# Search for the Chiral Magnetic Effect in nuclear collisions – status and prospects

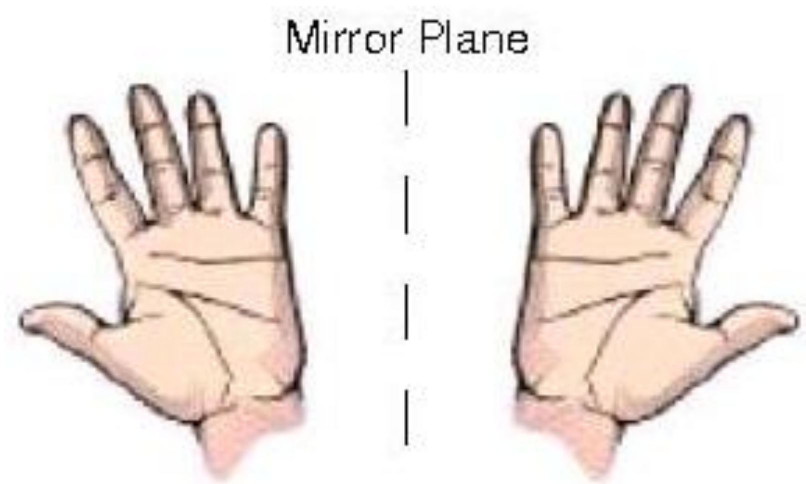
Wei Li
Rice University, Houston

CIPANP 2018
cipanp18.berkeley.edu

# Chirality

*Object and its mirror image are non-superimposable*

*– Chiral*



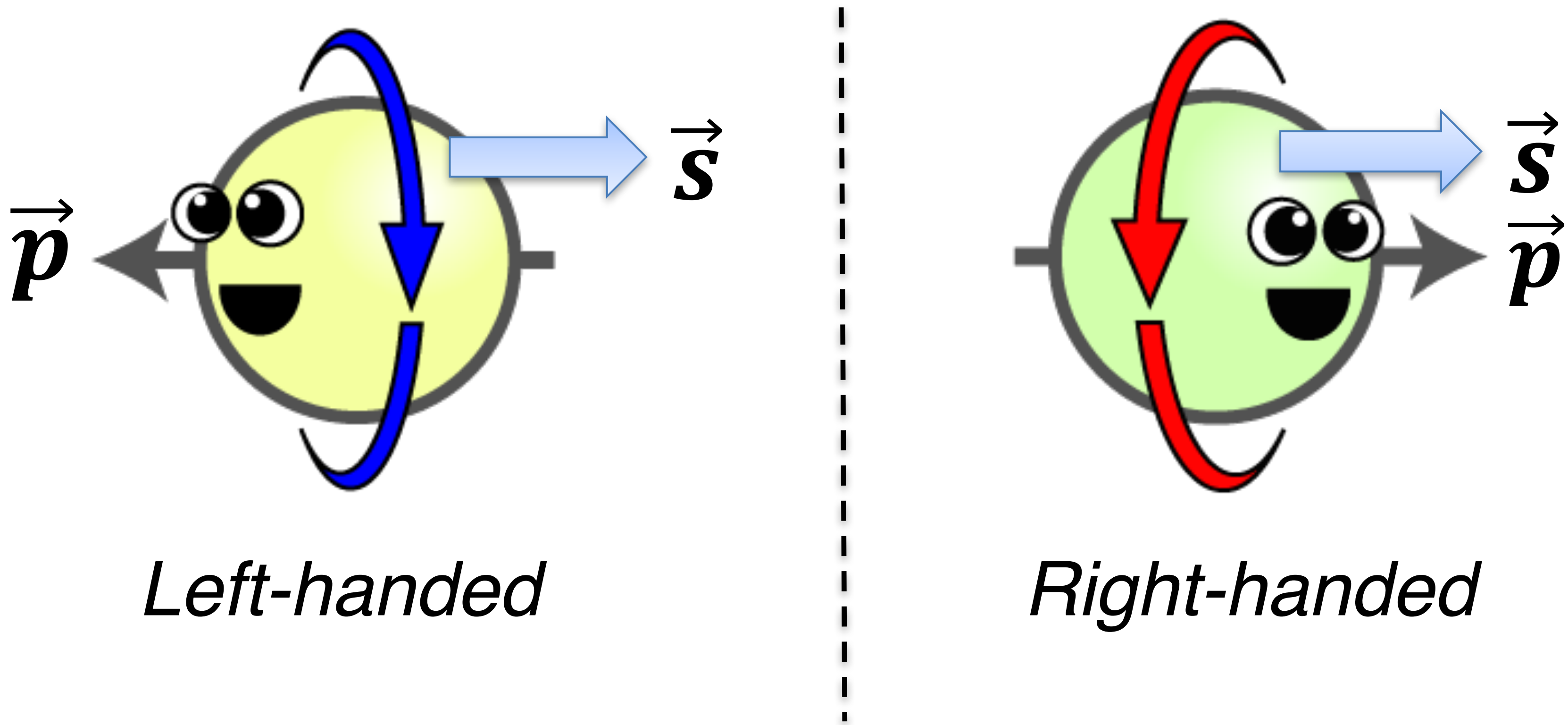

- Chirality in DNA

# Chirality

In particle physics,

chirality related to inherent quantum properties

**Chirality** = **Helicity** for *massless* particles




*Left-handed*

*Right-handed*

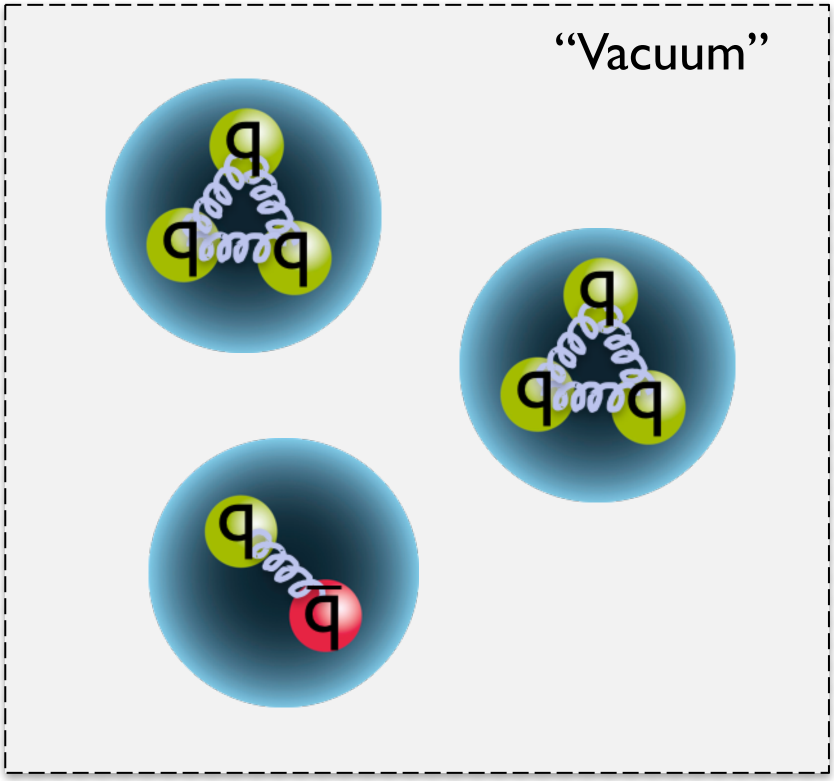
# Chiral symmetry in QCD

Chiral symmetry broken in the QCD vacuum

➡ chiral condensates

➡ **"massive" quarks**

account for 99% of the hadron mass



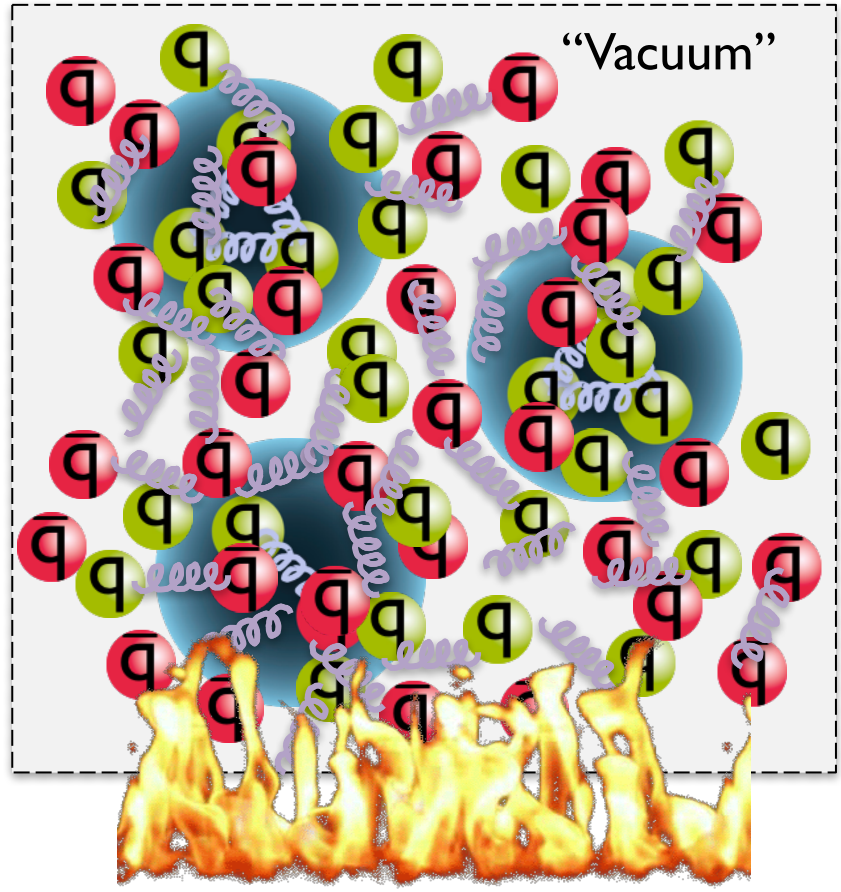
# Chiral symmetry in QCD

Chiral symmetry broken in the QCD vacuum

➡ chiral condensates

➡ **"massive" quarks**

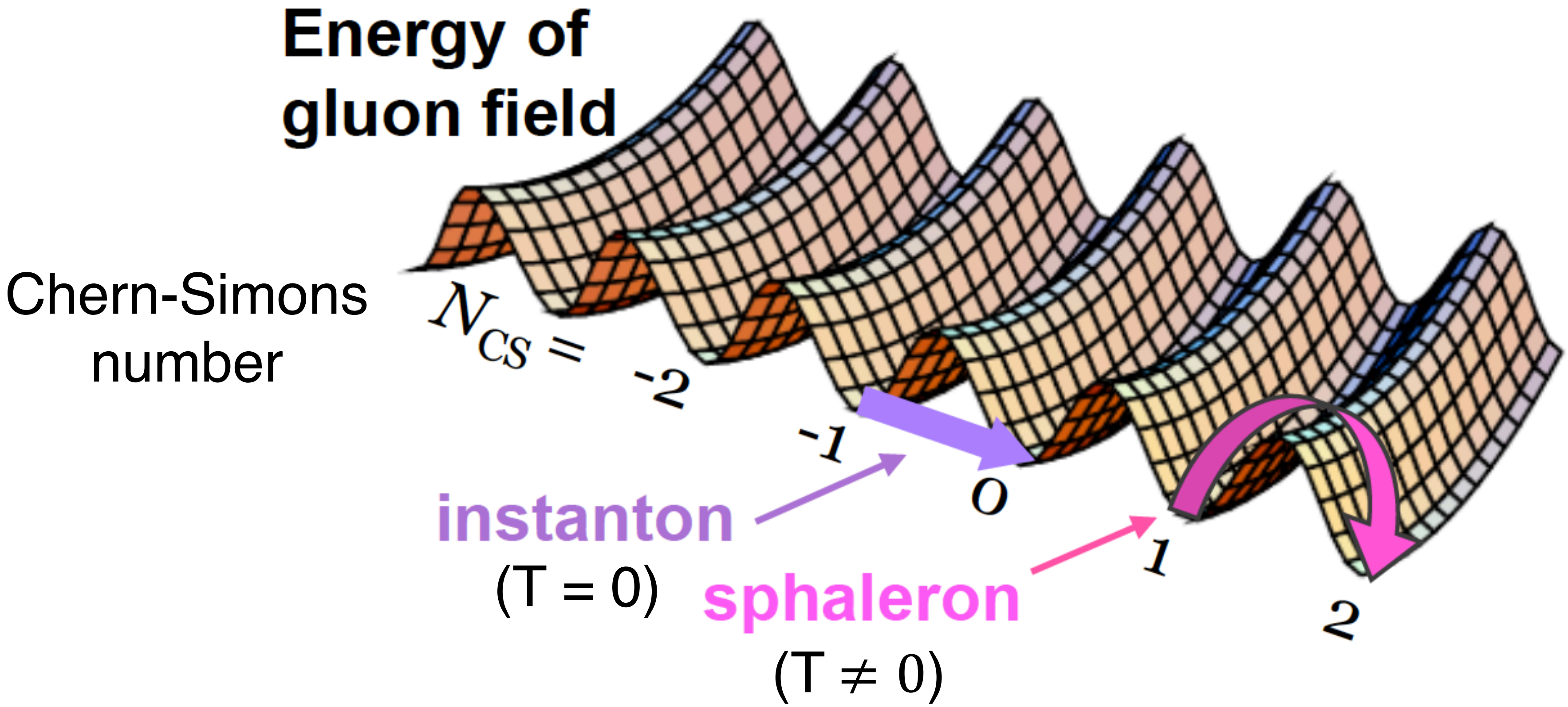
account for 99% of the hadron mass




Chiral symmetry expected to restored at high temperature (≳154 MeV from lattice),

➡ **quarks becomes nearly "massless" or "chiral"**

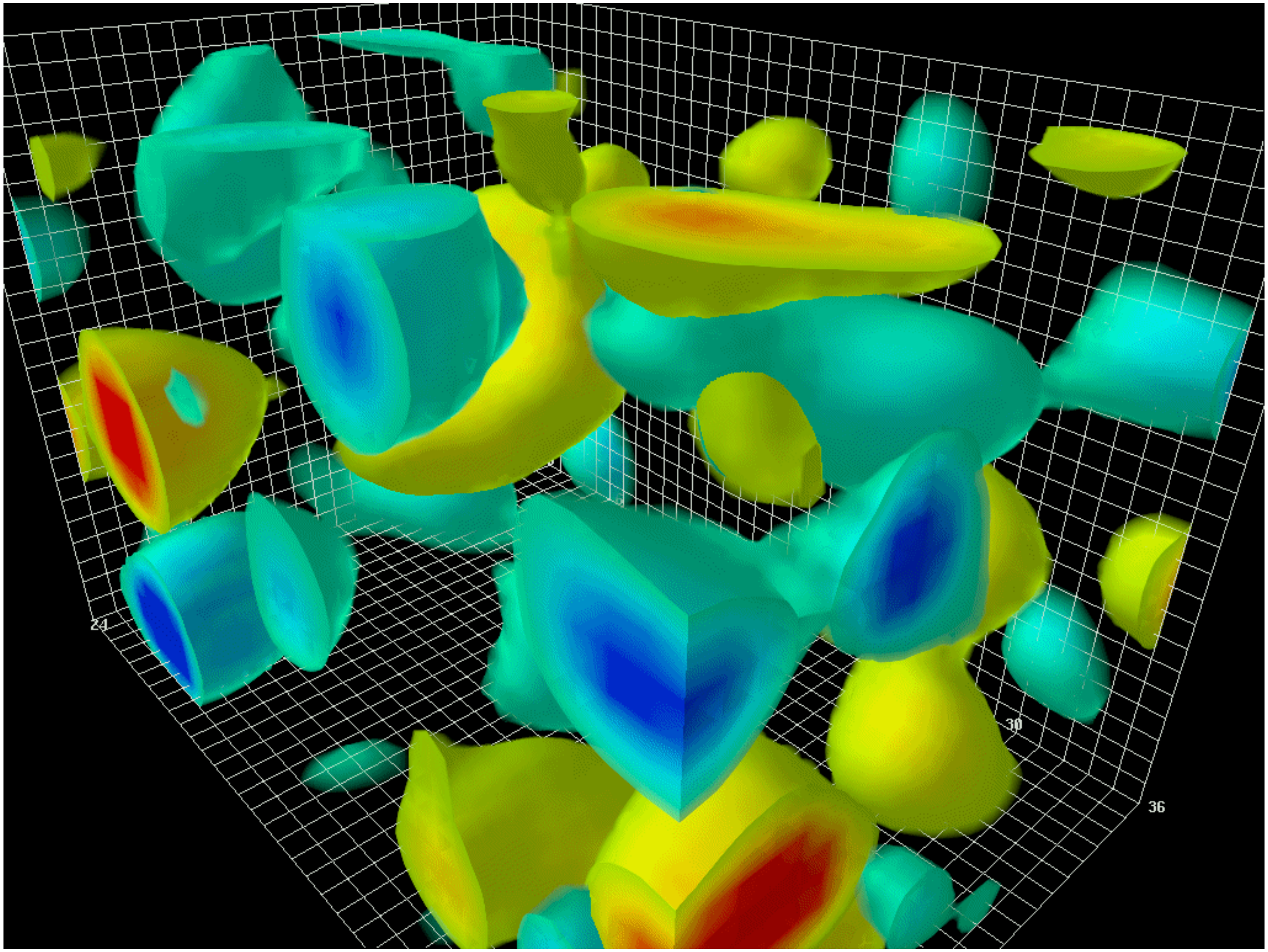
# Gauge field and topological charges




Topological charges (or winding number):

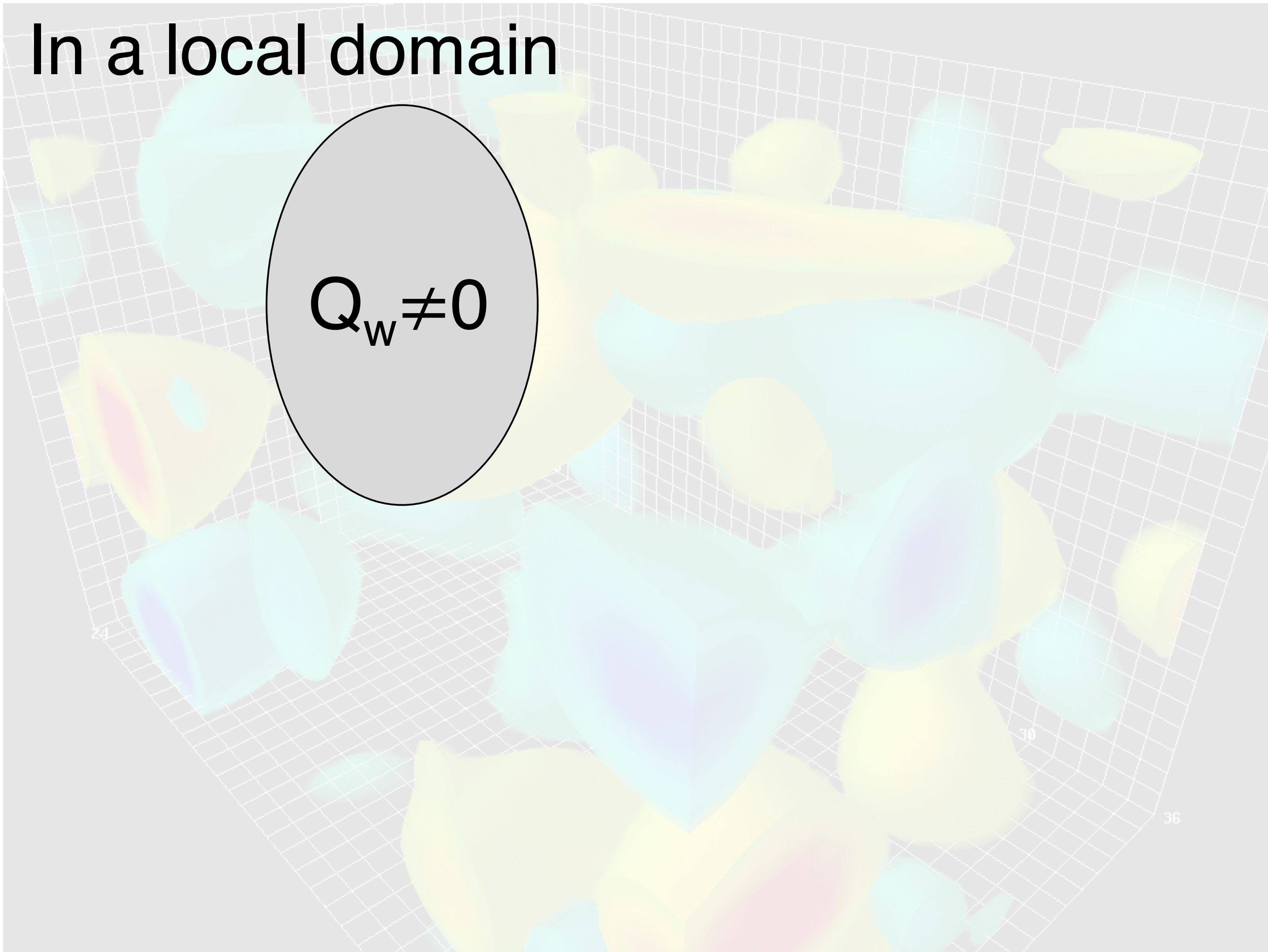
$$Q_w \sim \boldsymbol{E}^a \cdot \boldsymbol{B}^a$$ **– parity violating!**

