(Di-)jets & Di-hadrons from HI studies to ep and eA [some liberties taken on definitions]

1st International Workshop on a 2nd Detector for the Electron-Ion Collider

Helen Caines, Wright Lab, Yale

Di-jets and di-hadrons in Yellow Report

Too many topics to cover in 20 mins includes:

Access to the gluon Wigner distribution,
Probing the linearly polarized Weizsaecker-Williams gluon TMDs
Probing the gluon Sivers function
Exploring the (un)polarized hadronic structure of the photon
Constraining (un)polarized quark and gluon PDFs at moderate to high momentum fraction (x)
Studies of hadronization and cold nuclear matter properties

In this talk I will focus on topics on which I have expertise/ knowledge as a HI physicist

plus studies with recent results from RHIC and LHC

Kinematics and Properties of Jets at EIC

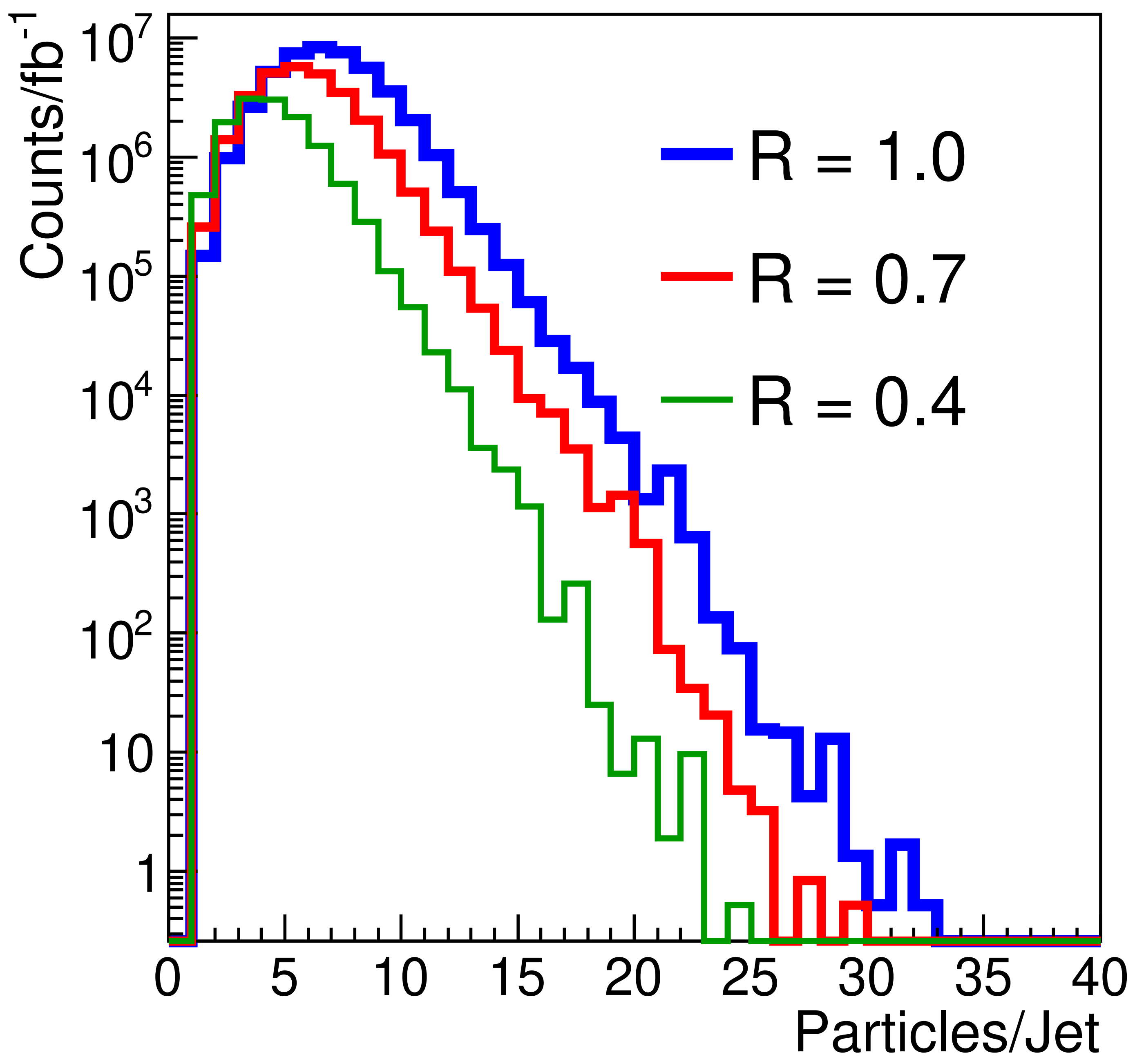
Jets:

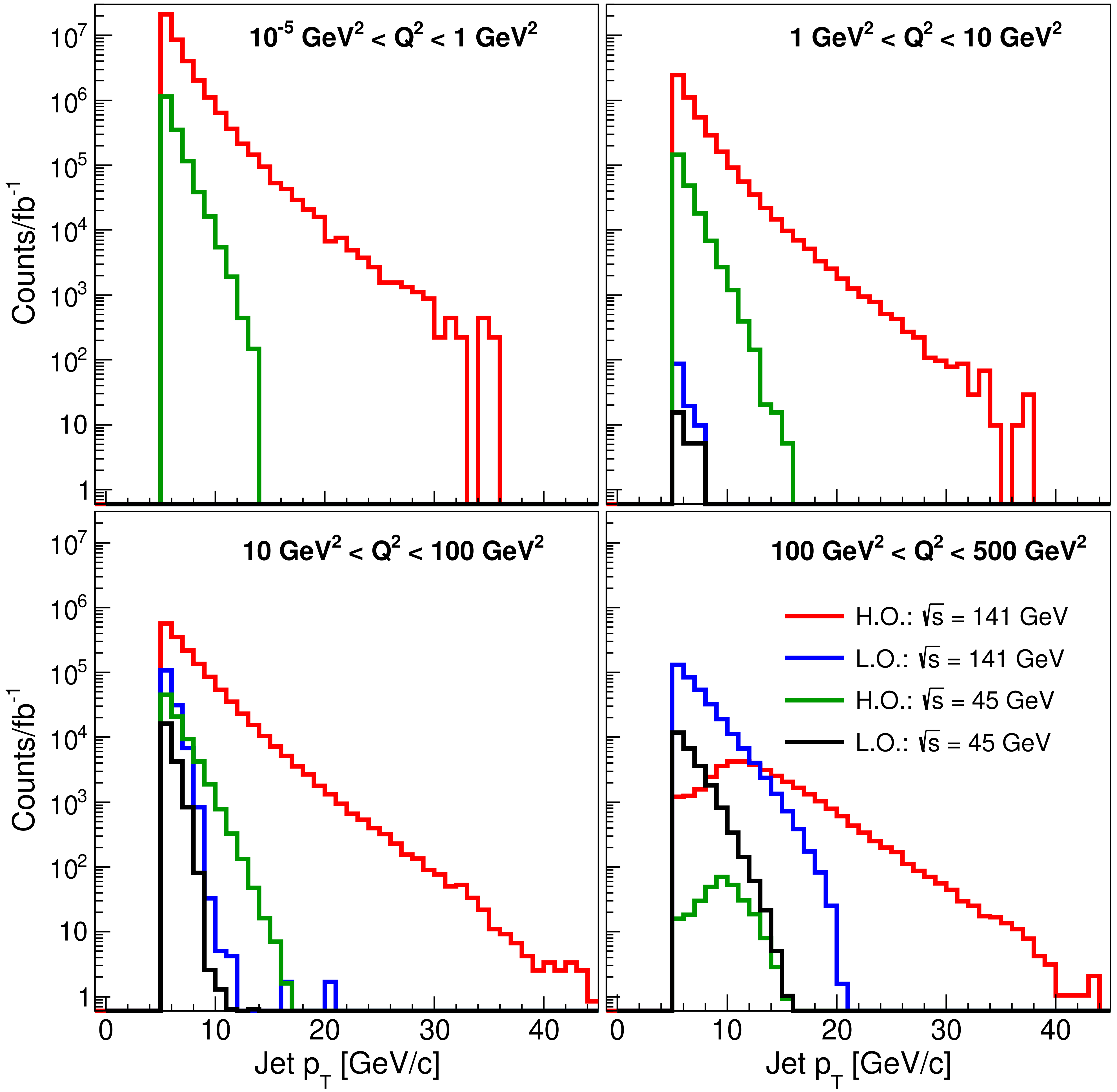
p_T < 20 GeV/c

~2 jets per event

~5-10 particles per jet

Largely studying non-perturbative regime/ hadronization





B. Page et al. PRD 101, 072003 (2020)

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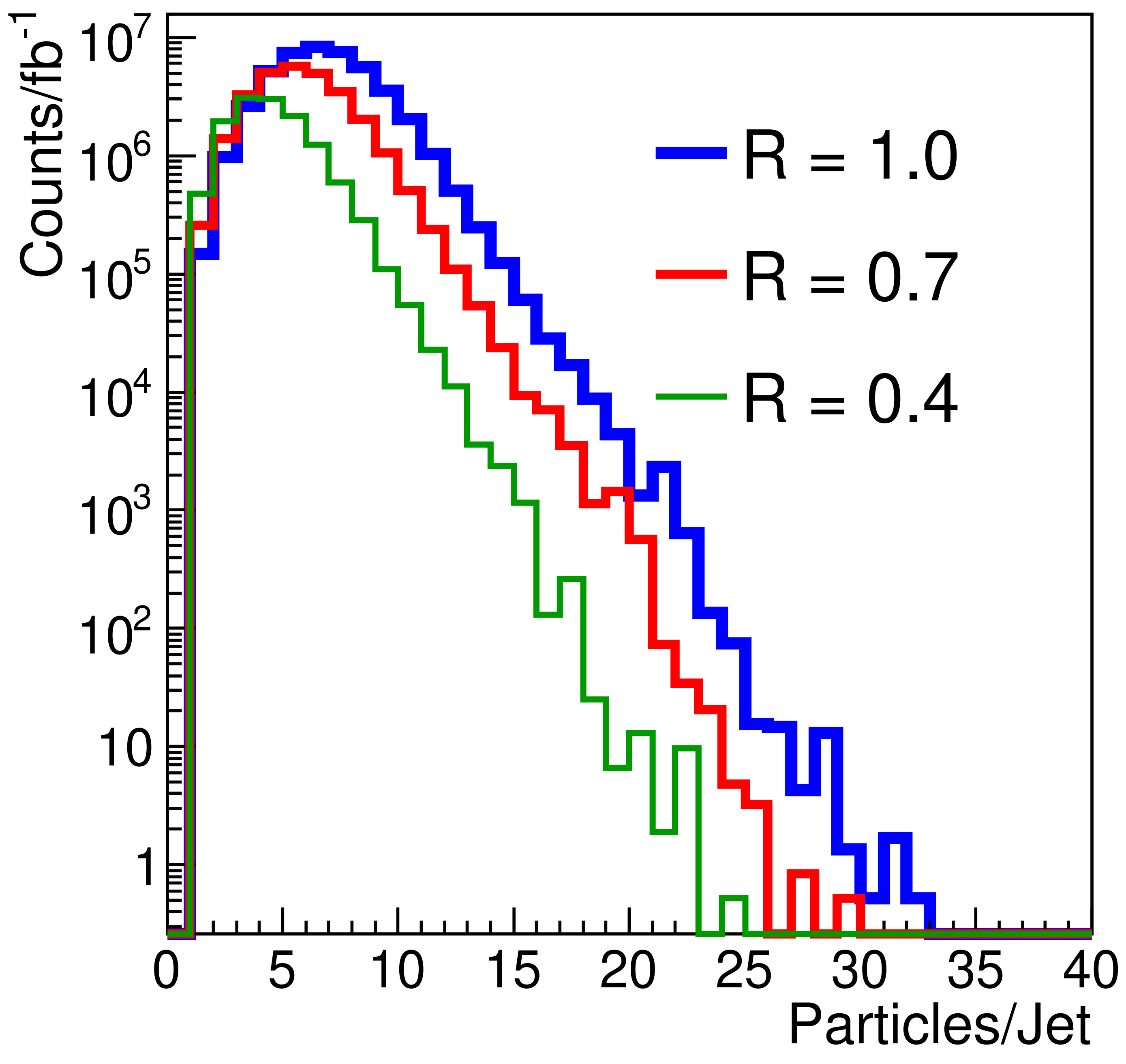
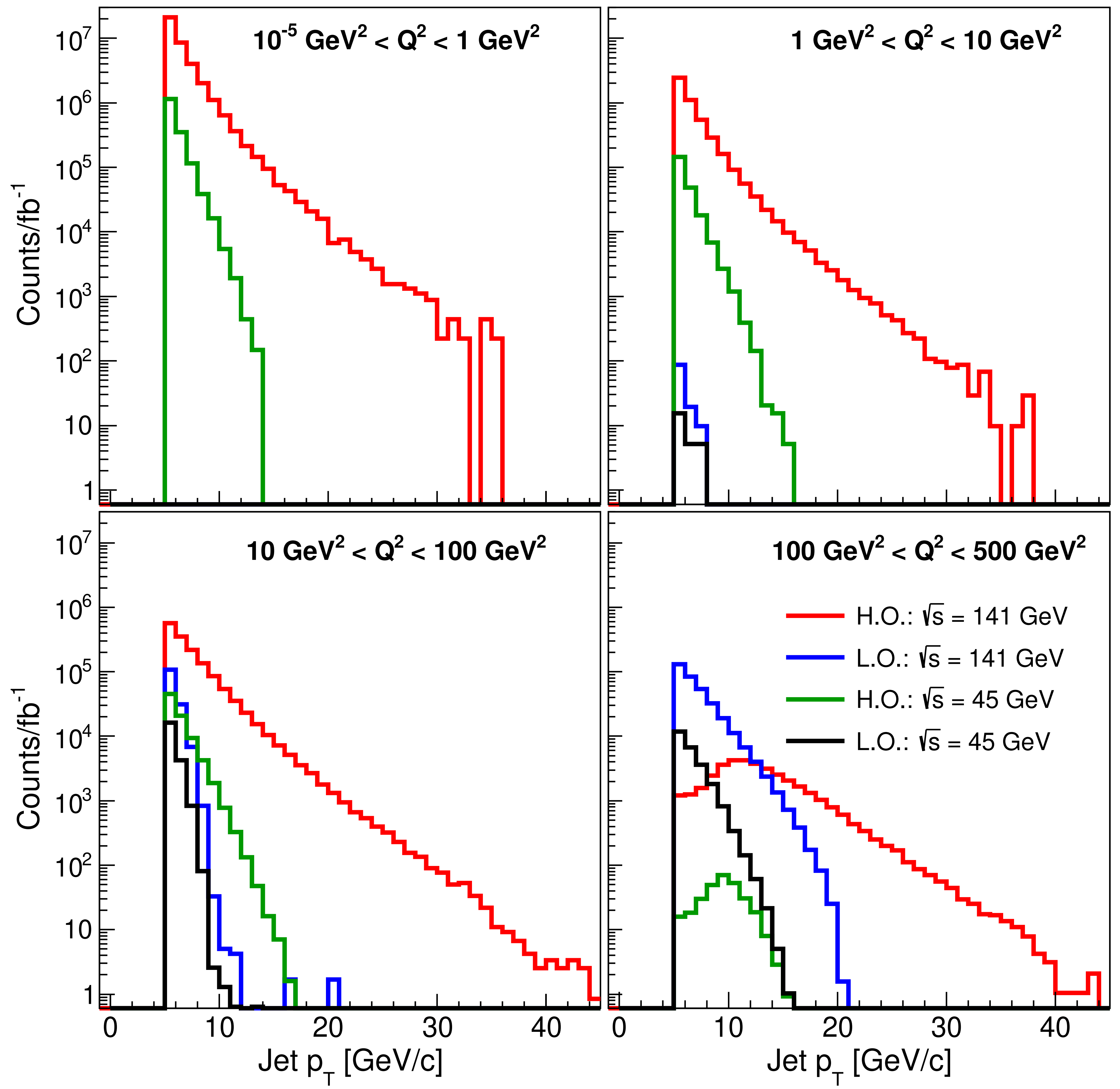




Larger R:

Better representation of partonic kinematics

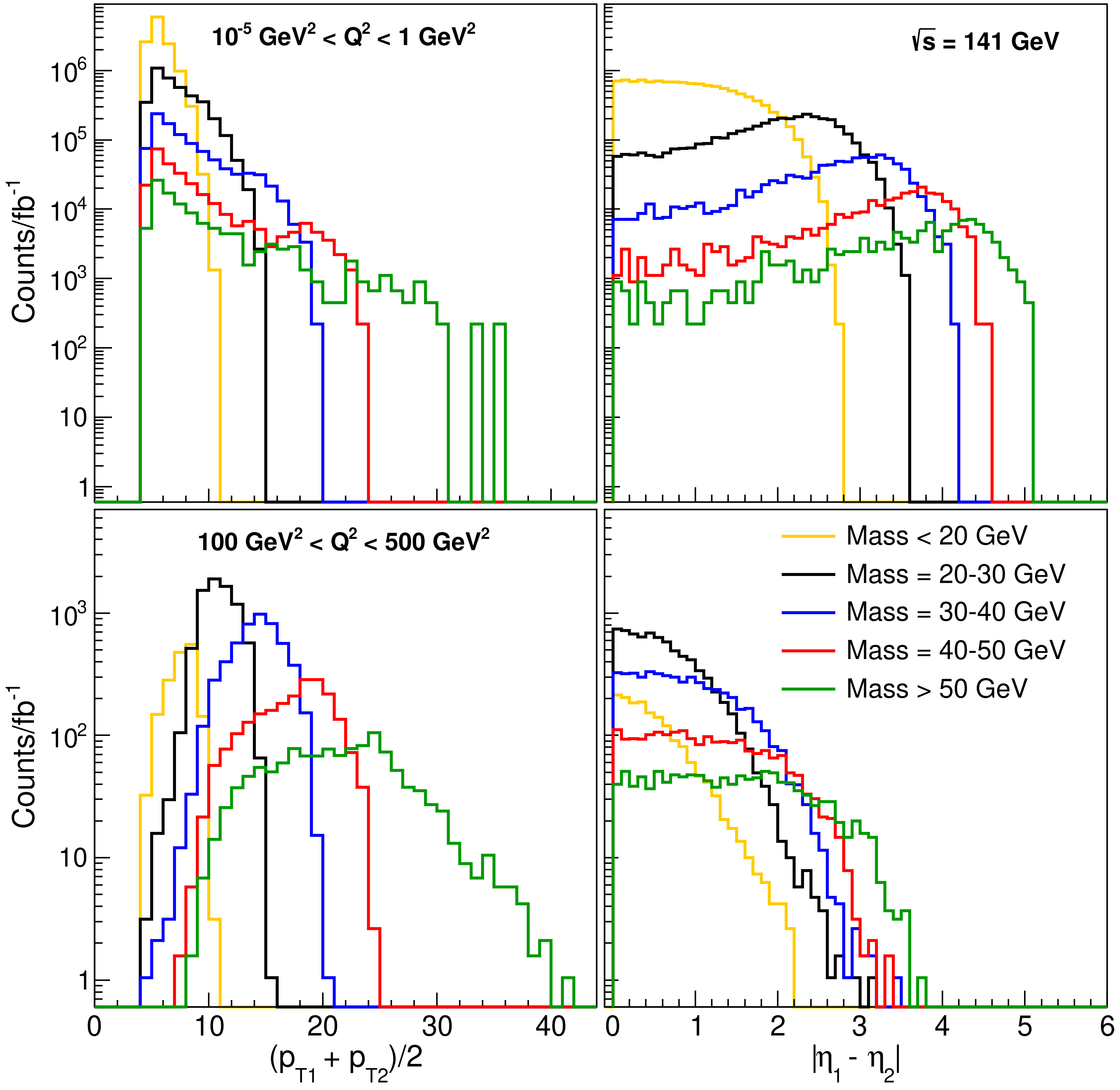
More UE included

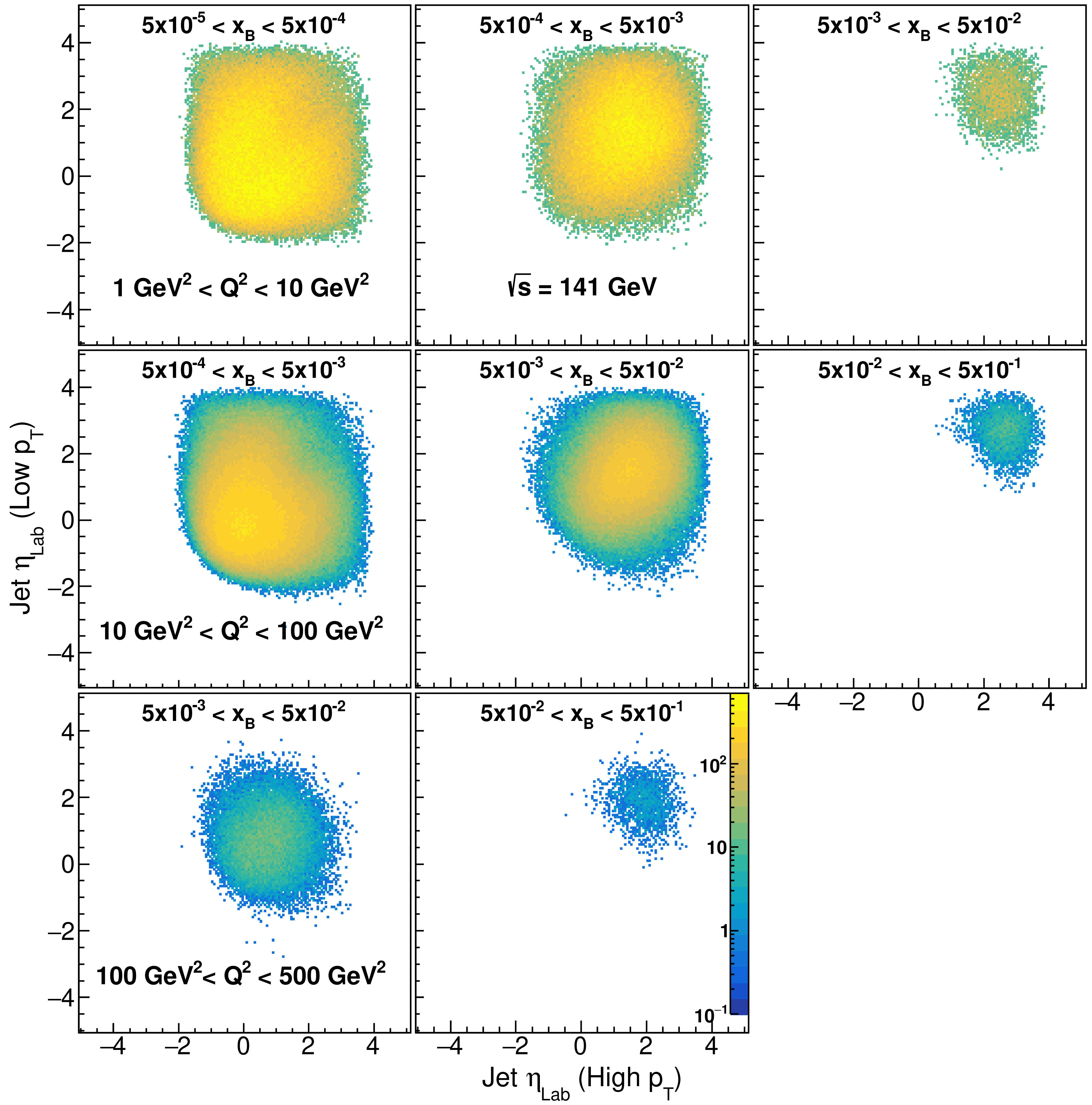
RHIC and LHC usually anti-k_T with E-scheme:

