Parity and Time-Reversal Violation Studies in Heavy-Ion Collisions at STAR

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For the STAR collaboration

- Motivation
- Analysis Techniques
- First Look at STAR Data
- ‘Fake’ Signals

QCD and CP

QCD Lagrangian for u,d,s quarks

$$L_{QCD} = -\sum_f \bar{q}_f(-i\gamma_\mu D^\mu + m_f)q_f - G_{\mu\nu}G^{\mu\nu}$$

has $U_V(1)$ x$SU_V(3)$x$U_A(1)$x$SU_A(3)$ symmetry if quark masses are 0

The 9 chiral ' approximate symmetries' are broken by quark condensate but there are only 8 'nearly Goldstone' bosons Q: Why?

A: There is no conserved current associated with $U_A(1)$ because of '$U_A(1)$ anomaly' AND state of QCD vacuum.

Effectively, to solve this problem, must add to Lagrangian a term

$$L_{CP} \propto \bar{\theta} G_{\mu\nu}\tilde{G}^{\mu\nu} \propto \vec{E}_c \bullet \vec{B}_c$$

CP violation is allowed in QCD, but not yet observed.

P,T violation in Heavy-Ion Collisions

- Kharzeev et. al. (PRL 81, 512)model QCD with an effective Lagrangian.
- In this model, if $U_A(1)$ symmetry is restored above some critical temperature, regions of 'false' vacua may be created that behave as if θ is non-zero $\Rightarrow$P,T violation.
- This may happen in RHIC collision and cause "non-zero" values for (P,T odd) event-by event observables such as

$$\vec{J}_c \bullet \vec{K}_t = \sum_{+,-} (\hat{p}_+ \times \hat{p}_-) \bullet (\sum_{+} \hat{p}_+ - \sum_{-} \hat{p}_-) \operatorname{sgn}(p_{z+} p_{z-})$$

A "non-zero" value for $J_c K_t$ in a RHIC event implies a P,T violation

Spontaneous P,T violation

Effect on $J_c K_t$ is far too small to be detected in one event, so we must look at distribution of $J_c K_t$ over many events.

Problem: $J_c K_t$ is just as likely to be shifted in '+' direction as '-' direction in any given event.

Possible Solutions:

(1) 'KNOW' what width would be without P,T violation: Mixed Events

(2) Split events into two halves and look for correlated shifts in each half (Sub-event method).

With SUBEVENT method, we look for a SHIFT in the mean of a distribution away from zero.

