



Initial Stages 2023

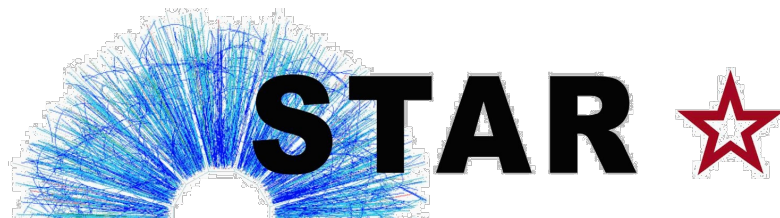
Copenhagen, June 19-23

Measurements of jet substructure in $p+p$
and jet-event activity correlations in $p+Au$
collisions at $\sqrt{s_{NN}} = 200$ GeV at STAR

David Stewart for the STAR Collaboration

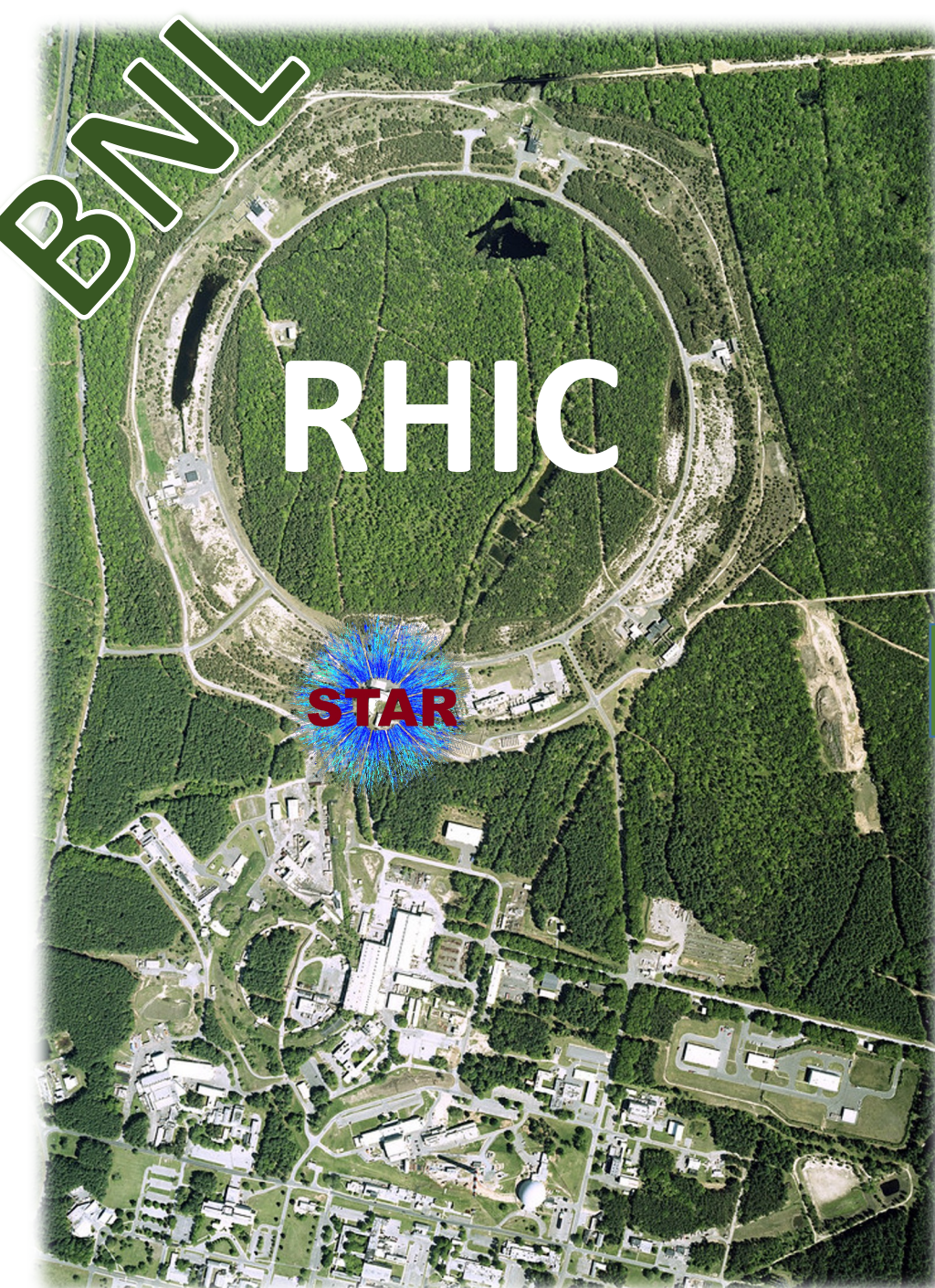


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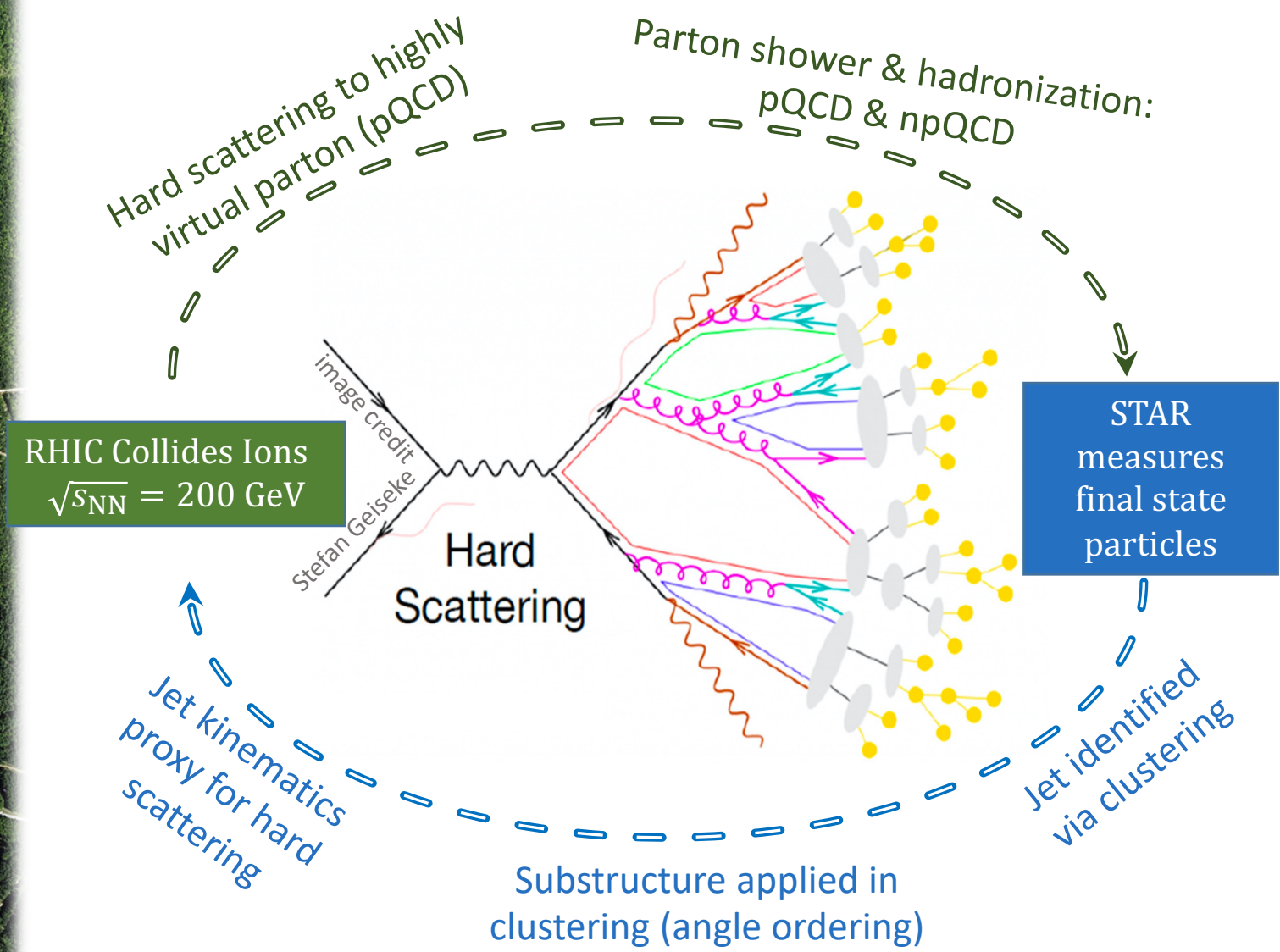


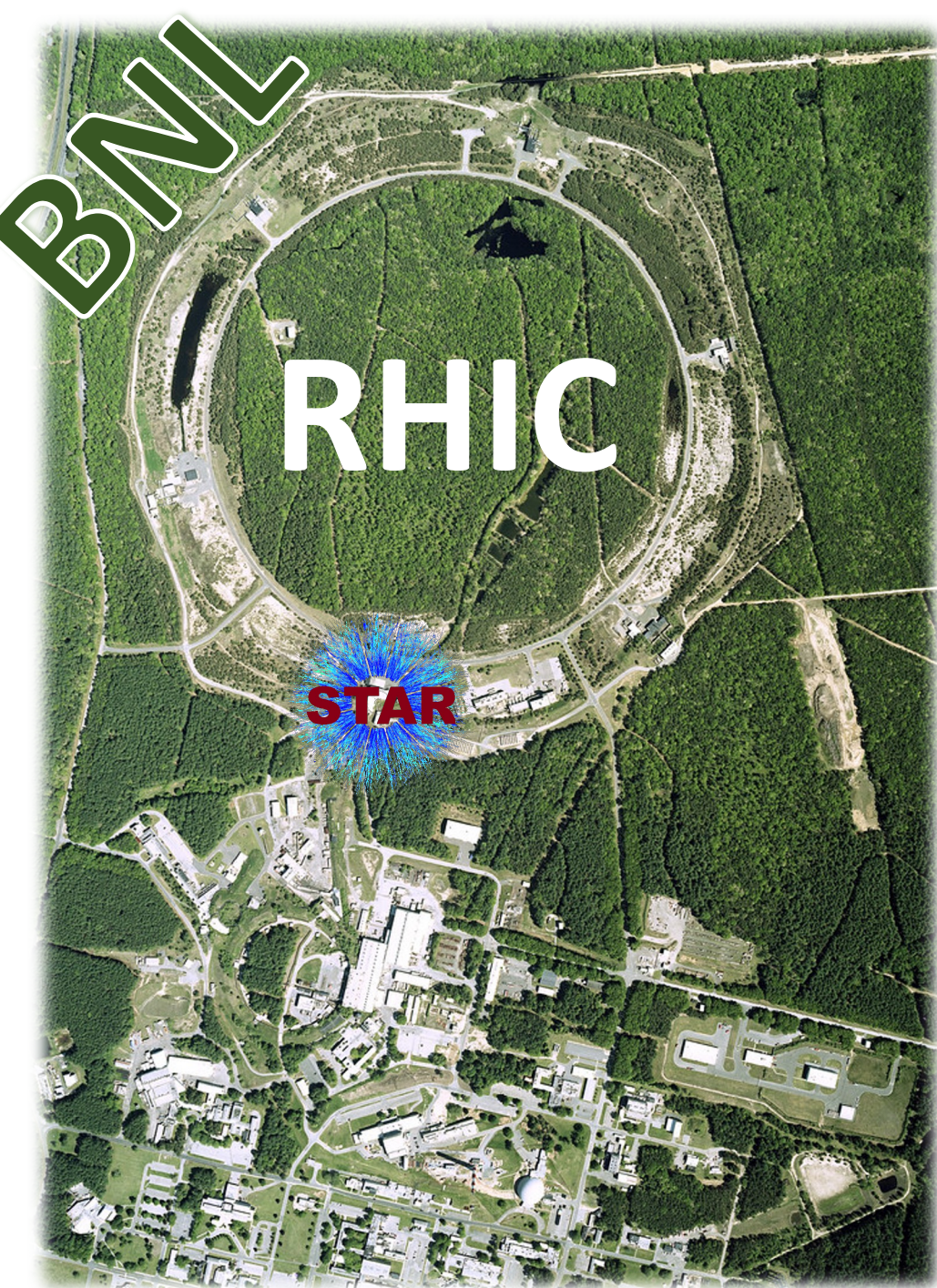
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Jets: probe initial stages





This presentation

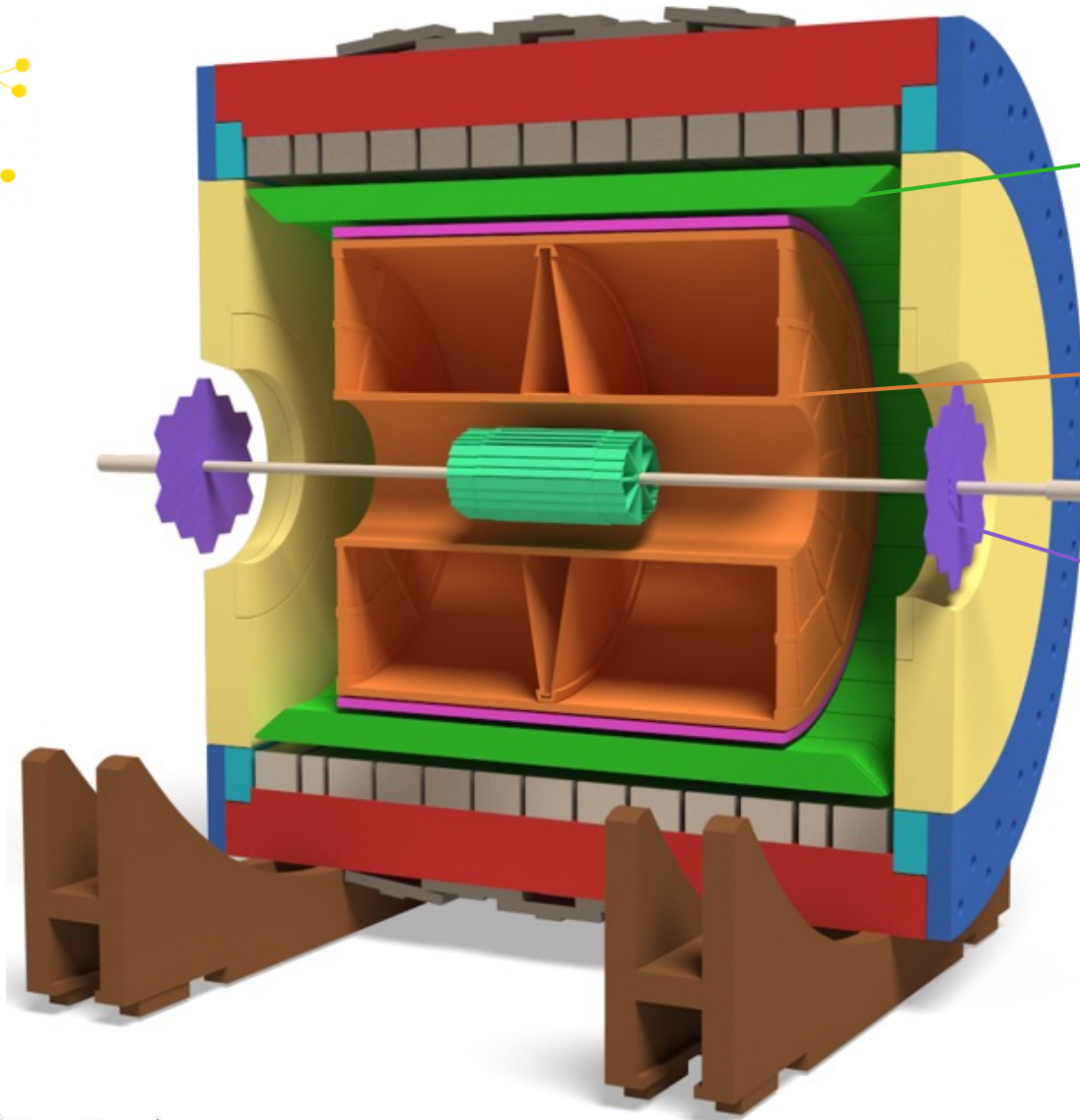
$p + p$ Collisions:

