Initial Stages 2023

Copenhagen, June 19-23

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

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WAYNE STATE UNIVERSITY

STAR

supported in part by

U.S. DEPARTMENT OF ENERGY

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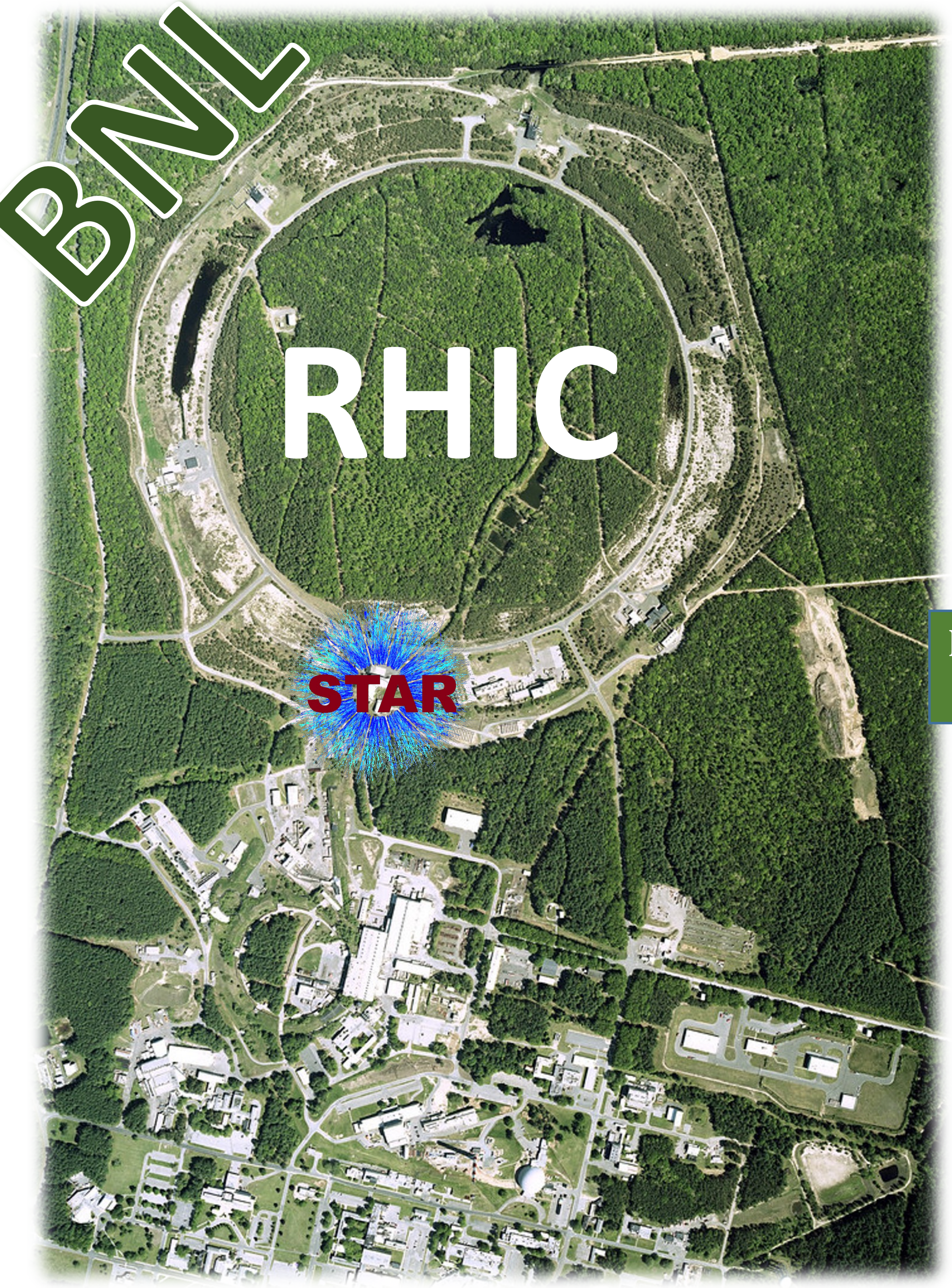
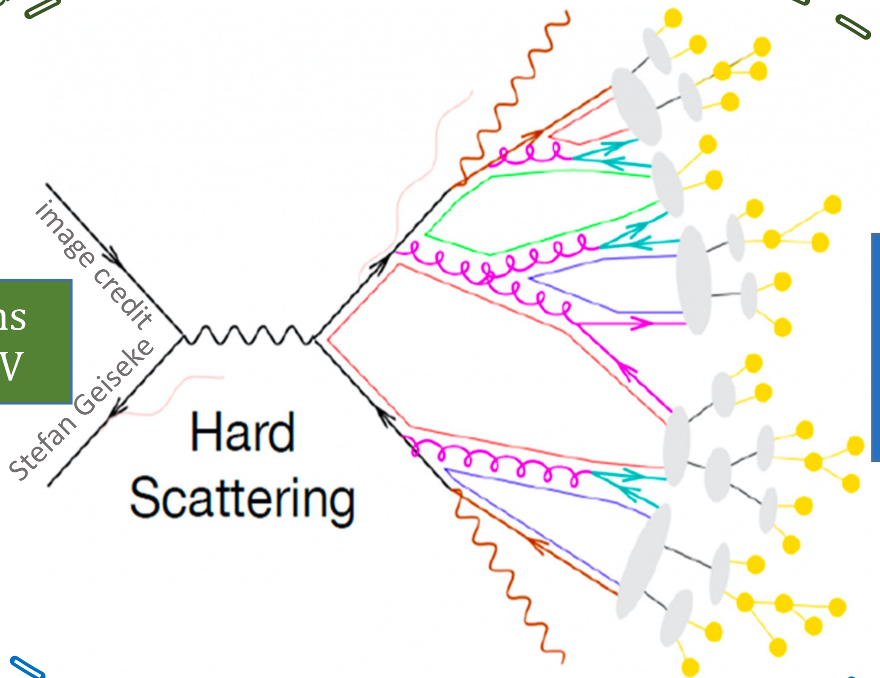


Jets: probe initial stages

Hard scattering to highly virtual parton (pQCD)

Parton shower & hadronization: pQCD & npQCD

RHIC Collides Ions $\sqrt{s_{NN}} = 200$ GeV

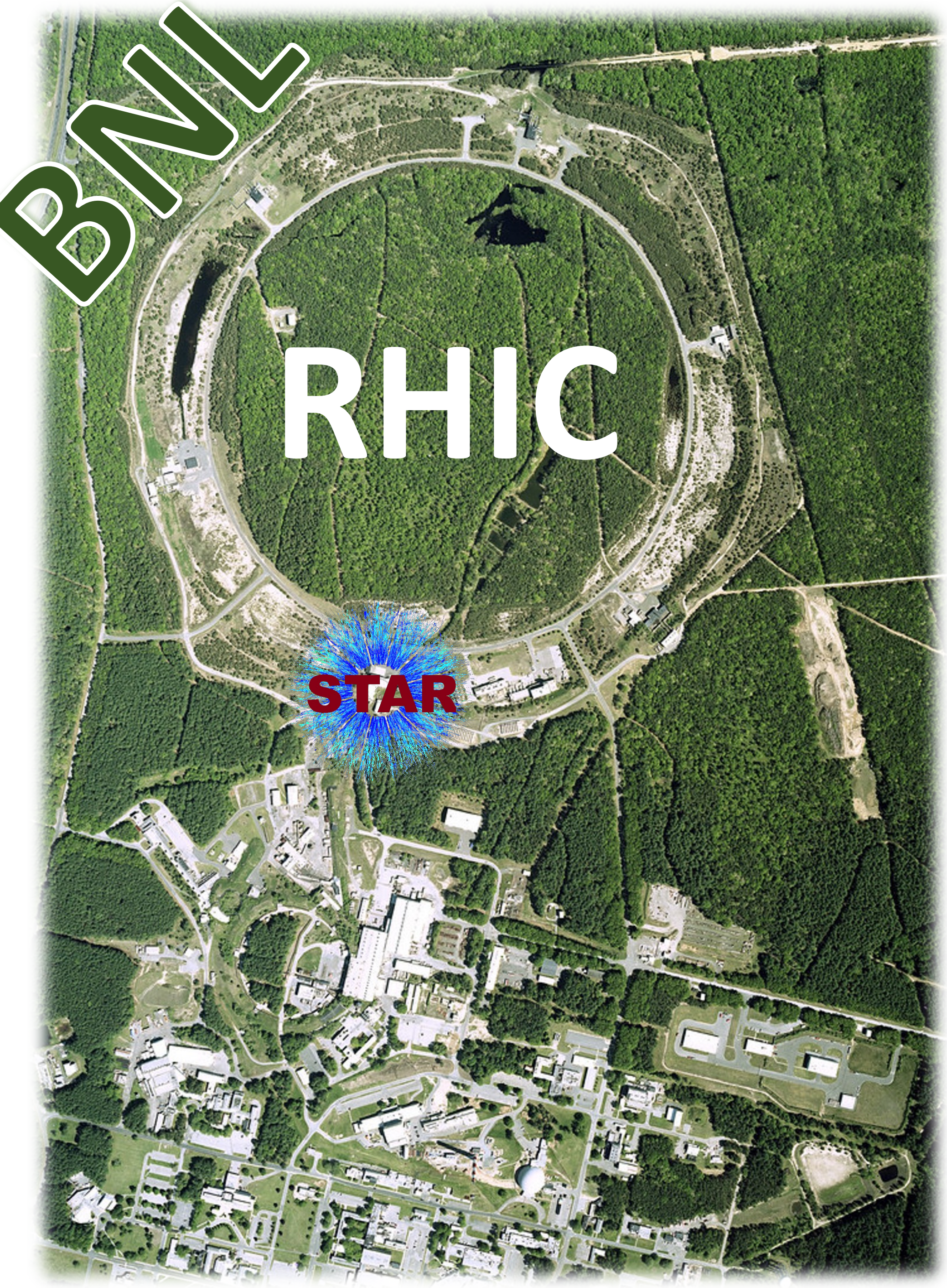


STAR measures final state particles

Jet identified via clustering

Substructure applied in clustering (angle ordering)

Jet kinematics proxy for hard scattering



This presentation

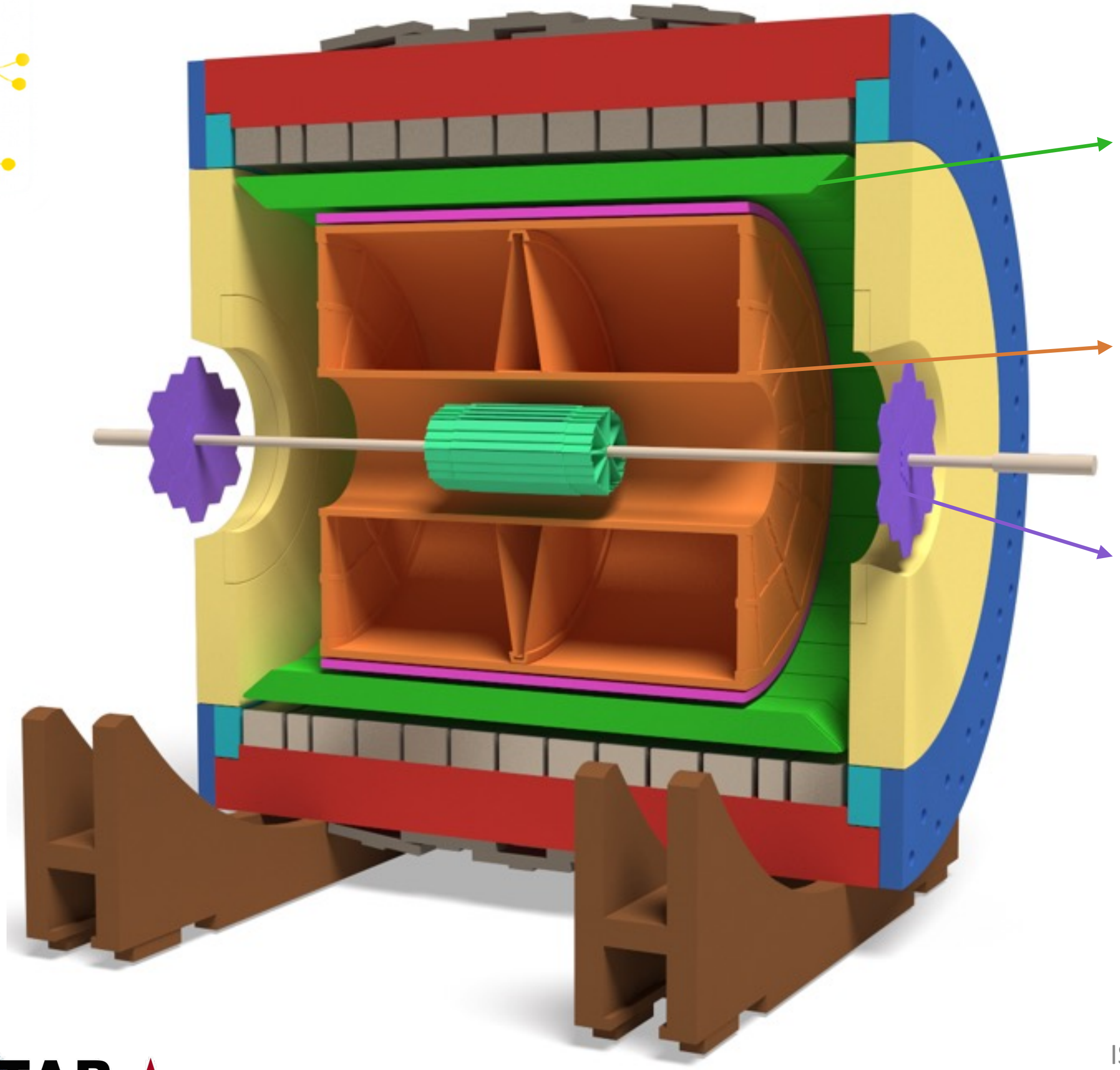
p + p Collisions:

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

p + 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
- $|\eta| \leq 1$

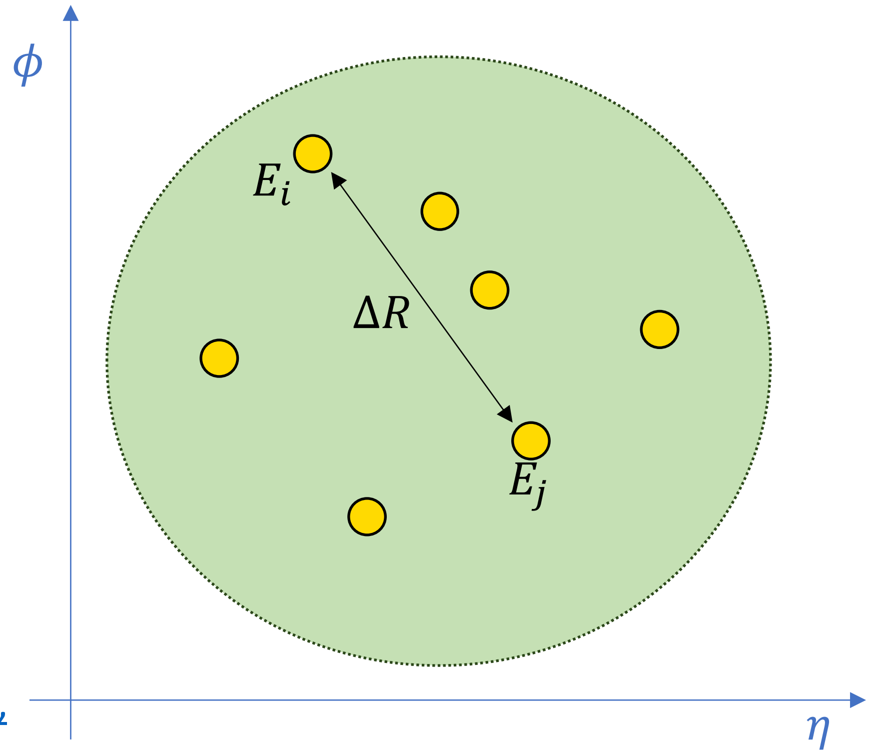
Beam Beam Counter (BBC):
- Charged particles
- $|\eta| \in [3.4,5]$

Particles → Jets

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

Measure QCD hadronization scale?

