

Hard Probes in Heavy-Ion Collisions at RHIC:

STAR Measurements on the QGP Medium

Nihar Ranjan Sahoo

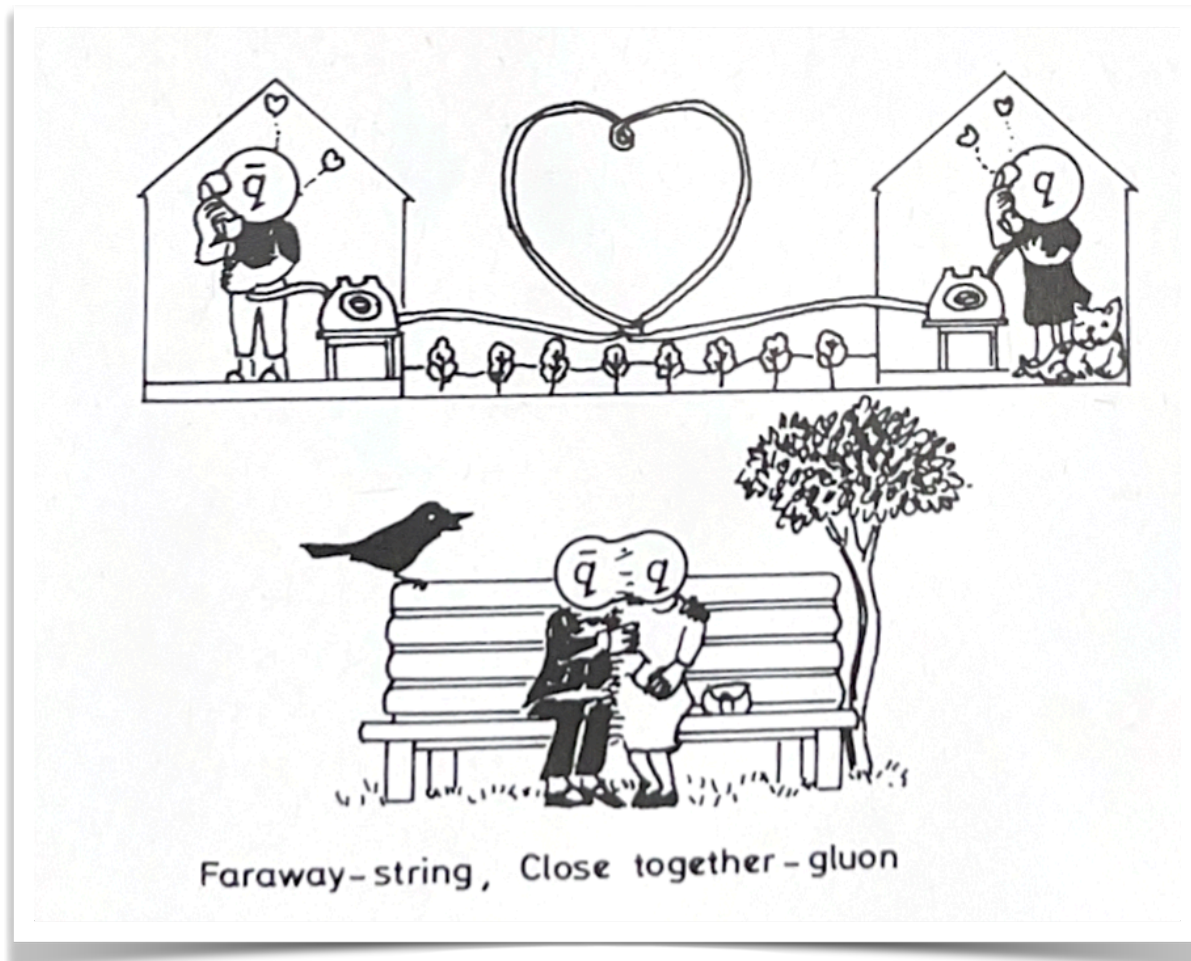


India-JINR Workshop on Particle, Nuclear, Neutrino Physics and Astrophysics, NISER

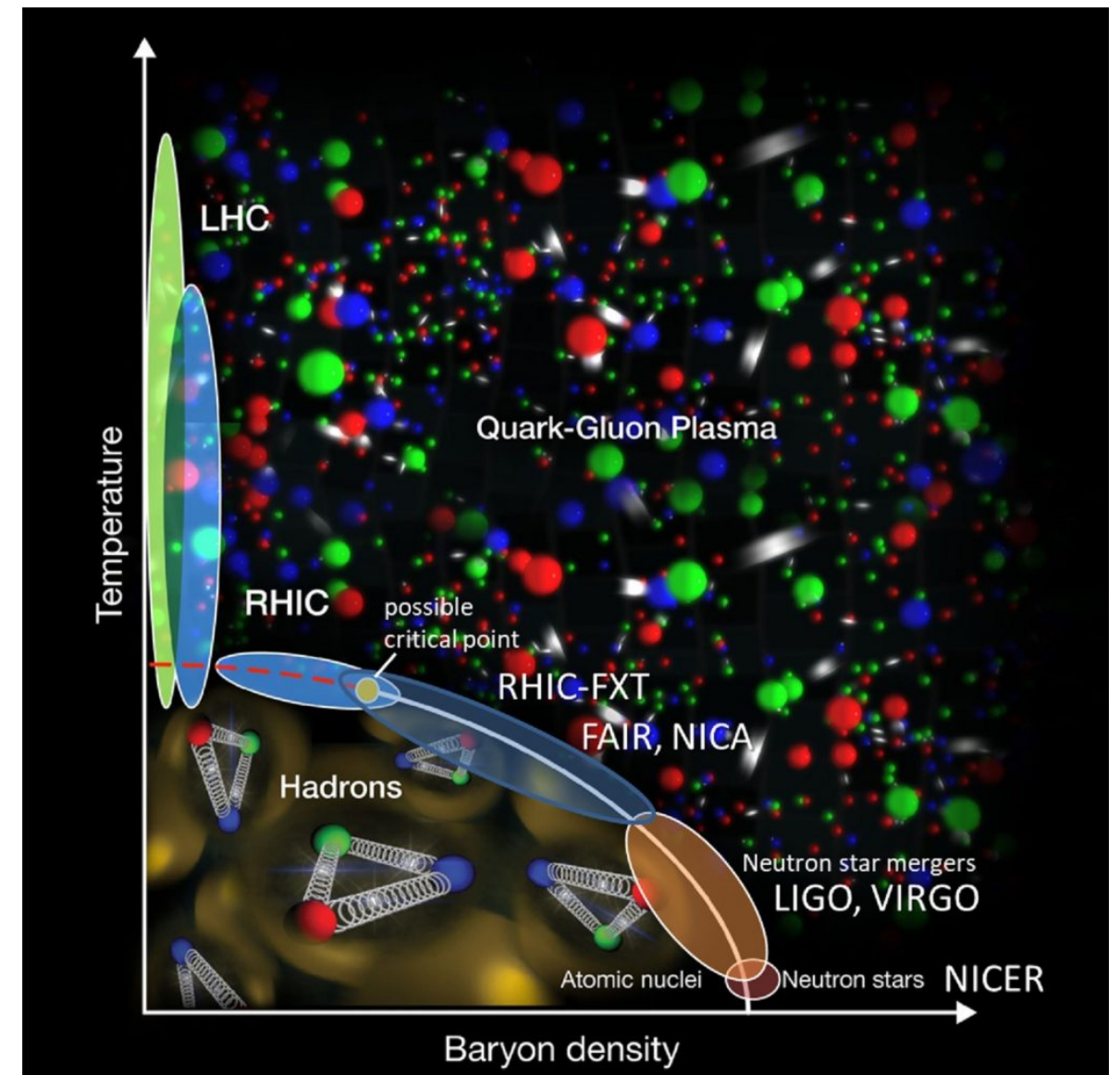
Nov 10-12, 2025

Finite temperature QCD medium: Quark-Gluon Plasma

Faraway-string, Close together-gluon



Book by Y. Nambu:
Quarks: Frontiers In Elementary particle Physics



<https://www.scientia.global/dr-rene-bellwied-understanding-the-nature-of-matter-through-quark-gluon-plasmas/>

Hard probes—jet and heavy flavours—used to study Quark-Gluon Plasma in heavy-ion collisions

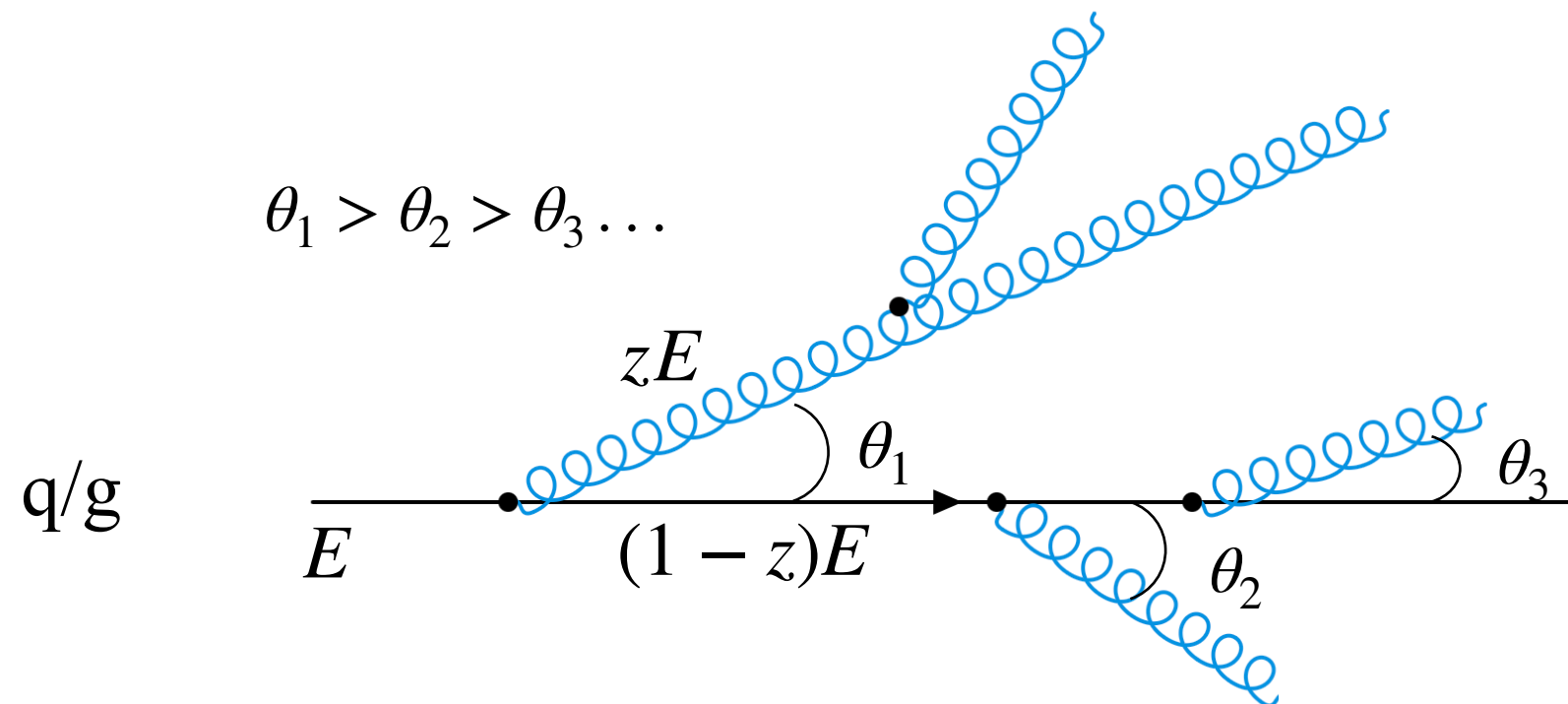
A high energetic parton moving in vacuum

q/g



A high energetic parton moving in vacuum

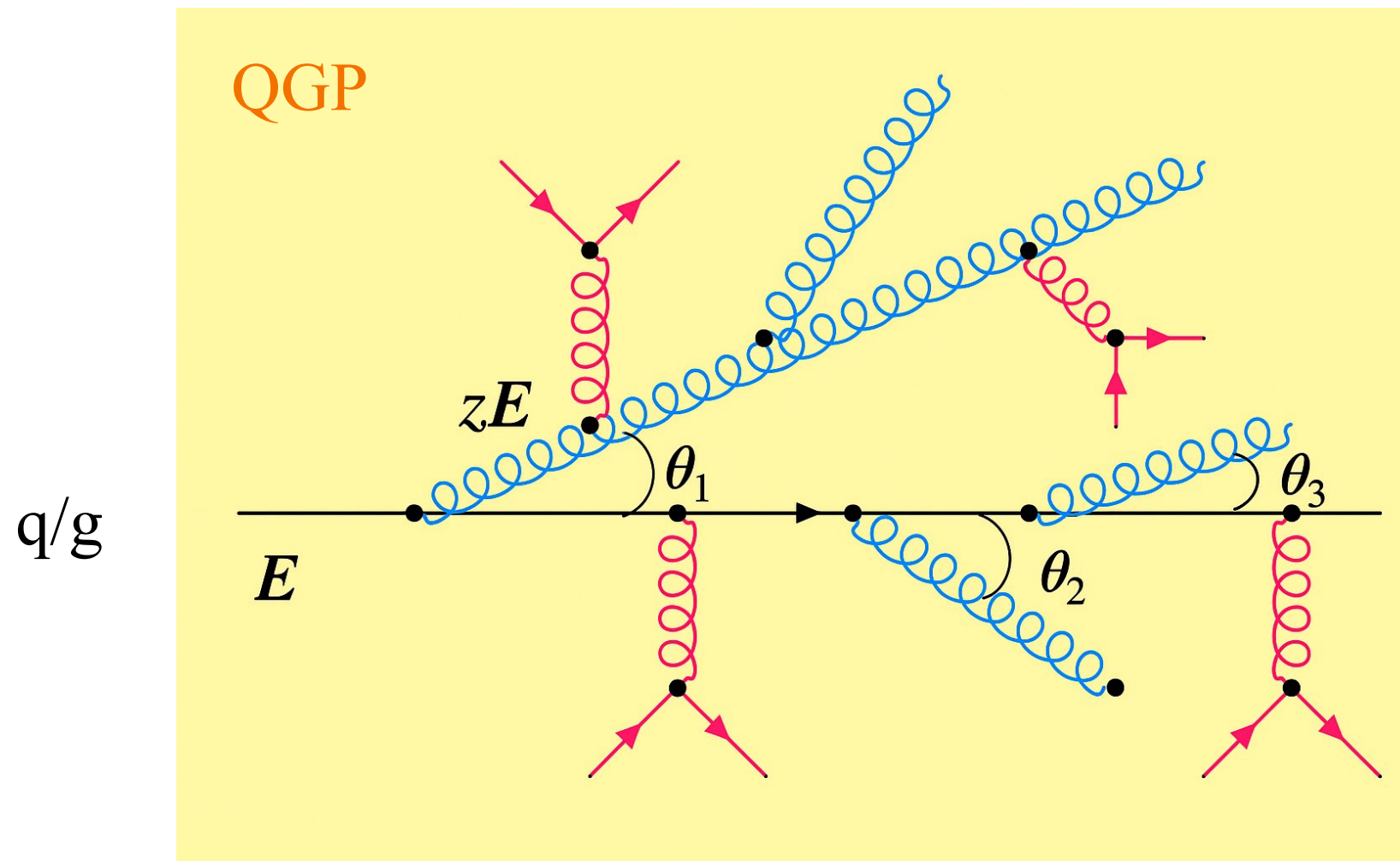
Radiate gluons following angular ordering



