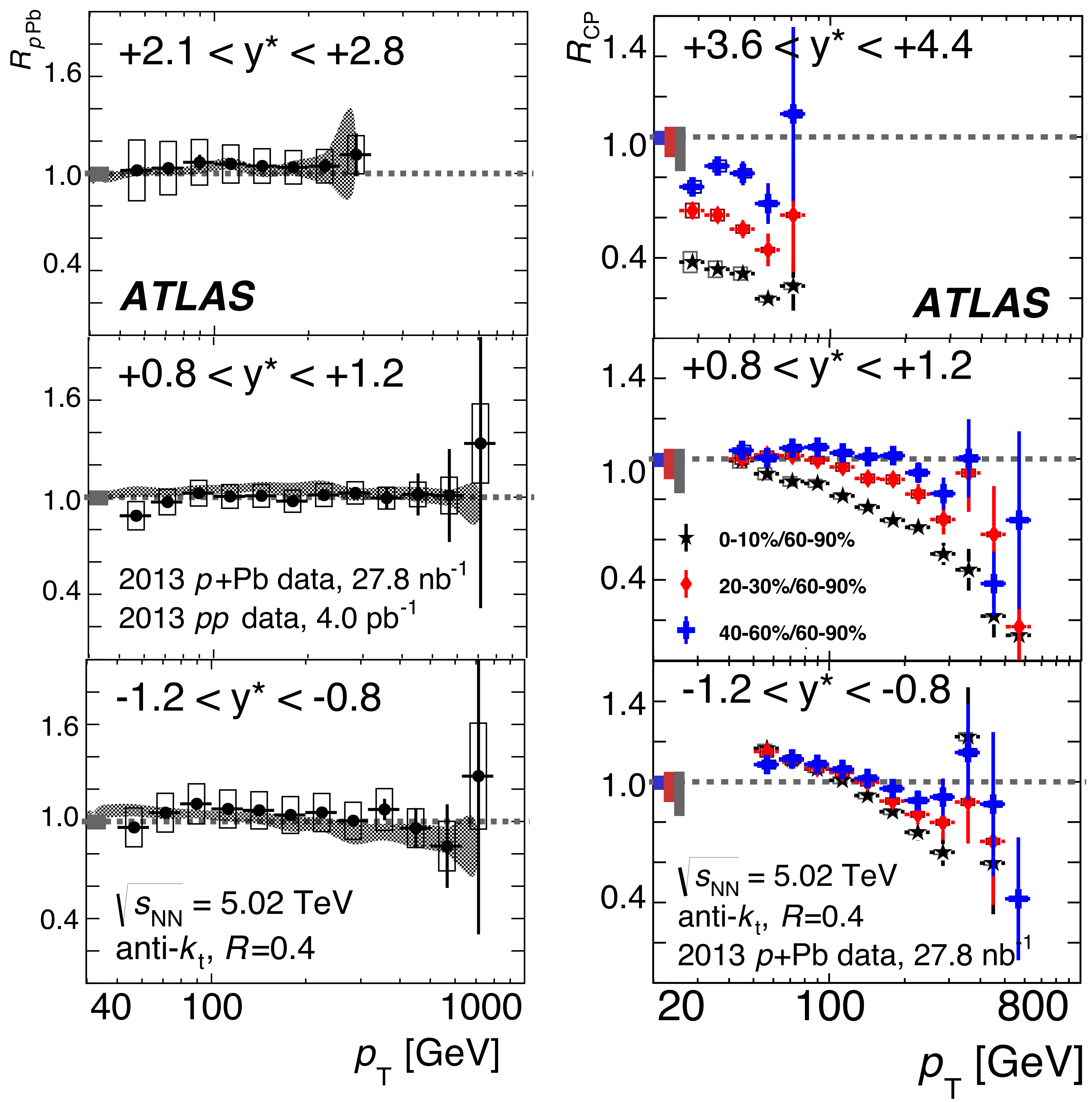
P.Paakkinen
PRD 105, L031504 (2022)



Dijet measurements to inform O nPDF parameterizations

Color fluctuation effects

JET PRODUCTION AND EVENT ACTIVITY BIAS IN P+PB

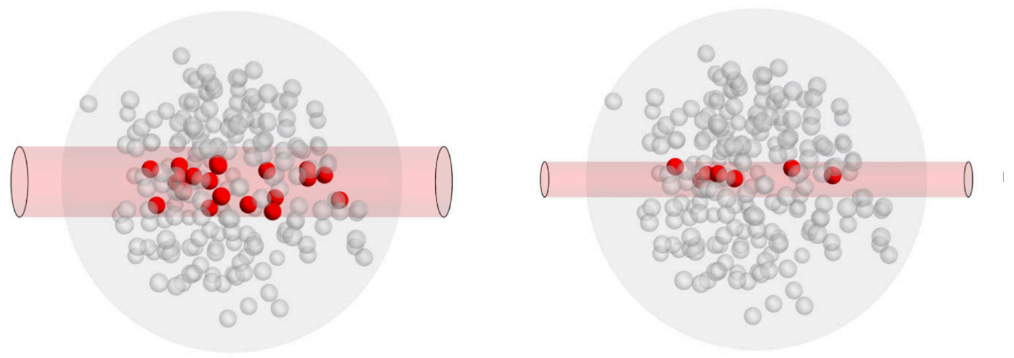


PLB 748 (2015) 392–413:

- R_{pPb} results: no evidence for large modification of the total yield of jets relative to the geometric expectation observed
- R_{CP} results: suppression of central events compared to peripheral found to be function of the jet energy, suggesting direct link to initial state kinematics

COLOR FLUCTUATIONS EFFECTS IN JET EVENTS

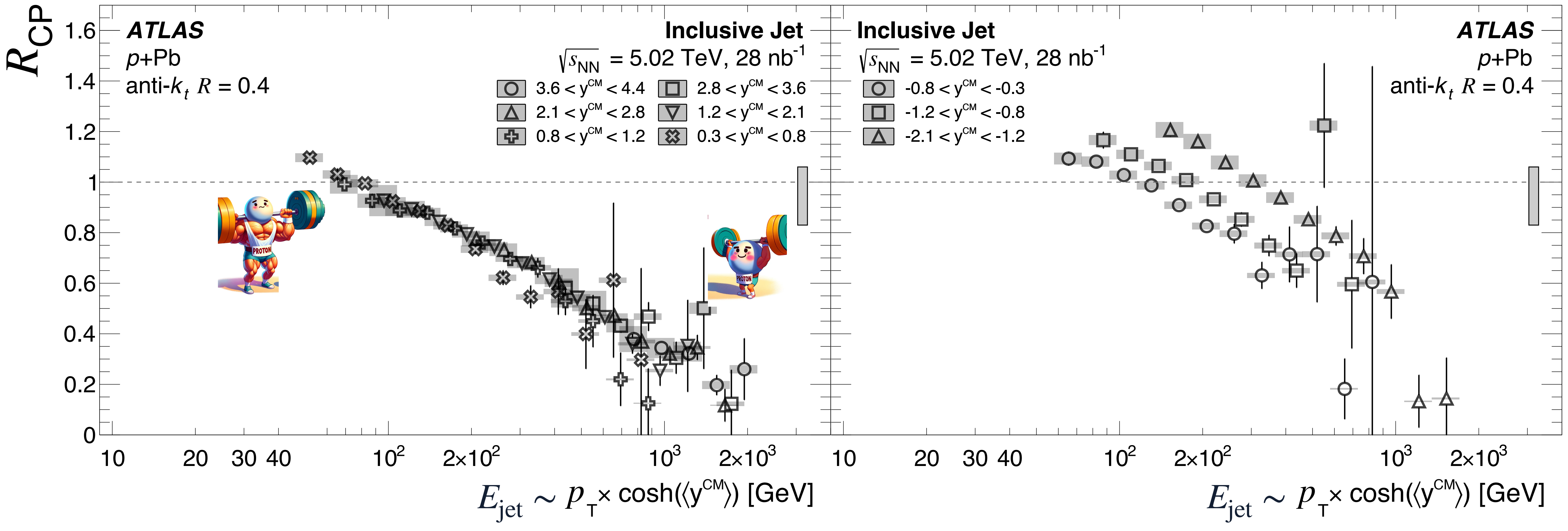
_p_ w/ average configuration



_p_ w/ high-x parton

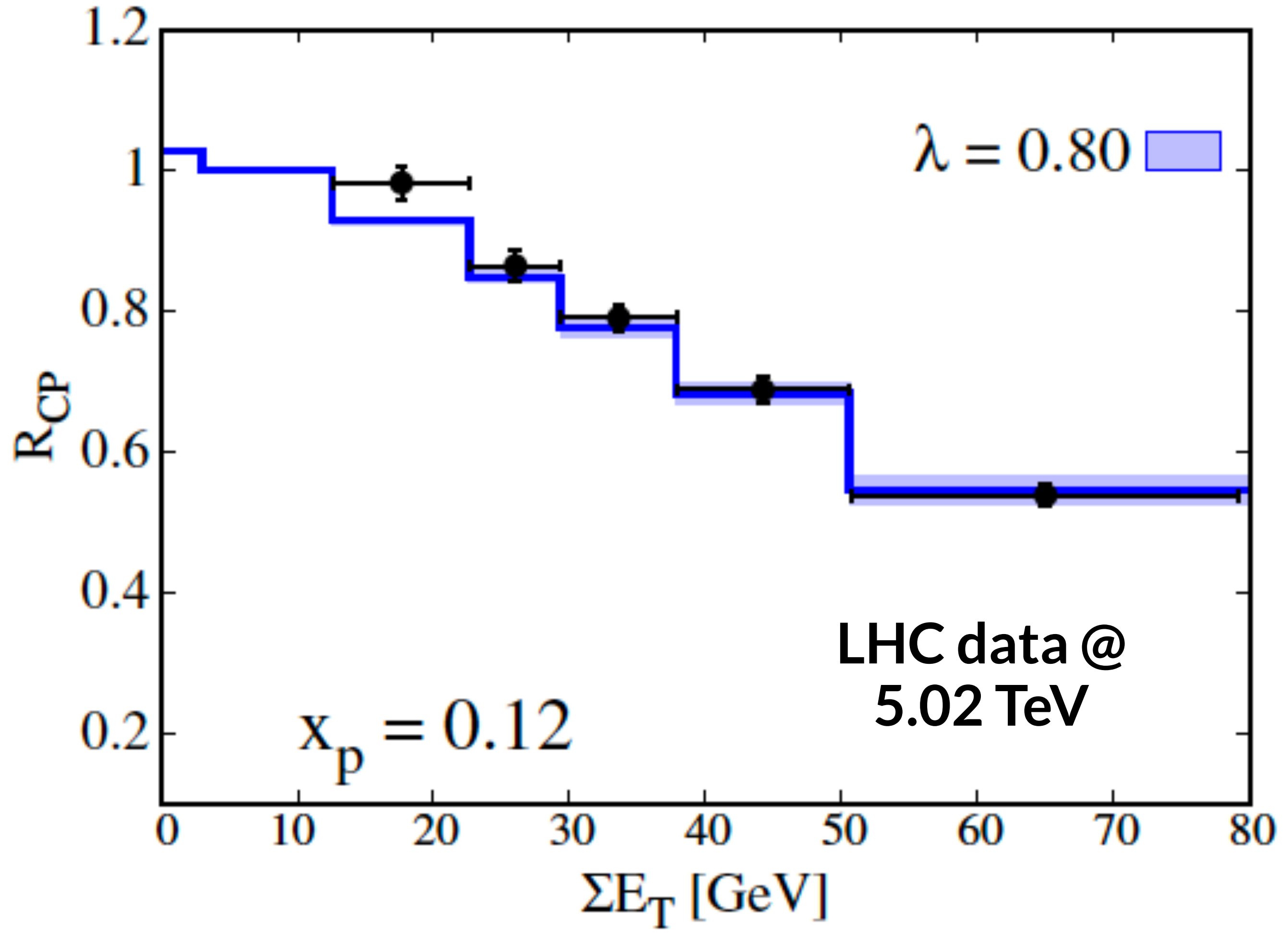
Alvioli et al.
PRD 98 (2018) 071502

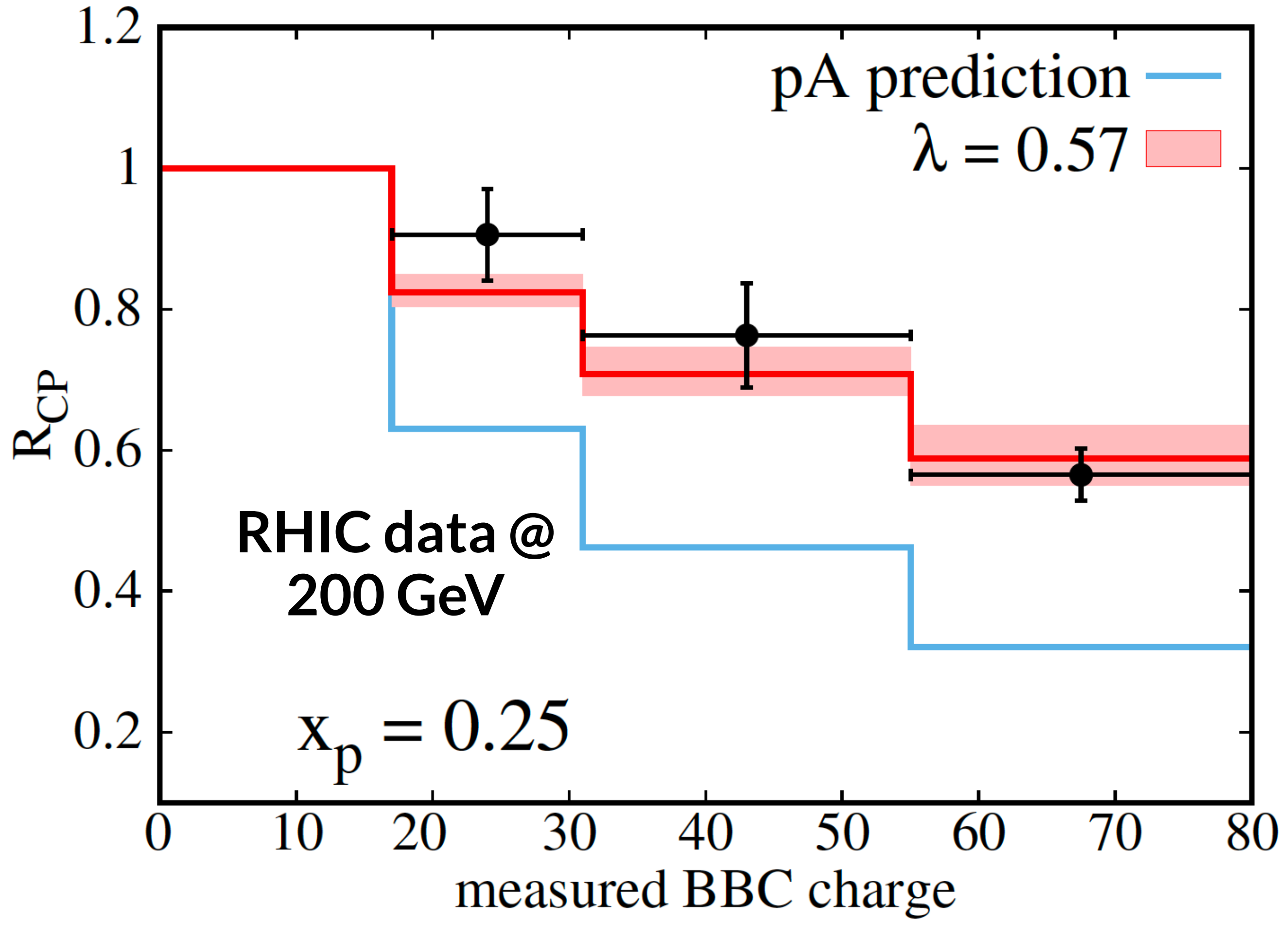
PLB 748 (2015) 392–413



_p_ containing a parton with large _x_ interacts with a nuclear target with a smaller than average cross-section and smaller than average size (***manifestation of color fluctuations***)

Model with x_p-dependent shrinking of the average interaction strength at a given collision energy capable of describing both RHIC and LHC data





COLOR FLUCTUATIONS EFFECTS IN DIJET EVENTS

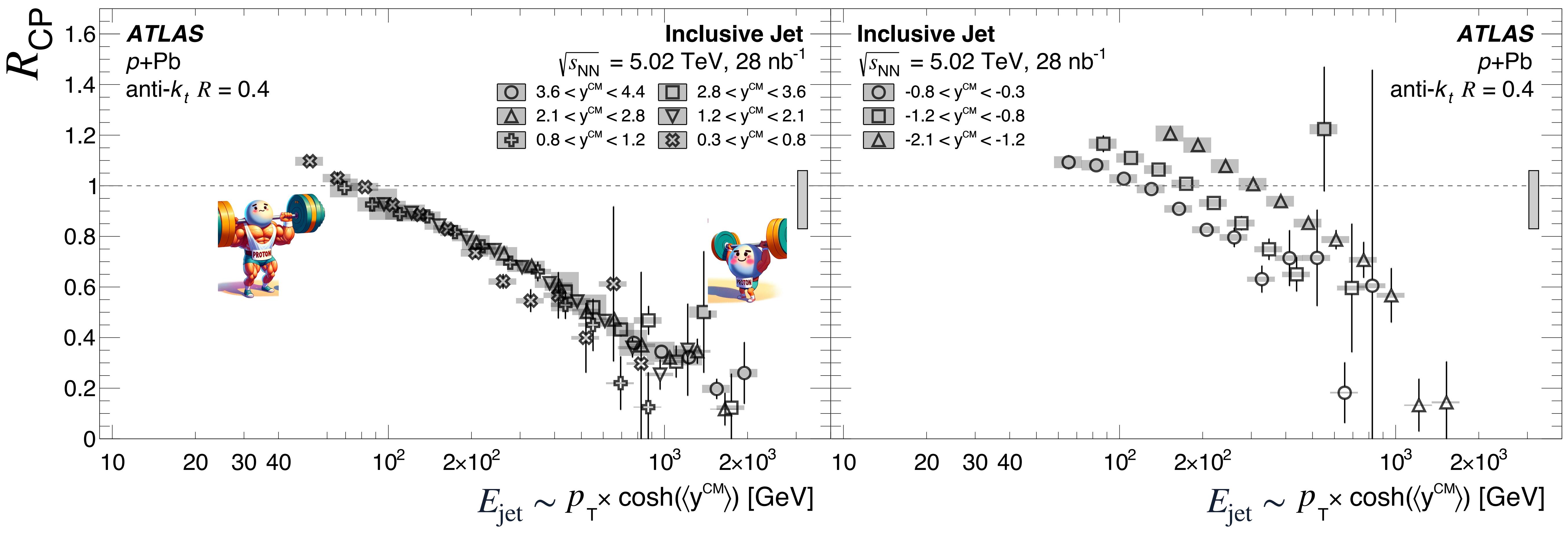
$$p_{T,Avg} = \frac{p_{T,1} + p_{T,2}}{2}, \quad y_b = \frac{y_1^{CM} + y_2^{CM}}{2} \quad y^* = \frac{|y_1^{CM} - y_2^{CM}|}{2}$$

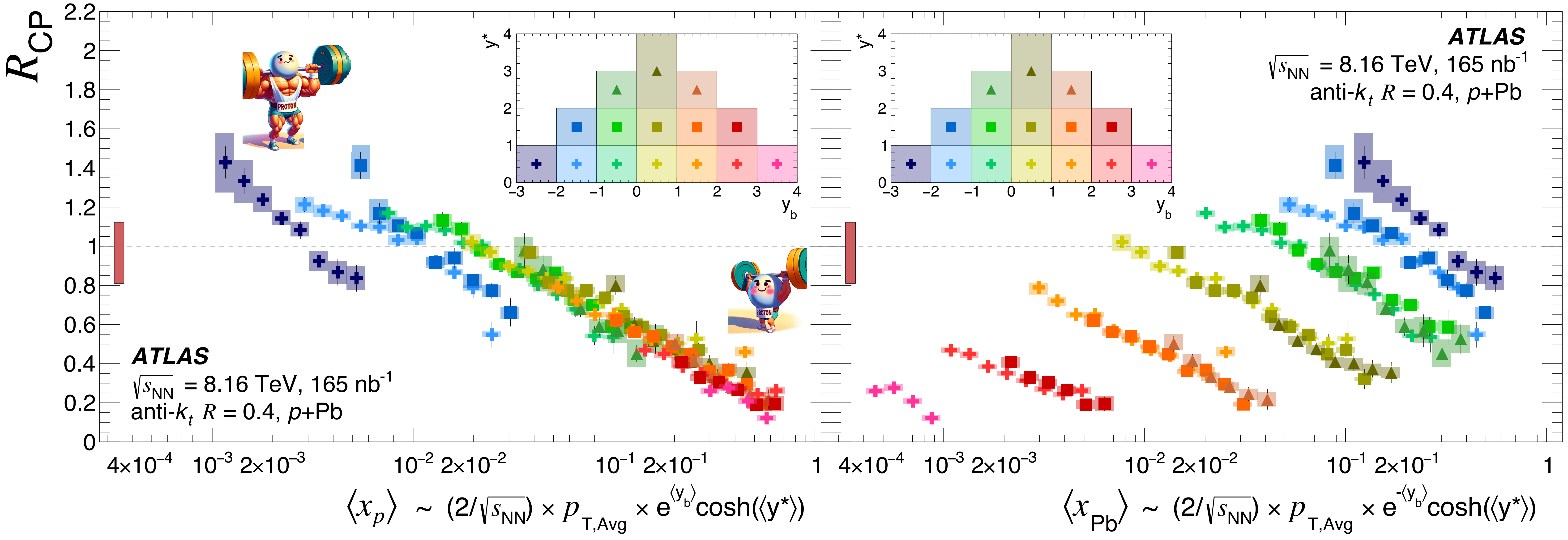
Dijets provide direct access to the kinematics of the hard-scattering

$$x_p \simeq \frac{2p_{T,Avg}}{\sqrt{s_{NN}}} e^{y_b} \cosh(y^*)$$

$$x_{Pb} \simeq \frac{2p_{T,Avg}}{\sqrt{s_{NN}}} e^{-y_b} \cosh(y^*)$$

PLB 748 (2015) 392–413





Striking scaling of the R_{CP} as a function of x_p!

Phys. Rev. Lett. 132 (2024) 102301

COLOR FLUCTUATIONS EFFECTS IN DIJET EVENTS

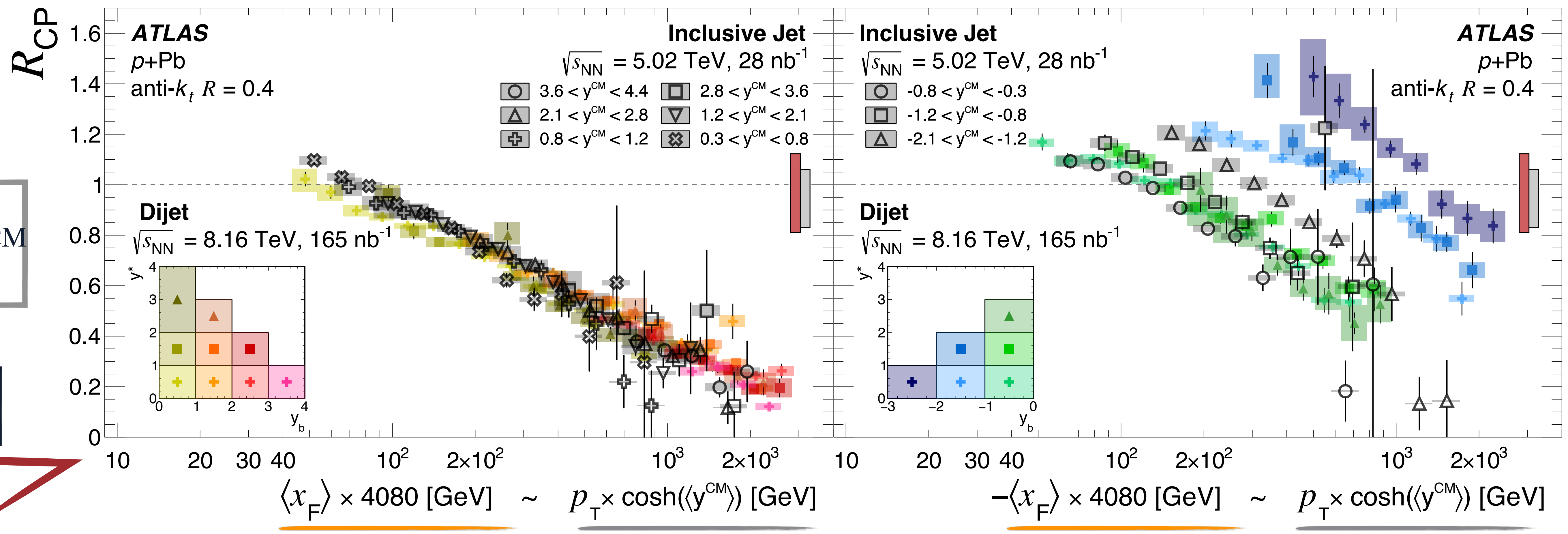
Comparison between the two measurements achieved via x_F

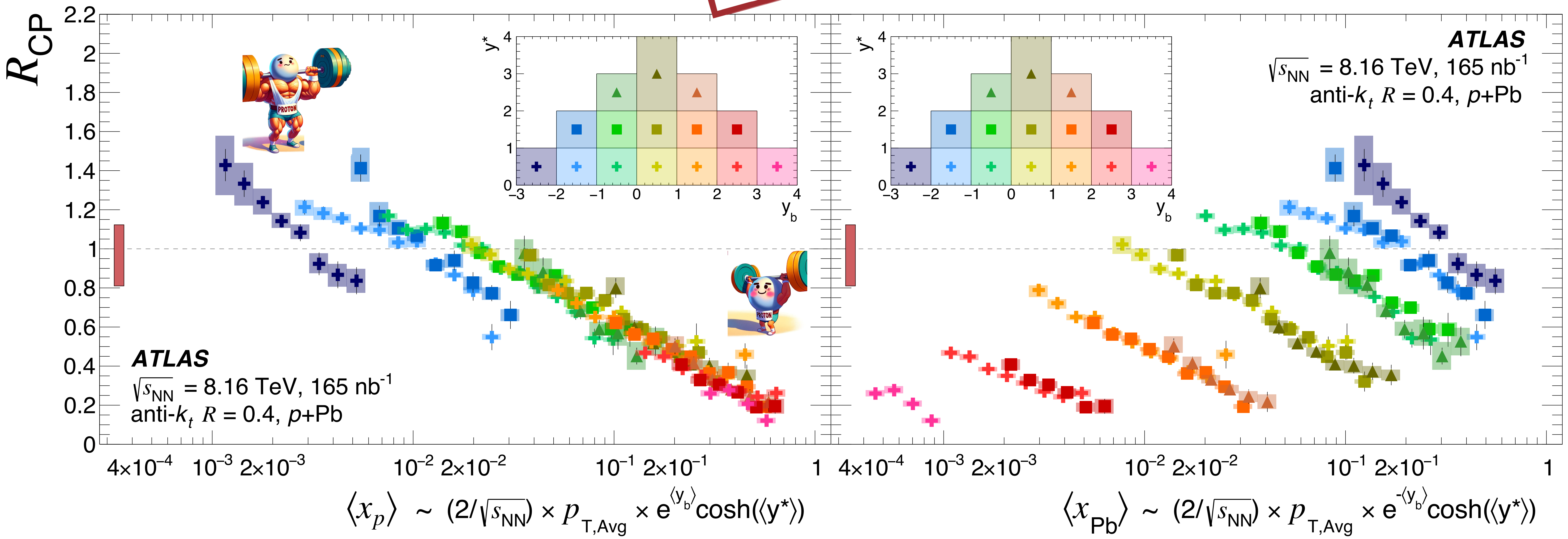
$$x_p - x_{Pb} = x_F = \frac{2p_z}{\sqrt{s_{NN}}} \sim \pm 2\frac{p_T \times \cosh y^{CM}}{\sqrt{s_{NN}}} \rightarrow \pm\frac{\sqrt{s_{NN}}}{2} \times x_F \sim p_T \times \cosh y^{CM}$$

Initial state definition | Final state definition

Assuming

$$m_T = \sqrt{m^2 + p_T^2} \sim p_T \qquad \sinh y^{CM} \sim \pm\cosh y^{CM} \text{ if } |y^{CM}| \gg 0$$





SAME PHYSICS EFFECT, DRIVEN BY THE INITIAL STATE PROTON KINEMATICS!

Phys. Rev. Lett. 132 (2024) 102301

NUCLEAR BREAKUP IN P+PB & UPCS

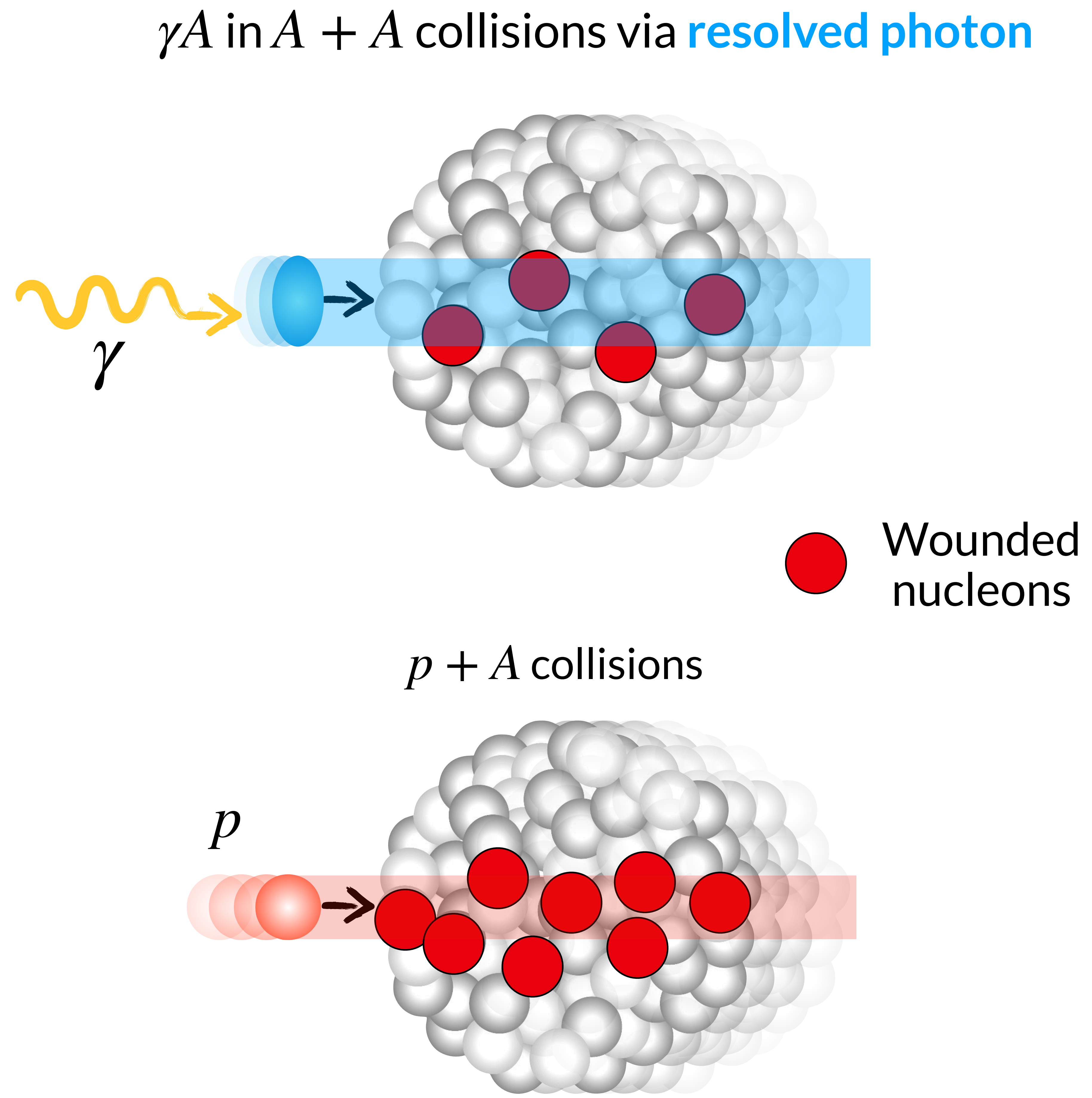
How well do we understand the nuclear breakup in *p*+Pb collisions?

