Hard Probes 2013, Cape Town

Inclusive Spectrum of Fully Reconstructed Charged Jets in Central Au+Au Collisions at $\sqrt{s_{NN}}$=200 GeV by the STAR Collaboration

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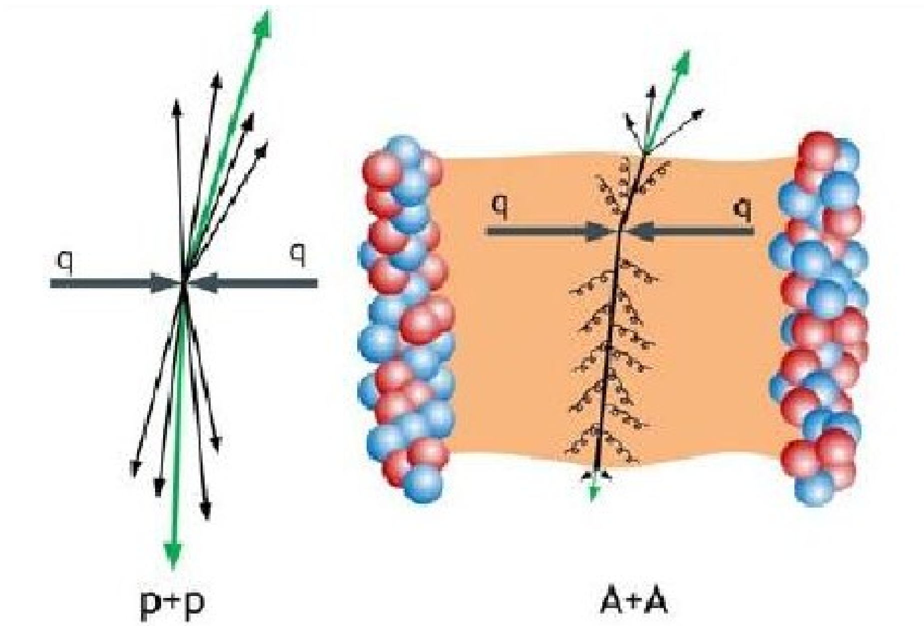
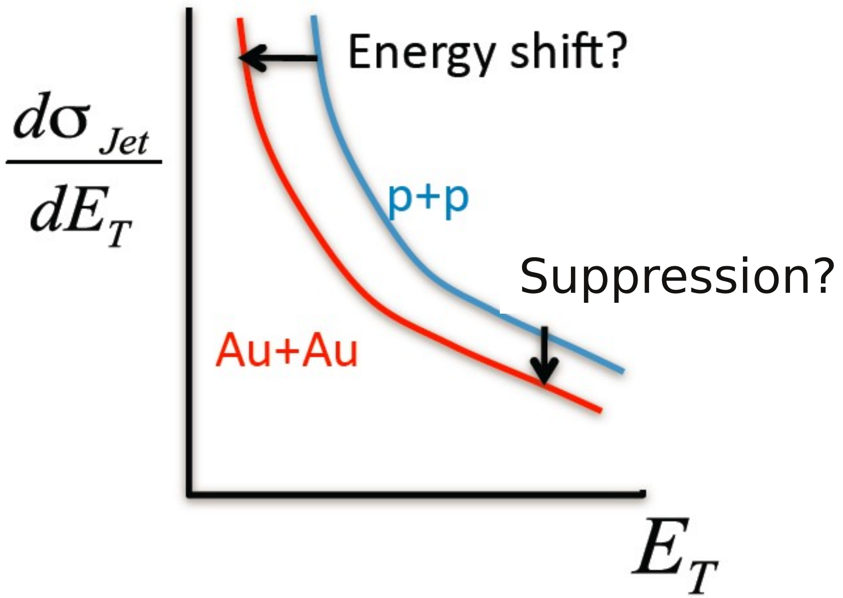
Motivation: jets as a probe of nuclear matter

- jets are collimated sprays of hadrons created by fragmentation and hadronization of hard-scattered partons
- in heavy-ion collisions: probe of hot and dense nuclear matter

  jet quenching – modification of fragmentation

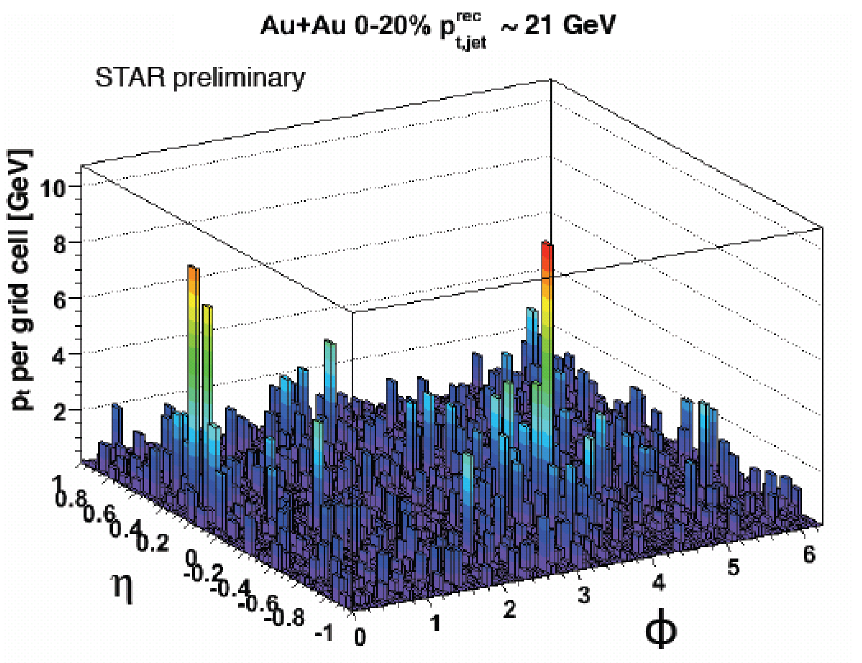




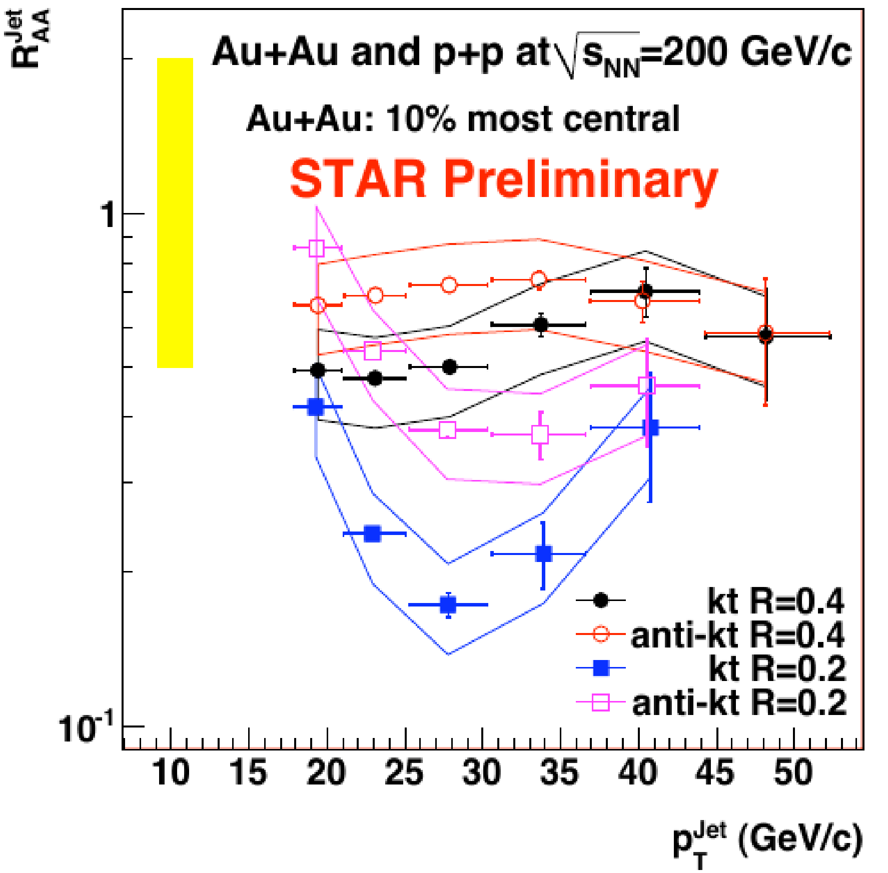
However: Jet reconstruction is an extremely challenging task in the high multiplicity environment and large and fluctuating background …

Full jet reconstruction in Au+Au collisions at STAR

Early Quark Matter '09 results on Run 7 Au+Au data at 200 GeV
- limited statistics, new methods developed since then



Full jet R_{AA}



M. Ploskon, Nucl.Phys.A830:255c-258c,2009

Jet tomography in A+A collisions: requirements

- well defined and transparent selection of jet population

  - understand what biases we impose

- direct comparison to theory

  - jet distributions corrected for background and instrumental effects to particle level

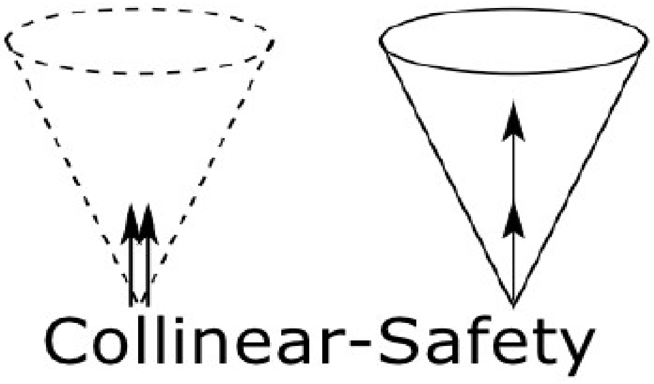
- same approach and algorithms at RHIC and LHC over the full jet kinematic range: p_T^{jet} > ~15 GeV/c

  - to achieve a well controlled energy evolution of quenching

- collinear safety – as close as possible, low infrared (IR) cutoff:

  - no background suppression via cuts on jet constituents

Caveat! Detector response also imposes infrared cutoffs

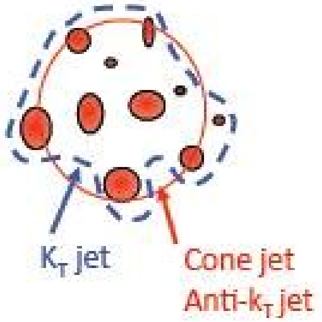


Jet Reconstruction

reconstructed jet (jet candidate) = output of the jet reconstruction algorithm

FASTJET [Eur.Phys.J. C72 (2012) 1896]

- implements fast IR and collinear safe algorithms
- sequential clustering algorithms: kT, anti-kT
    - cluster hadrons into jet objects over a range specified by parameter *R*
    - in our analysis: *R*=0.2, 0.3, 0.4



Clustering:

$$d_{ij} = min(p^a_{T,i}, p^a_{T,j}) \frac{(\Delta\varphi)^2 + (\Delta\eta)^2}{R^2}$$

$$d_{iB} = \frac{p^a_{T,i}}{R}$$

$\rightarrow min(d_{iB}, d_{ij})$

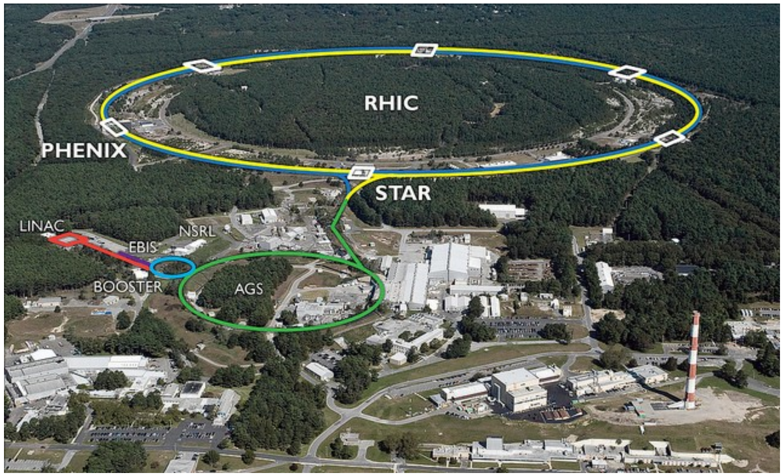
- d_{ij} → add to jet
- d_{iB} → final jet

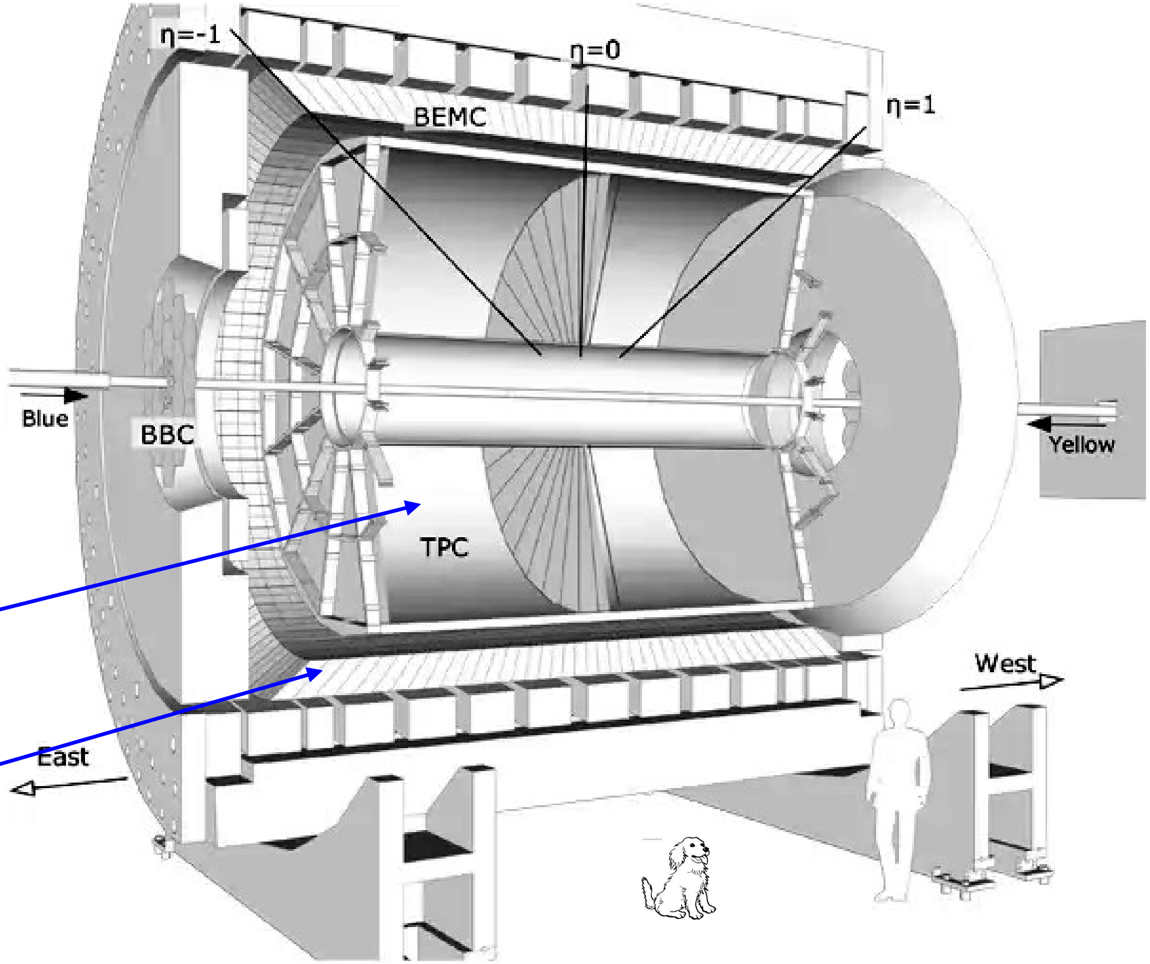
Where a =2 for kT and -2 for anti-kT

STAR Detector

Relativistic Heavy Ion Collider (RHIC)

Solenoidal Tracker at RHIC (STAR)





Time Projection Chamber

Barrel Electromagnetic Calorimeter

full azimuthal coverage
pseudo-rapidity coverage: $-1<\eta<1$

Data Sample and Charged Jet Analysis

Data set:
- RHIC Run11 data
- Au+Au @ $\sqrt{s_{NN}}$=200 GeV
- 10% most central Au+Au collisions from minimum bias (MB) trigger
- Integrated luminosity ~ 60μb^{-1}
  (15% of total production of Run11 data)

Event selection:
- |z(vertex)|<30cm

Charged track selection:
- reconstructed in TPC
- DCA < 1cm
- Number of fit hits > 20
- # of fit hits/# of max. available > 0.55

Jet reconstruction:

- Charged jets
- anti-k_T jet reconstruction algorithm

resolution parameter: R=0.2, 0.3, 0.4

- very low IR cutoff:
  p_T(constituent) > 0.2 GeV/c
- jet active area: A > 0.4 Sr (R=0.4)
  A > 0.2 Sr (R=0.3)
  A > 0.09 Sr (R=0.2)
- fiducial jet acceptance: |η|<1-R

