Search for Chiral & Vortical effects at RHIC

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BROOKHAVEN
NATIONAL LABORATORY

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APS physics™

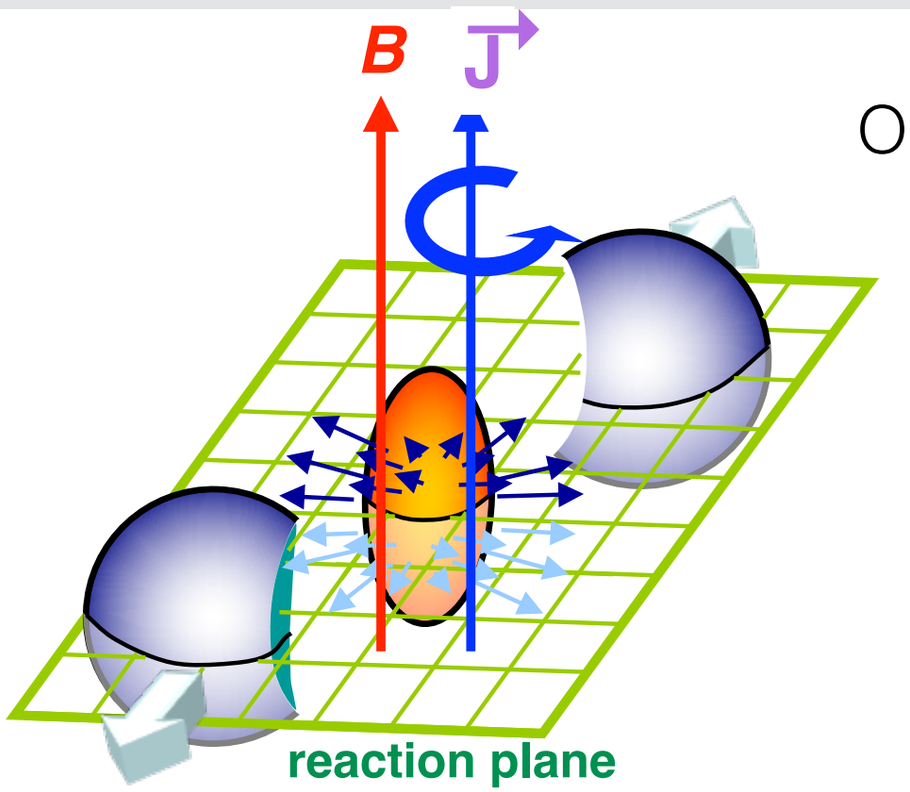
U.S. DEPARTMENT OF ENERGY | Office of Science

Outline

Strong magnetic field

$B \sim 10^{18}$ Gauss

D. Kharzeev, L. McLerran, and H. Warringa, Nucl.Phys.A803, 227 (2008)
McLerran and Skokov, Nucl. Phys. A929, 184 (2014)



Orbital angular momentum

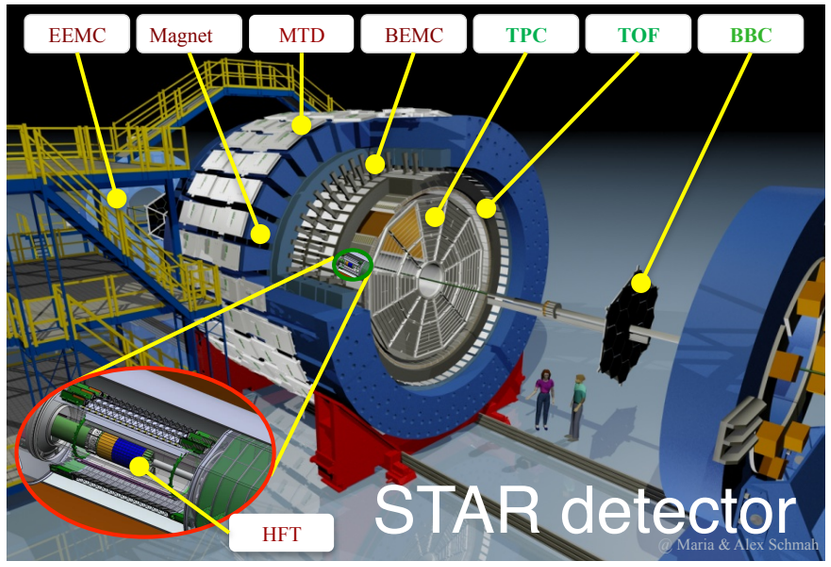
$L \sim 10^{3} \hbar$

Z.-T. Liang and X.-N. Wang, PRL94, 102301 (2005)

Relativistic Heavy Ion collisions can produce large electro-magnetic fields and angular momentum → what are the observable consequence?

I will focus on RHIC measurements and particularly from STAR on the search for Vortical & Chiral effects

200 GeV : U+U, Cu+Cu, p+Au, d+Au
Ru+Ru, Zr+Zr, 7.7-200 GeV : Au+Au BES

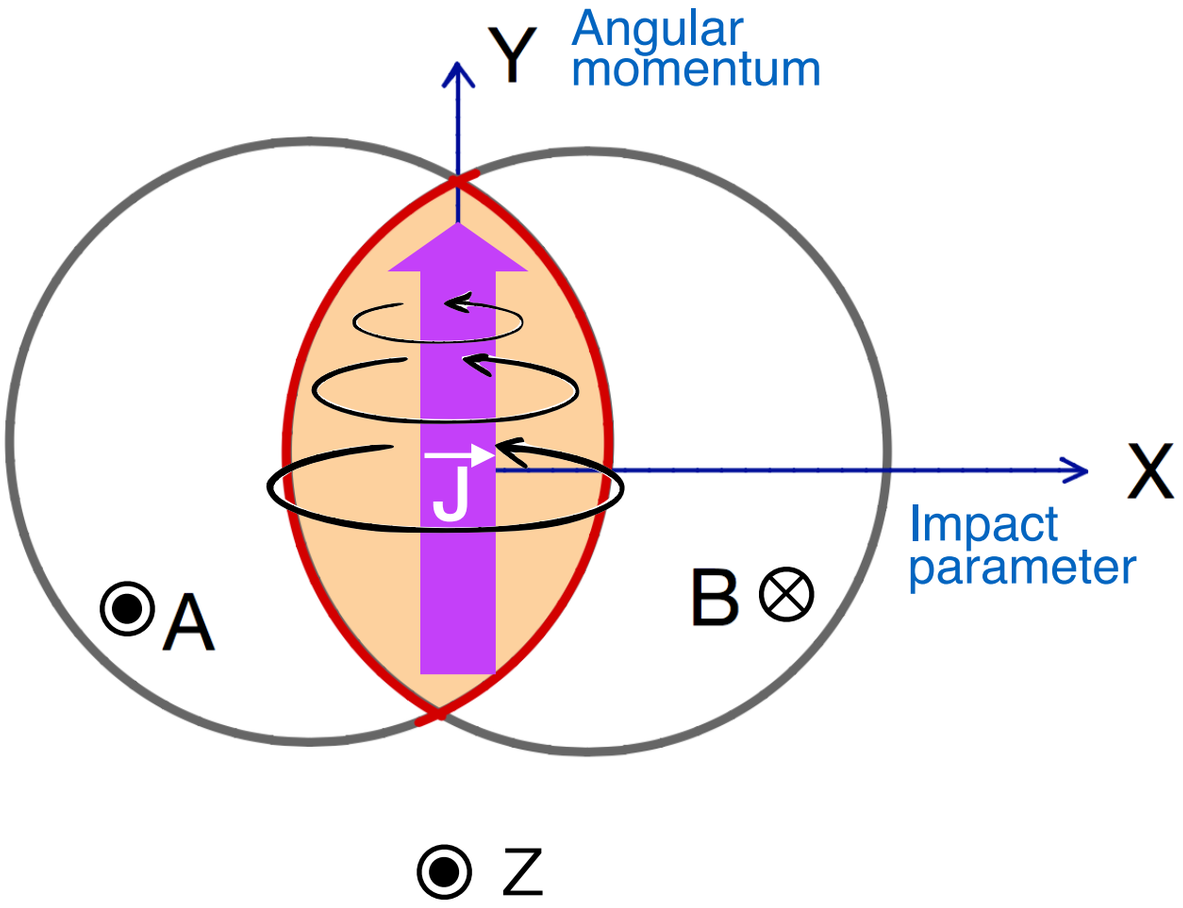


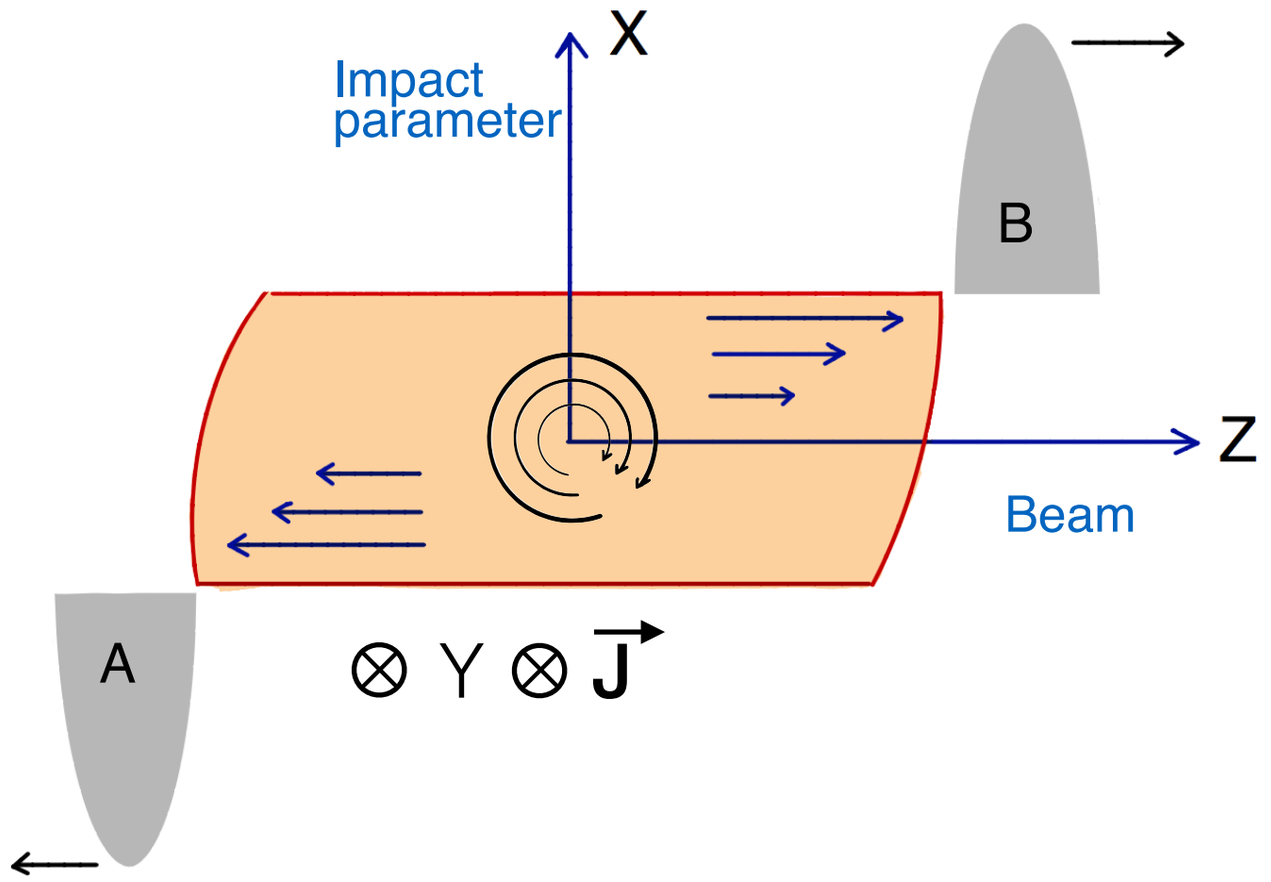
Search for vortical effects

Angular momentum in HICs

Collisions of two relativistic nuclei generate large angular momentum ($\vec{J}$)

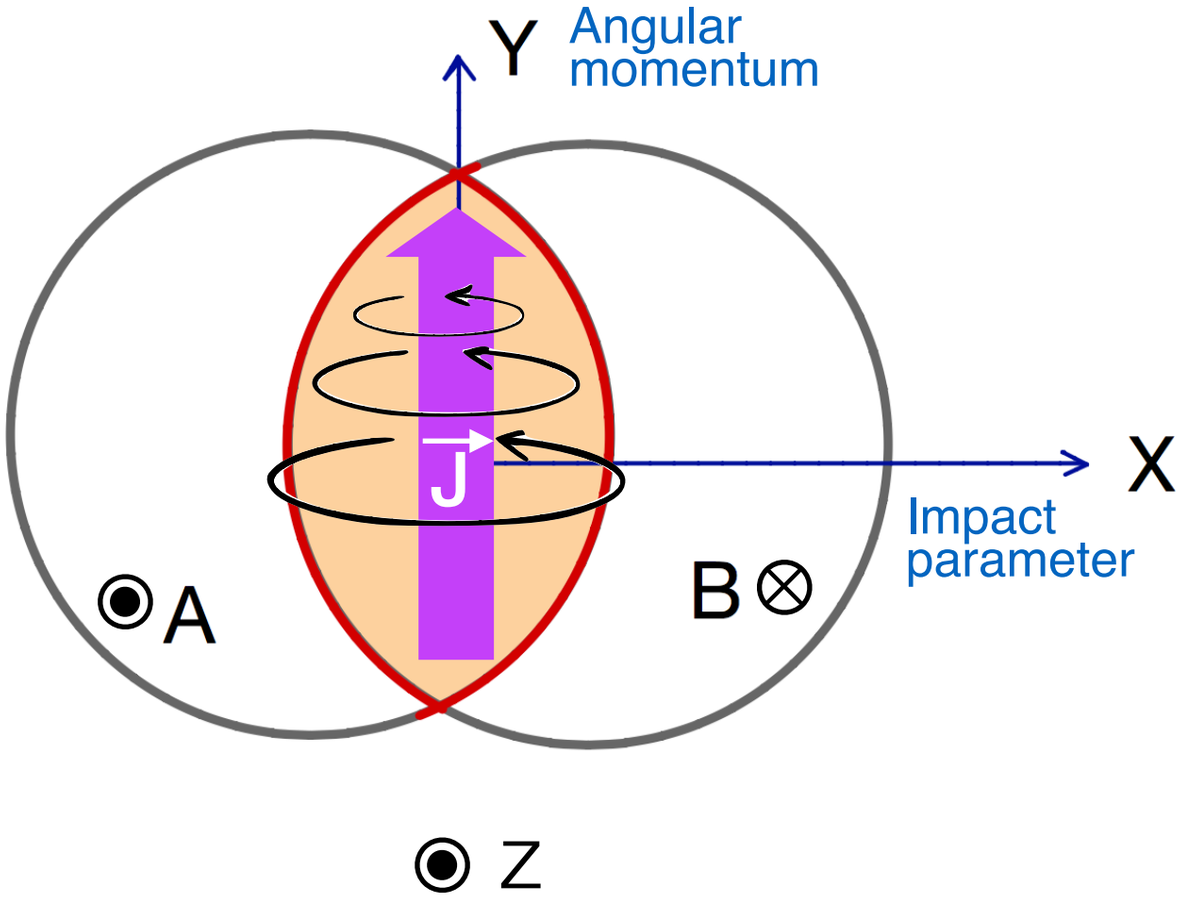
$\vec{J}$ points perpendicular to the plane of beam axis & impact parameter ($\vec{b}$)

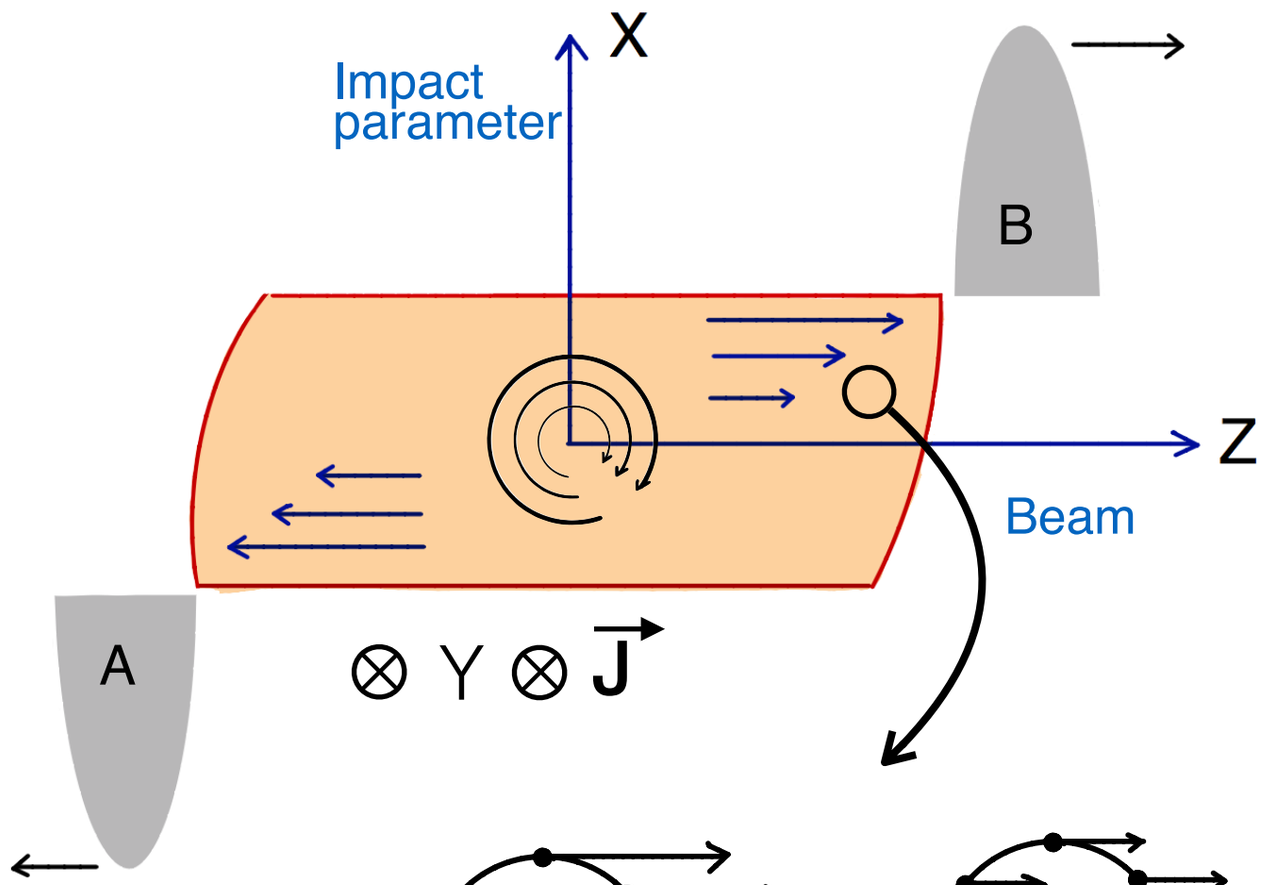




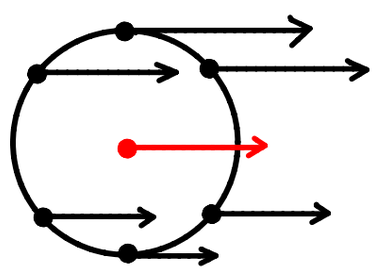
Angular momentum in HICs

Large angular momentum leads to local vorticity ($\vec{\omega}$) in the created medium

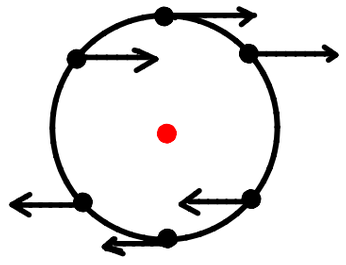




Vorticity: $\vec{\omega} \equiv \frac{1}{2}\nabla \times \vec{v} \approx \frac{1}{2}\frac{\partial v_z}{\partial x}$



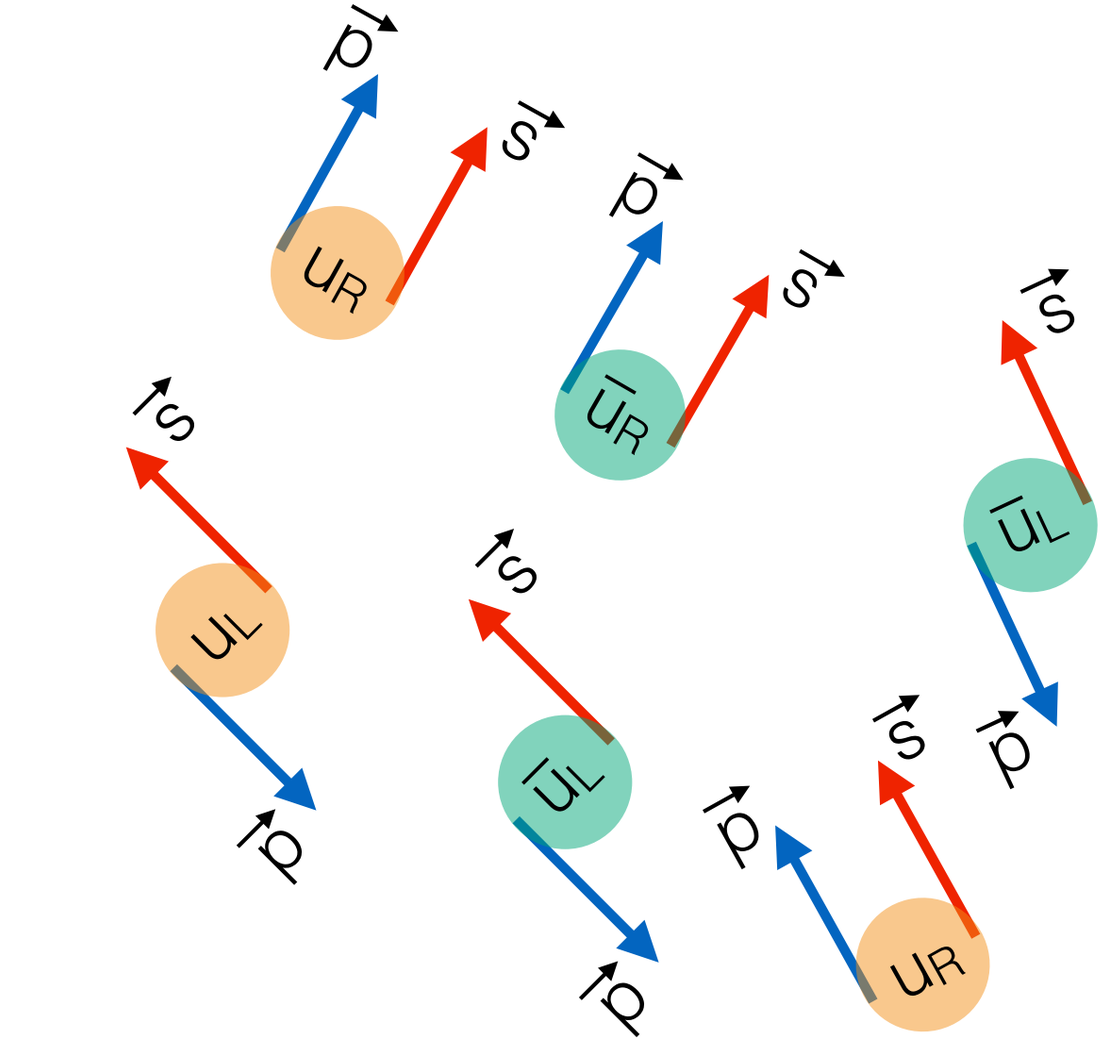
lab frame

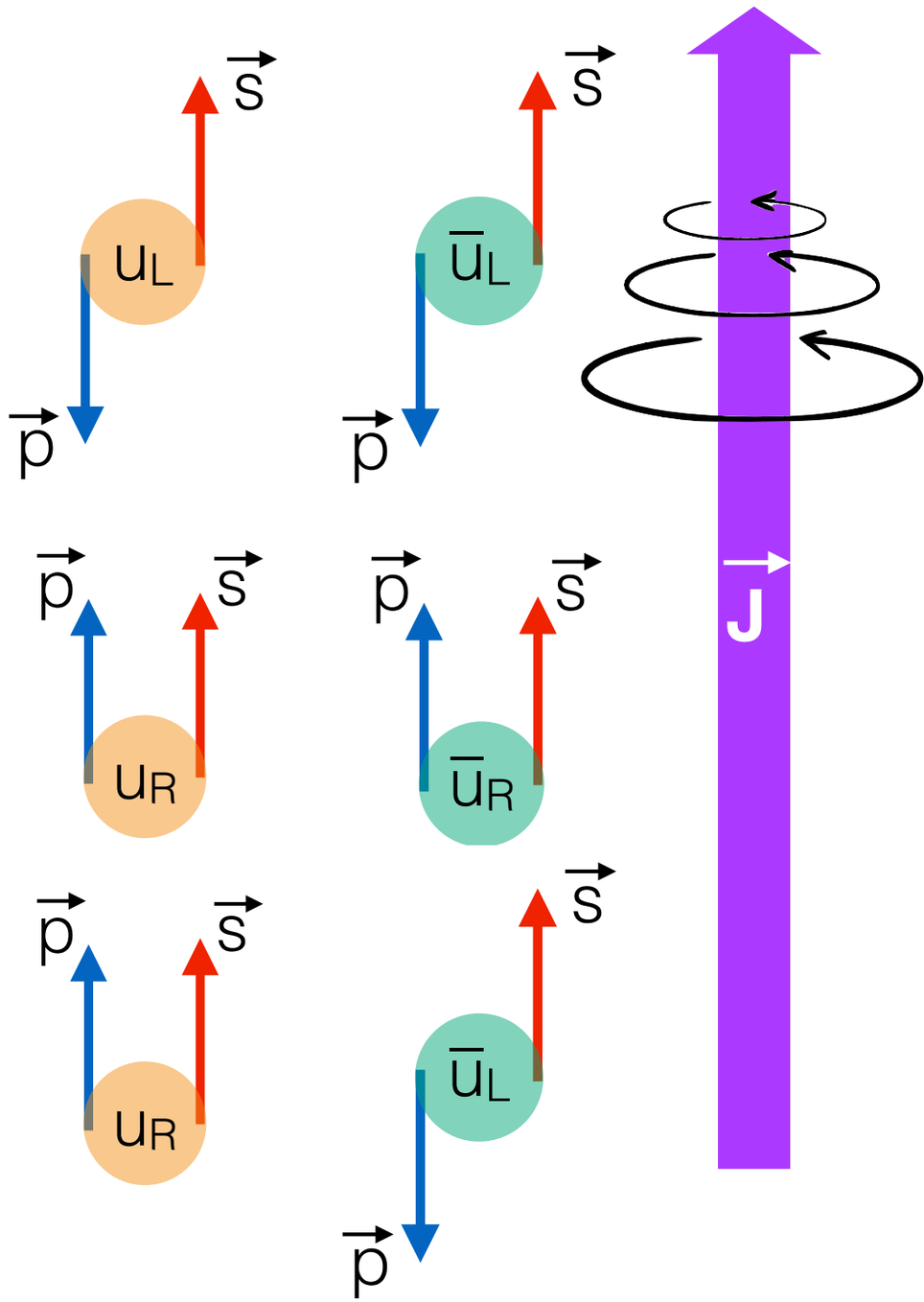


fluid frame

Global polarization due to vorticity

Angular momentum ($\vec{J}$) → Vorticity ($\vec{\omega}$) → Polarization (spin orbit coupling)





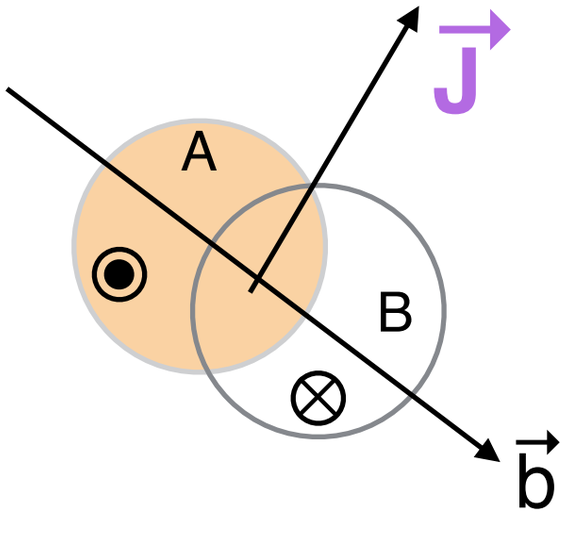
quarks anti-quarks

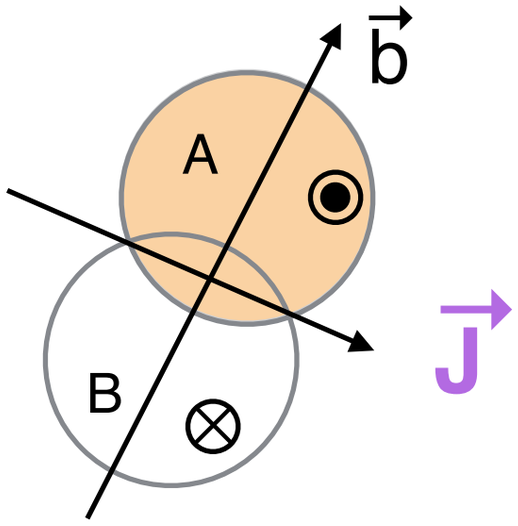
L : left-handed **R** : right-handed

How to observe this ?

