Jet quenching in varying system sizes at RHIC: experimental search for the critical scale

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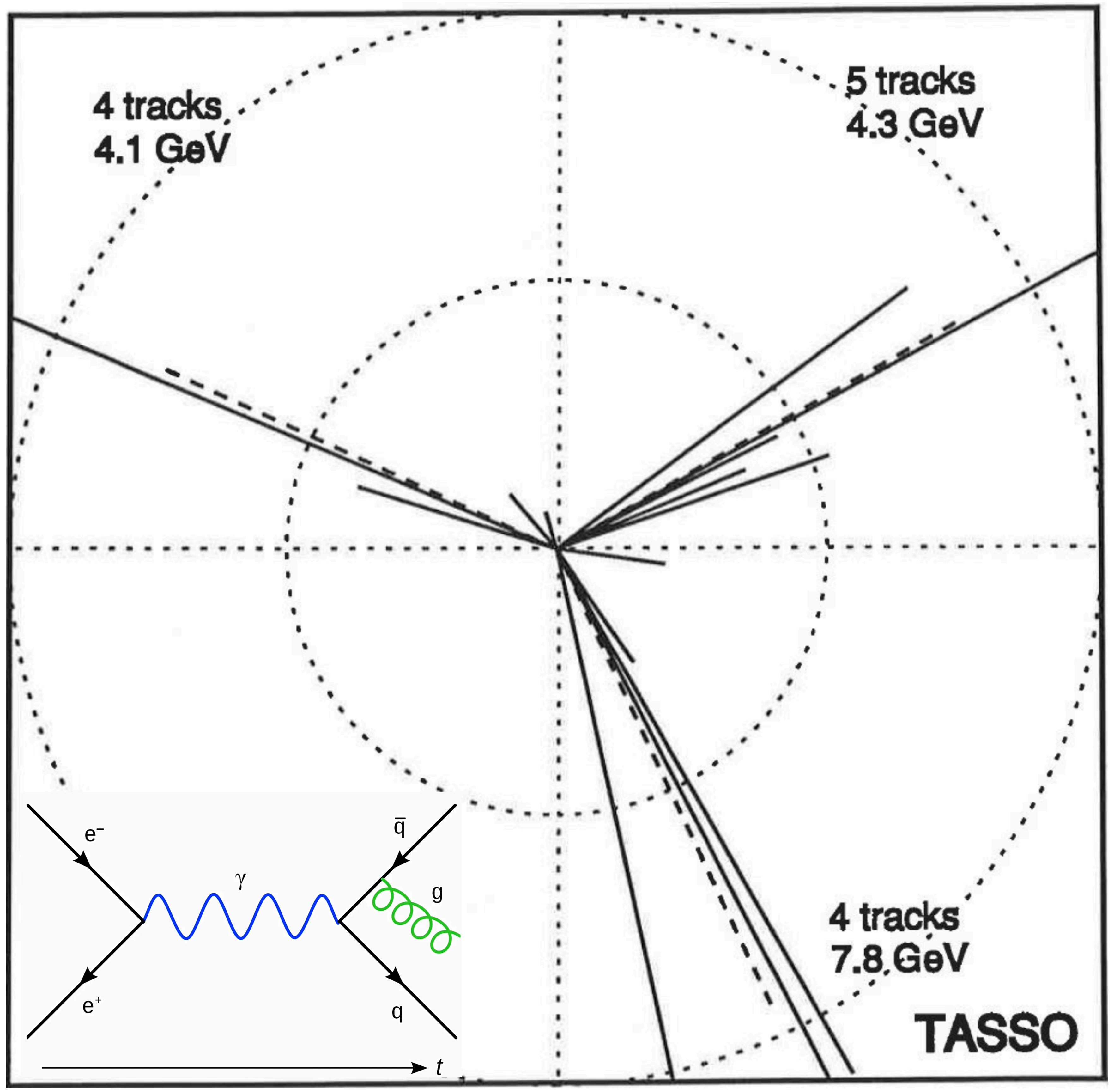
Jets in high energy physics

Sau Lan Wu, Discovery of the Gluon



- Three-jet event: discovery of the Gluon

VOLUME 39, NUMBER 23 PHYSICAL REVIEW LETTERS 5 DECEMBER 1977

Jets from Quantum Chromodynamics

George Sterman
Institute for Theoretical Physics, State University of New York at Stony Brook, Stony Brook, New York 11790

and

Steven Weinberg
Lyman Laboratory of Physics, Harvard University, Cambridge, Massachusetts 02138

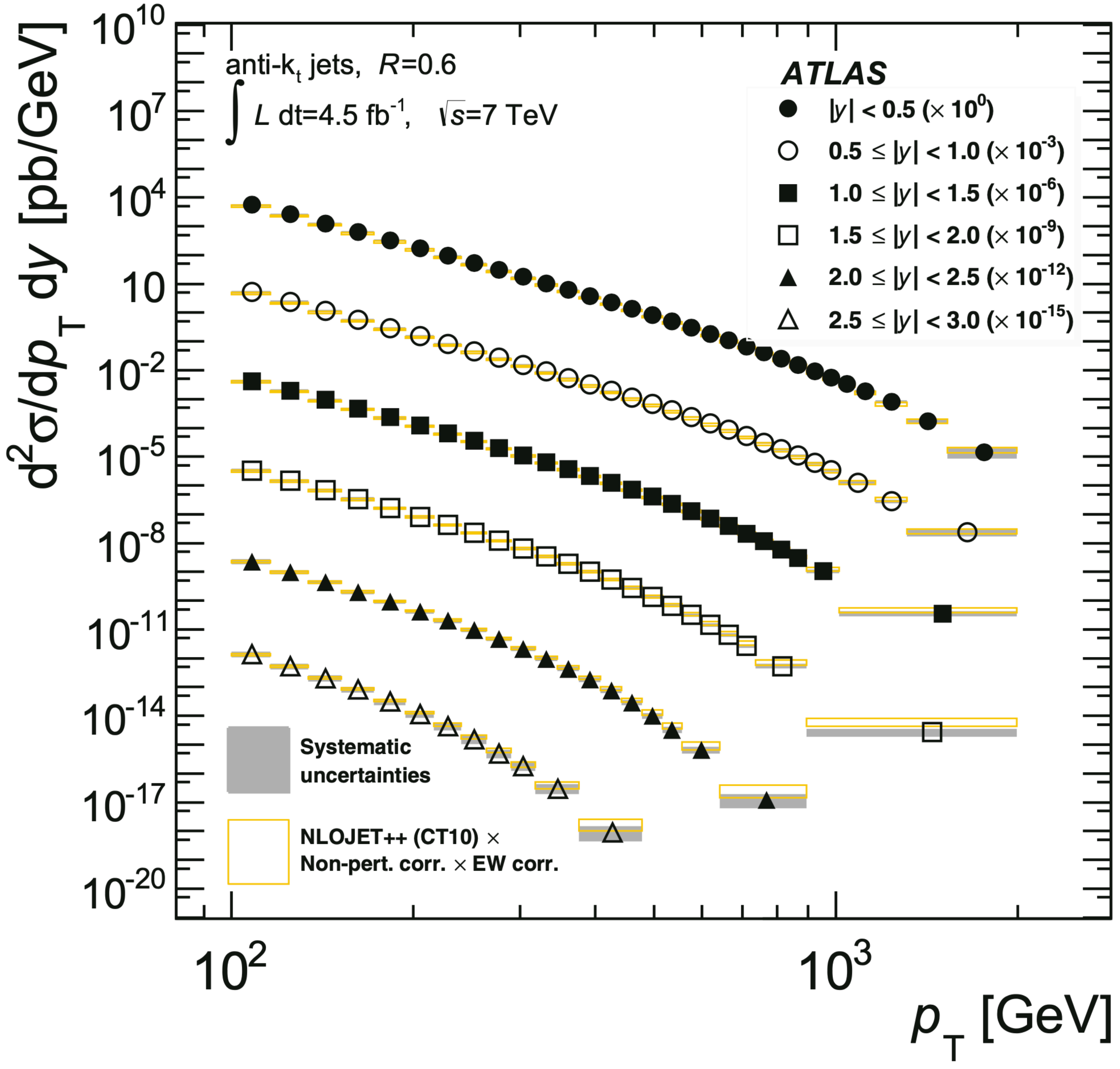
(Received 26 July 1977)

The properties of hadronic jets in e^+e^- annihilation are examined in quantum chromodynamics, without using the assumptions of the parton model. We find that two-jet events dominate the cross section at high energy, and have the experimentally observed angular distribution. Estimates are given for the jet angular radius and its energy dependence. We argue that the detailed results of perturbation theory for production of arbitrary numbers of quarks and gluons can be reinterpreted in quantum chromodynamics as predictions for the production of jets.

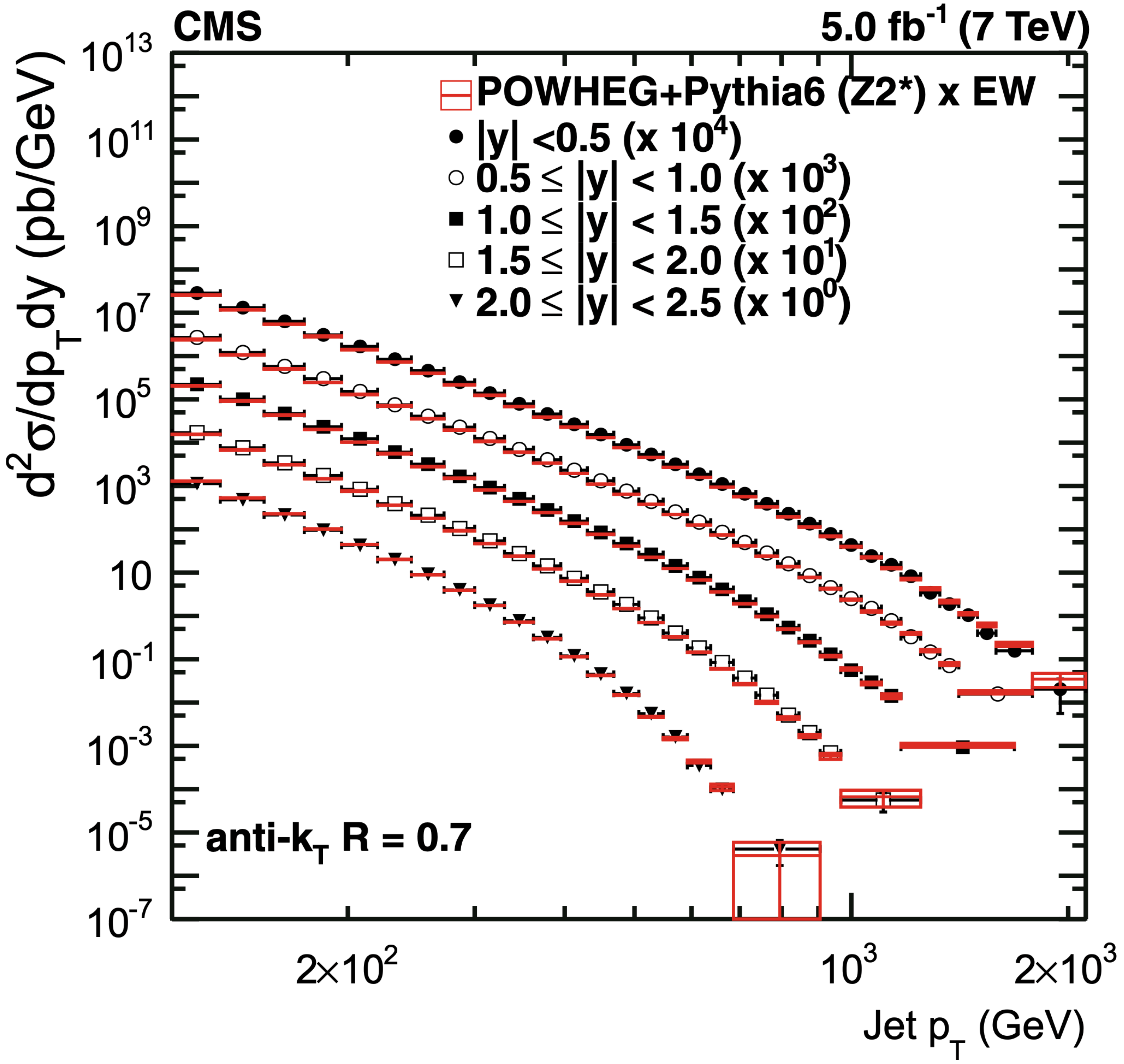
- Infrared-safe jet definitions cancel mass singularities, making pQCD predictions reliable at high energies.
- Jets: new and powerful tools to study QCD physics.

Jet spectra in p+p collisions

ATLAS, JHEP 02 (2015) 153

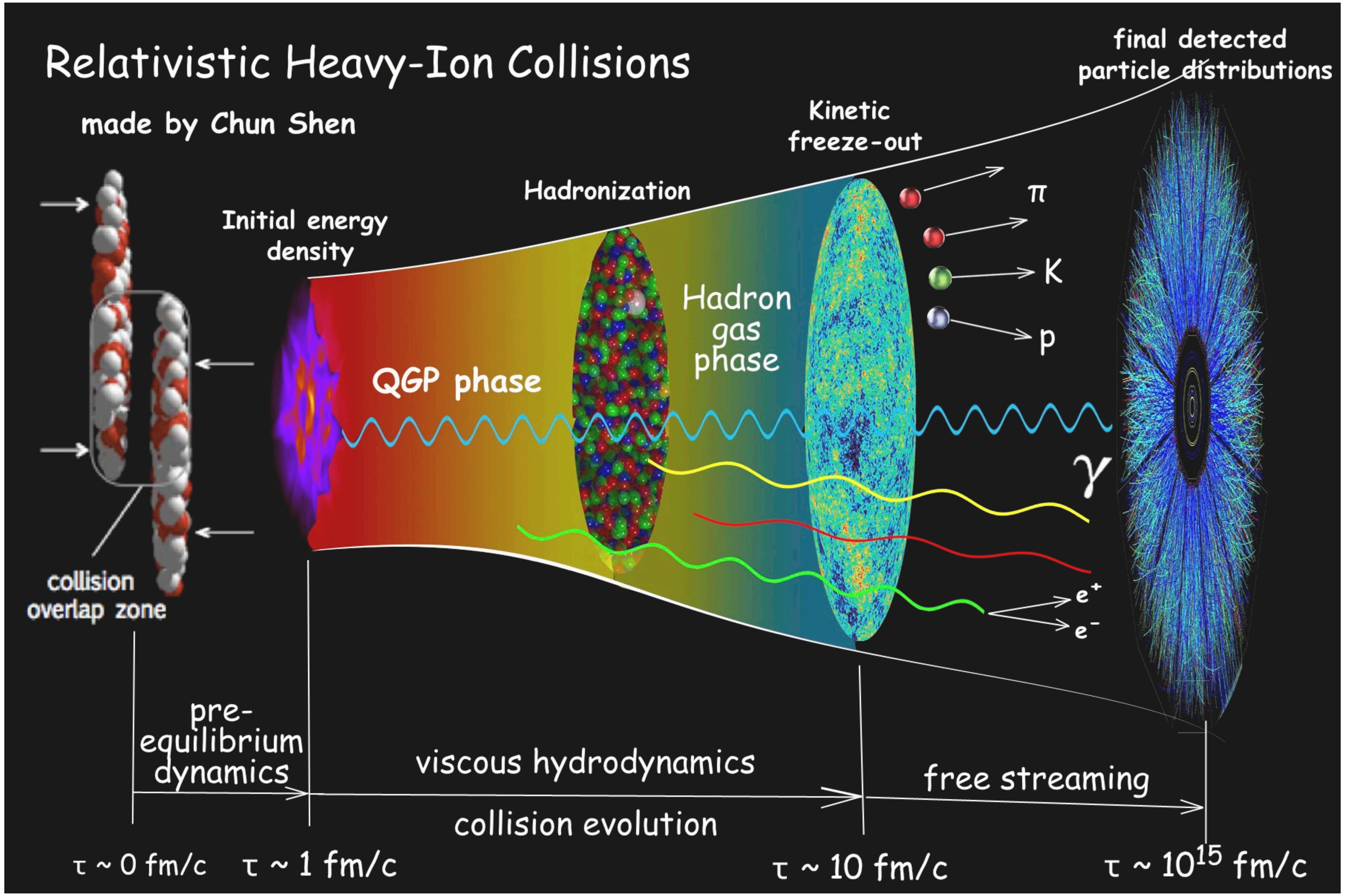


CMS, Eur. Phys. J. C (2015) 75:288



◉ **Jet production from p+p collisions are well understood, consistent with NLO calculations across many orders.**

Relativistic heavy-ion collisions: the little bang



Dynamical system

Property ⟷ **Dynamics**

EM probes: Medium response to EM interaction

Direct photon, Dilepton …

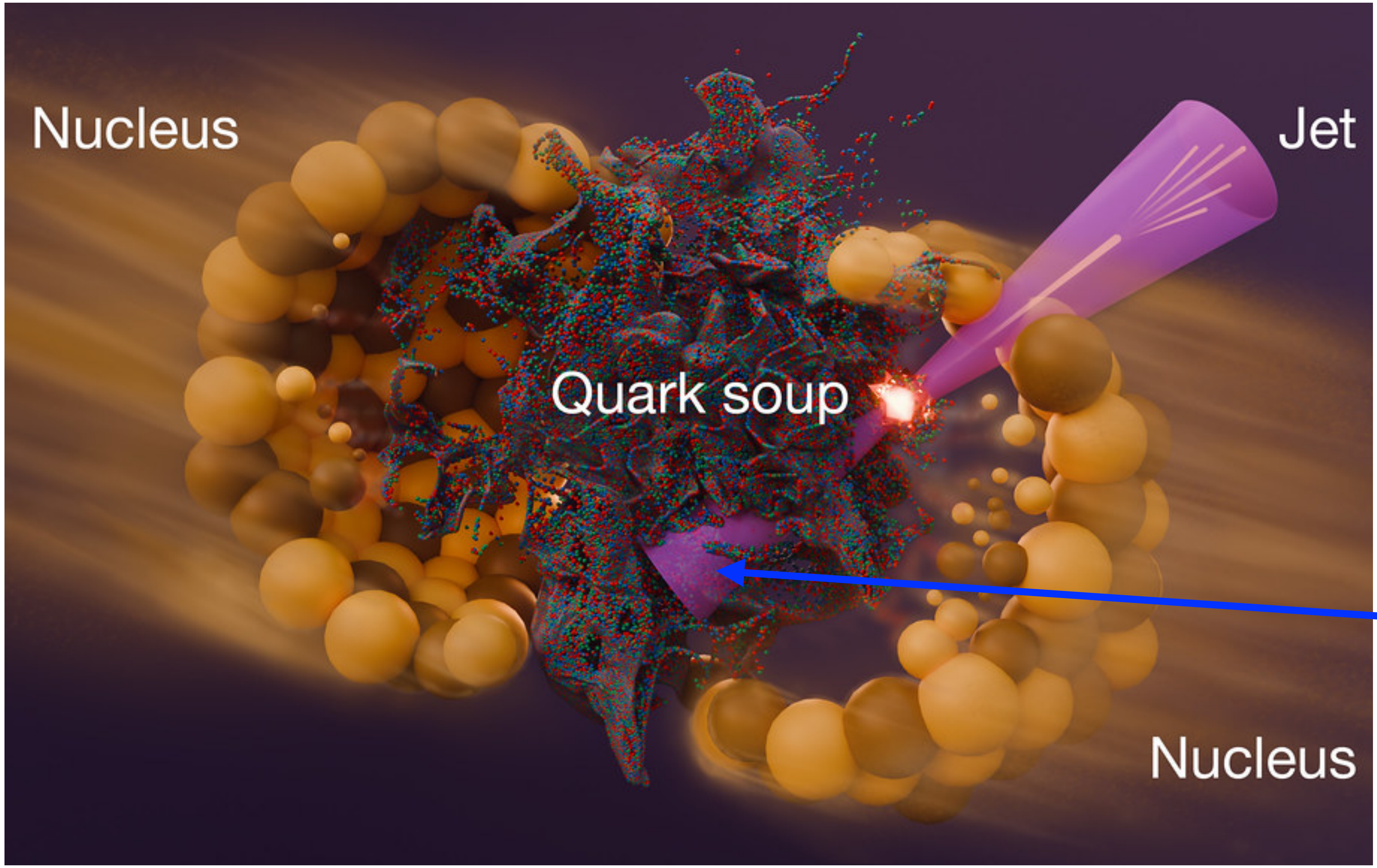
Soft probes: Bulk properties of medium

Collective flow, Particle spectra

Hard probes: Medium response to strong interaction

Jet quenching, Heavy flavor…

Jets in heavy-ion collisions



BNL news

Jet: a collimated spray of particles produced by a high momentum quark or gluon at initial stage.

- **High energetic parton cannot be measured directly.**
- **Measure final state particles with jet reconstruction.**

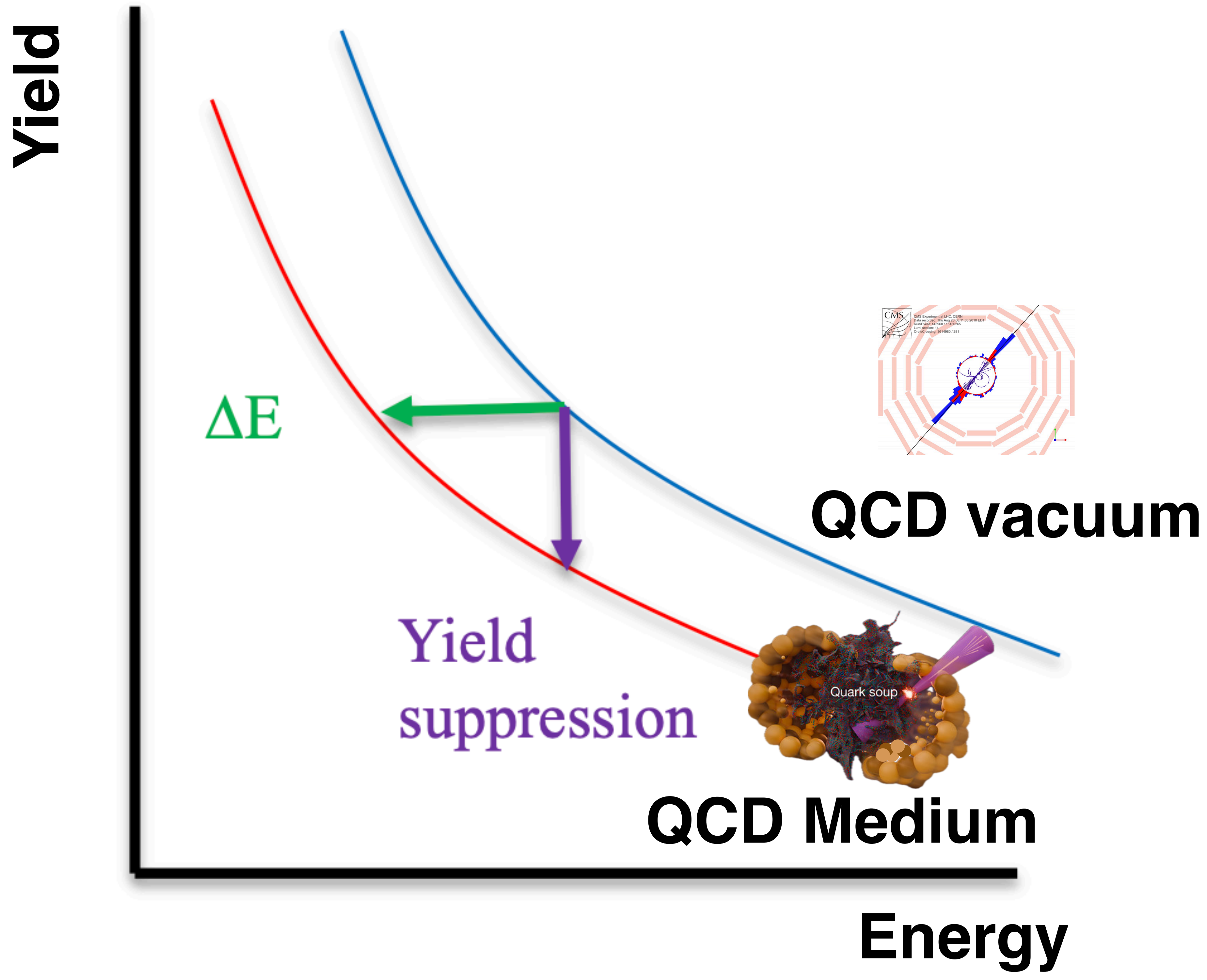
Jet quenching:

In medium parton energy loss

Key signature of QGP

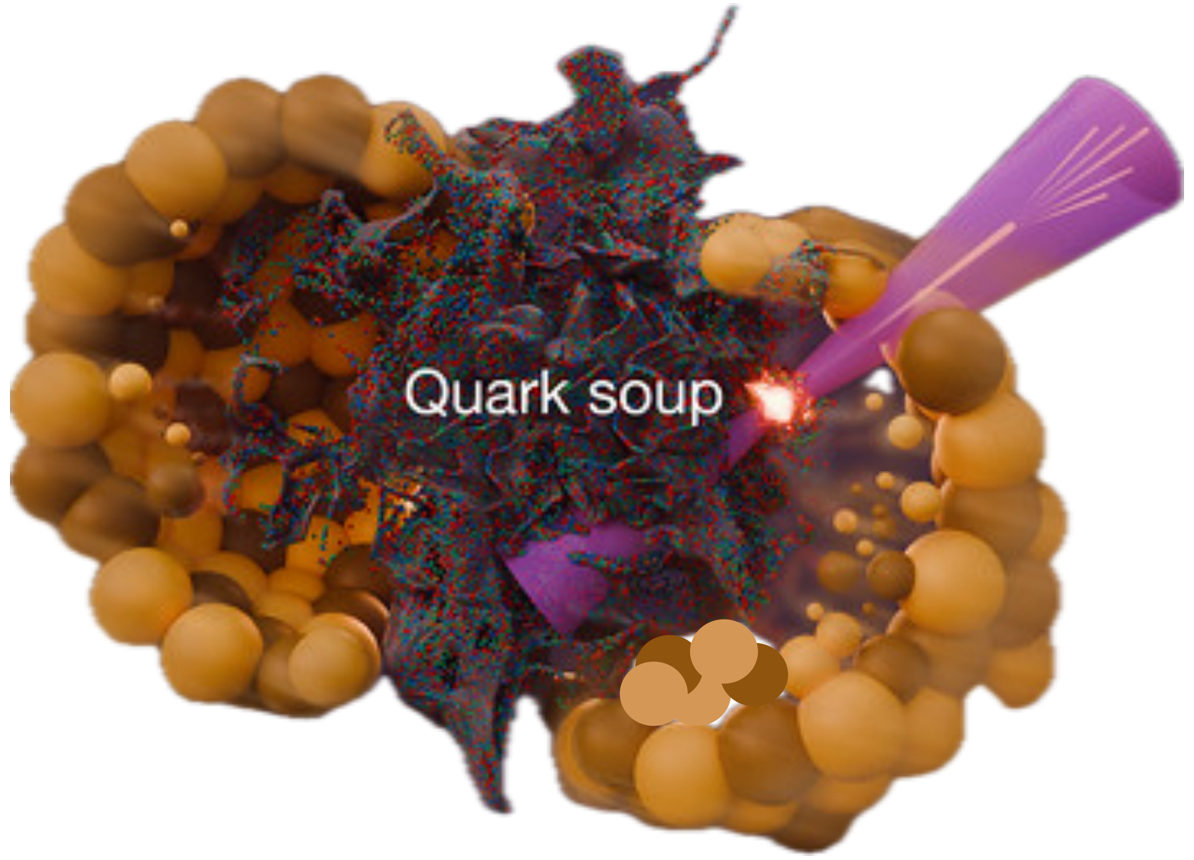
Jet quenching as a signature of QGP

Parton energy loss: leads to jet yield suppression in A+A system in comparison to p+p.

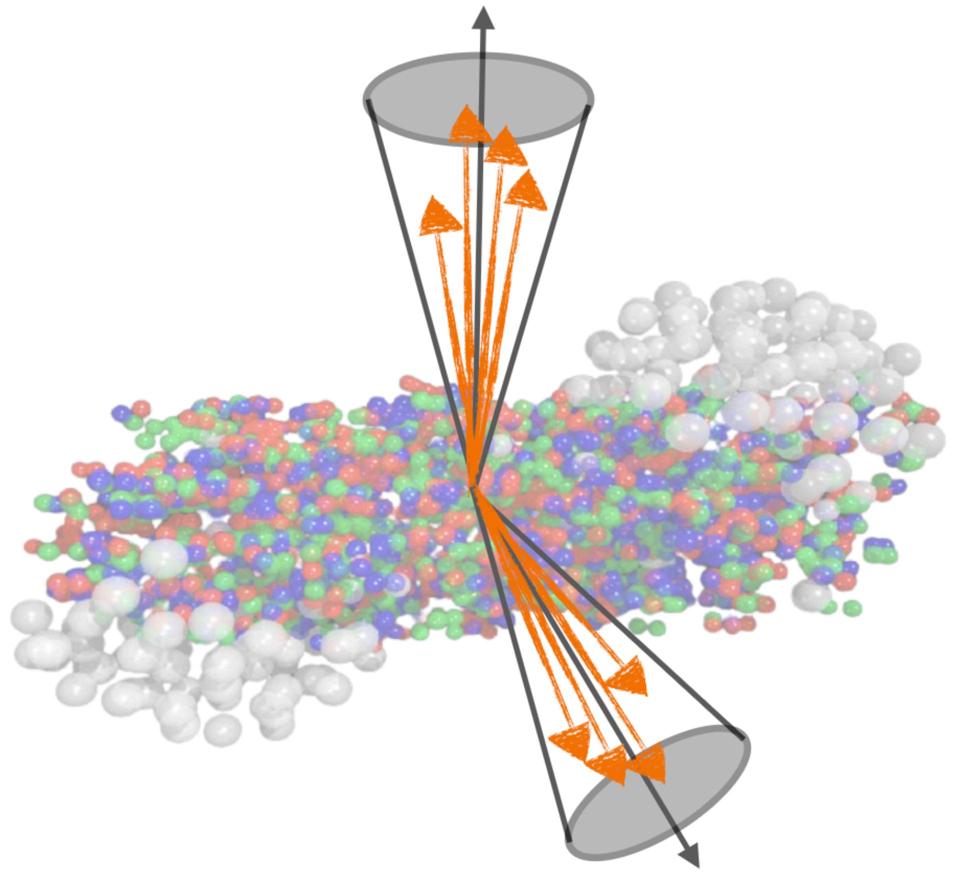


Where does the quenched energy go?

Medium response: medium-induced jet modification.



Modification of jet substructure.



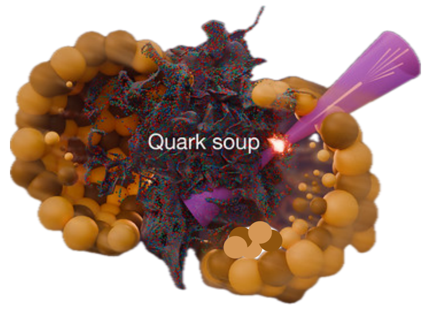
Deflection of the jet induced by multiple scatterings or single hard scatterings with QGP quasi-particles?