A high energetic parton moving in vacuum

Radiate gluons following angular ordering

Additional in-medium radiation due to QGP

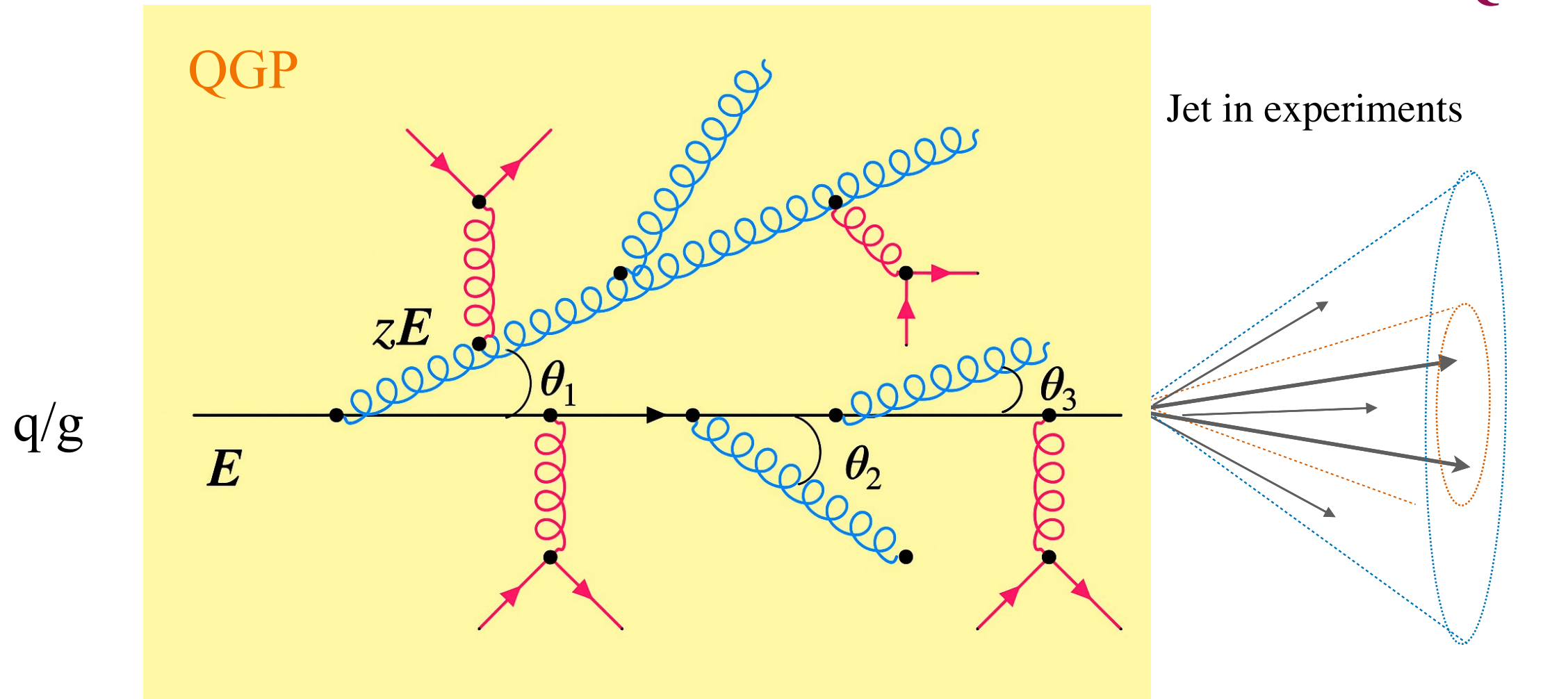


Radiative Energy Loss: BDMPS-Z, AMY, and Higher Twist
Collisional Energy Loss

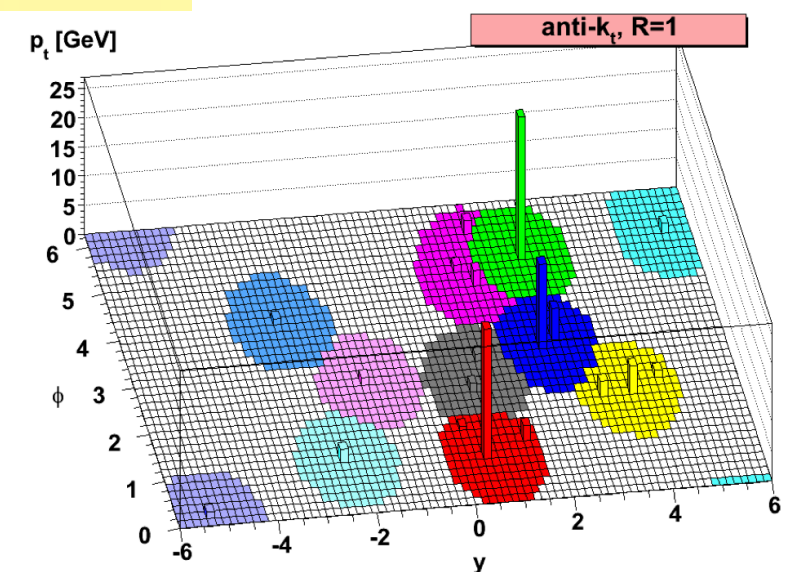
A high energetic parton moving in vacuum

Radiate gluons following angular ordering

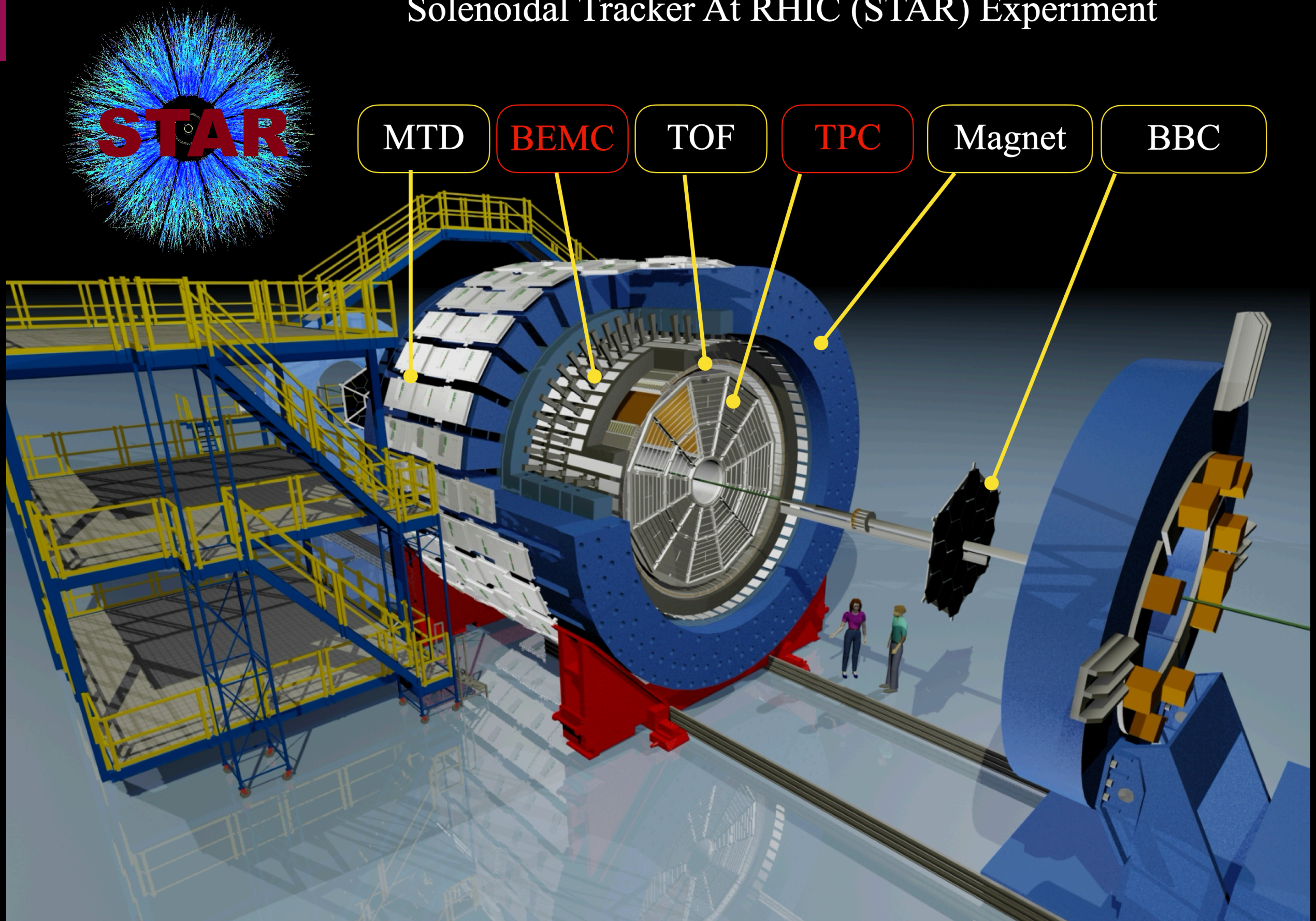
Additional in-medium radiation due to QGP



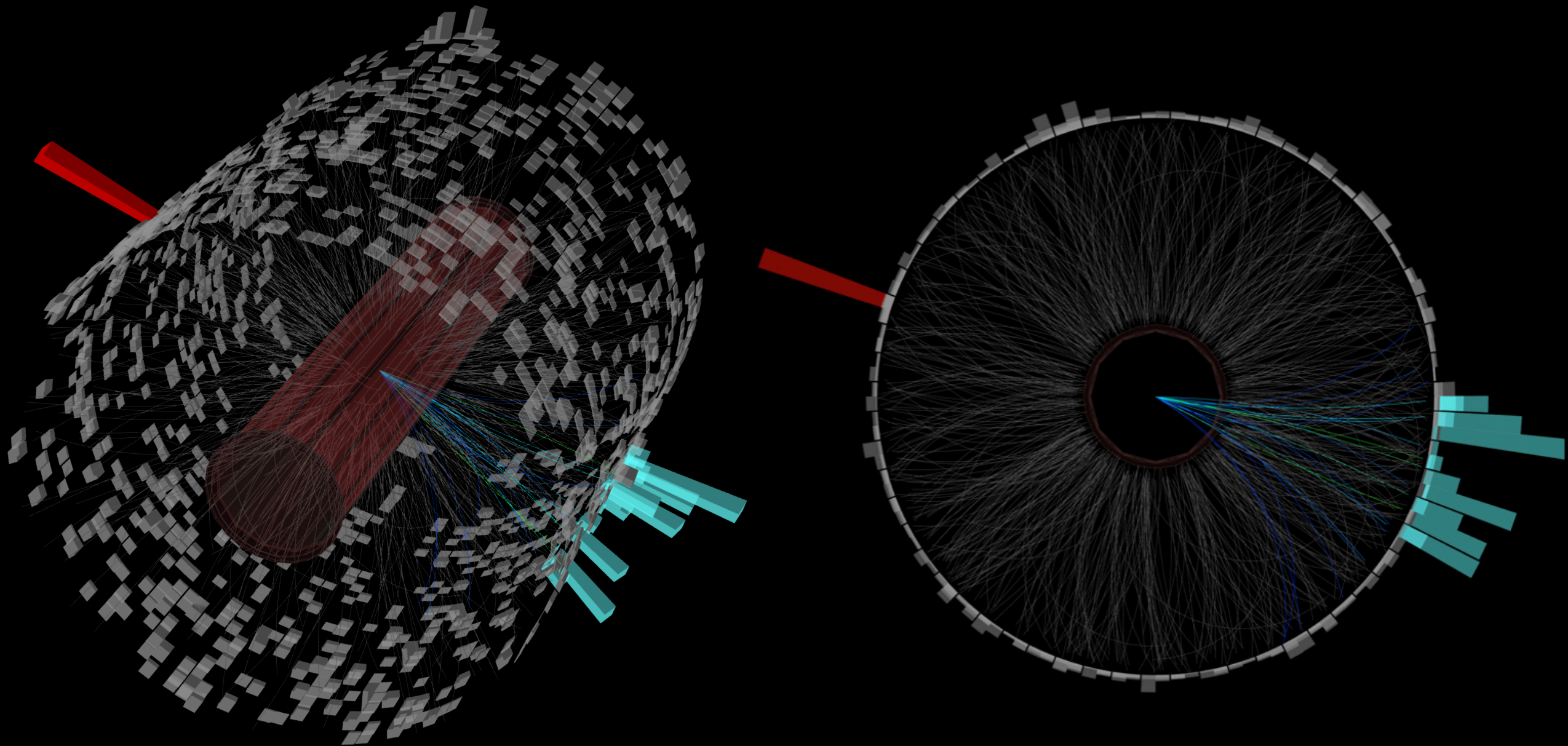
IRC safe jet reconstruction algorithms
(anti- k_T : popular one)



Solenoidal Tracker At RHIC (STAR) Experiment



γ + jet event display in Au+Au collisions using TPC and BEMC detectors



STAR Experiment

Au+Au $\sqrt{s_{\text{NN}}} = 200$ GeV

Apr 06, 2014 09:22:51 EDT

Event ID: 2056716

γ + jet event

$E_{\text{T}} : 17.6$ GeV

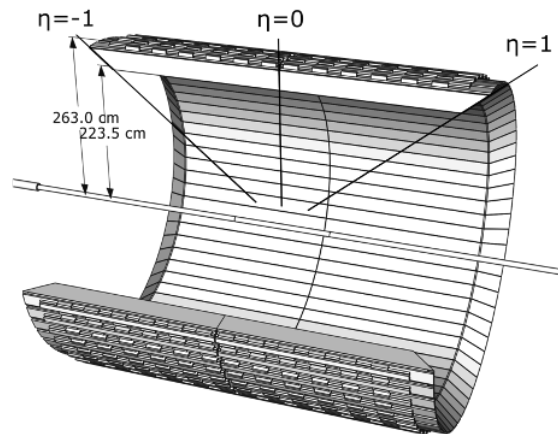
$p_{\text{T}}^{\text{jet}} = 13.2$ GeV/c

Direct photon and π^0 measurements at STAR

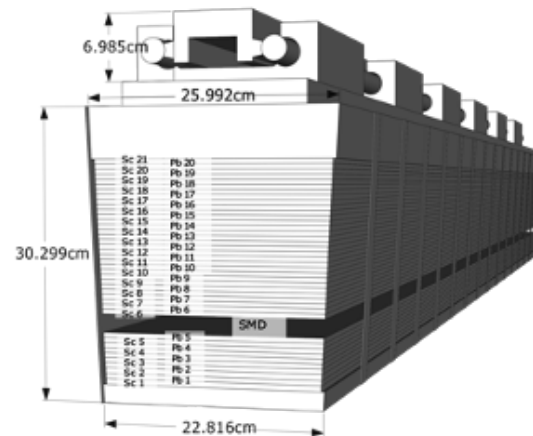
STAR γ/π^0 discrimination techniques:

Barrel Electromagnetic Calorimeter (BEMC) and Barrel Shower maximum detector (BSMD)

