Jet Measurements at STAR

Jan Rusňák for the STAR Collaboration

Nuclear Physics Institute ASCR

Outline

Jets in p+p:

test of pQCD

baseline for Au+Au measurements

Jets in Au+Au:

access to medium properties

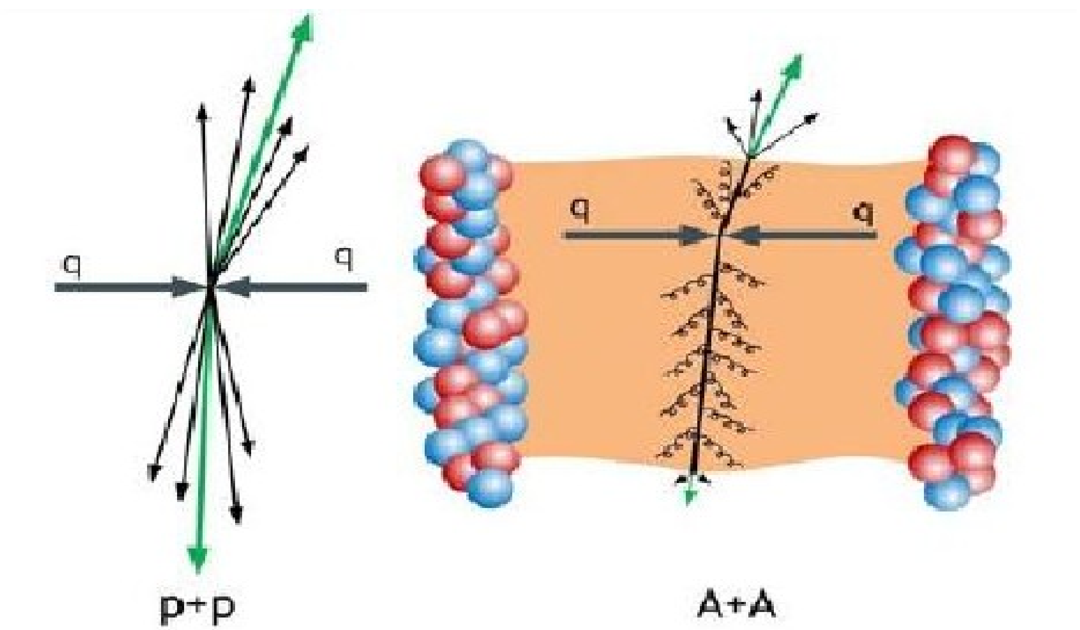
- Inclusive Charged Jets
- Semi-inclusive Recoil Charged Jets
- Di-jet Asymmetry A_J

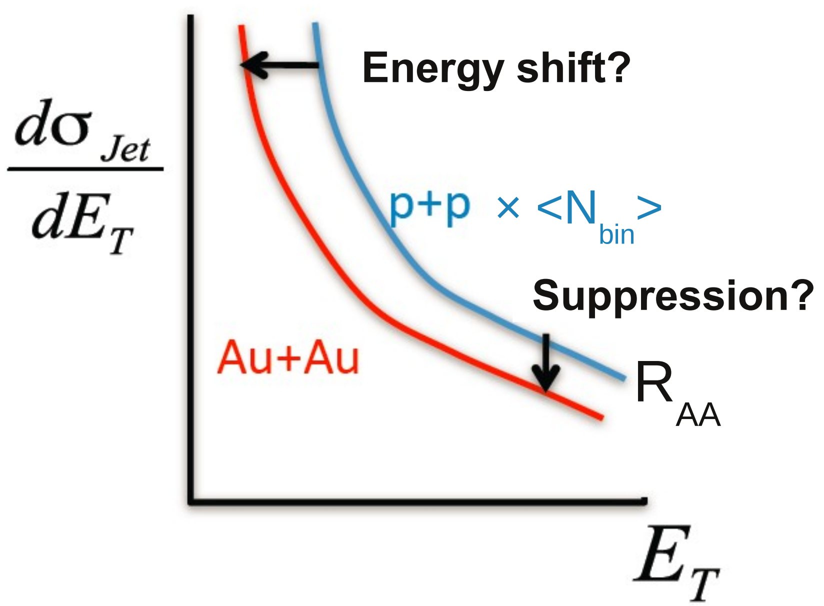
Motivation for Jet Studies

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

Elementary collisions: fundamental test of pQCD

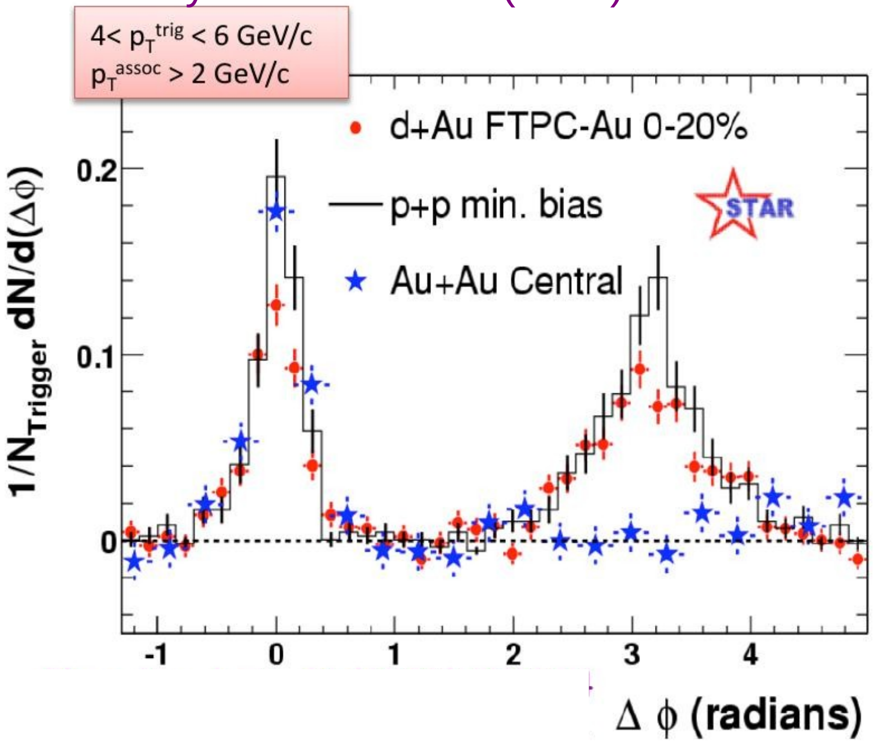
Heavy-ion collisions: probe of hot and dense nuclear matter





Di-hadron Measurements: Proxy to Jets

Phys. Rev. Lett. 91 (2003) 072304



intermediate trigger momentum:

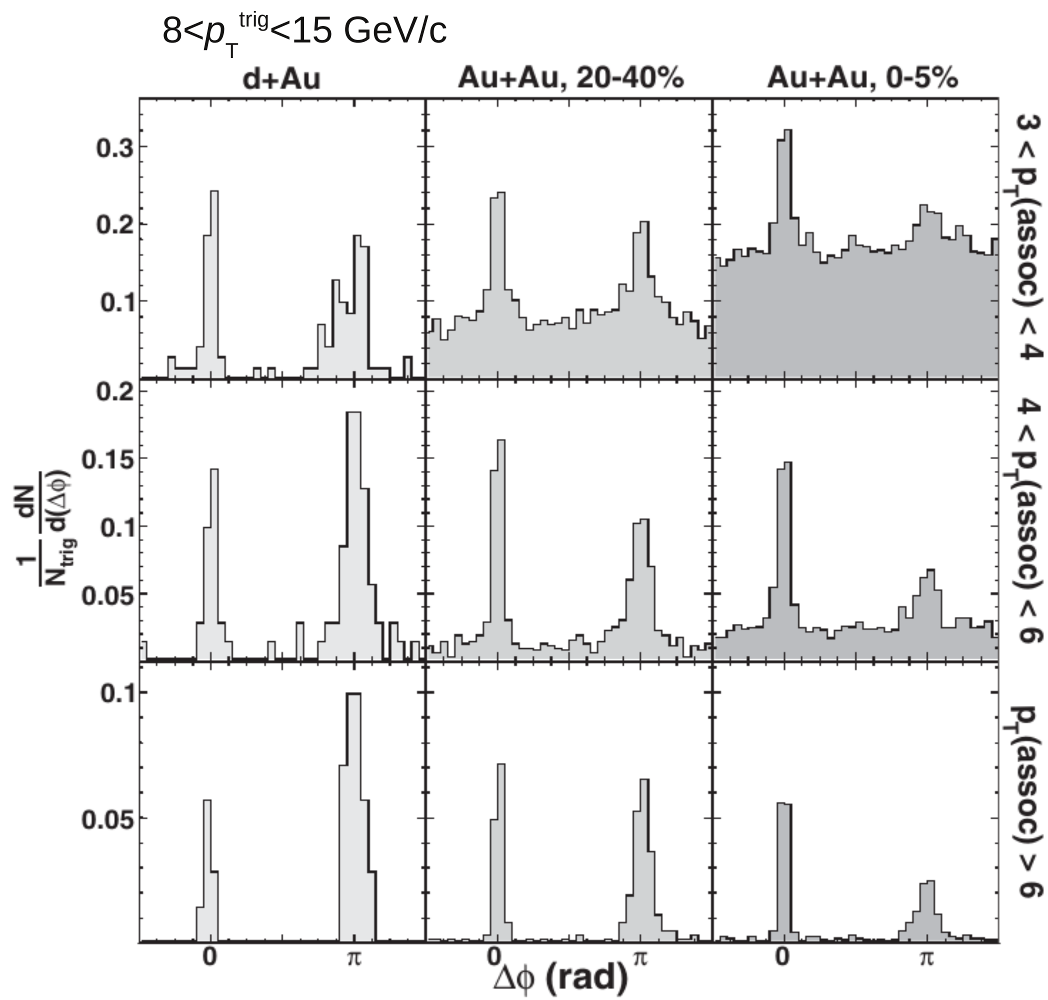
Central Au+Au collisions: suppression

of away side jet - “jet quenching“

d+Au: no suppression -> medium effect

Better understanding of jet quenching
=> full jet reconstruction

Phys. Rev. Lett. 97 (2006) 162301

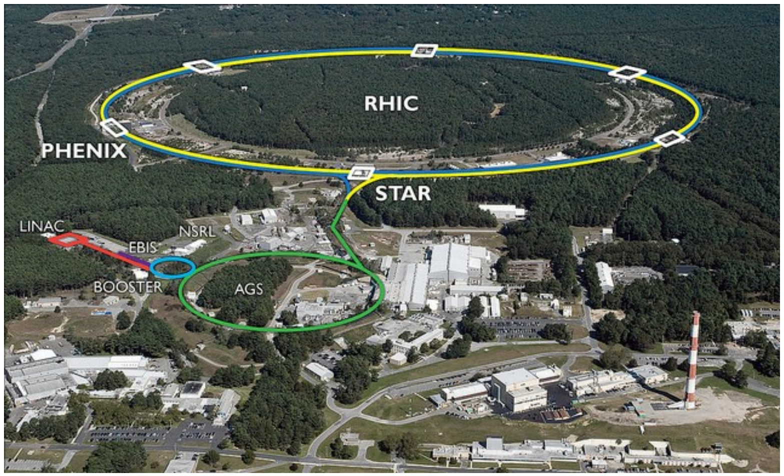


high trigger momentum:

Central Au+Au: away-side “jet” suppression
of the order of charged hadrons suppression

STAR Experiment

Relativistic Heavy Ion Collider (RHIC)