Since EIC reasonably "empty" choice not critical

B. Page et al. PRD 101, 072003 (2020)

Kinematics and Properties of Di-jets at EIC

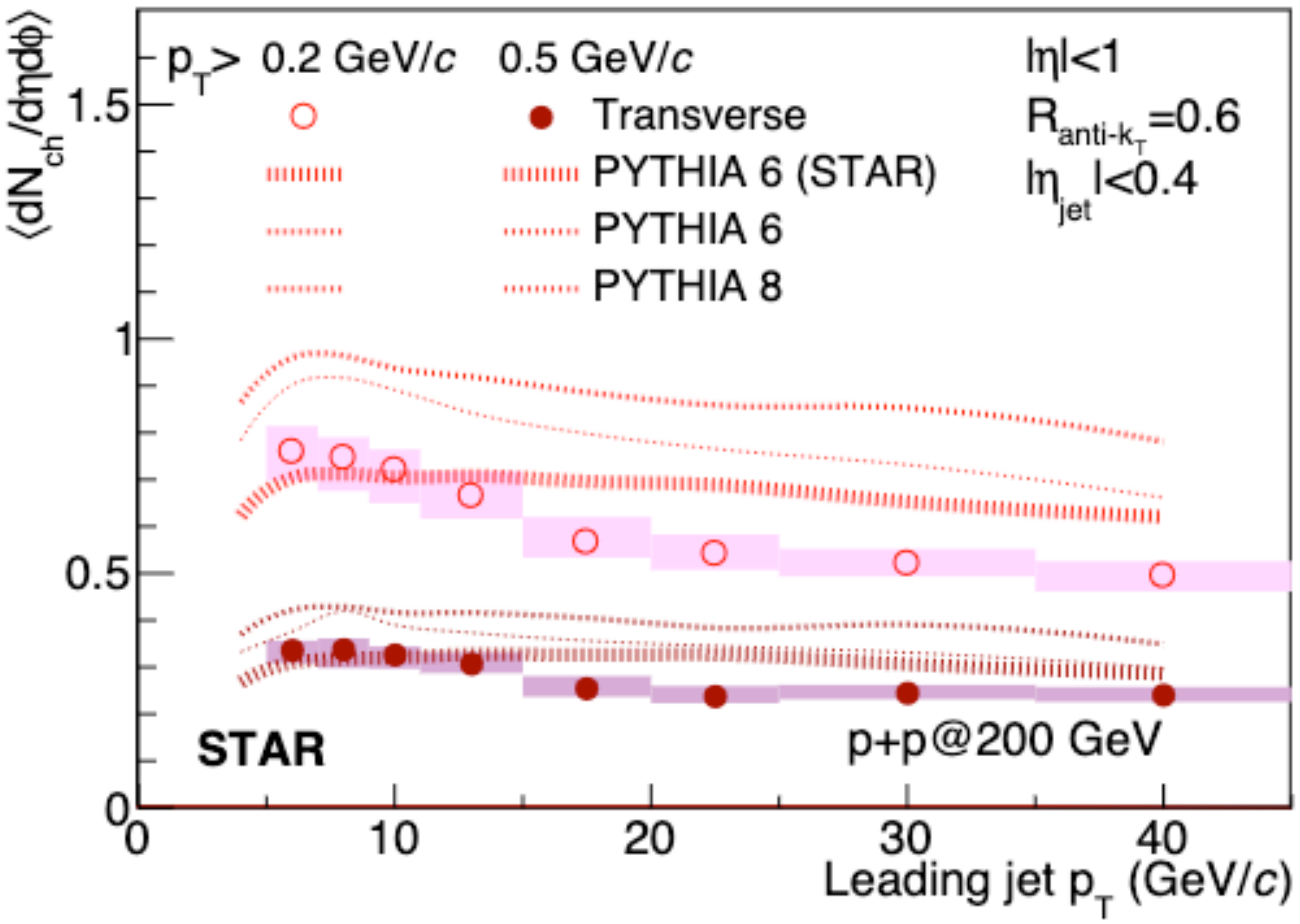


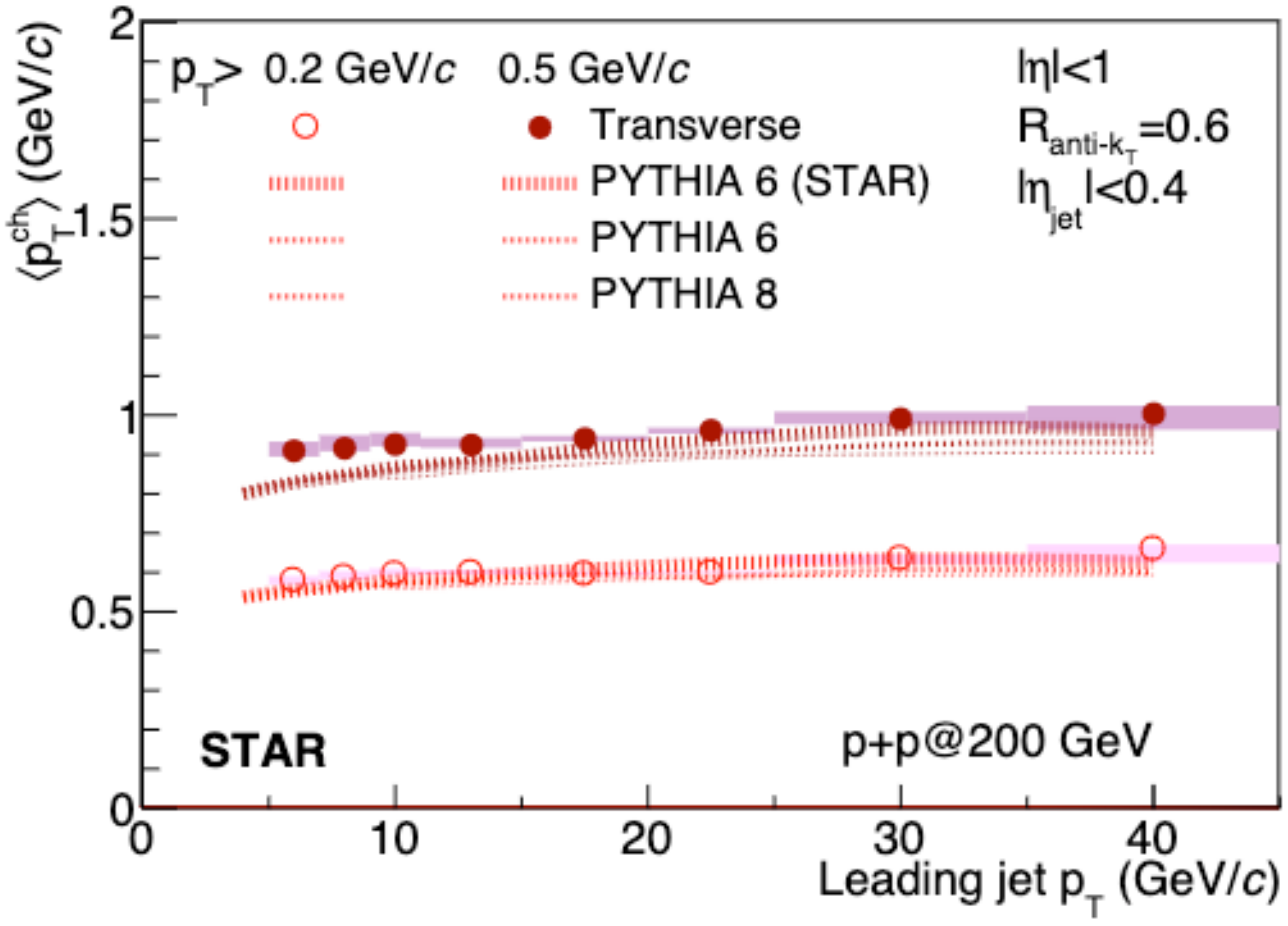


Di-jet η swing is important

B. Page et al. PRD 101, 072003 (2020)

Underlying Event at RHIC





At mid rapidity UE for jet p_T >15 GeV/c

Average charged particle density = 0.4-0.6

Mean p_T = 0.5-0.7 GeV/c

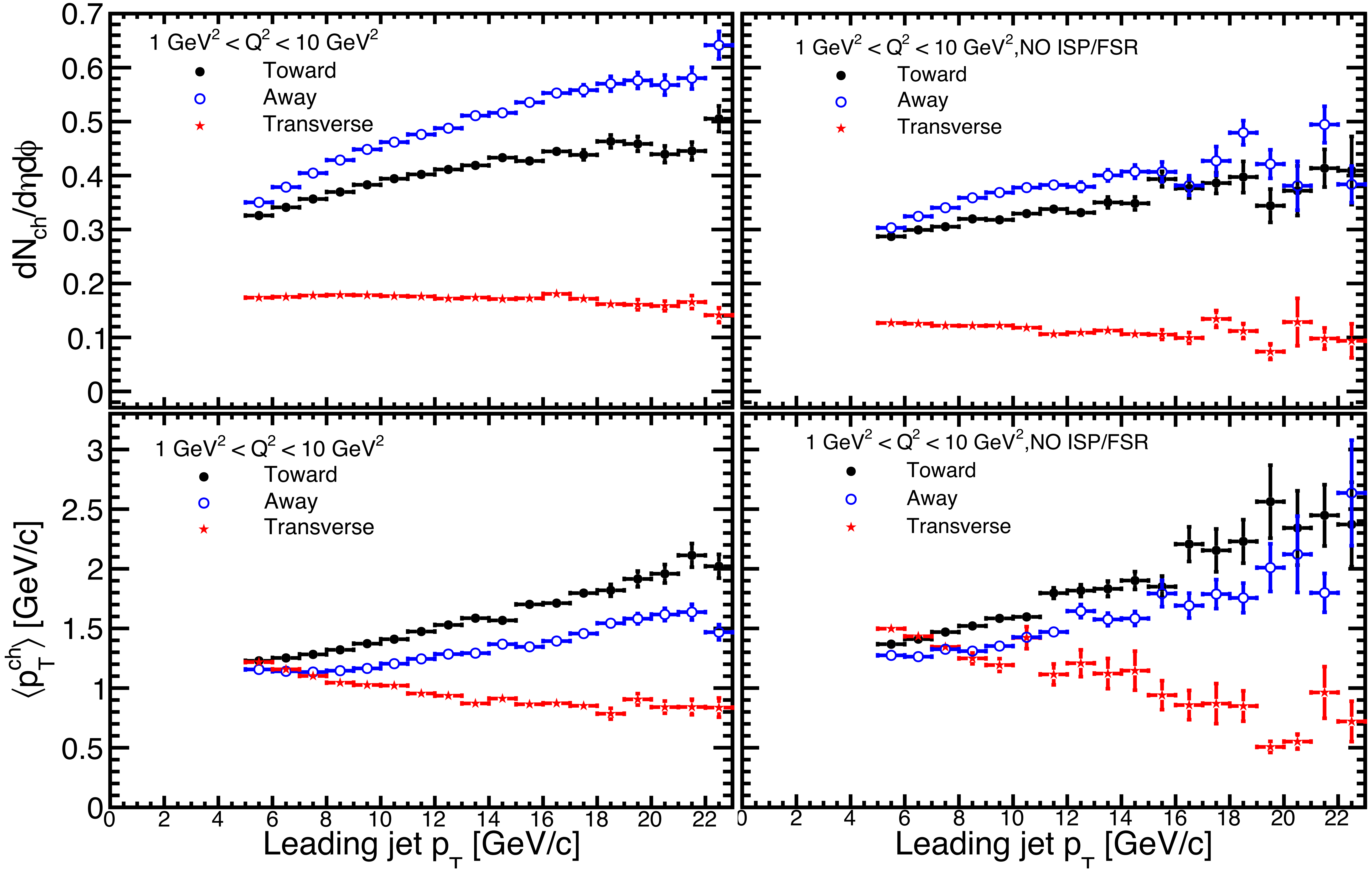
Largely independent of jet p_T

Significant dependence on low p_T cut-off

For jet with R= 0.4:
Charged particle contamination from UE ~150 MeV

STAR: PRD **101** (2020) 52004

Underlying Event at EIC



UE for jet p_T >5 GeV/c

Average charged particle density = 0.1-0.2

Mean p_T = 1-1.2GeV/c
(p_T of UE increased because using Breit frame)

For jet with R= 0.4:
Charged particle contamination from UE ~80 MeV

EIC measurements will be over large rapidity
- Need to check on UE rapidity dependence
- Potential solution to use off-axis technique

B. Page et al. PRD 101, 072003 (2020)

Detector Requirements for (Di-)jets at EIC

Hermetic detector

(similar for di-hadrons)

Tracking:

- efficient with excellent momentum and angular resolution
- large range of rapidity [jets only back-to-back in azimuth]
- single hadrons $p_T > 100$ MeV/c
- 3σ $\pi/K/p$ B: up to 7 GeV/c, C: up to 10 GeV/c, F: up to 50 GeV/c, [species dependent FF]

Electromagnetic calorimetry:

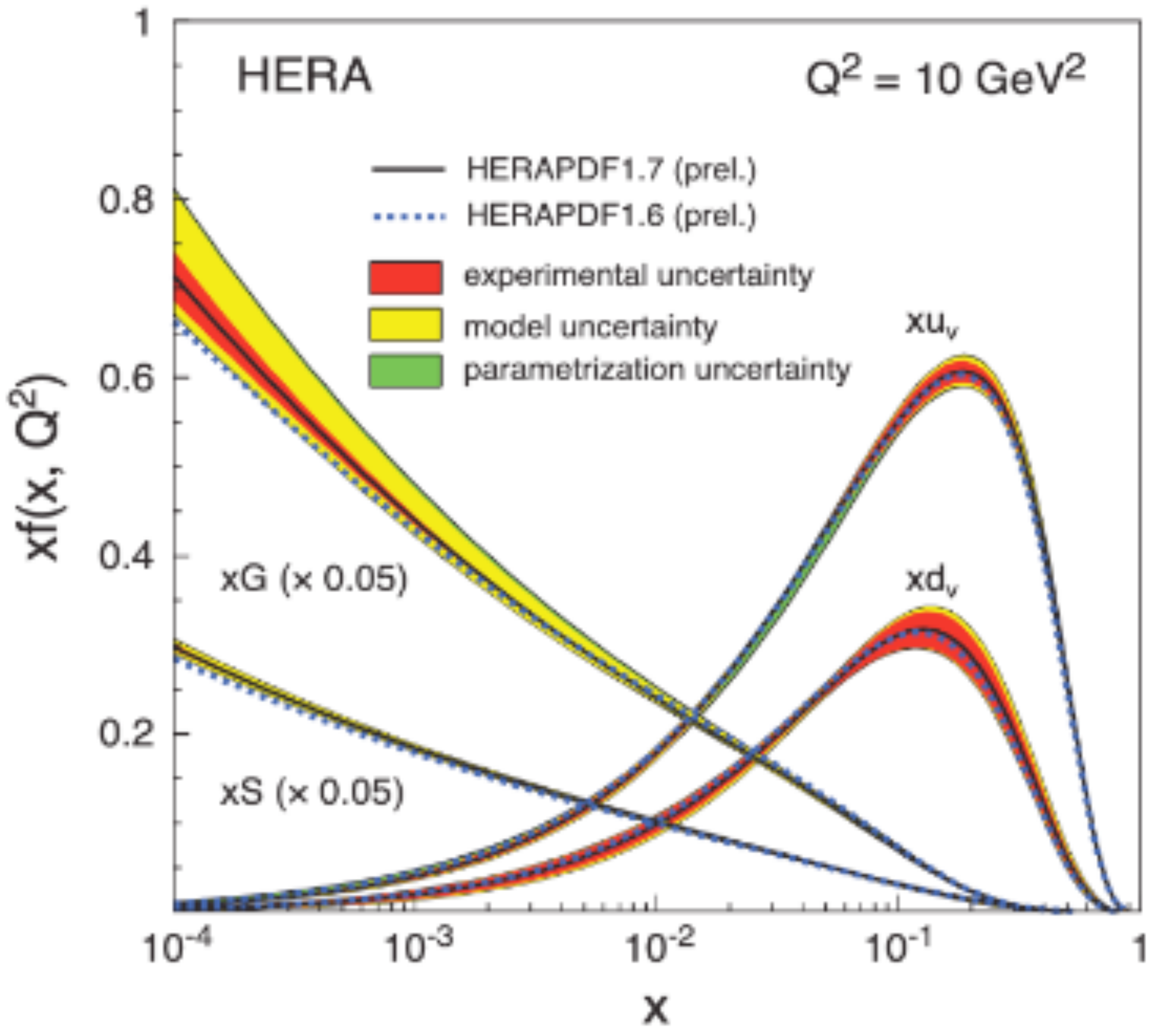
- Resolution: B: $\sigma(E)/E \approx 2\%/\sqrt{E} \oplus 1 - 3\%$ [drives jet performance capabilities], C: $\sigma(E)/E \approx 10 - 12\%/\sqrt{E} \oplus 1 - 3\%$ [sufficient, take advantage of excellent tracking], F: $\sigma(E)/E \approx 4.5/\sqrt{E}$

Hadron calorimetry:

- Neutral hadron isolation [important for jet energy scale and resolution, especially F and B]
- Resolution: B: $\sigma(E)/E \approx 50\%/\sqrt{E} \oplus 6\%$, C: $\sigma(E)/E \approx 85\%/\sqrt{E} \oplus 7\%$, F: $\sigma(E)/E \approx 35\%/\sqrt{E}$
- Minimum energy: 500 MeV/c

Yellow Report

Gluon Saturation



Rapid increase of gluon density as lower x

- saturation when splitting rate matches rate of recombination
- saturation scale at Q_s

$Q_s \propto A^{1/3}$:

More suppression for heavier nuclei

Forward for low-x

D.Kharzeev et al. NPA 748, 627 (2005)

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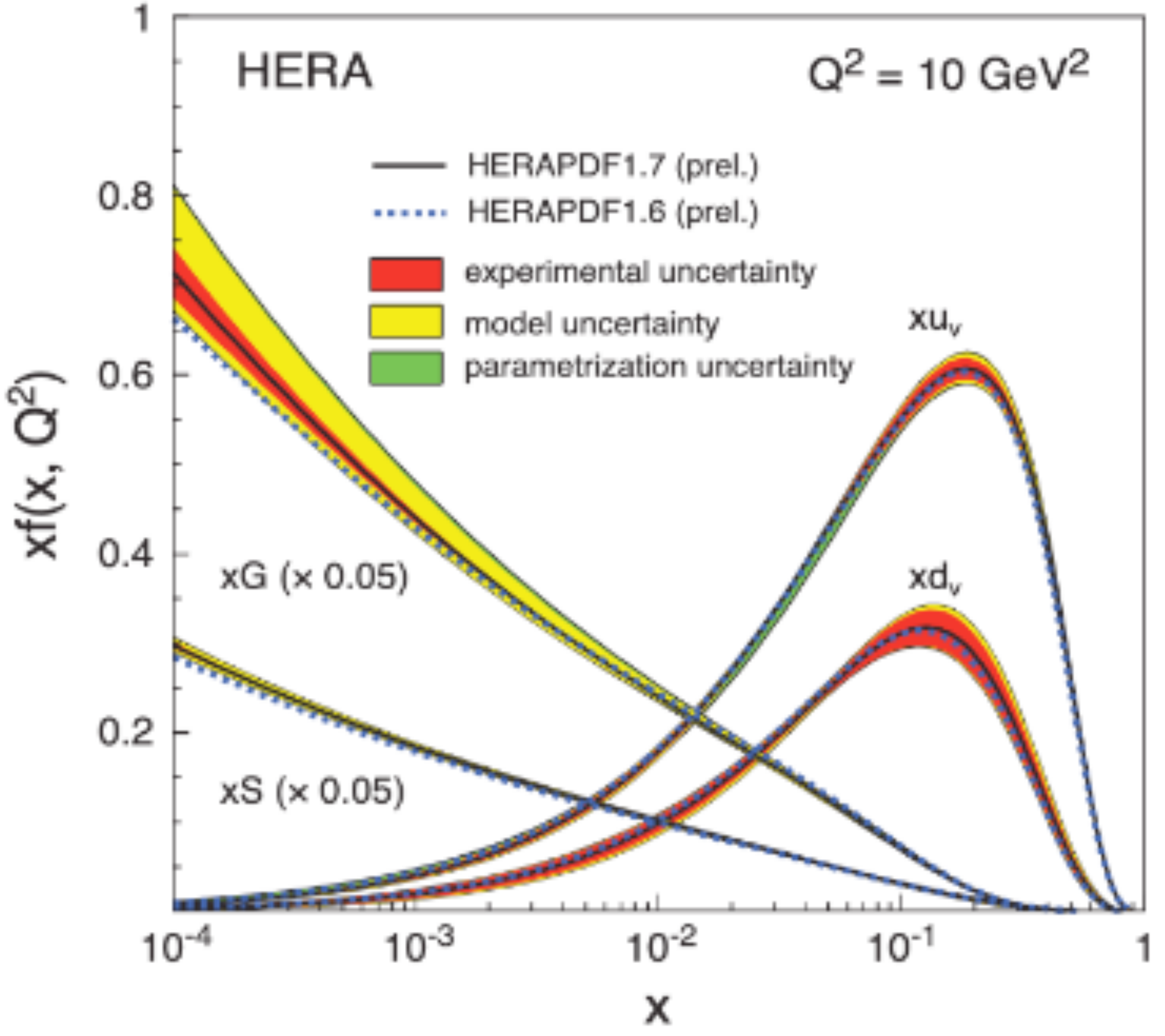

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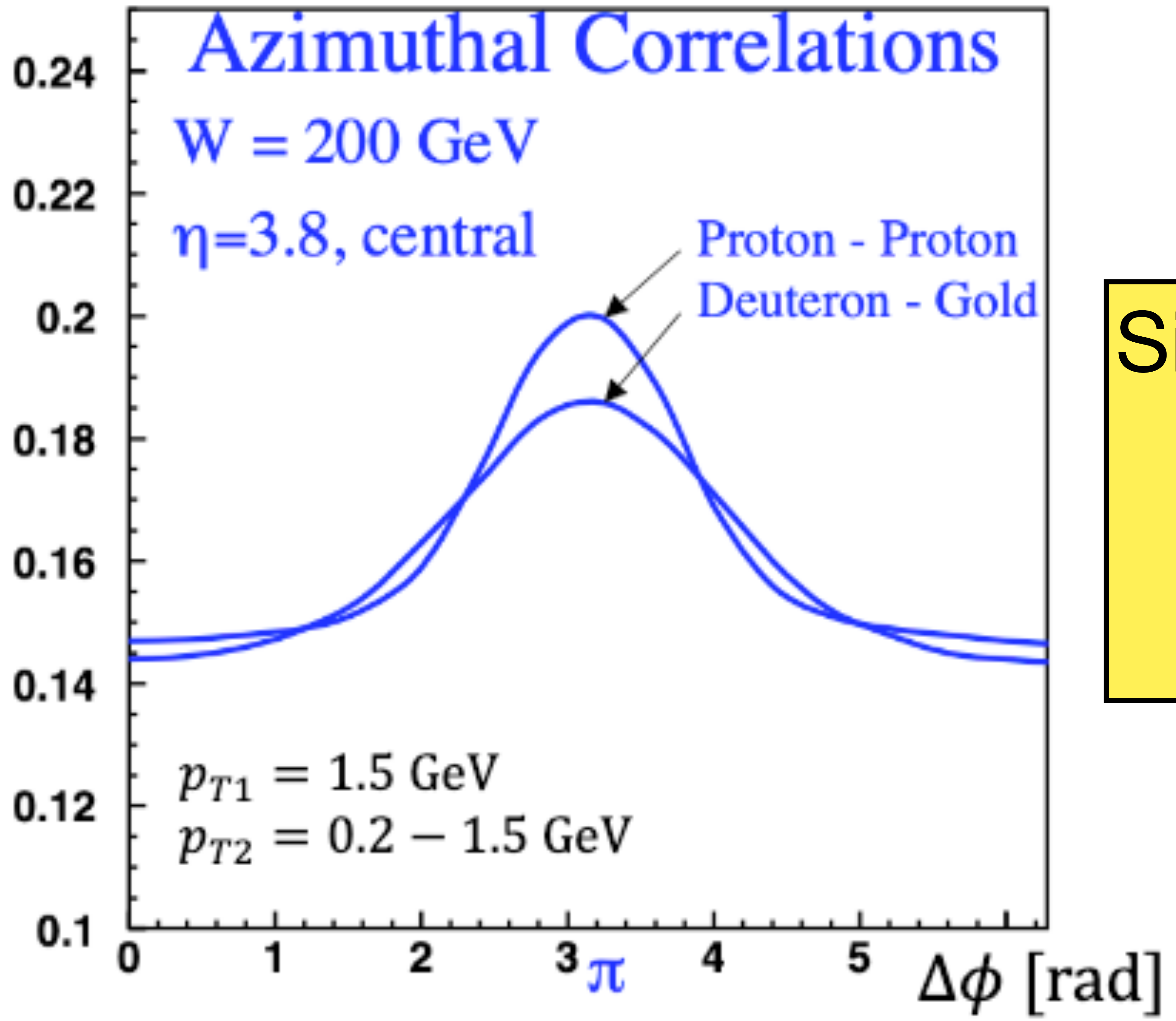

