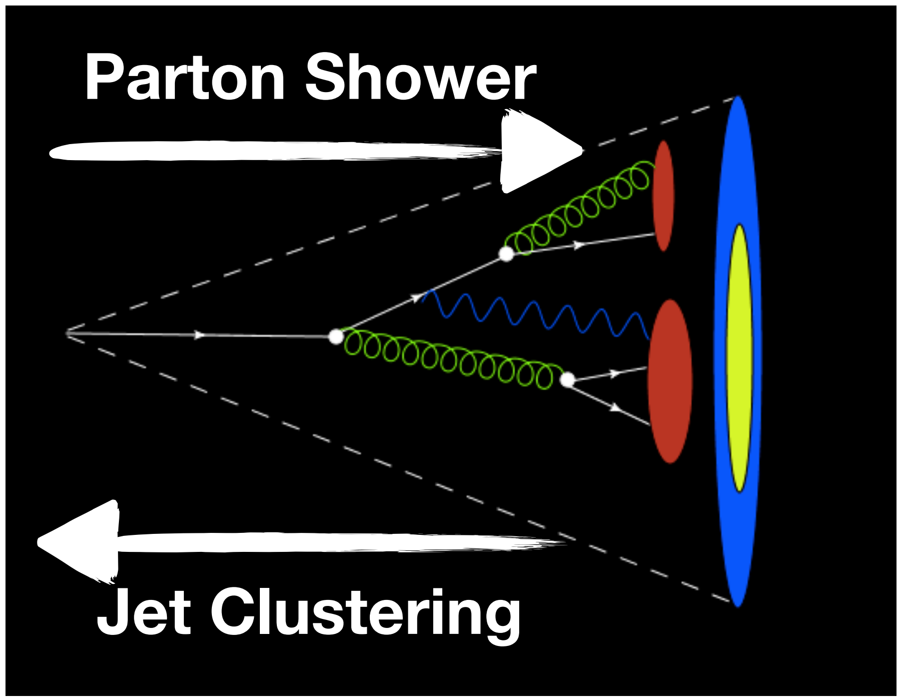
Supported in part by: U.S. DEPARTMENT OF ENERGY | Office of Science; WAYNE STATE UNIVERSITY; STAR

Jet and jet substructure measurements at STAR

Isaac Mooney for the STAR Collaboration
isaac.mooney@wayne.edu

RHIC & AGS Annual Users' Meeting
Jet Workshop
October 22, 2020

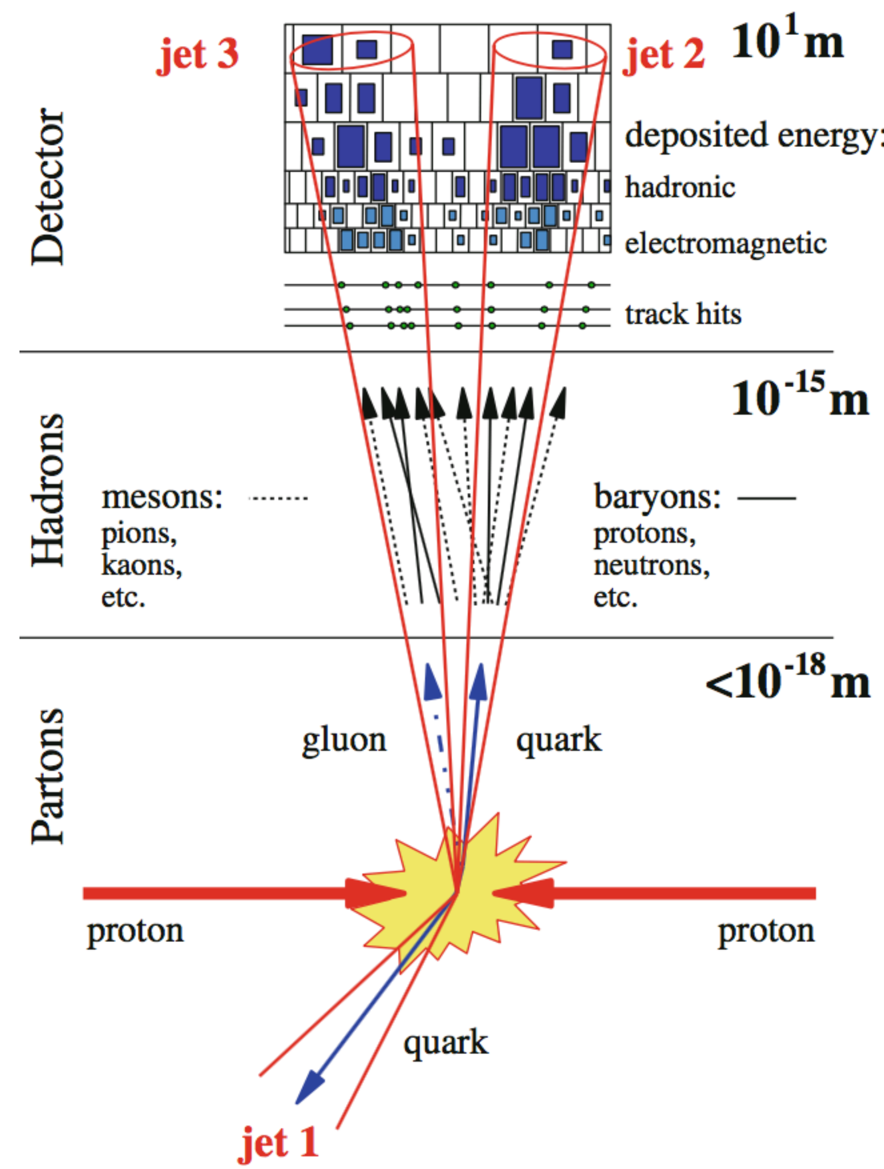
Accessing scales of jet evolution



Jet evolution/parton shower in vacuum is described by two fundamental scales - momentum and angle/virtuality

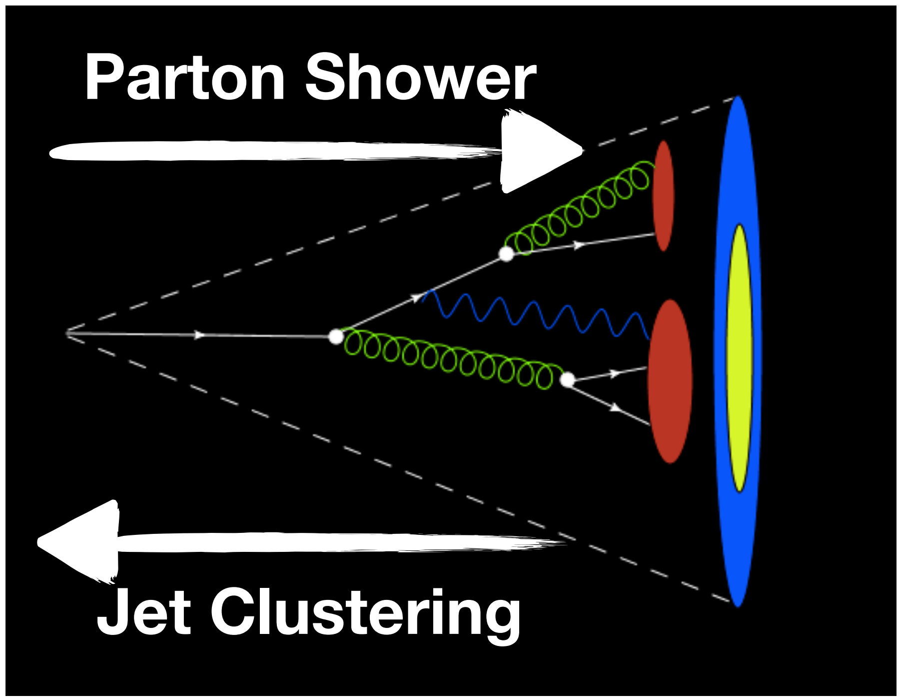
Splitting probability in collinear limit:

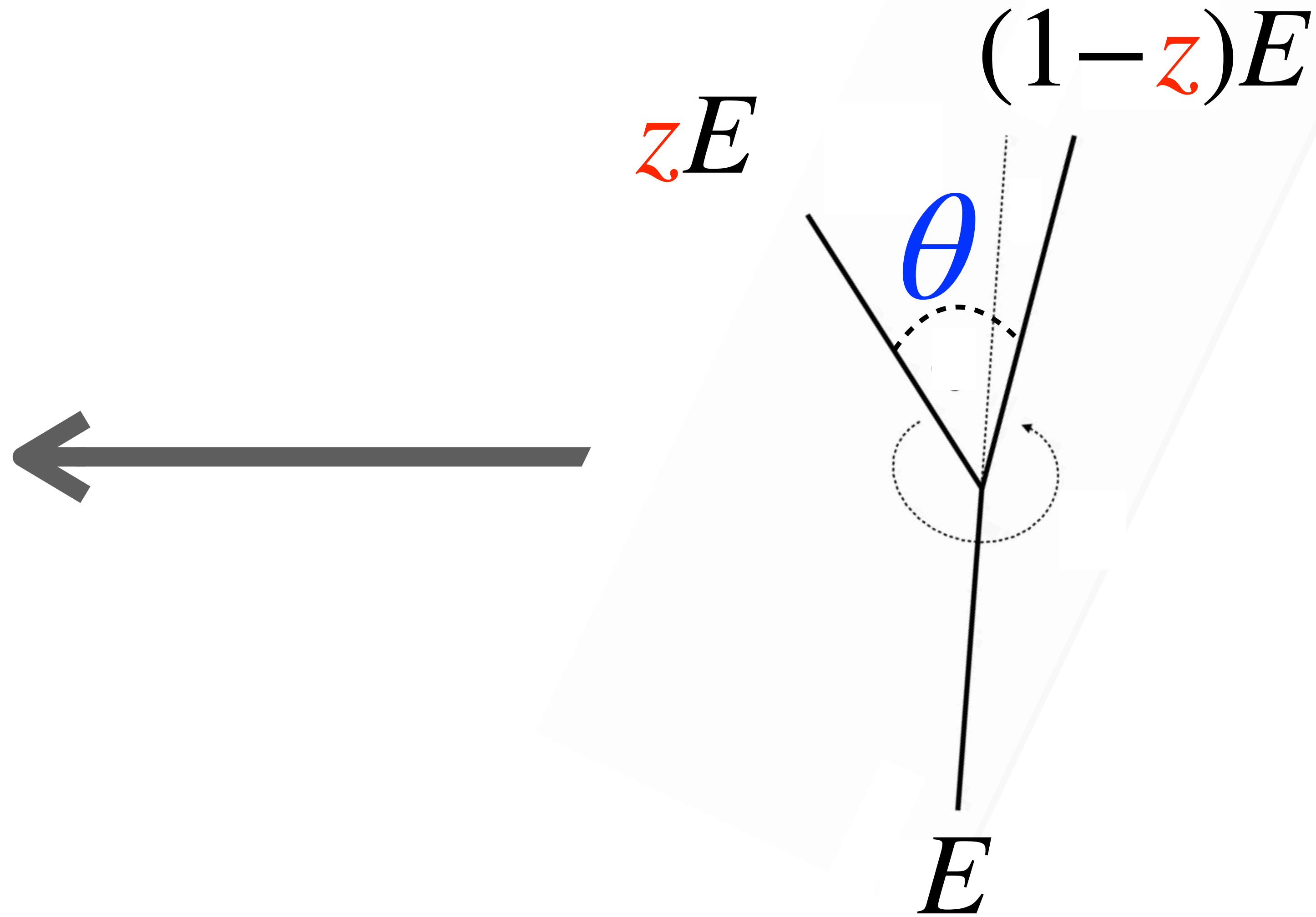
$$d\sigma \sim \frac{d\theta^2}{\theta^2}\frac{dz}{z}$$



Carli, Rabbertz, Schumann, *Studies of Quantum Chromodynamics at the LHC*

Accessing scales of jet evolution





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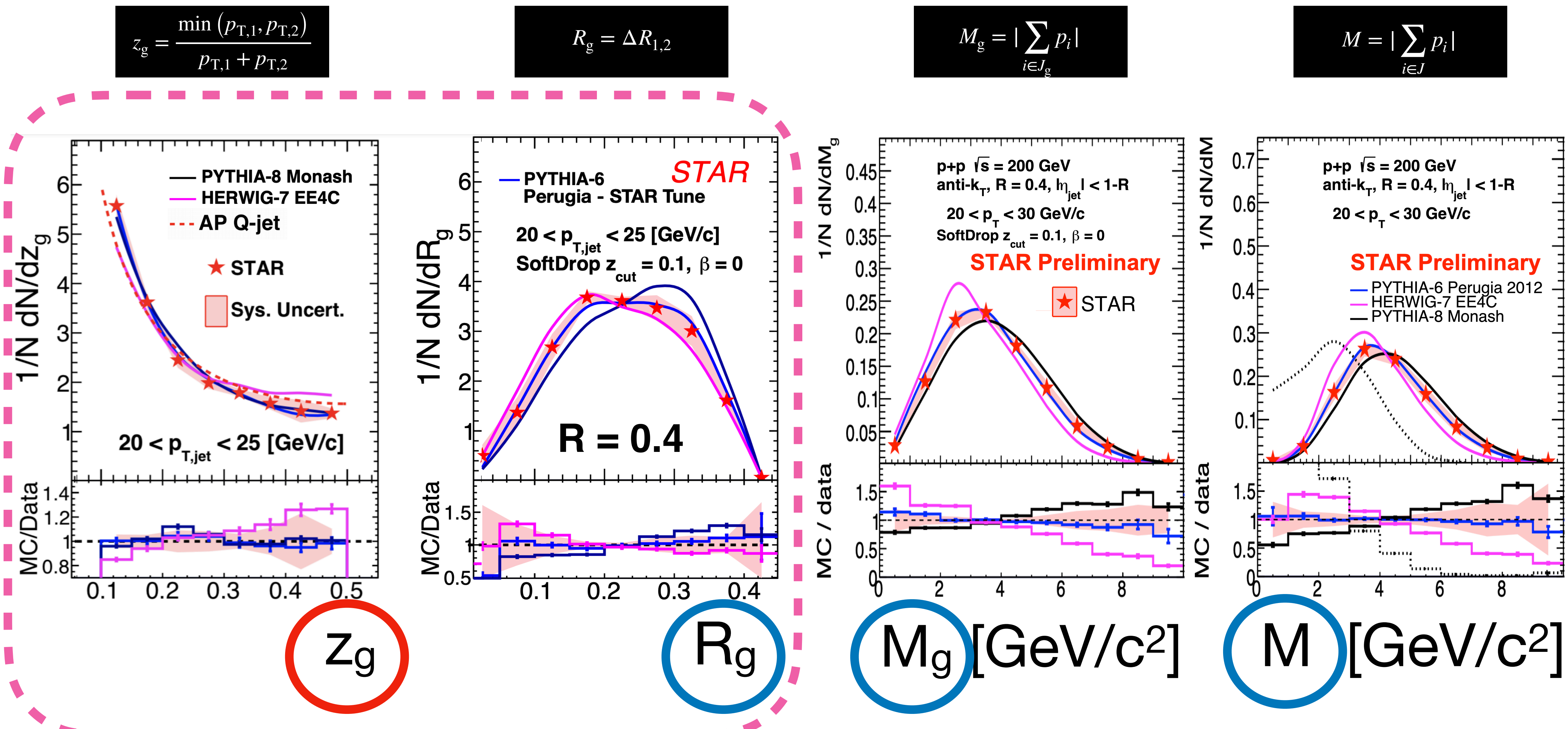
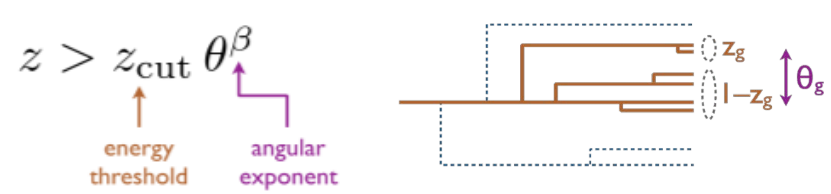
Jet substructure in *pp* collisions

STAR has established a *pp* jet substructure baseline which agrees with STAR-tuned LO MC (PYTHIA-6)



arXiv:2003.02114 (accepted to PLB)



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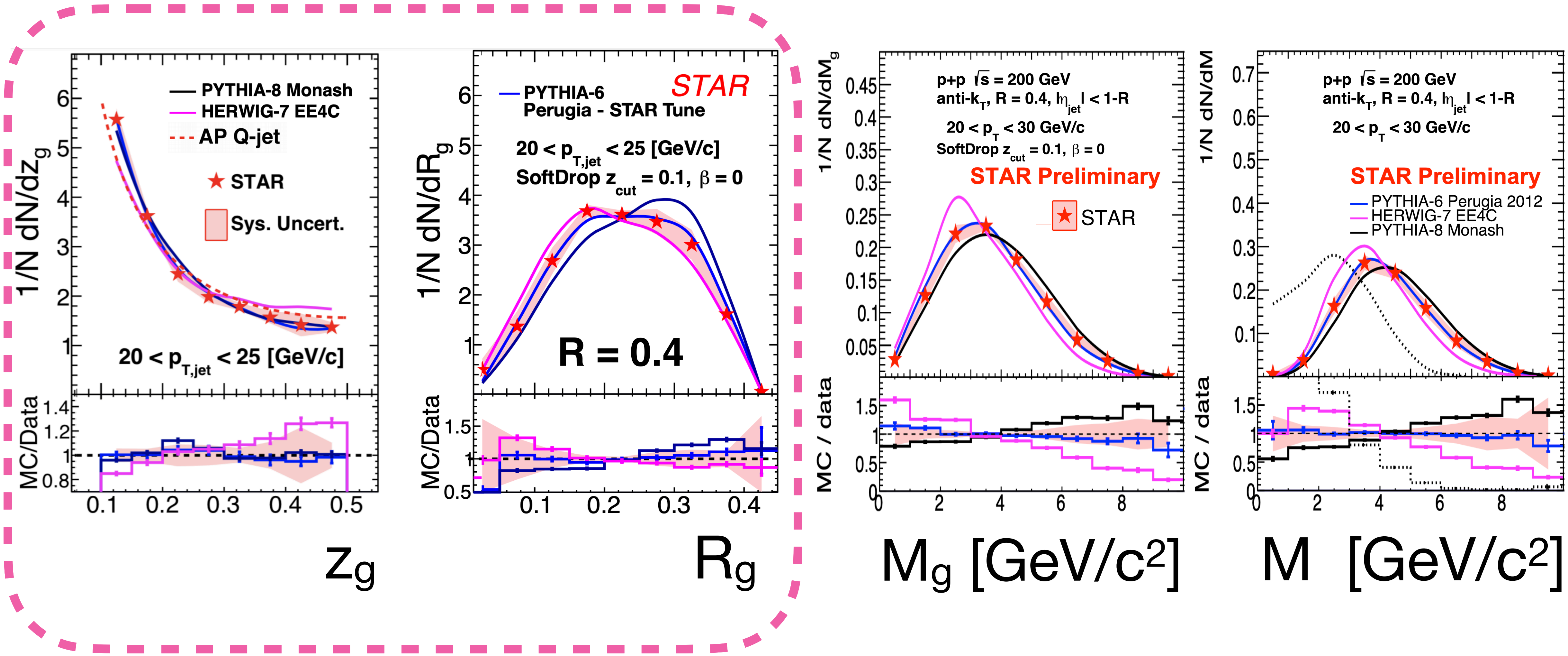
Opportunity for further tuning of PYTHIA-8 and HERWIG-7, which over- and under-predict data, respectively



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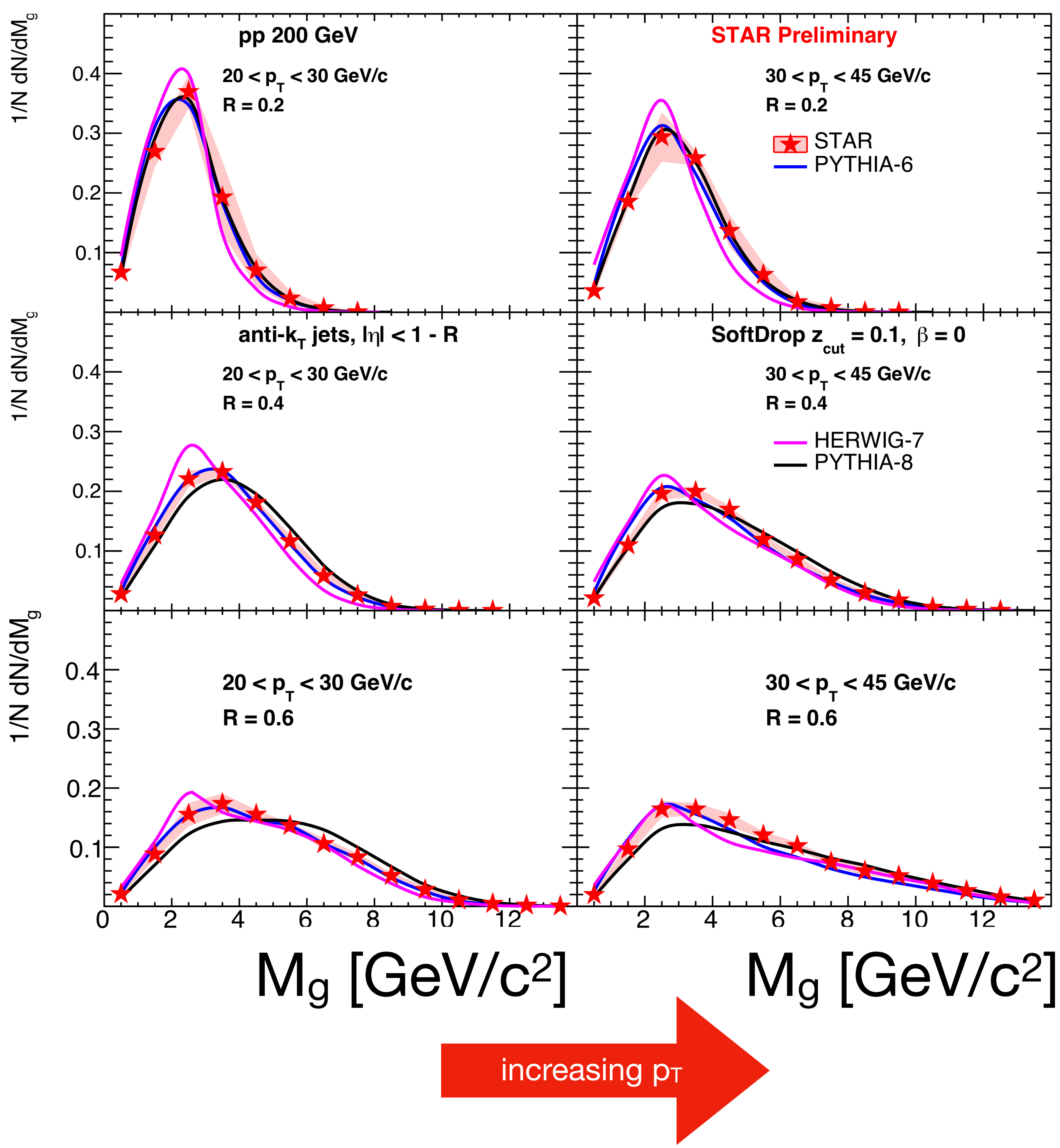
Jet substructure in *pp* collisions