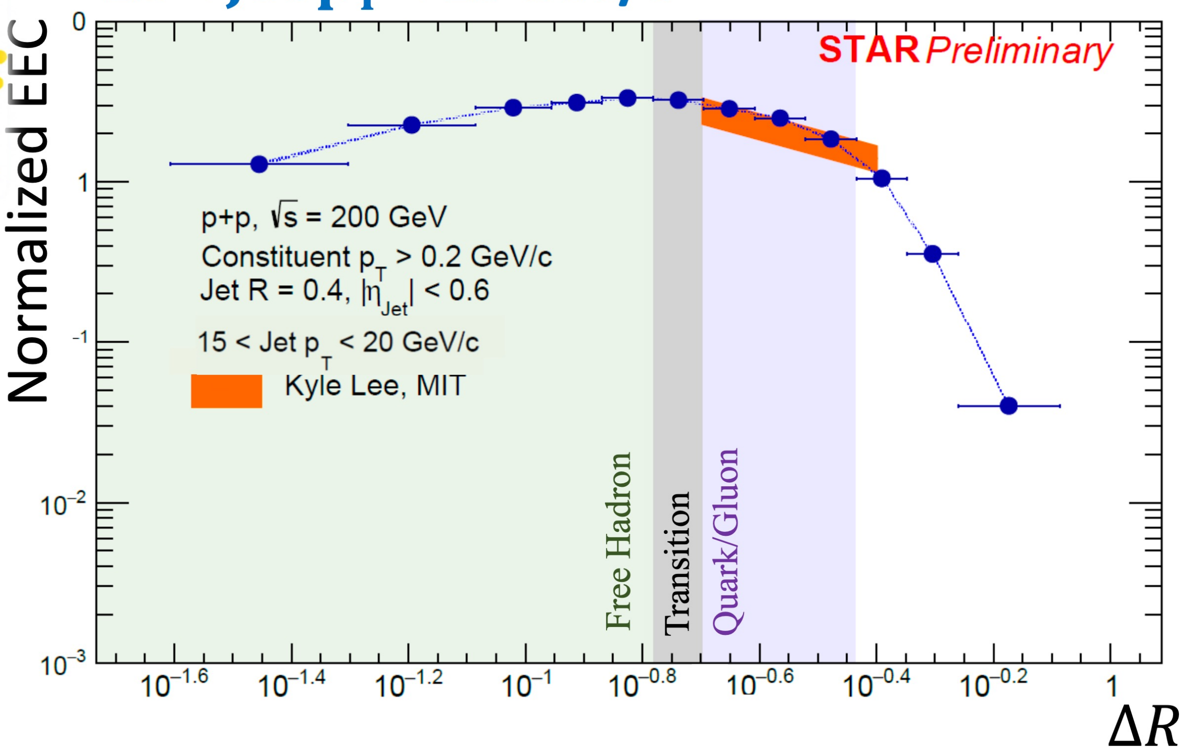
- "Energy-Energy Correlators" (EEC, Lee, Meçaj, and Moult, arXiv 2205.03414) probe hadronization scale (Andres, et al., arXiv 2209.11236)
- Normalized EEC $\equiv \frac{1}{\Sigma_{\text{Jets}}\Sigma_{i\neq j}\frac{E_i E_j}{p^2_{\text{T,jet}}}} \frac{d\left(\Sigma_{\text{Jets}}\Sigma_{i\neq j}\frac{E_i E_j}{p^2_{\text{T,jet}}}\right)}{d(\Delta R)}$
- EEC (ΔR) corresponds to
  - at small ΔR: free hadrons
  - at large ΔR: perturbative quark & gluon interactions
  - at ΔR between: $\Delta R_{\text{Turnovoer}} \propto \frac{\Lambda_{\text{QCD}}}{p_{\text{T}}^{\text{Jet}}}$ (Komiske et al, 2023, PRL 130, 051901)



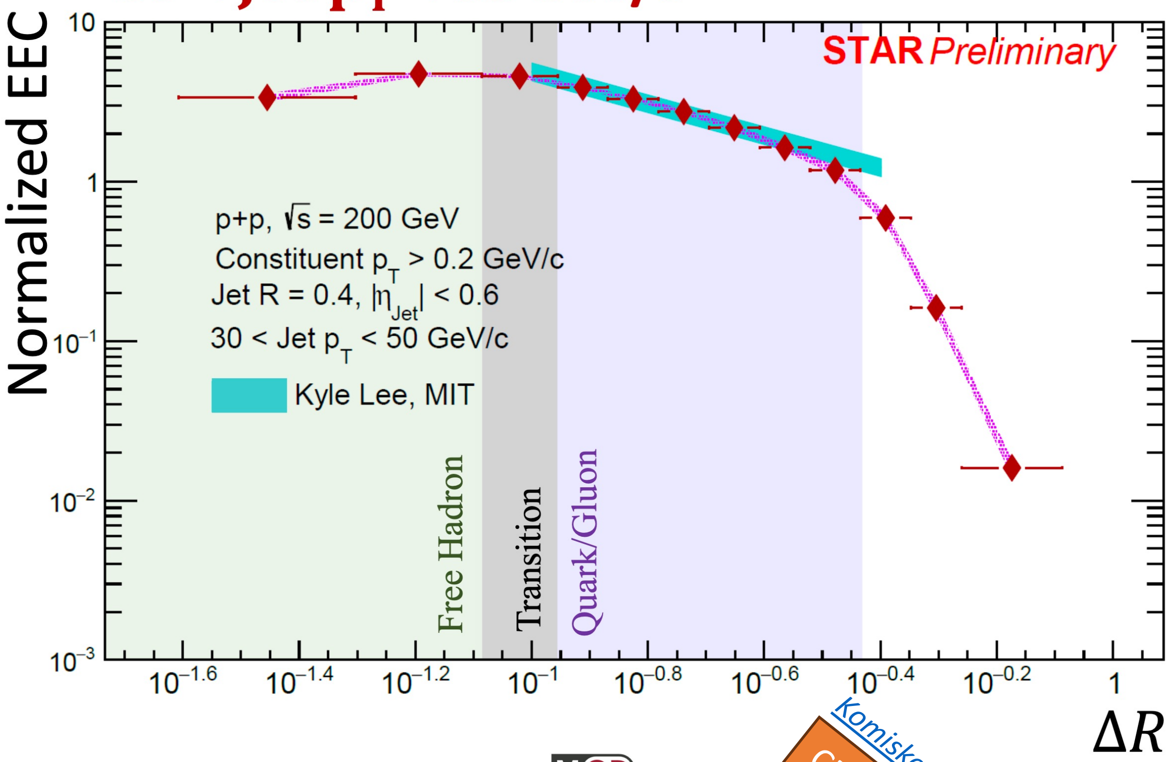
→ $\Lambda_{\text{QCD}} \propto \Delta R_{\text{Turnover}}\, p_{\text{T,Jet}}$ at all scales

First EEC measurement at RHIC

15 < Jet p_T < 20 GeV/c

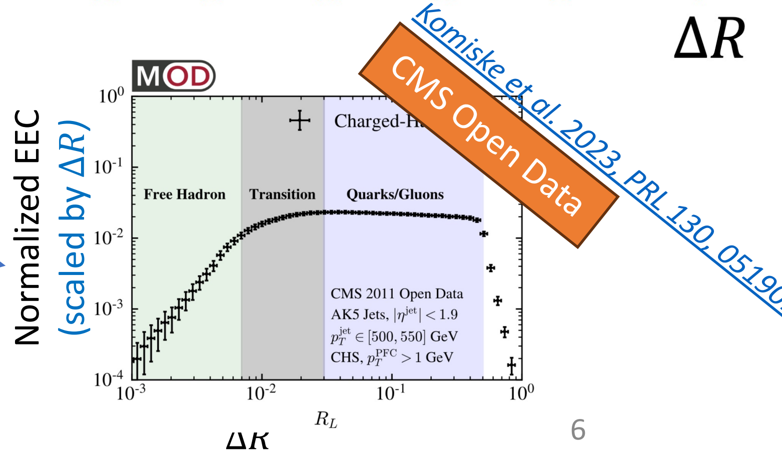


30 < Jet p_T < 50 GeV/c



- $p_{\mathrm{T,Low}}^{\mathrm{Jet}} \Delta \mathrm{R}_{\mathrm{Turnover}} = 10^{-0.75}\left(15\,\frac{\mathrm{GeV}}{c}\right) = 2.7\,\frac{\mathrm{GeV}}{c}$

  → scale appears universal between RHIC and LHC (CMS ≈ $2.5\,\frac{\mathrm{GeV}}{c}$)
- $\Delta \mathrm{R}_{\mathrm{Turnover}}$ depends on quark/gluon fraction



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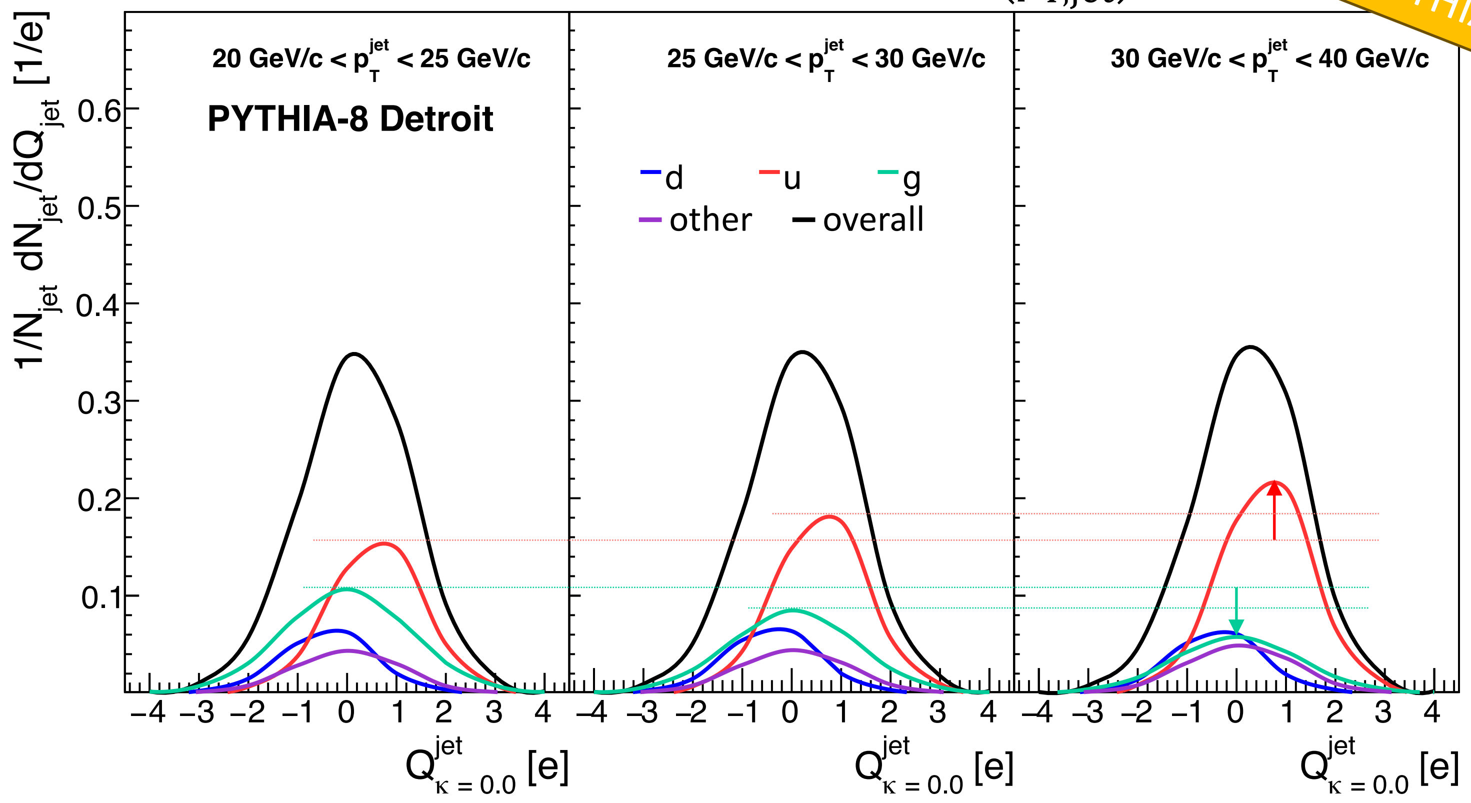
Measure initiating quark/gluon fractions?

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

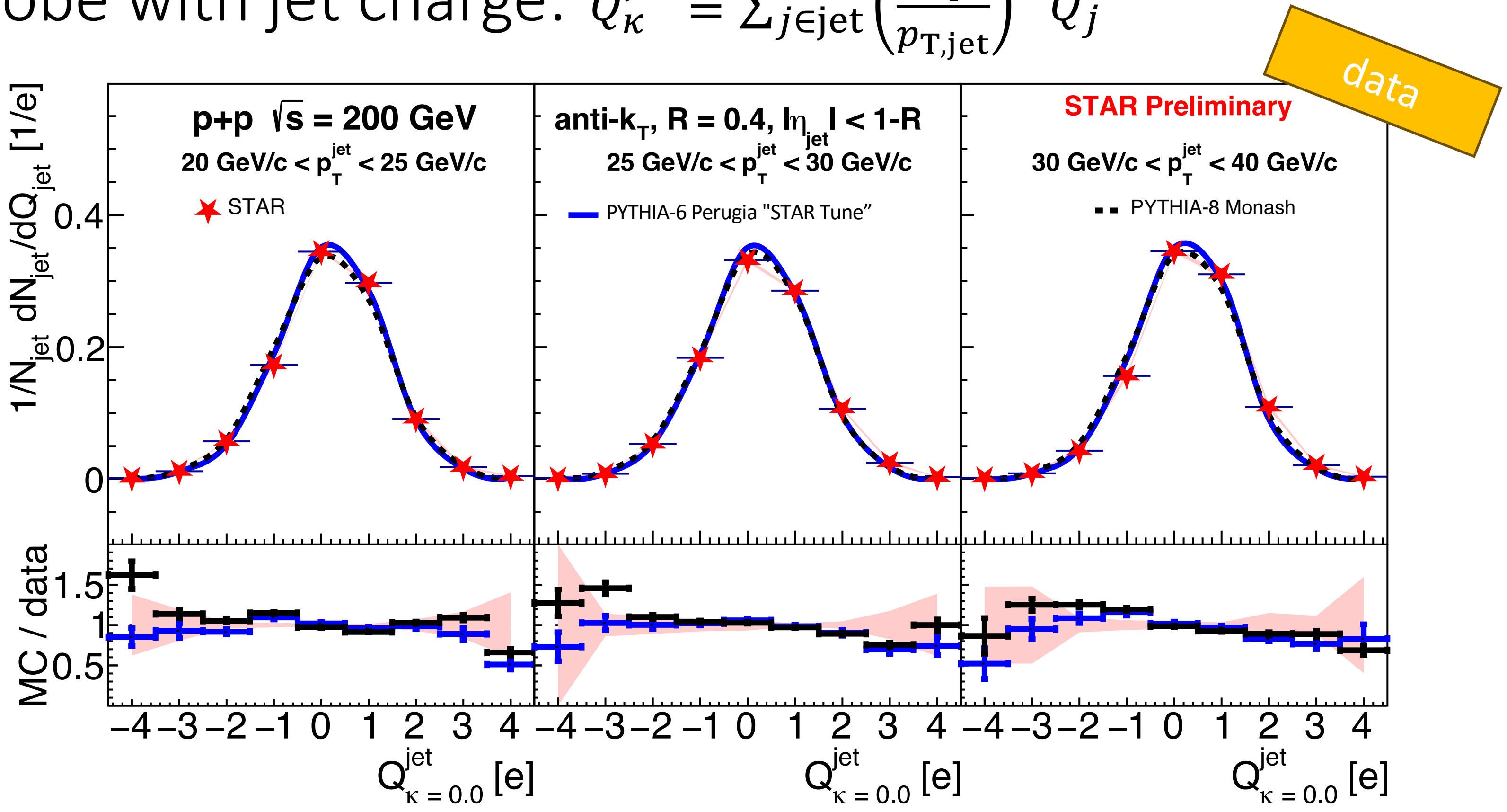
PYTHIA-8



- 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 $p_{\mathrm{T}}^{\mathrm{jet}}$

