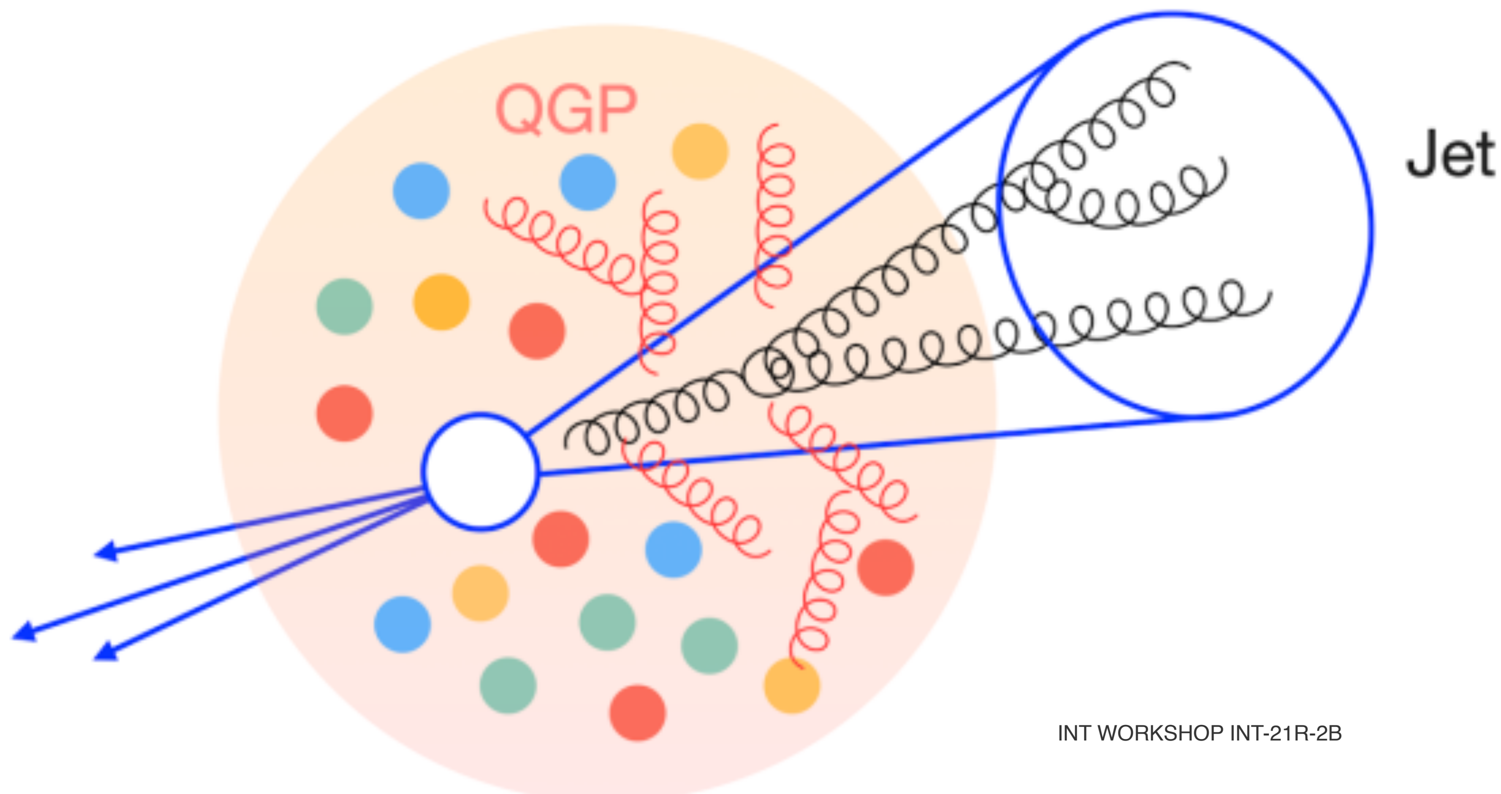
Jet quenching in heavy-ion collisions at RHIC and LHC

[What have we observed and learned so far?]

Nihar Ranjan Sahoo (IISER Tirupati)

Jan 13 – 16, 2025

Jet quenching in heavy-ion collisions



Jet quenching: jet-QGP interaction

- What are the different manifestations of jet quenching in heavy-ion collisions?
- What can it tell us about the QGP or finite temperature QCD?

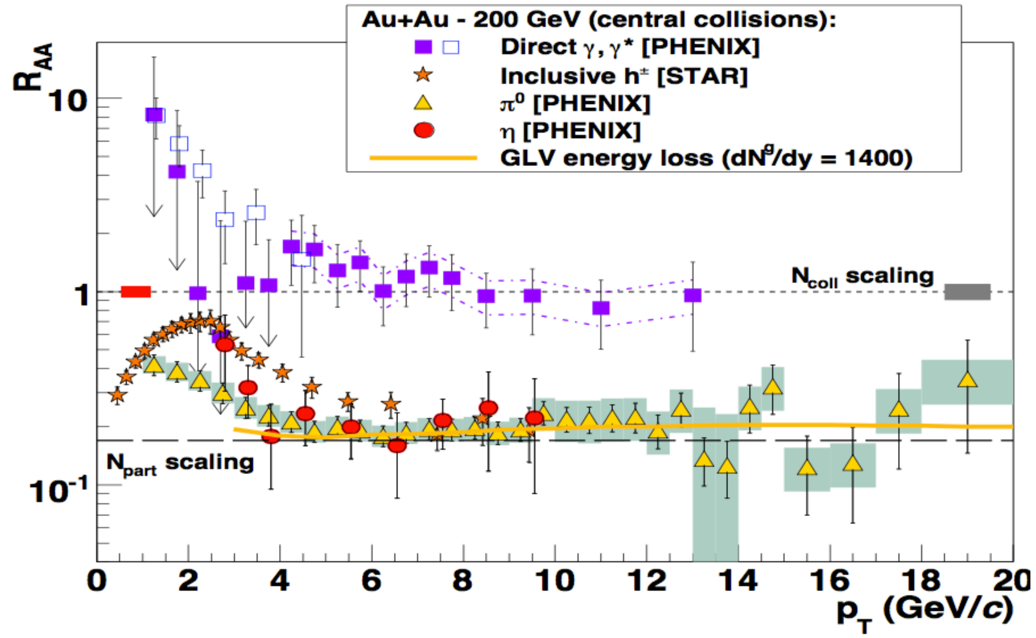
Let's revisit the early observations of jet quenching…

Jet quenching in heavy-ion collisions

Nuclear modification factor

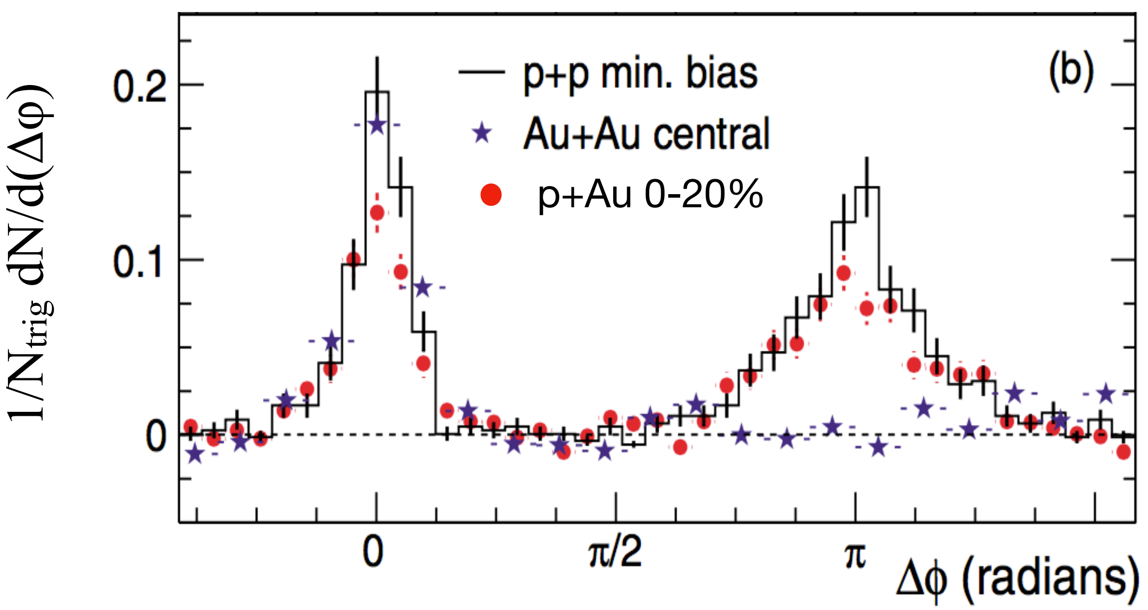
$$R_{AA} = \frac{\text{Yield}(p_T)|^{AA}}{< T_{AA} > \text{Yield}(p_T)|^{pp}}$$

PHENIX: PRC 75 (2007) 024909

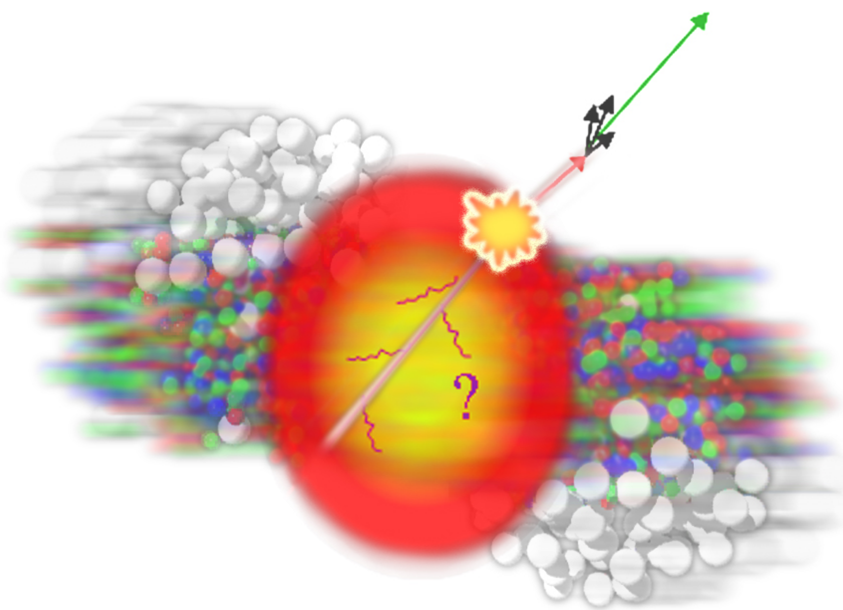


Di-hadron correlation measurements

STAR: PRL 91, 072304 (2003)



