Probing hadronization with the charge correlator ratio in p+p and Ru+Ru/Zr+Zr collisions at STAR

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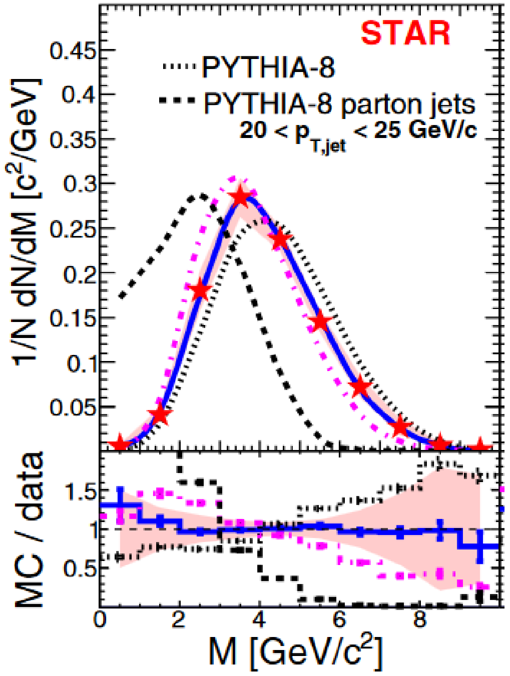
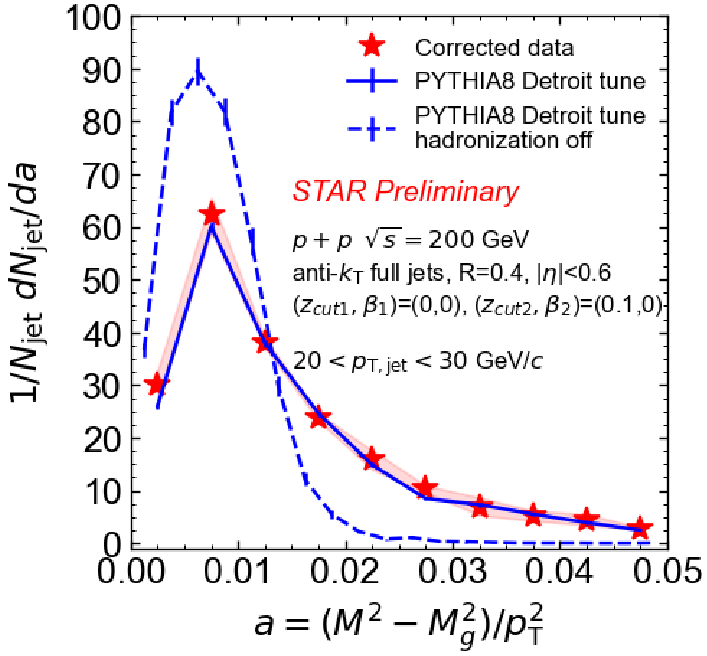
Motivation: Understand jet substructures

- Hadronization is important for many jet substructure measurements

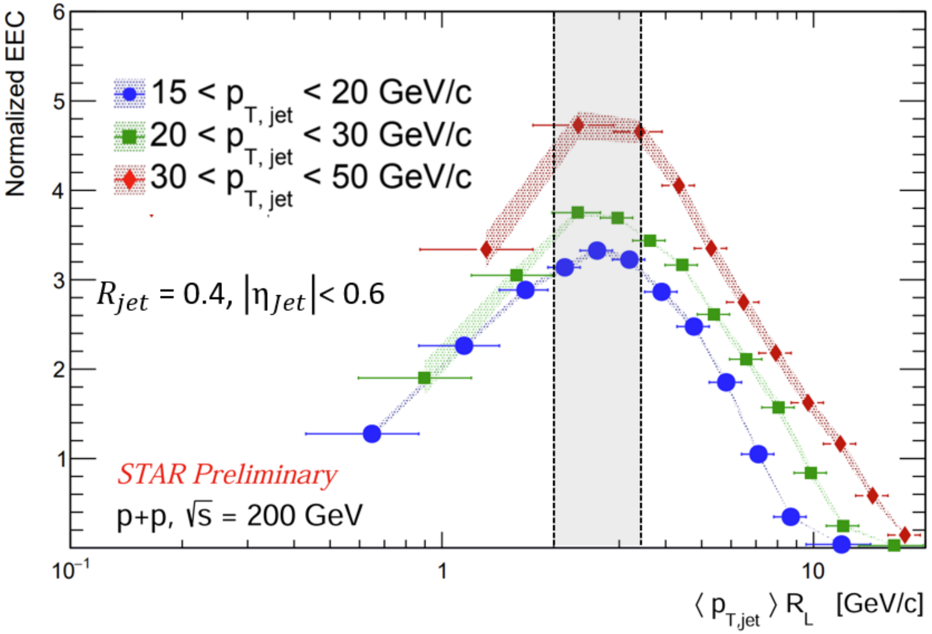
Jet mass:
STAR. PRD 104, 052007(2021)



CollinearDrop jet mass:
STAR. arXiv:2307.07718
See theory talk by Yang-Ting Chien @ 3:20pm on 9/23



Energy correlators:
See STAR talk by Andrew Tamis @ 10:50am on 9/24



- Distributions shifted due to hadronization
- Turnover location related to confinement scale

Motivation: Study hadronization

$$r_c = \frac{\text{same} - \text{opposite}}{\text{same} + \text{opposite}}$$

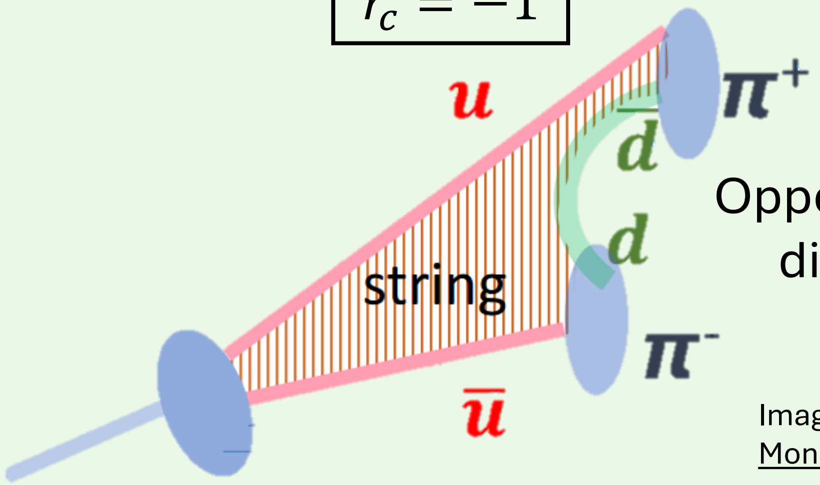
- Definition of the **charge correlator ratio r_c**: Chien et al. PRD 105 051502 (2022)

$$r_c(X) = \frac{\mathrm{d}\sigma_{h_1 h_2}/\mathrm{d}X - \mathrm{d}\sigma_{h_1 \bar{h}_2}/\mathrm{d}X}{\mathrm{d}\sigma_{h_1 h_2}/\mathrm{d}X + \mathrm{d}\sigma_{h_1 \bar{h}_2}/\mathrm{d}X}$$

$h_1 h_2$: same charge leading di-hadrons,
$h_1 \bar{h}_2$: opposite charge leading di-hadrons

- Lund **string fragmentation**: expect charge correlation between leading di-hadrons in jets

$$\boxed{r_c = -1}$$

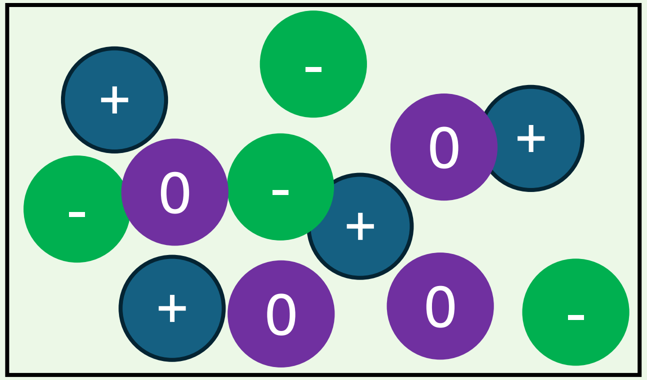


Opposite charge di-hadrons

Image credit: Mondal DIS 2022

- **Infinite bath** with no net charge: expect no charge correlation among pairs

$$\boxed{r_c = 0}$$



Motivation: Study hadronization

$$r_c = \frac{\text{same} - \text{opposite}}{\text{same} + \text{opposite}}$$

STAR

- Definition of the **charge correlator ratio r_c**: Chien et al. PRD 105 051502 (2022)

$$r_c(X) = \frac{\mathrm{d}\sigma_{h_1h_2}/\mathrm{d}X - \mathrm{d}\sigma_{h_1\bar{h}_2}/\mathrm{d}X}{\mathrm{d}\sigma_{h_1h_2}/\mathrm{d}X + \mathrm{d}\sigma_{h_1\bar{h}_2}/\mathrm{d}X}$$

h_1h_2: same charge leading di-hadrons,
$h_1\bar{h}_2$: opposite charge leading di-hadrons

