Jet production in heavy ion collisions:

γ_{dir}+jet and h+jet at mid-rapidity and a perspective for forward upgrade in STAR

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Outline

- Semi-inclusive jet measurement in STAR

  γ_{dir} +jet, π^0 +jet, and h+jet

- Another facet of this measurement

  π^0 +jet (γ_{dir} +jet) $\Delta\varphi$ angular correlations

  Medium-induced acoplanarity

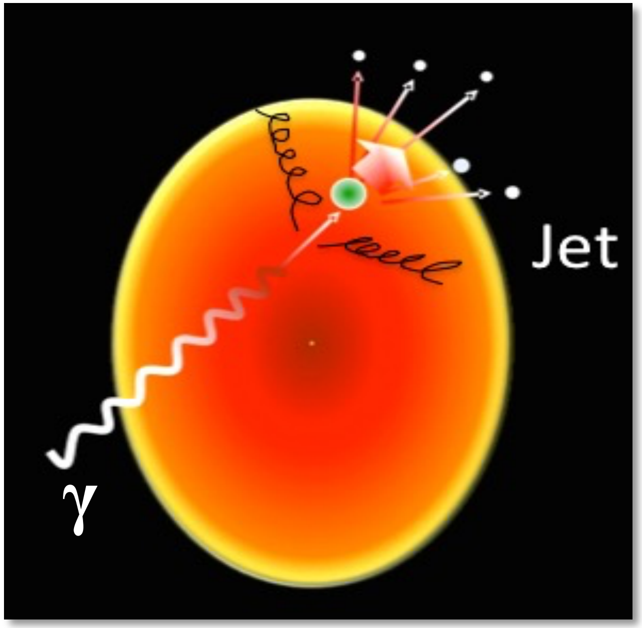
- A perspective for forward upgrade in STAR

γ_{dir}+jet at RHIC

- Quantitative understanding of parton energy loss in QCD medium
  - Parton energy loss as a function of path length, color factor, parton energy
  - Redistribution of lost energy inside the medium [Jet radius]
  - RHIC vs. LHC [dependence on temp. and initial gluon density]
- This can be addressed using vector-boson-tagged jet
  - Trigger energy approximates the initial recoil parton energy
  - γ_{dir}+jet is accessible at RHIC

First fully corrected γ_{dir}+jet measurement at top RHIC energy.

And a comparison between γ_{dir}+jet and $h(\pi^0)$+jet.



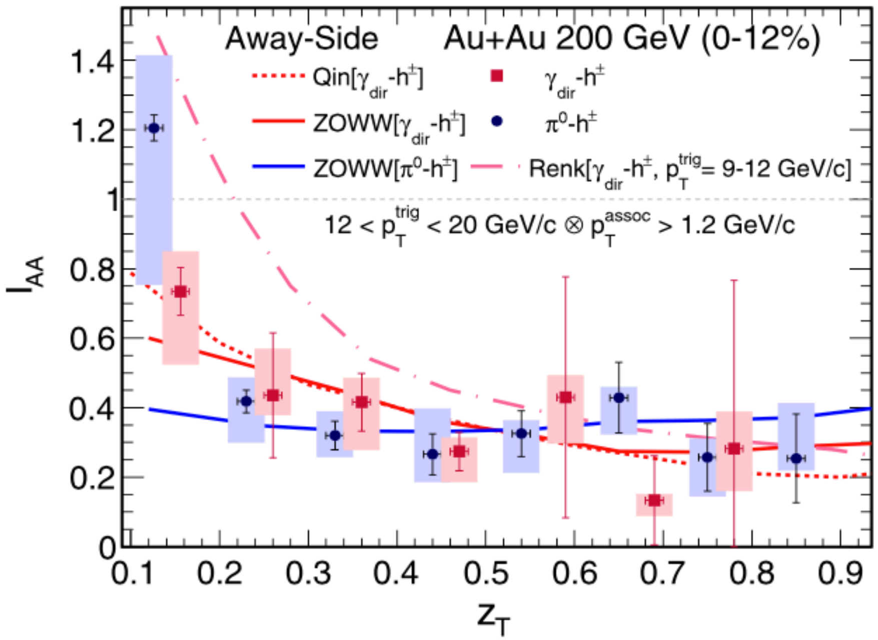
Besides, we can study the microscopic length scale of QGP (*quasi-particle picture*) using π^0+jet and γ_{dir}+jet.

Two important tools developed in STAR

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

STAR: PLB 760 (2016) 689

- γ_{dir}/π^0: trigger and discrimination

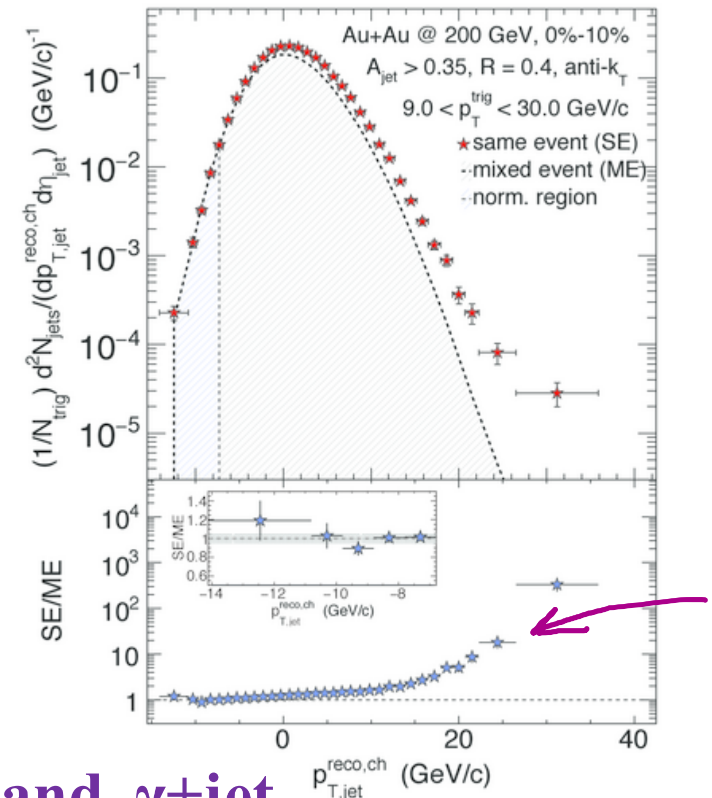


$$I_{AA}(p_T, z_T) = \frac{Y^{\text{Au+Au}}(p_T, z_T)}{Y^{\text{p+p}}(p_T, z_T)}$$

$h^{\pm}$+jet

STAR:PRC 96, 024905 (2017)

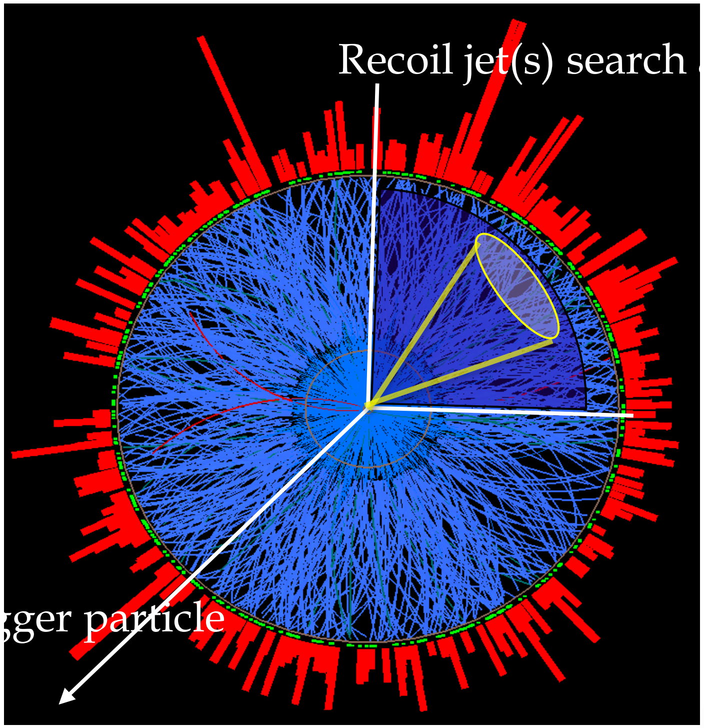
- Handel over uncorrelated background jet
- Final recoil jet correction (Unfolding)



Splicing these two analyses → **π^0+jet and γ+jet**

STAR event display of triggered event

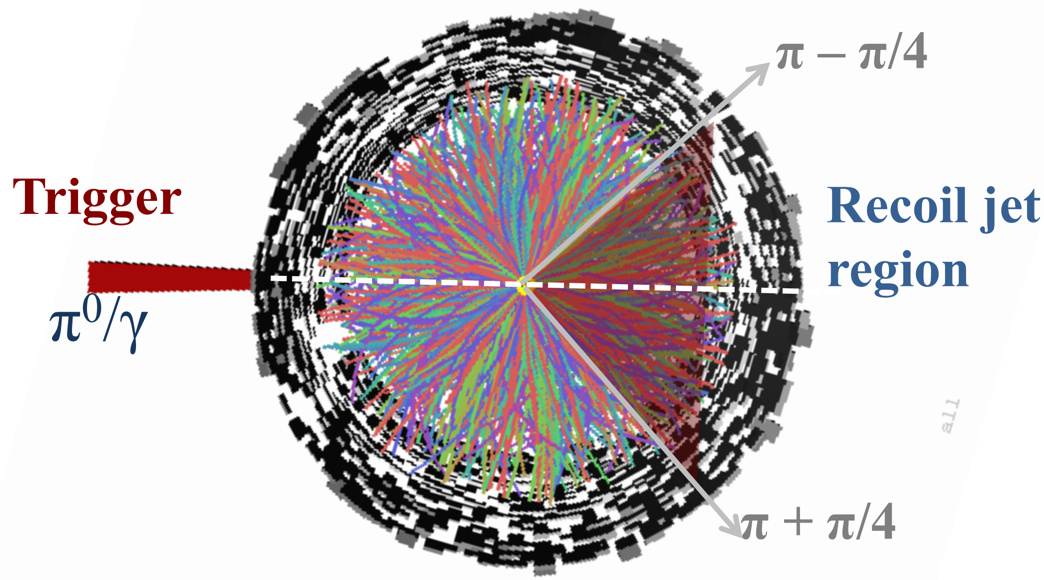
$h^{\pm}$+jet



- Using only TPC

STAR:PRC 96, 024905 (2017)