Heavy Ion Jet Reconstruction

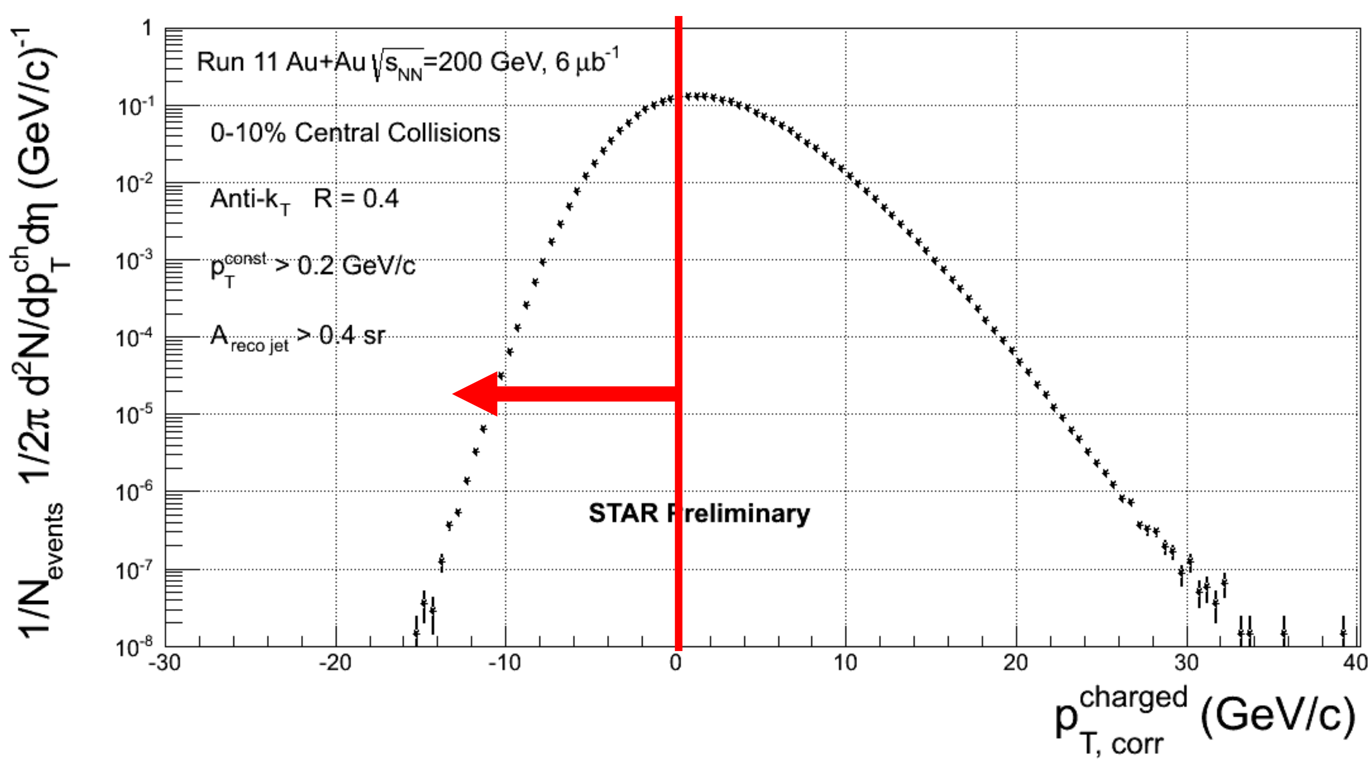
- take all jets in acceptance
- Jet candidates: reconstructed using anti-*kT* algorithm
- jet area *A*: Fastjet definition
- bckd. energy density – calculated event-wise (*kT*):

  (hard jets not discarded for the calculation)

$$\rho = med\left\{\frac{p_{T,i}}{A_i}\right\}$$

- distribution corrected for bckd. energy density:

$$p_{T,corr} = p_T - A_{jet} \times \rho$$



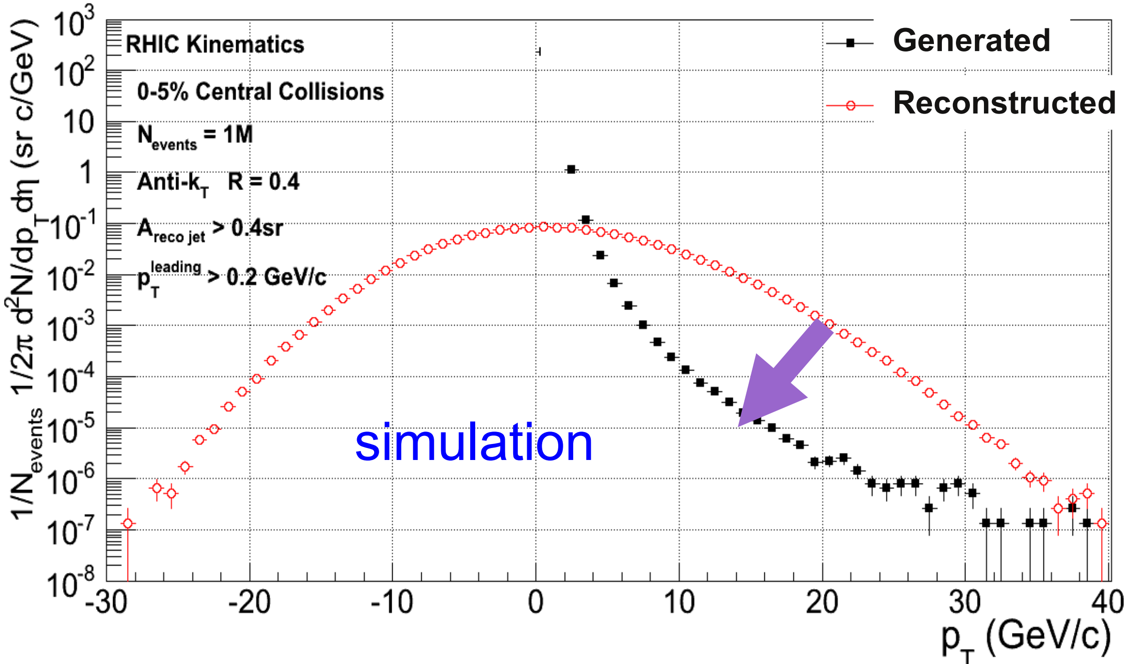
~half of the jet candidates have negative p_T^{corr}

we don't discard them (for now)

contain crucial information about background

Unfolding of Measured Spectra

- Undo the effects of smearing on hard jet spectrum
- In order to compare measured data directly with theory
- Correction for BG fluctuations
- Correction for detector effects



- "Inversion" of response matrix => unfolding matrix
- We use iterative method based on Bayes' theorem *[G. D'Agostini, arXiv:1010.0632]*
- Singular Value Decomposition (SVD) unfolding used to validate Bayesian for background fluctuations. Full unfolding with SVD in progress *[Nucl.Inst.Meth.A372:469-481,1996]*

Toward the Inclusive Jet Spectrum

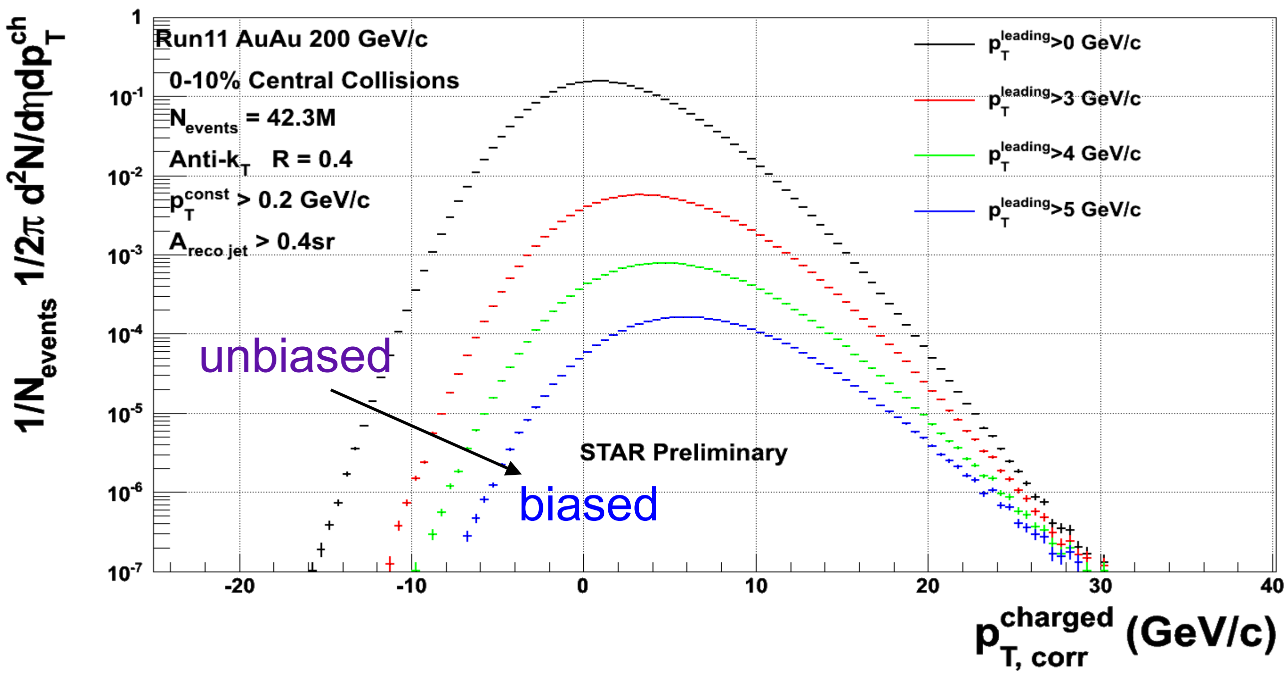
- Stable unfolding of inclusive jet spectrum:

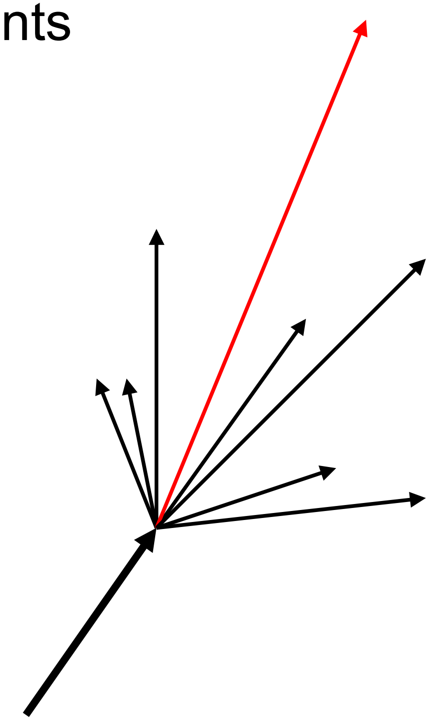
  need to reduce the combinatorial background prior to unfolding

  [G. de Barros et al, Hard Probes 2012, arXiv:1208.1518v2]

- Combinatorial background is reduced by *p*T cut on jet's leading hadron
- Large fraction of jet energy can be carried by soft radiation
  - May be important for jet quenching measurements

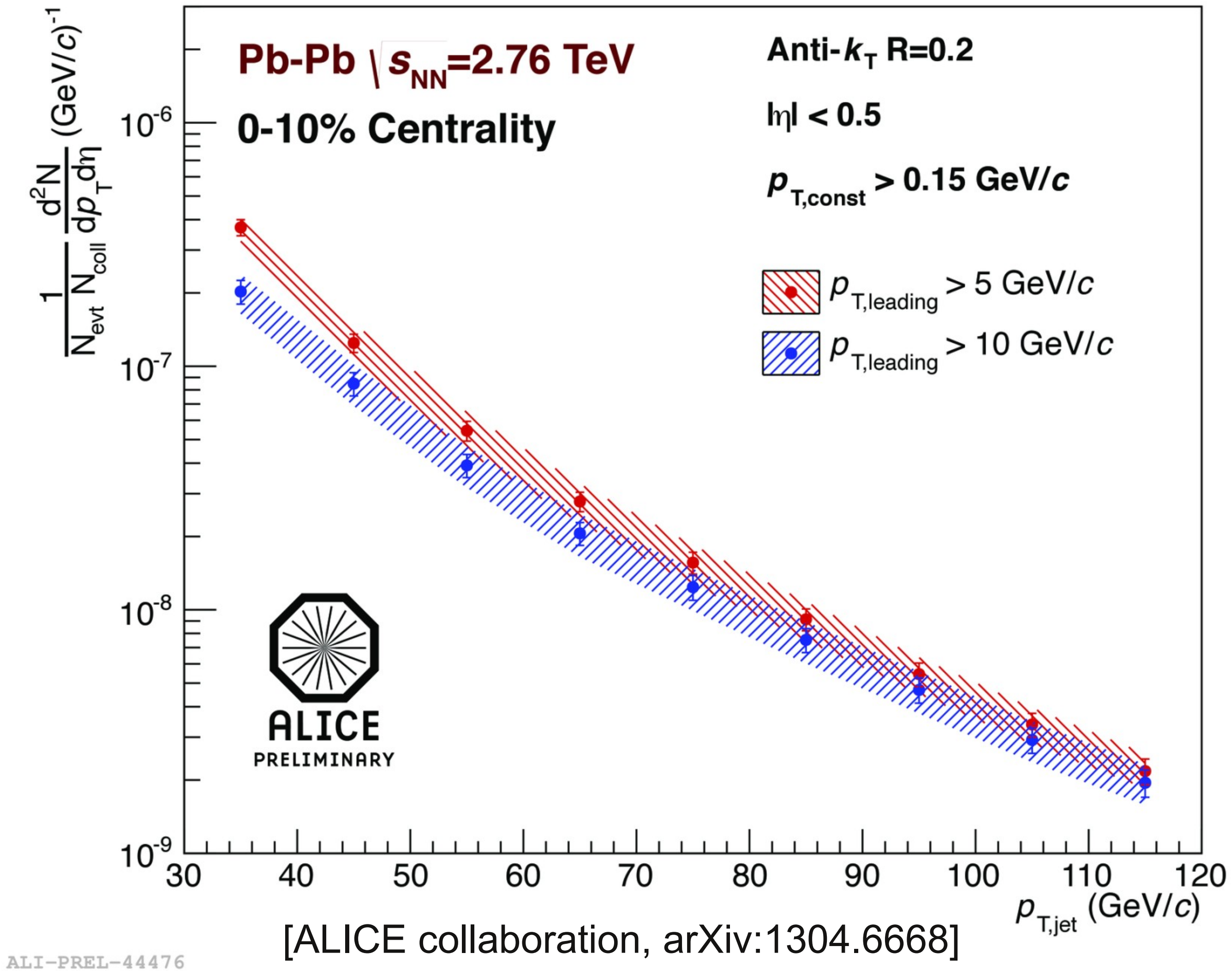
pTleading> 0, 3, 4, 5 GeV/*c*





Methodology

- Method has been successfully used by ALICE collaboration
- We have tested the method on toymodel and now we are applying the same method to STAR data



[ALICE collaboration, arXiv:1304.6668]

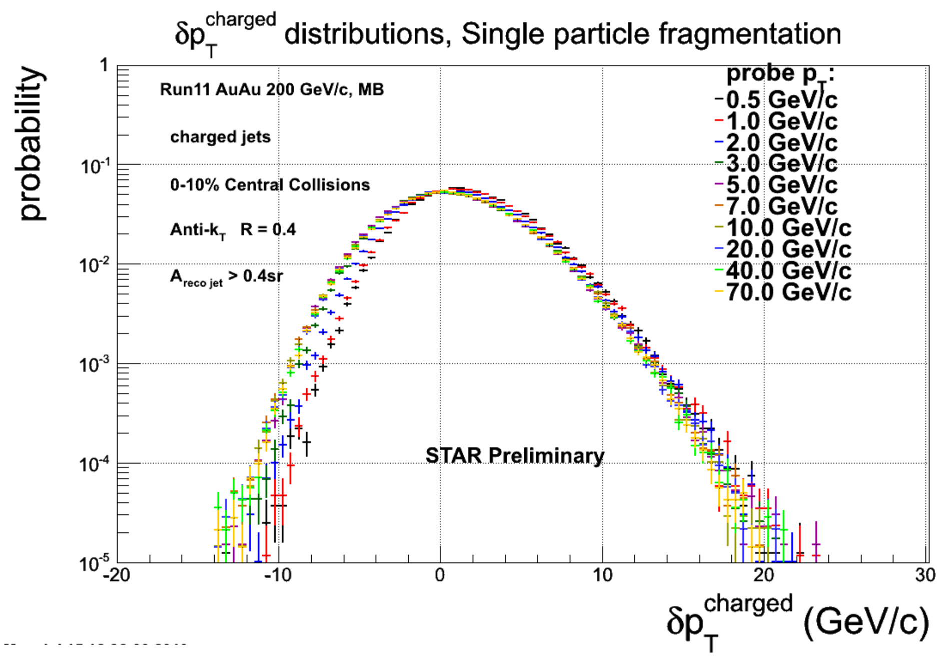
Response of jet to soft background: δ(p_T) distribution

