Recent results of inclusive jet production in Au+Au collisions at $\sqrt{s_{NN}}$ = 200 GeV by the STAR experiment

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Motivation - QGP

- **Quark-Gluon Plasma** (**QGP**) created in high-energy nucleus-nucleus (A+A) collisions
- **QGP** - new state of matter at extreme temperature and/or density
- **Probes** for QGP
  - Soft - collective behavior of matter
  - Electromagnetic - photons, leptons
  - Hard - **jets**, quarkonia, heavy quarks

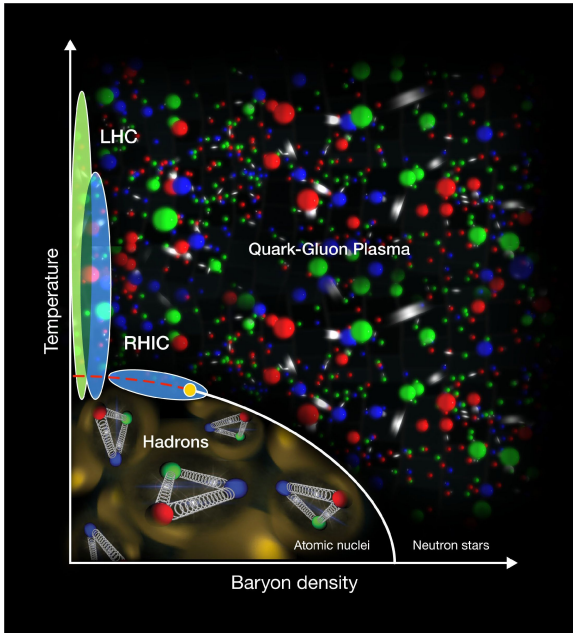
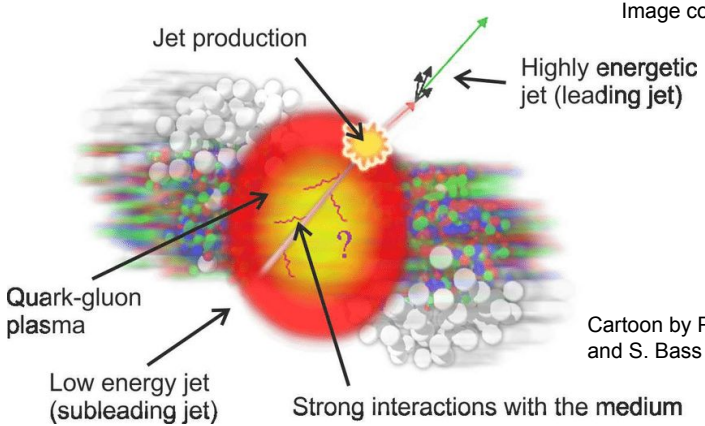


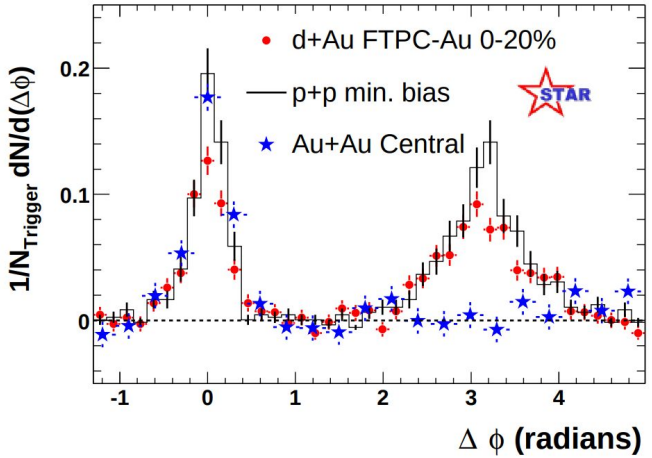
Image courtesy of BNL



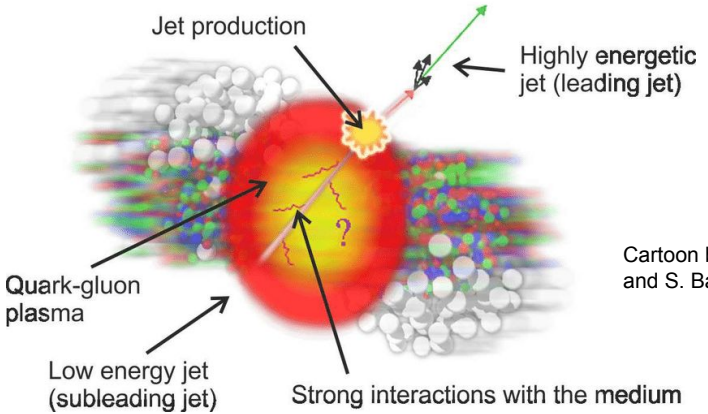
Cartoon by P. Jacobs and S. Bass

Motivation - Why Jets?

- **Hard** process - can be calculated by pQCD
- Created **early** (before QGP) - experiences **entire evolution** of the medium
- **Strong interaction** with the medium
- **Jet quenching** - clear evidence of **QGP** formation



STAR, PRL 91 (2003) 072304

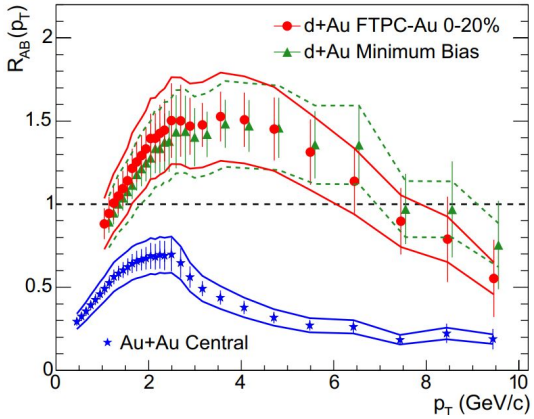


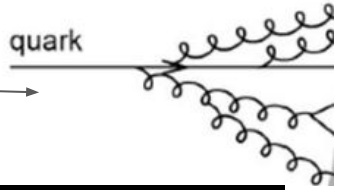
Cartoon by P. Jacobs and S. Bass

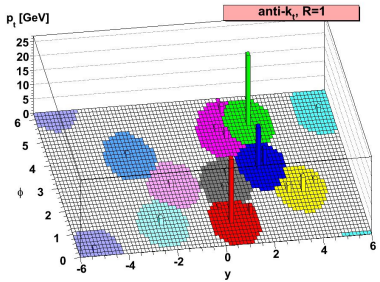
Motivation - Jets

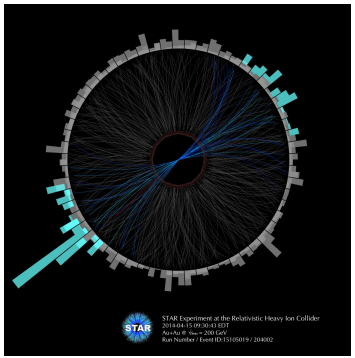
- **High-p_T hadron suppression** - extensively measured at RHIC and the LHC
- **Reconstructed jets** - broader exploration of jet quenching mechanisms
- **Jets**:
  - products of hard **parton** (q/g) **fragmentation**
  - **collimated** sprays of **hadrons**
  - **jet-finding algorithm** outputs