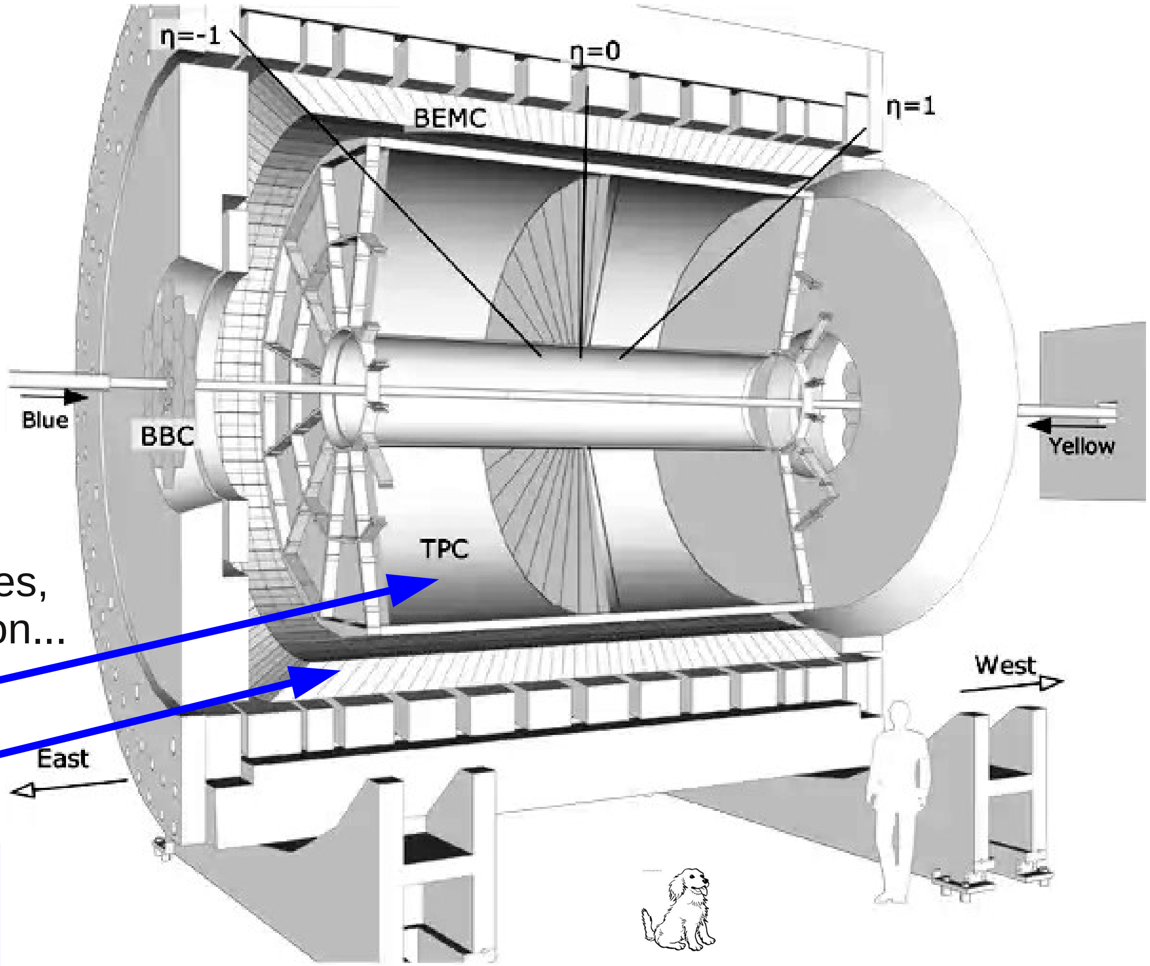


Unique machine:
polarized *p+p* collisions, wide range of species, $\sqrt{s_{NN}}$ from 5.5 to 510 GeV, asymmetric collision...

Time Projection Chamber

Barrel ElectroMagnetic Calorimeter

Solenoidal Tracker at RHIC (STAR)



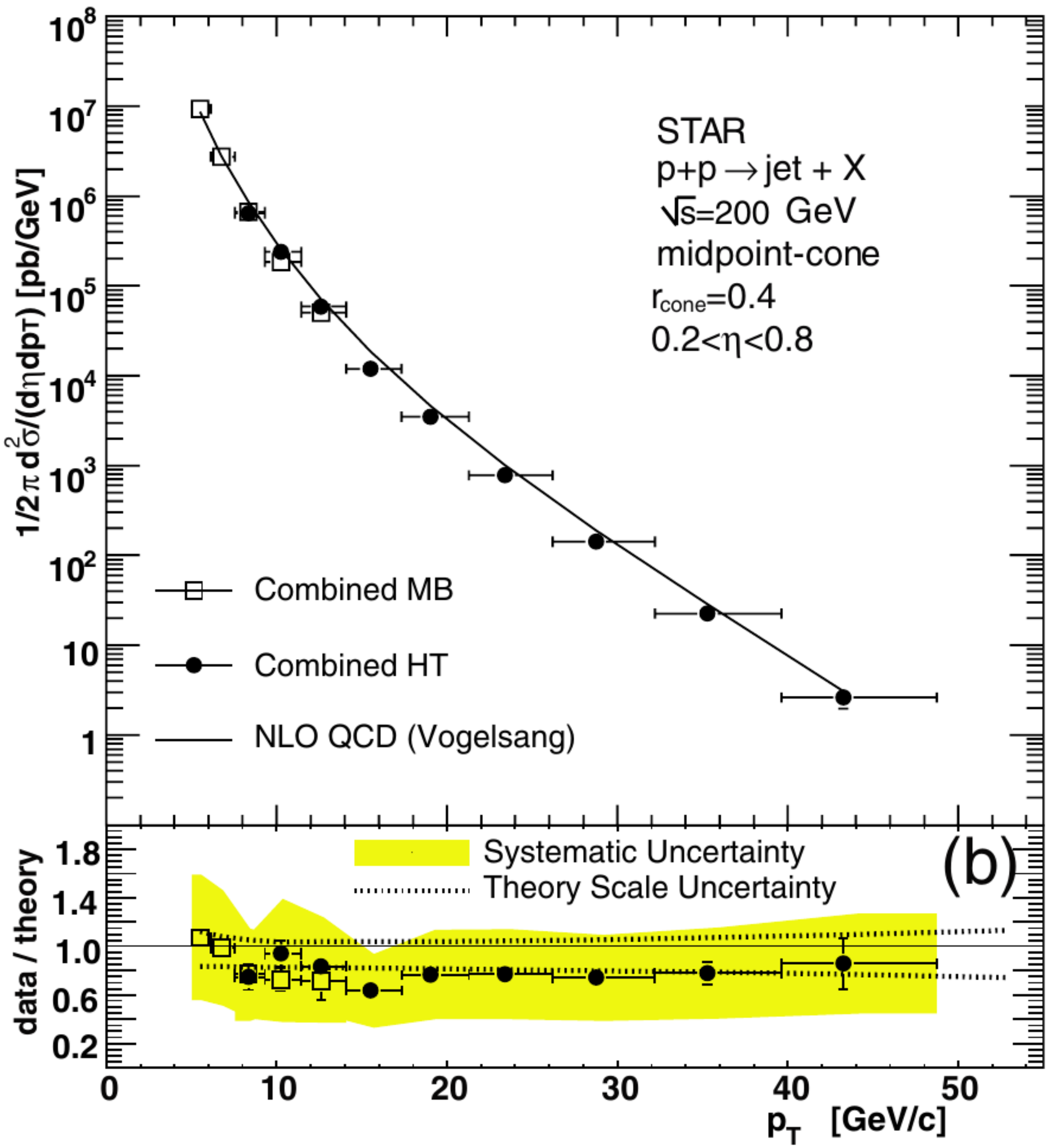
Inclusive jets, hadron+jet:
- TPC tracks only
- Run 11 Au+Au $\sqrt{s_{NN}}$=200GeV

Di-jet asymmetry A_J:
- TPC tracks + BEMC towers
- Run 7 Au+Au $\sqrt{s_{NN}}$=200GeV

full azimuthal coverage
pseudo-rapidity coverage: -1<η<1
TPC: low-momentum tracking (0.1 GeV/c)

Inclusive Full Jets in p+p Collisions

Phys.Rev.Lett.97:252001



First measurement (2006):

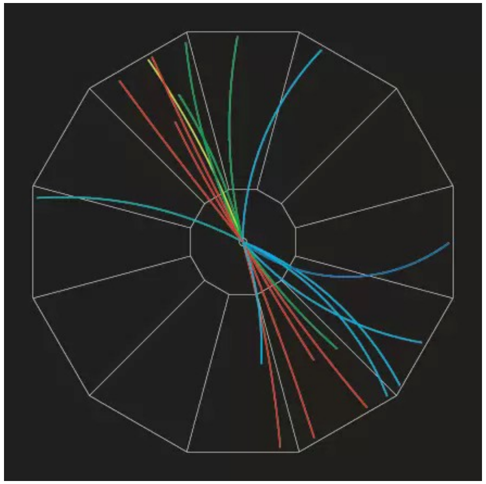
- midpoint-cone algorithm
- good agreement with pQCD

new measurement using high statistics Run9 data on the way

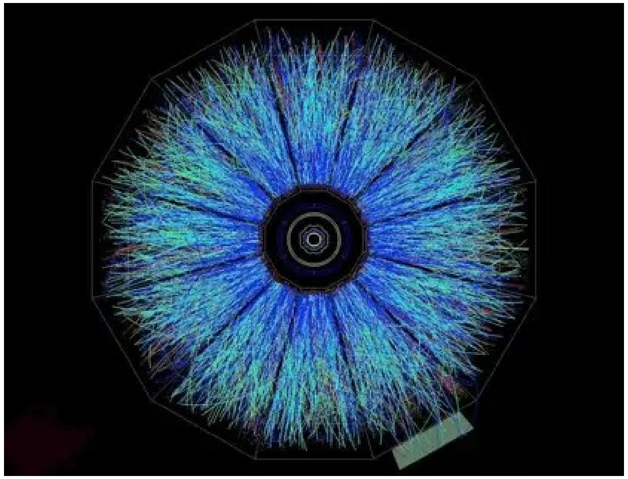
Jet Reconstruction in Heavy Ion Collisions

- extremely challenging task – due to high multiplicity environment with **large and fluctuating background**
- discrimination between hard jets and "combinatorial" fake jets: not strictly possible on event-by-event basis
- jet quenching over a wide kinematic region can only be studied on an ensemble-averaged basis

p+p

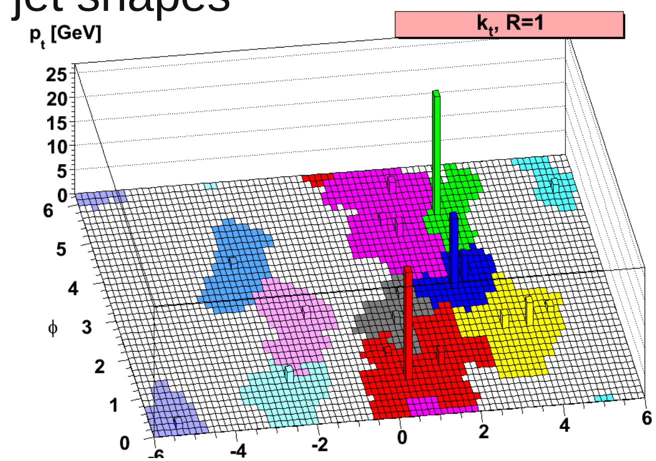


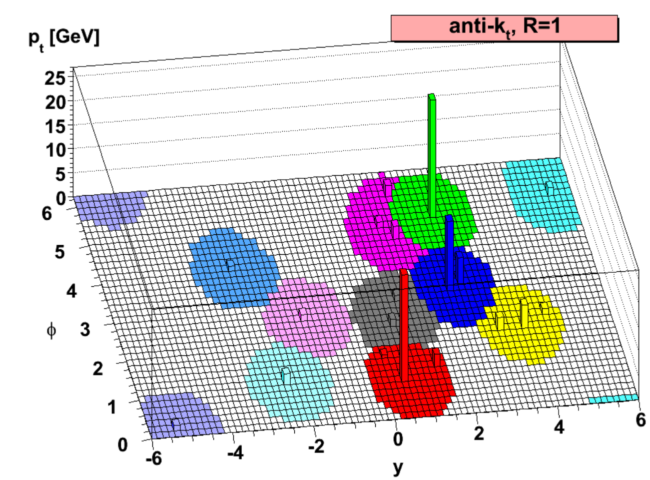
Au+Au



Jet Reconstruction Algorithms

- infrared and collinear safe reconstruction algorithms
  (FASTJET [Cacciari, Salam, Soyez : Eur.Phys. J. **C72** (2012) 1896])
- clustering algorithms:
  - k_T- starts clustering from low-p_T particles; irregular jet shapes
  - anti-k_T - starts clustering from high-p_T particles; cone-like jet shapes





arXiv:0906.1598

<u>key steps:</u>

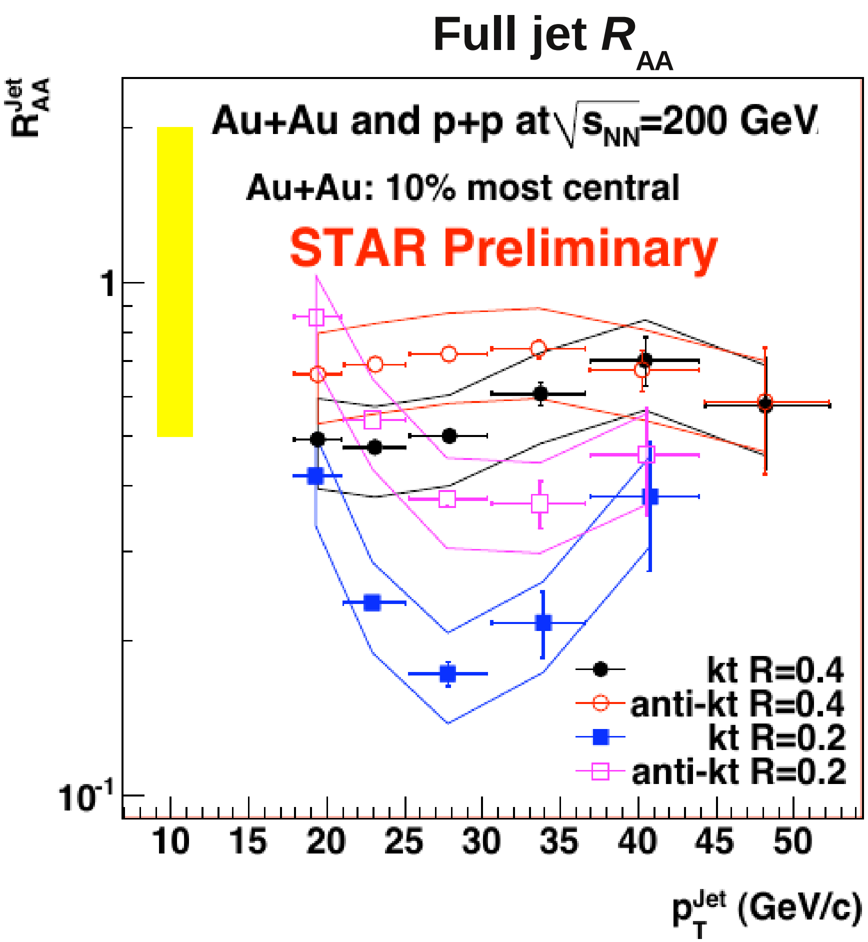
- jet reconstruction: different resolution parameters *R*
- correction for background energy density $\rho = med\left\{\frac{p_{T,i}}{A_i}\right\}$ $\quad A_i$ ...jet area