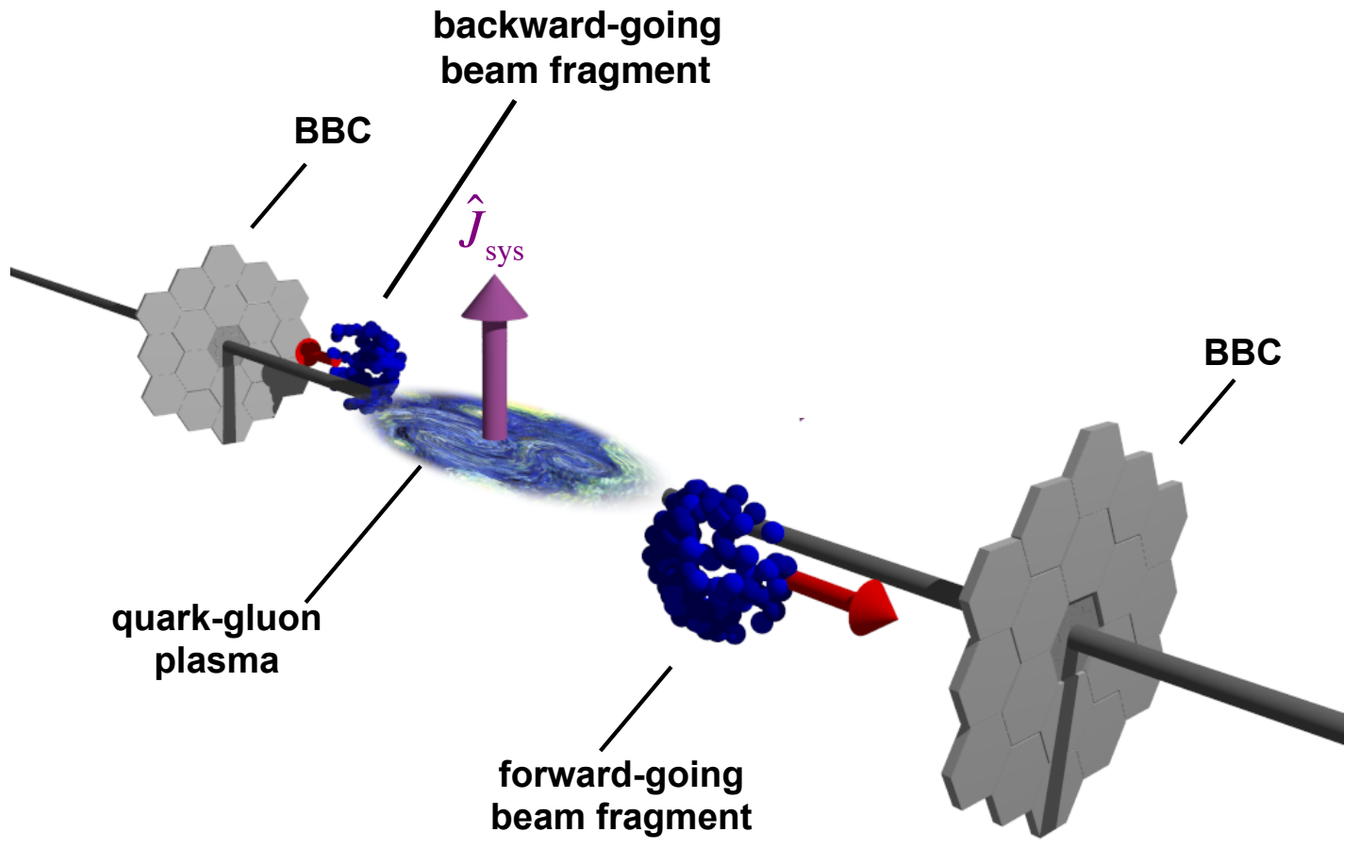
#1 : Measure the direction of angular momentum

We know the beam direction, and by measuring beam fragments (BBC low √s & ZDC high √s) we know the event-by-event direction of $\vec{J}$





STAR Collaboration Nature 548 (2017) 62-65

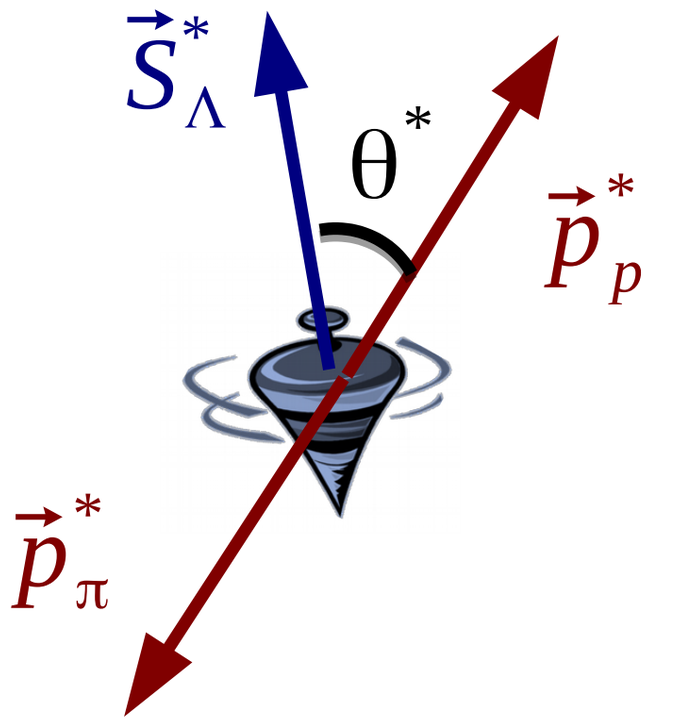


The vector joining the two beam fragments give the direction of impact parameter $\vec{b}$ & $\vec{J}$

#2: measure the spin polarization of particles

Measuring spin of particles in not easy but we can make use of the parity-violating decay of hyperons such as Lambdas

$$\Lambda \rightarrow p + \pi^- \quad \text{(BR: 63.9\%, } c\tau\text{~7.9 cm)}$$



The Feynman Lectures on Physics, Volume III, chapter 17-5

In Lambda decays the proton momentum direction is correlated to the spin polarization direction of Lambda

$$\frac{dN}{d\Omega^*} = \frac{1}{4\pi}(1 + \alpha_H \mathbf{P}_H \cdot \mathbf{p}^*_\mathbf{p})$$

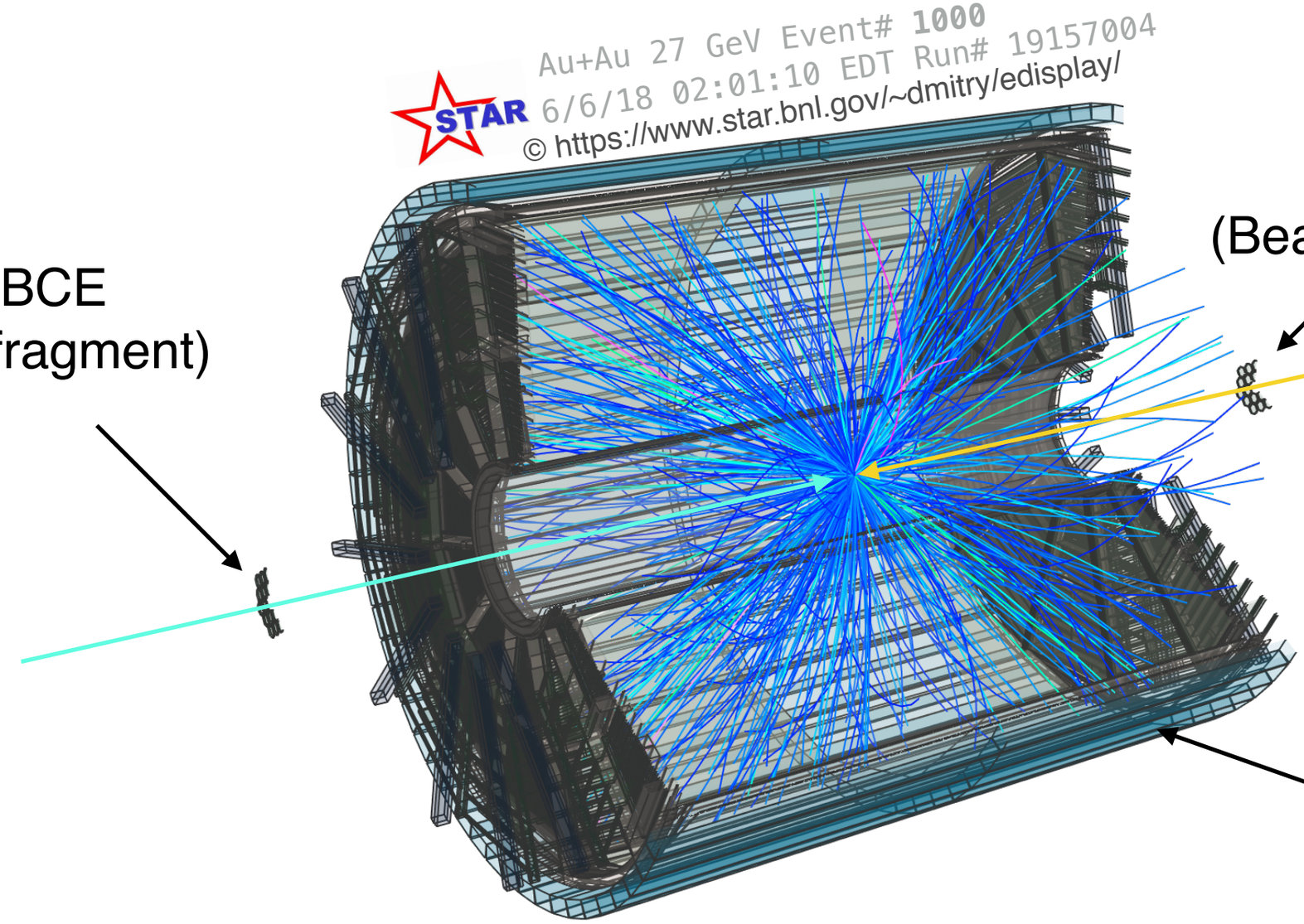
P_H: Λ polarization

p_p^*: proton momentum in the Λ rest frame

α_H: Λ decay parameter

($\alpha_\Lambda = -\alpha_{\bar{\Lambda}} = 0.642 \pm 0.013$)

Measurements by STAR



BBCE
(Beam fragment)

BBCW
(Beam fragment)

Also TOF used
for particle ID

TPC
(Tracking)

The polarization of Λ :

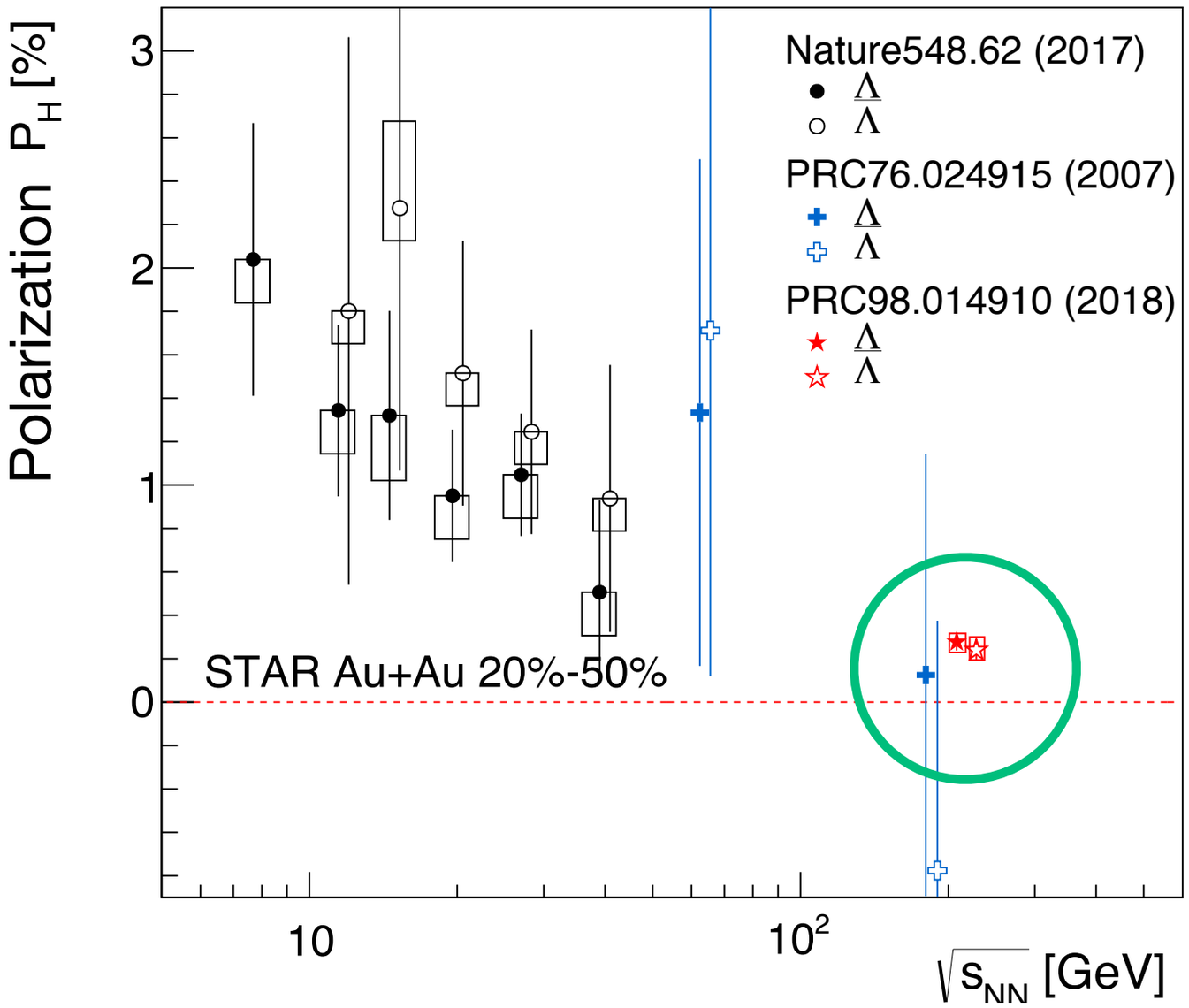
Proton angle in Λ rest-frame (Λ spin)

Direction of $\vec{J}$

$$\overline{\mathcal{P}}_{\mathrm{H}} \equiv \langle \vec{\mathcal{P}}_{\mathrm{H}} \cdot \hat{J}_{\mathrm{sys}} \rangle = \frac{8}{\pi \alpha_{\mathrm{H}}} \frac{\left\langle \cos\left(\phi_p^* - \phi_{\hat{J}_{\mathrm{sys}}} \right) \right\rangle}{R_{\mathrm{EP}}^{(1)}}$$

Resolution of $\phi_{\hat{J}_{\mathrm{sys}}}$

What's new : more precise measurements



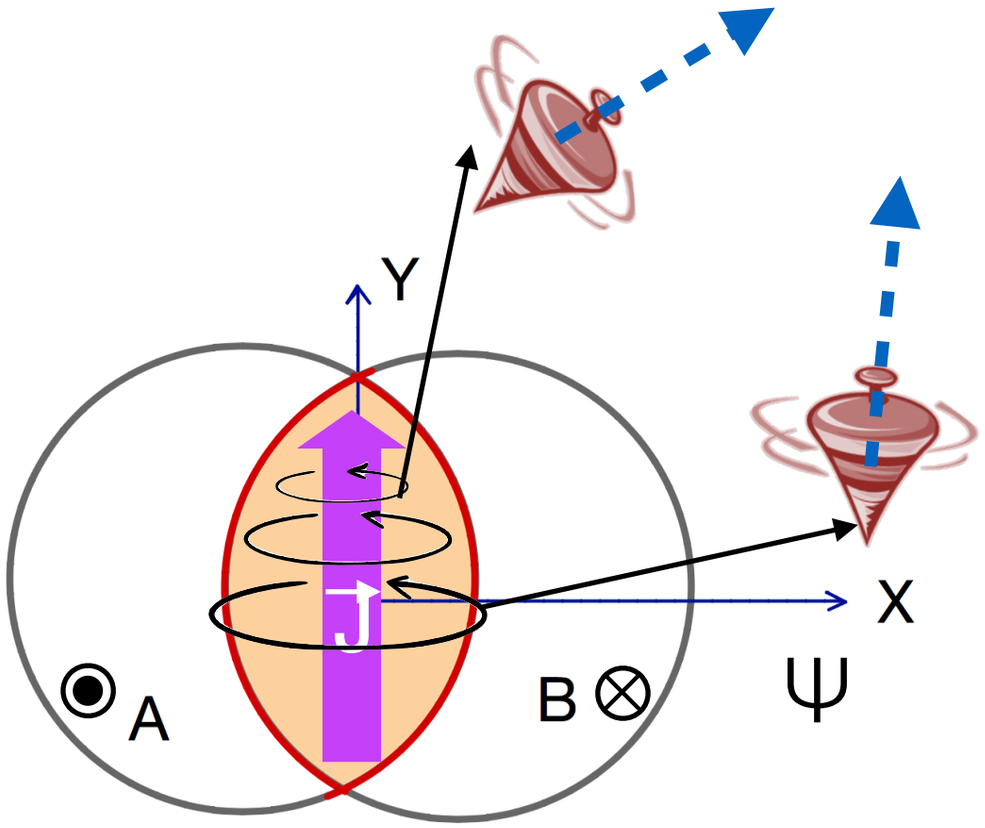
Measurements in Au+Au collisions from STAR & discovery of most vortical fluid with BES-I data

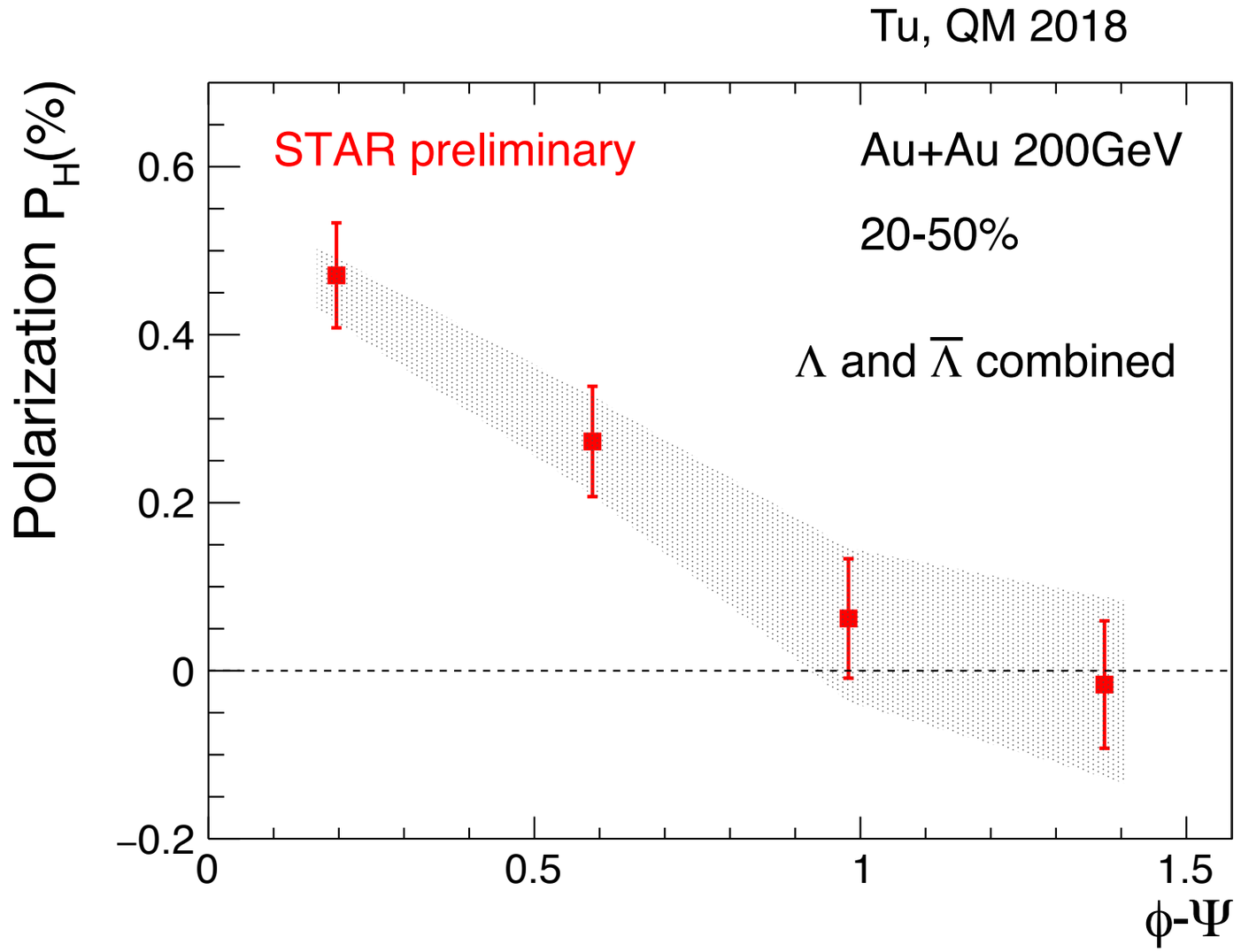
Non-zero significant polarization $P_H(\Lambda)$ & $P_H(\bar{\Lambda}) > 0$, hint of $P_H(\Lambda) > P_H(\bar{\Lambda})$

Improved significance (150 more data), non-zero polarization (<1%) observed in Au+Au 200 GeV

Opens a path for more differential studies & phenomenology

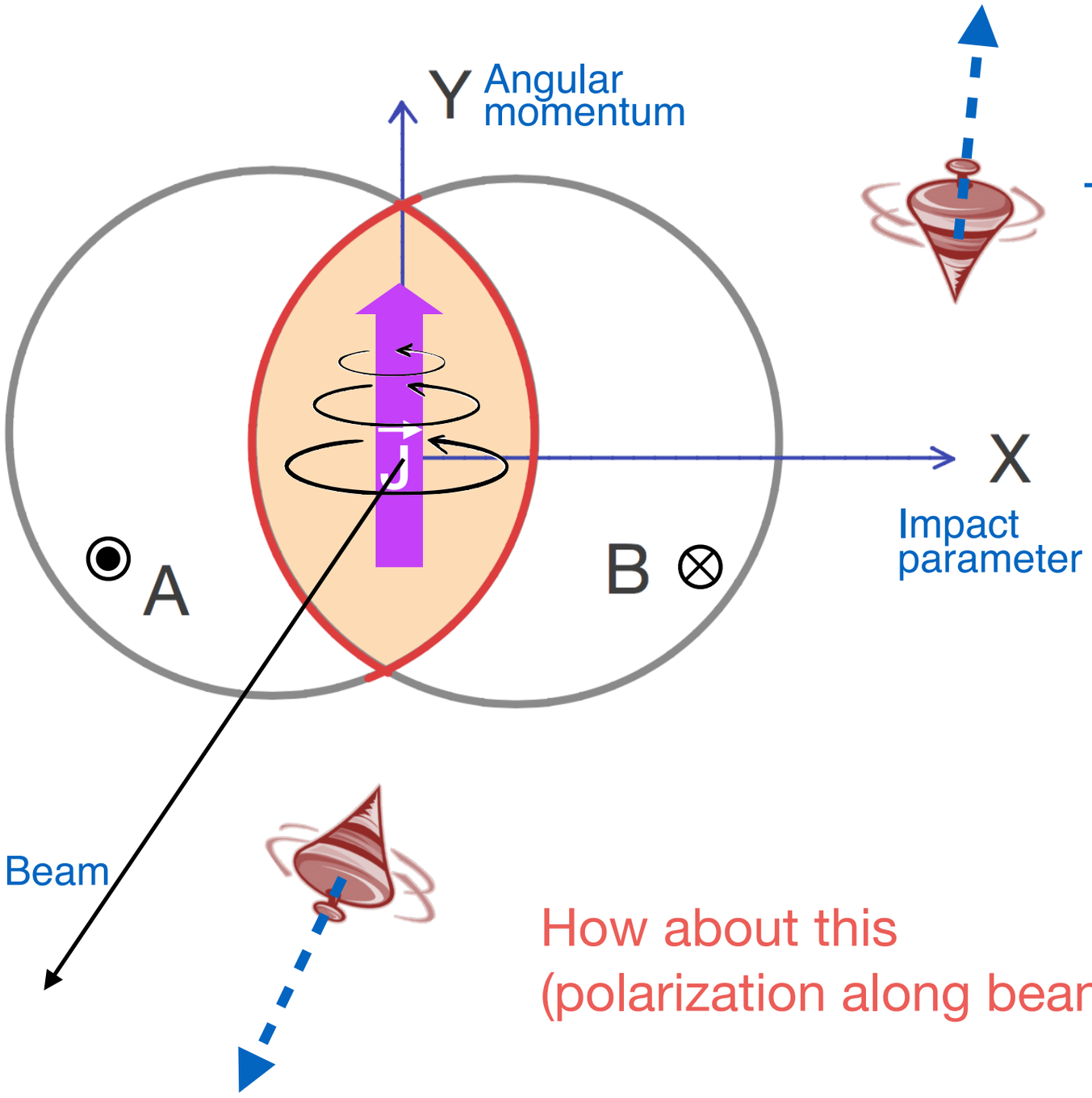
What's new : reaction plane dependence





Strongest polarization is seen for Lambdas emitted (in-plane) where the vorticity is expected to be the largest

What's new : Longitudinal polarization

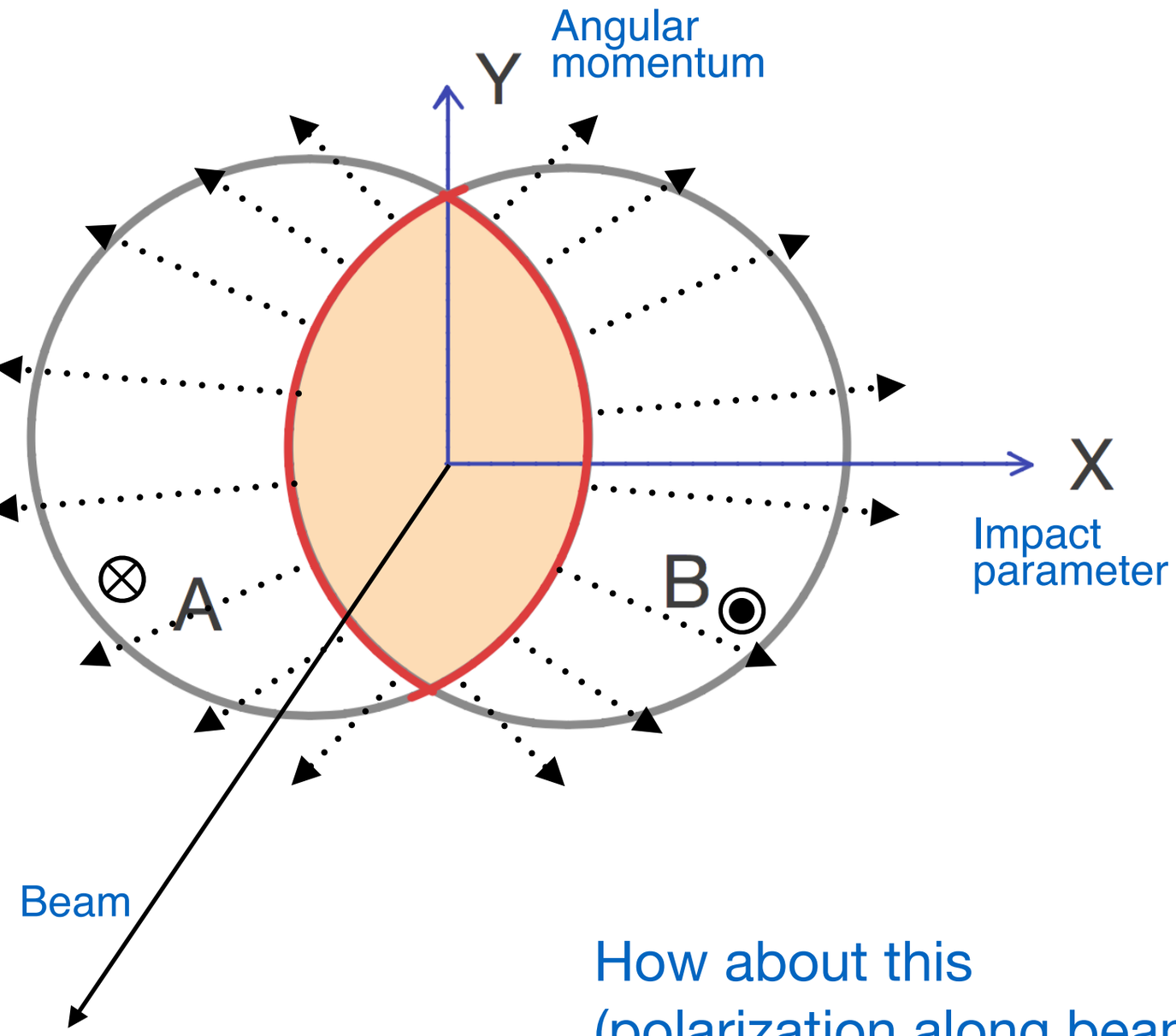


This has been observed

How about this
(polarization along beam axis ?)

