Search for Chiral Effects at RHIC : status and the future

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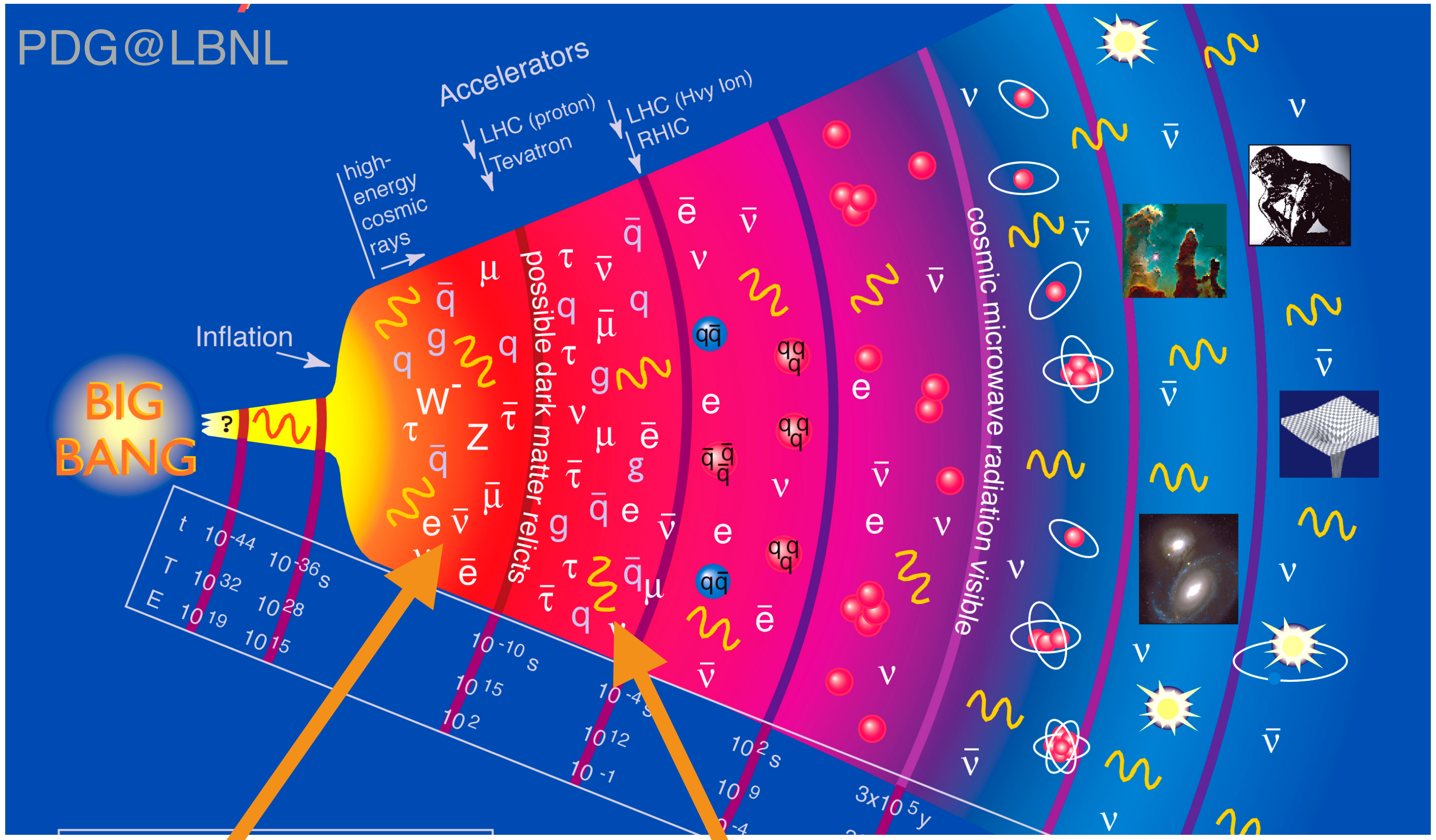
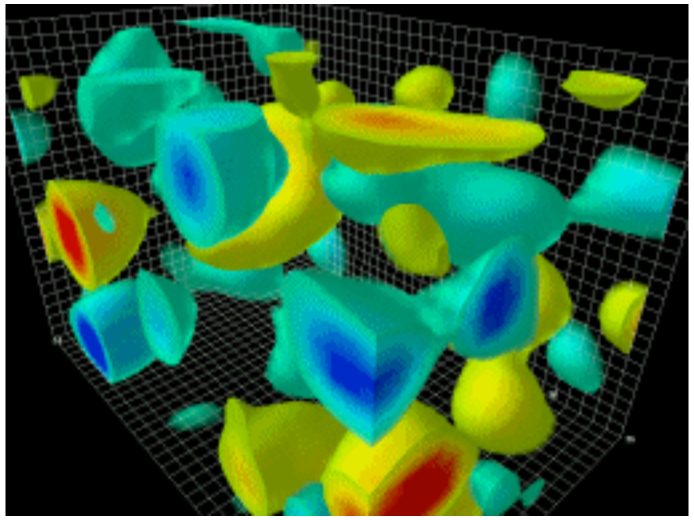
Why is this so exciting ?

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 ?

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

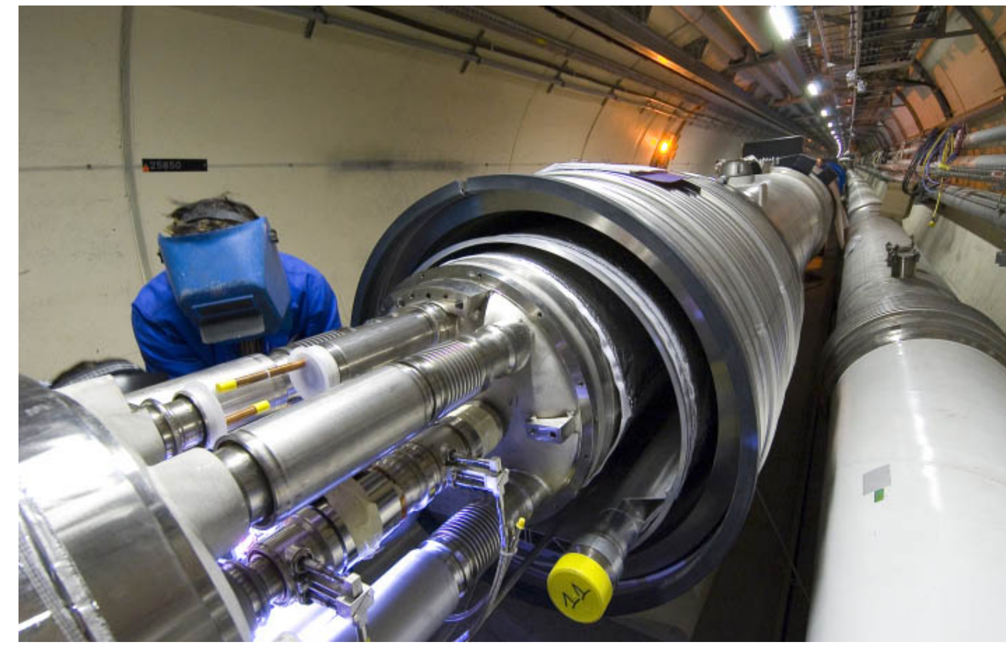
Experimental searches for chiral effects

Relativistic Heavy Ion collider (RHIC)

200 GeV : U+U, Cu+Cu, p+Au, d+Au

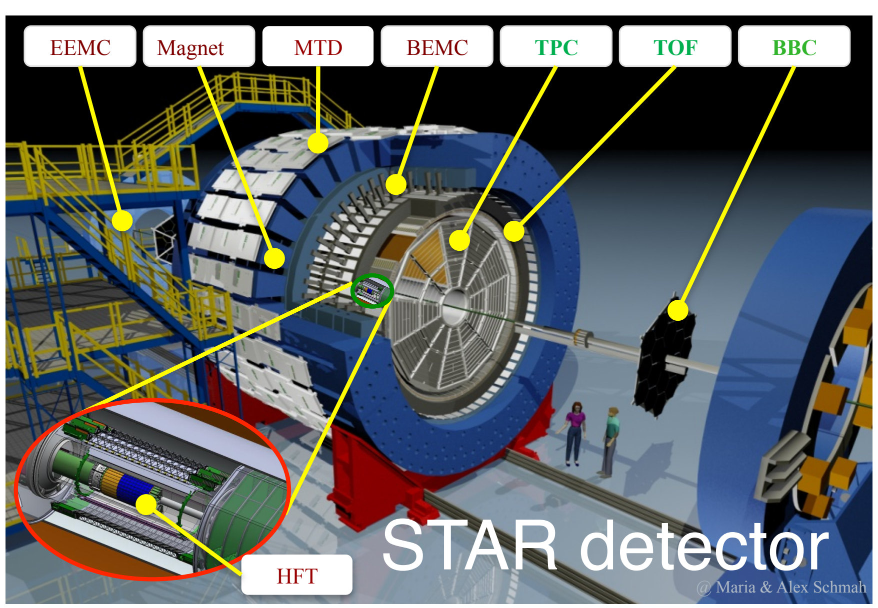
Ru+Ru, Zr+Zr, 7.7-200 GeV : Au+Au

Large Hadron Collider (LHC)



5 TeV : Pb+Pb, p+Pb

see talk by Wei

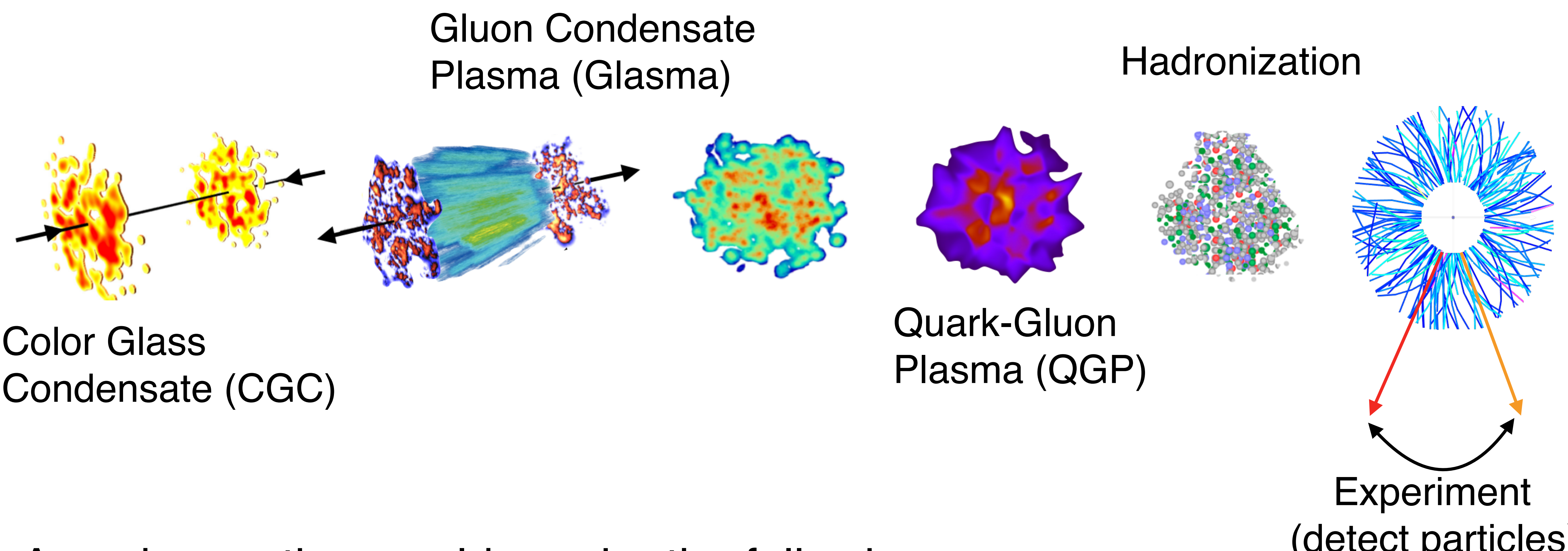


This talk

1. Chiral Magnetic Effect
2. Chiral Magnetic Wave
3. Chiral Separation Effect

Search for local parity violation in QCD

QCD allows topologically distinct states to violate P and CP (locally)



Any observation would require the following

- Non-conservation of chirality ($n_L - n_R \neq 0$)
- De-confinement & restoration of chiral symmetry (m~0 fermions)
- Presence of strong magnetic field (B)

→ Chiral Magnetic Effect

#1: Non-conservation of chirality

Early stages of heavy ion collisions → gauge field configurations with non-trivial topologies

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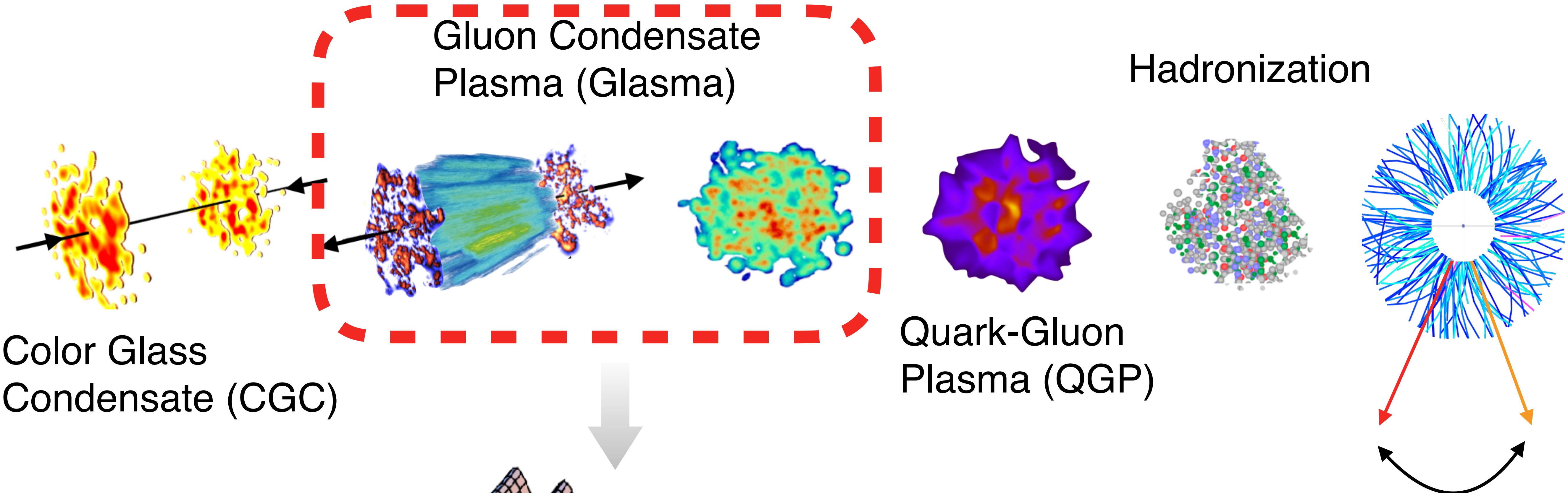
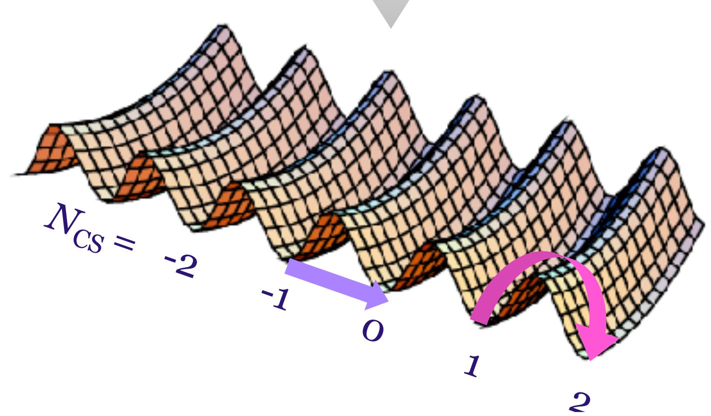


Experiment
(detect particles)



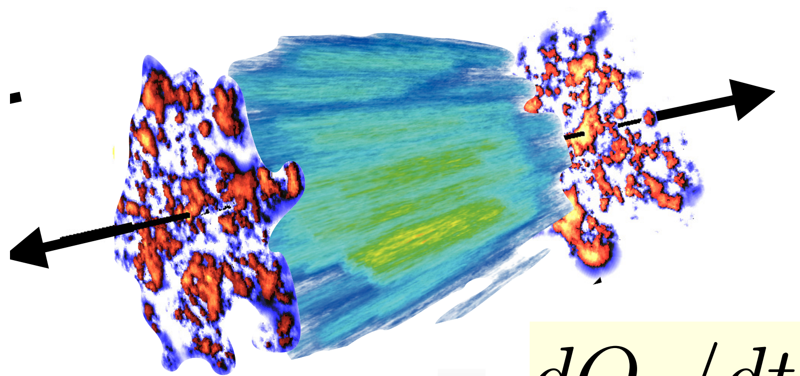
Kharzeev, Krasnitz, Venugopalan hep-ph/0109253, Buividovich 0907.0494, Mace, Schlichting, Venugopalan 1601.07342 L.

$dQ_5/dt \propto \mathbf{E}\cdot\mathbf{B}$ → (n_L-n_R ≠0)

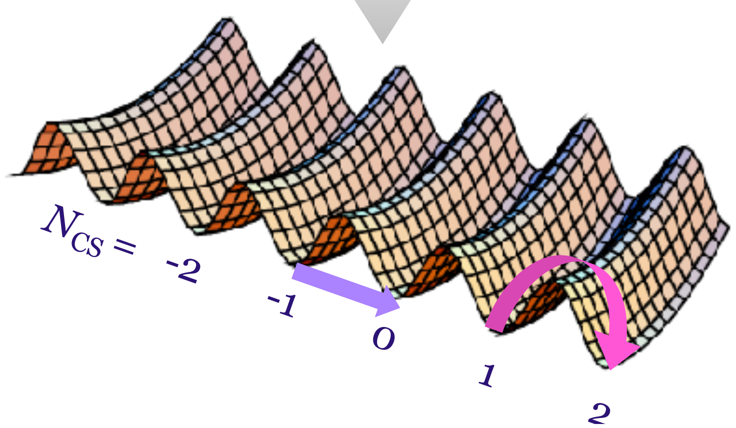
#1: Non-conservation of chirality

Sphaleron transition in Glasma —> non zero axial (Chern-Simons) current

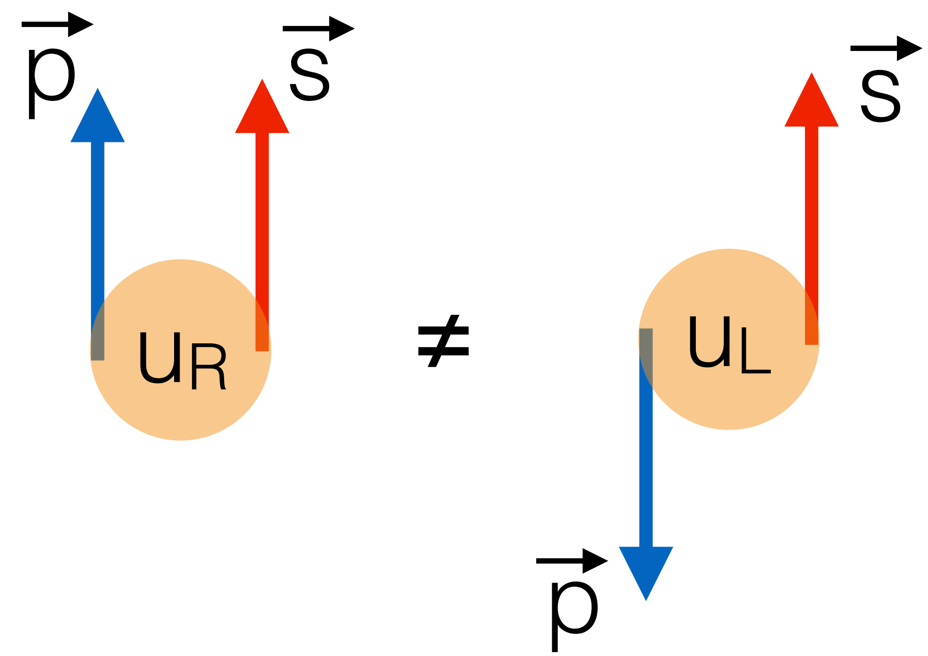
Glasma



$dQ_5/dt \propto \mathbf{E}\cdot\mathbf{B}$



Chirality non-conservation



Right-handed helicity

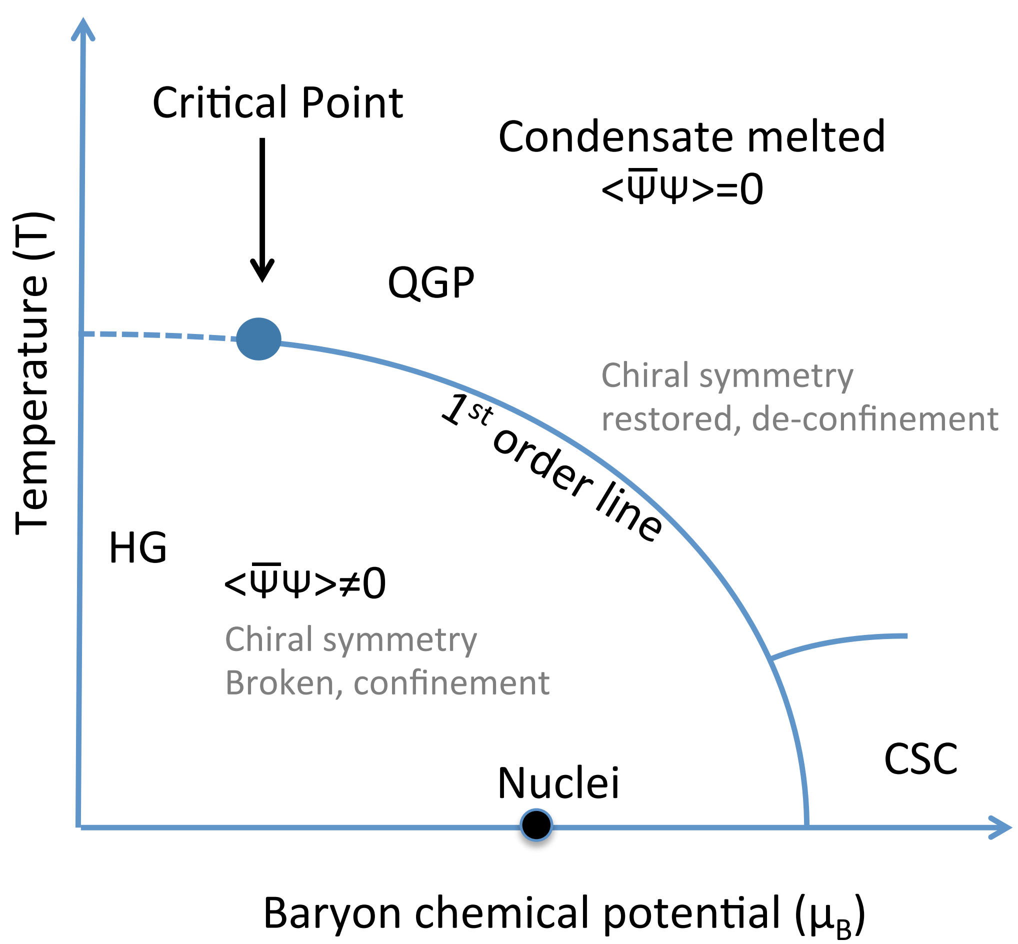
Left-handed helicity

(~massless fermions)

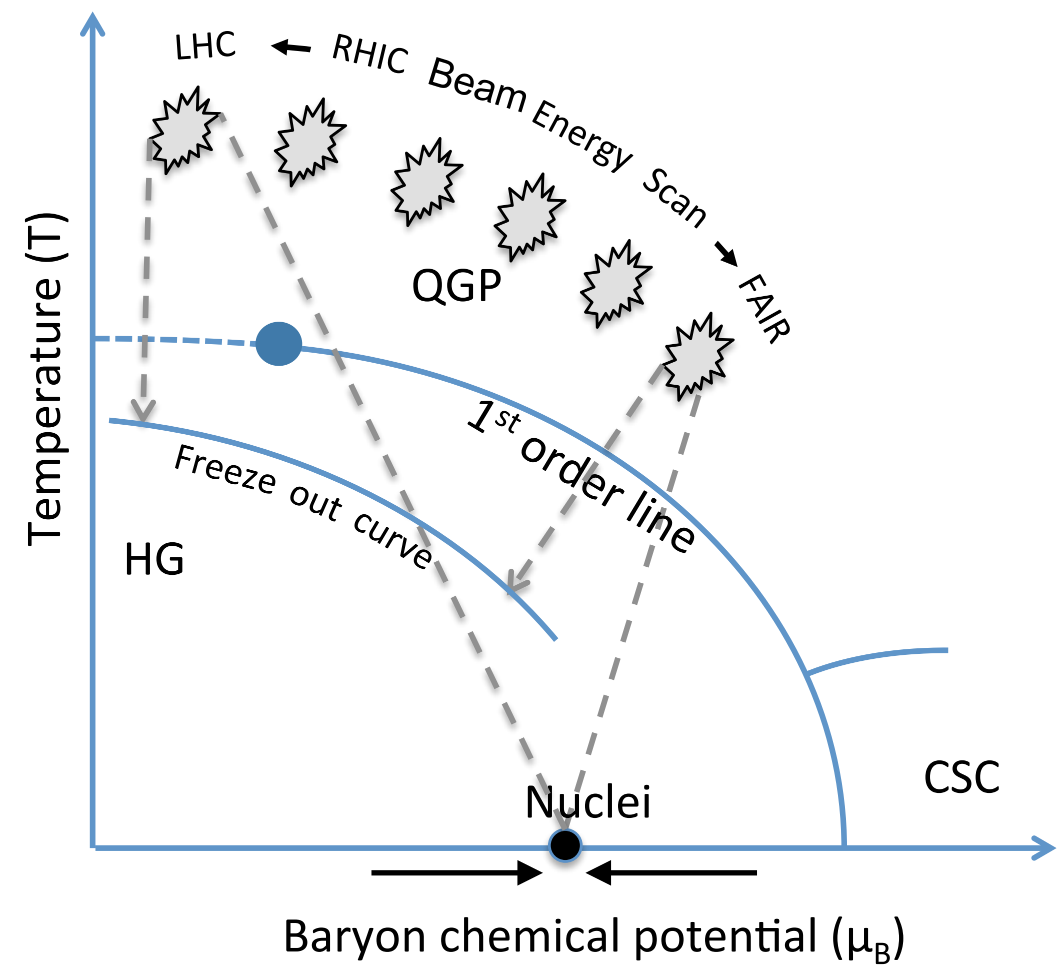
Kharzeev, Krasnitz, Venugopalan hep-ph/0109253,
Buividovich 0907.0494,
Mace, Schlichting, Venugopalan 1601.07342 L.