Consistent substructure picture, comparing to evolution seen in R_g (see backup) with jet radius, given

$$M_g \sim z_g R_g^2$$

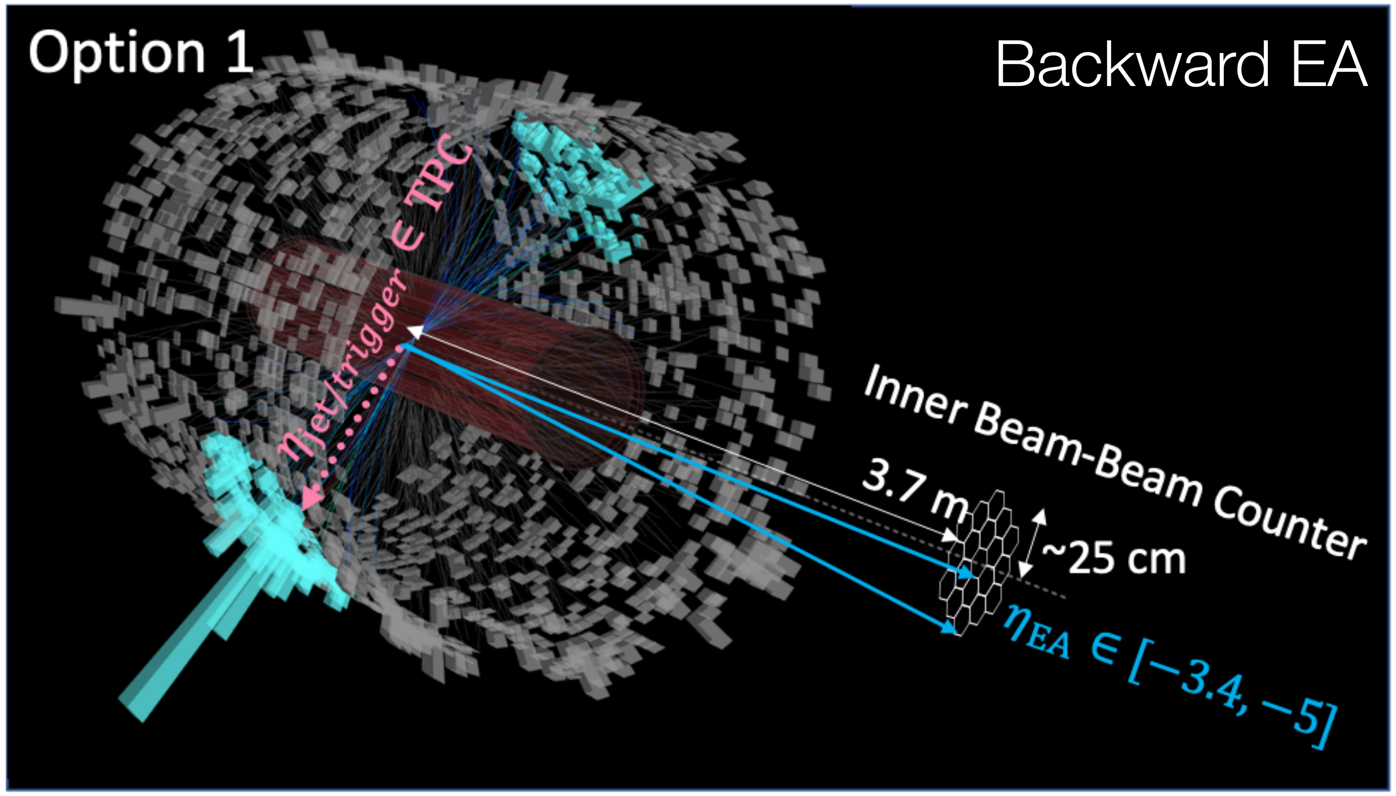
Consistent with pQCD expectation:

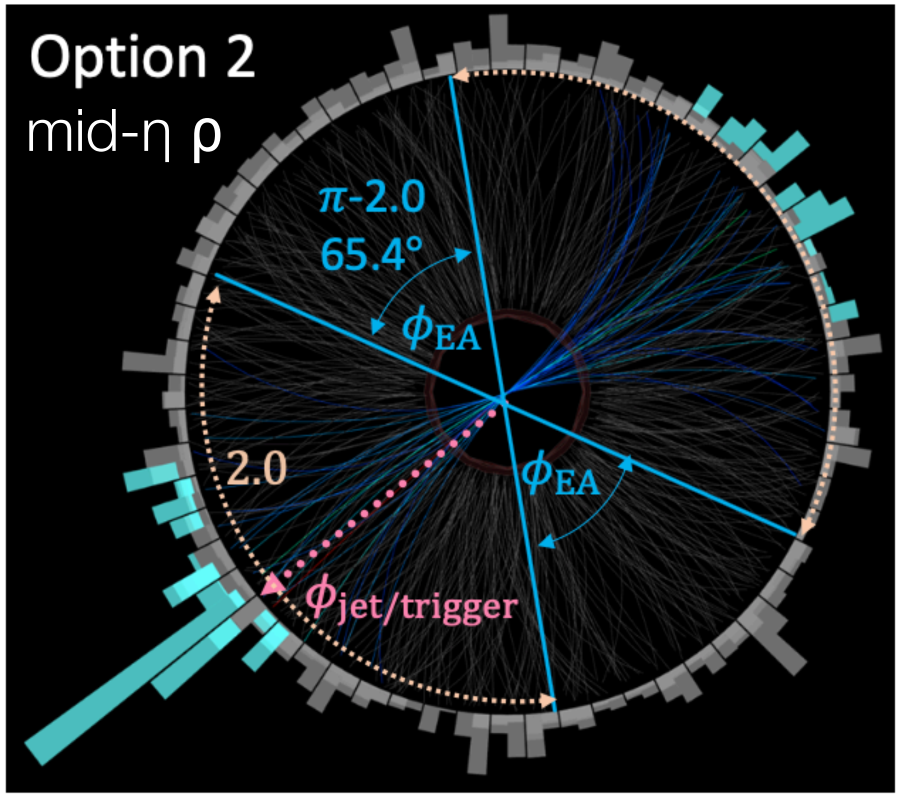
increased R & p_T
→ increased phase space for radiation
→ increased mass

Jet measurements in *p*A collisions

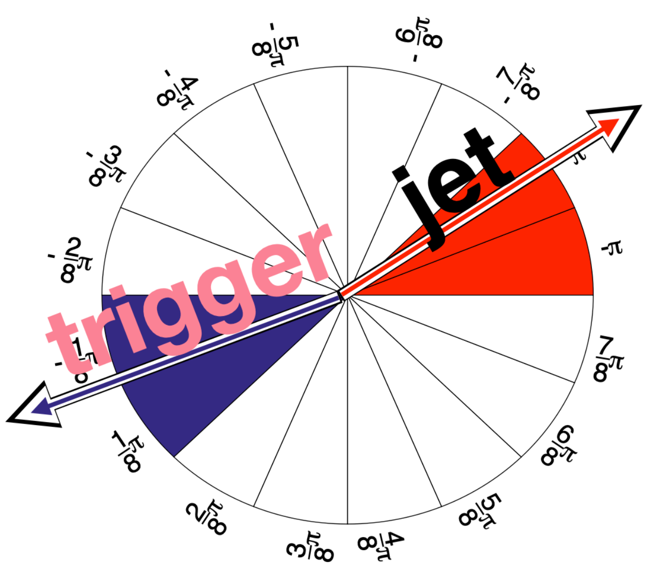
To have a calibrated probe of the microscopic structure of the hot QCD medium (QGP) in A+A collisions, need to assess potential cold nuclear matter (CNM) effects

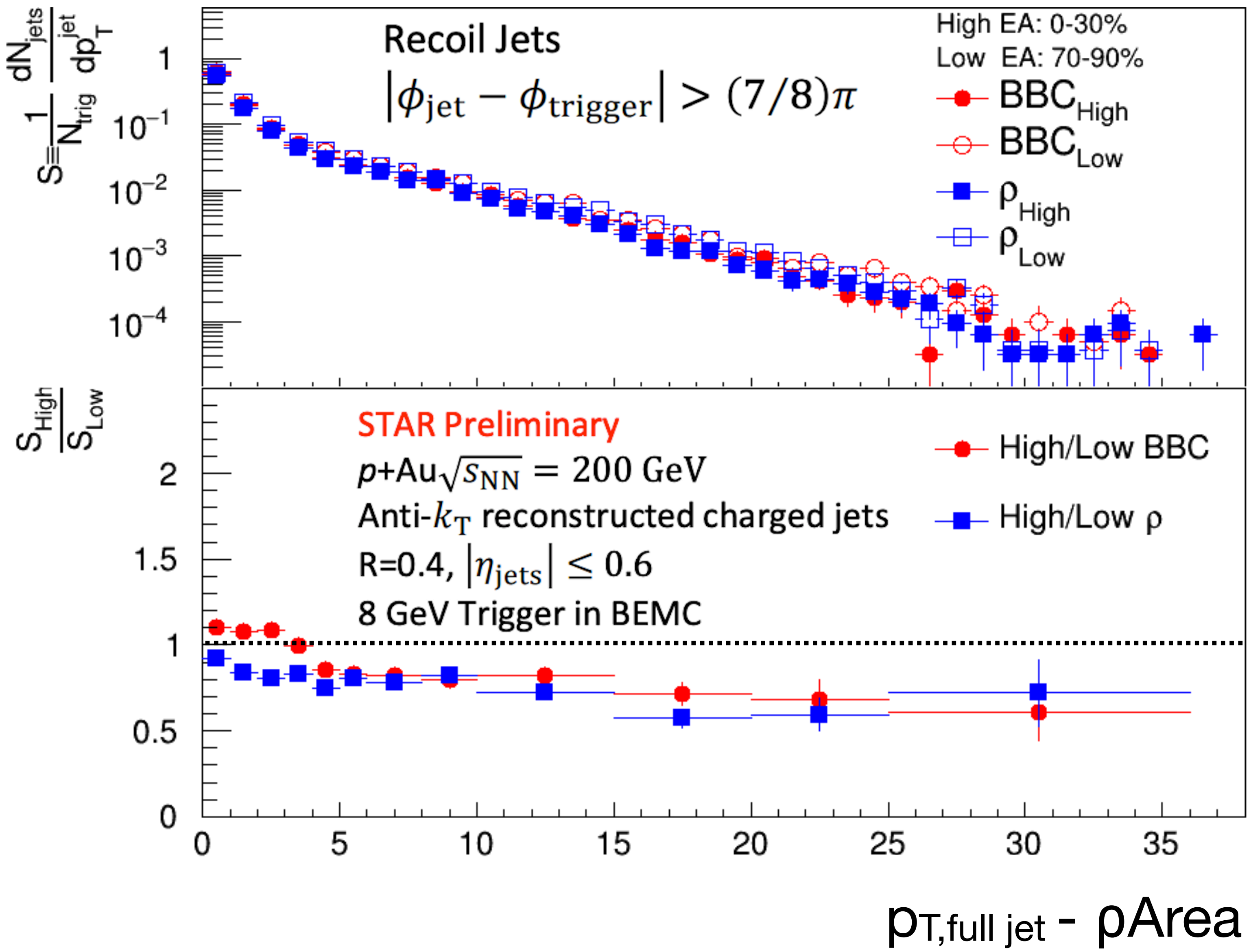
Currently in STAR, we have two options for definition of the activity of an event away from the jet in *p*A collisions





Semi-inclusive jet spectra

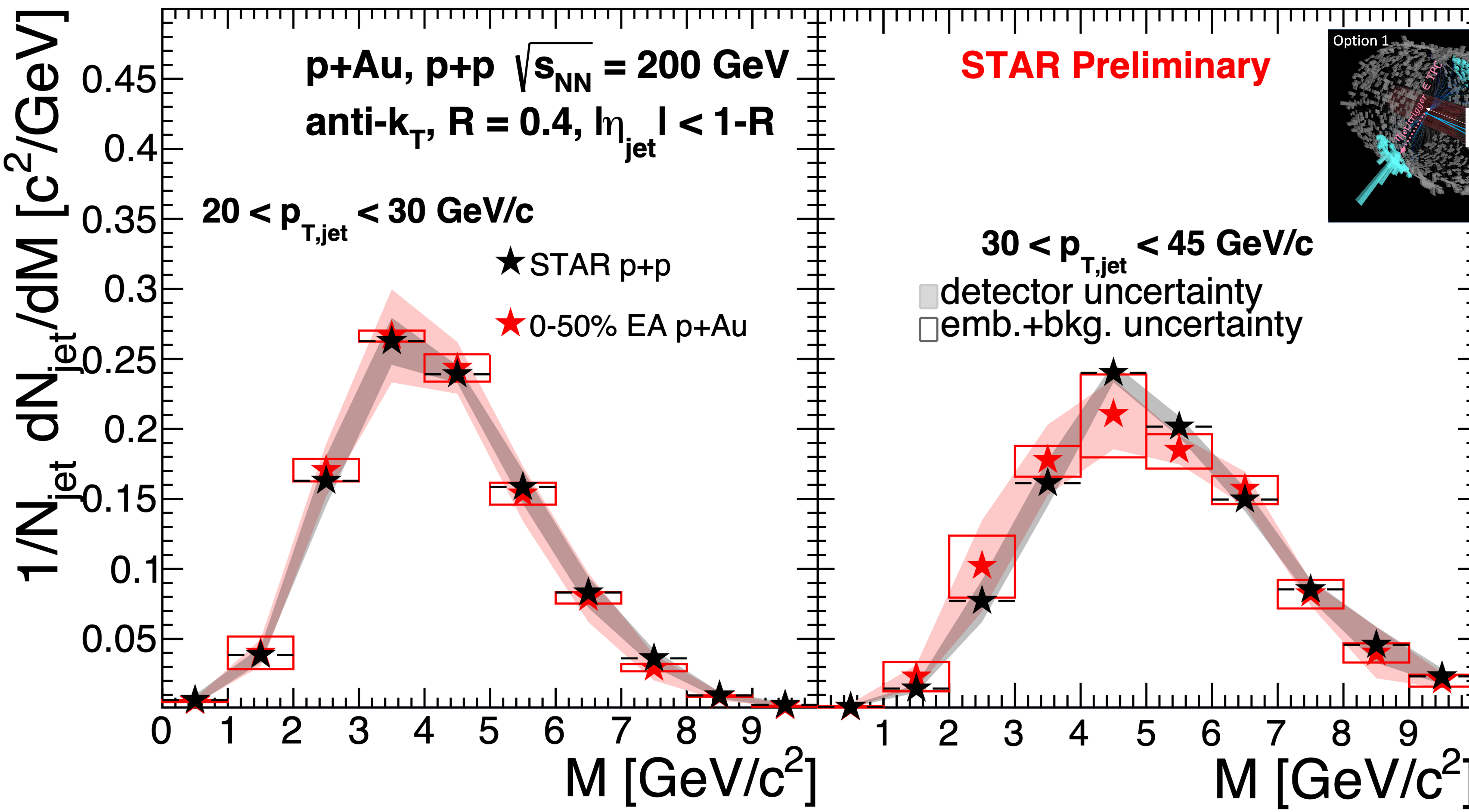


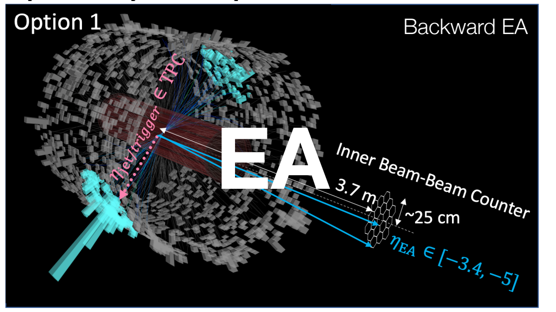


p_T-dependent suppression of recoil jet yield (and trigger jet - see backup) for both definitions of activity, more strongly for mid-η ρ

CNM effects / potential jet quenching in small systems?
Are jet substructure quantities affected?

Jet mass: high EA

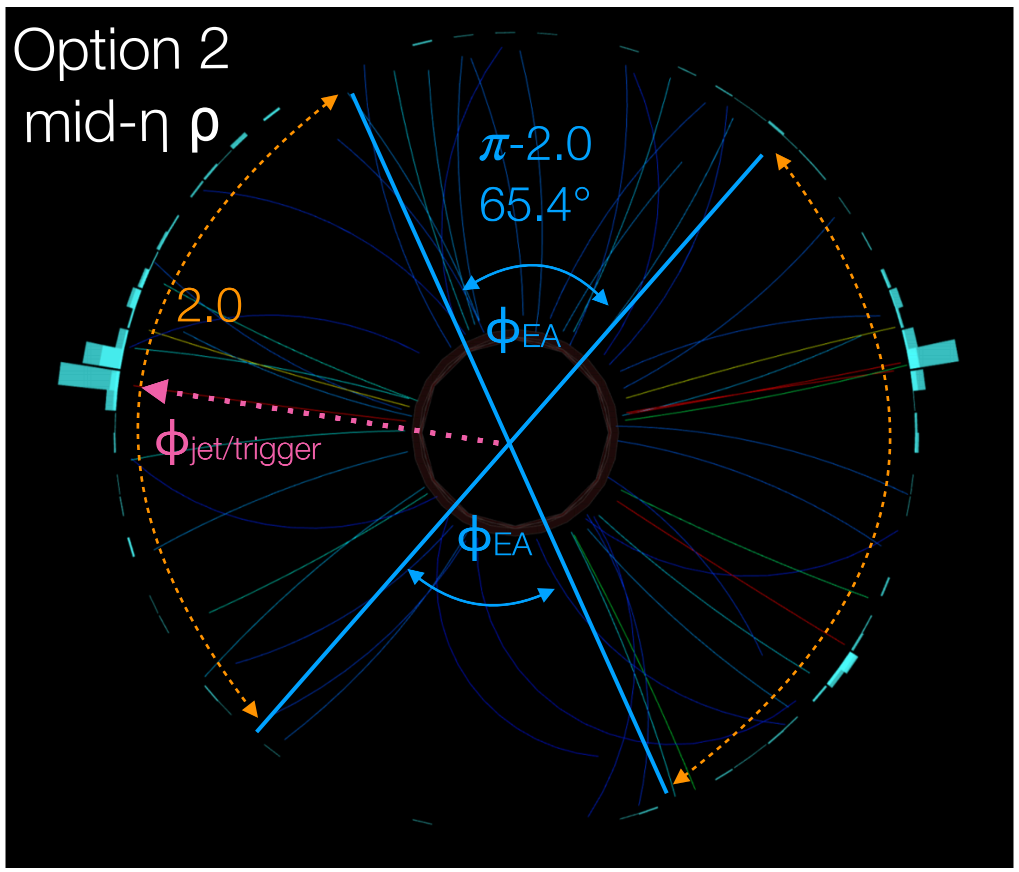




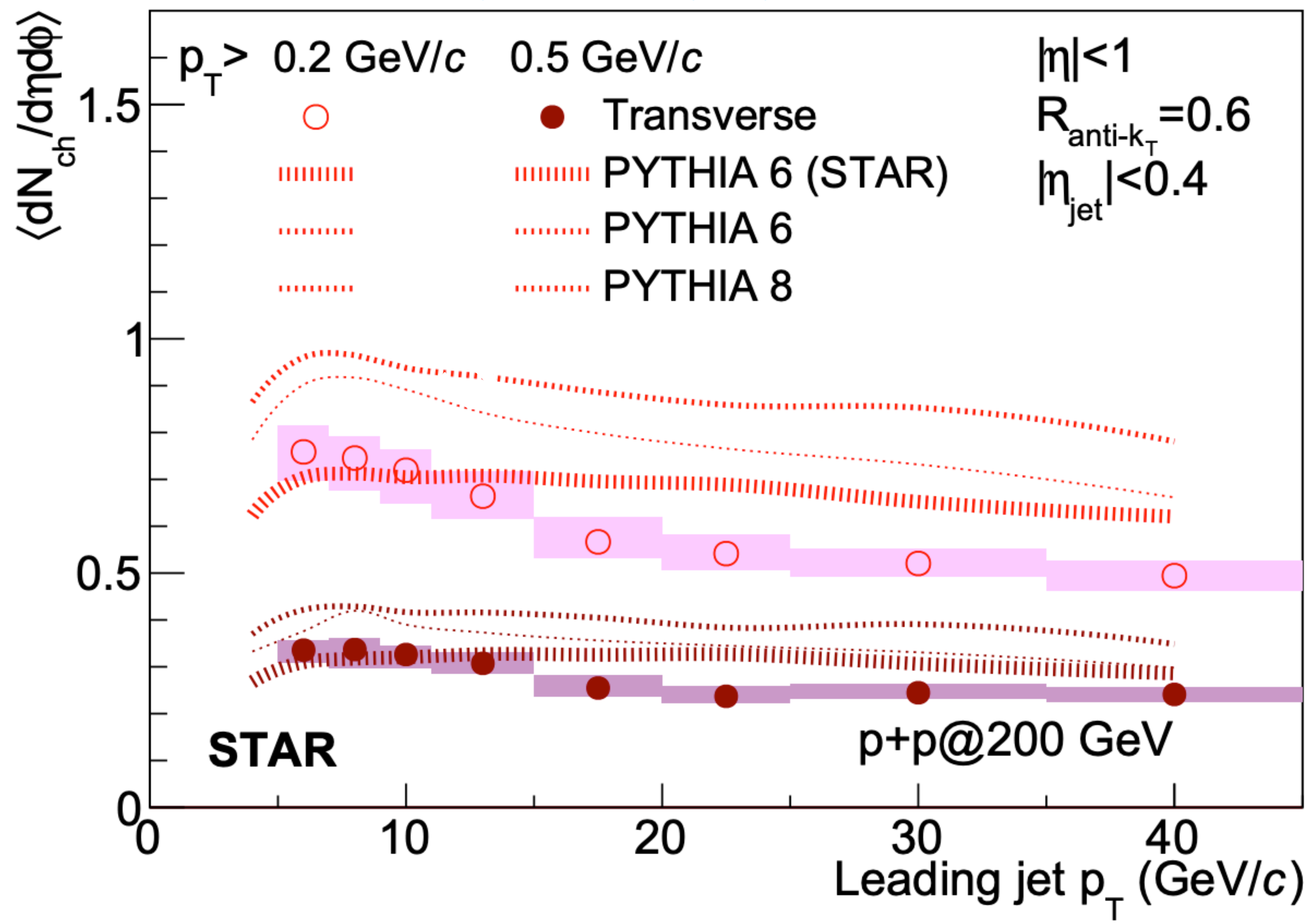
High-EA *pAu* jet mass consistent with *pp* within systematic and statistical uncertainties

No significant modification to jet mass is observed in *p*+Au!

