CME Search Before Isobar Collisions and Blind Analysis From STAR

Prithwish Tribedy
for the STAR collaboration

BROOKHAVEN NATIONAL LABORATORY

The 36th Winter Workshop on Nuclear Dynamics

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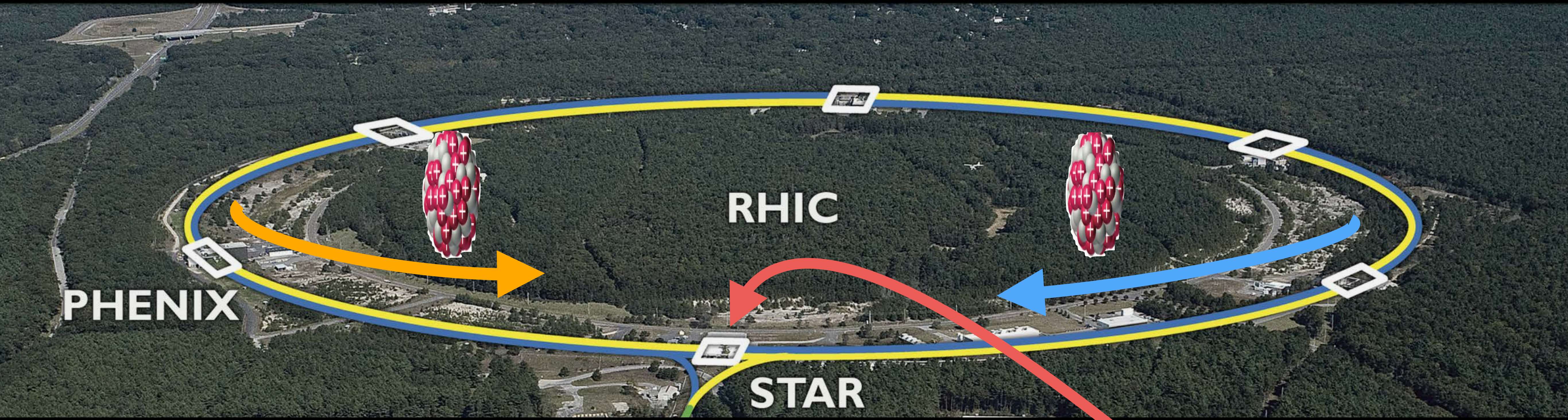
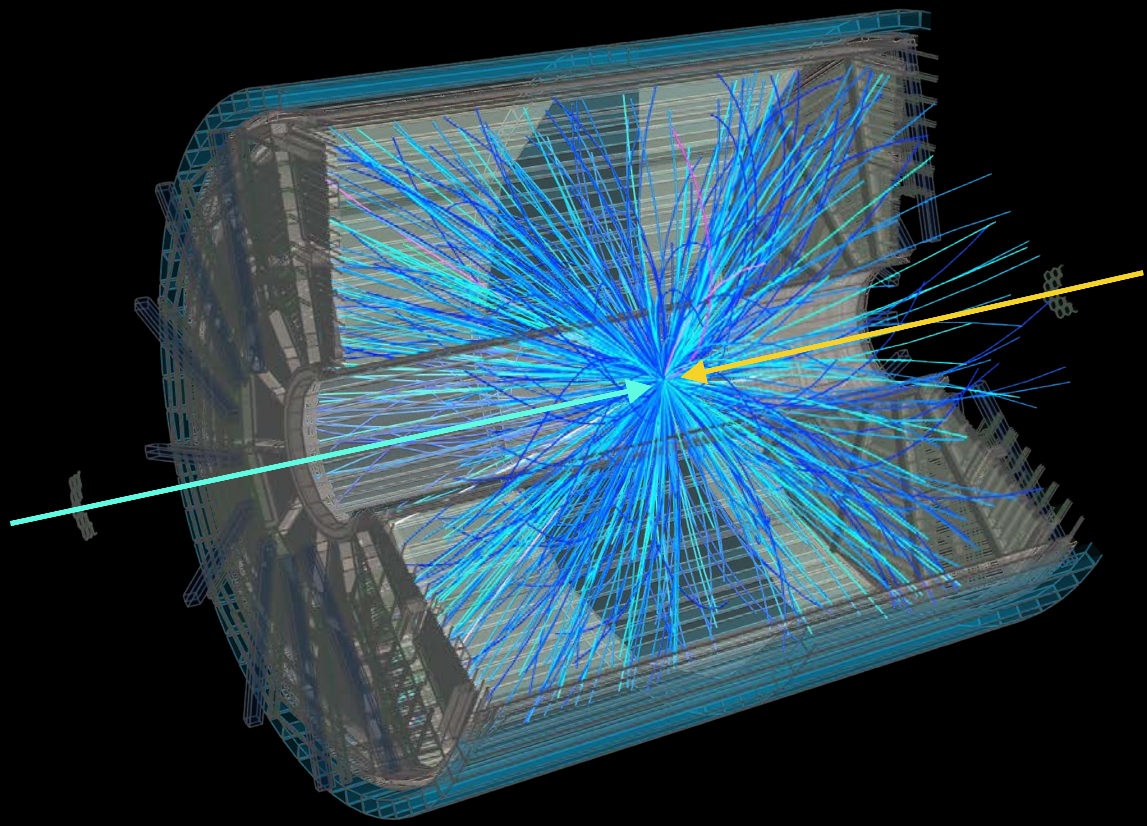
In part supported by
U.S. DEPARTMENT OF ENERGY | Office of Science

Introduction



Solenoidal Tracker at RHIC (STAR)

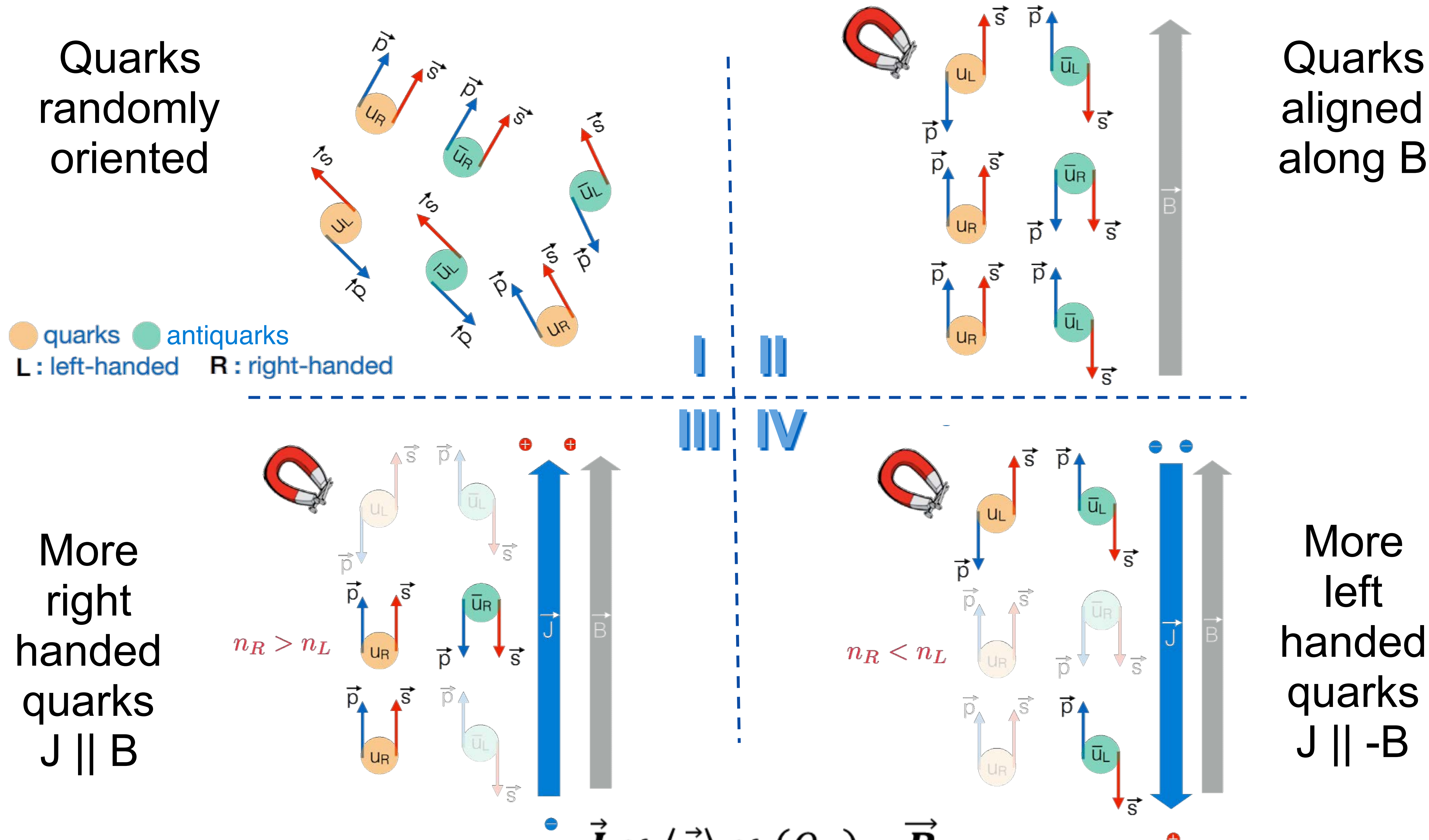
RHIC has collided multiple ion species; year 2018 was dedicated to search for effects driven by strong electromagnetic fields by STAR



Isobars: Ru+Ru, Zr+Zr @ 200GeV (2018)
Low energy: Au+Au 27 GeV (2018)

Large systems : U+U, Au+Au @ 200 GeV

The Chiral Magnetic Effect (Cartoon Picture)



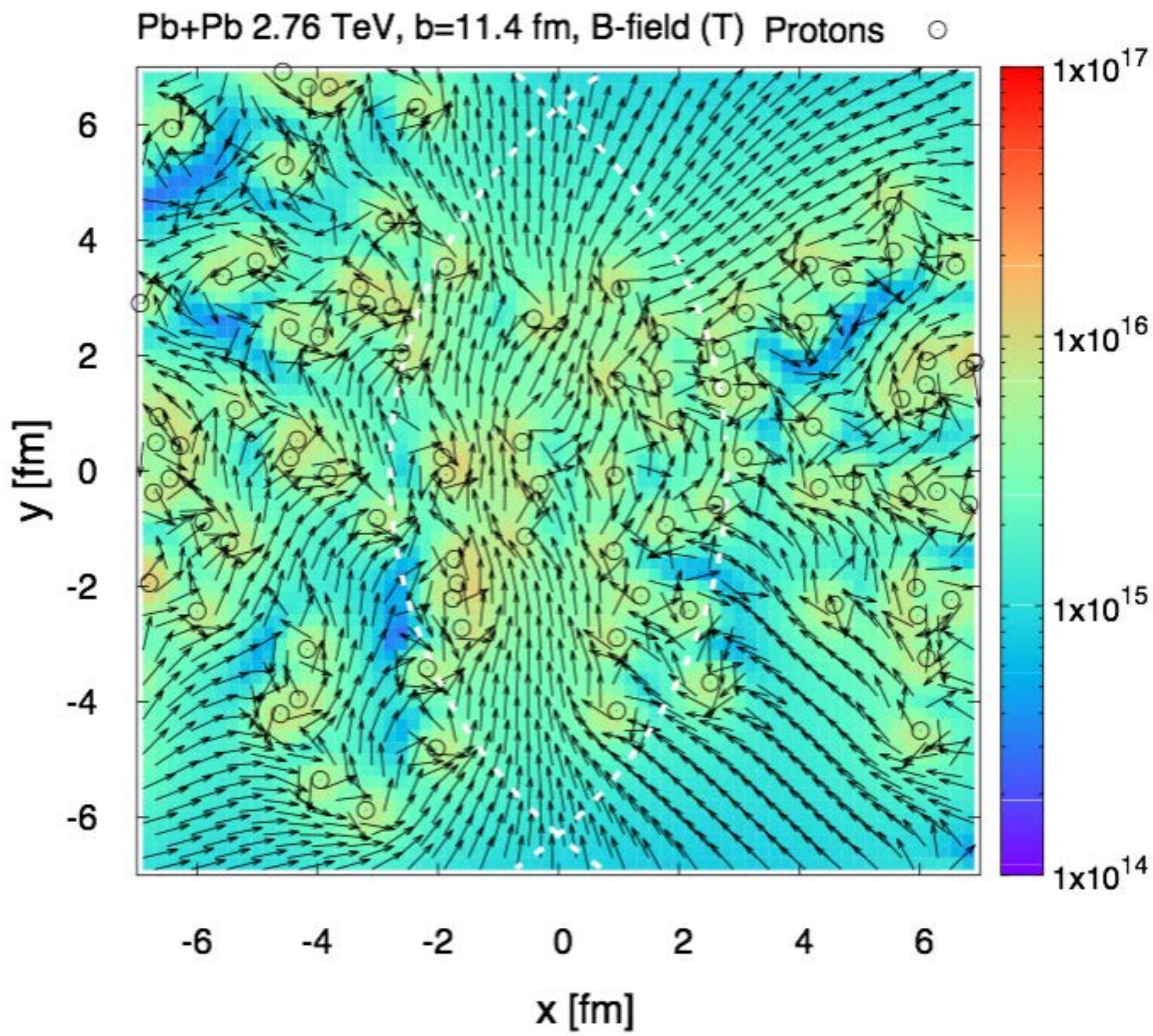
$$\vec{J} \propto \langle \vec{p} \rangle \propto (Qe)\mu_5 \vec{B}$$

CME converts chiral imbalance to observable electric current

New Theory Guidance : Complexity Of An Event

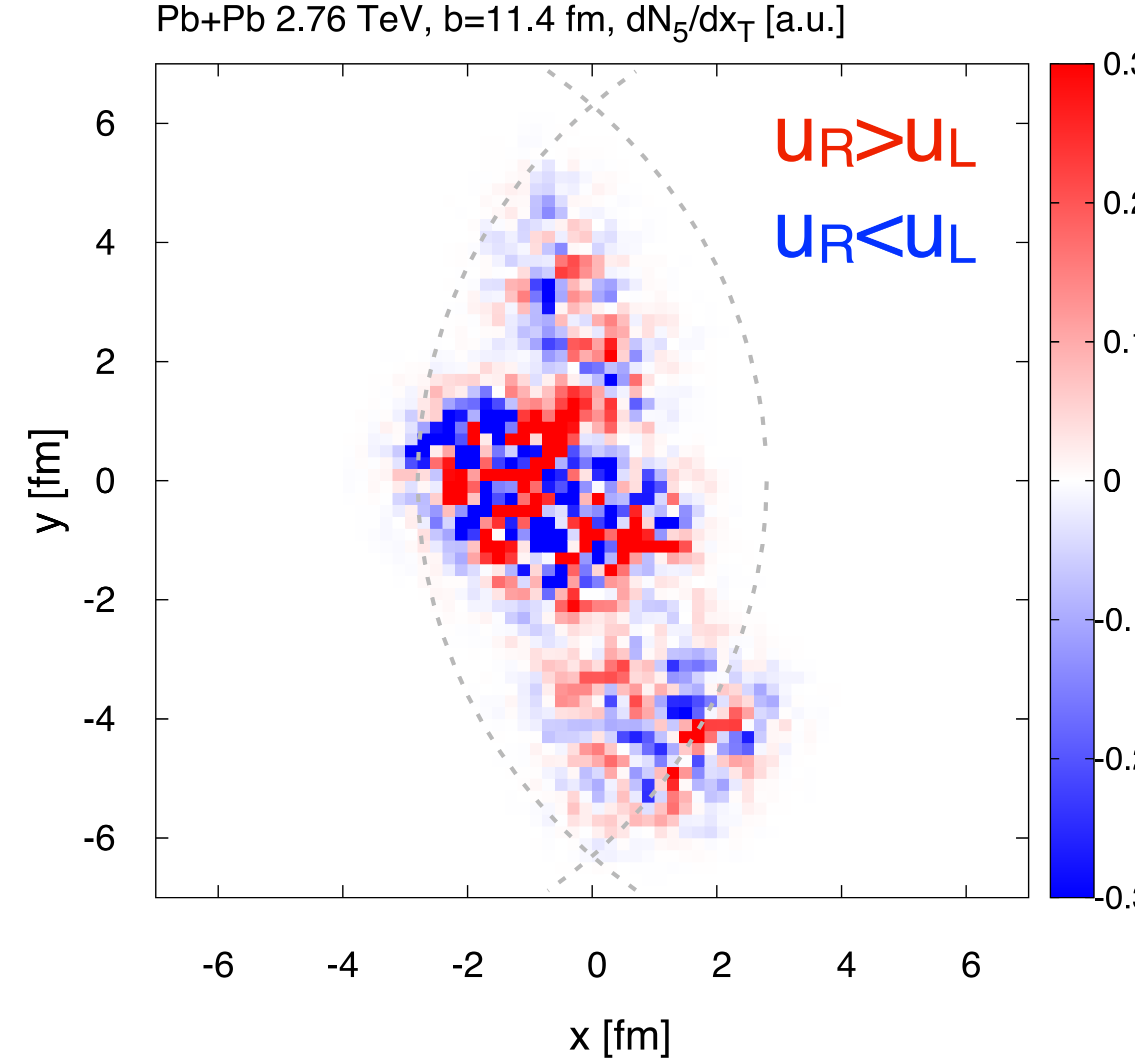
Pb+Pb @ 2.76 TeV
b=11.4 fm, N_{part}=56

Magnetic field map



Based on: Chatterjee, Tribedy, Phys. Rev. C 92, 011902 (2015)

Axial charge profile



Based on: Lappi, Schlichting, Phys. Rev. D 97, 034034 (2018)

Going beyond cartoon picture: 1) Fluctuations dominate e-by-e physics, 2) B-field & domain size of axial-charge change with √s

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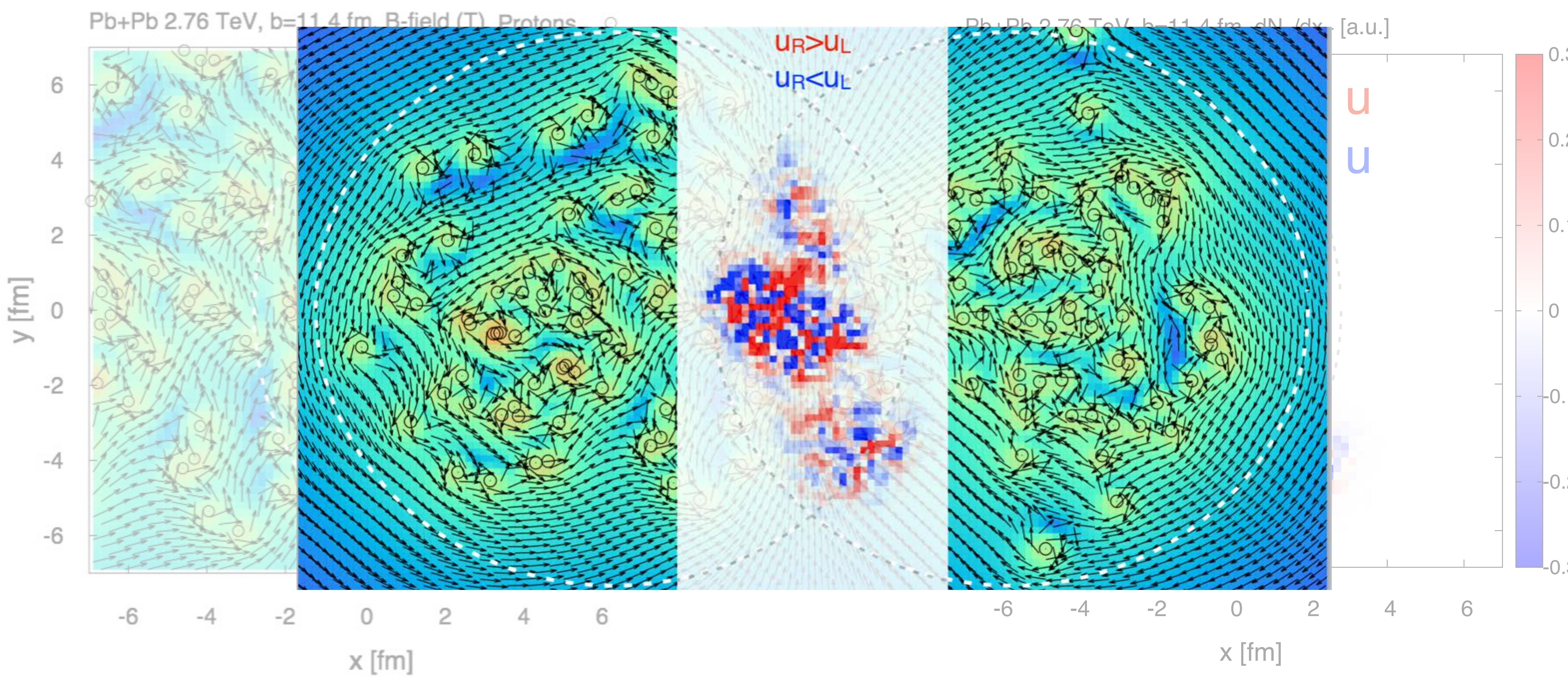