#2: Restoration of chiral symmetry

Chiral symmetry restoration in the medium created in A+A collisions



Conjectured phase diagram

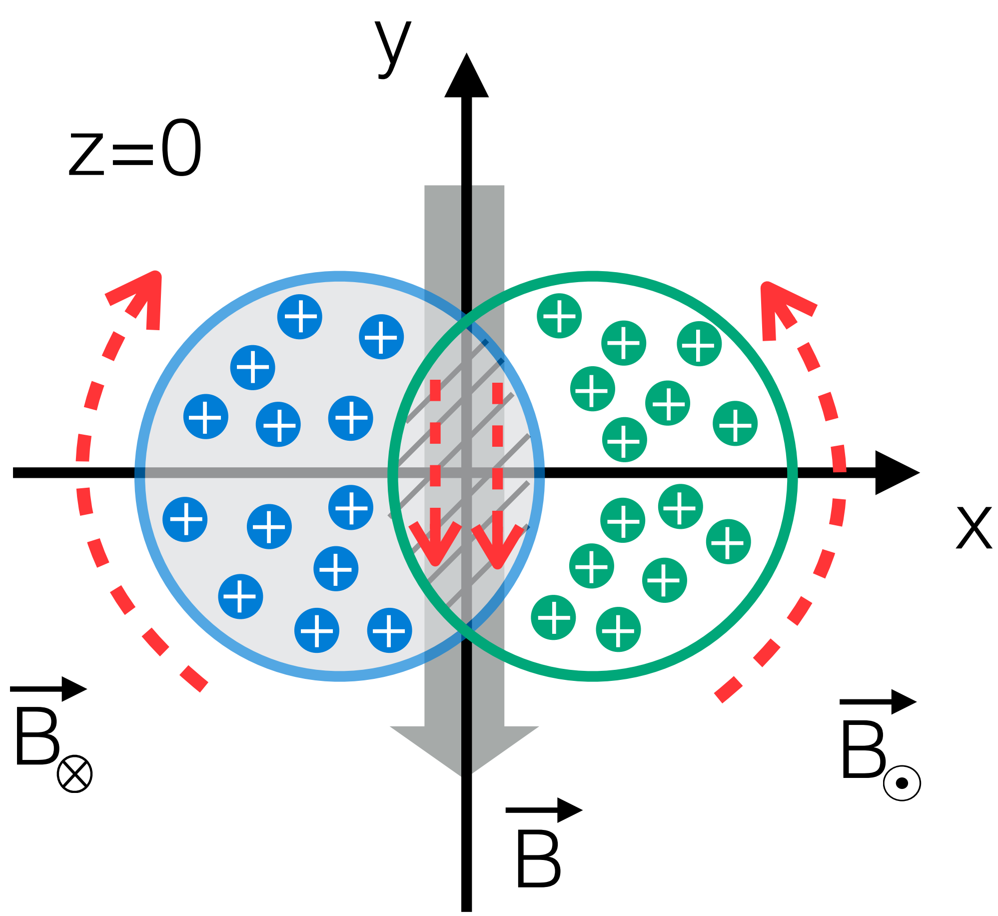


How experiments scan it

A+A collisions at sufficiently high energy -> deconfined massless fermions

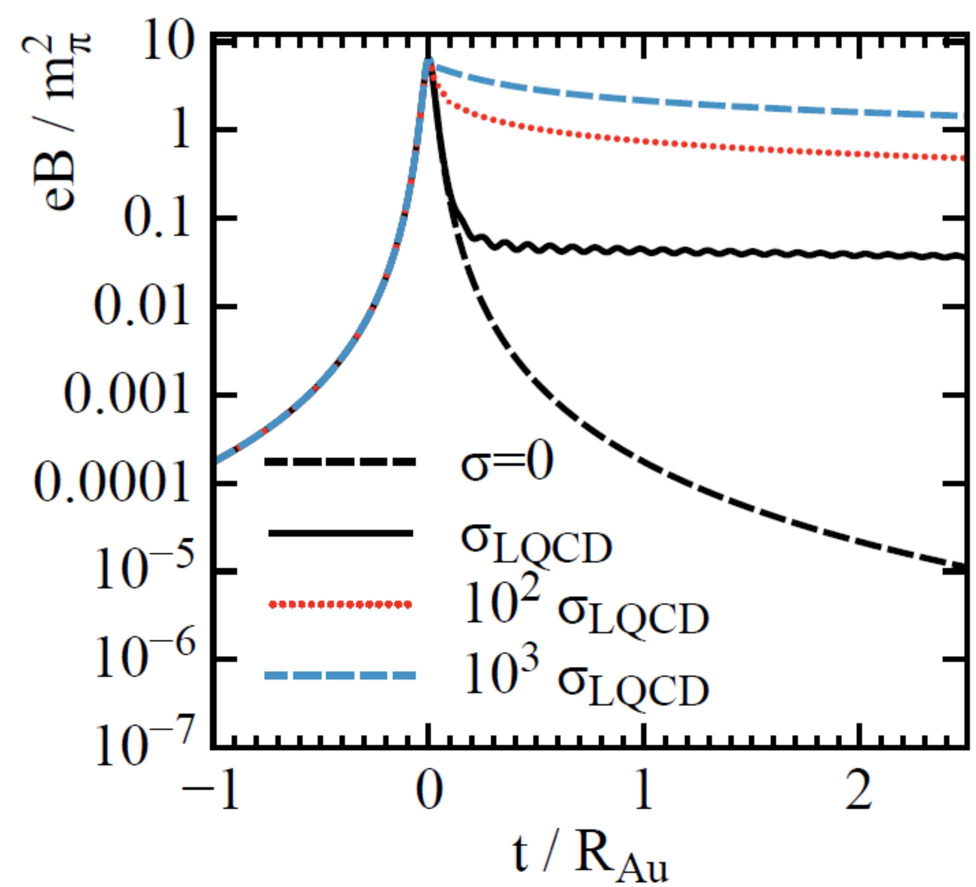
#3: Presence of strong magnetic field

Strong B-fields ~10^{18} Gauss are generated in non-central heavy ion collisions



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

McLerran, Skokov, 1305.0774

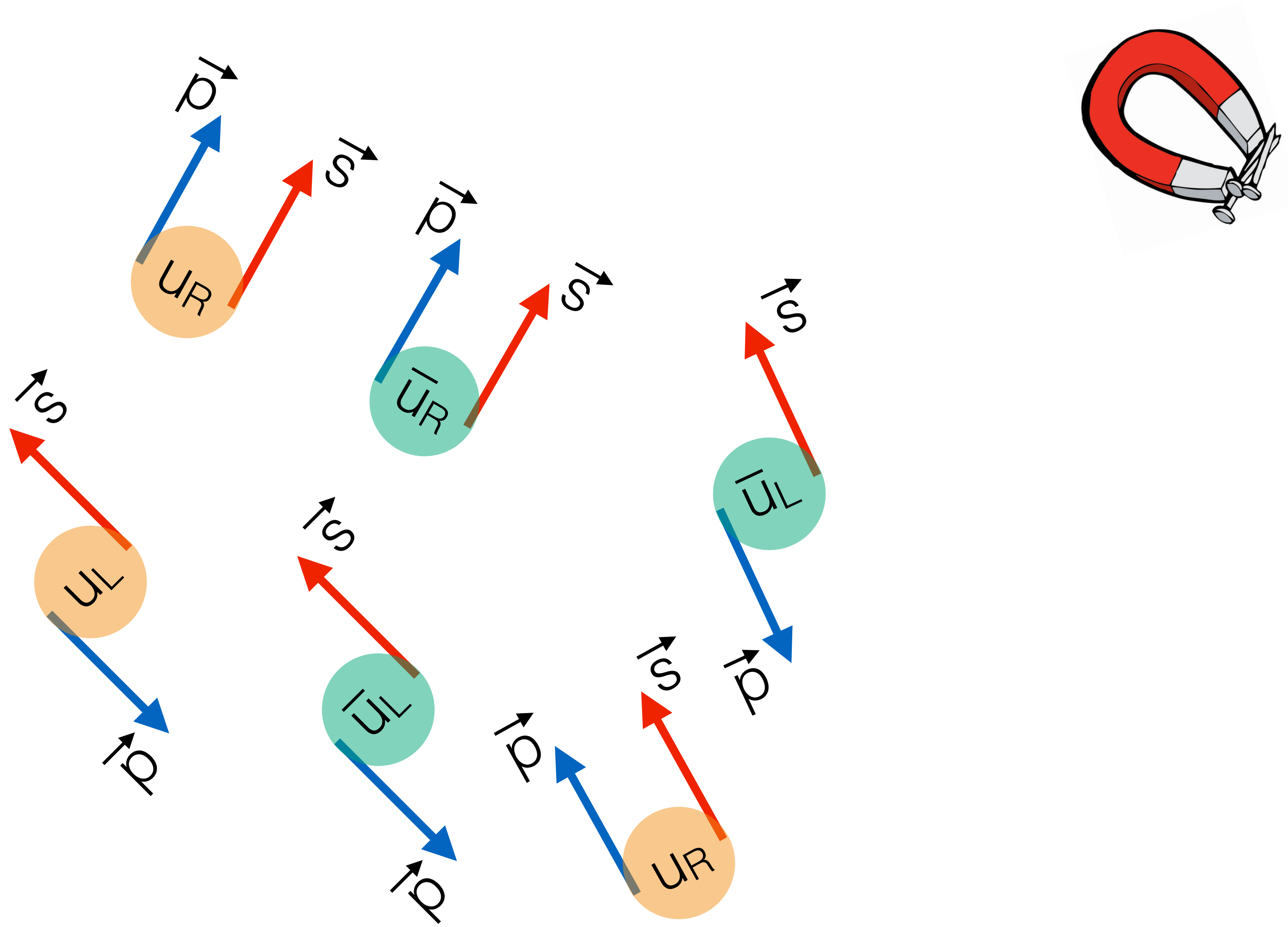


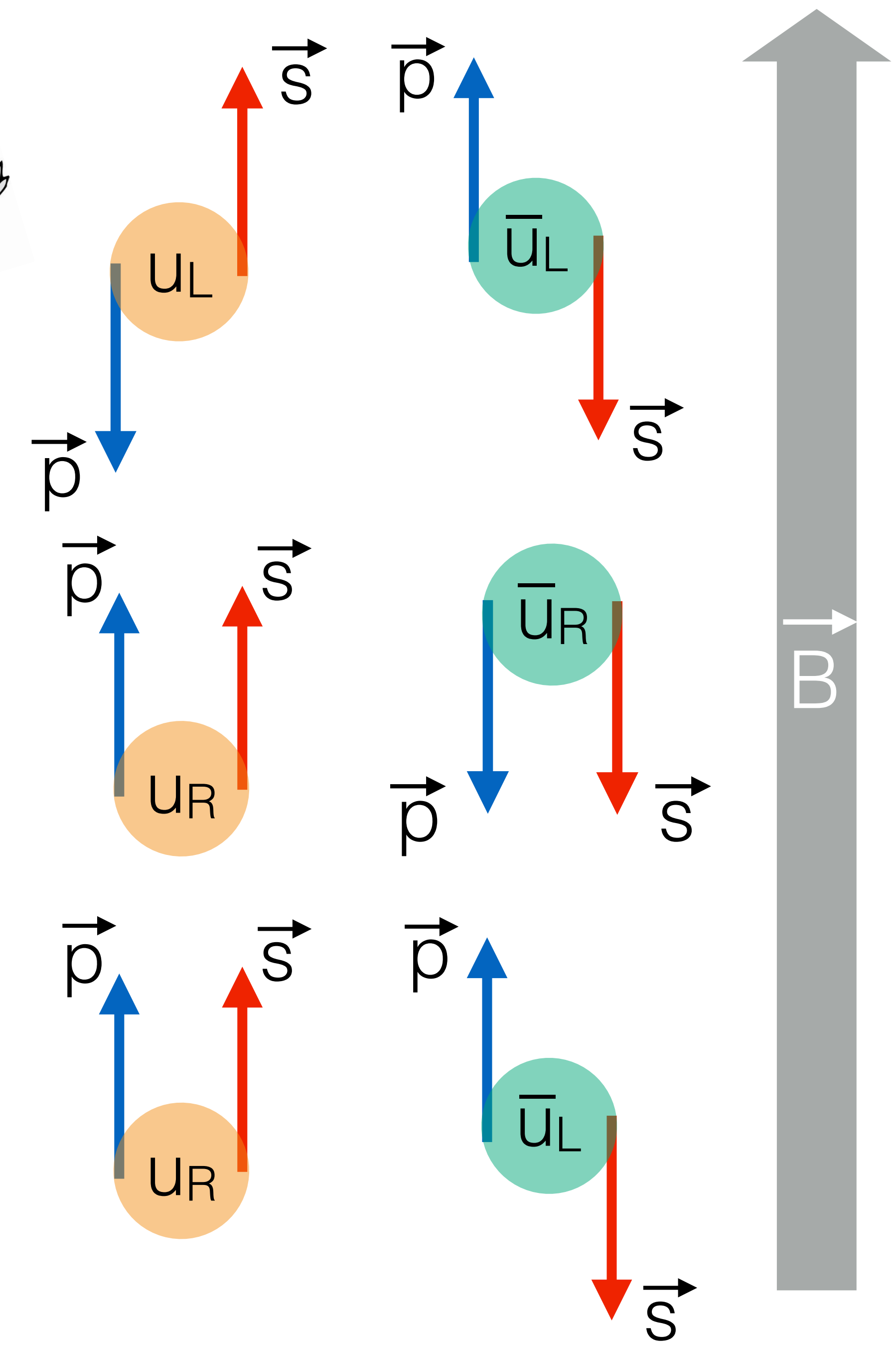
B-field direction → perpendicular to collision plane
B-field magnitude → ~Z^2, ~ γ
B-field lifetime → ~ $1/\gamma$, conductivity of the medium
B-field strength → decrease with impact parameter/overlap

Chiral Magnetic Effect

The Chiral Magnetic Effect

The B-field will align the fermions





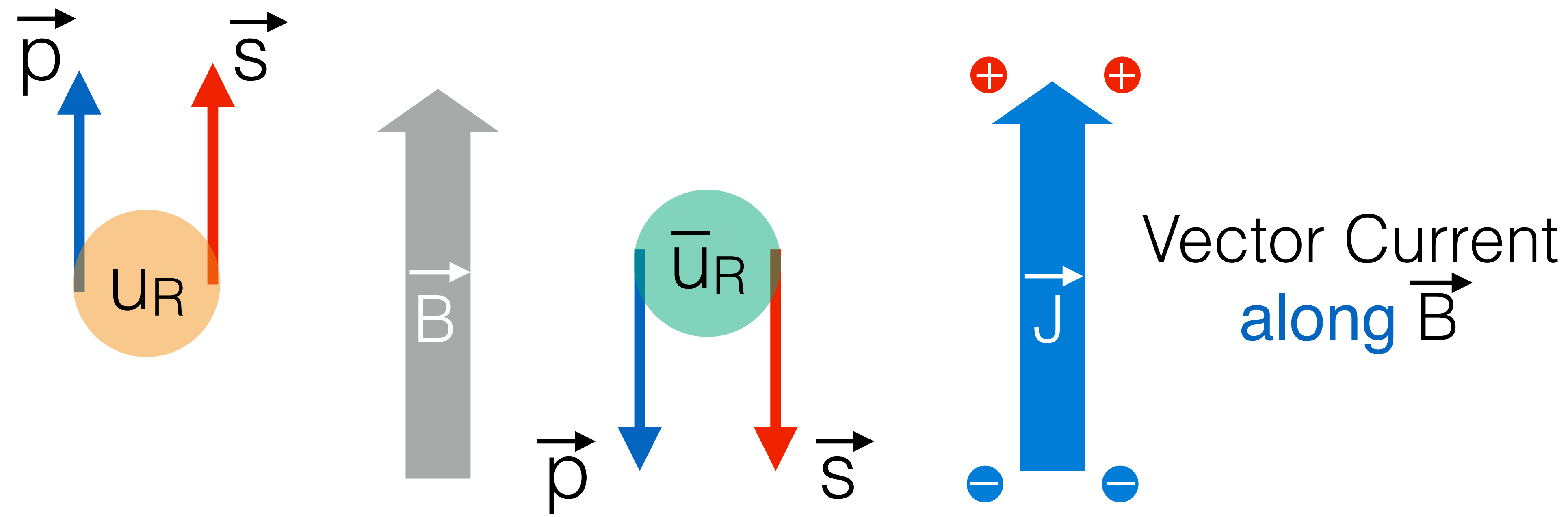
$$\langle \vec{p} \rangle \propto (Qe)\mu_5 \vec{\mathbf{B}}$$

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

fig: based on Kharzeev, McLerran,Warringa 0711.0950

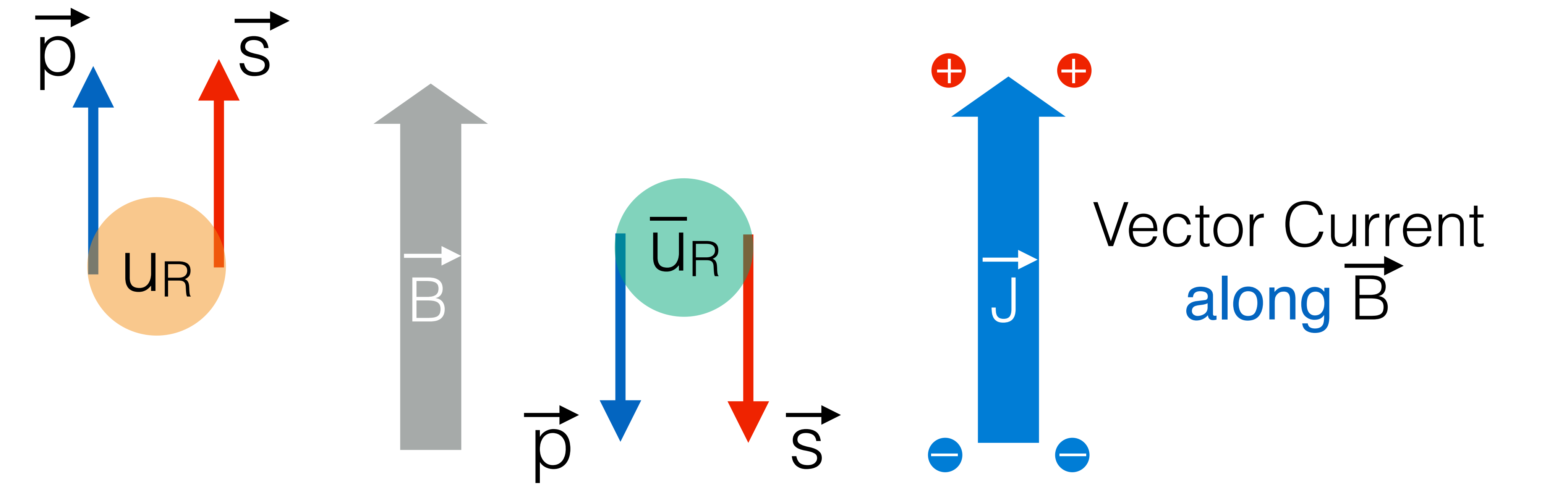
The Chiral Magnetic Effect : a closer look

