Measurements of semi-inclusive γ+jet and hadron+jet distributions in heavy-ion collisions at $\sqrt{s_{NN}}$ = 200 GeV with STAR

Yang He
(for the STAR Collaboration)
Shandong University

2023 HARD PROBES Aschaffenburg

In part supported by U.S. DEPARTMENT OF ENERGY | Office of Science

Outline

Recoil jet study in Au+Au collisions exploring

Part 1. Jet suppression with different triggers

Part 2. Jet acoplanarity with different triggers

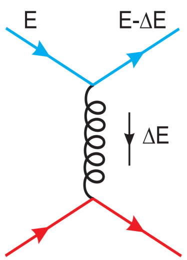
Part 3. Outlook on jet study in smaller collision systems

Probing QGP through jet-medium interaction

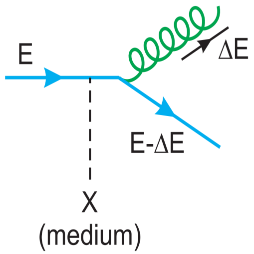
Jet: a collimated spray of hadrons produced by energetic quark or gluon

Jet production calculable in QCD

Parton energy loss in medium



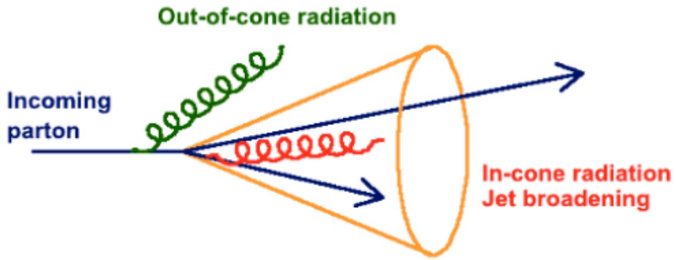
collisional energy loss



radiative energy loss

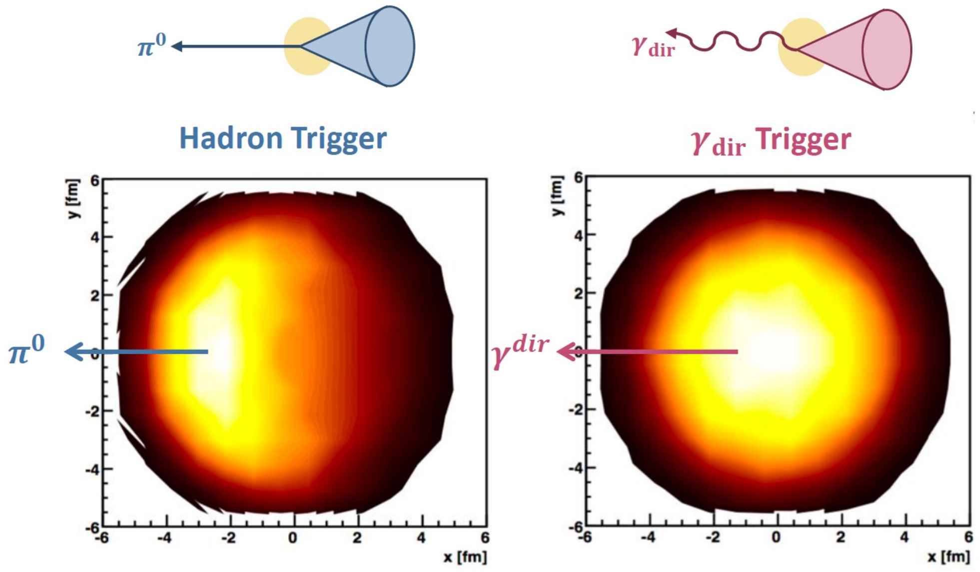
Consequences of parton-medium interaction

- Jet energy loss
- Acoplanarity
- Substructure modifiication



Jet energy loss (yield suppression) and jet acoplanarity (excess jet yield away from back-to-back) can be studied using semi-inclusive recoil jet

$\gamma_{\rm dir}/\pi^0$+jet to study jet energy loss



Adapted from
Renk, PRC **88**, 054902 (2013)

- Direct-photon ($\gamma_{\rm dir}$) triggers are of great interest as they constrain the scattering kinematics

- Comparison between $\gamma_{\rm dir}$+jet and π^0+jet
  q/g fraction; path length dependence; spectrum shape

Trigger-normalized yield of jets recoiling from a high p_T trigger hadron

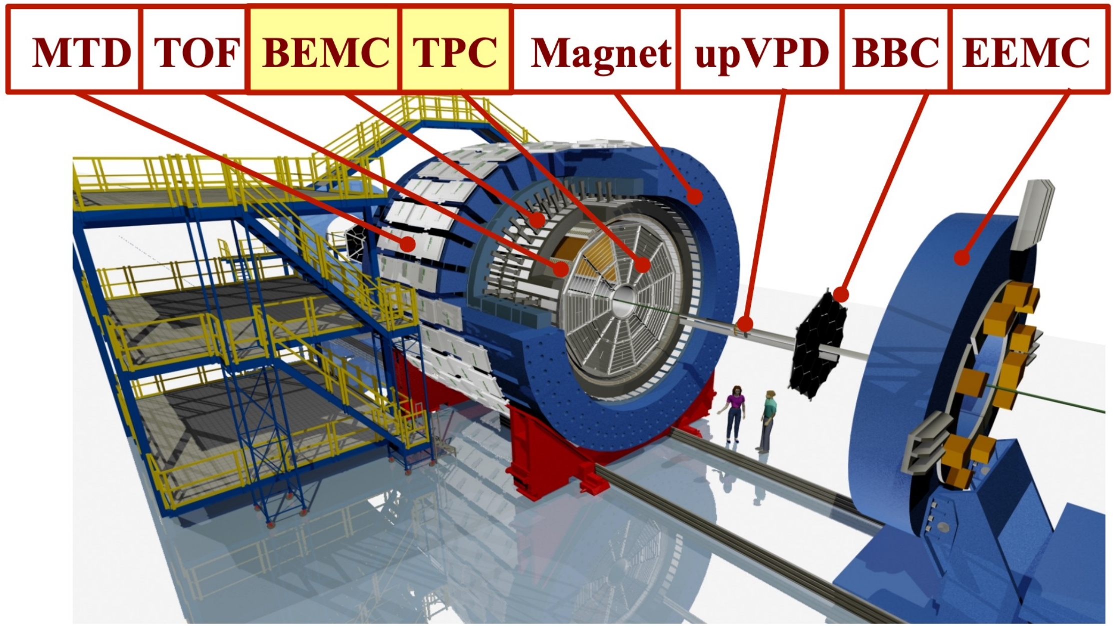
$$\frac{1}{N_{\rm trig}^{\rm AA}} \cdot \frac{d^3 N_{\rm jet}^{\rm AA}}{dp_{\rm T,jet}^{\rm ch}\, d\Delta\phi\, d\eta_{\rm jet}}\Bigg|_{p_{\rm T,trig}} = \left(\frac{1}{\sigma^{\rm AA\to h+X}} \cdot \frac{d^3\sigma^{\rm AA\to h+jet+X}}{dp_{\rm T,jet}^{\rm ch}\, d\Delta\phi\, d\eta_{\rm jet}}\right)\Bigg|_{p_{\rm T,trig}}$$