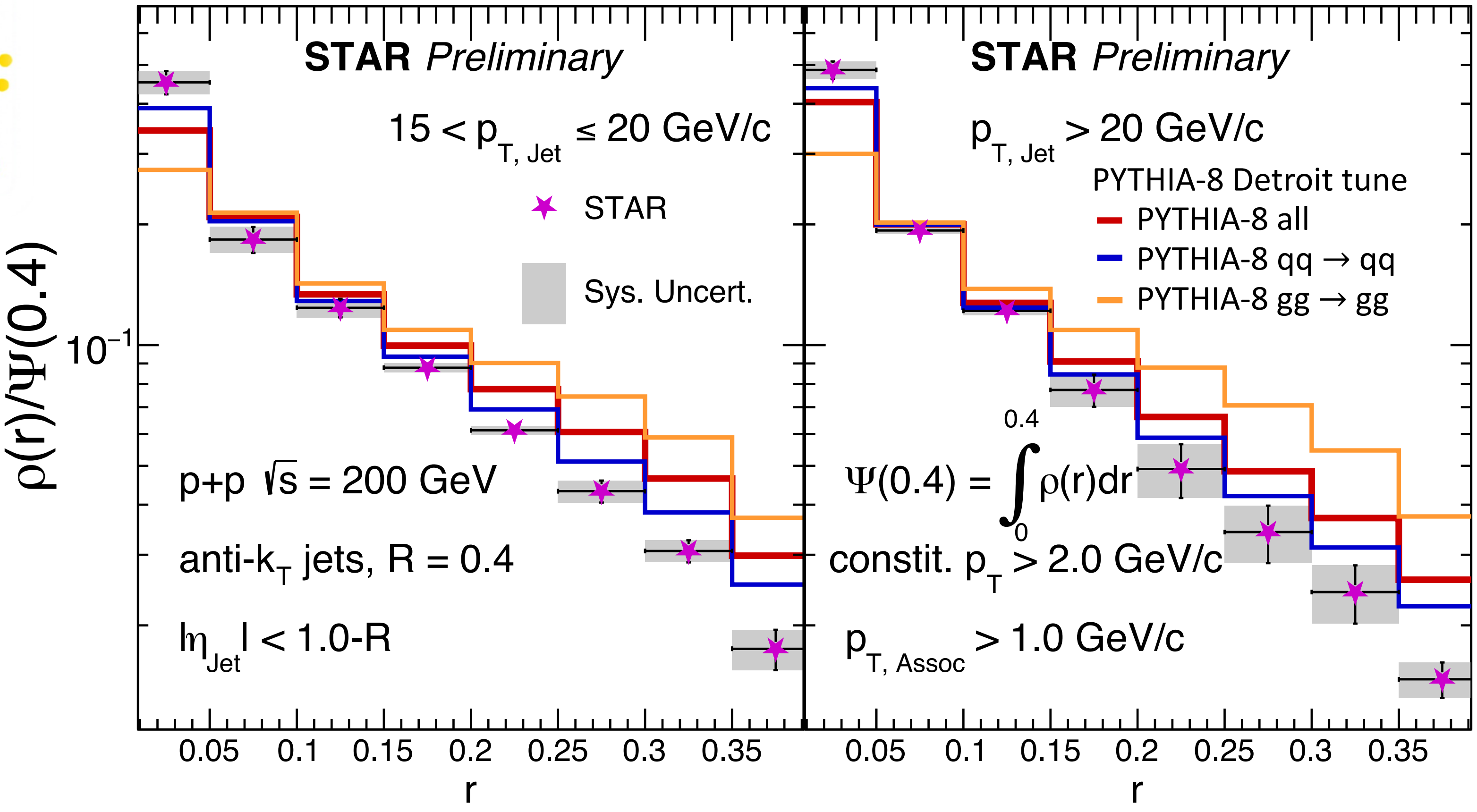
Measure initiating quark/gluon fractions?

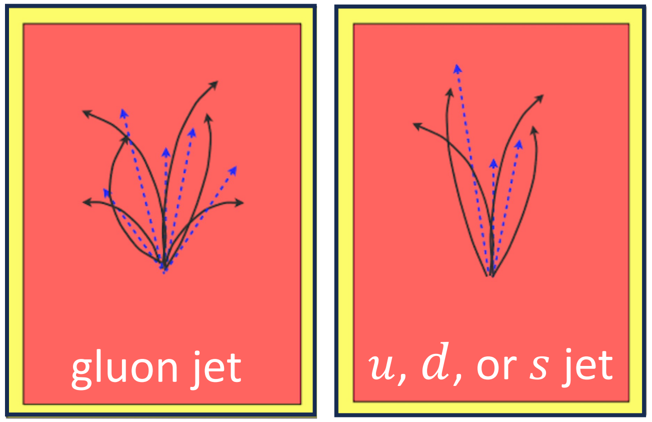
Probe with jet charge: $Q_\kappa^{\text{jet}} \equiv \sum_{j \in \text{jet}} \left(\frac{p_T^j}{p_{T,\text{jet}}} \right)^\kappa Q_j$



- 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



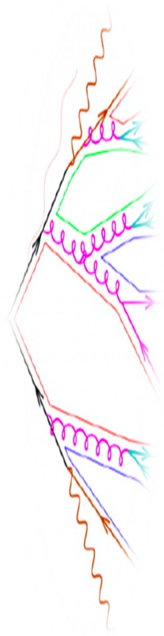


$$\rho(\Delta R) \equiv \lim_{\delta r \to 0} \left\langle \frac{1}{\delta r} \frac{\sum_{|\Delta R|<\delta r} p_{T,i}}{p_{T,jet}} \right\rangle$$

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

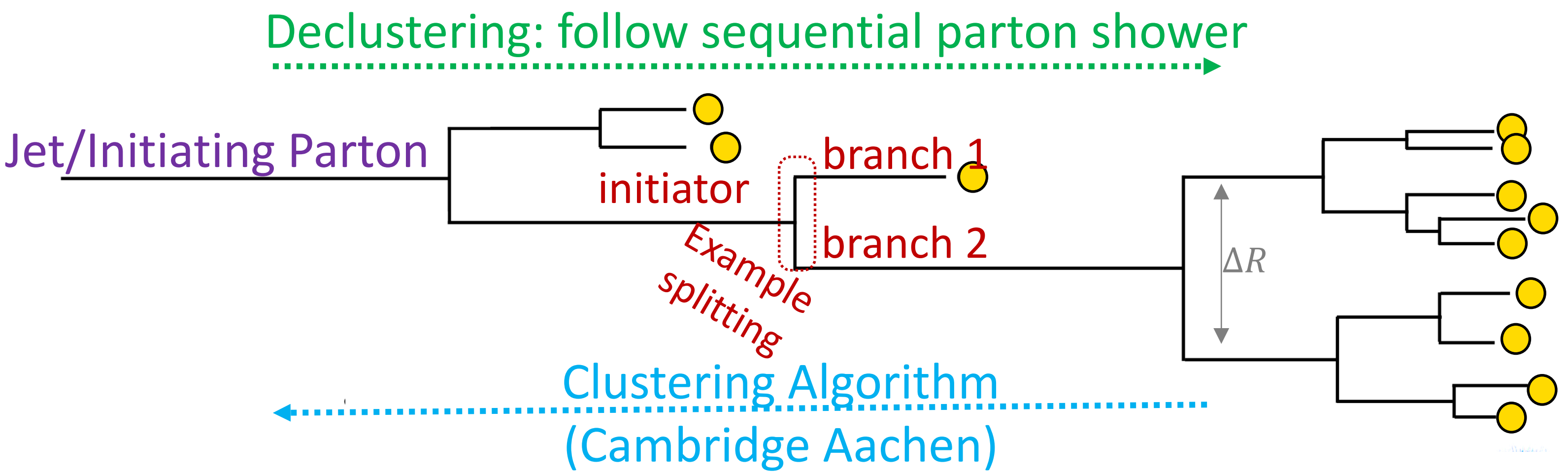
Represent jet as a parton shower

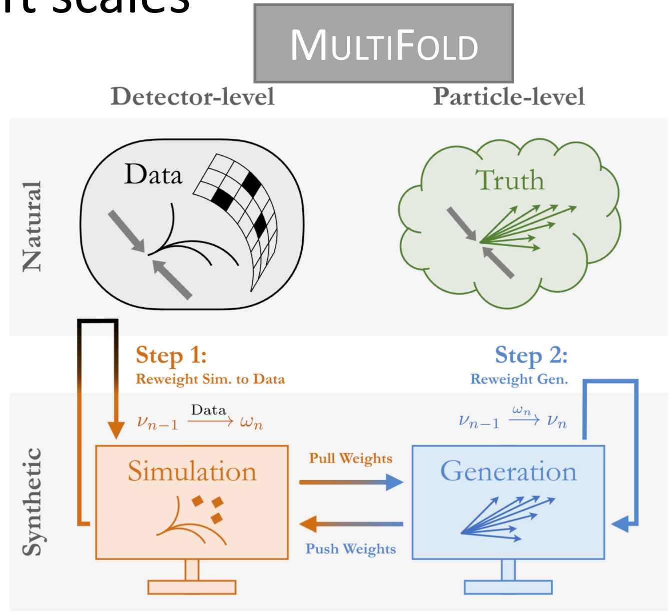
- Contains both soft- and hard-scale physics
- SoftDrop criterion selects "first hard branching":

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

- 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



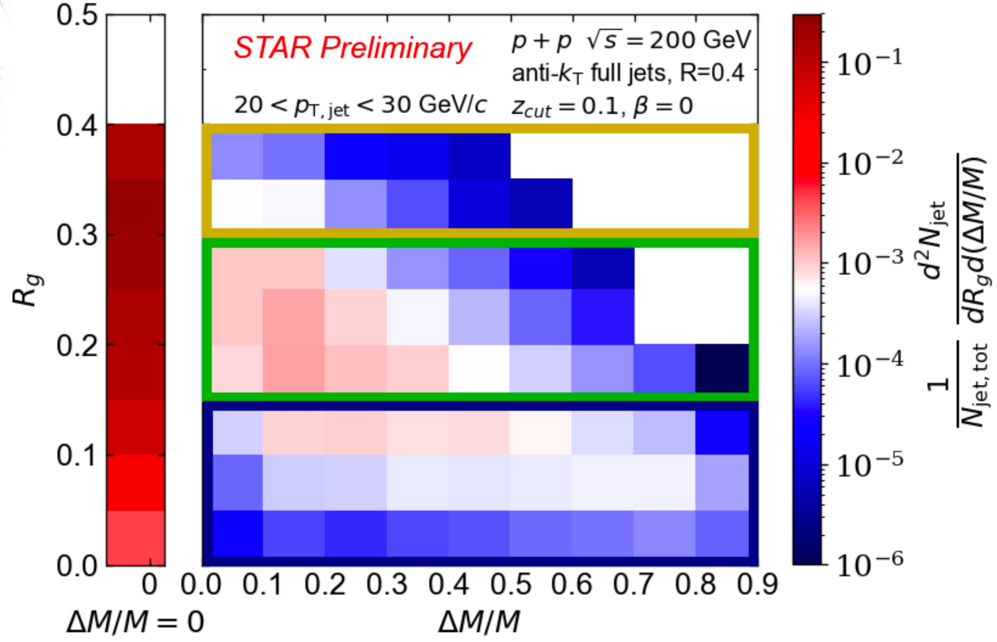


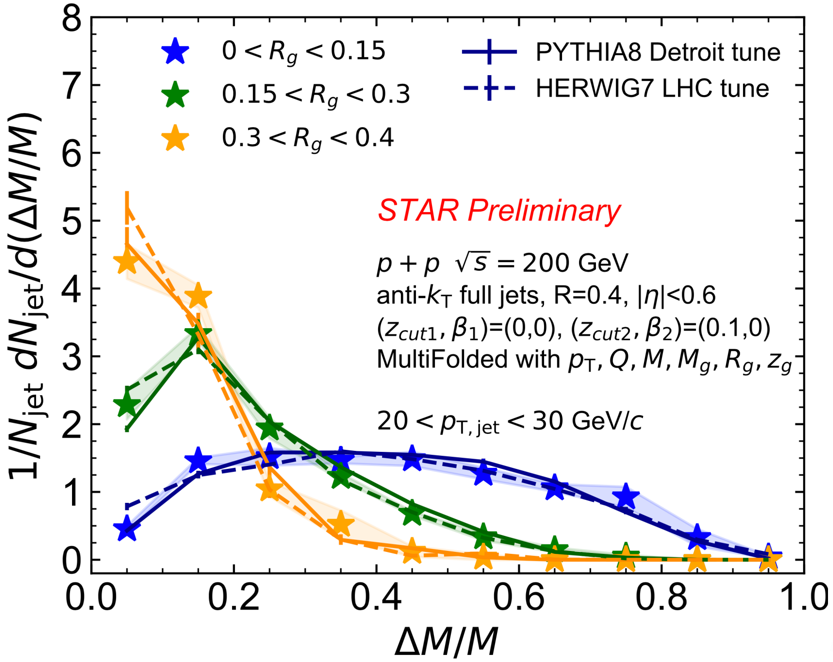
Andresson et al, PRL 124, 182001)

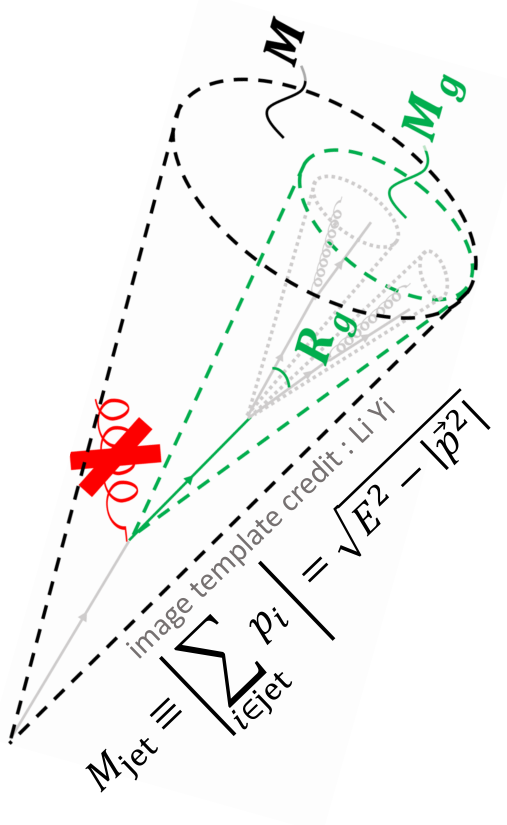
Correlation: soft radiation to hard splitting angle