What's new : Longitudinal polarization

Pressure gradient → anisotropic expansion → gradient in transverse velocity → vorticity



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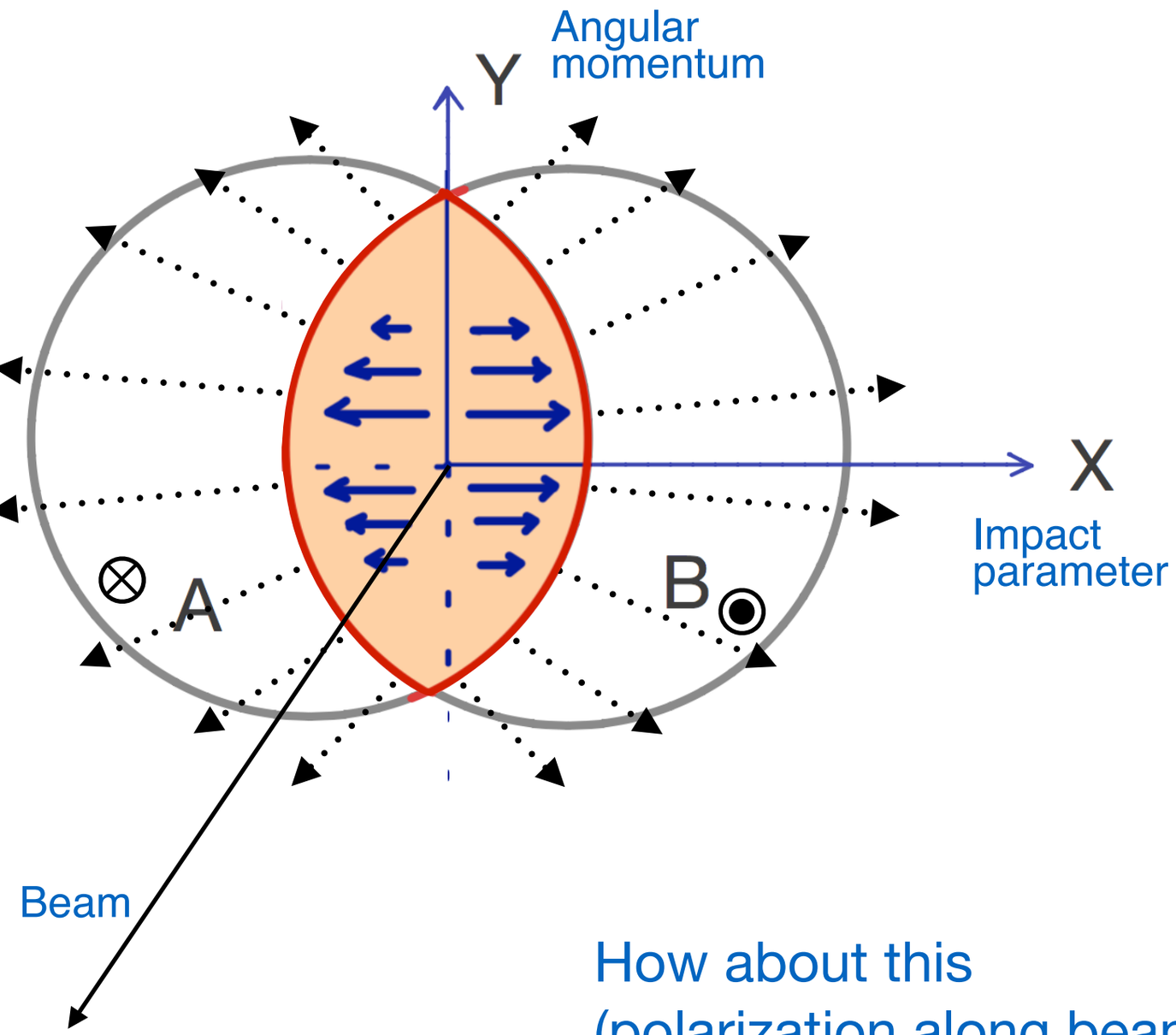

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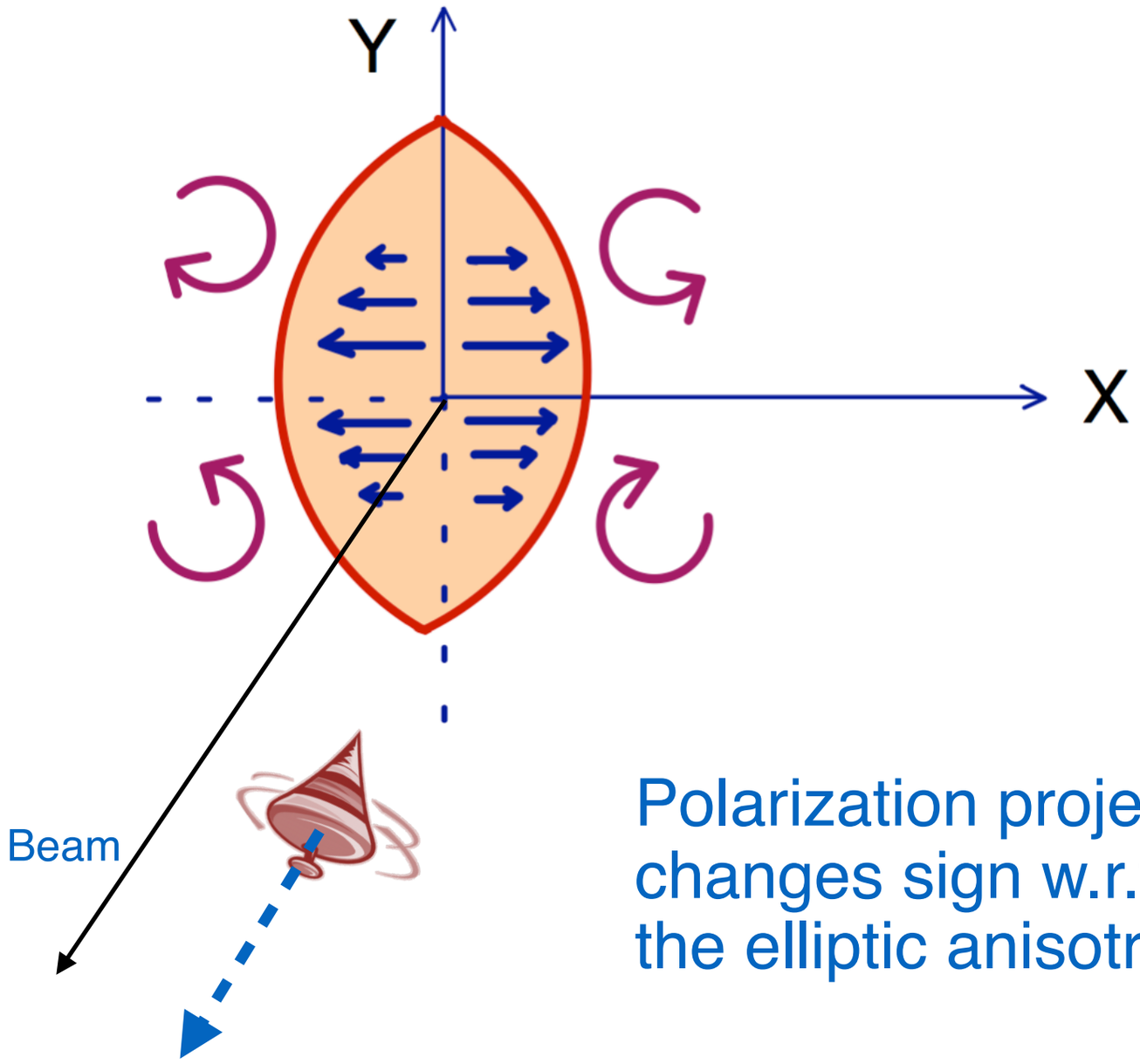

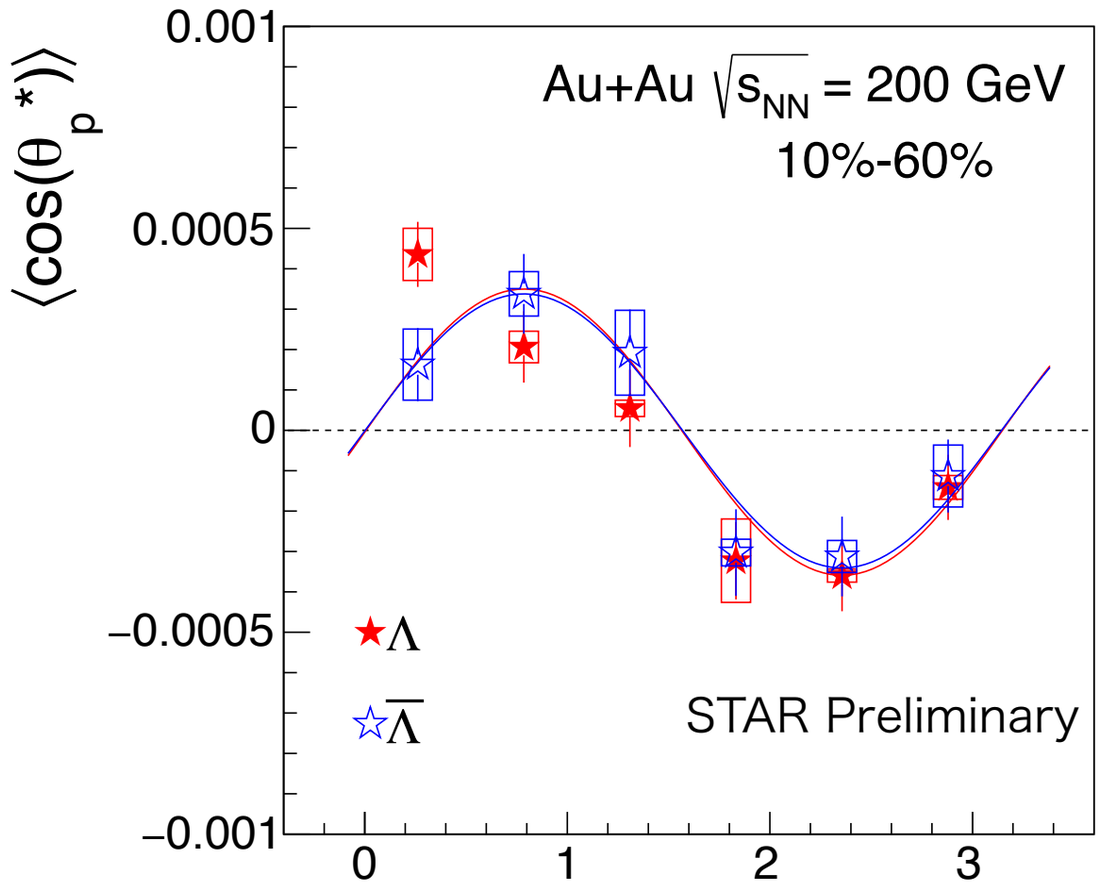

Polarization projected onto beam axis changes sign w.r.to to the direction of the elliptic anisotropy Ψ_2

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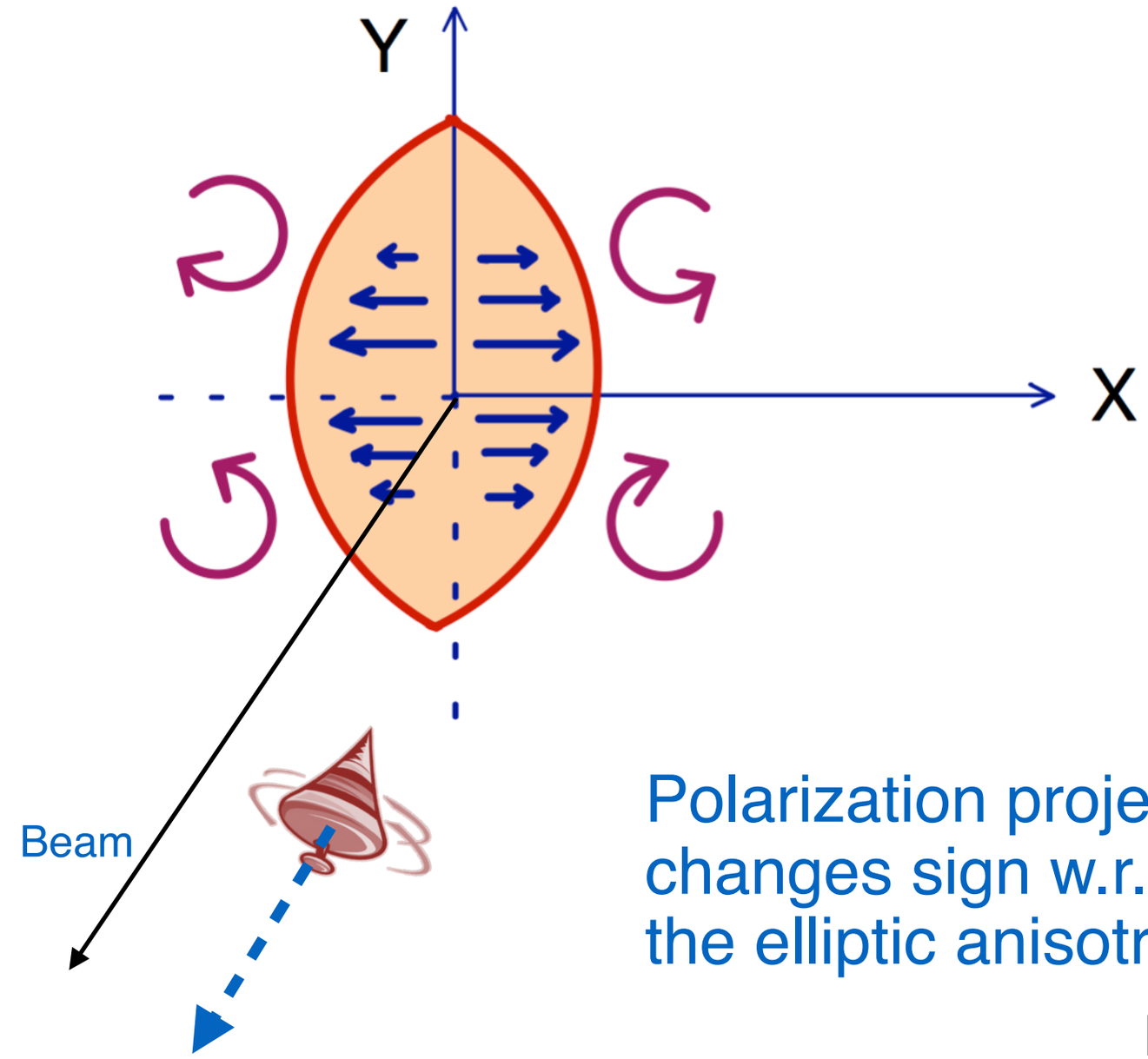
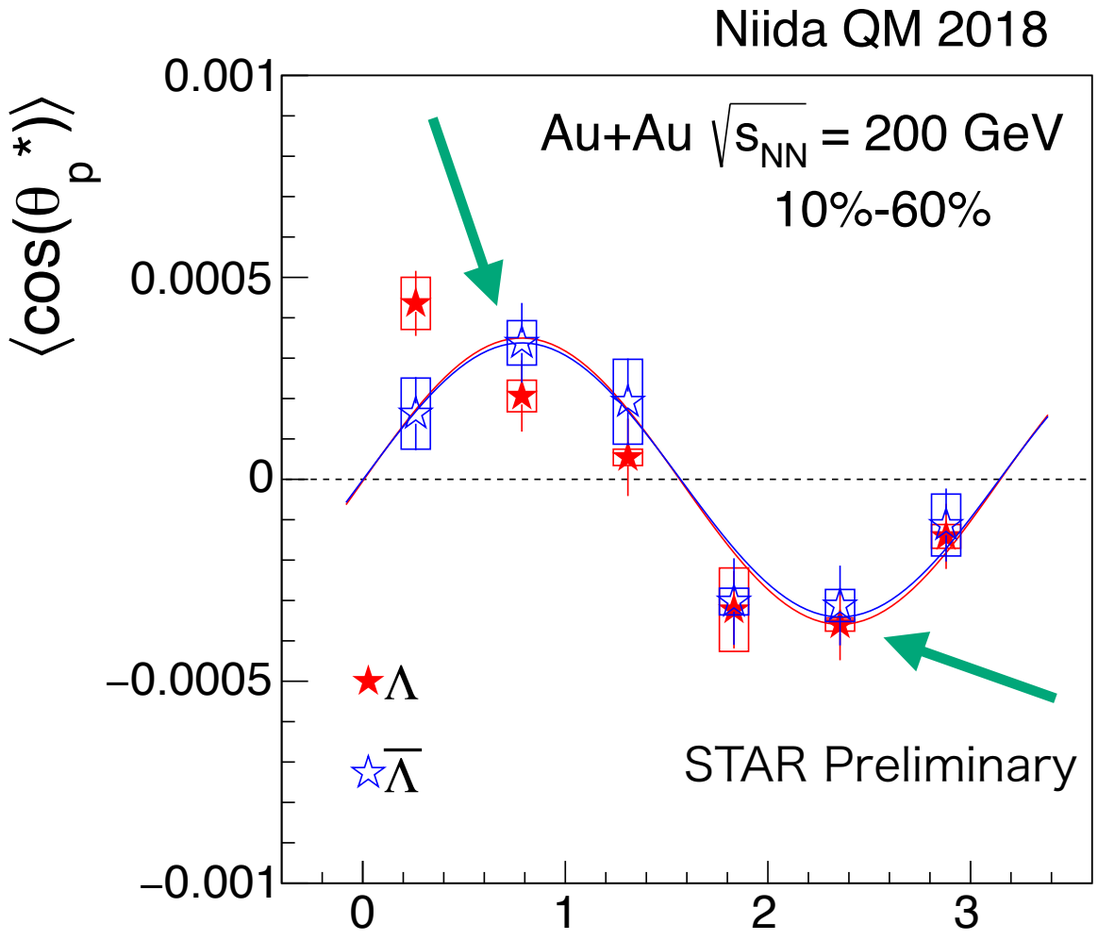




Polarization projected onto beam axis changes sign w.r.to to the direction of the elliptic anisotropy Ψ_2

Hydro calculation predicts opposite trend

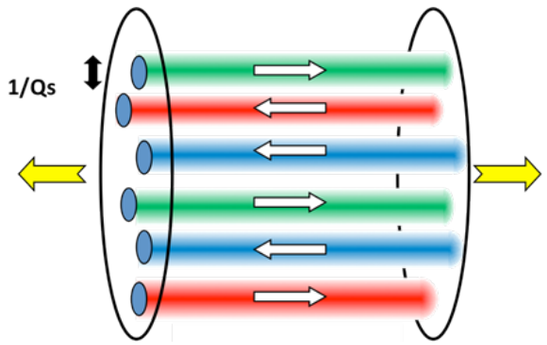
Becattini and Karpenko PRL 120, 012302 (2018)

Search for chiral effects

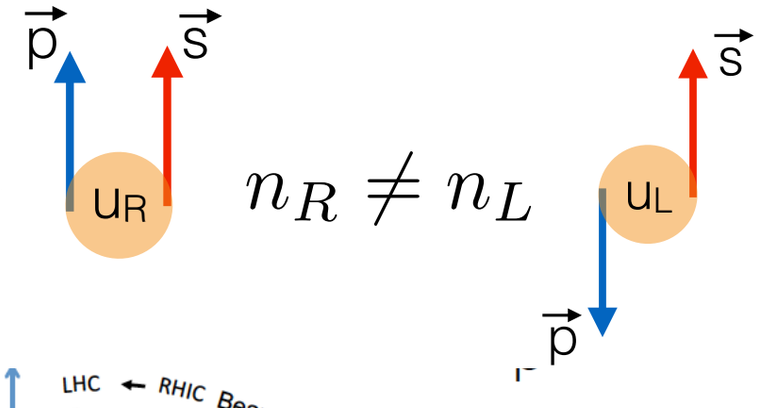
Heavy ion collisions are the right place

#1: Non-conservation of chirality: Collisions generate fluctuating parallel chromo E & B fields

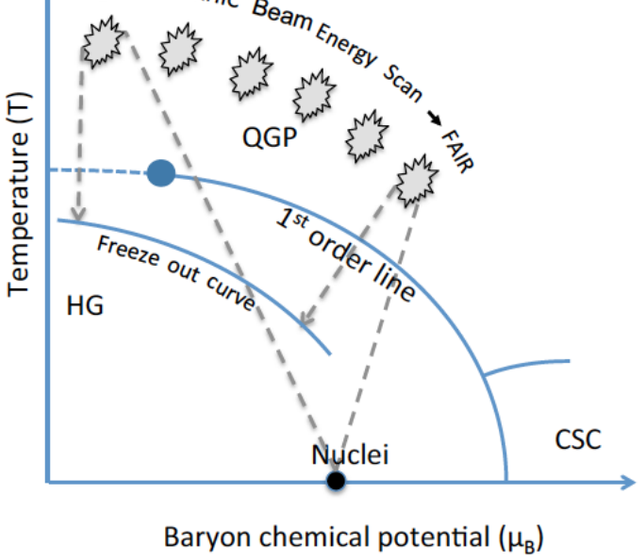
Kharzeev et al, hep-ph/0109253, Buividovich 0907.0494, Mace et. al 1601.07342

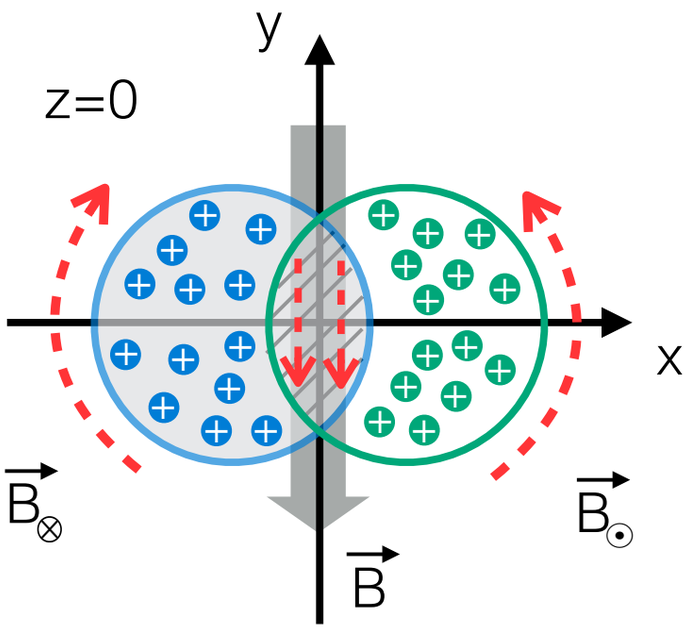


$$E \parallel B \parallel \hat{z} \quad \Rightarrow \quad dQ_5/dt \propto \mathbf{E}\cdot\mathbf{B}$$



#2: A deconfined medium of massless fermions (chiral symmetry restoration)