Jet quenching observable

I_{AA}<1 quantifies jet energy loss

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

STAR detector and dataset



Time Projection Chamber (TPC)

charged particles ($|\eta| < 1$, full azimuth)

Barrel Electromagnetic Calorimeter (BEMC)

trigger on energetic γ_{dir}/π^0

Barrel Shower Maximum Detector (BSMD)

discriminates γ_{dir}/π^0 based on transverse shower profile

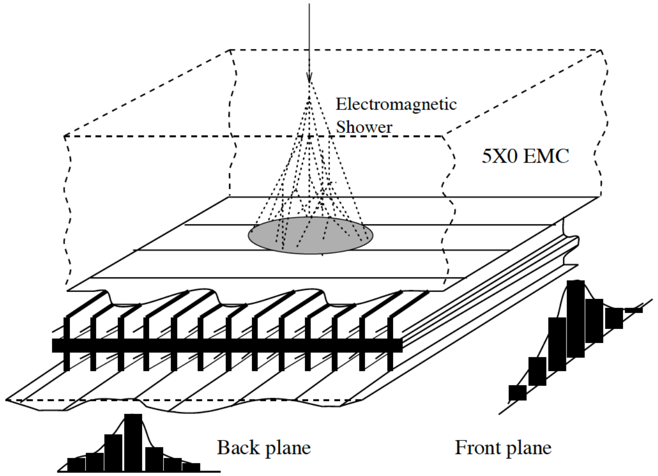
Au+Au (2014) and p+p (2009) at $\sqrt{s_{NN}}$ = 200 GeV

BEMC trigger ($E_T^{tower} \gtrsim 6$ GeV)

Charged particles: $|\eta| < 1$

Ru+Ru and Zr+Zr (2018) at $\sqrt{s_{NN}}$ = 200 GeV

Charged particles: $|\eta| < 1$



BSMD

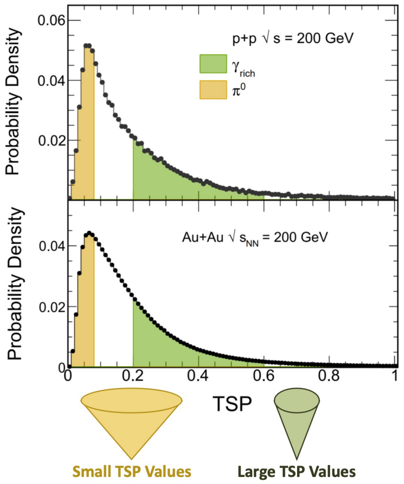
Analysis procedure of recoil jet yield

Discrimination of $\gamma_{\text{dir}}/\pi^0$ → Recoil jet yield → Uncorrelated background subtraction → Correction for detector and heavy-ion background effects (Using unfolding)

Transverse Shower Profile (TSP):

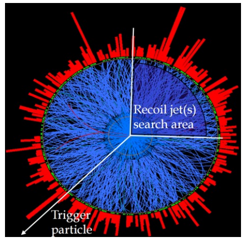
$$TSP \equiv \frac{E_{\text{cluster}}}{\sum_i e_i r_i^{1.5}}$$

E_{cluster} : cluster energy
r_i : distance of the SMD strips from the center of cluster
e_i : individual SMD strip energy



Analysis procedure of recoil jet yield

anti-k_T algorithm
$|\eta_{jet}| < 1 - R_{jet}$
$|\phi_{trig} - \phi_{jet}| < \pi/4$

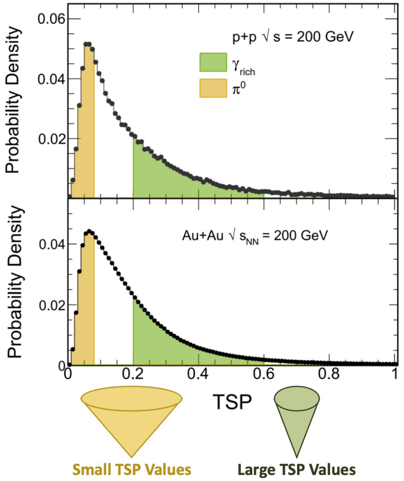


Discrimination of γ_{dir}/π^0 → **Recoil jet yield** → Uncorrelated background subtraction → Correction for detector and heavy-ion background effects (Using unfolding)

Transverse Shower Profile (TSP):

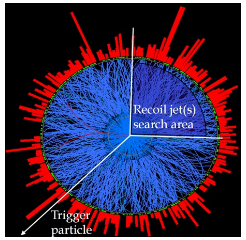
$$TSP \equiv \frac{E_{\text{cluster}}}{\sum_i e_i r_i^{1.5}}$$

$E_{cluster}$: cluster energy
r_i : distance of the SMD strips from the center of cluster
e_i : individual SMD strip energy



Analysis procedure of recoil jet yield

anti-k_T algorithm
$|\eta_{jet}| < 1 - R_{jet}$
$|\phi_{trig} - \phi_{jet}| < \pi/4$

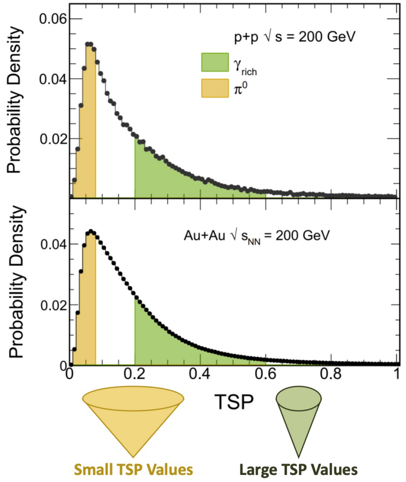


Discrimination of γ_{dir}/π^0 → **Recoil jet yield** → **Uncorrelated background subtraction** → **Correction for detector and heavy-ion background effects (Using unfolding)**

Transverse Shower Profile (TSP):

