Semi-inclusive γ+jet and h+jet in *STAR experiment*

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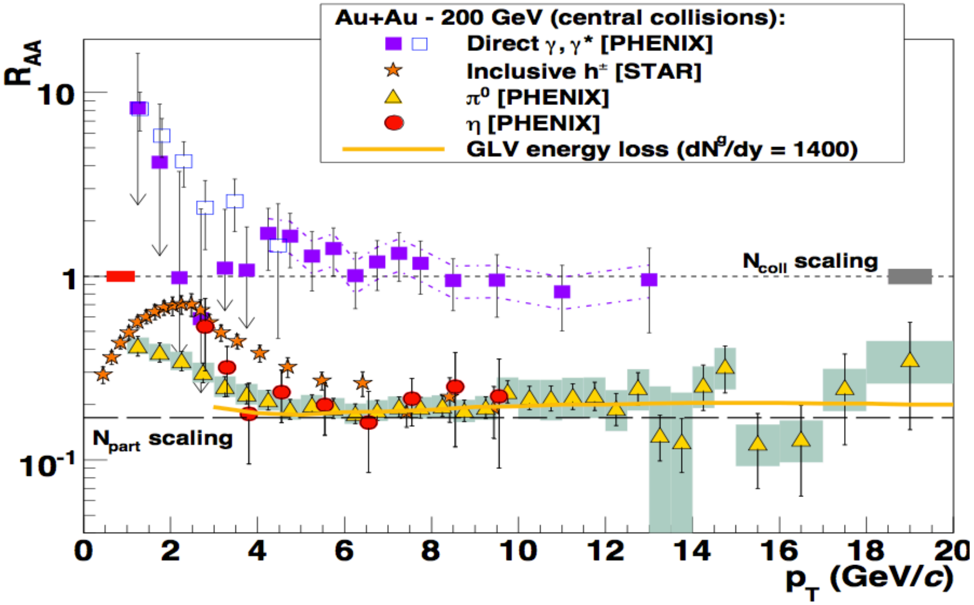
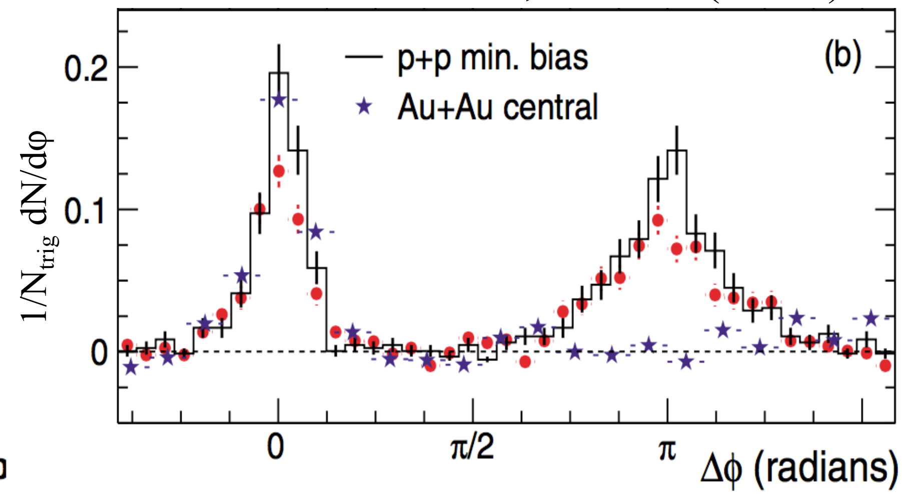
High Energy Nuclear Physics in China (HENPIC), 27 Feb 2020

Jet quenching at RHIC

Early RHIC measurements



STAR: PRL 91, 072304 (2003)



- Suppression of inclusive charged/neutral hadrons at high-p_T
- No suppression of vector-bosons (γ, W, Z)
- Away-side jet suppression

Indication of Hot-dense QCD medium (QGP)

Inclusive hadron p_T spectrum

Jet Fragmentation Functions R_{CP} Jet geometry engineering

I_{CP} Jet shape Dihadron correlations R_{pA} Jet v_2

Dijet acoplanarity Dijet imbalance **Jet-like correlation**

Quark/gluon jet **Jet Quenching** Jet splitting

R_{AA} I_{AA} Inclusive jet Jet mass x_J Nuclear modification factor

Heavy flavor-jet z_g Z+jet Semi-Inclusive jet Jet Charge

Rg Jet substructure

Dijet **γ+jet** Softdrop grooming A+A p+p

π^0+jet hadron+jet Jet+hadron correlation

γ+hadron correlation Large angle deflection

Jet modification in p+p high multiplicity events

Jet as a tool to study QCD at collider experiments

In hot-dense QCD medium:

- Quantitative estimation of parton energy loss

  Its dependence on path length, Casmiri factor, initial parton energy, etc.

- Redistribution of lost energy inside the medium [*Jet R*]
- RHIC vs. LHC [*dependence on temp. and initial gluon density*]

  What about lower beam energy or small system in HIC?

- Modification of jet shape inside a hot QCD medium

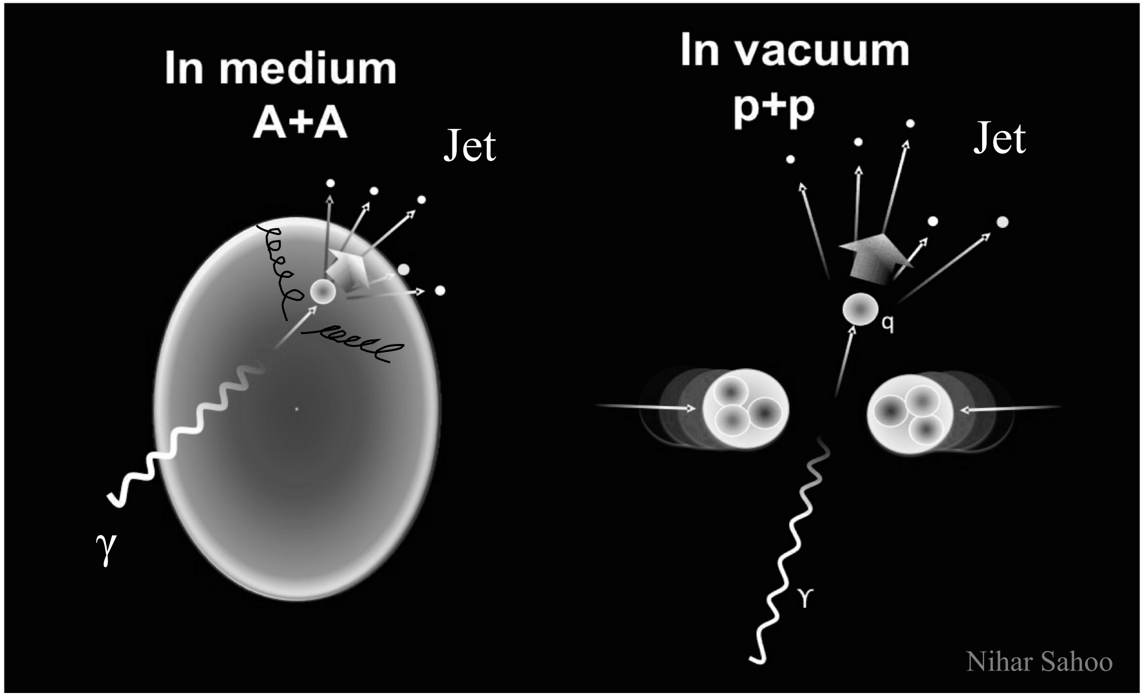
  RHIC vs. LHC

- Deflection of recoil jet

Contents:

- γ+jet and π^0+jet in Heavy-Ion collisions
  - Jet-R dependence of Jet-quenching
  - Large angle deflection of π^0+jet

γ+jet and h+jet in A+A/p+p collisions



γ+jet:

$$qg \rightarrow q\gamma$$

$$q\bar{q} \rightarrow g\gamma$$

Dijet/h+jet:

$$qg \rightarrow gq$$

$$qq \rightarrow qq$$

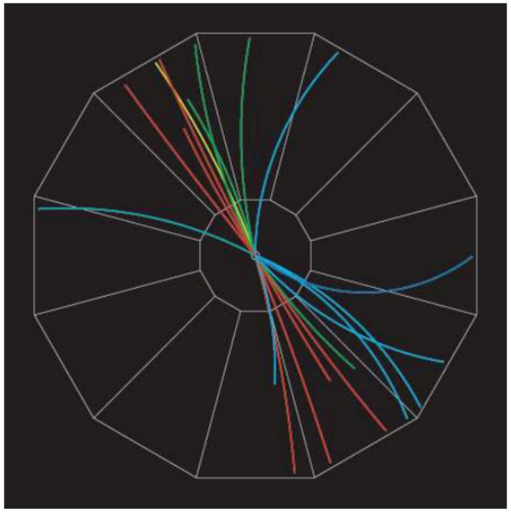
$$\bar{q}q \rightarrow \bar{q}q$$

$$gg \rightarrow gg$$

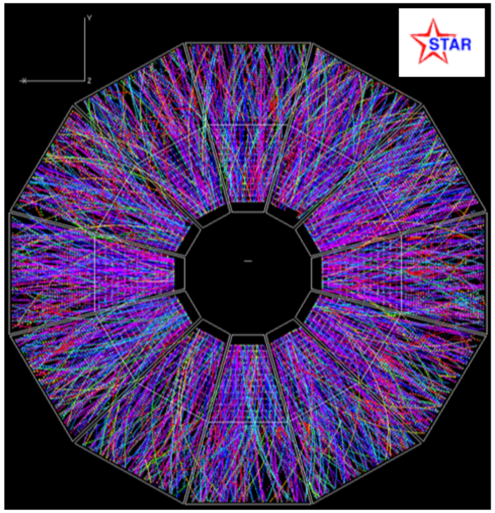
$$\ldots$$

Challenges in heavy-ion collisions to study jet

In Heavy-Ion collisions, Soft background energy fluctuations and uncorrelated jet contributions make it difficult.