Signal of saturation: suppression of away-side jet correlation

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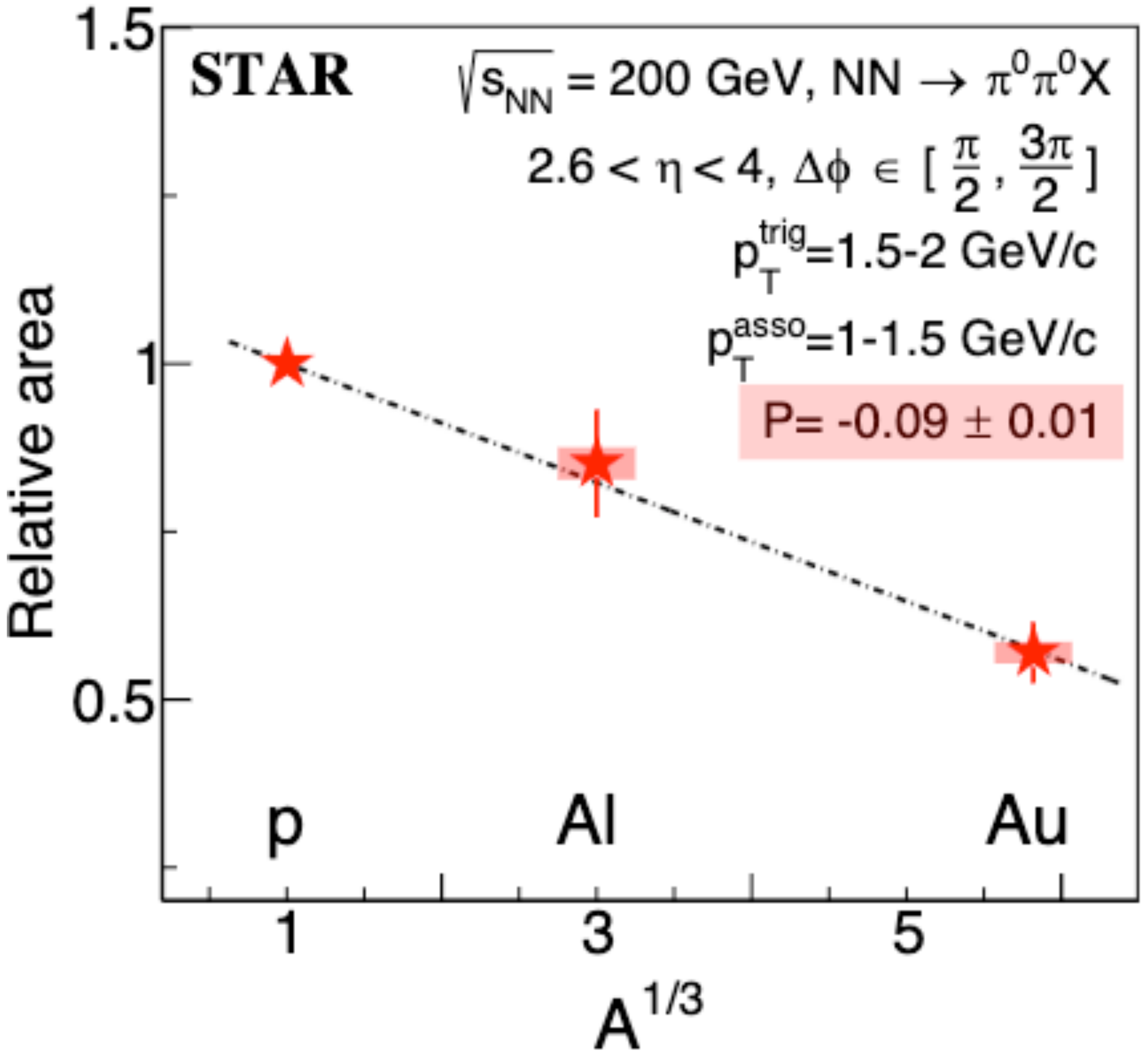
Di-pi Correlations at RHIC



Suppression in pA:

- Dependence on A
- Dependence on EA (related to but not b)
- Only at low p_T
- No broadening

STAR: PRL 129, 092501 (2022)
PHENIX: PRL 107, 172301 (2011)

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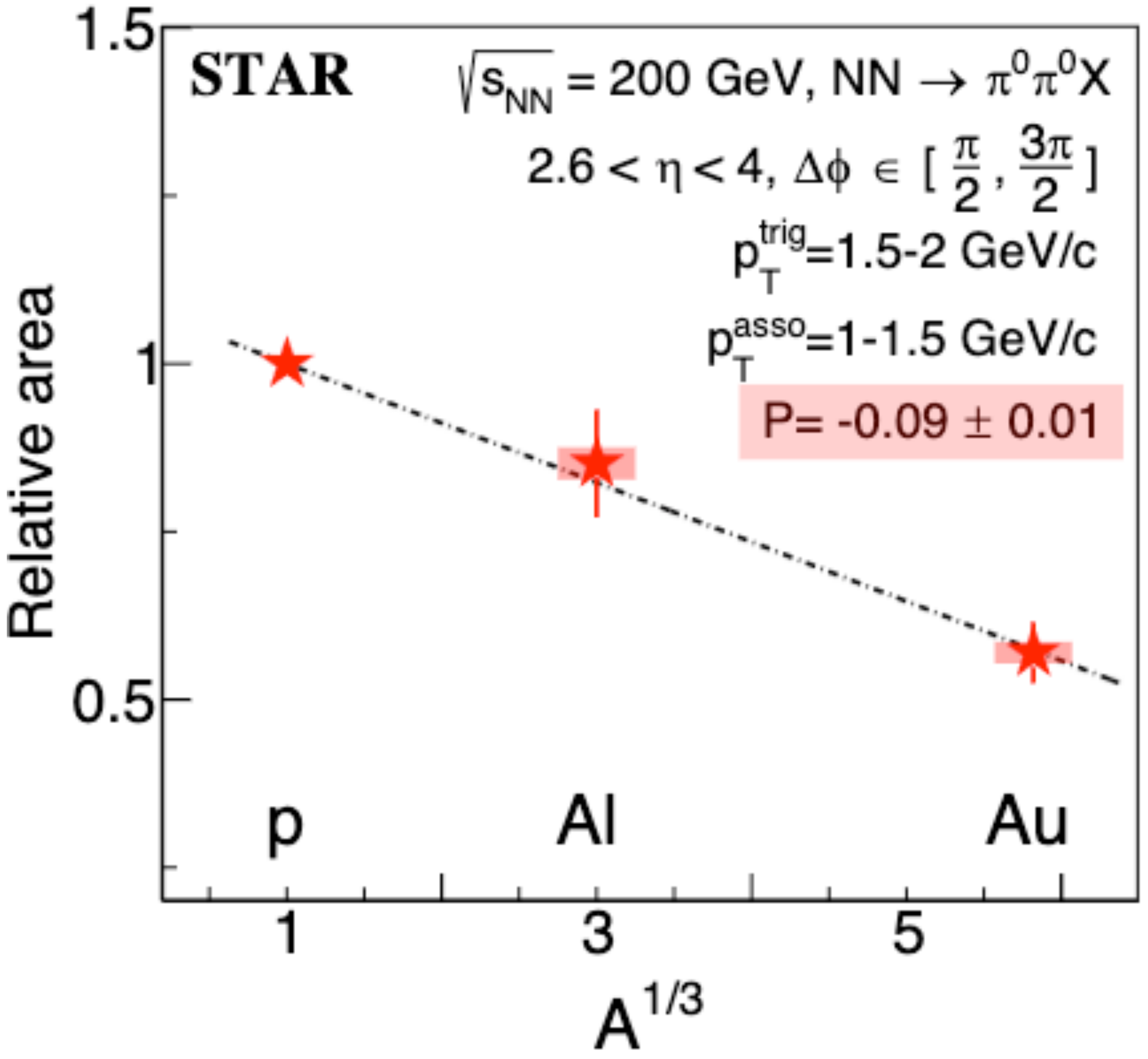

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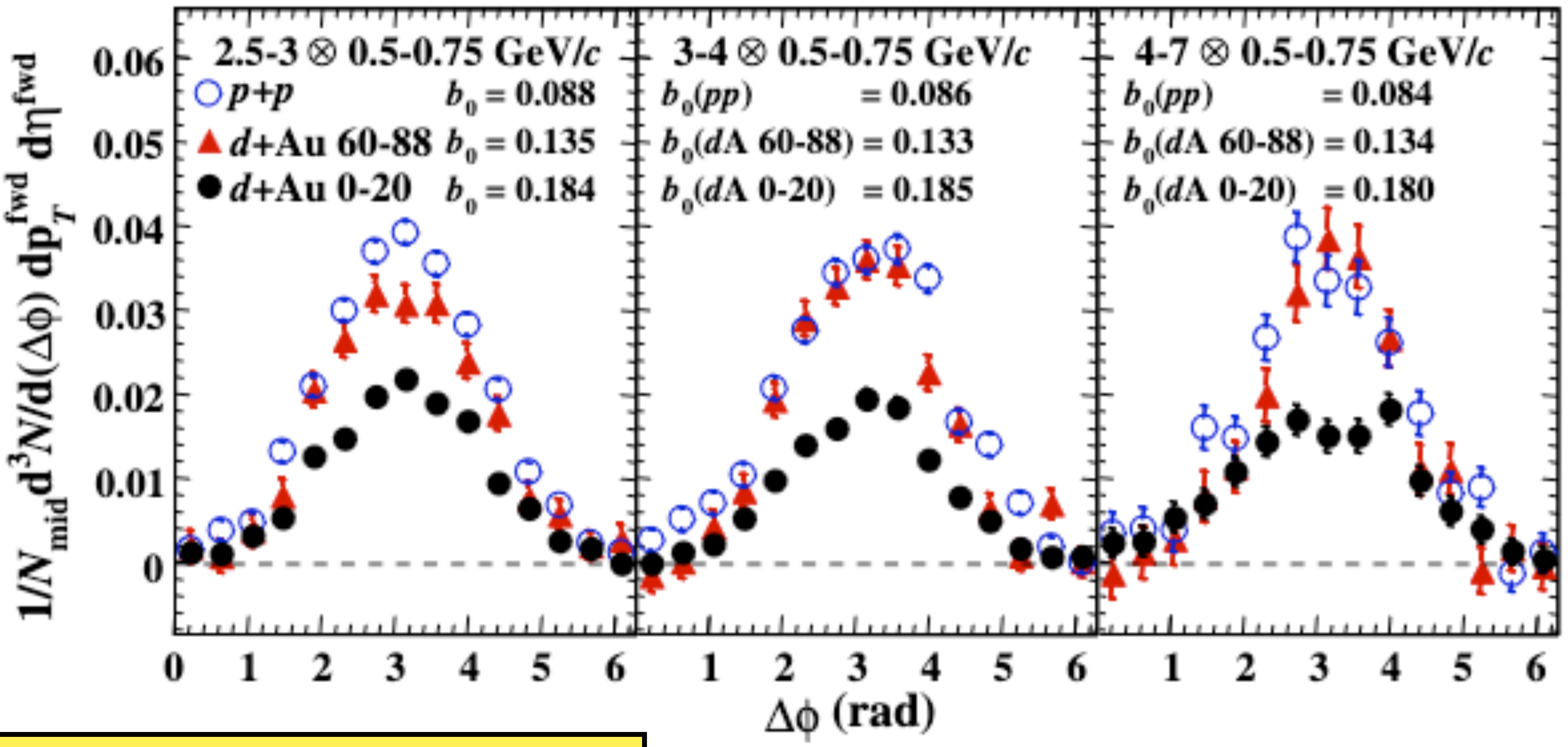


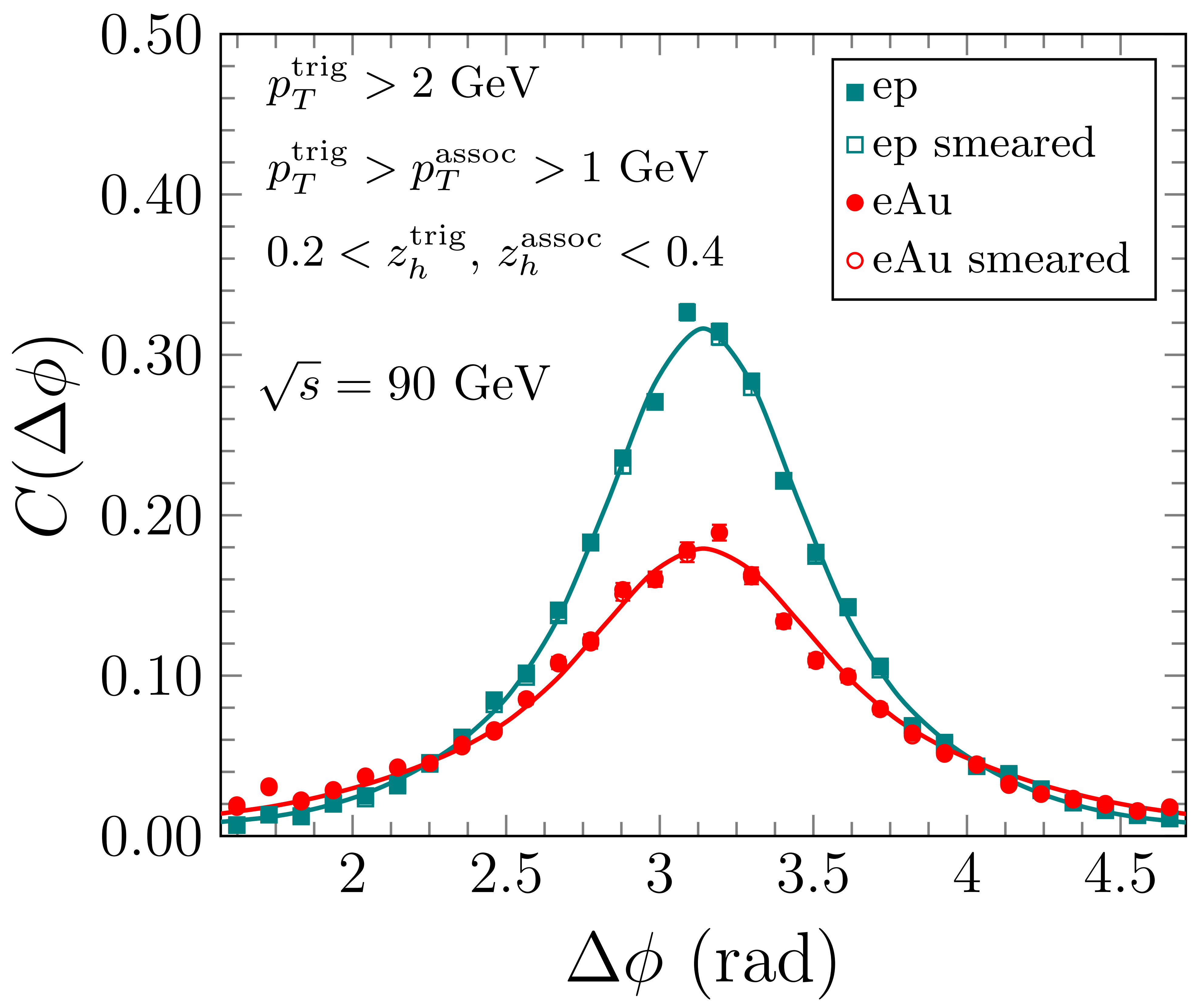
Suppression in dAu:

- Only at low p_T
- Only in central events

Hints of reaching saturation at RHIC
- 2024: unique opportunity with STAR forward upgrades

STAR: PRL 129, 092501 (2022)
PHENIX: PRL 107, 172301 (2011)

Opportunities at the EIC



Events with inelasticity $0.6 < y < 0.8$

Pairs $|\eta| < 3.5$

Integrated luminosity 10 fb^{-1}/A

stat uncertainties smaller than markers

RHIC

- Similar Moderate-Q^2-low x
- Similar collision energy
- Complimentary probes (e vs p)

LHC

- High Q^2 - low x
- Complimentary probes (e vs p)

EIC

- Study wide range of ion beams from deuterons to heavy nuclei (Au, Pb, U)

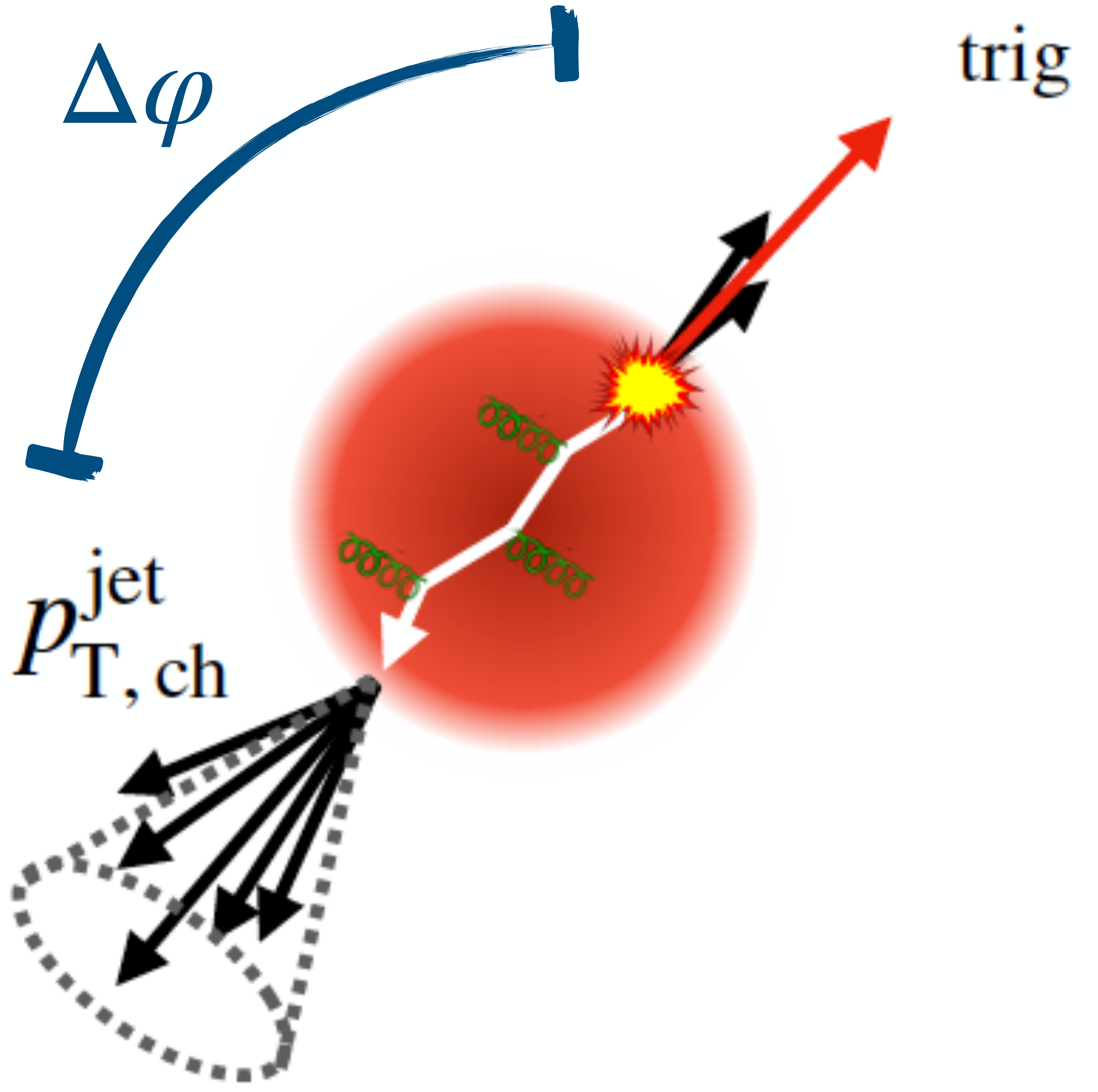
Definitive measurements at EIC?

Yellow Report

Jet Deflection in HI Collisions

Scattering off "quasi-particle" in medium results in deflection of jet

Recoil jet no longer acoplanar (back-to-back)



STAR: Y. Hu HP 2023
ALICE: Y. Hou HP 2023

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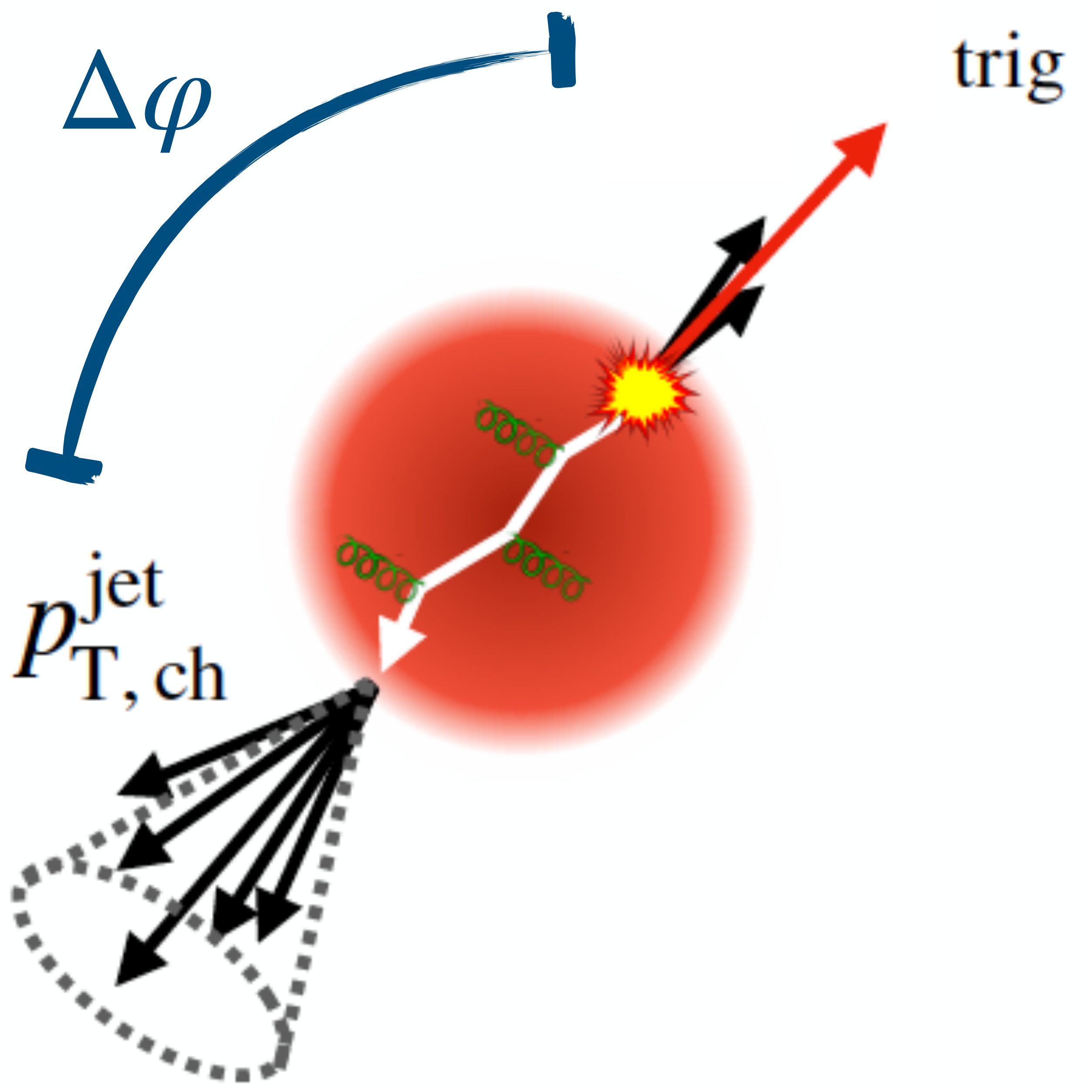

