Quark Matter 2019

Wuhan, China 4-9 November

LUX ET VERITAS

Correlation measurements of charged particles and jets at mid-rapidity with event activity at backward-rapidity in $\sqrt{s_{\mathrm{NN}}} = 200\,\mathrm{GeV}$ p+Au collisions at STAR

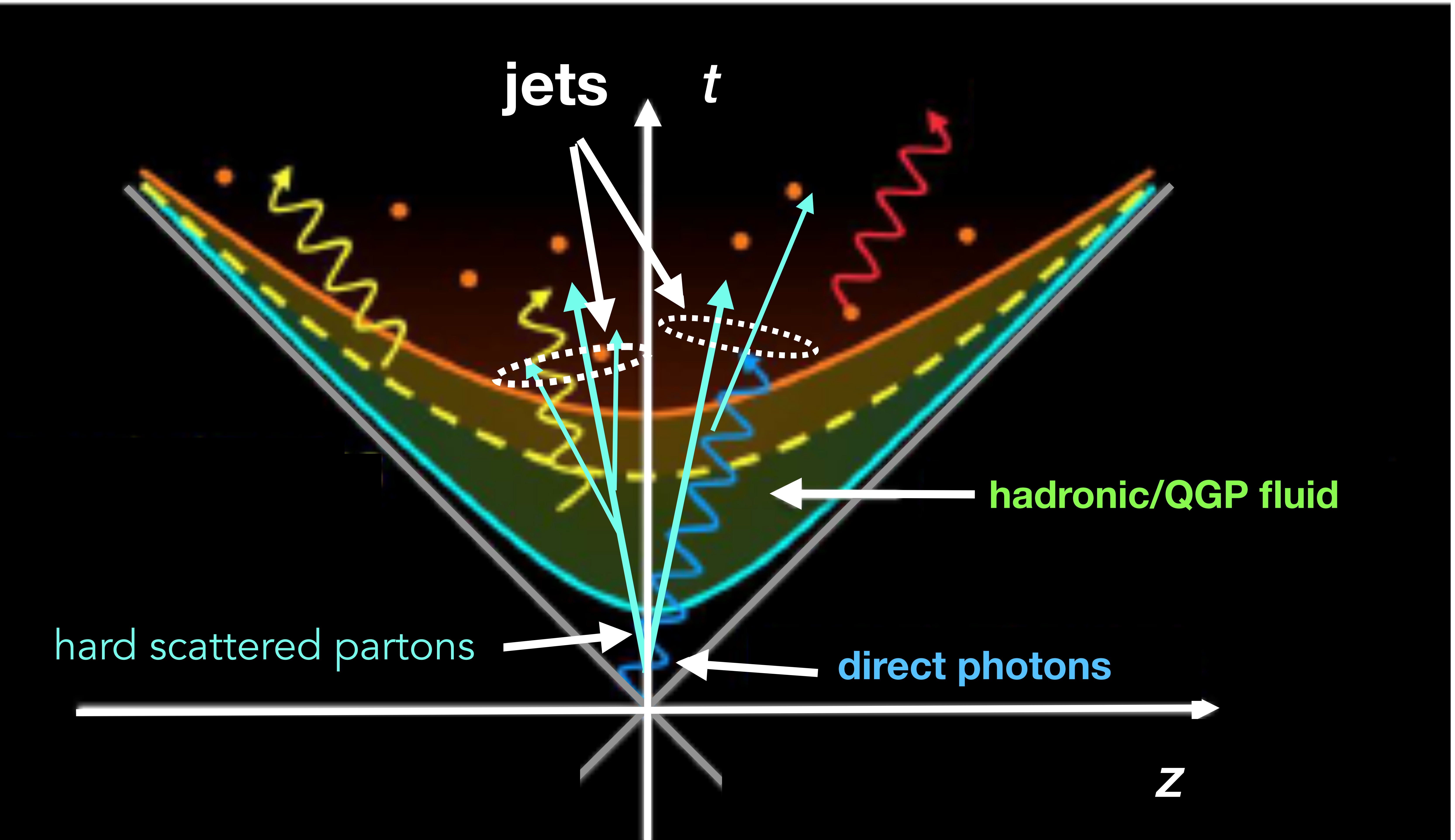
David Stewart, Yale University, for the STAR Collaboration

Wright Laboratory

STAR

Funded in part by U.S. DEPARTMENT OF ENERGY Office of Science

Jets: what and why



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

- Hard scatterings of partons occur early in collisions and subsequent products may interact with a medium
- Jets found via clustering algorithm (de facto standard: anti-k_T) allow access to hard scattered parton kinematics
- Modification of jets is used to probe existence and properties of a QGP

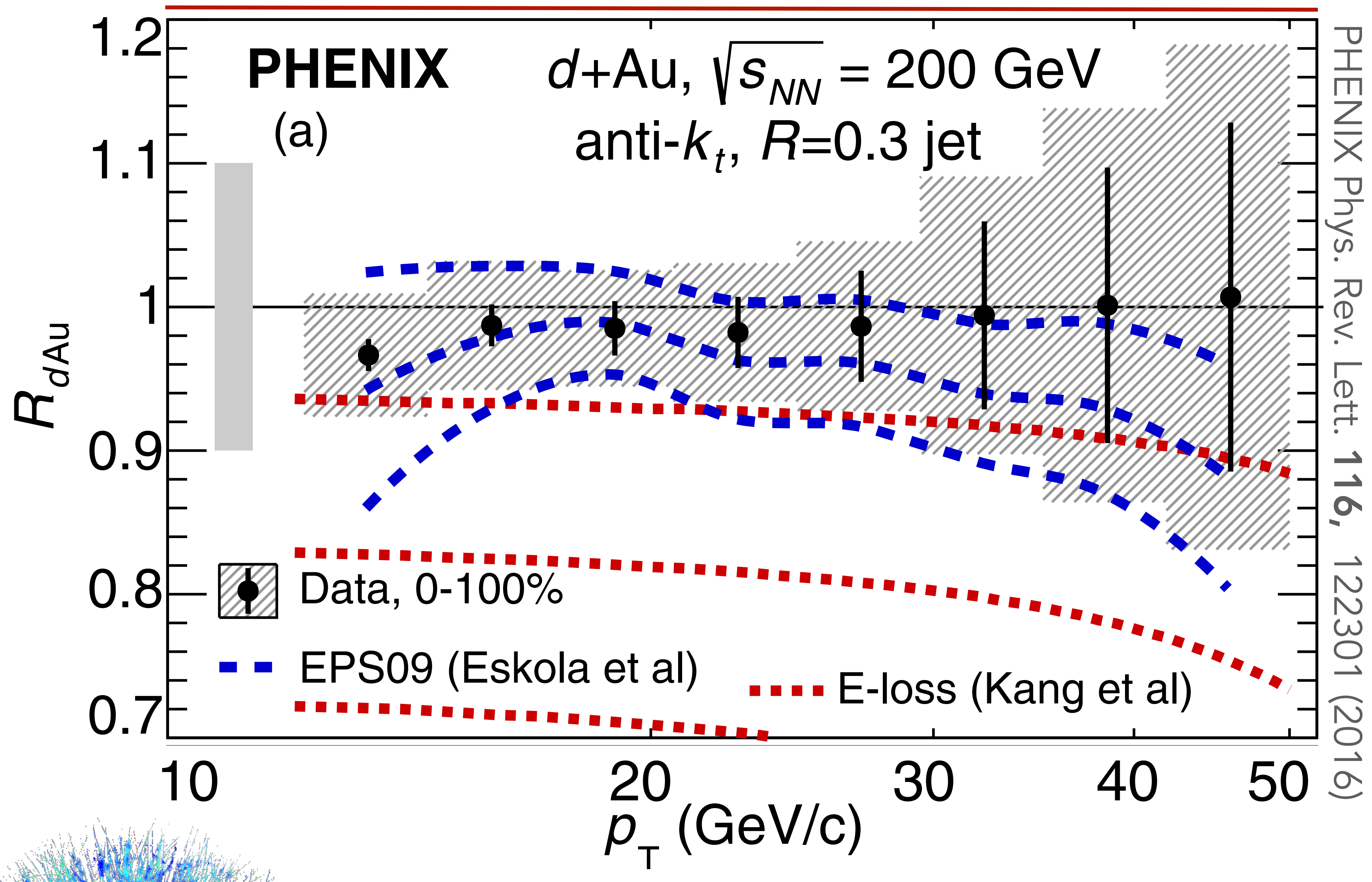
Inclusive jet measurements in small systems

- Measure event activity (EA) at large backward rapidity and map geometrically to N_{coll}
- Probe for final state effects with nuclear modification factor

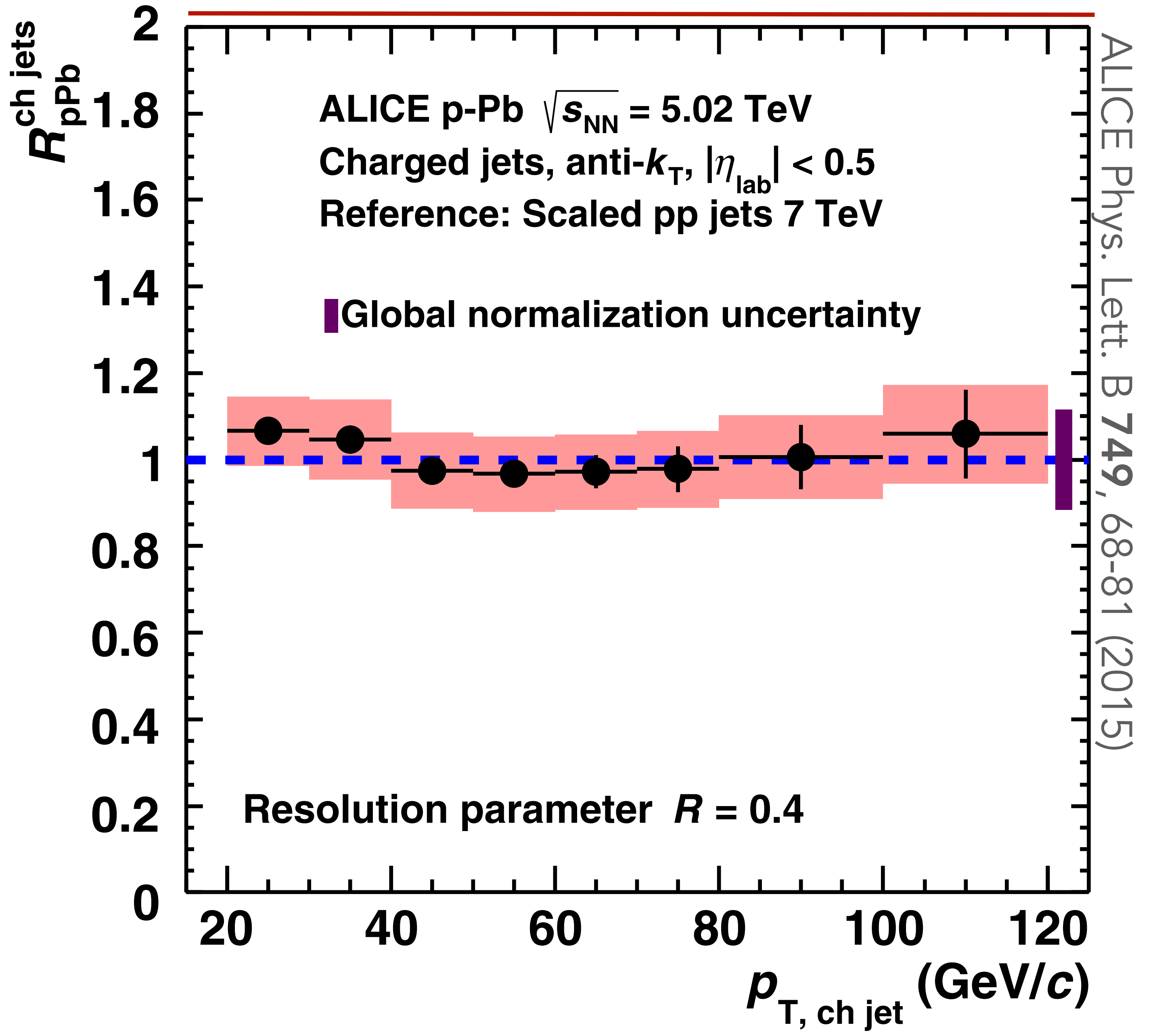
$$R_{\mathrm{p/d+Au}} \equiv \frac{\mathrm{d}N^{\mathrm{p/d+A}}/\mathrm{d}p_{\mathrm{T}}}{\left\langle T_{\mathrm{p/d+A}} \right\rangle \mathrm{d}\sigma_{\mathrm{pp}}^{\mathrm{INEL}}/\mathrm{d}p_{\mathrm{T}}} = \frac{\mathrm{Yield}_{\mathrm{p/d+A}}}{\left\langle N_{\mathrm{coll}} \right\rangle \mathrm{Yield}_{\mathrm{pp}}}$$

- $R_{\mathrm{p/d+A}} \approx 1 \Rightarrow$ no net final state effects

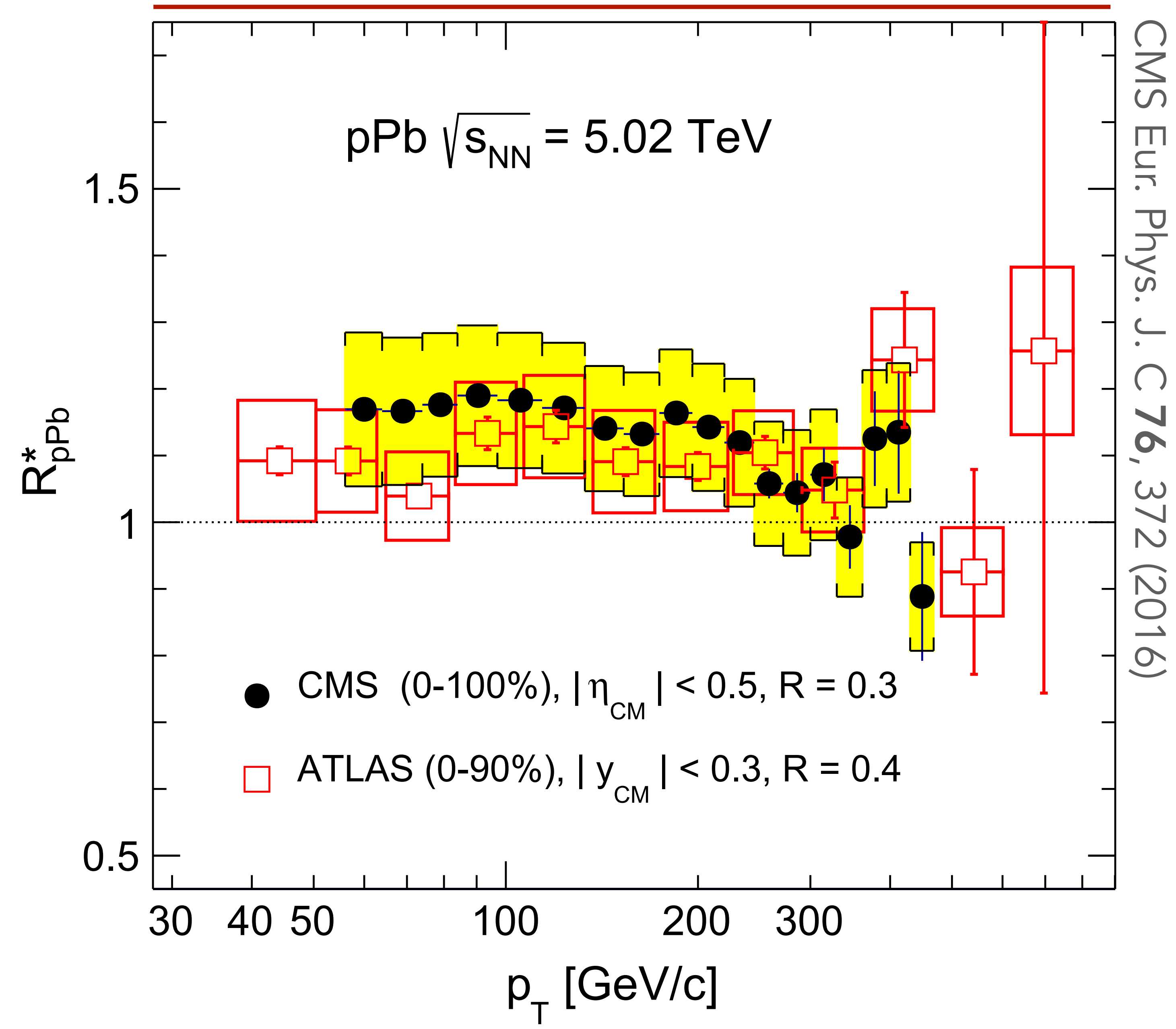
PHENIX



ALICE

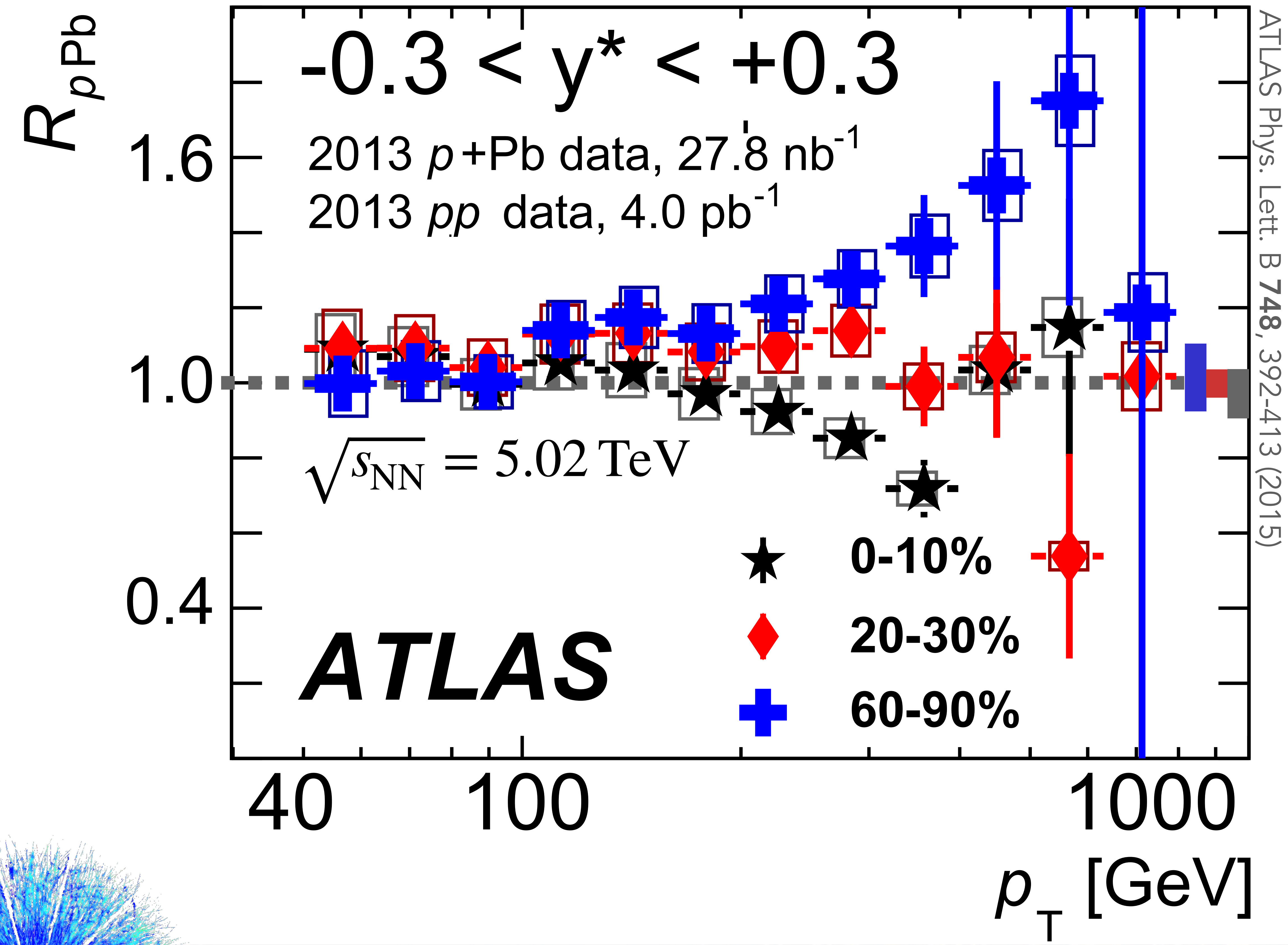


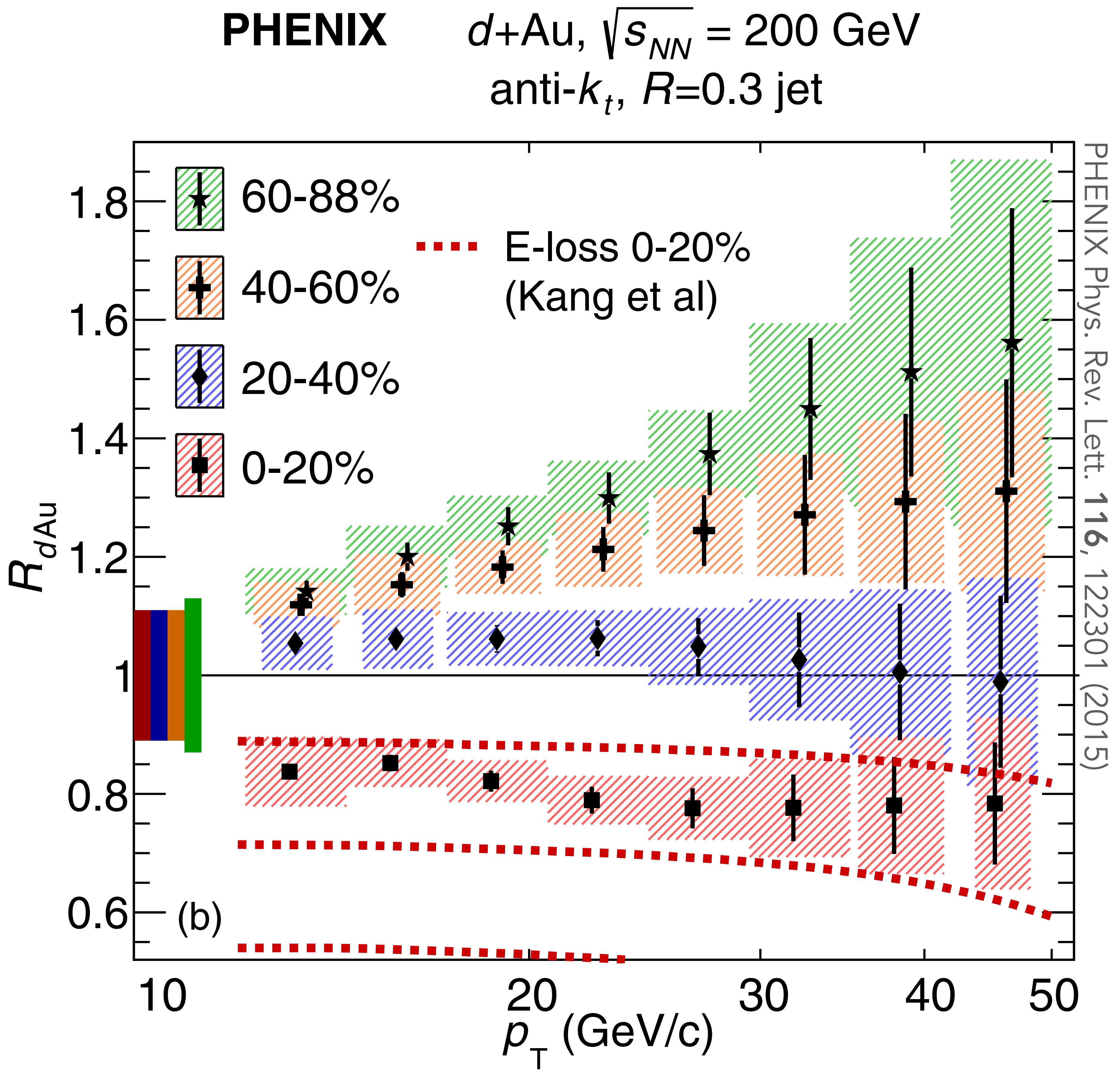
ATLAS & CMS



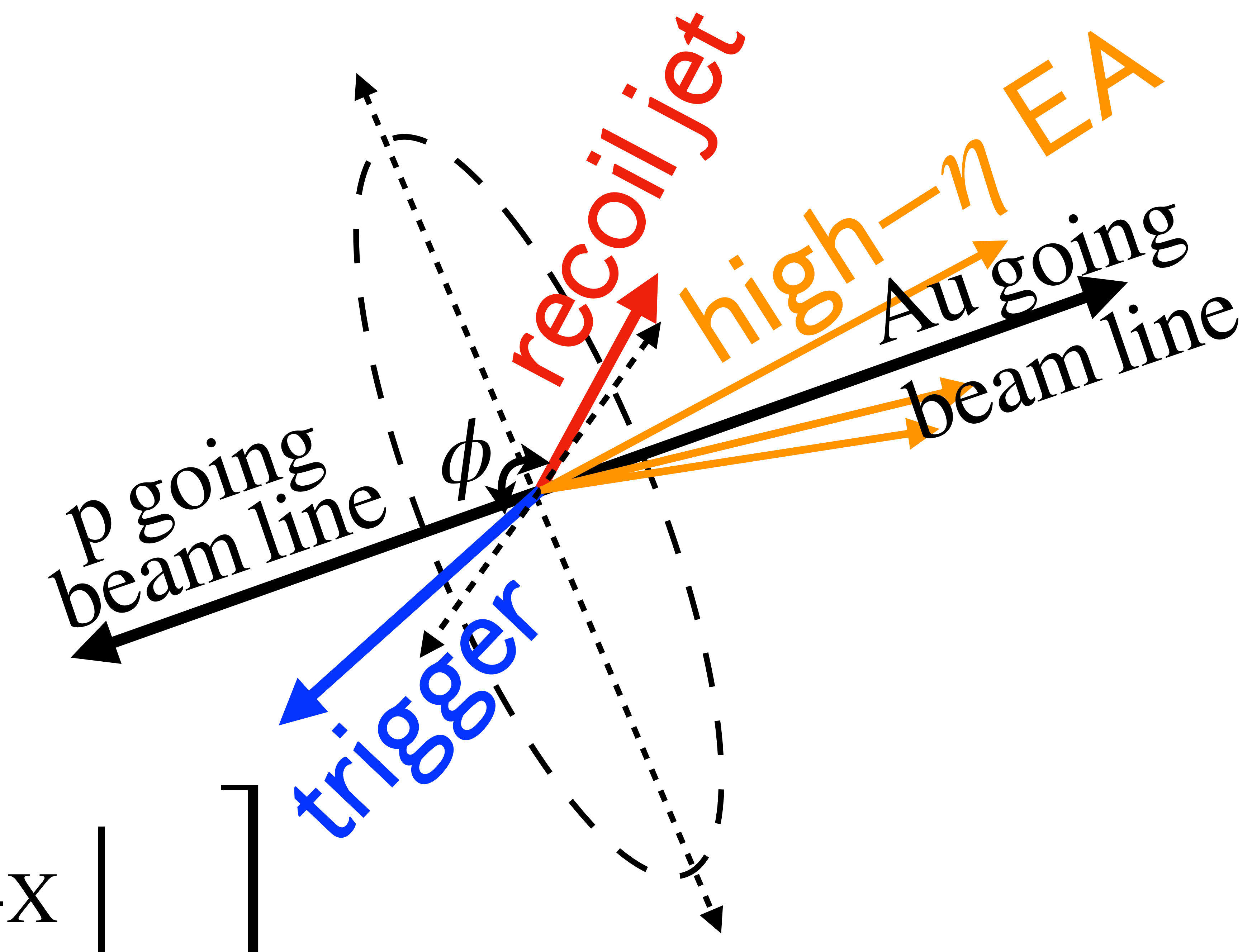
$R_{p/d+Au} \neq 1$ when binned by event-activity (EA)

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





Semi-inclusive jet measurement



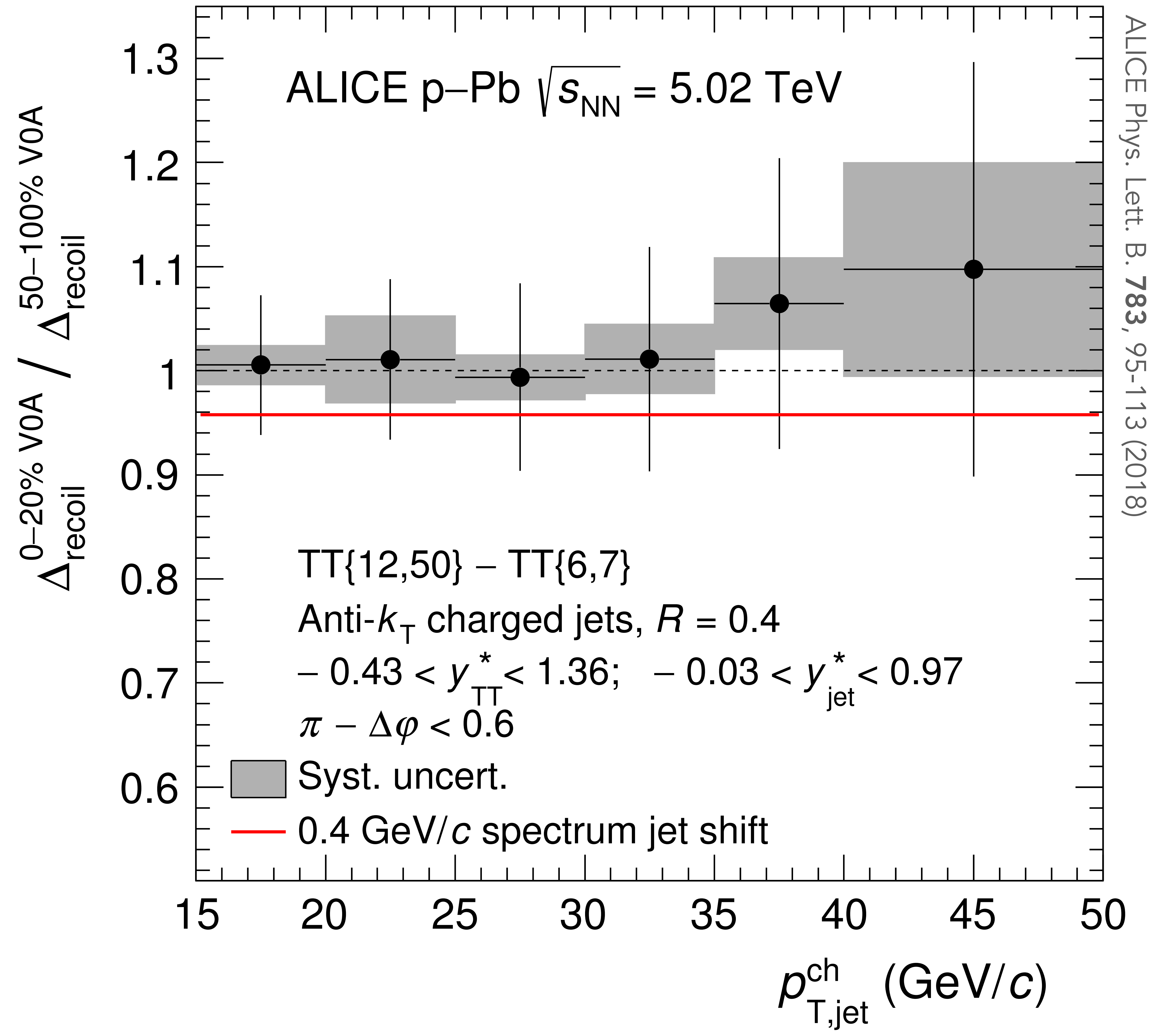
- Measure jet spectra per trigger (S) in EA bins
- S_{EA} is self-normalized with respect to collision geometry

$$S_{\mathrm{EA}} \equiv \frac{\mathrm{d}N_{\mathrm{jet}}/\mathrm{d}p_{\mathrm{T}}}{N_{\mathrm{trigger}}} = \frac{\cancel{L}}{\cancel{L}}\frac{\mathrm{d}}{\mathrm{d}p_{\mathrm{T}}}\left[\frac{\cancel{\langle N_{\mathrm{coll}}\rangle}}{\cancel{\langle N_{\mathrm{coll}}\rangle}}\frac{\sigma^{\mathrm{pp}\to\mathrm{trigger+jet}|_{\mathrm{TPC}}+\mathrm{X}}}{\sigma^{\mathrm{pp}\to\mathrm{trigger+X}}}\Bigg|_{\mathrm{EA}}\right]$$

- $S_{\mathrm{EA-high}}/S_{\mathrm{EA-low}}$ tests EA dependency of net final state effects

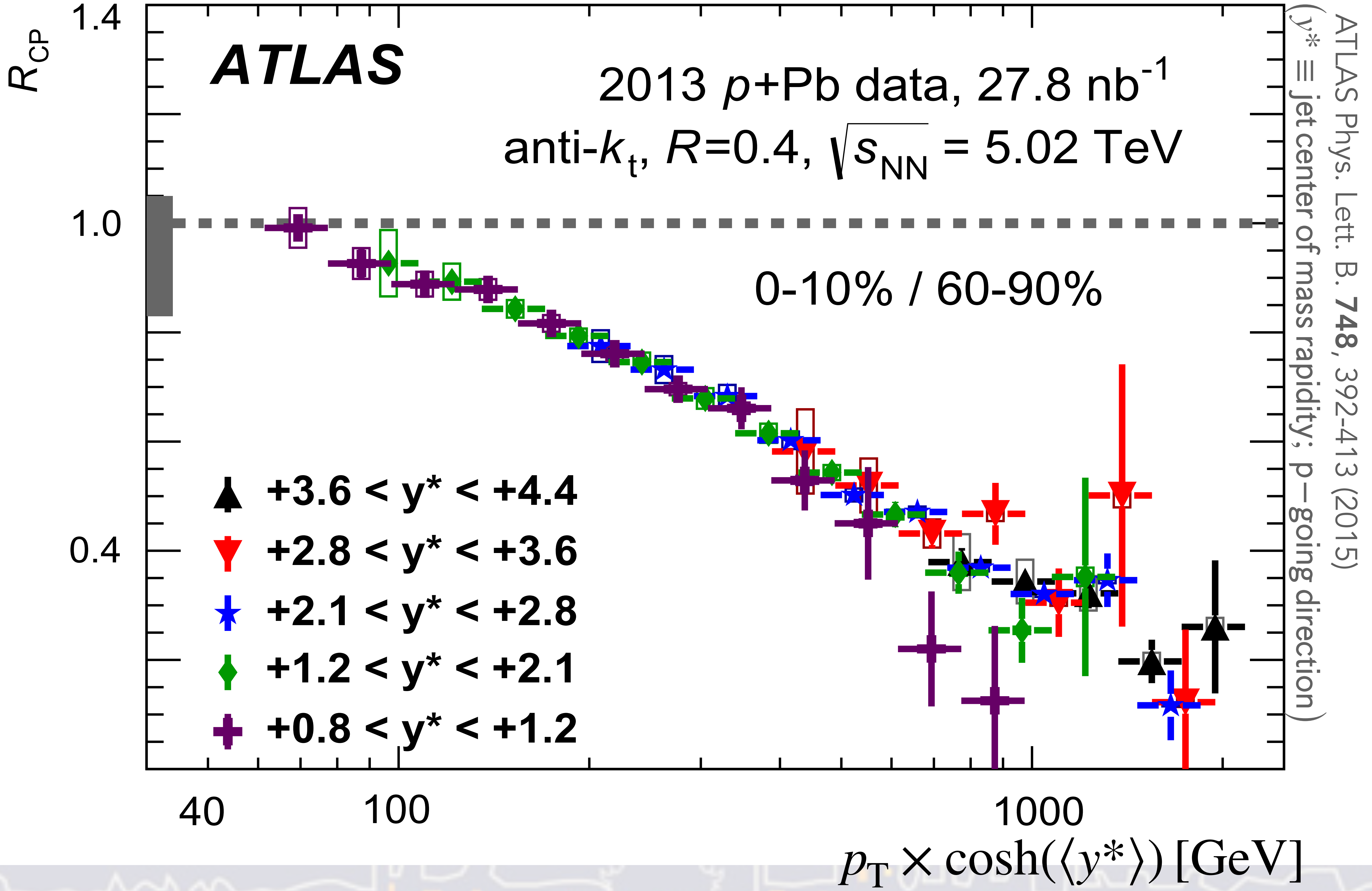
ALICE h+jet (semi-inclusive) measurement

- 2018: Measured jet spectra per trigger (S) recoiling from high p_T hadrons (semi-inclusive)
  - Took ratio of spectra:
    $$S_{0-20\%\mathrm{EA}}/S_{50-100\%\mathrm{EA}}$$
  - Set upper limit on out-of-cone energy transport (jet quenching), using jets up to x_p~0.02
  - If applicable at all x_p, limit is not consistent with ATLAS and PHENIX measurements



Current status + STAR preliminary

- ATLAS measurement hints that jet spectra modification scales with x_p



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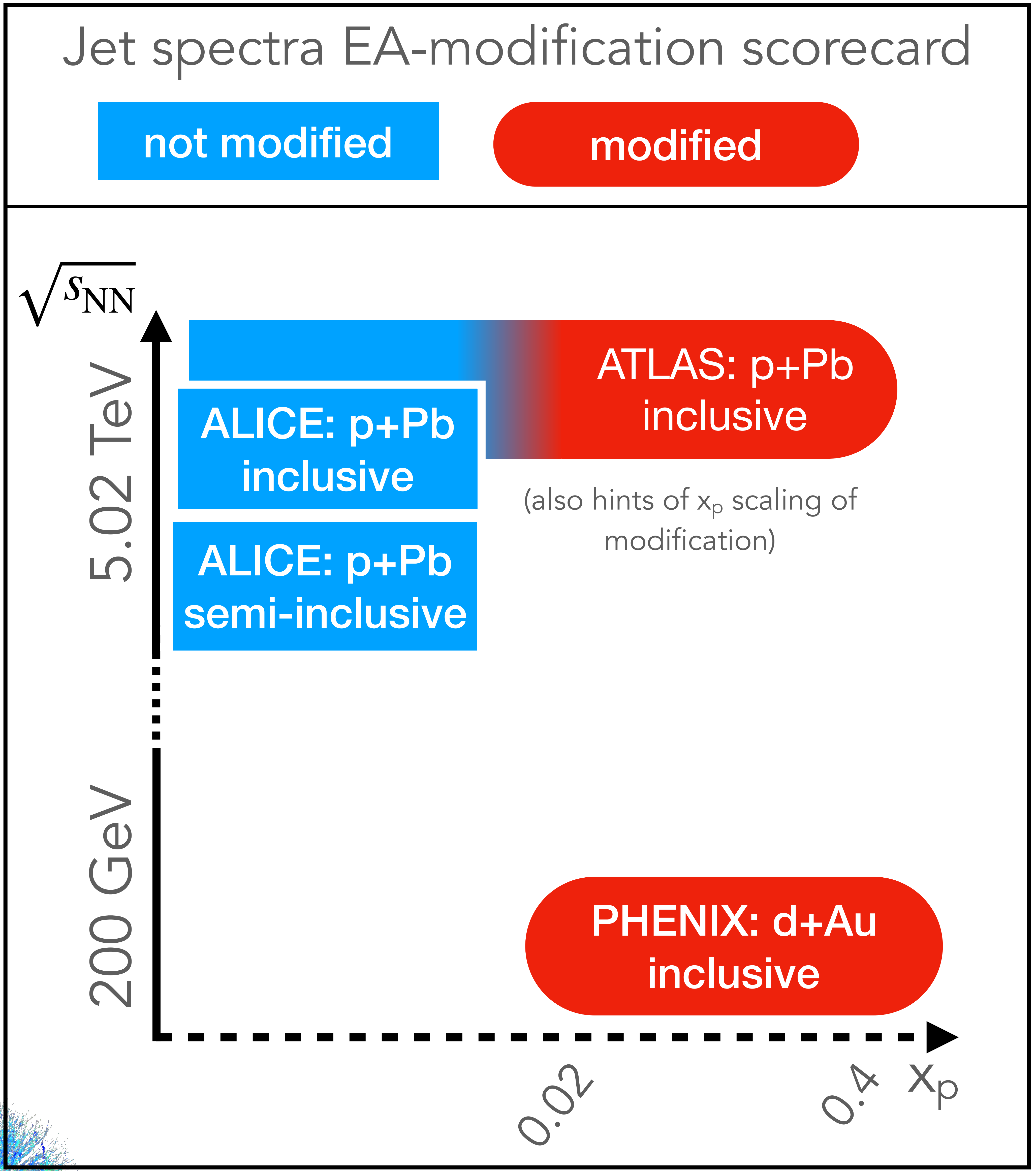

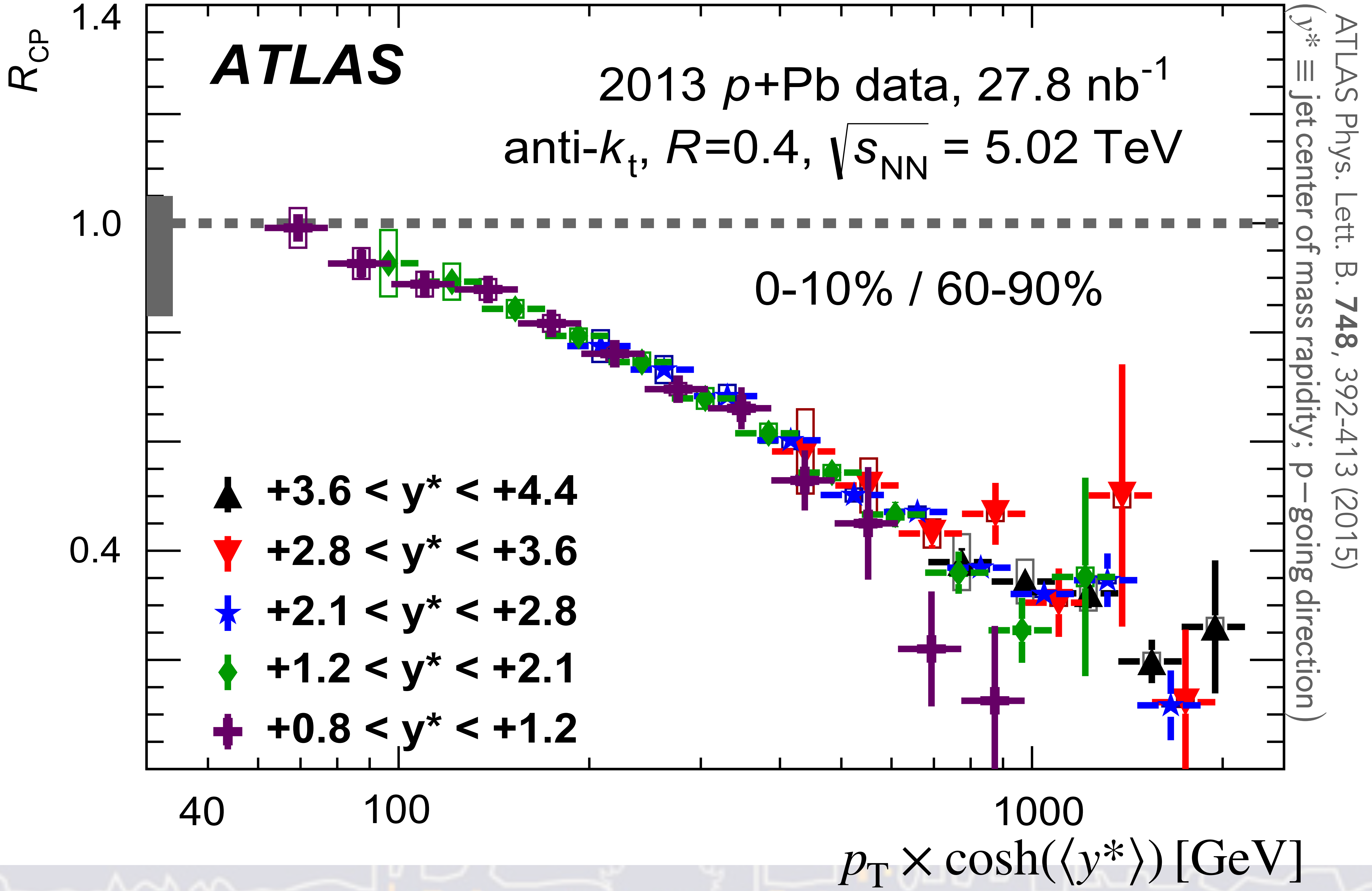

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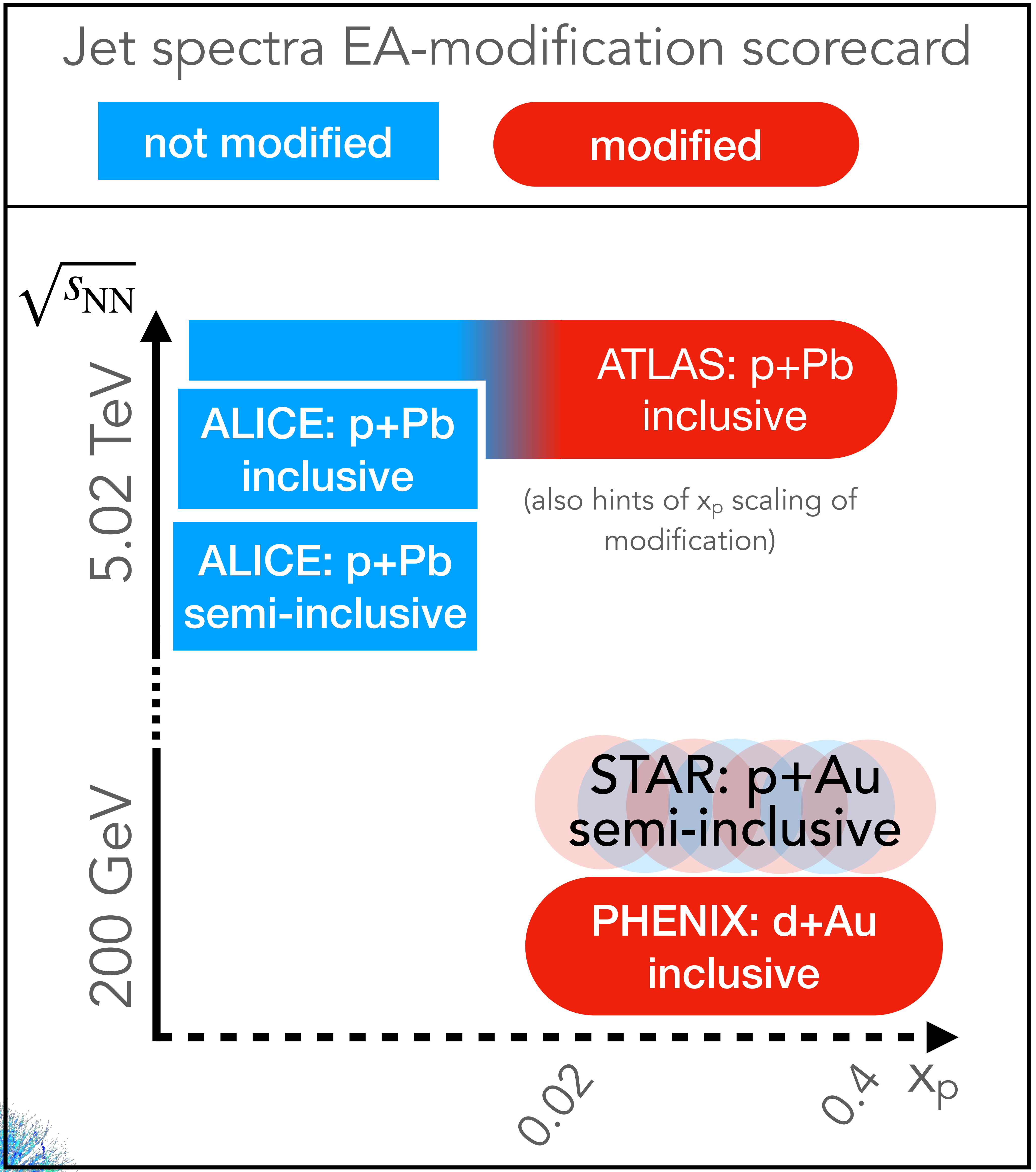
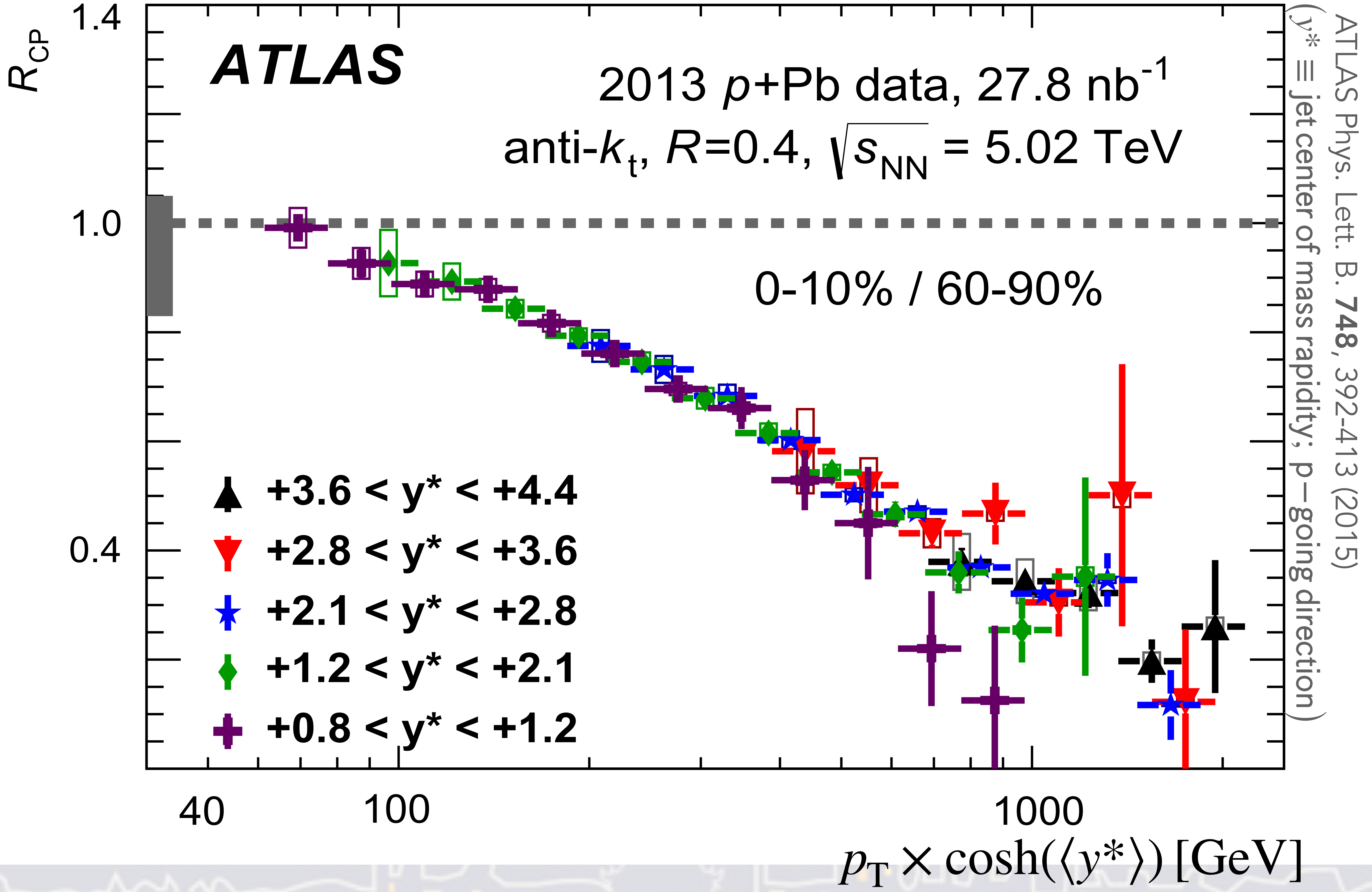
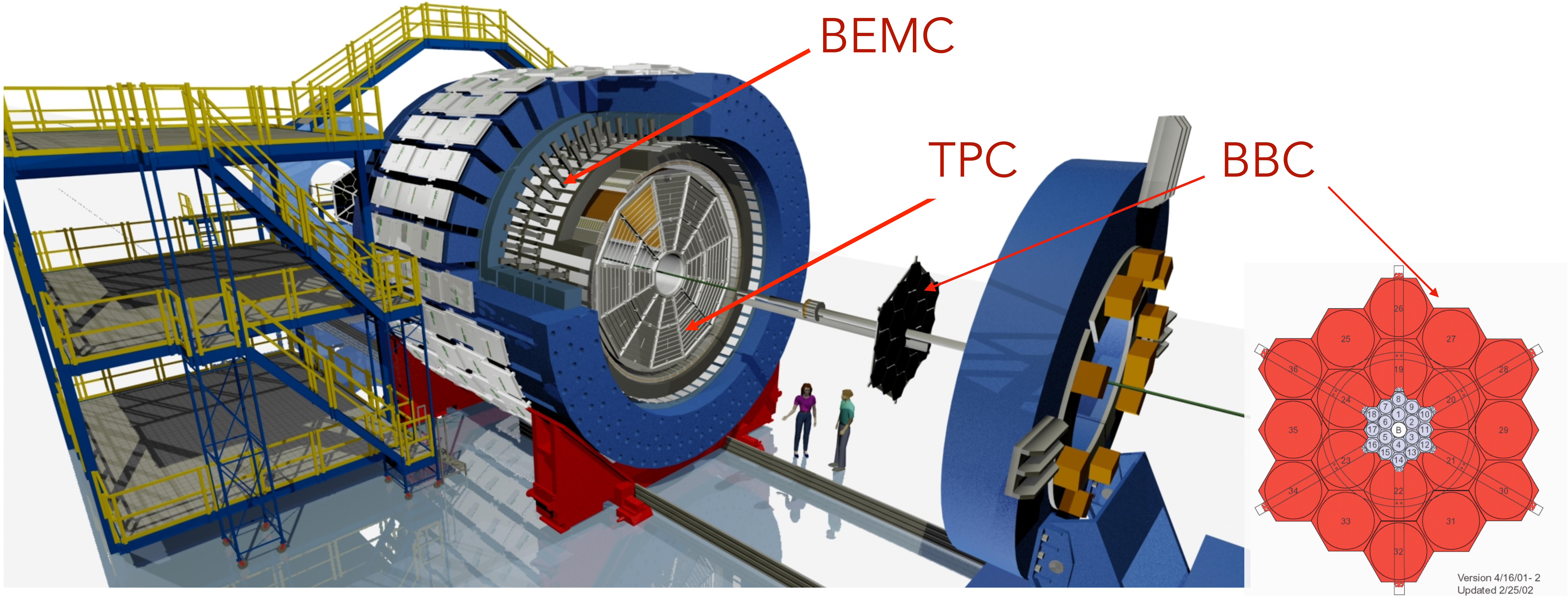


- ATLAS measurement hints that jet spectra modification scales with x_p
- This talk presents first p+Au, high-x_p, geometry-independent measurement at RHIC energies



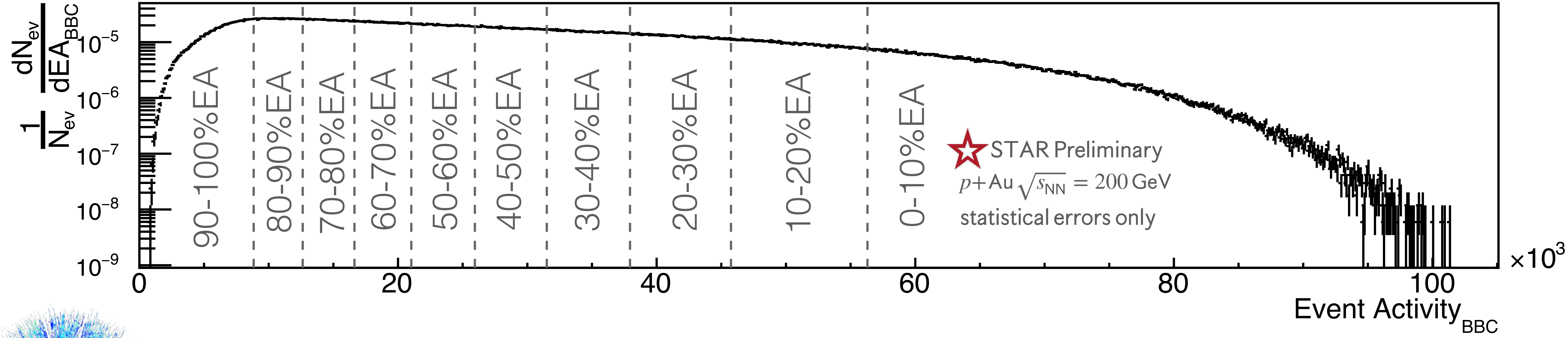
Jet and EA measurement at STAR



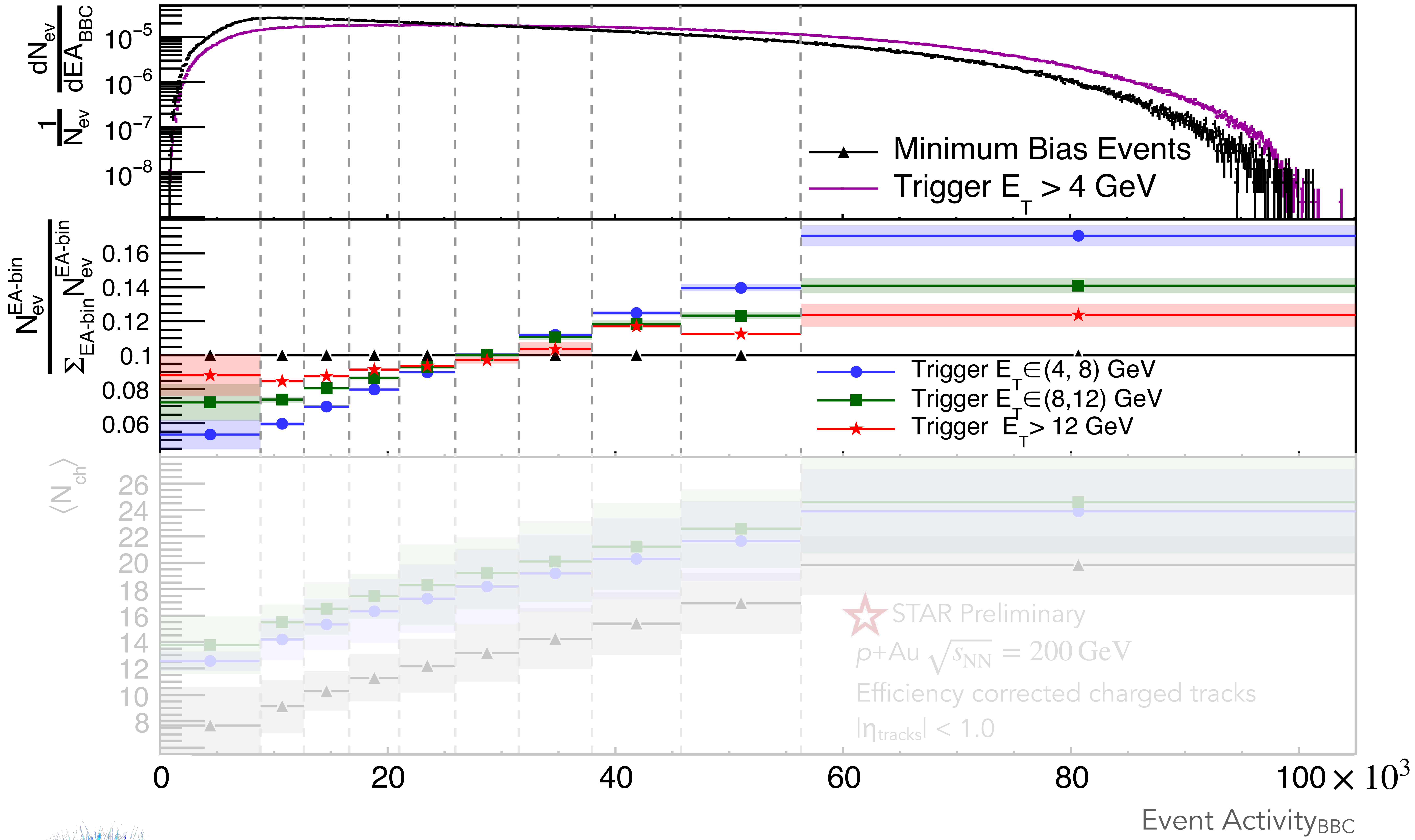
- ✦Time Projection Chamber (TPC): charged tracks with p_T at $|\eta|<1.0$
- ✦Barrel Electromagnetic Calorimeter (BEMC): energy deposition, primarily neutral particles at $|\eta|<1.0$
- ✦Beam-Beam Counter (BBC): plastic scintillators in two rings: $2<|\eta|<3.4$ and $3.4<|\eta|<5.0$
  - ✦BBC, in Au-going direction, corrected for z-vertex and luminosity, is EA estimator

STAR p+Au collisions in 2015: EA deciles, triggers, and jets

- Minimum bias events: set EA deciles definition
- BEMC triggered events: high transverse energy (E_T) hits in BEMC:
  $\mathrm{p} + \mathrm{Au} \rightarrow \mathrm{trigger}^{\mathrm{BEMC\,hit}} + \mathrm{X}$
- Charged jet spectra in TPC



BBC signal (EA) to mid-η correlations



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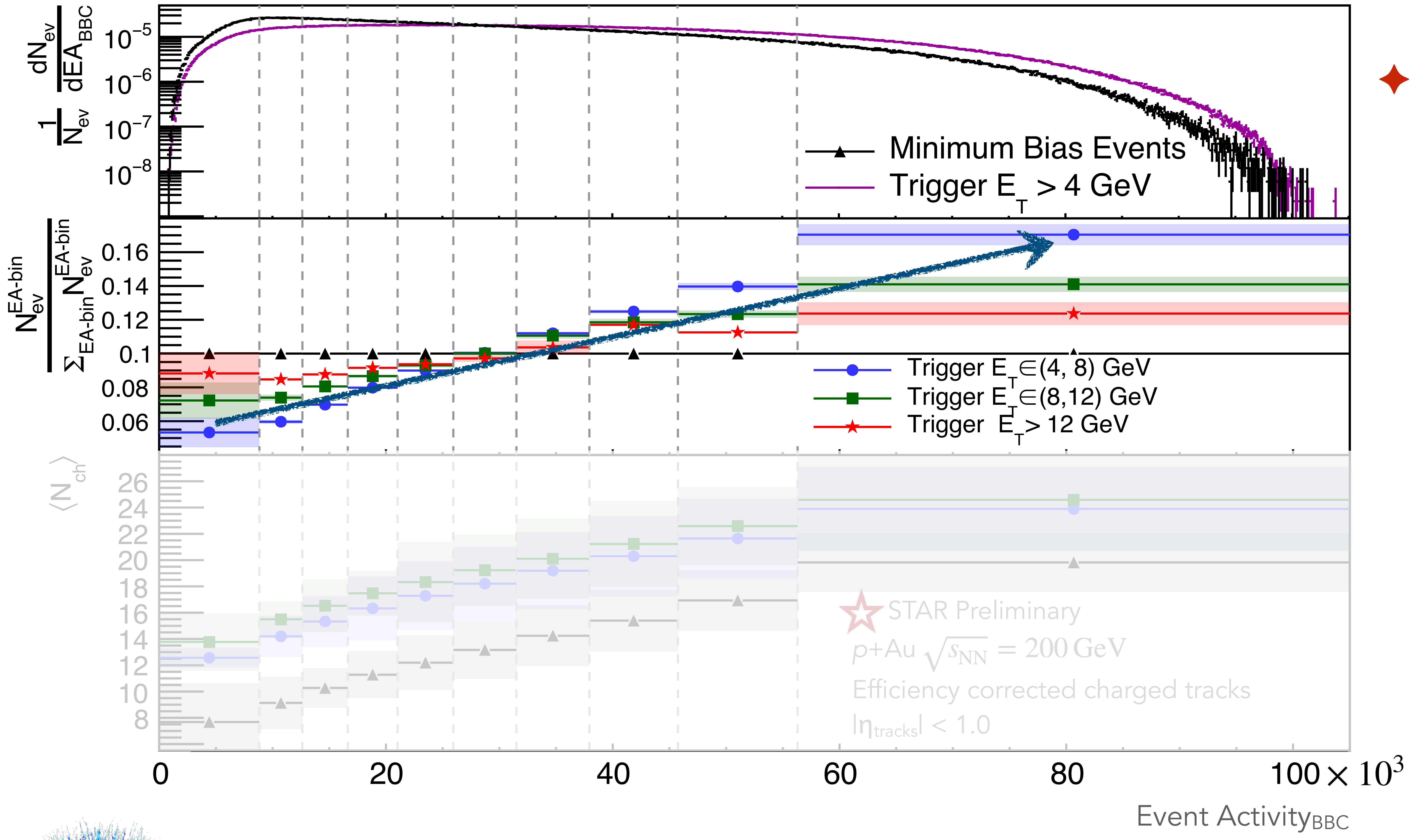
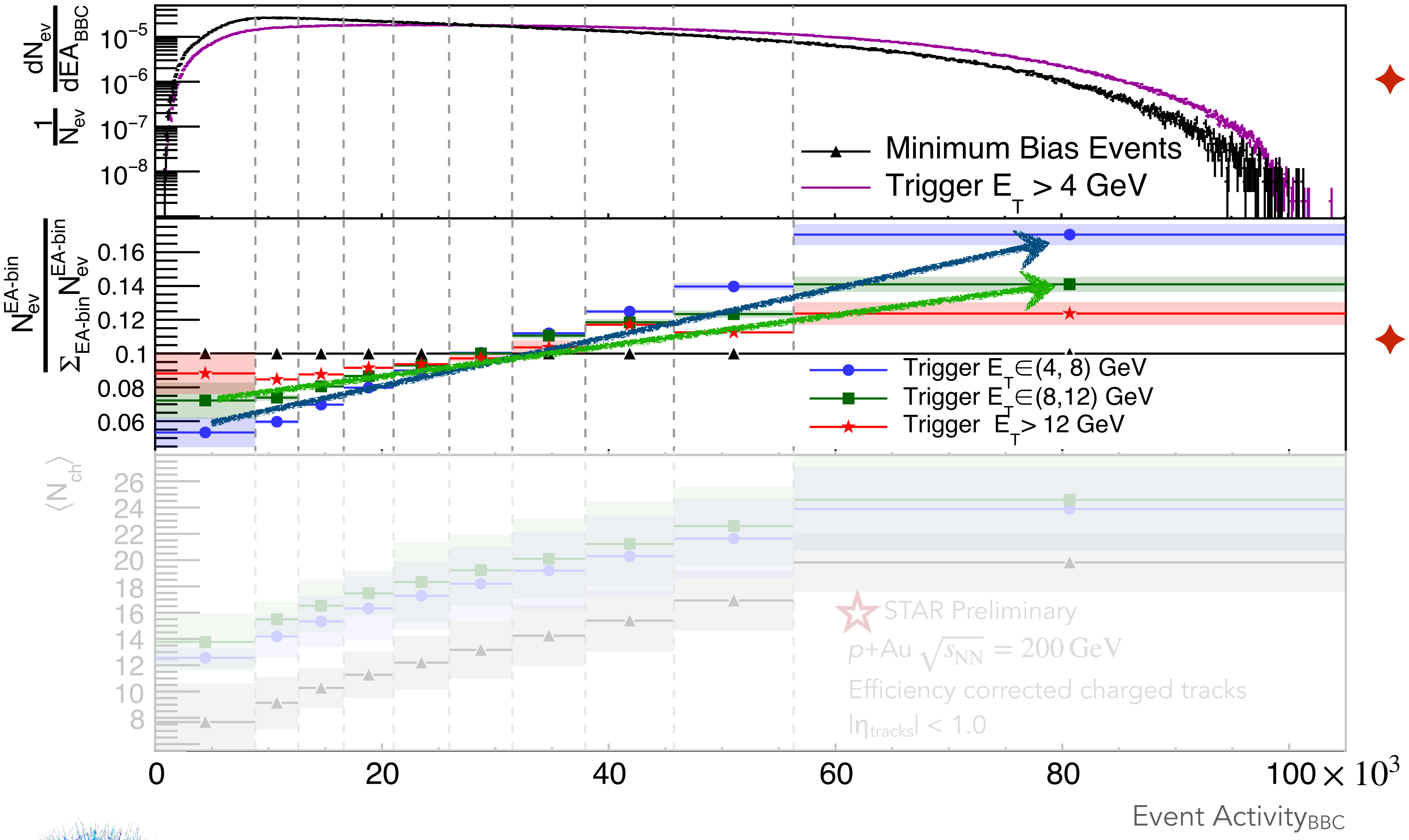


- Confirmed expectation of positive correlation between EA and probability of BEMC trigger

BBC signal (EA) to mid-η correlations



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- Correlation weakens for increasing trigger E_T

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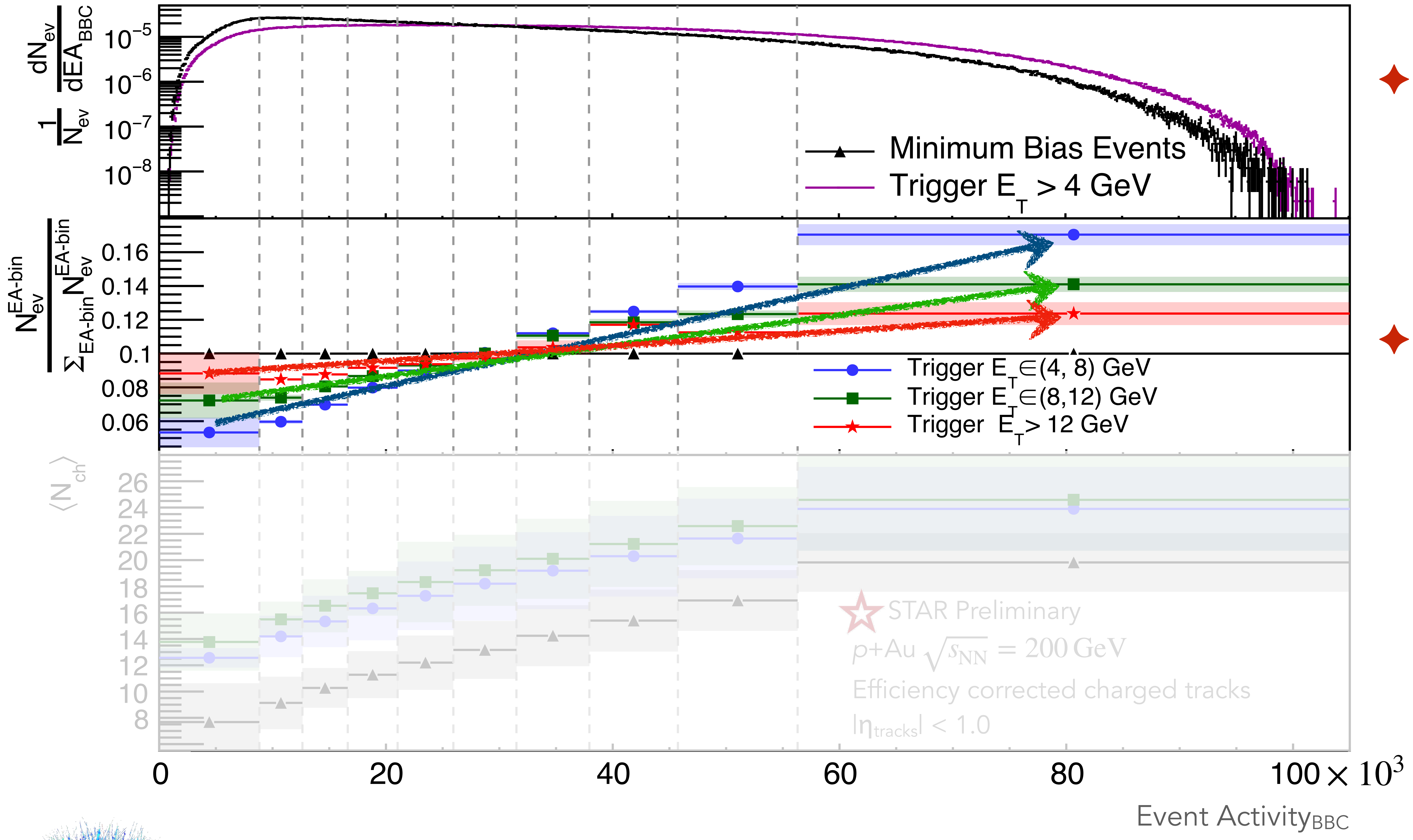

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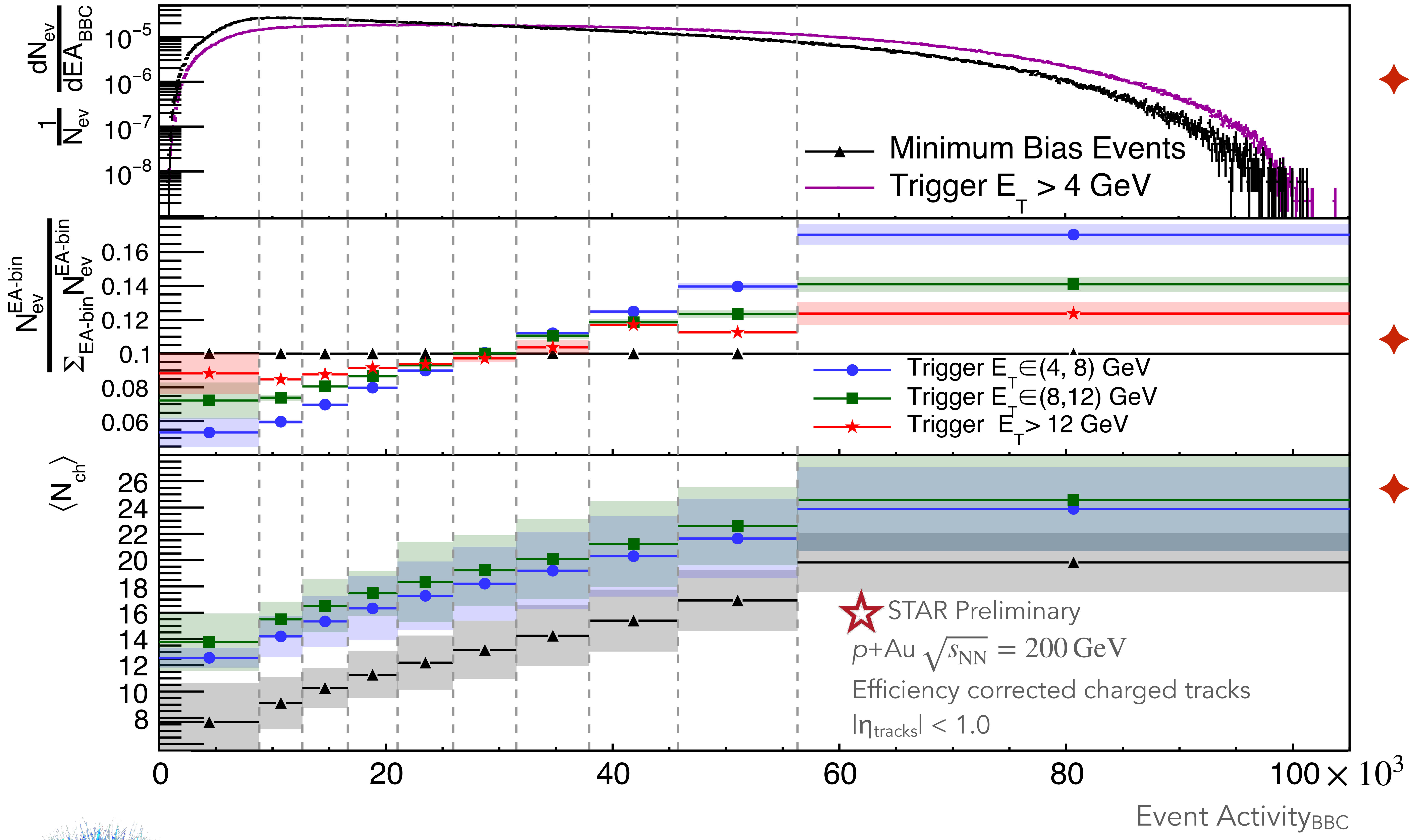
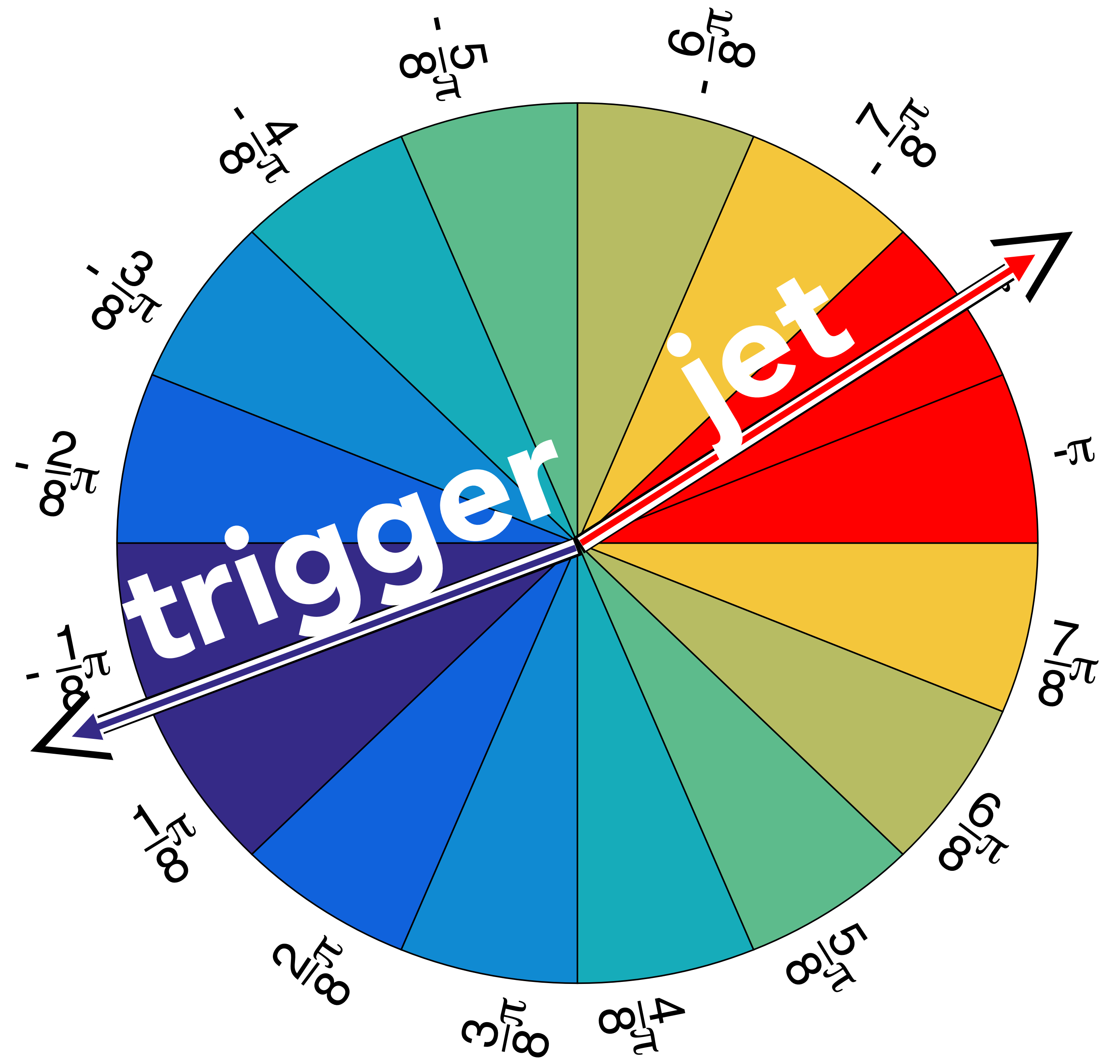
BBC signal (EA) to mid-η correlations

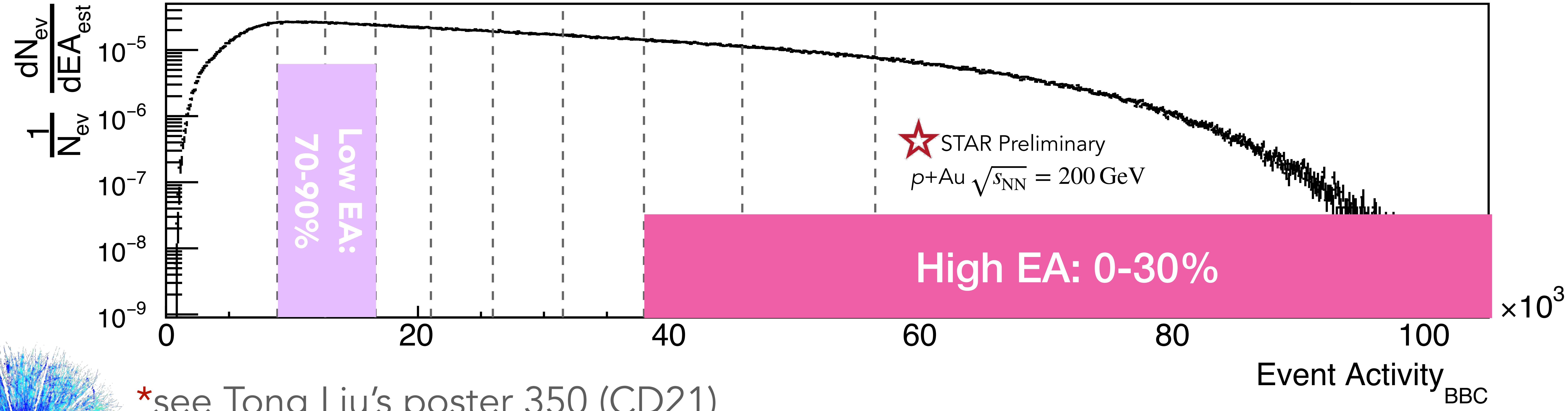


- ✦ Confirmed expectation of positive correlation between EA and probability of BEMC trigger
- ✦ Correlation weakens for increasing trigger E_T
- ✦ $\langle N_{ch} \rangle$ indicates an "underlying event" which grows with EA combined with an approximately constant $\langle N_{ch} \rangle$ from triggers

Clustering charged tracks into jets

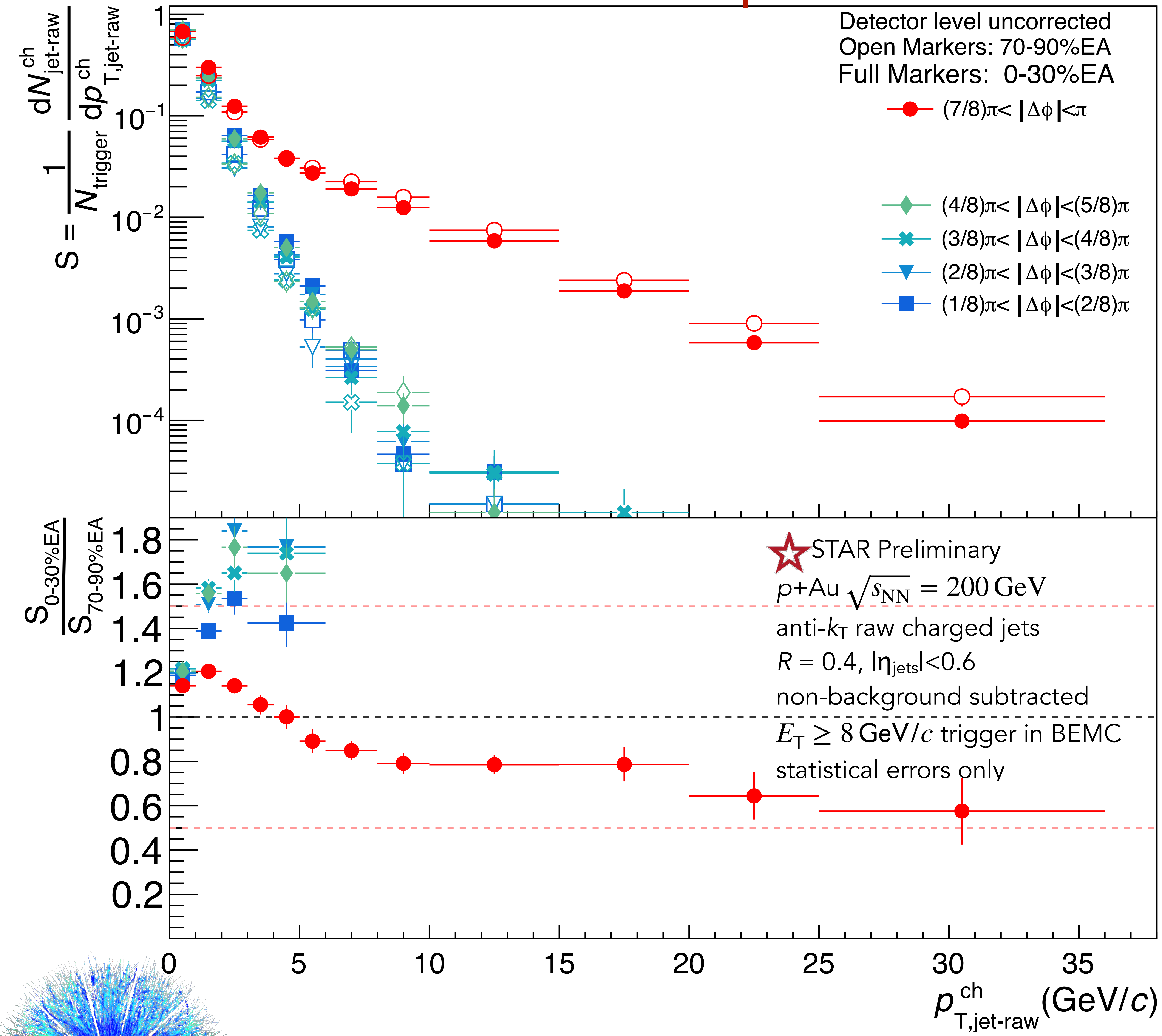
- Jets:
  - anti-k_T
  - R=0.4
  - $|\eta|<0.6$
- Binned in $\Delta\varphi$ in $\pi/8$ slices from the trigger
- Jet spectra presented in this talk are raw uncorrected, detector level
- Tracking efficiency is EA-independent* & negligible underlying event
  - ➡ $S_{0-30\%\mathrm{EA}}/S_{70-90\%\mathrm{EA}}$ expected to be insensitive to track corrections





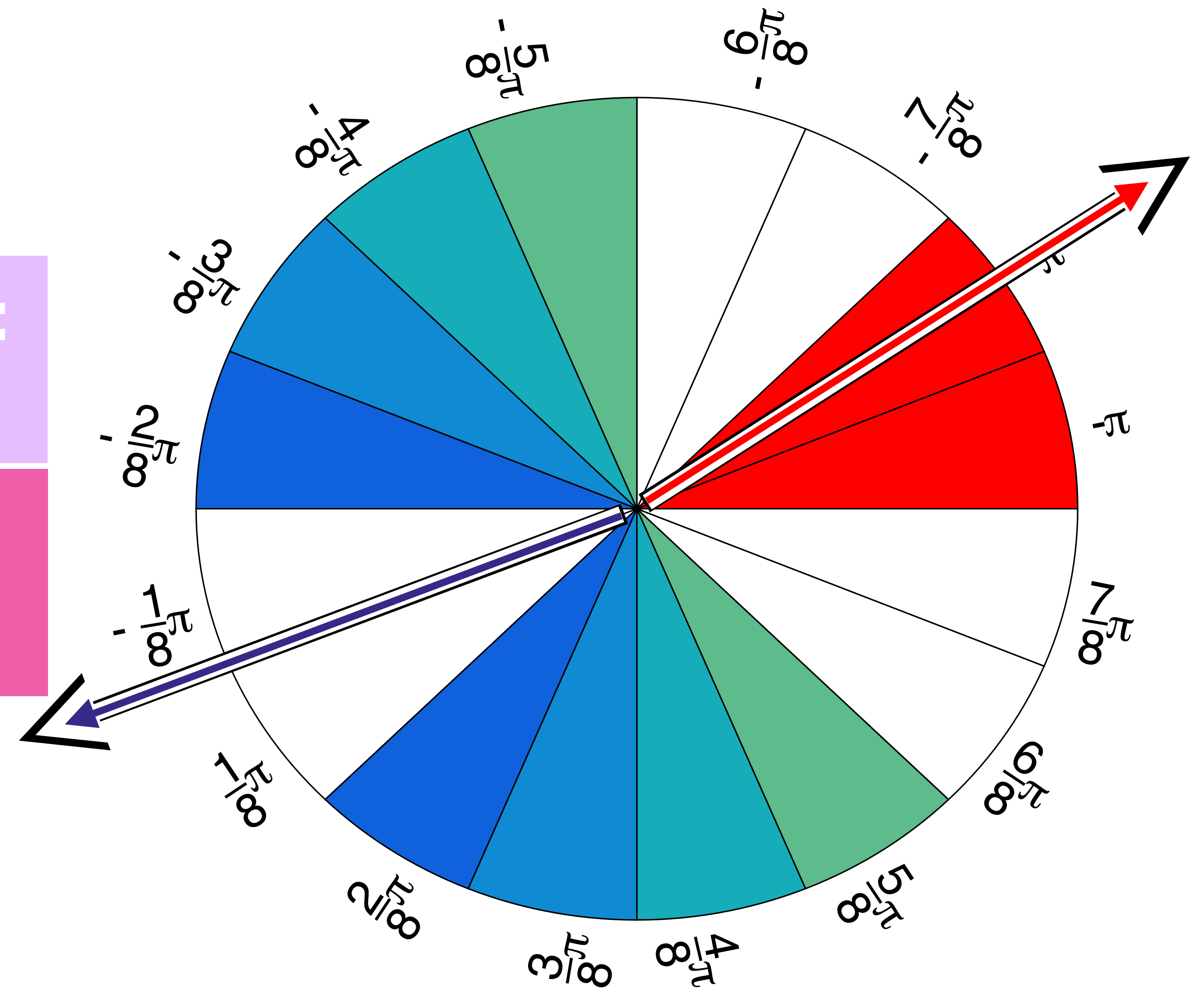
*see Tong Liu's poster 350 (CD21)

Recoil and transverse spectra



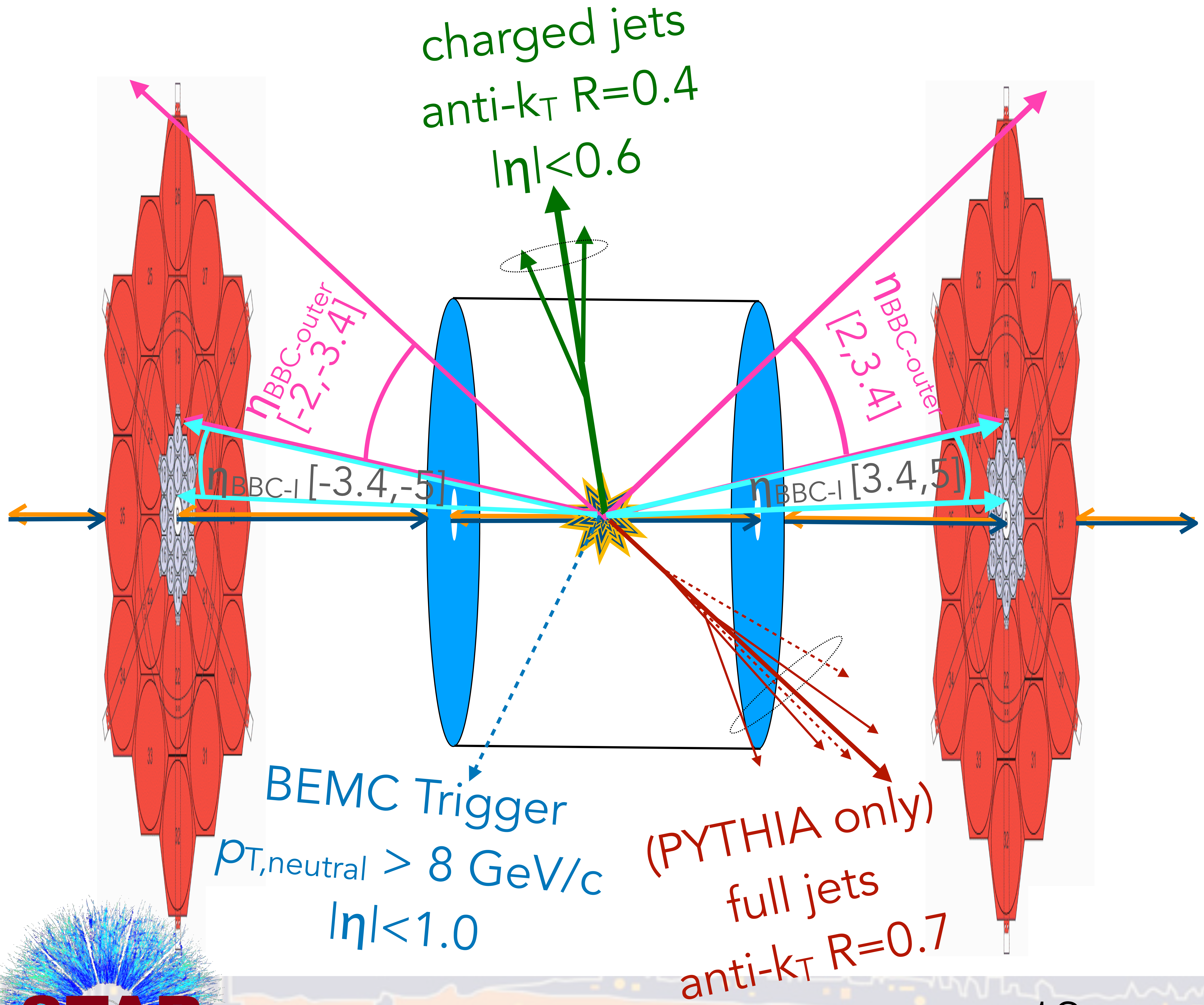
Open Markers: Low EA: 70-90%EA

Full Markers: High EA: 0-30%EA



- At "jet-like" p_T (>~8 GeV/c) transverse Δφ (background) negligible compared to recoil spectra
  - ➡ negligible background correction
- Clear suppression of $S_{0-30\%EA}/S_{70-90\%EA}$ for $p^{ch}_{T,jet-raw} > 8$ GeV/c

$S_{0-30\%EA}/S_{70-90\%EA}$ suppression caused by simple dijet kinematics?



Hard parton scatterings result in jets that influence both:

- ✦ Charged jet spectra at $|\eta| < 1$
- ✦ EA from BBC at $-5 < \eta < -2$
  (outer BBC η ∈ $-2, -3.4$
  inner BBC η ∈ $-3.4, -5$)

➡ EA dependent bias in

$$\left.\frac{\sigma^{pp\to\text{trigger}+\text{jet}|_{TPC}+X}}{\sigma^{pp\to\text{trigger}+X}}\right|_{EA} ?$$

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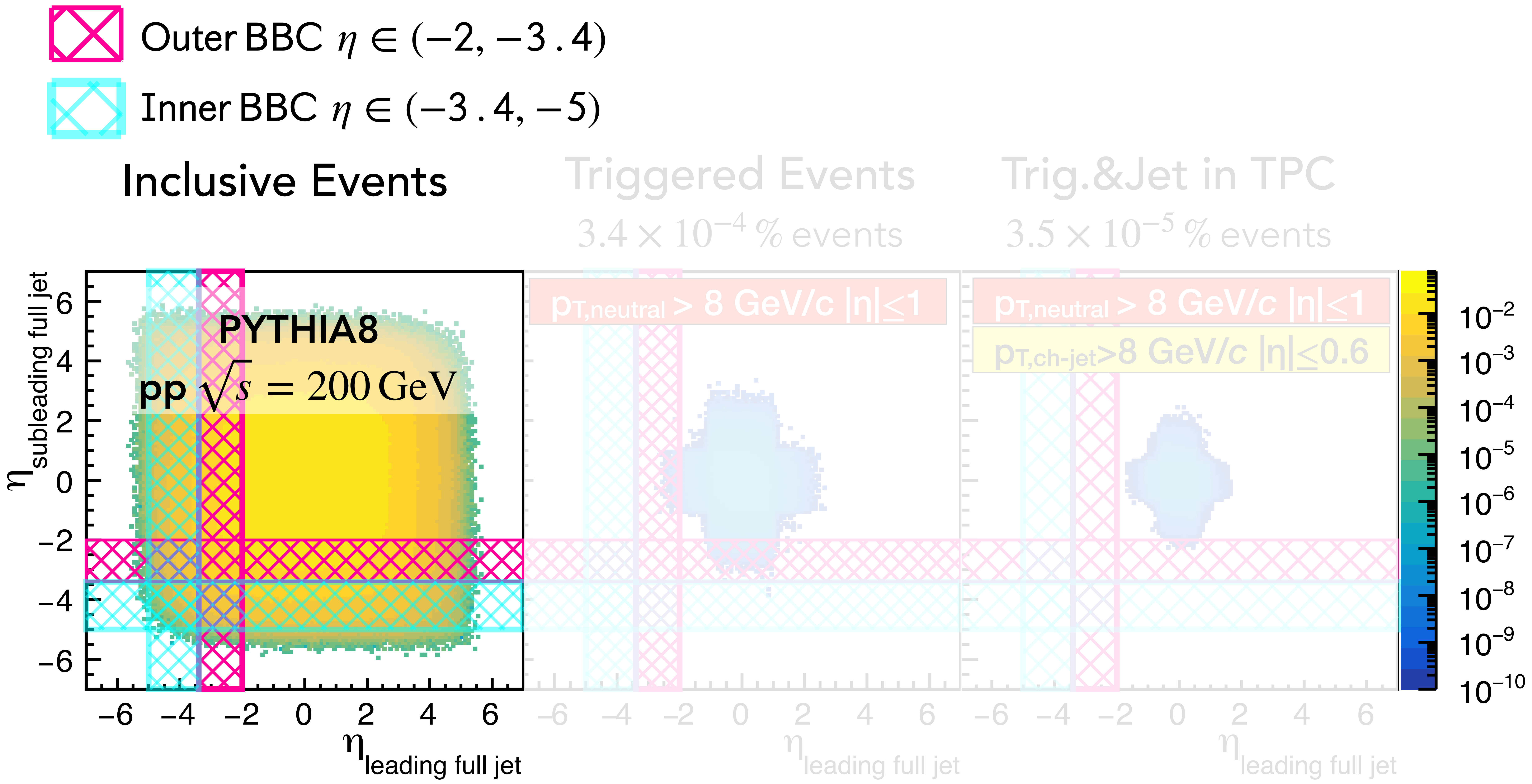
PYTHIA study — where the leading full jets go

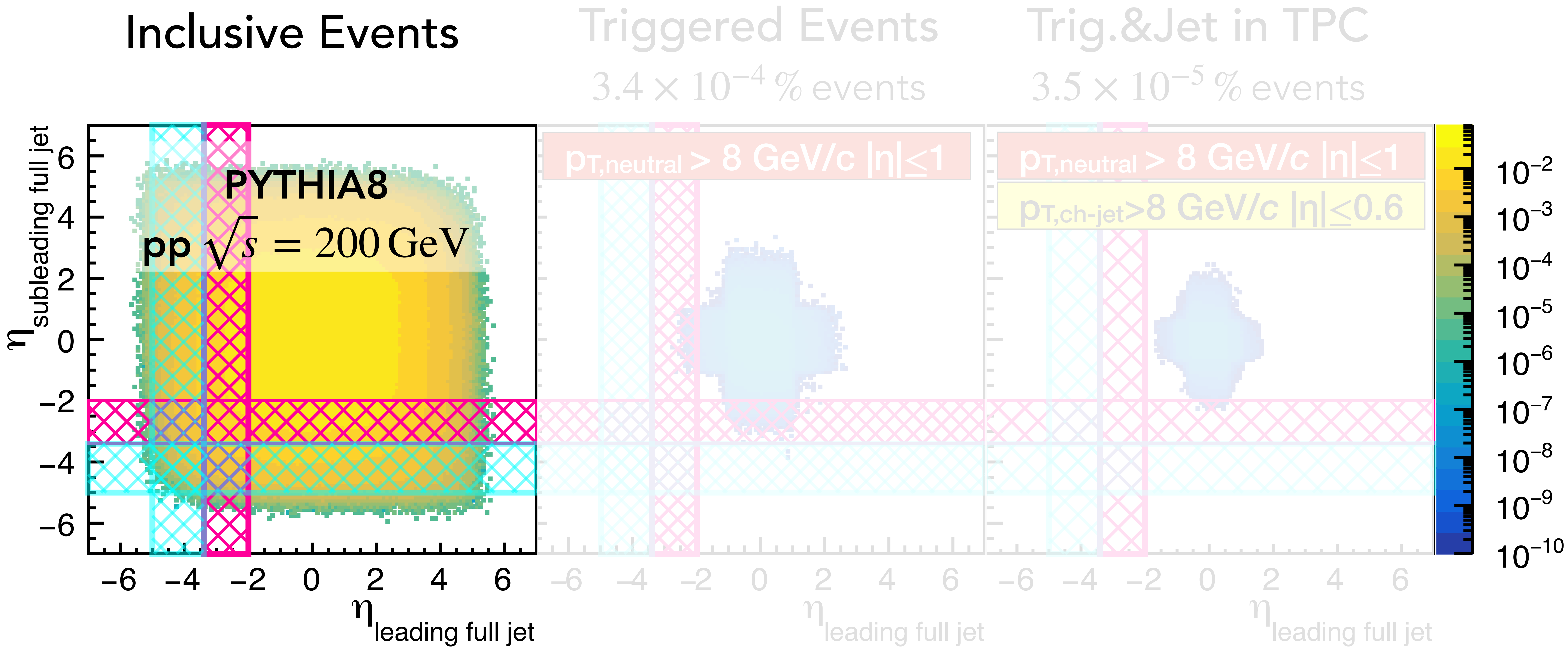


- ✦ Cluster R=0.7 full jets for $|\eta| < 7$
  - ✦ Two with max p_T are "leading" and "subleading"

PYTHIA study — where the leading full jets go

Outer BBC $\eta \in (-2, -3.4)$

Inner BBC $\eta \in (-3.4, -5)$



~30% Events in BBC_{outer}

~9% Events in BBC_{inner}

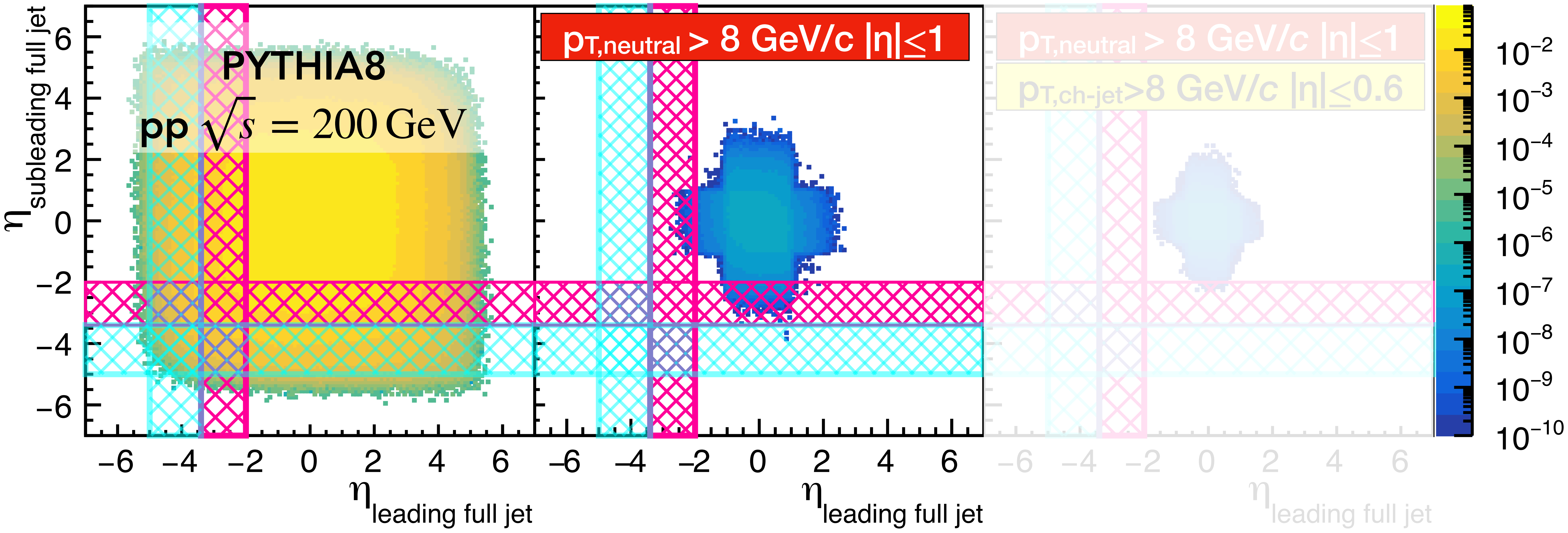
- Cluster R=0.7 full jets for $|\eta| < 7$
  - Two with max p_T are "leading" and "subleading"
- A leading jet axis hits BBC in ~40% of inclusive events

PYTHIA study — where the leading full jets go

Outer BBC $\eta \in (-2, -3.4)$

Inner BBC $\eta \in (-3.4, -5)$

Inclusive Events	Triggered Events	Trig.&Jet in TPC
	3.4×10^{-4} % events	3.5×10^{-5} % events



~30% Events in BBC_{outer}	~2% Events in BBC_{outer}
~9% Events in BBC_{inner}	~1×10^{-3}% Events in BBC_{inner}

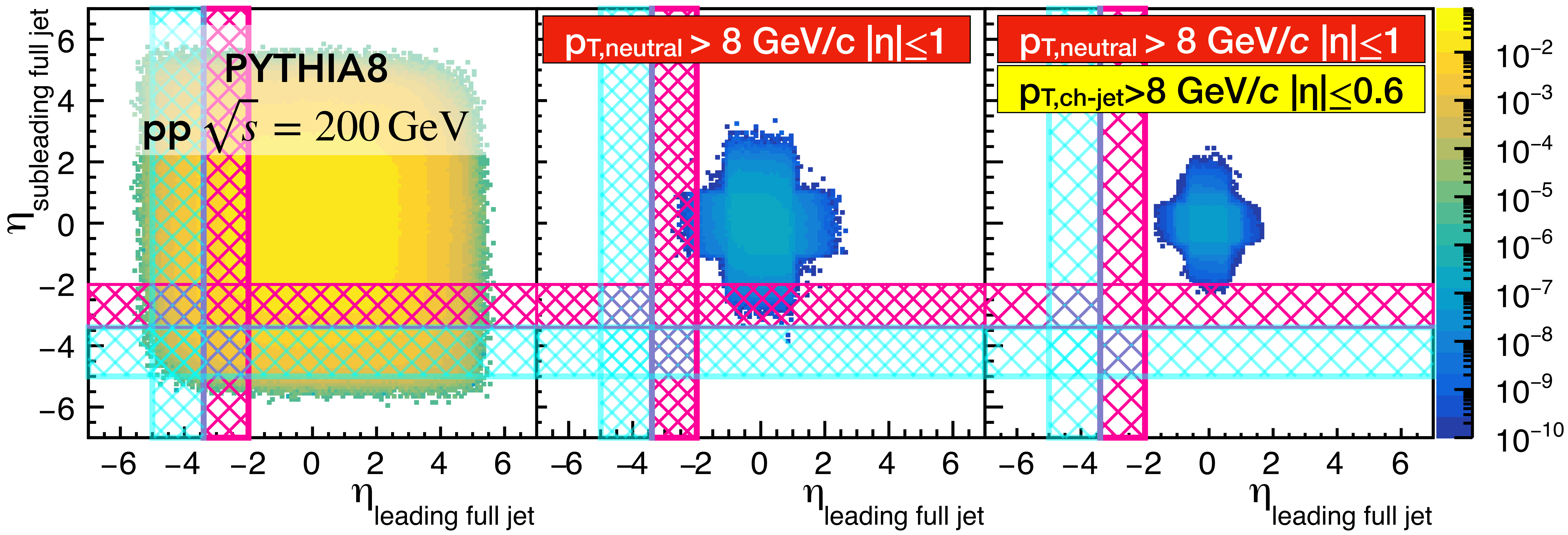
- ✦ Cluster R=0.7 full jets for $|\eta| < 7$
  - ✦ Two with max p_T are "leading" and "subleading"
- ✦ A leading jet axis hits BBC in ~40% of inclusive events
- ✦ Hits outer BBC in ~2% of triggered events
  - ➡ inflates EA

PYTHIA study — where the leading full jets go

Outer BBC $\eta \in (-2, -3.4)$

Inner BBC $\eta \in (-3.4, -5)$

Inclusive Events | **Triggered Events** $3.4 \times 10^{-4}\,\%$ events | **Trig.&Jet in TPC** $3.5 \times 10^{-5}\,\%$ events



Inclusive Events	Triggered Events	Trig.&Jet in TPC
~30% Events in BBC_{outer}	~2% Events in BBC_{outer}	~0.1% Events in BBC_{outer}
~9% Events in BBC_{inner}	~1x10^{-3}% Events in BBC_{inner}	No BBC_{inner} hits in 5.9x10^{7}+ (Trig&Jet) events

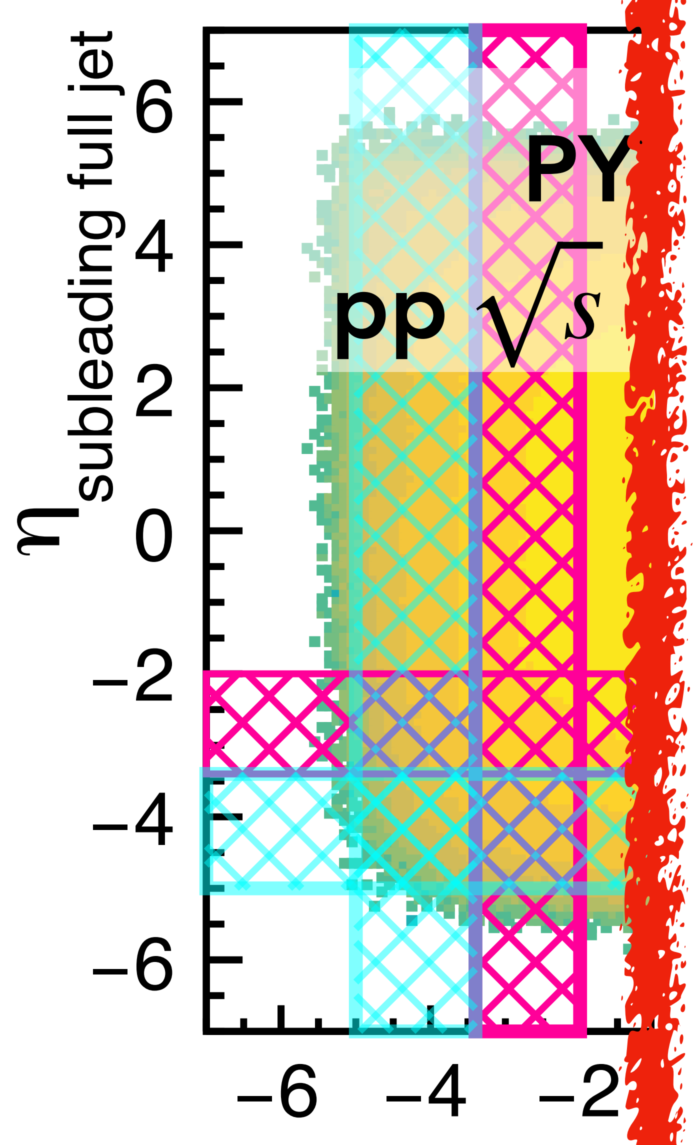
- Cluster R=0.7 full jets for $|\eta| < 7$
  - Two with max p_T are "leading" and "subleading"
- A leading jet axis hits BBC in ~40% of inclusive events
- Hits outer BBC in ~2% of triggered events
  - ➡ inflates EA
- Rarely hits outer BBC in triggered events with 8 GeV/c charged jet

PYTHIA study — where the leading full jets go

Outer BBC $\eta \in (-2, -3.4)$

Inner B

Inclusiv



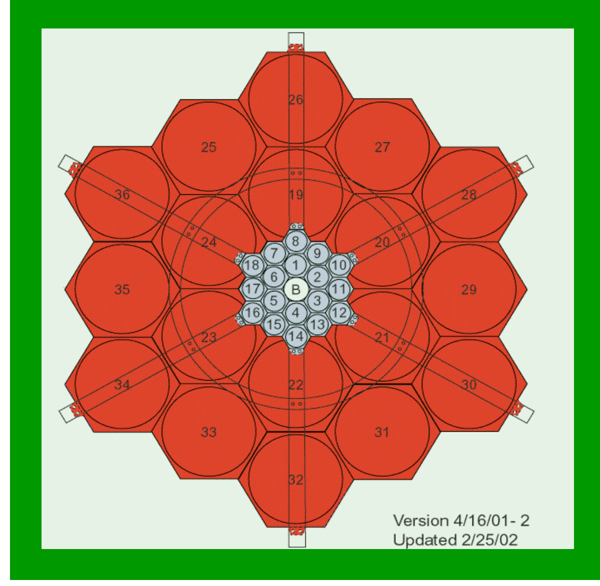
- ✦ EA$_{\text{high}}$ biased towards *triggered+(jet in/near BBC)* events
- ➡ Suppresses $S_{\text{high EA}}$

~30% Eve

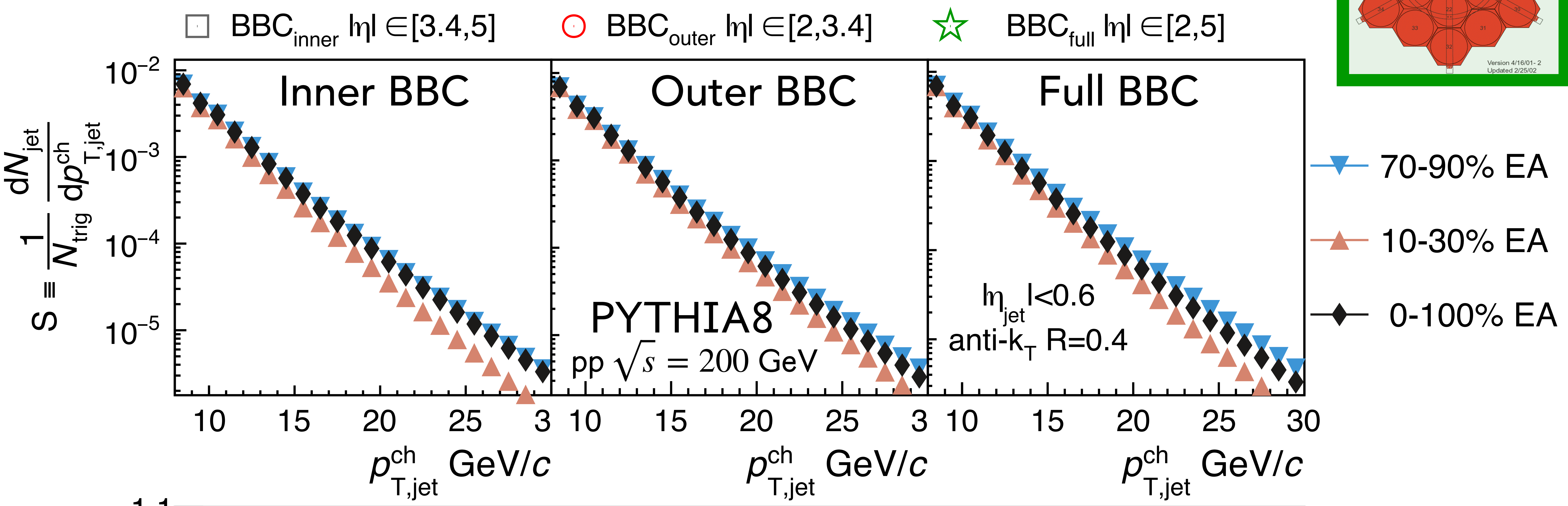
~9% Events in BBC$_{\text{inner}}$	~1x10^{-3}% Events in BBC$_{\text{inner}}$	No BBC$_{\text{inner}}$ hits in 5.9x10^{7}+ (Trig&Jet) events

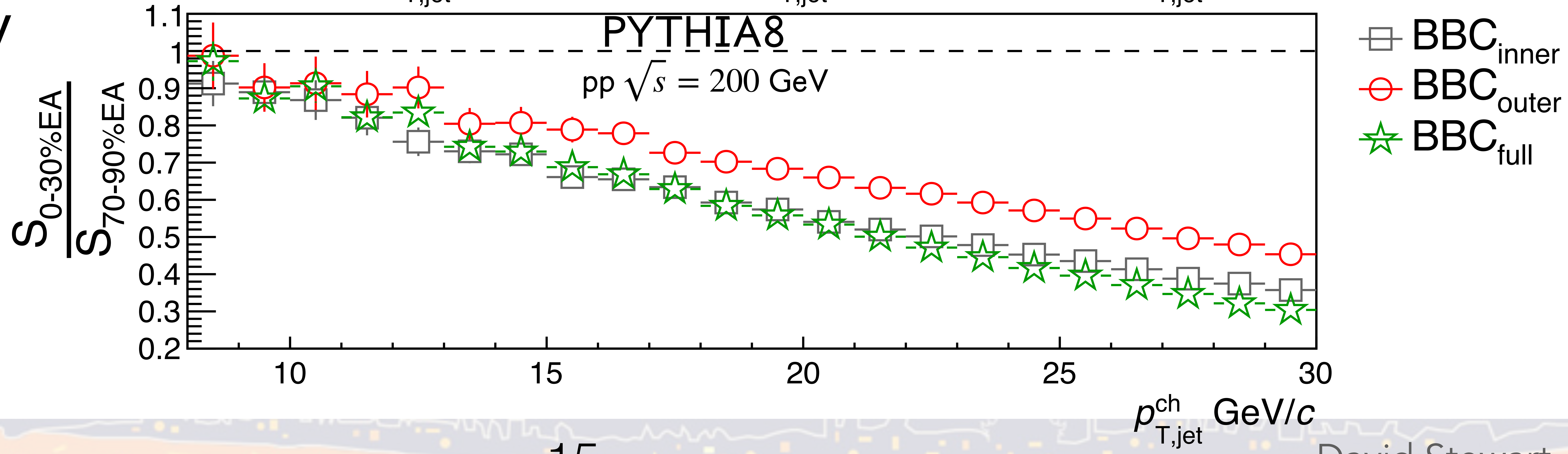
- ✦ Cluster R=0.7 full jets for $|\eta| < 7$
- Two with max p_T are "leading" and "subleading"
- leading jet axis hits BC in ~40% of nclusive events
- its outer BBC in ~2% f triggered events
- inflates EA
- arely hits outer BBC in triggered events with 8 GeV/c charged jet

PYTHIA jet spectra results



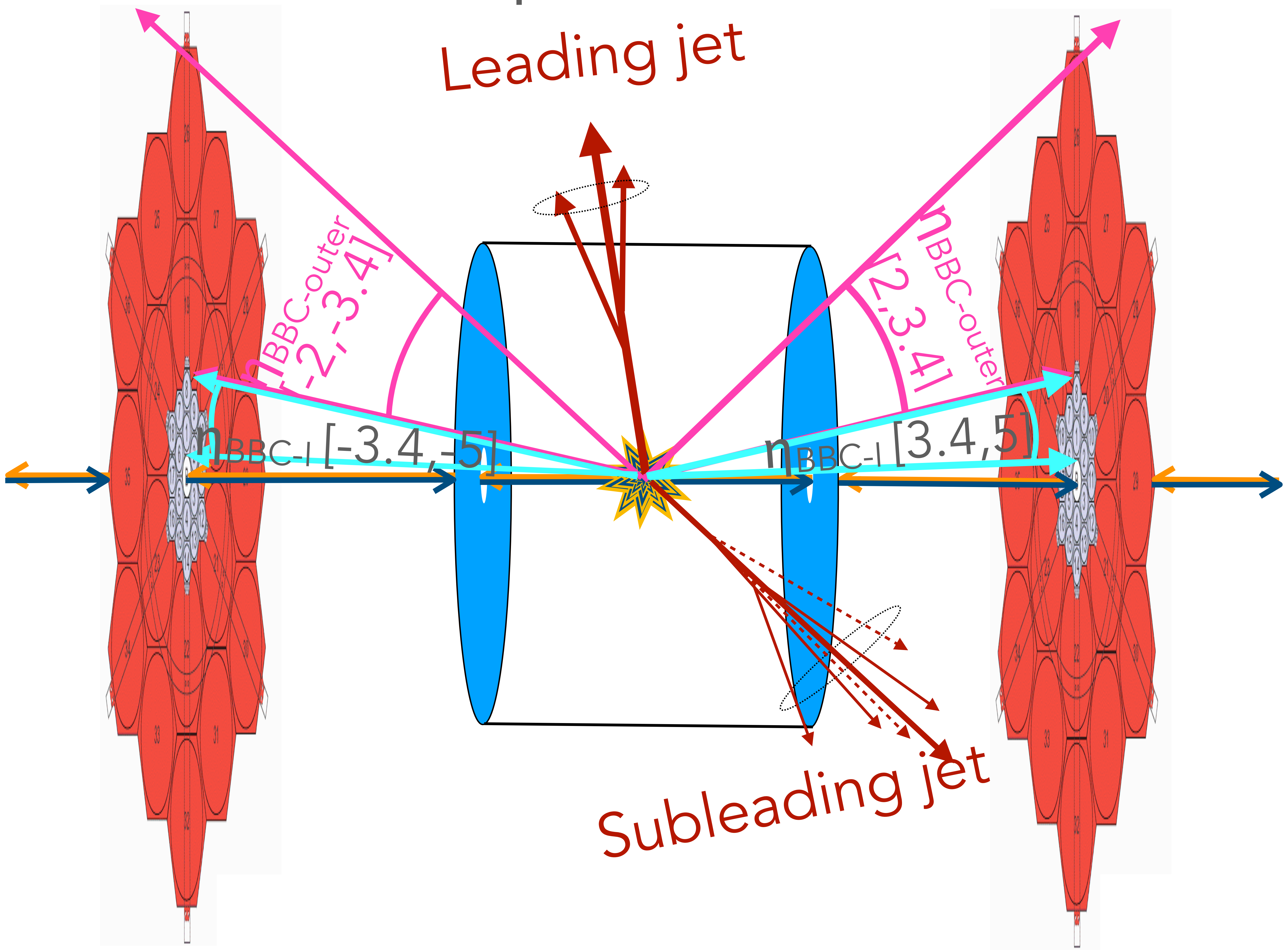
- Expect less suppression in inner BBC where there is very minimal dijet bias





PYTHIA jet spectra if dijet bias is removed

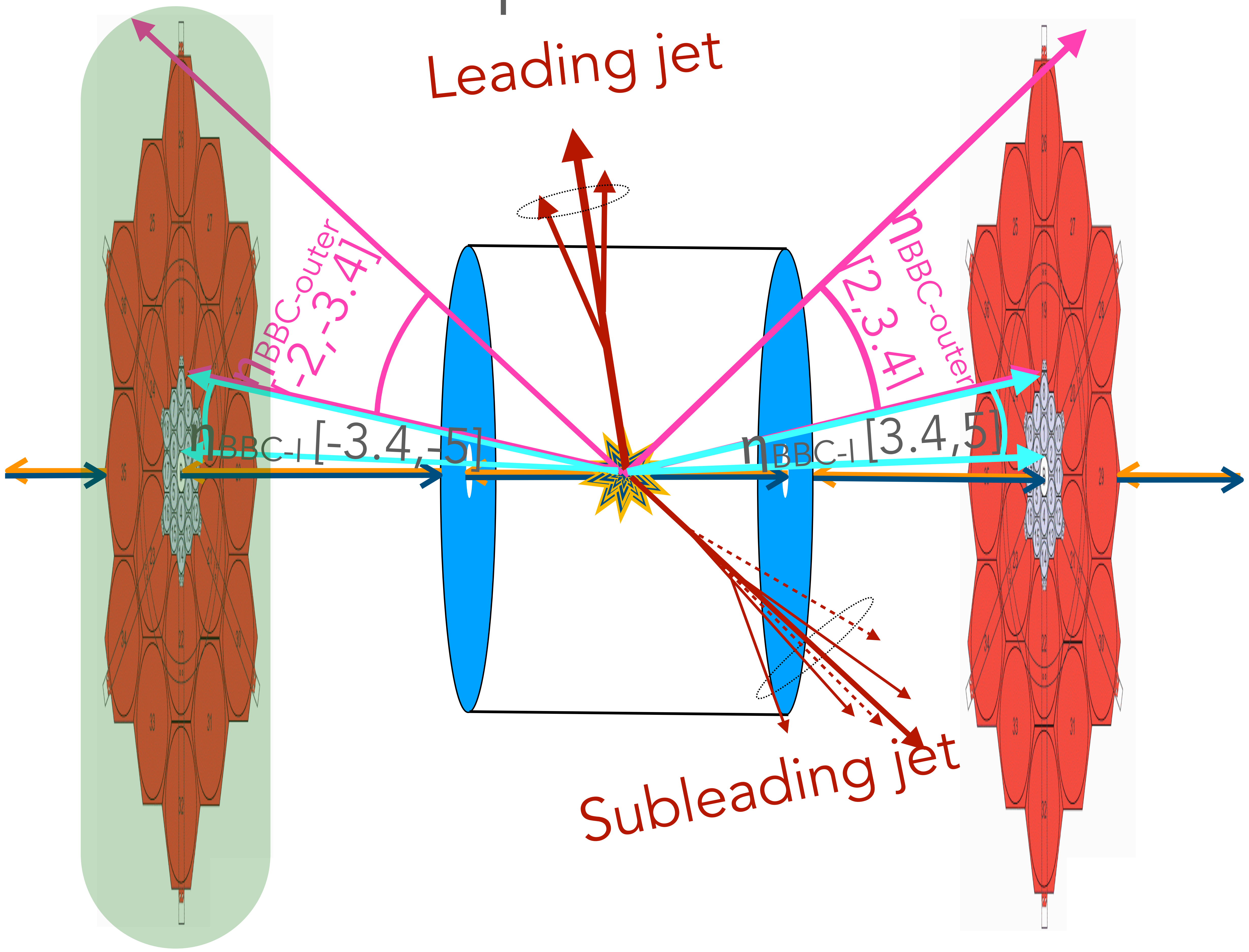
Example event



Method

PYTHIA jet spectra if dijet bias is removed

Example event

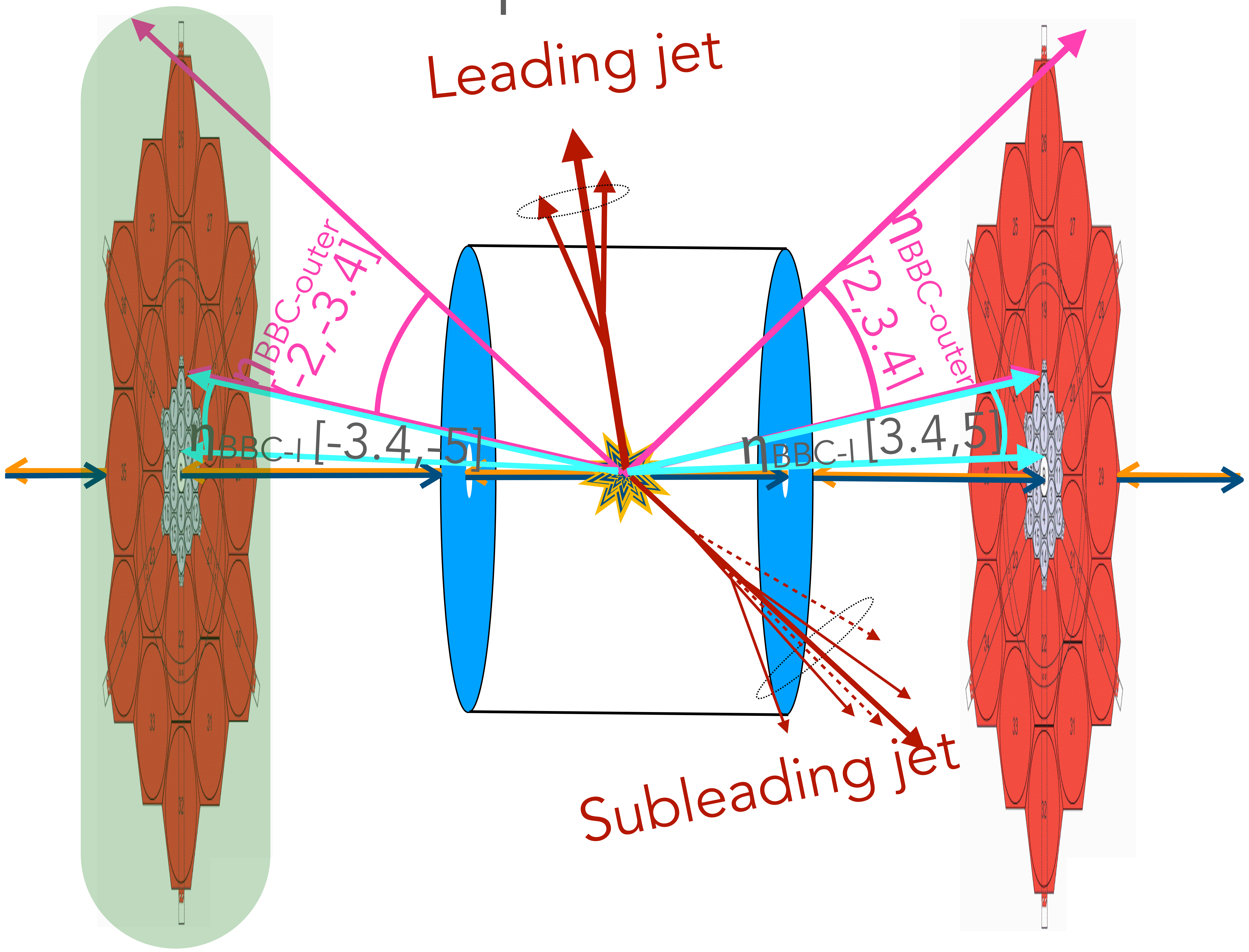


Method

- In each event, read EA signal from the BBC opposite of leading/ subleading jet with max(|η|)

PYTHIA jet spectra if dijet bias is removed

Example event

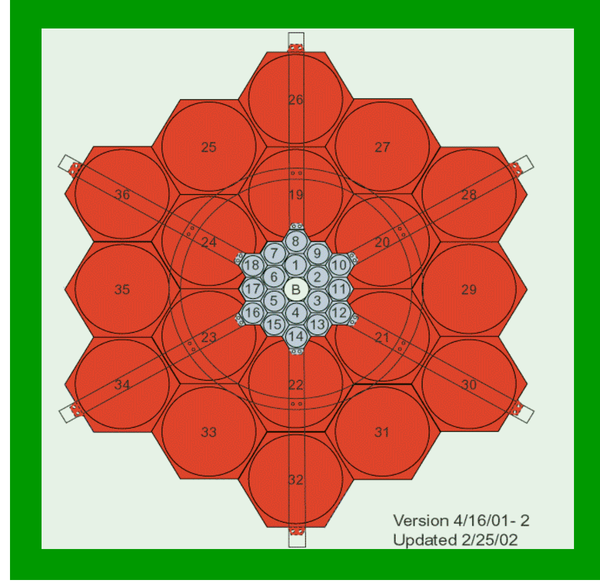


Method

- ✦ In each event, read EA signal from the BBC opposite of leading/subleading jet with max(|η|)
  - ➡ Remove all dijet constituents from BBC
  - ➡ Remove suppression of $S_{0-30\%EA}/S_{70-90\%EA}$ due to dijets in outer BBC

STAR

PYTHIA $S_{0-30\%EA}/S_{70-90\%EA}$ with and without dijet bias



- Using "opposite-side" BBC for EA sorting reduces suppression by ~constant factor for outer and full, but not inner, BBC

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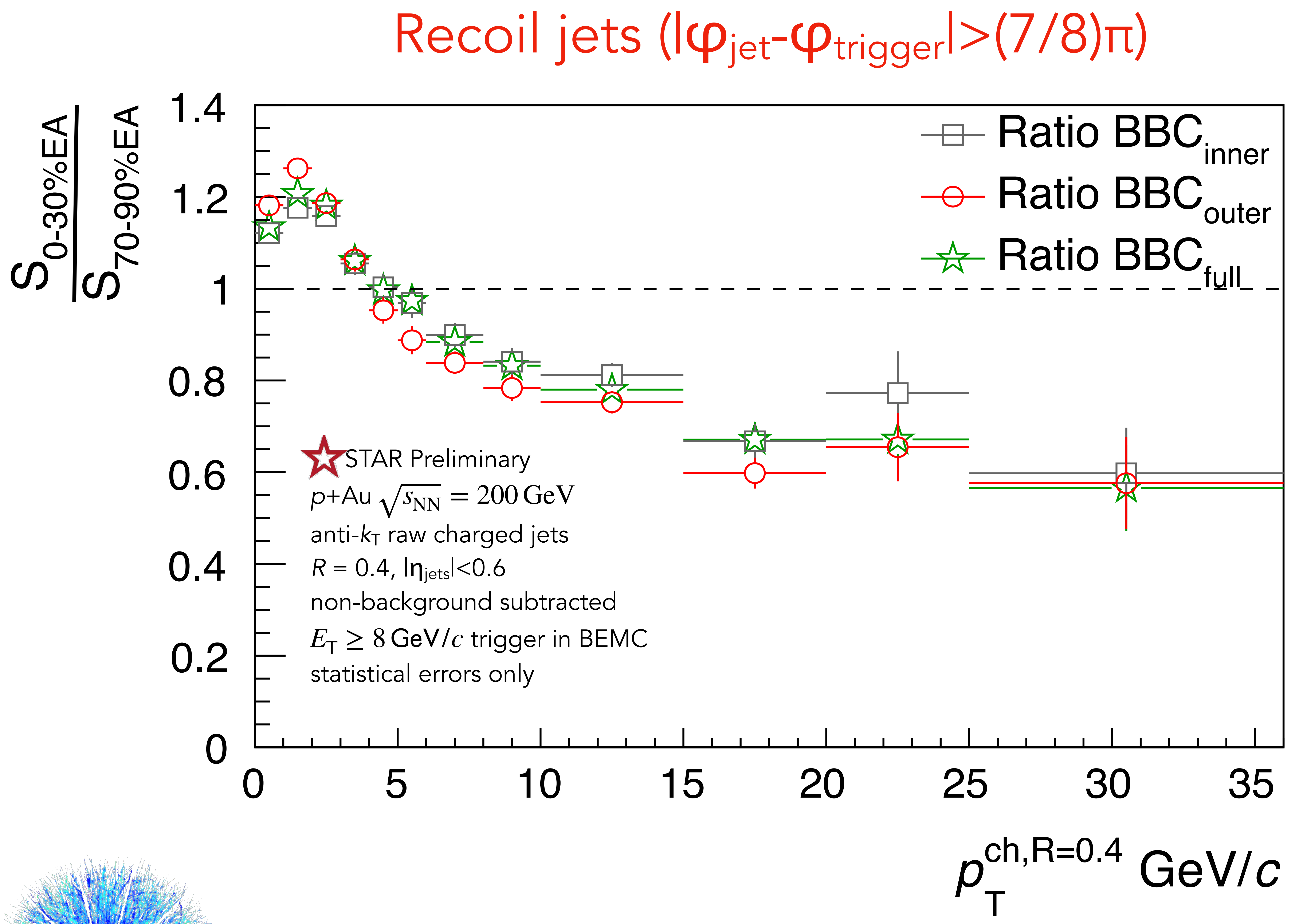
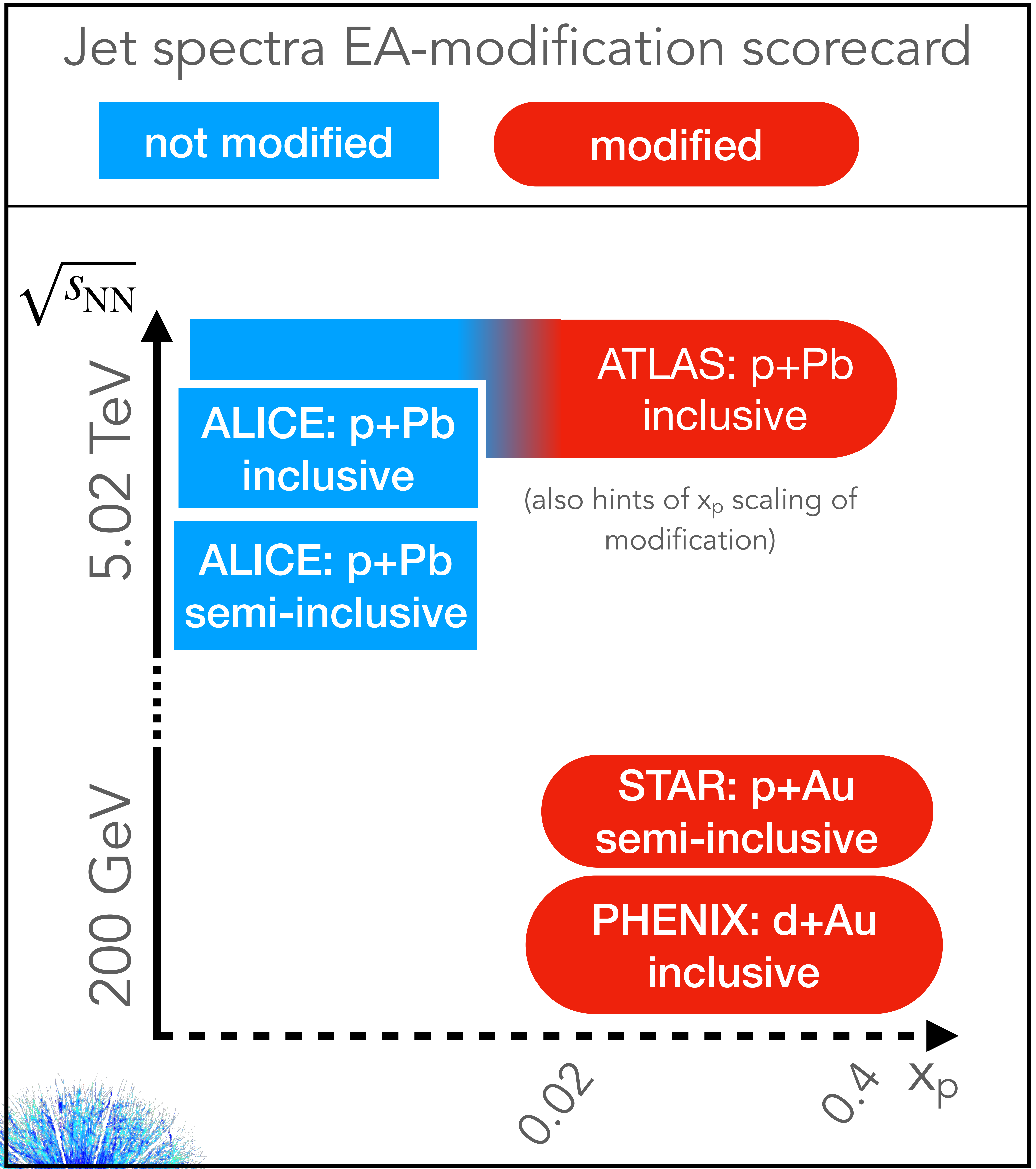
Suppression persists with BBC_{inner} EA selection



- Smaller expected dijet kinematic effects in p+Au collisions than pp collisions, due to multiple soft collisions measured with hard collisions
- Suppression of $S_{0-30\%}/S_{70-90\%}$ persists with EA selection by BBC_{inner} or BBC_{outer} instead of BBC_{full}

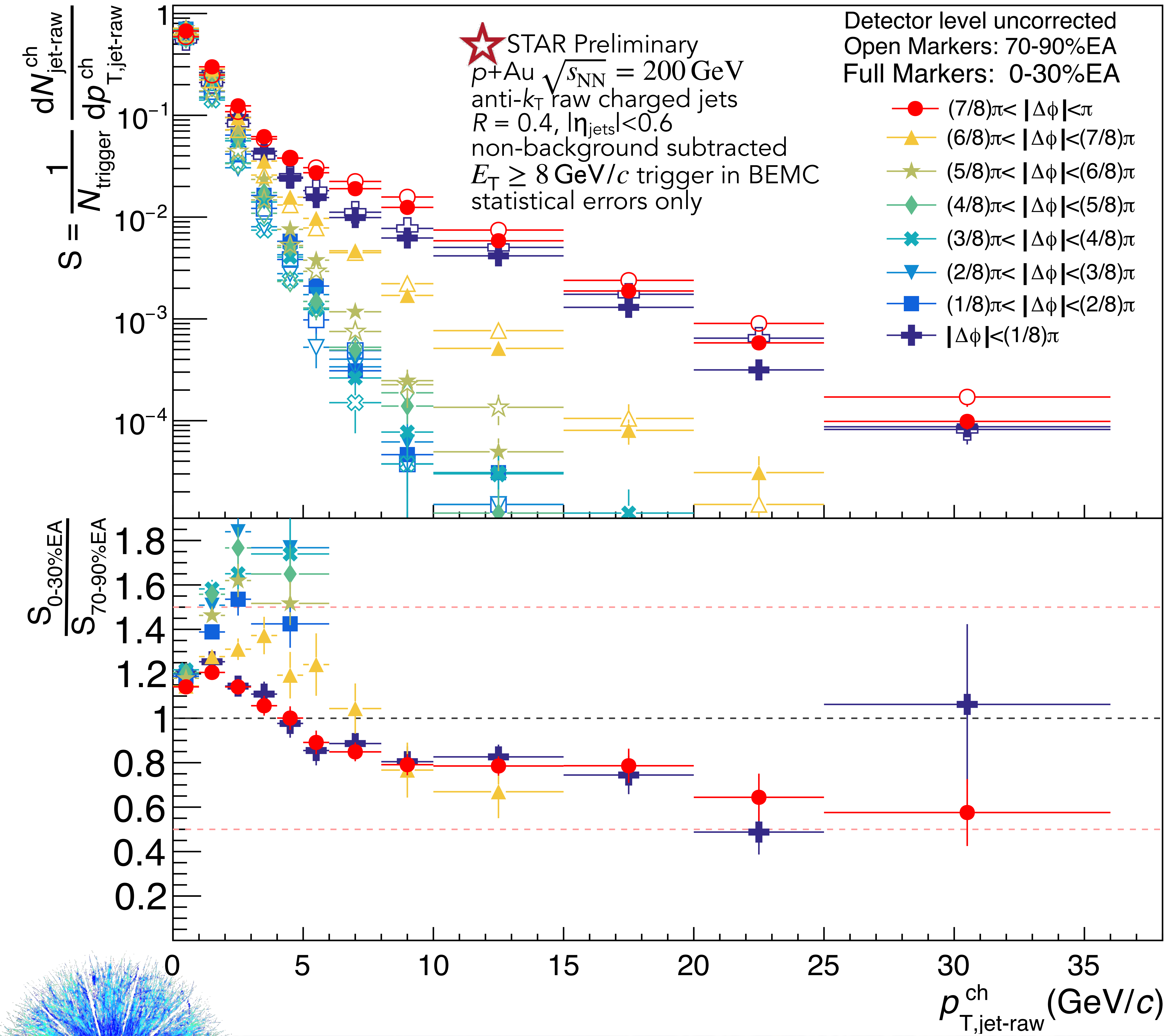
Conclusion



- Clear suppression of $S_{0-30\%}/S_{70-90\%}$ in 200 GeV p+Au collisions at STAR
- Suppression indicates there is either:
  A. Event activity related modification of jet spectra
  B. EA bias for $\sigma_{\text{trigger+jet}}\big|_{\text{TPC}}$ relative to σ_{trigger}
     - Not a trivial dijet bias
- Suppression measured in similar x_p ranges as in d+Au and p+Pb at RHIC and LHC energies, respectively

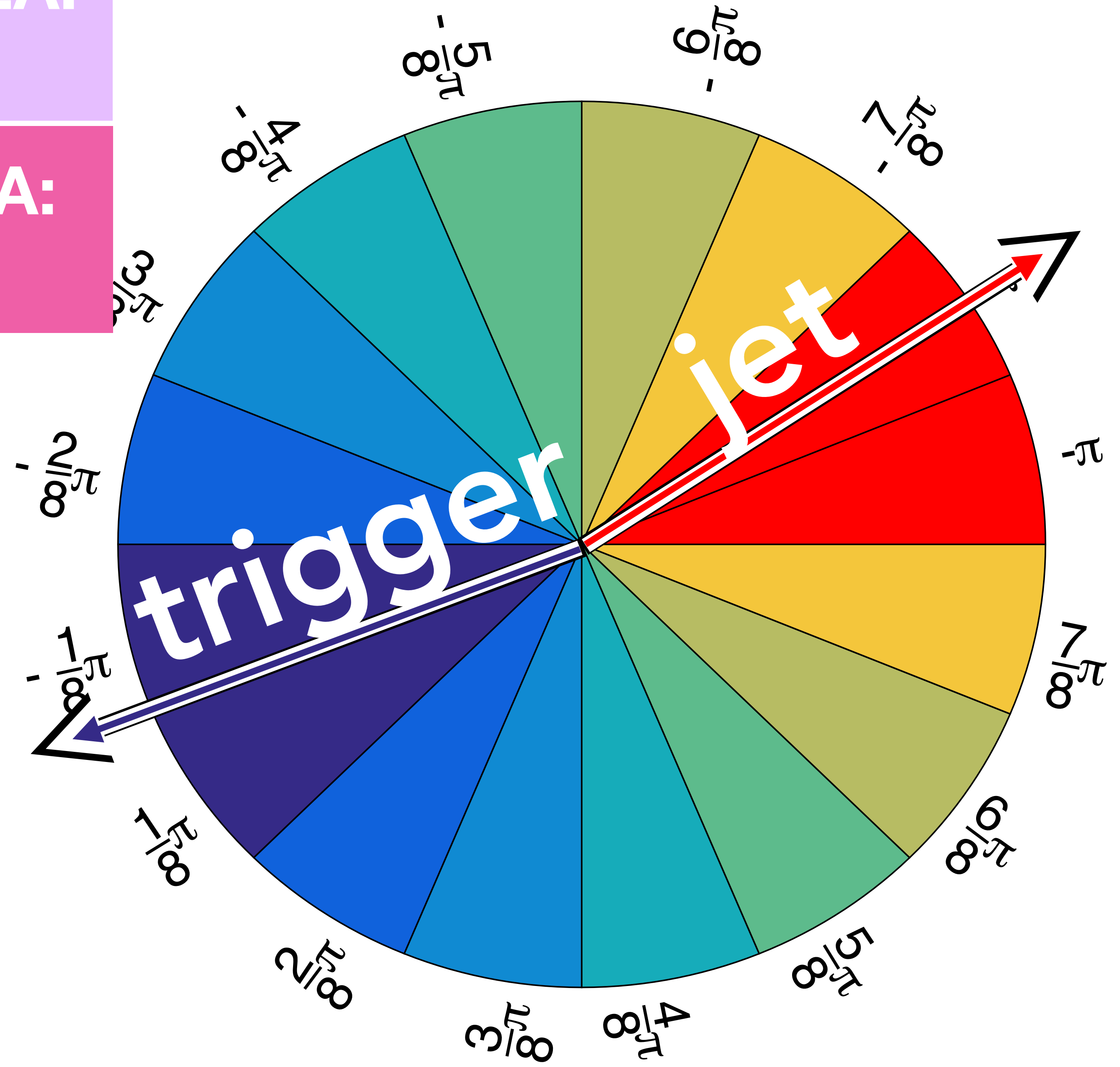
Extra Slides

$S_{0-30\%}/S_{70-90\%}$ all $\Delta\phi$ bins



Open Markers: Low EA: 70-90%

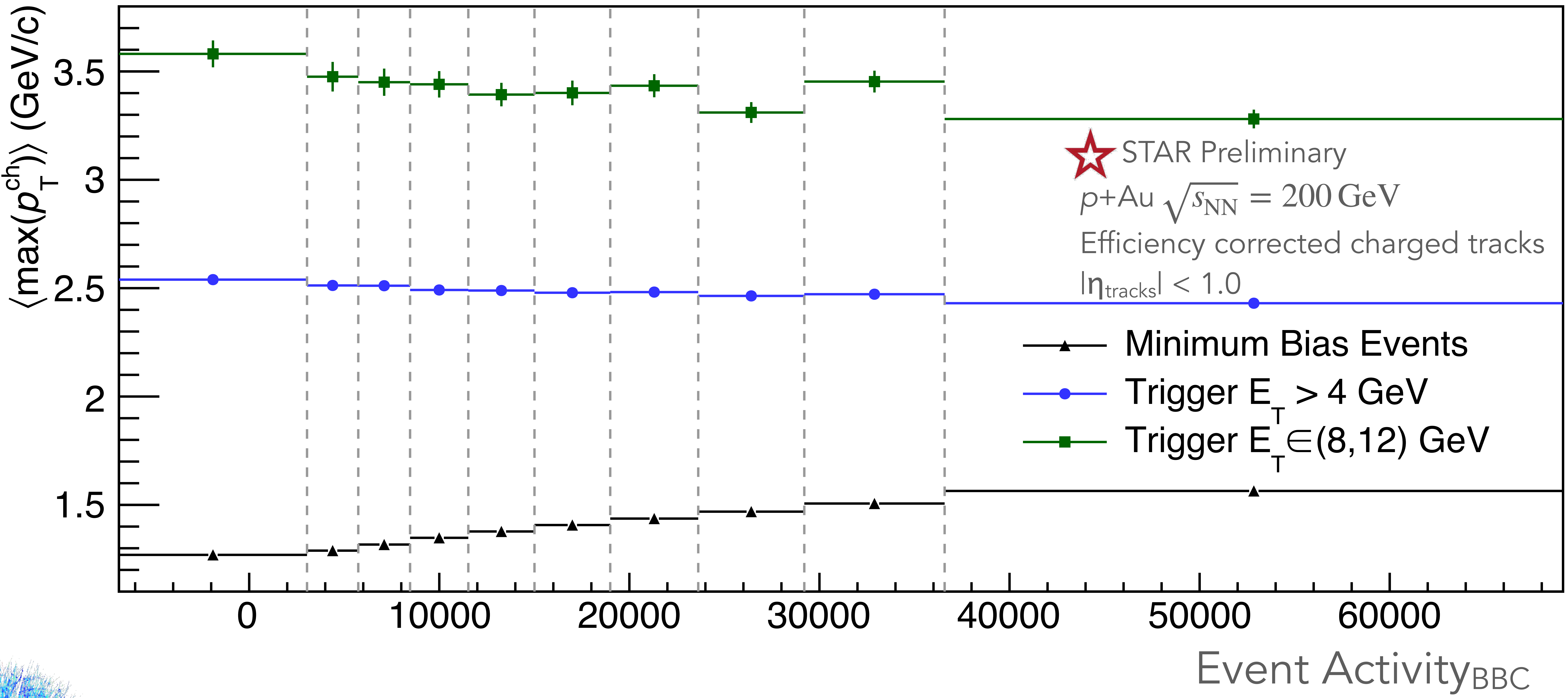
Full Markers: High EA: 0-30%



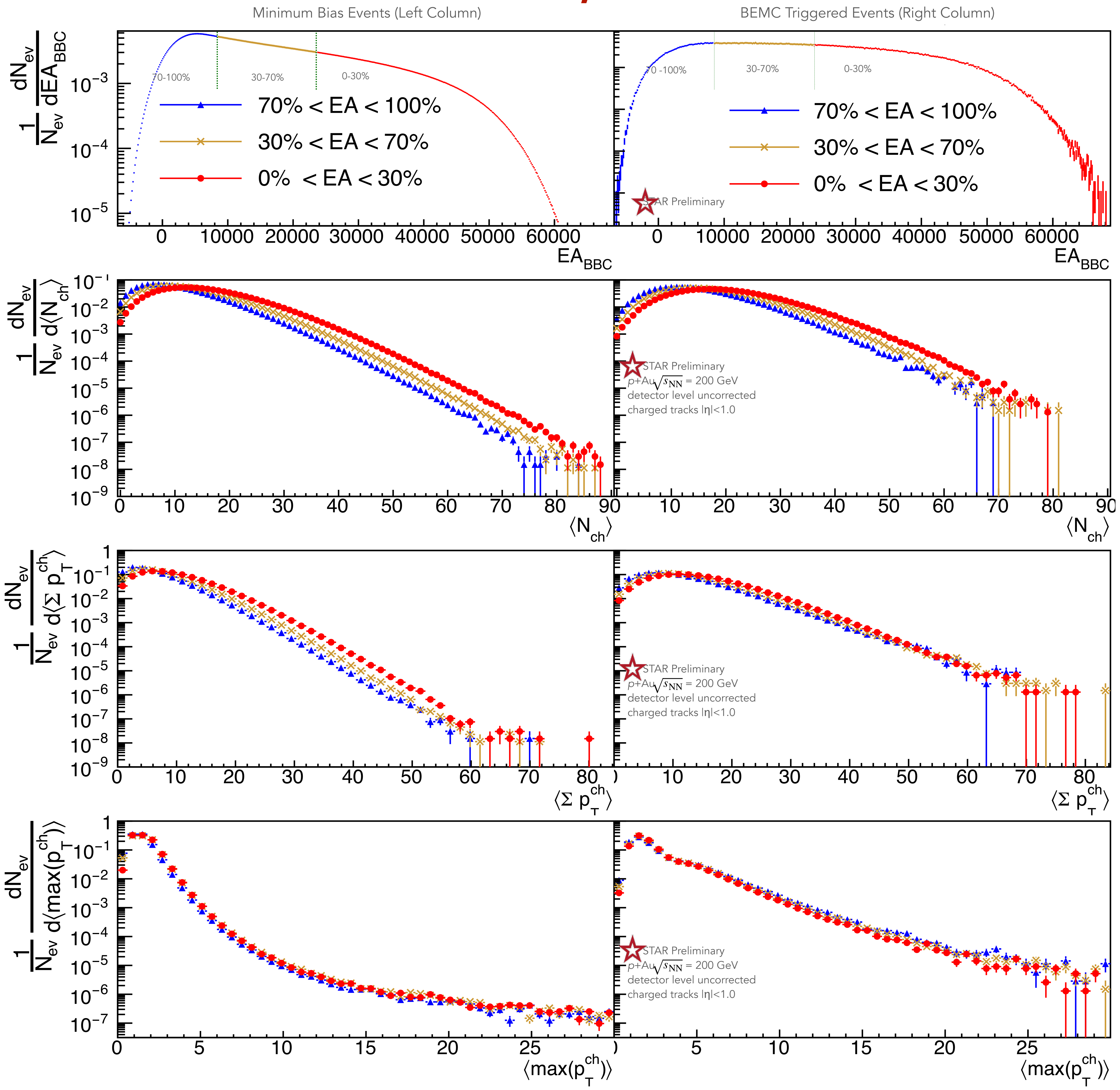
- Both near and recoil jets suppressed in high EA relative to low EA
- n.b.: These are charged jet spectra; the near-side jets have a neutral energy fraction (NEF) bias because near side must also always contain the neutral trigger
  - This NEF bias is not present in the recoil jets
  - This NEF bias on the near-side is expected to decrease at higher $p_{T,jet}$

Average maximum track p_T per event

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



Spectra in three EA bins for raw, uncorrected tracks



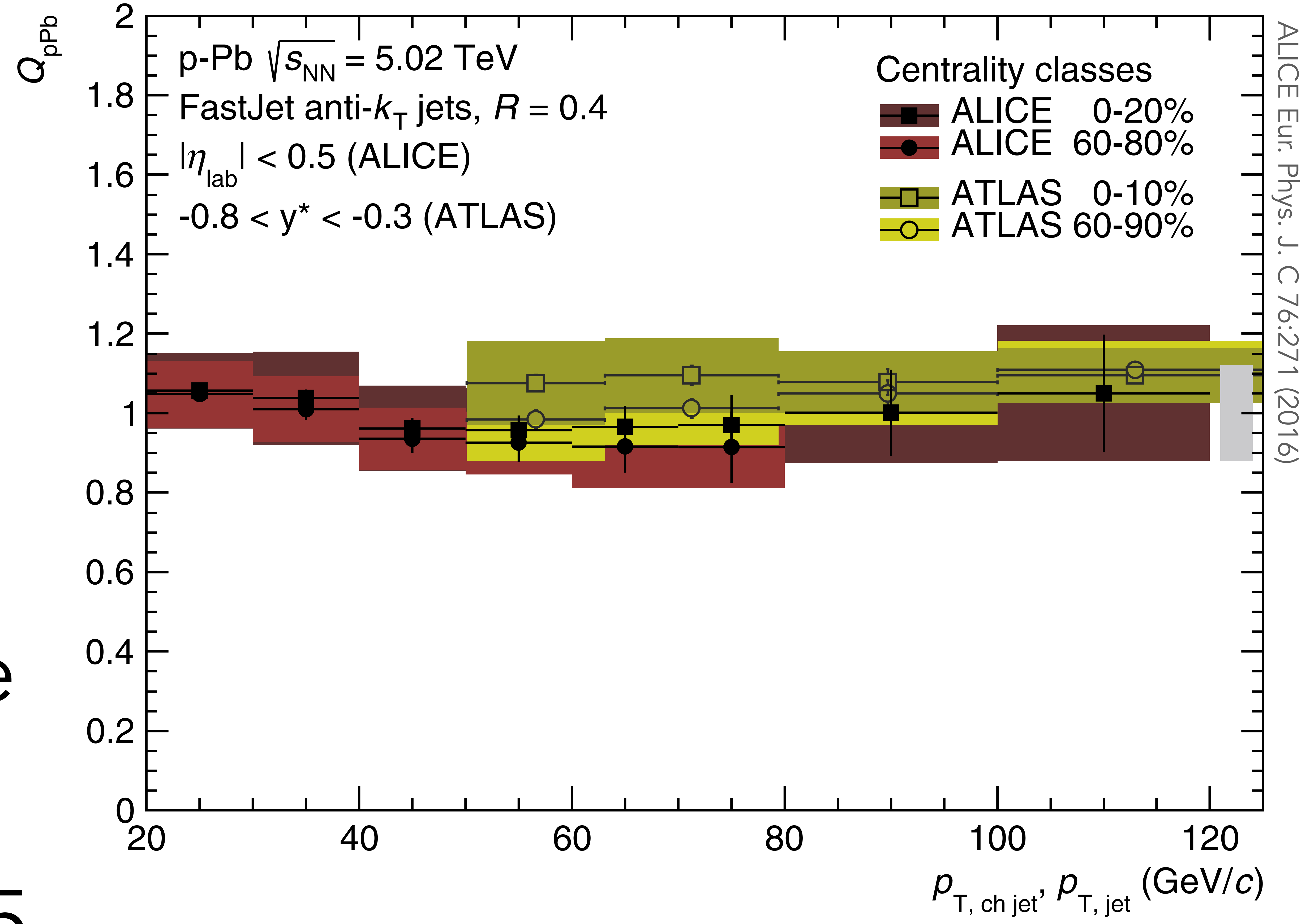
Event and track cuts

- 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
  - $0.2\ \text{GeV} < p_{\text{T, track}} < 30\ \text{GeV}$
  - $|\eta|<1.0$

- 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

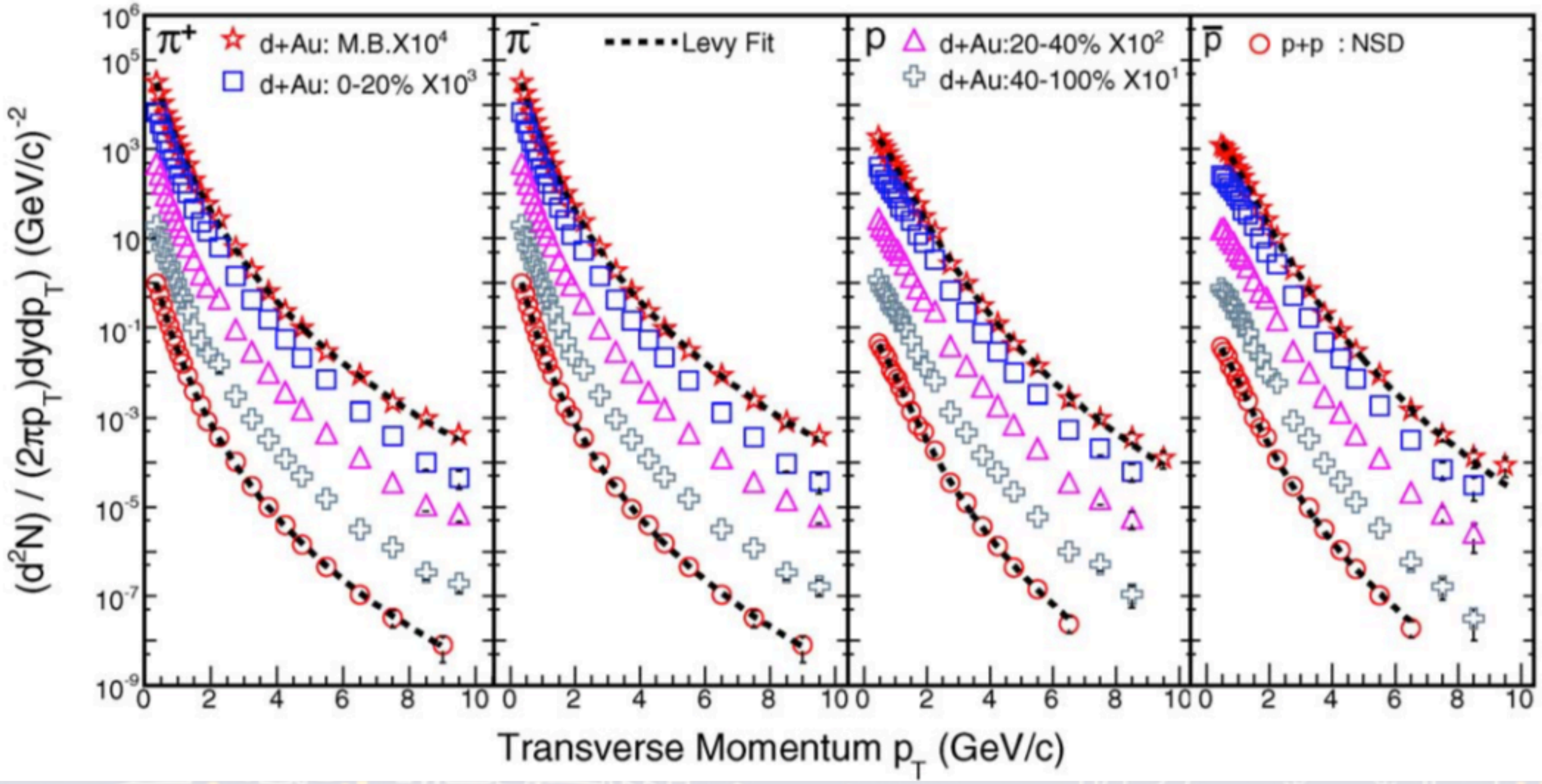
ALICE 2016 measurement: R_{CP} binned by EA

- Hybrid method developed to remove dynamical biases in N_{coll} determination
- Resulting EA binned R_{p+Pb} (labeled as Q_{pPb} to indicate use of hybrid method) found consistent with unity at x_P~0.05



Priors and Unfolding

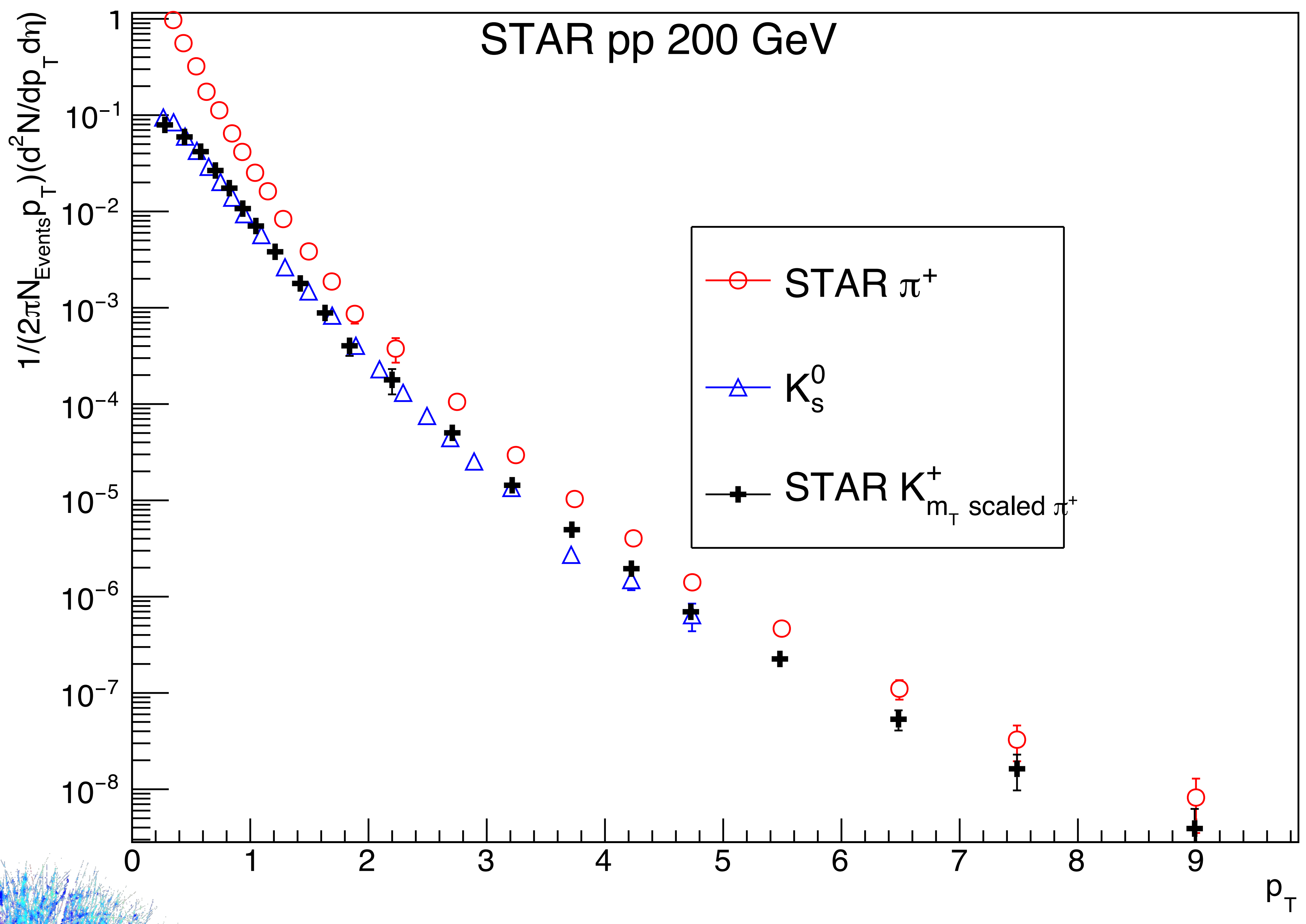
- ✦A single embedding response matrix was generated for all charged tracks, necessitating the relative production spectra of each particle species
- ✦Measurements of π^+, π^-, p, and anti-proton data up to about 10 GeV at exist at STAR for d+Au and pp collisions at 200 GeV
- ✦ spectrum has been measured 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))

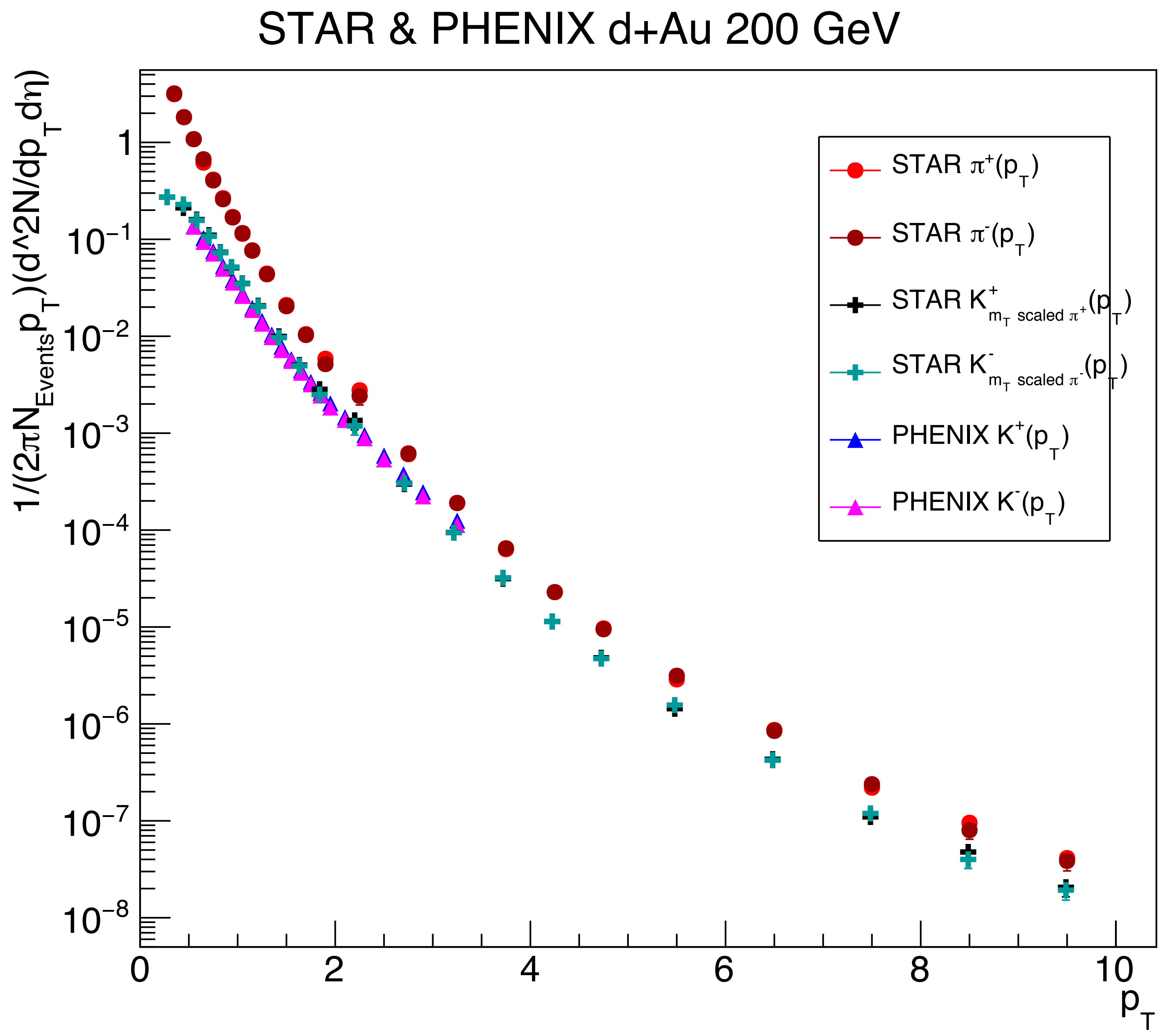


STAR Phys. Lett. B **748**, 392-413 (2015)

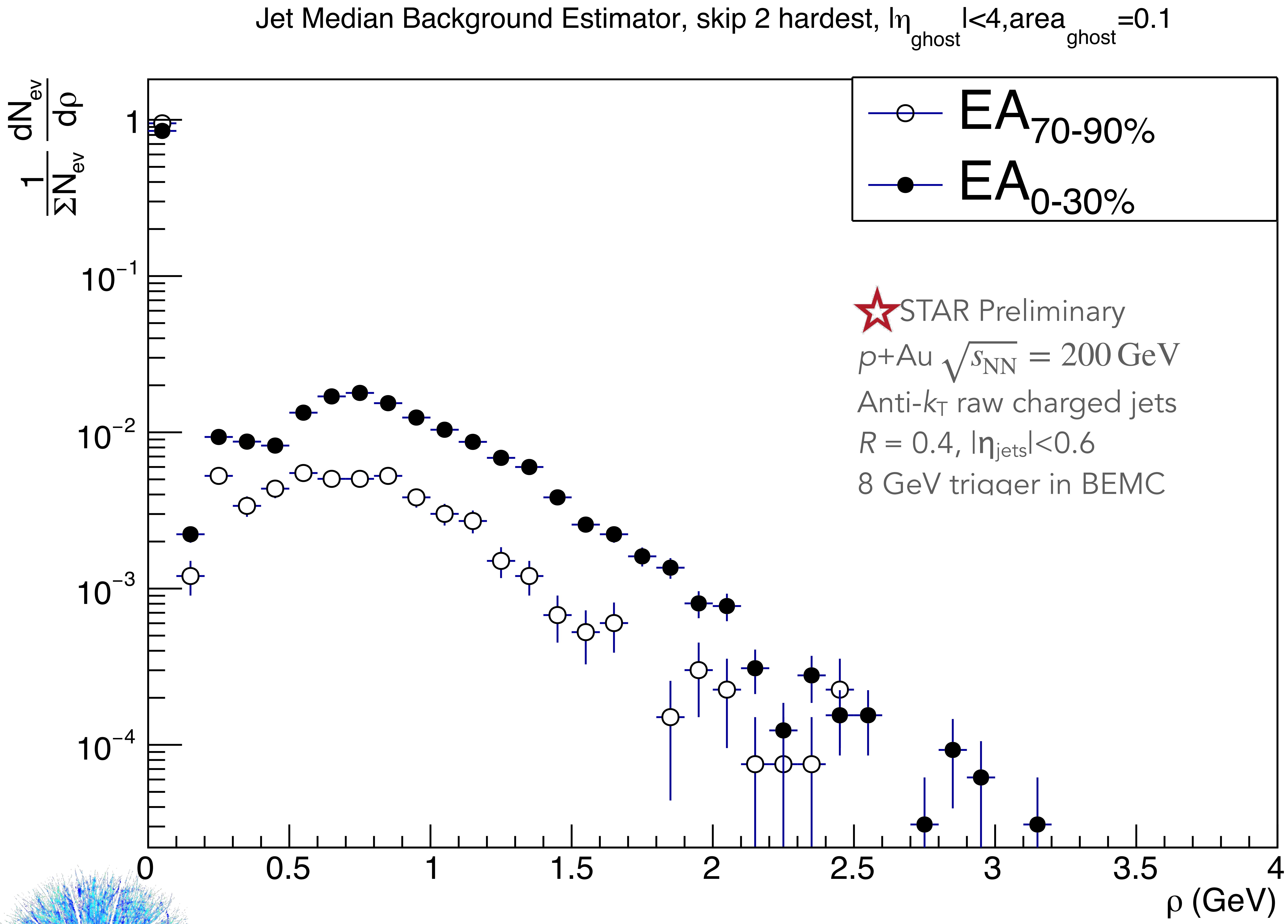
Kaon prior

- 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. See prior slide for reference for measured data.





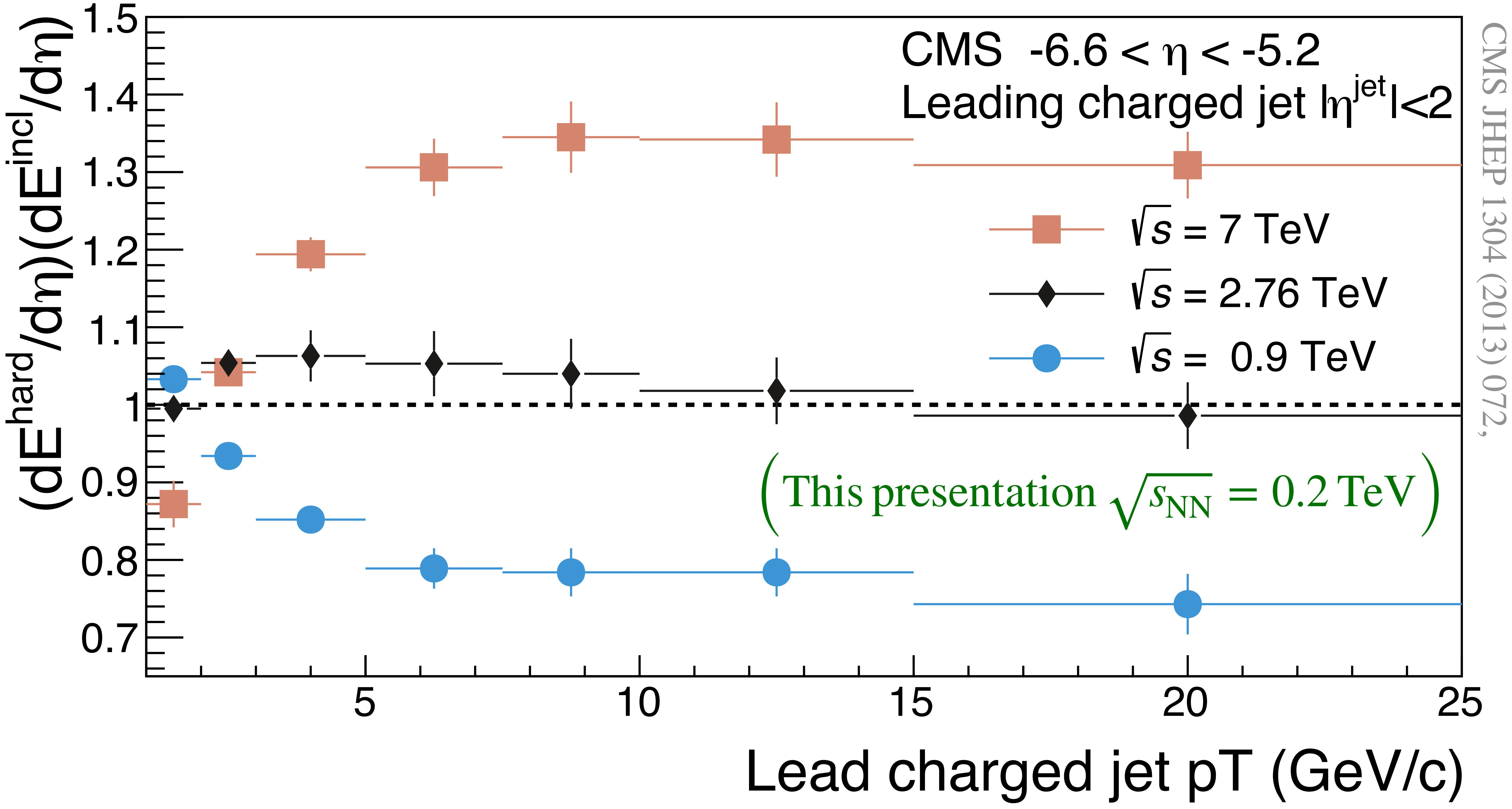
Standard FastJet3 background estimator



- Background is 0 for:
  - $EA_{70\text{-}90\%}$: 95% of events
  - $EA_{0\text{-}30\%}$: 85% of events

$\sqrt{s_{NN}}$ correlation of mid-η hard jet to backward-η energy deposition

- CMS measured energy deposition at $-6.6 < \eta < -5.2$ as a function of leading charged jet at $|\eta| < 2$
  - This is plotted to the right as a ratio the energy deposition in inclusive events
- Found for increasing mid-η jets:
  - Enhancement in $\sqrt{s} = 7$ TeV collisions
  - Slight enhancements that turns over in $\sqrt{s} = 2.76$ TeV
- Suppression for $\sqrt{s} = 0.9$ TeV Present study at STAR even lower at $\sqrt{s} = 0.2$ TeV
- Suggested in study possible cause of energy conservation



- Would naively artificially depress EA classification of events with hard mid-η jets
  - ➡ Enhance $S_{70-90\%}$ and suppress $S_{0-30\%}/S_{70-90\%}$

Theory result: modify Glauber to conserve $p_{tot}(p/d)$ in p/d+A 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 misbinning EA

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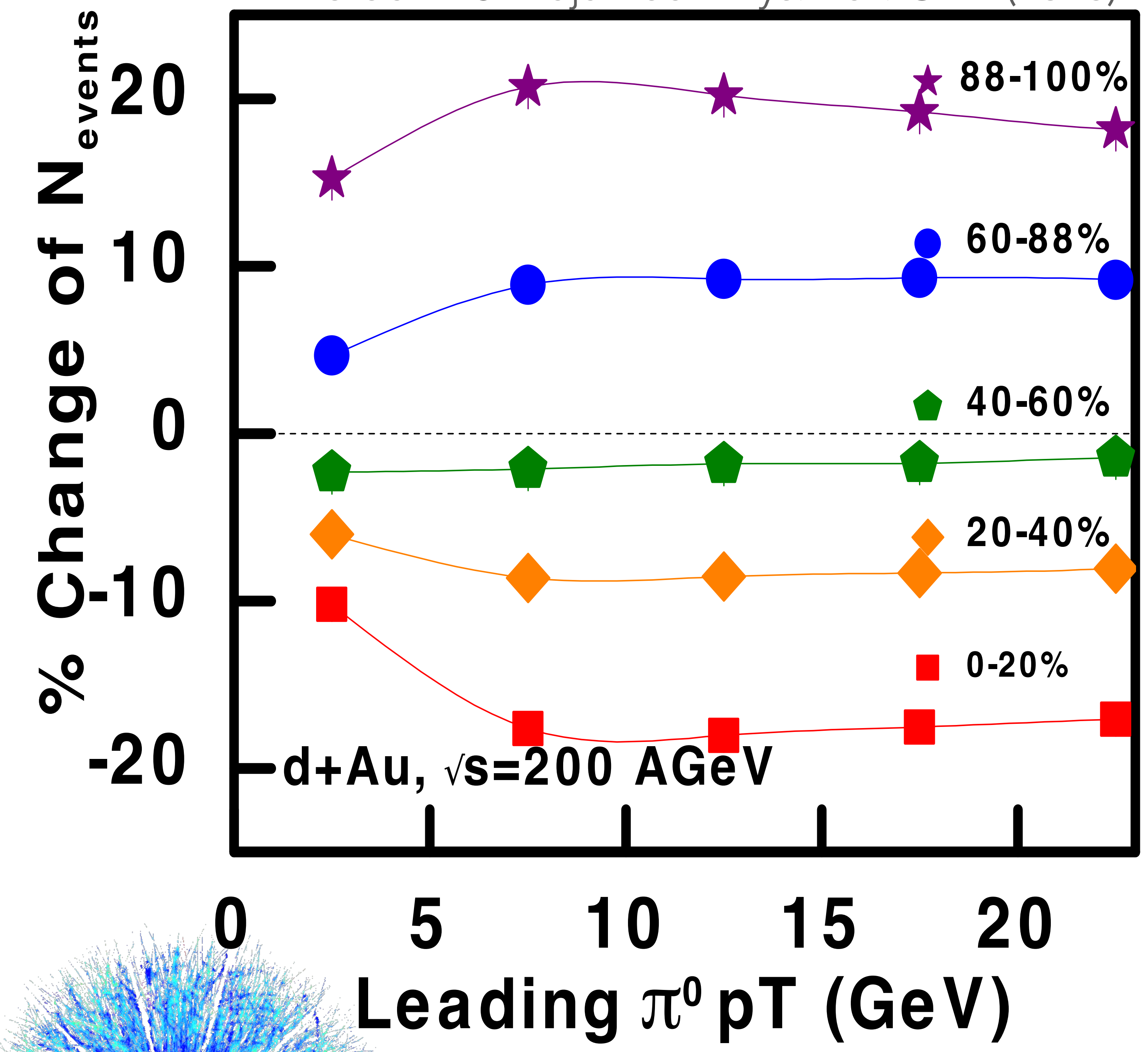

$$R^{jet\ \mathrm{High\ EA}}_{(p/d)\mathrm{A}} < 1 \quad \& \quad R^{jet\ \mathrm{Low\ EA}}_{(p/d)\mathrm{A}} > 1$$

Low EA events getting extra counts

High EA events getting less counts