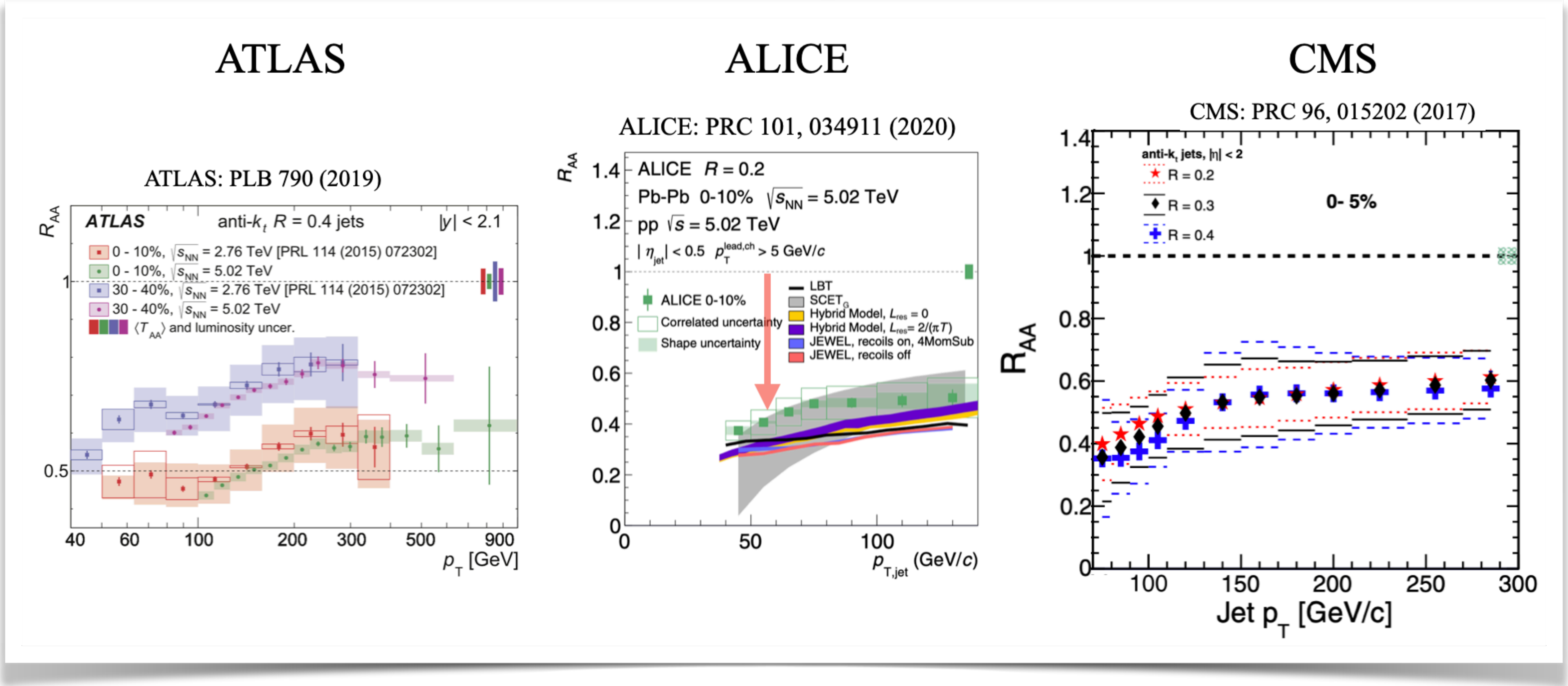
- Suppression of inclusive charged/neutral hadrons at high-p_T
- No suppression of vector boson (γ)
- Away-side jet suppression



Key signature of Quark-Gluon Plasma at RHIC

Jet quenching in heavy-ion collisions

Using jet reconstruction algorithm (Jet: a proxy of hard scattered partons q/g)



$$R_{AA} = \frac{\mathrm{Yield}(p_T)|^{AA}}{< T_{AA} > \mathrm{Yield}(p_T)|^{pp}}$$

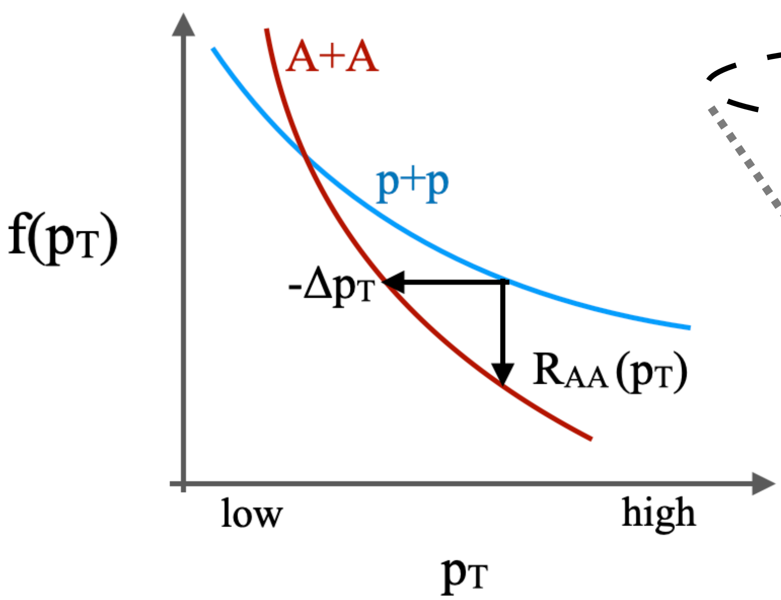
Jet quenching confirmed at LHC

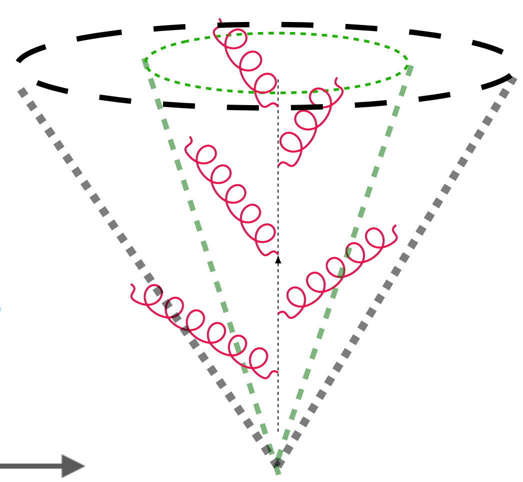
Is this an end of the story or a new beginning in QCD?

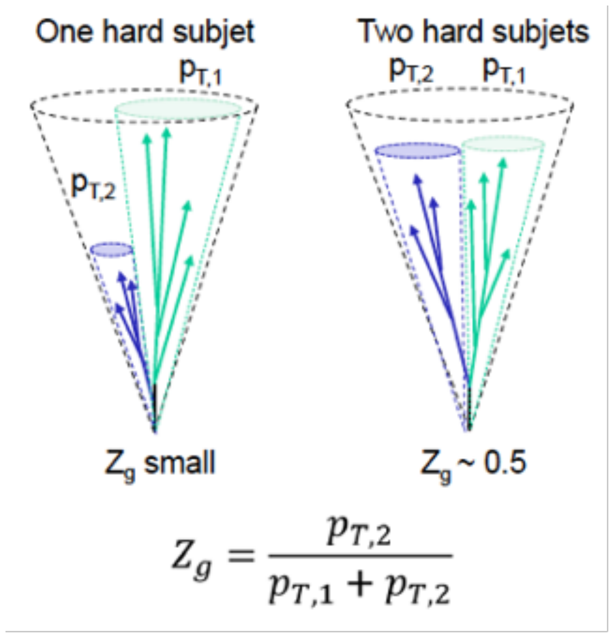
What more can we uncover about jet quenching and finite-temperature QCD?

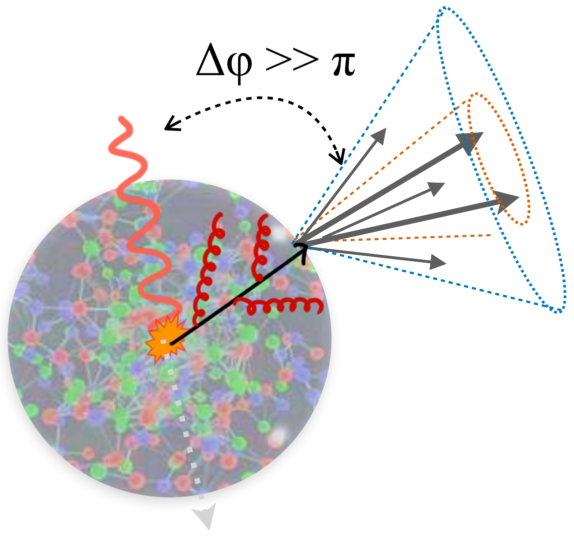
Different manifestations of jet quenching in heavy-ion collisions

Jet energy loss	Jet broadening	Modification of jet substructure	Jet acoplanarity





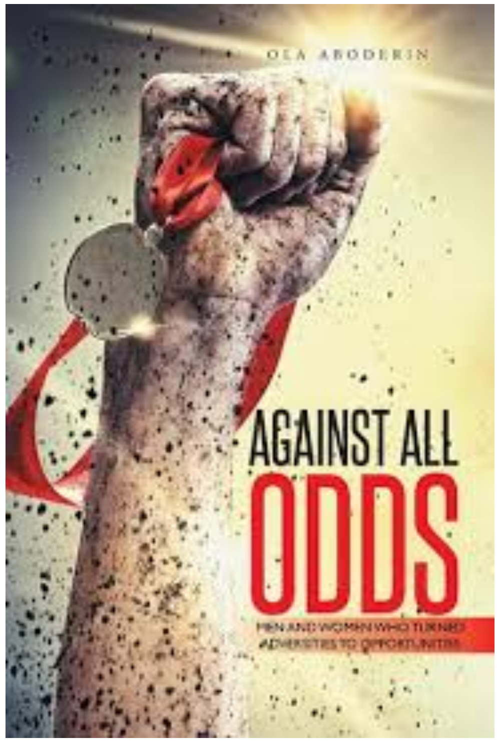




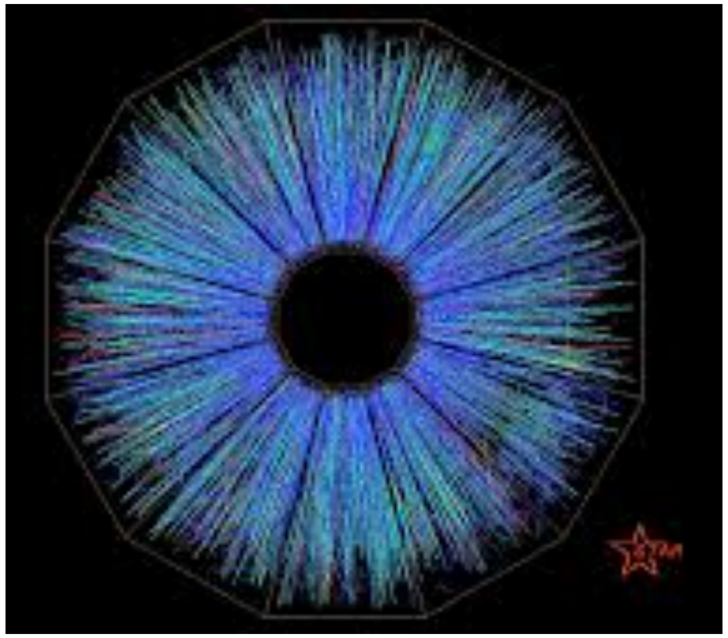
Keen to investigate the dependence of parton energy loss on

- color factor ($C_A/C_F = 9/4$), path length, and flavor (light vs. heavy)
- Effect of cold nuclear matter and vacuum radiation

What are the experimental challenges in jet quenching measurements?

