Heavy Ion Workshop

Jet Reconstruction in Au+Au 200 GeV Collisions at STAR

Jan Rusňák

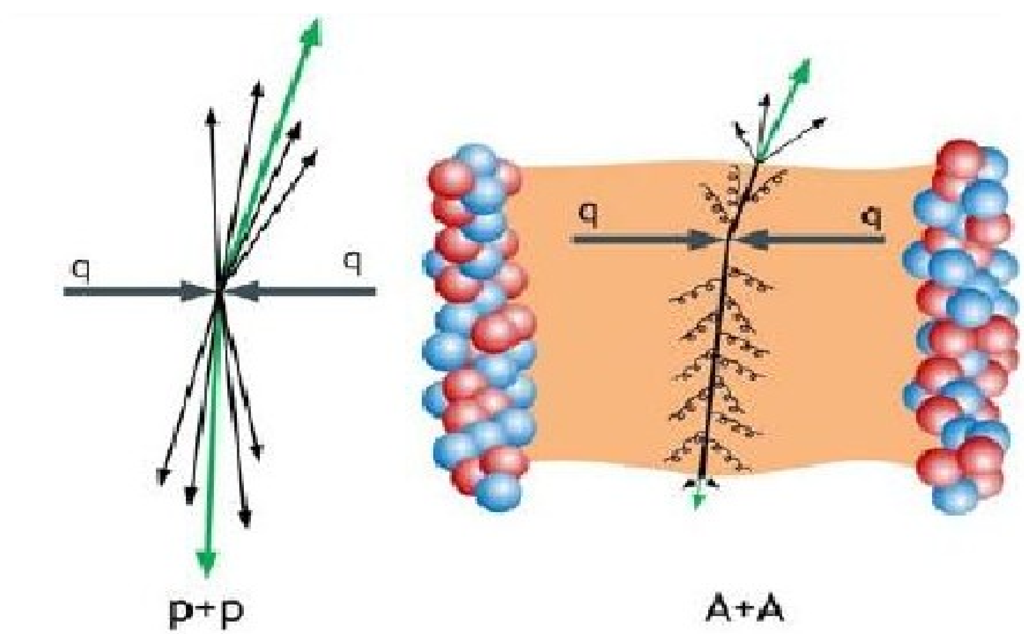
Nuclear Physics Institute, CAS

Motivation for Jet Studies

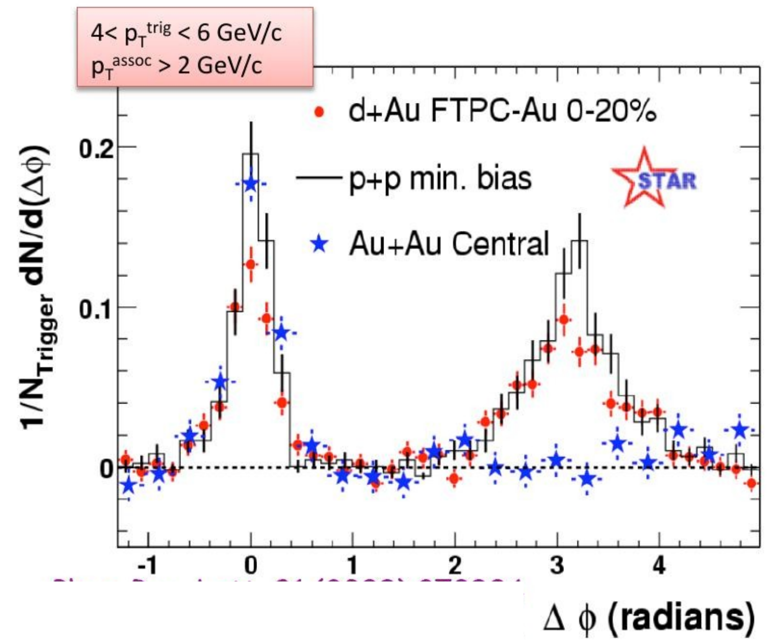
Jets: collimated sprays of hadrons created by fragmentation and hadronization of hard-scattered partons

Elementary collisions: fundamental test of pQCD

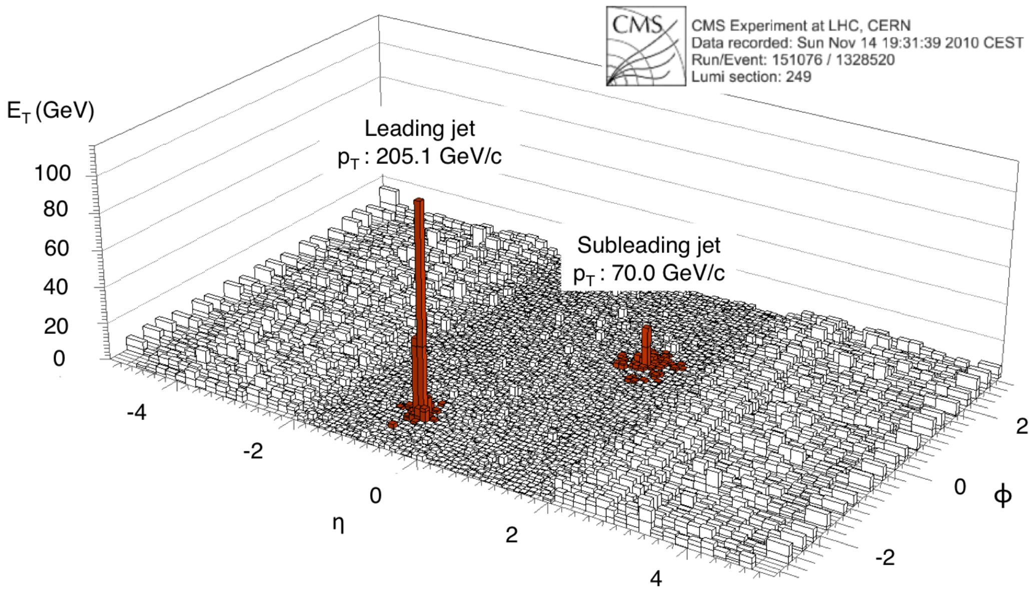
Heavy-ion collisions: energy loss mechanism in Quark Gluon Plasma (QGP)



Phys. Rev. Lett. 91 (2003) 072304



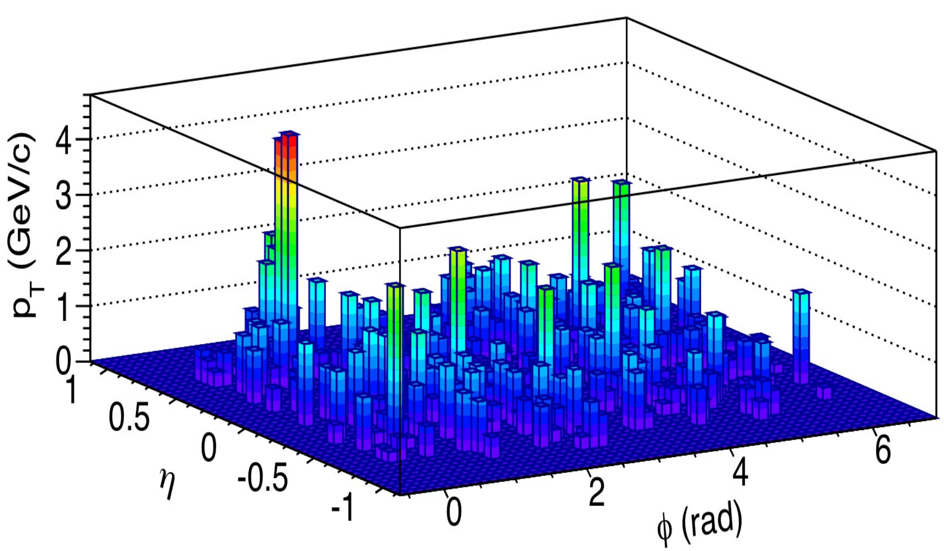
Jet Reconstruction in Heavy Ion Collisions



LHC:

- Jets dominate over the background

→ Clear jet identification (at high p_T)



RHIC:

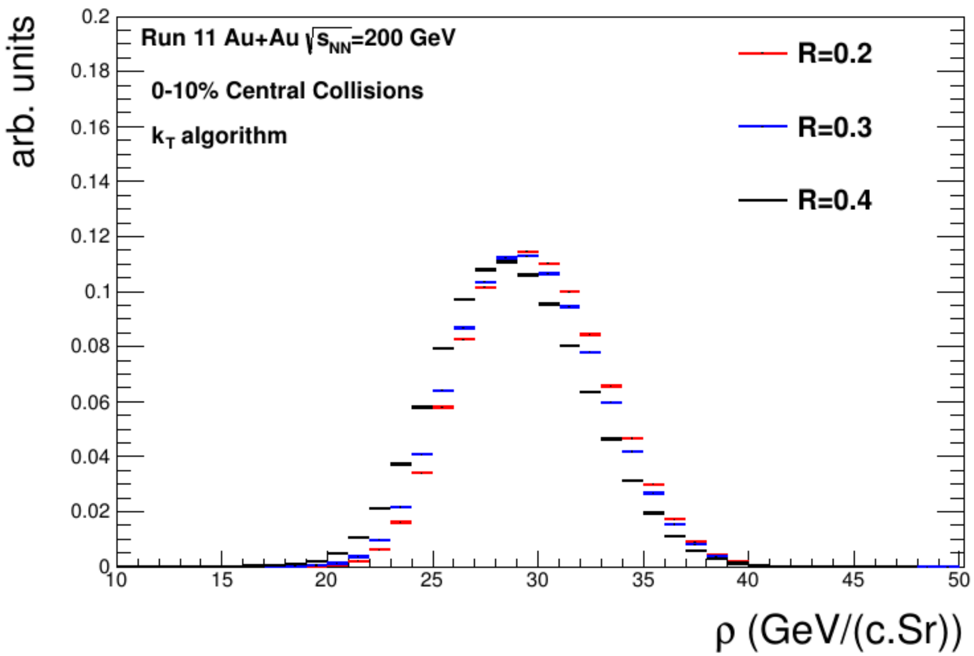
- **Background fluctuations comparable to signal** → Jet identification is extremely challenging task
- Signal identification on statistical basis

I) Inclusive Jet Reconstruction

- using FASTJET 3 [Cacciari, Salam, Soyez : Eur.Phys. J. **C72** (2012) 1896]
- jet reconstruction: anti-kT algorithm, different resolution parameters *R=0.2, 0.3, 0.4*
- correction for pedestal energy:

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

A_i ...jet area

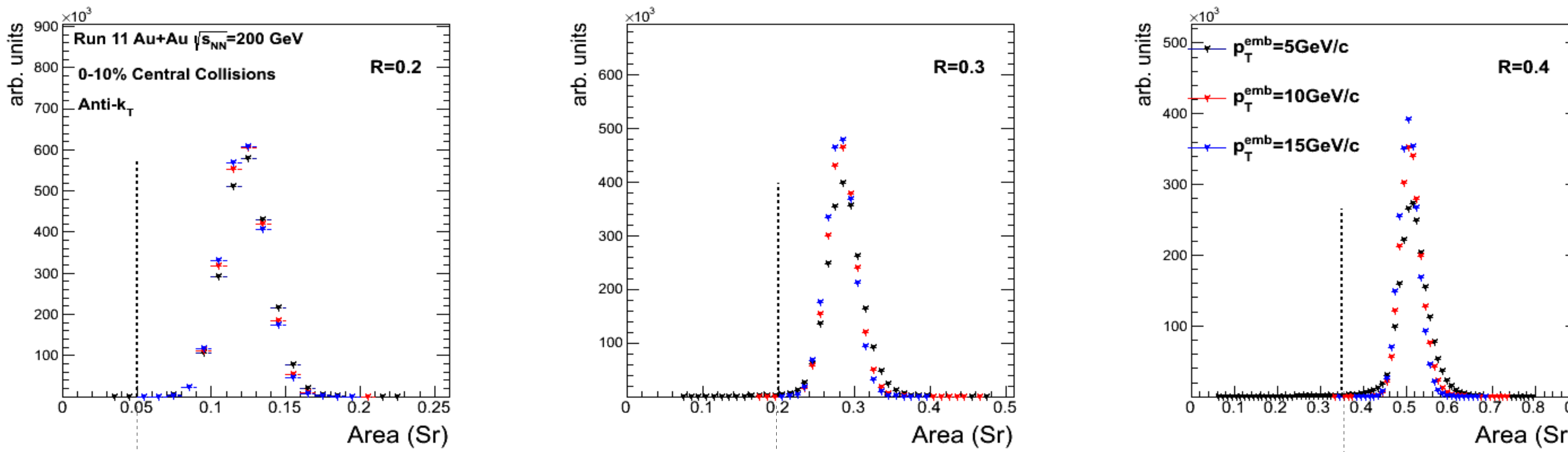


- transverse momentum after pedestal subtraction:

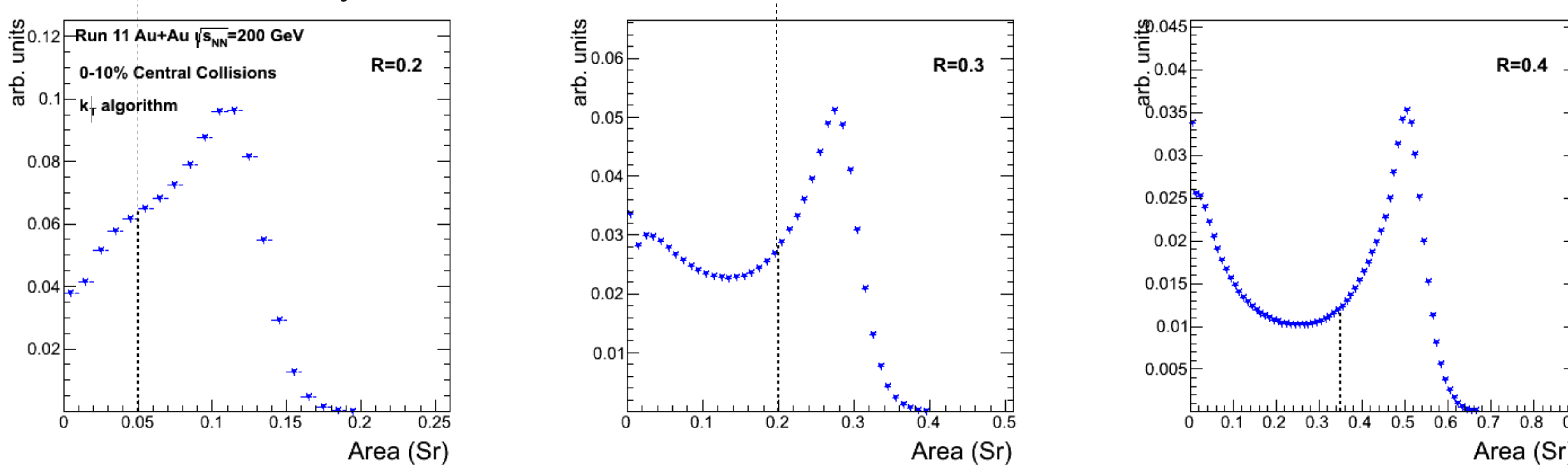
$$p_{T,reco} = p_T - A_{jet} \times \rho$$