- Measure hadronization scale
- Measure gluon and quark jet fractions
- Measure parton showers, correlate hard and soft processes
- Compare/benchmark measurements to MC

$p + \text{Au}$ Collisions:

- Report unexpected anticorrelation in hard and soft particle production across wide rapidity gap
- Probe if anticorrelation results from jet quenching

Experimental data: particles in STAR detector



Subsystems (full azimuth coverage):

Barrel ElectroMagnetic Calorimeter (BEMC):

- EM interacting particles
- $|\eta| \leq 1$

Time Projection Chamber (TPC):

- Charged particles
- $|\eta| \leq 1$

Beam Beam Counter (BBC):

- Charged particles
- $|\eta| \in [3.4, 5]$

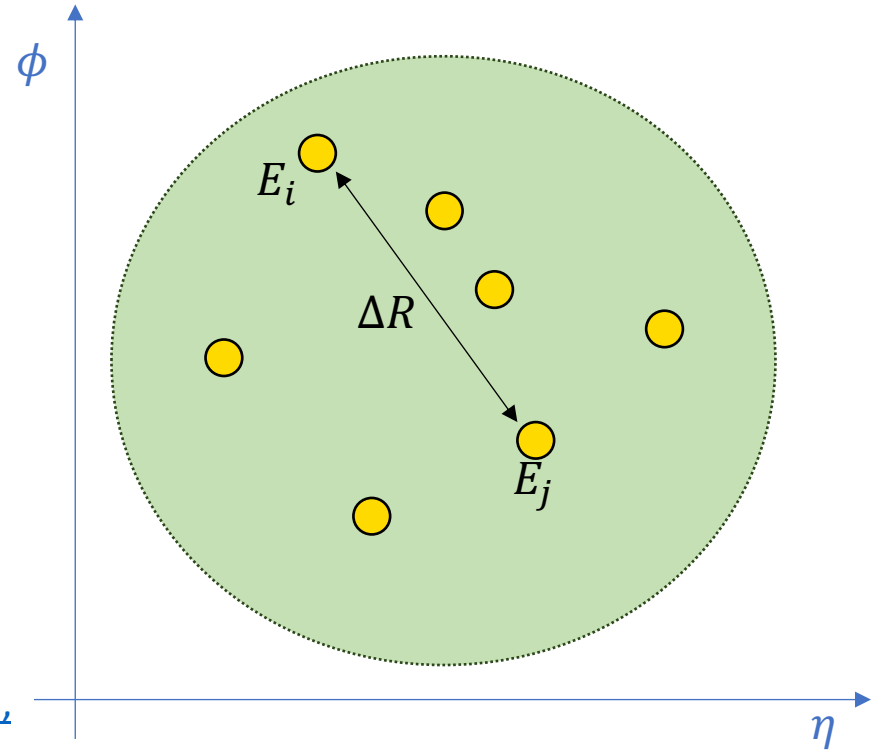
Particles \rightarrow Jets

- Charged jets: TPC particles
- Full jets: TPC + BEMC particles
- Jet finding/clustering: anti- k_T algorithm

Measure QCD hadronization scale?

- “Energy-Energy Correlators” (EEC, [Lee, Meçaj, and Moulton, arXiv 2205.03414](#)) probe hadronization scale ([Andres, et al., arXiv 2209.11236](#))

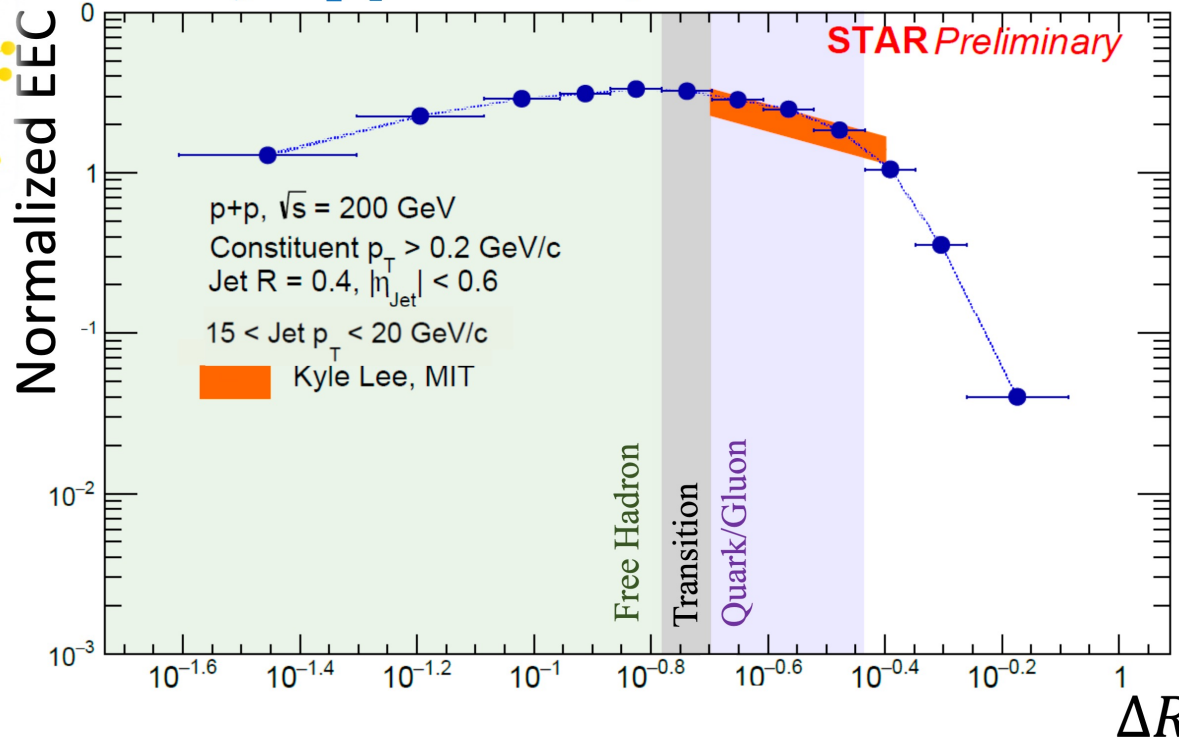
- Normalized EEC $\equiv \frac{1}{\sum_{\text{Jets}} \sum_{i \neq j} \frac{E_i E_j}{p_{T,\text{jet}}^2}} \frac{d\left(\sum_{\text{Jets}} \sum_{i \neq j} \frac{E_i E_j}{p_{T,\text{jet}}^2}\right)}{d(\Delta R)}$
- EEC (ΔR) corresponds to
 - at small ΔR : free hadrons
 - at large ΔR : perturbative quark & gluon interactions
 - at ΔR between: $\Delta R_{\text{Turnover}} \propto \frac{\Lambda_{\text{QCD}}}{p_{T,\text{Jet}}}$ ([Komiske et al, 2023, PRL 130, 051901](#))



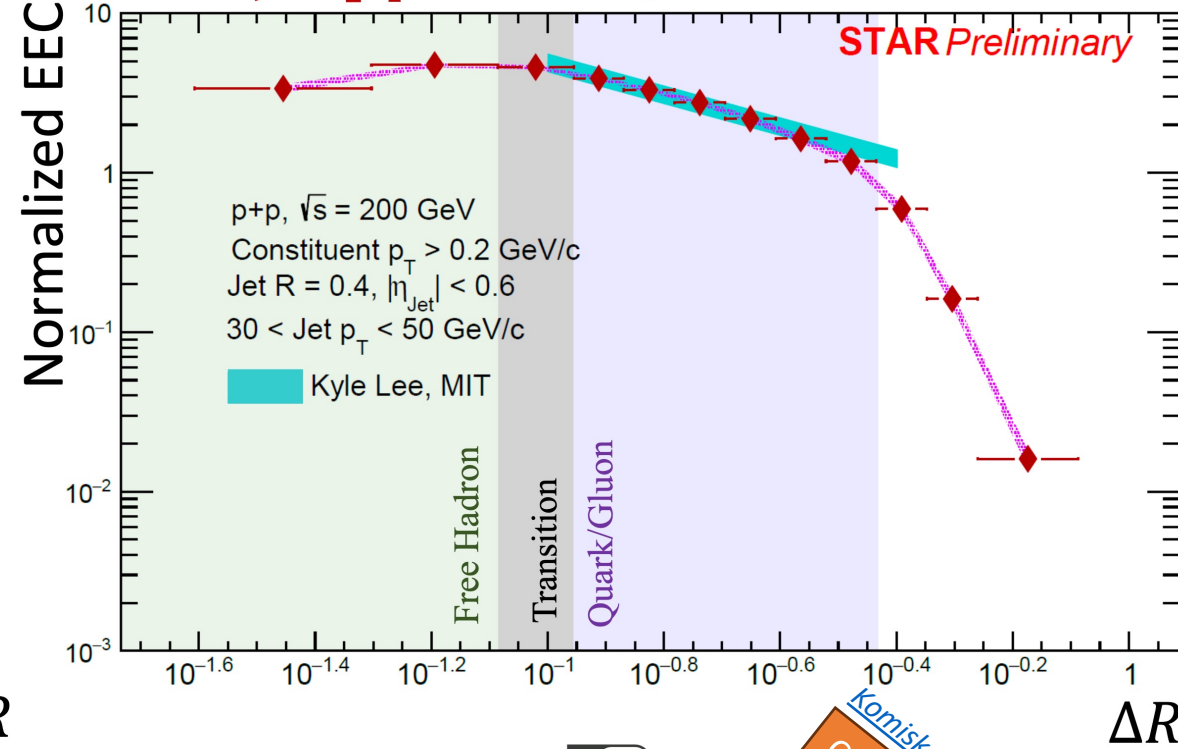
$\rightarrow \Lambda_{\text{QCD}} \propto \Delta R_{\text{Turnover}} p_{T,\text{Jet}}$ at all scales

First EEC measurement at RHIC

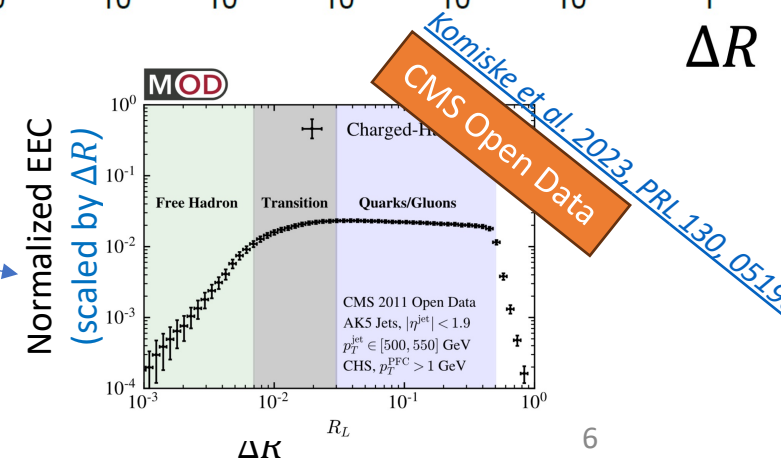
15 < Jet p_T < 20 GeV/c



30 < Jet p_T < 50 GeV/c



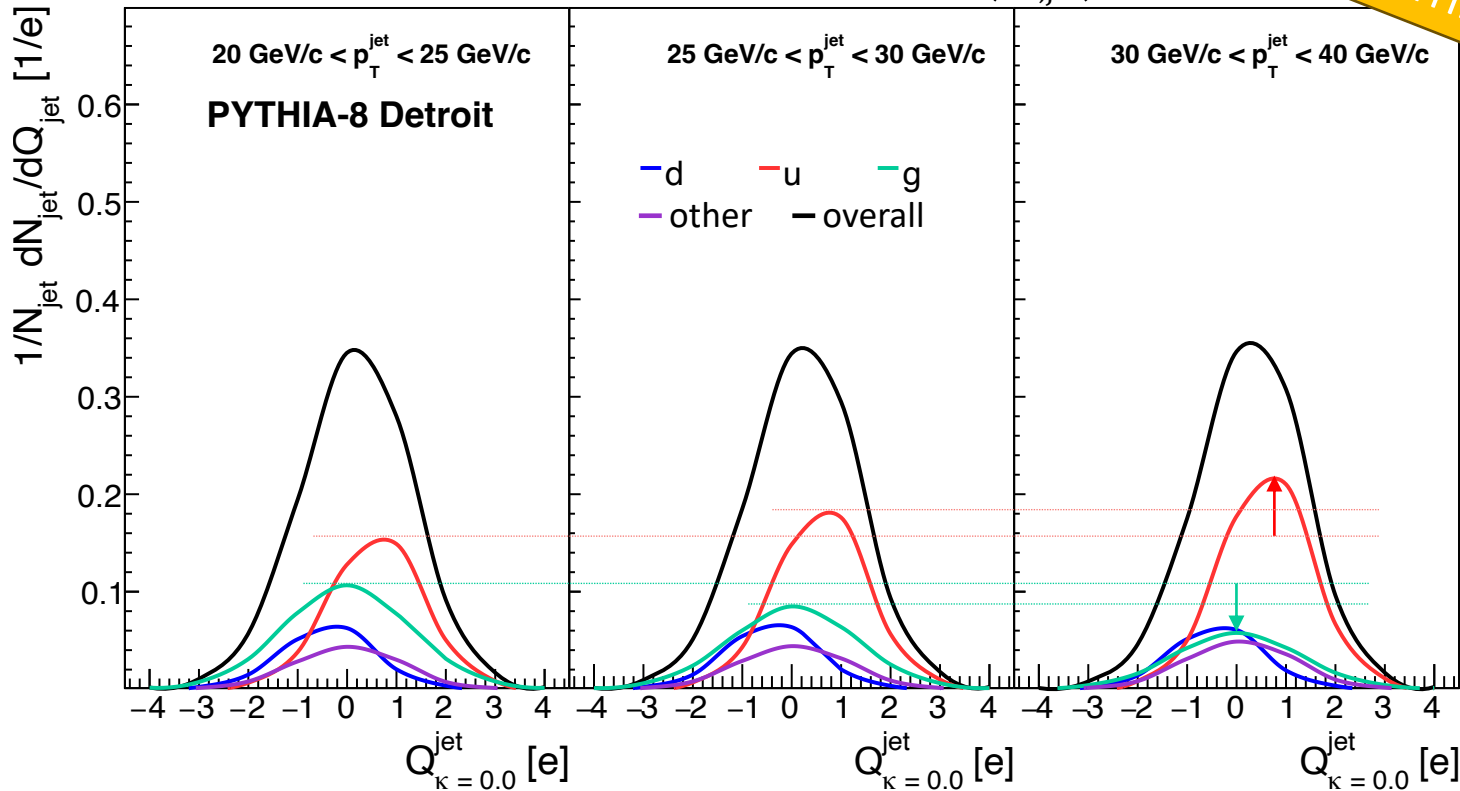
- $p_{T,Low}^{Jet} \Delta R_{Turnover} = 10^{-0.75} \left(15 \frac{GeV}{c} \right) = 2.7 \frac{GeV}{c}$
 → scale appears universal between RHIC and LHC (CMS $\approx 2.5 \frac{GeV}{c}$)
- $\Delta R_{Turnover}$ depends on quark/gluon fraction



Measure initiating quark/gluon fractions?