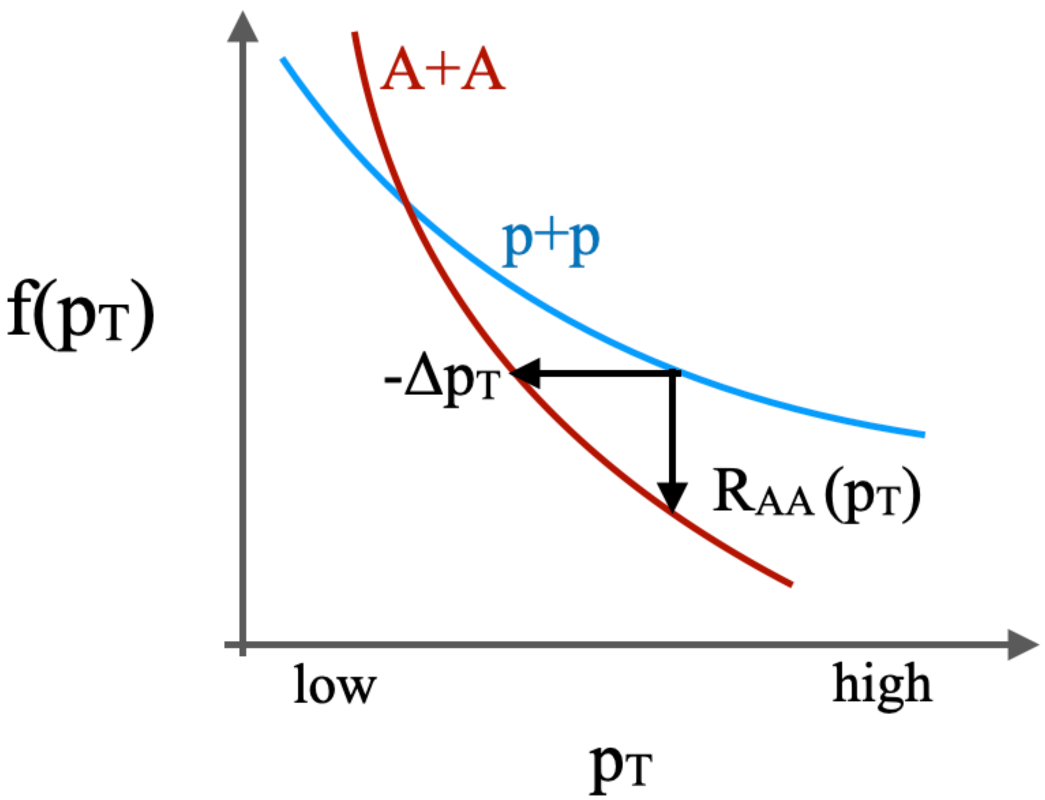


- Jet reconstruction (IRC safe algorithm, jet cone, etc)
- Uncorrelated background particles in heavy-ion collisions
- Hard-scattered high-p_T jet vs low-p_T (un)correlated jet (different origins?)
- Experimental kinematic coverage
- Correction for detector effects
- Sensitivity of certain jet observables
- Fragmentation and Hadronization effects (np-QCD effects)
- …



Despite all odds, over the years, experimentalists have addressed these challenges or mitigate their effects…

Jet energy loss

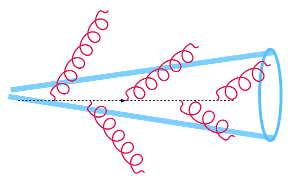


Investigation of the dependence of parton energy loss on

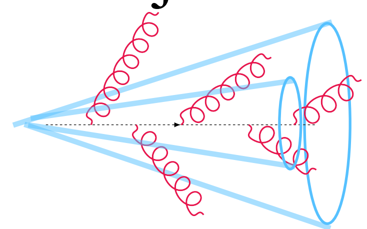
- color factor ($C_A/C_F = 9/4$)
- path length, and
- flavor (light vs. heavy)

Jet suppression: γ+jet and π^0+jet

jet R = 0.2

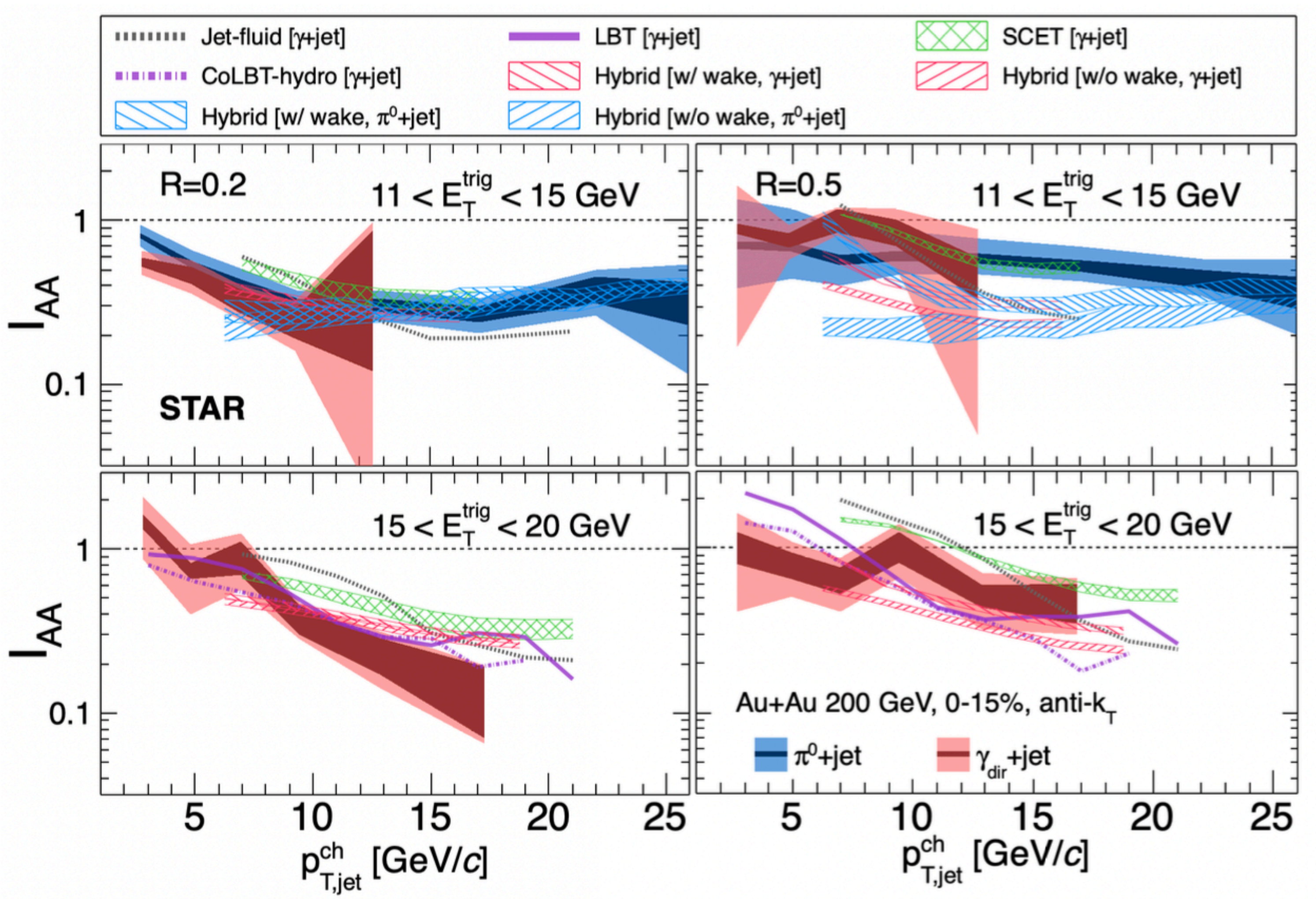


jet R = 0.5



STAR:
arXiv: 2309.00156
arXiv: 2309.00145

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



Observed jet R dependence of suppression

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

→ **Redistribution of lost energy in QGP**

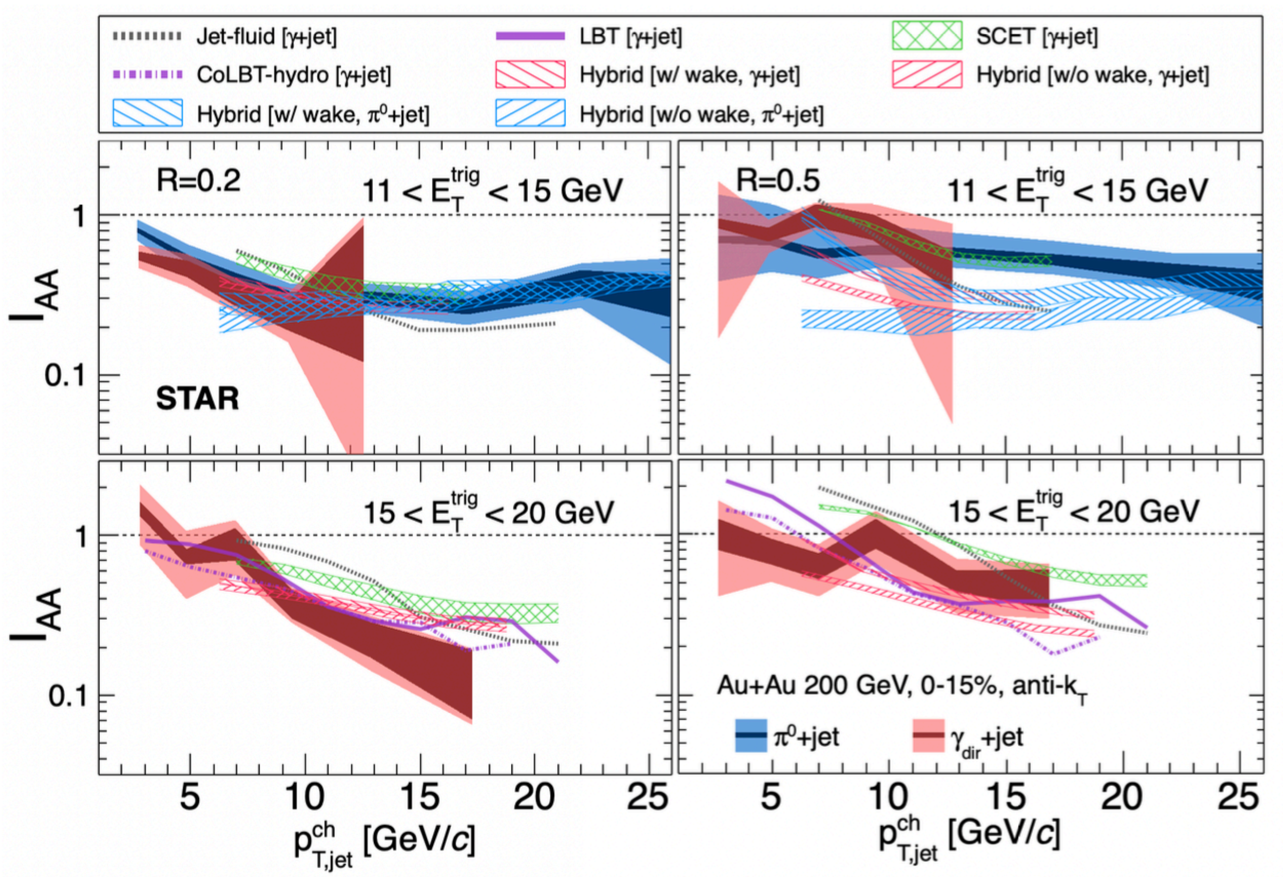
Jet suppression: γ+jet and π^0+jet

Jet suppression depends on:

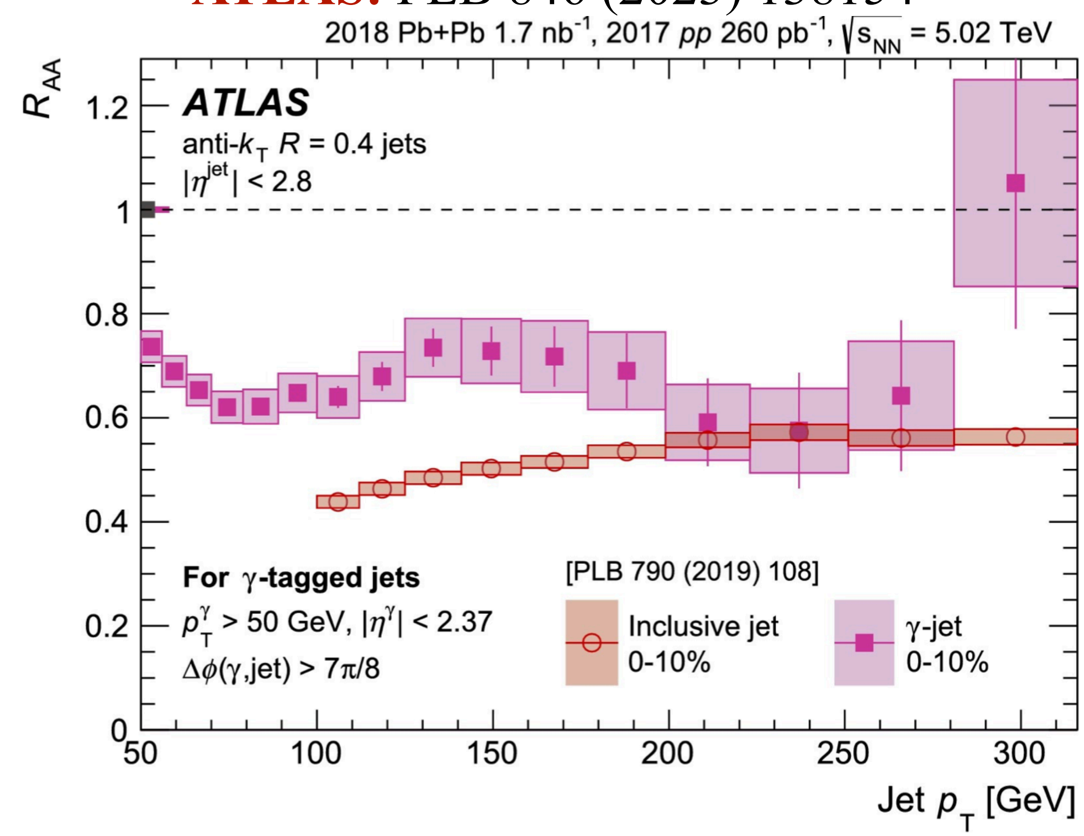
1. q/g recoil jets ($C_A/C_F = 9/4$)
2. vary recoil mean path length