# Topological charge fluctuations in QCD vacuum



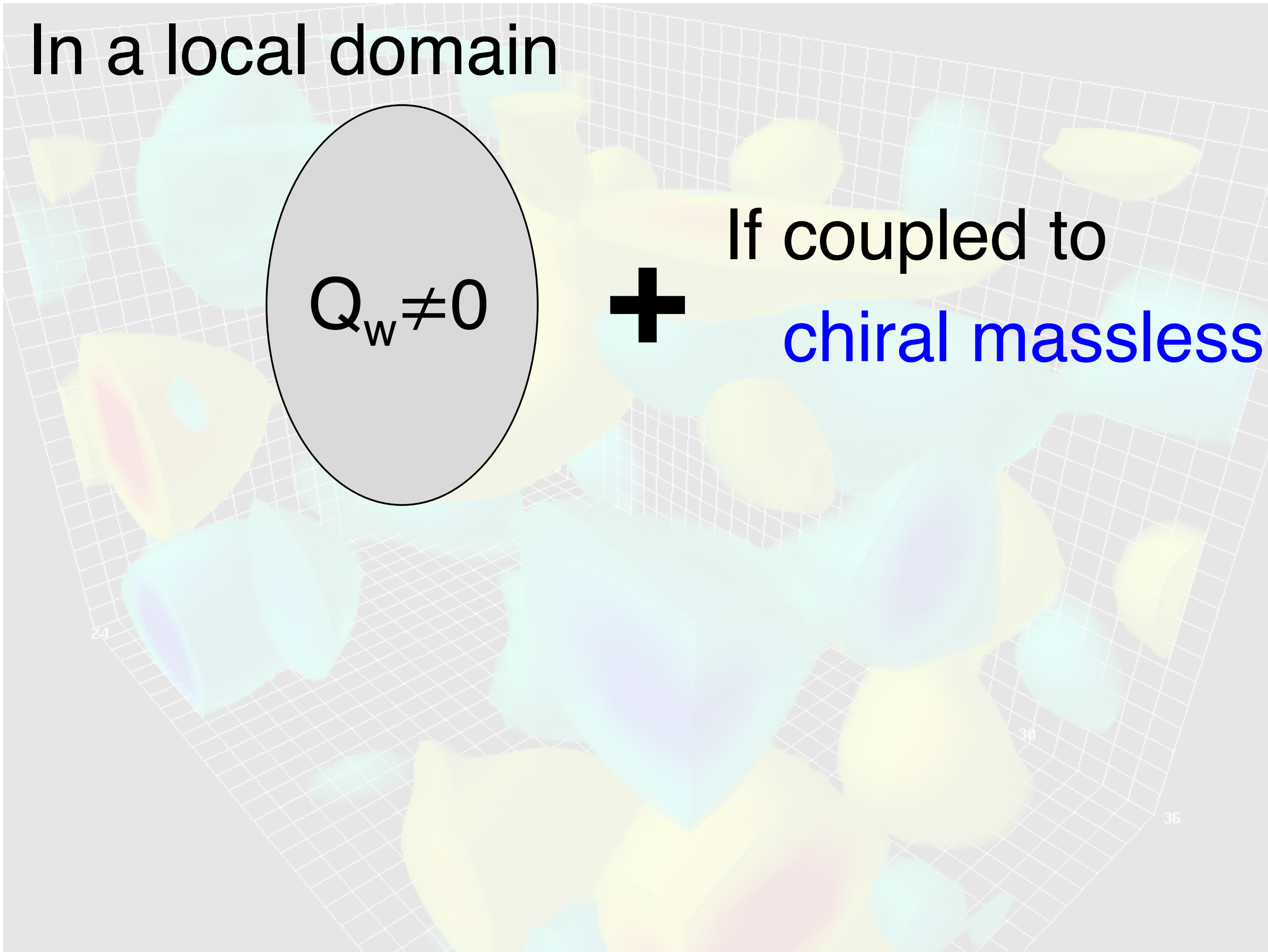

Lattice simulation from D Leinweber, Univ. of Adelaide

# Topological charge fluctuations in QCD vacuum




Lattice simulation from D Leinweber, Univ. of Adelaide

# Topological charge fluctuations in QCD vacuum

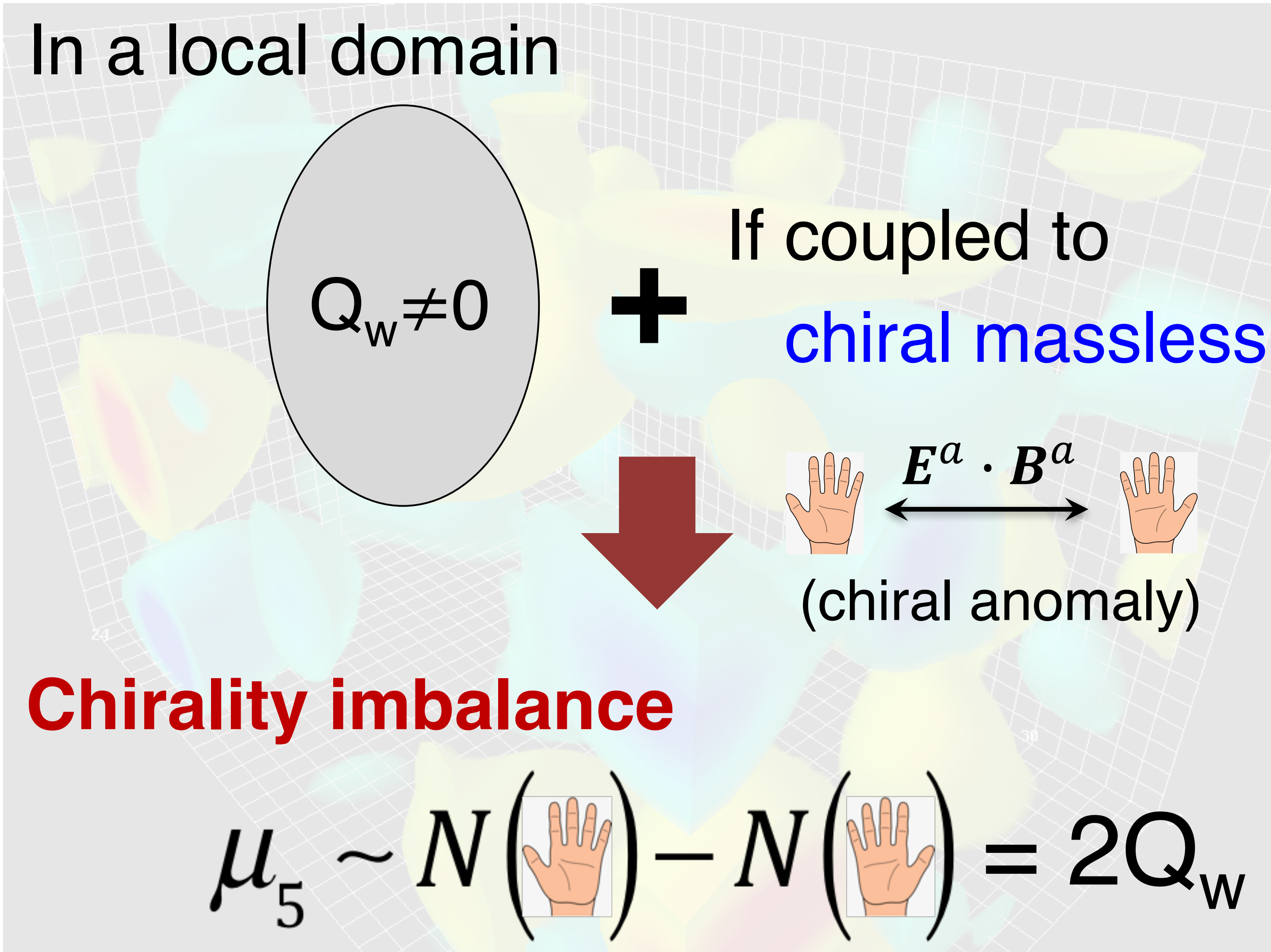


In a local domain

$Q_w \neq 0$ **+** If coupled to chiral massless quarks

Lattice simulation from D Leinweber, Univ. of Adelaide

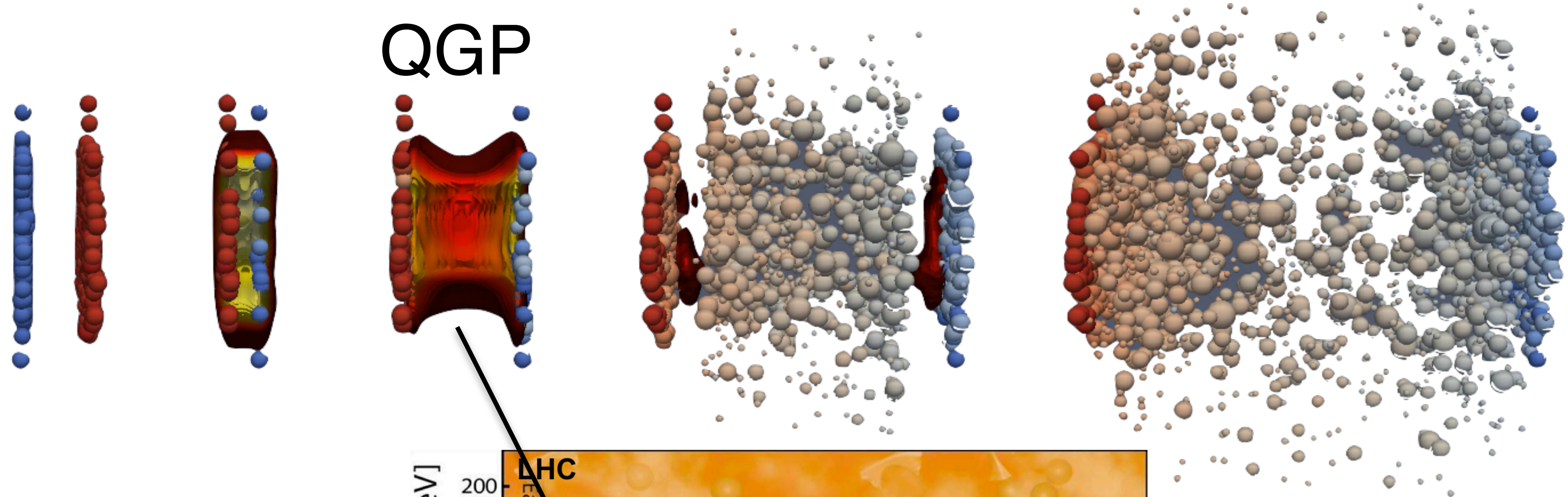
# Topological charge fluctuations in QCD vacuum

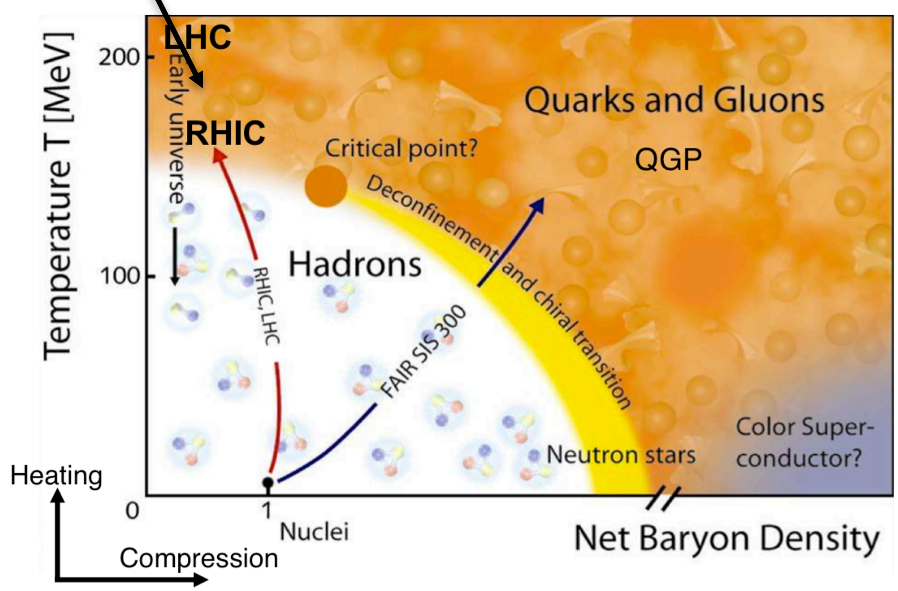



Lattice simulation from D Leinweber, Univ. of Adelaide

Electroweak sphalerons ➡ cosmo baryon asymmetry

# Relativistic nuclear collisions

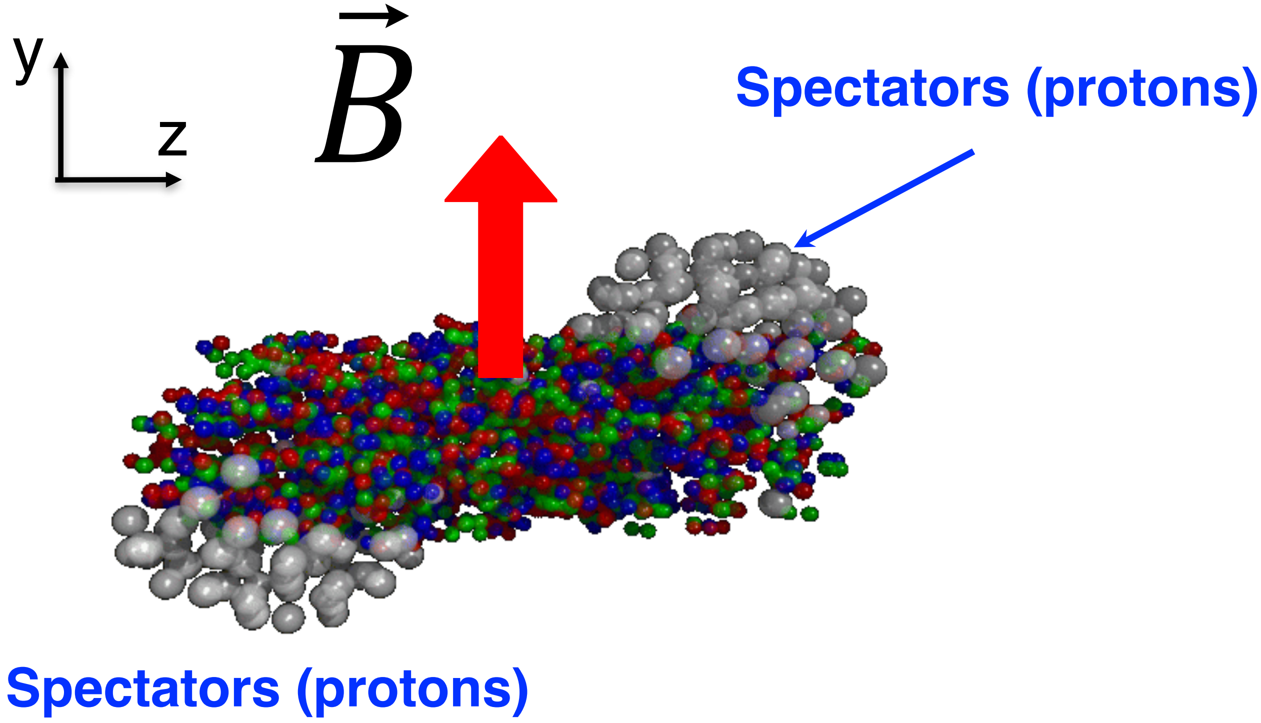


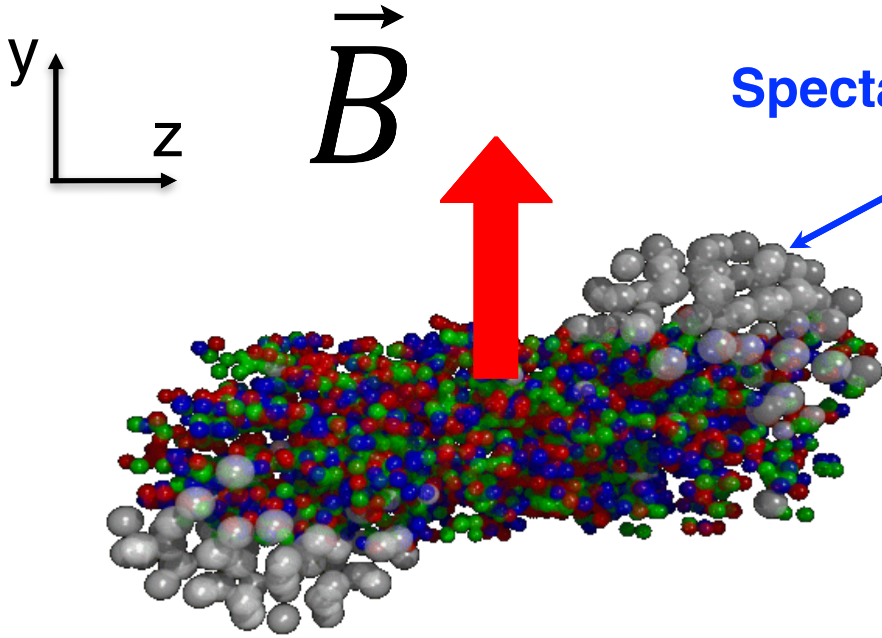

Domains of imbalanced left- and right-handed quarks speculated to form in the hot QGP fluid

Morley & Schmidt (1985) and Kharzeev, Pisarski & Tytgat (1998)

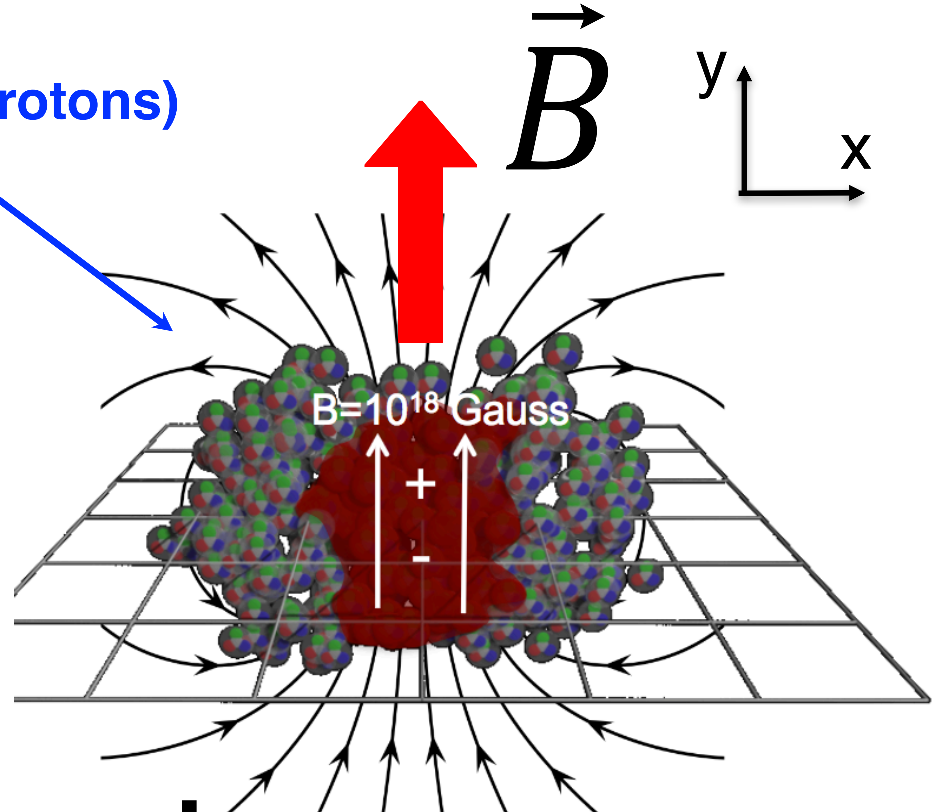
# External magnetic field



# External magnetic field




Spectators (protons)




Spectators (protons)

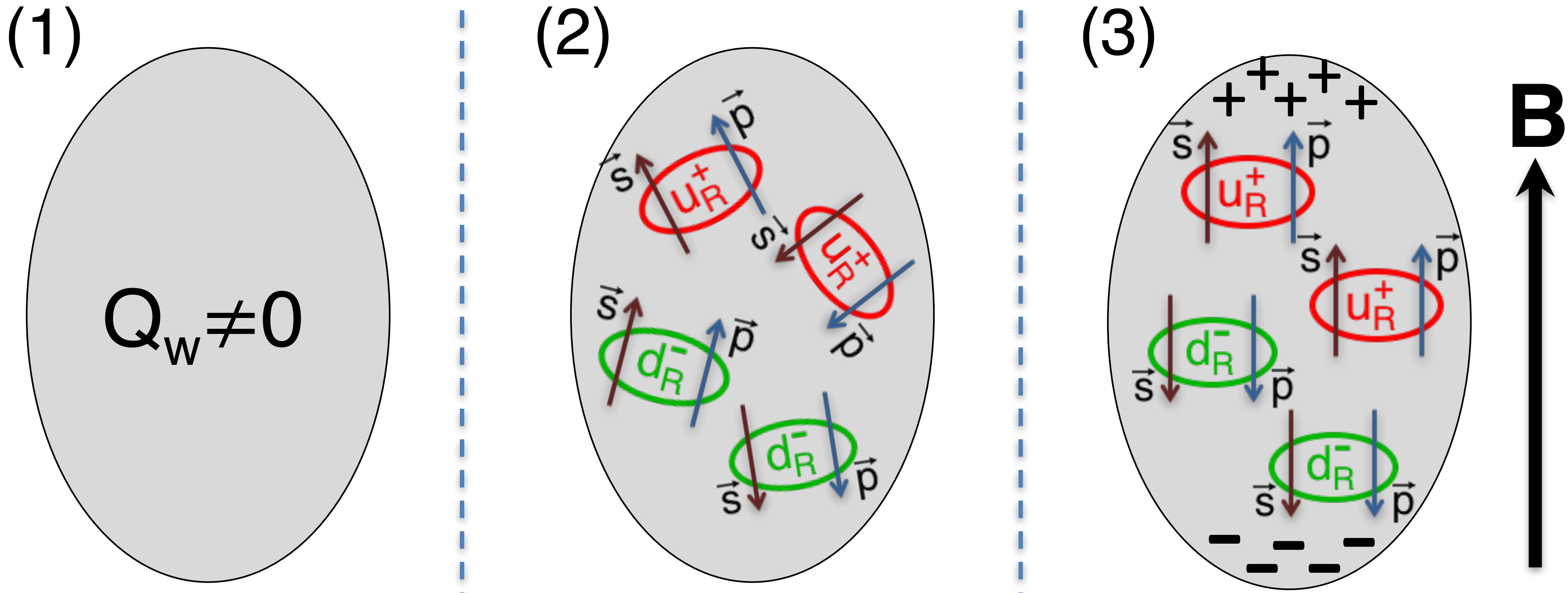
**B ~ $10^{18}$ Gauss!**

Strongest magnetic field achieved in the lab

*highly time-dependent, and short-lived*

~ $(\Lambda_{QCD})^2$ – observable effect in QCD

# The Chiral Magnetic Effect

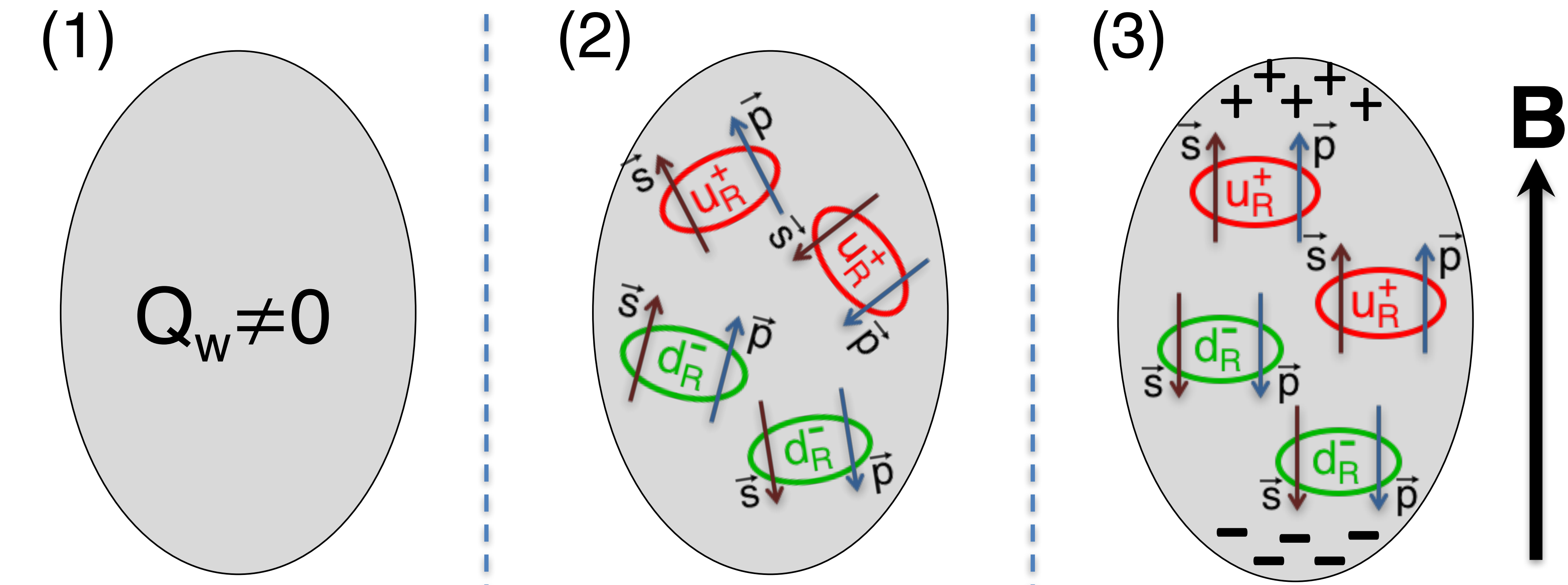



Topological charges

Chirality imbalance
($\mu_5 \neq 0$)