- In vacuum, probe for contribution of **string-like fragmentation**

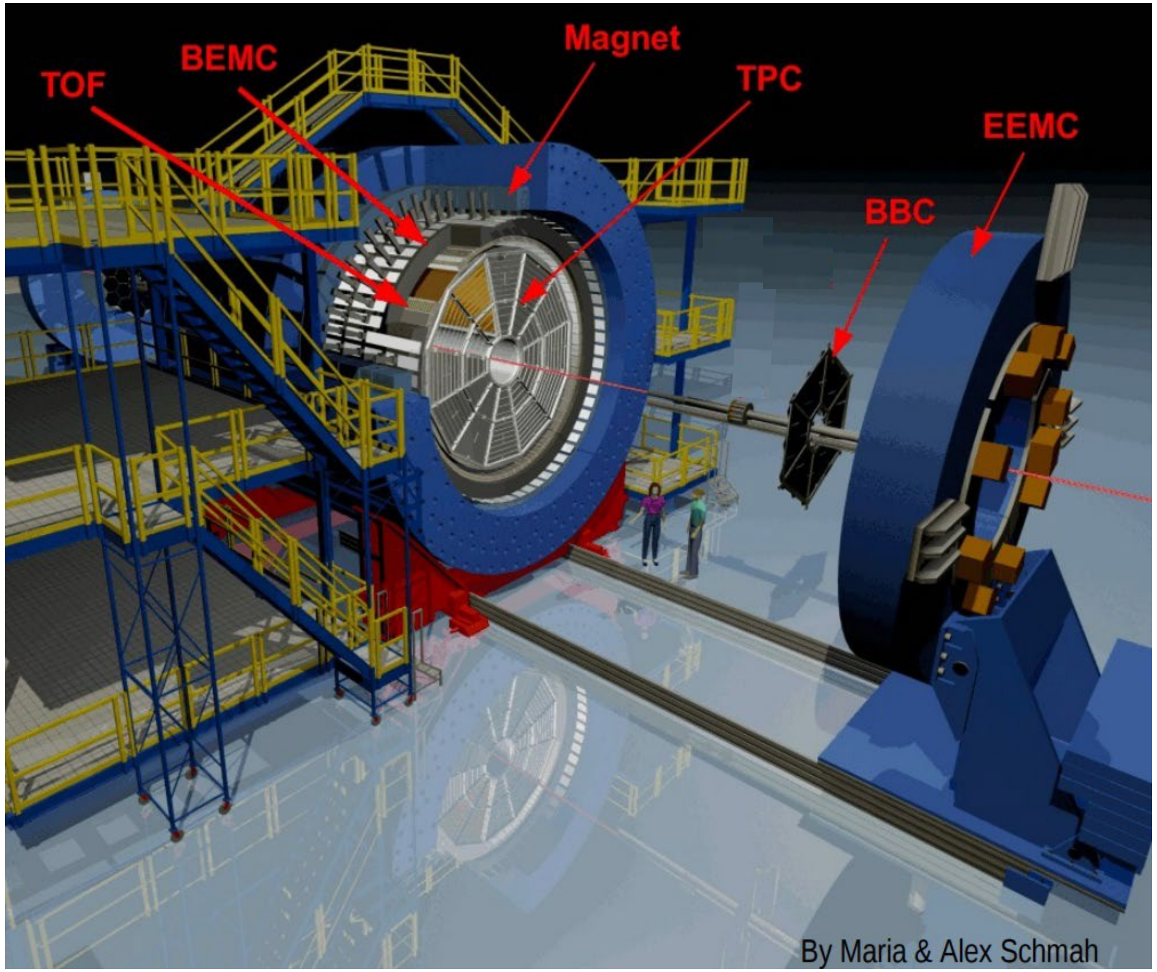
  → measured in e+p collisions at HERA (Mondal, DIS 2022) and in $\boxed{\text{p+p collisions at STAR}}$

- In heavy ions, probe for potential **modification to hadronization** due to the presence of the QGP Chien et al., HP 2023

  → measurement $\boxed{\text{ongoing in Ru+Ru and Zr+Zr collisions at STAR}}$

Focus of this talk today

The STAR detector



Important subdetectors for **200 GeV p+p** collisions data-taking during 2012 RHIC run

- **TPC** (Time Projection Chamber)
  - For **charged** particle track reconstruction
  - $|\eta| < 1$, full azimuthal coverage

- **BEMC** (Barrel ElectroMagnetic Calorimeter)
  - For **neutral** energy measurement and triggering
  - $|\eta| < 1$, full azimuthal coverage

How to measure r_c

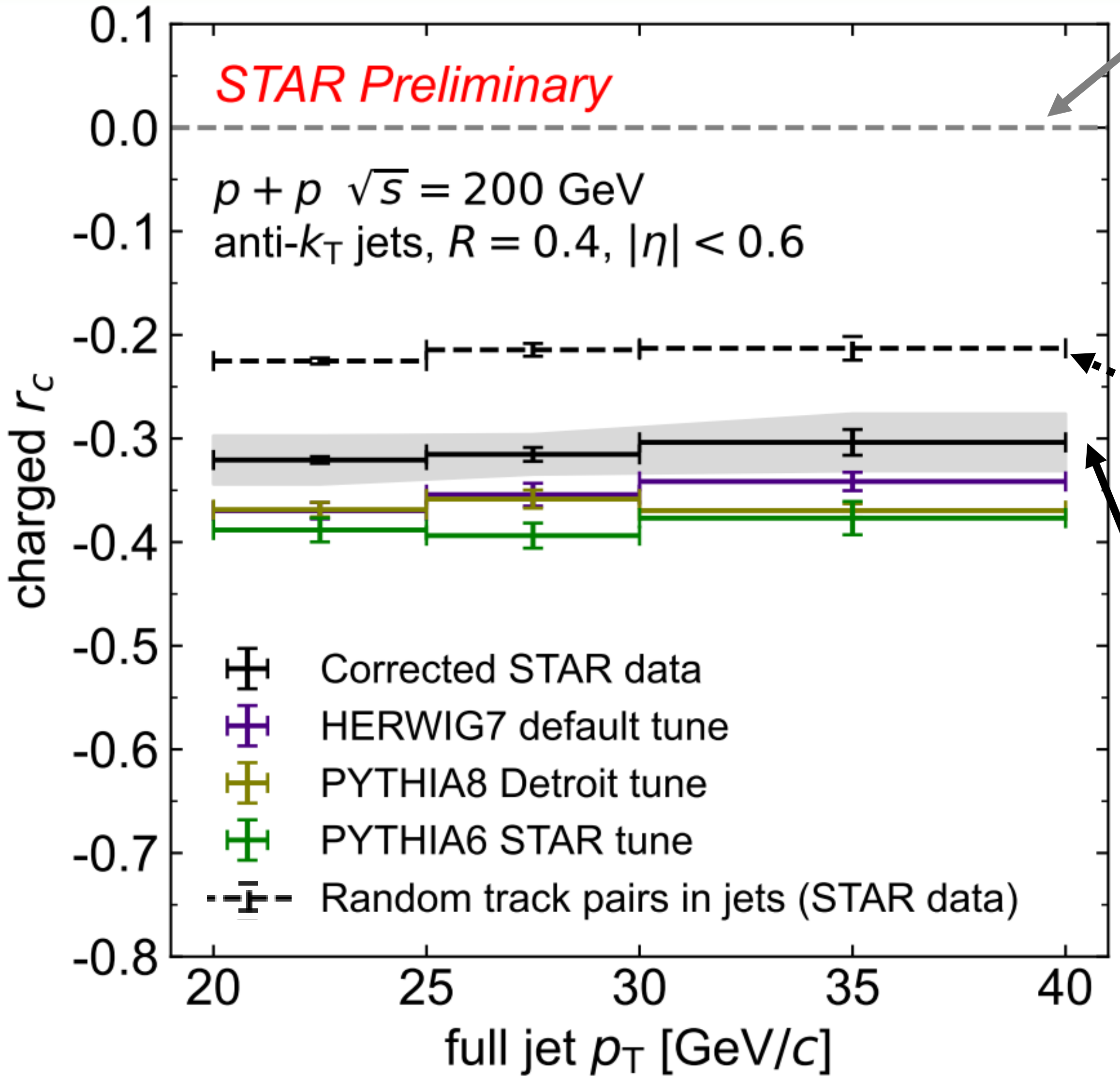
- Find jets → anti-k_T full jets with $R = 0.4$ from 200 GeV p+p
- Count the number of **leading** and **subleading** ~~hadron~~ **track** pairs that have the same (opposite) electric charge (see backup for details) → Slightly modified definition from Chien et al. but comparison with MC models is still meaningful!
- Correct for detector effects (see backup for details)

$$r_c(X) = \frac{\mathrm{d}\sigma_{h_1 h_2}/\mathrm{d}X - \mathrm{d}\sigma_{h_1 \bar{h}_2}/\mathrm{d}X}{\mathrm{d}\sigma_{h_1 h_2}/\mathrm{d}X + \mathrm{d}\sigma_{h_1 \bar{h}_2}/\mathrm{d}X}$$