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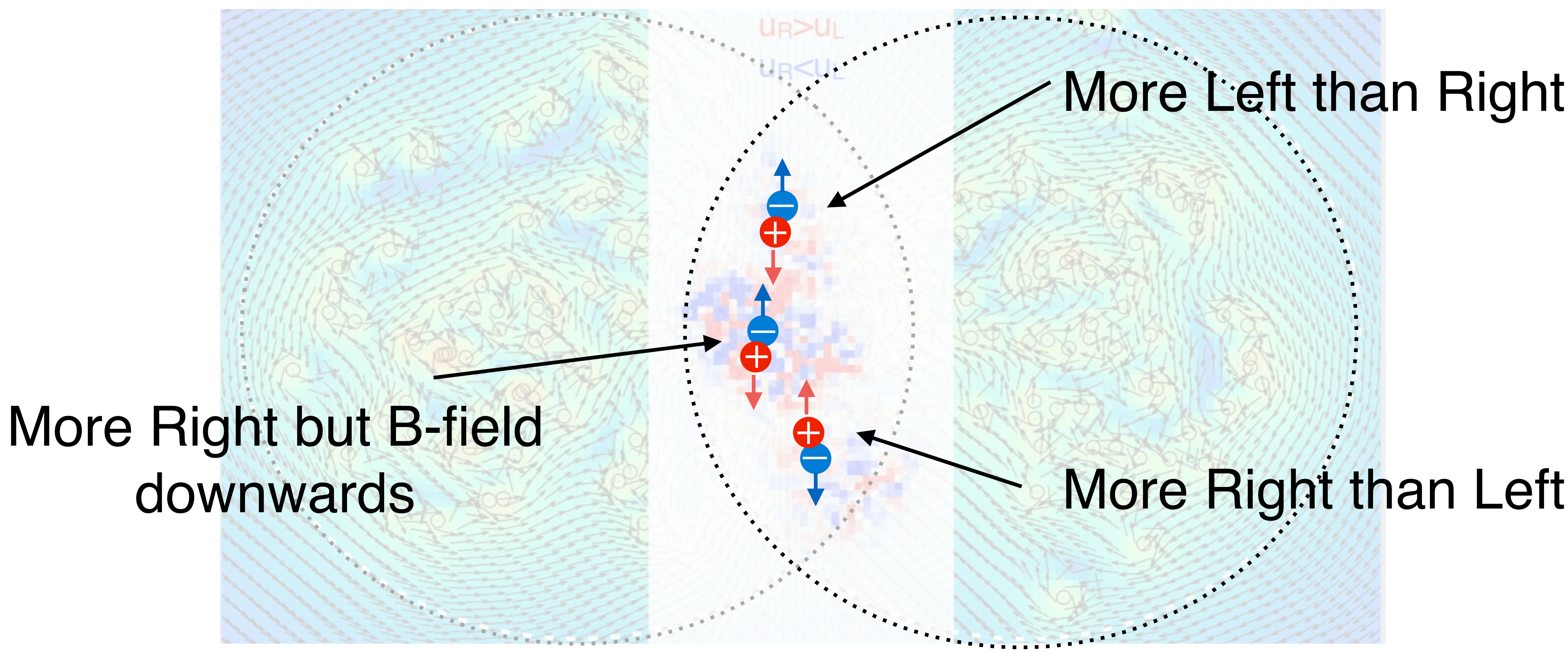

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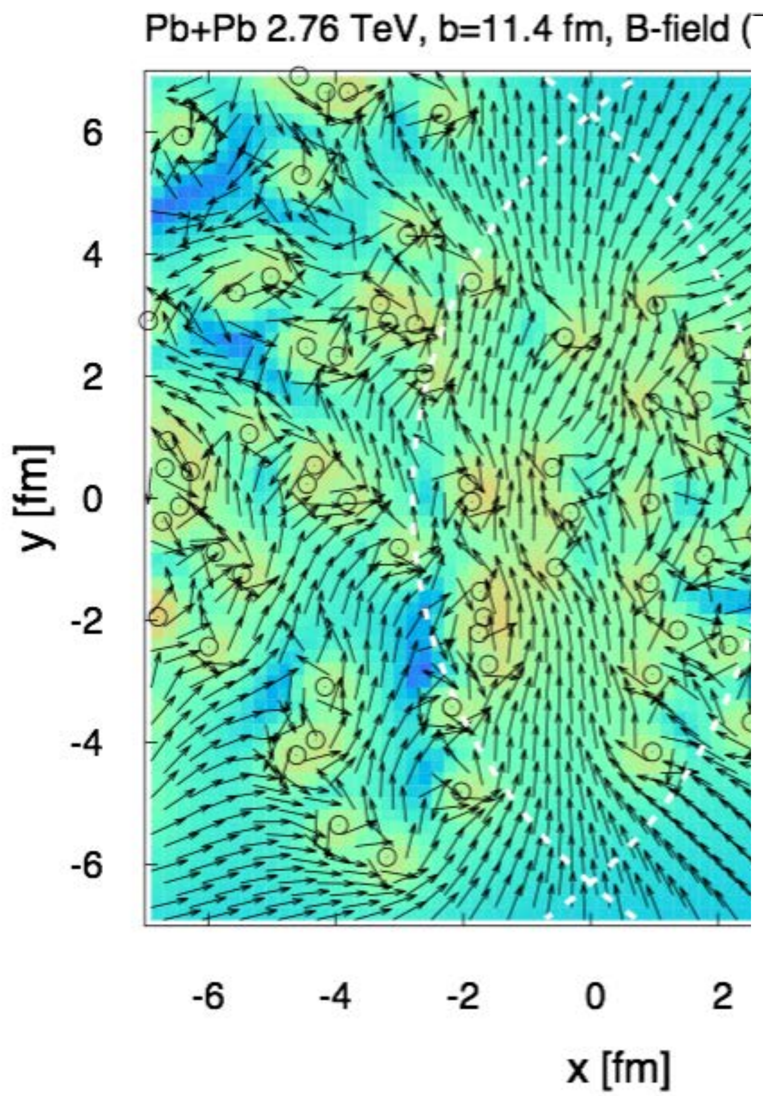

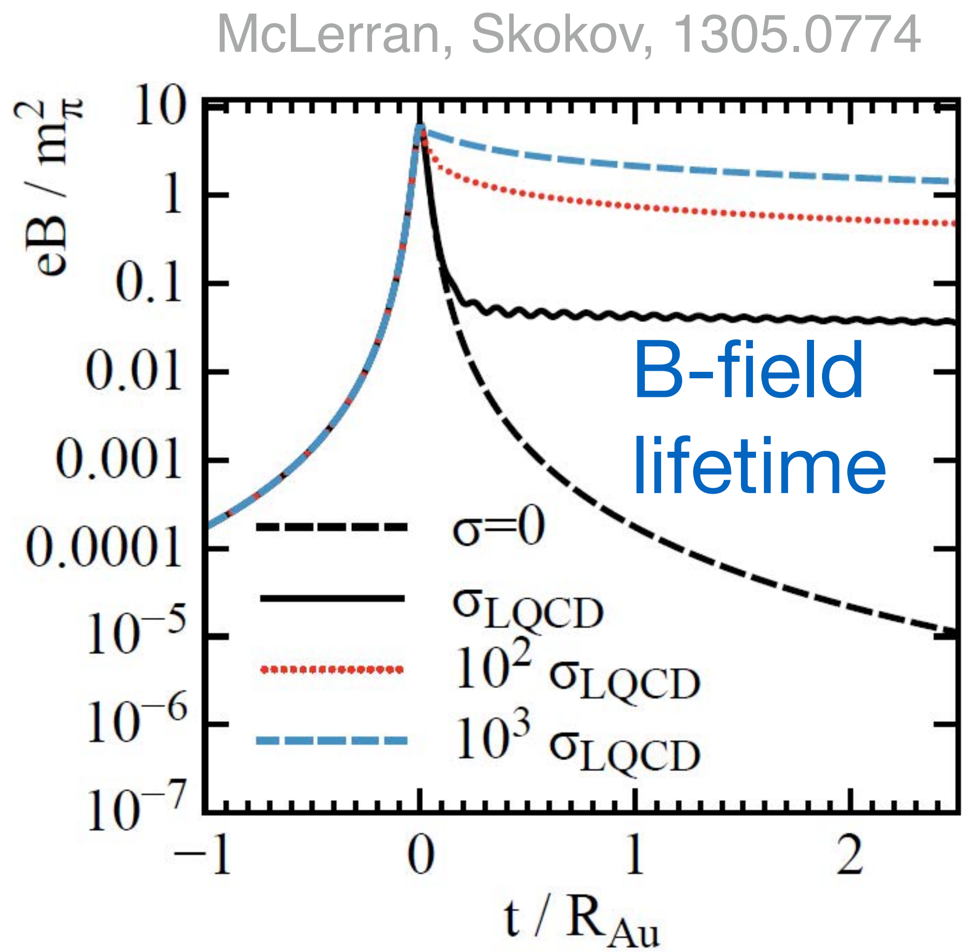

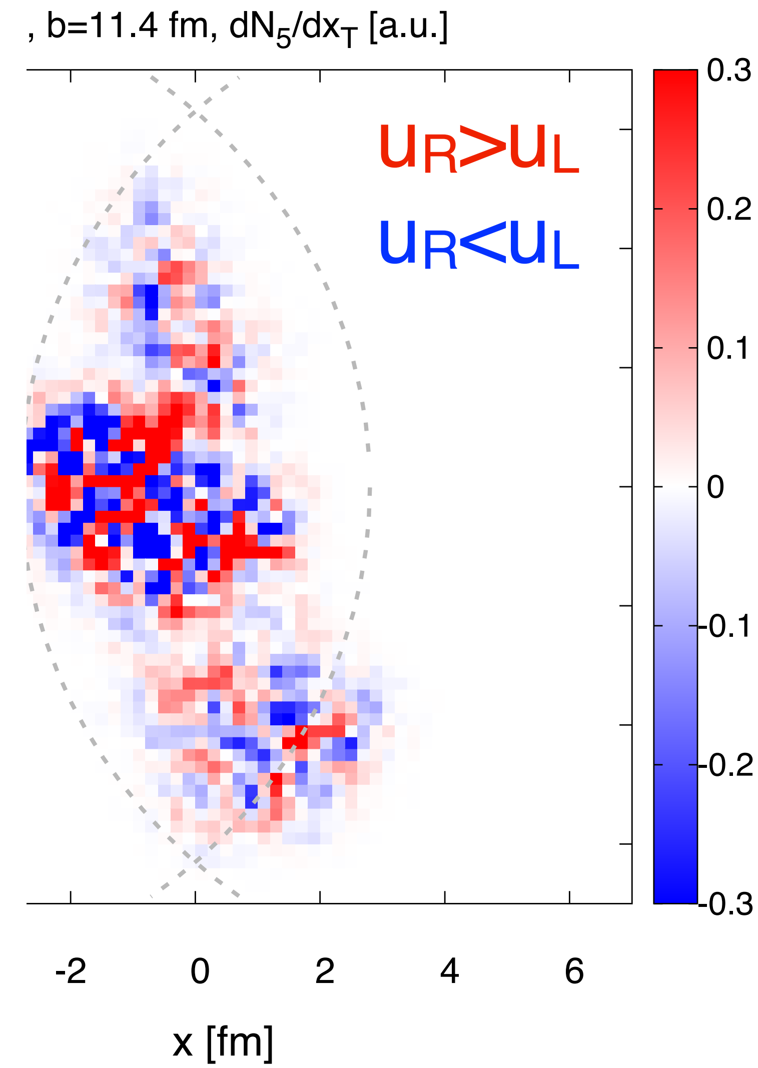

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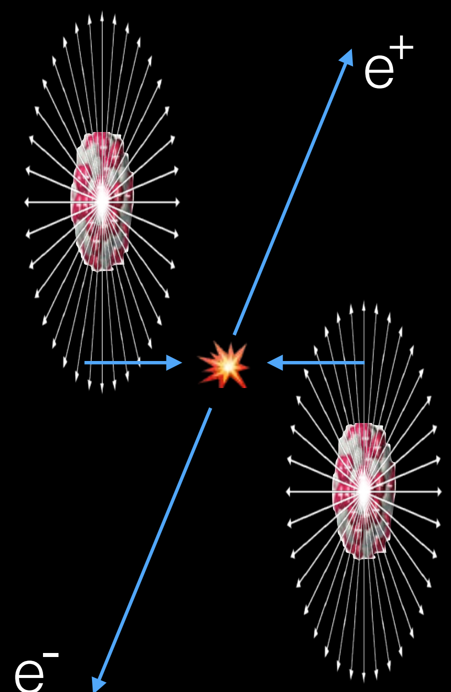
Going beyond cartoon picture: 1) Fluctuations dominate e-by-e physics, 2) B-field & domain size of axial-charge change with √s

Motivations: time for 1) decisive test, 2) revisit CME search at low √s

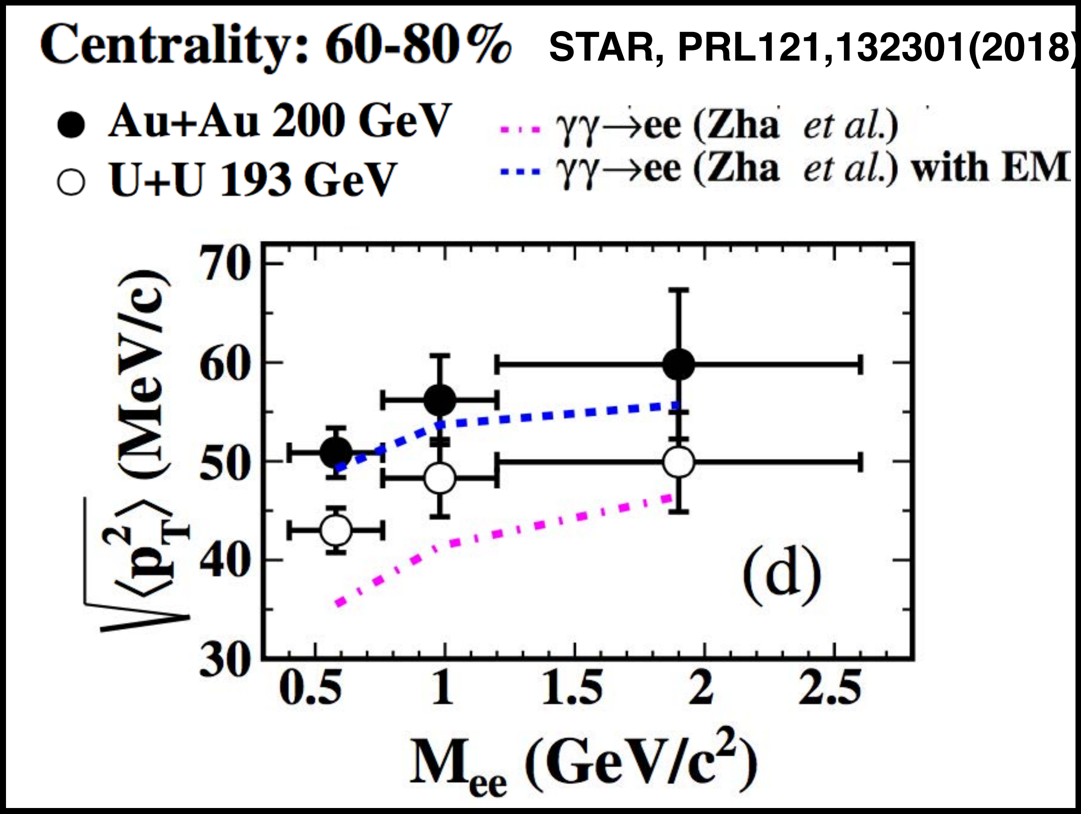
STAR Search For Other B-field Driven Effects

"Discovery of Breit-Wheeler Process"
STAR Collaboration, arXiv:1910.12400



see talk by D. Brandenburg
Tue 3/3

$$eB > eB_C \approx m_e^2 \approx 10^8 \text{ Tesla}$$



eBL ≈ 30 MeV/c, B ~ 10^{14} T, L ~1 fm

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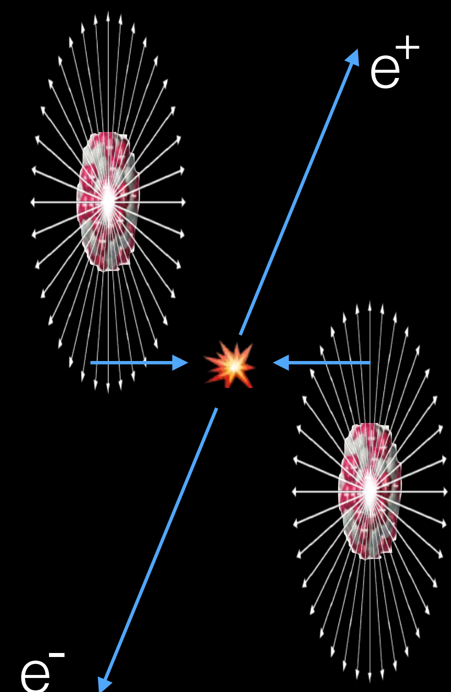

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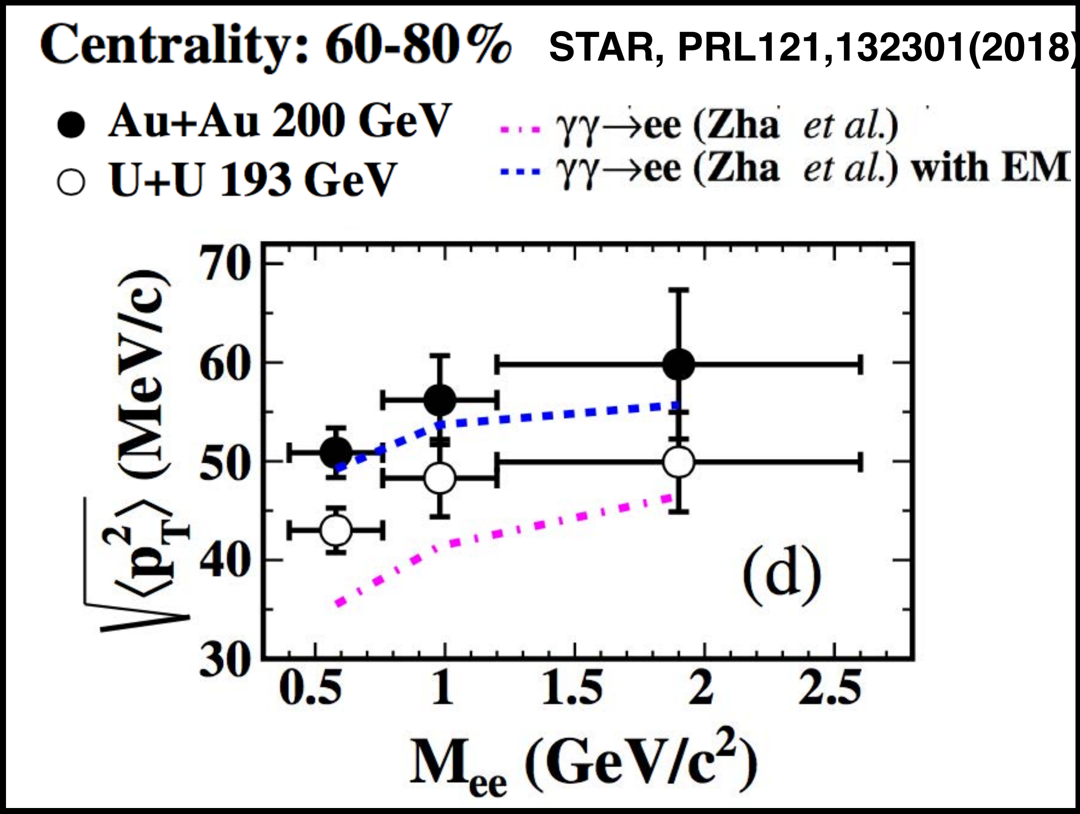

eBL ≈ 30 MeV/c, B ~ 10^{14} T, L ~1 fm

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Polarization of Lambda & Anti-Lambda

$$\vec{P}_\Lambda \,||\, -\hat{J}_{sys} \qquad \vec{P}_{\bar{\Lambda}} \,||\, +\hat{J}_{sys}$$