Electric current

# The Chiral Magnetic Effect




Topological charges

Chirality imbalance ($\mu_5 \neq 0$)

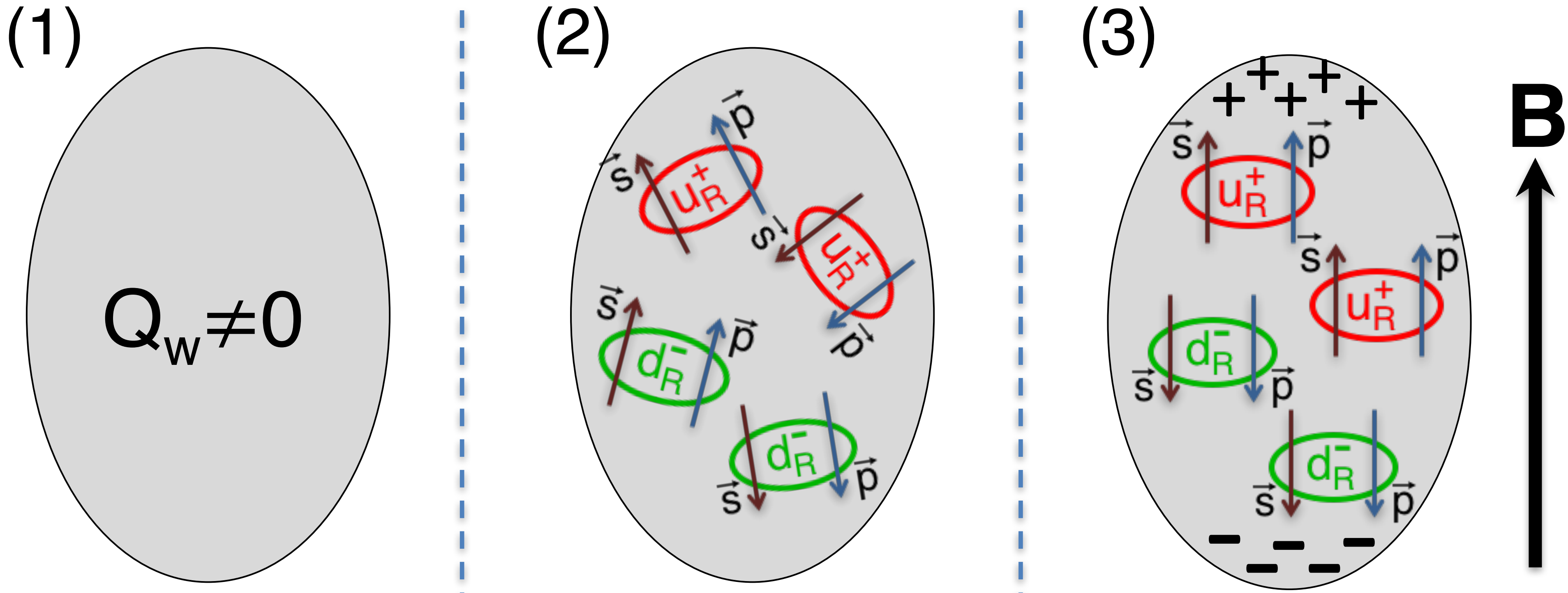
Electric current

**CME:** an electric current induced by ***B field***

$$\vec{J} = \sigma_5 \vec{B} = \left( \frac{(Qe)^2}{2\pi^2} \mu_5 \right) \vec{B}$$ → **Charge separation**

Kharzeev, McLerran, Warringa, NPA 803 (2008) 227

# The Chiral Magnetic Effect




Topological charges

Chirality imbalance
($\mu_5 \neq 0$)

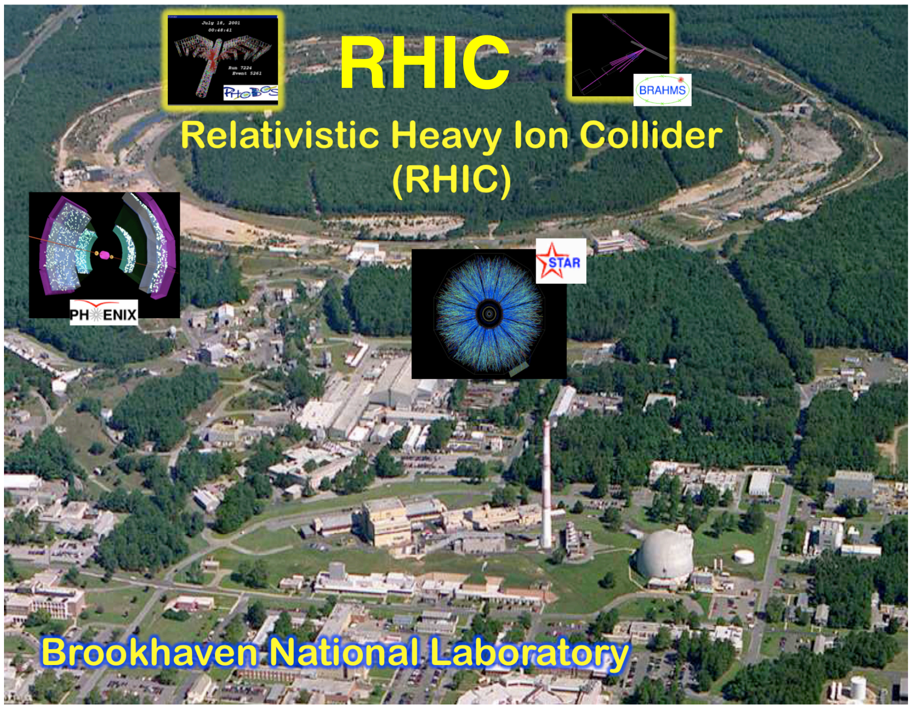
Electric current

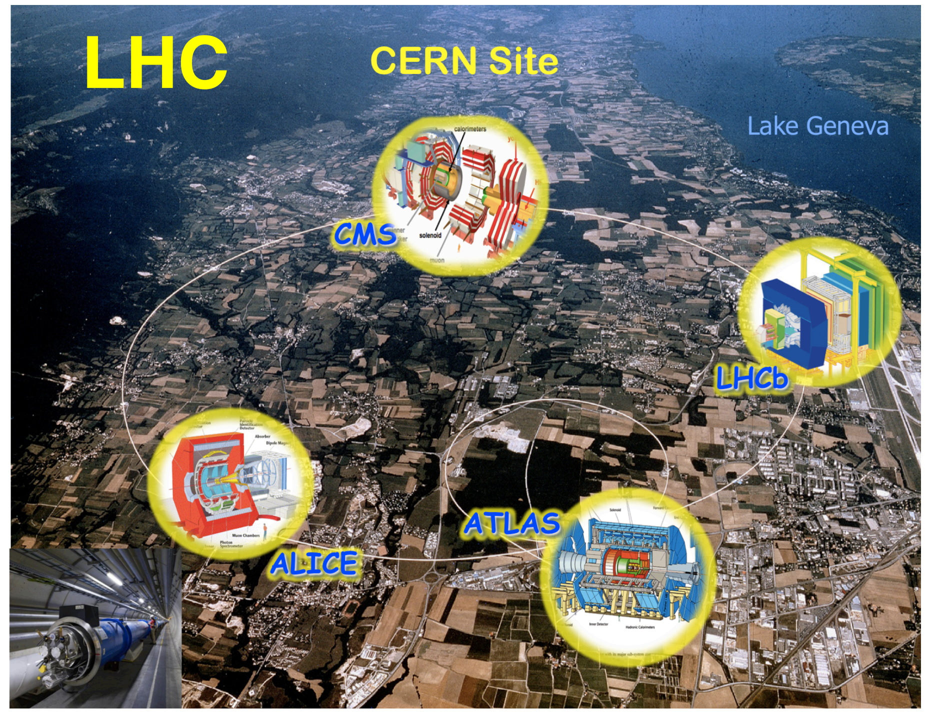
**CME:** an electric current induced by ***B field***

$$\vec{J} = \sigma_5 \vec{B} = \left( \frac{(Qe)^2}{2\pi^2} \mu_5 \right) \vec{B}$$ → **Charge separation**

Kharzeev, McLerran, Warringa, NPA 803 (2008) 227

# Experimental search for the CME in nuclear collisions




2000 –

- pAu, dAu, $He^3$Au, CuCu, AuAu, UU
- $\sqrt{s_{NN}}$ ~ **0.008 – 0.2 TeV**

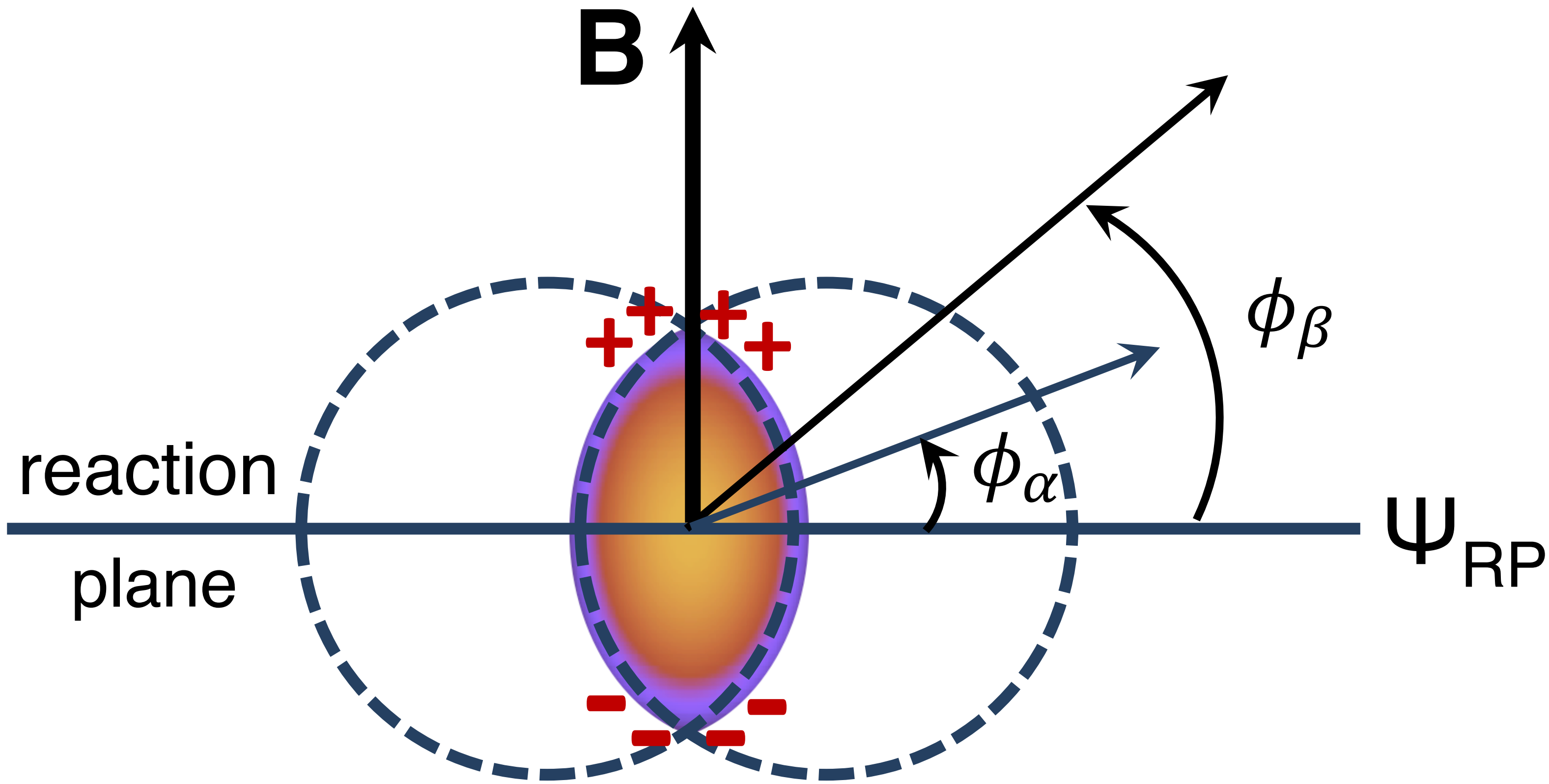
2010 –

- pPb, PbPb
- $\sqrt{s_{NN}}$ ~ **2.76 – 8 TeV**

# How to measure the CME in AA?

$$\gamma^{(\pm,\pm)} \equiv \left\langle \cos\left(\phi_\alpha^{\pm} + \phi_\beta^{\pm} - 2\Psi_{RP}\right)\right\rangle$$

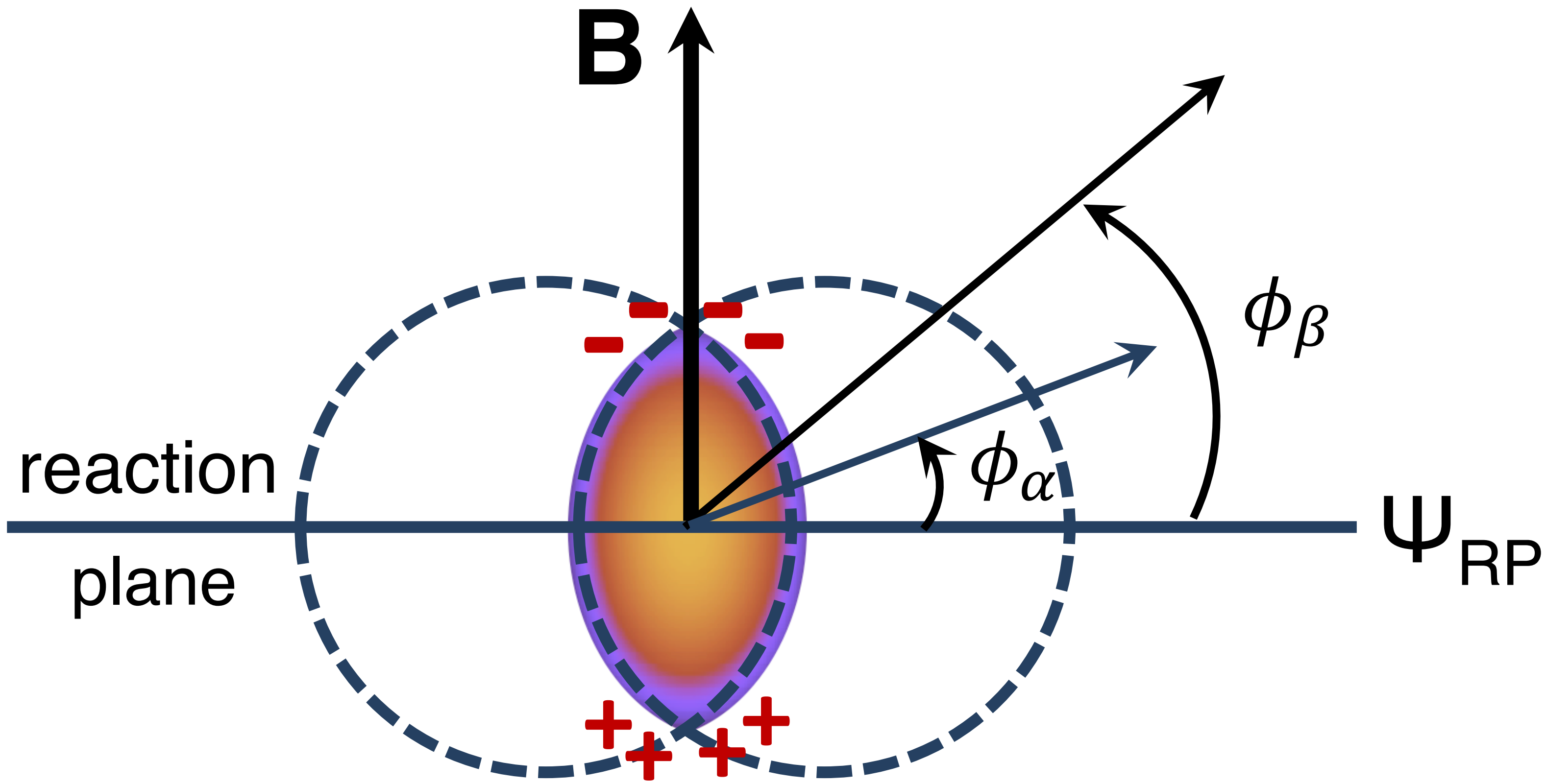
(Voloshin, arXiv:hep-ph/0406311)



# How to measure the CME in AA?

$$\gamma^{(\pm,\pm)} \equiv \left\langle \cos\left(\phi_\alpha^\pm + \phi_\beta^\pm - 2\Psi_{RP}\right)\right\rangle$$

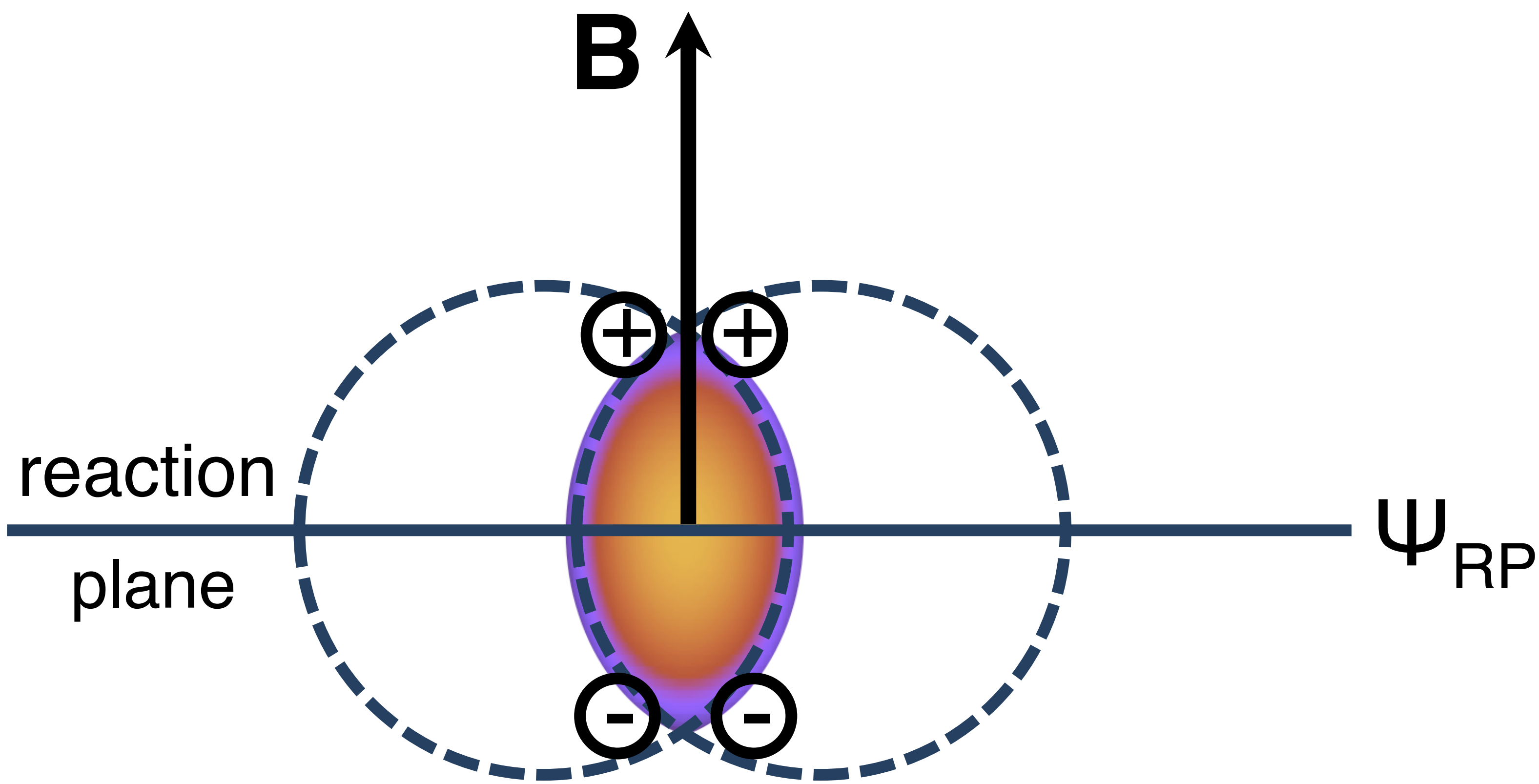
(Voloshin, arXiv:hep-ph/0406311)



# How to measure the CME in AA?

$$\gamma^{(\pm,\pm)} \equiv \langle \cos(\phi_\alpha^\pm + \phi_\beta^\pm - 2\Psi_{RP}) \rangle$$

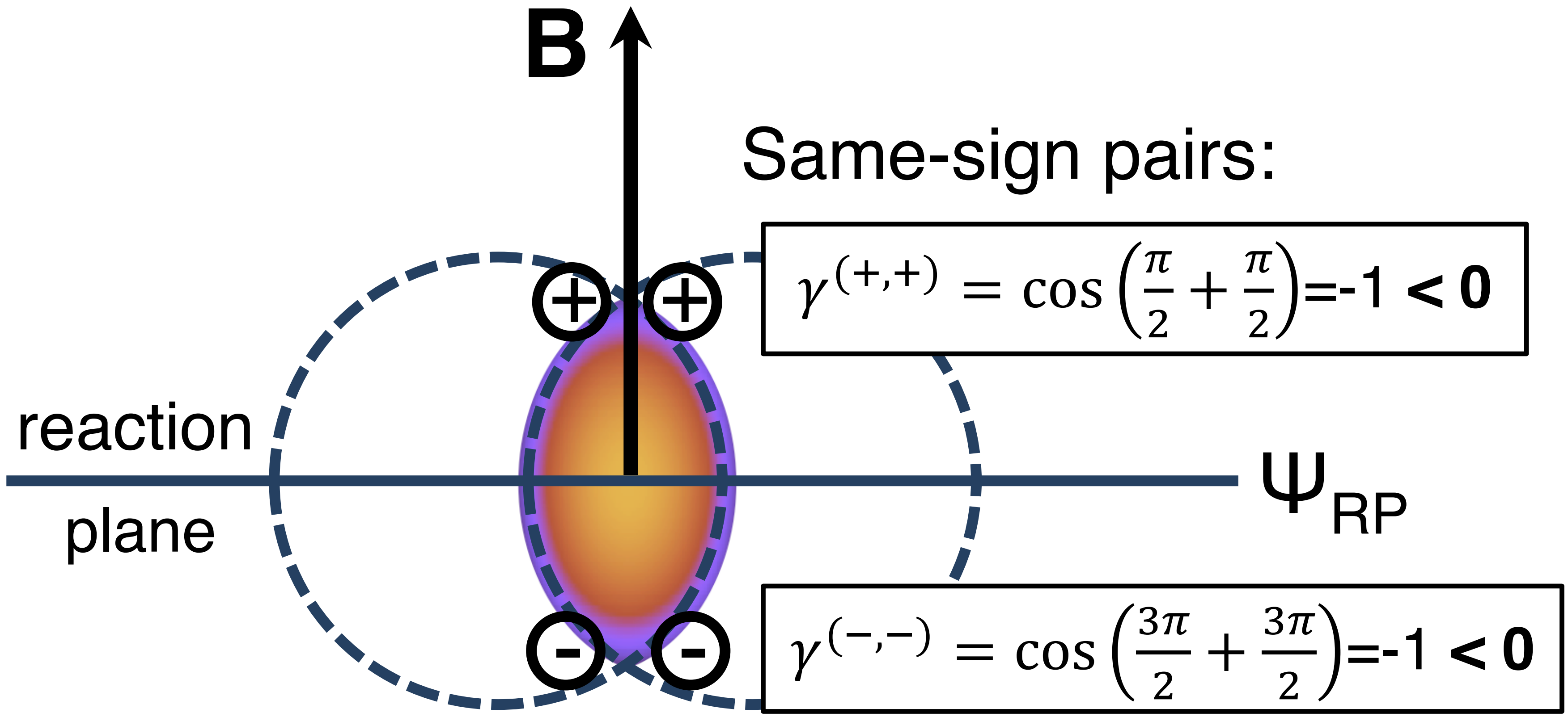
(Voloshin, arXiv:hep-ph/0406311)