BEMC

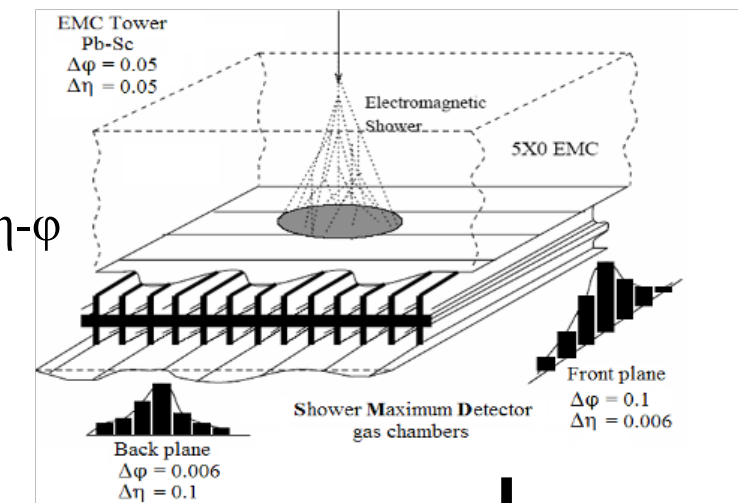


BEMC Tower



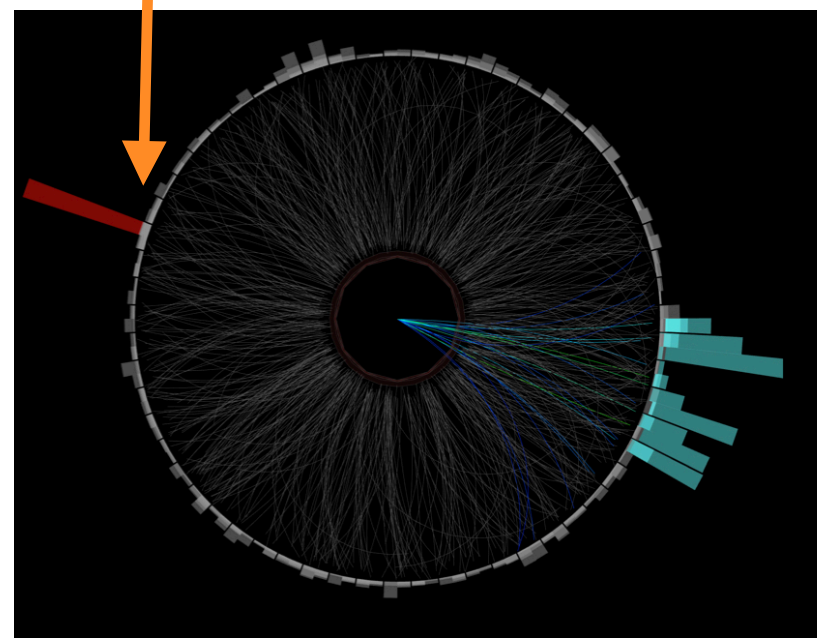
Energy deposition in η - ϕ

BSMD eta-phi strips



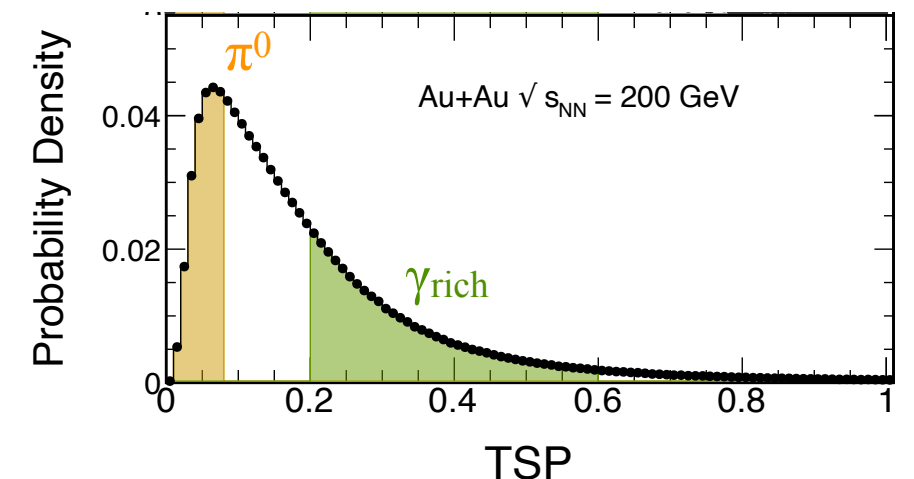
Analyse shower shape

STAR γ +jet event display
In Au+Au collision



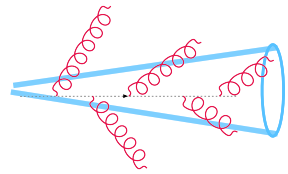
$$\text{TSP} = \frac{E_{\text{cluster}}}{\sum_i r_i e_i^{1.5}}$$

Clustering 2x2 towers (3x3 also)
Measuring shower shape



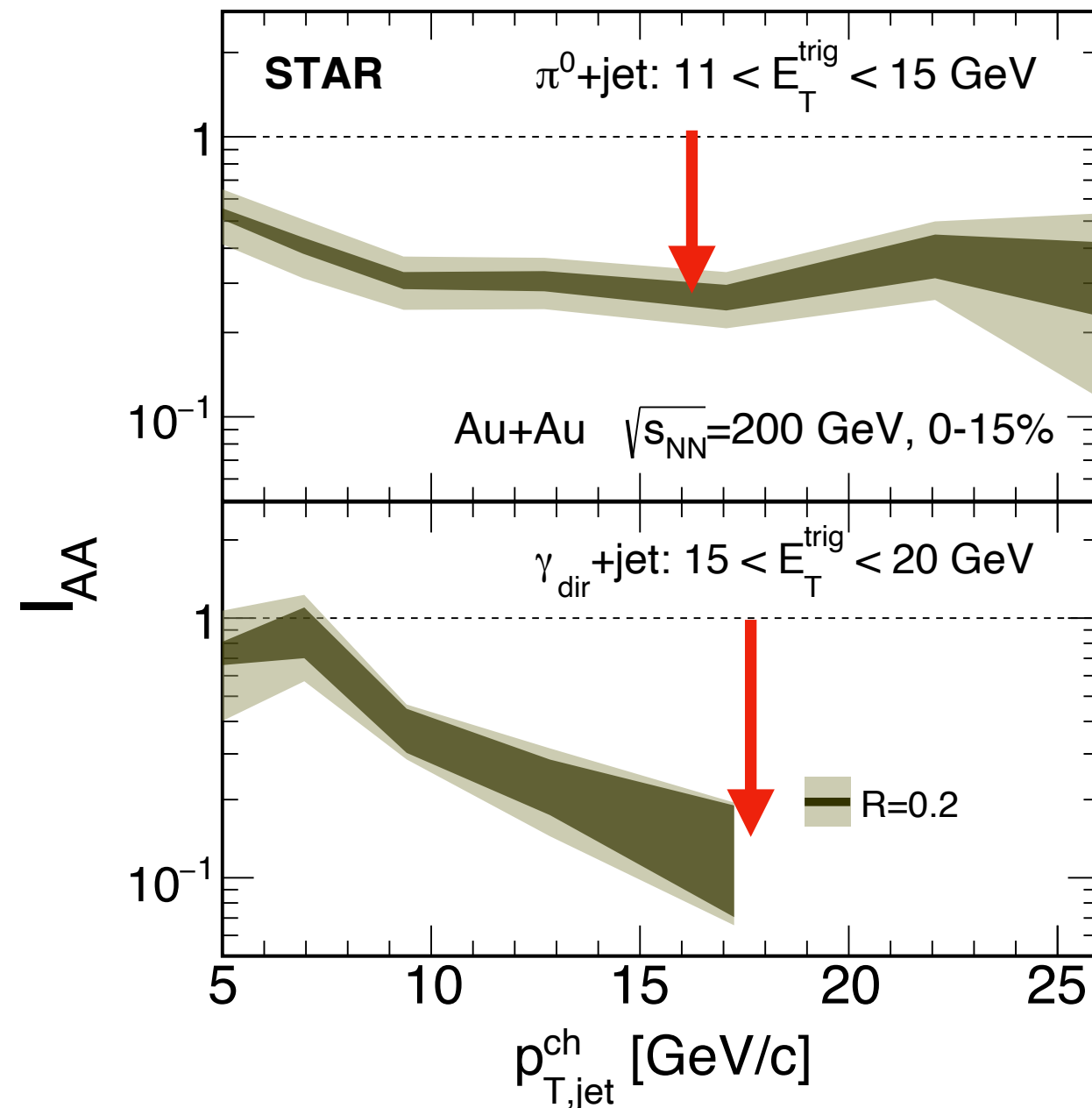
Jet suppression: γ +jet and π^0 +jet

Jet cone $R = 0.2$



Jet radius dependence of suppression (energy loss)

STAR: PRL 134 (2025) 23, 232301



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

$I_{\text{AA}} = 1$ No suppression

< 1 Suppression

> 1 Enhancement

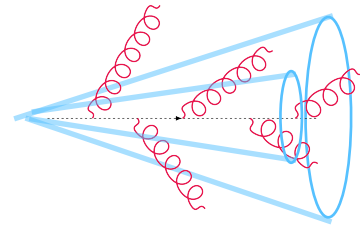
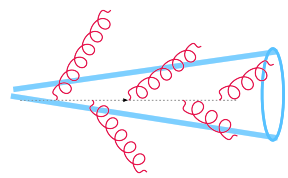
Jet suppression: γ +jet and π^0 +jet

R-dependence

Jet radius dependence

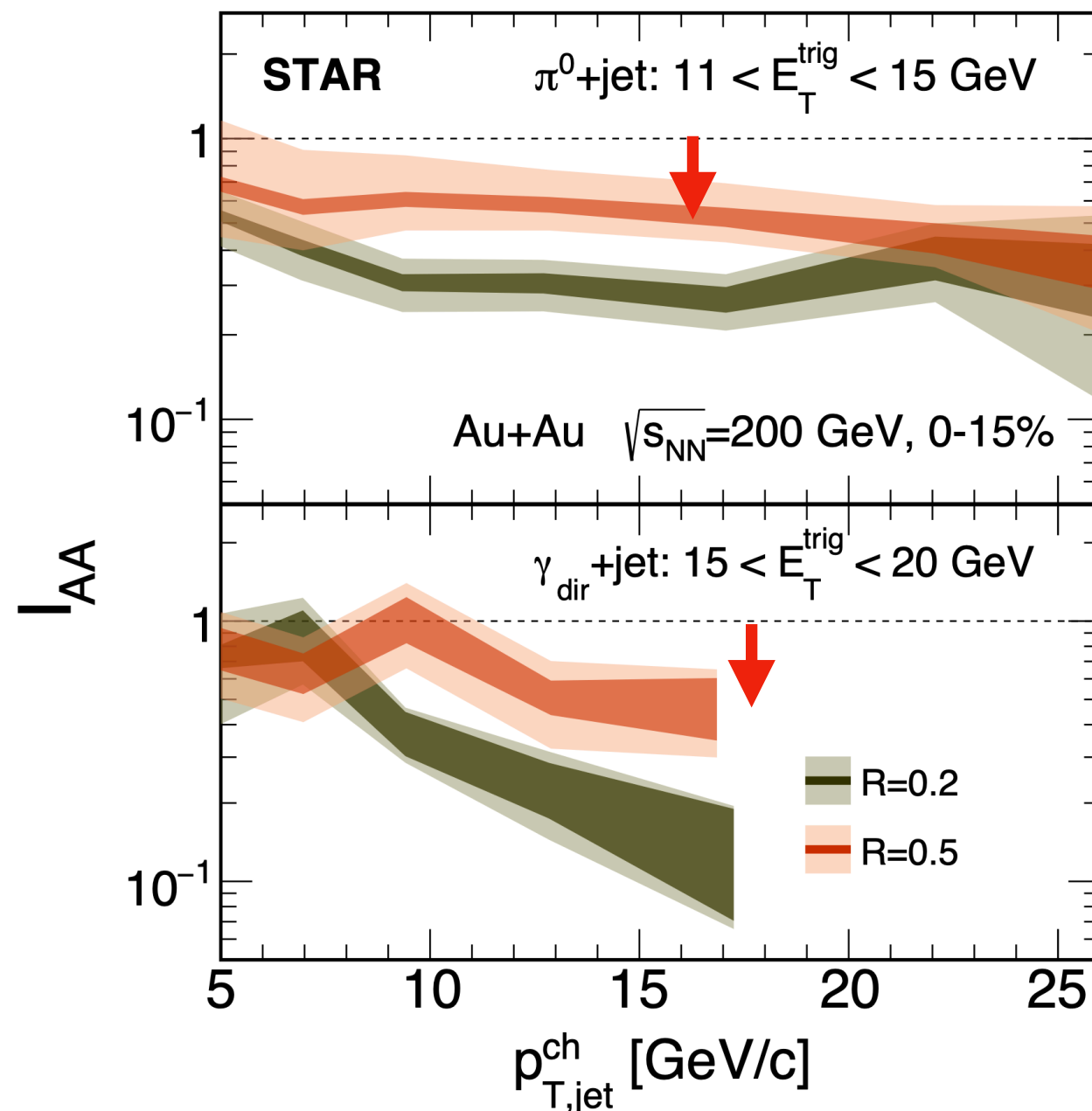
R = 0.2

R = 0.5



Jet radius dependence of suppression (energy loss)

STAR: PRL 134 (2025) 23, 232301



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

$I_{\text{AA}} = 1$ No suppression

< 1 Suppression

> 1 Enhancement

Observed jet R dependence of suppression

Larger cone size encapsulates lost energy of initial parton in the QGP

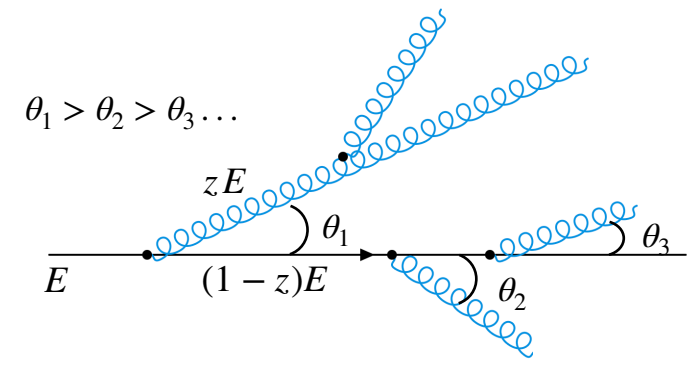
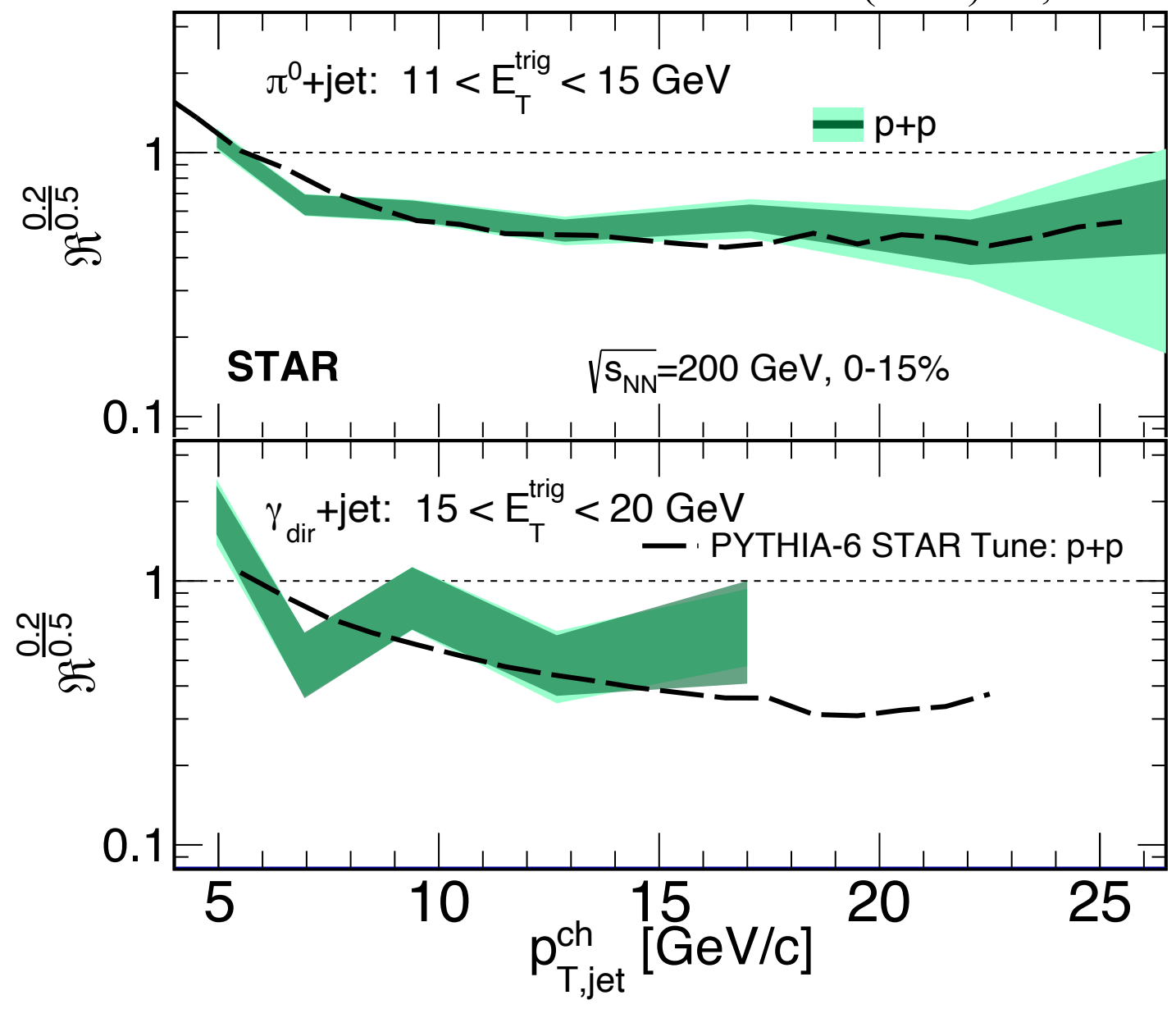
→ Redistribution of lost energy in QGP