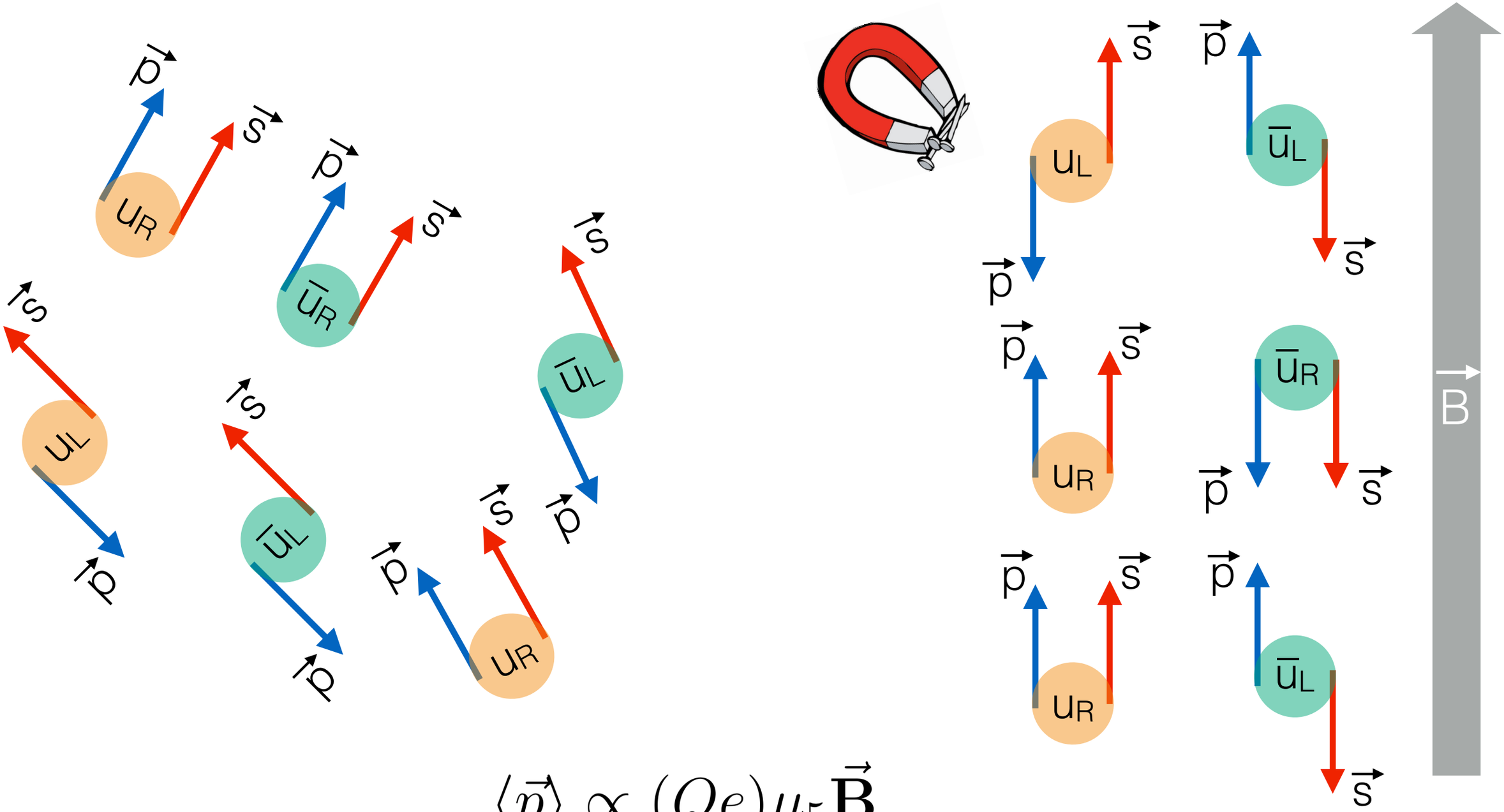


#3: Creation of strong magnetic-field ~10^{18} Gauss

Kharzeev, McLerran, and Warringa 0711.0950, Skokov, Illarionov, Toneev 0907.1396, McLerran, Skokov, 1305.0774

The Chiral Magnetic Effect

The B-field will align the spins due to magnetic moments



quarks anti-quarks

L : left-handed **R :** right-handed

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

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

Kharzeev, McLerran,Warringa 0711.0950

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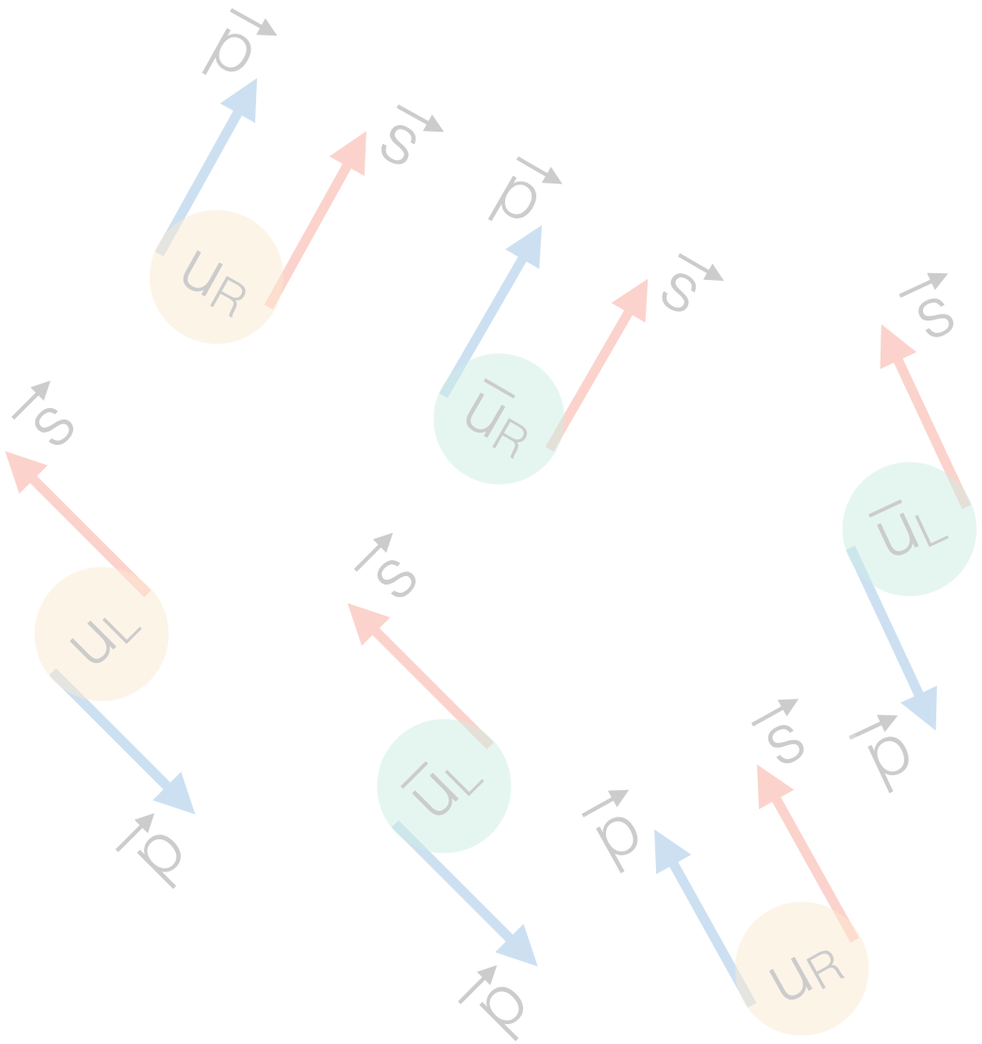
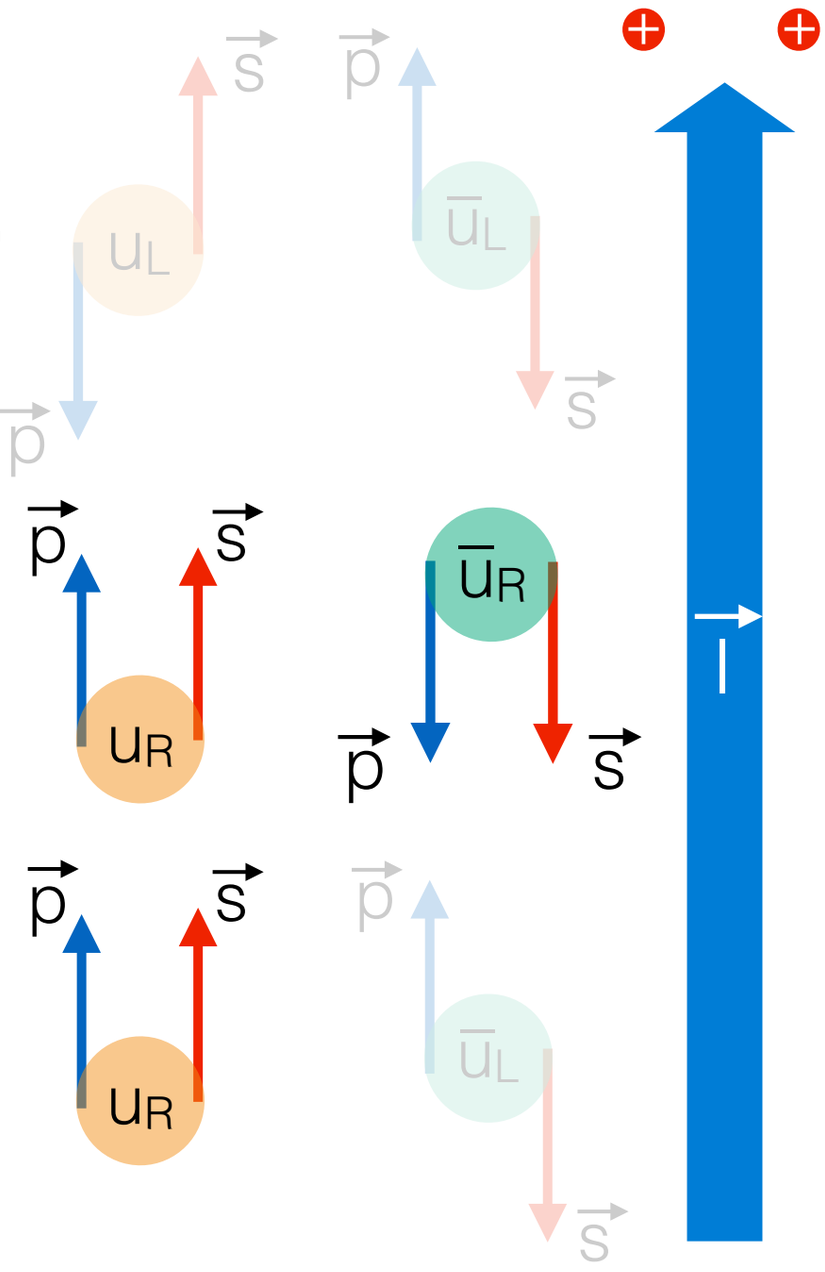


$$n_R > n_L$$



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

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

quarks anti-quarks

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Kharzeev, McLerran,Warringa
0711.0950

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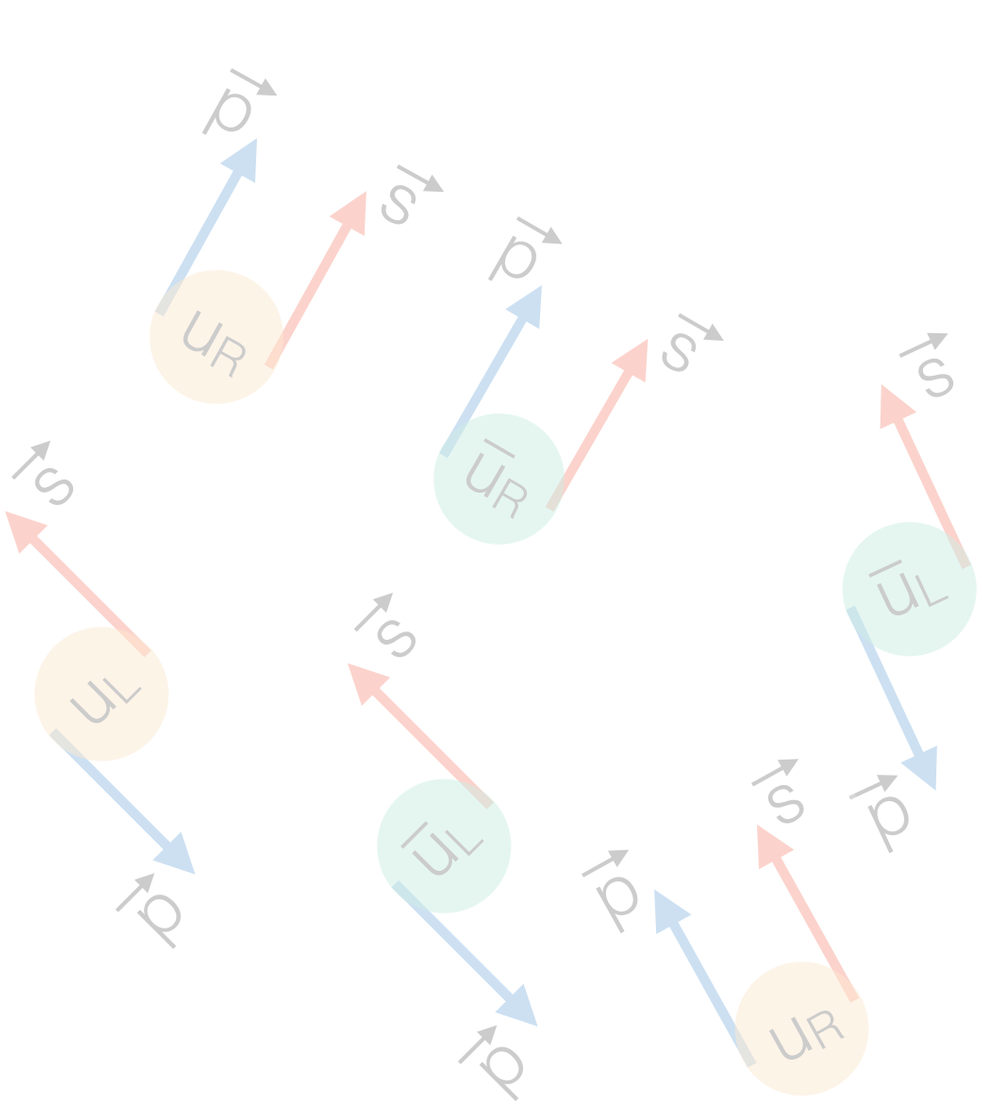

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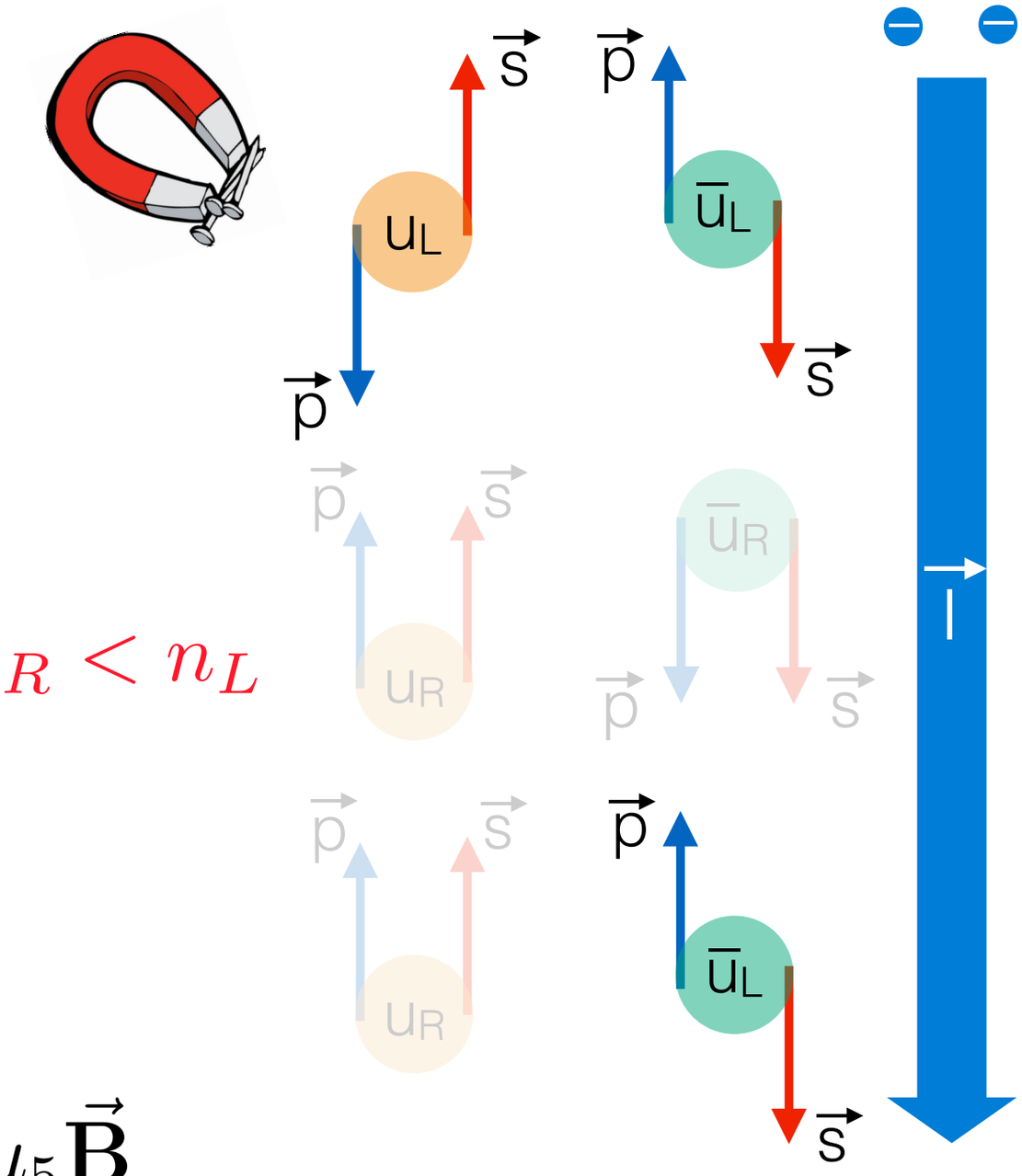

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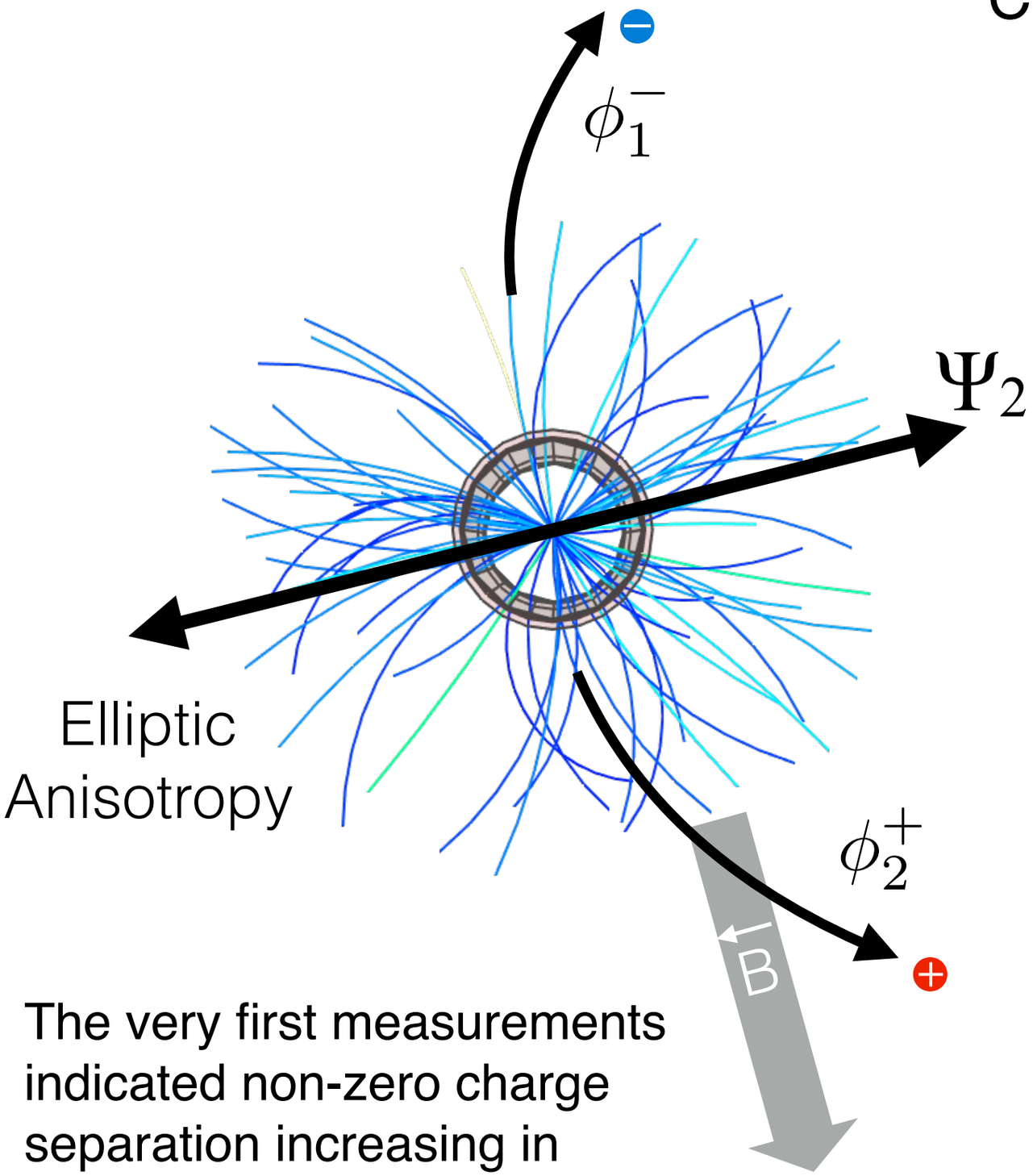
Kharzeev, McLerran,Warringa 0711.0950

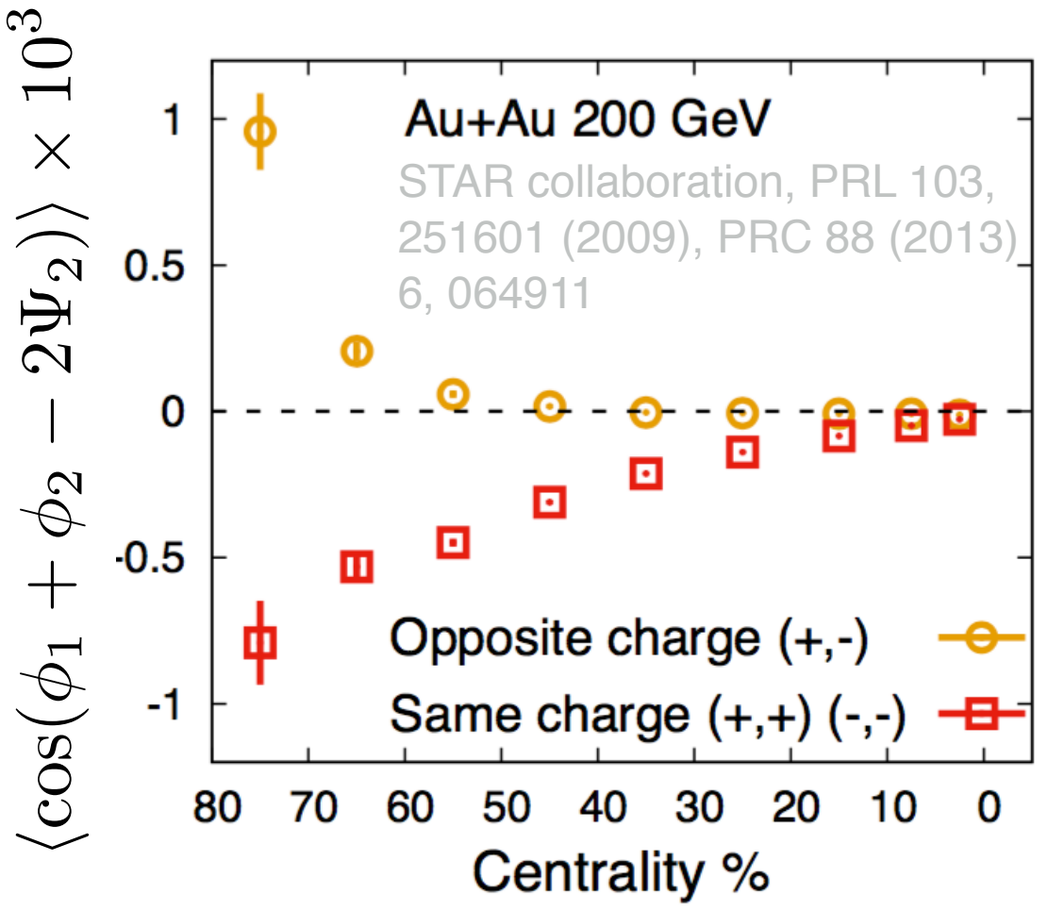
The first measurements at RHIC: 200 GeV Au+Au

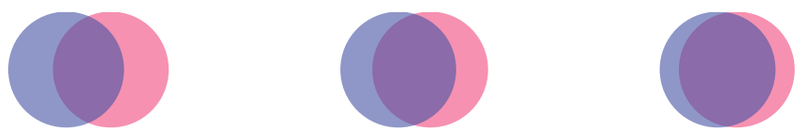


The very first measurements indicated non-zero charge separation increasing in peripheral events

Charge separation perpendicular to Ψ_2

$$\gamma^{+-} = \langle \cos(\phi_1^+ + \phi_2^- - 2\Psi_2) \rangle$$



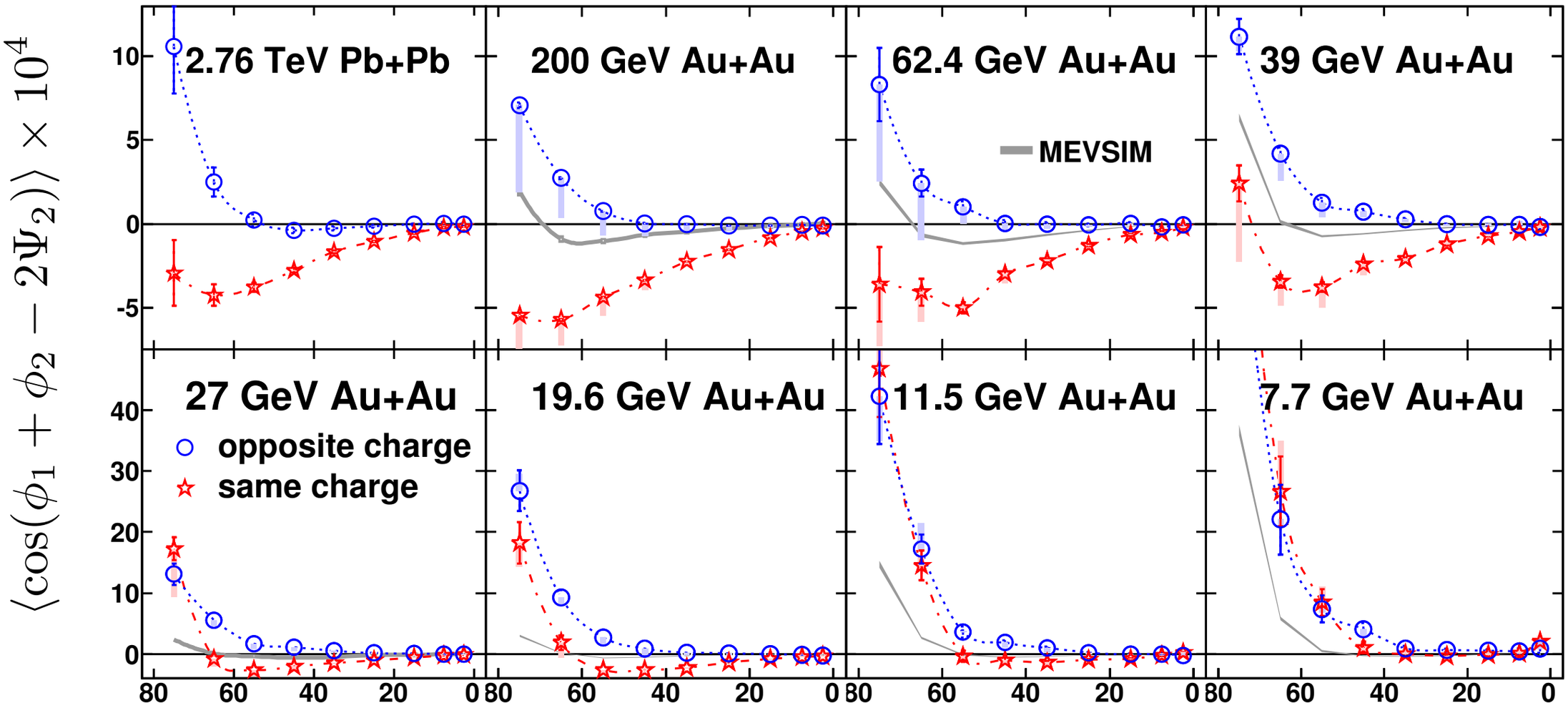


Large-B-field ? Small-B-field ?

The first measurements at RHIC: BES data

Charge separation vanishes at the lowest energy

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



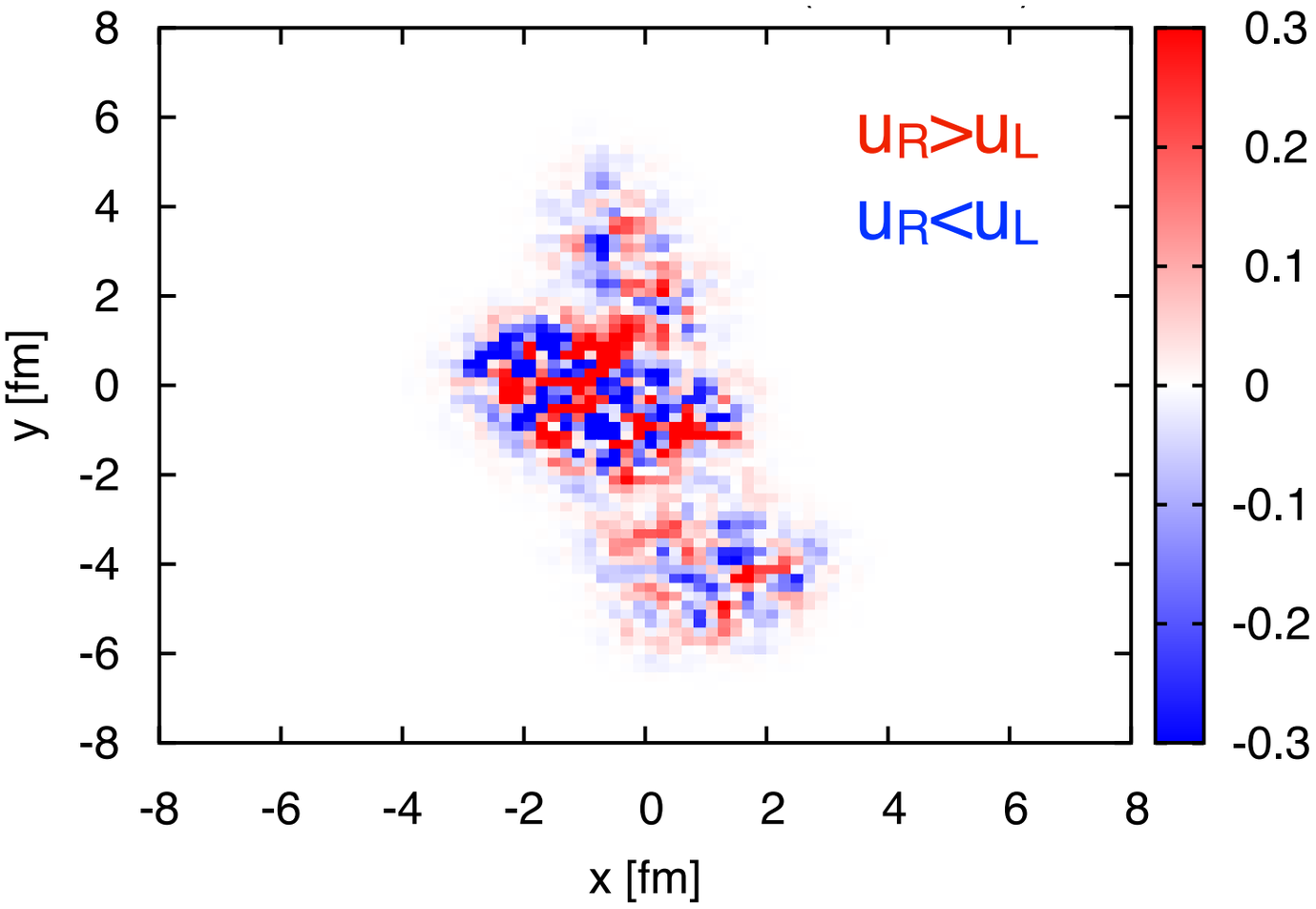
Expectation consistent disappearance of deconfinement / chiral symmetry restoration ?

Beyond the simple cartoon picture of CME

(Peripheral Pb+Pb)

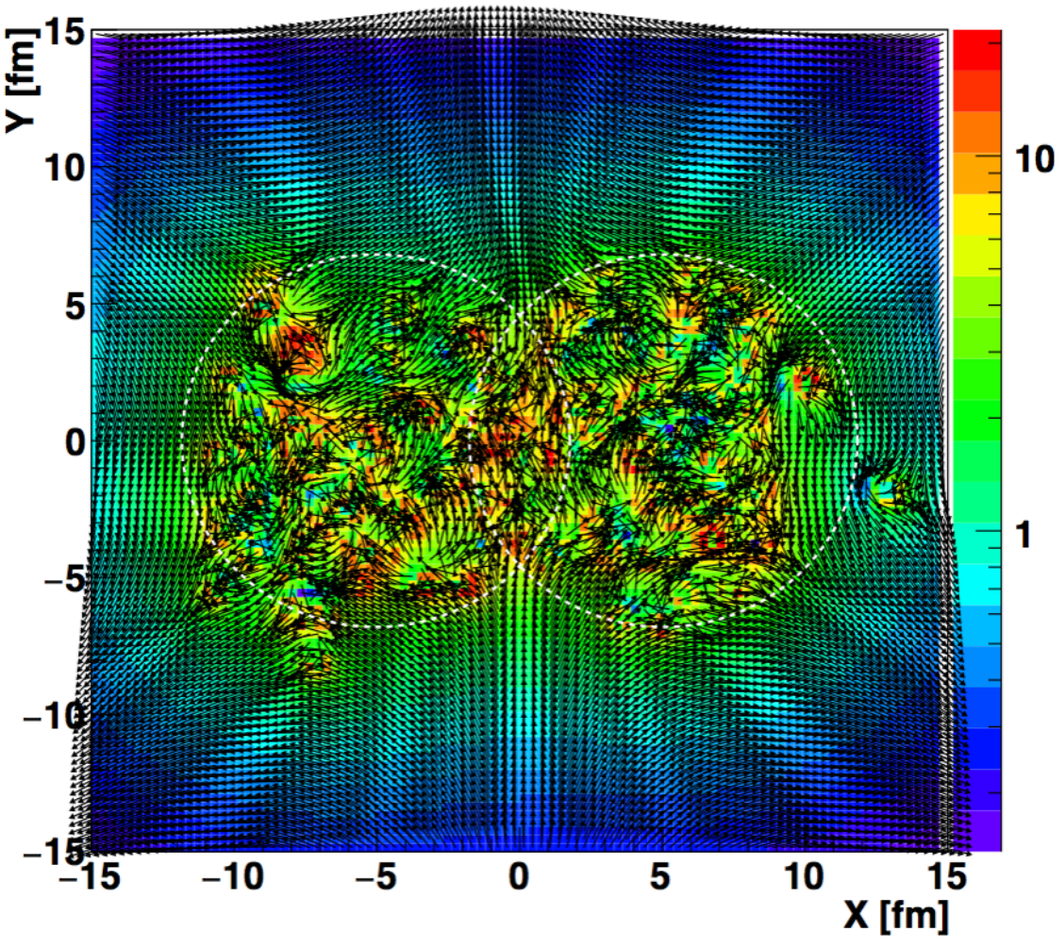
Axial charge profile

Lappi, Schlichting, 1708.08625



Magnetic field map

Belmont, Nagle, 1610.07964



Fluctuations, quenching & collective expansion should be dominant

Beyond the simple cartoon picture of CME

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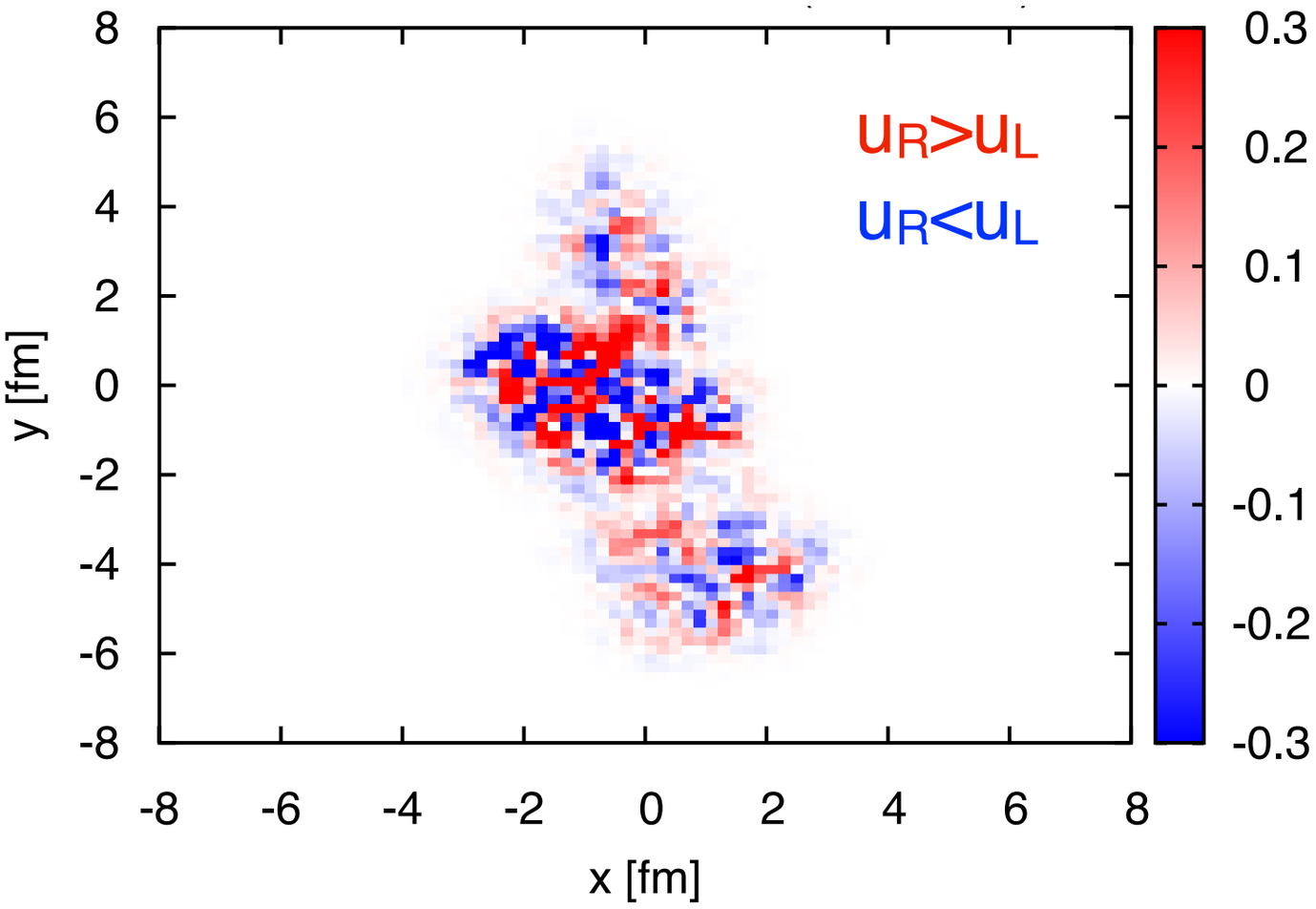

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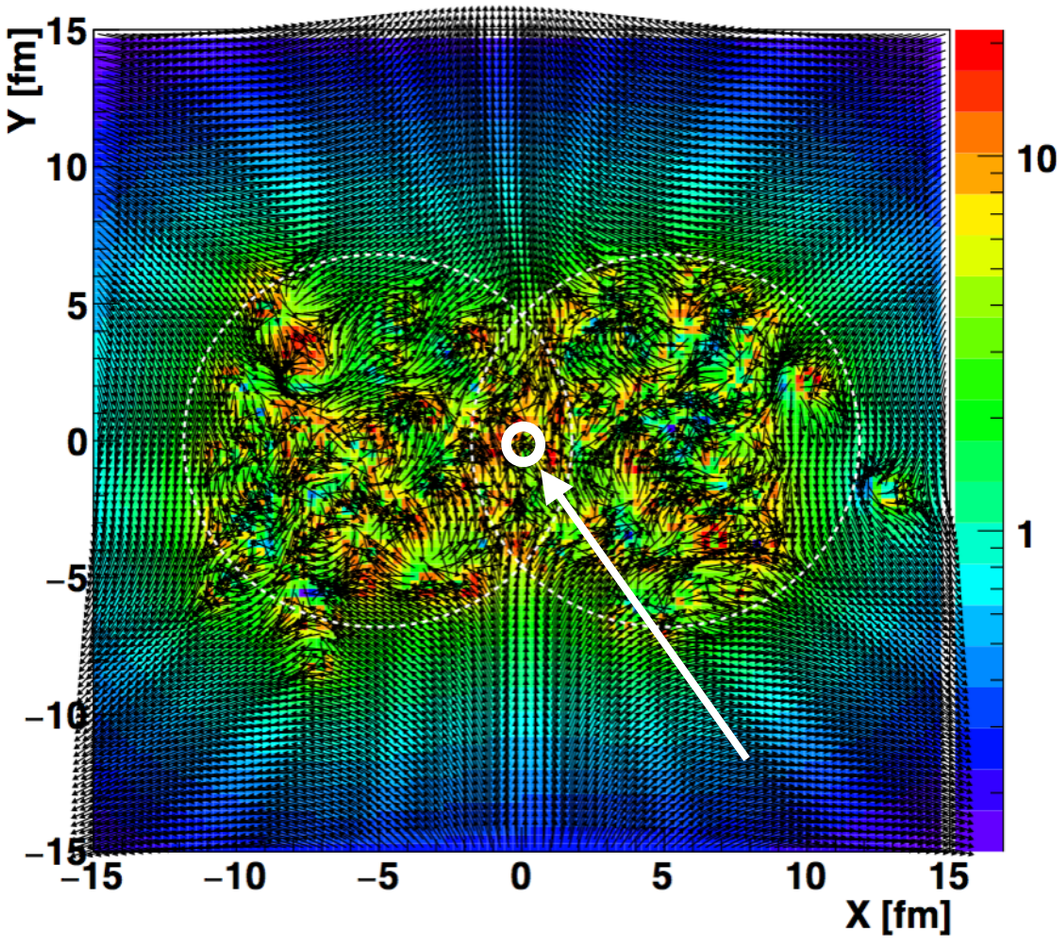
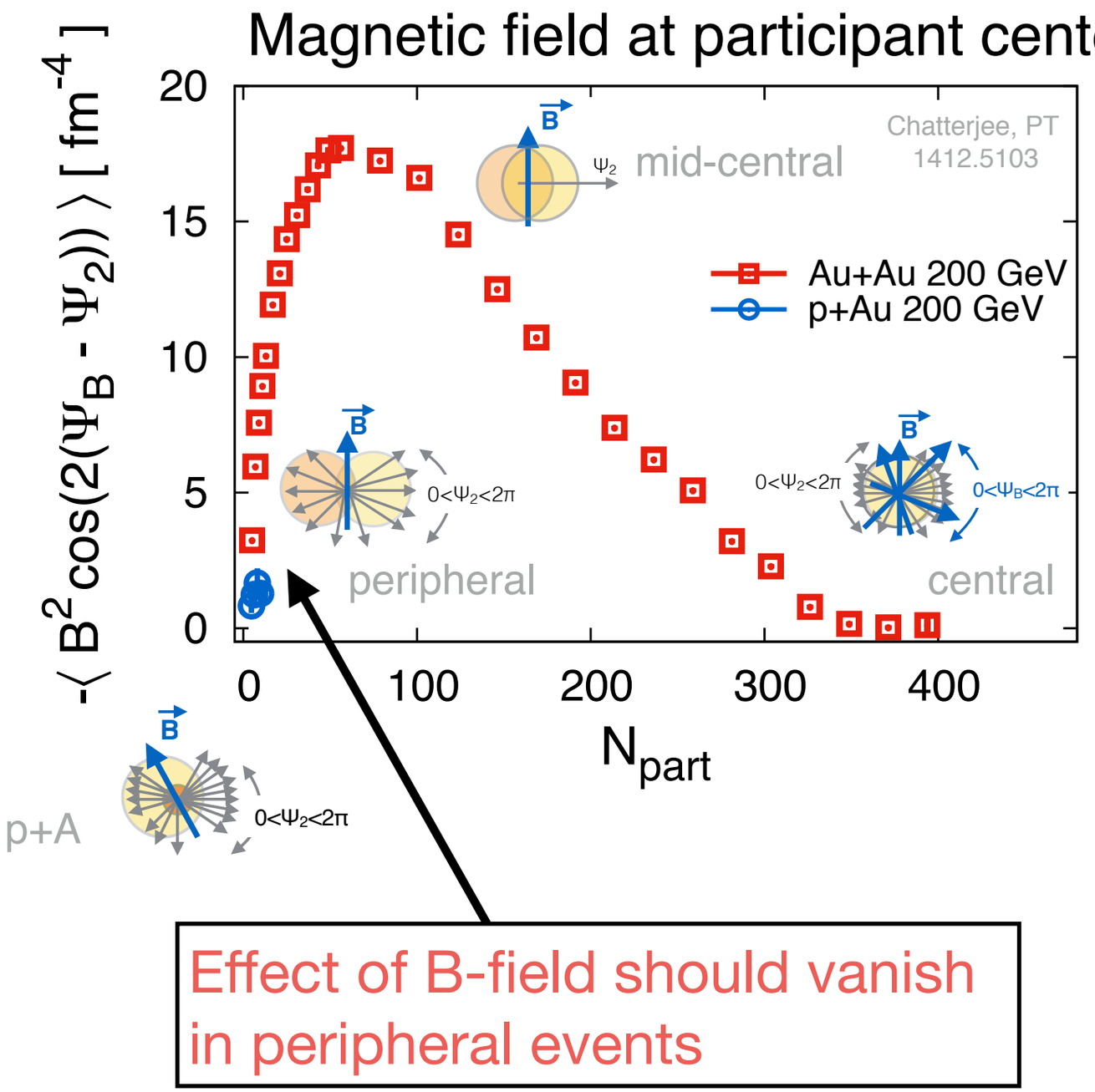
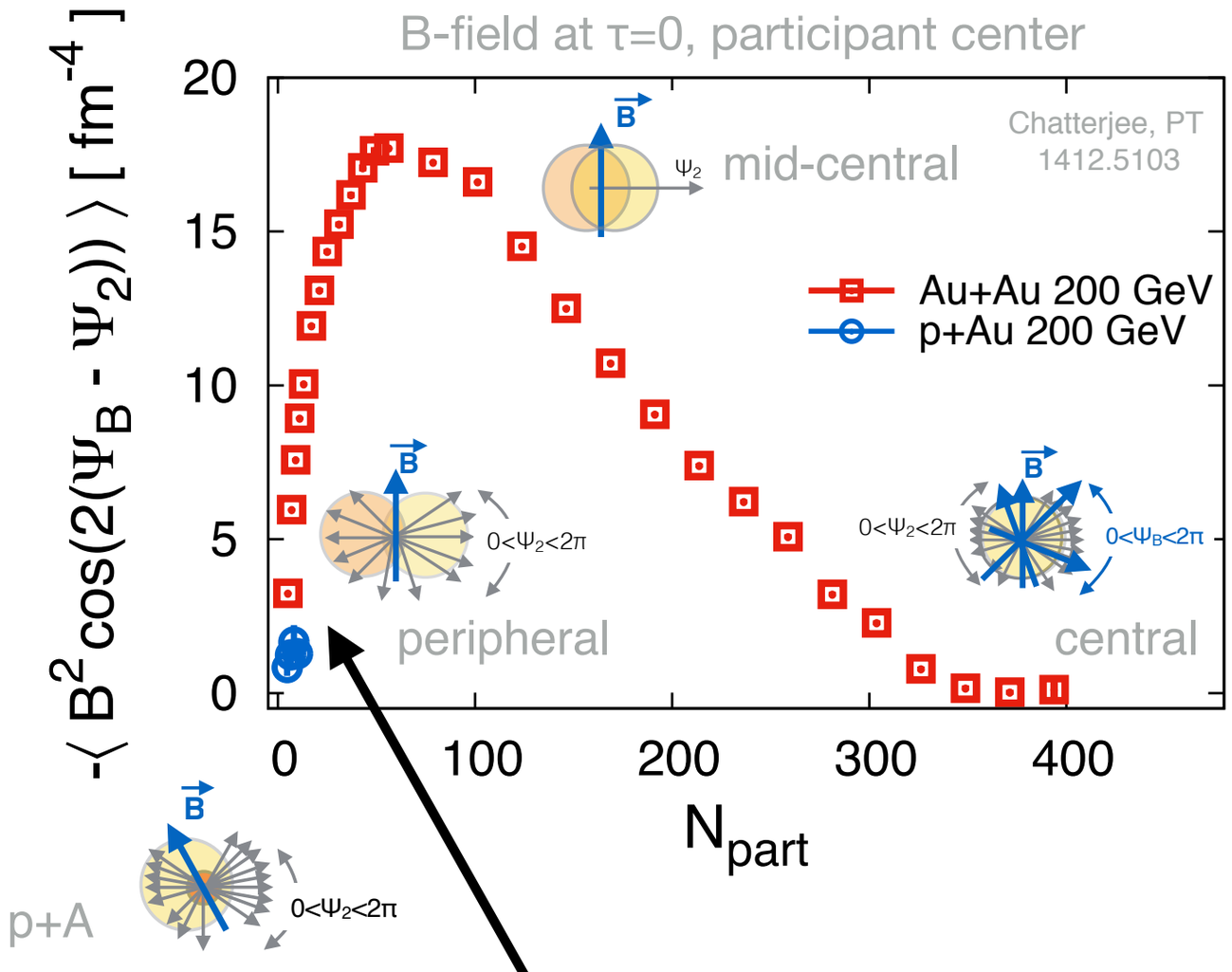


Fluctuations, quenching & collective expansion should be dominant

Magnetic field vs. collision centrality



Signal should vanish in peripheral events

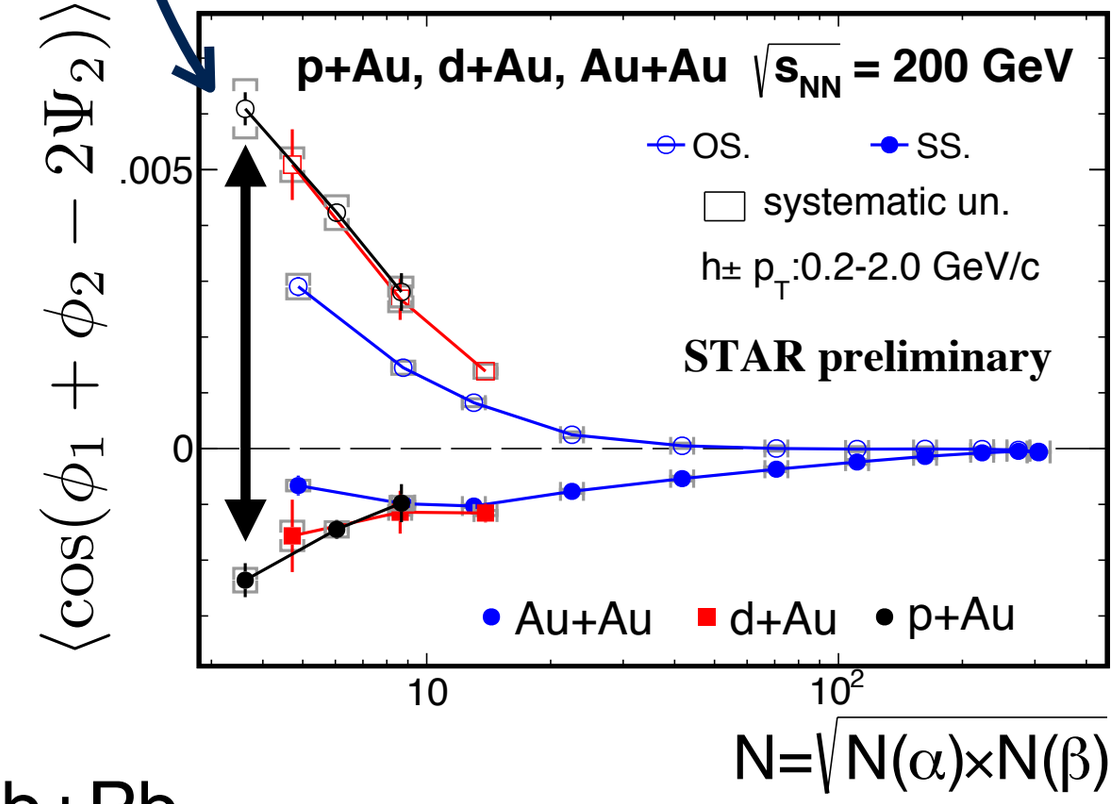


Effect of B-field should vanish in peripheral events

CMS collaboration PRL 118 (2017) 122301

Large charge separation in peripheral A+A & p/d+A

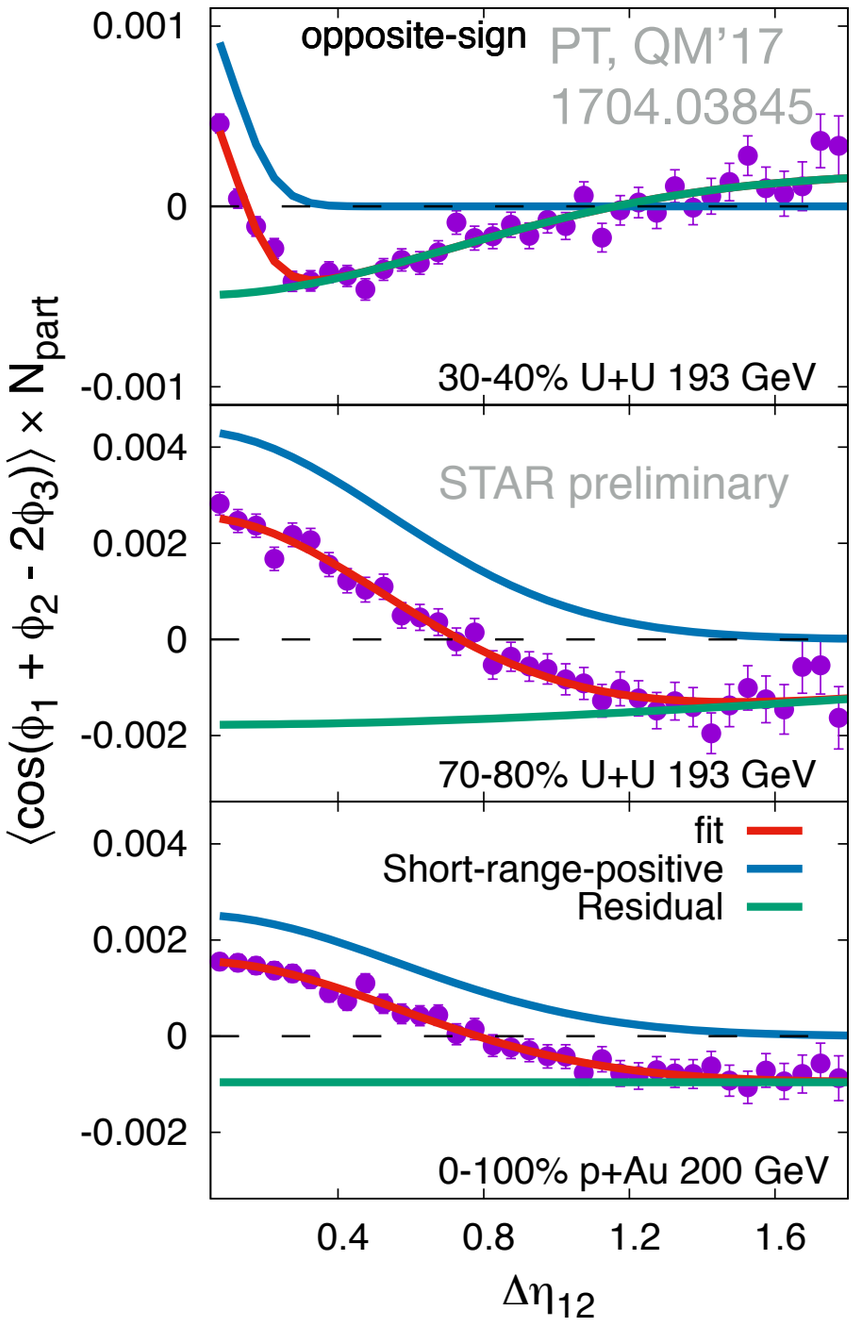
Zhao, arXiv:1712.00394



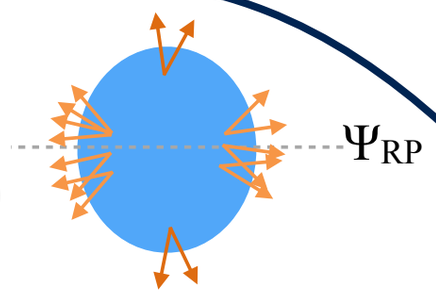
First seen at LHC in p+Pb & peripheral Pb+Pb

Why so large signal in p+A, peripheral A+A ?