Underlying event in *pp*



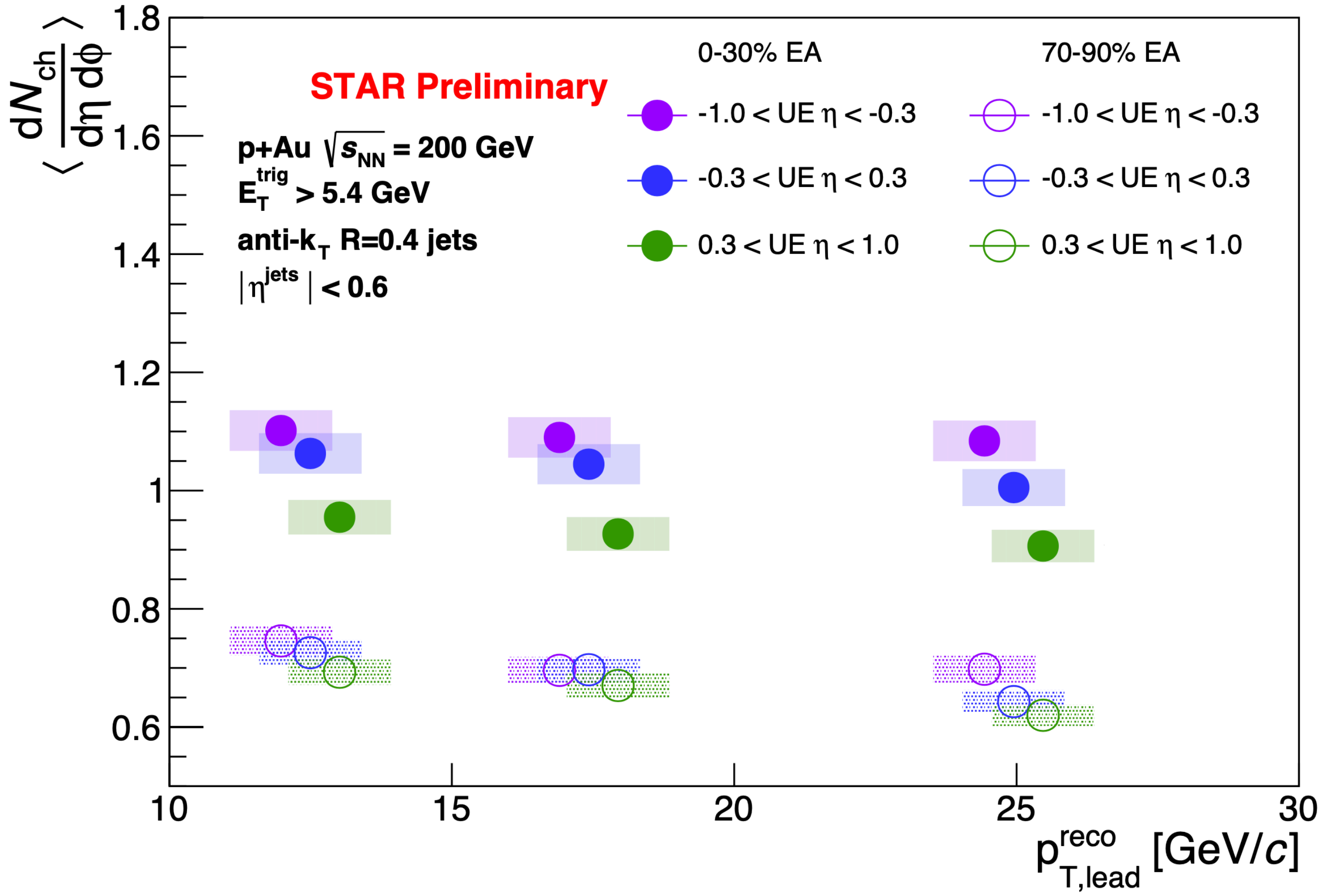
STAR Collaboration, Phys. Rev. D 101 (2020), 052004



UE decreases with increasing jet p_T but fairly flat above 20 GeV/c

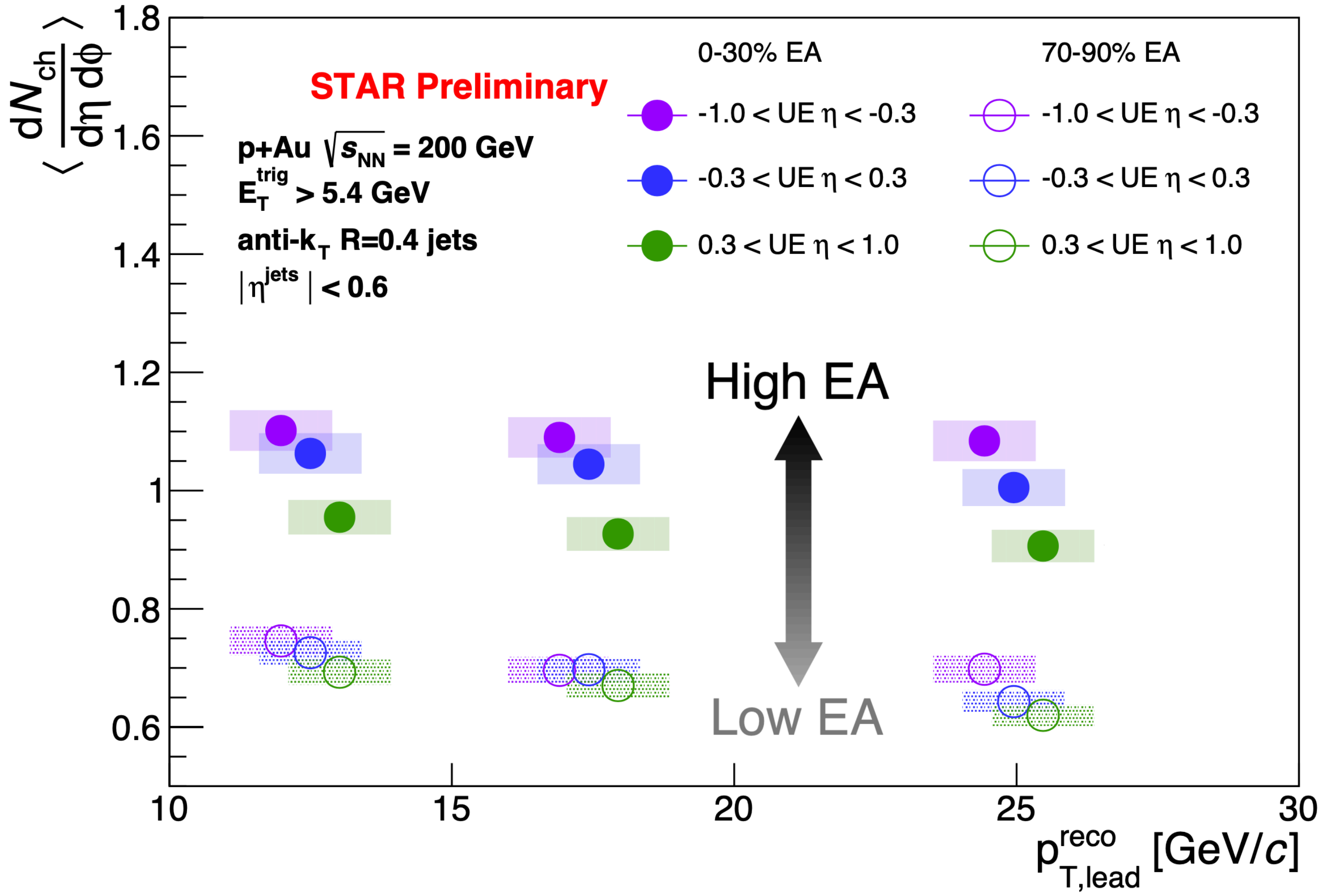
Is this measure of activity correlated with backward-rapidity activity in *p*Au events?

Underlying event in *pA*



Underlying event production:

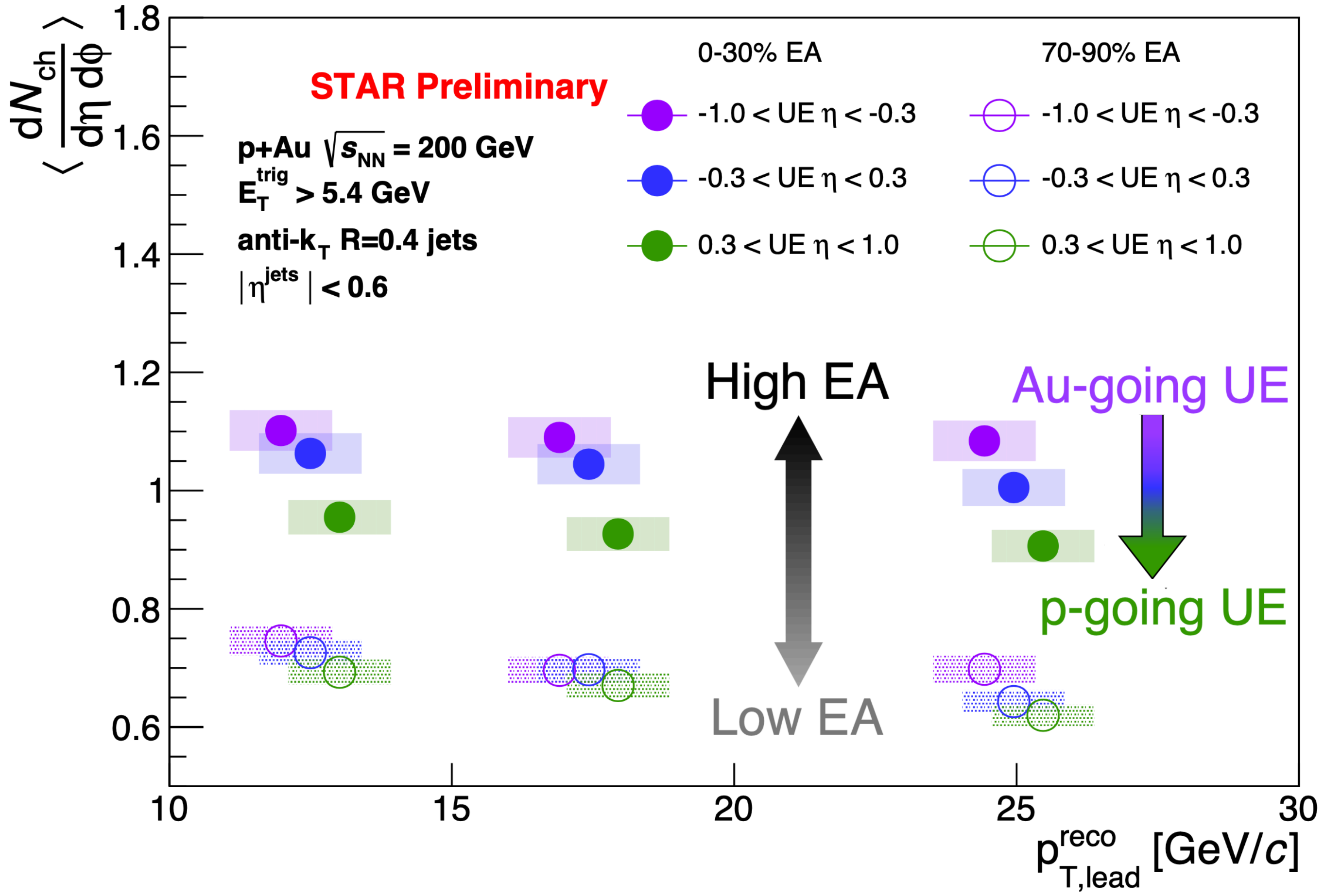
Underlying event in *pA*



Underlying event production:

- correlates with event activity at backward-rapidity

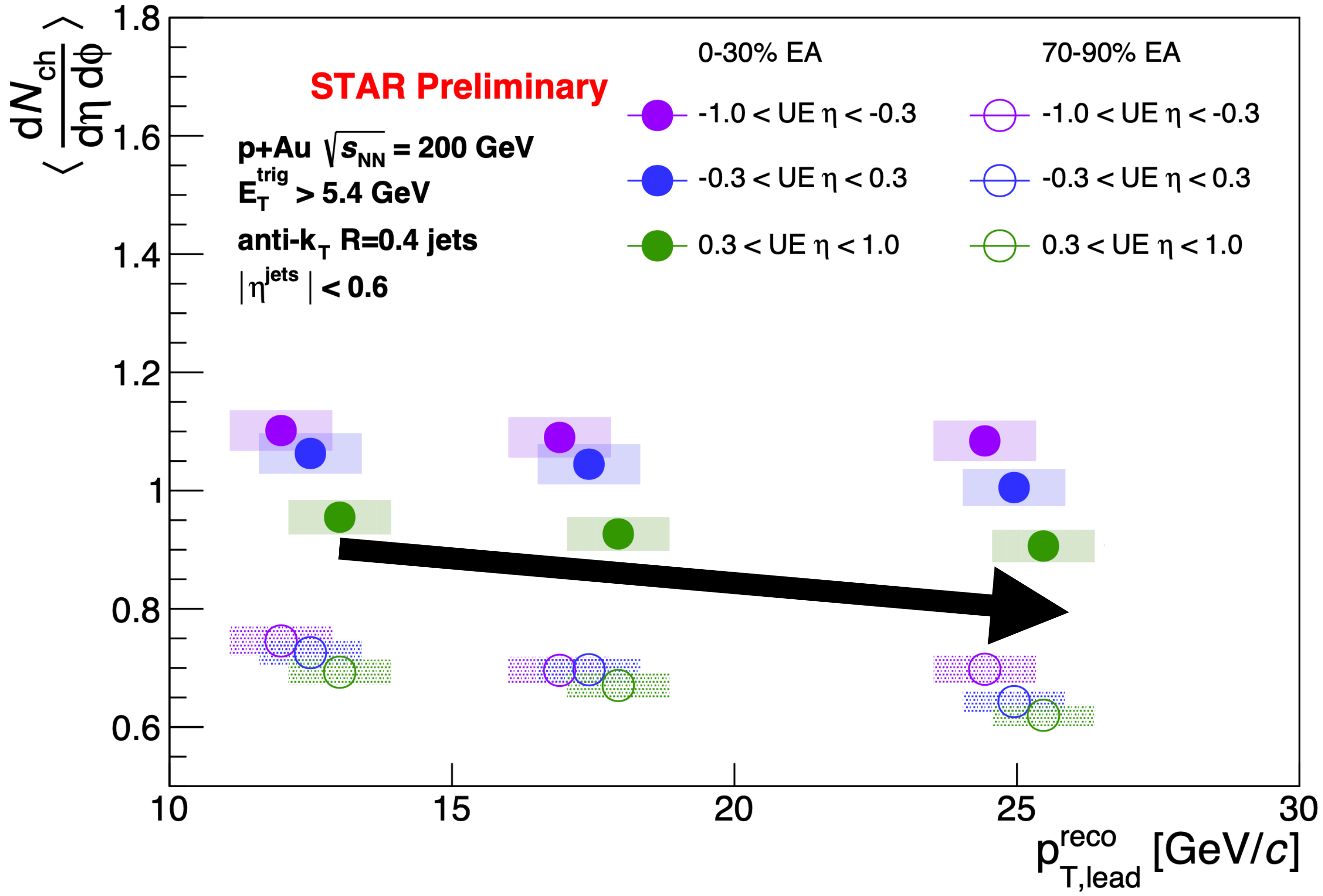
Underlying event in *pA*



Underlying event production:

- correlates with event activity at backward-rapidity
  - larger in the Au-going direction

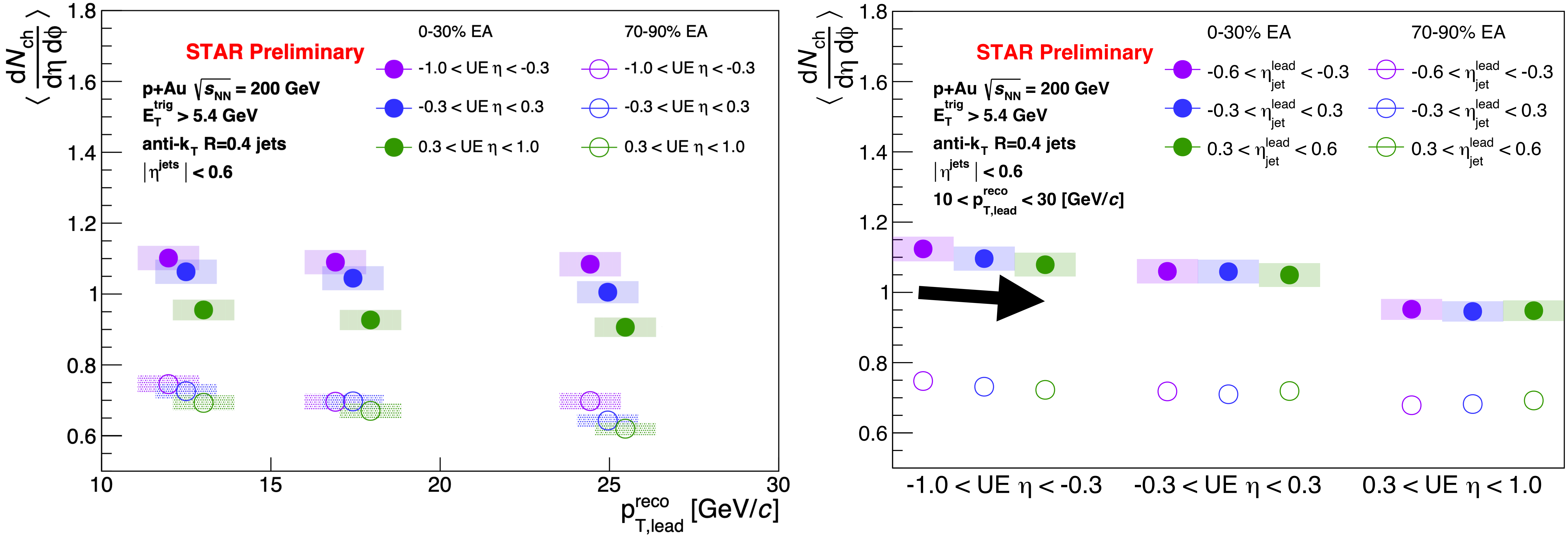
Underlying event in *pA*



Underlying event production:

- correlates with event activity at backward-rapidity
  - larger in the Au-going direction
    - slight anti-correlation with lead-jet p_T

