Semi-inclusive γ+jet And h+jet: *Heavy-ion Collisions, Future STAR Forward Upgrade And EIC Physics*

(A+A and p+p ⟶ p+A and p+p ⟶ e+p and e+A)

Nihar Ranjan Sahoo
Shandong University (SDU), Qingdao, China

QCD with EIC, IIT Mumbai, India
4-7 Jan 2020

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

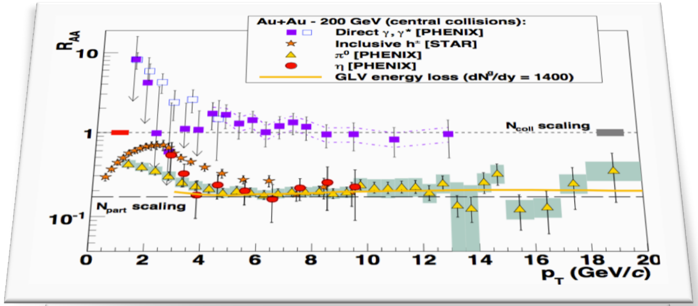
γ+hadron correlation Large angle deflection

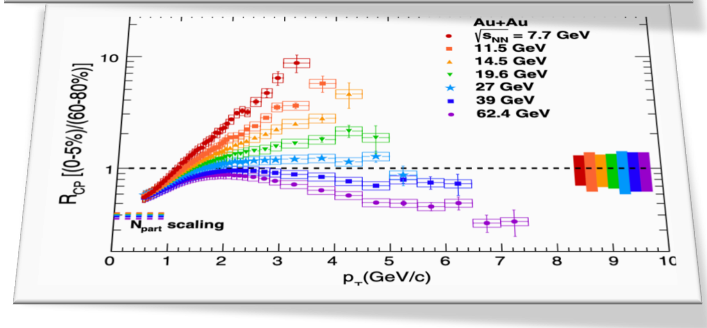
Jet modification in p+p high multiplicity events

Jet as a tool to study QCD at collider experiments

In hot-dense QCD medium:

- Quantitative estimation of parton energy loss as a function of path length, Casmiri factor, initial parton energy, etc.
- Redistribution of lost energy inside the medium [*Jet R/medium*]
- RHIC vs. LHC [*dependence on temp. and initial gluon density*] What about lower beam energy in HIC?
- Modification of jet shape inside a hot QCD medium

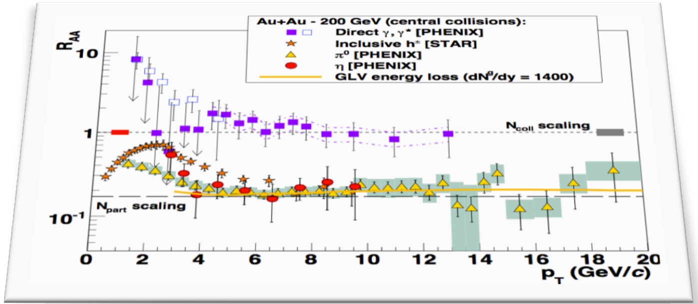


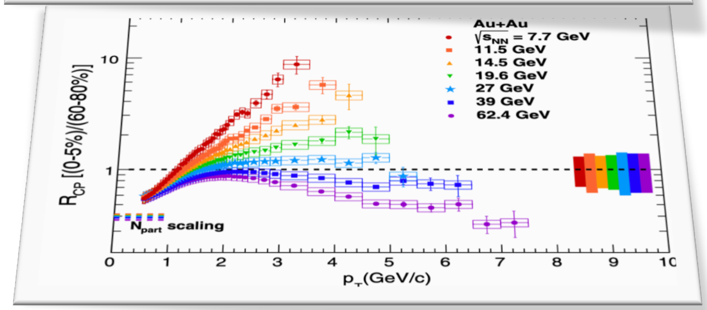


Jet as a tool to study QCD at collider experiments

In hot-dense QCD medium:

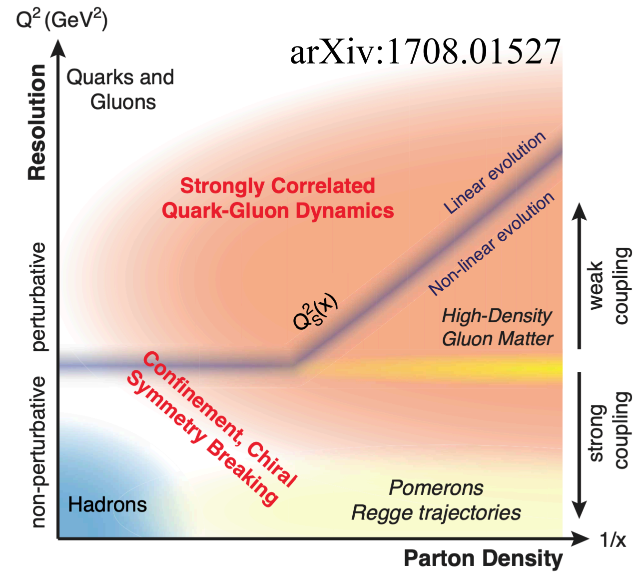
- Quantitative estimation of parton energy loss as a function of path length, Casmiri factor, initial parton energy, etc.
- Redistribution of lost energy inside the medium [*Jet R/medium*]
- RHIC vs. LHC [*dependence on temp. and initial gluon density*] What about lower beam energy in HIC?
- Modification of jet shape inside a hot QCD medium



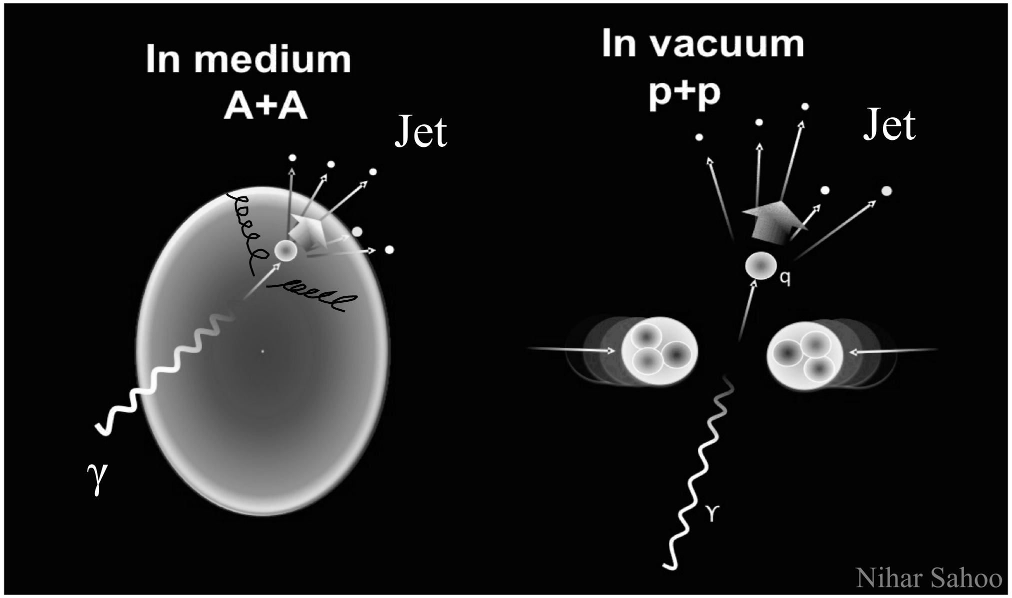


In Cold-dense QCD medium:

Jet as a tool to study nonlinear gluon saturation regime



Semi-inclusive γ+jet and h+jet in Heavy-Ion collisions



γ+jet:

$qg \rightarrow q\gamma$

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

Dijet/h+jet:

$qg \rightarrow gq$

$qq \rightarrow qq$

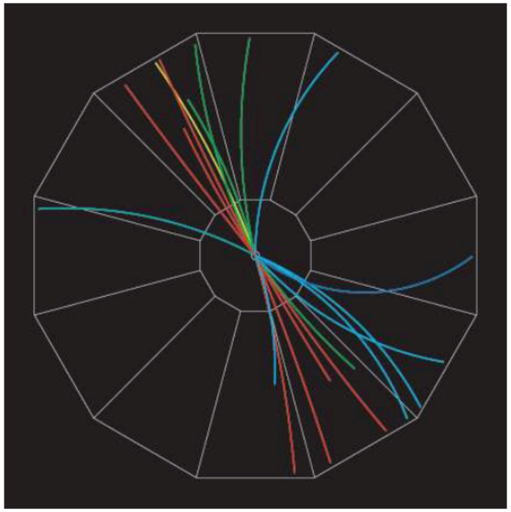
$\bar{q}q \rightarrow \bar{q}q$

$gg \rightarrow gg$

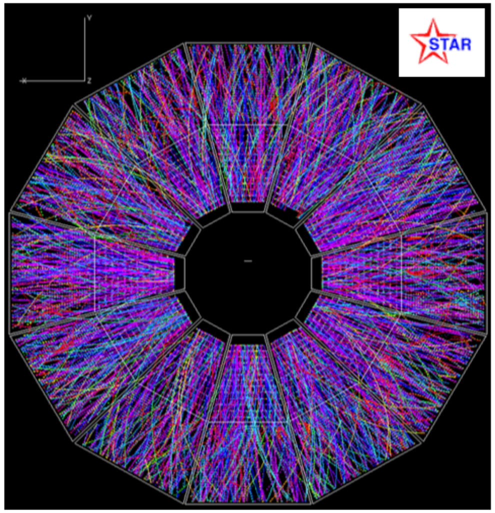
...

Challenges in heavy-ion collisions to study jet

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

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

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

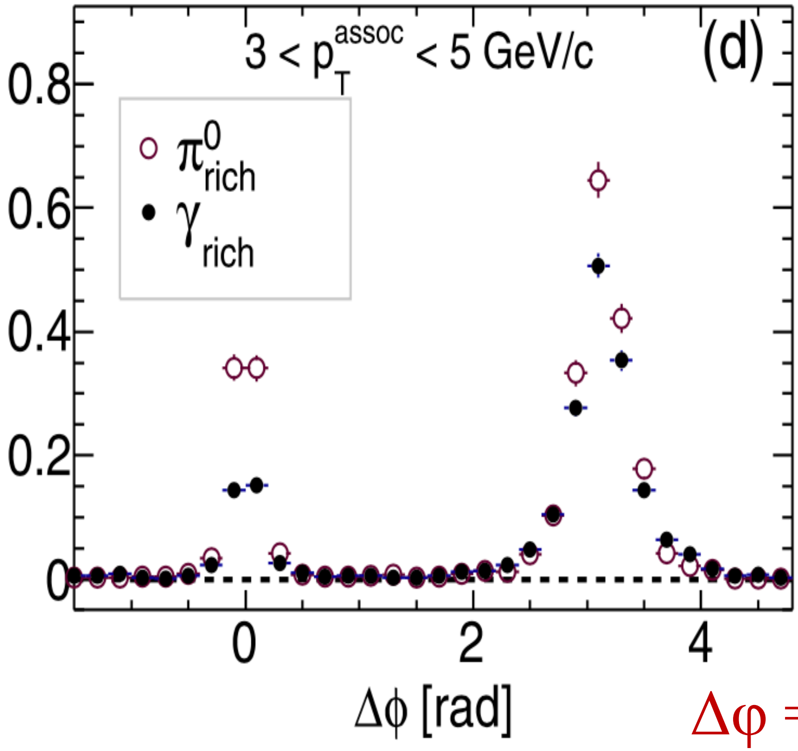
Mid-rapidity: $|\eta| < 1.0$

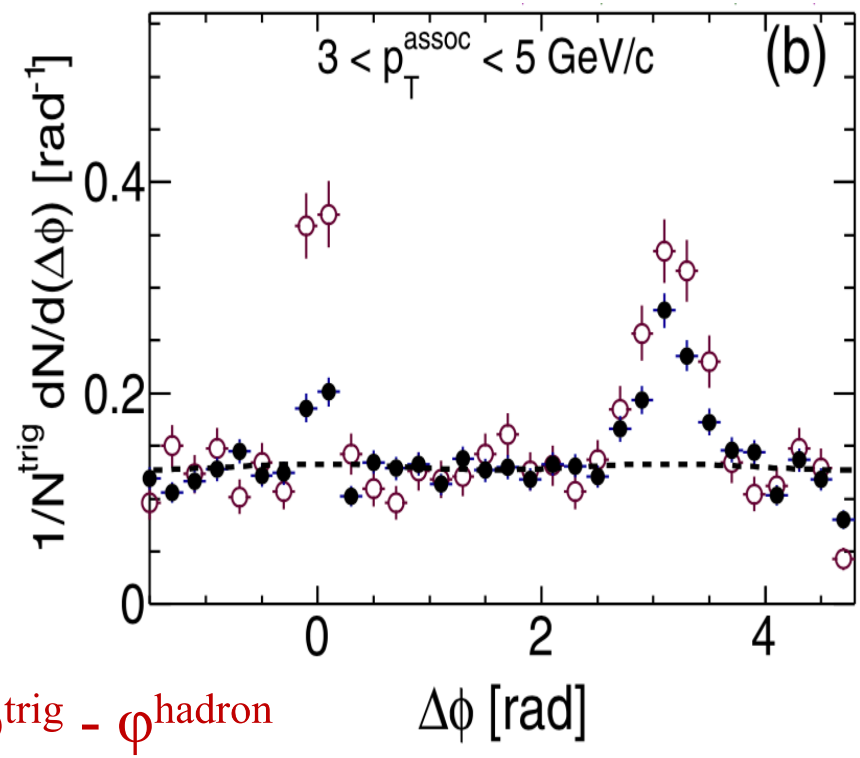
STAR: PLB 760 (2016) 689

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

p+p 200 GeV collisions

Au+Au 200 GeV collisions





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

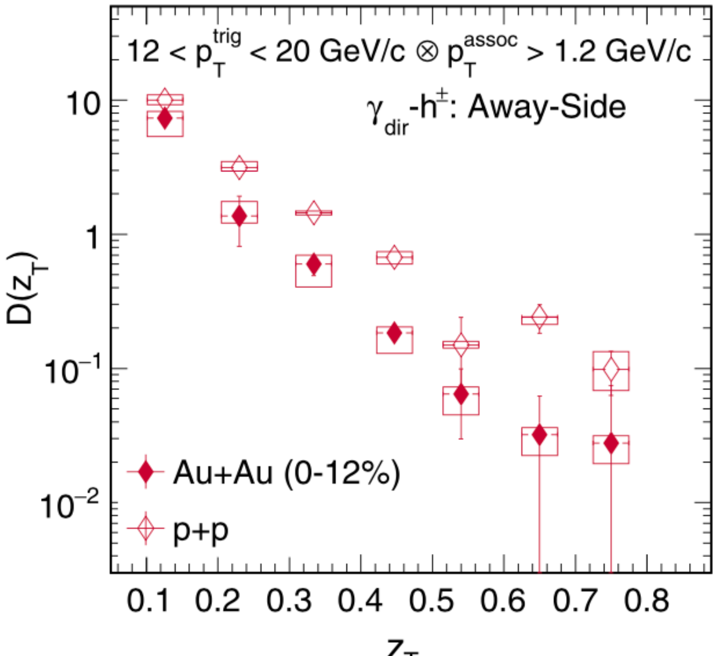
- γ_{rich} enriched sample of γ_{dir}
- In p+p collisions, uncorrelated background is negligible compared to Au+Au