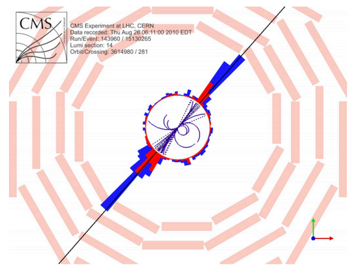
Jet quenching at RHIC

X. N. Wang and M. Gyulassy, Phys. Rev. Lett. 68 (1992) 1480-1483
X. N. Wang, Phys. Rev. C 58 (1998) 2321

Nuclear modification factor

$$R_{AA} = \frac{\sigma_{pp}^{inel}}{N_{coll}} \frac{d^2N_{AA}/dp_T d\eta}{d^2\sigma_{pp}/dp_T d\eta} \sim$$

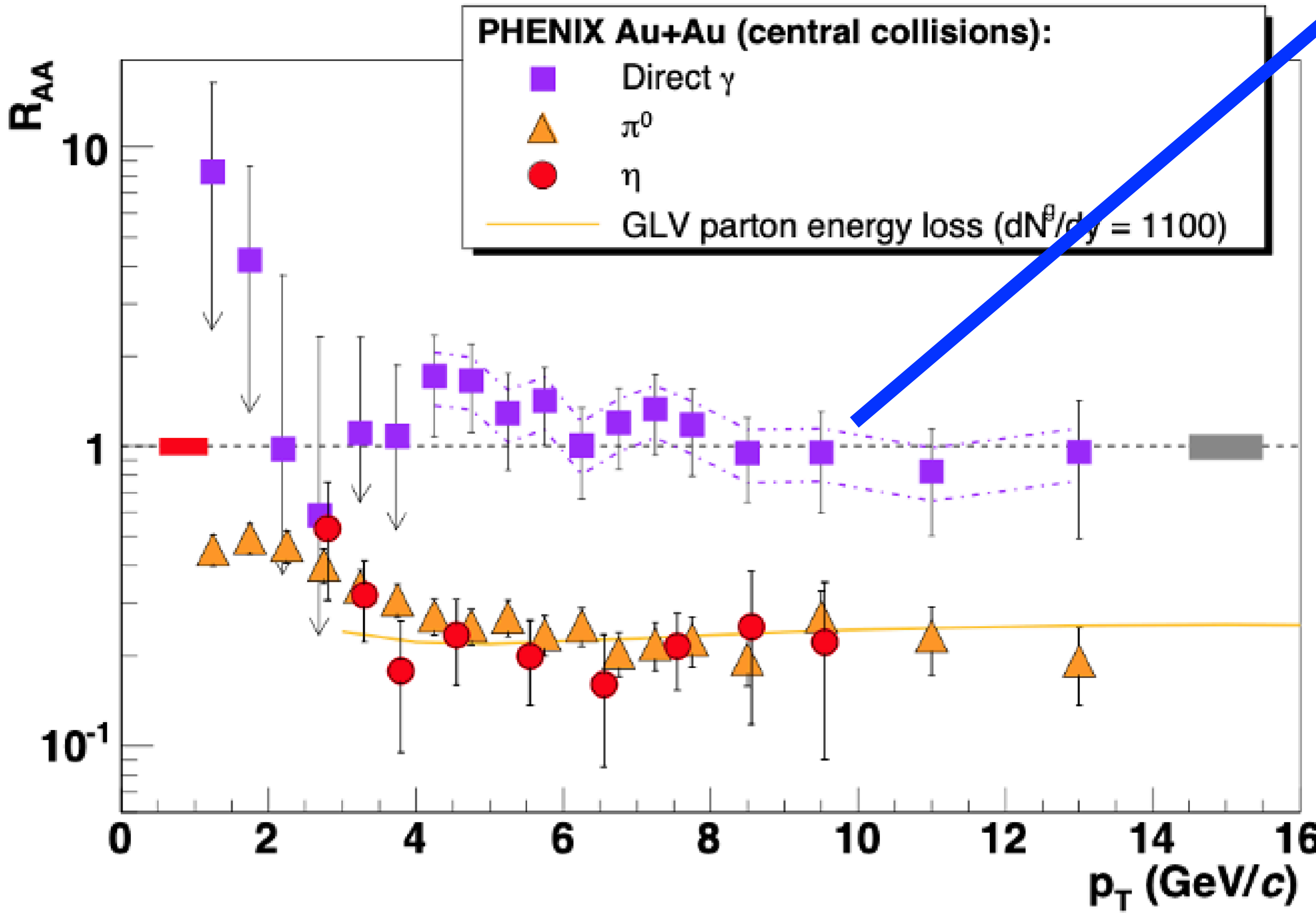




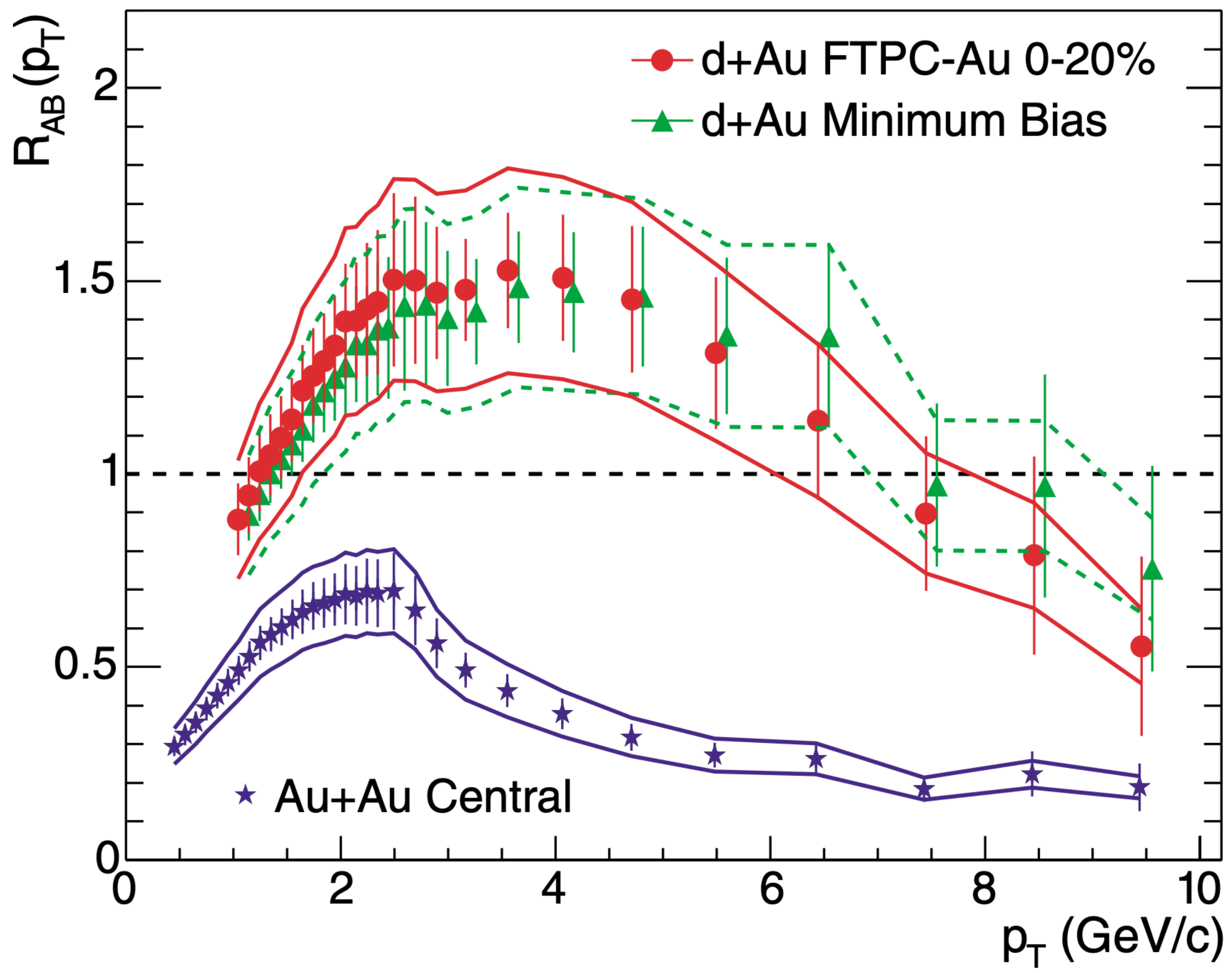
$$\begin{cases} R_{AA} > 1 \quad \text{(enhancement)} \\ R_{AA} = 1 \quad \text{(no medium effect)} \\ R_{AA} < 1 \quad \text{(suppression)} \end{cases}$$

Colorless probes validate the Ncoll scaling.

PHENIX, Phys. Rev. Lett. 109 (2012) 152302



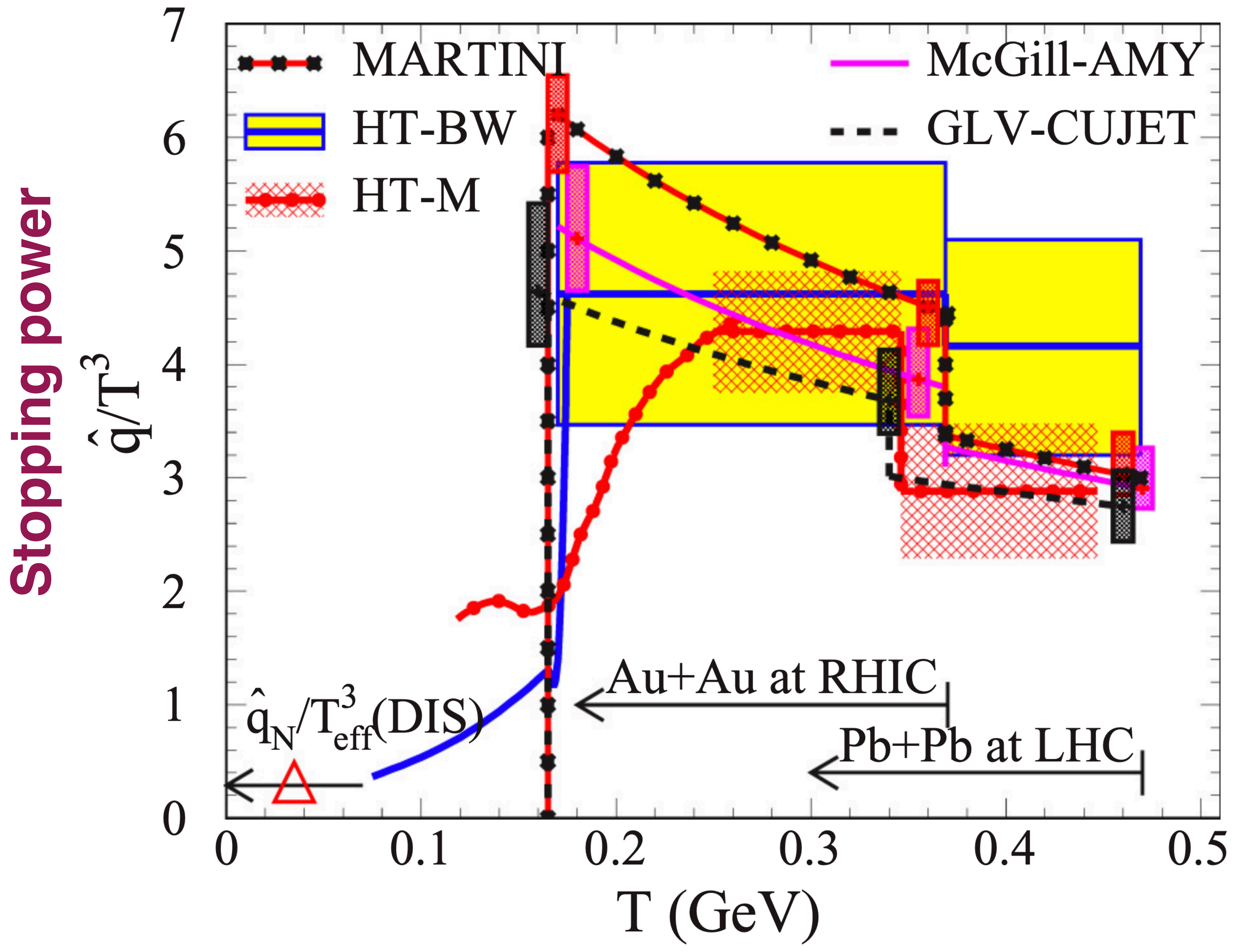
STAR Collaboration, Phys. Rev. Lett. 91 (2003) 072304



Clear suppression at high p_T in central Au+Au 200 GeV.

Extraction of the medium properties

JET Collaboration, Phys. Rev. C 90 (2014) 1, 014909



Extract **jet transport coefficient** **from parton energy loss via theory/data comparison**

$$\hat{q} = \begin{cases} 1.2 \pm 0.3 \\ 1.9 \pm 0.7 \end{cases} GeV^2/fm \ at \ \begin{matrix} T = 370\ MeV, \ RHIC \\ T = 470\ MeV, \ LHC \end{matrix}$$

Constrain QGP stopping power.

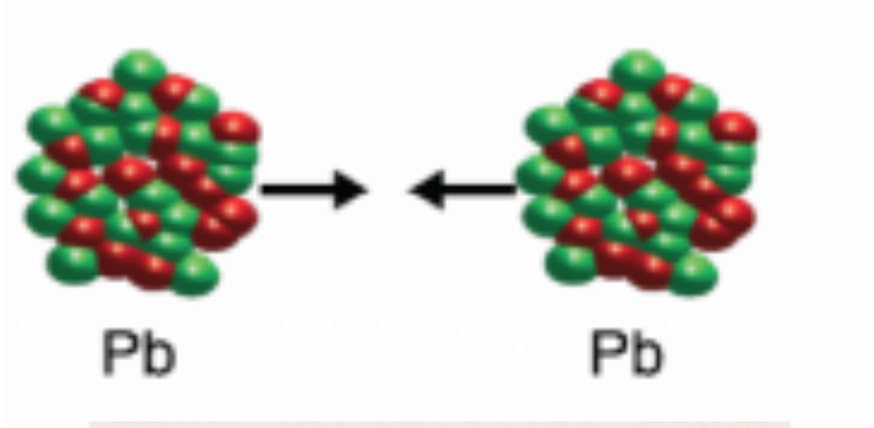
$\hat{q}$ in hot QCD is approximately two orders of magnitude larger than in cold QCD.

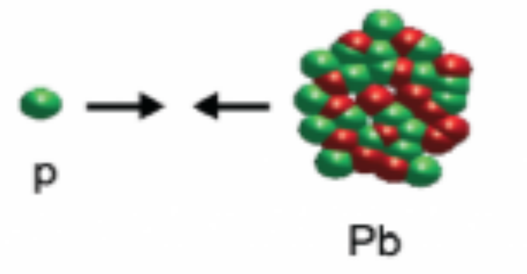
$$\hat{q}_{\text{Hot}} \sim 100\, \hat{q}_{\text{Cold}}$$

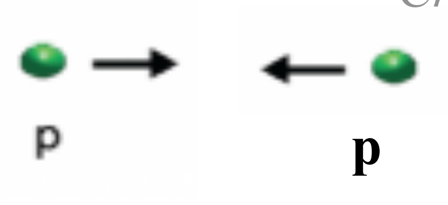
Latest results see: JETSCAPE, Phys. Rev. C 111, 054913 (2025)

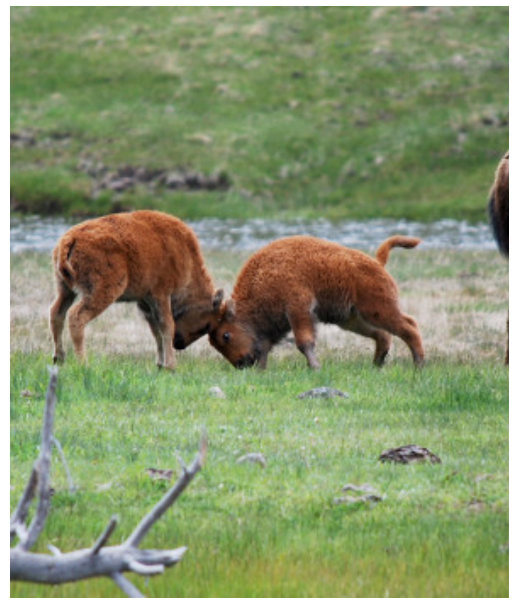
“Ridge” from large to small systems

Credit: J. Schukraft, NBI 2017

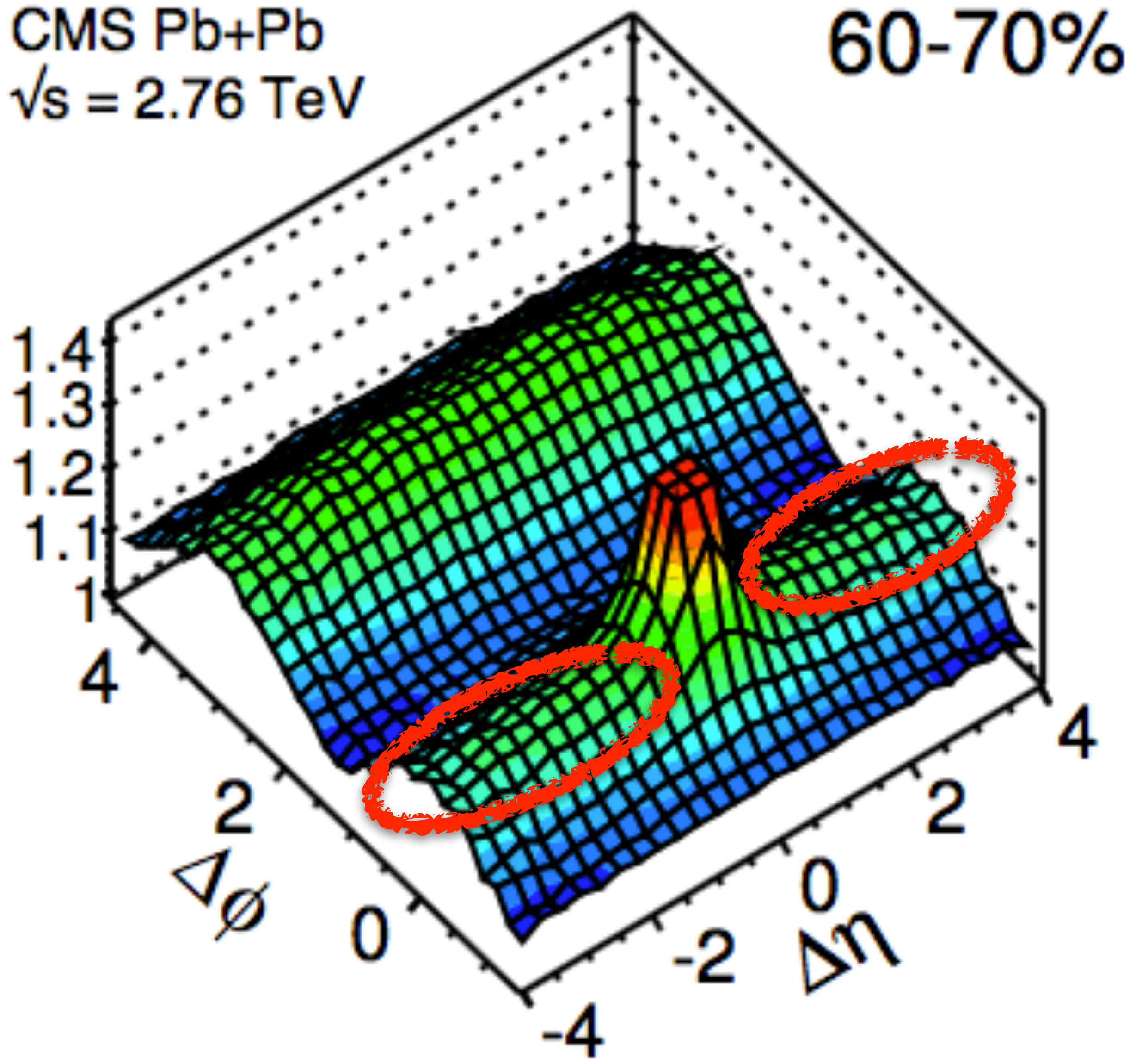




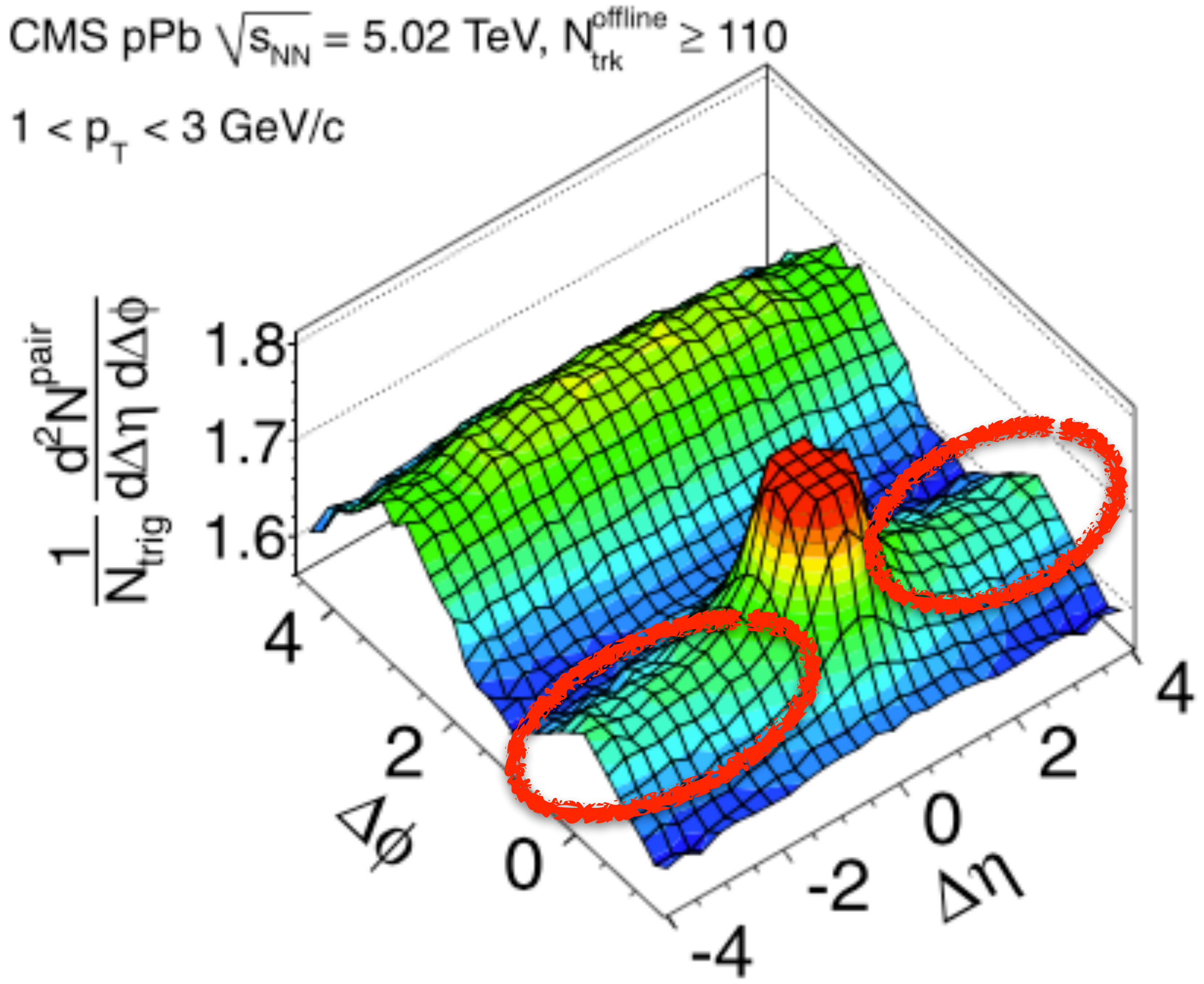




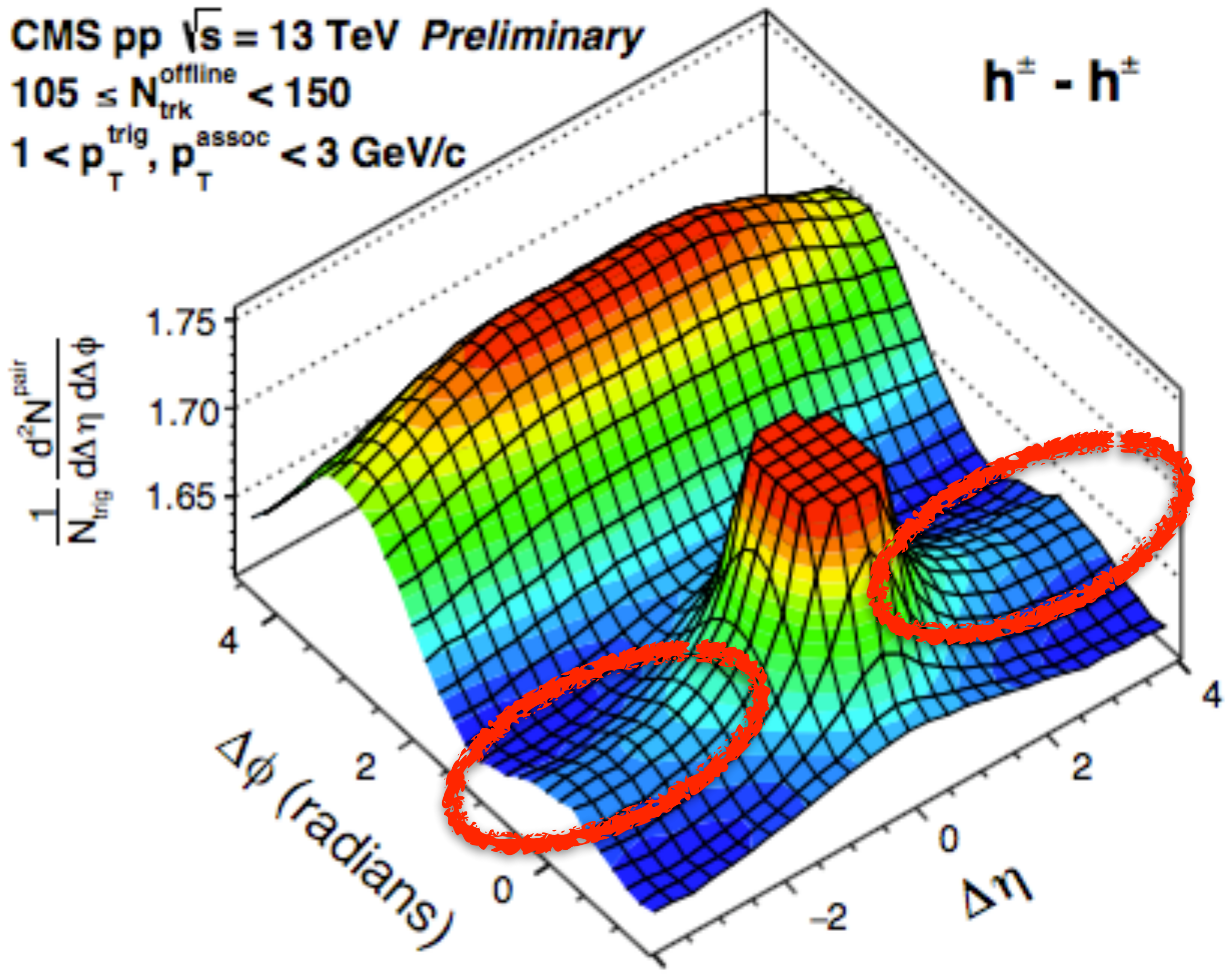
CMS, PLB 718, 795 (2013)



CMS, PRL116, 172302 (2016)

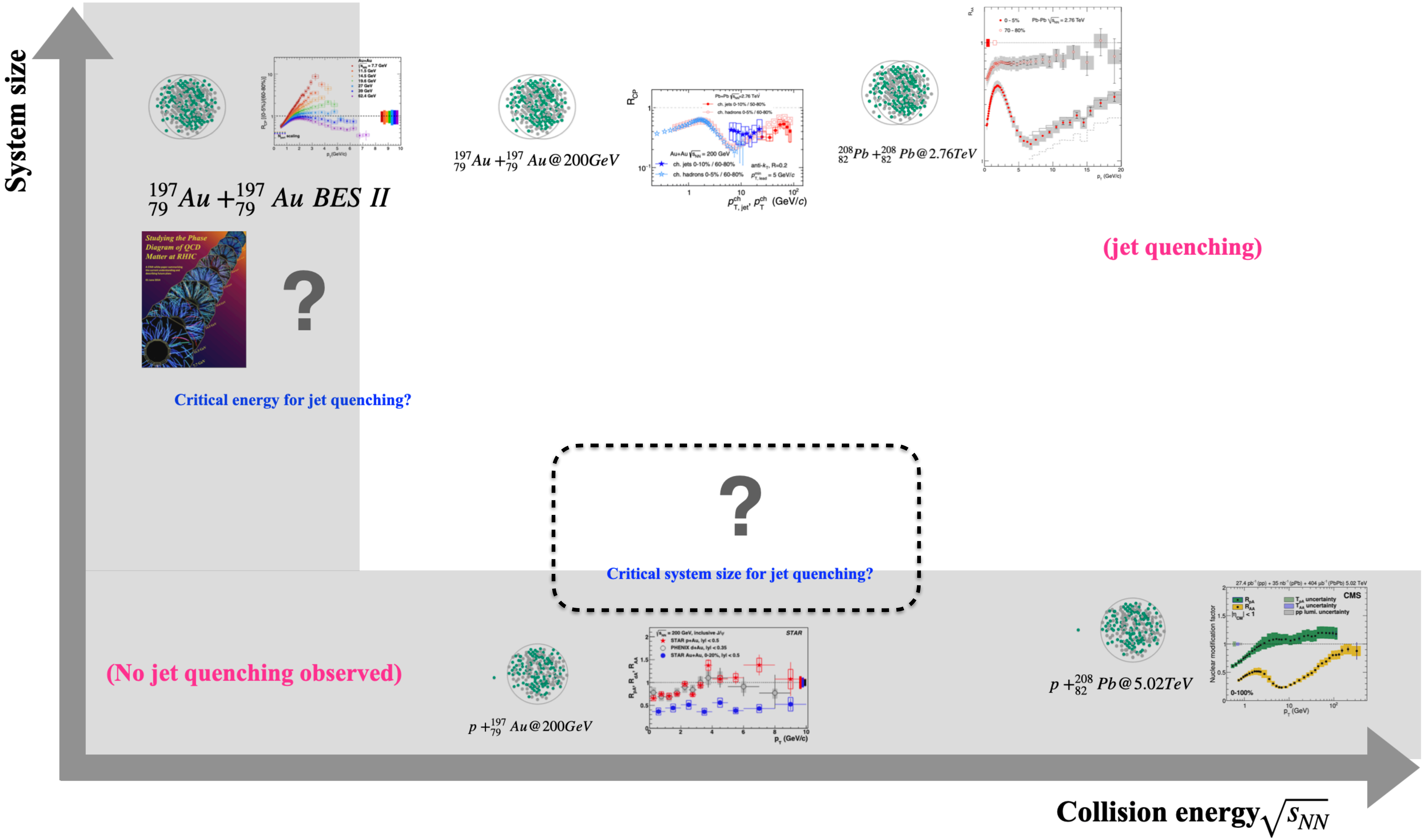


CMS. EPJC 72, 2012 (2012)



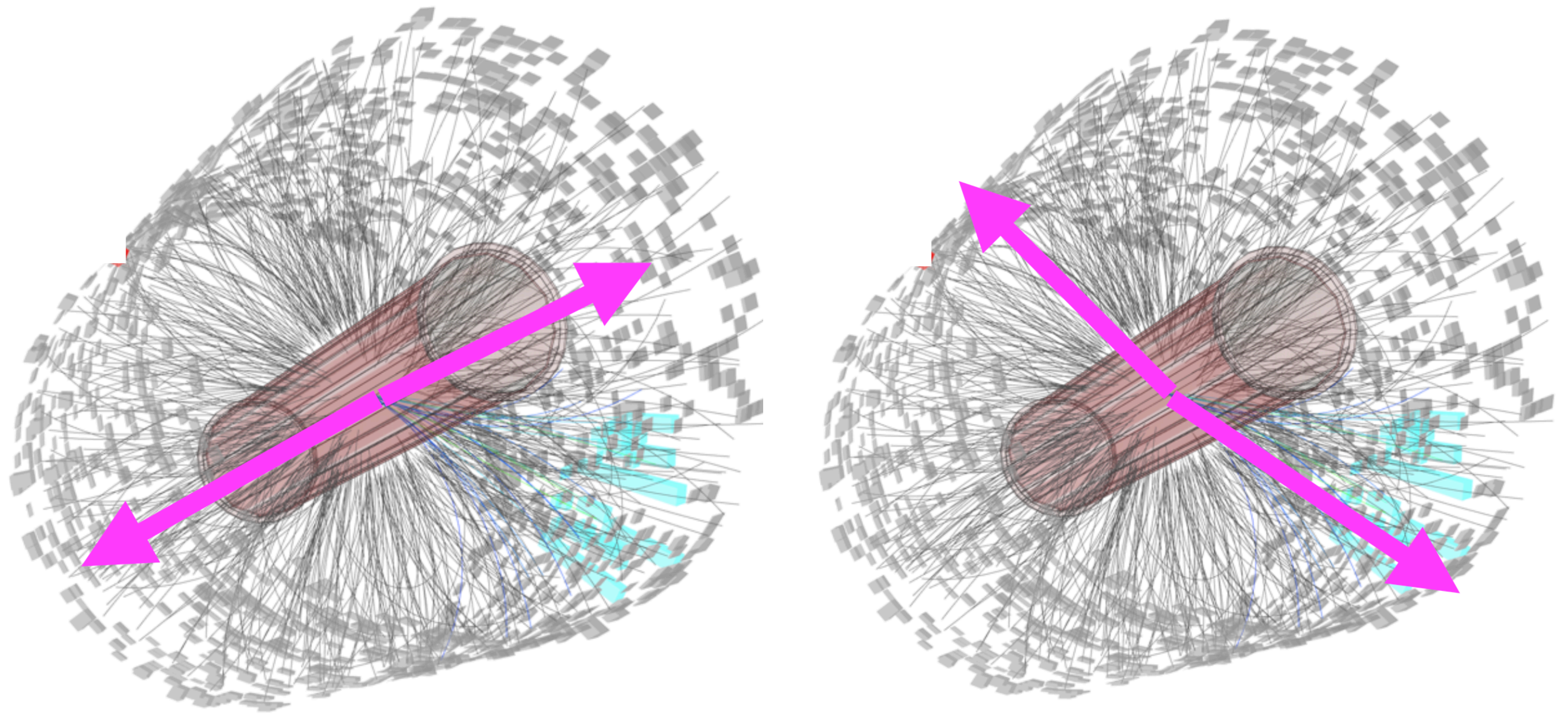
Do we also observed jet quenching in small systems?