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

Full jet reconstruction in Au+Au collisions at STAR

- STAR: first experiment to perform full jet reconstruction in HI collisions

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

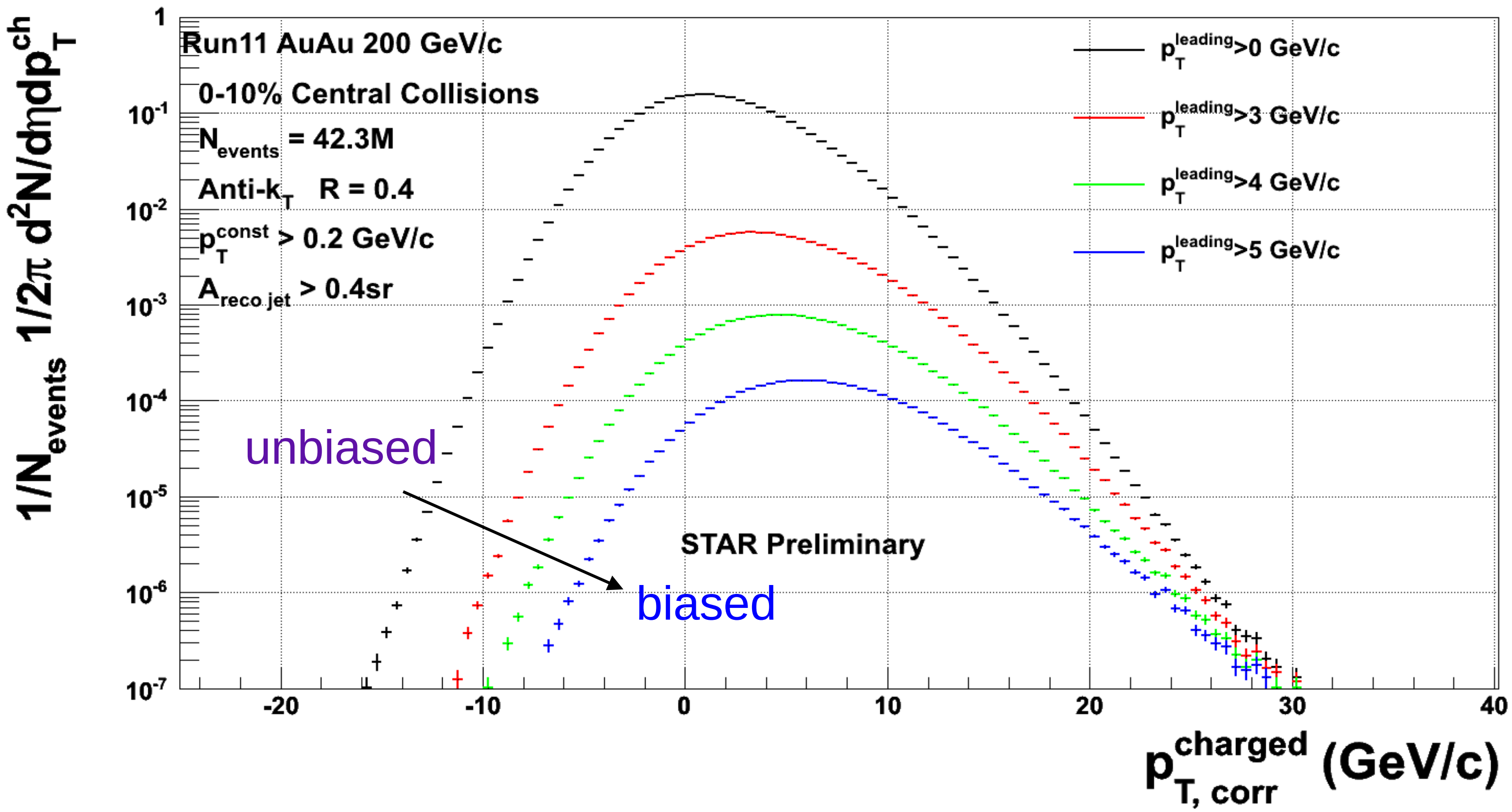


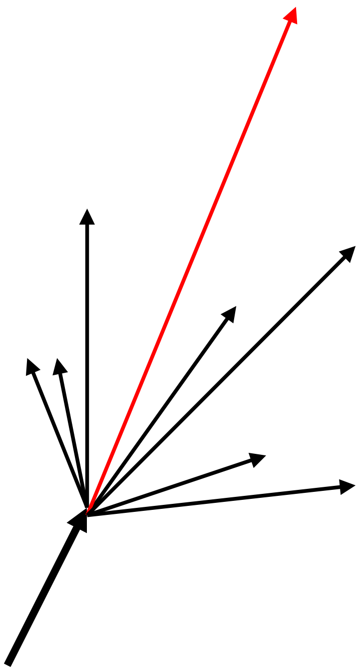
- Run 7 data
- Baseline: Run 6 *p+p* data
- R_{AA} inconclusive: large systematic uncertainties

Higher statistics recorded, new techniques developed since then

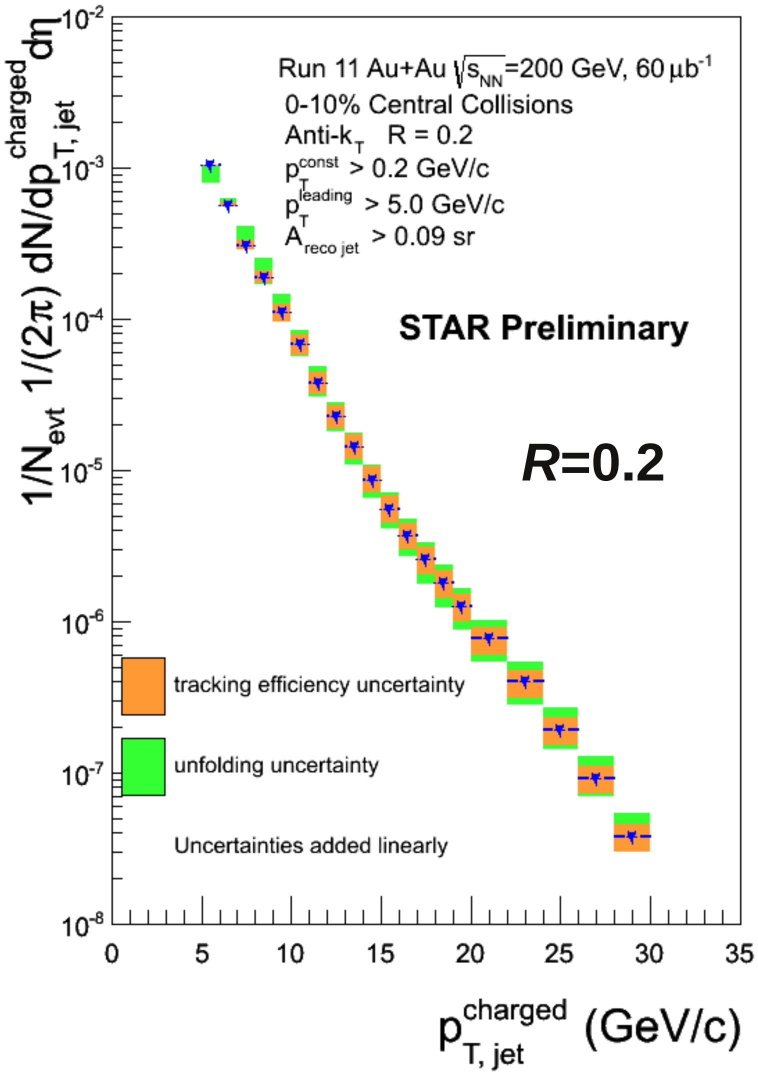
Inclusive Jet Measurement

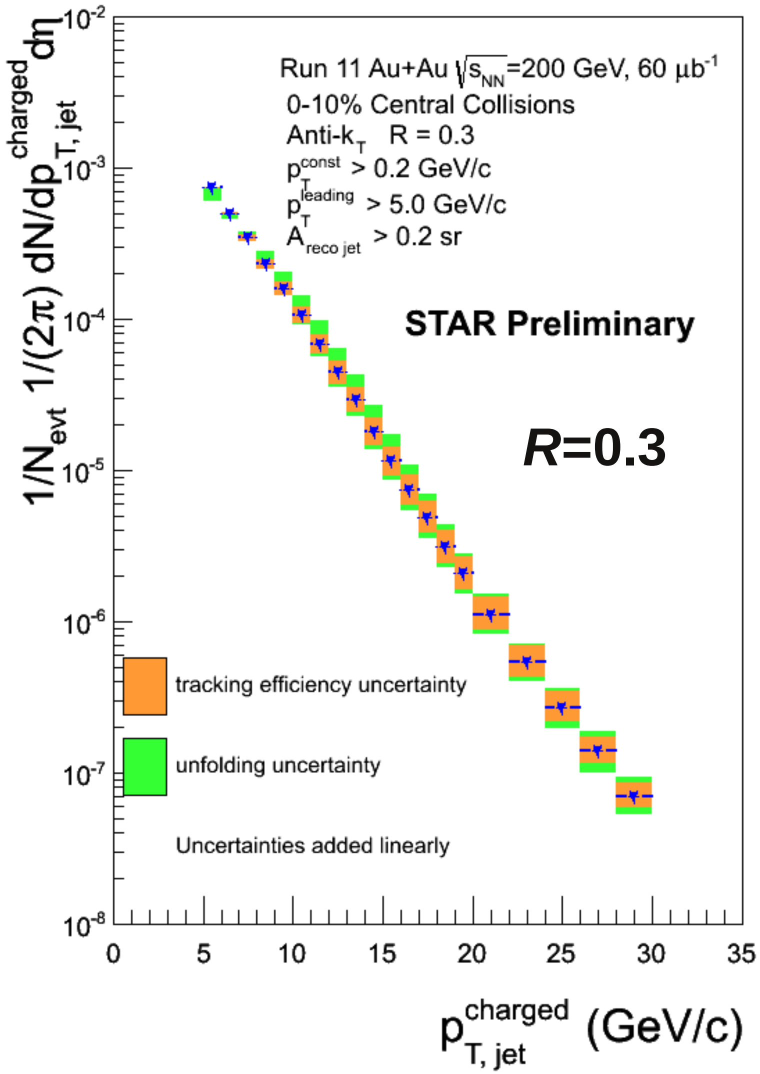
- combinatorial background reduced by a cut on leading hadron p_T
  [G. de Barros et al, Nucl. Phys. A910:314-318, 2013]
- induces bias (however jet can still contain many soft constituents)