Sub-Event Method

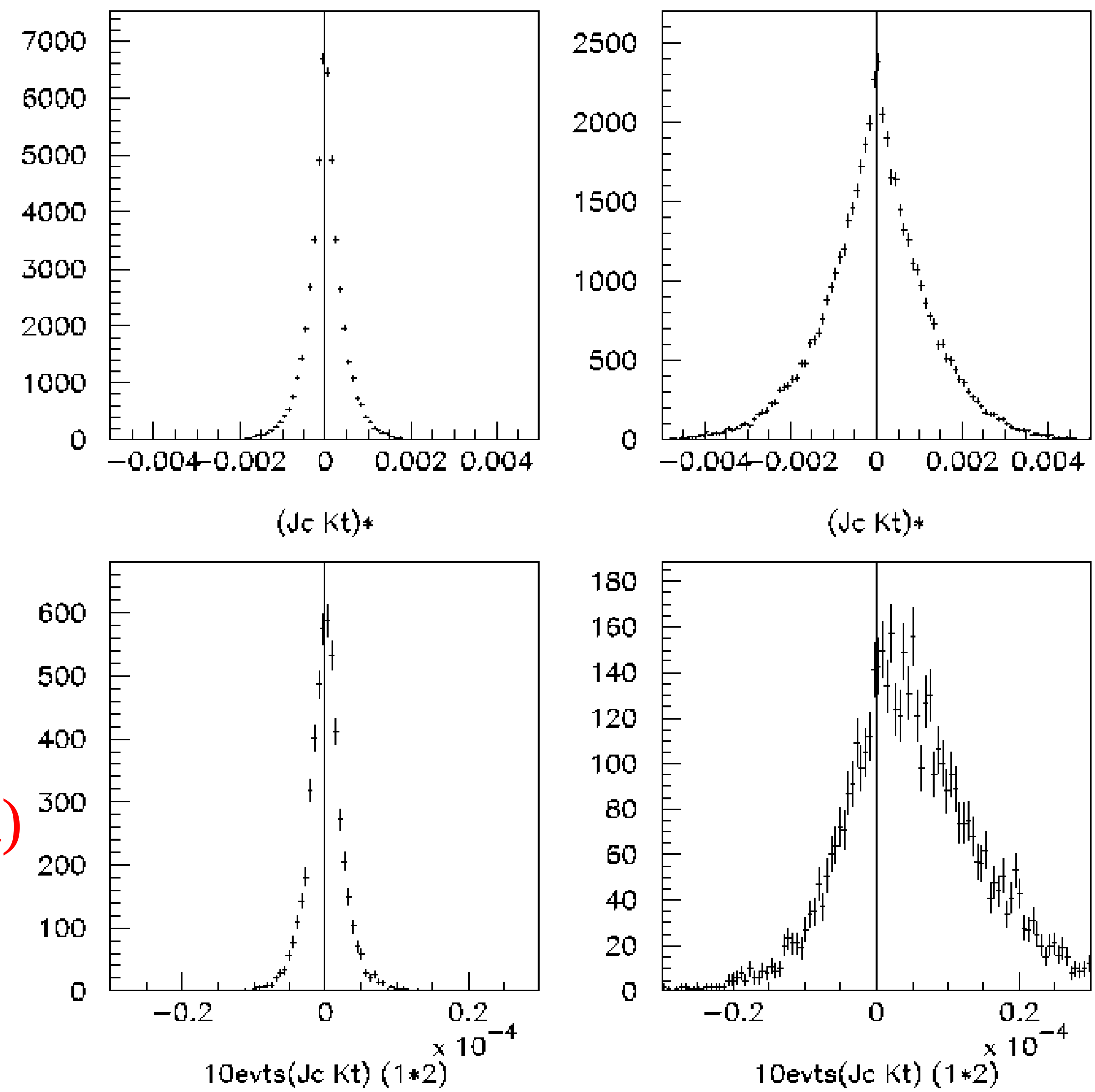
1) Separate tracks into two independent sub-events
2) Calculate global observable, e.g. JcKt, for each sub-event.
3) Multiply $JcKt_{(subevt1)} \times JcKt_{(subevt2)}$.