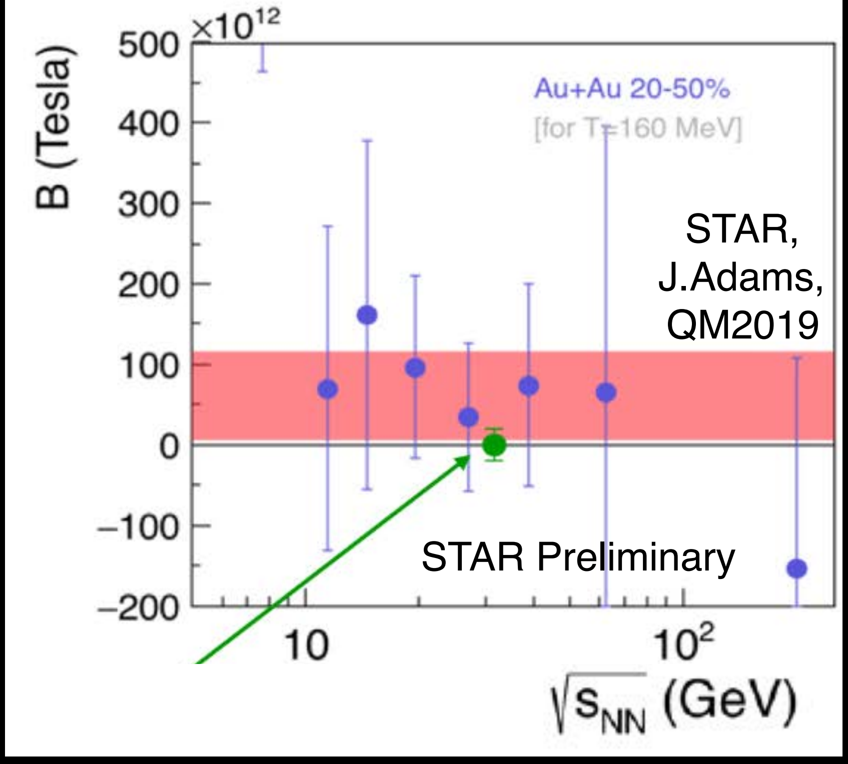
magnetic

Λ

$$\vec{P}_\Lambda \,||\, +\hat{J}_{sys} \qquad \vec{P}_{\bar{\Lambda}} \,||\, +\hat{J}_{sys}$$

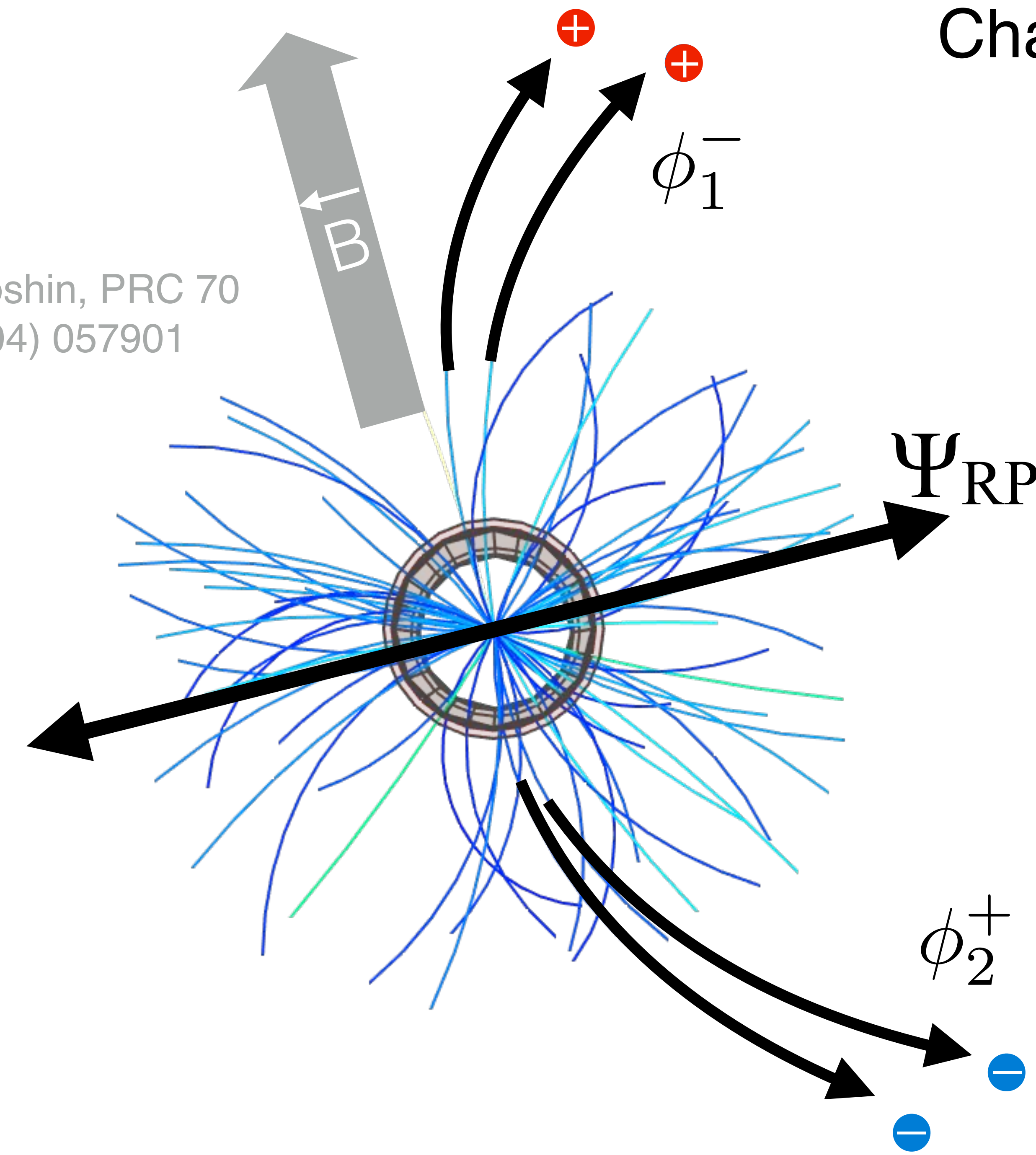
spin-orbit

$\bar{\Lambda}$



Independent limits on B-field : important for CME search

CME Search Using The γ-Correlator Observable



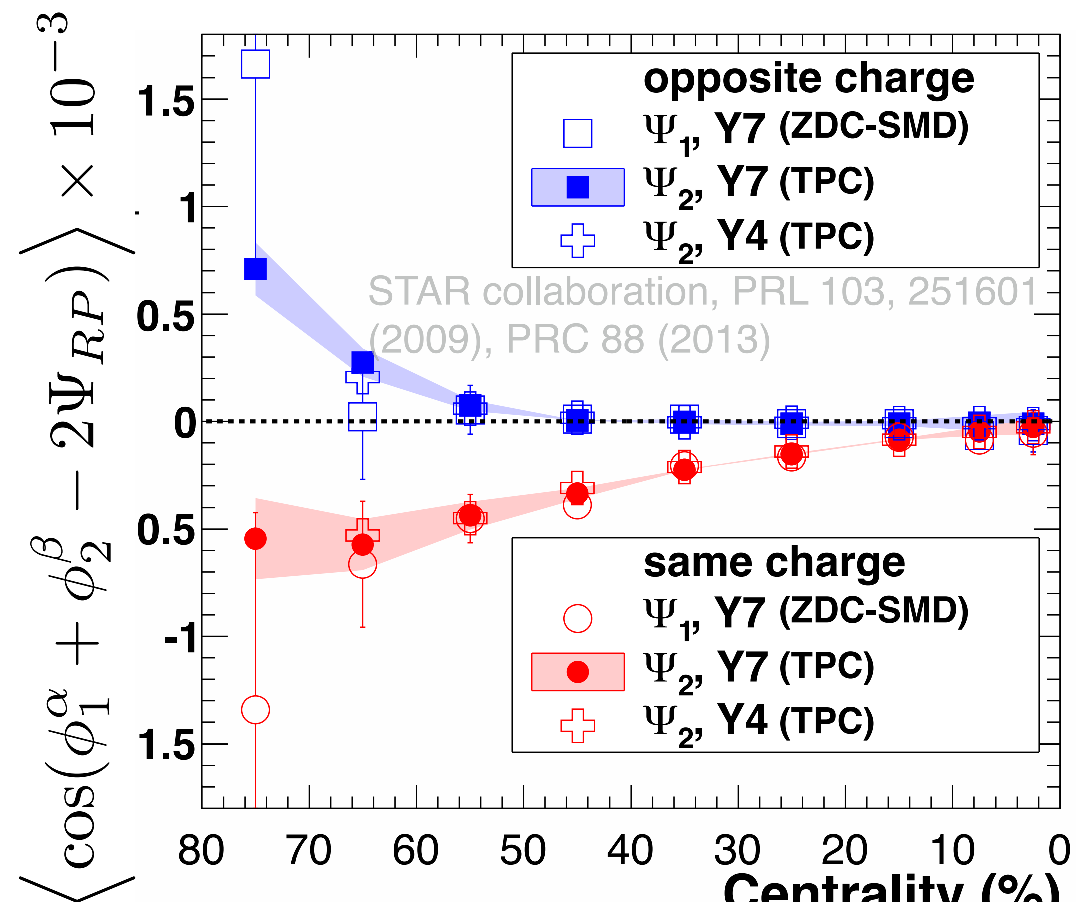
Voloshin, PRC 70 (2004) 057901

Charge separation perpendicular to Ψ_{RP}

$$\gamma^{\alpha,\beta} = \left\langle \cos(\phi_1^\alpha + \phi_2^\beta - 2\Psi_{RP}) \right\rangle$$

CME expectation

$$\gamma^{+-} = \cos(\pi/2 - \pi/2 + 0) = 1$$
$$\gamma^{++,--} = \cos(\pi/2 + \pi/2 + 0) = -1$$



p+A measurements indicate the rapid rise in peripheral events→ due to background

STAR Collaboration, Phys.Lett. B798 (2019) 134975

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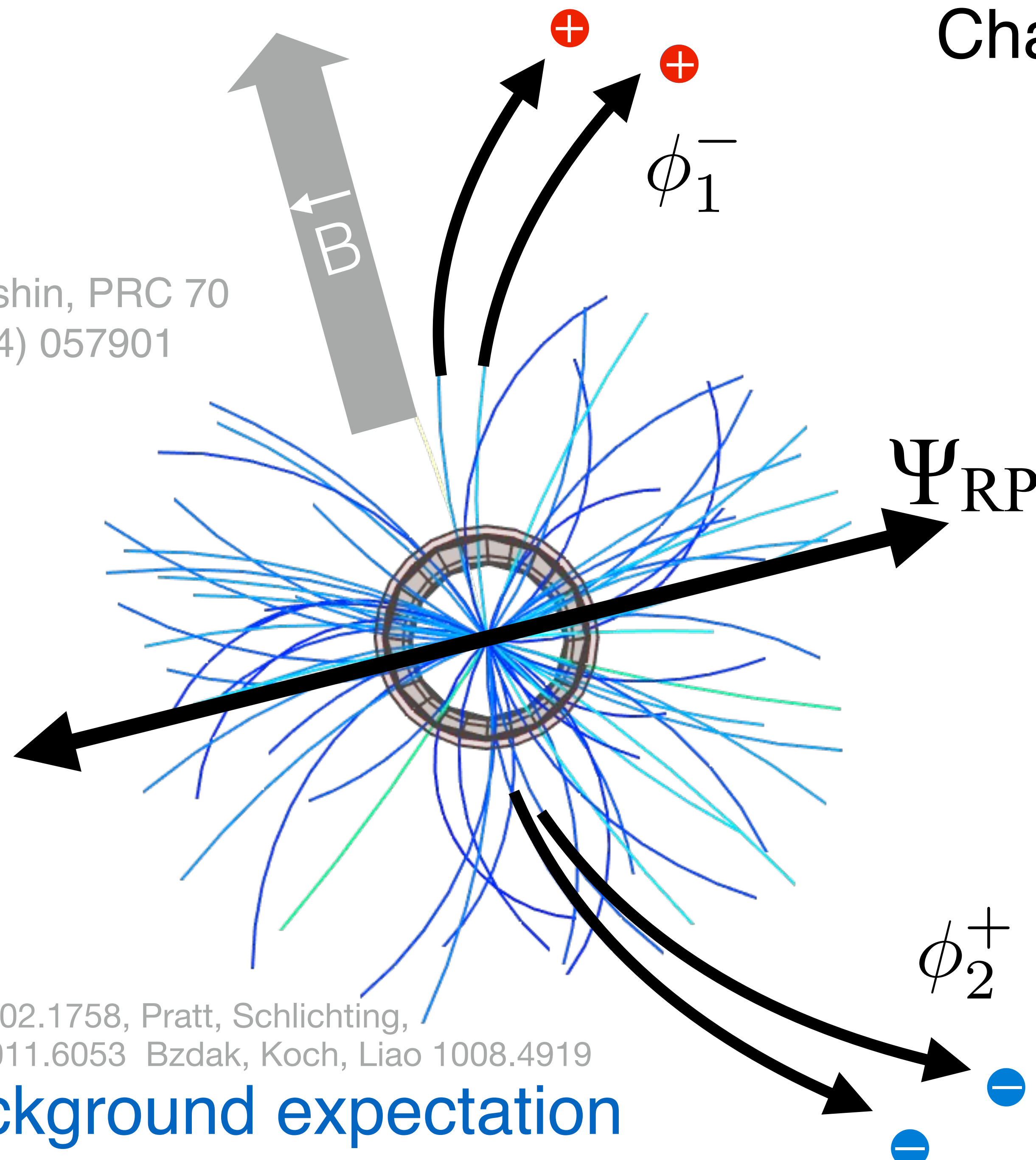

Voloshin, PRC 70 (2004) 057901

Pratt 1002.1758, Pratt, Schlichting, Gavin1011.6053 Bzdak, Koch, Liao 1008.4919

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Neutral resonance decays + flow + momentum conservation can mimic CME

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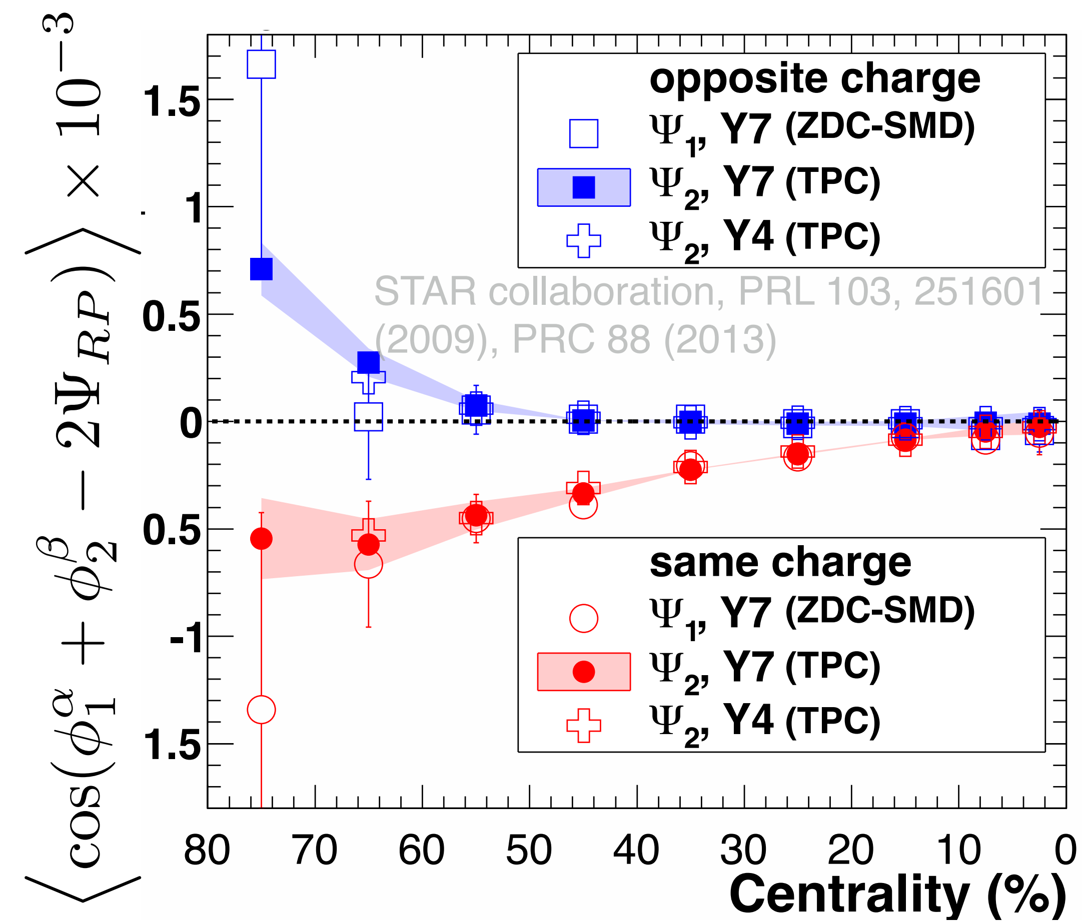

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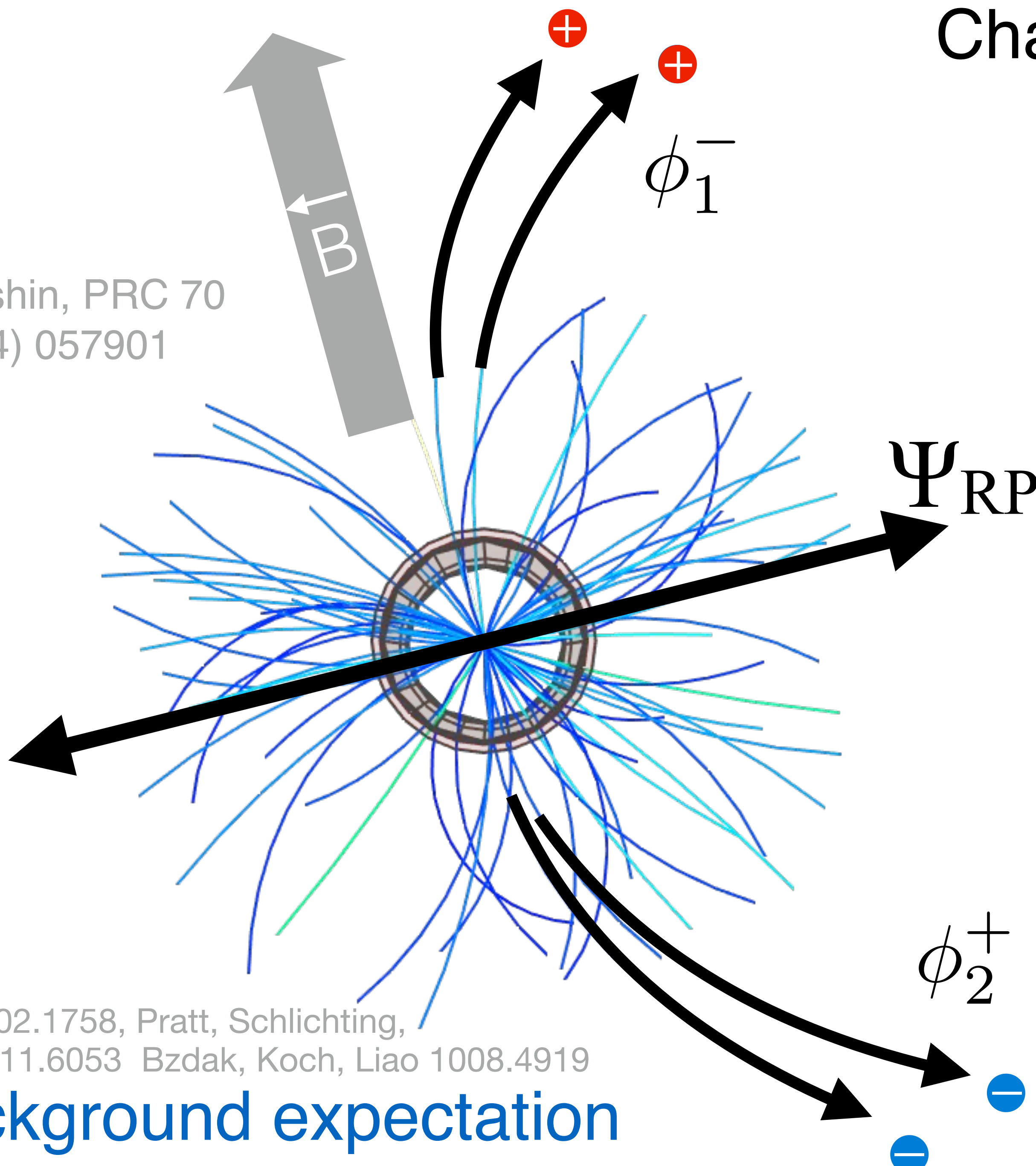