RHIC vs. LHC

STAR: arXiv: 2309.00156



ATLAS: PLB 846 (2023) 138154



- RHIC: color-factor dependence of suppression not seen within uncertainty (needed precision measurement)

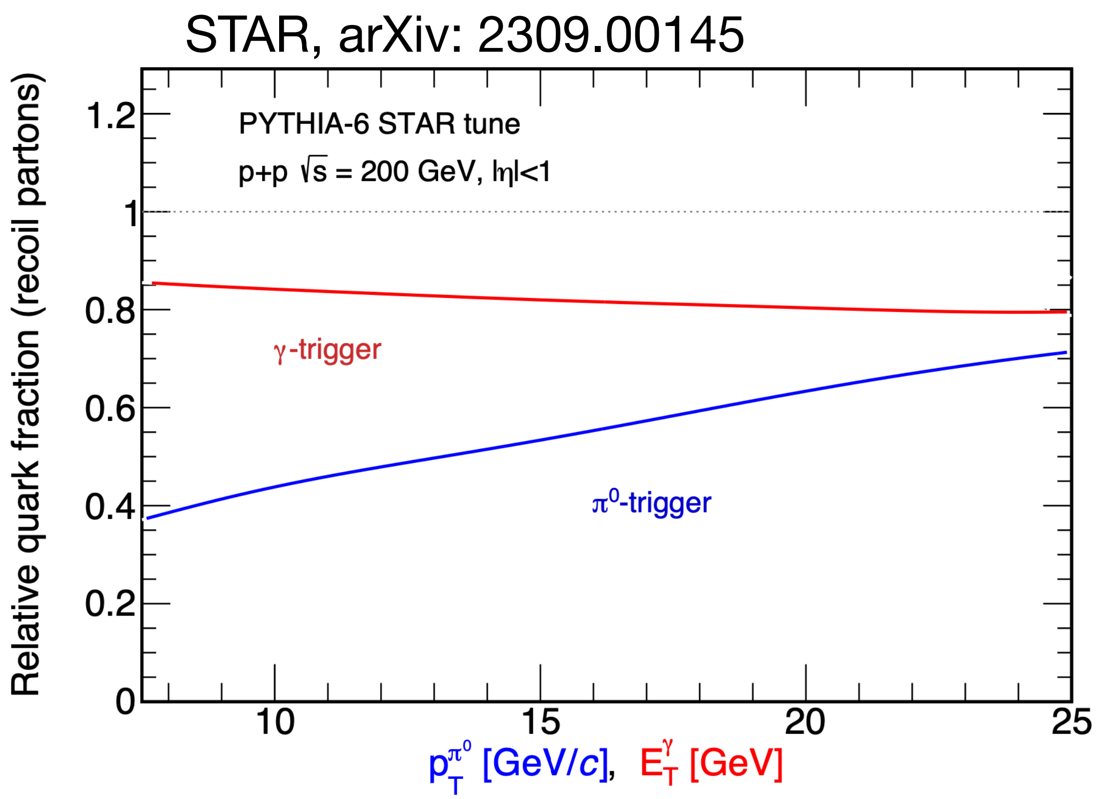
LHC: Jet energy loss sensitive to color-factor of initial parton

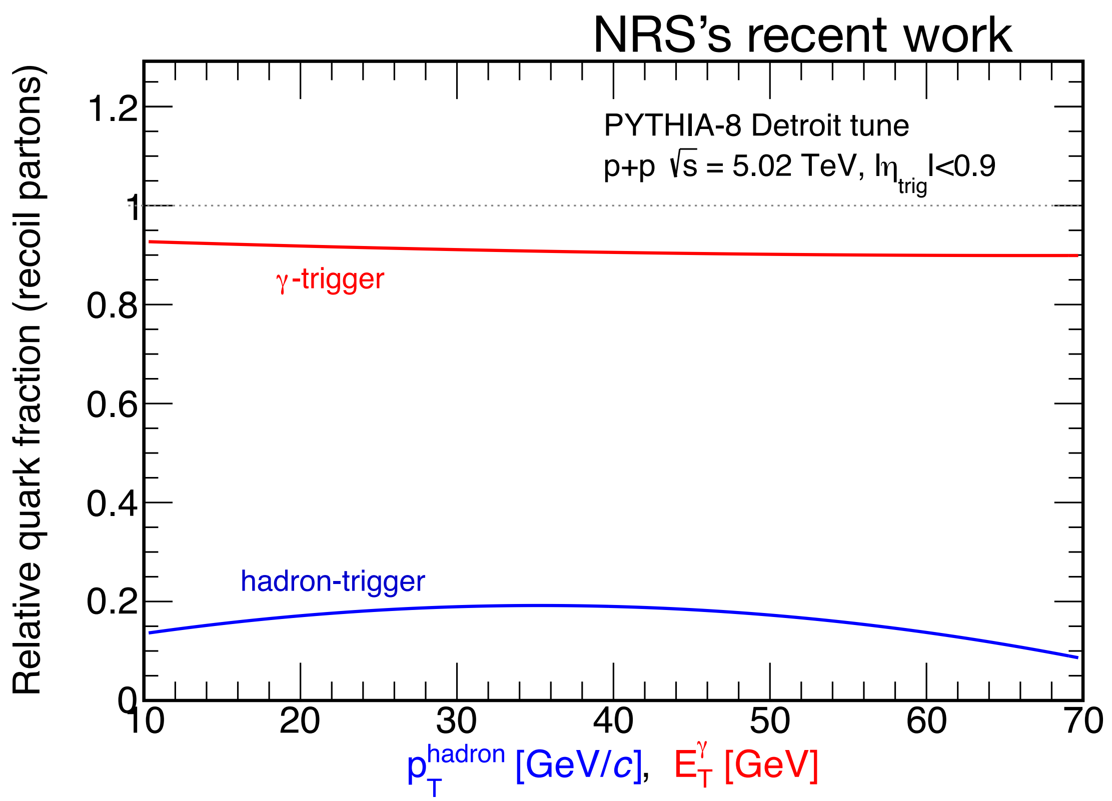
Semi-inclusive vs inclusive jet measurement?

What could be the reason…

Jet suppression: γ+jet vs. π⁰+jet/inclusive jet

RHIC vs LHC: gluon fraction dominates at LHC energy [PYTHIA study]



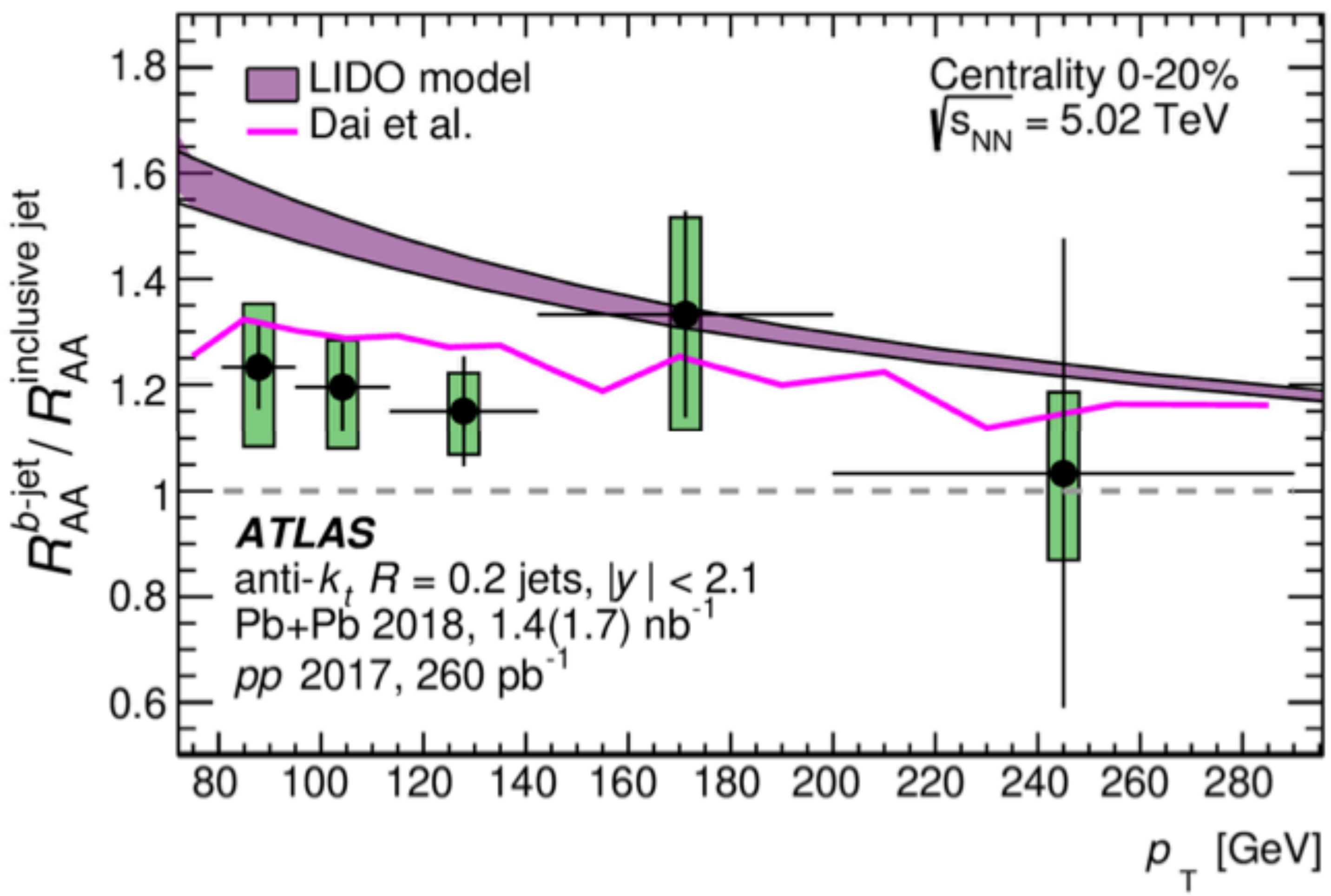


At LHC, gluon jet dominates (Run-3 data)

Additionally, precision measurement is needed at RHIC (Run23-25 data)