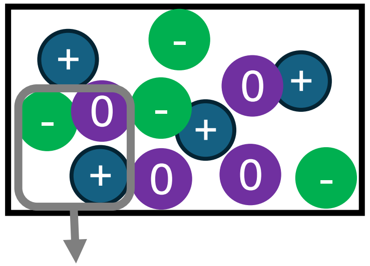
$h_1 h_2$: same charge leading **track** pairs,
$h_1 \bar{h}_2$: opposite charge leading **track** pairs
X: any jet observable, e.g., jet p_T

Result in p+p

$$r_c = \frac{\text{same} - \text{opposite}}{\text{same} + \text{opposite}}$$



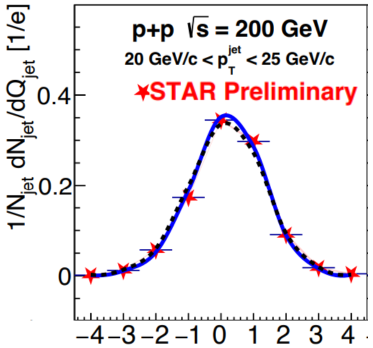
Random pairs in an uncorrelated (infinite) bath with no net charge: $r_c = 0$



Data show a preference of opposite sign pairs over same sign pairs, in:

- pair of **random track pairs in jet**;

  influenced by jet charge ~ 0 on average: $r_c \approx -0.2$



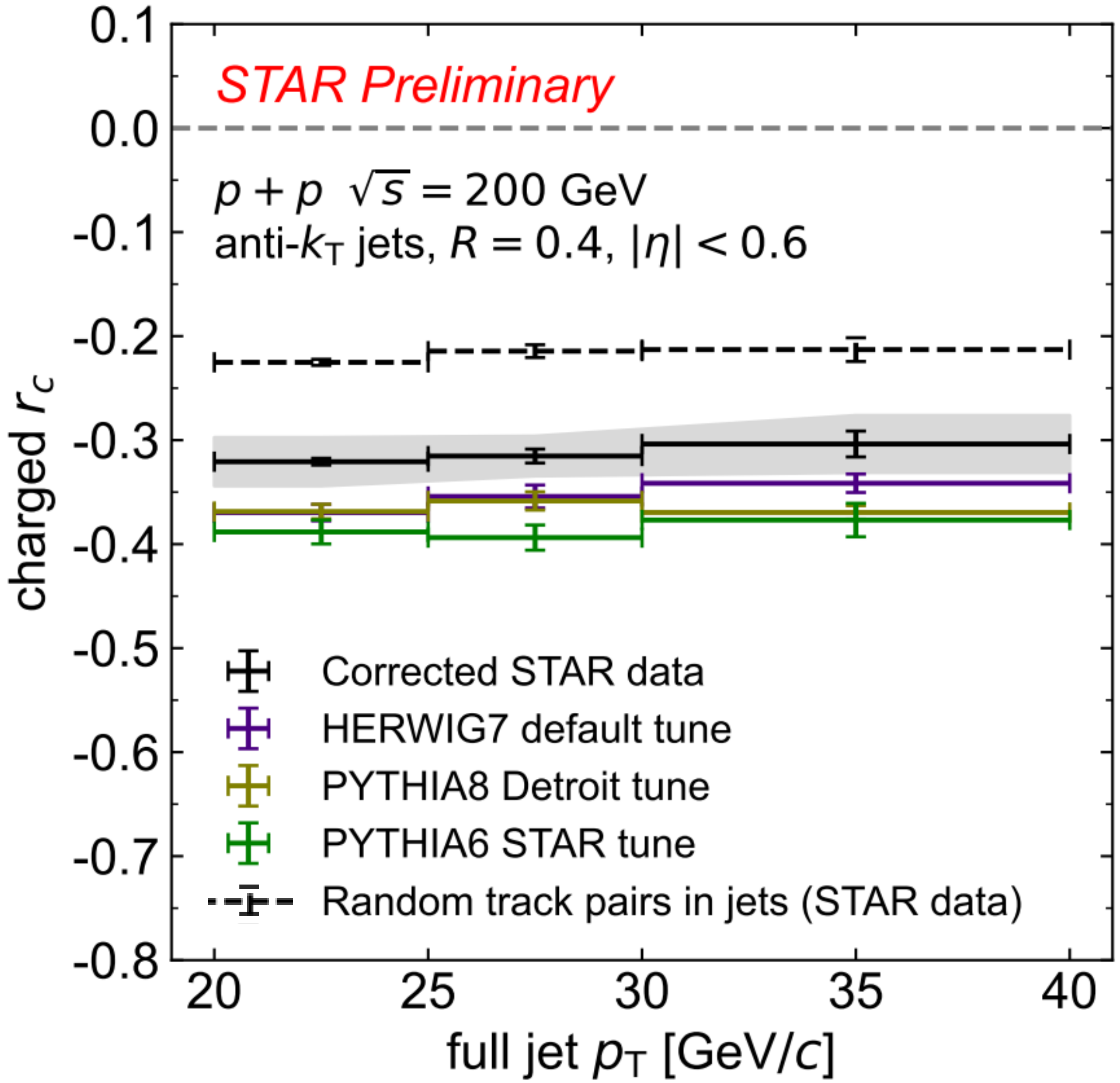
- **leading track pairs in jet**.

  additional correlation from fragmentation: $r_c \approx -0.3$

PYTHIA6 Perugia + STAR tune: Skands. PRD 82, 074018 (2010)
J. K. Adkins, PhD thesis (Kentucky U., 2015)
PYTHIA8 Detroit tune: Aguilar et al. PRD 105, 016011(2022)
HERWIG7: Bellm, et al. EPJC 76, 196 (2016)

Result in p+p

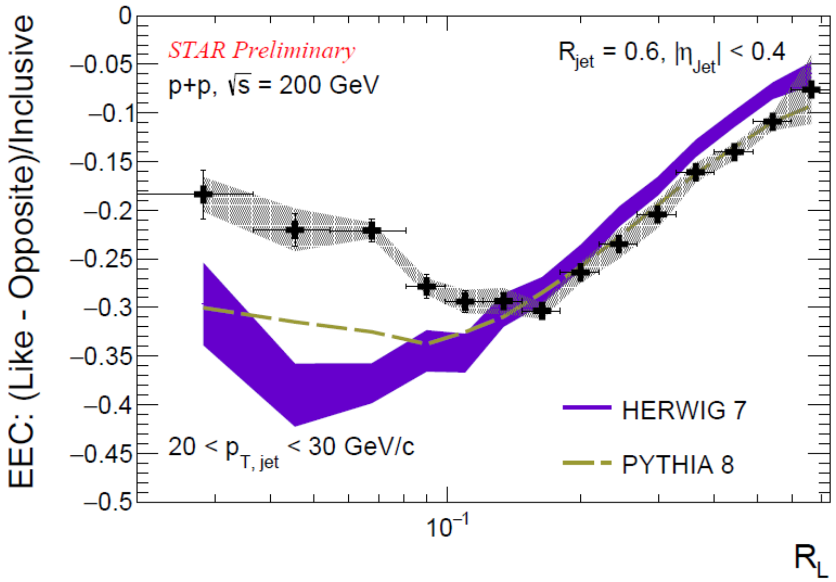
$$r_c = \frac{\text{same} - \text{opposite}}{\text{same} + \text{opposite}}$$



No dependence on jet p_T in 20-40 GeV/c

Models based on Lund string fragmentation and cluster hadronization both **underpredict r_c** in data.

- Same trend observed in charged EEC



Talk by Andrew Tamis @ 10:50am, 9/24

What else affects r_c?

$$r_c = \frac{\text{same} - \text{opposite}}{\text{same} + \text{opposite}}$$

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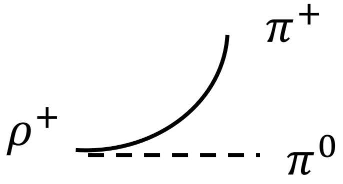
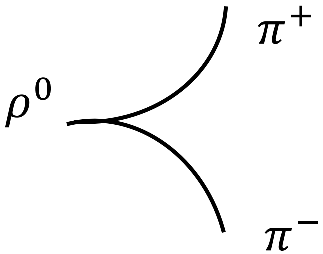
- Where does a π^+ **leading** track in jet come from?

	PYTHIA8	HERWIG7
fragmentation	(Di)quarks: 47%	Cluster: 29%
$\rho(770)^+$	21%	23%
$\rho(770)^0$	16%	17%

- How do resonances affect r_c?