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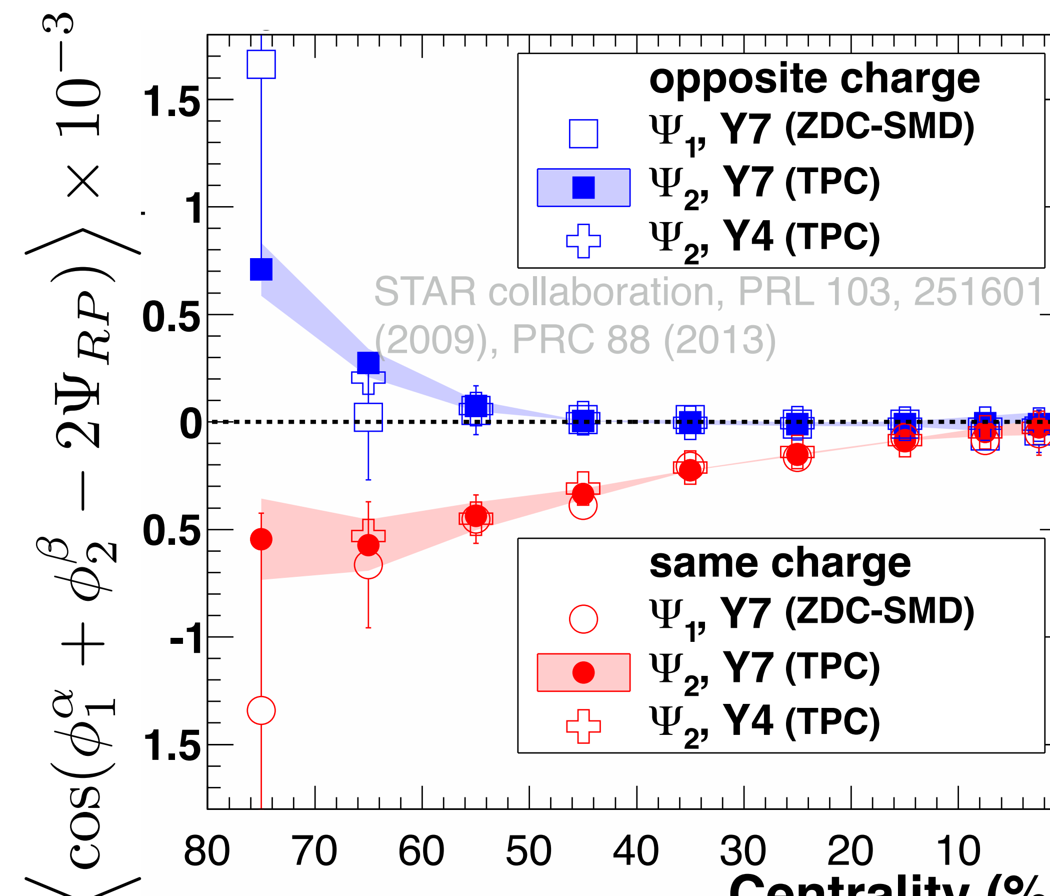


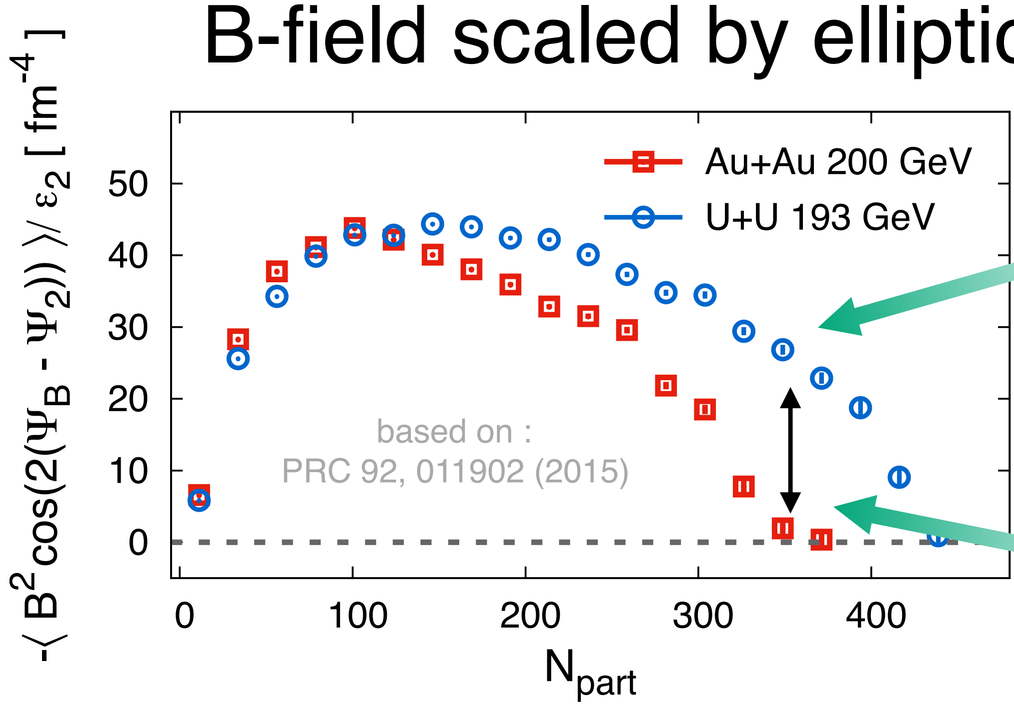
p/d+A measurements indicate the rapid rise of γ in peripheral events→ due to background

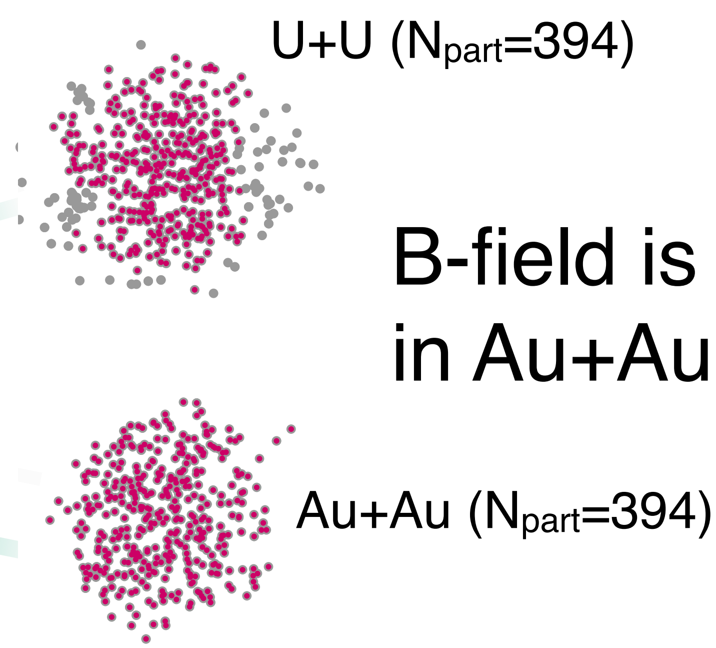
STAR Collaboration, Phys.Lett. B798 (2019) 134975

CME Search@200 GeV & Glimpse From QM2019

Some Guidance From Models

B-field scaled by ellipticity

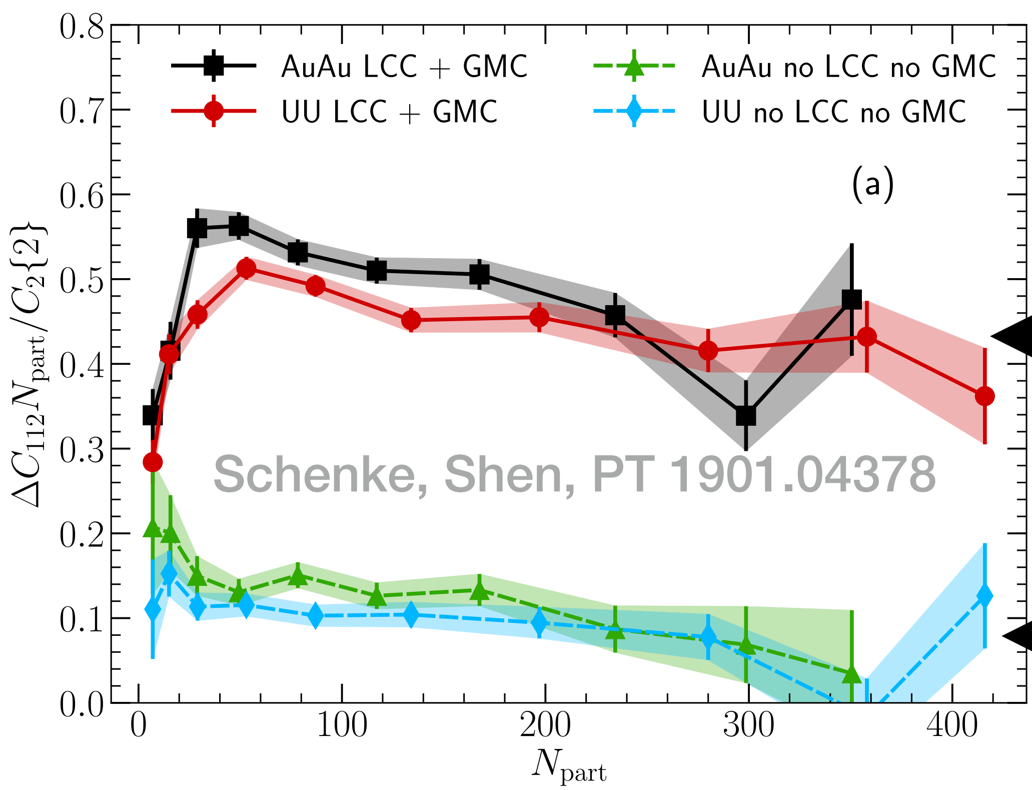




B-field is different in Au+Au and U+U

U+U & Au+Au provides unique two system configuration to contrast signal & background

Hydro + local charge conservation

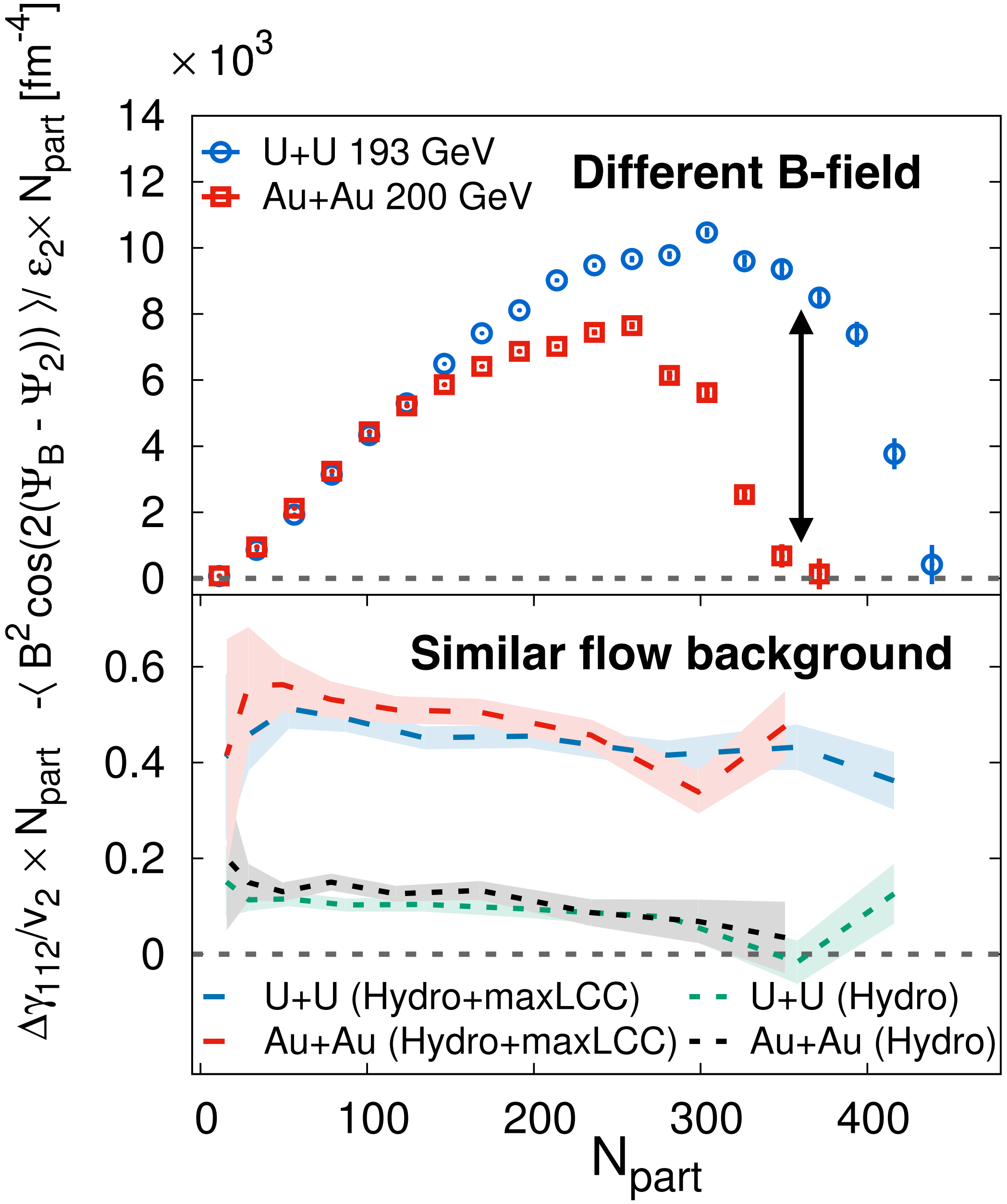


Maximum possible background

Minimum possible background

Mixed Harmonics In U+U And Au+Au

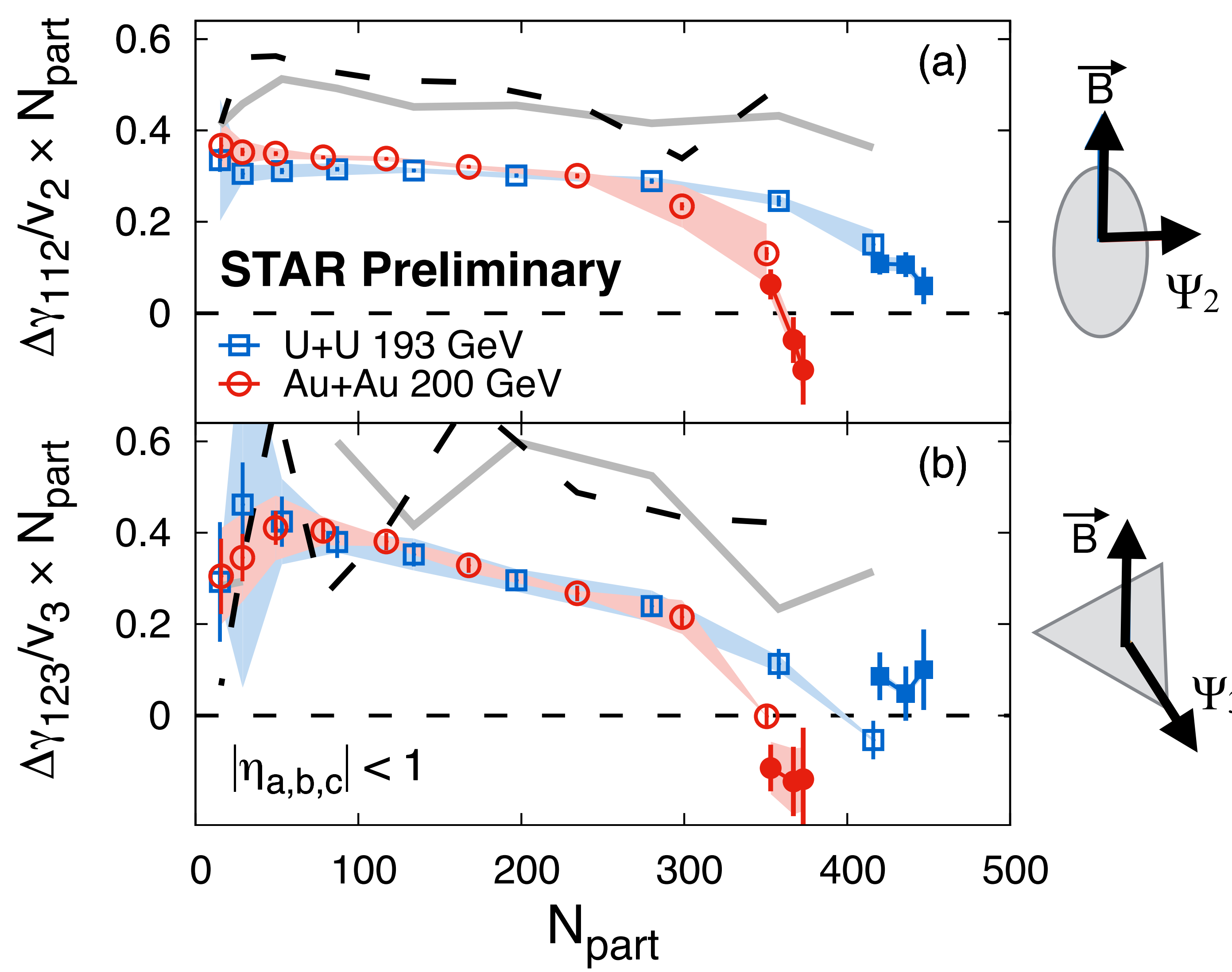
Models: signal & background expectations are different for Au+Au and U+U



Models tested with mixed harmonics:

$$\gamma_{112} = \left\langle \cos(\phi_1^\alpha + \phi_2^\beta + 2\Psi_2) \right\rangle$$

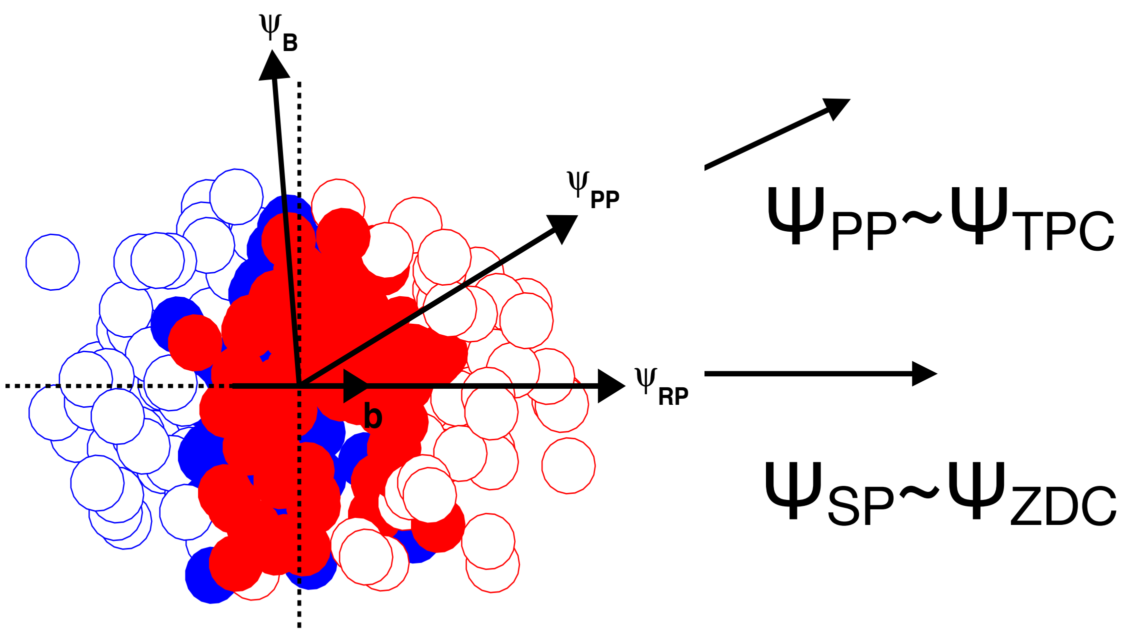
$$\gamma_{123} = \left\langle \cos(\phi_1^\alpha + 2\phi_2^\beta - 3\Psi_3) \right\rangle$$



- Data do not conform with either of B-field or Hydro+LCC expectations
- Mixed harmonics γ_{123} (100% background) provides data-driven baseline
- $\gamma_{112} \to 0$ in central events, also seen for γ_{123}, new understanding on background