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

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





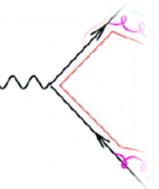


$\Delta M/M$ distribution is anti-correlated with groomed jet radius R_g

→ 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 shadowing) to then calculate $\mathrm{R_{AA}}$ in Au+Au collisions

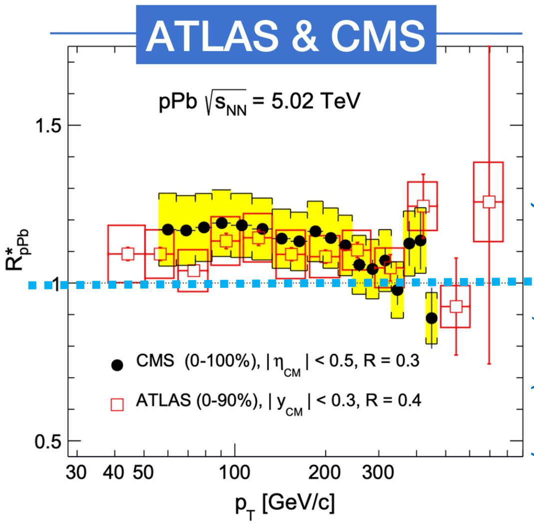
→ Quantify jet quenching in Au+Au via $\mathrm{R_{AA}}$: $\dfrac{\text{Jet yield from AA}}{(\text{geom. scaling}) \times (\text{jet yield from pp})}$

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

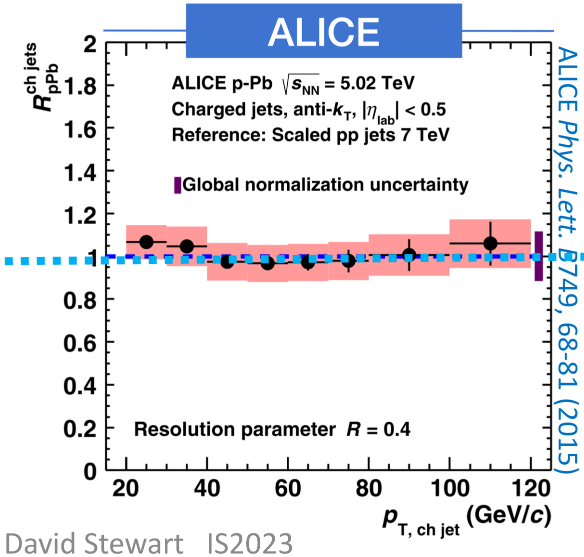
In p+A, no jet quenching (i.e. $\mathrm{R_{AA}} \approx 1$) anticipated

Results: (p/d)+A

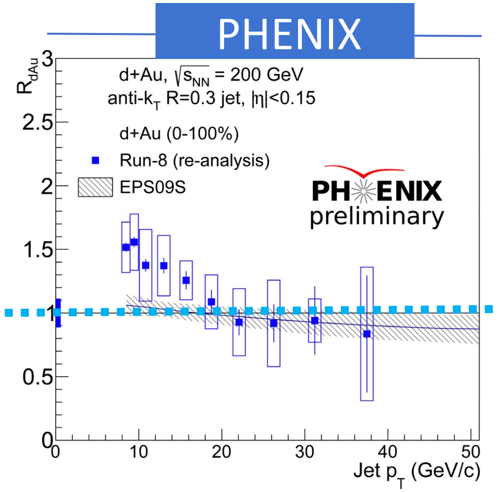
Inclusive measurements @ all EA: $R \approx 1$ → don't see quenching



CMS *Eur. Phys. J. C* **76**, 372 (2016)



ALICE *Phys. Lett. B* 749, 68-81 (2015)



(PRL 116, 122301, erratum in preparation)

Supersedes previously published result

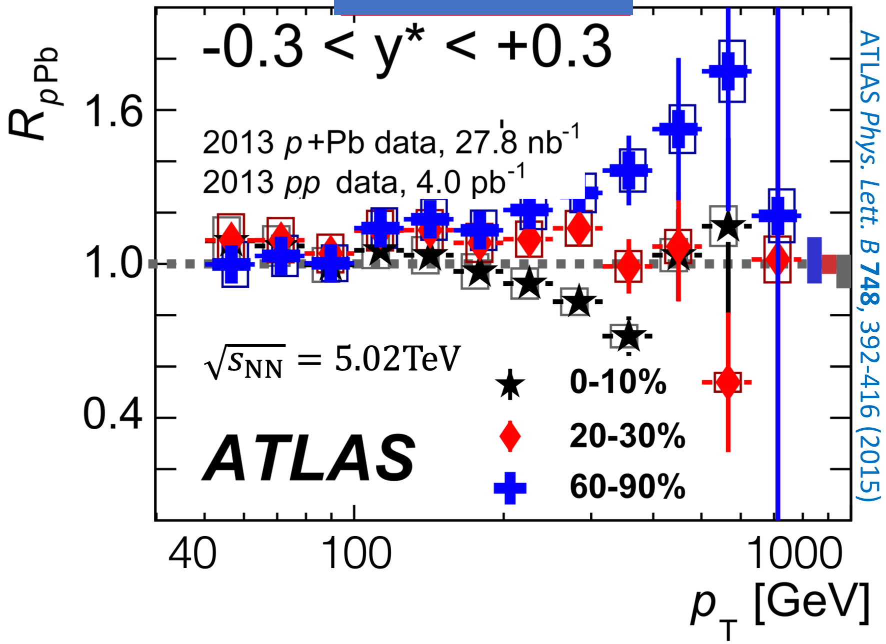
John Lajoia for PHENIX, Moriond 2021 (link).

Surprises: R_{AA} in EA selected events

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

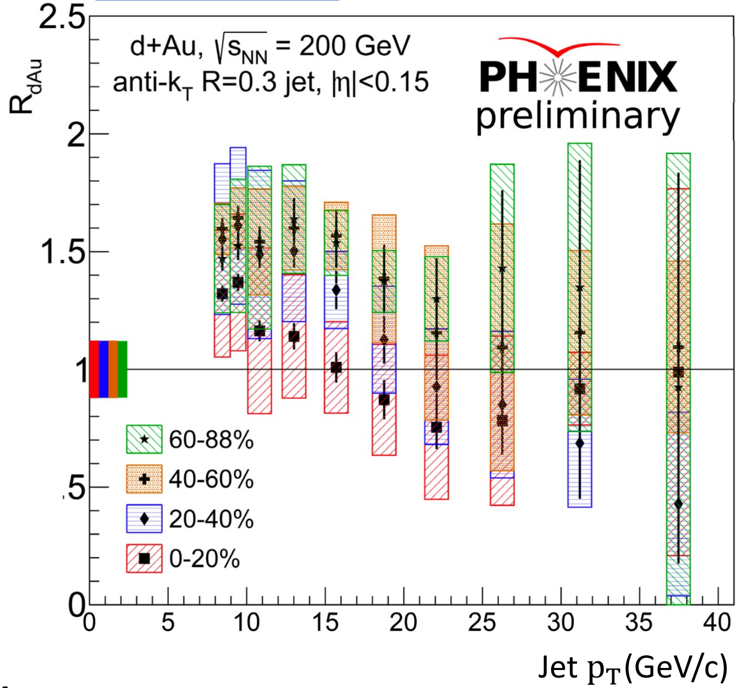
Results: (p/d)+A

ATLAS



ATLAS Phys. Lett. B 748, 392-416 (2015)

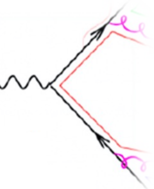
PHENIX

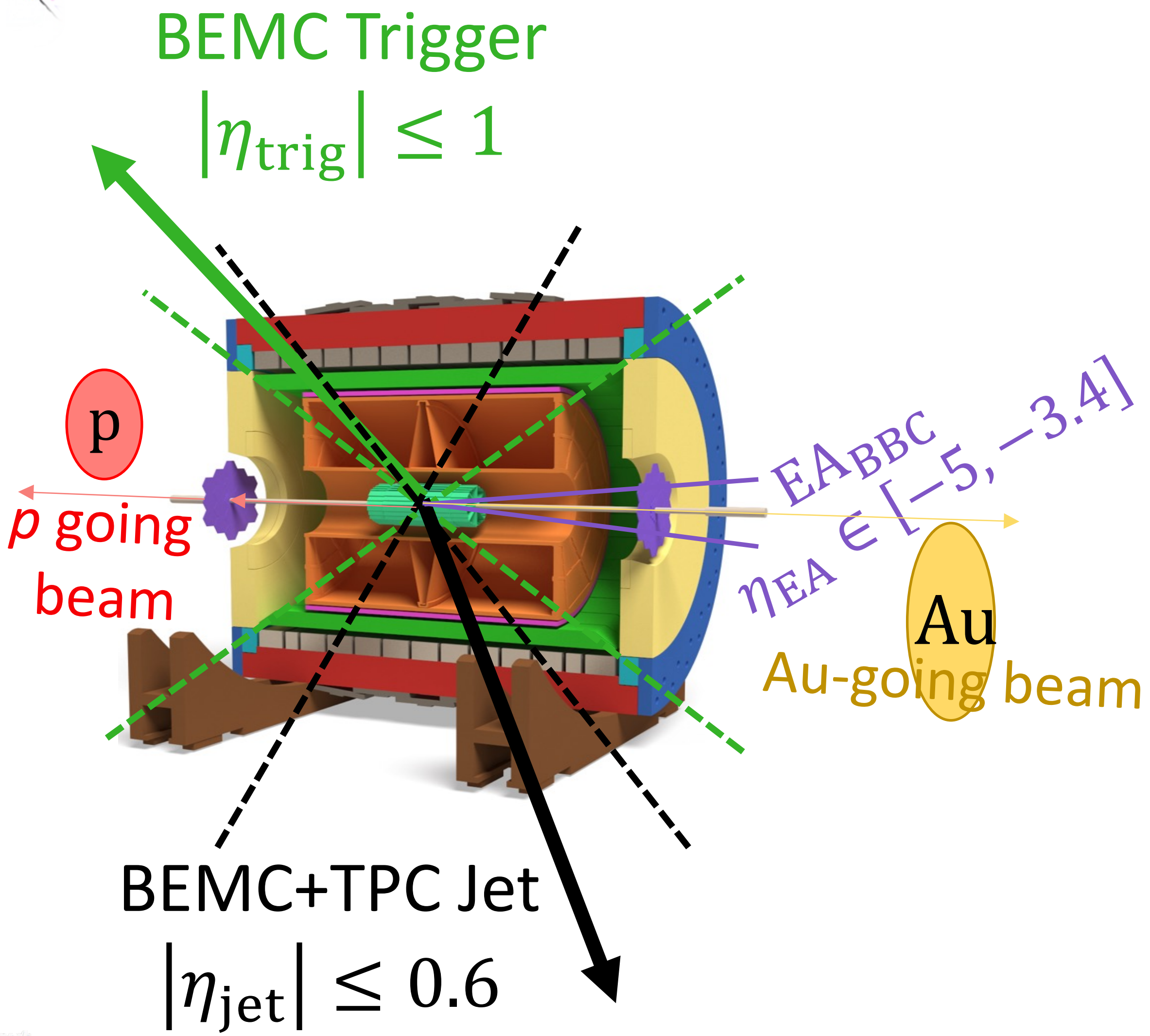


John Lajoia for PHENIX, Moriond 2021 (link).
Supersedes previously published result
(PRL 116, 122301, erratum in preparation)

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

p + Au measurements: trigger + jet + EA





- EA ≡ 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

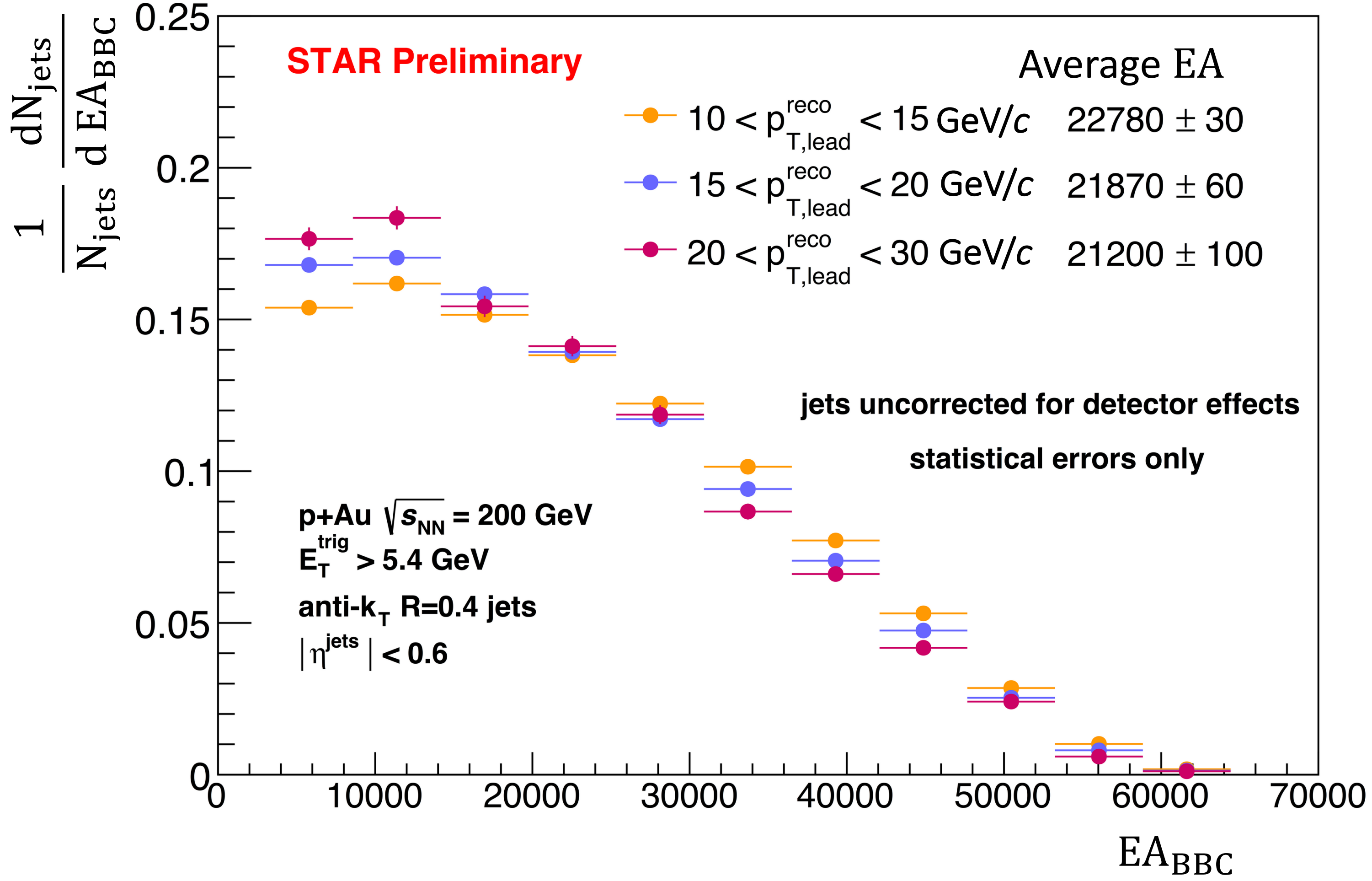
(2) jet in TPC, and

(3) a dijet partner in BBC

→ No "auto-correlation" from directly measuring high EA from dijet partners hitting BBC