# How to measure the CME in AA?

$$\gamma^{(\pm,\pm)} \equiv \langle \cos(\phi_\alpha^\pm + \phi_\beta^\pm - 2\Psi_{RP}) \rangle$$

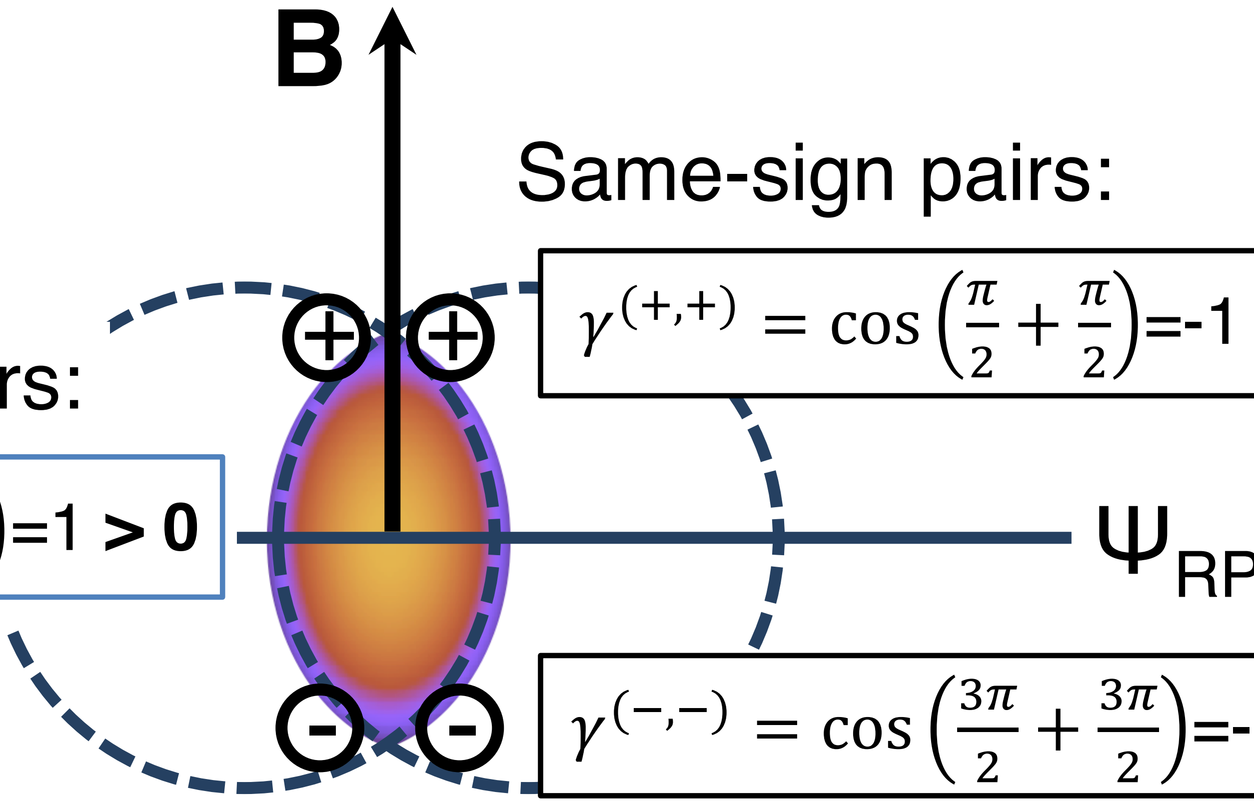
(Voloshin, arXiv:hep-ph/0406311)



# How to measure the CME in AA?

$$\gamma^{(\pm,\pm)} \equiv \langle \cos(\phi_\alpha^\pm + \phi_\beta^\pm - 2\Psi_{RP}) \rangle$$

(Voloshin, arXiv:hep-ph/0406311)




Same-sign pairs:

$\gamma^{(+,+)} = \cos\left(\frac{\pi}{2} + \frac{\pi}{2}\right)$=-1 **< 0**

$\gamma^{(-,-)} = \cos\left(\frac{3\pi}{2} + \frac{3\pi}{2}\right)$=-1 **< 0**

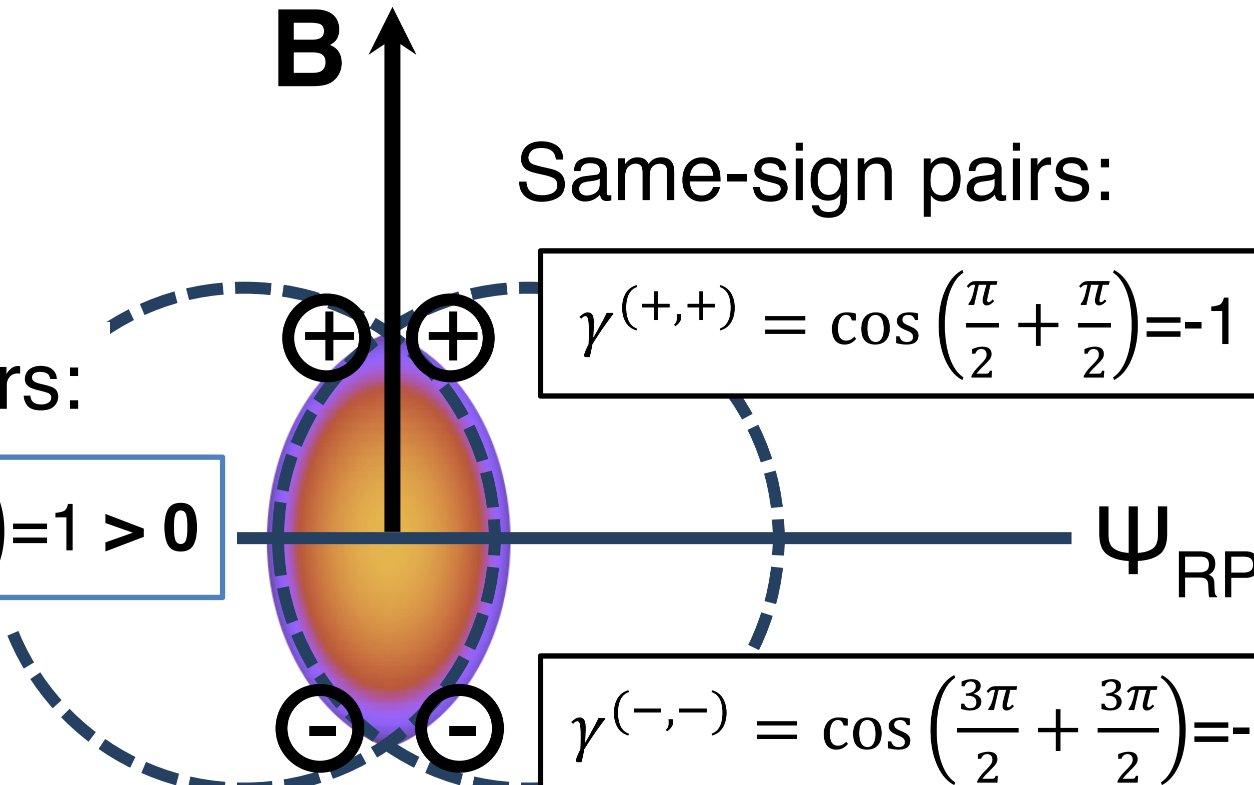
Opposite-sign pairs:

$\gamma^{(+,-)} = \cos\left(\frac{\pi}{2} + \frac{3\pi}{2}\right)$=1 **> 0**

# How to measure the CME in AA?

$$\gamma^{(\pm,\pm)} \equiv \left\langle \cos\left(\phi_\alpha^\pm + \phi_\beta^\pm - 2\Psi_{RP}\right)\right\rangle$$

(Voloshin, arXiv:hep-ph/0406311)




Same-sign pairs:

$\gamma^{(+,+)} = \cos\left(\frac{\pi}{2} + \frac{\pi}{2}\right)$**=-1 < 0**

$\gamma^{(-,-)} = \cos\left(\frac{3\pi}{2} + \frac{3\pi}{2}\right)$**=-1 < 0**

Opposite-sign pairs:

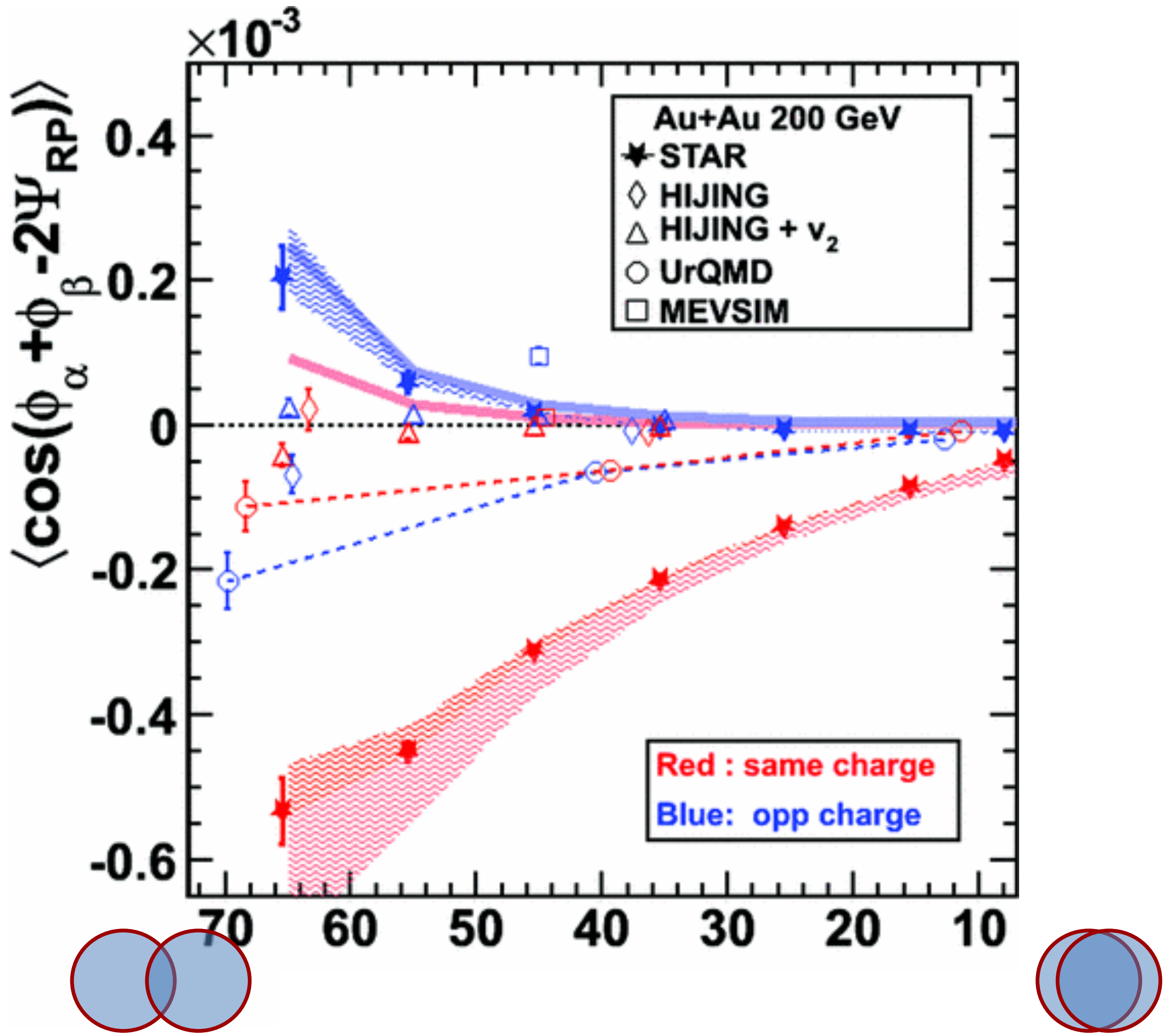
$\gamma^{(+,-)} = \cos\left(\frac{\pi}{2} + \frac{3\pi}{2}\right)$**=1 > 0**

Difference: $\Delta\gamma \equiv 2\gamma^{(+,-)} - \gamma^{(+,+)} - \gamma^{(-,-)} > 0$

Selected for a Viewpoint in *Physics*
PRL **103,** 251601 (2009) PHYSICAL REVIEW LETTERS week ending 18 DECEMBER 2009

# Azimuthal Charged-Particle Correlations and Possible Local Strong Parity Violation

(STAR Collaboration) (RHIC)



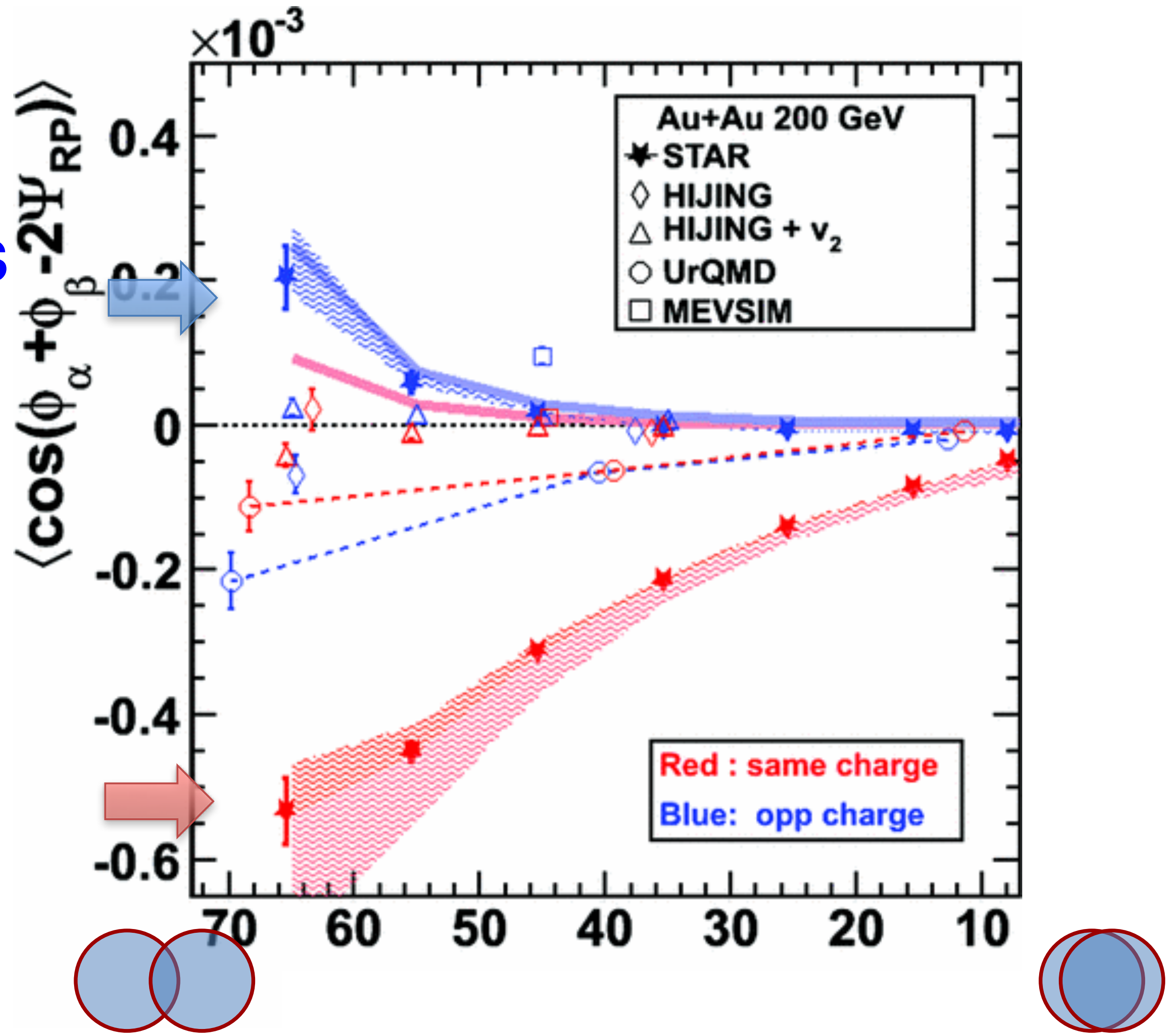
PRL 103, 251601 (2009) | Selected for a Viewpoint in *Physics* PHYSICAL REVIEW LETTERS | week ending 18 DECEMBER 2009

# Azimuthal Charged-Particle Correlations and Possible Local Strong Parity Violation

(STAR Collaboration) (RHIC)

Opposite-sign pairs
(OS, +-/-+)

Same-sign pairs
(SS, ++/--)



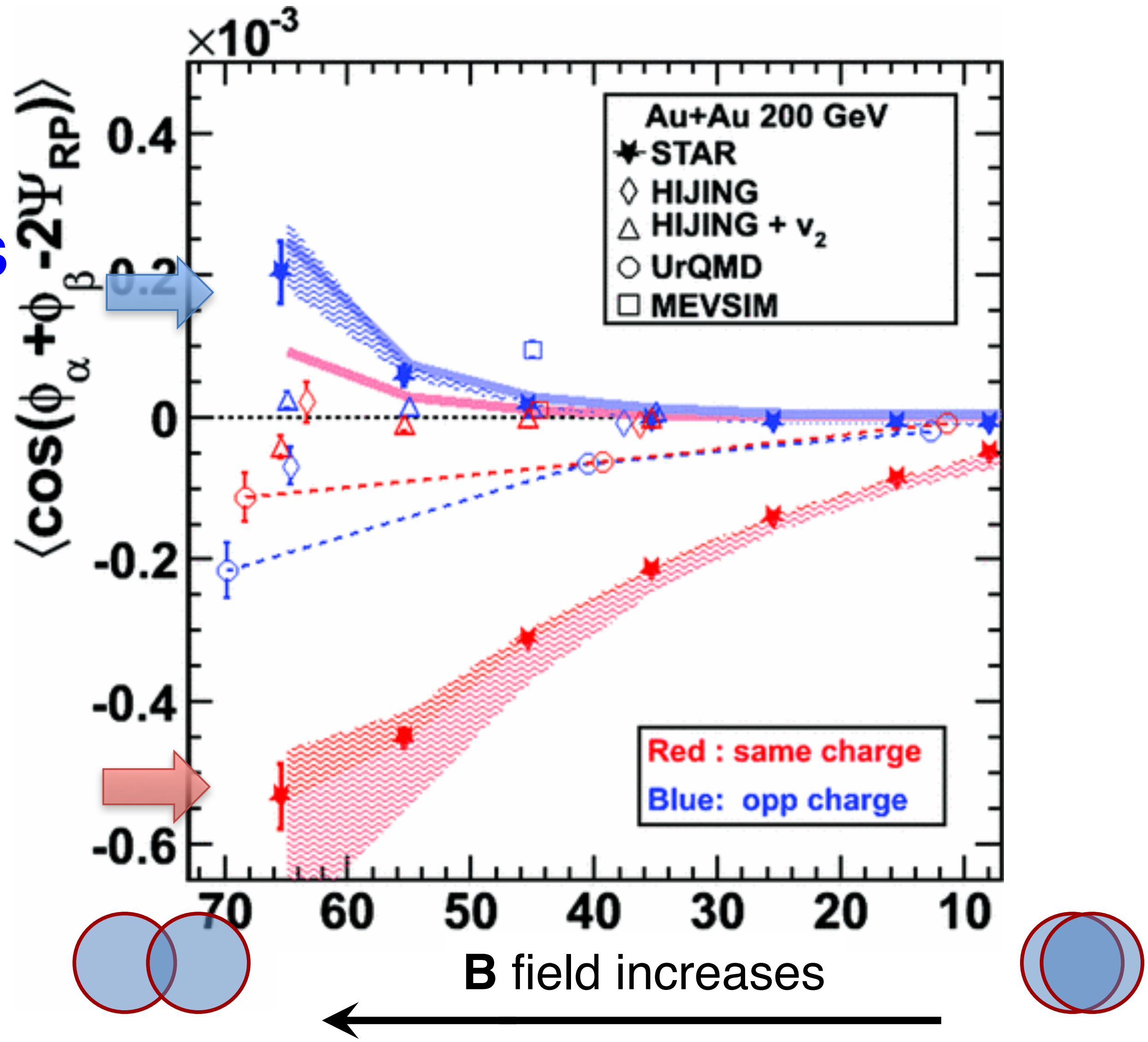
Selected for a Viewpoint in *Physics*
PRL **103**, 251601 (2009) PHYSICAL REVIEW LETTERS week ending 18 DECEMBER 2009

# Azimuthal Charged-Particle Correlations and Possible Local Strong Parity Violation

(STAR Collaboration) (RHIC)

Opposite-sign pairs
(OS, +-/-+)

Same-sign pairs
(SS, ++/--)



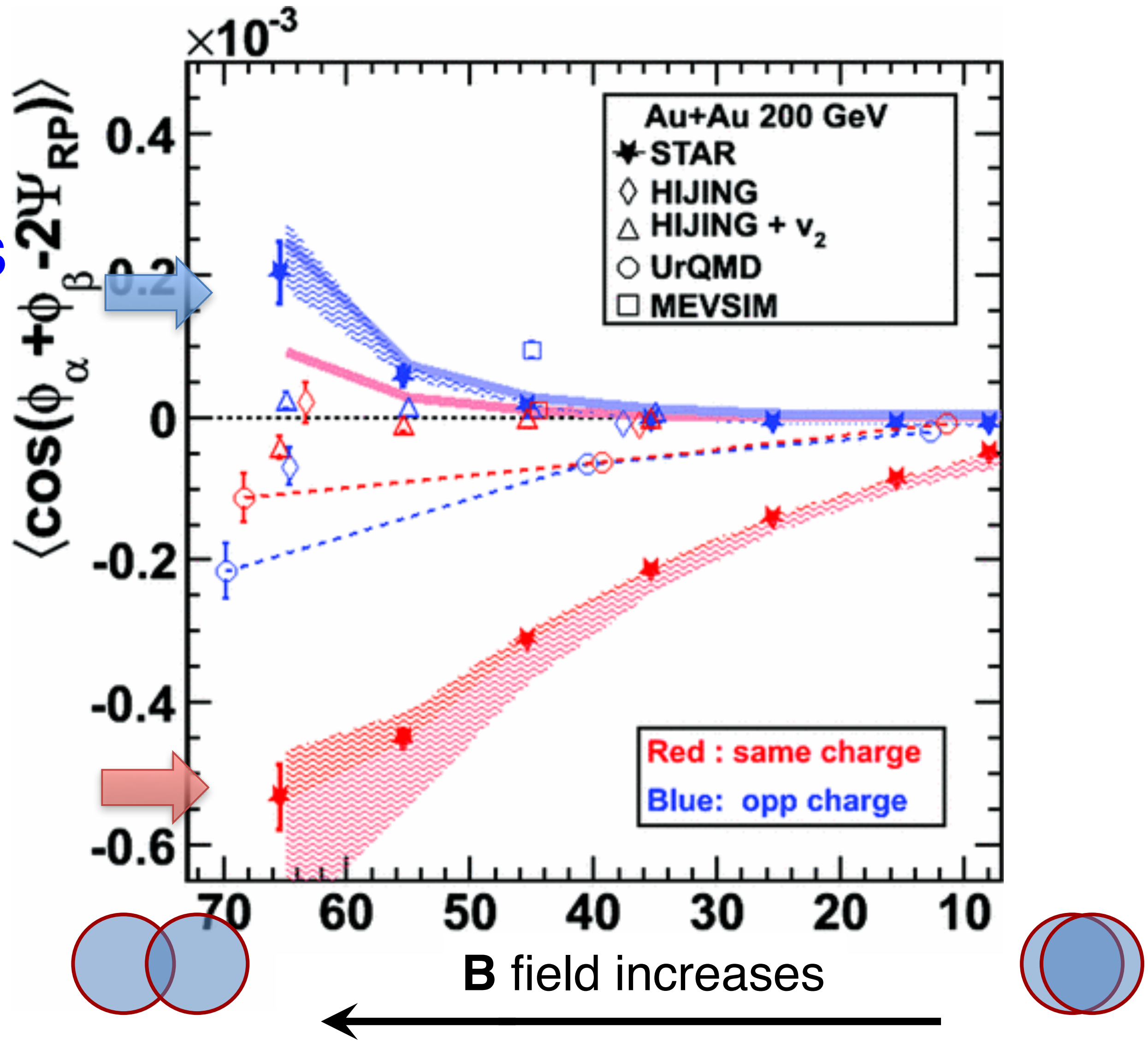
PRL 103, 251601 (2009) | Selected for a Viewpoint in *Physics* PHYSICAL REVIEW LETTERS | week ending 18 DECEMBER 2009