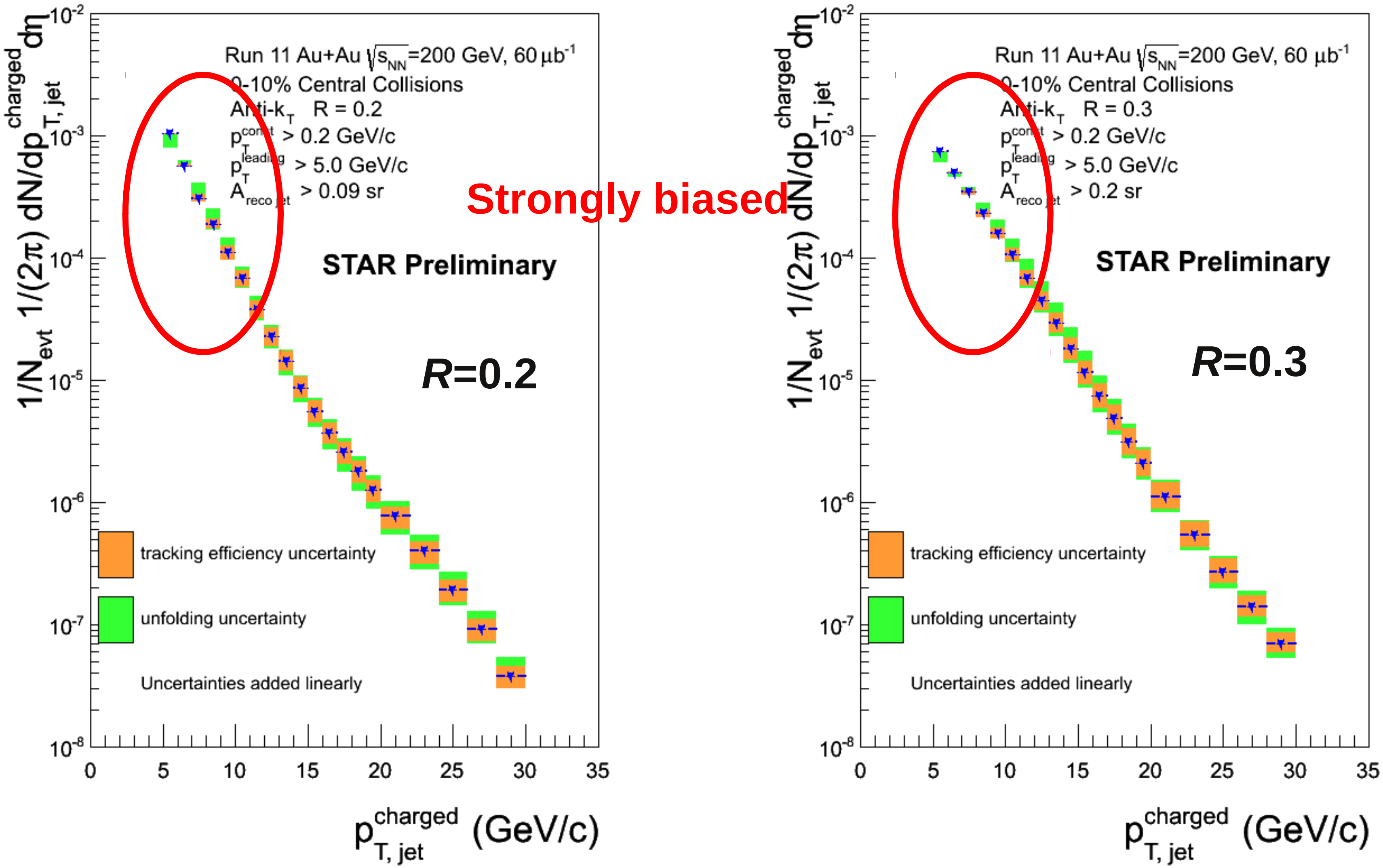
Inclusive Charged Jet Spectra





- Measured spectra corrected via Bayesian unfolding
- Jet energy scale resolution: roughly 5% (mainly due to track. eff. uncertainty)
- R_{AA}: Work in progress: further systematic uncertainties, pp baseline improvement

Inclusive Charged Jet Spectra



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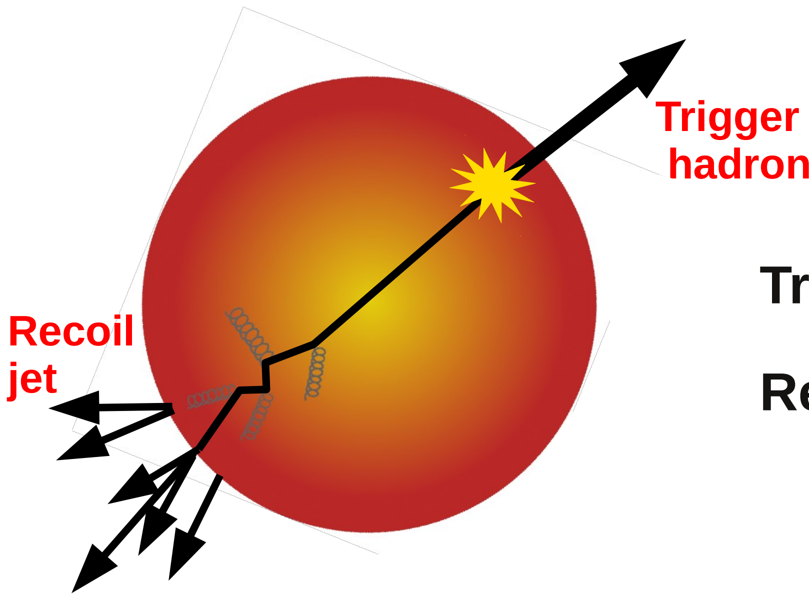
Semi-inclusive Recoil Jets



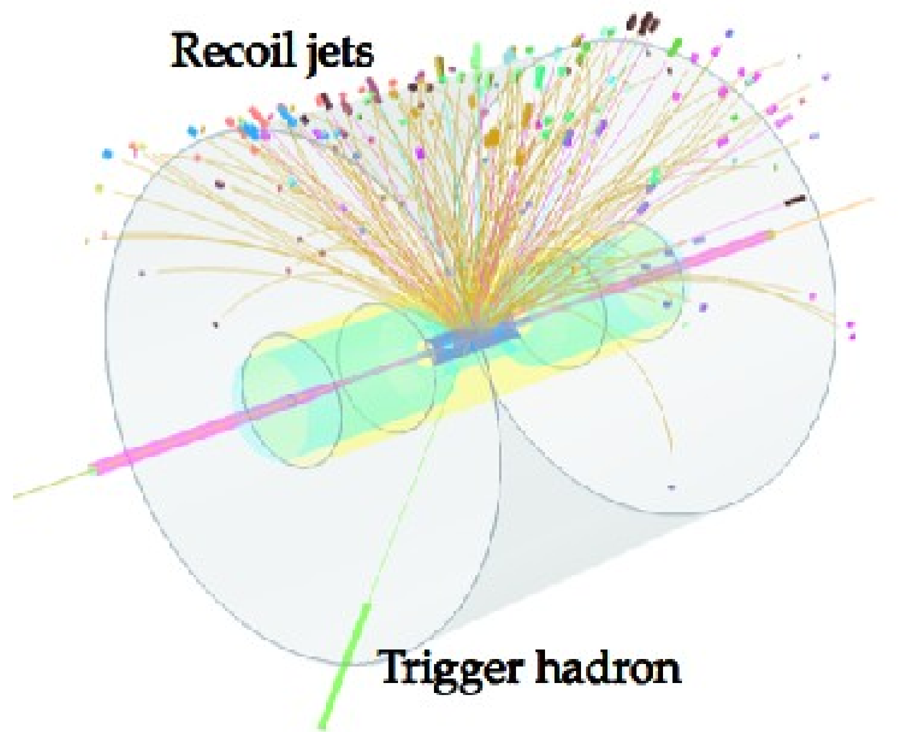
Trigger: high-p_T hadron => selects hard event

Recoil jet: no further cuts => unbiased

Observable:
Recoil jets per trigger

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

Measured | Calculable in NLO pQCD



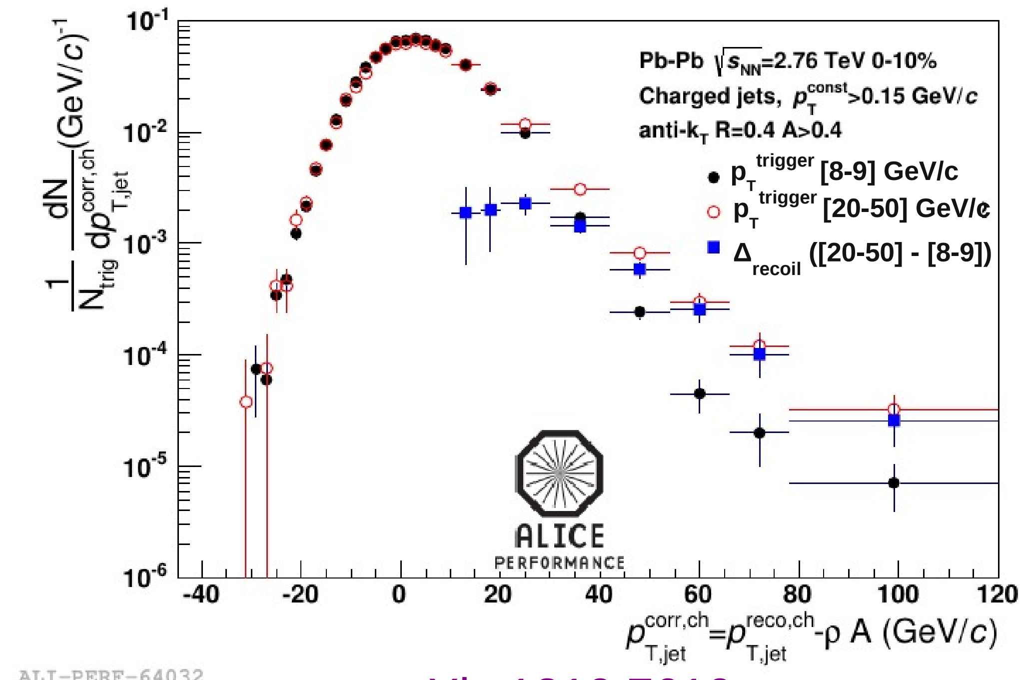
Semi-inclusive Recoil Jets

Analysis in STAR:

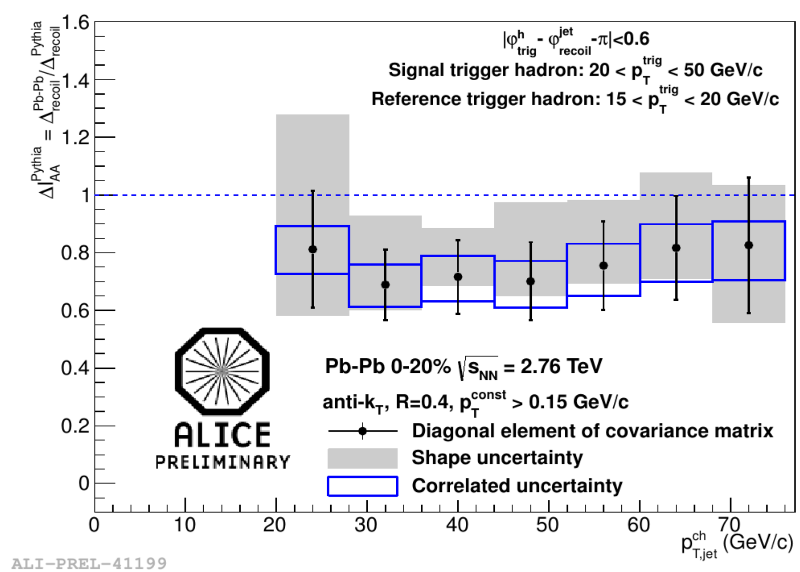
- Recoil jet azimuth: |Δφ-π|<π/4
- No rejection of jet candidates on jet-by-jet basis
- Jet measurement is collinear-safe with low infrared cutoff (0.2 GeV/c)
- **BKG subtraction: Mixed event technique**

ALICE:

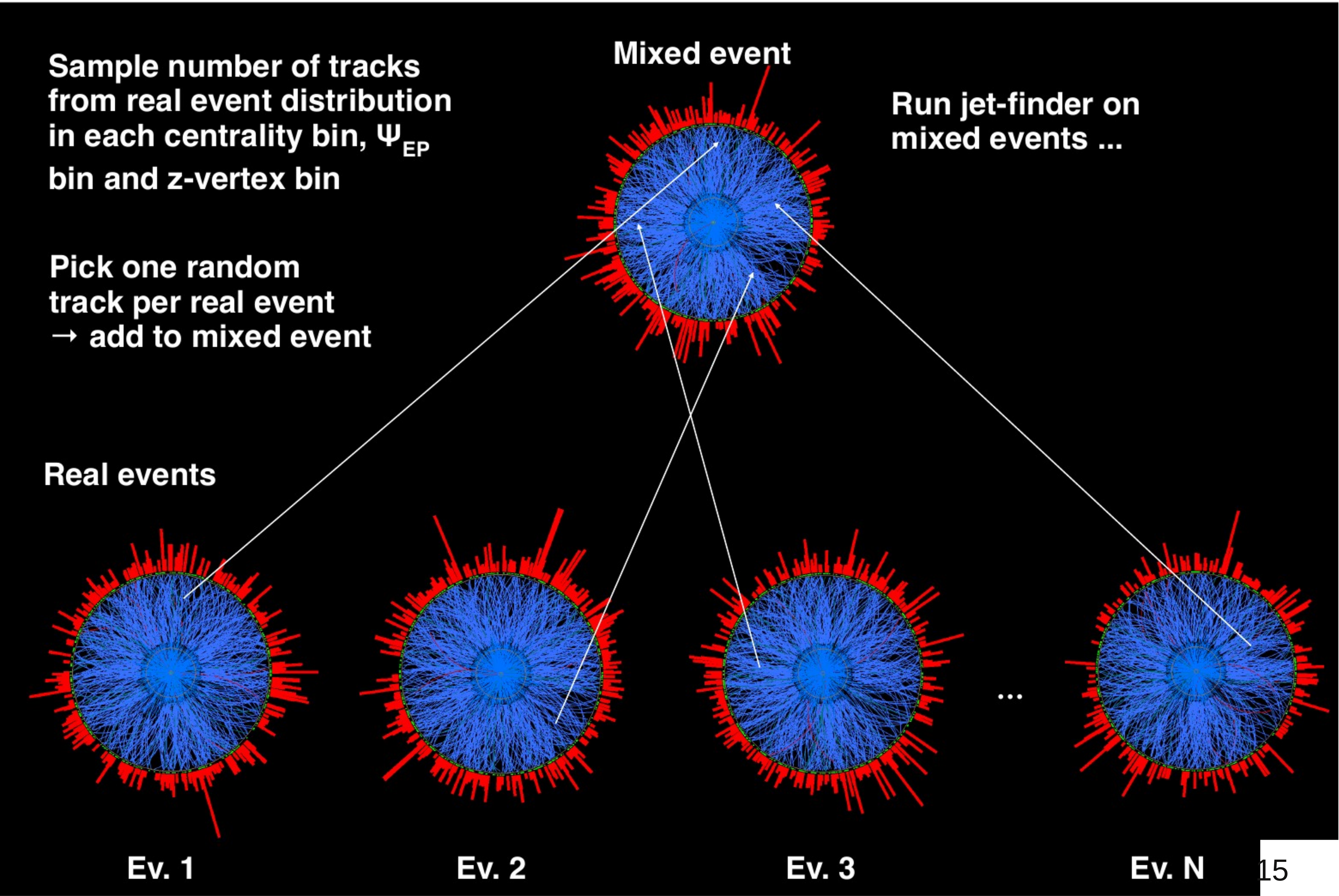
- **BKG subtraction: two different trigger pT ranges**



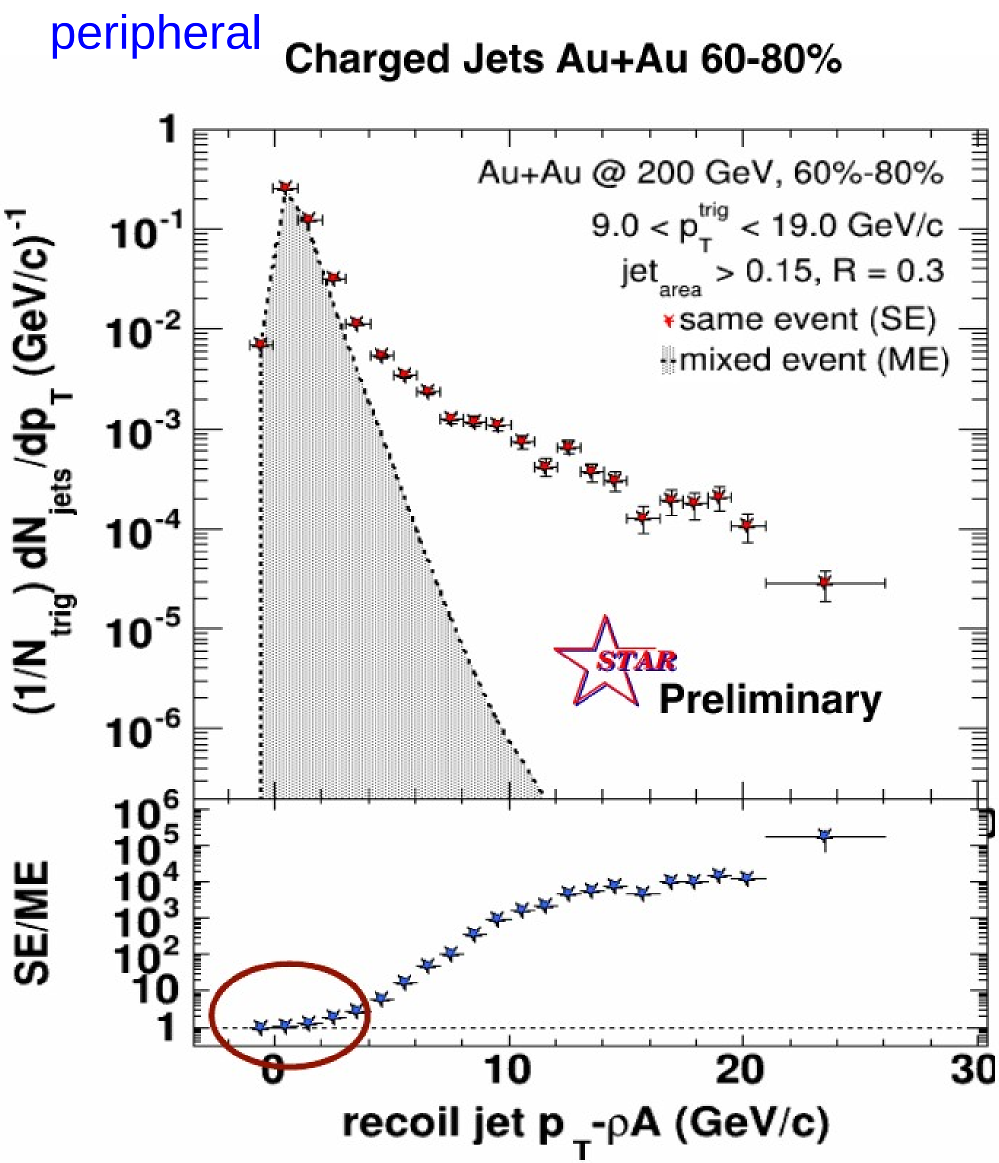
arXiv:1210.7610

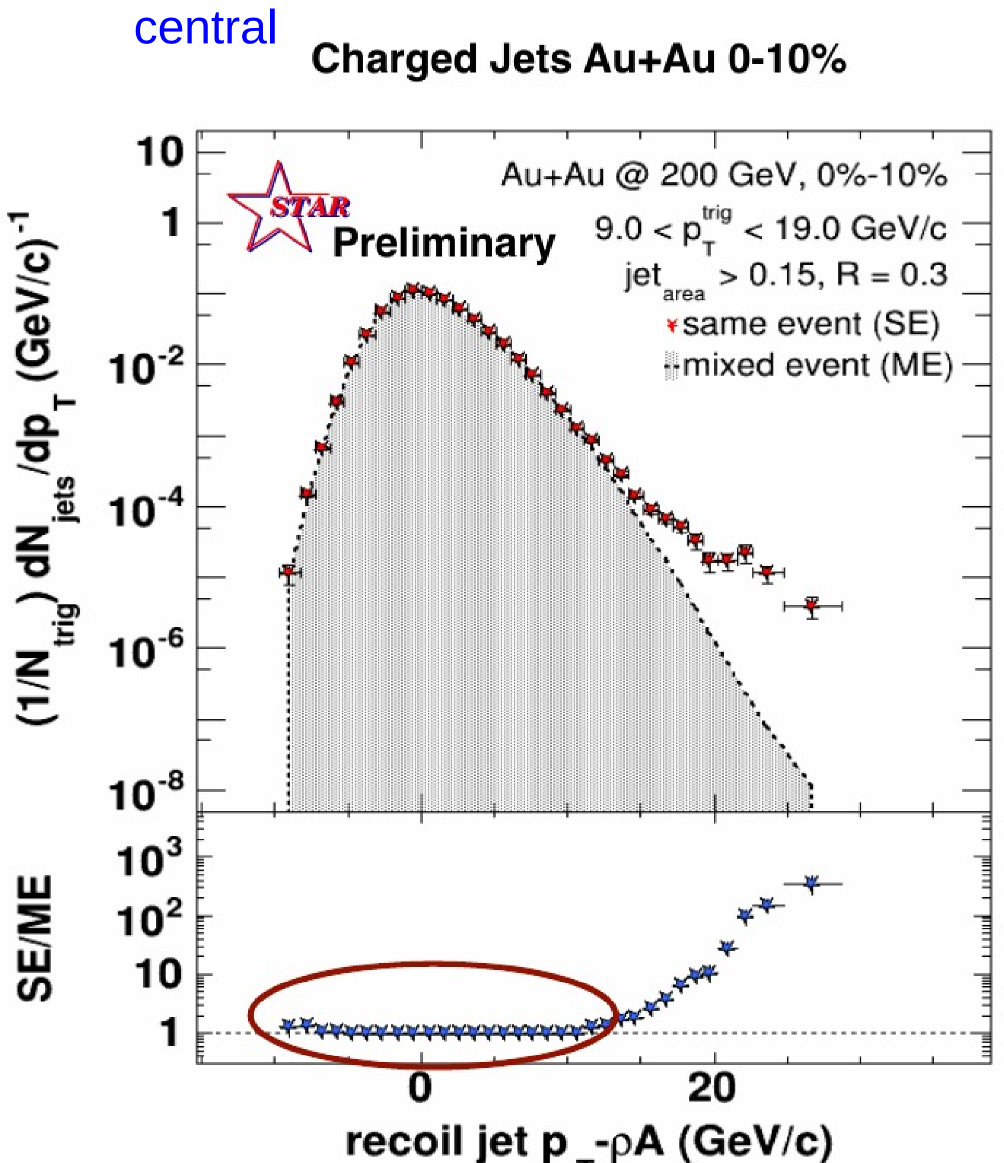


Background Estimation: Mixed Events



Semi-incl. Recoil Jets: Same Event and Mixed Event



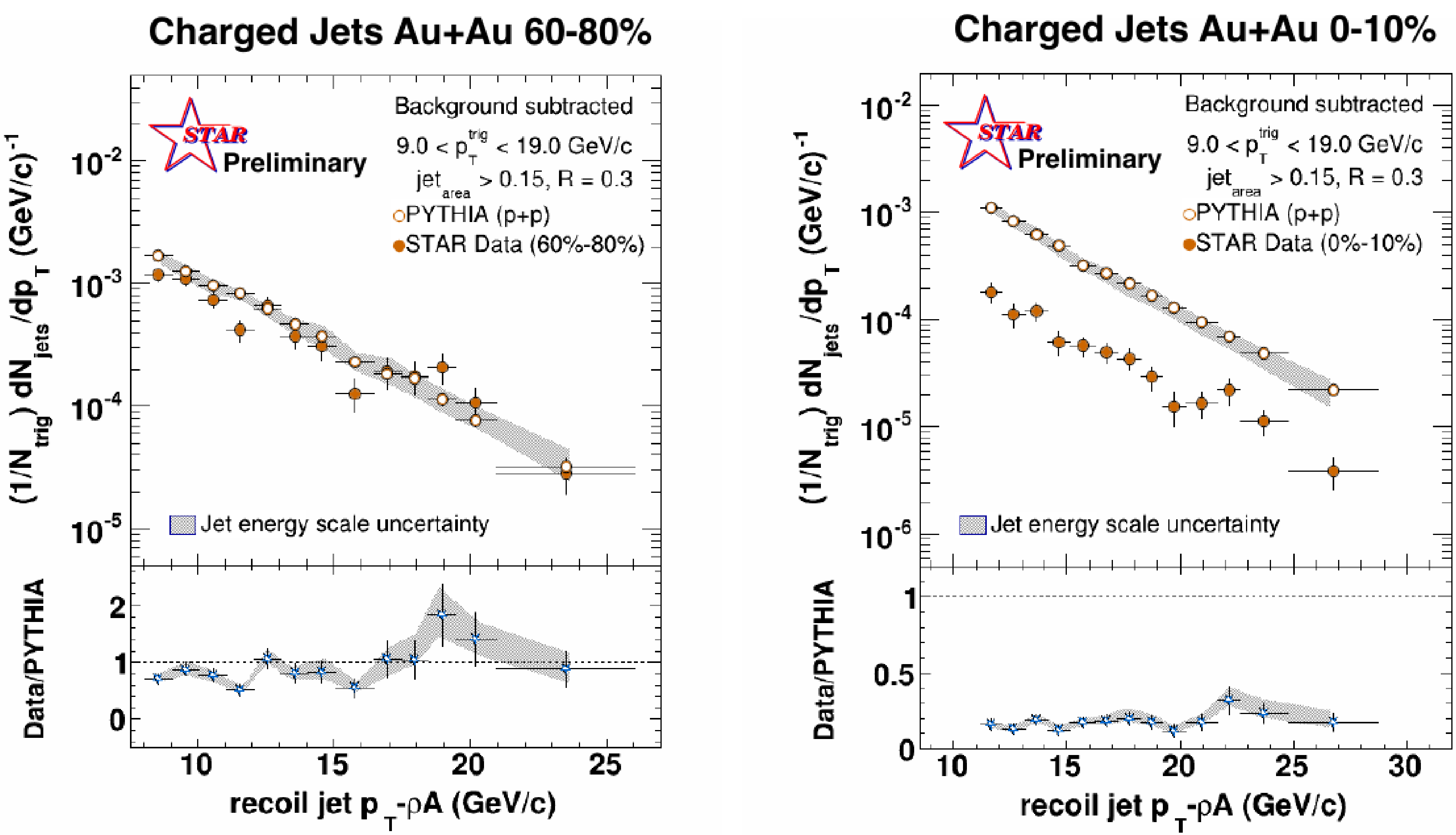


- Mixed Event describes combinatorial background well

Signal = (SE-ME) distribution

Semi-inclusive Recoil Jets: Signal (SE-ME)