No P,T violation

With P,T violation

JcKt

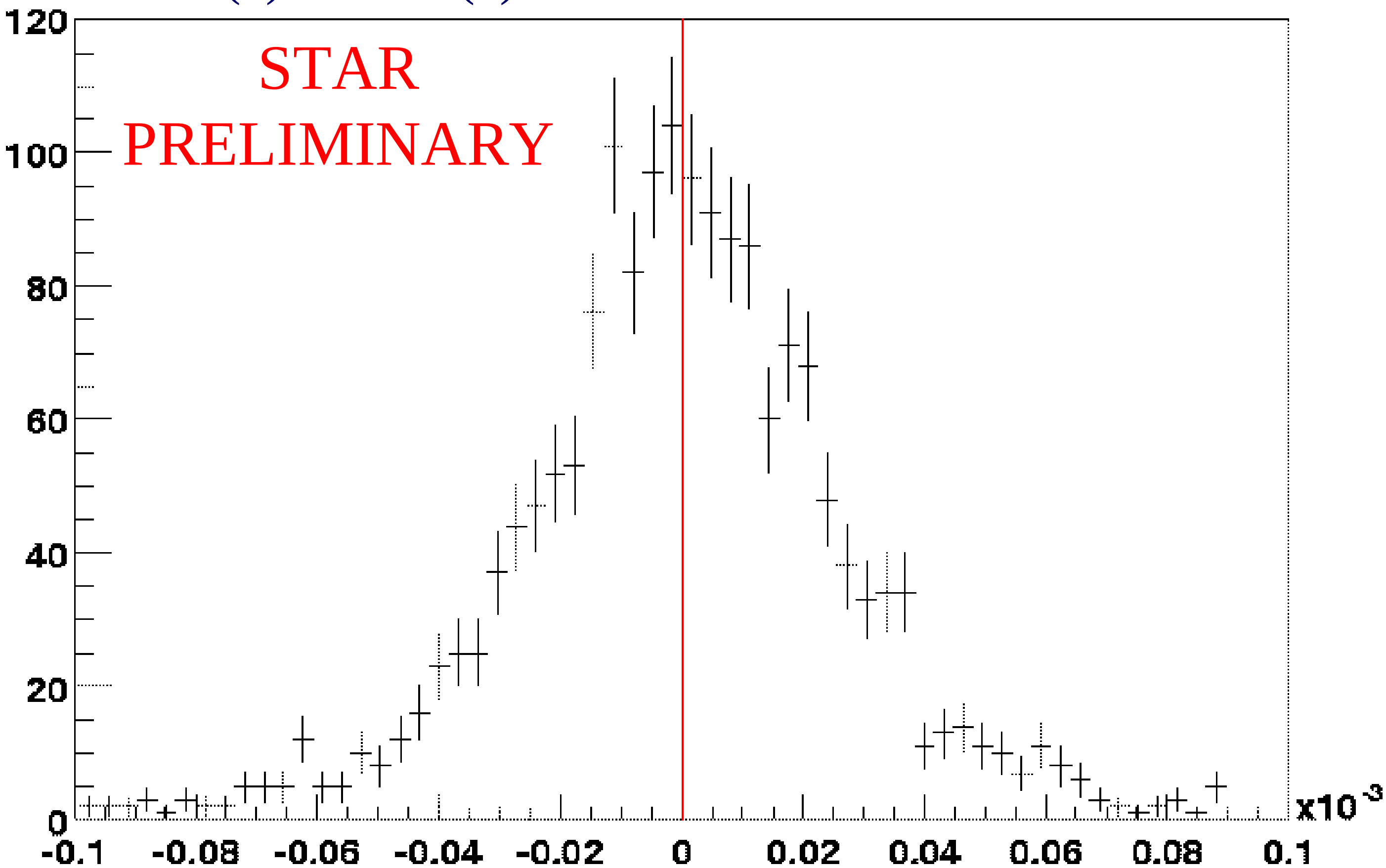
$\{JcKt_{(1)} \times JcKt_{(2)}\}$ (Sub-event)



‘First Look’ at STAR Data

- 17K central events with $-50\text{cm}<z<50\text{cm}$
- Identified pions with $-1.2<y<1.2$

$JcKt_{(1)} \times JcKt_{(2)}$ (sub-event method)



Result: Mean = $(7 \pm 60) \times 10^{-8}$

$\Rightarrow$ Consistent with No Signal.

‘Fake’ signals

- Flow (finite impact parameter): Potentially a problem, particularly for mixed event method, but has known dependence on event centrality which we don’t expect P,T violation to have.
- Hyperon decays :does not seem to be a problem.
- Detector efficiencies :the observables we are looking at are very robust against most of these; Mixed Event method is helpful