STAR, PRL 91 (2003) 072304





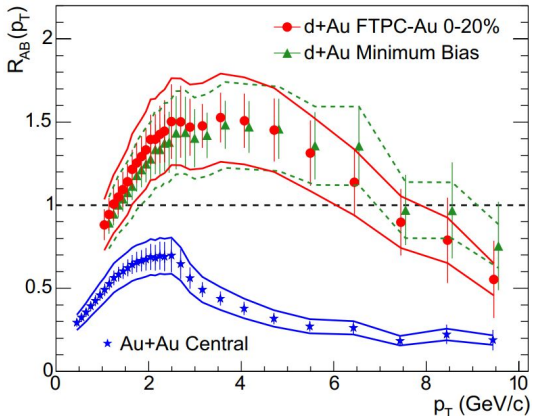




M. Cacciari *et al.*, JHEP 0804 (2008) 063

Motivation - Jets

STAR, PRL 91 (2003) 072304



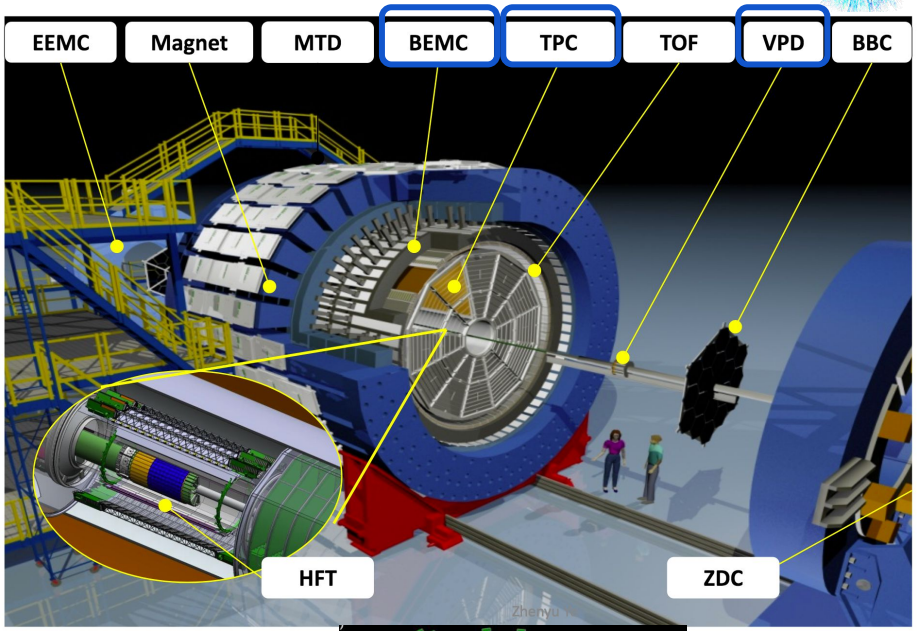
- **High-p_T hadron suppression** - extensively measured at RHIC and the LHC
- **Reconstructed jets** - broader exploration of jet quenching mechanisms
- Different jet measurement channels: **inclusive**, coincidence, heavy flavor,...
- This talk:
  - **First inclusive charged-particle jet measurements in Au+Au collisions at $\sqrt{s_{NN}}$ = 200 GeV** STAR, arXiv:2006.00582
  - **First look at fully-reconstructed inclusive jets in Au+Au collisions at $\sqrt{s_{NN}}$ = 200 GeV**

STAR Experiment

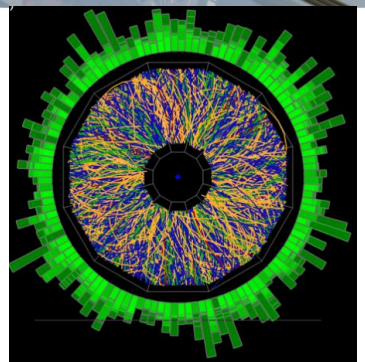
This analysis utilizes:

- **Time Projection Chamber** (TPC)
  - Charged-particle identification and precise momentum reconstruction
- **Barrel Electromagnetic Calorimeter** (BEMC)
  - Detection of photon and electron/positron energy
  - Fast detector used for triggering
- **Vertex Position Detector** (VPD)
  - Minimum-bias trigger
  - Fast detector for pile-up event rejection

Full azimuthal coverage; $|\eta| < 1$



STAR central Au+Au event:



Robert Licenik, CCSP 2020

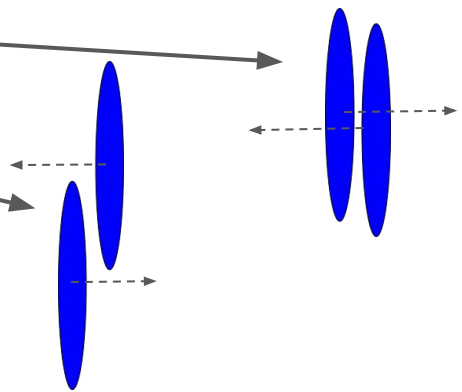
Dataset and Analysis Details

Data sample: Au+Au at $\sqrt{s_{NN}}$ = 200 GeV:

- 2011 minimum-bias, L_{int} = 6 μb^{-1} (charged jets)
- 2014 minimum-bias and BEMC-triggered, L_{int} = 5.2 nb^{-1} (full jets)

Centrality: Determined from charged-track multiplicity within $|\eta_{track}| < 0.5$

- Central (0-10%)
- Peripheral (60-80%)



Event selection:

- $|V_z^{TPC}| < 30$ cm, $|V_z^{TPC} - V_z^{VPD}| < 3$ cm

Primary track selection:

- $|\eta_{track}| < 1$
- Number of TPC hits > 14; ratio of used to maximum possible TPC hits > 0.52
- DCA < 1 cm

***p+p* reference:** PYTHIA 6.428, Perugia 2012, STAR tune

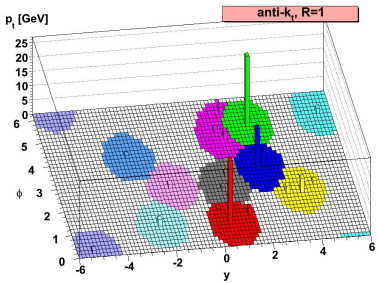
Details in: STAR, PRD 100 (2019) 052005

Jet Reconstruction

- **Charged-particle jets**: charged tracks from TPC
- **Fully-reconstructed jets**: charged tracks from TPC + neutral energy from BEMC clusters, corrected for charged particle energy deposition in BEMC

Details in: STAR, PRL 115 (2015) 092002

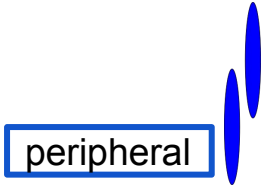
- Anti-k_T algorithm, R = 0.2, 0.3, 0.4
- Fiducial acceptance cut: $|\eta_{jet}| < 1 - R$
- Constituents:
  - charged: $0.2 < p_T < 30.0$ GeV/c
  - neutral: $0.2 < E_T < 30.0$ GeV

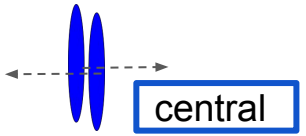


$$d_{ij} = \min(1/p_{ti}^2, 1/p_{tj}^2)\,\Delta R_{ij}^2/R^2$$

- **Inclusive jet analysis: two-step correction (event-by-event, ensemble)**

Fully-corrected Inclusive Charged-particle Jet Spectra



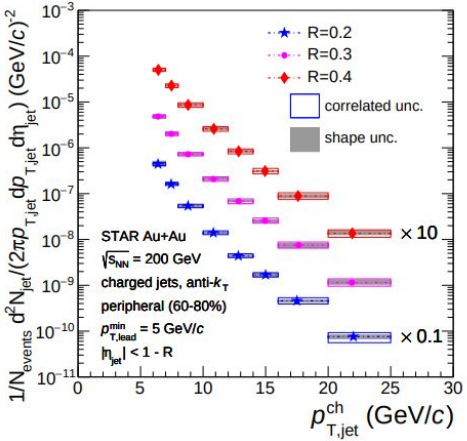


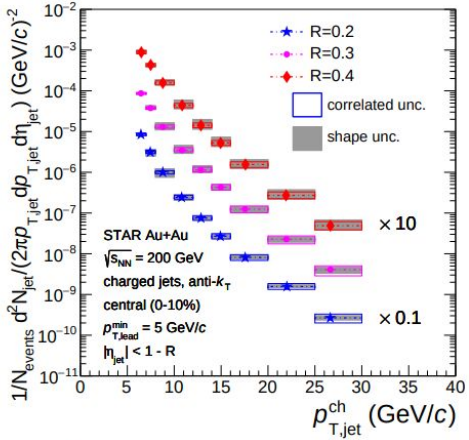
$p_{T,lead} > 5$ GeV/c

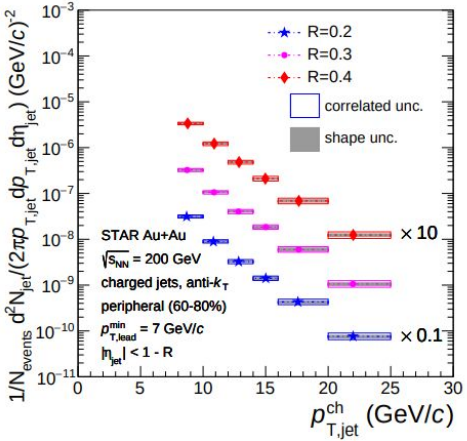
- Central (0-10%) and peripheral (60-80%) collisions