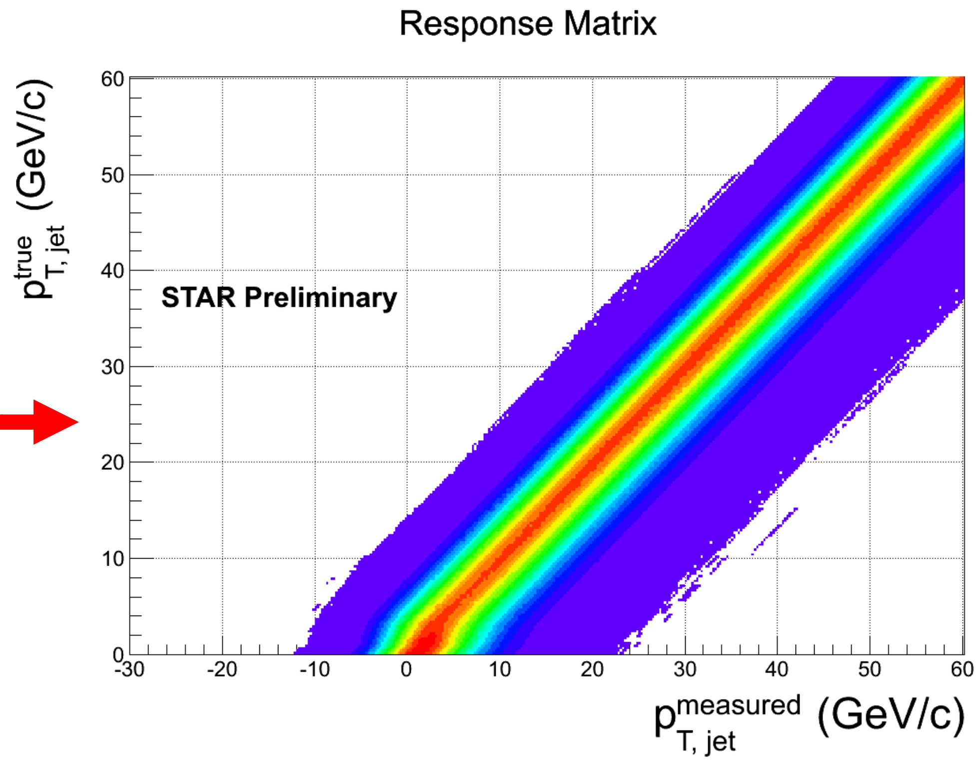
- embedding of a simulated jet into an event => jet reconstruction

$$\delta p_T = p_{T,corr} - p_{T,emb} = p_T - A_{jet} \times \rho - p_{T,emb}$$

ρ ~ 29 GeV/Sr, $A_{R=0.4}$~0.5 Sr

- ensemble-averaged δ(p_T) distribution => determination of the response matrix

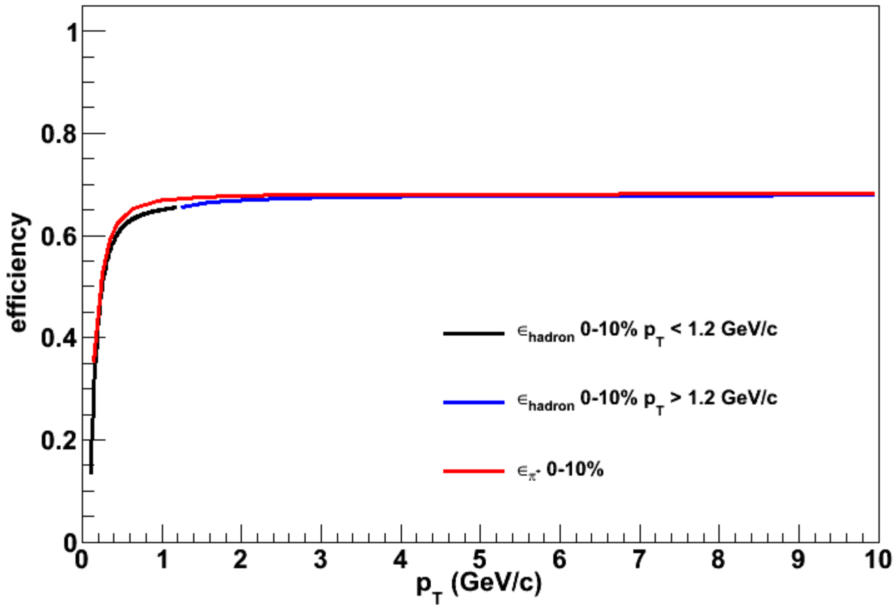


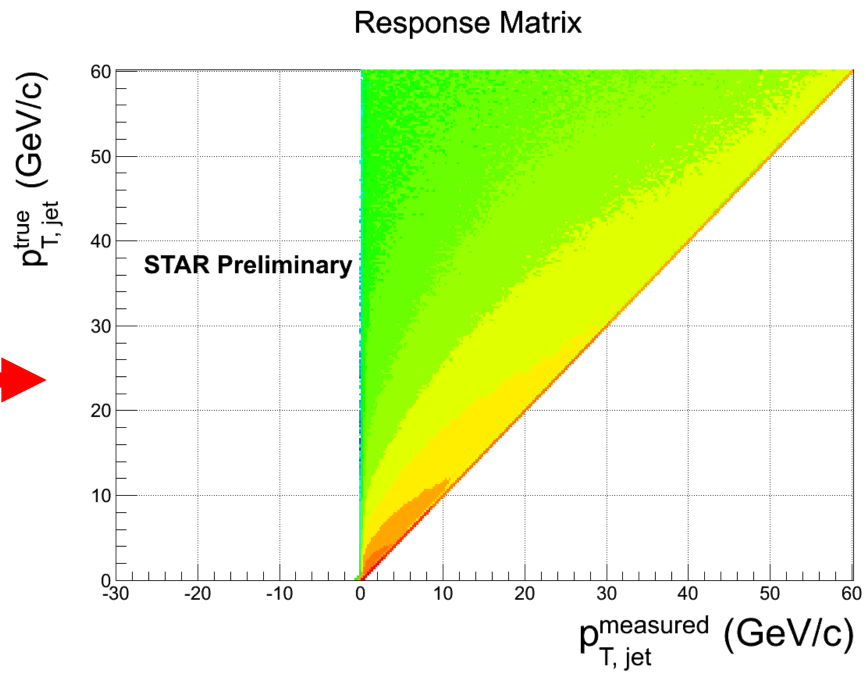


Response of jet due to detector efficiency

- detector response: dominated by tracking efficiency
- we utilize PYTHIA jets (to do: other fragmentation models)

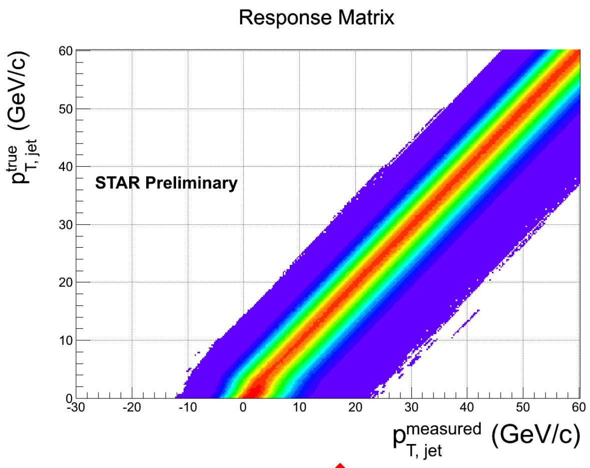
Single hadron reconstruction efficiency





- tracking efficiency: ~5% uncertainty

Response of jet to soft background and detector efficiency



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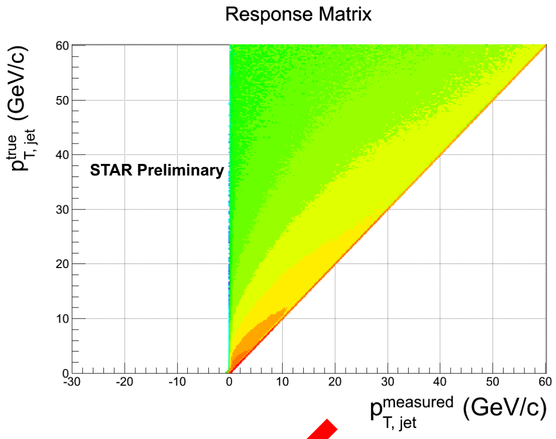
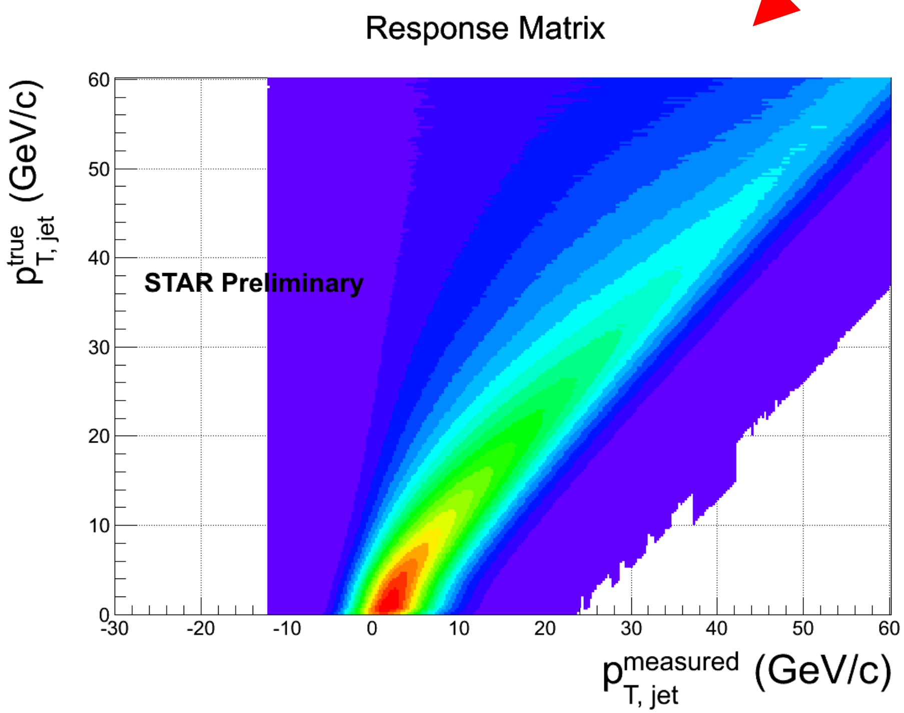
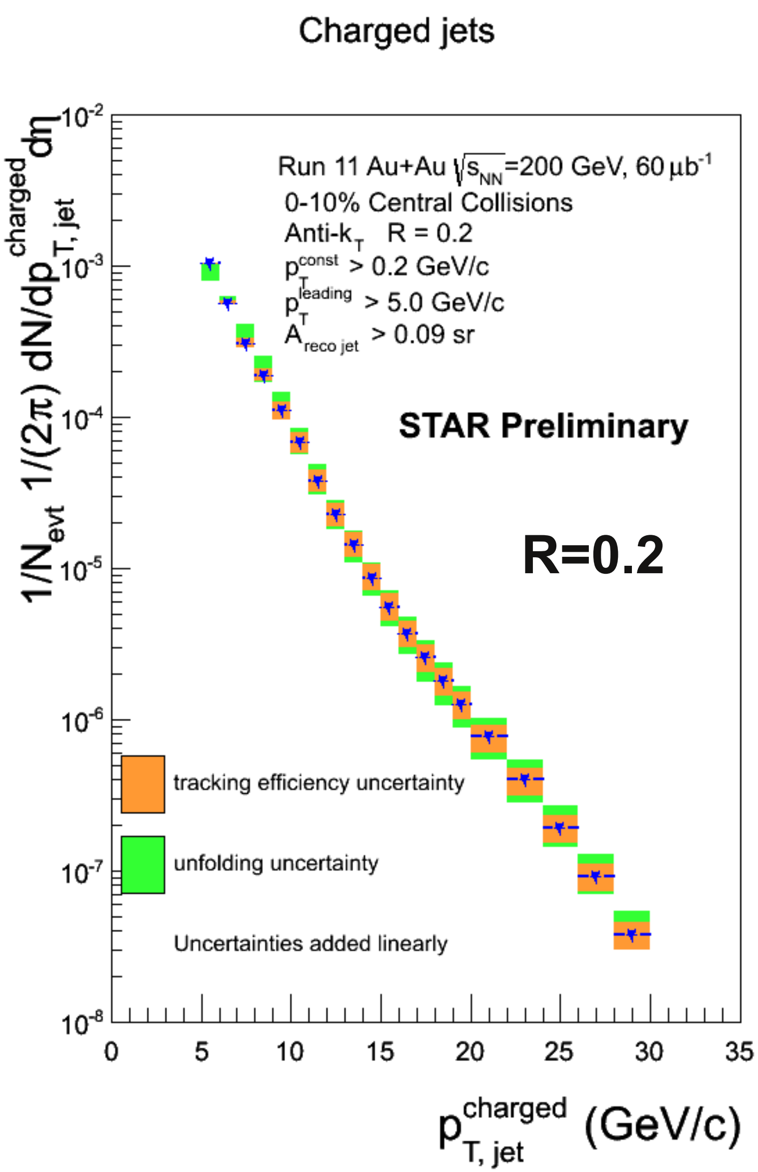


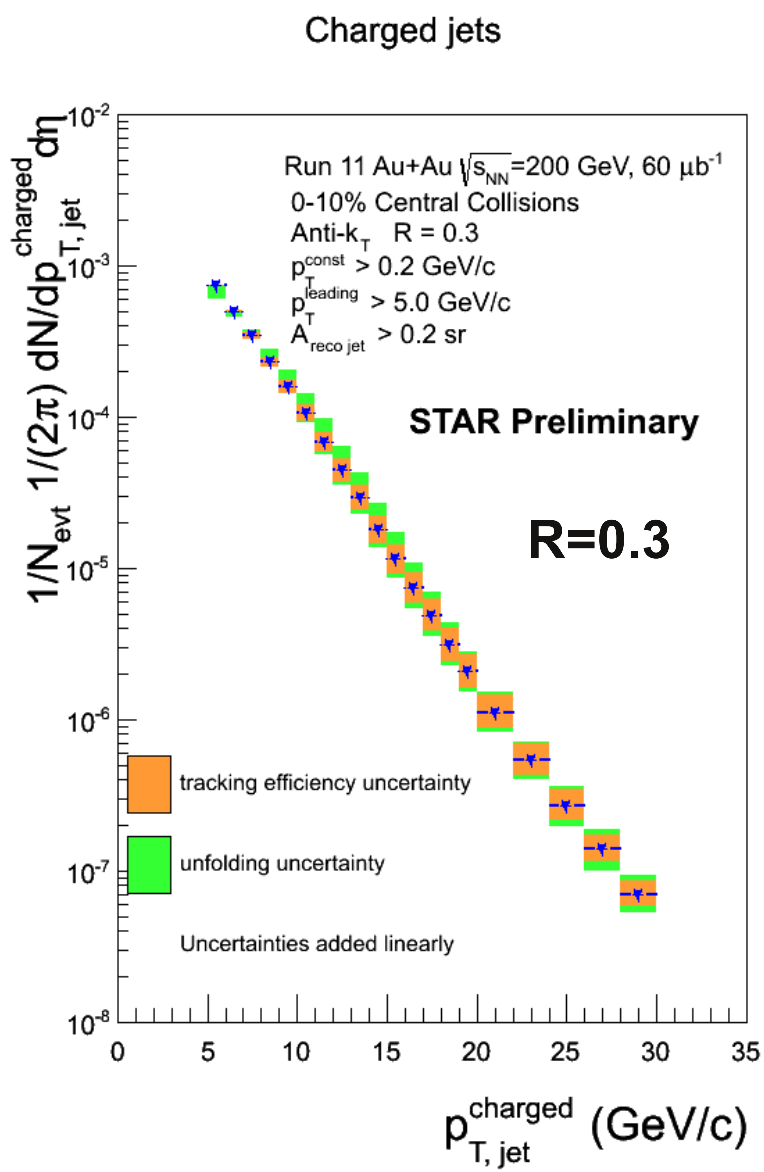
Overall response matrix:



Corrected Spectra

$p_T^{leading}$>5GeV/c

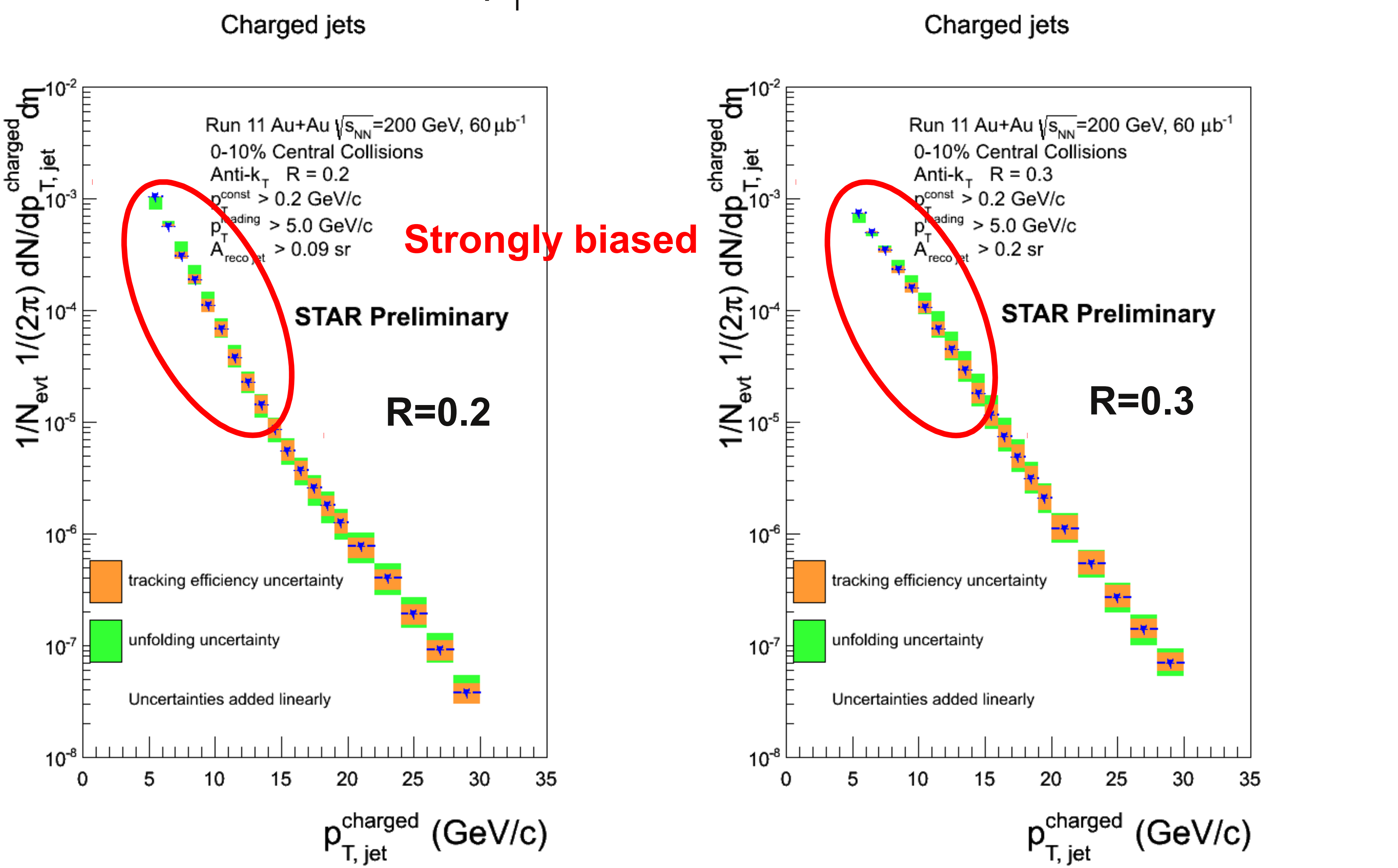




Jet energy scale resolution: ~5% (due to tracking efficiency uncertainty)

Corrected Spectra

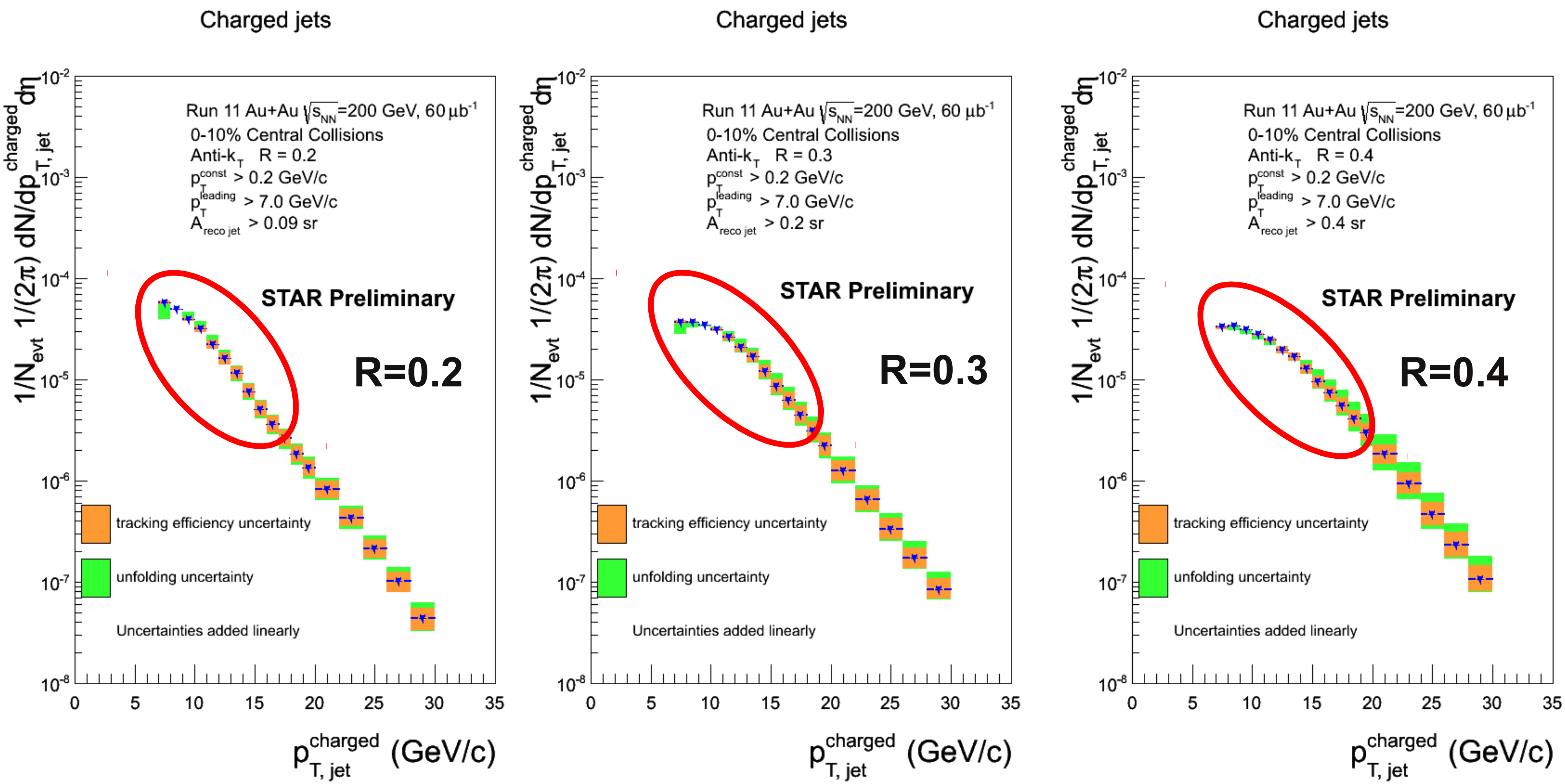
$p_T^{leading}$>5GeV/c



Jet energy scale resolution: ~5% (due to tracking efficiency uncertainty)

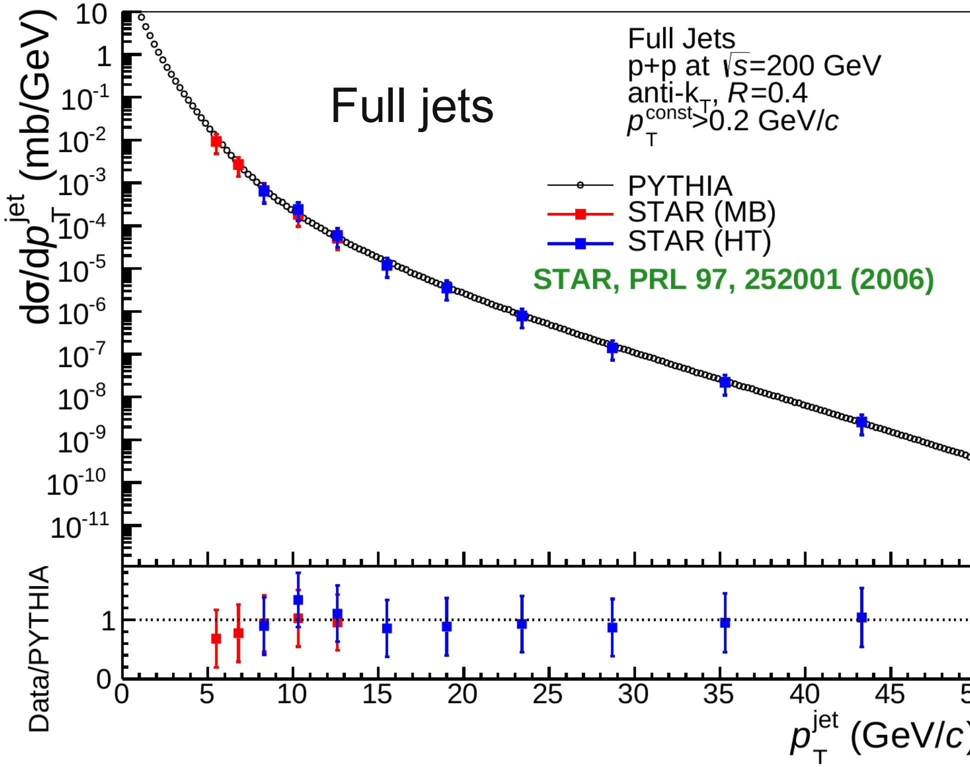
Corrected Spectra

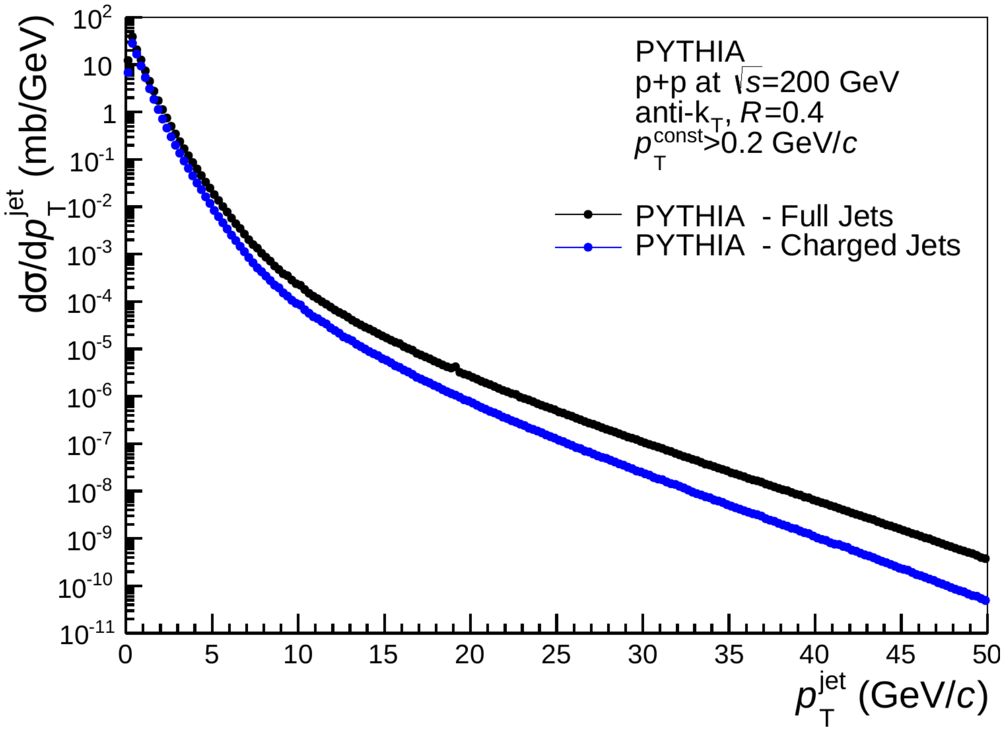
$p_T^{leading}$>7GeV/c



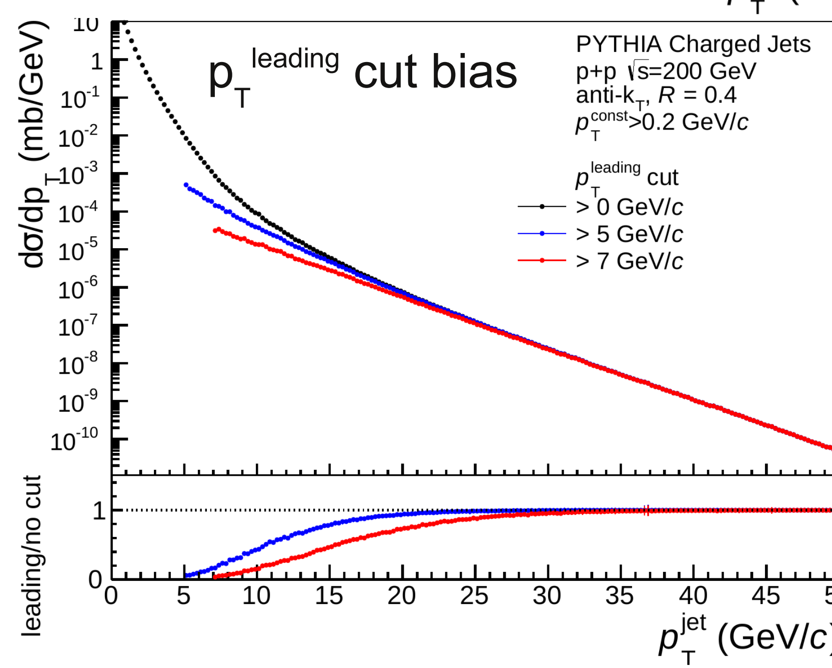
p+p reference

- Pythia 6.4 - Tune A used as p+p reference agrees well with STAR p+p data (for full jets)





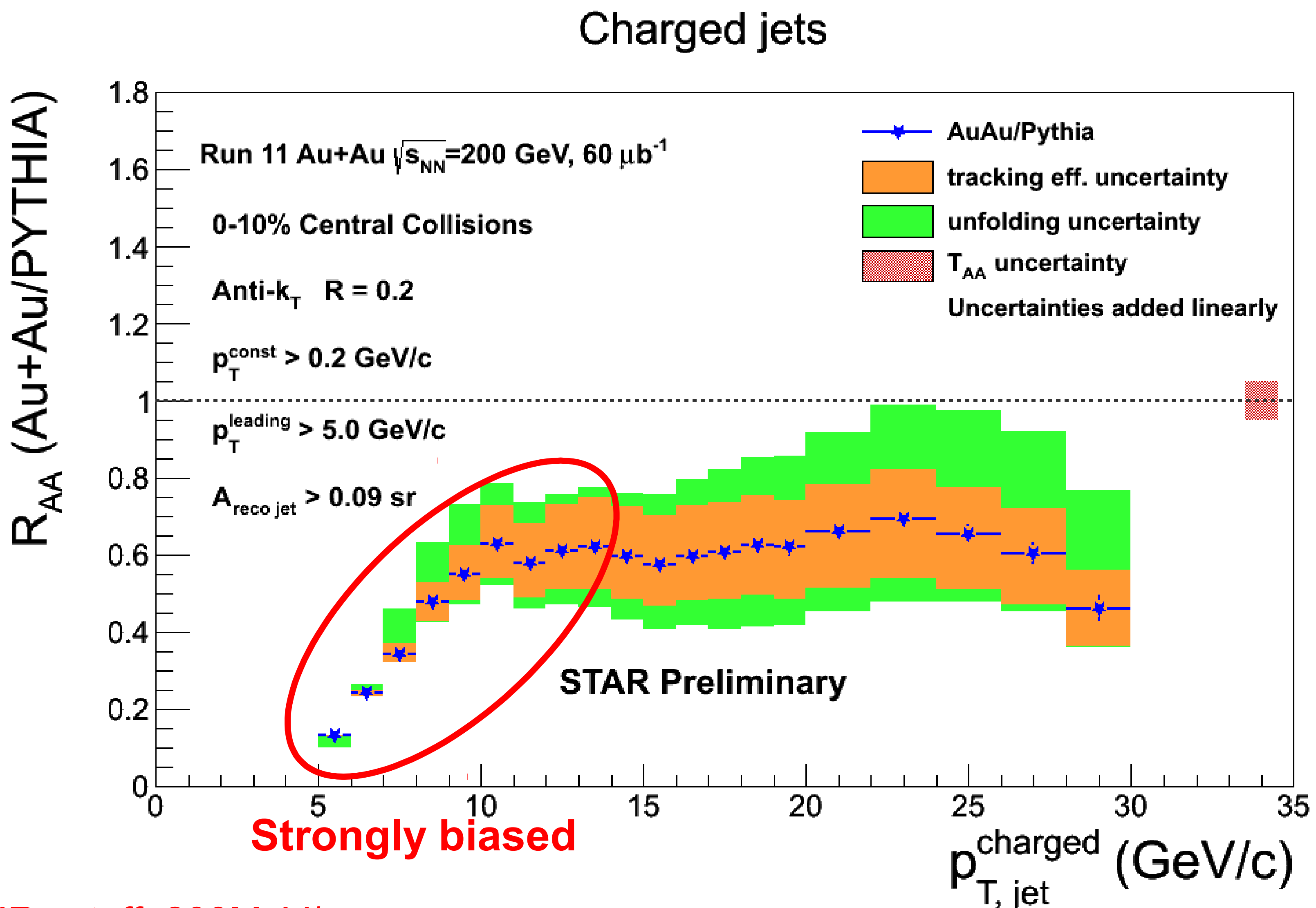
- Pythia: full jets → charged jets
  (accept only final particles which are charged)



- $p_T^{leading}$ bias – up to 3-4x $p_T^{leading}$ (R=0.2 – 0.4)