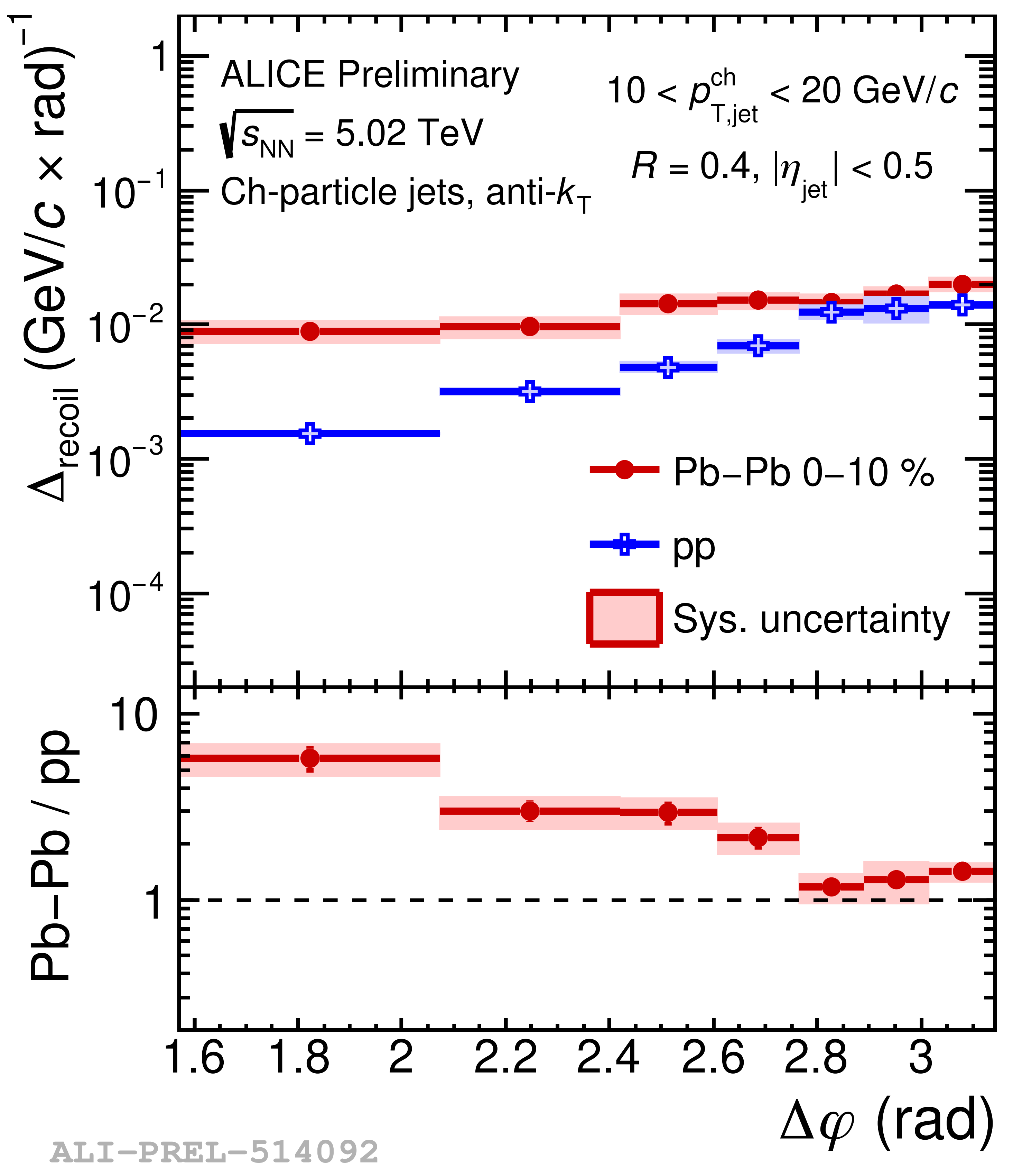

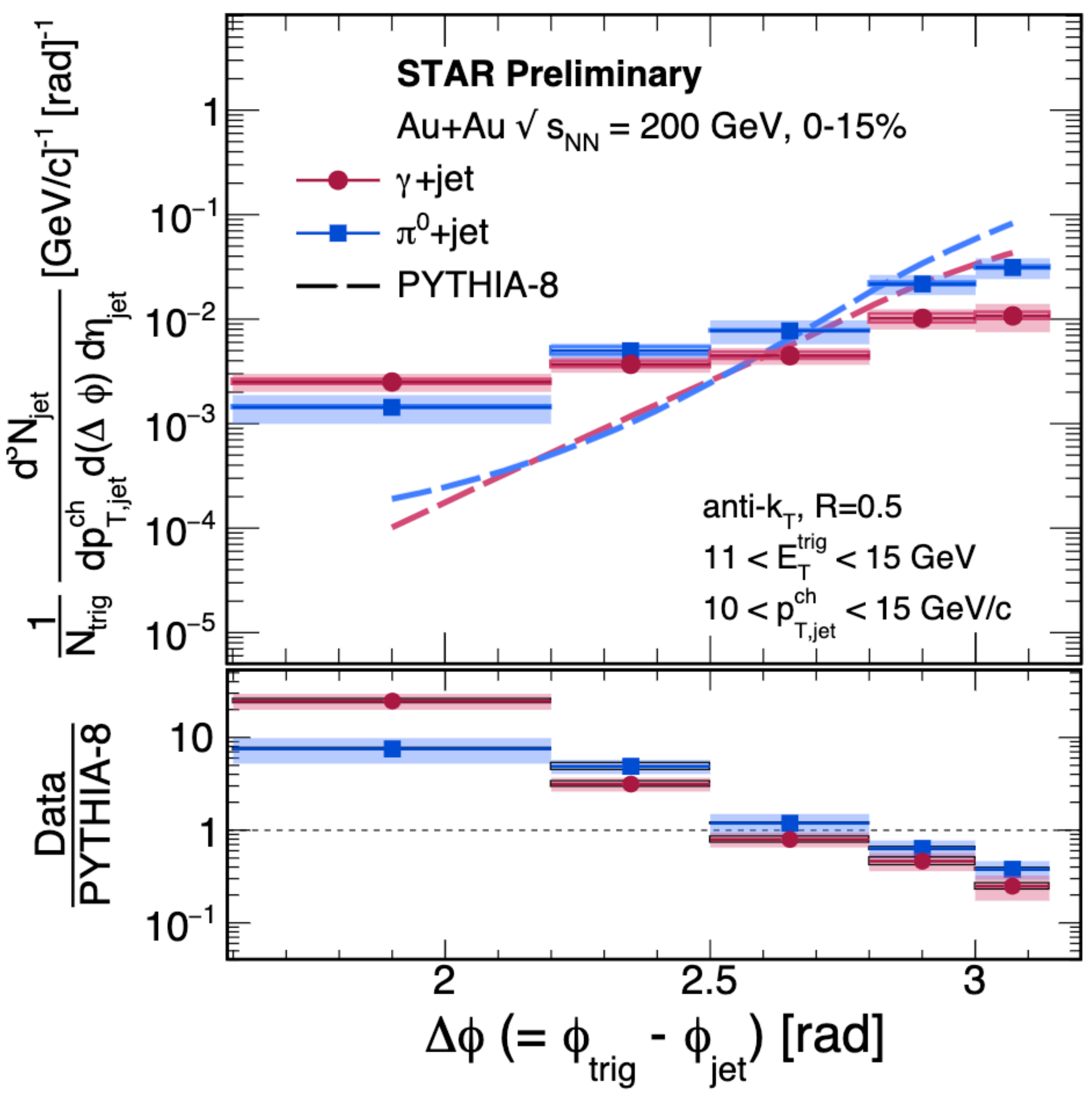

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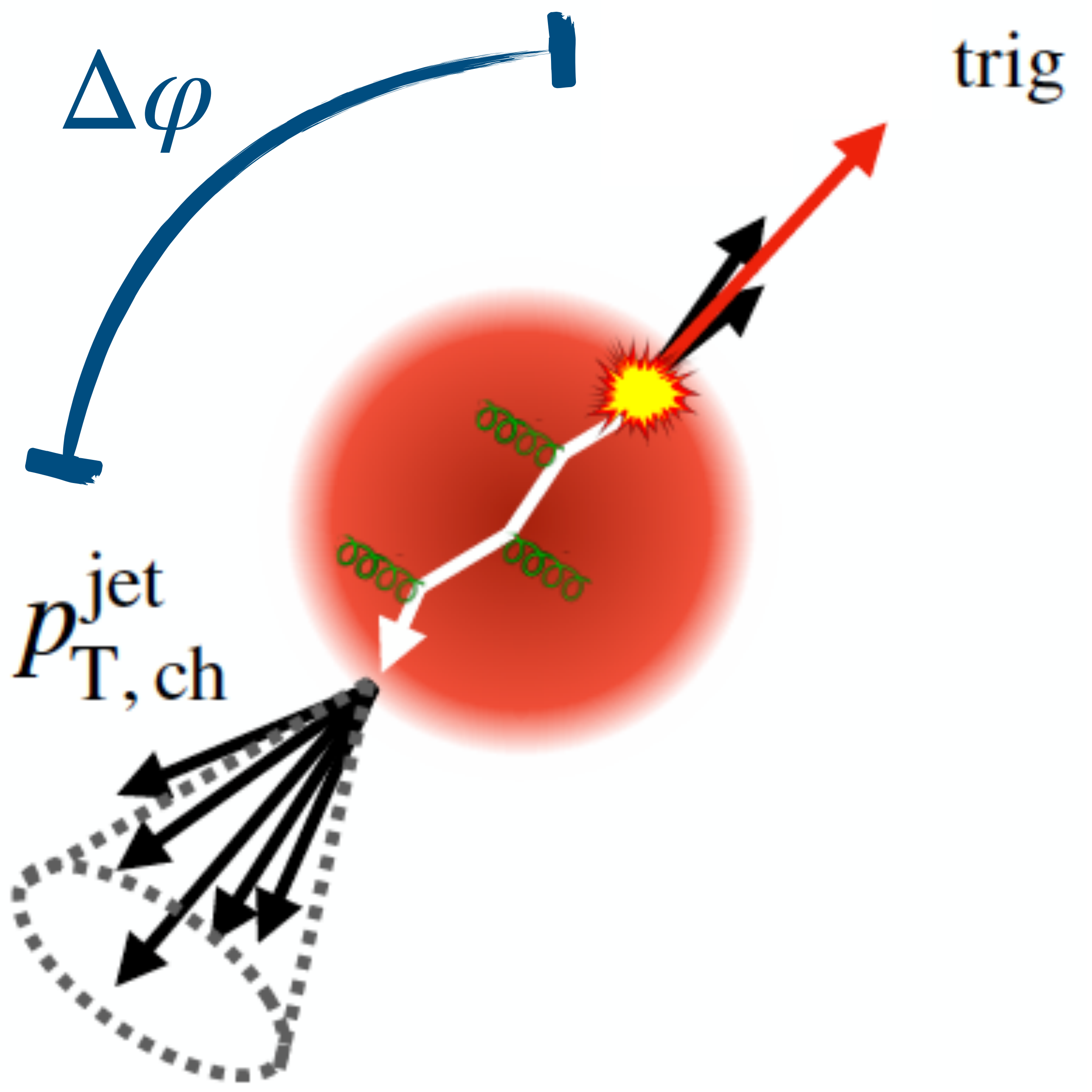

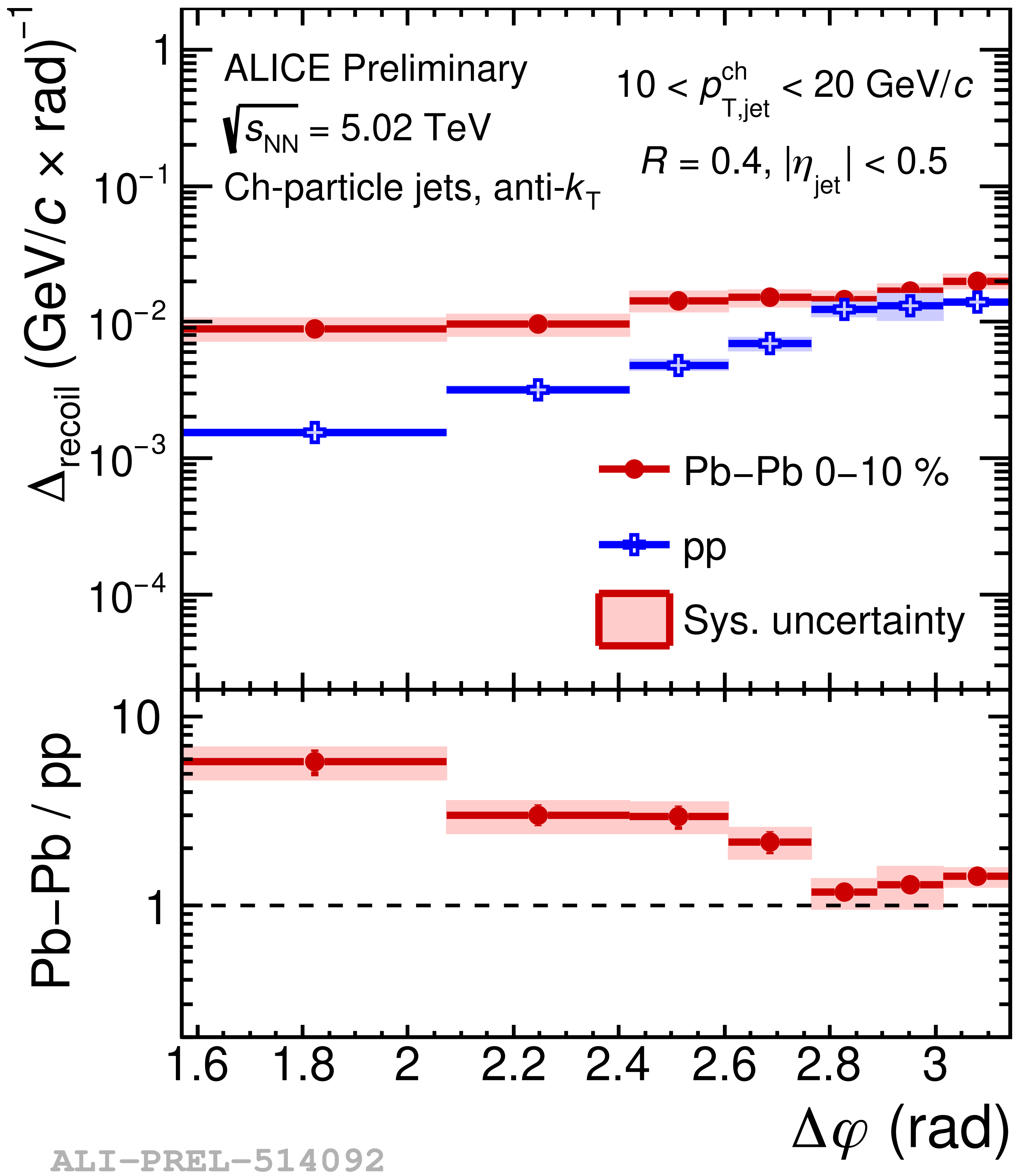

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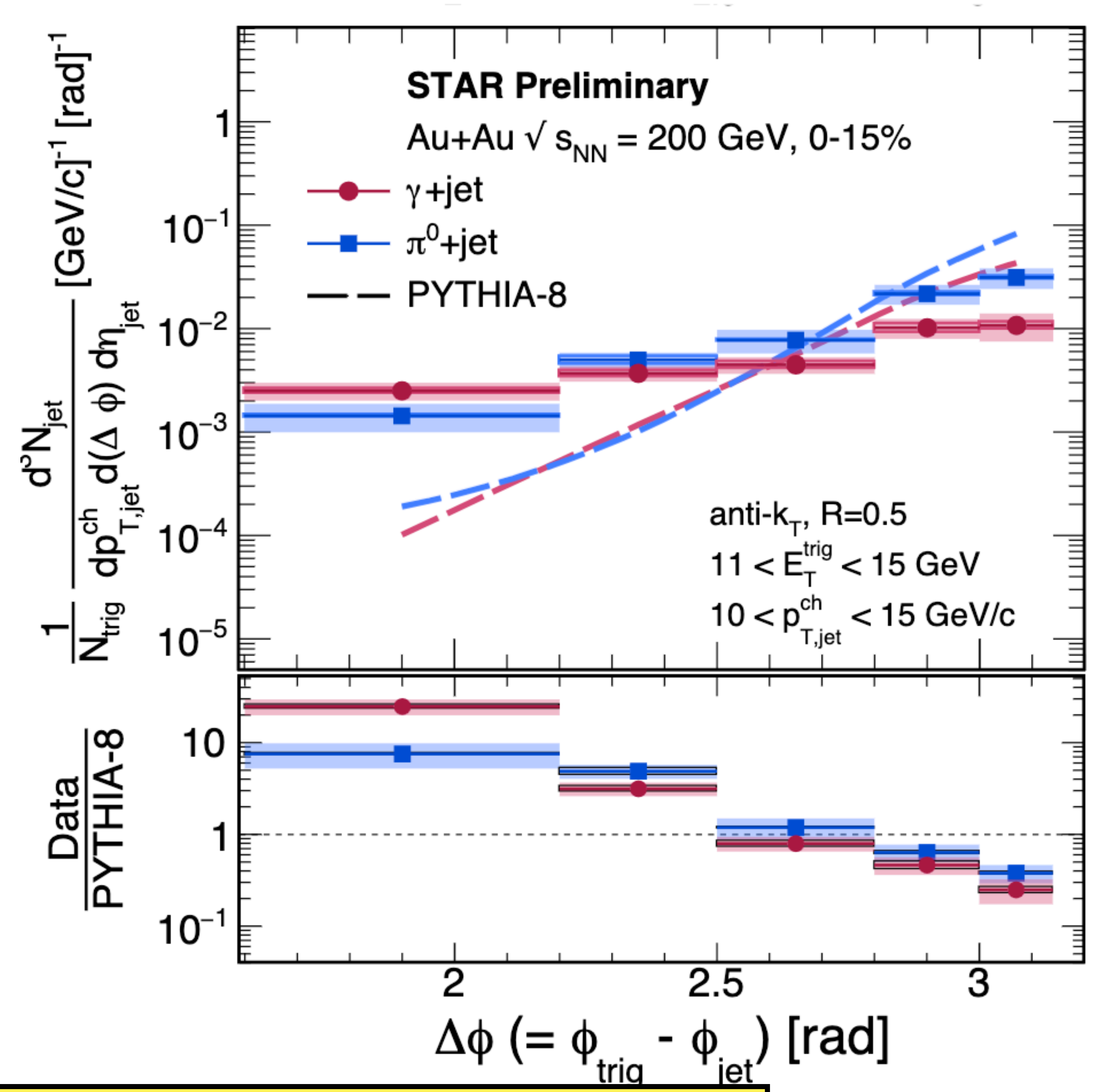
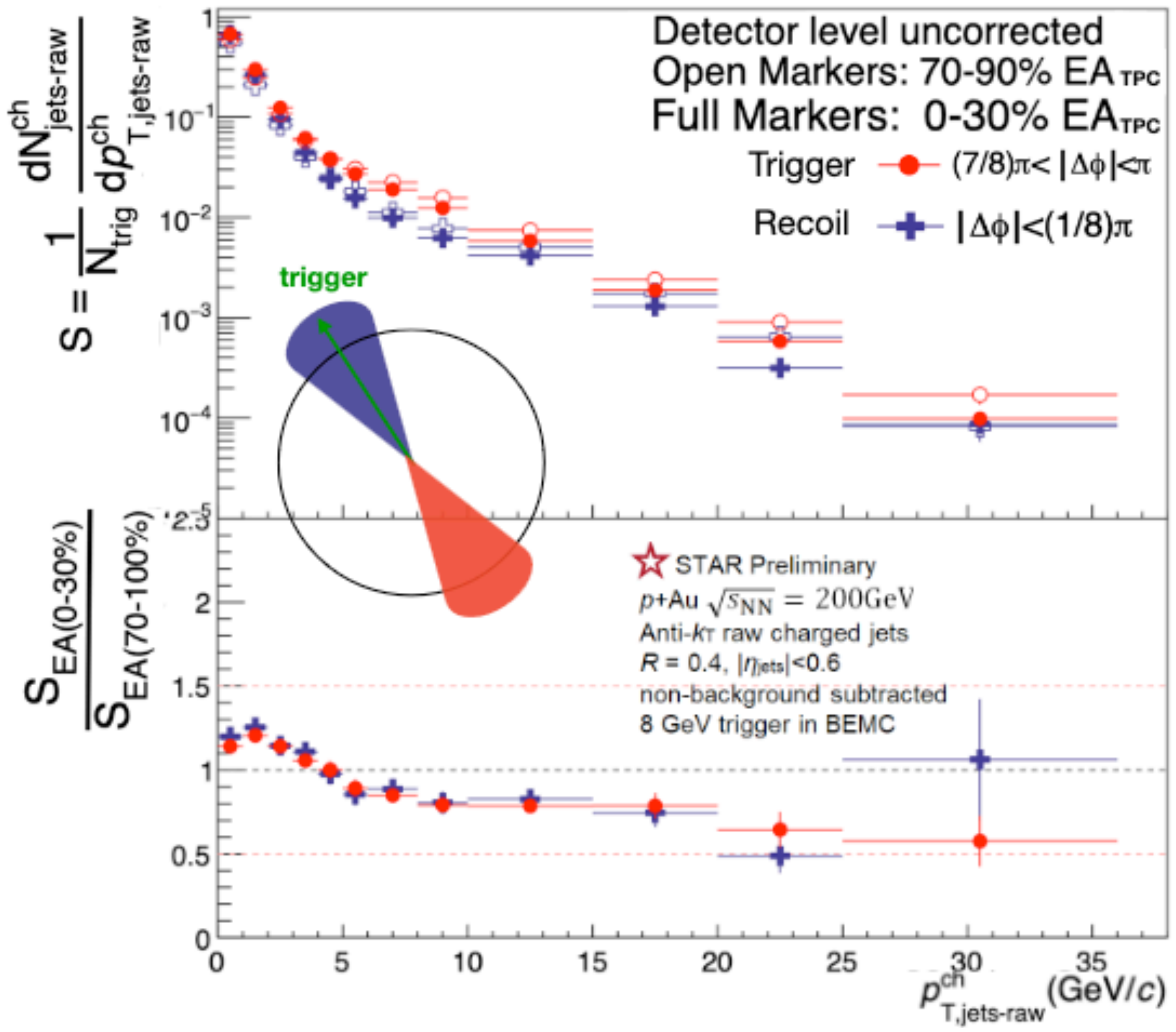


No acoplanarity seen as function of EA in pAu at STAR

Acoplanarity in A-A due to scattering or medium response to jet?