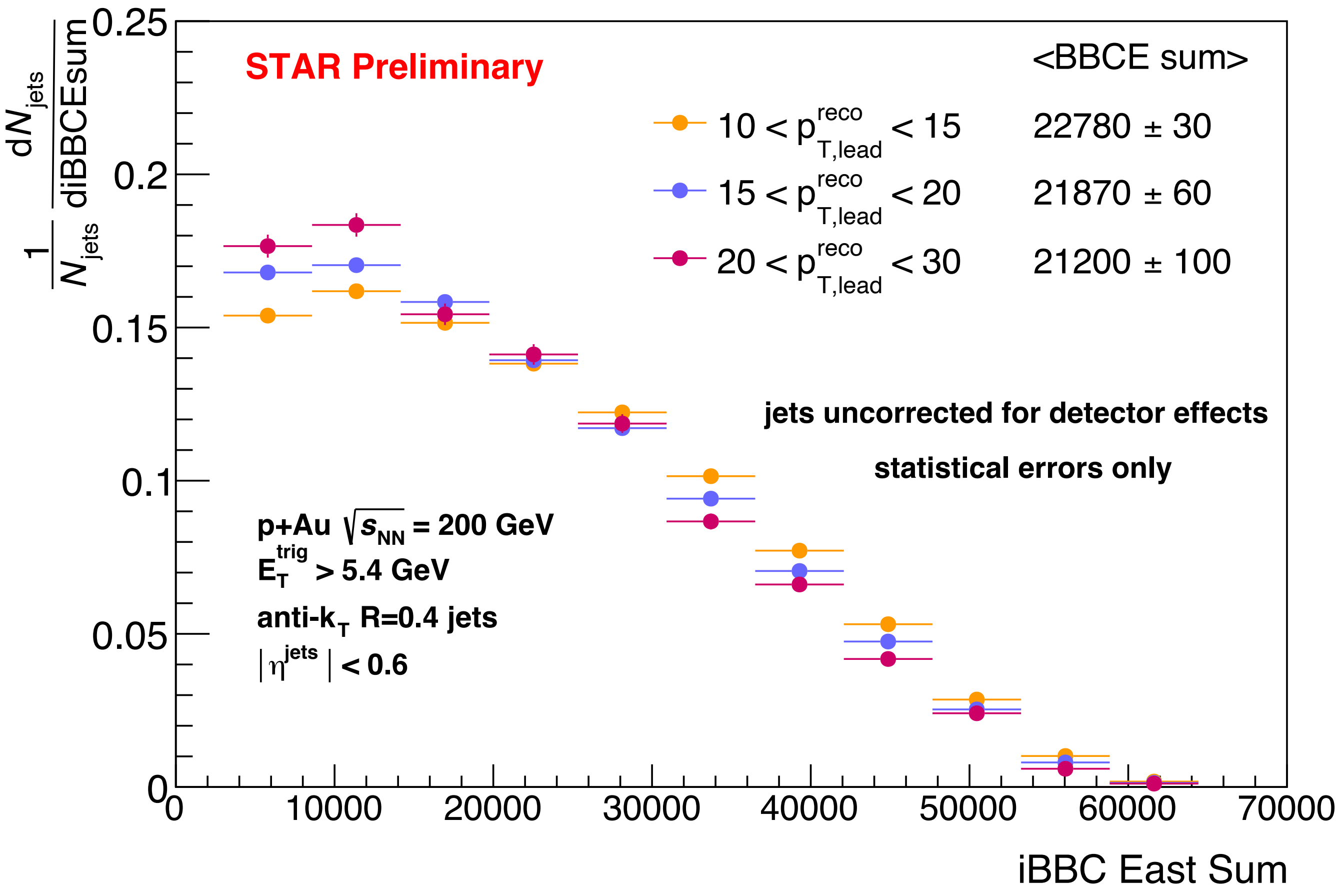
Underlying event in pA

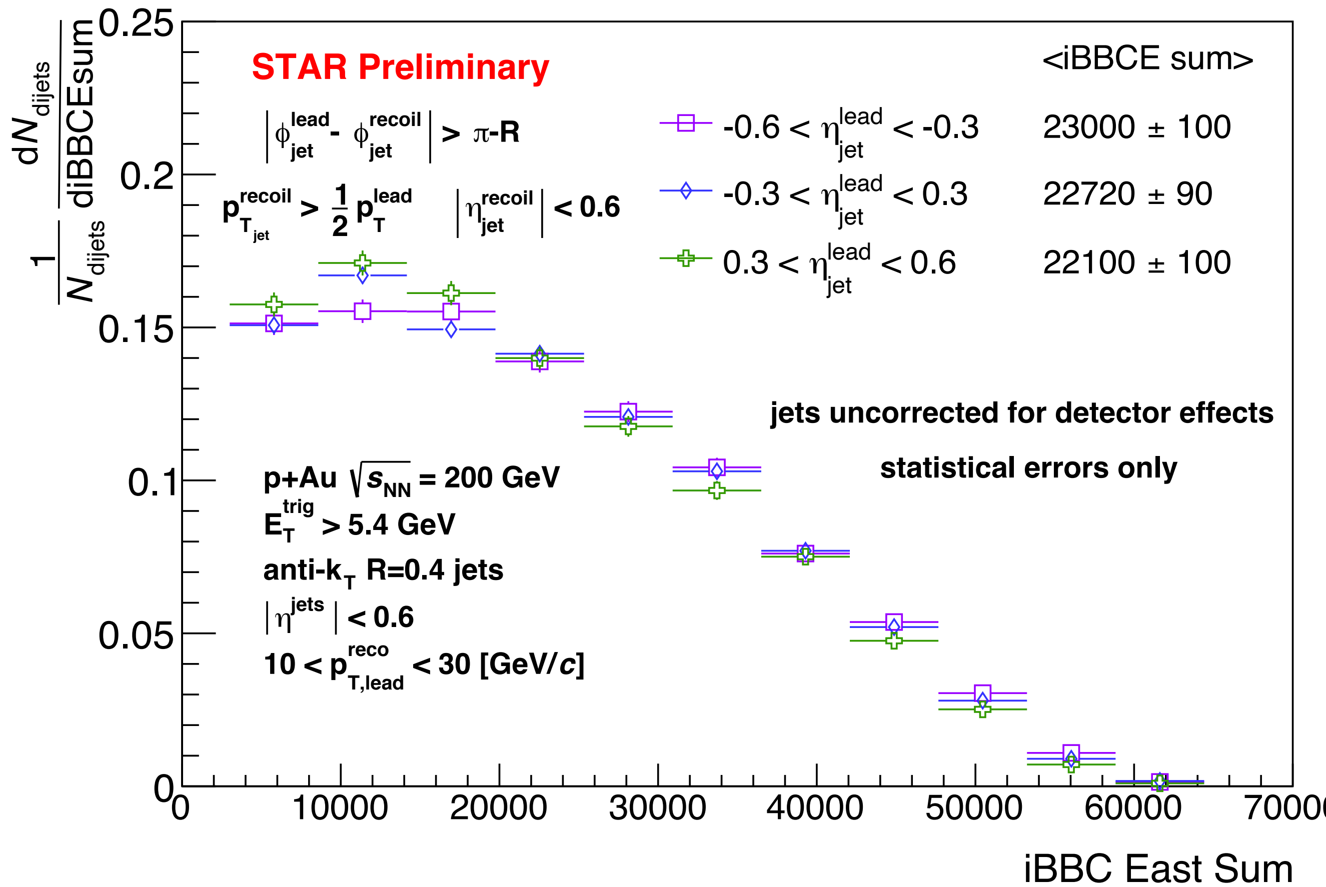


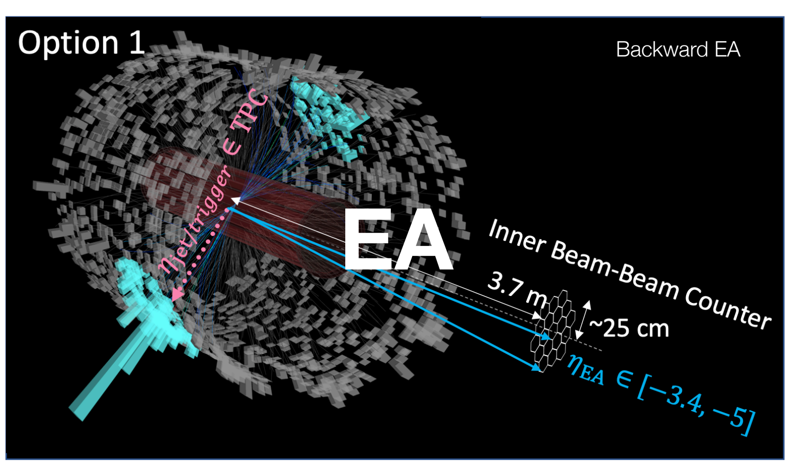
Underlying event production:

- correlates with event activity at backward-rapidity
  - larger in the Au-going direction
    - slight anti-correlation with lead-jet p_T
      - no significant correlation with lead-jet η

Event activity in *pA*







Event activity at large rapidity “biased” by jet rapidity and p_T at mid-rapidity

→ presence of high-Q^2 process affects activity measure at backward-rapidity!

→ *early-time effect*!

Summary of *p*A measurements

STAR

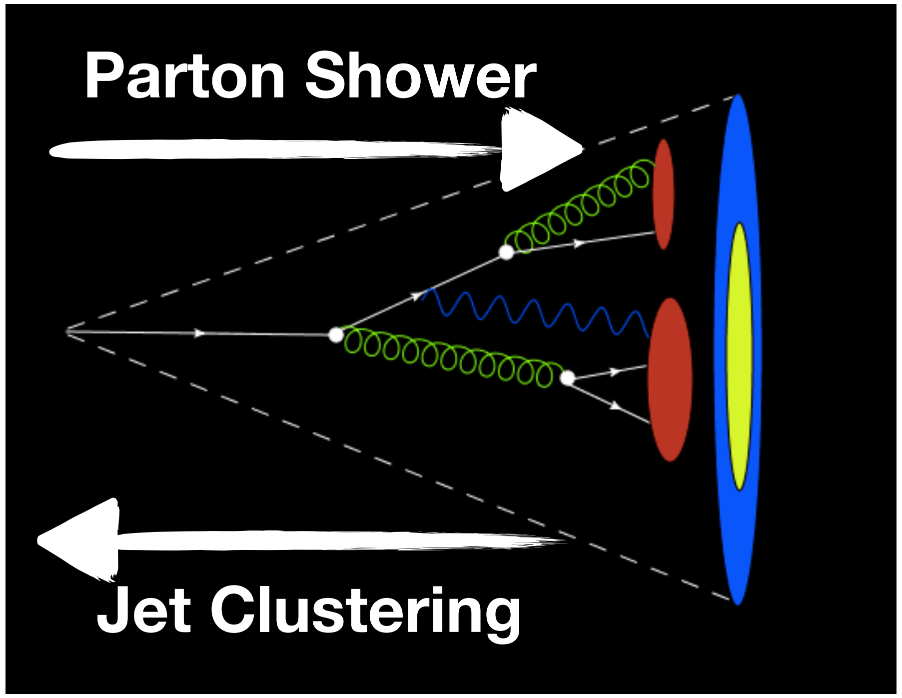
Observed a suppression of jet yields in high-activity *p*Au collisions using two (correlated) activity measures, EA & ρ

But no modification of a jet substructure observable (jet mass)

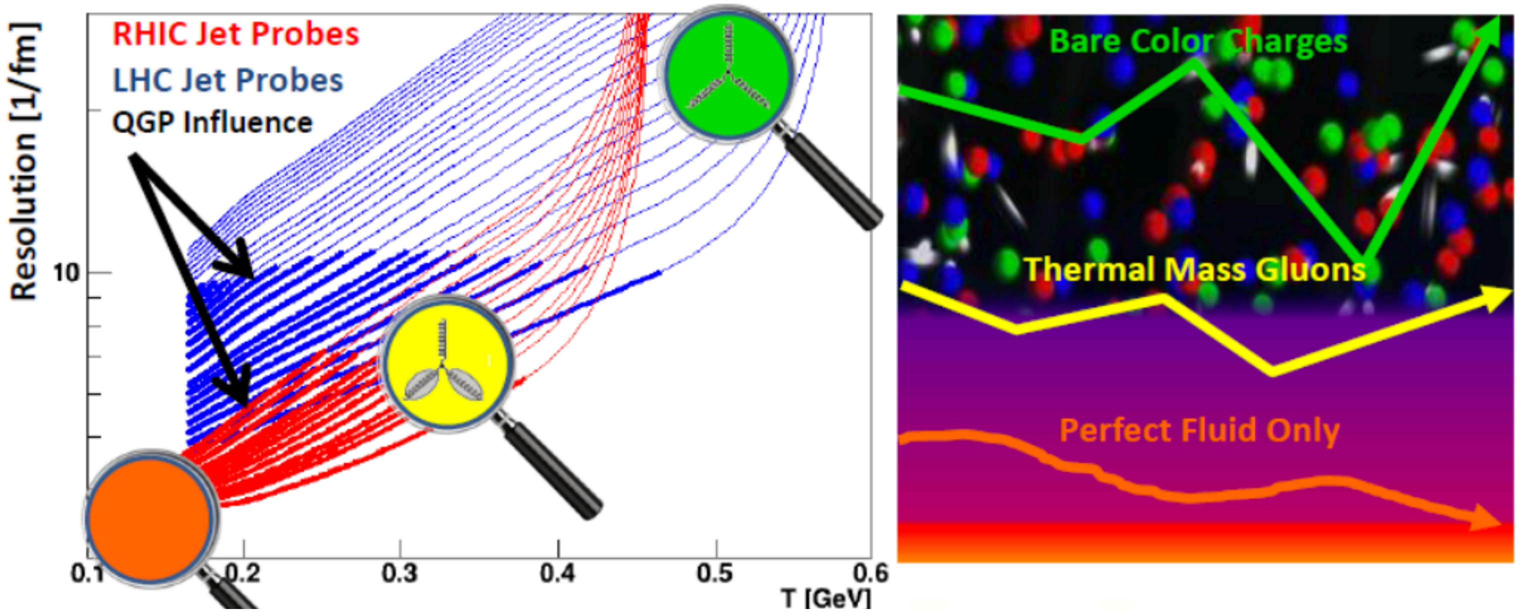
Observed correlation between hard and soft processes (used to define event activity) suggests the yield suppression is related to event activity classification

Can move forward with using jets as a calibrated probe of the hot QCD medium

Resolution scale in probing QGP



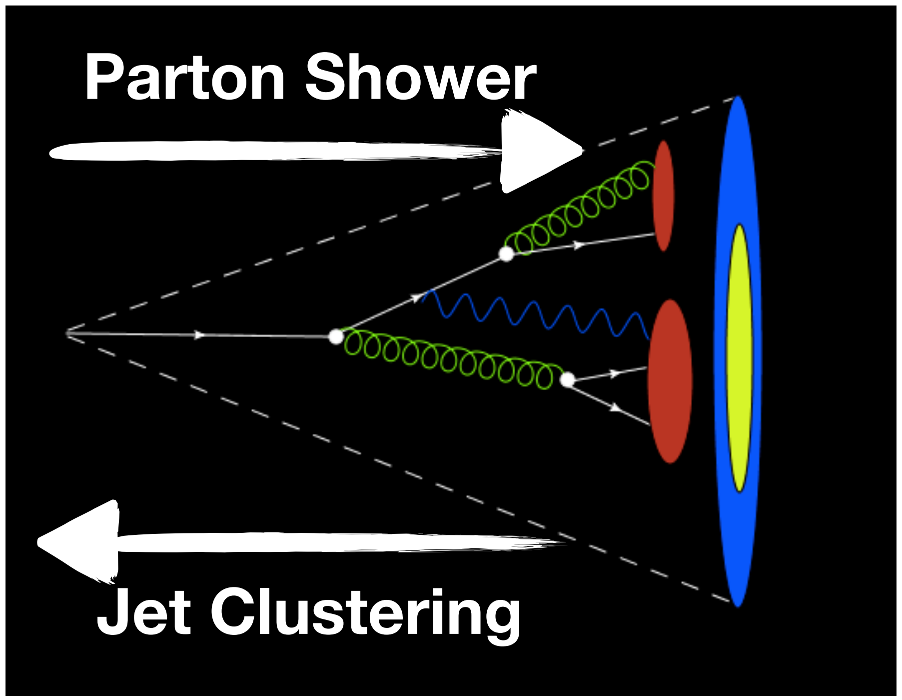
2015 NP LRP



Jet evolution/parton shower in vacuum is described by two fundamental scales - angle/ virtuality and momentum

This angle can be translated to a resolution scale in the medium!

Resolution scale in probing QGP



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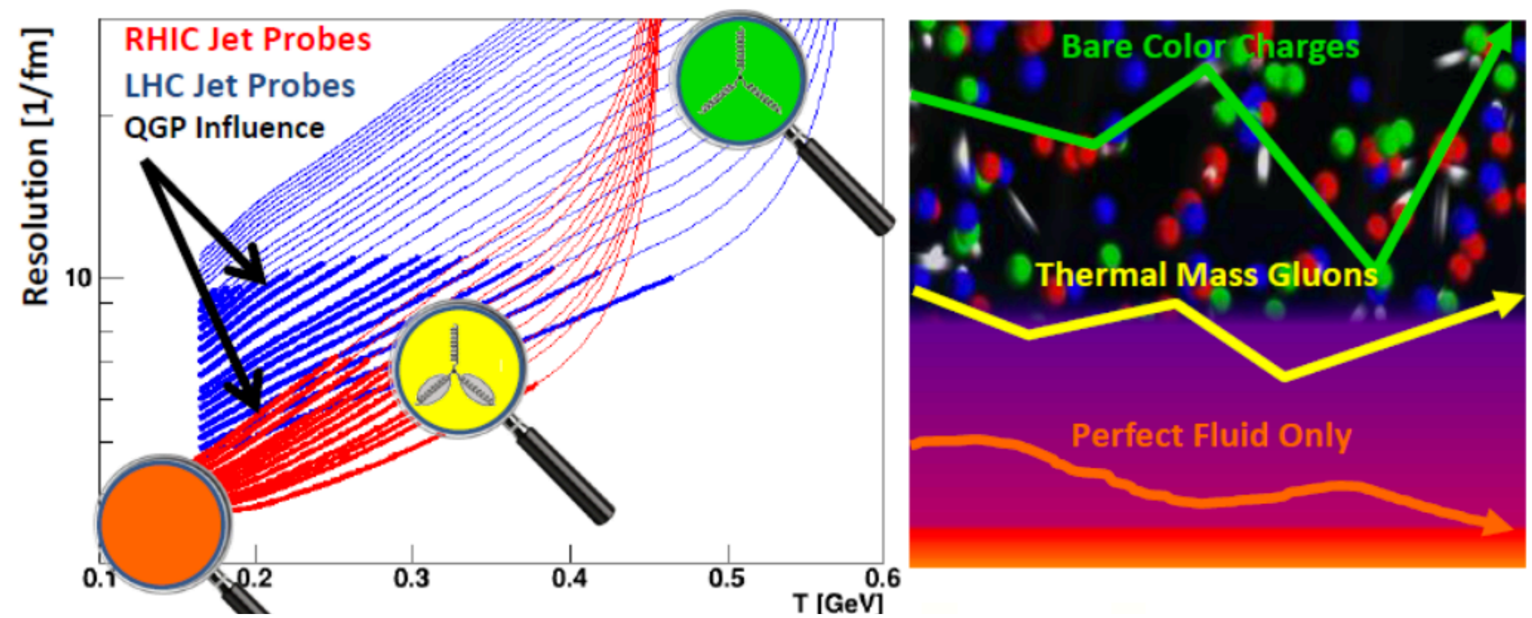

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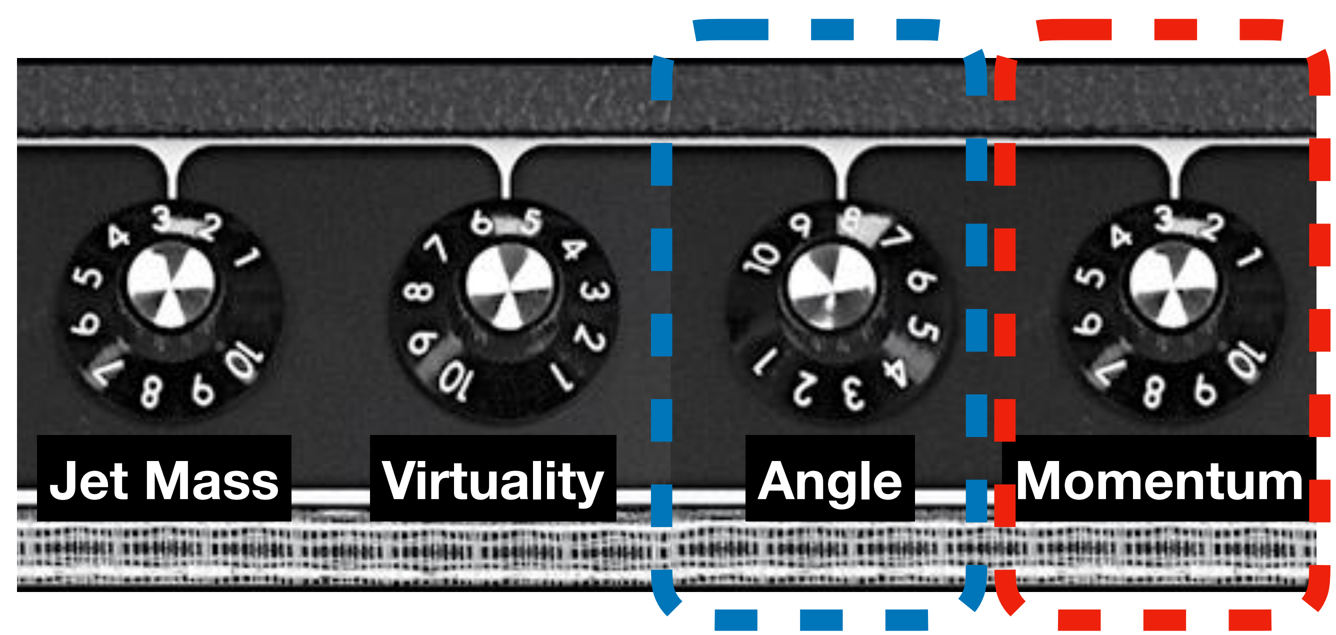
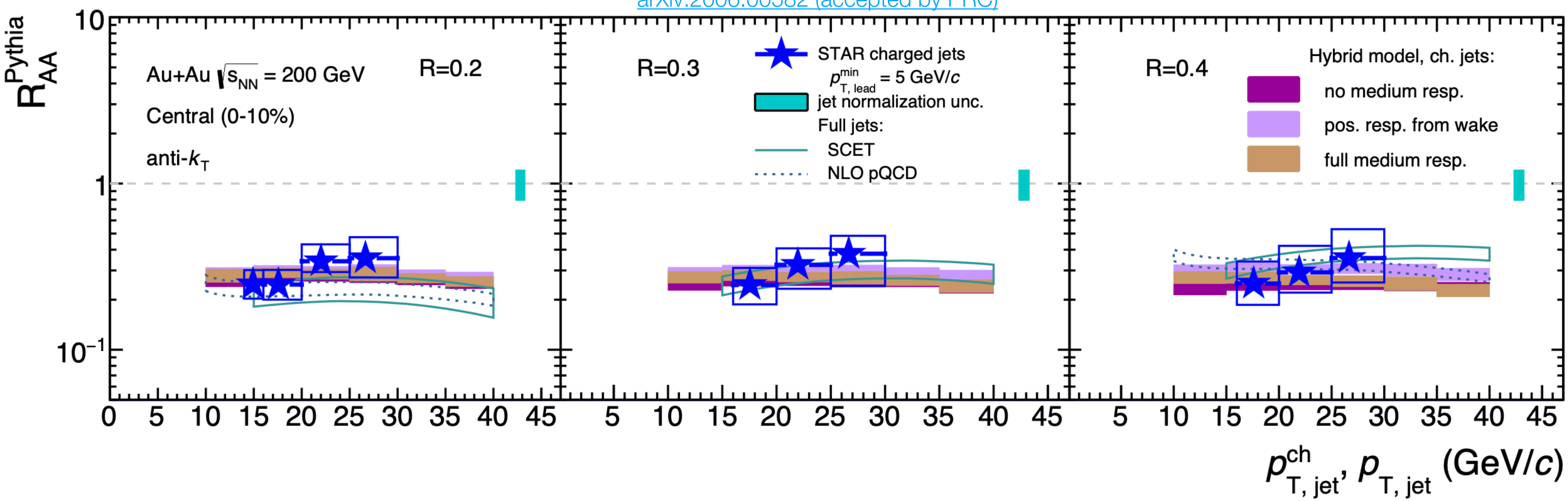


Inclusive jet yields

$$R_{AA} = \frac{dN^{AA}_{jet}/dp_{T,jet}}{\langle T_{AA}\rangle d\sigma^{pp}_{jet}/dp_{T,jet}}$$

arXiv:2006.00582 (accepted by PRC)

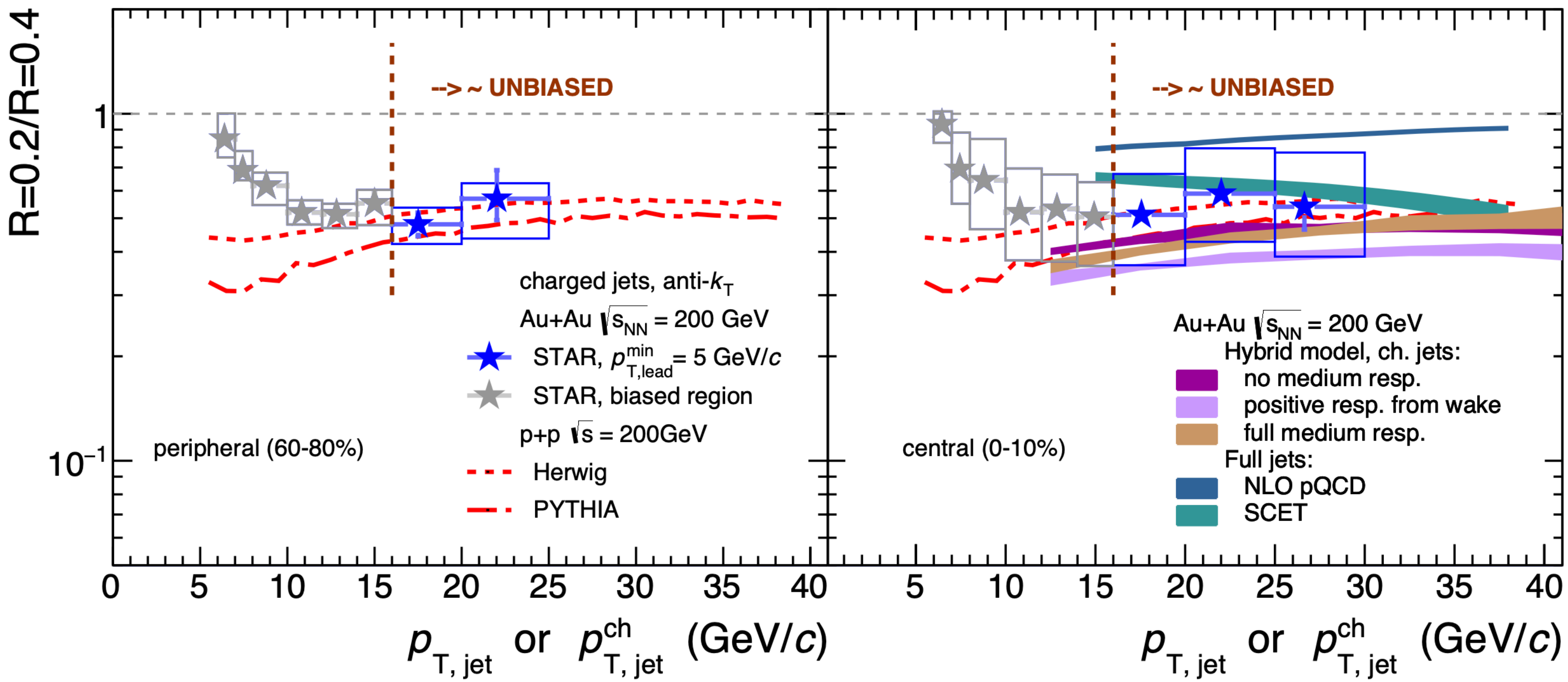


Using STAR-tuned PYTHIA-6 Perugia 2012 as baseline, charged-jet R_{AA} measured for the first time at RHIC in Au+Au collisions!

Suppression in Au+Au collisions consistent with all models tested

Jet broadening?

[arXiv:2006.00582 (accepted by PRC)]

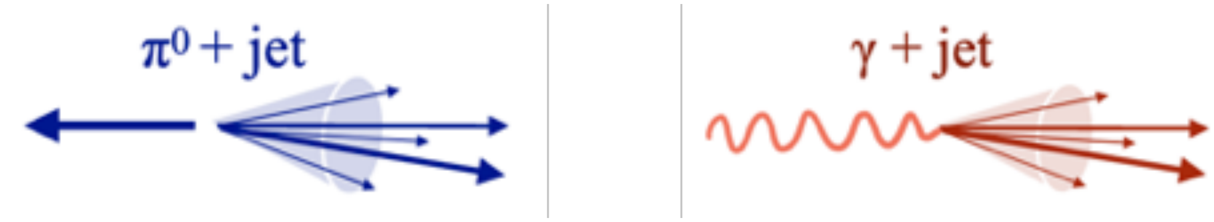


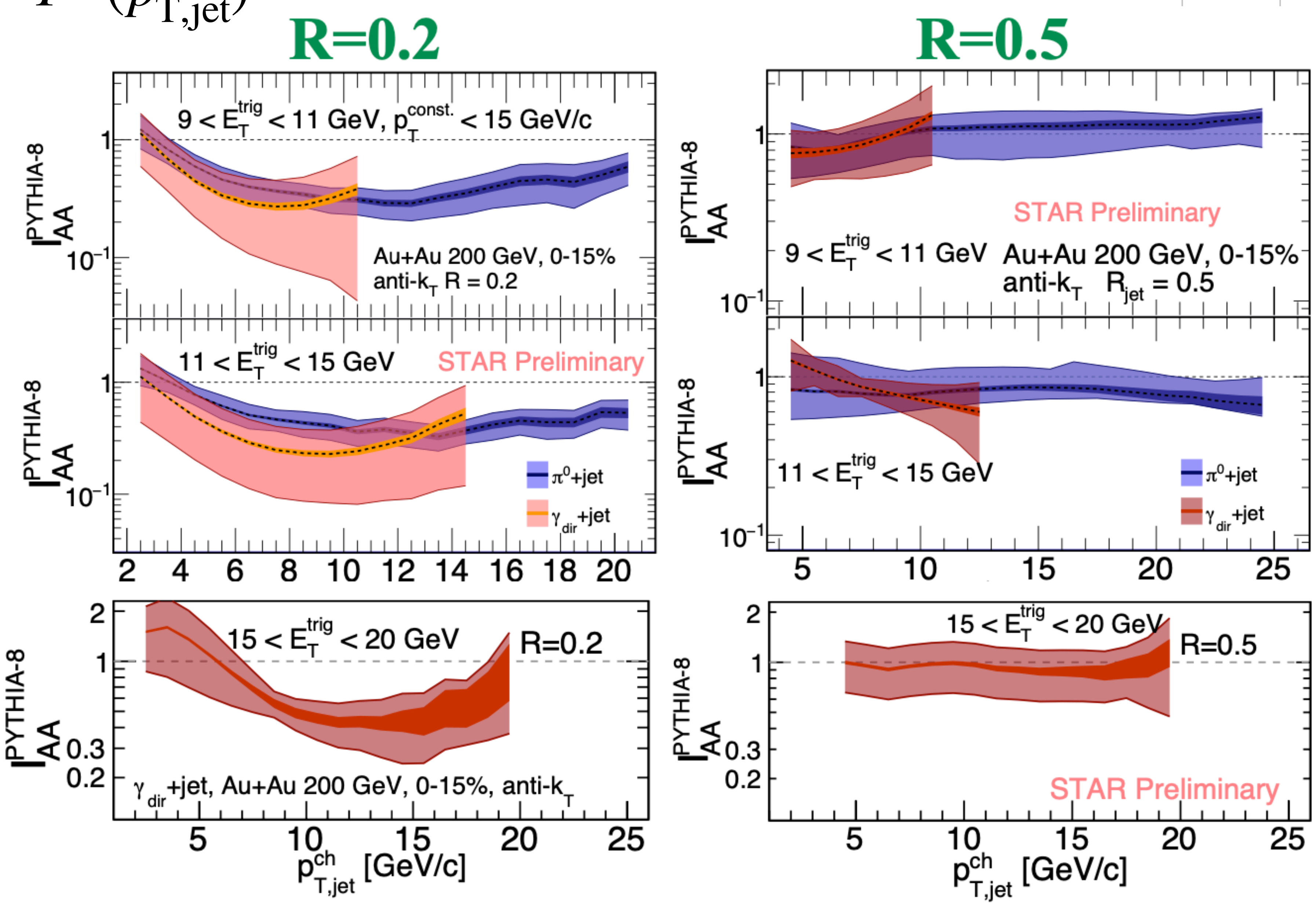
Inclusive jet yield ratio for R = 0.2 / R = 0.4: Central Au+Au ~ *pp*

→ within systematics, the observable shows no significant medium-induced broadening in the measured kinematics

Semi-inclusive jet yields

$$I_{AA}(p_{T,jet}^{ch}) = \frac{Y^{AA}(p_{T,jet}^{ch})}{Y^{pp}(p_{T,jet}^{ch})}$$



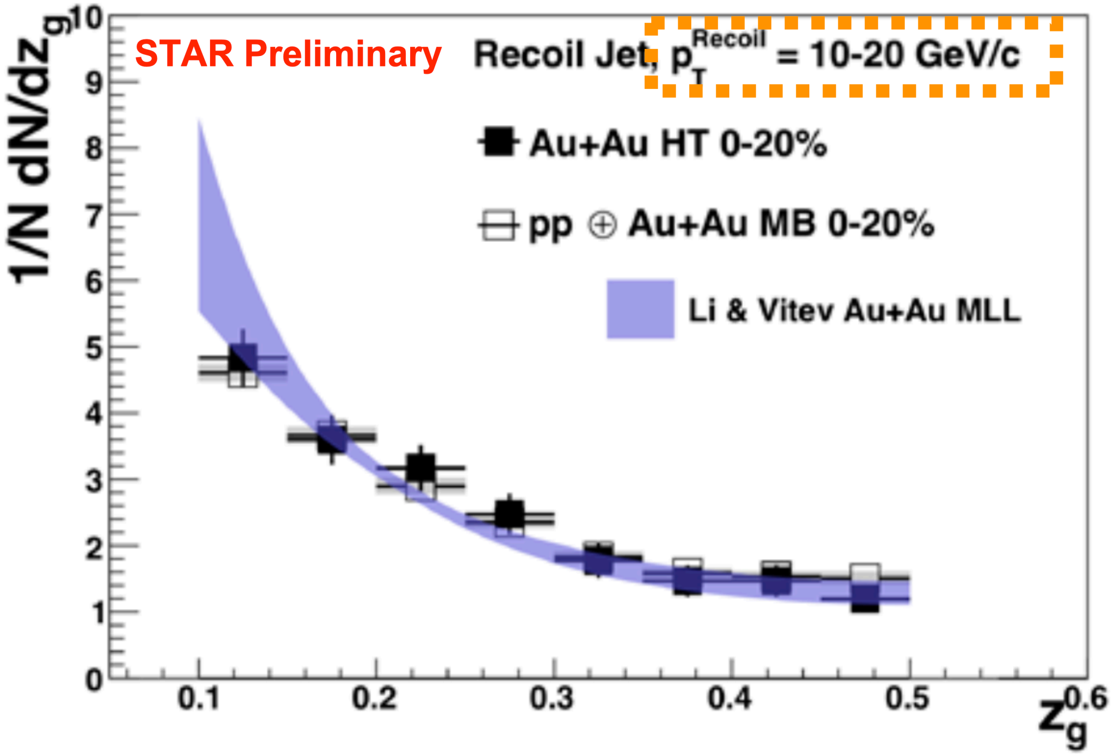


*See backup for comparison to PYTHIA-*6*

Suppression for R = 0.2 recoil jets relative to PYTHIA-8* (independent of trigger energy) but not R = 0.5

Groomed momentum fraction

For STAR's hardcore dijet selection, no significant modification to this momentum-scale observable



$$z > z_{\text{cut}}\,\theta^{\beta}$$

energy threshold

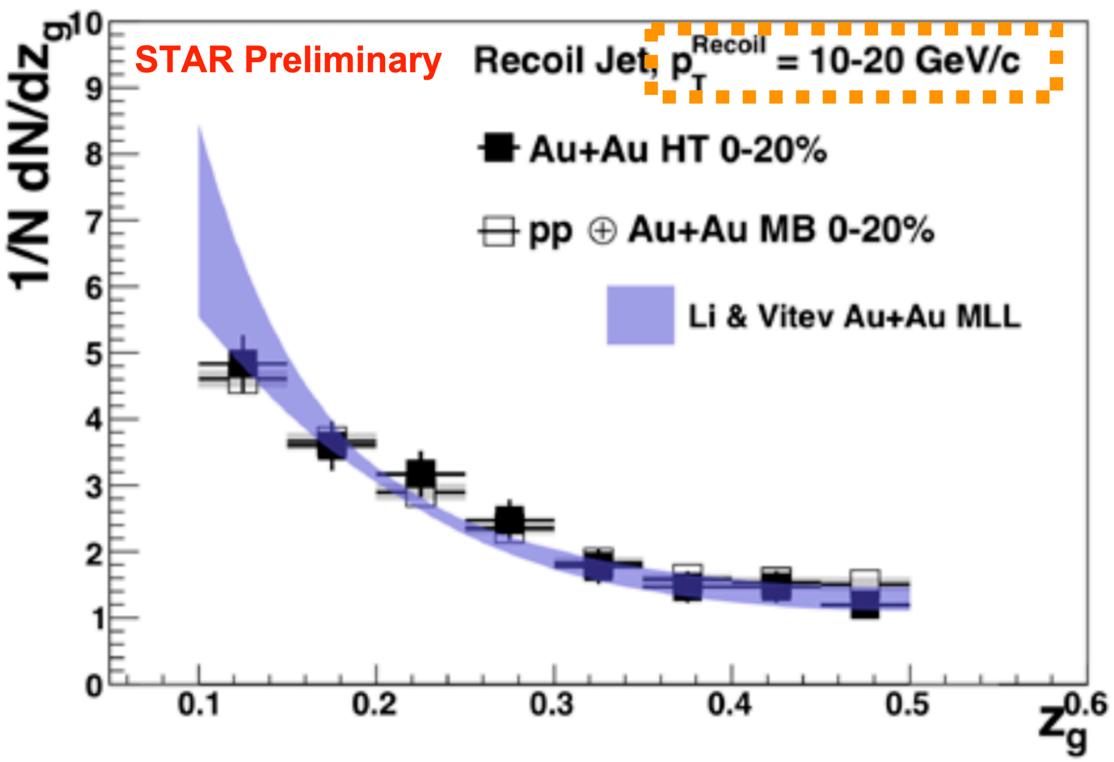
angular exponent

$$z_g = \frac{\min\left(p_{T1}, p_{T2}\right)}{p_{T1} + p_{T2}}$$

What about semi-inclusive population?

Groomed momentum fraction

For STAR's hardcore dijet selection, no significant modification to this momentum-scale observable



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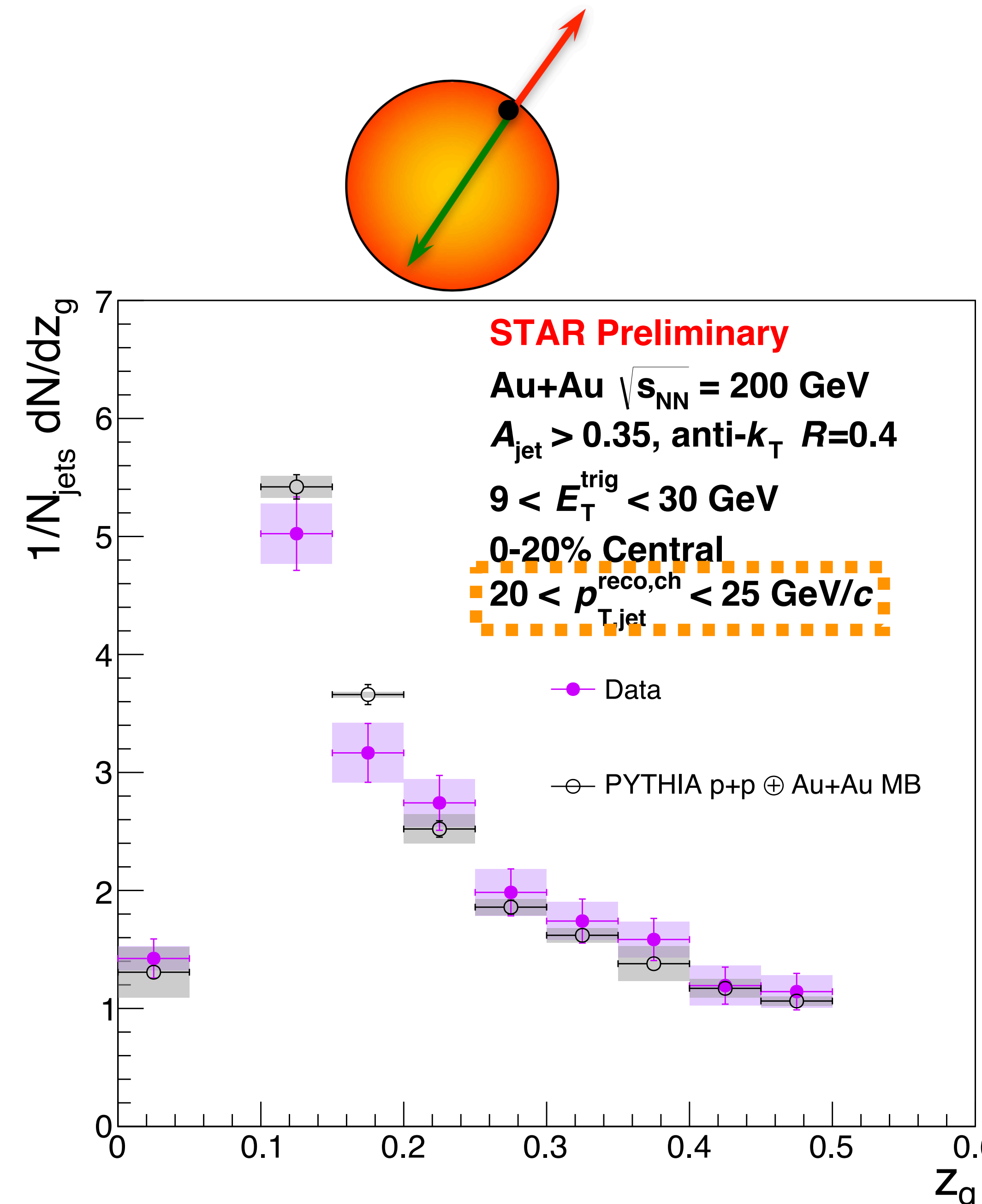
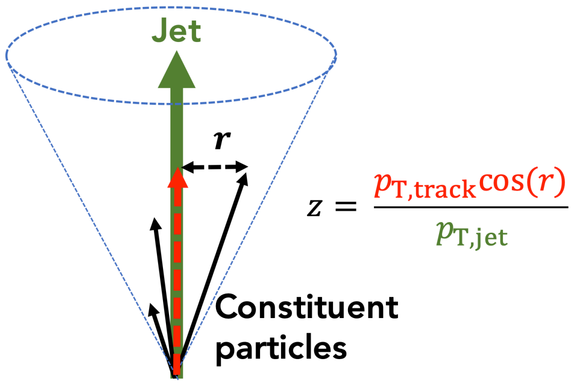