Δη dependence of charge separation → di-jets dominate peripheral A+A & p+A

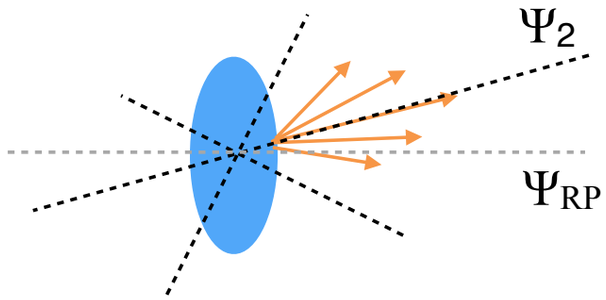


HBT, Coulomb

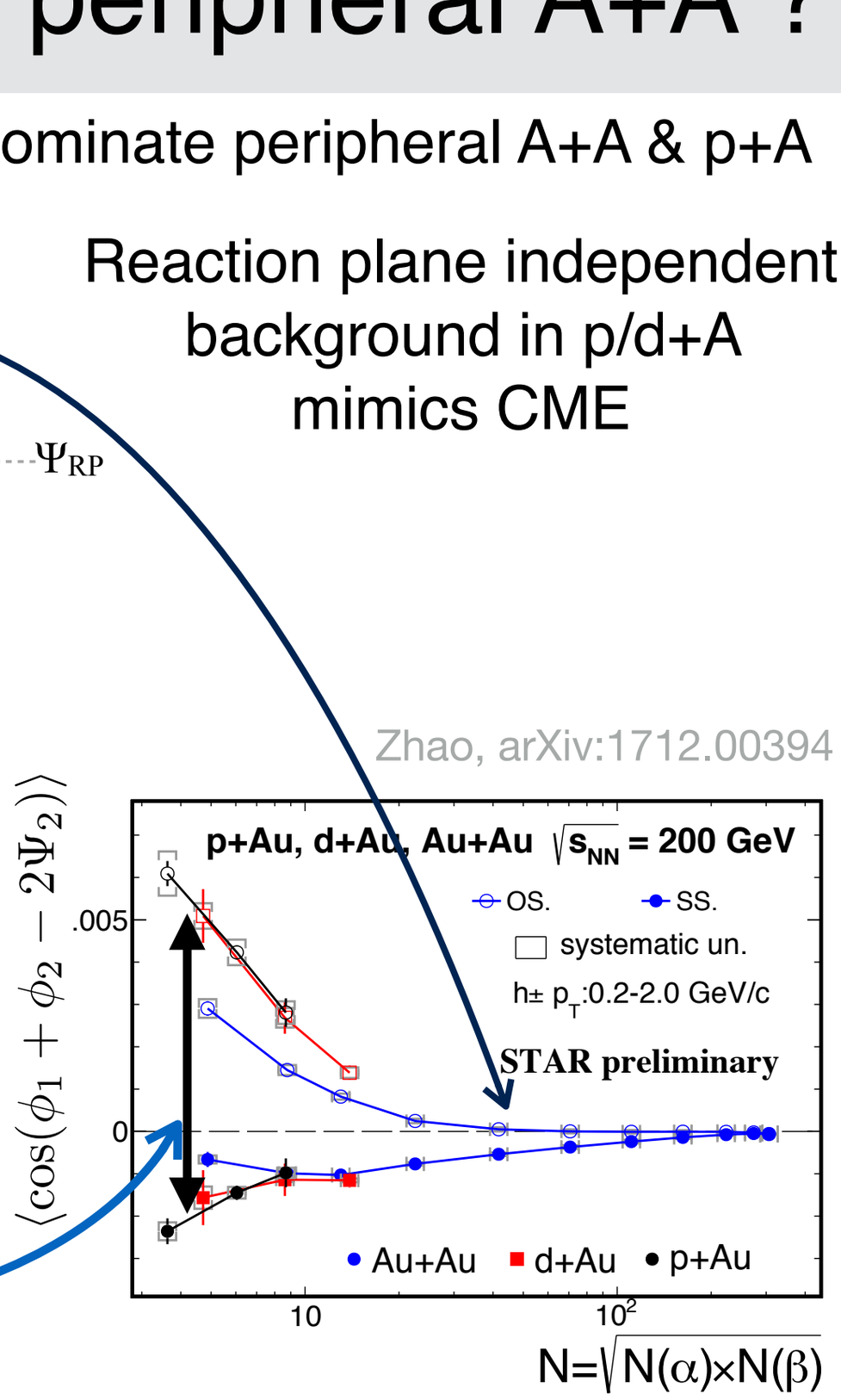


Reaction plane independent background in p/d+A mimics CME

Di-jet fragmentation



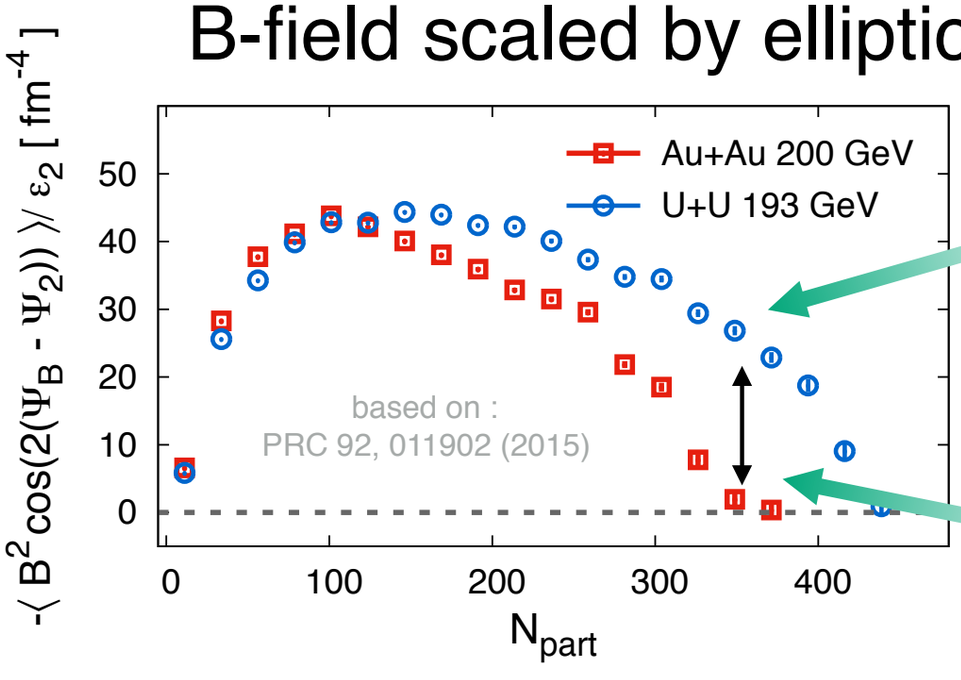
Zhao, arXiv:1712.00394

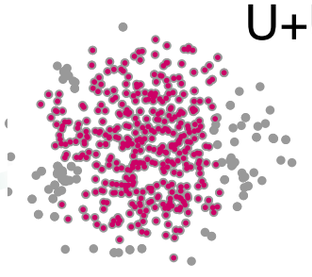


p+A is baseline for peripheral A+A but not central A+A

One more attempt using Au+Au & U+U collisions

B-field scaled by ellipticity



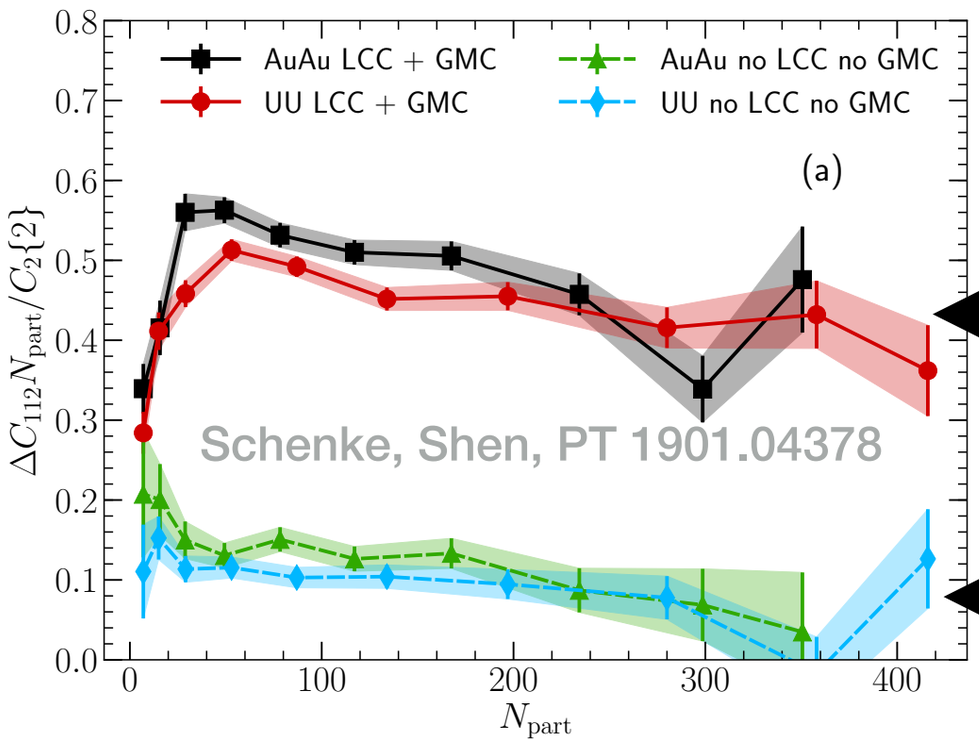


U+U (N_{part}=394)

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

Au+Au (N_{part}=394)

Hydro + local charge conservation

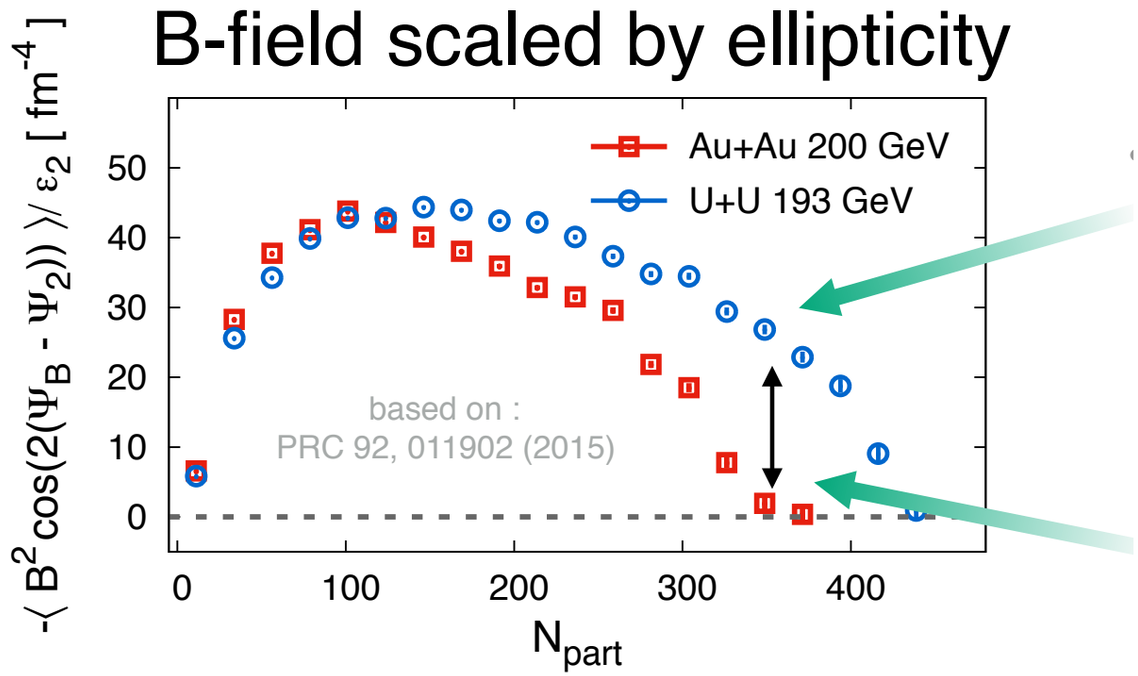


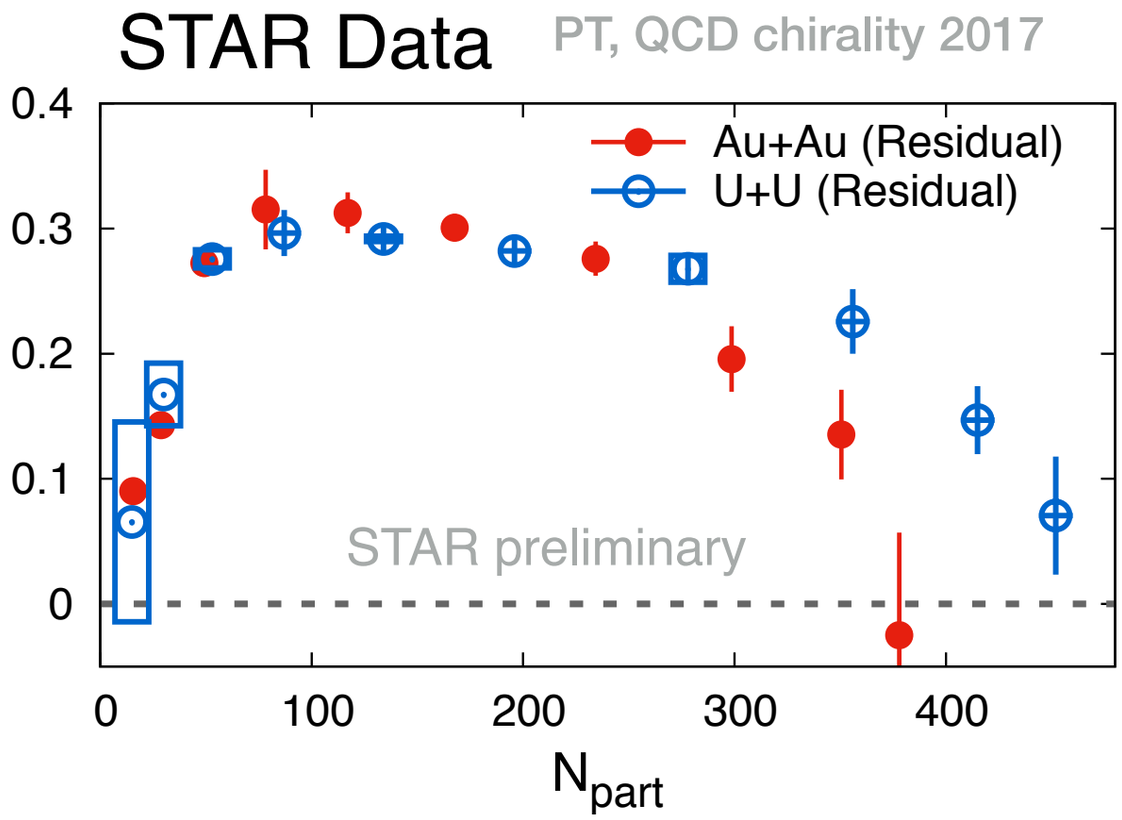
Attempt to mimic Isobar collisions

Maximum possible background

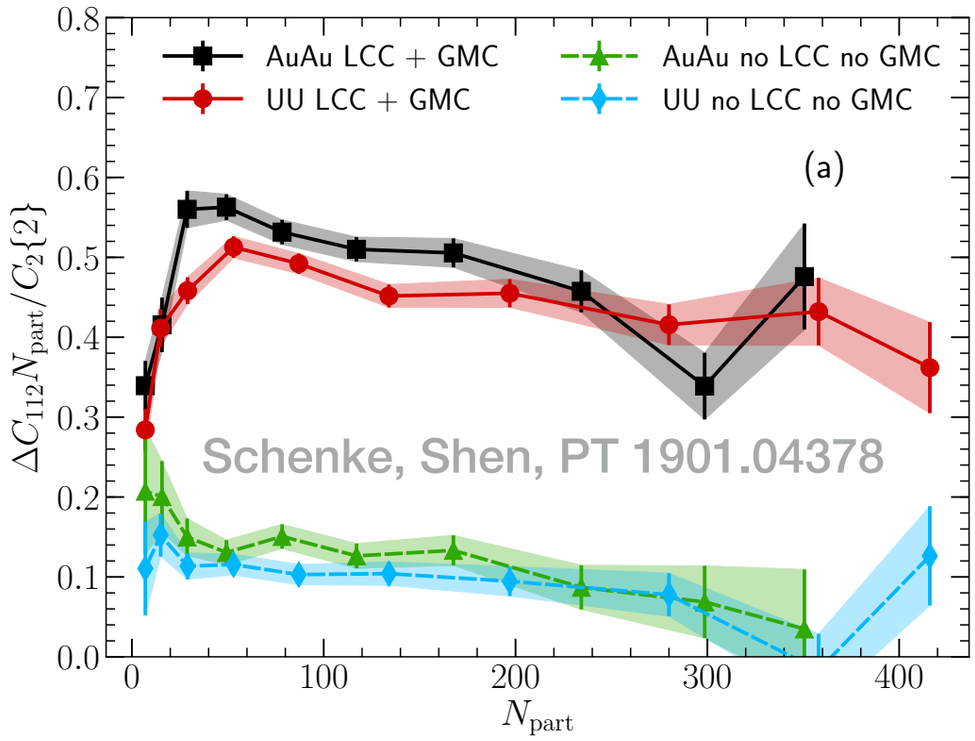
Minimum possible background

One more attempt using Au+Au & U+U collisions





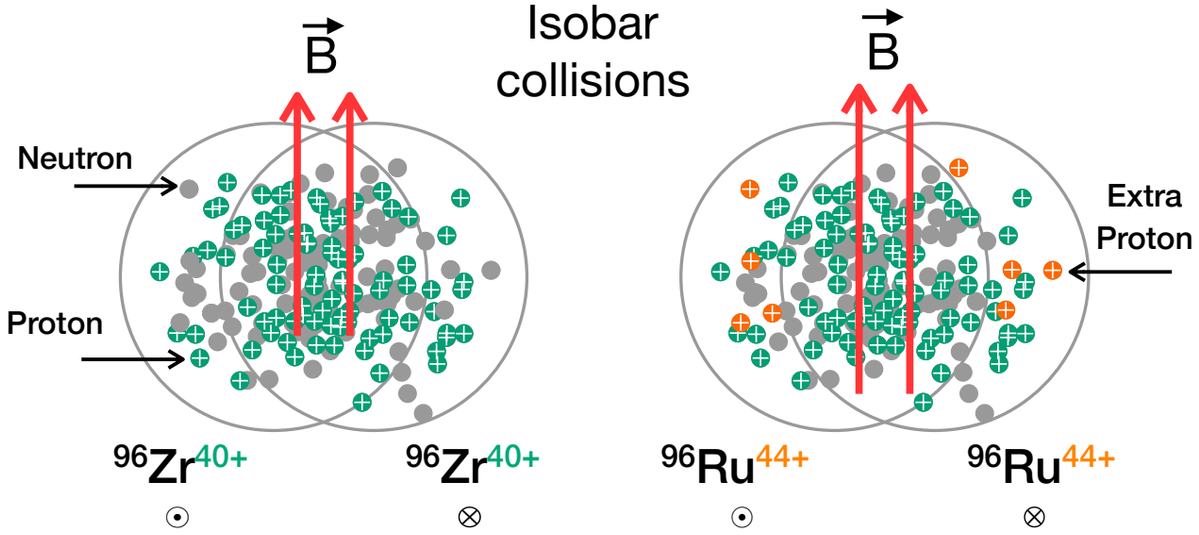
Hydro + local charge conservation



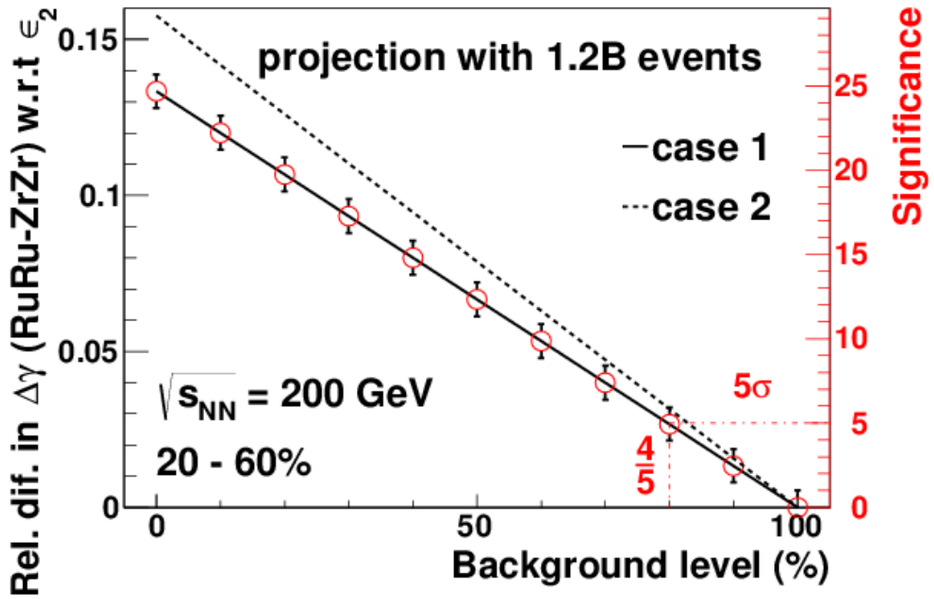
Interesting but an experimental baseline for background needed (w.r.to Ψ_3 plane)

Decisive tests of Chiral Effects

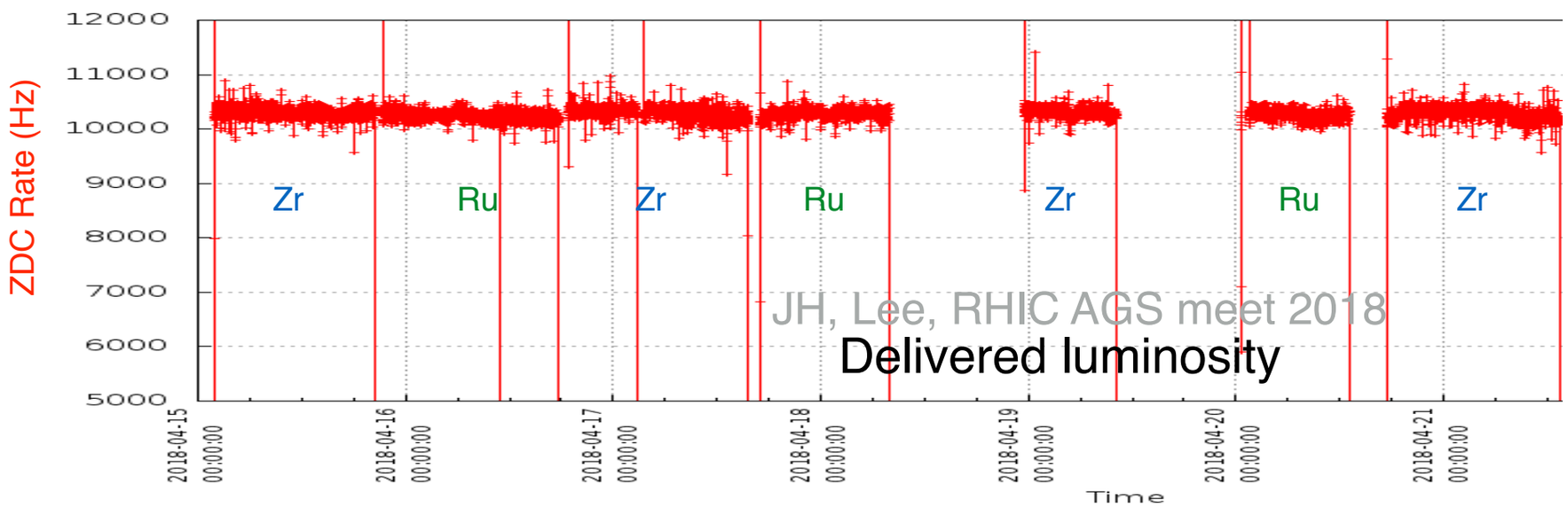
Better and controlled experiment : Isobar collisions



Deng et al Phys.Rev. C94 (2016) 041901

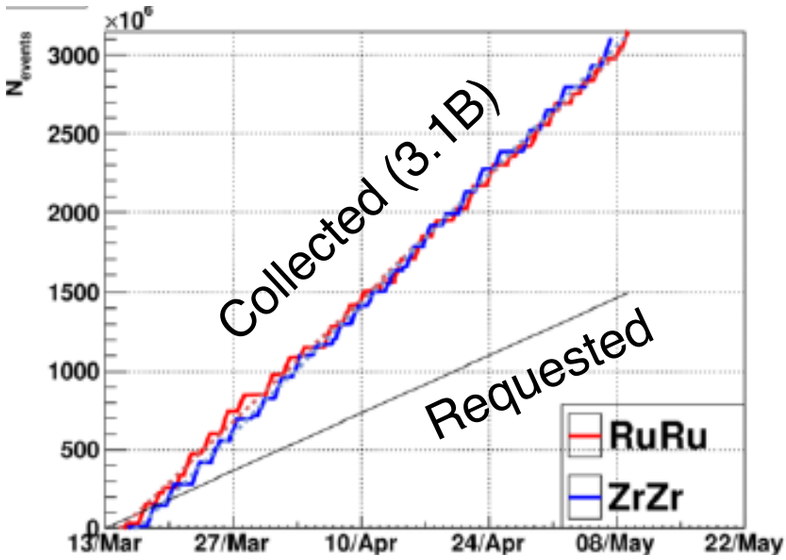


10% larger B-field in Ru+Ru
but same background as Zr+Zr



JH, Lee, RHIC AGS meet 2018

Delivered luminosity



3.1B events for both Ru+Ru, Zr+Zr collected over 8 weeks
Blind analyses is ongoing by the STAR collaboration