No show-stoppers

Summary

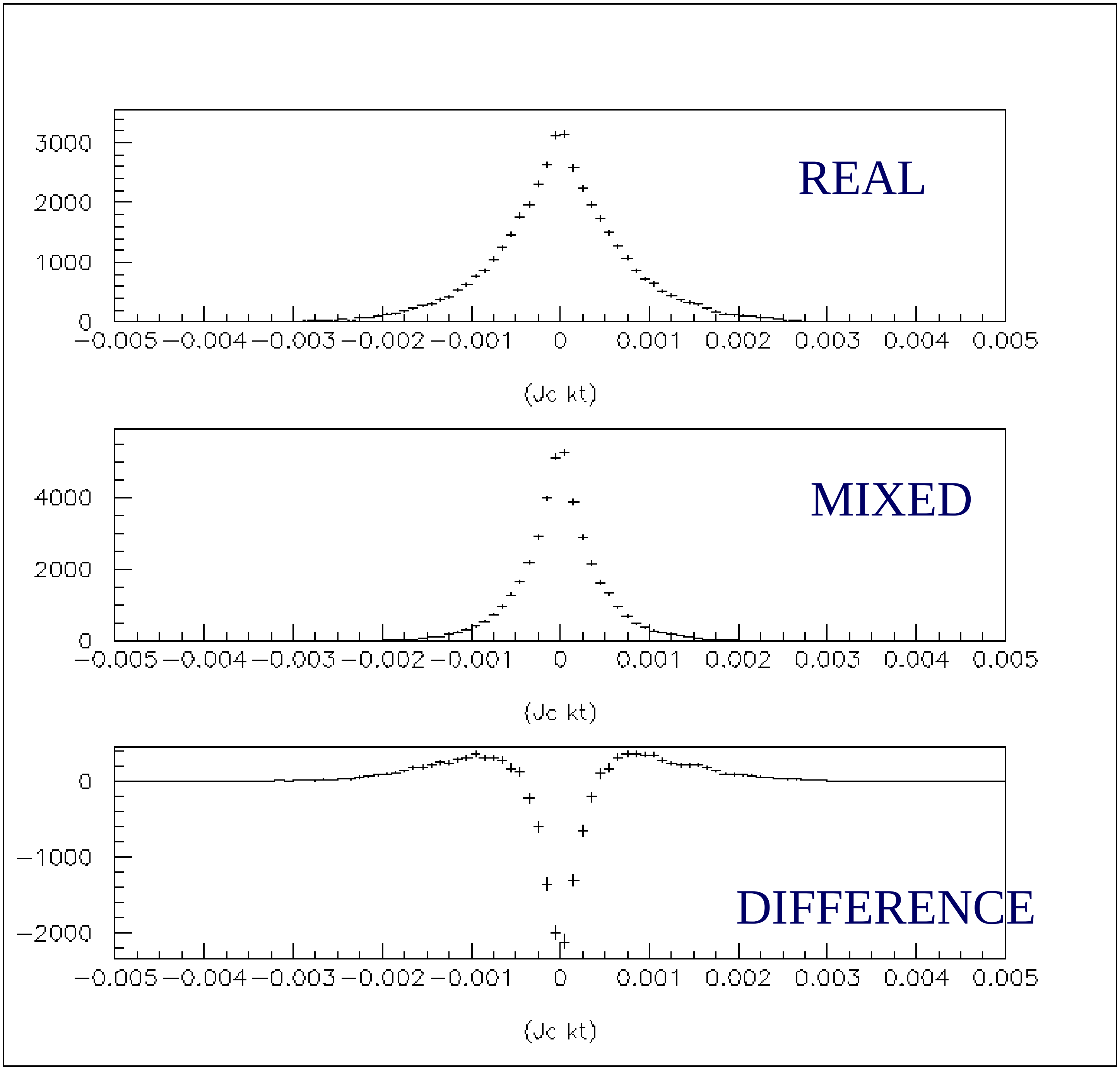
- P,T violation in strong interactions may occur in heavy-ion collisions (even for $\theta = 0$)
- First look at data: no signal in 20K central events.

Looking Ahead:

- Still evolving: several different techniques and observables. (proton-antiproton as well)
- Few $\times$100K events available from first year STAR run.

Mixed Event Subtraction

- Build mixed events, each out of chunks of 100 different events, and look at difference of distributions from real and mixed events.