Probe with jet charge: $Q_{\kappa}^{\text{jet}} \equiv \sum_{j \in \text{jet}} \left(\frac{p_T^j}{p_{T,\text{jet}}} \right)^{\kappa} Q_j$

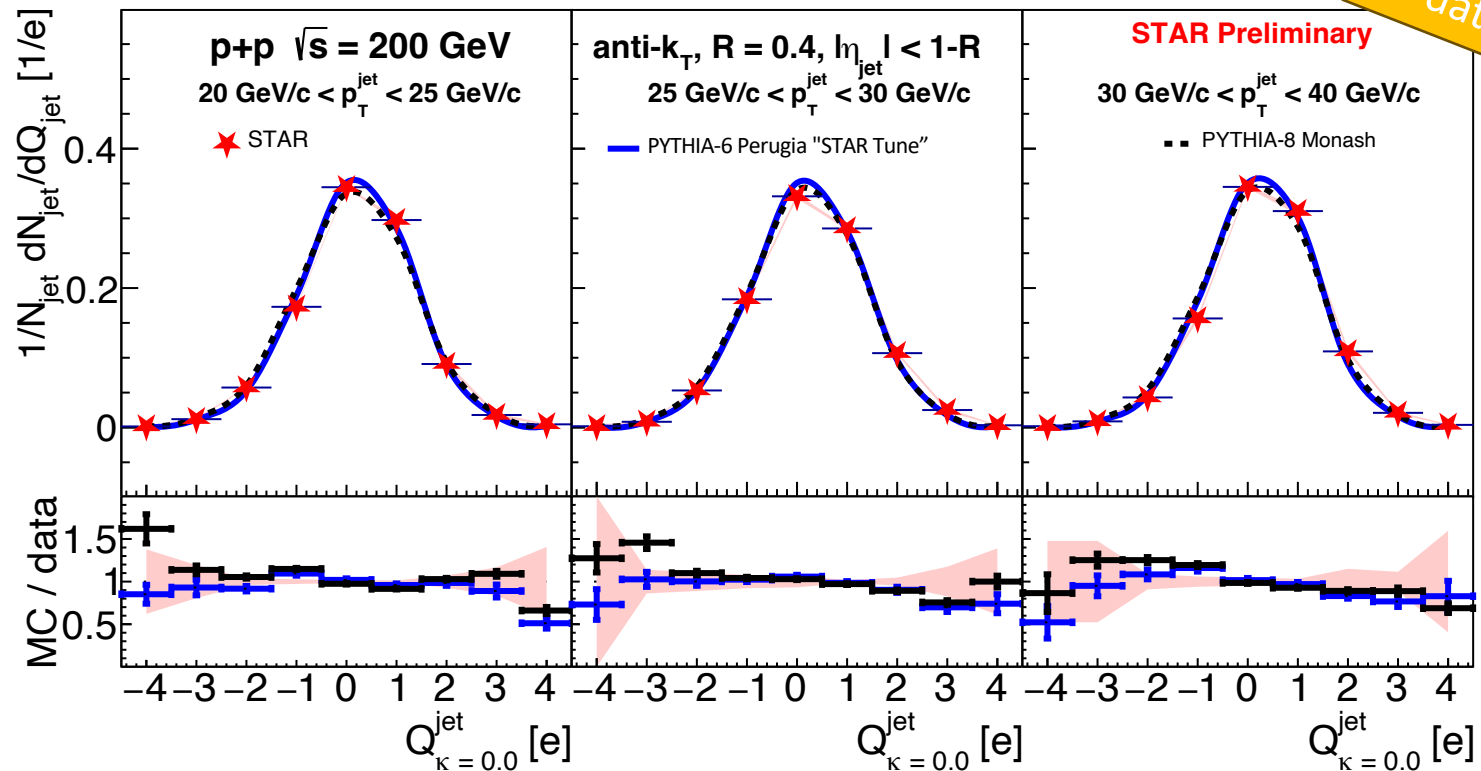
PYTHIA-8



- Goal: template fit PYTHIA (u, d, g, other) Q^{jet} to data
 → measure proper (u, d, g, other) fraction of initiators
- Q^{jet} in PYTHIA8 increases and is more quark dominated with increasing p_T^{jet}

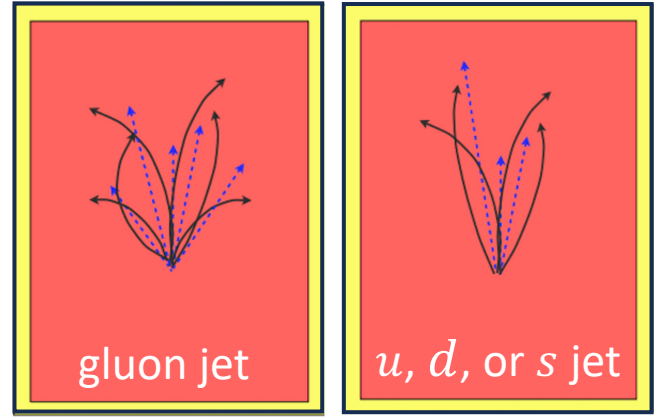
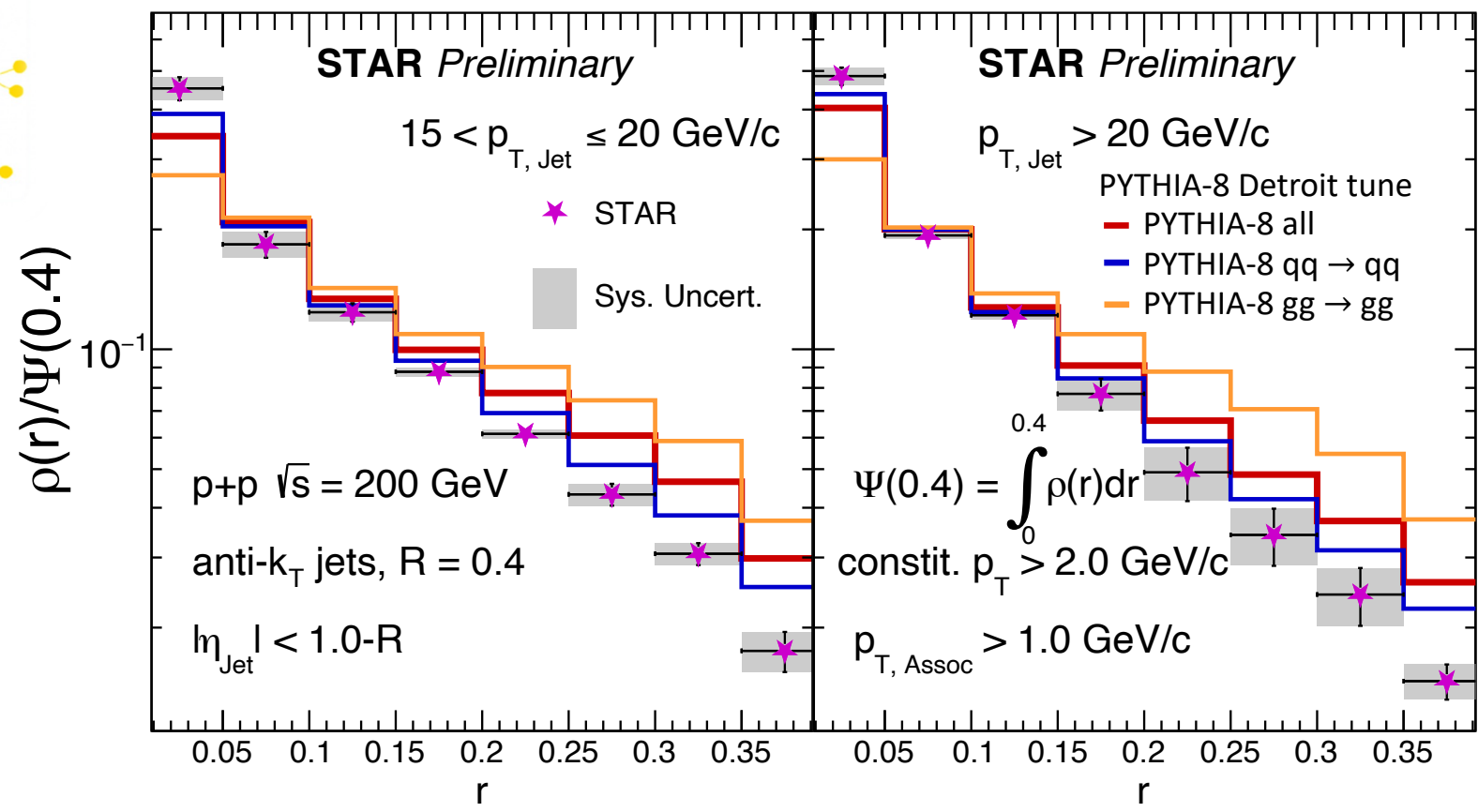
Measure initiating quark/gluon fractions?

Probe with jet charge: $Q_{\kappa}^{\text{jet}} \equiv \sum_{j \in \text{jet}} \left(\frac{p_T^j}{p_{T,\text{jet}}} \right)^{\kappa} Q_j$



- Both PYTHIAs perform well relative to data
 - Hint of preference for PYTHIA-6 Perugia tune
 - **Data mean shifts to the right -> more up quark dominated**

Jet radial constituent p_T profile



$$\rho(\Delta R) \equiv \lim_{\delta r \rightarrow 0} \left\langle \frac{1}{\delta r} \frac{\sum_{|\Delta R| < \delta r} p_{T,i}}{p_{T,jet}} \right\rangle$$

PYTHIA-8 overestimates broader (gluon-like?) jets relative to data

- Provides vacuum-like baseline for Au+Au collisions to measure hot-dense QCD effects

*Plot in backup shows same result for jet girth

Probe parton shower more differentially

Represent jet as a parton shower

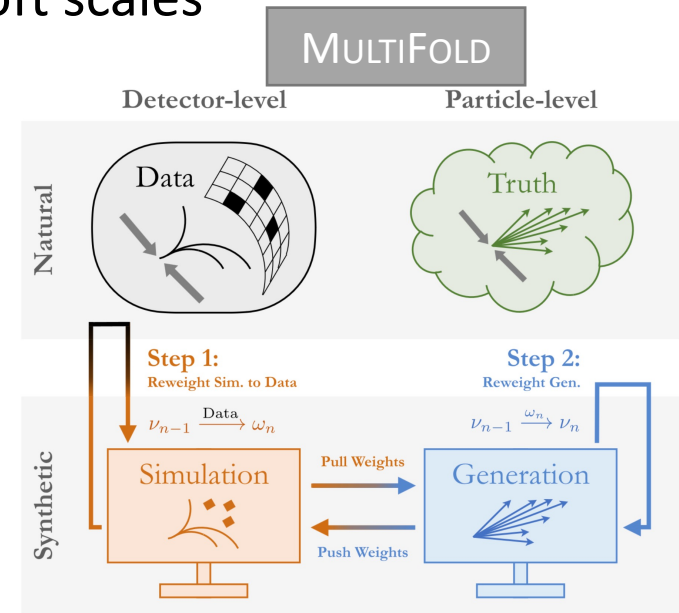
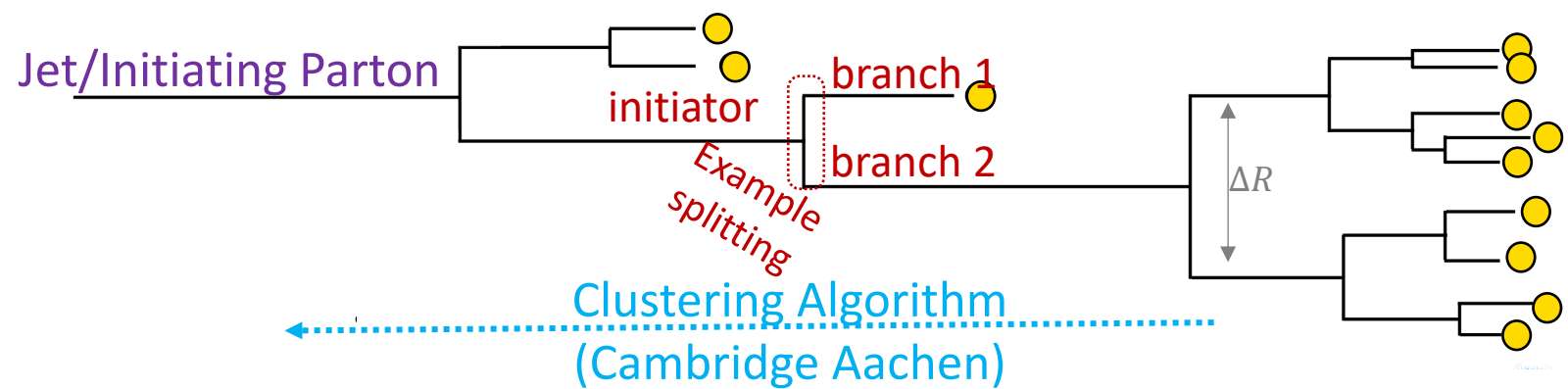
- Contains both soft- and hard-scale physics
- SoftDrop criterion selects “first hard branching”:

$$\frac{\min(p_{T,1}, p_{T,2})}{p_{T,1} + p_{T,2}} > 0.1 \quad (0.1 \text{ from generalized case } z_{\text{cut}} \left(\frac{\Delta R_{12}}{R_{\text{jet}}}\right)^\beta \text{ with } z_{\text{cut}} = 0.1 \ \& \ \beta = 0)$$

- ML software (MULTIFOLD) corrects unbinned observables for detector effects (MULTIFOLD, applied for first time at RHIC)

→ Probe correlations between observables and hard and soft scales

Decustering: follow sequential parton shower

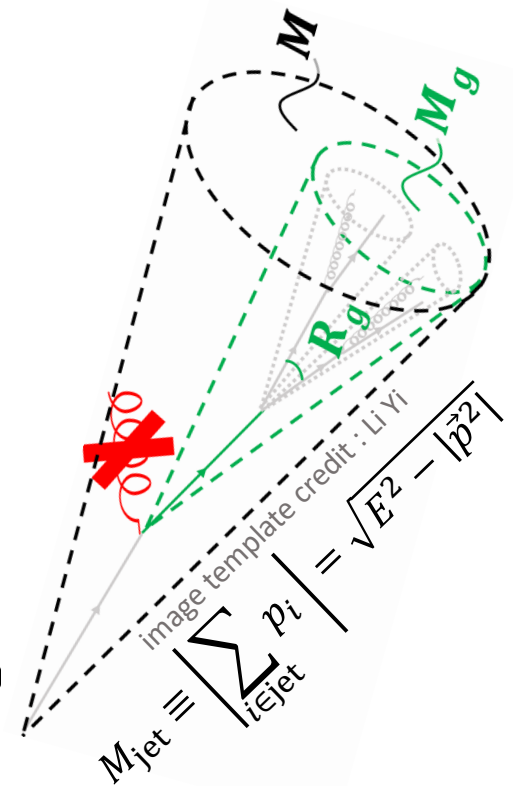
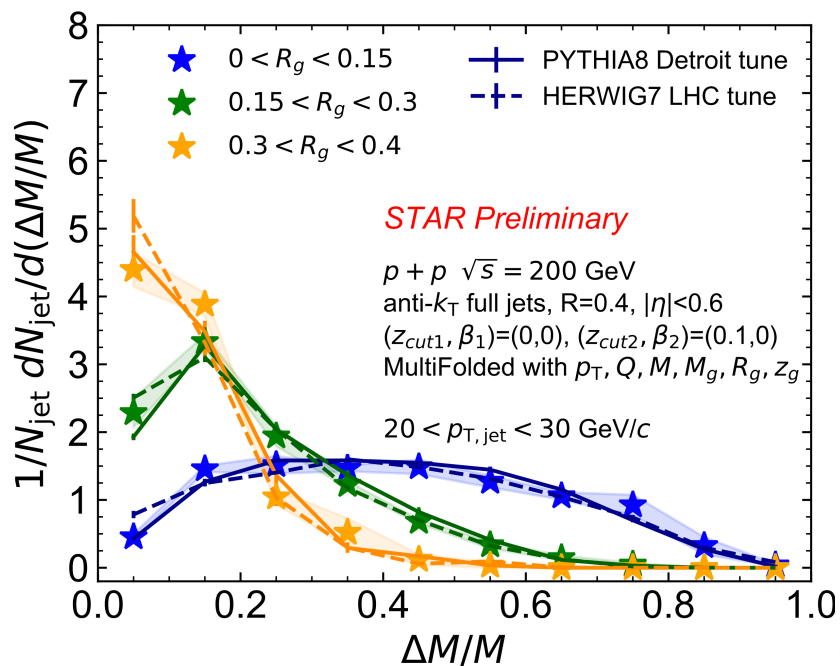
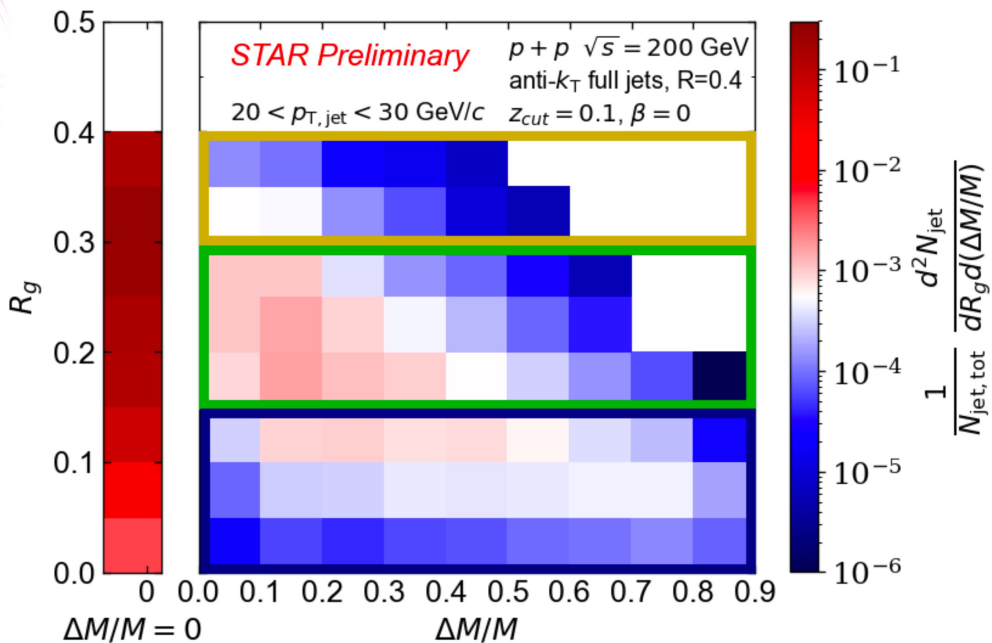
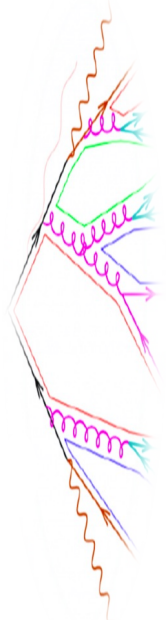