$$TSP \equiv \frac{E_{cluster}}{\sum_i e_i r_i^{1.5}}$$

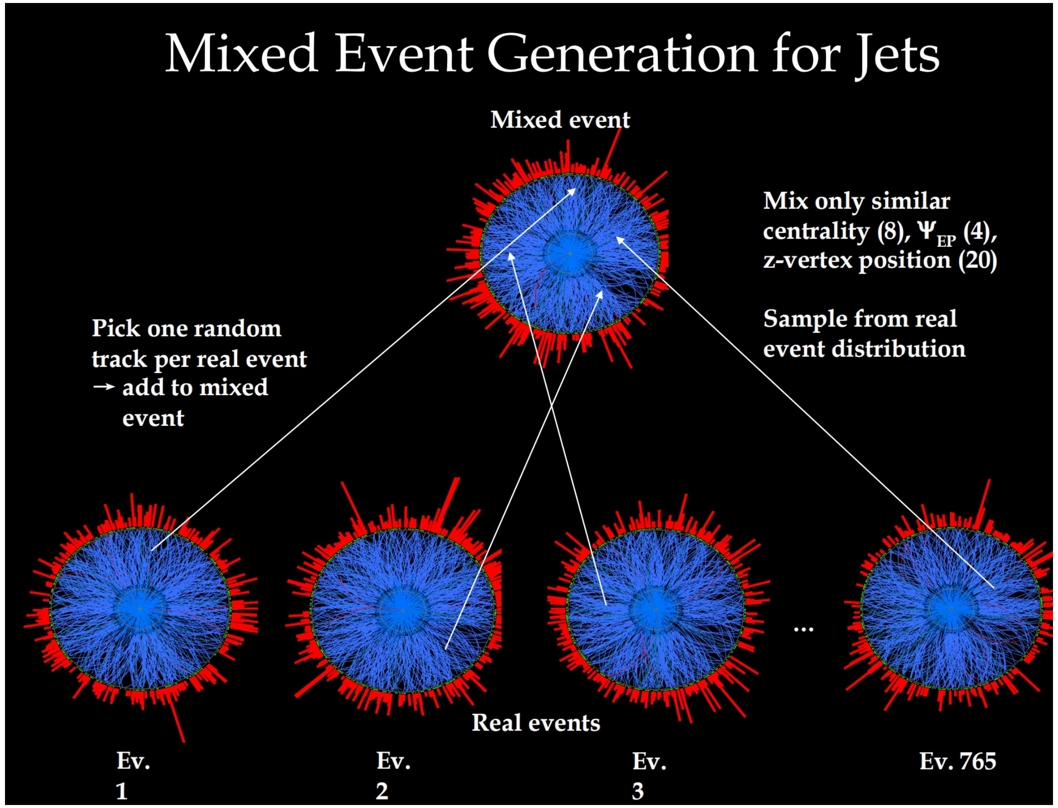
$E_{cluster}$: cluster energy
r_i : distance of the SMD strips from the center of cluster
e_i : individual SMD strip energy



Mixed-Event(ME) approach

Analysis procedure of recoil jet yield

Mixed-Event(ME) approach

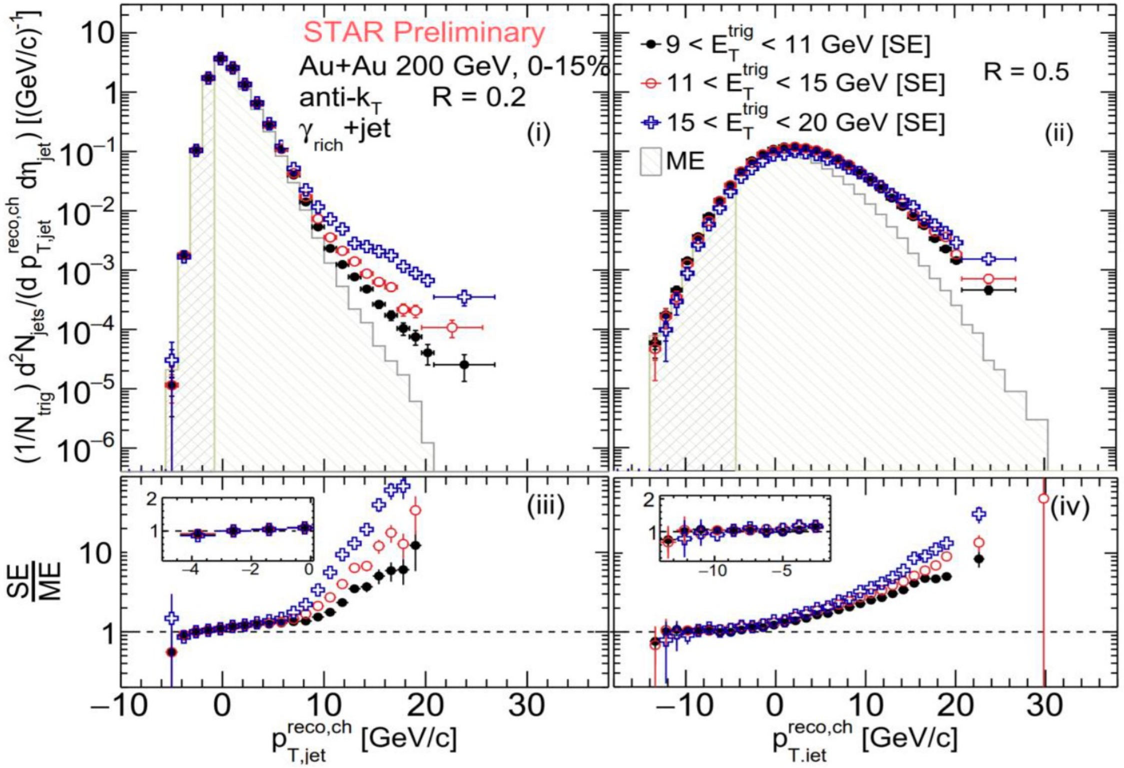


Courtesy of A. Schmah

All ME tracks are fully uncorrelated to estimate combinatorial jet background

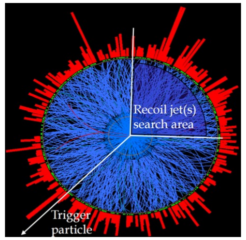
jet yield = Same Event - f^{ME} * Mixed Event

(f^{ME}: normalization factor extracted from data)



Analysis procedure of recoil jet yield

anti-k_T algorithm
$|\eta_{jet}| < 1 - R_{jet}$
$|\phi_{trig} - \phi_{jet}| < \pi/4$



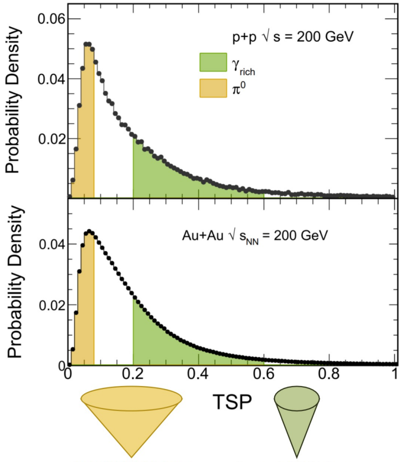
Unfold measured to true jet population

Discrimination of γ_{dir}/π^0 → **Recoil jet yield** → **Uncorrelated background subtraction** → **Correction for detector effects and heavy-ion background(Using unfolding)**

Transverse Shower Profile (TSP):

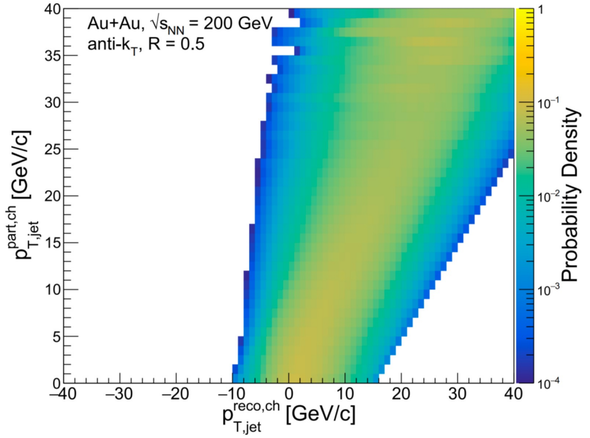
$$TSP \equiv \frac{E_{cluster}}{\sum_i e_i r_i^{1.5}}$$