STAR: Y. Hu HP 2023
ALICE: Y. Hou HP 2023

Energy Loss to p(d)-Au Medium at RHIC



I_{pAu} for recoil jet

Normalization per high p_T trigger object

Suppression on near and away-side similar; inconsistent with E_{loss}

PHENIX: arXiv:2303.12899

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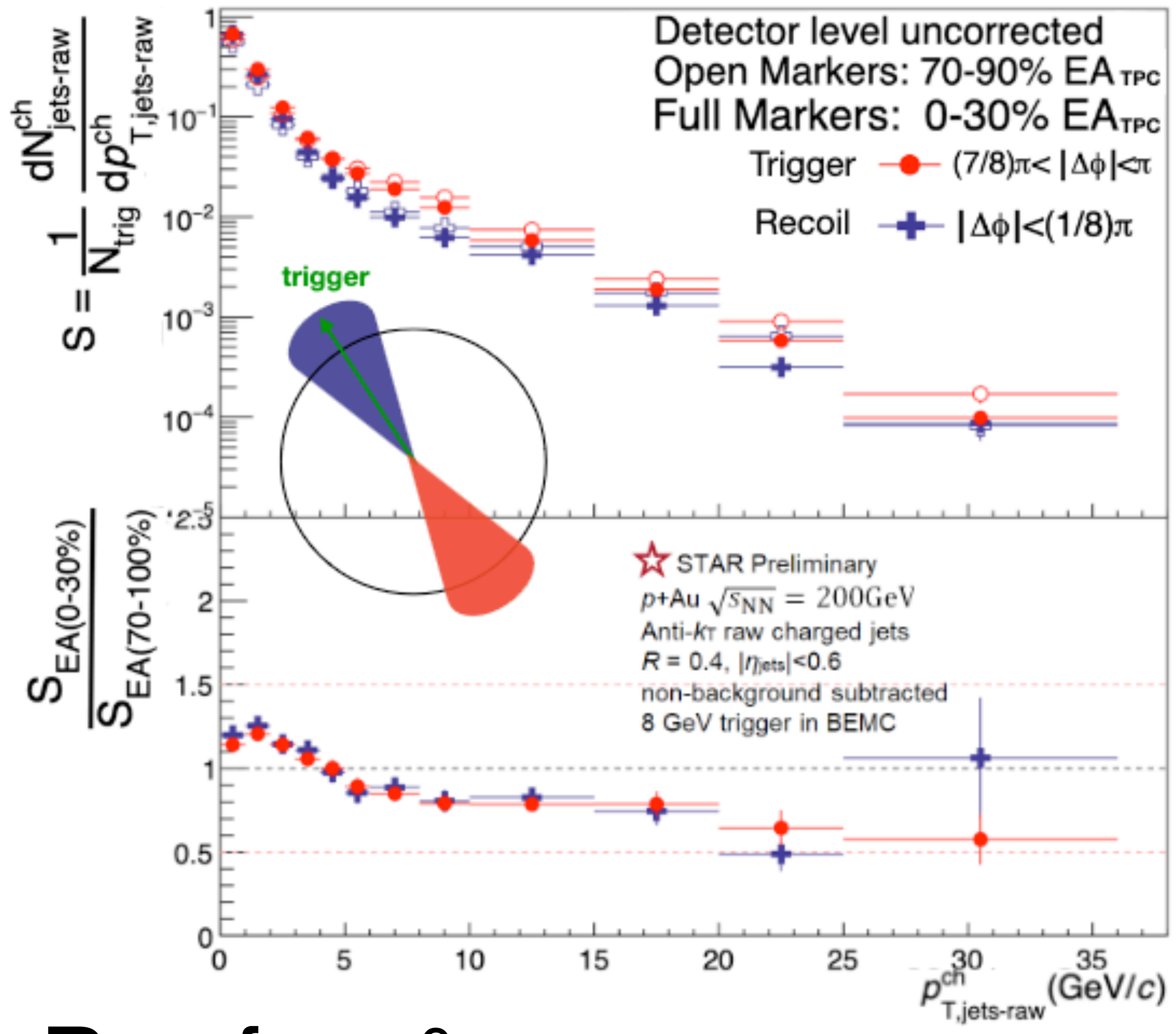

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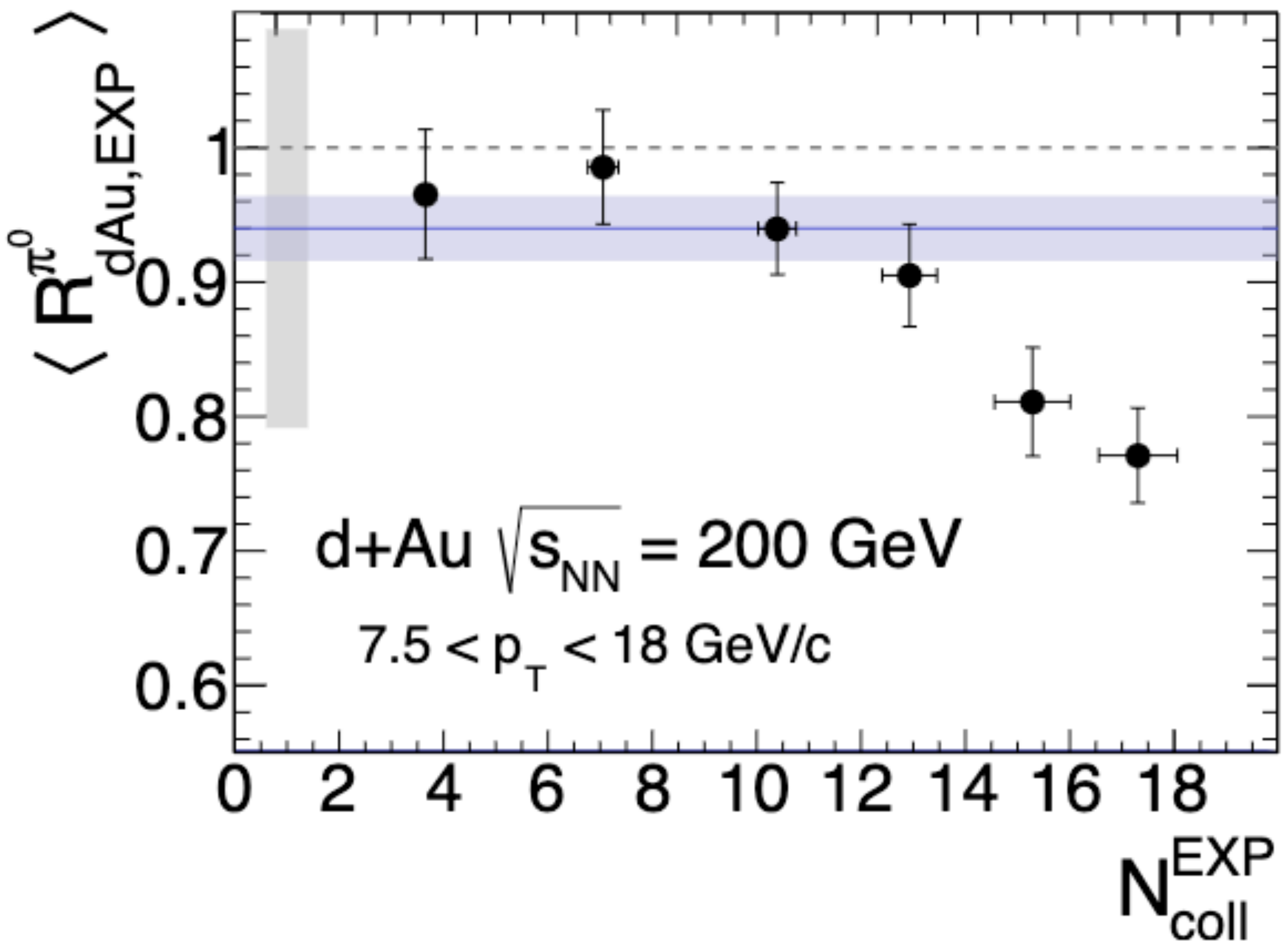

R_{dAu} for π^0

N_{bin} determined by forcing R_{dAu} γ to unity (colorless object no interaction with medium)

Qualitatively consistent with predictions of E_{loss} in small systems

A. Huss et al. PRC103, 054903 (2021). W. Ke, I. Vitev arXiv:2204.00634

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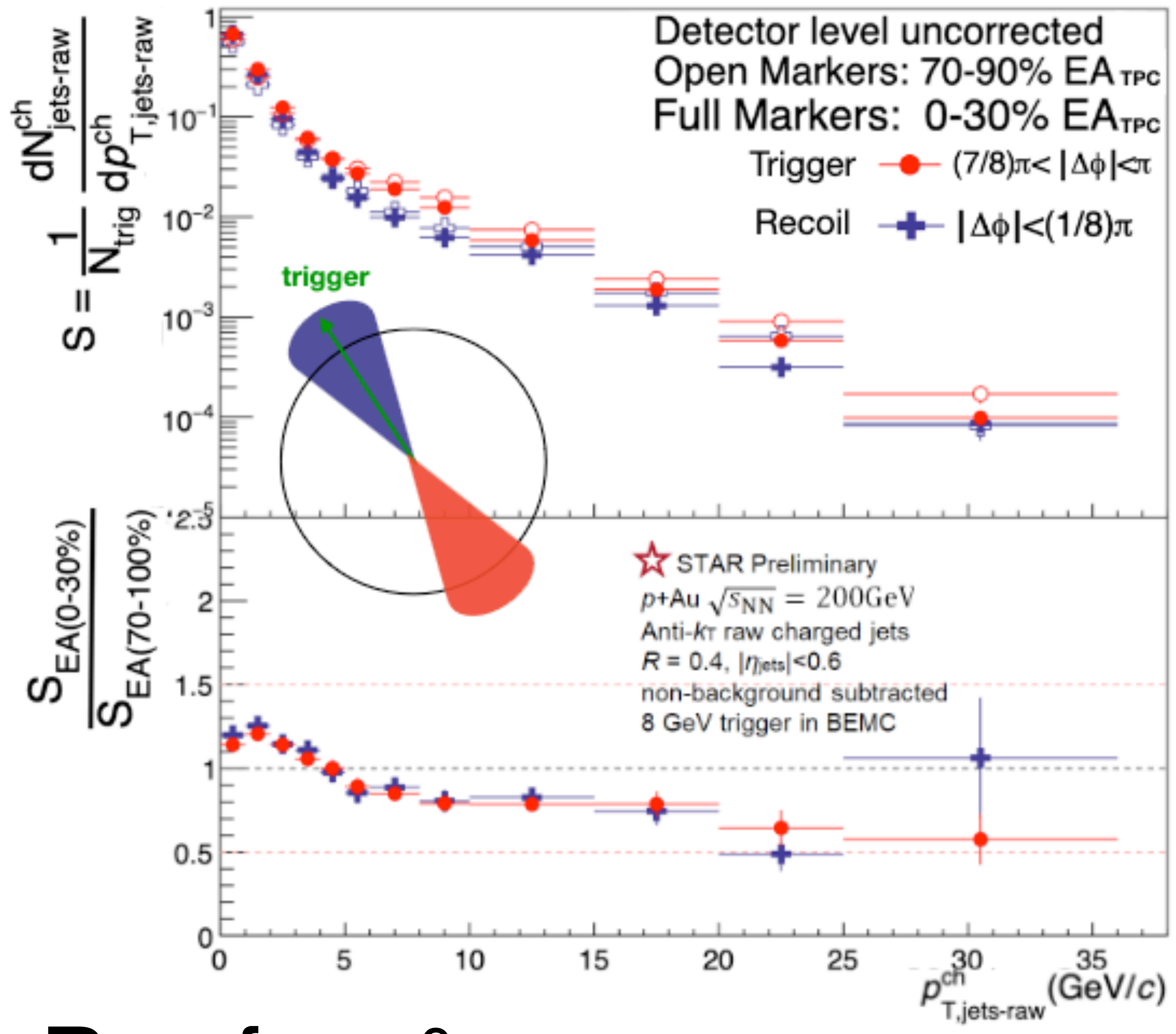

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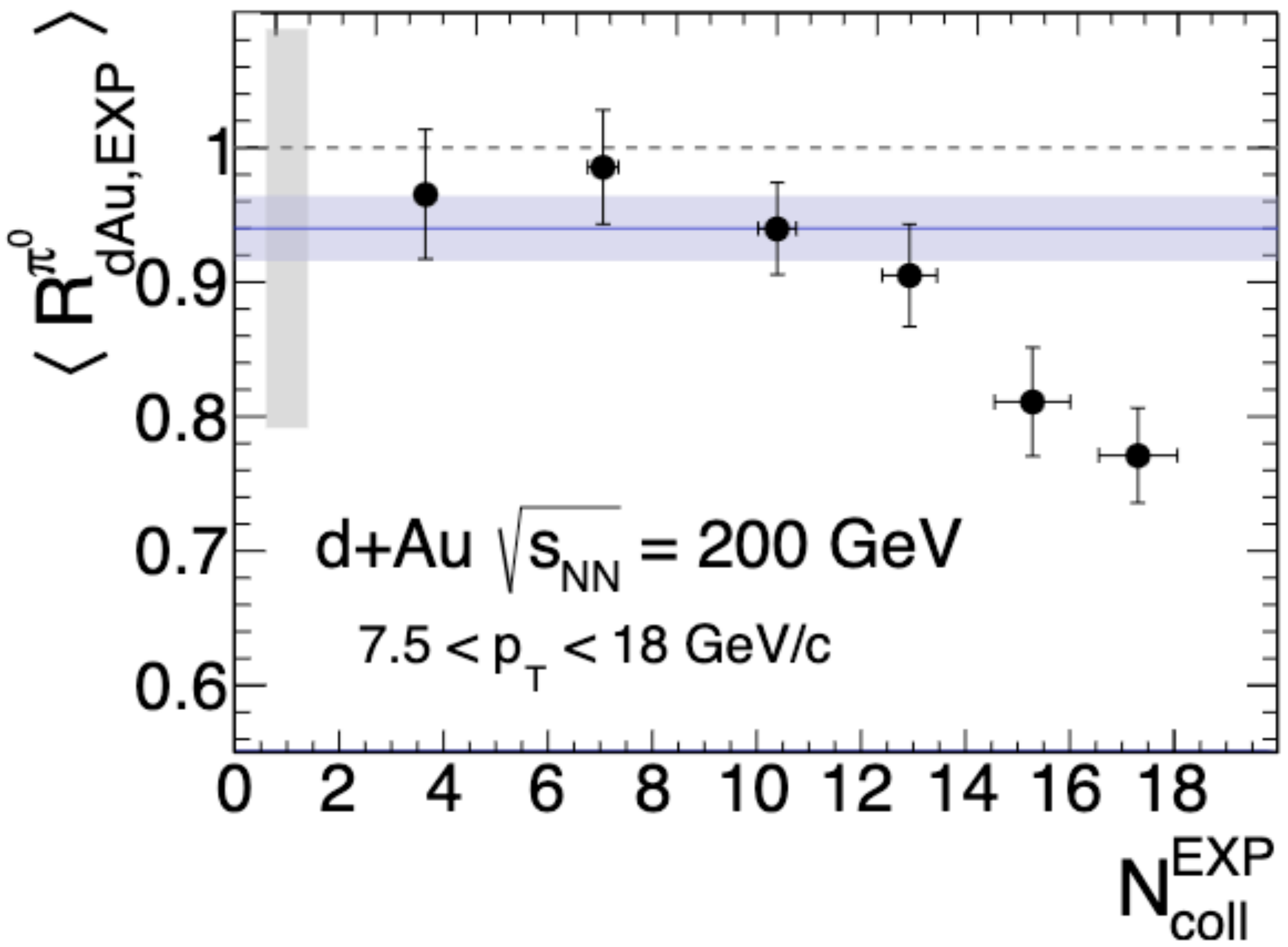
What will we see at EIC?



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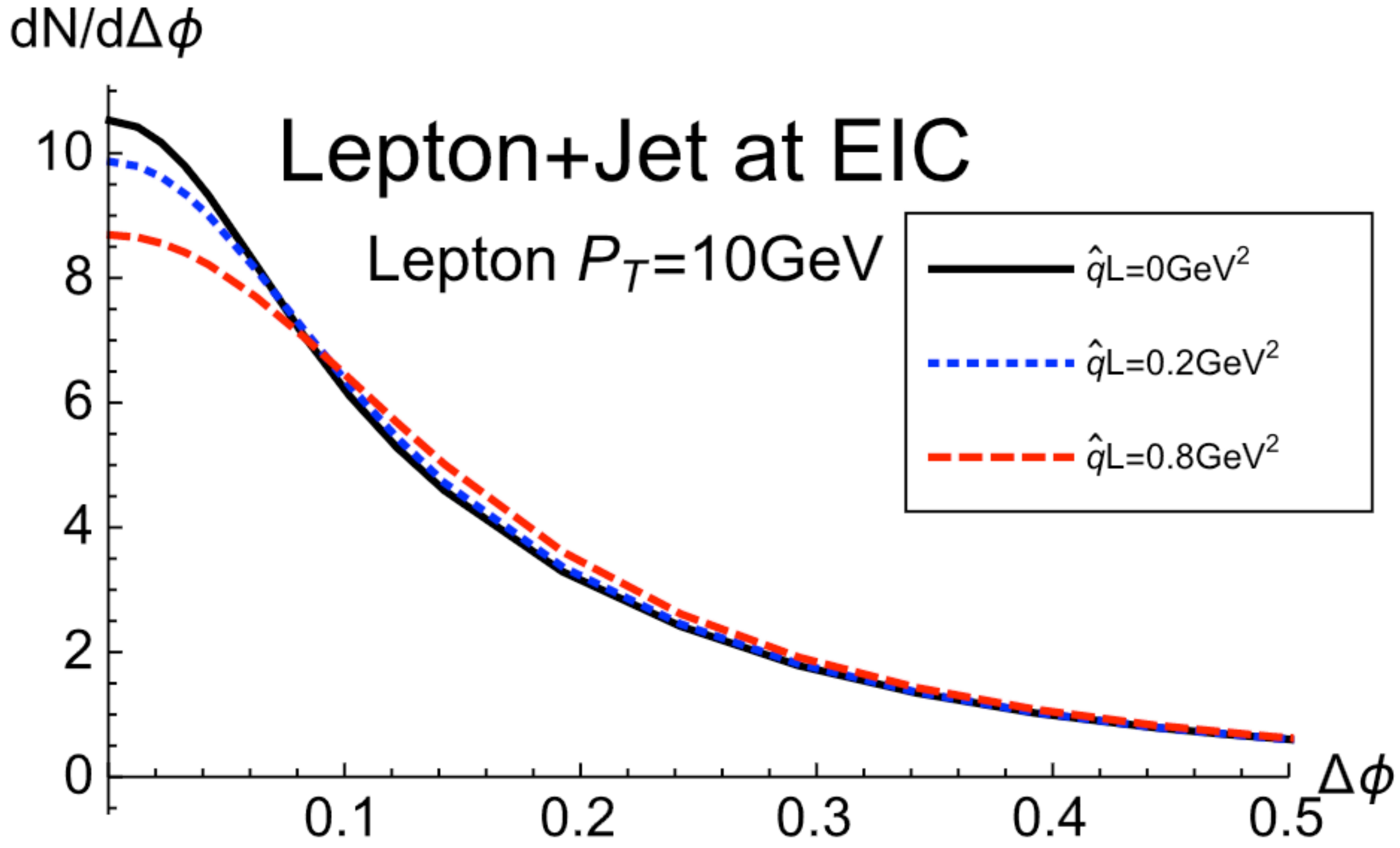
Jet Azimuthal Broadening at the EIC

Lepton-jet correlations in DIS in eA



Multiple interactions of hard scattered parton as it exits the target nucleus generates p_T-broadening/deflection

- similar concept used to explain Cronin effect in pA collisions

c

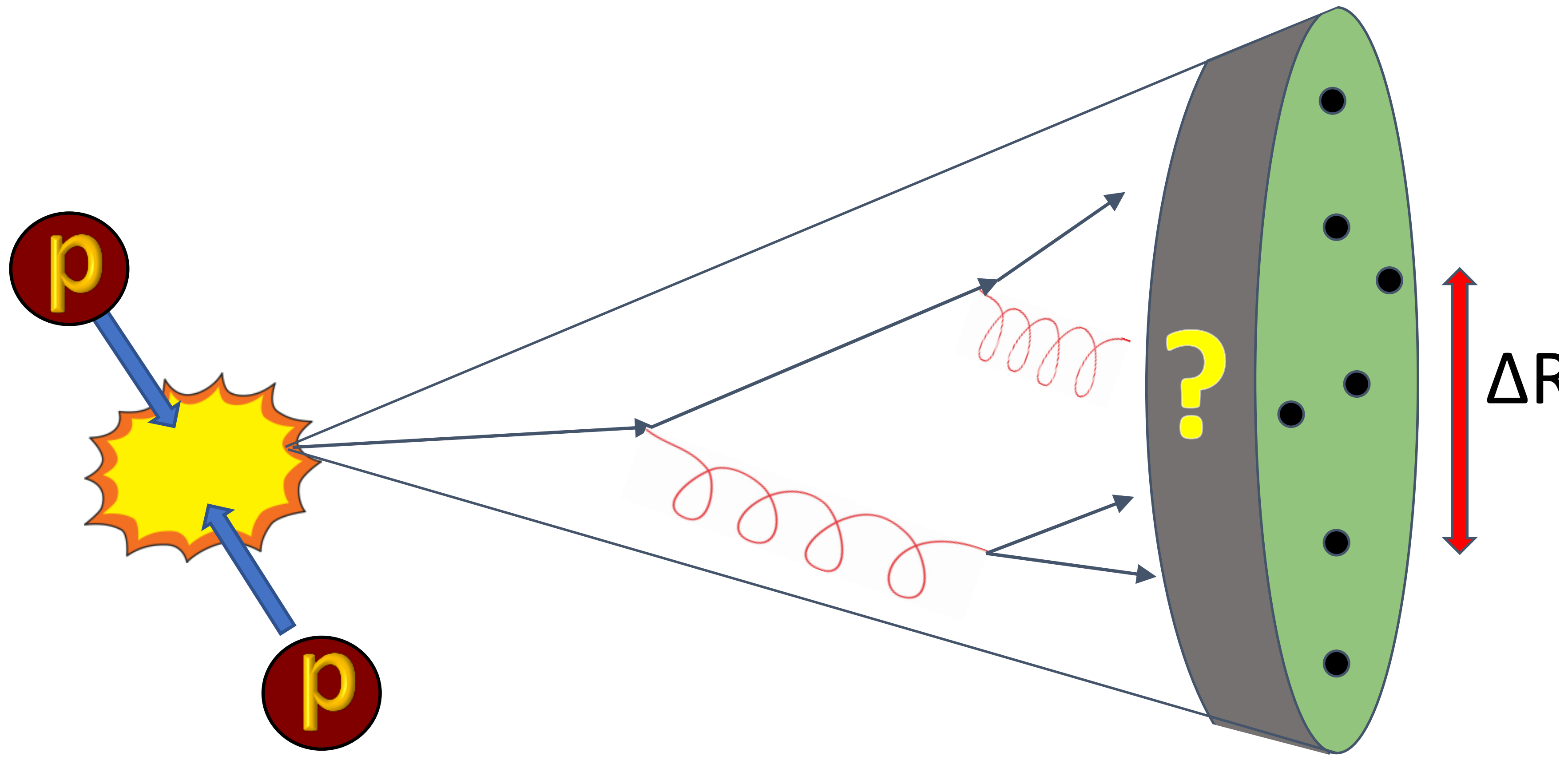
Sensitivity to E_{loss} in Cold nuclear matter

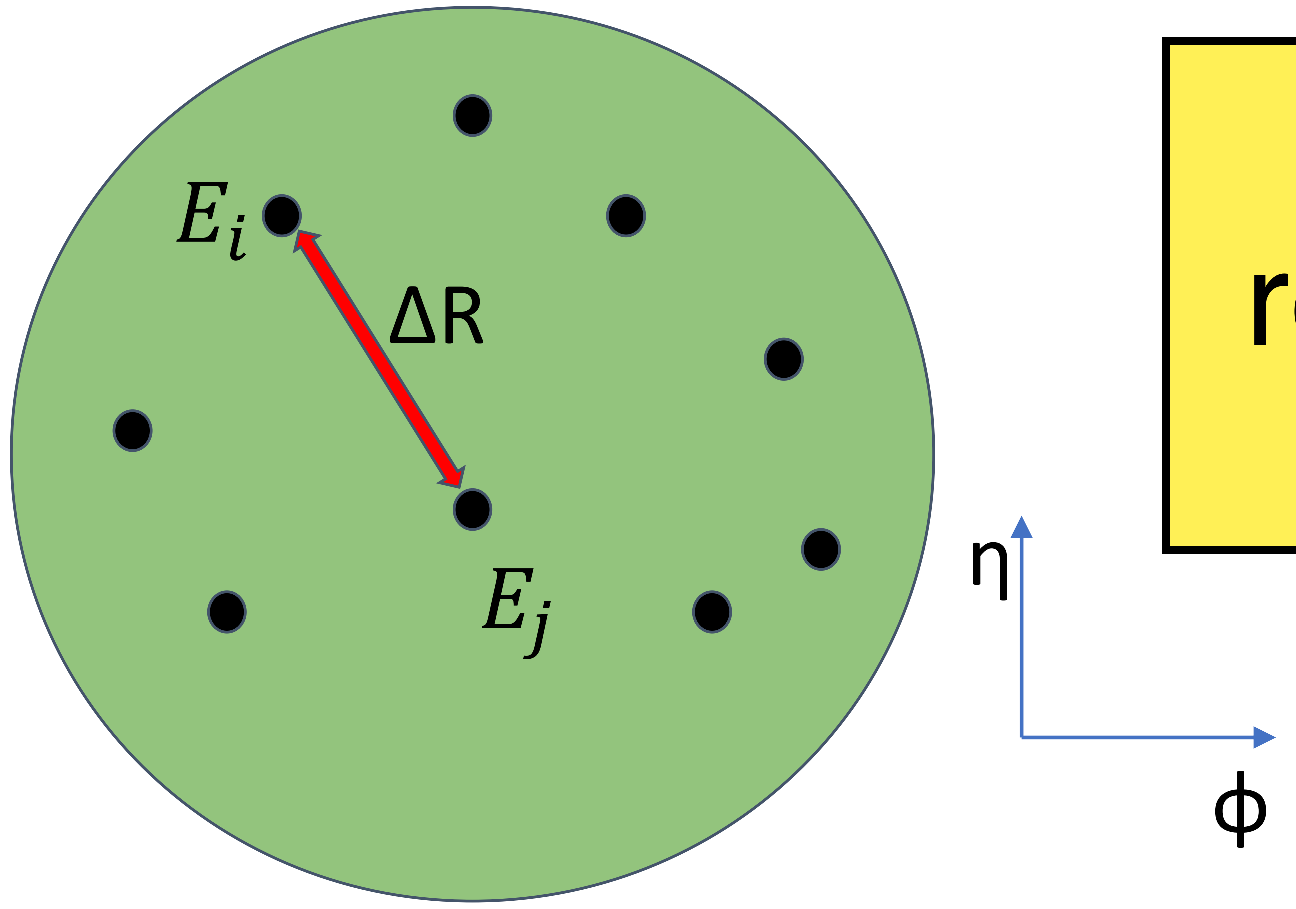
X. Liu et al. PRL 122, 192003 (2019)