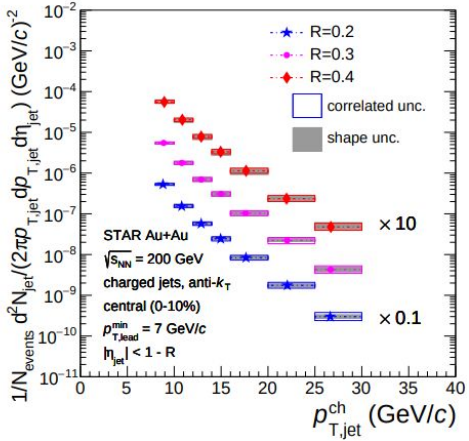
- Spectra biased by $p_{T,lead}$ cut

$p_{T,lead} > 7$ GeV/c





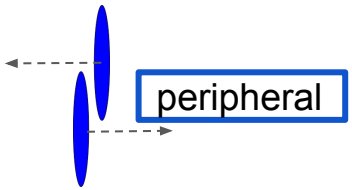




STAR, arXiv:2006.00582

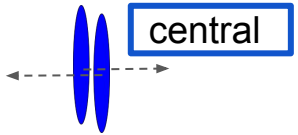
Unbiased Region Determination

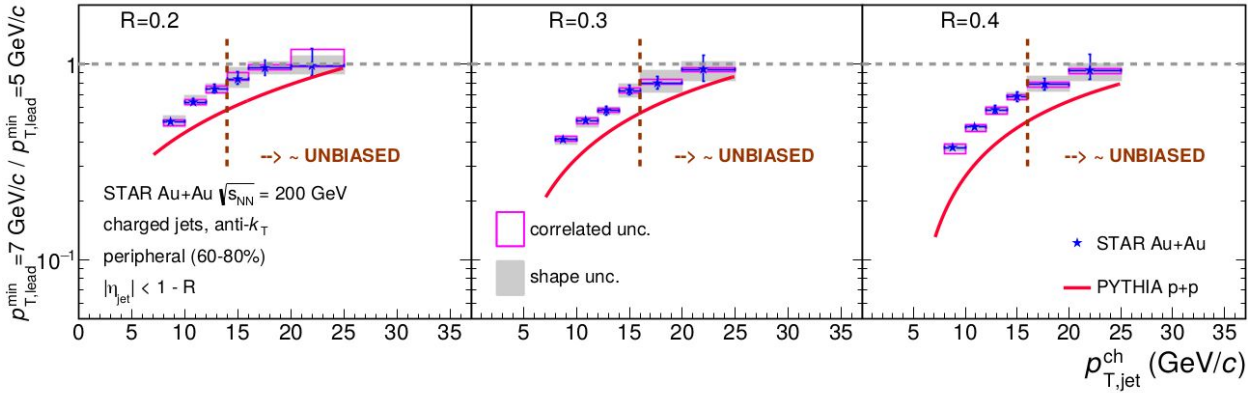
- **Unbiased region** estimated from the ratio of yields with $\frac{p_{\mathrm{T,lead}} > 7\ \mathrm{GeV}/c}{p_{\mathrm{T,lead}} > 5\ \mathrm{GeV}/c}$

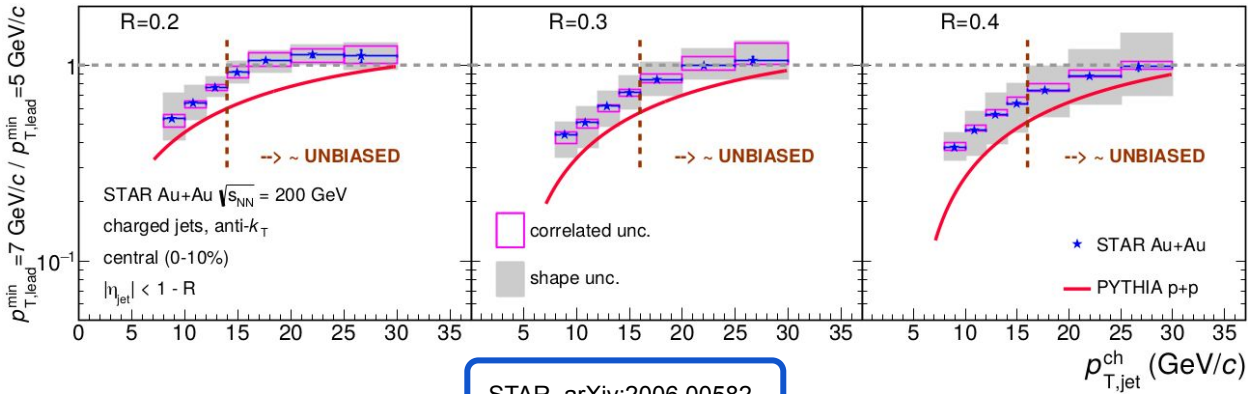


- **~unbiased** = ratio > 0.9

- Physics comparisons in **~unbiased** region only





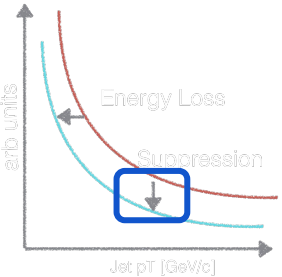


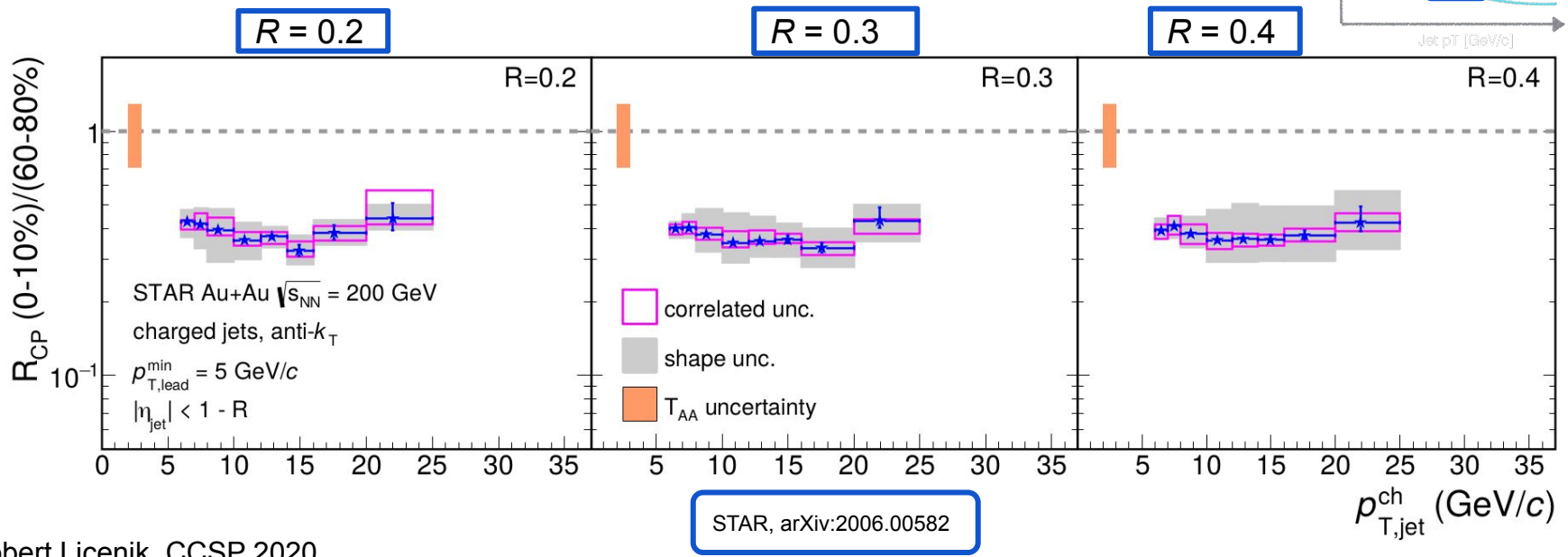
STAR, arXiv:2006.00582

Charged-particle Jet R_{CP}

$$R_{CP} = \frac{\frac{1}{\langle T_{AA} \rangle} \frac{1}{N_{evt}} \frac{d^2 N_{ch\ jet}}{dp_{T,ch\ jet} d\eta_{ch\ jet}}\Big|_{central}}{\frac{1}{\langle T_{AA} \rangle} \frac{1}{N_{evt}} \frac{d^2 N_{ch\ jet}}{dp_{T,ch\ jet} d\eta_{ch\ jet}}\Big|_{peripheral}}$$

- **Strong suppression** of central vs peripheral
- **Weak p_T-dependence**
- Weak *R* dependence