**Azimuthal Charged-Particle Correlations and Possible Local Strong Parity Violation**

(STAR Collaboration) (RHIC)

Opposite-sign pairs (OS, +-/-+)

Same-sign pairs (SS, ++/--)

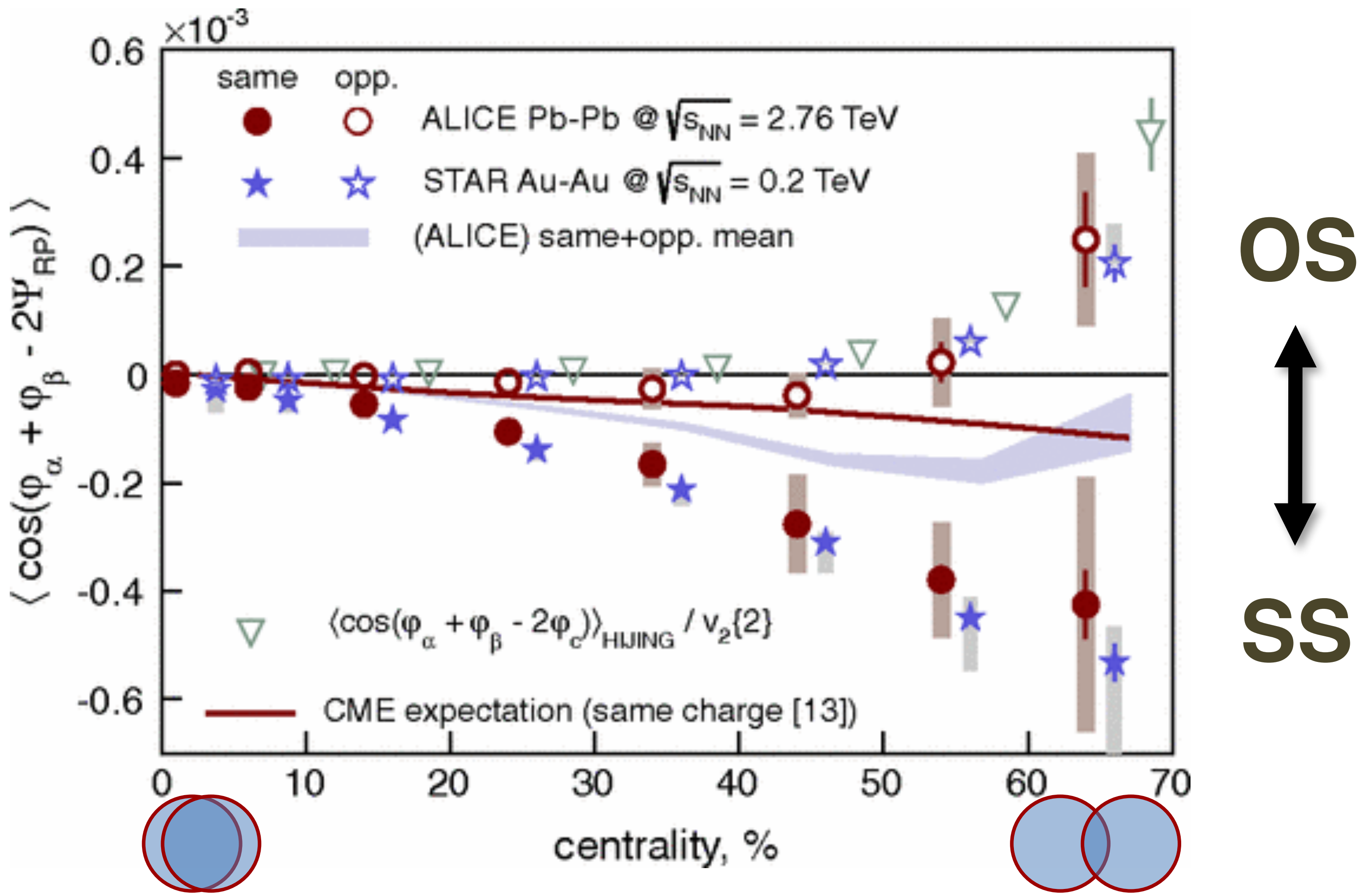



**Charge separation from the CME!?**

PRL 110, 012301 (2013) PHYSICAL REVIEW LETTERS week ending 4 JANUARY 2013

# Charge separation relative to the reaction plane in Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV

(ALICE Collaboration) (LHC)




**CME signal comparable at 0.2 TeV vs 2.76 TeV!?**

# Extraordinary Discovery Requires Extraordinary Evidence

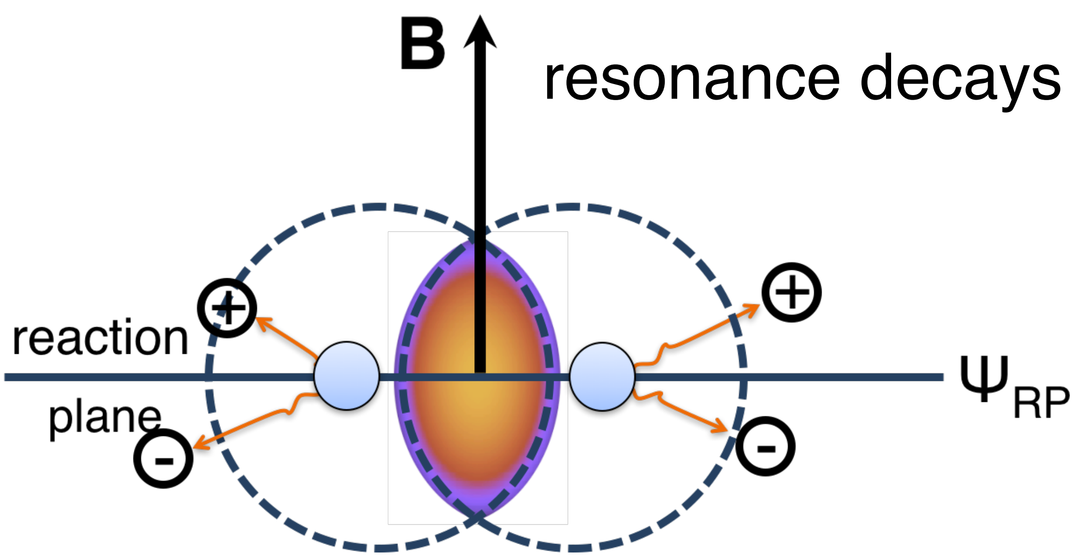
*There are backgrounds!*

$\Delta\gamma\ (\gamma^{os} - \gamma^{ss})$ = **SIGNAL** + **BKG**

# Extraordinary Discovery Requires Extraordinary Evidence

*There are backgrounds!*

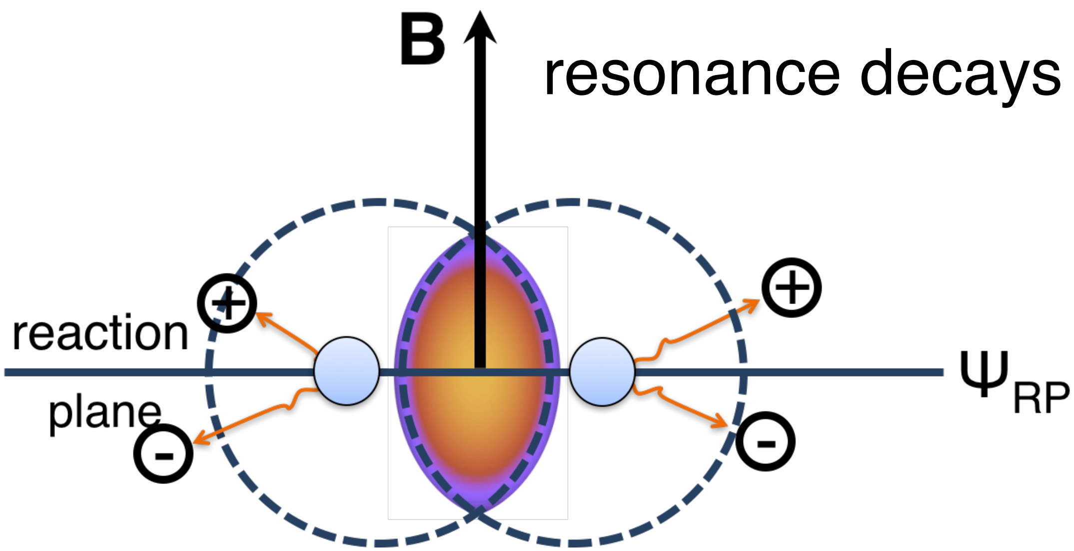
$$\Delta\gamma\ (\gamma^{os} - \gamma^{ss}) = \text{SIGNAL} + \text{BKG}$$

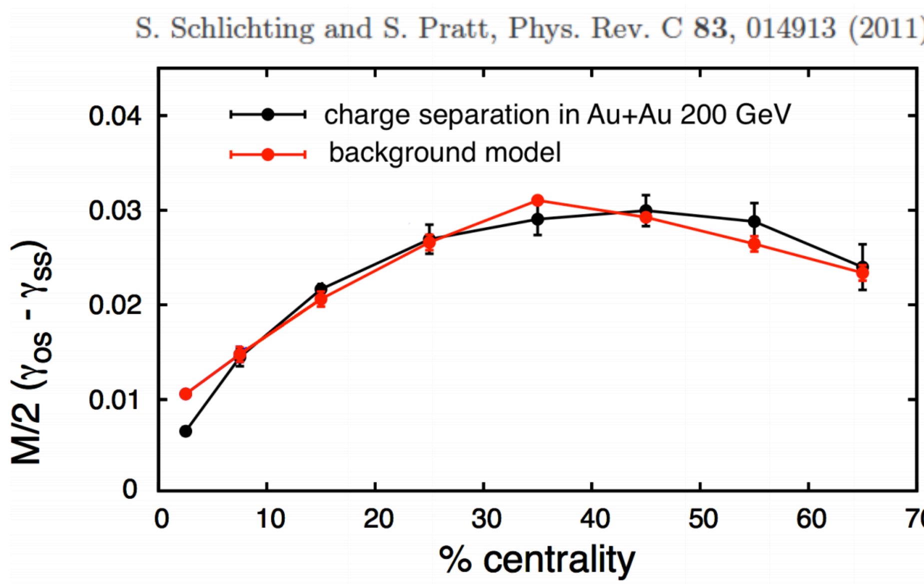


# Extraordinary Discovery Requires Extraordinary Evidence

*There are backgrounds!*

$\Delta\gamma\ (\gamma^{os} - \gamma^{ss}) =$ SIGNAL + **BKG**




**Local charge conservation (LCC) + elliptic flow ($v_2$)**
can describe the charge-dependent correlations

# Extraordinary Discovery Requires Extraordinary Evidence

*There are backgrounds!*

$$\Delta\gamma\ (\gamma^{os} - \gamma^{ss}) = \boxed{\textbf{SIGNAL}} + \boxed{\textbf{BKG}}$$

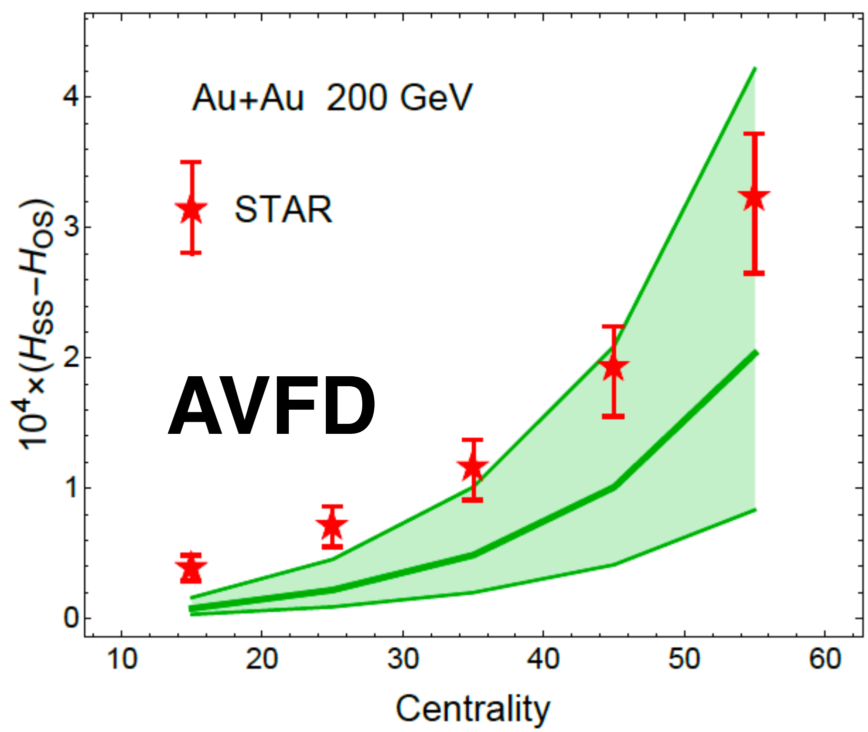
Large uncertainties in predicting the CME signal

*Lifetime of B field*

*Chiral quark formation time*

*Axial charge ($\mu_5$) diffusion*

*…*




J. Liao et al, arXiv:1711.02496

# Extraordinary Discovery Requires Extraordinary Evidence

*There are backgrounds!*

$\Delta\gamma$ $(\gamma^{os} - \gamma^{ss})$ = **SIGNAL** + **BKG**

Can we rule out the null hypothesis:

*$\Delta\gamma$ data 100% consistent with the BKG?*

in **data-driven** approach

# Extraordinary Discovery Requires Extraordinary Evidence

*There are backgrounds!*

$\Delta\gamma\ (\gamma^{os} - \gamma^{ss}) =$


$+$ **BKG**

Can we rule out the null hypothesis:

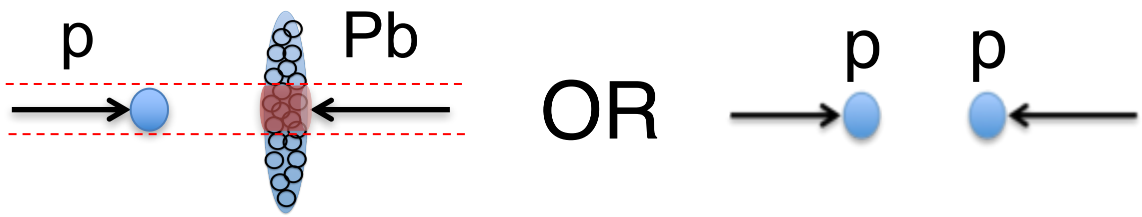
<u>*Δγ data 100% consistent with the BKG?*</u>

in **data-driven** approach

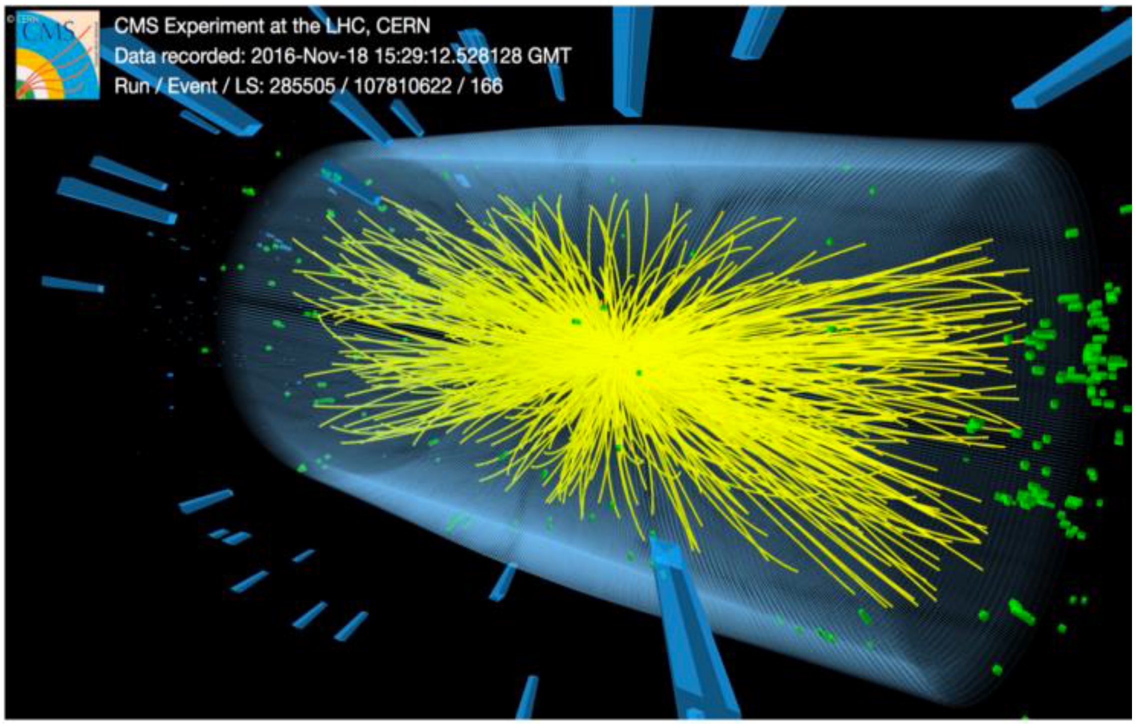
Any way to turn on/off signal in a control way?

- Compare $\Delta\gamma$ w and w/o the CME signal

# Surprises in small systems




In AA-like, rare high-multiplicity events,



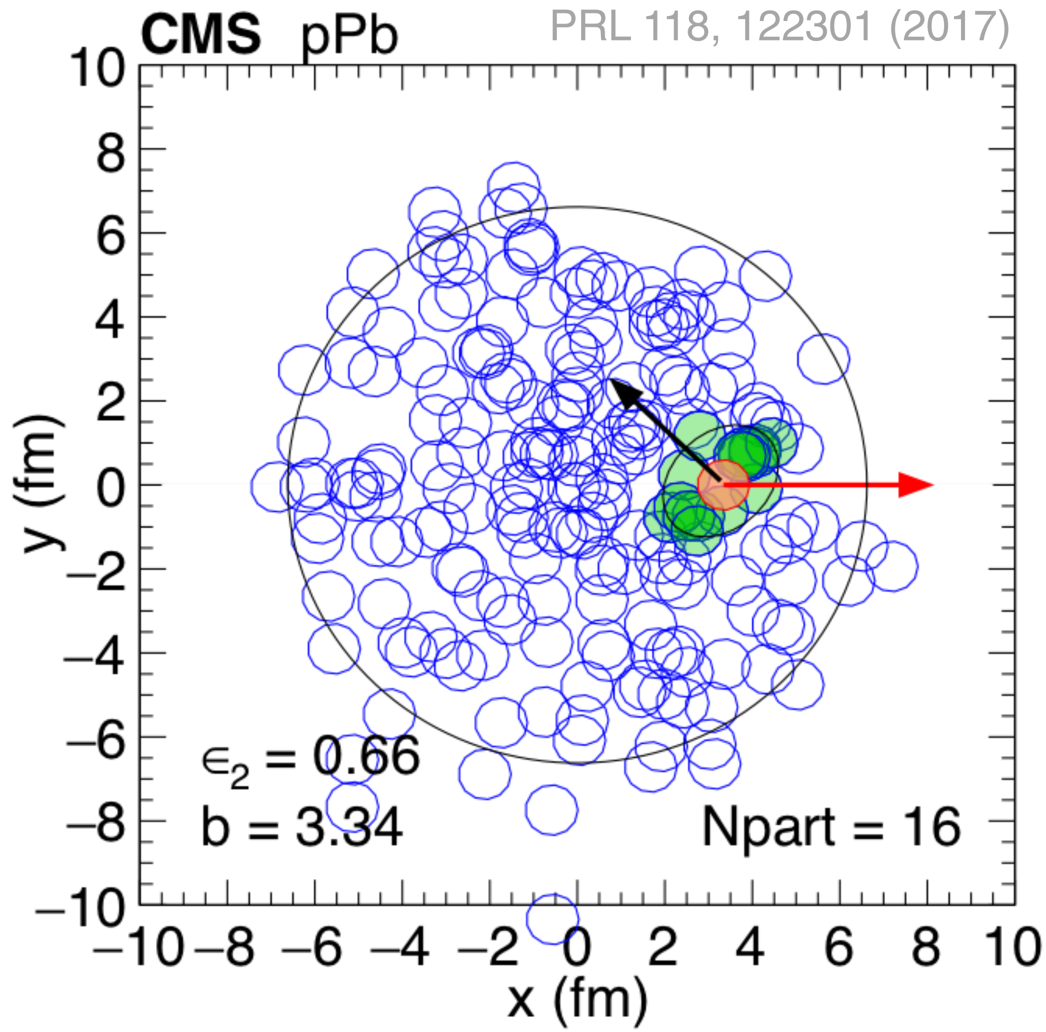

Signatures of QGP discovered (e.g., elliptic flow)!