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

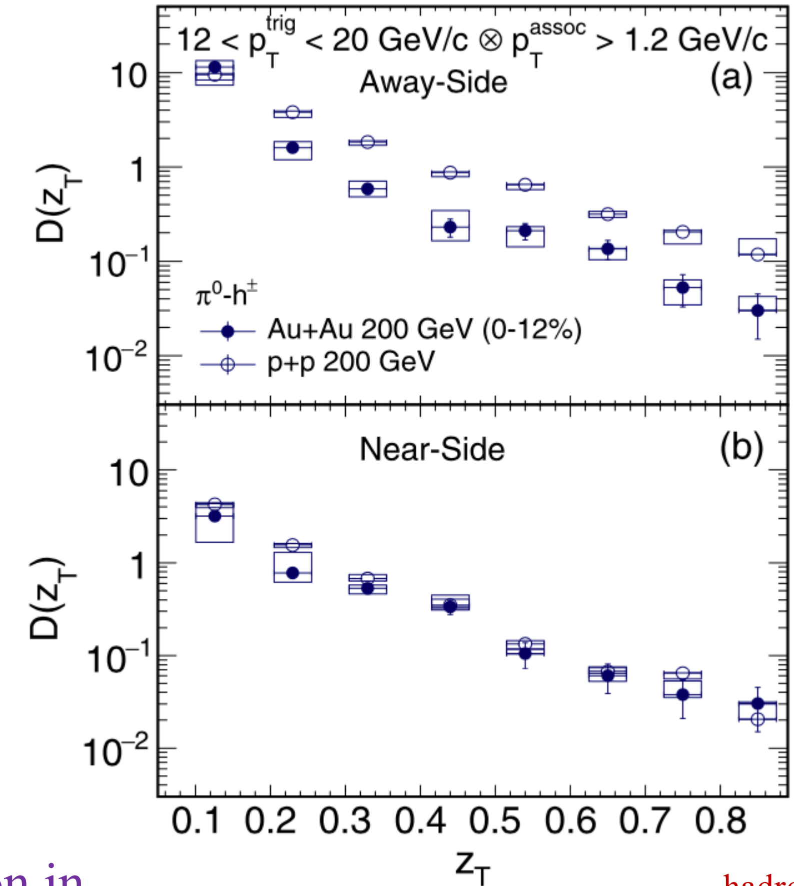
Mid-rapidity: $|\eta| < 1.0$

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

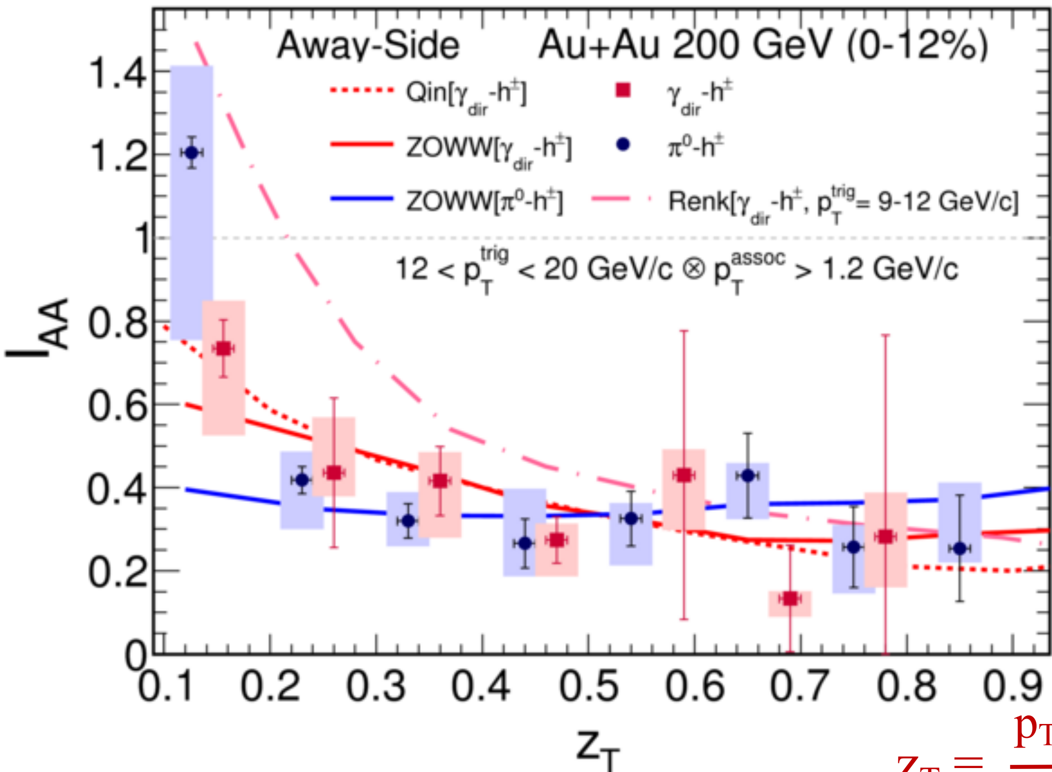
$$z_T = \frac{p_{T,i}^{hadron}}{p_T^{trig}}$$

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



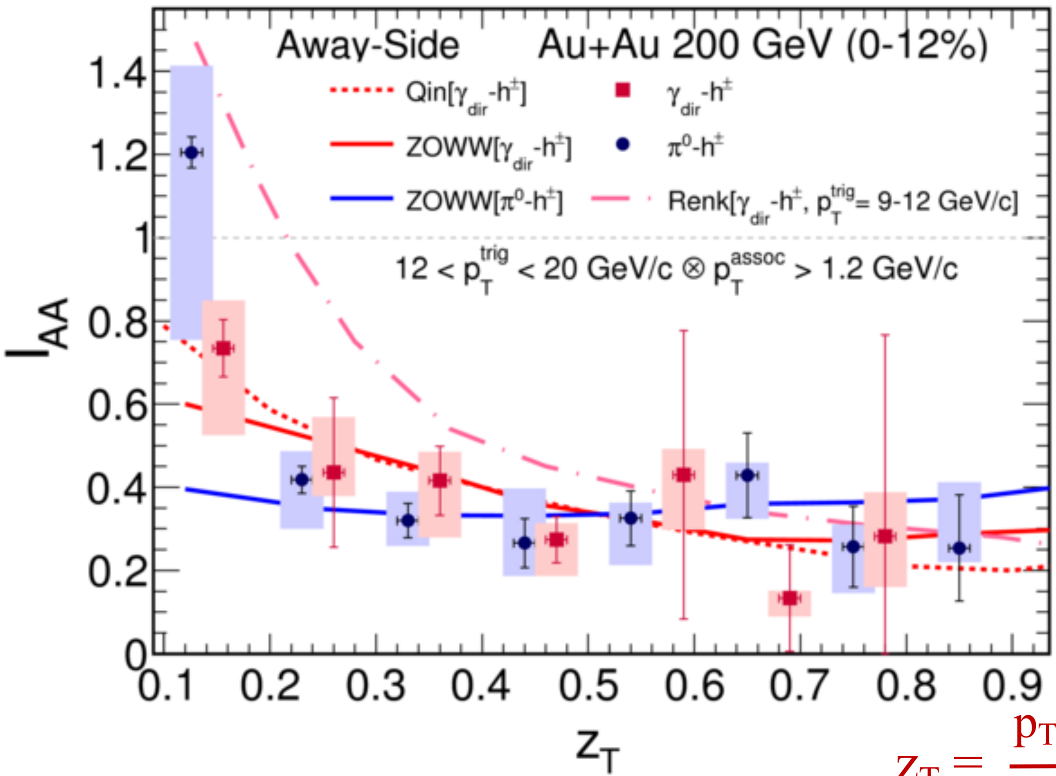
$$z_T = \frac{p_{T,i}^{hadron}}{p_T^{trig}}$$

- 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

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

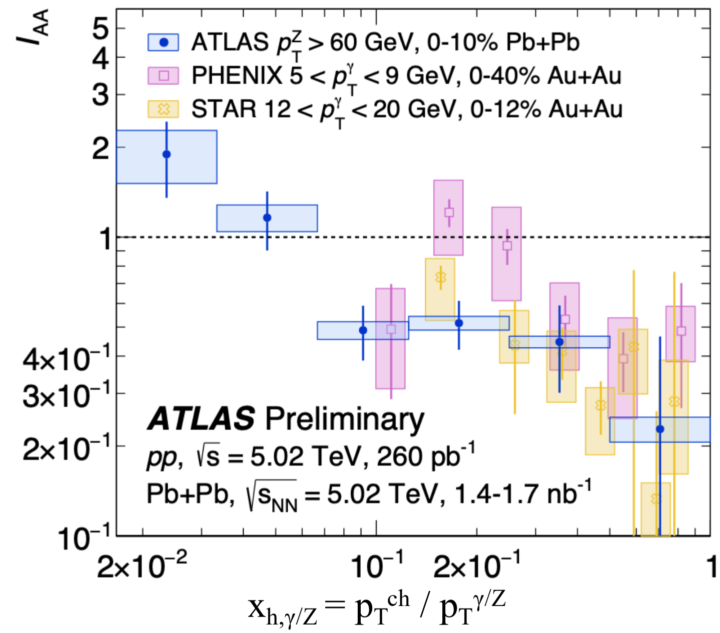
STAR: PLB 760 (2016) 689



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

γ/Z + jet: RHIC vs. LHC

LHC: Dennis V. Perepelitsa, QM19

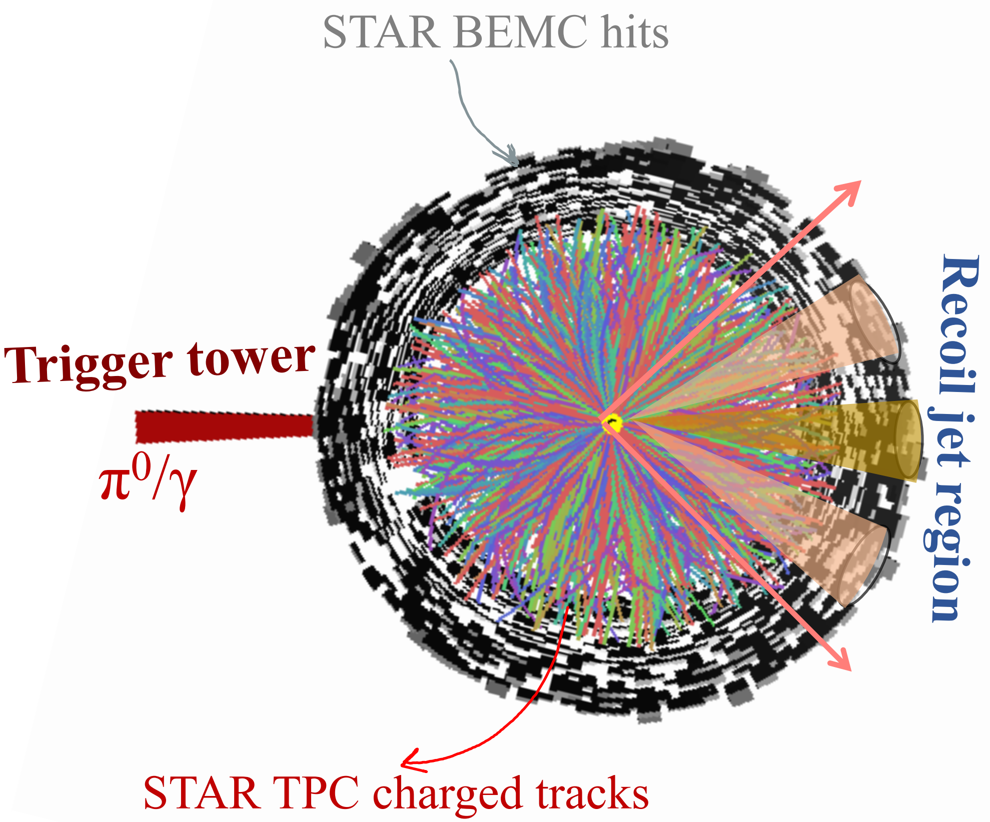


LHC vs. RHIC: Almost same suppression
(Caveat: centrality, phase space, etc.)

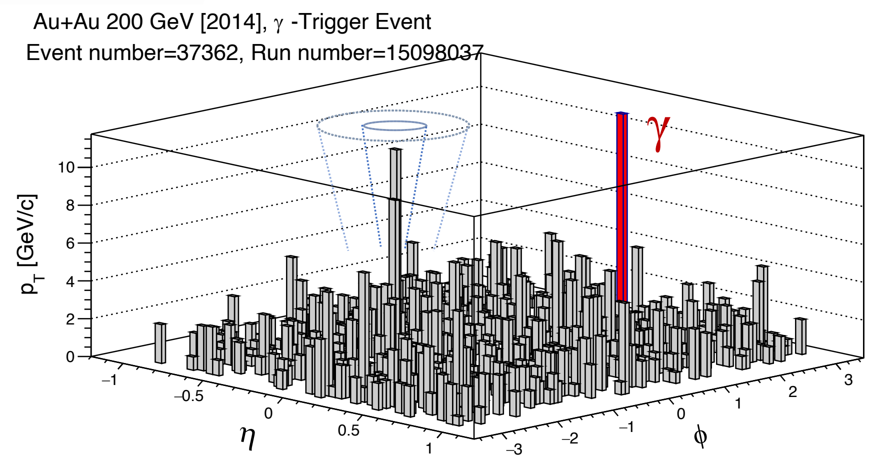
- Soft associated particles are less suppressed compared with high p_T
- Within uncertainty, no trigger (γ_{dir}/ π^0) bias can be observed

Jet study in a high soft-background energy environment

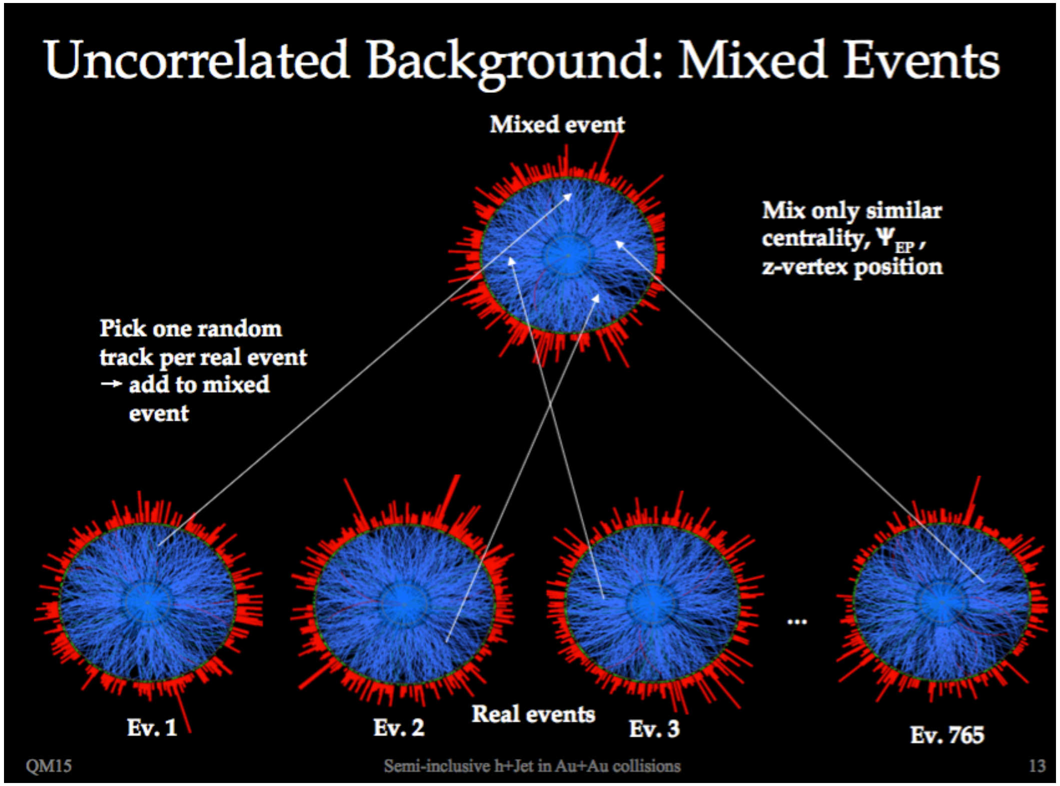
In Heavy-Ion collisions: Soft-background energy fluctuations and uncorrelated jet background contributions make life difficult.