Jet shape modification in QGP

vacuum

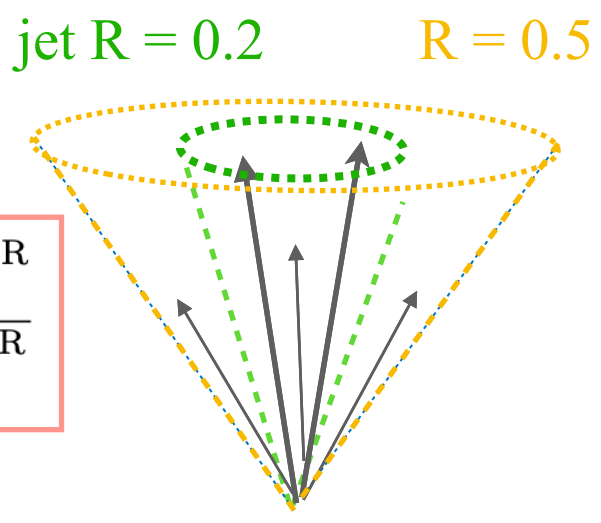
Intra-jet broadening

STAR: PRL 134 (2025) 23, 232301



Vacuum parton shower

$$\mathcal{R}_{\text{large}-R}^{\text{small}-R} = \frac{Y(p_T^{\text{jet,ch}})^{\text{small}-R}}{Y(p_T^{\text{jet,ch}})^{\text{large}-R}}$$



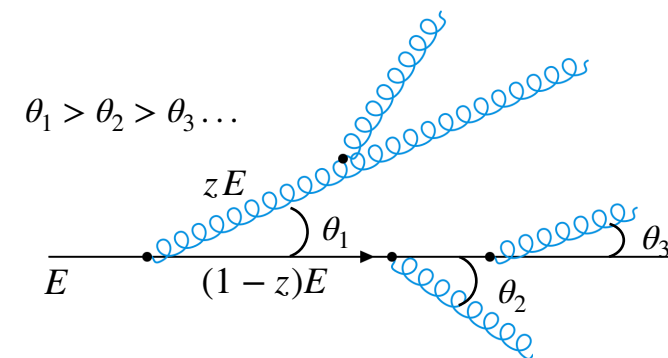
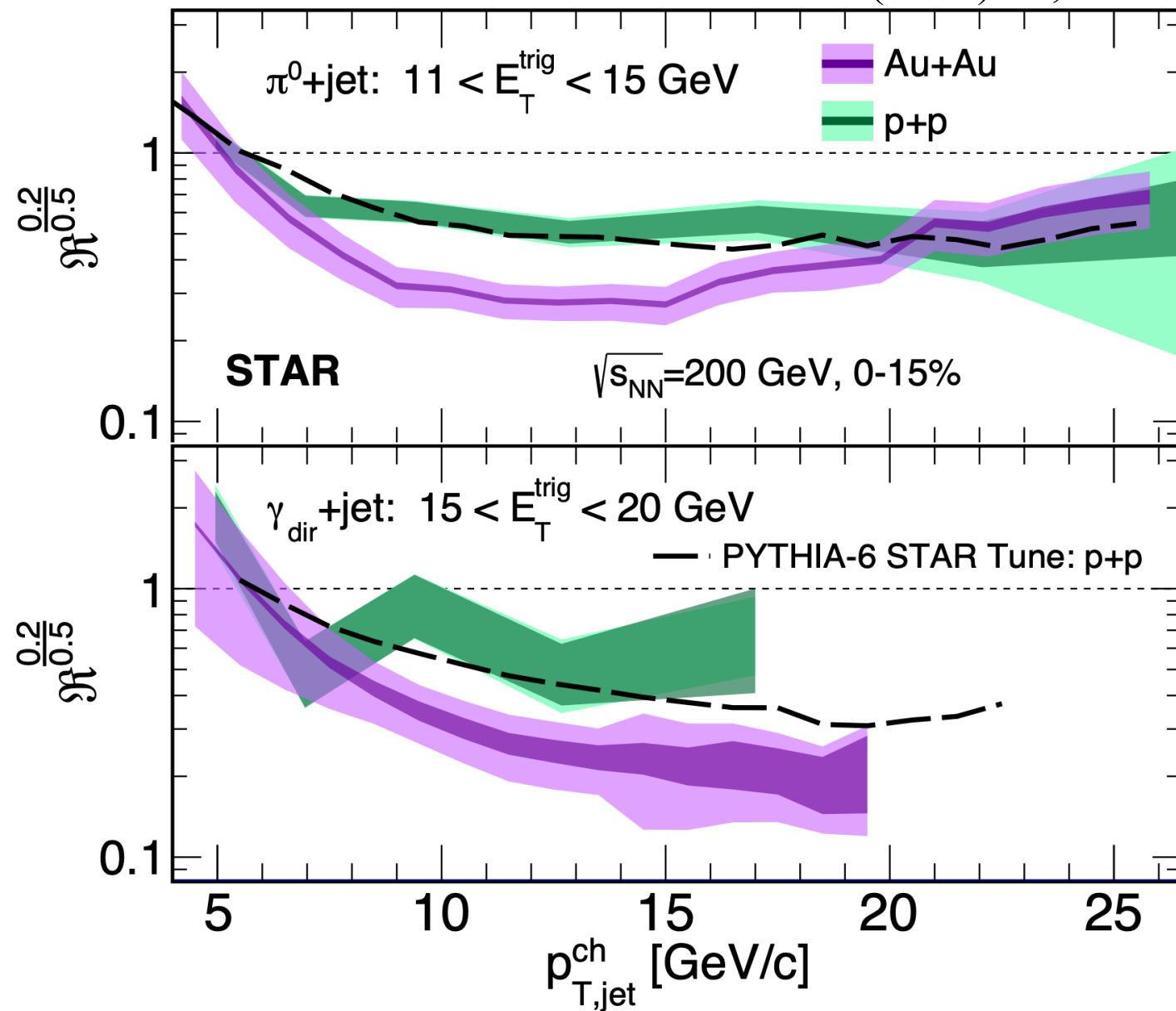
Only vacuum cascade effect in QCD

Jet shape modification in QGP

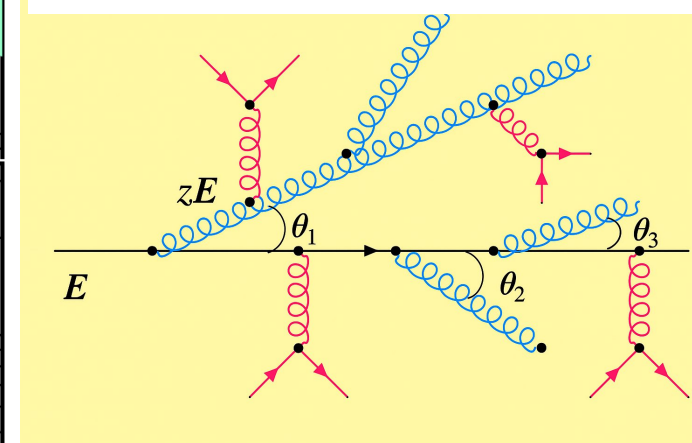
vacuum+QGP effect

Intra-jet broadening

STAR: PRL 134 (2025) 23, 232301



Vacuum parton shower

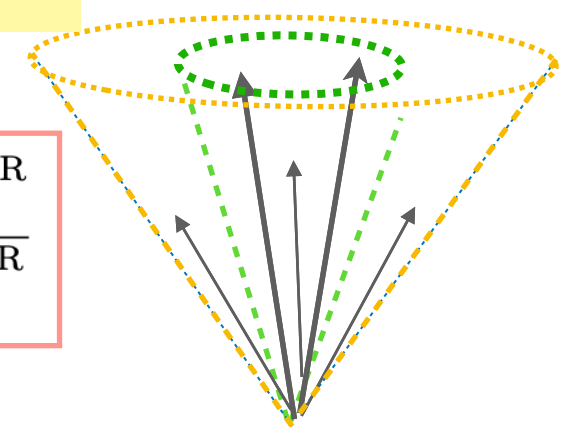


Medium-induced gluon radiation

$R = 0.2$

$R = 0.5$

$$\mathcal{R}_{\text{large}-R}^{\text{small}-R} = \frac{Y(p_T^{\text{jet,ch}})^{\text{small}-R}}{Y(p_T^{\text{jet,ch}})^{\text{large}-R}}$$



Intra-jet broadening due to medium induced gluon radiations in hot-dense QCD medium

Theory comparisons

Jet fluid: PRC 94, 024902

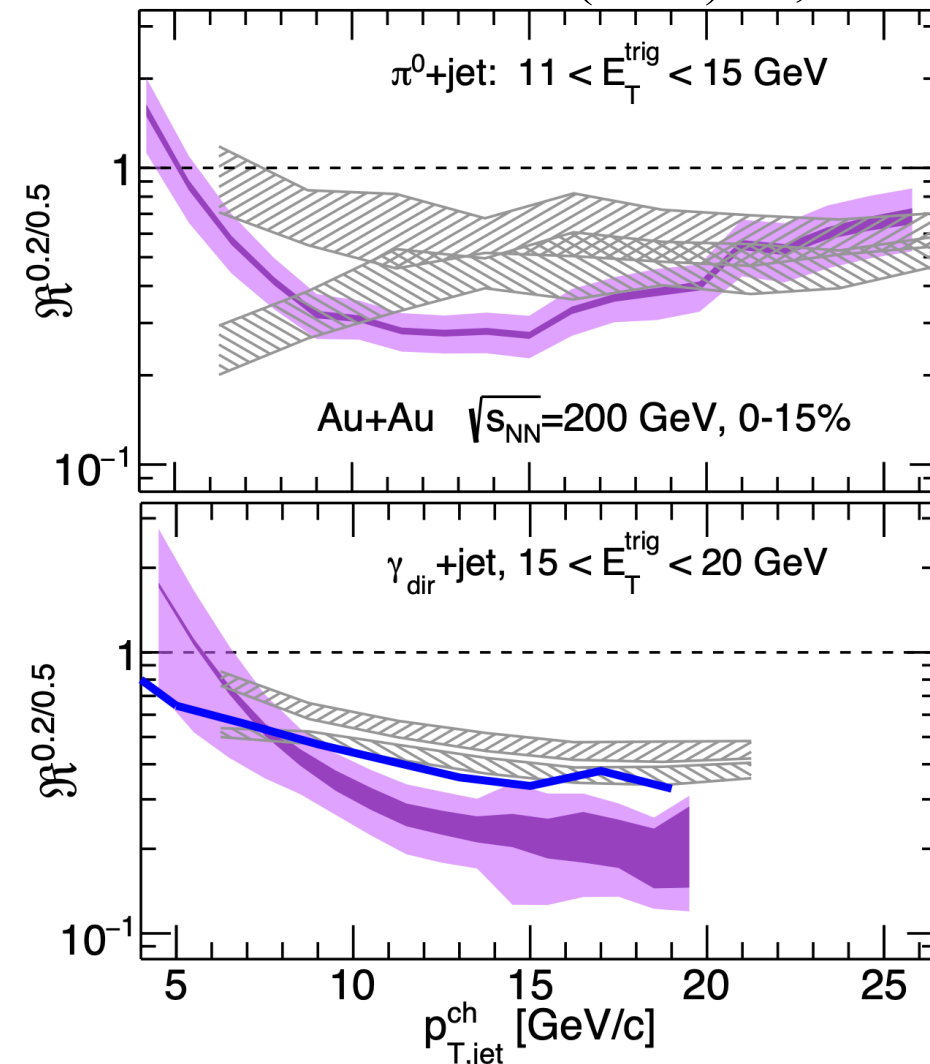
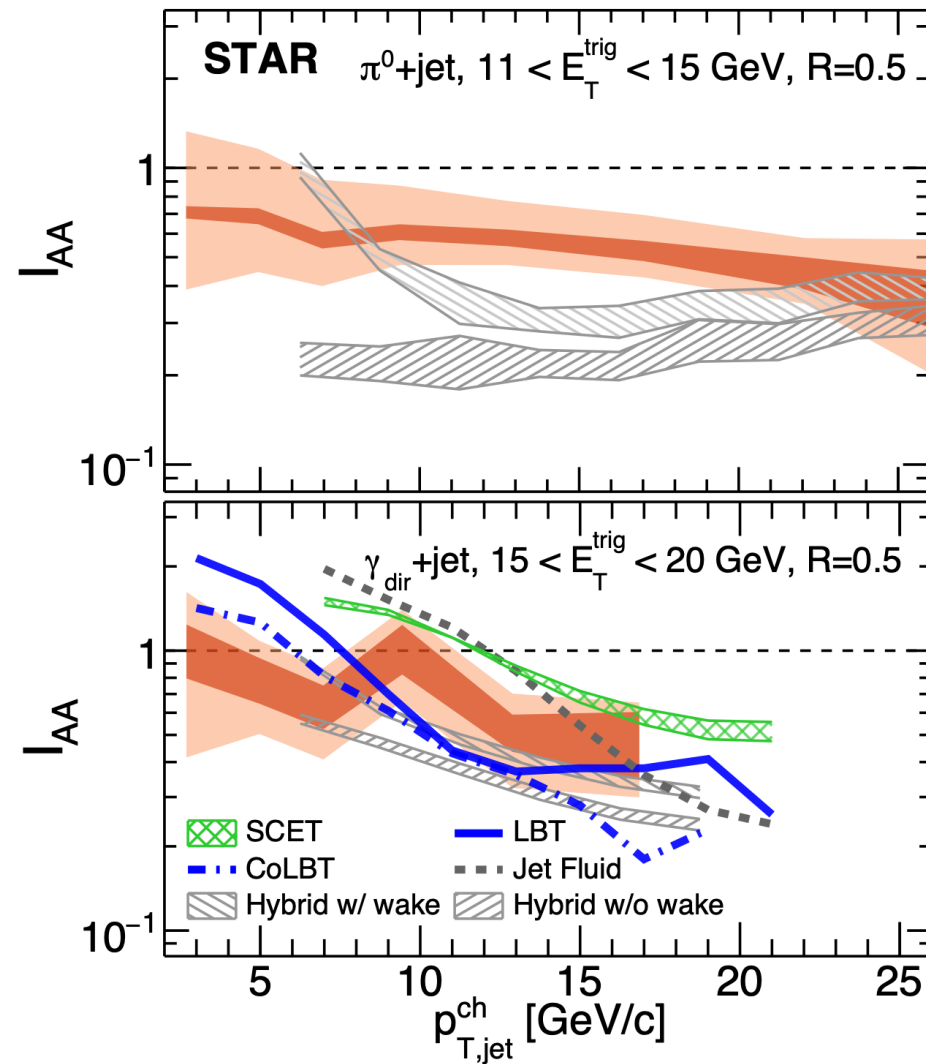
Linear Boltzmann Transport (LBT): PLB 782, 707 (2018)

Coupled linear Boltzmann transport+hydro: PRL 128, 022302 (2022)

Soft Collinear Effective Theory: PLB 795, 502 (2019)

Hybrid model: PRC 99, 051901 (2019)