$E_{cluster}$: cluster energy
r_i : distance of the SMD strips from the center of cluster
e_i : individual SMD strip energy



Mixed-Event(ME) approach

Mapping from “truth” to “measured”



Semi-inclusive recoil jet spectra

Trigger E_T:

π^0: [9, 11], [11, 15] GeV

γ_{dir}: [9, 11], [11, 15], [15, 20] GeV

Statistical errors: dark band

Systematic uncertainty (light band) is dominated by:

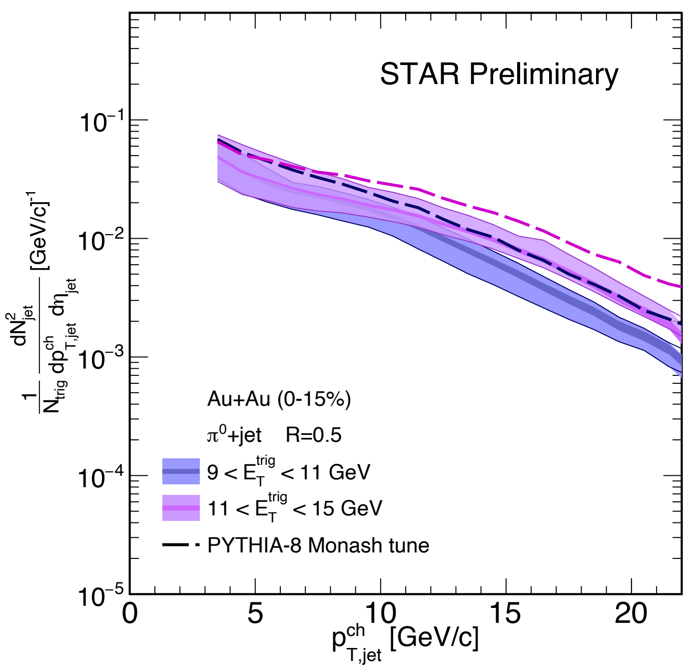
Unfolding procedure

Tracking efficiency

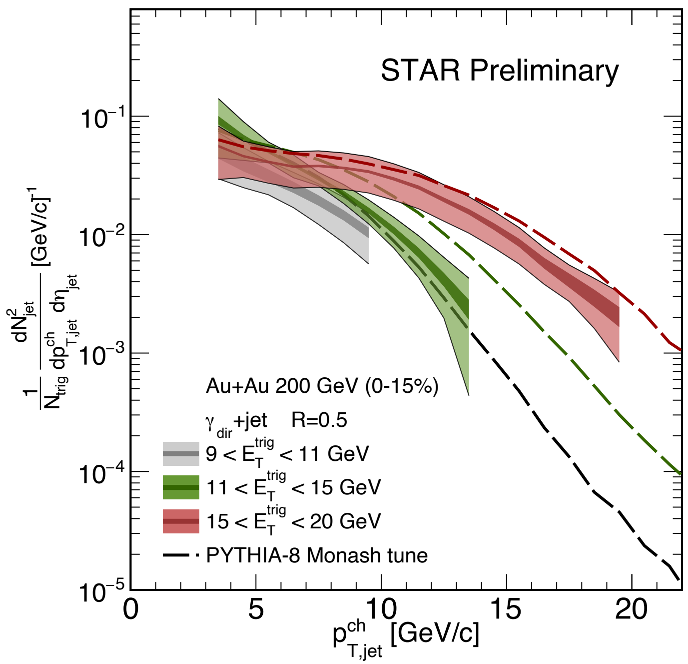
Direct photon purity

Dashed line: PYTHIA-8 (MONASH tune)