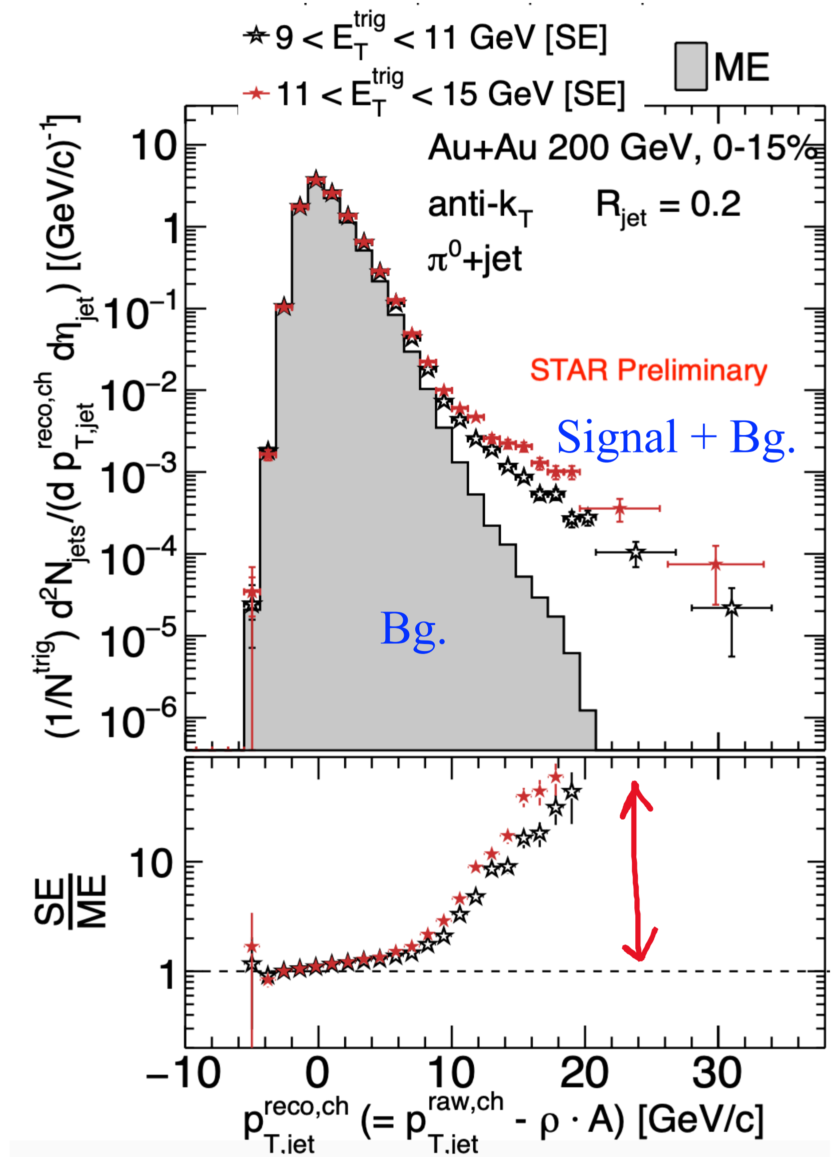


One trigger event



Mixed event: Uncorrelated jet subtraction



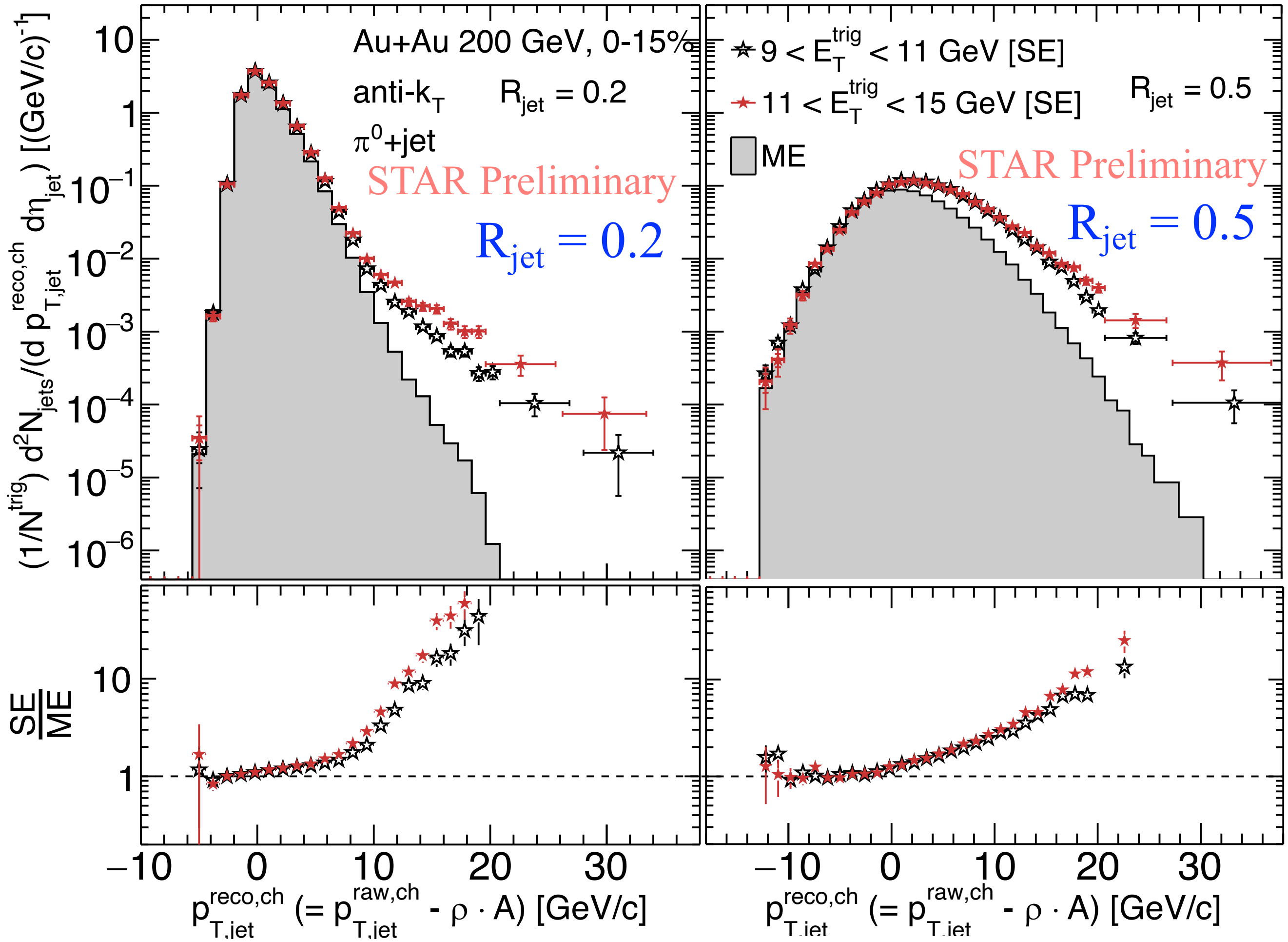


Same Event (SE) and Mixed Event (ME): same background energy density

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

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

Recoil charged Jet spectrums for different trigger E_T windows

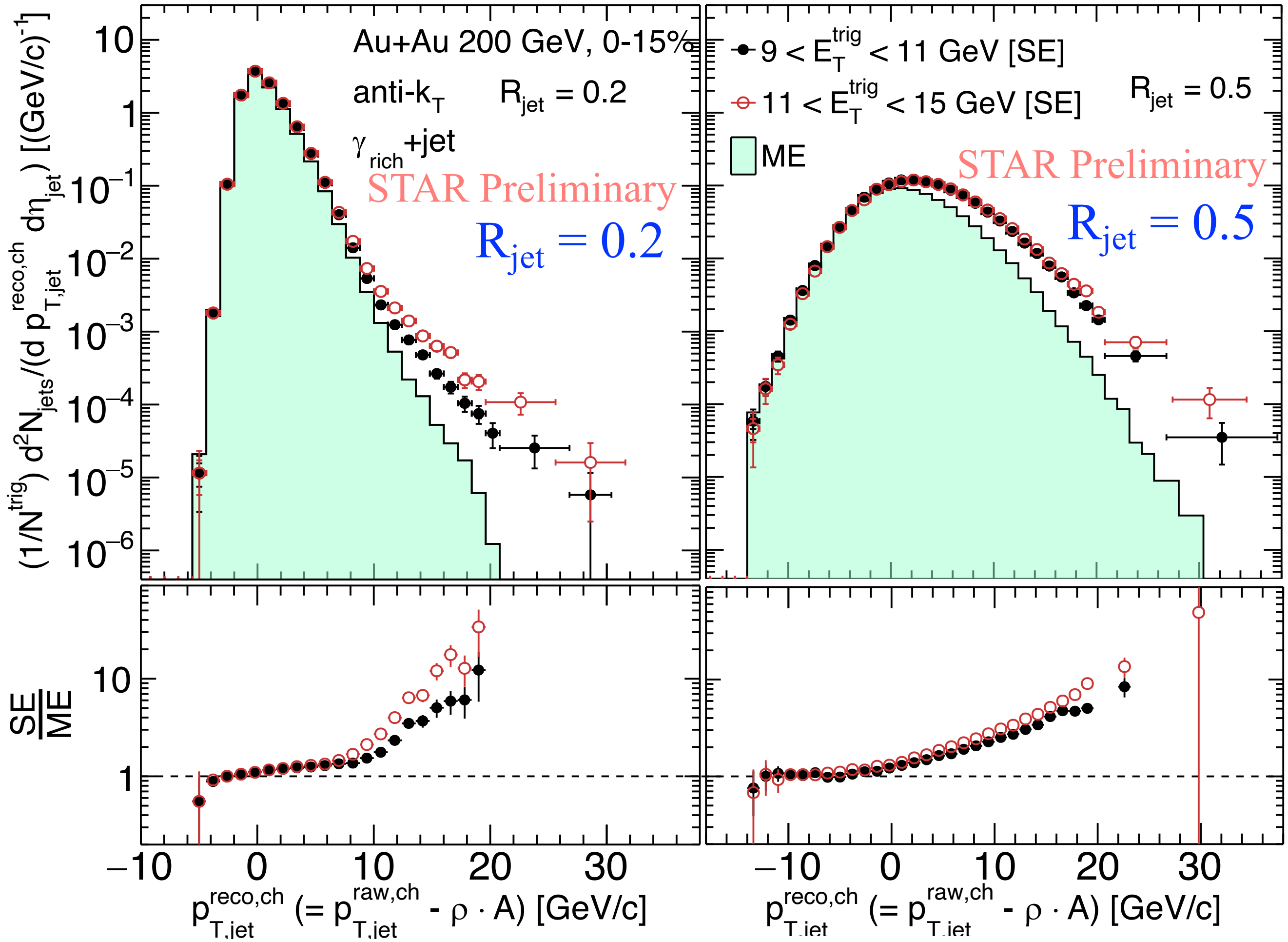


STAR: Nihar Sahoo, QM2019

A clear trigger dependence can been seen.

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

Recoil charged Jet spectrums for different trigger E_T windows



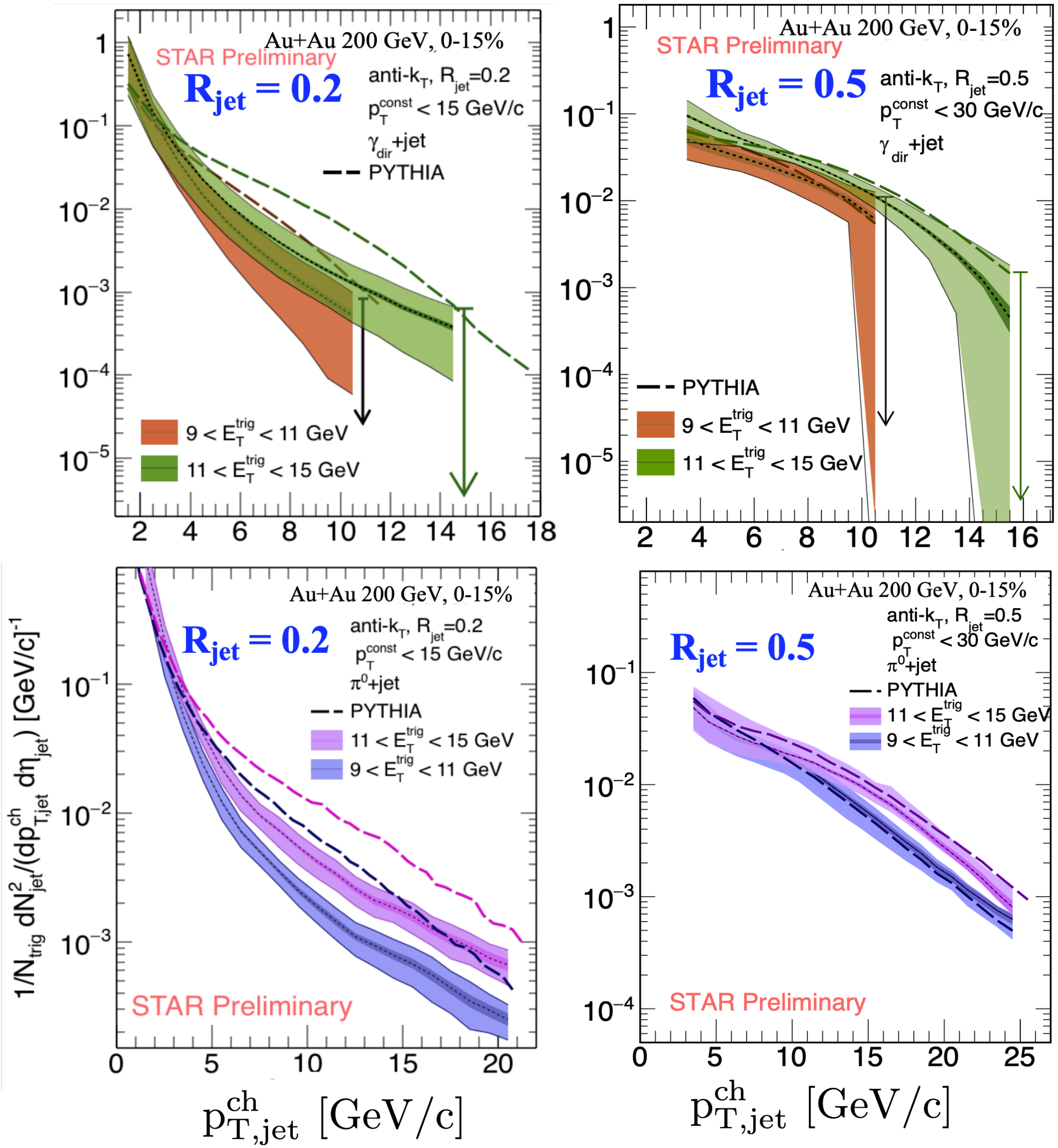
STAR: Nihar Sahoo, QM2019

A clear trigger dependence can been 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:

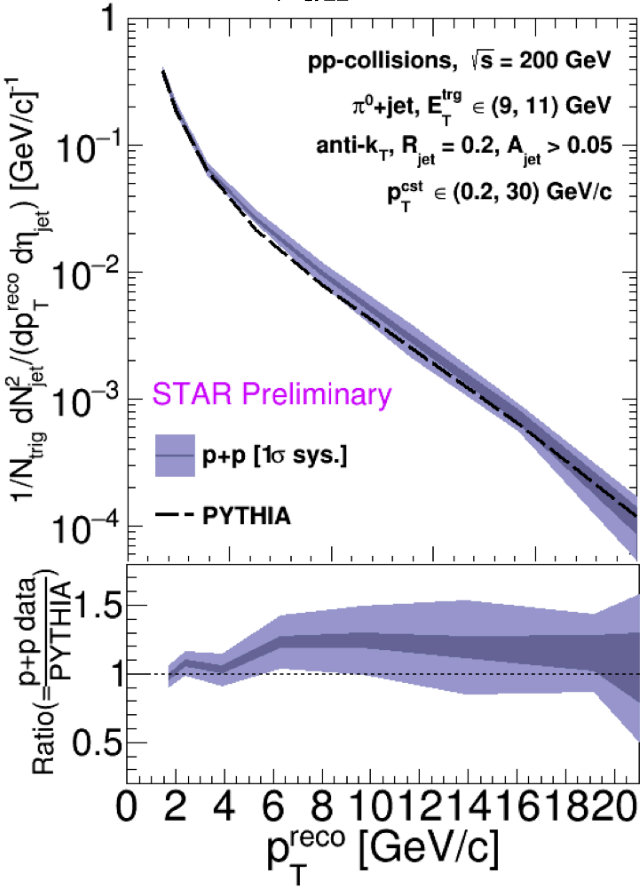
p+Au data can help to study the initial k_T smearing effect

