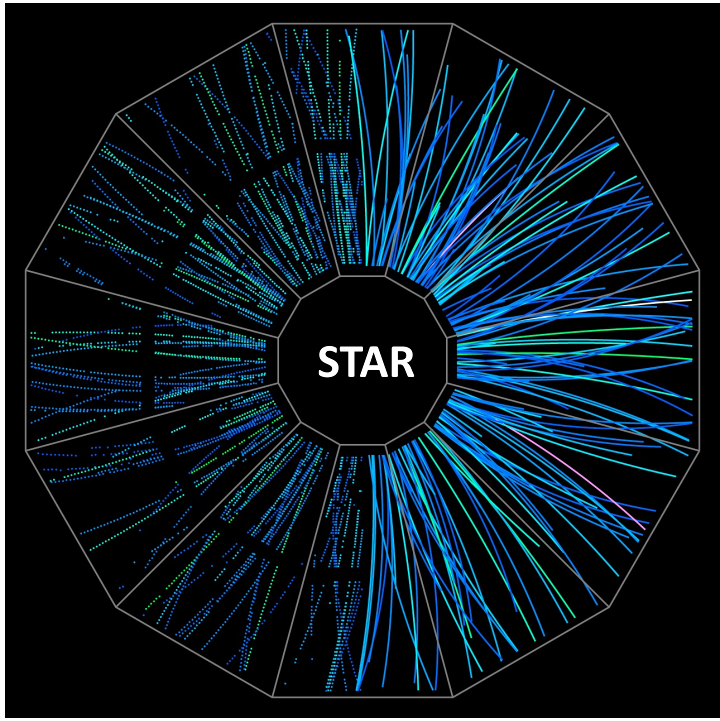
Recent Jet Measurements at STAR

Diptanil Roy
(*On behalf of the STAR Collaboration*)
Rutgers University
roydiptanil@gmail.com



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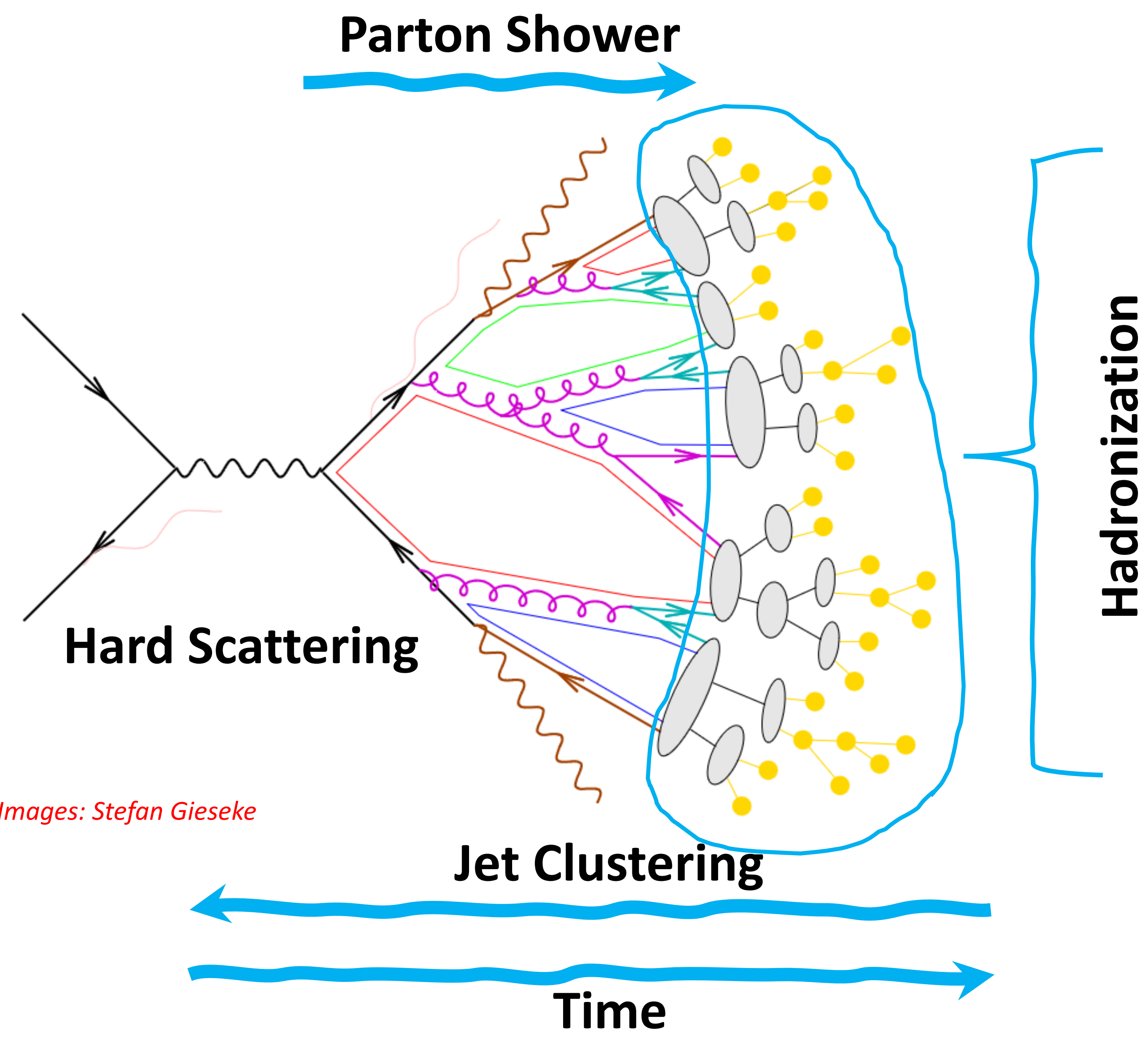
Introduction: Jets in Vacuum

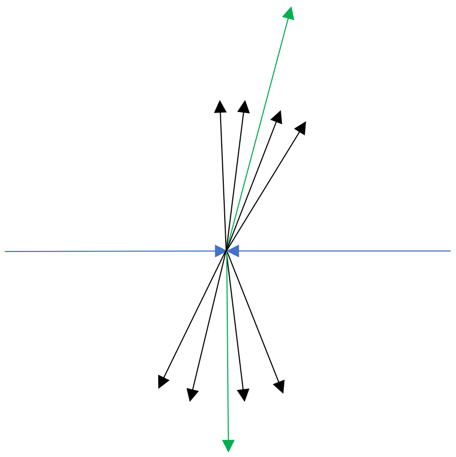


- Proxies for hard scattered partons
- Production rate calculable by pQCD
- Clustering algorithms use final state particles to reconstruct jets
- Jet substructure holds information about fragmentation and hadronization processes

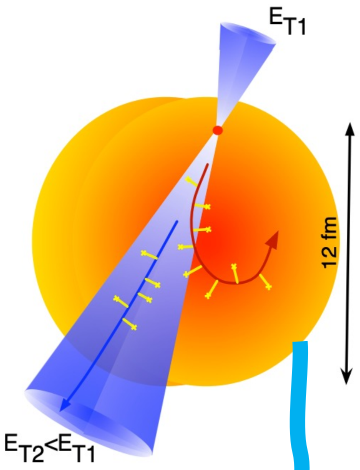
Can we disentangle perturbative and non-perturbative physics in vacuum?

Do jet substructures differ due to quark-like or gluon-like jets?

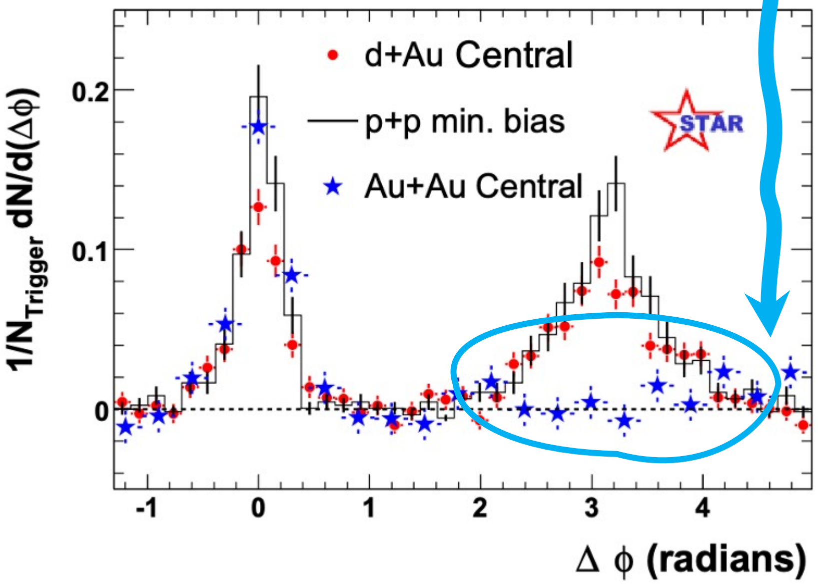
Introduction: Jets in Heavy Ion Collisions



p + p



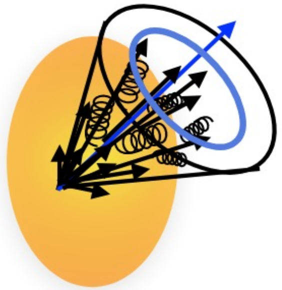
A + A



Elastic collisions (collisional)

Images: Laura Havener,

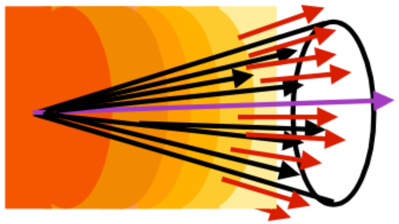
Multiple Scattering



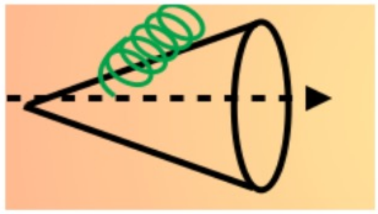
Wide-angle Scattering

Inelastic collisions (radiative)

Medium Response



Medium-induced Splitting



Is jet yield suppression system size and geometry dependent?

Does the medium change the chemistry of the hard scattered jets?

The STAR Detector

Beam-beam counter (BBC)

- ✓ Trigger detector in the forward region

Time Projection Chamber (TPC)

- ✓ Measures momenta of charged tracks
- ✓ $|\eta| < 1, 0 < \phi < 2\pi$
- ✓ PID using dE/dx

Barrel Electromagnetic Calorimeter (BEMC)

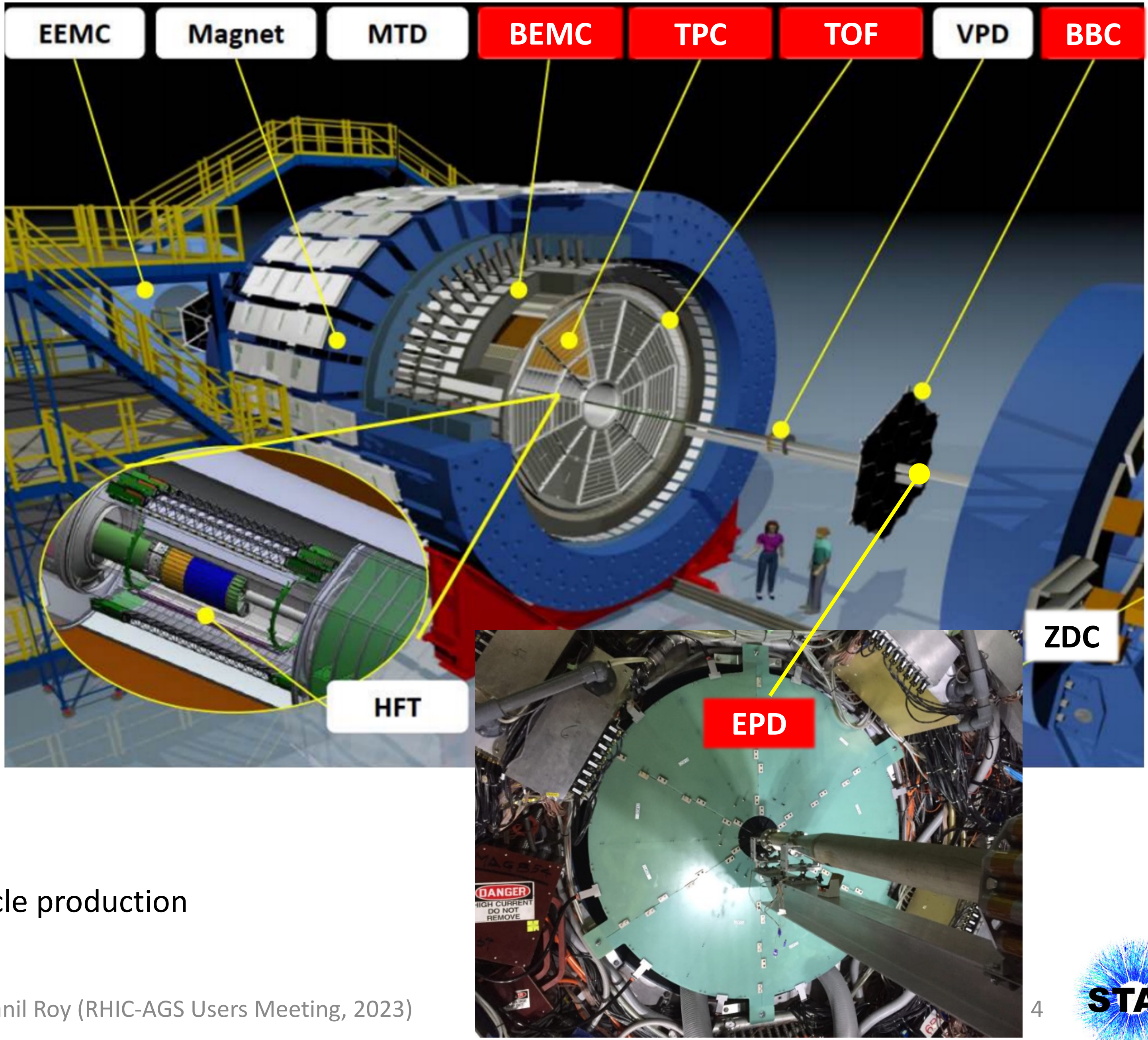
- ✓ Measures neutral component of jet energy
- ✓ $|\eta| < 1, 0 < \phi < 2\pi$