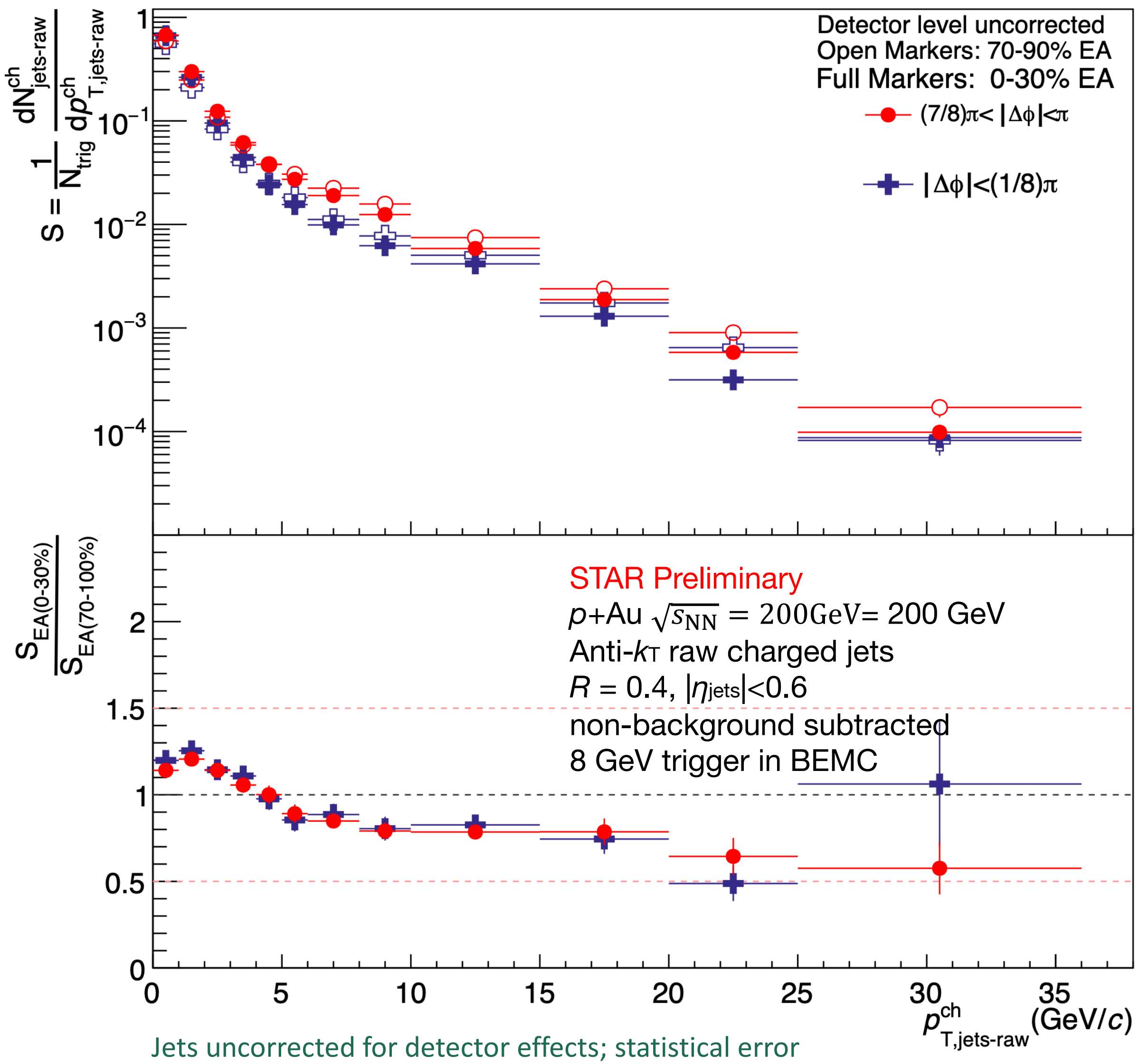
- Per-trigger normalization doesn't use geometric scaling used in R_{AA}

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

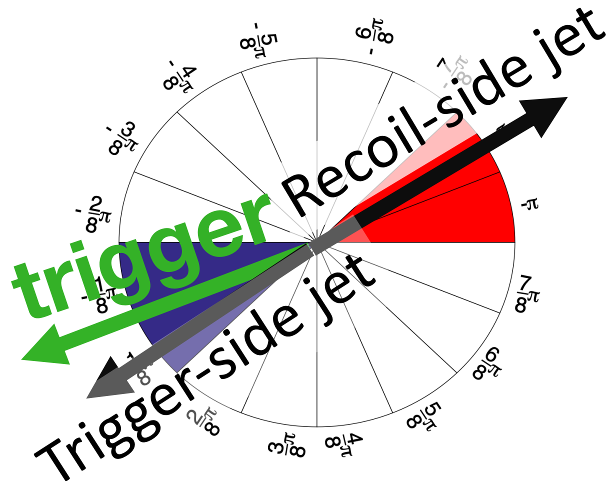


- Anti-correlation: EA distribution is
  - softest in events with a high-p_{T} jet
  - harder in events with a mid-p_{T} jet
  - hardest in events with a low-p_{T} jet
- i.e.: significant drop in mean EA with increasing $p_{\mathrm{T,lead}}^{\mathrm{reco}}$

Jet spectra per triggered event suppressed at high-EA



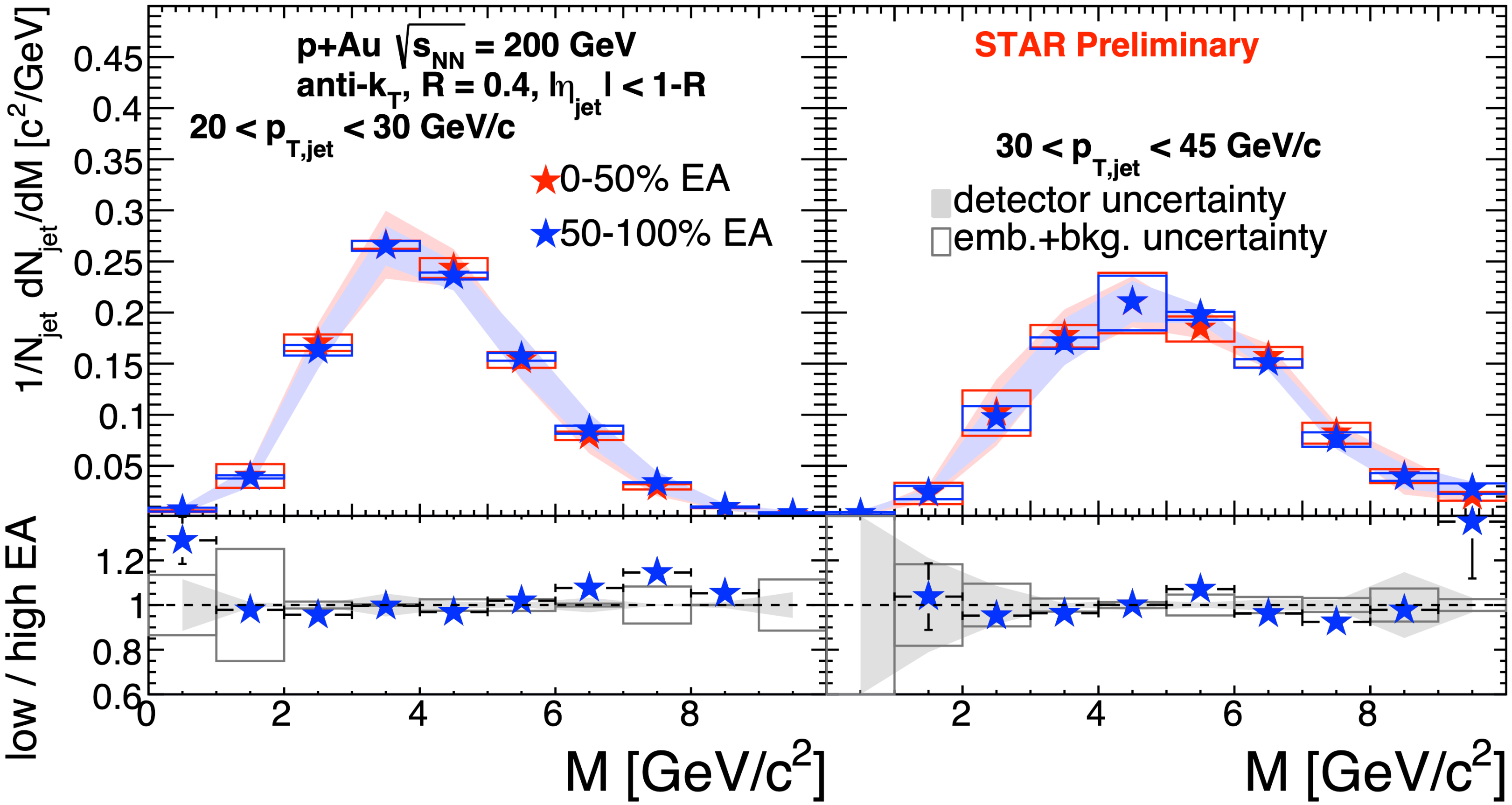
Jets uncorrected for detector effects; statistical error bars only; however, detector effects cancel in the ratio



- 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

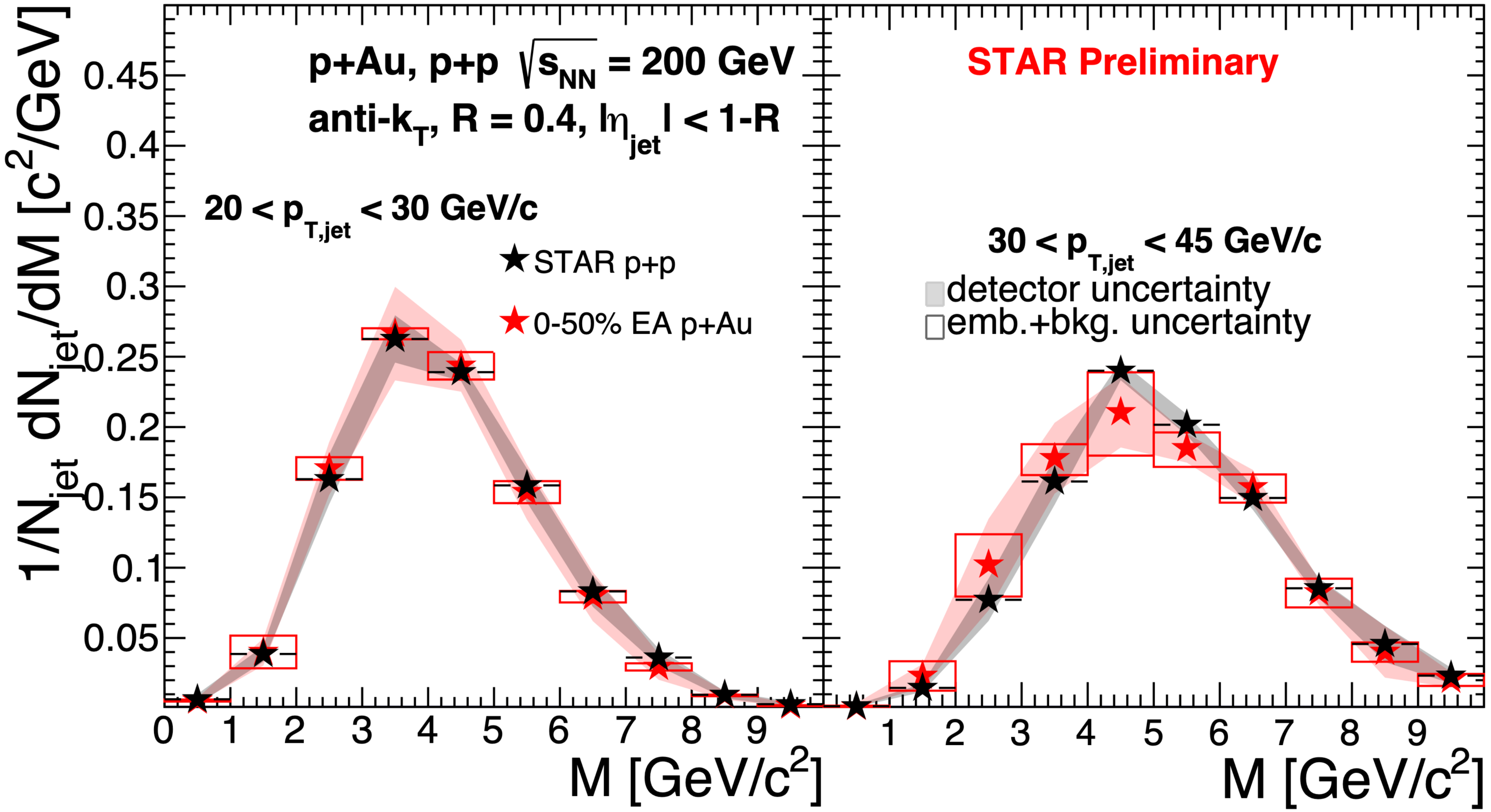
Test for p + Au jet quenching via jet mass



Jet mass distribution not EA dependent

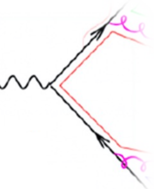
→ null result for jet quenching

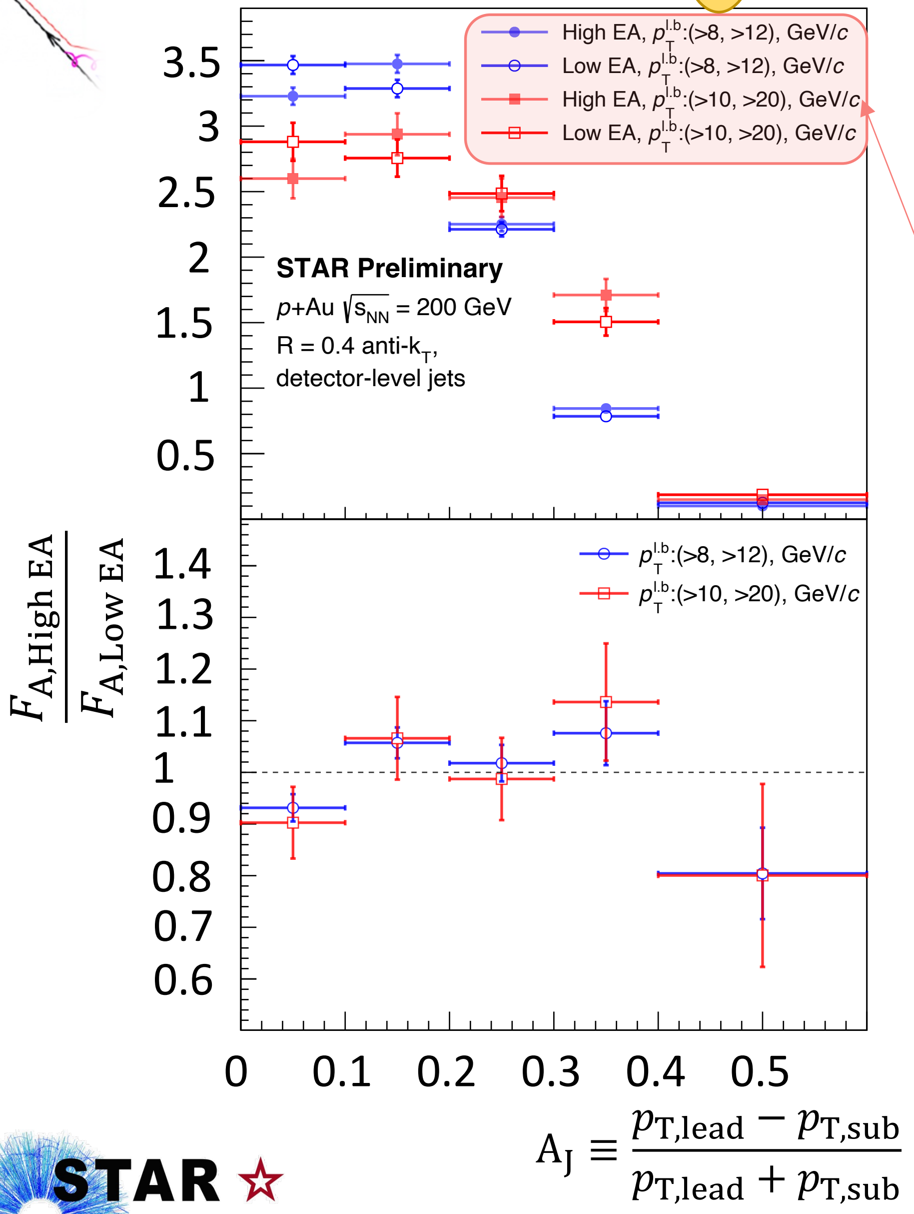
Test for p+Au jet quenching via jet mass