Jet R_{AA}

R=0.2, $p_T^{leading}$>5GeV/c

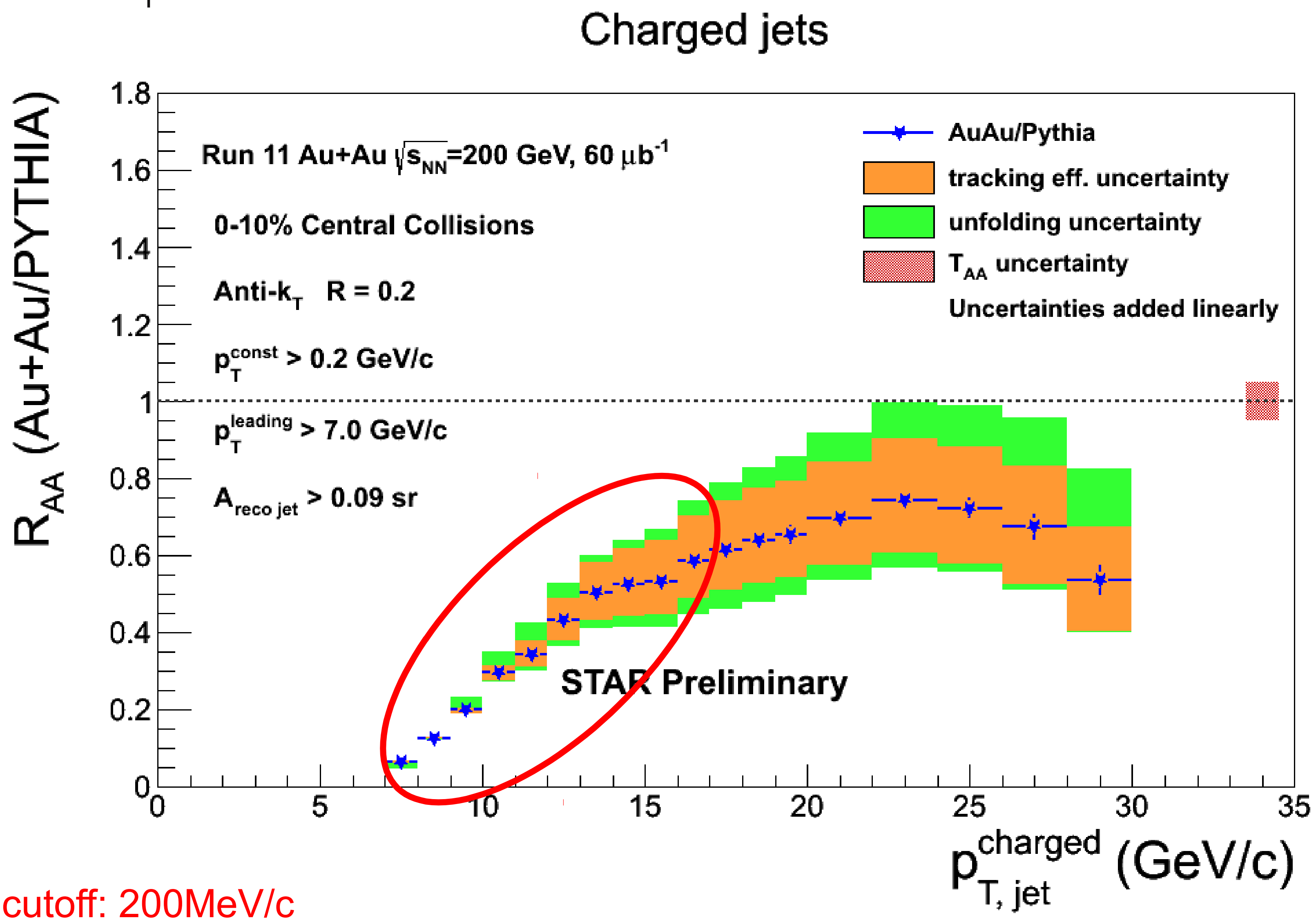


IR cutoff: 200MeV/c

Yield-weighted jet R_{AA} is consistent with inclusive hadron R_{AA} at pT~5 GeV

Jet R_{AA}

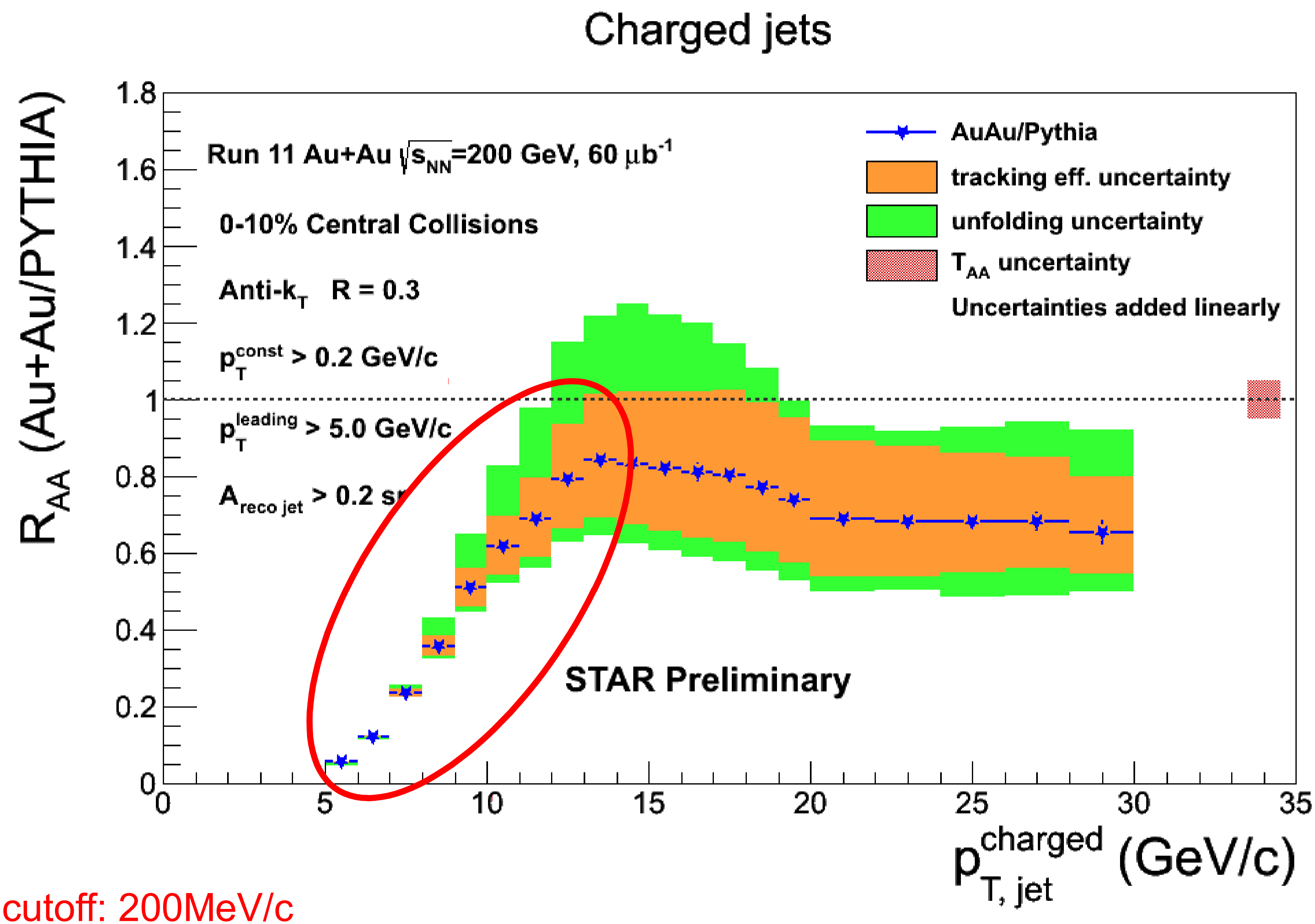
R=0.2, $p_T^{leading}$>7GeV/c



IR cutoff: 200MeV/c

Jet R_{AA}

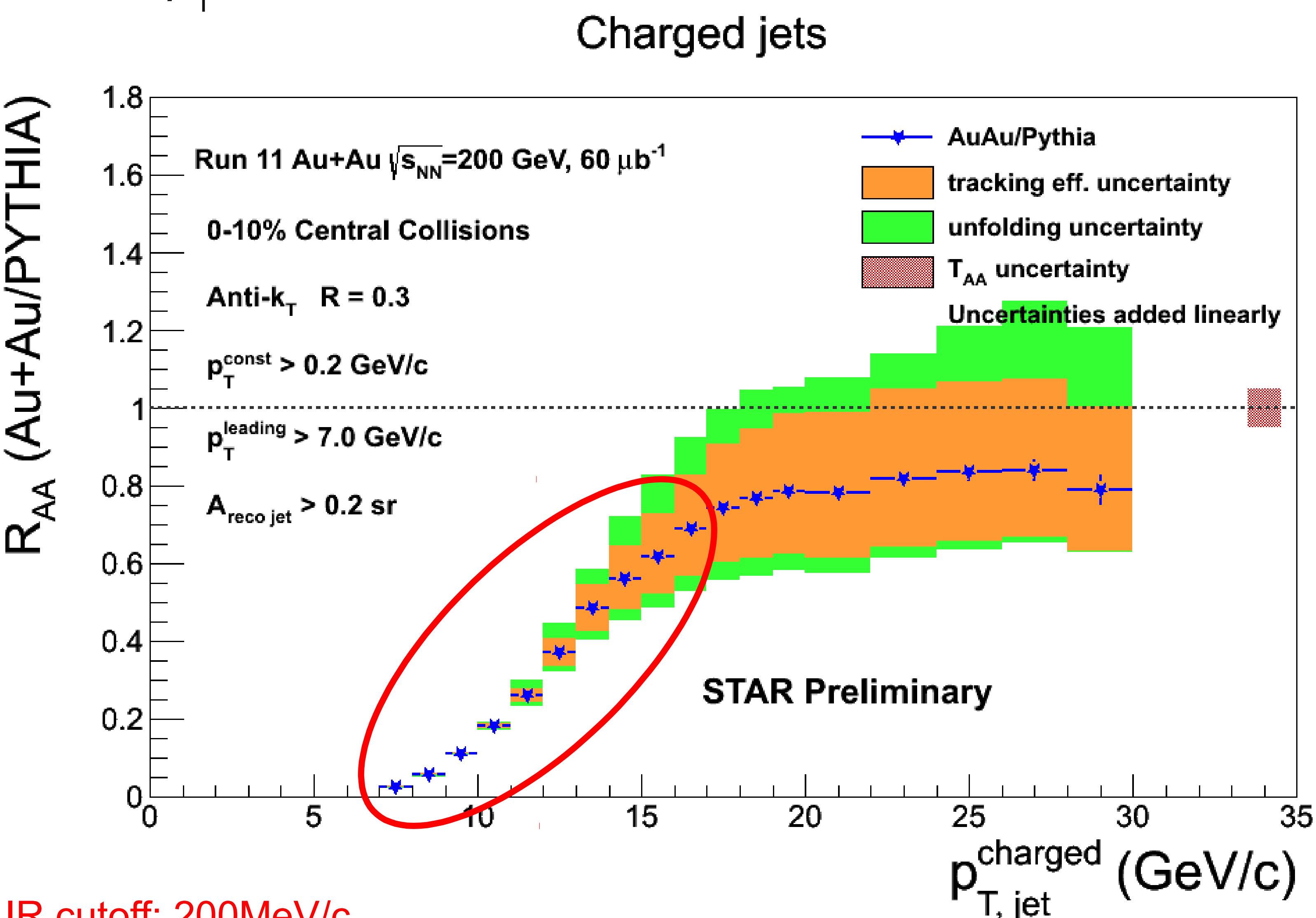
R=0.3, $p_T^{leading}$>5GeV/c



IR cutoff: 200MeV/c

Jet R_{AA}

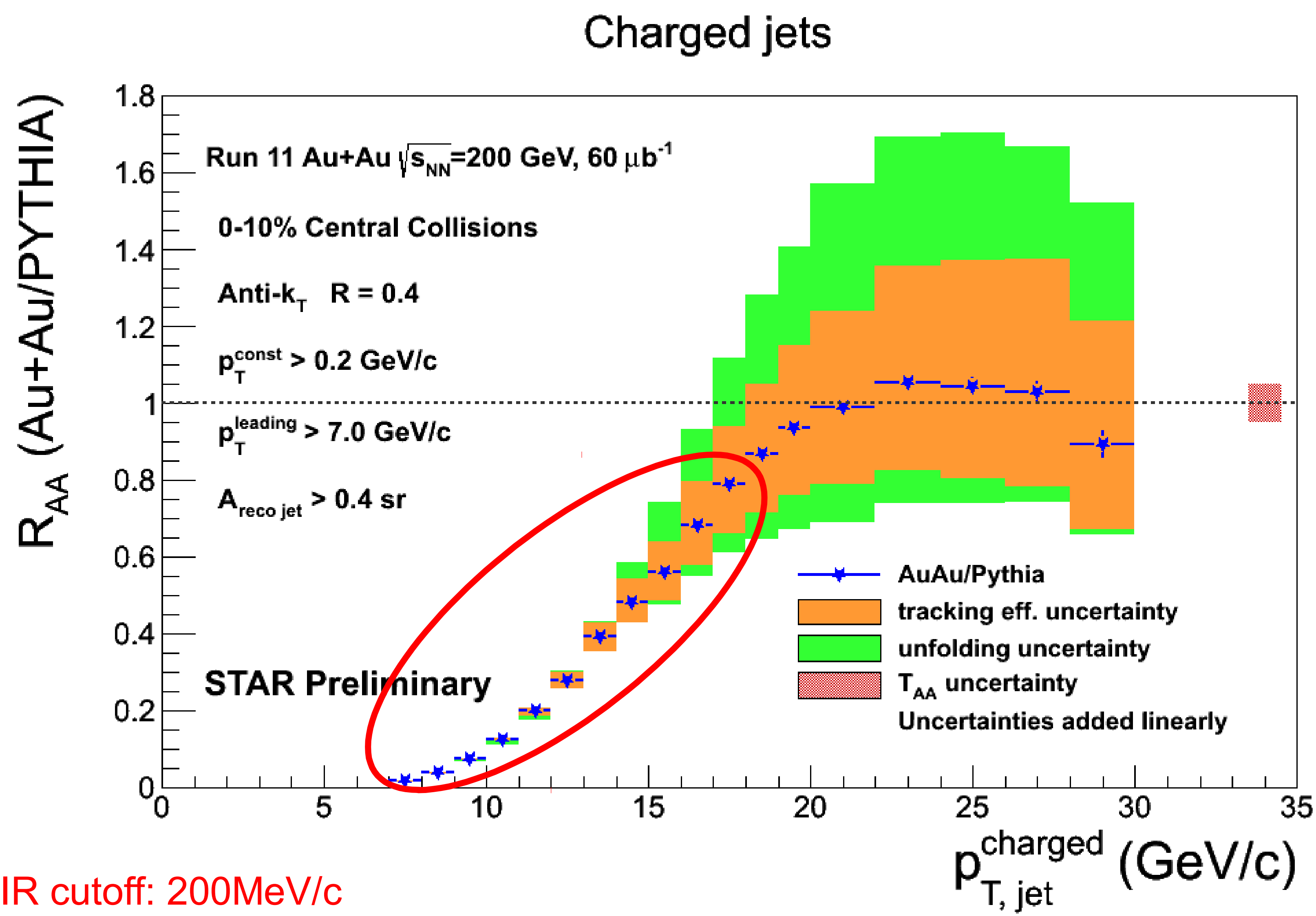
R=0.3, $p_T^{leading}$>7GeV/c



IR cutoff: 200MeV/c

Jet R_{AA}

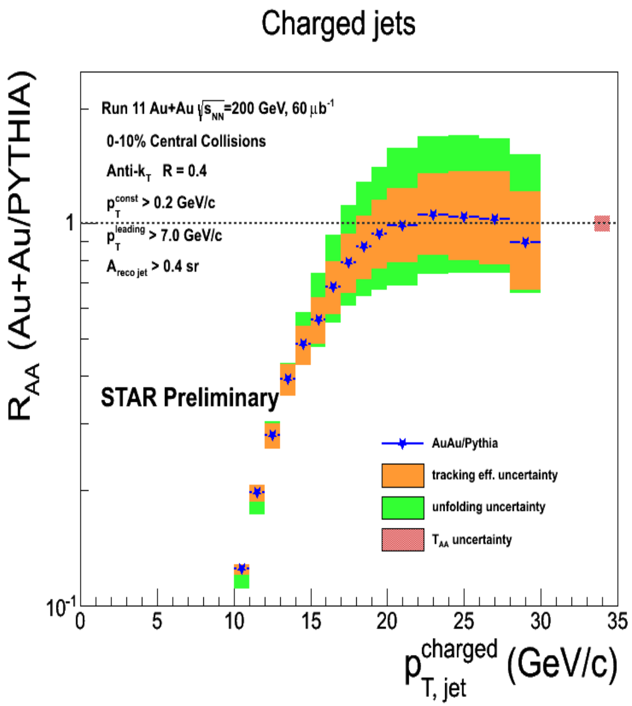
R=0.4, $p_T^{leading}$>7GeV/c



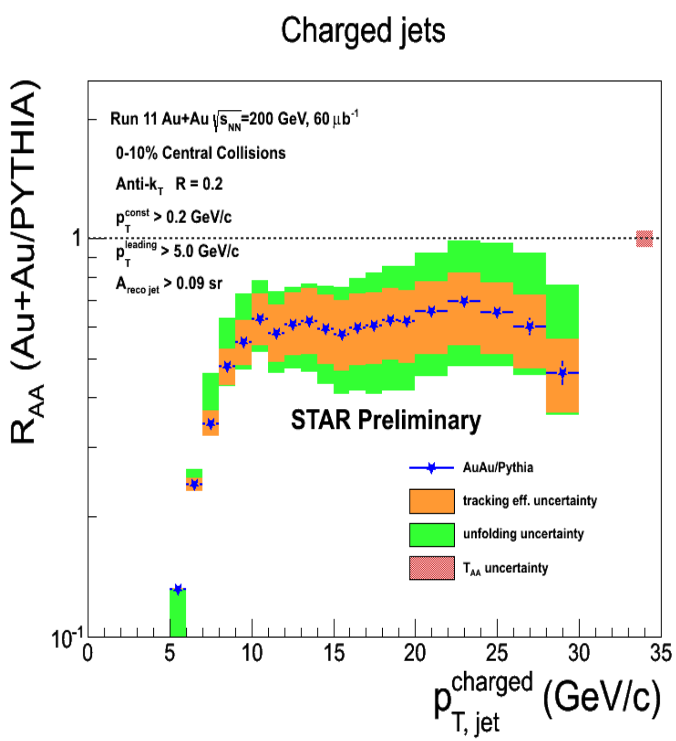
IR cutoff: 200MeV/c

Comparison of old and new STAR results

R=0.4

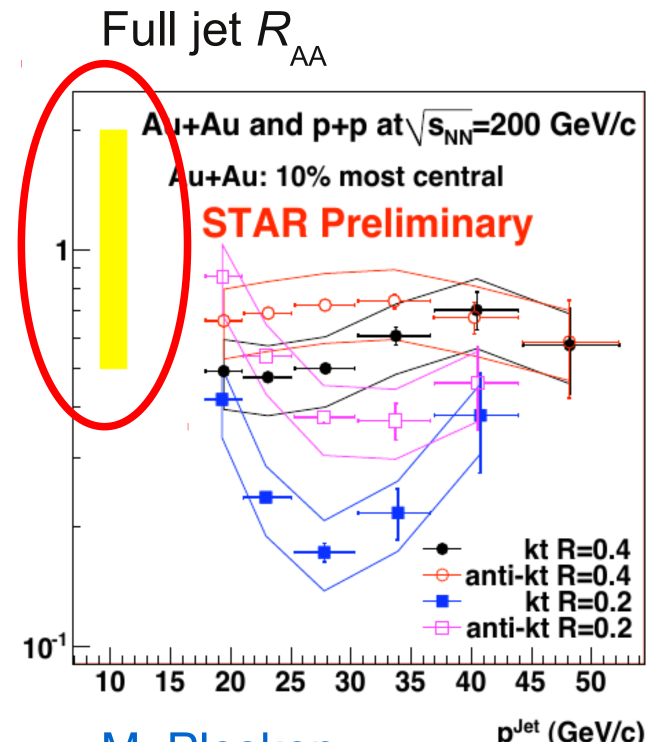


R=0.2



QM '09 results

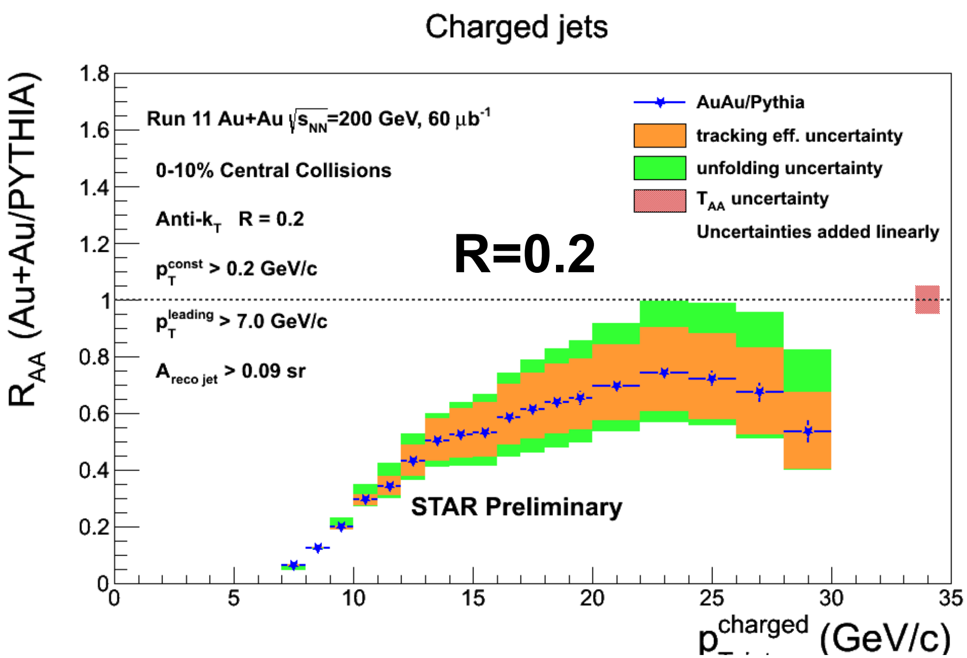
Full jet R_{AA}

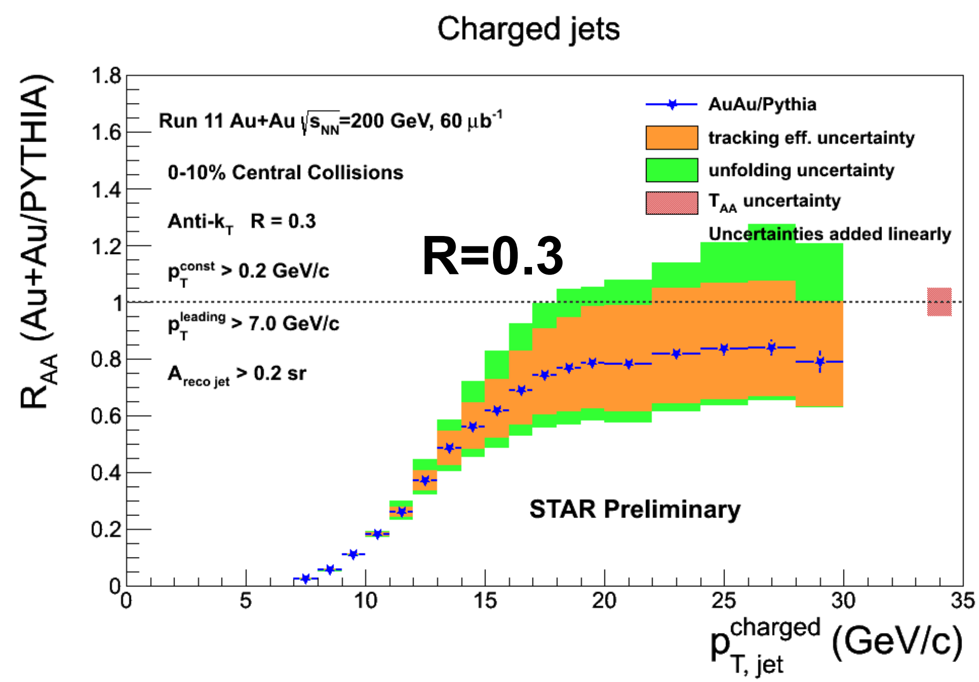


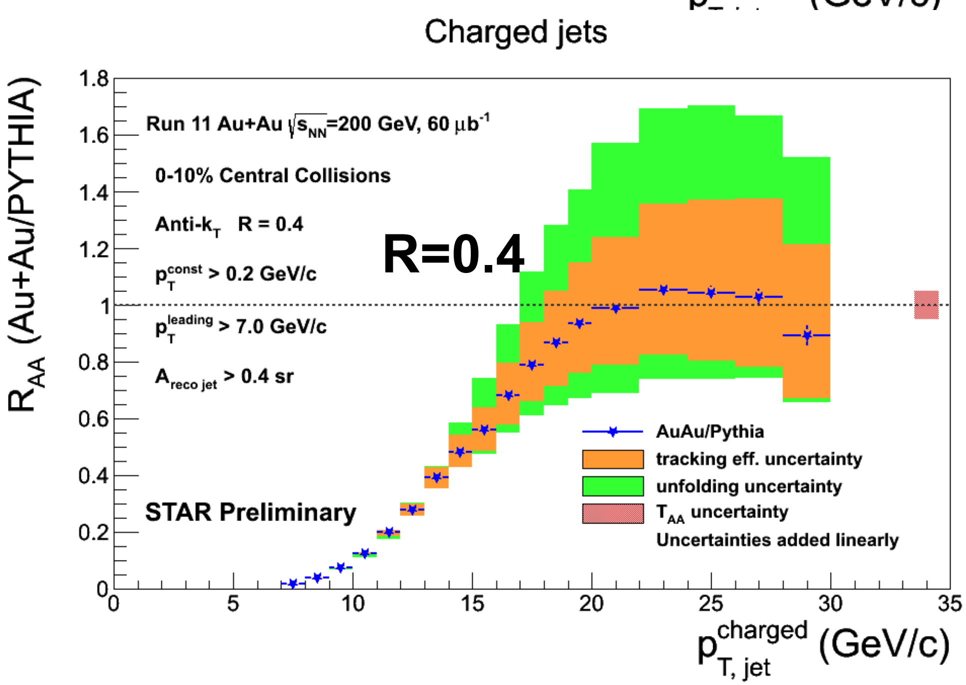
M. Ploskon, Nucl.Phys.A830:255c-258c, 2009

- Results are consistent
- Old results – large systematic uncertainty on normalization
- New methodology – better understood systematics