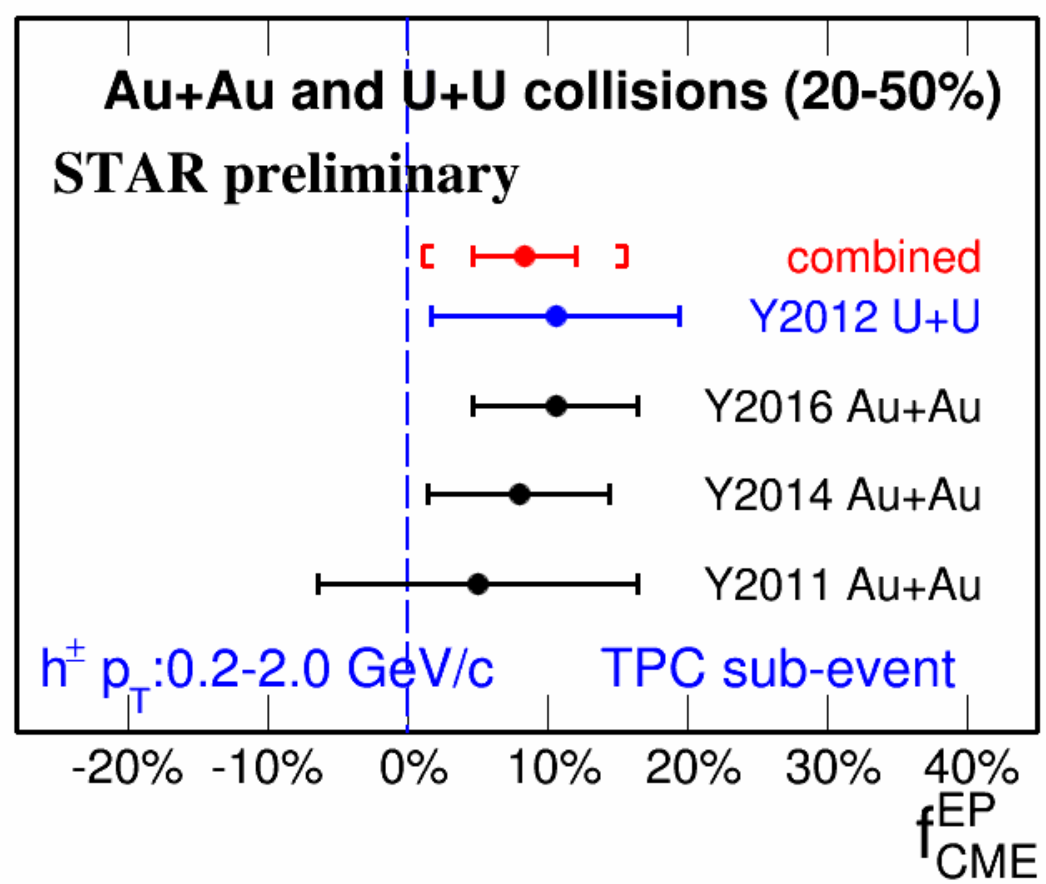
Correlation Along Participant vs. Spectators Planes

Ψ_B H-J. Xu, *et al*, CPC 42 (2018) 084103



Exploit the correlation of B-field with participants vs. spectator planes :
Small CME fraction & dominance of background

J. Zhao, QM 2019



Fraction of CME-like signals can be extracted based on the following three assumptions:

$$\Delta\gamma^{tot} = \Delta\gamma^{\rm CME} + \Delta\gamma^{\rm bkg}$$

$$\frac{\Delta\gamma^{\rm CME}(SP)}{\Delta\gamma^{\rm CME}(PP)} = \frac{v_2(PP)}{v_2(SP)}$$

$$\frac{\Delta\gamma^{\rm bkg}(SP)}{\Delta\gamma^{\rm bkg}(PP)} = \frac{v_2(SP)}{v_2(PP)}$$

also see: Voloshin, Phys. Rev. C 98, 054911 (2018)

Using Balance Function To Search For CME

Use Signed Balance Function for boosted charge pairs in three steps:

Y. Lin , QM 2019

1) Count pair momentum ordering in p_y:

$$B_{P,y}(S_y) = \frac{N_{+-}(S_y) - N_{++}(S_y)}{N_+}$$

$$B_{N,y}(S_y) = \frac{N_{-+}(S_y) - N_{--}(S_y)}{N_-}$$

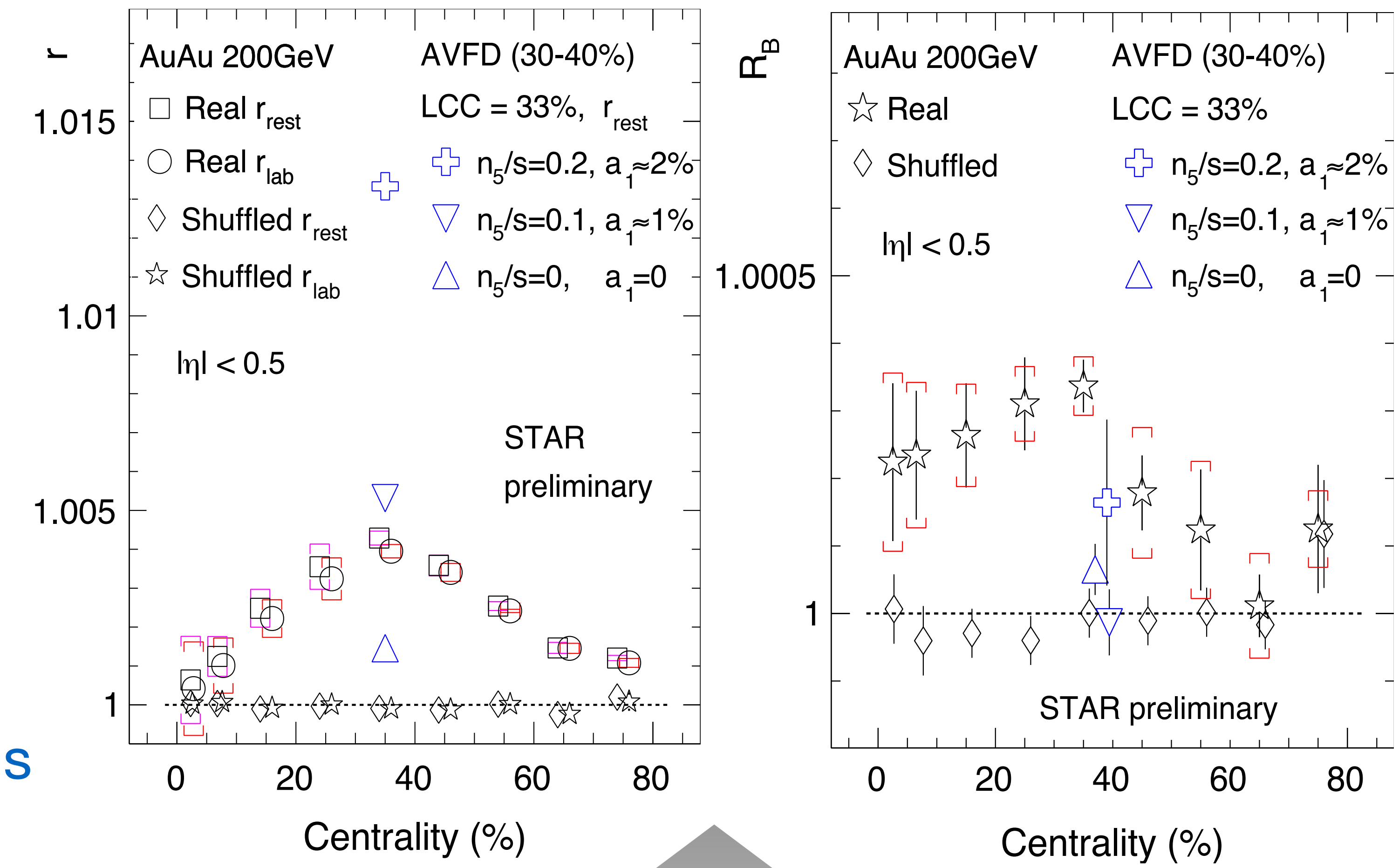
2) Count net ordering (excess of pos. leading neg.) for each event:

$$\delta B_y(\pm 1) = B_{P,y}(\pm 1) - B_{N,y}(\pm 1)$$

$$\Delta B_y = \delta B_y(+1) - \delta B_y(-1)$$

3) Look for enhanced e-by-e fluctuations of net ordering in y-direction:

$$r = \frac{\sigma_{\Delta B_y}}{\sigma_{\Delta B_x}}$$ (>1 with CME)



Both r_{rest} and R_B are larger than model calculation with no CME.

A. Tang, arXiv:1903.04622

Data difficult to explain by only backgrounds.

Other Observable

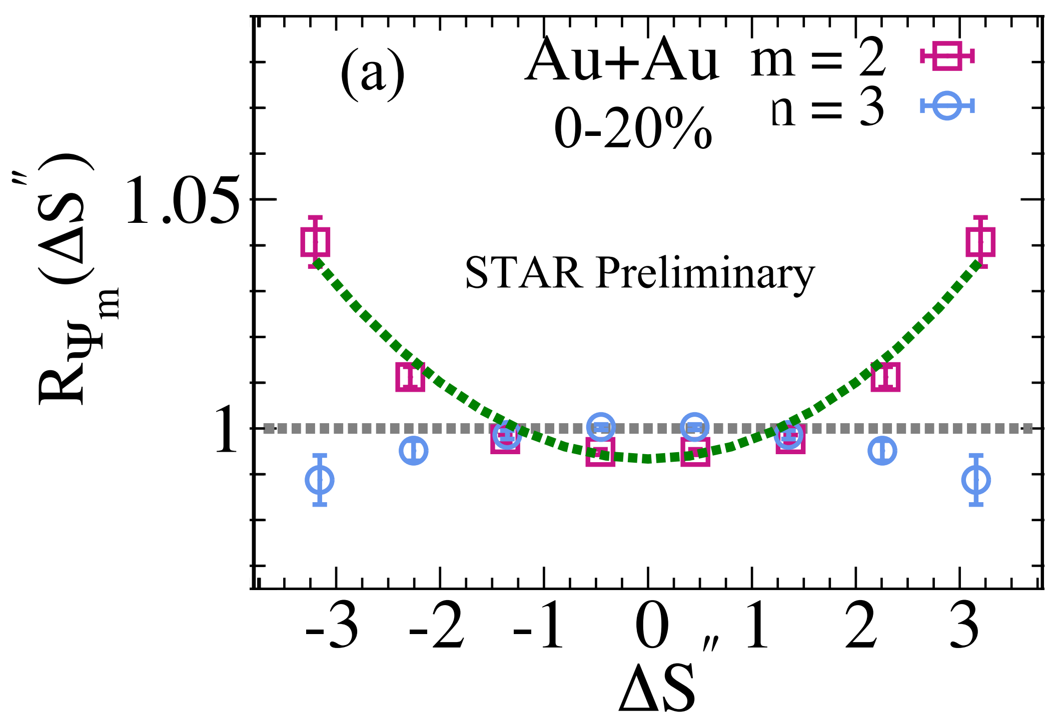
Alternate Observable To Study CME

We use $R_{\Psi_m}(\Delta S)$ correlator to study charge separation

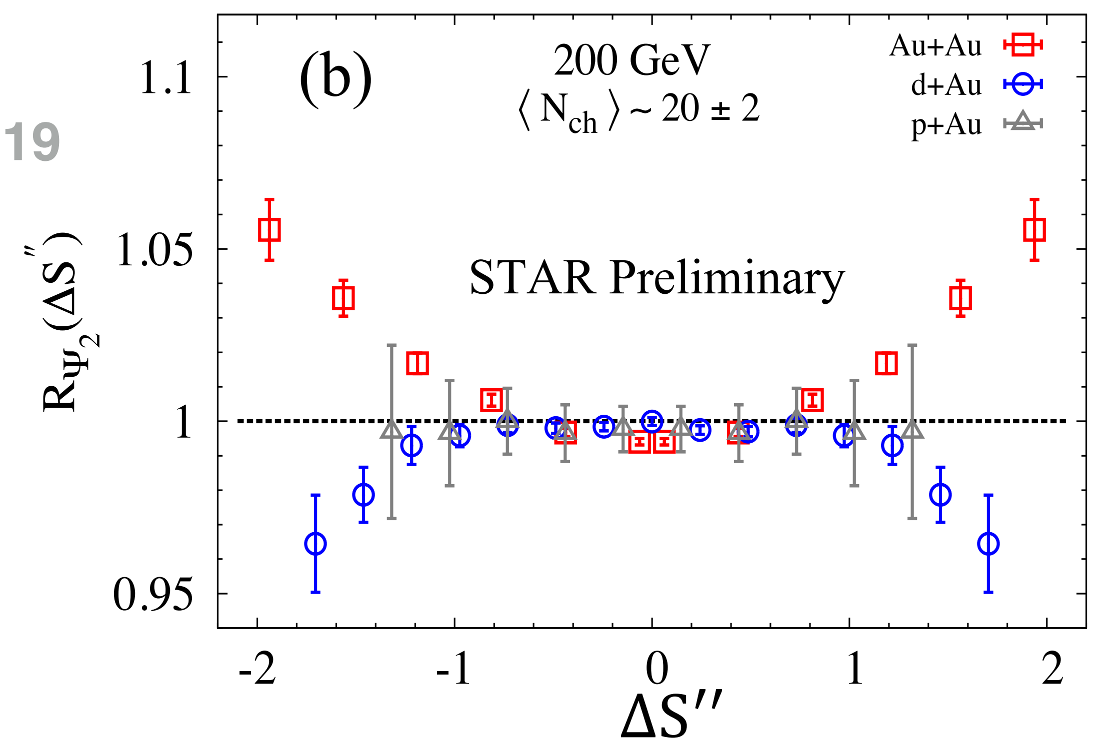
$$R_{\Psi_m}(\Delta S) = \frac{C_{\Psi_m}(\Delta S)}{C_{\Psi_m^{\perp}}(\Delta S)}, m = 2, 3$$

N. Magdy, et al.
PRC 97, 061901 (2018)

$R_{\Psi_2}(\Delta S) \rightarrow$ charge separation parallel/perpendicular to B-field (CME sensitive)
$R_{\Psi_3}(\Delta S) \rightarrow$ baseline, insensitive to CME but sensitive to background



N. Magdy, QM 2019



Different response for
R_{Ψ_2} & R_{Ψ_3}

Different response for
p/d+Au and Au+Au

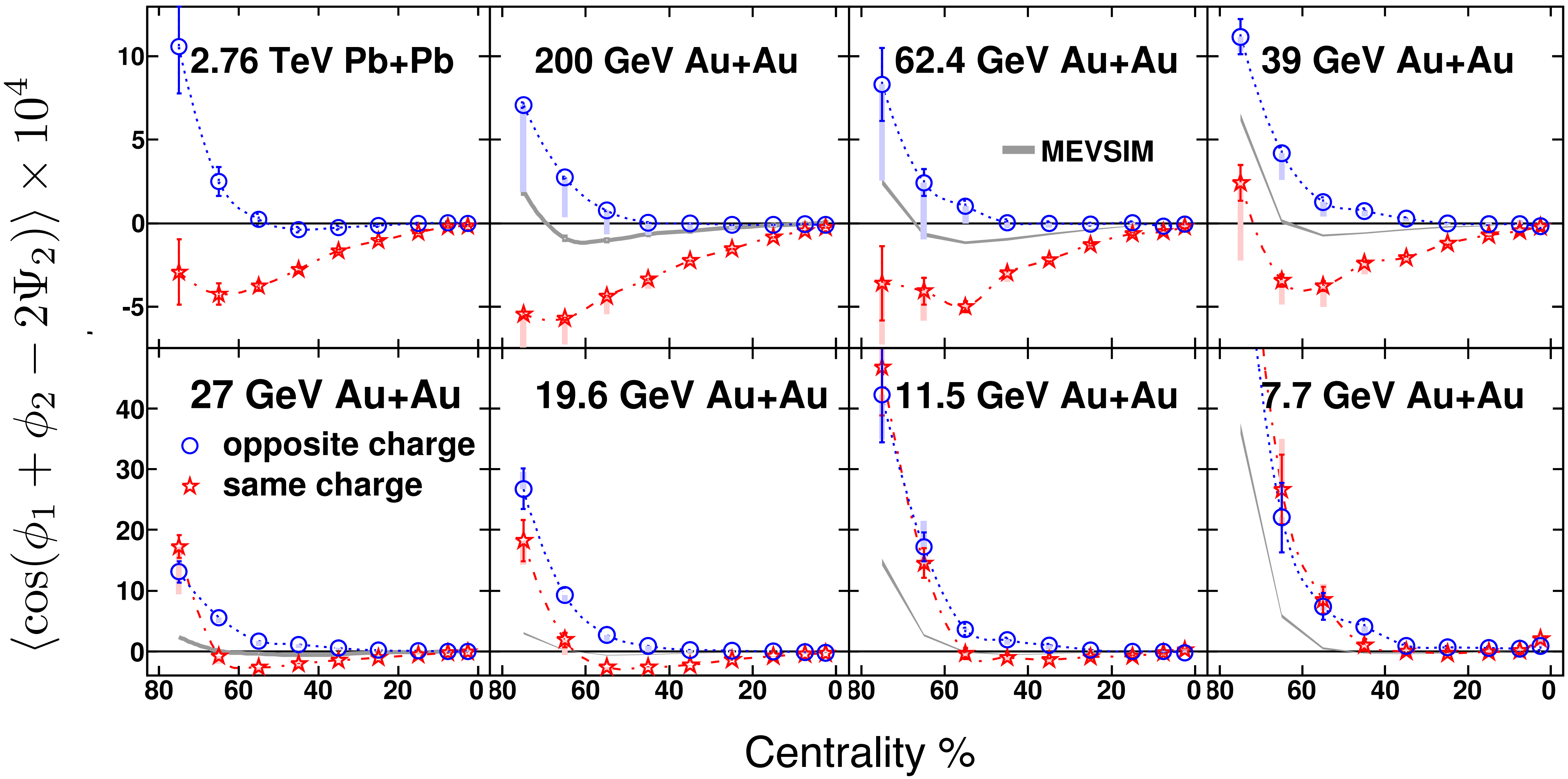
Observation consistent with expectation for CME-driven charge separation

New Developments: CME Search At Low $\sqrt{s}$

The First Measurements At RHIC: BES-I data

Charge separation vanishes at the lowest energy

L. Adamczyk et al. (STAR Collaboration), PRL 113 (2014) 052302.

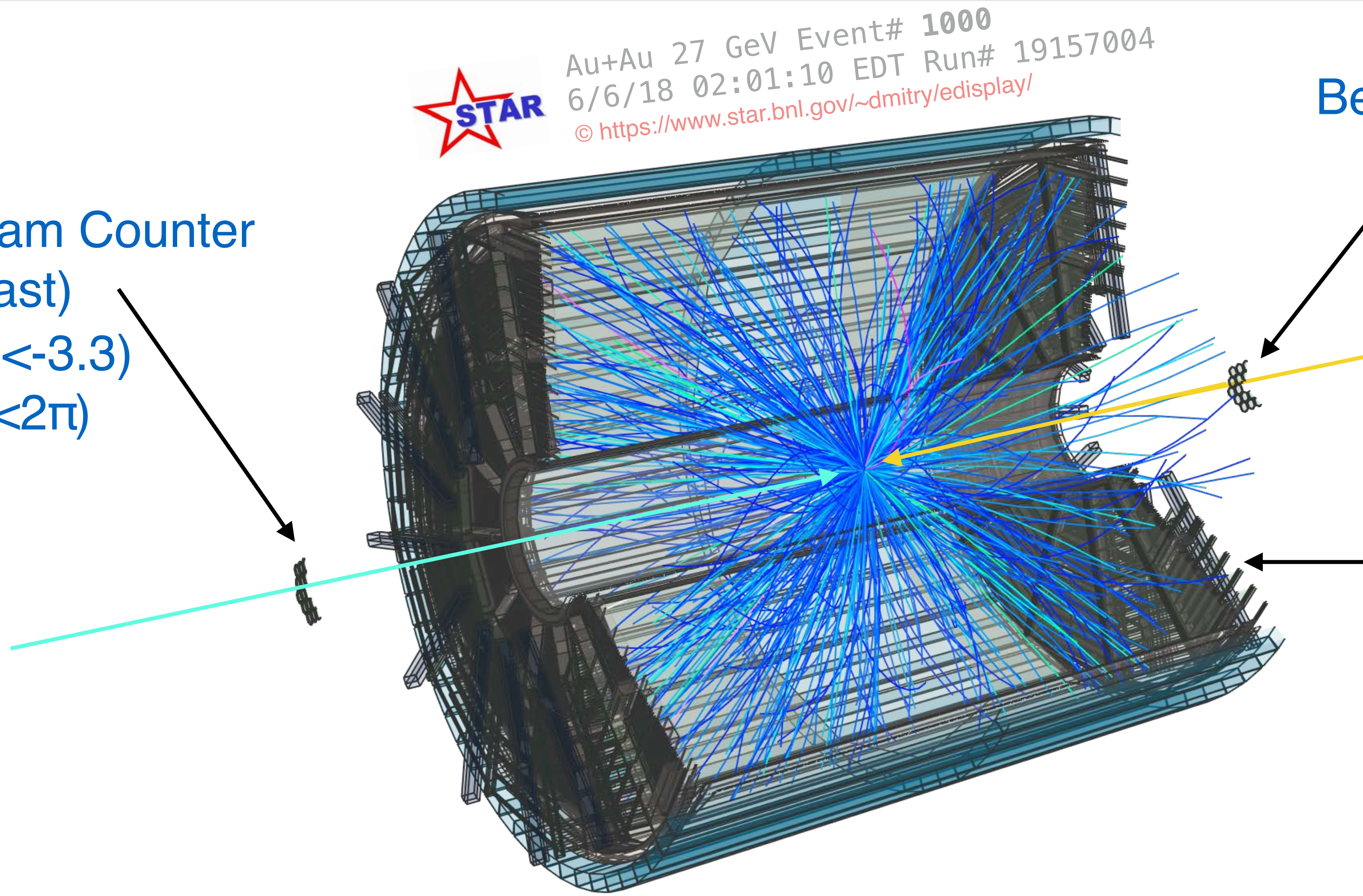


Why does charge separation disappear at lower $\sqrt{s}$?