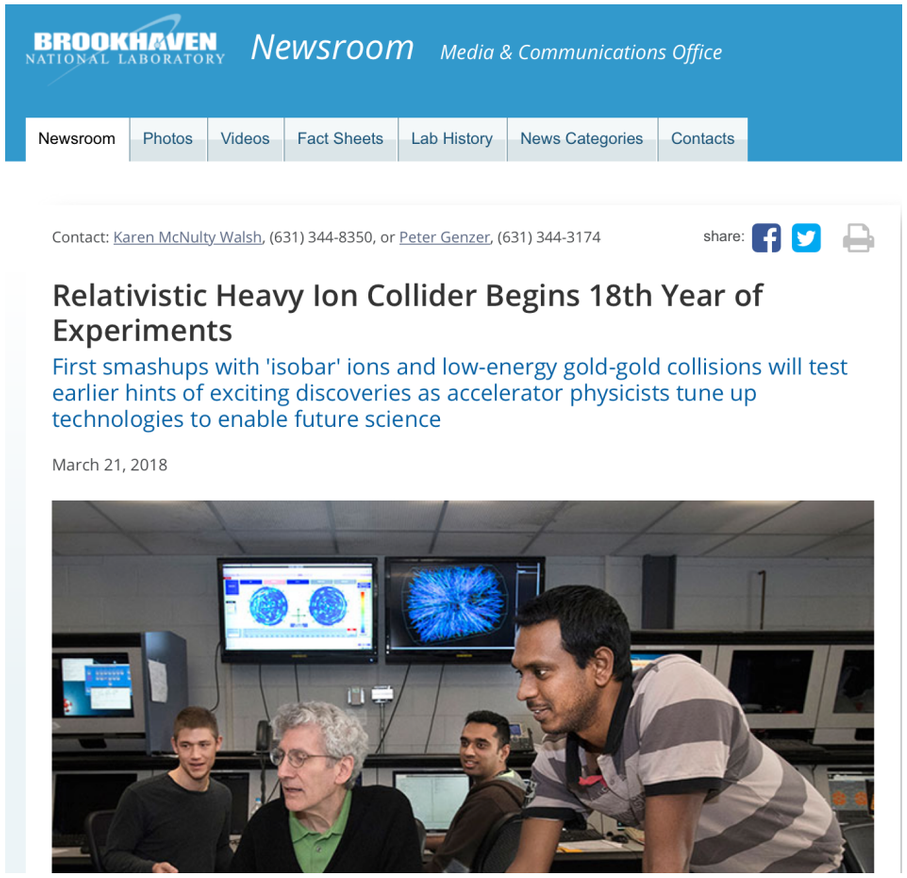
Summary

Very exciting time for RHIC

1) New high statistics measurements of vortical effects, STAR upgrade with new detectors will improve measurements of Lambda polarization

2) Comprehensive set of measurements on CME, CMW, several new approaches to quantify CME signals but no decisive tests yet

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



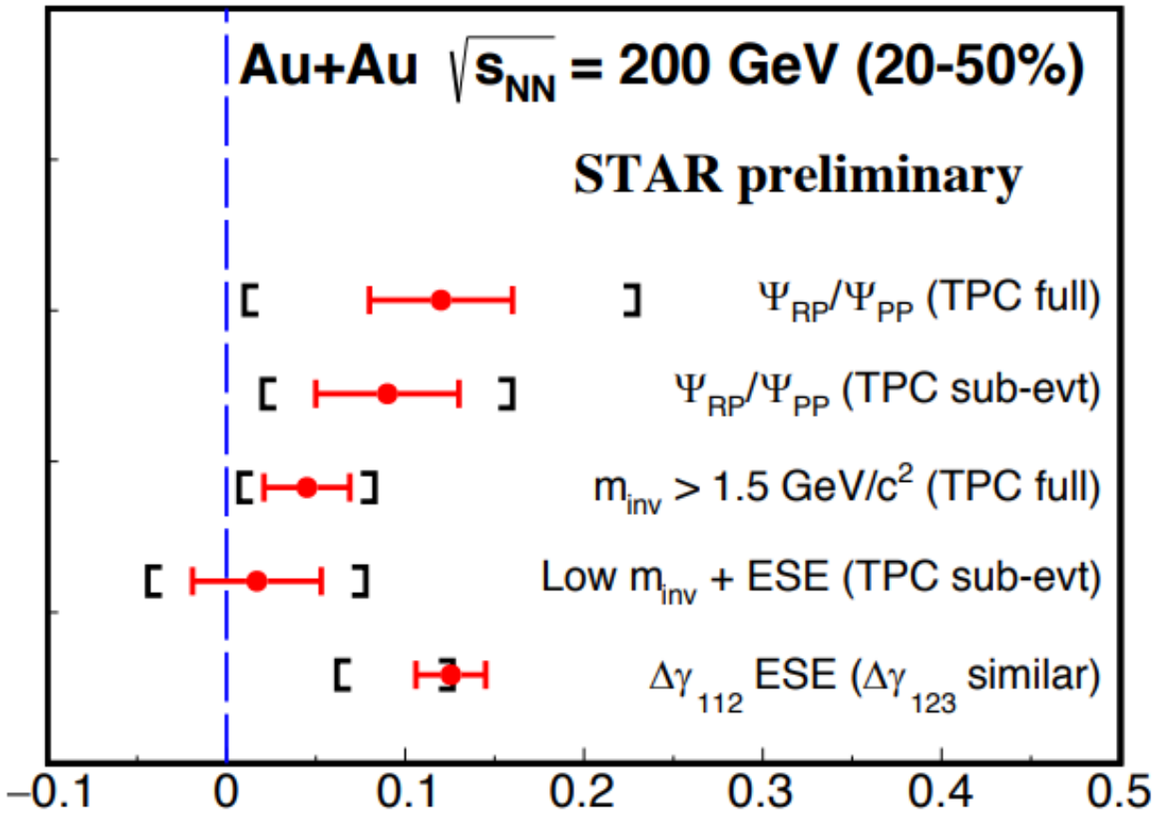
Things I couldn't cover: CMW, CSE Interplay of Chiral & Vortical effects

Thank You

Backup

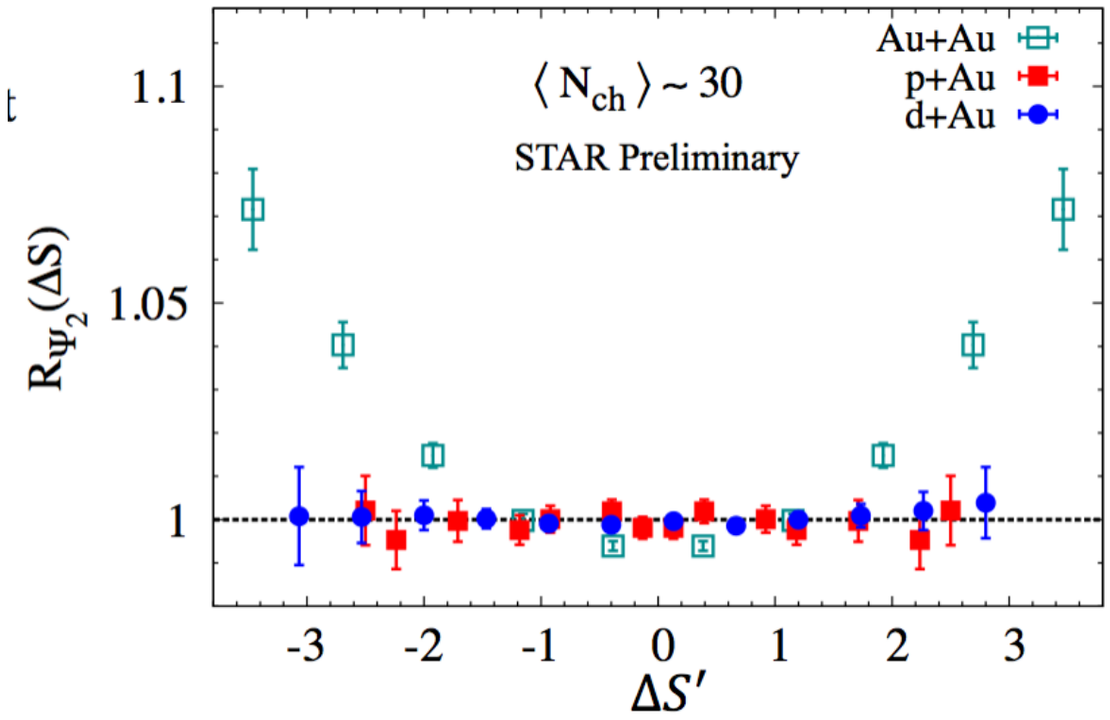
Recent attempts to quantify the fraction of signals

STAR Collaboration, Ye, QM 2018



Several estimations of possible signal fraction of CME, large uncertainties and also some model dependence is needed

Magdy, QM 2018

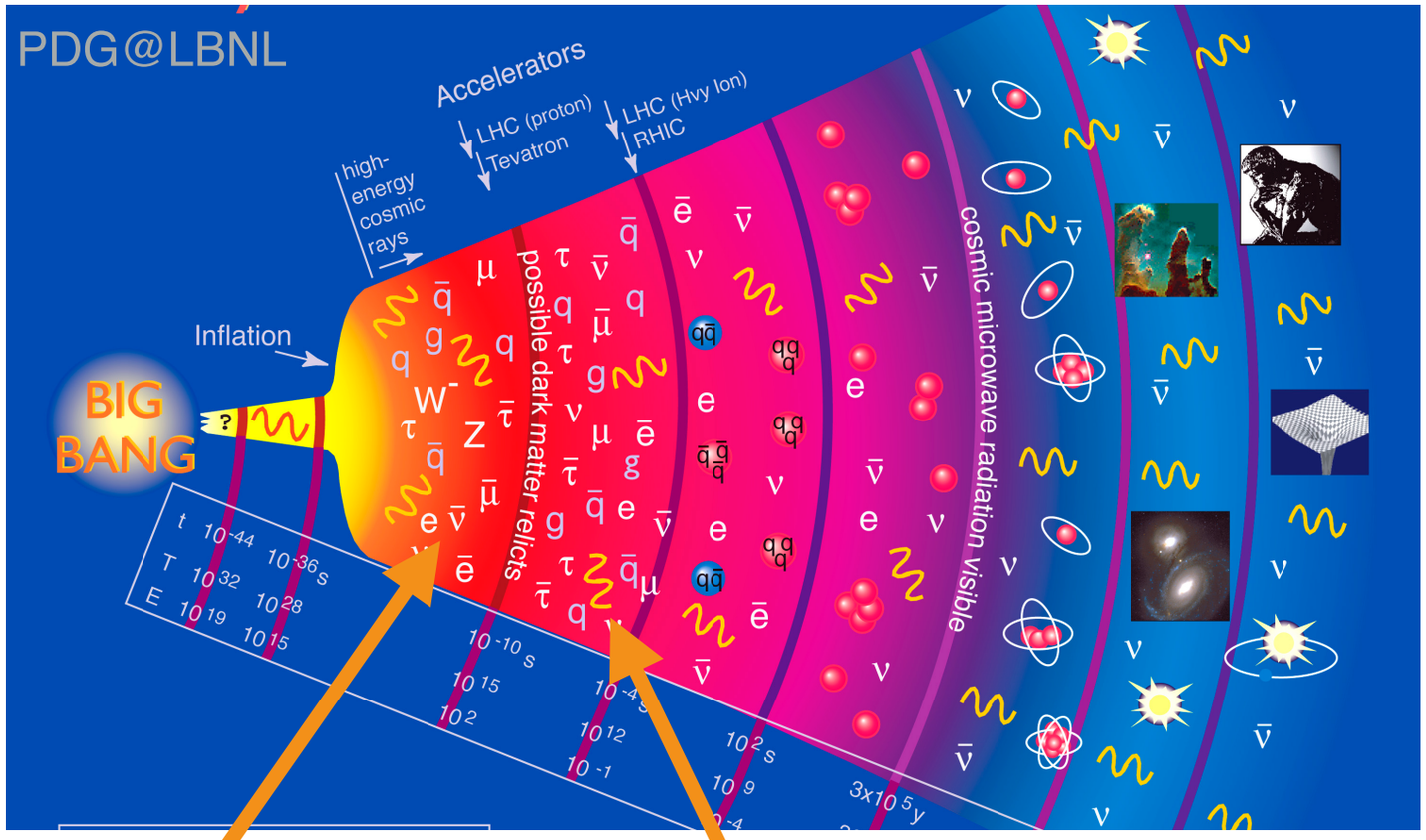


Results using a new observable to study CME looks interesting

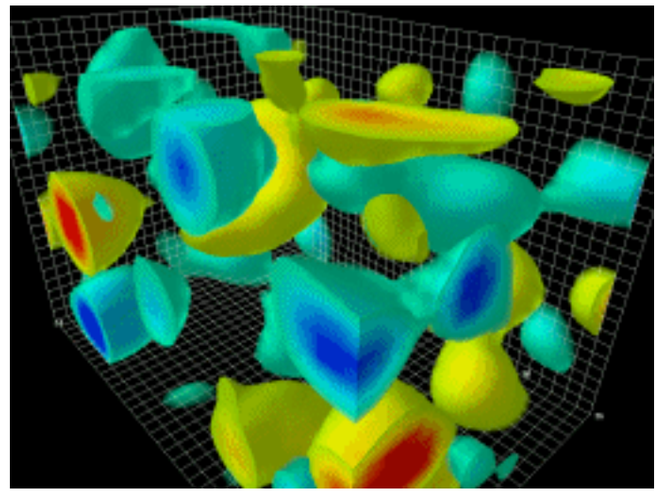
Why is this so exciting ?

Baryon number violation in early universe → matter-antimatter asymmetry

Non-trivial topologies of gauge fields → violation of P & CP



Derek Leinweber



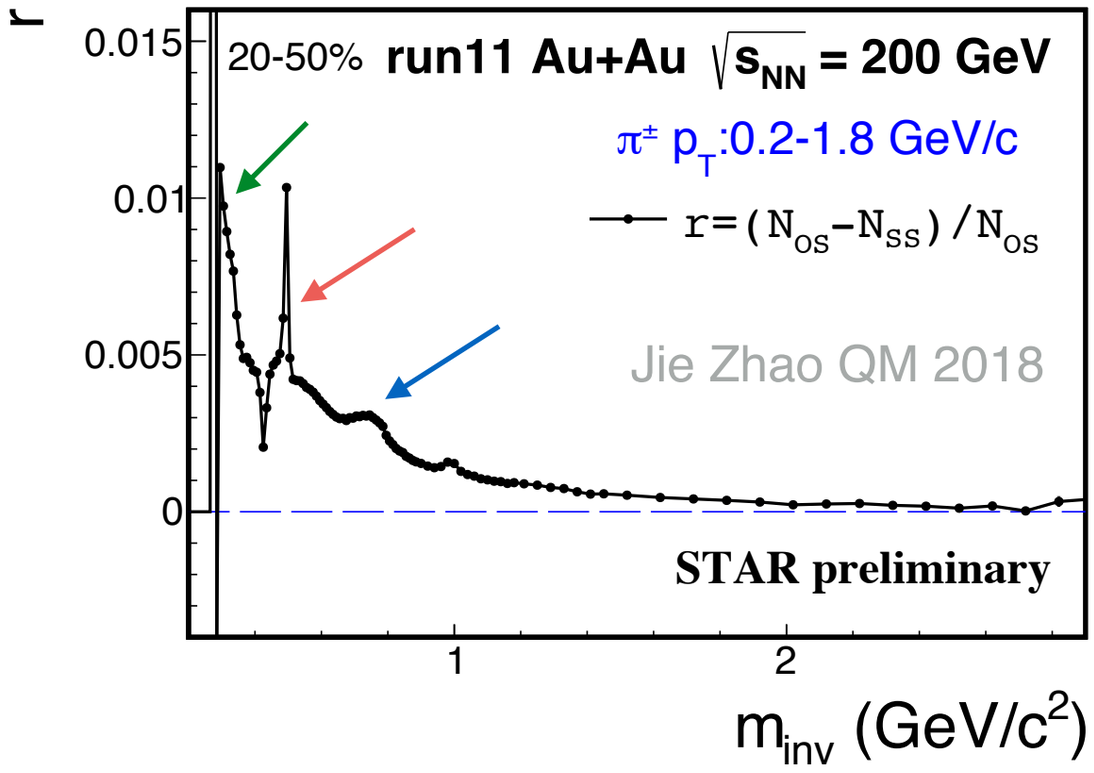
Baryogenesis (Electroweak) ⇒ "Chirality-genesis" (QCD) ⇒ Can we observe in the hot & dense QCD medium of heavy ion collisions ?

$$\partial_\mu J^\mu_B \neq 0 \qquad \partial_\mu J^\mu_5 \neq 0$$

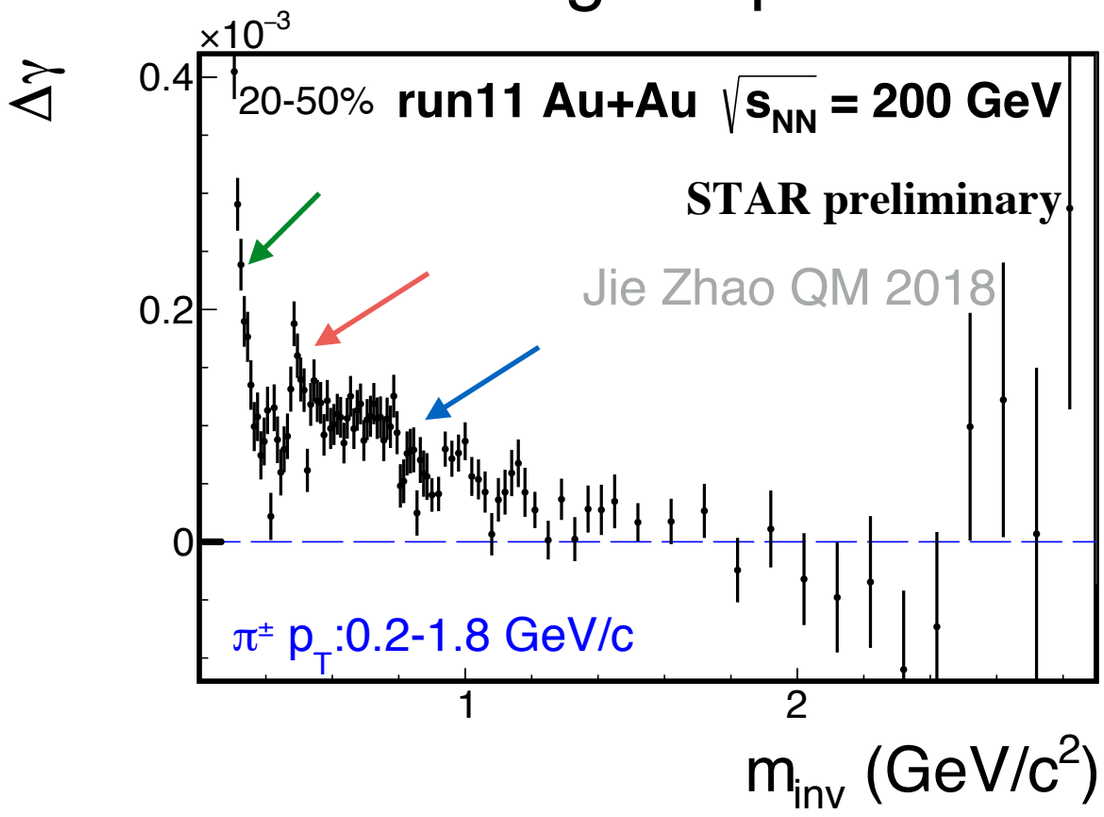
Another source is flowing resonance

Flowing resonances can mimic CME in mid-central A+A

Neutral resonance yield



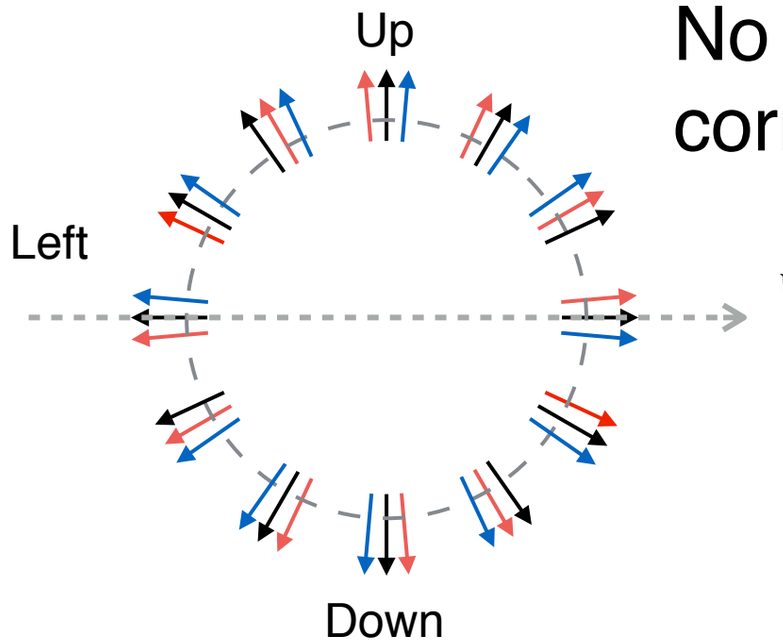
Charge separation



One can subtract the resonance contribution if the invariant mass distribution for CME is known

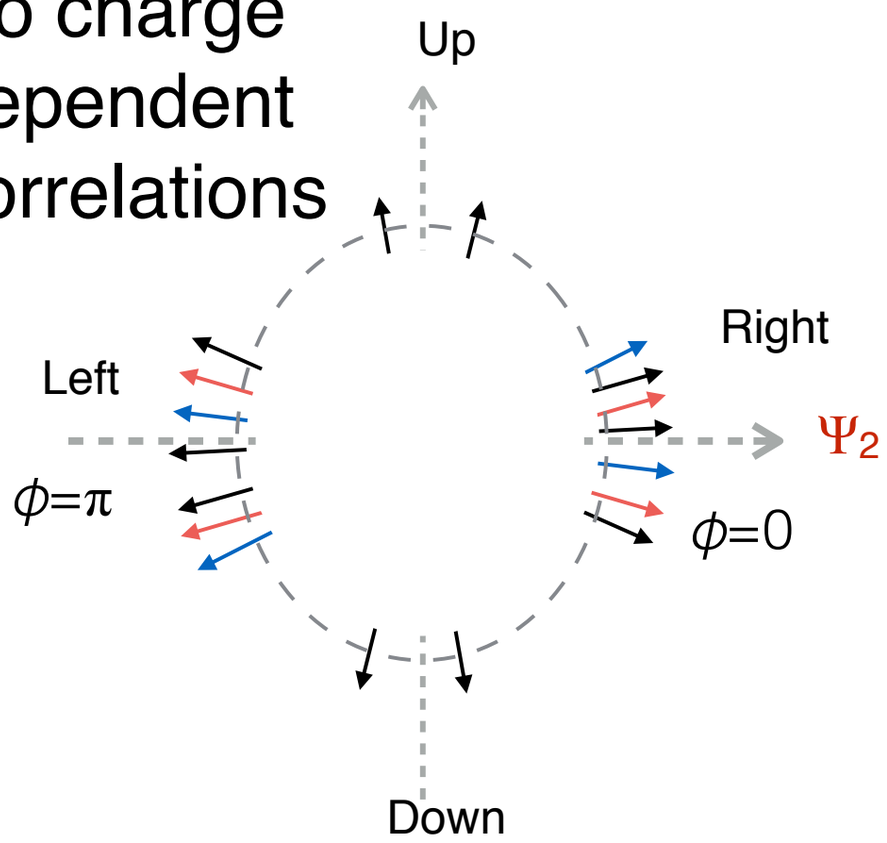
Another source of background: flowing cluster