(see a review: K. Dusling, WL, B. Schenke, arXiv:1509.07939)

# Surprises in small systems

**Charge separation signal:** $\Delta\gamma \sim \left\langle B^2 \cos 2\left(\Psi_B - \Psi_{RP}\right)\right\rangle$

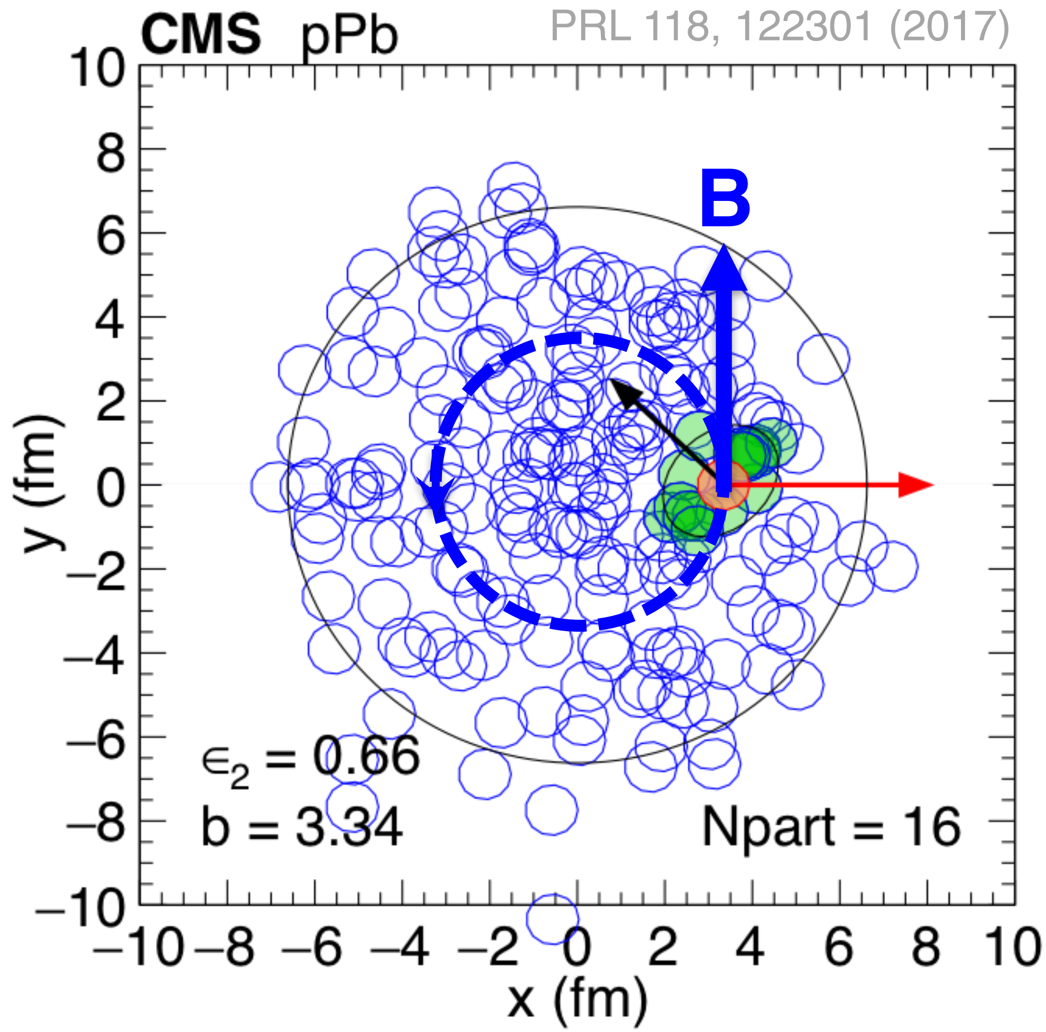
PRL 118, 122301 (2017)



# Surprises in small systems

**Charge separation signal:** $\Delta\gamma \sim \left\langle B^2 \cos 2\left(\Psi_B - \Psi_{RP}\right)\right\rangle$

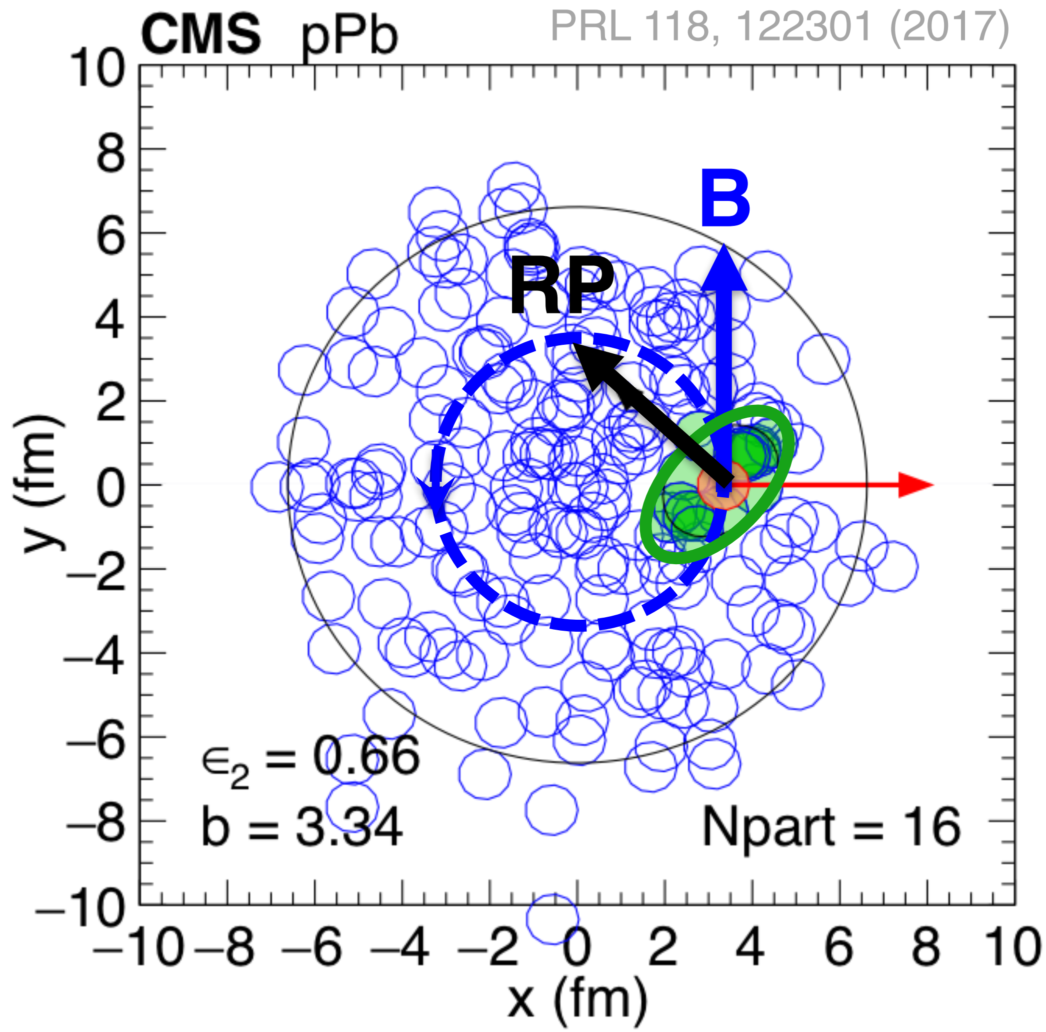
PRL 118, 122301 (2017)



# Surprises in small systems

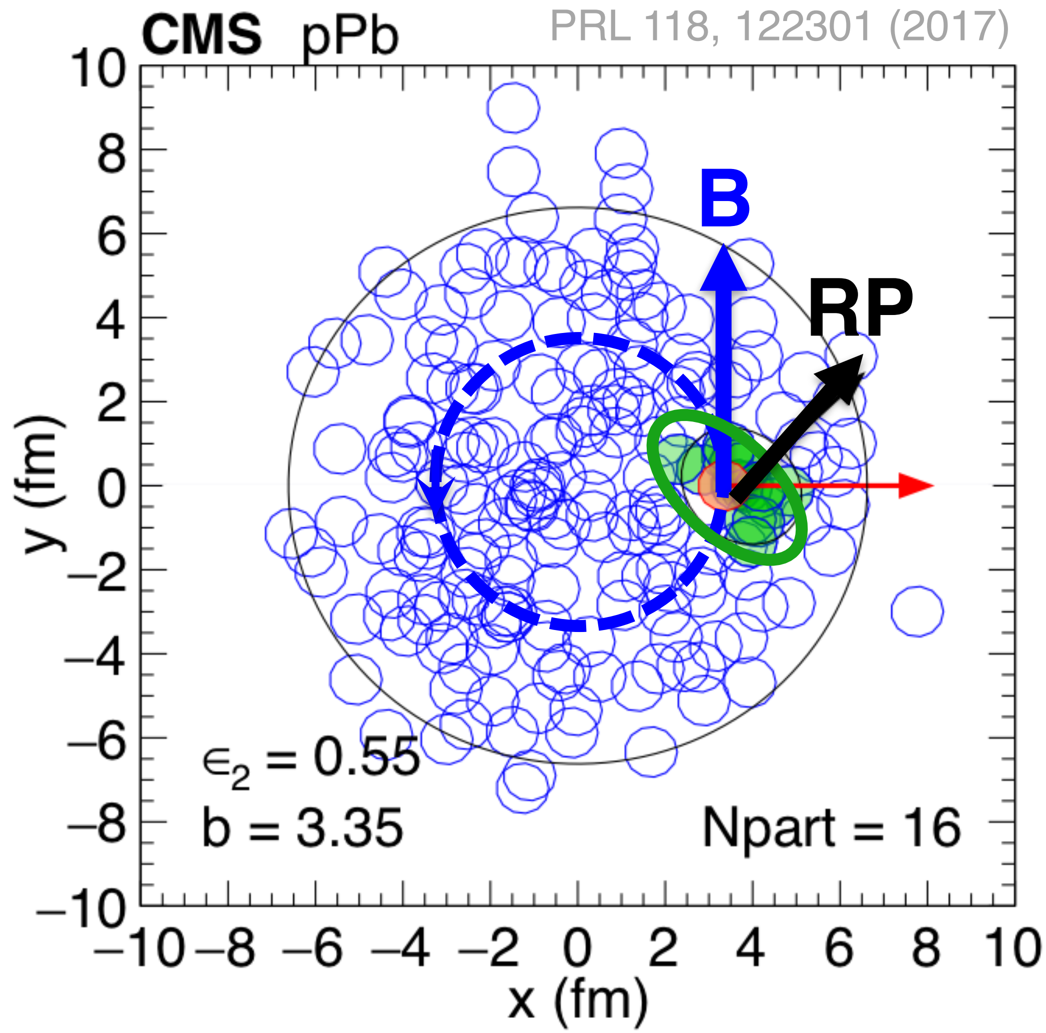
**Charge separation signal:** $\Delta\gamma \sim \left\langle B^2 \cos 2\left(\Psi_B - \Psi_{RP}\right)\right\rangle$

PRL 118, 122301 (2017)



# Surprises in small systems

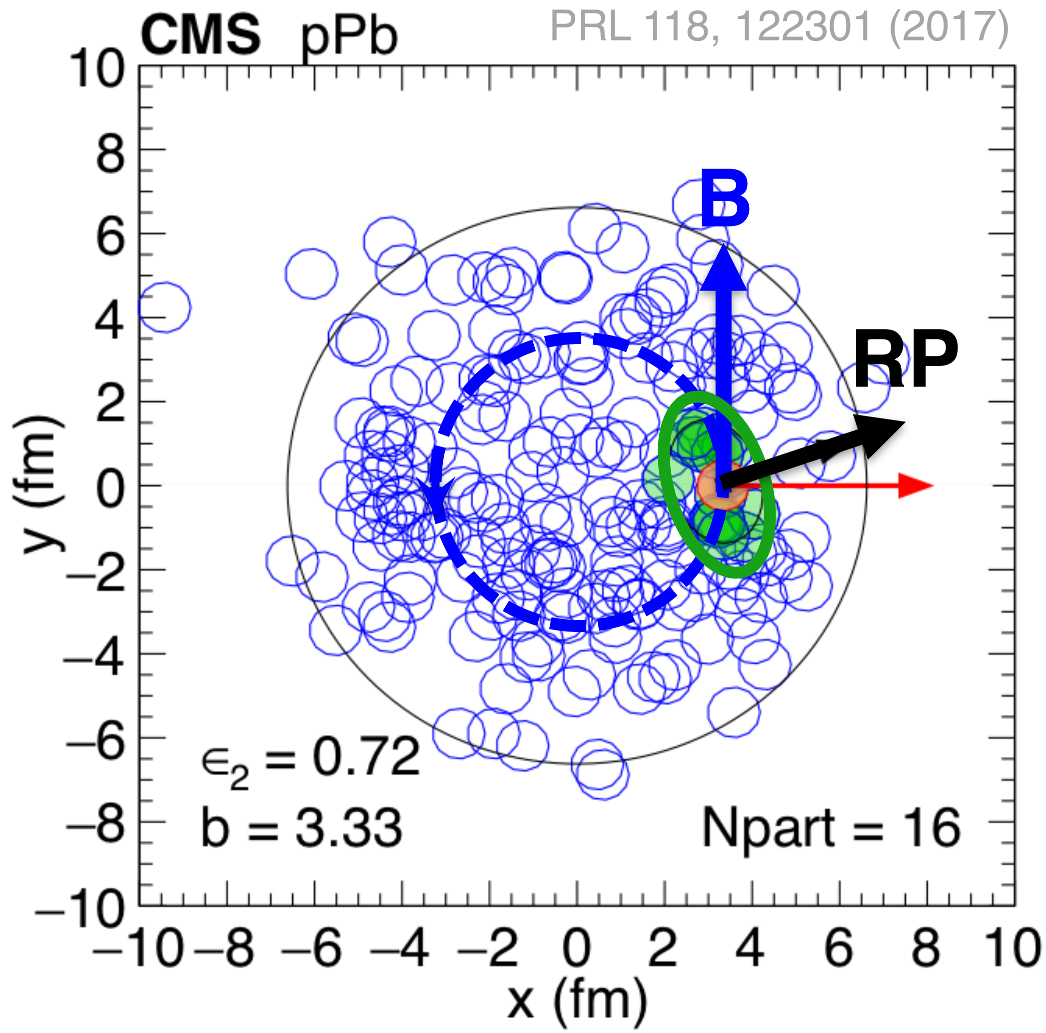
**Charge separation signal:** $\Delta\gamma \sim \left\langle B^2 \cos 2\left(\Psi_B - \Psi_{RP}\right)\right\rangle$



# Surprises in small systems

**Charge separation signal:** $\Delta\gamma \sim \left\langle B^2 \cos 2\left(\Psi_B - \Psi_{RP}\right)\right\rangle$

PRL 118, 122301 (2017)



# Surprises in small systems

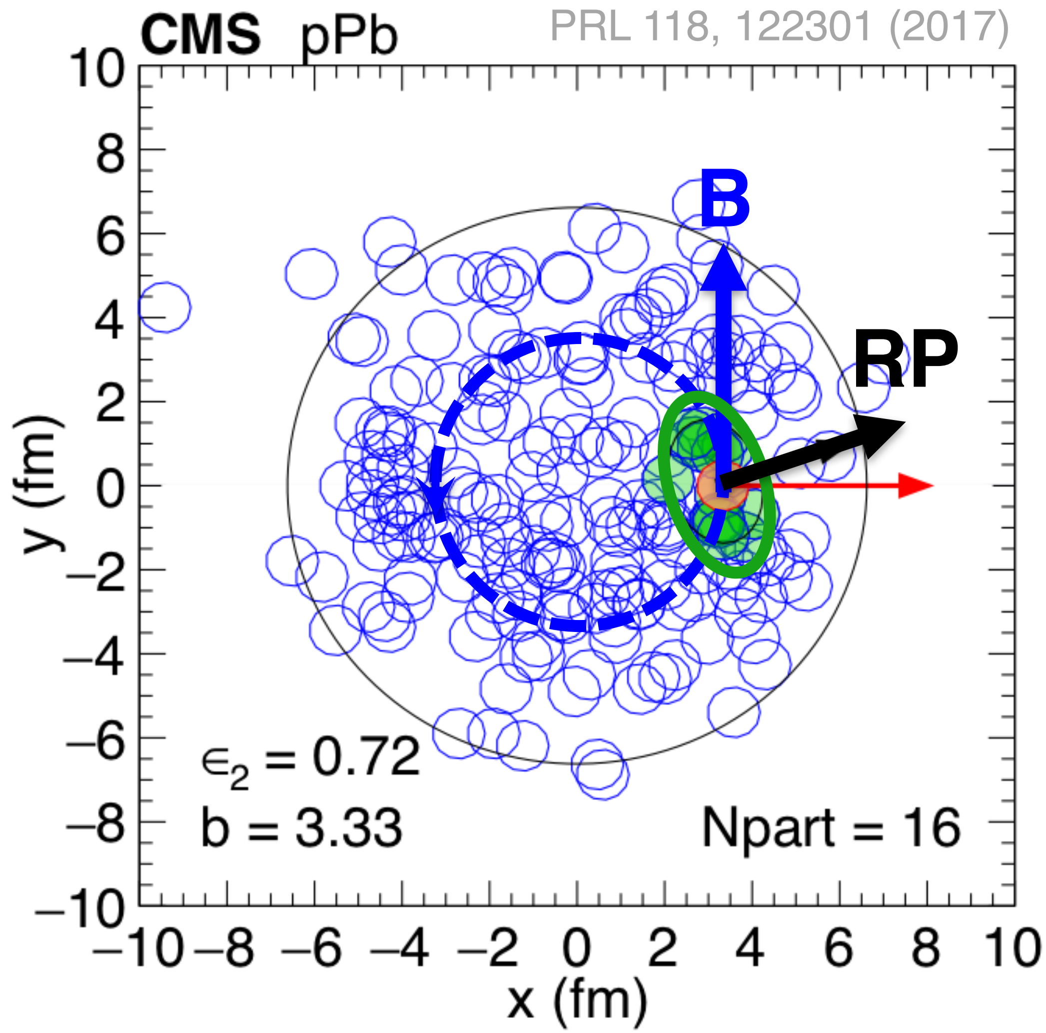
**Charge separation signal:** $\Delta\gamma \sim \left\langle B^2 \cos 2\left(\Psi_B - \Psi_{RP}\right)\right\rangle$

In pA, $\left\langle \cos 2\left(\Psi_B - \Psi_{RP}\right)\right\rangle \approx 0$

$\Rightarrow \Delta\gamma^{\text{CME}} \approx 0$

(turn off the signal)

PRL 118, 122301 (2017)



# Surprises in small systems

**Charge separation signal:** $\Delta\gamma \sim \left\langle B^2 \cos 2\left(\Psi_B - \Psi_{RP}\right)\right\rangle$

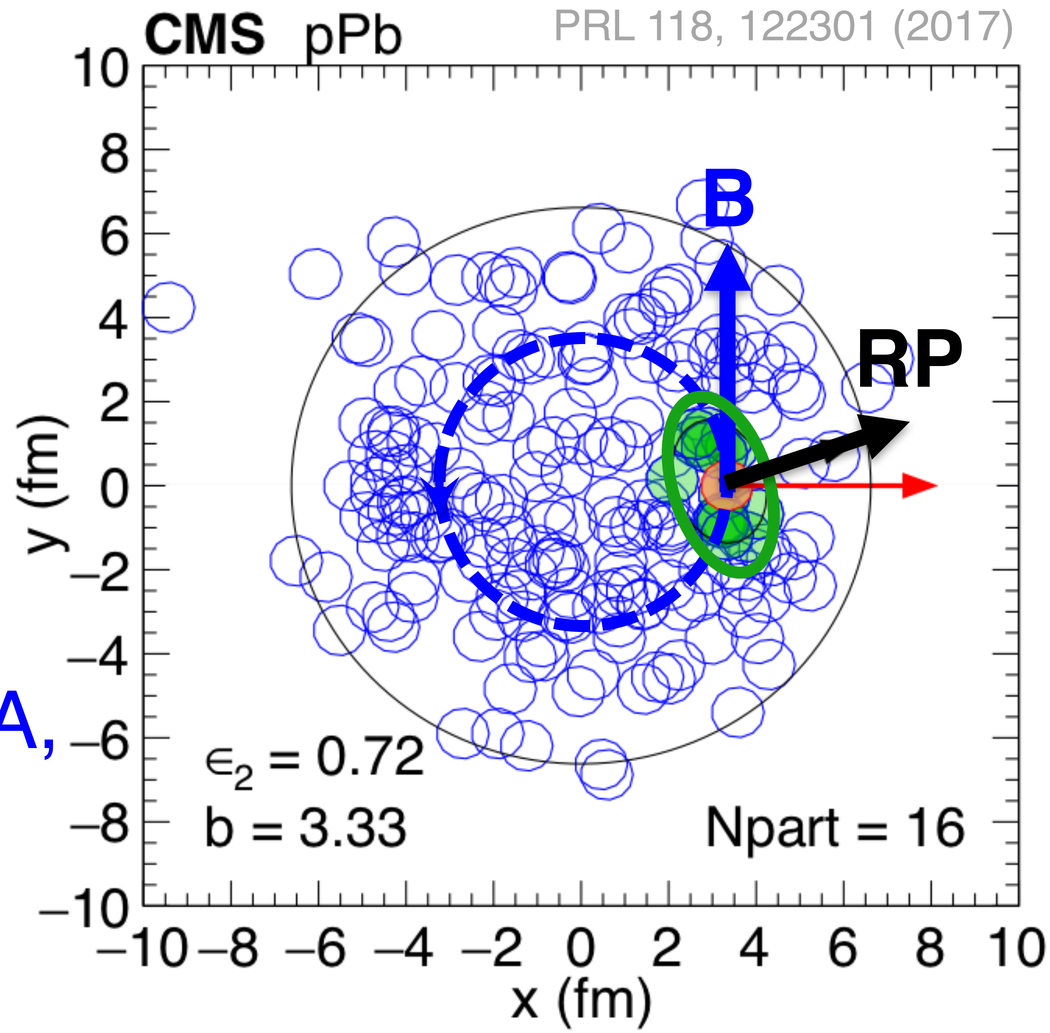
In pA, $\left\langle \cos 2\left(\Psi_B - \Psi_{RP}\right)\right\rangle \approx 0$

$\Rightarrow \Delta\gamma^{\mathrm{CME}} \approx 0$

(turn off the signal)

If CME signal dominant in AA,

$\Delta\gamma^{\mathrm{PbPb}} \gg \Delta\gamma^{\mathrm{pPb}}$

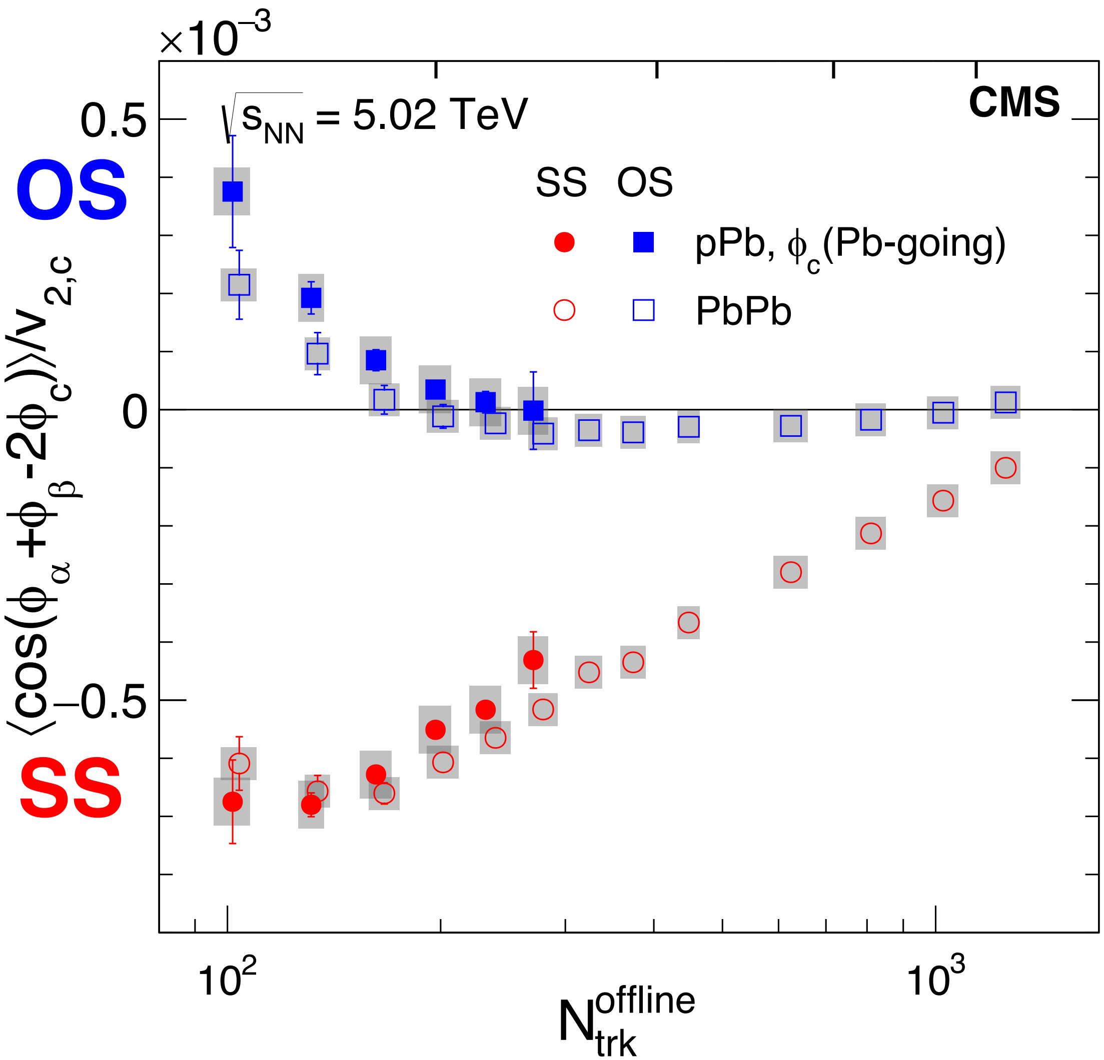



**A litmus test of the CME!**

PRL 118, 122301 (2017) PHYSICAL REVIEW LETTERS week ending 24 MARCH 2017

**Observation of Charge-Dependent Azimuthal Correlations in *p*-Pb Collisions and Its Implication for the Search for the Chiral Magnetic Effect**

(CMS Collaboration) (LHC)




pPb v.s. PbPb:

– nearly **identical**!