π^0+jet

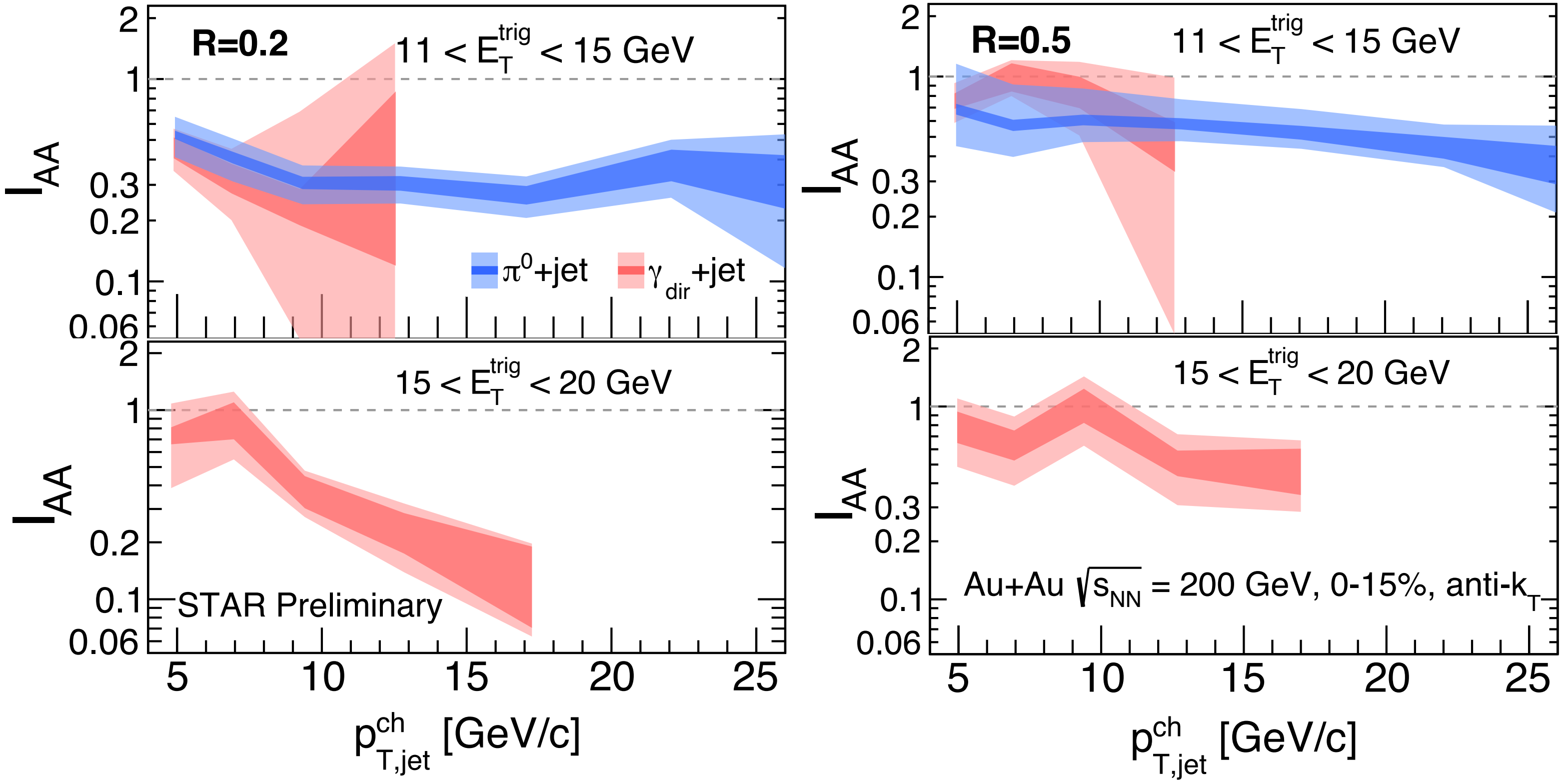


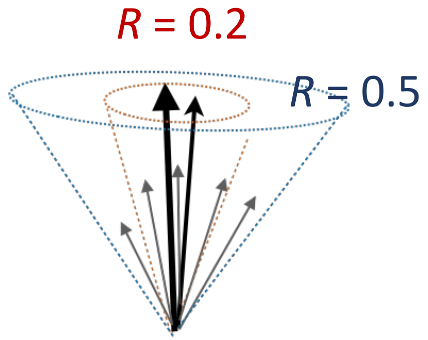
γ_{dir}+jet



Nuclear modification factor I_{AA}

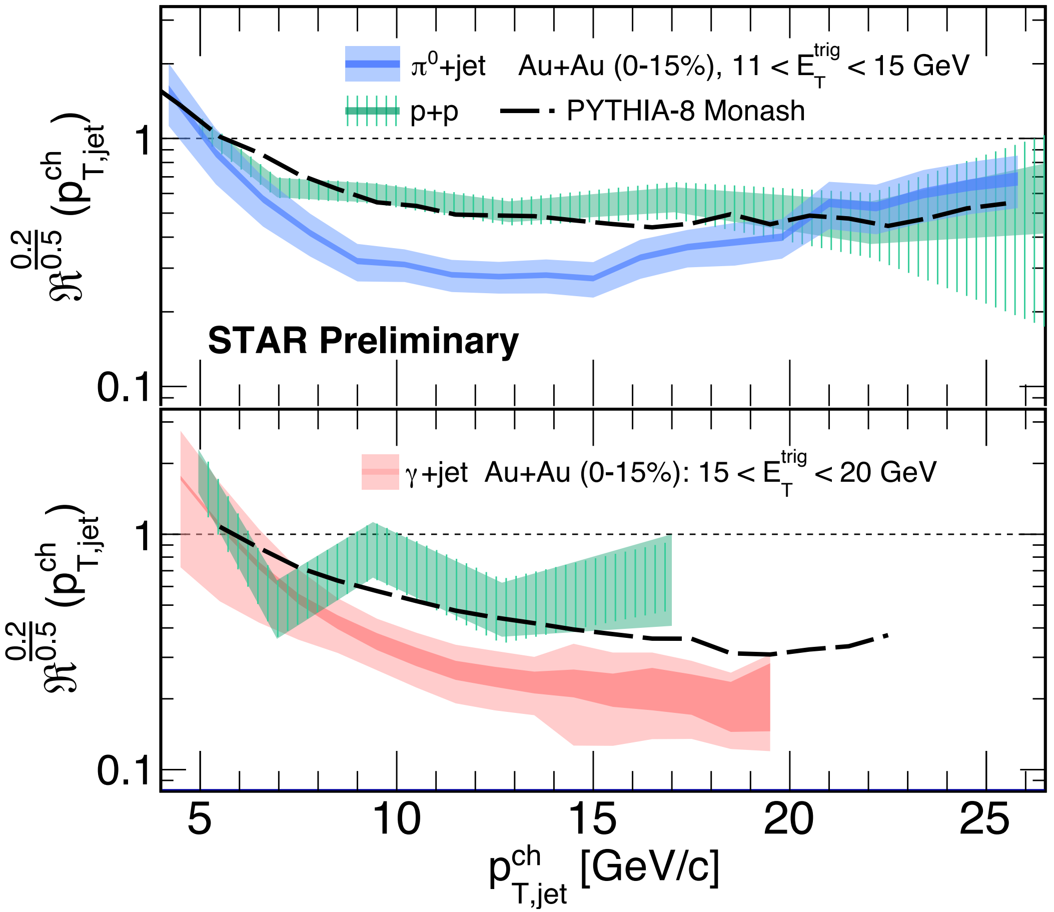
$$I_{AA} = \frac{Y^{AuAu}}{Y^{pp}}$$





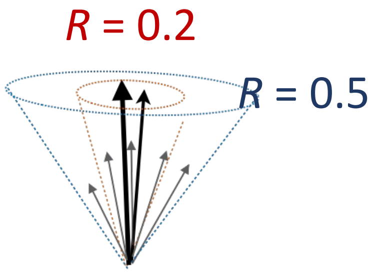
- Recoil jet yield is more suppressed for R=0.2 than R=0.5 indicating jet energy redistribution
- γ_{dir}+jet and π^0+jet show similar level of suppresssion

Recoil jet yield dependence on jet R



π^0+jet

γ_{dir}+jet



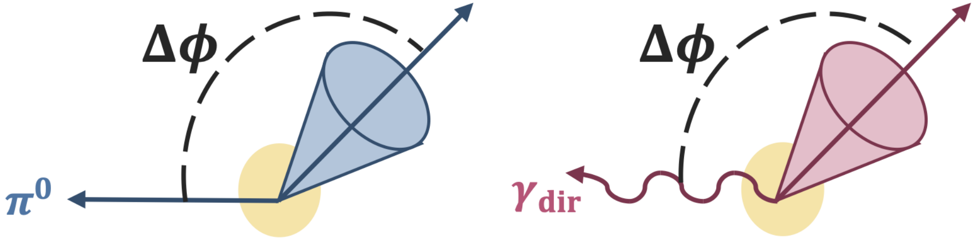
$$\Re = \frac{Y^{R=0.2}}{Y^{R=0.5}}$$

- $\Re^{0.2/0.5} < 1$ in p+p collisions due to jet radial profile in vacuum
- $\Re^{0.2/0.5}$ is smaller in Au+Au than in p+p indicating in-medium broadening of jet shower

Semi-inclusive γ_{dir}/π^0+jet azimuthal correlation

Acoplanarity: recoil jet deflected from γ_{dir}/π^0 axis

$$\Delta\phi = \phi_{trig} - \phi_{jet}$$



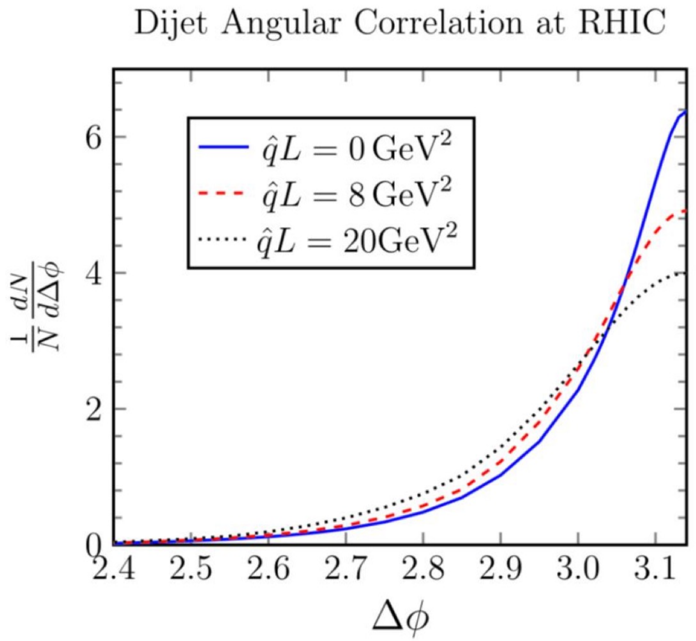
Trigger-jet azimuthal correlation distributions

$$\frac{1}{N_{trig}} \cdot \frac{dN_{jet}}{d(\Delta\phi)}\bigg|_{E_T^{trig}} = \left(\frac{1}{\sigma^{AA\to trig}} \cdot \frac{d\sigma^{AA\to trig+jet}}{d(\Delta\phi)}\right)\bigg|_{E_T^{trig}}$$

Contributions to the azimuthal de-correlation

In vacuum: Sudakov radiation

In medium: multiple soft scattering (pT broadening)
scattering off QGP quasi-particles



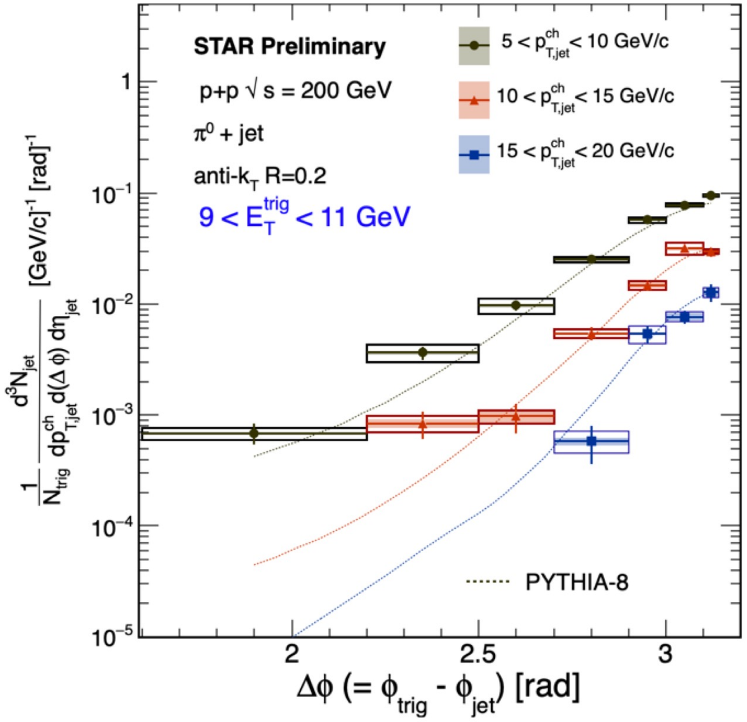
Mueller et al, PLB 763, 208 (2016)

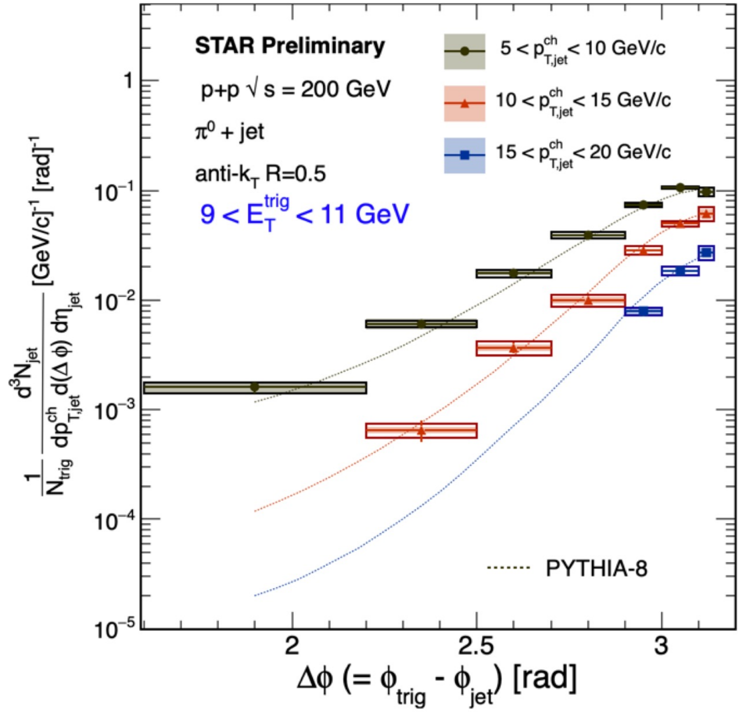
π^0 +jet azimuthal correlation in p+p collisions

$\Delta\phi$ spectra measurements: $\frac{1}{N_{trig}} \cdot \frac{dN_{jet}}{d(\Delta\phi)}\Big|_{E_T^{trig}} = \left(\frac{1}{\sigma^{AA\to trig}} \cdot \frac{d\sigma^{AA\to trig+jet}}{d(\Delta\phi)}\right)\Big|_{E_T^{trig}}$

E_T^{trig} = [9,11] GeV/c

R=0.2





R=0.5

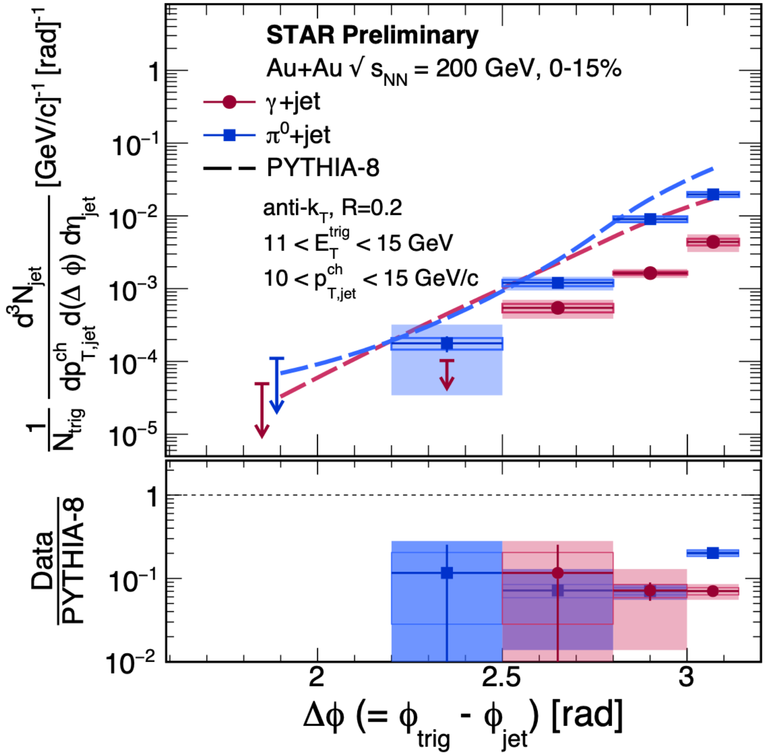
PYTHIA-8 (MONASH tune) is consistent with p+p data

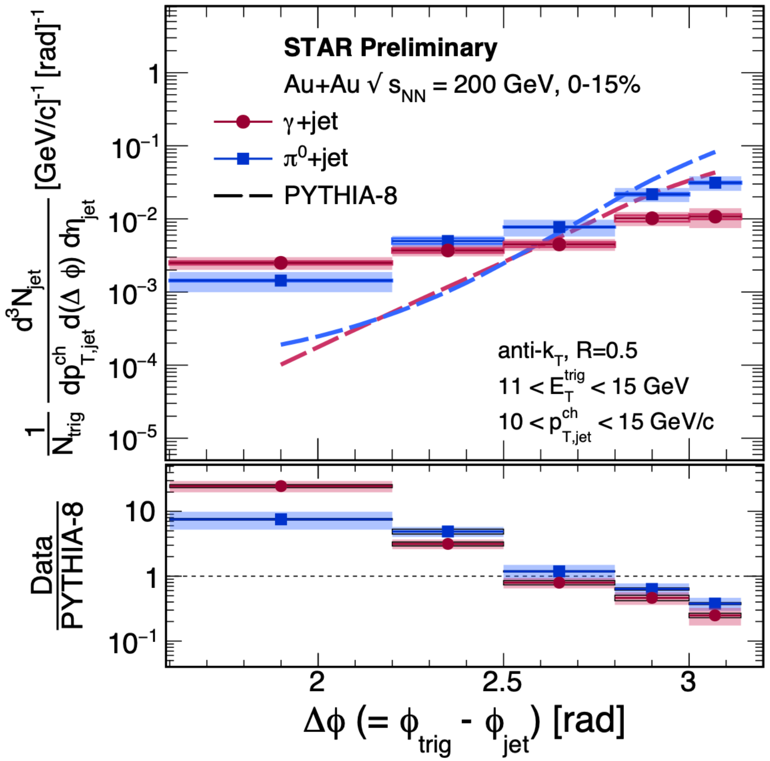
γ_{dir}/π^0+jet azimuthal correlation in Au+Au collisions

STAR

E_T^{trig} = [11,15] GeV/c

R=0.2



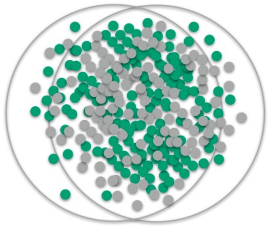


R=0.5

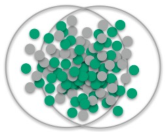
Evidence for medium-induced acoplanarity in the QGP for R = 0.5 jets

Jet deflection in the medium? Medium response? ...

System size dependence of hadron suppression

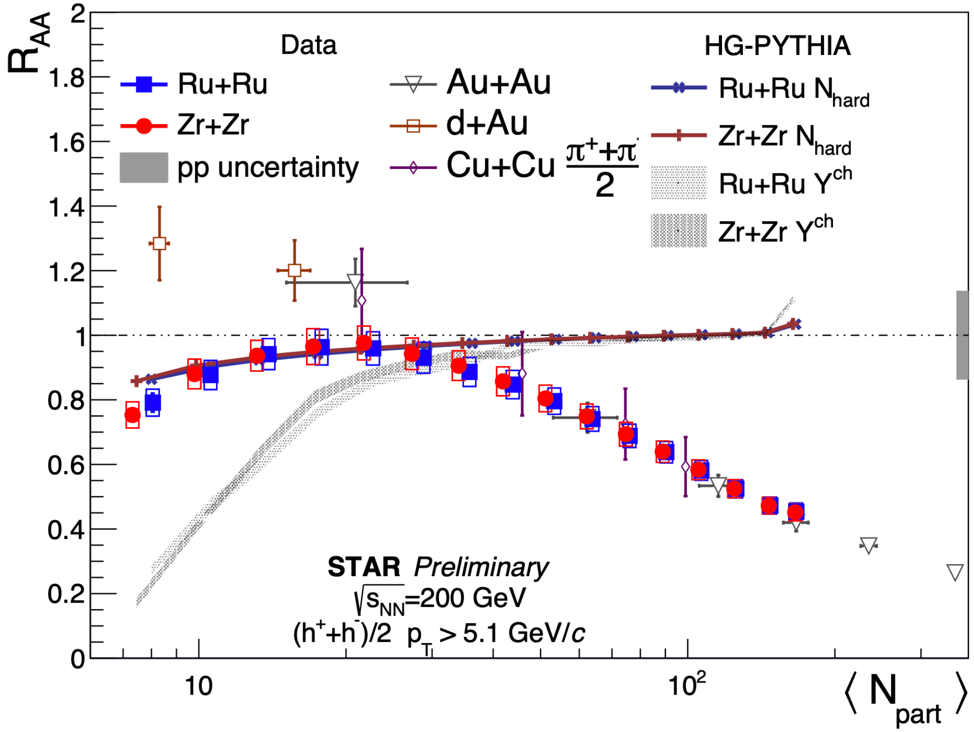


$^{197}_{79}Au + ^{197}_{79}Au$



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

$$R_{AA} = \frac{1}{N_{ev}^{AA}} \frac{d^2N^{AA}/d\eta dp_T}{T_{AA} d^2\sigma^{NN}/d\eta dp_T}$$



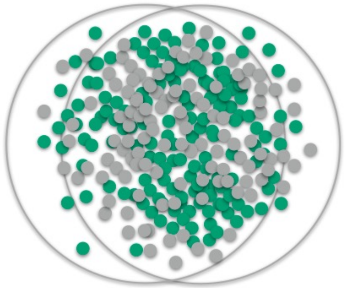
Similar R_{AA} suppression at comparable $<N_{part}>$

energy density drives the quenching, rather than the collision geometry

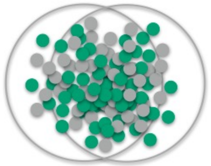
How about jets?

Talk: Tristan Protzman (Mar. 29th, 15:00)
Poster: Isaac Mooney (HMHC-8)

Outlook on system size dependence of jet quenching



$^{197}_{79}Au + ^{197}_{79}Au$



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

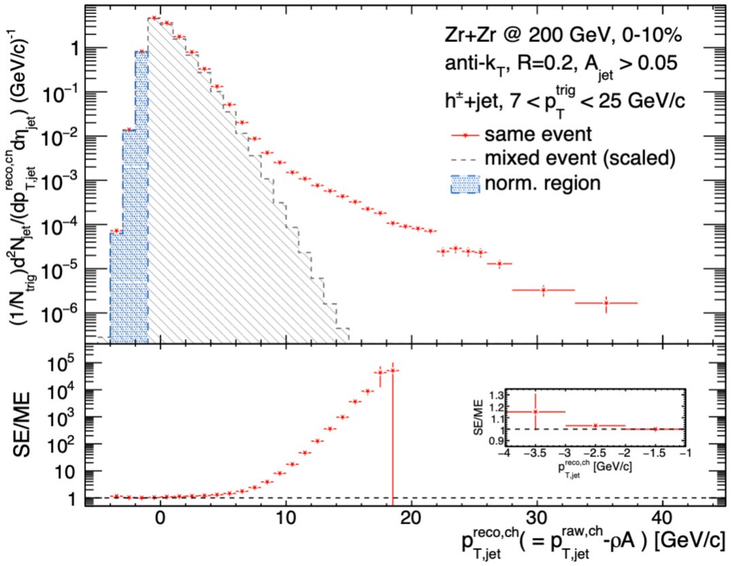
Jet quenching comparison for different collision systems:

gain further insights into parton energy loss dependence on initial energy density vs. collision geometry

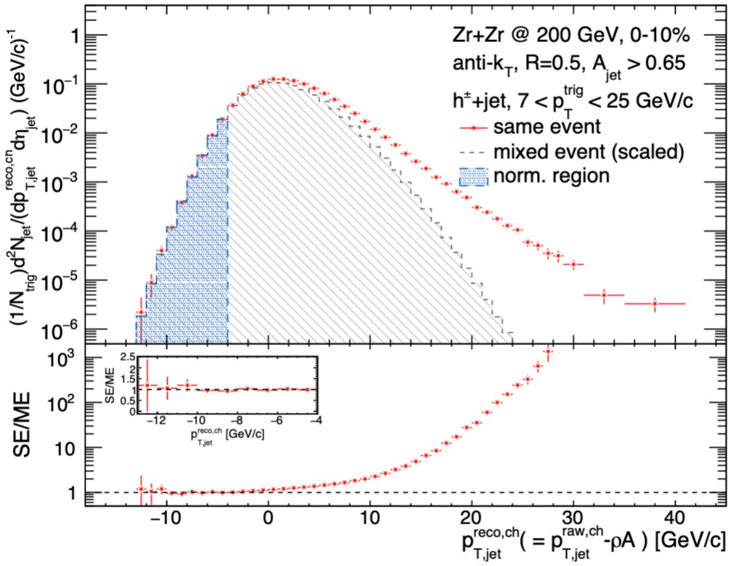
Trigger statistics for 7< $p_{T,trig}$<25 GeV/c

	0-10%	60-80%
Zr+Zr	~454 k	~60 k
Ru+Ru	~457 k	~62 k

R=0.2



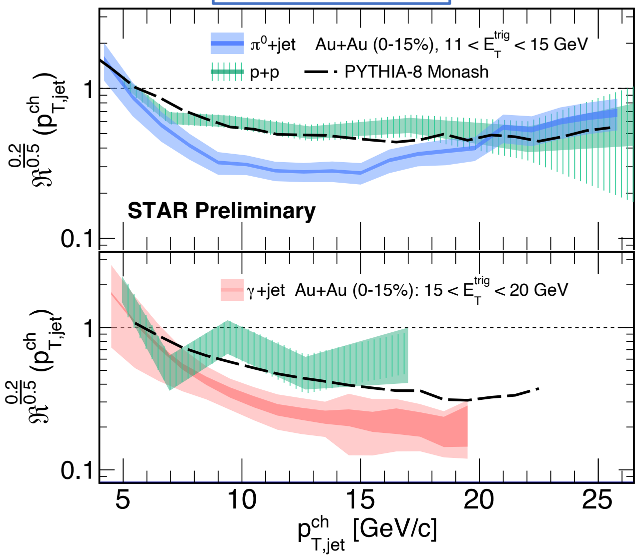
R=0.5



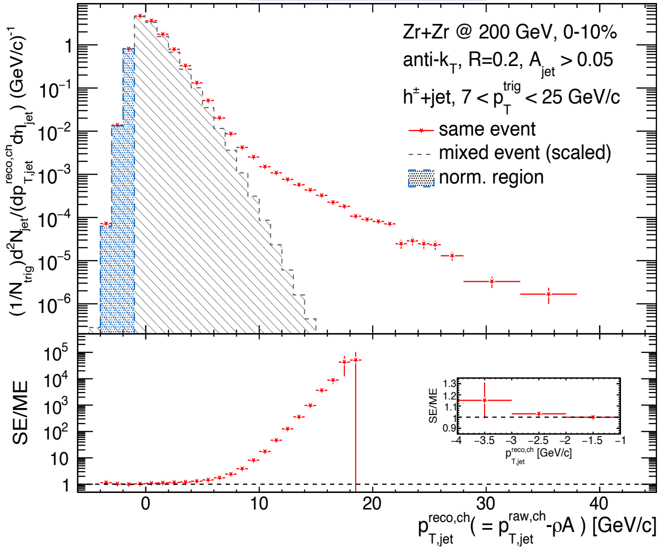
Ongoing measurement…

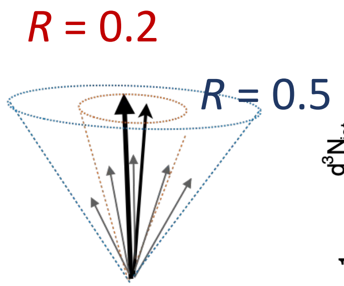
Summary

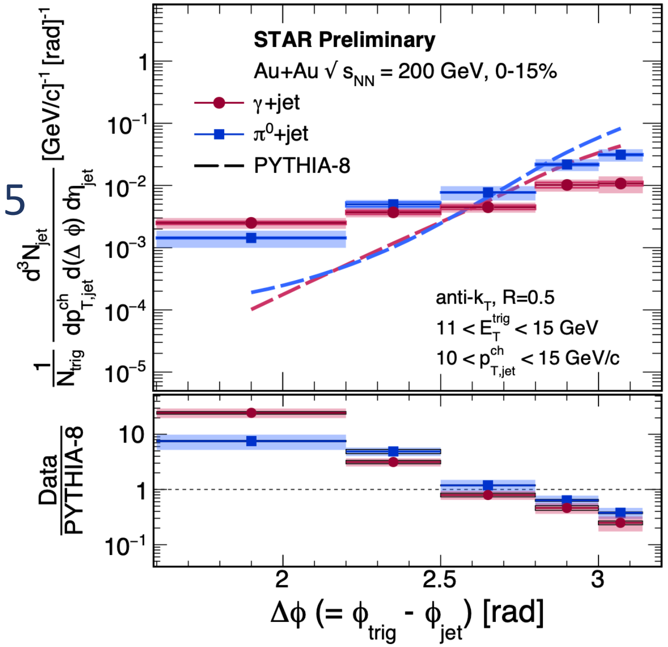
Au+Au



Zr+Zr







- Au+Au
  I_{AA} are consistent between γ_{dir}+jet and π^0+jet
  $\mathfrak{R}^{0.2/0.5}$ demonstrate intra-jet broadening
- h+jet study in Zr+Zr and Ru+Ru is ongoing

- $\Delta\phi$ distributions of γ_{dir}/π^0+jet in Au+Au: observed excess of jet yield away from back-to-back
  Jet scattering?
  Medium response?