→ π^0+Jet

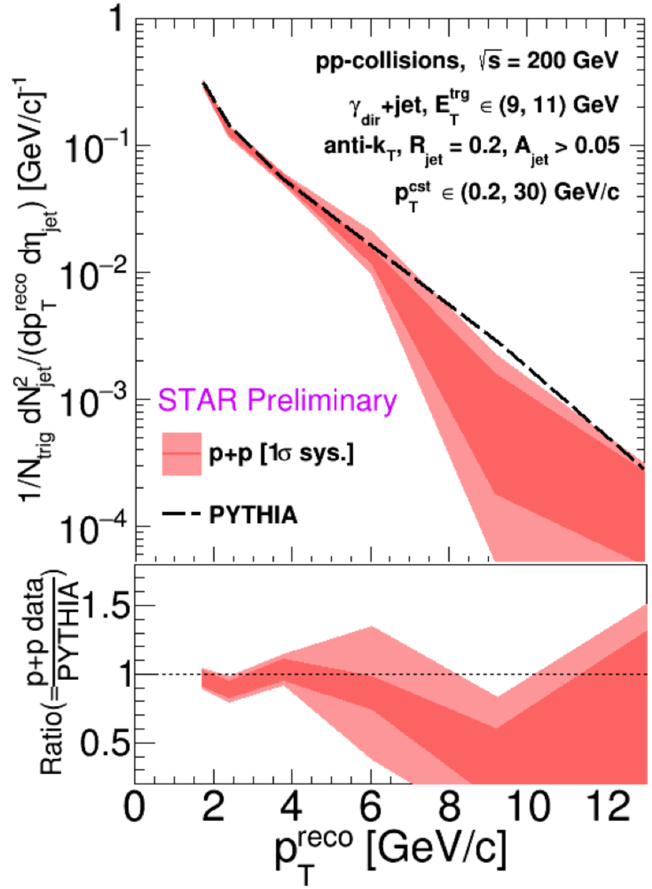
STAR: Nihar Sahoo
HP2018, QM2019

p+p collision scenario

γ_{dir}+Jet



π^0+Jet



Derek Anderson, ISMD2019

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

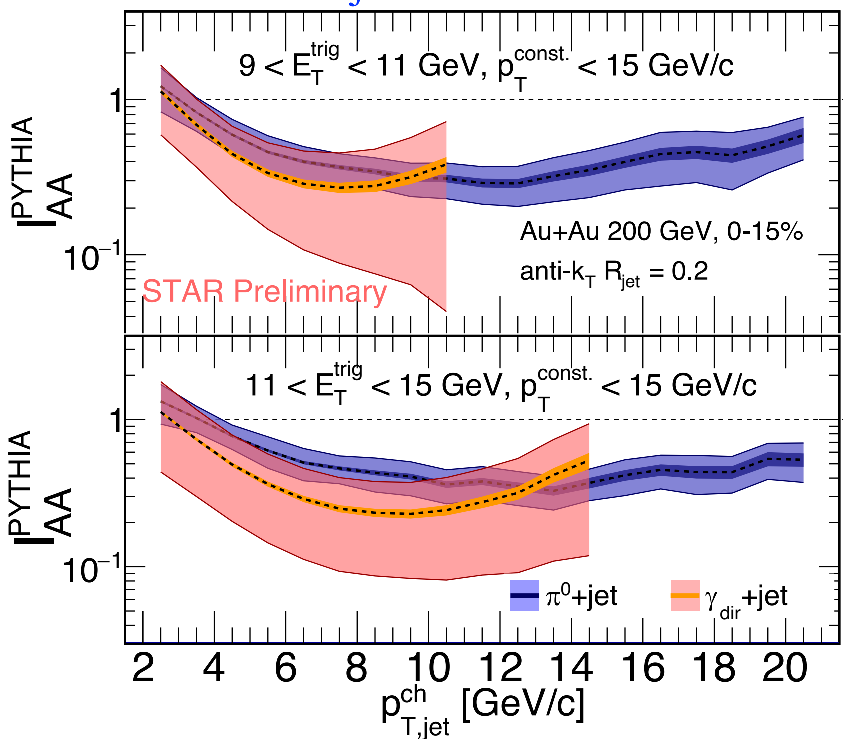
- Not enough trigger statistics for the precision γ_{dir}/π^0 +Jet measurement
- However, within uncertainty, corrected data consistent with Pythia8
- PYTHIA8 is used as p+p baseline for Au+Au collisions

Nuclear Modification factor

STAR:
Nihar Sahoo,
HP2018,QM2019

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

$R_{jet} = 0.2$



Compelling observations at RHIC:

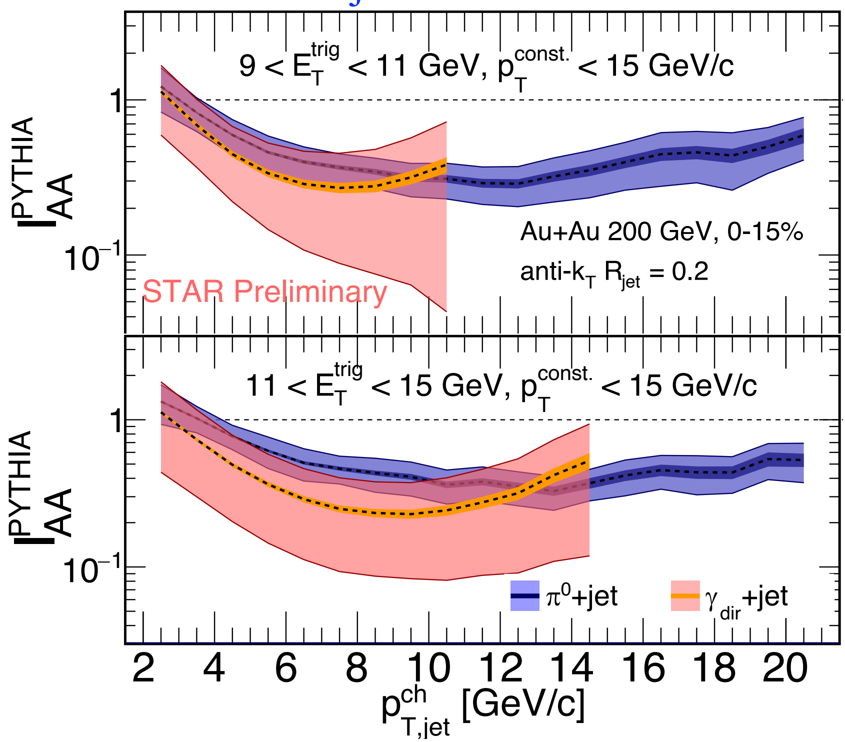
- Recoil jet with R_{jet} =0.2 → strong suppression;
- Same level of suppression for γ_{dir}+jet and π^0+jet

Nuclear Modification factor: Au+Au 200 GeV

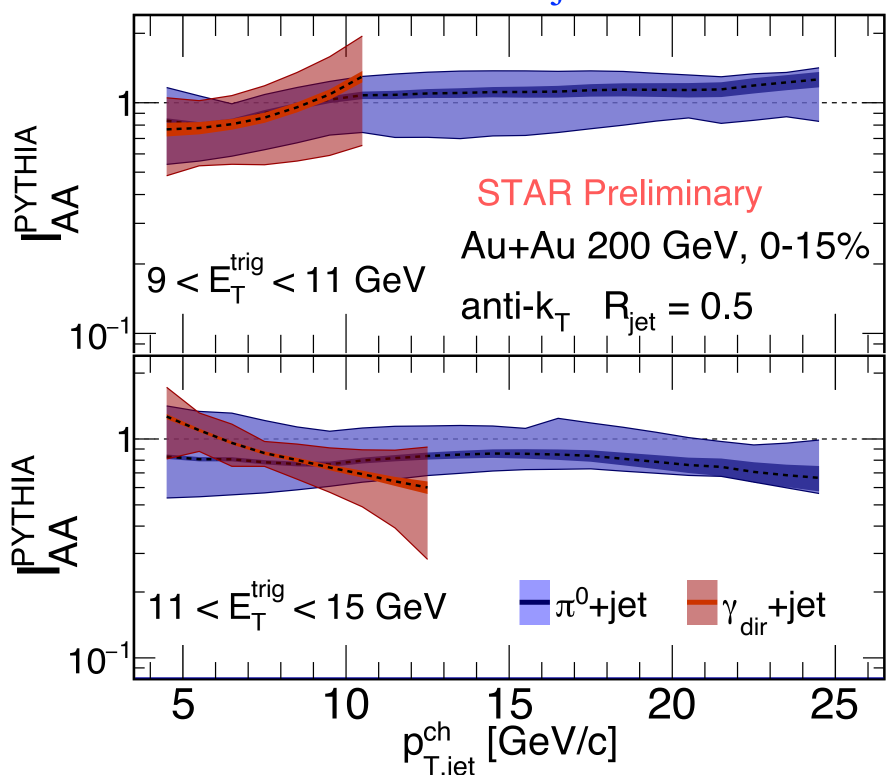
STAR:
Nihar Sahoo,
HP2018,QM2019

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

$R_{jet} = 0.2$



$R_{jet} = 0.5$

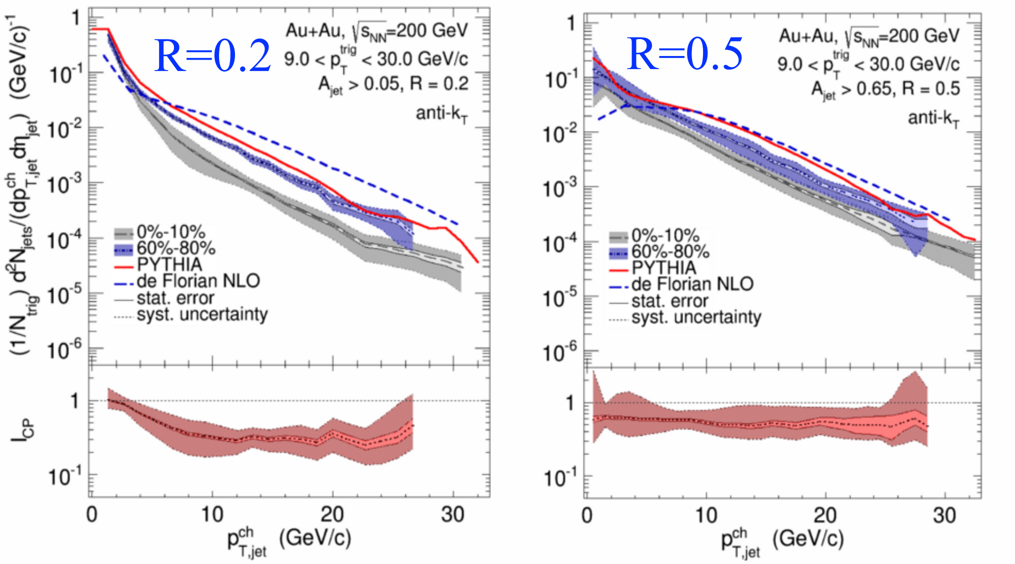


Compelling observations at RHIC:

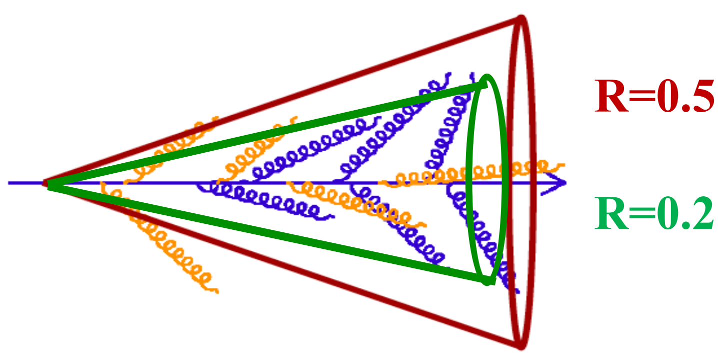
- Recoil jet with Rjet =0.2 → strong suppression;
  whereas for Rjet=0.5 → relatively less suppression.
- Same level of suppression for γ_{dir}+jet and π^0+jet

What about other RHIC (STAR) measurements?

Semi-inclisive h+jet STAR:PRC 96, 024905 (2017)

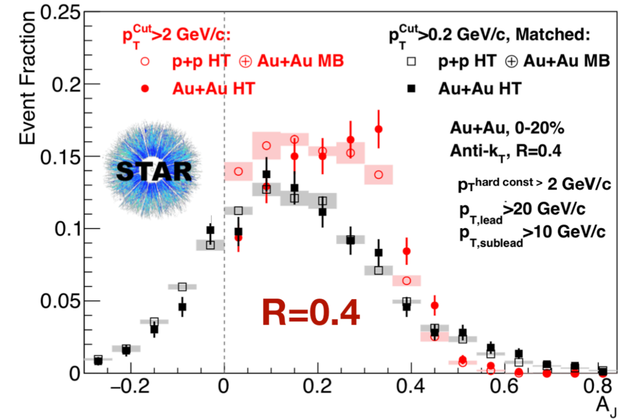


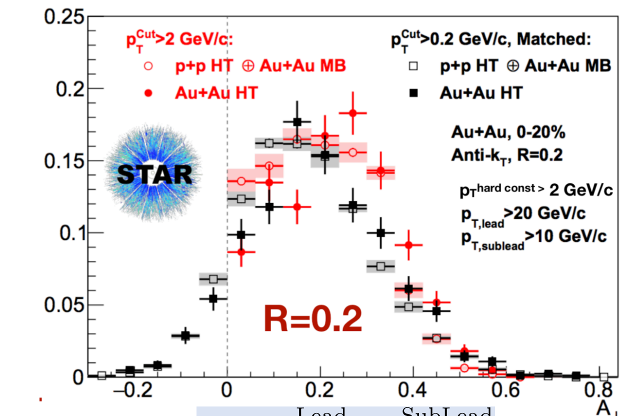
Energy transported out of the cone due to jet-quenching (Partonic energy loss)



In-medium parton shower

Dijet asymmetry in Au+Au collisions





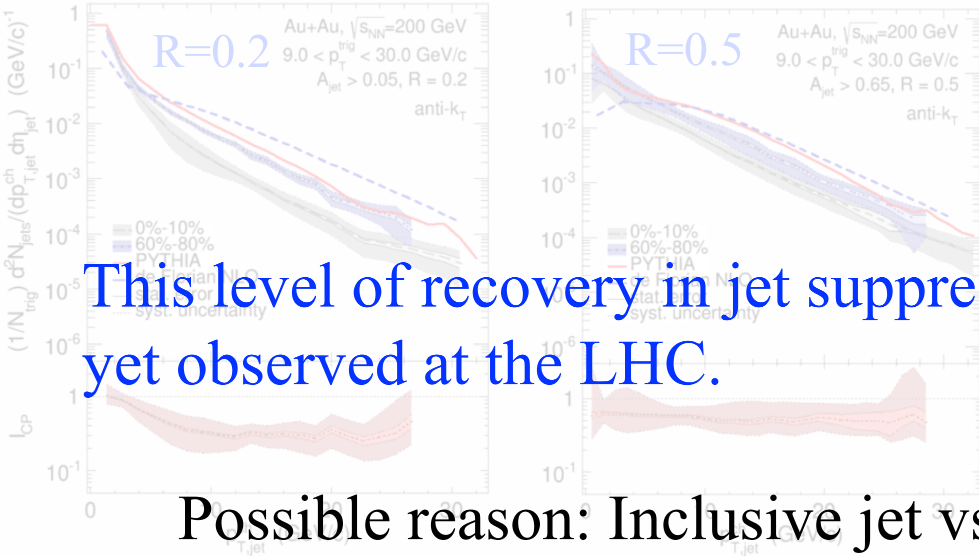
$$A_J = \frac{p_T^{\rm Lead} - p_T^{\rm SubLead}}{p_T^{\rm Lead} + p_T^{\rm SubLead}}$$

Recovery of jet energy loss from R=0.2 to 0.4

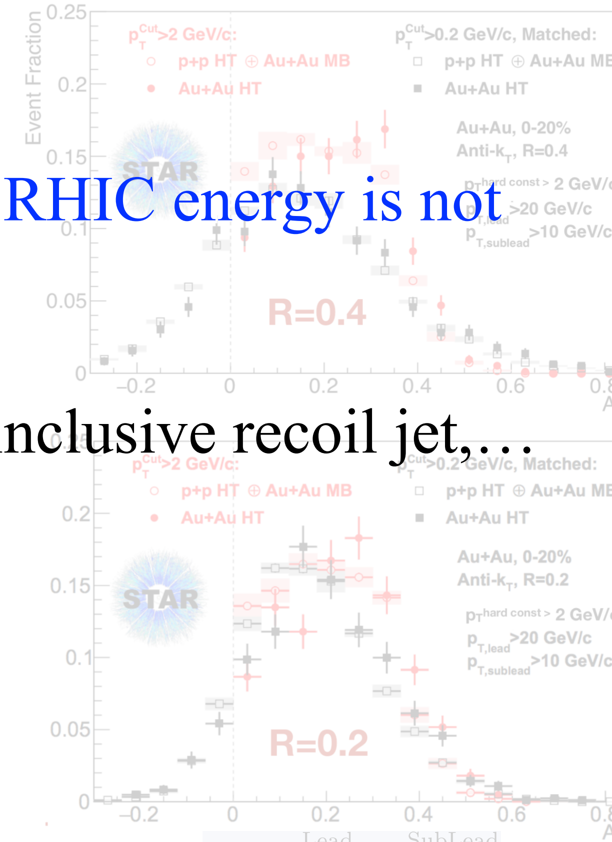
What is the threshold for recovery?