$p + p \rightarrow \text{jet} + \text{jet}$



$\text{Au} + \text{Au} \rightarrow \text{X}$

Recently, in RHIC/LHC experiments many techniques/tools are developed to overcome this hurdle

- Jet+hadron, γ+hadron, h+Jet, γ+Jet, Dijet, Inclusive jet, SoftDrop-grooming, etc.

Jet study in heavy-ion collisions

Different ways to study jet-quenching:

- Inclusive hadron spectrum (R_{AA})
- Jet-like azimuthal correlation (I_{AA} : Di-hadron, γ+hadron, Z+hadron (LHC) correlations)
- Semi-inclusive recoil jet (I_{AA}: h+jet, γ+jet, Z+jet, etc)
- Inclusive jet measurement (R_{AA})

Difference between R_{AA} and I_{AA} :

$$\frac{\text{Hot and dense QCD medium}}{\text{Vacuum}}$$

$$\sim \frac{O_{A+B}(p_T, \eta, \phi)}{O_{p+p}(p_T, \eta, \phi)}$$

$$\sigma_{AB}^{hard} = T_{AB}\ \sigma_{pp}^{\text{hard}} \rightarrow R_{AA}$$

$$\sigma_{AB}^{hard} = \sigma_{pp}^{\text{hard}} \rightarrow I_{AA}$$

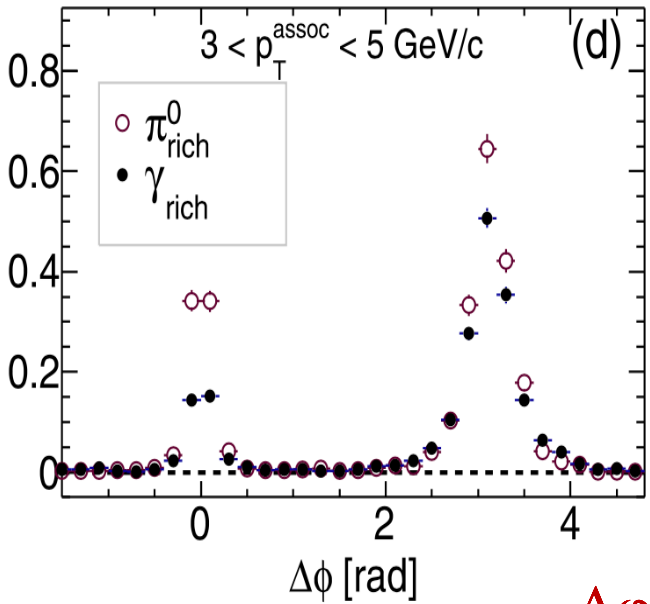
Jet-like γ_{dir}+hadron and π^0+hadron correlations

Mid-rapidity: $|\eta| < 1.0$

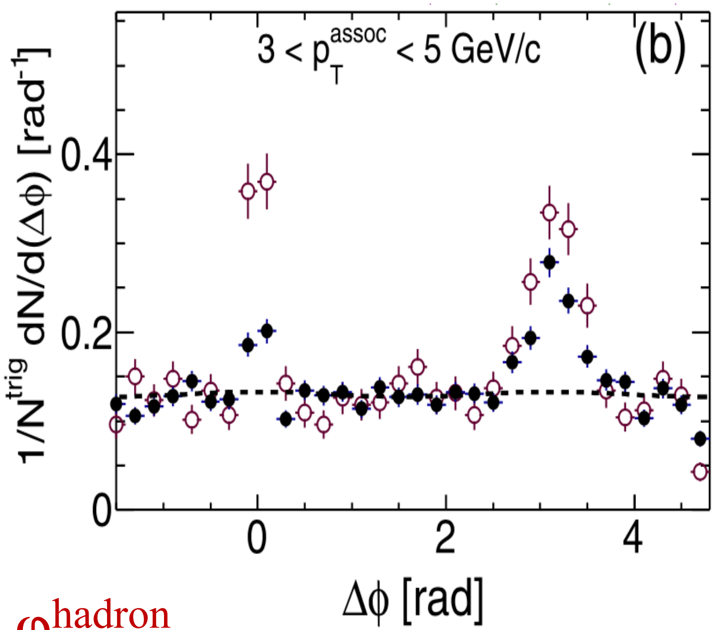
STAR: PLB 760 (2016) 689

$12 < p_T^{\gamma/\pi 0} < 20$ GeV/c

p+p 200 GeV collisions



Au+Au 200 GeV collisions



$\Delta\varphi = \varphi^{trig} - \varphi^{hadron}$

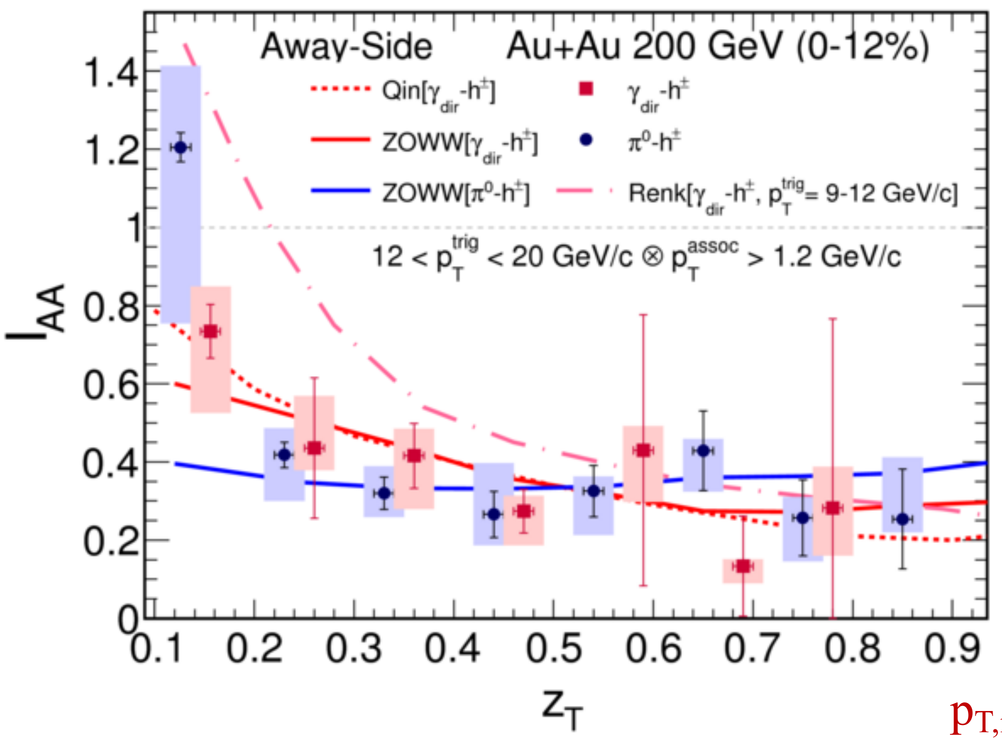
- γ_{rich} enriched sample of γ_{dir}
- In p+p collisions, uncorrelated background is negligible compared to Au+Au

Nuclear Modification factor

γ_{dir}+hadron and π^0+hadron correlations

$$I_{AA}(x) = \frac{Y^{Au+Au}(x)}{Y^{p+p}(x)}$$

STAR: PLB 760 (2016) 689



$$z_T = \frac{p_{T,i}^{hadron}}{p_T^{trig}}$$

- Soft associated particles are less suppressed compared with high p_T
- Within uncertainty, no trigger (γ_{dir}/ π^0) bias can be observed

Nuclear Modification factor

γ_{dir}+hadron and π^0+hadron correlations

$$I_{AA}(x) = \frac{Y^{Au+Au}(x)}{Y^{p+p}(x)}$$

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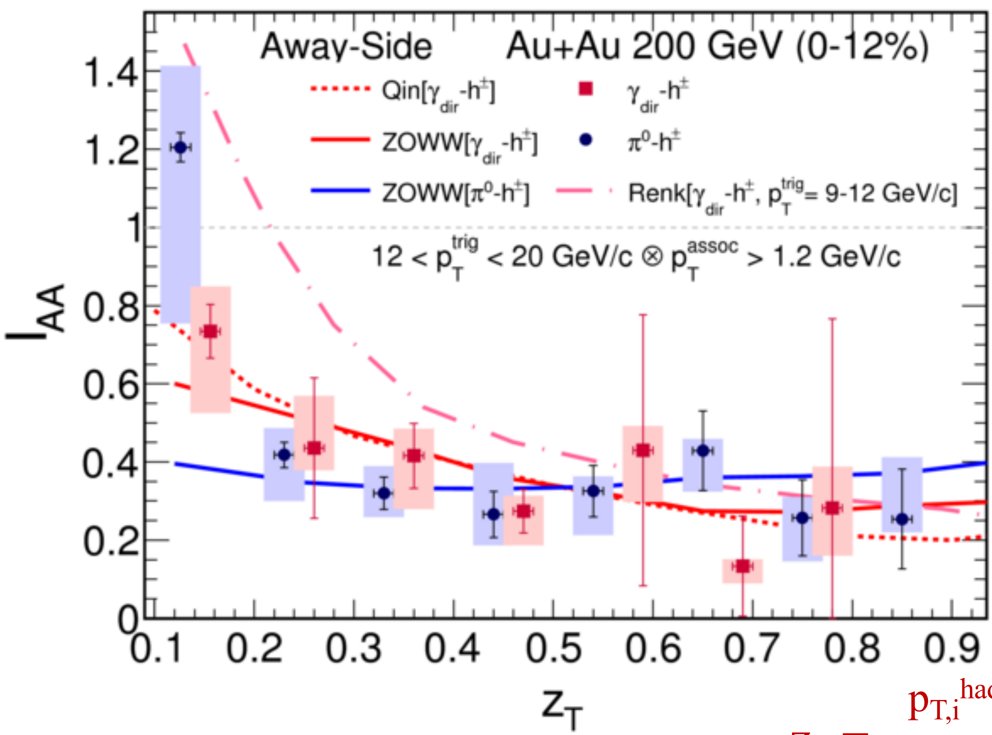
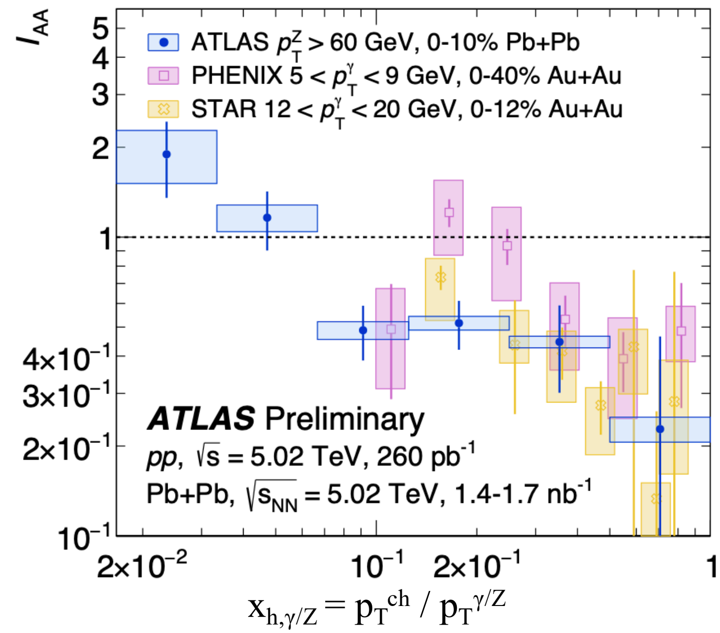