BKG dominant!?

*A major challenge to the CME mechanism!*

# New opportunities from small systems (pPb)

i. Understand the exact origin of BKG

ii. Any CME signal, if BKG is removed?

# New opportunities from small systems (pPb)

i. Understand the exact origin of BKG

ii. Any CME signal, if BKG is removed?

$$\Delta\gamma = \Delta\gamma^{\mathbf{CME}} + \kappa \cdot v_2 \cdot \Delta\delta$$

(Signal) (LCC ackground)

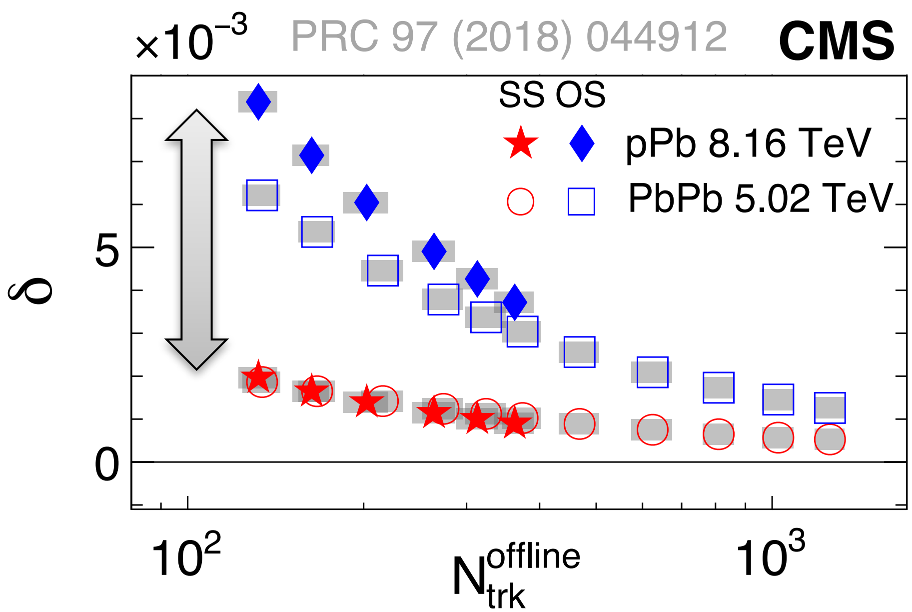
# New opportunities from small systems (pPb)

i. Understand the exact origin of BKG

ii. Any CME signal, if BKG is removed?

$$\Delta\gamma = \Delta\gamma^{\mathrm{CME}} + \kappa \cdot v_2 \cdot \Delta\delta$$

(Signal) (LCC ackground)




$$\delta^{(\pm,\pm)} \equiv \langle \cos(\phi_\alpha^\pm - \phi_\beta^\pm) \rangle$$

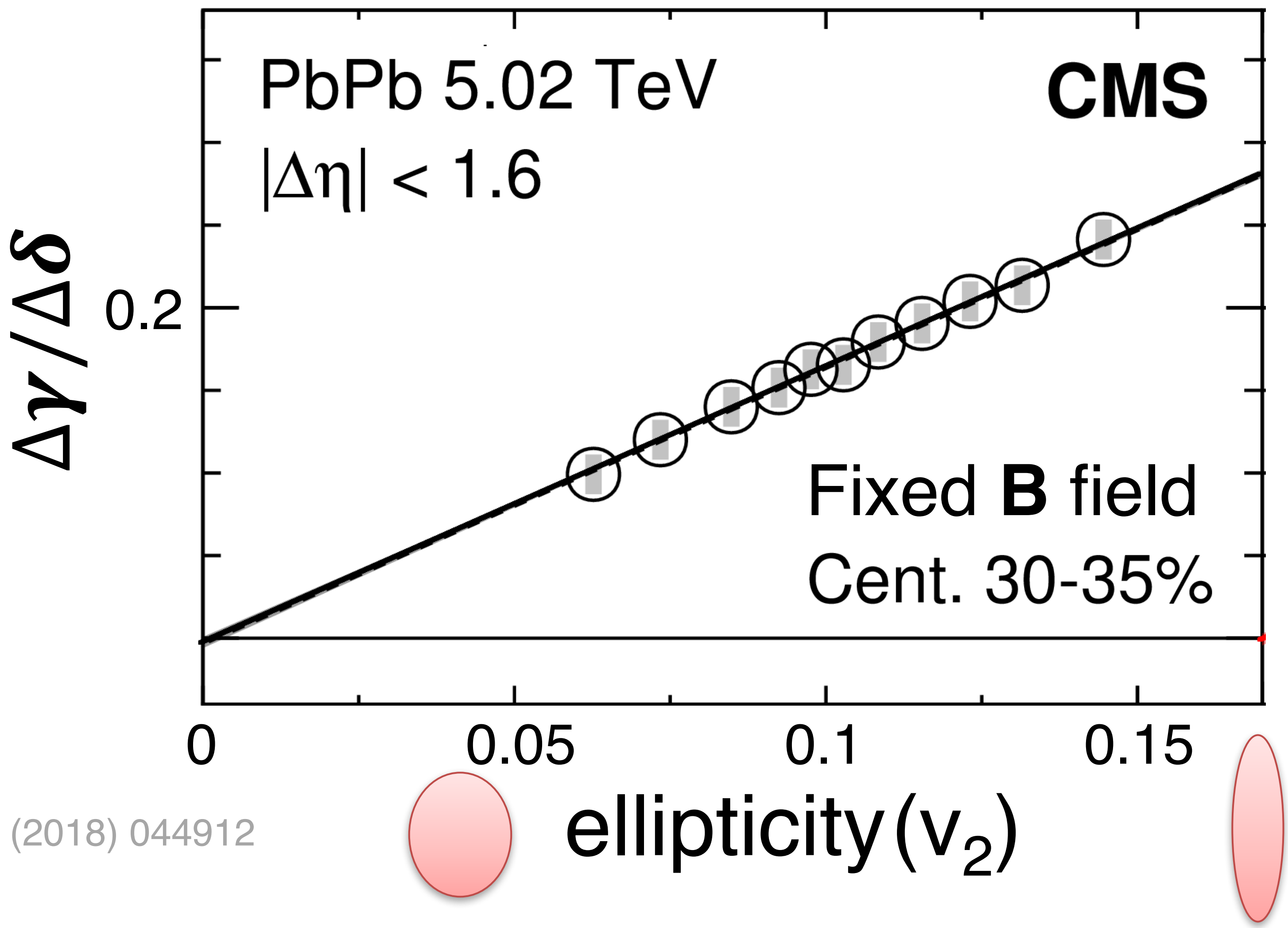
(Two-particle correlations)

Sizable!

# Engineer the "event shape" ($v_2$)

Turn off BKG by extrapolating to $v_2 = 0$

$$\Delta\gamma/\Delta\delta = \kappa \cdot v_2 + \Delta\gamma^{\mathrm{CME}}/\Delta\delta$$

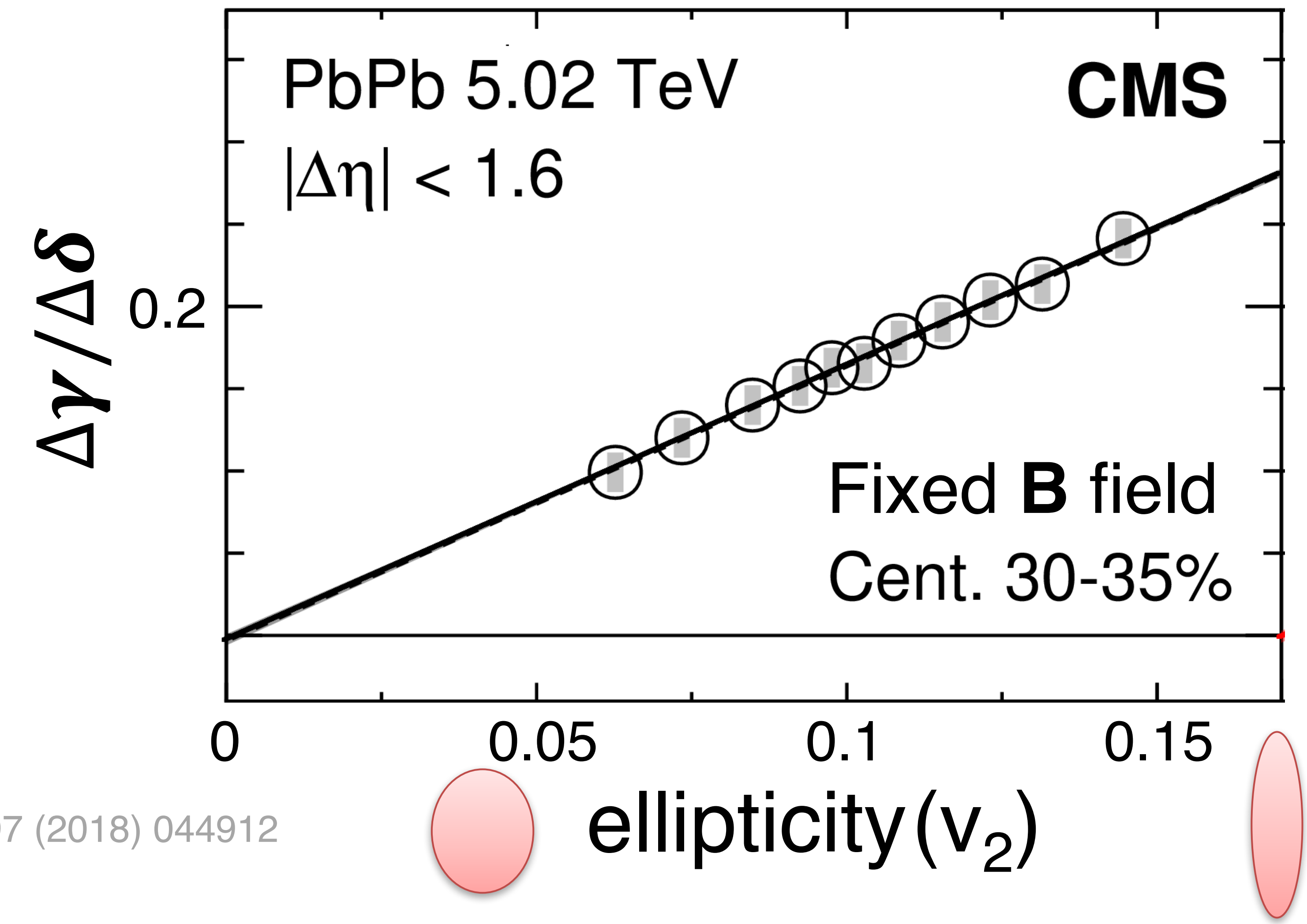



PRC 97 (2018) 044912

# Engineer the "event shape" ($v_2$)

Turn off BKG by extrapolating to $v_2 = 0$

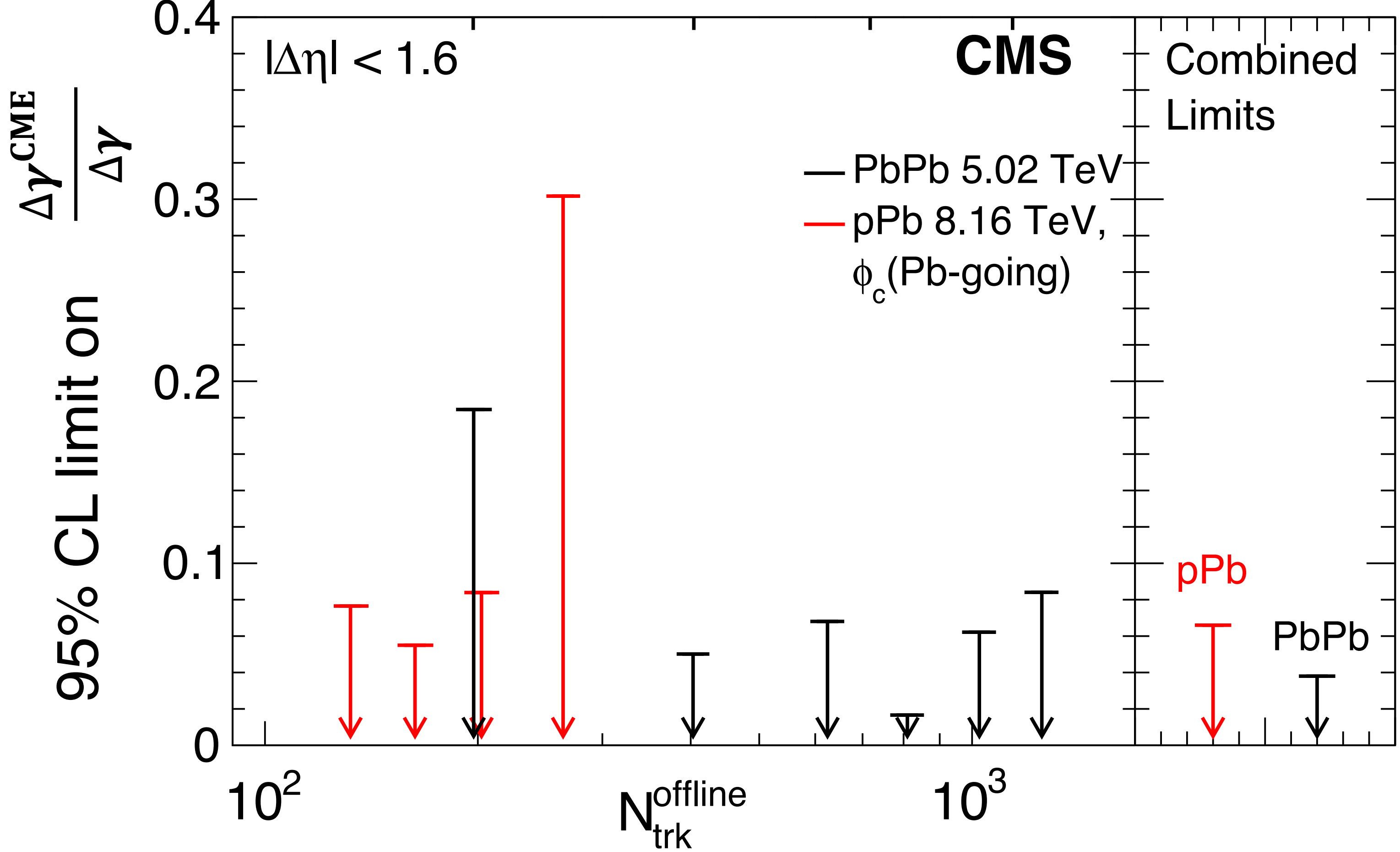
$$\Delta\gamma/\Delta\delta = \kappa \cdot v_2 + \boxed{\Delta\gamma^{\mathrm{CME}}/\Delta\delta}$$ intercept ~ 0




PRC 97 (2018) 044912

# Upper limits on the $\Delta\gamma^{CME}$ *at the LHC*

PRC 97 (2018) 044912

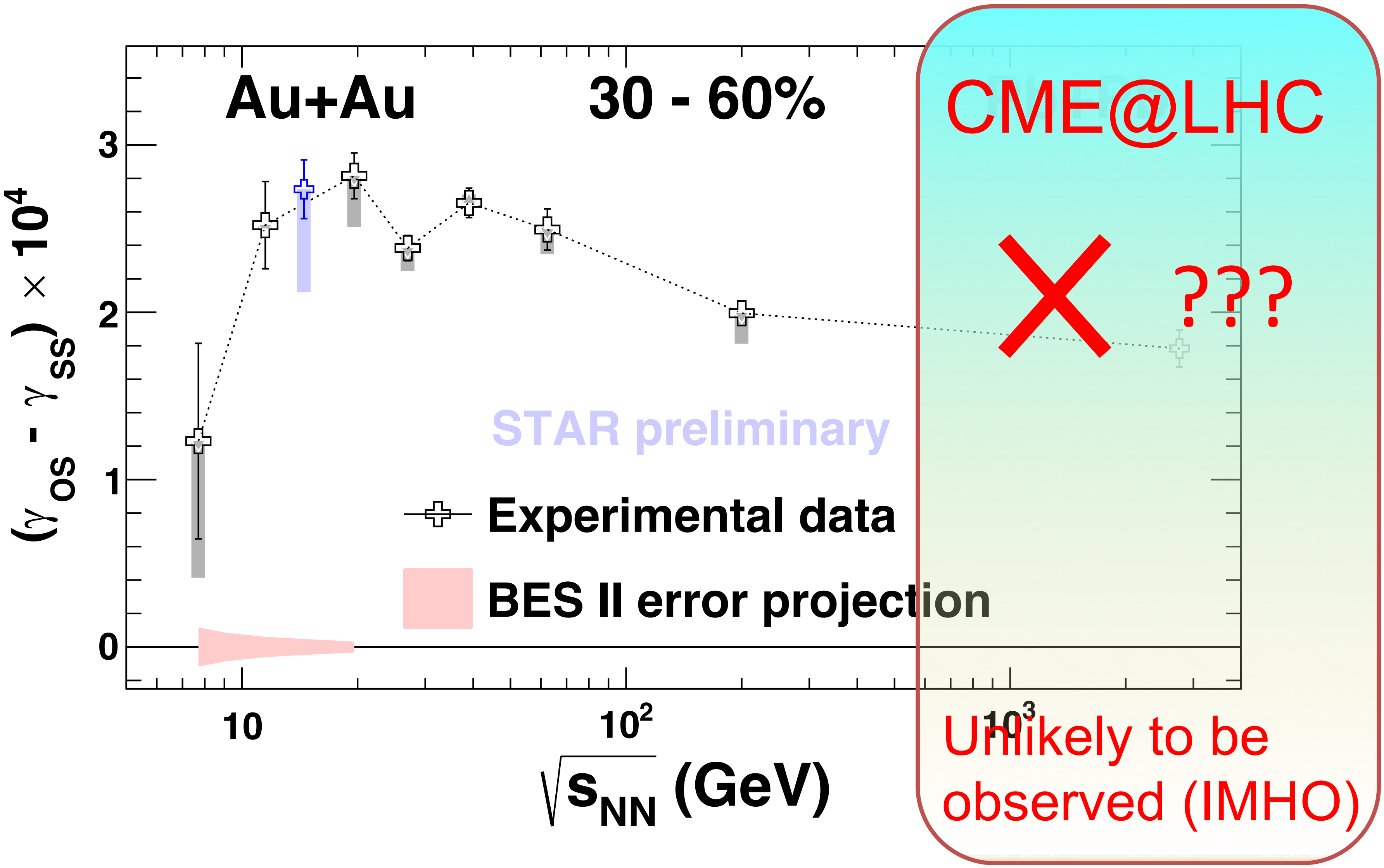



**< 7% in PbPb**
(95% C.L.)

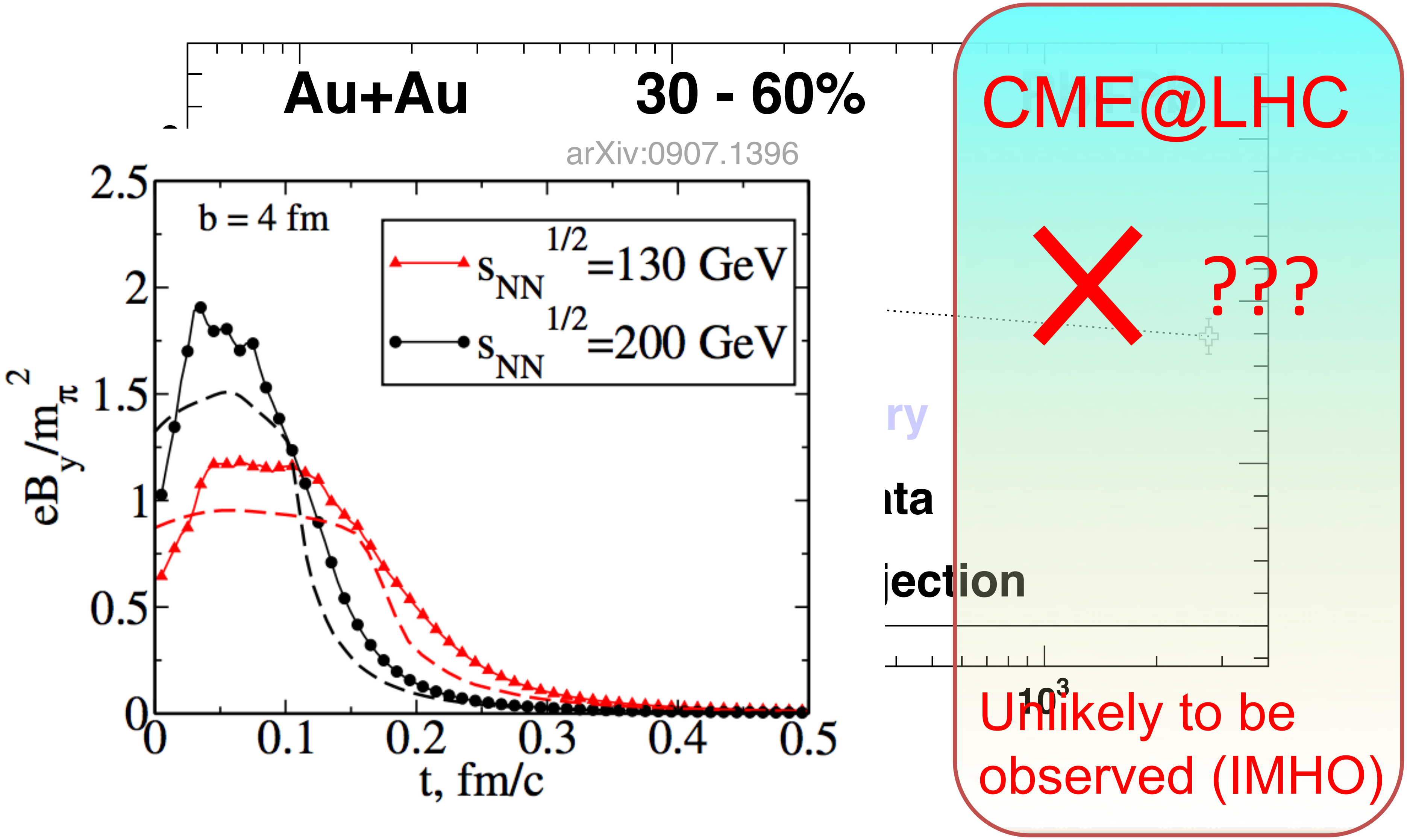
ALICE

< 30% in PbPb
(95% C.L.)