What about other RHIC (STAR) measurements?

Semi-inclisive h+jet STAR:PRC 96, 024905 (2017)



Dijet asymmetry in Au+Au collisions



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

Possible reason: Inclusive jet vs. semi-inclusive recoil jet,…

Need further investigation…

Energy transported out of the cone due to jet-quenching (Partonic energy loss)

In-medium parton shower

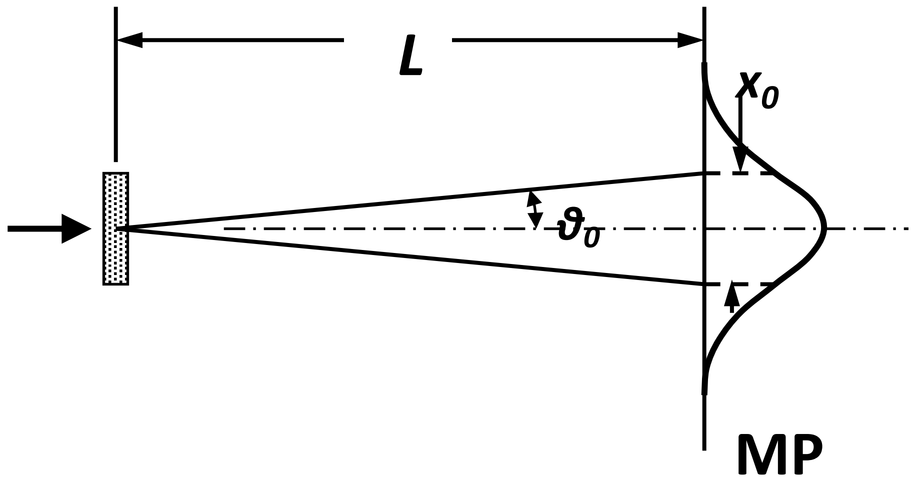
$$A_J = \frac{p_T^{\rm Lead} - p_T^{\rm SubLead}}{p_T^{\rm Lead} + p_T^{\rm SubLead}}$$

Recovery of jet energy loss from R=0.2 to 0.4

What is the threshold for recovery?

Dijet $\Delta\varphi$ angular correlation: A large angle deflection in HICs

Multiple Scattering (QED Molière Scattering)



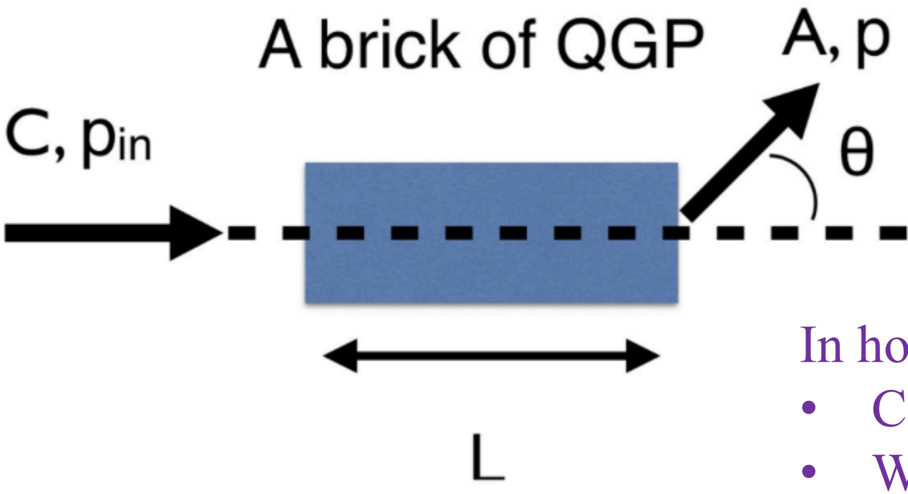
https://gray.mgh.harvard.edu/attachments/article/213/06_Scattering.ppt

- 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 $1/p^2 \rightarrow$ large for small momenta

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

What about a recoil parton/jet passing through the hot-dense and cold(-dense) QCD matter?

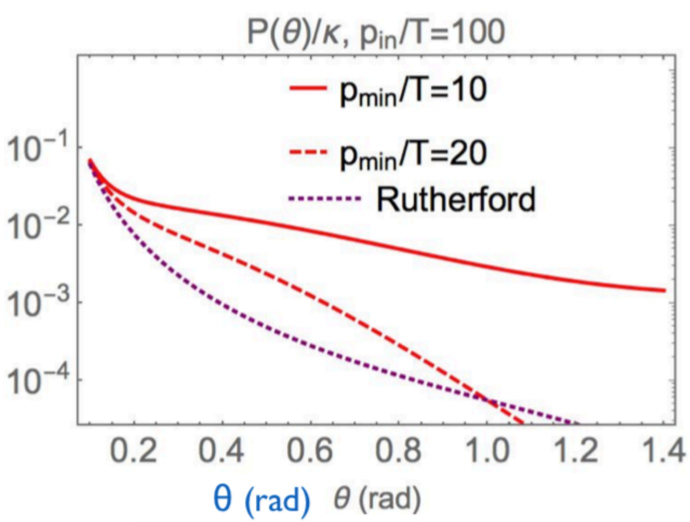
Single scattering in a brick of QGP



QCD Molière Scattering: A rare large angle scattering

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

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



In hot-dense QCD

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

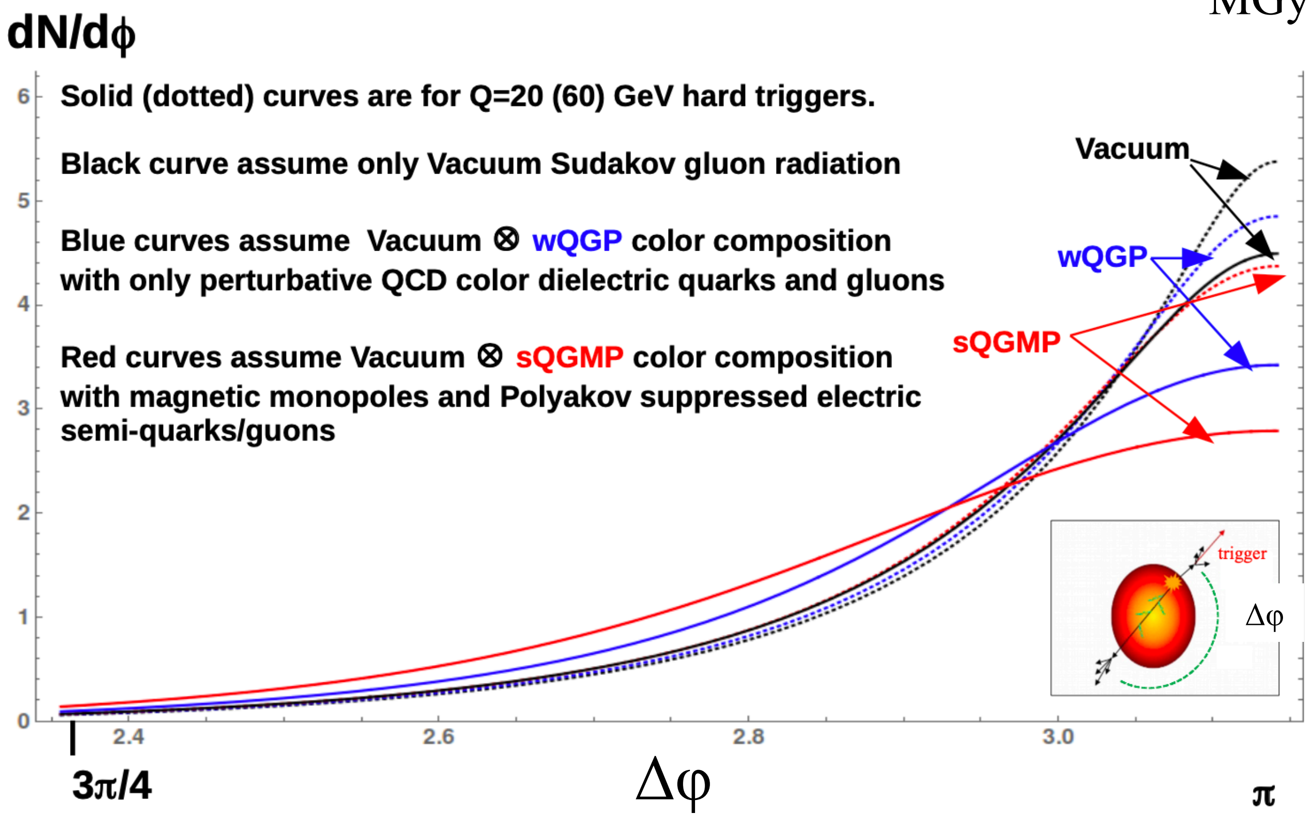
Equally important to study this effect in the cold QCD matter?

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

Rutherford Scattering like, gg→gg

Dijet acopanarity

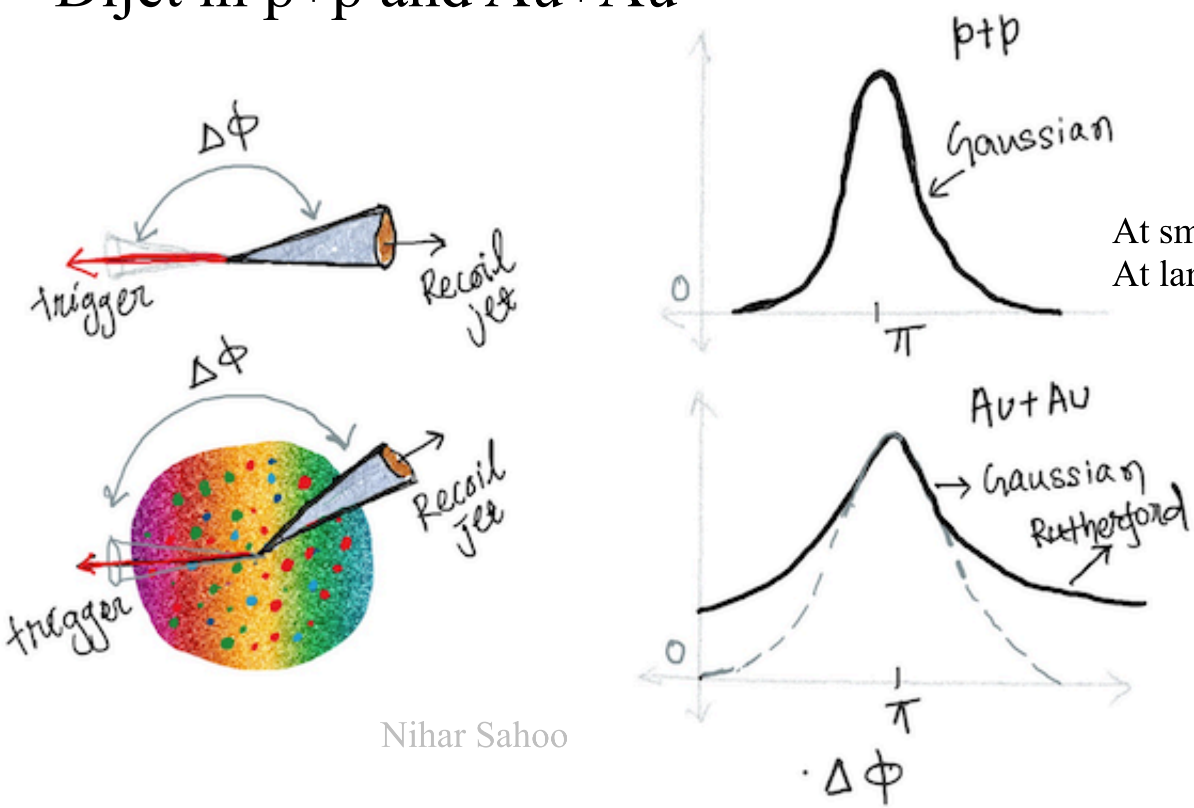
MGyulassy QM2019



- 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)

In heavy-ion collisions

Dijet in p+p and Au+Au



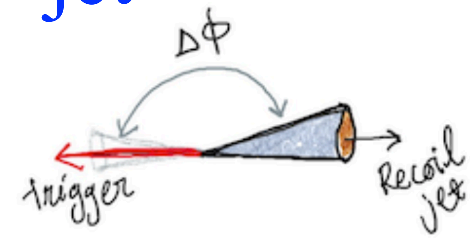
At small angle ⟶ Gaussian Shape
At large angle ⟶ Rutherford Scattering

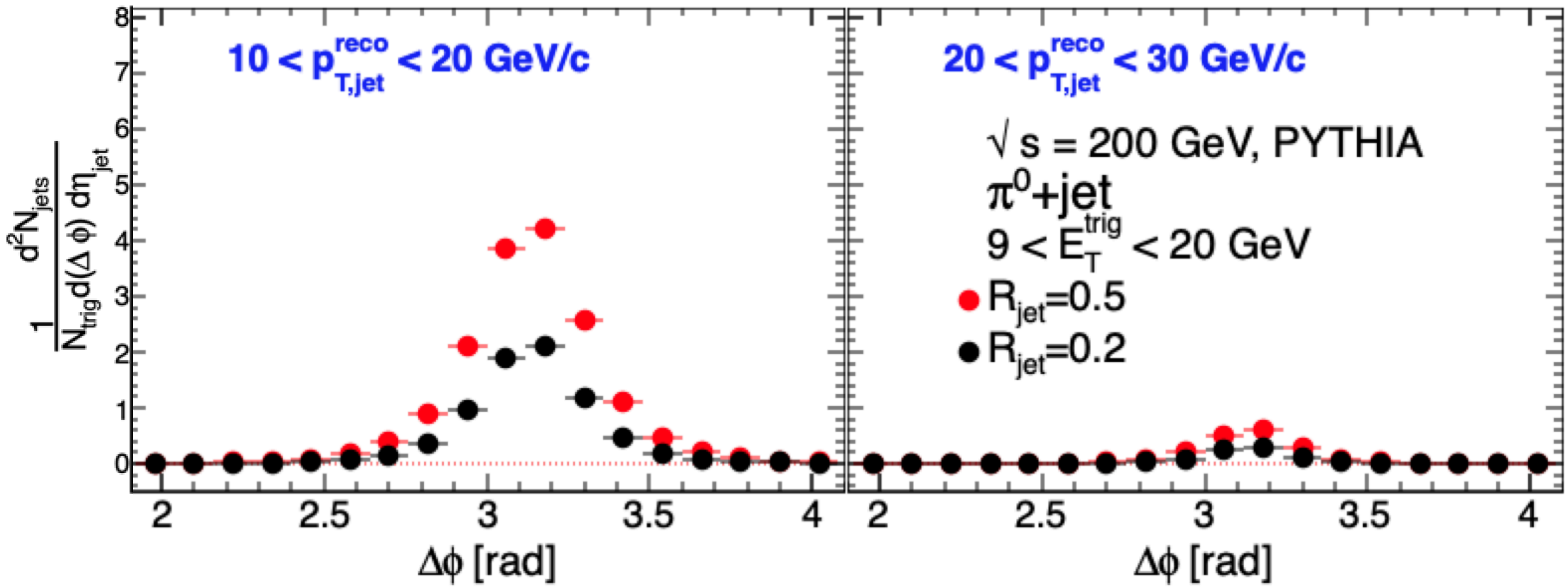
- Scattering of a recoil-jet off quasi-particles in the QGP
  - Intra-jet broadening (Δφ)
  - Other effects like B-field, MPI may play a role here…

    But no such effect in eA and ep collisions

p+p PYTHIA expectation: π^0+jet

$\Delta\varphi$ ($=\varphi^{\pi 0} - \varphi^{\text{recoil jet}}$) distributions at different recoil jet p_T bins





(Simulation study)

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

Workshop on Heavy-Ion JEt results and Developing Ideas 2020 (HI-JEDI2020)

1-3 April 2020
山东大学，青岛
Asia/Shanghai timezone

Search

Shandong University (SDU)
Qingdao Campus

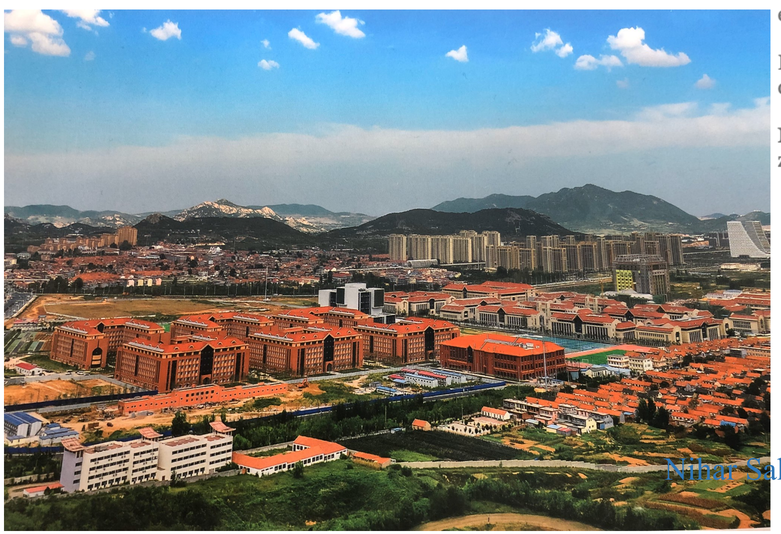
- Overview
- Timetable
- Contribution List
- Registration
  - Registration Form
- Participant List

In this workshop, we plan to discuss the recent p+p and Heavy-Ion collisions jet results from the LHC and RHIC experiments, and also recent theoretical developments in this direction. Some of the emerging topics in both theory and experiments will be discussed: the redistribution of lost energy by a parton traversing in the hot-dense QCD medium (jet R dependence), large azimuthal angle deflection of recoil jet, modification of jet shapes, Inclusive jet vs. semi-inclusive recoil jet from hadron and direct photon trigger, jet in the small system, etc.