Current status of jet quenching studies



Challenges in jet quenching studies in small systems (1)

EA and Q^2 anti-correlation

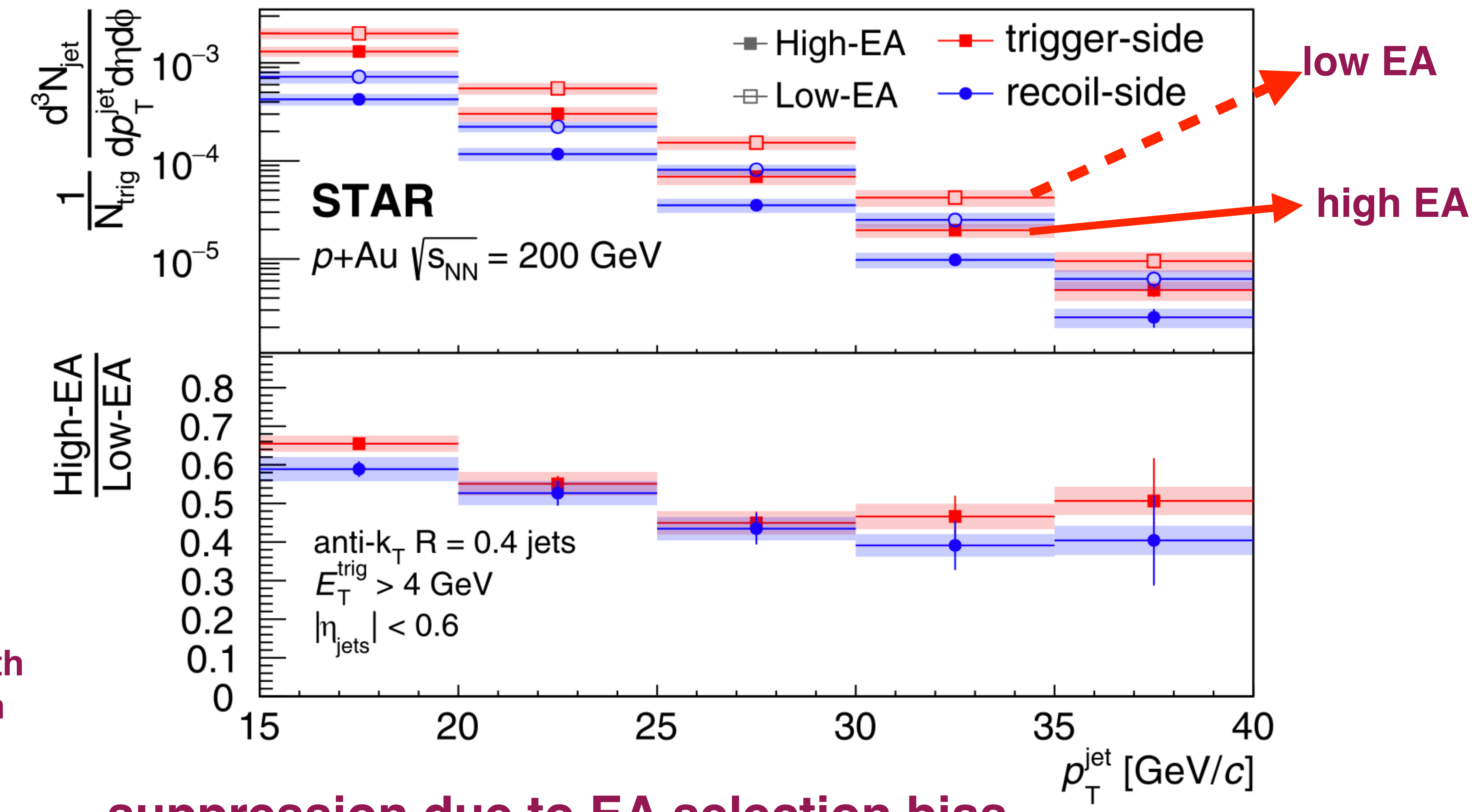


Assume two event with same tracks, one has a forward dijet and one has a mid-rapidity dijet.

Forward dijet event is more likely to tag with high EA events, and cannot reconstruct jet in mid-rapidity.

Mid-rapidity dijet event is more likely to tag with low EA events, and can reconstruct jet in mid-rapidity.

STAR, Phys. Rev. C 110, 044908 (2024)



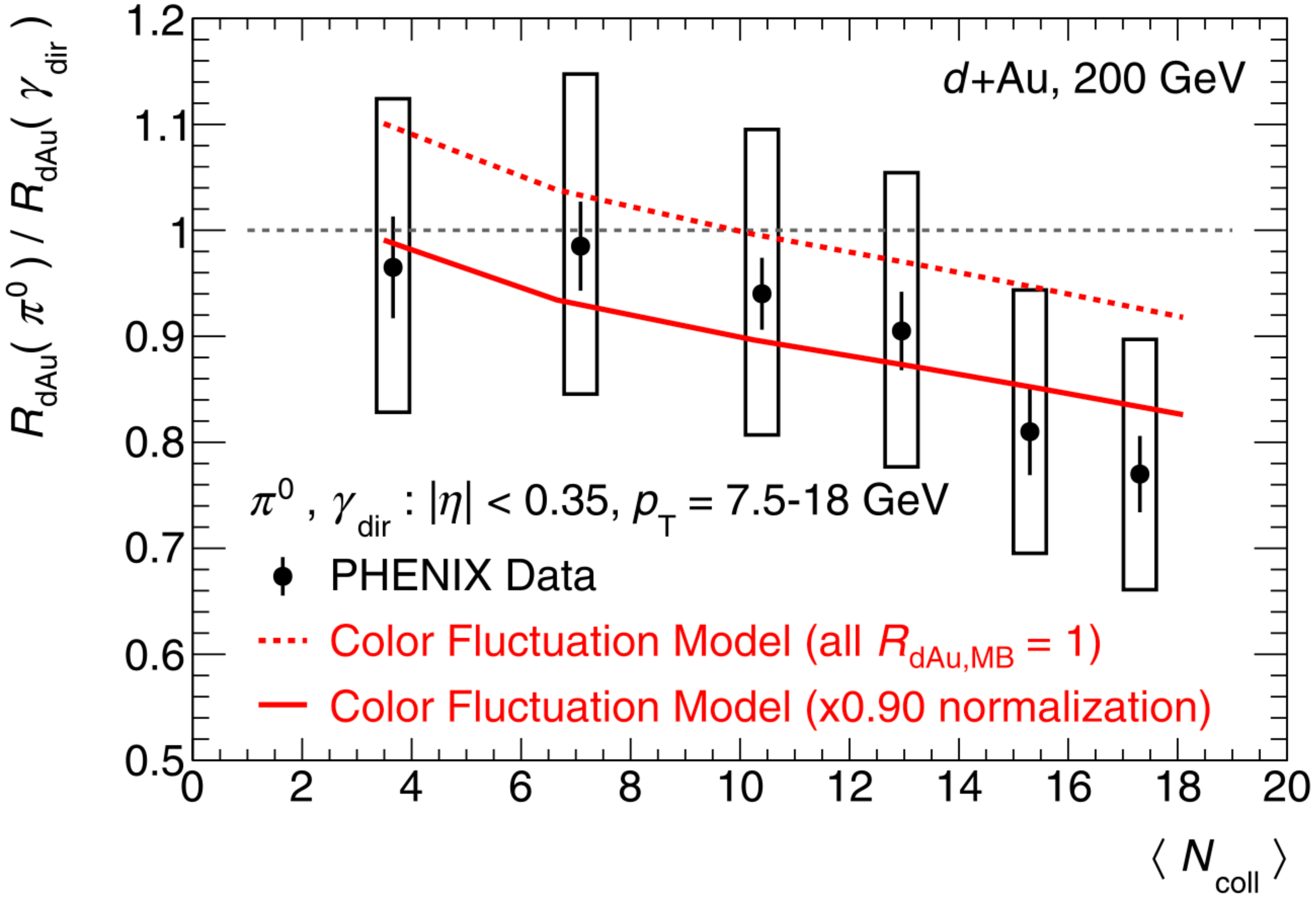
suppression due to EA selection bias

- Hard scattering yields are overestimated at high EA and underestimated at low EA.
- EA selection bias?

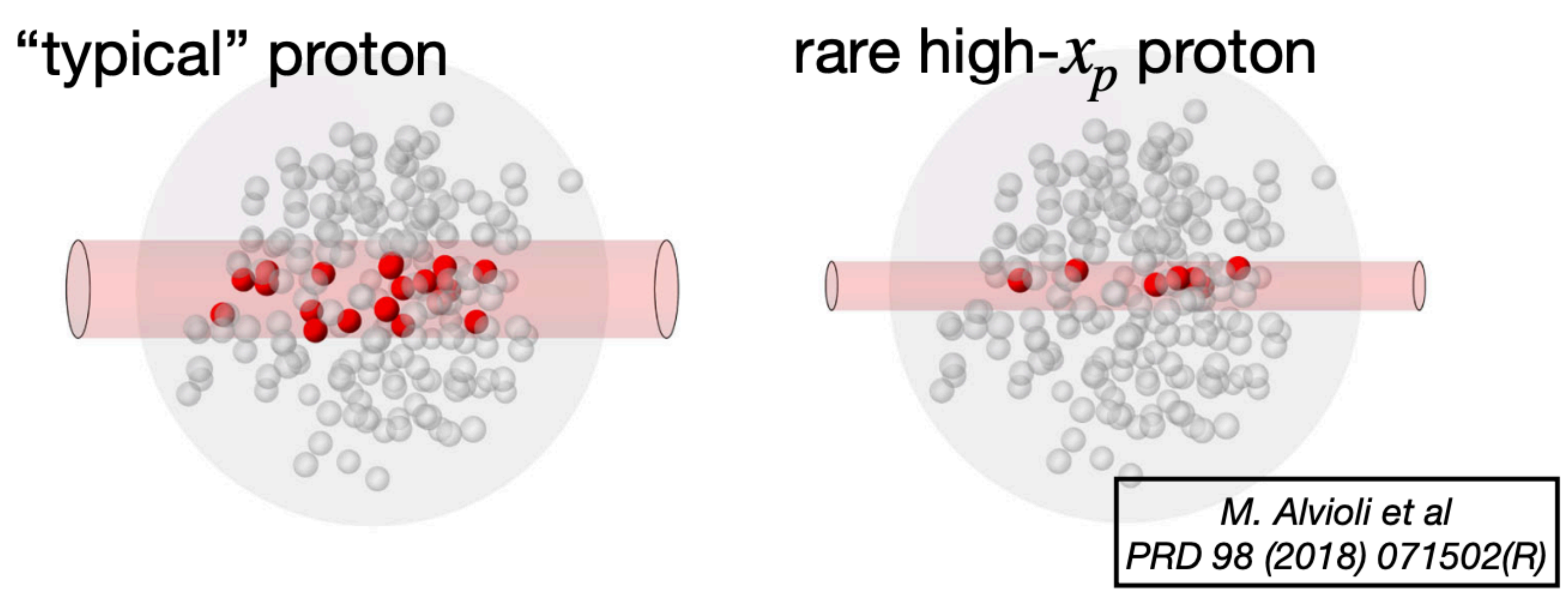
Challenges in jet quenching studies in small systems (2)

PHENIX, Phys. Rev. Lett. 134, 022302 (2025)

D. Perepelitsa, Phys. Rev. C 110, L011901 (2024)



PHENIX measures the double ratio $R_{dAu}(\pi^0)/R_{dAu}(\gamma_{dir})$ in small systems



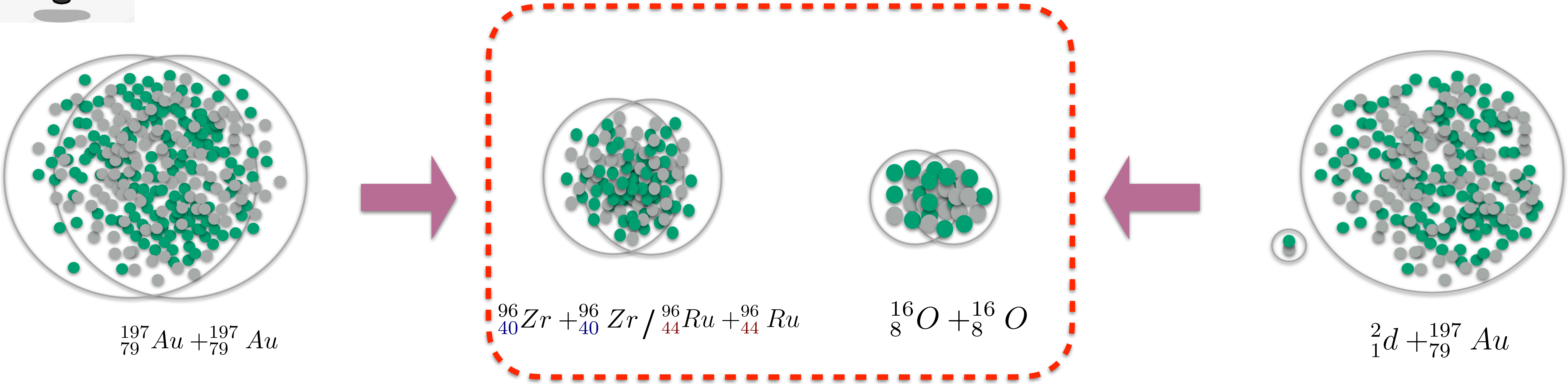
- One compelling explanation: **proton color fluctuations**

◉ **High Bjorken-x proton configurations "shrink", weakening interactions and reducing hard scattering yields.**

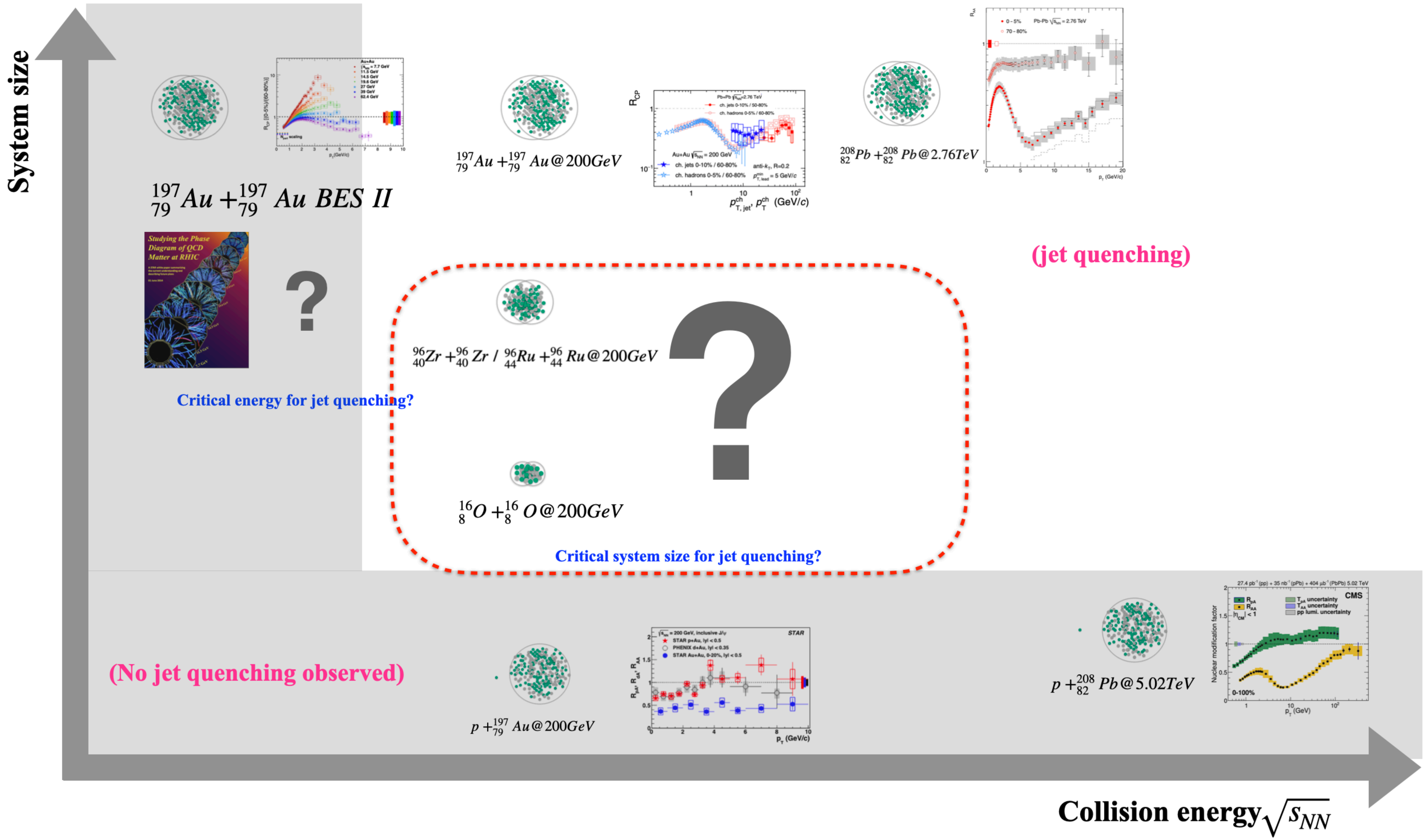
◉ **Color fluctuation (initial state) vs. jet quenching (final state)?**

Search for jet quenching in intermediate-sized collision systems

A viable solution: intermediate-size collision systems

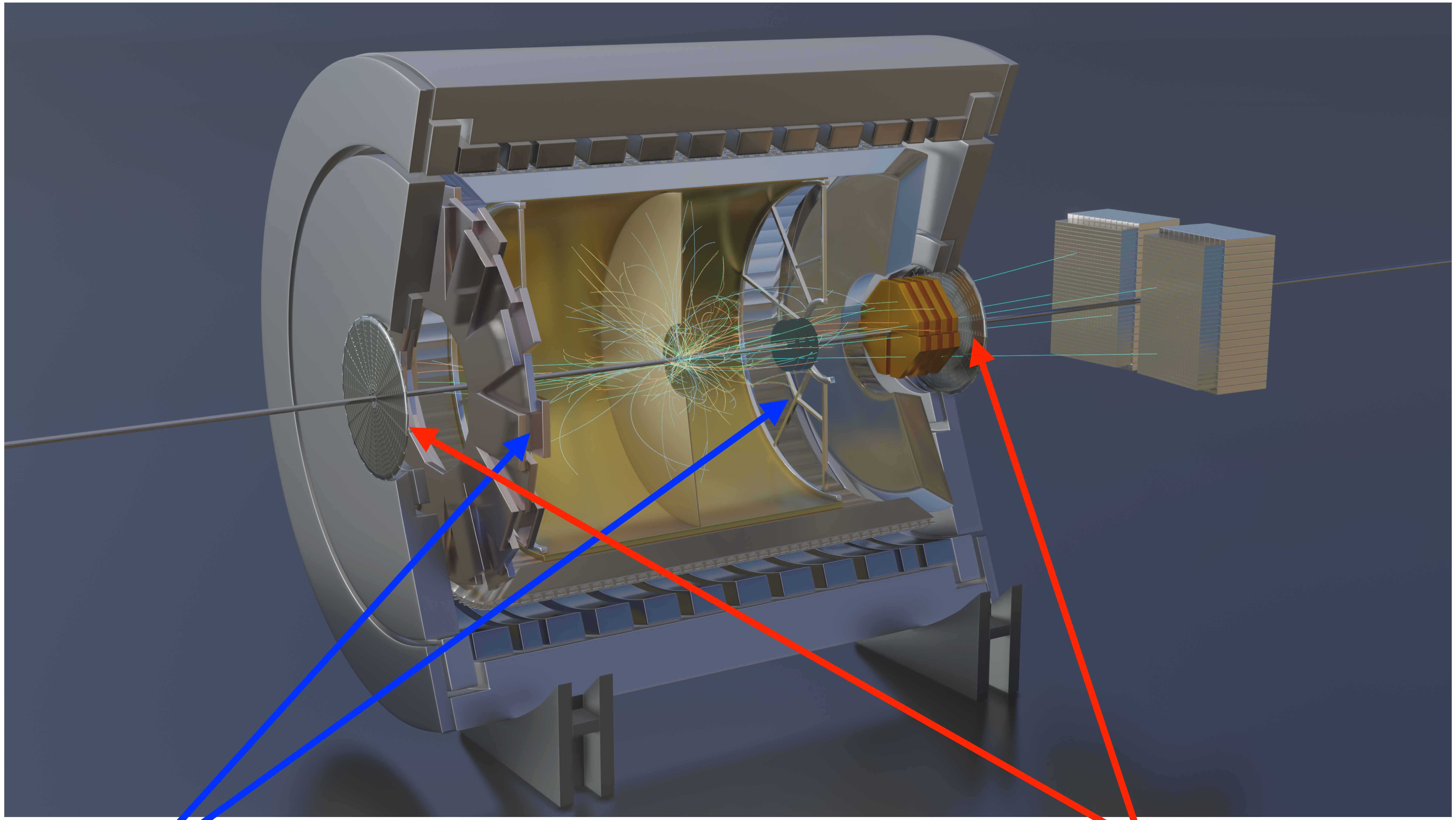


Search for jet quenching in intermediate-sized collision systems



Solenoidal Tracker at RHIC

Credit: Ting Lin (SDU)



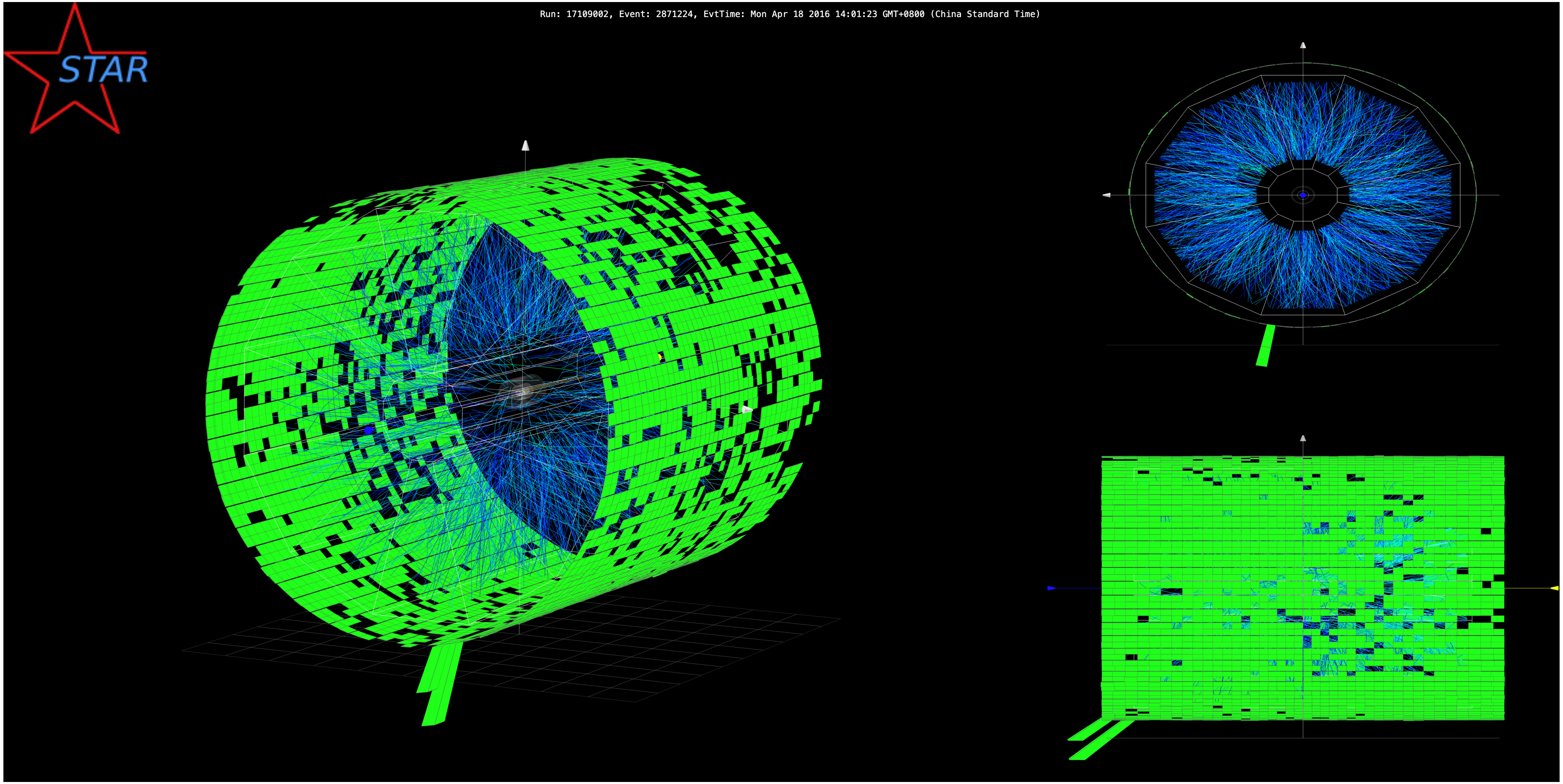
Time Projection Chamber $|\eta| < 1(1.5)$

charged hadron

Event Plane Detector $2.1 < |\eta| < 5.1$

Event plane & Event centrality

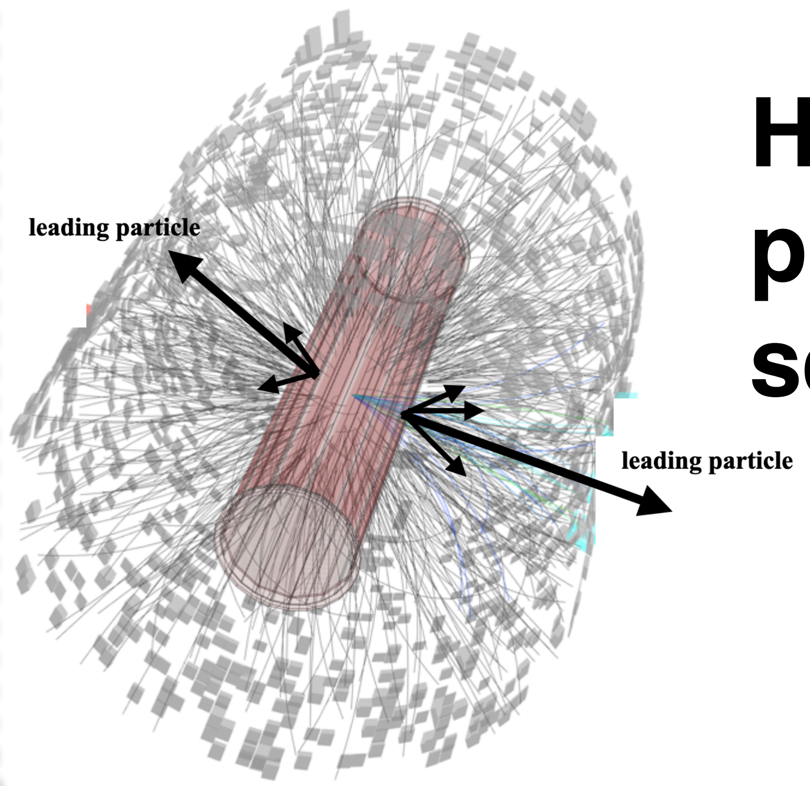
An example of jet event in Au+Au 200GeV



Jet quenching observables

High p_T hadron

Inclusive hadron R_{AA}, R_{CP}:



High pT charged particles as proxy of jet, leading order of jet, sensitive to parton energy loss.