Sign-preserving decays maintain $\boldsymbol{r_c}$ from fragmentation



Neutral resonance decays can bring $\boldsymbol{r_c}$ down

- PYTHIA vs HERWIG
    - Similar $\boldsymbol{r_c}$ predictions
    - Different contributions from fragmentation vs decays. **Effect of different hadronization mechanism?**

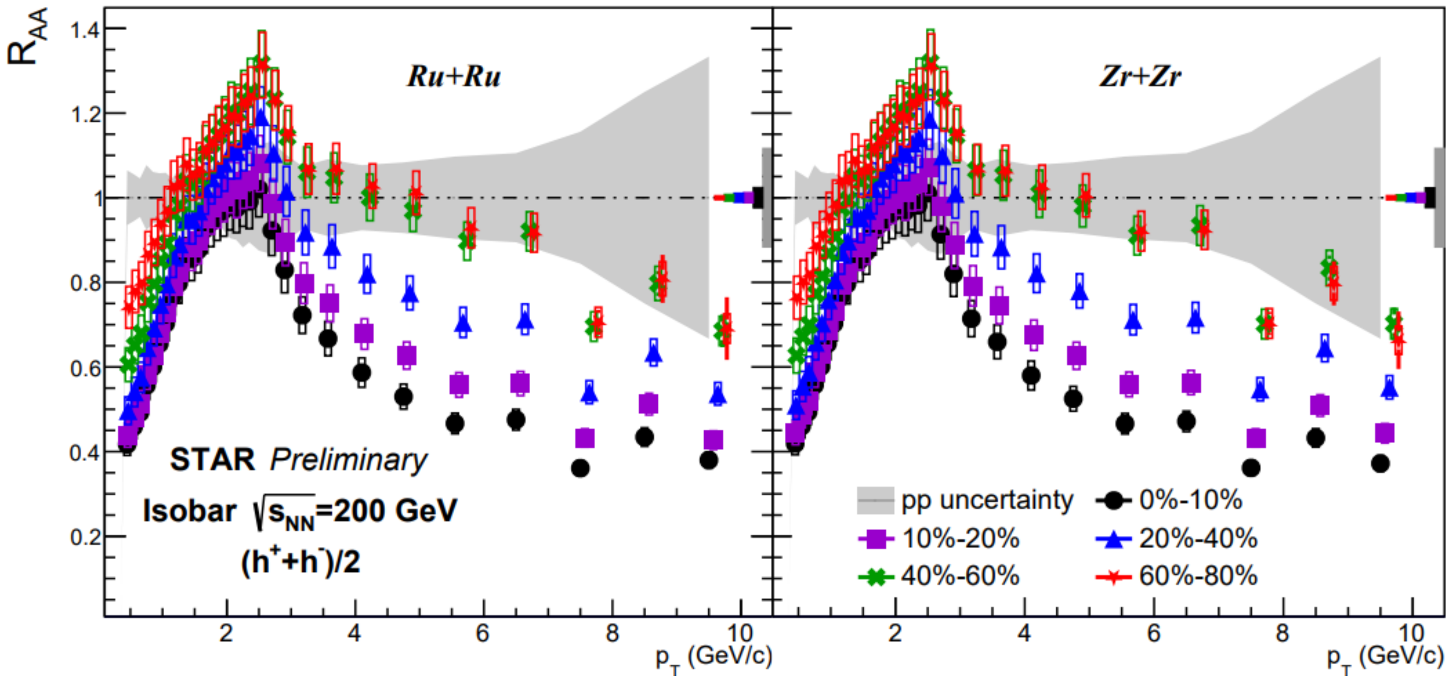
Moving to heavy ions

Isobar collisions: Ru+Ru and Zr+Zr, A = 96, $\sqrt{s_{NN}} = 200$ GeV

In central events, observed **jet quenching**

→ next step: study modification to **jet substructure**

→ **medium-sized** collision systems → background easier to control than in Au+Au



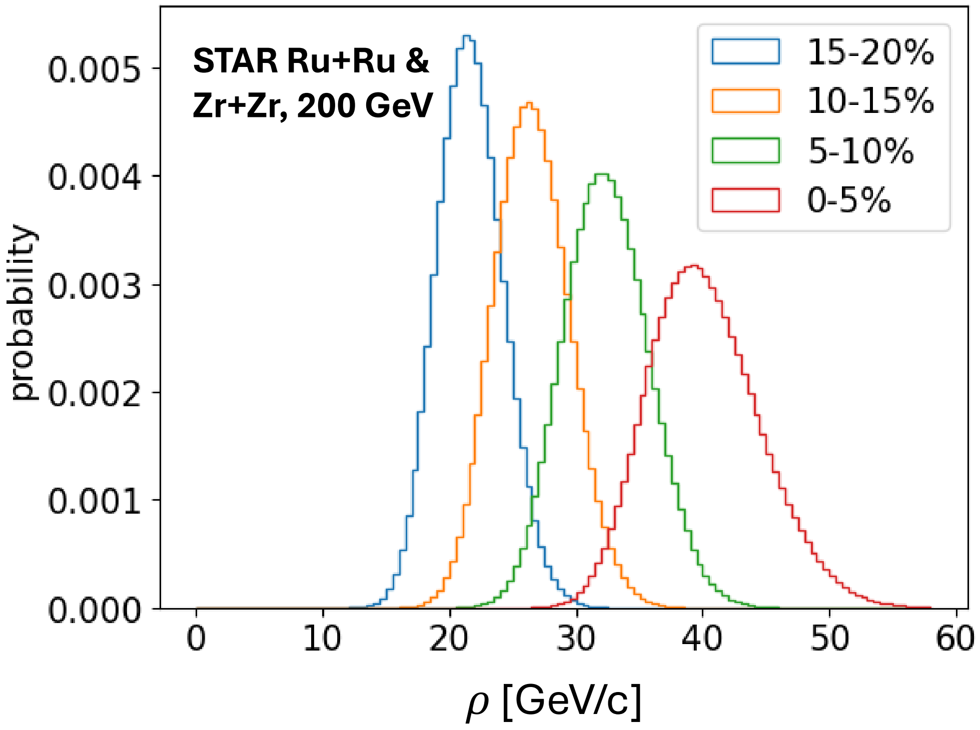
Moving to heavy ions

To remove combinatorial jets, could do leading track p_T selection, but that introduces a **fragmentation bias**

Instead **impose a strict cut** of $p_T - \rho A > 20$ GeV/c

- Background subtracted p_T **over 10σ more than fluctuations** → significantly reduce combinatorial background

  - Width $\sigma(\rho) \sim 4.4$ GeV/c in 0-5% → $\sigma(\rho A) \lesssim 2$ GeV/c

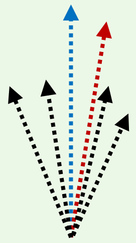


How to measure r_c in heavy ions:

background subtraction

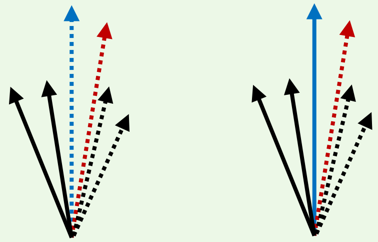
r_c(raw)
= **Prob(comb)** $\times$ r_c**(comb)**
+ **Prob(BB)** $\times$ r_c**(BB)**
+ **Prob(SB)** $\times$ r_c**(SB)**
+ **Prob(SS)** $\times$ r_c**(SS)**

Types of background contribution to r_c



combinatorial jet **(comb)**

Legend:
background track
signal track
leading track
subleading track



jets from fragmentation,

but leading track from BKG, and subleading from BKG **(BB)**

but one of leading and subleading from BKG, the other a signal particle **(SB)**

Embed PYTHIA jets into isobar events. There are caveats to this study!

- enhanced S/B
- no effect from jet quenching
- no background-jet correlation from flow

→ proof of principle where **Prob factors are known** and r_c for each term **can be easily modeled**

How to measure r_c in heavy ions:

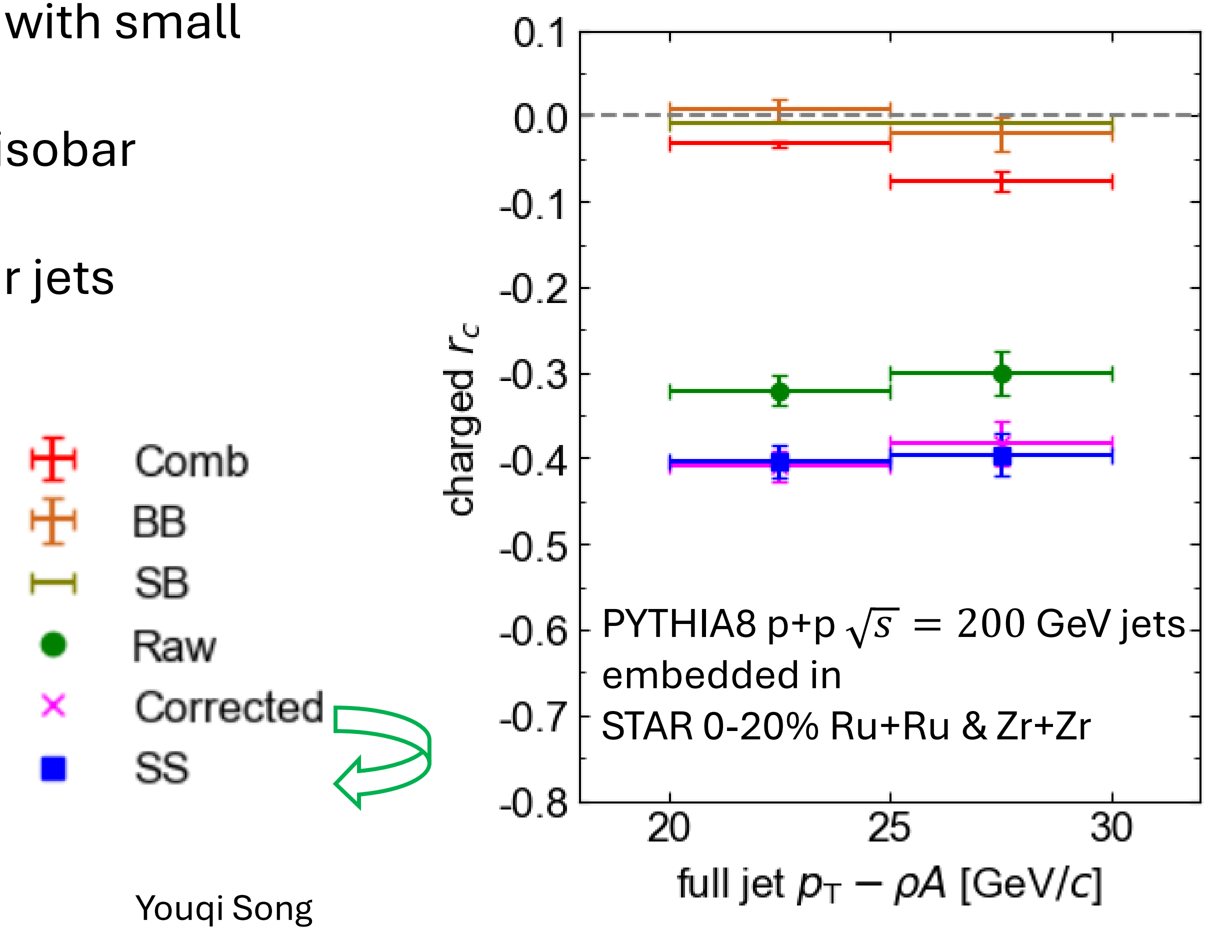
background subtraction experiment

r_c(raw)
= **Prob(comb)** $\times$ r_c**(comb)**
+ **Prob(BB)** $\times$ r_c**(BB)**
+ **Prob(SB)** $\times$ r_c**(SB)**
+ **Prob(SS)** $\times$ r_c**(SS)**

- PYTHIA jets + 0-20% isobar event → **embedded jets**
- Background subtraction: $p_T - \rho A > 20$ GeV/c

- Roughly, r_c**(comb)** = r_c**(BB)** = r_c**(SB)** **~ 0**, with small deviations from:
  - **comb** = combinatorial + real jets in isobar events
  - **BB** = 2 background particles + isobar jets overlapping with PYTHIA jets

- Remove all background contributions to r_c and compare result
  - Good agreement between **corrected** and **embedded matched (SS)**

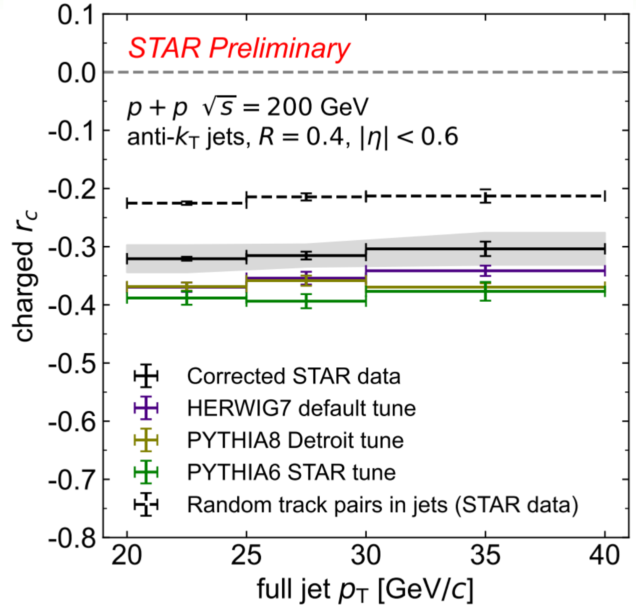


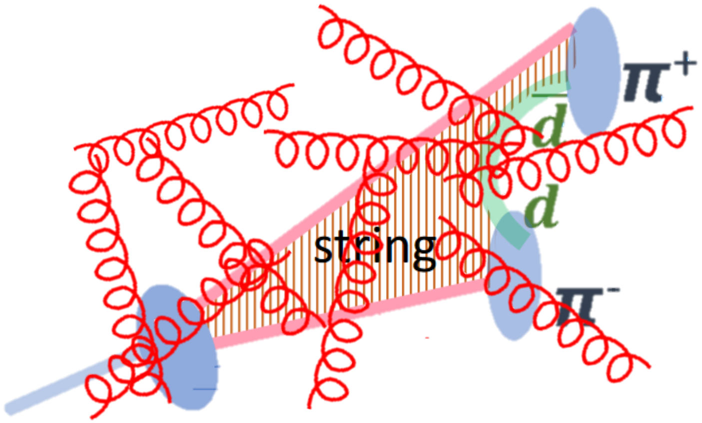
Conclusions & outlook

- First measurement of r_c in hadron collisions, looking for evidence of **string-like fragmentation**
  - In **p+p** 200 GeV at STAR, data show a **weaker correlation** between leading and subleading particles in jet than models

- How to better **disentangle models**?
  - r_c as a function of $(k_\mathrm{T}, t_f, z\ldots)$, for identified particles? →ongoing effort at STAR
  - r_c at the future EIC! Chien et al. PRD 105 051502 (2022)

- Ongoing measurement in heavy ion collisions, probing for **potential modification of hadronization** due to QGP
  - Background subtraction experimented with **isobar** embedding at STAR, good **closure** shown
  - Stay tuned for results!





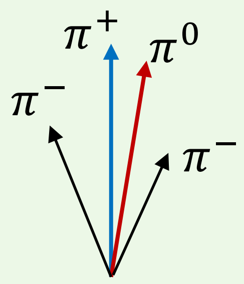
Backup

How to measure r_c: Revisiting the definition

- Find jets → anti-k_T full jets with $R = 0.4$ from 200 GeV pp collisions
- For each jet, examine the **leading** and **subleading** constituent pairs
- Count the number of constituent pairs that have the same (opposite) electric charge

E.g. PYTHIA jet → GEANT jet

PYTHIA jet	GEANT jet
π^+ 6 GeV	track(+) 6 GeV
π^0 4 GeV	track(-) 3 GeV
π^- 3 GeV	tower 2 GeV
π^- 1 GeV	tower 2 GeV
	track(-) 1 GeV



- What if the **leading constituent is neutral**?
  - Definition by Chien et al. PRD 105 051502 (2022) :
    - Don't consider these jets
  - But we may not easily identify them experimentally

$$r_c(X) = \frac{\mathrm{d}\sigma_{h_1 h_2}/\mathrm{d}X - \mathrm{d}\sigma_{h_1 \bar{h}_2}/\mathrm{d}X}{\mathrm{d}\sigma_{h_1 h_2}/\mathrm{d}X + \mathrm{d}\sigma_{h_1 \bar{h}_2}/\mathrm{d}X}$$

where
$h_1 h_2$: same charge leading di-hadrons,
$h_1 \bar{h}_2$: opposite charge leading di-hadrons
X: any jet observable, e.g., jet p_T

How to measure r_c: Revisiting the definition

- Find jets
- For each jet, examine the **leading** and **subleading track** pairs
- Count the number of **track** pairs that have the same (opposite) electric charge
- Correct for detector effects

E.g. PYTHIA jet → GEANT jet

PYTHIA jet	GEANT jet
π^+ 6 GeV	**track(+) 6 GeV**
π^0 4 GeV	**track(-) 3 GeV**
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π^- 1 GeV	tower 2 GeV
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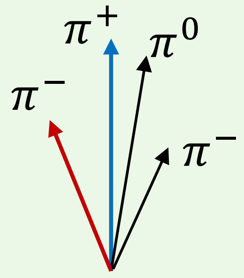


- Slightly modified the definition from <u>Chien et al.</u> but comparison with MC models is still meaningful!

$$r_c(X) = \frac{\mathrm{d}\sigma_{h_1h_2}/\mathrm{d}X - \mathrm{d}\sigma_{h_1\bar{h}_2}/\mathrm{d}X}{\mathrm{d}\sigma_{h_1h_2}/\mathrm{d}X + \mathrm{d}\sigma_{h_1\bar{h}_2}/\mathrm{d}X}$$

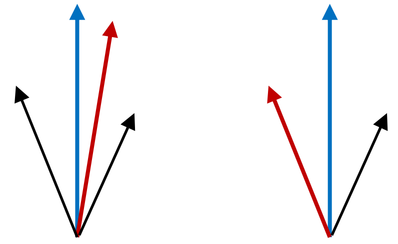
where
h_1h_2: same charge leading di-**tracks**,
$h_1\overline{h}_2$: opposite charge leading di-**tracks**
X: any jet observable, e.g., jet p_T