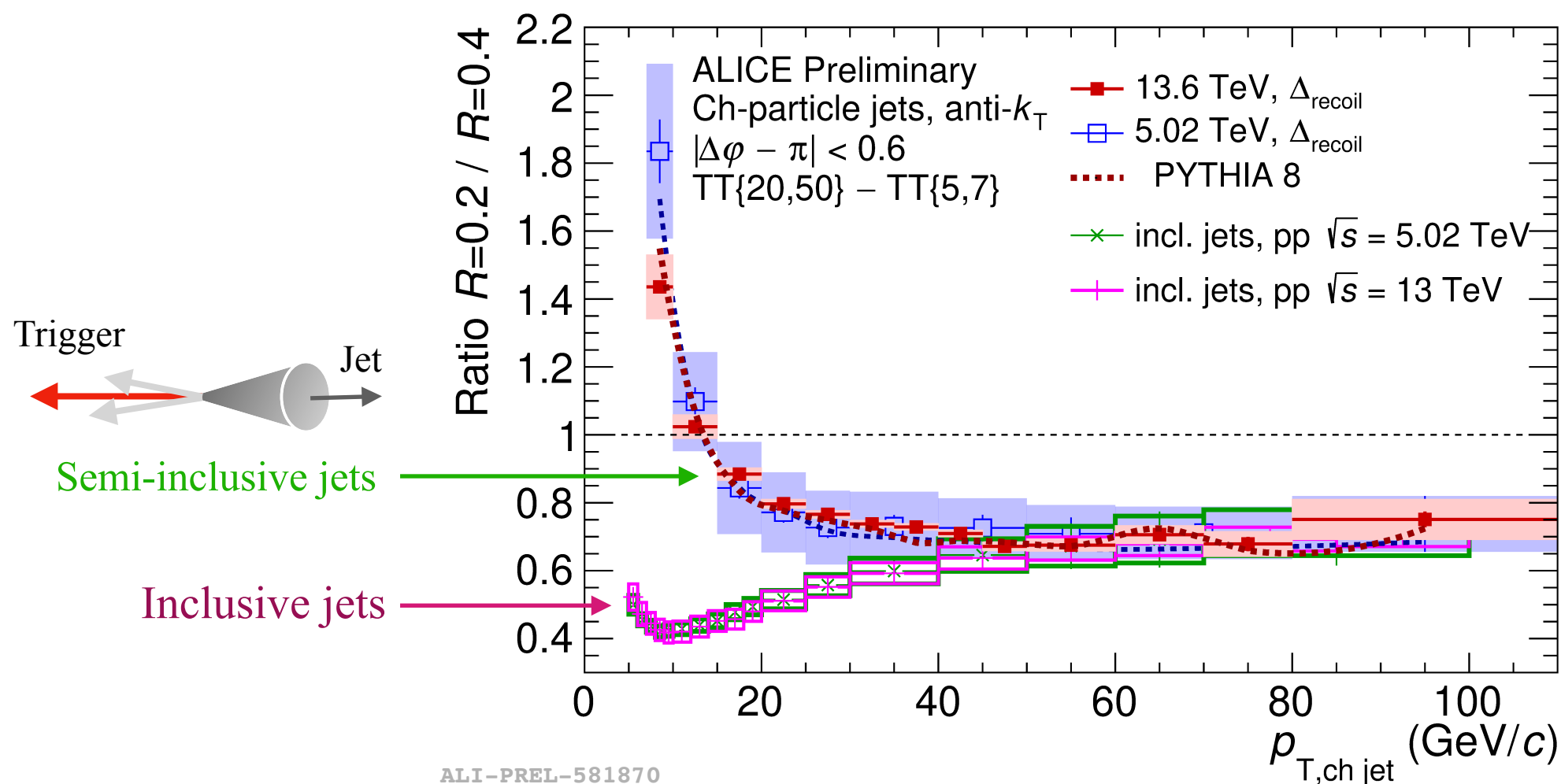
STAR: PRL 134 (2025) 23, 232301



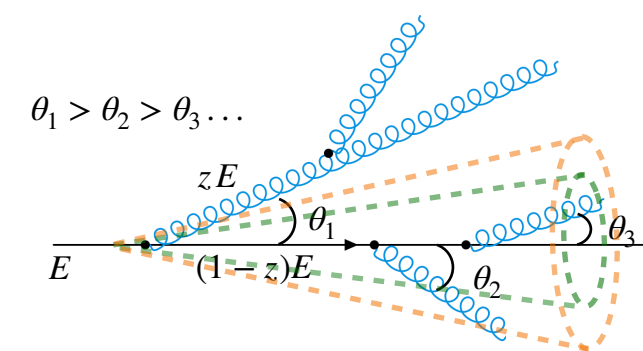
Different model calculations incorporating jet quenching are not fully consistent with the observations

Jet shape in vacuum at LHC: Intra-jet broadening

ALICE: Inclusive jet and semi-inclusive jet in p+p collisions



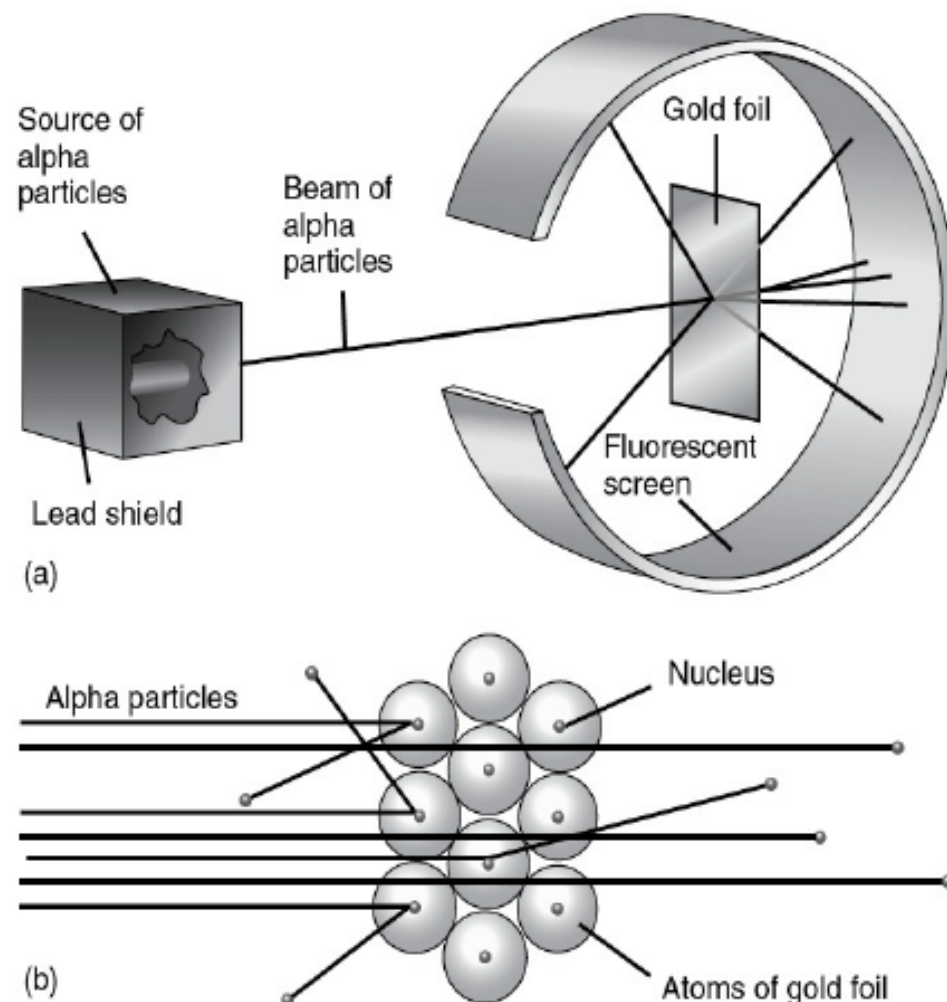
vacuum radiation in pp



- Inclusive jet and semi-inclusive jet agreement at high $p_{T,\text{jet}}$ but differ at low $p_{T,\text{jet}}$
- Number of narrower jets enhanced at low $p_{T,\text{jet}}$ for semi-inclusive case
- Jet-splitting? Why sensitive to triggered semi-inclusive measurements?

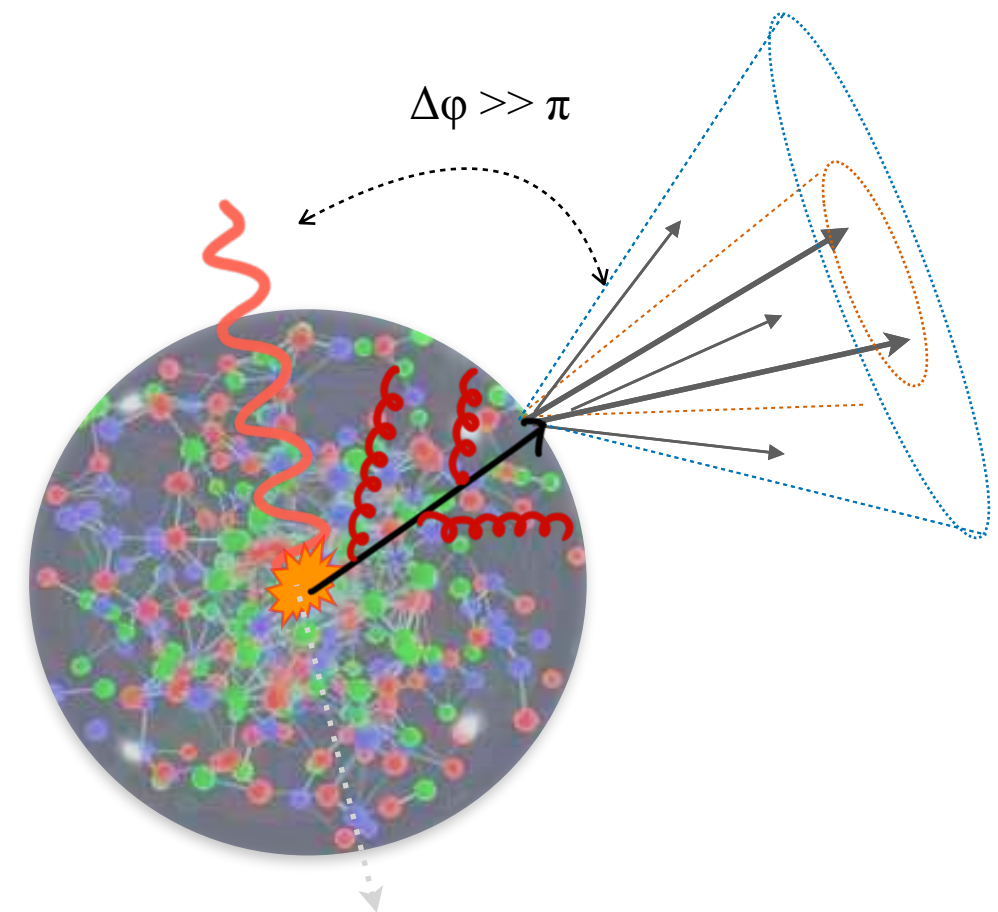
Searching for Rutherford-like scattering in QGP

Rutherford scattering ($\approx 1 \text{ fm} = 10^{-15} \text{ m}$)



Small-dense nucleus at the centre of the atom

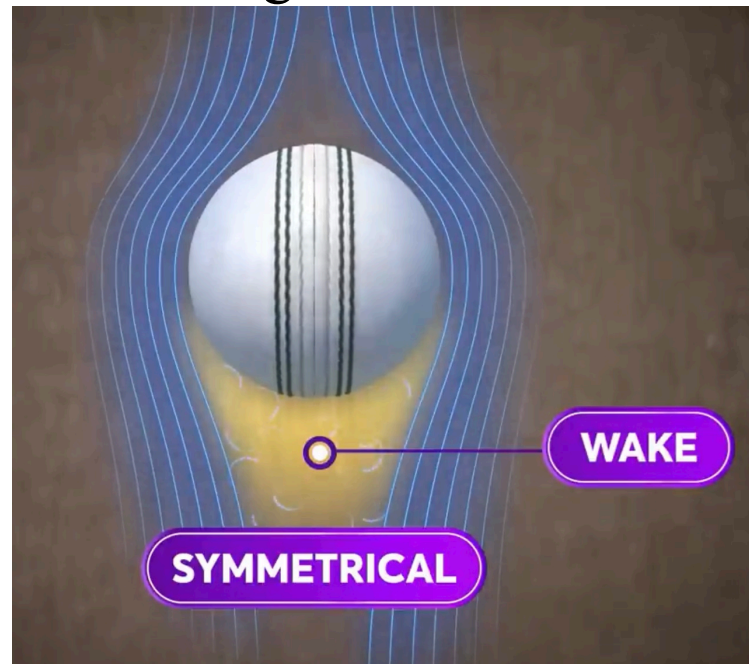
Rutherford-like scattering in QGP ($\leq (\Lambda_{\text{QCD}})^{-1}$)



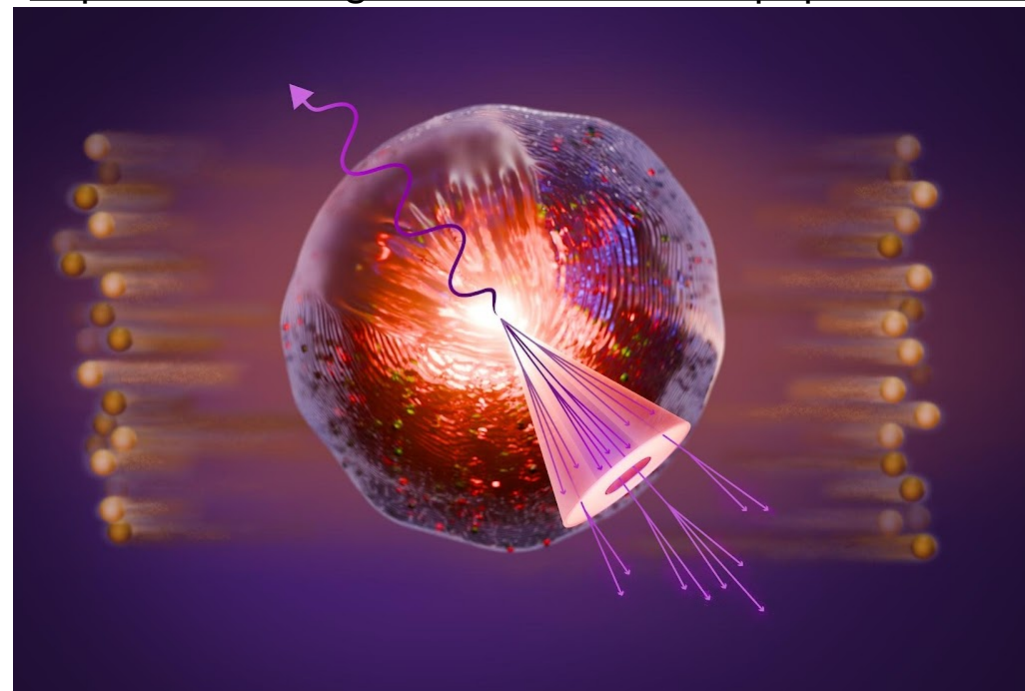
Microstructure of the QGP:
Scattering of Energetic Partons
off Quasiparticles

Diffusion wake in QGP

Wake behind the fast moving cricket ball



<https://www.bnl.gov/newsroom/news.php?a=122311>

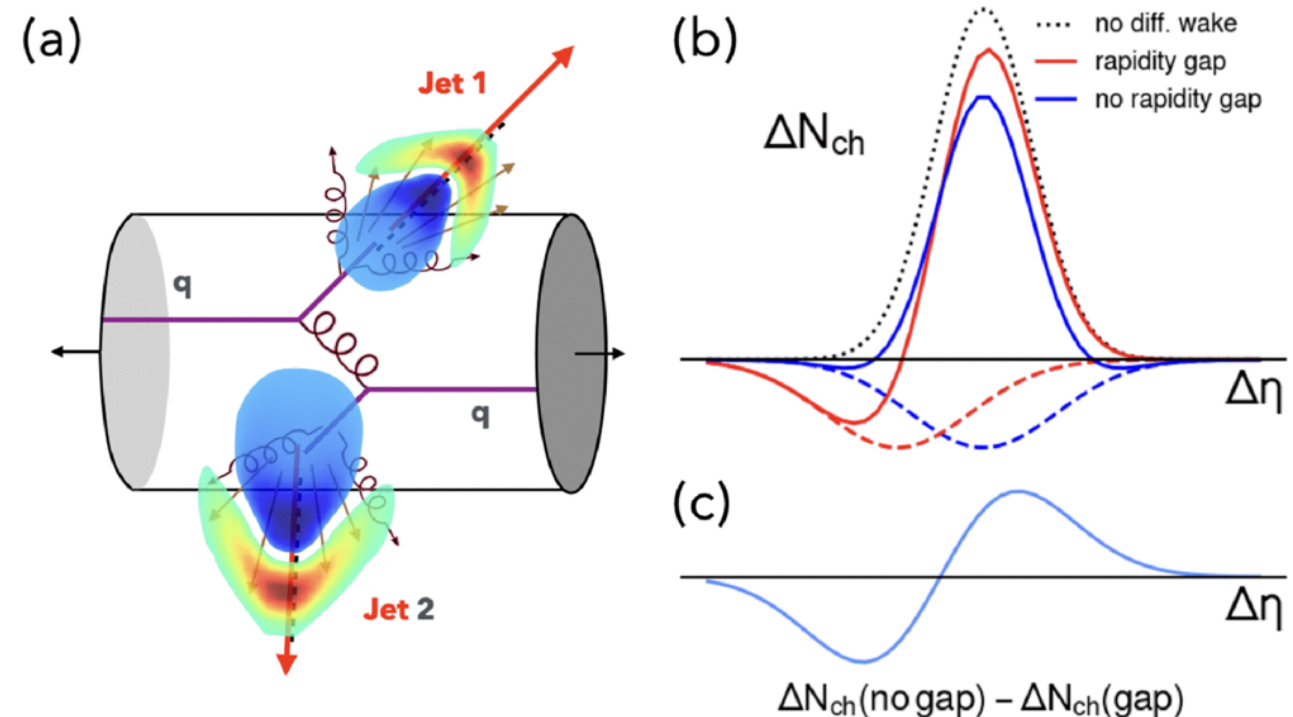


Yang and Wang:
PRL 135, 072303 (2025)

