Initial Stages 2019

Correlation measurements of mid-rapidity charged particles and jets with event activity at backward-rapidity (Au-going) in 200 GeV p+Au collisions at STAR

David Stewart for the STAR Collaboration

Why small systems?

Initially

Stepping stone towards probing the Quark Gluon Plasma (QGP) in "large" systems …

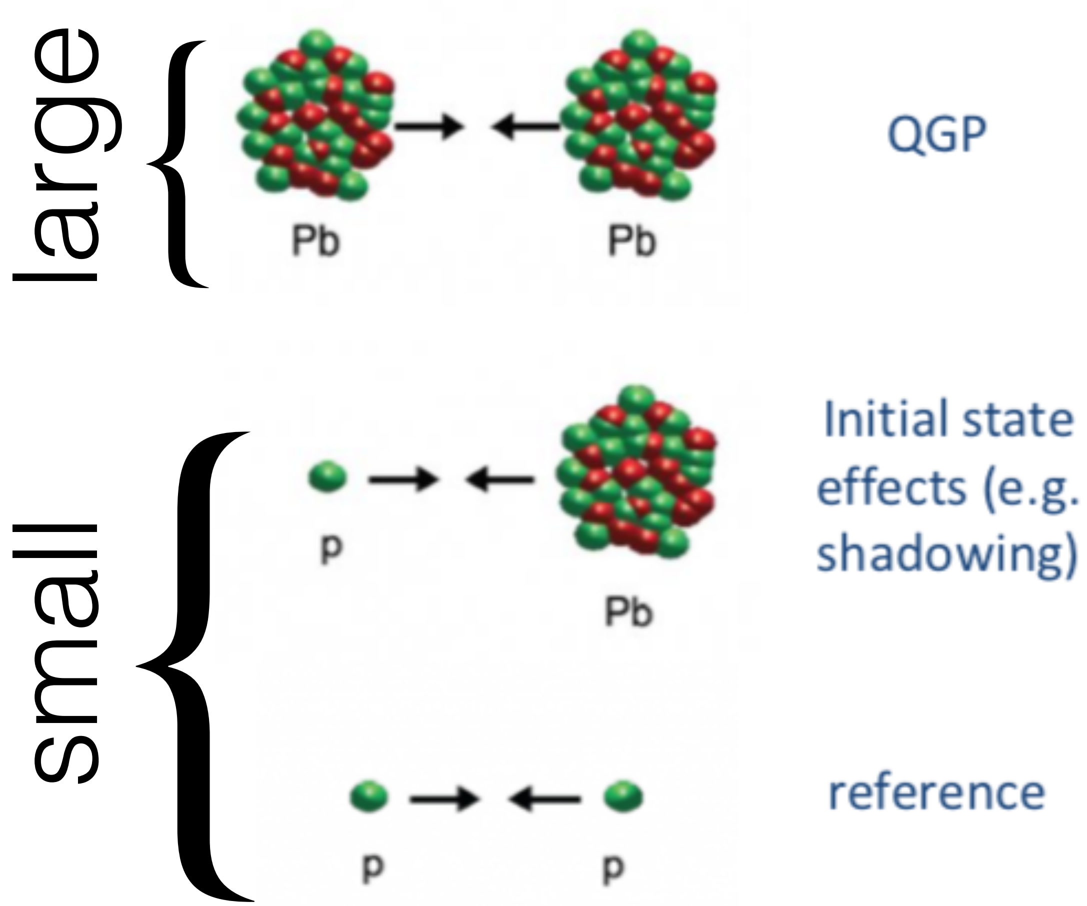


image and points: Livio Bianchi @ QuarkMatter2018

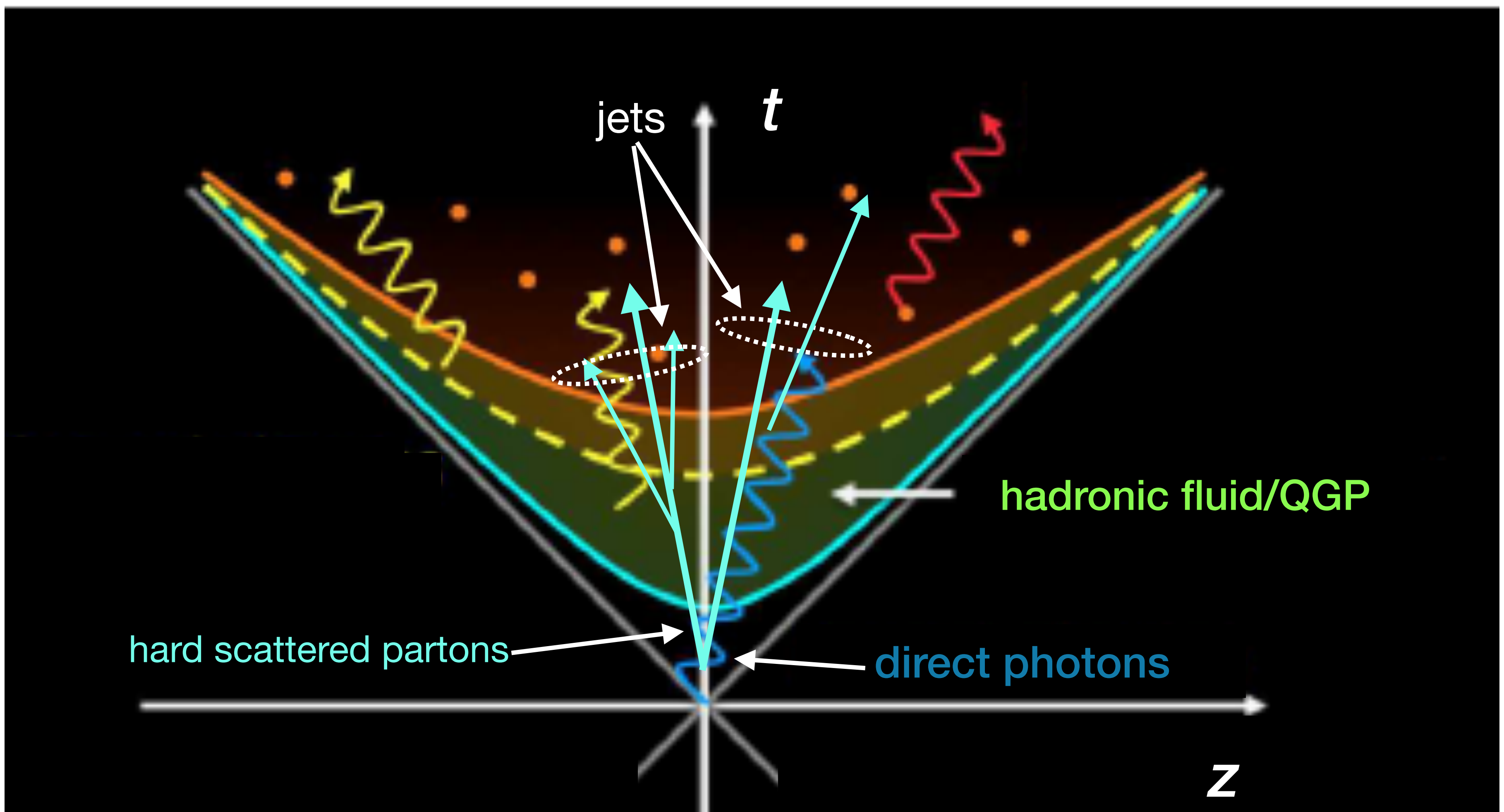
Currently

… with discovery of flow-like signals, small systems are being actively probed for other QGP-like signals

- Soft physics
  - Collective flow, particle spectra at freeze-out etc…
- Hard physics
  - $\boxed{\text{Jet quenching/modification}}$, high p_T particle suppression…

Jet introduction

- Hard scatterings of partons occur early in collisions and subsequent products may interact with a medium
- Final state particles are algorithmically clustered together into objects called jets which are associated (by the observer) with the initially scattered partons
- Modification of jets is used to probe existence and properties of a QGP

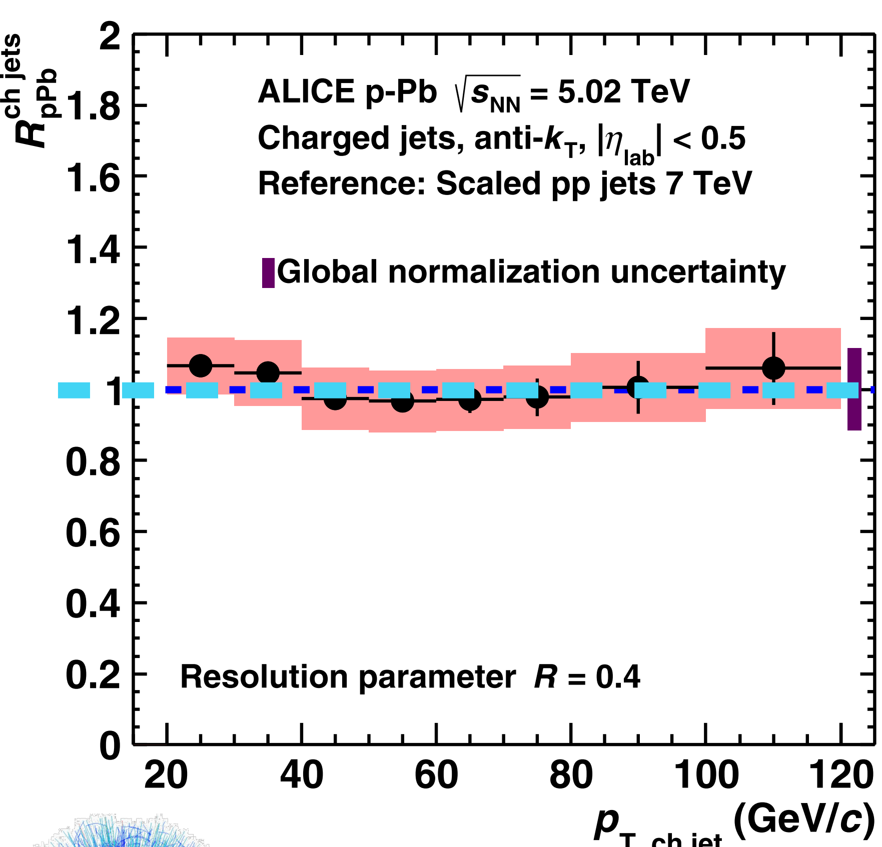


modified from Fig. 1 of http://de.arxiv.org/abs/1412.7781v1

Minimum bias jet measurements in small systems

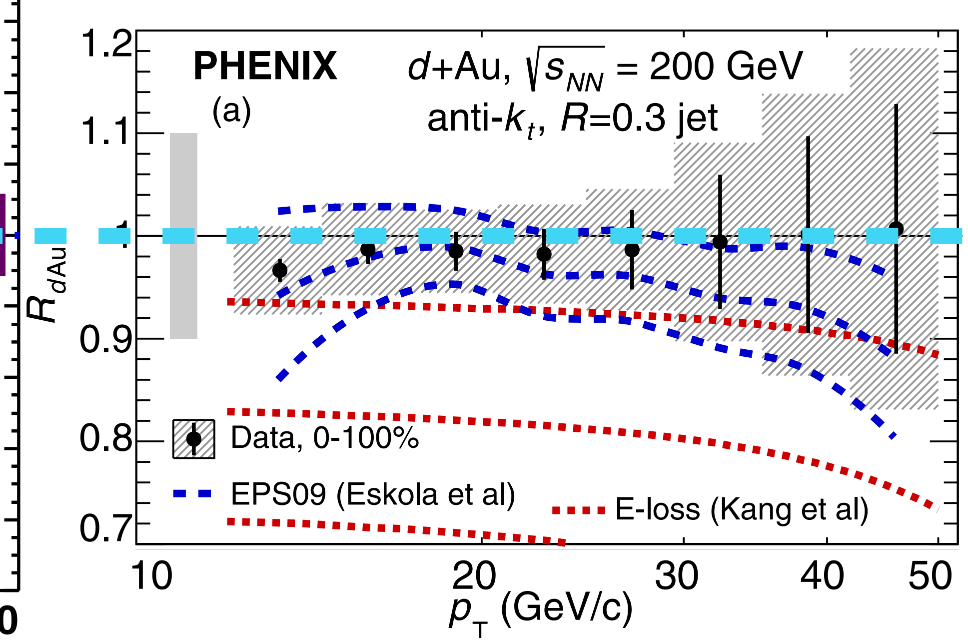
- Small systems have been studied for evidence of jet modification / suppression
- If we anticipate no final state effects, we expect the ratio of jet spectra per binary collision in p+A collisions to pp collisions to be unity ($R^{\mathrm{ch\,jet}}_{\mathrm{p+A}} \approx 1$)
  - Caveat: even if a strong interacting medium were formed, it may be too small to modify jet spectra

ALICE

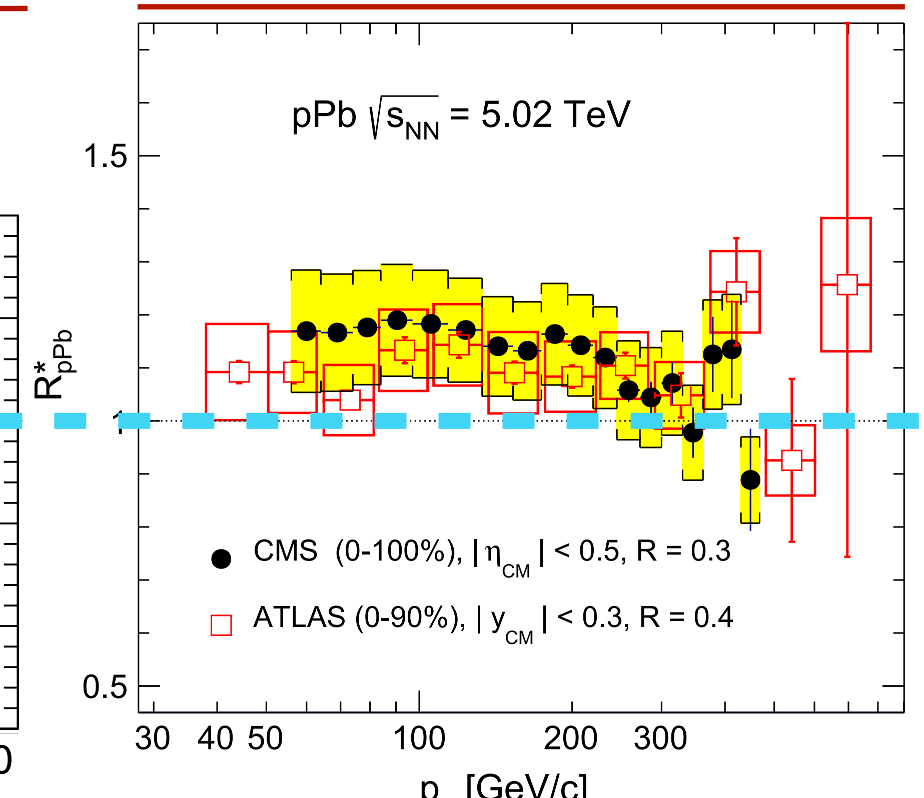


PHENIX

ALICE *Phys. Lett.* *B749 (2015) 68-81*
PHENIX *Phys. Rev. Lett.* **116,** 122301 (2016)
CMS Eur. Phys. J. C **76**, 372 (2016)



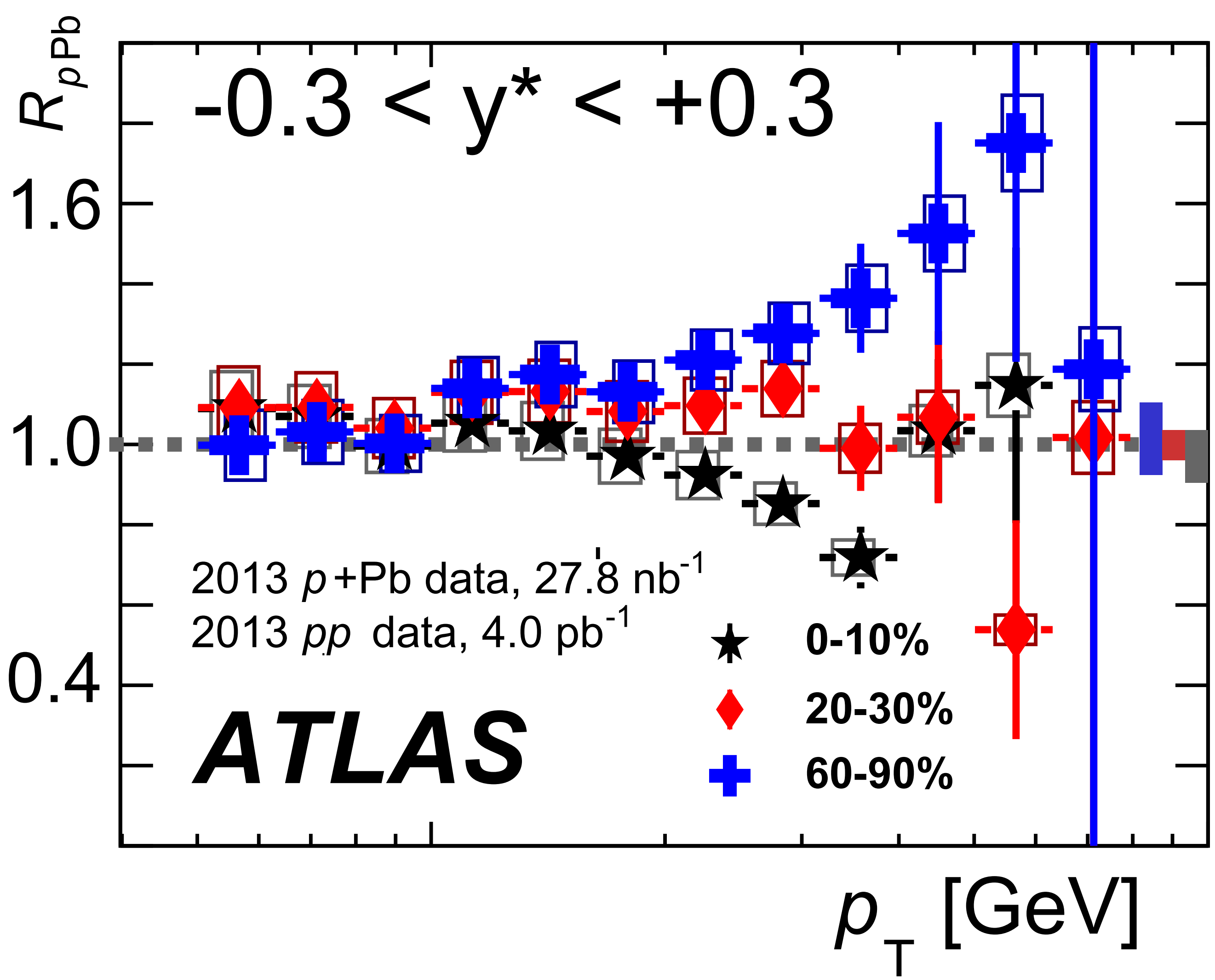
ATLAS & CMS

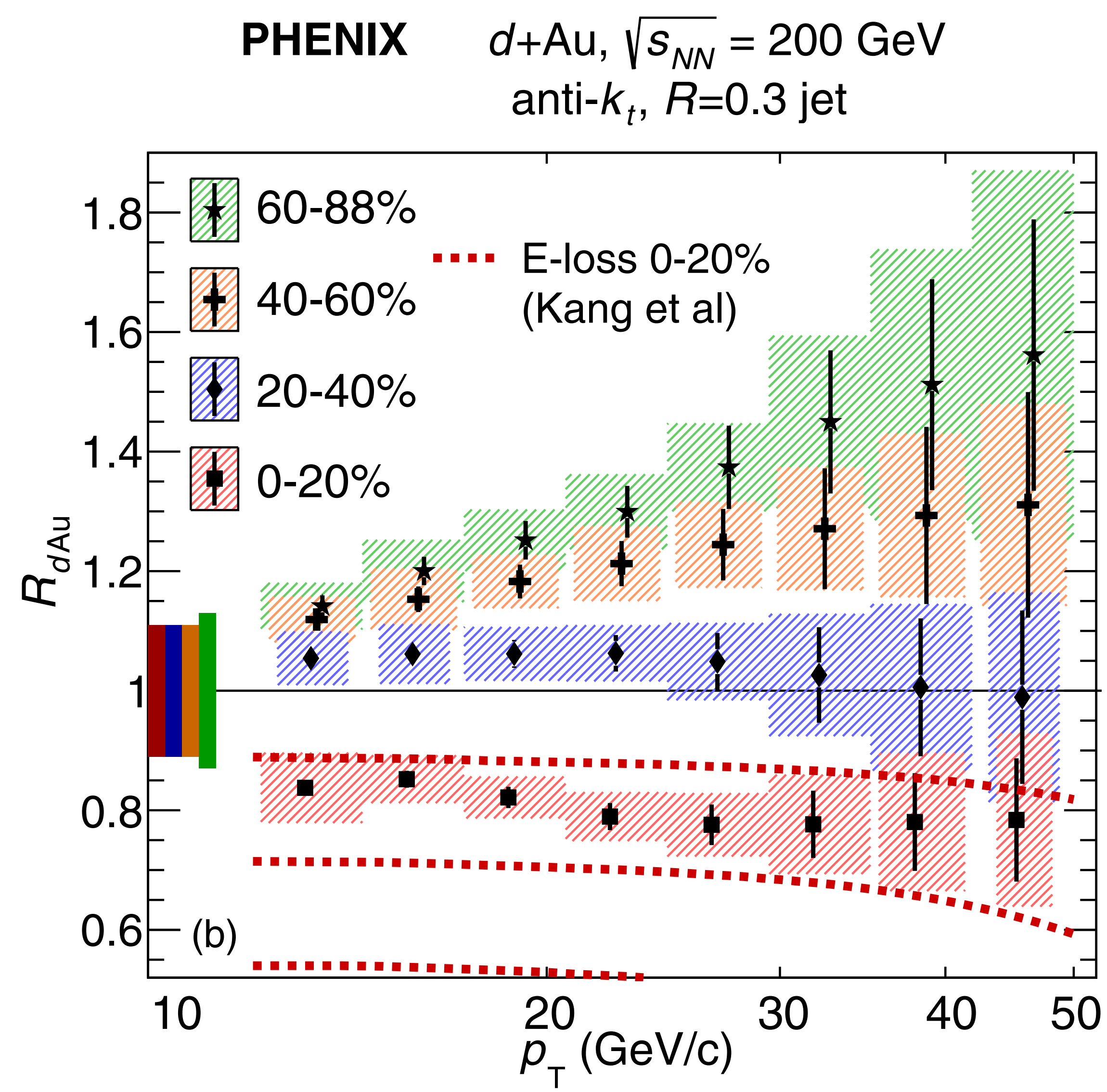


Event-activity (EA) dependent jet measurements in small systems

- When binned by high-|η| Event Activity, findings:

$$R^{\text{jet High EA}}_{(p/d)+A} < 1 \quad \& \quad R^{\text{jet Low EA}}_{(p/d)+A} > 1$$





PHENIX Phys. Rev. Lett. 116, 122301 (2016)
ATLAS Phys. Lett. B 748, 392–413 (2015)

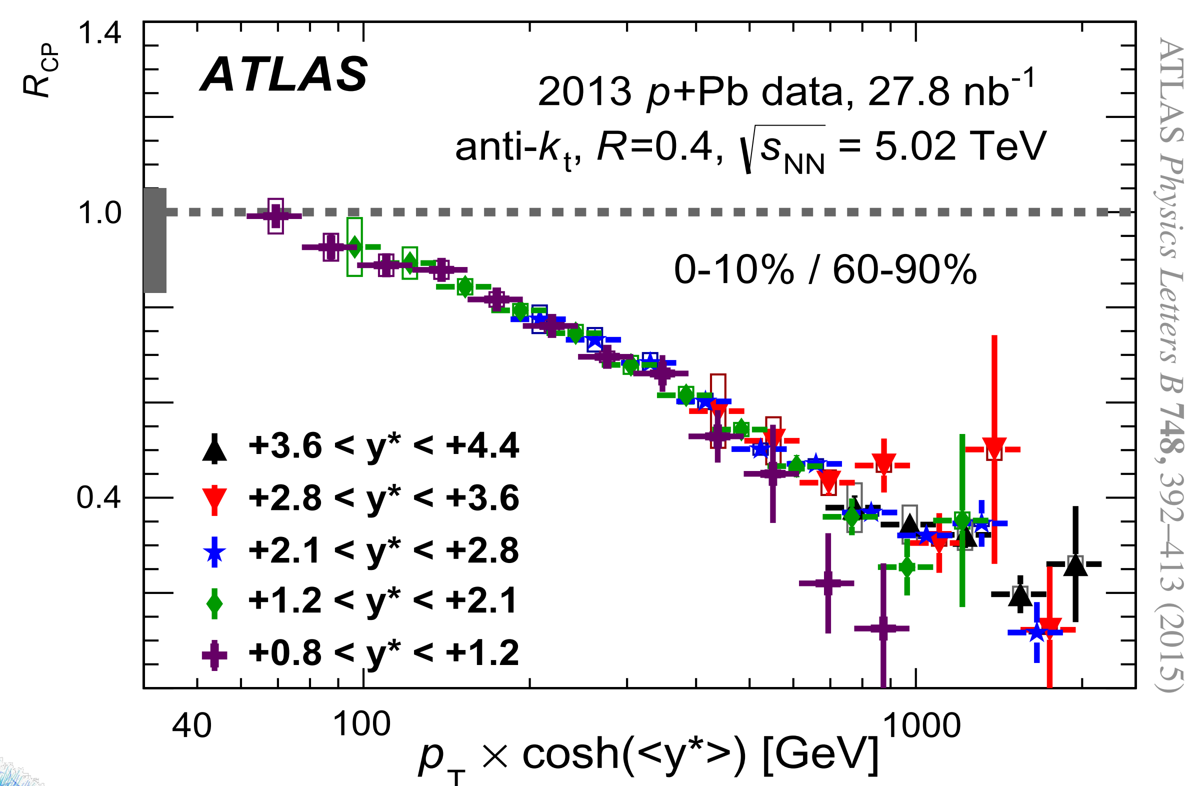
What happened?

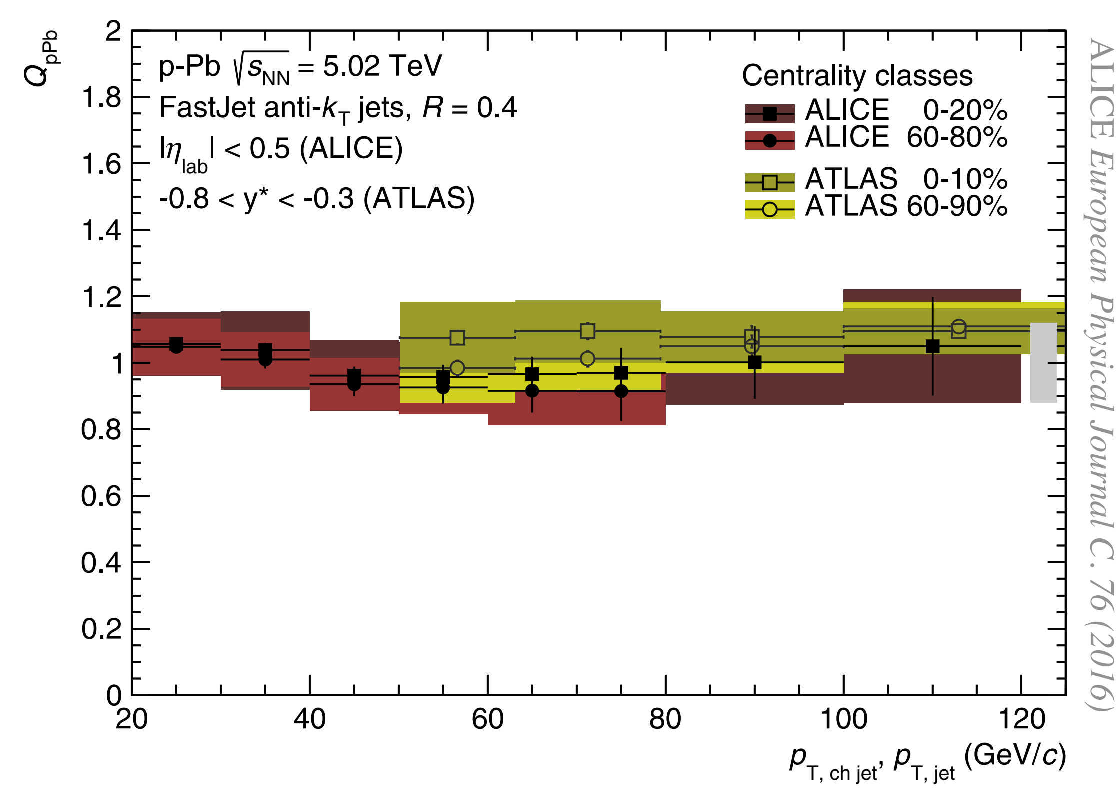
Possibilities

- ✦ Number of binary collisions (N_{coll}) from Glauber model is OK:
  - ✦ Jet modification present
  - ✦ Physics of each binary collision not uniform
- ✦ Determination of N_{coll} and/or mapping of EA to N_{coll} is uniquely different in small systems

Current results/thoughts

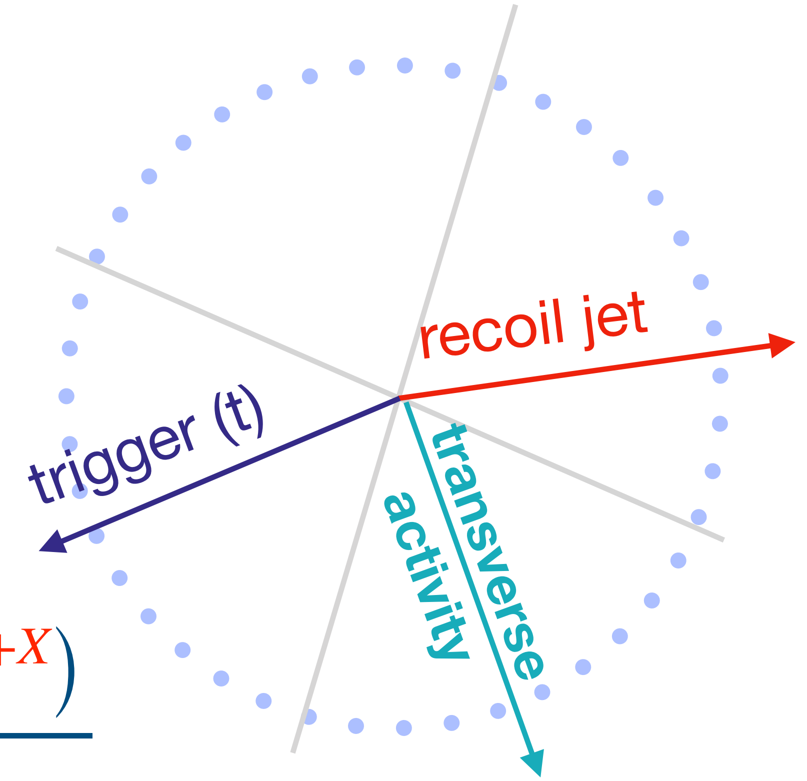
- ✦ Theory conserving p(/d) energy suggests anti-correlation between multiplicity & hard scattering (therefore modify Glauber) (e.g. Kordell II & Majumder, PRC 97 (2018))
- ✦ Correlation between suppression and total p-going jet momentum (p_{tot} vs p_T at ATLAS)
- ✦ Semi-inclusive measurements, circumventing N_{coll} entirely at ALICE, report null result at mid-rapidity (low p_{tot}) (PRC 91 (2015))





Motivation to measure semi-inclusive jet spectra

- Jet spectra per trigger ("S" in the equations below) in process "p+Au→t+jet+X" can probe if all the following are not simultaneously true without actually calculating N_{coll}:
  A. Trigger and jet production both scale with N_{coll}
  B. Event activity (**EA**) selection, while scaling monotonically in N_{coll}, not autocorrelated with jet or trigger generation
  C. No EA related modification of jet spectra



- Specifically:

$$S \equiv \frac{1}{N_{\mathrm{trig}}}\frac{dN_{\mathrm{jet}}}{dp_{\mathrm{T,jet}}} = \frac{1}{\cancel{L}\sigma^{p+Au\to t+X}}\frac{d\left(\cancel{L}\sigma^{p+Au\to t+jet+X}\right)}{dp_{\mathrm{T,jet}}}$$

- By condition A:

$$\sigma^{p+Au\to X} = N_{\mathrm{coll}}\sigma^{pp\to X} \Rightarrow S = \frac{1}{\cancel{N}_{\mathrm{coll}}\sigma^{pp\to t+X}}\frac{d\left(\cancel{N}_{\mathrm{coll}}\sigma^{pp\to t+jet+X}\right)}{dp_{\mathrm{T,jet}}}$$

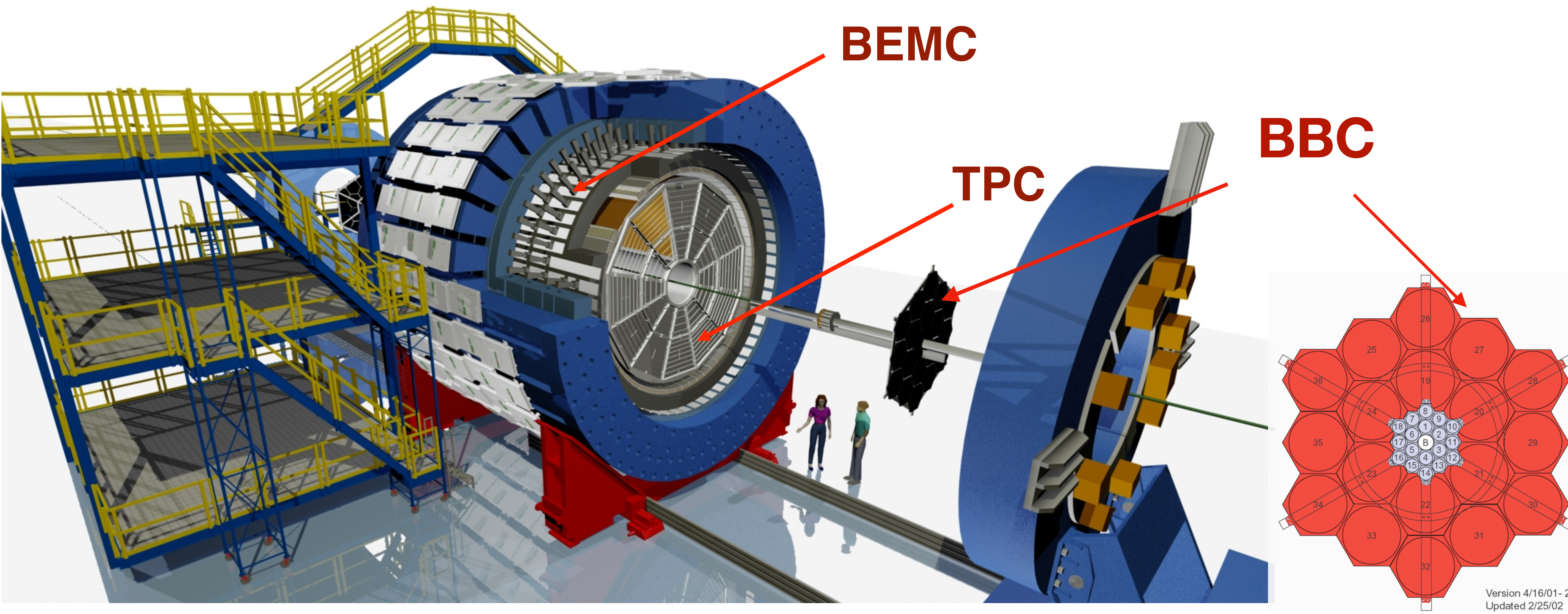
- Therefore by B and C:

$$S \equiv \frac{1}{N_{\mathrm{trig}}}\frac{dN_{\mathrm{jet}}}{dp_{\mathrm{T,jet}}} = \frac{1}{\sigma^{pp\to t+X}}\frac{d\sigma^{pp\to t+jet+X}}{dp_{\mathrm{T,jet}}} = \frac{1}{\sigma^{p+Au\to t+X}}\frac{d\sigma^{p+Au\to t+jet+X}}{dp_{\mathrm{T,jet}}}$$

- If $\dfrac{S_{[\mathrm{high\ EA}]}}{S_{[\mathrm{low\ EA}]}} \neq$ unity then A & B & C cannot all be true

STAR introduction – TPC, BEMC, & BBC

STAR detector system

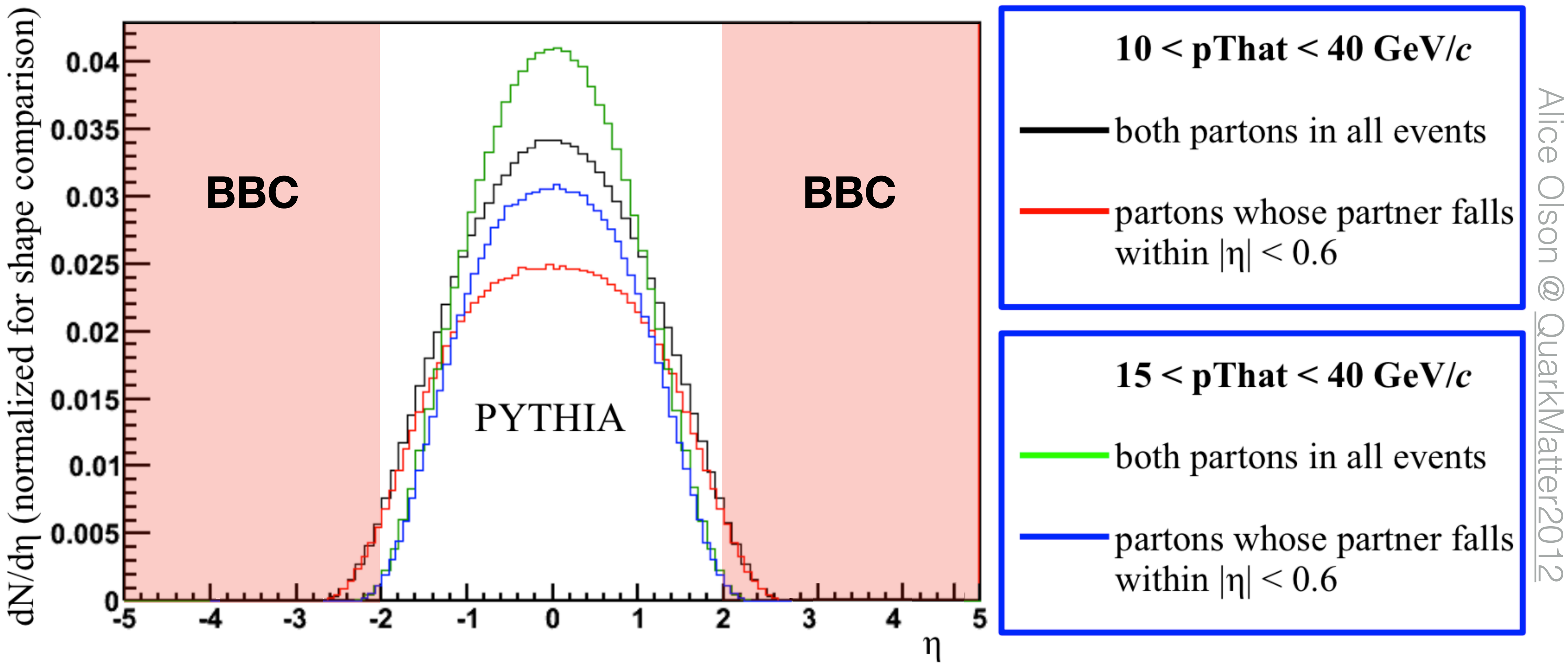


Subsystems of interest

- Time Projection Chamber (TPC): charged tracks with p_T
- Barrel Electromagnetic Calorimeter (BEMC): energy deposition, primarily neutral particles
- Beam Beam Counter (BBC): plastic scintillators ($2<|\eta|<5.0$)
  - BBC, in Au-going direction, corrected for z-vertex and luminosity, is EA estimator

Motivation to measure EA at high-η in Au-going direction

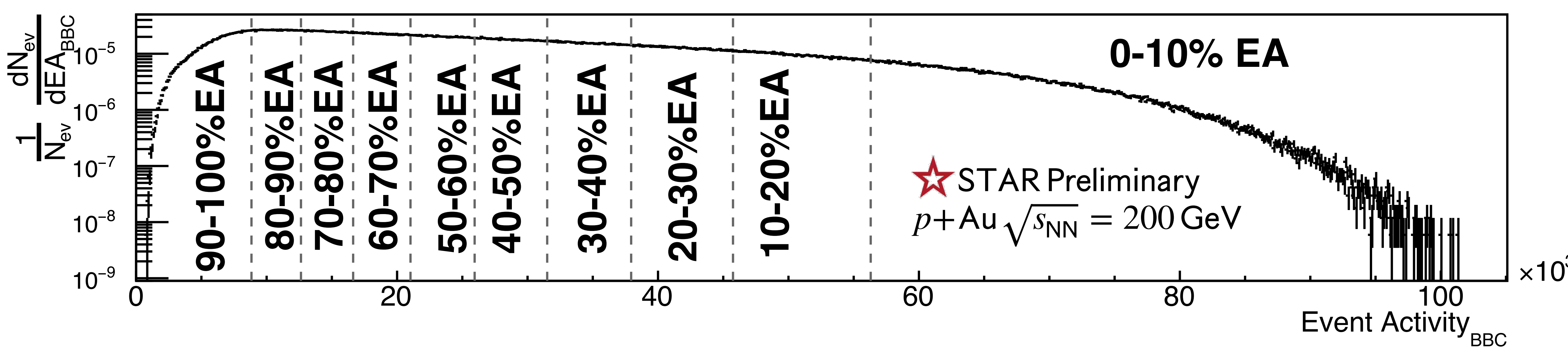
- Traditionally, EA at STAR has been measured by activity in TPC ($-1<\eta<1$)
- However, when measuring jets in small systems, activity of jets strongly autocorrelates to mid-rapidity EA
- Therefore, EA is determined by activity in BBC at Au-going rapidity from $-5<\eta<-2$



- At RHIC energies, kinematics are such that Δη swing of recoil jets from high p_T triggers in TPC rarely reaches BBC acceptance

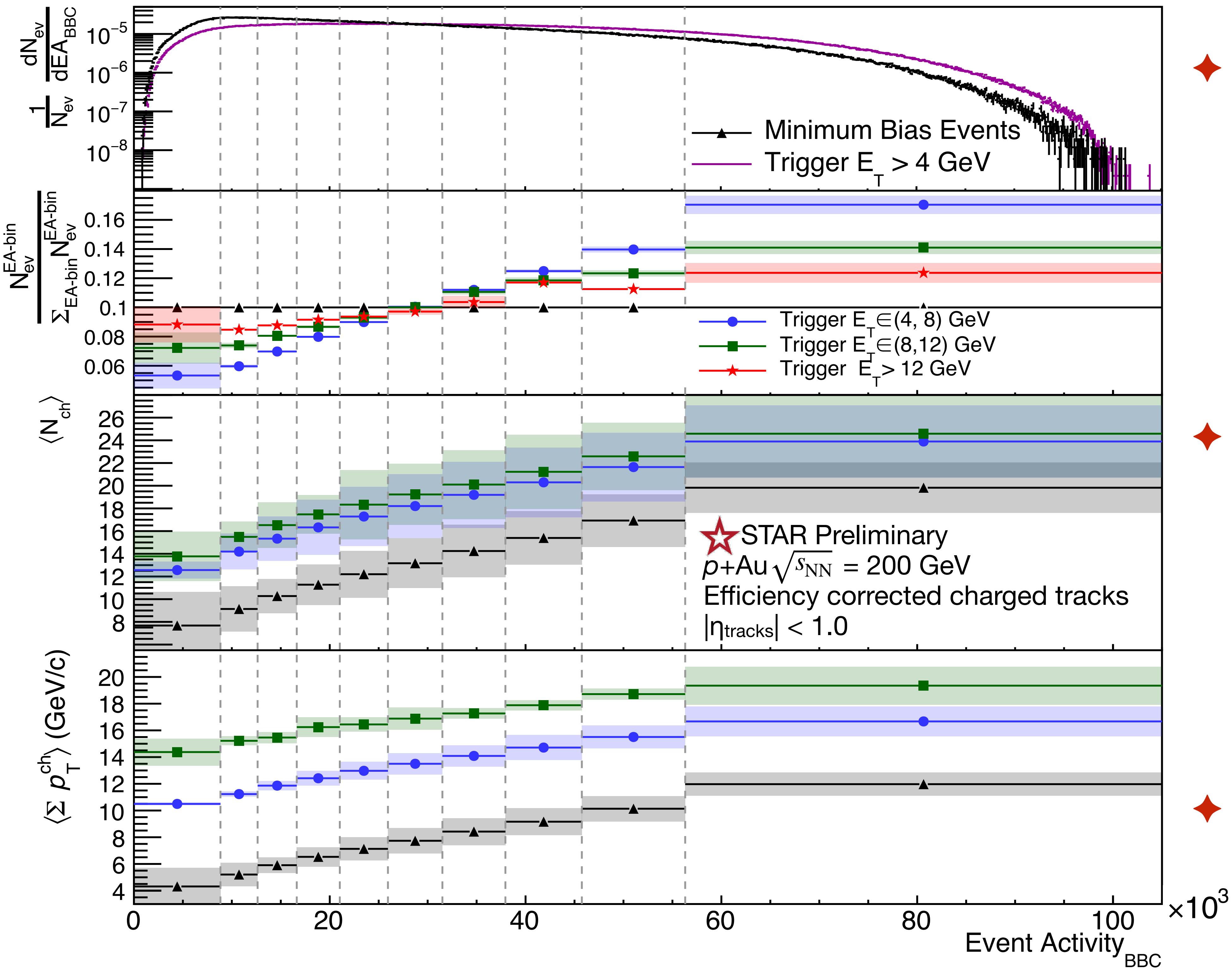
Dataset & verification of BBC as EA estimator

- STAR has a large p+Au 200 GeV dataset measured in 2015 with events triggered by both:
  A. minimum bias triggers
  B. high transverse energy (E_T) hits in BEMC, i.e.: p+Au→$BEMC_{hit}$+jet+X
- EA spectra presented are determined by signal in BBC in Au-going direction



Measured correlations: mid-rapidity tracks to EA at backward-η

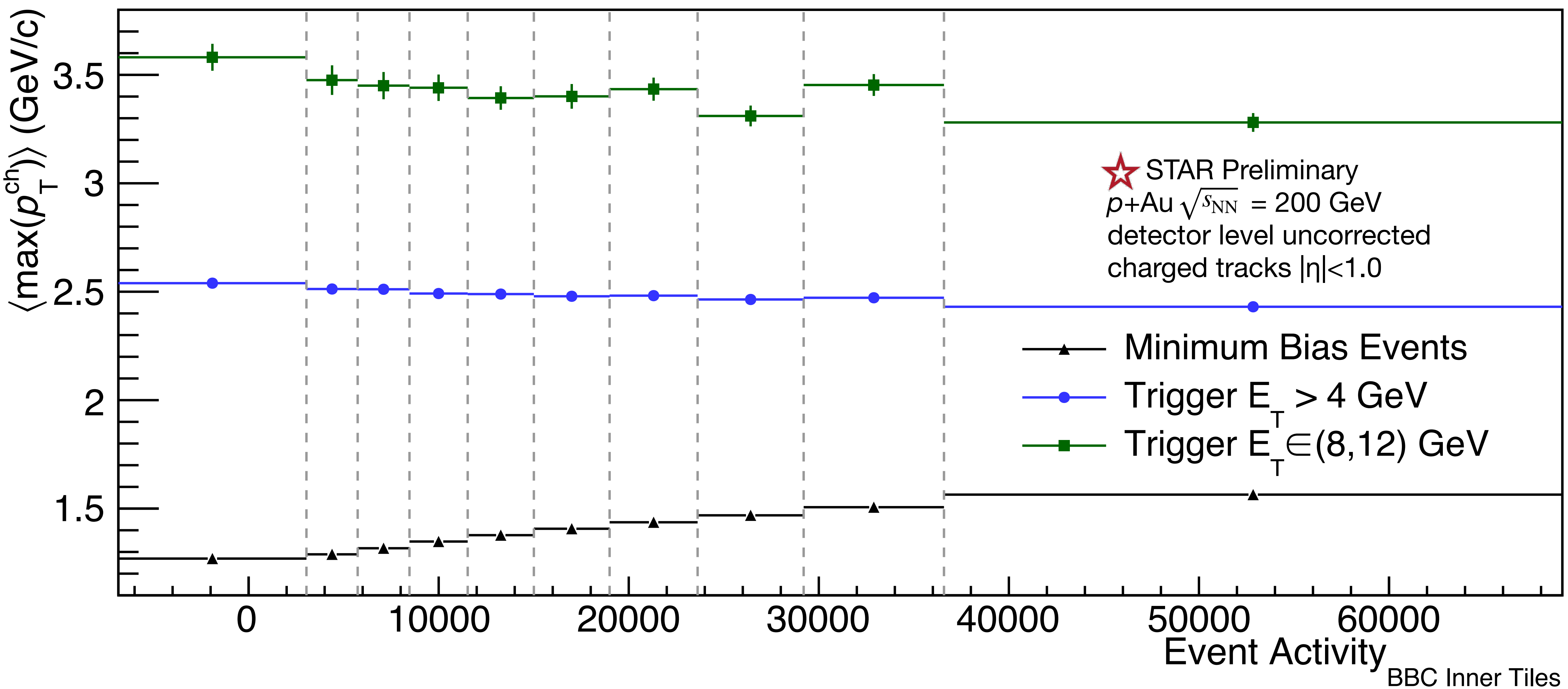
- Unfolding p_T spectra in each bin using a response matrix of embedded tracks provides a measure of average N_{ch} and Σp_T as correlated to EA



- Expected positive correlation between EA and probability of a mid-rapidity trigger weakens for increasing trigger energies
- $\langle N_{ch} \rangle$ increases substantially moving from min bias to a 4-8 GeV trigger, but only modestly with a 8-12 GeV trigger
- Total number of tracks and sum p_T scale as expected

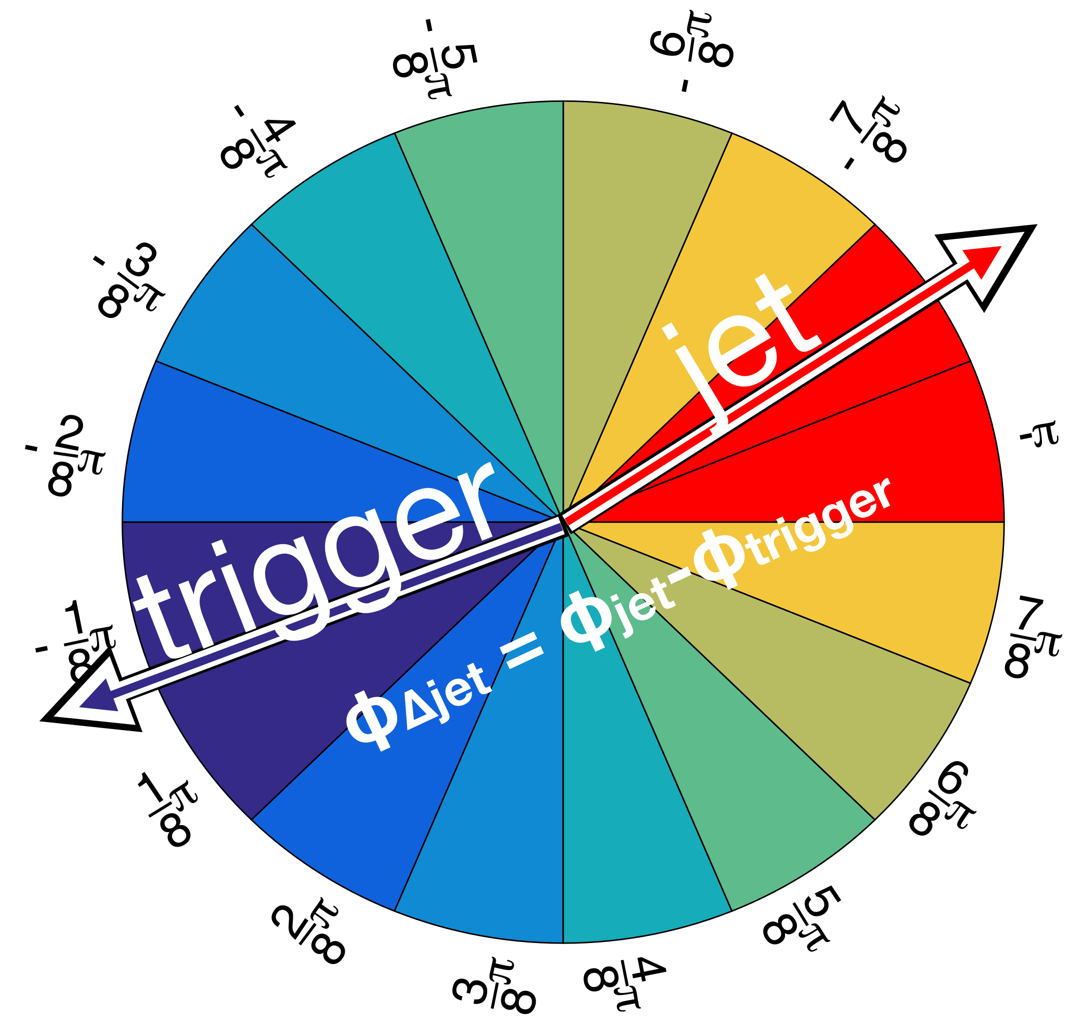
Average maximum track p_T per event

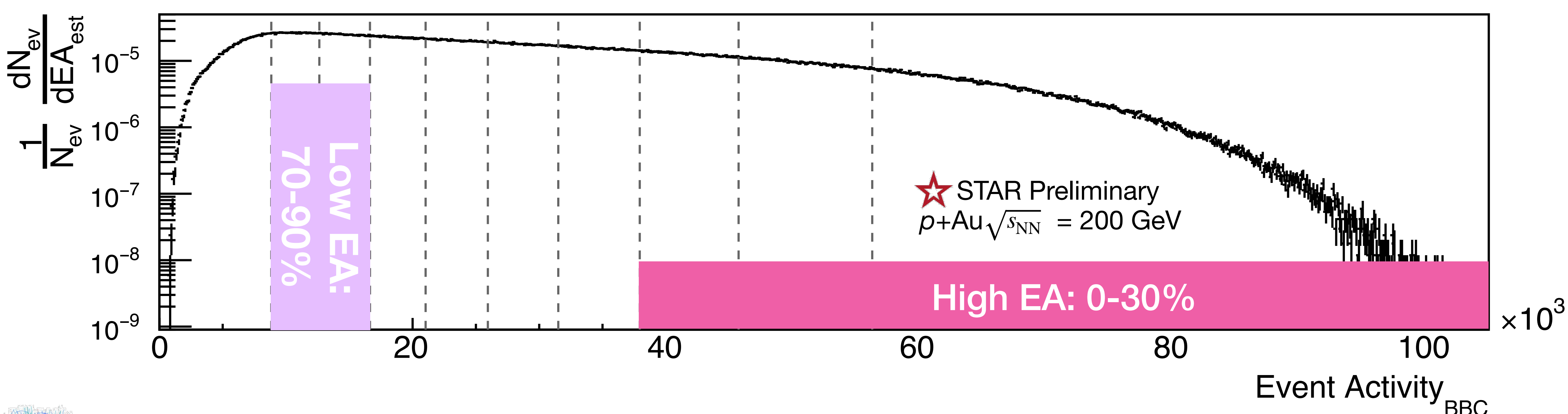
- Strong positive correlation evolves to anti-correlation with harder triggers



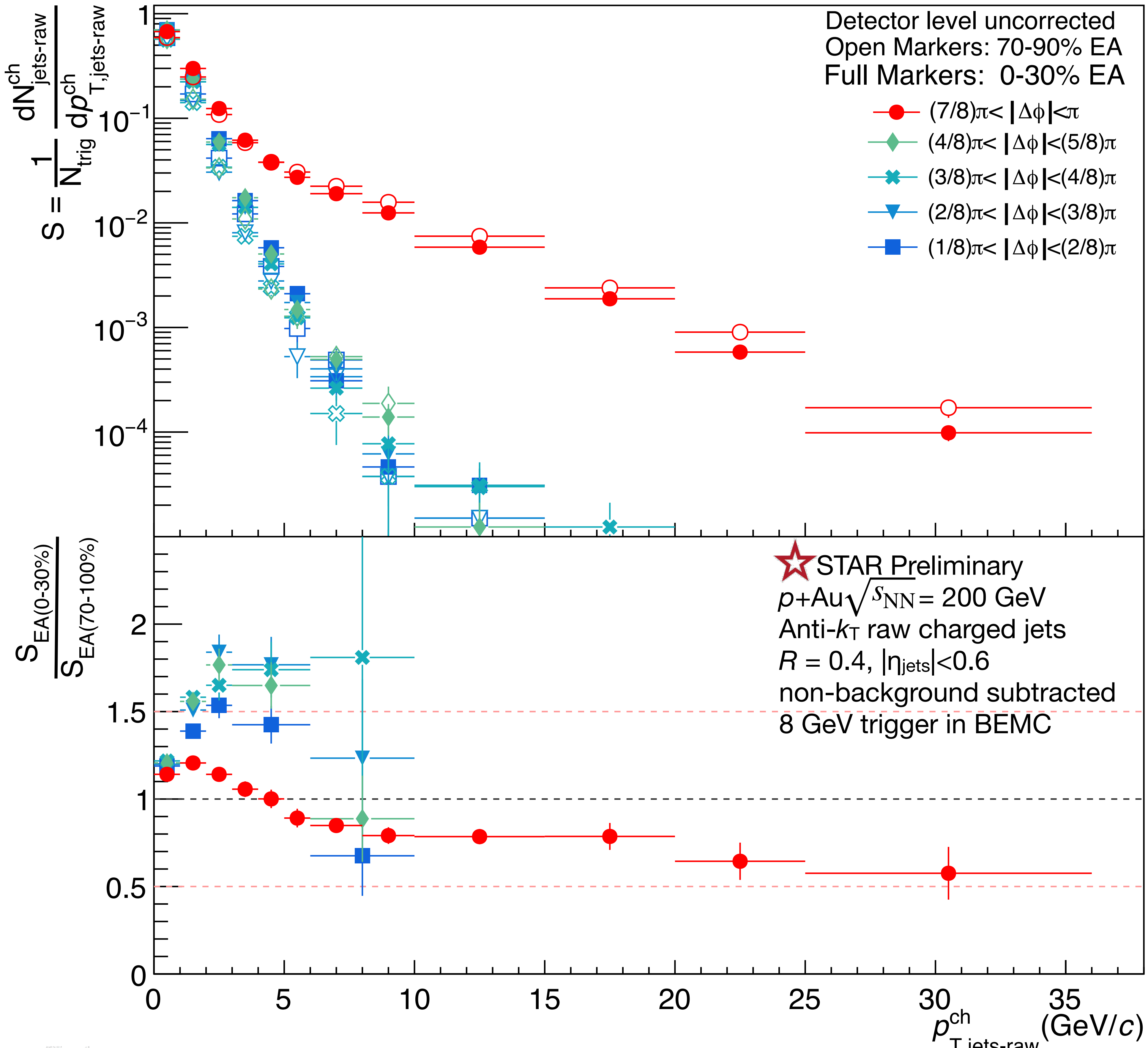
Clustering uncorrected tracks into jets

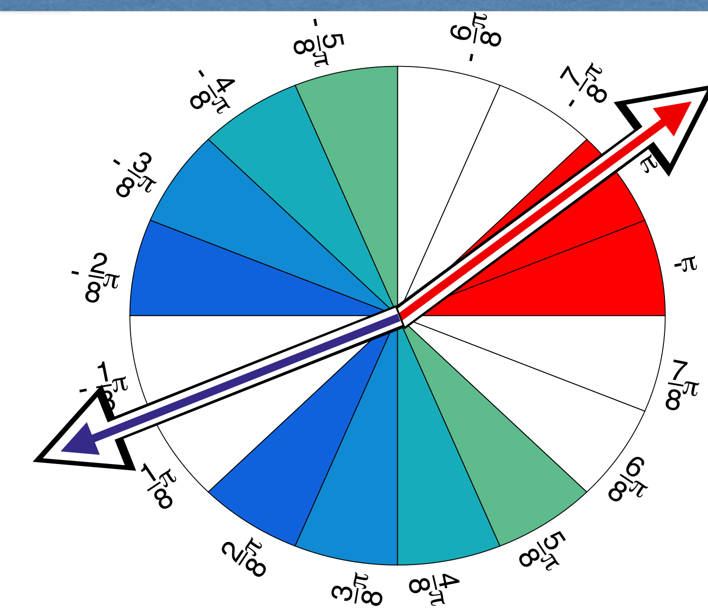
- Same charged tracks (uncorrected) have been clustered into jets, and compared in highest 0-30% and lowest 70-90% EA
- Data binned in Δφ in π/8 slices
- N.B.: Jet embedding is ongoing; jets presented in this talk are raw, uncorrected, detector level





Recoil and transverse spectra



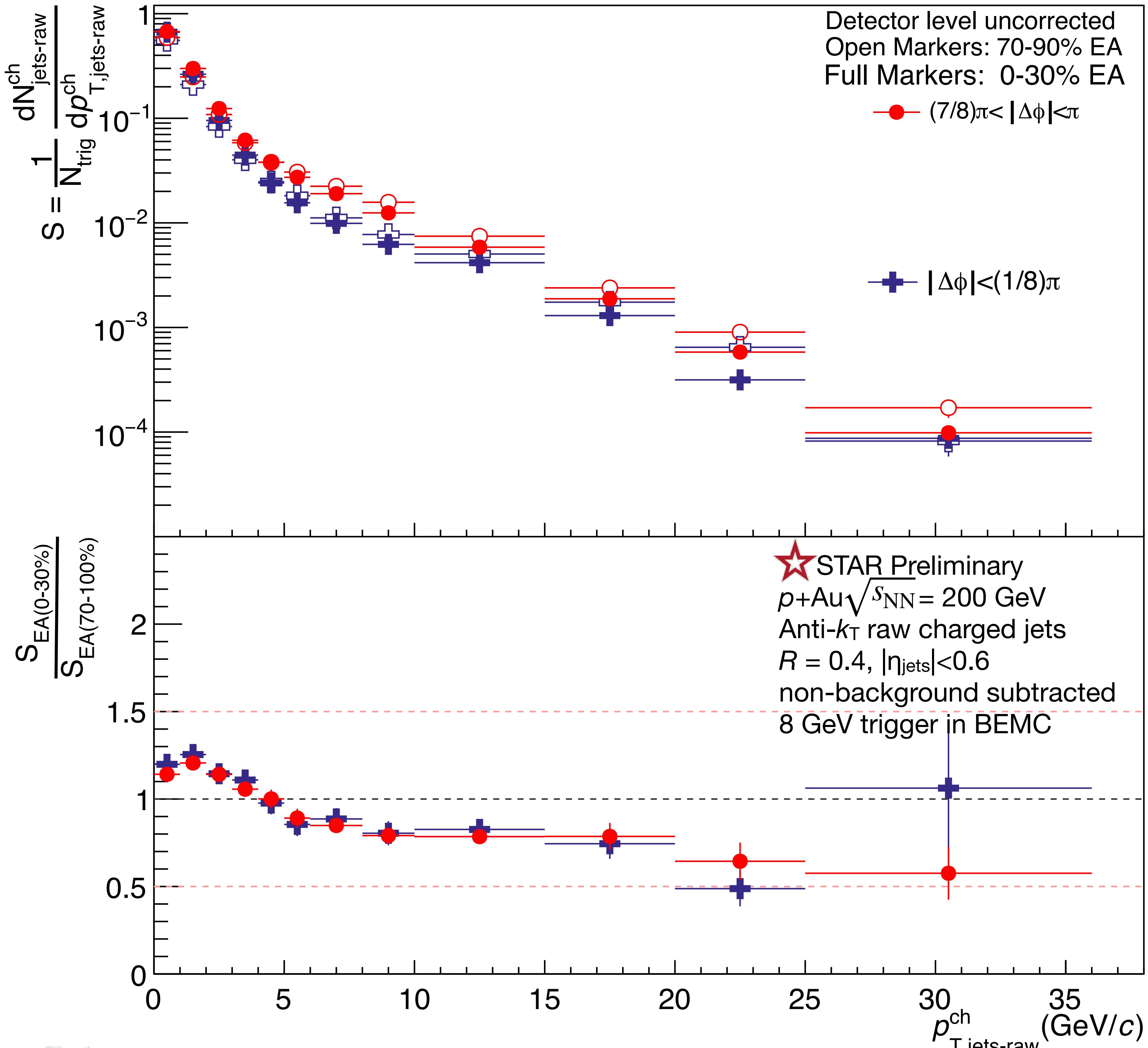


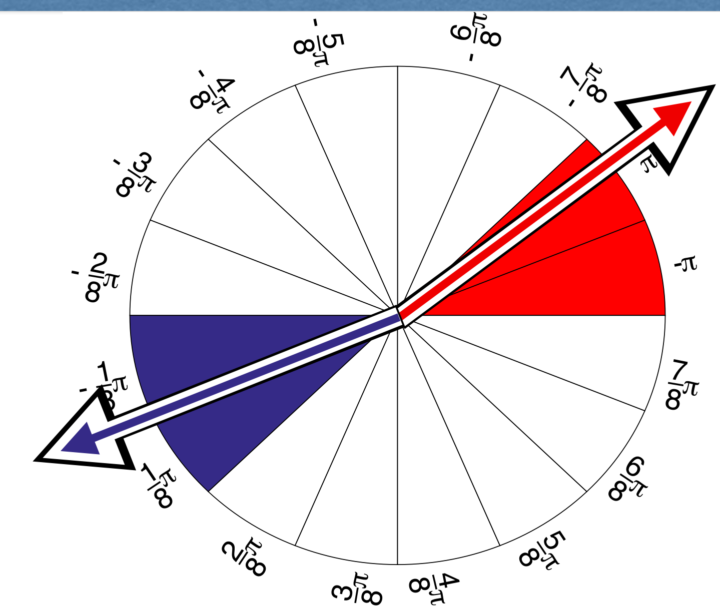
Open Markers: Low EA: 70-90%

Full Markers: High EA: 0-30%

- At "jet-like" p_T, background (transverse $\Delta\varphi$) negligible compared to recoil spectra

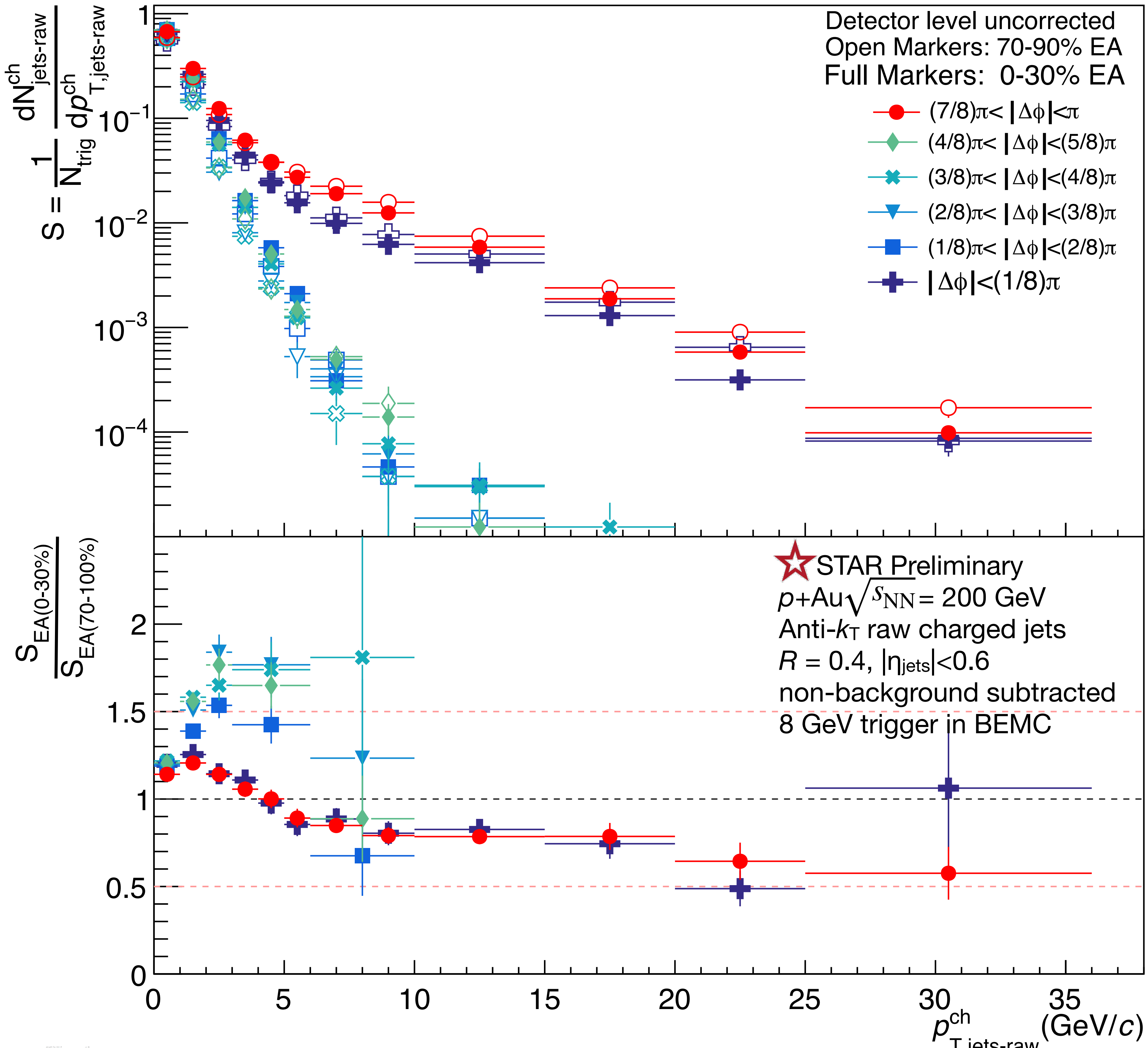
Same-side and recoil spectra

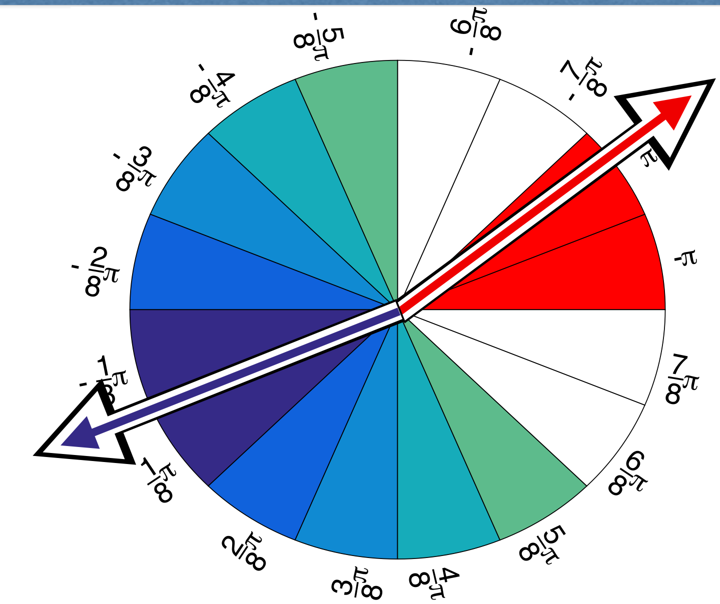




- The 8 GeV trigger biases the dijet selection
- Bias expected to decrease at higher $p_{T,jet}$

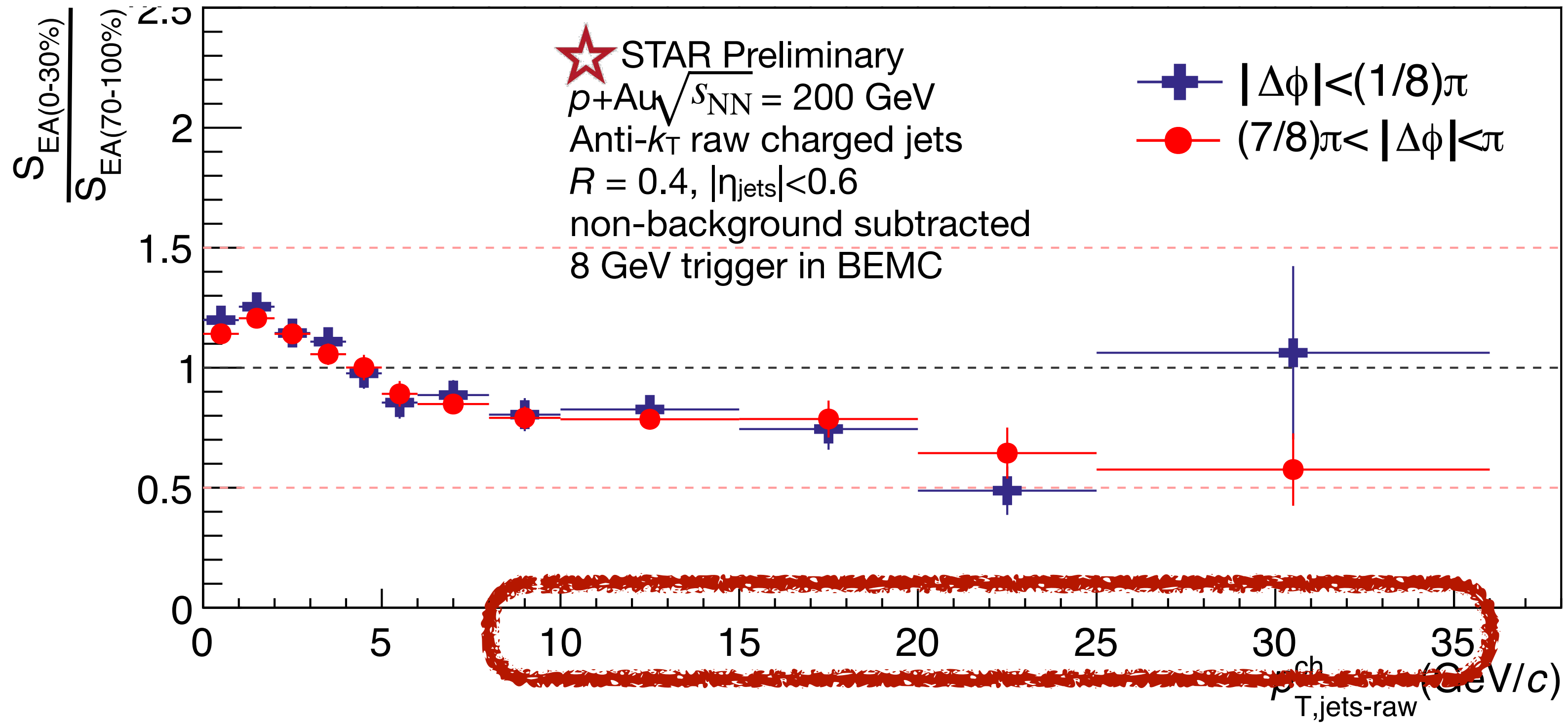
Suppression of all spectra



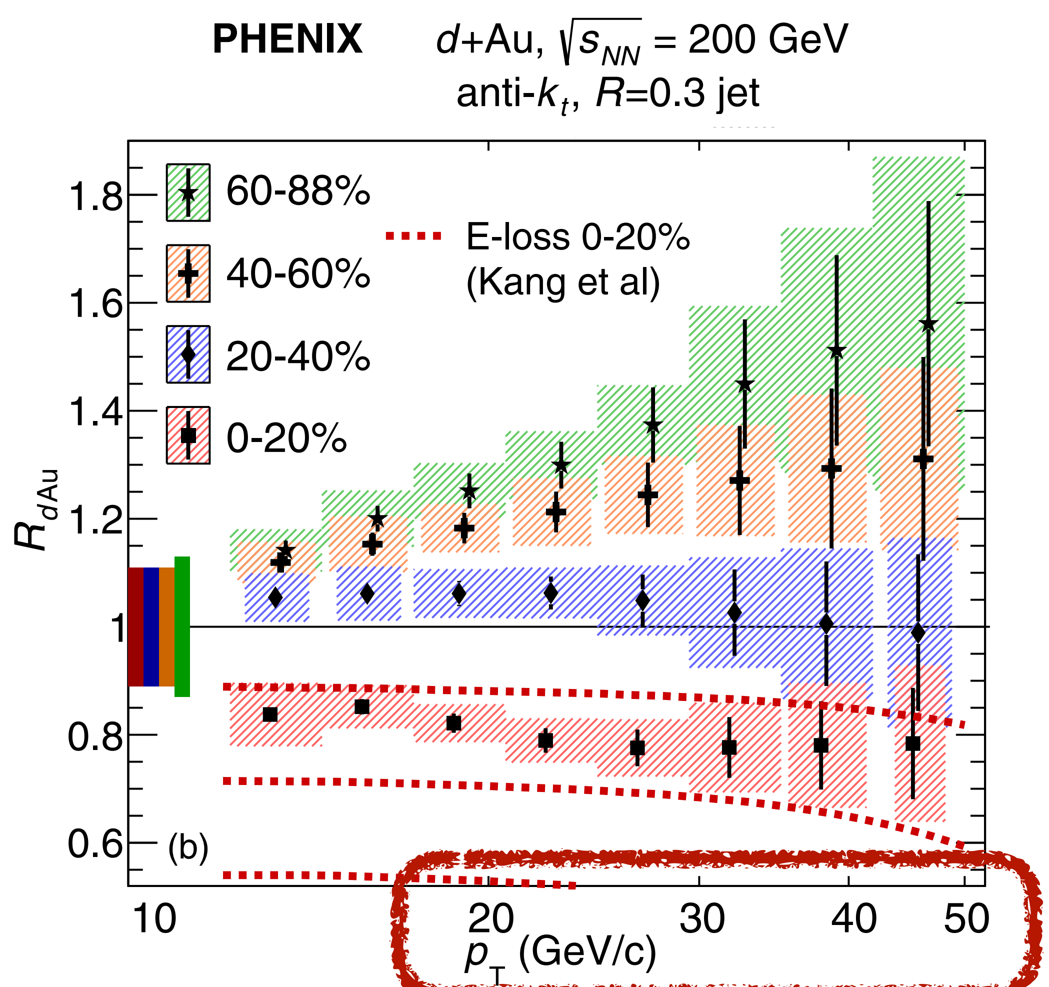


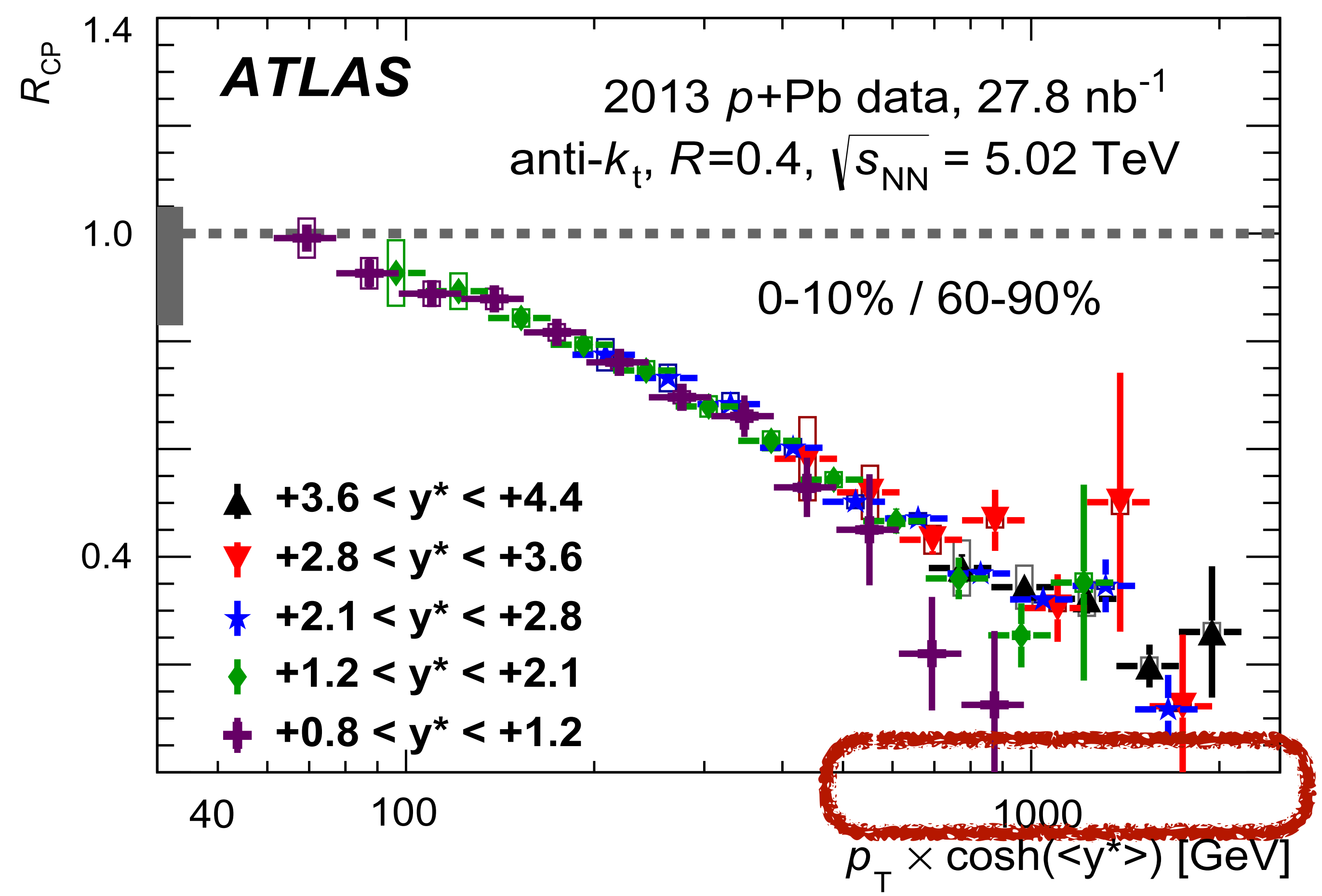
- At p_T above ~10 GeV/c clear suppression in high-EA events compared to low-EA events

Summary



- Clear spectra modification:
  - STAR 200 GeV p+Au, charged, raw jets
  - PHENIX 200 GeV d+Au fully corrected jets
  - ATLAS 5020 GeV p+Pb fully corrected jets



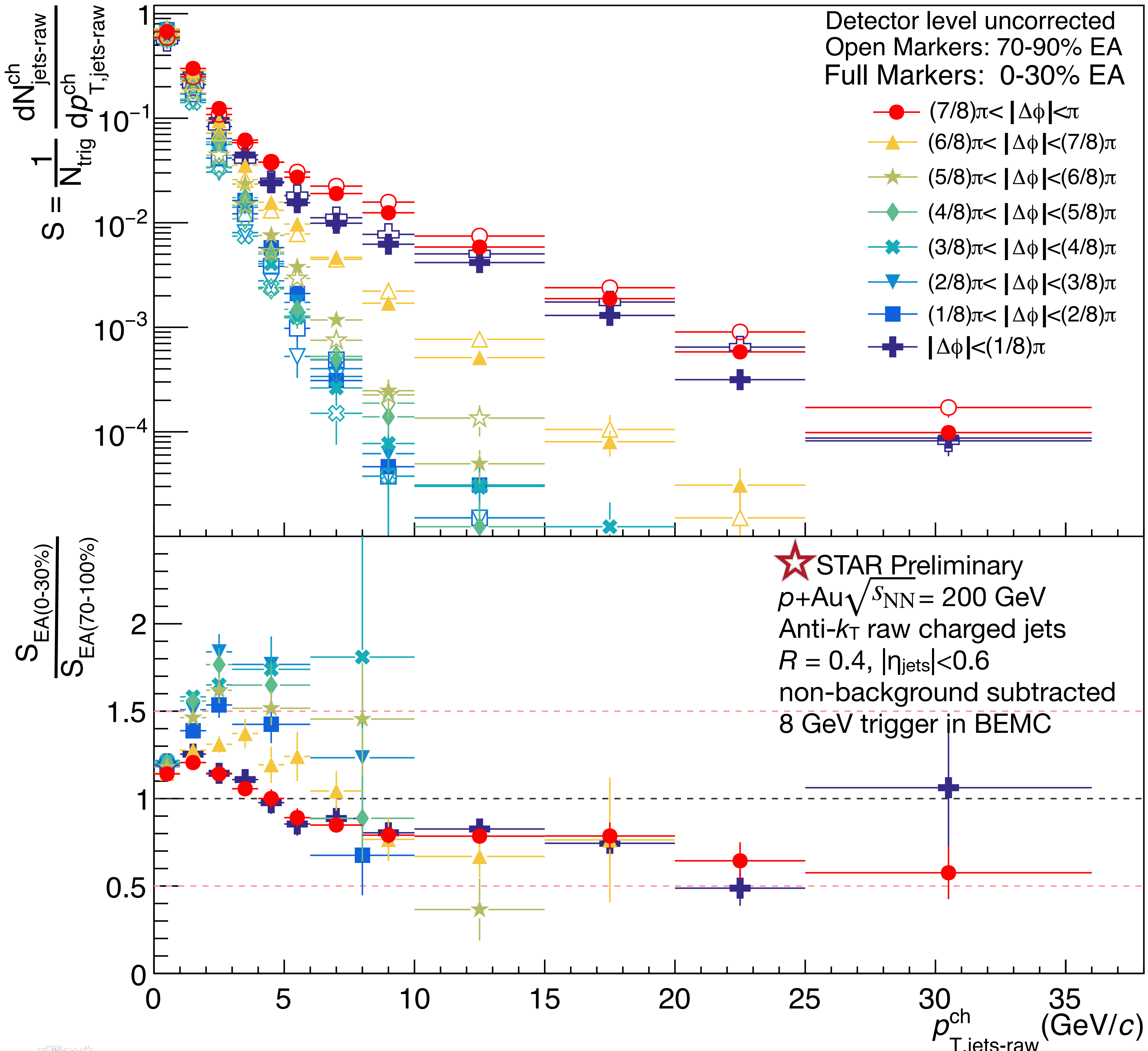


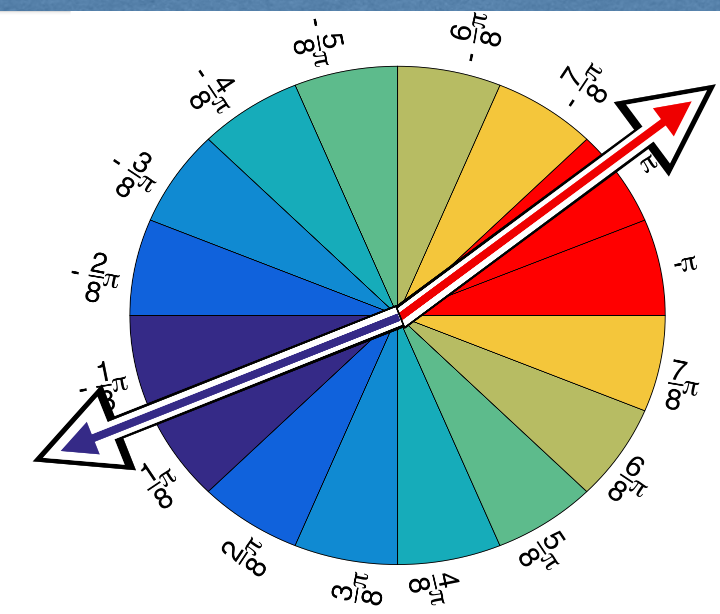
Conclusion and outlook

- Clear suppression of high EA semi-inclusive jet spectra observed in 200 GeV p+Au collisions at STAR
- This suppression indicates that for p+Au 200 GeV, at least one of the following is not true:
  A. Trigger and jet production both scale with N_{coll}
  B. Event activity (EA) at backward-η is not autocorrelated with jet or trigger production
  C. There is no EA-related modification of jet spectra
- These can be further probed with:
  - Checking if scaling of trigger and soft production can be separated
    - Probe with underlying event in transverse direction
  - Studying full jets and varying trigger p_T
    - Address effects of using a neutral particle as a trigger with charged jets
  - Comparison to theory
    - Unfold jets

Extra Slides

All spectra





- There is an enhancement over background from the recoil angle in φ in the (6/8)π-(7/8)π and (5/8)π-(6/8)π bins
- This compares reasonably with recoil Δφ swings in jets in Au+Au 200 GeV collisions

Jet η swing of recoil jets in φ for Au+Au at STAR

PHYSICAL REVIEW C **96**, 024905 (2017)

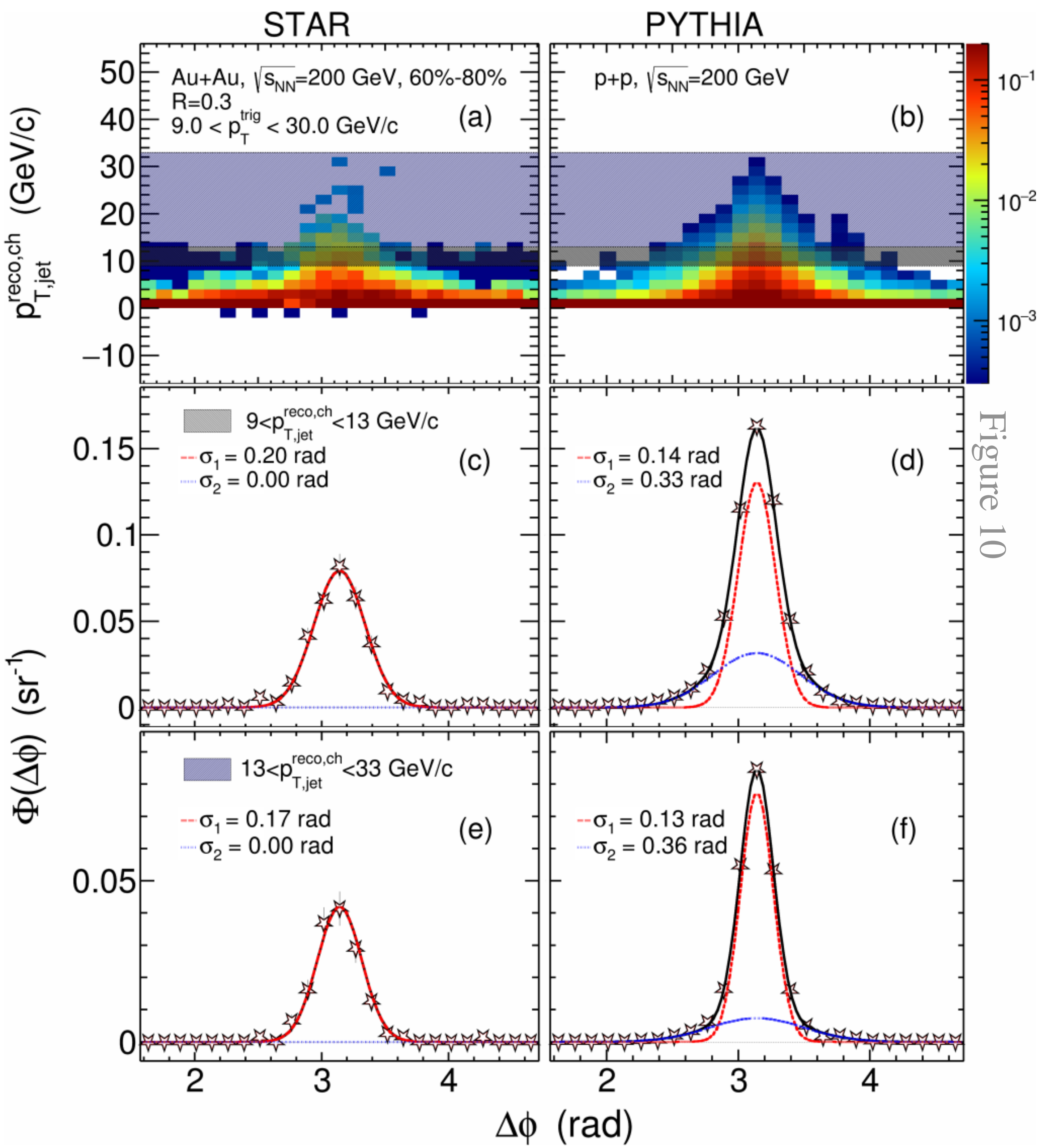
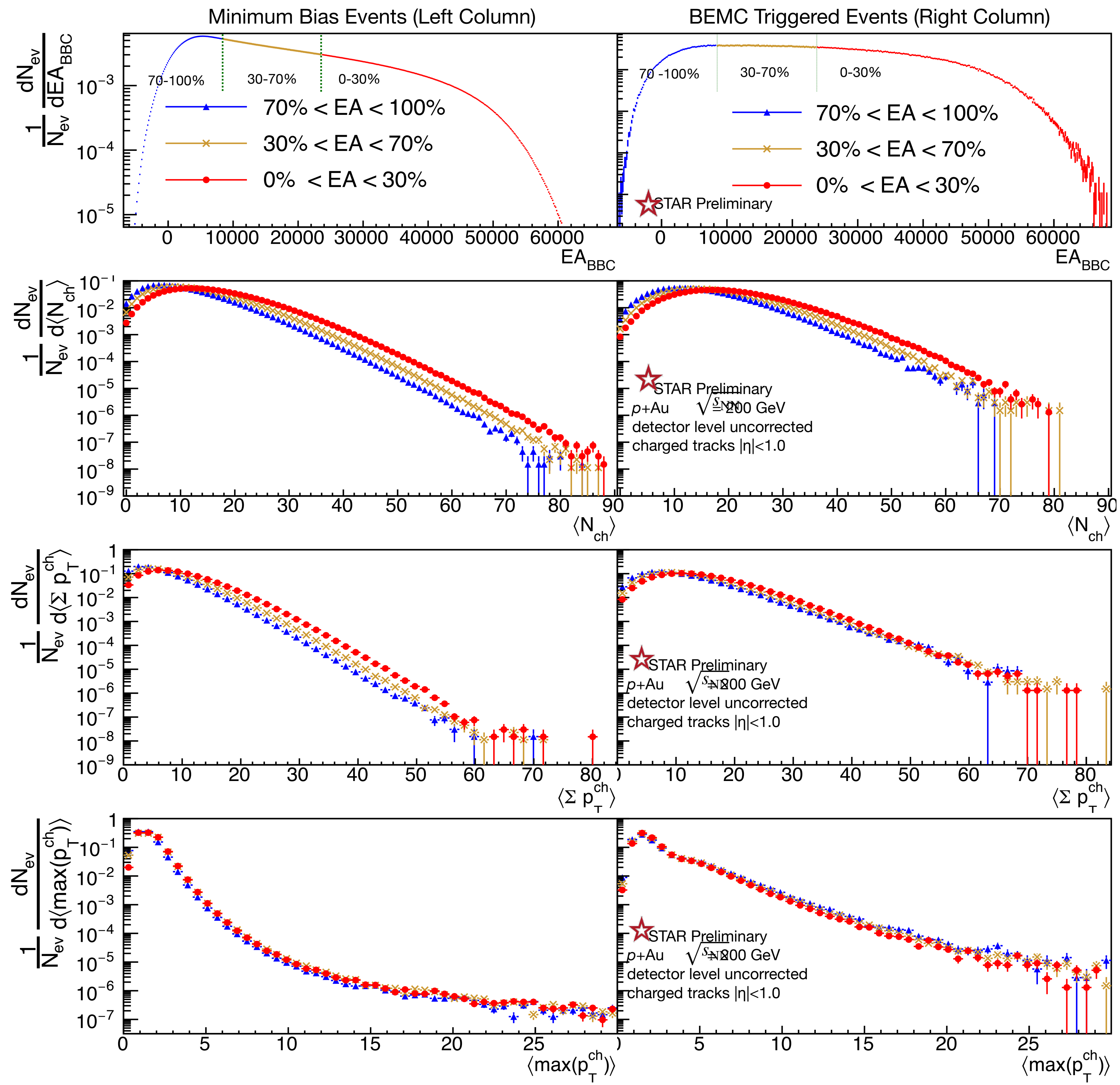


Figure 10

Event and Track Cuts

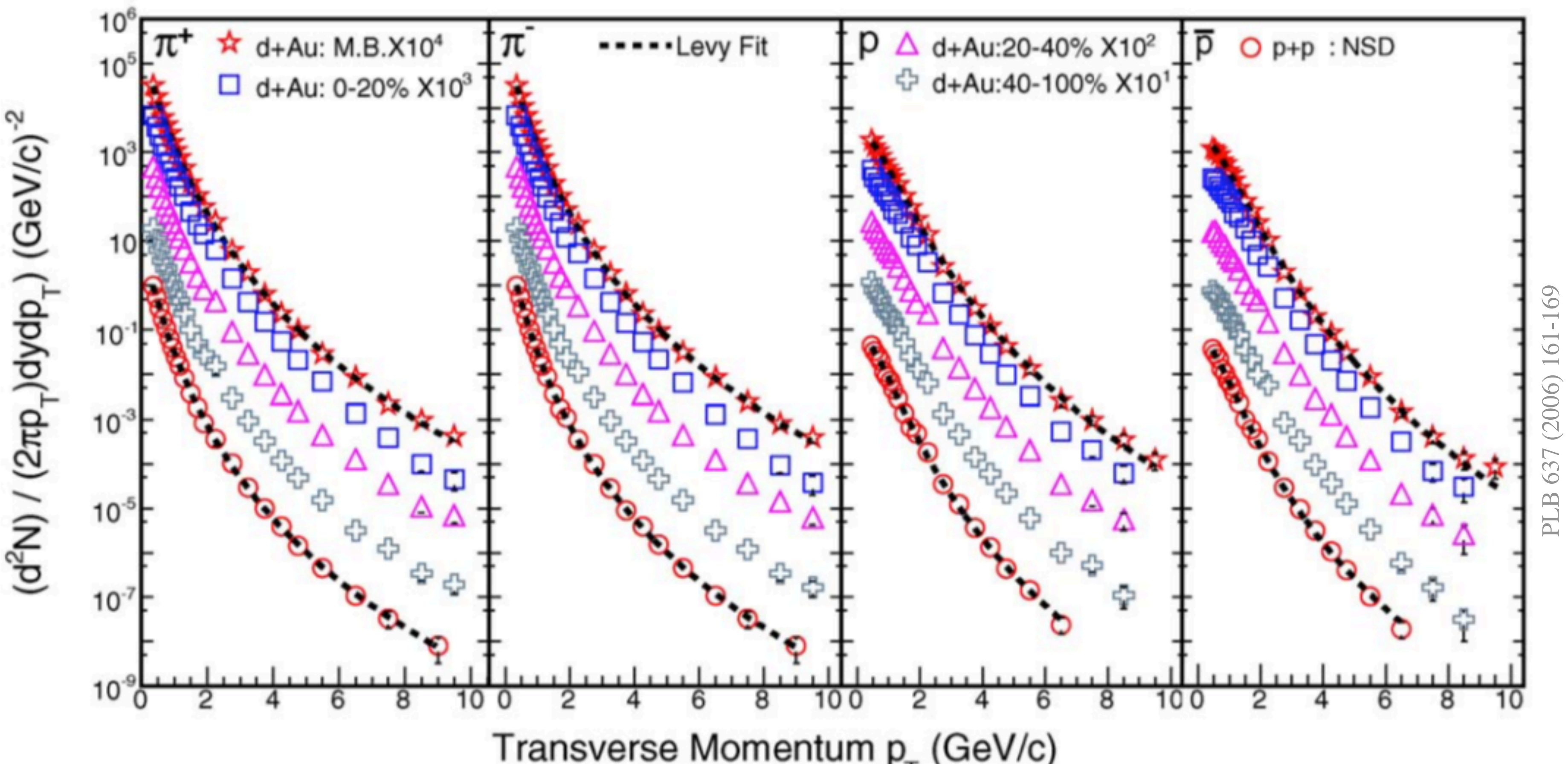
- Event cuts:
  - Vertex Ranking > 0
  - $|Z_{\text{primary vertex}}| < 10$ cm
  - ZDCx < 27,000
  - $|Z_{\text{vertex}} - Z_{\text{vertex position detector}}| < 6$ cm
- Track cuts
  - $N_{\text{hits}}/N_{\text{hits-possible}} > 0.52$
  - $DCA_{\text{track}} < 3$ cm
  - 0.2 GeV < $p_{T,\text{ track}}$ < 30 GeV
  - $|\eta|<1.0$
- Jets:
  - R=0.4
  - anti-k_T clustering algorithm using FastJet 3.3.0
  - composed of detector level, un-corrected tracks
  - $|\eta|<0.6$ (for jet center – individual tracks may extend to $|\eta|<1.0$)
  - Are not background subtracted
- The trigger which defines $\varphi=0$ is defined as the highest E_T BEMC hit in the event
- The azimuth of the jets are relative to the trigger in the event

Spectra in three EA bins for raw, uncorrected tracks



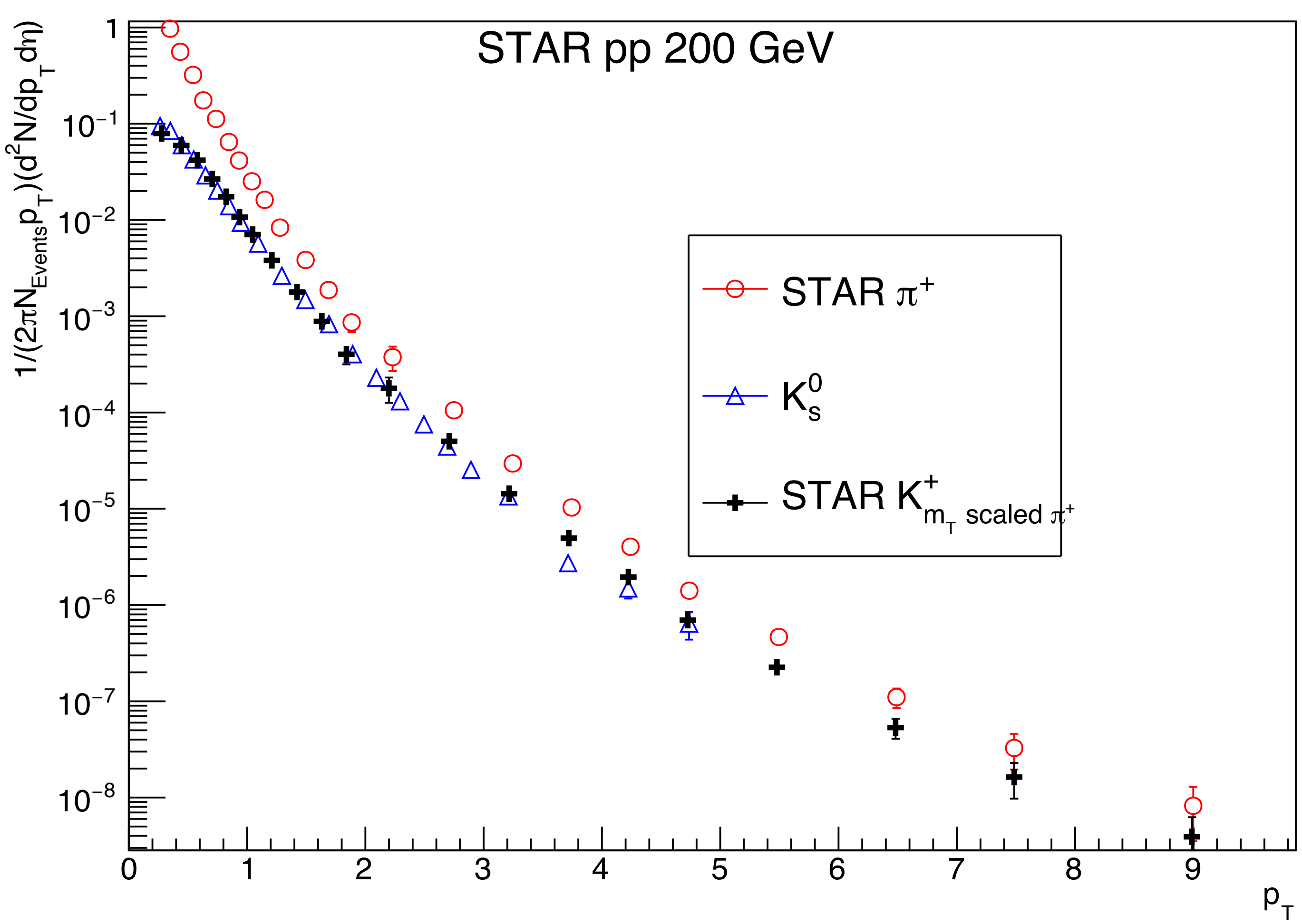
Priors and Unfolding

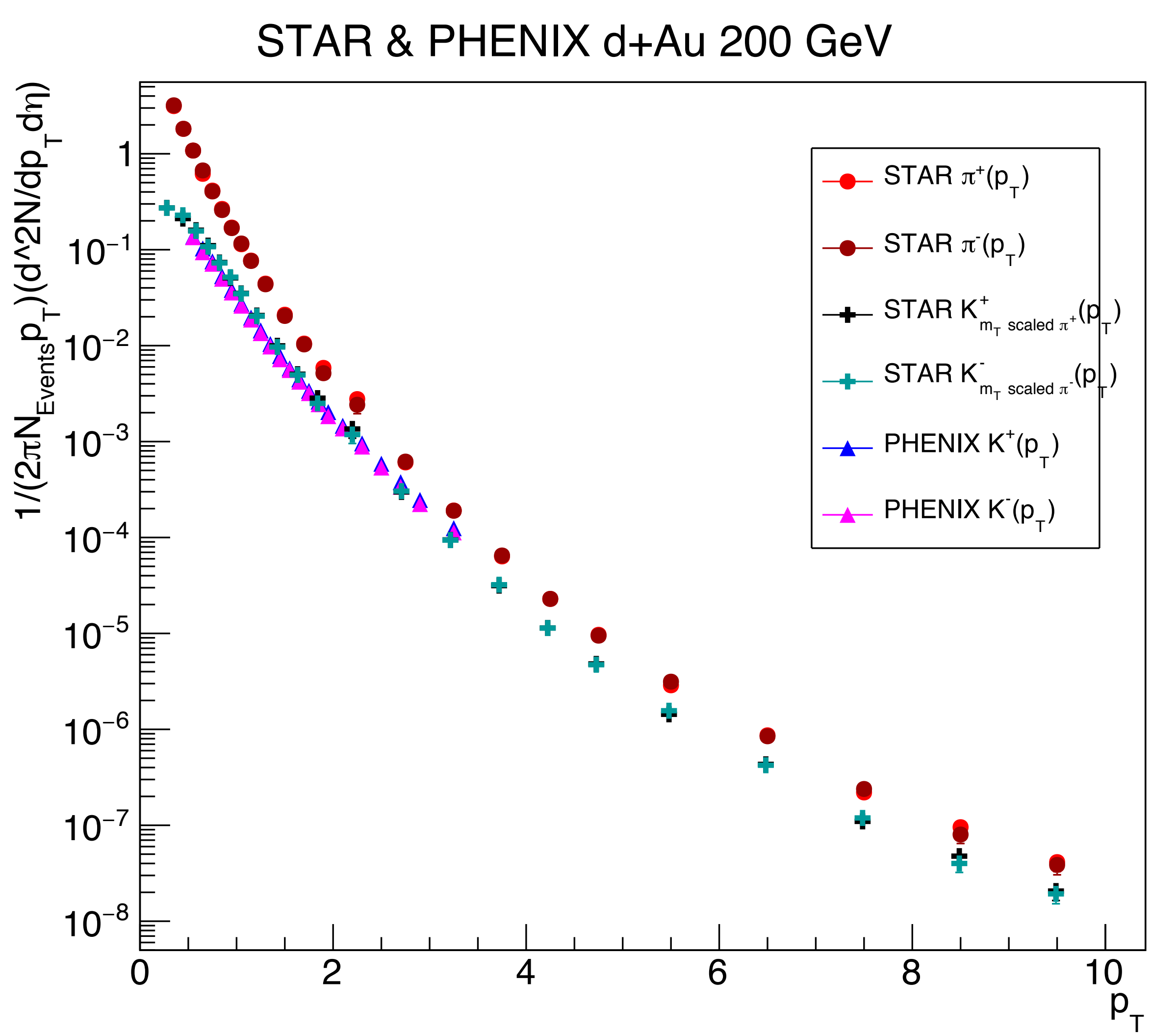
- A single embedding response matrix was generated for all charged tracks, necessitating the relative production spectra of each particle species
- Measurements of π⁺, π⁻, p, and anti-proton data up to about 10 GeV at exist at STAR for d+Au and pp collisions at 200 GeV
- K_S^0 spectrum has been measured up to about 5 GeV/c in 200 GeV pp collisions at STAR (PLB616, 8 (2005))
- K⁺ spectrum has been measured up to about 2.3 GeV/c in 200 GeV d+Au collisions at PHENIX (PRC 75, 64901 (2007))



Kaon prior

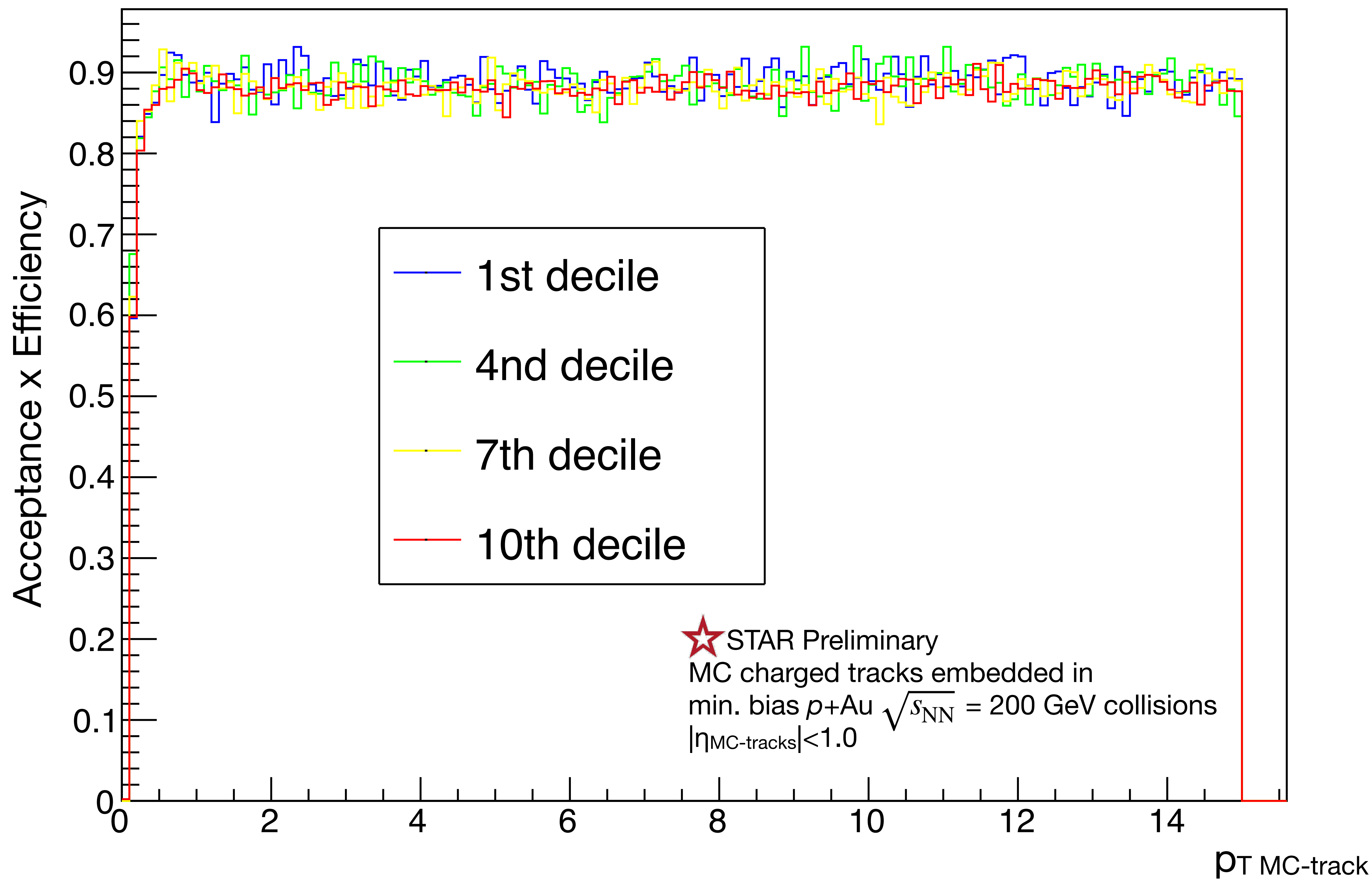
- From both the pp and d+Au data, the π^+ and π^- spectra were m_T scaled (with a scaling factor of 2.0 from (PRC 75, 064901 (2007)) to generate the K^+ and K^- spectra
- Each spectra was fit with a Levy function; these functional forms provided the priors uses to weight and sum the six particle species' response matrices to a single charge particle response matrix
- Differences in the final result from using the Kaon spectra from the d+Au collisions vs using the spectra from the pp collisions were accounted in the systematic errors fo the results



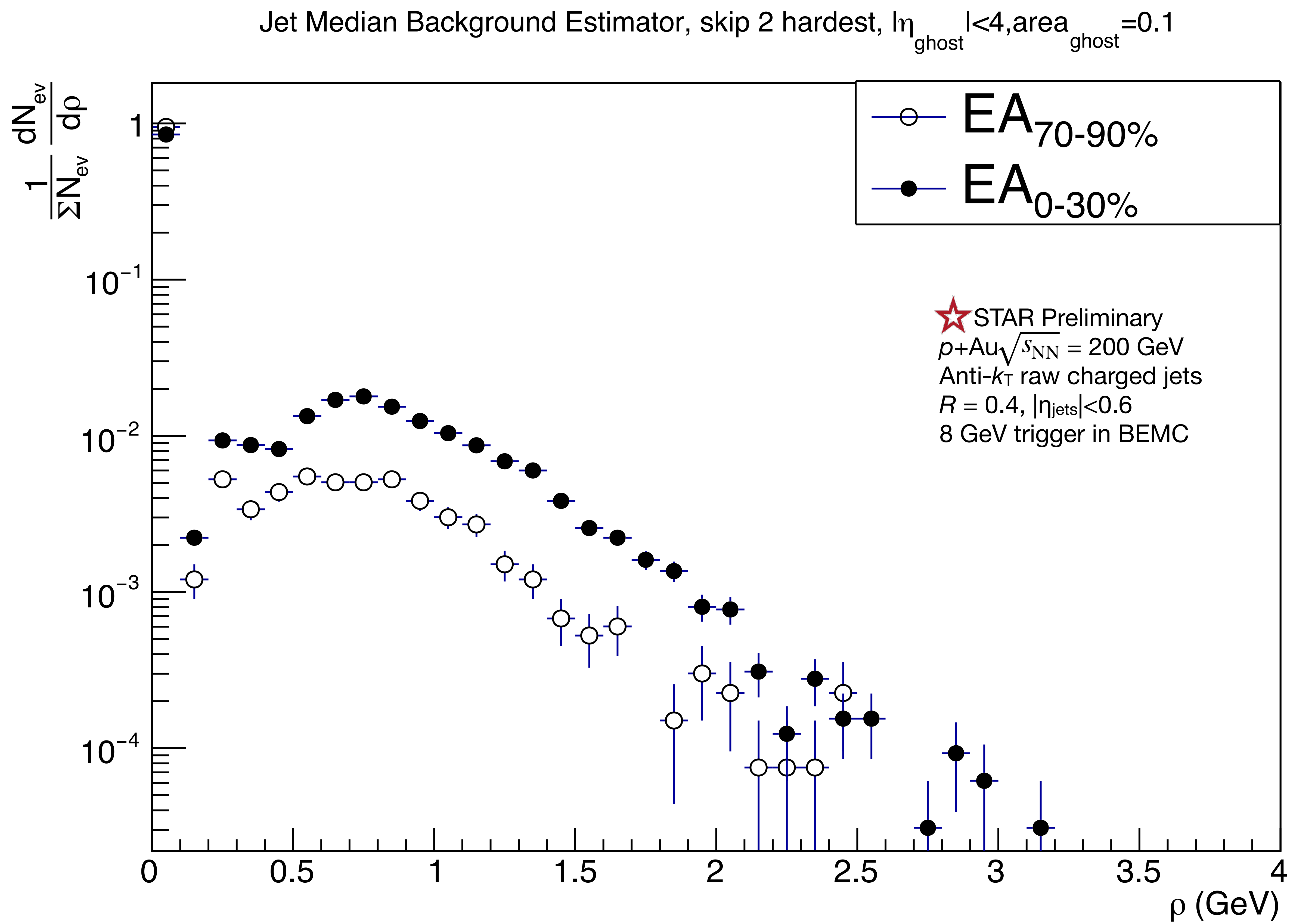


Percentage of matched tracks does't change with EA_{BBC} decile

- Embedded track efficiency x acceptance independent of EA_{BBC} decile of backward (Au-going) activity



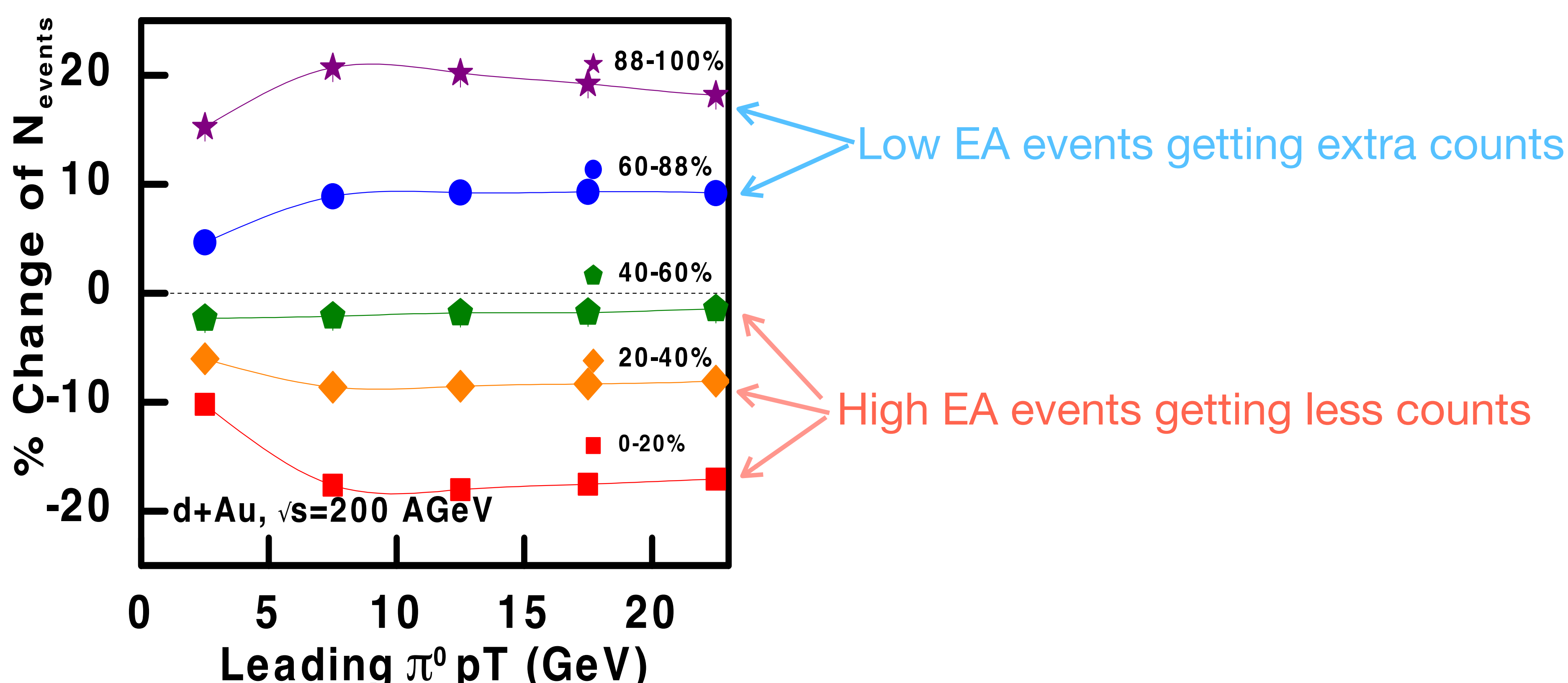
Standard FastJet3 background estimator: background = 0, 85% & 95% of time



Theory result for modifying Glauber to converse p_{tot} of d/p in binary collisions

- Traditional Glauber treats all N_{coll} collisions as equal
- Modify Glauber for depletion of energy (p_{total}) of the proton/deuteron
- Primary result: more high energy jets (from N_{coll}) are correlated with lower overall multiplicity (by energy conservation)
- Takeaway: jet suppression and enhancement is predicted to result from mis-binning EA

$$R^{jet\ \mathrm{High\ EA}}_{(p/d)\mathrm{A}} < 1 \quad \& \quad R^{jet\ \mathrm{Low\ EA}}_{(p/d)\mathrm{A}} > 1$$



Kordell II & Majumder *Physical Review C* **97**, (2018)