Is this because signal vanishes or background vanishes?

Many new insights since 2014 on how to handle background

STAR Capability For CME Search At Low Energy

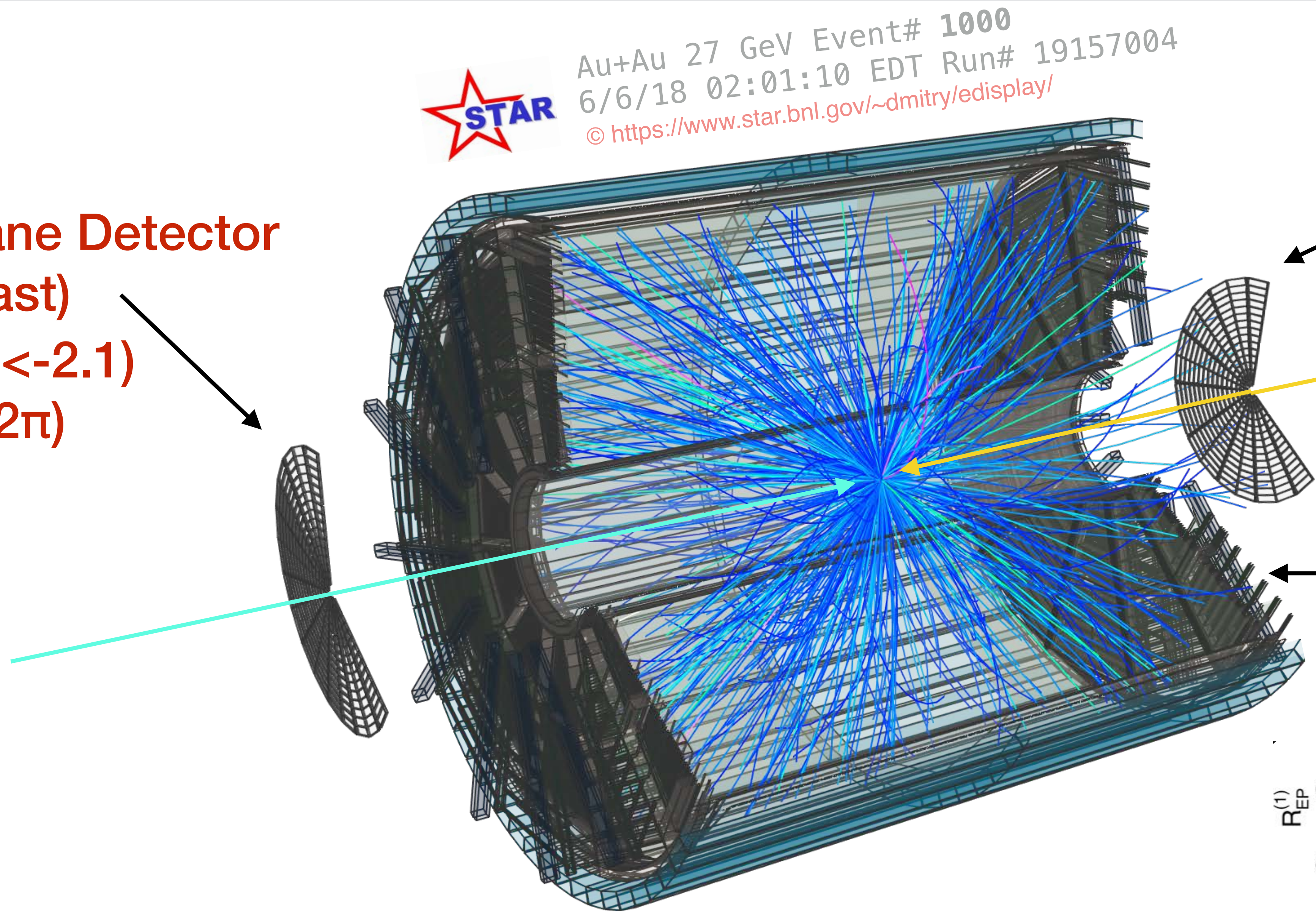


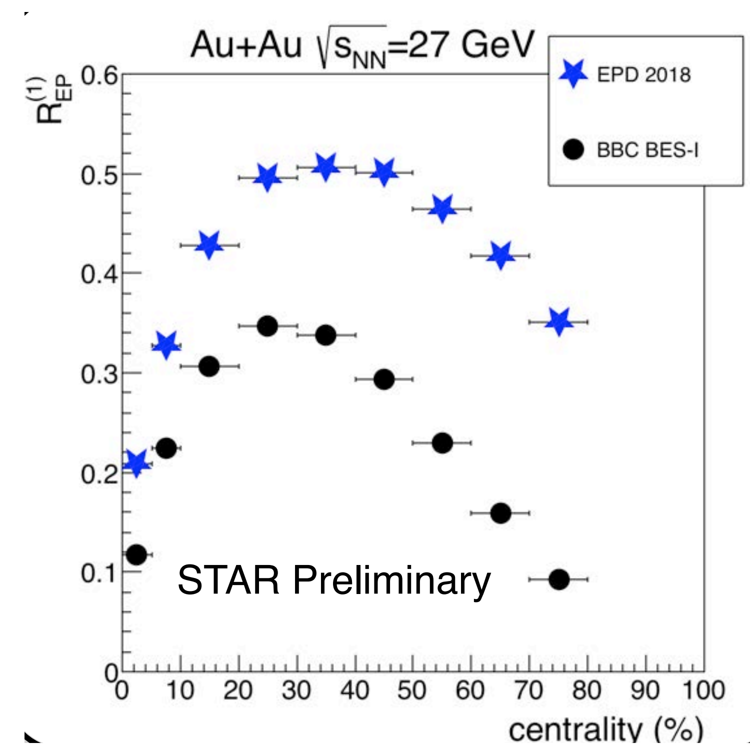
Beam-Beam Counter (East)
(-5.1<η<-3.3)
(0<ϕ<2π)

Beam-Beam Counter (West)
(3.3<η<5.1)
(0<ϕ<2π)

Time Projection Chamber
(-1<η<1)
(0<ϕ <2π)

STAR Capability For CME Search At Low Energy



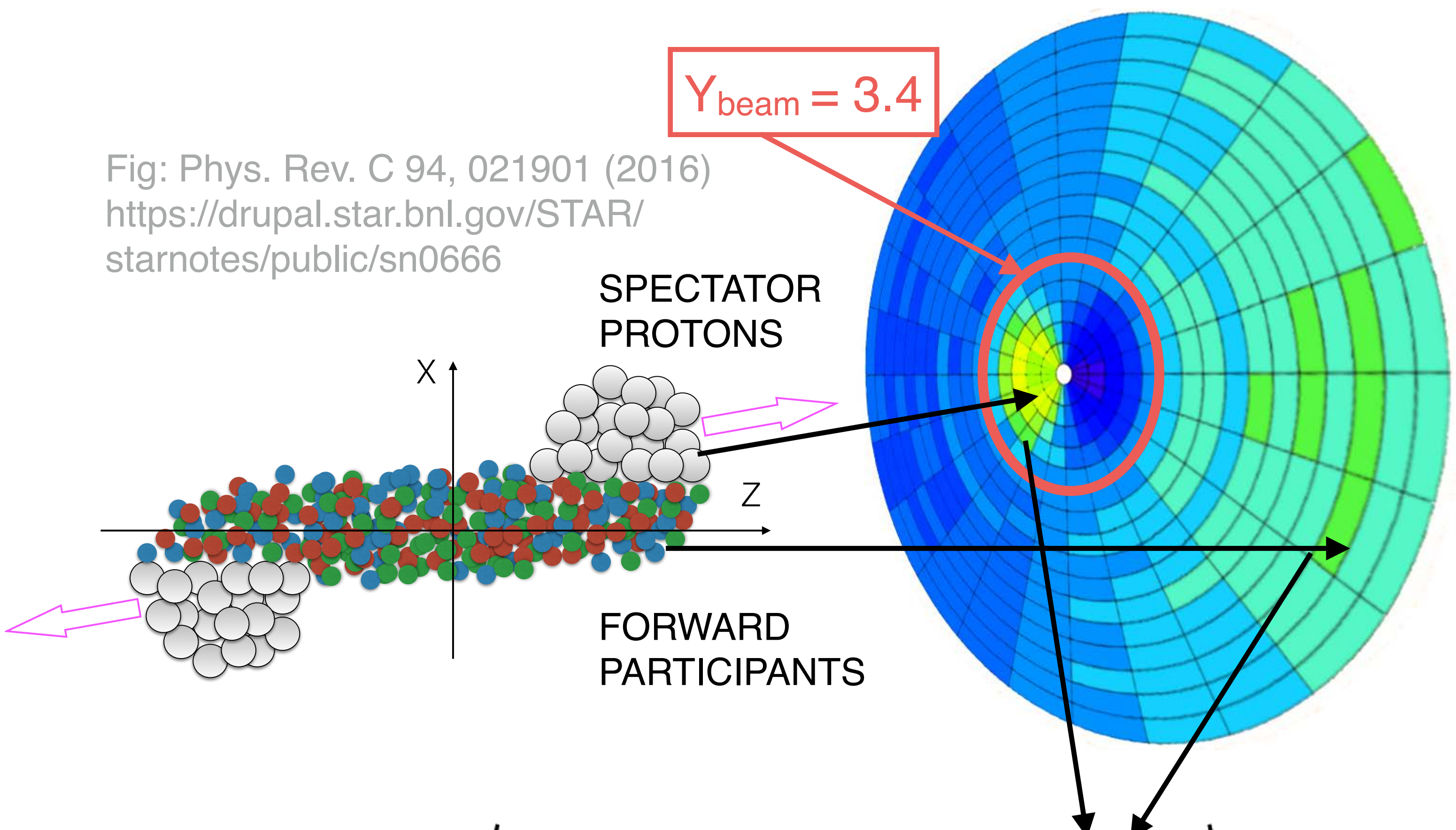


Event Plane Detector : A major upgrade for BES-II, fully installed in 2018, factor of two increase in EP resolution, reduction in non flow due to η-gap

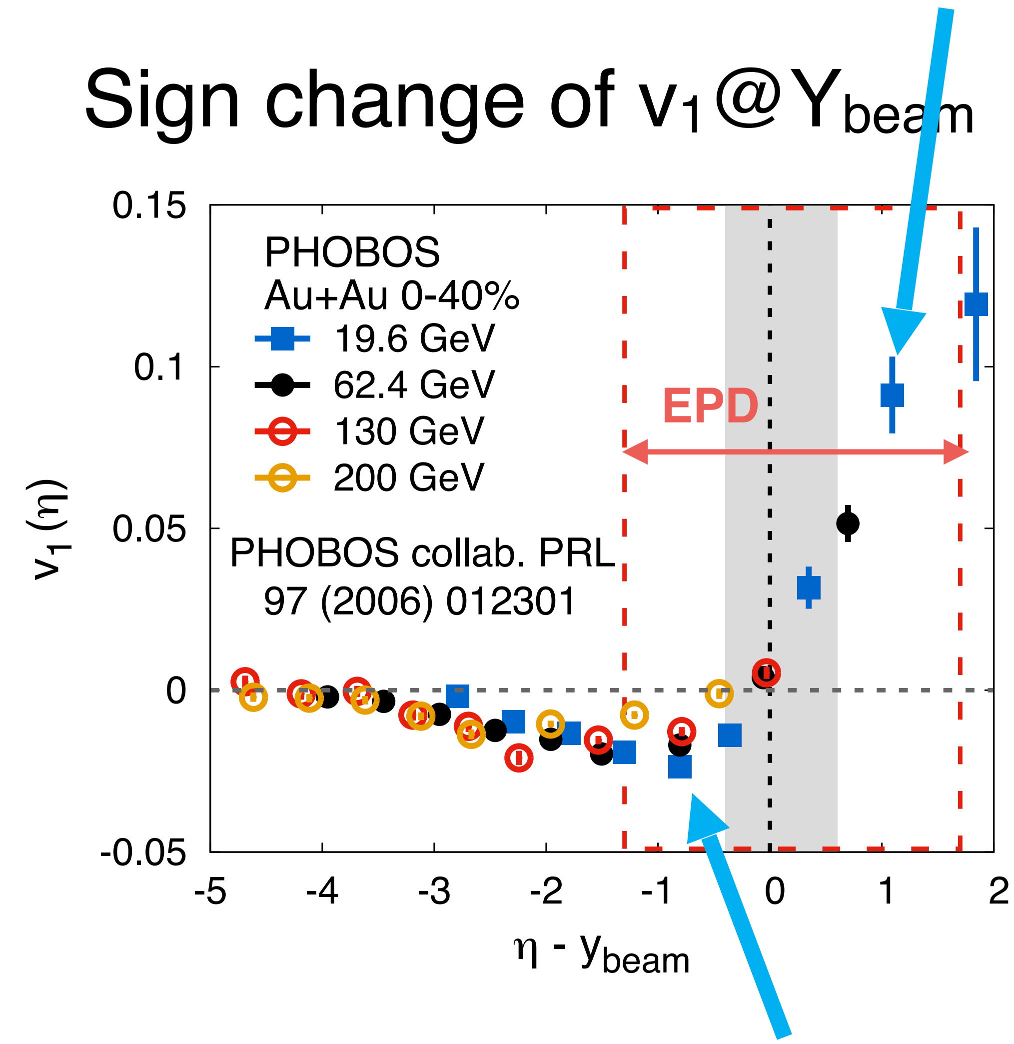
Measurements of large v_1@forward η at low $\sqrt{s}$ → new capability at STAR

Unique Advantage Of EPD At 27 GeV

STAR Event Plane detector acceptance: $2.1<|\eta|<5.1$
Beam rapidity for Au+Au 27 GeV, $Y_{beam}=3.4$



Sign change of $v_1@Y_{beam}$



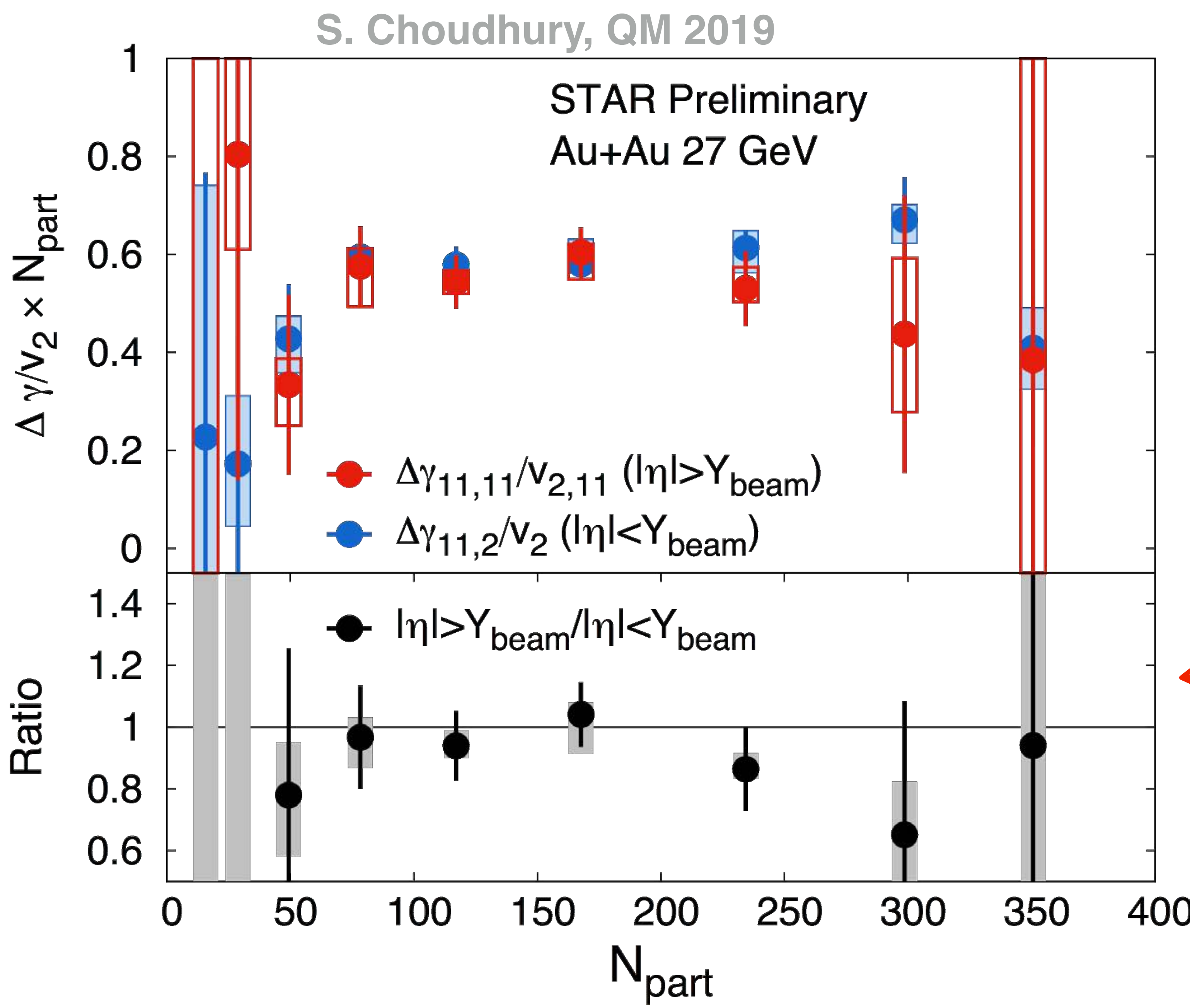
$$\gamma^{\alpha,\beta} \equiv \left\langle \cos\left(\phi_a^\alpha + \phi_b^\beta - 2\psi_{RP}\right)\right\rangle$$

We can use two planes from EPD as proxies for Ψ_{RP}

Ψ_1 ($\eta > Y_{beam}$): 1st-order plane, proton-rich (spectators, beam-fragments)
Ψ_2 ($\eta < Y_{beam}$): 2nd-order plane of forward produced particle

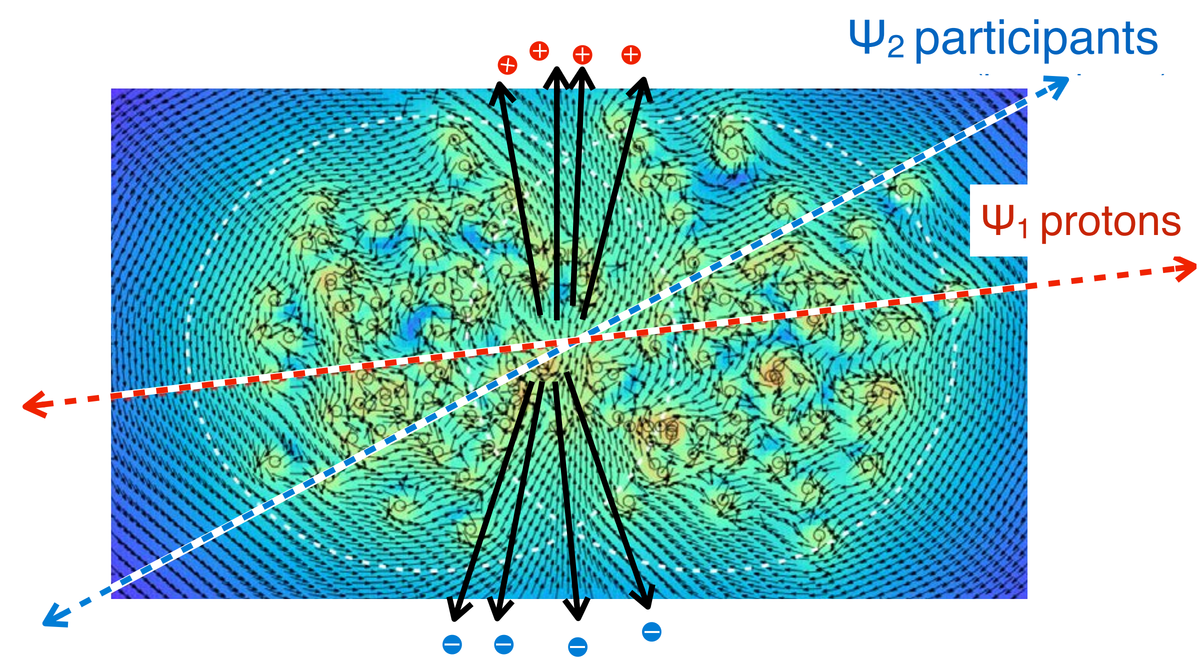
New Measurement Of Charge Separation: 27 GeV

Charge separation normalized by v_2 for planes at $|\eta|<Y_{beam}$ & $|\eta|>Y_{beam}$



Blue Symbols:
(forward particles)

Red Symbols:
(spectator protons)



No significant difference in the scaled charge separation w.r.t. spectator proton & produced particle event planes.