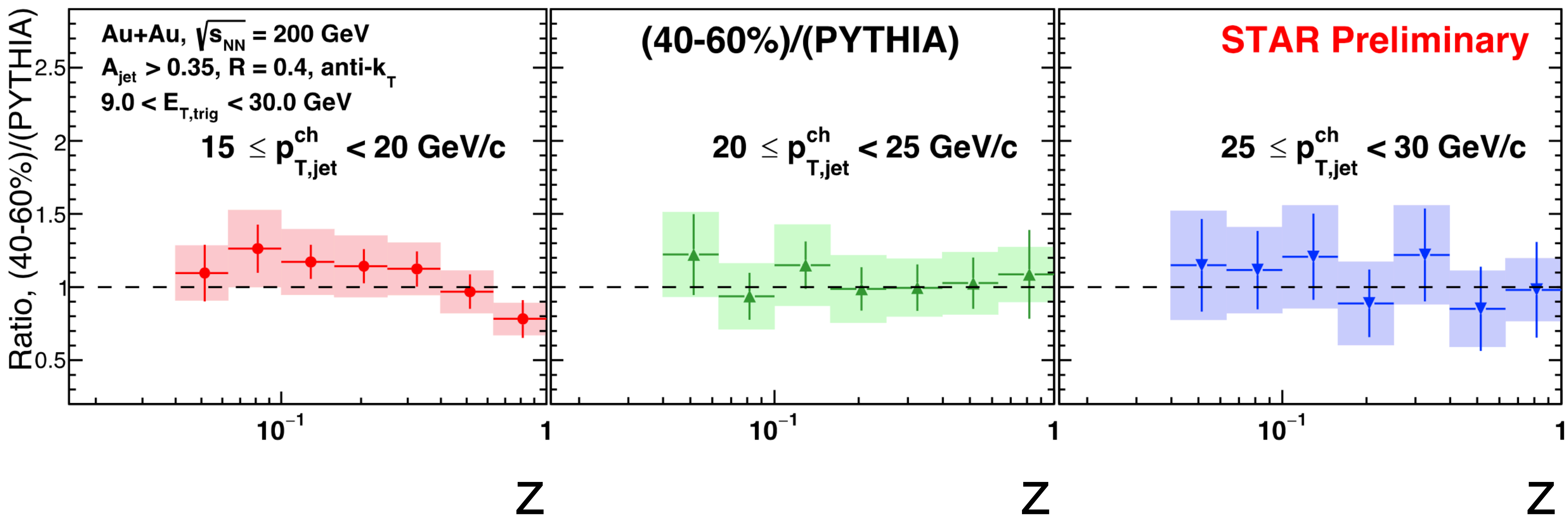
Central Au+Au z_g not significantly different than vacuum z_g for charged jets. Will be extended to lower-p_T!

Fragmentation function



$$D(z) = \frac{1}{N_{jet}(p_{T,jet})} \frac{dN_{track}(z, p_{T,jet})}{dz}$$

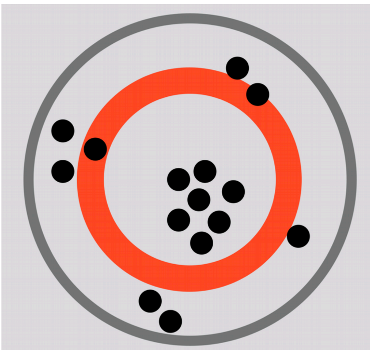
increasing p_T



No modification of *D*(*z*) observed for semi-inclusive recoil charged-jet population in peripheral collisions (40-60%)

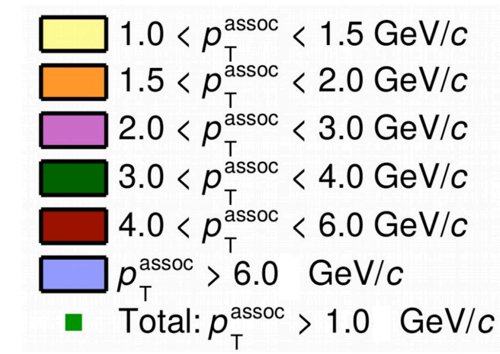
Will be extended to central collisions

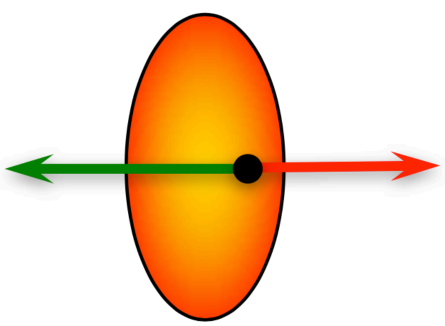
Differential jet shape

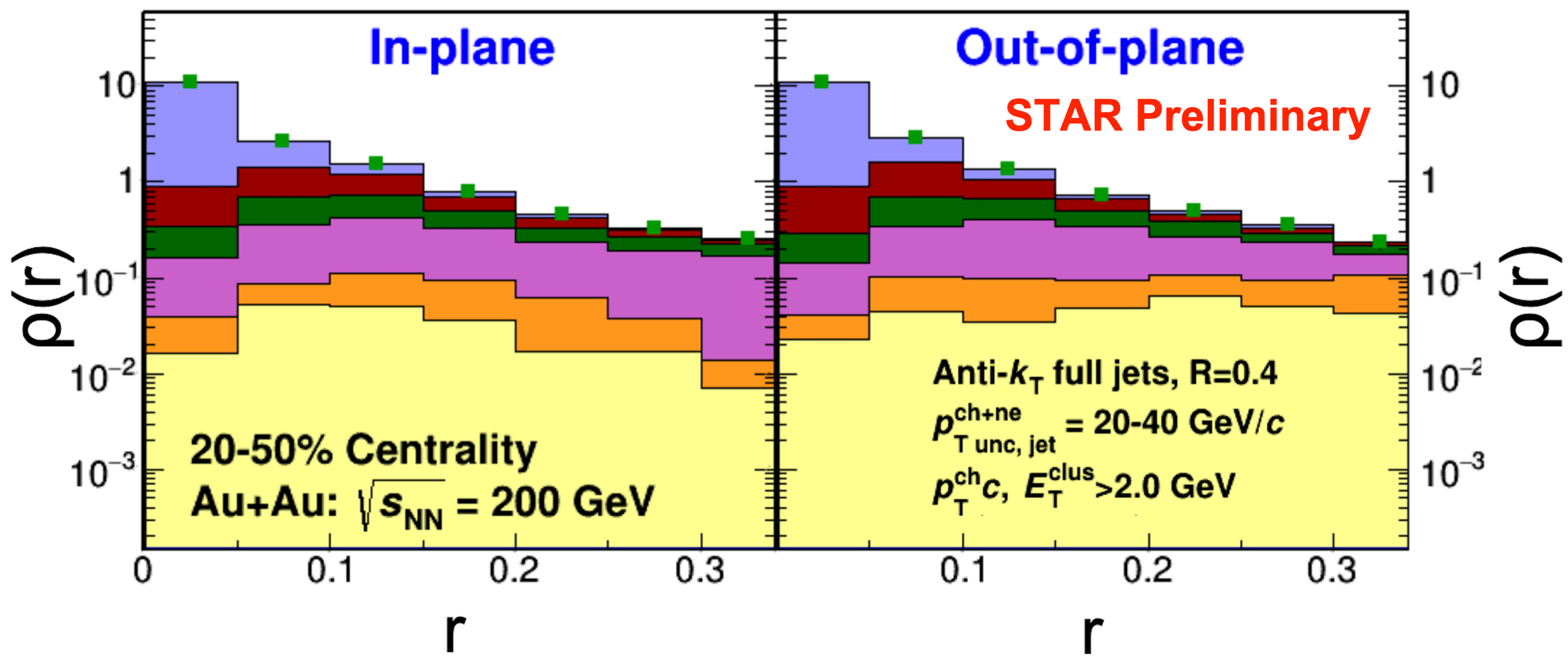


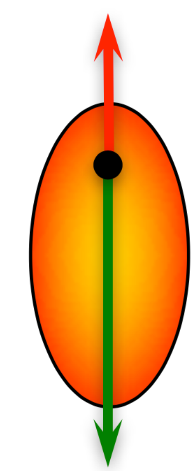
Gavin Salam

$$\rho(r) = \frac{1}{N_{\mathrm{jet}}} \frac{1}{\delta r} \sum_{\mathrm{jets}} \frac{\sum_{\mathrm{tracks} \in (r_a, r_b)} p_T^{\mathrm{track}}}{p_T^{\mathrm{jet}}}$$







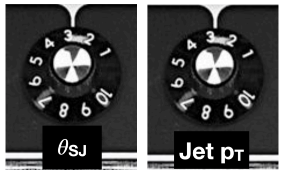


Constituents more collimated with increasing p_T

More low-p_T wide-angle constituents for out-of-plane jets

Comparison to vacuum baseline forthcoming

Work ongoing on additional substructure observables (p_TD, g, LeSub)

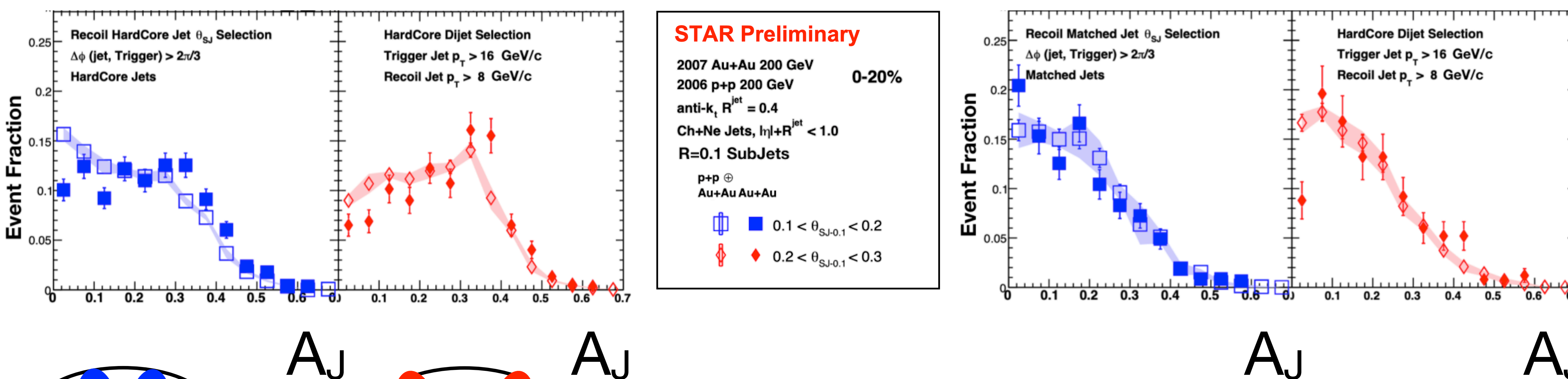


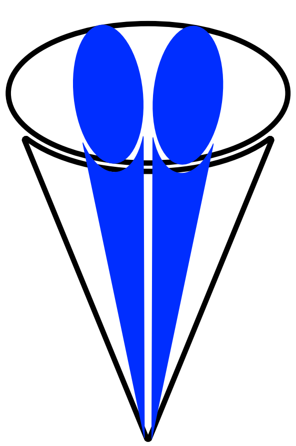
Dijet asymmetry

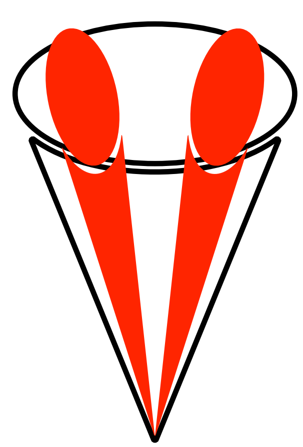
Differentially selecting dijet population based on recoil jet's subjet opening angle, θ_{SJ}

$$A_J = \frac{p_T^{trig} - p_T^{recoil}}{p_T^{trig} + p_T^{recoil}}$$

High-p_T constituents only | **Including soft particles**







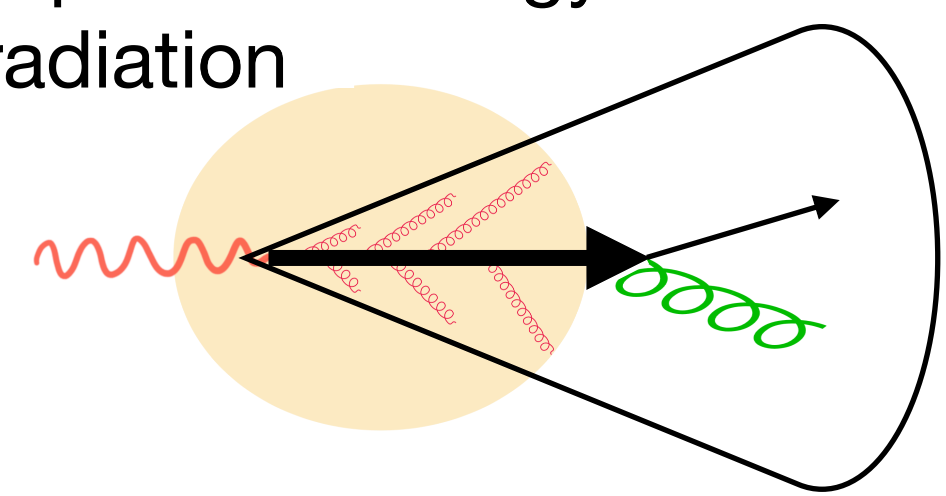
No significant differences in A_J for different θ_{SJ} selections: energy recovered within jet radius

Summary

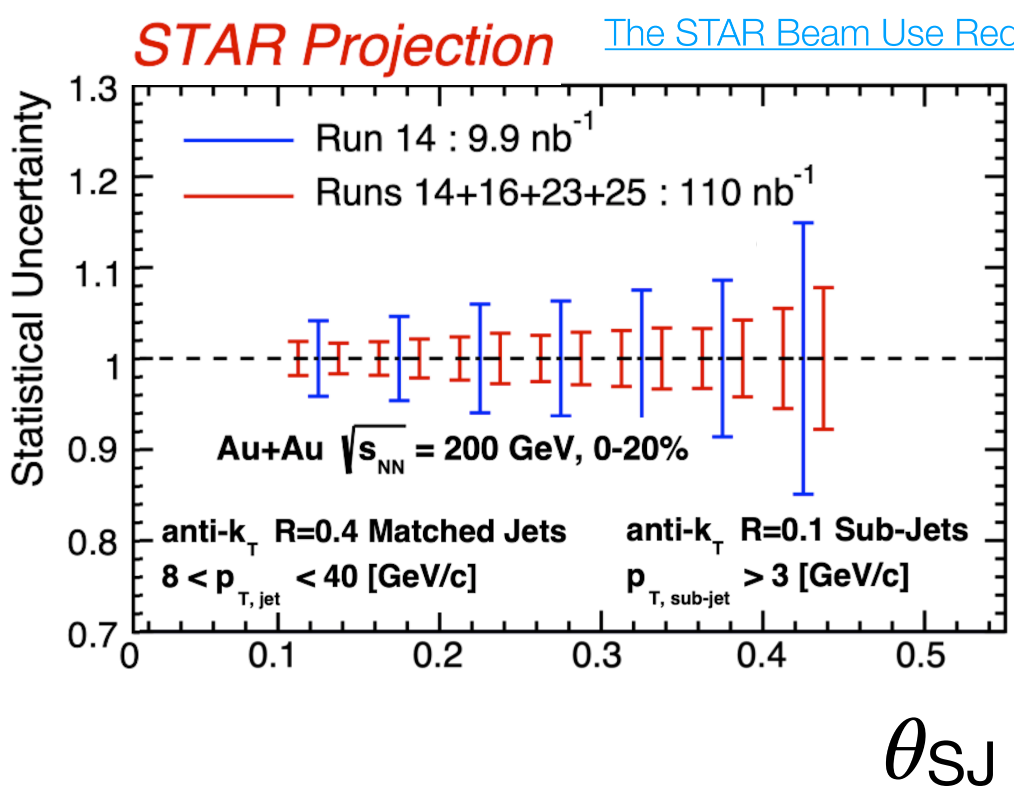
pp: substructure observables established; good agreement with STAR-tuned MC, opportunity for further tuning of other MCs

*p*A: anti-correlation between soft activity (at mid- and high-rapidity) and high-Q^2 production suggests suppression in yield with respect to *pp* reference is likely caused by event activity classification rather than jet quenching
Jet mass shows no signs of significant modification due to CNM effects or potential jet quenching

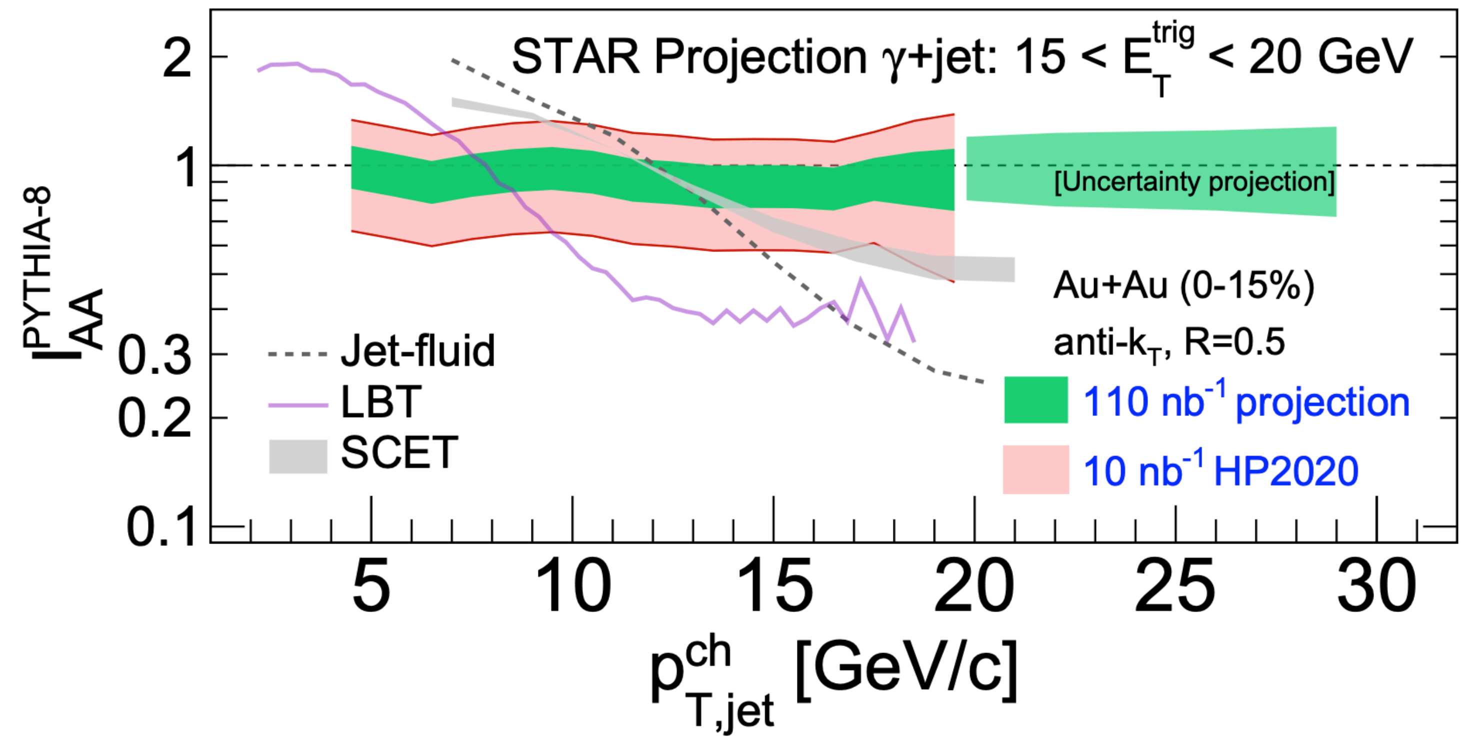
A+A: qualitatively consistent picture of jet quenching measurements at STAR indicates that partonic energy loss is due mainly to soft medium-induced radiation



The future



The STAR Beam Use Request for Run-21, Run-22 and data taking in 2023-35



Run 14, 16, 23 datasets will increase statistical precision for jet and jet substructure measurements, and allow for more differential measurements (e.g. selections in both momentum and angular scales for more homogeneous classes of probes of the hot QCD medium)

Recent STAR jet papers

- Underlying event measurements in p+p collisions at $\sqrt{s} = 200$ GeV at RHIC, J. Adam *et al.* (STAR Collaboration), Phys. Rev. D 101, 052004
  - Published March 10, 2020