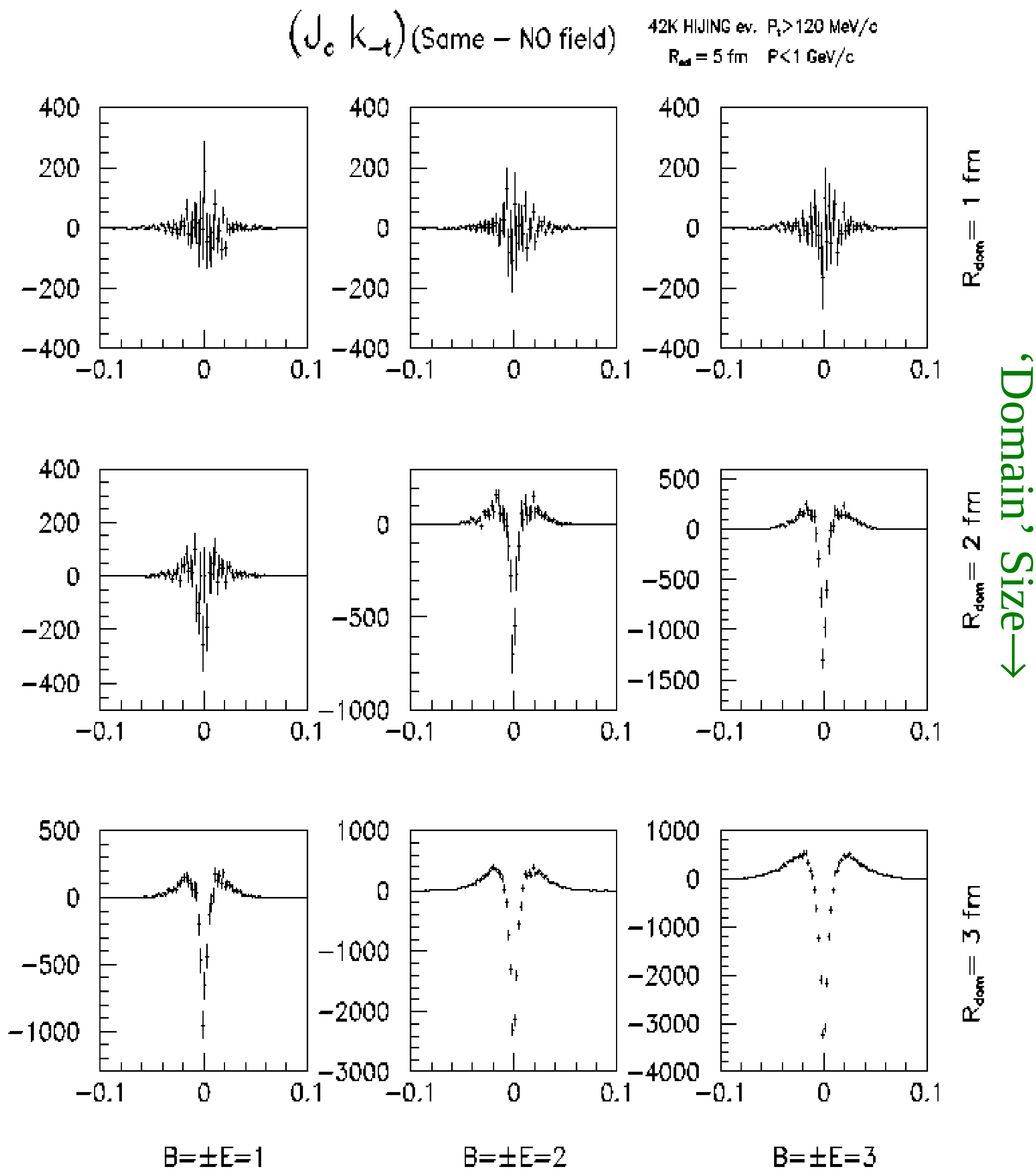
Simulations:

Basic experimental questions:

- What are the best observables to construct ?
- How sensitive may STAR be in ideal case ?

⇒Create a simulation model of the P,T violation. One model: finite $E \bullet B|_{em}$ fields within P,T violating 'bubbles' inside collision region. Adjust the field strength and bubble size to match expected strong fields.