Time-Of-Flight (TOF)

- ✓ PID using TOF measurement
- ✓ $|\eta| < 1, 0 < \phi < 2\pi$

Event Plane Detector (EPD)

- ✓ Estimates event-plane by measuring charged particle production
- ✓ $2.14 < |\eta| < 5.09$



Isolating perturbative and non-perturbative physics in vacuum(p-p) jets

SoftDrop: Groom a reconstructed jet to remove soft wide-angle radiation

[Hard Probes 2023]

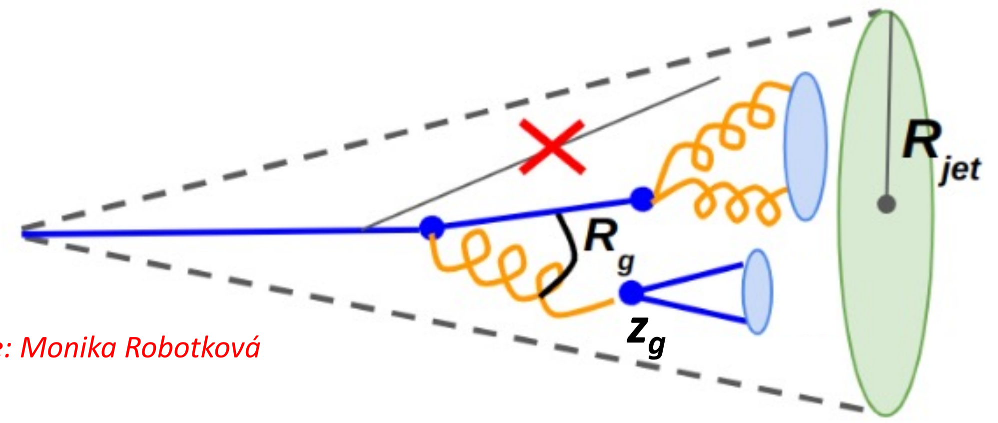


Image: Monika Robotková

Grooming condition: Require subjet momentum fraction to pass

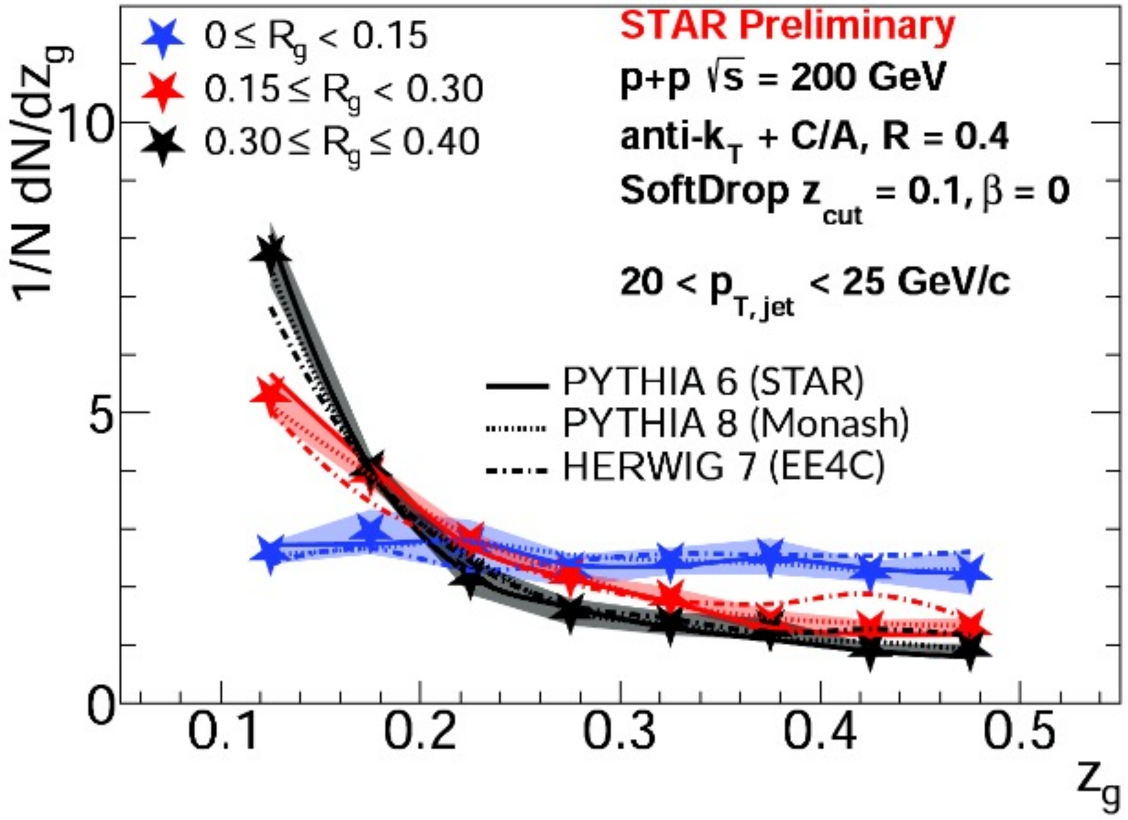
$$z_g = \frac{\min(p_{T,1}, p_{T,2})}{p_{T,1} + p_{T,2}} > z_{cut}(R_g/R_{Jet})^{\beta}$$

$$z_{cut} = 0.1$$

$$\beta = 0$$

z_g = Shared Momentum Fraction

R_g = Distance of subjets at first split

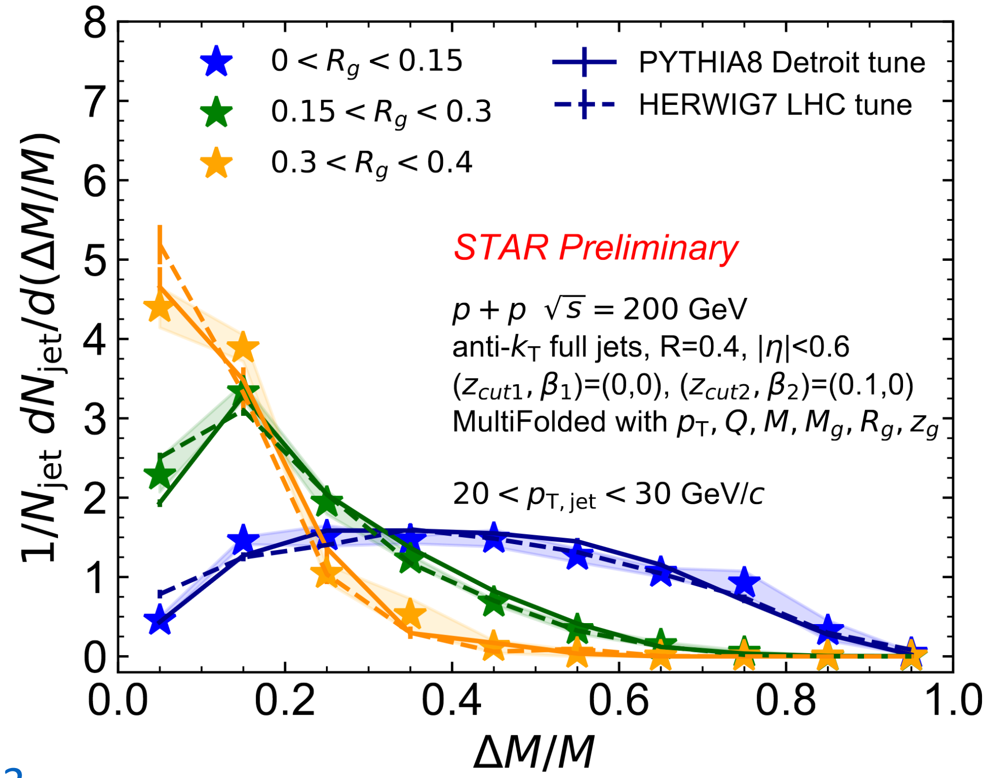


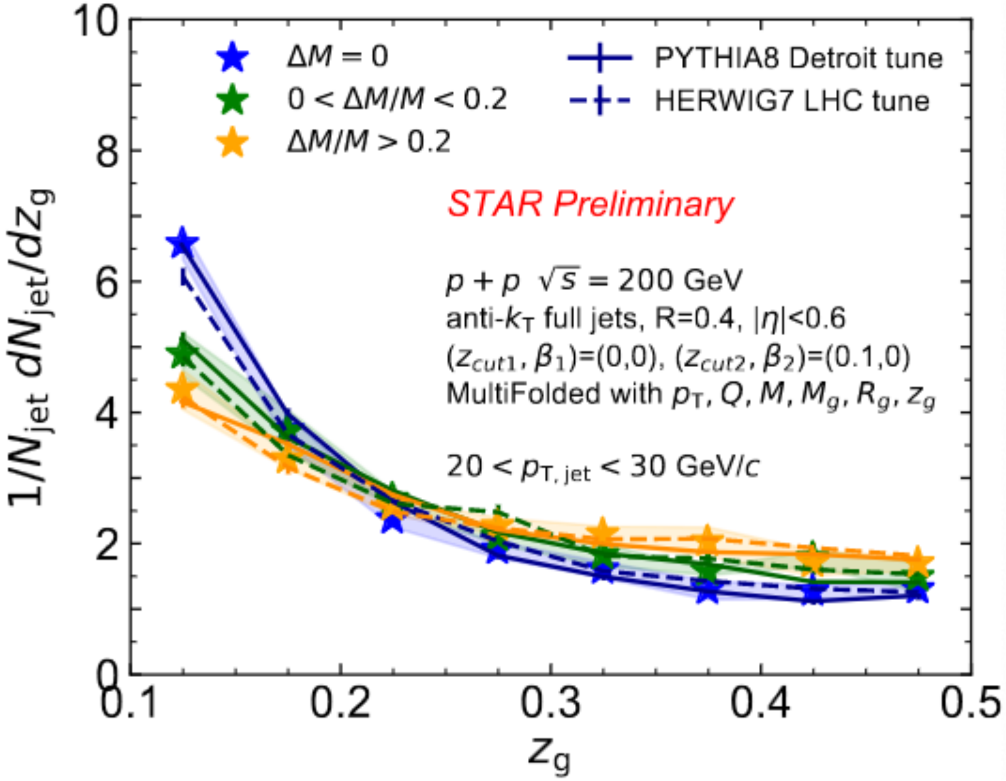
Collinear Splitting → Smaller R_g → Flatter z_g → Less perturbative

Wide-Angle Splitting → Larger R_g → Steeper z_g → More Perturbative

Isolating perturbative and non-perturbative physics in vacuum(p-p) jets

CollinearDrop: Difference of an observable for an ungroomed vs groomed jet → Access to soft component of jet





DIS 2023

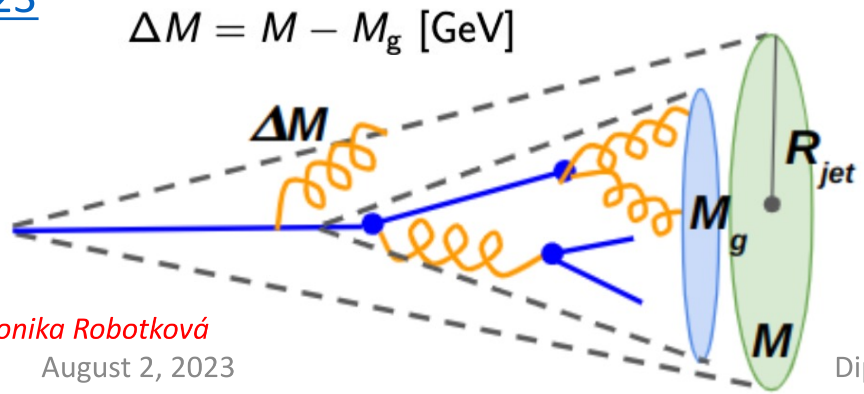
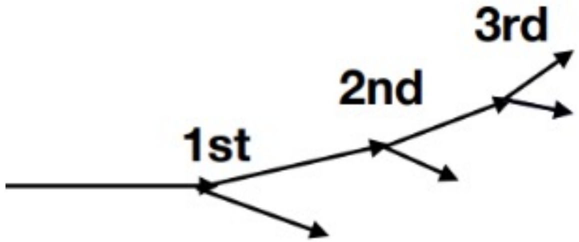