- Measurement of D^0-meson + hadron two-dimensional angular correlations in Au+Au collisions at $\sqrt{s_{\mathrm{NN}}} = 200$ GeV, J. Adam *et al*. (Star Collaboration), Phys. Rev. C 102, 014905
  - Published July 6, 2020

- Measurement of away-side broadening with self-subtraction of flow in Au+Au collisions at $\sqrt{s_{\mathrm{NN}}} = 200$ GeV, J. Adam *et al.* (Star Collaboration), Chin. Phys. C 44, 104001
  - Published September 10, 2020

- Measurement of Groomed Jet Substructure Observables in p+p collisions at $\sqrt{s} = 200$ GeV with STAR, arXiv:2003.02114
  - Accepted by Phys. Lett. B

- Measurement of inclusive charged-particle jet production in Au+Au collisions at $\sqrt{s} = 200$ GeV, arXiv:2006.00582
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David Stewart, *p*A Modification of semi-inclusive jet spectra

Session EB: Heavy Ions and Jets II
10:30 AM–12:30 PM, Friday, October 30, 2020

Daniel Nemes, semi-inclusive z_g

Session FB: Heavy Ions and Jets III
2:00 PM–4:00 PM, Friday, October 30, 2020

Veronica Verkest, *p*A jet and dijet UE

Session LB: Heavy Ions and Jets IV
10:30 AM–12:18 PM, Saturday, October 31, 2020

More at DNP2020

I.M., *pp* and *p*A jet substructure

Session FB: Heavy Ions and Jets III
2:00 PM–4:00 PM, Friday, October 30, 2020

Moshe Levy, jet shape measurements

Session QA: Conference Experience for Undergraduates Poster Session VI (5:20pm - 5:55pm)
5:20 PM, Saturday, October 31, 2020

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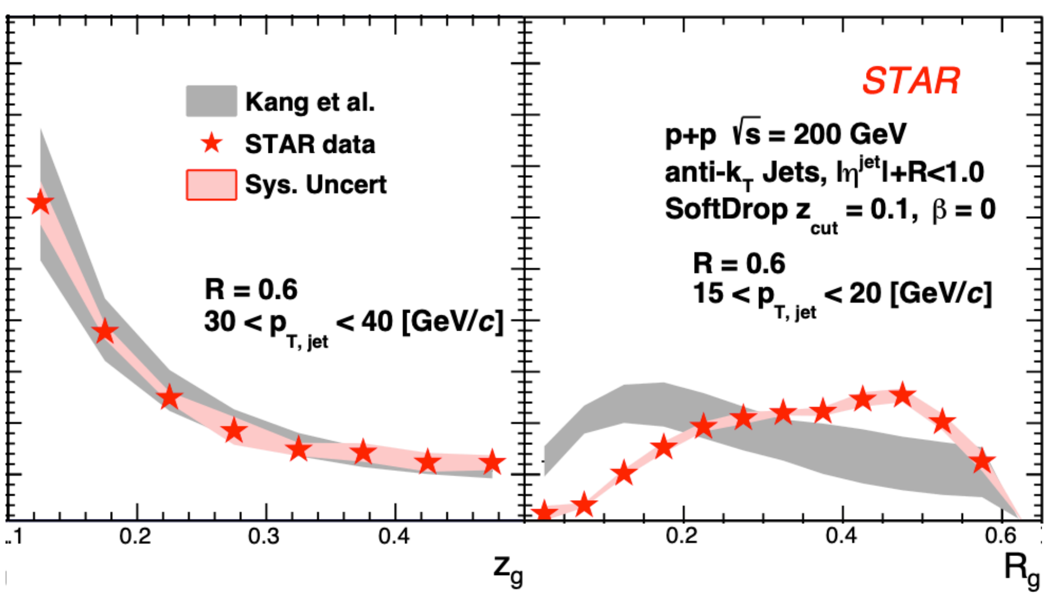
Backup

Jet substructure in *pp* collisions

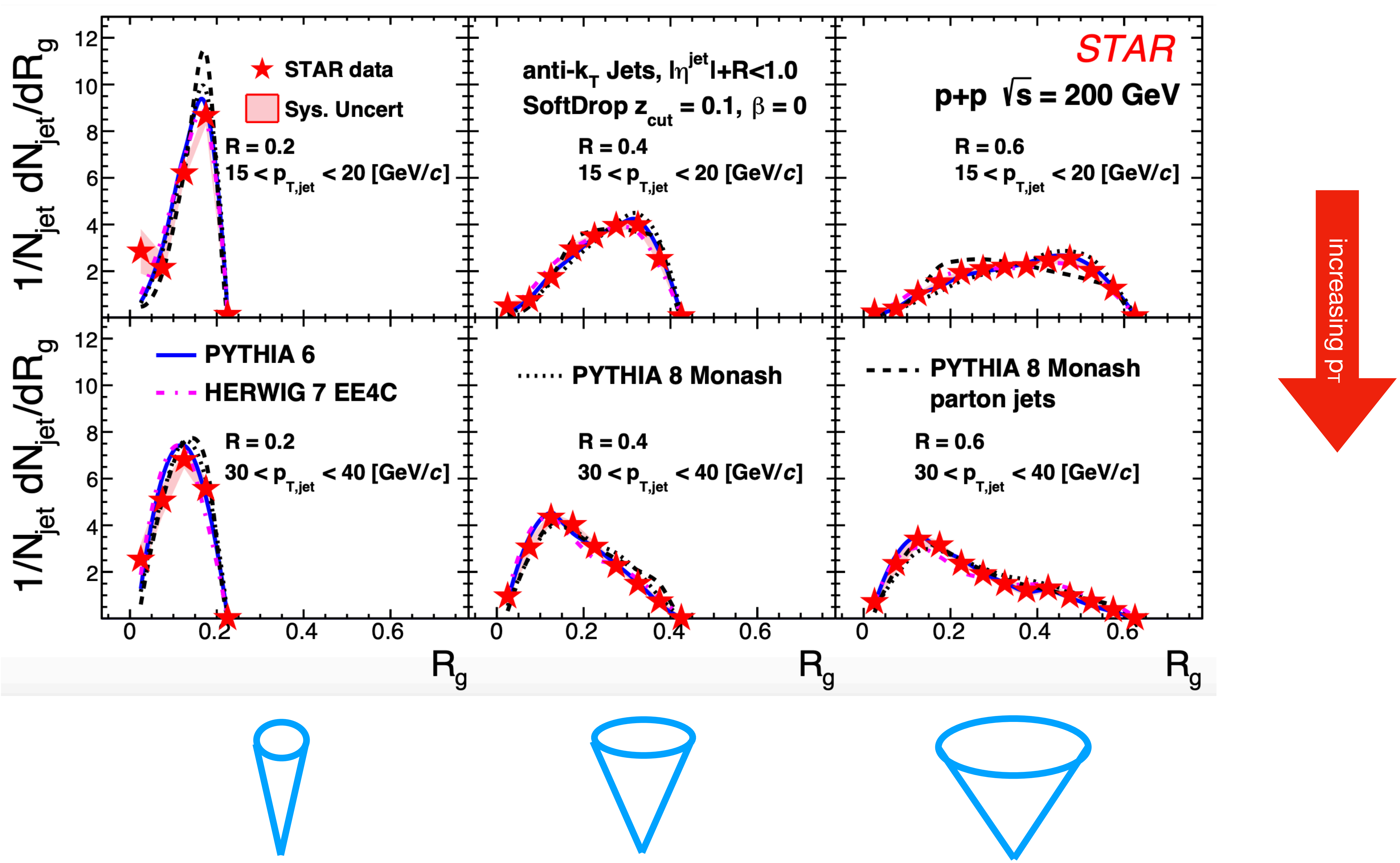
STAR has established a *pp* jet substructure baseline which agrees with STAR-tuned LO MC (PYTHIA-6)

Compared to predictions from NLL parton-level calculations, R_g exhibits more disagreement — need to understand angular scale of jets quantitatively!

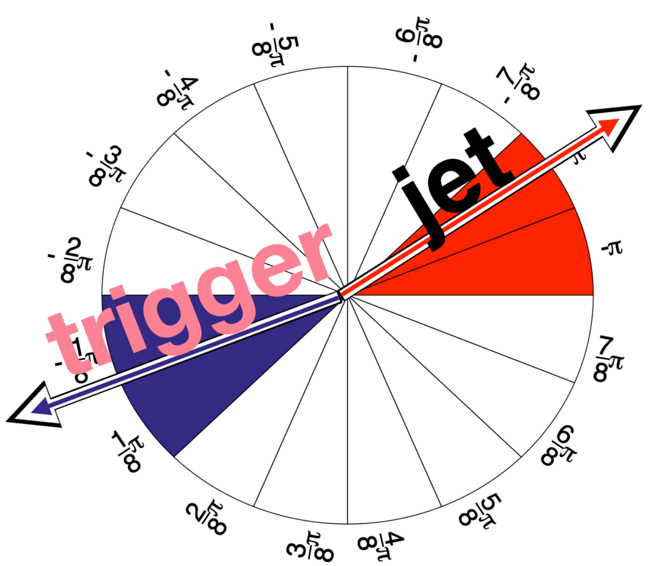


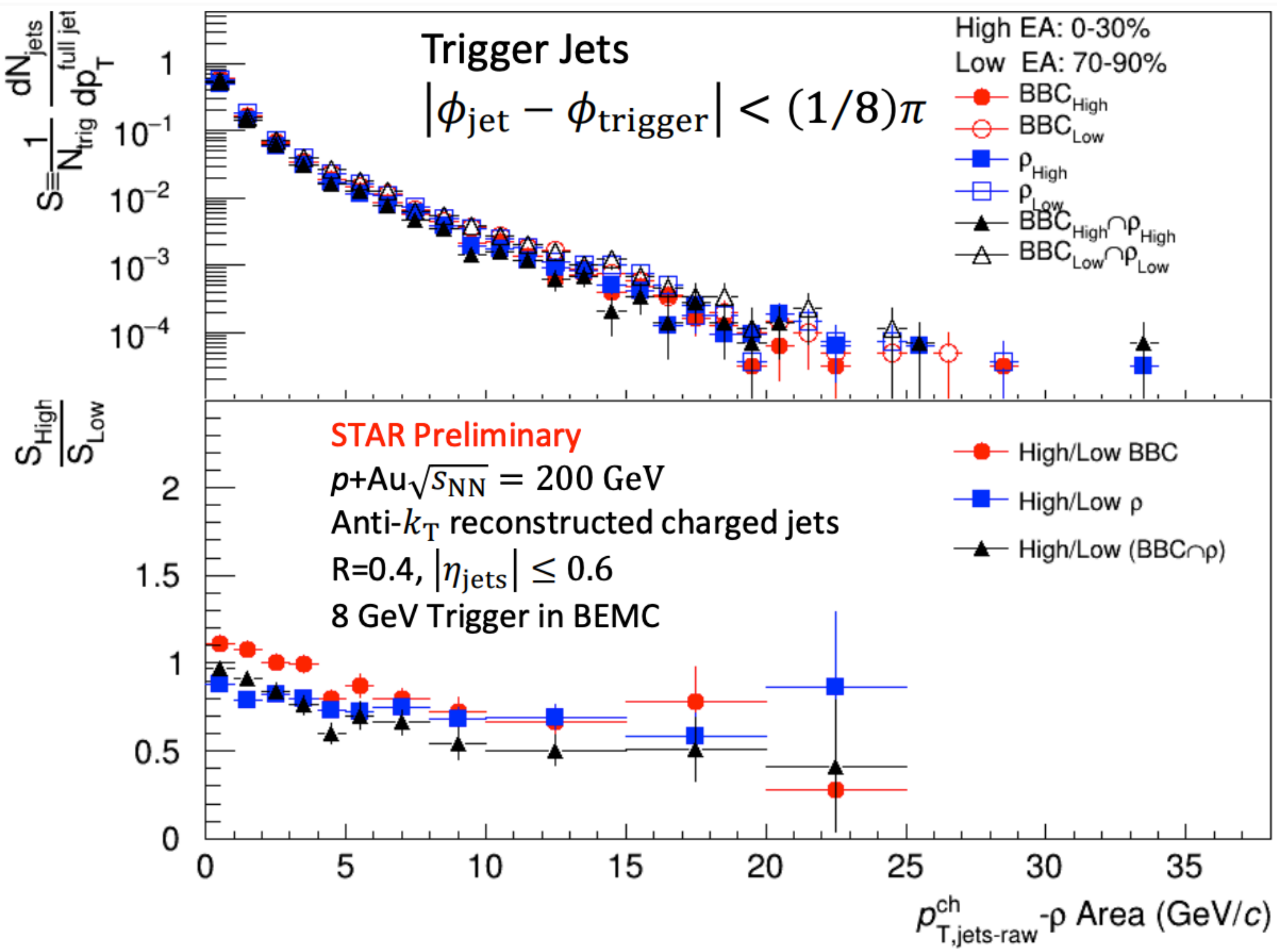
arXiv:2003.02114 (accepted to PLB)

R_g evolution



Semi-inclusive jet spectra





*p*T-dependent suppression of recoil jet yield (and trigger jet - see backup) for both definitions of activity, more strongly for mid-η ρ

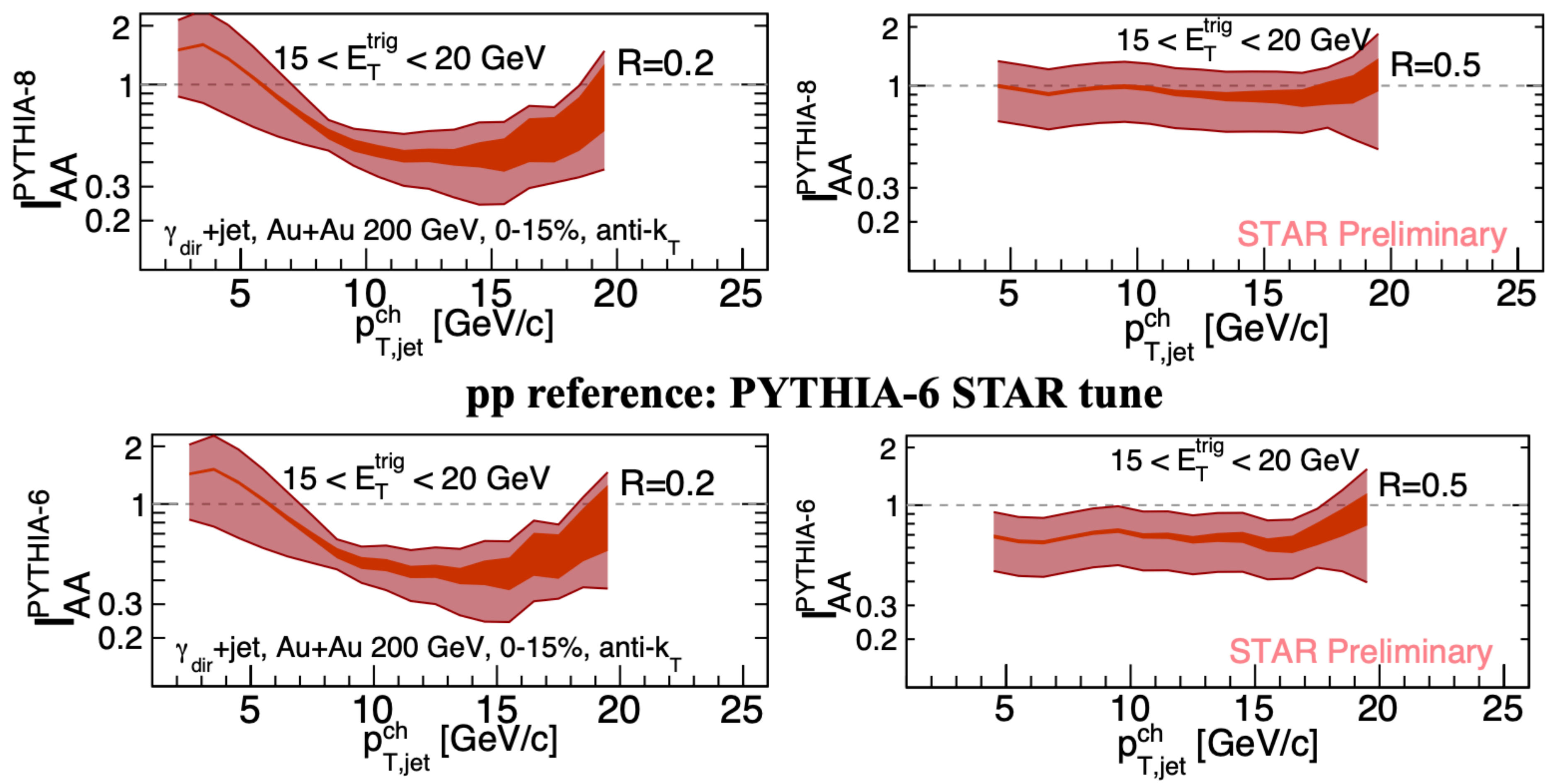
CNM effects / potential jet quenching in small systems?
Are jet substructure quantities affected?

I_{AA}: PYTHIA-6 STAR v. PYTHIA-8

STAR

γ_{dir}+jet: $15 < E_T^{trig} < 20$ GeV

R=0.2 **pp reference: PYTHIA-8** **R=0.5**



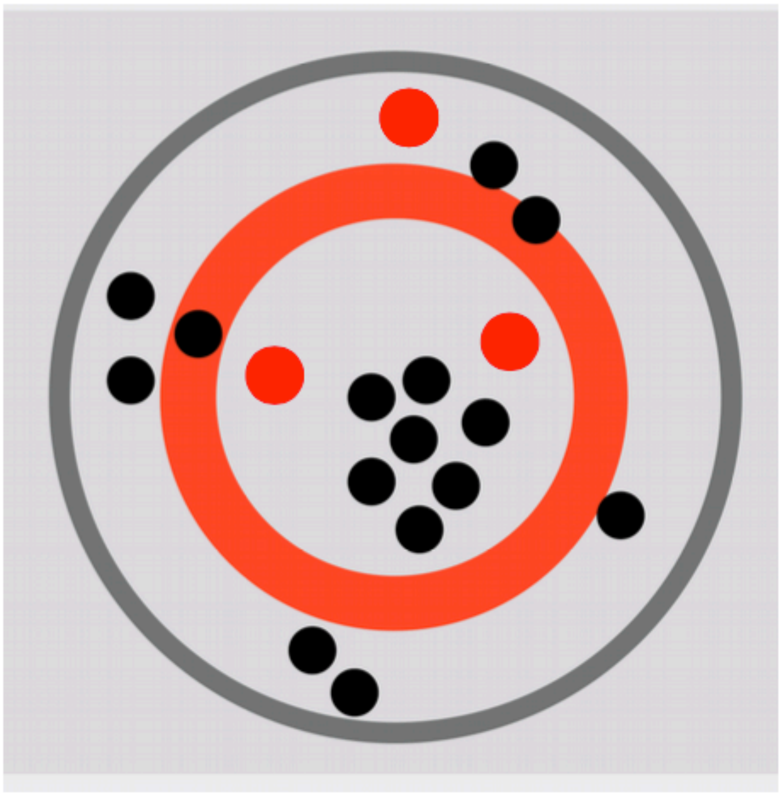
PYTHIA-6 STAR tune vs PYTHIA-8:

- R=0.2: negligible change
- R=0.5: significant shift in central value but consistent within other systematic uncertainties

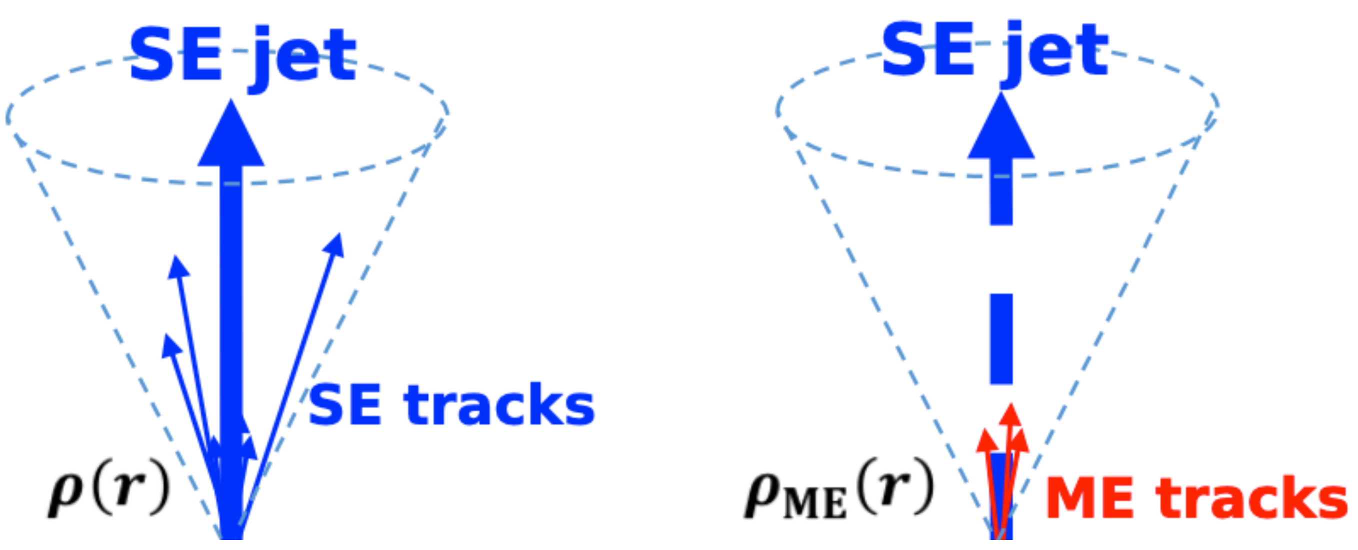
Systematic (lighter band) and statistical (darker band) uncertainties