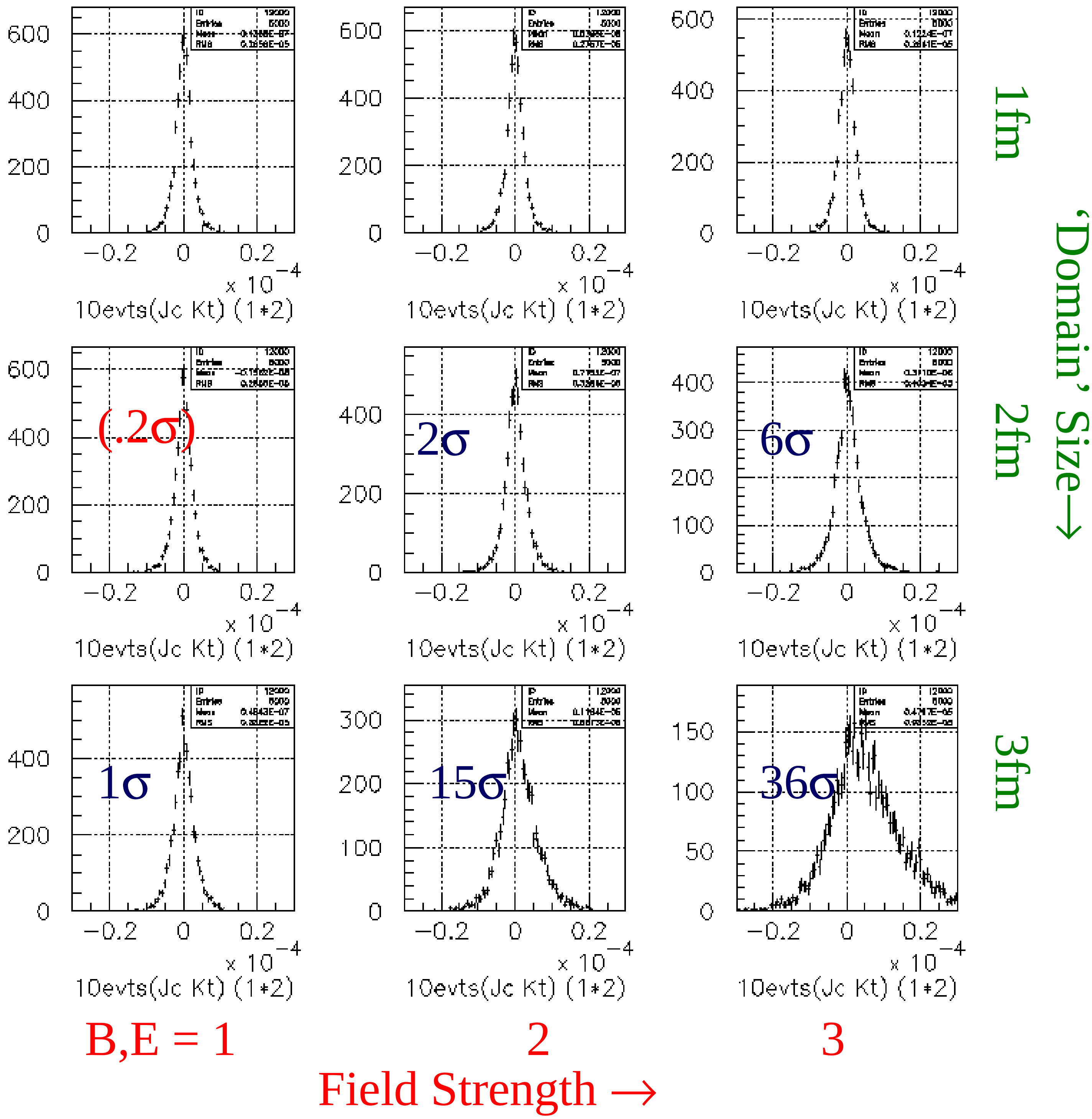
Some Simulation Results: 'Mixed Event' Method



Field Strength →

Some Simulation Results: ‘Subevent’ Method

50K ‘HIJING’ EVTS: $JcKt_{(1)} \times JcKt_{(2)}$



From Another Angle...

- JcKt is a parity odd observable
- Initial state $|\alpha>$ is a parity eigenstate, i.e. Can have no handedness $<\alpha|JcKt|\alpha>=0$.
- If, for the final state $|\beta>$, we find $<\beta|JcKt|\beta> \neq 0$, then $|\beta>$ has handedness (i.e. Is a combination of even and odd parity states). This implies that the interaction does not conserve parity.