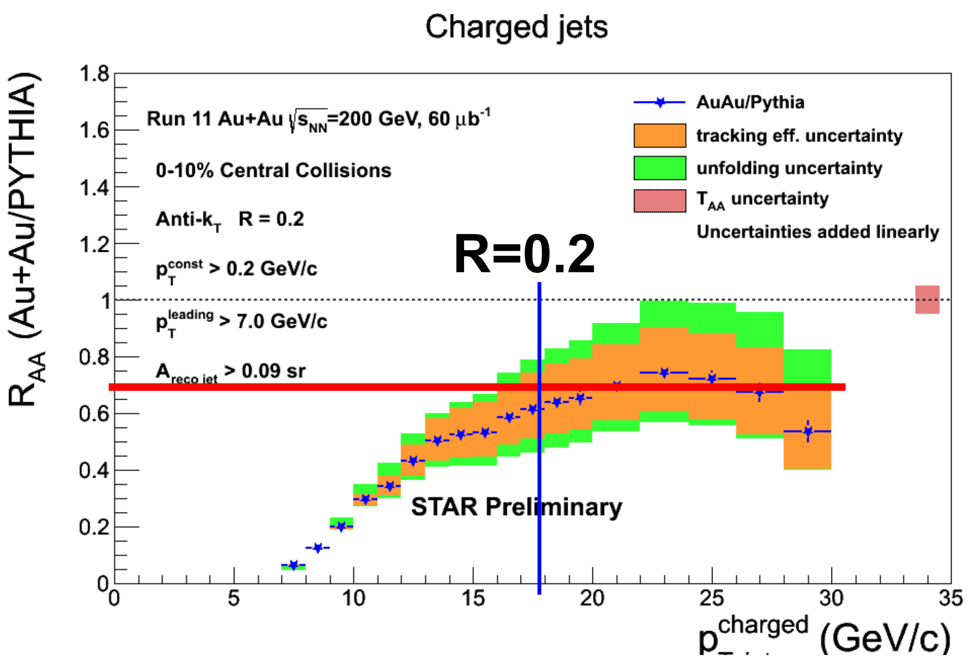
Jet R_{AA} for different R

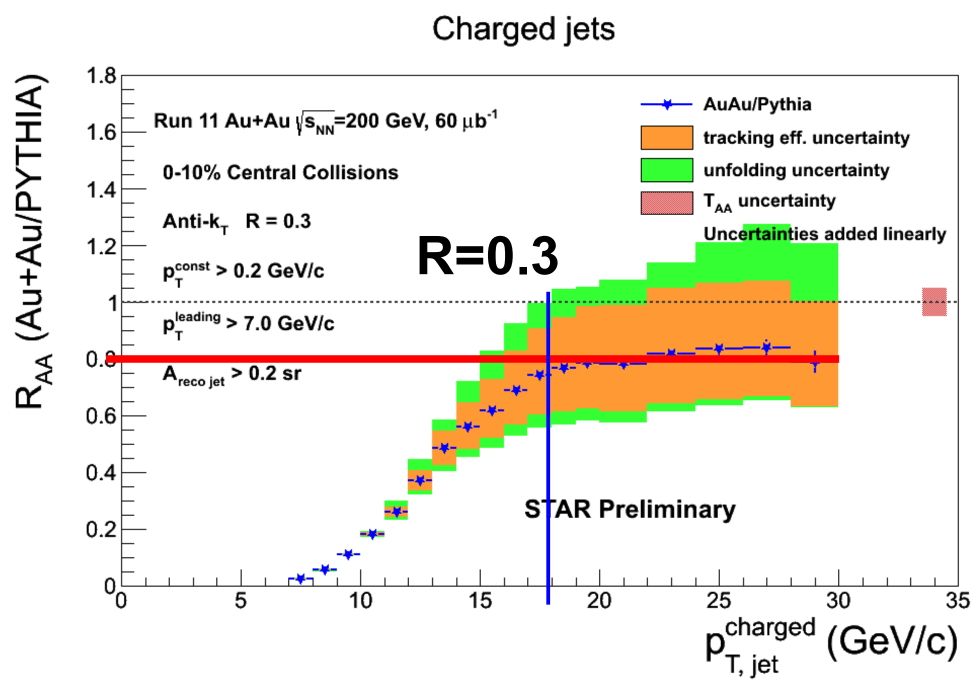


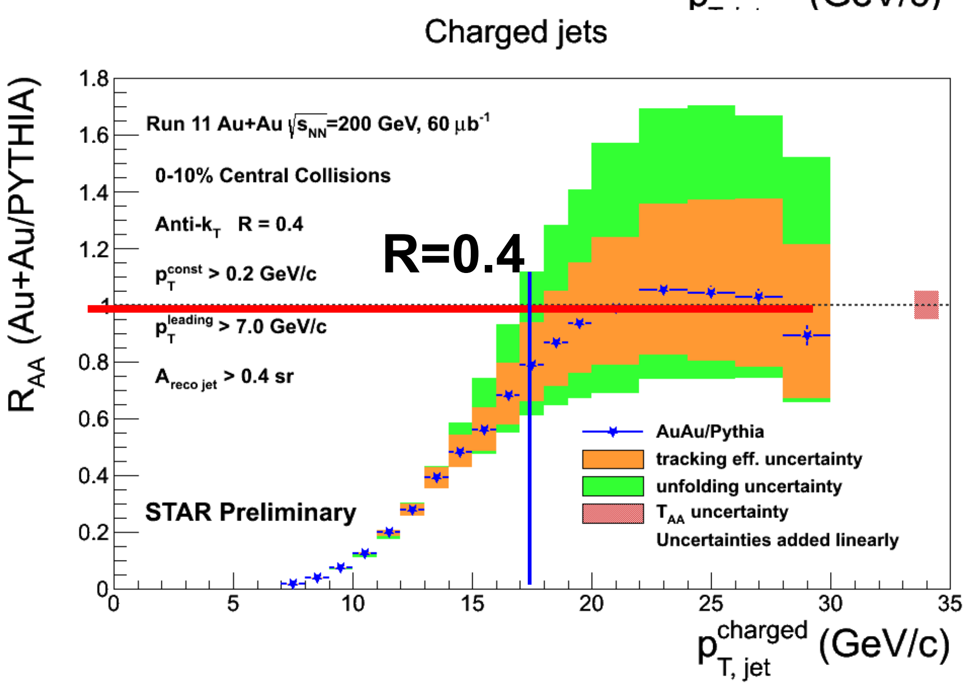




Jet R_{AA} for different R



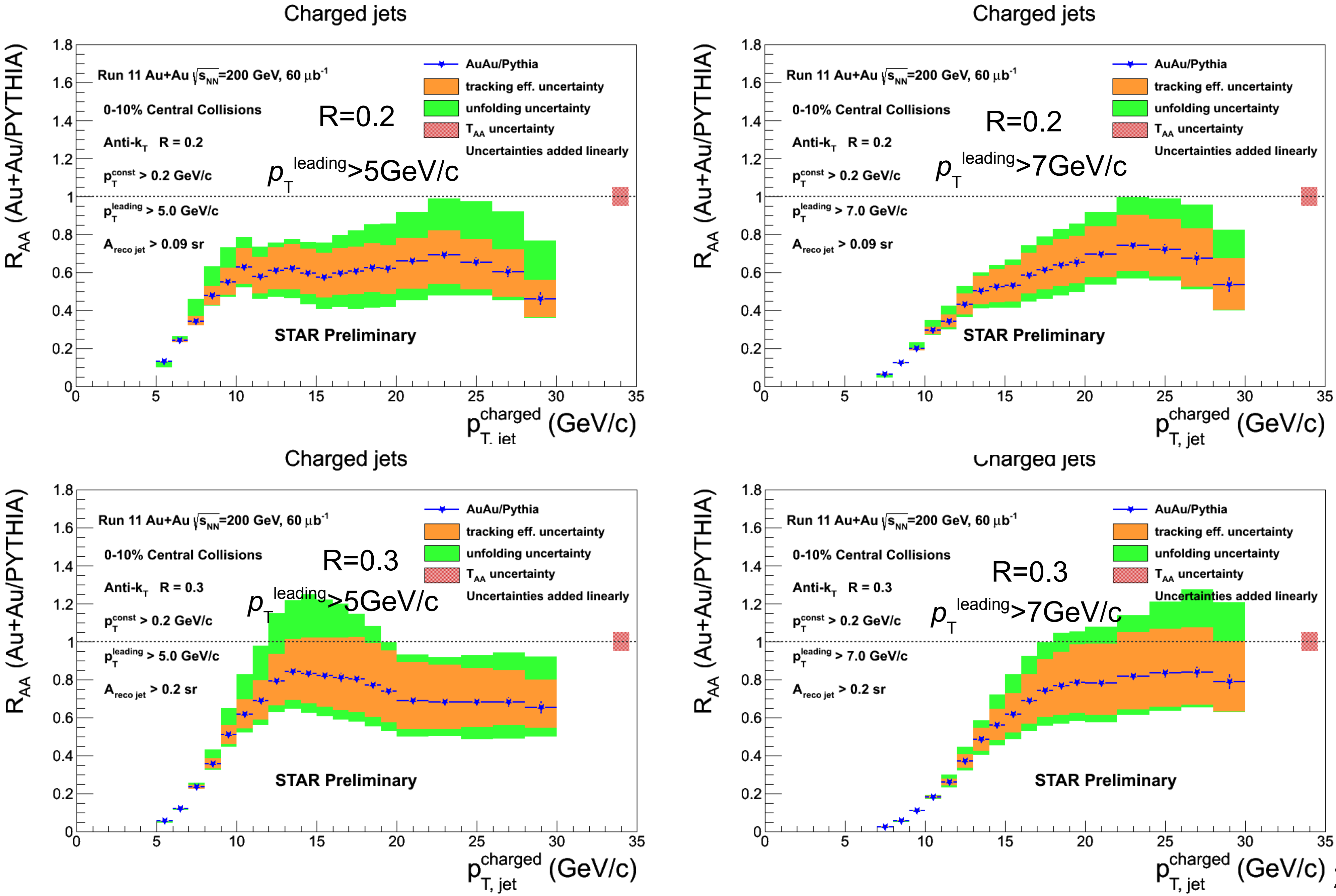




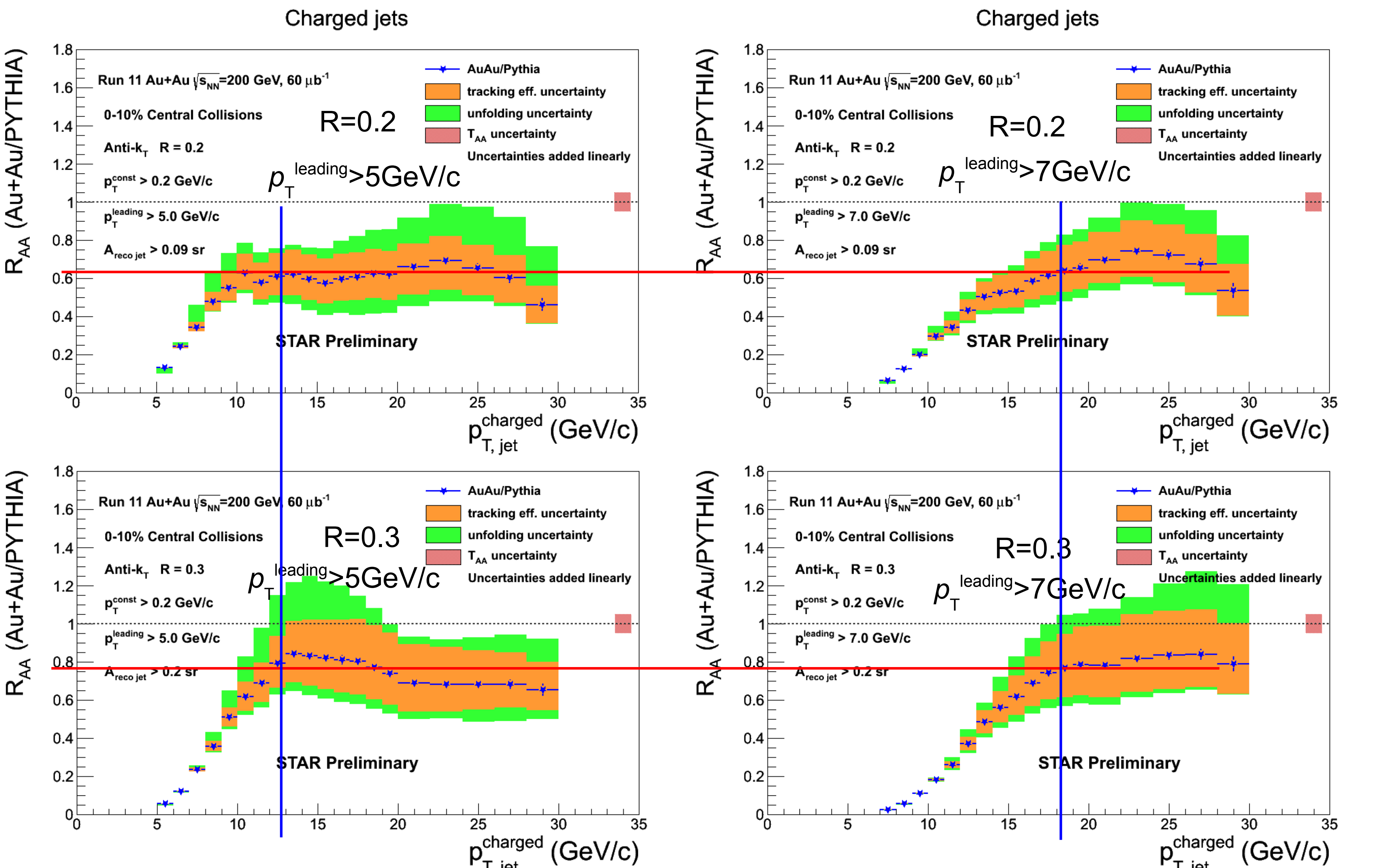
- Growth in R_{AA} central value with rising *R?*
- Uncertainties too large for definitive statement

- To do: Ratios of distributions (correlated uncertainties cancel)

Jet R_{AA} for different $p_T^{leading}$ cut



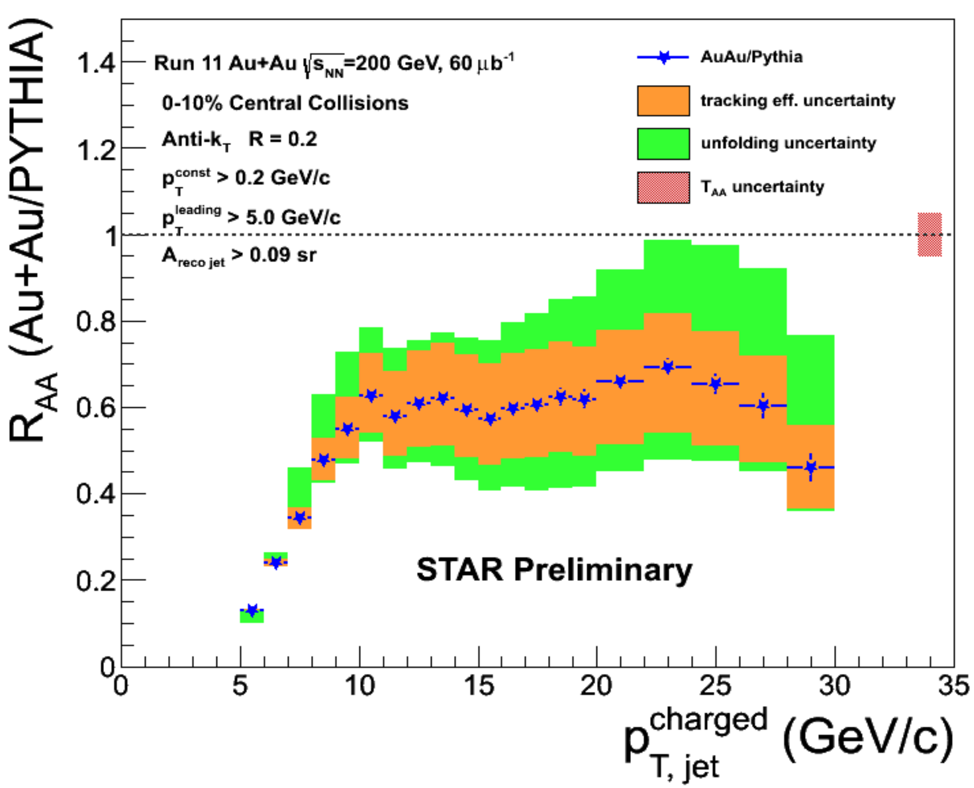
Jet R_{AA} for different $p_T^{leading}$ cut



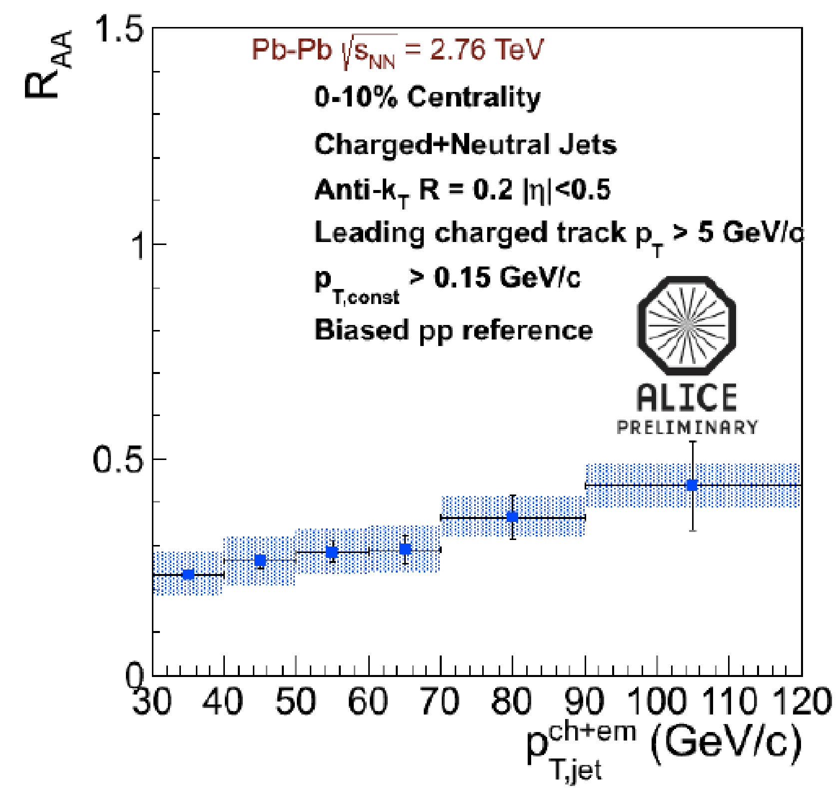
central value of R_{AA} approximately same for both values of $p_T^{leading}$ cut

Comparison with ALICE results

Charged jets

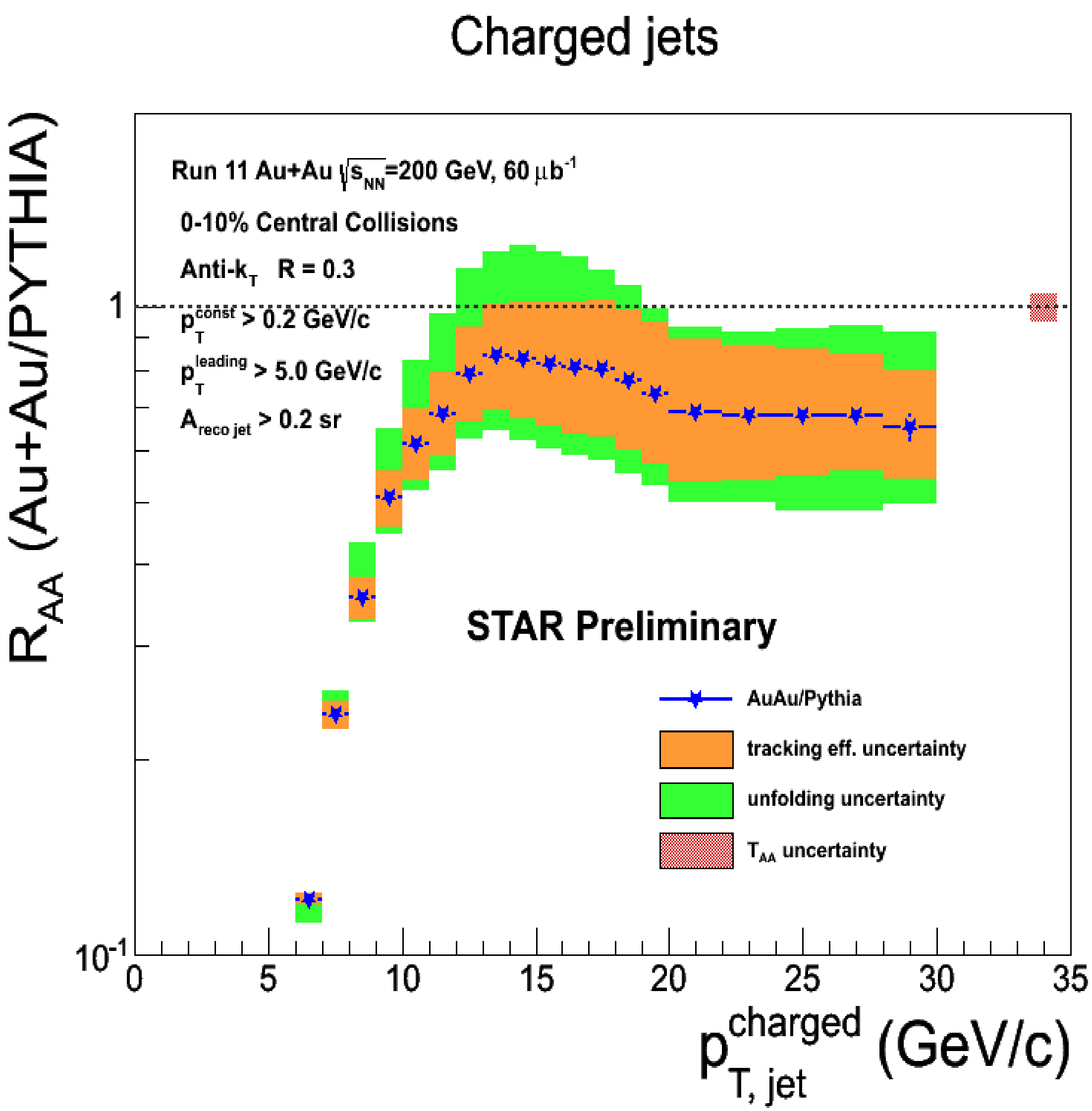


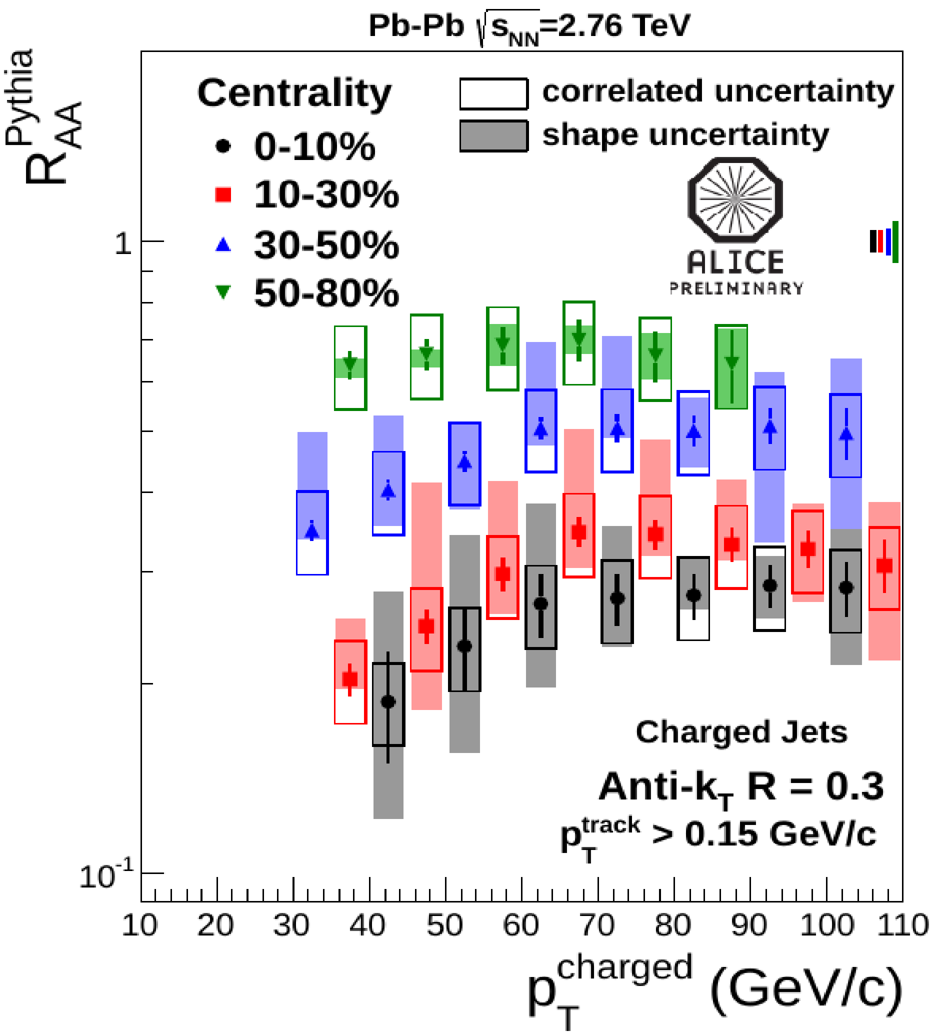
Full jets, biased p+p reference



[ALICE: arXiv:1304.5945]

Comparison with ALICE results





- R_{AA} at RHIC appears to be larger than at the LHC

M. Verweij (ALICE)
NPA 904-905 (2013) 1015c

Conclusions

New analysis of inclusive charged jet R_{AA} in central Au+Au collisions at $\sqrt{s}$ = 200GeV, utilizing the high statistics and high quality Run11 data (so far only 15% of total int. luminosity)

Dominant instrumental uncertainty is tracking efficiency (JES uncert. ~ 5%)

Charged jet R_{AA}:

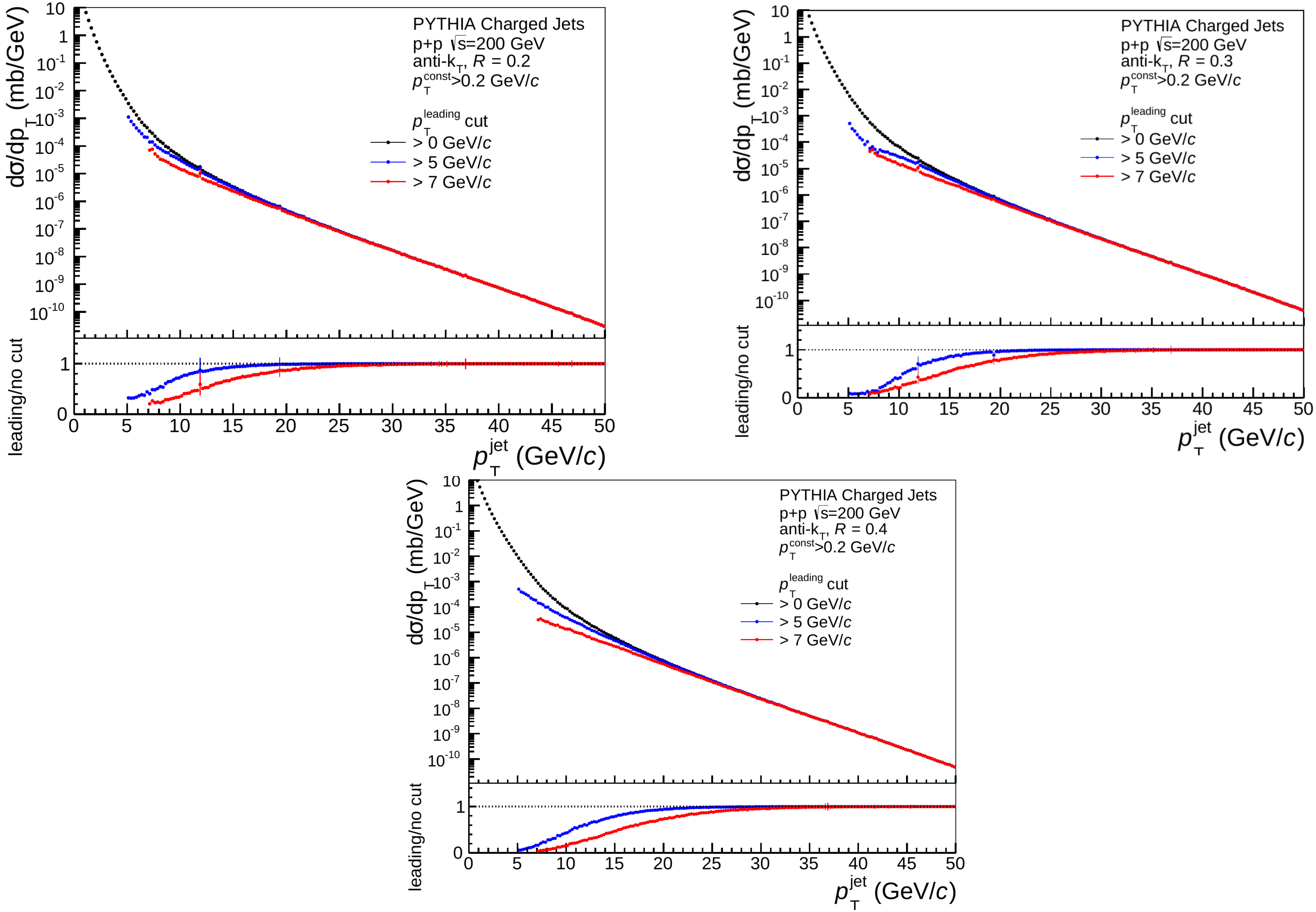
- $R_{AA} \gtrsim 0.5$
- R_{AA} appears to be larger at RHIC (25-30GeV/c) than at the LHC (30-40GeV/c)
- growth in central value with increasing *R?*
- (need to assess correlated and uncorrelated uncert. for definitive statement)

Next steps:

- Cross check with other unfolding methods (Singular Value Decomposition)
- Full jets - incorporating BEMC, use triggered data

BACKUP SLIDES

$p_T^{leading}$ cut bias



Tracking Efficiency Correction

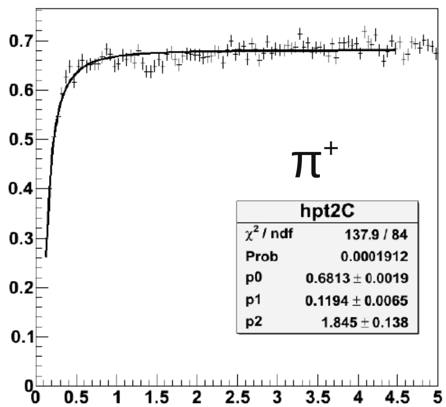
charged hadron reconstruction efficiency:

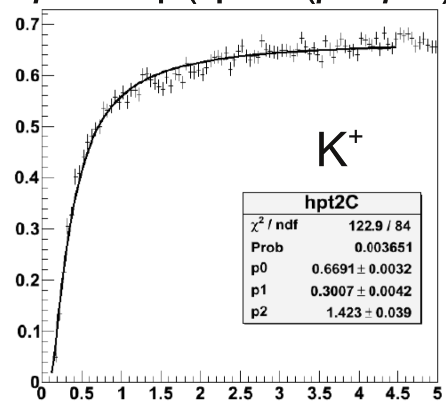
- from embedding of protons, pions and kaons (Run11)

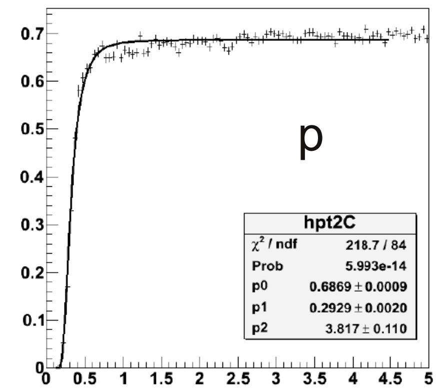
$$eff_{hadron} = \frac{\sum_i sp_i \, eff_i}{\sum_j sp_j}$$

where sp_i is the efficiency corrected single particle spectra and eff_i is the single particle efficiency

$eff_i = p0*\exp(-\mathrm{pow}(p1/pT), p2)$

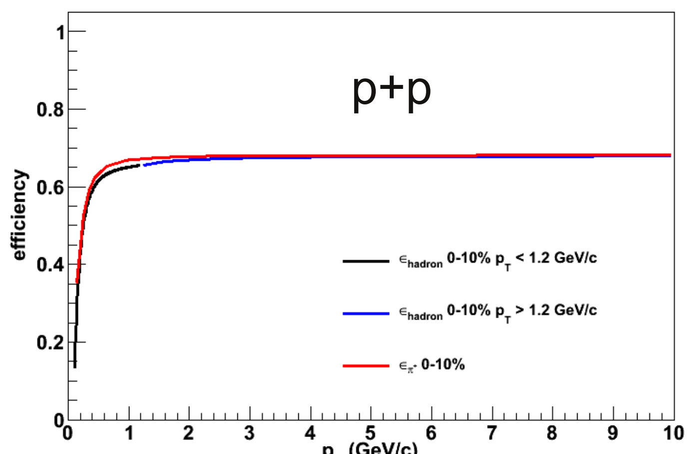


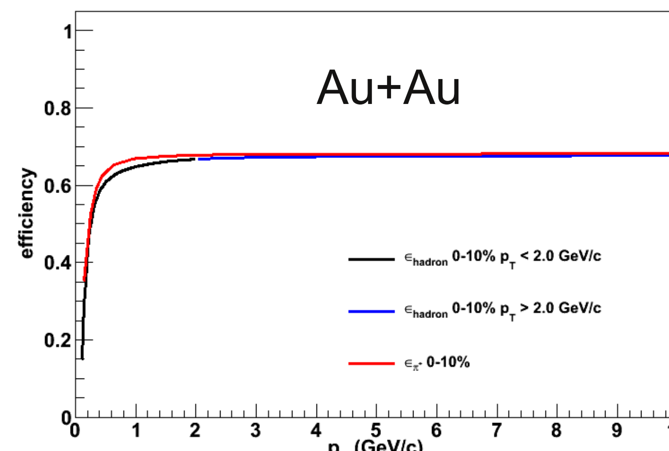




pion/proton/kaon ratios:

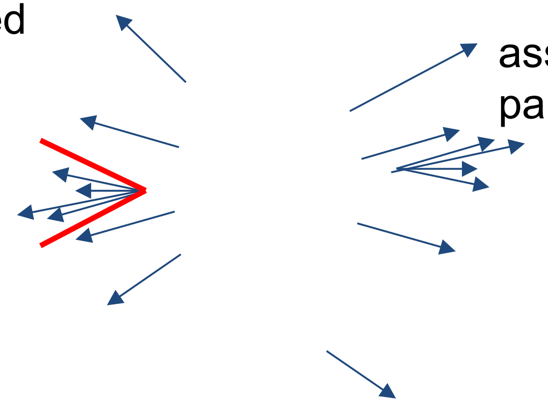
- p+p
- Au+Au



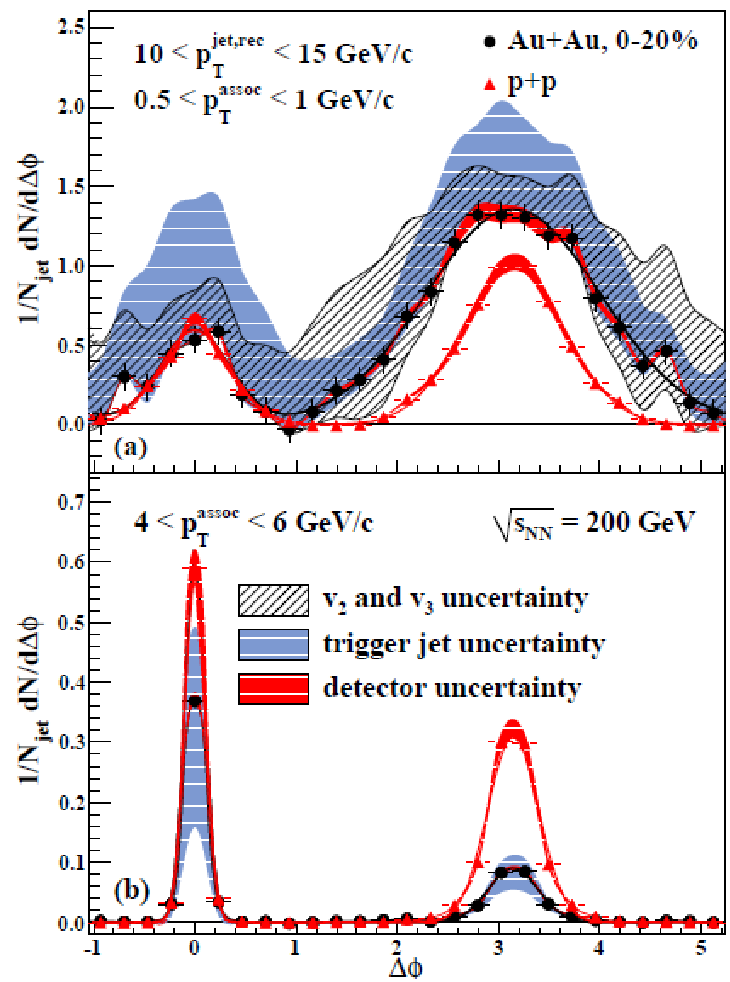


- do unfolding for both scenarios separately and compare results
- both eff. are relatively similar => main source of error will come from embedding uncertainties

Jet-hadron correlations



larger kinematic reach compared to di-hadron correlations

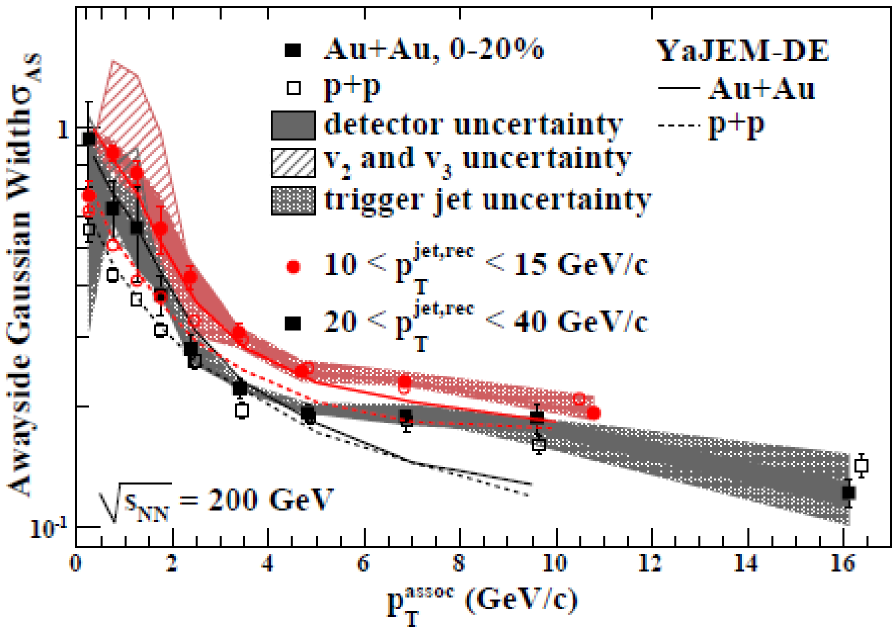


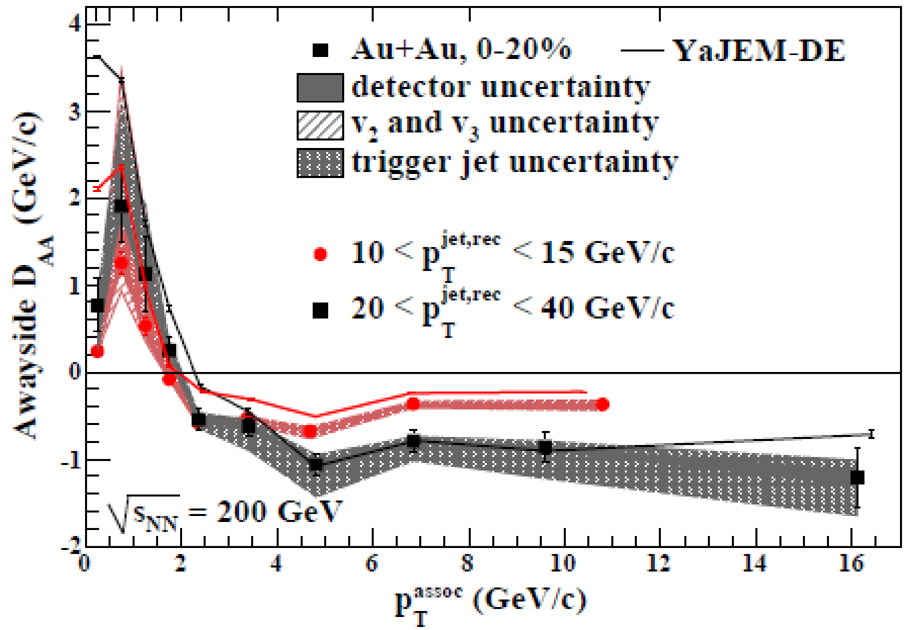
- jet reconstruction: anti-k_T algorithm (R = 0.4)
  with a trigger tower in BEMC with E_T > 6 GeV
  and constituent tracks/towers with $p_T(E_T)$>2 GeV
  to reduce background fluctuations
  (NOTE: "a highly biased jet population")

- recoil (away-side) jet fragmentation is unbiased

Quantifying properties of jet-hadron correlations

STAR, arXiv: 1302.6184 ; YaJEM-DE, T. Renk, PRC 87 (2013) 2, 024905





Away-side Gaussian width:

suggestive of medium induced broadening

BUT!

highly depends on *v*3 → further information on *v*2jet and *v*3jet needed

Away-side energy balance:

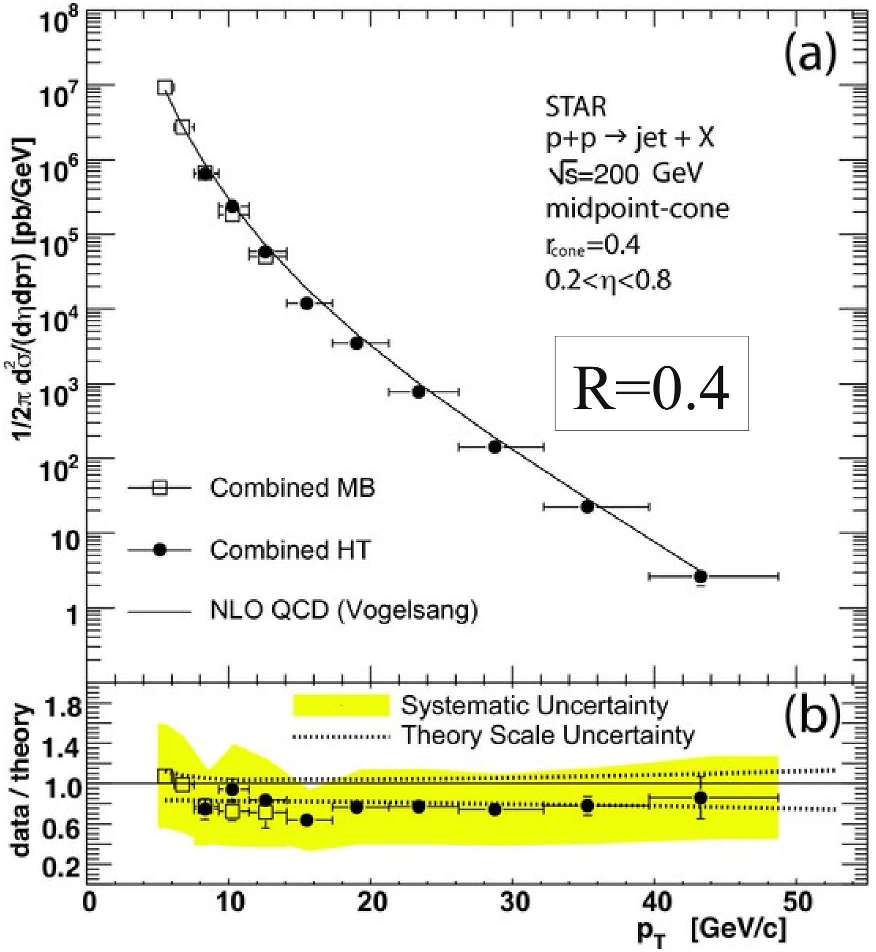
$$D_{AA}(p_T^{assoc}) = Y_{AuAu}(p_T^{assoc}) \cdot \langle p_T^{assoc} \rangle_{AuAu} - Y_{pp}(p_T^{assoc}) \cdot \langle p_T^{assoc} \rangle_{pp}$$

Suppression of high-pT associated hadron yield ~ balanced by enhancement at low-pT.

The redistribution of energy quantitatively consistent with YaJEM-DE model of in-medium shower modification.

Estimate of jet yields in Run11 Au+Au data

p+p jet spectrum (from Run 3 + 4)



[STAR, Phys. Rev. Lett. 97 (2006) 252001]

Run 11 Au+Au integrated luminosity:
~ 2.8nb^{-1}

Estimate jet production yield
(i.e. R_{AA}=1):

$$\sim T_{AA} \cdot \frac{d\sigma_{pp}^{jet}}{dp_T d\eta}$$

10% central Au+Au in Run11:
We expect ~2K jets with p_T>50 GeV/c
(full jets with BEMC).

Our analysis:
charged-only jets, no trigger, 40 million minimum bias events (~ 60μb^{-1})

R_{AA}

$$R_{AA} = \frac{1/N_{events} \dfrac{dN_{AuAu}}{dp_T \, d\eta}}{T_{AA} \dfrac{d\sigma_{pp}}{dp_T \, d\eta}}$$

$$T_{AA} = \frac{\langle N_{bin} \rangle}{\sigma_{inelastic}} \simeq 22.2 \pm 1 \, mb^{-1}$$ for 0-10% Au+Au