Wake on the surface of water due to moving boat



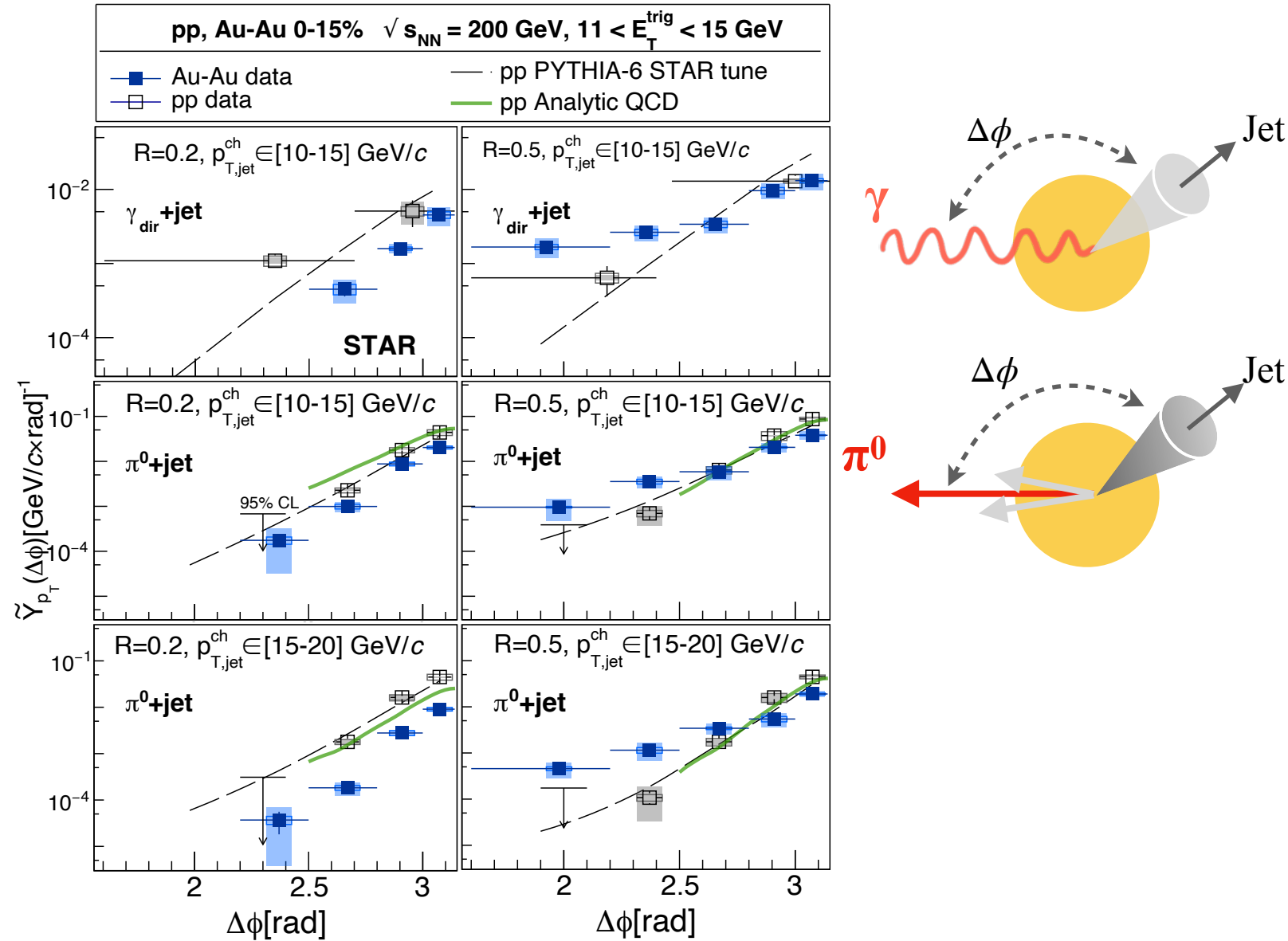
Wake effect in QGP to high energetic parton: along $\Delta\eta$



STAR measurements of jet acoplanarity

arXiv: 2505.05789 (Accepted by PRC)

Measuring two probes in STAR experiment

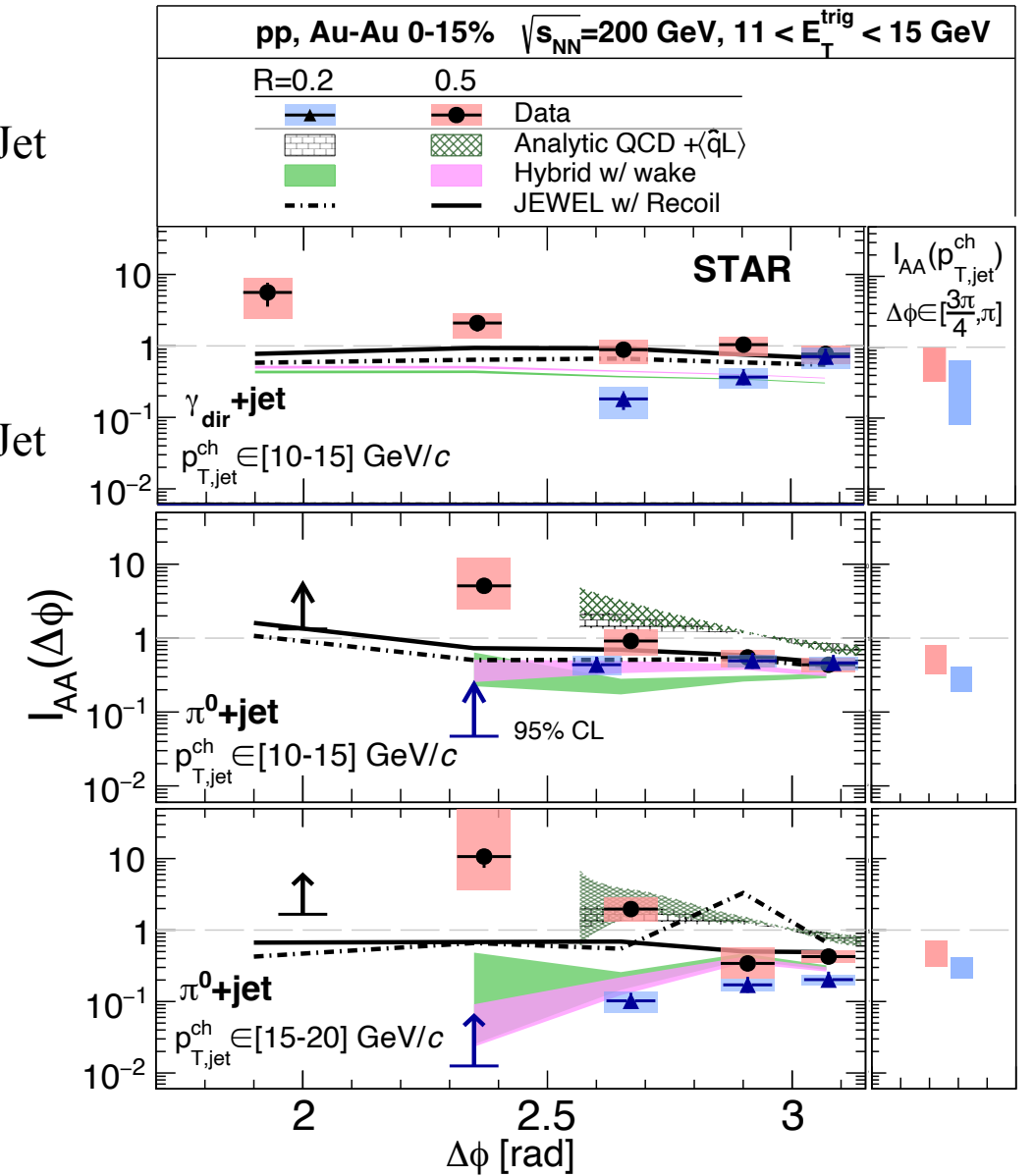
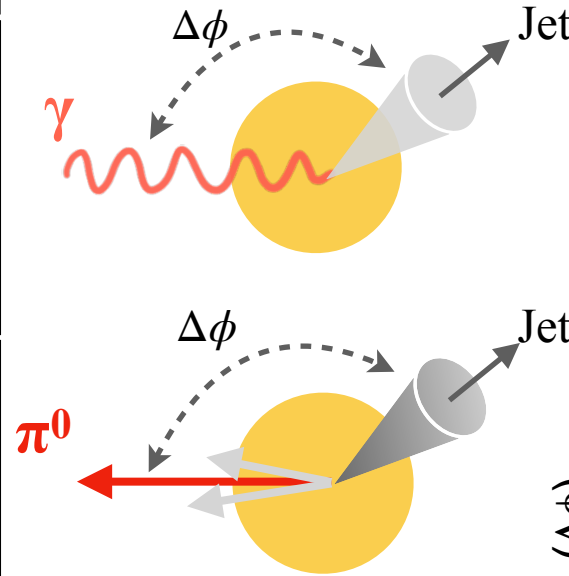
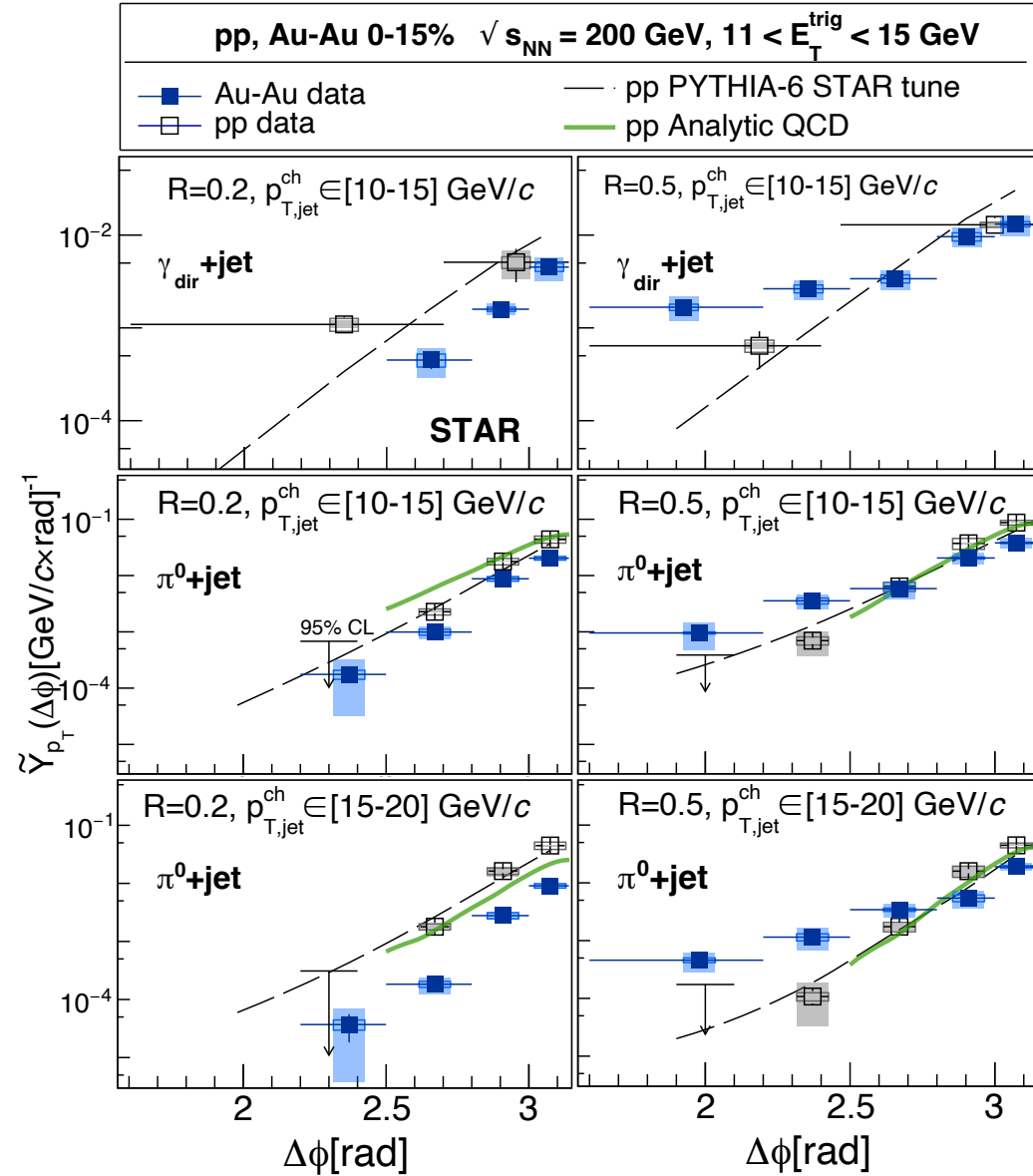


- Strong enhancement in Au+Au relative to p+p for jet $R=0.5$ at $\Delta\phi \approx \pi/2$ in contrast to jet $R=0.2$

STAR measurements of jet acoplanarity

arXiv: 2505.05789 (Accepted by PRC)

Measuring two probes in STAR experiment



- Strong enhancement in Au+Au relative to p+p for jet $R=0.5$ at $\Delta\phi \approx \pi/2$ in contrast to jet $R=0.2$
- No theory calculations explain this observation for both the jet radii
- Indication of the response of the Quark–Gluon Plasma to excitation

STAR and ALICE measurements of jet acoplanarity

PRL 133 (2024) 022301

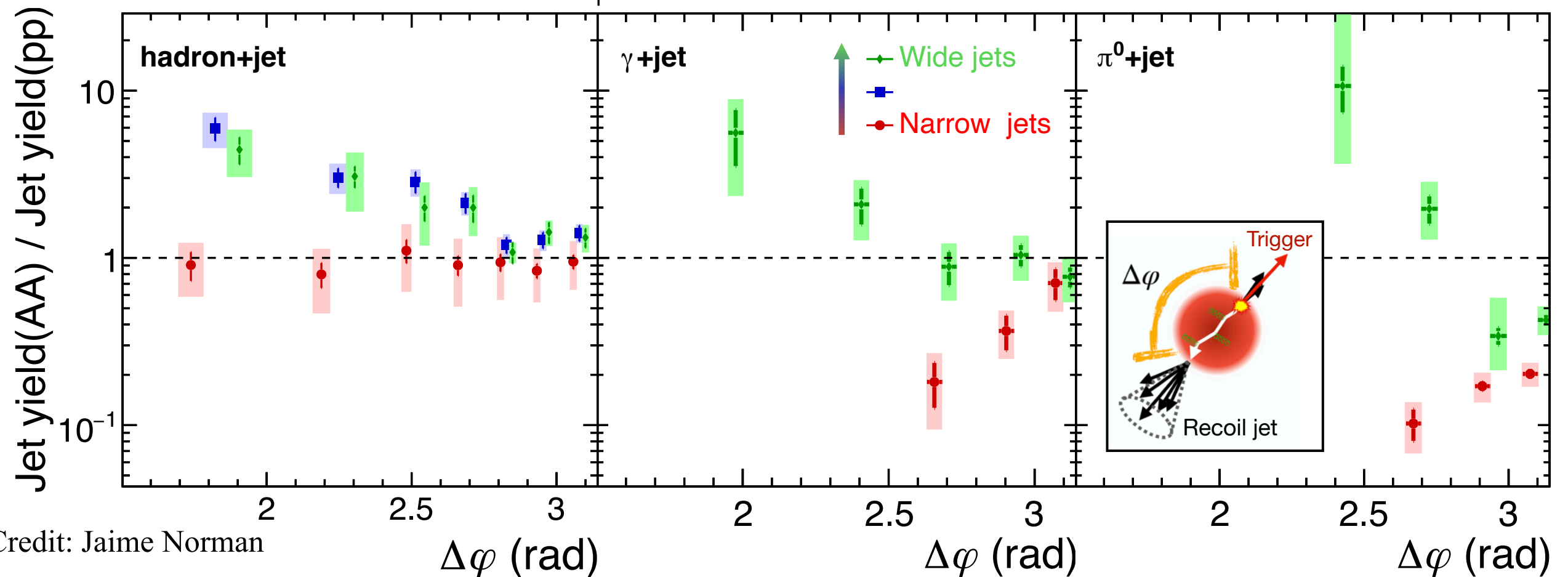
ALICE experiment

Lead-ion collisions at LHC

arXiv: 2505.05789

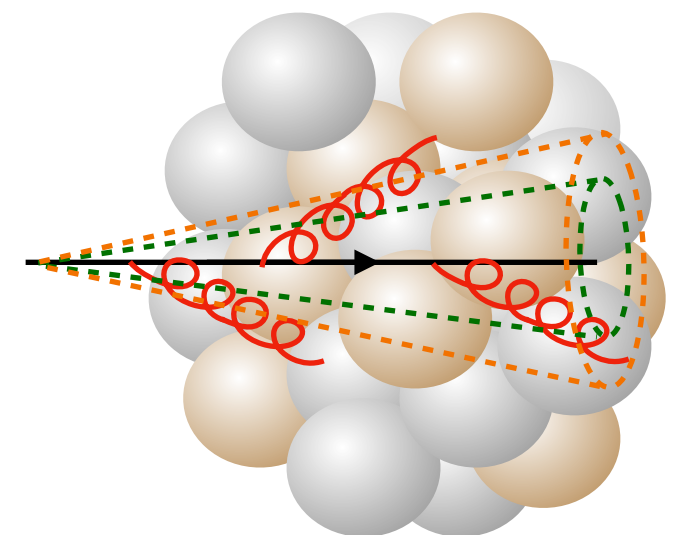
STAR experiment

Gold-ion collisions at RHIC



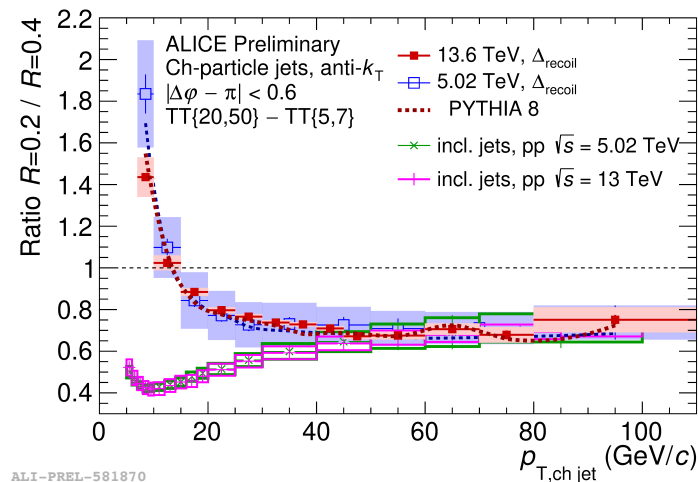
Credit: Jaime Norman

Consistent observation from both these experiments (RHIC to LHC)