A Decisive Tests Of CME Using Isobar Collisions

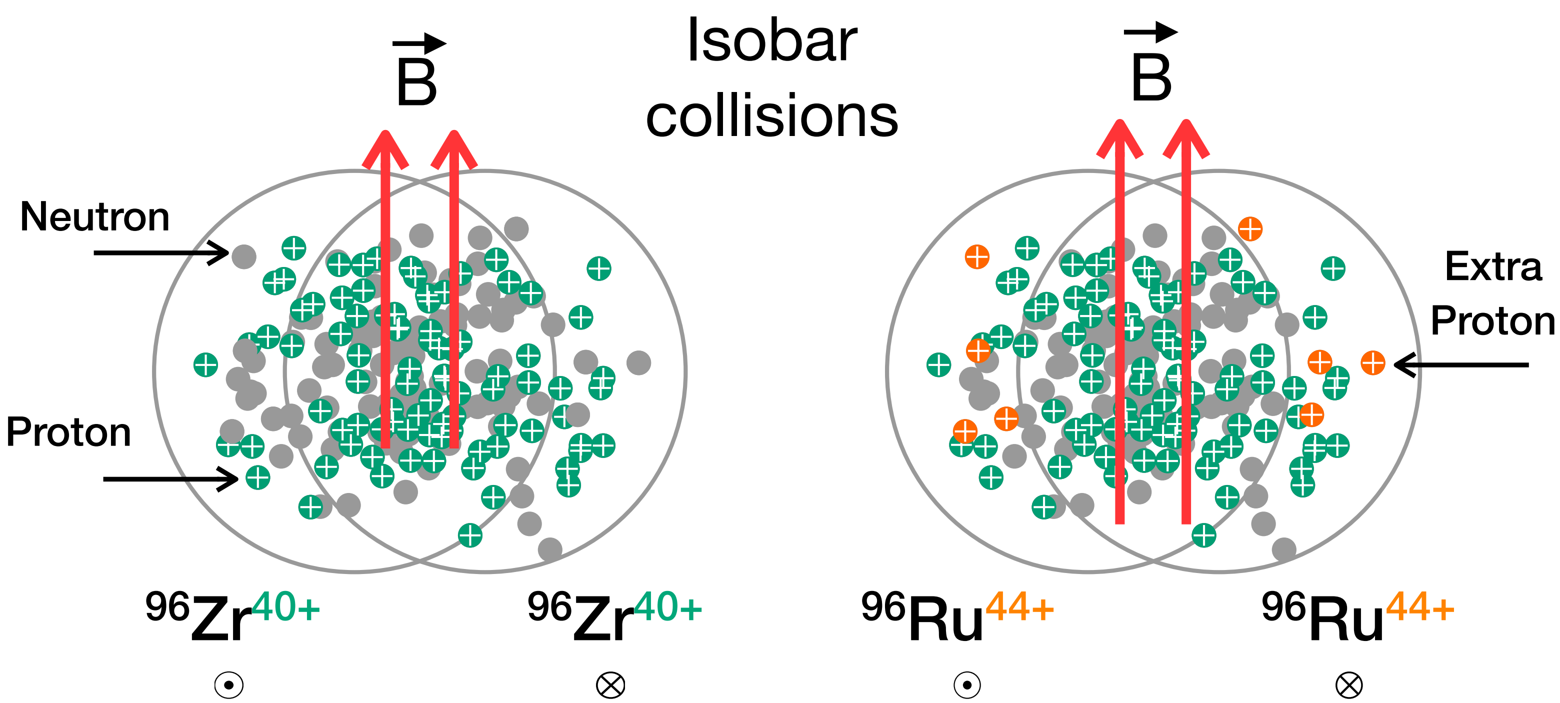
Decisive Tests Of CME Using Isobar Collisions

Phys.Rev.Lett. 105 (2010) 172301

Testing the Chiral Magnetic Effect with Central $U+U$ collisions

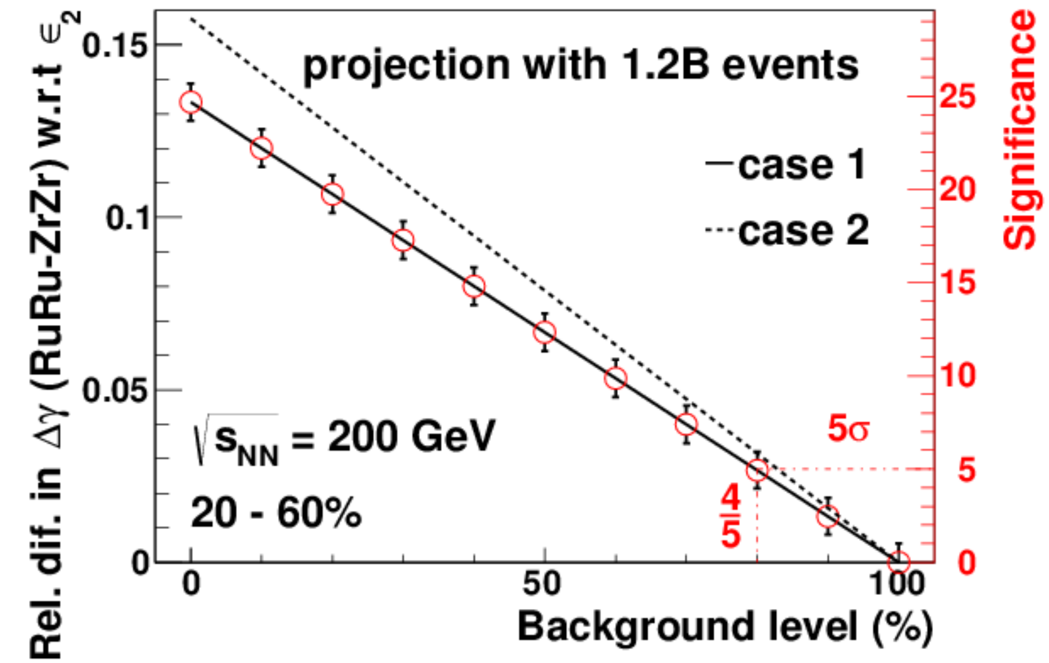
Sergei A. Voloshin
Wayne State University, Detroit, Michigan 48201, USA

The charge separation dependence on the strength of the magnetic field can be further studied with collision of isobaric nuclei, such as ${}^{96}_{44}Ru$ and ${}^{96}_{40}Zr$. These nuclei have the same mass number, but differ by the charge.



STAR's proposal and projections

https://drupal.star.bnl.gov/STAR/system/files/STAR_BUR_Run1718_v22_0.pdf



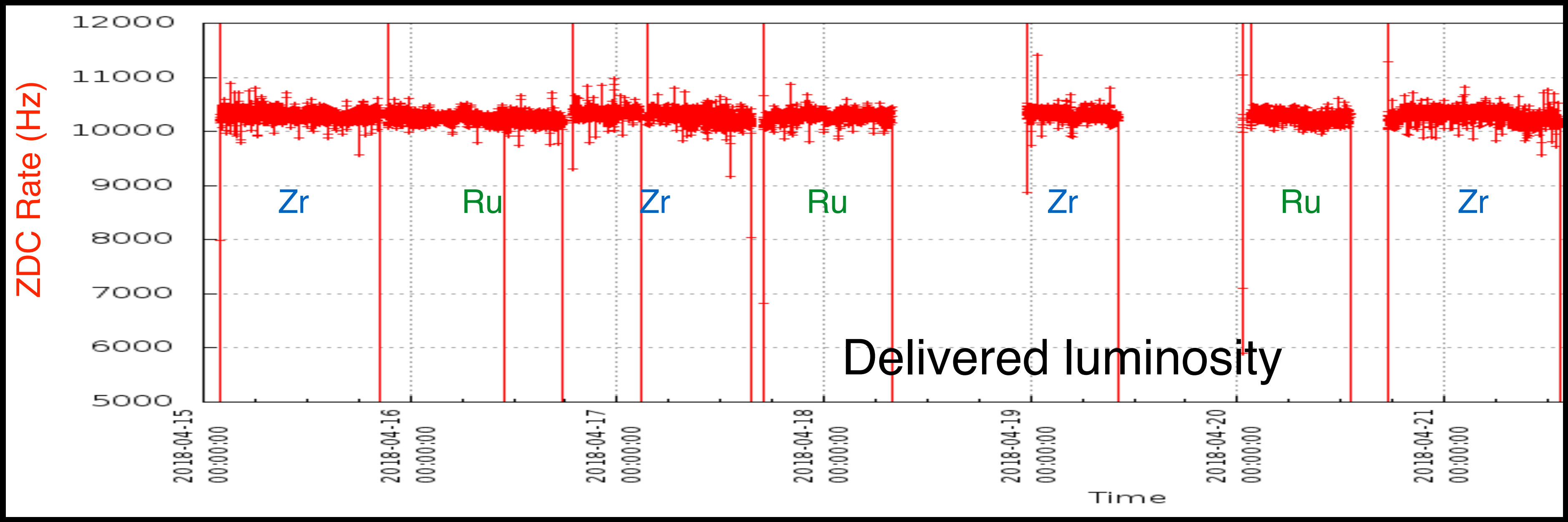
5σ difference in Δγ observable if signal is at 20% level

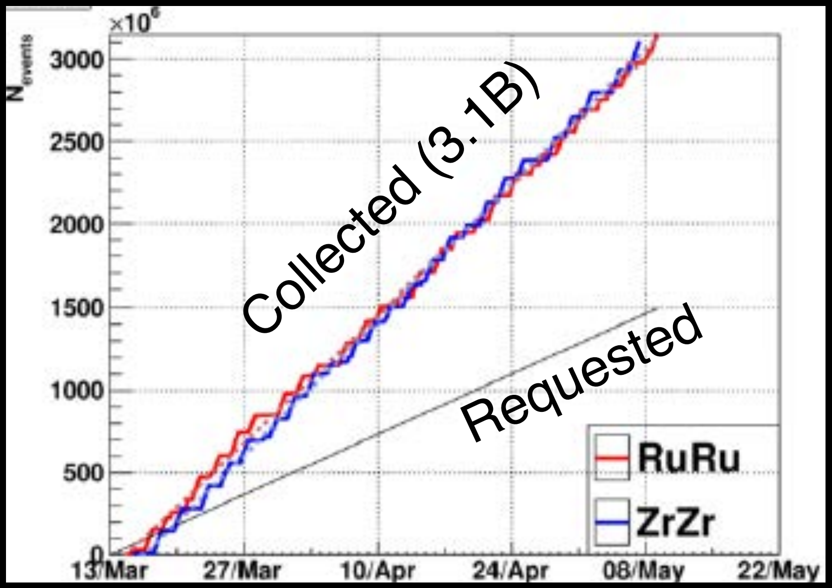
~10% larger B-field in Ru+Ru but similar background as Zr+Zr makes isobar collisions ideal to make a decisive test of CME

Many more model studies on the observability of CME with Isobar collisions have come up

Shi et al. Annals Phys. 394 (2018) 50-72 arXiv:1711.02496 [nucl-th]
Sun et al. Phys.Rev. C98 (2018) no.1, 014911 arXiv:1803.06043 [nucl-th]
Xu et al. Phys.Rev.Lett. 121 (2018) no.2, 022301 arXiv:1710.03086 [nucl-th]
Deng et al. Phys.Rev. C97 (2018) no.4, 044901 arXiv:1802.02292 [nucl-th]
Schenke et al., Phys.Rev. C99 (2019), 044908 arXiv:1901.04378 [nucl-th]
Hammelmann et al, arXiv:1901.04378

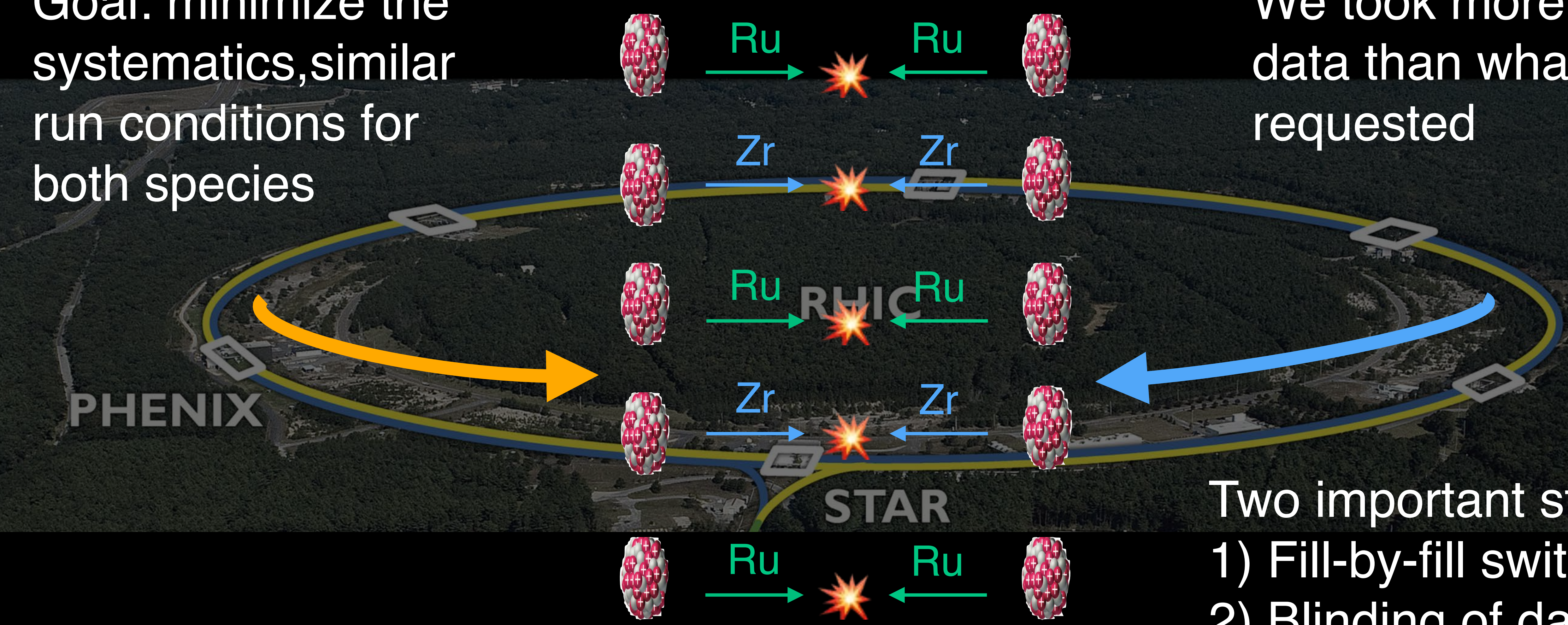
Details Of The Data Taking Of The Isobar Run





Goal: minimize the systematics,similar run conditions for both species

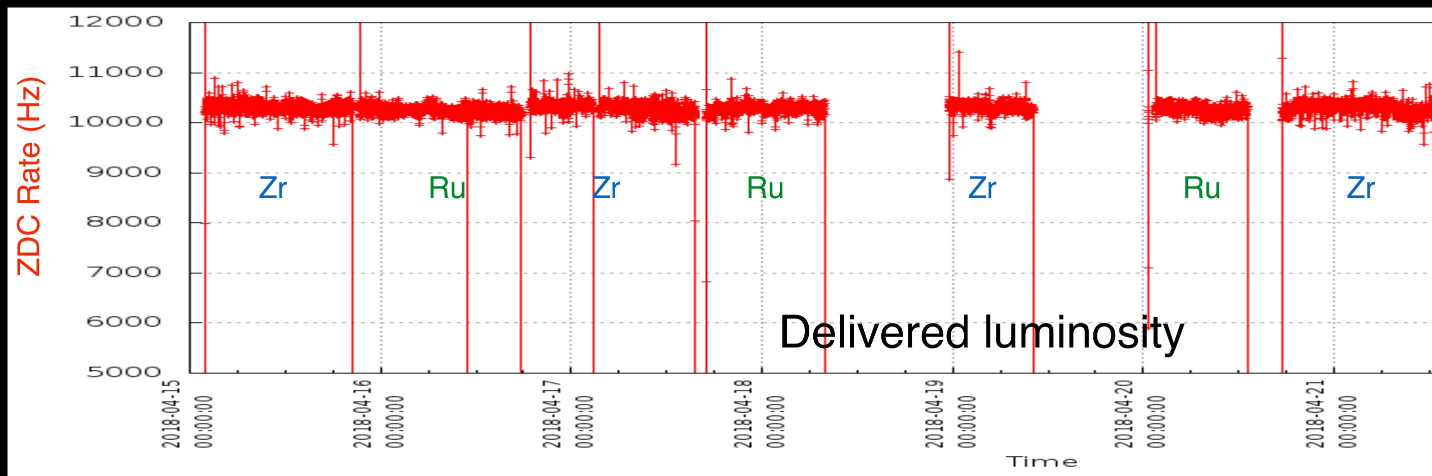
We took more data than what we requested



Two important steps:

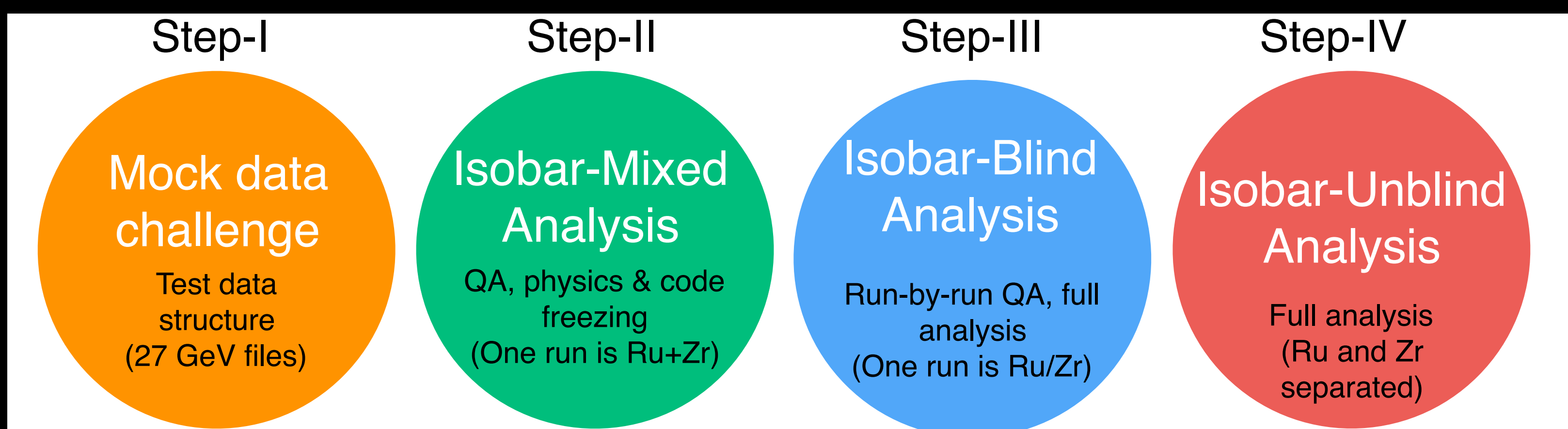
1) Fill-by-fill switching
2) Blinding of data