R=0.3, p_T^{trig}>9 GeV/c

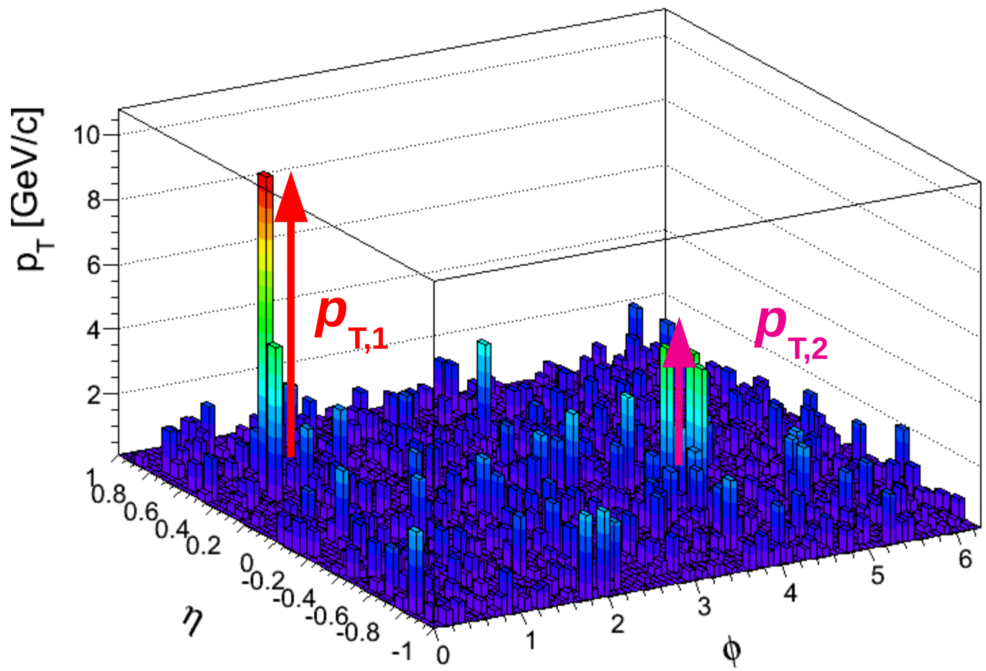


- PYTHIA smeared by simulation of detector effects and BKG fluctuations
- Central collisions show strong suppression with respect to peripheral

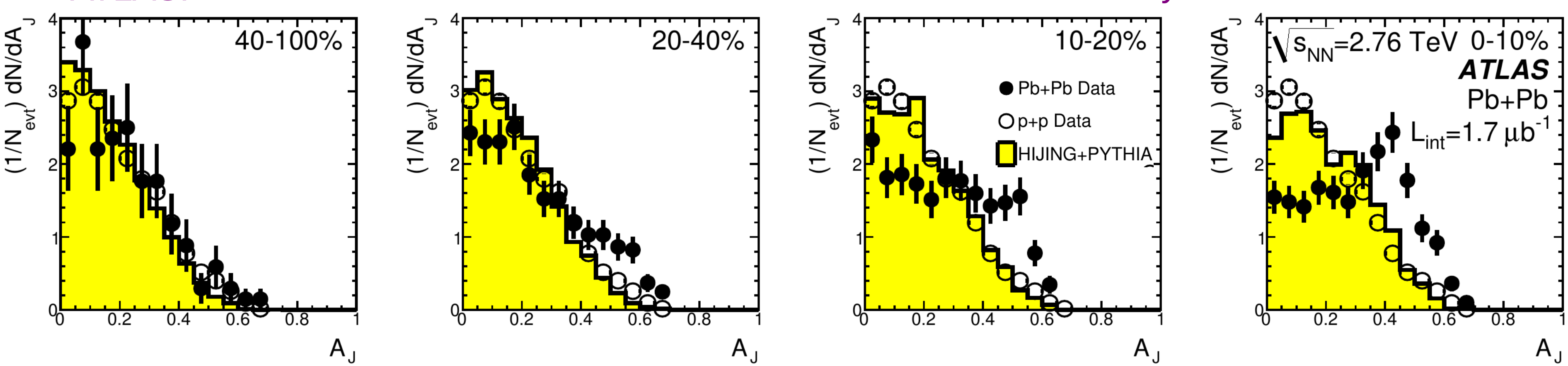
Jet Imbalance A_J Measurements

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

- di-jet momentum asymmetry
- signal of medium-induced jet modification

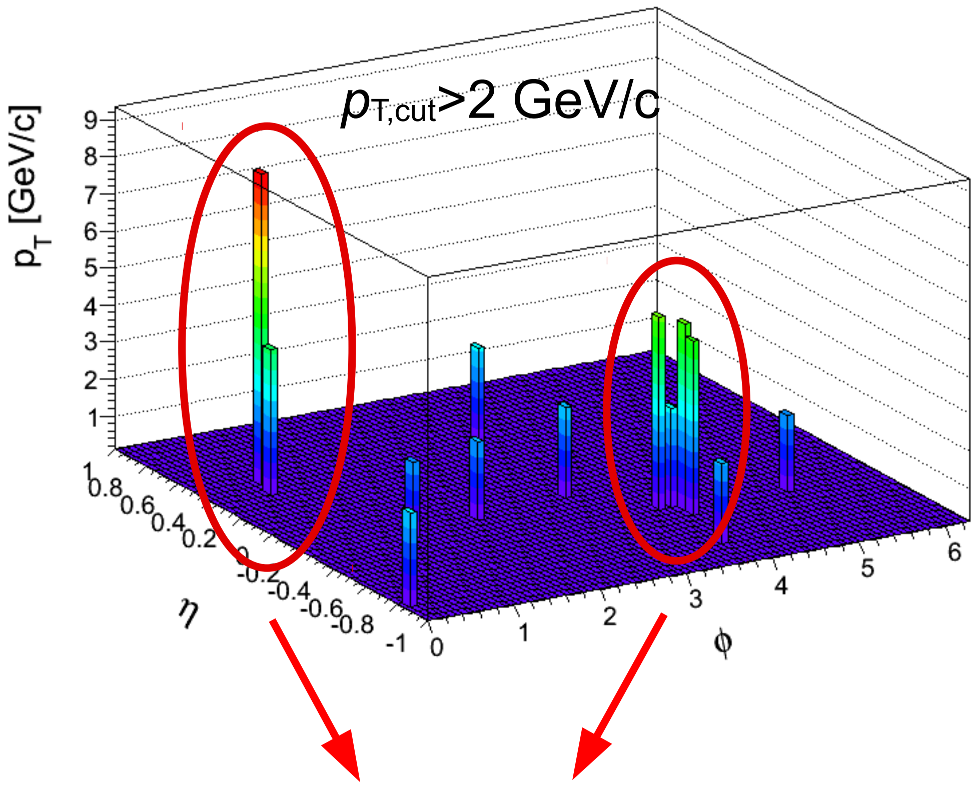


ATLAS: Phys. Rev. Lett. 105 252303



A_J Calculation in STAR

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



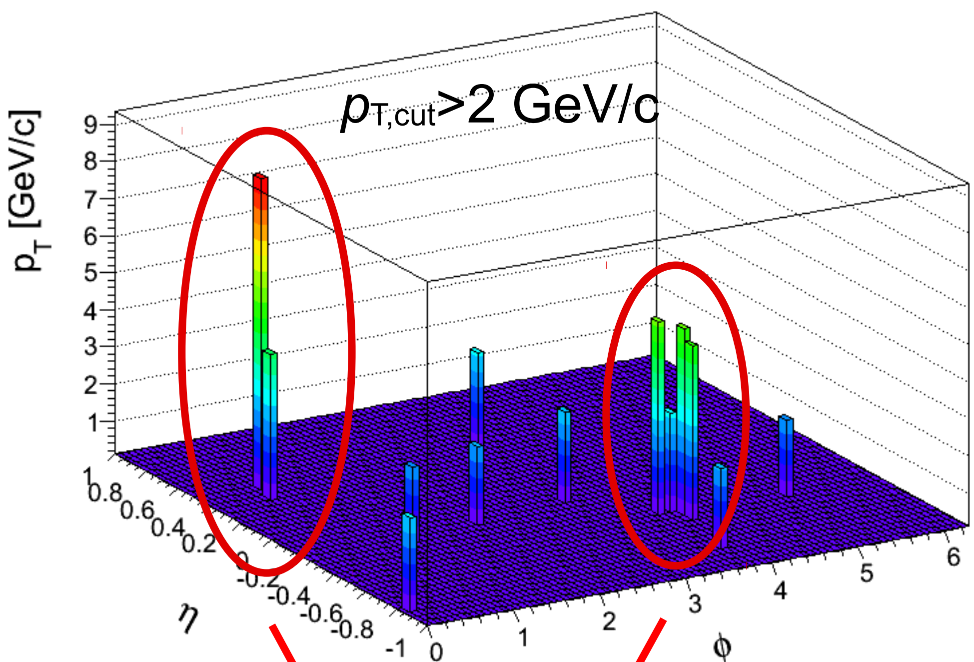
Calculate A_J with constituent
HIGH $p_{T,cut}$>2 GeV/c

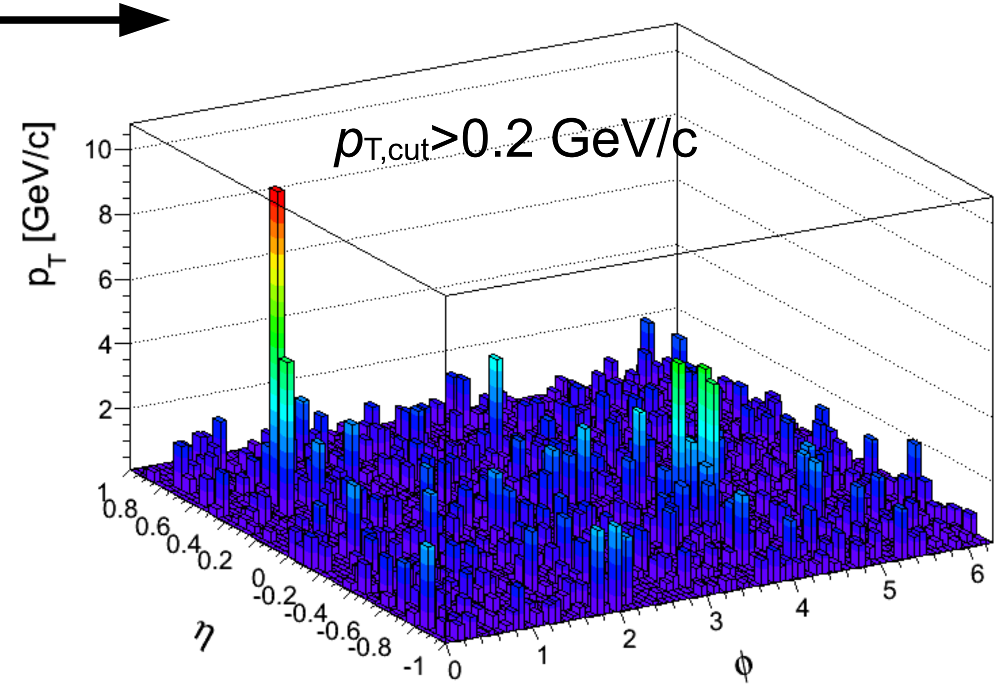
$$A_J = \frac{p_{T,1} - p_{T,2}}{p_{T,1} + p_{T,2}}, \quad p_T = p_T^{rec} - \rho \times A$$

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 ...