π^0+jet and γ+jet

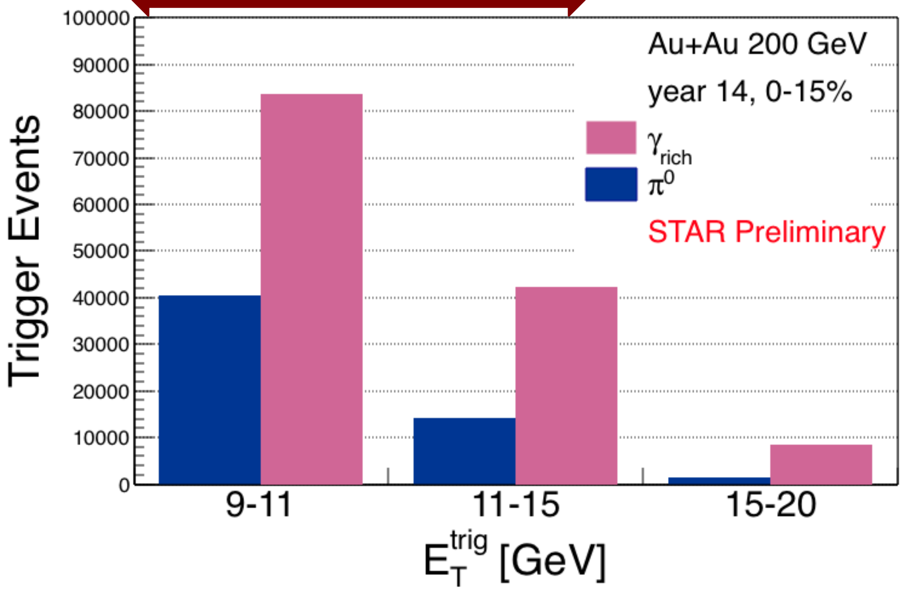


- TPC for charged tracks
- BEMC/BSMD for π^0/γ discrimination

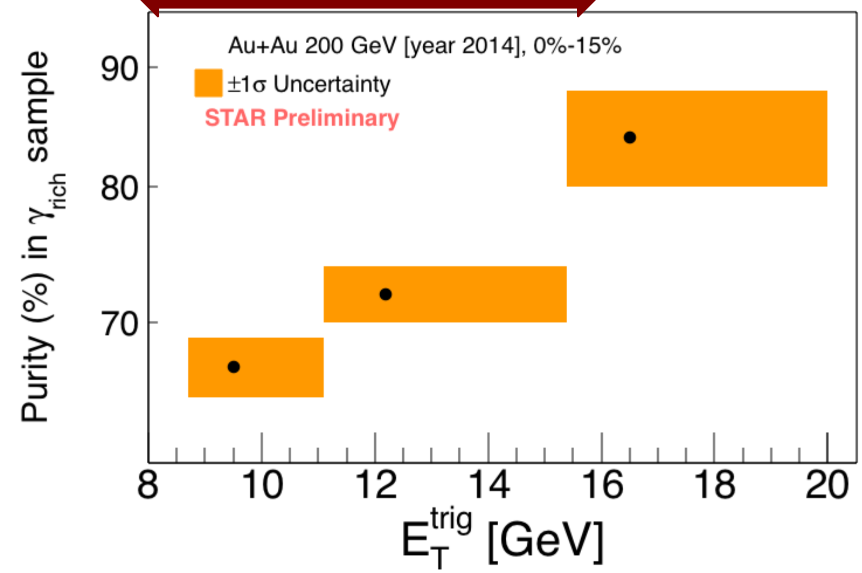
Event statistics and γ_{dir} purity

- Au+Au collisions at $\sqrt{s_{NN}}$ = 200 GeV
- Integrated luminosity of 13 nb^{-1} in the year 2014

Results in this talk

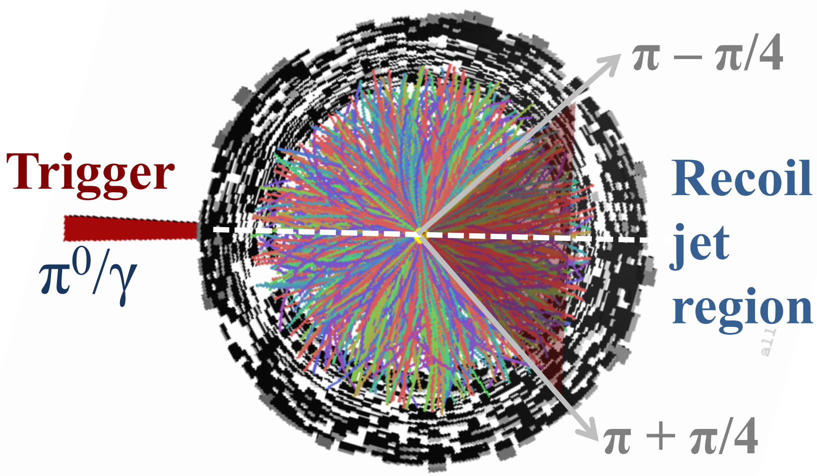


Results in this talk



- γ_{rich}: Mixture of decay and direct photons
- Purity of direct photons varies between 65% and 89% for $9 < E_T^{trig} < 20$ GeV
- High-purity criteria for π^0 selection limits the statistics
  - Similar procedure as in the previous STAR γ_{dir}+hadron correlation analysis [PLB 760 (2016) 689-696]

Semi-inclusive π^0/γ+jet

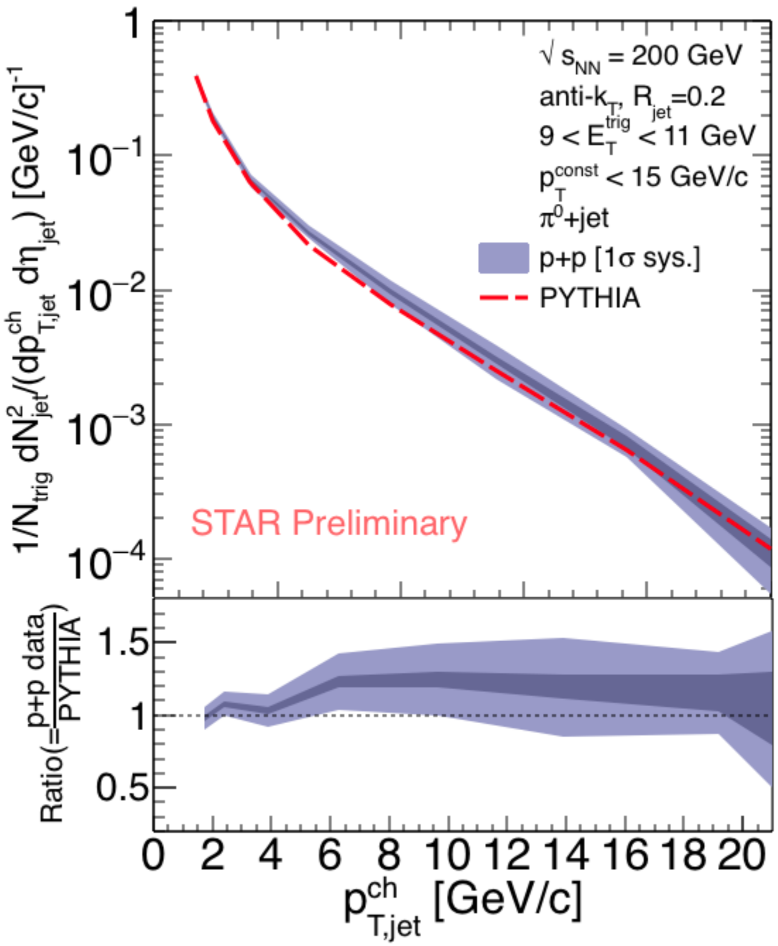


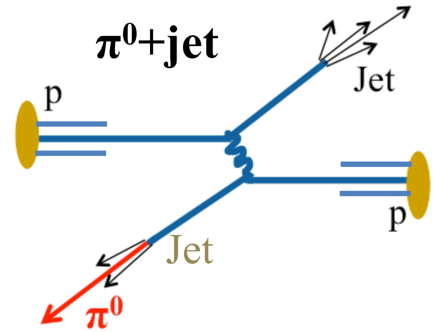
- Recoil jets from triggered events
  - With high-E_T trigger: $E_T^{trig} > 9$ GeV
    - High-Q^2 process
  - (Charged) Jet reconstruction:
    - Charged hadron constituents: $p_T^{const} < 15$ GeV/c (Now we extend to 30 GeV/c, for final results)
    - Algorithm: anti-k_T [Fastjet]
    - Recoil jet region:[π-π/4, π+π/4]
    - Jet radius = 0.2, $|\eta_{jet}| < 1$-R

    (also finished R=0.5 for paper proposal and QM2019)

- Event-mixing technique
  - Uncorrelated jet background
  - Based on h+jet analysis [STAR: PRC **96**, 024905 (2017)]
  - Using same analysis conditions as applied in Same Event (SE)

π^0-trigger charged recoil jets in p+p collisions





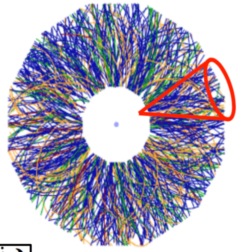
HP2018 talk

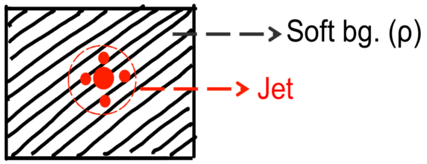
- p+p $\sqrt{s_{NN}}$ = 200 GeV/c
- π^0 triggers with $9 < E_T^{trig} < 11$ GeV, fully unfolded charged jets
  - zero background energy density(ρ)
  - And like heavy-Ion collisions, no Jet p_T smearing due to soft background, only detector effect correction
- π^0-triggered charged-jet spectrum consistent with PYTHIA8.

(Derek Anderson, Ph.D student, TAMU)

Factorizing heavy-Ion effects

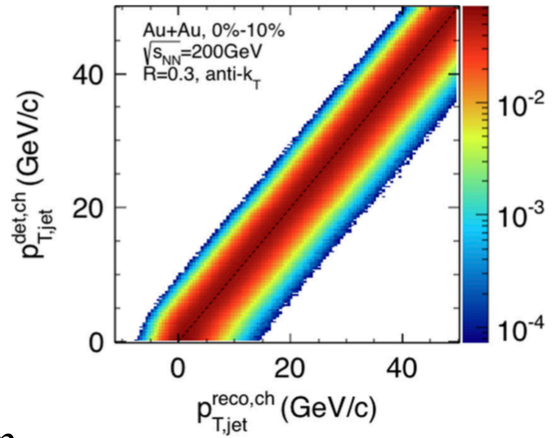
- Mixed event: to subtract out Uncorrelated jets
- Event-level soft background correction using background energy density (ρ)





$$p_{\mathrm{T,jet}}^{\mathrm{reco,ch}} = p_{\mathrm{T,jet}}^{\mathrm{raw,ch}} - \rho \cdot A$$

$$\rho = \mathrm{median}\left\{ \frac{p_{\mathrm{T,jet}}^{\mathrm{raw,i}}}{A_{\mathrm{jet}}^{\mathrm{i}}} \right\}$$

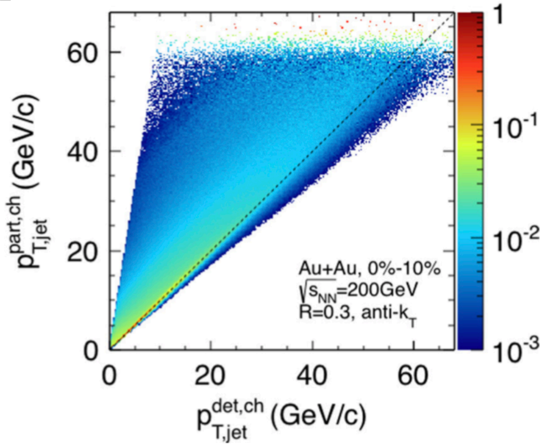


- In heavy-ion collisions:
  - i) Soft background fluctuations, and
  - ii) Detector effects

  can be handled by factorizing these effects.

- Response matrix for unfolding the semi-inclusive jet spectrum

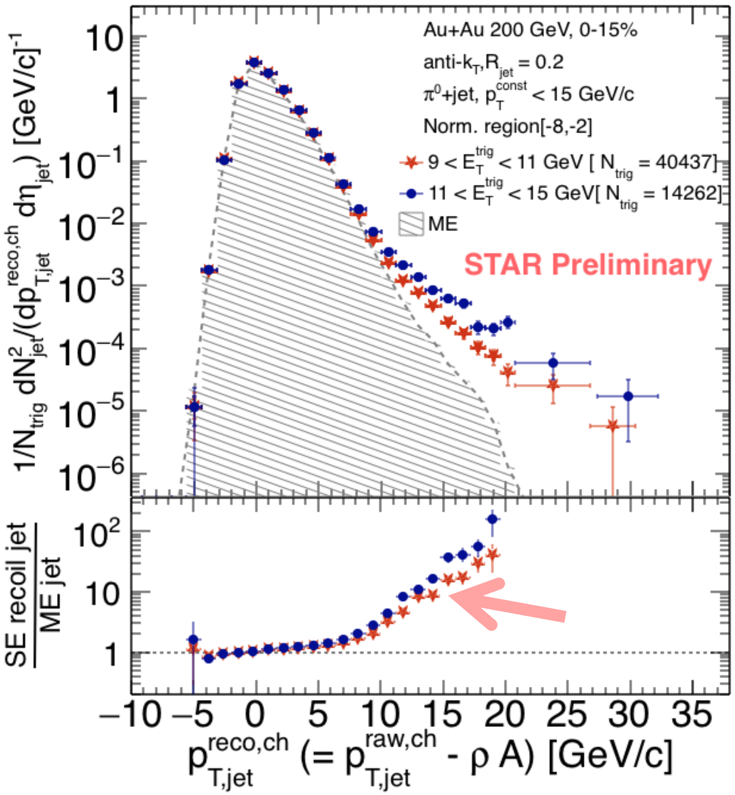
$$M\left(p_{\mathrm{T,jet}}^{\mathrm{reco,ch}}\right) = \left[R_{\mathrm{bkg}}\left(p_{\mathrm{T,jet}}^{\mathrm{reco,ch}}, p_{\mathrm{T,jet}}^{\mathrm{det,ch}}\right) R_{\mathrm{det}}\left(p_{\mathrm{T,jet}}^{\mathrm{det,ch}}, p_{\mathrm{T,jet}}^{\mathrm{part,ch}}\right)\right] T\left(p_{\mathrm{T,jet}}^{\mathrm{part,ch}}\right).$$

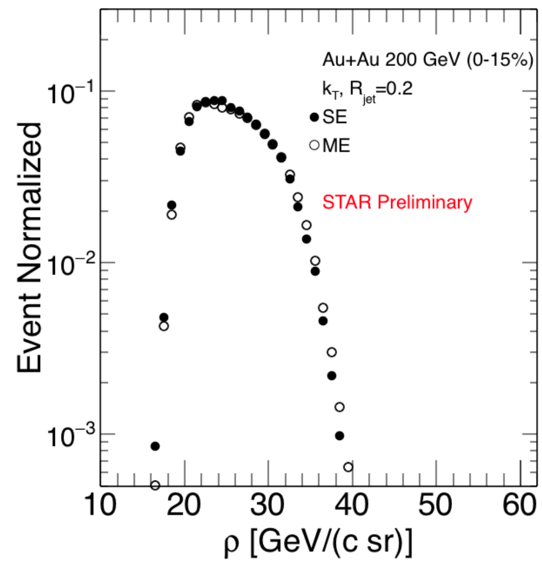


This procedure has been meticulously checked through simulation

Semi-inclusive recoil π^0+jet

SE: Same Events from triggered events, **ME**: Mixed Events from MB dataset





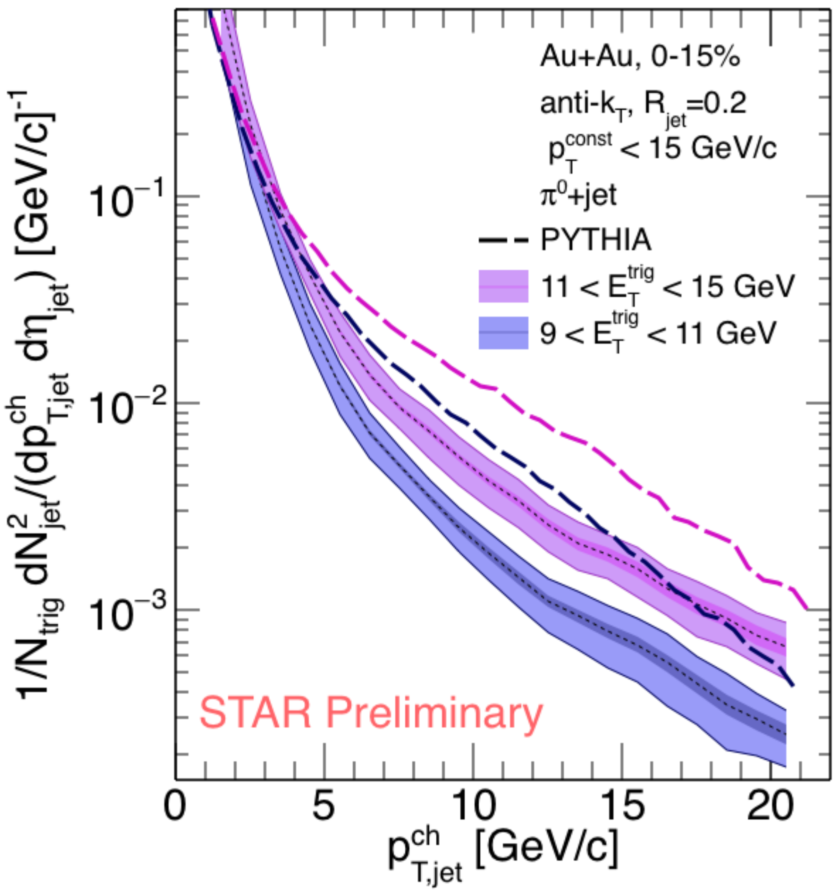
$$\rho = \text{median}\left\{\frac{p_{\mathrm{T,jet}}^{\mathrm{raw,i}}}{A_{\mathrm{jet}}^{\mathrm{i}}}\right\}$$

- Similar background density distribution for SE and ME

- A clear trigger E_T^{trig} dependence: 9-11 and 11-15 GeV
- Recoil jets dominate (above ~10 GeV/c) over uncorrelated jet background from mixed events
- These uncorrelated jets can be subtracted out using mixed event jets

π^0-triggered charged jets in Au+Au collisions

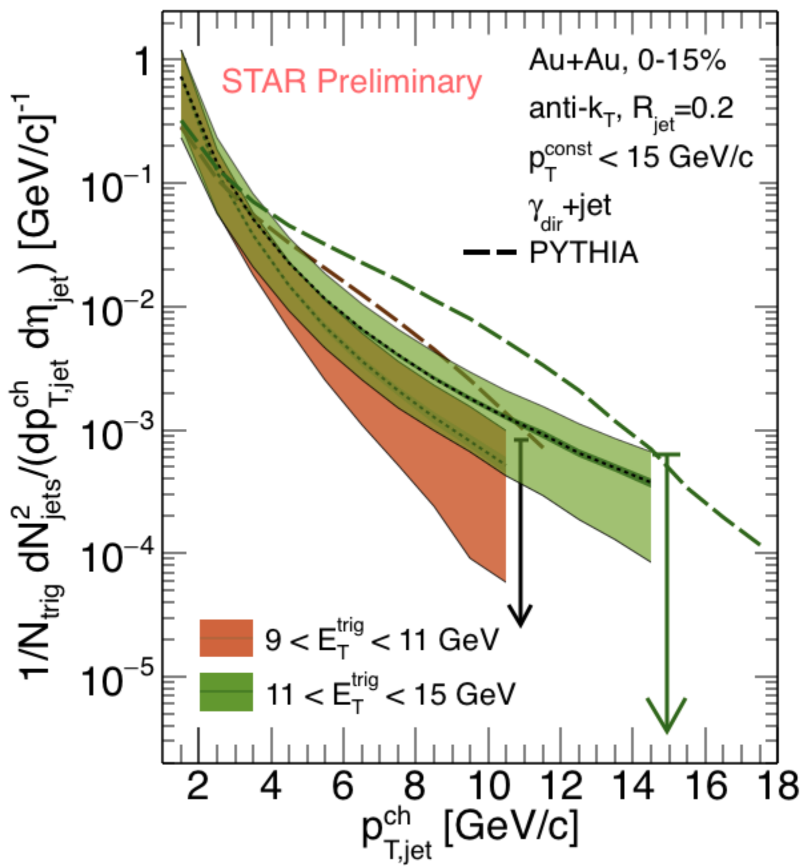
HP2018 talk



- π^0-triggered charged recoil jets
  - Fully unfolded spectrum
- A clear difference between recoil-jet spectra for different trigger-E_T: $9 < E_T^{trig} < 11$ GeV vs. $11 < E_T^{trig} < 15$ GeV
- Clear suppression with respect to PYTHIA8

γ_{dir}-triggered charged jets in Au+Au collisions

HP2018 talk



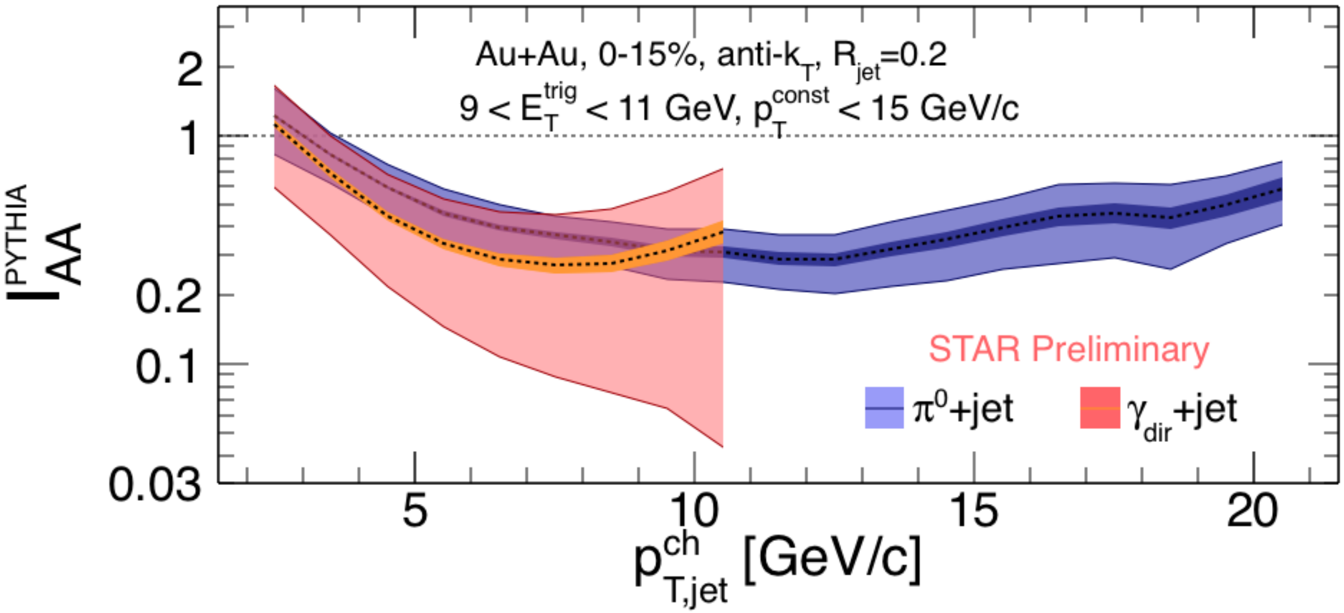
- Indication of systematic difference between recoil-jet spectra for different trigger-E_T: $9 < E_T^{trig} < 11$ GeV vs. $11 < E_T^{trig} < 15$ GeV
  - Downward arrow represents upper limit in yield at:
    $p_{T,jet}^{ch} = 11$ GeV/c for $9 < E_T^{trig} < 11$ GeV,
    $p_{T,jet}^{ch} = 15$ GeV/c for $11 < E_T^{trig} < 15$ GeV.
- Clear suppression with respect to PYTHIA8

Systematic uncertainties have been improved in the present analysis.

Recoil jet yield suppression: γ_{dir}+jet vs. π^0+jet

$9 < E_T^{trig} < 11$ GeV

HP2018 talk



Systematic (lighter band) and statistical (darker band) uncertainties

Systematic uncertainties have been improved in the present analysis.

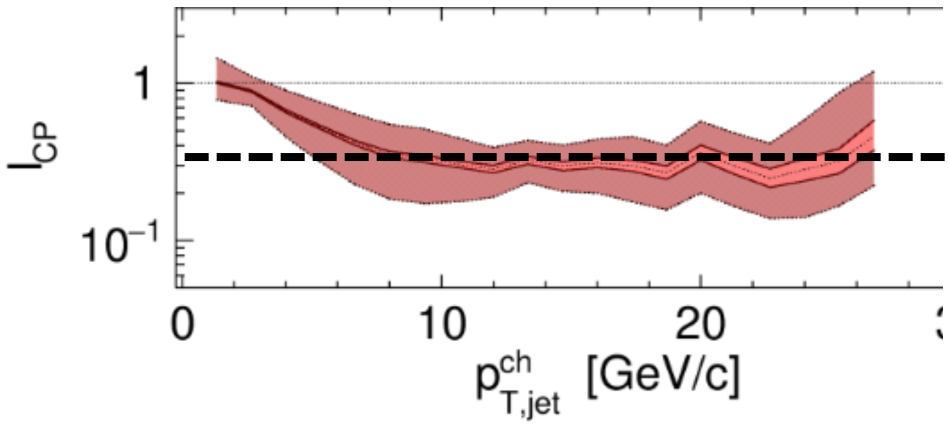
- I_{AA}^{PYTHIA} is the ratio of per triggered recoil jet yield in central Au+Au collisions to PYTHIA
- Clear suppression for both trigger types with respect to PYTHIA8
- Similar level of suppression in γ_{dir}+jet and π^0+jet, within uncertainties
  - γ_{dir}+jet runs out of kinematic reach above $p_{T,jet} > 11$ GeV/c

Comparison of $h^{\pm}$+jet to π^0+jet

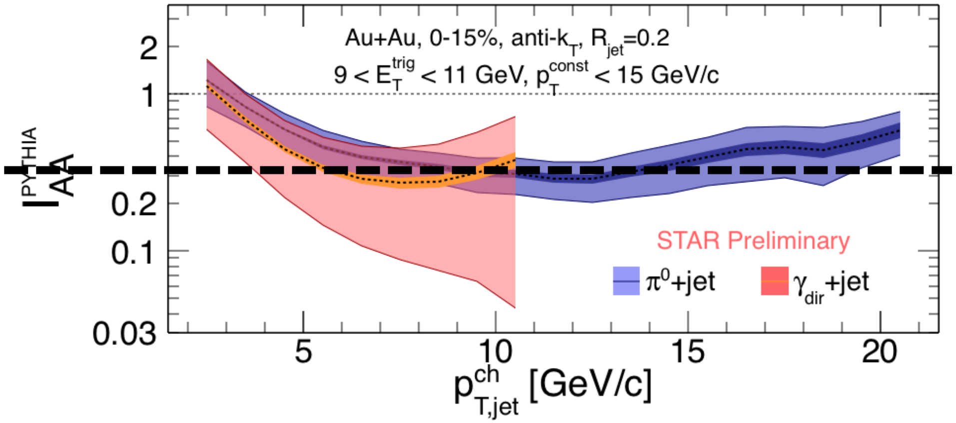
Au+Au 200 GeV

STAR: PRC **96**, 024905 (2017)

$h^{\pm}$+jet: $9 < p_T^{trig} < 30$ GeV/c



This analysis: $9 < E_T^{trig} < 11$ GeV



Systematic (lighter band) and statistical (darker band) uncertainties

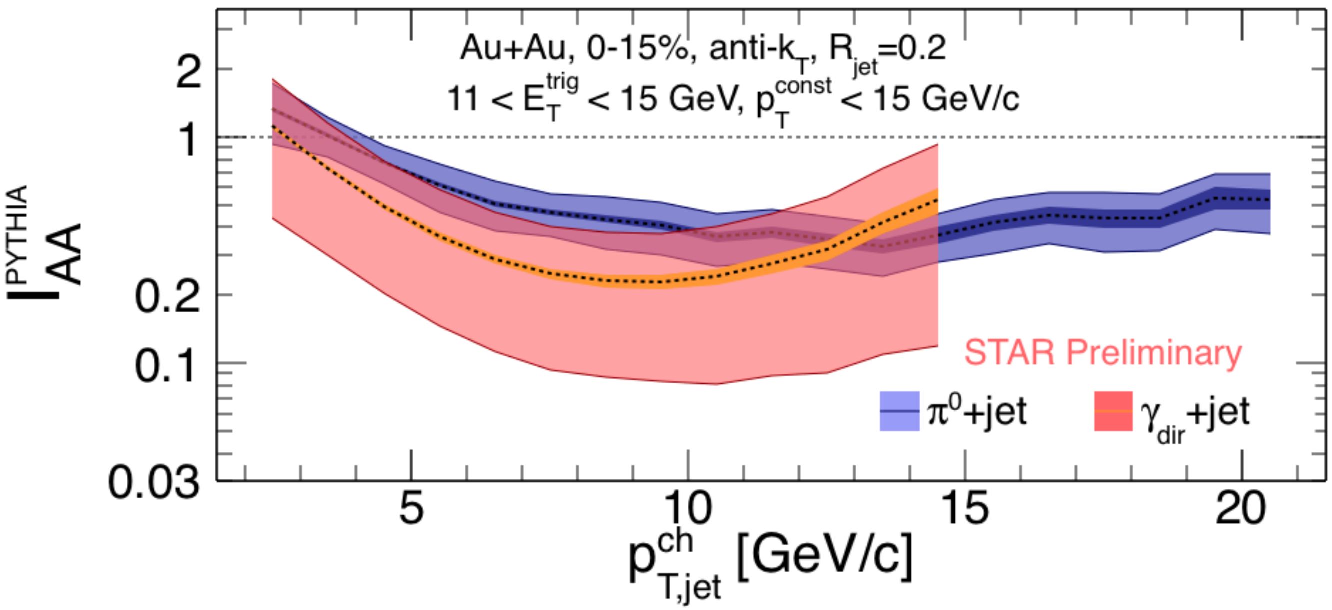
- Same level of suppression above $p_{T,jet}^{ch} > 9$ GeV/c
  - $h^{\pm}$+jet is I_{CP}, whereas π^0+jet is I_{AA}^{PYTHIA}

Recoil jet yield suppression: γ_{dir}+jet vs. π^0+jet

What about at higher trigger E_T?

$11 < E_T^{trig} < 15$ GeV

HP2018 talk



Systematic (lighter band) and statistical (darker band) uncertainties

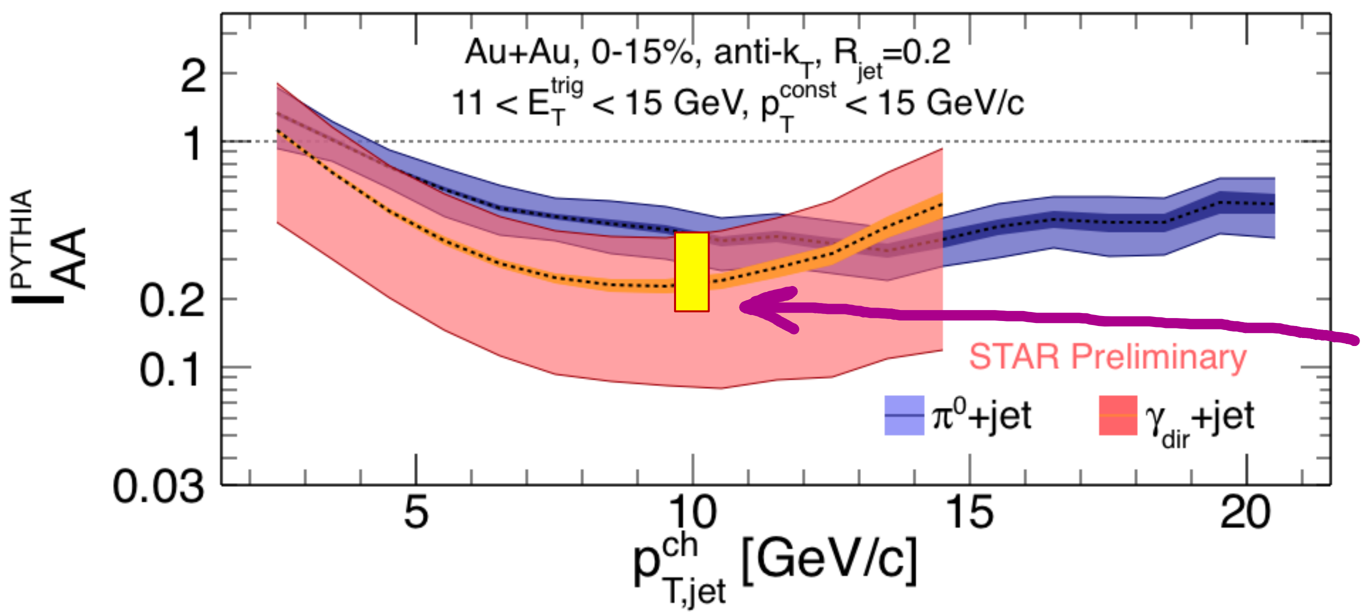
Systematic uncertainties have been improved in the present analysis.

- Almost same level of suppression in both cases, within uncertainties

Recoil jet yield suppression: γ_{dir}+jet vs. π^0+jet

What about at higher trigger E_T?

$11 < E_T^{trig} < 15$ GeV



Systematic (lighter band) and statistical (darker band) uncertainties

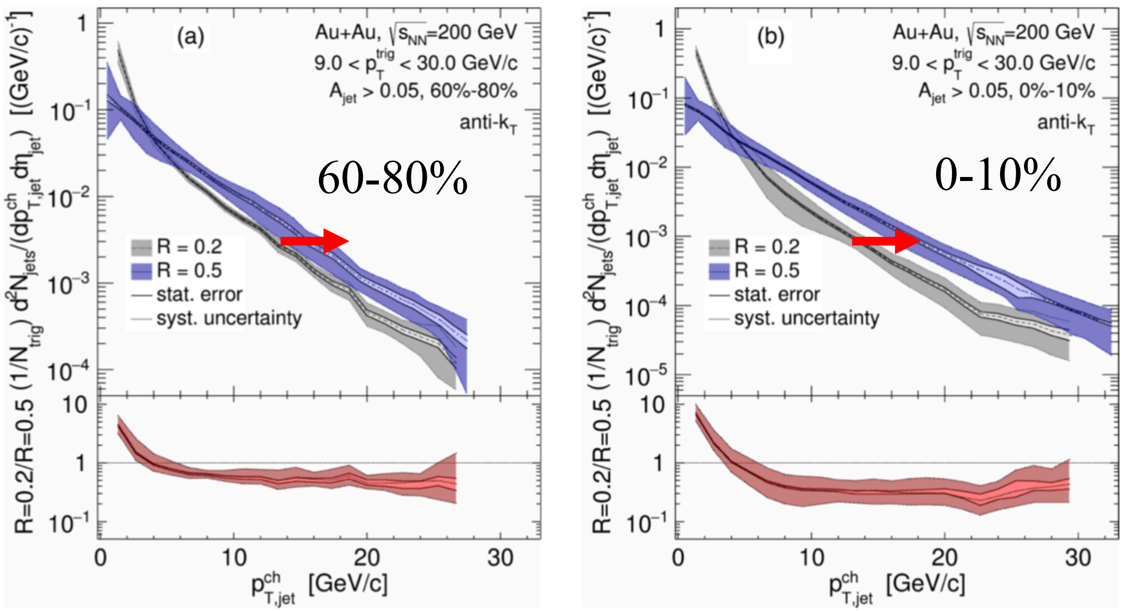
(Current Sys. Uncrnt.) Systematic uncertainties have been improved in the present analysis.

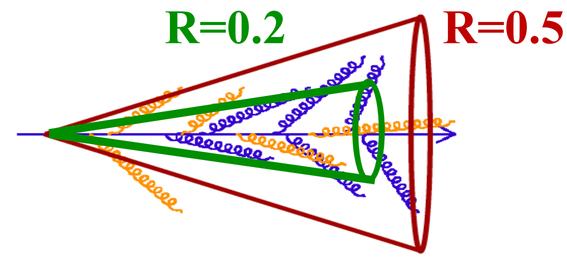
- Almost same level of suppression in both cases, within uncertainties

Modification of jet shape: h+jet

Medium induced broadening!

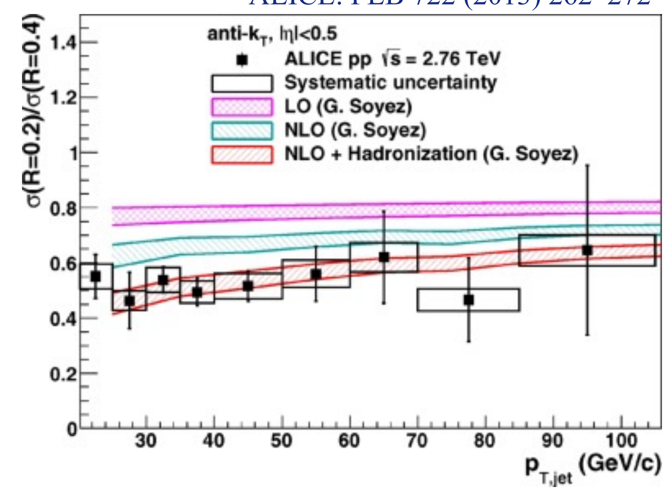
STAR:PRC 96, 024905 (2017)





Intrajet distribution of energy transverse to the jet axis

ALICE: PLB 722 (2013) 262–272



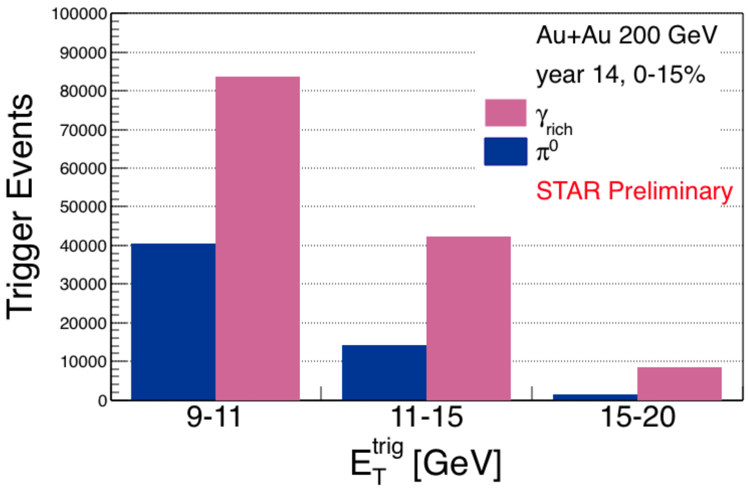
- Horizontal pT-shift between 10-20 GeV/c:
  - 60-80%: 2.9 ± 0.4(stat) ± 1.9(sys) GeV/c
  - 0-10%: 5.0 ± 0.5(stat) ± 2.3(sys) GeV/c
  - Consistent within uncertainty

No evidence of broadening of the jet shower due to jet quenching like in p+p and Pb+Pb at LHC

Recoil jet yield suppression: γ_{dir}+jet vs. π^0+jet

Two jet radii
- R=0.2 and 0.5 [to explore medium-induced broadening]

Three trigger E_T bins of γ_{dir} and π^0
- $9 < E_T^{trig} < 11$ GeV
- $11 < E_T^{trig} < 15$ GeV
- $15 < E_T^{trig} < 20$ GeV [STAR capability of γ_{dir} measurement at very high E_T^{trig}]



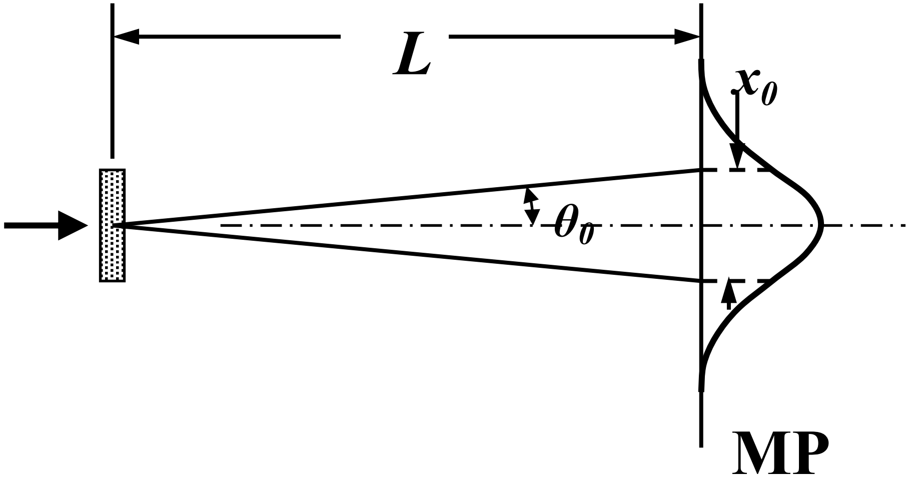
Results will be shown in Quark Matter 2019, Wuhan.

π^0+jet (γ_{dir}+jet) $\Delta\varphi$ angular correlation

‘'A possible signature of Quasi-particle nature of QGP ’’

Ongoing work in STAR…

Multiple Scattering (QED Molière Scattering)



https://gray.mgh.harvard.edu/attachments/article/213/06_Scattering.ppt

- When a proton passes through a slab of material they suffer millions of collisions with atomic nuclei (potential hills)
  - That creates a *multiple scattering angle* whose distribution is approximately Gaussian but with large tails **(Central limit theorem)**
- Strength of scattering depends on $1/p^2$ → large for small momenta

H. A. Bethe, Phys. Rev. 89(1953) 1256-1266

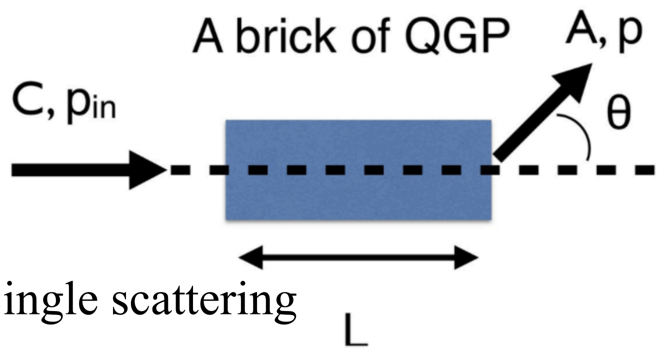
What about in the case of recoil-jet pass through the hot-dense QCD matter?

Scattering in a brick of QGP

F. D'Eramo, K. Rajagopal, Y. Yin; arXiv:1808.03250

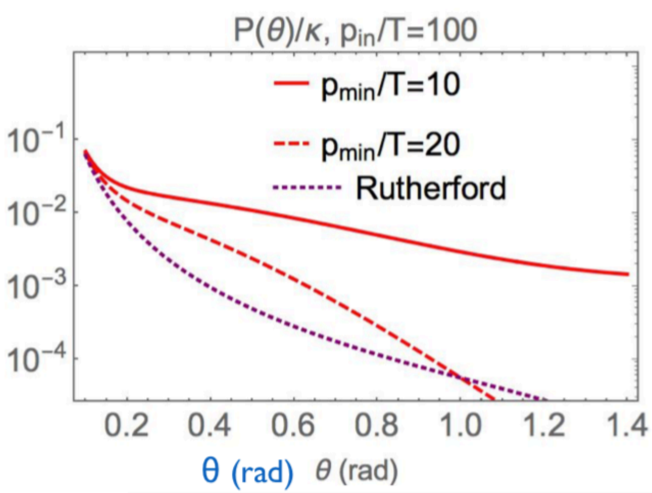
QCD Molière Scattering:

A rare large angle scattering



Single scattering

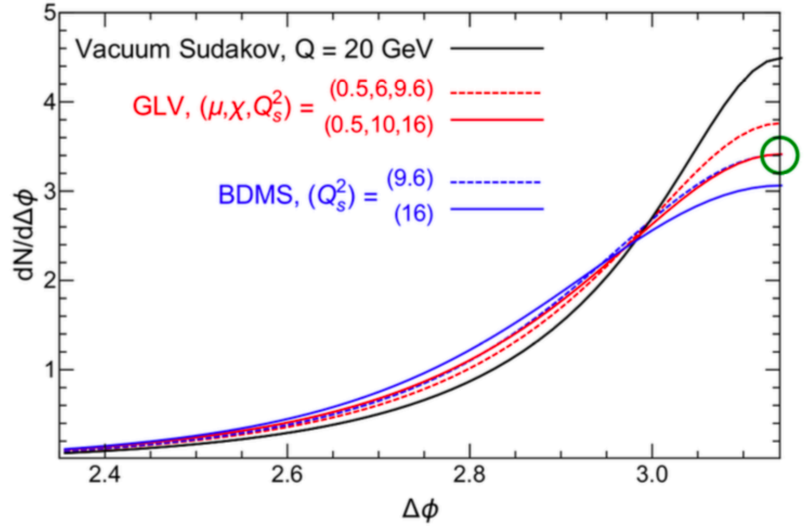
Angle distribution $P(\theta) \equiv \int_{p_{\rm min}} dp F(p,\theta)$

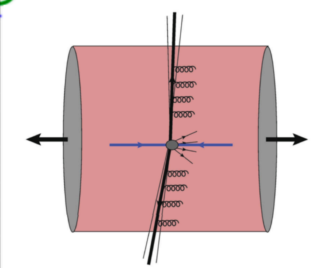


M. Gyulassy, et al, QM2018

Dijet acoplanarity:

Vacuum Sudakov vs. vacuum + medium





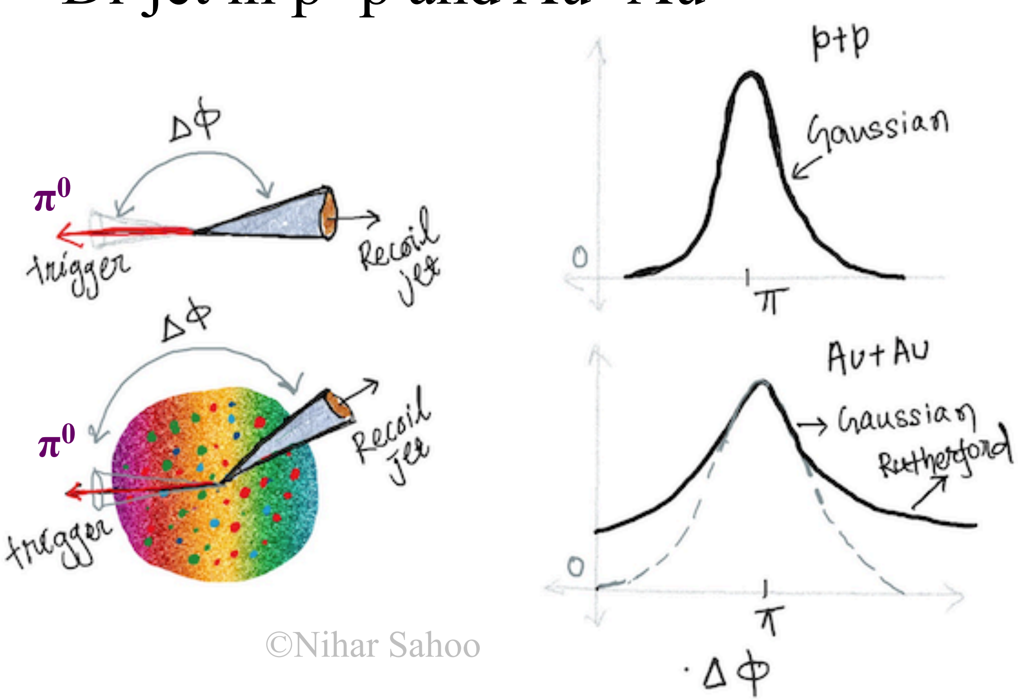
In hot-dense QCD

- Can we see this effect?
- Single vs. Multiple scattering domain?
- QCD medium response

"Quasi-particle nature of QGP"