Image: Monika Robotková

Smaller R_g → Larger $\langle \Delta M/M \rangle$ → Flatter z_g → Less perturbative

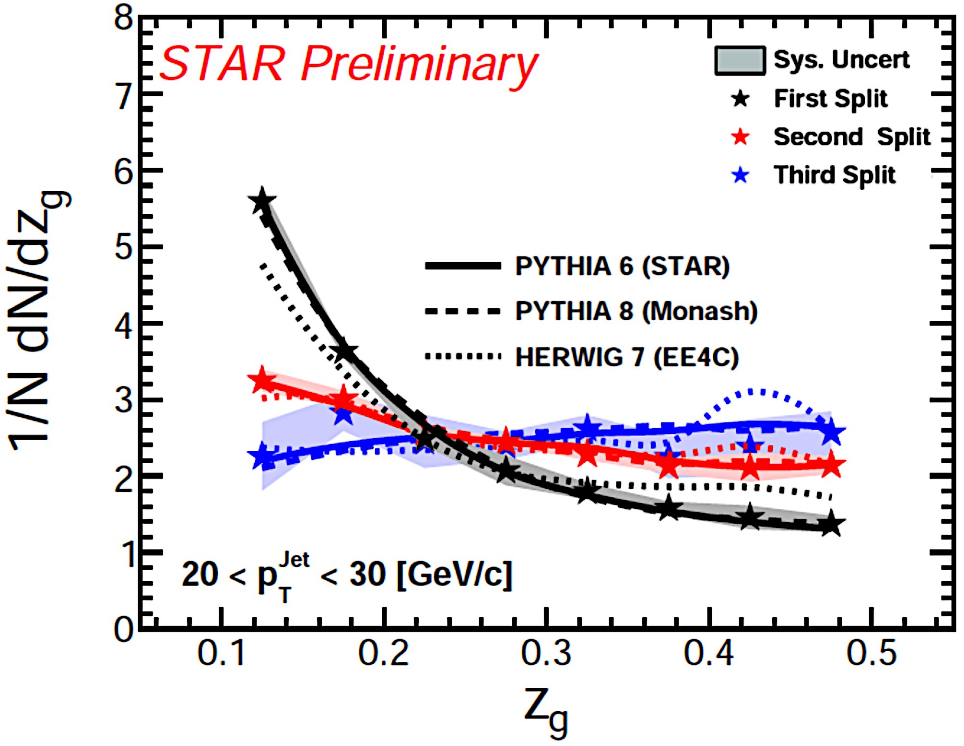
Larger R_g → Smaller $\langle \Delta M/M \rangle$ → Steeper z_g → More Perturbative

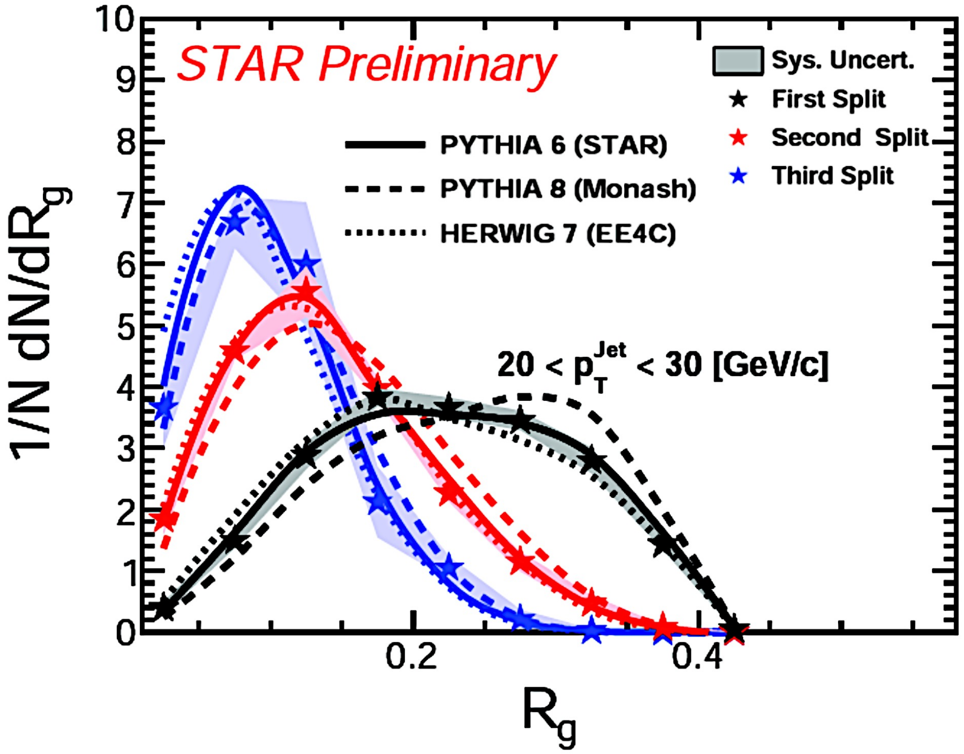
Time evolution of the vacuum(p-p) jet



Iterative SoftDrop: Access to 1st, 2nd, 3rd hard splits of the parton shower

Hard Probes 2023





z_g becomes flatter over time → Consistent with perturbative to non-perturbative transition

R_g becomes narrower over time → Change from soft wide-angle to hard collinear splitting

Can we pinpoint a distinct transition region?

Time evolution of the vacuum(p-p) jet

Energy-Energy Correlators: Normalized EEC = $\frac{1}{\sum_{Jets}\sum_{i\neq j}\frac{E_iE_j}{p_{T,Jet}^2}}\frac{d\left(\sum_{Jets}\sum_{i\neq j}\frac{E_iE_j}{p_{T,Jet}^2}\right)}{d(\Delta R)}$

Hard Probes 2023

Formation Time: $t_f \propto \frac{1}{\Delta R^2}$

Apolinário, Cordeiro, & Zapp EPJC 81 (2021)

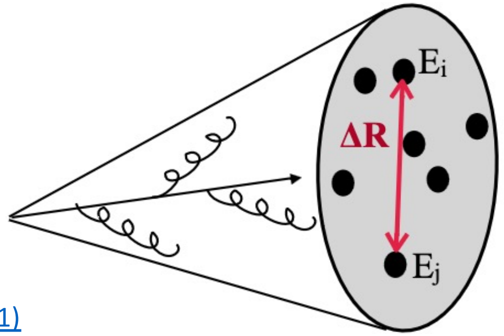
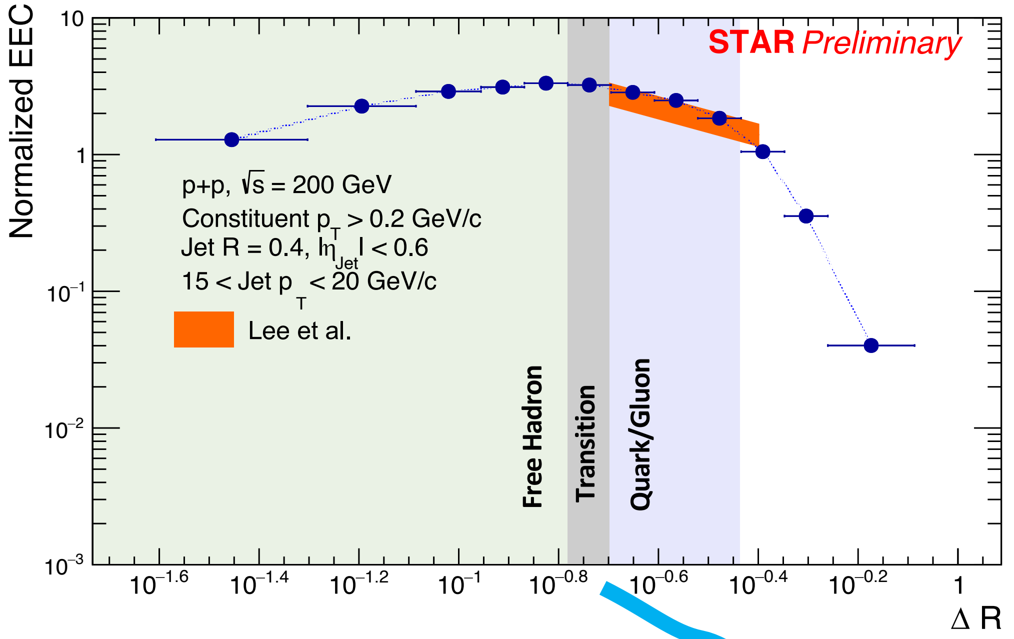
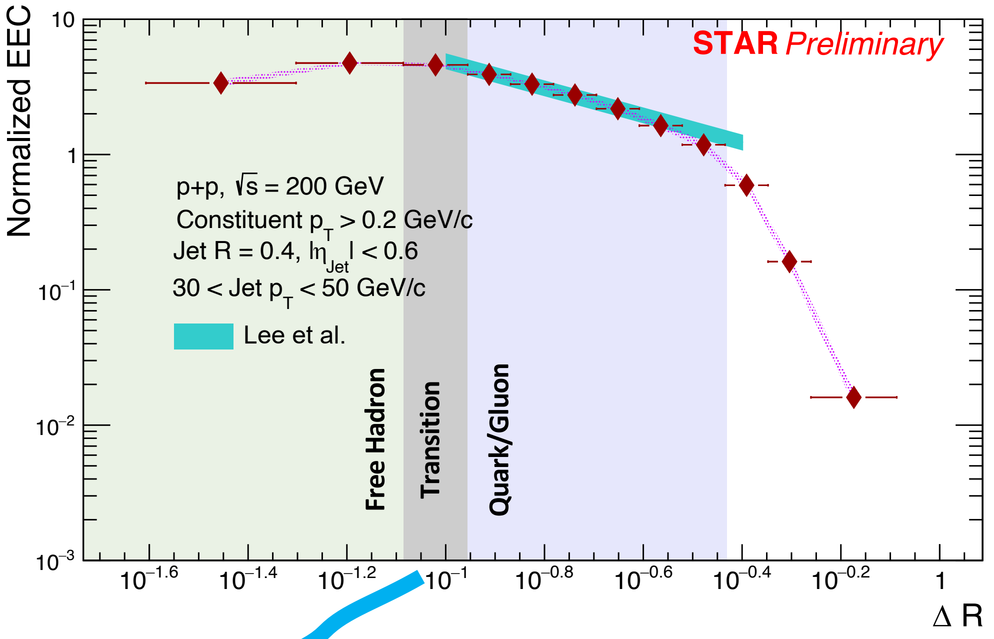


Image: Nihar Sahoo





Transition Region at $\Delta R_{\text{Turnover}} \times p_T^{\text{Jet}}$ ~ 2 – 3 GeV → No p_T^{Jet} dependence

Hard Probes 2023

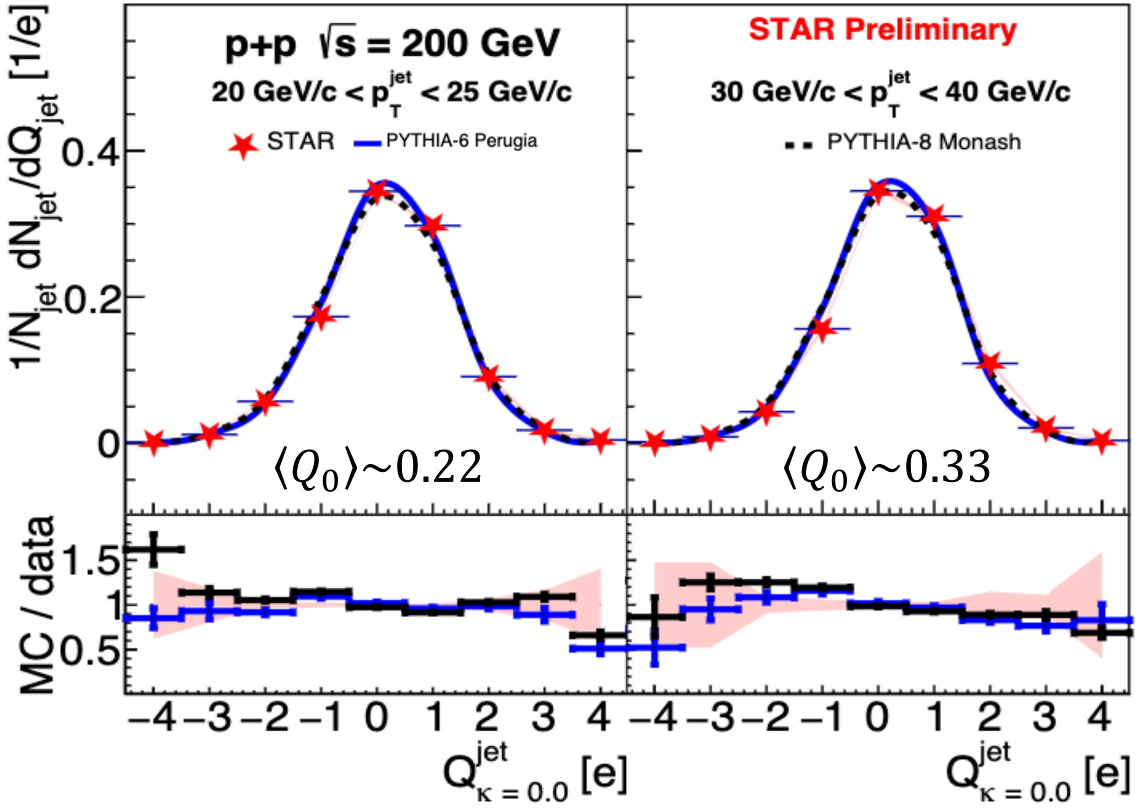
Universal scale for confinement of quark/gluon to hadrons

Vacuum(p-p) jet substructure

(Weighted) Jet Charge: $Q_\kappa^i = \sum_{j \in jet} \left(\frac{p_T^j}{p_T^{jet}} \right)^\kappa Q_j$

DNP 2022

$\kappa = 0$ (Chosen for this analysis)



Mean shifts higher with higher jet p_T

Vacuum(p-p) jet substructure

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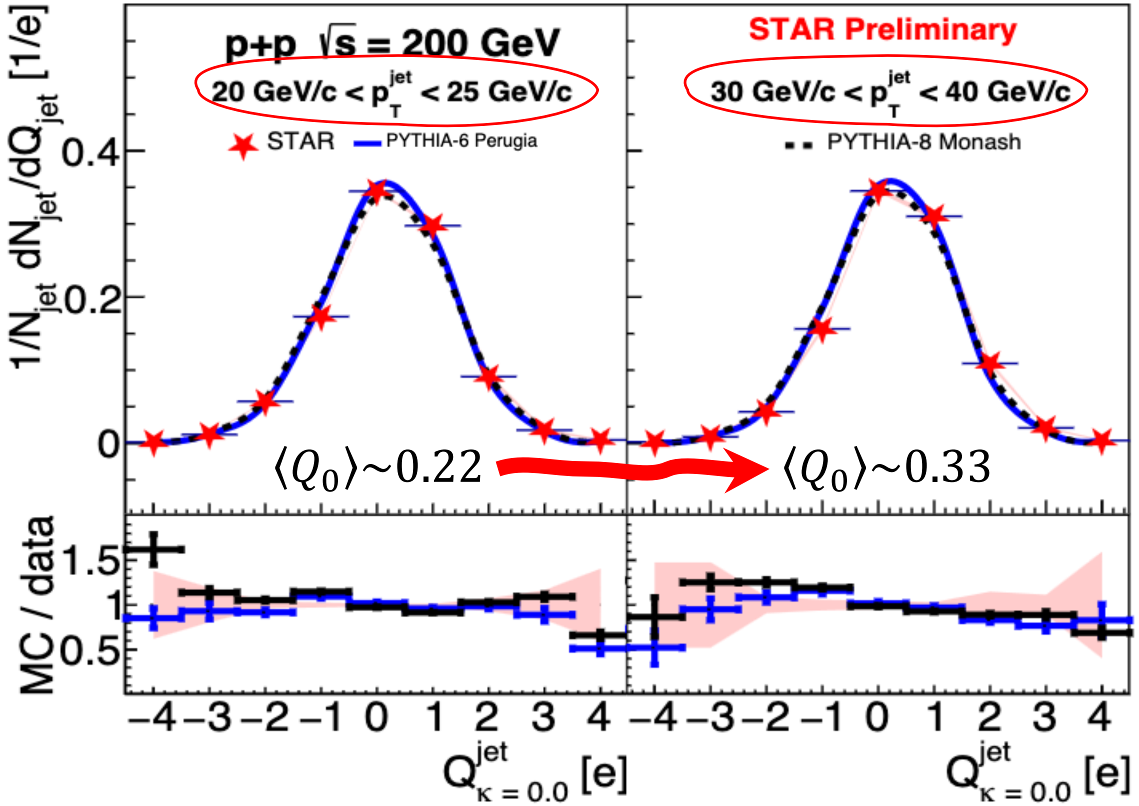
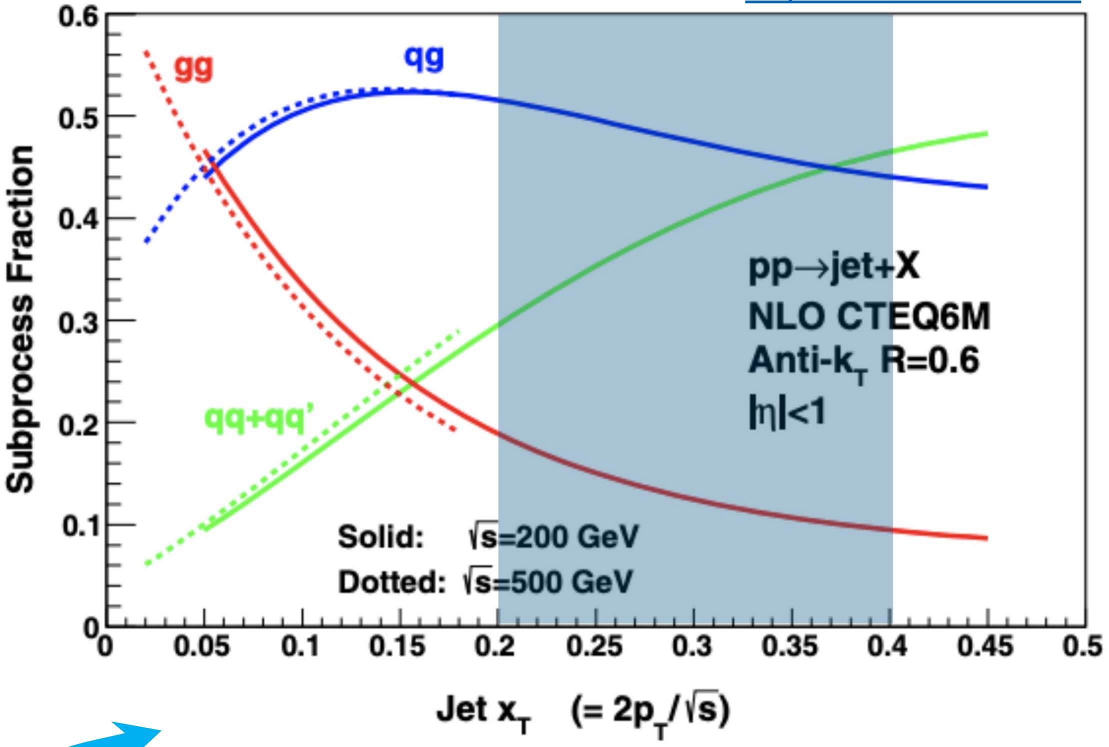


Mean shifts higher with higher jet p_T

PhysRevD.100.052005



More quark-initiated jets at higher p_T

Vacuum(p-p) jet substructure

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DNP 2022

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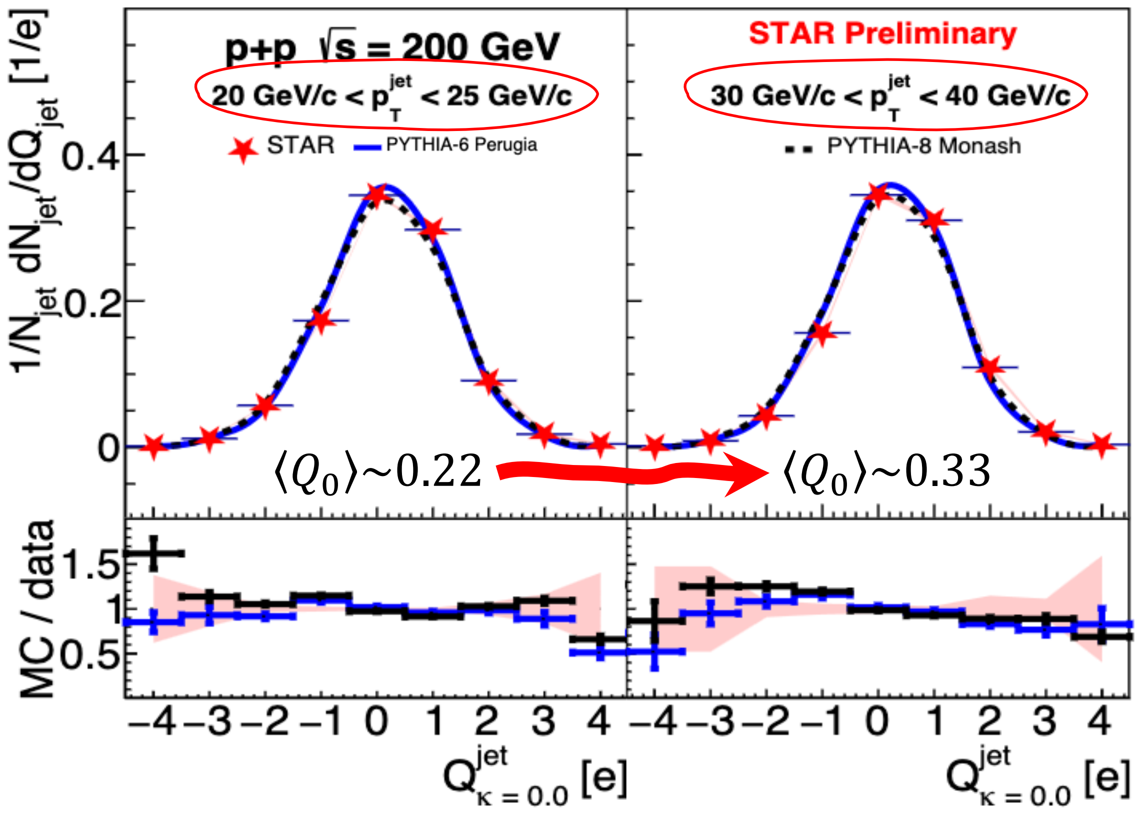
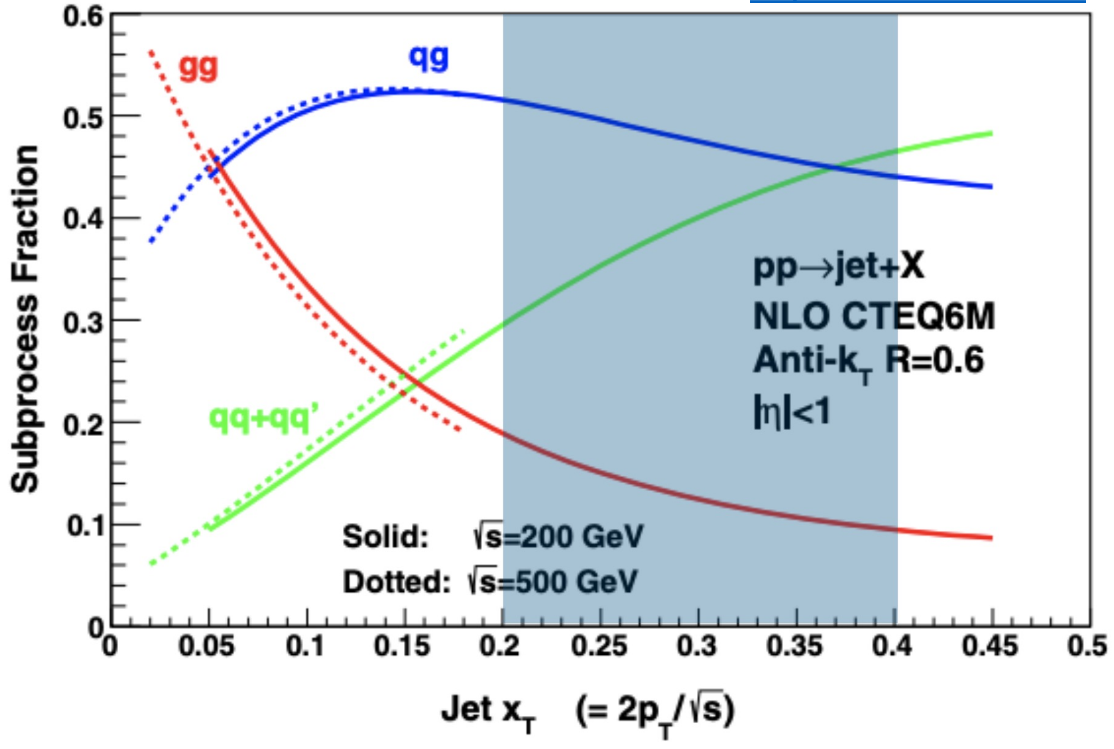


Good agreement with both PYTHIA 6 and PYTHIA 8

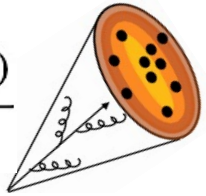
PhysRevD.100.052005



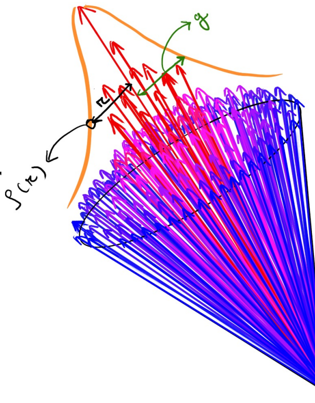
More quark-initiated jets at higher p_T

Vacuum(p-p) jet substructure

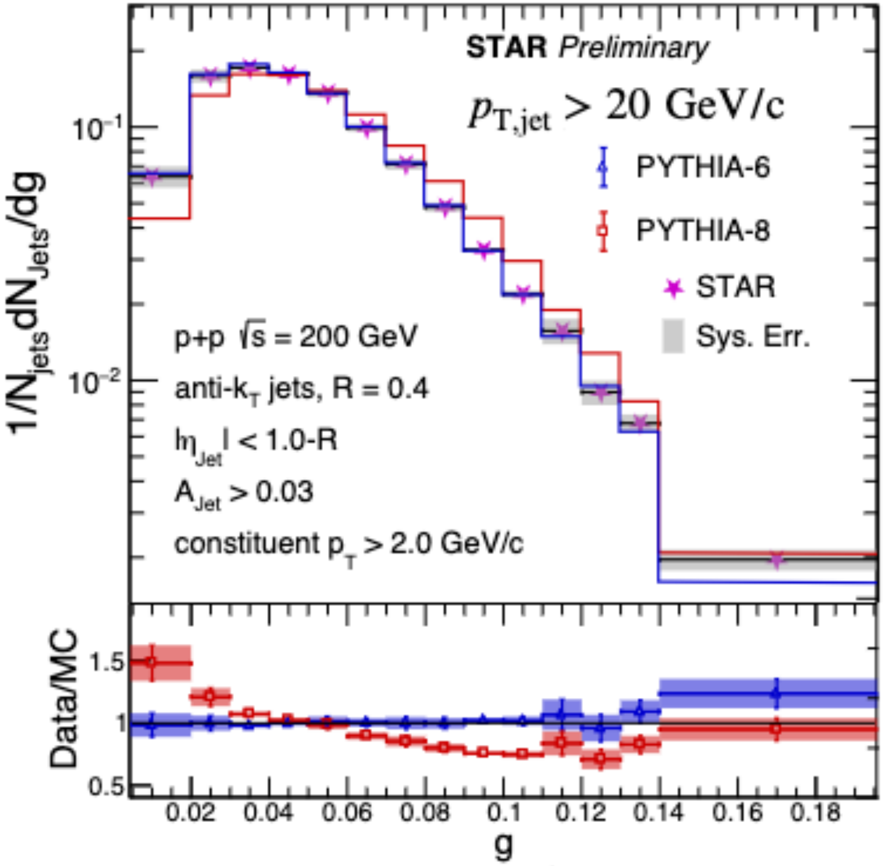
Girth: $g = \frac{\sum_{\text{trks}} p_{\text{T,trk}}(\Delta R)}{p_{\text{T,jet}}}$

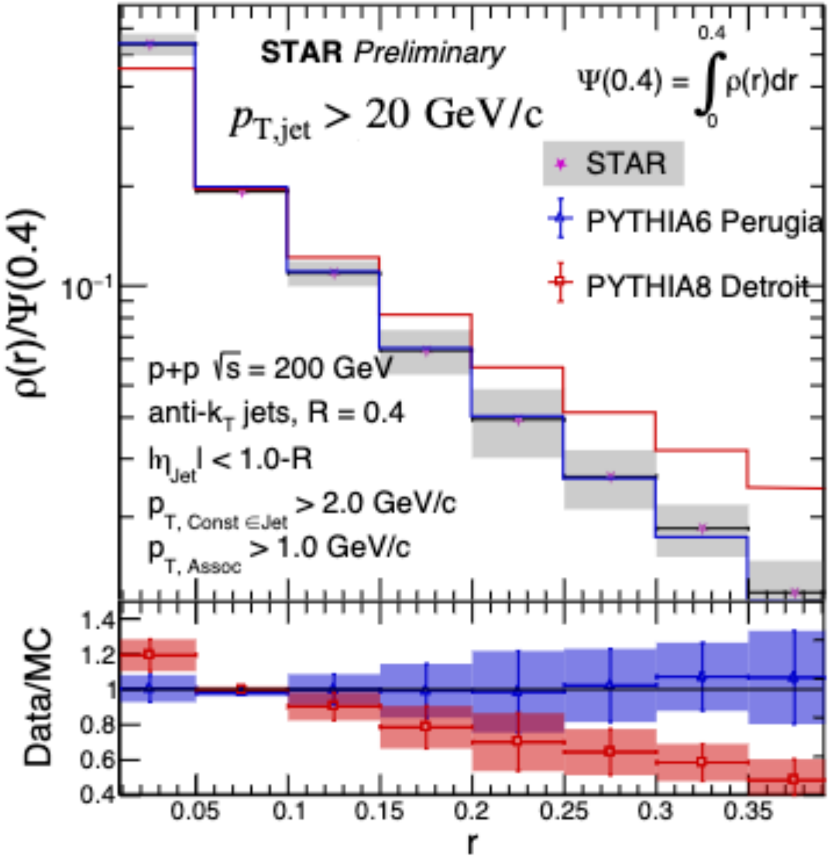


Differential Jet Shapes: $\rho(\text{r}) = \frac{1}{\delta r}\frac{1}{N_{\text{jets}}}\sum_{\text{jets}}\frac{\sum_{r^{\text{trk}}\in(r-\delta r/2,\, r+\delta r/2)} p_{\text{T,trk}}}{p_{\text{T,jet}}}$



Images: Tanmay Pani





Larger girth/differential jet shape → Broader jets

PYTHIA 6 in agreement

Hard Probes 2023

PYTHIA 8 Detroit tune overestimates broader (gluon-like ?) jets

Further tuning of PYTHIA 8 fragmentation parameters required at STAR for generalized angularities

Jets in cold nuclear matter (p-A)

[Initial Stages 2023](#)

Event Activity:

Soft Particle Production
Similar to centrality

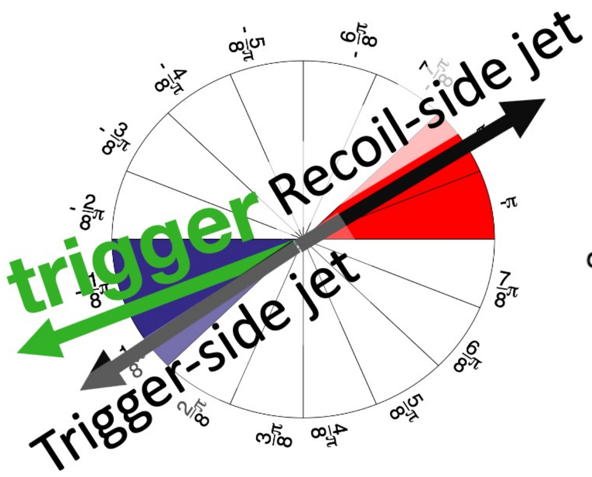
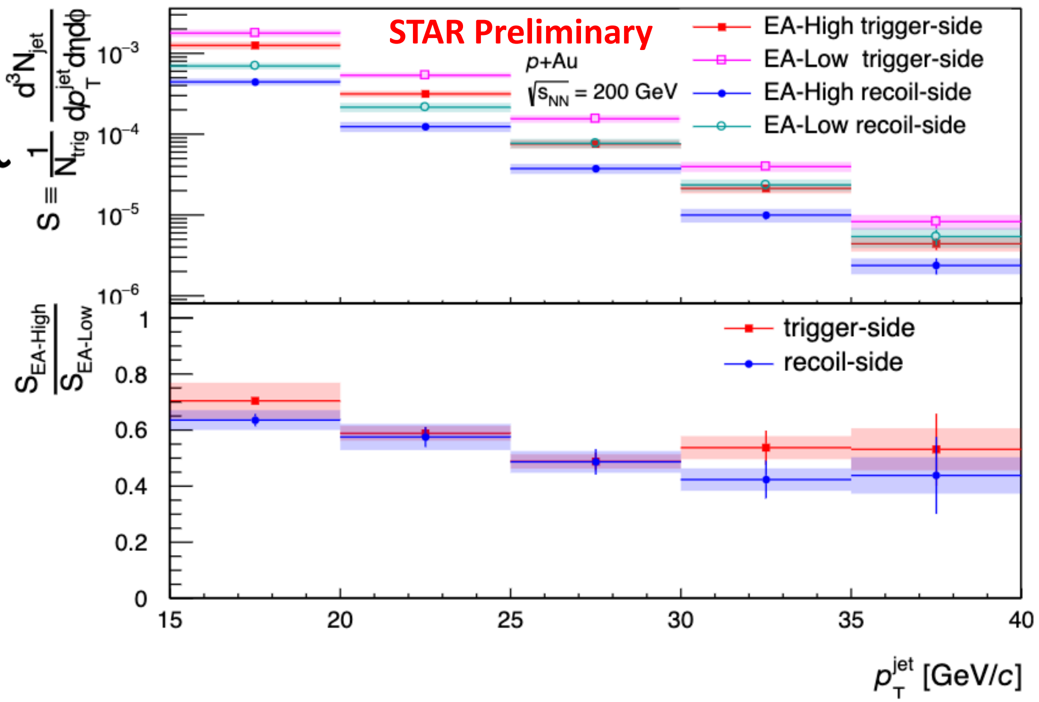


Image: David Stewart

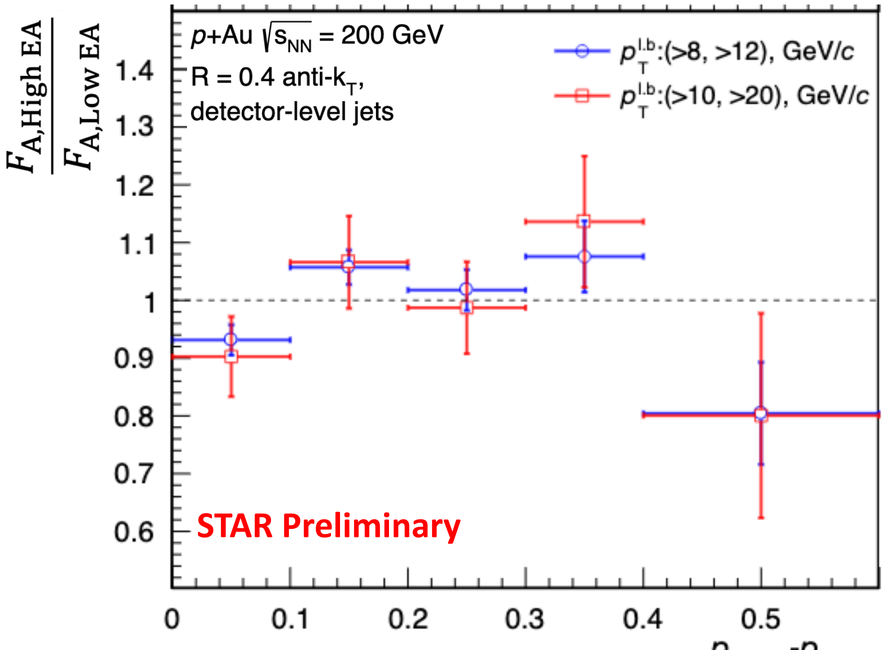
Semi-inclusive Jet Spectra



Similar suppression on the trigger-side and recoil-side

Dijet Imbalance

$$F_{A_J} \equiv \frac{1}{N_{dijets}} \frac{dN_{dijets}}{A_J}$$



$$A_J \equiv \frac{p_{T,lead} - p_{T,sub}}{p_{T,lead} + p_{T,sub}}$$

Dijet momentum imbalance independent of EA

Jets in cold nuclear matter (p-A)

Initial Stages 2023

Event Activity:

Soft Particle Production

Similar to centrality

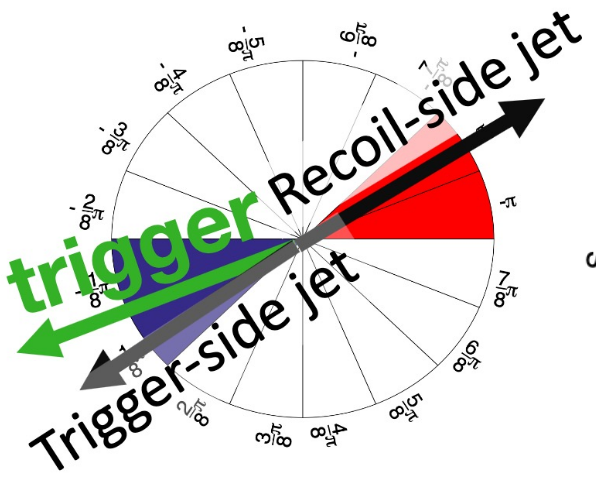


Image: David Stewart

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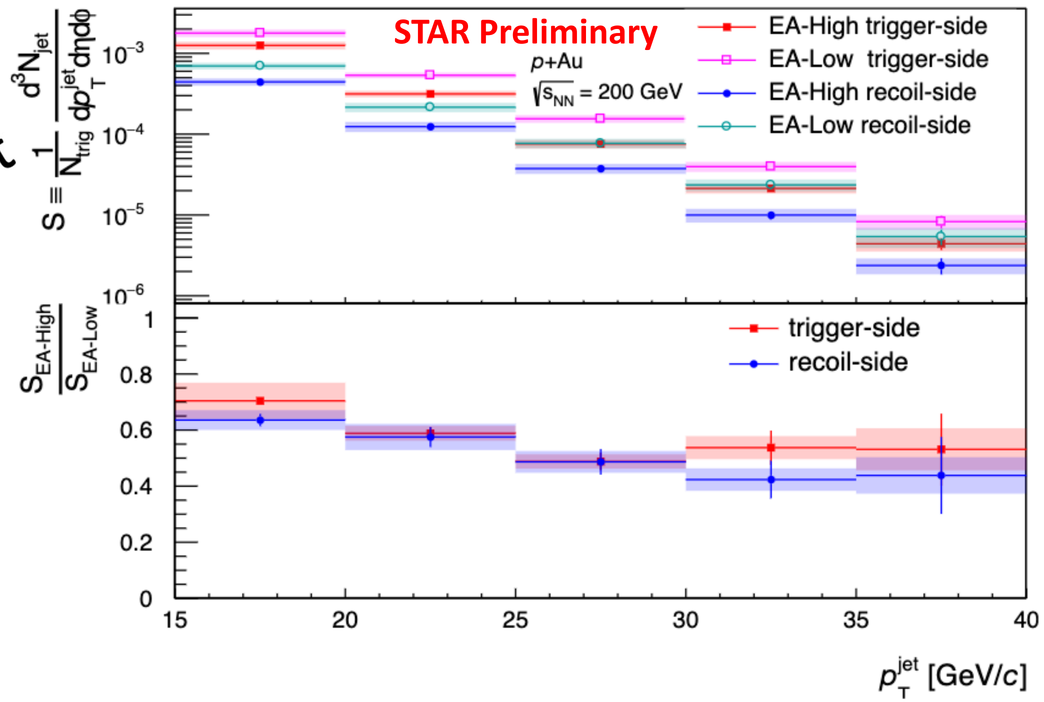

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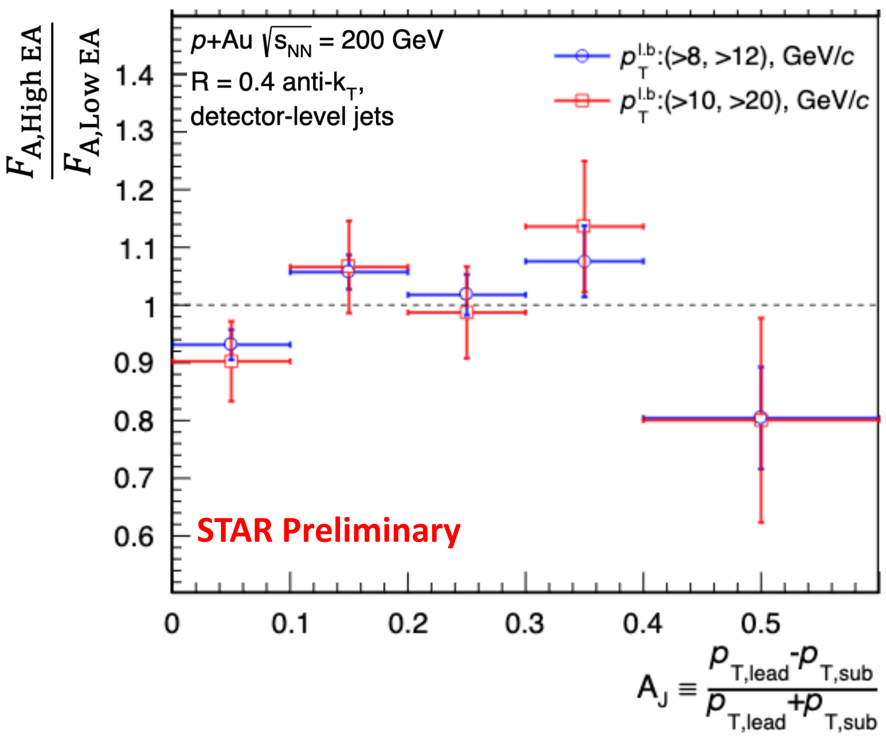


Similar suppression on the trigger-side and recoil-side

Dijet momentum imbalance independent of EA

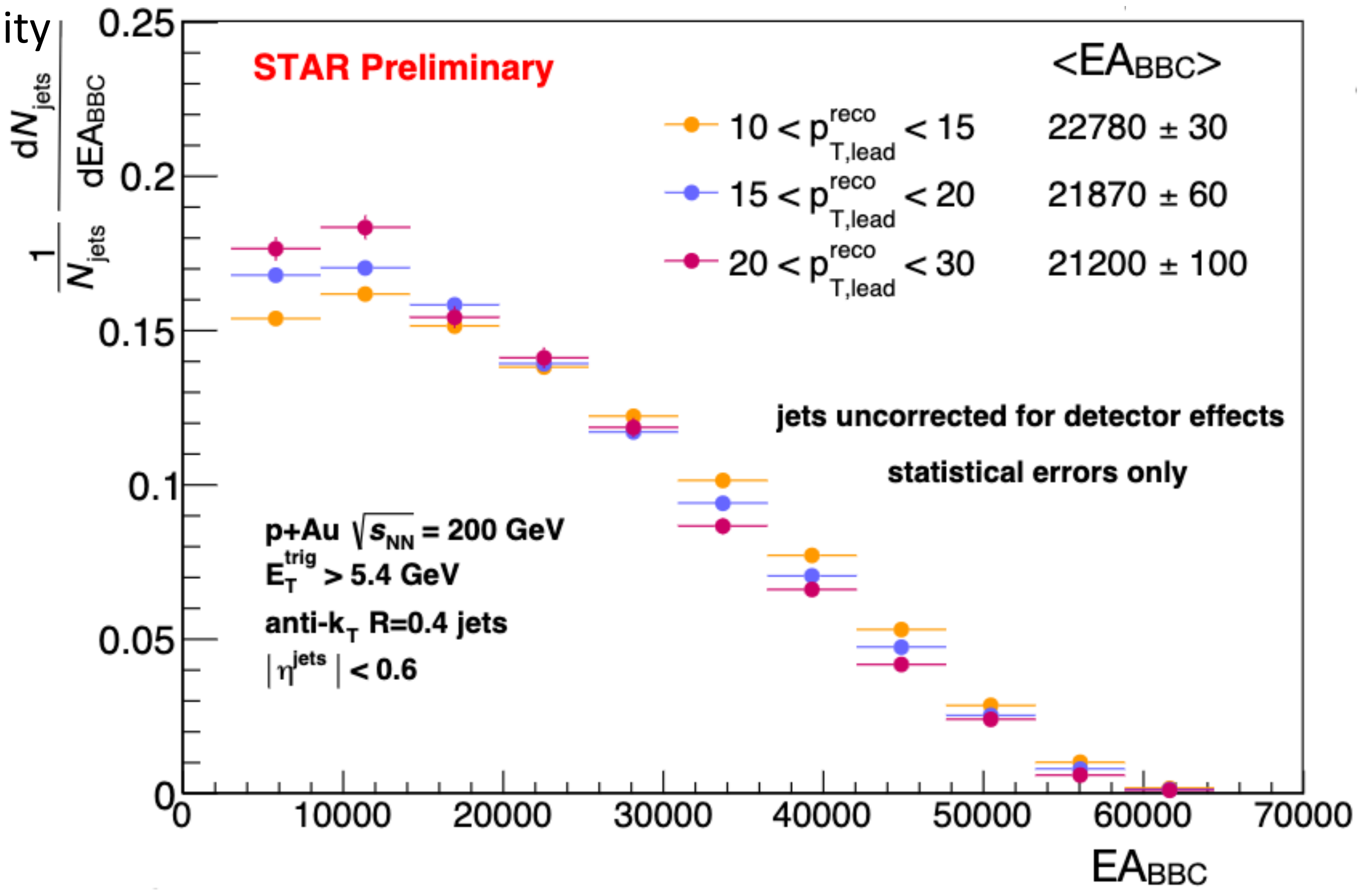
Inconsistent with in-medium energy loss (jet quenching)

STAR

Jets in cold nuclear matter (p-A)

Event Activity:
Soft Particle Production
Similar to centrality

Event Activity vs Leading Jet p_T



High <EA> → Lower Lead Jet p_T

Low <EA> → Higher Lead Jet p_T

i.e.

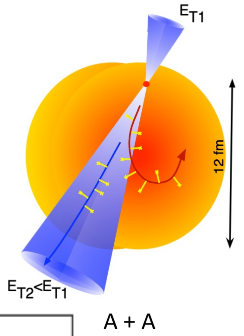
EA and Leading Jet p_T anti-correlated

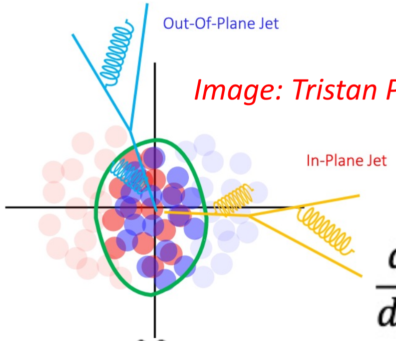
[Initial Stages 2023](#)

Hard and soft particle production correlated due to early time effects (?)

Jets in QGP (N-N)