Andresson et al, PRL 124, 182001

Correlation: soft radiation to hard splitting angle

Ratio of jet mass removed (groomed): $\frac{\Delta M}{M} = \frac{M - M_g}{M}$

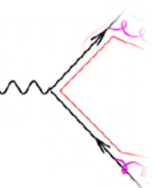
Hard splitting angle: $R_g = \sqrt{(\phi_1 - \phi_2)^2 + (\eta_1 - \eta_2)^2}$



$\Delta M/M$ distribution is anti-correlated with groomed jet radius R_g

→ Consistent with angular ordering the parton shower

- Large groomed jet radius → small $\Delta M/M$, little/no soft wide-angle radiation in shower
- MC models fit trends in data



Jets in p+A collisions

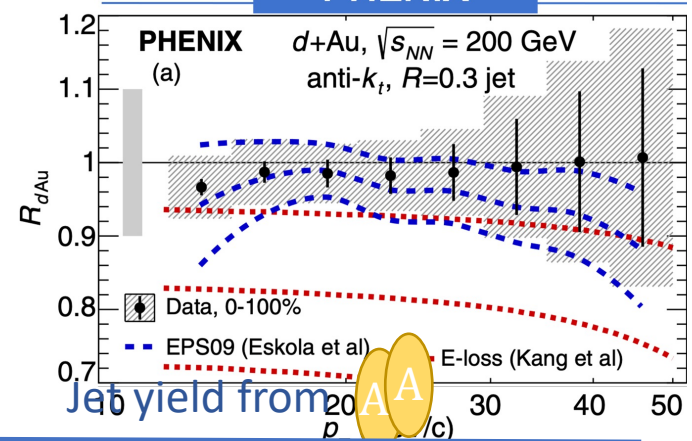
Benchmark cold nuclear matter effects (Cronin, nuclear calculate R_{AA} in Au+Au collisions

→ Quantify jet quenching in Au+Au via R_{AA} : $\frac{\text{jet yield from Au+Au}}{\text{geom. scaling} \times \text{jet yield from pp}}$

Classify events by “Event Activity” (EA) – soft particle production

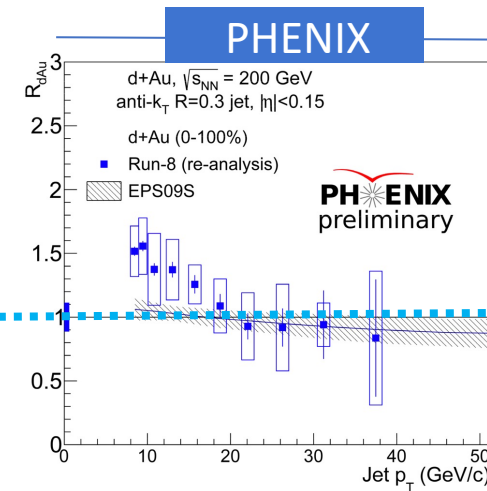
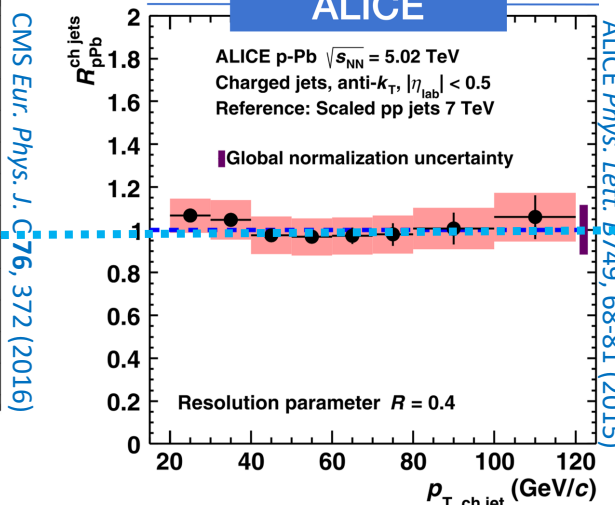
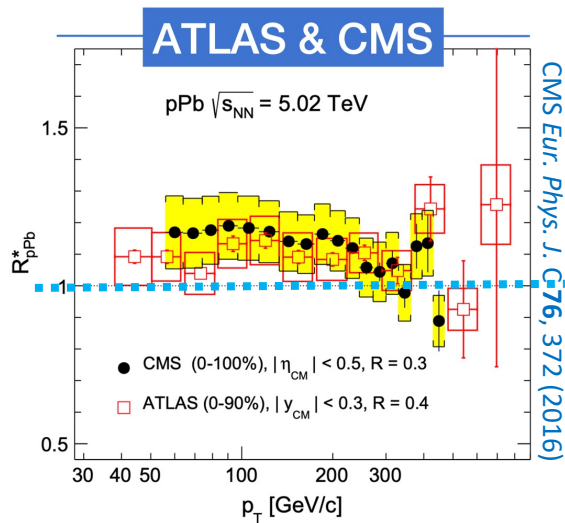
In p+A, no jet quenching (i.e. $R_{AA} \approx 1$) anticipated

PHENIX



Results: (p/d)+A

Inclusive measurements @ all EA: $R \approx 1 \rightarrow$ don't see quenching



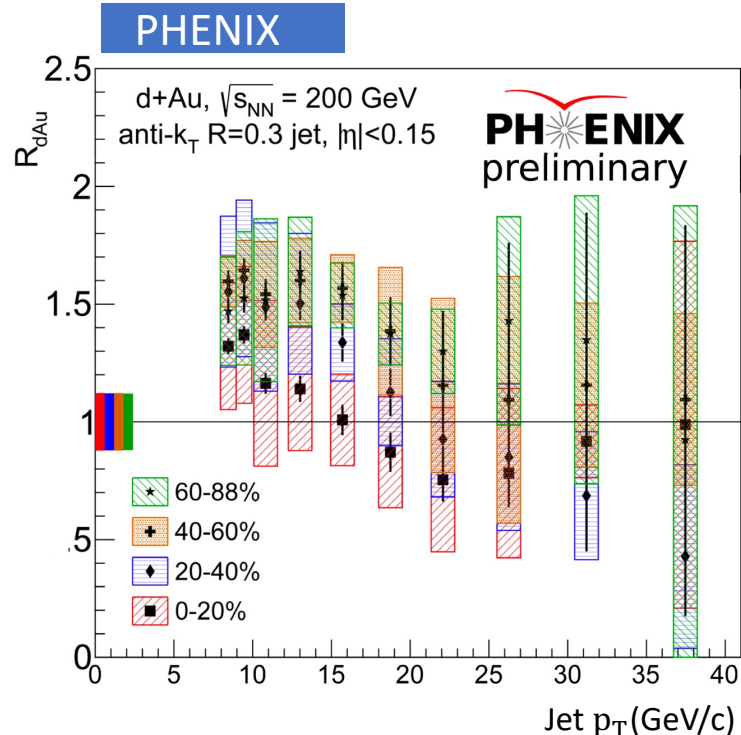
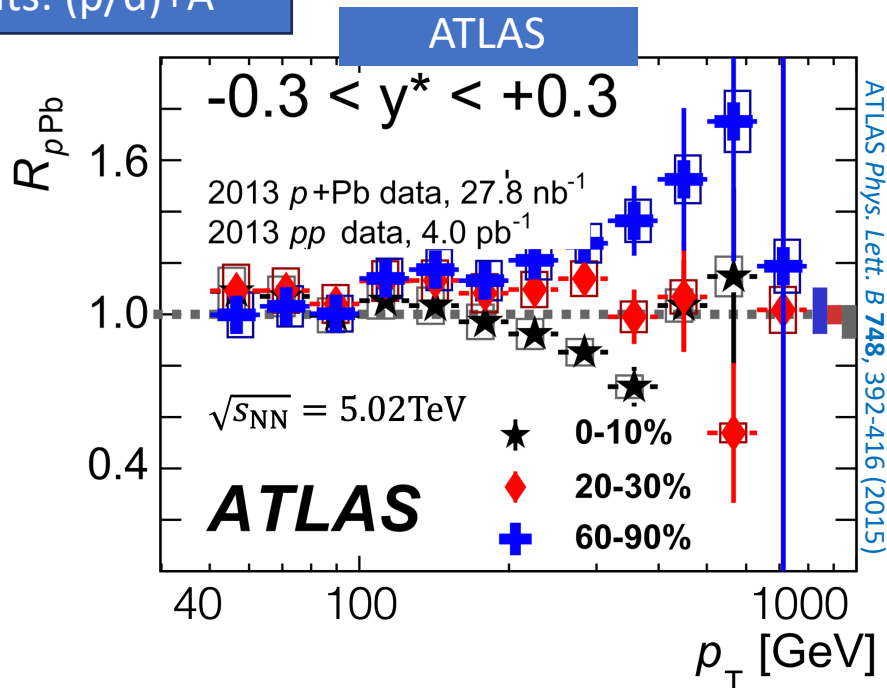
John Lajoia for PHENIX, Moriond 2021 (link), Supersedes previously published result (PRL 116, 122301, erratum in preparation)



Surprises: R_{AA} in EA selected events

- Suppressed for high-EA (“central”) central events
- Enhanced for low-EA (“peripheral”) events

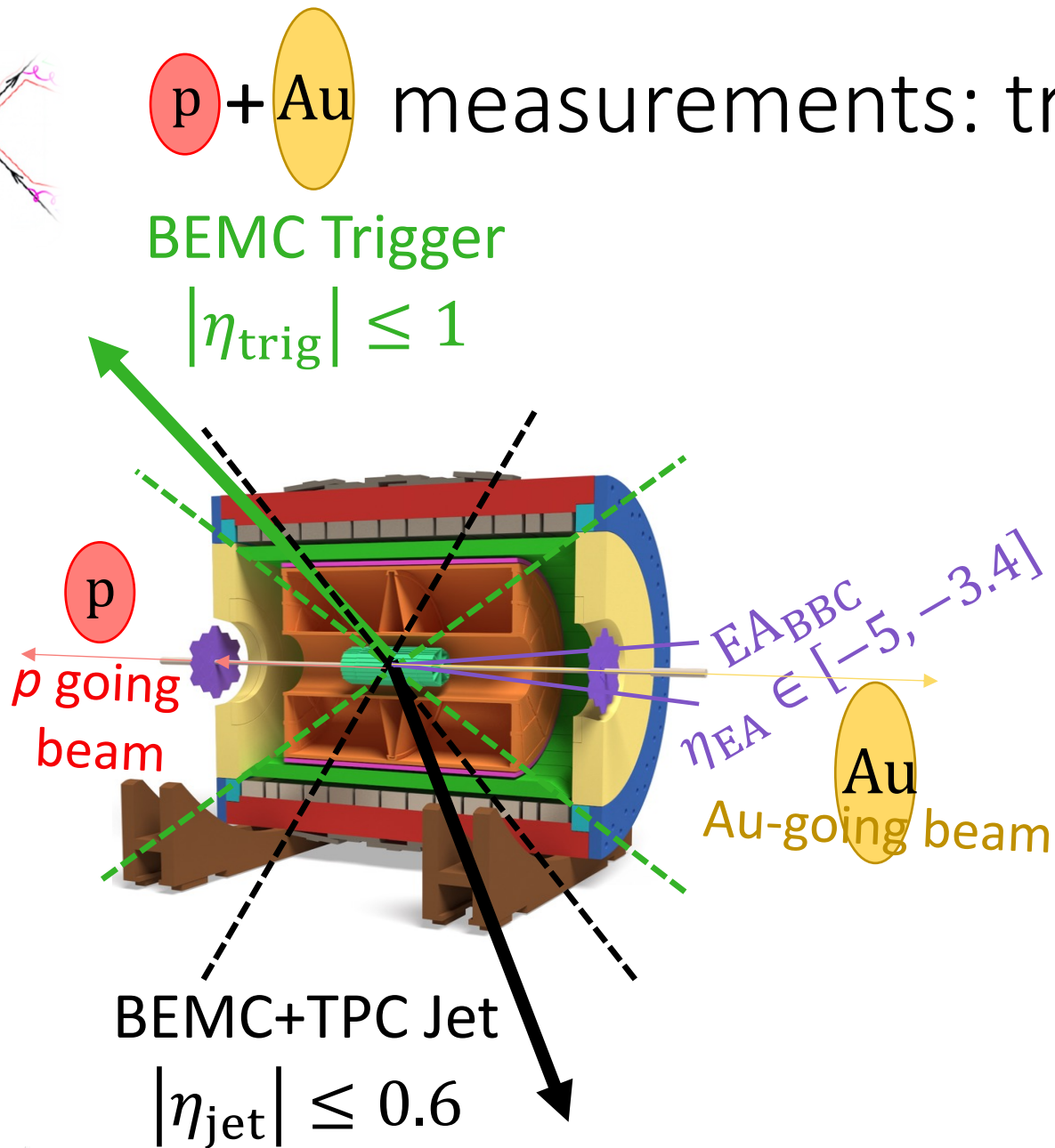
Results: (p/d)+A



John Lajoia for PHENIX, Moriond 2021 [link](#).
 Supersedes previously published result
 (PRL 116, 122301, erratum in preparation)

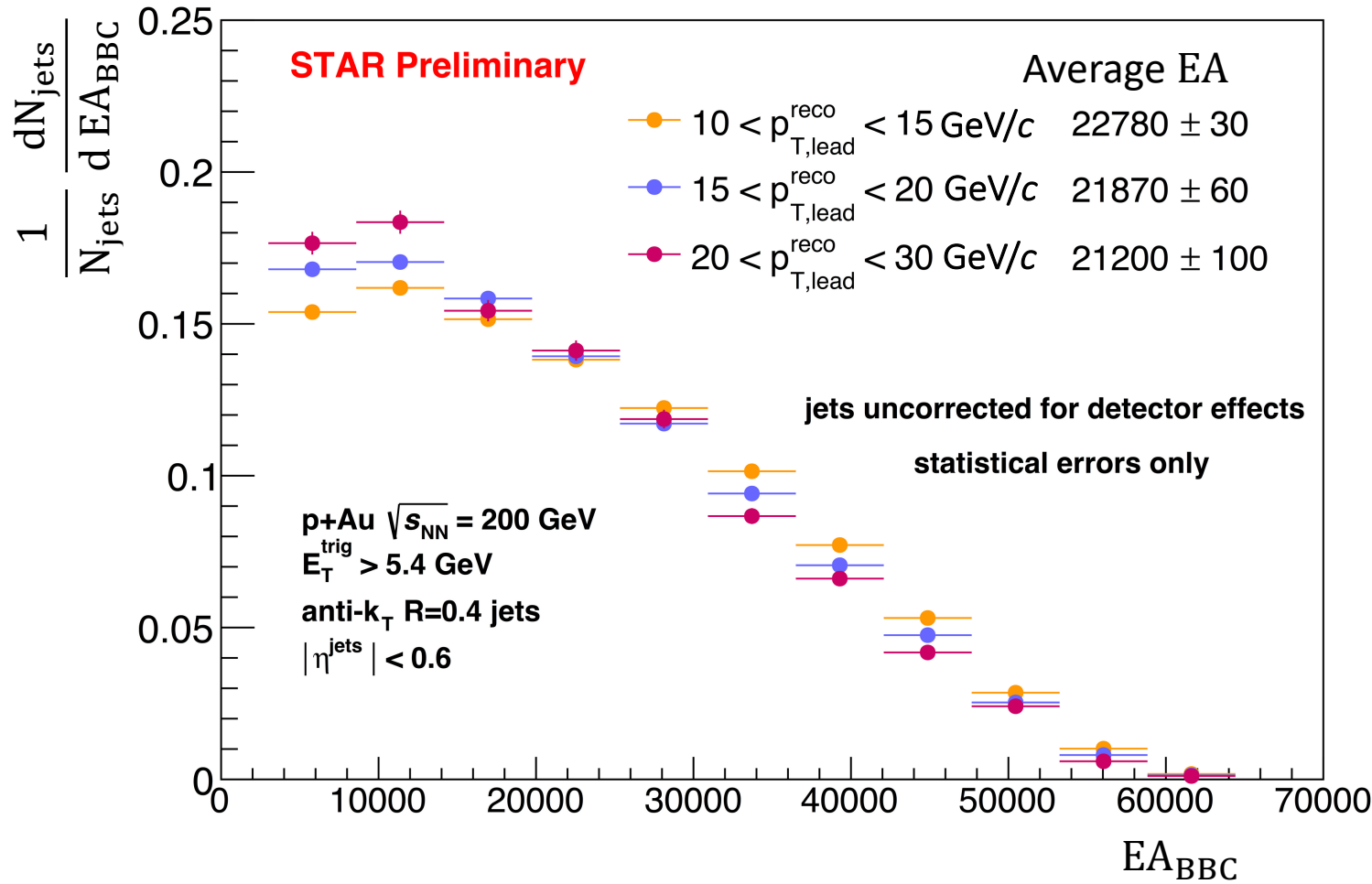
- Why is there a jet spectra to EA correlation:
 Jet quenching? Centrality selection? Phase space configuration? ...

p + Au measurements: trigger + jet + EA



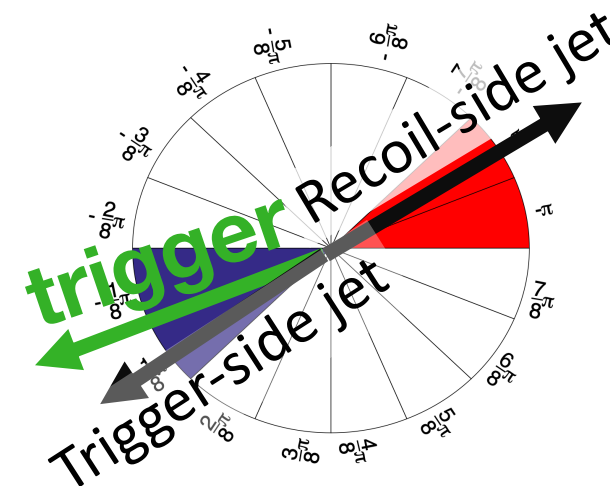
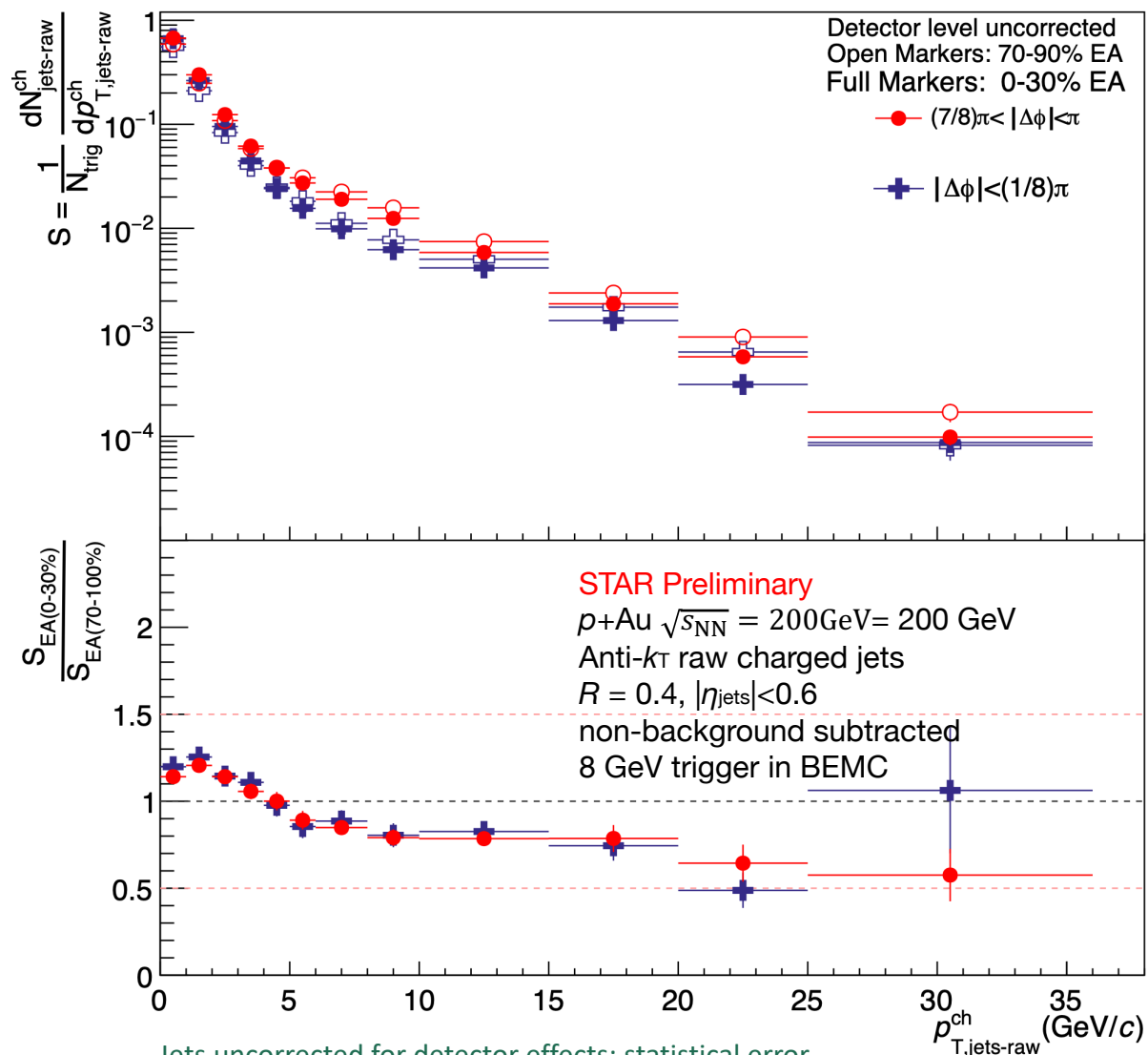
- EA \equiv sum of signal in BBC inner tiles
- At STAR kinematics, there **is not** enough phase space for an event to have
 - (1) trigger in BEMC
 - (2) jet in TPC, and
 - (3) a dijet partner in BBC
- No “auto-correlation” from directly measuring high EA from dijet partners hitting BBC
- Per-trigger normalization doesn’t use geometric scaling used in R_{AA}

EA distribution anticorrelated with $p_{T,lead}^{reco}$



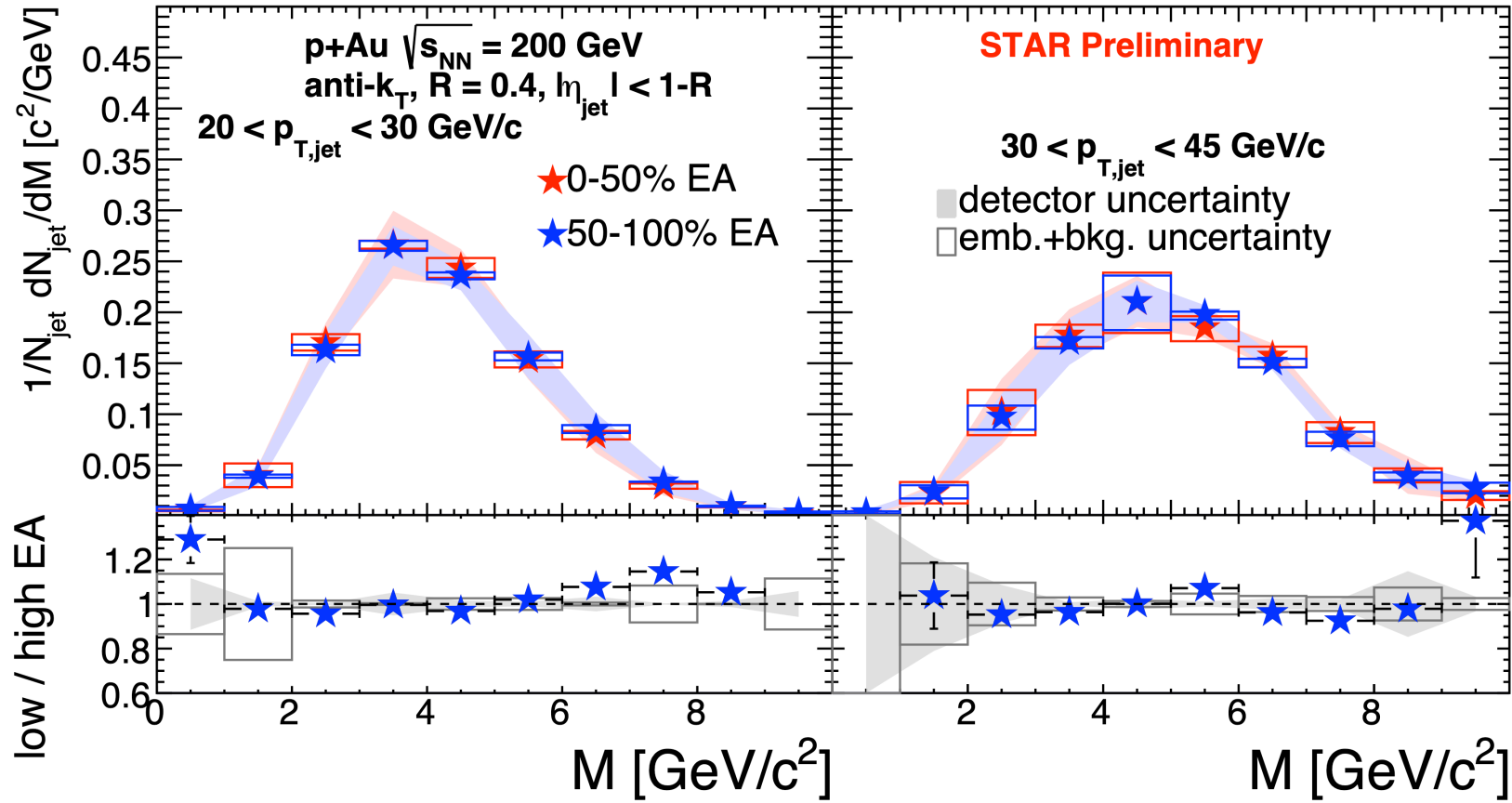
- **Anti-correlation:** EA distribution is
 - softest in events with a **high- p_T jet**
 - harder in events with a **mid- p_T jet**
 - hardest in events with a **low- p_T jet**
- i.e.: significant drop in mean EA with increasing $p_{T,lead}^{reco}$

Jet spectra per triggered event suppressed at high-EA



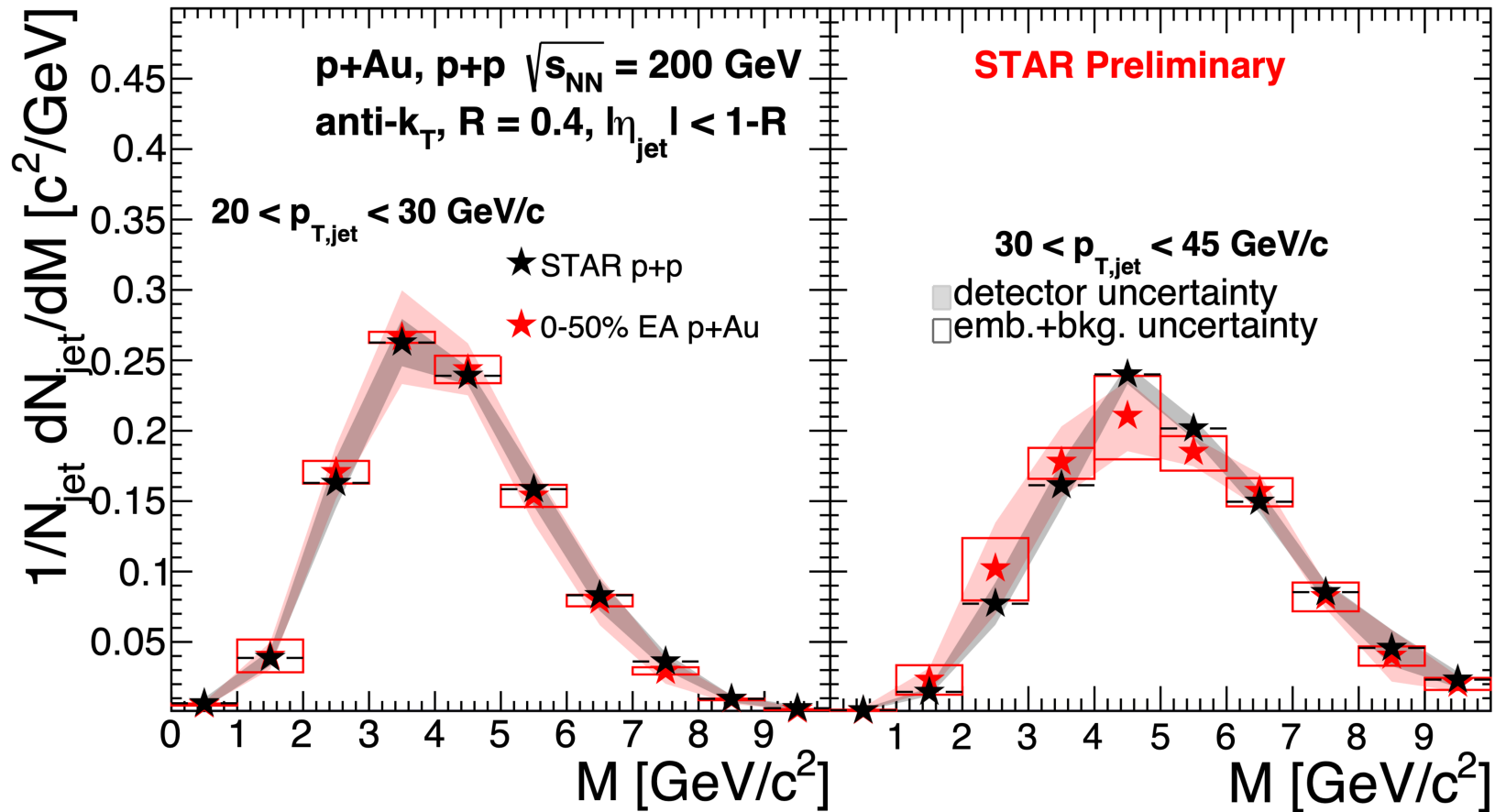
- **Anti-correlation**
- Both trigger- and recoil-side jets suppressed in high EA relative to low EA
- Qualitatively different from quenching in QGP in A+A collisions:
In A+A collisions, away-side jets are preferentially more quenched due to trigger surface bias

Test for p + Au jet quenching via jet mass



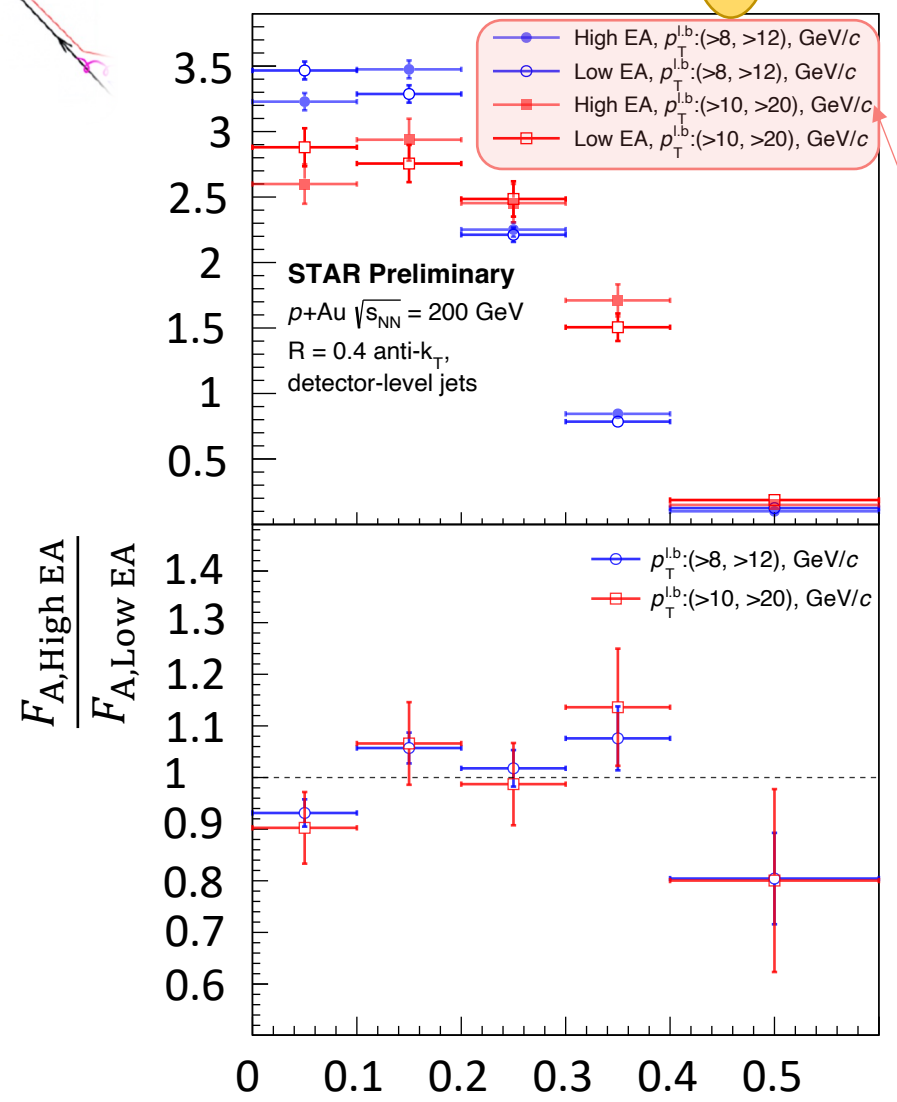
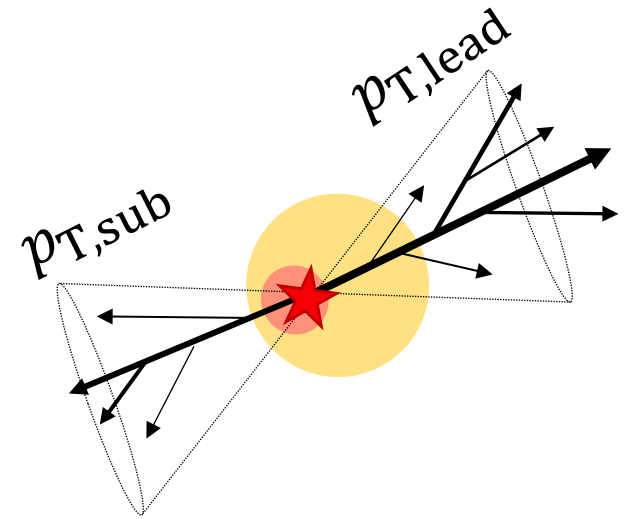
Jet mass distribution not EA dependent
 → null result for jet quenching

Test for p + Au jet quenching via jet mass



M distribution in (high-EA) p+Au consistent with p+p

Test for p + Au jet quenching via dijet p_T balance



Require:

- p_T cut on leading (highest p_T) & subleading (2nd highest p_T jet)
- Require azimuthally recoiling:
 $|\phi_{\text{lead}} - \phi_{\text{sub}}| > (\pi - R)$

- High EA, $p_T^{l.b.} (>8, >12)$ GeV/c
- Low EA, $p_T^{l.b.} (>8, >12)$ GeV/c
- High EA, $p_T^{l.b.} (>10, >20)$ GeV/c
- Low EA, $p_T^{l.b.} (>10, >20)$ GeV/c

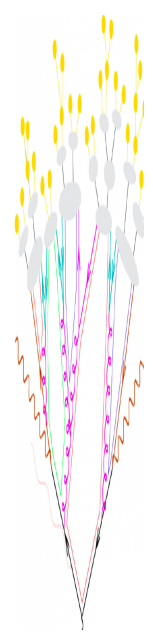
Dijet p_T balance distribution not EA dependent

→ null result for jet quenching

Jets are uncorrected for detector effects

Events corrected for luminosity and underlying event density → detector and event effects cancel in the ratio

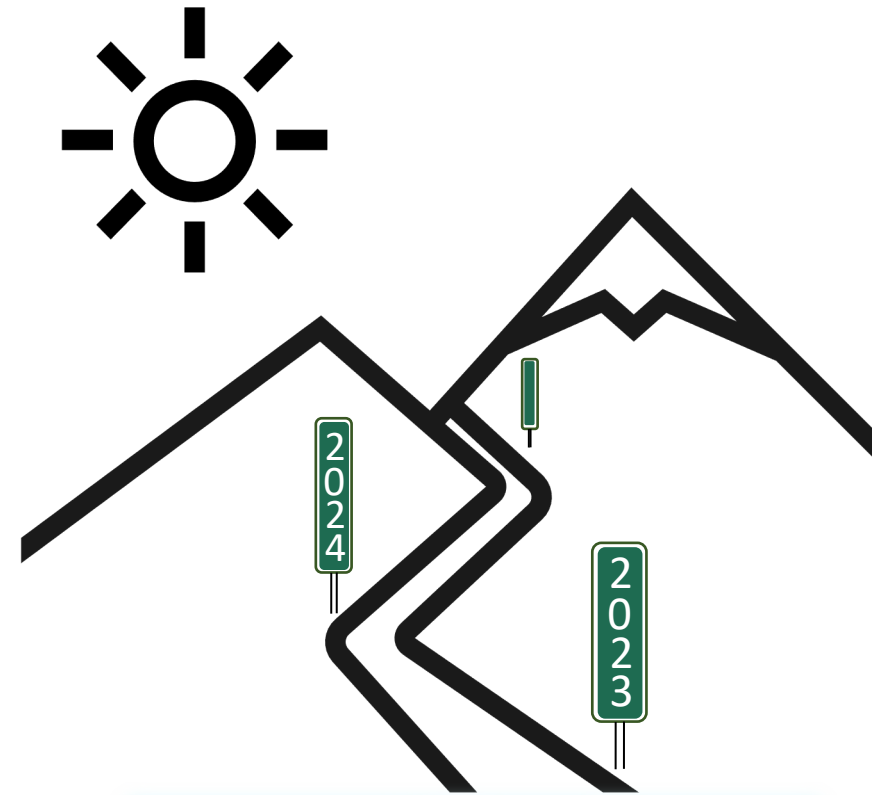
$$A_J \equiv \frac{p_{T,\text{lead}} - p_{T,\text{sub}}}{p_{T,\text{lead}} + p_{T,\text{sub}}}$$



Measurement Summary

Anti-correlation, over large rapidity gap,
between hard and soft particle production

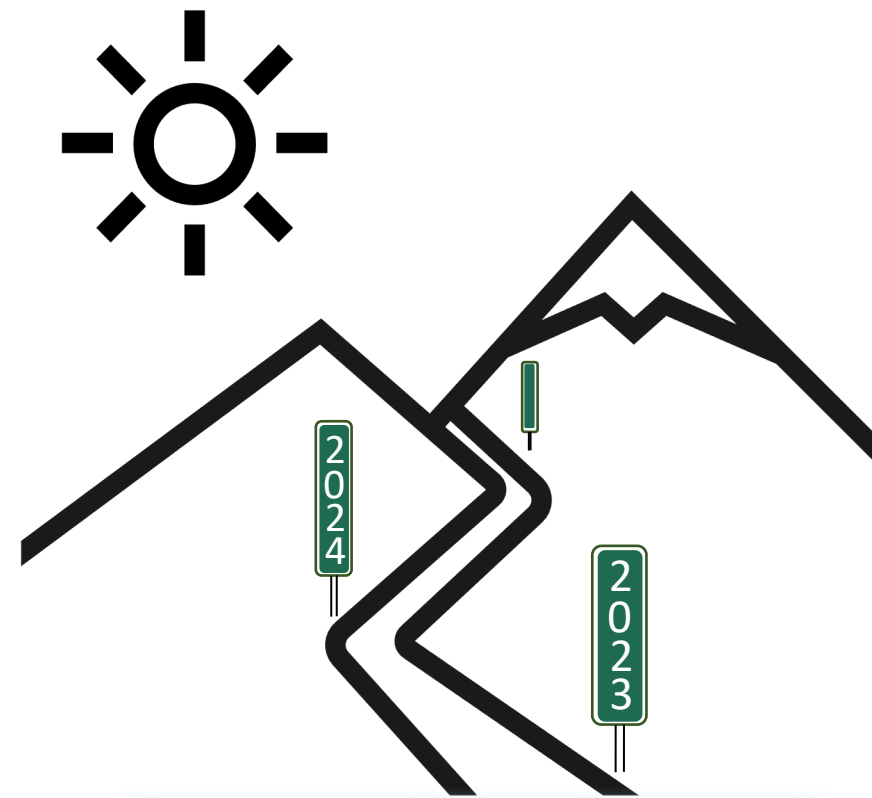
- No jet quenching within kinematics measured
- Rapidity gap shows correlation results from earliest collision stages and/or pre-collision dynamics





$p p$ Measurement Summary

- Energy-Energy Correlator
 - **measured QCD hadronization scale**
 - shows universal scale at LHC and RHIC energies
- Jet charge and radial density profiles
 - sensitive to jet initiating partons (gluon vs quark and quark flavor)
 - PYTHIA simulations generally validated
 - **future looking: measure distribution of gluon, quark, and quark-flavor of jets**
- Jet substructure groomed by SoftDrop
 - **groomed mass ratio vs hard splitting angle: consistent with angular ordering**
 - **mass shared fraction in hard splitting: parton virtuality decreases faster in more collinear splittings**



Backup Slides

MultFold Variables

- Jet measurements need to be corrected for detector effects for comparison with theory/model
- Unfolding methods:
 - Iterative Bayesian unfolding ([D'Agostini, arXiv:1010.0632\(2010\)](#))
 - **MultFold** ([Andreassen et al. PRL 124, 182001 \(2020\)](#))
 - Machine learning driven
 - Unbinned
 - **Simultaneously** unfolds multiple observables → **Correlation** information is retained!
- First application of MultiFold on RHIC data!

- Jet observables

- p_T : transverse momentum

- $Q^\kappa = \frac{1}{(p_{T\text{jet}})^\kappa} \sum_{i \in \text{jet}} q_i \cdot (p_{Ti})^\kappa$ → Choose $\kappa=2$

- $M = |\sum_{i \in \text{jet}} p_i| = \sqrt{E^2 - |\vec{p}|^2}$

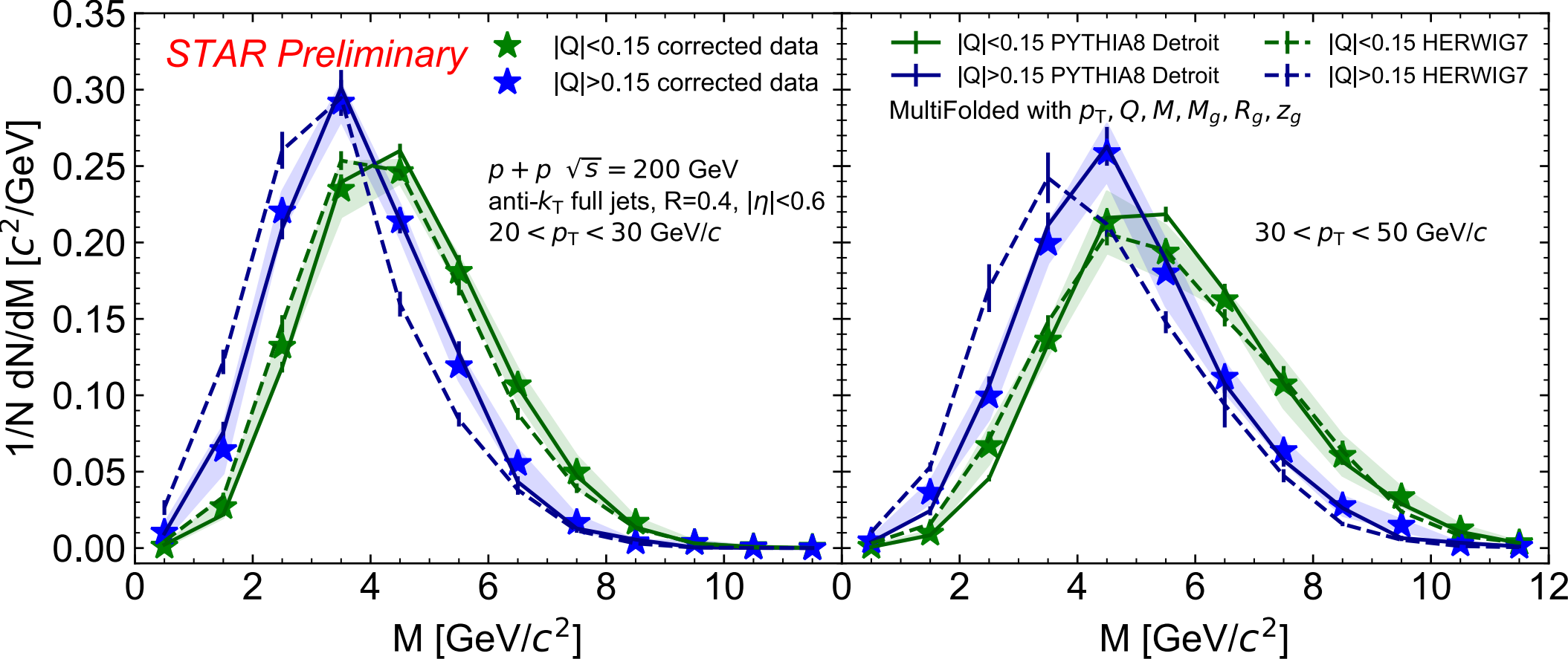
4-momentum of the constituent i

- R_g : groomed jet radius
- z_g : shared momentum fraction
- M_g : groomed jet mass

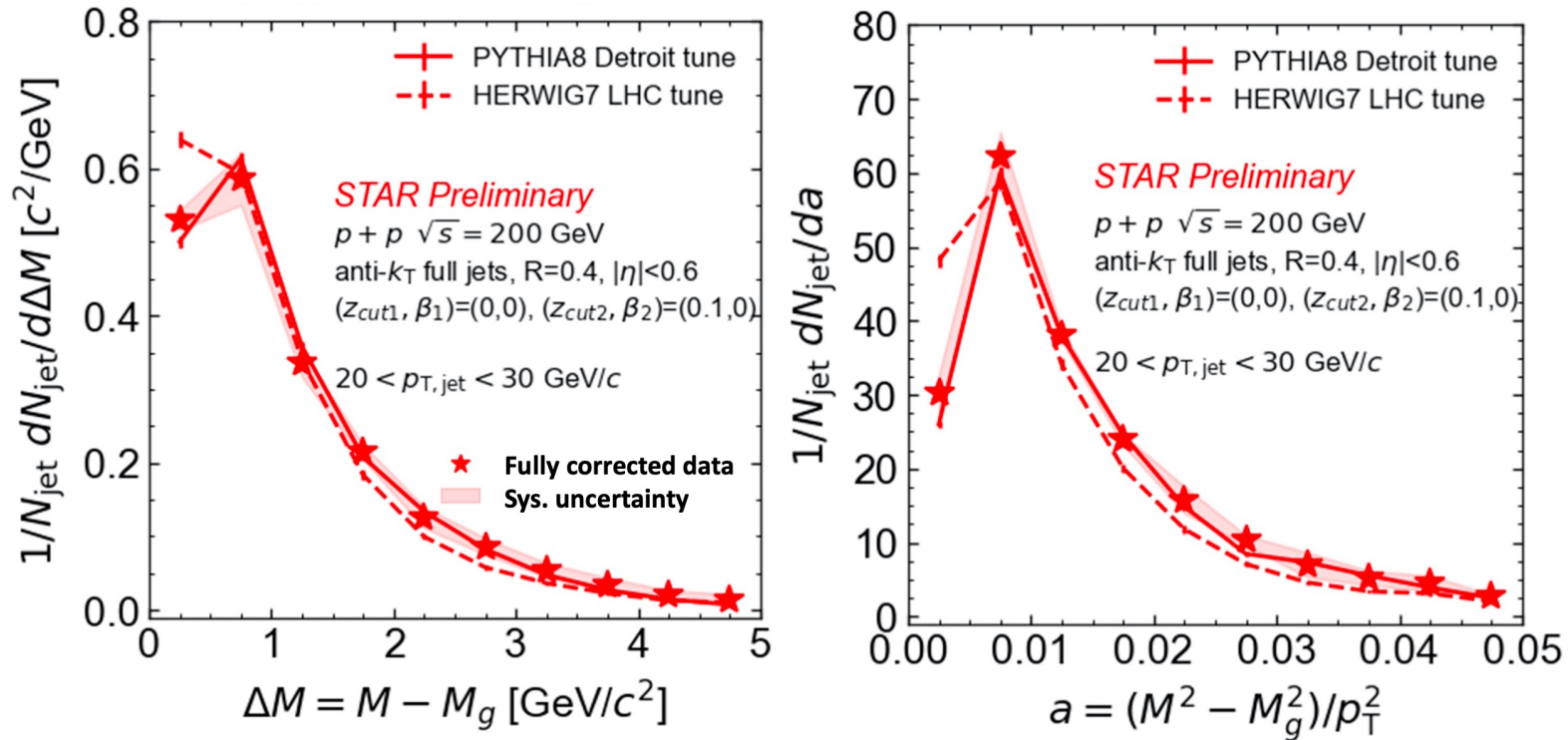
All 6 observables are simultaneously unfolded in an unbinned way!

- Uncertainties due to prior choice accounted for through 6D reweighting based on PYTHIA8 or HERWIG

Multifold vs RooUnfold



Collinear drop groomed jet mass



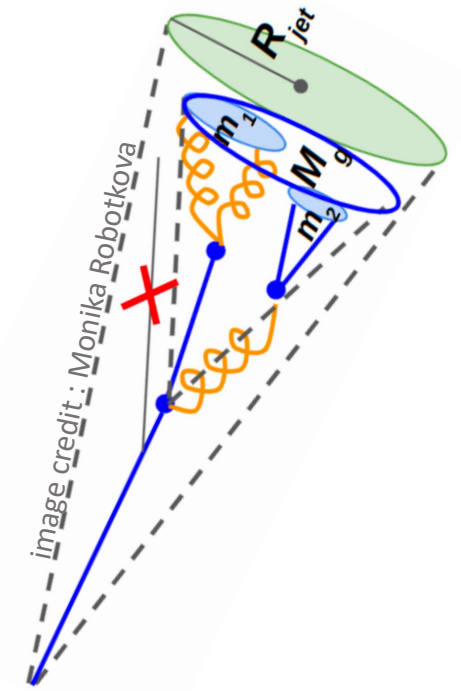
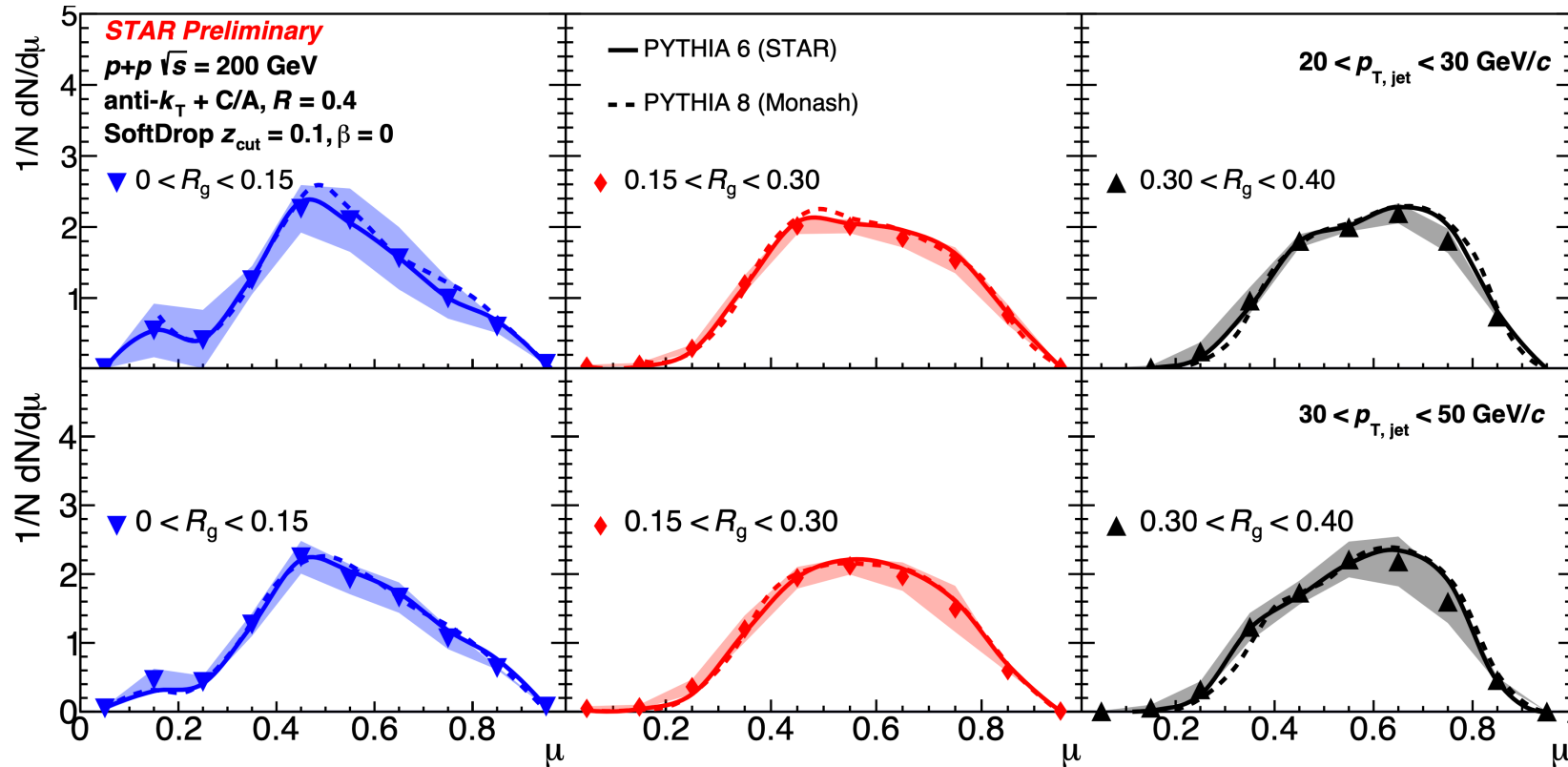
PYTHIA8 Perugia 2012 STAR tune: Skands, PRD 82, 074018 (2010)
 PYTHIA8 Detroit tune: Aguilar et al. PRD 105, 016011(2022)
 HERWIG7: Bellm, et al. PRC 76, 1-8 (2016)

Measurement excludes jets with $\Delta M = 0$ (45.5% of jets in this jet p_T range)

- First collinear drop groomed jet measurement, sensitive to soft radiation within jets
- MC predictions qualitatively consistent with data; some tension from HERWIG in small ΔM region
- MultiFold allows us to correlate (combinations of) unfolded quantities

Correlate: groomed mass fraction “ μ ” vs $p_{T,jet}$ vs R_g

$$\mu = \frac{\max(m_1, m_2)}{m_2 + m_1}$$

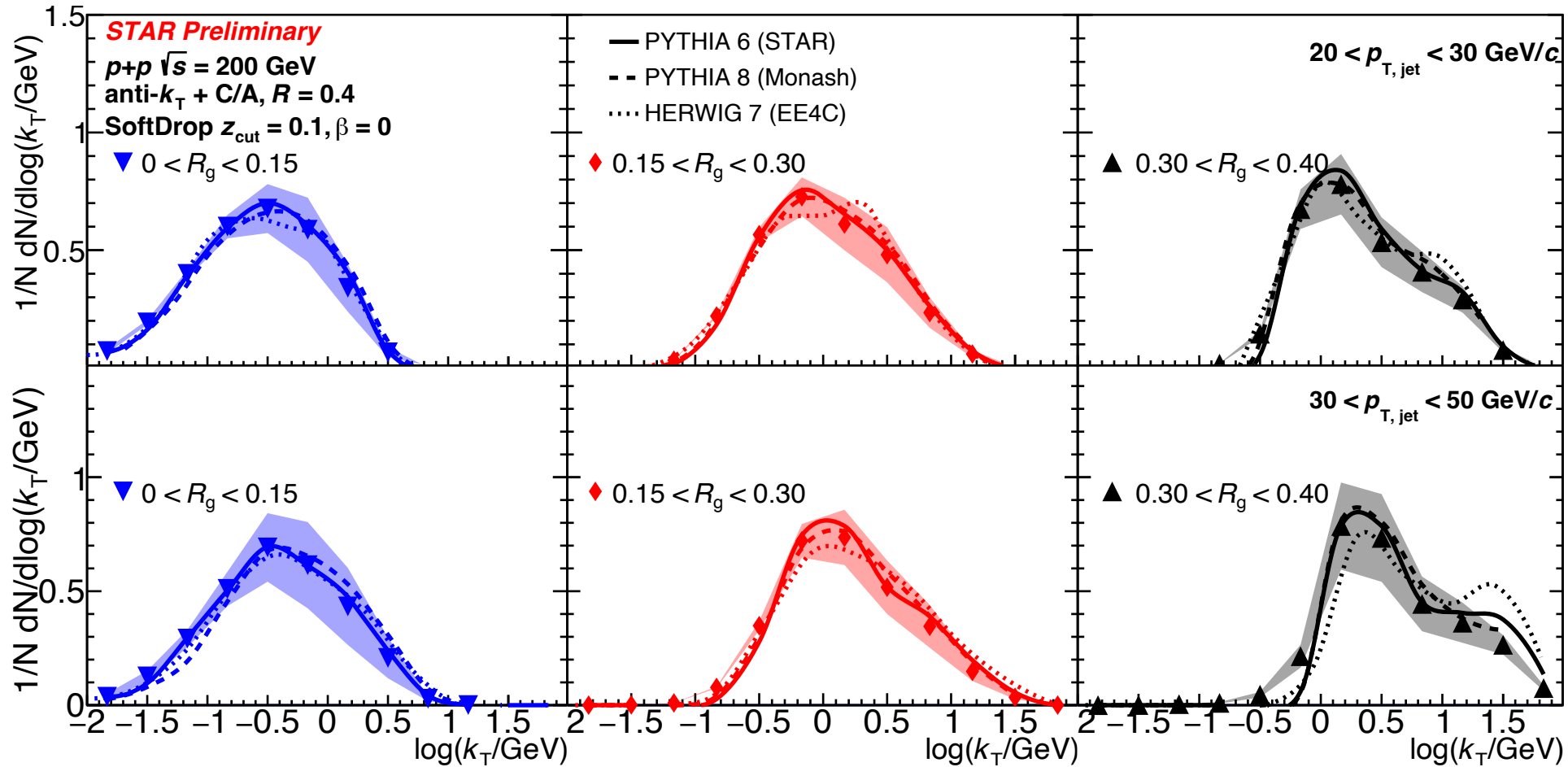


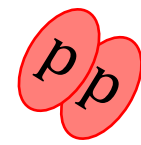
μ smaller at smaller R_g

→ indicates faster reduction of virtuality in the jet shower

Correlate splitting scale to hard splitting angle

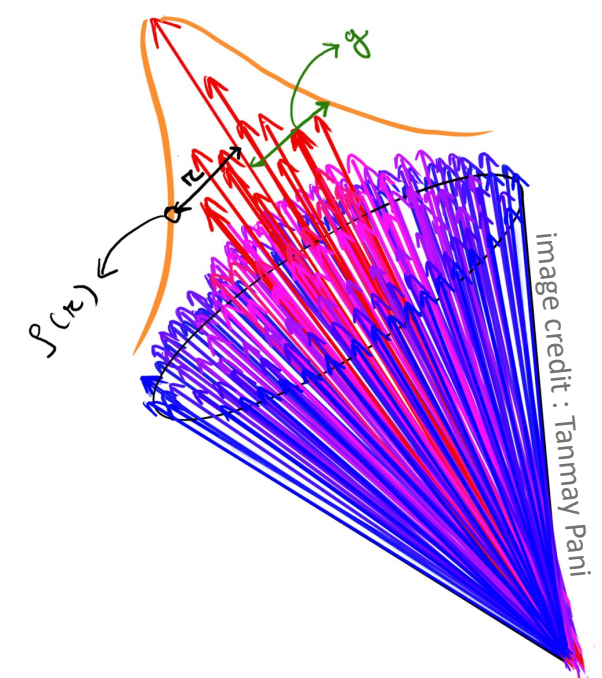
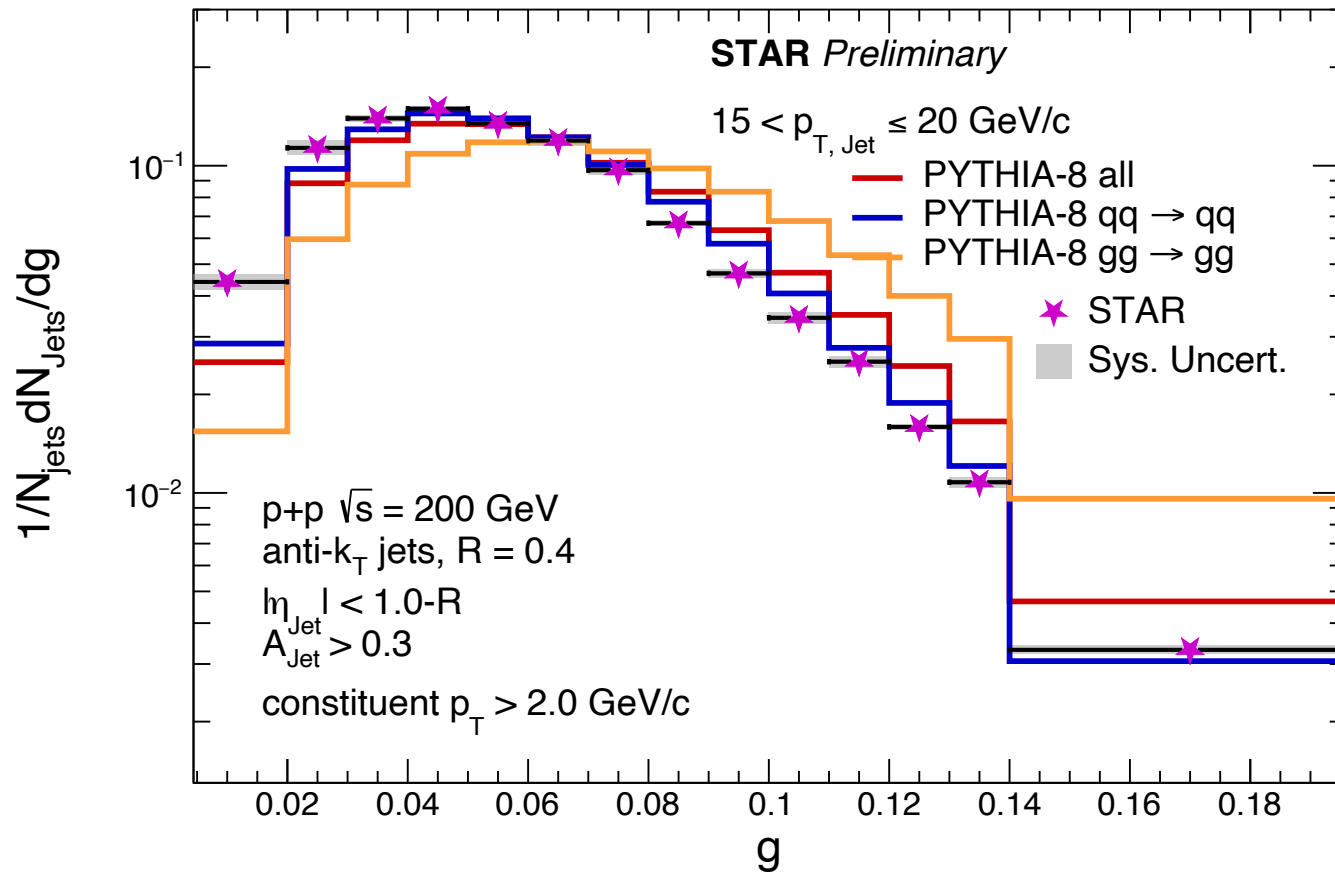
Splitting scale: $k_T = z_g p_{T,\text{jet}} \sin(R_g)$





Measure initiating quark/gluon fractions?

Measure jet girth

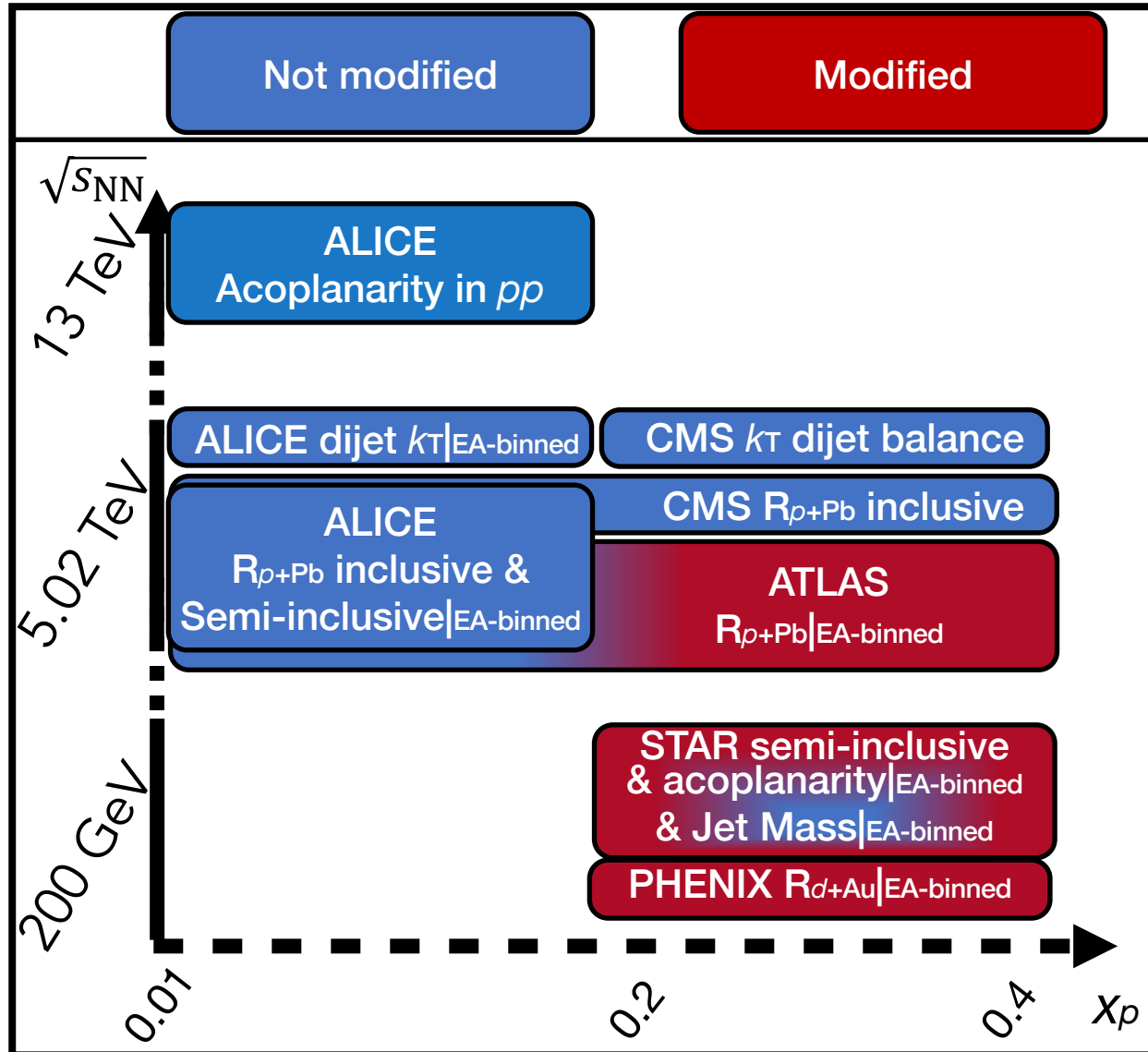


$$g \equiv \frac{\sum_{\text{Tracks}} p_T^{\text{track}} r_{\text{track}}}{p_T^{\text{jet}}}$$

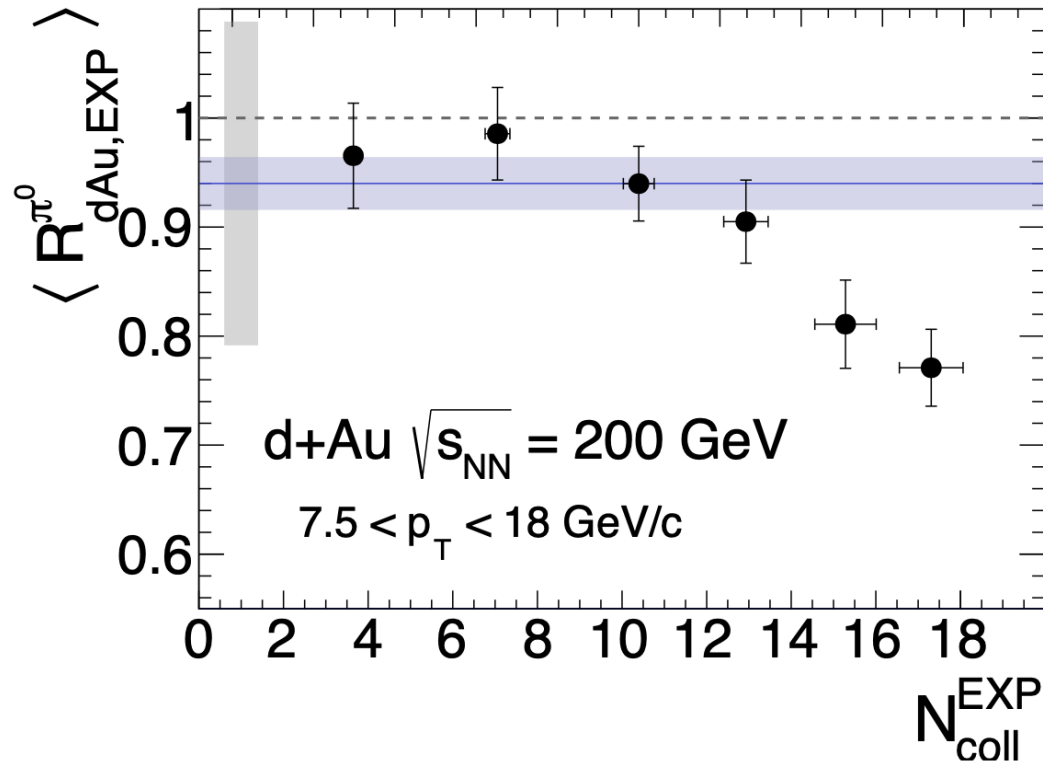
PYTHIA-8 overestimates broader (gluon-like?) jets relative to data

- Provides vacuum-like baseline for Au+Au collisions to measure hot nuclear effects

Small system jet modification score card





PHENIX measurement: $\langle R_{dAu,EXP}^{\pi^0} \rangle$

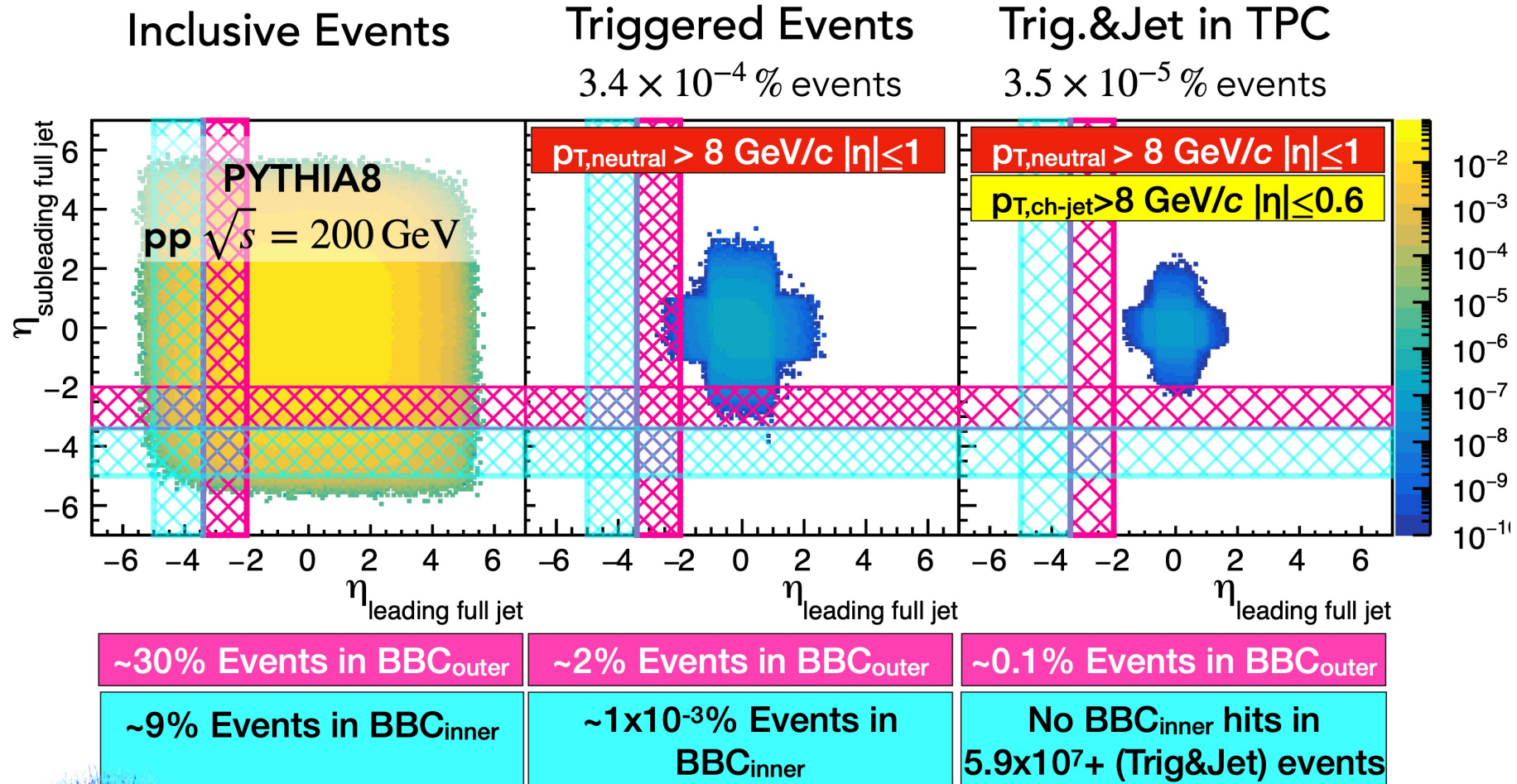


PHENIX 2023, arXiv: <https://arxiv.org/pdf/2303.12899.pdf>

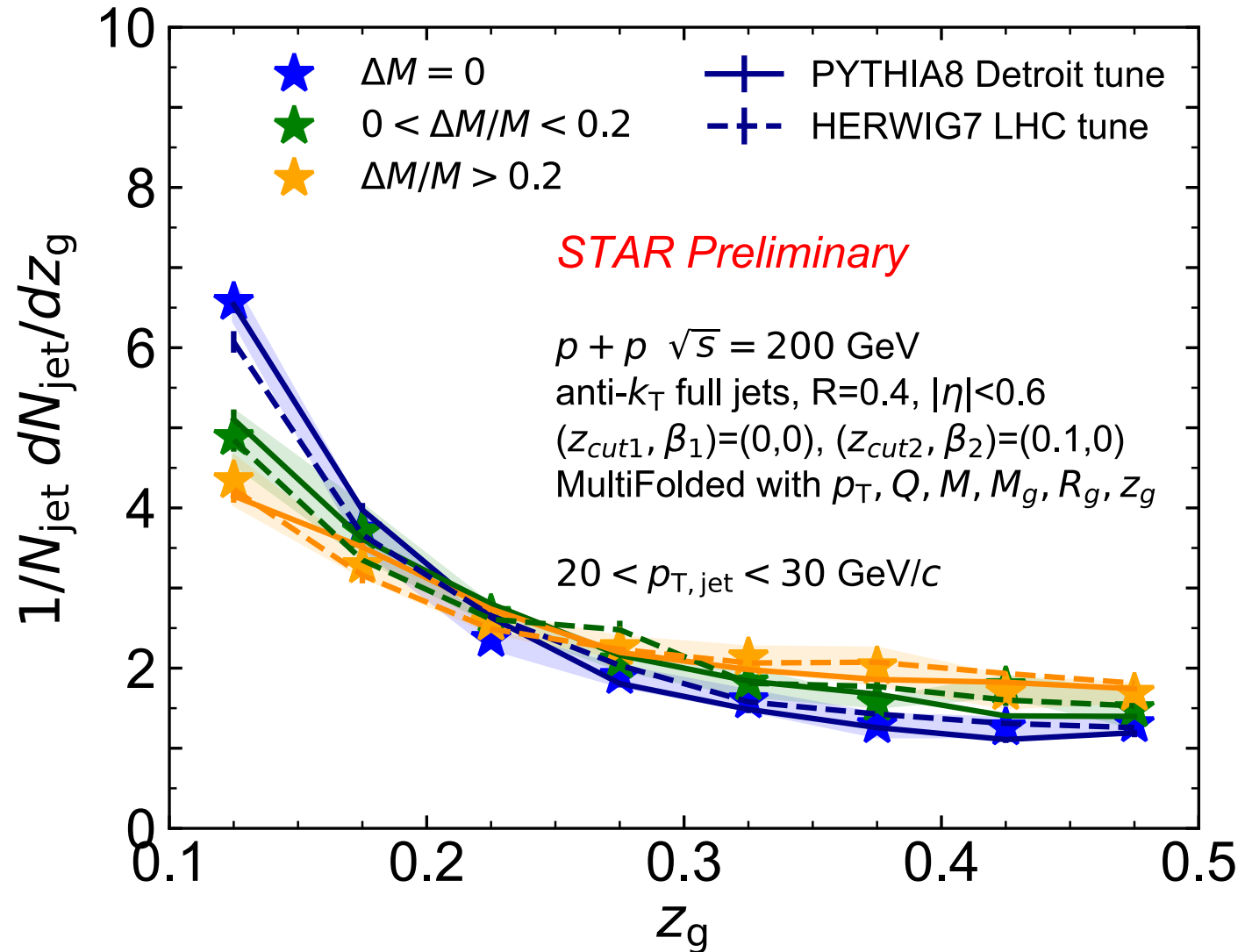
STAR spectra modification *not* due to dijets hitting BBC

 Outer BBC $\eta \in (-2, -3.4)$

 Inner BBC $\eta \in (-3.4, -5)$



Shared momentum fraction vs mass pruned



STAR EEC for three different jet p_T selections