In heavy-ion collisions

Di-jet in p+p and Au+Au



At small angle ⟶ Gaussian Shape

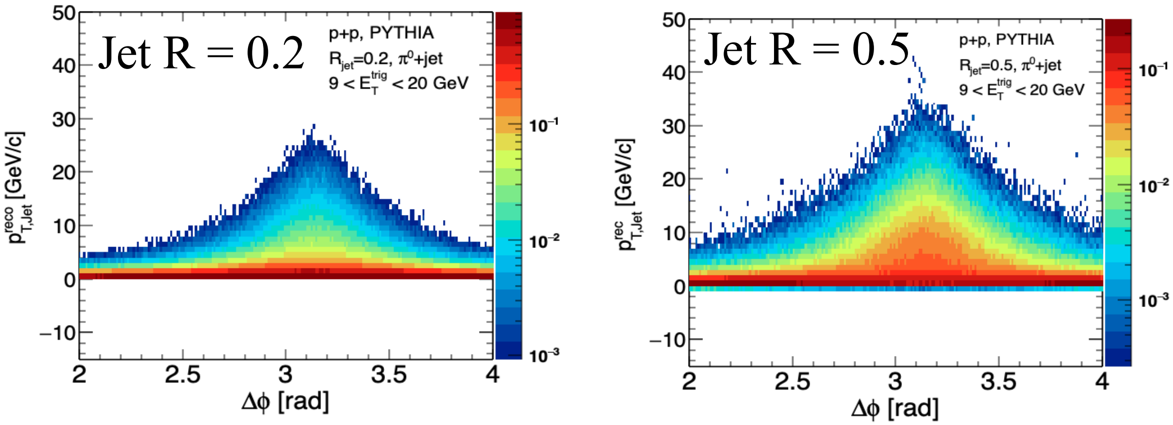
At large angle ⟶ Rutherford Scattering

- Scattering of a recoil-jet off quasi-particles in the QGP
    - Intra-jet broadening (Δφ)
- Intriguing to study Δφ correlations for different recoil jet radii and jet p_T in heavy-ion collisions

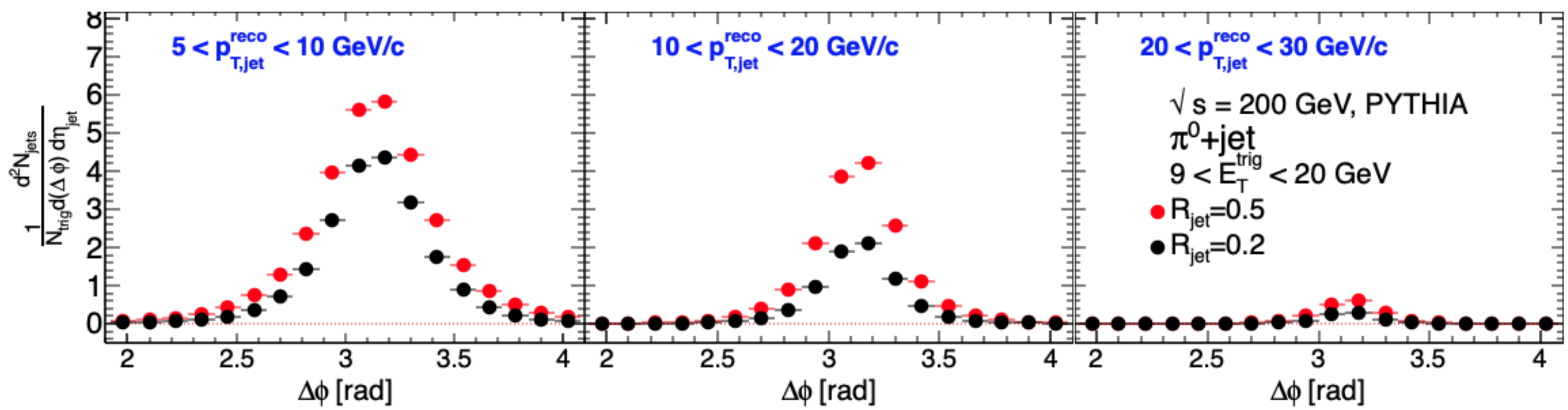
p+p PYTHIA expectation: π^0+jet

Jet p_T vs. $\Delta\varphi$ correlation function

Jet p_T



$\Delta\varphi$ distributions at different jet p_T bins

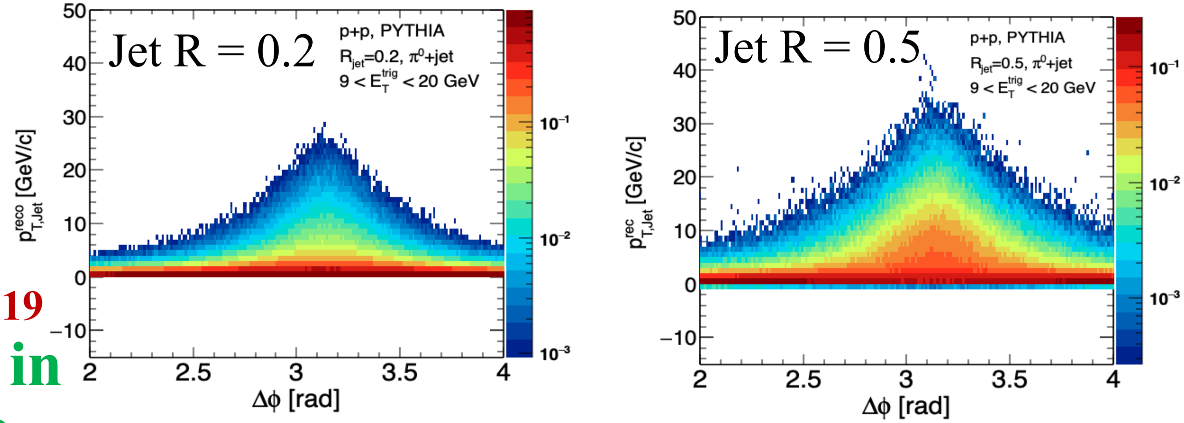


No significant yield at large angular deviation in p+p

p+p PYTHIA expectation: π^0+jet

Jet p_T vs. $\Delta\varphi$ correlation function

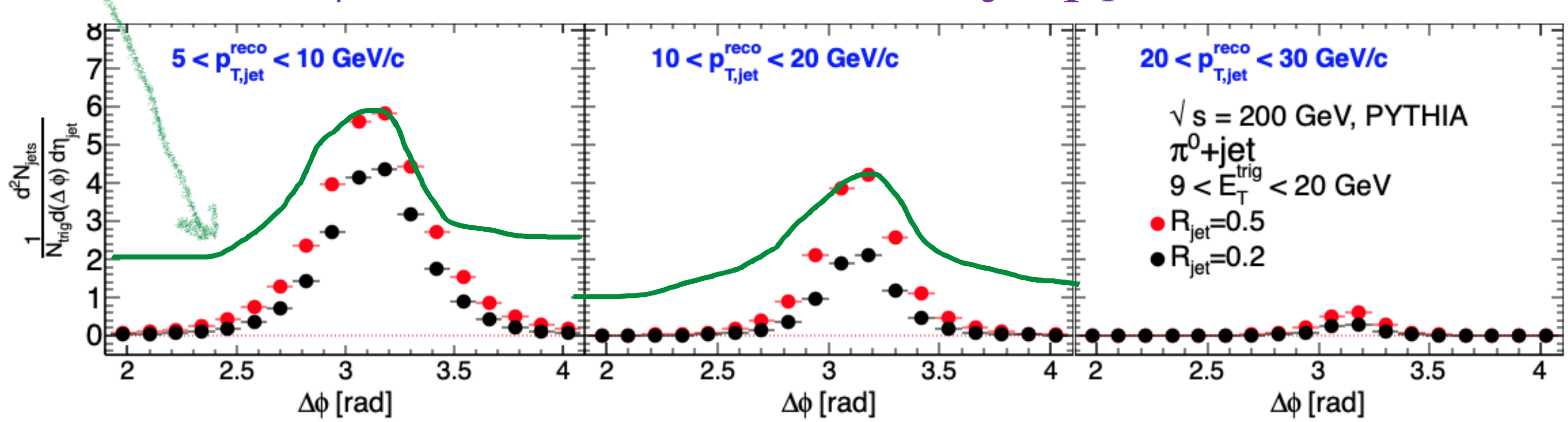
Jet p_T



Quark Matter 2019

Can we see in Heavy-Ion?

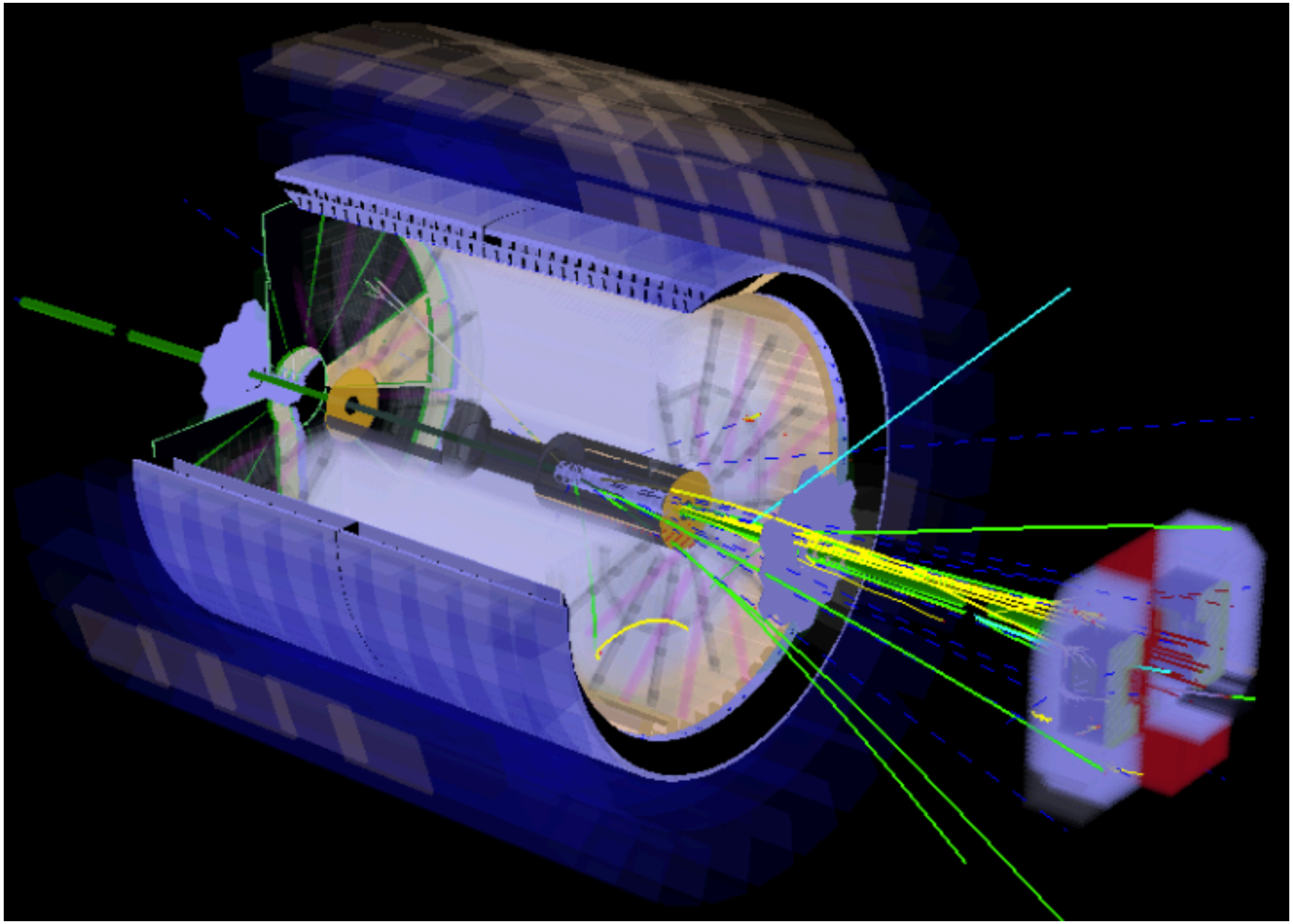
$\Delta\varphi$ distributions at different jet p_T bins



Analysis is underway in Au+Au collision for different jet radii and jet p_T.