How to measure r_c: Correcting for detector effects

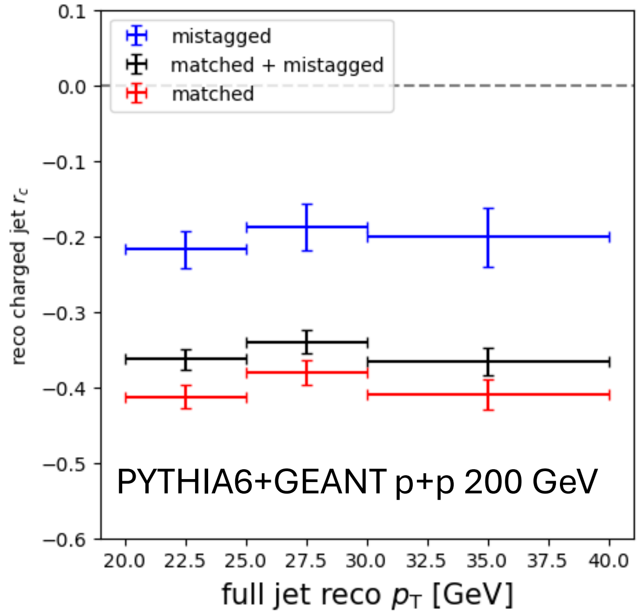
1 **mistagged subtraction** to account for incorrectly identifying tracks that are not leading/subleading

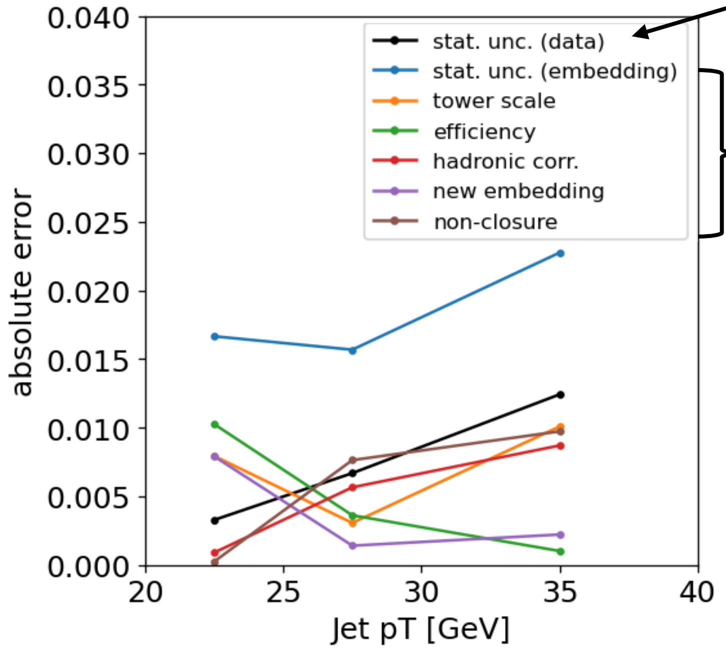
Tracking inefficiency → mistagged correlation

PYTHIA → GEANT



Mistagged example





Statistical uncertainty

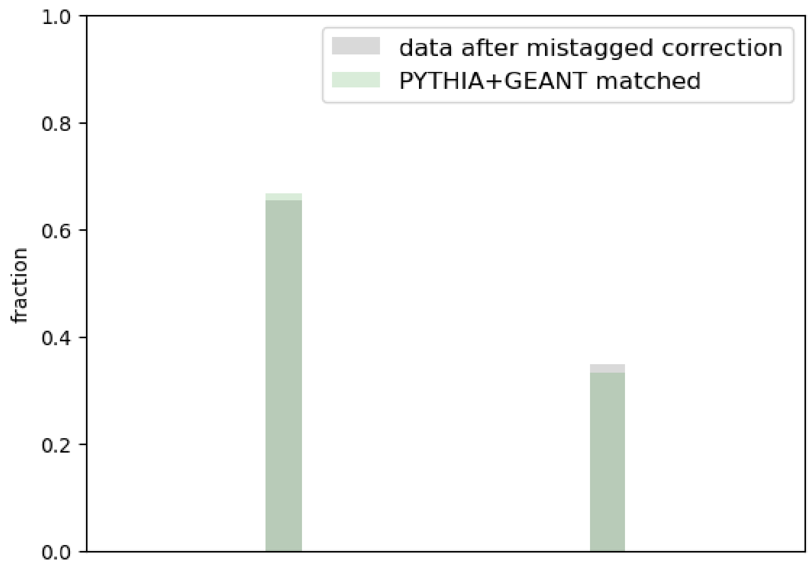
Systematic uncertainty

2 bin-by-bin p_T **correction** to jet energy scale: next slide

How to measure r_c: Correcting for detector effects

2 Bin-by-bin **p_T correction** to jet energy scale

- For each detector-level pT bin, reweight the charge sign distribution in embedding, to match data after mistagged correction.

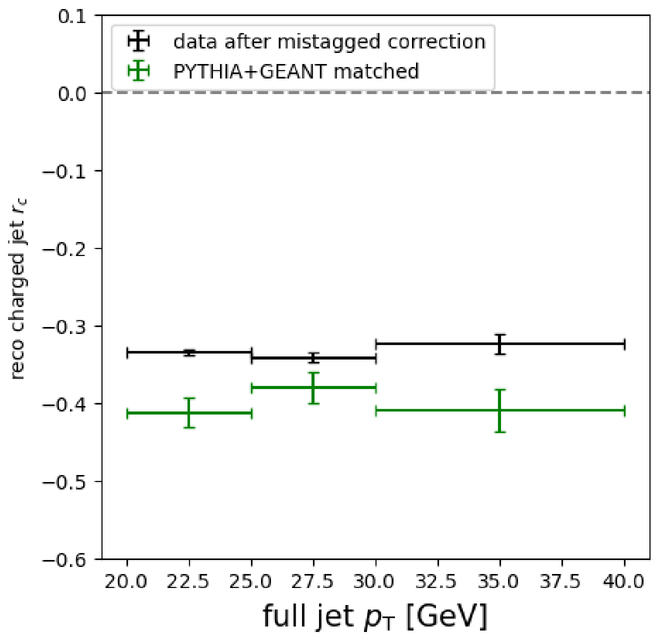


Leading dihadrons are opposite sign

Leading dihadrons are same sign

Example: 20 < pT,reco < 25 GeV

Reweights = [0.94, 1.13]

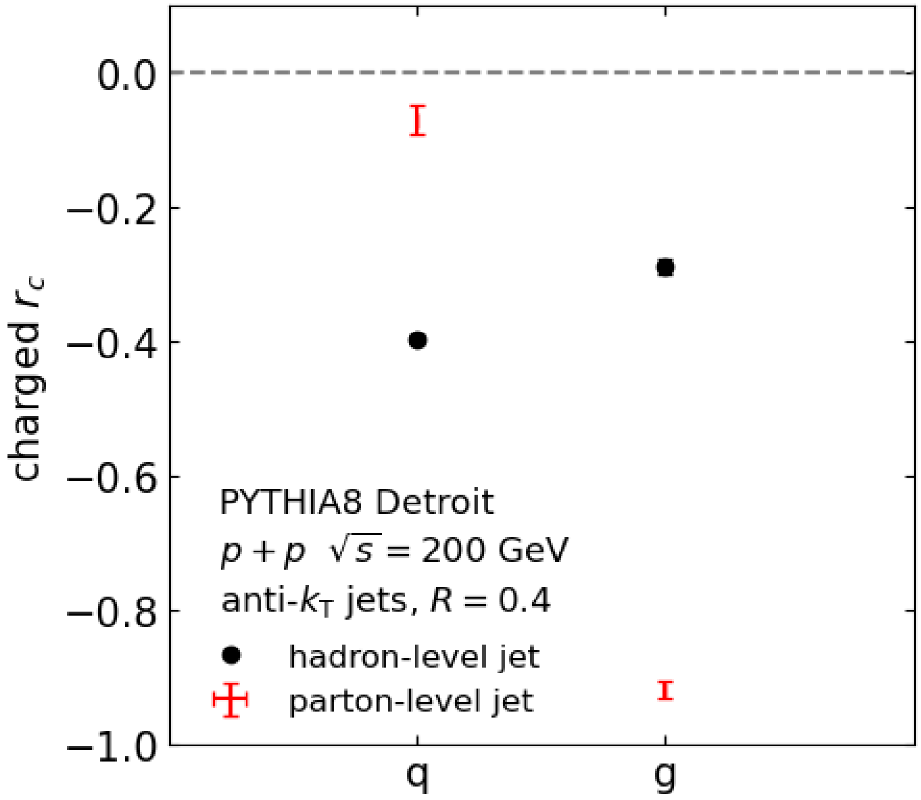


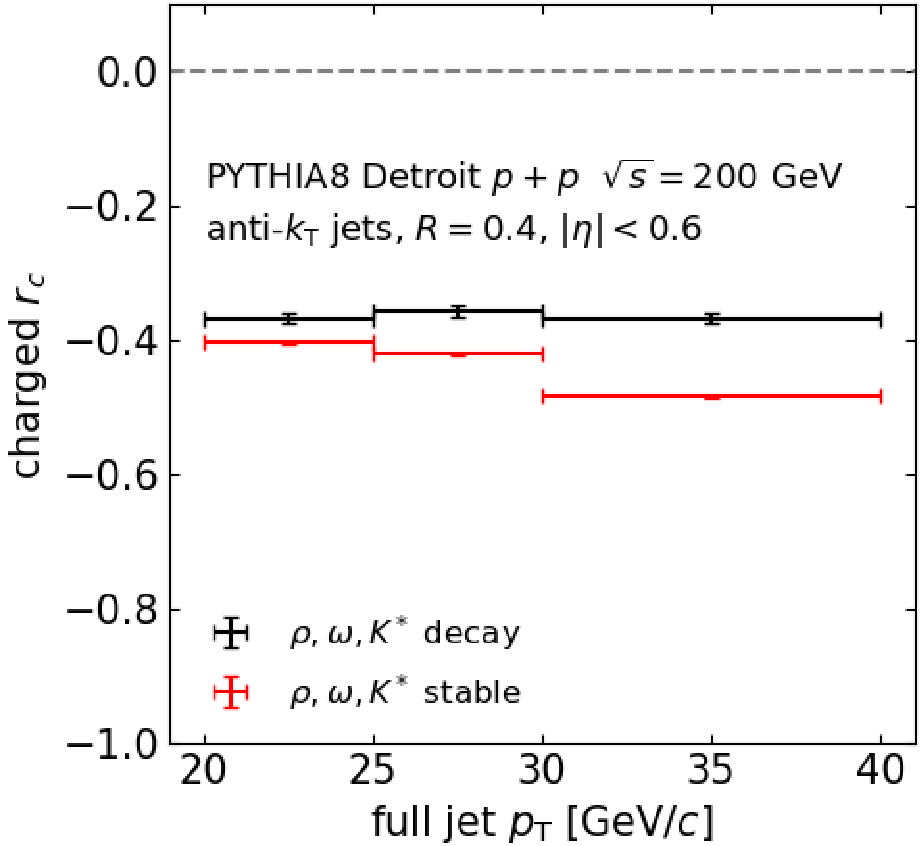
- This means, if we weight the opposite pair jets down (0.94) and the same sign jets up (1.13) in PYTHIA+GEANT, then we can get the PYTHIA+GEANT rc to match data (after mistagged subtraction).

- Since jets are matched between PYTHIA and PYTHIA+GEANT, the reweights automatically carry onto the PYTHIA jets too. This matching essentially serves the role of a response matrix, since it also contains the information such as the truth jet pT distribution given a reconstructed pT.

Decays

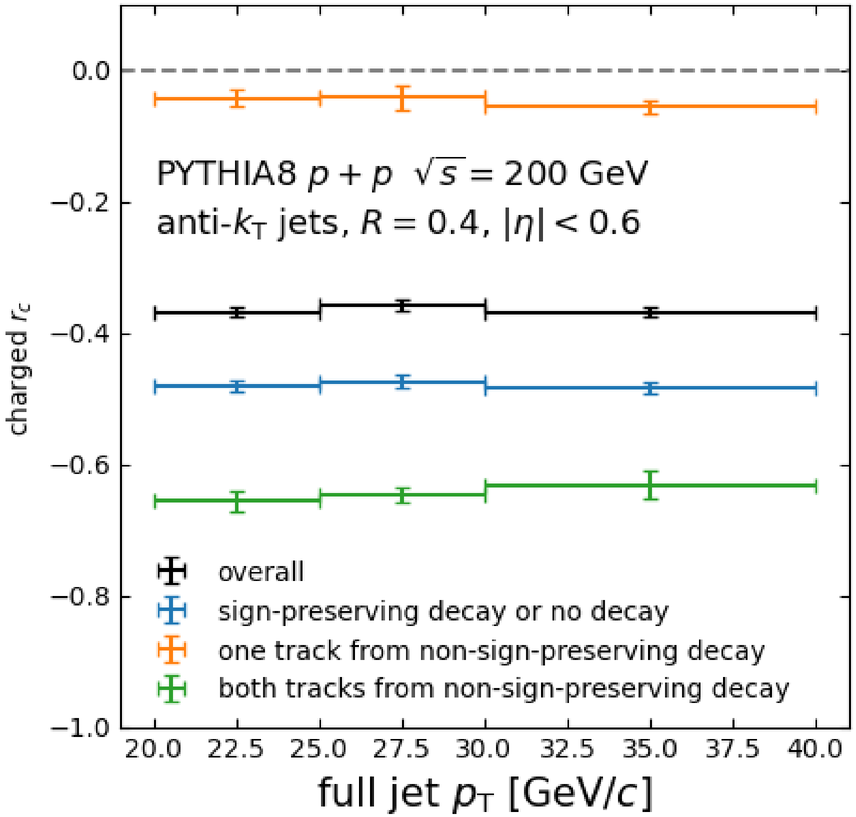
- Resonance decays affect r_c, but the effect is small compared to hadronization





Decays

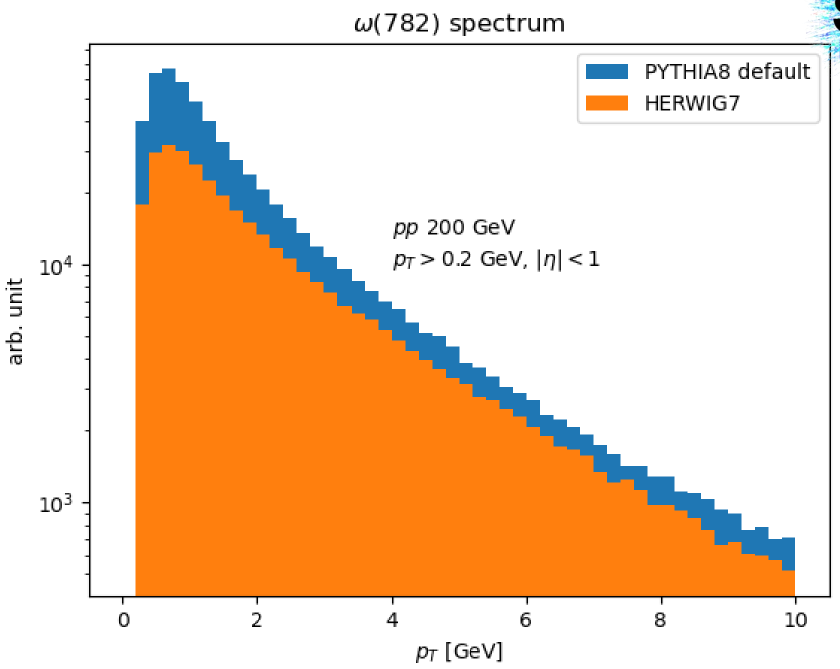
- In PYTHIA8, for leading tracks in jets, 47% of them come from resonance decays
  - Some of these decays preserve charge signs
    - $\rho^{+}(770) \rightarrow \pi^{+}\pi^{0}$
    - $K^{*}(892)^{+} \rightarrow K^{+}\pi^{0}$
    - $\Delta^{+} \rightarrow p\pi^{0}$
  - 26% of them come from non-sign-preserving decays



Resonances

- **Where does a π^+ leading track in jet come from?**

		PYTHIA8	HERWIG7	Decays
		(Di)quarks: 47%	Cluster: 29%	-
213	$\rho(770)^+$	21%	23%	$\pi^+\pi^0$, ~100%
113	$\rho(770)^0$	16%	17%	$\pi^+\pi^-$, ~100%
223	$\omega(782)$	9%	3%	$\pi^+\pi^-\pi^0$, 89%



- **Where does a π^+ subleading track in jet come from?**

	PYTHIA8	HERWIG7
	(Di)quarks: 40%	Cluster: 22%
$\rho(770)^+$	19%	22%
$\rho(770)^0$	18%	18%
$\omega(782)$	13%	4%
$K^*(892)^+$	3%	4%
$K^*(892)^0$	2%	2%

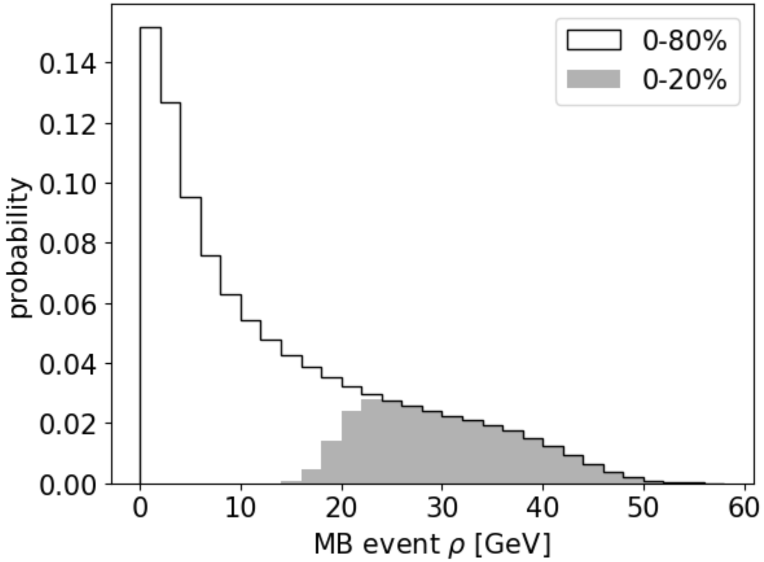
- Probability < 1e-7 in PYTHIA8 but > 1% in HERWIG: 3% $f_2(1270)$, 2% $a_2^+(1320)$, 1% $a_0^+(980)$
- Not "seen" by PYTHIA8 (off by default) but > 1% in HERWIG: 2% $b_1^+(1235)$, 1% $a_2^0(1320)$, 1% $\rho^+(1700)$
  - a pseudovector multiplet with *L=1, S=0, J=1*;
  - a scalar multiplet with *L=1, S=1, J=0*;
  - a pseudovector multiplet with *L=1, S=1, J=1*;
  - a tensor multiplet with *L=1, S=1, J=2*.