Energy-Energy Correlators

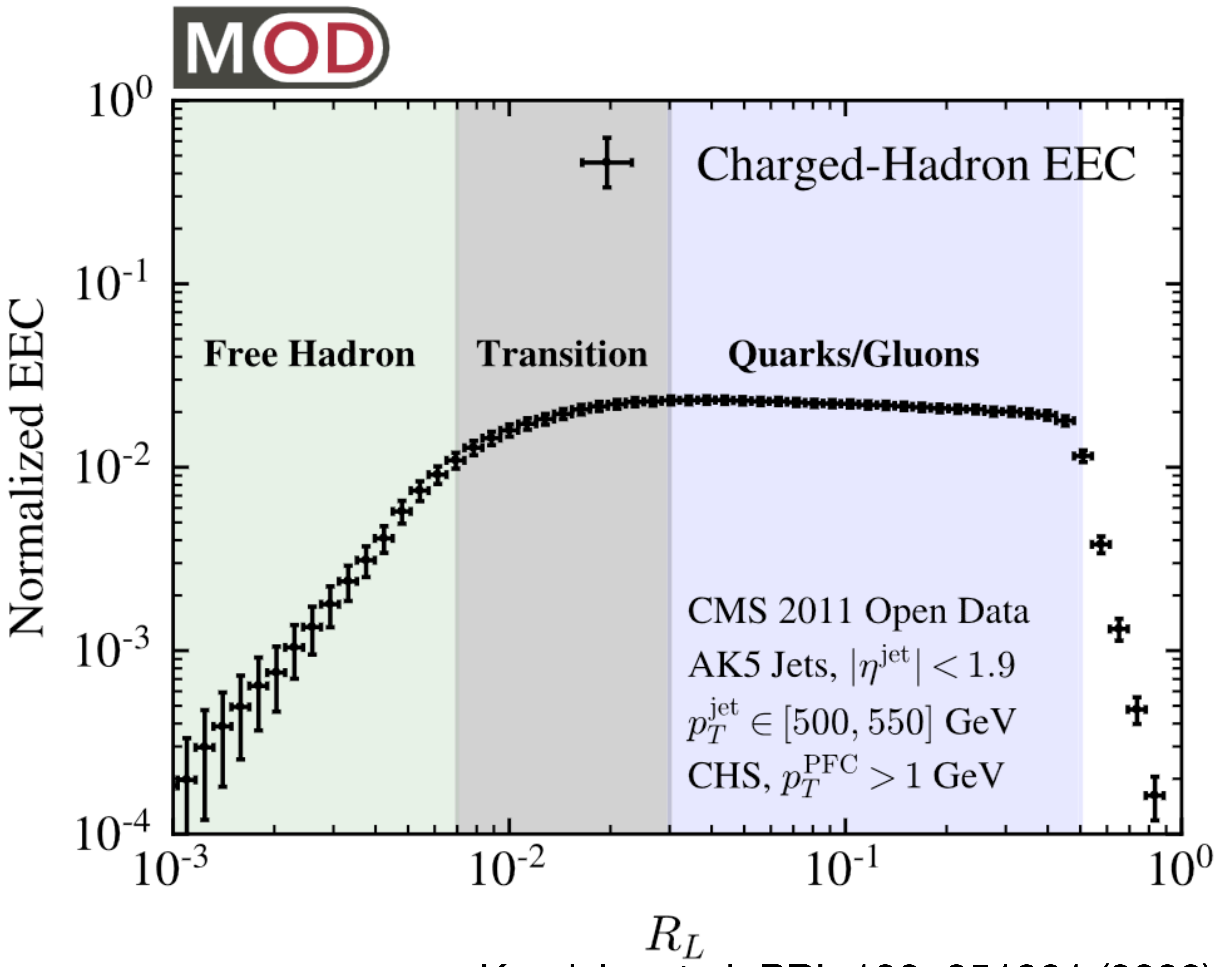
The ultimate di-hadron correlation

$$\text{Normalized EEC} = \frac{1}{\sum_{Jets}\sum_{i\neq j}\frac{E_iE_j}{p_{T,Jet}^2}} \frac{d\left(\sum_{Jets}\sum_{i\neq j}\frac{E_iE_j}{p_{T,Jet}^2}\right)}{d\,(\Delta R)}$$





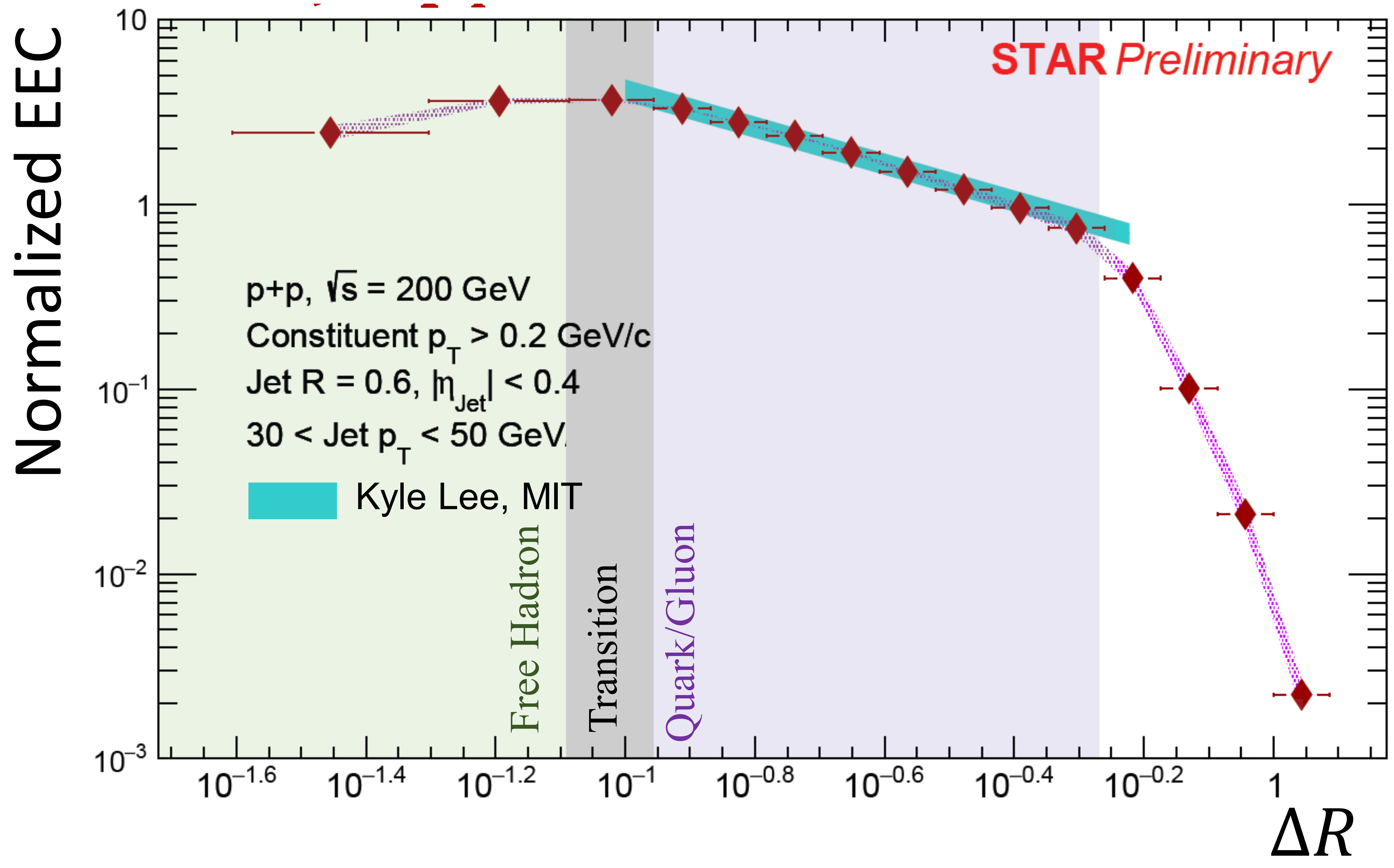
2-point correlator reveals confinement transition region

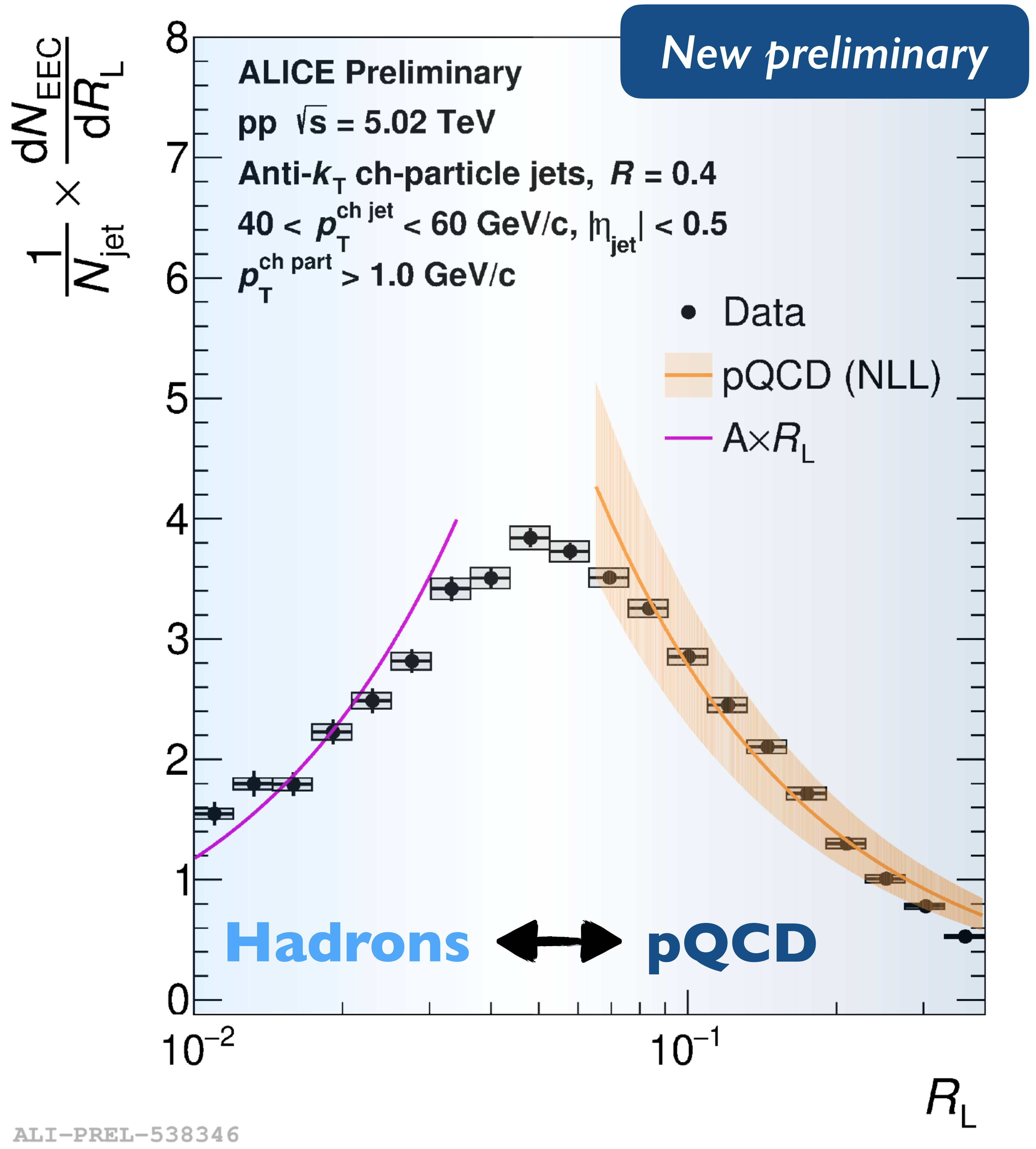


Komiske et al. PRL 130, 051901 (2023)

Energy-Energy Correlators in pp

First experimental measurements underway





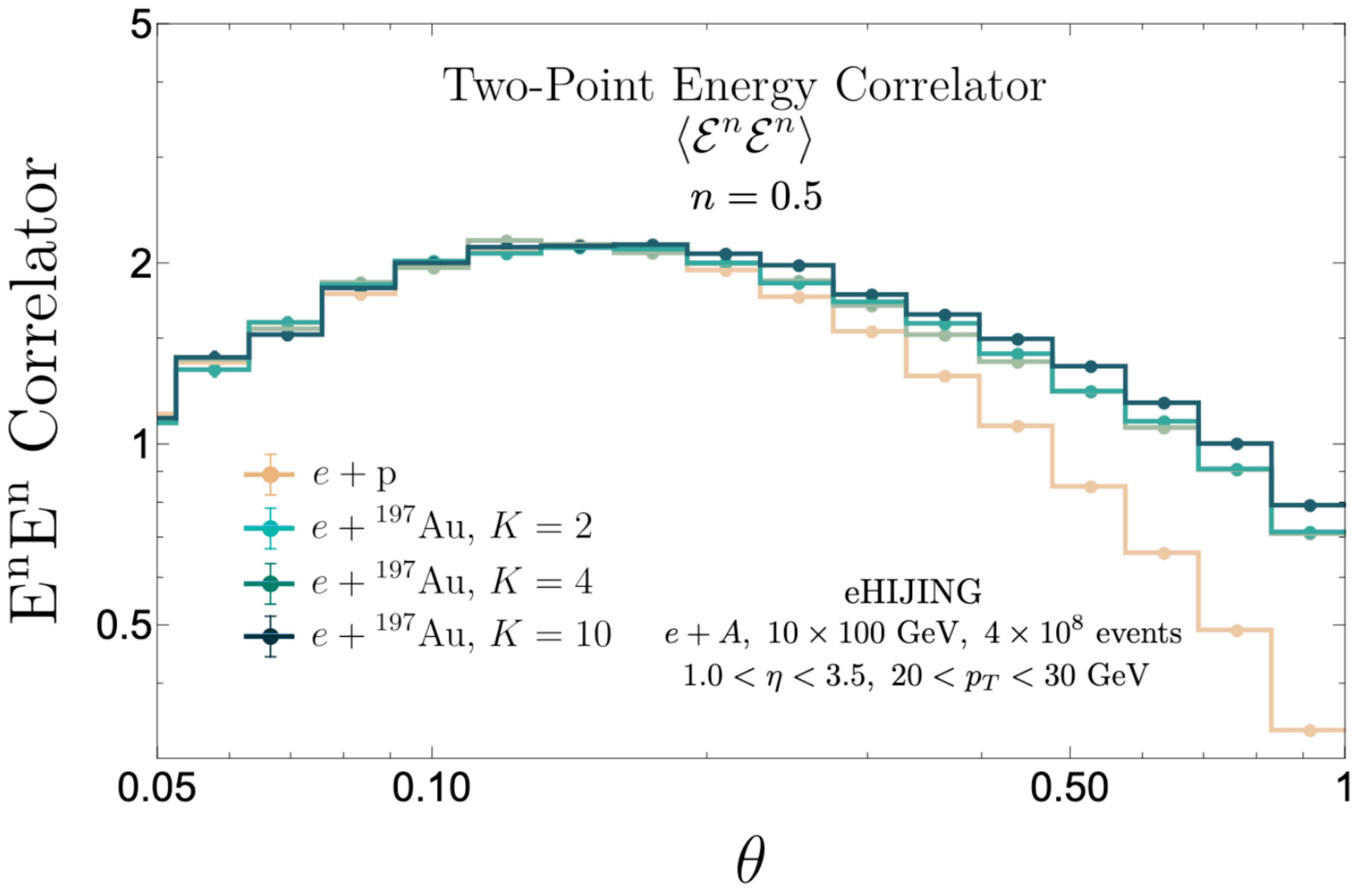
Good theory-date agreements

$R_L * p_T \sim \text{constant} * \Lambda_{QCD}$

Universal turning point across large range in jet p_T

STAR: A. Tamis HP 2023
ALICE: R. Cruz-Torres HP 2023

Energy-Energy Correlators at the EIC



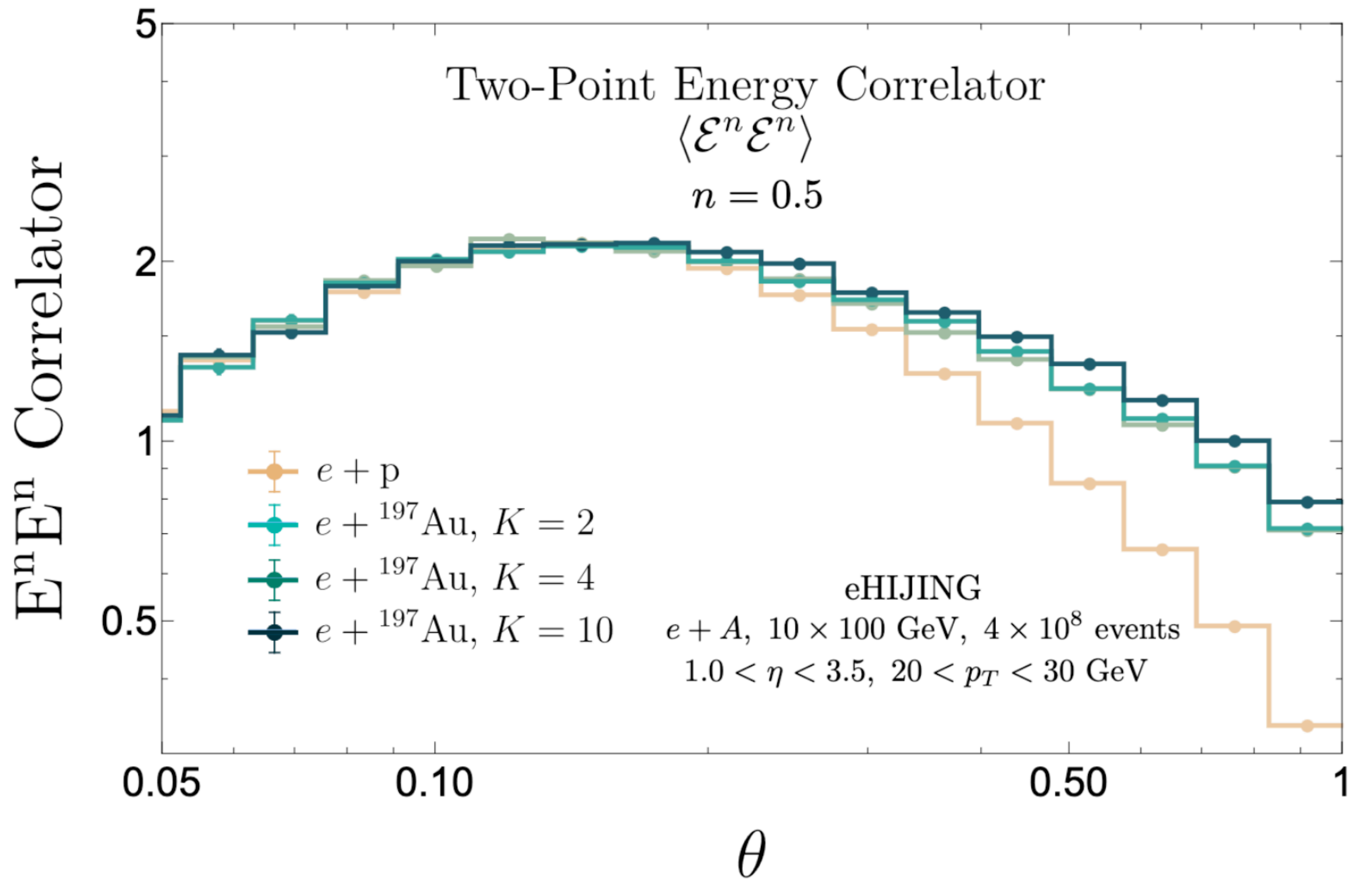
Medium-induced radiation effects expected at :

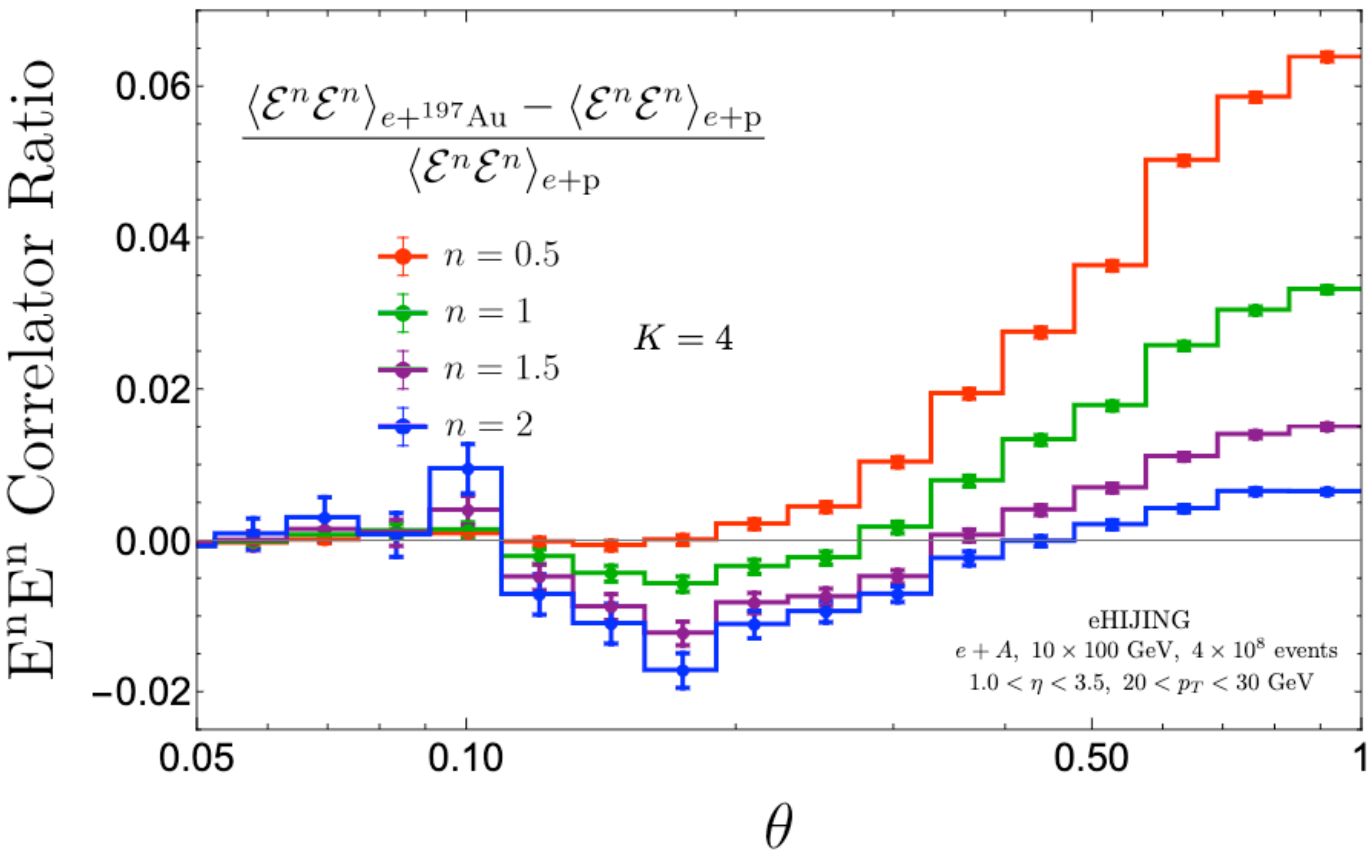
$\theta^2{}_L p_T\, L \sim 1$

$\theta_L \propto 1/\sqrt{p_T\, L} \propto 1/(\sqrt{pT}\, A^{1/6})$

K.Devereaux et al. arXiv:2303.08143v1

Energy-Energy Correlators at the EIC





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Can enhance contribution from soft radiation by changing power E^n