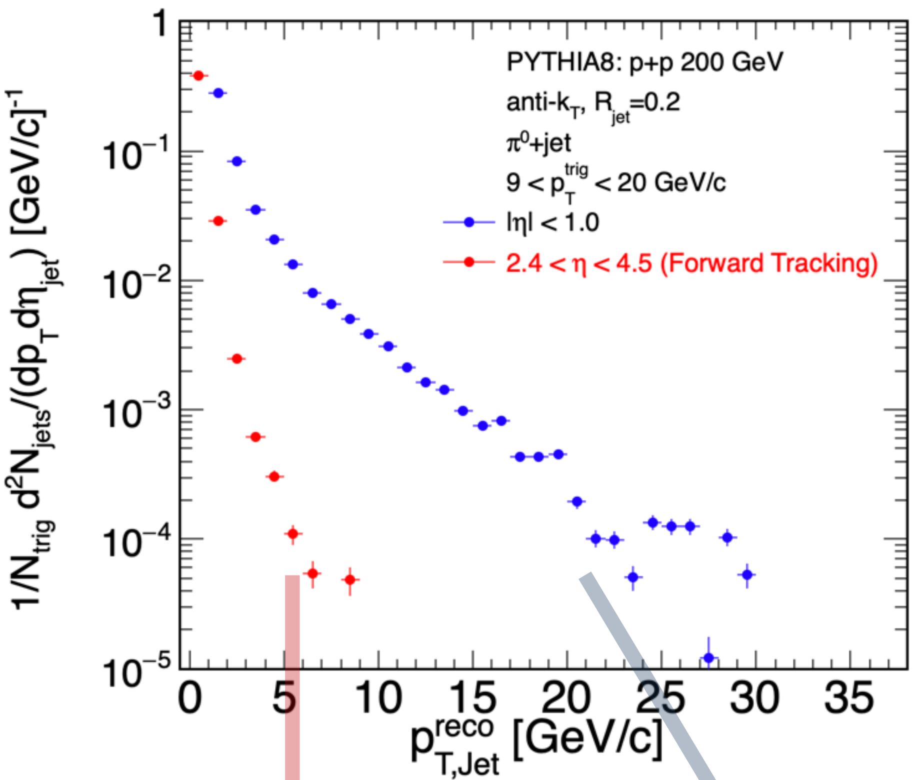
It would be an interesting measurement for p+Au collisions and also at forward recoil jet (sea quark).

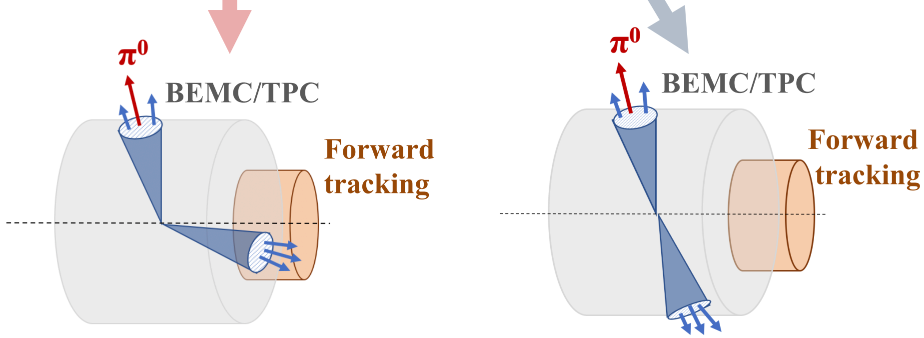
Physics for forward tracking in STAR
(in a perspective of semi-inclusive jet measurement)

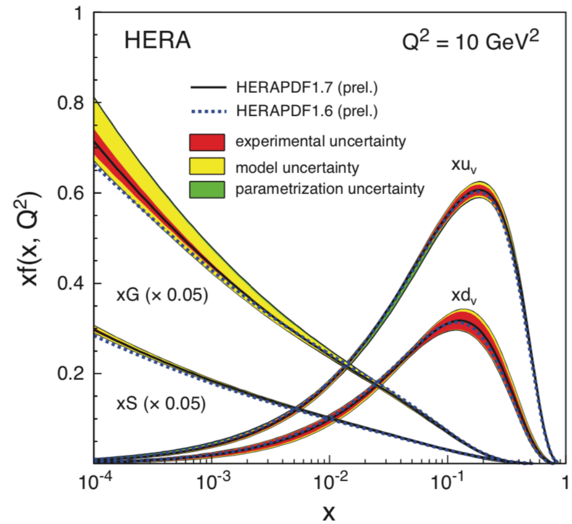


An aspect for mid and forward rapidity jet measurement

PYTHIA simulation: π^0+jet







PDFs of sea quarks and gluons are scaled down by factor 20.

Relation between y and p_T:

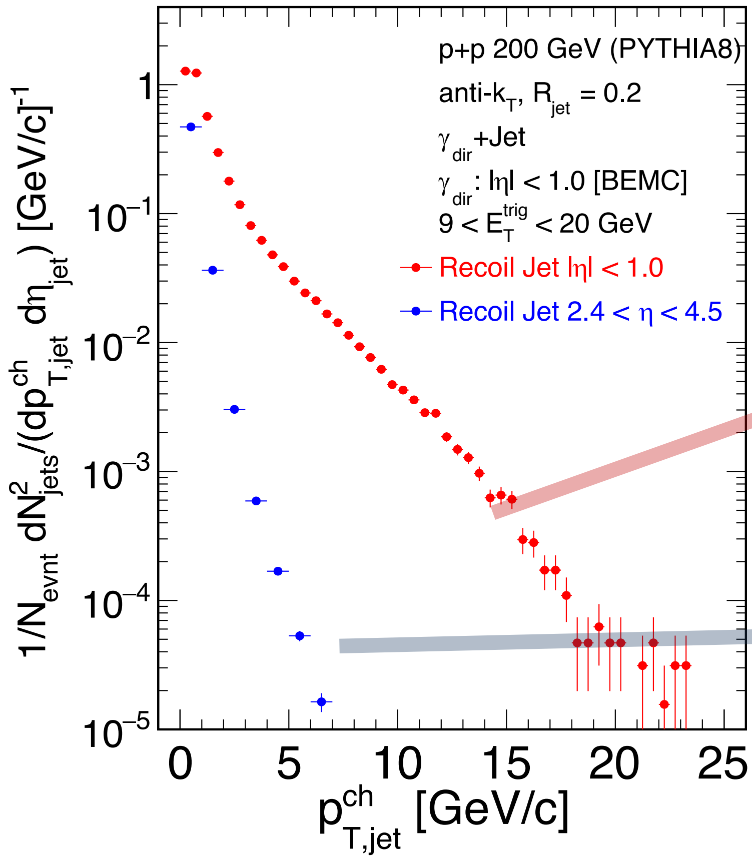
Fractional longitudinal momenta of produced partons/particles with mass *m*:

$$x_{1,2} = e^{\pm y}\sqrt{(p_T^2 + m^2)/s}$$

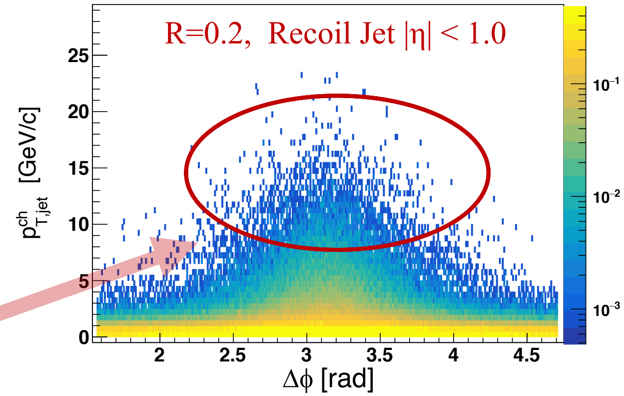
- At RHIC, "sea" quark effects become measurable at large forward rapidity, y = 2 - 4 for x_2
- Even at moderate x~0.1, sea quark dominates.

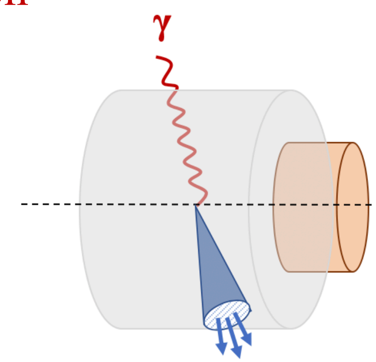
An aspect for mid and forward rapidity jet measurement

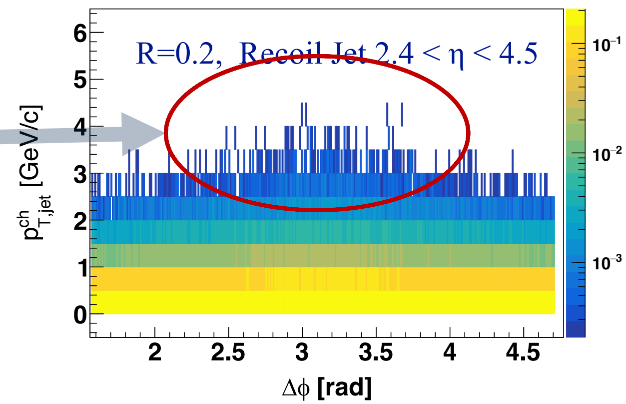
PYTHIA simulation: γ_{dir} +jet

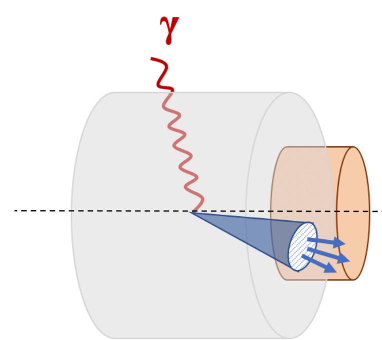


Recoil jet population in recoil region









- At moderate x (~0.1), sea quark dominates: sea vs. valance quarks contribution
- Quark jet, at mid and forward rapidity, recoiling from direct photon comparison can help to understand QCD at different parton momentum fraction

What physics we can study from the STAR forward-upgrade?

- A comparison between recoil jet at mid and forward rapidity
  - Small-x at forward rapidity → study the sea quark contribution

- π^0+ Jet $\Delta\varphi$ correlation analysis in Au+Au [**Medium-induced acoplanarity**]
  - Can we observe any large angle yield at forward rapidity recoil jet, or not?
  - A comparison between p+p, p+Au and Au+Au can provide a comprehensive understanding of this effect in vacuum, hot-dense, and cold QCD medium

Summary

- First γ_{dir}+jet and π^0+jet measurements in Au+Au collisions at $\sqrt{s_{NN}}$= 200 GeV at RHIC
- p+p collisions at 200 GeV: π^0-triggered recoil-jet yield consistent in data and PYTHIA8
- Central Au+Au at 200 GeV:
  - A strong suppression of γ_{dir}+jet and π^0+jet
  - Suppression of recoil-jet yield consistent in both cases, for $9 < E_T^{trig} < 15$ GeV

Outlook

Ongoing work in the direction of γ_{dir}+jet and π^0+jet analysis in STAR :

- $E_T^{trig} > 15$ GeV ; larger $p_{T,jet} > 20$ GeV/c; $R_{jet} = 0.5$
- π^0+jet (γ_{dir}+jet) $\Delta\varphi$ angular correlation