Flavour dependence of parton energy loss

b-jet vs. inclusive jet measurement



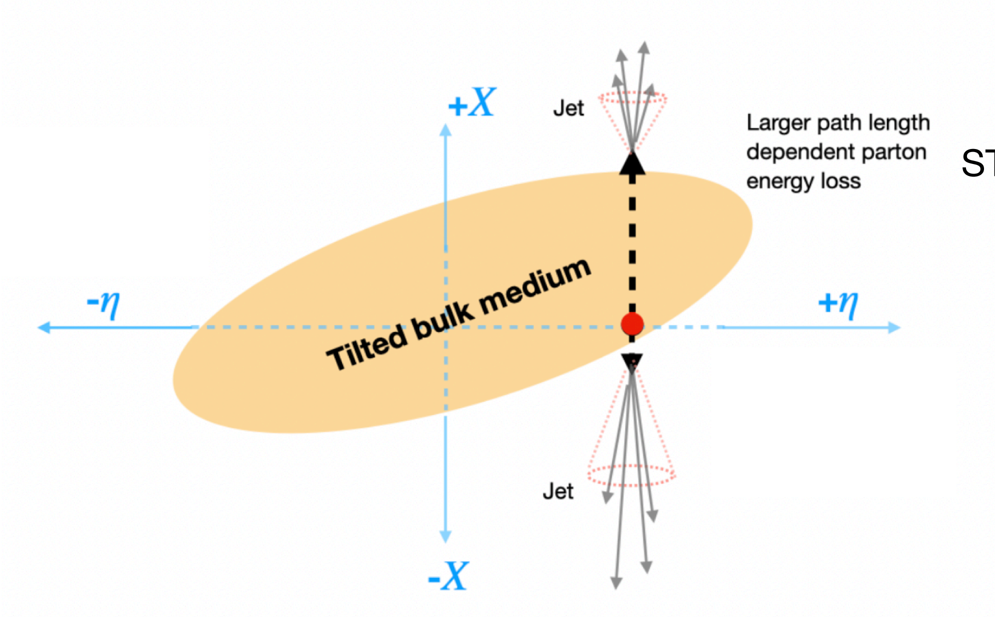
b-jets tagged by requiring a muon within jet cone

Relatively large suppression of heavy flavour compare to lighter

Double ratio between b-jet and inclusive jet R_{AA}

→ b-jet 20% less suppressed than inclusive jet

Path length dependence of jet energy loss



- **In mid-central collisions, large D^0 v_1 observed than bulk v_1**

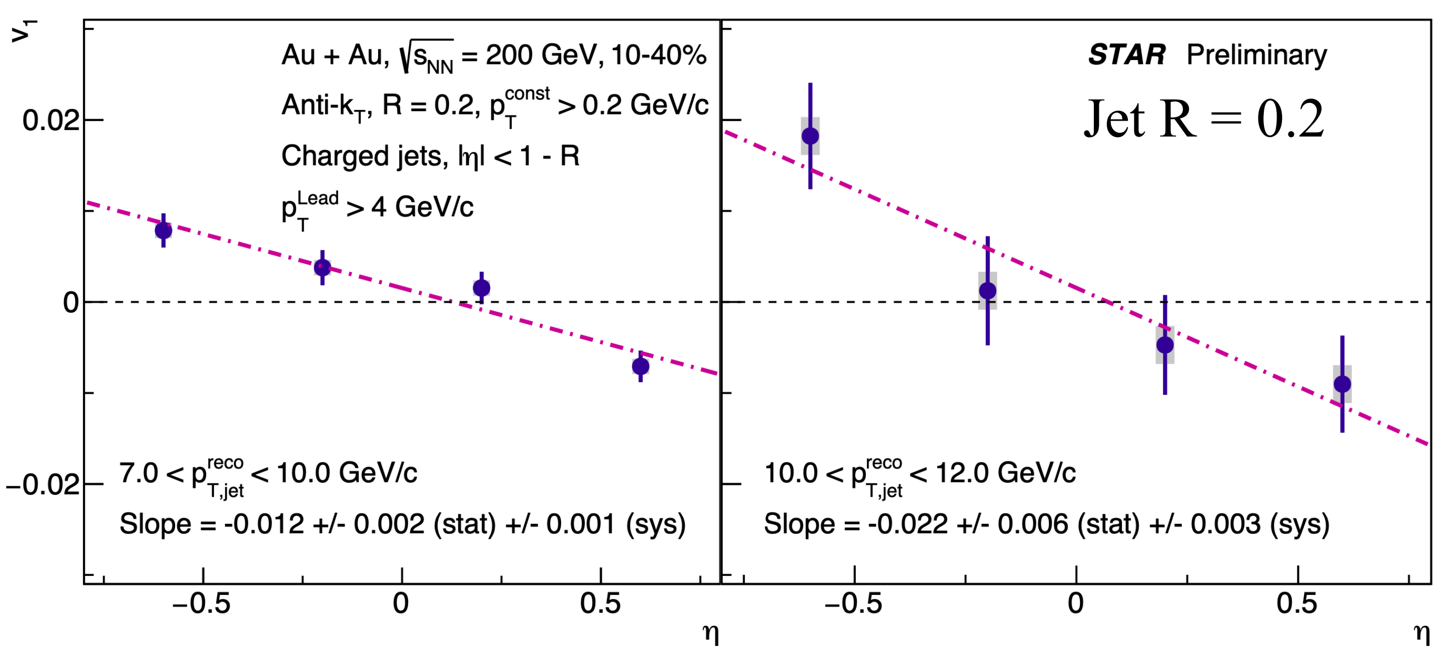
STAR D0: Phys. Rev. Lett. 123, 162301 (2019), S. Chatterjee et al. Phys. Rev. Lett. 120, 192301 (2017)

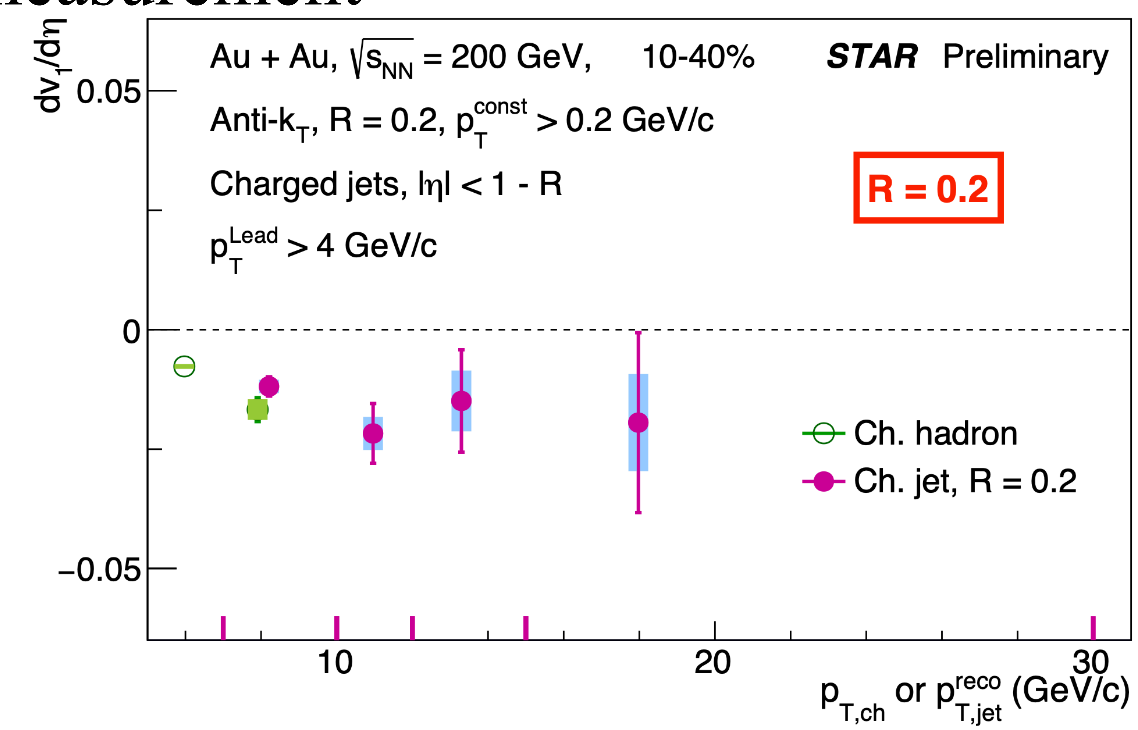
- **No asymmetry for hard production from binary n-n scattering**

M. Gyulassy et al. Phys. Rev. C 72, 034907, (2005)

$$v_1 = \langle \frac{p_x}{p_T} \rangle$$

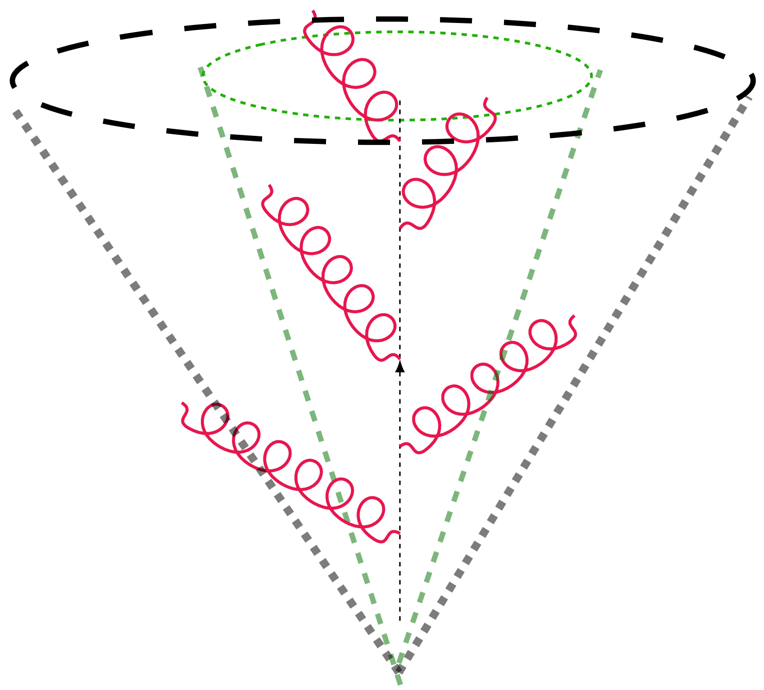
Recent STAR measurement





- Mean momentum asymmetry = 0.232 +/- 0.068 (stat) +/- 0.03 (sys) GeV/c for R = 0.2
- Related to path length dependence of jet energy loss