Inclusive Hadron Suppression

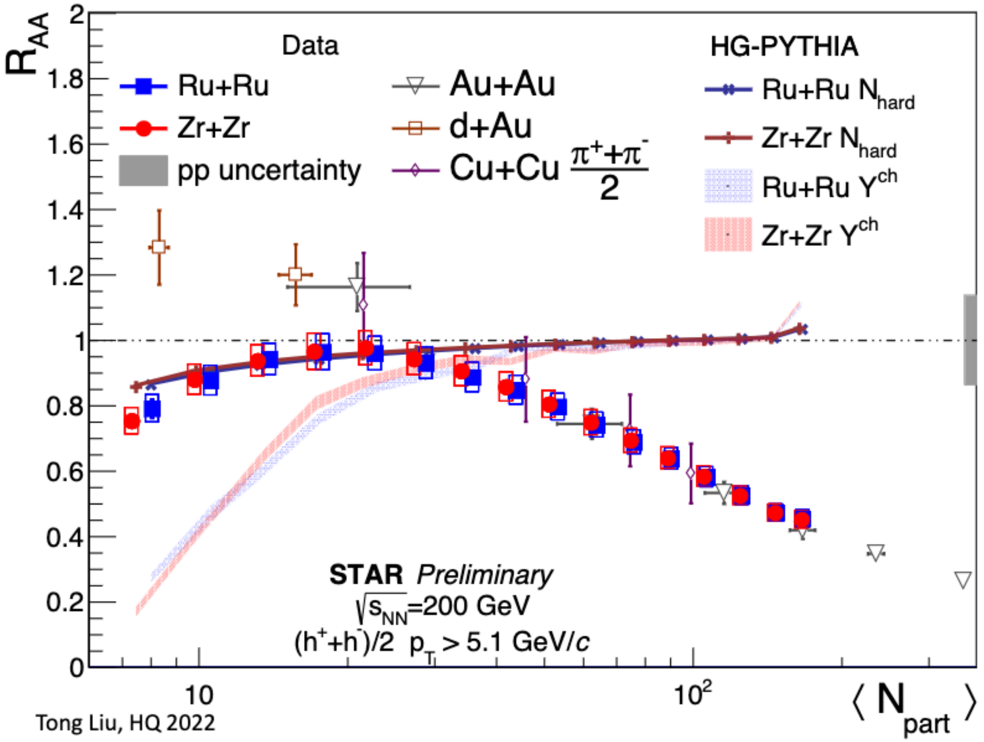


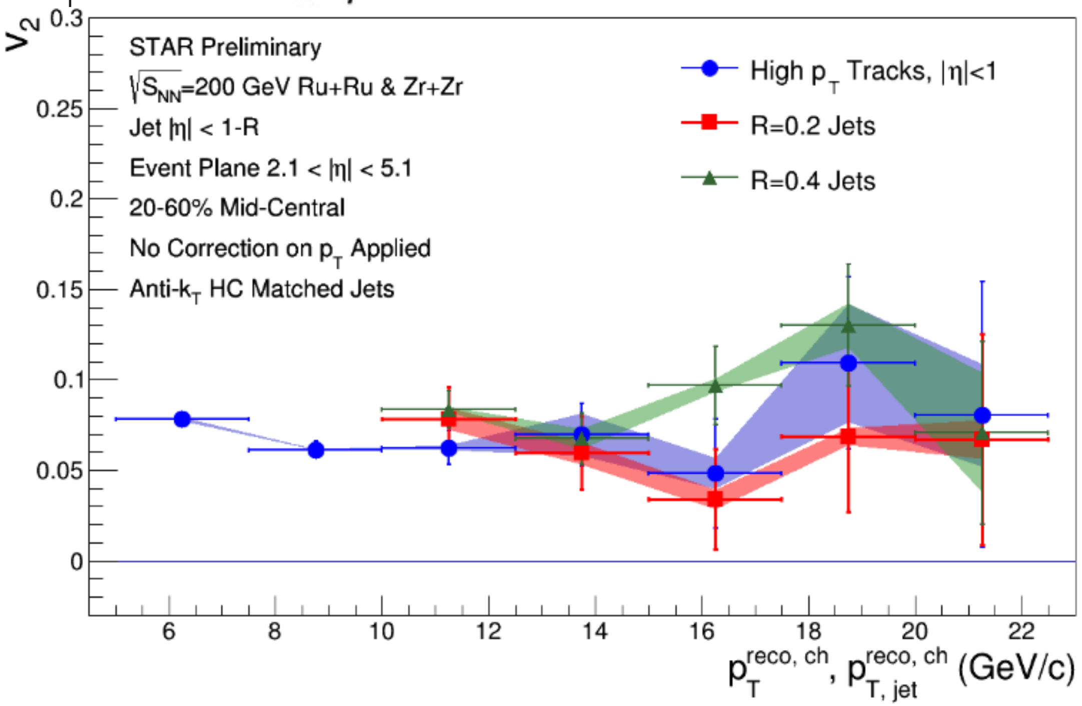


Hard Probes 2023

Inclusive Jet v_2

$$\frac{dN}{d\Delta\phi} \propto 1 + 2\,v_2\cos(2(\phi - \Psi_2))$$





$v_2 > 0$ for high p_T jets

R_{AA} suppression comparable between system sizes at same $<N_{part}>$

Energy loss driven by energy density rather than initial geometry

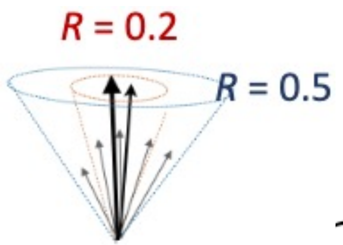
Quark Matter 2022

Hint of **path length dependent quenching**

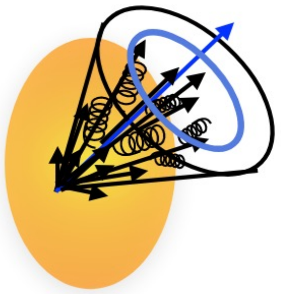
No jet R dependence of v_2 – hard-core selection bias(?)

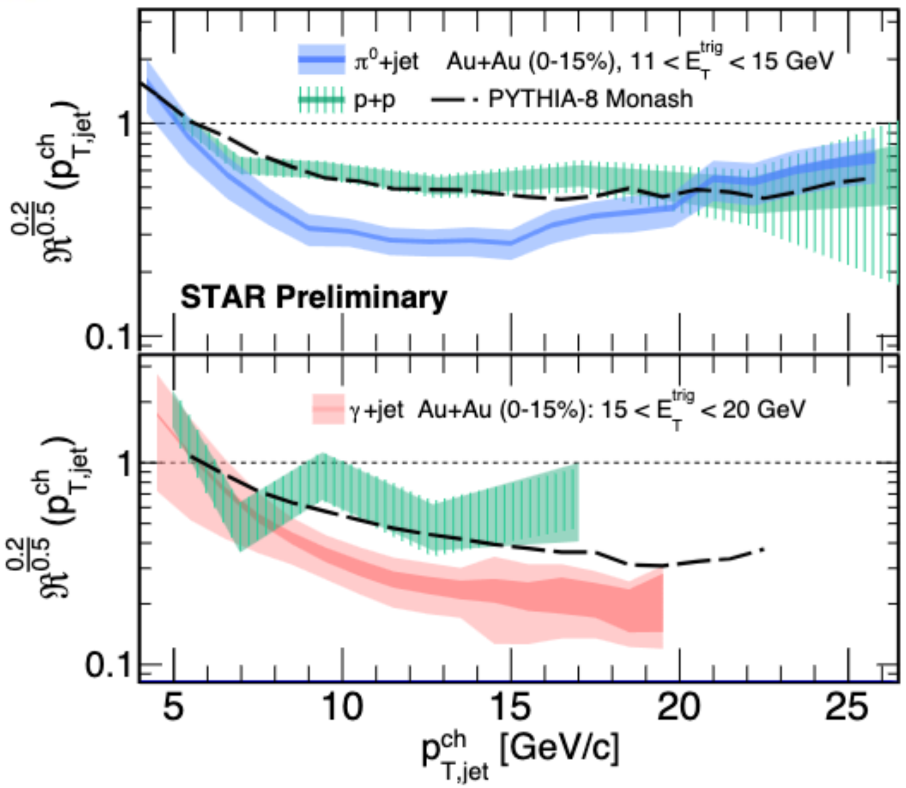
Jets in QGP (N-N)

Recoil Jet Yield vs Jet Radius for γ^{dir}/π^0 + Jet



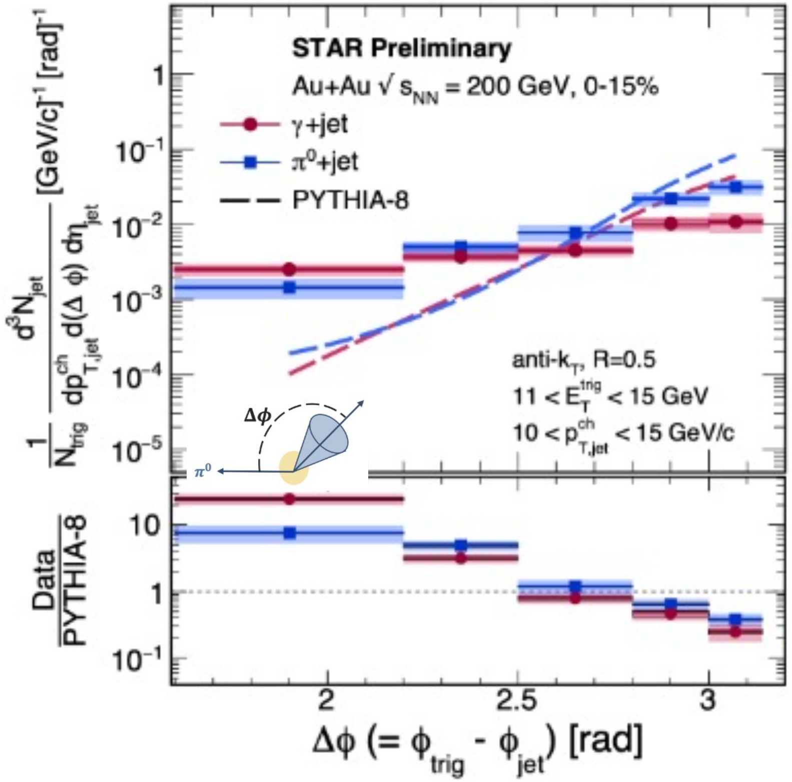
$$\Re = \frac{Y^{R=0.2}}{Y^{R=0.5}}$$



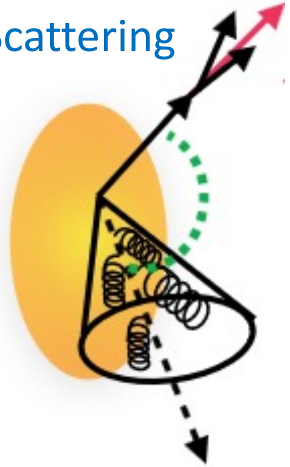


Ratio in-medium lower than in vacuum

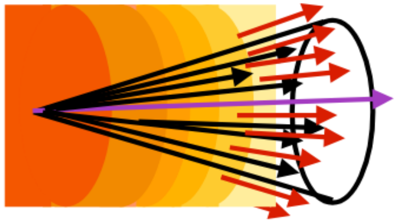
Azimuthal Correlation of γ^{dir}/π^0 and Jet



Scattering



Medium Response



Excess of jets away from back-to-back in-medium (Acoplanarity)

In-medium jet broadening

Due to scattering? Medium response?

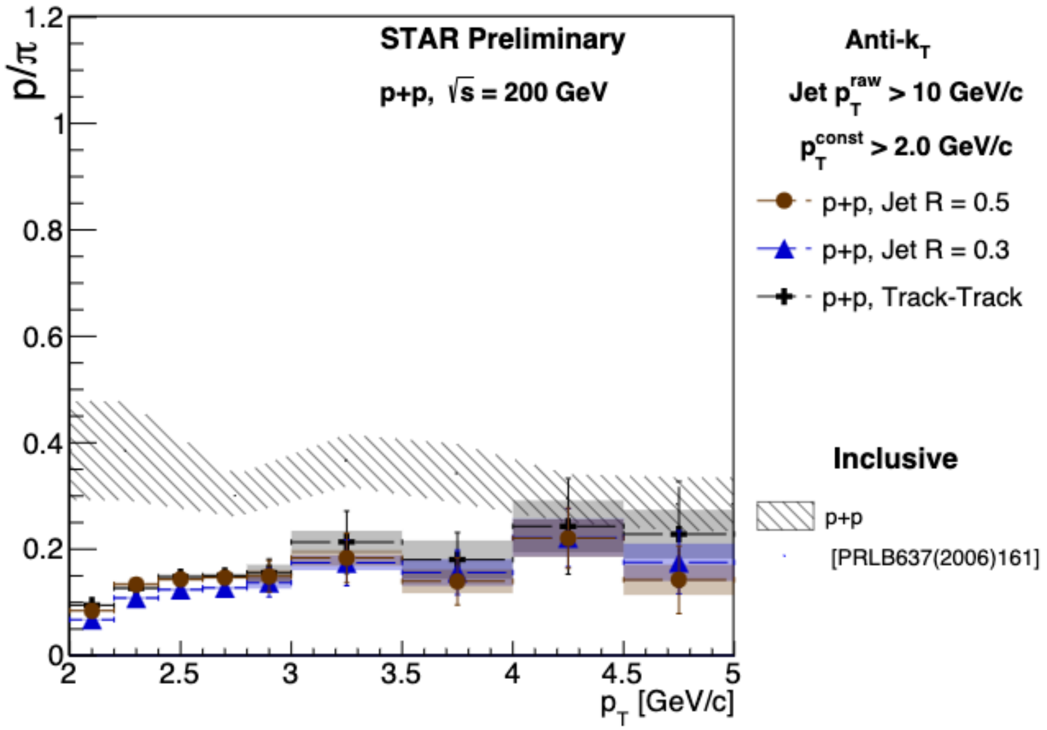
Need more statistics to study the wide $\Delta\phi$ jets. Similar behavior in smaller systems?

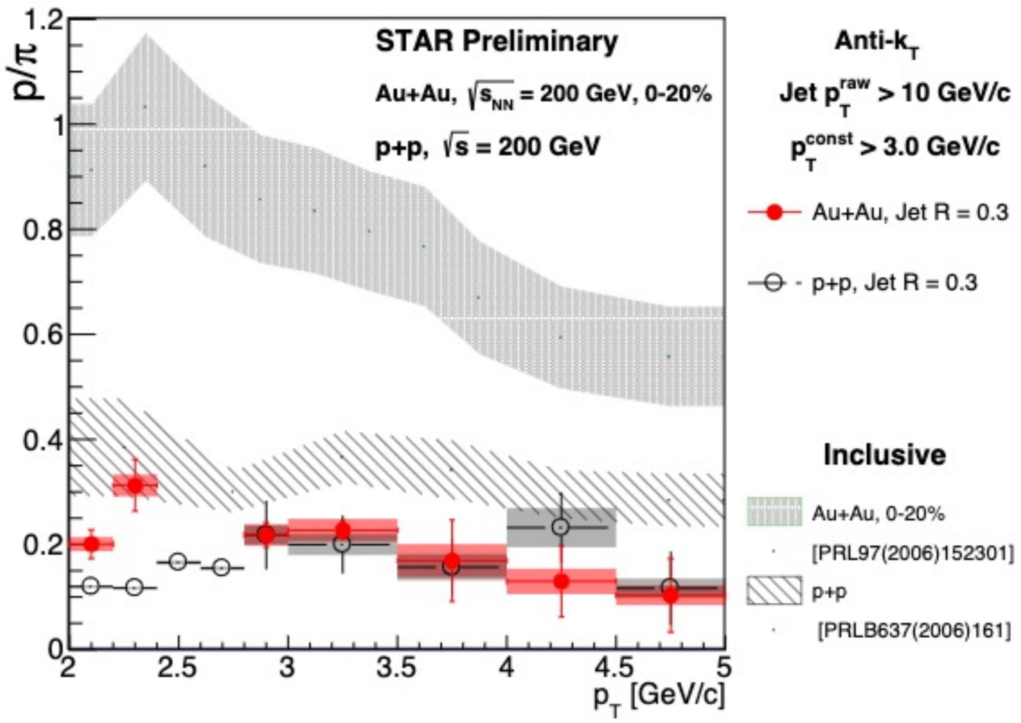
Jets in QGP (N-N)

Baryon-To-Meson Ratio in p-p and Au-Au

$$\frac{p^+ + p^-}{\pi^+ + \pi^-}$$

Hard Probes 2023





Pion production preferred over proton

No significant difference in AuAu p/π ratio compared to pp

Stronger preference for pions in jets compared to inclusive pp

Hard-core selection bias (?) Survivor bias(?)