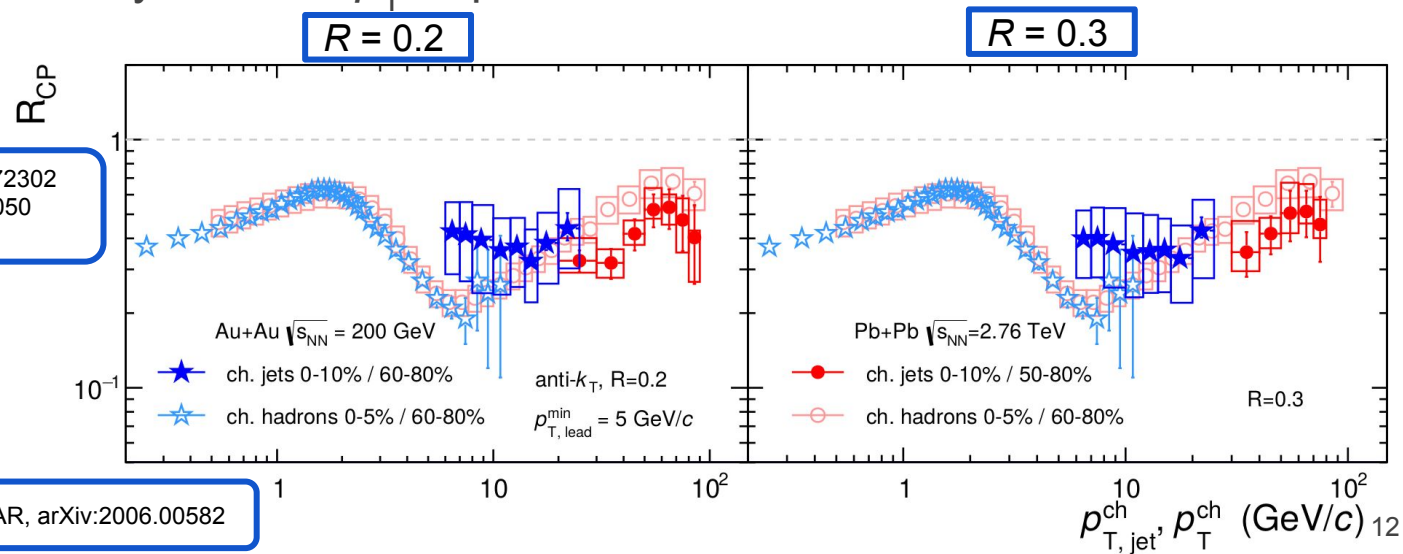
STAR, arXiv:2006.00582

Charged-particle Jet R_{CP}: Comparison with LHC

- **Strong suppression** of central vs peripheral, **weak p_T-dependence**
- Suppression level and p_T-dependence consistent with LHC jet measurements at higher $p_{T,jet}$
- Similar level of suppression as RHIC & LHC inclusive hadron R_{CP} for p_T above 10 GeV/c, possibly different p_T-dependence

RHIC ch. hadrons: STAR, PRL 91 (2003) 172302
LHC ch. hadrons: ATLAS, JHEP 09 (2015) 050
LHC ch. jets: ALICE, JHEP 30 (2014) 013

Centrality selection different for different measurements



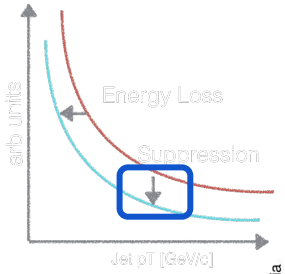
STAR, arXiv:2006.00582

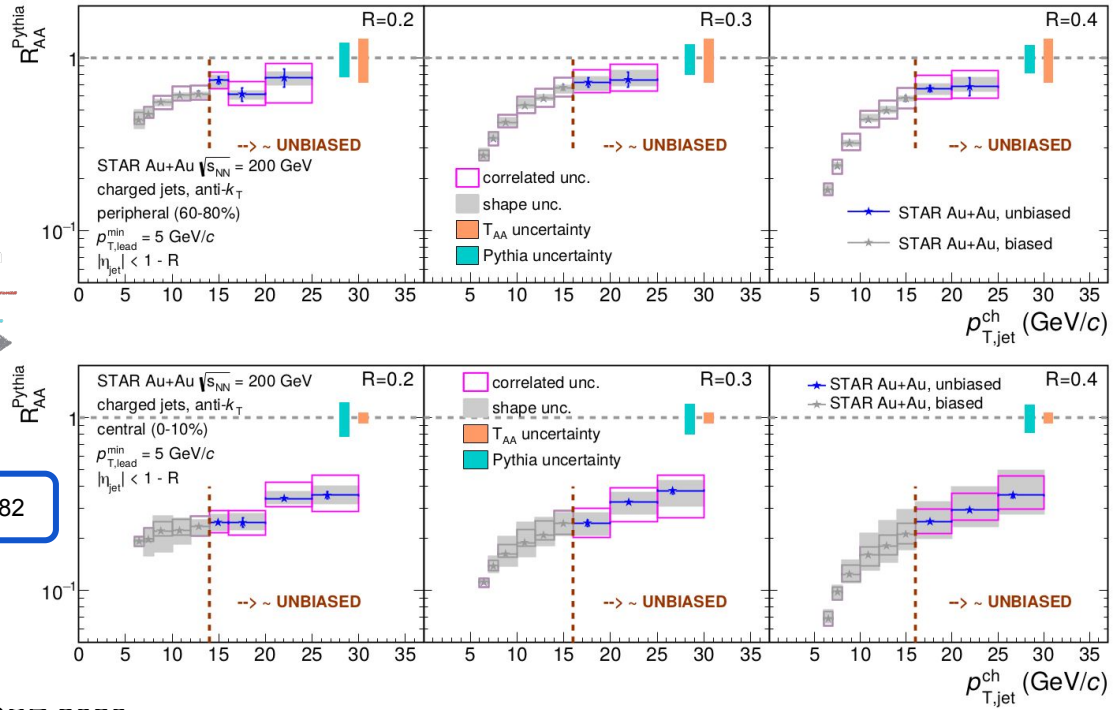
Charged-particle Jet R_{AA}

- *p+p* baseline: PYTHIA 6.428, Perugia 2012, STAR tune

Details in: STAR, PRD 100 (2019) 052005

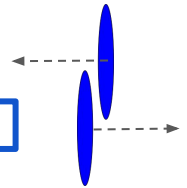
- Significant **jet yield suppression** in central collisions



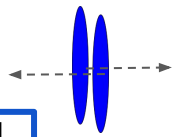


STAR, arXiv:2006.00582

peripheral



$$R_{AA} = \frac{\frac{d^2 N_{AA}}{dp_T dy}}{\langle N_{coll} \rangle \times \frac{d^2 N_{pp}}{dp_T dy}}$$

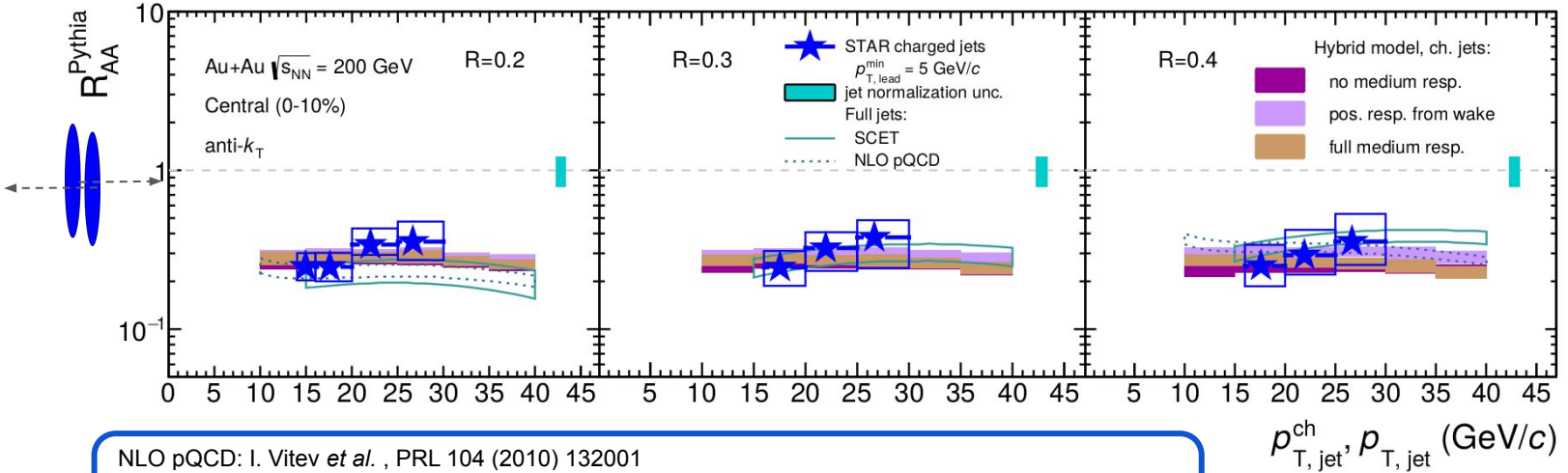


central

Charged-particle Jet R_{AA}: Model Comparison

Only **~unbiased** data points shown

STAR, arXiv:2006.00582

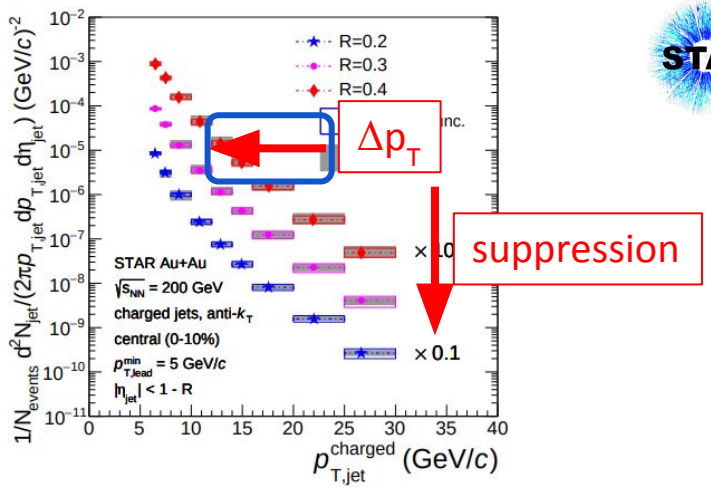


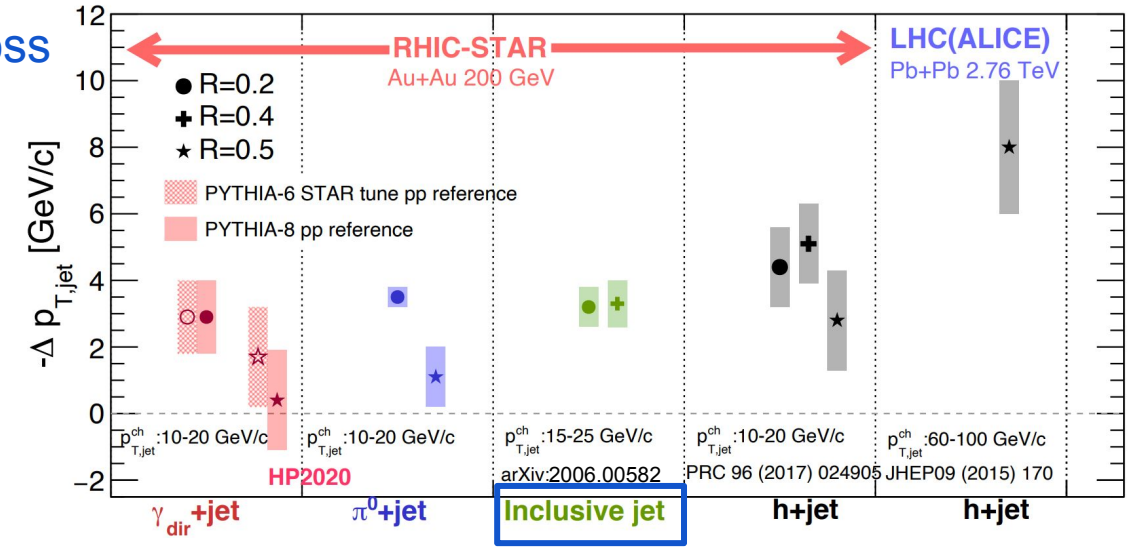
NLO pQCD: I. Vitev *et al.* , PRL 104 (2010) 132001
Soft-Collinear Effective Theory (SCET): Y-T. Chien *et al.*, PRD 93 (2016) 074030,
Y-T. Chien *et al.*, JHEP 05 (2016) 023
Hybrid strong/weak coupling model of jet quenching: J. Casalderrey-Solana *et al.*, JHEP 03 (2017) 135

- All **calculations consistent** with our measurement
- Models predict similar R_{AA}: current precision does not enable us to discriminate between models

Transverse Momentum Shift

- No *R*-dependence observed in inclusive jet production
- Energy loss consistent with semi-inclusive results at RHIC
- Indication of smaller energy loss at RHIC than the LHC

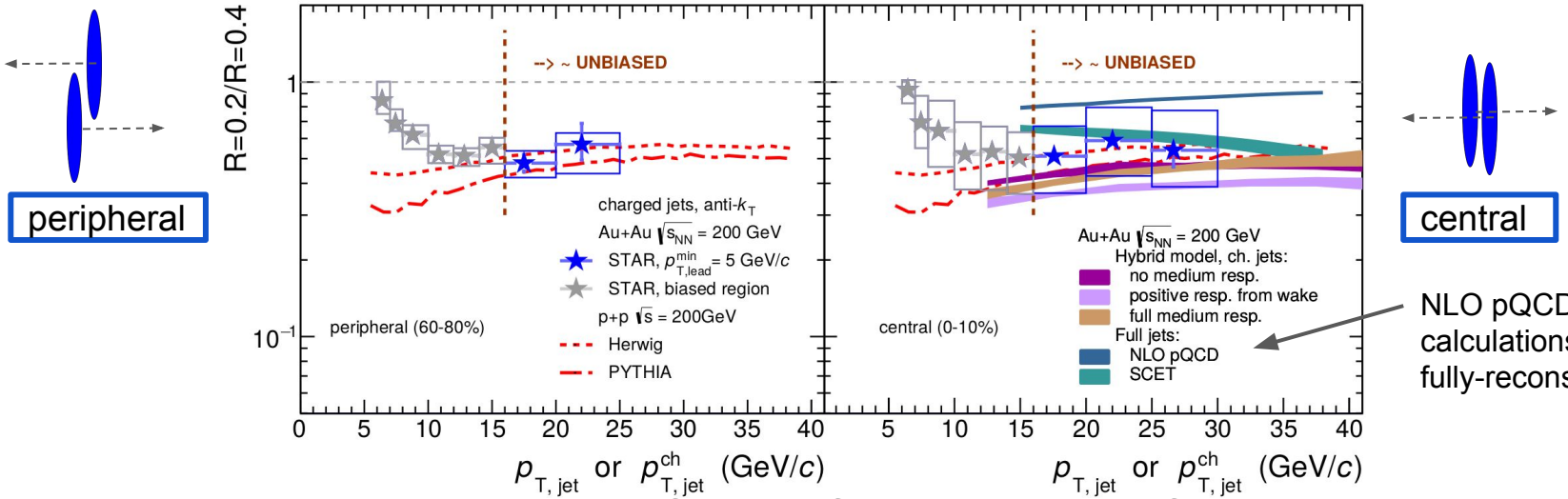




Medium-induced Jet Broadening

- Ratio of inclusive cross sections with different R at fixed $p_{T,jet}$ measures jet energy profile
  - Significant uncertainties cancel

STAR, arXiv:2006.00582



NLO pQCD and SCET calculations are for fully-reconstructed jets

- **Peripheral**: No observed modification of transverse jet profile compared to p+p collision reference (< 1 for both HERWIG and PYTHIA)
- **Central**: Dispersion of models greater than for R_{AA} - strong physical motivation to improve systematic uncertainties and study fully-reconstructed jets

Outlook: Inclusive Fully-reconstructed Jet p_T Spectra

- Raw inclusive **full-jet spectra** reconstructed from large-statistics BEMC-triggered dataset

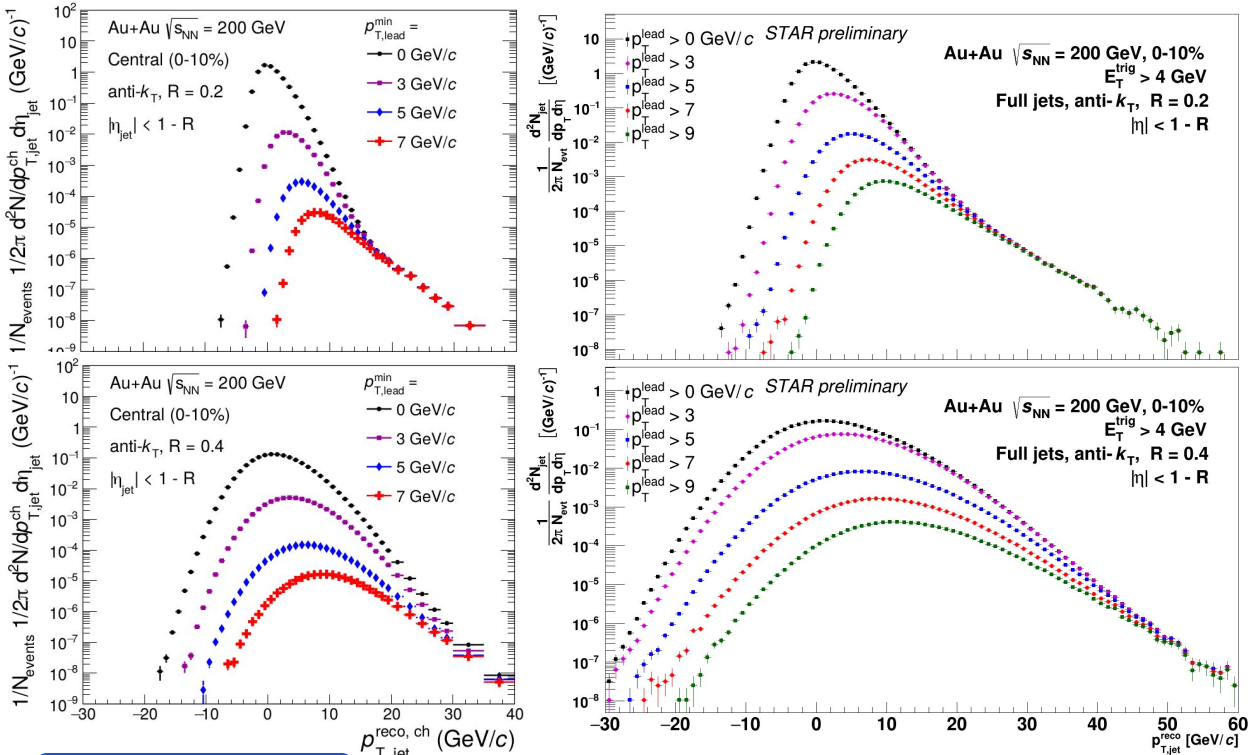
  $R = 0.2$

- **Increase in kinematic reach** for future STAR inclusive jet results

  $R = 0.4$

charged-particle jets, 2011

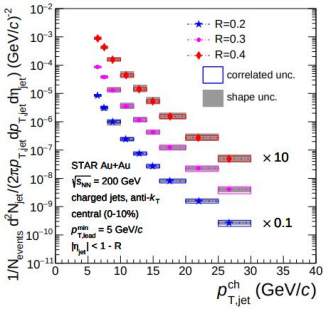
fully-reconstructed jets, 2014

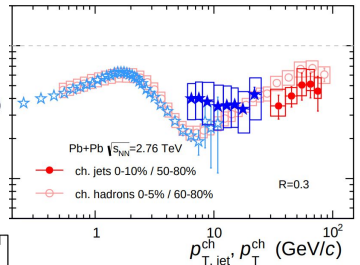


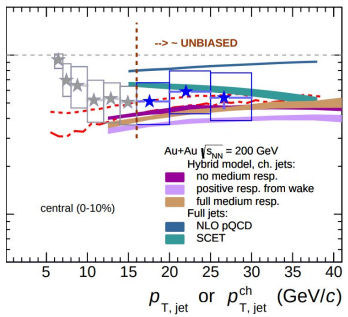
STAR, arXiv:2006.00582

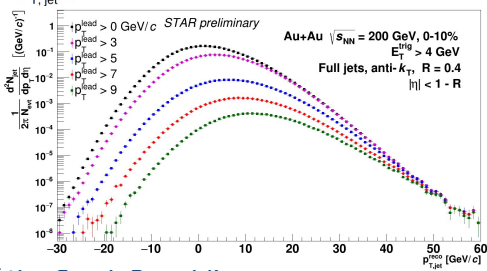
Summary

- First measurement of **inclusive charged-particle jet** distributions in Au+Au collisions at $\sqrt{s_{NN}}$ = 200 GeV
- **Significant yield suppression** in central Au+Au with respect to peripheral Au+Au (data) and *p*+*p* (PYTHIA) collisions
- Magnitude of **suppression similar** to inclusive hadrons (RHIC & LHC) and jets at the LHC
- **No** evidence of **medium-induced broadening** for $R \leq 0.4$
- **Quenching** models largely **consistent** with inclusive jet measurements but opportunities for higher precision
- High-statistics measurements of **fully-reconstructed jets** in Au+Au collisions **in progress**









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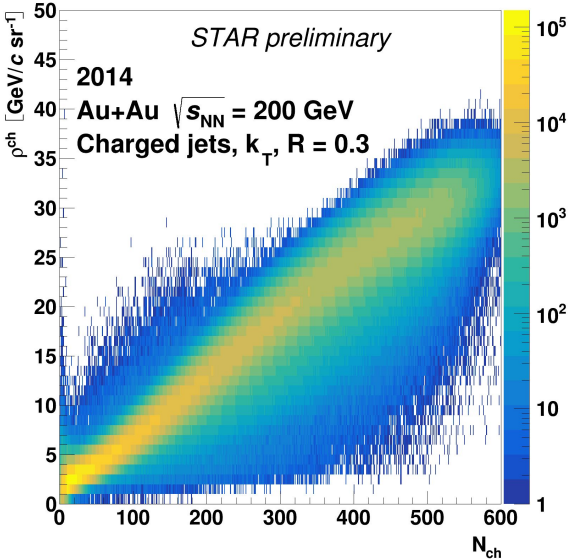
BACKUP

Event-by-event Correction Details

- Area cut: A_{jet} >= 0.07 / 0.2 / 0.4 sr for R = 0.2 / 0.3 / 0.4
- Approximate jet-wise **background subtraction** (FastJet)

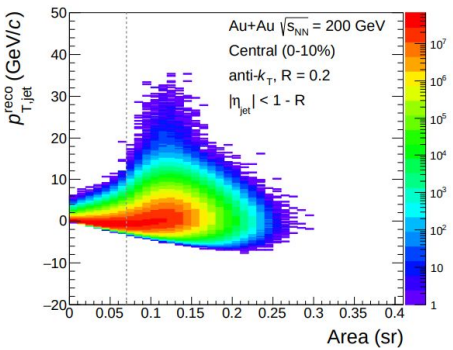
$$p_{\mathrm{T,jet}}^{\mathrm{reco,i}} = p_{\mathrm{T,jet}}^{\mathrm{raw,i}} - \rho \cdot A_{\mathrm{jet}}^{\mathrm{i}}, \text{ where } \rho = \mathrm{median}\left\{ \frac{p_{\mathrm{T,jet}}^{\mathrm{raw,i}}}{A_{\mathrm{jet}}^{\mathrm{i}}} \right\}$$

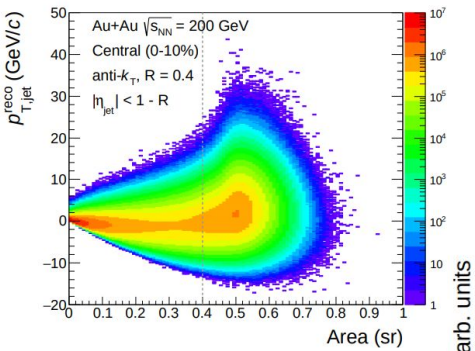
- Combinatorial jets suppressed by imposing a cut on **leading hadron** transverse momentum ($p_{T,lead}$)
  - Imposes **bias** on jet fragmentation and breaks collinear safety
    → as low threshold as possible ($p_{T,lead}$ > 5 GeV/c)
  - Measure bias using $p_{T,lead}$ > 7 GeV/c

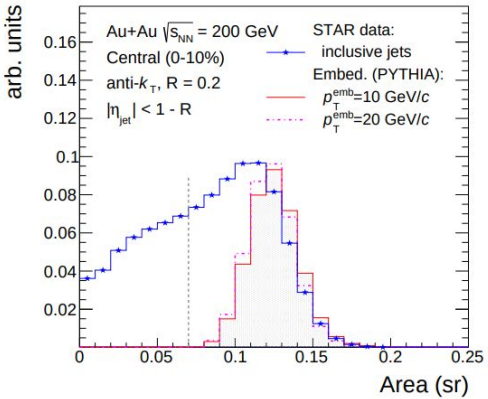


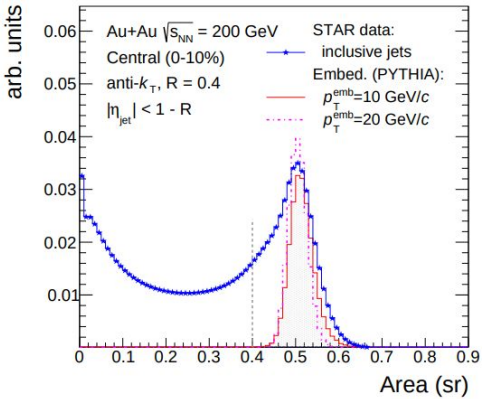
Jet Area Cut

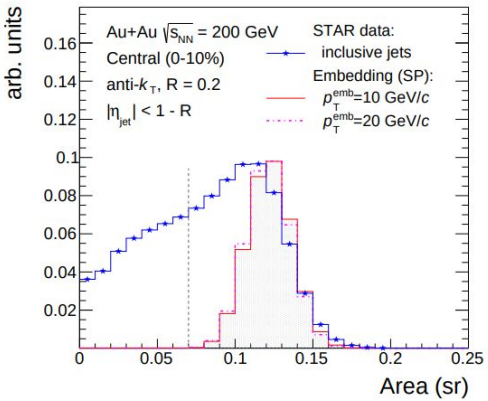
- Area >= 0.07, 0.2, 0.4

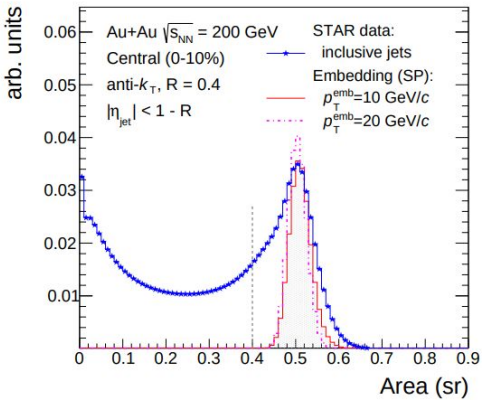












Inclusive Charged-particle Jet Spectrum

- **Raw charged-particle jet spectra** reconstructed in central and peripheral collisions with various $p_{\mathrm{T,lead}}$ thresholds

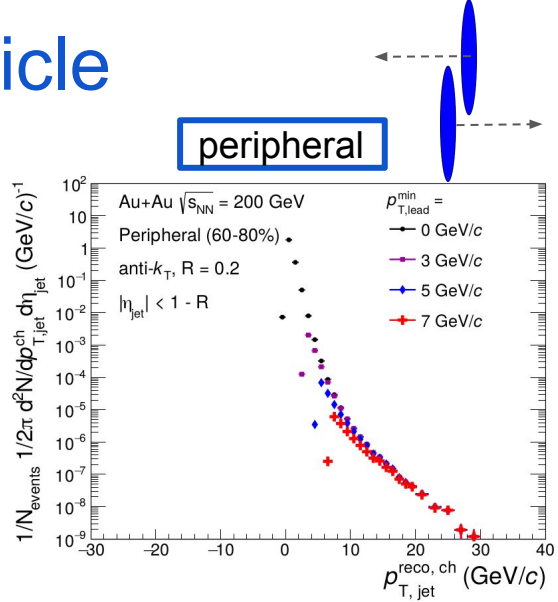
R=0.2

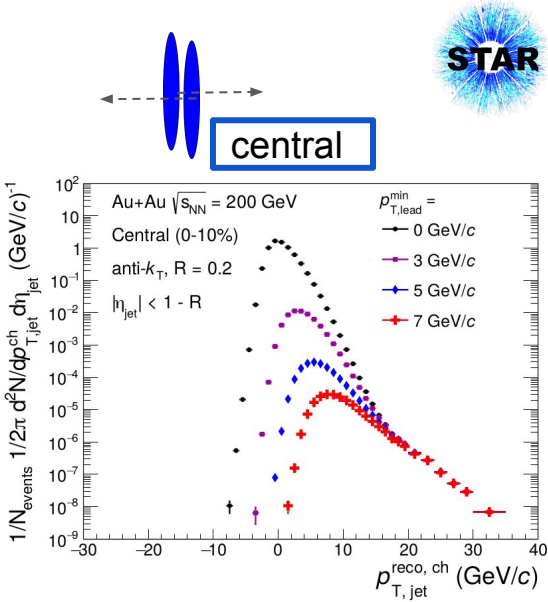
- High $p_{\mathrm{T,lead}}$ cut preferentially suppresses yield at low and negative $p_{\mathrm{T,jet}}^{\mathrm{reco,ch}}$, where combinatorial jet contribution is largest

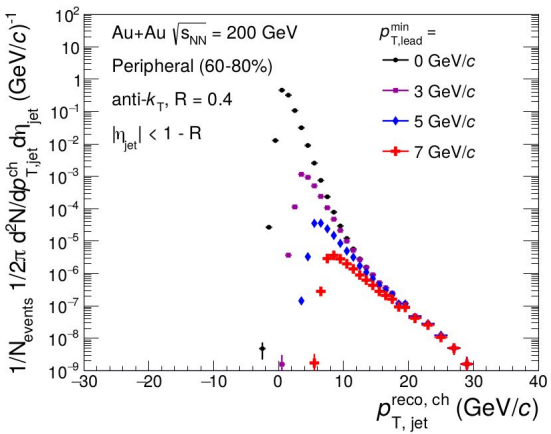
R=0.4

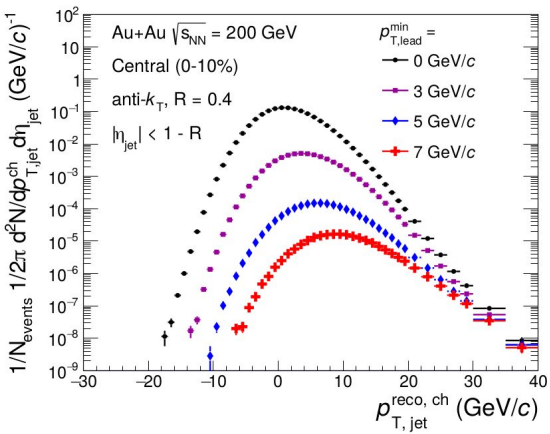
peripheral

central



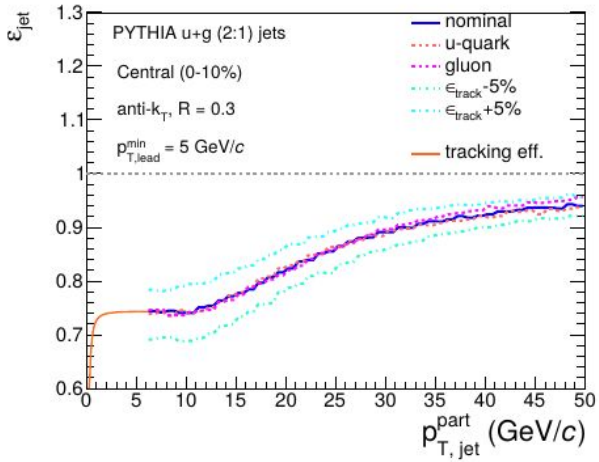


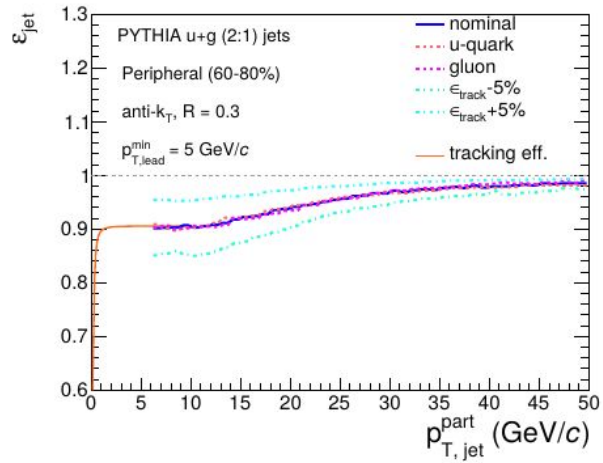




Jet Reconstruction Efficiency

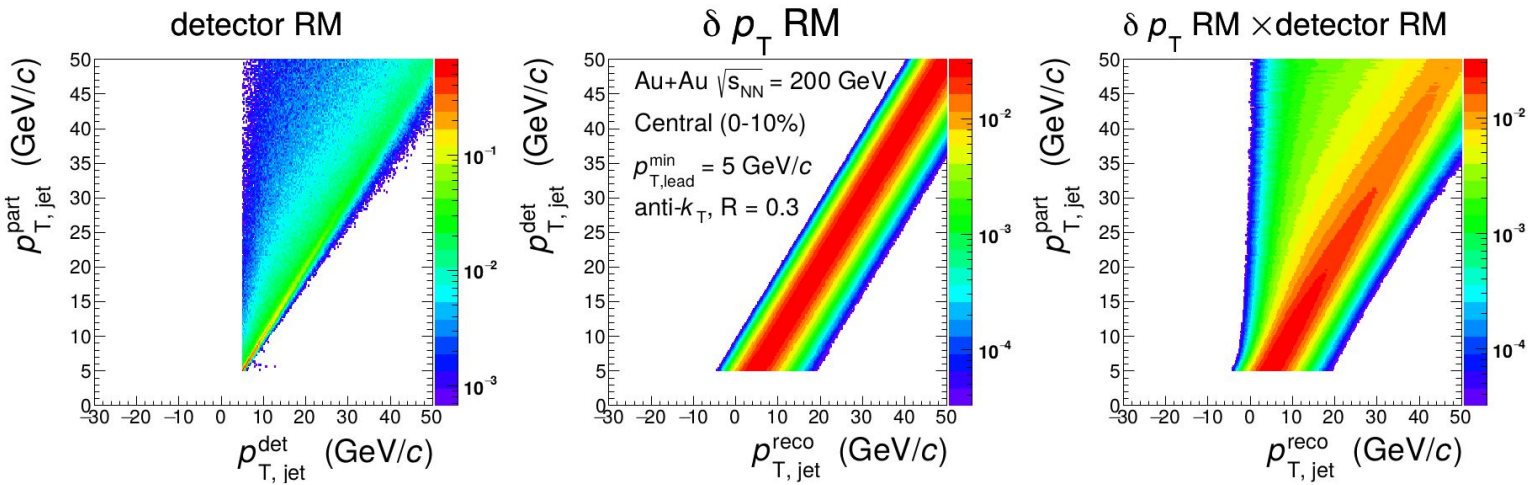
- Estimated from comparing matched parton- and detector-level jets generated by PYTHIA6
- Negligible difference on parton type (u/g)
- Dominated by TPC **tracking efficiency**
- Variations used for systematic uncertainty estimation