Reducing Combinatorial Jets – Cut on Jet Area

single particle jets embedded in real data (5, 0, 15 GeV/c):



reconstructed real event jets:

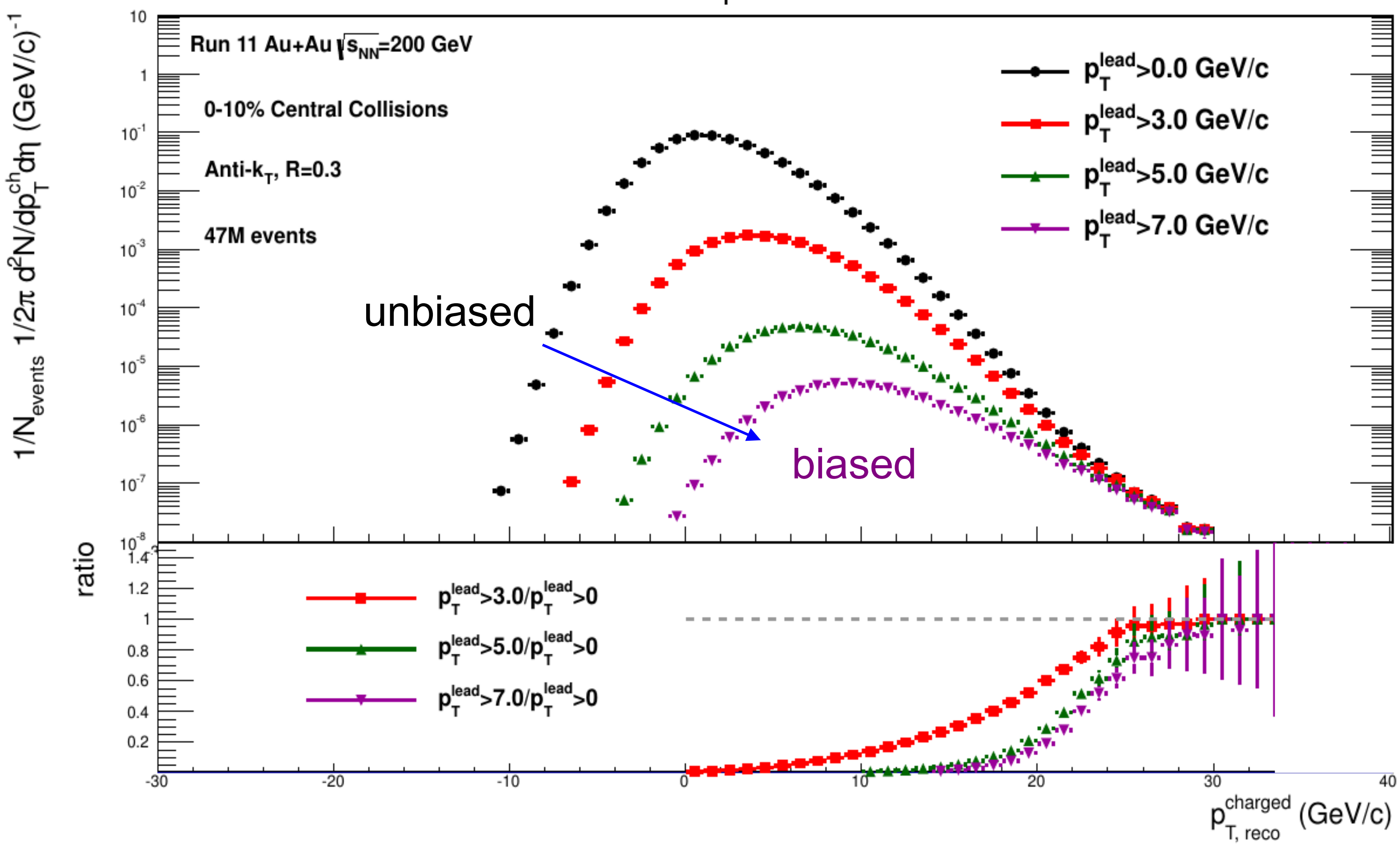


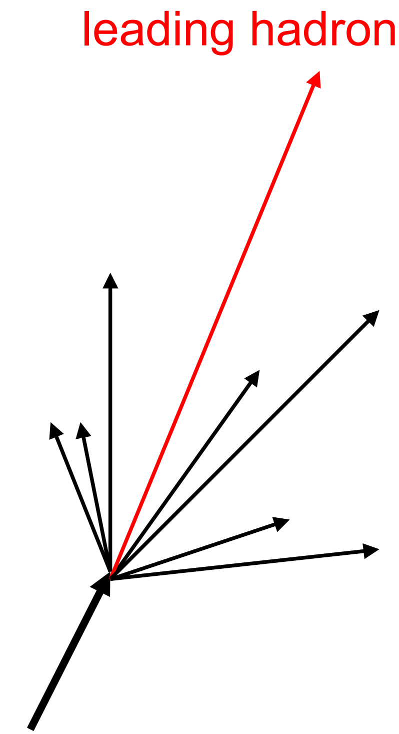
5

R=0.2, A>0.05 R=0.3, A>0.2 R=0.4, A>0.35

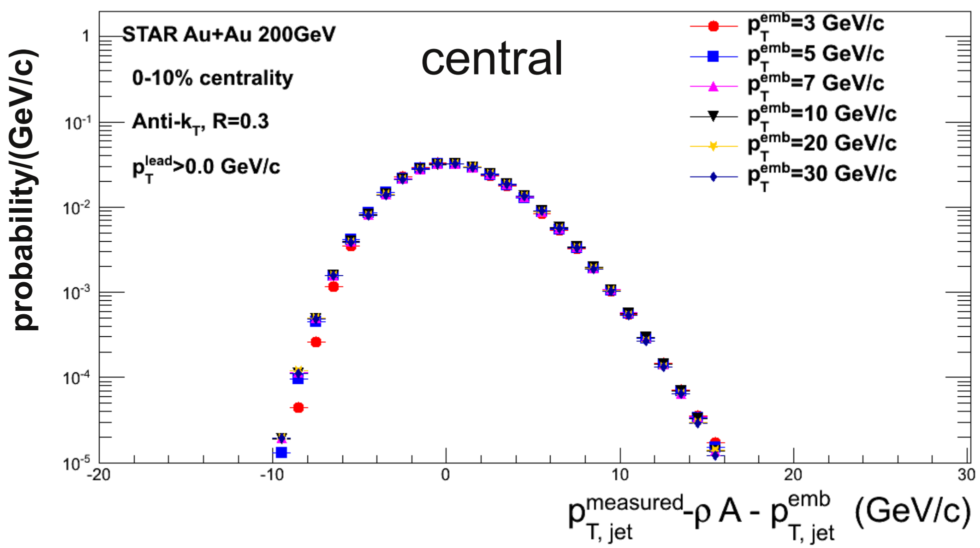
Reducing Combinatorial Jets

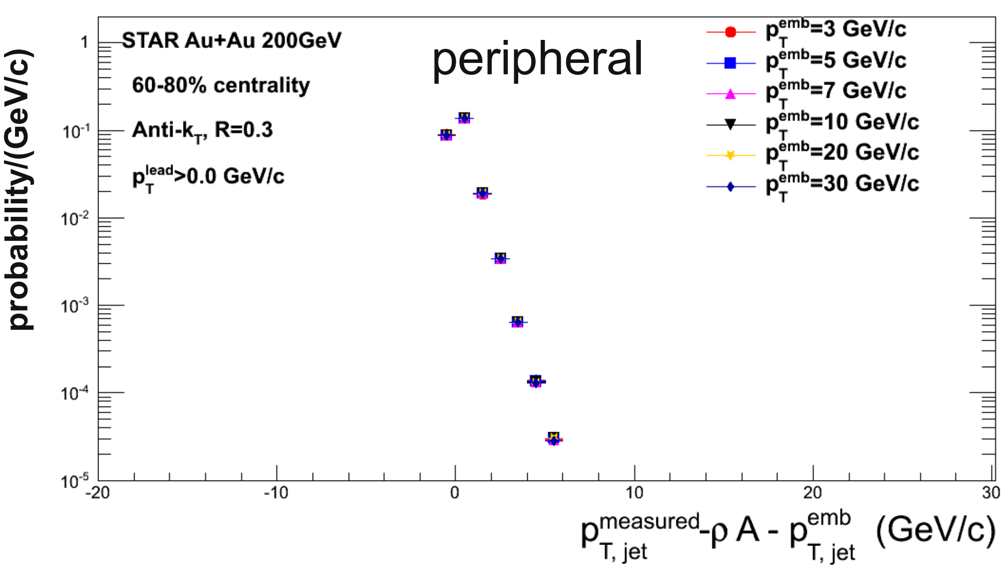
- combinatorial background reduced by a cut on leading hadron p_T
  [G. de Barros et al, Nucl. Phys. A910:314-318, 2013]
- breaks collinear safety: induces bias, however jet can still contain many soft constituents
- we don't discard negative p_T





Correction I: Background Fluctuations





- embedding simulated jets into real events to determine effect of background fluctuations on jet momentum

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

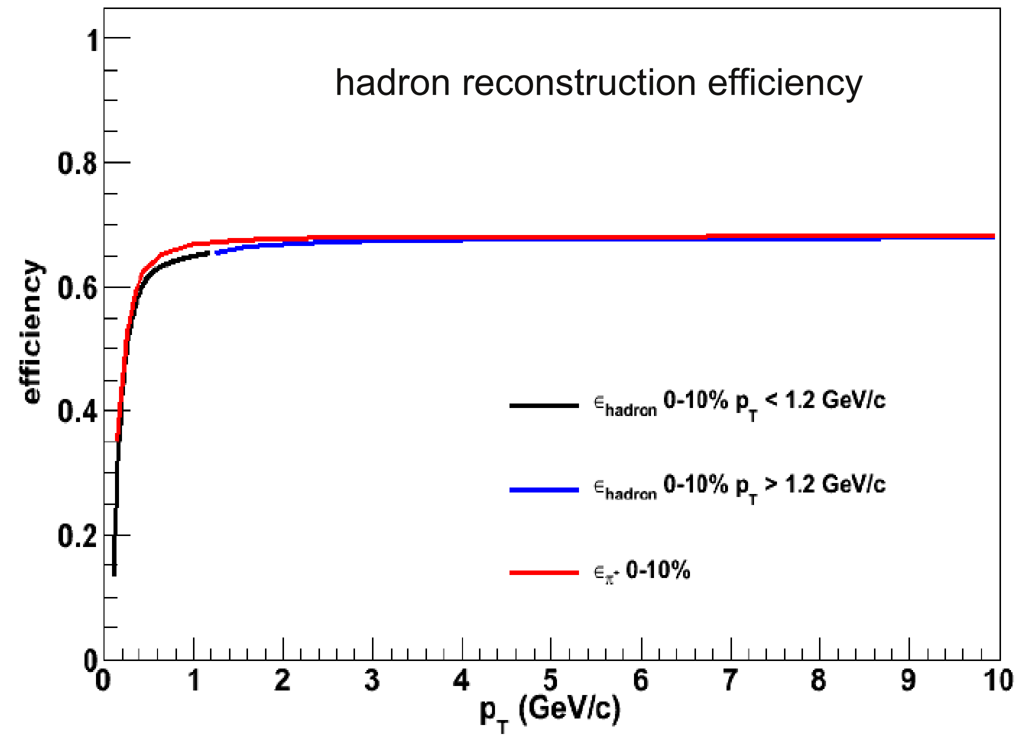
- δp_T depends weakly on embedded particle momentum

- δp_T used to correct the spectrum for background fluctuations

Correction II: Instrumentation Effects

- dominated by TPC tracking efficiency and track momentum resolution
  - parametrization of TPC tracking efficiency from embedding
  - momentum resolution parametrization:

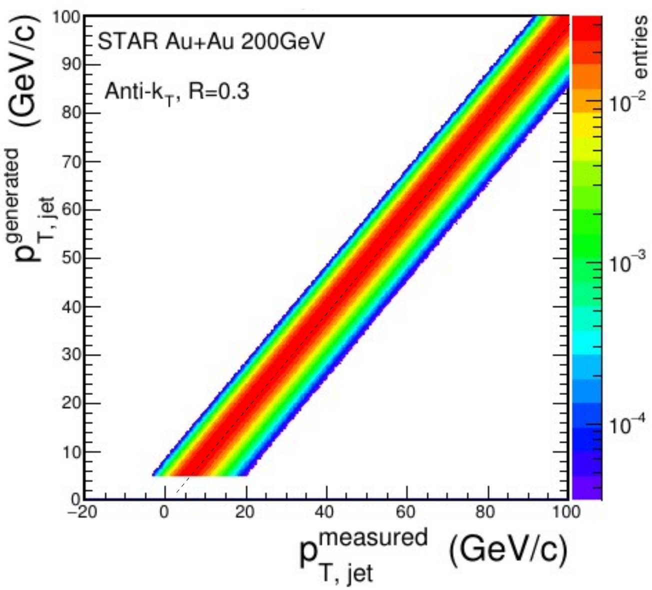
$$p_{\mathrm{T}}^{smeared} = \mathrm{N}(\mu, \sigma) = \mathrm{N}(p_{\mathrm{T}}, 0.01 \cdot (p_{\mathrm{T}})^2)$$