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A_J Calculation in STAR

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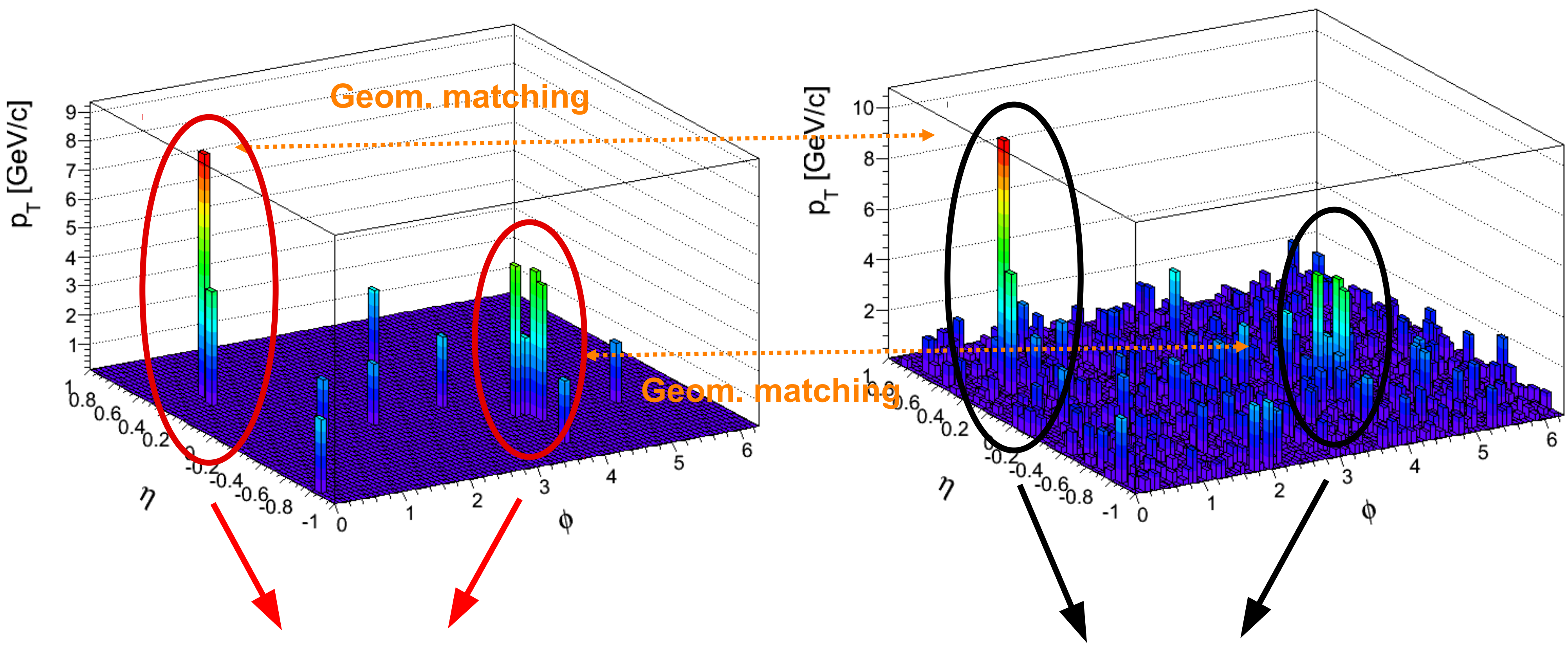
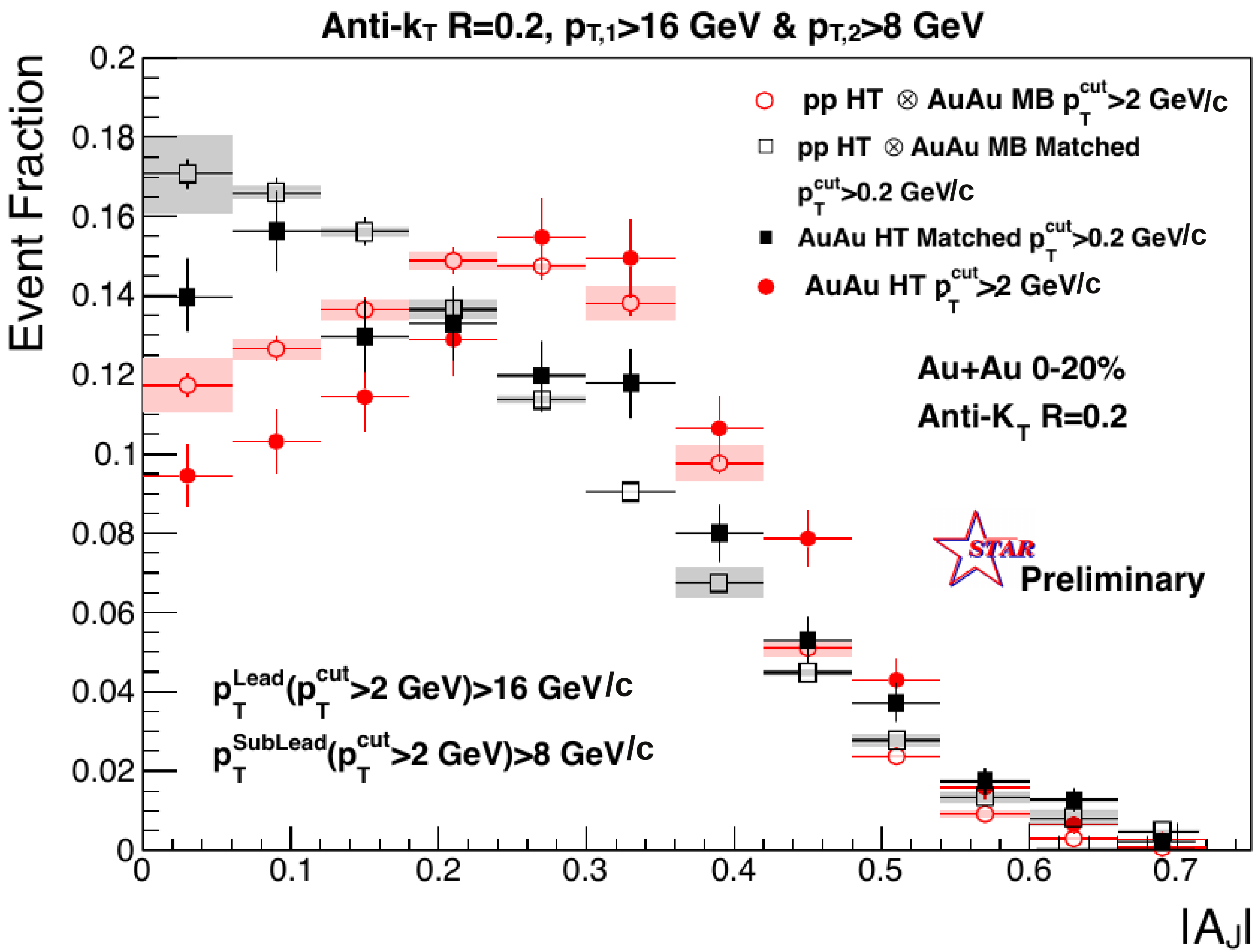


Calculate A_J with constituent **HIGH $p_{T,cut}$>2 GeV/c**

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

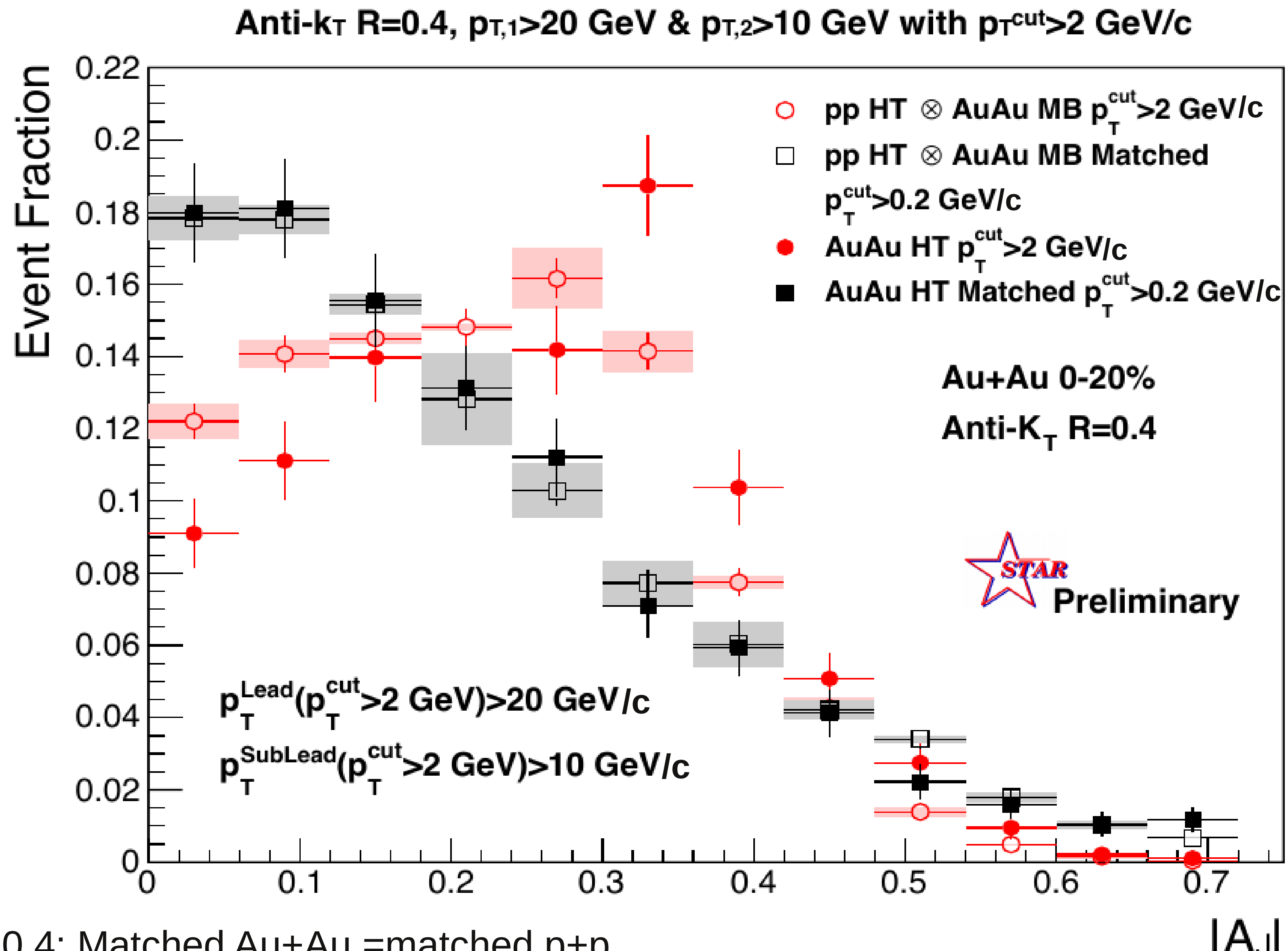


p-value<10^{-10}
(stat. error only)

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

Summary

- **Inclusive charged jet spectrum extracted**

- **Semi-inclusive recoil charged jets:**
  - Background estimated with the new mixed event technique
  - Suppression in HI collisions with respect to PYTHIA for R=0.3 jets

- **Di-jet asymmetry A_J:**
  - no significant difference between Au+Au and p+p

    for low p_T constituent cut for R=0.4

OUTLOOK:

- utilize Run 14 statistics + BEMC

BACKUP

Heavy Ion Jet Reconstruction

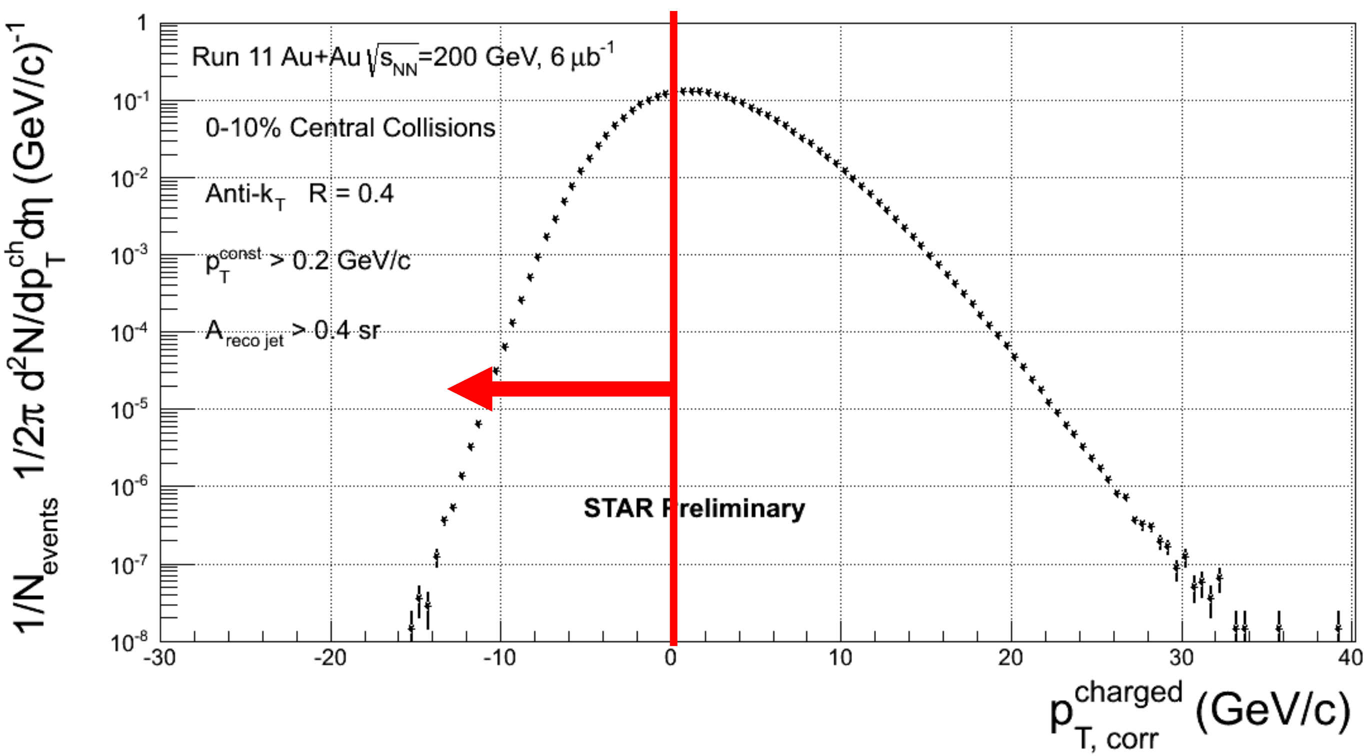
- take all jets in acceptance
- Jet candidates: reconstructed using anti-*kT* algorithm
- jet area *A*: Fastjet definition
- bckd. energy density – calculated event-wise (*kT*):

  (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

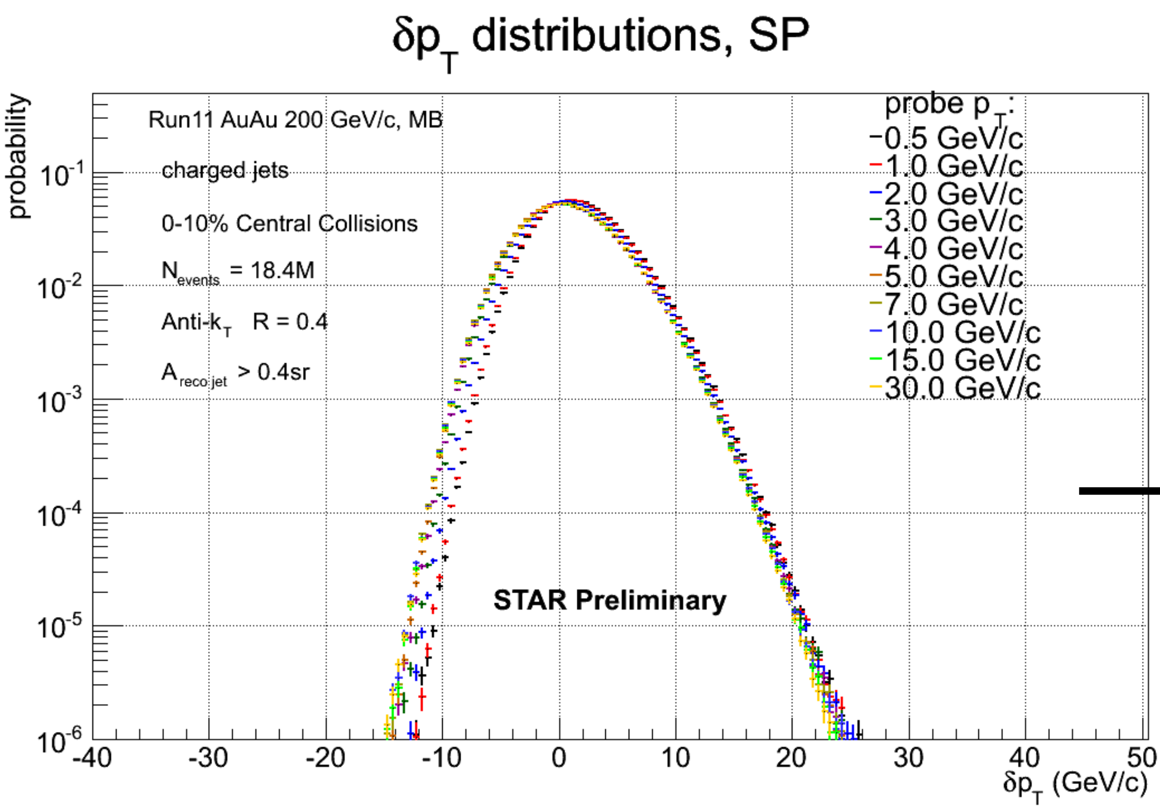
Influence of bckg fluctuations: δp_T Distribution

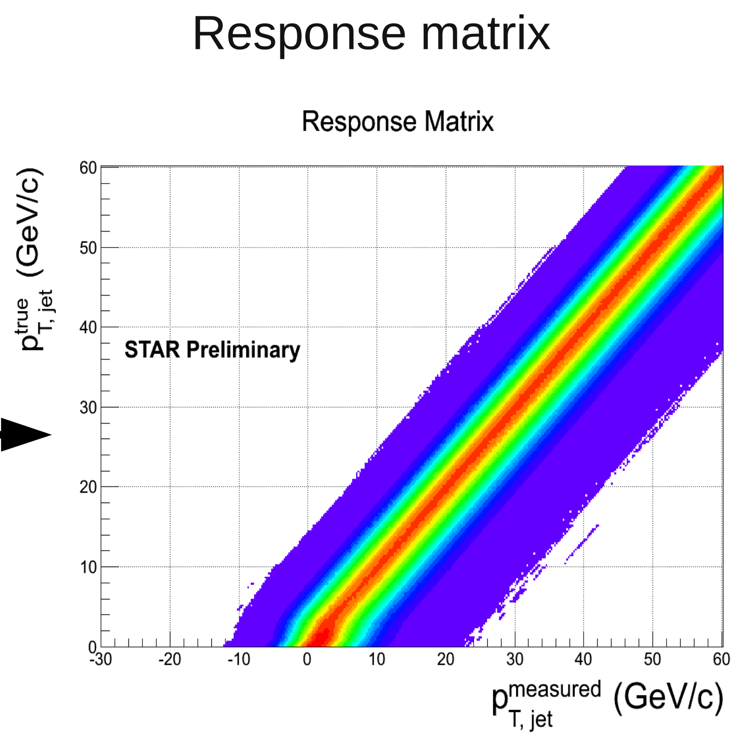
Effect of background on jet finding:

- embedding of a known jet into an event -> jet reconstruction -> δp_T

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

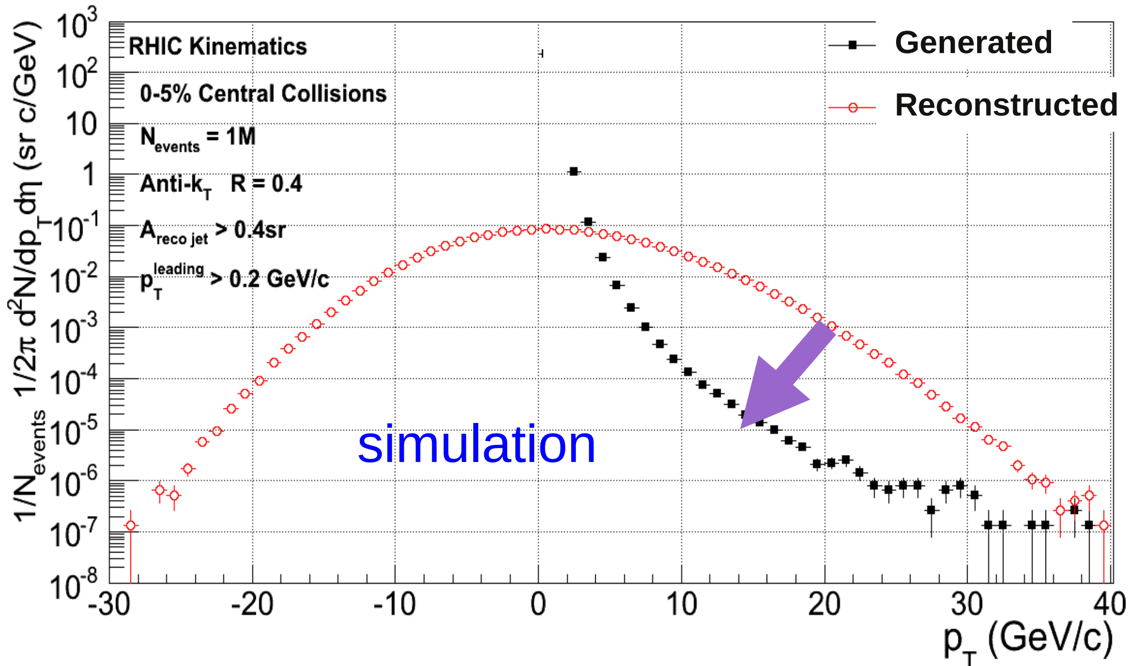
- ensemble-averaged δpT distribution -> measurement of the response matrix





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]*

.::Unfolding Based on Bayes' Theorem::.

- first attempt - we use an iterative procedure based on Bayes' theorem
- it relates the conditional probability for a Cause to generate given Effect

$P(C_i|E_j)$ to its inverse $P(E_j|C_i)$

$$P(C_i|E_j) = \frac{P(E_j|C_i) \cdot P_0(C_i)}{\sum_{l=1}^{n_C} P(E_j|C_l) \cdot P_0(C_l)}$$

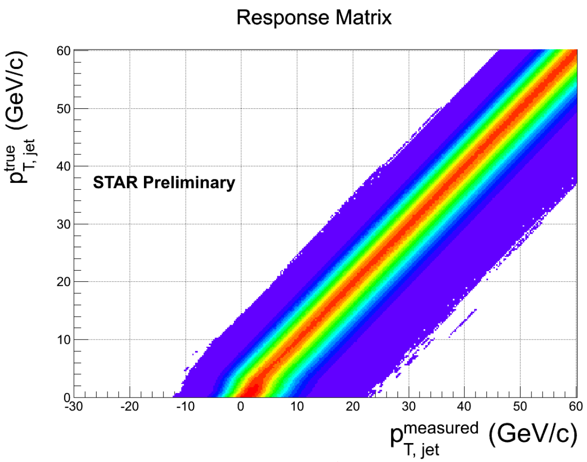
the Effect distribution can be then “unfolded” to the cause distribution:

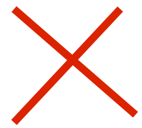
$$n(C_i) = \frac{P(E_j|C_i) \cdot P_0(C_i)}{\sum_{l=1}^{n_C} P(E_j|C_l) \cdot P_0(C_l)} \cdot n(E_j)$$

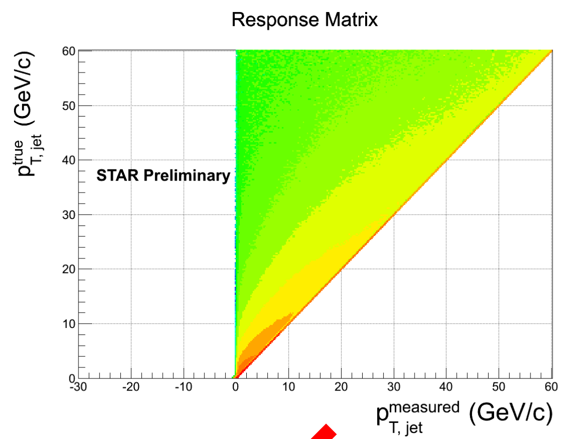
next iteration: $n(C_i) \Rightarrow P_0(C_i)$

[1] G. D'Agostini, Nucl.Instrum.Meth. A362 (1995) 487-498

Including Detector Effects







Detector effects: paremetrized tracking efficiency

Overall response matrix: