Correlations between semi-inclusive jet production and event activity in $\sqrt{s_{\mathrm{NN}}} = 200\ \mathrm{GeV}$ *p*+Au collisions at STAR

2021 Fall Meeting of the APS Division of Nuclear Physics

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David Stewart (Yale University) for the STAR collaboration

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

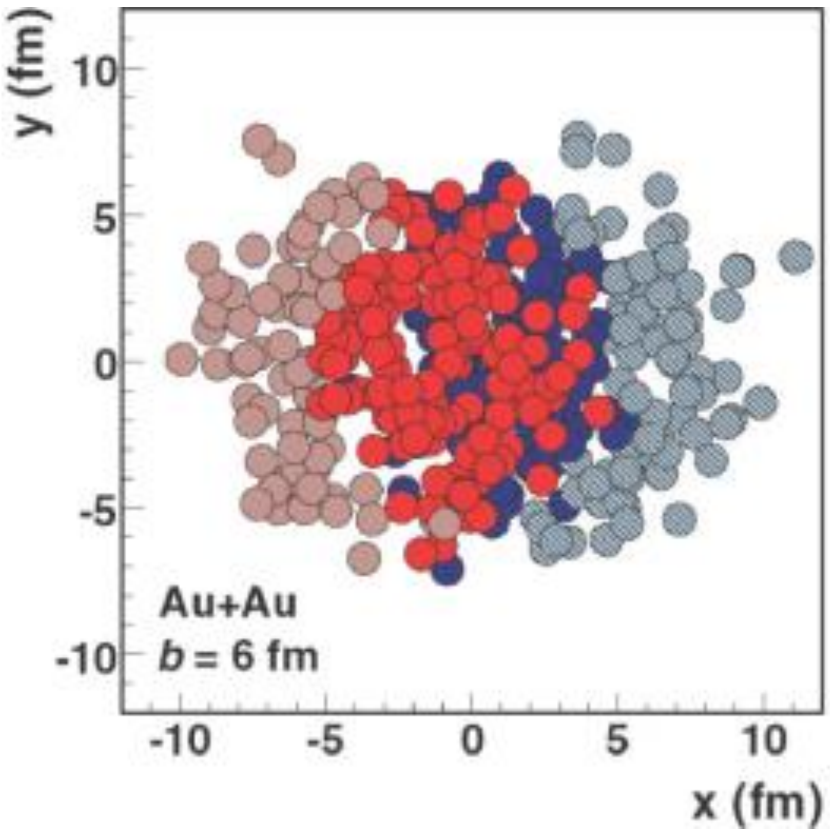
Hard and soft processes

Event Activity (EA) *scales with* → N_{part} (Number of nucleon participants)

- Overall result of common, low-Q^2 processes
- Governed by npQCD

Jets *scales with* → N_{coll} (Number of binary nucleon-nucleon collisions)

- Results of rare high-Q^2 processes
- Governed by pQCD



Ann.Rev.Nucl.Part.Sci. 57 (2007), 205-243 (modified)

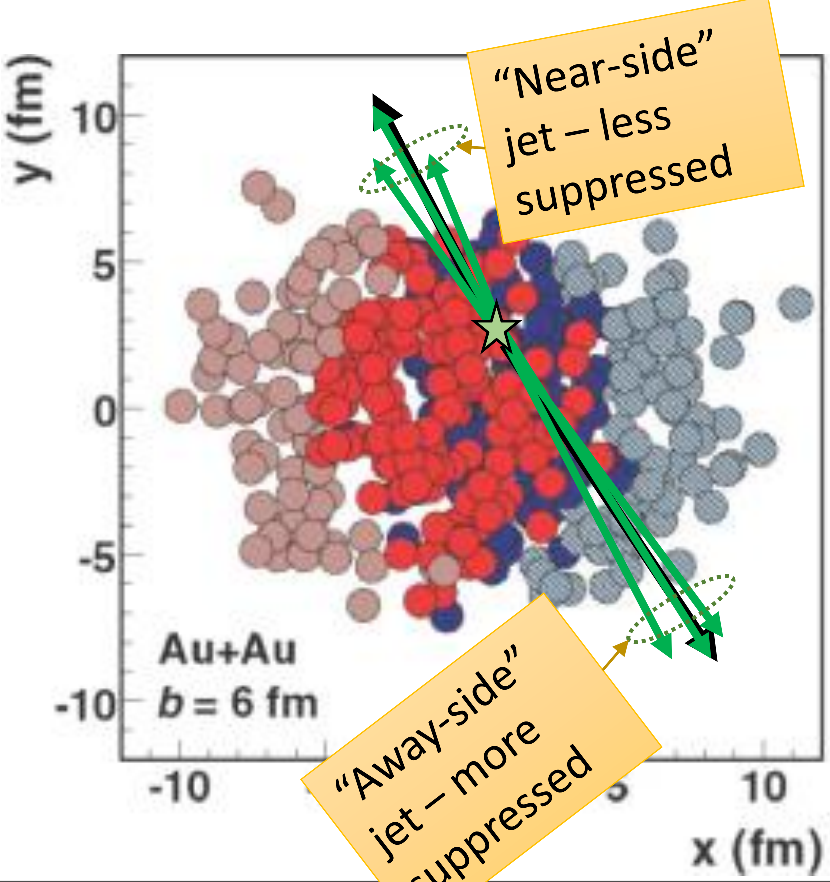
In A+A collisions

EA $\propto N_{\text{part}}$

- EA scales nicely with geometric centrality
- Bin events by EA and get bin average N_{part} and N_{coll}

Jets $\propto N_{\text{coll}}$

- Compare jet yield per N_{coll} in A+A collisions to jet yield per *pp* collision
- *Suppression of jet yield per N_{coll} in high-EA (i.e. central) events is an important signal of QGP formation*



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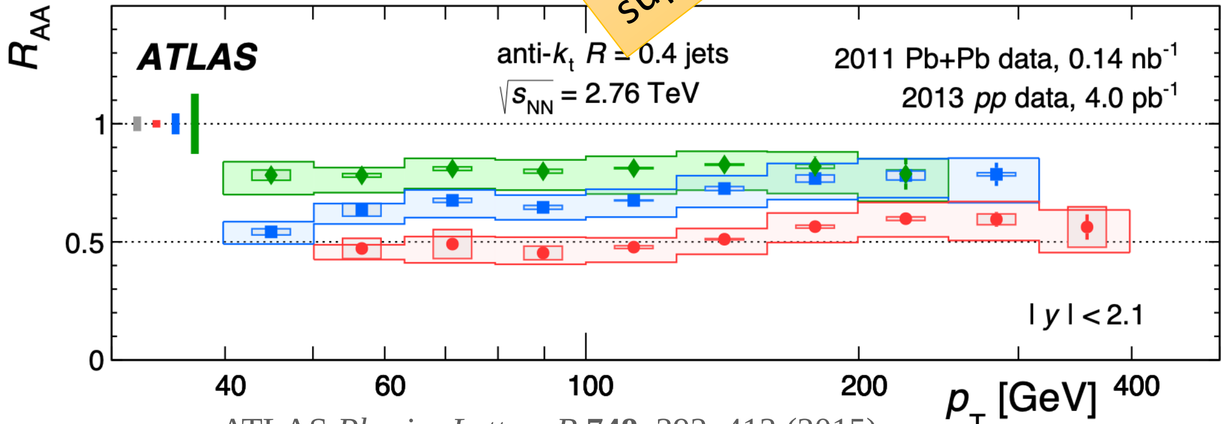


ATLAS *Physics Letters B* **748,** 392–413 (2015)

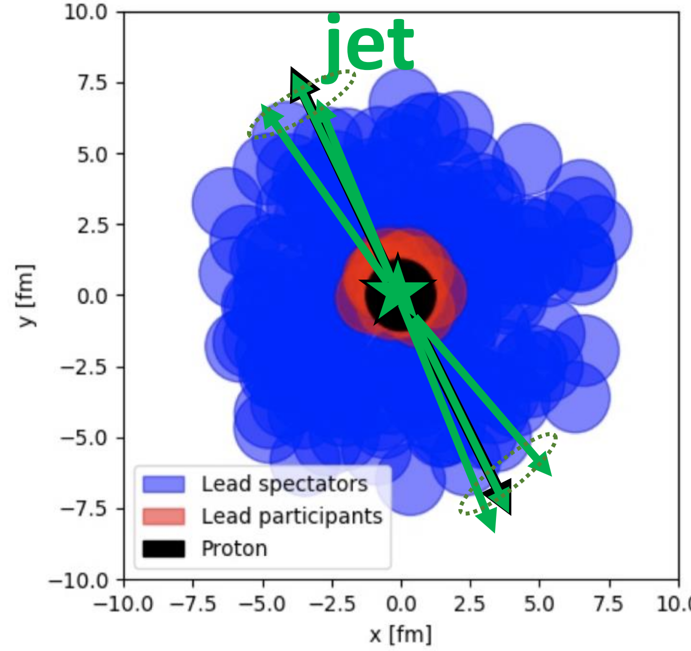
In p+A collisions

EA $\propto N_{\text{part}}$

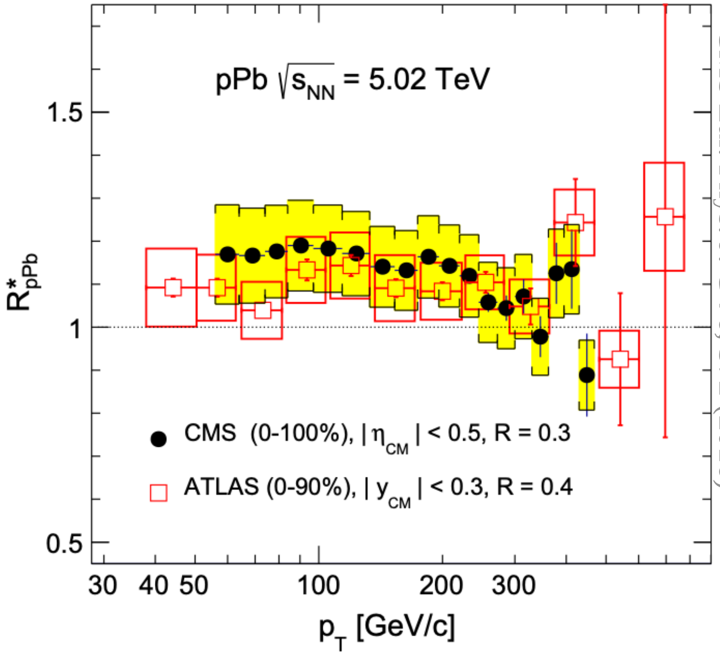
- EA relationship to geometry? Smaller system, larger fluctuations… much messier
- Trivially, $N_{\text{part}} = N_{\text{coll}} + 1$

Jets $\propto N_{\text{coll}}$

- *No suppression of jets per binary collision for inclusive (unbinned in* ***EA****) data*
- Consistent with p+A events too small to form QGP



https://bierlich.net/files/pPb-cartoon.jpg (modified)



CMS Eur. Phys. J. C **76**, 372 (2016)

In p+A collisions

Strong effect on jet yield per N_{coll} when binned by EA

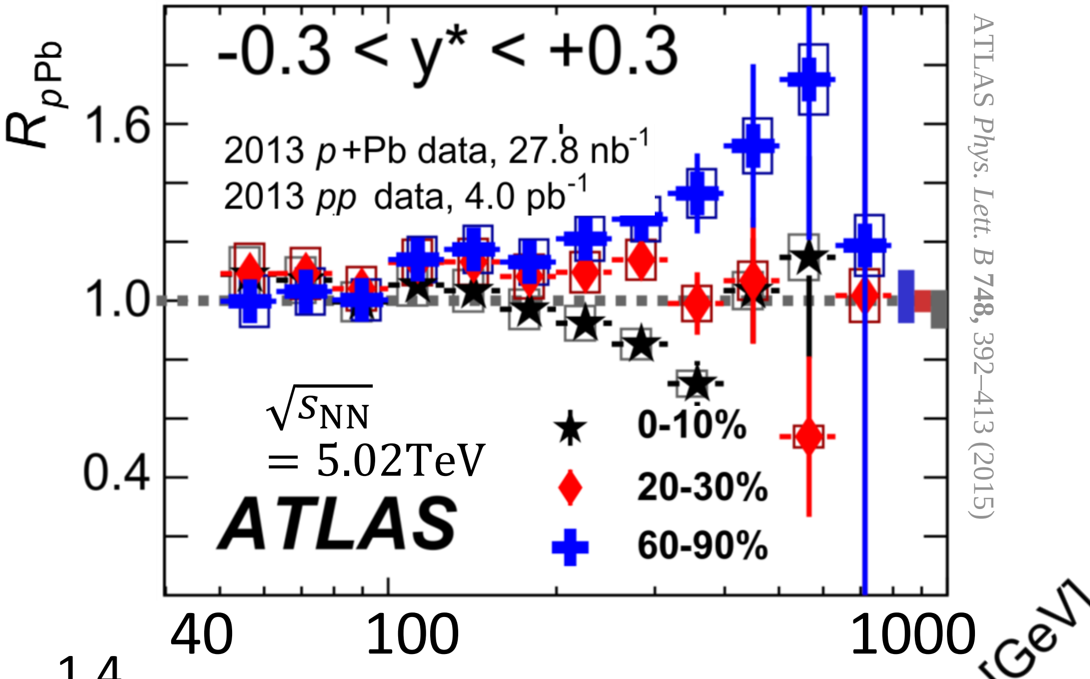
- Depends on $x_p \left(\approx \frac{2E_{\text{jet}}}{\sqrt{s}}\right)$
- Starts at $x_p \sim 0.1$
- In tension with jets-per-trigger measurements at lower x_p at ALICE

Motivates high-x_p jet measurements at RHIC

- Lower p_{T} reach, but measure jets up to $x_p \sim 0.5$

For $\sqrt{s_{\text{NN}}} = 200$ GeV collisions:

$$x_p \approx \frac{2E_{\text{jet}}}{\sqrt{s}} = \frac{2\ E_{\text{jet}}}{200\text{ GeV}} = \frac{1}{100}\, p_{\text{T, jet}} \overbrace{\cancel{\cosh \eta}}^{\sim 1} \approx \frac{1}{100}\, p_{\text{T, jet}} \text{ or } \frac{1}{100}\, E_{\text{T, trigger}}$$



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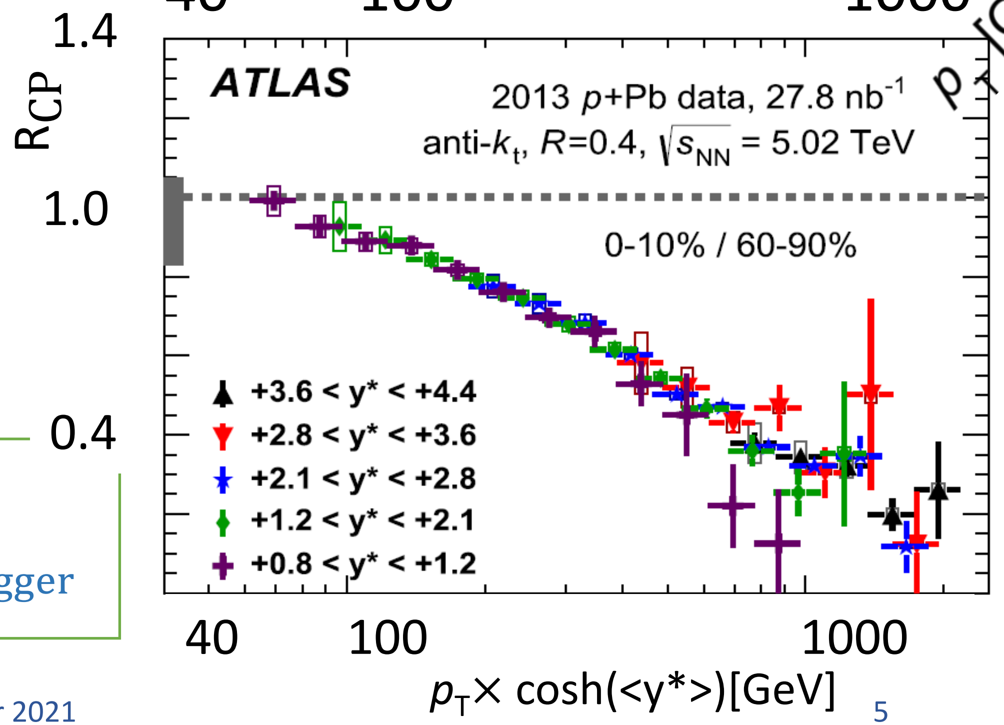
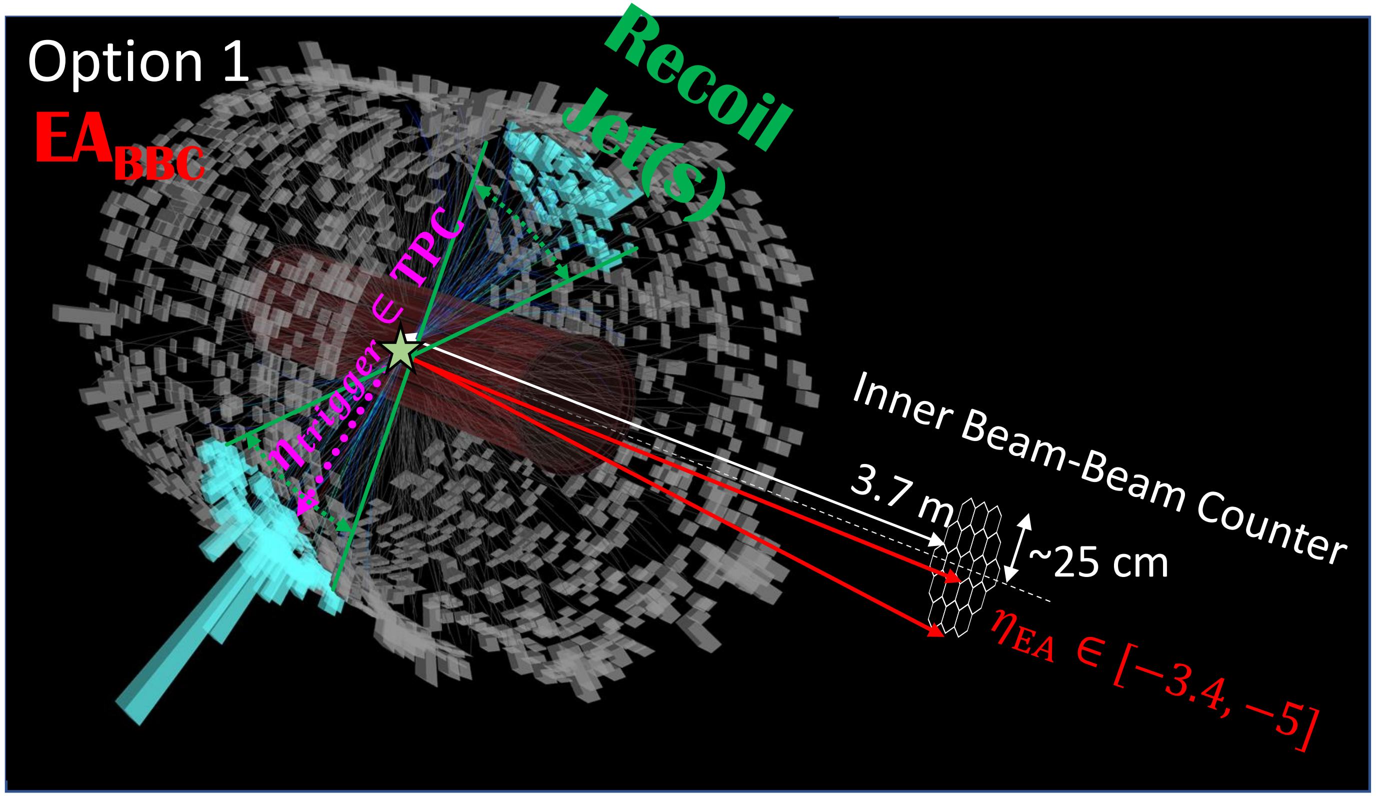
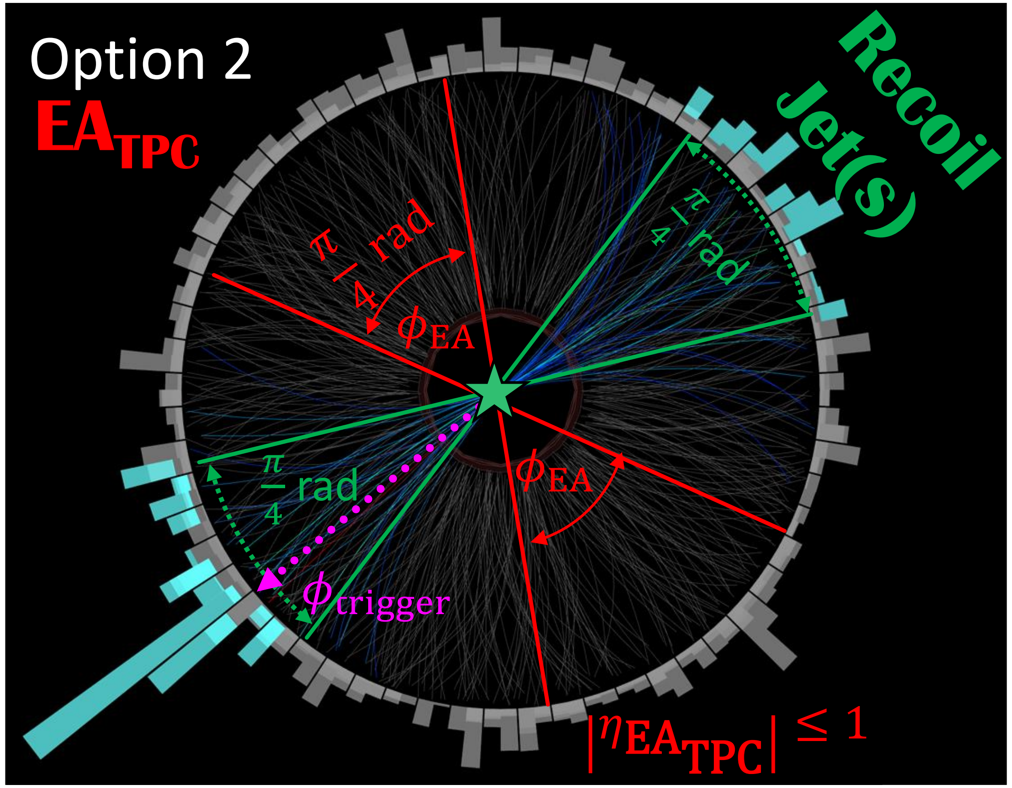


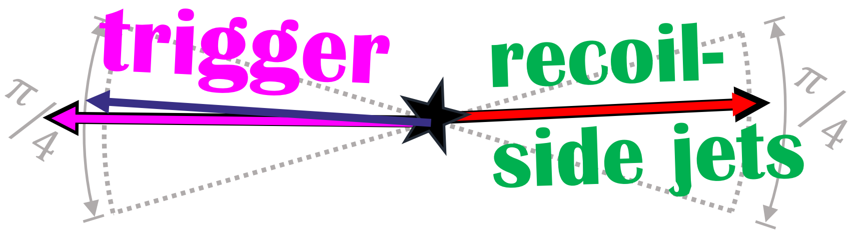
Measuring **event activity (EA)** at STAR

- Measure the jet (& possibly triggers)
- Measure **EA** elsewhere, separated in η-ϕ phasespace





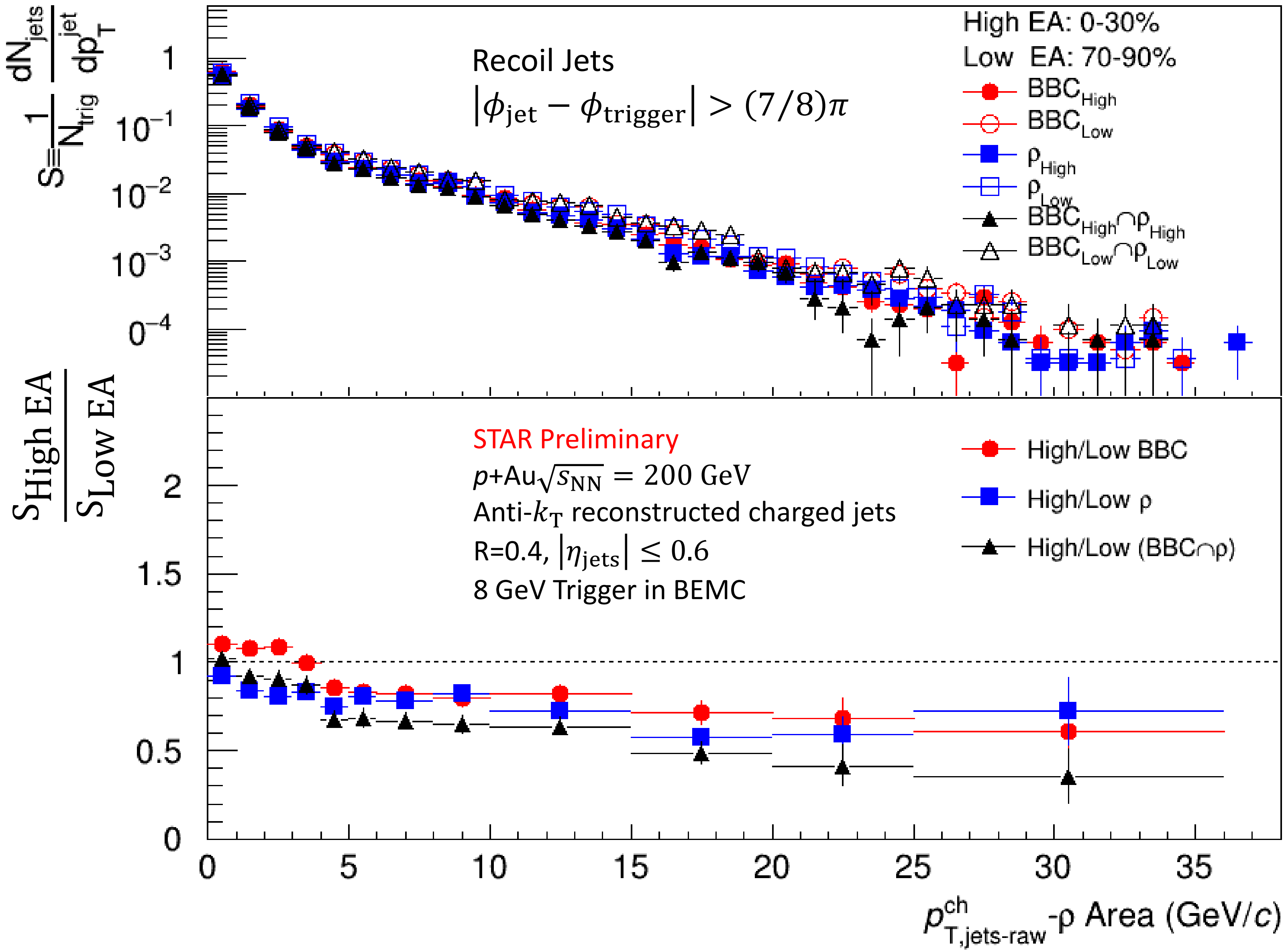
Results:



Using:

- **EA (high-η)** ($\mathbf{EA_{BBC}}$)
- **EA (transverse-ρ)** ($\mathbf{EA_{\rho}}$)
- or both ($\mathbf{EA_{BBC}} \cap \mathbf{EA_{\rho}}$)

→ charged jet spectra per trigger are suppressed in **high-EA** events relative to **low-EA** events



How can charged jet spectra (per trigger) be suppressed at **high-EA**?

- Trivial autocorrelation

  Jets selectively contaminate **EA** signal at **high/low-EA**?

- Jet quenching at **high-EA**
- High x_p scatterings ($\Rightarrow$ Trigger/jet spectra formation) correlate to **EA** due to effects before QGP formation

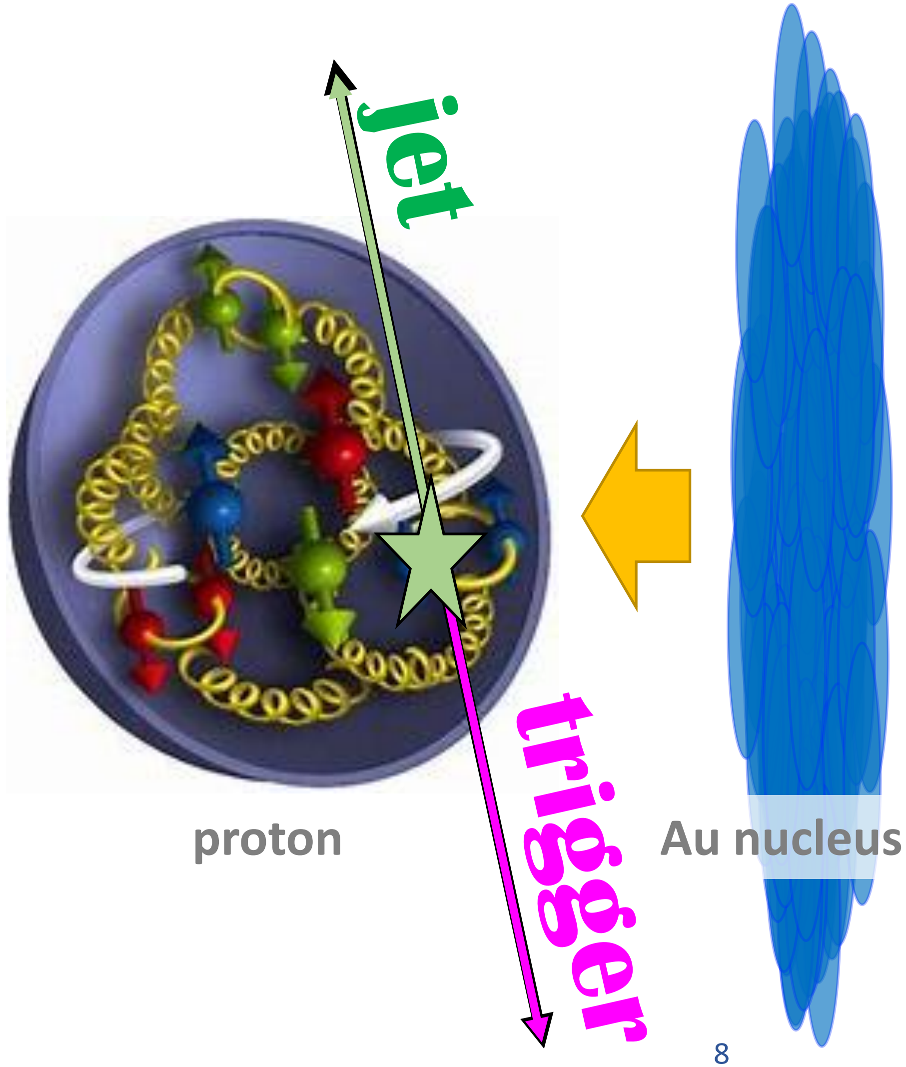


image: https://phys.org/news/2014-11-proton-puzzle-reveals-gluons-significant.html

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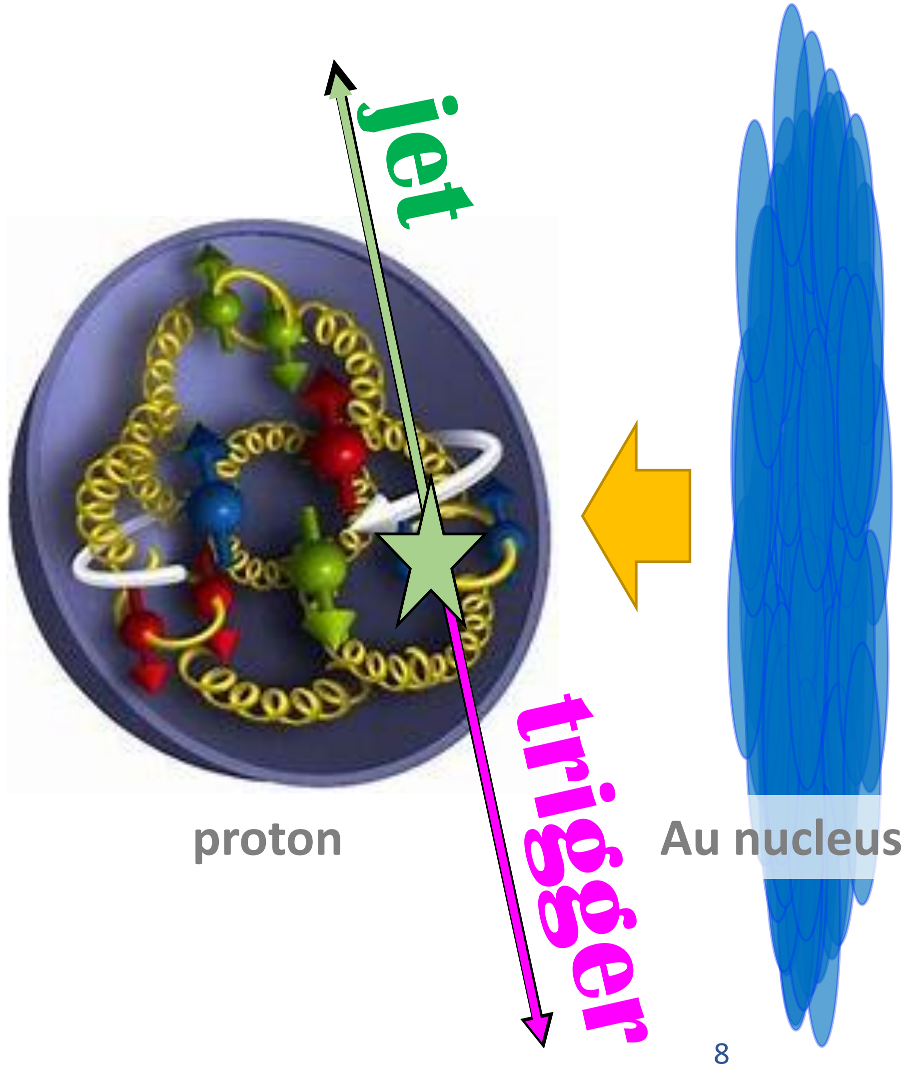

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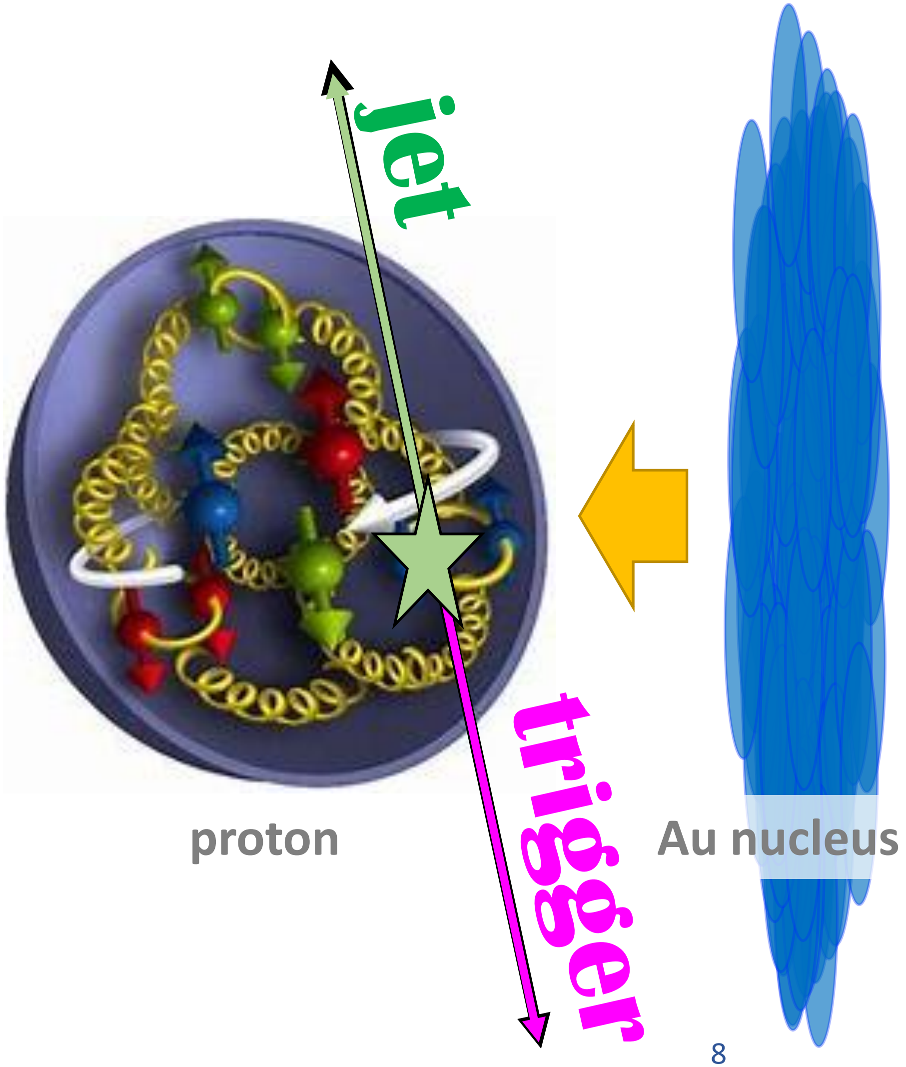

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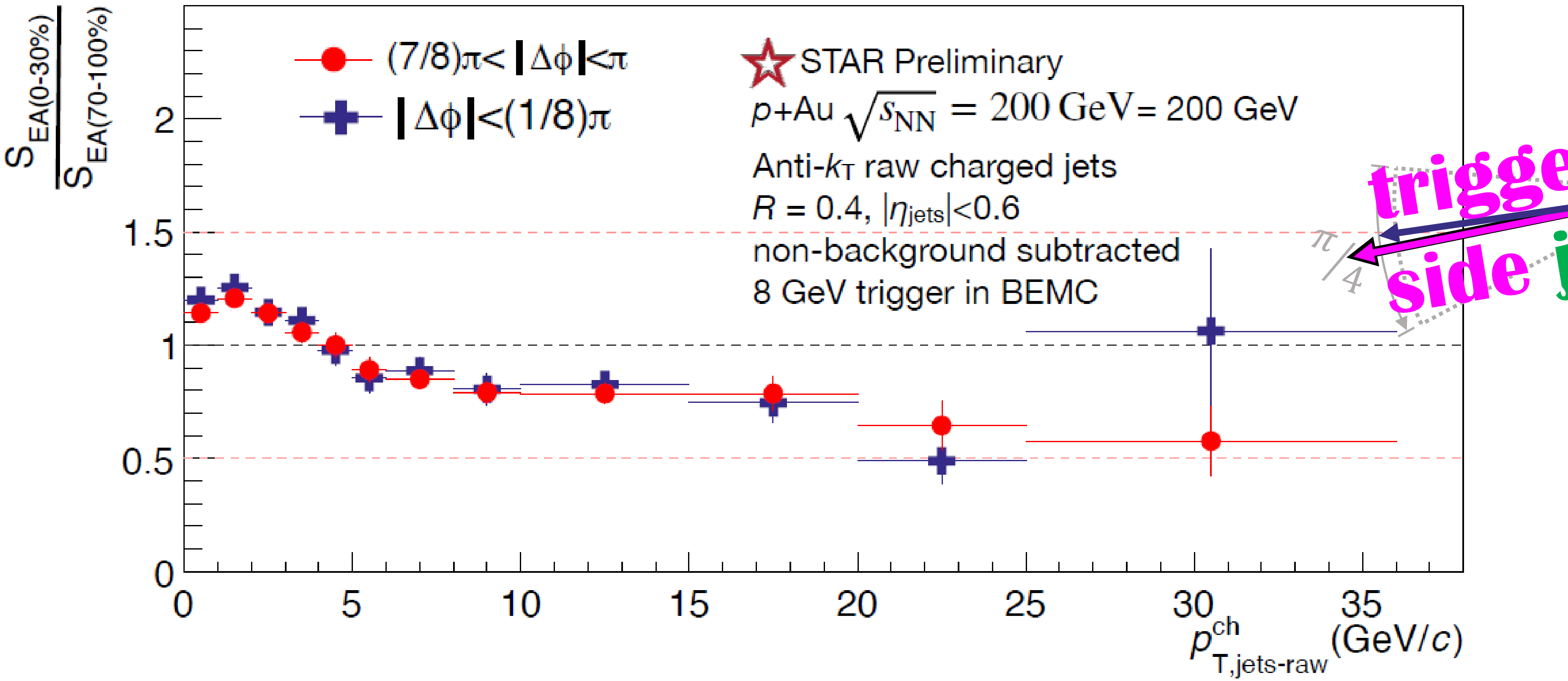
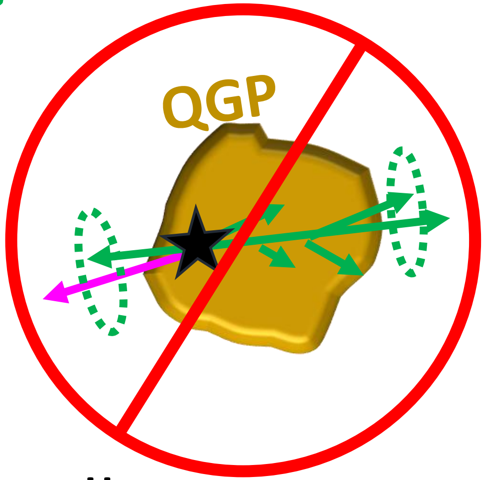
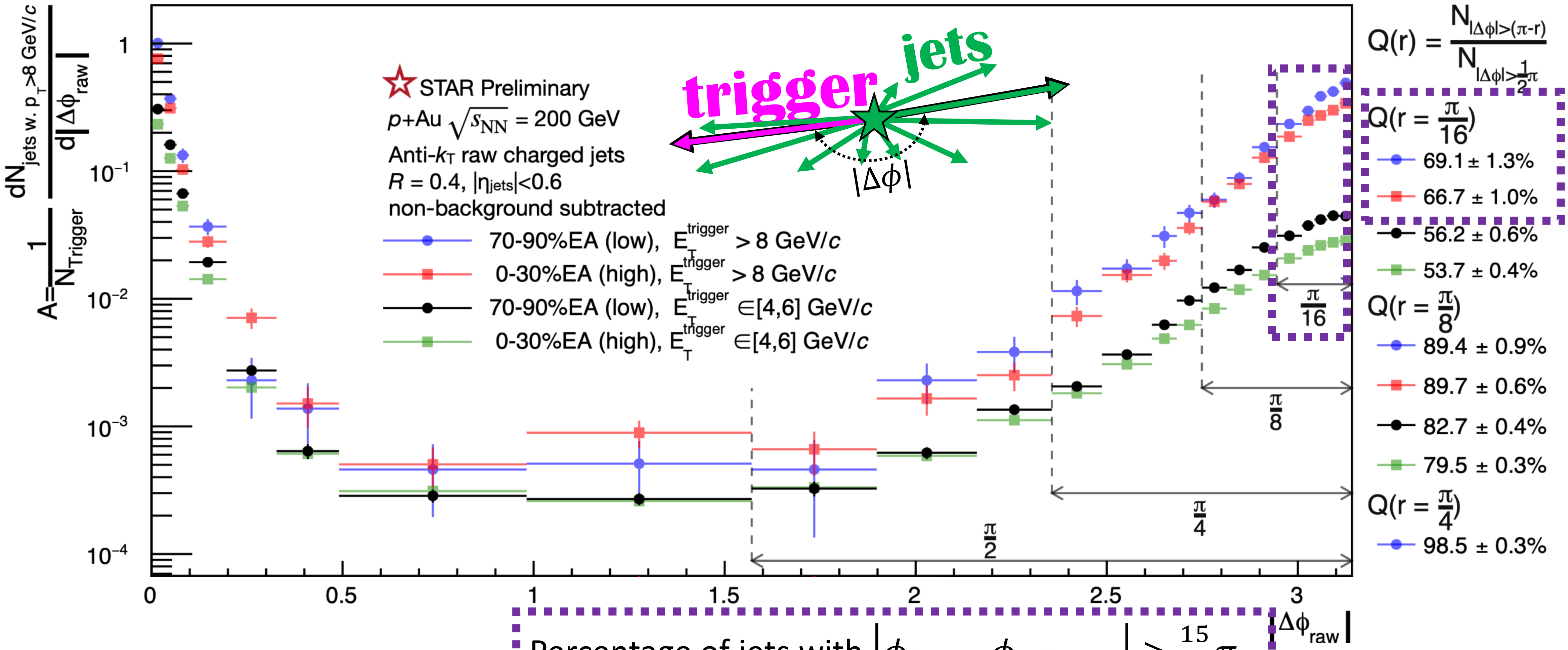
Results: no recoil-side bias in jet quenching (EA_{BBC})





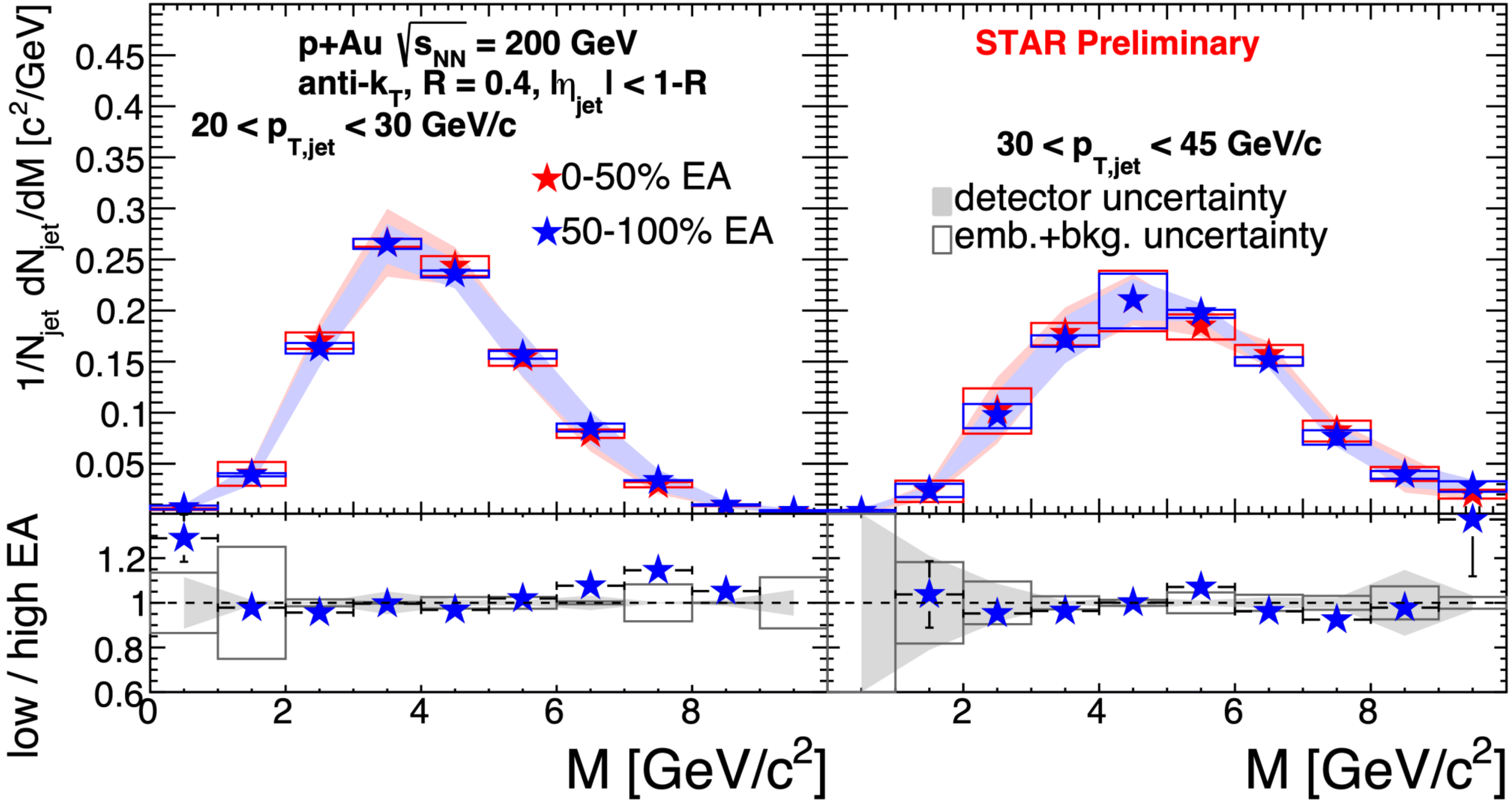
- **Not like jet quenching:** trigger-side and recoil-side equally suppressed
    - No surface bias/path length dependence of observed jet yield suppression

Results: no broadening of acoplanarity with $\mathbf{EA_{BBC}}$



Percentage of jets with $\left|\phi_{\text{jet}} - \phi_{\text{trigger}}\right| > \frac{15}{16}\pi$ decreases by 1.5 σ from **low-EA** to **high-EA**

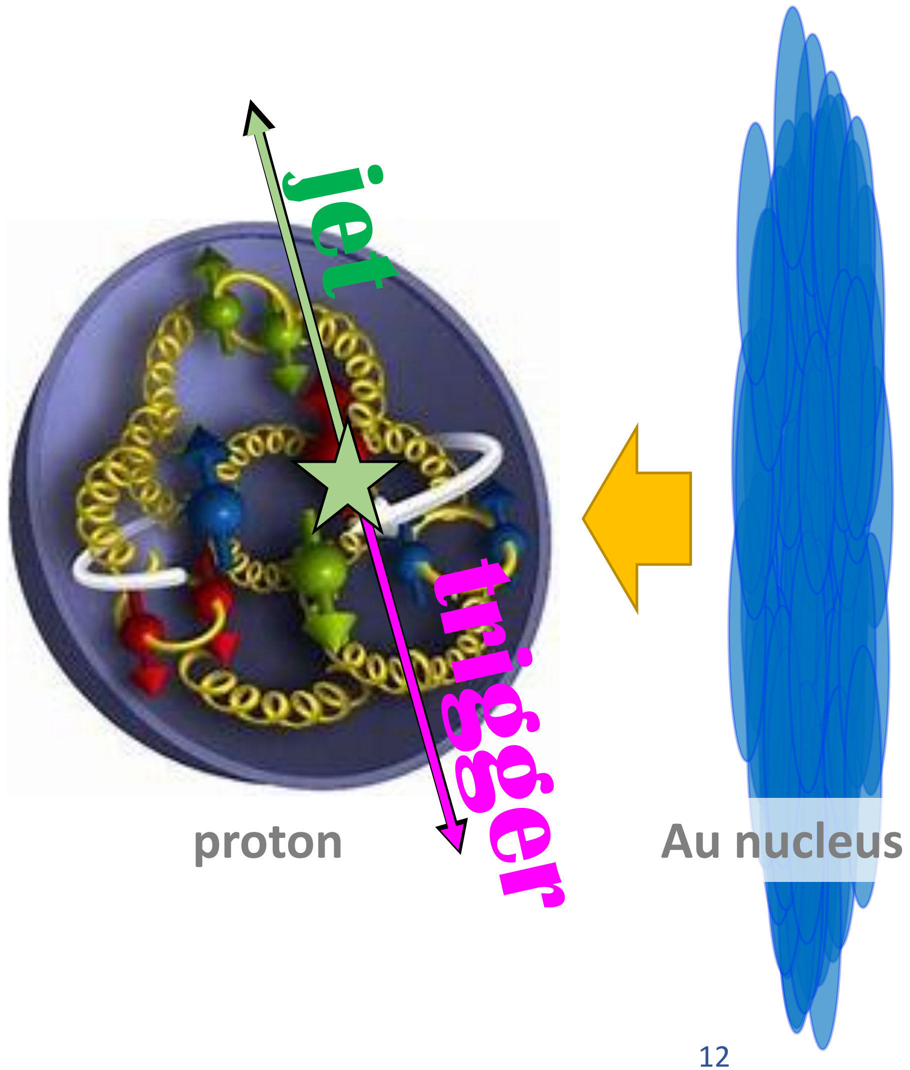
Results: jet mass distribution independent of EA_{BBC}



Not indicative of jet quenching

How can charged jet spectra (per trigger) be suppressed at **high-EA**?

- Trivial autocorrelation
  ~~Jets selectively contaminate EA signal at high/low-EA~~?
- Jet quenching at **high-EA** ?
- High x_p scatterings (⇒ Trigger/jet spectra formation) correlate to EA due to effects before QGP formation ?



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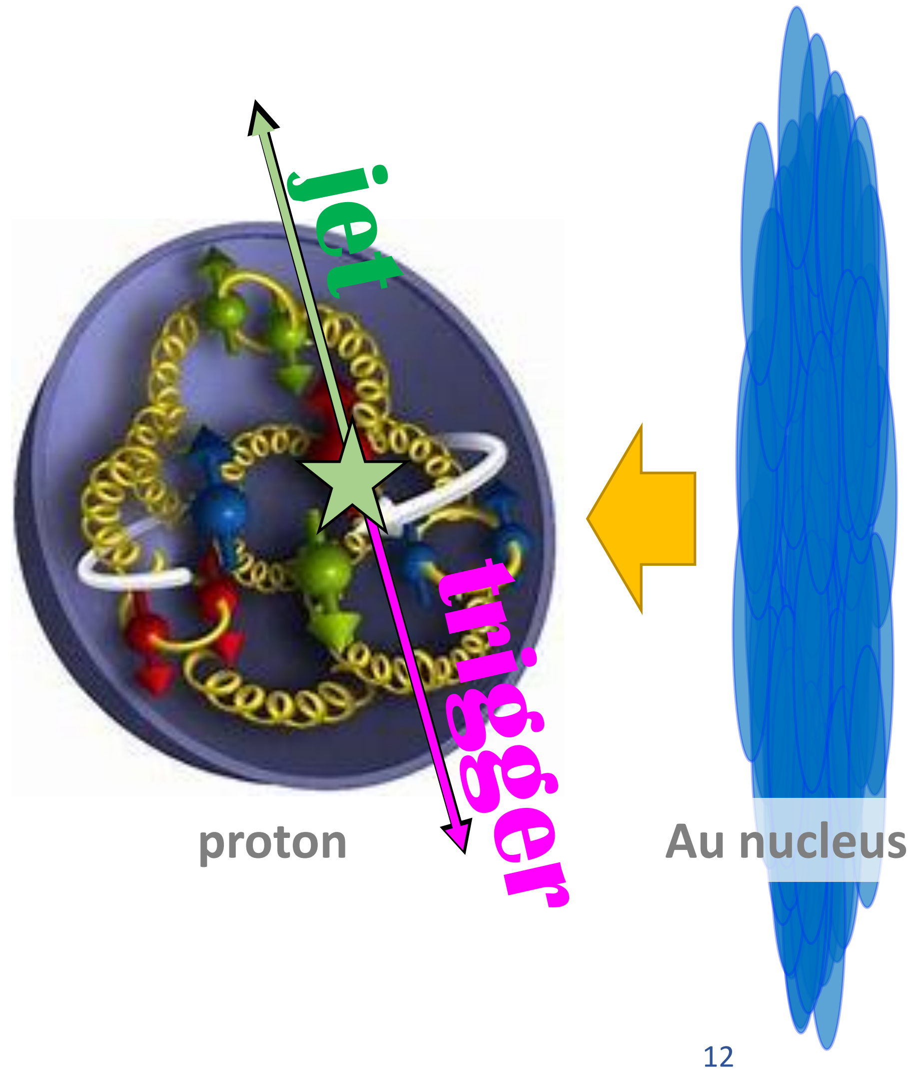

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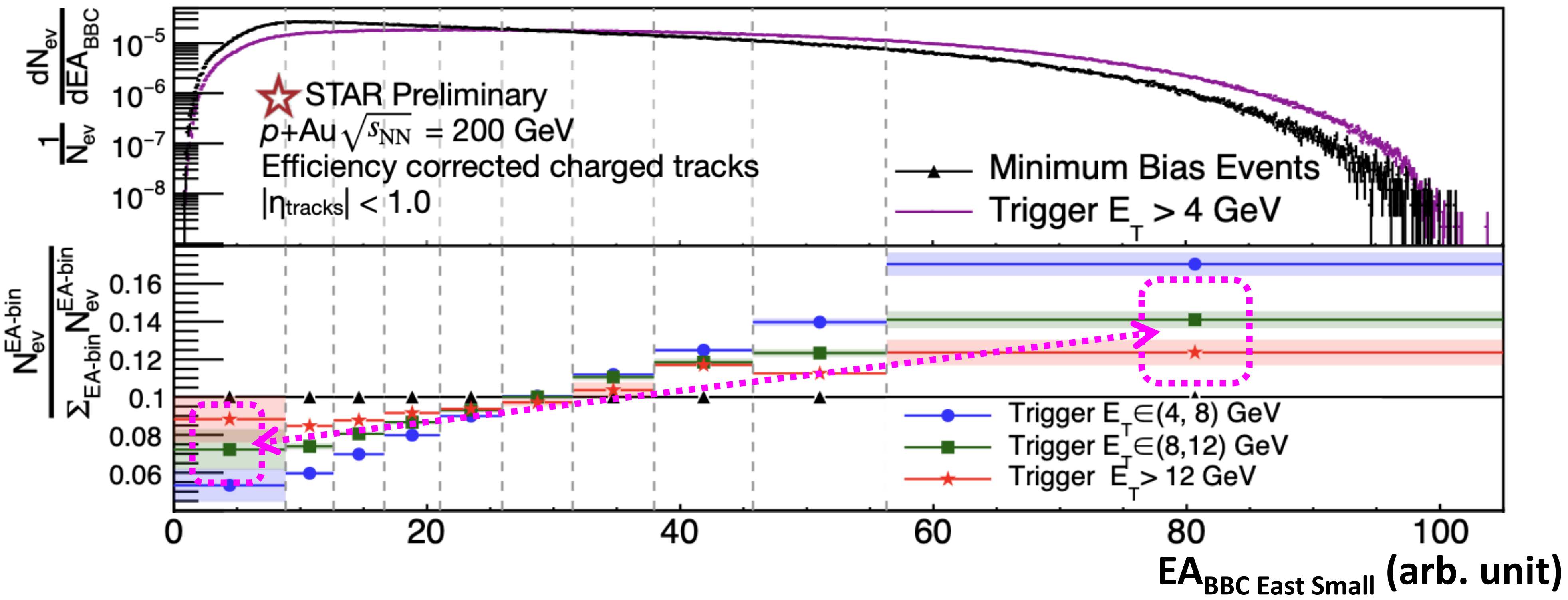
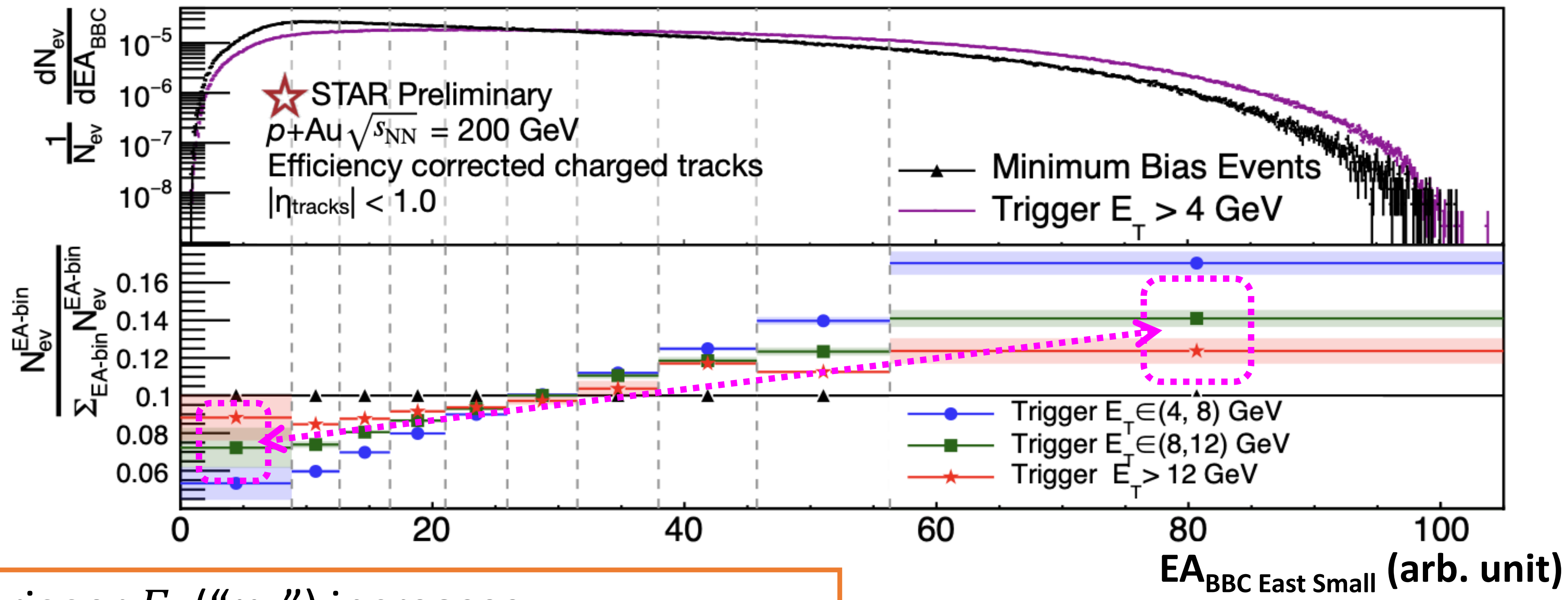
“Hard” trigger suppression in EA$_{BBC}$ deciles



Note: $\langle E_T \rangle$ scales mono-tonically with Q^2

“Hard” trigger suppression in $\mathbf{EA_{BBC}}$ deciles



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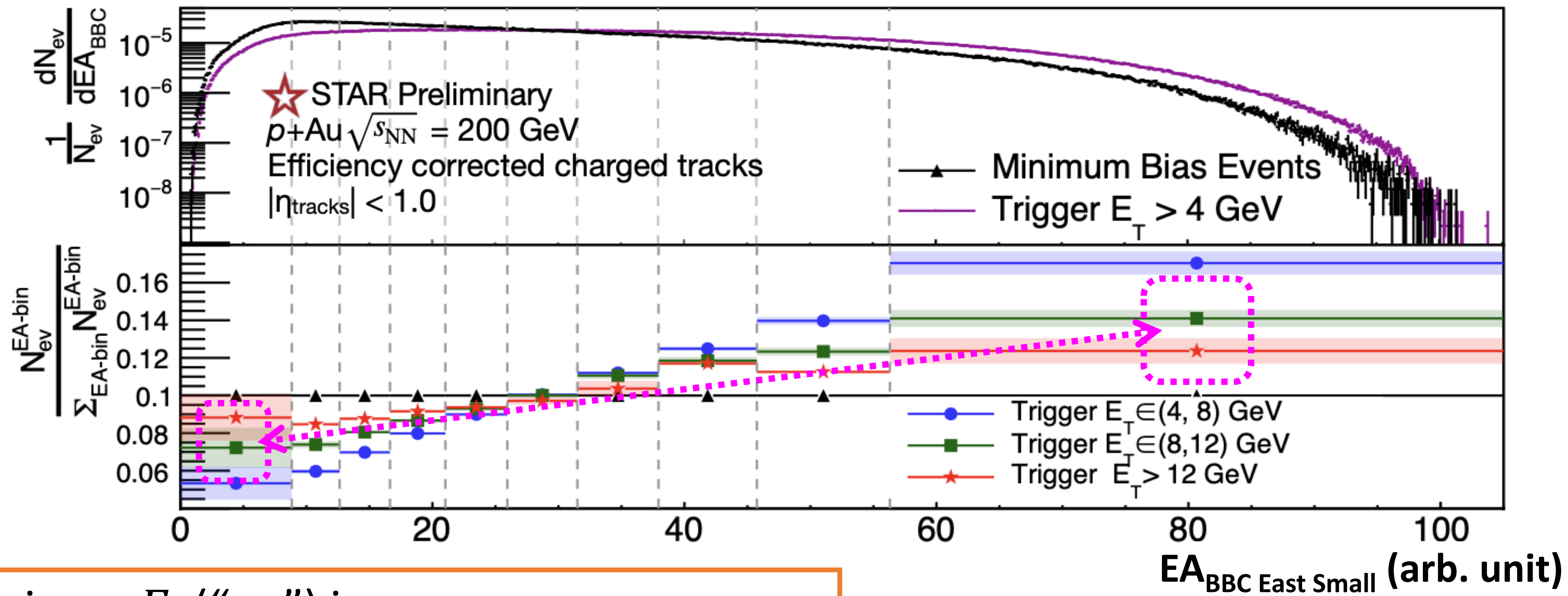
As trigger E_T(“x_p”) increases

$[0.08, 0.12]$ ( ) → $[0.12, 0.30]$ ( )

Ratio **highest-EA** : **lowest-EA** drops by **30%**:

2:1 ( ) →**1.4:1** ( )

"Hard" trigger suppression in **EA$_{\text{BBC}}$** deciles



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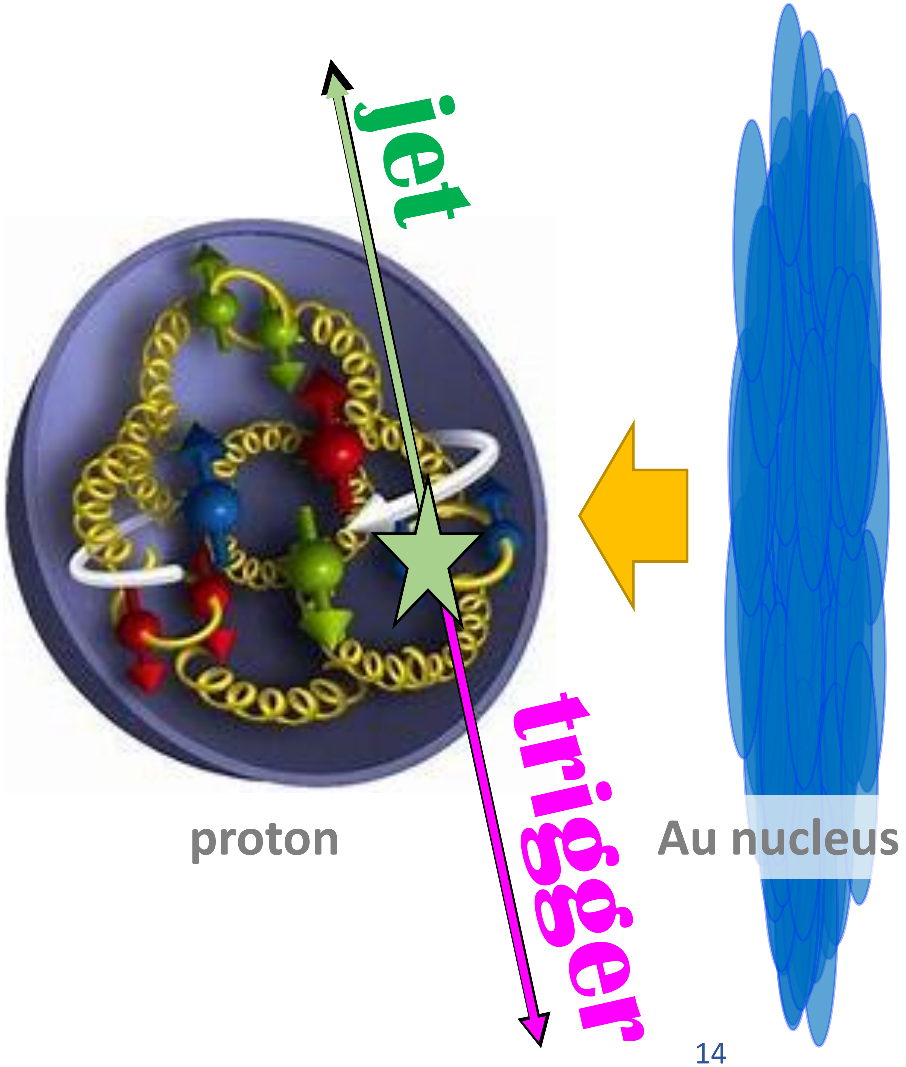
2:1 ( ) →**1.4:1** ( )

For measurements of X per trigger using both triggers $[\mathbf{0.08, 0.30}]$ (+), any X produced only by ( ) would be "suppressed" in per-trigger normalization by ~30%

How can charged jet spectra (per trigger) be suppressed at **high-EA**?

- Trivial autocorrelation
  - ~~Jets selectively contaminate **EA** signal at **high/low-EA**?~~
- ~~Quenching of jets & triggers at **high-EA**~~ ?
- High x_p scatterings (⇒ Trigger/jet spectra formation) correlates to **EA** due to effects before QGP formation



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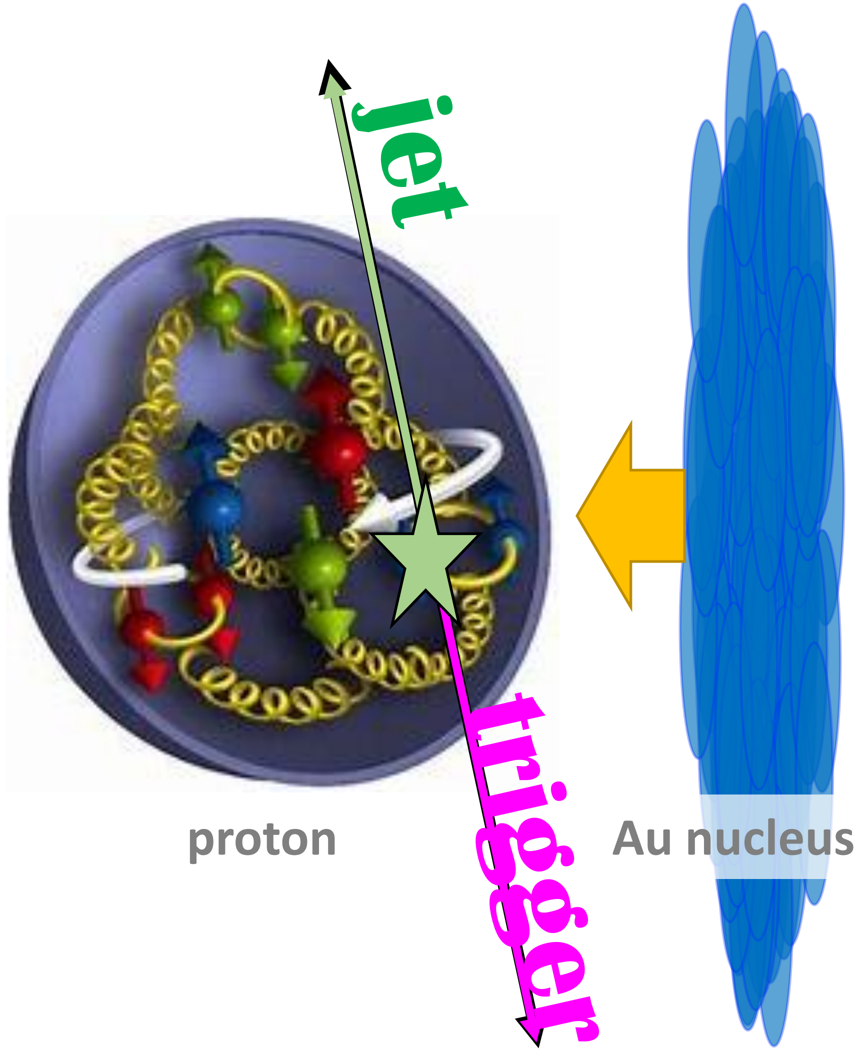
Summary-Outlook

- **EA** correlated with $x_p \left(\equiv \frac{2\, p_{\mathrm{T}}}{\sqrt{s_{\mathrm{NN}}}} \right)$

  $\Rightarrow$ Biases p_{T}-spectra normalized per trigger

- Jet mass and acoplanarity are not **EA**-dependent
- **Within precision of measurements, jet quenching not observed**
- **Opportunity to probe initial state conditions**
  - Mechanism behind correlations not yet known:
    - "Simple" energy conservation?
    - "Color transparency" / shrinking proton?
    - Communication between successive *p*+nucleon collisions?



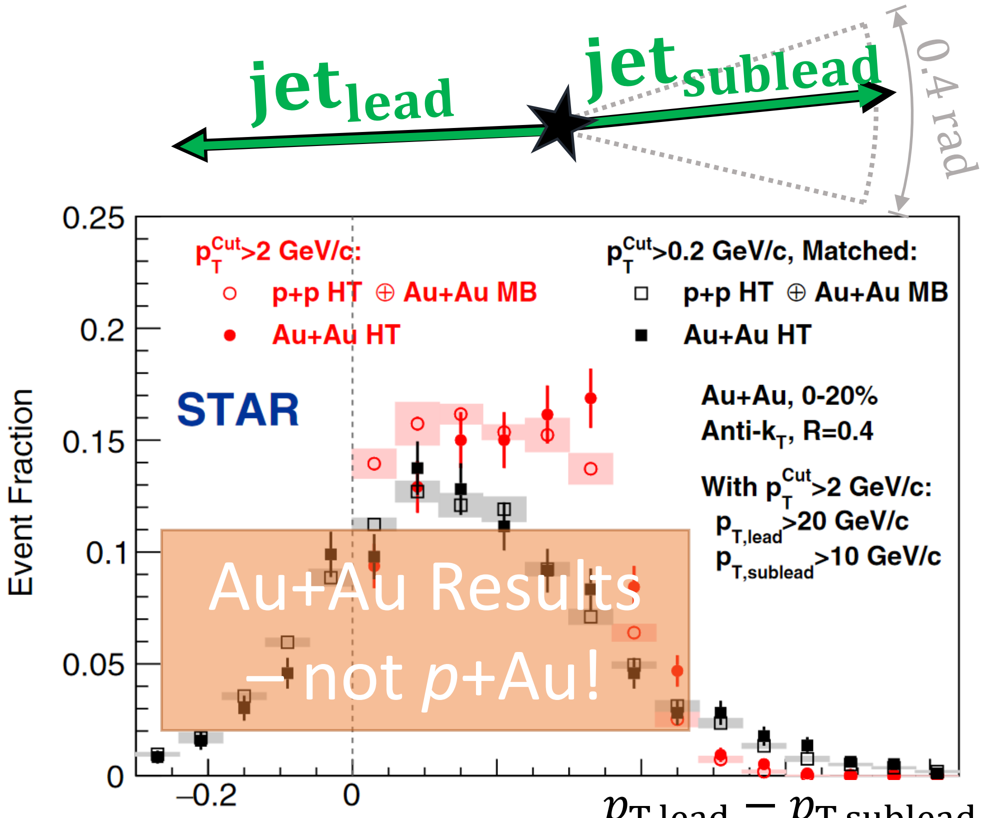
the end

Thank You!

Backup

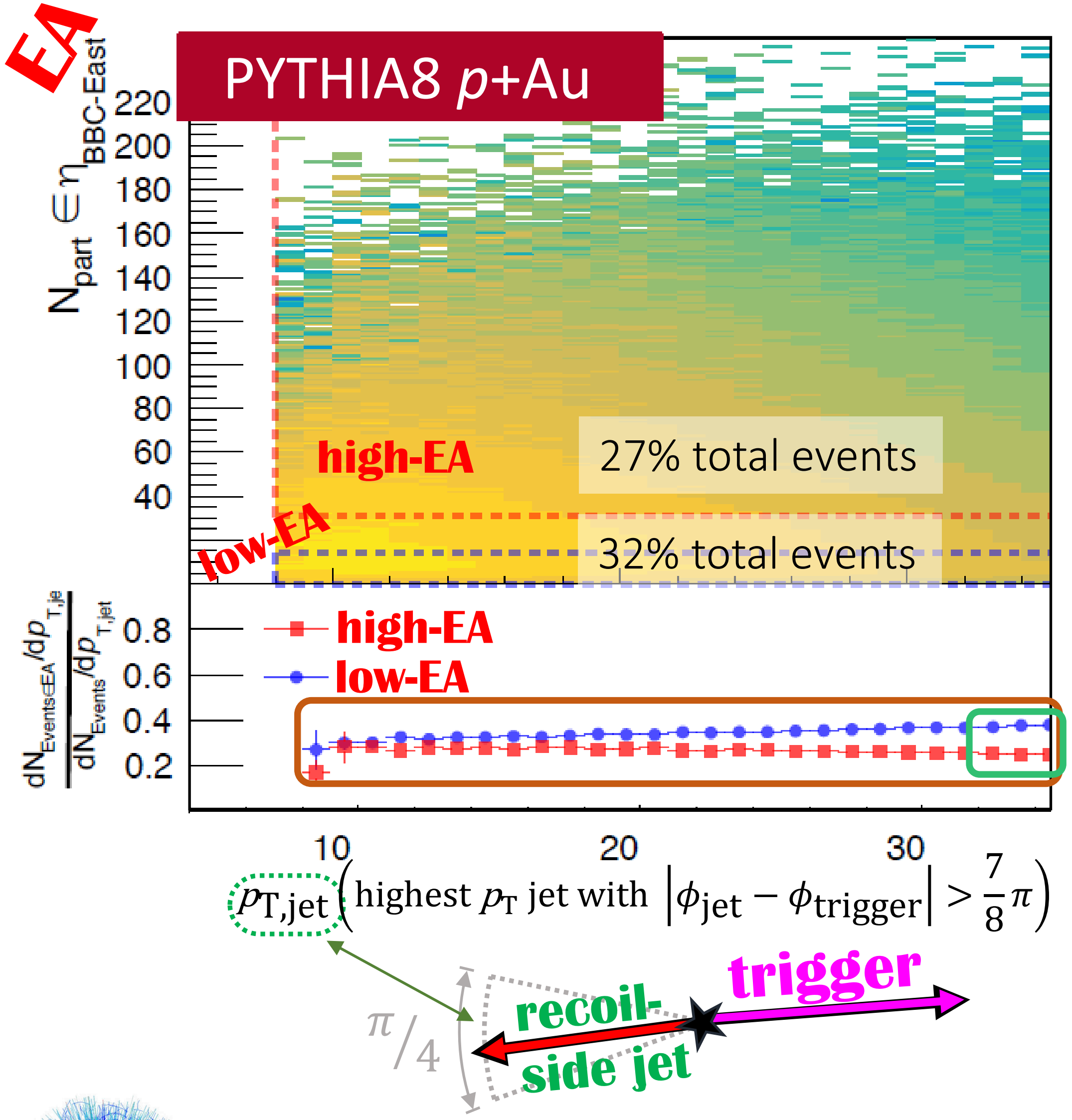
Measure di-jet momentum asymmetry vs EA

- p_{T} balance of leading to subleading (recoil) jet distribution
- predicted to not be EA dependent



$$A_{\mathrm{J}} \equiv \frac{p_{\mathrm{T,lead}} - p_{\mathrm{T,sublead}}}{p_{\mathrm{T,lead}} + p_{\mathrm{T,sublead}}}$$

Simulated phase-space caused semi-inclusive suppression



- Each entry includes the single leading jet
  - $N_{jets}:N_{triggers}:N_{events}$ = 1:1:1
- For jets ~30 GeV/*c*:

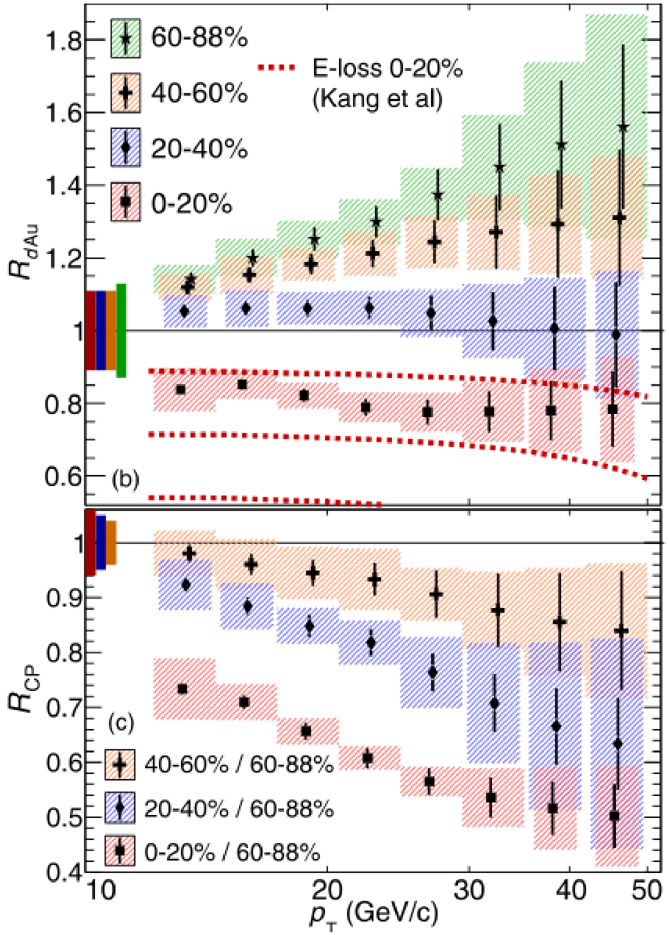
$$\frac{S_{high-EA}}{S_{low-EA}} = \overset{\sim 0.7}{\left.\frac{N_{jets}^{high-EA}}{N_{jets}^{low-EA}}\right|_{p_{T,jet}\approx 30\mathrm{GeV}}} \overset{\sim 1.4}{\left.\frac{N_{triggers}^{low-EA}}{N_{triggers}^{high-EA}}\right|_{p_{T,jet}\approx 30\mathrm{GeV}}} = 1.0$$

- In experiment, normalization is set by all **high-EA** and **low-EA** triggers:

$$\frac{S_{high-EA}}{S_{low-EA}} = \overset{\sim 0.7}{\left.\frac{N_{jets}^{high-EA}}{N_{jets}^{low-EA}}\right|_{p_{T,jet}\approx 30\mathrm{GeV}}} \overset{\sim 1.2}{\left.\frac{N_{triggers}^{low-EA}}{N_{triggers}^{high-EA}}\right|_{\text{all events}}} \approx 0.84$$

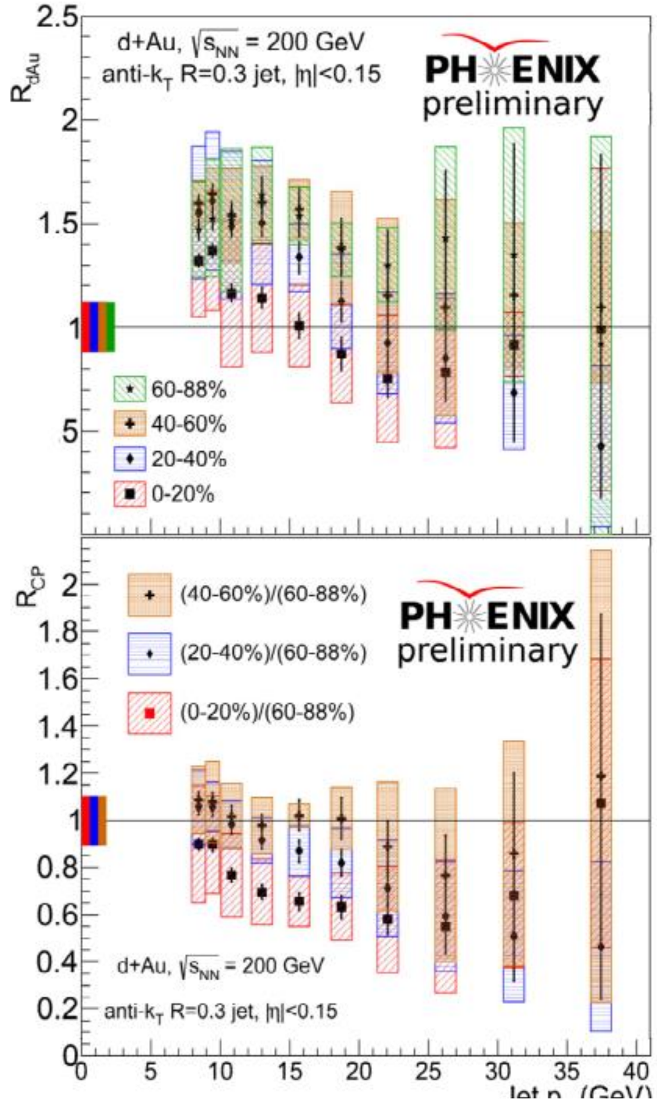
~**16%** suppression of 30 GeV/*c* jets from **EA** to Q^2 correlation

PHENIX Results



PHENIX *Phys. Rev. Lett.* **116**, 122301 (2016)

Current Published

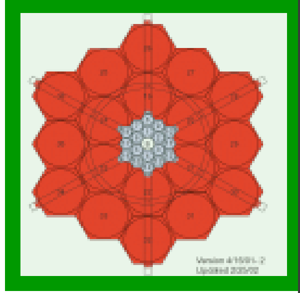


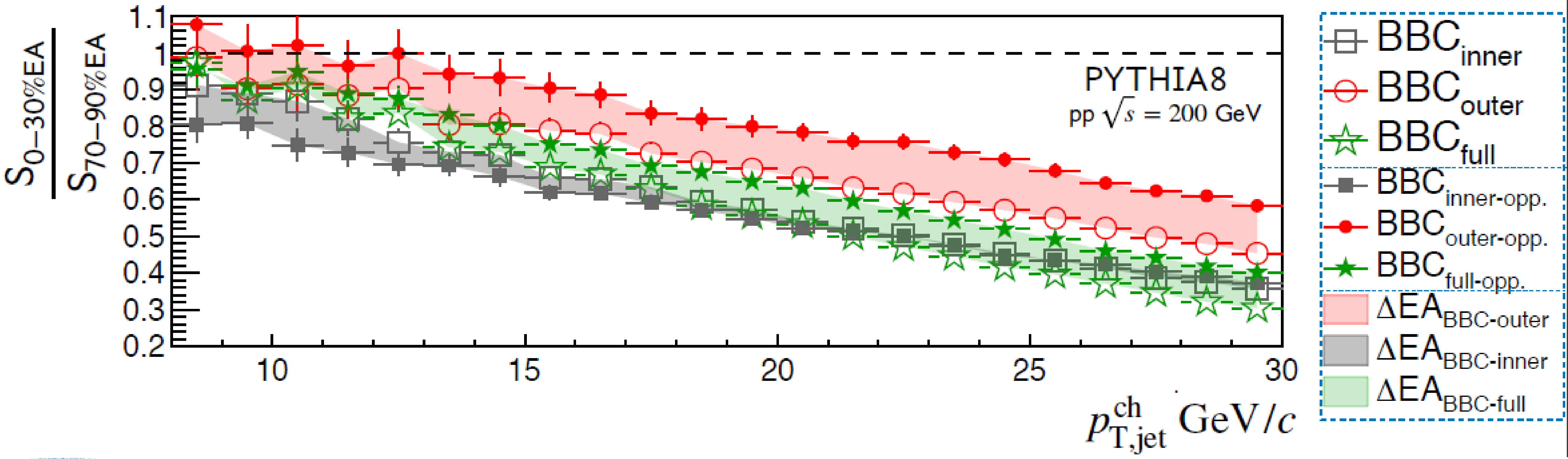
Moriond QCD 2021 (https://moriond.in2p3.fr/QCD/2021/FridayAfternoon/Lajoie.pdf), 2021

Preliminary of Erratum

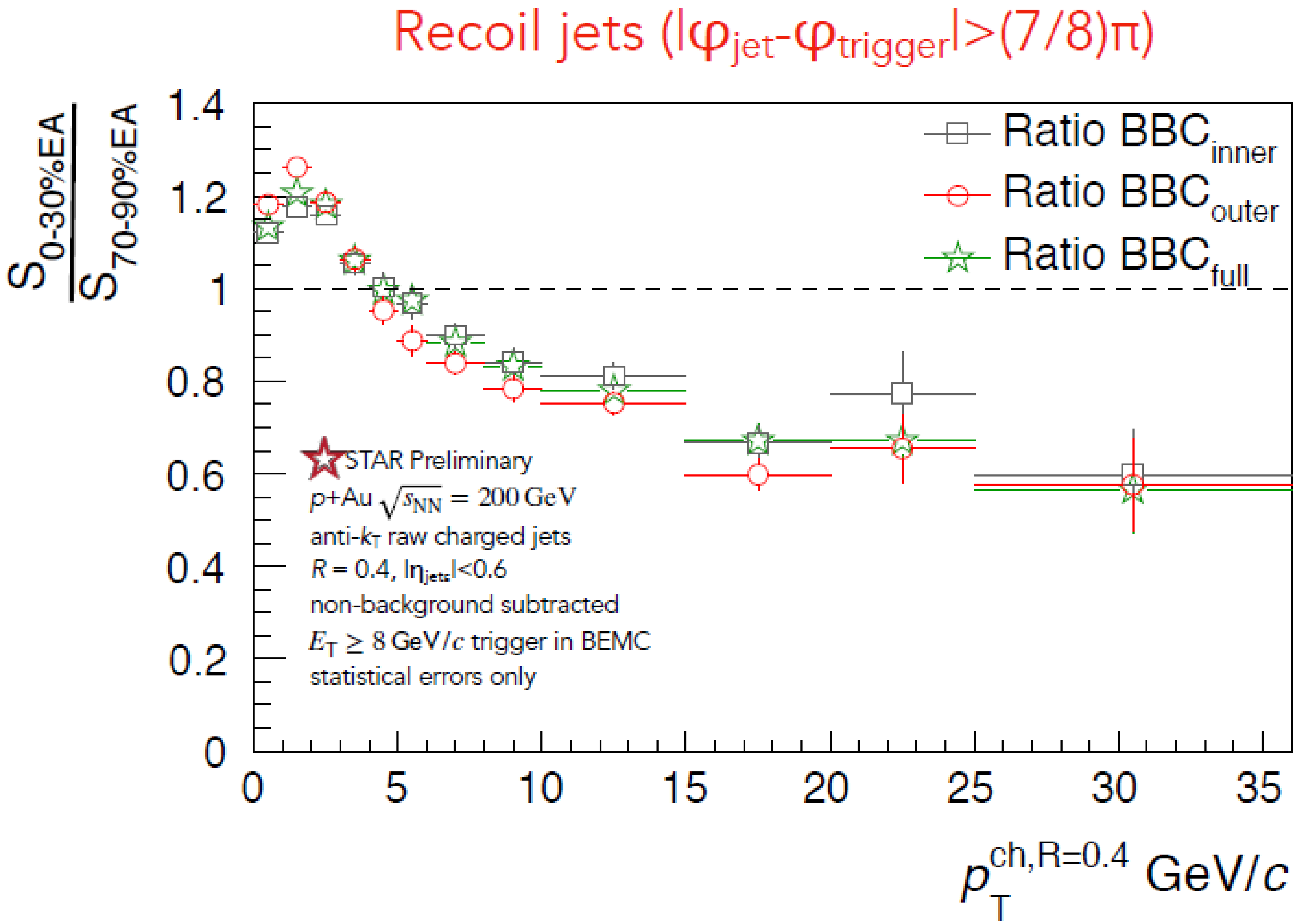
PYTHIA $S_{0-30\%\text{EA}}/S_{70-90\%\text{EA}}$ with and without dijet bias

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



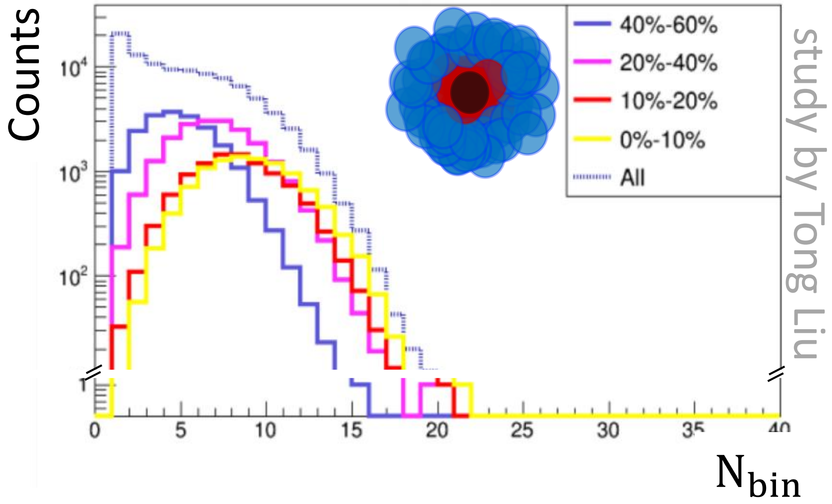


Suppression persists with BBC_{inner} EA selection



- 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}

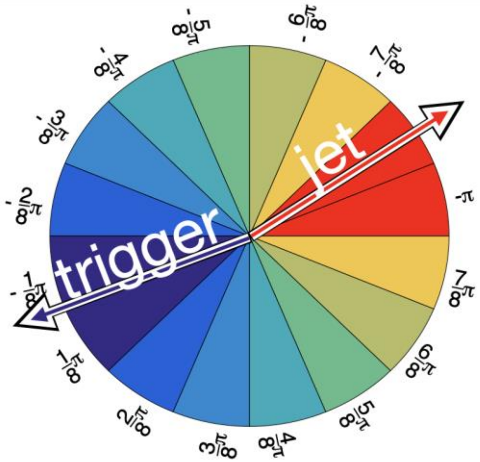
How to compare jet spectra



study by Tong Liu

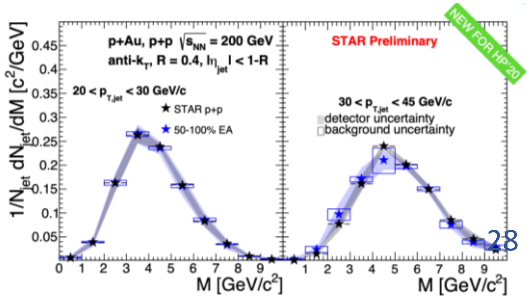
a. Per N_{bin} (inclusive):
- Measure all jet spectra
- Sort by EA into centrality bins
- Compare to *pp* jet spectra scaled by N_{bin} from Glauber model

b. Per-trigger (semi-inclusive)
- Measure $p + \mathrm{Au} \rightarrow \mathrm{trigger} + \mathrm{jet} + X$
- Separate into EA bins
- Measure jet per trigger spectra (S_{EA})
- Compare spectra in high to low EA ($S_{\mathrm{EA-high}}/S_{\mathrm{EA-low}}$)



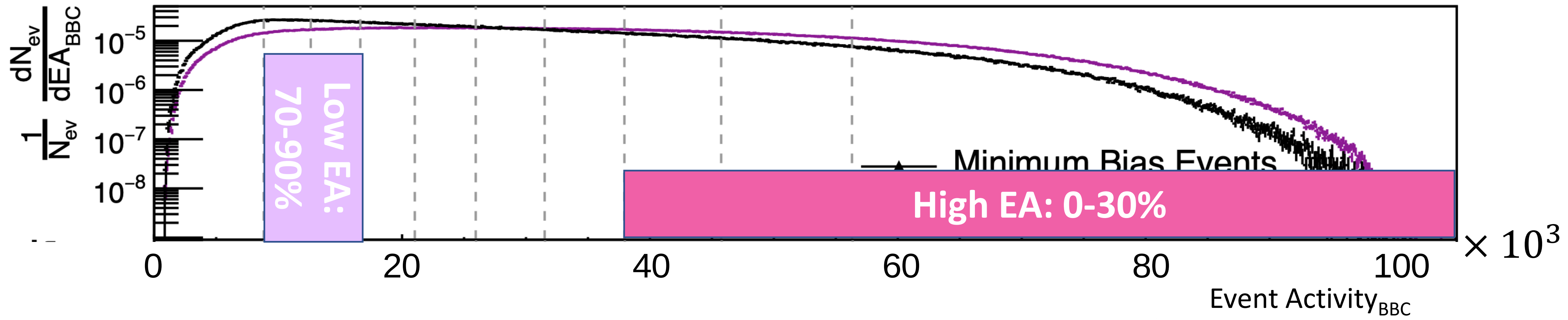
c. Per-jet (shape)
- Compare shapes in different EA bins

Example: jet mass distribution



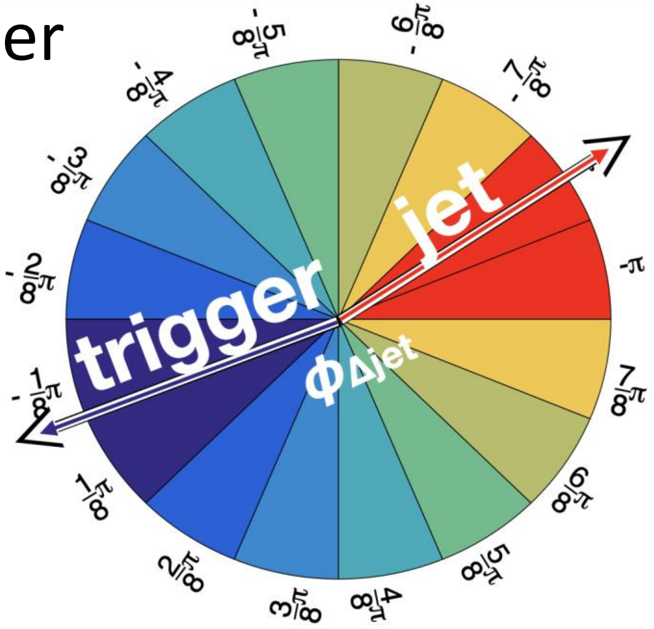
study by Isaac Mooney

Data: BBC Event Activity Selection and Jet ϕ binning

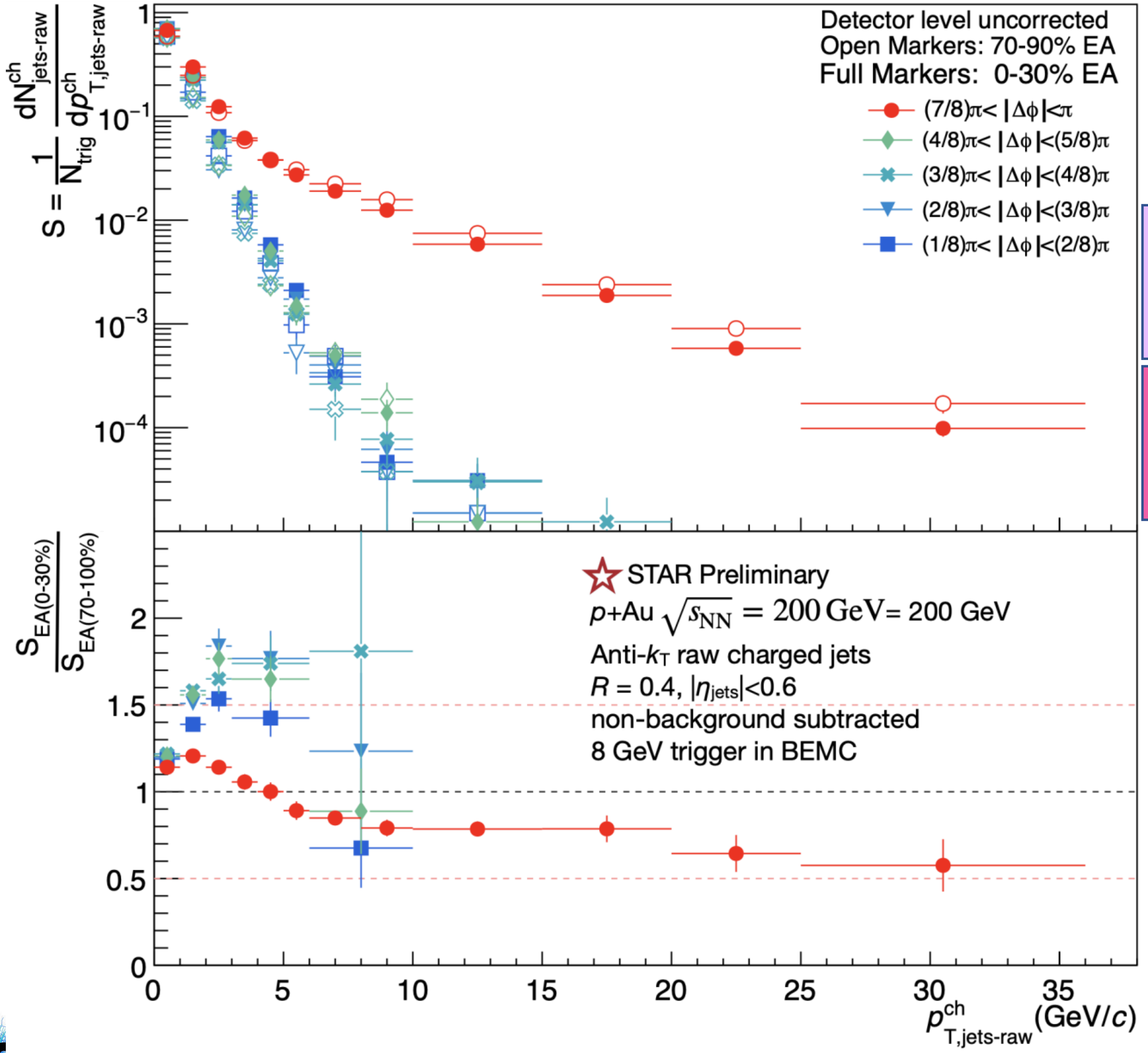


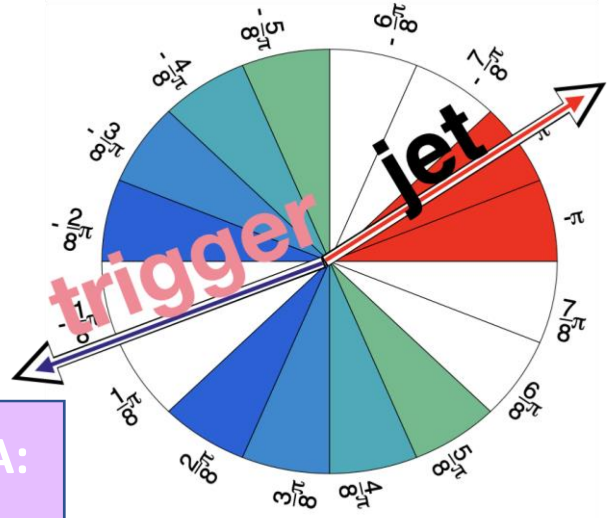
- Jets:
  - anti-kT
  - R=0.4
  - |η|<0.6

- Binned in Δϕ in π/8 slices from the trigger
- Jet spectra (S) presented in this talk are raw uncorrected, detector level
- Tracking efficiency is EA-independent & negligible underlying event
  - $S_{0\text{-}30\%EA}/S_{70\text{-}90\%EA}$ expected to be insensitive to corrections



Suppressed recoil & negligible transverse spectra





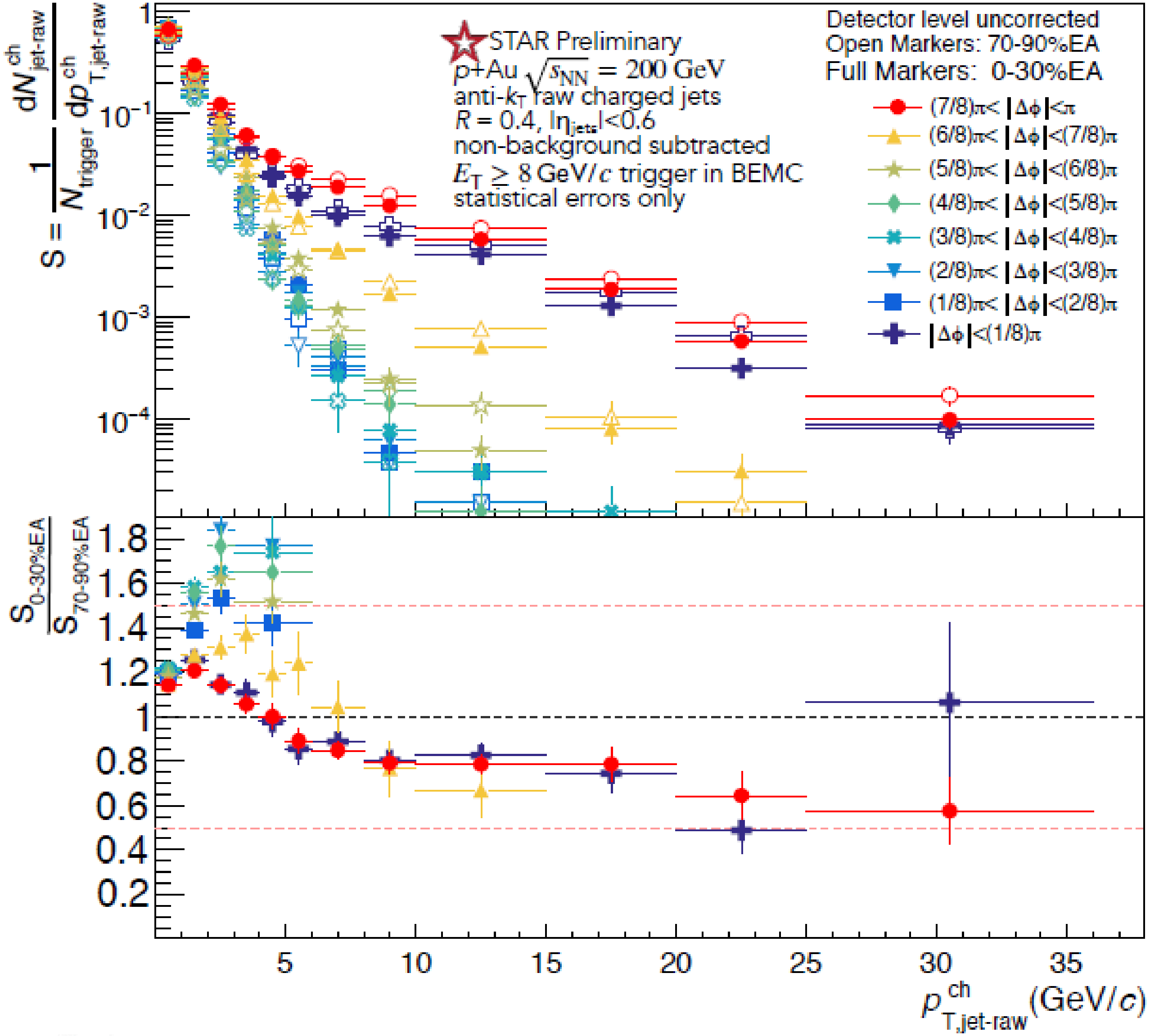
Open Markers: Low EA: 70-90%

Full Markers: High EA: 0-30%

- At "jet-like" p_T (>~8 GeV/c) transverse $\Delta\phi$ (background) negligible compared to recoil spectra

  ⇒ background correction negligible for $S_{0\text{-}30\%EA}$ & $S_{70\text{-}90\%EA}$

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



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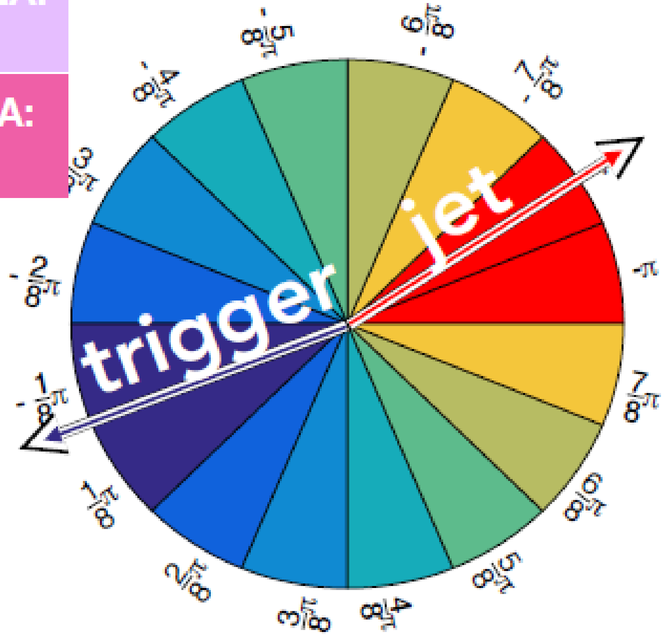
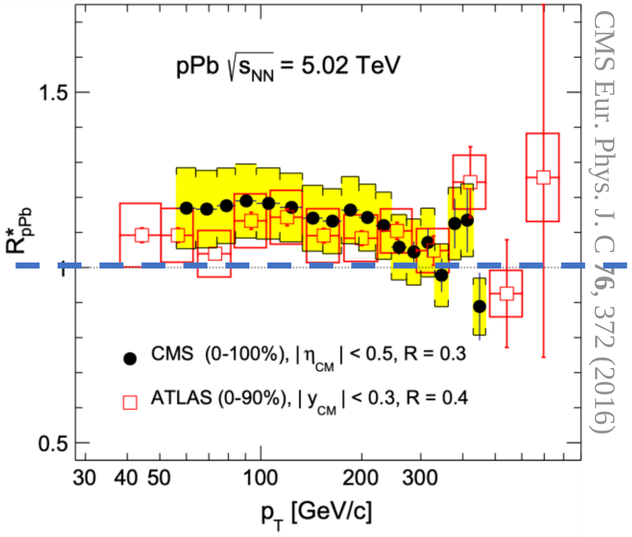


- Both near and recoil jets suppressed in high EA relative to low EA
- n.b.: These are charged jet spectra; the near-side jets have a neutral energy fraction (NEF) bias because near side must also always contain the neutral trigger
  - This NEF bias is not present in the recoil jets
  - This NEF bias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

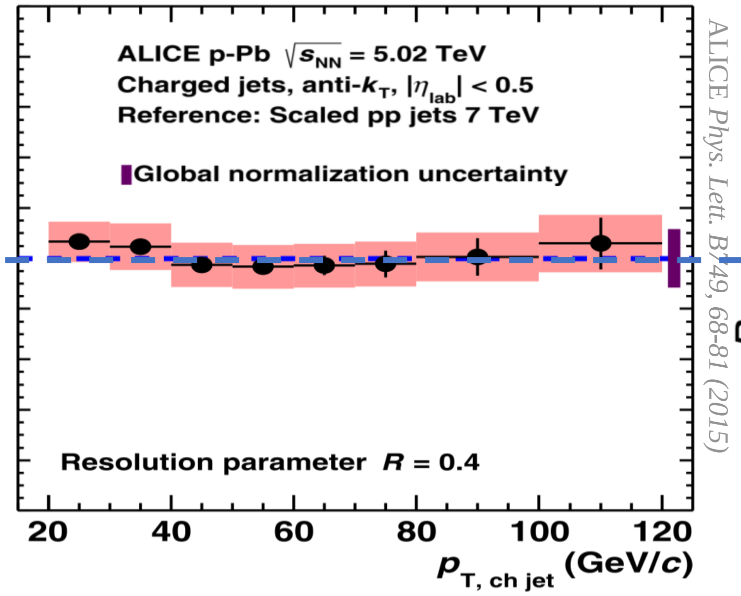
Geometry: Jets/N_{coll} over all *b* are as expected

2015 & 2016: $R_{p/d}$+A consistent with unity

ATLAS & CMS



ALICE



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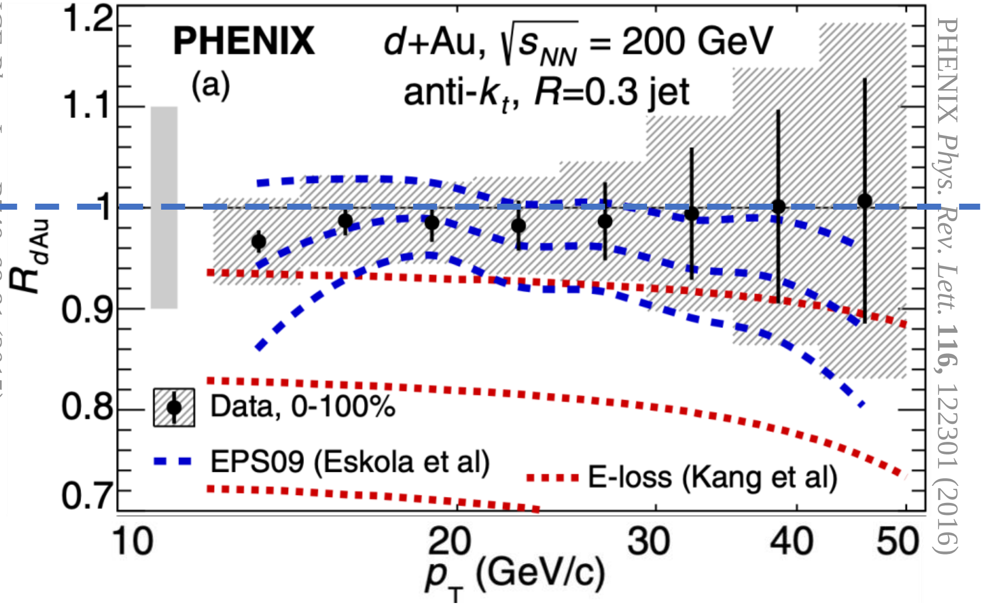
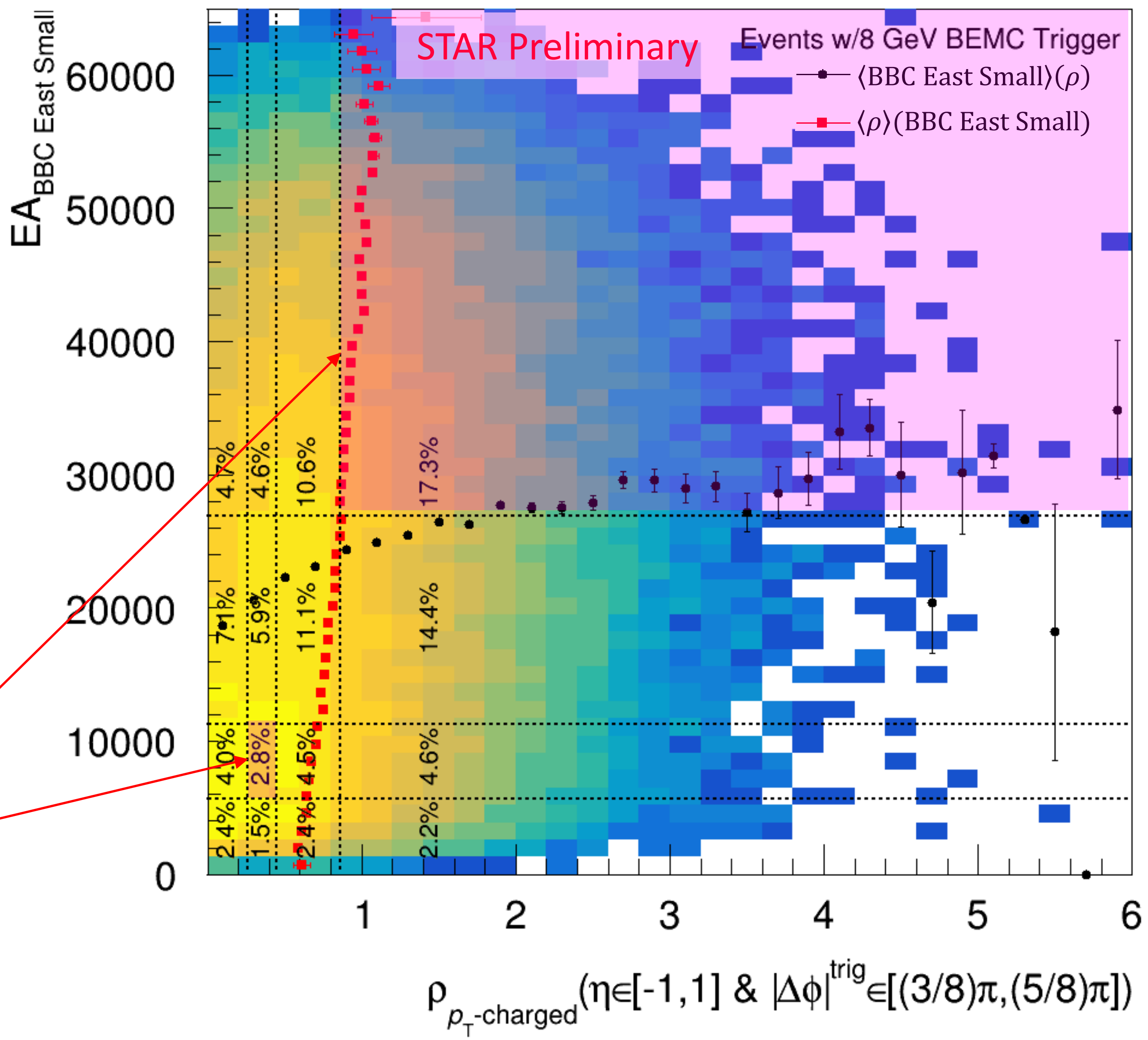


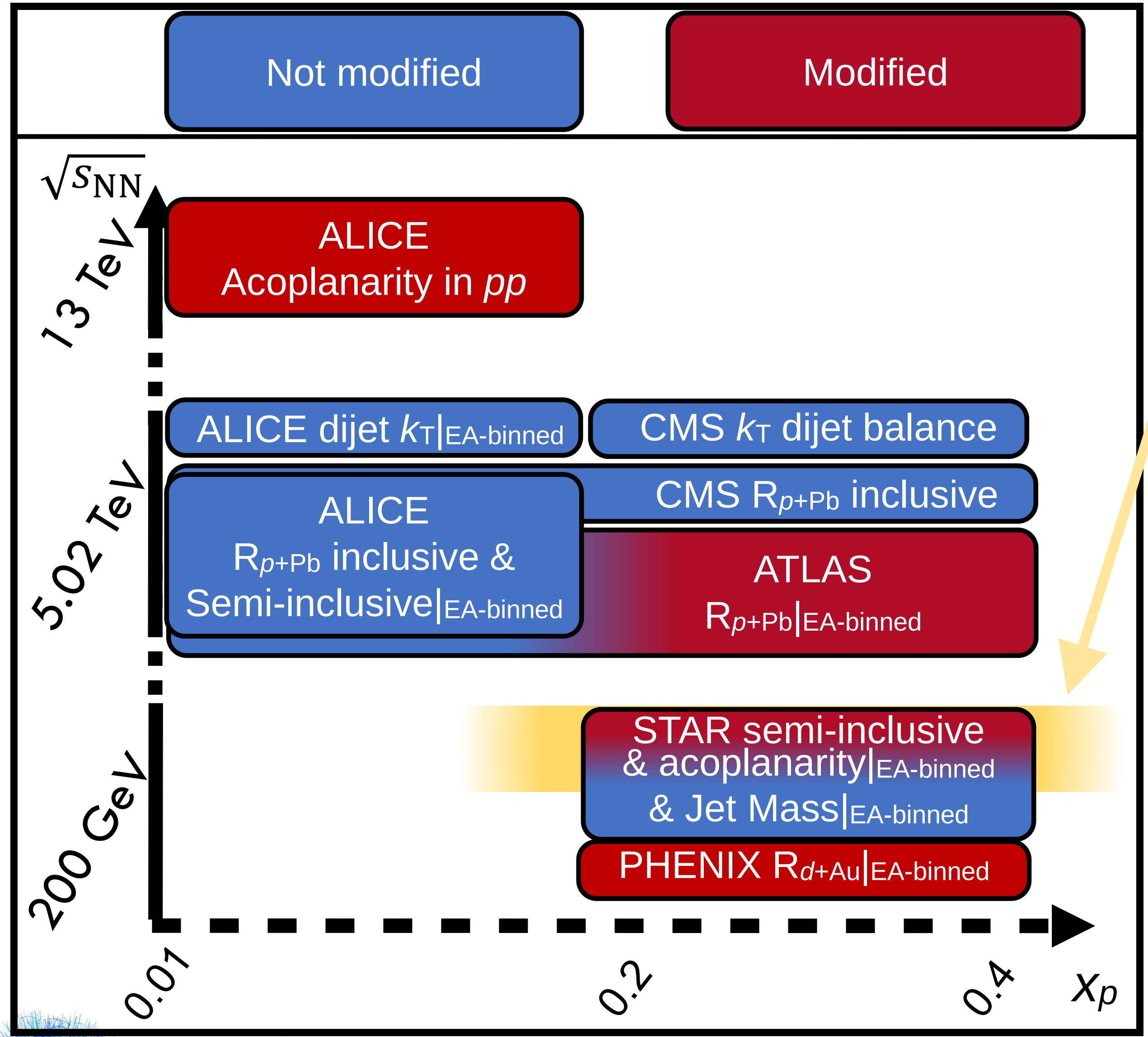
- The average number of jets per N_{coll} (integrated over all *b*) is identical for *p*/*d*+A collisions as in *pp* collisions (values of R≈1)

STAR data: EA

- EA_{BBC} & EA_{TPC} positively correlated
- Can compare **high-EA** events to **low-EA** events using:
  - EA_{BBC}
  - EA_{TPC}
  - Both: $EA_{BBC} \cap EA_{TPC}$

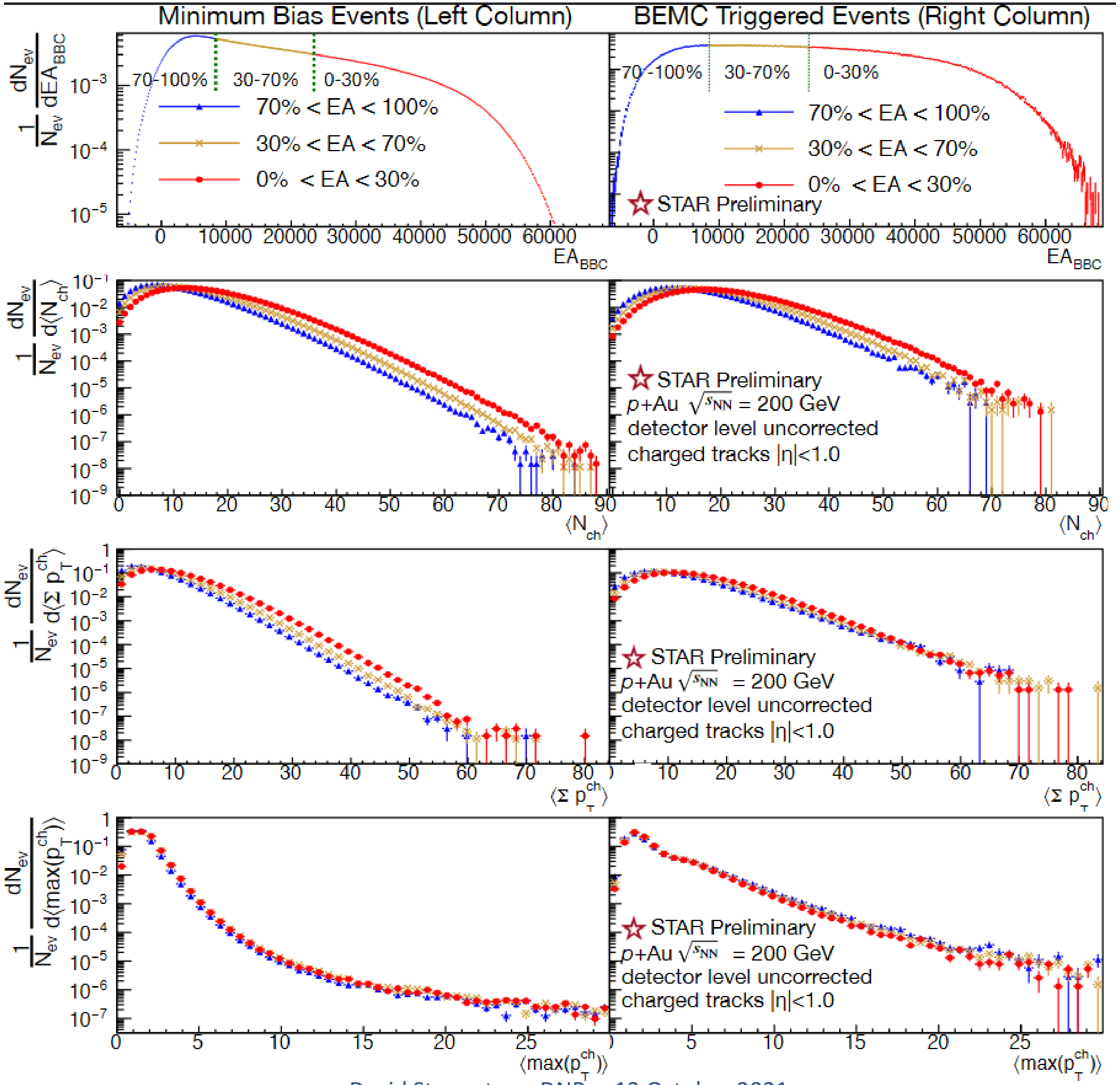


Where these fit in small system measurements



Semi-inclusive small system jet measurements:

- First at high x_p
- First at high RHIC energies
- Jet spectra per trigger suppression results at least partially from correlation:
  - Higher Q^2 scattering:
    - $\Rightarrow$ Higher p_T jets
    - $\Rightarrow$ Lower activity everywhere outside of dijet (both in η and ϕ)
- No jet mass modification
- Predict dijet momentum balance and other jet substructure observables EA independent


Minimum Bias Events (Left Column)
BEMC Triggered Events (Right Column)
70-100%
30-70%
0-30%
70% < EA < 100%
30% < EA < 70%
0% < EA < 30%
STAR Preliminary
p+Au √sNN = 200 GeV
detector level uncorrected
charged tracks |η|<1.0
EA_BBC
⟨N_ch⟩
⟨Σ p_T^ch⟩
⟨max(p_T^ch)⟩

STAR