Jet broadening

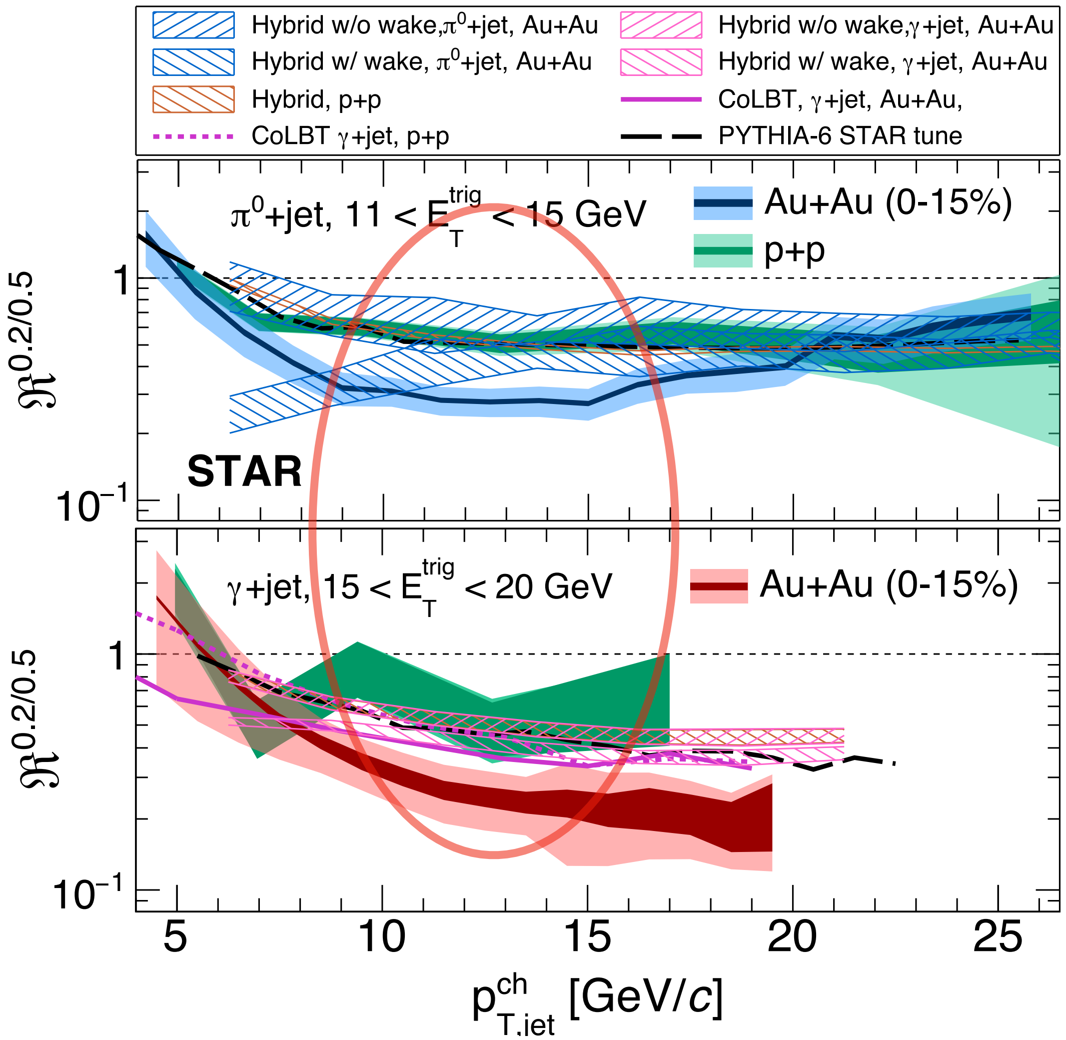


Vacuum radiation + in-medium gluon radiation

Intra-jet broadening in heavy-ion collisions: RHIC and ALICE

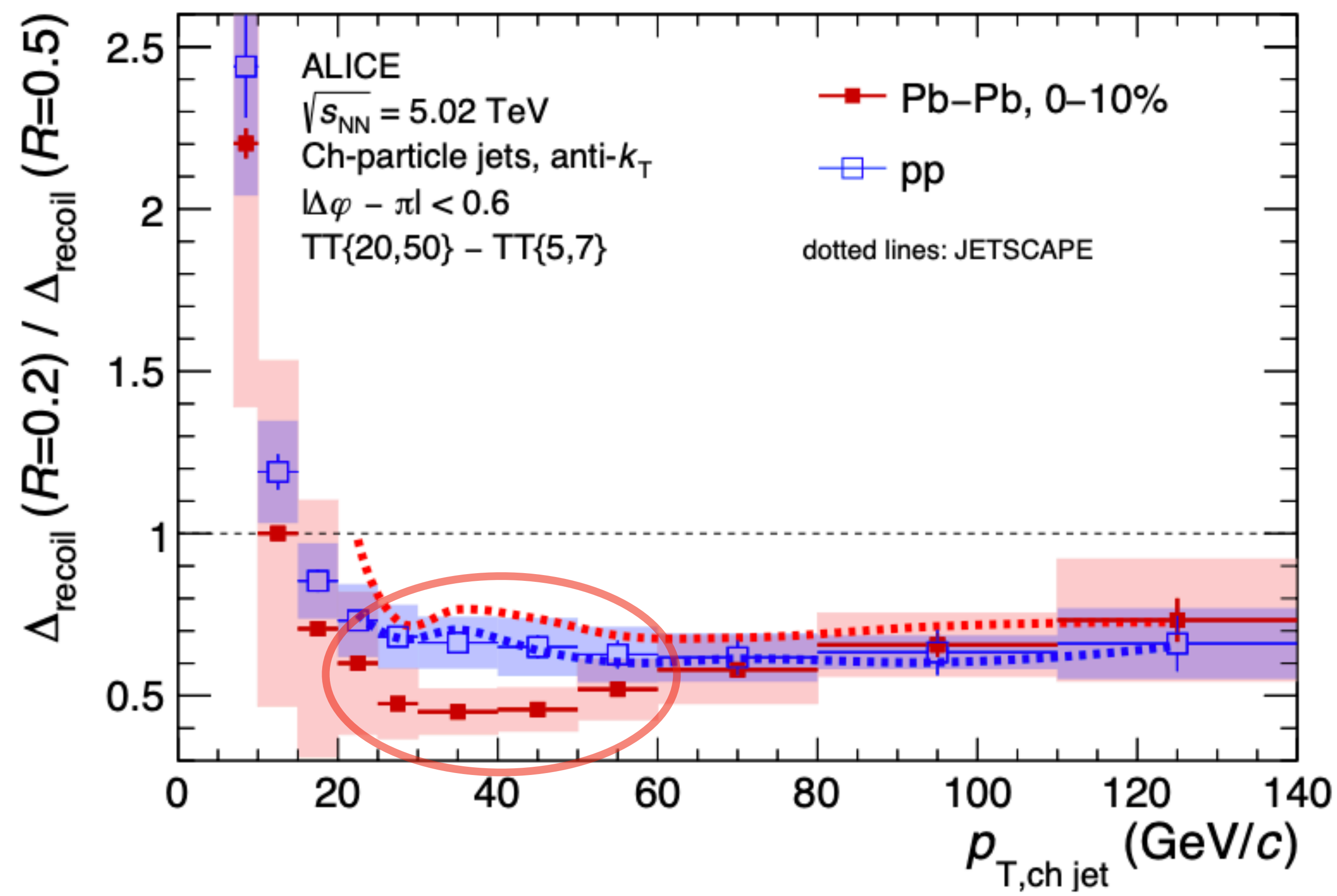
arXiv: 2309.00156

STAR: γ+jet and π^0+jet in Au+Au and p+p



PRL 133 (2024) 2, 022301

ALICE: h+jet in Pb+Pb and p+p

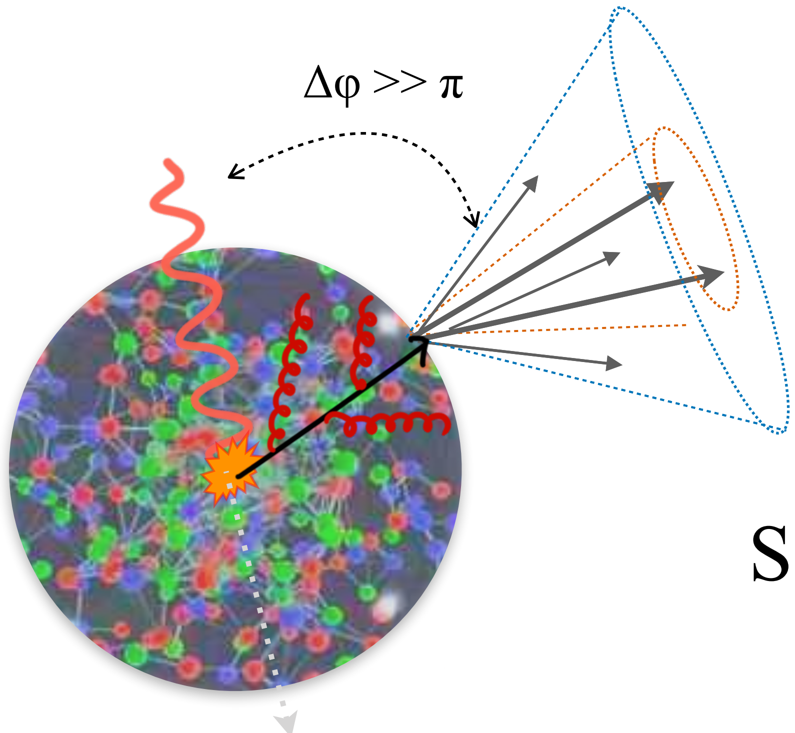


$$\mathfrak{R}^{\frac{\text{small}-R}{\text{large}-R}} = \frac{\mathrm{Y}(p_{\mathrm{T}}^{\text{jet,ch}})^{\text{small}-\mathrm{R}}}{\mathrm{Y}(p_{\mathrm{T}}^{\text{jet,ch}})^{\text{large}-\mathrm{R}}}$$

- Similar intra-jet broadening observation at STAR and ALICE
- Different uncorrelated background correction methods

Can we see such effects in pA collisions?

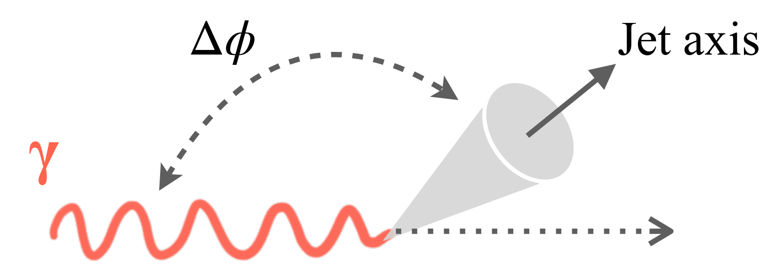
Jet acoplanarity



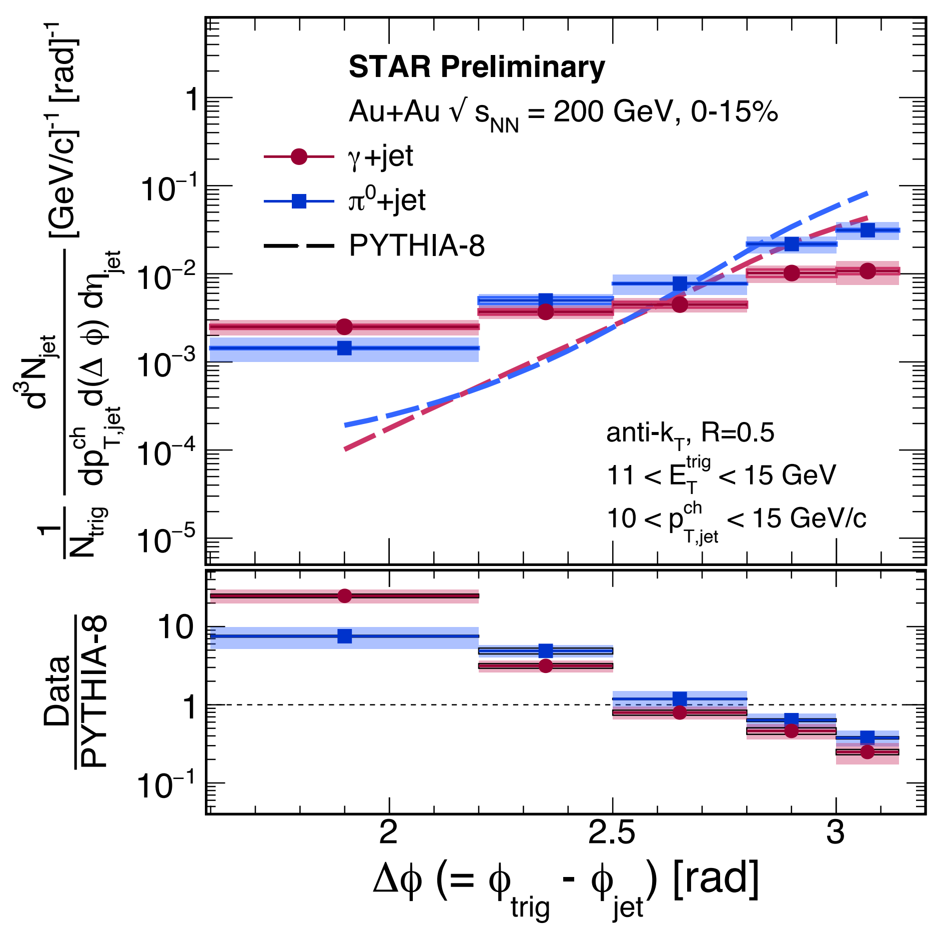
Search for quasi-particle scattering in QGP

Rutherford/Moliere scattering vs. diffusion wake (effect of medium response)

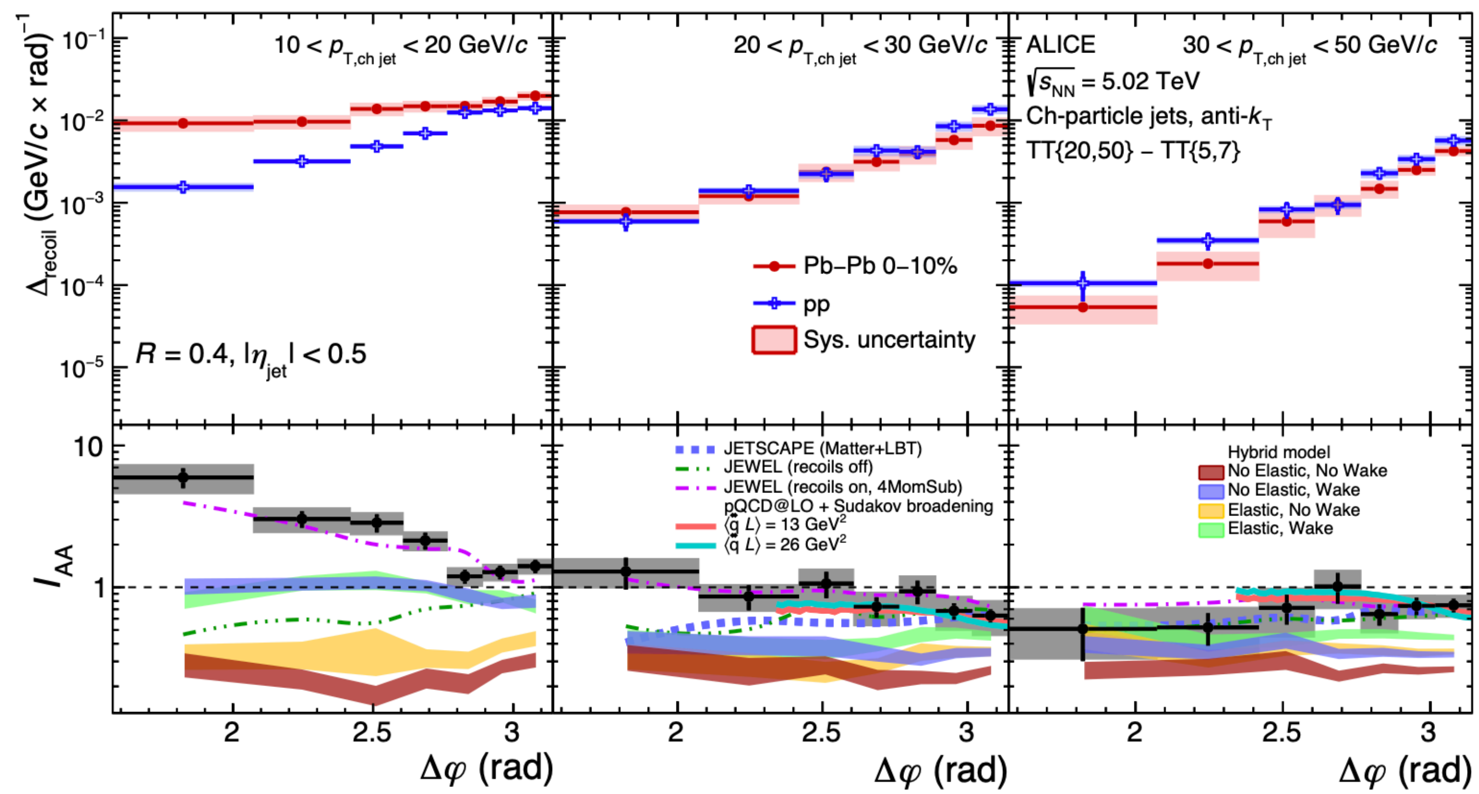
Jet acoplanarity measurement at STAR and ALICE



STAR: γ+jet and π⁰+jet [manuscript in preparation]



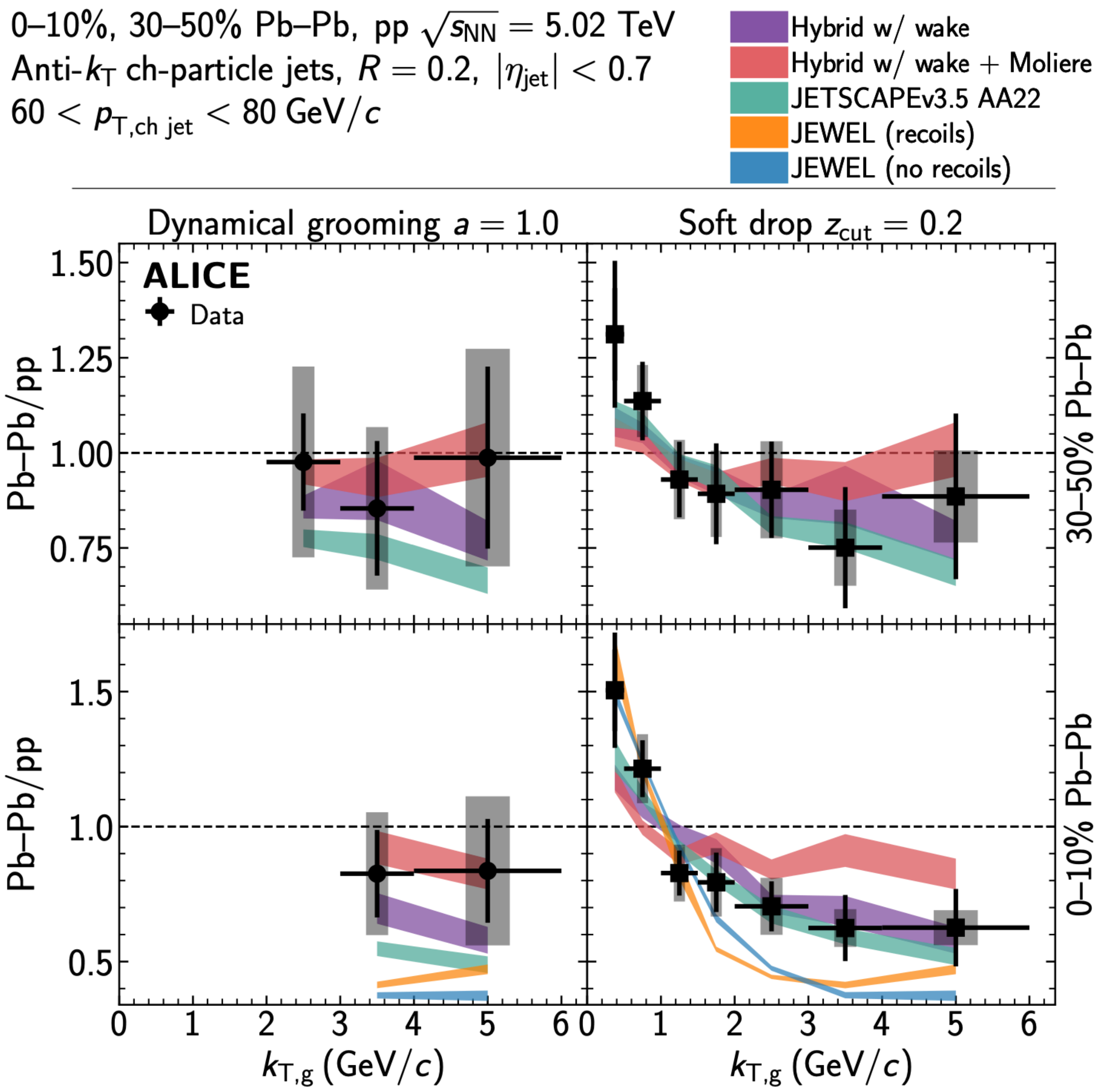
ALICE: h+jet *PRL* 133 (2024) 2, 022301



- Two independent measurements with two different methods show the same results
- Shows recoil jet p_T and R dependence
- Diffusion wake vs. quasi-particle picture? Need further study…
- Further study is ongoing to understand: RHIC/LHC

ALICE measurement: using jet substructure

ALICE: arXiv: 2409.1283



$$z > z_{cut}(\Delta R/R)^{\beta}$$

$$\kappa \propto z(1-z)p_{T,split}(\Delta R/R)^{a}$$

$$k_T = p_{T,subleading}\sin\Delta R$$

After SoftDrop (SD) or dynamical grooming (DyG),

$$k_T \rightarrow k_{T,g}$$

Allowing only hard splittings inside jet

SD shows modification in PbPb relative to pp at high $k_{T,g}$

Does jet quenching mask the Moliere scattering?

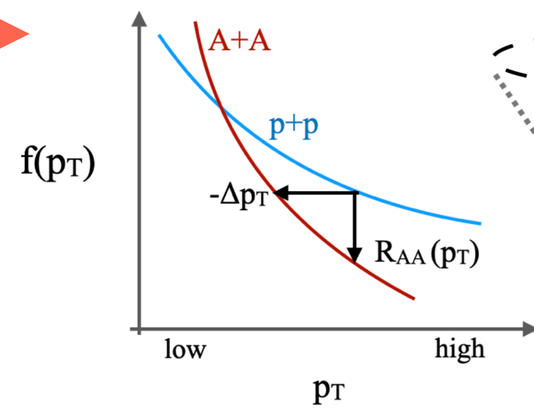
Let’s summarise…

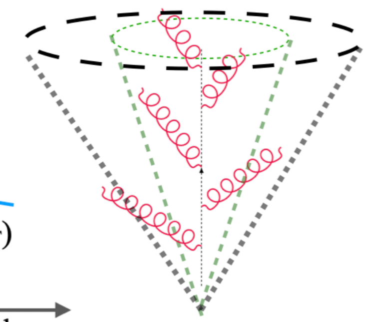
What have we learned from jet quenching measurements so far?

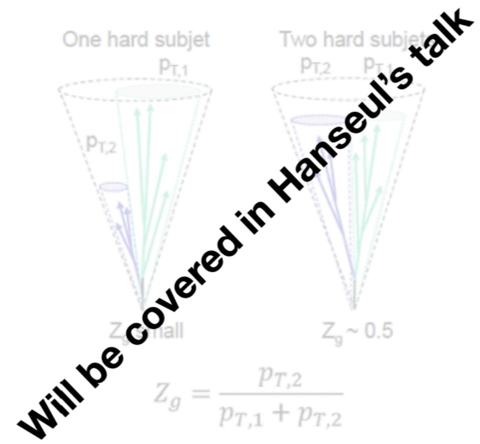
Different manifestations of jet quenching in heavy-ion collisions

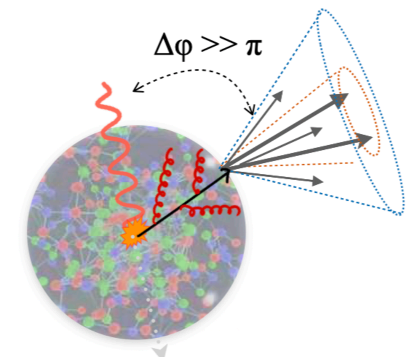
Explored and observed all in recent measurements

Jet energy loss	Jet broadening	Modification of jet substructure	Jet acoplanarity









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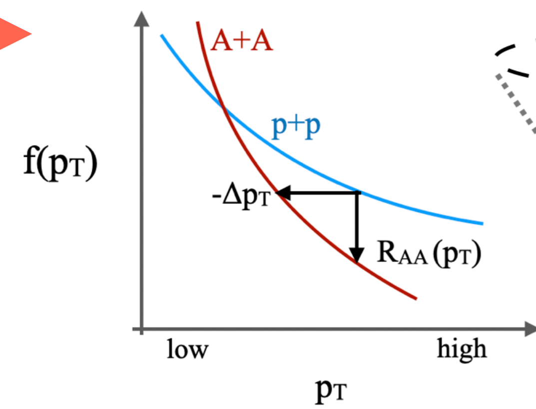

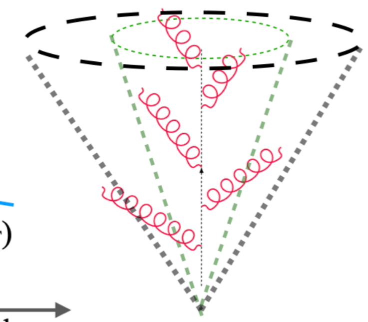

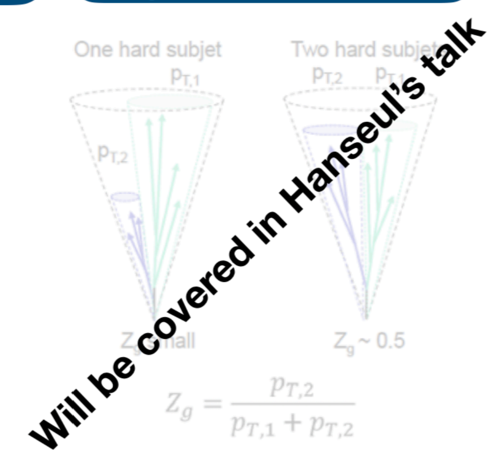

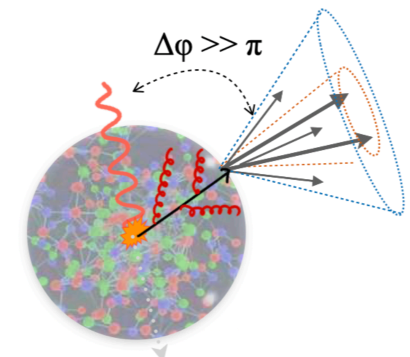

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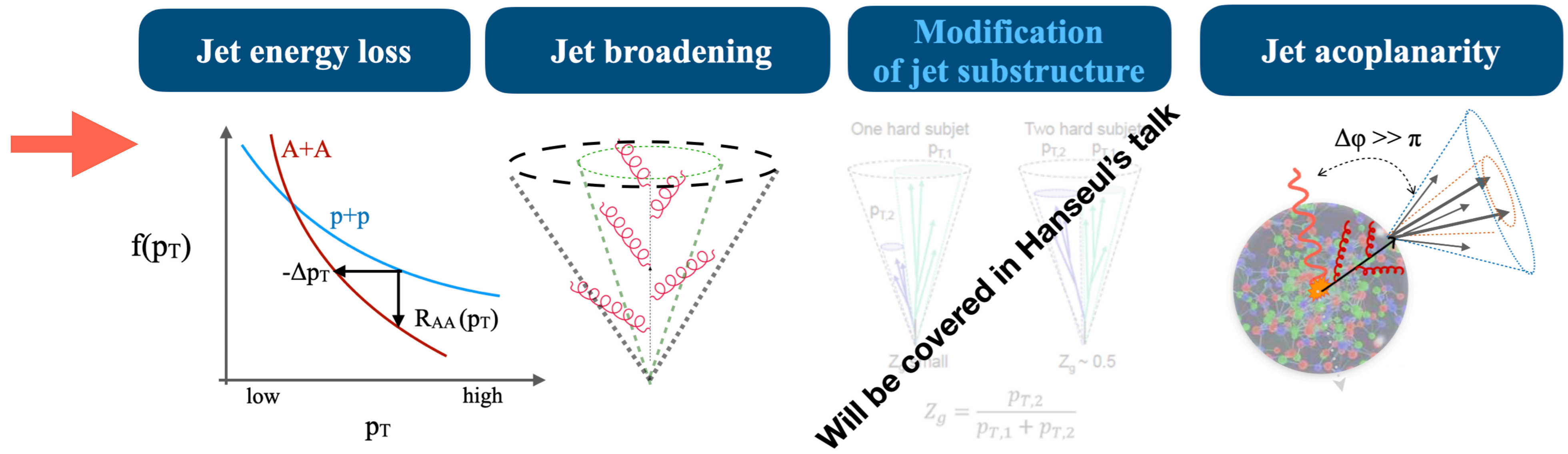

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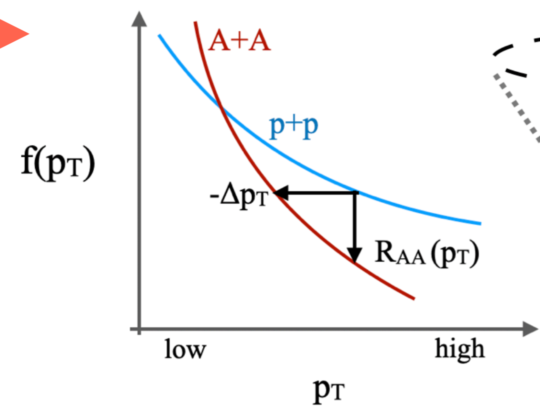

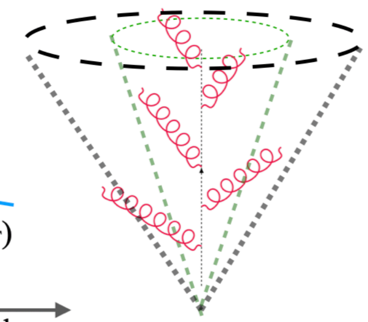

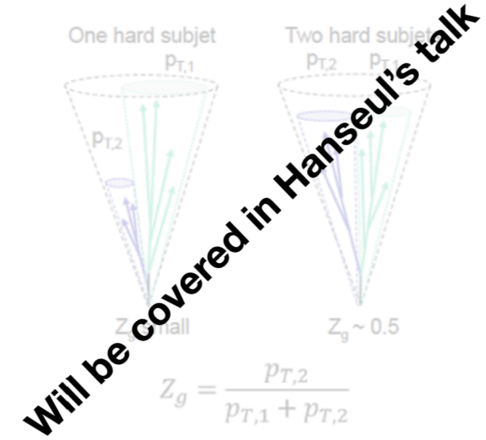

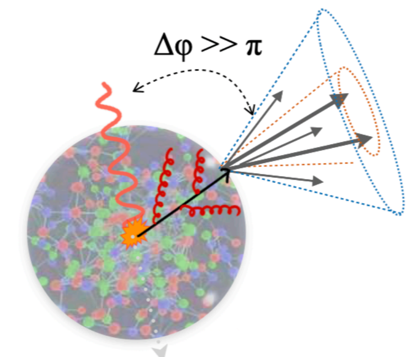

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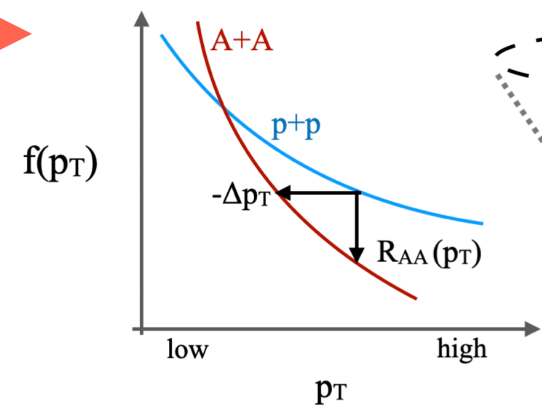
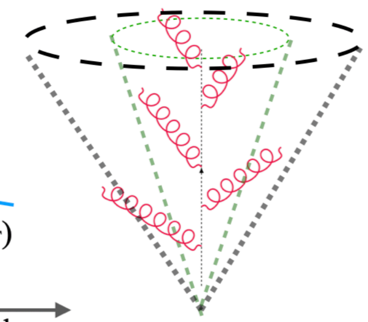
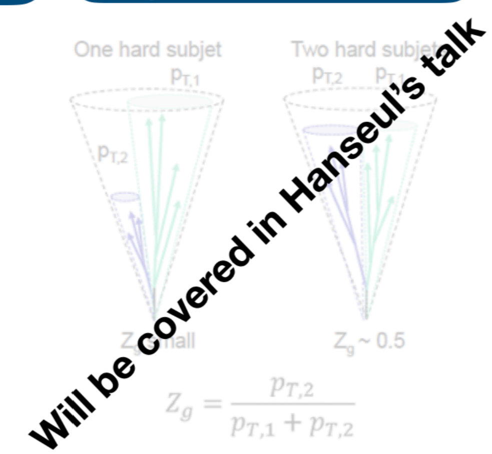


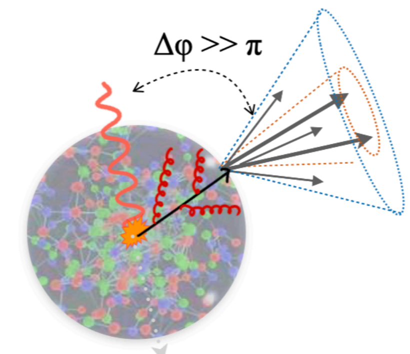
Jet broadening



Modification of jet substructure



Jet acoplanarity



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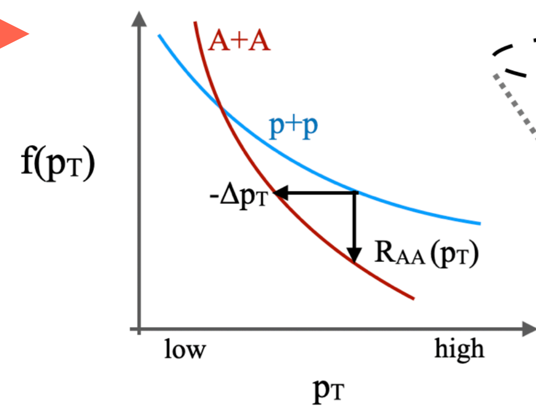

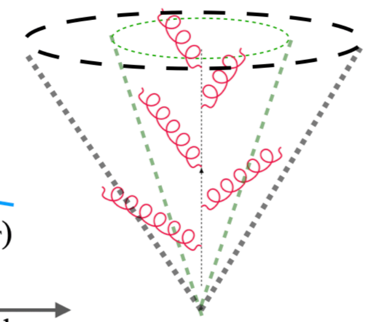

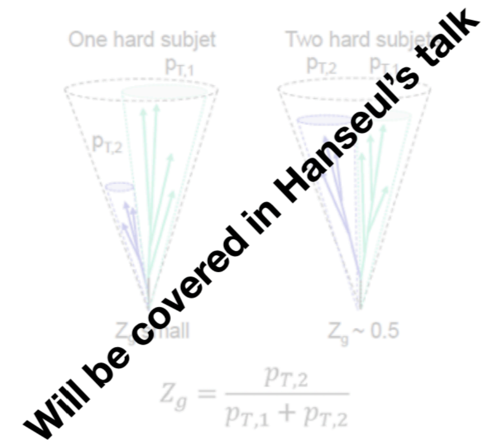

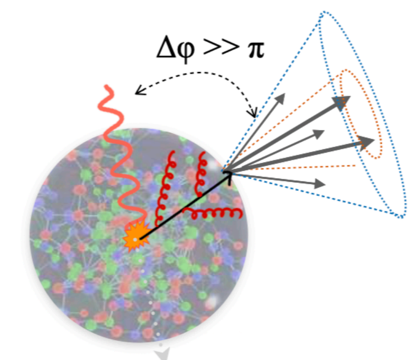

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5. **Potential New Physics**: Possibility of uncovering new physics or phenomena in QCD through continued exploration using different experimental techniques and methods

Announcement and promotion…

ICTS INTERNATIONAL CENTRE *for* THEORETICAL SCIENCES

TATA INSTITUTE OF FUNDAMENTAL RESEARCH

10 days School

"Hard probes in non-equilibrium QCD matter"

Mar 16-27, 2026

Topics:

1. Heavy flavor (Lattice QCD, theory, experiment)
2. Jet and jet quenching (theory and experiment)
3. Bayesian inference and ML

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Organizers:

Santosh Das (IIT-Goa)

Sayantan Sharma (IMSC, Chennai)

Nihar Ranjan Sahoo (IISER-Tirupati)

Total 26 Students/postdocs (Accommodation and meals will be provided and no registration fee)

New IISER Tirupati Campus

Thank you