There will be devoted discussion sessions each day to discuss different experimental techniques used in the LHC and RHIC experiments and the ongoing and future theoretical developments for understanding experimental results.

Besides, we also plan to have a dedicated session to discuss other interesting topics, e.g. the STAR forward detector upgrade, the small system, the recent Heavy-flavor, and Dilepton results.

Note: Participation is by invitation. If you are interested, please send an email to nihar@sdu.edu.cn and zhenyuchen@sdu.edu.cn



Starts Apr 1, 2020 08:00
Ends Apr 3, 2020 18:00
Asia/Shanghai

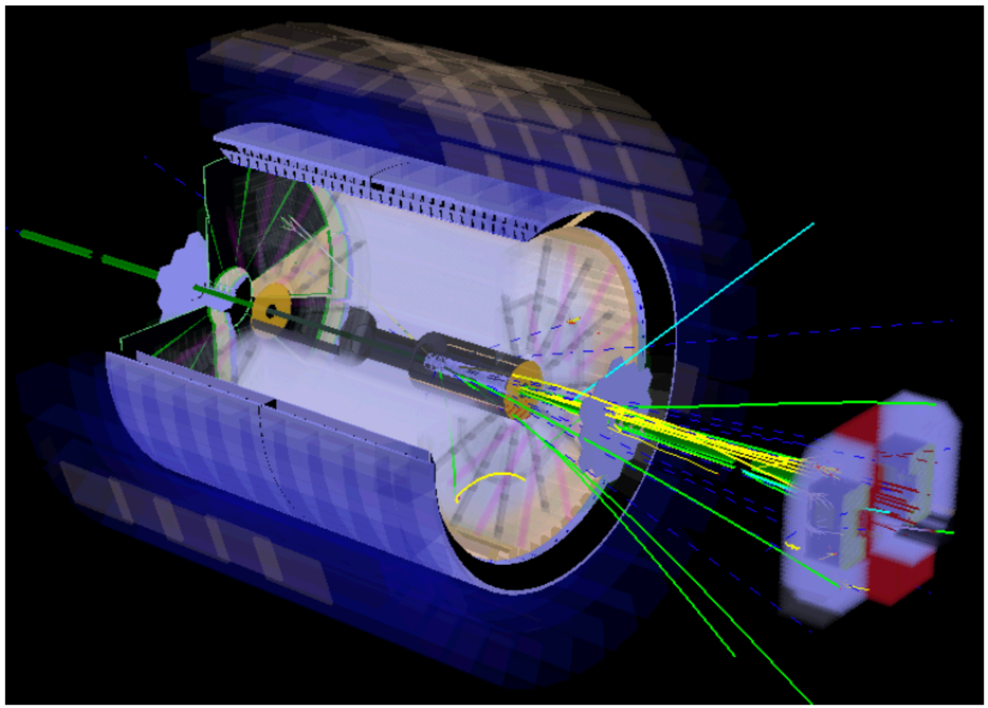
山东大学，青岛

ZHOU, Mengli
陈, 震宇
Sahoo, Nihar

nihar@sdu.edu.cn
zhenyuchen@sdu.edu.cn

STAR Forward upgrade and its physics

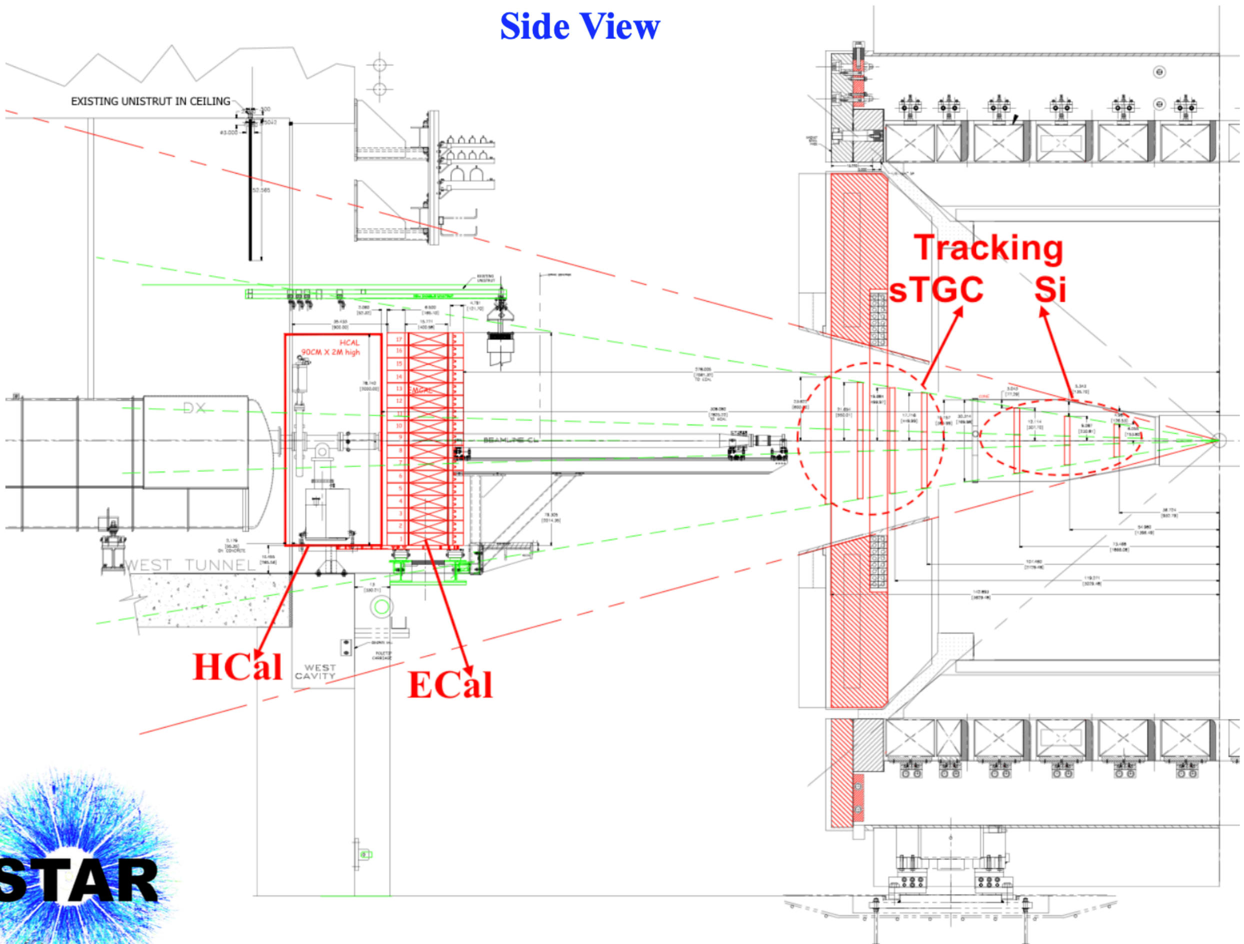
The STAR Forward Calorimeter System and Forward Tracking System



https://drupal.star.bnl.gov/STAR/system/files/Proposal.ForwardUpgrade.Nov_.2018.Review.pdf

Tollgate to an EIC era…

Forward Upgrade: fSTAR



- Coverage: $2.5 < \eta < 4$
- Electromagnetic and Hadronic Calorimetry
- Forward tracking: Silicon detectors and small-strip Thin Gap Chamber (sTGC) [contribution from Shandong University]

Detector	pp and pA	AA
ECal	~10%/√E	~20%/√E
HCal	~50%/√E+10%	---
Tracking	charge separation photon suppression	$0.2<p_T<2$ GeV/c with 20-30% $1/p_T$

STAR Forward upgrade and its physics

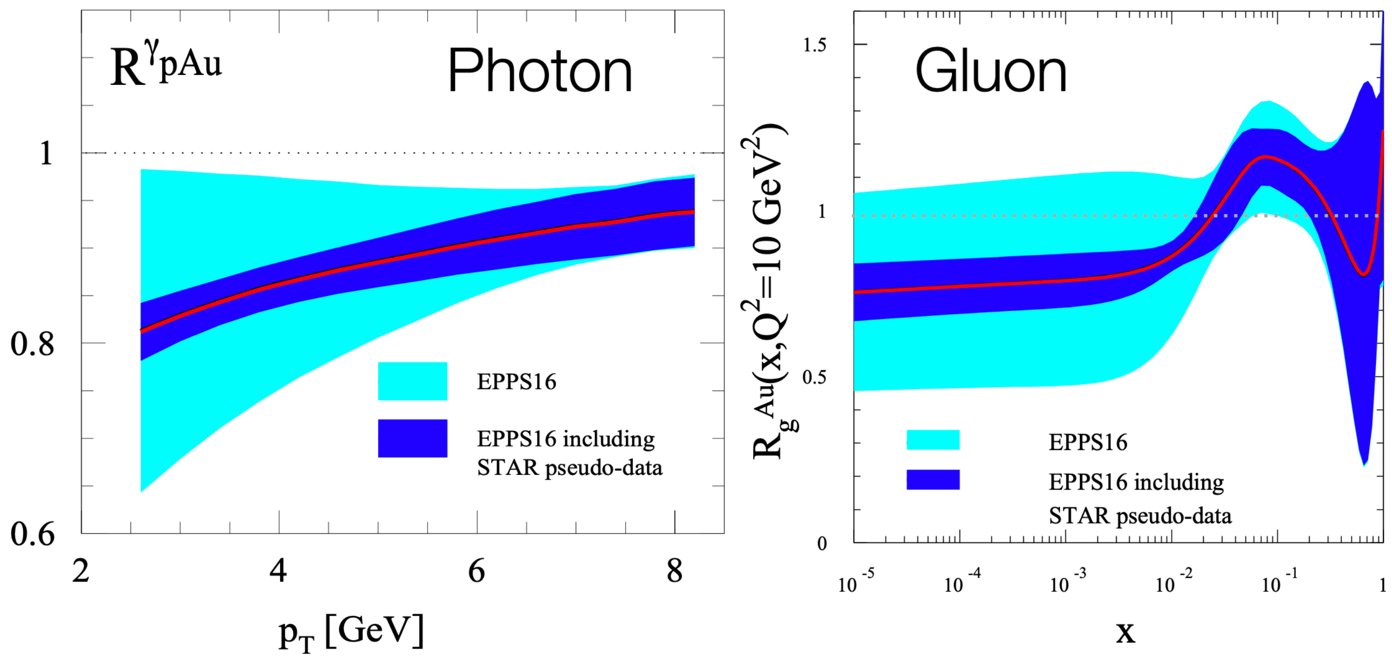
	Year	$\sqrt{s}$ (GeV)	Delivered Luminosity	Scientific Goals	Observable	Required Upgrade
Scheduled RHIC running	2023	$p^{\uparrow}p$ @ 200	300 pb^{-1} 8 weeks	Subprocess driving the large A_N at high x_F and η	A_N for charged hadrons and flavor enhanced jets	Forward instrum. ECal+HCal+Tracking
	2023	$p^{\uparrow}Au$ @ 200	1.8 pb^{-1} 8 weeks	What is the nature of the initial state and hadronization in nuclear collisions Clear signatures for Saturation	R_{pAu} direct photons and DY Dihadrons, γ-jet, h-jet, diffraction	Forward instrum. ECal+Hcal+Tracking
	2023	$p^{\uparrow}Al$ @ 200	12.6 pb^{-1} 8 weeks	A-dependence of nPDF, A-dependence for Saturation	R_{pAl}: direct photons and DY Dihadrons, γ-jet, h-jet, diffraction	Forward instrum. ECal+HCal+Tracking
Potential future running	2021	$p^{\uparrow}p$ @ 510	1.1 fb^{-1} 10 weeks	TMDs at low and high x	A_{UT} for Collins observables, i.e. hadron in jet modulations at $\eta > 1$	Forward instrum. ECal+HCal+Tracking
	2021	$\vec{p}\vec{p}$@ 510	1.1 fb^{-1} 10 weeks	$\Delta g(x)$ at small x	A_{LL} for jets, di-jets, h/γ-jets at $\eta > 1$	Forward instrum. ECal+HCal

Table 2-1: Summary of the pp and pA measurements as planed in the years 2021 and 2023. The most right coloumn summarizes, which detector of the forward upgrade is essential for the measurement.

- Year 2021/2022, possible dedicated STAR pp run for froward upgrade
- Year 2023/2025, pp, pA and AA run

https://drupal.star.bnl.gov/STAR/system/files/Proposal.ForwardUpgrade.Nov_.2018.Review.pdf

Nuclear Parton Distribution Function (nPDF)



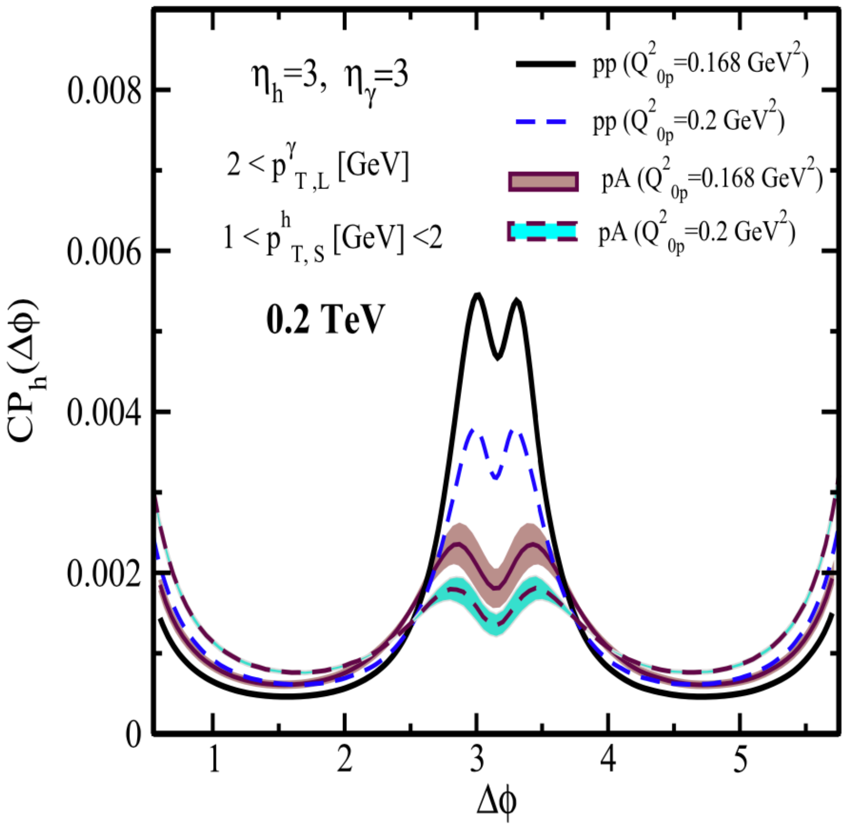
For Run-2023:
L_{pAu} = 1.8 pb^{-1} and
L_{pp} = 300 pb^{-1}

RHIC can provide a moderate Q^2 and medium-to-low x kinematic regime.