Jet shape background

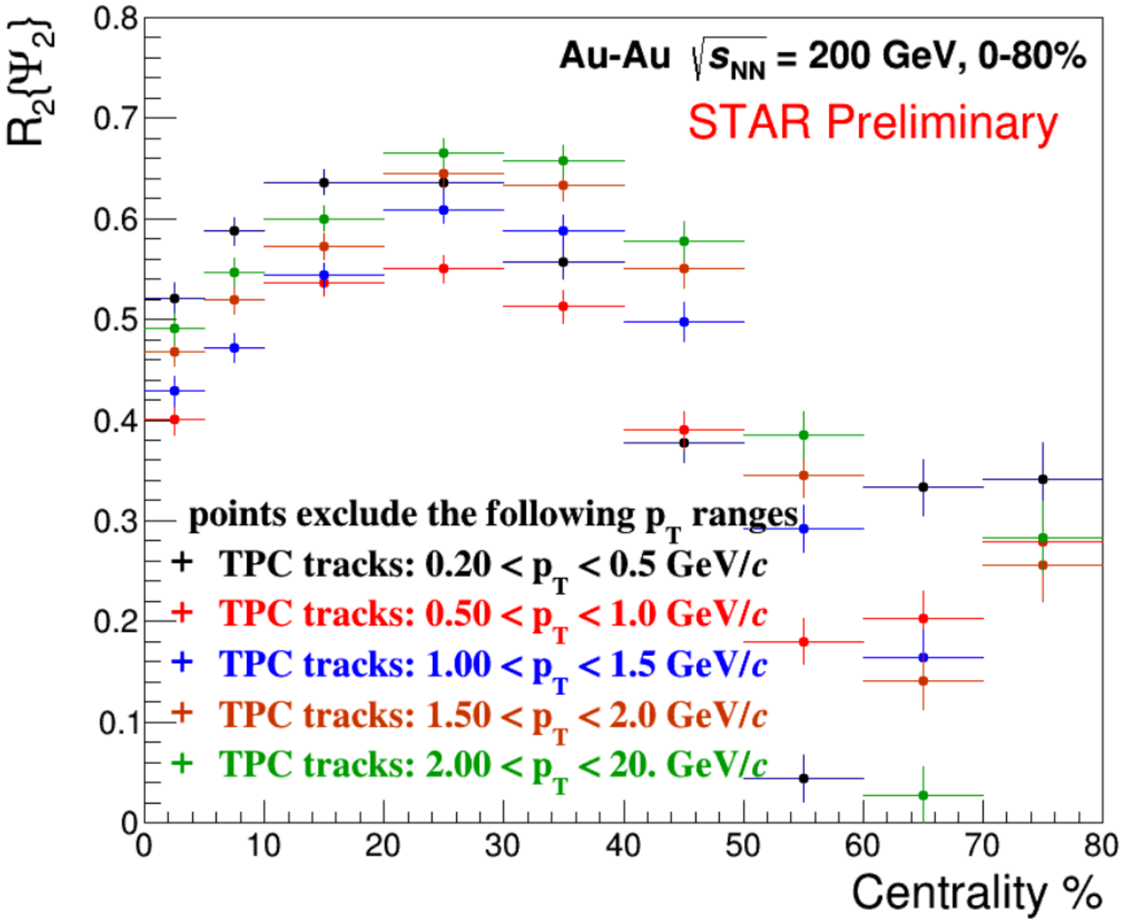
$$\rho(r) = \frac{1}{\delta r}\frac{1}{N_{\mathrm{jet}}}\sum_{\mathrm{jet}}\frac{\sum_{\mathrm{track}\in(r-\delta r/2,\, r+\delta r/2)} p_{\mathrm{T,track}}}{p_{\mathrm{T,jet}}}$$



- Full (charged + neutral) jets reconstructed with high-momentum tracks and towers with $p_{\mathrm{T,track}}$ ($E_{\mathrm{T,tower}}$) > 2.0 GeV/c (**HardCore** jet selection)
- Background contributions in ρ(r) are estimated by placing same-event jets ($p_{\mathrm{T,jet}}$ and jet axis) into mixed-events. Background jet shape, ρ_{ME}(r), is calculated and then subtracted from ρ(r), accordingly



Event plane resolution



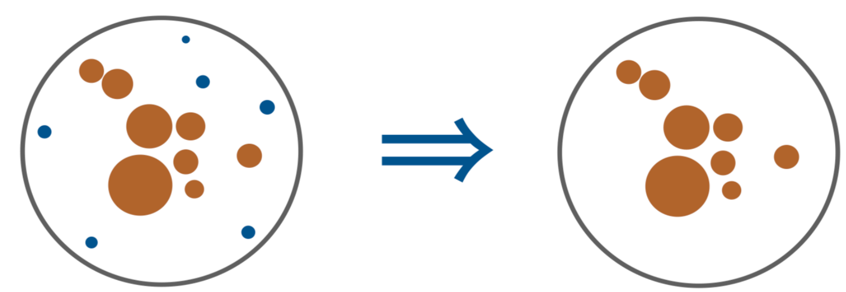
- Due to finite multiplicity of each event, there will be a difference between the reconstructed event plane and underlying symmetry plane: Ψ_2

$$R_n = \langle \cos(n(\psi_{n,true} - \psi_{n,reco})) \rangle$$

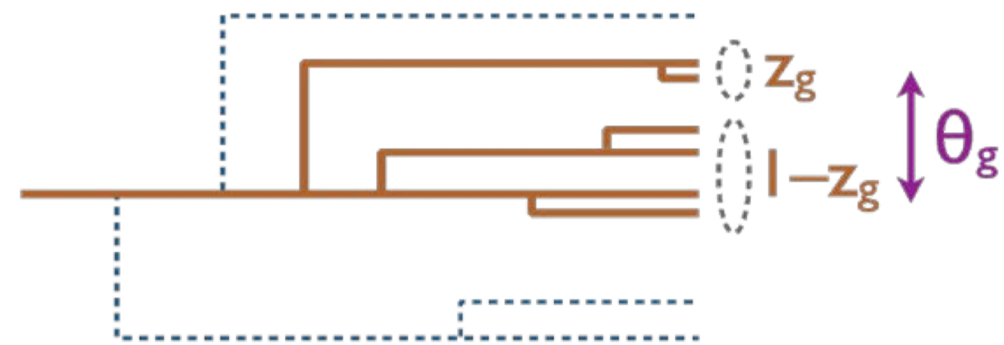
- Using modified reaction-plane (MRP) method, for p_T associated bins STAR, Phys. Rev. C **89** (2014) 041901(R)
  - Improvement over typical EP measurements with the TPC and BBC
- Peak for 20-30% and 30-40% centrality
- Excluding track with p_T = 0.5-1.0 GeV/*c* gives lowest R_2

SoftDrop grooming

Suppress wide-angle non-perturbative radiation for more direct theory comparison; closer to parton-level



momentum fraction, z_g **angle, R_g** **groomed mass, M_g**



https://arxiv.org/pdf/2003.02114.pdf
(accepted to PLB)

$$z > z_{\mathrm{cut}}\ \theta^{\beta}$$

energy threshold — angular exponent

Approach: decluster angular-ordered splitting tree by removing prongs which fail the criterion

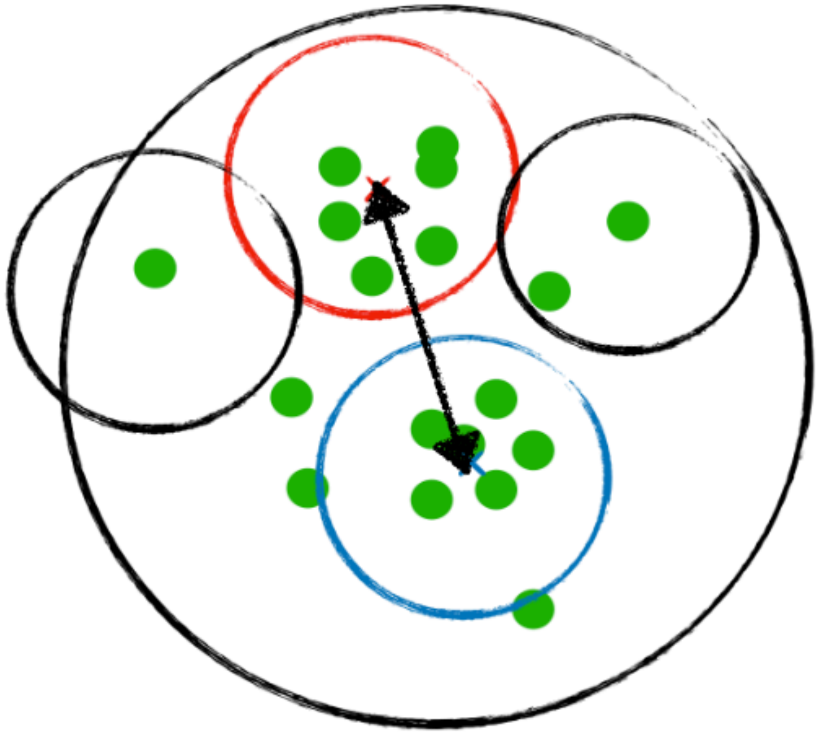
$$z_g = \frac{\min(p_{T1}, p_{T2})}{p_{T1} + p_{T2}}$$

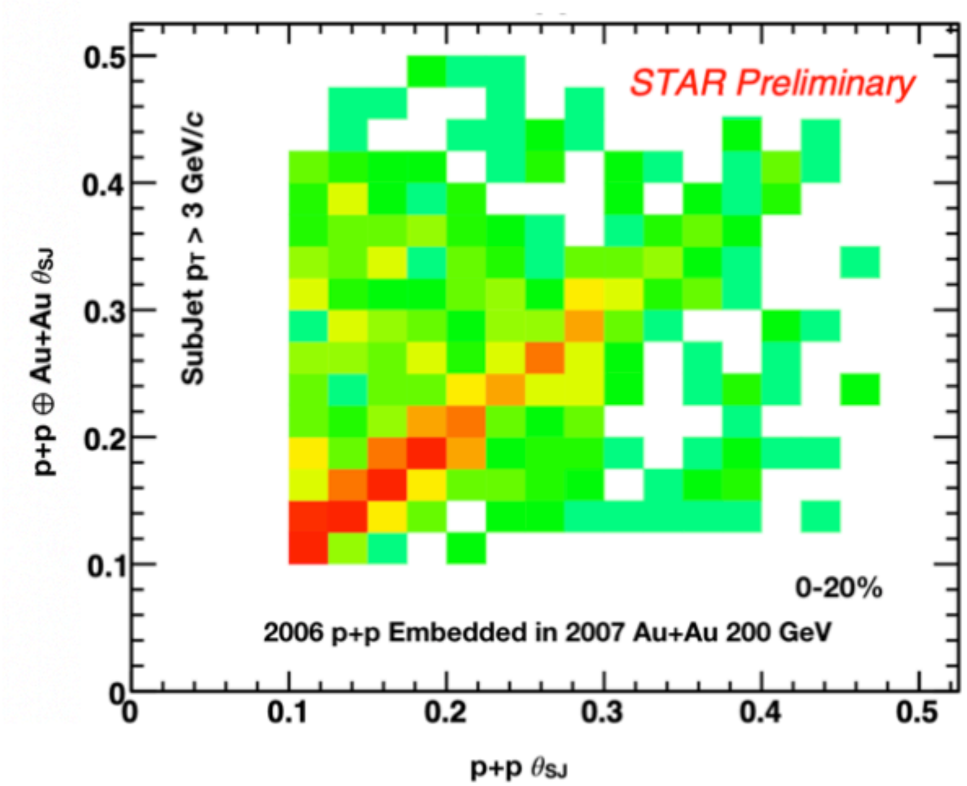
We consider jets with $z_g > 0.1$ ($\beta = 0$)

Larkoski, Marzani, Soyez, Thaler, JHEP 05 (2014) 146

Utilizing subjets of smaller R

Need techniques and observables that are robust to underlying event background especially at RHIC





anti-k_T R=0.4, 20 < p_T < 30 GeV/c
Constituent-Subtracted Jets

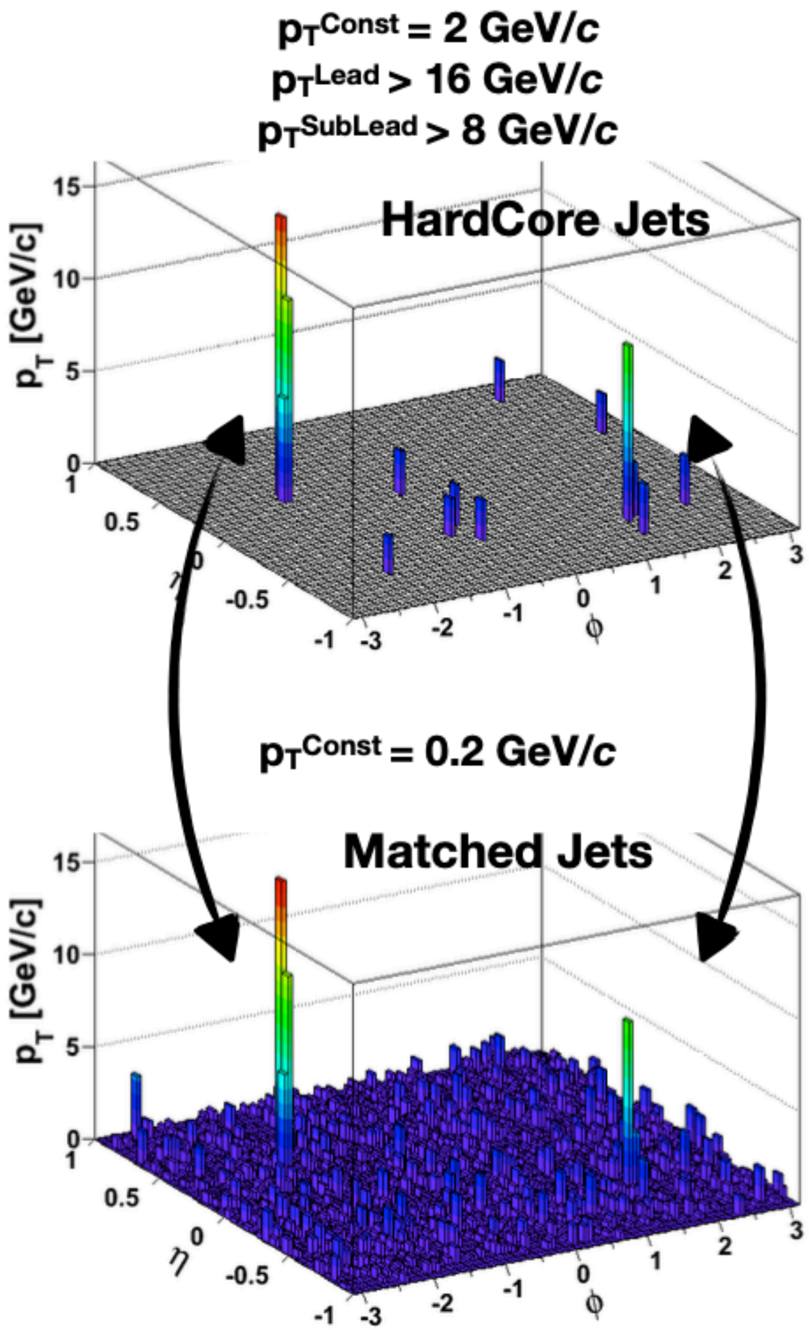
Berta, P et al. JHEP 06 (2014) 092

θ_{SJ} (w/ R=0.1 subjets) less sensitive Au+Au underlying event

Comparisons between Au+Au and p+p embedded in Au+Au to isolate quenching effects

- **Recluster jet constituents with a smaller radius** - identify regions of jet-like features within the mother jet
- Choose the **leading** and **subleading** Subjets
- z_{SJ} = **subleading p_T** / (**subleading p_T** + **leading p_T**); θ_{SJ} = ΔR (**subleading**, **leading**)

Identifying dijets



- Dijet selection with both leading and subleading momentum threshold
  STAR, PRL 119 062301 (2017)
- HardCore selection removes combinatorial jets
- Matching recovers the jet fragments/particles down to 0.2 GeV/*c*
- Dijet finding introduces a bias - Let's utilize the bias in a systematic fashion

MC tunes

PYTHIA-6.4.28: Perugia 2012 tune."This combination overestimates the inclusive $\pi^{\pm}$ yields by up to 30% for $p_T < 3$ GeV/c, when compared to the previously published STAR measurements at $\sqrt{s}$ = 200 GeV [47,48]. To compensate, a single parameter in the Perugia 2012 PYTHIA tune, PARP(90), was reduced from 0.24 to 0.213. PARP(90) controls the energy dependence of the low-p_T cut-off for the UE generation process."[1]

PYTHIA-8.23: Monash tune[2]

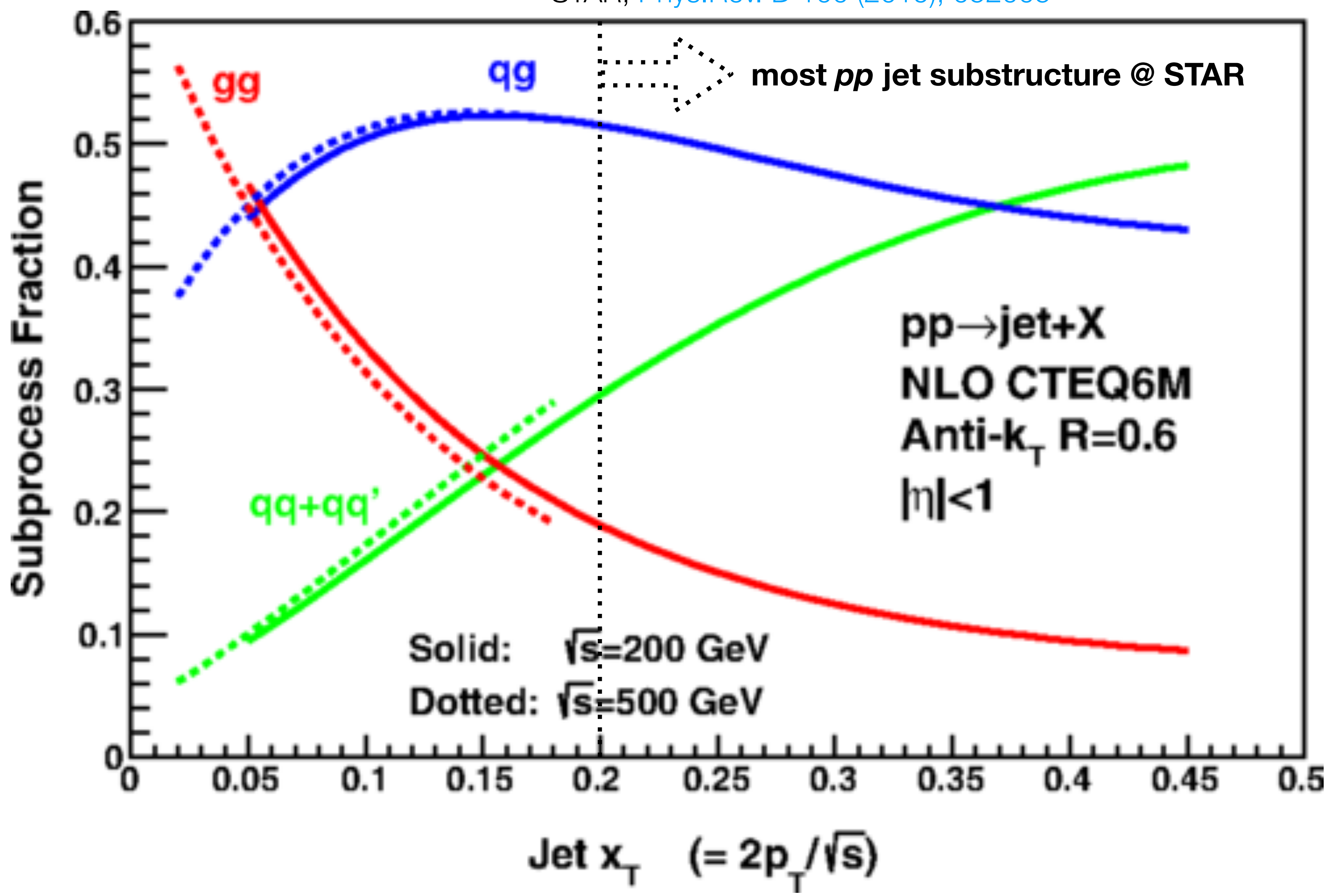
[1] STAR, Phys. Rev. D 100 (2019), 052005
[2] Skands, Carrazza, Rojo, Eur. Phys. J. C 74 (2014), 3024
[3] Gieseke, Rohr, Siodmok, Eur. Phys. J. C 72 (2012), 2225

HERWIG-7: LHC-UE-EE-4-CTEQ6L1 underlying event tune[3]

Note: relatively stable particles are left undecayed until interaction with the detector material in the GEANT-3 simulation. These "stable" particles include $\pi^0, \pi^{\pm}, \eta, K^+, K^0_S, K^0_L, \Sigma^{\pm}, \bar{\Sigma}^{\pm}, \Lambda, \bar{\Lambda}, \Xi^-, \bar{\Xi}^+, \Omega^-, \bar{\Omega}^+$

Quark and gluon fractions

STAR, Phys.Rev. D 100 (2019), 052005



Gluon jets have larger mass than quark jets ($C_A/C_F = 9/4$)
Majority of jets are quark-initiated in this kinematic regime