# How about at lower energies?

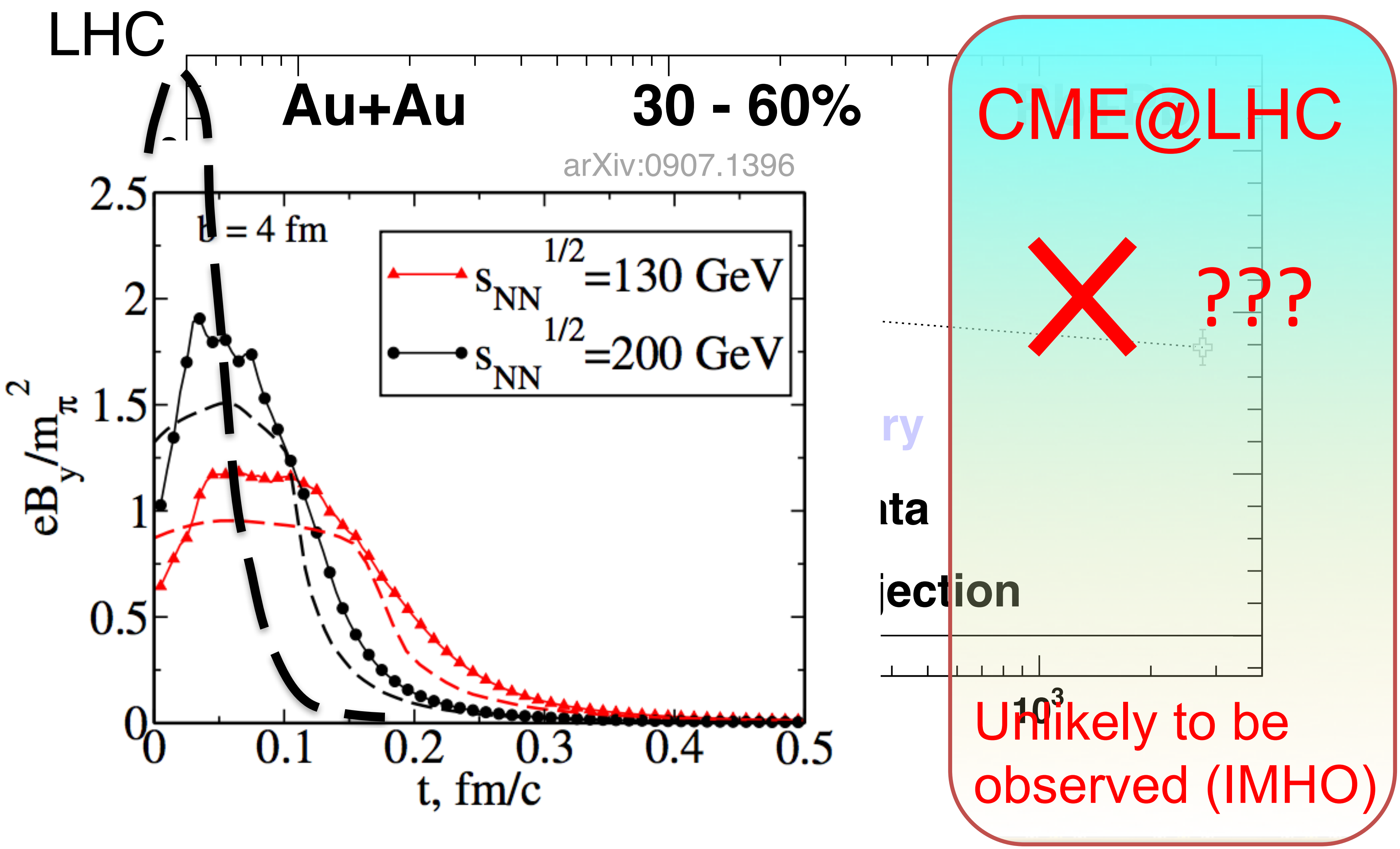


# How about at lower energies?




Magnetic field last longer at RHIC energies?

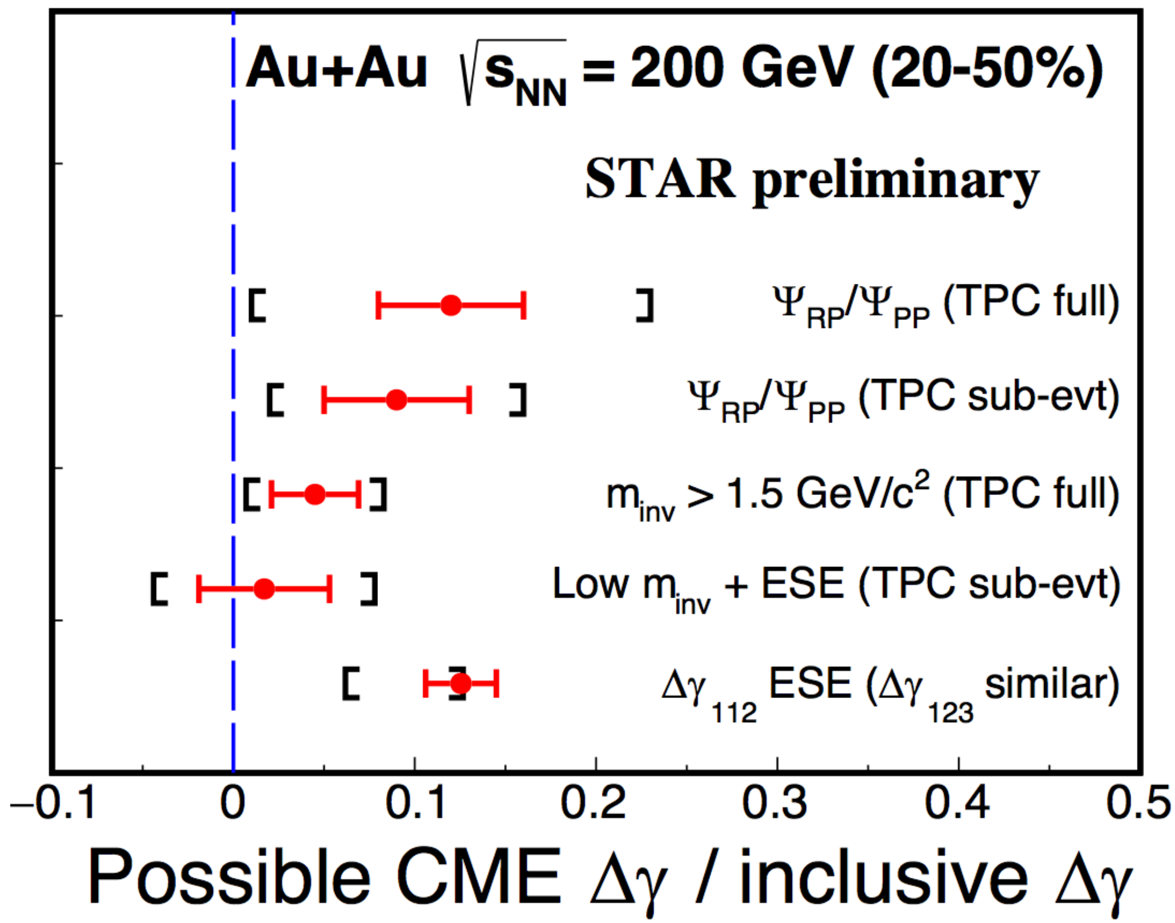
# How about at lower energies?




Magnetic field last longer at RHIC energies?

# Extracting the CME signal at RHIC

*(STAR overview talk by Z. Ye @ Quark Matter 2018)*



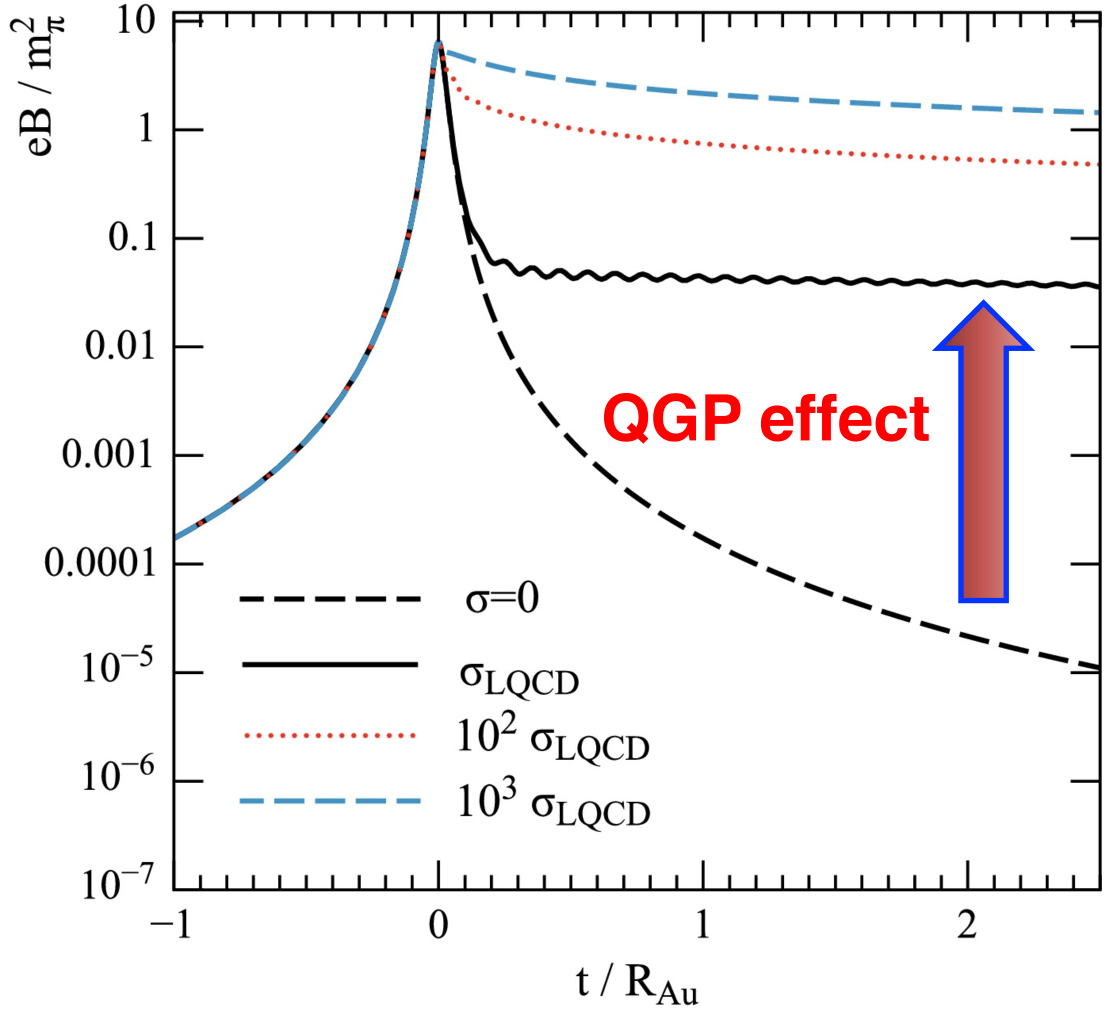

} Engineer the event shape

AuAu 200 GeV: CME fraction < **5~20%**

*Consistent with LHC energy*

# Magnetic field

NPA 929 (2014) 184



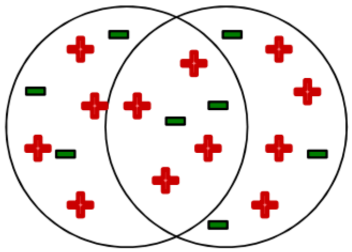

QGP fluid with electric conductivity

In the vacuum

Independent constraint on the magnetic field crucial!
(e.g., directed flow of charm v.s. anticharm)

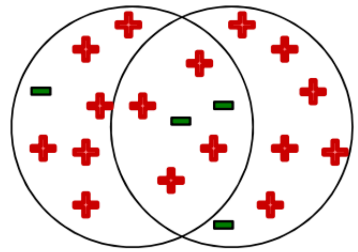
# What's next for the CME?

- Isobaric collisions at 200 GeV at RHIC in 2018



$_{40}Zr^{96} + {}_{40}Zr^{96}$

Vs



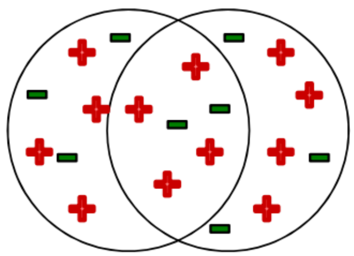
$_{44}Ru^{96} + {}_{44}Ru^{96}$

Expect similar BKG but **10%** difference in **B** field

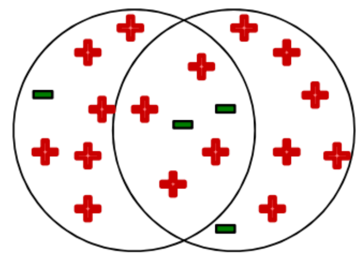
$\Rightarrow \Delta\gamma_{RuRu}^{CME} > \Delta\gamma_{RuRu}^{CME}$

# What's next for the CME?

- Isobaric collisions at 200 GeV at RHIC in 2018



Vs



${}^{96}_{40}Zr + {}^{96}_{40}Zr$  ${}^{96}_{44}Ru + {}^{96}_{44}Ru$

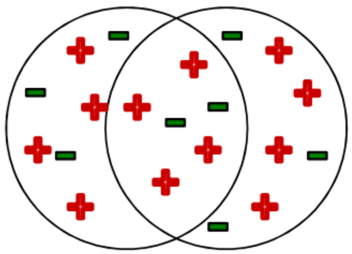
Expect similar BKG but **10%** difference in **B** field

$\Rightarrow \Delta\gamma^{CME}_{RuRu} > \Delta\gamma^{CME}_{RuRu}$

If $\frac{\Delta\gamma^{\text{CME}}}{\Delta\gamma} \sim 10\%$, **3-4σ** difference in $\Delta\gamma$ with 6B events

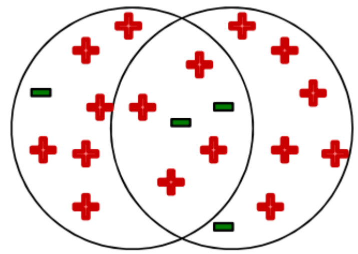
# What’s next for the CME?

- Isobaric collisions at 200 GeV at RHIC in 2018



$^{96}_{40}Zr + ^{96}_{40}Zr$

**Vs**



$^{96}_{44}Ru + ^{96}_{44}Ru$

Expect similar BKG but **10%** difference in **B** field

⇨ $\Delta\gamma^{CME}_{RuRu} > \Delta\gamma^{CME}_{RuRu}$

If $\frac{\Delta\gamma^{\mathrm{CME}}}{\Delta\gamma} \sim 10\%$, **3-4σ** difference in $\Delta\gamma$ with 6B events

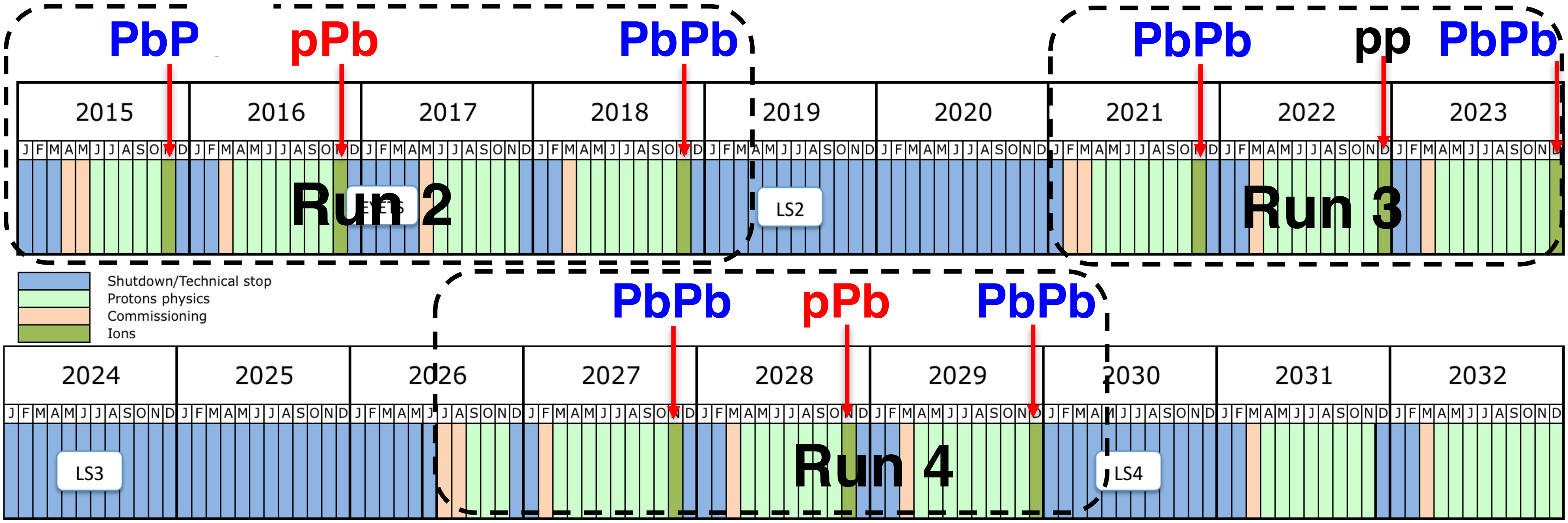
- Beam Energy Scan II at RHIC: 2019-2021

  explore lower energy range: 7.7 - 200 GeV

# What's next for the CME?

LHC

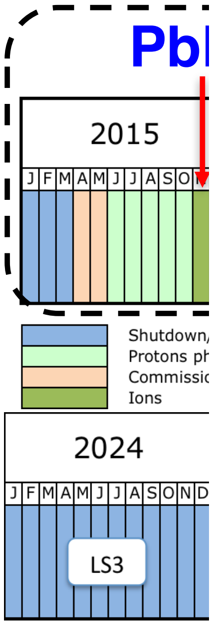
We are here

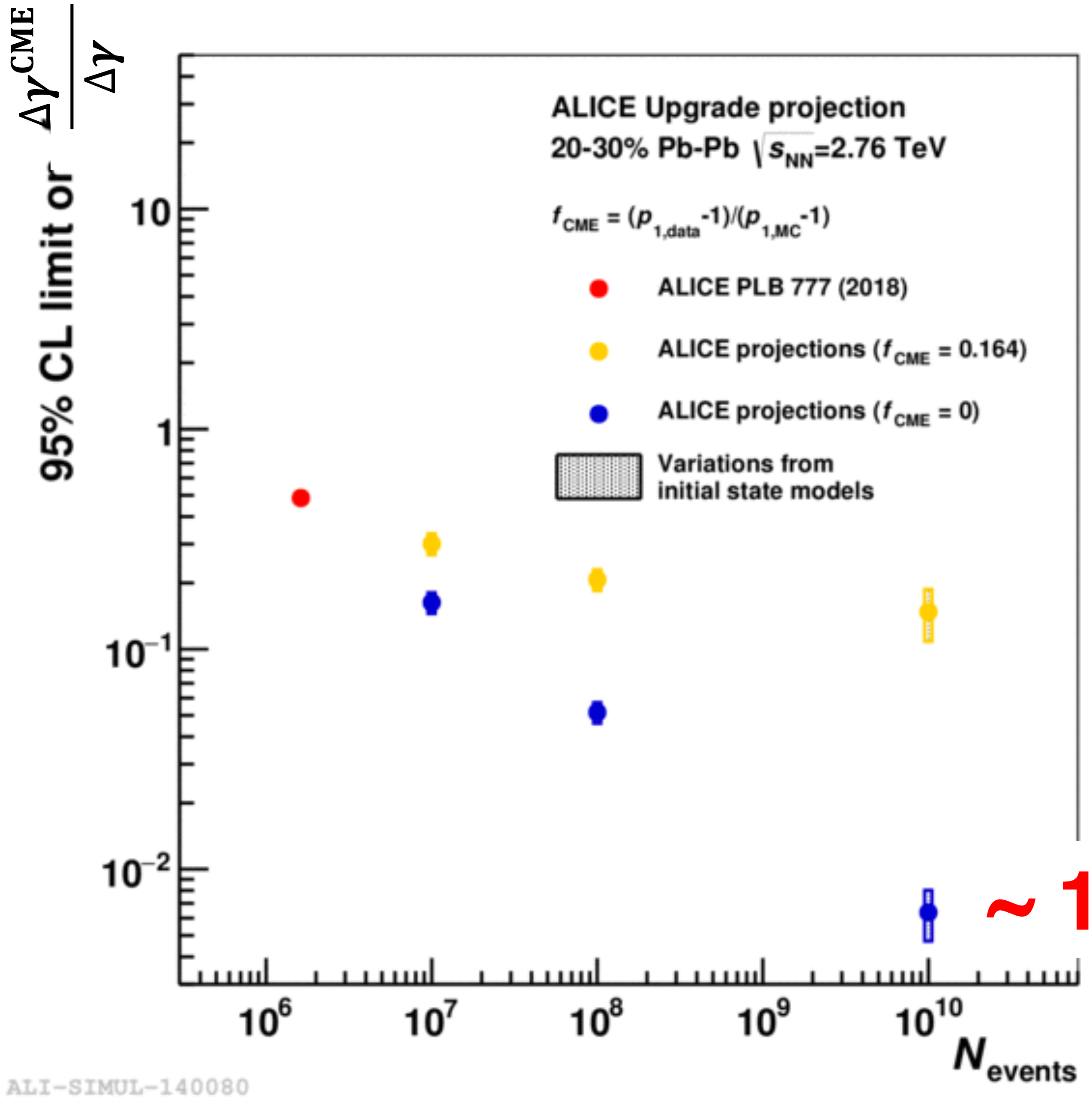


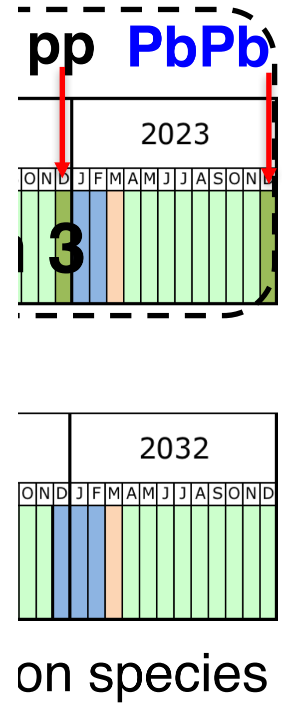

possibly also other smaller ion species

# What's next for the CME?

LHC



# Summary

## Rich physics of the CME in QCD and QGP

- Topological phases in QCD
- Deconfinement, chiral symmetry restoration
- Initial strongest magnetic field

***Three birds with one stone!***

## Hints of the CME seen but backgrounds substantial

- ✓ pPb data suggest background dominant at the LHC
- ✓ Upper limit of the signal fraction: **< a few %** in PbPb

## Future programs promising for definitive answer!

Isobars, BESII@RHIC;  HL-LHC