Gluon Saturation effect: semi-inclusive γ-hadron correlations

$$CP_h(\Delta\phi; p^h_{T,S}, p^\gamma_{T,L}; \eta_\gamma, \eta_h) = \frac{2\pi \int_{p^\gamma_{T,L}} dp^\gamma_T p^\gamma_T \int_{p^h_{T,S}} dp^h_T p^h_T \frac{dN^{pA\to h(p^h_T)\gamma(p^\gamma_T)X}}{d^2\vec{p}^\gamma_T d^2\vec{p}^h_T d\eta^\gamma d\eta^h}}{\int_{p^\gamma_{T,L}} d^2\vec{p}^\gamma_T \frac{dN^{pA\to\gamma(p^\gamma_T)X}}{d^2\vec{p}^\gamma_T d\eta_\gamma}}$$

Amir H. Rezaeian: PRD 86, 094016 (2012)

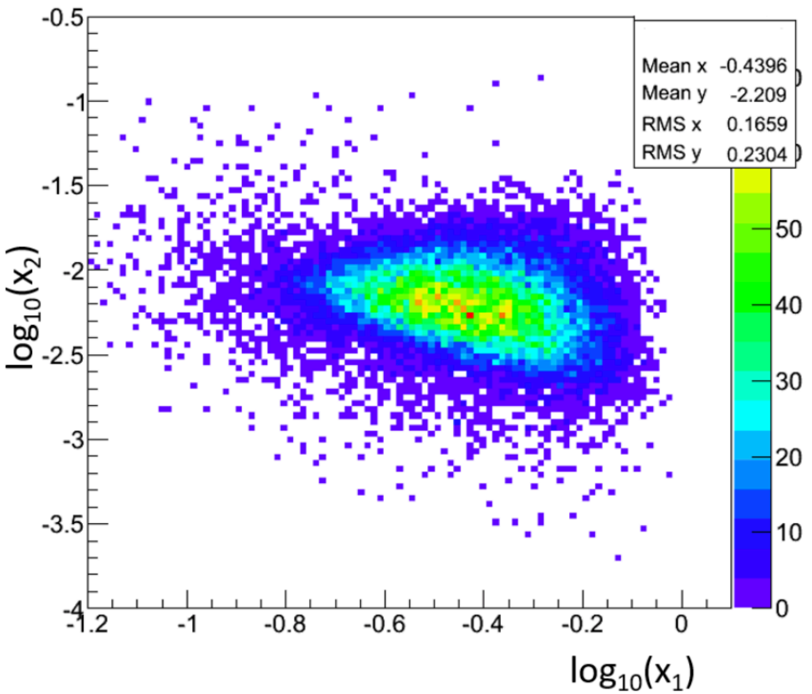


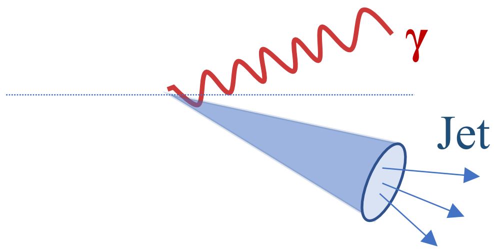
- p+p and p+Au: A double-peak away-side structure is predicted in the CGC framework
- Similar effect is also predicted from the Drell-Yan Lepton-Pair-Jet correlation in p+A collisions [Phys. Rev. D 86, 014009 (2012)]

Δφ: azimuthal correlation between final-state quark and photon

QCD Saturation effect: semi-inclusive γ-hadron correlations

STAR forward upgrade, a feasibility study at forward rapidity





PYTHIA8.189: p+p 200 GeV

- Both γ and jet in forward acceptance $1.3 < \eta < 4.0$ with $p_T > 3.2$ GeV/c
- $|\varphi^{\gamma} - \varphi^{jet}| > 2\pi/3$ and $0.5 < p^{\gamma}_T / p_T^{jet} < 2.$
- With a photon Isolation cut
- Jet R = 0.5
- Gluon density in $0.001 < x < 0.005$ in the Au nucleus

(STAR Forward upgrade proposal)

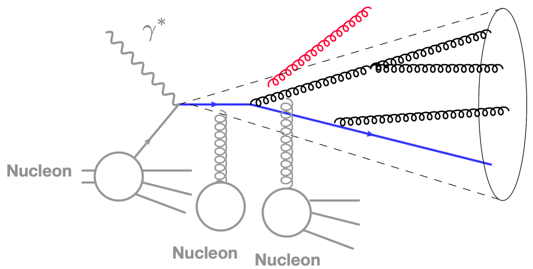
https://drupal.star.bnl.gov/STAR/system/files/Proposal.ForwardUpgrade.Nov_.2018.Review.pdf

Physics at EIC

In a perspective of semi-inclusive recoil jet measurement: (along with spin physics)

- Gluon radiation by a parton in a cold QCD matter

  Presence of bkg. classical field



Courtesy: Yacine Mehtar-Tani

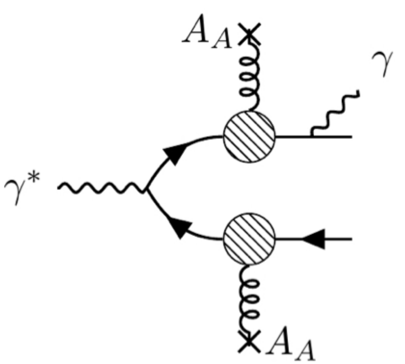
- Dijet acoplanarity

- Gluon saturation effects
  - Semi-inclusive photon-hadron correlation

    [Amir H. Rezaeian: PRD 86, 094016 (2012)]

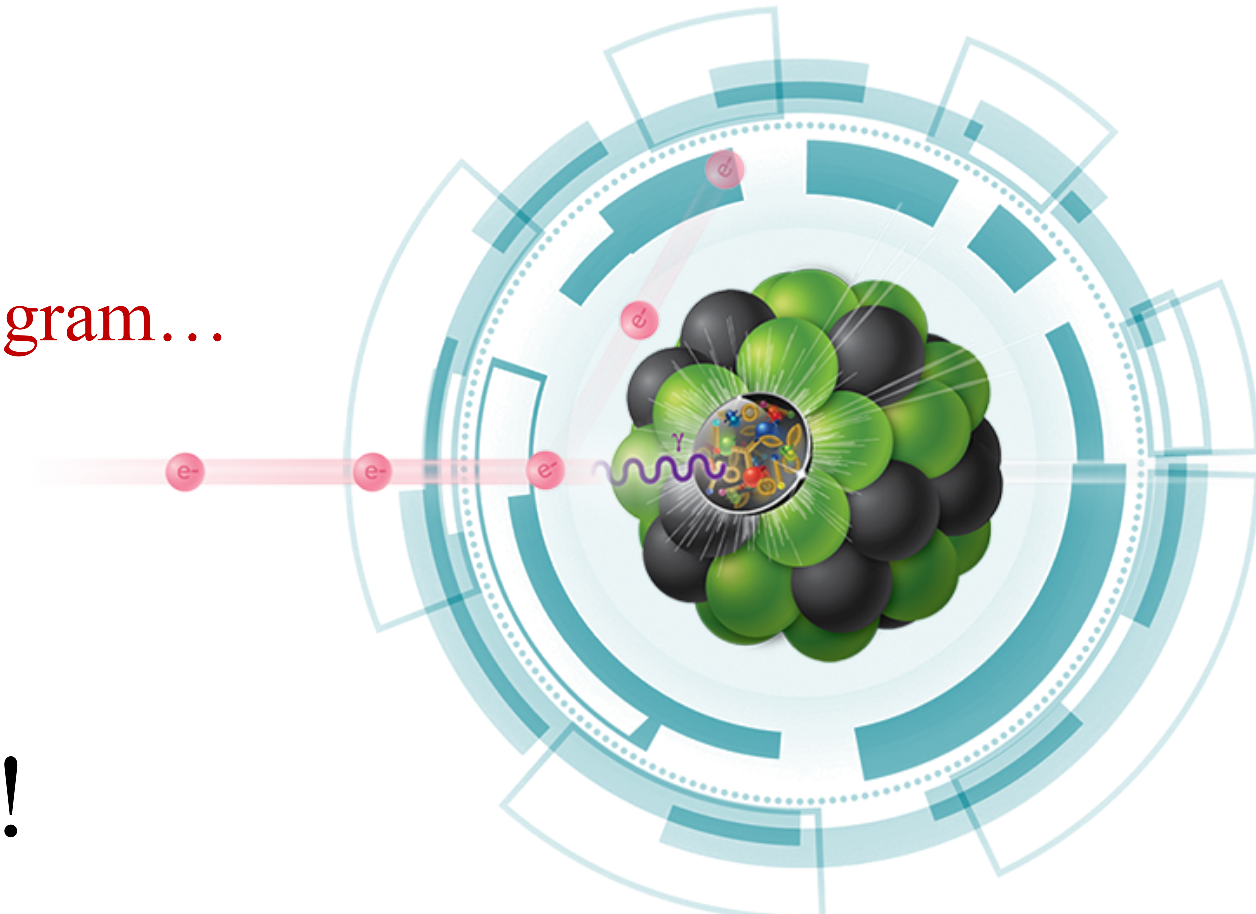
  - Inclusive photon+dijet production in e+A DIS

    [K. Roy, R. Venugopalan, arXiv: 1911.04519, arXiv: 1911.04530]



STAR forward upgrade program, at RHIC with p+Au data, can serve an important role to study EIC saturation physics and also the other QCD effects.

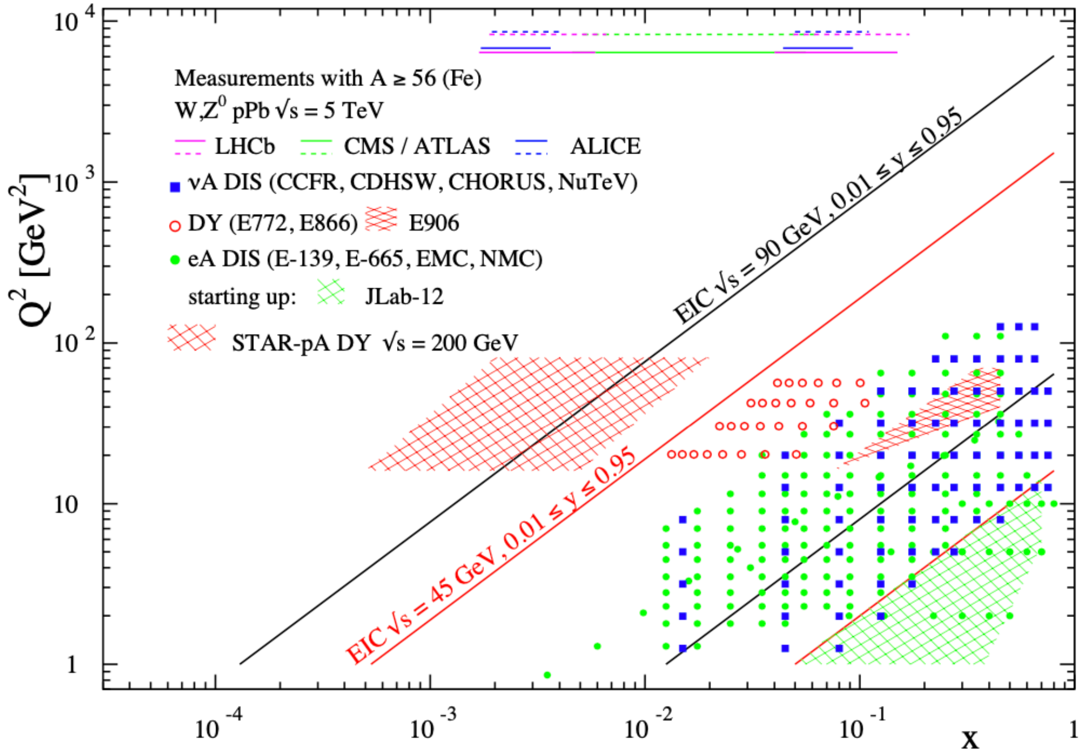
Future EIC program…



Thank you!

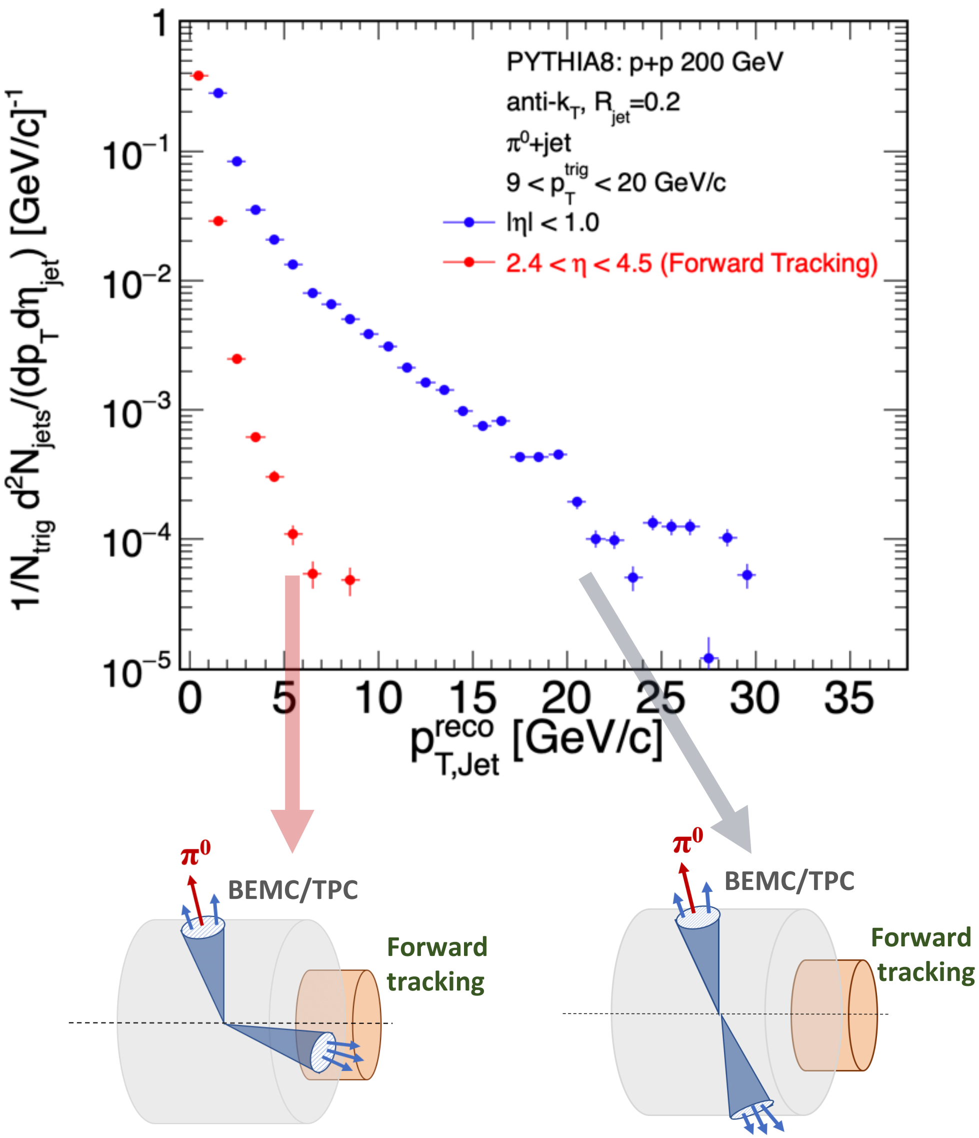
Backup

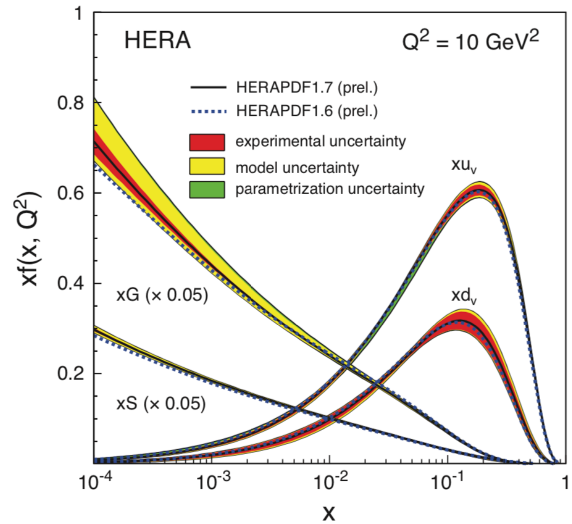
Kinematic coverage in x–Q^2



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*:

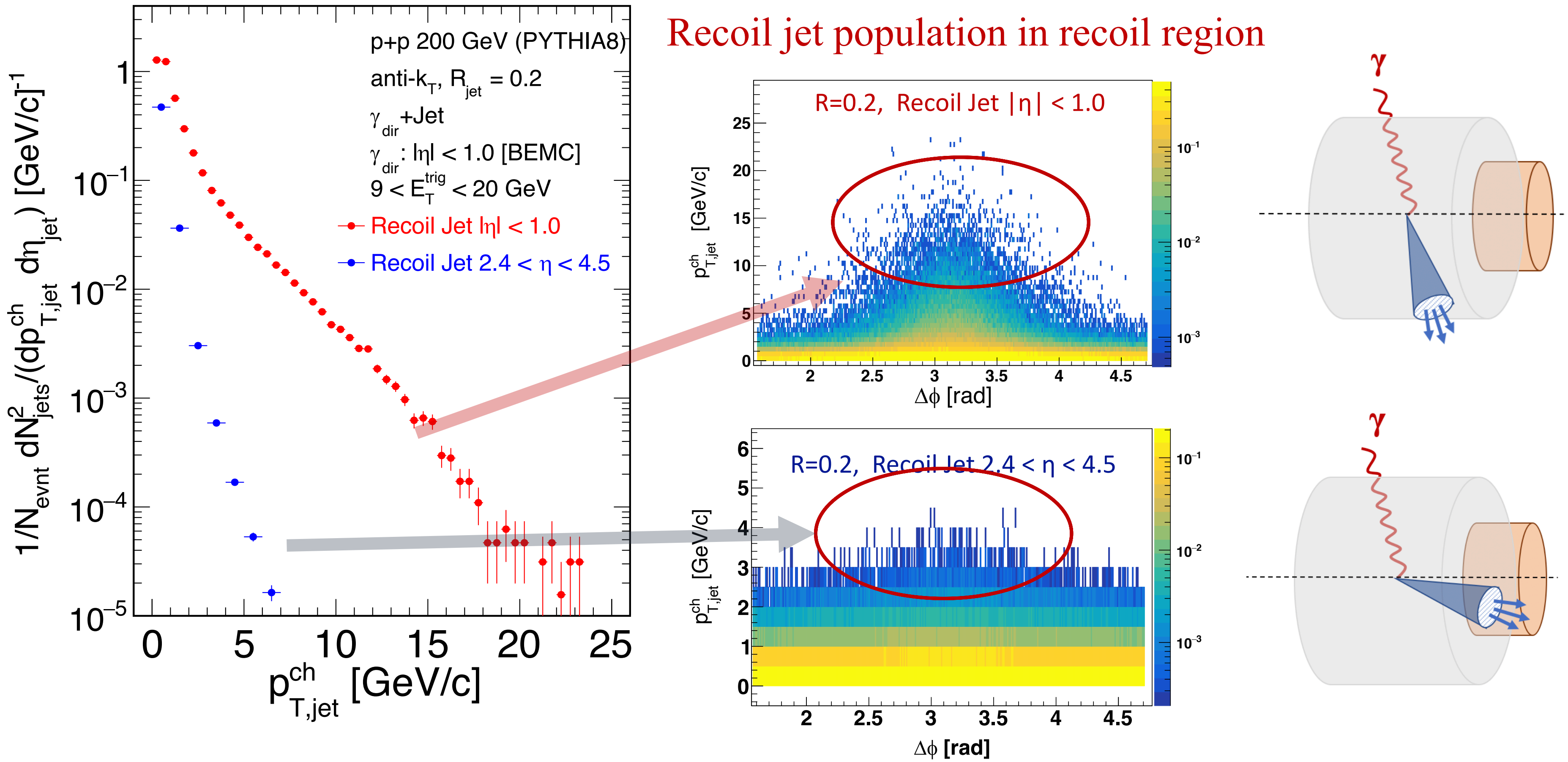
$$x_{1,2} = e^{\pm y}\sqrt{(p_T^2 + m^2)/s}$$

- At RHIC, sea quark effect 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

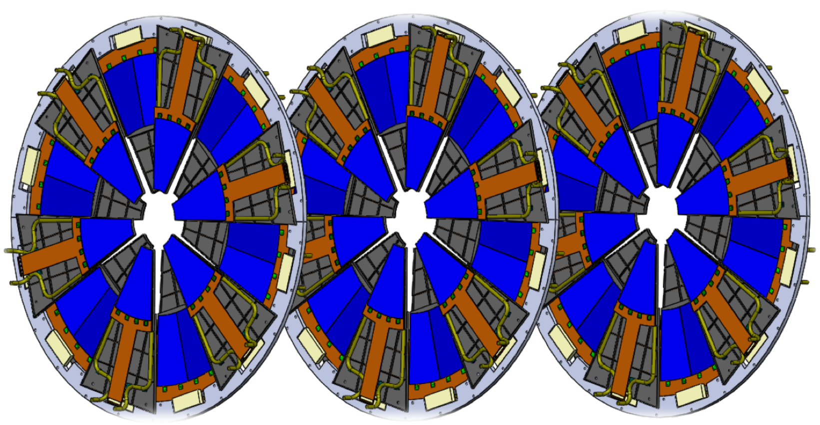
Recoil jet population in recoil region

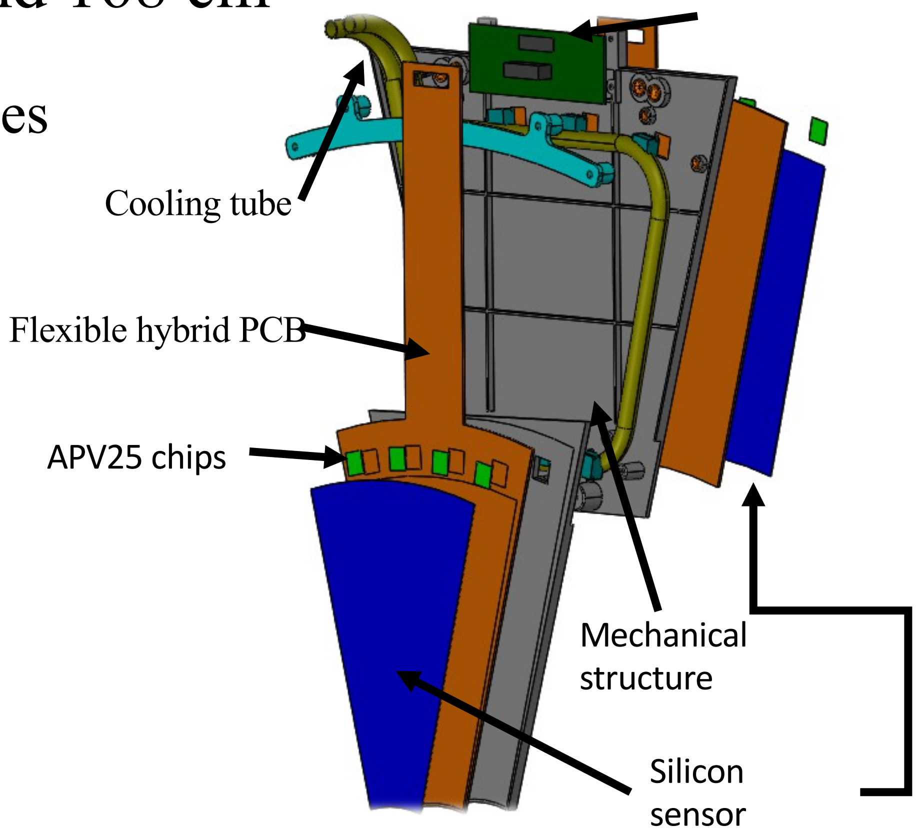


- At moderate x (~0.1), sea quark dominates: sea vs. valance quarks contribution
- Quark jet, at mid and forward rapidity, recoiling from direct photon comparison can help to understand QCD at different parton momentum fraction

Silicon Microstrip Tracker

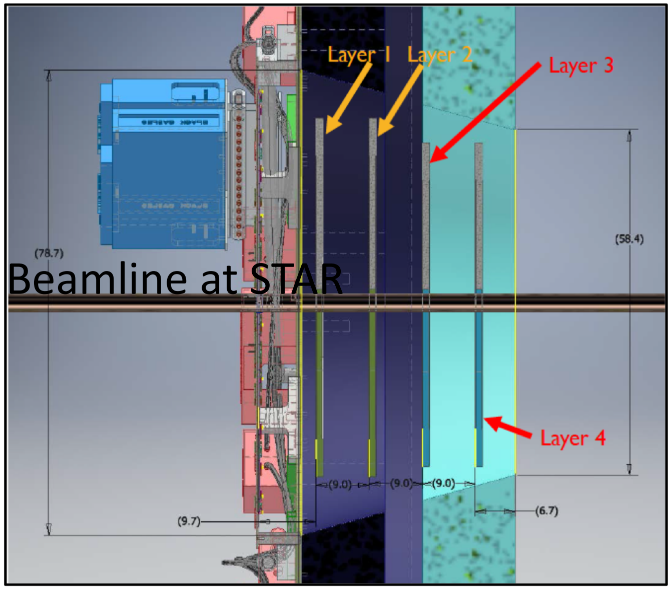
- 3 disks located at 140, 154, and 168 cm from STAR IP
  - Each disk has 12 Single Modules
- Full 2π azimuthal coverage



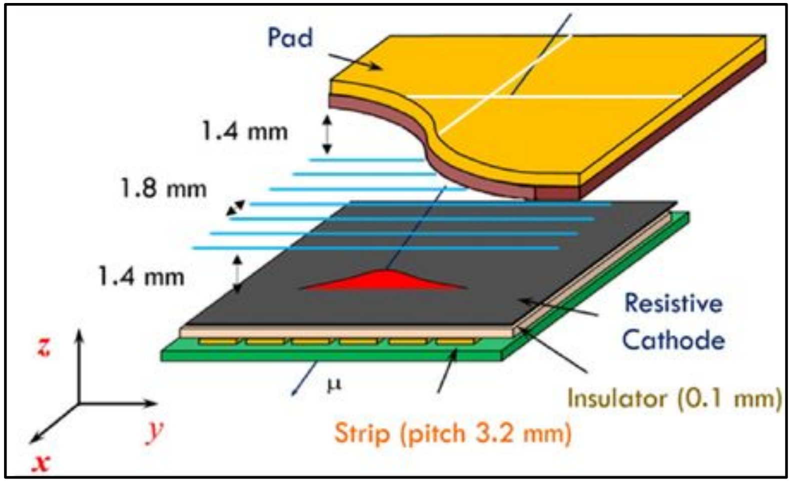


small-strip Thin Gap Chamber (sTGC)

- 4 layers located 273, 303, 333 and 363 cm from STAR IP
- Each layer is double sided
  - Provides (diagonal) x-y coordinates
- Position resolution ~100um
- Roughly full 2π coverage
  - Need room for beam pipe support
- Prototype successfully used in Run 2019
- Inspired by ATLAS sTGCs
- Alternative for EIC GEM trackers

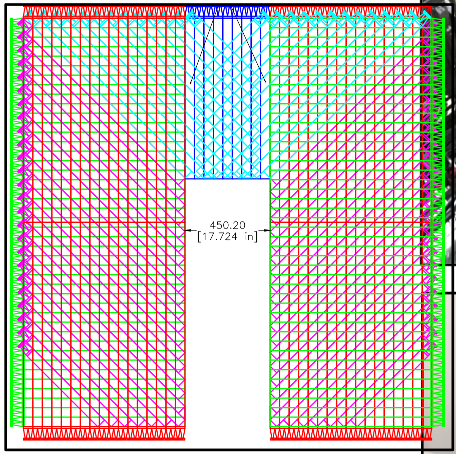


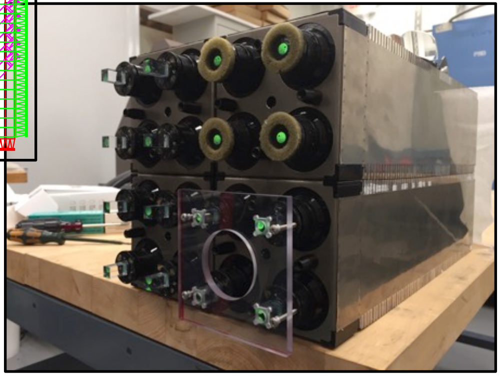
A grid of 50 μm diameter gold-plated tungsten wires, with a 1.8 mm pitch, sandwiched between two cathode planes located at a distance of 1.4 mm from the wire plane



Electromagnetic Calorimeter and Preshower

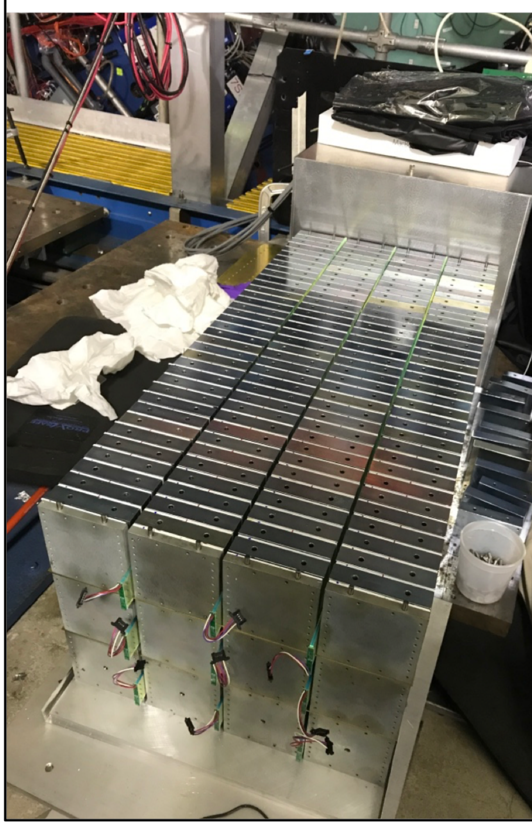
- Scintillator (Sc) Hodoscope Preshower
- Pb/Sc sandwich Ecal (repurposed from PHENIX)
  - Cost reduction
- Both utilize SiPM readout
  - Build on successful use of SiPMs at STAR
- Split into two halves
  - Misses above and below beam pipe
  - Projective geometry
  - ~7m from STAR IP
- ECal 18 X_0
- Successful prototype in Run 19
- ECal installed at STAR (Oct 2019)

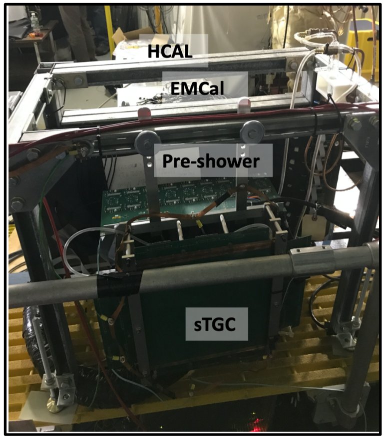




Hadronic Calorimeter

- First hadronic calorimeter at STAR
- Fe/Sc sandwich
  - 20mm Fe / 3mm Sc
  - Use SiPM readout
  - Directly behind ECal (projective)
- Consists of 520 towers
  - Lateral tower size is 10x10 cm^2
  - ~4.5 λ
  - Covers 2x2 towers of Ecal
- Successful Fermilab and Run 2019 prototype test
- Final Design & building in progress





Institutional Interest and Effort

sTGC

BROOKHAVEN NATIONAL LABORATORY

山东大学 SHANDONG UNIVERSITY

Silicon

UIC UNIVERSITY OF ILLINOIS AT CHICAGO

1958

INDIANA UNIVERSITY

BROOKHAVEN NATIONAL LABORATORY

山东大学 SHANDONG UNIVERSITY

NATIONAL CHENG KUNG UNIVERSITY 1931

ECal

KENTUCKY

VALPARAISC UNIVERSITY

ABILENE CHRISTIAN UNIVERSITY

HCal

UCLA

TEXAS A&M UNIVERSITY

INDIANA UNIVERSITY

RUTGERS

ABILENE CHRISTIAN UNIVERSITY

OHIO STATE

DAQ / Readout

BROOKHAVEN NATIONAL LABORATORY

INDIANA UNIVERSITY

KENTUCKY

UCLA

TEXAS A&M UNIVERSITY

Software

BROOKHAVEN NATIONAL LABORATORY

UIC UNIVERSITY OF ILLINOIS AT CHICAGO

INDIANA UNIVERSITY

TEXAS A&M UNIVERSITY

Integration

BROOKHAVEN NATIONAL LABORATORY

Calibration

UC RIVERSIDE

TEMPLE UNIVERSITY

Slow Controls

VALPARAISO UNIVERSITY

ABILENE CHRISTIAN UNIVERSITY