Ensemble Correction

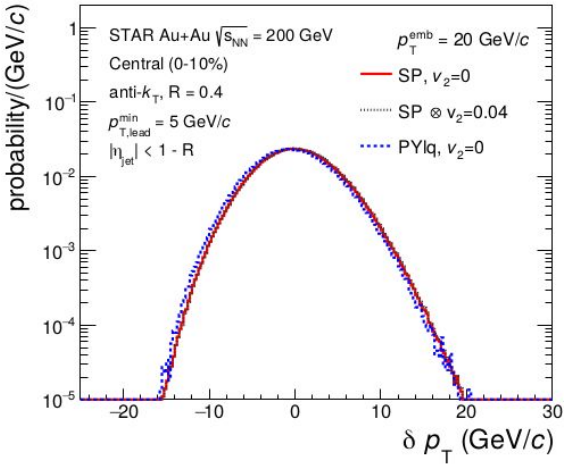
- **Unfolding**: iterative **Bayesian** and **SVD** (systematic uncertainty estimation)
- **Factorize** detector effects and background fluctuations

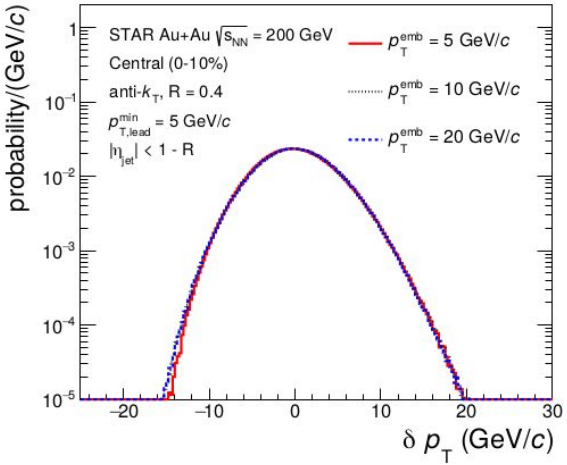


Inclusive Charged Jet Spectrum Analysis: Ensemble Step

- **Unfolding**: iterative **Bayesian** and **SVD** (systematic uncertainty estimation)
- **Factorize** background fluctuations and detector effects
- **Background fluctuations:** embed different jet-like objects
  - Variations of fragmentation pattern: Single Particle (SP), PYTHIA light-quark jet (PYlq)

$$\delta p_{\mathrm{T}} = p_{\mathrm{T,jet}}^{\mathrm{reco,ch}} - p_{\mathrm{T}}^{\mathrm{emb}}$$





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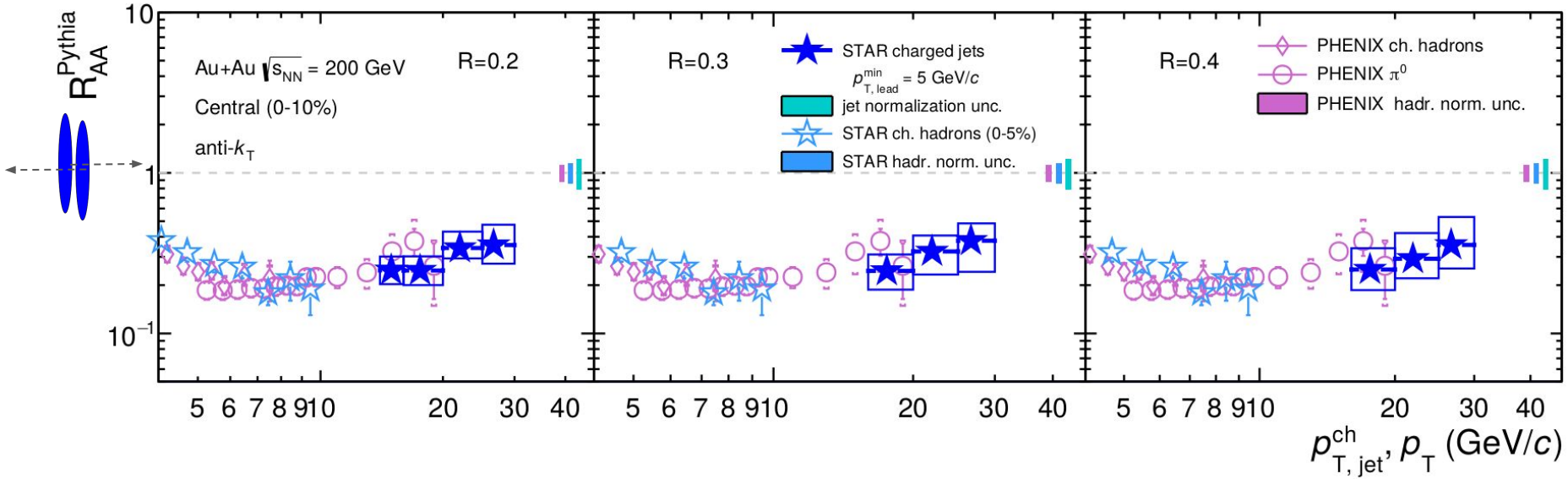
Charged-particle Jet R_{AA}: Comparison to Inclusive Hadrons

Only **~unbiased** data points shown

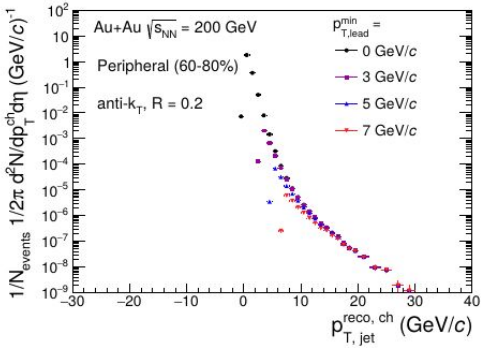


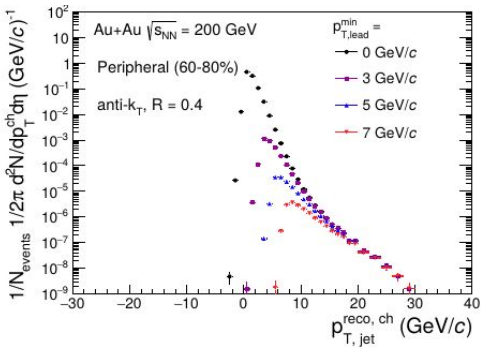
- Yield suppression **consistent with inclusive hadron** suppression in central Au+Au collisions at RHIC

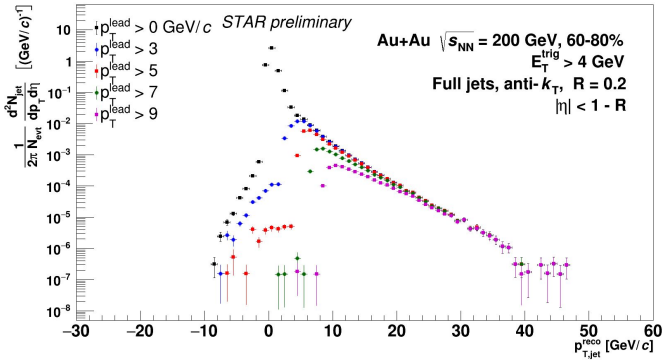
STAR ch. hadrons: PRL 91.172302 (2003)
PHENIX ch. hadrons: PRC 69, 034910 (2004)
PHENIX π^0: PRC 87, 034911 (2013)

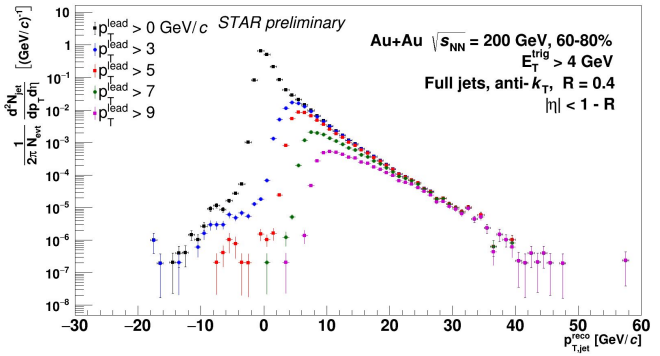
Outlook: Inclusive Full Jet p_T Spectra - peripheral

- Raw inclusive full-jet spectra reconstructed from large-statistics BEMC-triggered dataset
- Great potential for increase in kinematic reach for future STAR inclusive jet results









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