$$z_T = \frac{p_{T,i}^{hadron}}{p_T^{trig}}$$

γ/Z + jet: RHIC vs. LHC

LHC: Dennis V. Perepelitsa, QM19



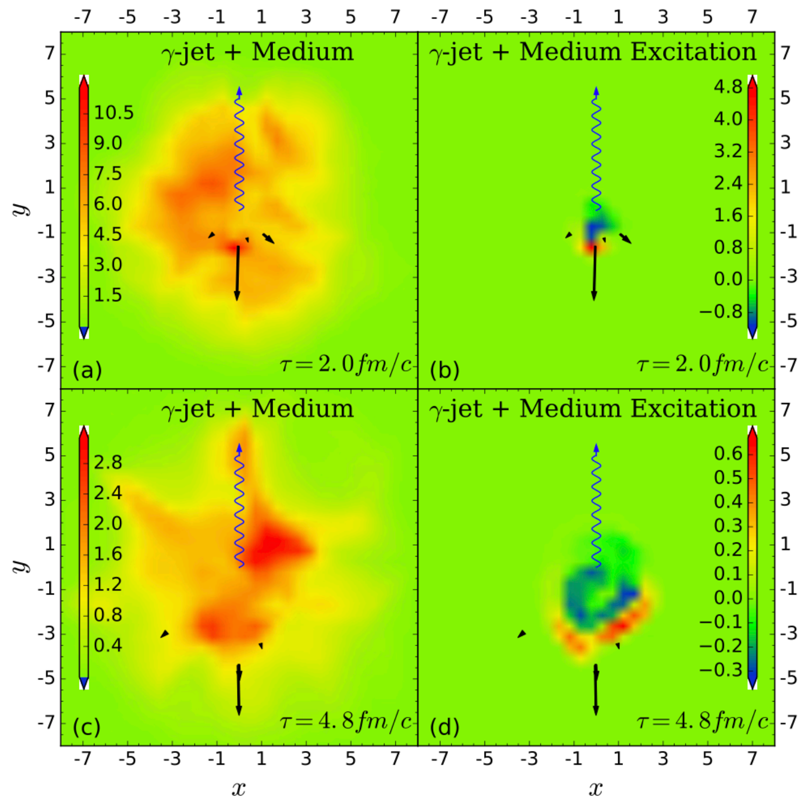
LHC vs. RHIC: Almost same suppression
(Caveat: centrality, phase space, etc.)

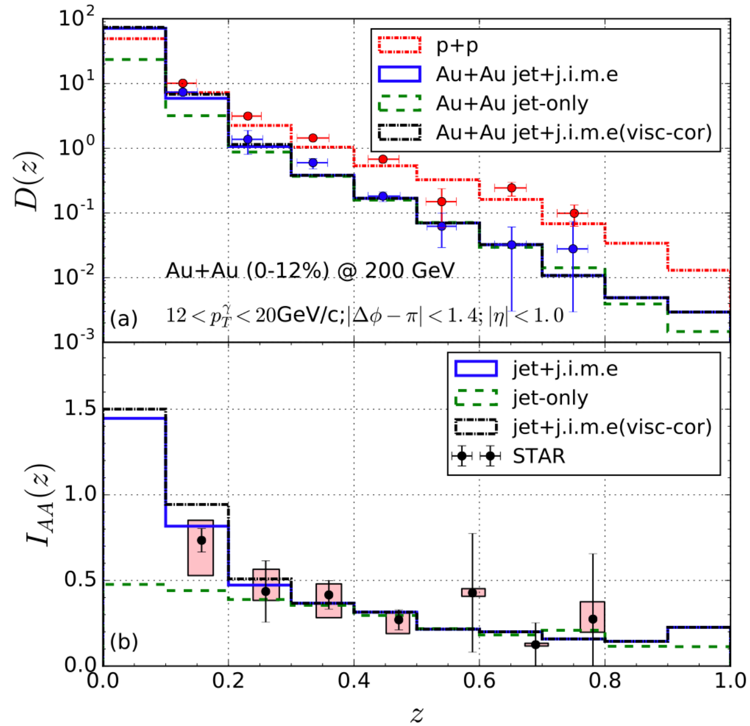
- Soft associated particles are less suppressed compared with high p_T
- Within uncertainty, no trigger (γ_{dir}/ π^0) bias can be observed

γ_{dir}+hadron: Theoretical development (CoLBT-hydro)

Jet transport and jet-induced medium excitation in CoLBT-hydro simulations.

W. Chen *et al.*, PLB 777 (2018) 86–90





Depletion of soft hadrons in γ direction

→ Diffusion wake left behind by the jet in QGP.

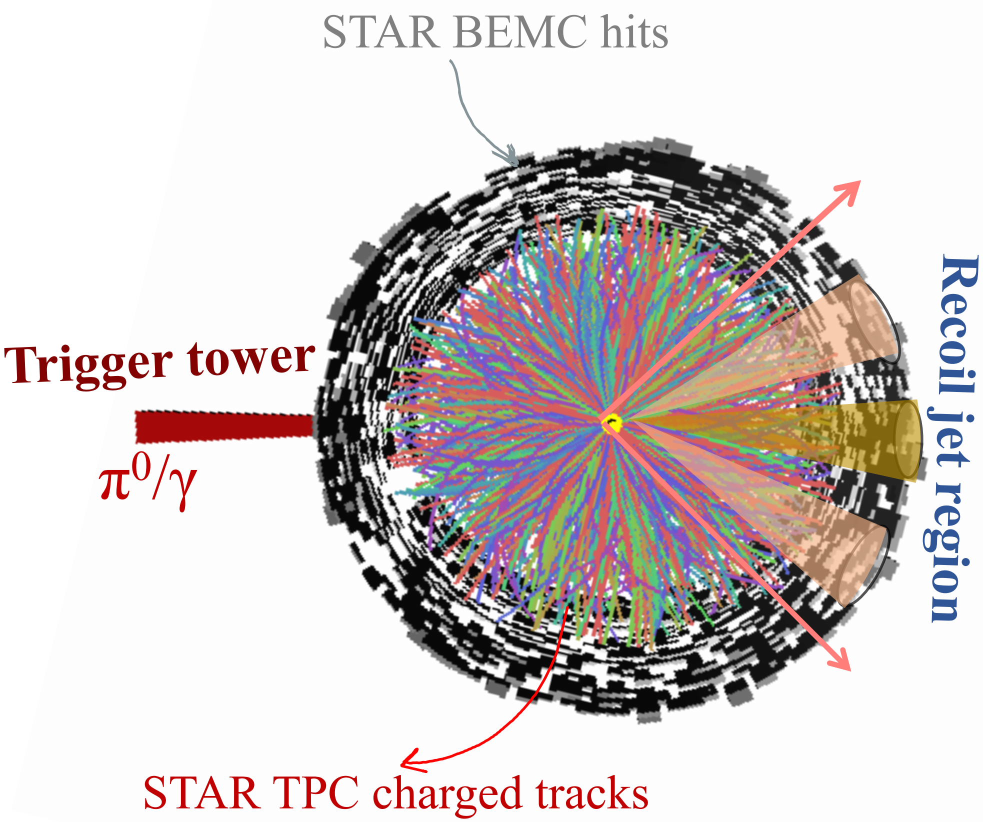
Data can be well reproducible by this model.

Ongoing work in the STAR experiment:

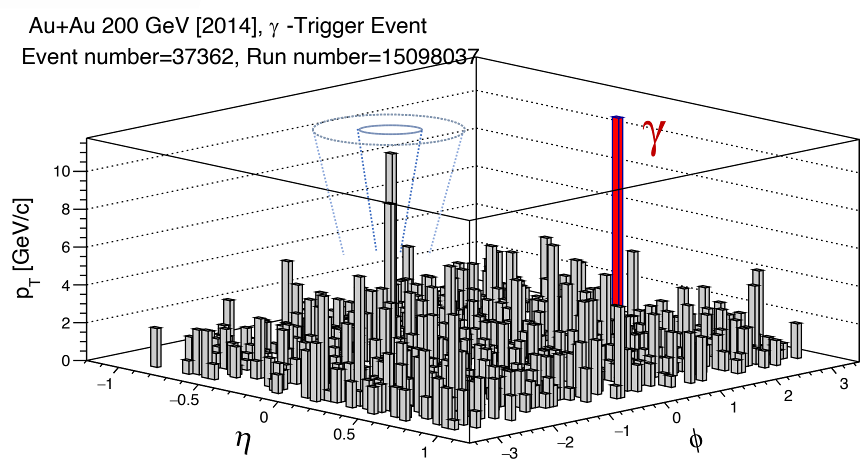
Semi-inclusive γ+jet and π^0+jet using jet reconstruction

Jet study in a high soft-background energy environment

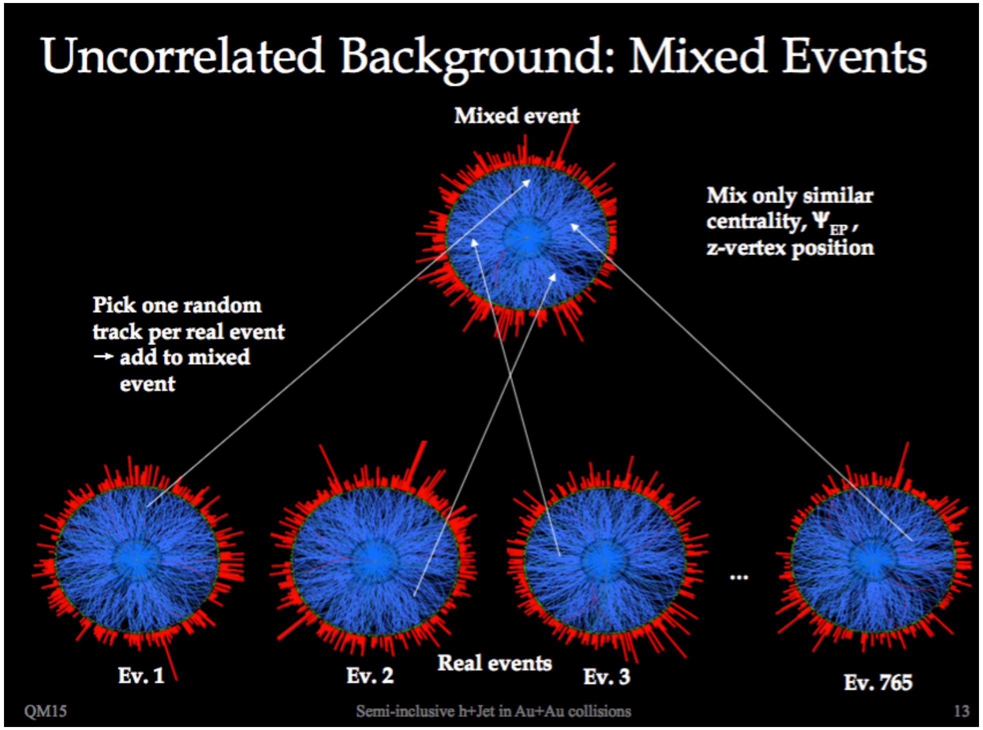
In Heavy-Ion collisions: Soft-background energy fluctuations and uncorrelated jet background contributions make life difficult.

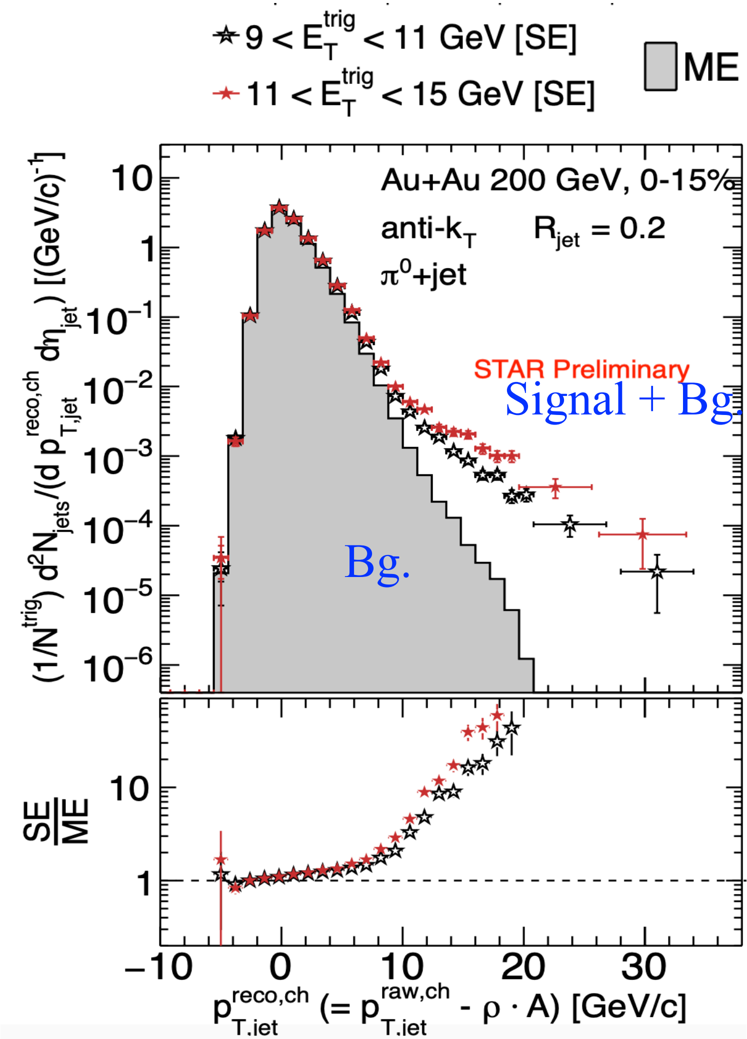


One trigger event



Mixed event: Uncorrelated jet subtraction



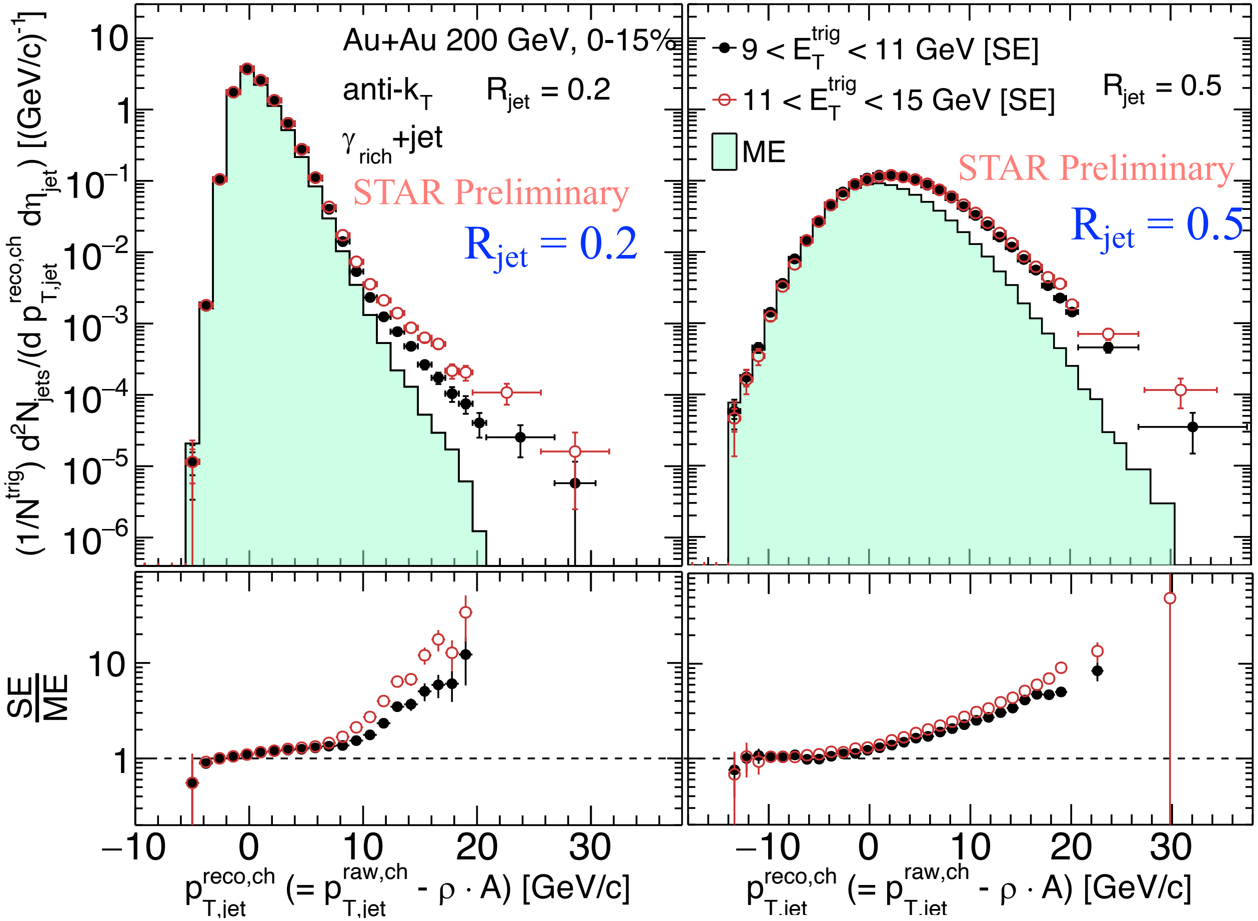


Same Event (SE) and Mixed Event (ME): same background energy density

An important tool to study semi-inclusive jet measurement at mid- and forward-rapidity.

γ_{rich}+jet at mid-rapidity in Au+Au collisions

Recoil charged jet spectrums for different trigger E_T windows



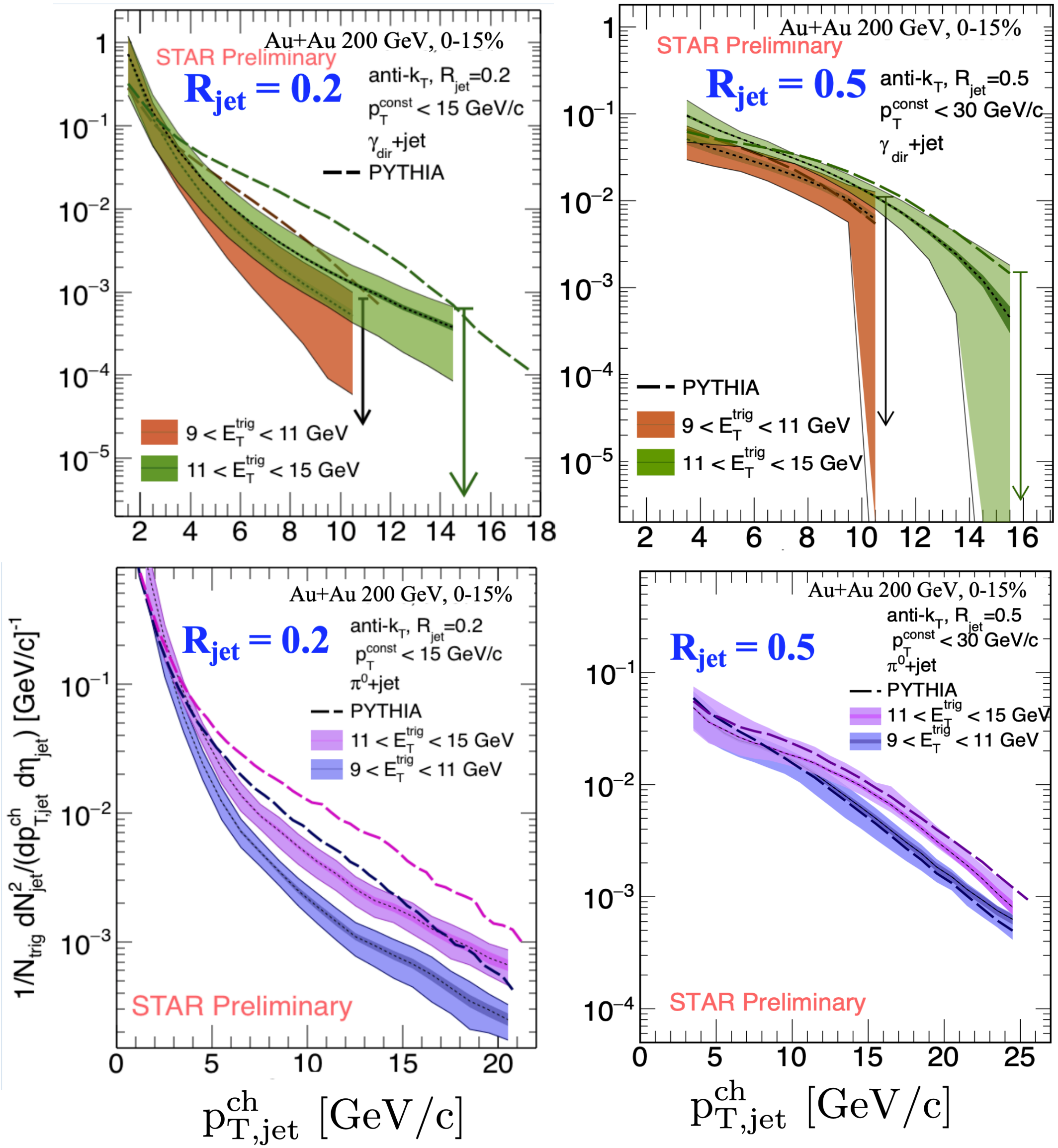
STAR: Nihar Sahoo, QM2019

A clear trigger dependence can be seen.

- γ_{rich} enriched sample of γ_{dir}

γ_{dir}+jet/π^0+jet at mid-rapidity in Au+Au collisions

Recoil charged jet spectrums for different trigger E_T windows and jet radii



After full correction: uncorrelated jet bkg. and detector effects

→ γ_{dir}+jet

→ π^0+jet

STAR: Nihar Sahoo
HP2018, QM2019

Work is underway to improve systematic uncertainties and also $15 < E_T^{trig} < 20$ GeV.

Nuclear Modification factor

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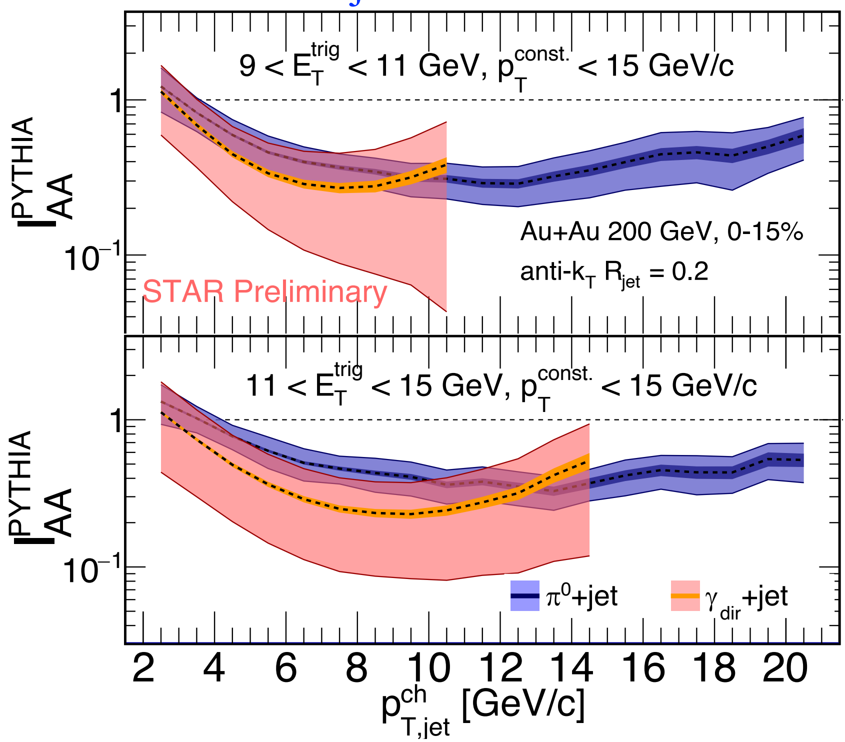
HP2018,QM2019

$$I_{AA}(p^{ch}_{T,jet}) = \frac{Y(p^{ch}_{T,jet})^{Au+Au}}{Y(p^{ch}_{T,jet})^{p+p}}$$

$R_{jet} = 0.2$



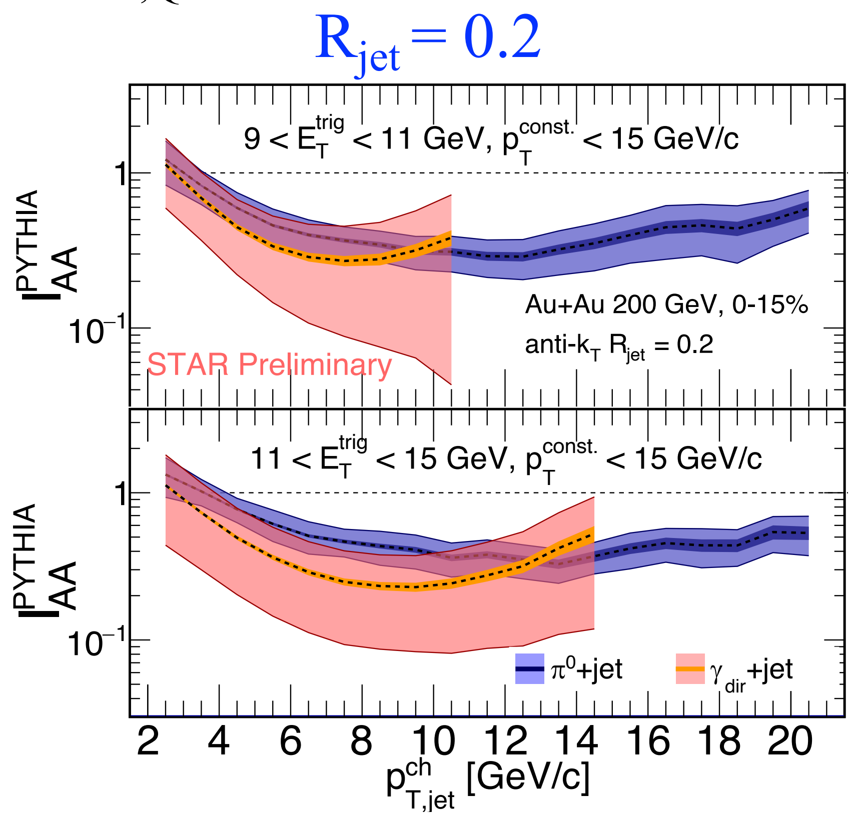
Compelling observations at RHIC:

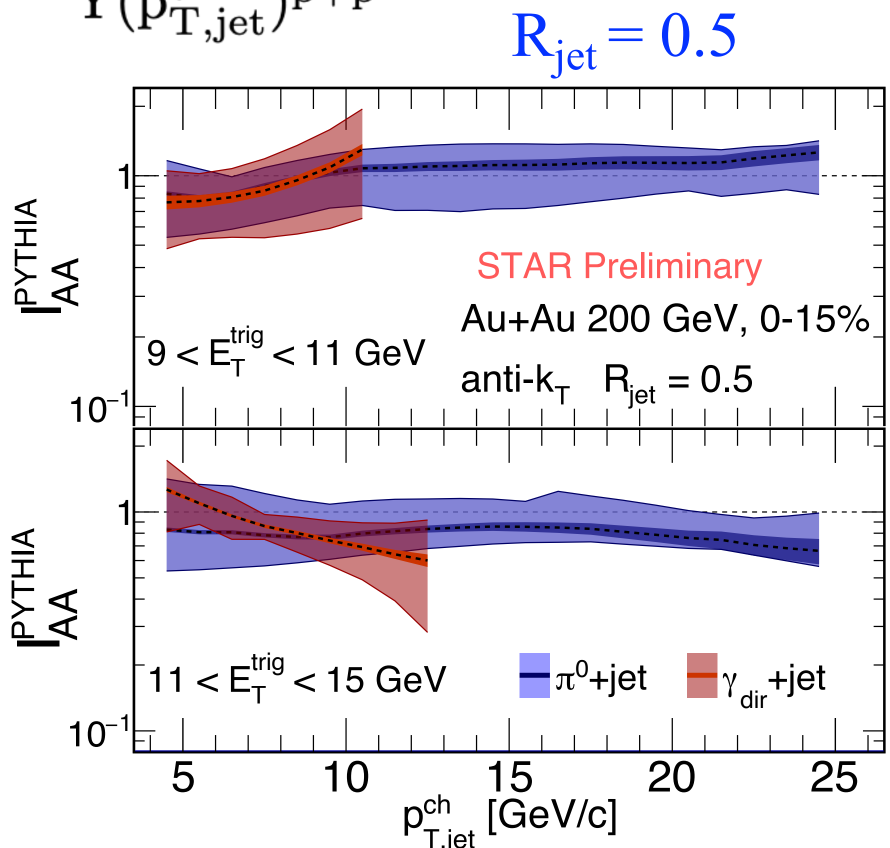
- Recoil jet with R_{jet} =0.2 → strong suppression;
- Same level of suppression for γ_{dir}+jet and π^0+jet

Nuclear Modification factor: Au+Au 200 GeV

STAR:
Nihar Sahoo,
HP2018,QM2019

$$I_{AA}(p^{ch}_{T,jet}) = \frac{Y(p^{ch}_{T,jet})^{Au+Au}}{Y(p^{ch}_{T,jet})^{p+p}}$$



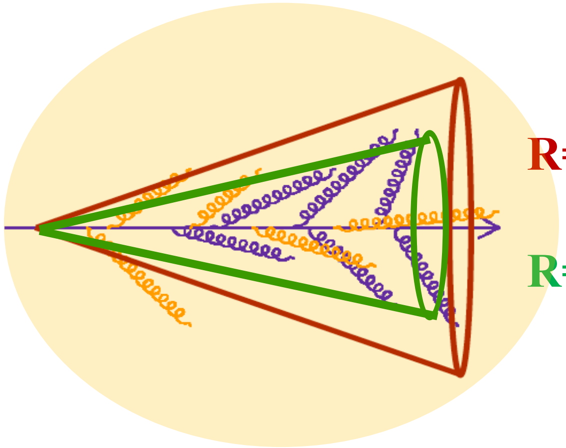


Compelling observations at RHIC:

- Recoil jet with R_{jet} =0.2 → strong suppression;
  whereas for R_{jet}=0.5 → relatively less suppression.
- Same level of suppression for γ_{dir}+jet and π^0+jet

In-medium recoil jet suppression at RHIC and LHC

In-medium parton shower



From this γ_{dir}+jet and π^0+jet measurement and h+jet [PRC 96, 024905 (2017)];
What do we observe?

Larger medium-induced recoil jet yield suppression for R=0.2 than for R=0.5

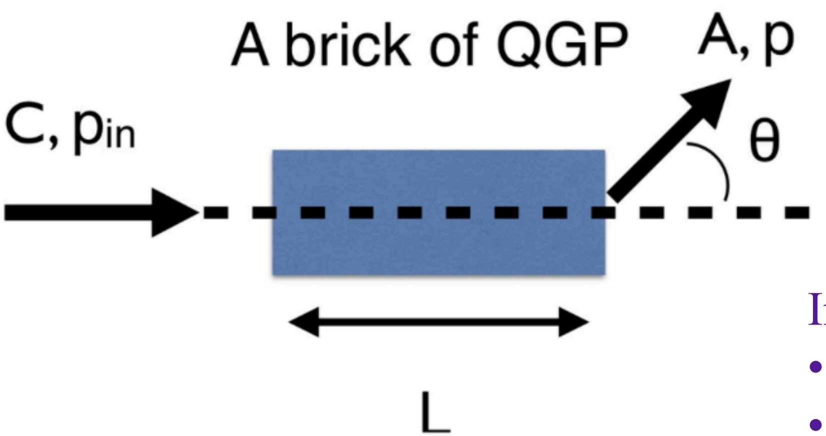
This level of recovery in jet suppression at RHIC energy has not been yet observed at the LHC.

- Different techniques for measuring jet in different experiments
- Does it indicate that jet-quenching at RHIC and LHC are different?
  Jet-shape modification

[We are exploring in current measurement to address this in some extent.]

Dijet Δφ angular correlation:
A large angle deflection in HICs

Single scattering in a brick of QGP



QCD Molière Scattering: A rare large angle scattering

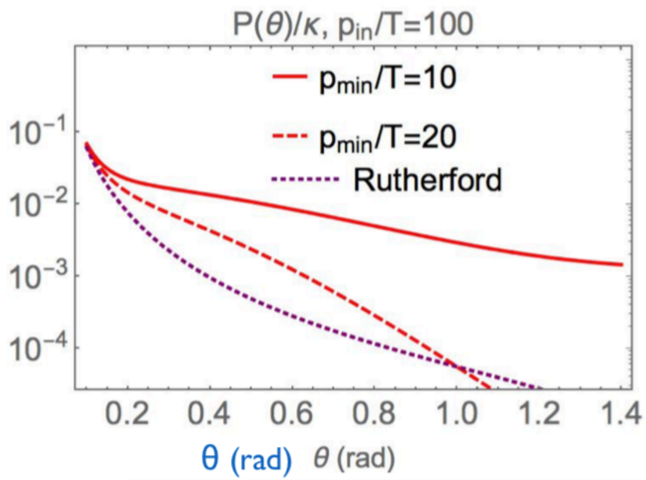
F. D'Eramo, K. Rajagopal, Y. Yin: JHEP01(2019)172

In hot-dense QCD

- Can we observe this effect?
- What is the parton momentum range?
- What is the QCD medium response?

Equally important to study this effect in the cold QCD matter?

Angle distribution $P(\theta) \equiv \int_{p_{\min}} dpF(p,\theta)$

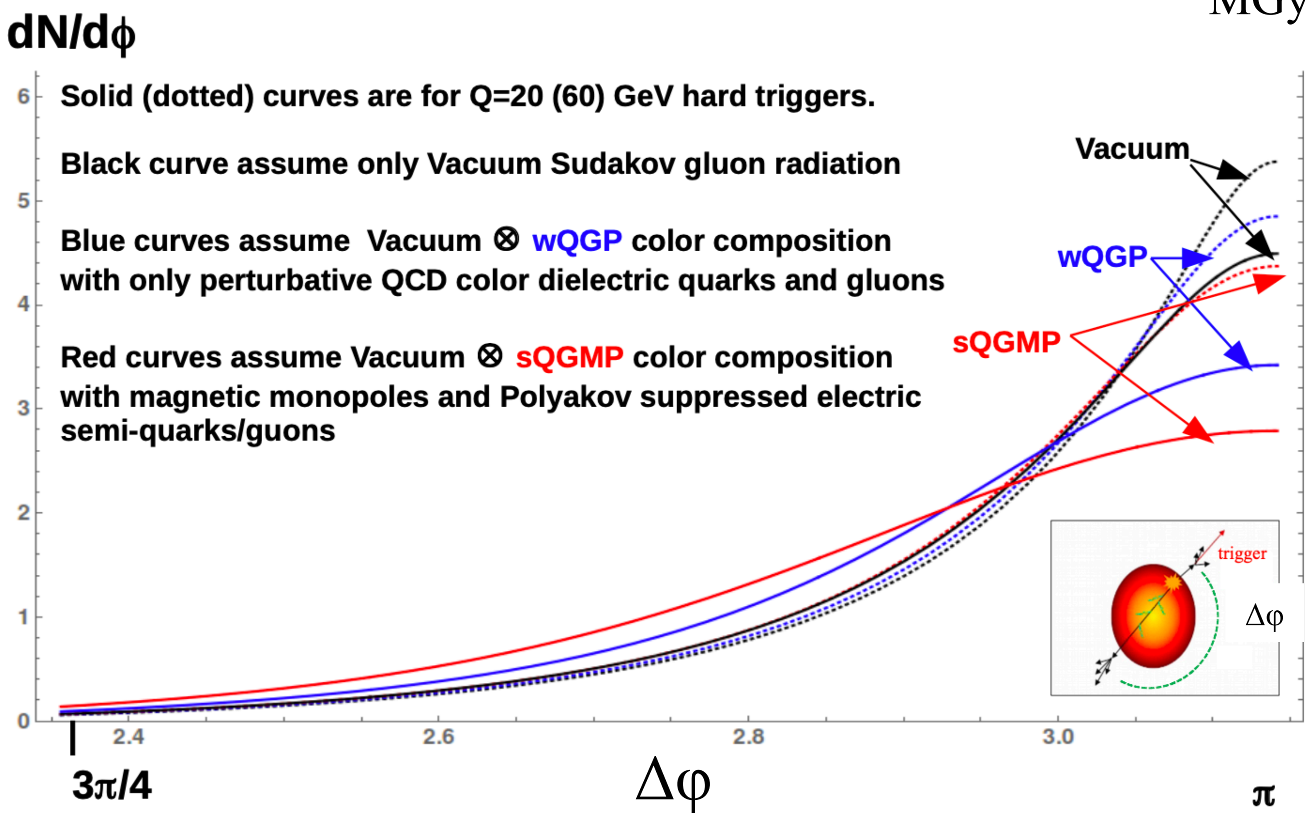


(An incident gluon with initial energy p_i =100T.)

Rutherford Scattering like, gg→gg

Dijet acopanarity

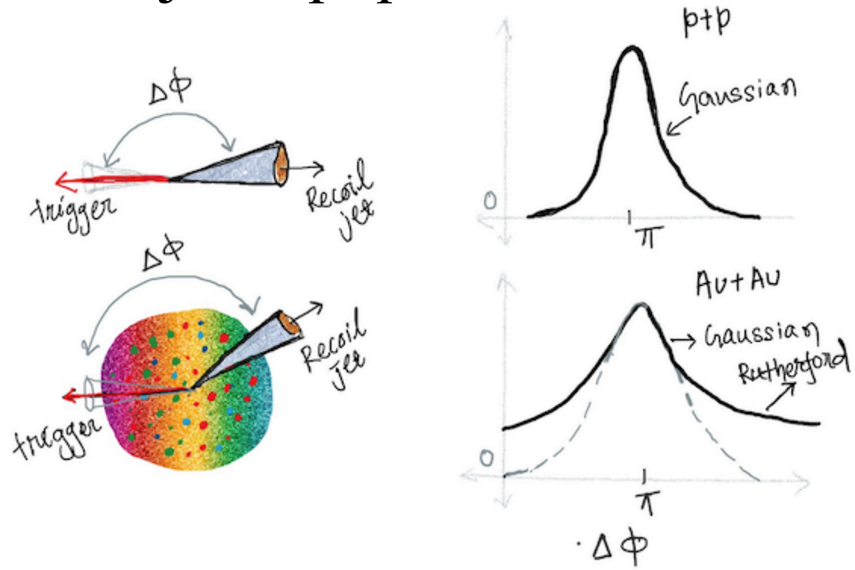
MGyulassy QM2019



- Convolution of Vaccum Sudakov and Medium induced transverse deflection; J. P. Blaizot,L. D. McLerran, PRD34, 2739 (1986)
- Color Magnetic Monopole: J. Liao and E. Shuryak , PRL102 (2009)

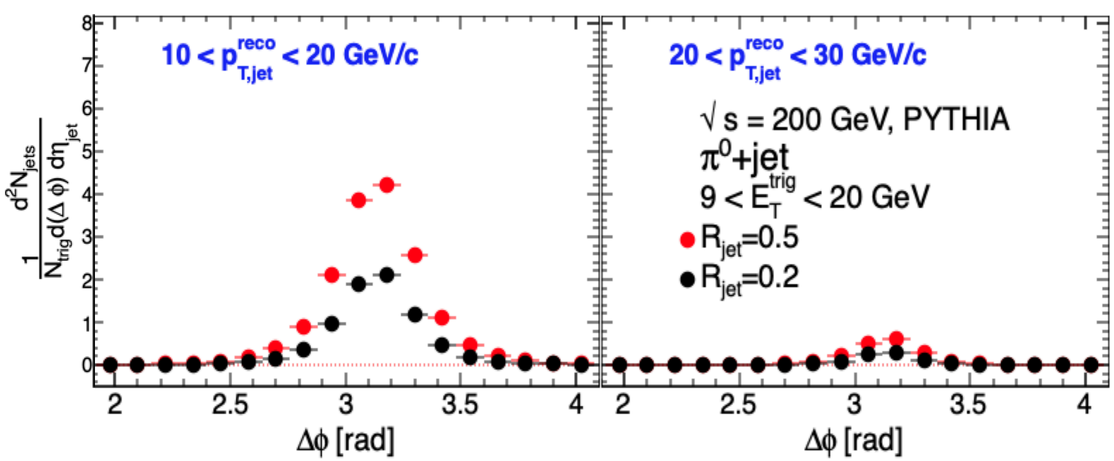
Search for the large angle deflection

Dijet in p+p and Au+Au



At small angle ⟶ Gaussian Shape
At large angle ⟶ Rutherford Scattering

Scattering of a recoil-jet off quasi-particles in the QGP → Intra-jet broadening (Δφ)



- No significant yield at large angular deviation in p+p
- STAR Exp.- Data analysis is underway in Au+Au collision

Summary and outlook

- STAR has produced compelling results on γ_{dir}+ hadron correlations and recent γ_{dir}+ jet (and π^0+jet) measurement at the top RHIC energy.
  - Provide very important information on in-medium parton energy loss at RHIC.
  - "Larger medium-induced recoil jet yield suppression for R=0.2 than for R=0.5 in γ_{dir}+ jet and π^0+jet (h+jet)"

  This is an important observation at RHIC that needs further study at both RHIC and LHC experiments, and in theory.

- Large angle deflection: a detail study is ongoing in STAR to understand the QGP medium response

- In addition, work is underway using semi-inclusive γ_{dir}+ jet and h+jet measurement at Mid-rapidity and in upcoming STAR forward detector upgrade to study the cold QCD matter [not covered in this talk]

Thank you!

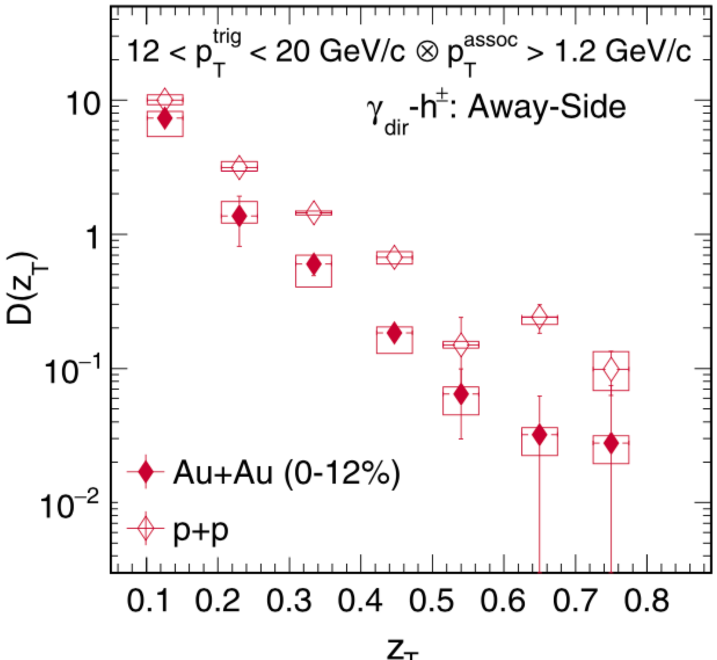
Backup

γ_{dir}+hadron and π^0+hadron correlations

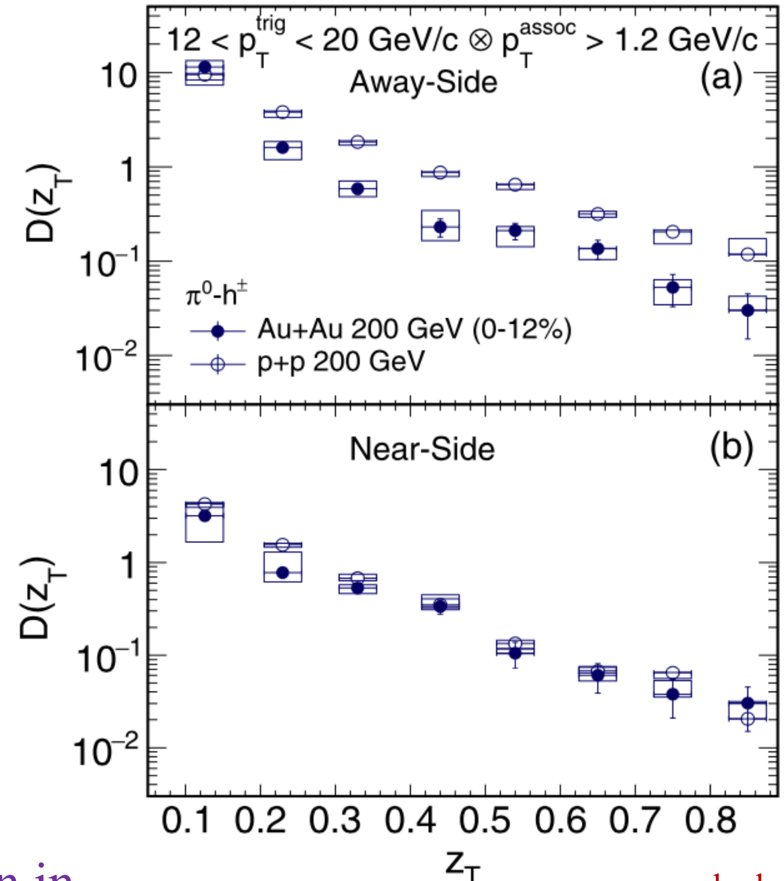
Mid-rapidity: $|\eta| < 1.0$

STAR: PLB 760 (2016) 689

γ_{dir}+hadron correlations:
Fragmentation Function



π^0+hadron correlations at mid-rapidity



$D(z_T)$: integrated away-side and near-side charged-hadron yields per trigger

- Per trigger yield is modified
- Away-side yields show suppression in Au+Au collisions as compared with p+p

$$z_T = \frac{p_{T,i}^{hadron}}{p_T^{trig}}$$

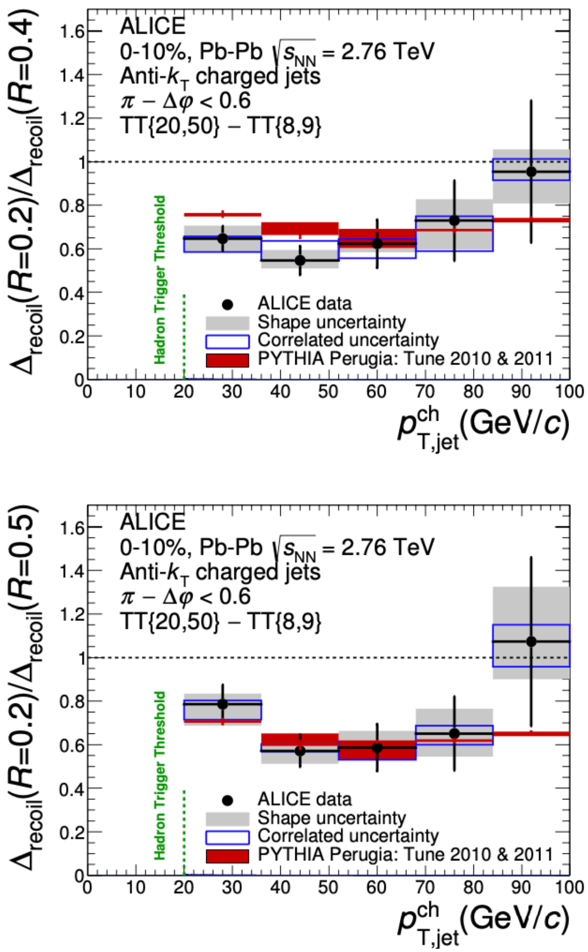
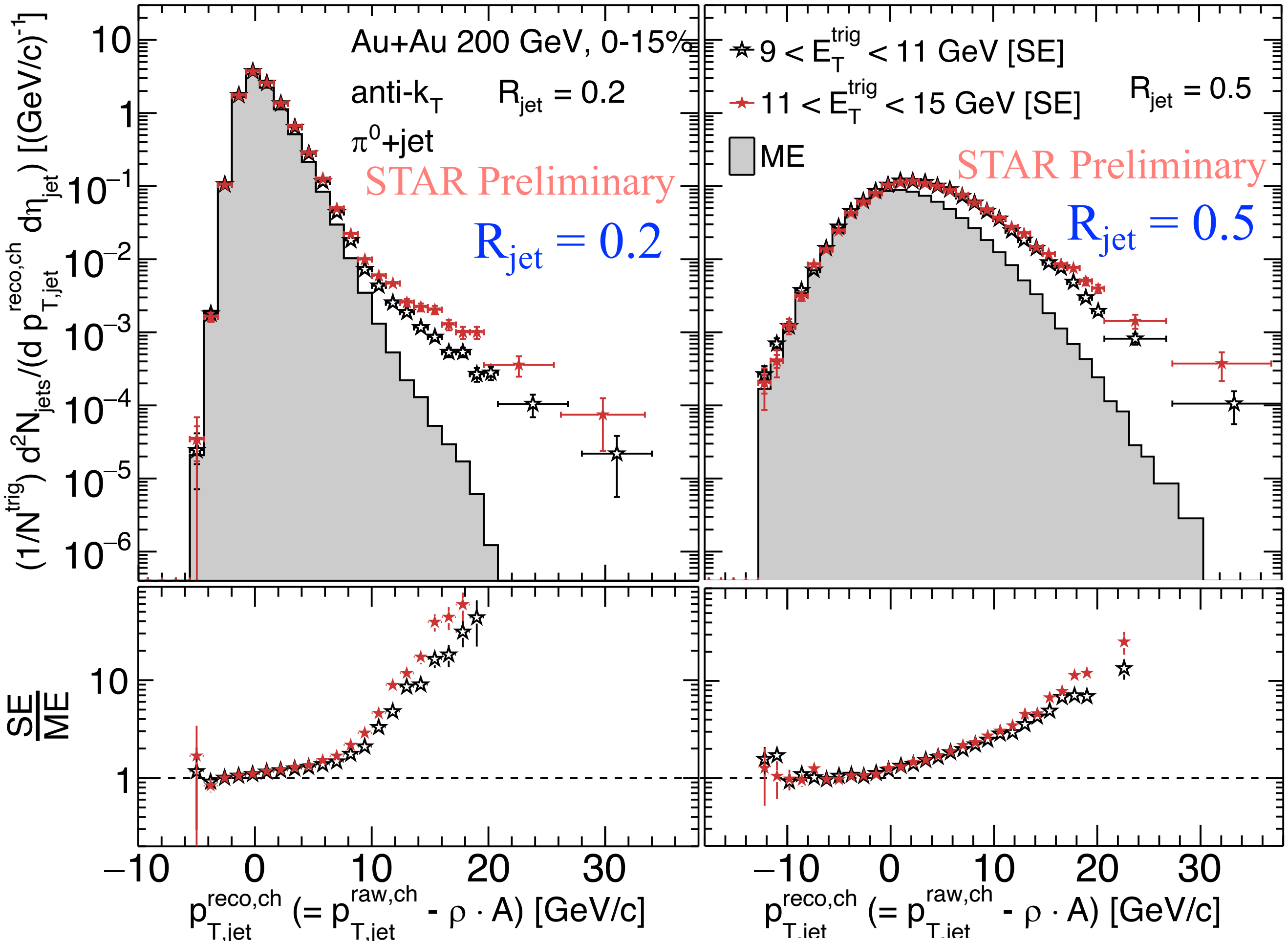


Figure 10. Ratio of Δ_{recoil} for $R = 0.2$ relative to $R = 0.4$ (top) and to $R = 0.5$ (bottom), for central Pb-Pb (black) and pp collisions simulated using PYTHIA (red) at $\sqrt{s} = 2.76$ TeV.

JHEP09(2015)170

π^0+Jet at mid-rapidity in Au+Au collisions

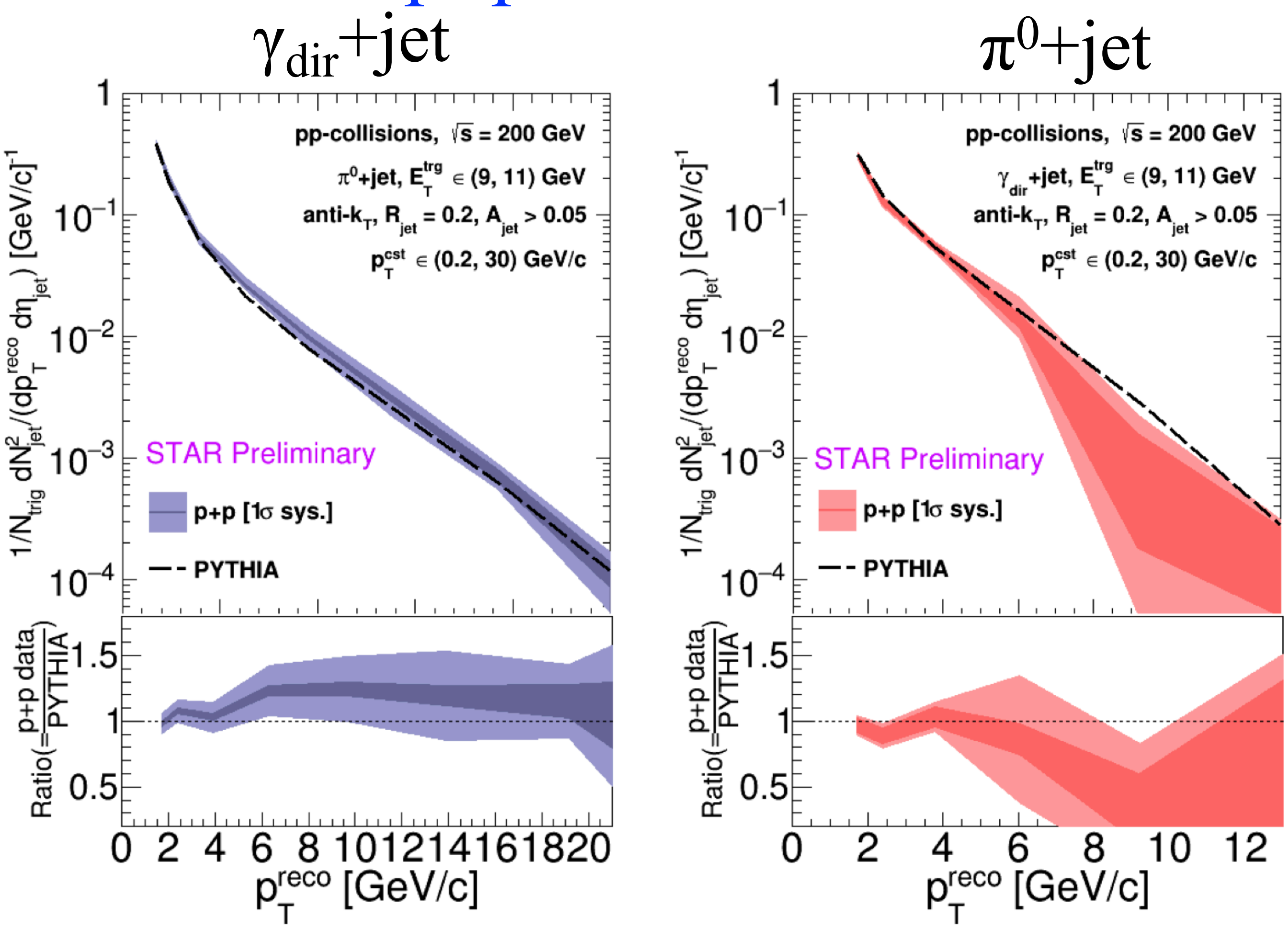
Recoil charged Jet spectrums for different trigger E_T windows



STAR: Nihar Sahoo, QM2019

A clear trigger dependence can been seen.

p+p collision scenario



Derek Anderson, ISMD2019

- $9 < E_T^{trig} < 11$ GeV
- $R_{jet} = 0.2$
- Charged jets

- Not enough trigger statistics for the precision γ_{dir}/π^0 +Jet measurement
- However, within uncertainty, corrected data consistent with Pythia8
- PYTHIA8 is used as p+p baseline for Au+Au collisions