Scenario-2 : Excess right handed

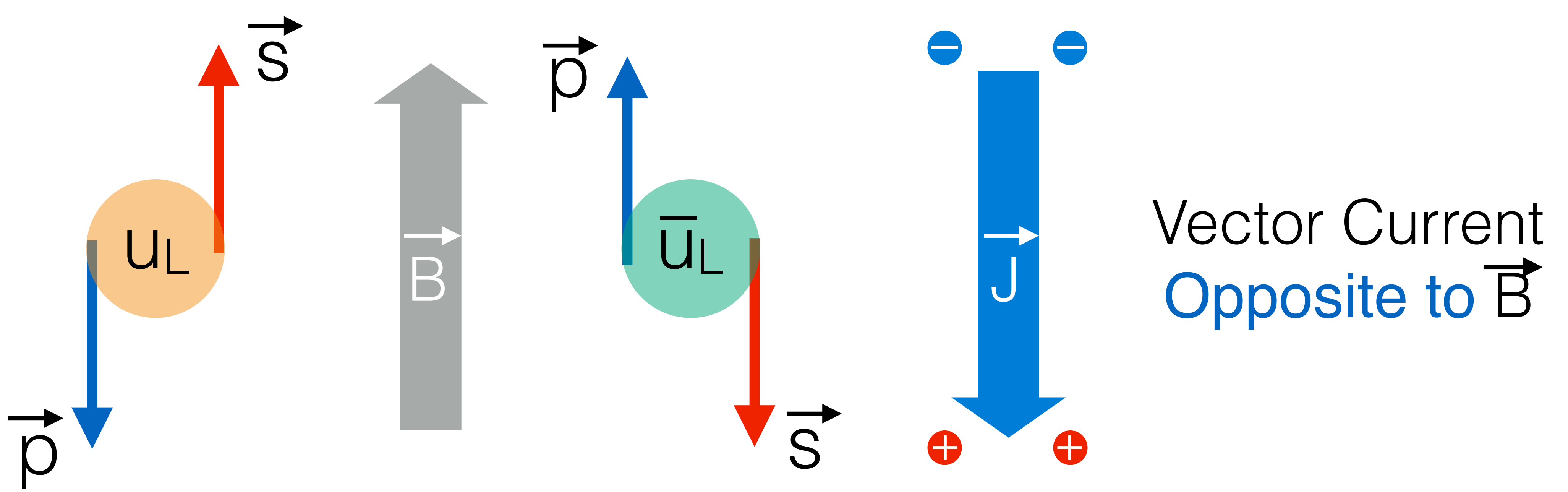


The Chiral Magnetic Effect : a closer look

Scenario-2 : Excess right handed

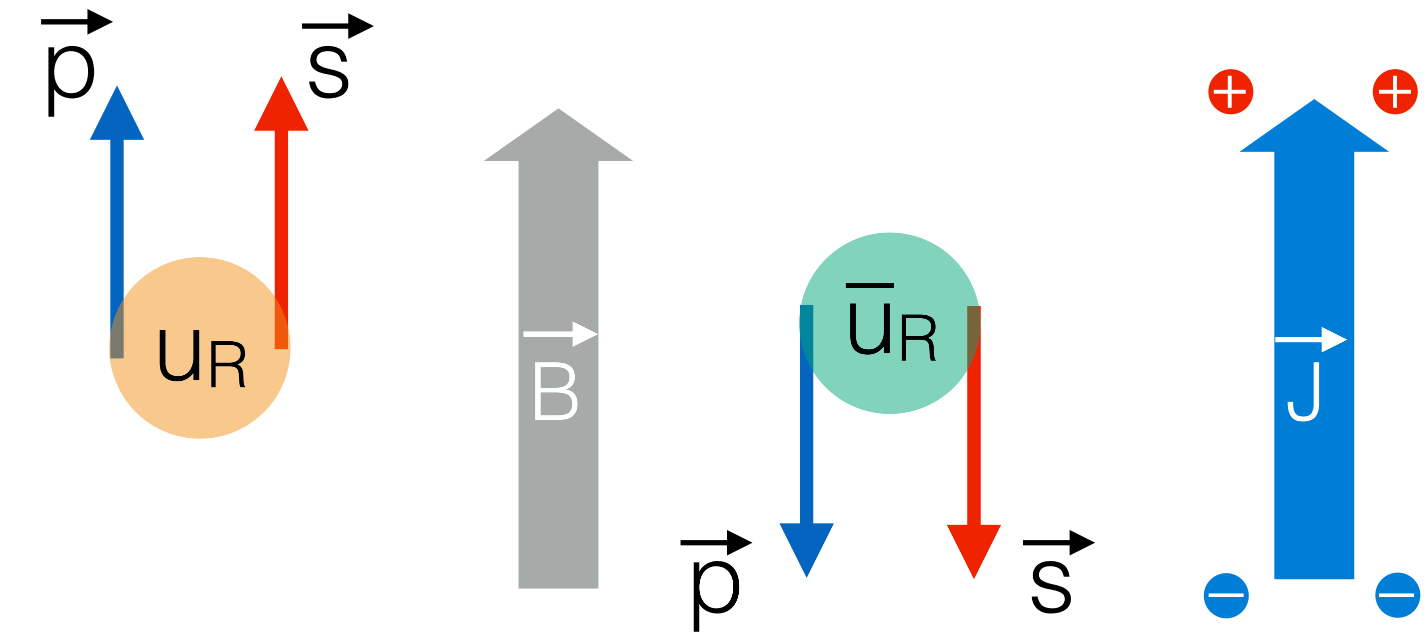


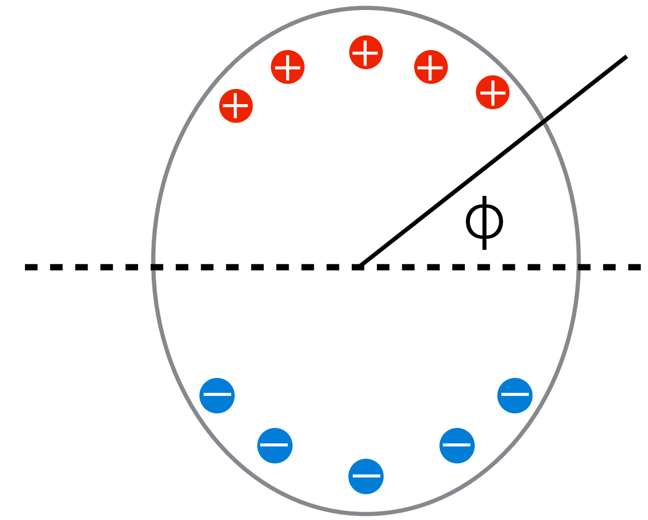
Scenario-2 : Excess left handed



The Chiral Magnetic Effect : a closer look

Scenario-2 : Excess **right** handed

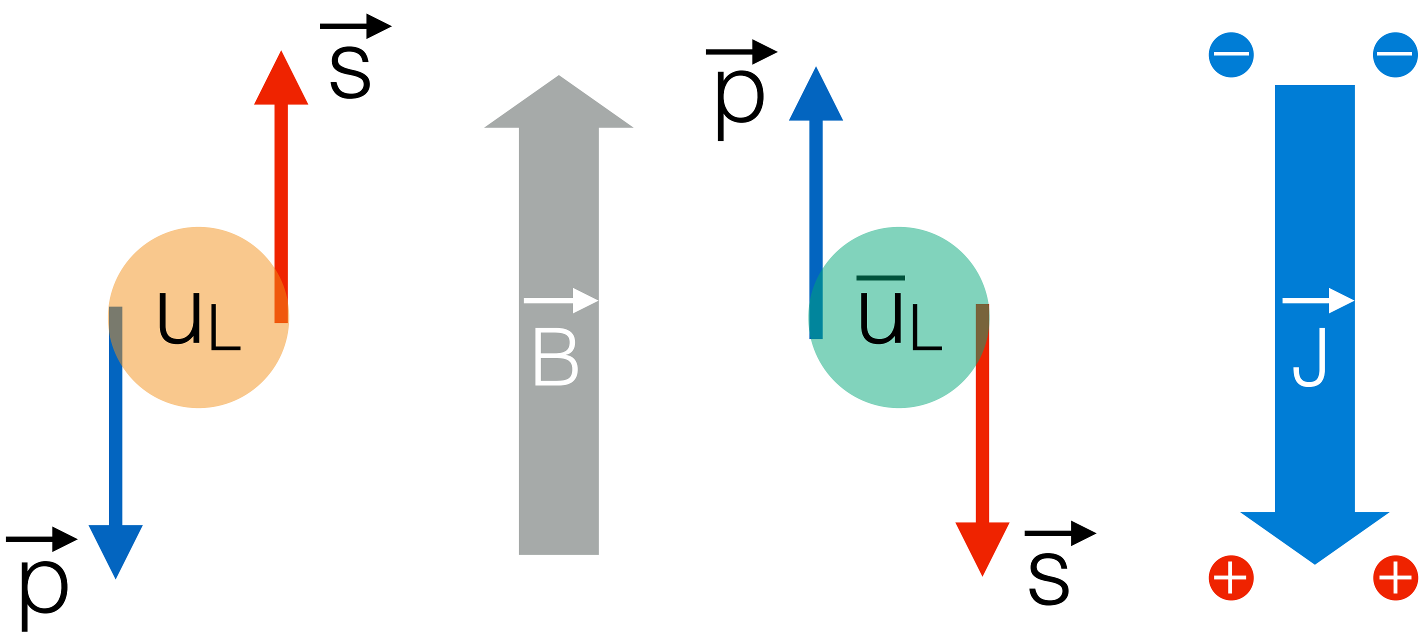


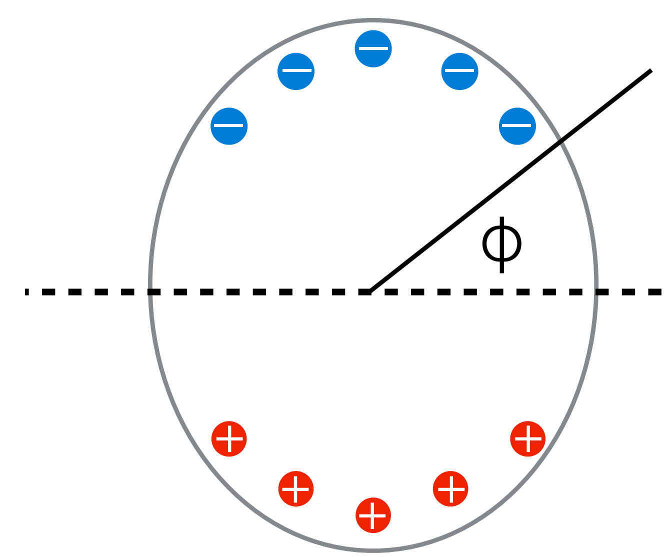


$$\frac{dN^{\pm}}{d\phi} \propto a_1^{\pm} \sin(\phi^{\pm})$$

$$a_1^{+} = -a_1^{-}$$

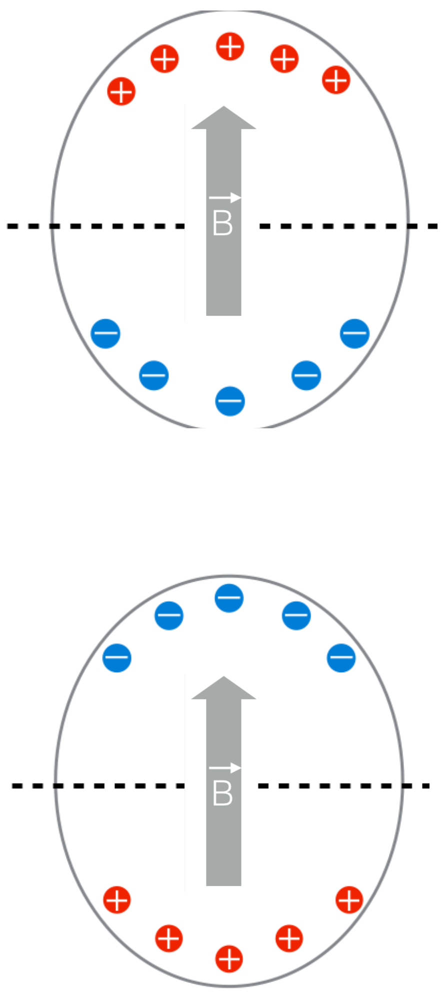
Scenario-2 : Excess **left** handed

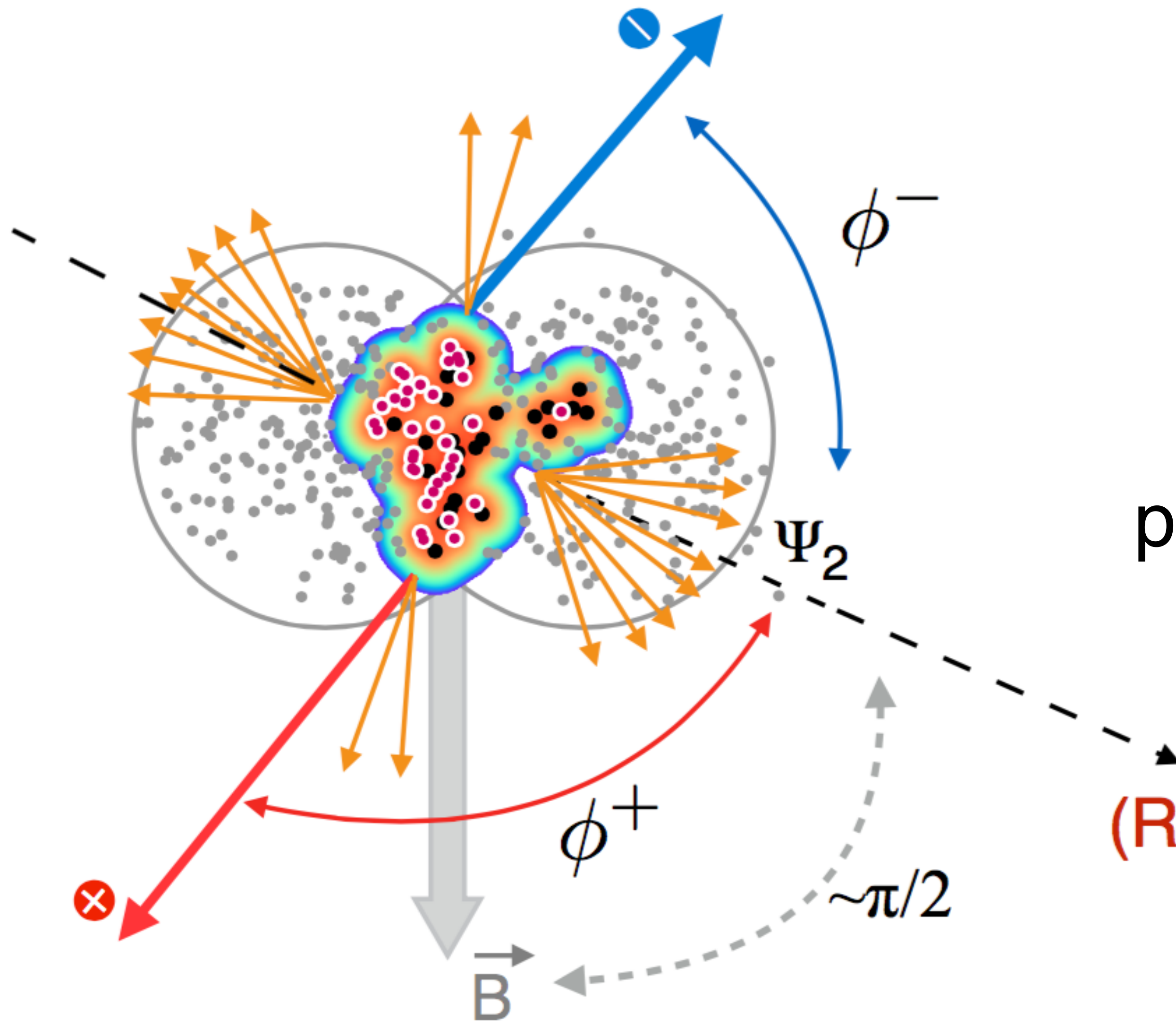




The Chiral Magnetic Effect : How to detect ?

Main challenge : the direction of B-field is unknown





(unknown)

~10% elliptic anisotropy in particle emission

Event plane
(Reference angle)

Parity-odd distribution

A charge dependent dipole anisotropy along B-field :

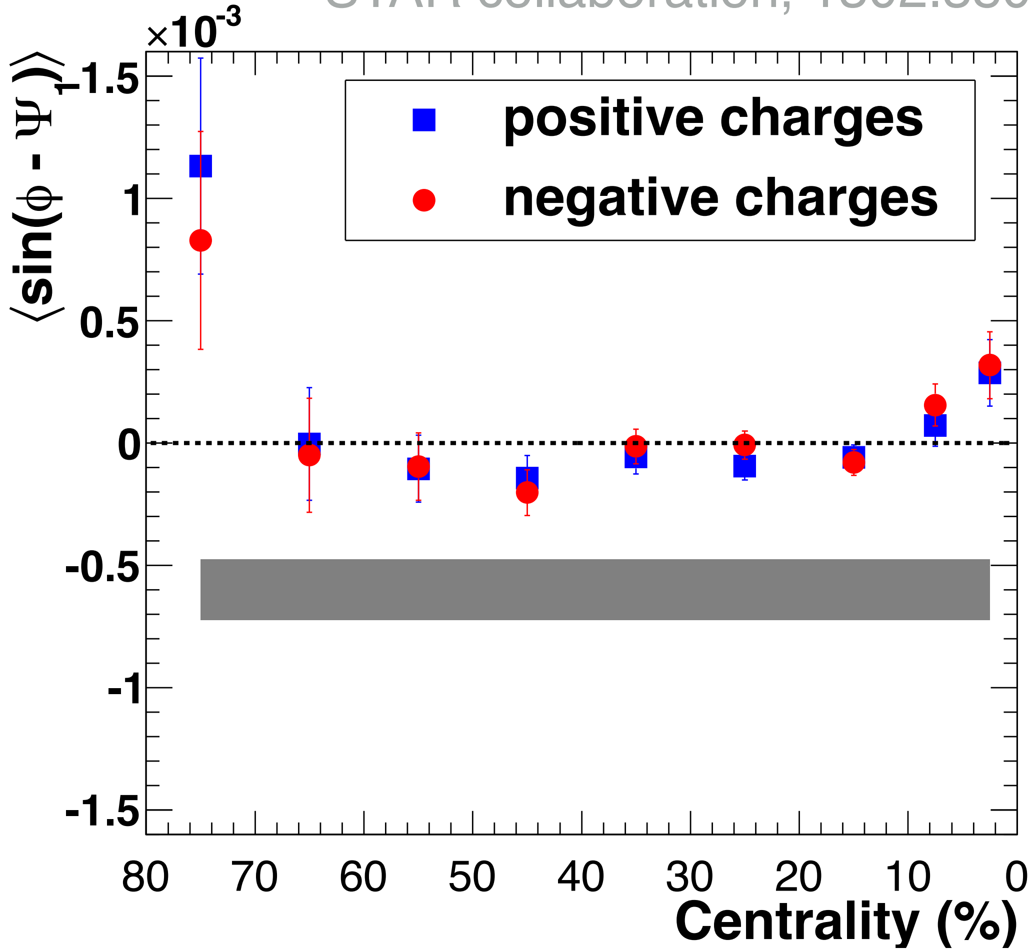
$$\frac{dN^{\pm}}{d\phi} \propto a_1^{\pm} \sin(\phi^{\pm} - \Psi_2)$$

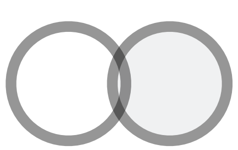
$$\Rightarrow a_1^+ = -a_1^-$$

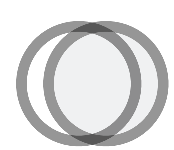
Early measurements from STAR

Measurements of dipole anisotropy : $\langle a_1^{\pm} \rangle = \langle \sin(\phi^{\pm} - \Psi_2) \rangle$

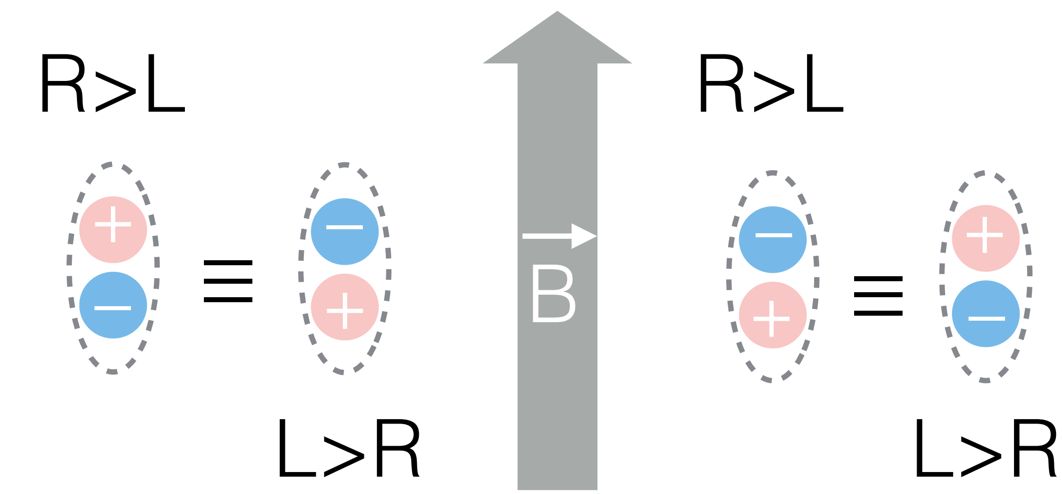
STAR collaboration, 1302.3802







$\langle a_1^{+} \rangle = \langle a_1^{-} \rangle$

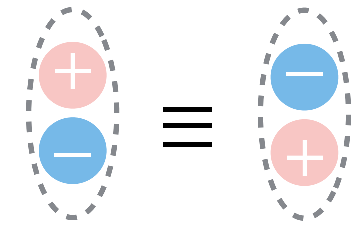


Event average charge separation vanishes :
no sign of global parity odd processes

A better observable : use two particles

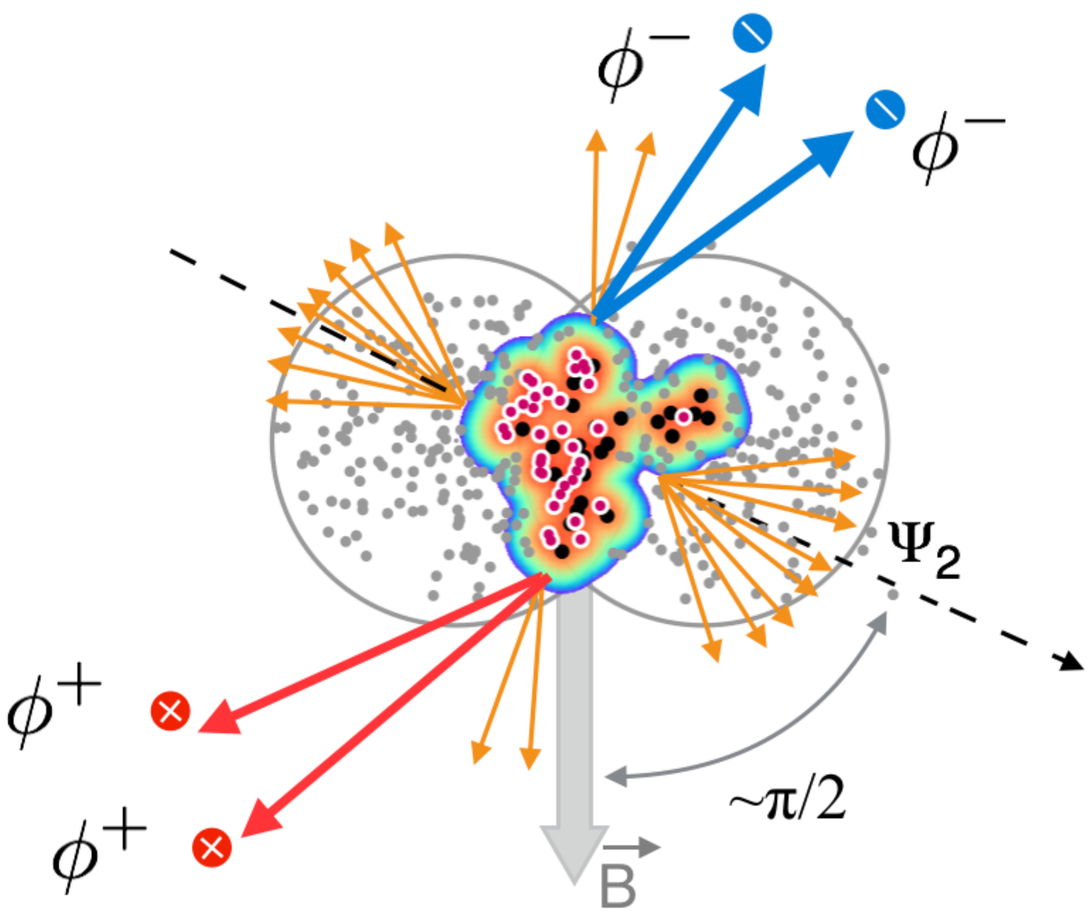
Only variance will survive flipping of dipole

$$\langle a_1^{\pm} \rangle = \langle \sin(\phi^{\pm} - \Psi_2) \rangle \Rightarrow \langle a_1^{+} \rangle = \langle a_1^{-} \rangle$$



$$\left\langle a_1^{\alpha} a_1^{\beta} \right\rangle = \langle \sin(\phi^{\alpha} - \Psi_2) \sin(\phi^{\beta} - \Psi_2) \rangle \Rightarrow \langle a_1^{\pm} a_1^{\pm} \rangle \neq \langle a_1^{\pm} a_1^{\mp} \rangle$$

Same-sign (SS) | Opposite-sign (OS)



We need to look at a pair of particles perpendicular to Ψ_2

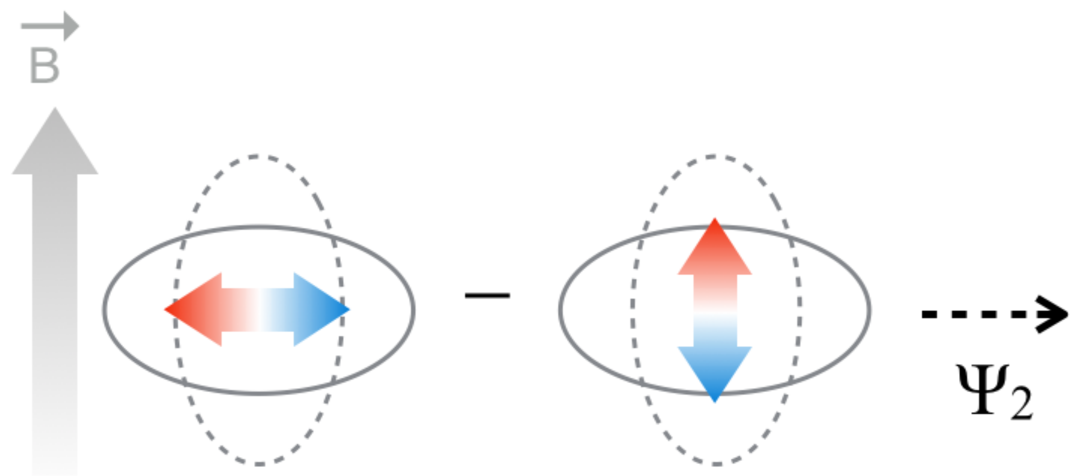
A better observable

However it becomes a parity-even variable, susceptible to background

Sergei's γ-correlator : $\gamma^{\alpha,\beta} = \left\langle a_1^\alpha a_1^\beta \right\rangle_\perp - \left\langle a_1^\alpha a_1^\beta \right\rangle_\parallel$

$$\gamma^{\alpha,\beta} = \langle \cos(\phi_\alpha - \Psi_2)\cos(\phi_\beta - \Psi_2)\rangle - \langle \sin(\phi_\alpha - \Psi_2)\sin(\phi_\beta - \Psi_2)\rangle$$
$$= \langle \cos(\phi_\alpha + \phi_\beta - 2\Psi_2)\rangle$$

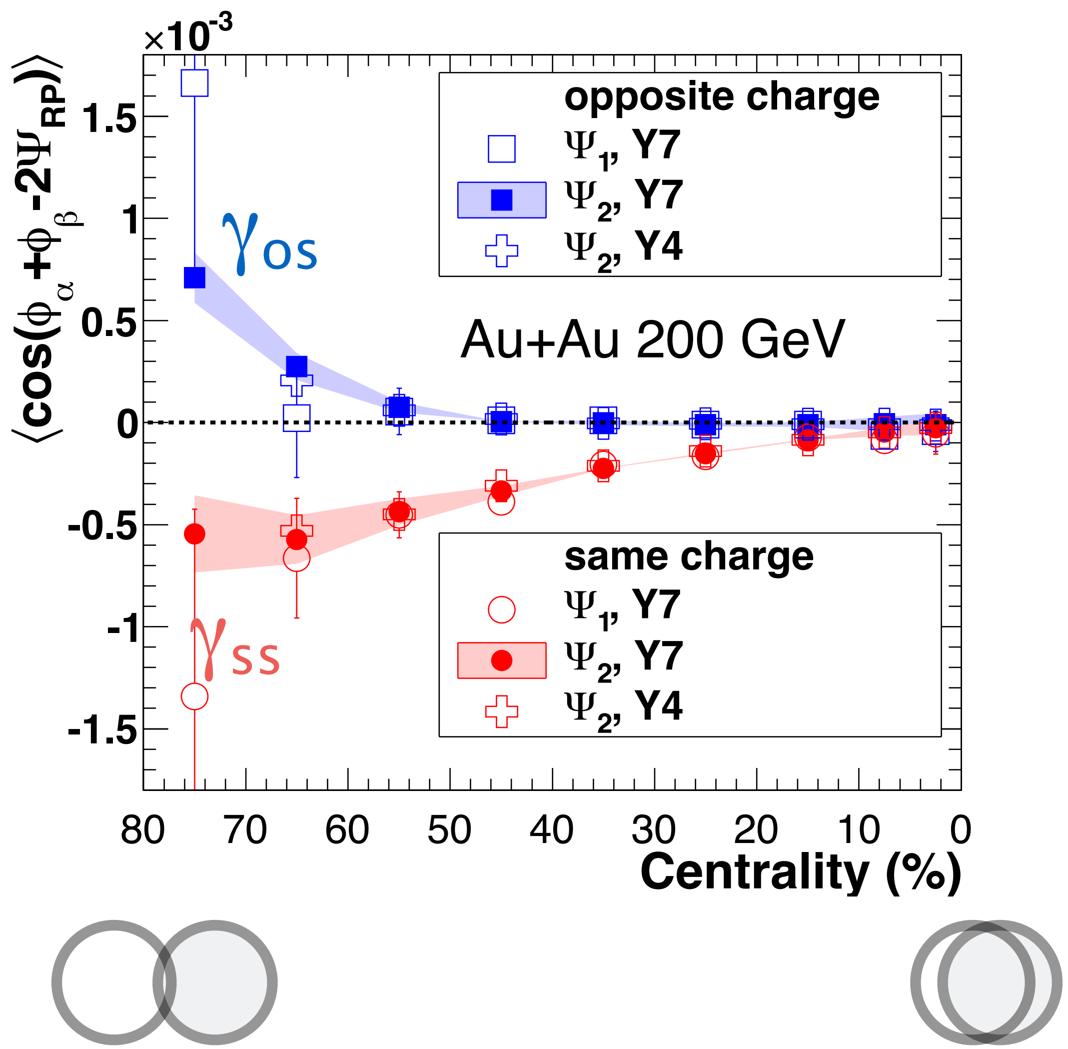
Voloshin, PRC 70 (2004) 057901



Difference between anisotropy perpendicular & parallel to B-field

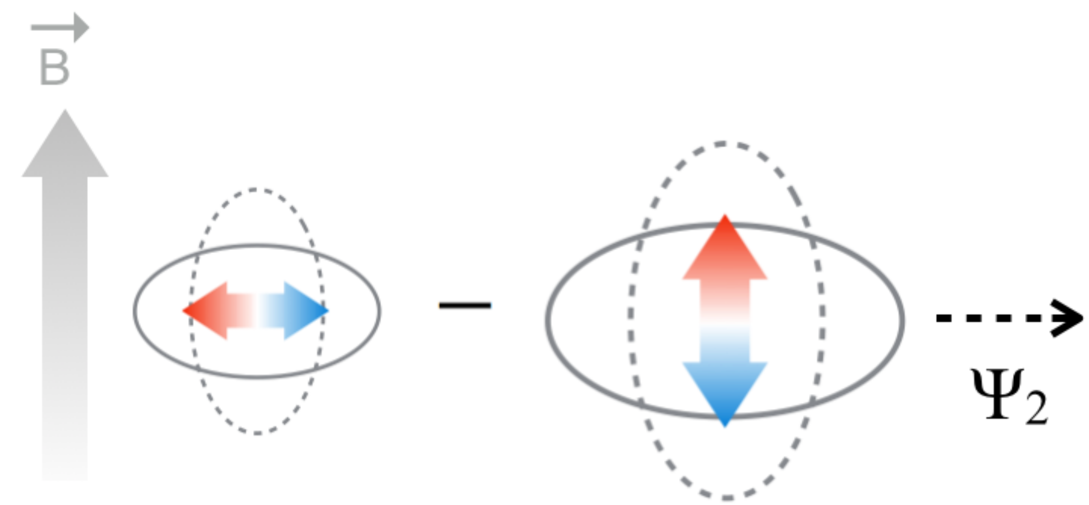
Early measurements from STAR

STAR collaboration PRL 103, 251601 (2009), PRC 88 (2013) 6, 064911



$$\gamma^{OS} = \langle \cos(\phi_1^{\pm} + \phi_2^{\mp} - 2\Psi_{RP}) \rangle$$

$$\gamma^{SS} = \langle \cos(\phi_1^{\pm} + \phi_2^{\pm} - 2\Psi_{RP}) \rangle$$



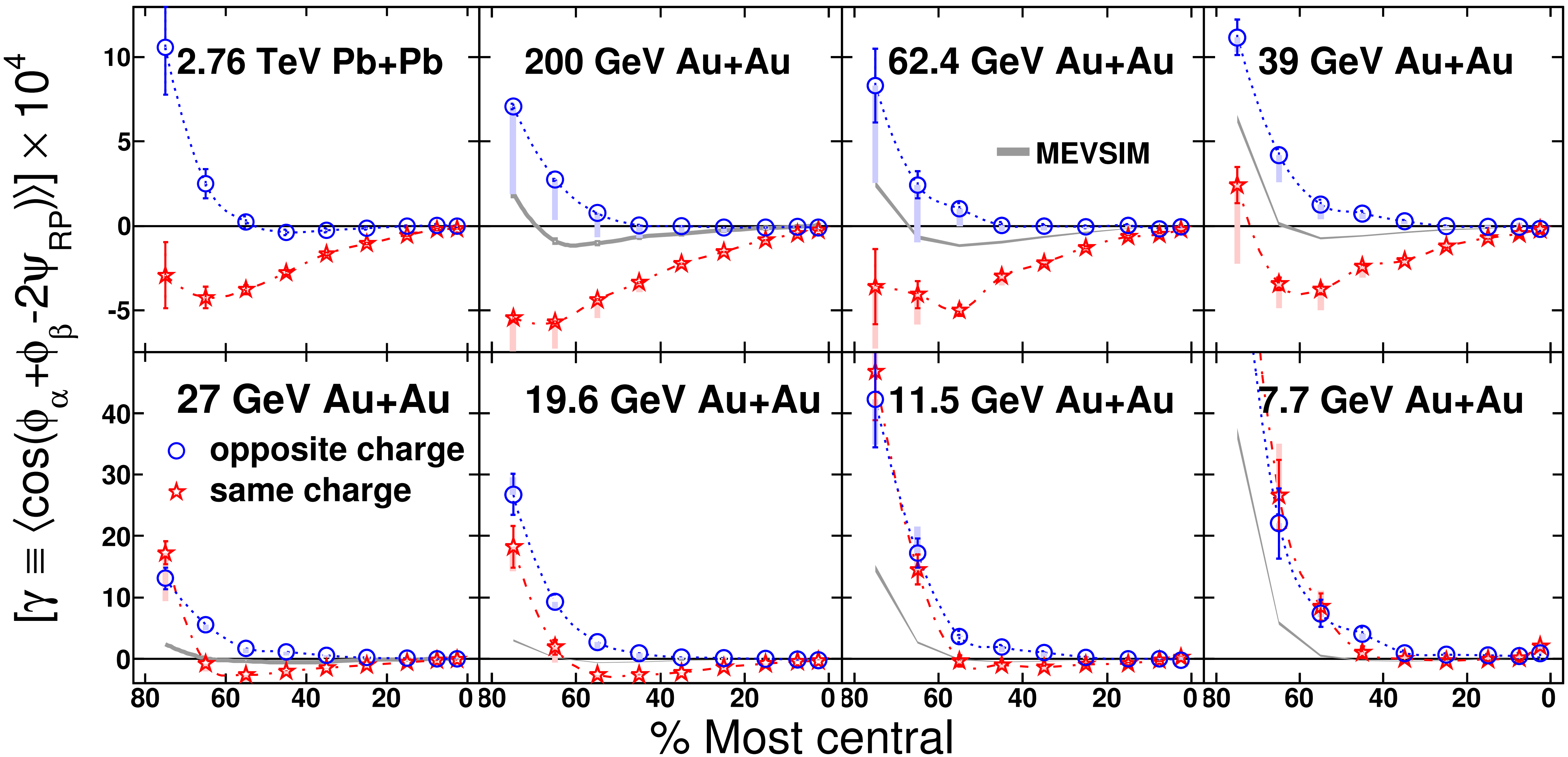
- Pairs of same-charges preferably flow together perpendicular to Ψ2
- Strength of such flow is strongest in peripheral event

Expectation consistent with the effect of B-field ?

How does the energy dependence look like ?

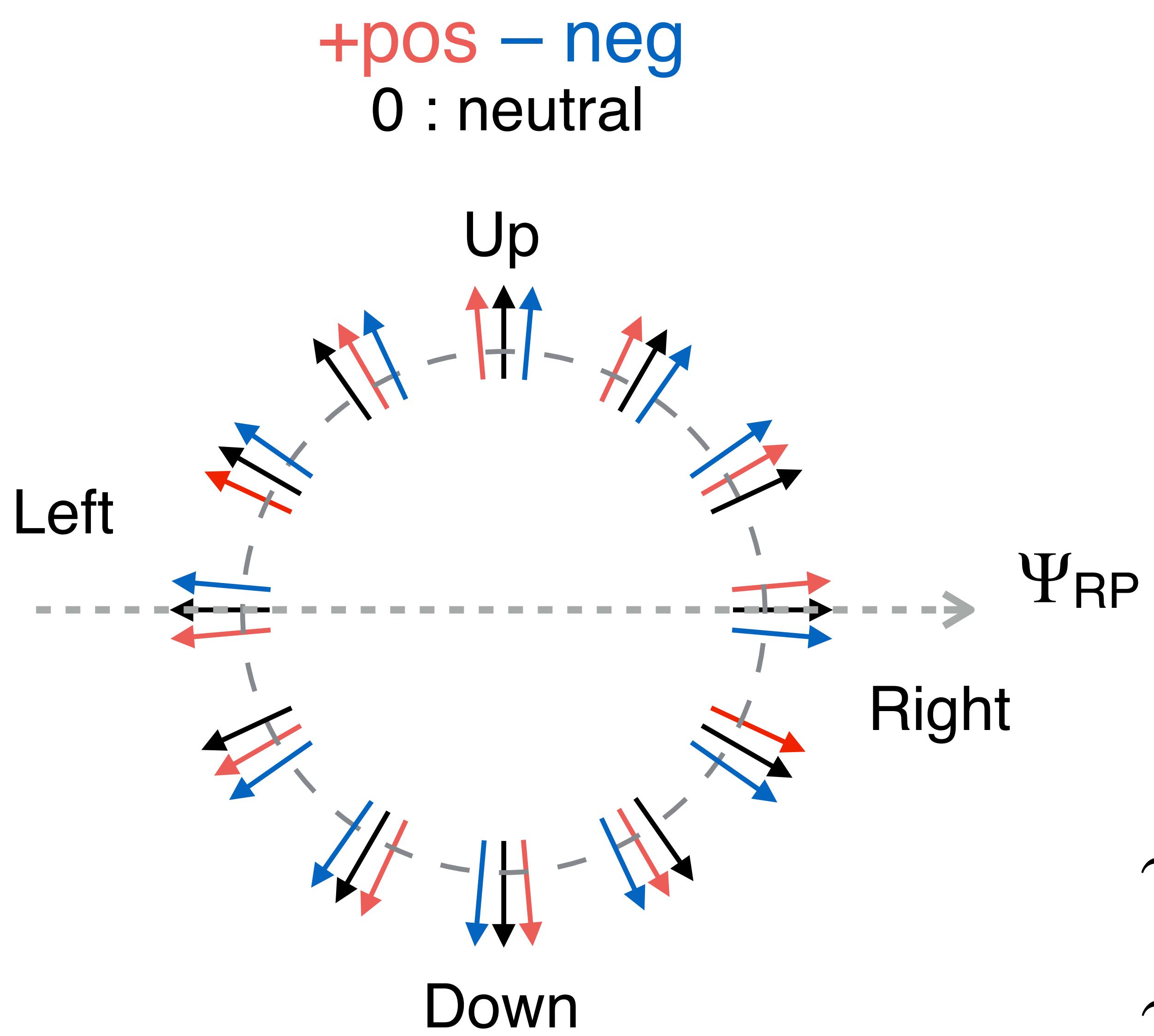
Charge separation vanishes at the lowest energy

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



Expectation consistent disappearance of deconfinement / chiral symmetry restoration ?

Background sources of charge separation



$$\gamma^{\alpha\beta} = \langle \cos(\phi_\alpha + \phi_\beta - 2\Psi_2) \rangle$$

Any value 0 < $\phi_1+\phi_2 < \pi$
equally probable

$$\gamma^{++} = \langle \cos(\phi_1^+ + \phi_2^+ - 2\Psi_{RP}) \rangle = 0$$

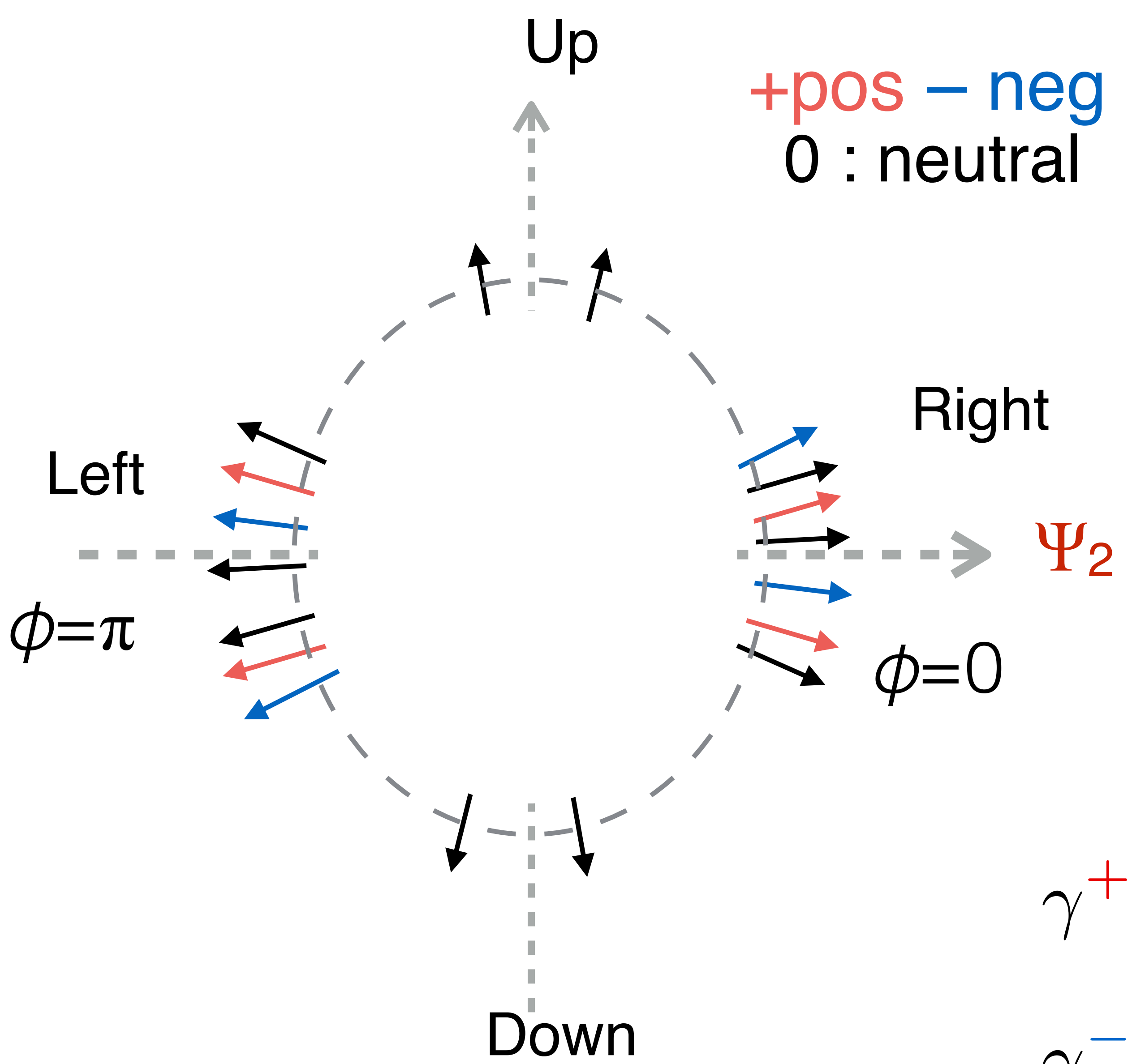
$$\gamma^{--} = \langle \cos(\phi_1^- + \phi_2^- - 2\Psi_{RP}) \rangle = 0$$

$$\gamma^{+-} = \langle \cos(\phi_1^+ + \phi_2^- - 2\Psi_{RP}) \rangle = 0$$

No correlation background if particles are emitted uniformly around Ψ_{RP}

Background : elliptic flow + momentum cons

In heavy ion collisions about ~10% more particles move left-right : FLOW



Flow ⇒ $(N_{U+} N_D)/(N_R+N_L) \sim v_2$

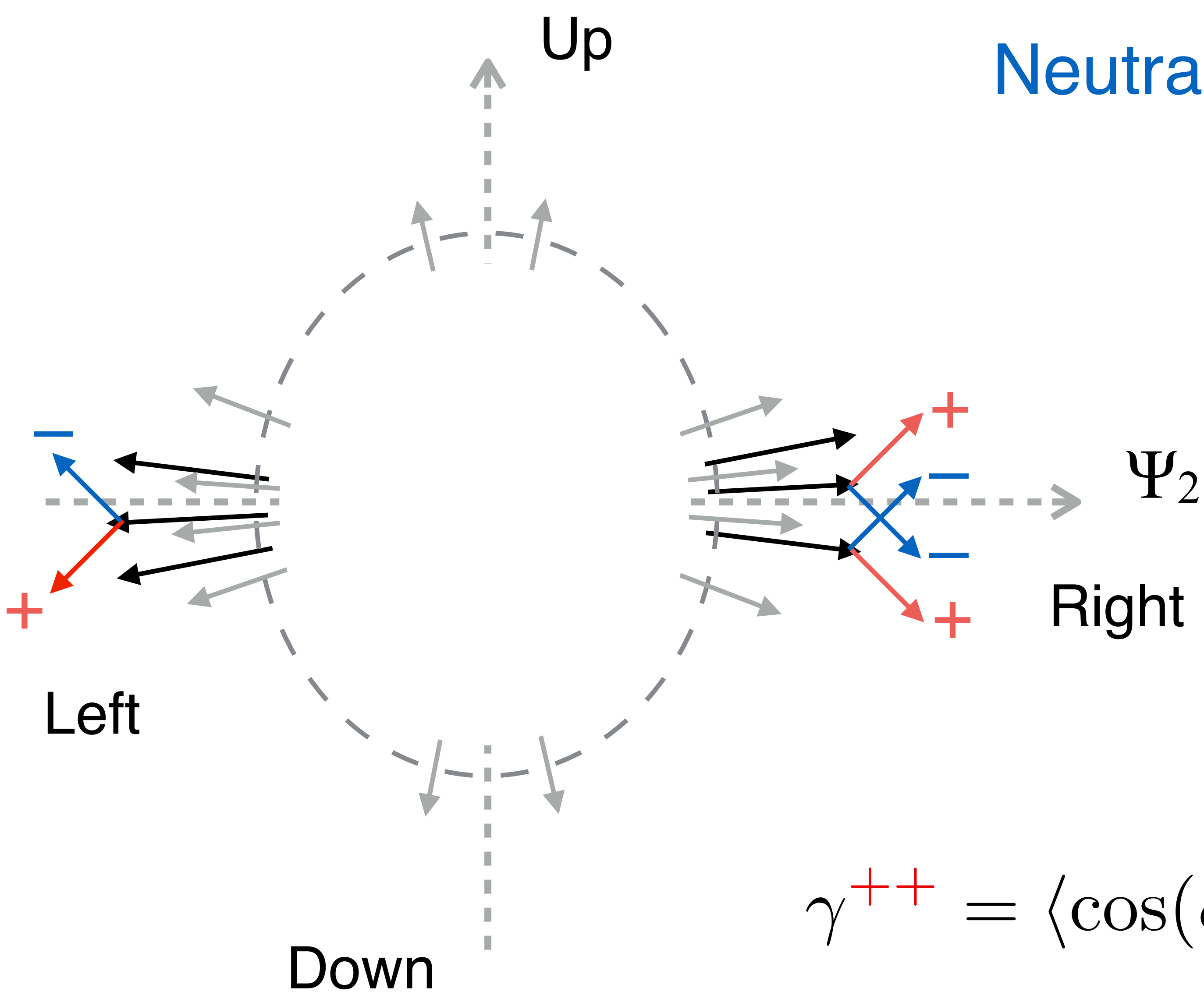
Momentum conservation ⇒ $N_R \sim N_L$

$$\gamma^{++} = \langle \cos(\phi_1^{+} + \phi_2^{+} - 2\Psi_{RP}) \rangle = -\frac{v_2}{N}$$

$$\gamma^{--} = \langle \cos(\phi_1^{-} + \phi_2^{-} - 2\Psi_{RP}) \rangle = -\frac{v_2}{N}$$

$$\gamma^{+-} = \langle \cos(\phi_1^{+} + \phi_2^{-} - 2\Psi_{RP}) \rangle = -\frac{v_2}{N}$$

Background : Neutral resonance decay



Neutral resonance decay can mimic CME

Neutral particle decays to a pair of opposite charges both them go either left or right

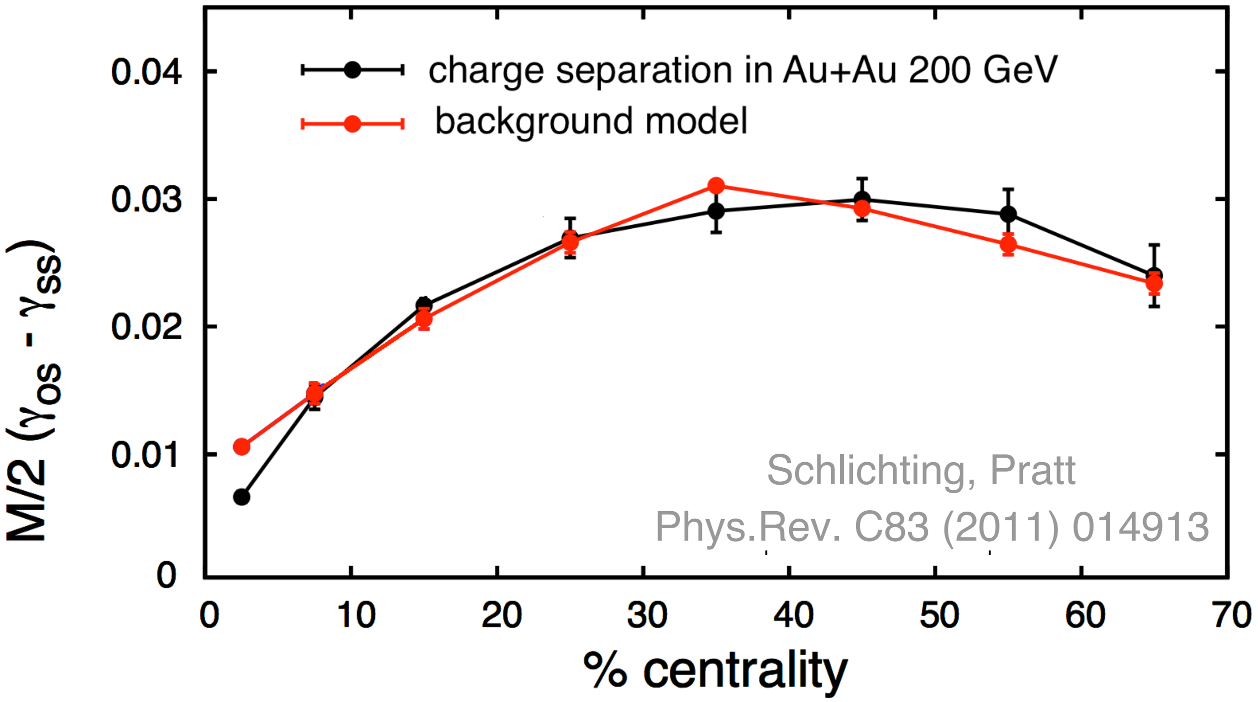
$$\gamma^{++} = \langle \cos(\phi_1^+ + \phi_2^+ - 2\Psi_{RP}) \rangle \propto \frac{(N_R - N_L)^2}{(N_R + N_L)^2} v_2$$

$$\gamma^{--} = \langle \cos(\phi_1^- + \phi_2^- - 2\Psi_{RP}) \rangle \propto \frac{(N_R - N_L)^2}{(N_R + N_L)^2} v_2$$

$$\gamma^{+-} = \langle \cos(\phi_1^+ + \phi_2^- - 2\Psi_{RP}) \rangle \propto \frac{(N_R - N_L)^2 - (N_R + N_L)}{(N_R + N_L)(N_R + N_L - 1)} v_2$$

Background : local charge conservation

$$\Delta\gamma^{Bkg} = \gamma_{\rm os} - \gamma_{\rm ss} \approx \frac{v_2}{N} > 0$$



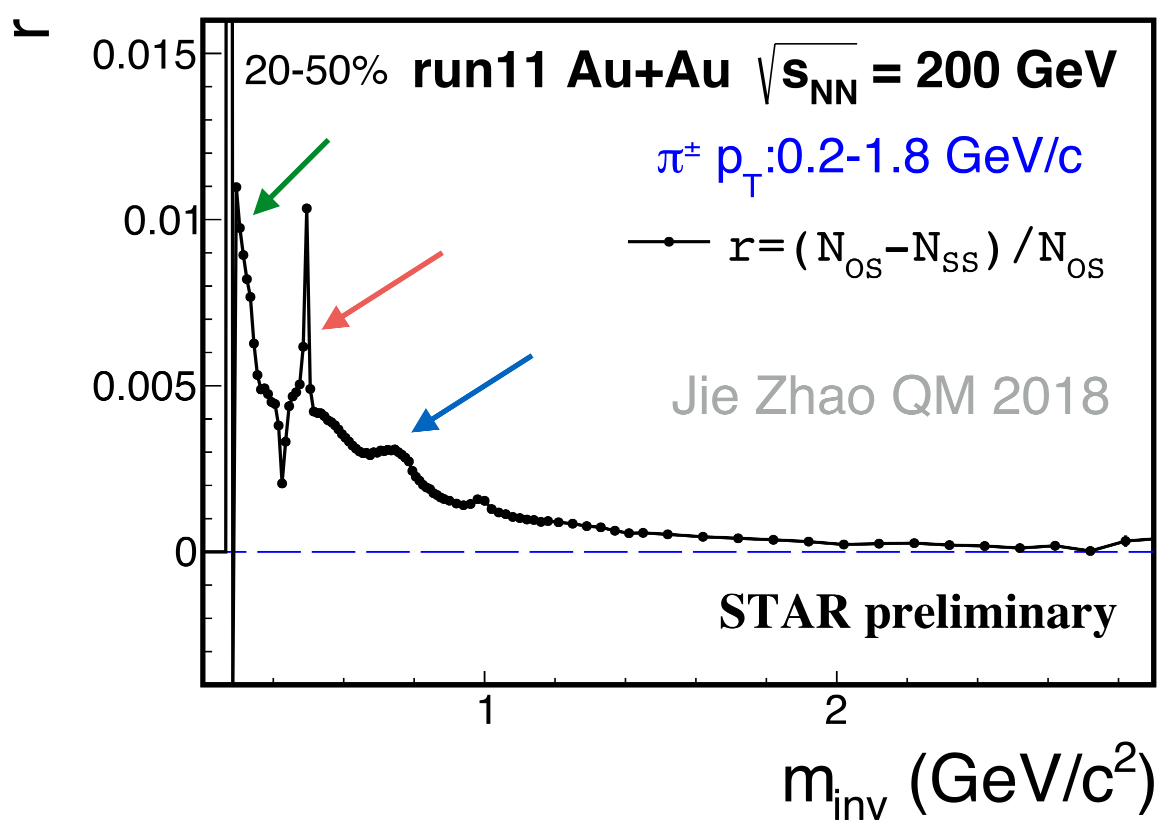
Background model nailed it down without invoking CME

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

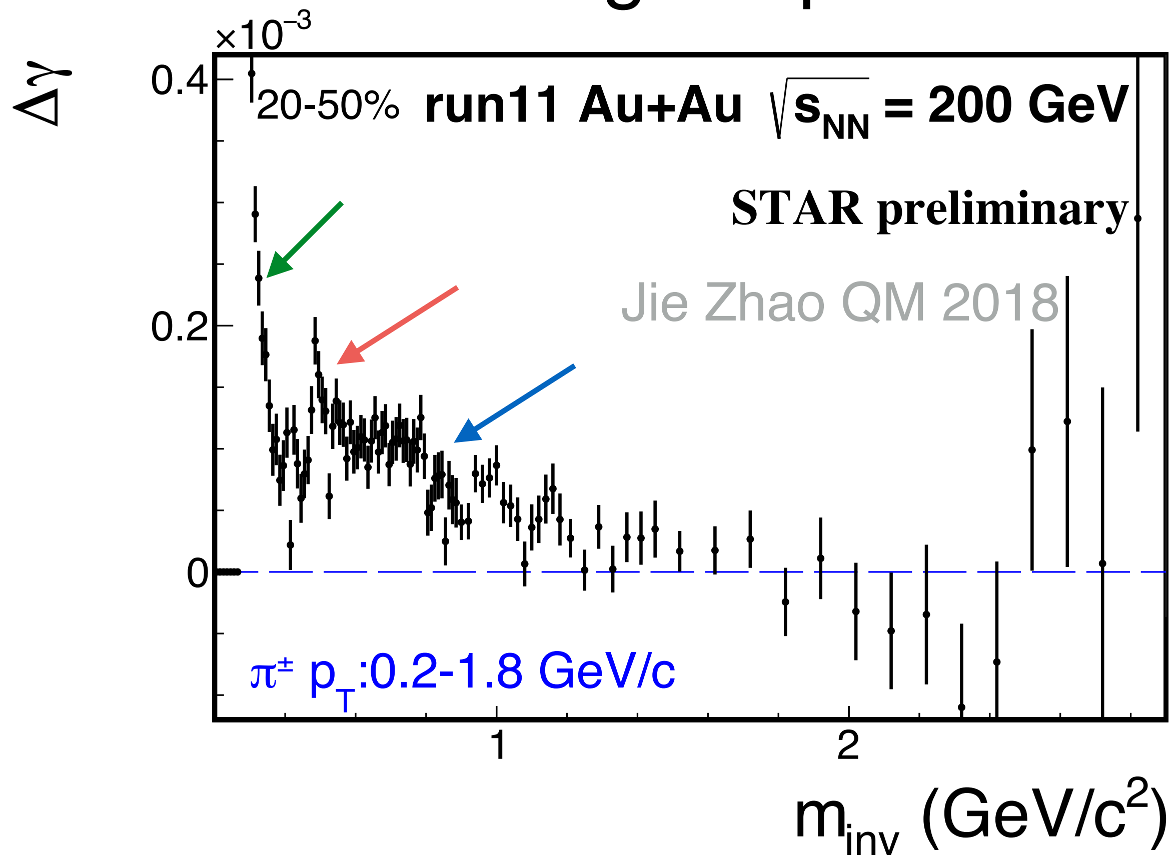
New measurements to estimate Background

Wherever there is a neutral resonance peak there is charge separation

Neutral resonance yield



Charge separation



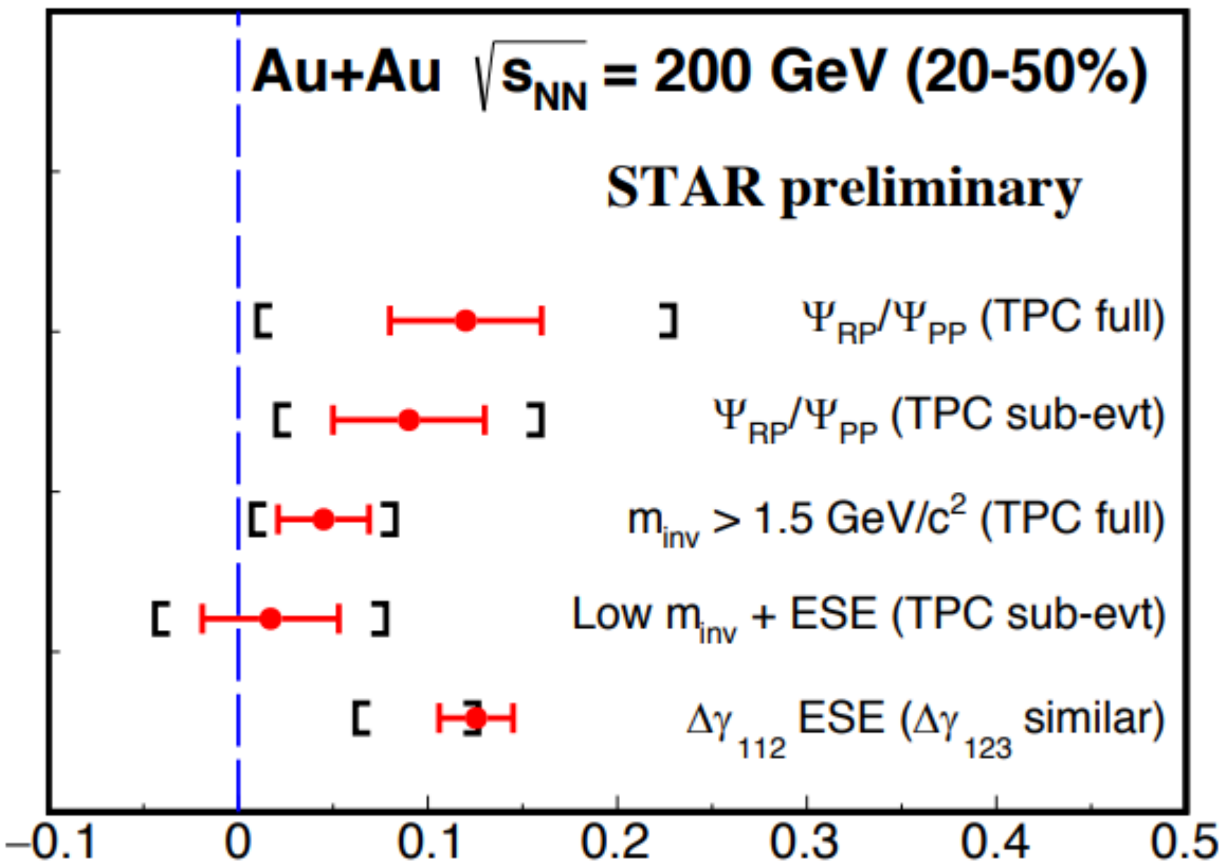
One can subtract the resonance contribution with some assumptions :

$$\Delta\gamma(m_{\rm inv}) = r(m_{\rm inv})R(m_{\rm inv}) + \Delta\gamma_{\rm CME}(m_{\rm inv})$$

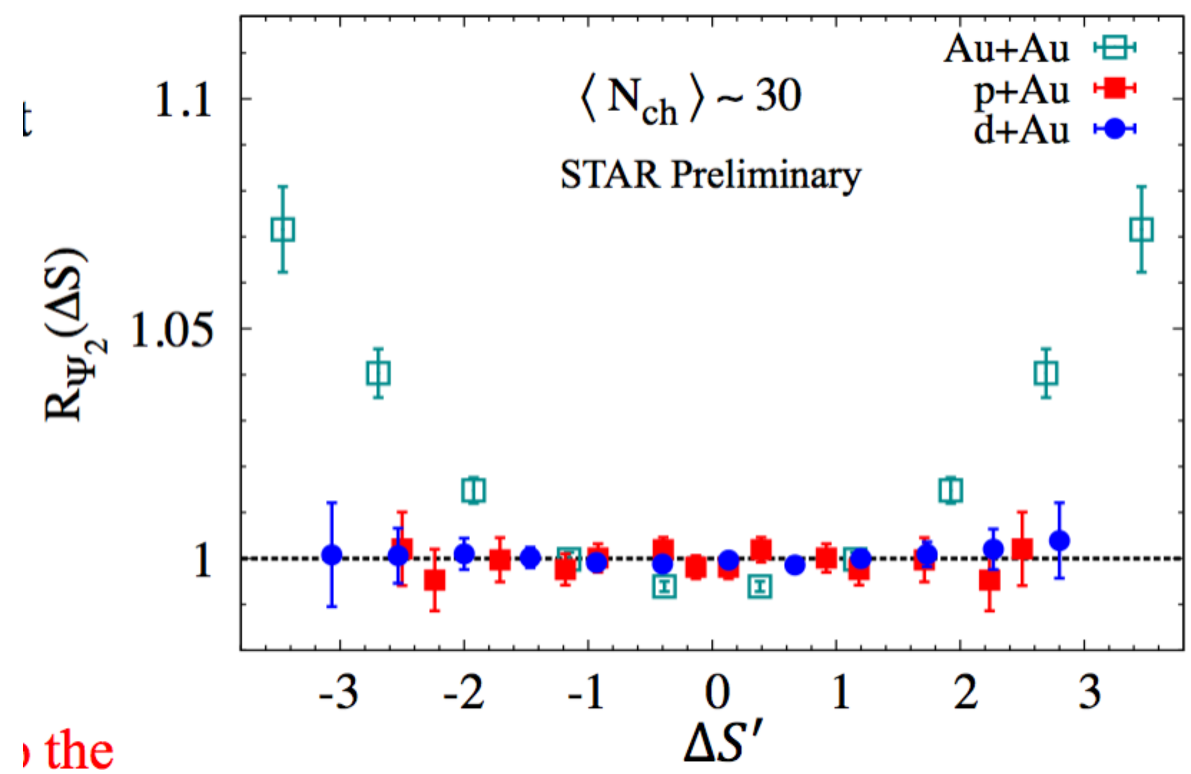
What is the invariant mass distribution for CME ?

Recent attempts to quantify the fraction of signals

Zhenyu Ye QM 2018,



Niseem Magdy QM 2018

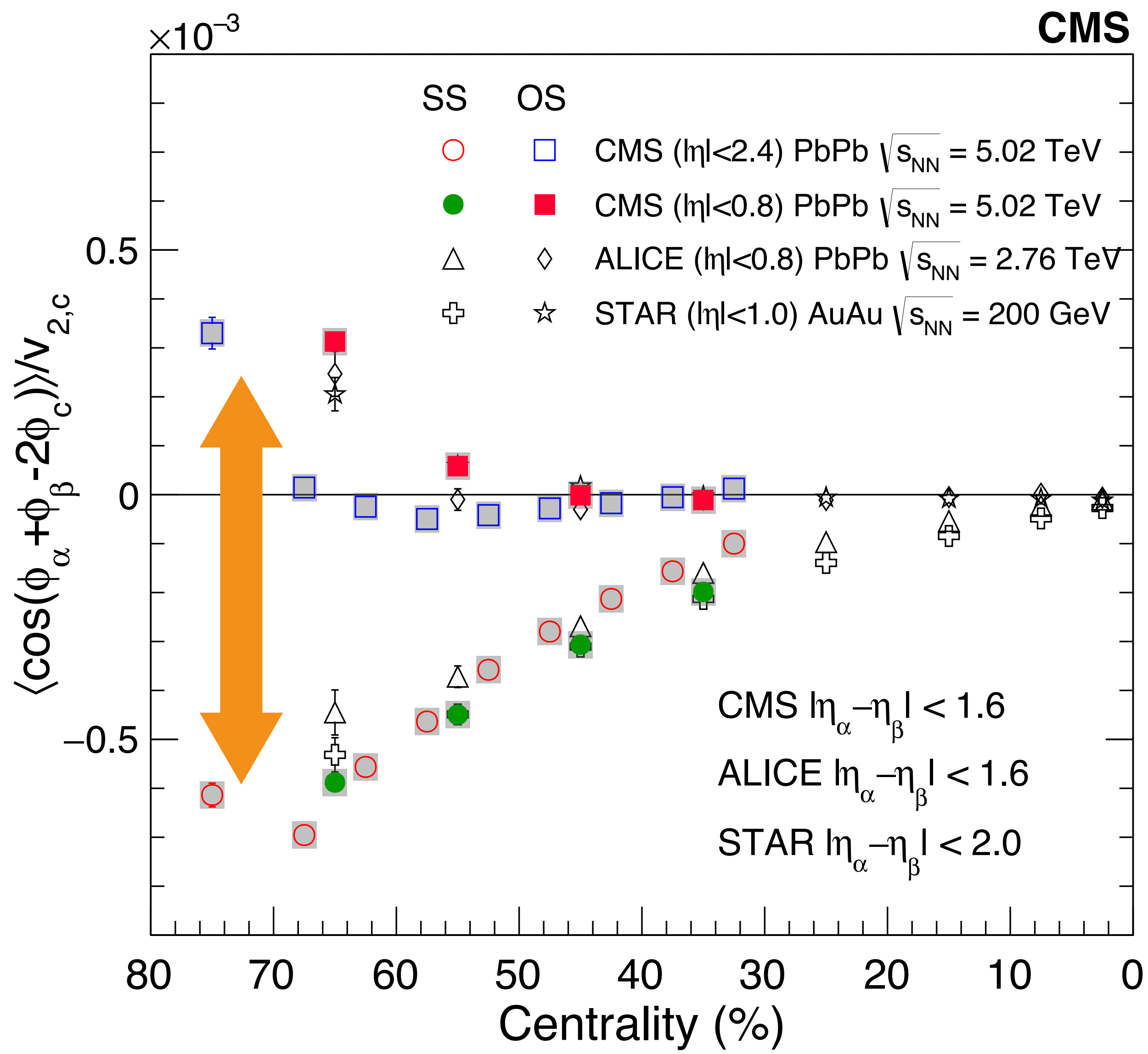


Several estimations of possible signal fraction of CME, large uncertainties and also some model dependence is needed

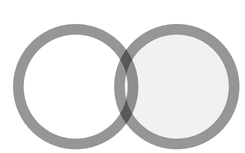
Results using a new observable to study CME looks interesting

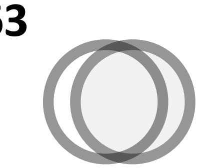
A new source of background is identified

New measurements at the LHC → new puzzles



arXiv:1610.00263

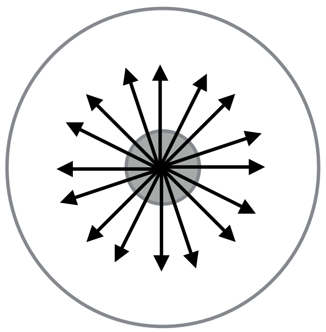




For a long time this was thought to be due to increase of B-field

Measurements by the CMS at LHC

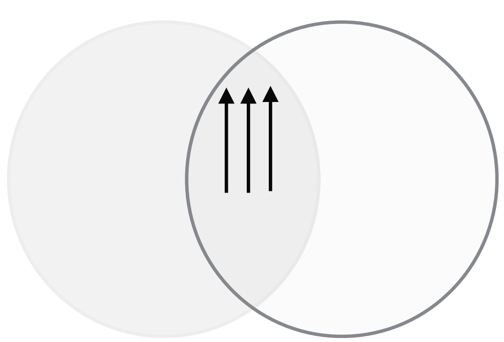
p+Pb high multiplicity



Random B-field

no CME expected

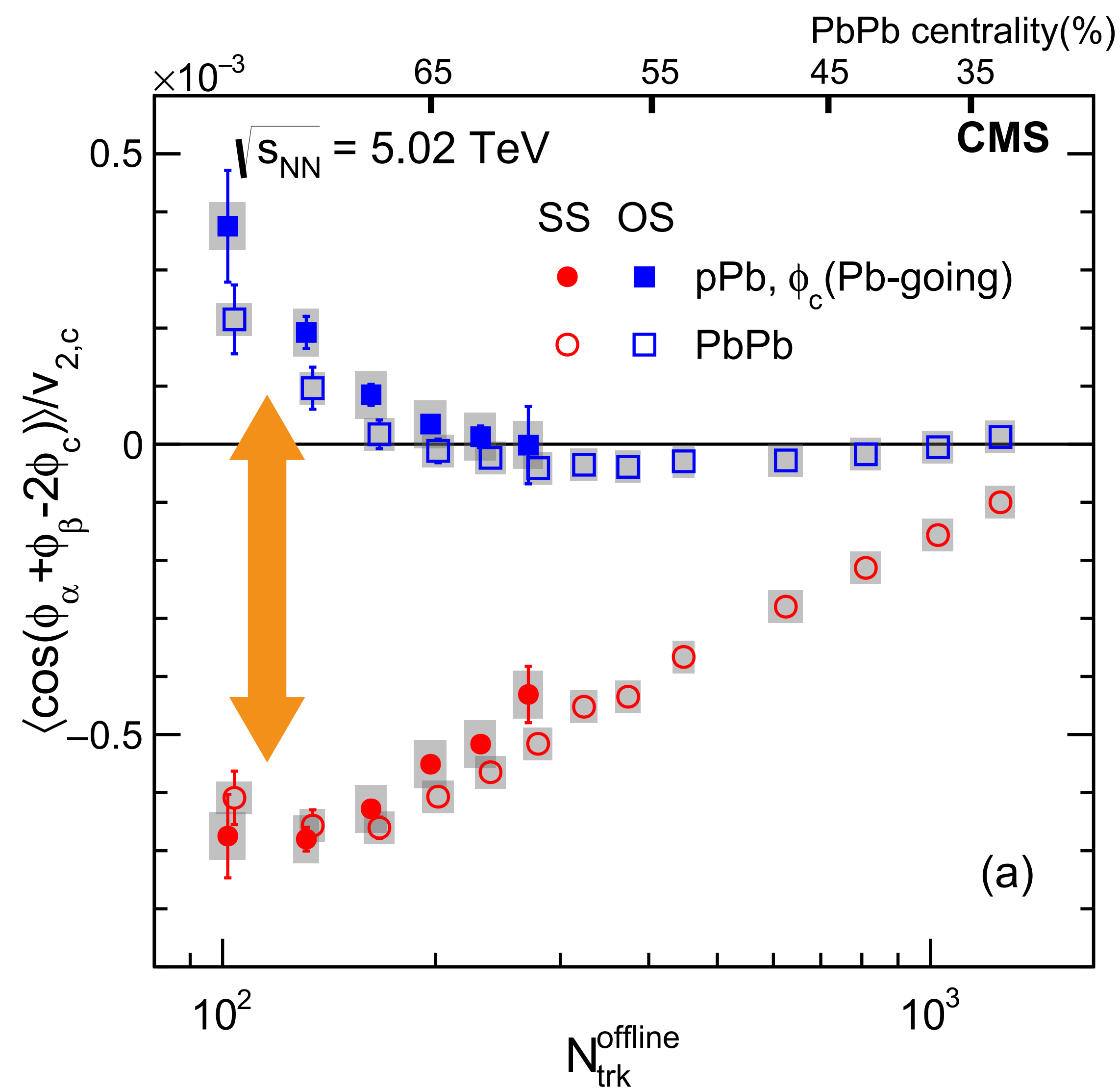
Pb+Pb peripheral (>60%)



Large B-field CME expected

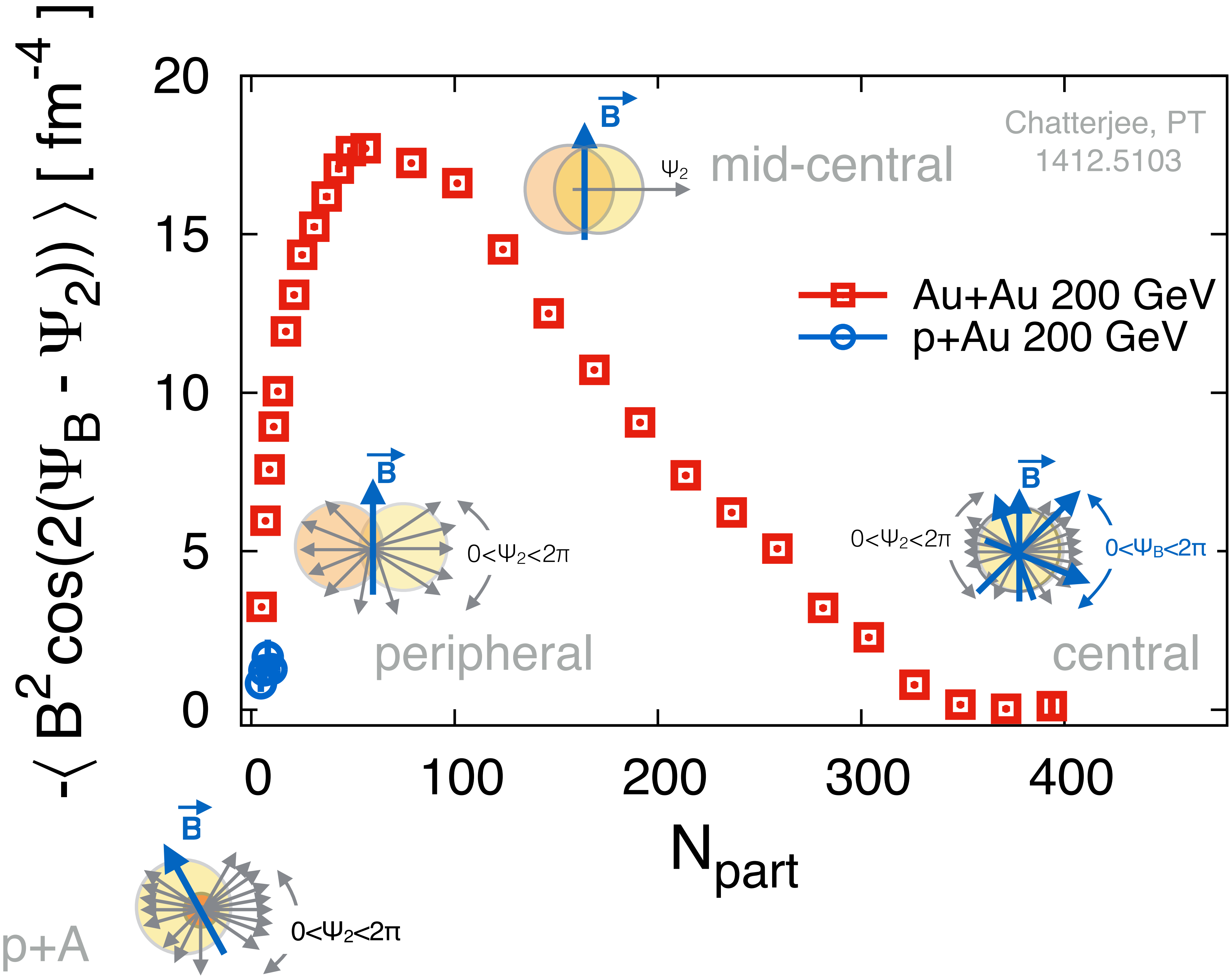
However the signal looks the same
must be some other source

CMS collaboration PRL 118 (2017) 122301



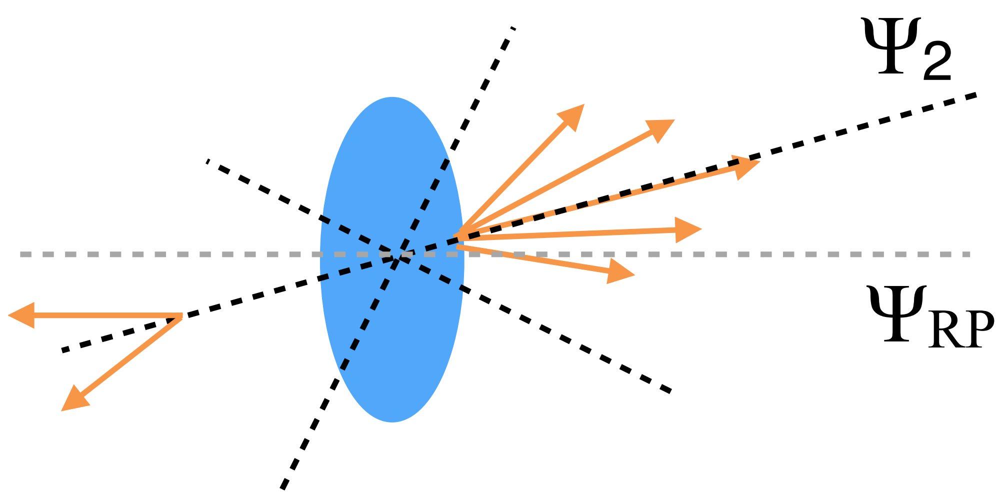
Talk by Wei

Revisit : Magnetic field calculations

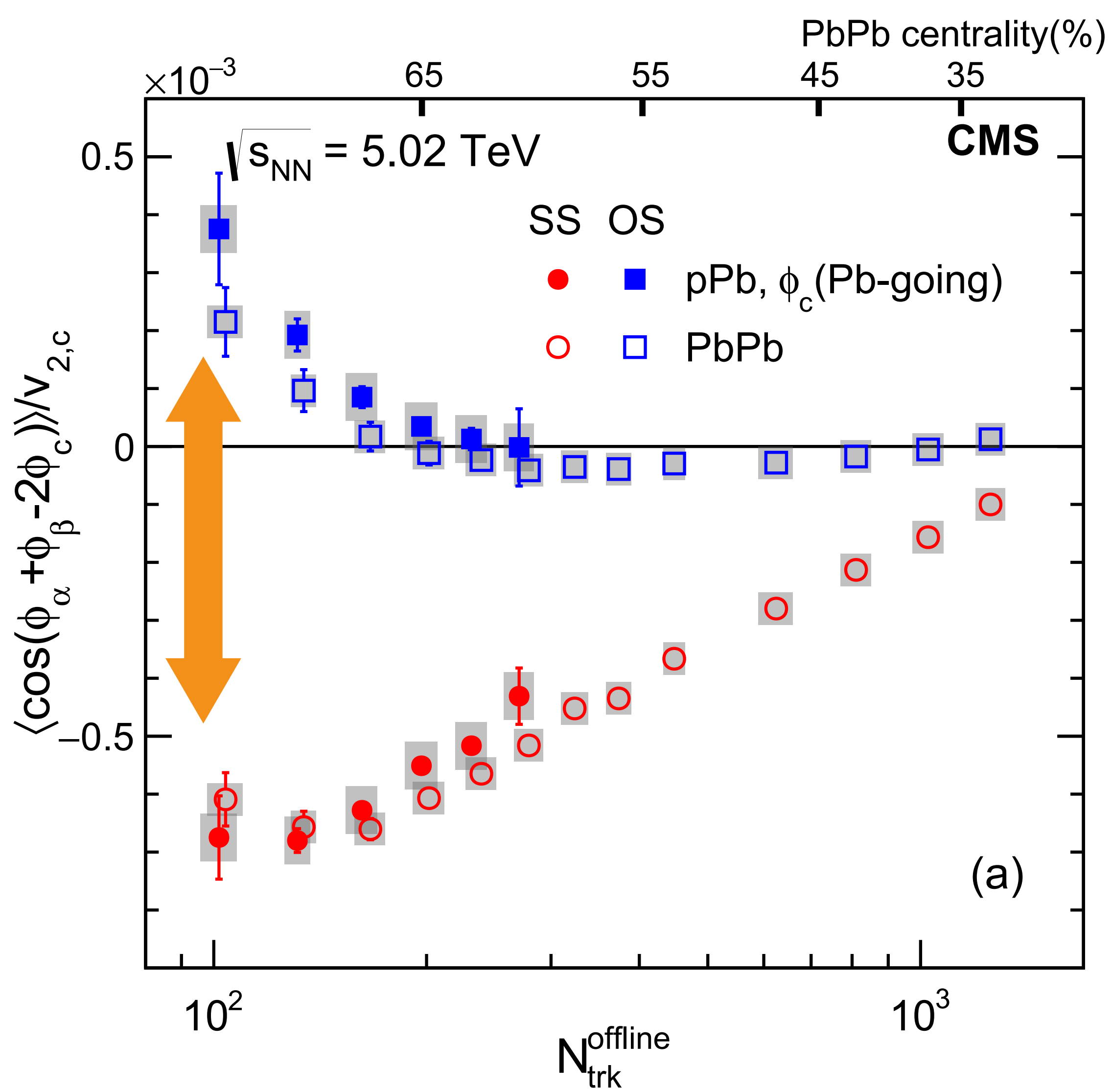


Measurements by the CMS collaboration

A possible explanation → di-jets



CMS collaboration PRL 118 (2017) 122301

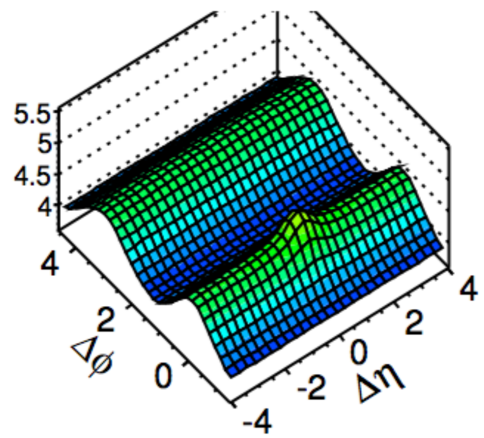


Background due to di-jets

Peripheral A+A and p+A data are dominated by di-jets

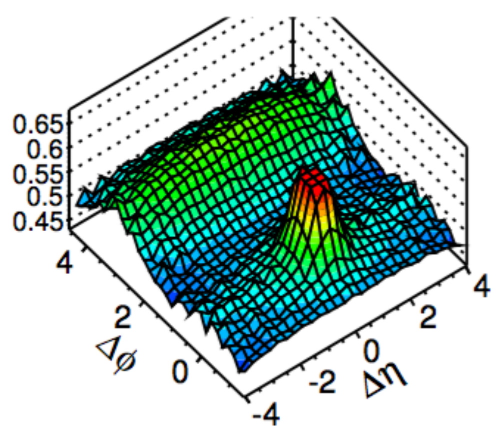
Mid-central A+A

di-jets quenched



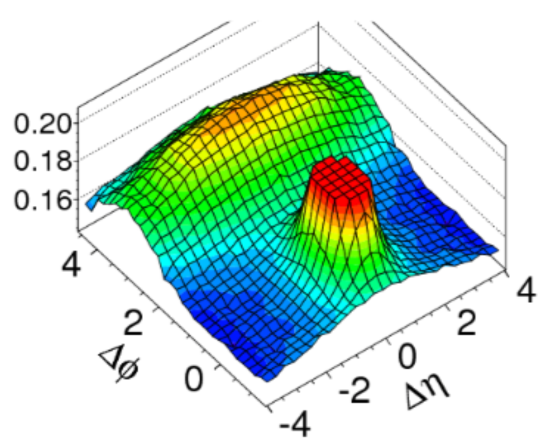
Peripheral A+A

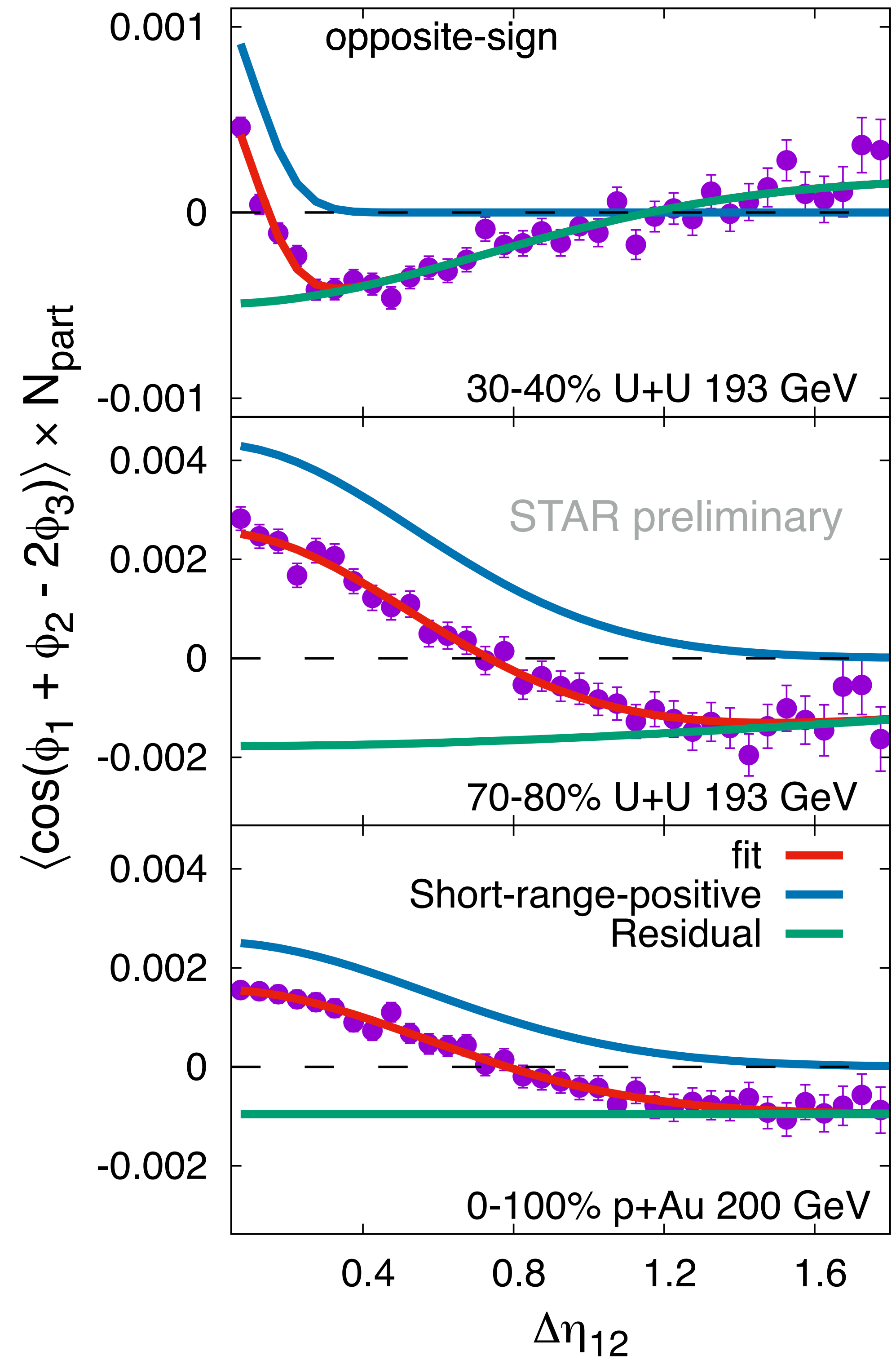
di-jets dominate



Min-bias p+A

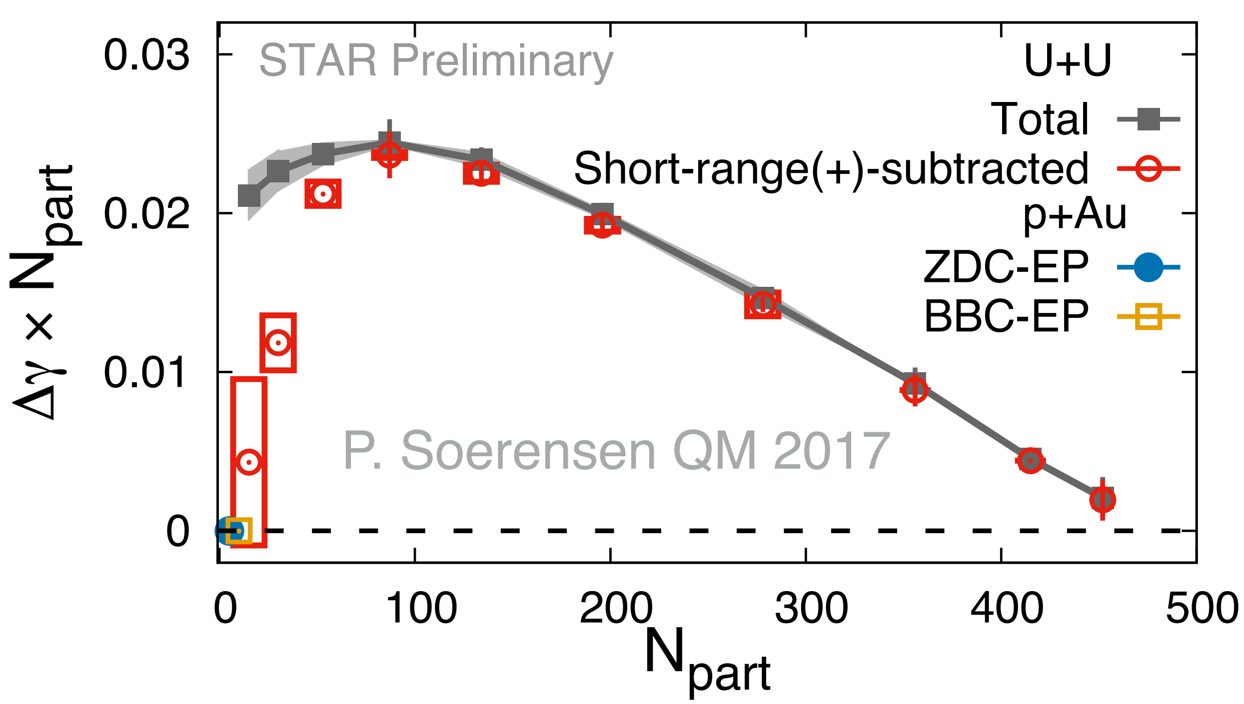
di-jets dominate



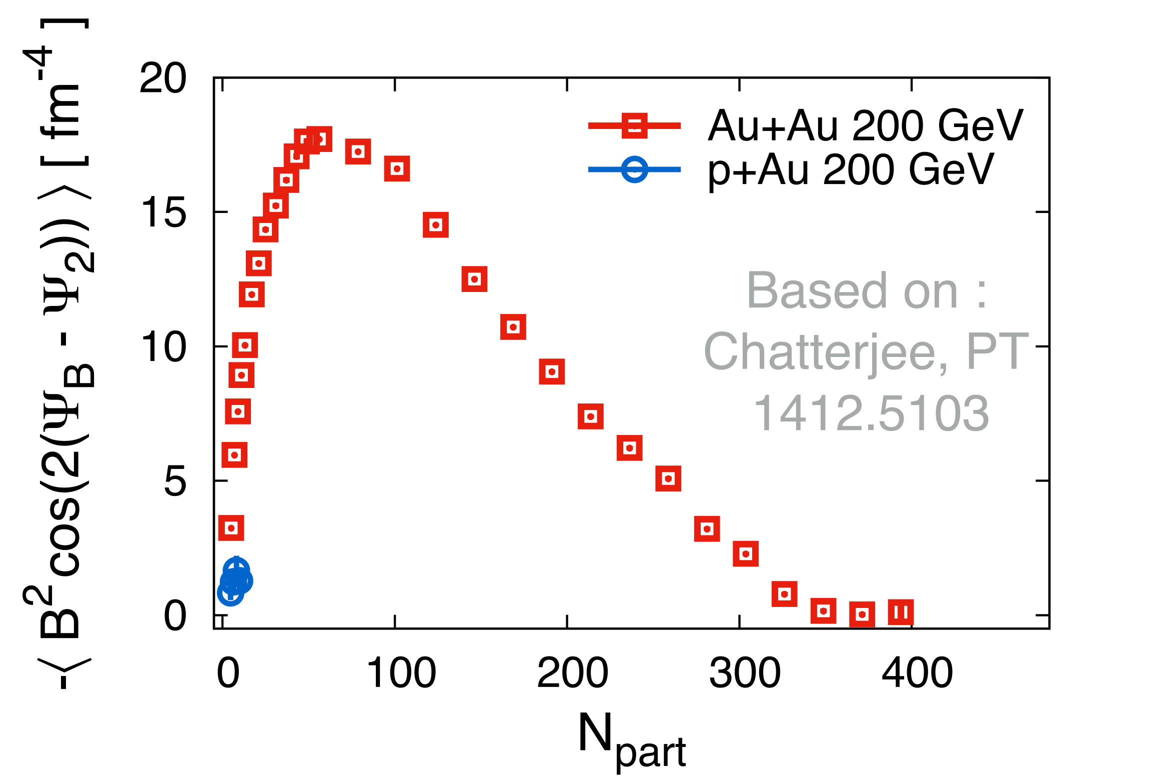


Data from RHIC after di-jet subtraction

Attempt to subtract di-jets

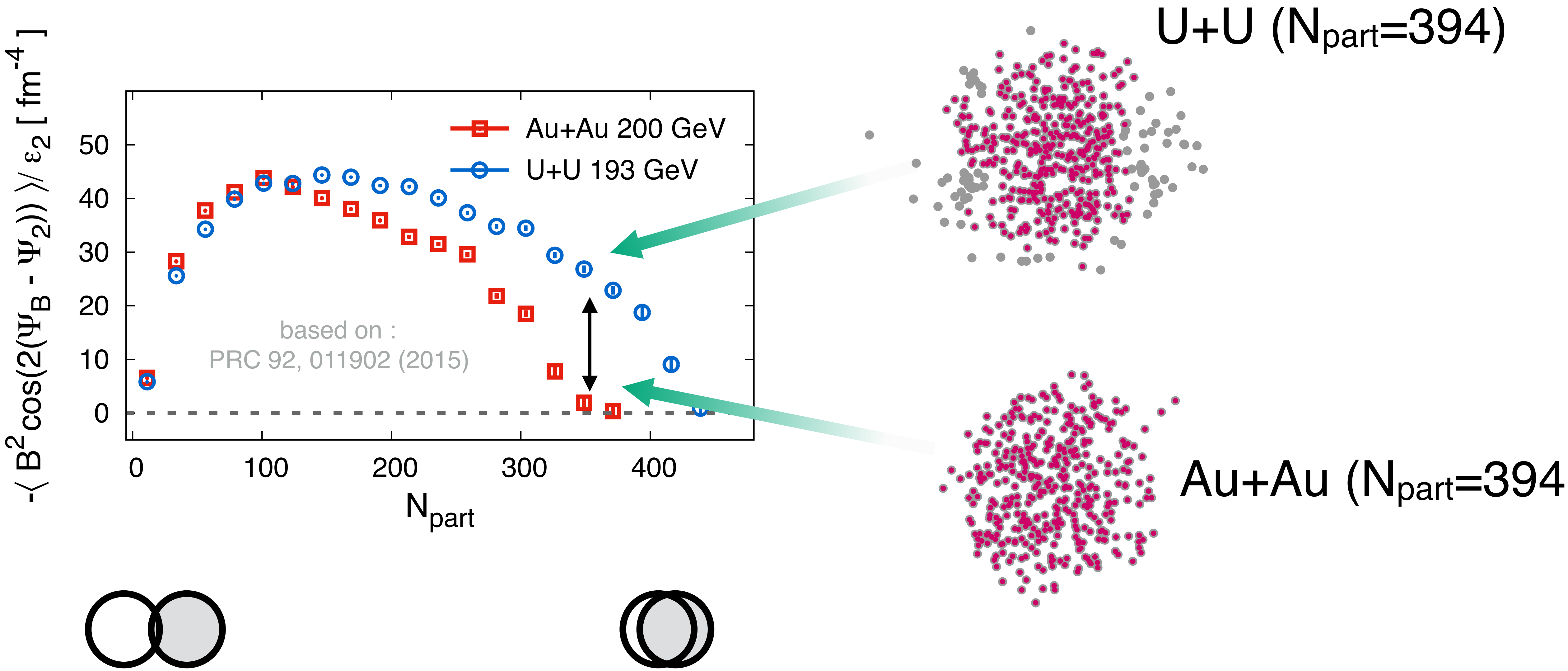


Magnetic field in A+A & p+A



Some similarities with the B-field expectation, more studies needed

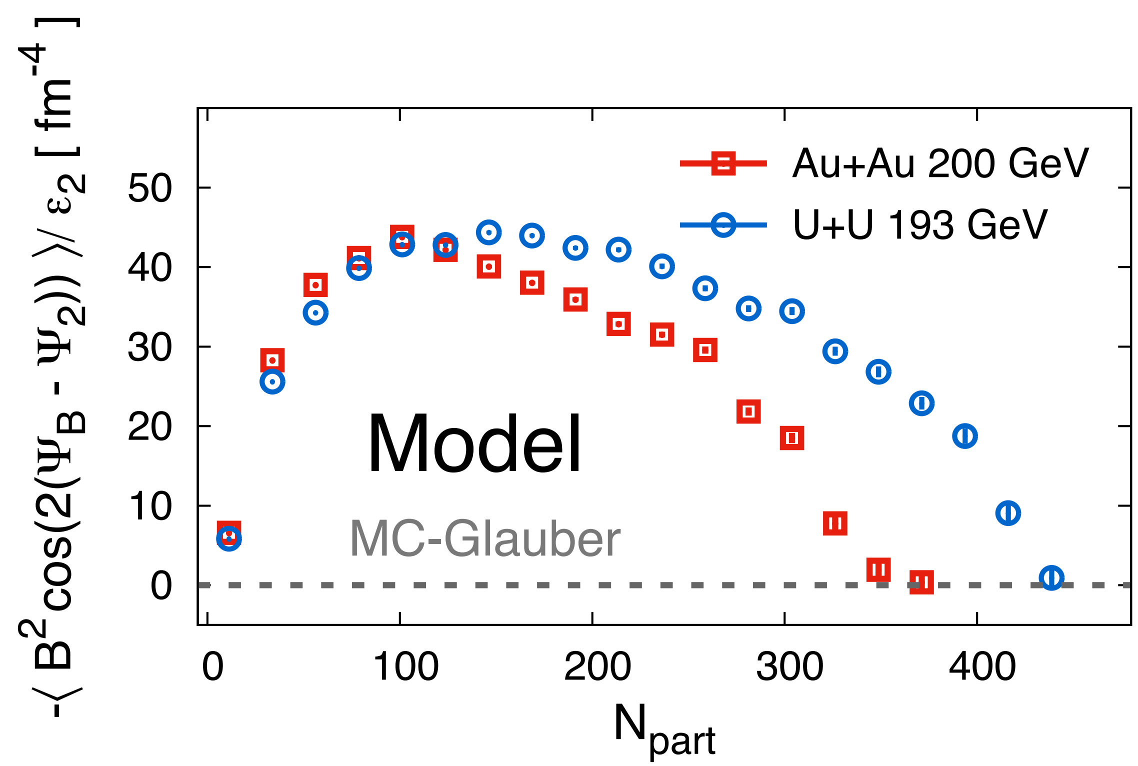
Results from RHIC on Au+Au & U+U collisions



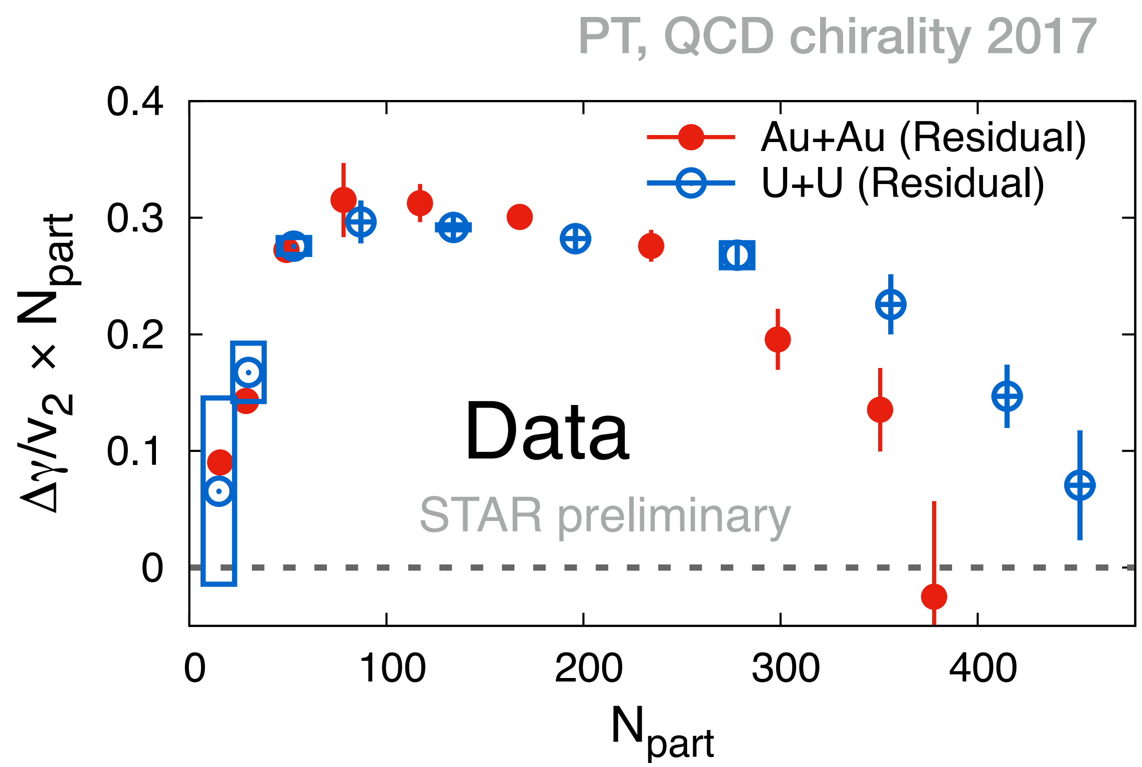
B-field is different in Au+Au and U+U → can be tested in data