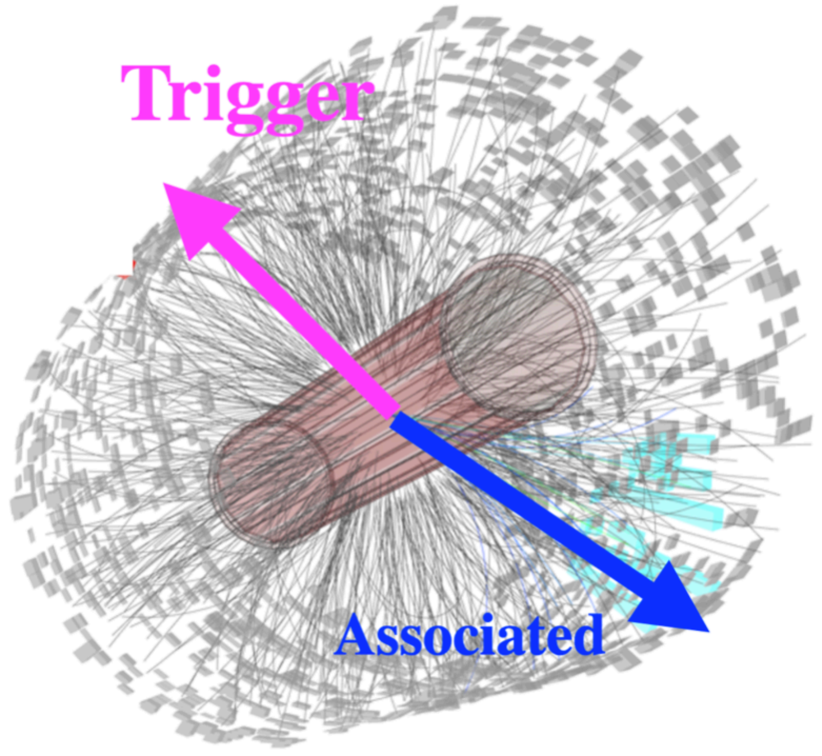
nuclear modification factor

$$R_{AA} = \frac{1}{\langle N_{coll} \rangle} \frac{(1/N_{evt}^{AA}) d^2N^{AA}/d\eta dp_T}{(1/N_{evt}^{pp}) d^2N^{pp}/d\eta dp_T}$$

Gold standard of jet quenching

$$R_{CP} = \frac{1/\langle N_{coll} \rangle^{cent}}{1/\langle N_{coll} \rangle^{prei}} \frac{(1/N_{cent}^{AA}) d^2N_{cent}^{AA}/d\eta dp_T}{(1/N_{peri}^{AA}) d^2N^{peri}/d\eta dp_T}$$

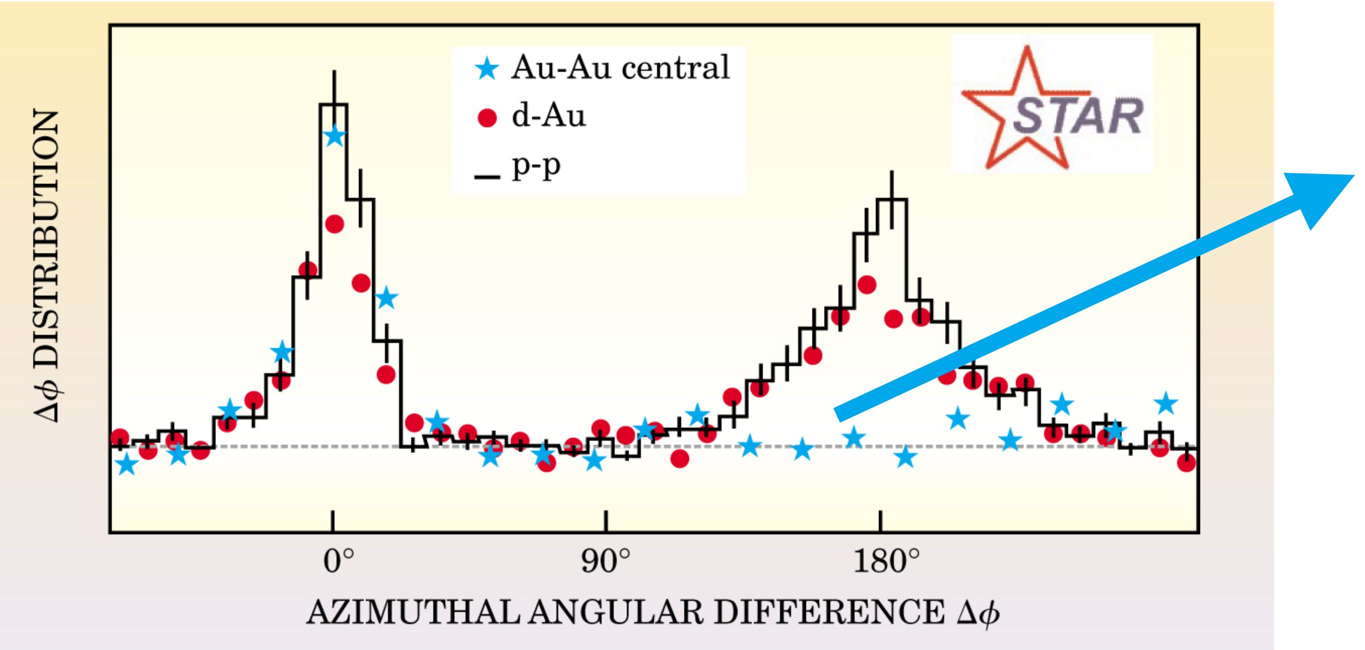
Di-hadron correlation I_{CP}:



Not only high-p_T hadrons yield but also back-to-back correlations are suppressed.

Ratio of associated yield per trigger, probes path-length dependence.

STAR, Phys. Rev. Lett. 91, 072304 (2003)



Disappearance of the away-side peak: A symbolic signature of jet quenching.

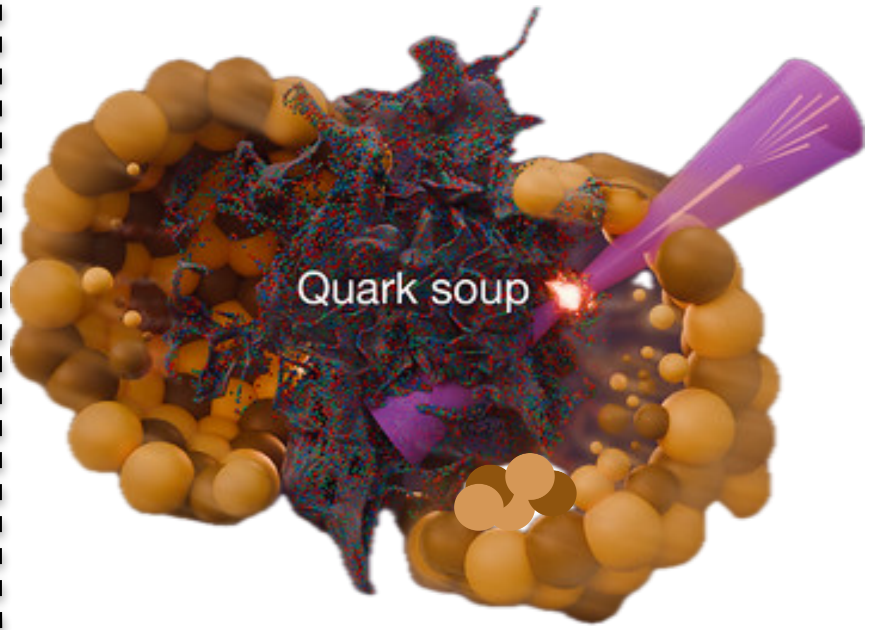
$$I_{CP} = \frac{Y^{central}}{Y^{peripheral}}$$

Yield of associated hadrons quantify jet quenching.

Jet quenching observables

Inclusive/semi-inclusive jets

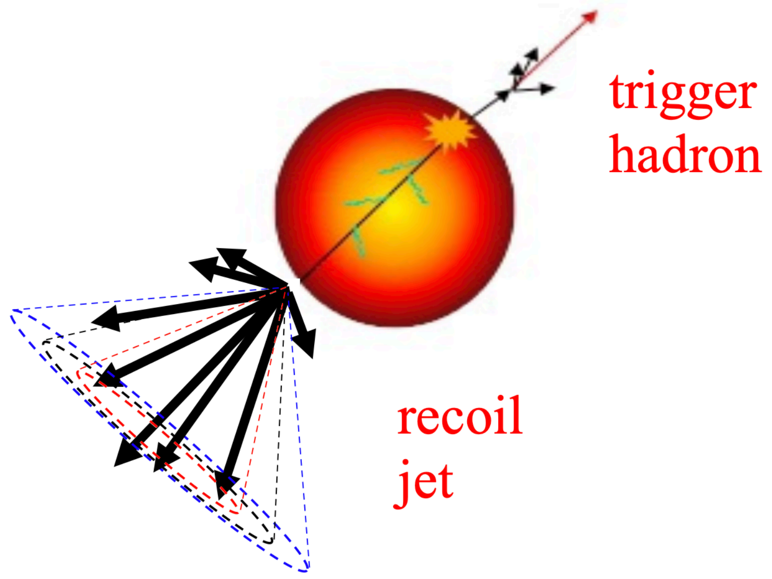
Inclusive charged jet R_{CP}:



Access to kinematics of partons scattered in initial stages of the collision.

$$R_{CP} = \frac{1/\langle N_{coll}\rangle^{cent}}{1/\langle N_{coll}\rangle^{prei}} \frac{(1/N^{AA}_{cent})d^2N^{AA}_{cent}/d\eta dp_T}{(1/N^{AA}_{peri})d^2N^{peri}/d\eta dp_T}$$

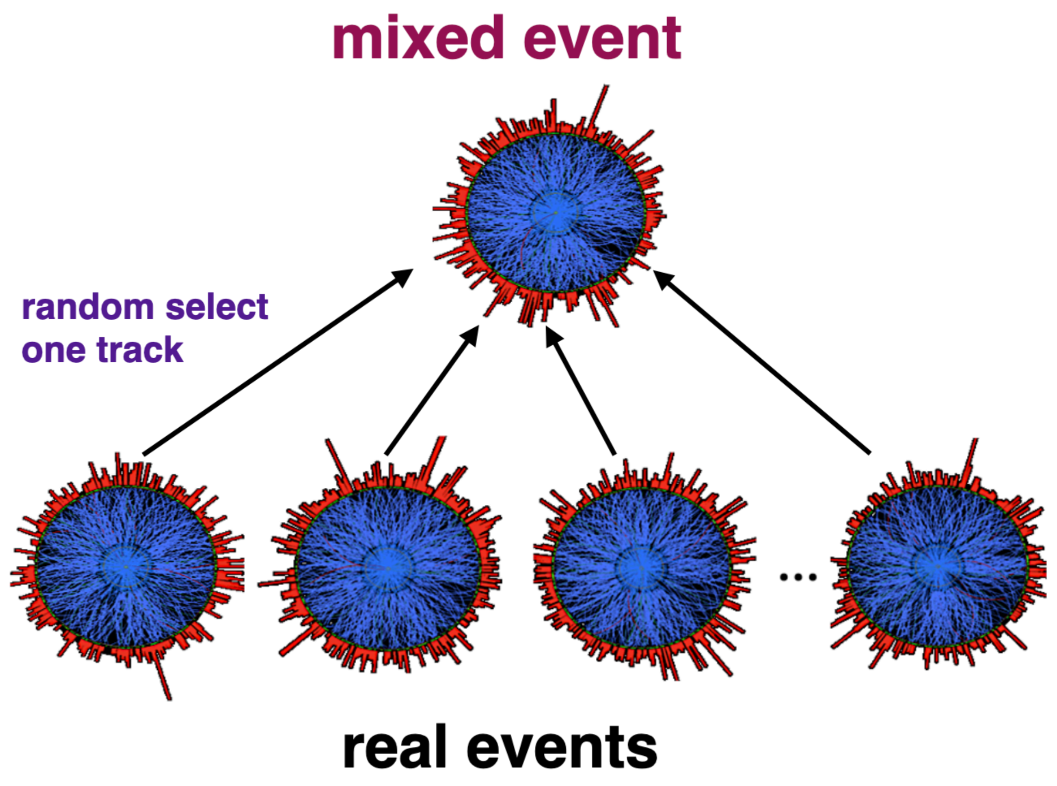
Semi-inclusive hadron-jet I_{CP}:



Jets recoiling from a high-pT trigger hadron

Expected "surface bias"

per-trigger normalized jet yield, do not depend on N_{coll}

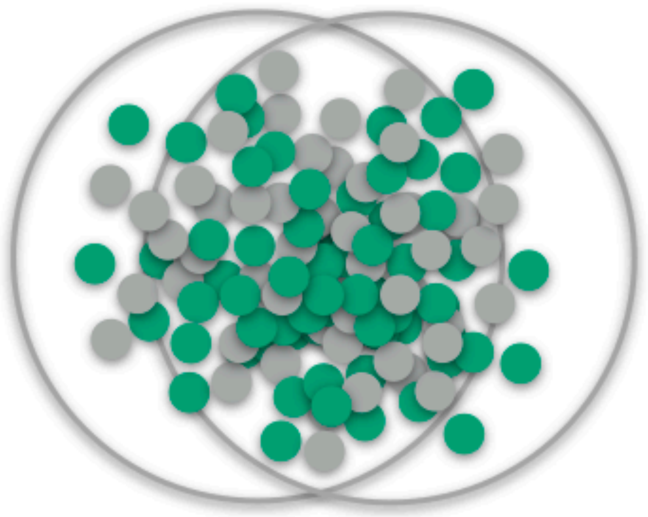


$$I_{AA} = \frac{Y^{AA}}{Y^{pp}}$$

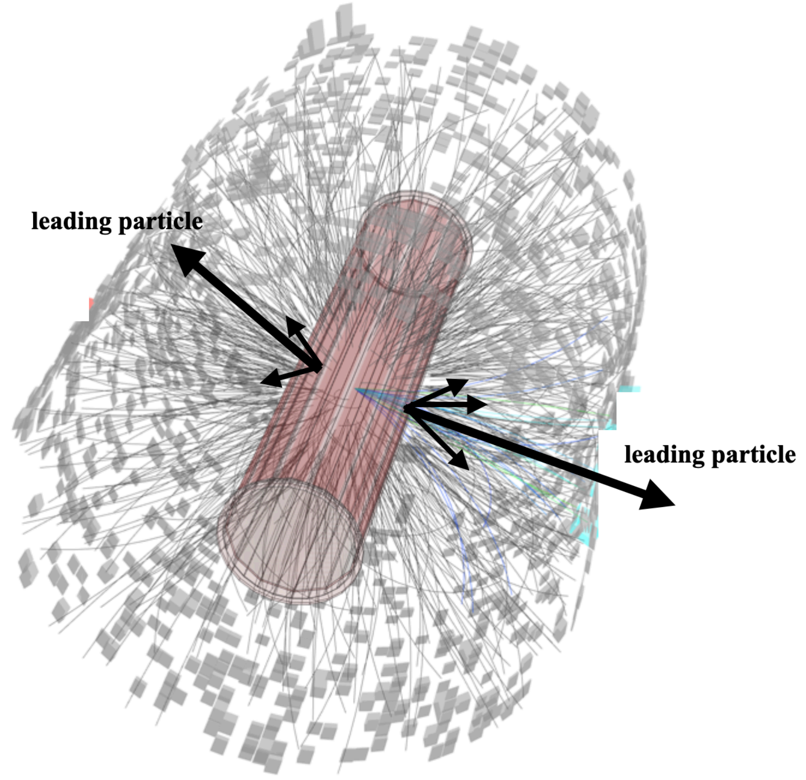
Combinatorial jet background: Correction for background fluctuations and instrumental effects

Allowing measurements to be extended to large jet R and low jet p_T.

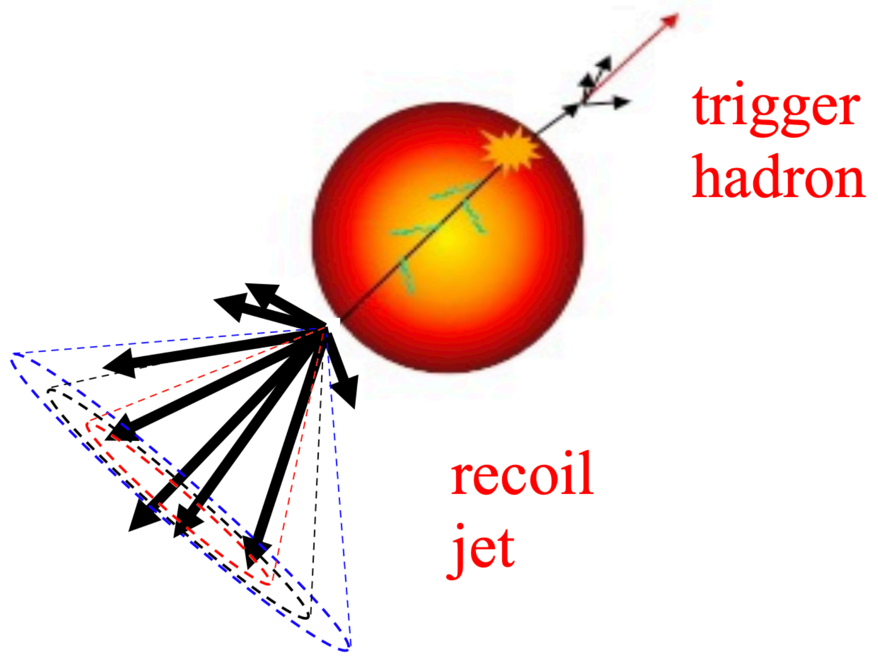
Isobar collision system



$^{96}_{40}Zr + ^{96}_{40}Zr / ^{96}_{44}Ru + ^{96}_{44}Ru$

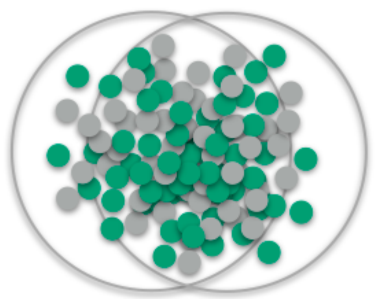


$\mathbf{R_{AA}}$

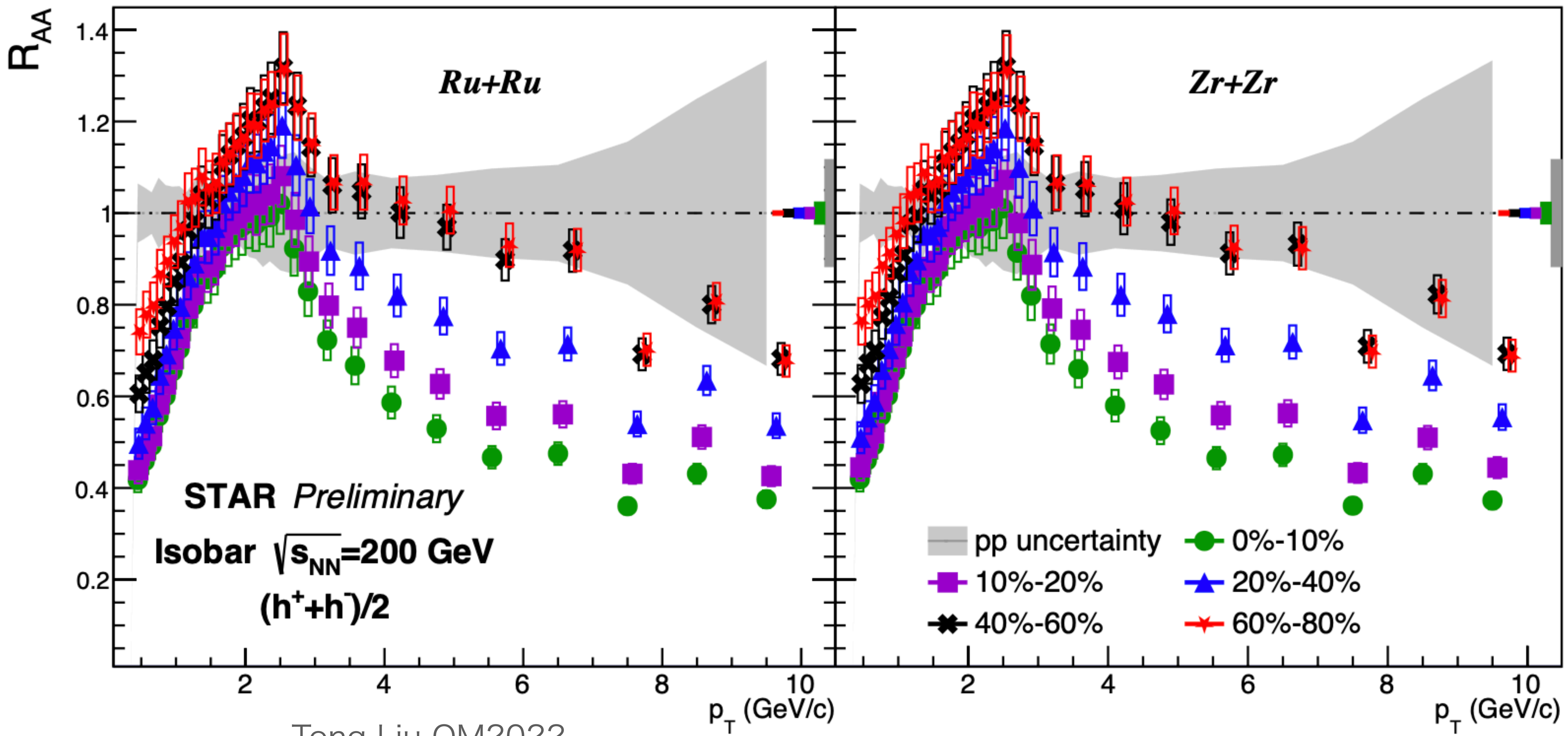


$\mathbf{I_{CP}}$

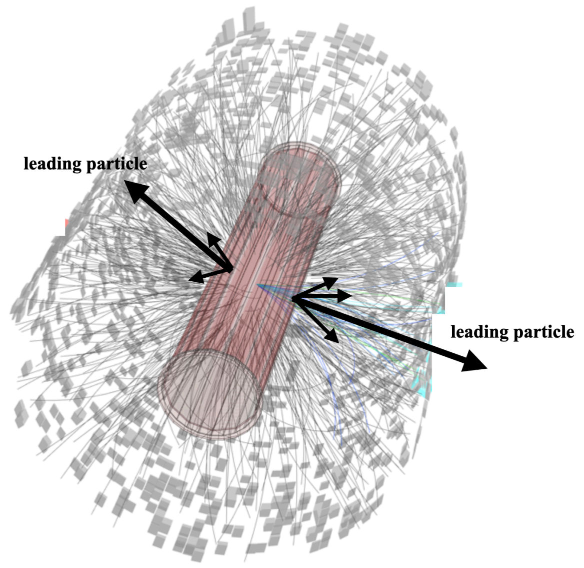
Inclusive hadron R_{AA} in isobar collisions



$^{96}_{40}Zr + ^{96}_{40}Zr$ / $^{96}_{44}Ru + ^{96}_{44}Ru$ @ 200GeV

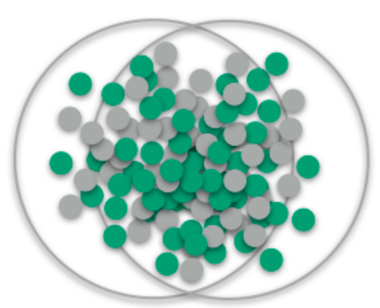


Tong Liu QM2022

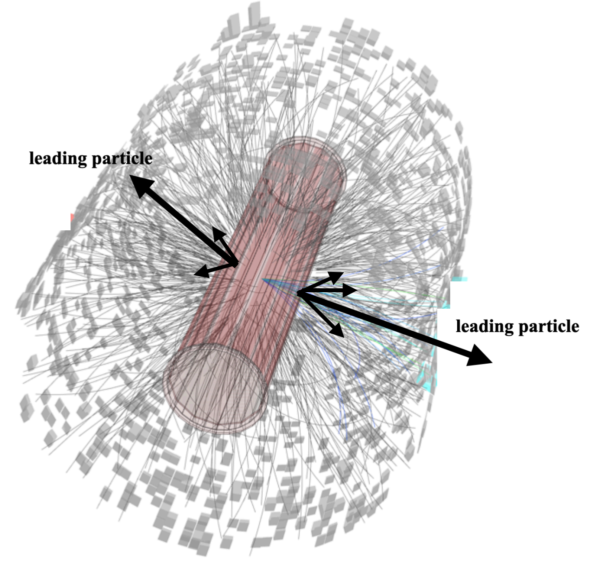


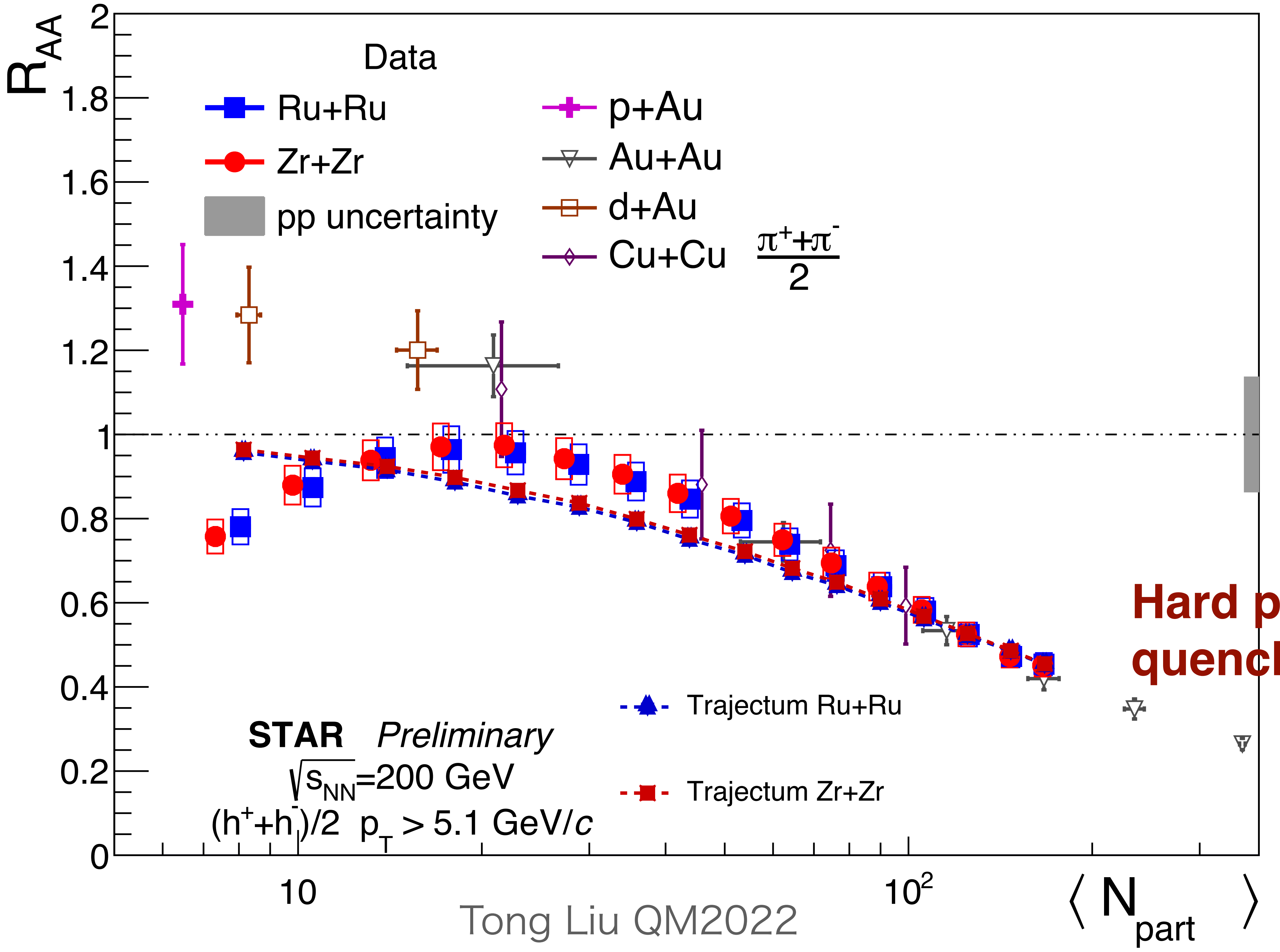
- ◉ **Significant high p_T suppression for central events.**
- ◉ **Ru+Ru & Zr+Zr show similar suppression.**

R_{AA} vs. N_{part}



$^{96}_{40}Zr + ^{96}_{40}Zr$ / $^{96}_{44}Ru + ^{96}_{44}Ru$ @ 200GeV

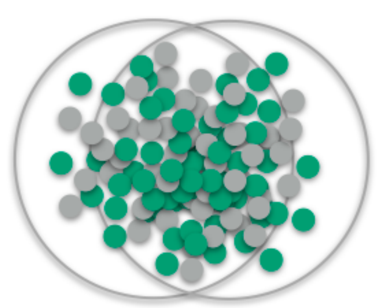




Hard partons experience more quenching as $\langle N_{part} \rangle$ increase.

◉ **R_{AA} mostly depends on energy density rather than geometry.**

R_{AA} vs. N_{part}



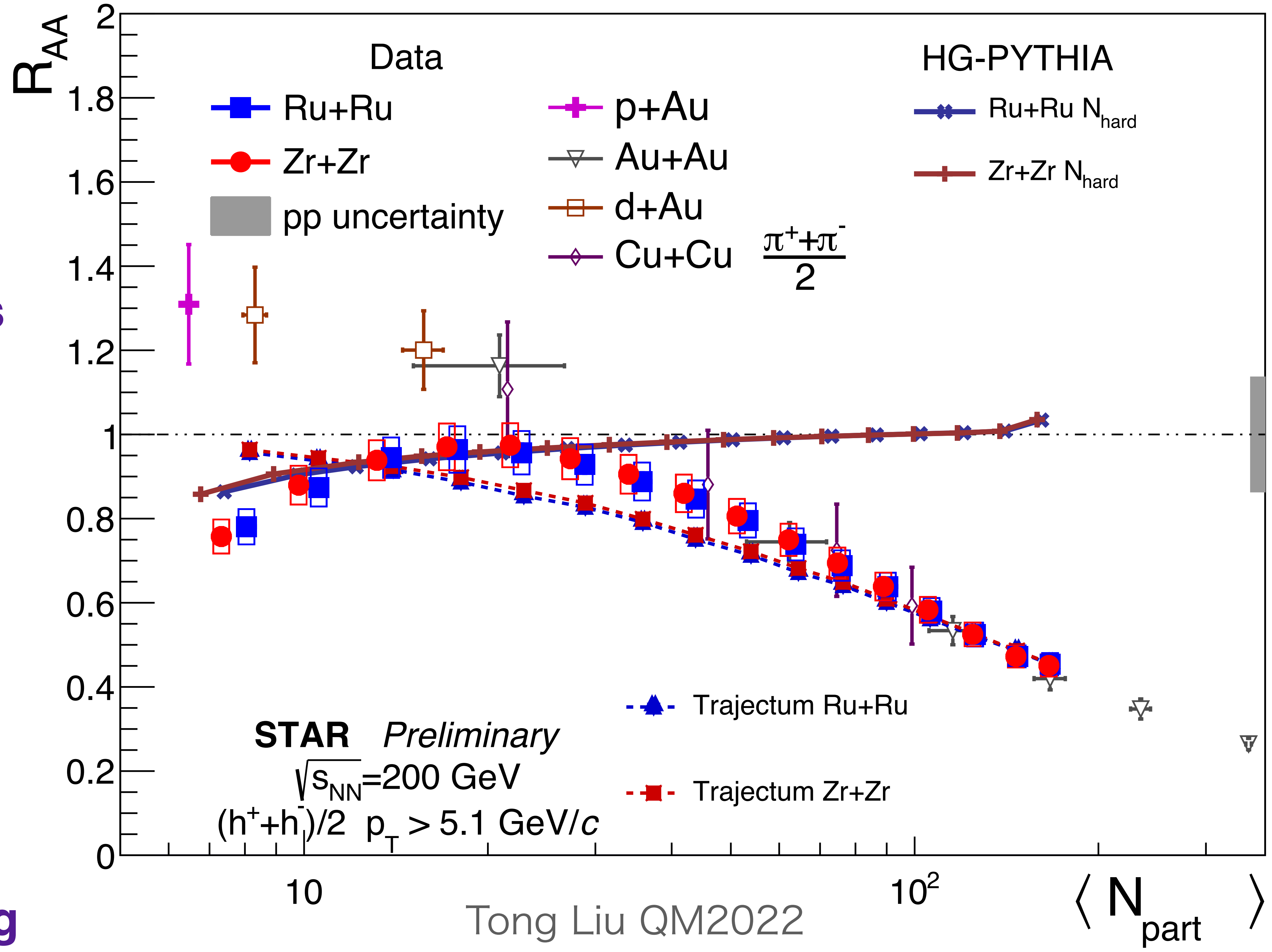
$^{96}_{40}Zr + ^{96}_{40}Zr$ / $^{96}_{44}Ru + ^{96}_{44}Ru$ @ 200GeV

high $Q^2 \propto N_{coll}$

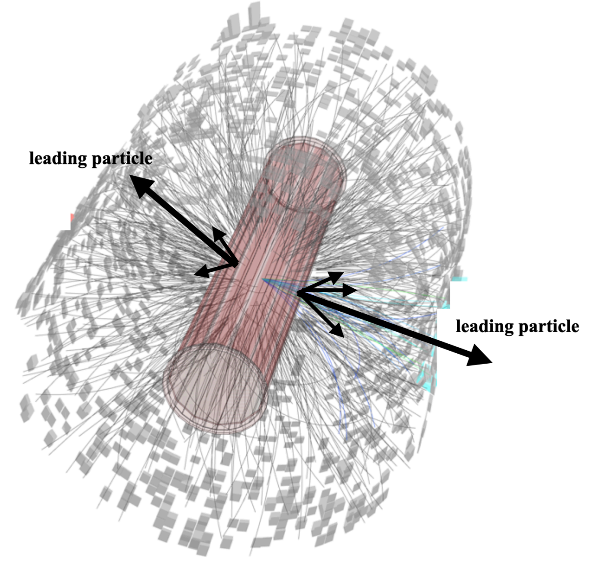
nucleon-nucleon (NN) collisions are NOT created equal