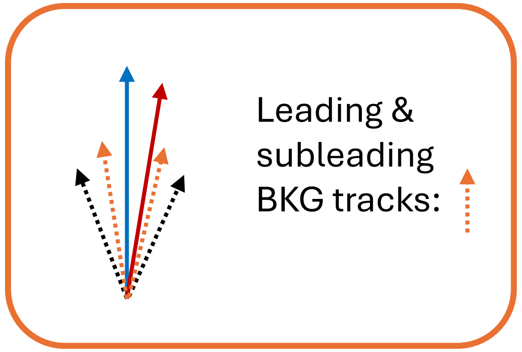
How to measure r_c in heavy ions:

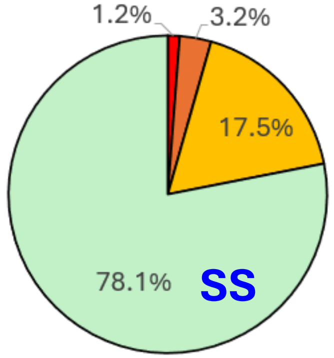
background subtraction experiment

Embedded jets breakdown:

- **comb**: jets not matched to PYTHIA jets within $\Delta R = 0.4$
  - may contain real jets in isobar events. To take care of them more carefully, need to do event mixing
  - for this study, obtain r_c**(comb)** from MB events **without embedding**
- **BB**: matched jets whose leading and subleading tracks both unmatched to PYTHIA leading and subleading
  - with embedding jets, obtain r_c**(BB)** between the leading and subleading **background tracks**, even if there are PYTHIA jet tracks that have higher p_T
- **SB** : should have no correlation in this study. For this study, r_c**(SB)** can be obtained by finding jets in MB events and excluding the leading dijets

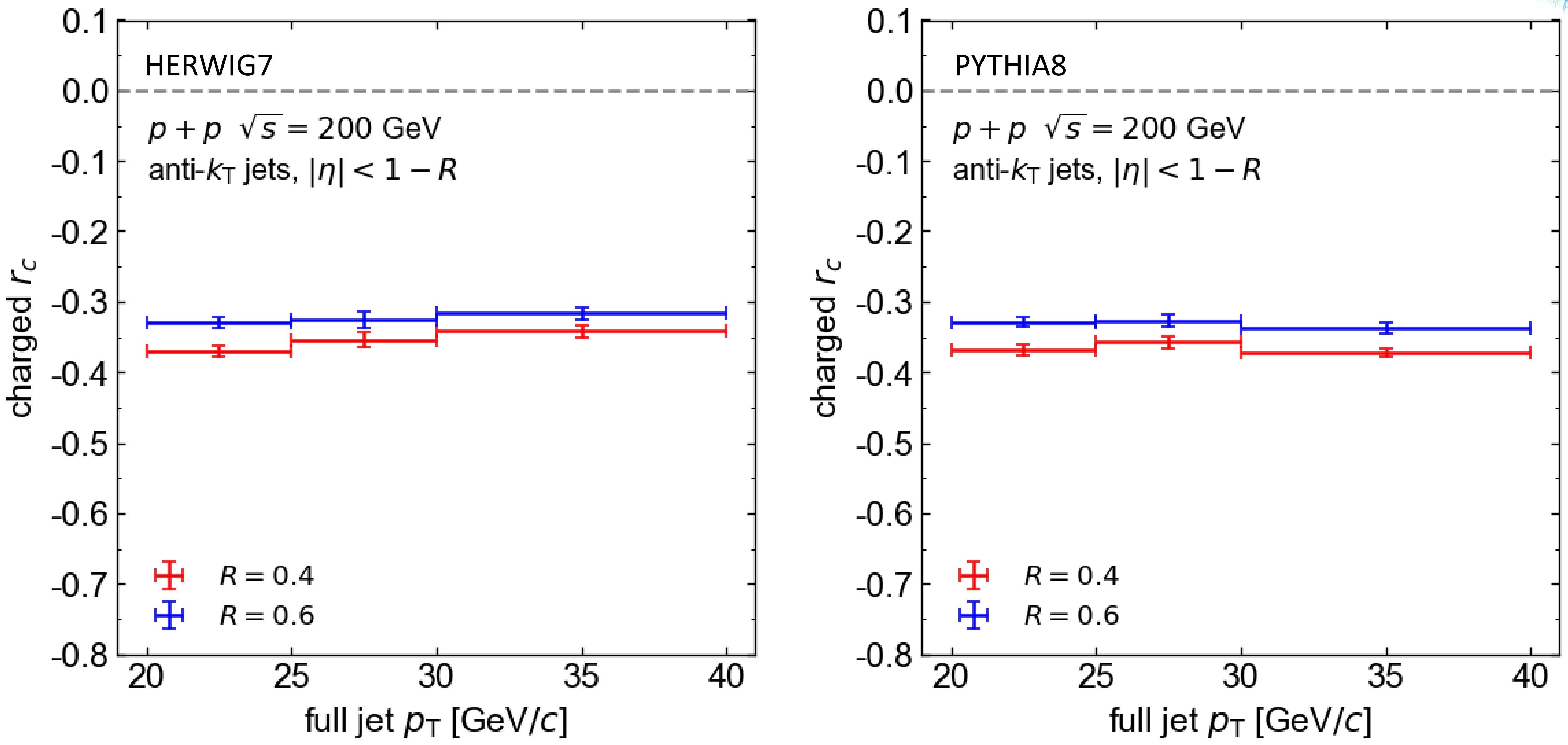






r_c(raw)
= Prob(comb) $\times$ r_c(comb)
+ Prob(BB) $\times$ r_c(BB)
+ Prob(SB) $\times$ r_c(SB)
+ Prob(SS) $\times$ r_c(SS)

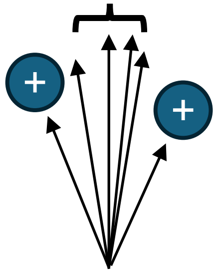
Jet radius dependence



Jet radius dependence

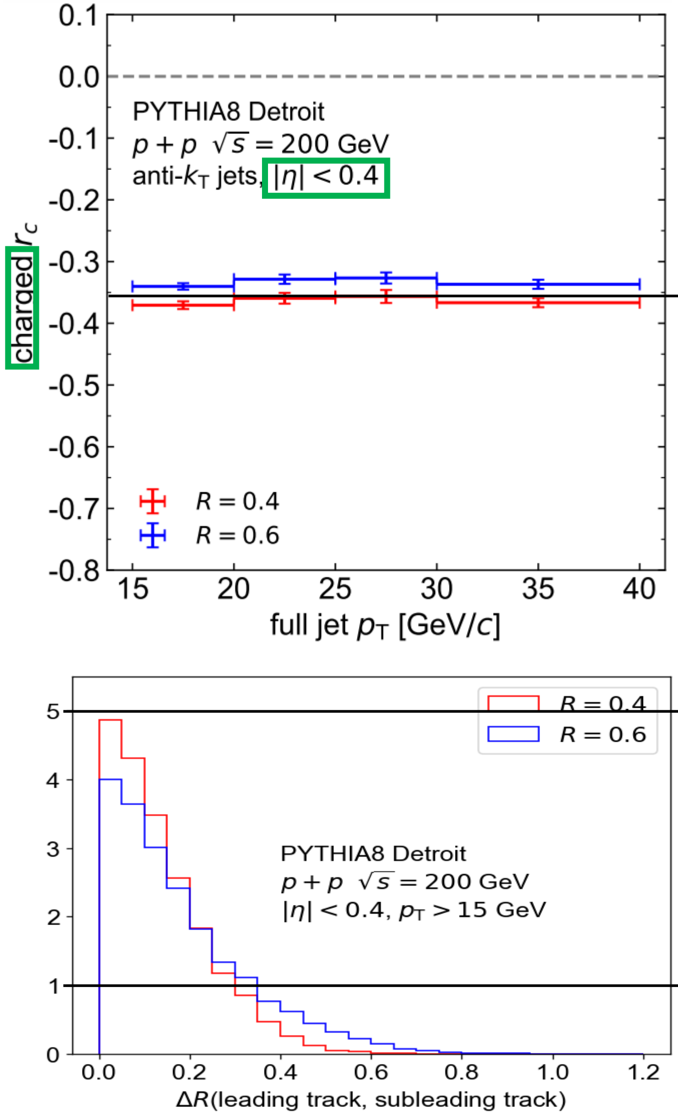
- $\boldsymbol{r_c}$ is less negative with larger jet R → likely that "background" track pairs are included with larger R
- Potentially introduce a jet neutral energy fraction requirement to reduce this effect
  - Fragmentation bias? Or does this bring us closer to the "original definition"?

Neutral particles



Example of a jet with a large R and large neutral core

Definition used in our measurement



Original definition as proposed by Chien et al. PRD 105 051502 (2022)