Studies ongoing with jets with different hard-core definitions

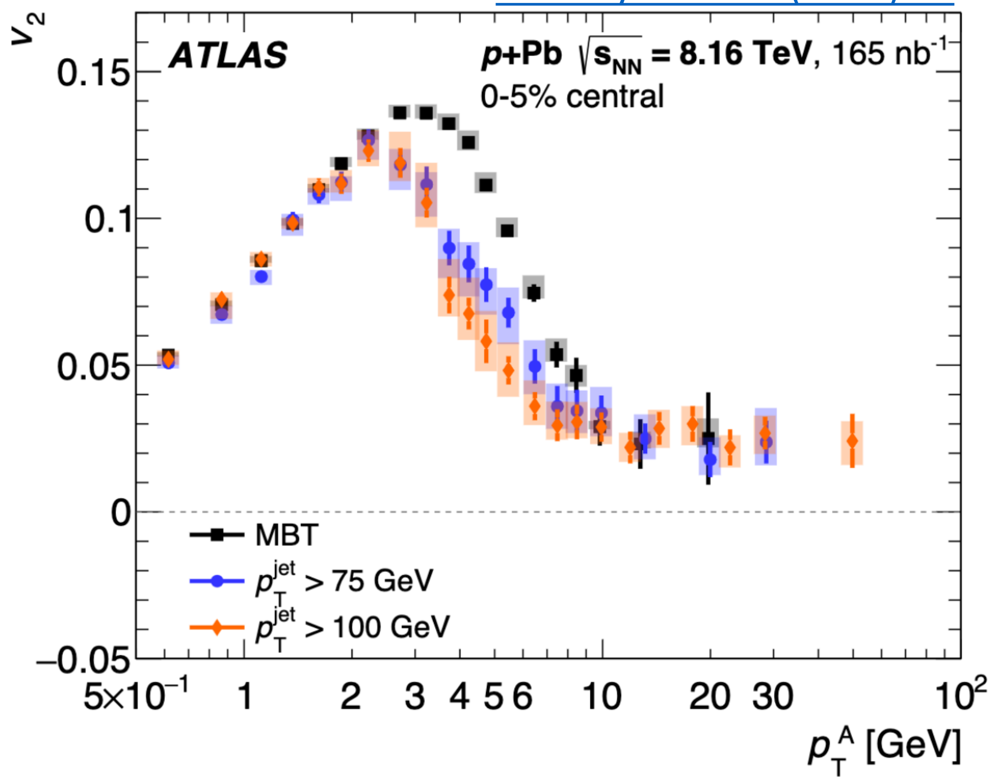
Looking forward – Future analyses

Detector Upgrades

STAR BUR, 2023

- ✓ EPD for triggering and independent event-plane determination
- ✓ Improved tracking and mid-rapidity acceptance from iTPC

Eur. Phys. J. C 80 (2020) 73



v_2 for **p+Au, O+O, Au+Au**

Along with current **Ru+Ru**, **Zr+Zr** measurements

Probing energy density dependence of flow by looking at different collision systems

Can probe questions like:

Why does p+A have positive v_2 at LHC, when there is no sign of quenching?

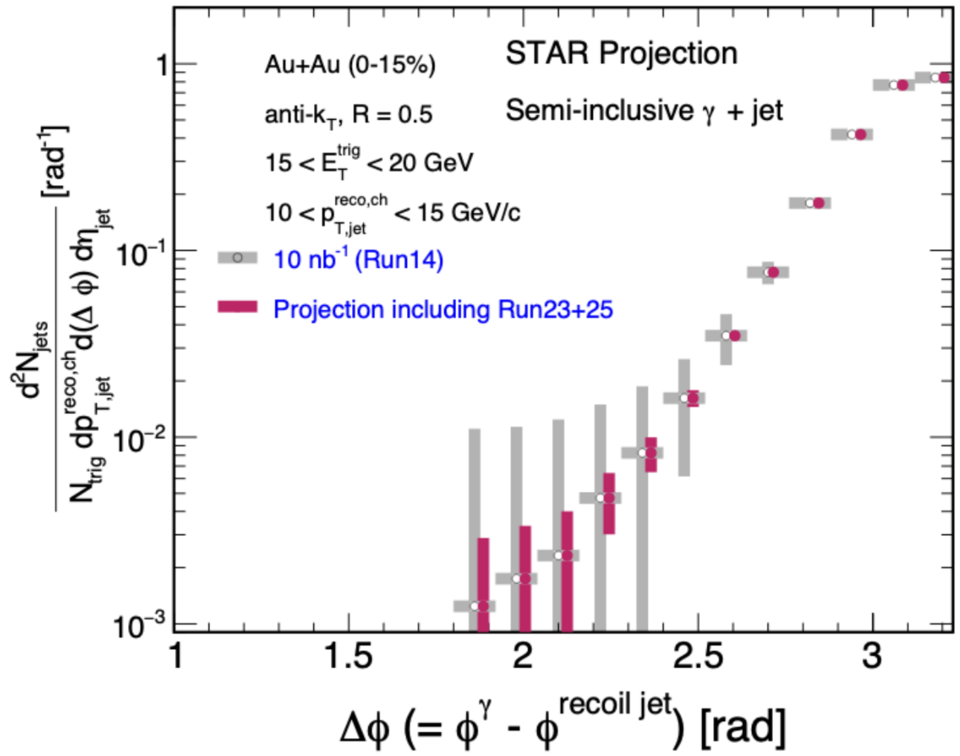
If there are competing effects, when does the transition happen?

Looking forward – Run 23 - 25

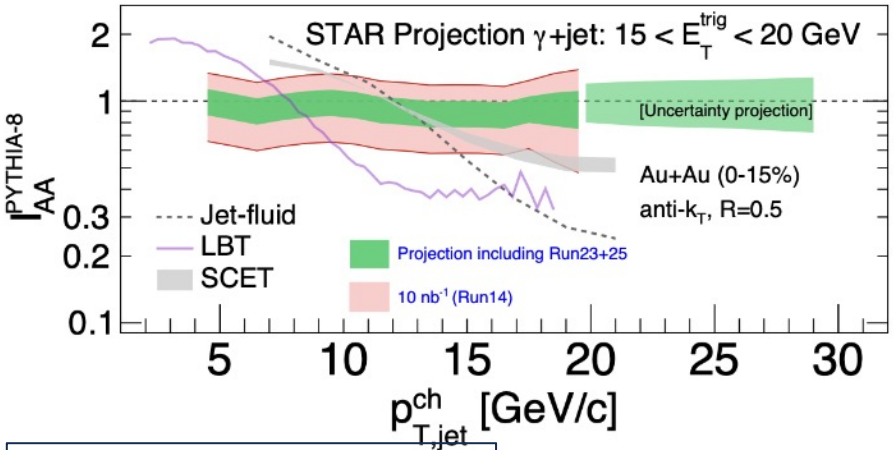
Increased Luminosity

STAR BUR for 2023-25

$\sqrt{s_{NN}}$ (GeV)	Species	Number Events/ Sampled Luminosity	Year
200	Au+Au	20B / 40 nb^{-1}	2023+2025
200	$p+p$	235 pb^{-1}	2024
200	p+Au	1.3 pb^{-1}	2024



Recoil Jets triggered by γ^{dir}



I_{AA} = Yield in AuAu/Yield in pp

- ✓ Higher p_T jets accessible for I_{AA} and acoplanarity measurements
- ✓ Improved precision for γ^{dir} triggered jet measurements
- ✓ Decreased uncertainty for model discrimination

STAR BUR, 2023

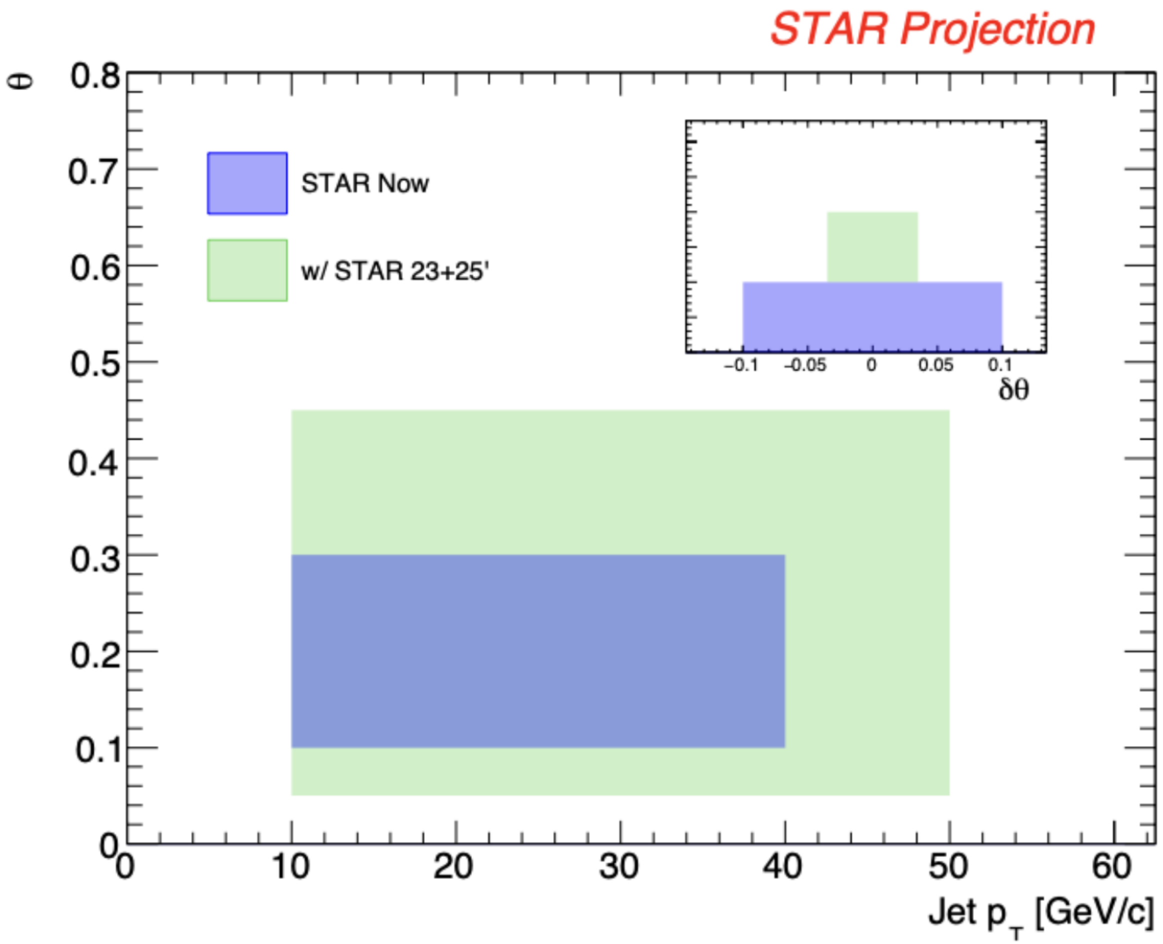
Looking forward – Run 23 - 25

Increased Luminosity

STAR BUR for 2023-25

$\sqrt{s_{NN}}$ (GeV)	Species	Number Events/ Sampled Luminosity	Year
200	Au+Au	20B / 40 nb^{-1}	2023+2025
200	$p+p$	235 pb^{-1}	2024
200	p+Au	1.3 pb^{-1}	2024

- ✓ Increased statistics for jet-substructure measurements
- ✓ Access to wide-angle emissions and high p_T jets
- ✓ Improved angular resolution from 0.1 to 0.025
- ✓ **Use jet substructure as taggers**



STAR BUR, 2023

Summary

Jets in vacuum (p-p)

- Jet-substructure measurements to probe time evolution of parton shower
- Baseline measurements for generalized angularities of jets
- Disagreement with STAR tuned PYTHIA8 for generalized angularities → Further study required into the models

Jets in cold nuclear matter (p-Au)

- Two null measurements for jet-quenching
- Anti-correlation between event-activity (centrality) and jet energy possible reason for jet-yield modification

Jets in QGP (N-N)

- Modified jet chemistry in medium → Ongoing studies to probe possible causes
- Jet acoplanarity observed in medium → System size dependent study to disentangle causes ongoing
- v_2 measurements for different system sizes ongoing → Probing energy density dependence of flow

Thank You