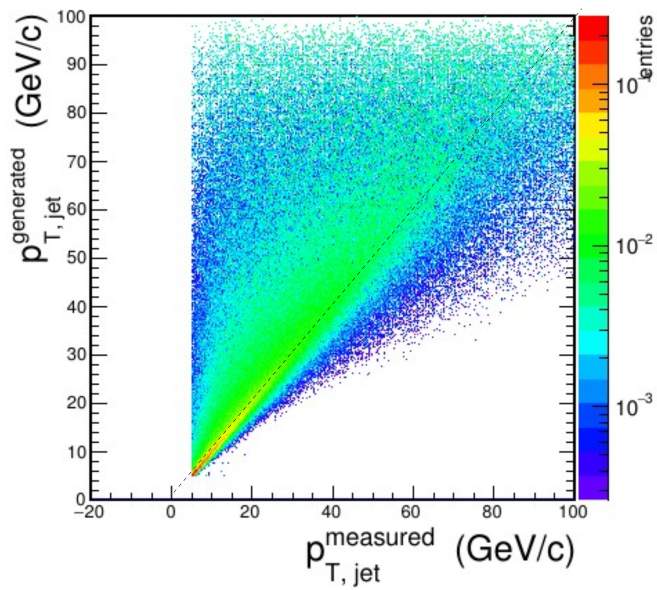
- PYTHIA 6 simulation:
  - **charged particles** saved -> jet reconstruction -> particle level jet (PL)
  - tracking efficiency and momentum smearing applied on the same group of charged particles -> jet reconstruction -> detector level jet (DL)
  - PL and DL jets are matched together (distance matching)

Response Matrix Calculation

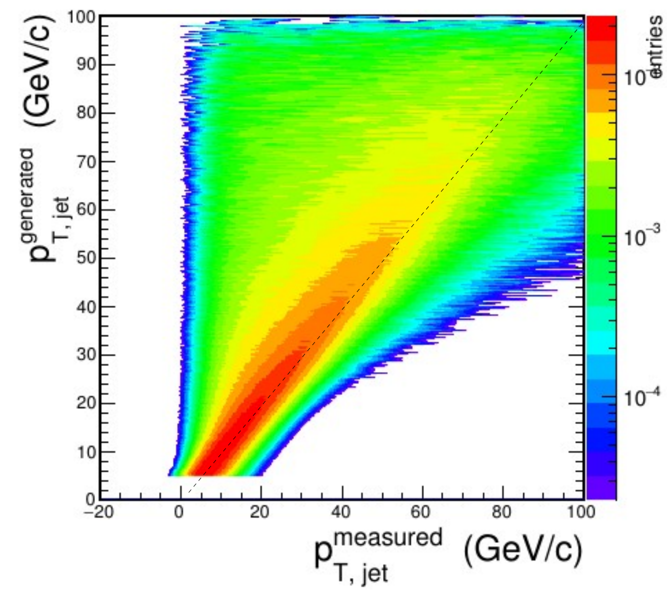
background
fluctuations



detector
effects



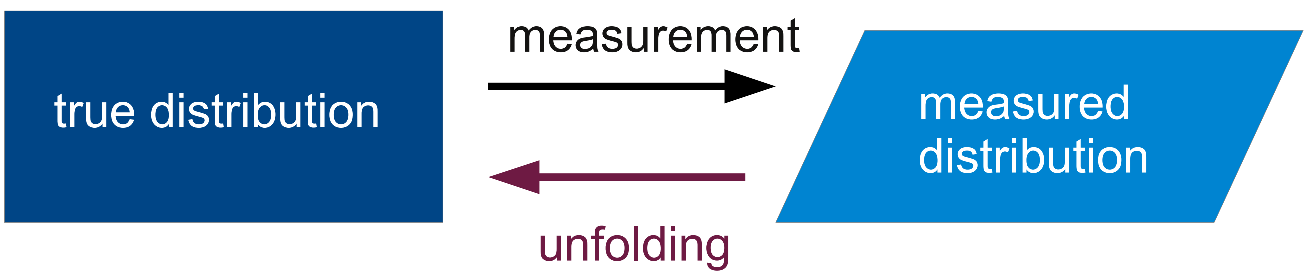
detector RM
$\otimes$
δ p_T RM



- full Response matrix is obtained by multiplying δp_T response matrix and detector response matrix
  - we assume the two effects are independent

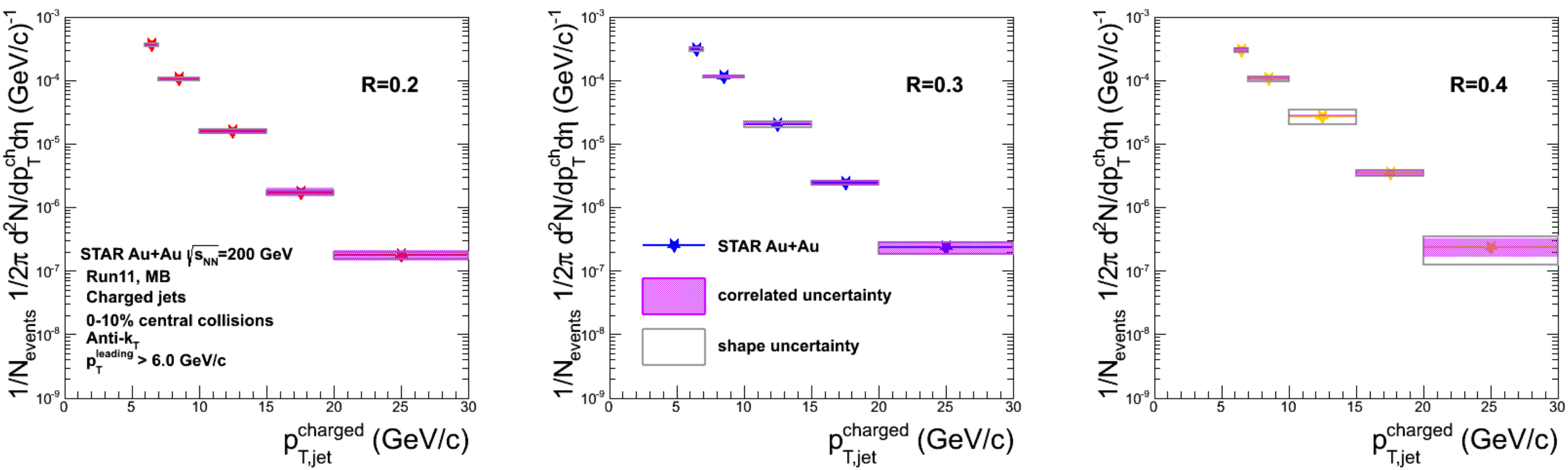
Unfolding of Measured Spectra

- Undo the effects of smearing on hard jet spectrum
- Correction for BG fluctuations + correction for detector effects

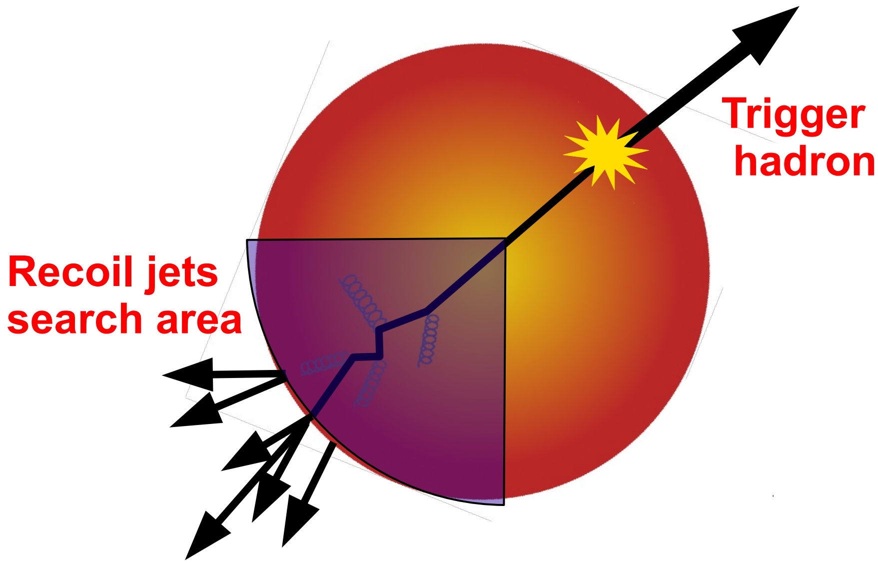


- Iterative method based on Bayes' theorem *[G. D'Agostini, arXiv:1010.0632]*
- Singular Value Decomposition (SVD) unfolding *[Nucl.Inst.Meth.A372:469-481,1996]*
- several (>10) different prior distributions used as the starting distribution
- optimal regularization parameter determined from simulation

0-10% central collisions



II) Semi-inclusive Recoil Jets



Trigger: high-p_T hadron → selects hard event

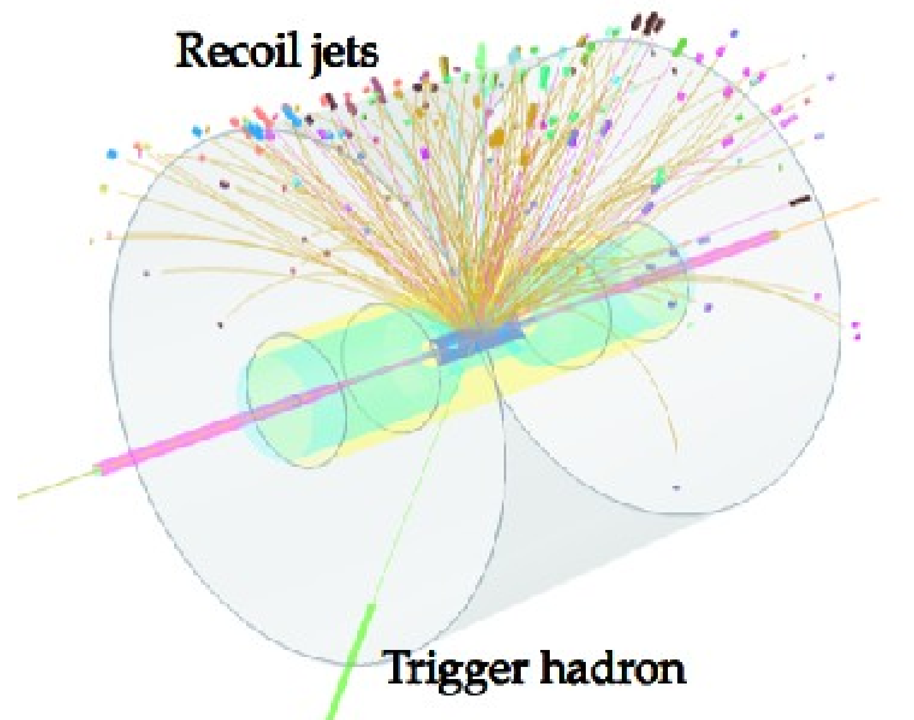
Recoil side: use all jet candidates within +/- 45°

→ **no fragmentation bias**

Observable:
Recoil jets per trigger

$$\frac{1}{N^{h}_{trig}} \frac{dN_{jet}}{dp_{T,jet}} = \frac{1}{\sigma^{AA \to h+X}} \frac{d\sigma^{AA \to h+jet+X}}{dp_{T,jet}}$$

Measured — Calculable in NLO pQCD



Semi-inclusive Recoil Jets

Analysis in STAR:

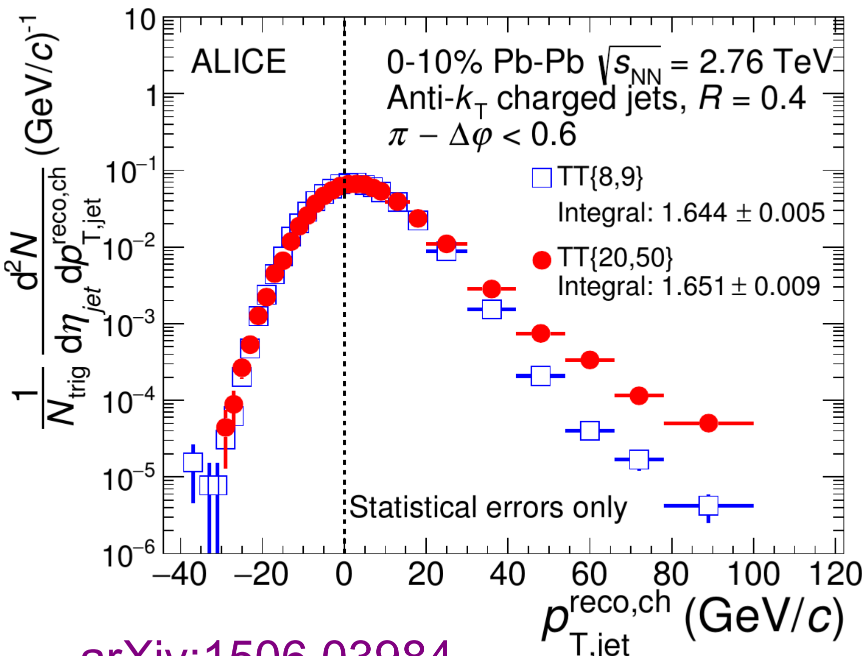
- Recoil jet azimuth: |Δφ-π|<π/4
- No rejection of jet candidates on jet-by-jet basis
- Jet measurement is collinear-safe with low infrared cutoff (0.2 GeV/c)
- **Background subtraction:**

  Mixed event technique

ALICE:

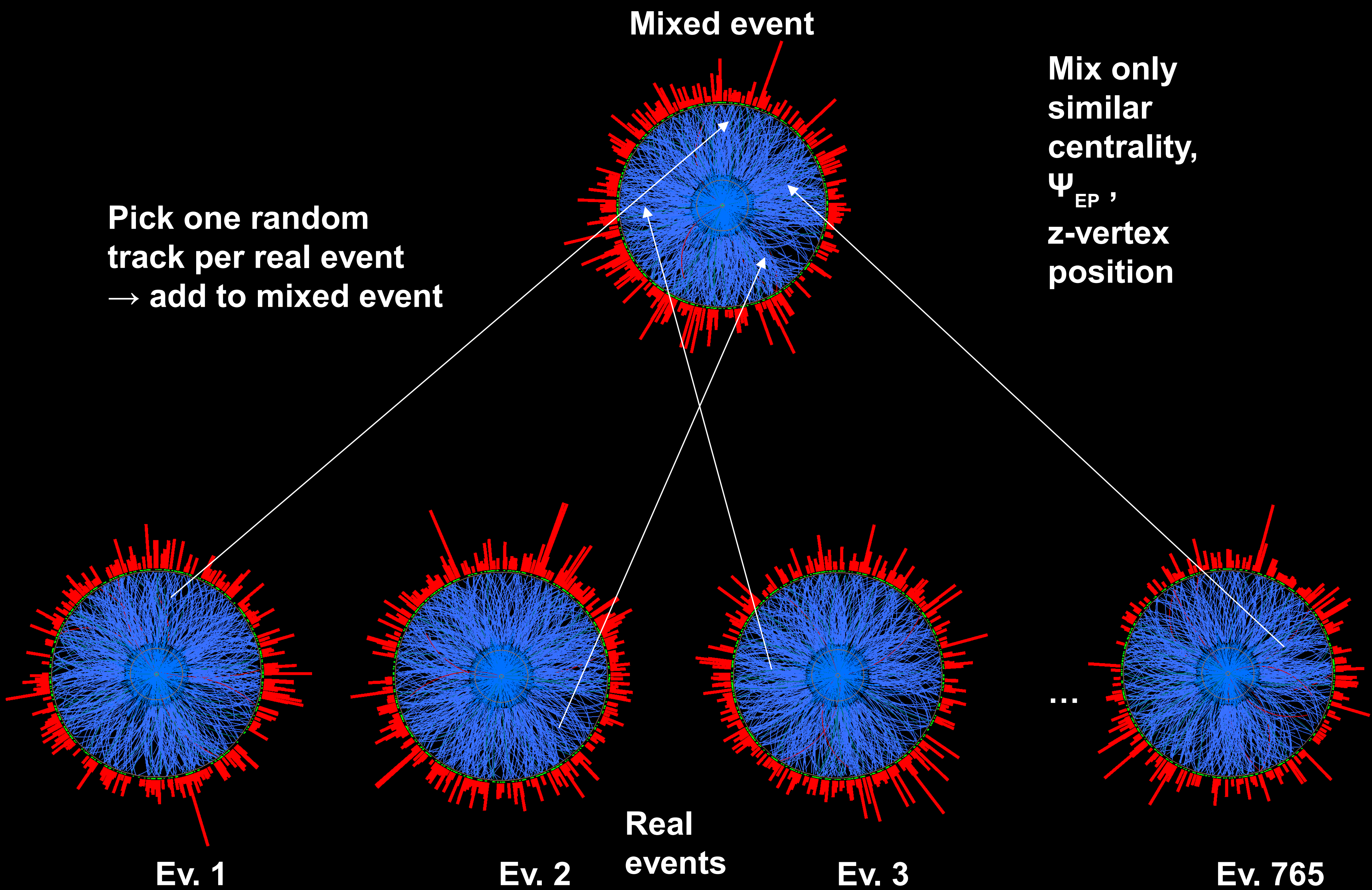
- **Background subtraction: two different trigger track (TT) p_T ranges**

$\Delta_{recoil} = TT_{signal} - TT_{reference}$



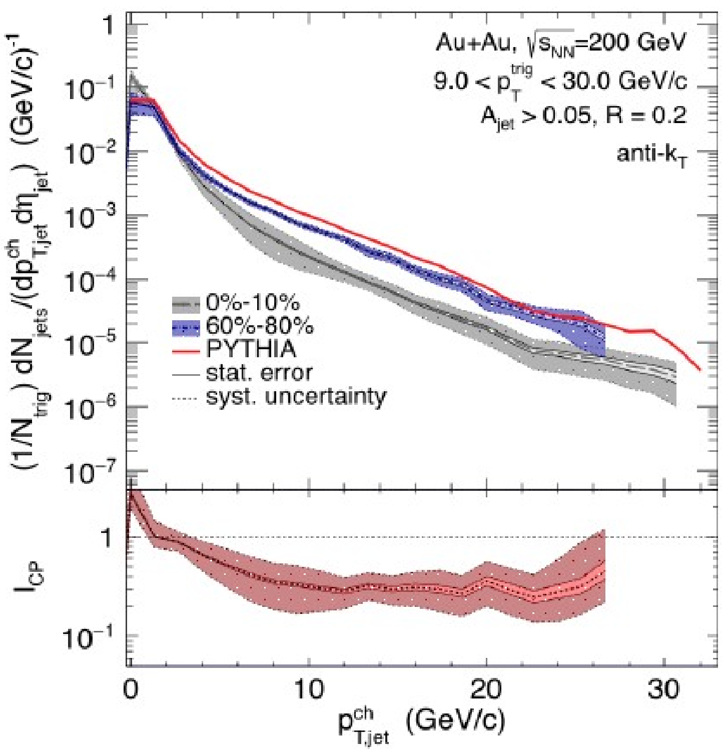
arXiv:1506.03984

Mixed Event Generation for Jets

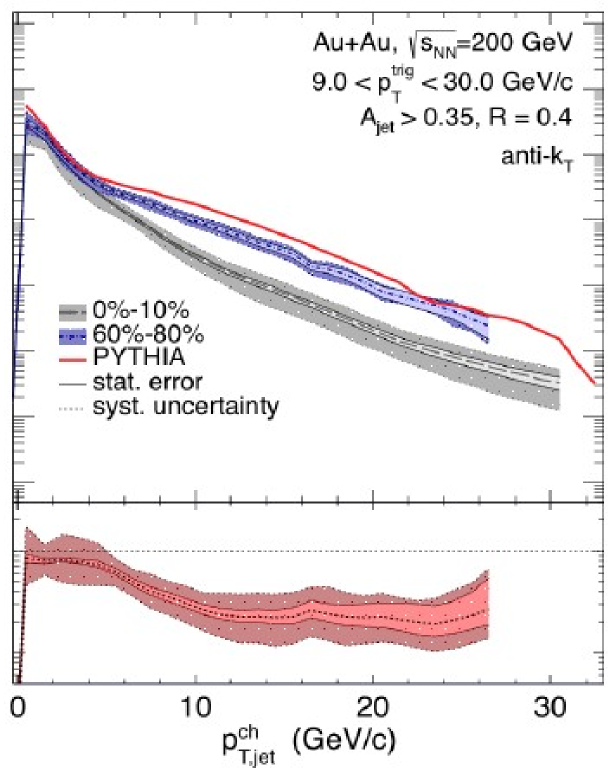


Corrected Spectra and I_{CP}

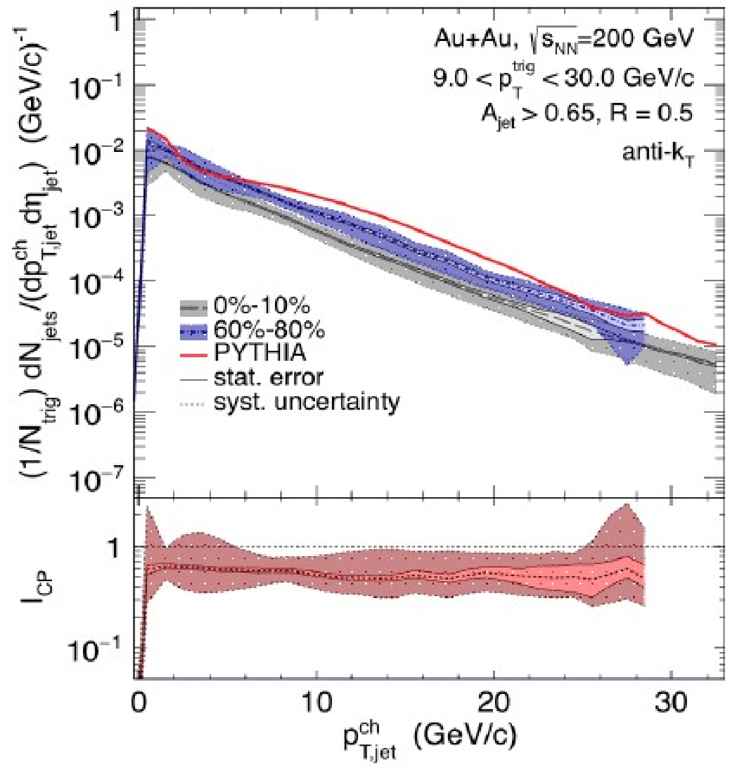
R=0.2



R=0.4



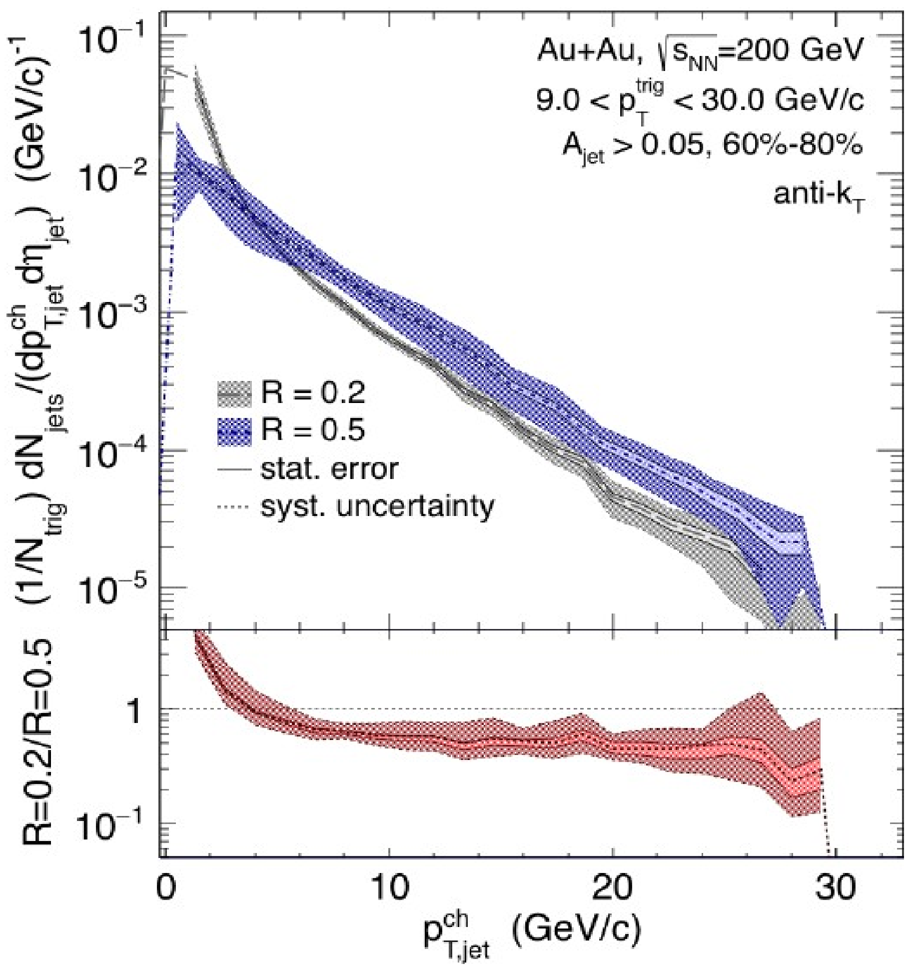
R=0.5



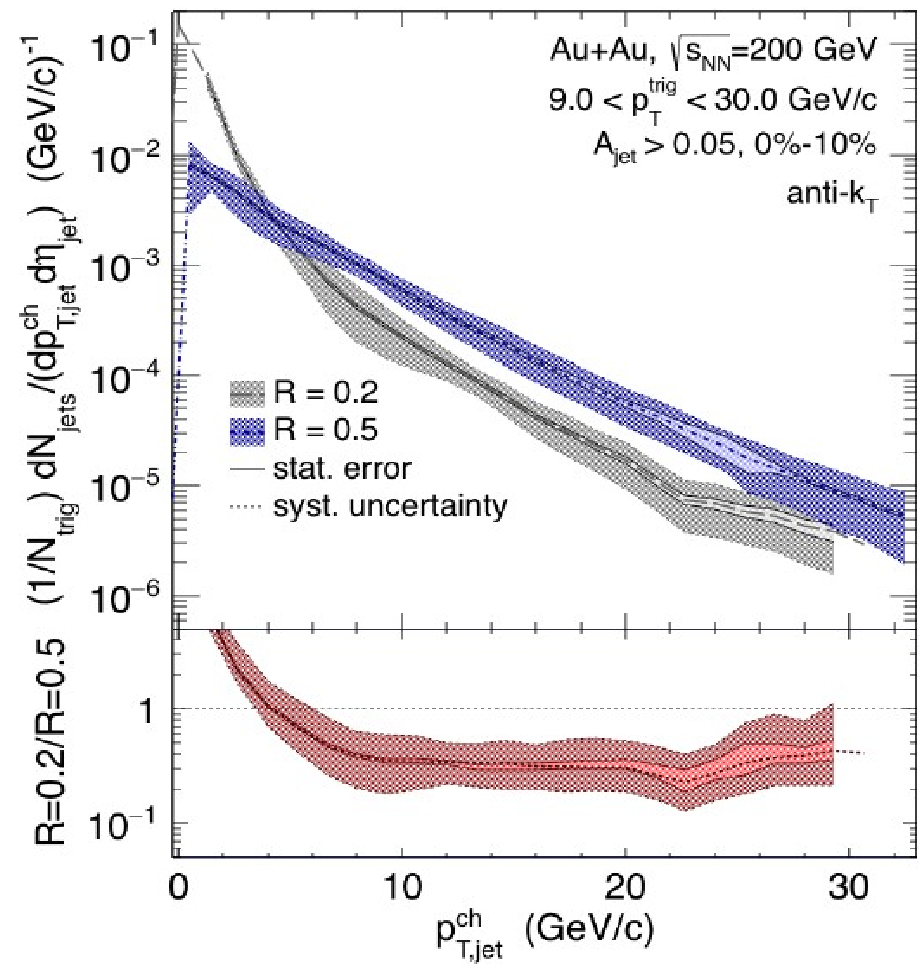
- significant suppression for R=0.2 – 0.4
- minimal suppression for R=0.5