N_{coll} **scaling is NOT precise enough to calculate peripheral collisions.**

N_{hard}**: number of hard scattering**

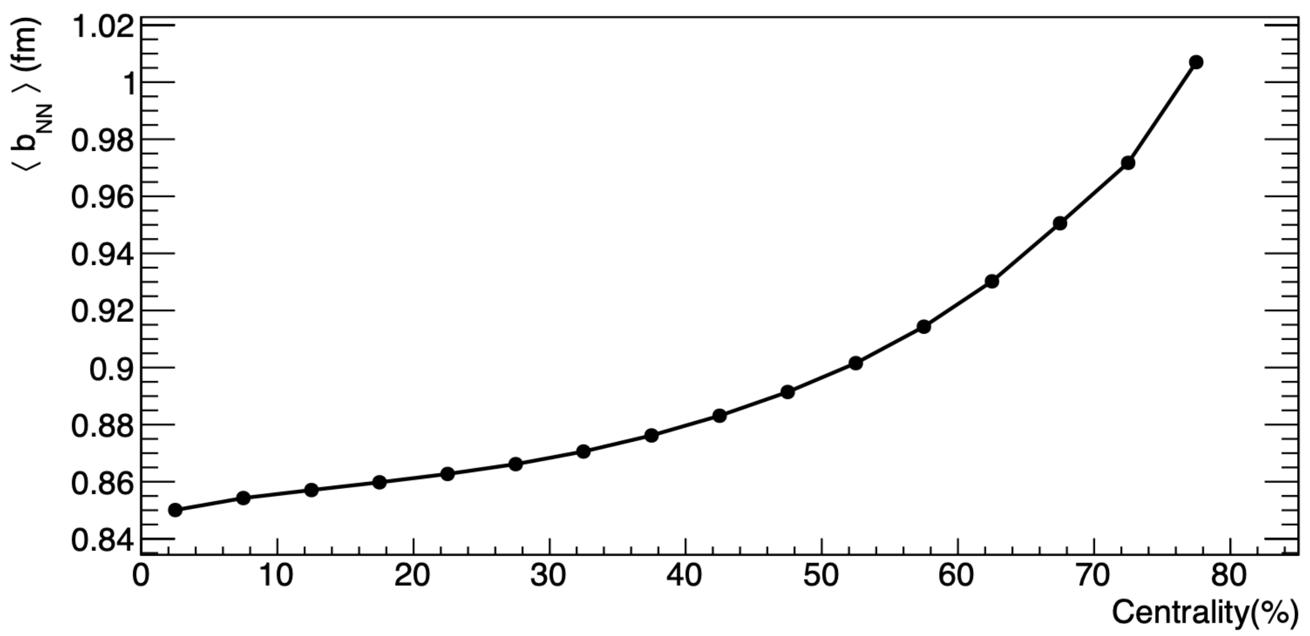


Tong Liu QM2022



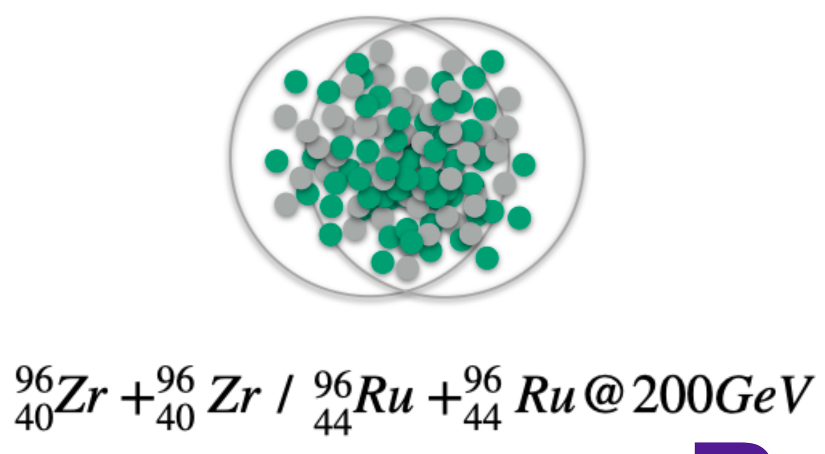
C. Loizides, A. Morsch, PLB 773 (2017) 408–411

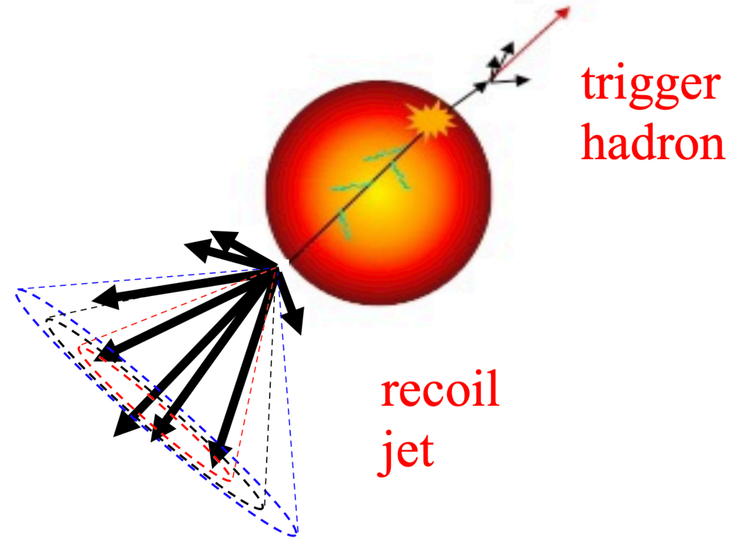
$$N_{\text{hard}} = \sum_{i=1}^{N_{\text{coll}}} N_{\text{hard}}^{i}\,(b_{\text{NN}}^{i})$$

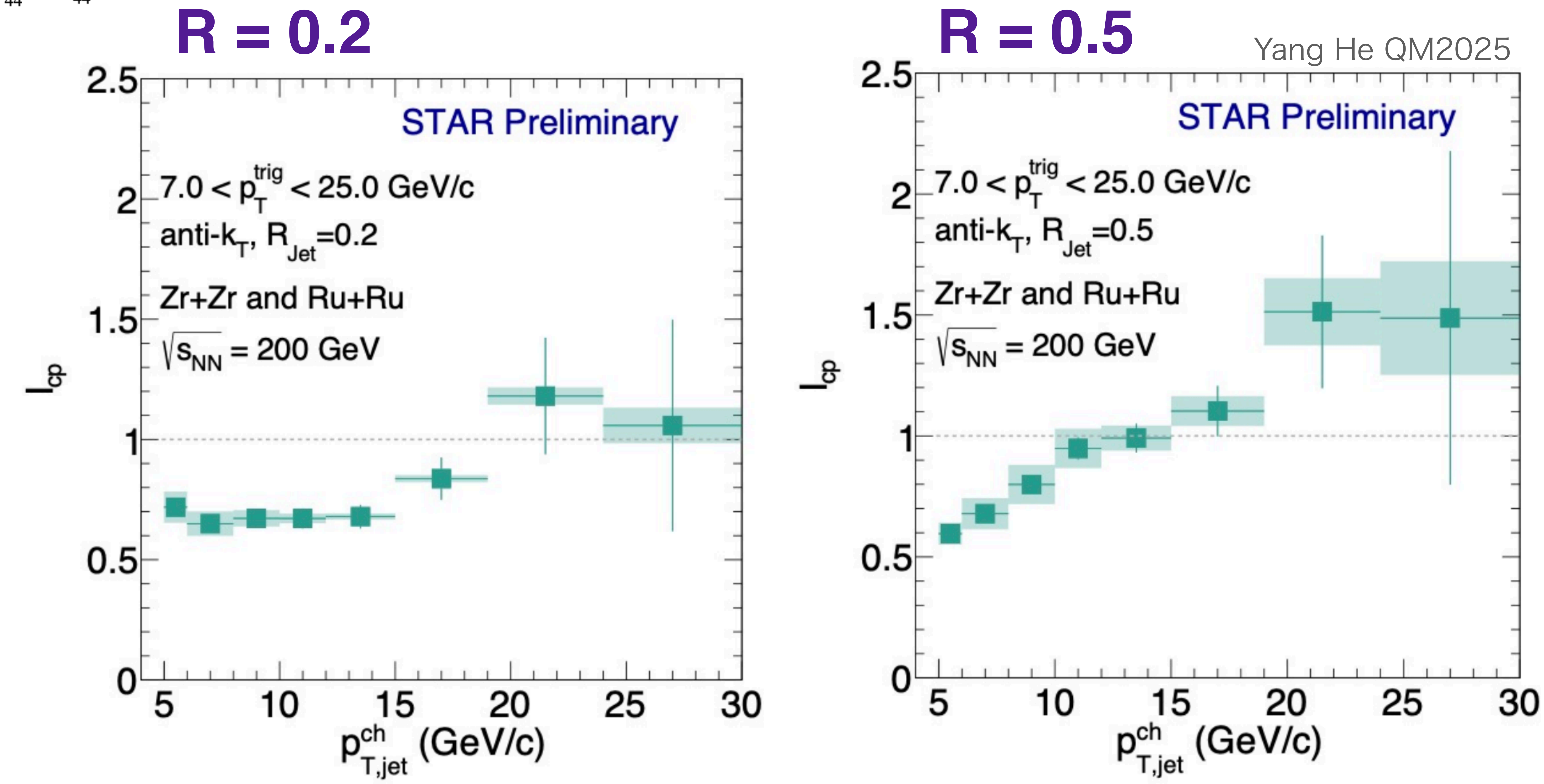


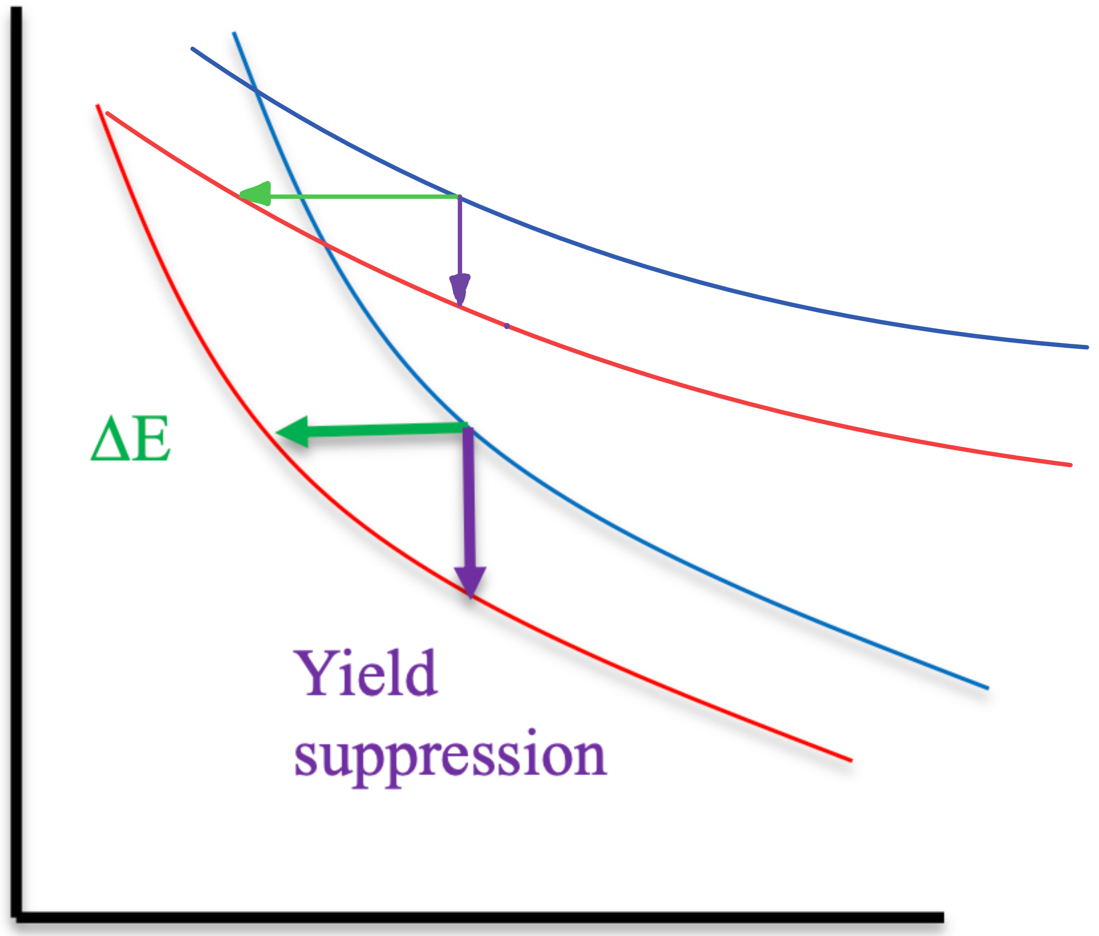
- **R_{AA} mostly depends on energy density rather than geometry.**
- N_{hard} **correction qualitatively describes the drop of R_{AA} in peripheral collisions.**

Icp vs. p_T





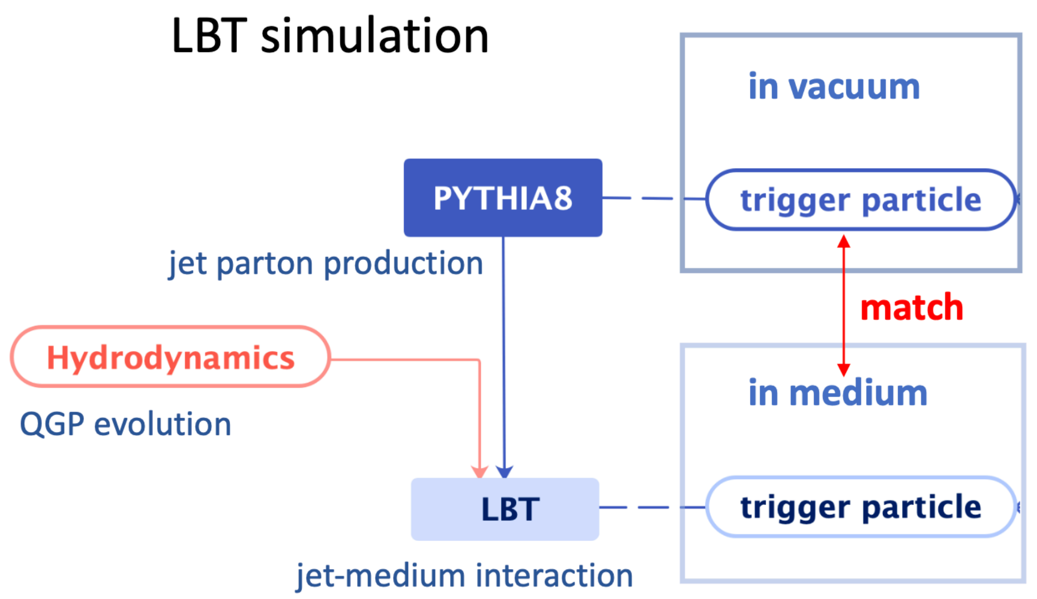




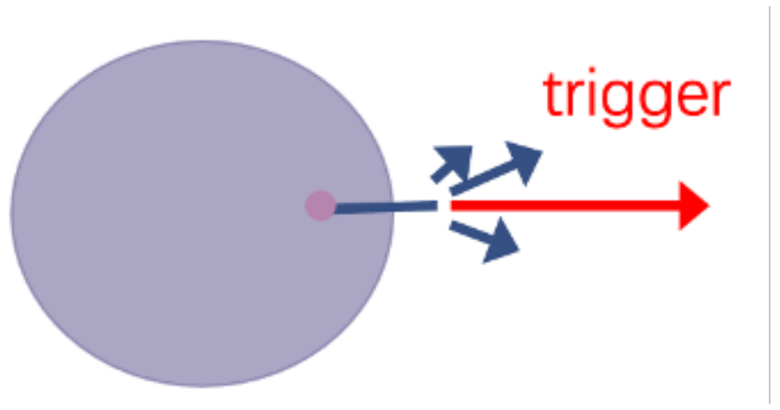
same energy loss, less yield suppression for less steep falling spectra

- **$I_{cp} < 1$, which indicate clear jet quenching signal.**
- **I_{cp} increase with p_T increasing, and can above unit?**

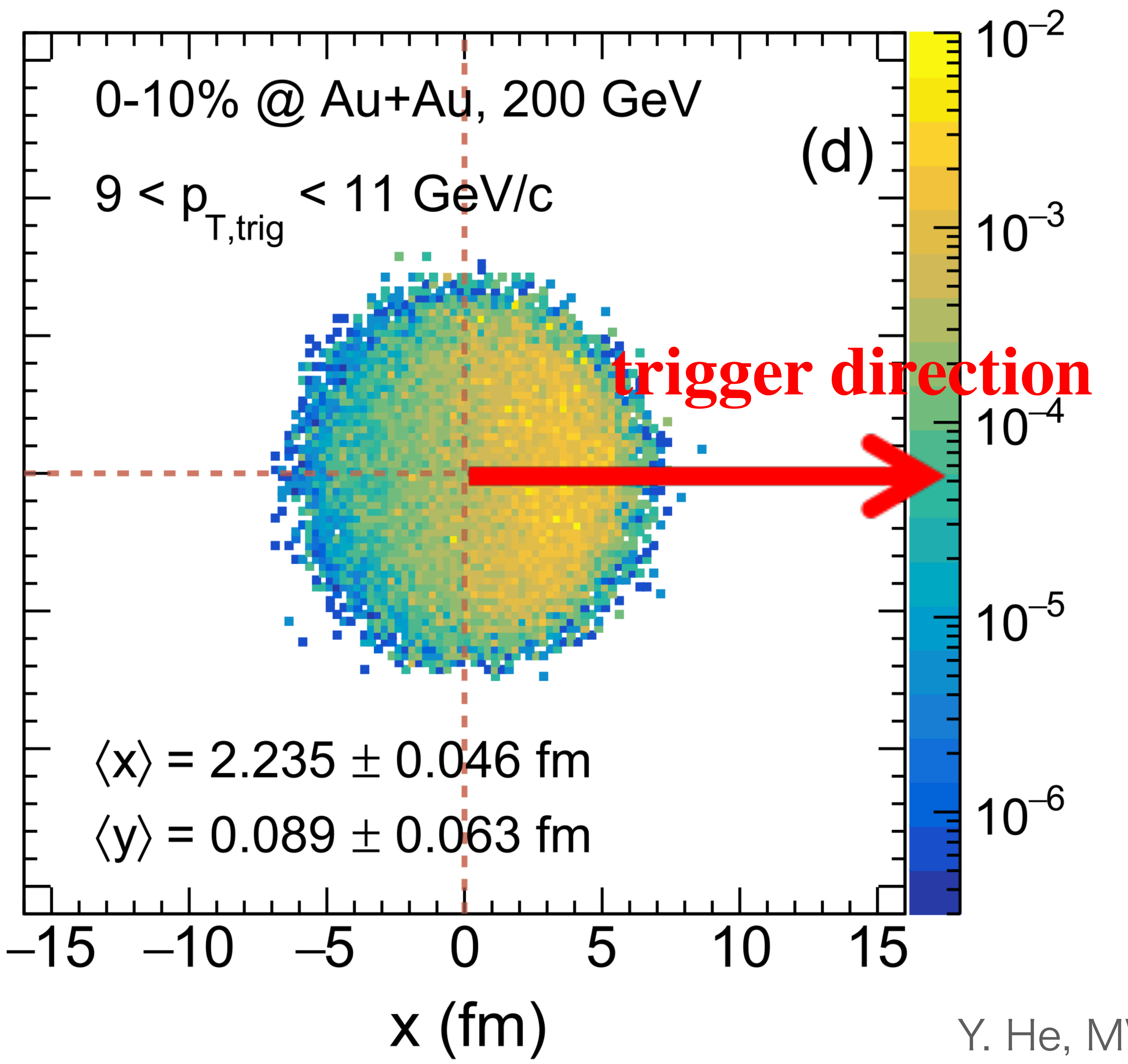
Energy loss for trigger hadron

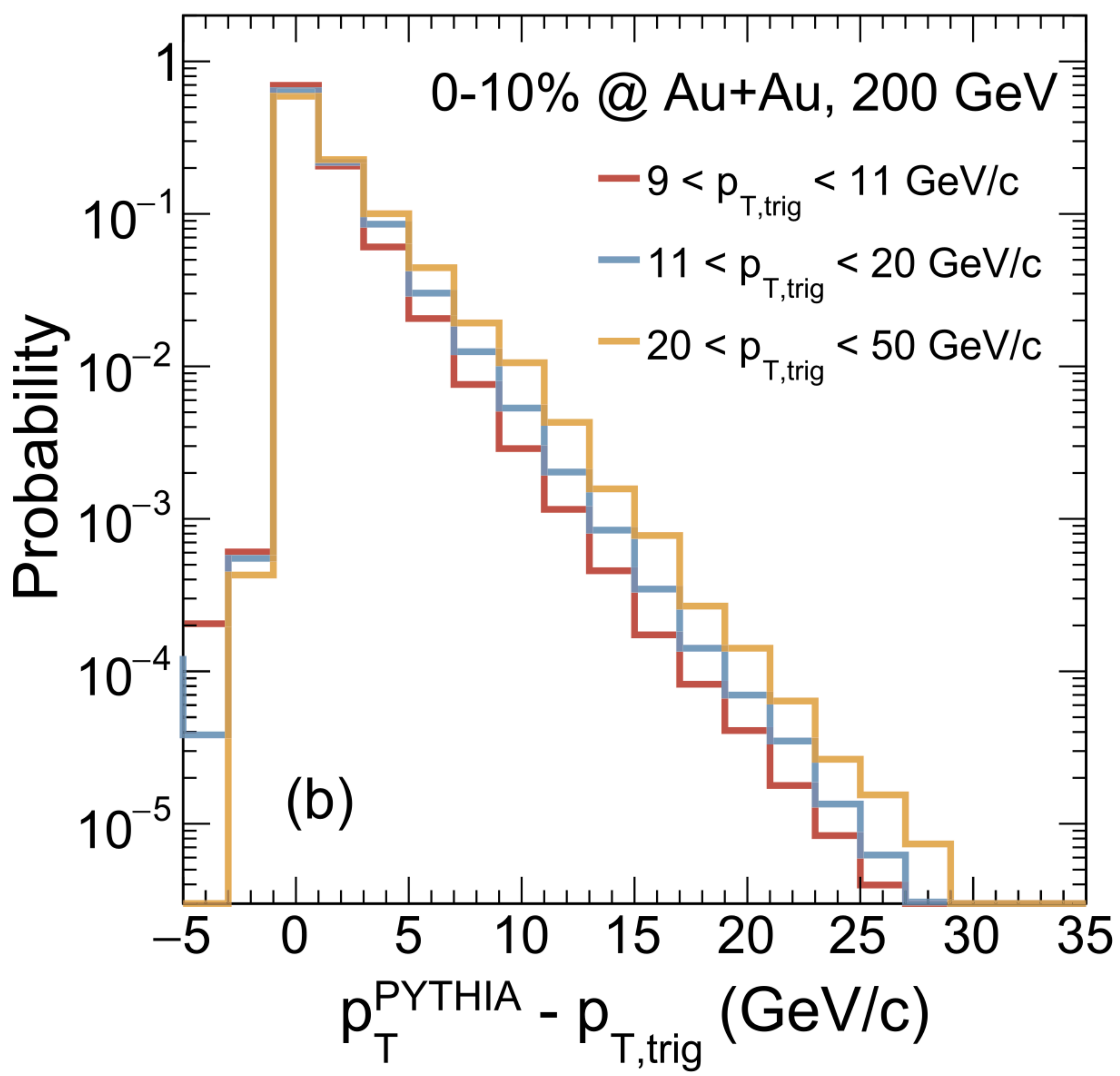


Surface bias: are triggers all produced at the surface?



Yang He HP2024





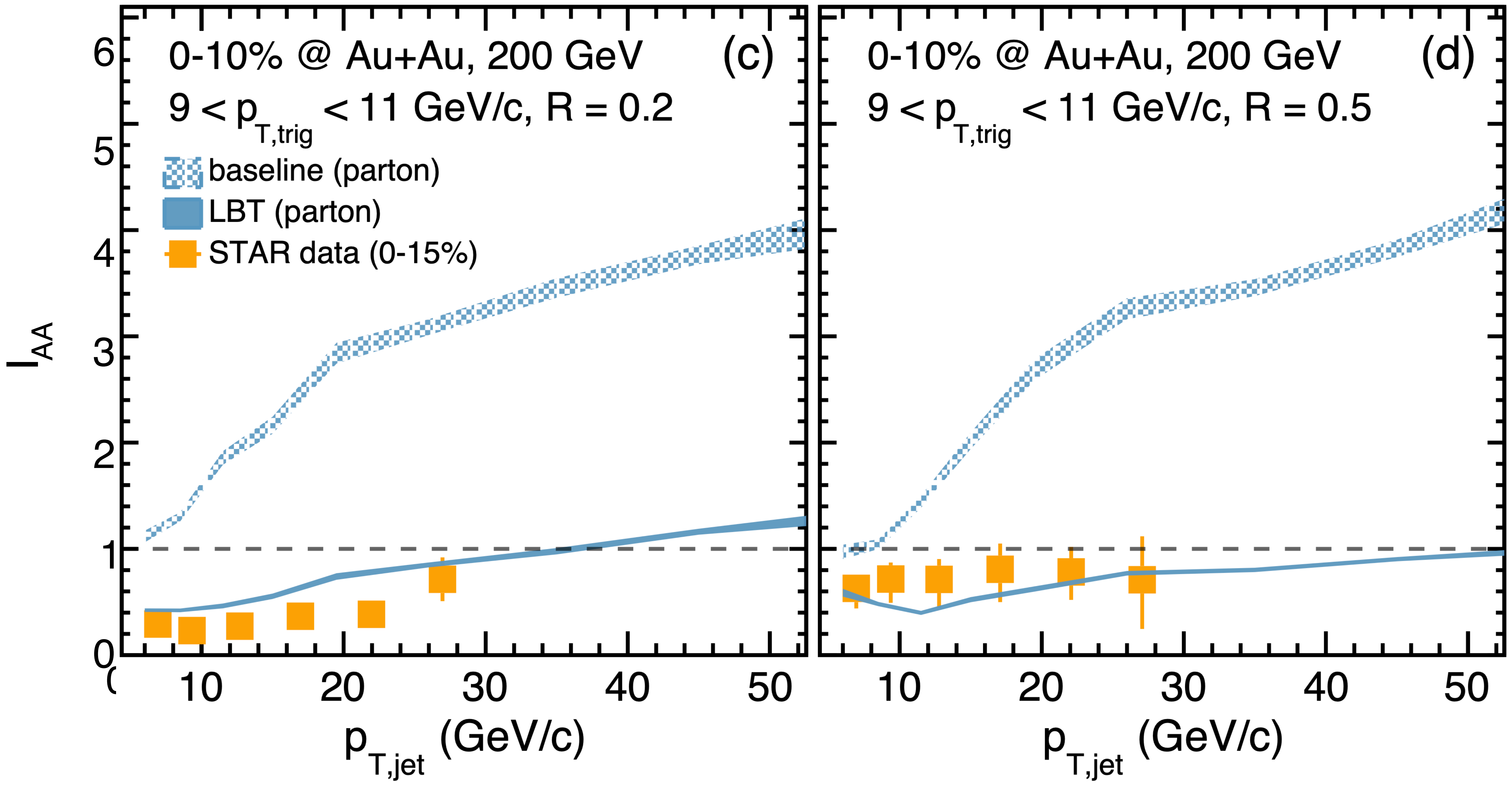
30% triggers lose energy over 1GeV/c

Y. He, MWN, S. Cao, R. Ma, L. Yi, H. Canies, Phys. Lett. B 854 (2024) 138739

- **Not all triggers produced at the edge of the system, sizable energy loss for these trigger particles.**

Decipher $I_{AA} > 1$ observed experimentally

Yang He HP2024



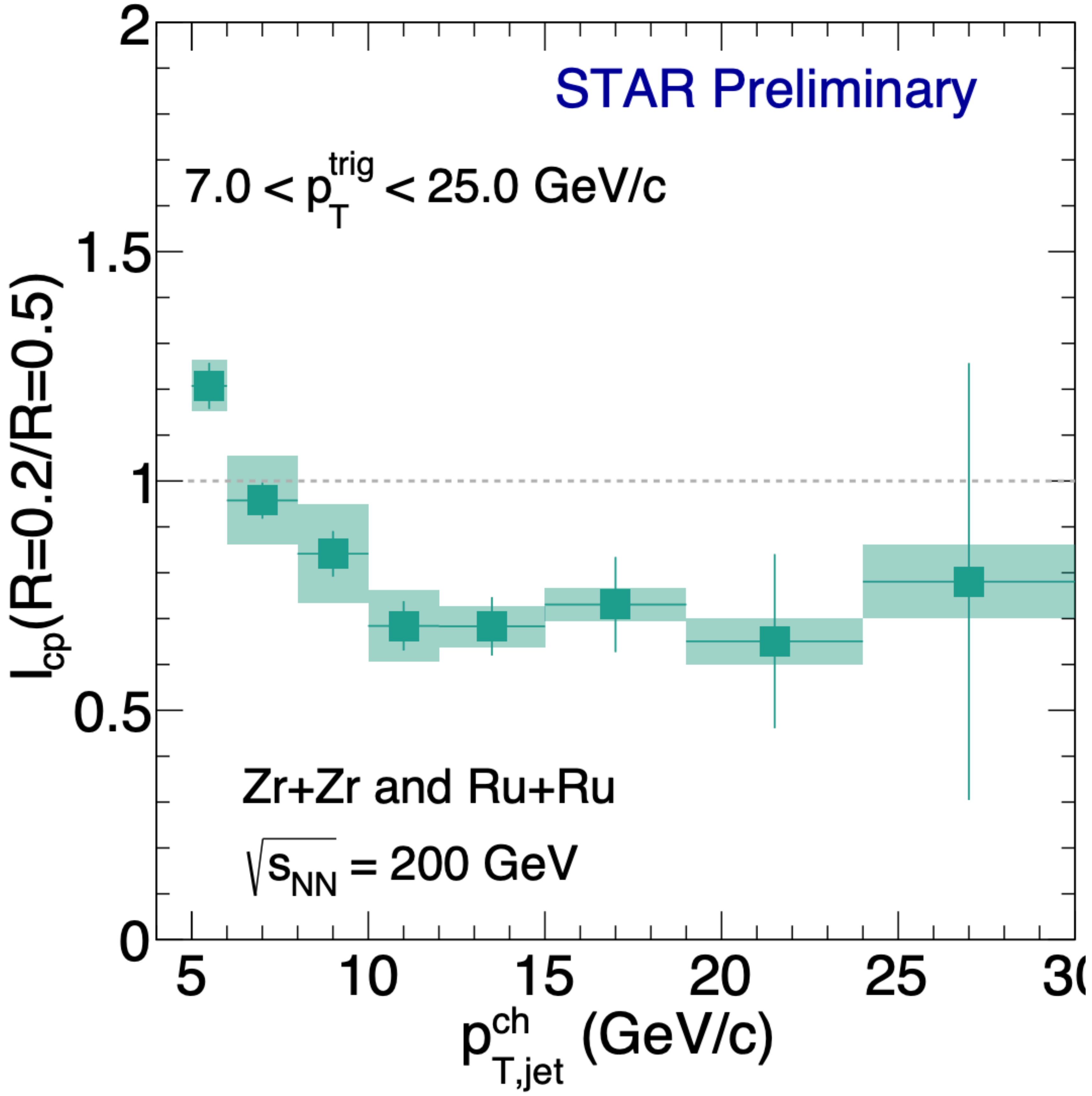
baseline need to reflect the trigger energy loss

Y. He, MWN, S. Cao, R. Ma, L. Yi, H. Canies, Phys. Lett. B 854 (2024) 138739

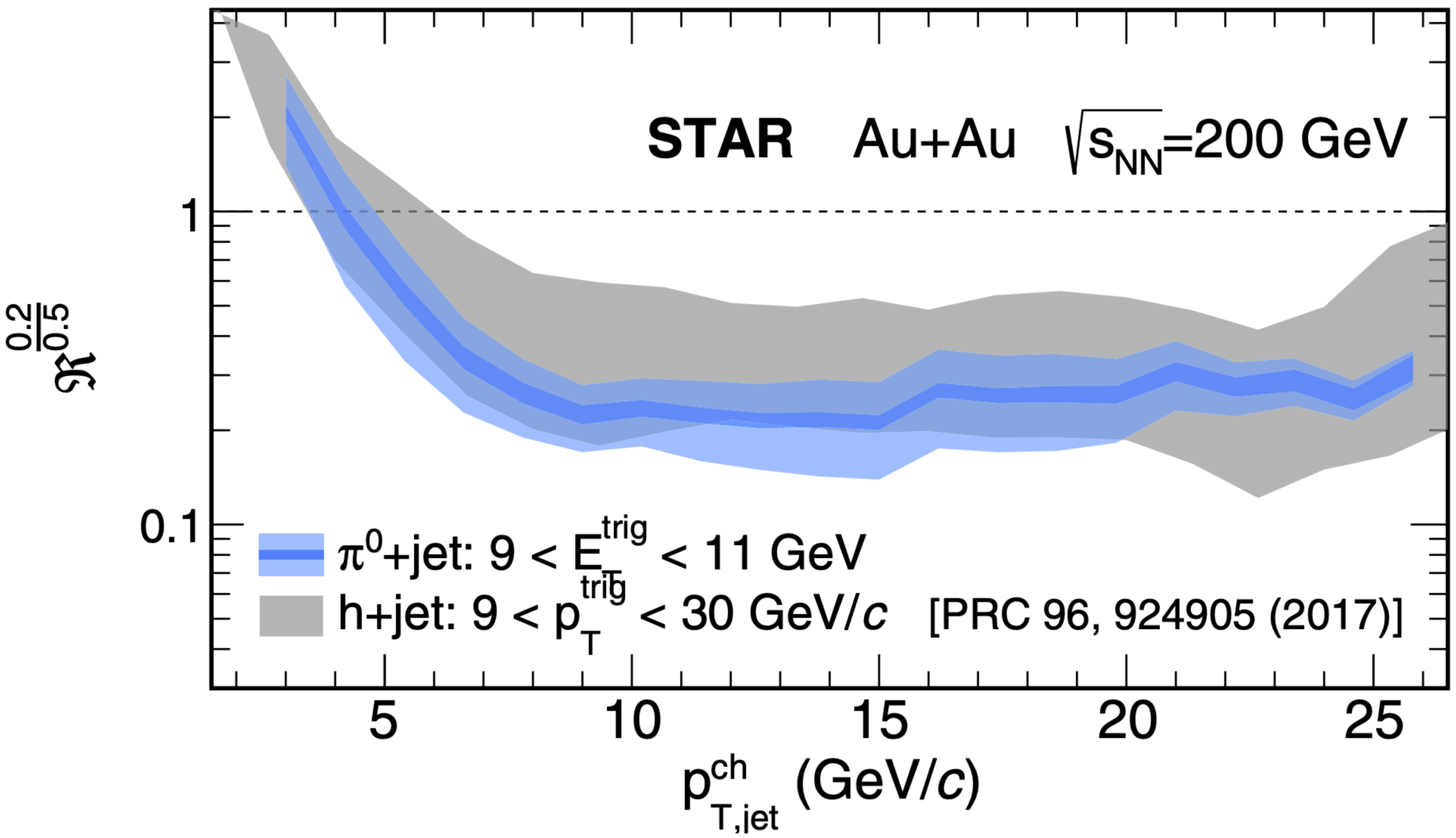
- **Energy loss of trigger particles leads to the true I_{AA} baseline above unity for recoil jets, which increases with jet p_T.**
- **$I_{AA} > 1$does not rule out jet quenching; this observable provides stricter constraints on theoretical models.**
- **Similar effect also observed in ALICE measurements.**

ALICE, Phys. Rev. Lett.133, 022301 (2024)
ALICE, Phys. Rev. C 110, 014906 (2024)

Intra-jet broadening: recoil yield vs. R



STAR, Phys. Rev. C 111, 064907 (2025)

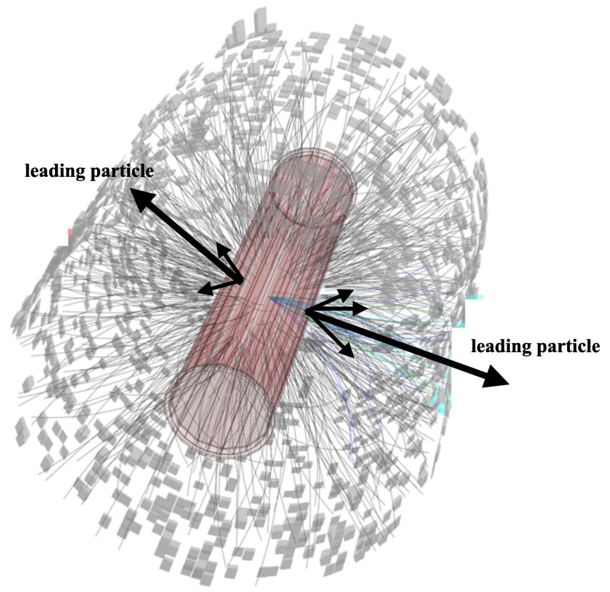


- Stronger suppression for R = 0.2; less suppression for R = 0.5.
- Clear signal for intrajet broadening, same as Au+Au.

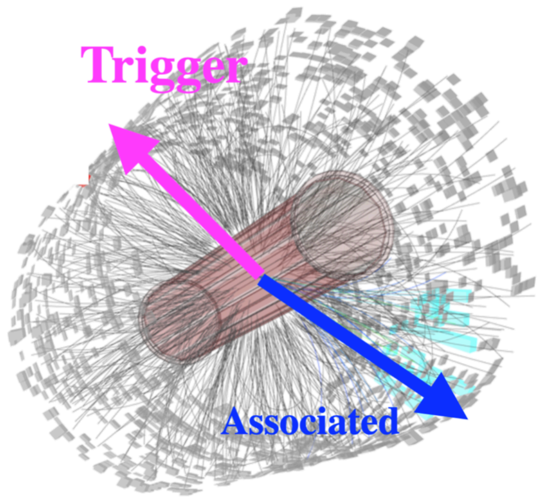
O+O Collisions

$^{16}_{8}O + ^{16}_{8}O$

Hadrons

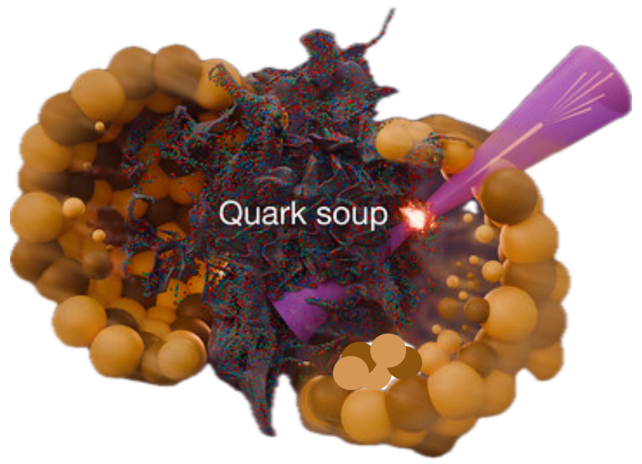


R_{CP}

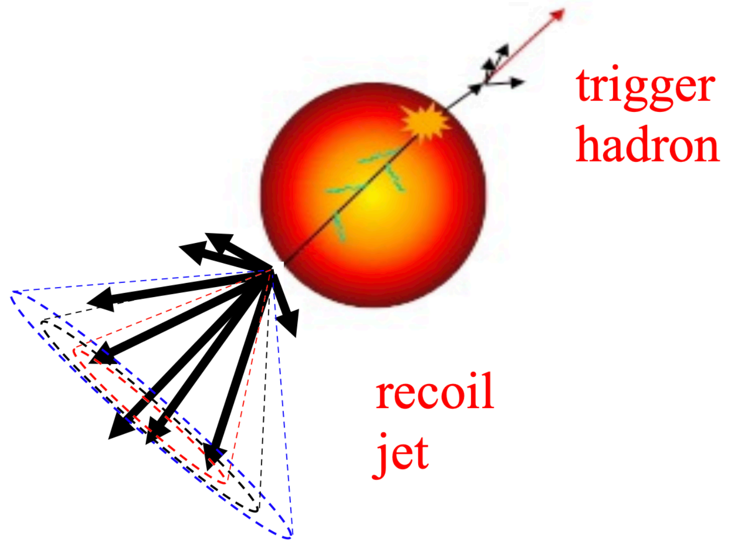


I_{CP}

Jets



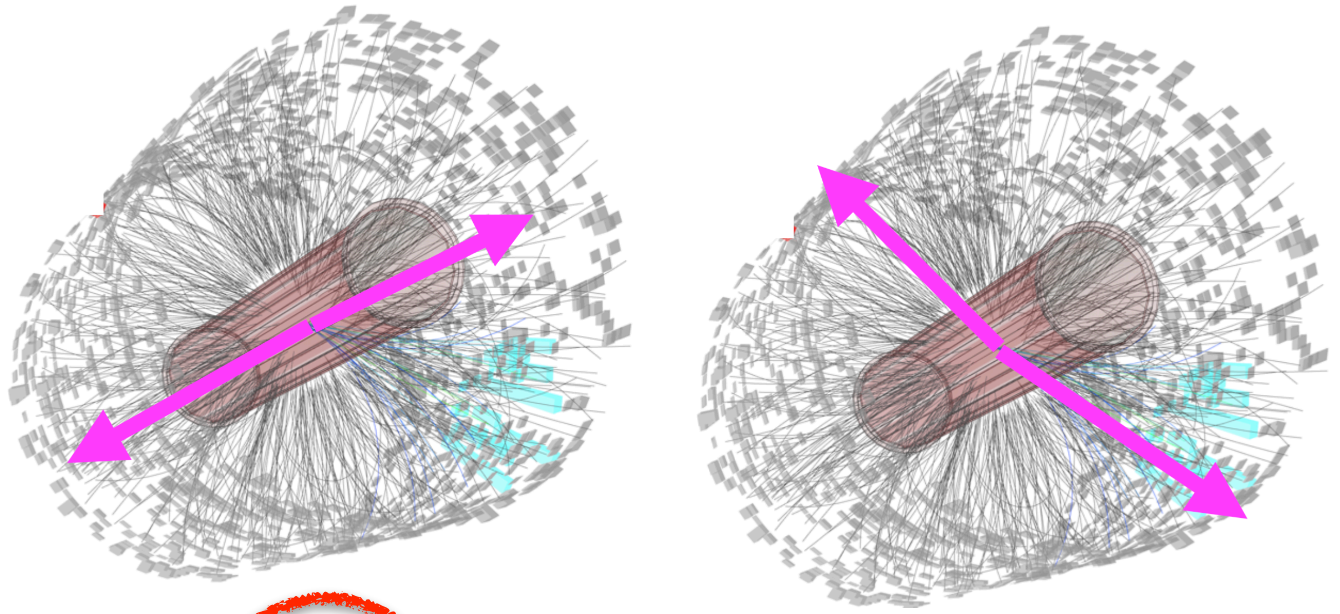
R_{CP}

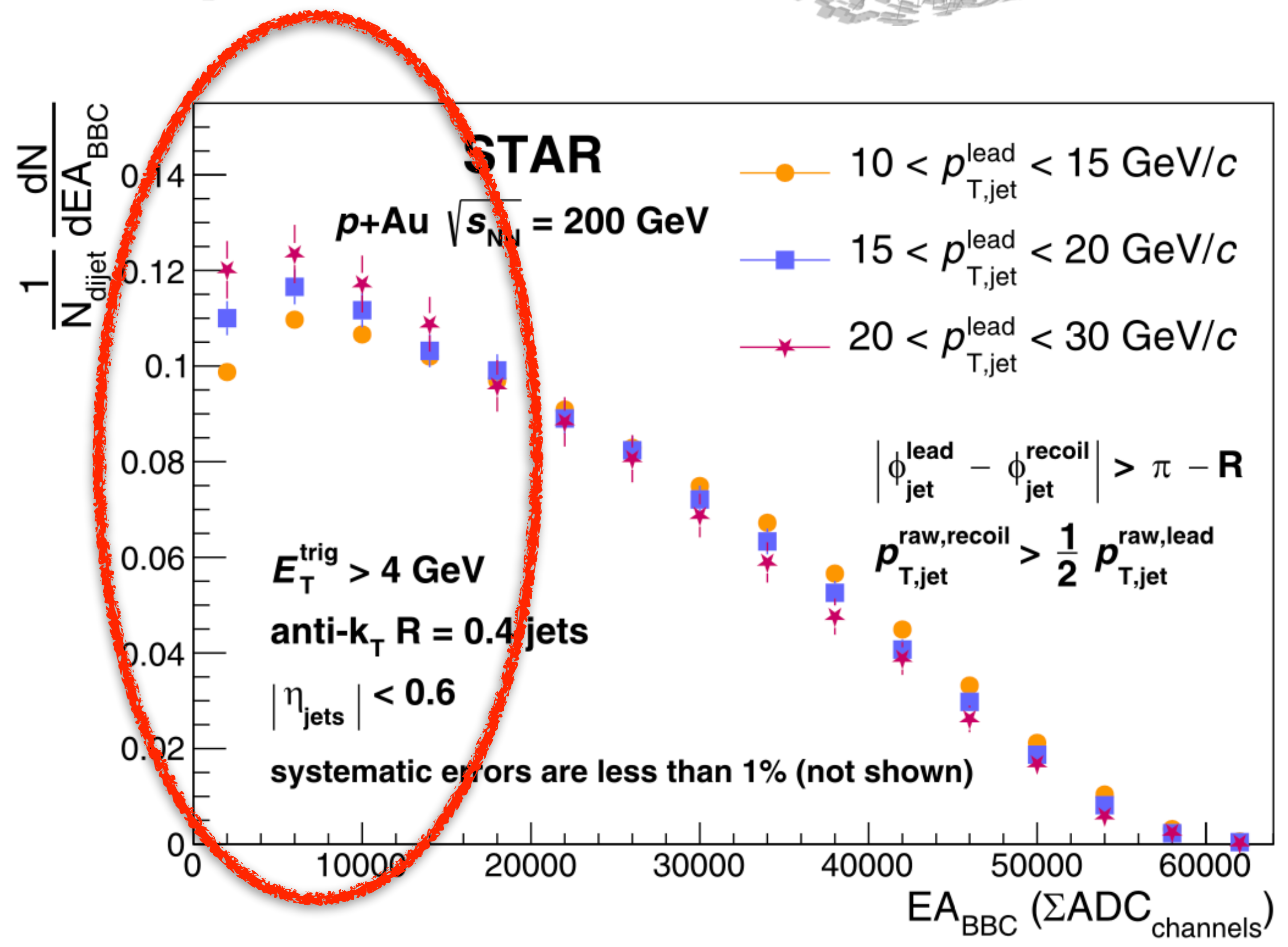


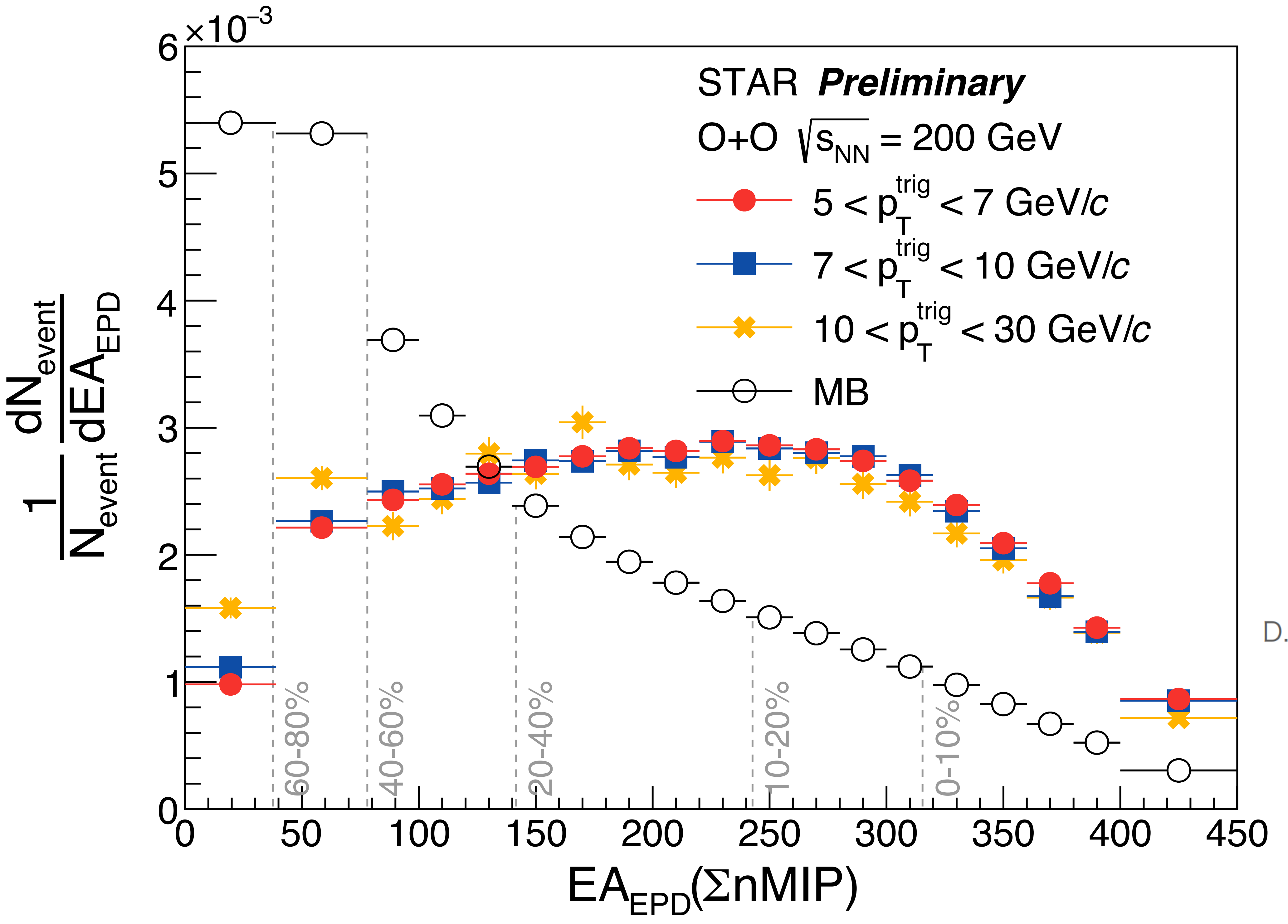
I_{CP}

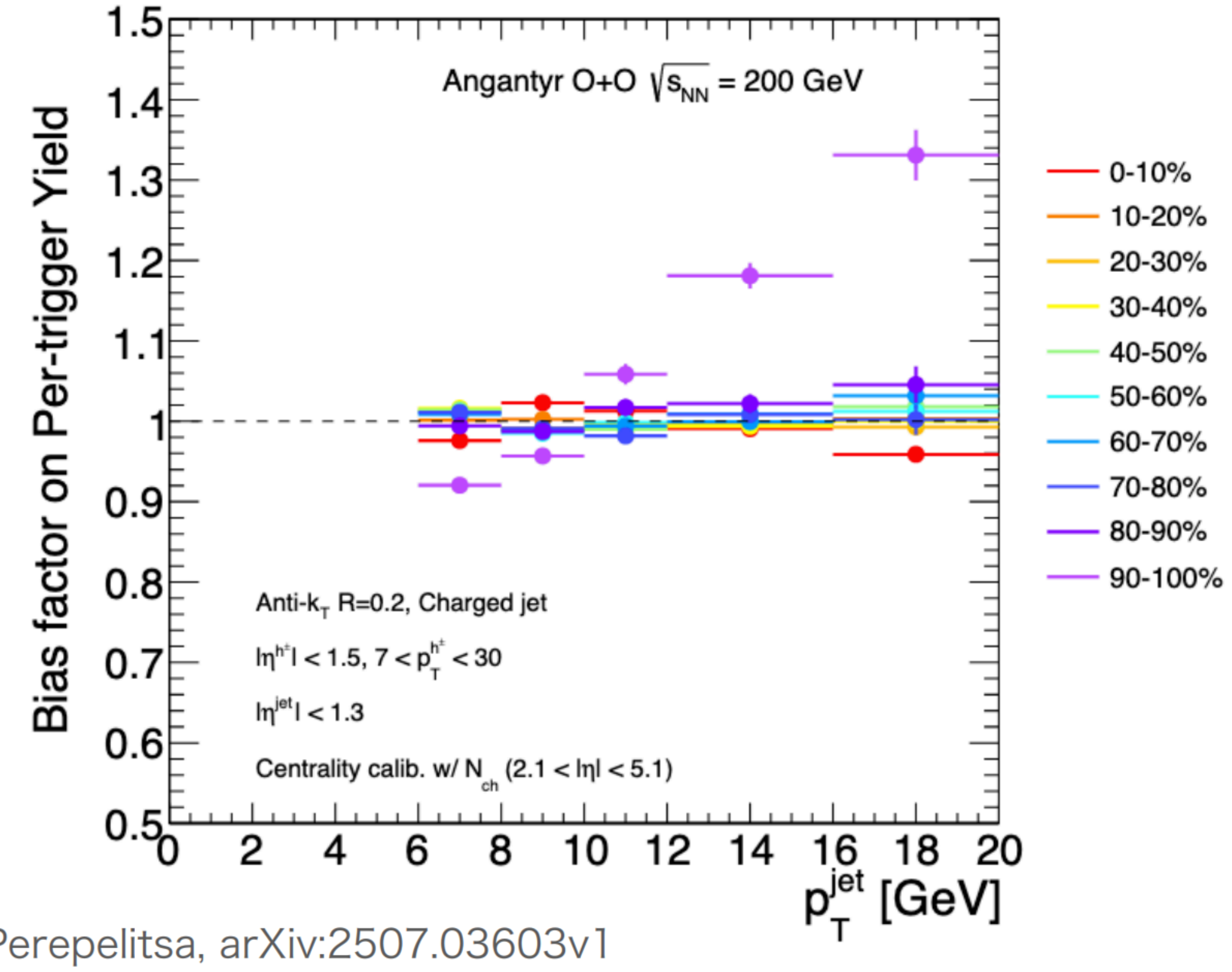
EA and Q^2 correlation in O+O

$^{16}_{8}O + ^{16}_{8}O @ 200 GeV$









D. Perepelitsa, arXiv:2507.03603v1

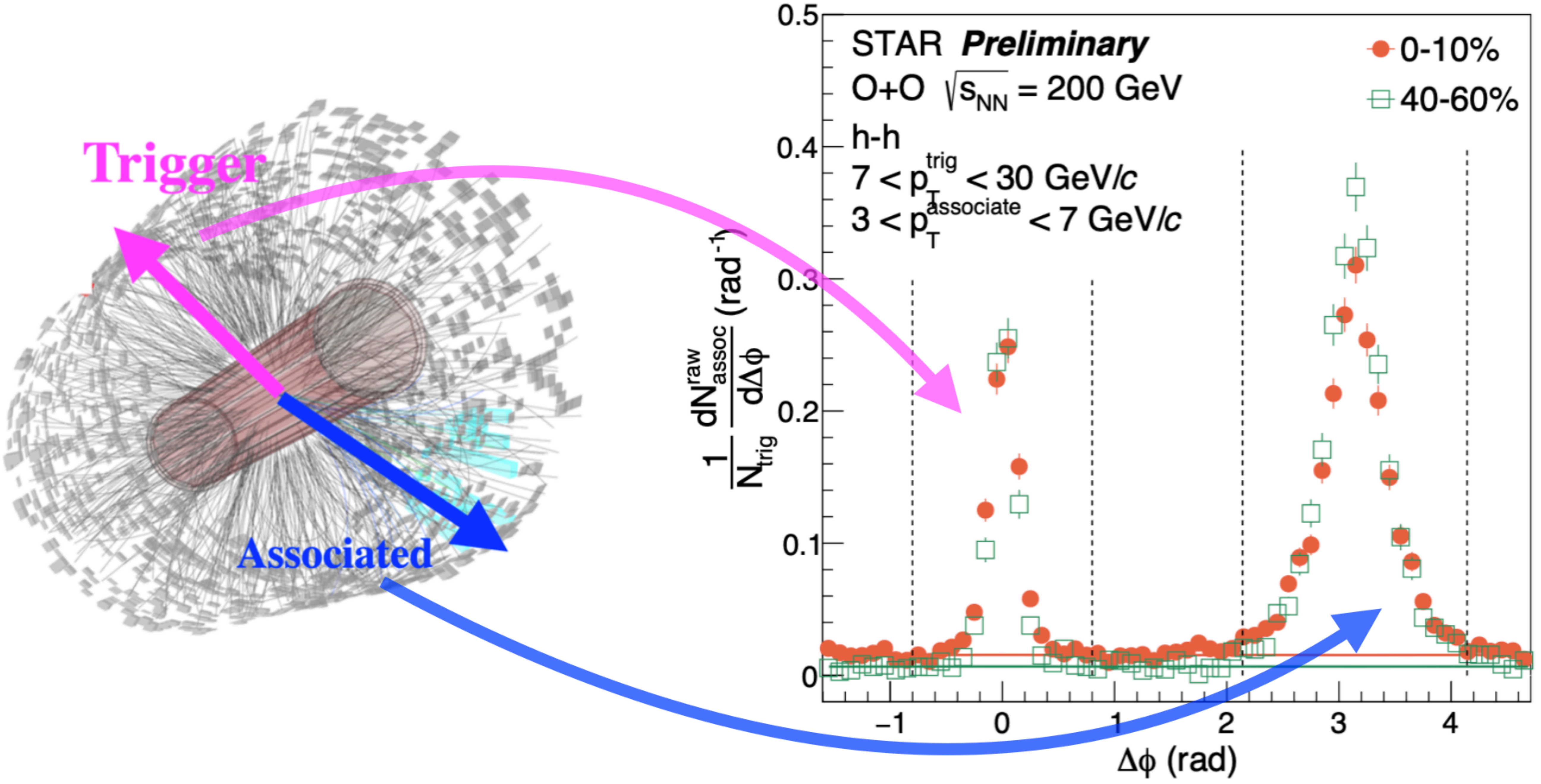
theoretical calculation suggests a negligible centrality bias effect in O+O

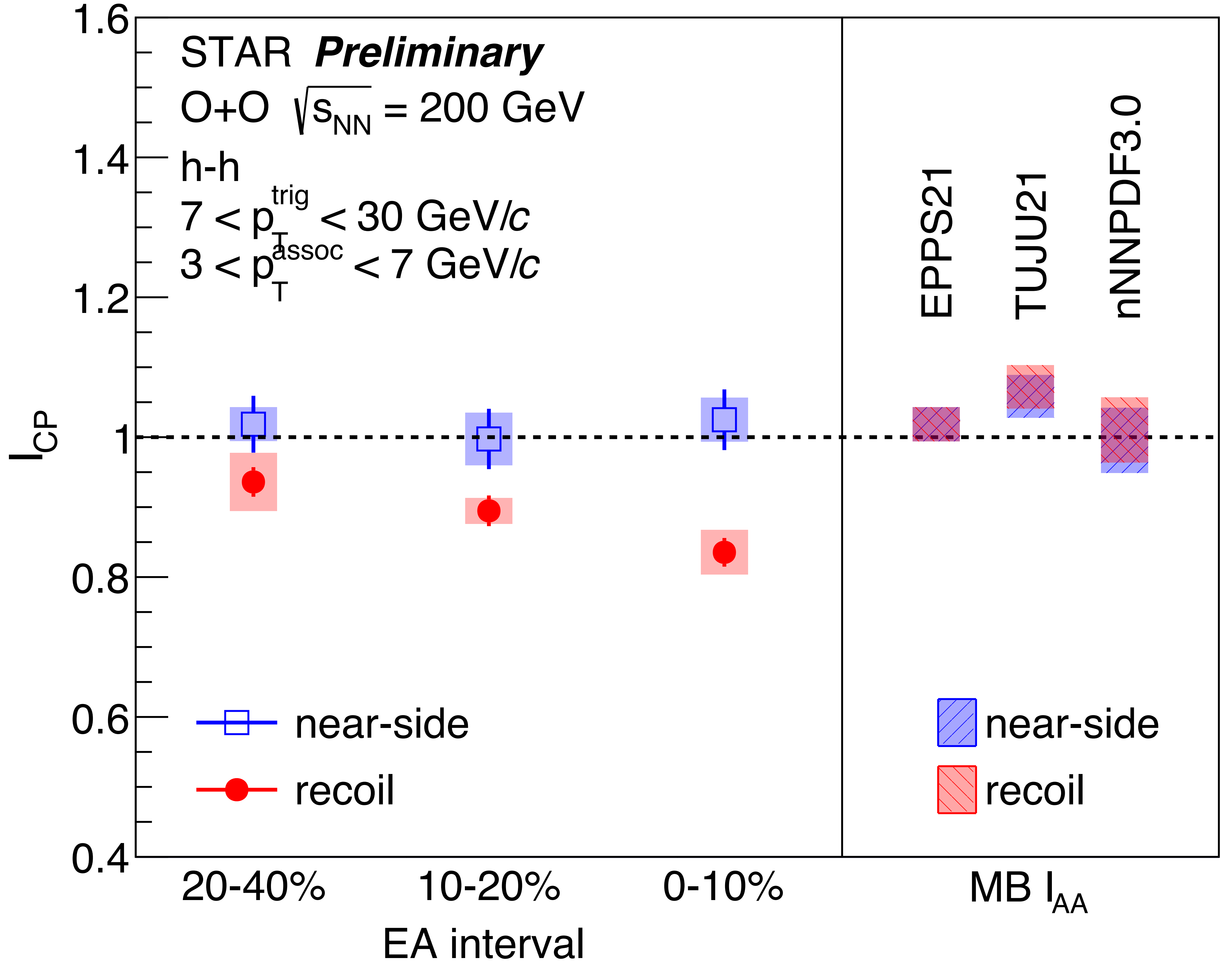
- **EPD distributions are independent of the choice of trigger p_T.**
- **EA-Q^2 anti-correlation effects are negligible.**