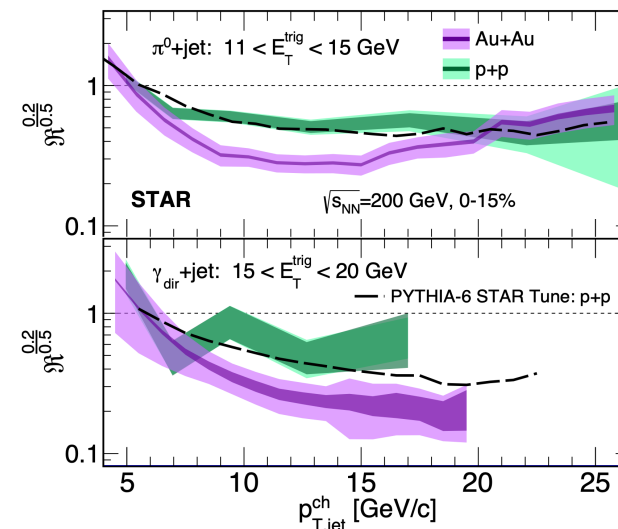


Topics need to be explored

pp at LHC



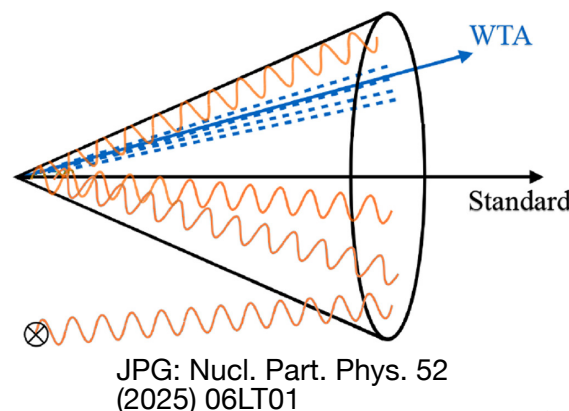
pp, AuAu at RHIC



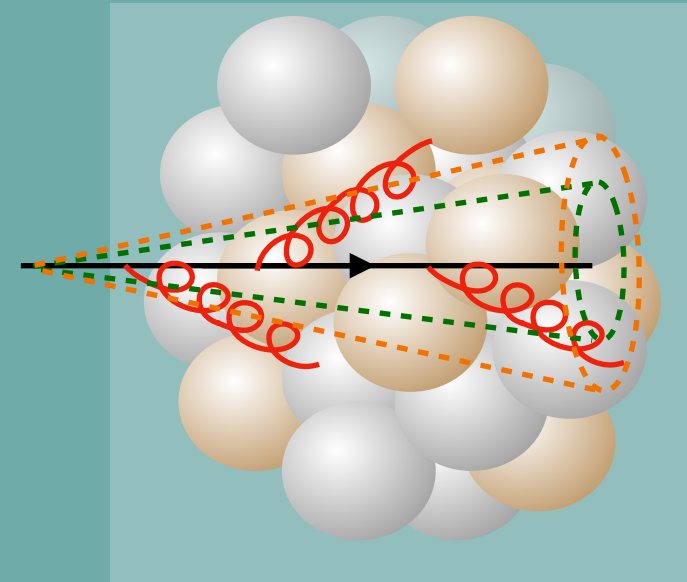
Intra-jet broadening and effect of jet-acoplanarity in different collisions systems

- p+p (vacuum radiation)
- A+A (Hot-dense Medium/QGP)
- p+A (Cold QCD medium) [Ongoing]
- What are high multiplicity events in p+p?
Why they are so? [RHIC and LHC]
- O+O collisions

Impact of soft QCD effect on jet acoplanarity (pp/pAu/AuA)



What about in p+Au/Pb collisions (nuclear medium effects)?

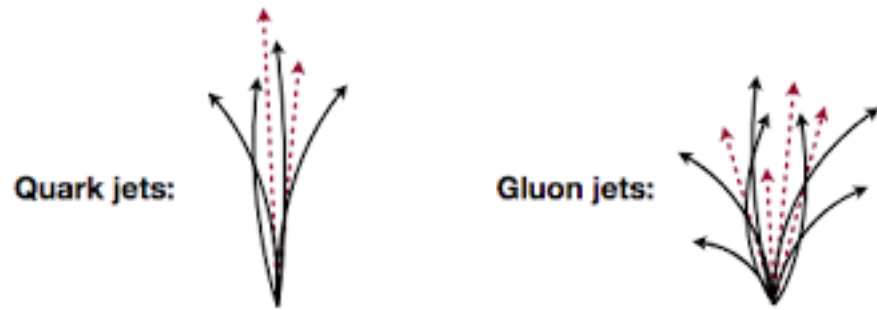


Important for EIC: Nuclear medium effect

Many measurements are ongoing in STAR to have deeper understanding on finite temperature QCD medium

Can ML help us to discriminate q/g jets?

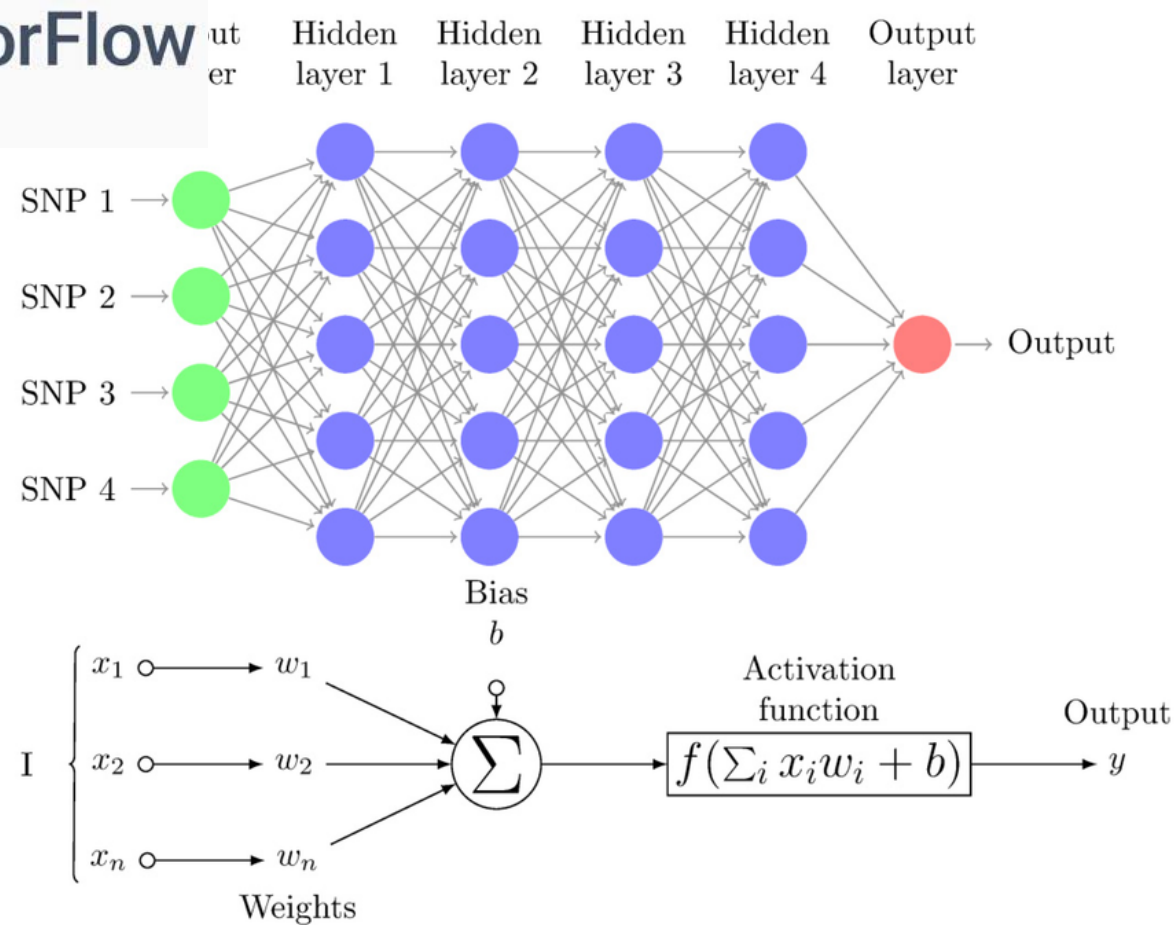
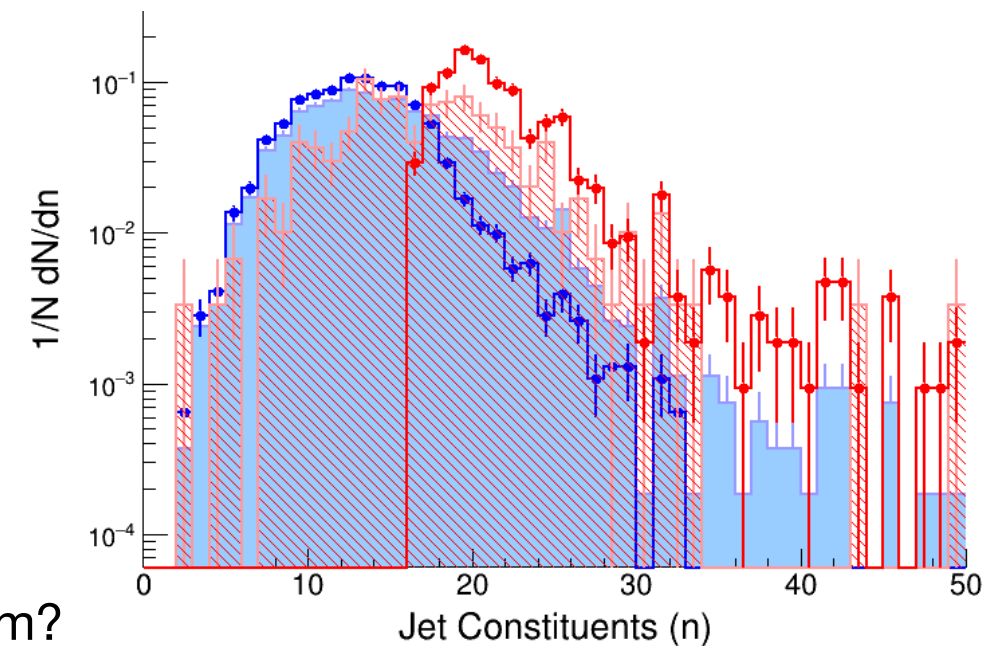
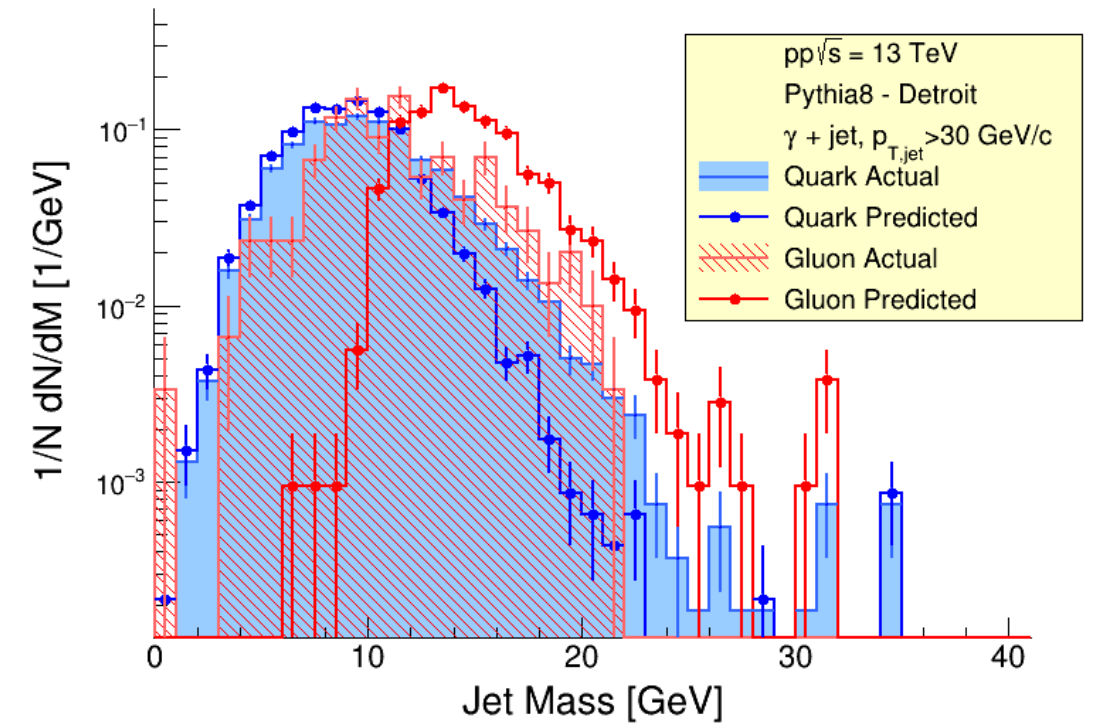
To study different splitting functions



Trying to develop a method to know uncertainties of ML

γ +jet

Monalini Samal (MS-Thesis student)
(Ongoing work)



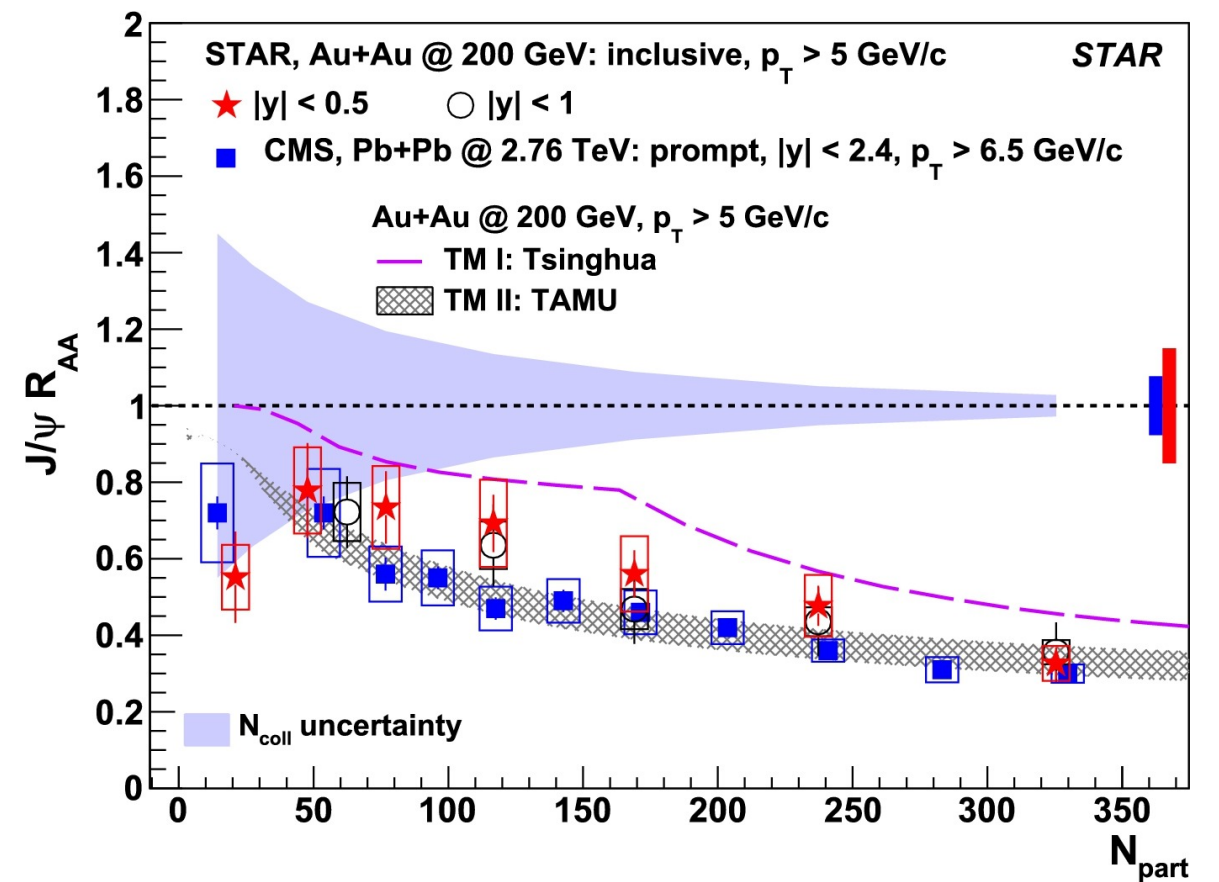
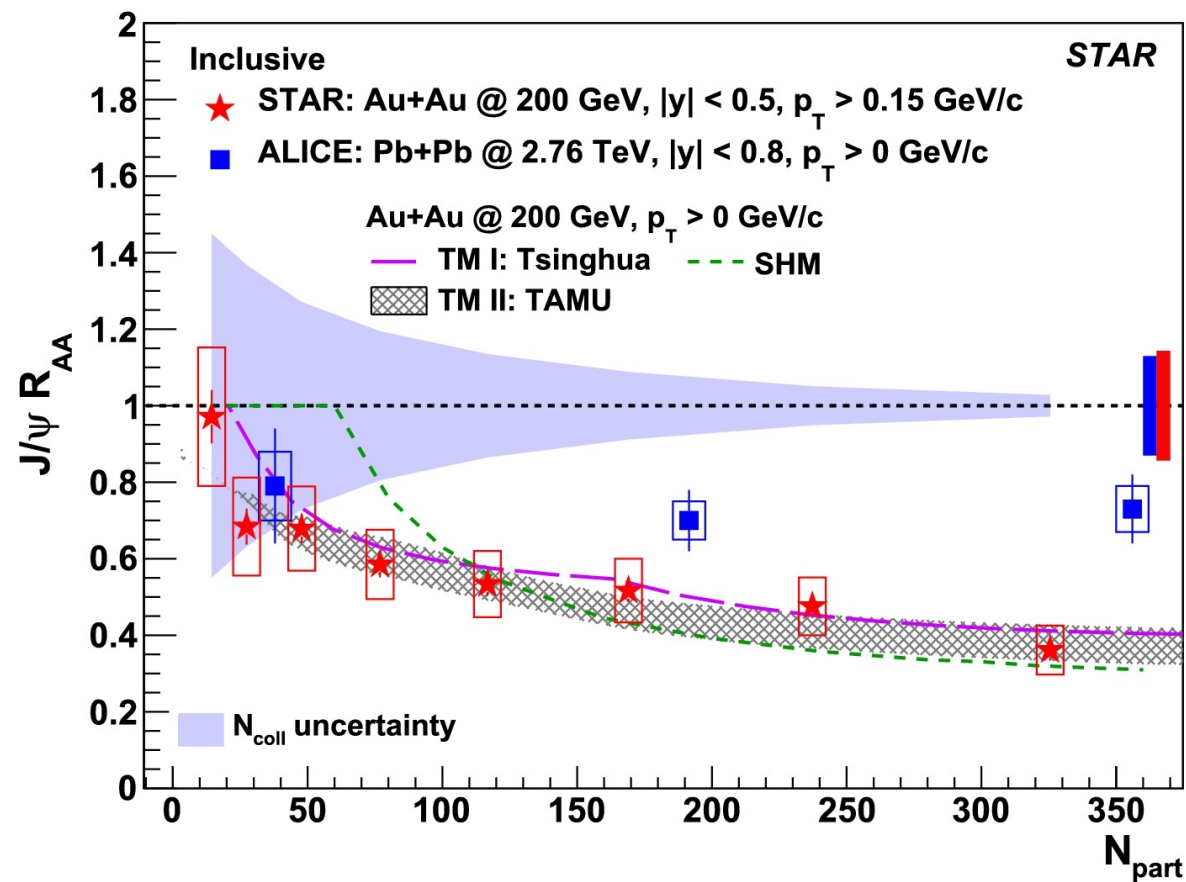
Can we use Multi-variable ML approach to address this QCD problem?

Charmonium suppression at RHIC

J/ψ suppression in STAR

STAR: PLB 797 (2019) 134917

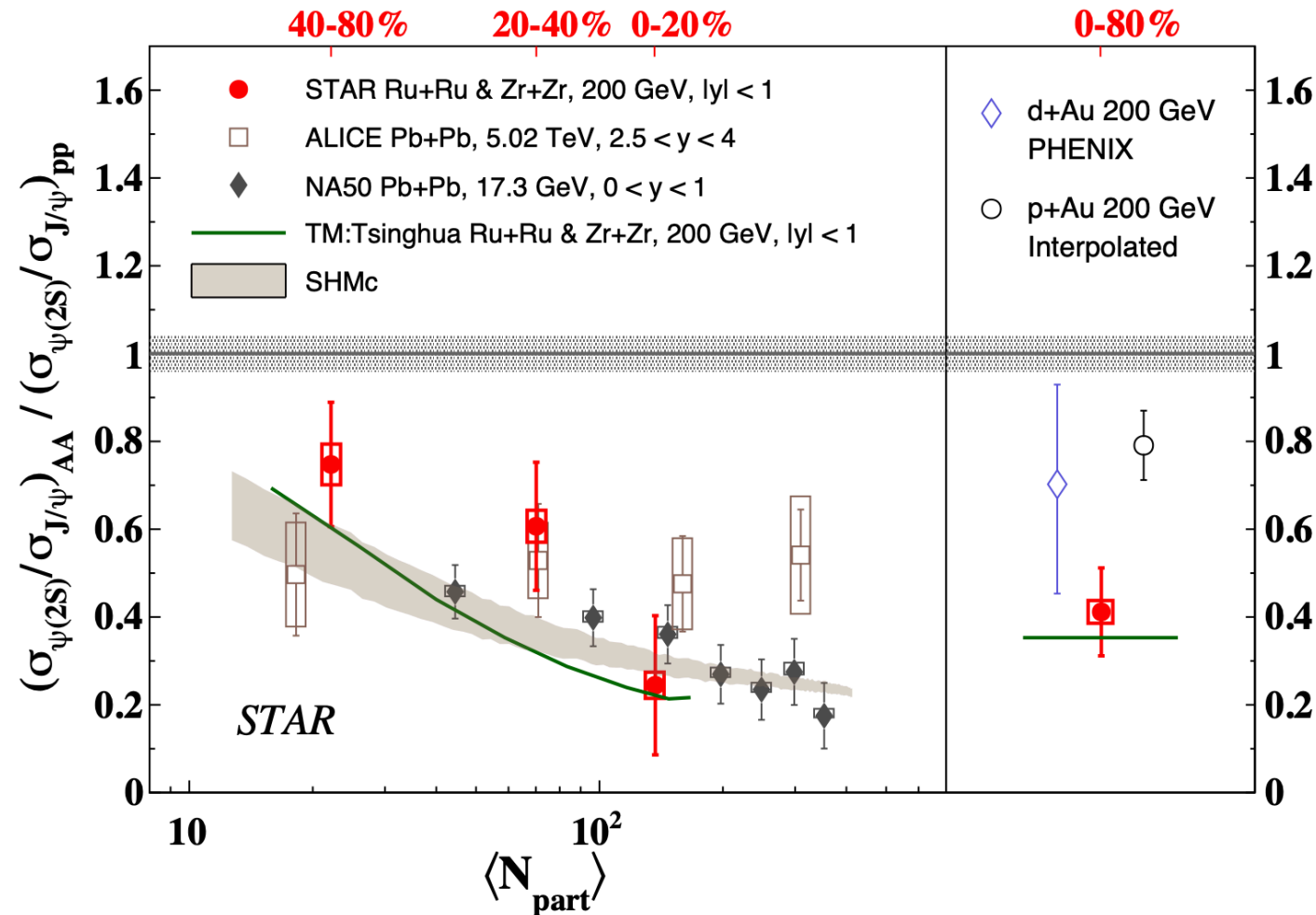
- Experience both static and dynamical dissociations in QGP
- Competing effects: dissociation and regeneration



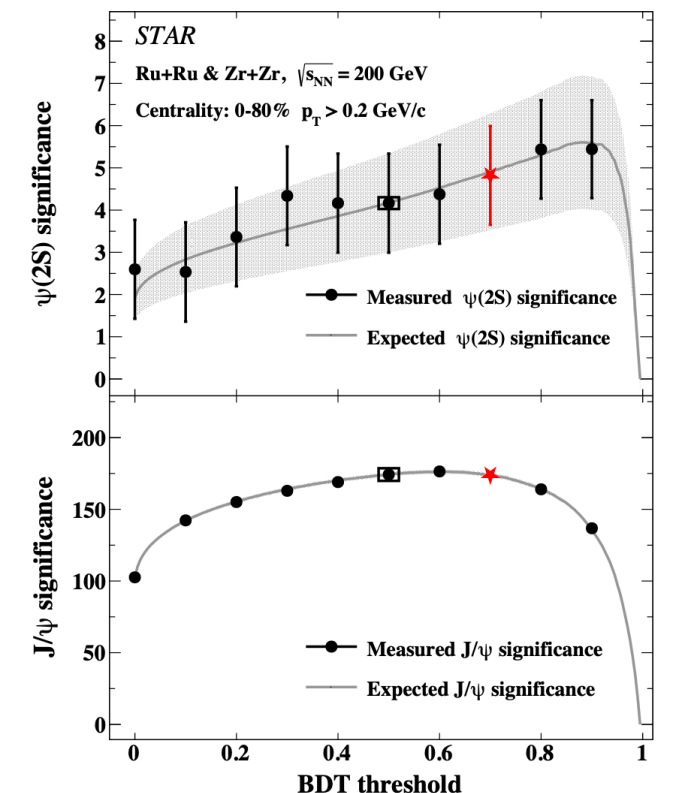
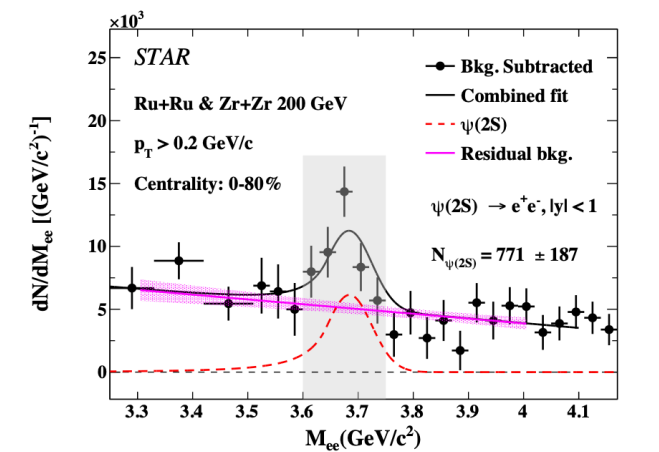
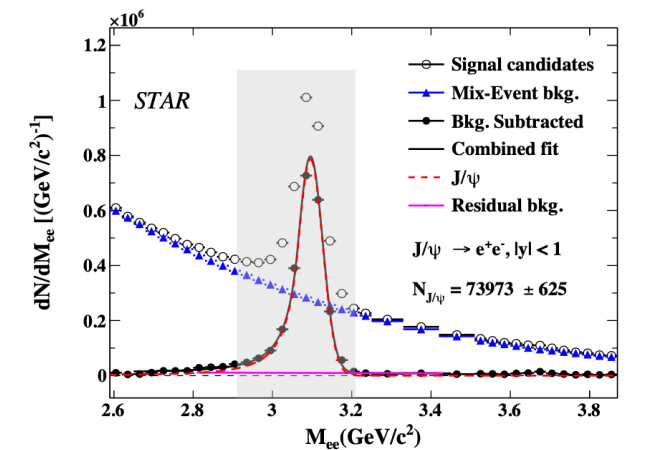
Observation charmonium sequential suppression in STAR

$\psi(2S)$ and J/ψ in Isobar collisions (using 4B MB events)

STAR: arXiv:2509.12842



- Double ratio of $\psi(2S)$ to J/ψ yield ratio between heavy-ion and p+p collisions below unity (5.6σ)
- Evidence that sequential suppression of charmonium at RHIC energy



What We Learned

Observed different manifestations of parton energy loss in QGP medium

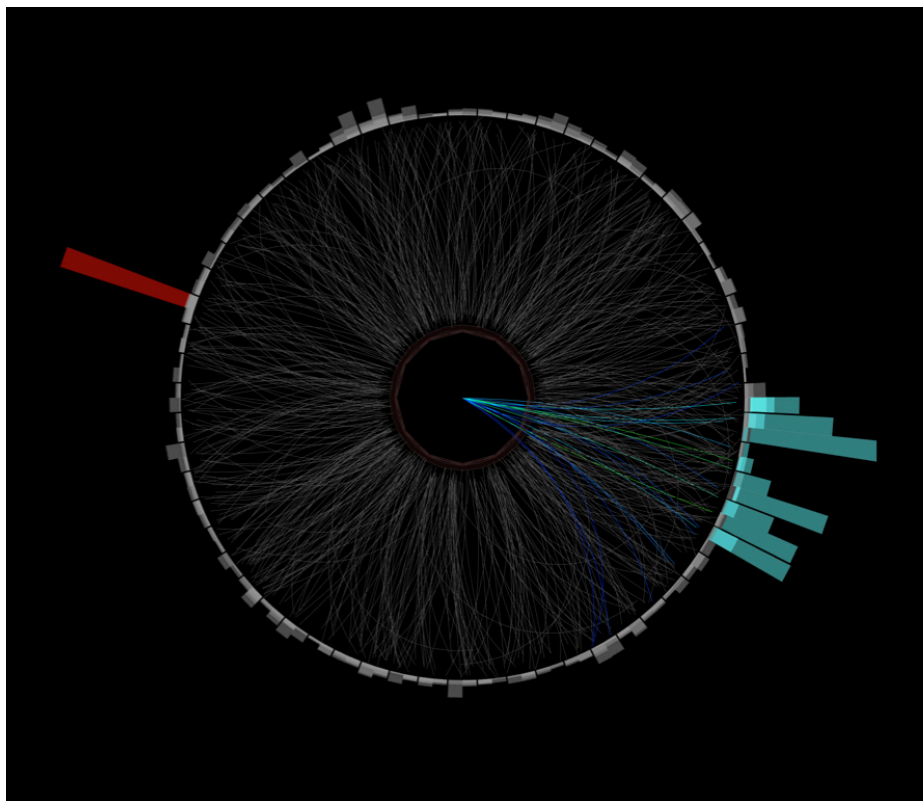
- Jet energy loss, intra-jet broadening, and jet acoplanarity

Observed sequential suppression of charmonia

- $\psi(2S)$ and J/ψ suppression

STAR's ongoing Hard Probes measurements

STAR experiment
25-years operation



Thank you!

Last Run25 Au+Au ongoing
Forthcoming precision measurements with
high luminosity data for Hard Probes