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

Test for p+Au jet quenching via dijet p_T balance



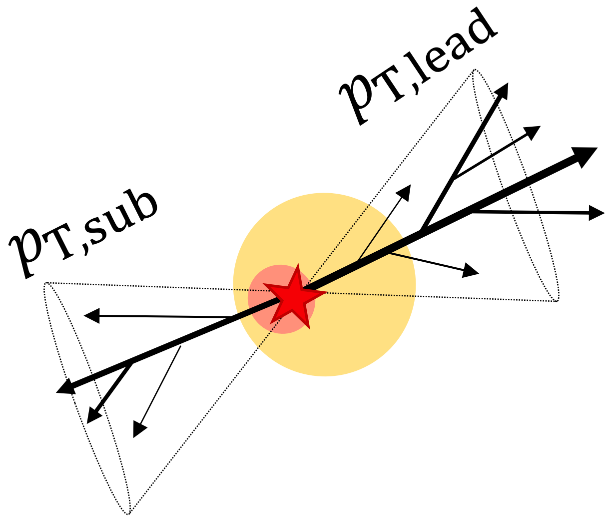


Require:

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

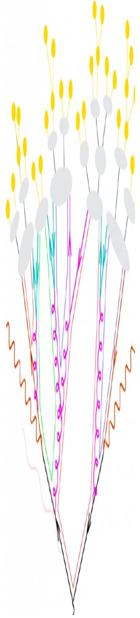


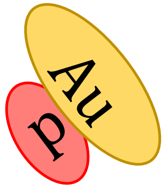
Dijet p_T balance distribution not EA dependent

→ null result for jet quenching

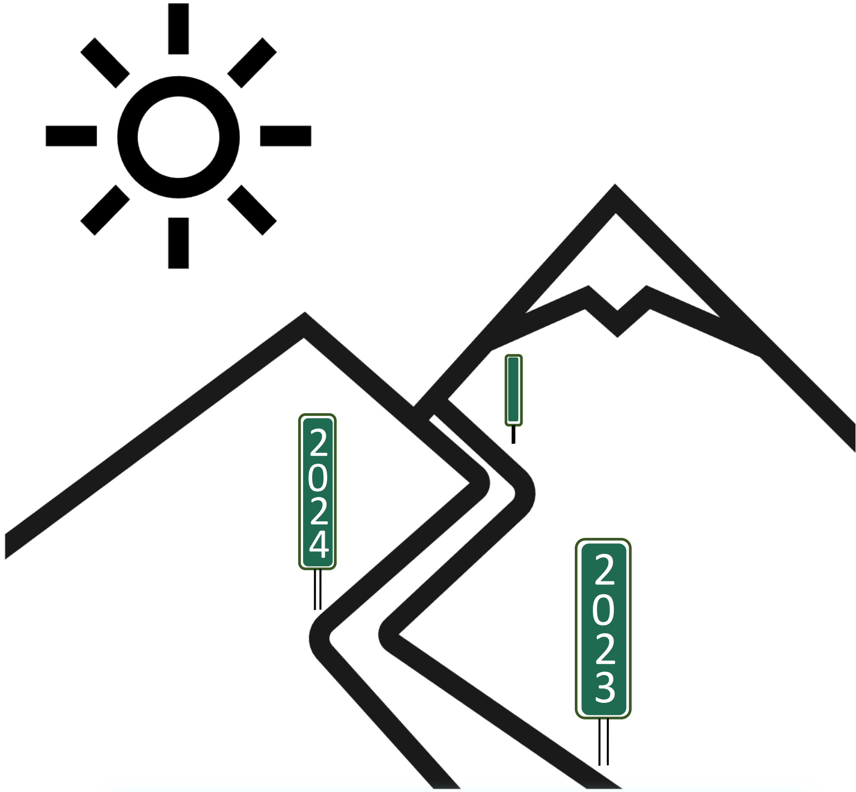
Jets are uncorrected for detector effects

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





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

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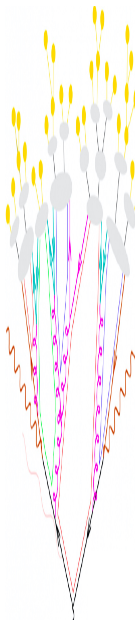
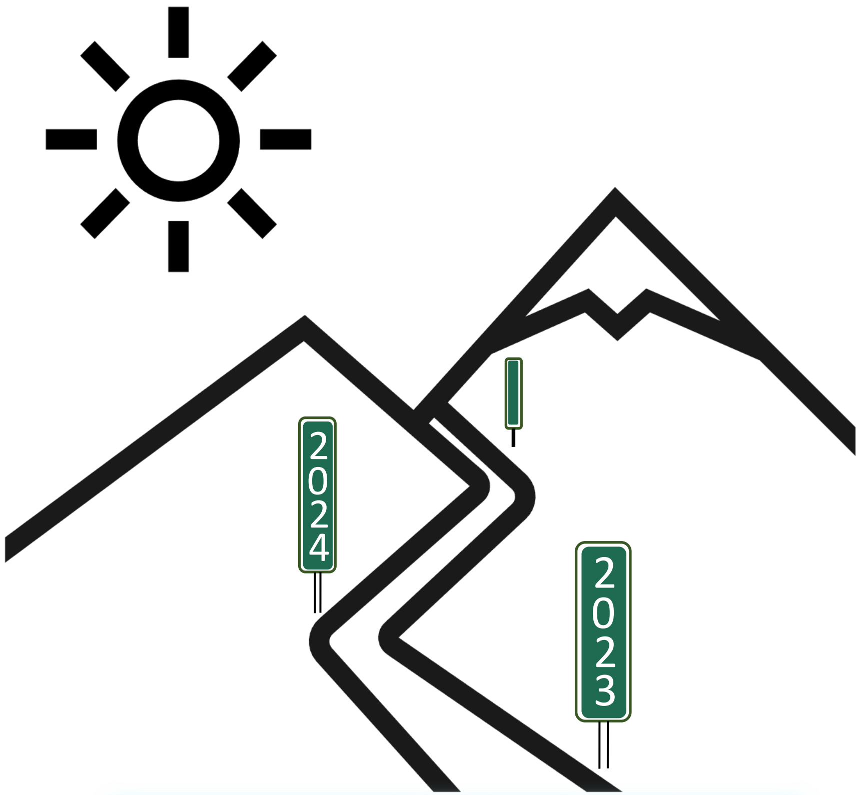


Measurement Summary

- 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))
  - **MultiFold** (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!

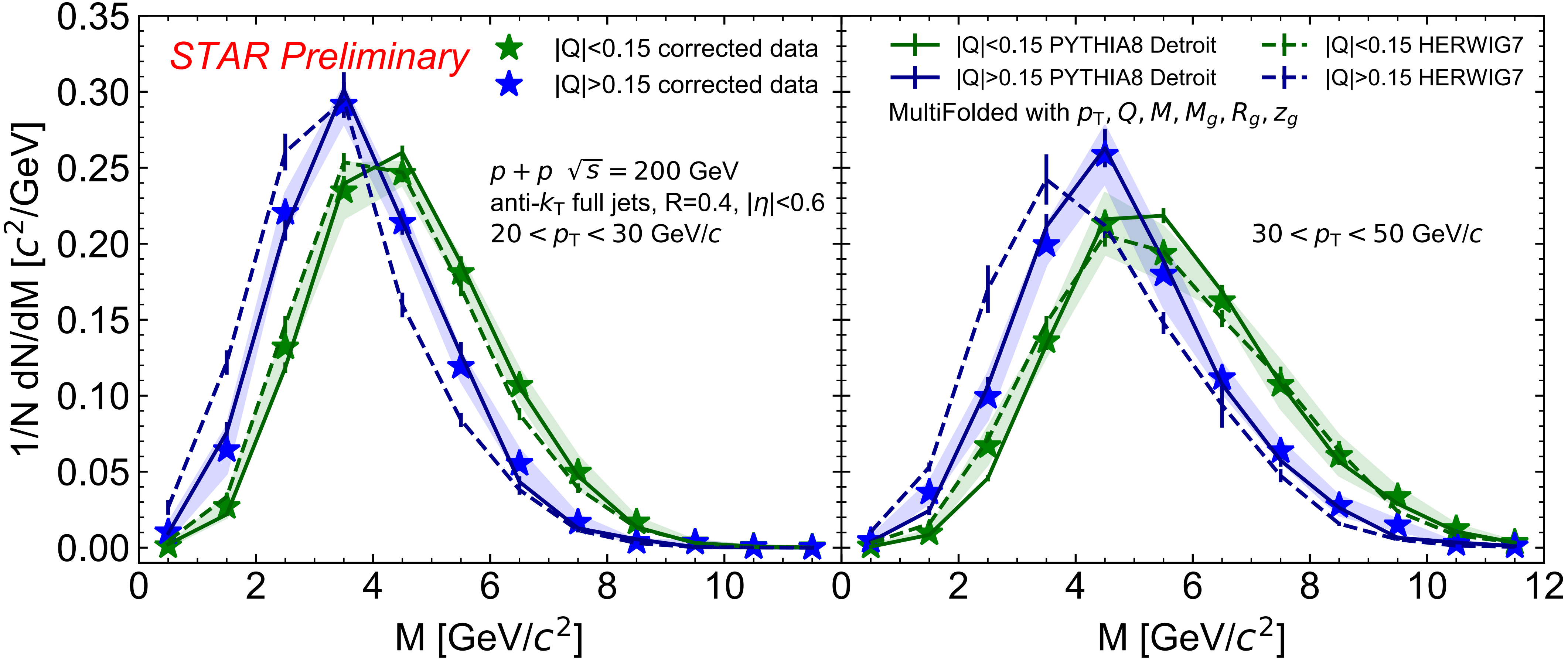
- Jet observables
  - p_{T}: transverse momentum
  - $Q^{\kappa} = \frac{1}{(p_{\mathrm{T jet}})^{\kappa}} \sum_{i \in \mathrm{jet}} q_i \cdot (p_{\mathrm{T}i})^{\kappa}$ → Choose K=2
  - $M = |\Sigma_{i \in \mathrm{jet}}\, p_i| = \sqrt{E^2 - |\vec{p}|^2}$

    4-momentum of the constituent i
  - R_g: groomed jet radius
  - z_g: shared momentum fraction
  - M_g: groomed jet mass

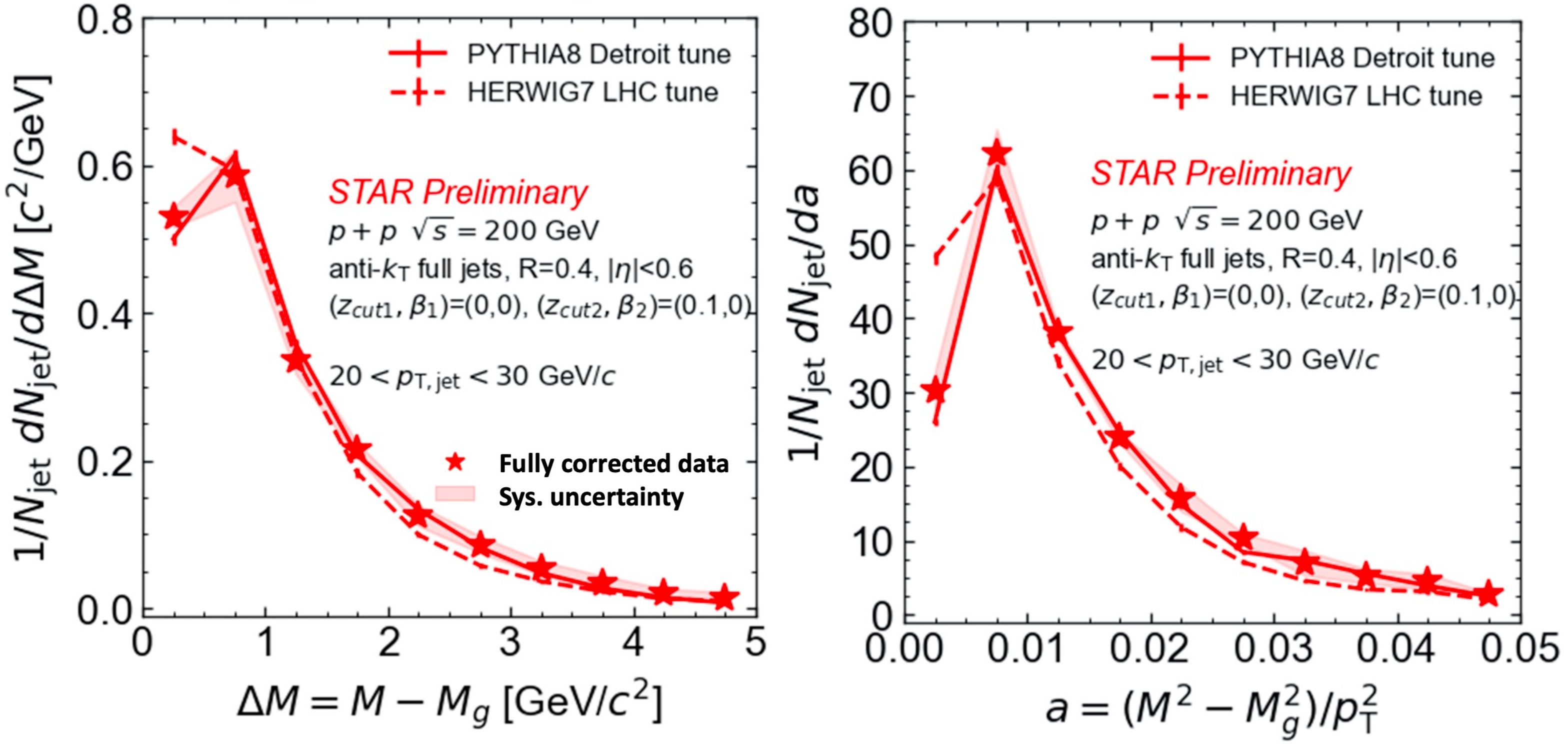
All 6 observables are simultaneously unfolded in an unbinned way!

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

Multifuld vs RooUnfold



Collinear drop groomed jet mass

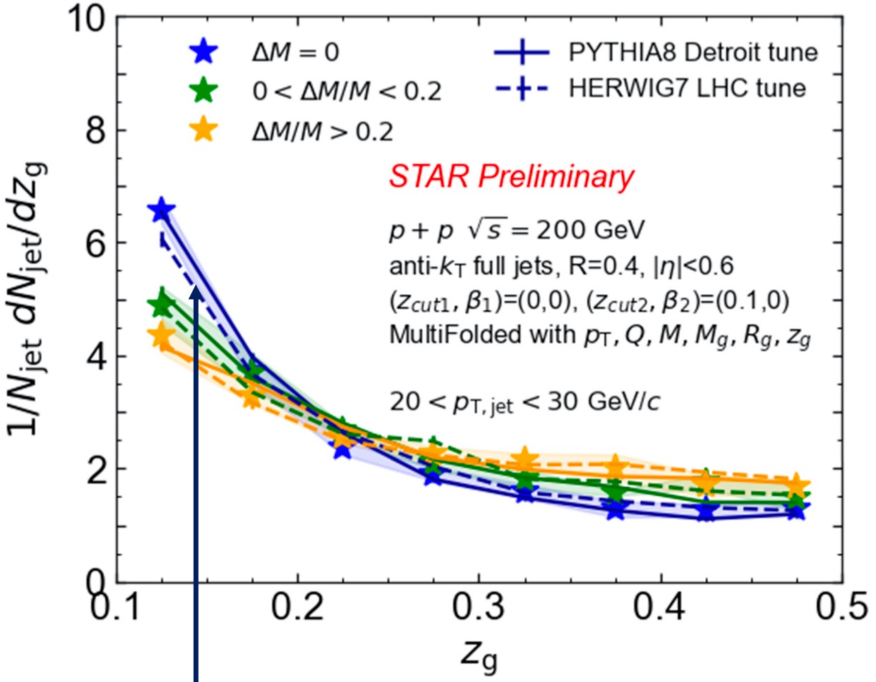


PYTHIA6 Perugia 2012 STAR tune: Skands, PRD 82, 074018 (2010)
PYTHIA8 Detroit tune: Aguilar et al. PRD 105, 016011(2022)
HERWIG7: Bellm, et al. PRC 76, 1-8 (2016)

Measurement excludes jets with ΔM = 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

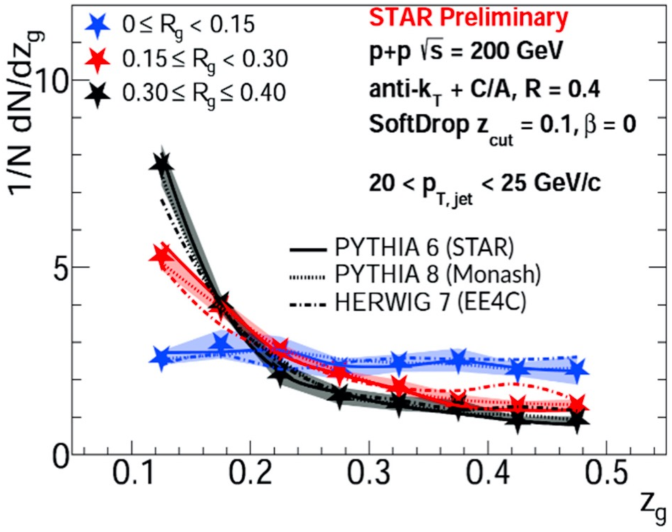
Soft radiation vs hard splitting momentum imbalance



Steeply falling ~ DGLAP 1/z: pQCD

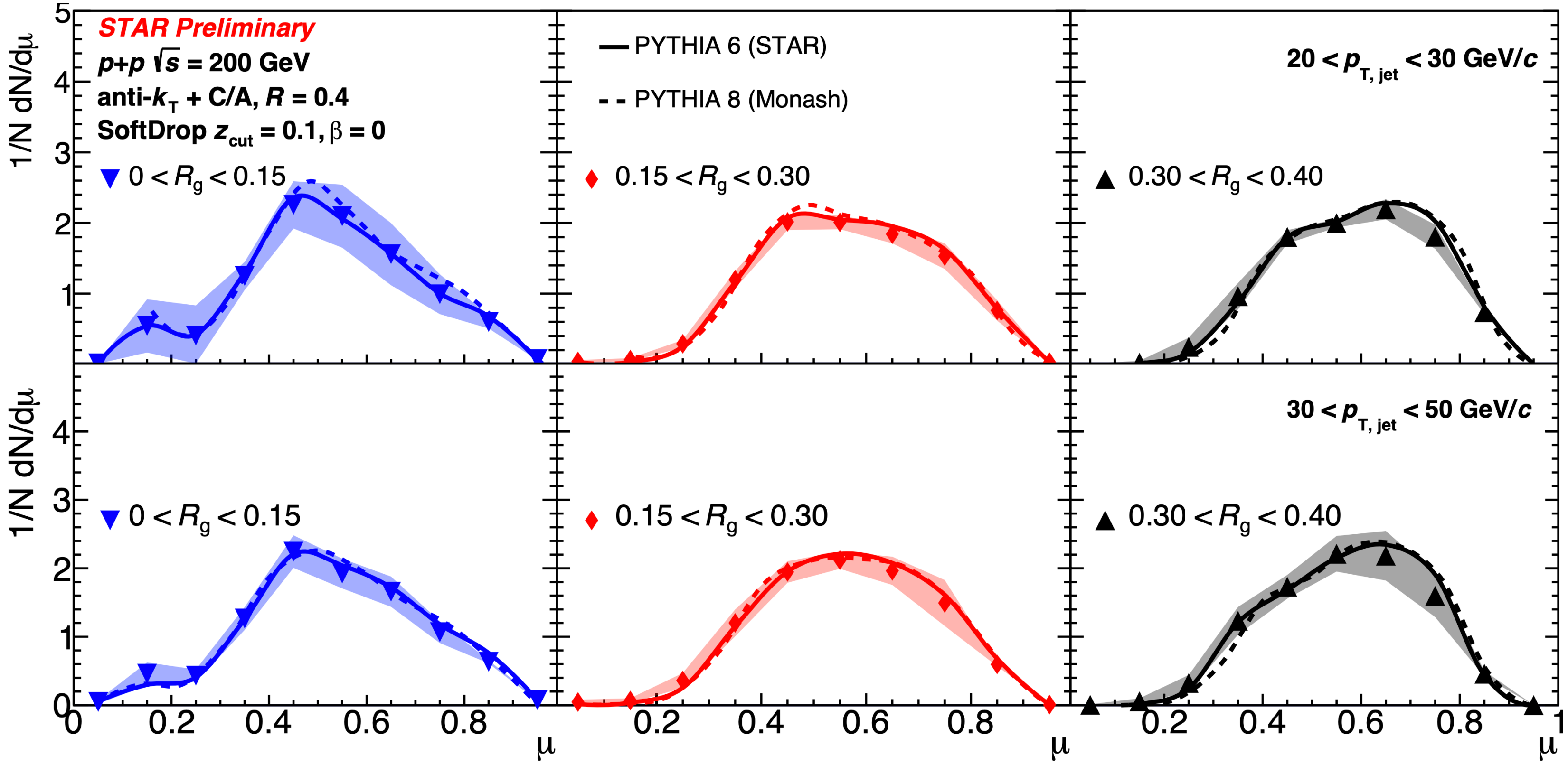
R_g and z_g are correlated, $\Delta M/M$ affects R_g
→ correlation between $\Delta M/M$ and z_g

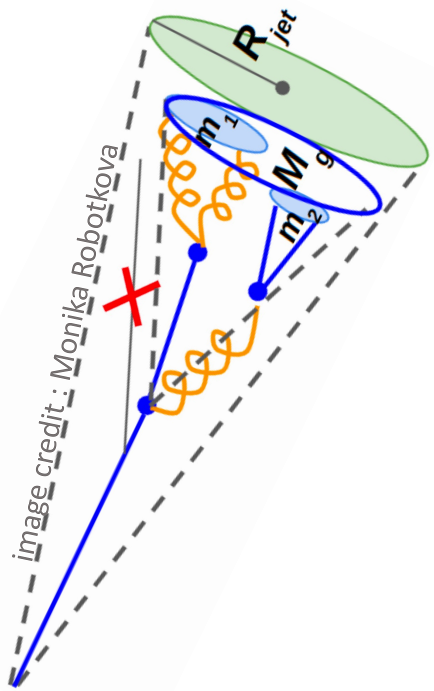
- The more mass that is groomed away relative to the original mass, the flatter the z_g distribution is
  - Demonstrates that **early** soft wide angle radiation constrains the momentum imbalance of & the amount of npQCD contributions to **later** splittings
- MC models describe the trend of data



Correlate: groomed mass fraction "μ" vs $p_{\mathrm{T,jet}}$ vs $\mathrm{R_g}$

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



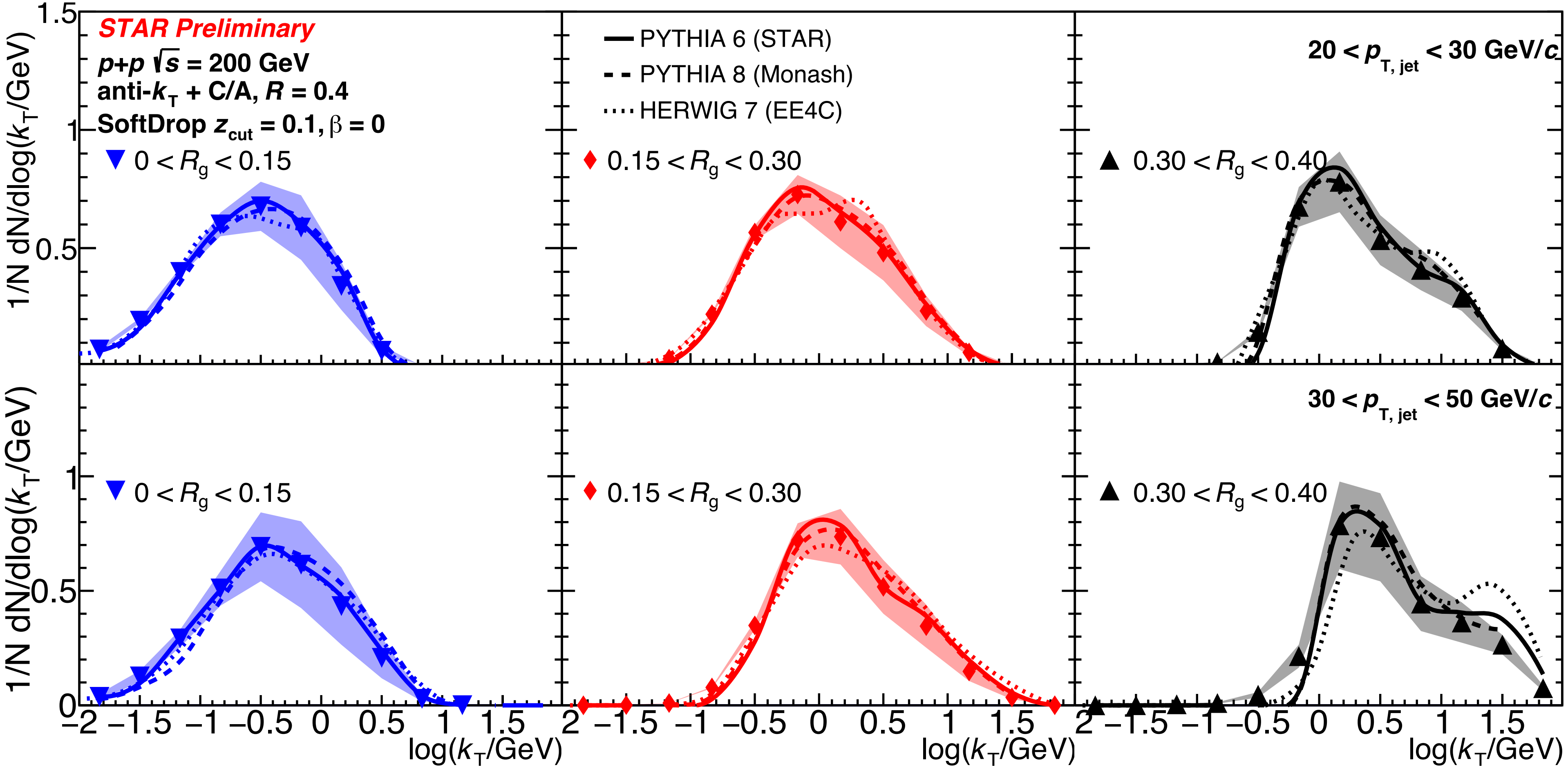


μ smaller at smaller $\mathrm{R_g}$

→ indicates faster reduction of virtuality in the jet shower

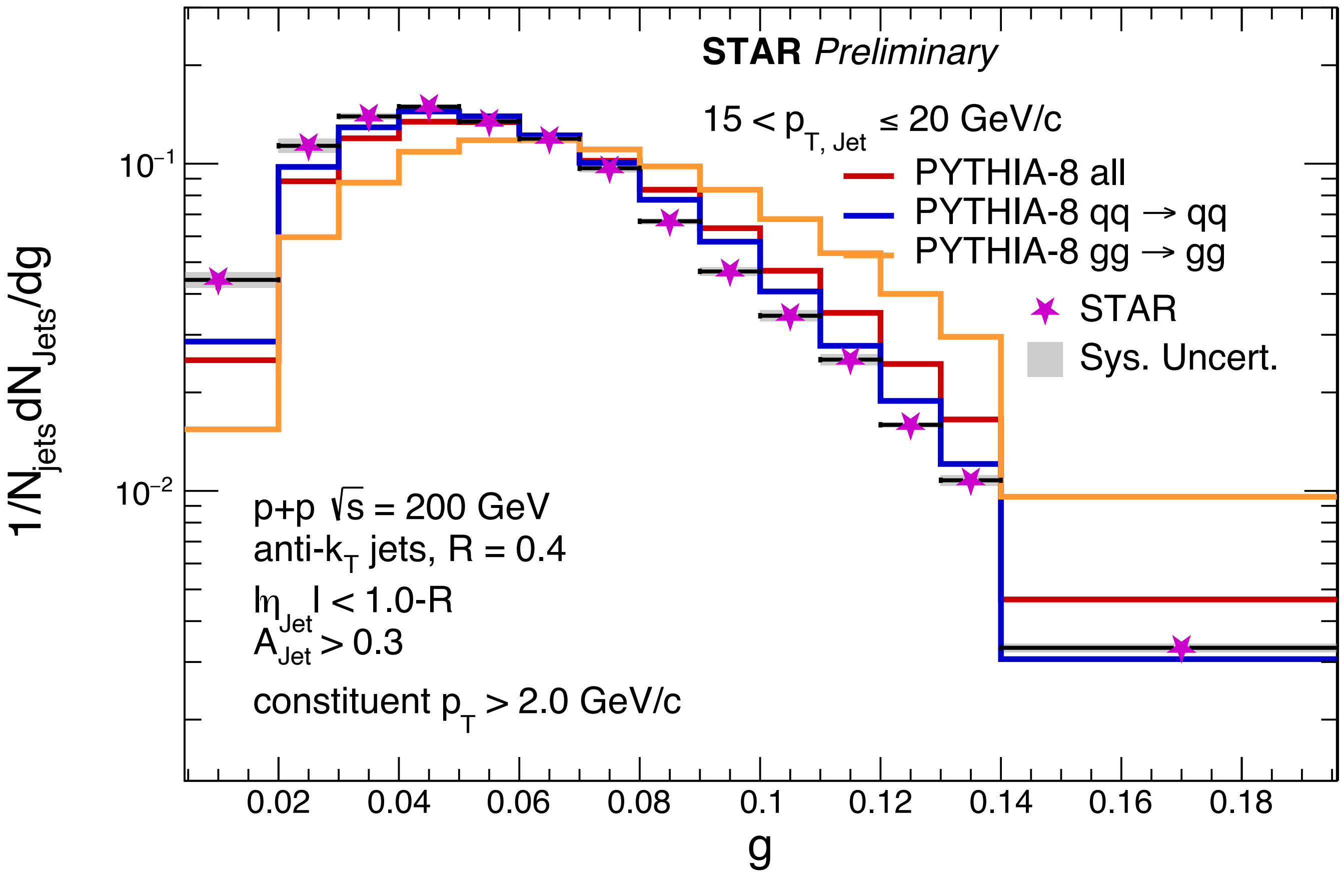
Correlate splitting scale to hard splitting angle

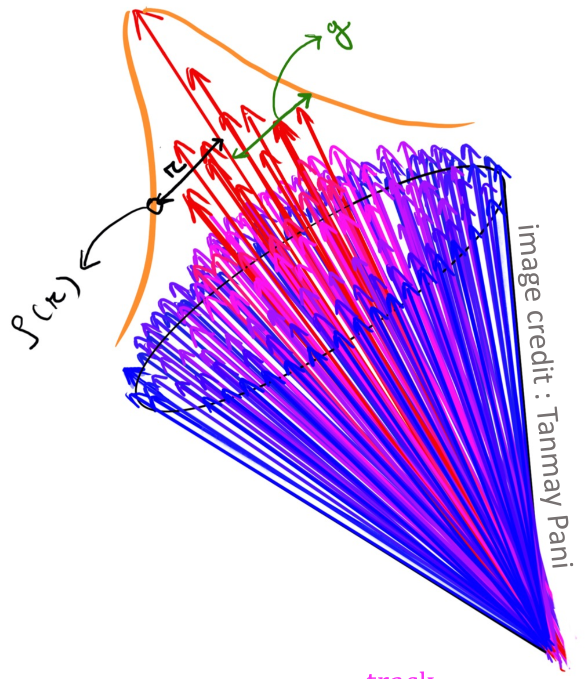
Splitting scale: $k_{\mathrm{T}} = z_{\mathrm{g}} p_{\mathrm{T,jet}} \sin(R_{\mathrm{g}})$



Measure initiating quark/gluon fractions?

Measure jet girth



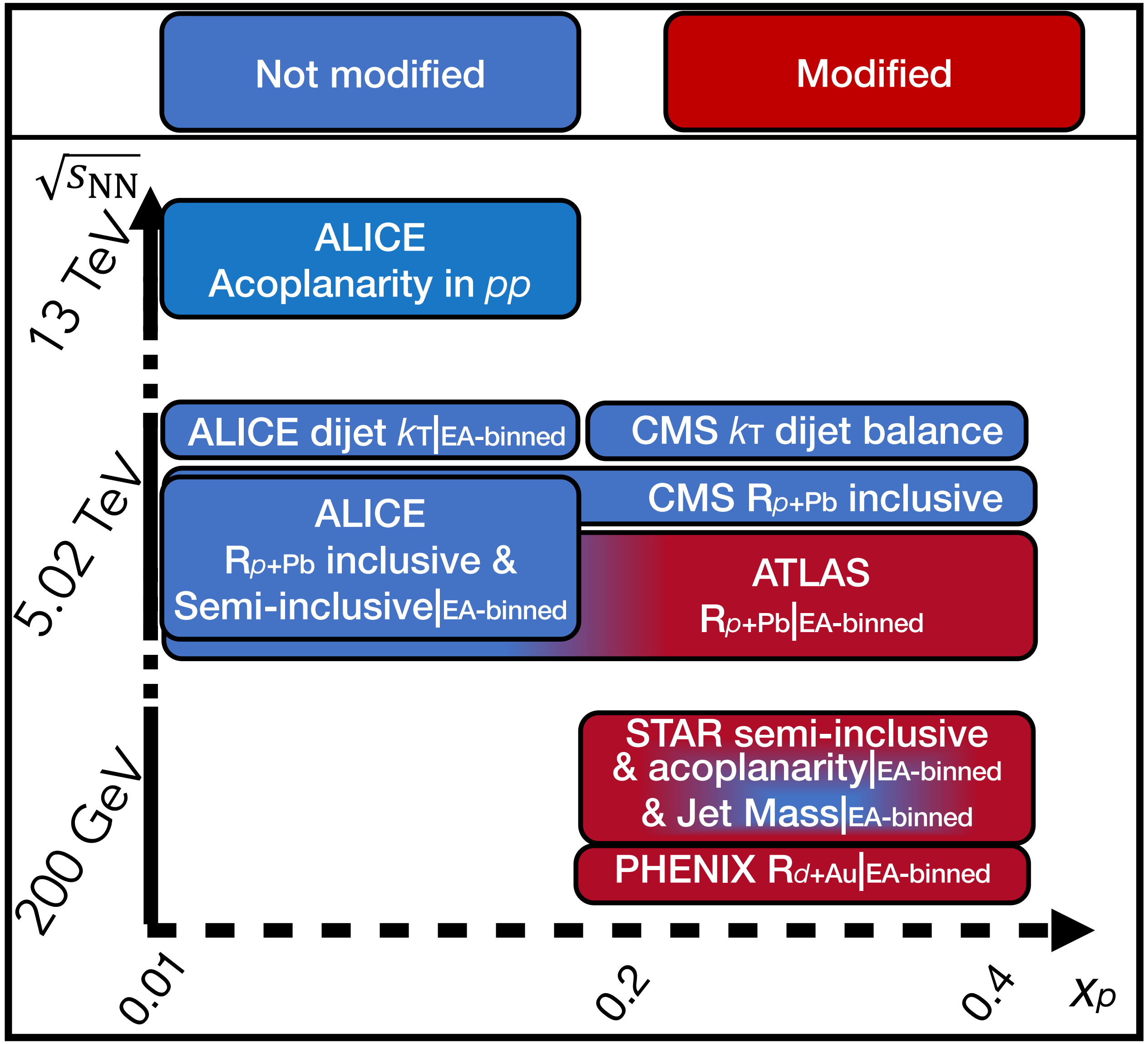


$$g \equiv \frac{\Sigma_{\text{Tracks}}\, p_{\text{T}}^{\text{track}}\, r_{\text{track}}}{p_{\text{T}}^{\text{Jet}}}$$

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

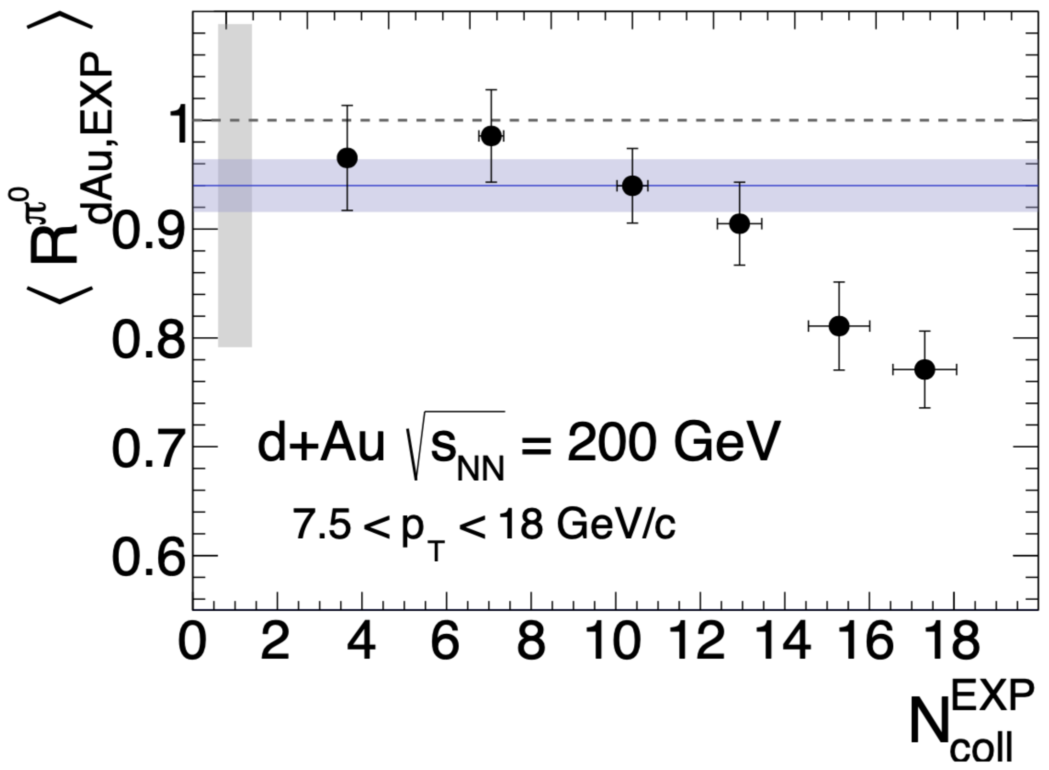
- Provides vacuum-like baseline for Au+Au collisions to measure hot nuclear effects

Small system jet modification score card



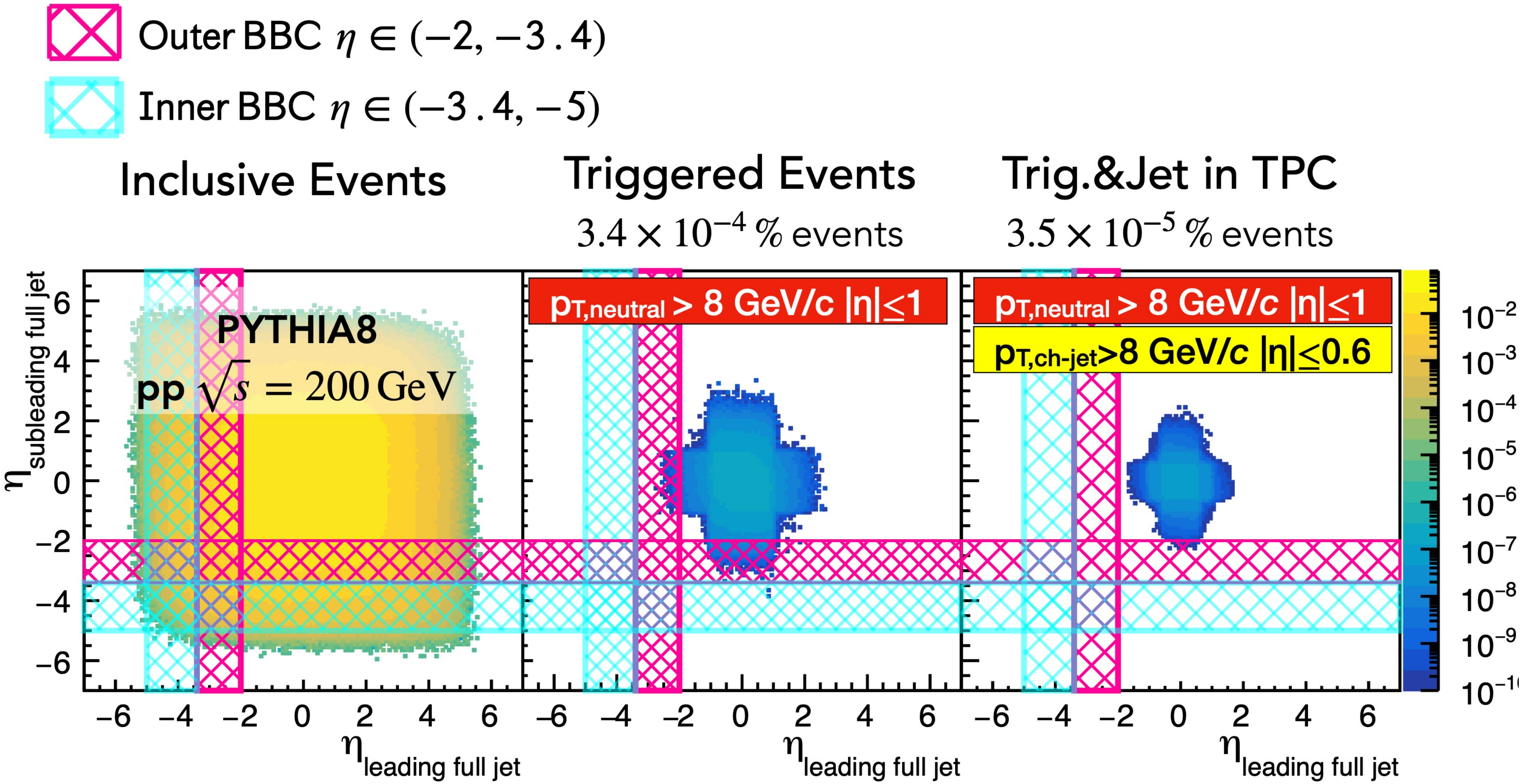
STAR

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



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

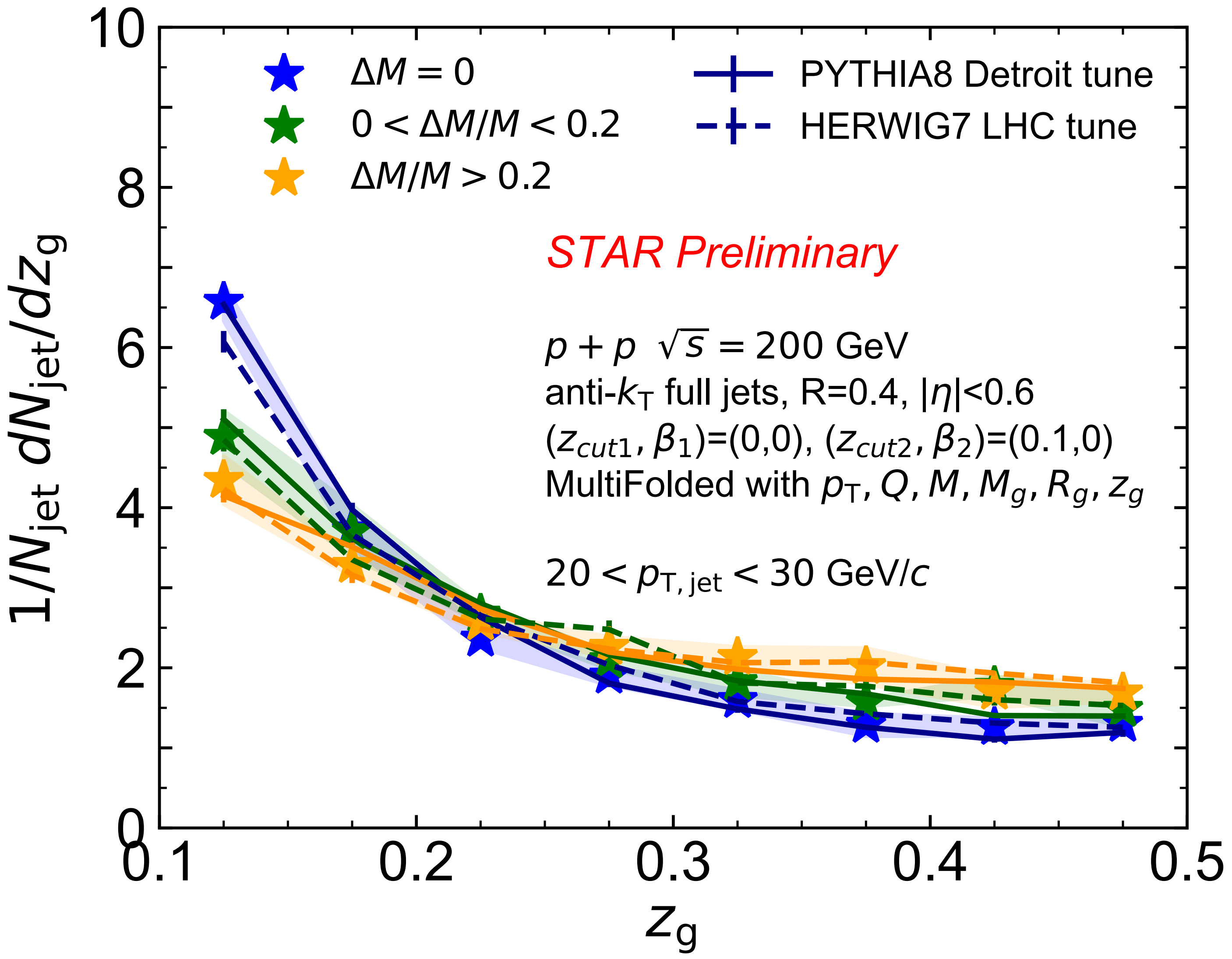
STAR spectra modification *not* due to dijets hitting BBC



~30% Events in BBC_{outer} | ~2% Events in BBC_{outer} | ~0.1% Events in BBC_{outer}

~9% Events in BBC_{inner} | ~1×10^{-3}% Events in BBC_{inner} | No BBC_{inner} hits in 5.9×10^{7}+ (Trig&Jet) events

Shared momentum fraction vs mass pruned



STAR EEC for three different jet p_{T} selections