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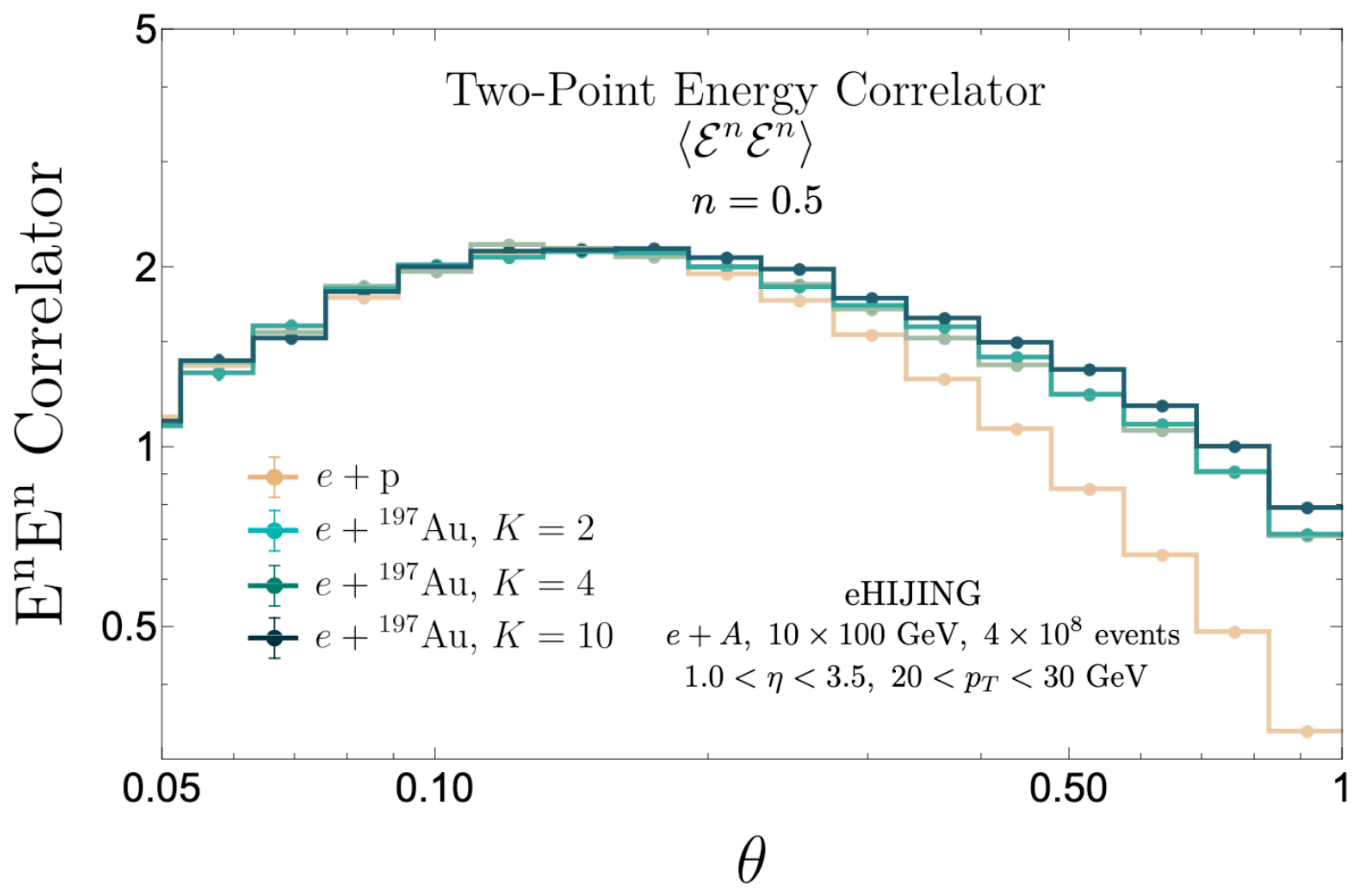

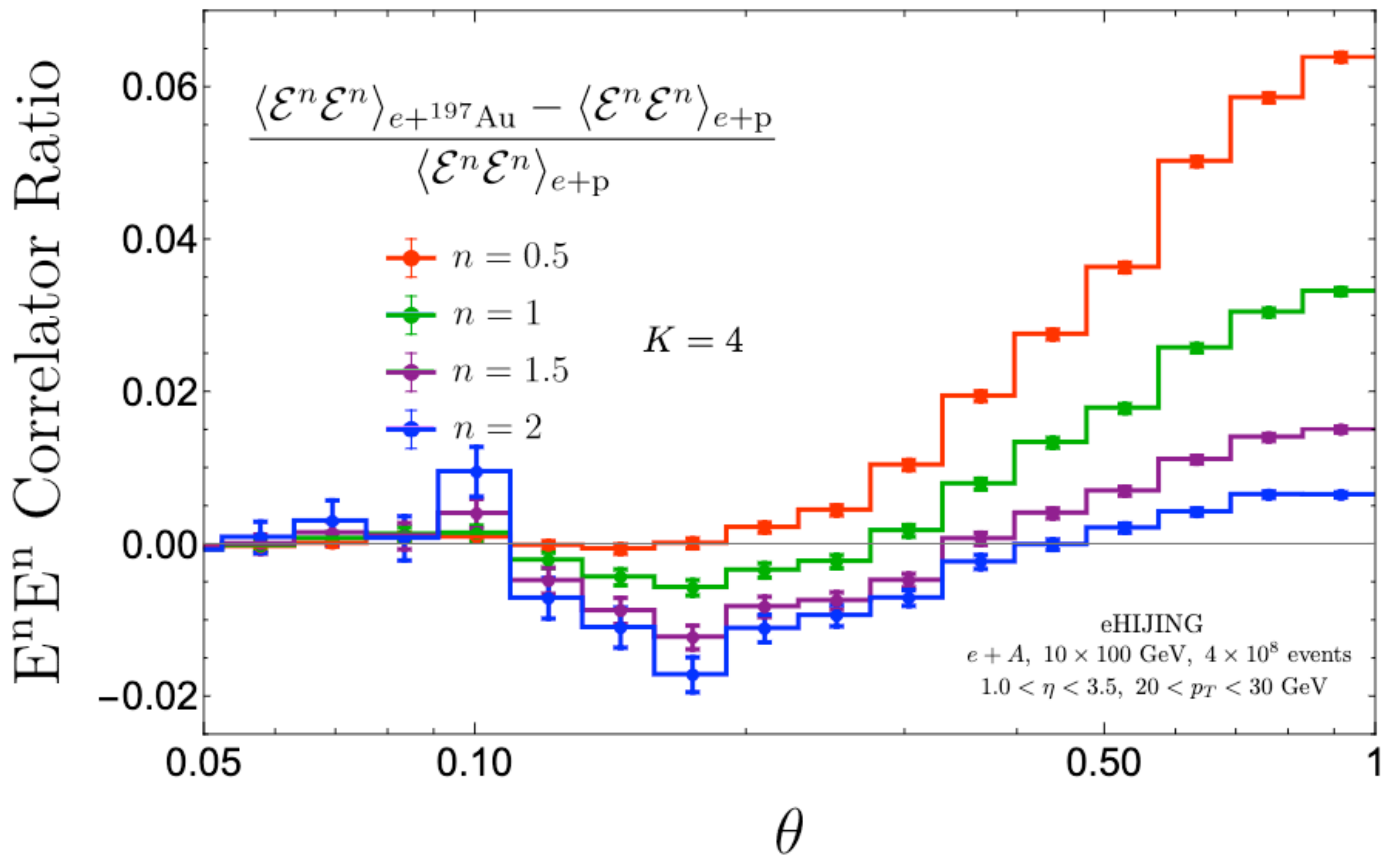

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Can enhance contribution from soft radiation by changing power E^n

EECs versatile tools with many other applications

K.Devereaux et al. arXiv:2303.08143v1

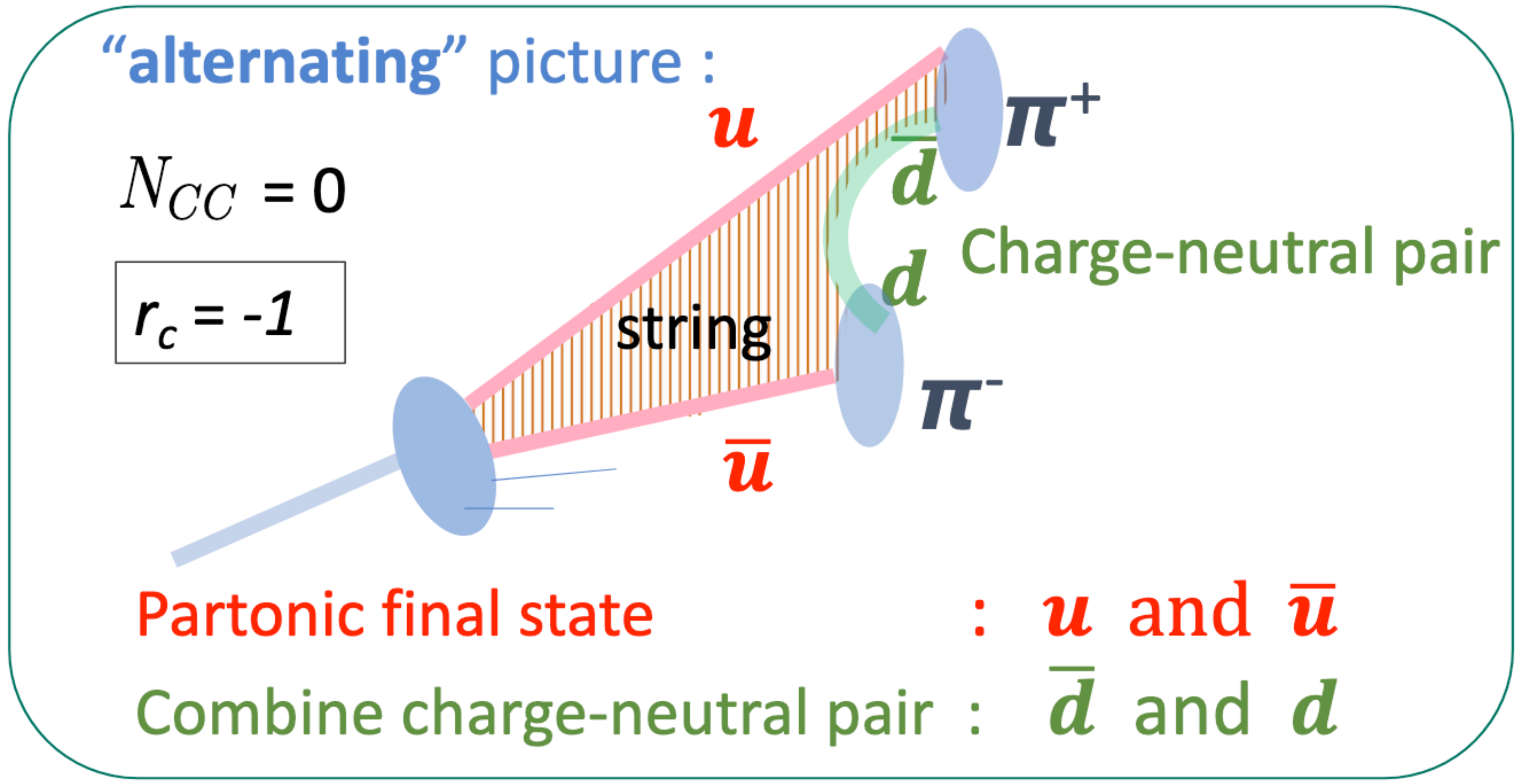
Charge Correlation Ratio

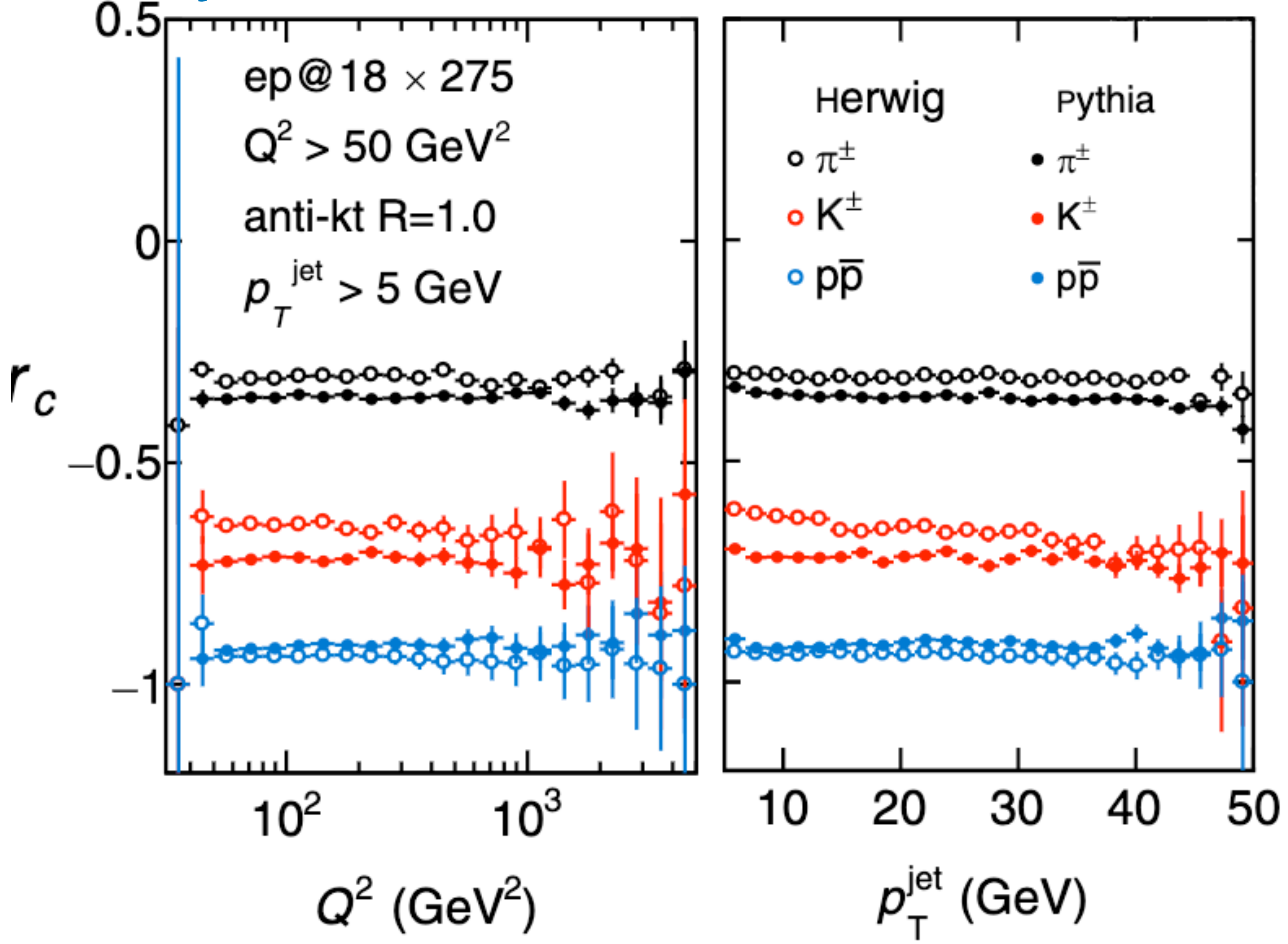
Access nonperturbative hadronization process with this di-hadron correlation

- Count leading and subleading particle in jet with SS and OS

$$r_c \equiv \frac{N_{CC} - N_{C\bar{C}}}{N_{CC} + N_{C\bar{C}}}$$

Random/No correlation: $r_c = 0$





Can also look at species correlations

Models invariant with Q^2 and p_T what does data show?

Y.T.Chien PRD 105, L051502 (2022)

Charge Correlation Ratio

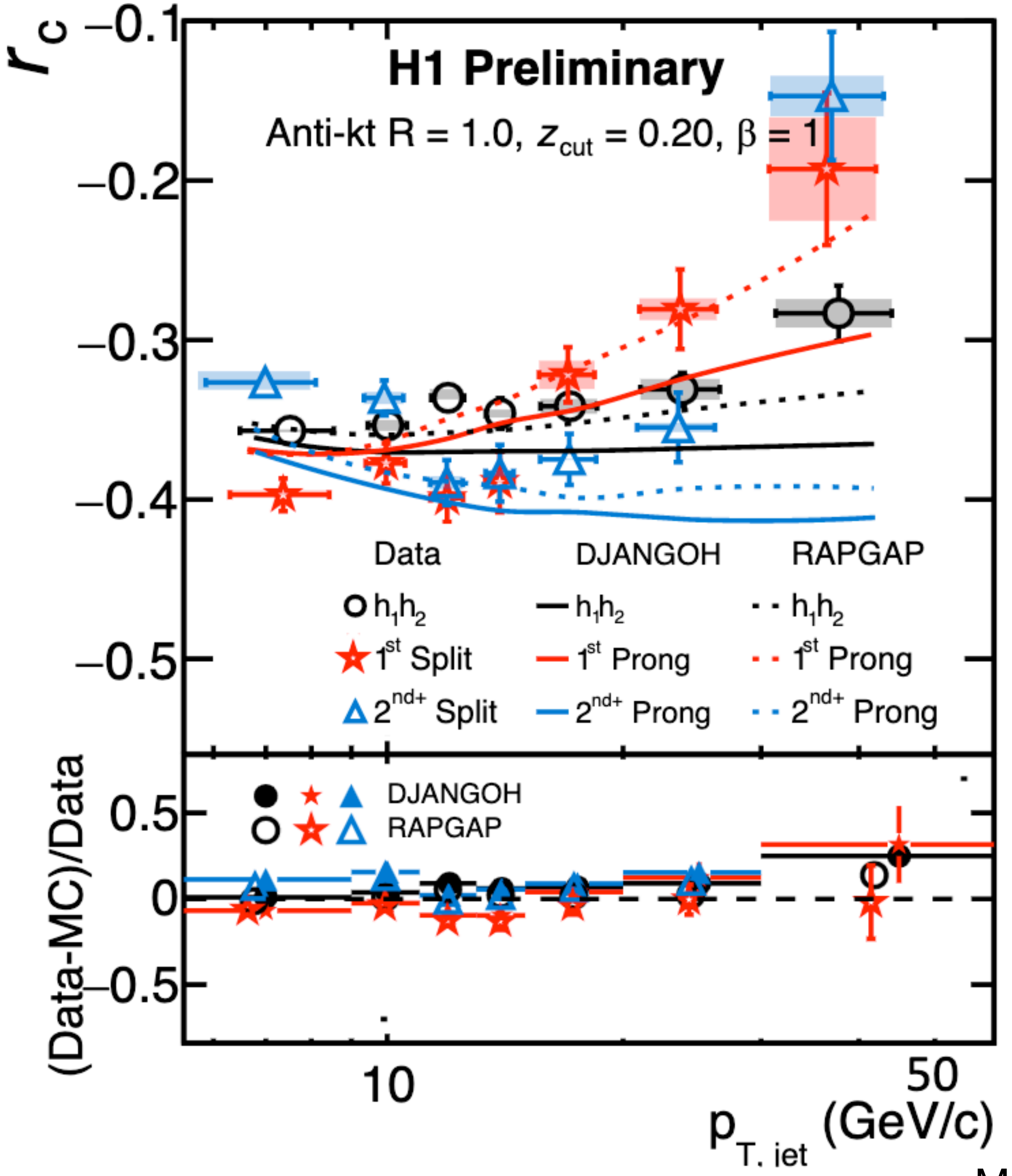
First preliminary results from H1

$$r_c \equiv \frac{N_{CC} - N_{C\bar{C}}}{N_{CC} + N_{C\bar{C}}}$$

Take one step further and look at rc for first and second split of jet using SoftDrop

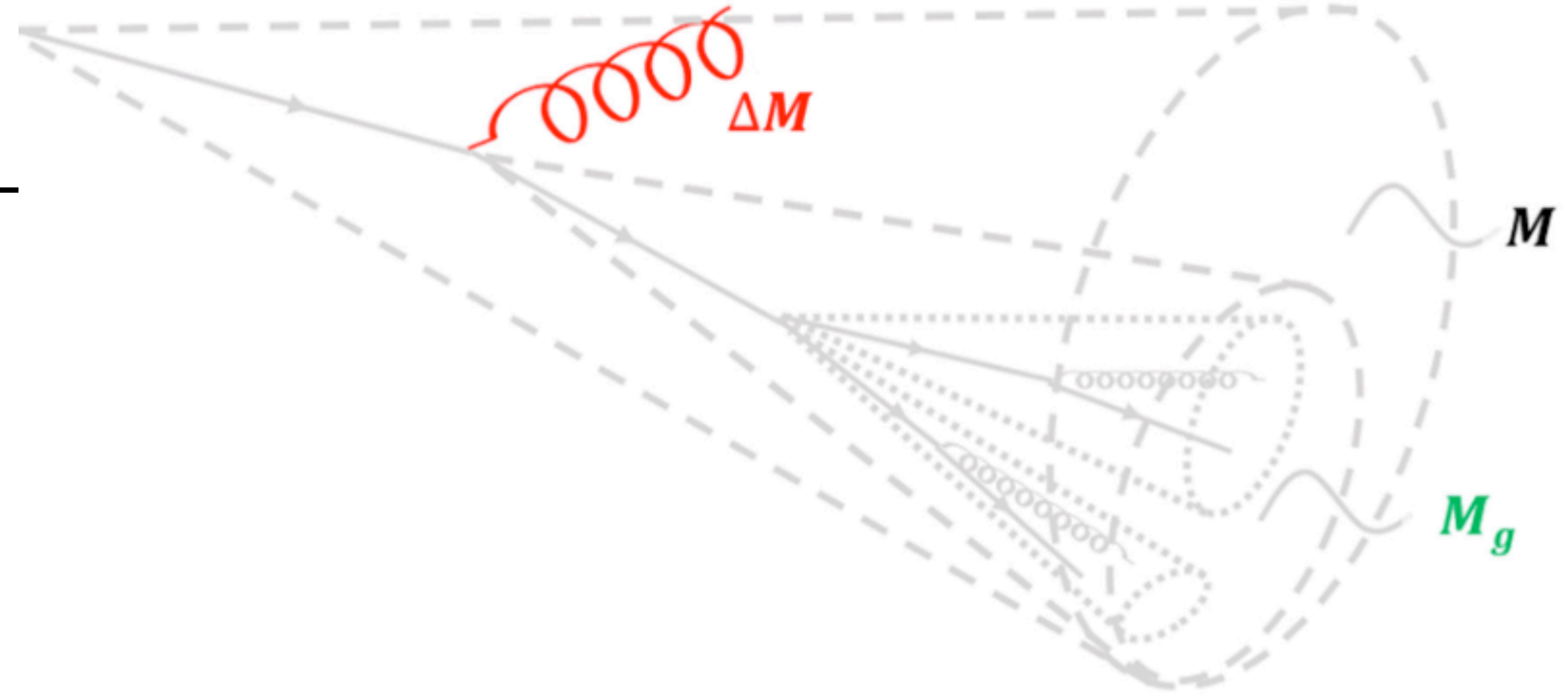
Models reproduce trends of the data

Need EIC to look at PID correlations



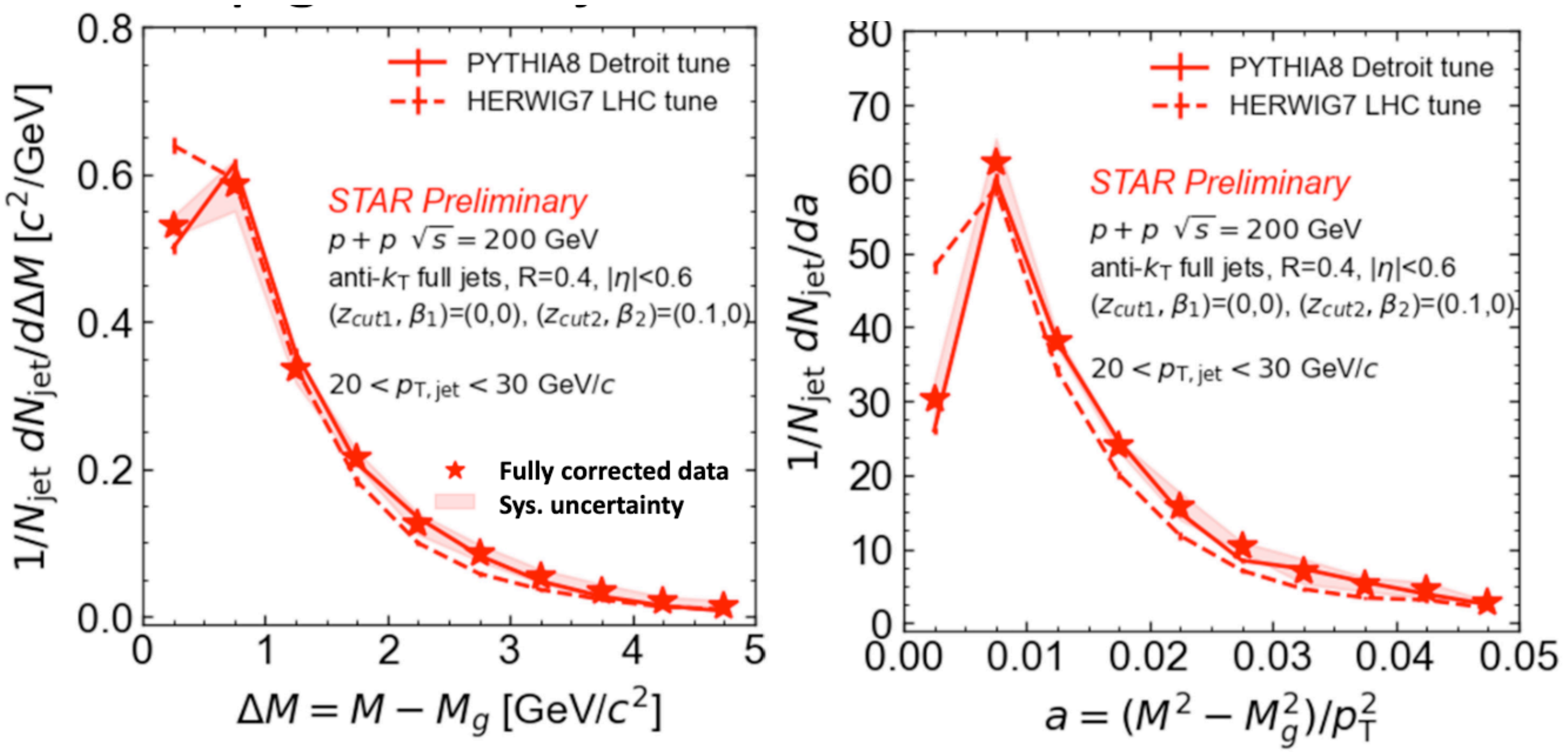
Mondal DIS2022

Exploiting Multifold



Correction tool just beginning to be used

Machine learning driven
- Unbinned
- Simultaneously unfolds multiple observables → Correlation information is retained



Use example collinear drop:
Probes soft component
STAR initial measured ΔM
Theory prefer M^2-M^2_g)/p^2_T
Because using multifold could calculate without redoing analysis

Could be powerful tool at EIC

Andreassen et al. PRL 124, 182001 (2020)
Chien and Stewart JHEP 2020, 64 (2020).
STAR: Y. Song DIS 2023

Summary

Many studies build on those occurring at RHIC, LHC and HERA

Exploit tools being developed now and over next few years

Wealth of di-jet and di-hadron correlations studies to be done at EIC
only scratched the surface in this talk

Success of the studies rely on meeting or exceeding detector requirements
- As ePIC design becomes set in stone will probably need D2 to do this

Kinematics and properties of (di)jets at EIC

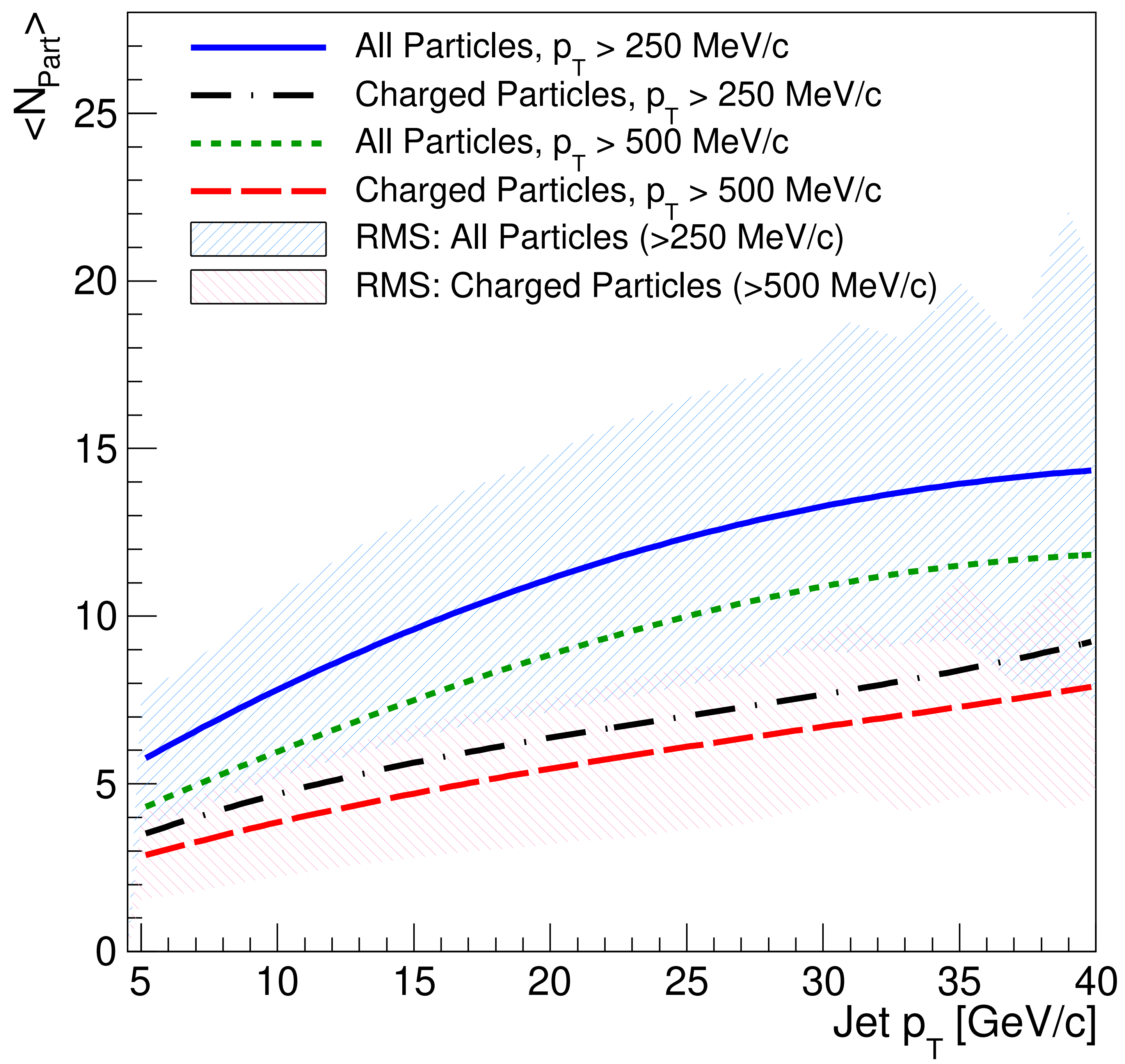
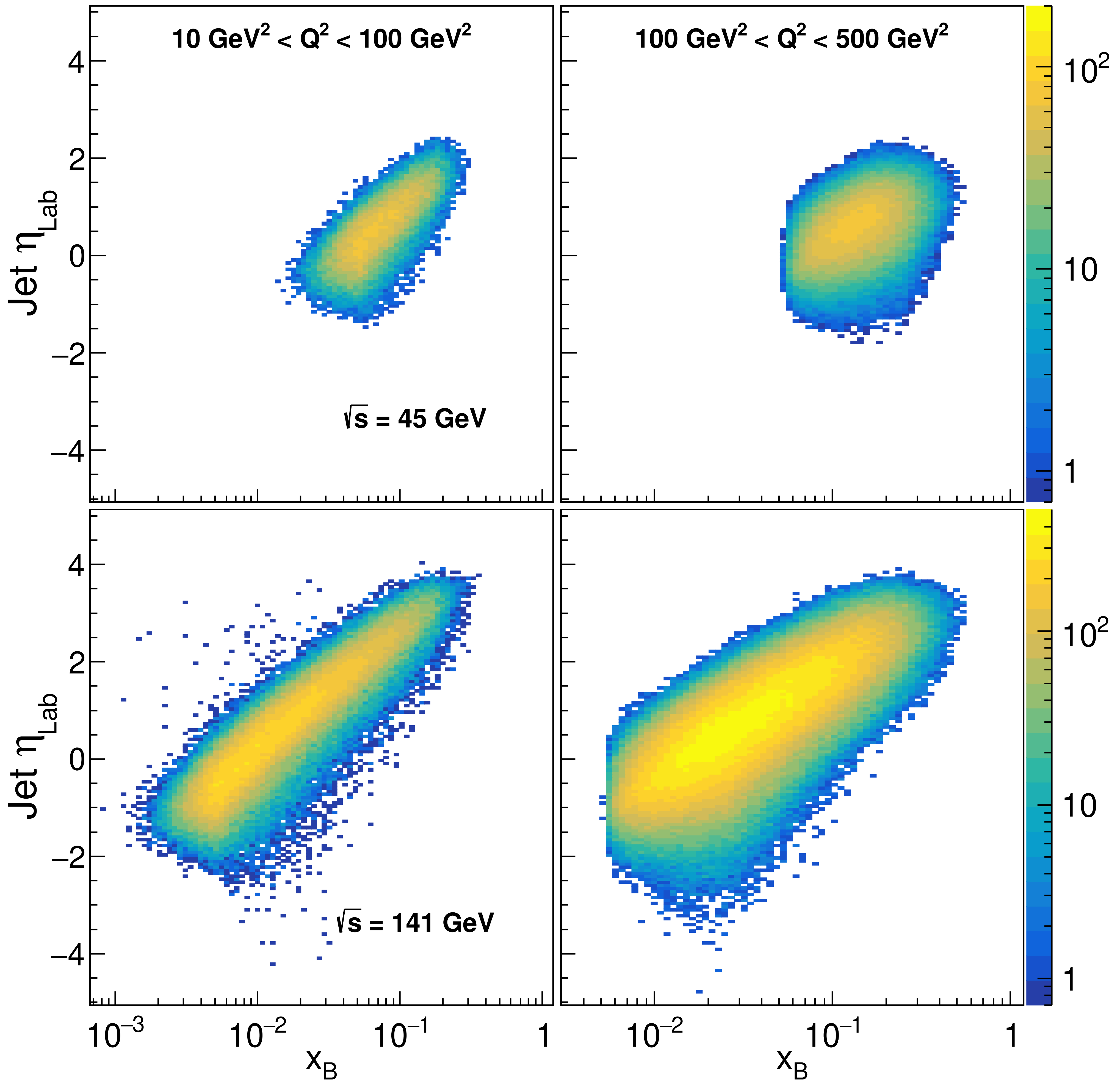


FIG. 11. [color online] The average number of particles in a jet as a function of the transverse momentum of the jet for all stable particles and only charged particles for minimum particle p_Ts of 250 and 500 MeV/c. Also shown are the RMS variations for all particles with $p_T > 250$ MeV/c and charged particles with $p_T > 500$ MeV/c.



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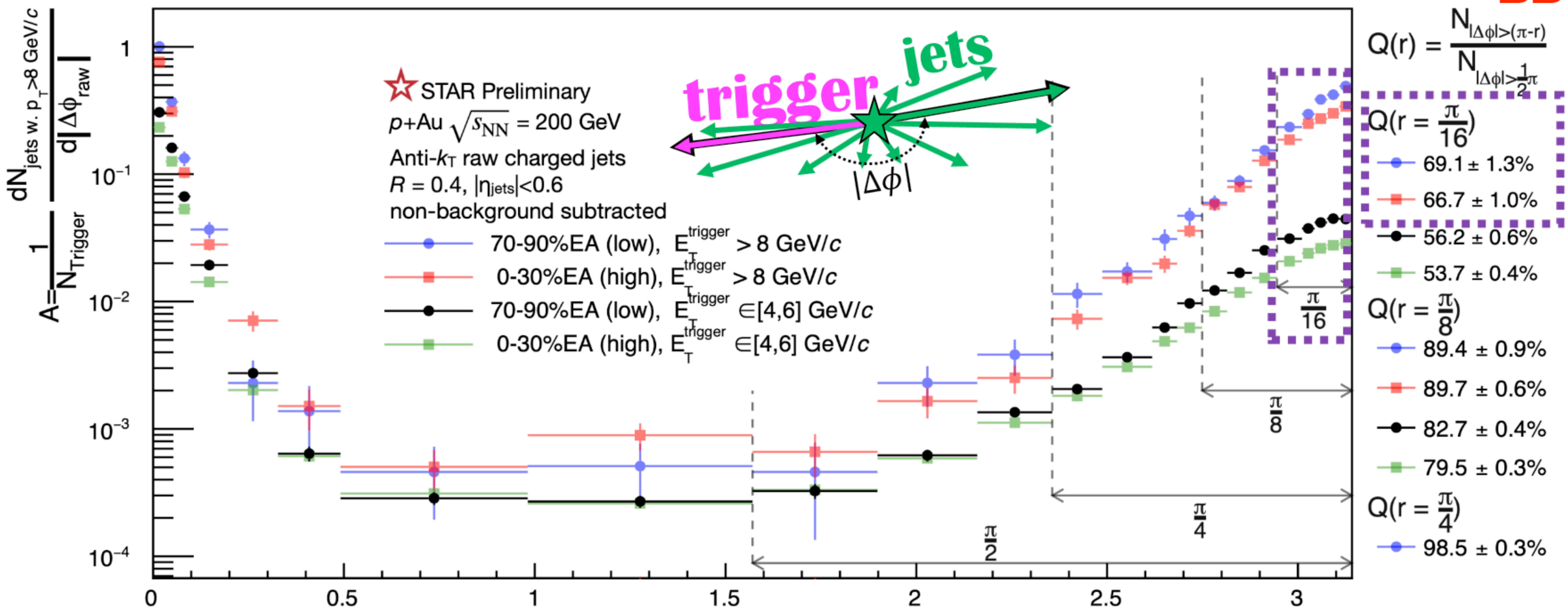
No broadening in pA at STAR

Results: no broadening of acoplanarity with EA_{BBC}



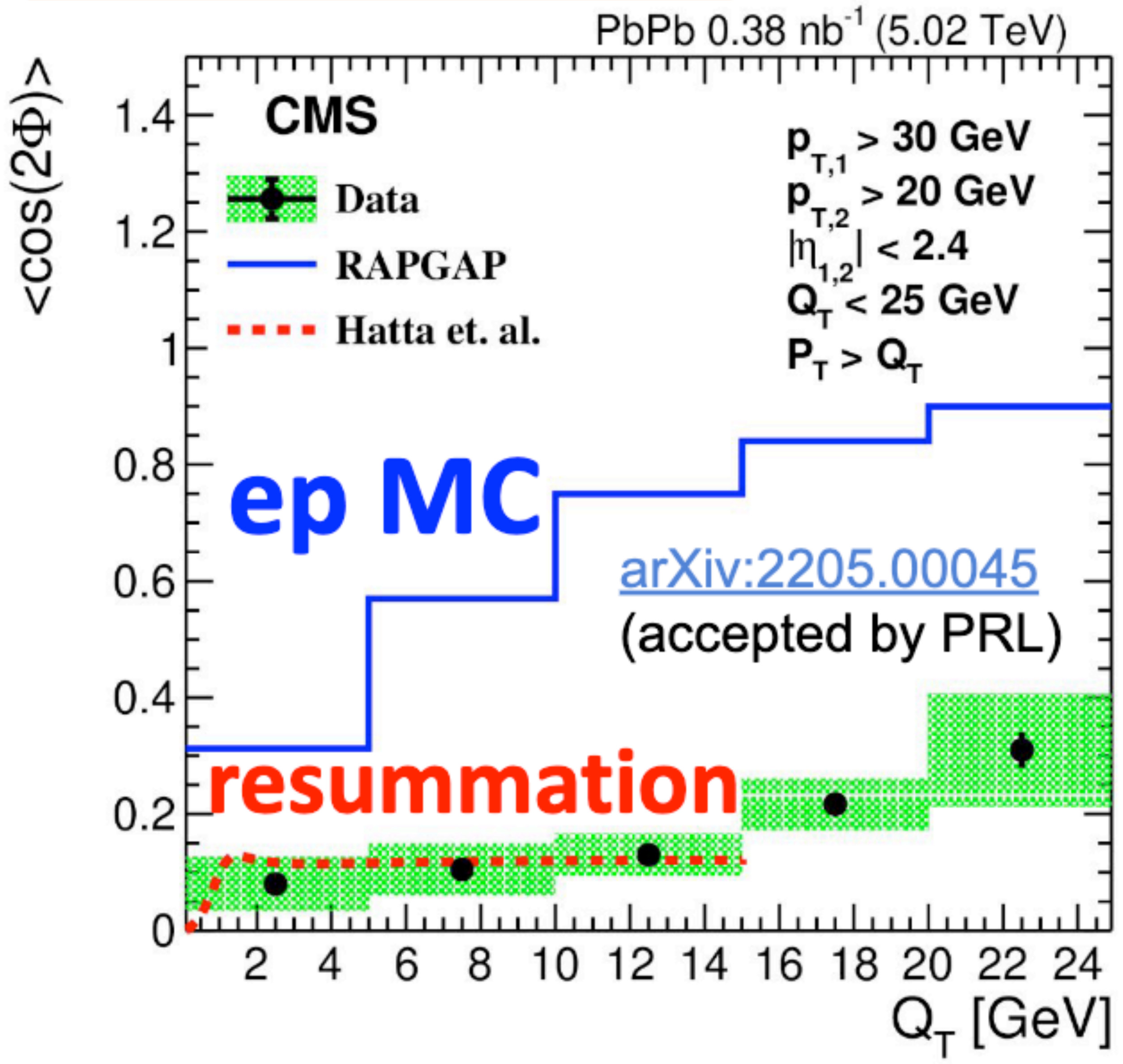
Percentage of jets with $|\phi_{jet} - \phi_{trigger}| > \frac{15}{16}\pi$ decreases by 1.5 σ from **low-EA** to **high-EA**

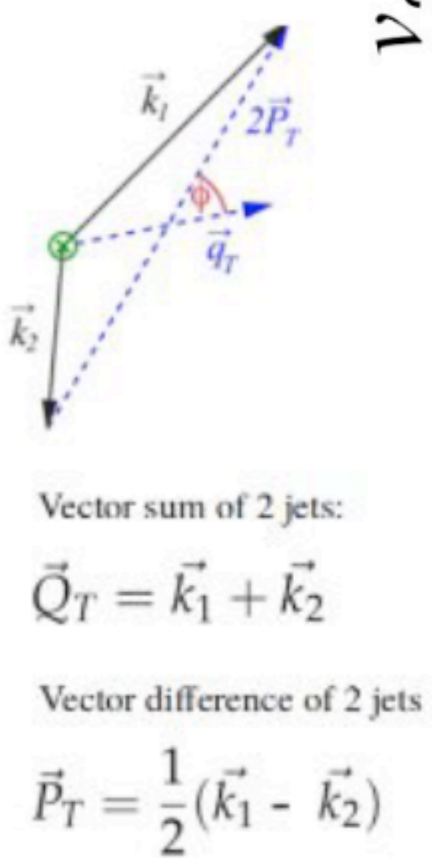
The Breit Frame

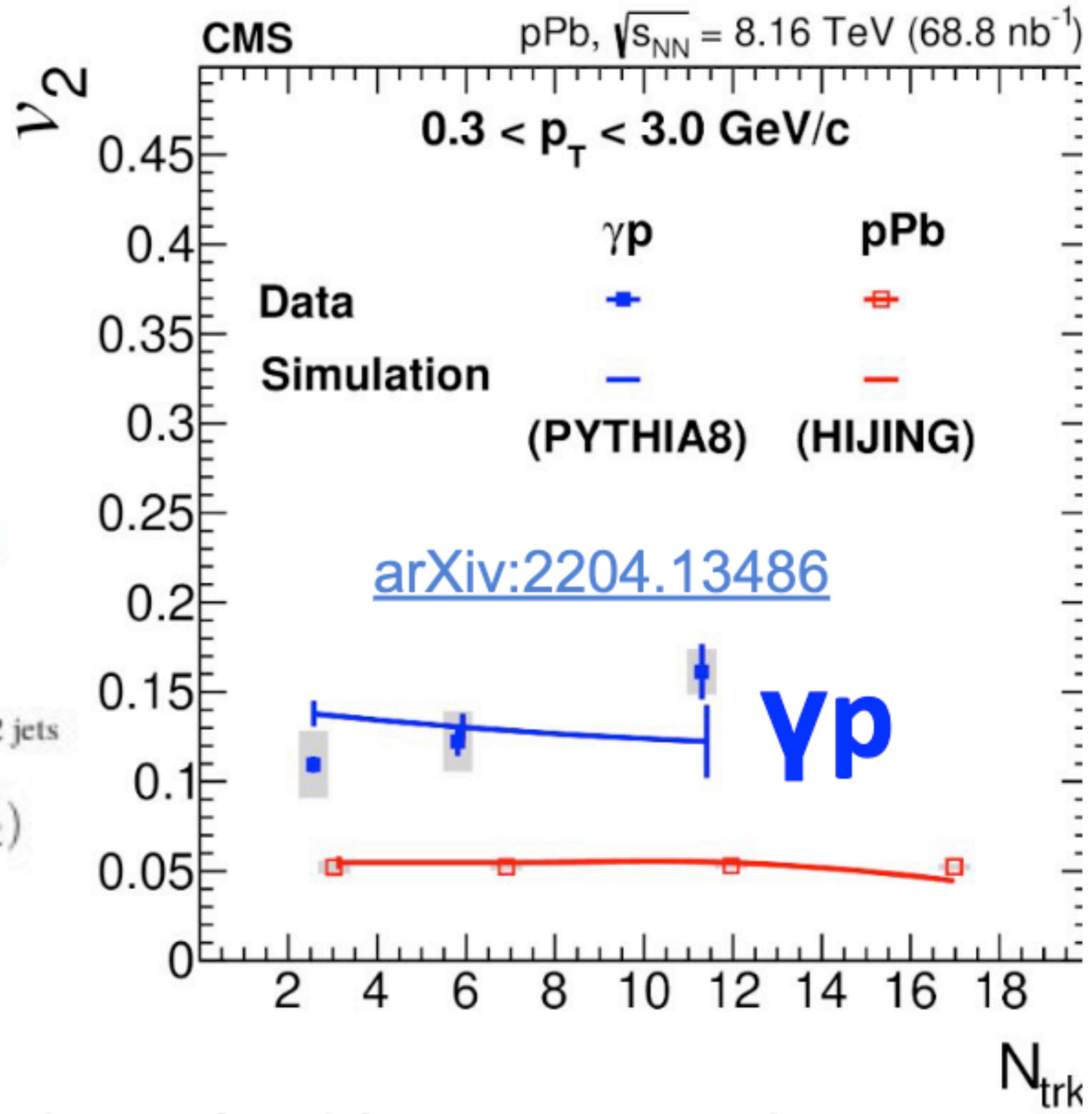
The Breit or "brick wall" frame is particularly useful for jet analyses
It is oriented such that for the DIS process $\gamma_* q \to q'$, the virtual photon and interacting quark collide head-on along the z-axis
It is then boosted such that t the virtual photon four-momentum (0,0,0,–Q)
This boost means
Incoming quark $p_z = Q/2$
Scattered quark $p_z = -Q/2$
Proton remnant $p_z = (1-x)Q/(2x)$.
Gives a natural separation between jets from struck quark and those associated with proton remnant.
Working in the Breit frame has the effect of suppressing contributions from the L.O. subprocess, as the scattered quark has zero transverse momentum by construction

Angular correlations in excl. dijet and γp events

S. Behera: Wed 3.20 pm







- <cos(2Φ)> for exclusive dijets not well described by MC tuned in ep
  - sensitive to primordial asymmetry due to the linearly polarized gluons
- Bridging large with exceedingly small systems
  - PYTHIA8 describes v_2 in γp too ⟶ jet-like correlations still dominate