Dihadron correlation

$^{16}_{8}O + ^{16}_{8}O @ 200 GeV$

SiJie Zhang Light Ion Workshop 2025

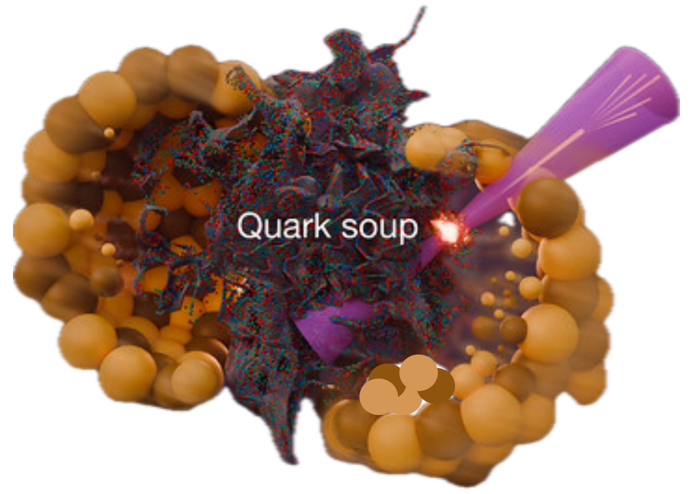




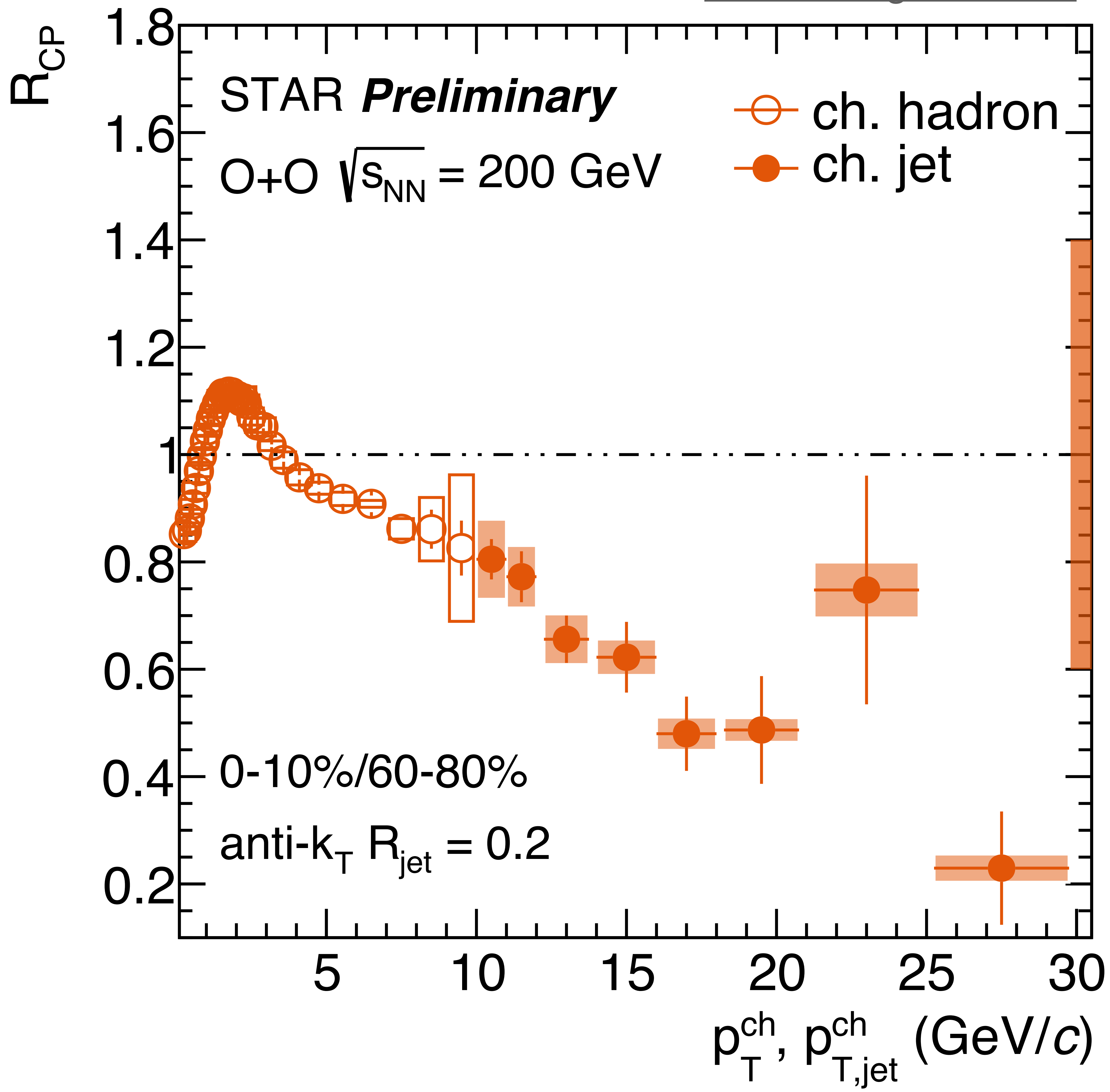
- **On the Associated side, a significant suppression is observed for high EA (0–10%) events compared to low EA (40–60%).**
- **I_{CP} results reveal consistency with unity on the trigger side, but a significant deviation on the Associated side.**
- **Theoretical calculations (without jet quenching) agree well with the Trigger side results.**

$^{16}_{8}O +^{16}_{8} O@200GeV$

R_{CP} vs. p_T



SiJie Zhang QM2025



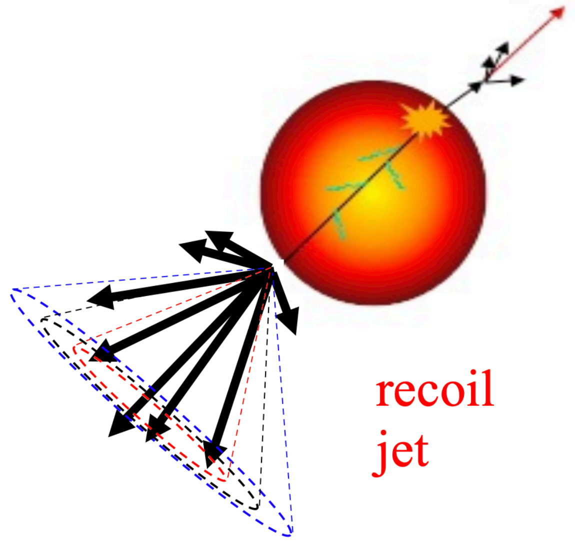
large Ncoll uncertainty needs to be taken into account

- **Both inclusive hadrons and jets exhibit consistent trends in R_{CP}, with R_{CP} for 0–10% vs. 60–80%.**

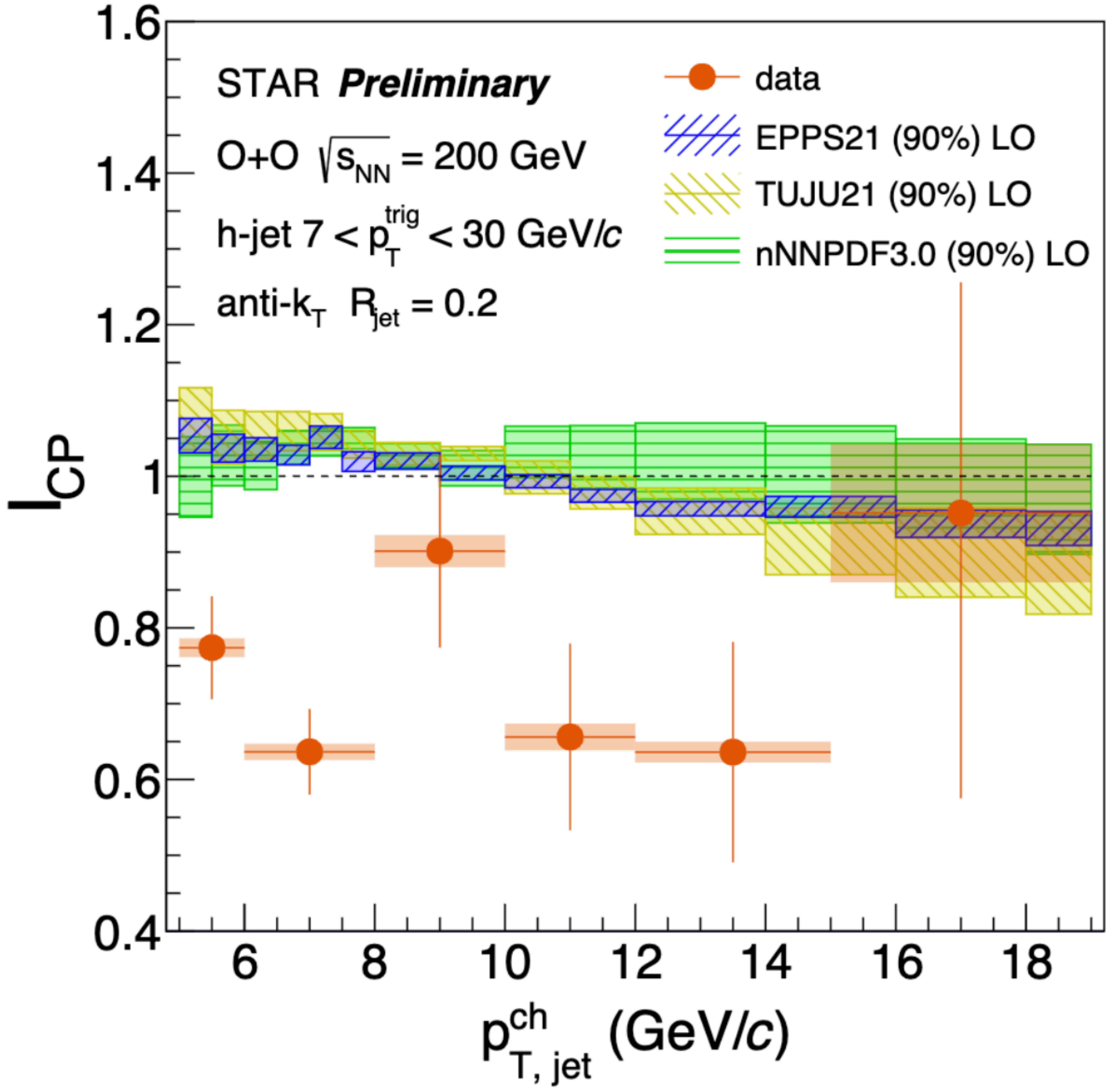
Coincidence semi-inclusive h+jet measurement, no need to use the model dependent parameter N_{coll}.

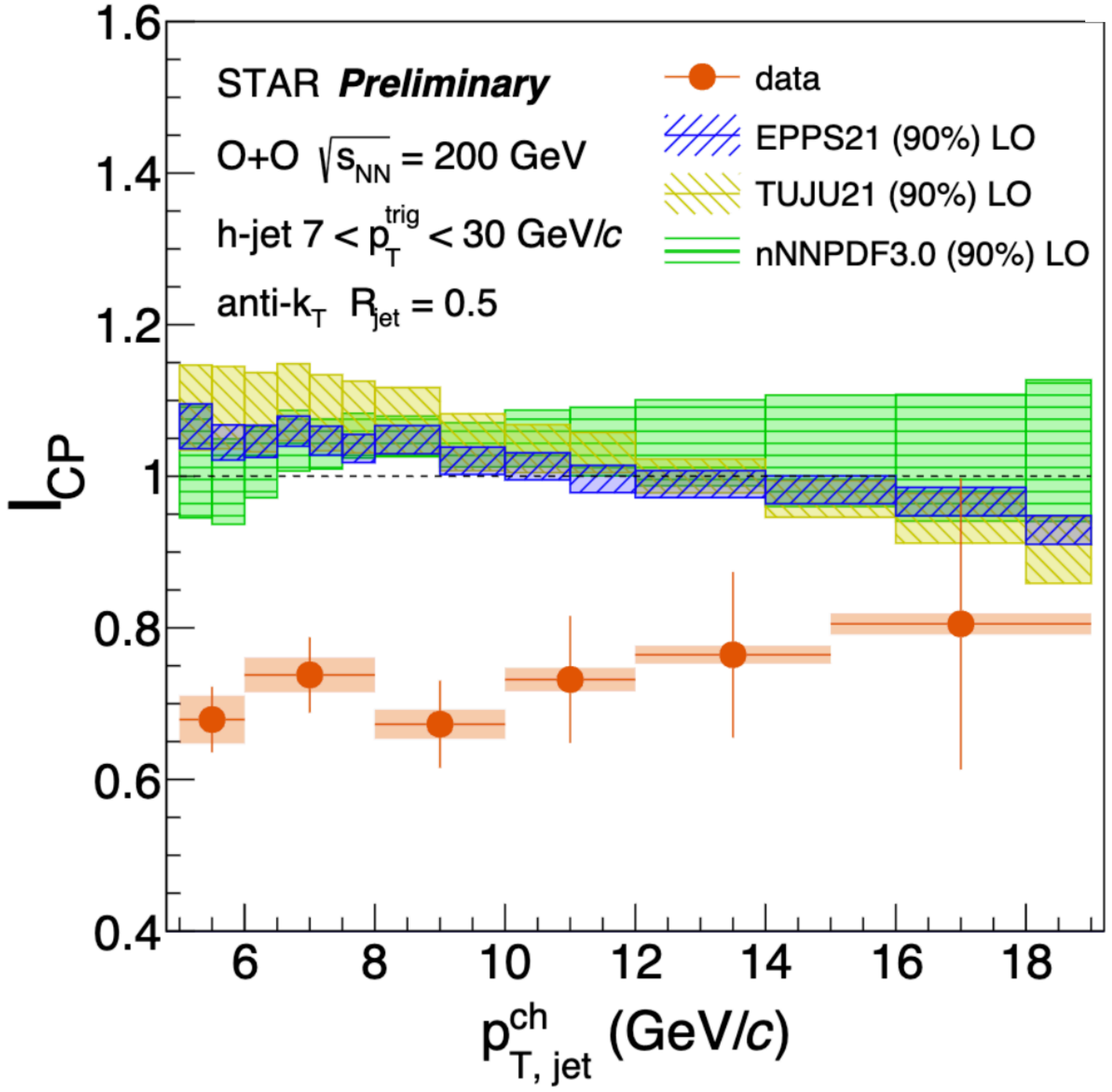
Icp vs. p_T

$^{16}_{8}O +^{16}_{8}O@200GeV$

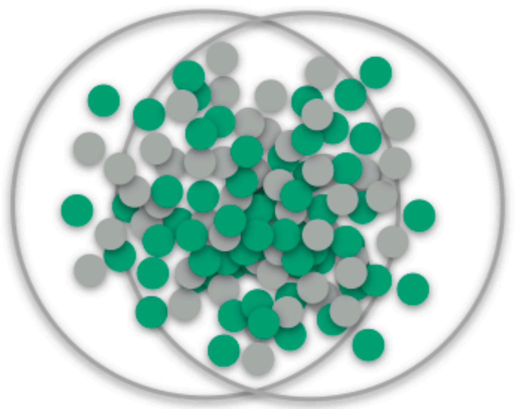


SiJie Zhang Light Ion Workshop 2025



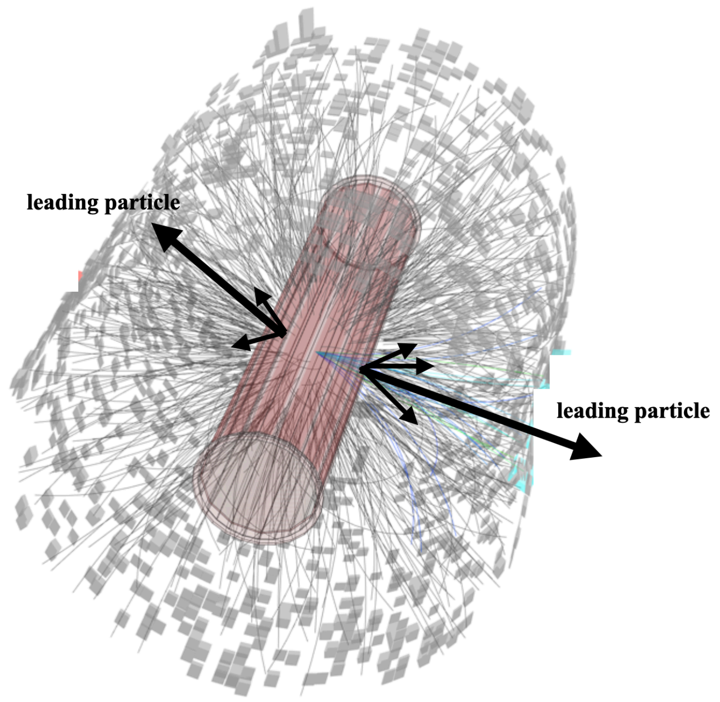


- **$I_{CP} < 1$ indicates a significant suppression of away-side jet yield.**
- **Theoretical calculations without jet quenching fail to describe the experimental data.**

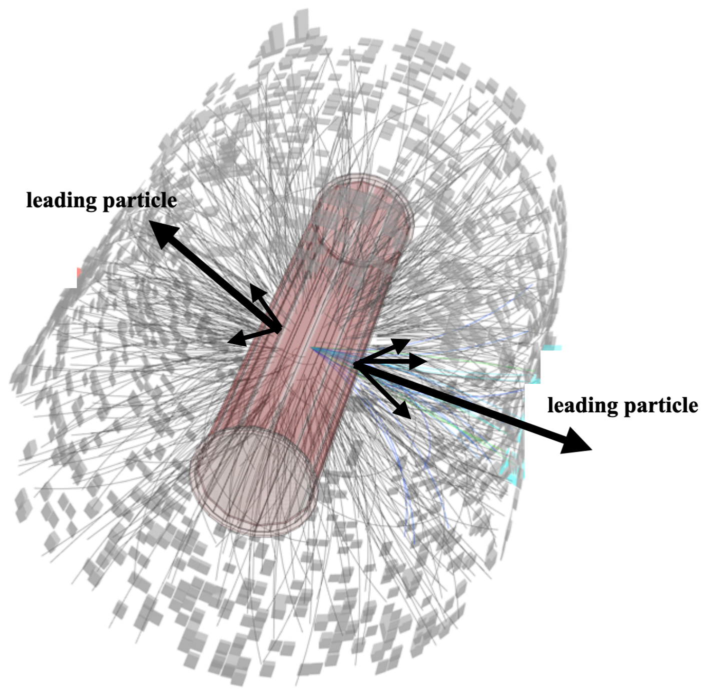


$^{96}_{40}Zr + ^{96}_{40}Zr / ^{96}_{44}Ru + ^{96}_{44}Ru$

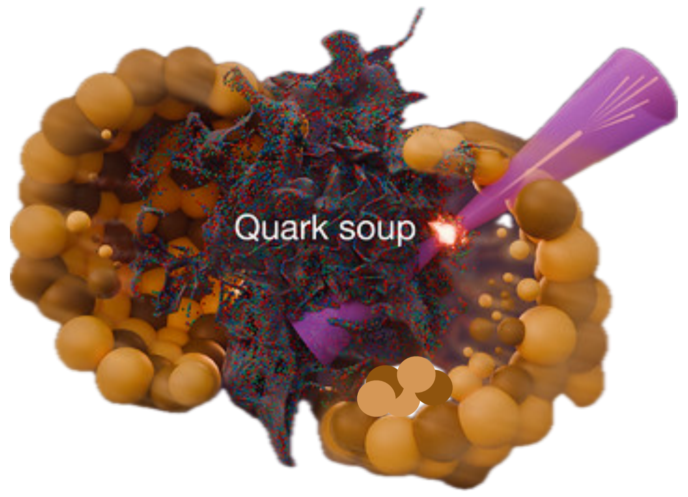
$^{16}_{8}O + ^{16}_{8}O$



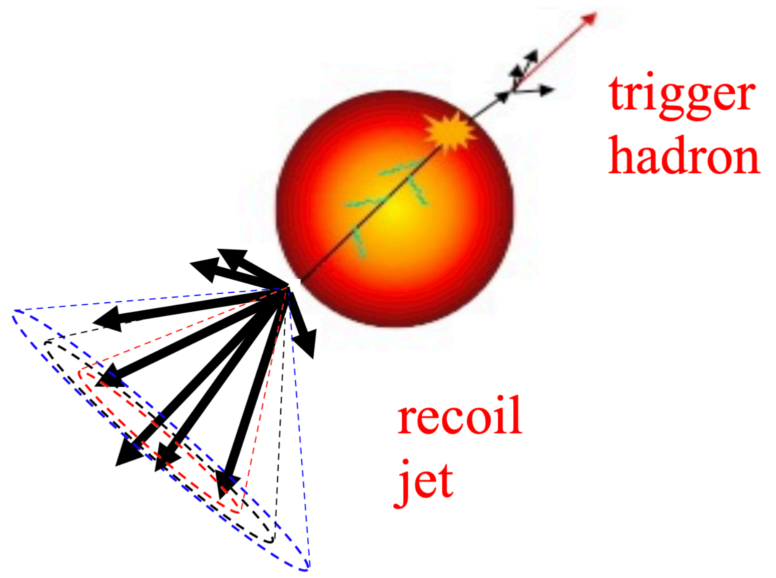
$R_{AA} < 1$



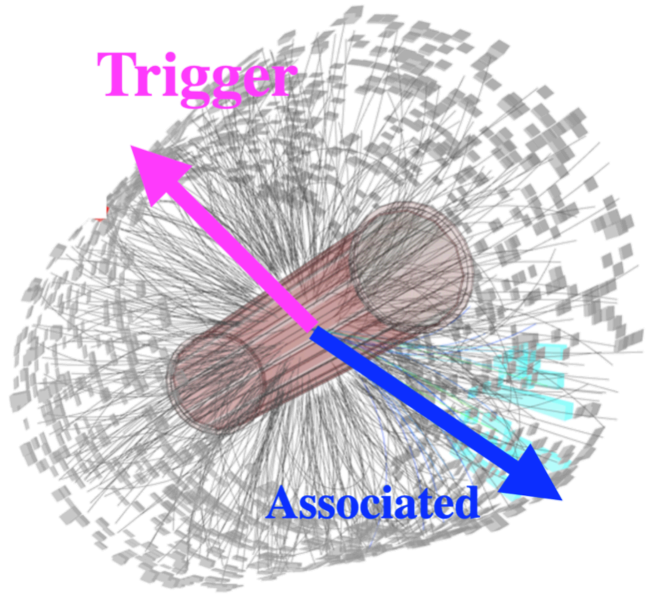
$R_{CP} < 1$



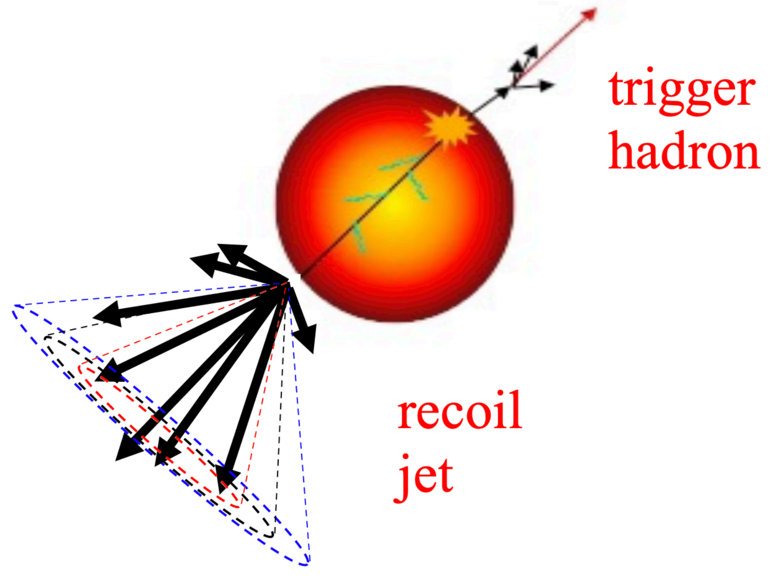
$R_{CP} < 1$



$I_{CP} < 1$

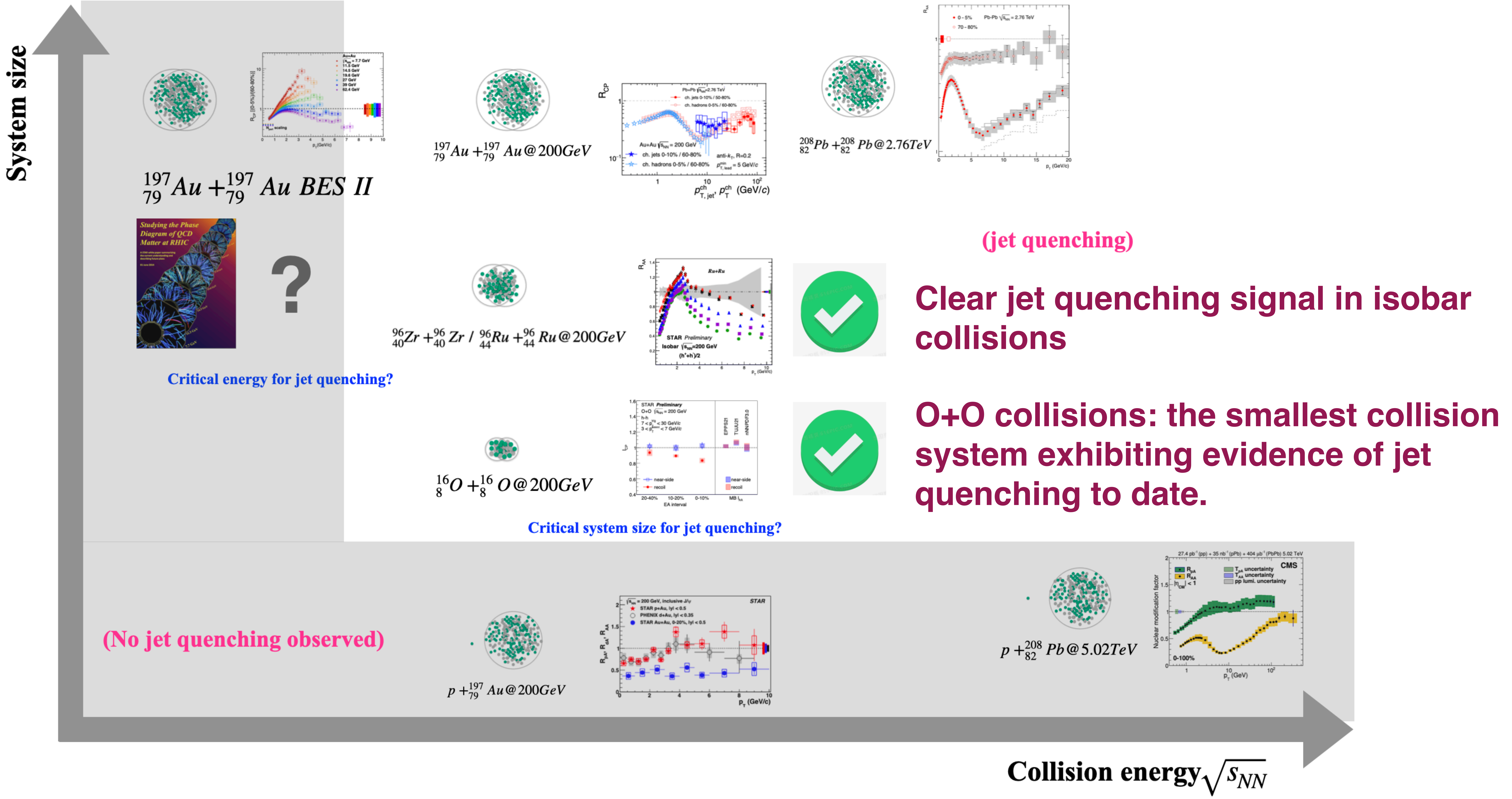


$I_{CP} < 1$



$I_{CP} < 1$

Summary



System size
$^{197}_{79}Au+^{197}_{79}Au\ BES\ II$
Studying the Phase Diagram of QCD Matter at RHIC
?
Critical energy for jet quenching?
$^{197}_{79}Au+^{197}_{79}Au@200GeV$
$^{208}_{82}Pb+^{208}_{82}Pb@2.76TeV$
(jet quenching)
$^{96}_{40}Zr+^{96}_{40}Zr\ /\ ^{96}_{44}Ru+^{96}_{44}Ru@200GeV$
Clear jet quenching signal in isobar collisions
$^{16}_{8}O+^{16}_{8}O@200GeV$
O+O collisions: the smallest collision system exhibiting evidence of jet quenching to date.
Critical system size for jet quenching?
(No jet quenching observed)
$p+^{197}_{79}Au@200GeV$
$p+^{208}_{82}Pb@5.02TeV$
Collision energy $\sqrt{s_{NN}}$

Outlook

- I_{CP} vs. I_{AA}? -> relative suppression vs. absolute suppression.
  - 3.4B low lumi. MB p+p data can serve as a solid baseline.
- Do we also expect medium response in these intermediate-sized collision systems?
  - Jet substructure and jet acoplanarity measurements.
- $\hat{q}$ in these intermediate-sized collision systems.
  - Theoretical inputs are needed.
- Over 10B Au+Au@200GeV data collected in 2023+2025.
  - Precise era of jet physics at STAR.

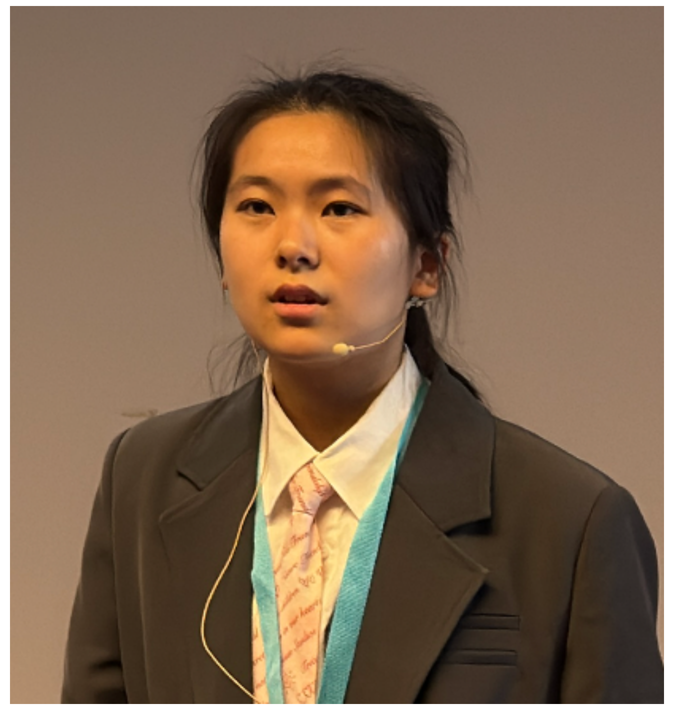
Thanks!