Spectra ratio for different R

peripheral



central

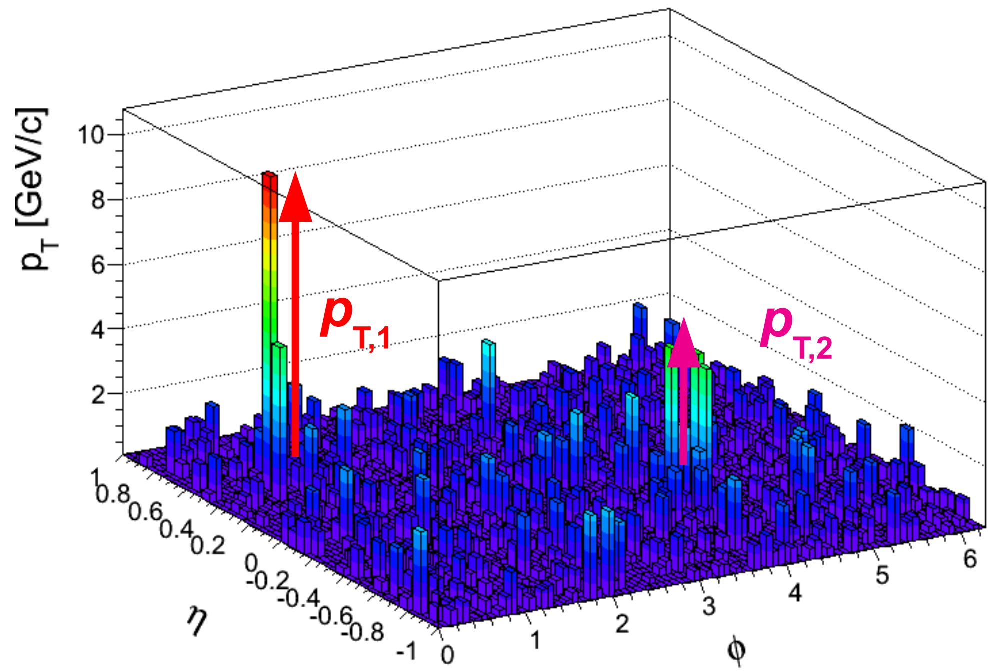


- suggests broadening of intra-jet structure due to jet quenching

Di-jet Momentum Imbalance

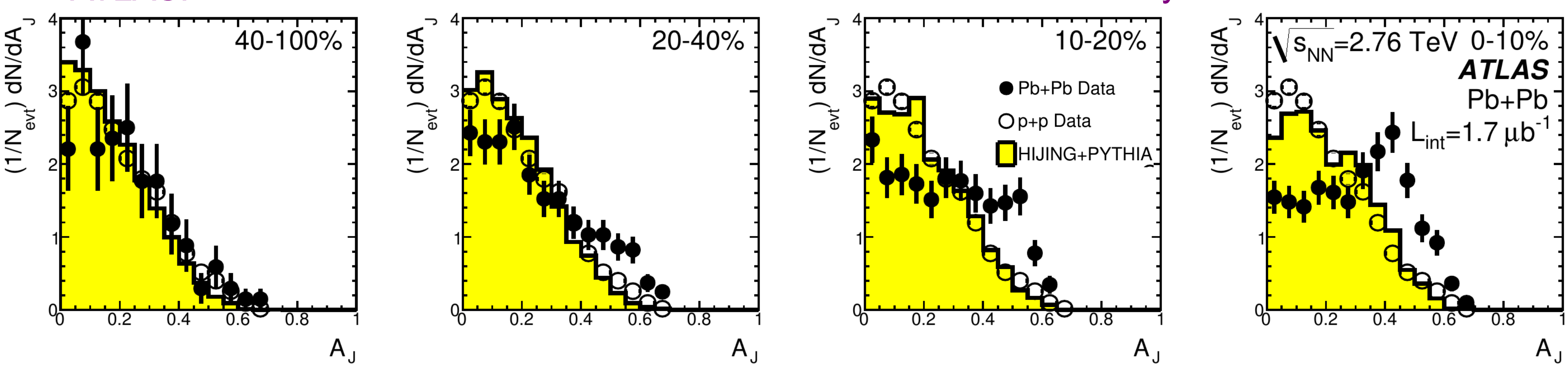
$$A_J = \frac{p_{T,1} - p_{T,2}}{p_{T,1} + p_{T,2}}$$

- di-jet momentum asymmetry
- signal of medium-induced jet modification
- measured for **full jets**



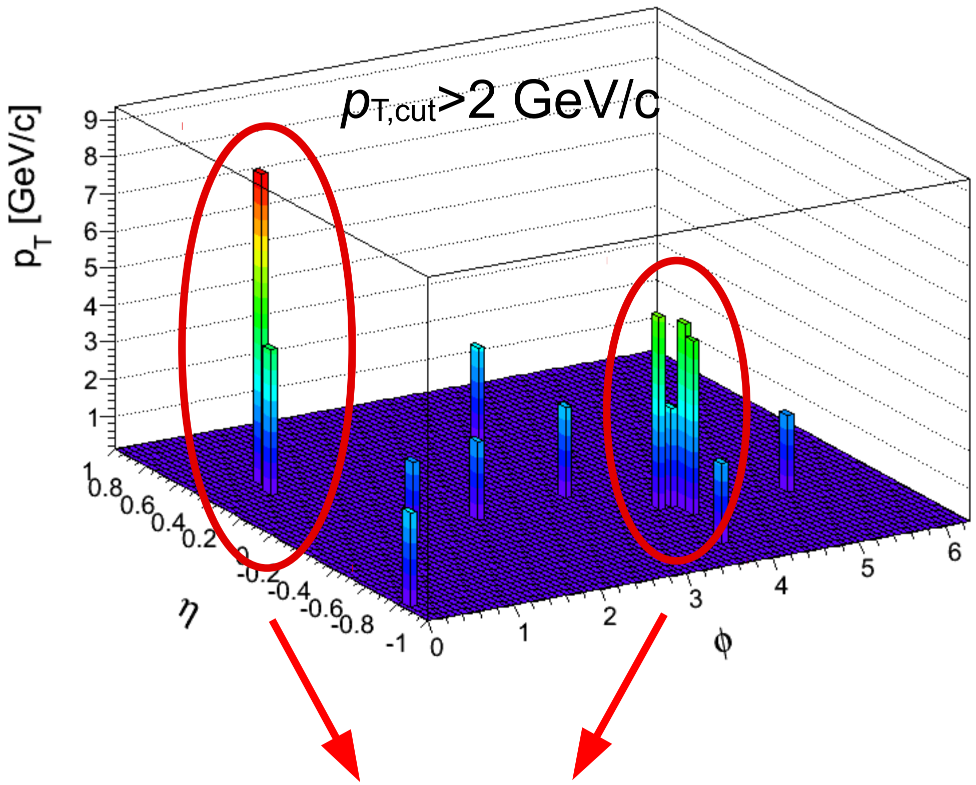
ATLAS:

Phys. Rev. Lett. 105 252303



A_J Calculation in STAR

p_T^{Lead}>20 GeV/c
$p_T^{SubLead}$>10 GeV/c
$\Delta\Phi_{Lead,SubLead}$ > 2/3 π



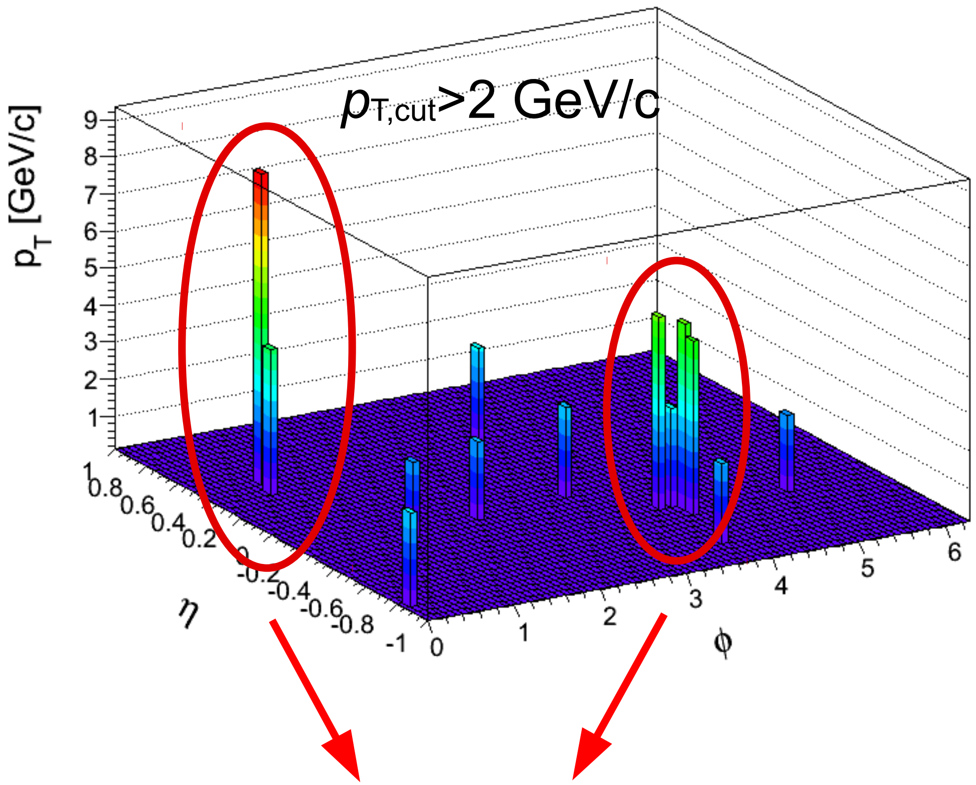
Calculate A_J with constituent
HIGH $p_{T,cut}$>2 GeV/c

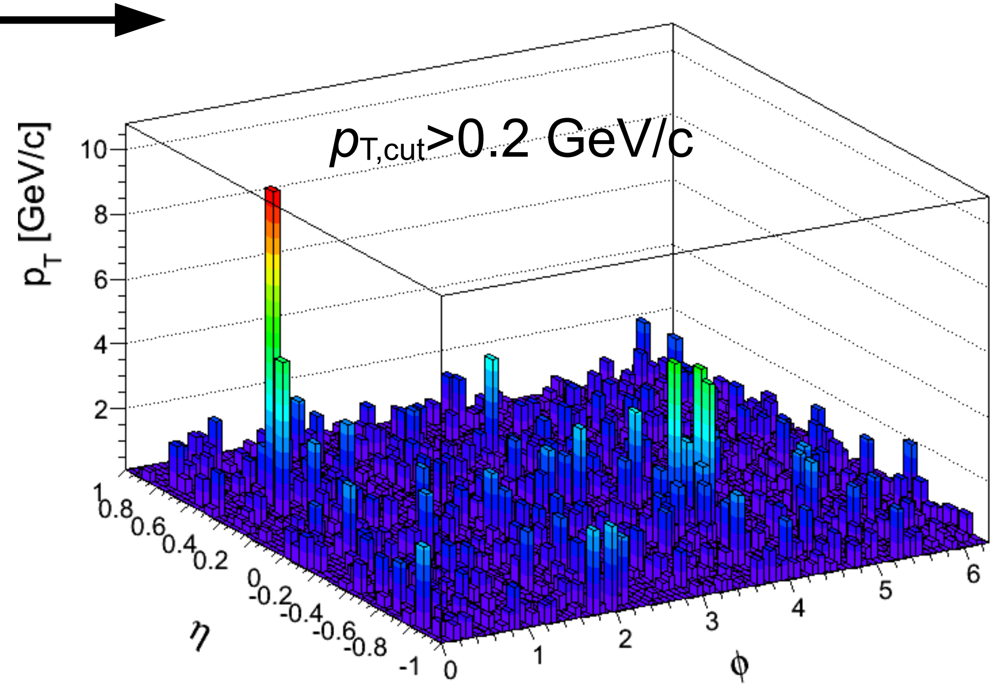
$$A_J = \frac{p_{T,1} - p_{T,2}}{p_{T,1} + p_{T,2}}, \quad p_T = p_T^{rec} - \rho \times A$$

A_J Calculation in STAR

p_T^{Lead}>20 GeV/c
$p_T^{SubLead}$>10 GeV/c
$\Delta\Phi_{Lead,SubLead}$ > 2/3 π

Rerun jet-finding algorithm anti-k_T on these events ...



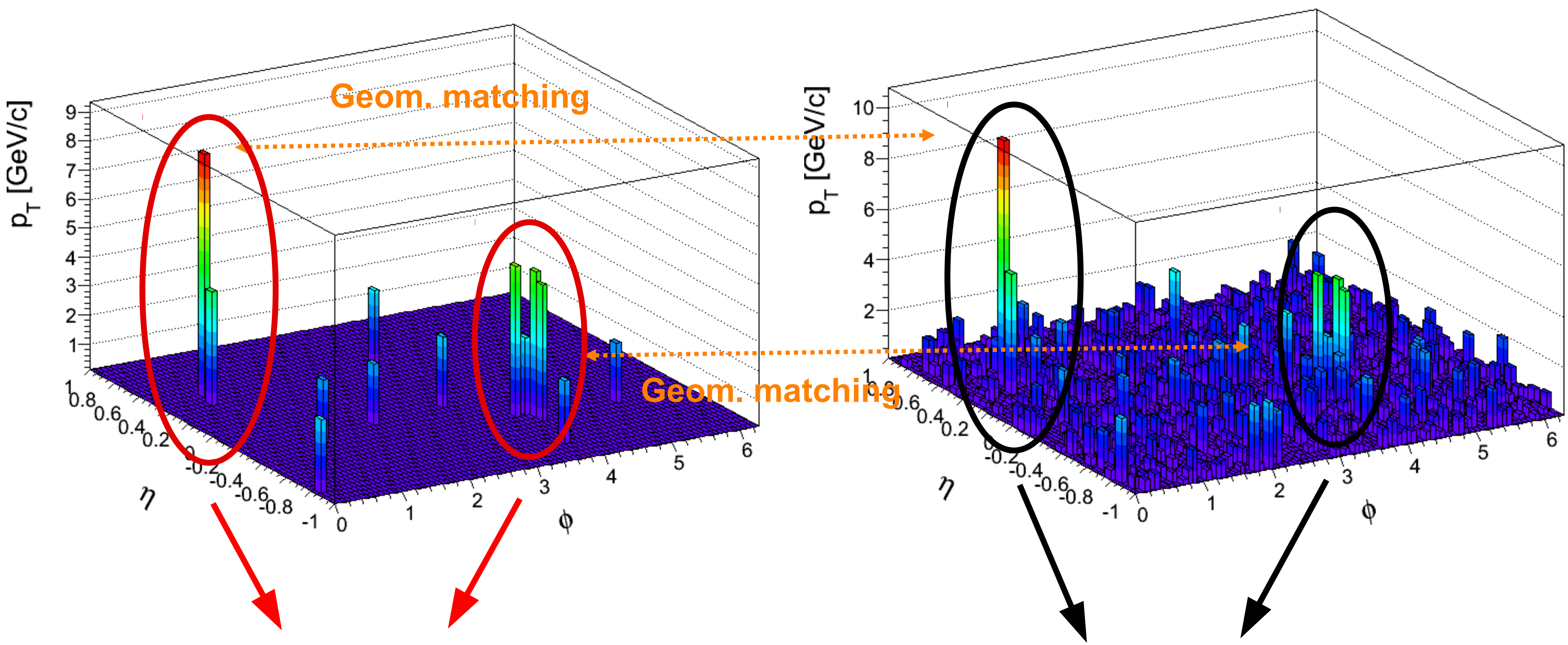


Calculate A_J with constituent
HIGH $p_{T,cut}$>2 GeV/c

$$A_J = \frac{p_{T,1} - p_{T,2}}{p_{T,1} + p_{T,2}}, \quad p_T = p_T^{rec} - \rho \times A$$

A_J Calculation in STAR

p_T^{Lead}>20 GeV/c
$p_T^{SubLead}$>10 GeV/c
$\Delta\Phi_{Lead,SubLead}$ > 2/3 π

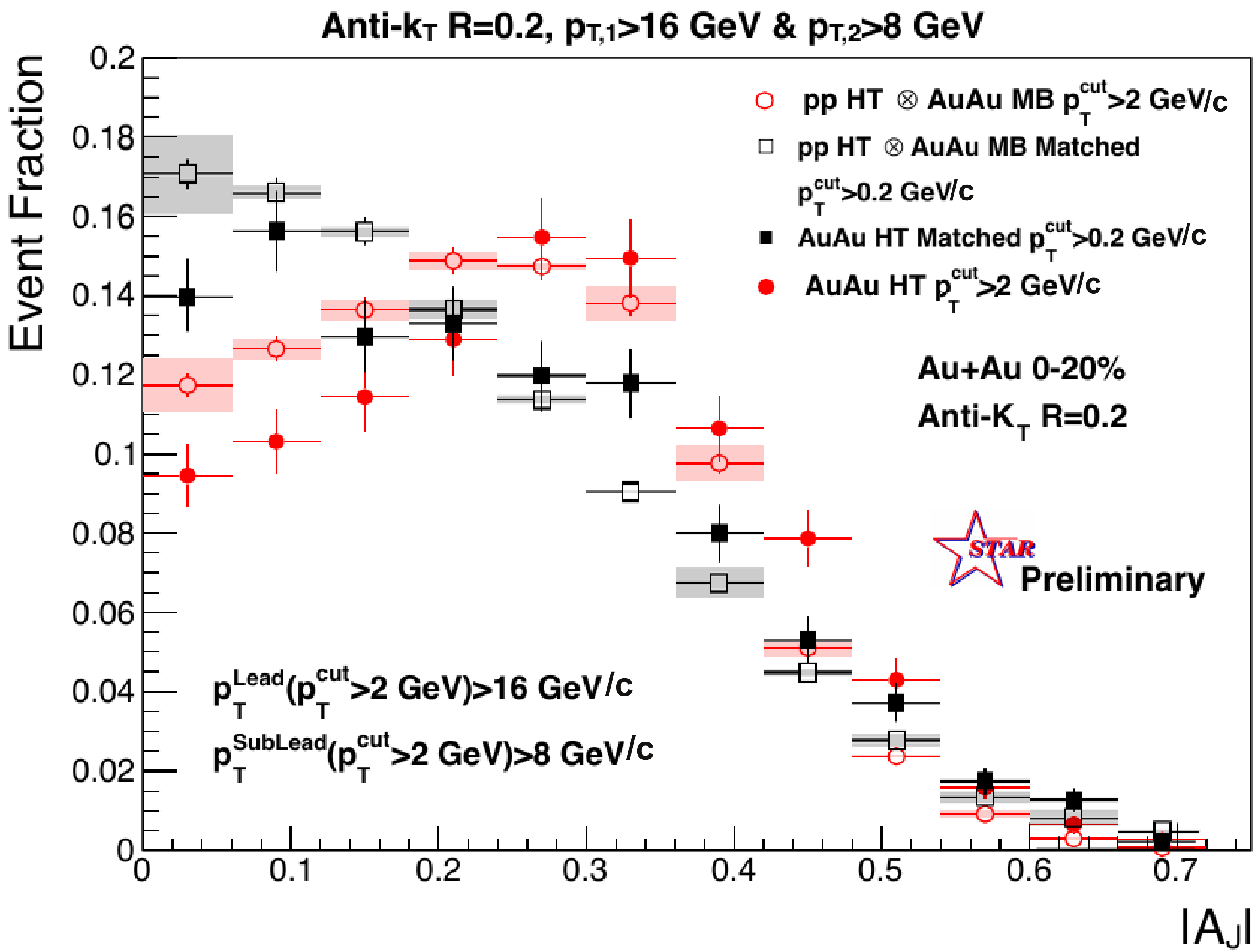


Calculate A_J with constituent
HIGH $p_{T,cut}$>2 GeV/c

Calculate “matched” A_J with constituent **LOW $p_{T,cut}$>0.2 GeV/c**

$$A_J = \frac{p_{T,1} - p_{T,2}}{p_{T,1} + p_{T,2}}, \quad p_T = p_T^{rec} - \rho \times A$$

A_J: R=0.2

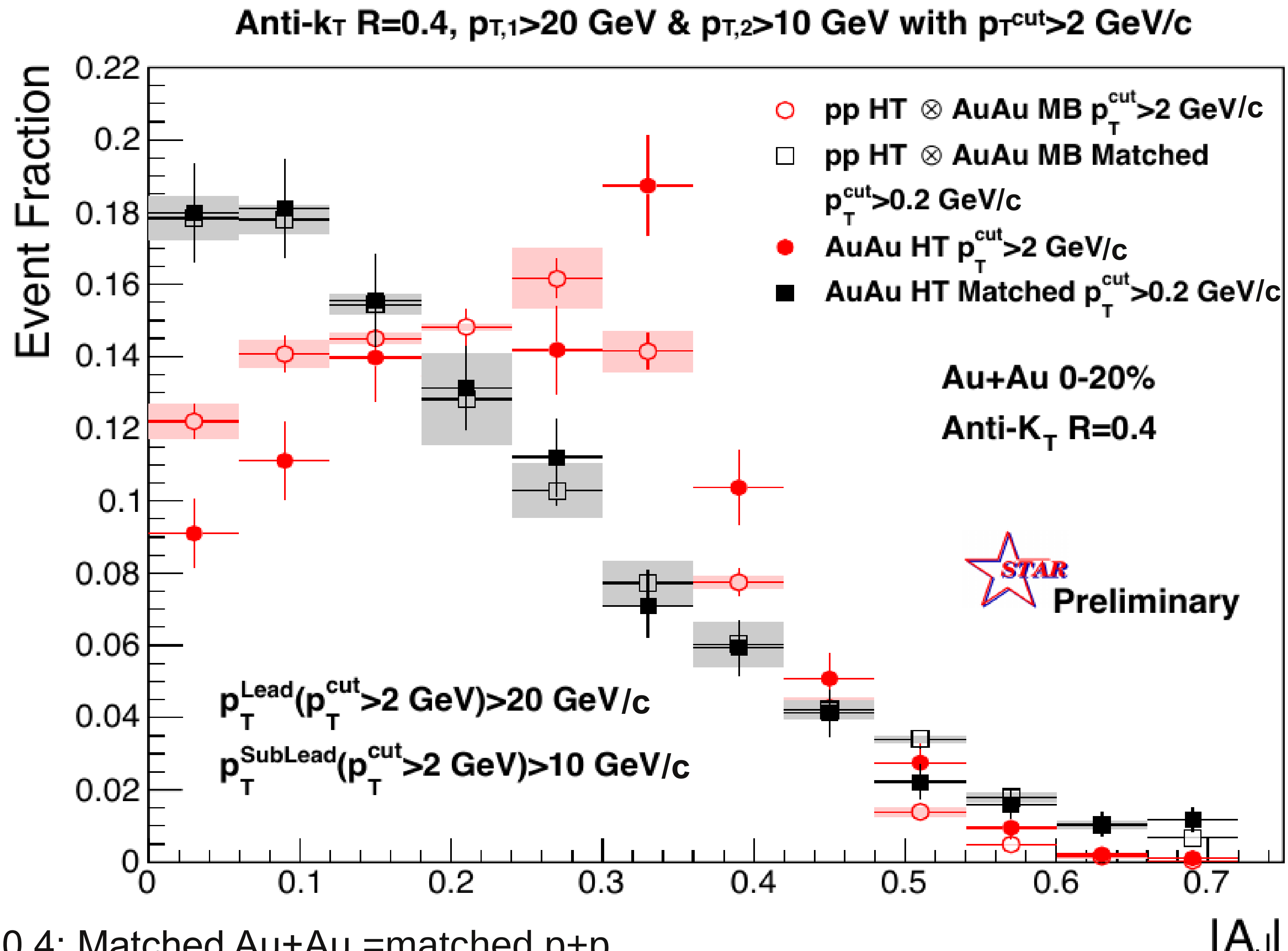


p-value<10^{-10}
(stat. error only)

p-value<10^{-4}
(stat. error only)

R=0.2: Matched Au+Au ≠ matched p+p

A_J: R=0.4



p-value<10[-5]
(stat. error only)

p-value~0.8
(stat. error only)

R=0.4: Matched Au+Au =matched p+p

=>Energy recovered for R=0.4 with low p_T particles (?)

Conclusion

- **Inclusive charged jet spectra measured at STAR**
  - pp baseline for R_{AA}: work in progress
- **Semi-inclusive recoil charged jet spectra measured at STAR**
  - mixed event technique used to reduce background
  - ratio of R=0.2/0.5 suggests broadening of intra-jet structure in central collisions due to jet quenching
- **Di-jet asymmetry A_J:**
  - no significant difference between Au+Au and p+p for low p_T constituent cut for R=0.4

BACKUP

Systematic Uncertainties

Shape (unfolding) uncertainties:

- SVD and Bayesian unfolding used
- 13 different prior functions
- optimal iteration, opt. Iter. +1
- 2*13*2 solutions => QA cuts => ~5-10 solutions

Correlated uncertainties:

- tracking efficiency +-5% (absolute)
- jet fragmentation: 2u+1g vs pure u or g sample (detector RM)
- uncorrected δpT => v2 corrected δpT
- pp-like hadron ratios => AuAu-like

} negligible

Optimal iteration/regularization parameter value

Properties to test:

- compare backfolded and measured distribution (comparison of 2 histograms)
- compare solutions for *i* and *i*+1 or *k* and *k*+1 (comparison of 2 histograms)
- smoothness of the unfolded spectra (property of 1 histogram)

How to compare two histograms:

- ~~χ^2 – test~~

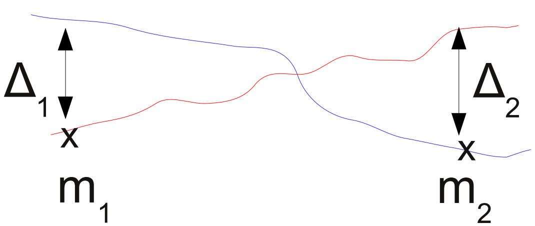
$$\chi^2/\mathrm{NDF} = \frac{1}{n}\sum_{i=1}^{n}\frac{(a_i - b_i)^2}{a_i + b_i}$$

- **average relative distance**

$$R = \frac{1}{n}\sum_{i=1}^{n}\frac{|a_i - b_i|}{\min(a_i, b_i)}$$

- ~~Kolmogorov-Smirnov test~~

$$\Delta_{\mathrm{KS}} = \max_j \left|\sum_{i=1}^{j}\left(\frac{a_i}{I_a} - \frac{b_i}{I_b}\right)\right|,\ \ j\epsilon\langle 1, n\rangle$$



Smoothness:

- curvature

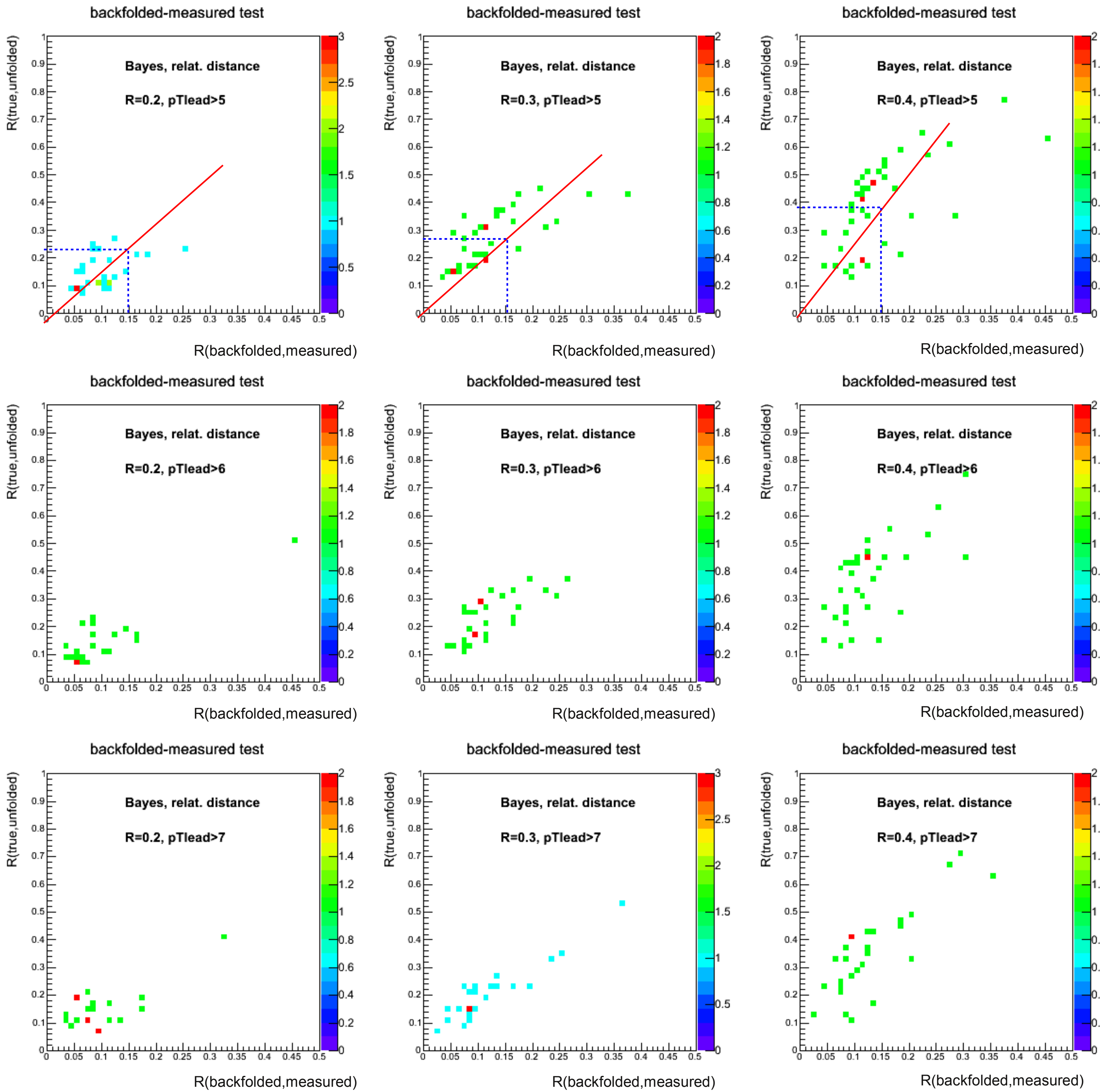
$$C = \frac{1}{n}\sum_{i=2}^{n-1}\frac{((w_{i+1} - w_i) - (w_i - w_{i-1}))^2}{w_i^2}$$

$$w_i \ldots \frac{content\ of\ i^{th}\ bin}{width\ of\ i^{th}\ bin}$$

$a_i, b_i \ldots$ *content of* i^{th} *bin*

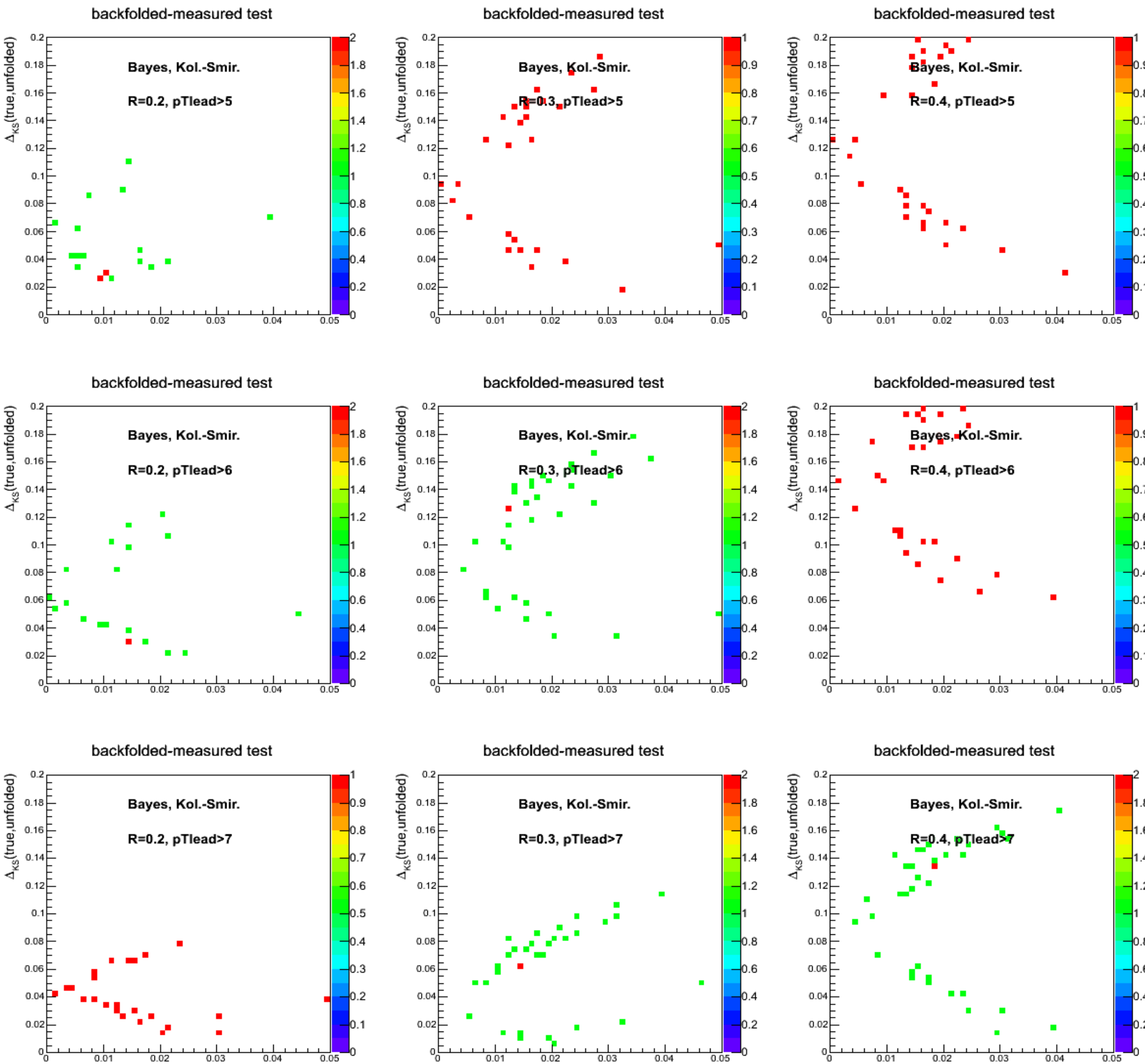
$I_a, I_b \ldots$ *total counts of the histogram*

Toymodel
stat. test
study
- example:



example:

(bad)

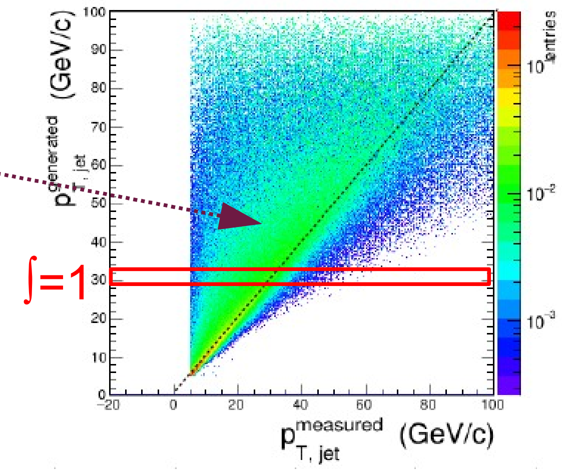

backfolded-measured test
Bayes, Kol.-Smir.
R=0.2, pTlead>5
backfolded-measured test
Bayes, Kol.-Smir.
R=0.3, pTlead>5
backfolded-measured test
Bayes, Kol.-Smir.
R=0.4, pTlead>5
backfolded-measured test
Bayes, Kol.-Smir.
R=0.2, pTlead>6
backfolded-measured test
Bayes, Kol.-Smir.
R=0.3, pTlead>6
backfolded-measured test
Bayes, Kol.-Smir.
R=0.4, pTlead>6
backfolded-measured test
Bayes, Kol.-Smir.
R=0.2, pTlead>7
backfolded-measured test
Bayes, Kol.-Smir.
R=0.3, pTlead>7
backfolded-measured test
Bayes, Kol.-Smir.
R=0.4, pTlead>7
Δ_{KS}(true,unfolded)

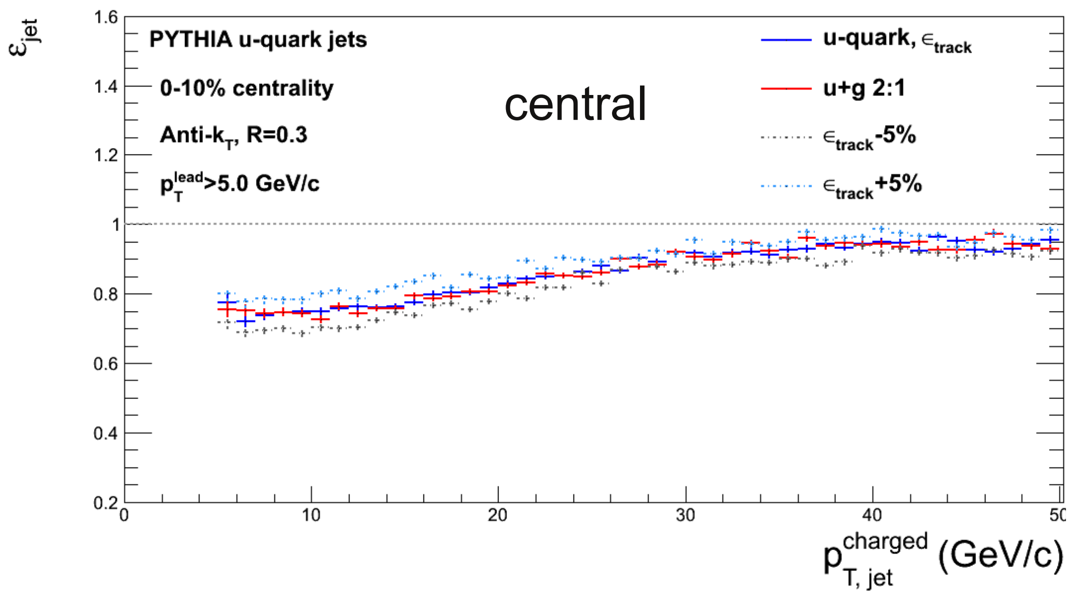
Jet Reconstruction Efficiency

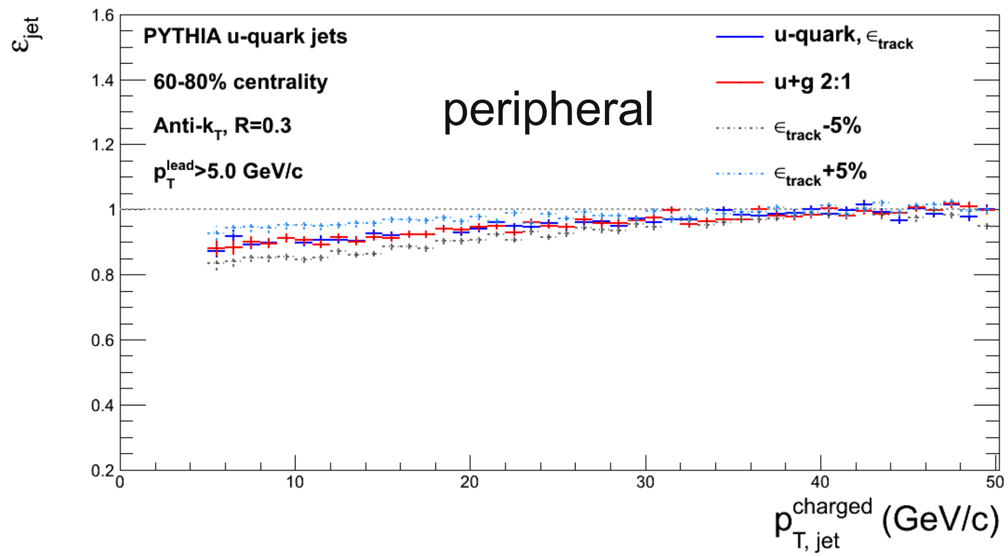
$$\varepsilon(p_{\mathrm{T,jet}}^{\mathrm{part}}) = \frac{\frac{\mathrm{d}N_{\mathrm{jet}}}{\mathrm{d}p_{\mathrm{T,jet}}^{\mathrm{det}}} \otimes \widetilde{\mathbf{R}^{-1}}\left[p_T^{jet,part} \rightarrow p_T^{jet,det}\right]}{\frac{\mathrm{d}N_{\mathrm{jet}}}{\mathrm{d}p_{\mathrm{T,jet}}^{\mathrm{part}}}}$$

unfolded DL spectrum

PL spectrum





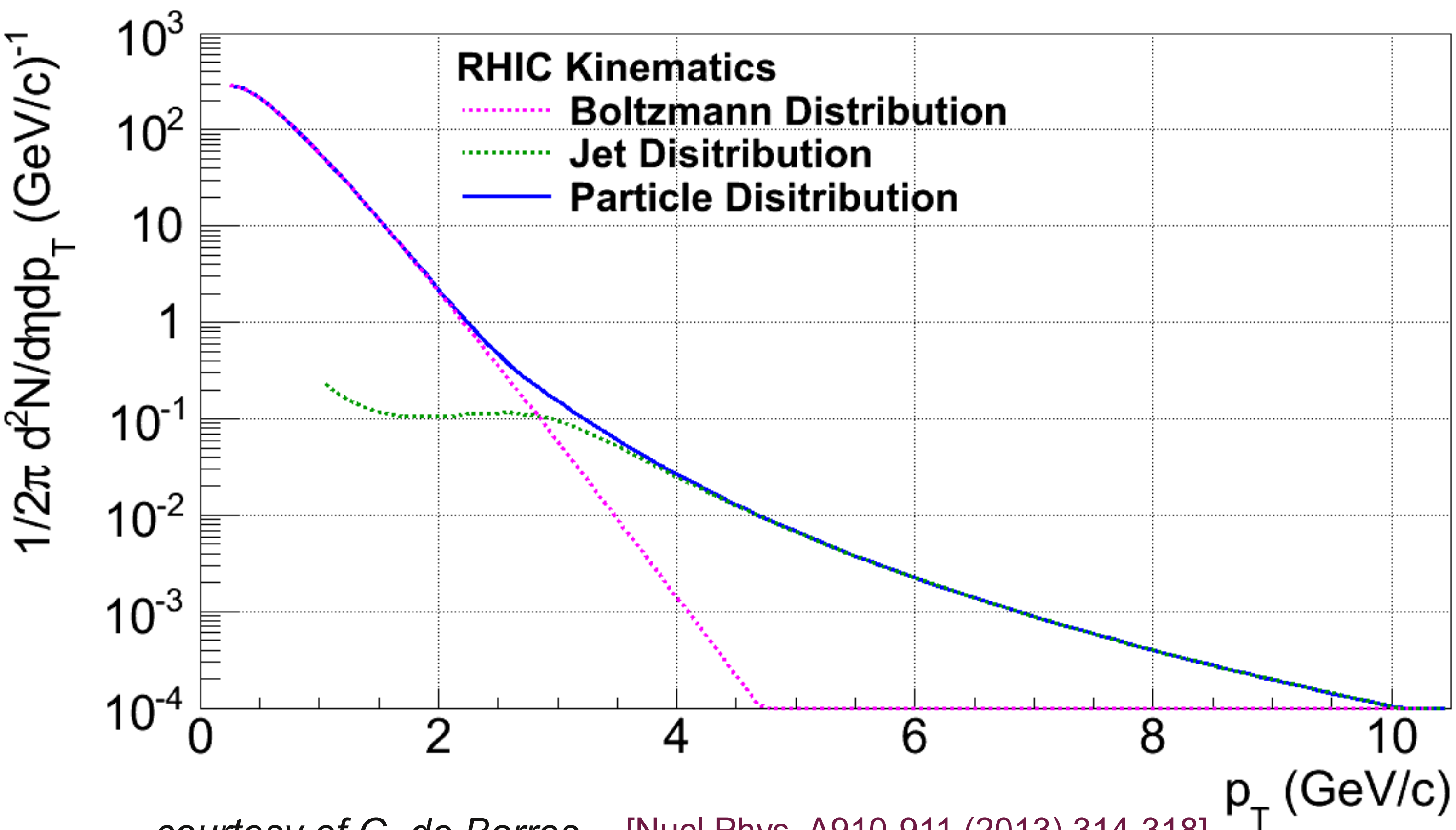


- applied after the unfolding

TOYMODEL

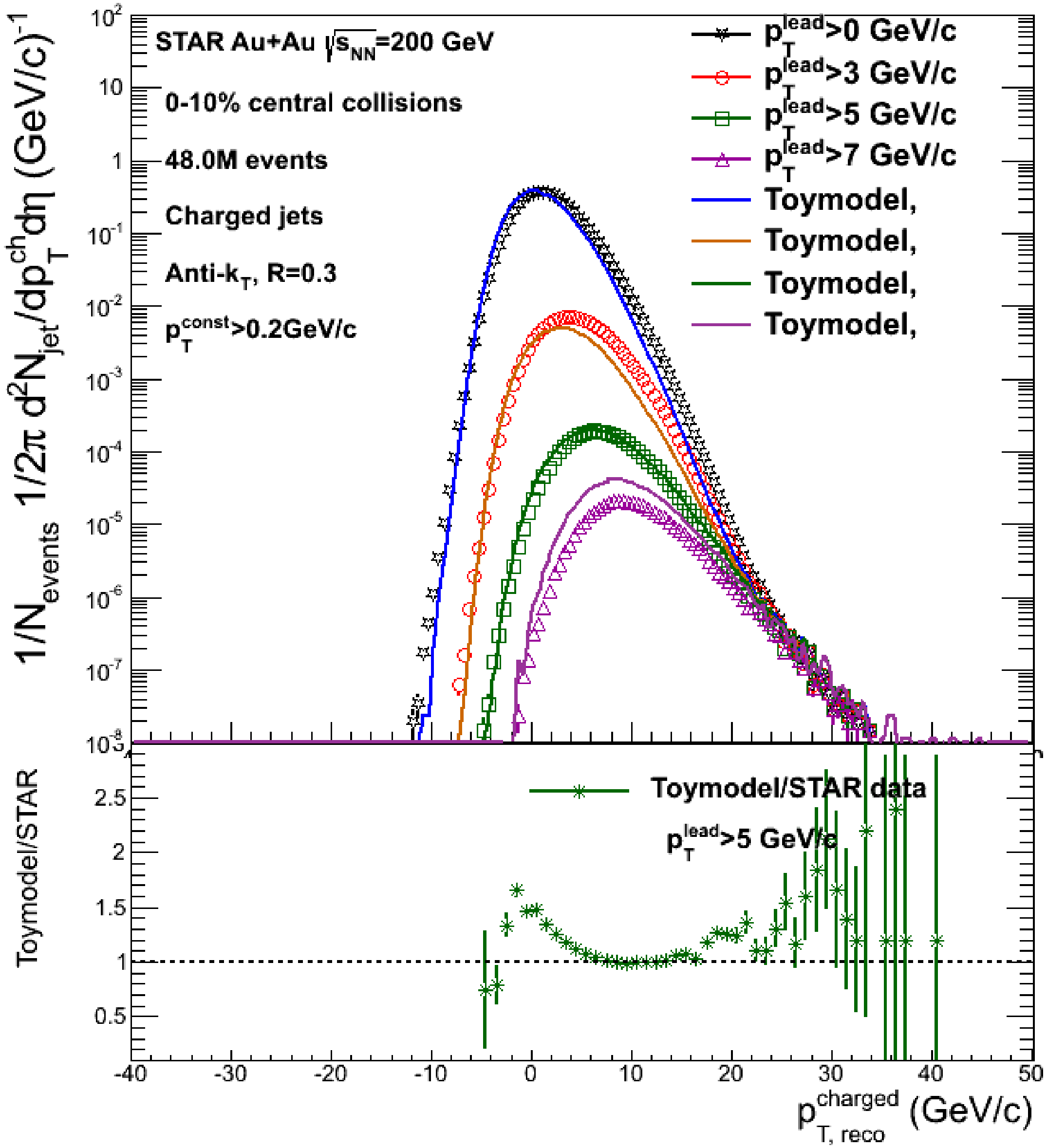
- used for closure test, test bench for unfolding,...
- 2 components:
  - soft thermal background – Boltzman distribution
  - hard jets (several spectra shapes, jet fragmentations –

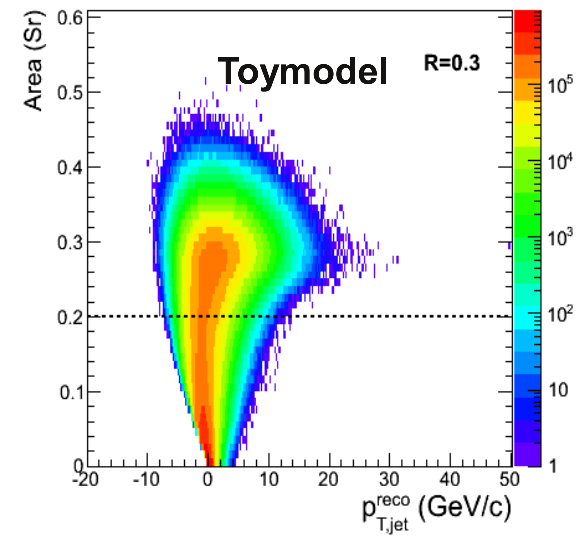
    we use TAA*PYTHIA spectrum w/ u-quark fragmentation)

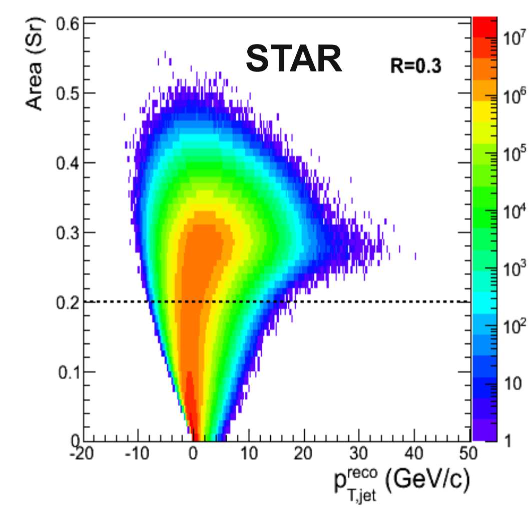


courtesy of G. de Barros [Nucl.Phys. A910-911 (2013) 314-318]

TOYMODEL vs STAR data







- despite its simplicity qualitatively agrees with data
  => multi-hadron correlations and other more complicated effects are not driving the features of jet distributions (same conclusion comes from Alex's mixed event studies)

Instrumentation Effects

Jet Matching:

- Corresponding PL jets and DL jets are matched on geometrical basis:
  - for given PL1 jet a closest DL1 jet is found (the distance has to be smaller than R)
  - for the matched DL1 jet a closest PL2 jet is found
  - if the PL1 = PL2 than the jets PL1 and DL1 are matched
- Detector level jet population is required to satisfy the same criteria as for real data analysis (acceptance, area cut, $p_T^{leading}$ cut)
- Particle level jet is required to satisfy only criteria on acceptance and $p_T^{leading}$ cut
- For each matched pair the corresponding bin in the detector response matrix is incremented

Bayesian Unfolding: choice of the optimal iteration *i*

- no general prescription
- depends on the prior choice
- too many iterations -> enhancement of statistical fluctuations

  => wild oscillations

SVD: choice of regularization parameter *k*

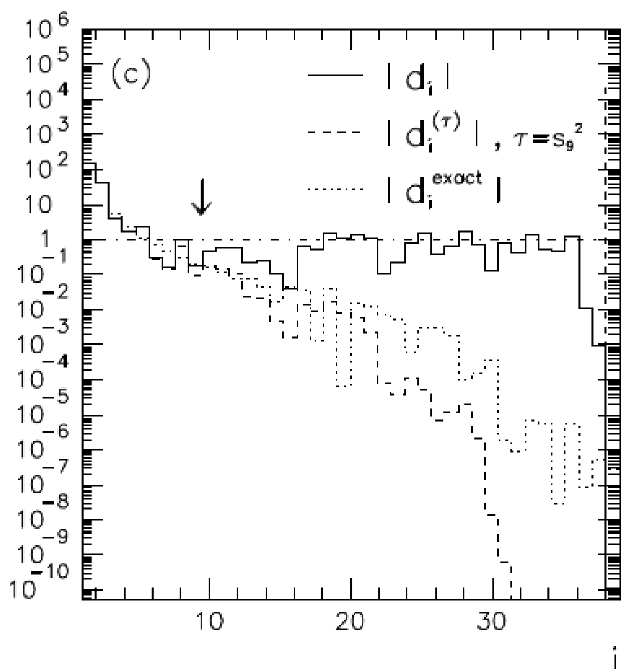
notation:

Rx=m //original problem

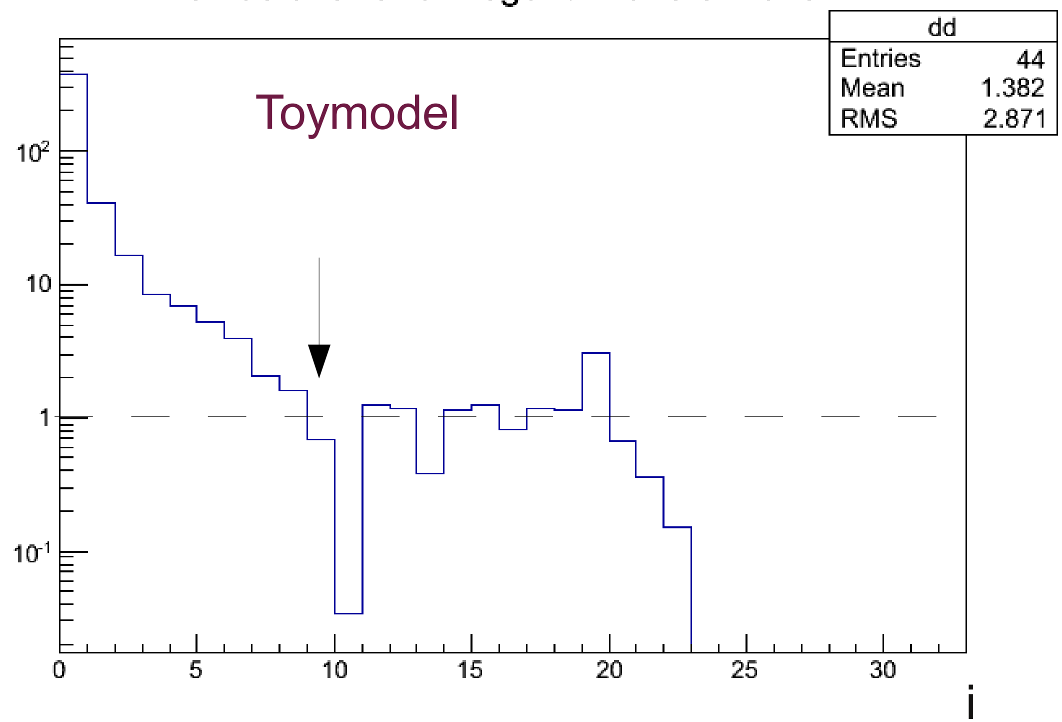
R=USV^T //SVD decomposition of R

d:=U^Tm' //definition of d vector

Nucl.Instrum.Meth. A372 (1996) 469-481



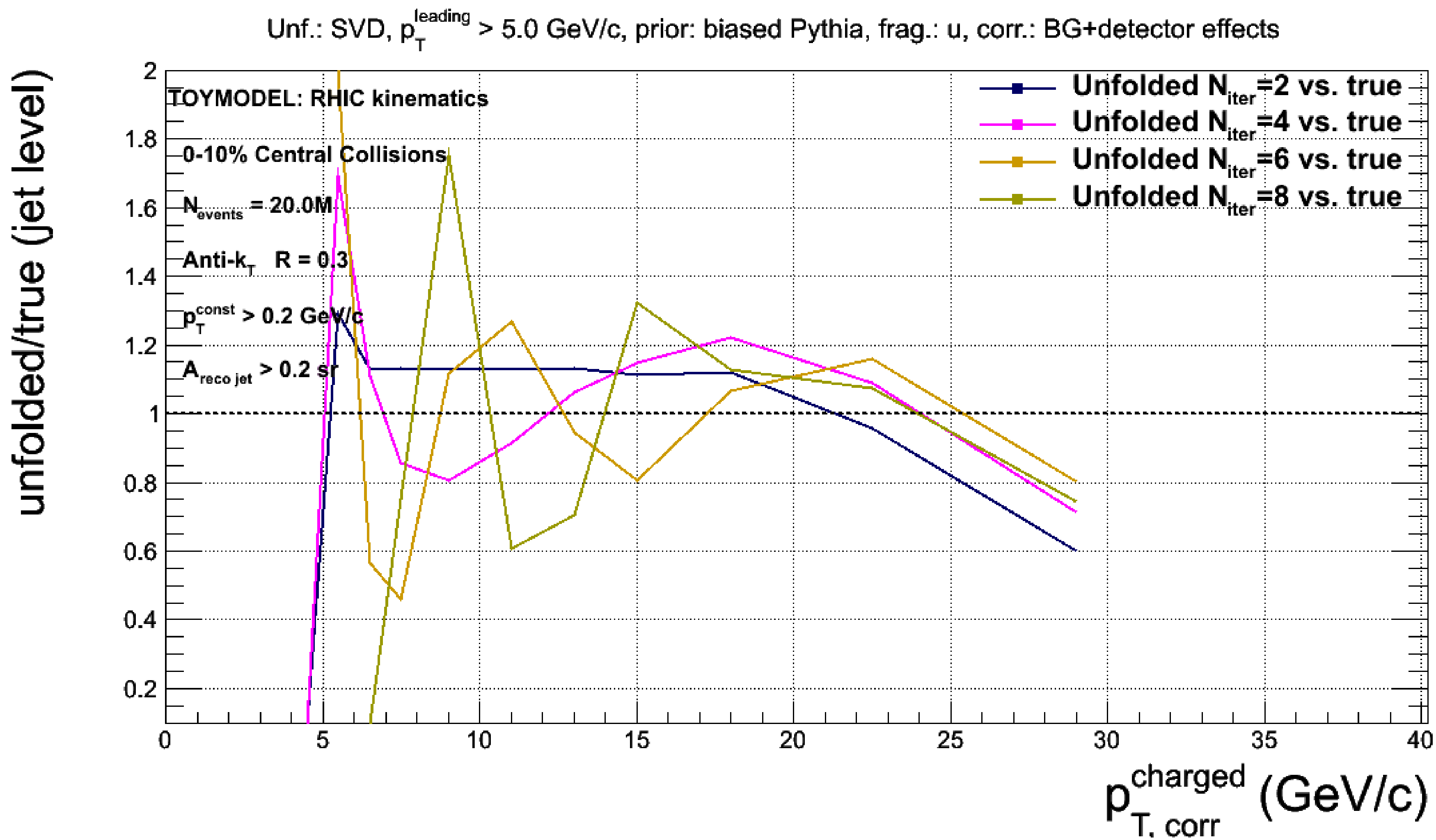
d vector after orthogonal transformation



=> in theory, optimal *k*=9-10...

SVD: choice of regularization parameter *k*

Toymodel simulation - closure test (we know the generated distribution):



...from closure test =>already *k*=8 very poor example:

(weak)