Results from RHIC Au+Au and U+U collisions

B-field with collision centrality



Data on Charge separation

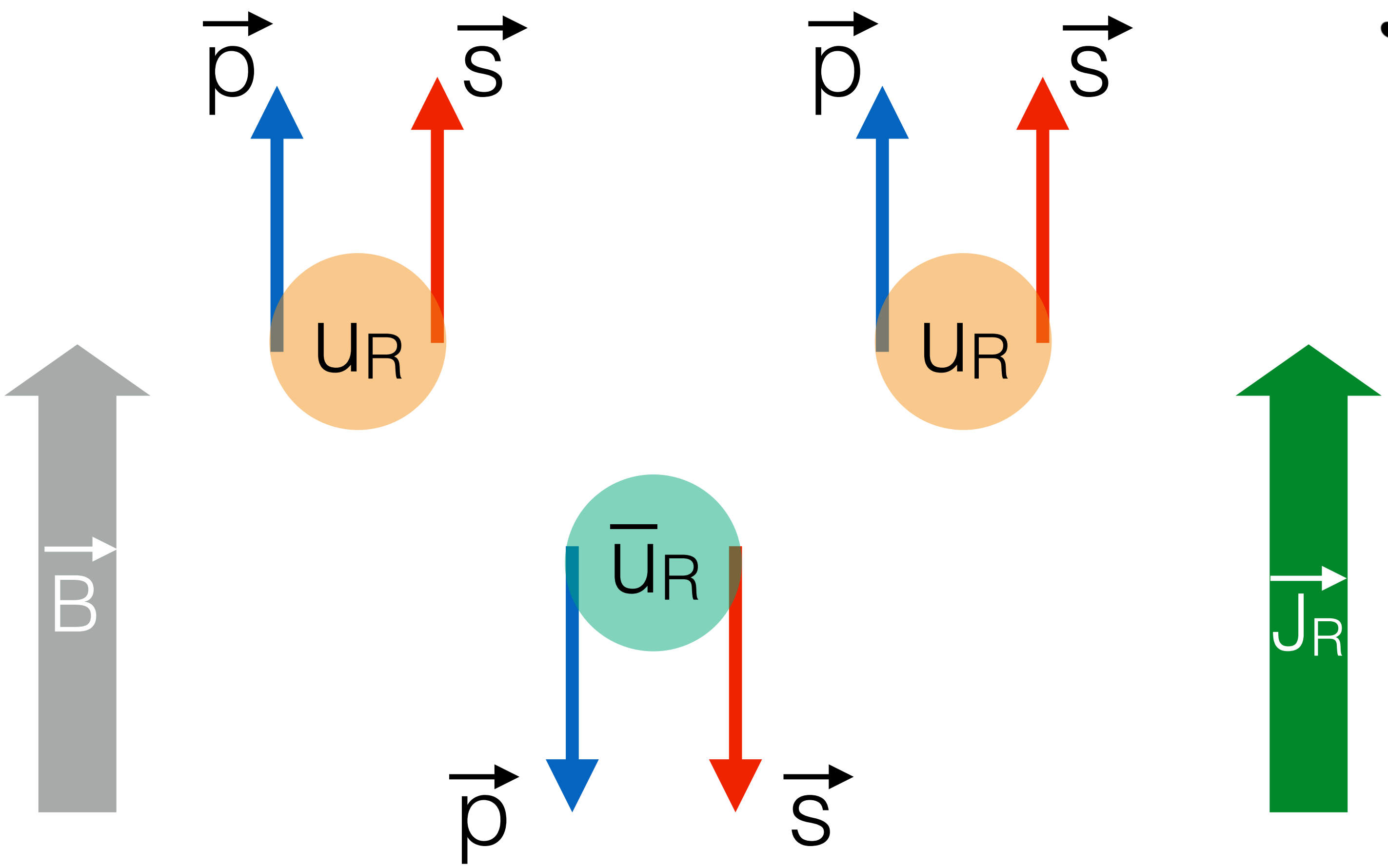


System dependence → not explained by naive background model

Measurement w.r.to third order event plane is underway

Chiral Separation Effect & Chiral Magnetic Wave

The Chiral Separation Effect : Quark > anti-Quark



Scenario-1 : Excess RH Quark

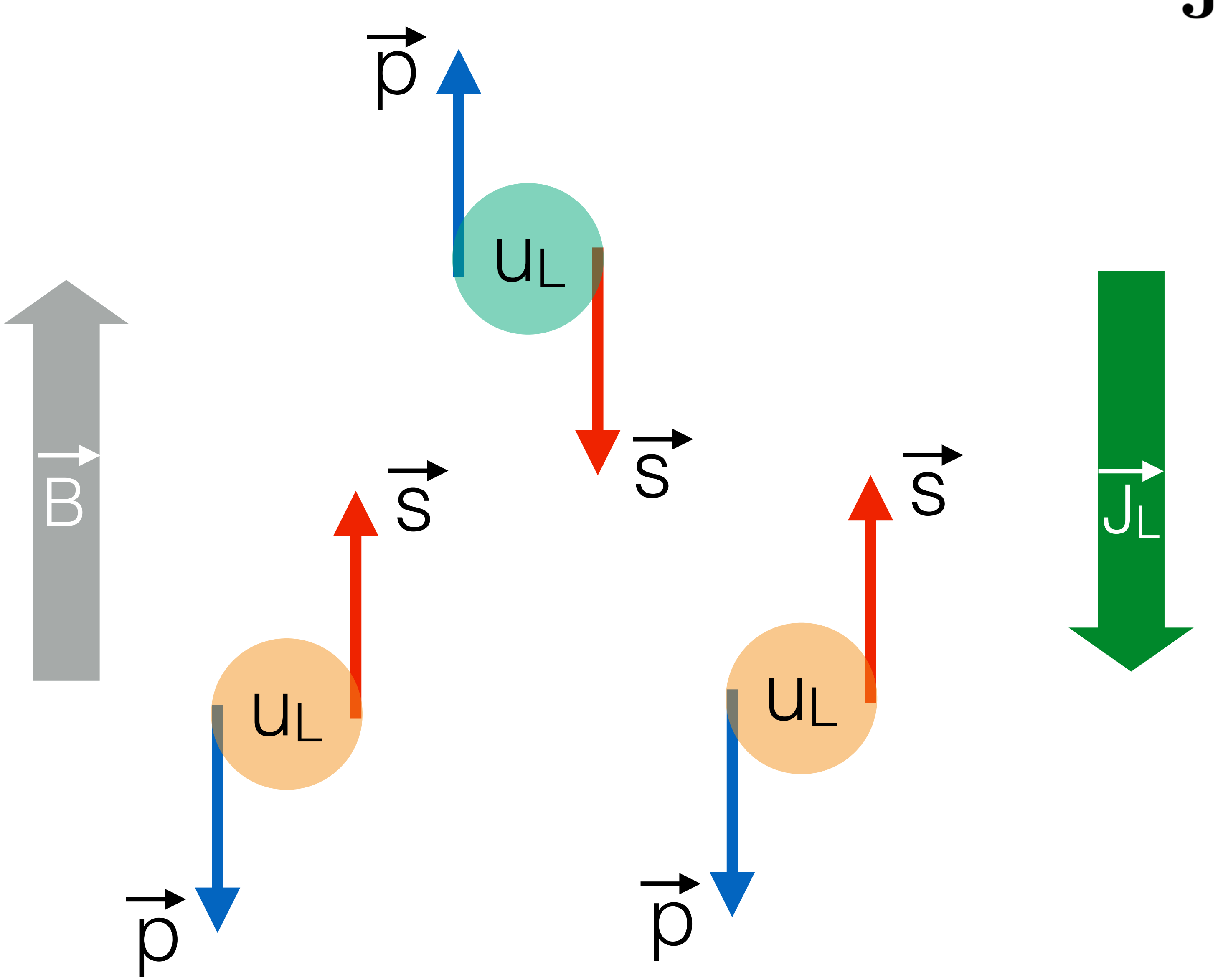
$$\vec{\mathbf{J}}_R \propto \langle \vec{p} \rangle (n_Q - n_{\bar{Q}}) \propto (Qe)\mu\vec{\mathbf{B}}$$

Excess quarks lead to axial current along B-field

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

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

The Chiral Separation Effect : Quark > anti-Quark



Scenario-2 : Excess LH Quark

$$\vec{\mathbf{J}}_L \propto -\langle \vec{p} \rangle (n_Q - n_{\bar{Q}}) \propto (Qe)\mu \vec{\mathbf{B}}$$

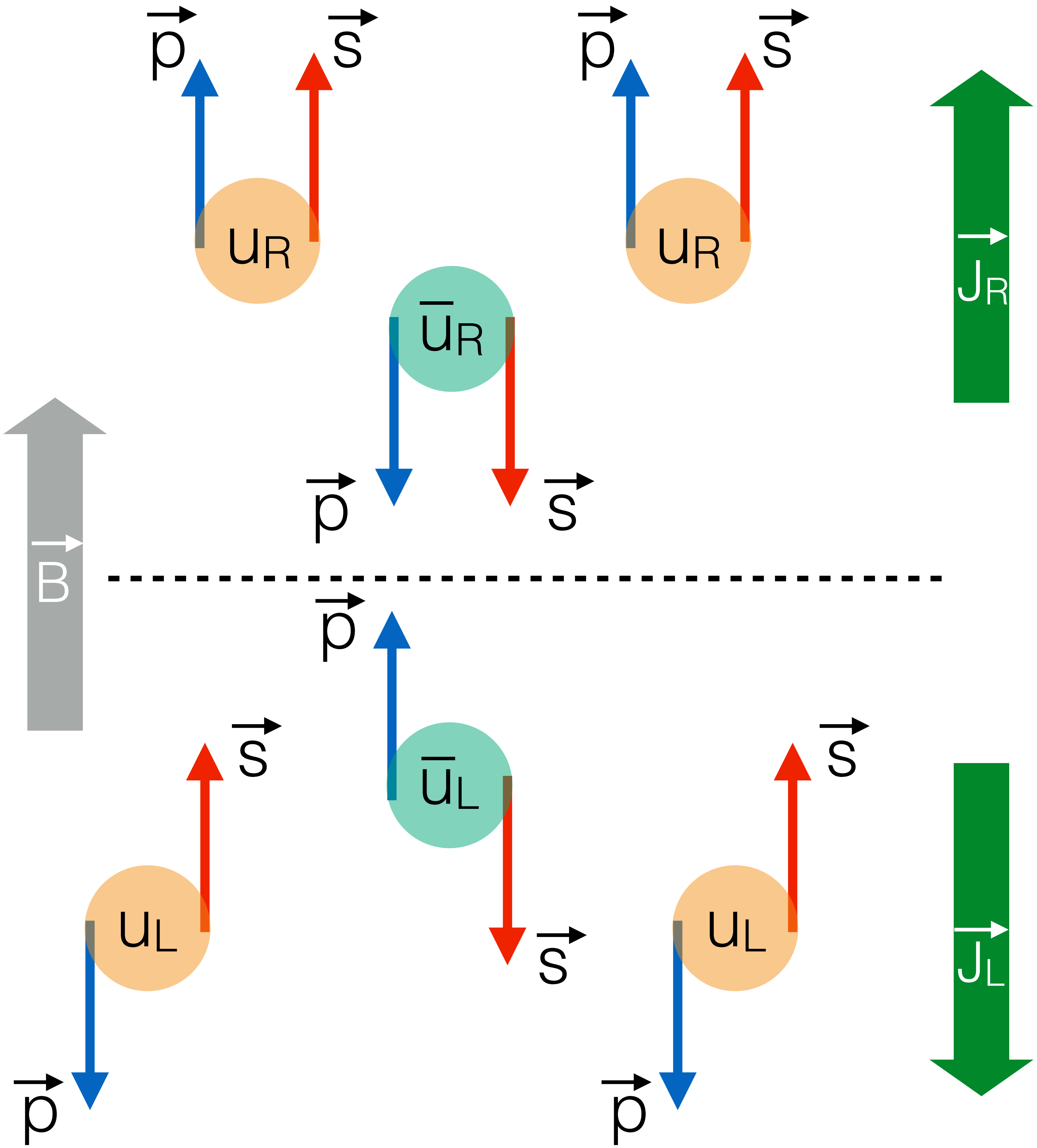
Excess quarks lead to axial current opposite to B-field

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

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

The Chiral Magnetic Wave

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

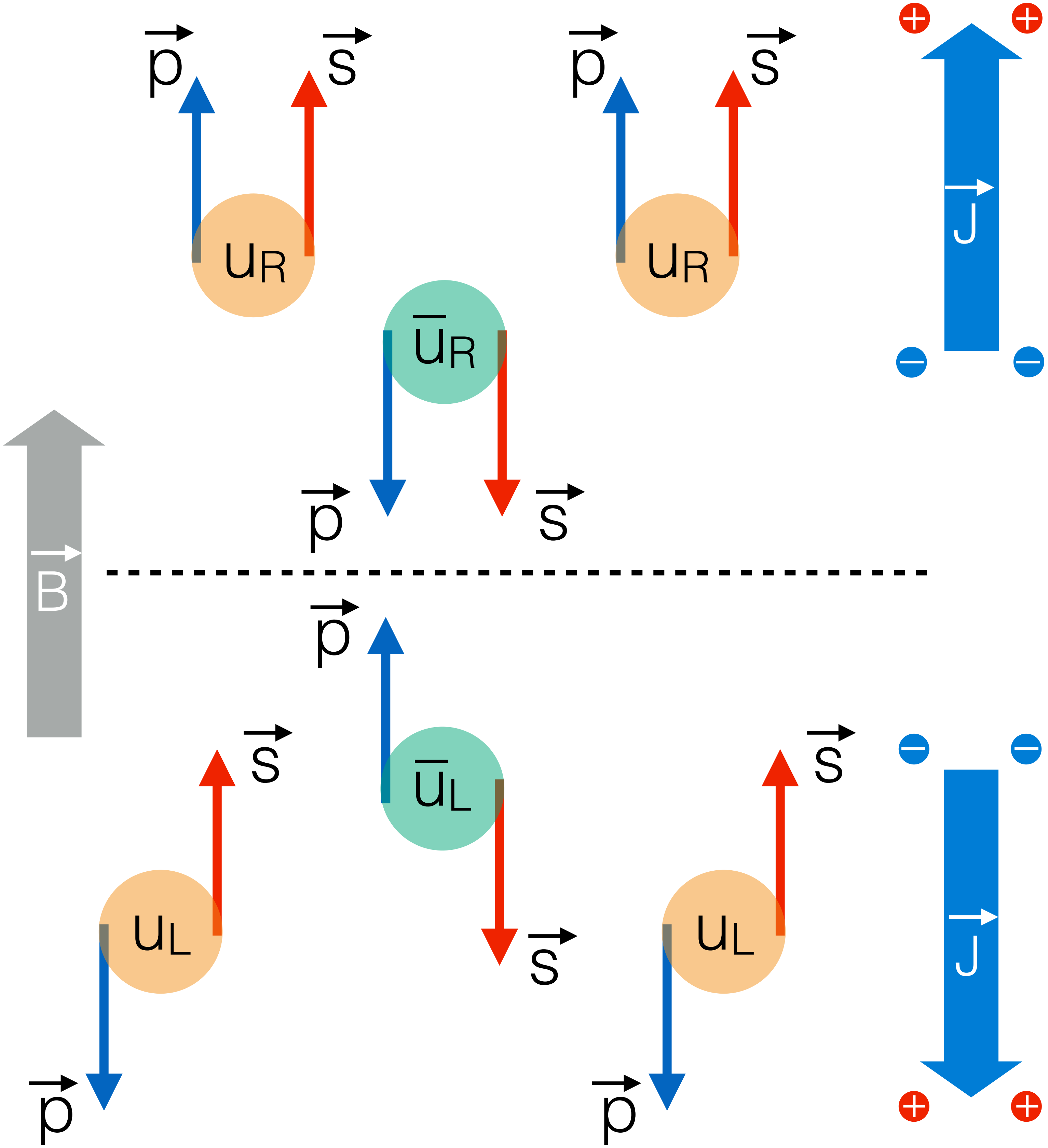


$$\vec{\mathbf{J}}_R \propto \langle \vec{p} \rangle (n_Q - n_{\bar{Q}}) \propto (Qe)\mu \vec{\mathbf{B}}$$

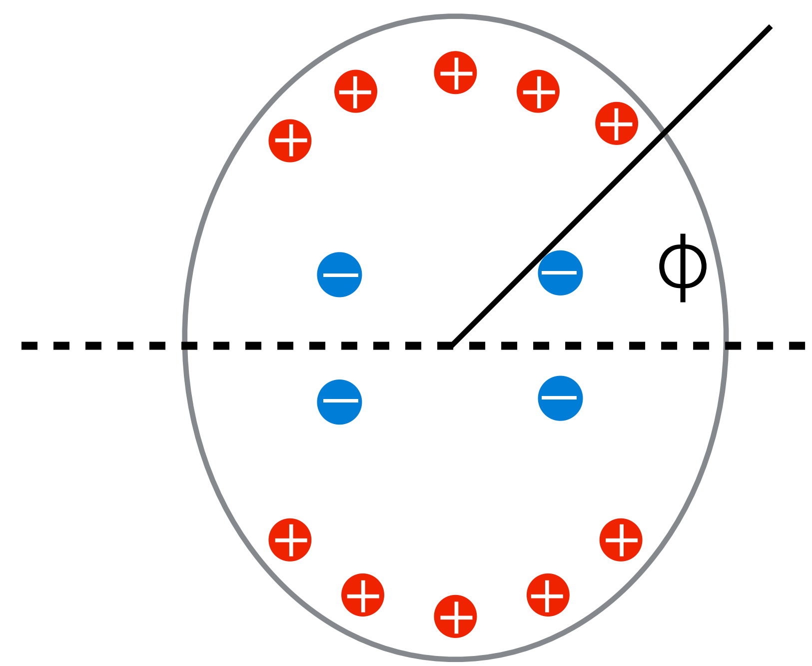
Excess quarks lead to axial current along B-field

$$\vec{\mathbf{J}}_L \propto - \langle \vec{p} \rangle (n_Q - n_{\bar{Q}}) \propto (Qe)\mu \vec{\mathbf{B}}$$

The Chiral Magnetic Wave : driven by CSE



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

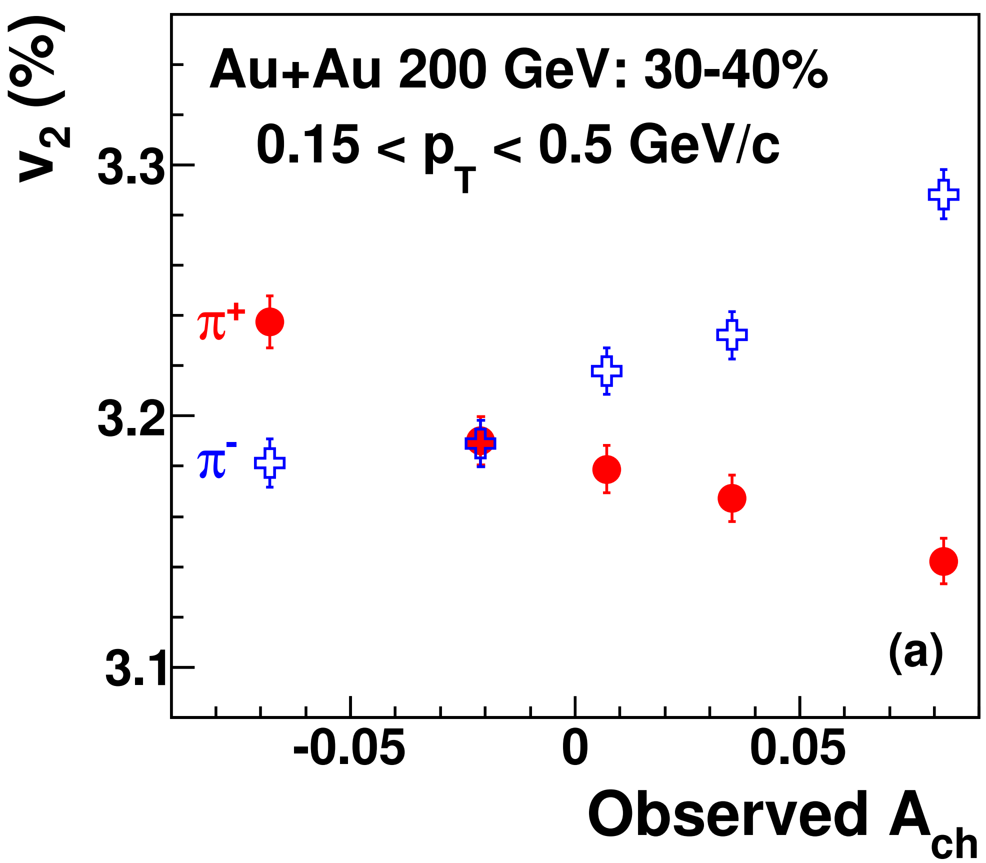


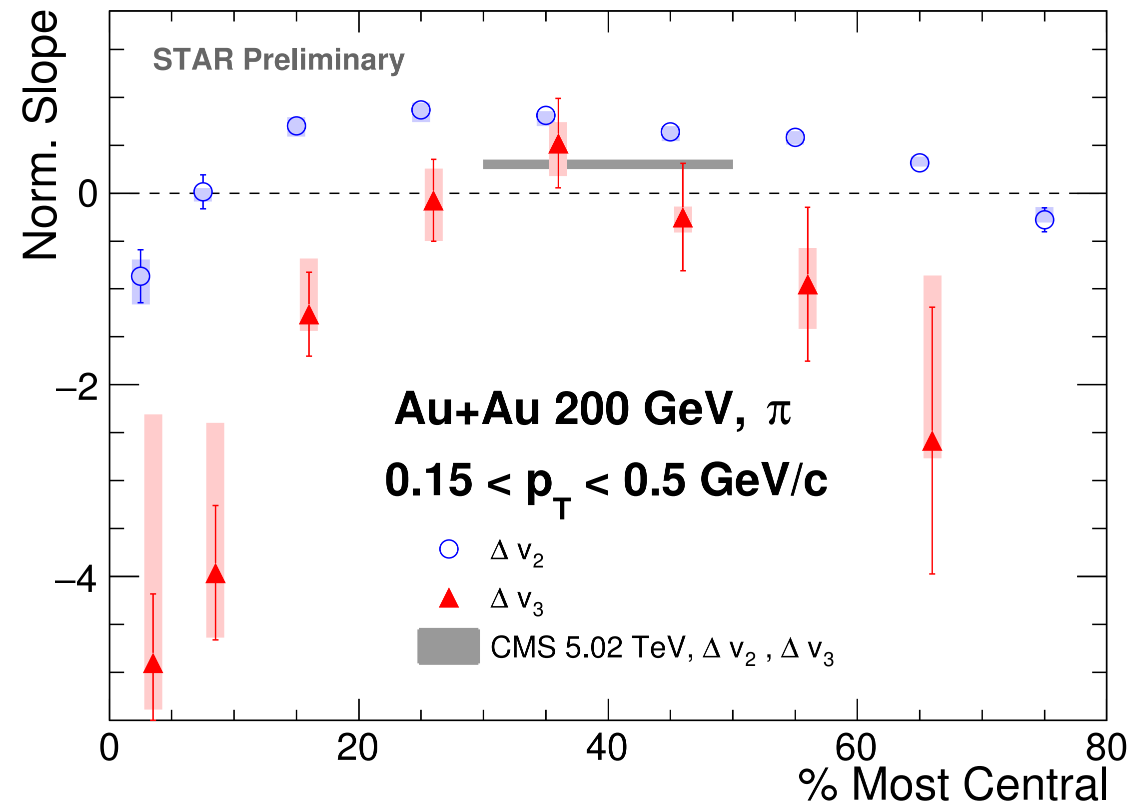
$$\frac{dN^{\pm}}{d\phi} \propto v_2^{\pm} \cos(2\phi^{\pm})$$