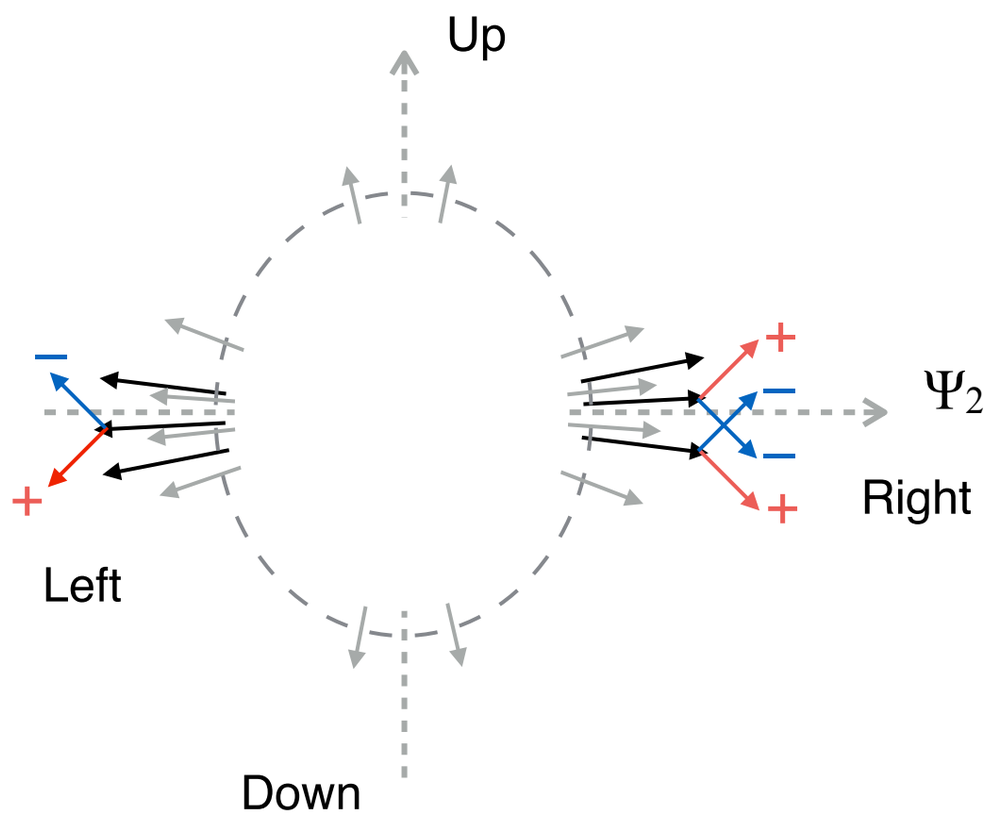
+pos – neg 0 : neutral



No charge dependent correlations

No charge dependent correlations

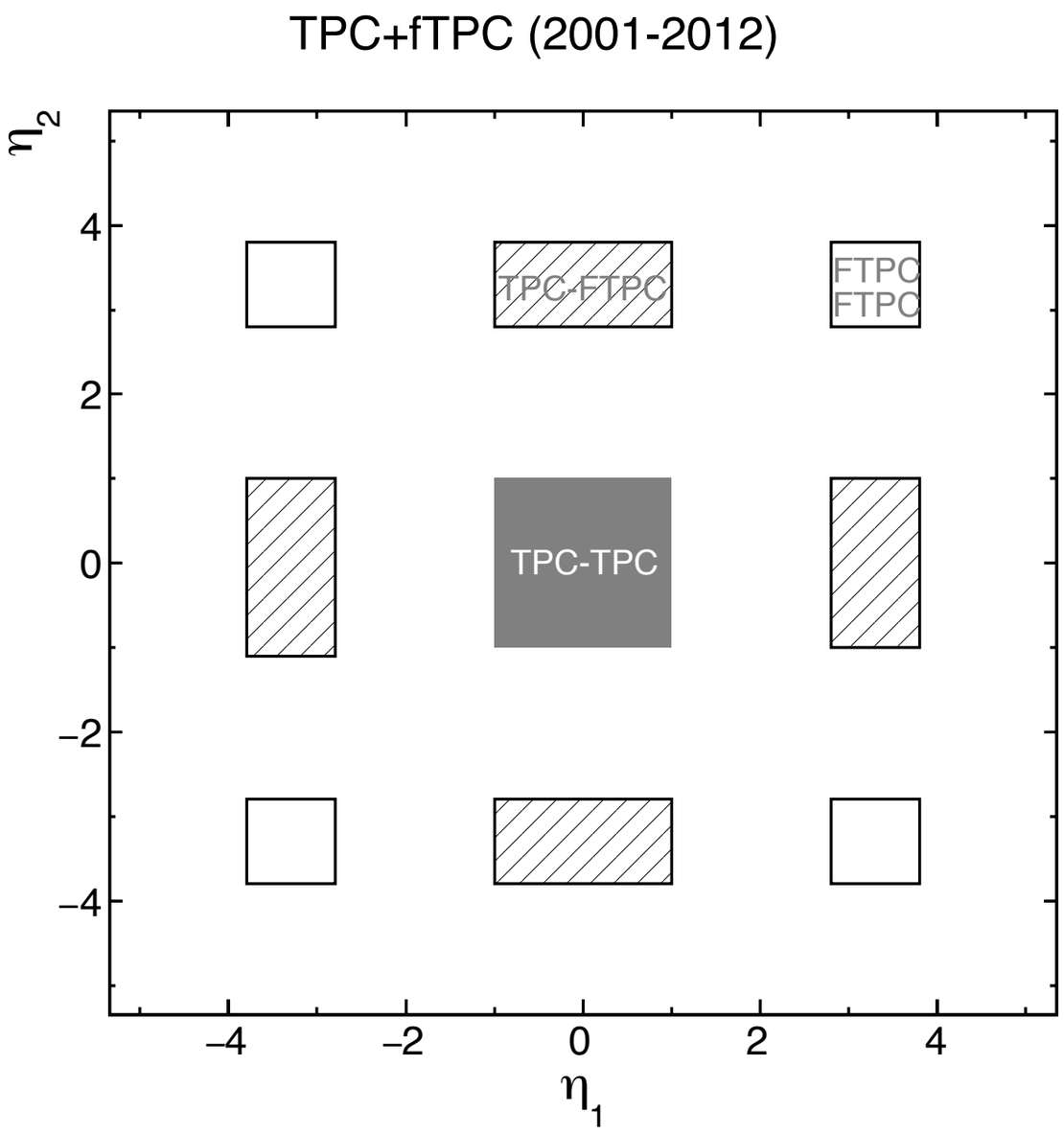


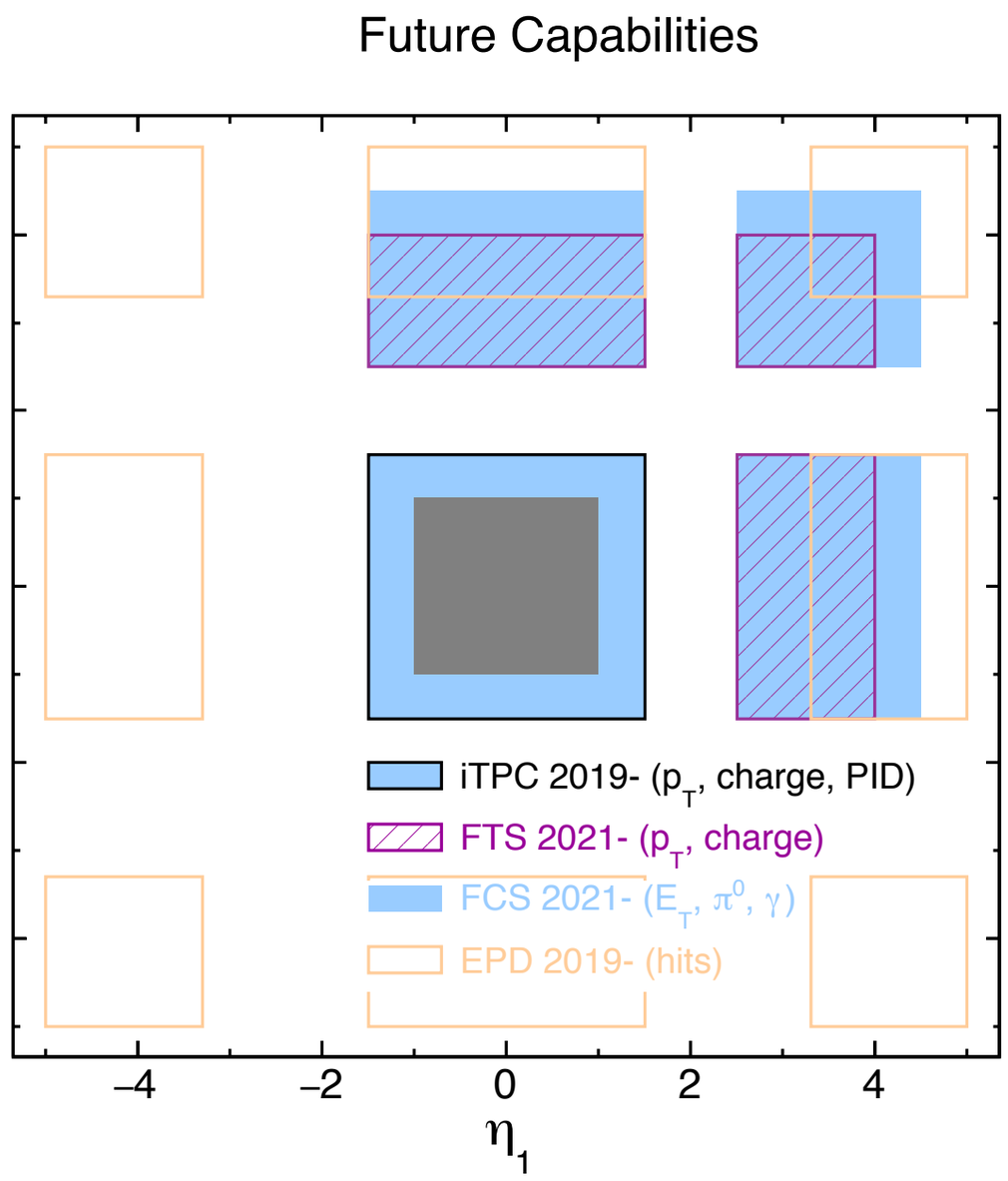


Background due to neutral resonance decay, local charge & momentum conservation

Flowing neutral cluster that produces charge pair will mimic CME

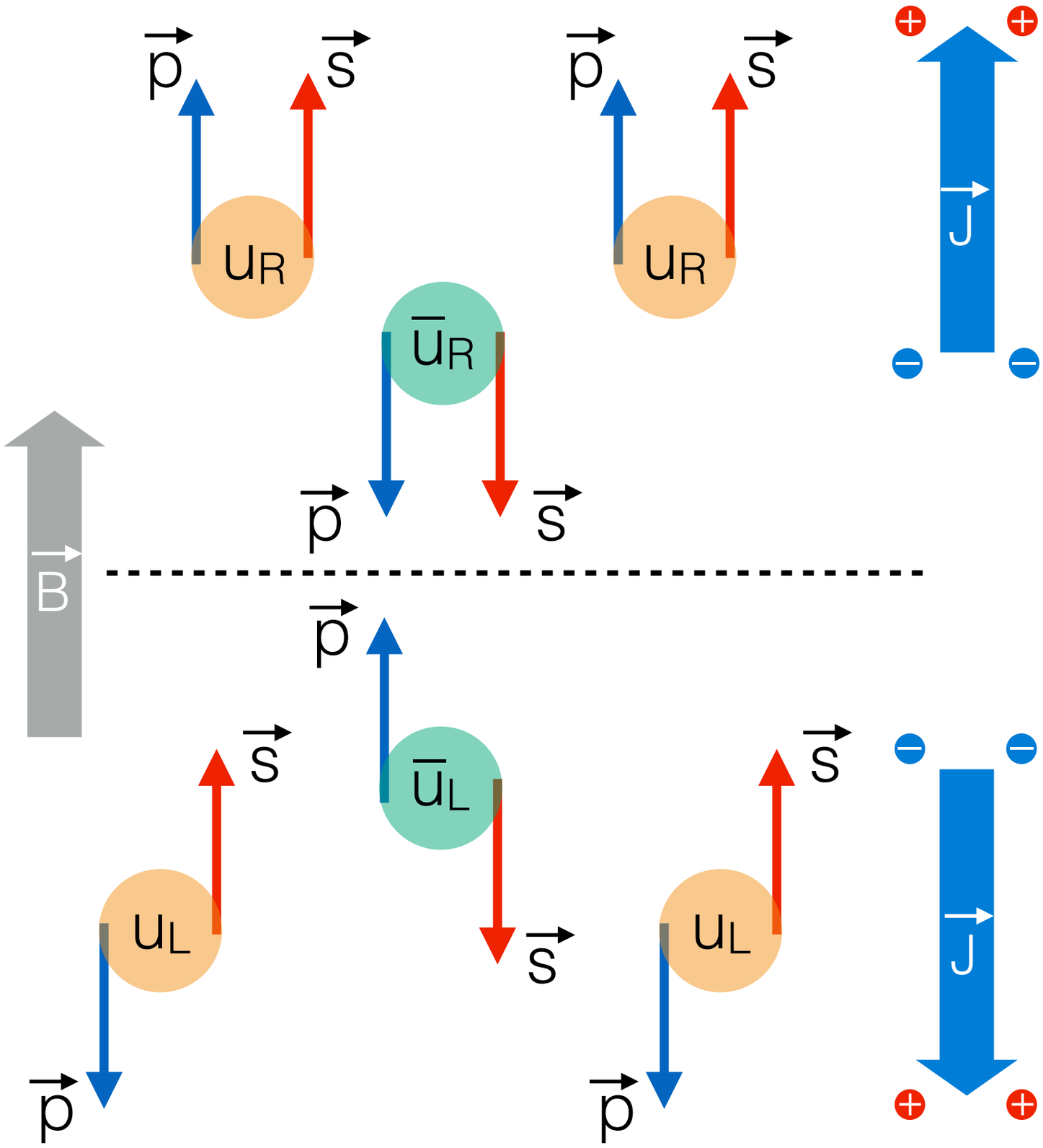
STAR experiment : Extended capabilities





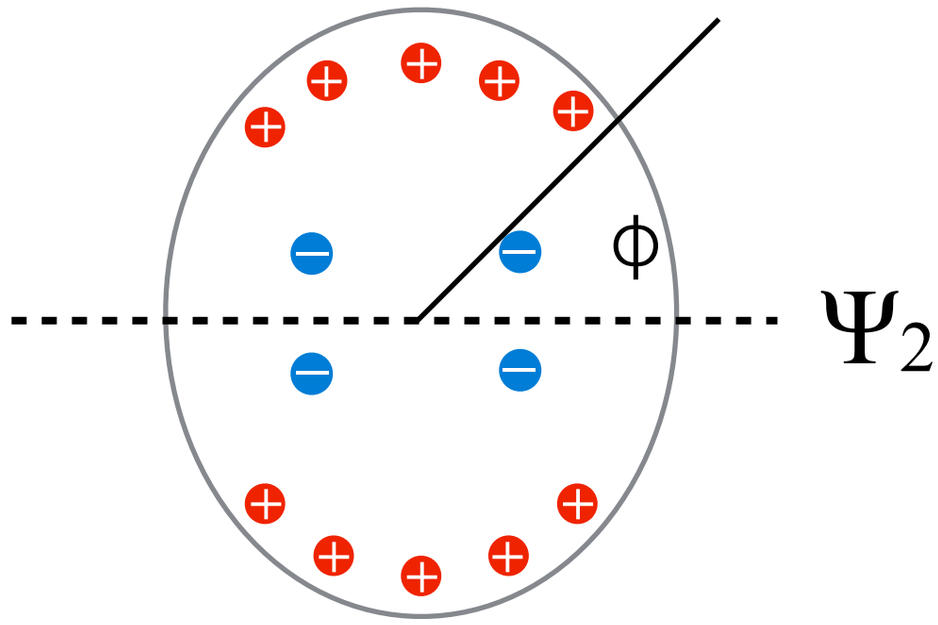
Chiral Separation Effect & Chiral Magnetic Wave

The Chiral Magnetic Wave : driven by CSE



Burnier, Kharzeev, Liao and Yee, PRL 107, 052303

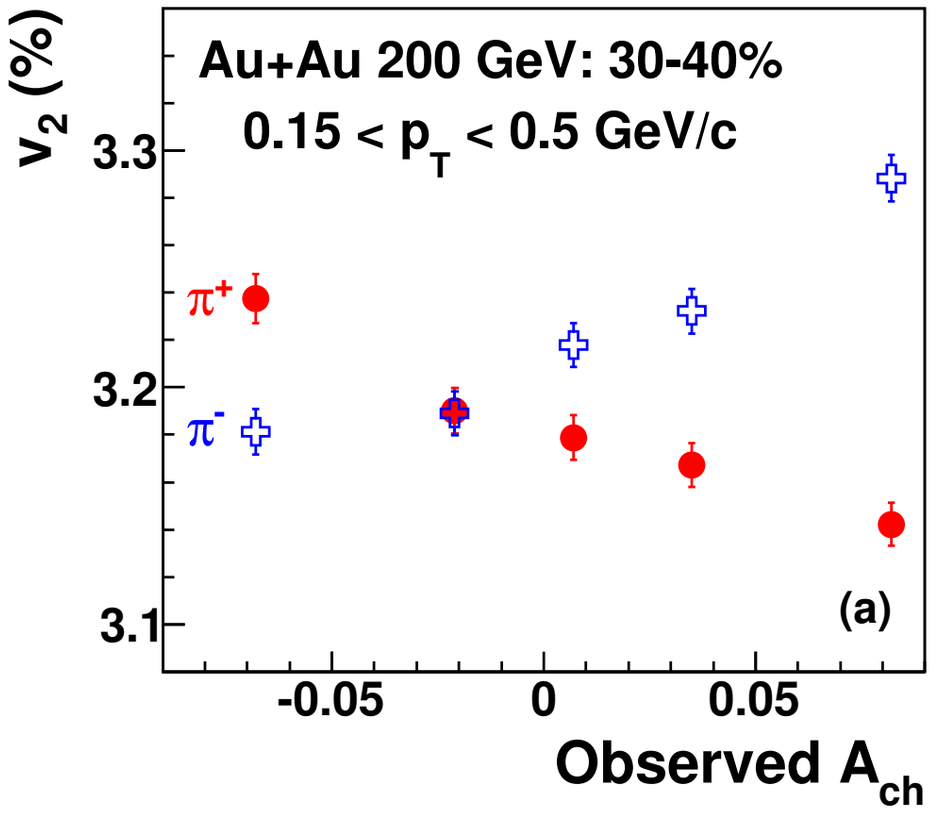
This phenomena is driven by excess quarks over anti-quarks does not require initial μ_5



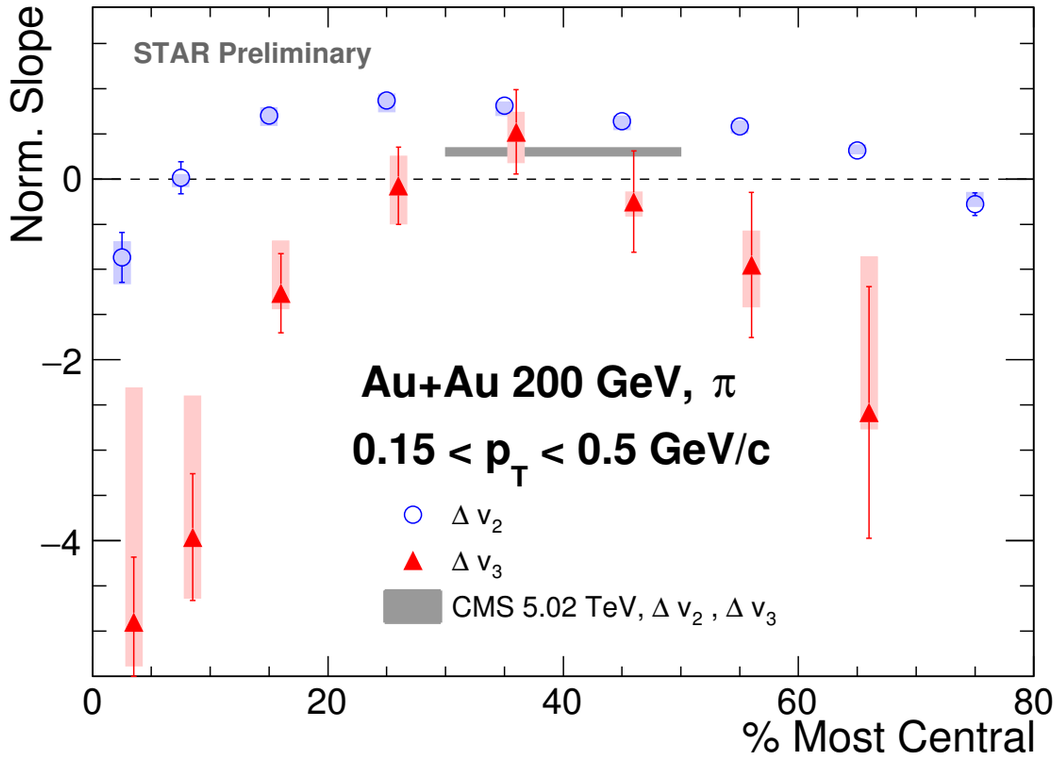
$$\frac{dN^{\pm}}{d\phi} \propto v_2^{\pm} \cos(2\phi^{\pm})$$

Search for the chiral magnetic wave at RHIC

L. Adamczyk et al. (STAR Collaboration) Phys. Rev. Lett. 114, 252302



Qi-Ye Shou QM 2018



Observation at RHIC is consistent to CMW expectation

$$A_{\rm ch} = \frac{N_+ - N_-}{N_+ + N_-} < 0,\ \ v_2(\pi^+) > v_2(\pi^-)$$

$$A_{\rm ch} = \frac{N_+ - N_-}{N_+ + N_-} > 0,\ \ v_2(\pi^+) < v_2(\pi^-)$$

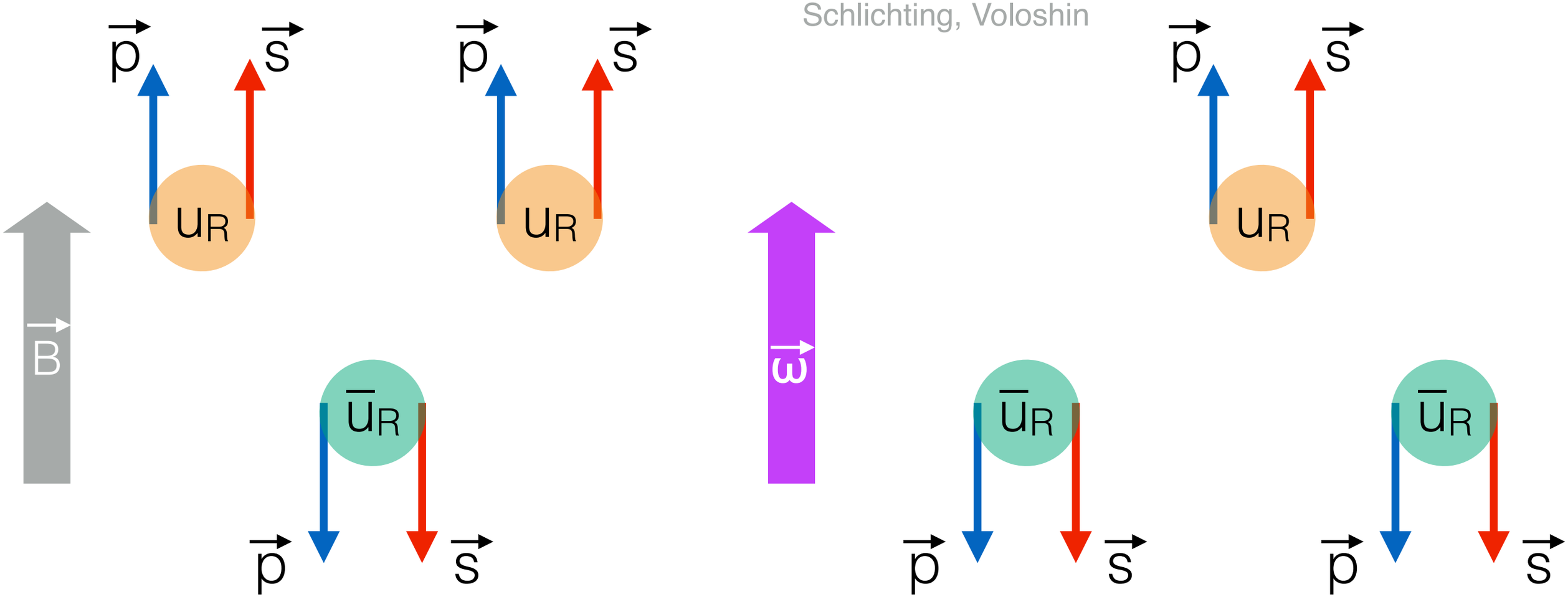
Unlike LHC, at RHIC effect $v_2 >> v_3$

Chiral and Vortical effects

Chiral separation effect and spin polarization

CSE enhances spin polarization along global angular momentum

Schlichting, Voloshin



$$A_{\rm ch} = \frac{N_+ - N_-}{N_+ + N_-} > 0$$

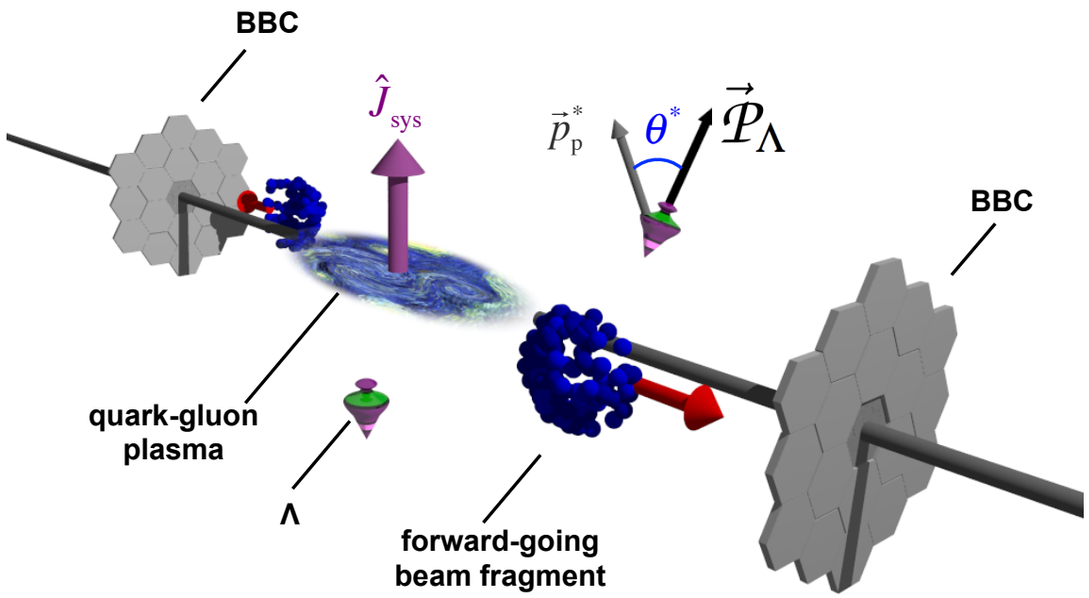
More spin polarized along $\vec{B}$ II $\vec{\omega}$

$$A_{\rm ch} = \frac{N_+ - N_-}{N_+ + N_-} < 0$$

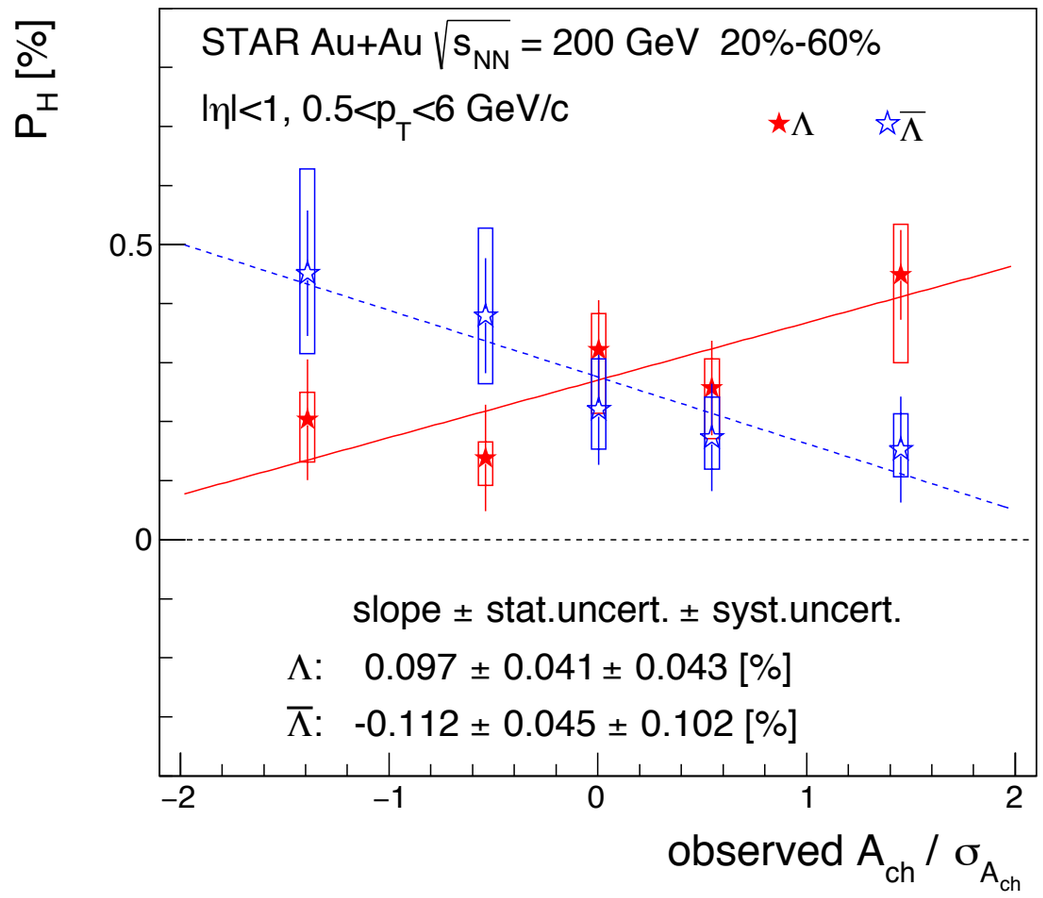
More spin polarized opps to $\vec{B}$ || $\vec{\omega}$

The connection between CSE and polarization

STAR Collaboration Nature 548 (2017) 62-65



Takafumi Niida, QM 2018



$$\overline{\mathcal{P}}_{\mathrm{H}} \equiv \langle \vec{\mathcal{P}}_{\mathrm{H}} \cdot \hat{J}_{\mathrm{sys}} \rangle = \frac{8}{\pi \alpha_{\mathrm{H}}} \frac{\left\langle \cos\left(\phi_p^* - \phi_{\hat{J}_{\mathrm{sys}}}\right) \right\rangle}{R_{\mathrm{EP}}^{(1)}}$$

Global polarization of Λ and $\overline{\Lambda}$ studied w.r.to charge asymmetry A_{ch}

Very first measurement looks promising, need more statistics