Isobar Run & Blind Analysis From STAR

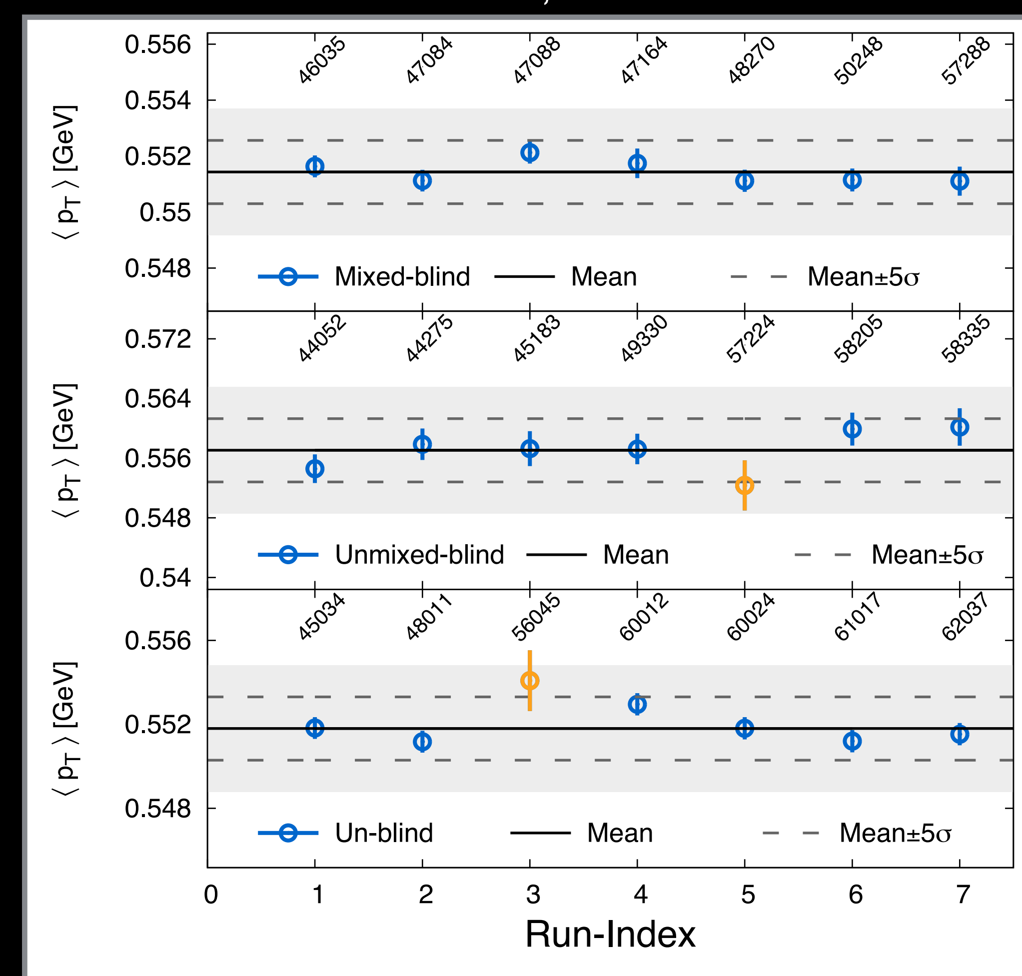


Multiple institutions actively participating in the blind analysis which is done in four steps

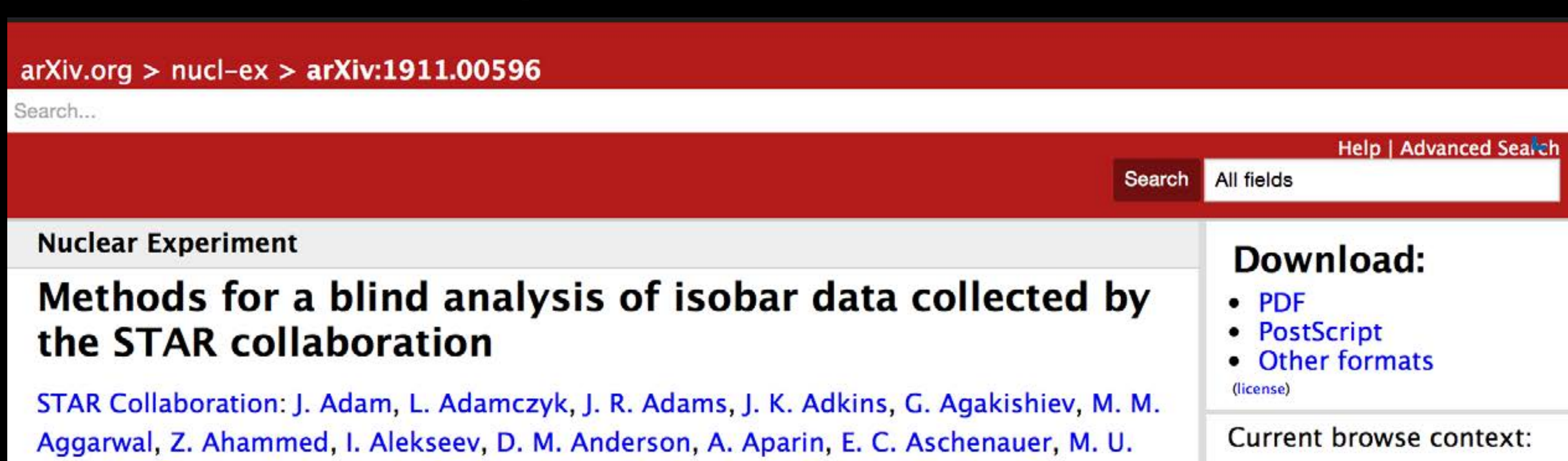
Goal is to eliminate "predetermined bias"



STAR collaboration, arXiv:1911.00596



All steps of the blind analysis were tested with mock data sample and documented


arXiv.org > nucl-ex > arXiv:1911.00596

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Nuclear Experiment

Methods for a blind analysis of isobar data collected by the STAR collaboration

STAR Collaboration: J. Adam, L. Adamczyk, J. R. Adams, J. K. Adkins, G. Agakishiev, M. M. Aggarwal, Z. Ahammed, I. Alekseev, D. M. Anderson, A. Aparin, E. C. Aschenauer, M. U.

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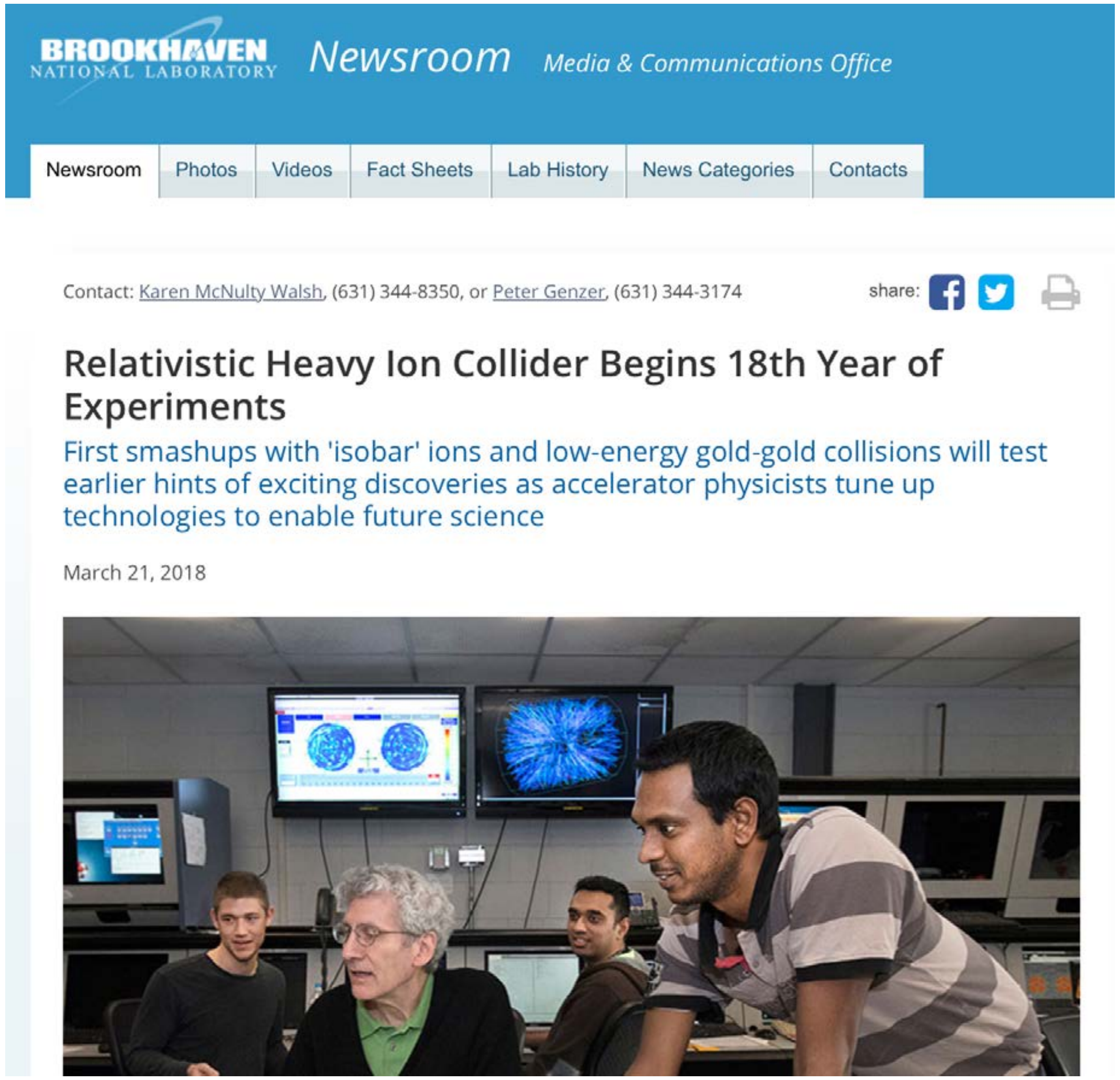
Current browse context:

Summary

Very exciting time at RHIC

1) Comprehensive set of measurements on CME, several new approaches indicate dominance of background and small CME signals but no decisive tests yet

3) Isobar data taking was a success, bind analysis is ongoing by STAR



We will hopefully have the answer to CME in a few months

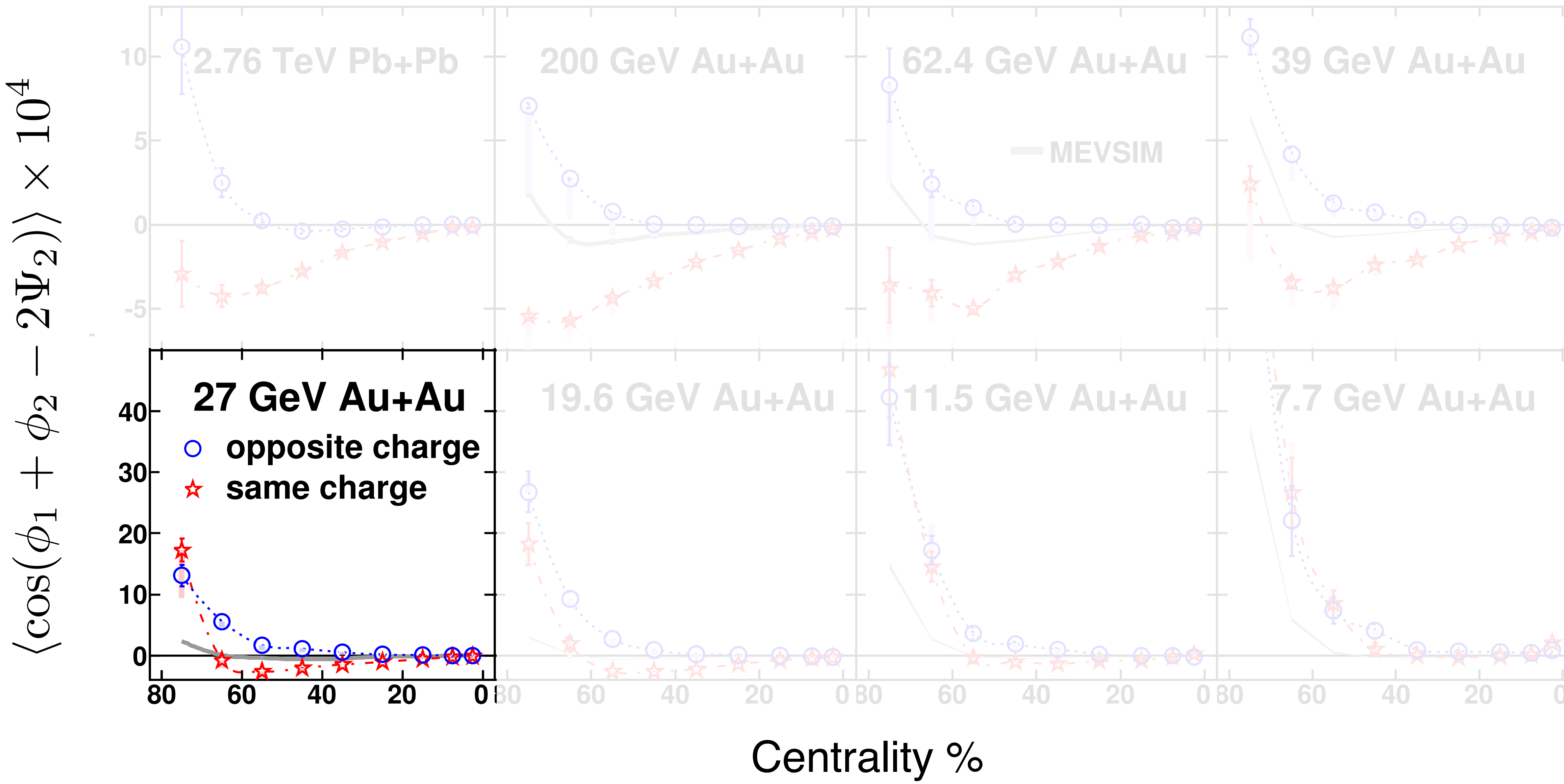
Thanks

Backup

The First Measurements At RHIC: BES-I data

Charge separation vanishes at the lowest energy

L. Adamczyk et al. (STAR Collaboration), PRL 113 (2014) 052302.



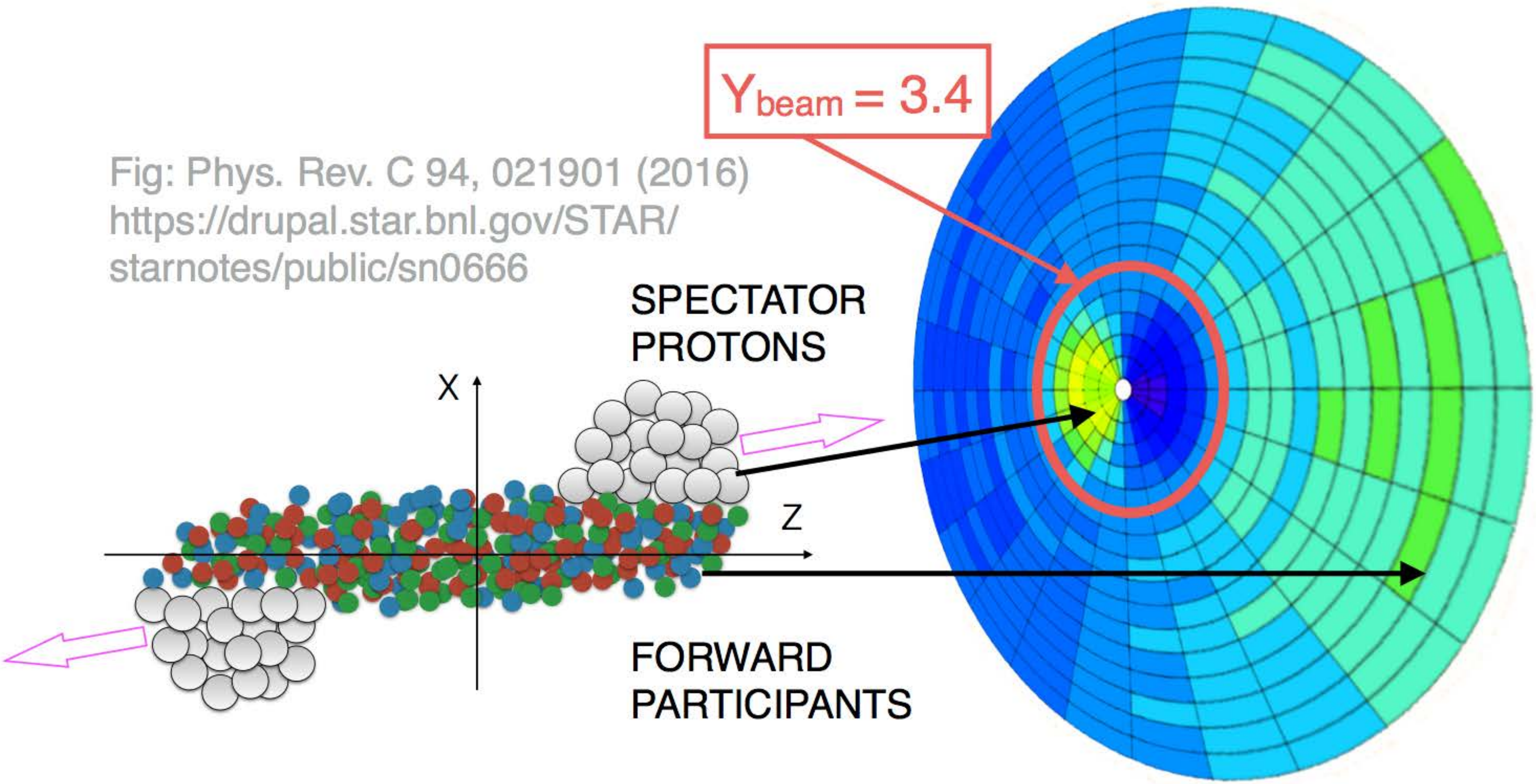
Why does charge separation disappear at lower √s ?

Is this because signal vanishes or background vanishes?

Many new insights since 2014 on how to handle background

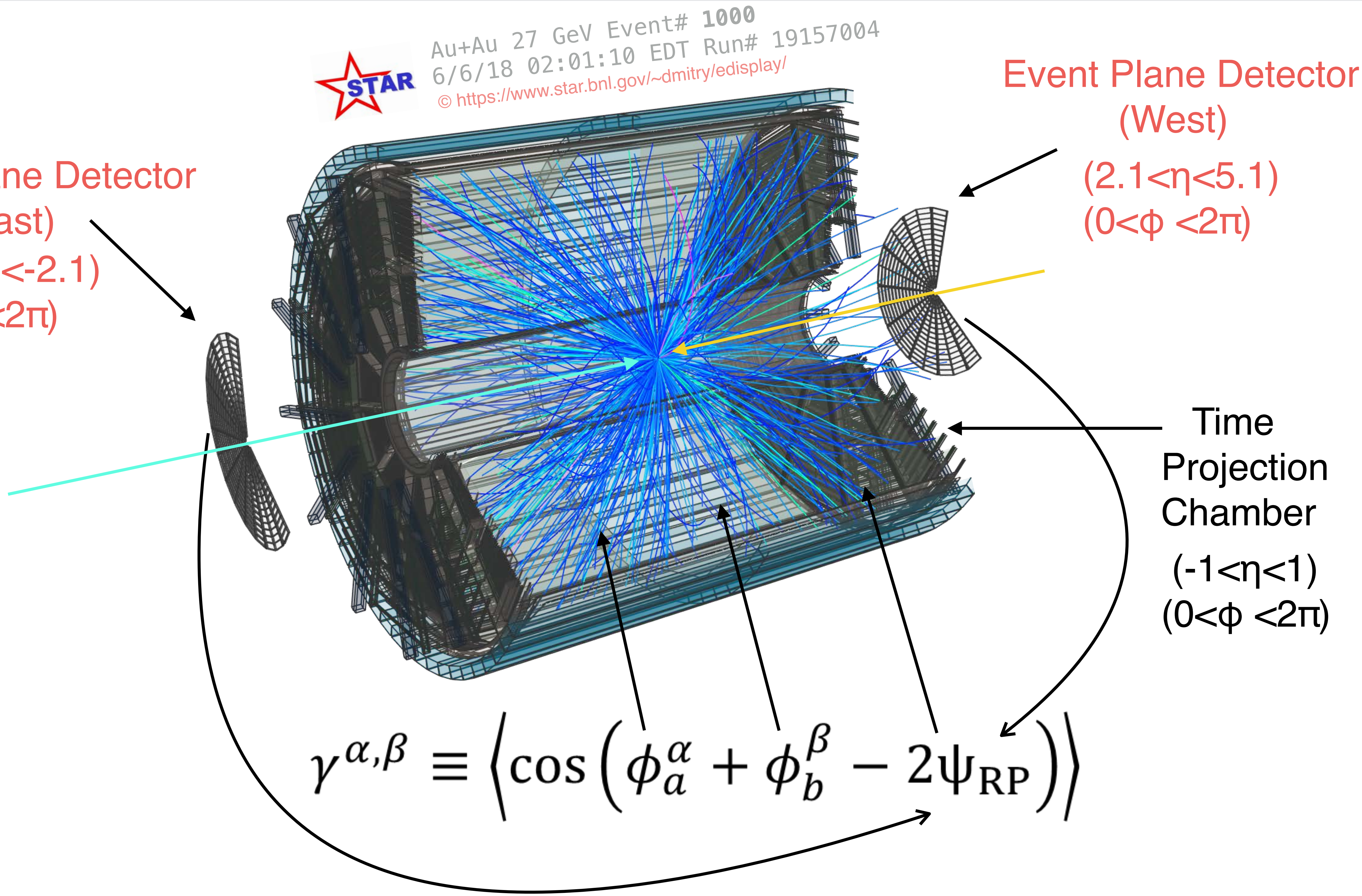
Unique advantage of EPD at 27 GeV

STAR Event Plane detector acceptance: $2.1<|\eta|<5.1$
Beam rapidity for Au+Au 27 GeV, $Y_{beam}=3.4$



EPD detects both participants & spectators

STAR capability for CME search at low energy



$$\gamma^{\alpha,\beta} \equiv \left\langle \cos\left(\phi_a^{\alpha} + \phi_b^{\beta} - 2\psi_{\mathrm{RP}}\right)\right\rangle$$

We measure charge-dependent azimuthal correlators using TPC and EPD