- So far - very little modeling available from HI generators

In addition - new idea proposed by Alvioli, Guzey and Strikman in PRC 110, 025205 (2024) for UPC collisions in Pb+Pb

- **Study nuclear breakup primarily in γA scatterings to provide new access to small-x dynamics**
- Correlation between the number of forward neutrons emitted in the nuclear breakup, the number of wounded nucleons, and the mechanism of nuclear shadowing
- Model dependence: impact of color fluctuations?
- **Can we study similar effects in p+Pb**?

In both cases - synergies with UPC dijet measurements

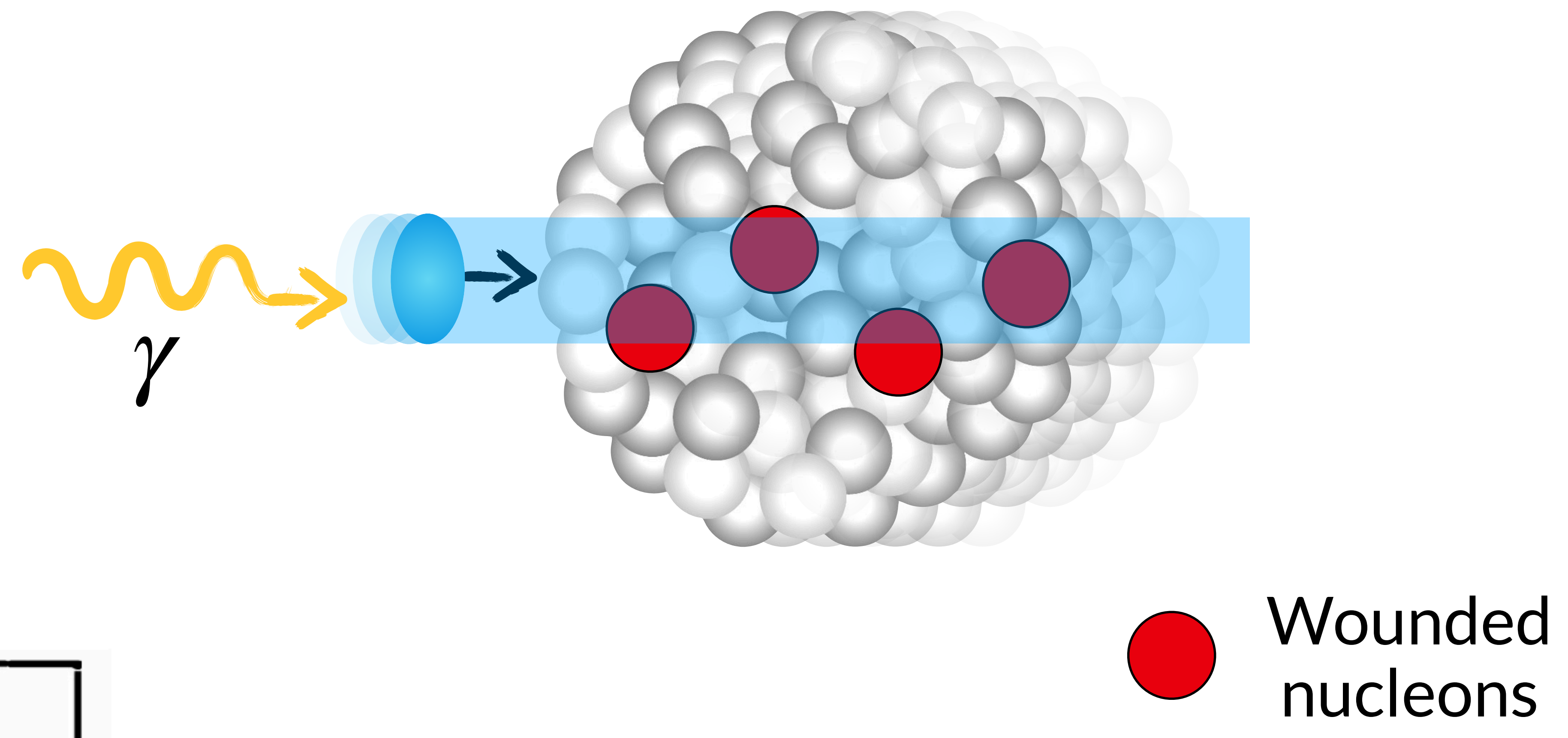


COLOR FLUCTUATIONS @ EIC?

How well do we understand the nuclear breakup in e+A collisions?

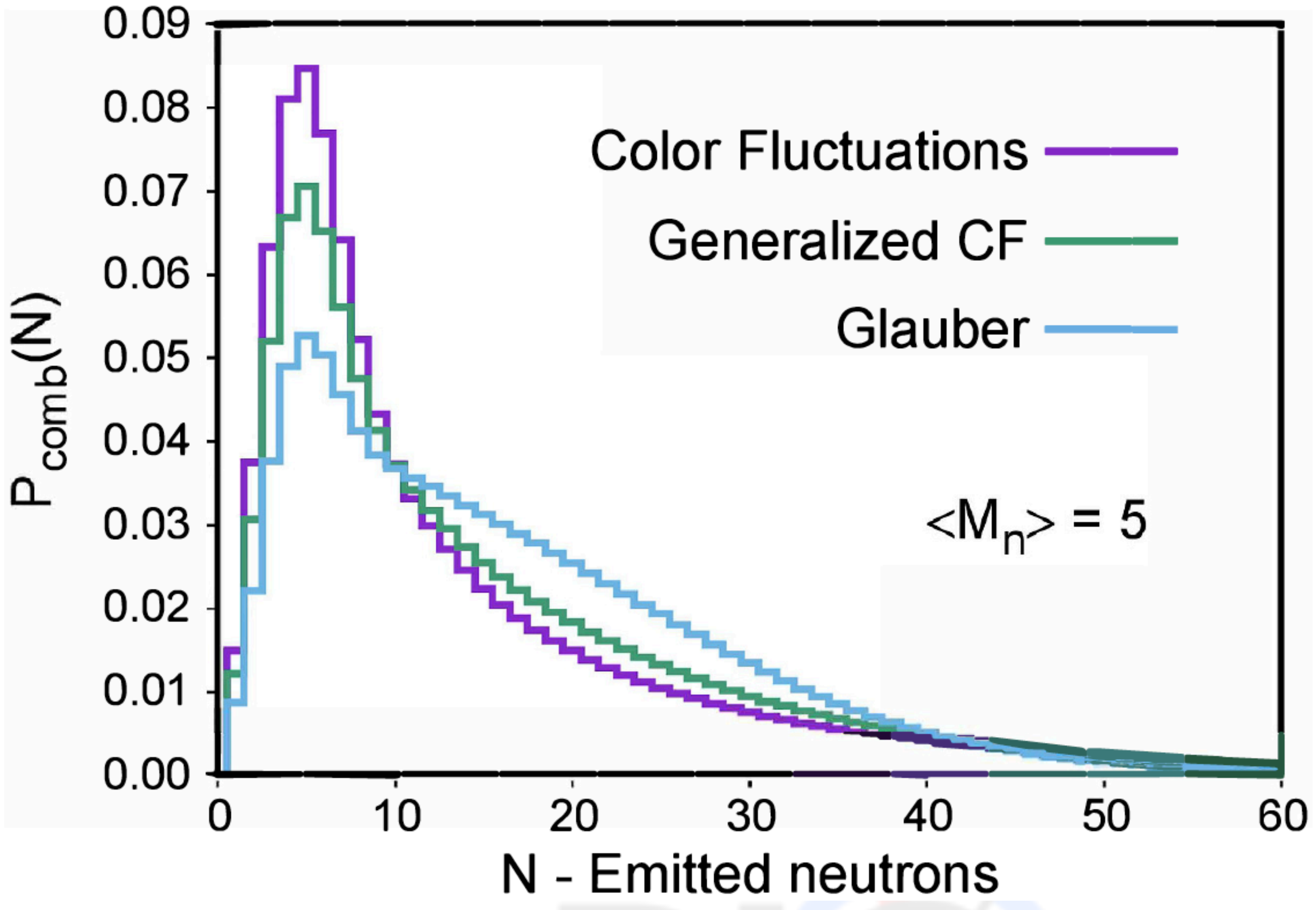
- Can we rely on forward neutrons to characterize the event geometry in *e*+A collisions (approach proposed by Zheng et al, **Eur. Phys. J. A (2014) 50: 189**) or could there be biases from kinematic-driven effects?

Also:
γA in $e^- + A$ collisions via **resolved photon**



Characterization of neutron multiplicities in p+A and in UPCs at the LHC can inform geometry determination in e+A

PRC 110, 025205 (2024)

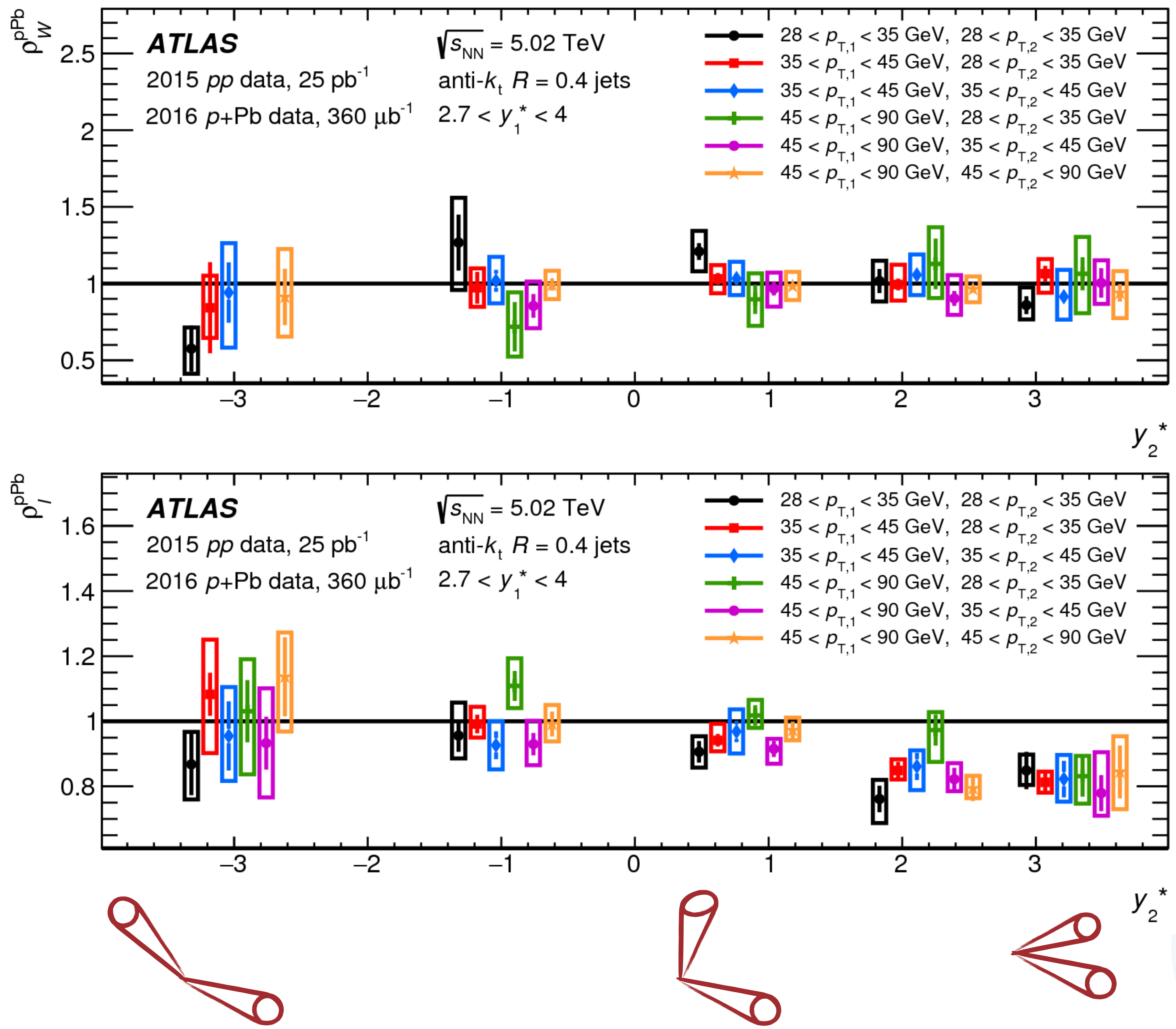


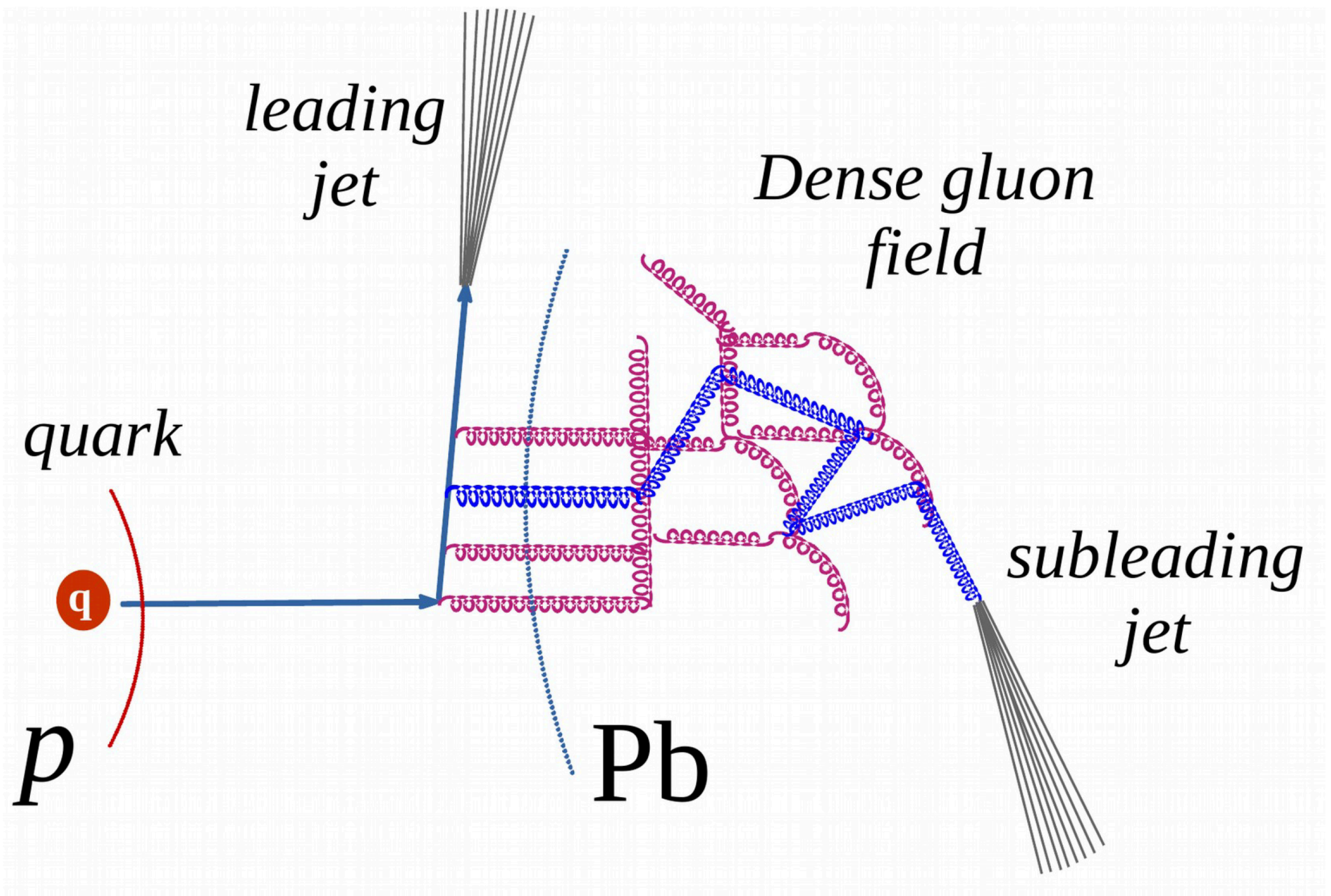
CFs are also relevant for result interpretation at RHIC energies, see D.Perepelitsa, **Phys. Rev. C 110, L011901** , for a recent use of the CF model to interpret PHENIX data

Saturation

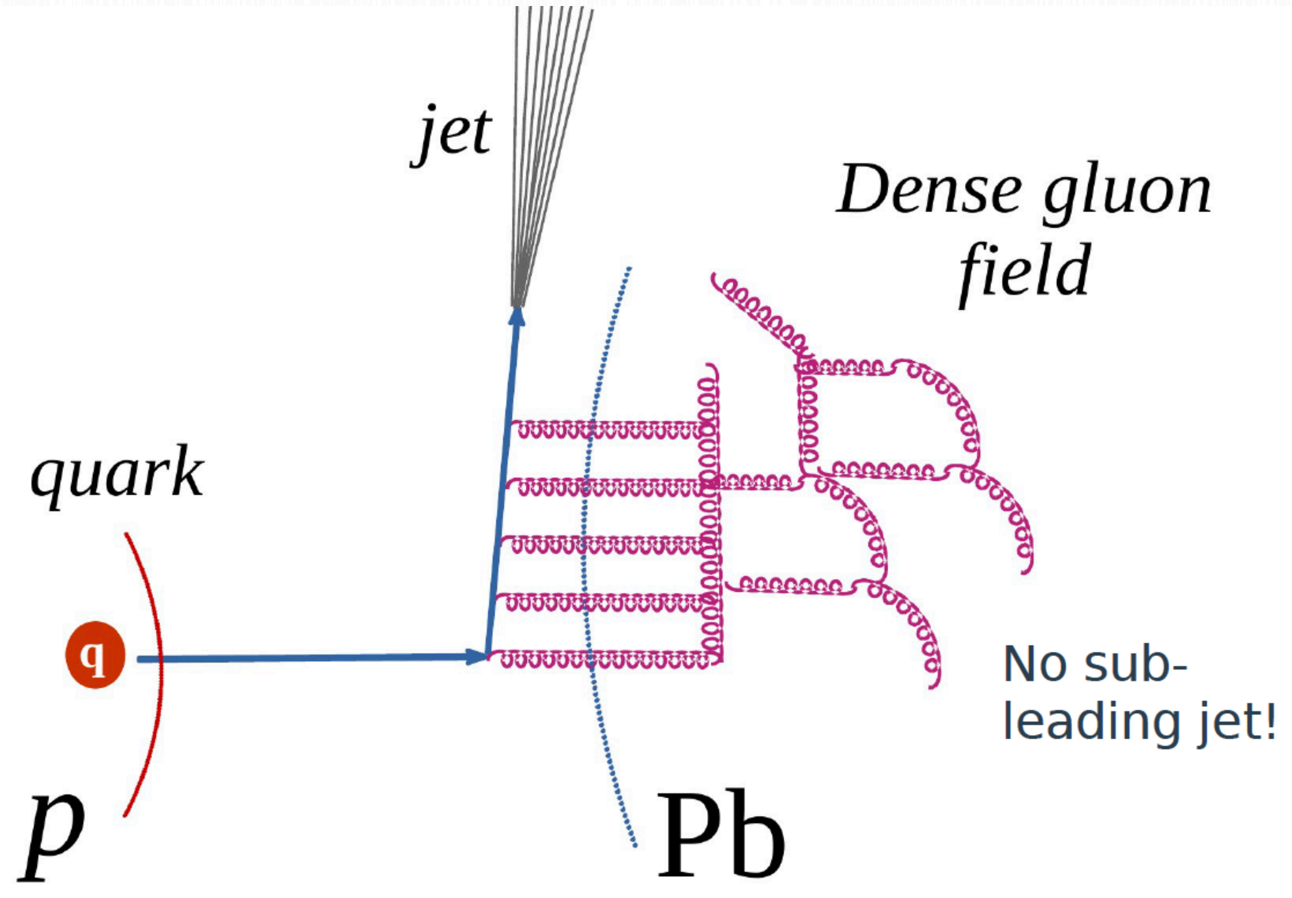
BEYOND CF: DIJETS IN P+PB TO SEARCH FOR SATURATION ONSET

Search for azimuthal broadening or forward dijet conditional yield suppression as a manifestation of CGC (see **Eur.Phys.J.C 83 (2023) 10, 947**)





Struck gluon in the nucleus scatters over other gluons before forming a jet → **azimuthal broadening** signature

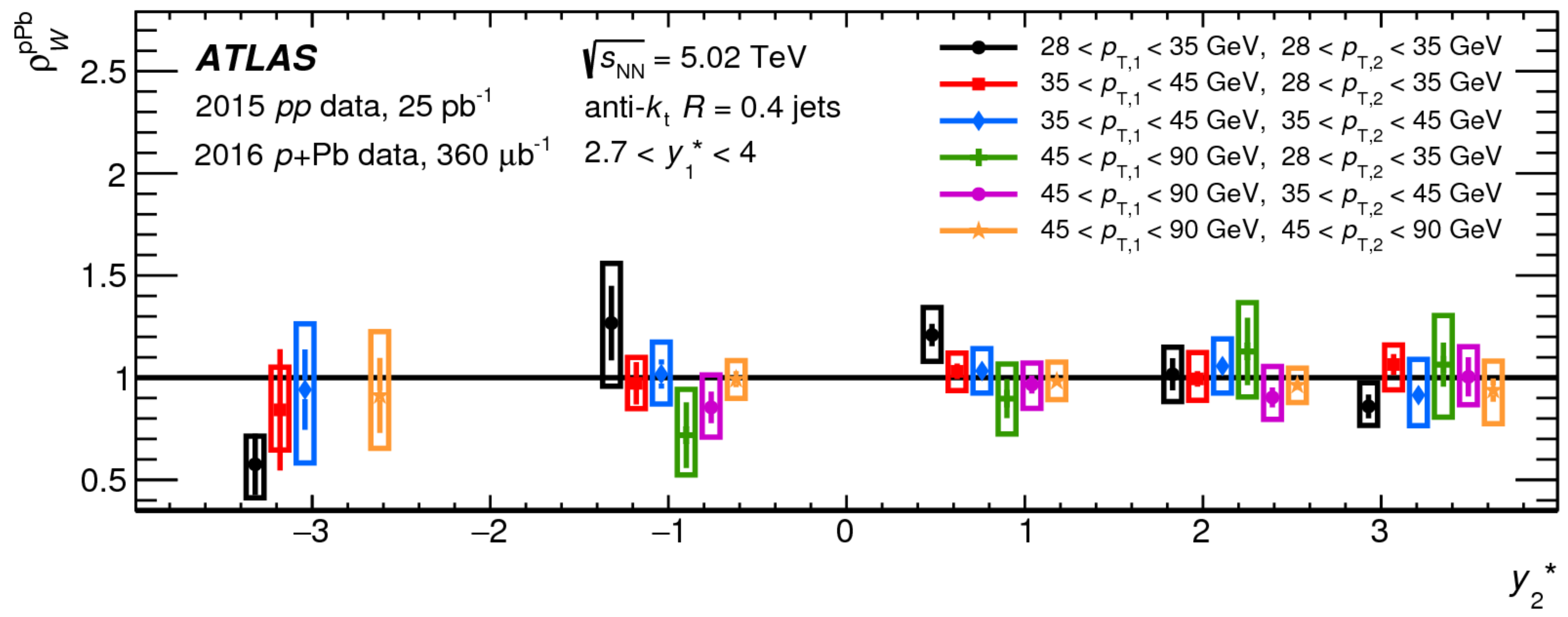


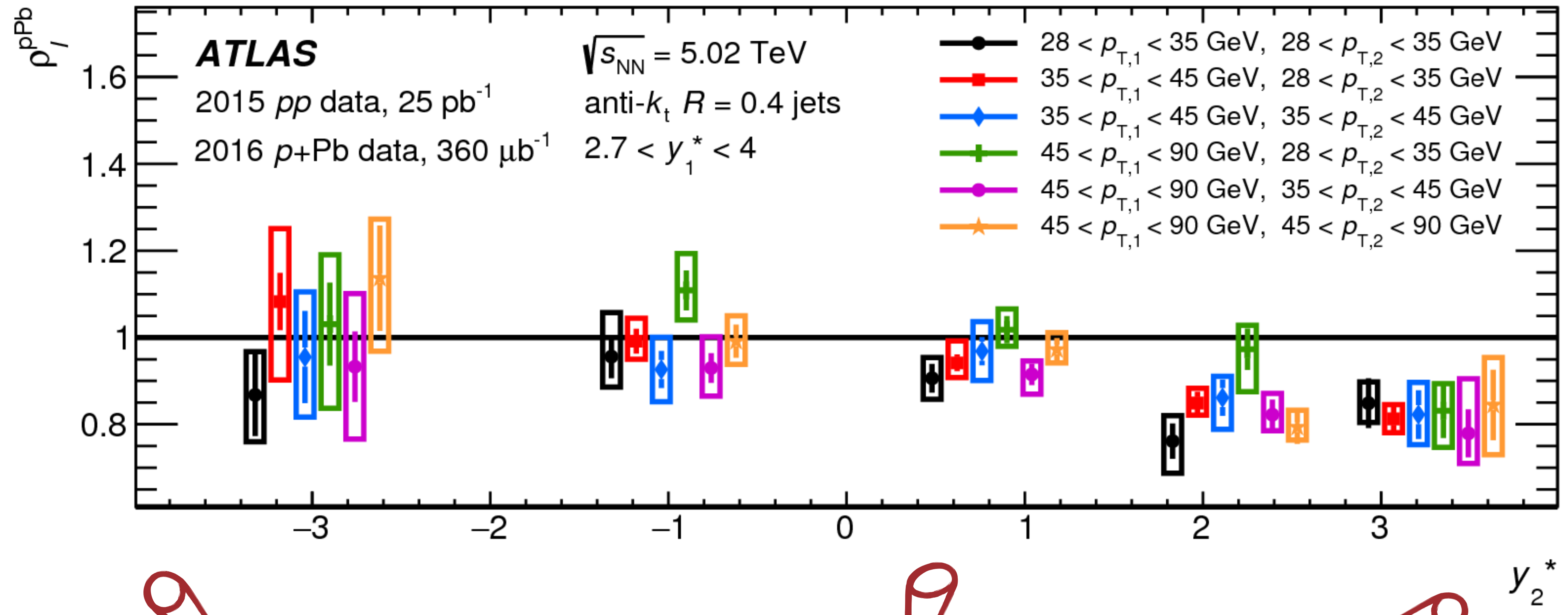
Incoming parton recoils off the lead nucleus coherently → **mono-jet** signature

Phys. Rev. C 100 (2019) 034903

BEYOND CF: DIJETS IN P+PB TO SEARCH FOR SATURATION ONSET

Search for azimuthal broadening or forward dijet conditional yield suppression as a manifestation of CGC (see **Eur.Phys.J.C 83 (2023) 10, 947**)



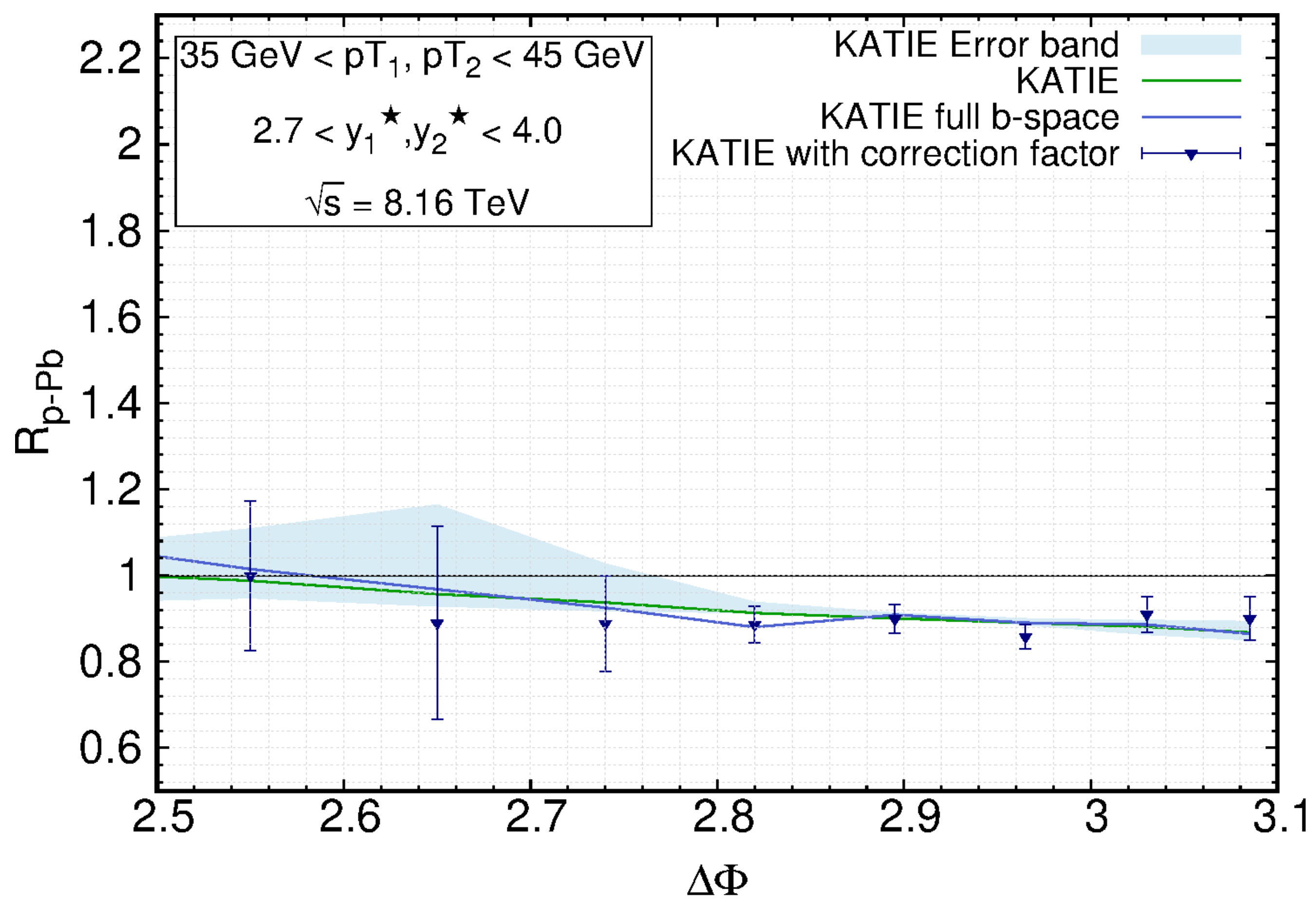


Phys. Rev. C 100 (2019) 034903

✗ NO EFFECT OBSERVED WITHIN AVAILABLE EXPERIMENTAL SENSITIVITY

SUPPRESSION OF CONDITIONAL YIELDS OF FORWARD DIJETS.
LIMITED PRECISION
OTHER EFFECTS (E.G. NPDFS?)

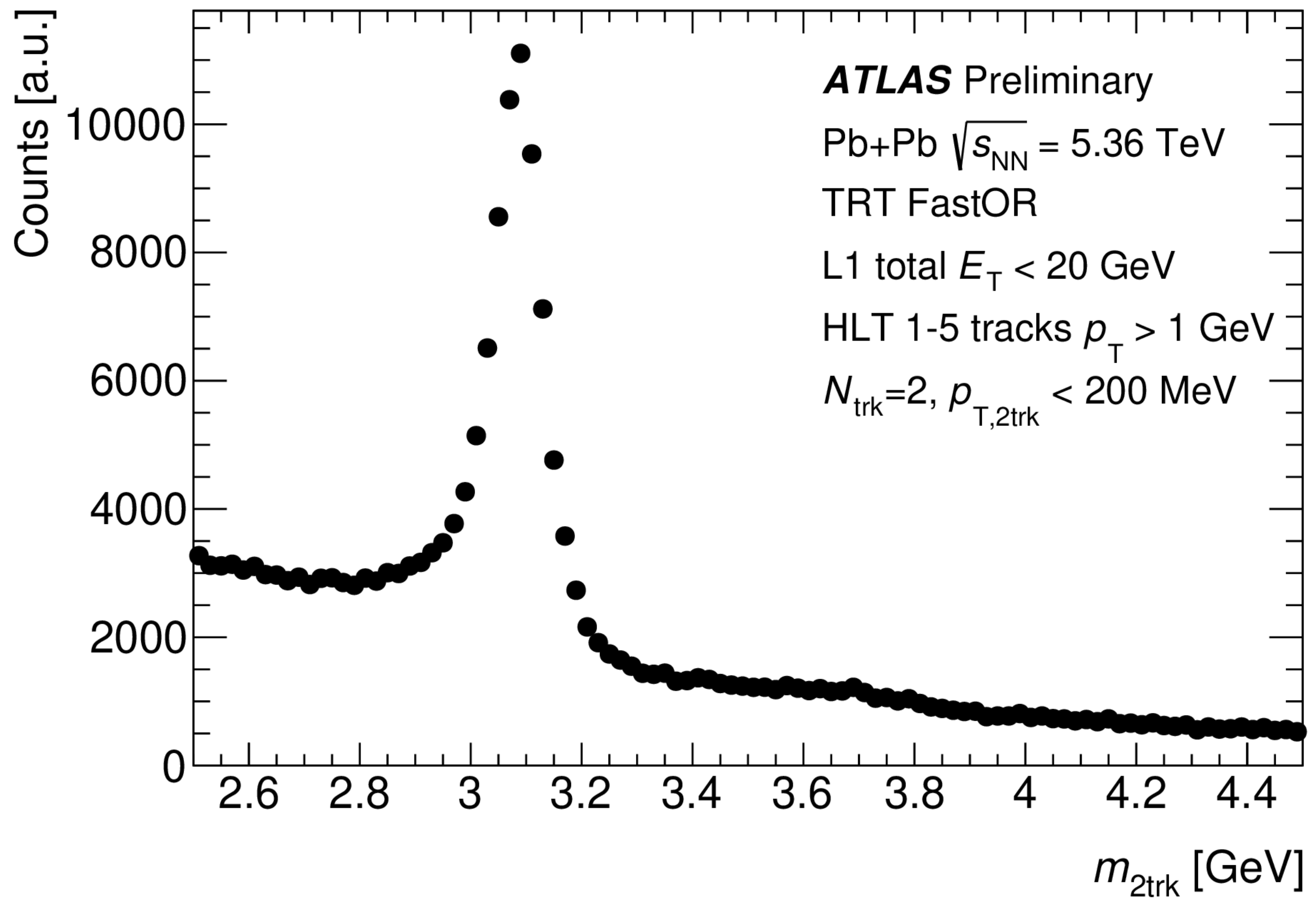
Van Hameren et al., Eur.Phys.J.C 83 (2023) 10, 947



Incoming parton recoils off the lead nucleus coherently → **mono-jet** signature

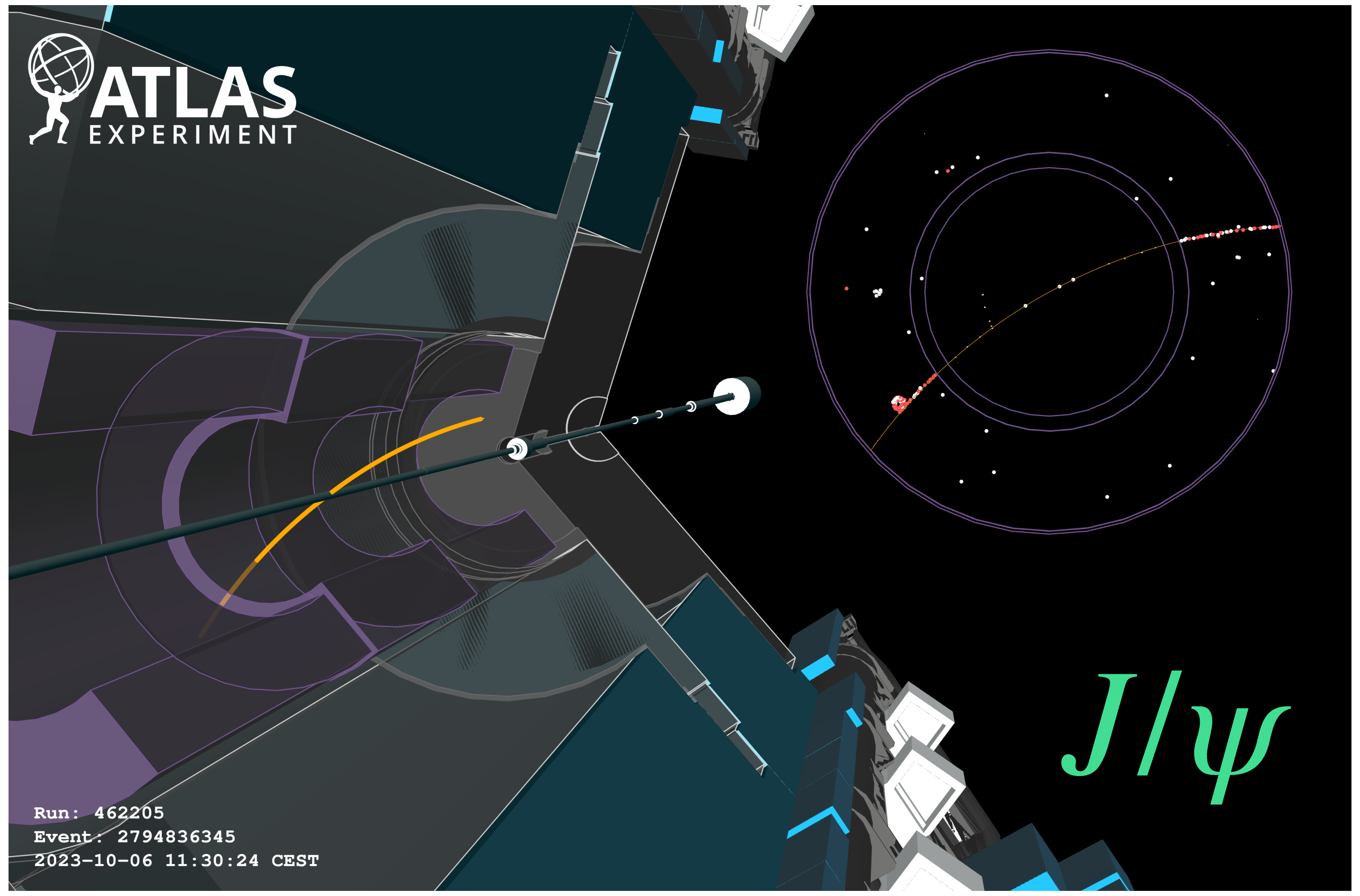
See talk by D.Perepelitsa on Thursday!

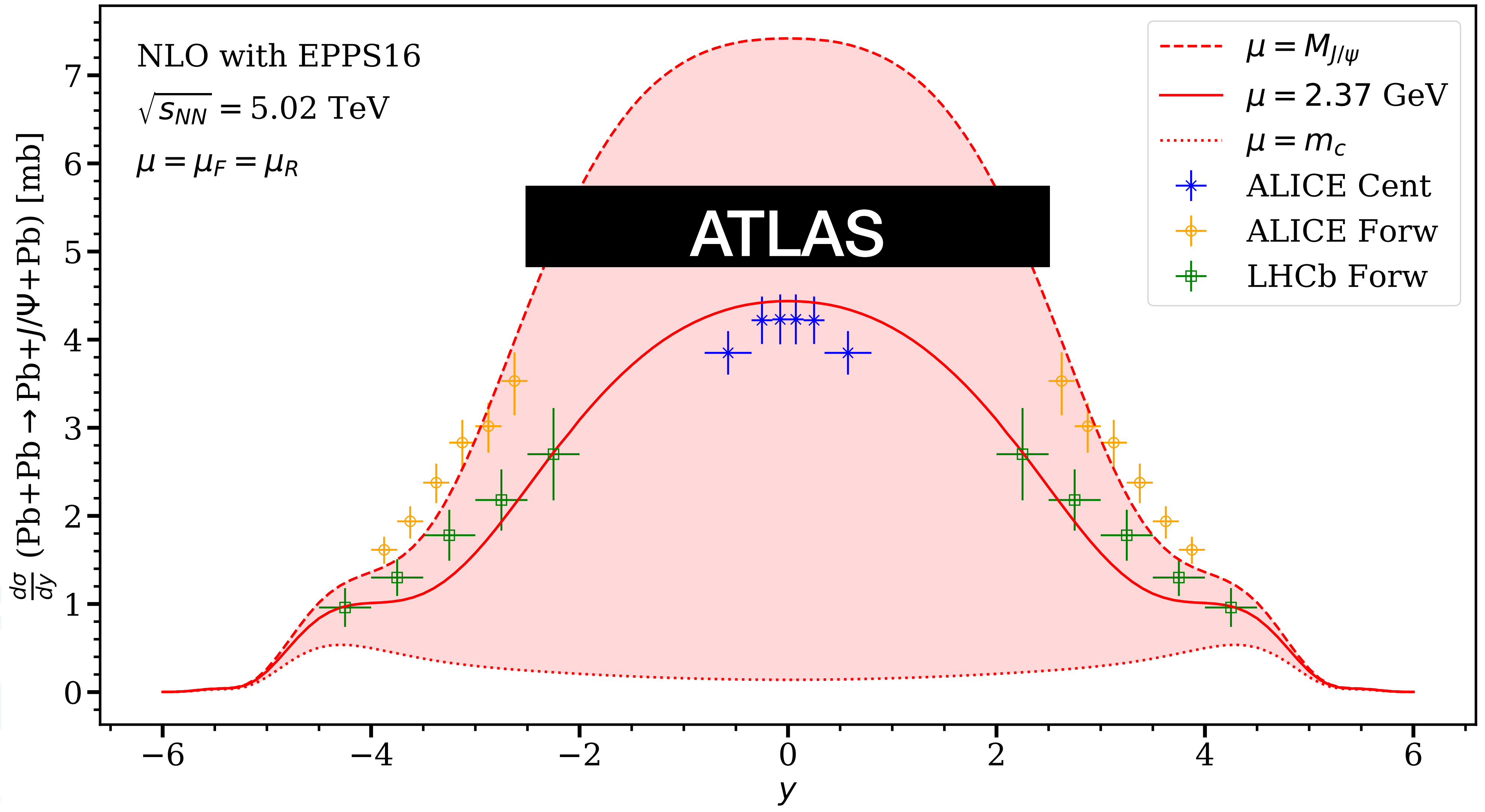
J/PSI @ ATLAS



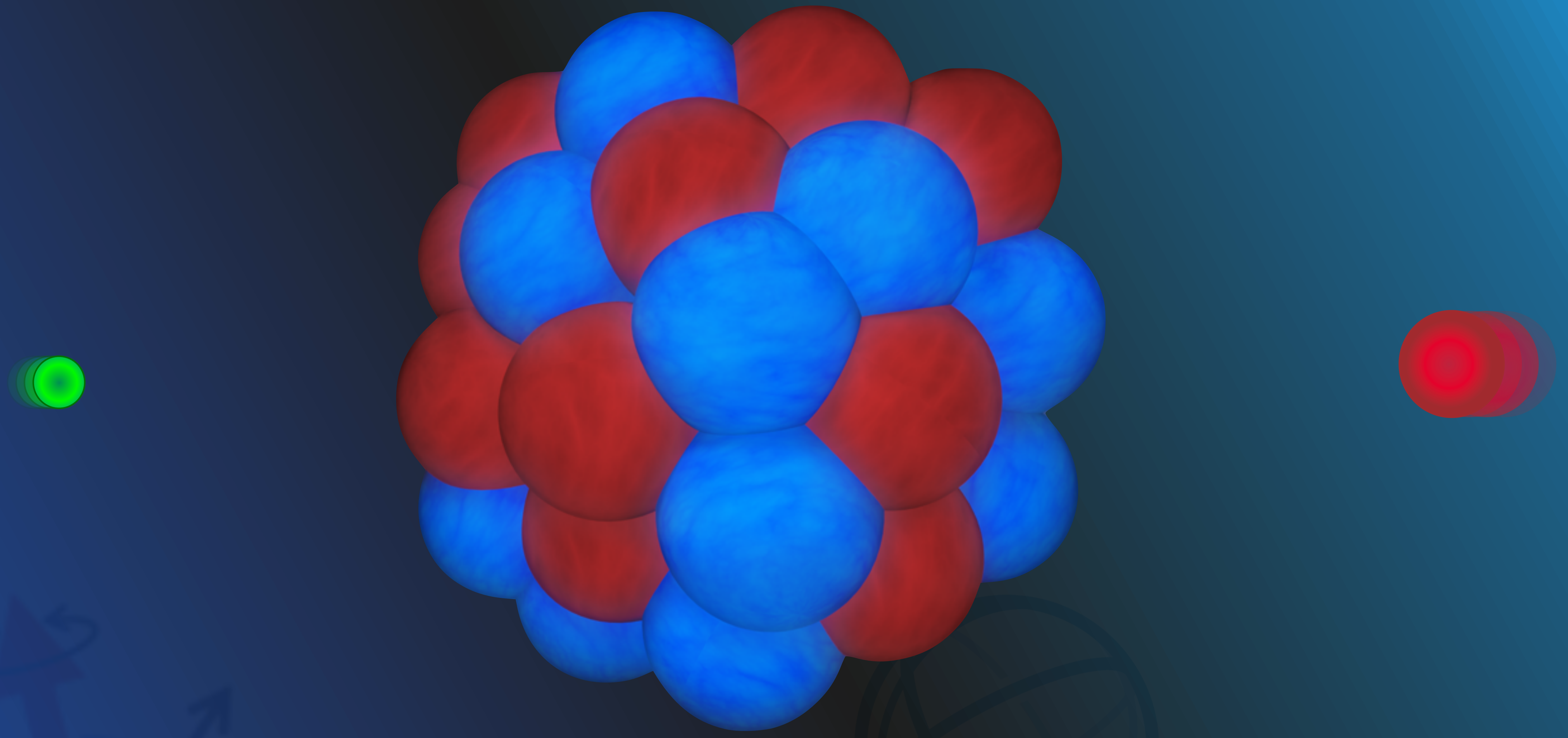
New TRT FastOr Level 1 trigger implemented in Run 3:

- Provides efficient L1 triggers for measurements based on low p_T dileptons
- Enable high-statistics coherent J/ψ analysis in UPC @ ATLAS
  - Will contribute to the exciting vector meson program at RHIC and the LHC
  - Coherent J/ψ measurements also major targets of the EIC program





Eskola et al, PRC 106 035202 (2022)

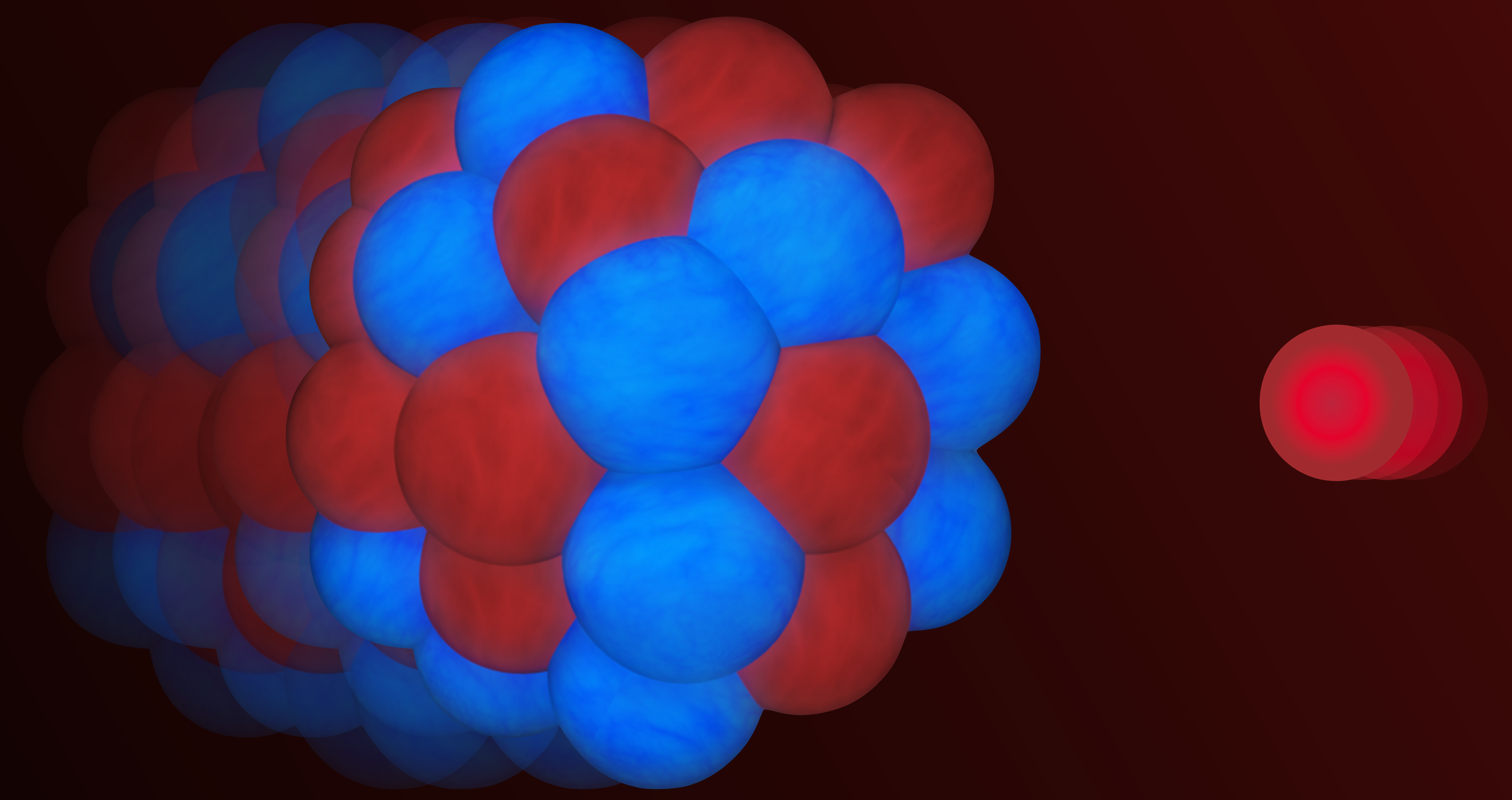


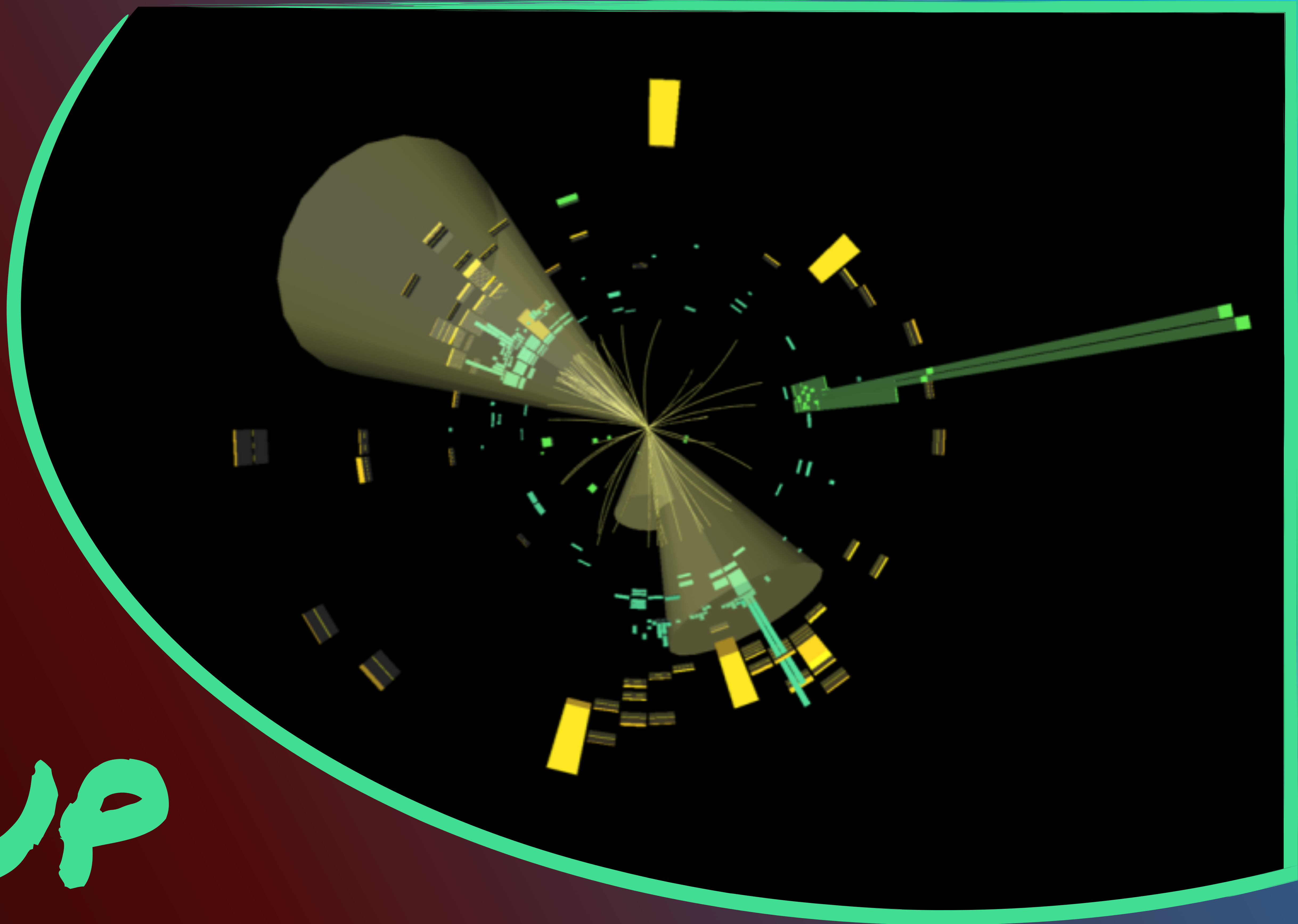
THANK YOU FOR YOUR ATTENTION!

SUMMARY

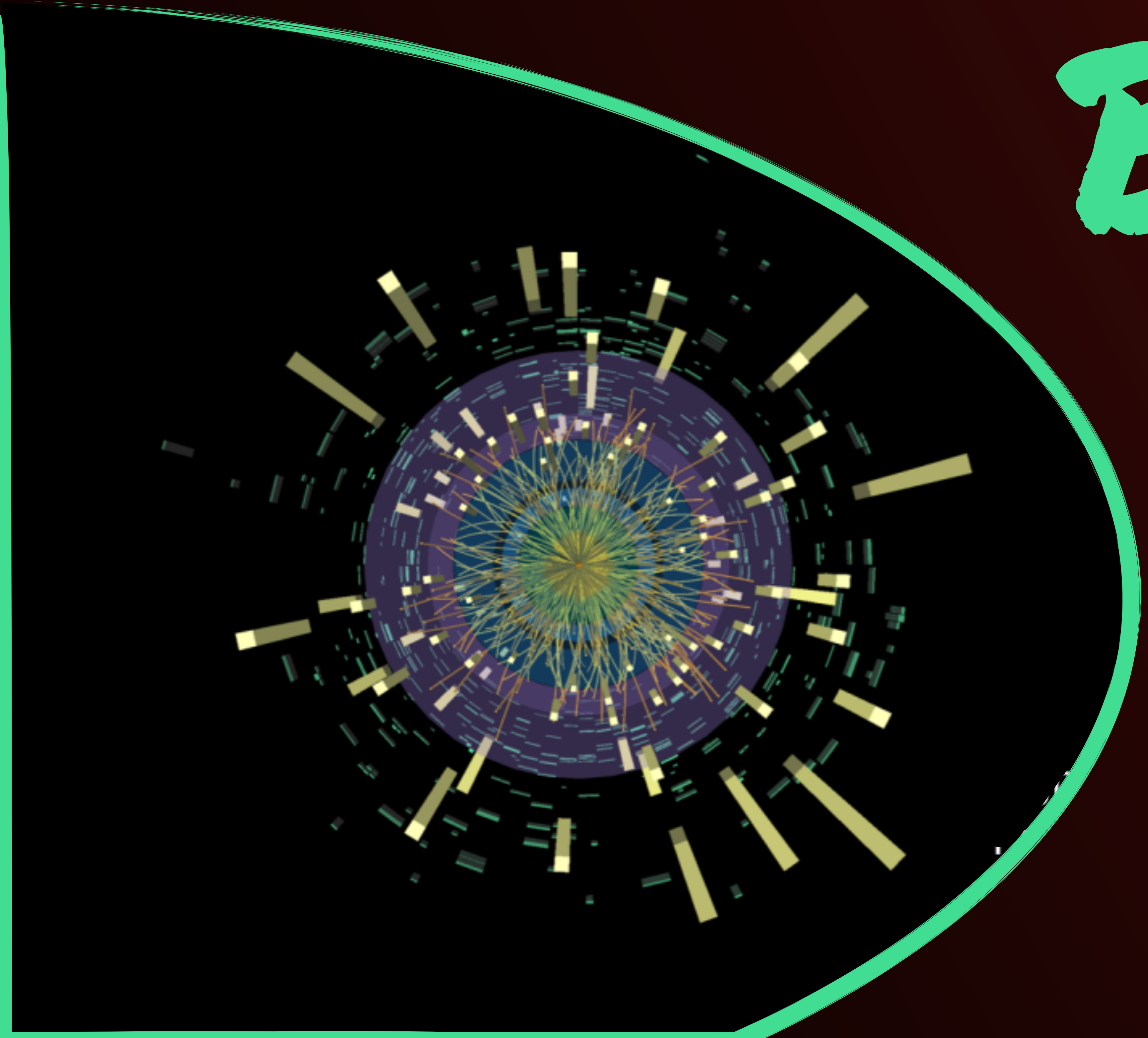
The ATLAS Heavy Ion Physics Program & the EIC have several points of contact

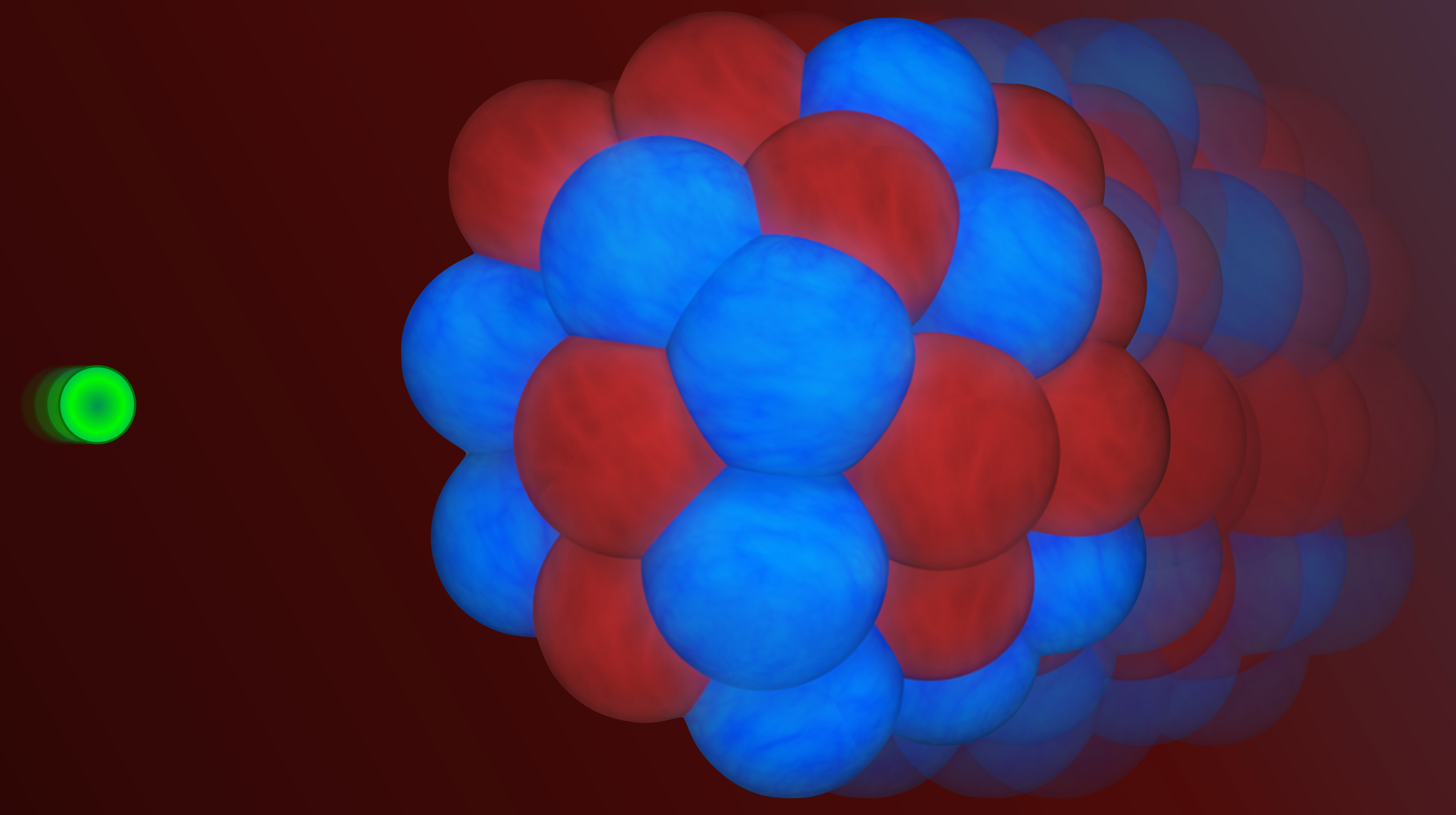
- Results on both sides will be complementary in boosting our understanding of hot and cold QCD.
- LHC data will provide significant physics input that will also benefit the advancement of the EIC physics case.
  - **Passage of color charge through cold nuclear matter:**
    - Cold Nuclear Matter & Color Fluctuation studies in p+A
  - **Nuclear PDFs**
    - Constrain nPDFs over a broad (x,Q^2) range using different channels (dijets in p+A & UPCs, ttbar…)
    - Provide input for different nuclei (Pb, O, ++) that could be investigated also at the EIC
  - **Search for the onset of gluon saturation**
    - Forward dijet broadening and yield modification to be studied with high-stat & good pp reference
    - New j/Psi opportunities with ATLAS Phase I and II upgrades
  - **Search for the onset of collectivity in small systems**
    - EIC as potential tie-breaker to understand the origin of long-range behavior observed in many collision systems



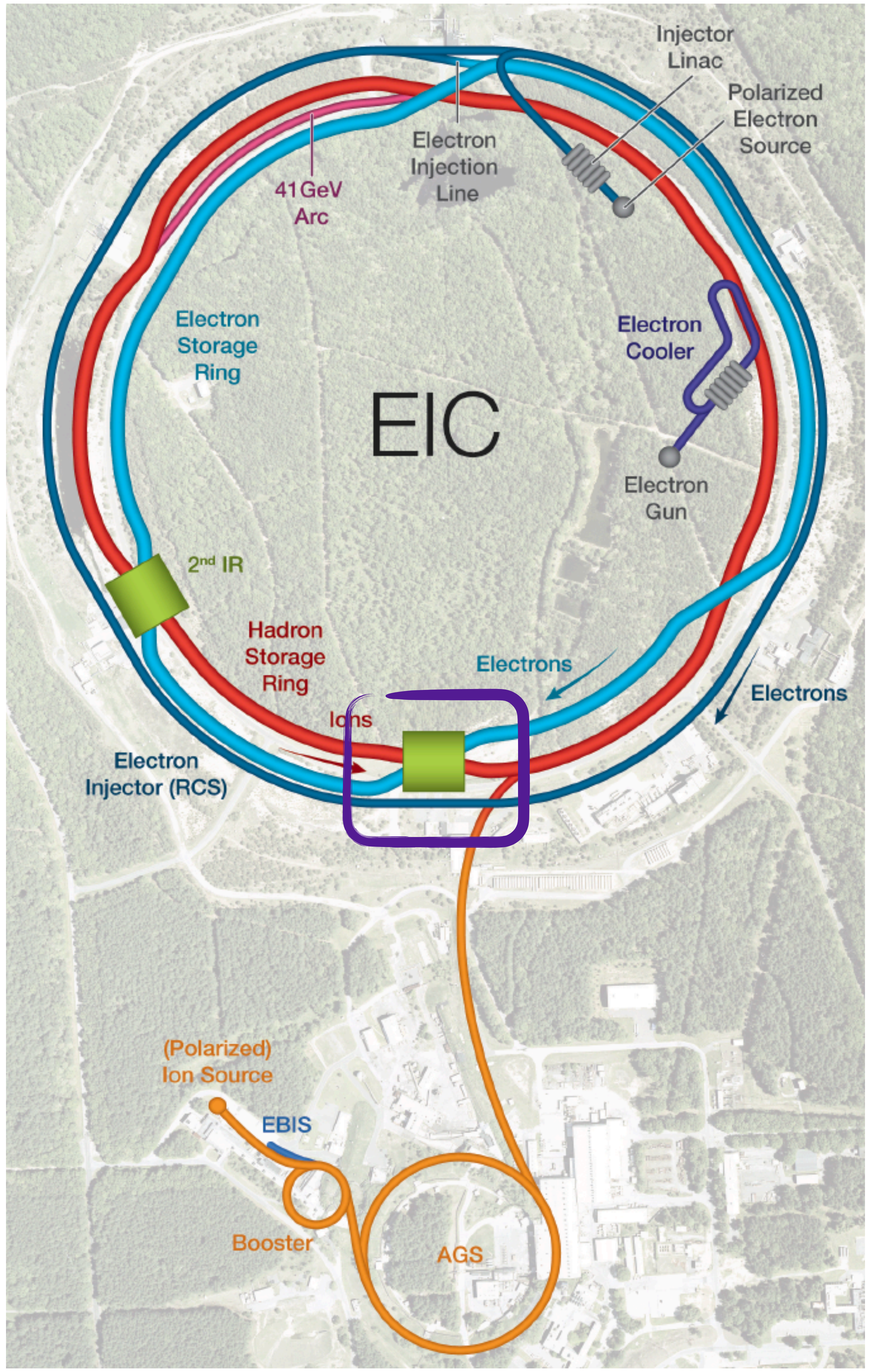


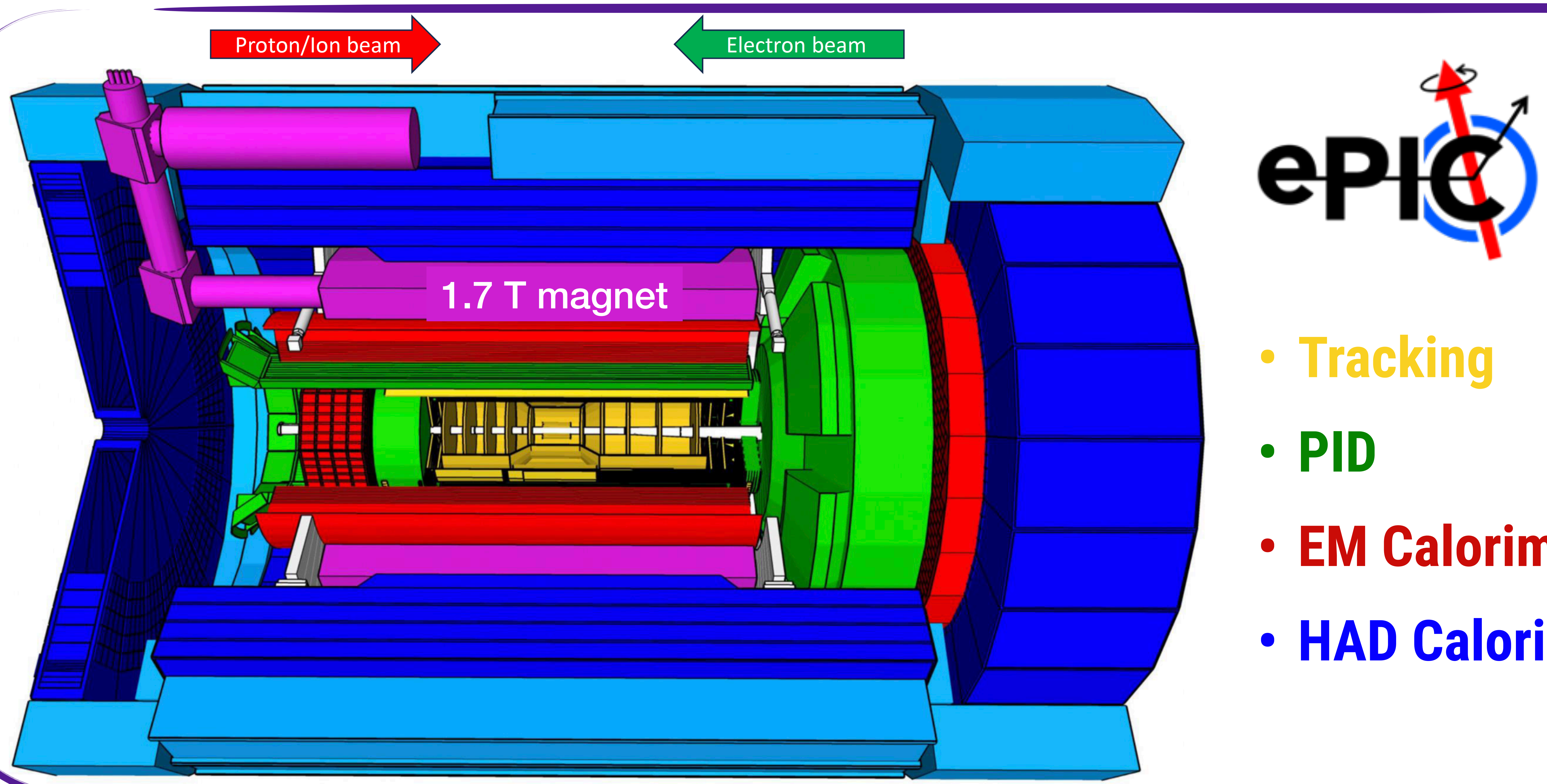
Backup





FACILITIES: EIC & EPIC

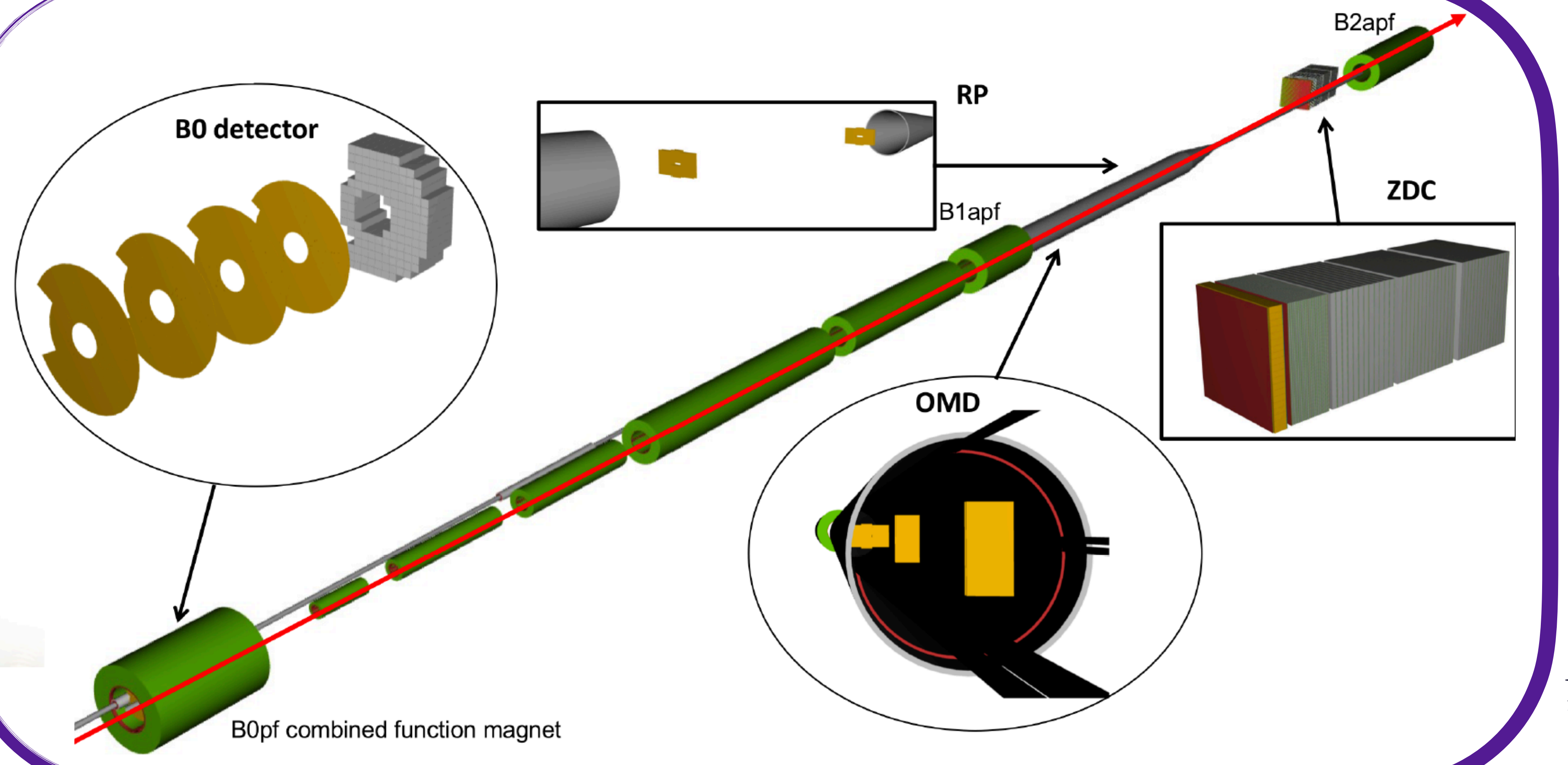




- Tracking
- PID
- EM Calorimeter
- HAD Calorimeter

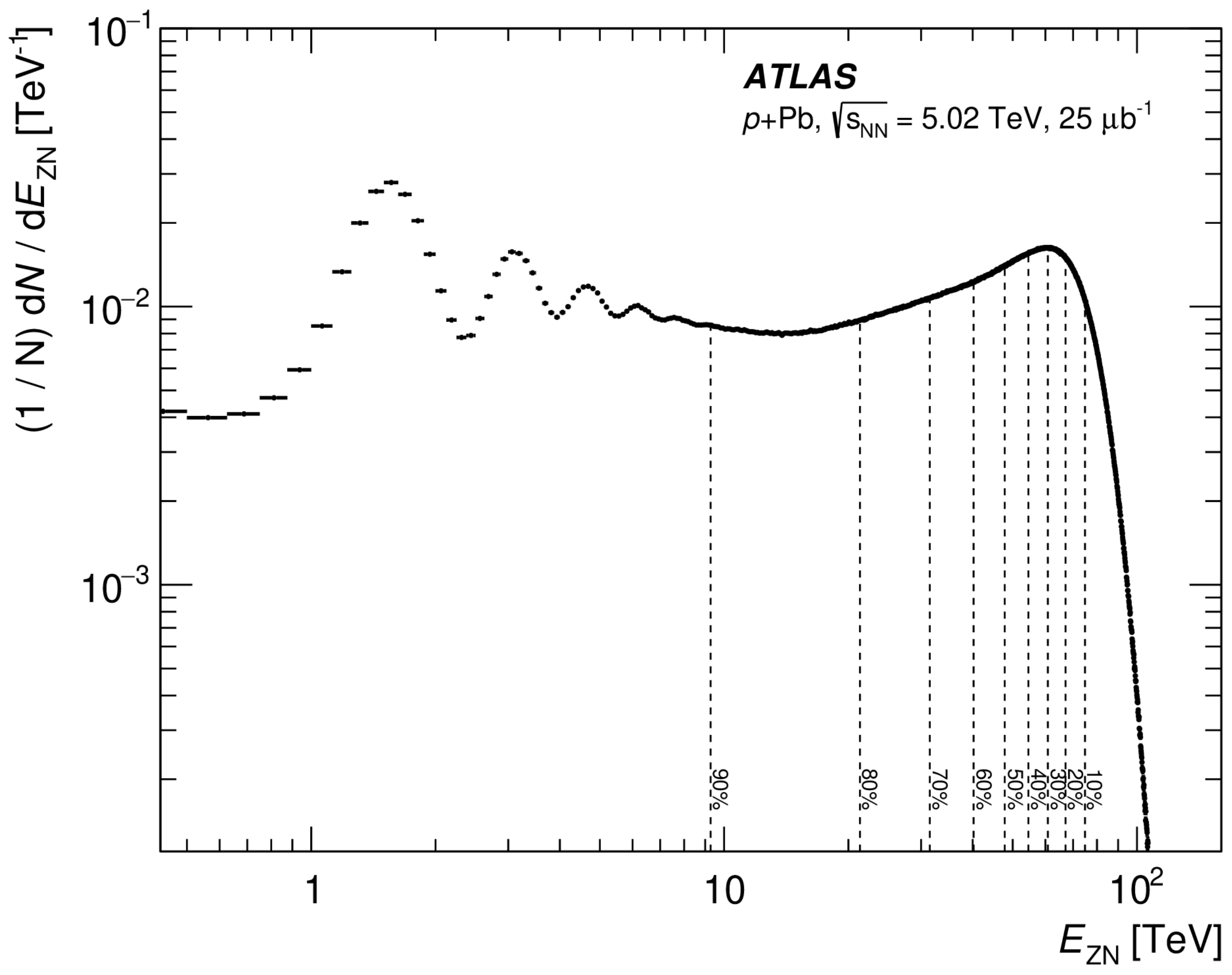
Hermetic barrel coverage ($|\eta| < 4$)

~Hermetic Far Forward detection capabilities, including *p* tagging and detection ion remnants

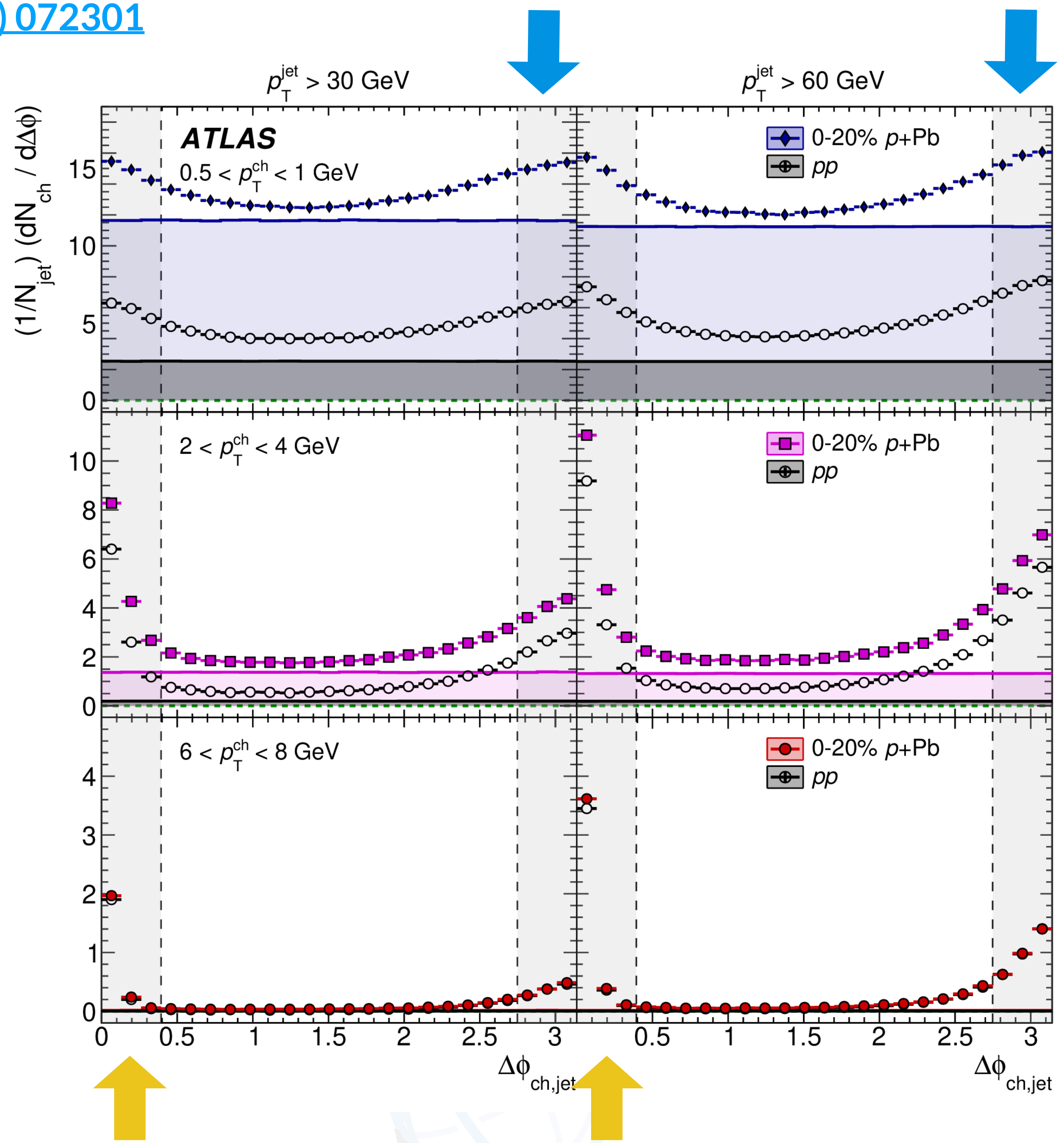


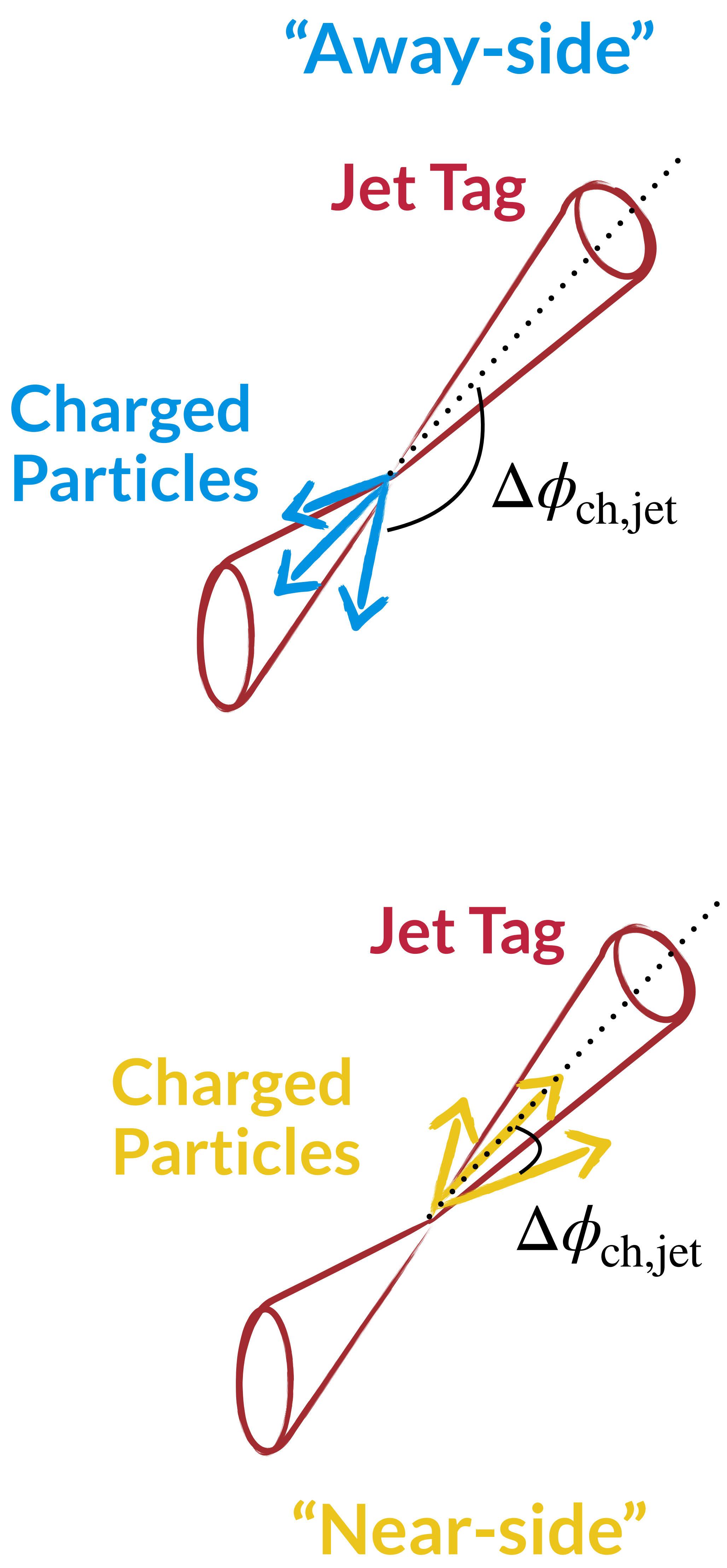
QGP-LIKE SIGNATURE: ENERGY LOSS ?

Phys. Rev. Lett. 131 (2023) 072301



Classification of event centrality by using Pb-going ZDC energy to reduce any selection correlation with central barrel activity



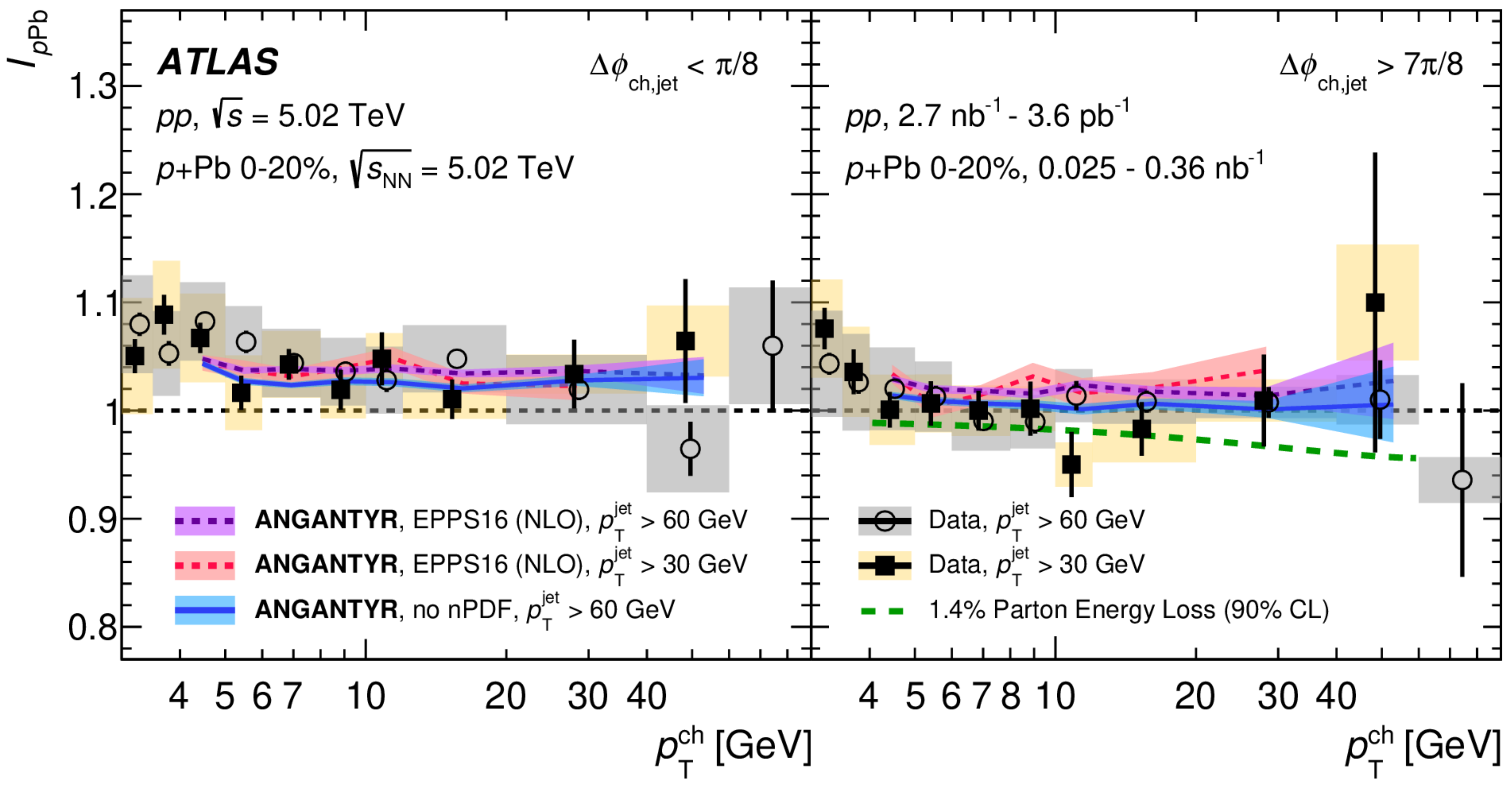


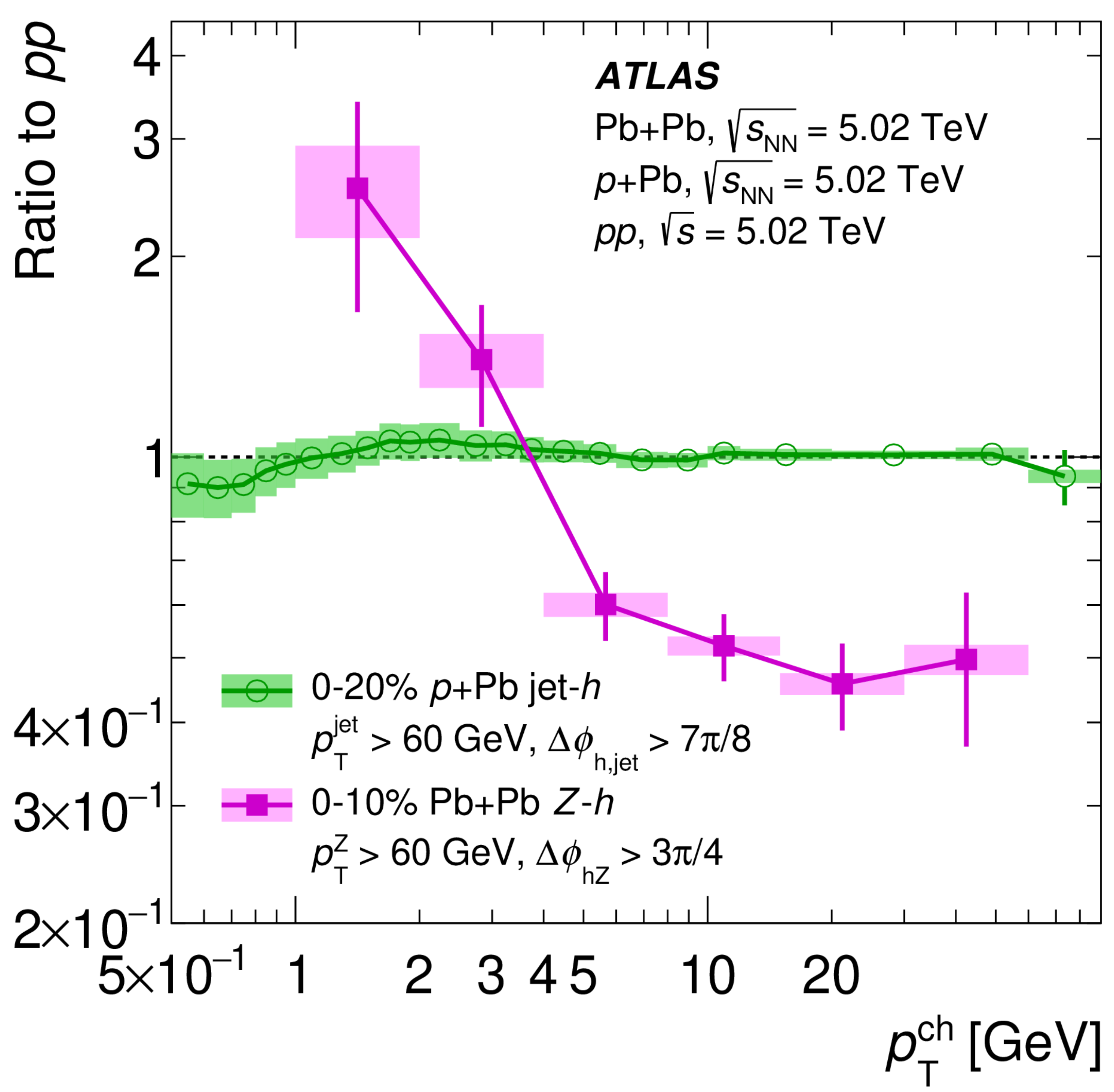
QGP-LIKE SIGNATURE: ENERGY LOSS ?

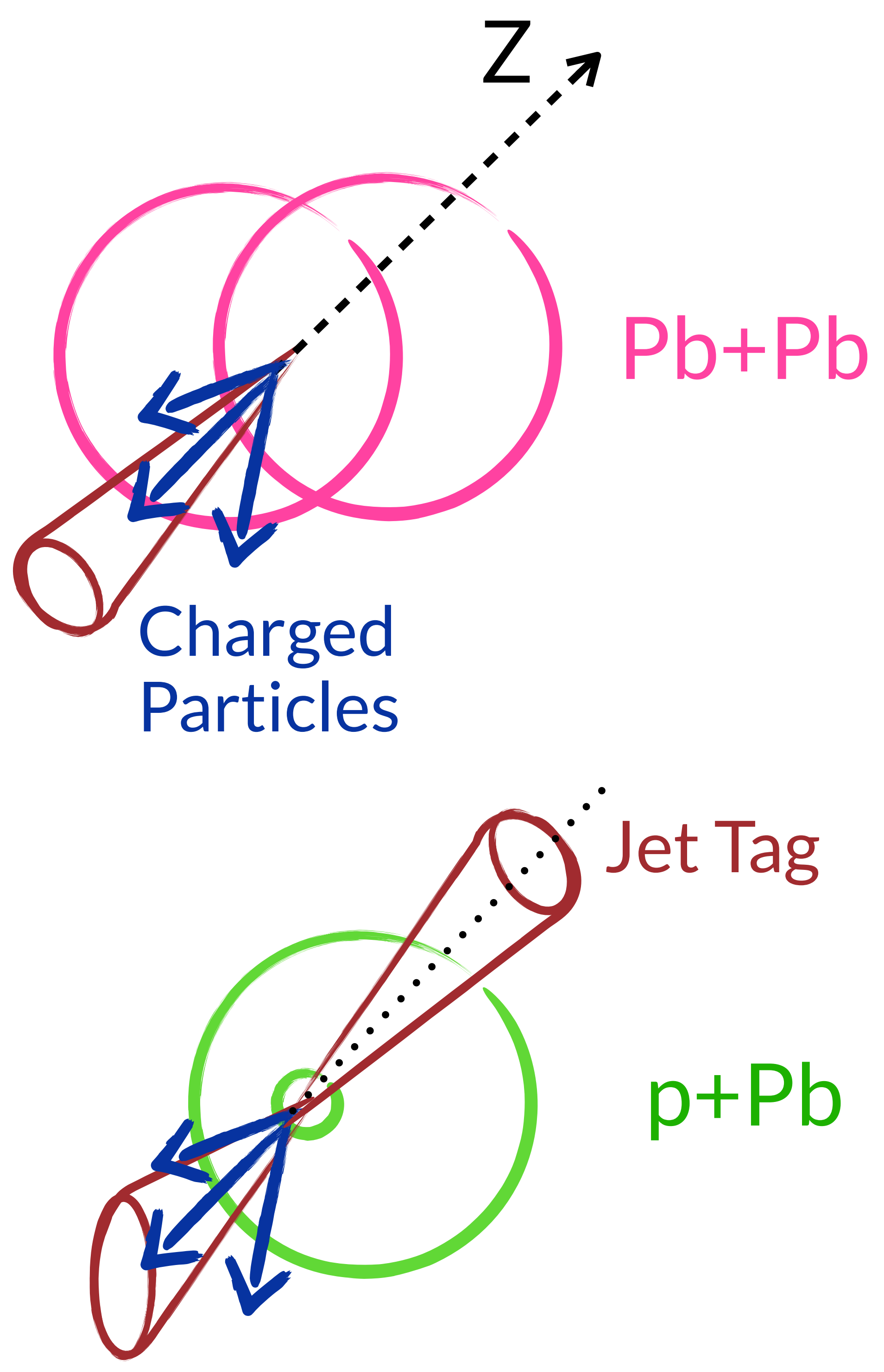
[Phys. Rev. Lett. 131 (2023) 072301]

$$I_{p\mathrm{Pb}} = \left(\frac{1}{N_{\mathrm{jet}}}\frac{dN_{\mathrm{ch}}}{dp_{\mathrm{T}}^{\mathrm{Ch}}}\right)_{p+Pb} \Big/ \left(\frac{1}{N_{\mathrm{jet}}}\frac{dN_{\mathrm{ch}}}{dp_{\mathrm{T}}^{\mathrm{Ch}}}\right)_{p+p}$$

"Near-side" "Away-side"







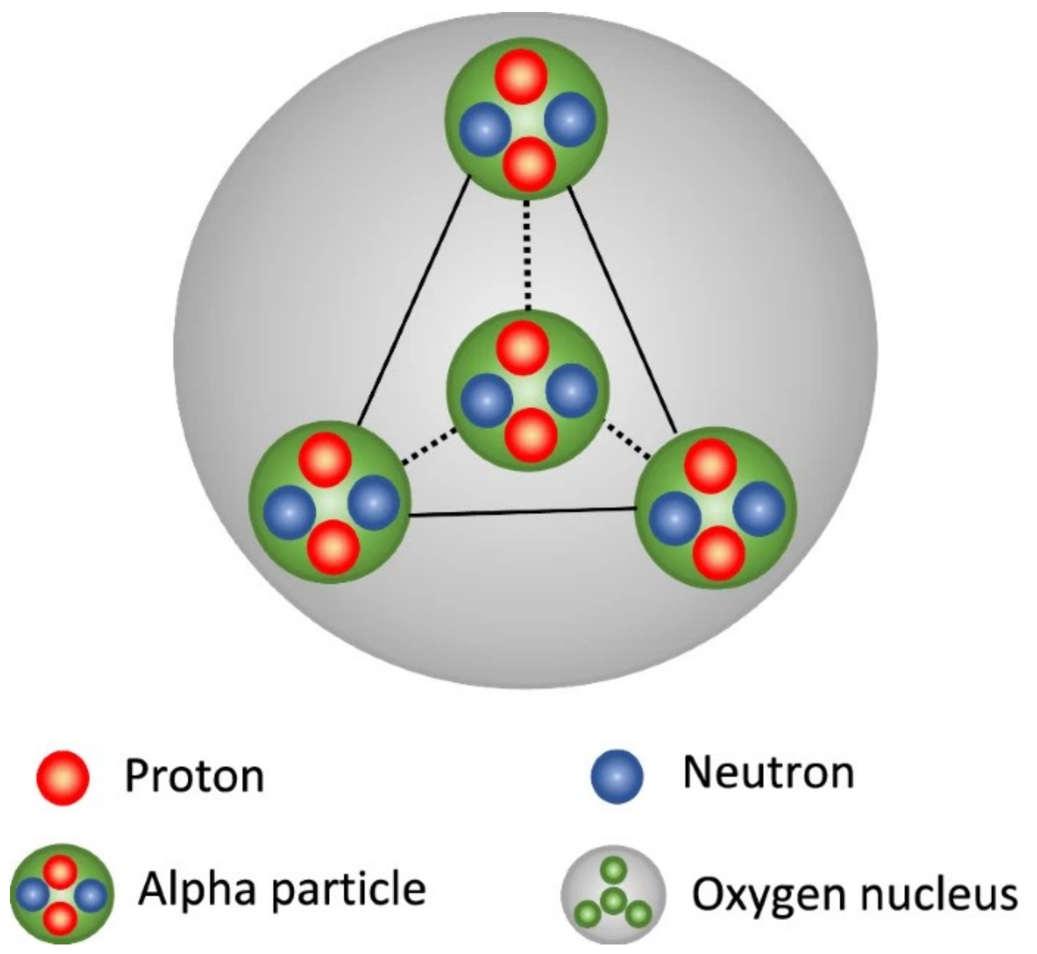
Comparison to Angantyr:

- No final state interactions - e.g. no jet quenching
- Consistent with data on both sides - no large effect from nPDFs

No evidence of **Jet quenching** in $I_{p\mathrm{Pb}}$ observable

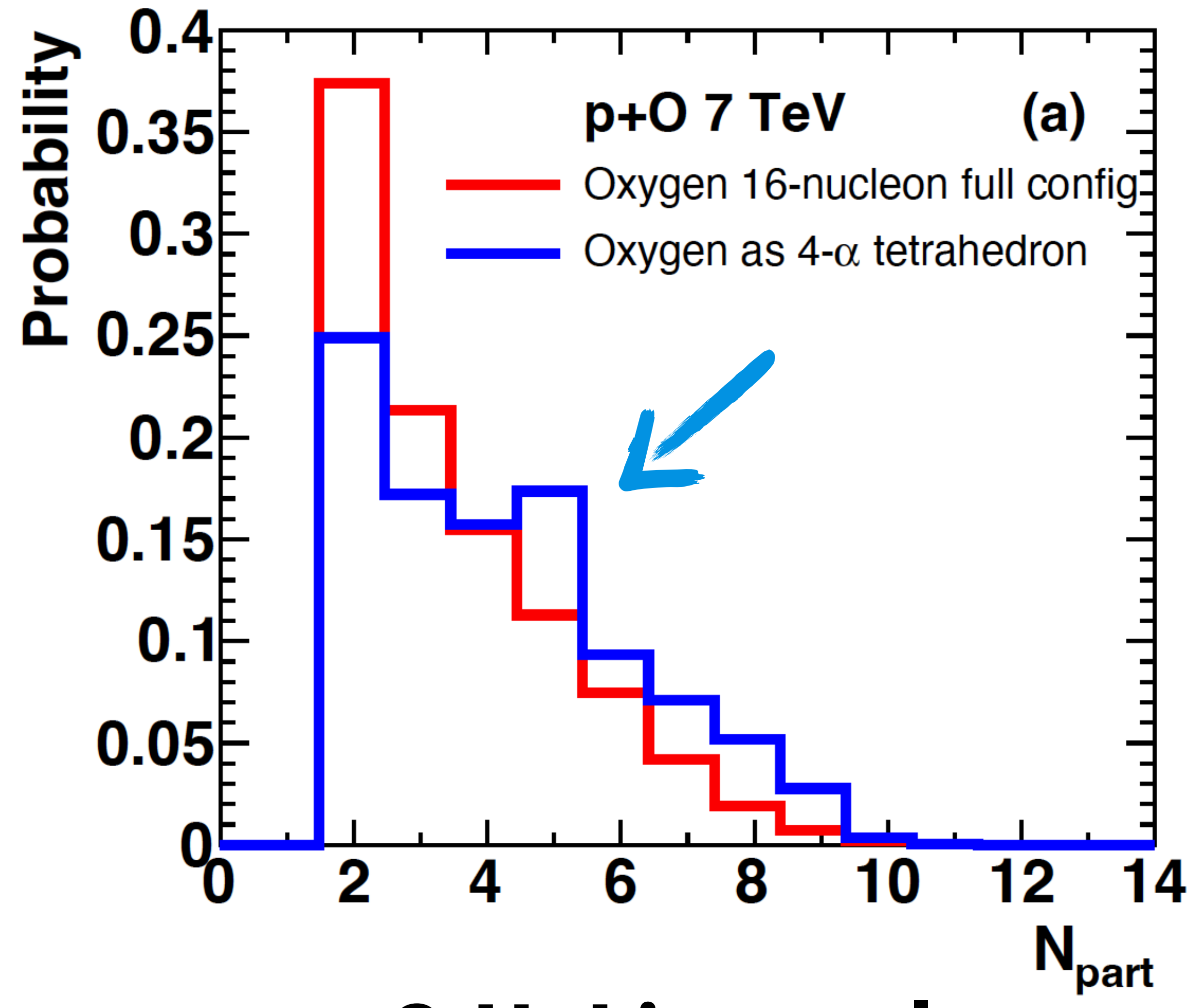
Parton energy loss constraint: 0.2 ± 0.5% and < 1.4% at 90% confidence level

P+O COLLISIONS TO UNDERSTAND OXYGEN STRUCTURE



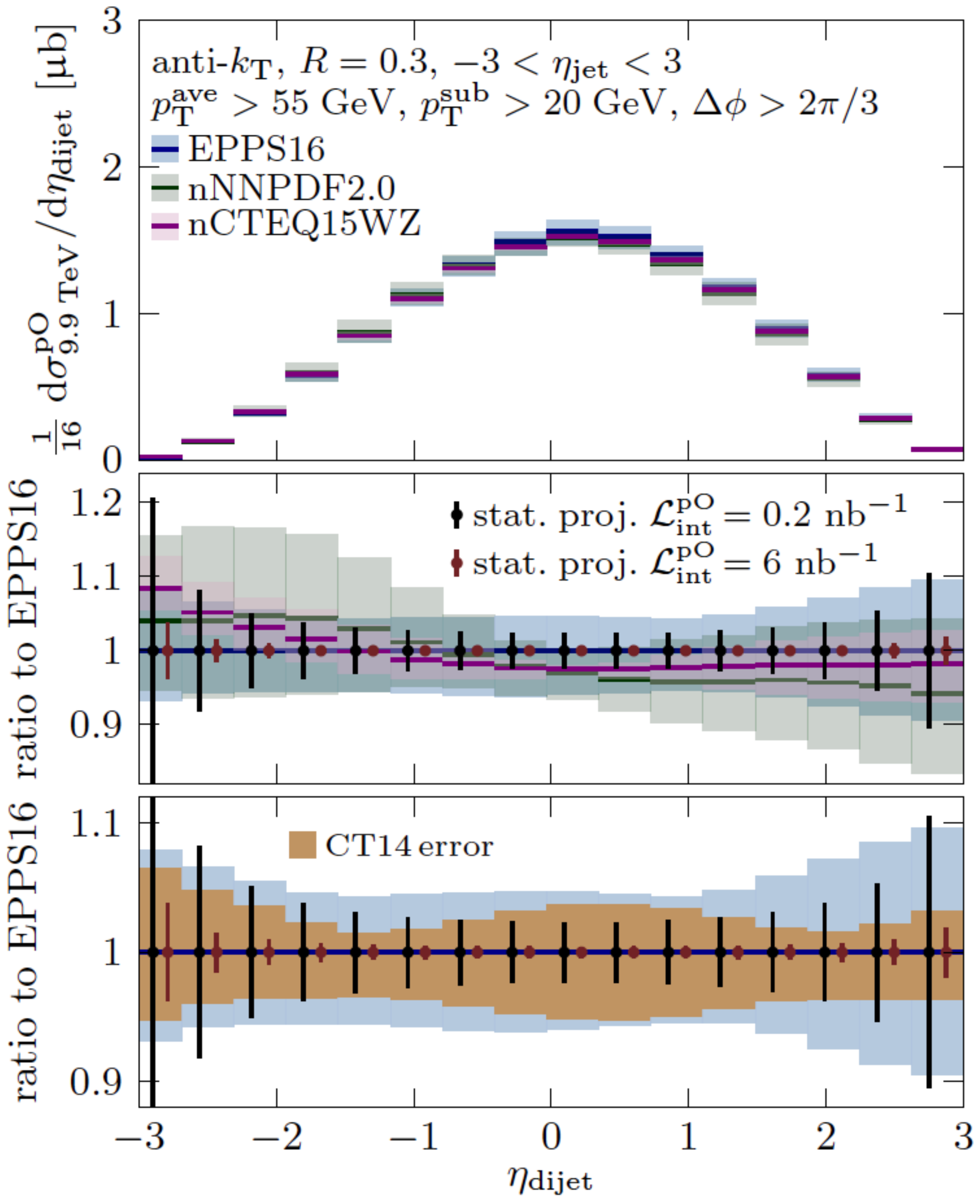
D.Behera et al
EPJ A 58, 175, (2022)

Tetrahedral structure of oxygen?



S.H. Lim et al
PRC 99, 044904 (2019)

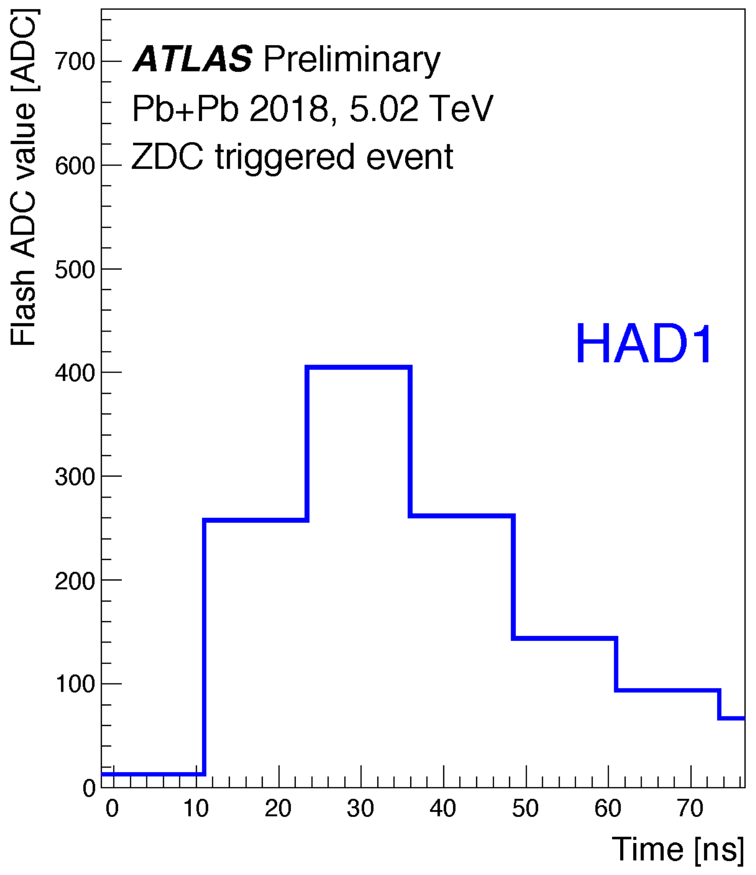
Peak at Npart = 5 expected from *p* collision with an α particle in the O

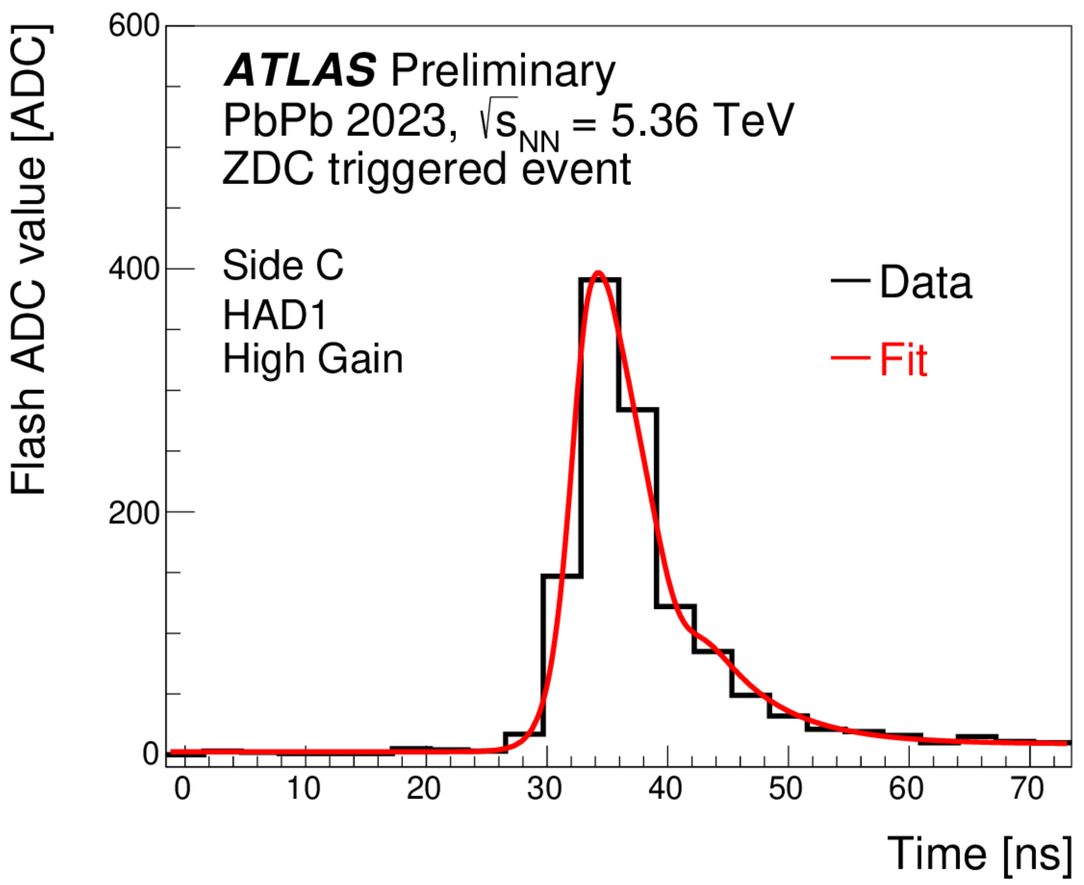


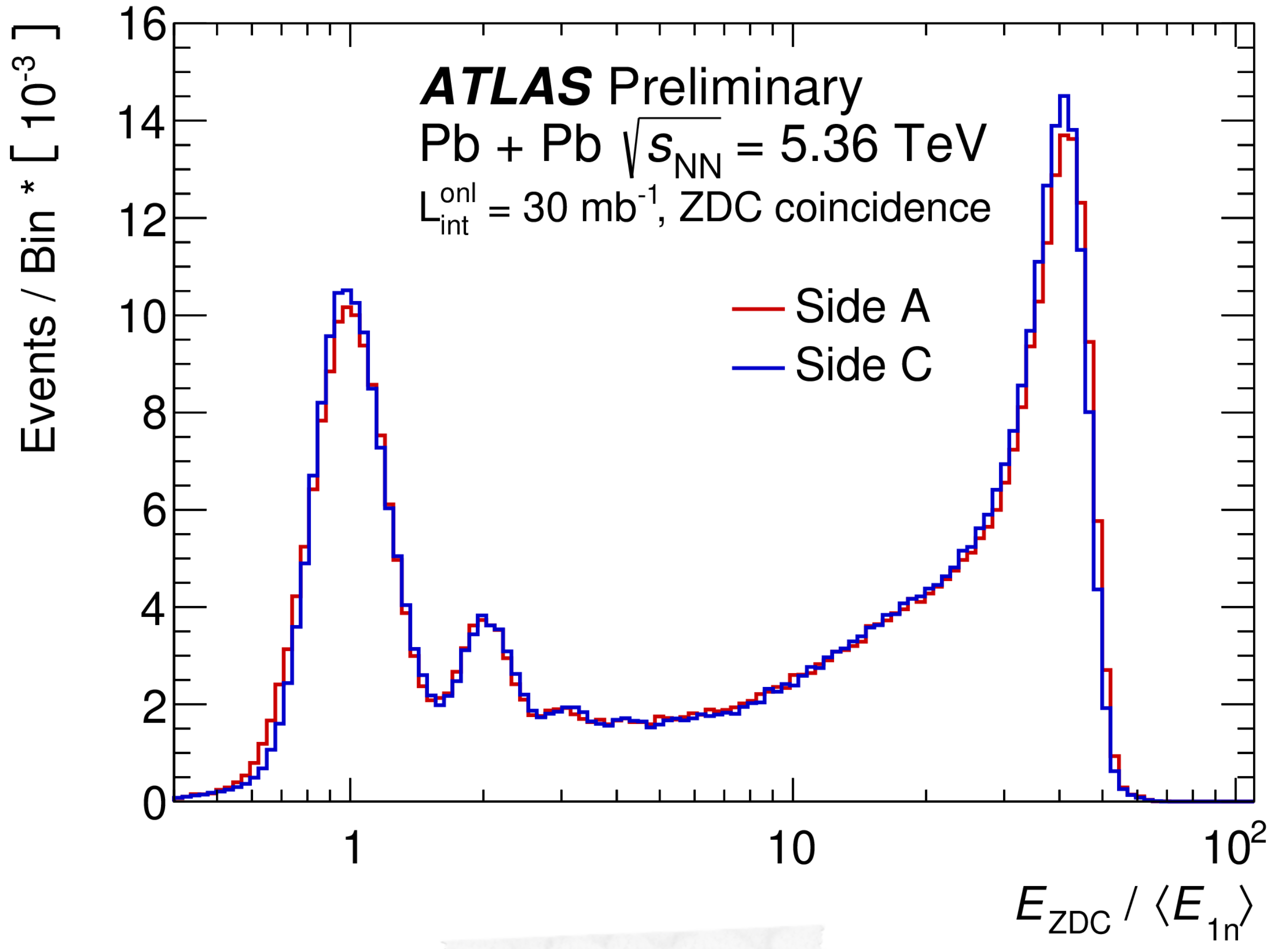
P.Paakkinen
PRD 105, L031504 (2022)

Dijet measurements to inform nPDF parameterizations

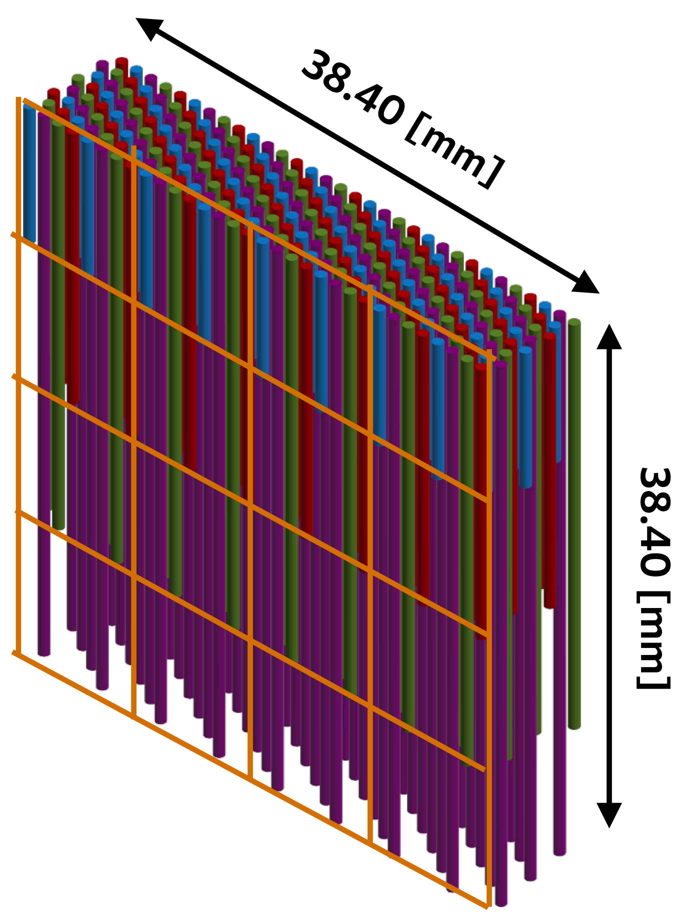
ATLAS DETECTOR IN RUN3: NEW ZDC OPPORTUNITIES





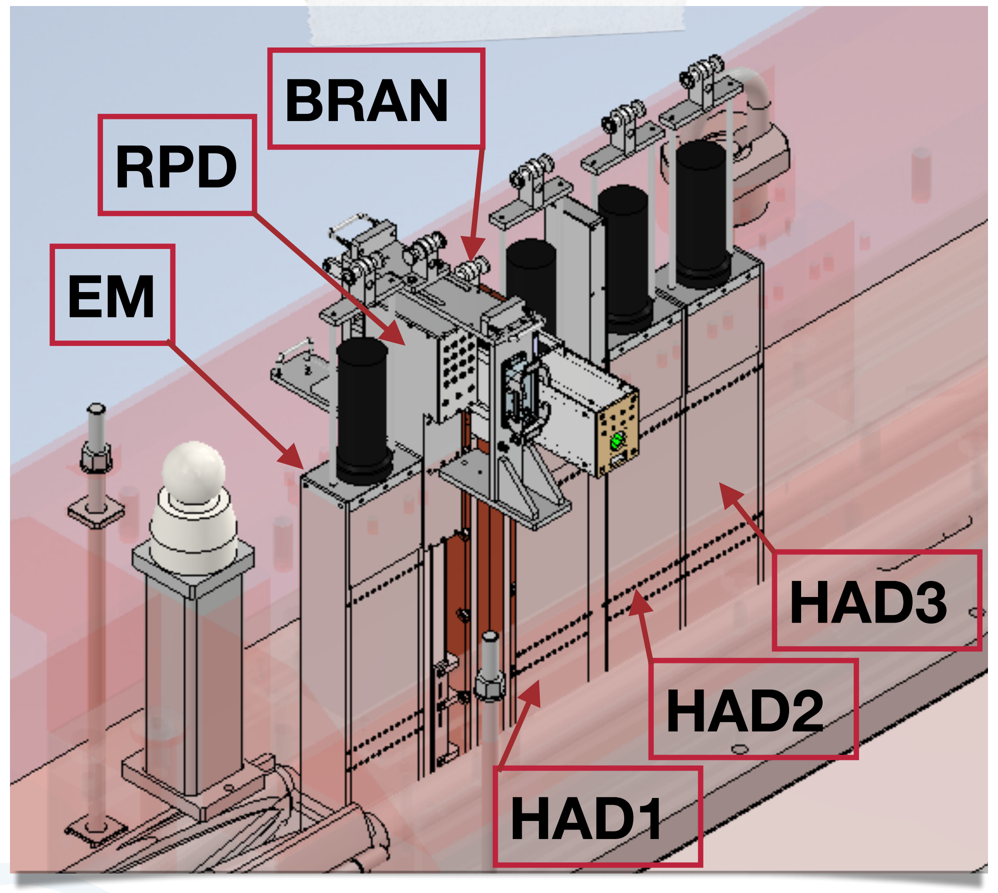


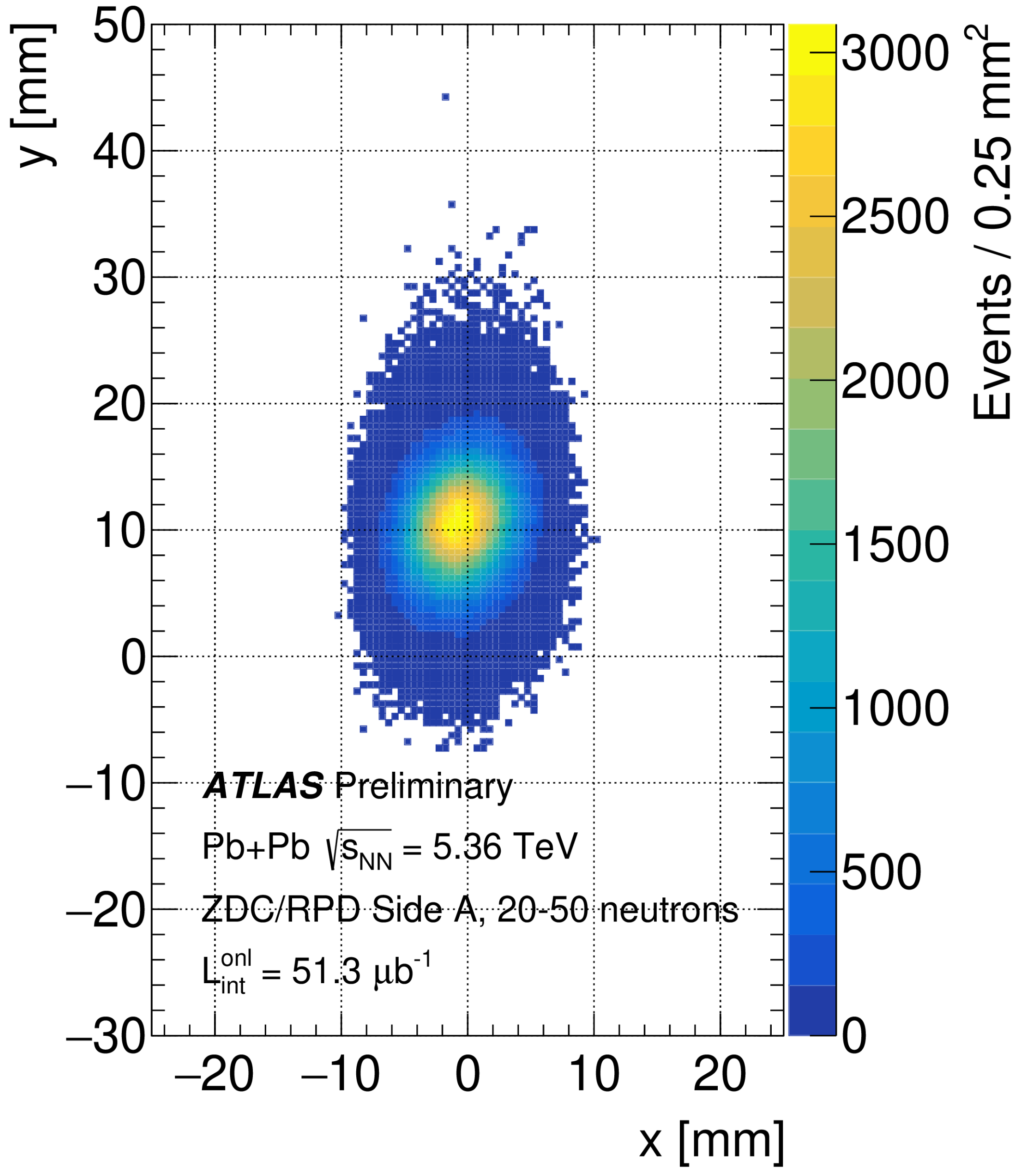
New ATLAS RPD



Refurbished Zero Degree Calorimeter

- New - radiation hard - fused silica rods
- New FE electronics with 320 MHz sampling
- New fully digital trigger
- New low-dispersion air-core cables
- New Reaction Plane Detector





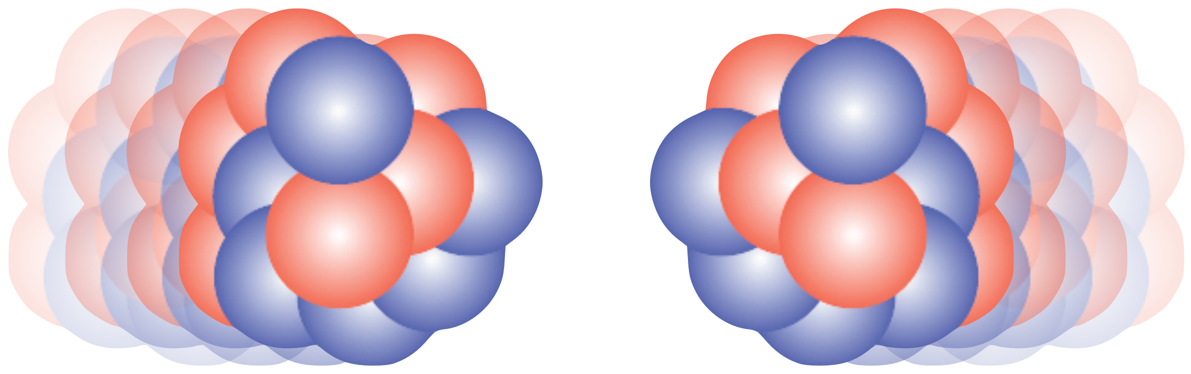
Improved forward neutron detection + new determination of the reaction plane using the spectator neutrons

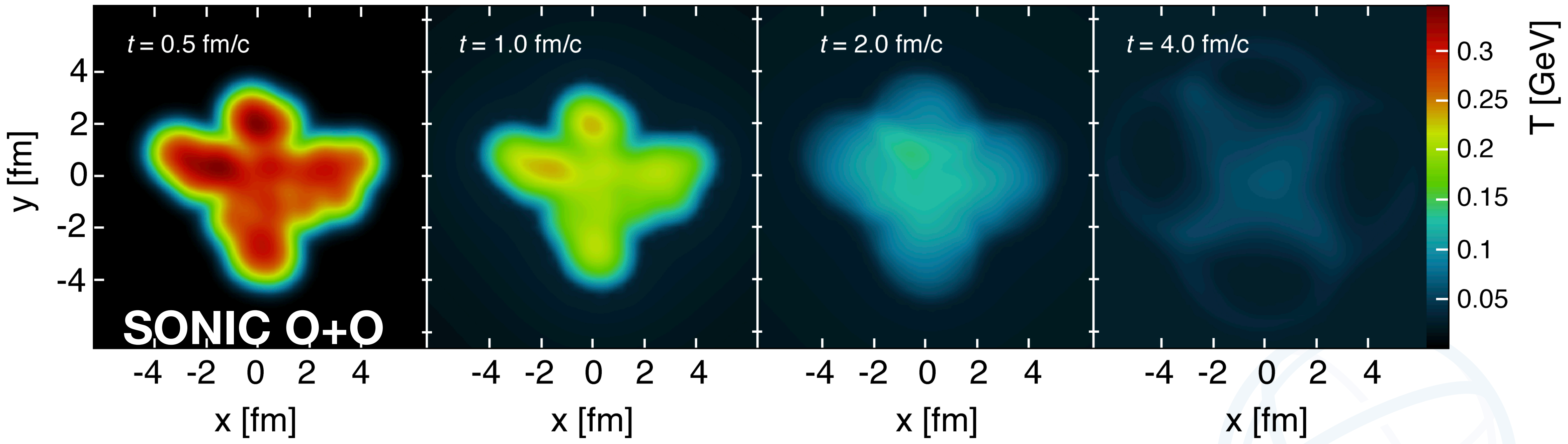
NEXT HI STEP: OXYGEN

At what system size can we observe the onset of energy loss effects?

Lighter ion collisions with different geometry but size similar to p+Pb could help in solving the puzzle

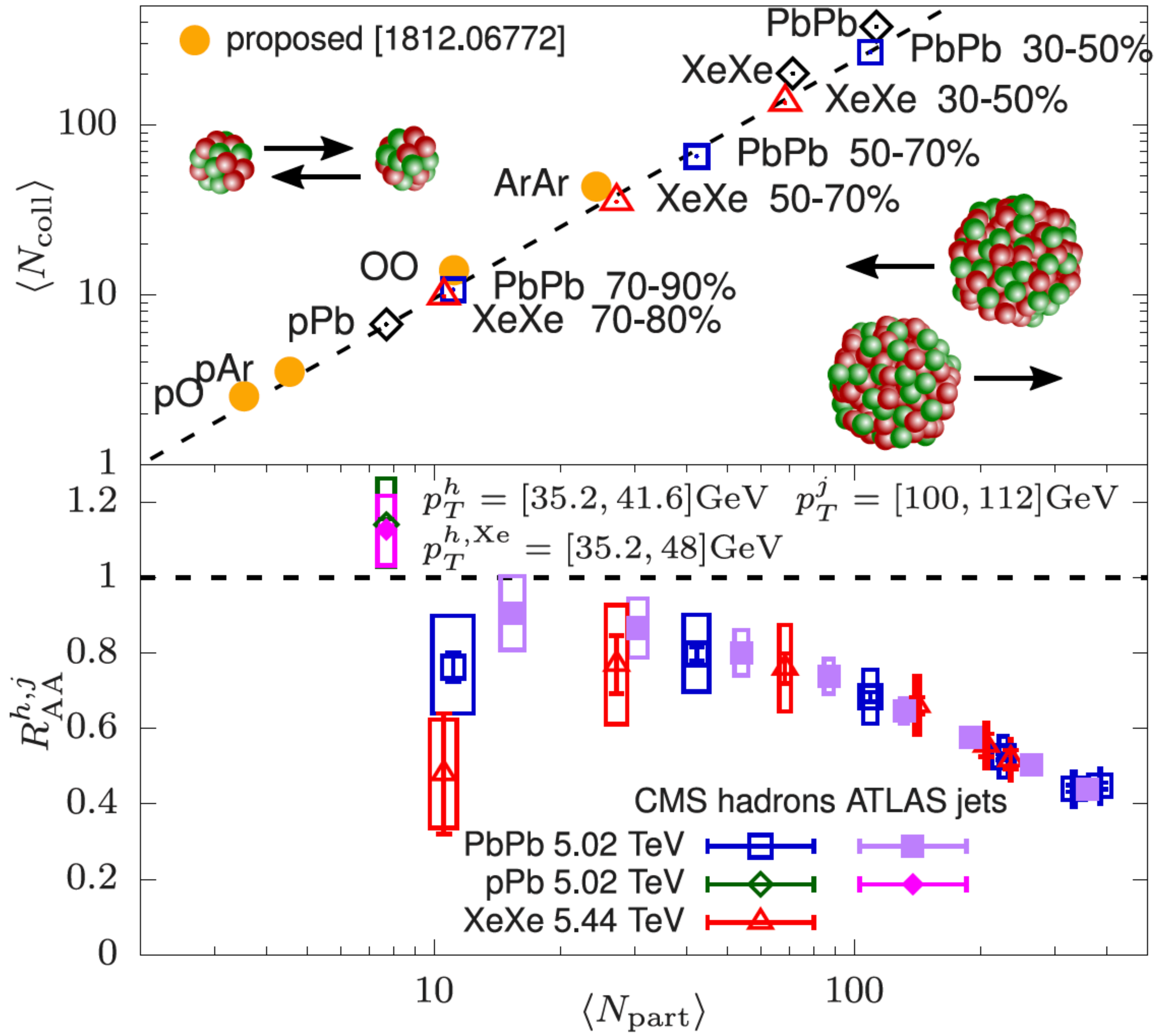
OXYGEN IS THE NEXT STEP!





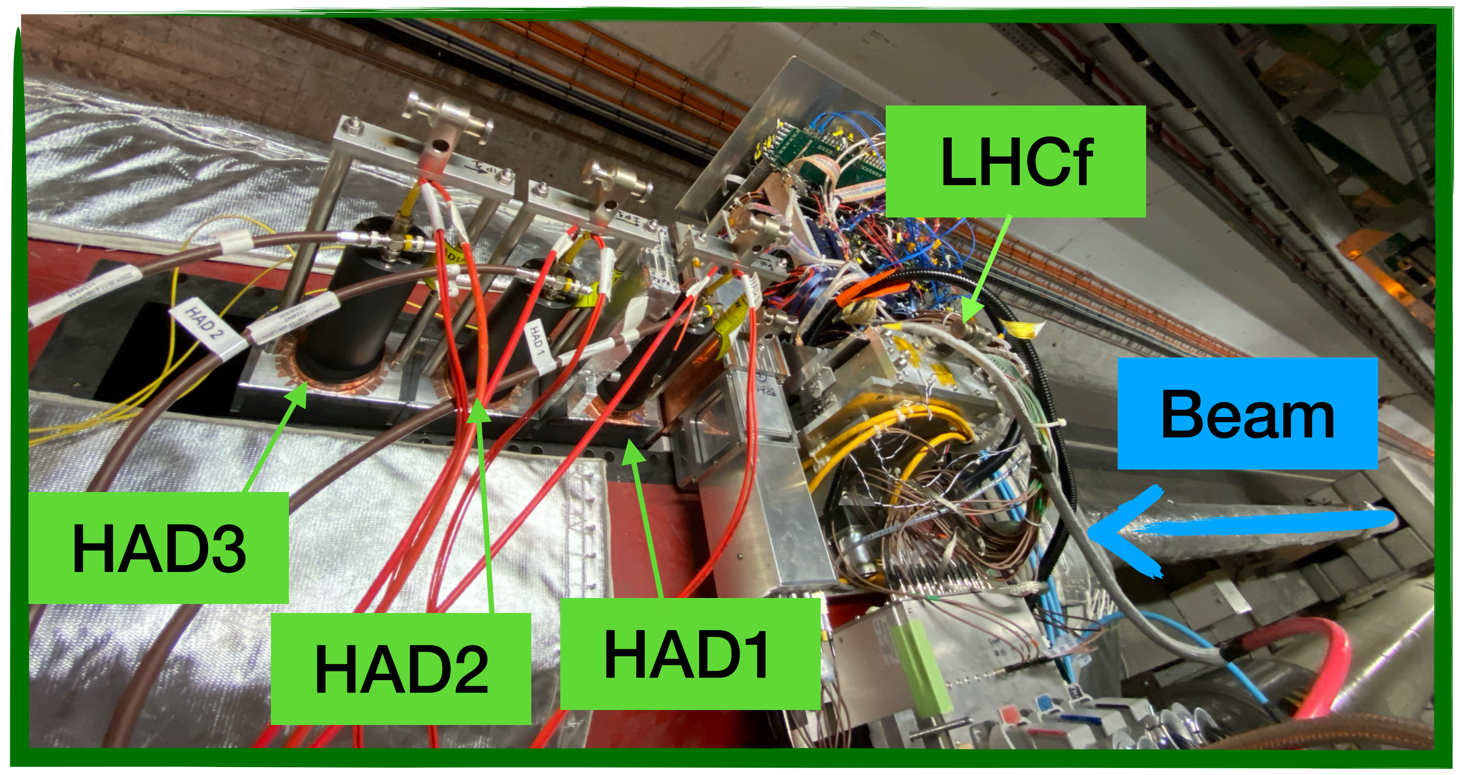
S.H. Lim et al
Phys. Rev. C 99, 044904 (2019)

A.Huss et al.,
PRL 126, 192301 (2021)

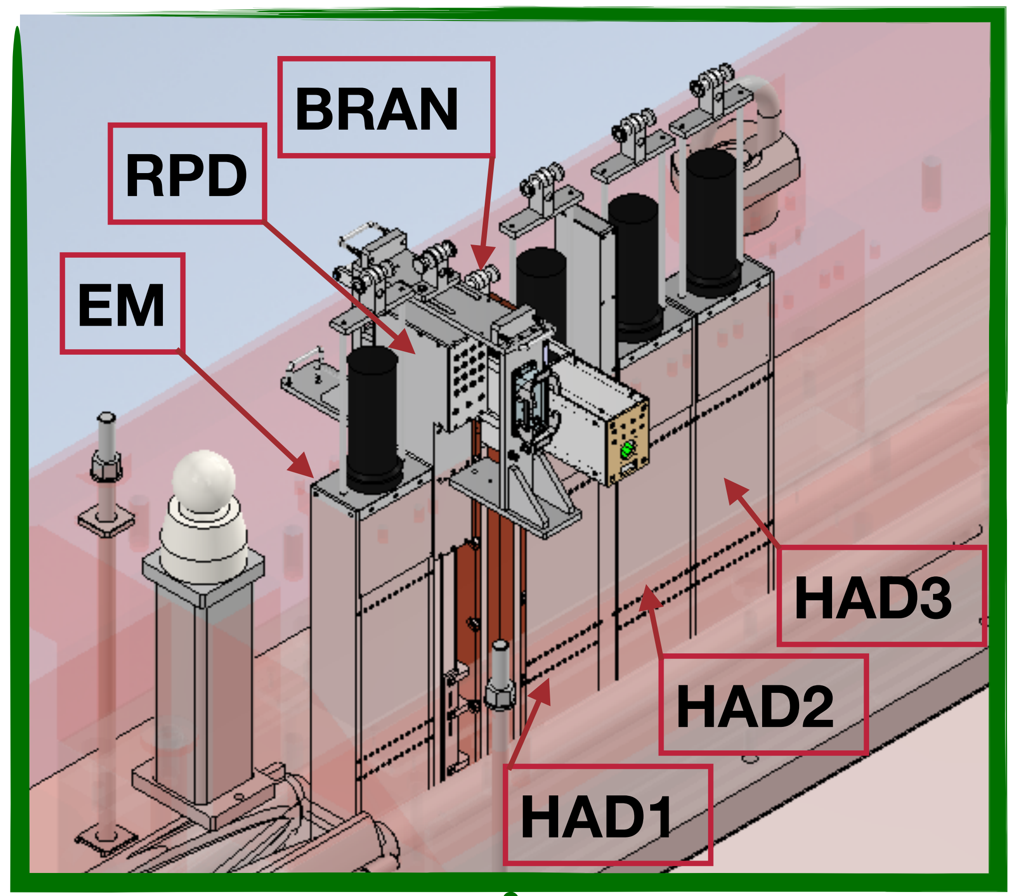


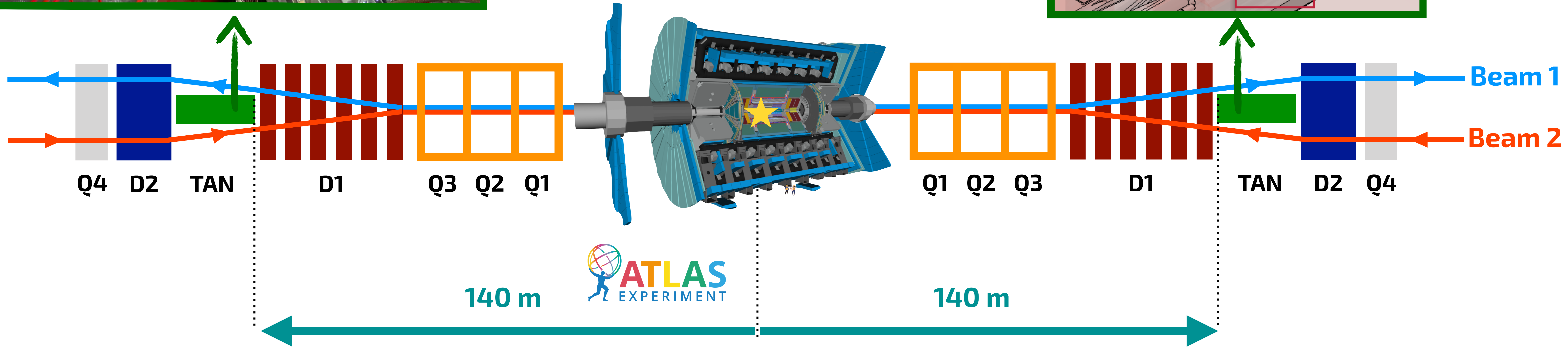
LHCF+ZDC OPPORTUNITIES IN RUN 3 P+O

LHCf + ZDC (pic from 2022 *pp* run)
Setup for *p*-going direction in *p*+O



Full ZDC+RPD on Pb-going side

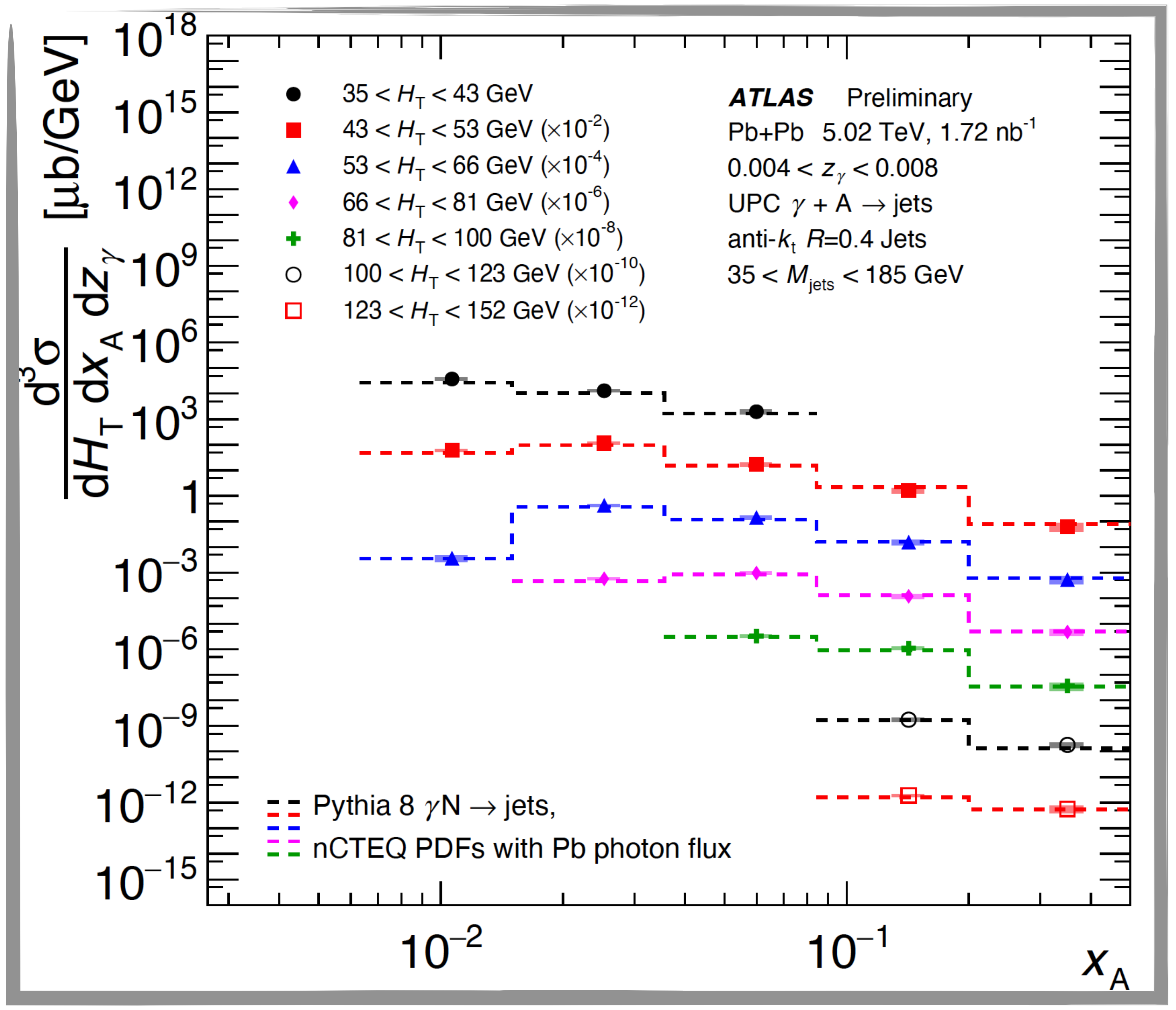


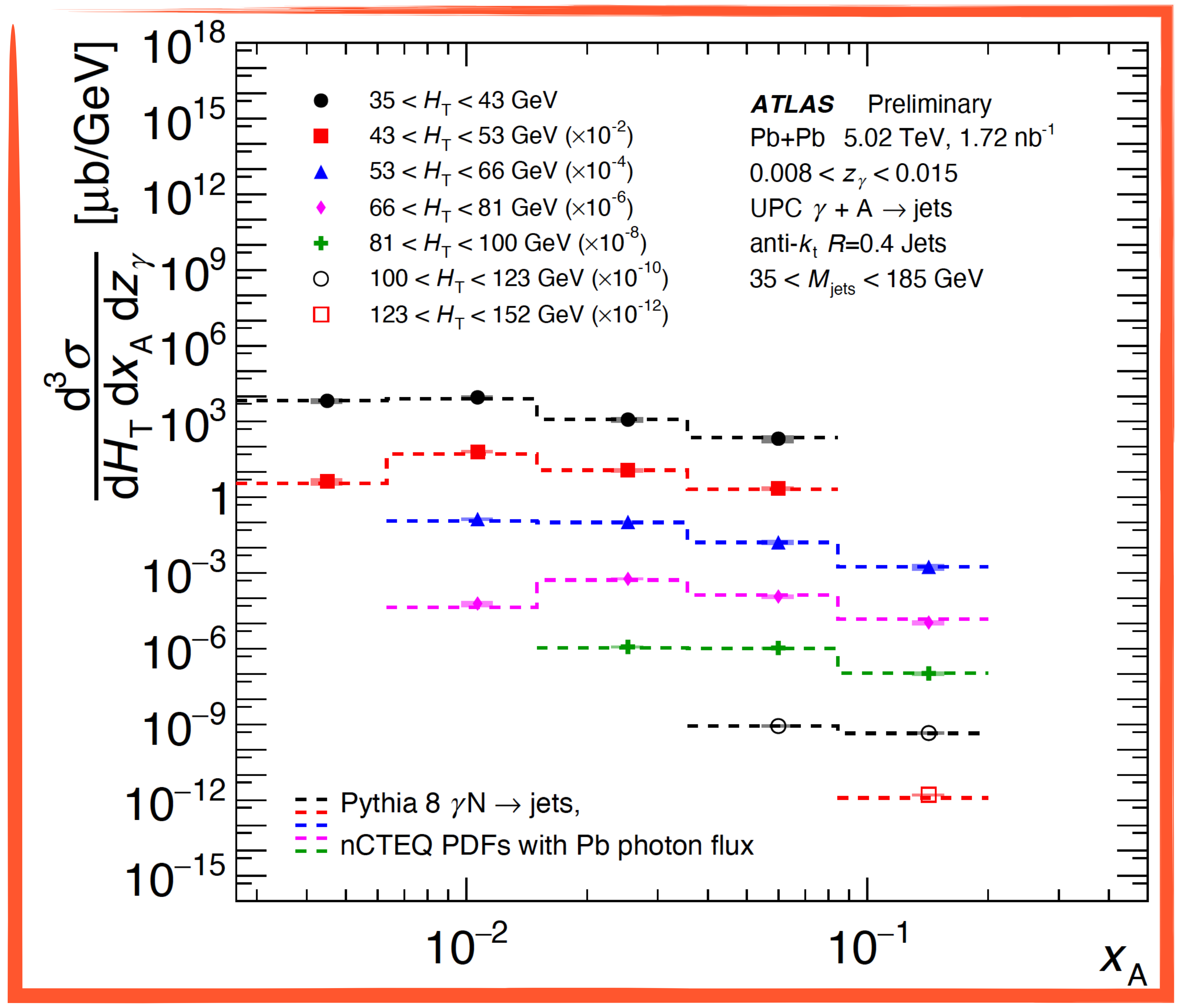


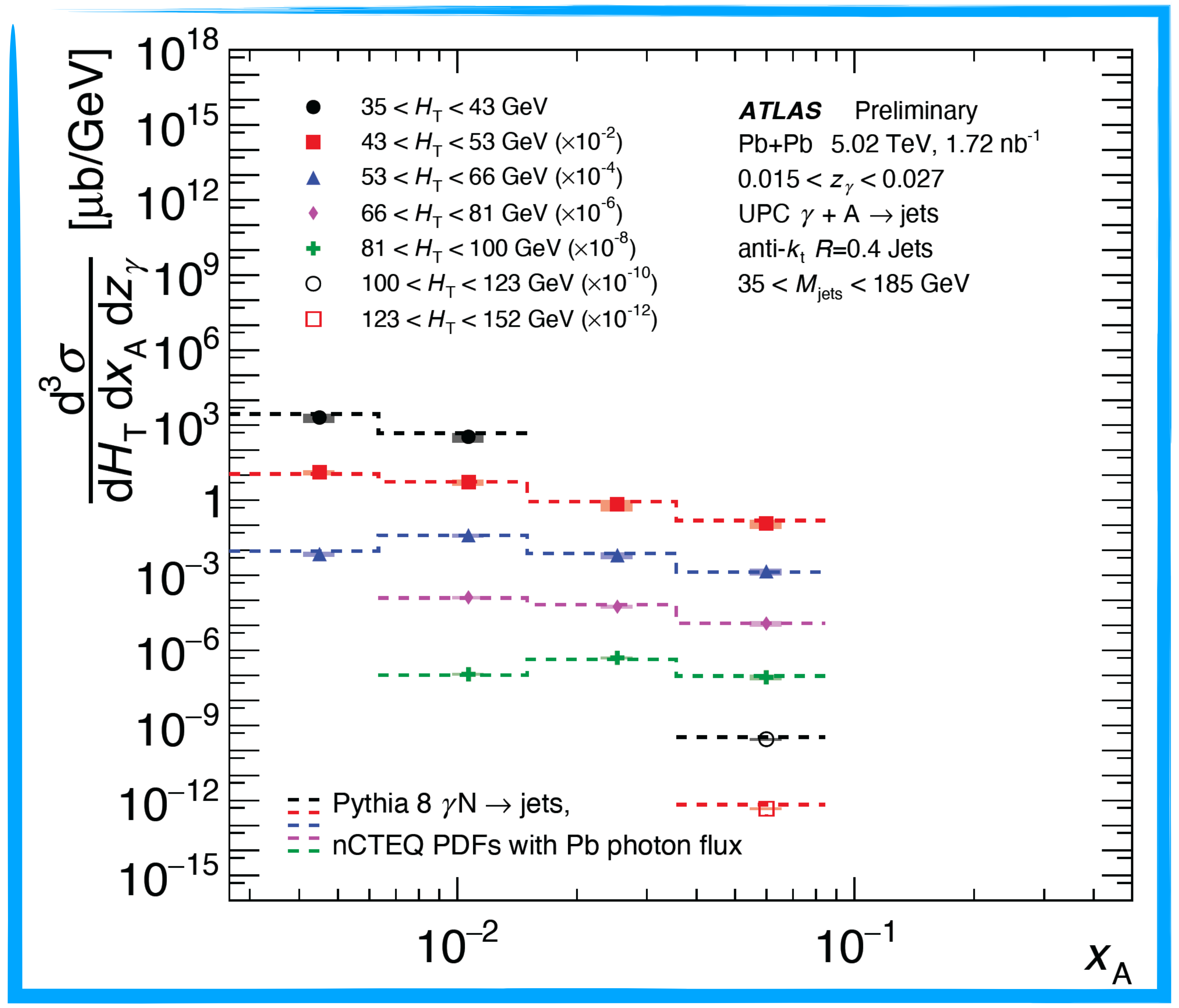
Unprecedented data taking & forward detection capabilities for neutral particles

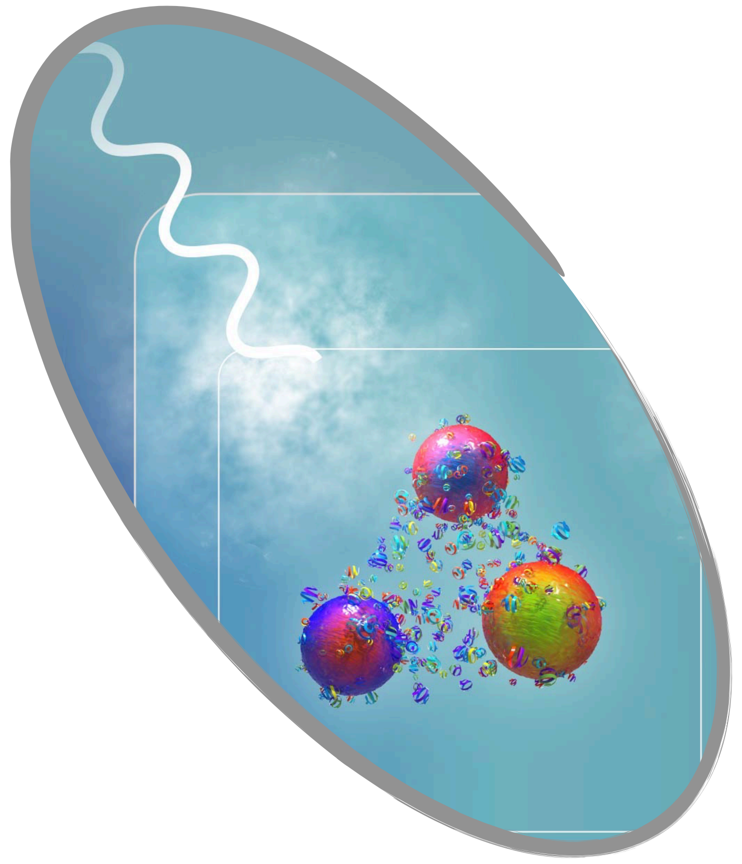
Several opportunities for cosmic-ray interpretation-related measurements!

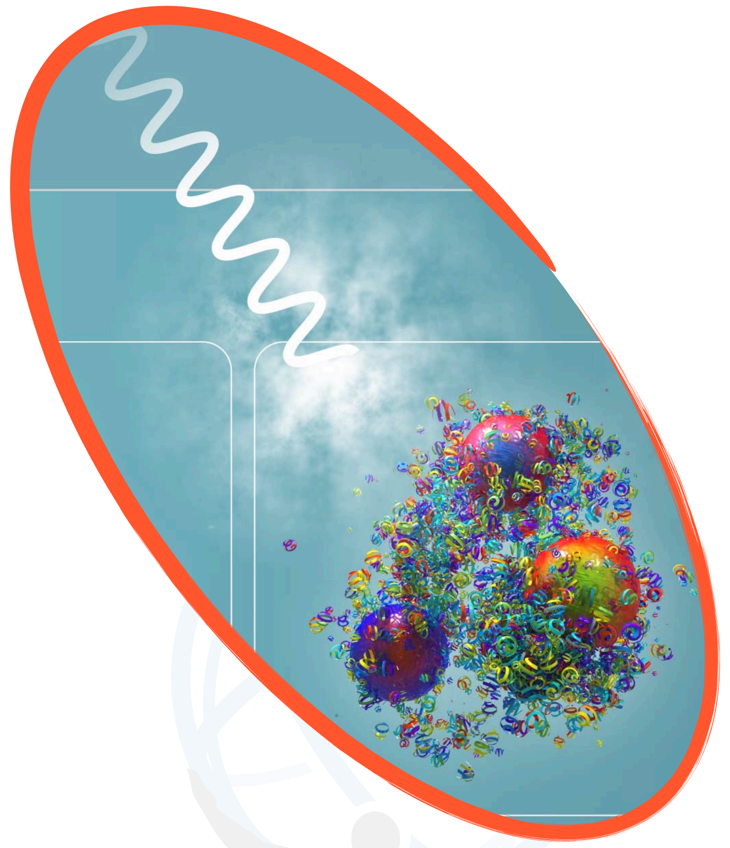
UPC DIJETS - SCANNING THE NUCLEUS W/ PHOTONS

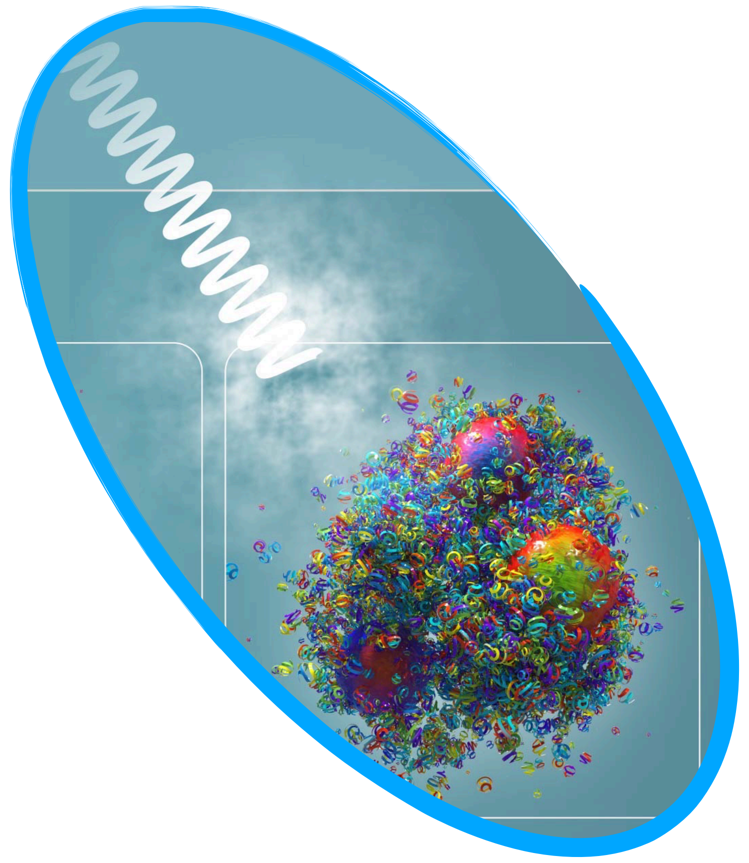




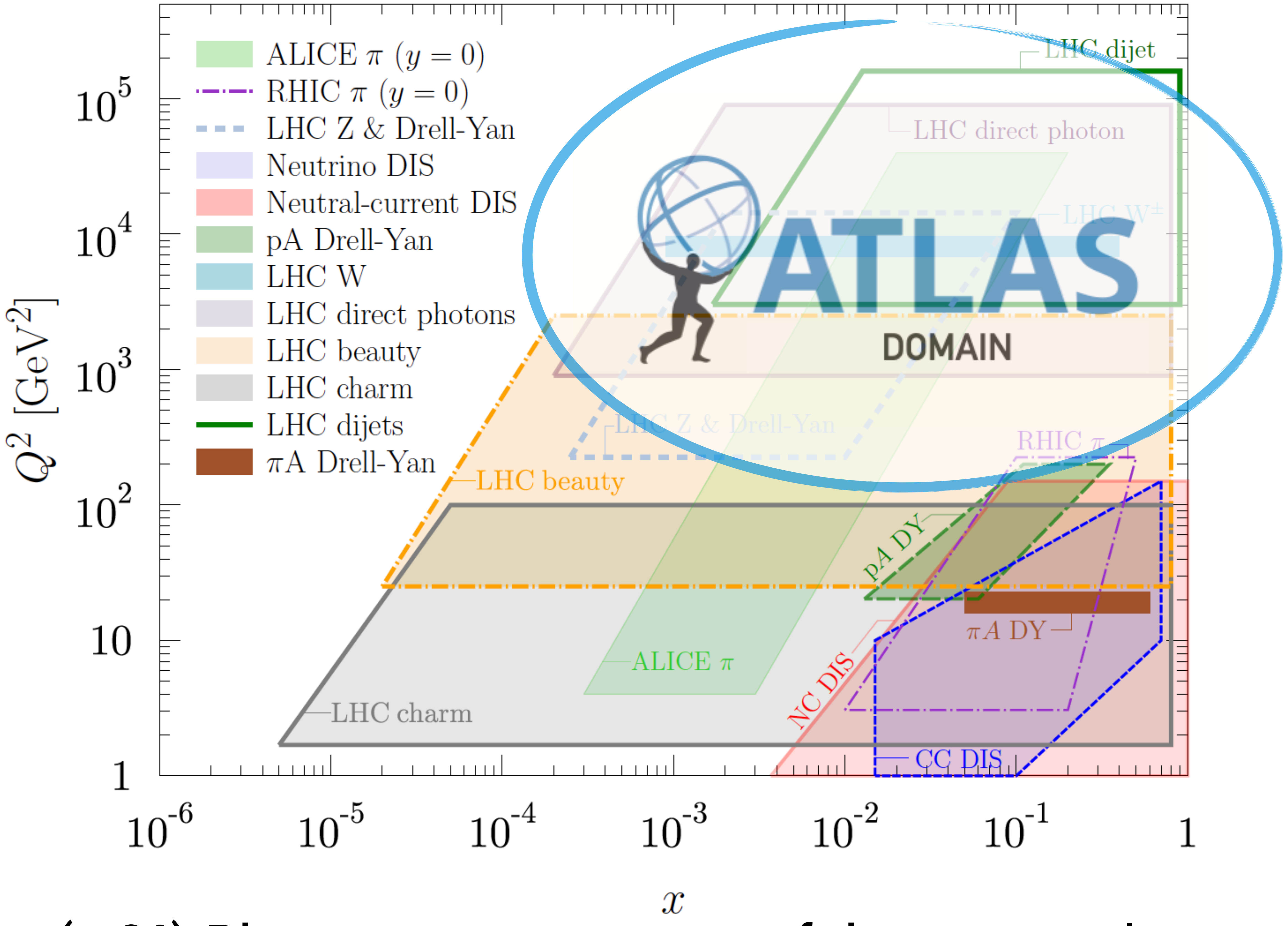








NPDF - CURRENT PICTURE

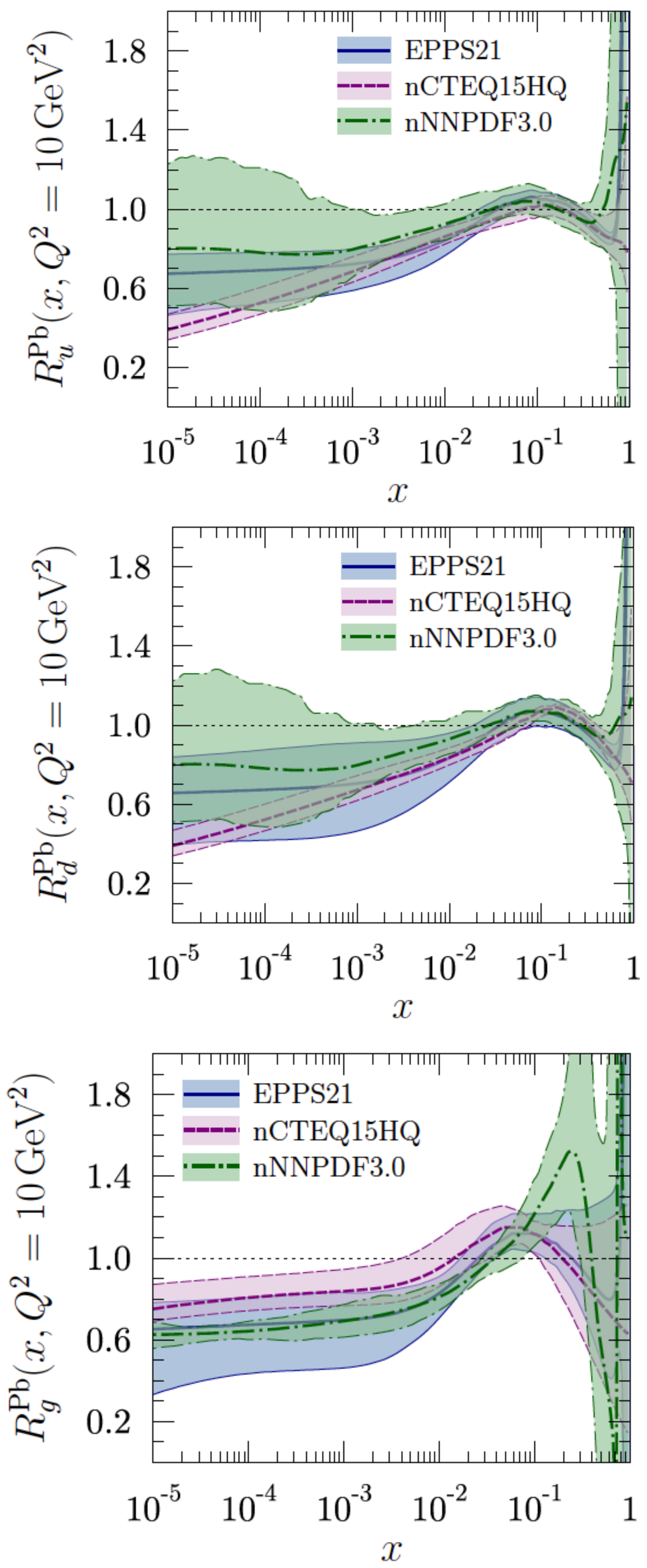


(x,Q²) Phase space coverage of data currently available on the market

Taken from Klasen & Paukkunen
Ann. Rev. Nucl. Part. Sci. 2024. 74:1–41

Large variety of data from different experiments, spanning over a wide (x,Q^2) range, down to x ~ 10^{-5}

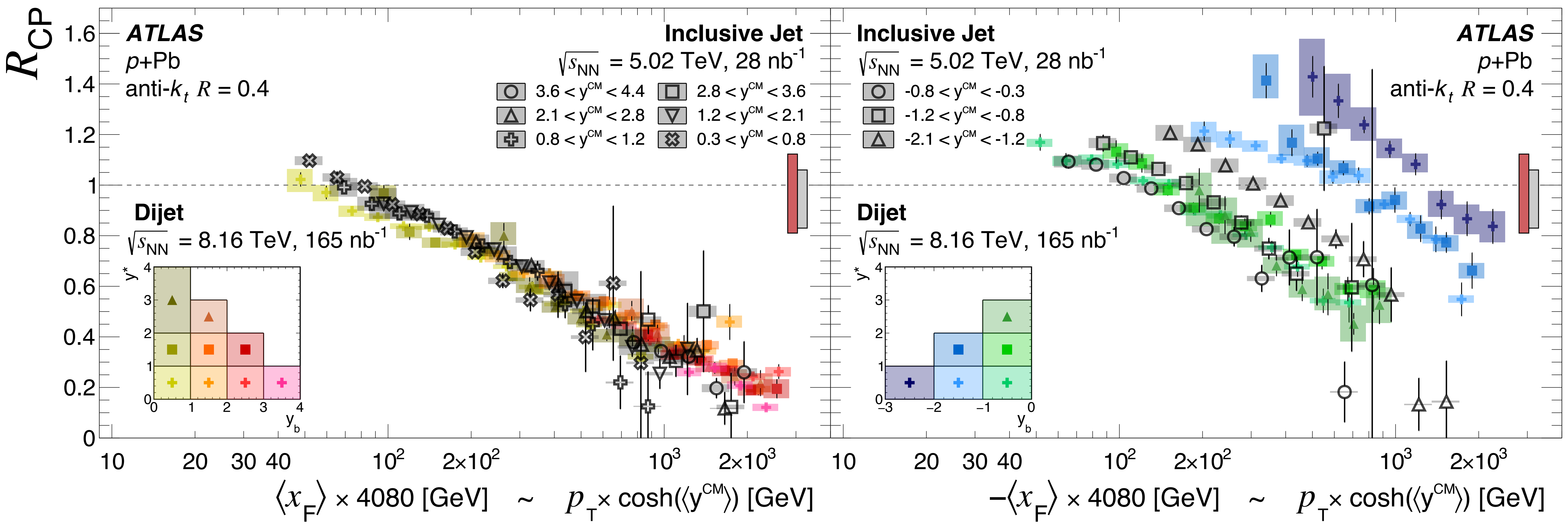
Different combinations of these data included in different nPDF parametrizations:
EPPS21
TUJU21
nCTEQ15HQ
nNNPDF3.0
KSAG20

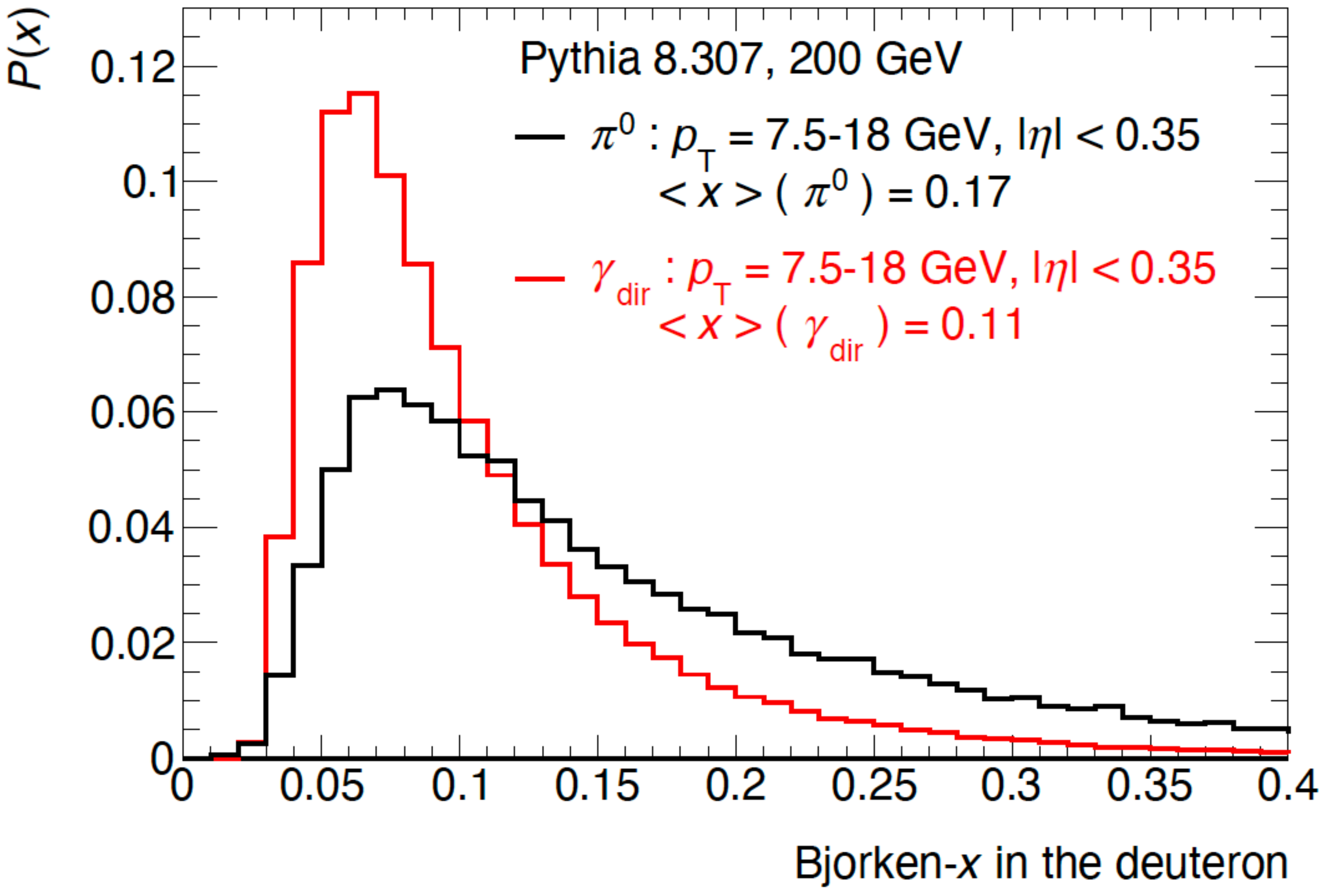


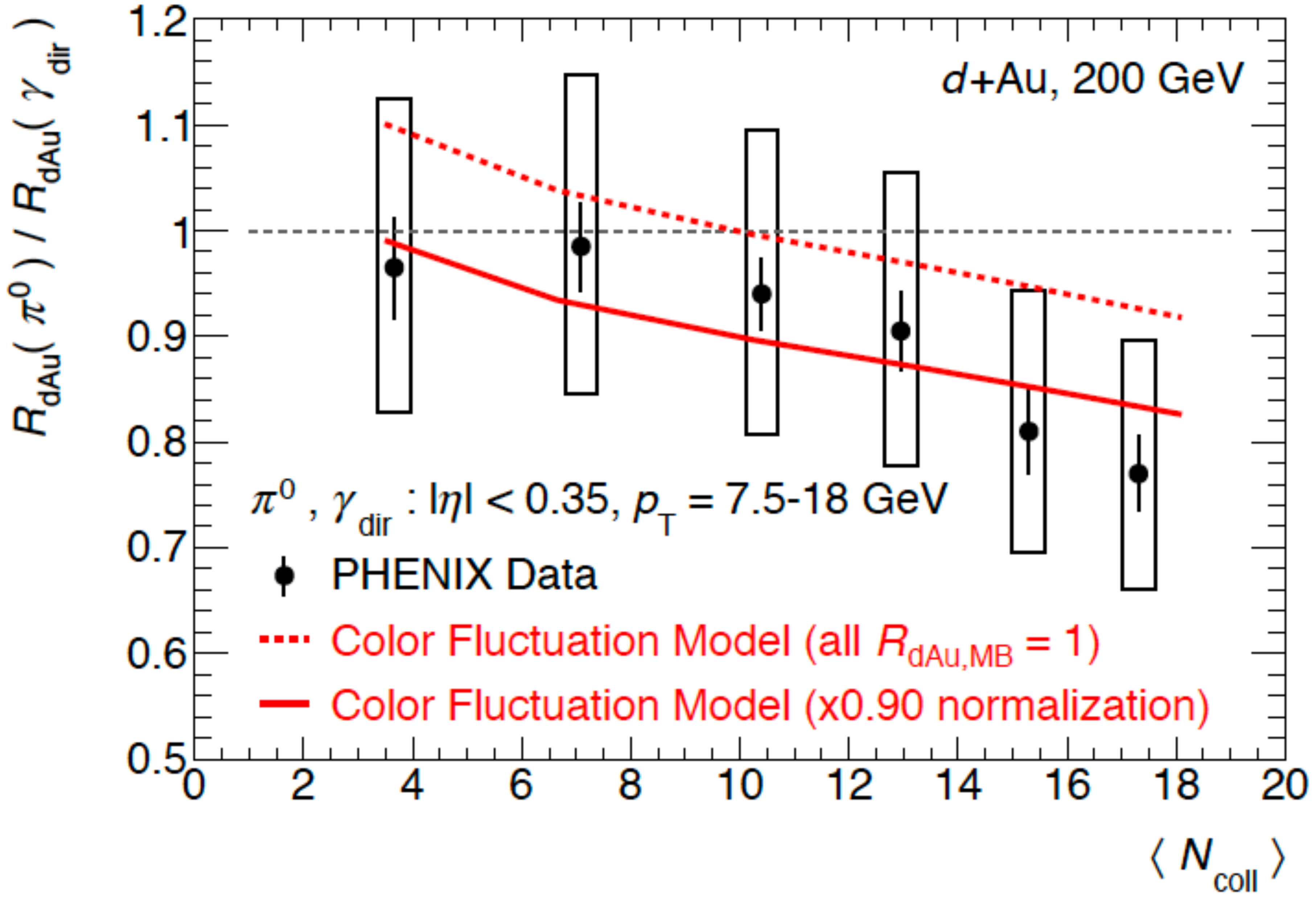
COLOR FLUCTUATIONS RELEVANCE: MOST RECENT EXAMPLE

Color fluctuations modeling recently helped in explaining recent PHENIX 'controversial' results on the production of high p_T π^0 and direct γ in d+Au collisions

D.Perepelitsa, Phys. Rev. C 110, L011901

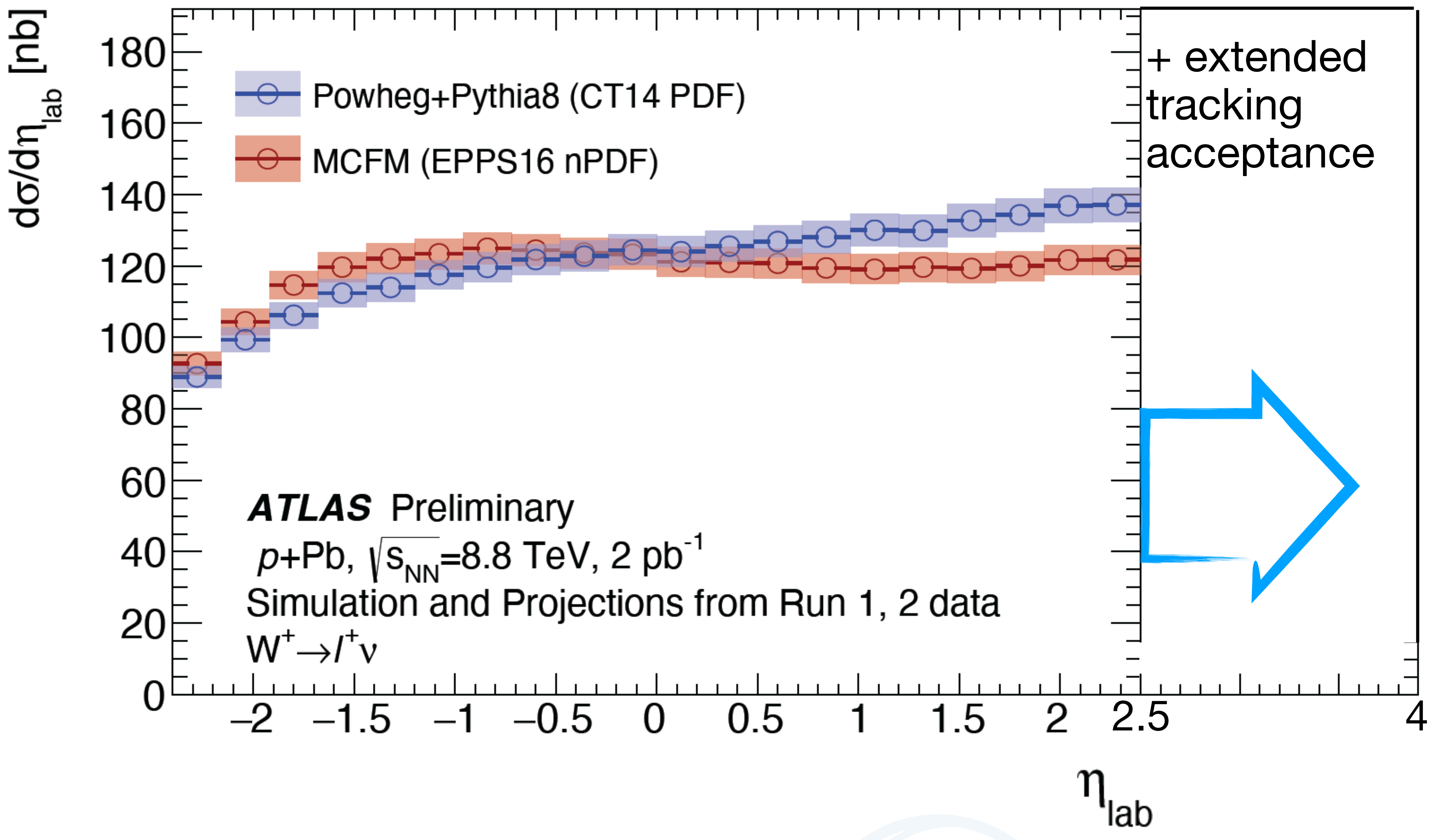


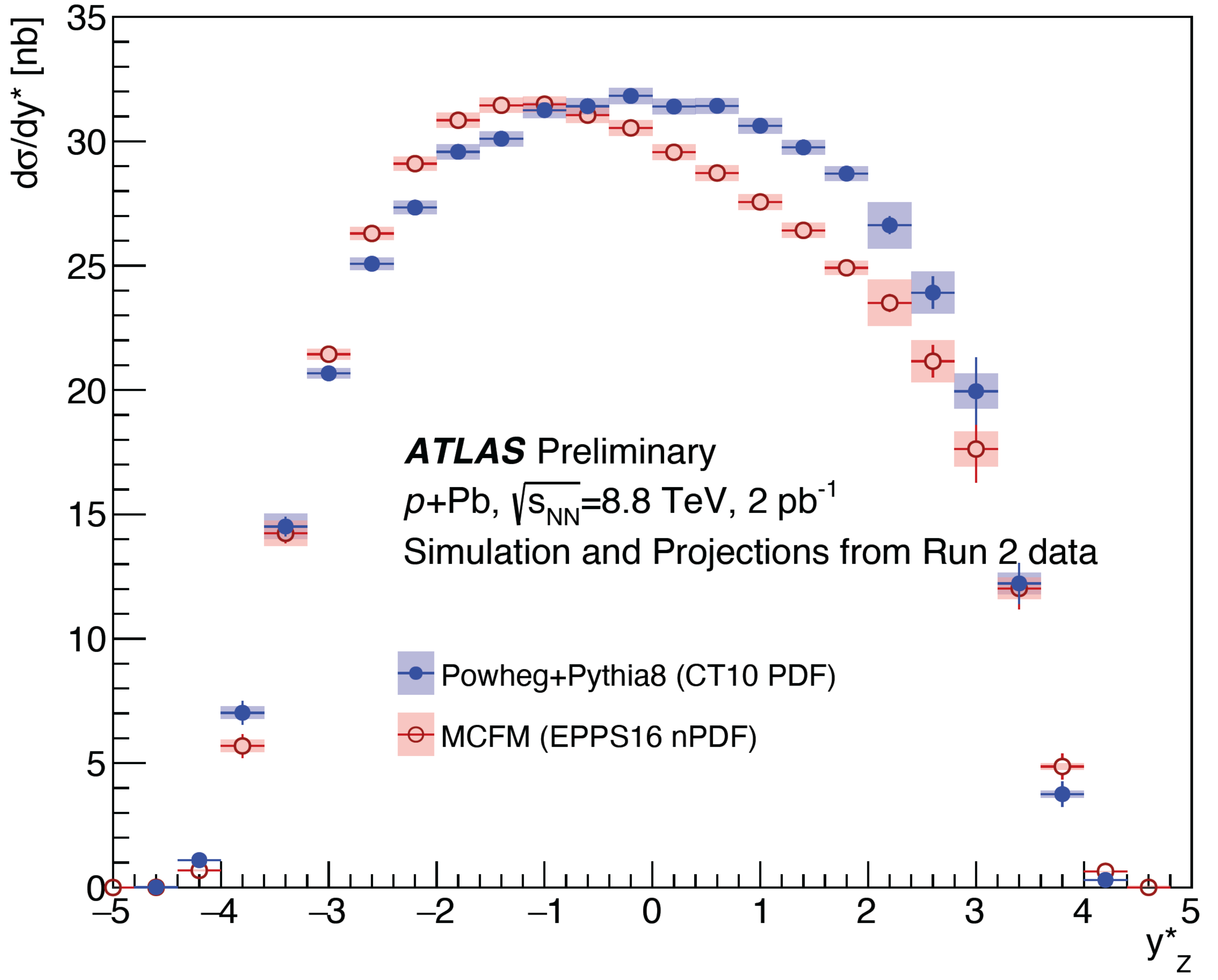




W and Z bosons production

High-precision nPDF-related measurements with improved detection performance thanks to extended tracking & calorimeter upgrade





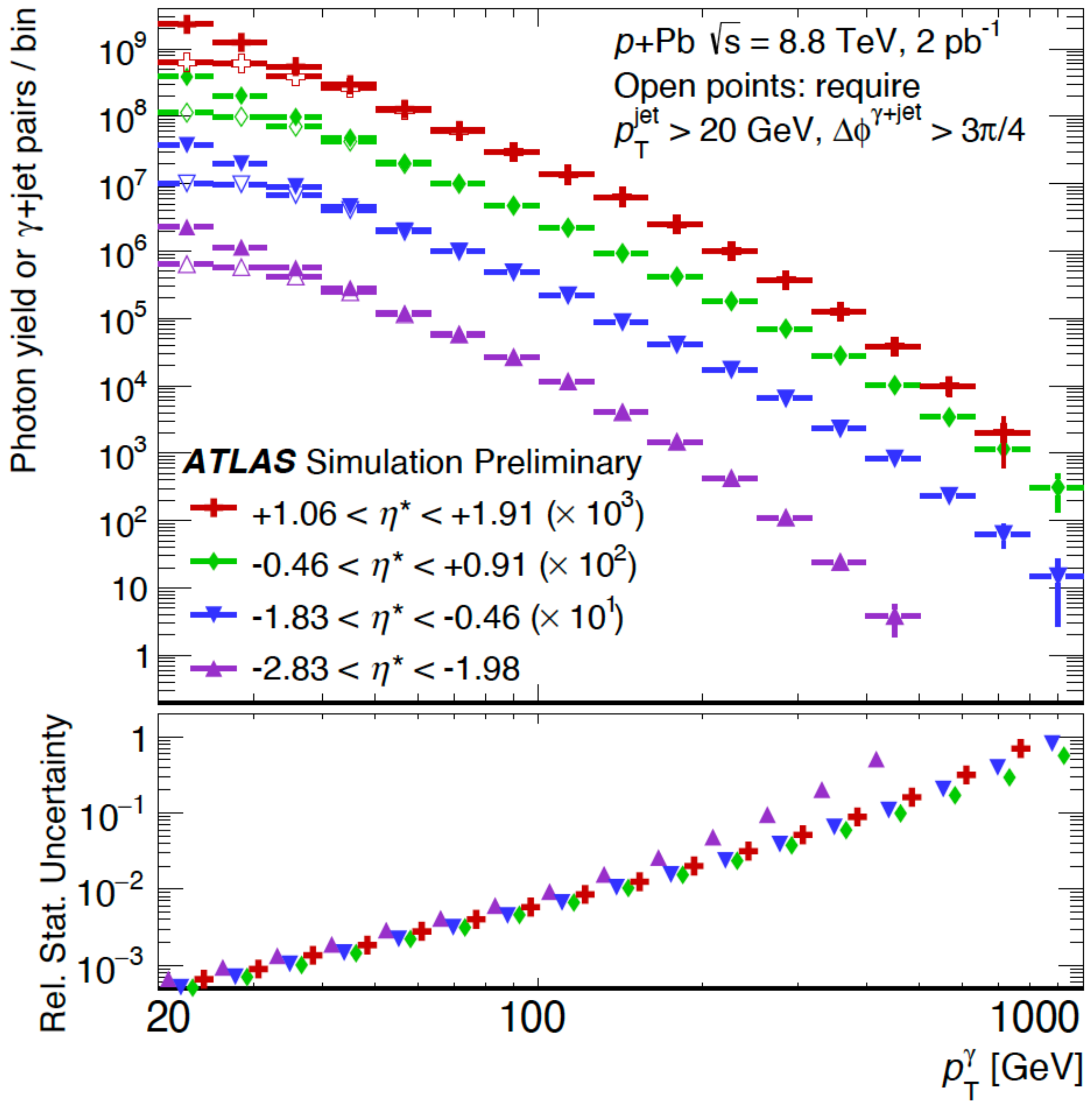
ATL-PHYS-PUB-2018-039

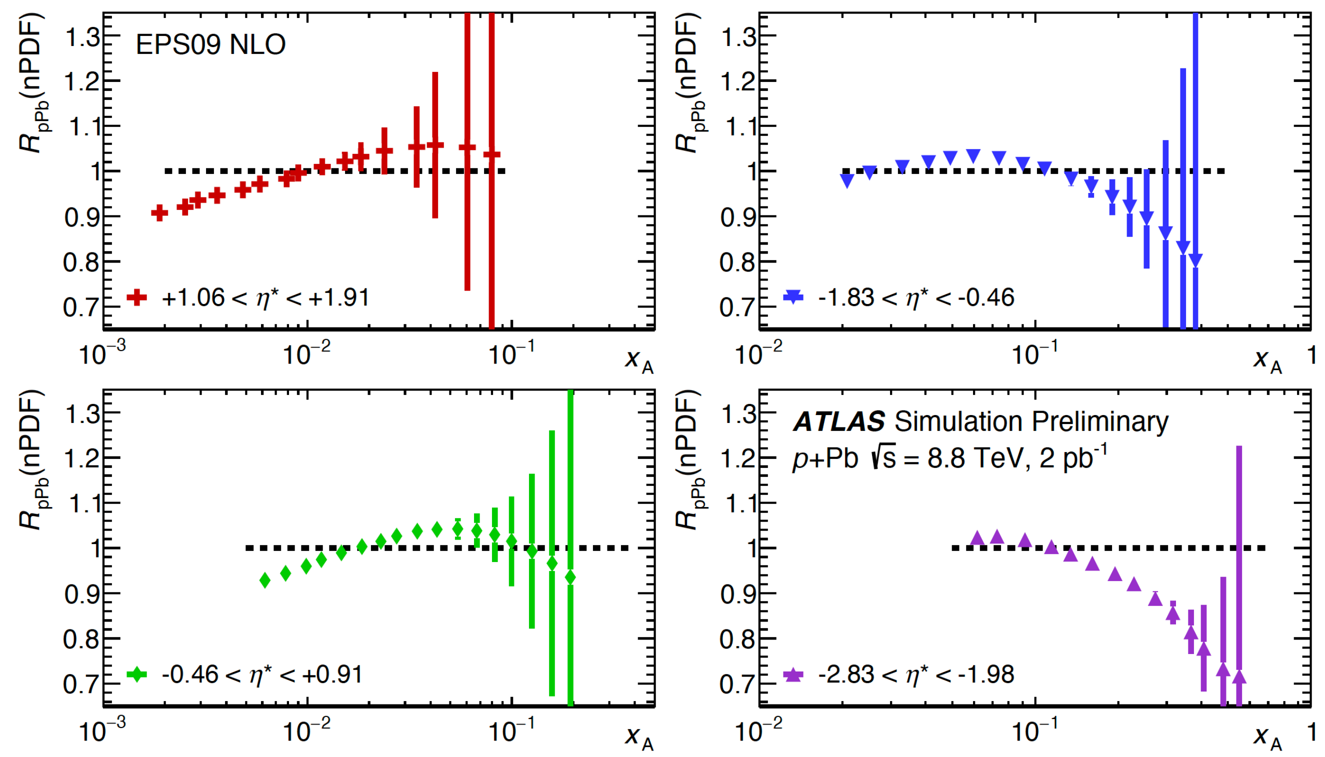
Projections do not account for extended tracking acceptance yet

RUN4: NPDF ORIENTED MEASUREMENTS

γ+JET PRODUCTION

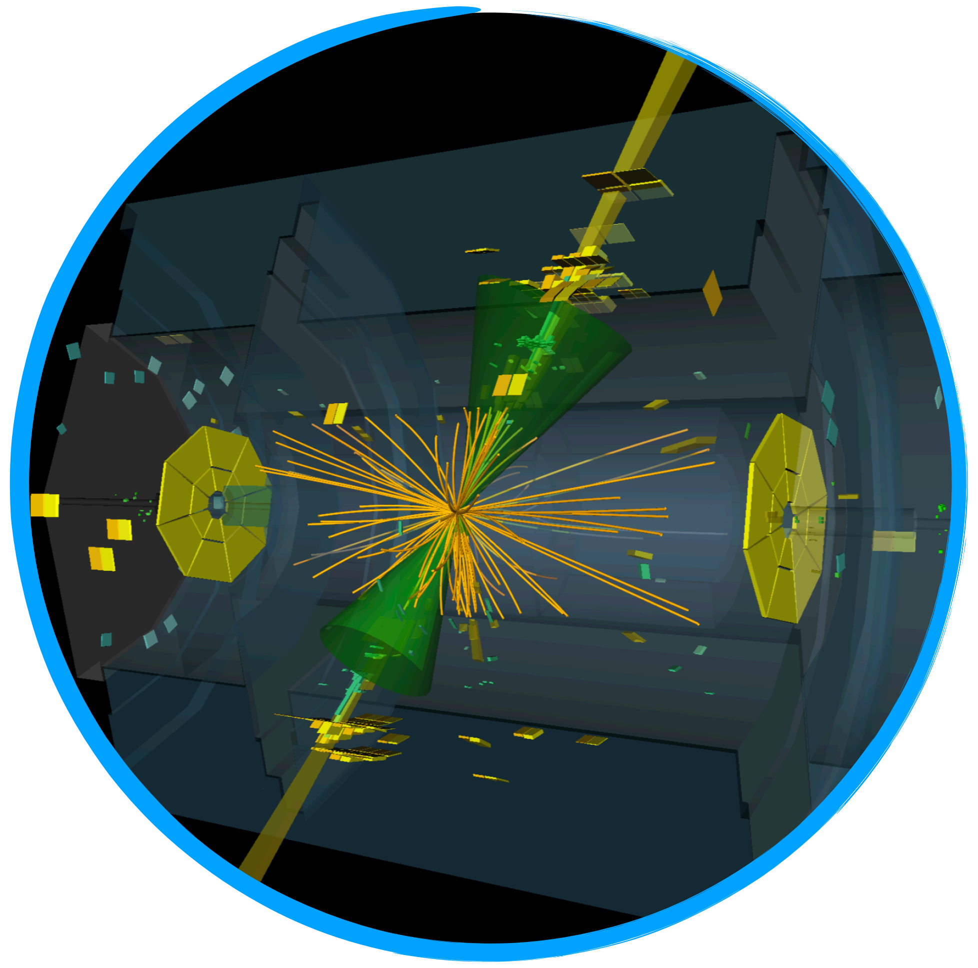
High-precision nPDF-related measurements with improved detection performance thanks to extended tracking & calorimeter upgrade



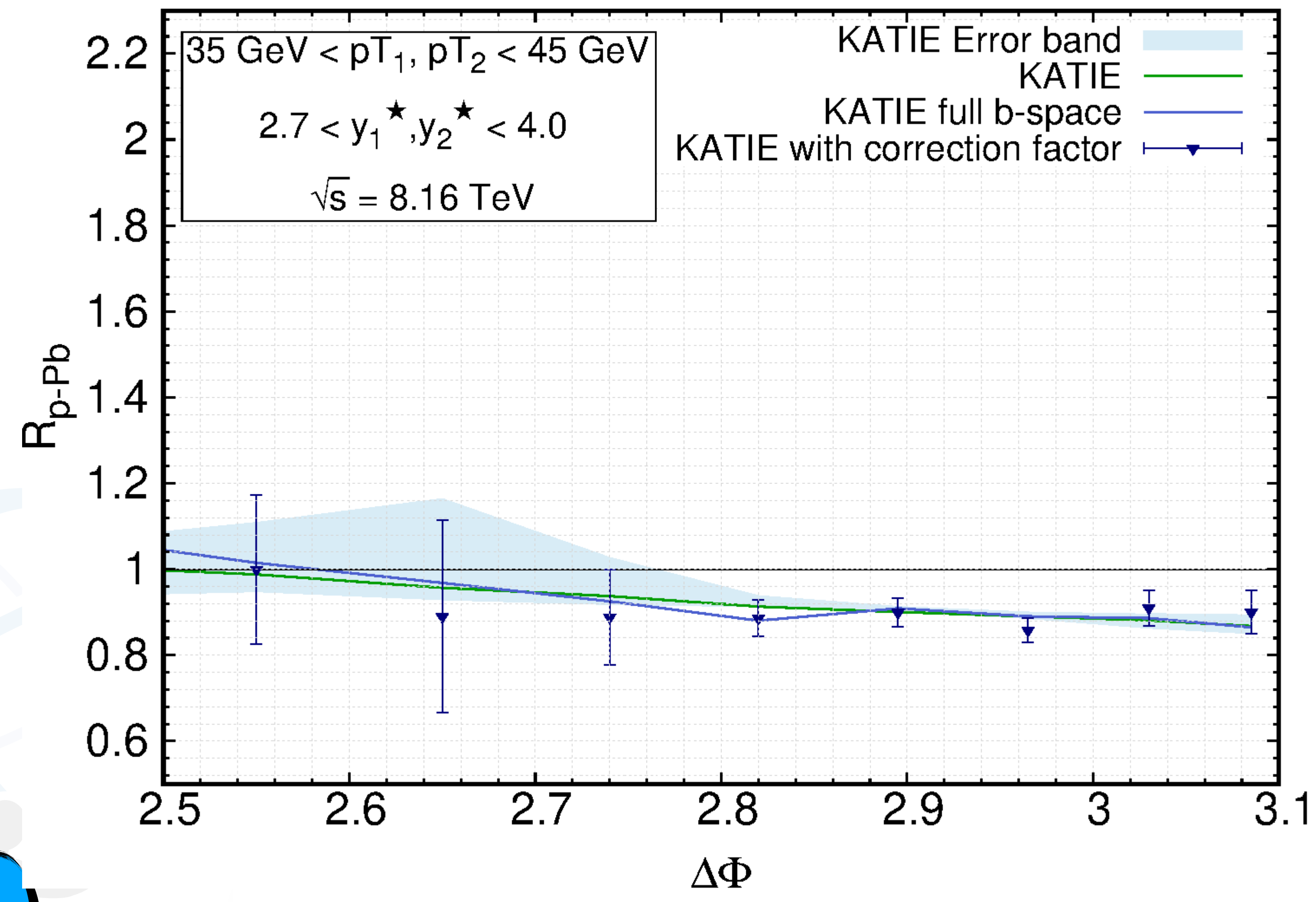


ATL-PHYS-PUB-2018-039

DIJETS



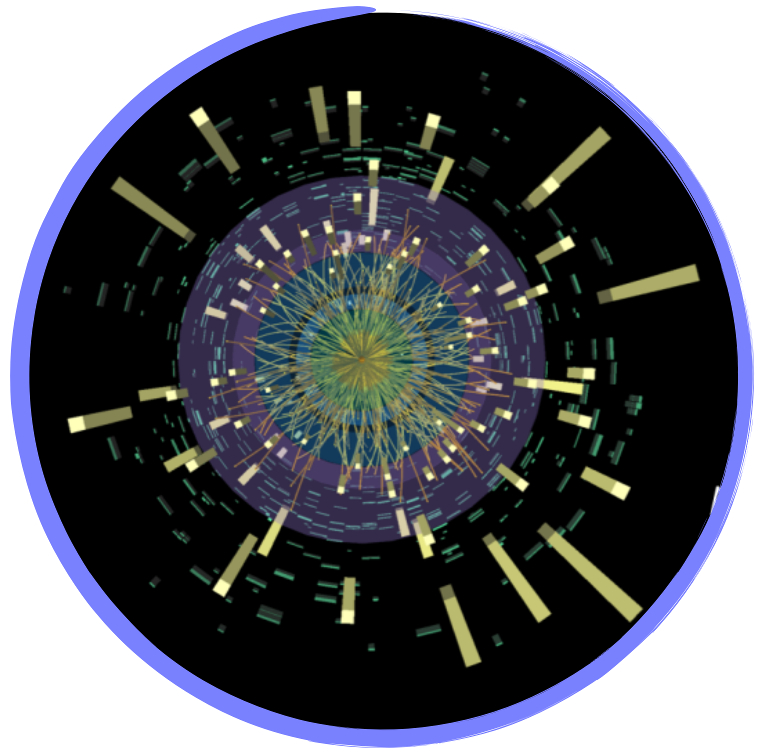
Multi-differential cross-section extraction using full acceptance of ATLAS calorimeter



Van Hameren et al., Eur.Phys.J.C 83 (2023) 10, 947
Forward dijets to search for saturation onset

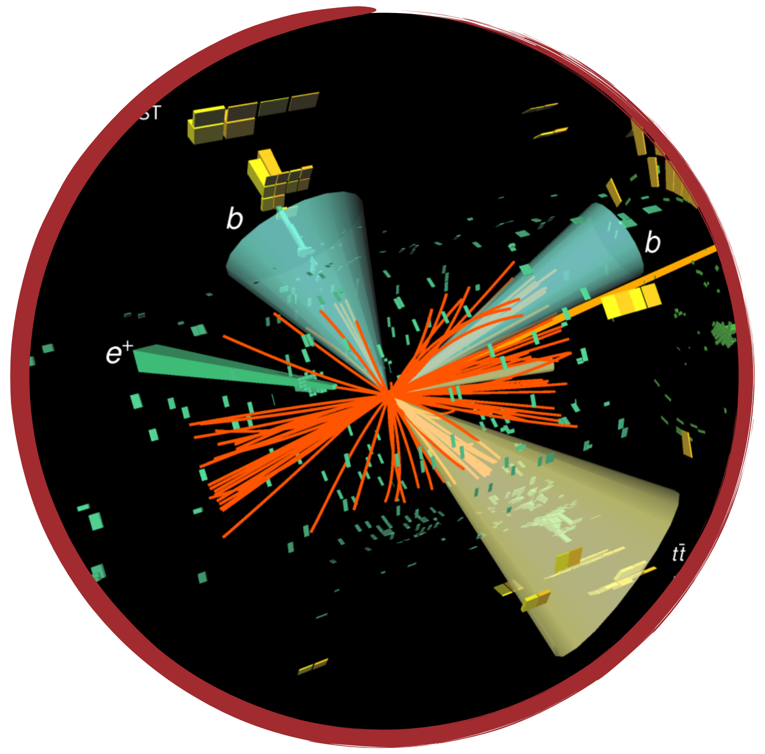
P+A @ ATLAS HISTORY

Run 1



2012
p+Pb @ 5.02 TeV
1 μb^{-1}

2013
p+Pb @ 5.02 TeV
29.8 nb^{-1}



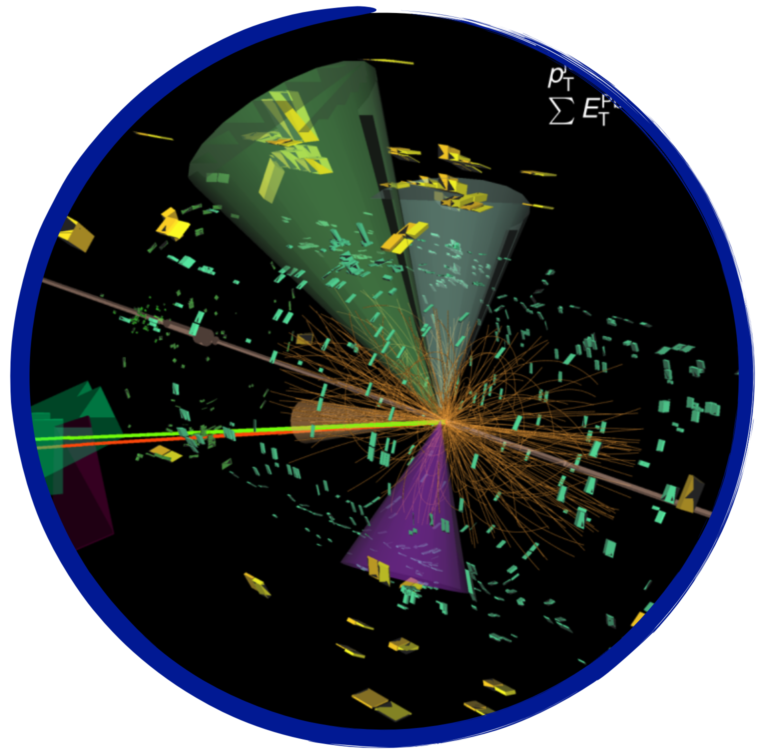
Phys.Rev.Lett. 110 (2013) 18, 182302
Phys. Lett. B 275 (2013) 60-78
Phys. Rev. C 90 (2014), 044906
Phys. Lett. B 748 (2015) 392-413
Phys. Rev. C 92, 034904 (2015)
Eur. Phys. J. C. (2016) 76:199
Phys. Rev. C. 92 (2015) 044915

Phys. Lett. B 763 (2016) 313
Phys. Rev. C 95 (2017) 064914
Eur. Phys. J. C 77 (2017) 428
Nucl. Phys. A 978 (2018) 65
Eur. Phys. J. C 78 (2018) 171
JHEP 07 (2023) 074

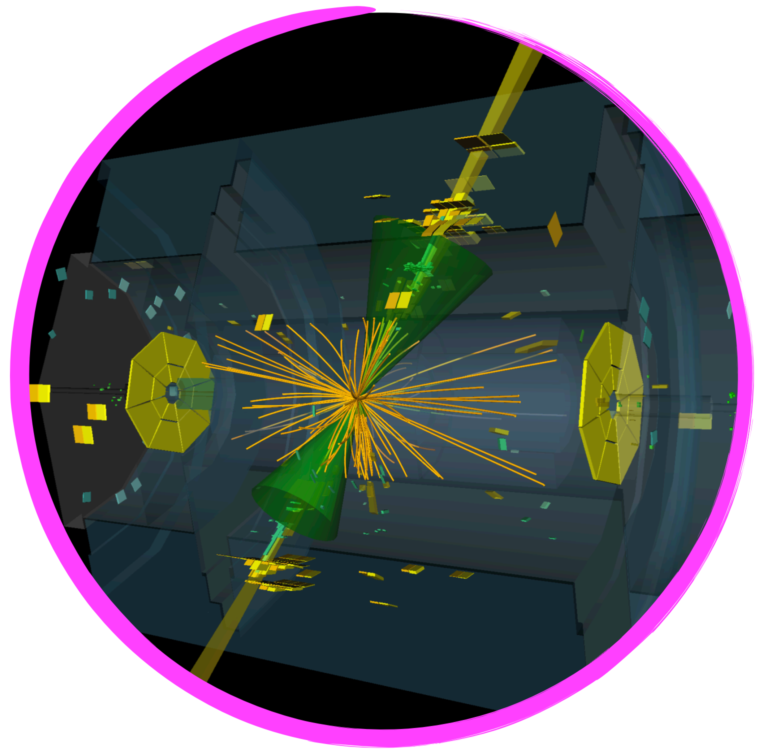
Run 2

2016
p+Pb @ 5.02 TeV
330 μb^{-1}

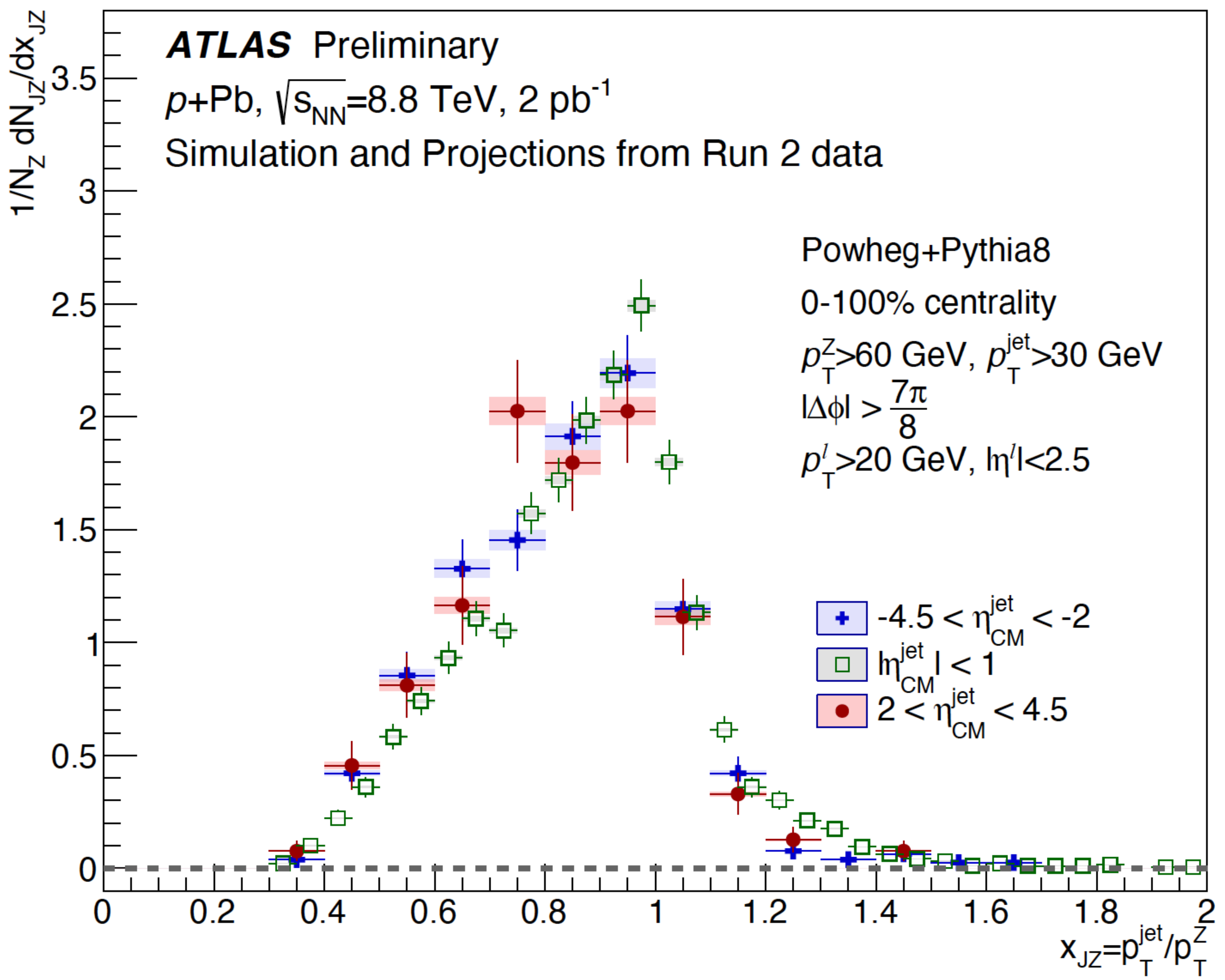
2016
p+Pb @ 8.16 TeV
165 nb^{-1}

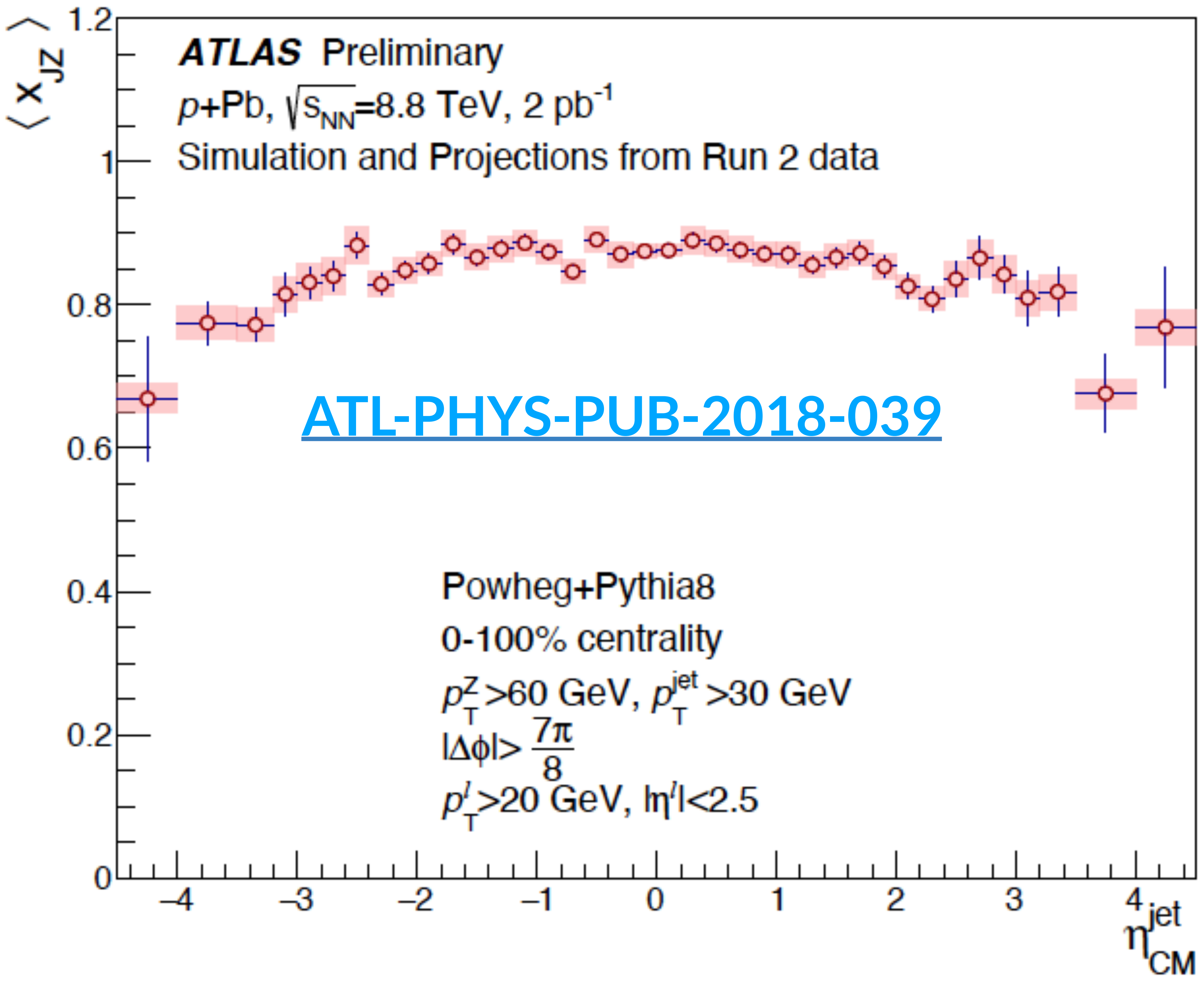


Phys. Rev. C 100 (2019) 034903
Phys. Lett. B 796 (2019) 230
Phys. Rev. Lett. 131 (2023) 072301
Phys. Rev. Lett. 132 (2024) 102301
arXiv:2405.05078 (sub. JHEP)



Collectivity and bulk properties
Saturation physics
Energy loss (?)
Color fluctuations
Nuclear effects on PDFs
Nuclear modification



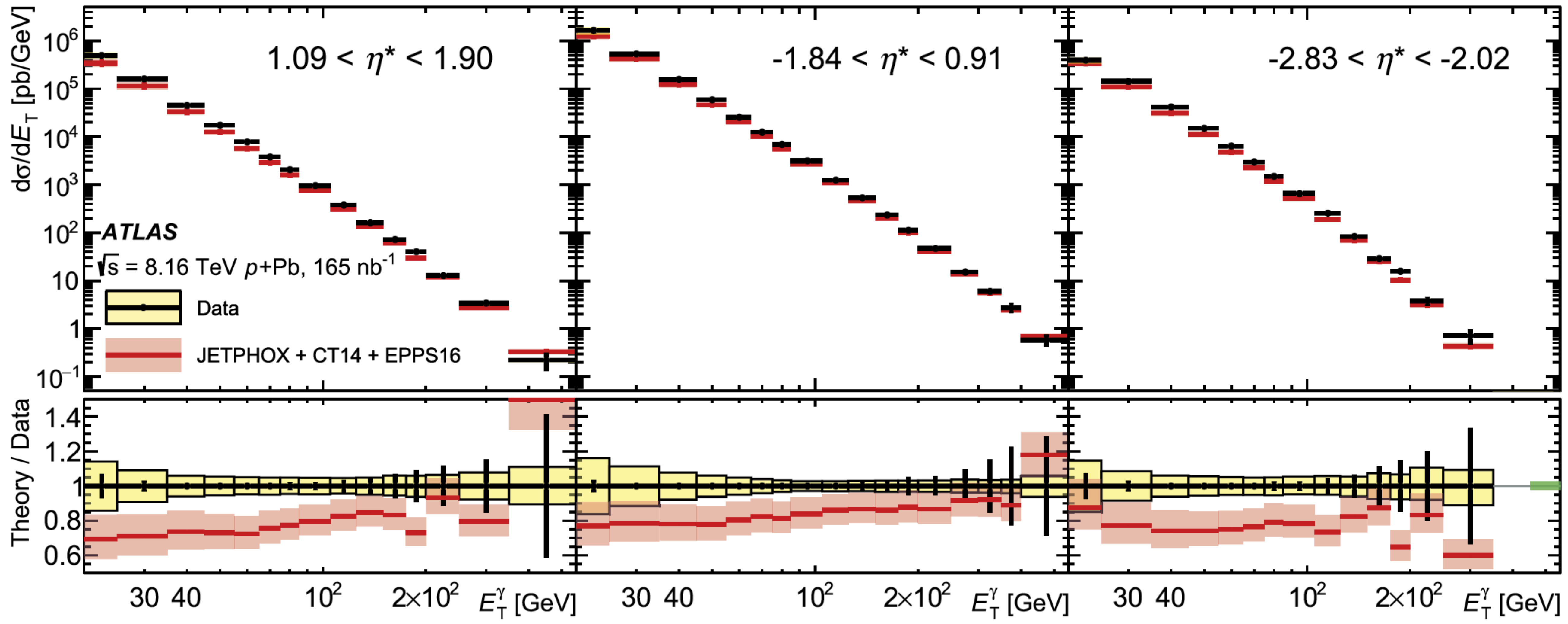


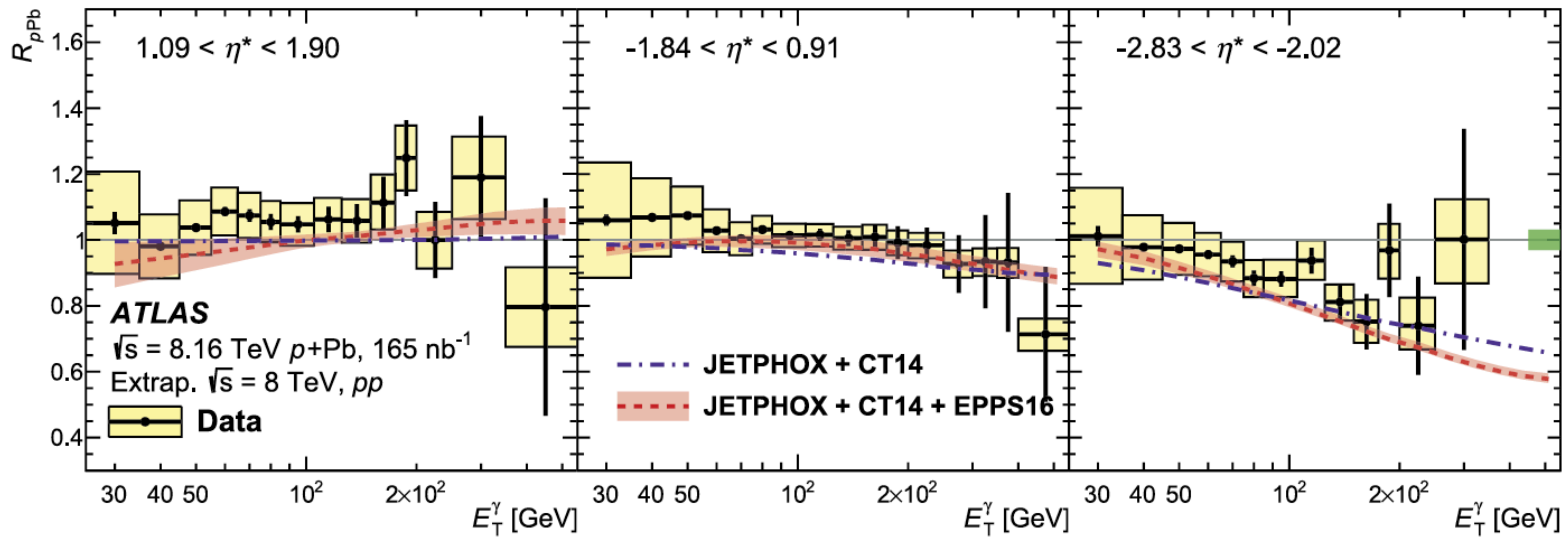
Projections do not account for extended tracking acceptance yet

Advantages: theoretically →the large Z boson mass sharply reduces fragmentation and decay contributions; experimentally → smaller backgrounds

Study of CNM effects and nPDFs

NPDF STUDIES VIA PROMPT PHOTONS IN P+PB





Physics Letters B796(2019)230–252