Contact information：

Maowu Nie: maowu.nie@sdu.edu.cn

Li Yi: li.yi@sdu.edu.cn

Thanks to my collaborators

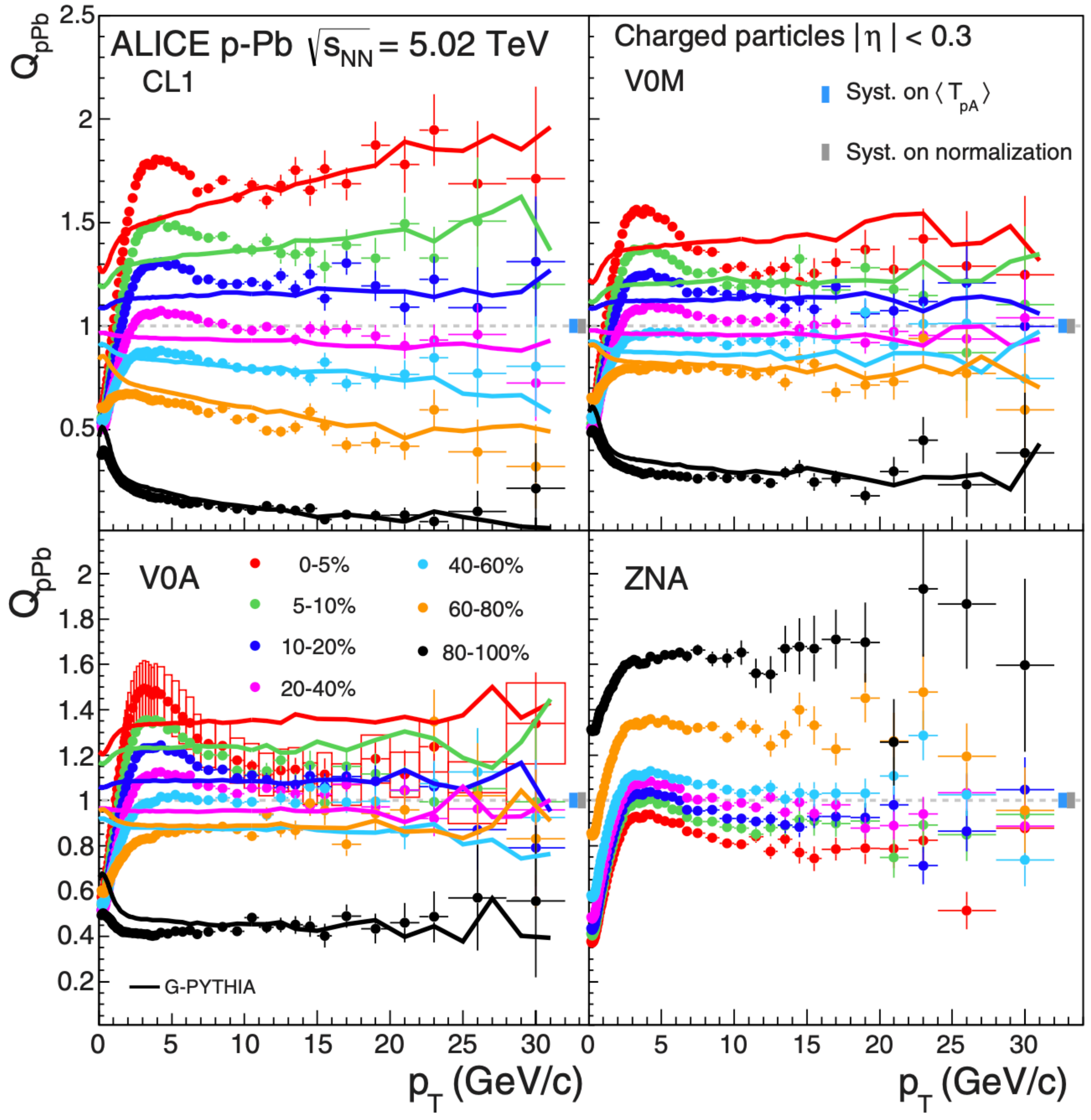



Yang He, Sijie Zhang, Tong Liu, Rongrong Ma, Shanshan Cao, Li Yi, and Helen Caines

Backup

“Multiplicity” bias

- Increased event activity in the presence of a hard-scattering
  - ➡ overestimate hard scattering yields in high-multiplicity events, underestimate them in low-multiplicity events
- This particular bias does not have a strong process ($\gamma_{\rm dir}$ vs. π^0) or kinematic dependence
  - ➡ the PHENIX strategy likely eliminates this particular bias ✅

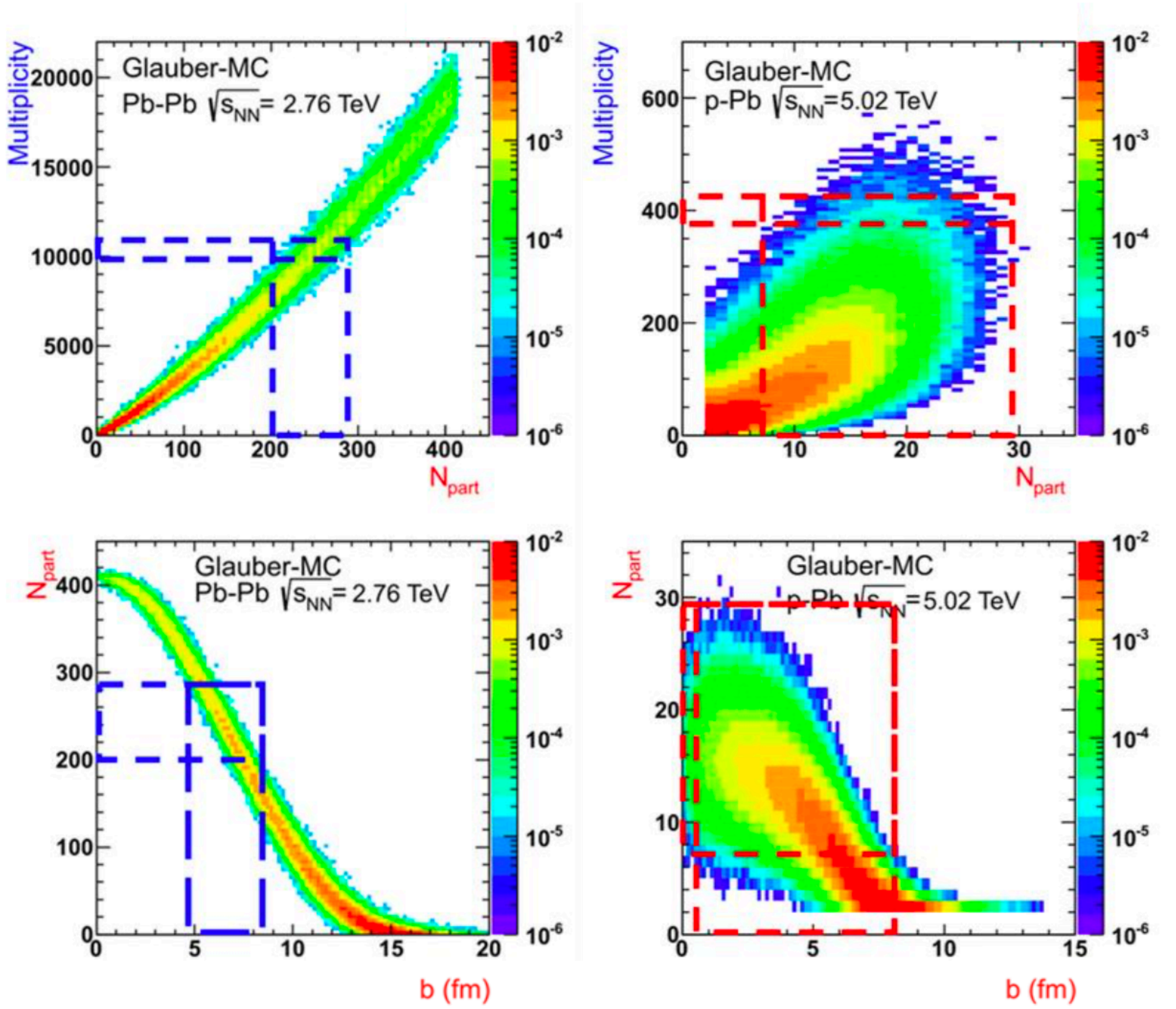


ALICE, PRC 91 (2015) 064905
+ much work by PHENIX, Steinberg, Morsch, Loizides, others

4

Ncoll in Glauber Model

ALICE: PRC91 (2015) 064905

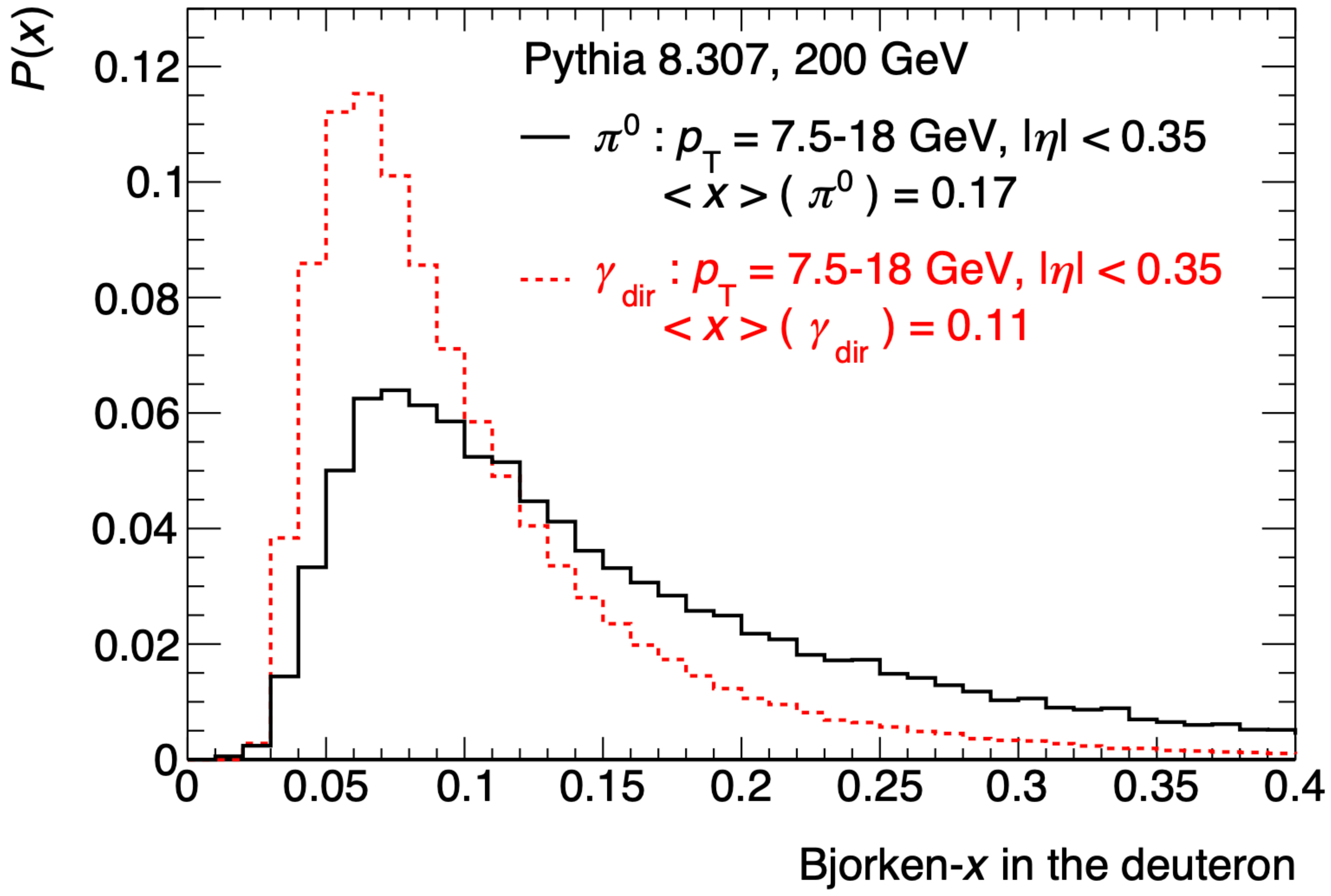


Red axis: theory / model calculations
Blue axis: experimentally measurable

$$\frac{dN_{ch}}{d\eta} \Rightarrow N_{coll} \underbrace{\Longrightarrow}_{Model/Theory} N_{par} \underbrace{\Longrightarrow}_{Theory} b$$

- Multiplicity window = centrality class
  - Measurable
- $N_{coll}^{GL} \propto \left(\frac{dN_{ch}}{d\eta}\right)^{a}$: Not directly measurable!
  - Obtained through Glauber model

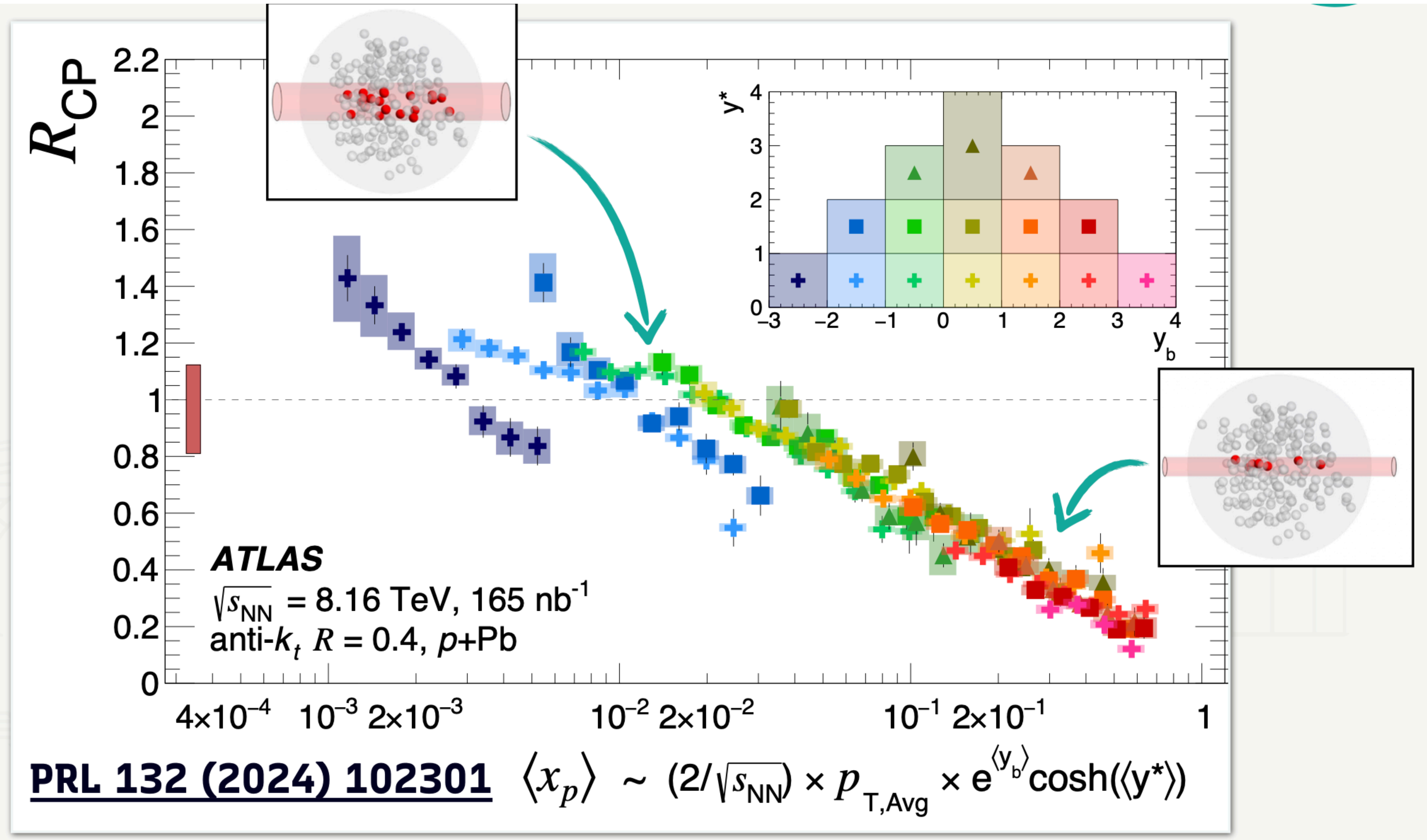
x_p ranges probed by PHENIX measurement



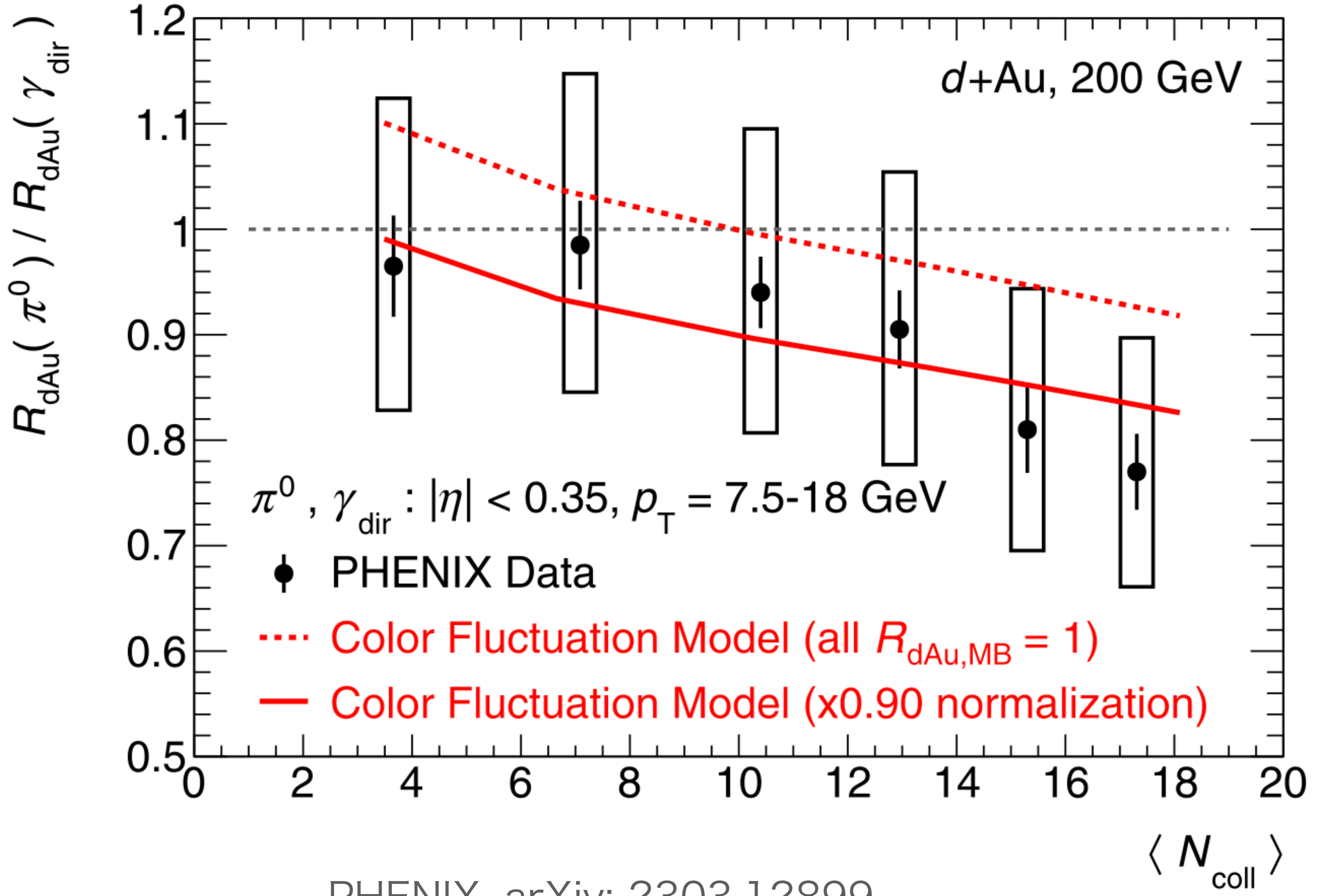
- MC simulation, matching specific PHENIX acceptance & kinematics
- For **direct photons**, typical x_p values probed are $x_p \sim p_T^\gamma / E_{\text{beam}} \sim 0.11$
- However, **neutral pions** carry only a fraction of the fragmenting parton's p_{T}
  - ➡ $\langle x_{\mathrm{p}} \rangle \approx 0.17$, with long tail to large-x_p values (28% from $x_p > 0.2$)
  - ➡ they will incur stronger CFM effects

Evidence of jet quenching in small systems?

p/d +A collisions



ATLAS, Phys. Rev. Lett. 132, (2024) 102301

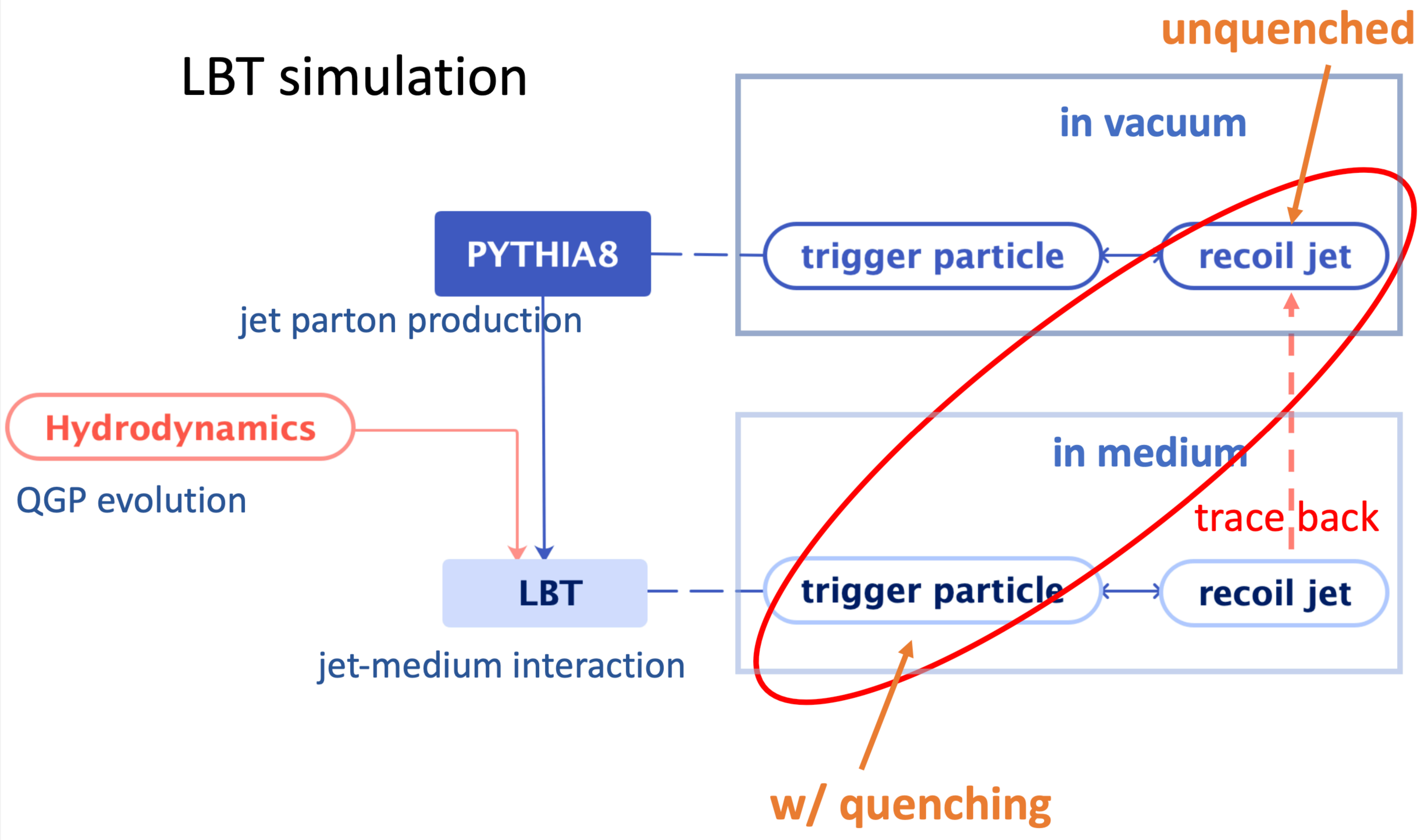


PHENIX, arXiv: 2303.12899,
D. Perepelitsa, Phys. Rev. C 110, L011901 (2024)

- R_{CP} suppression fully driven by the proton configuration.
- PHENIX results can be explained with color fluctuation model.

How do quenched triggers impact I_{AA} ?

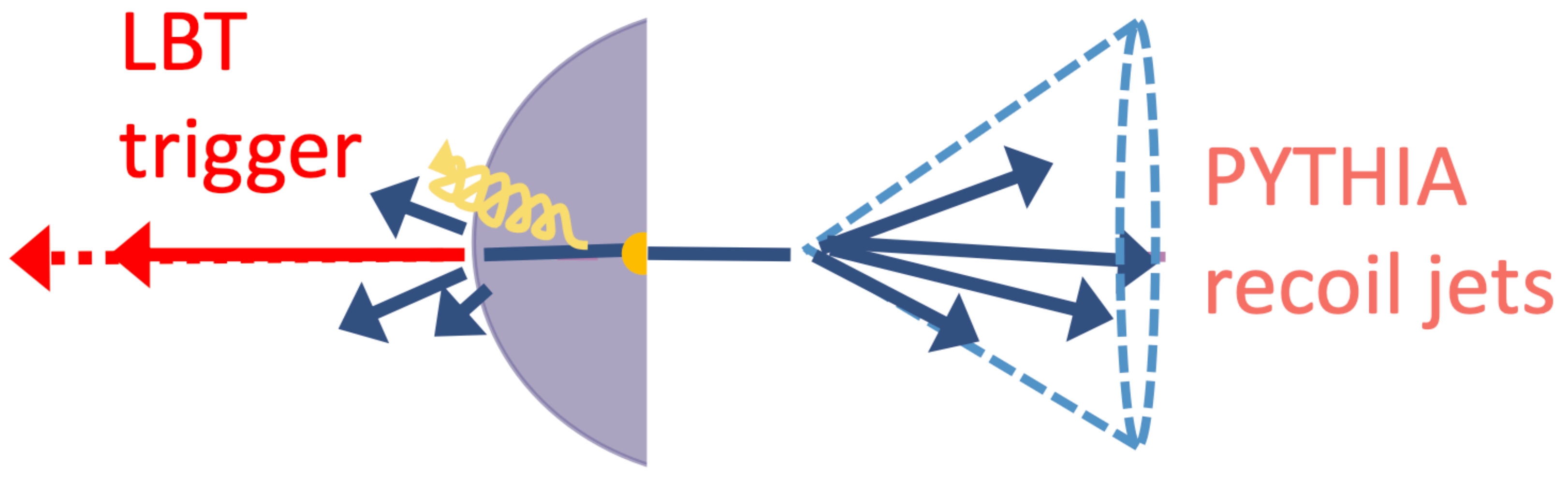
LBT simulation



Construct hybrid sample:

energy loss for trigger partons

no energy loss for recoil jets



"True" baseline

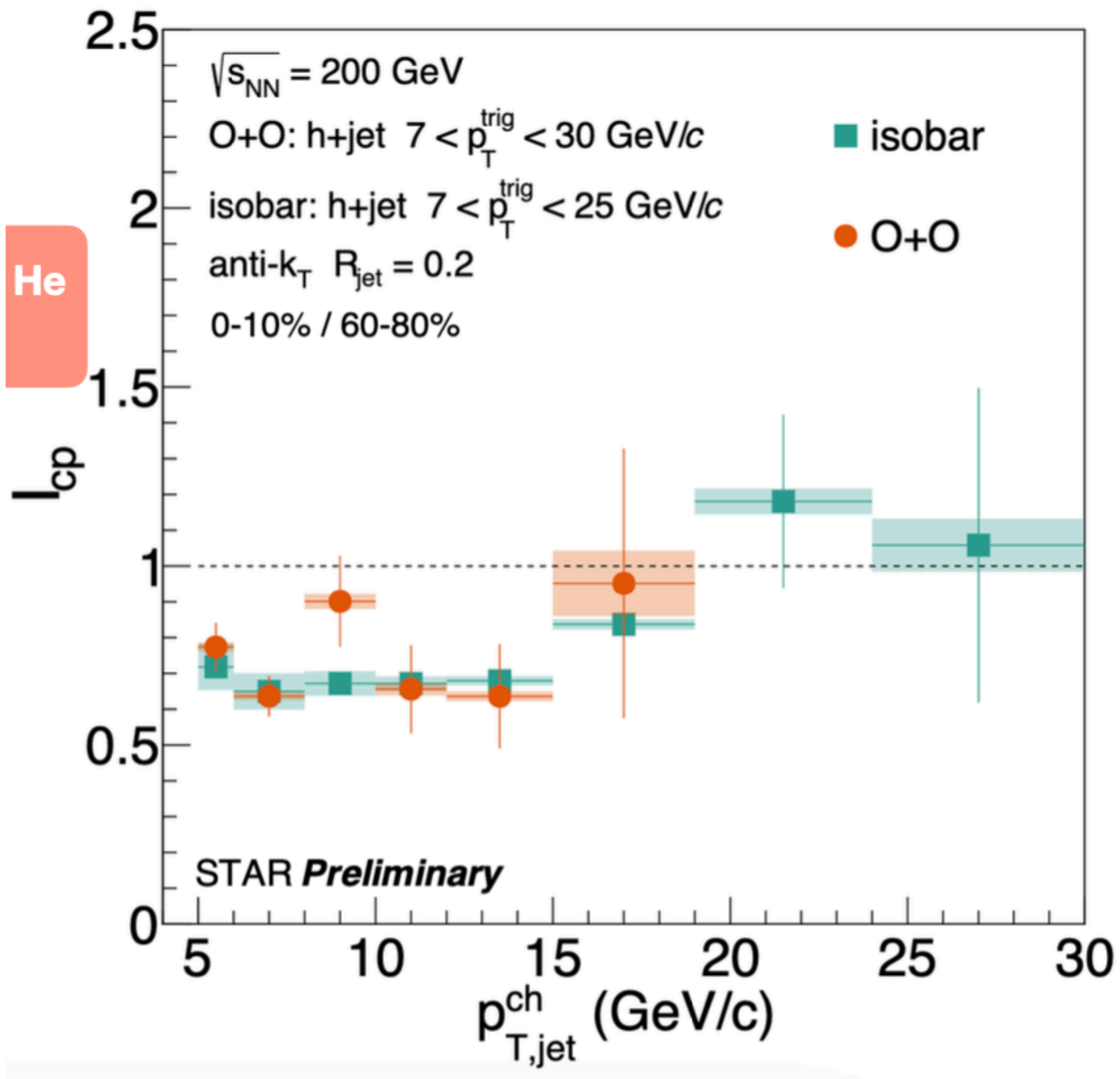
$$I_{AA}^{\text{baseline}} = \frac{1/N_{\text{trig}}^{\text{LBT}} dN_{\text{jet}}/dp_{\text{T,jet}}^{\text{PYTHIA}}}{1/N_{\text{trig}}^{\text{PYTHIA}} dN_{\text{jet}}/dp_{\text{T,jet}}^{\text{PYTHIA}}}$$

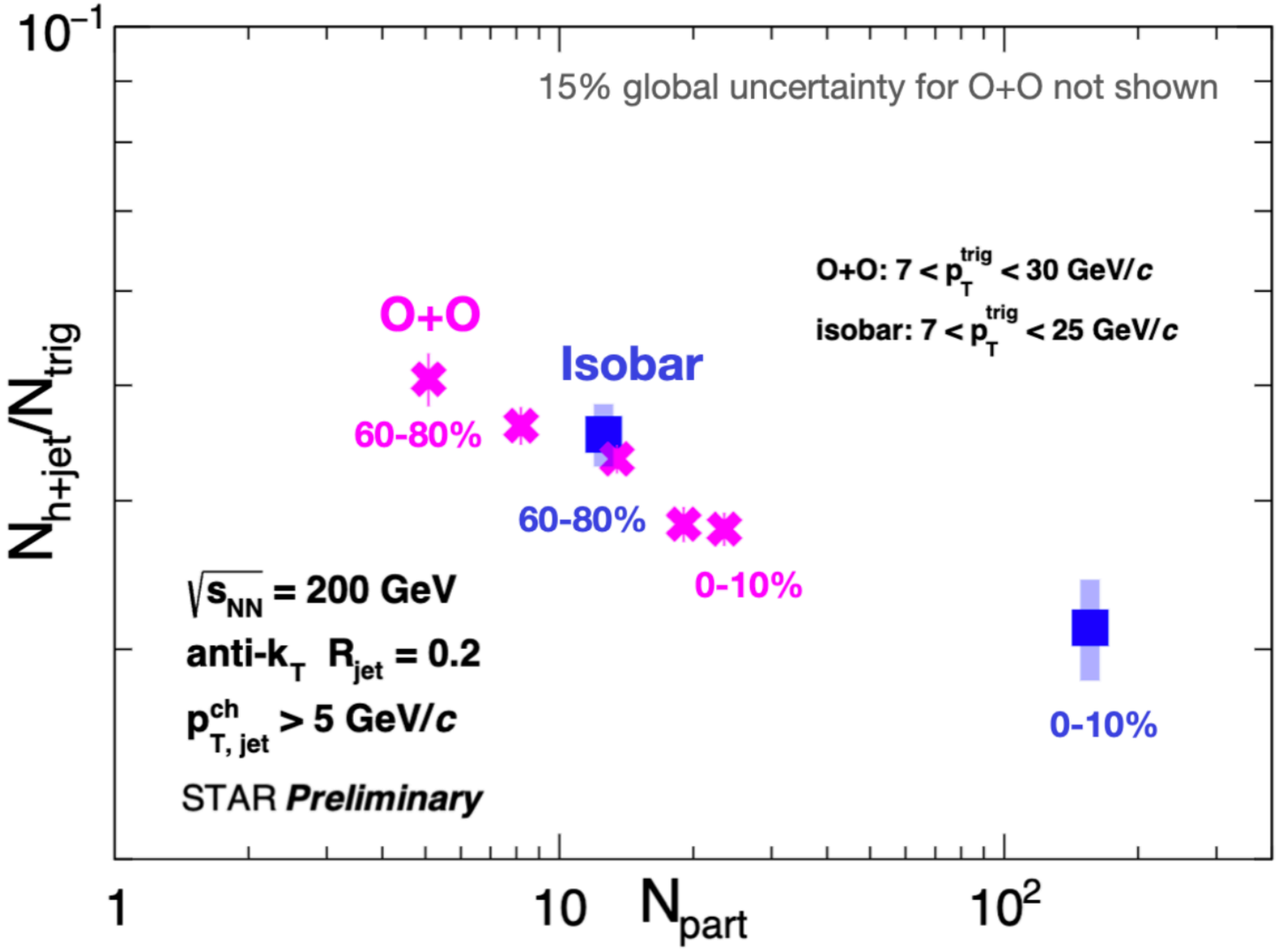
hybrid sample

PYTHIA sample

Trigger energy loss only

I_{cp}: Isobar vs. O+O





Extraction of the medium properties

JETSCAPE, Phys. Rev. C 111, 054913 (2025)