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

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

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

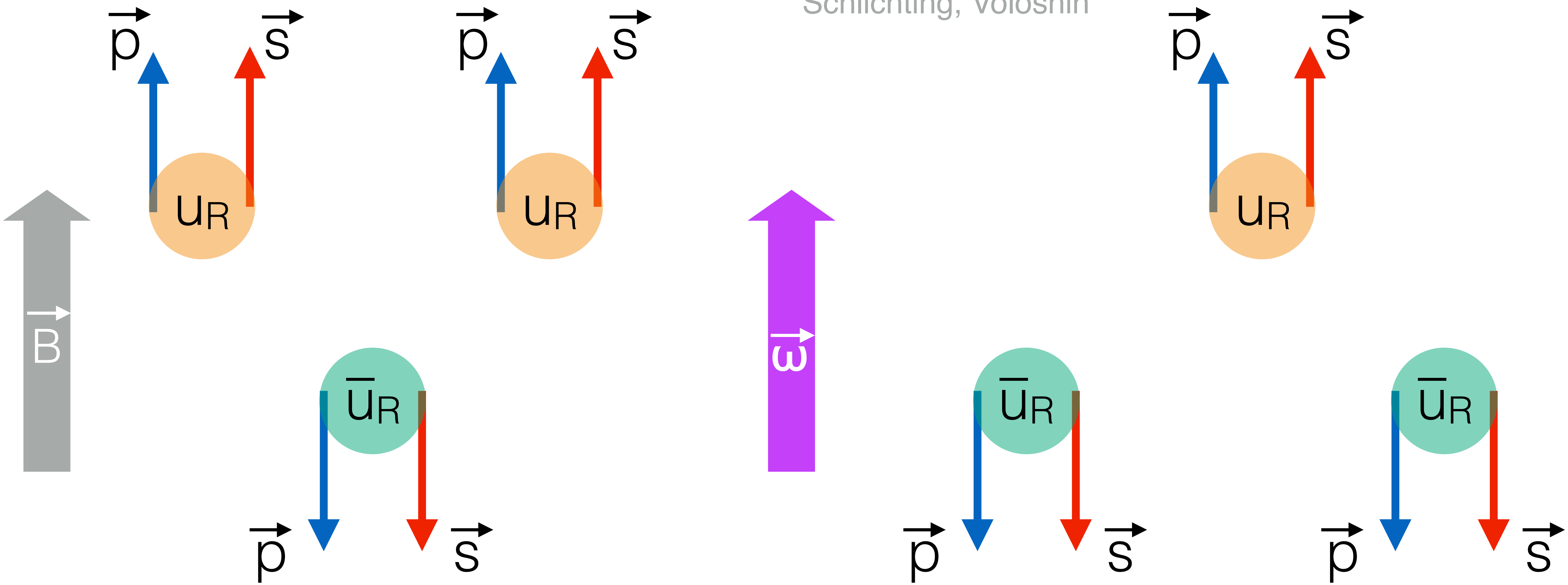
Unlike LHC, at RHIC effect $v_2 >> v_3$

Chiral Separation Effect & Spin polarization

Chiral separation effect and spin polarization

CSE enhances spin polarization along global angular momentum

Schlichting, Voloshin



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

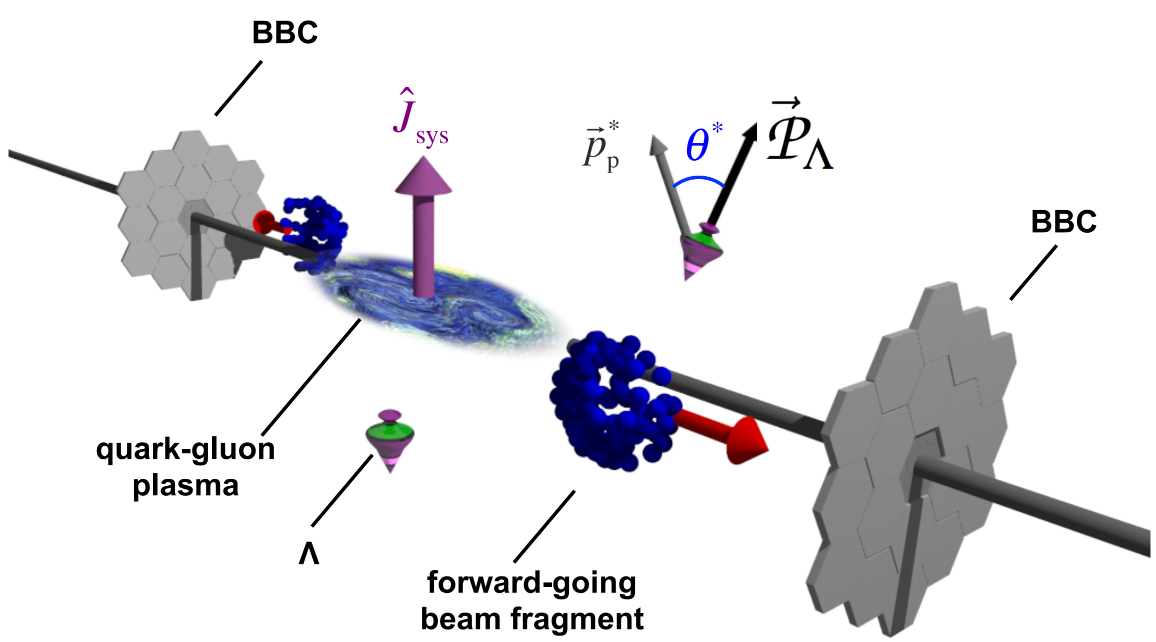
$$A_{\mathrm{ch}} = \frac{N_+ - N_-}{N_+ + N_-} < 0$$

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

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

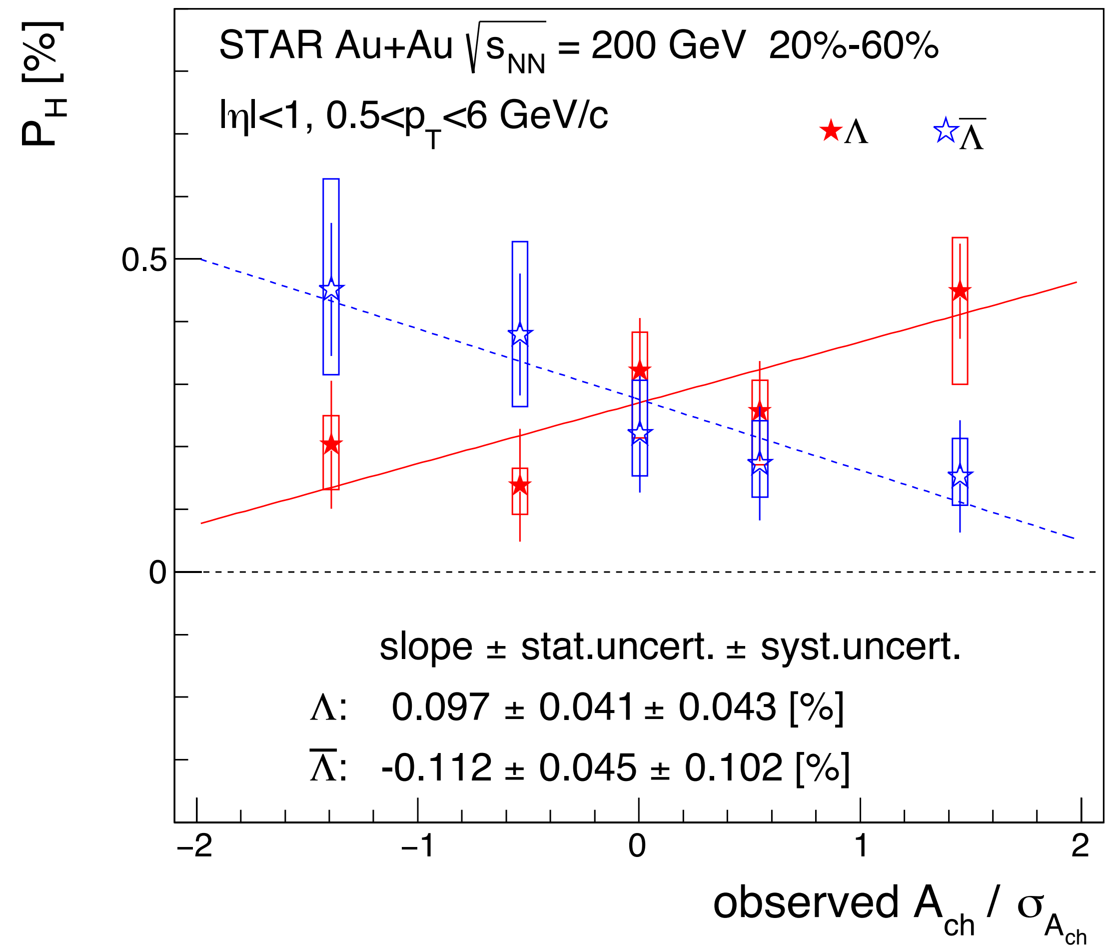
The connection between CSE and polarization

STAR Collaboration Nature 548 (2017) 62-65



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

Takafumi Niida, QM 2018

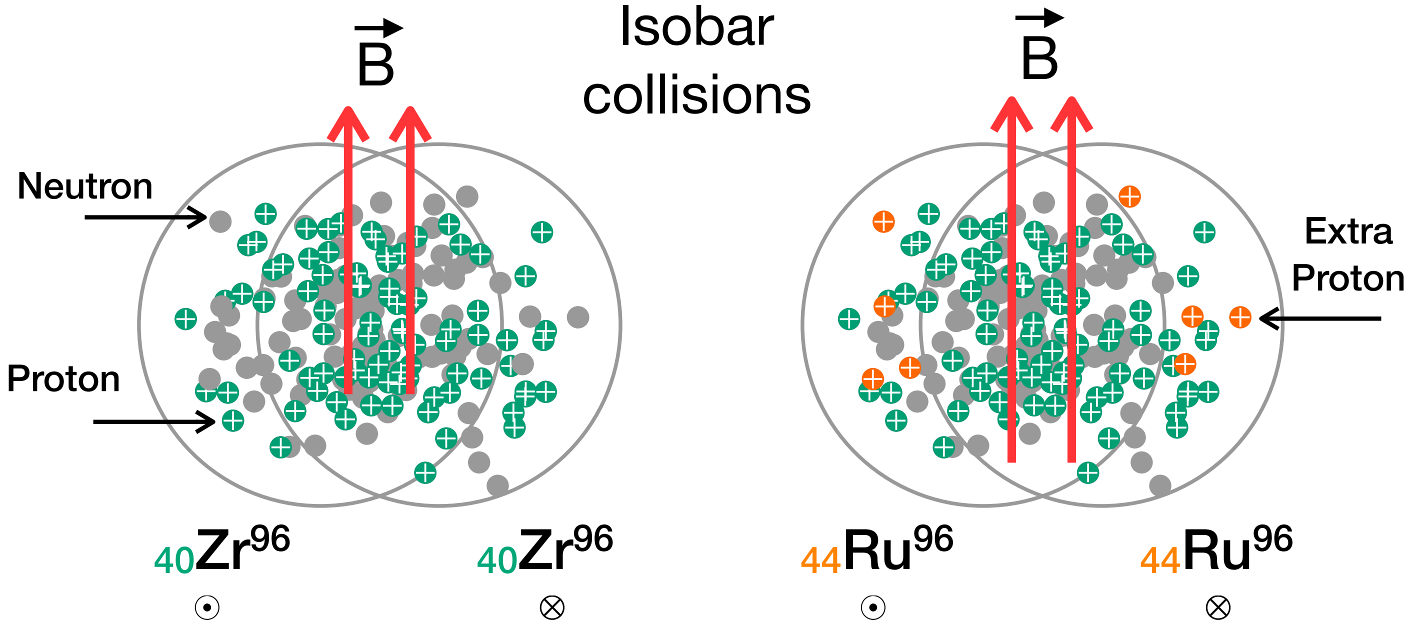


Global polarization of Λ and $\overline{\Lambda}$ studied w.r.to charge asymmetry A_{ch}

Very first measurement looks promising, need more statistics

Decisive tests of CME, CMW, CSE

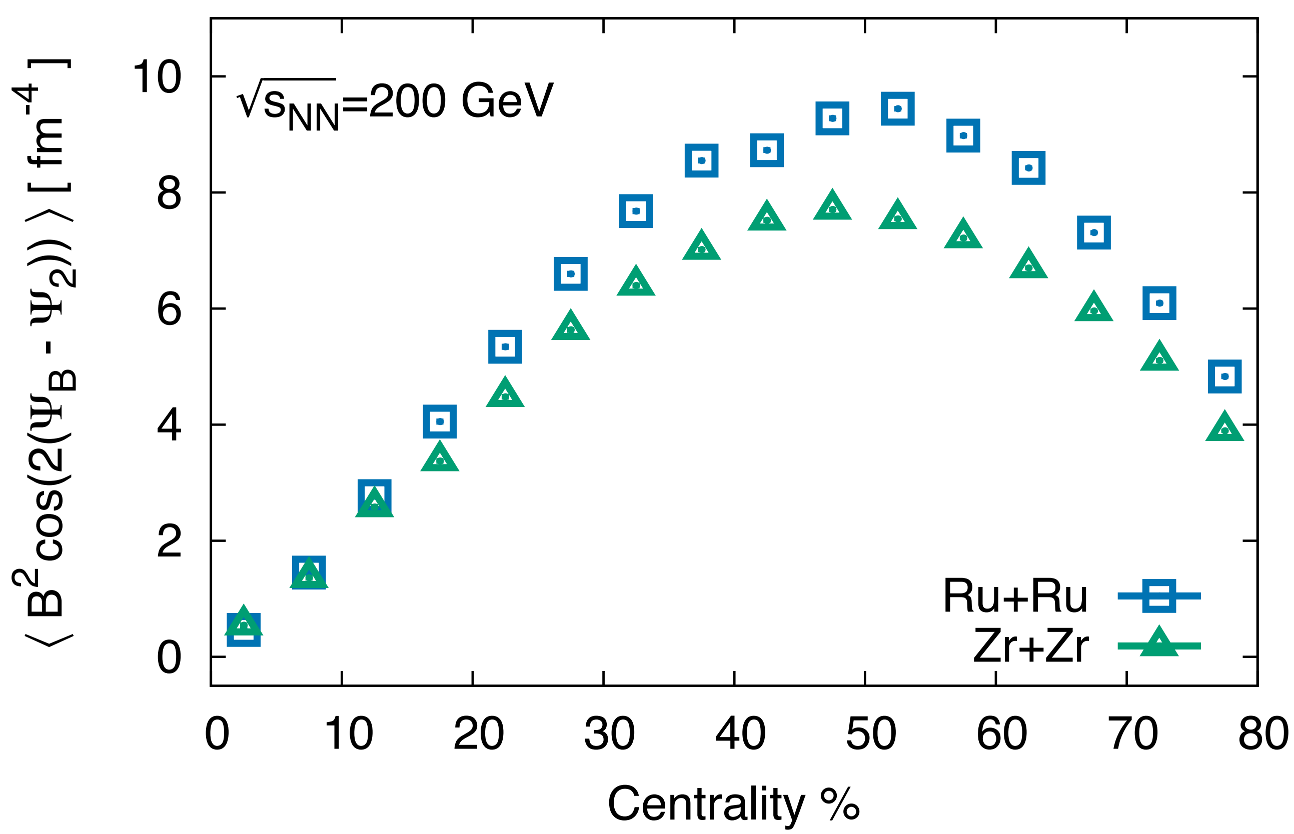
Better and controlled experiment : Isobar collisions



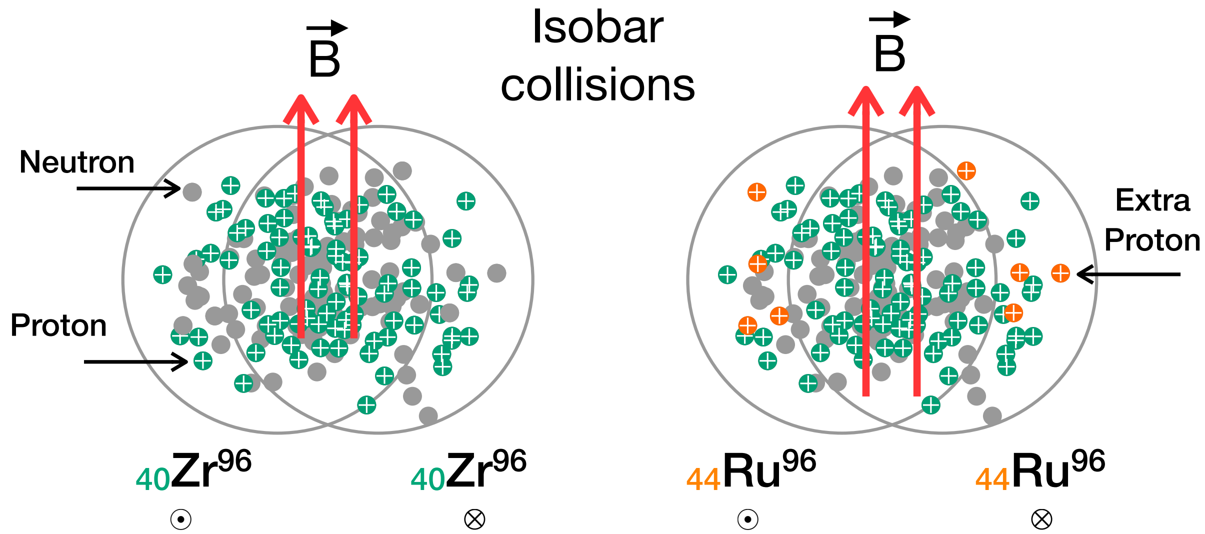
Voloshin, Phys. Rev. Lett. 105, 172301 (2010).

Ru+Ru will have 10% B-field than Zr+Zr, all

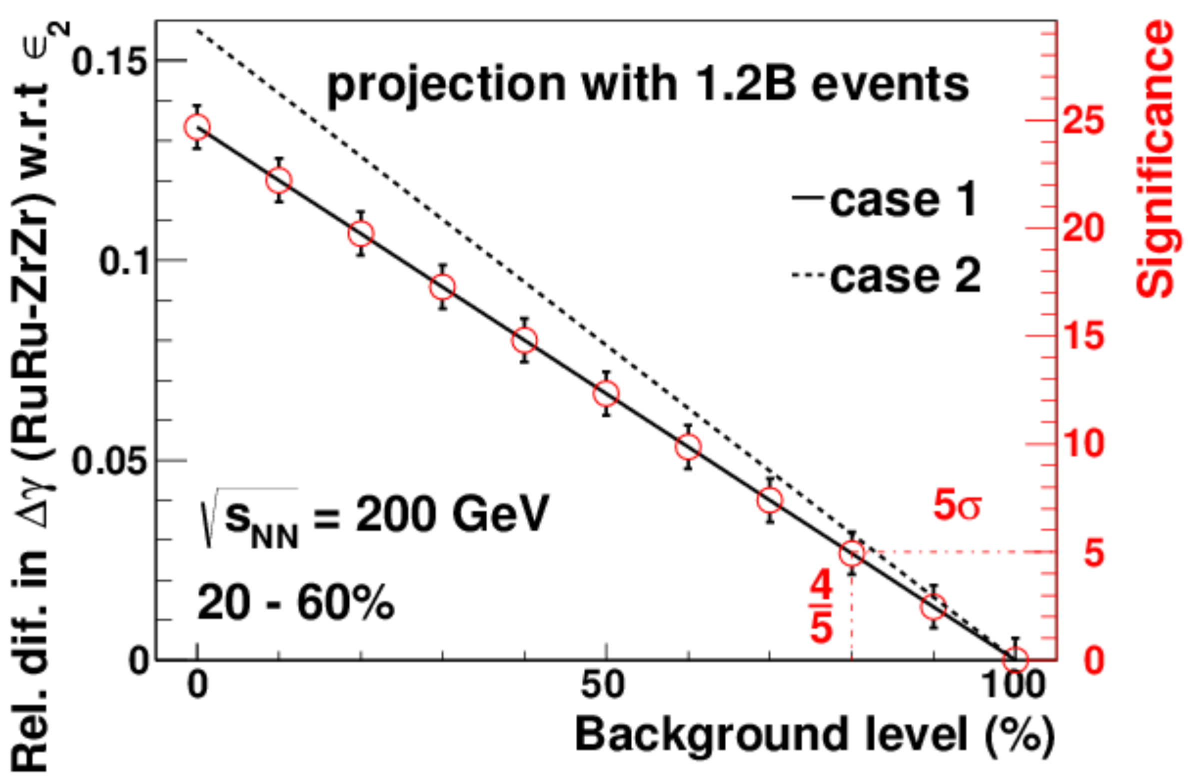
Isobars have same mass number but different charge, so produce identical systems with different B-field, ideal to test evidences of B-filed driven effects



Better and controlled experiment : Isobar collisions



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



3.1B events for both Ru+Ru, Zr+Zr collected over 8 weeks

Blind analyses is being planned

Summary

Very exciting time for STAR @ RHIC

1) Comprehensive set of measurements on CME, CMW

2) Many interesting results but no decisive tests yet

3) Several attempts to quantify signals

4) Isobar data taking was a success, bind analysis is being planned

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Relativistic Heavy Ion Collider Begins 18th Year of Experiments

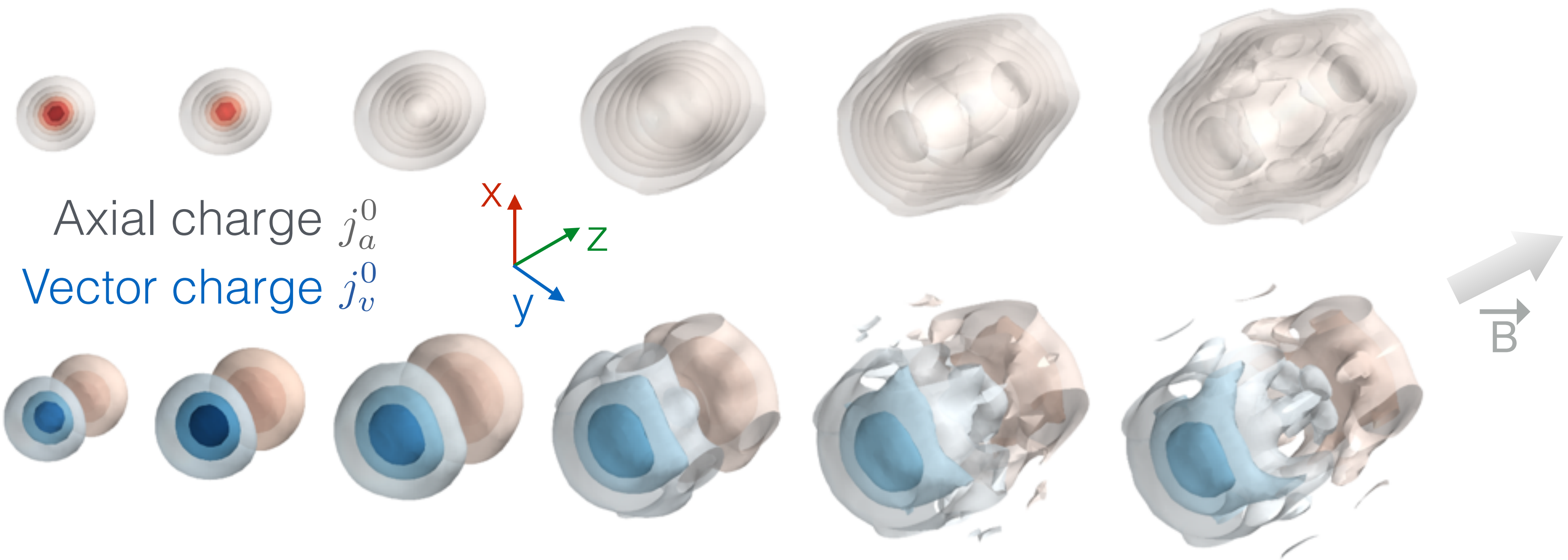
First smashups with 'isobar' ions and low-energy gold-gold collisions will test earlier hints of exciting discoveries as accelerator physicists tune up technologies to enable future science

March 21, 2018

Thank You

How much guidance do we have from theory ?

Real-time first principle lattice calculations of CME



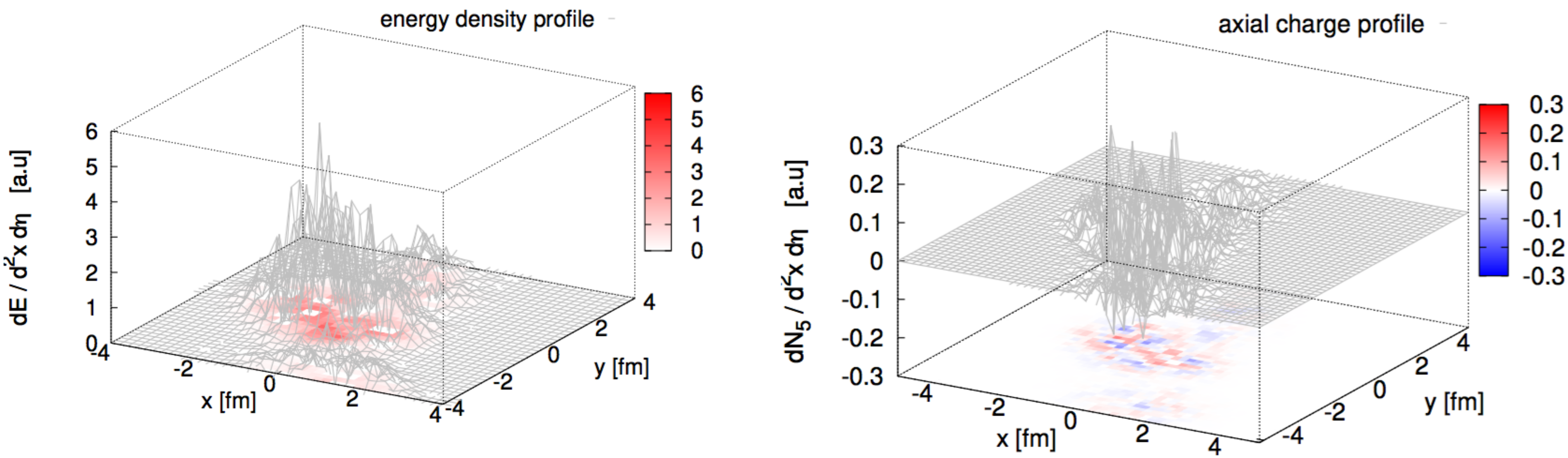
Muller, Schlichting, Sharma, PRL 117 142301 (2016)
Mace, Mueller, Schlichting, Sharma PRD 95, 036023 (2017)

We are looking for a signal of charge separation that :

1) will be correlated to event plane (Ψ_2) therefore must follow the correlation of B-field with Ψ_2 ,
2) requires time to build up during the early phases of collisions, so may be short-range in $\Delta\eta$ compared to flow.

How much guidance do we have from theory ?

A first principle calculations of axial charge density



Lappi , Schlichting PRD 97 034034 (2018)

We are looking for a signal of charge separation that :

1) is driven by structures of the axial charge density that is lumpy