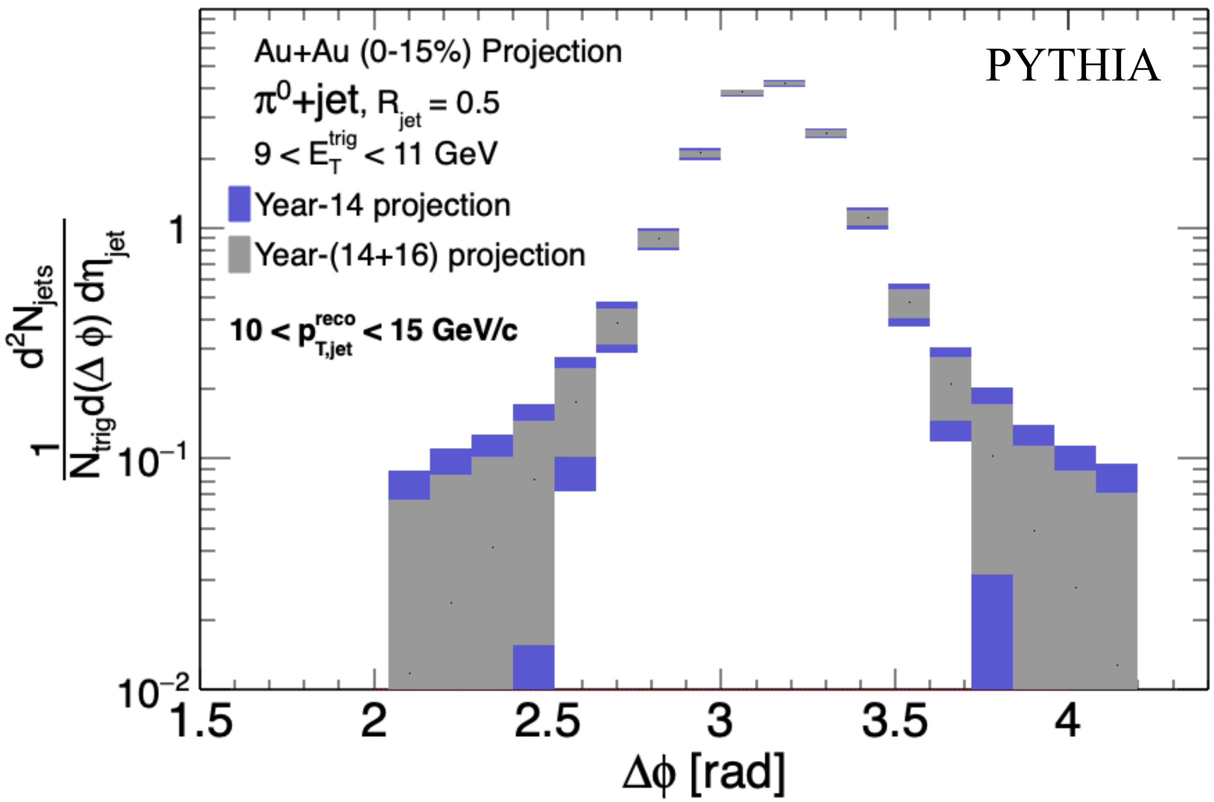
Forward upgrade:

- Many physics opportunity to be explored

Backup

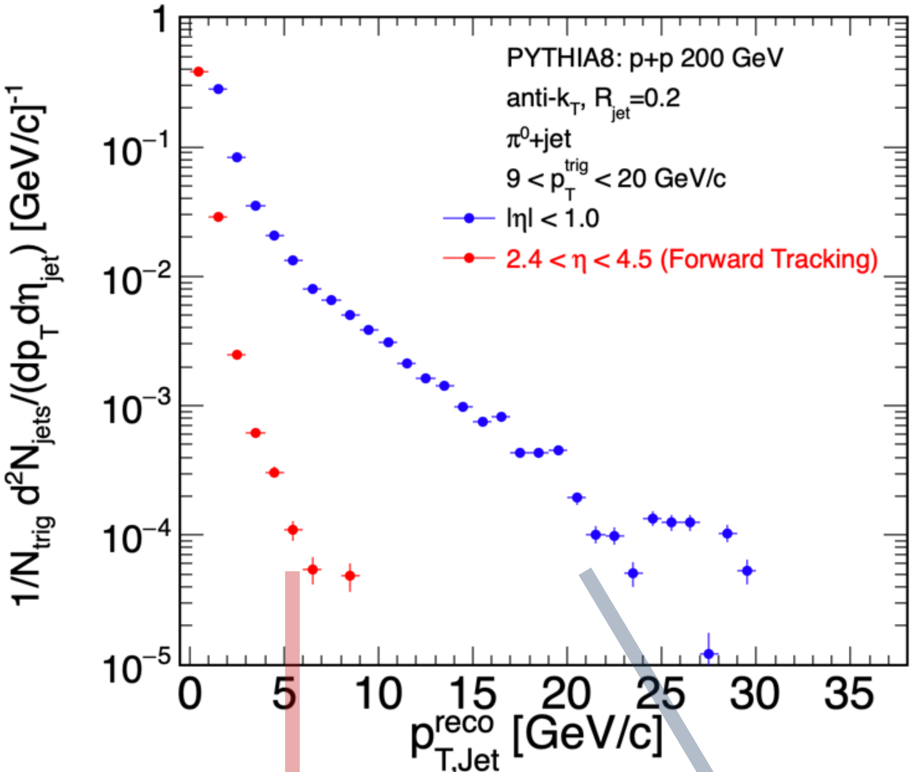
Heavy-Ion projection

STAR heavy-ion projection for this measurement
Au+Au 200 GeV year 2014 + year 2016:
~25 nb^{-1} Integrated Lumininosity

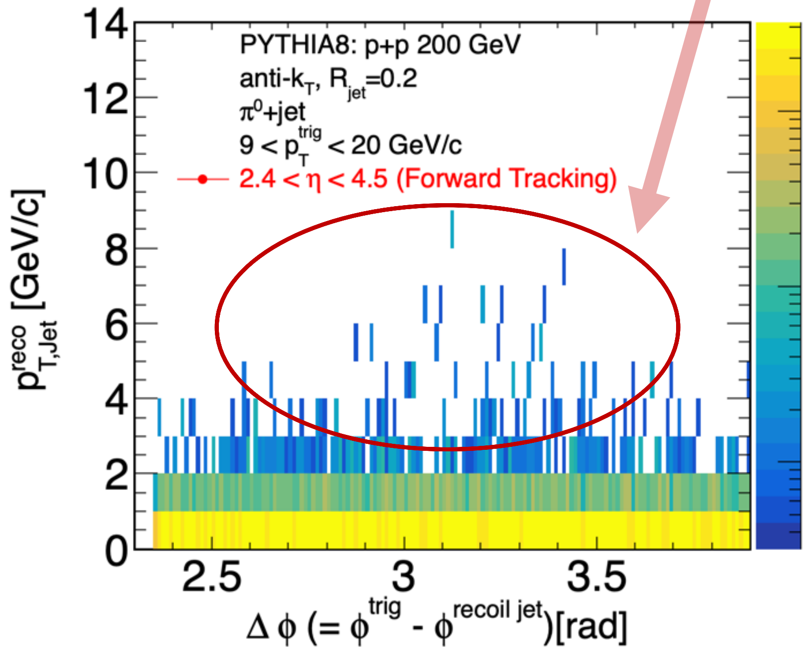


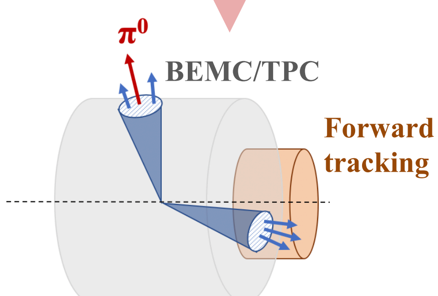
An aspect for mid and forward rapidity jet measurement

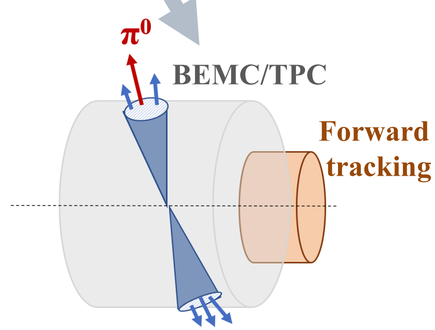
PYTHIA simulation: π^0+jet



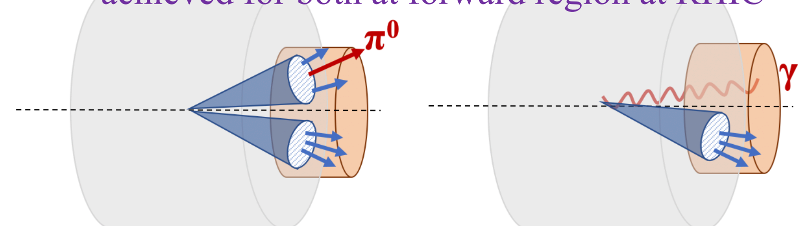
Recoil jet population in recoil region





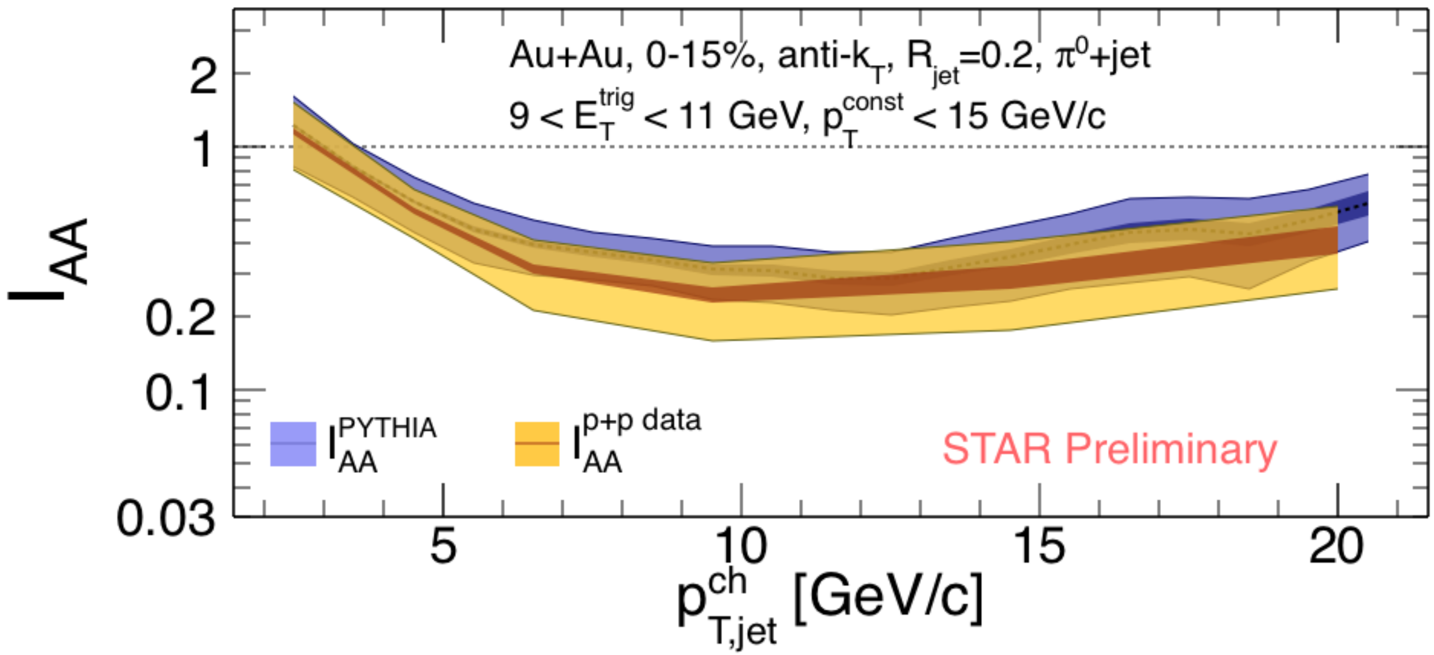


Relatively low (intermediate) $x_{1,2}$ can be achieved for both at forward region at RHIC



Recoil jet yield suppression: pp vs. PYTHIA

π^0+jet: $9 < E_T^{trig} < 11$ GeV



Systematic (lighter band) and statistical (darker band) uncertainties

- I_{AA} is the ratio of per triggered recoil jet yield in central Au+Au to p+p collisions
- Comparison between π^0-triggered charged jet I_{AA}^{PYTHIA} and $I_{AA}^{p+p\ data}$
- Consistent within uncertainties
- PYTHIA8 provides good representation of p+p data