# Search for Chiral Magnetic Effect at RHIC : challenges and opportunities

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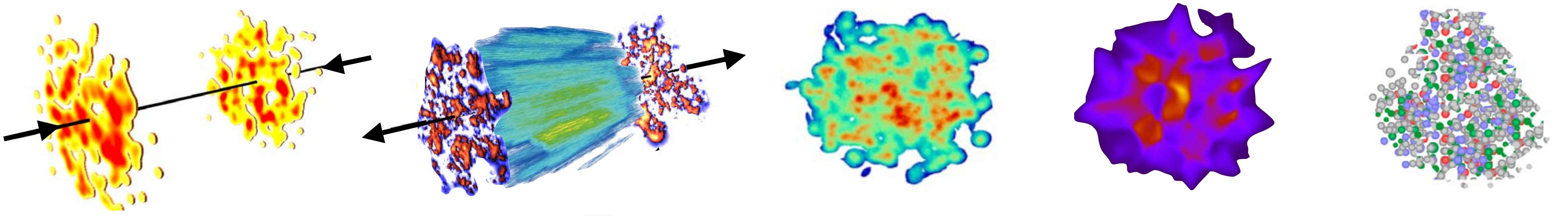
BNL seminar, April 18, BNL, Upton, NY, USA

Based on : arXiv : 1704.03845
And results presented at :
QCD workshop on Chirality, Vorticity and Magnetic Field in Heavy Ion Collision, UCLA, USA
Quark Matter 2017, Chicago, USA

# Early Stages of Heavy Ion collisions

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



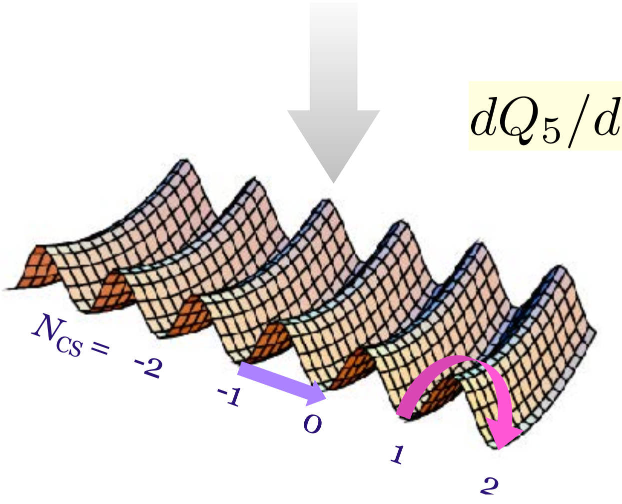
CGC

Glasma

Pre-equilibrium evolution

Hydrodynamic evolution

Hadronization



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

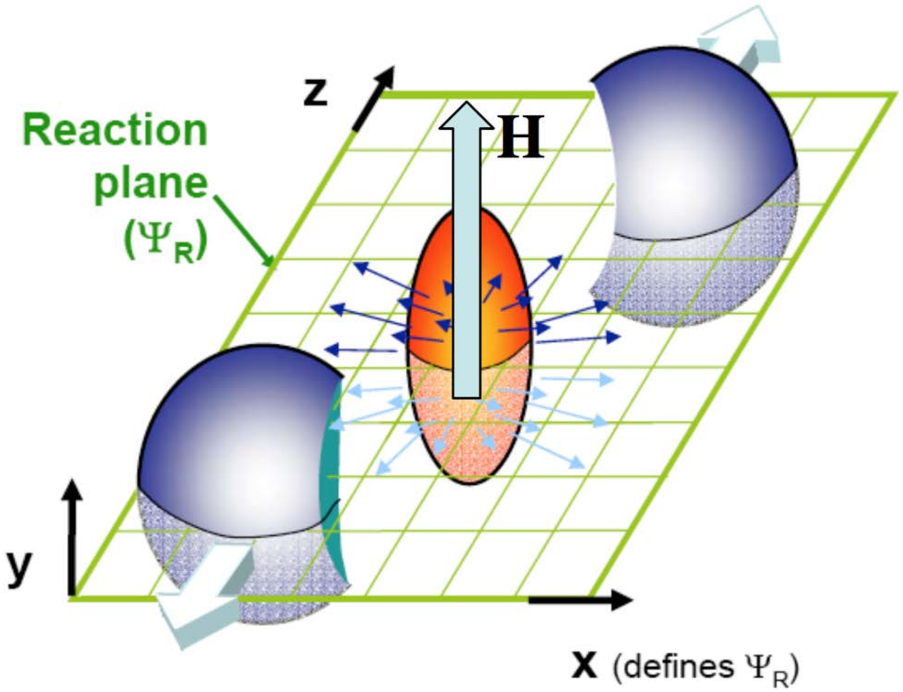
Chirality imbalance in the produced quarks at early times

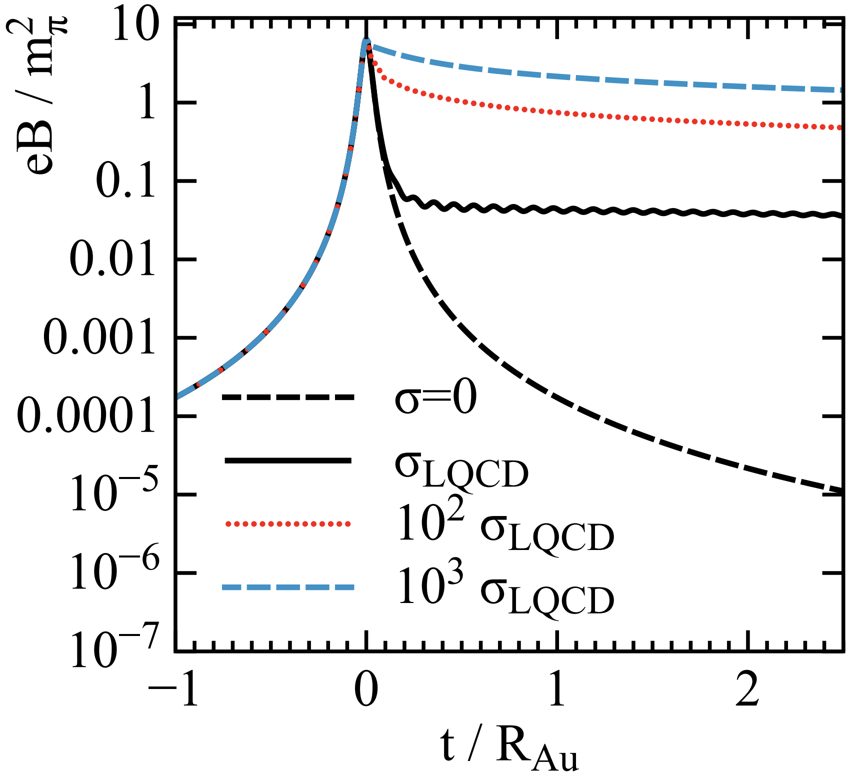
Kharzeev, Krasnitz, Venugopalan hep-ph/0109253,
Buividovich 0907.0494,
Mace, Schlichting, Venugopalan 1601.07342

Many references & recent review :
Kharzeev, Liao, Voloshin, Wang 1511.04050
Skokov *et al.* 1608.00982

# Early Stages of Heavy Ion collisions

Early stages of heavy ion collisions also produce strongest electro-magnetic field





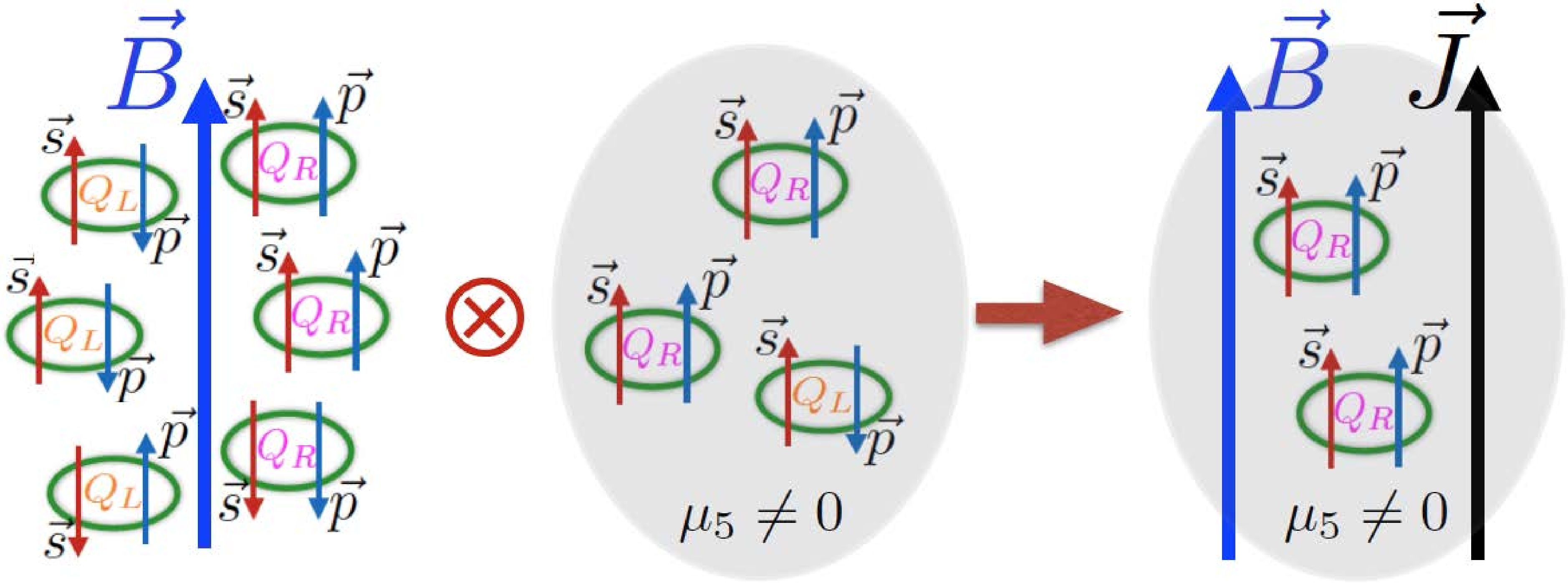
Strength : eB ~$(m_\pi)^2$ ~$10^{18}$ Gauss

Direction : ⊥ reaction plane $\Psi_{RP}$ (mid-central, symmetric A+A)

Kharzeev et al 0711.0950, Skokov et al 0907.1396, Bzdak, Skokov 1111.1949, McLerran, Skokov 1305.0774

# The Chiral Magnetic Effect

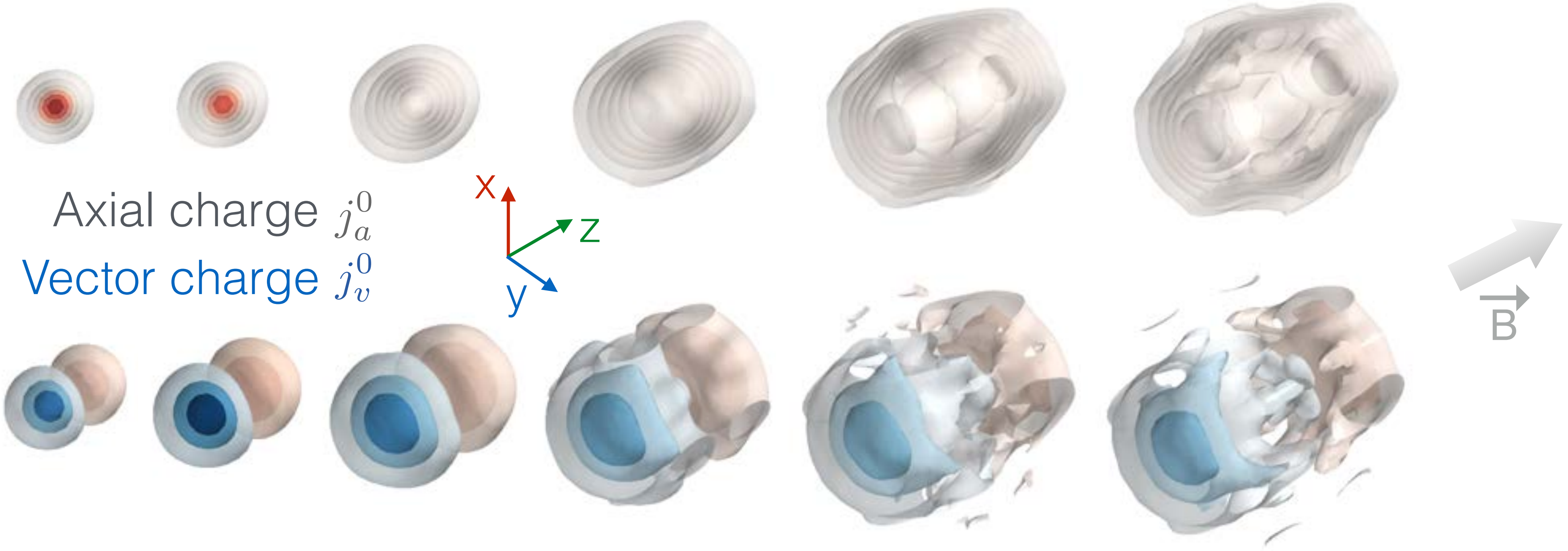
QCD anomaly driven chirality imbalance leads to current along B-field



Kharzeev hep-ph/0406125; Kharzeev, Zhitnitsky 0706.1026;
Kharzeev, McLerran, Warringa 0711.0950;
Fukushima, Kharzeev, Warringa 0808.3382

# The Chiral Magnetic Effect

Real-time first principle lattice calculations of CME

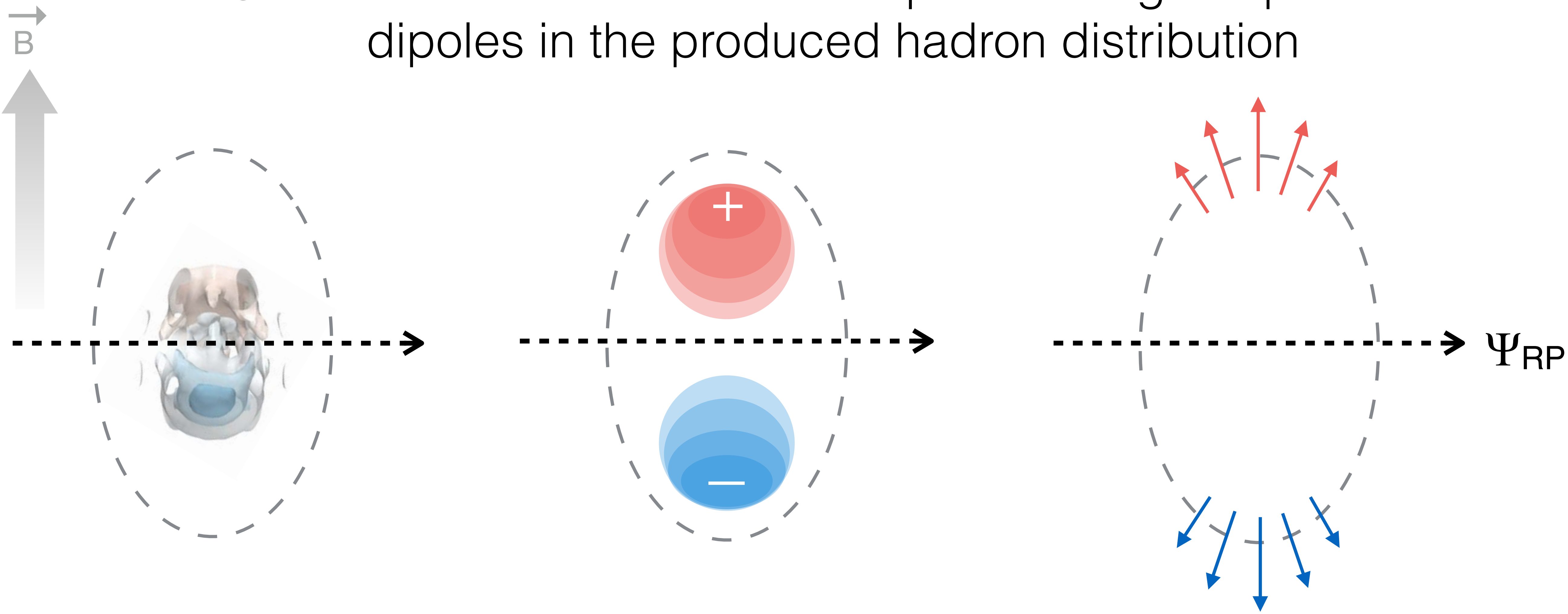


Muller, Schlichting, Sharma, PRL 117 142301 (2016)
Mace, Mueller, Schlichting, Sharma PRD 95, 036023 (2017)

Formation of dipoles in the initial charge distribution

# Observables of CME

CME current can lead to out-of-plane charge dependent dipoles in the produced hadron distribution



Dipole in the initial charge distribution

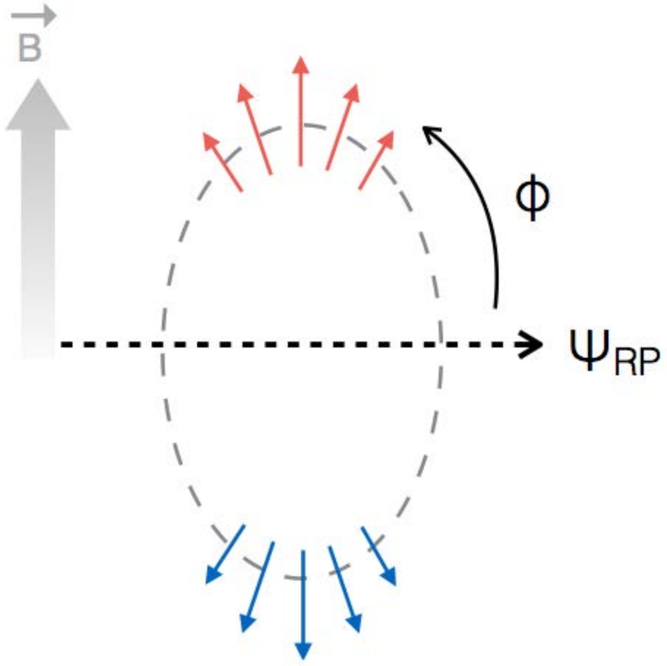
see Kharzeev, Liao, Voloshin, Wang 1511.04050

Dipole in distribution of produced hadrons :

$$\frac{dN_{\pm}}{d\phi} \propto 1 + 2v_1 \cos(\phi - \Psi_{\mathrm{RP}}) + 2v_2 \cos[2(\phi - \Psi_{\mathrm{RP}})] + \ldots + \boxed{2a_{\pm} \sin(\phi - \Psi_{\mathrm{RP}})} + \ldots,$$

# Observables of CME

Harmonic decomposition should reflect the P-odd effect

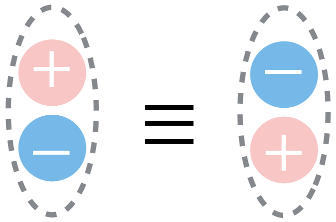


$$\frac{dN_\pm}{d\phi} \propto 1 + 2v_1\cos(\phi - \Psi_{\mathrm{RP}}) + 2v_2\cos[2(\phi - \Psi_{\mathrm{RP}})] + .$$

$$\ldots + \boxed{2a_\pm \sin(\phi - \Psi_{\mathrm{RP}})} + \ldots,$$

Only correlations survive flipping of dipole

$$\langle \sin(\phi_\alpha - \Psi_{RP})\sin(\phi_\beta - \Psi_{RP})\rangle$$

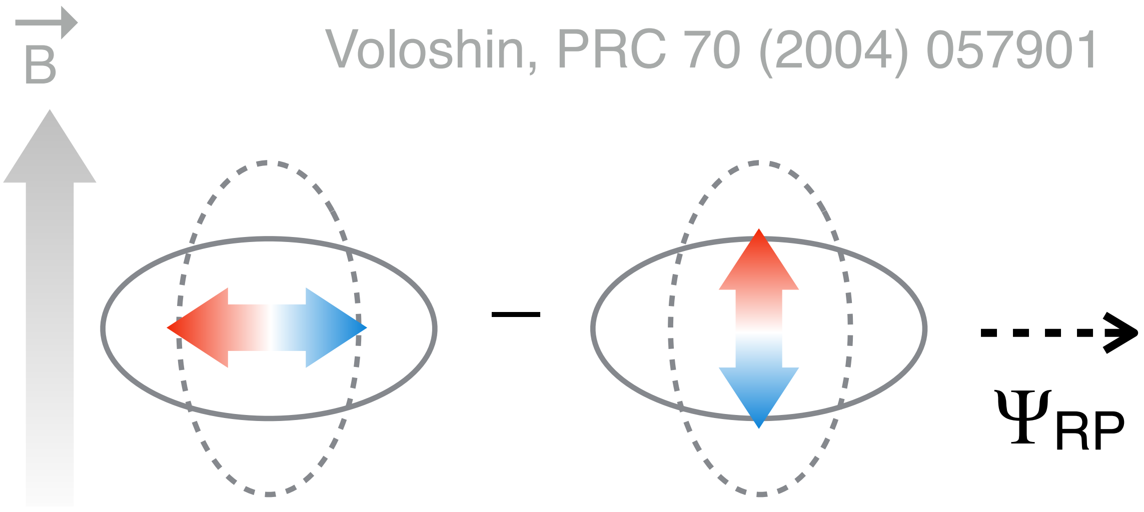


Sergei's γ-correlator :

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

$$= \langle \cos(\phi_\alpha - \Psi_{RP})\cos(\phi_\beta - \Psi_{RP})\rangle$$

$$-\langle \sin(\phi_\alpha - \Psi_{RP})\sin(\phi_\beta - \Psi_{RP})\rangle$$



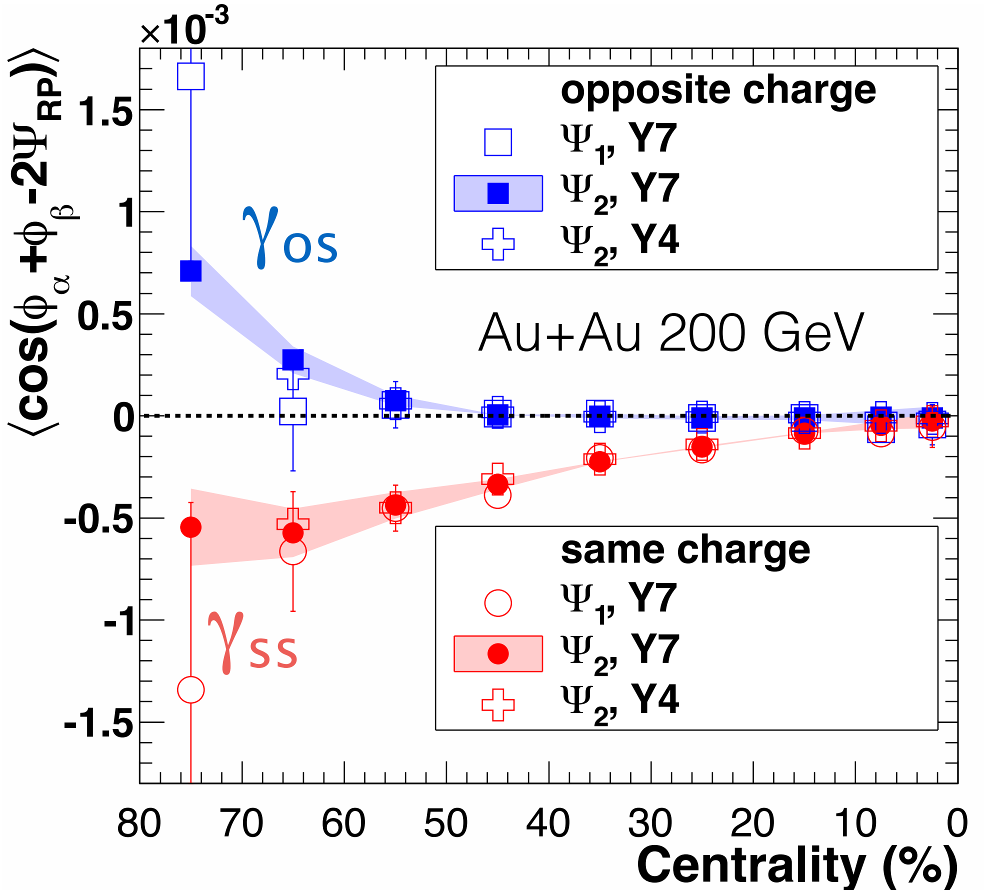
Voloshin, PRC 70 (2004) 057901

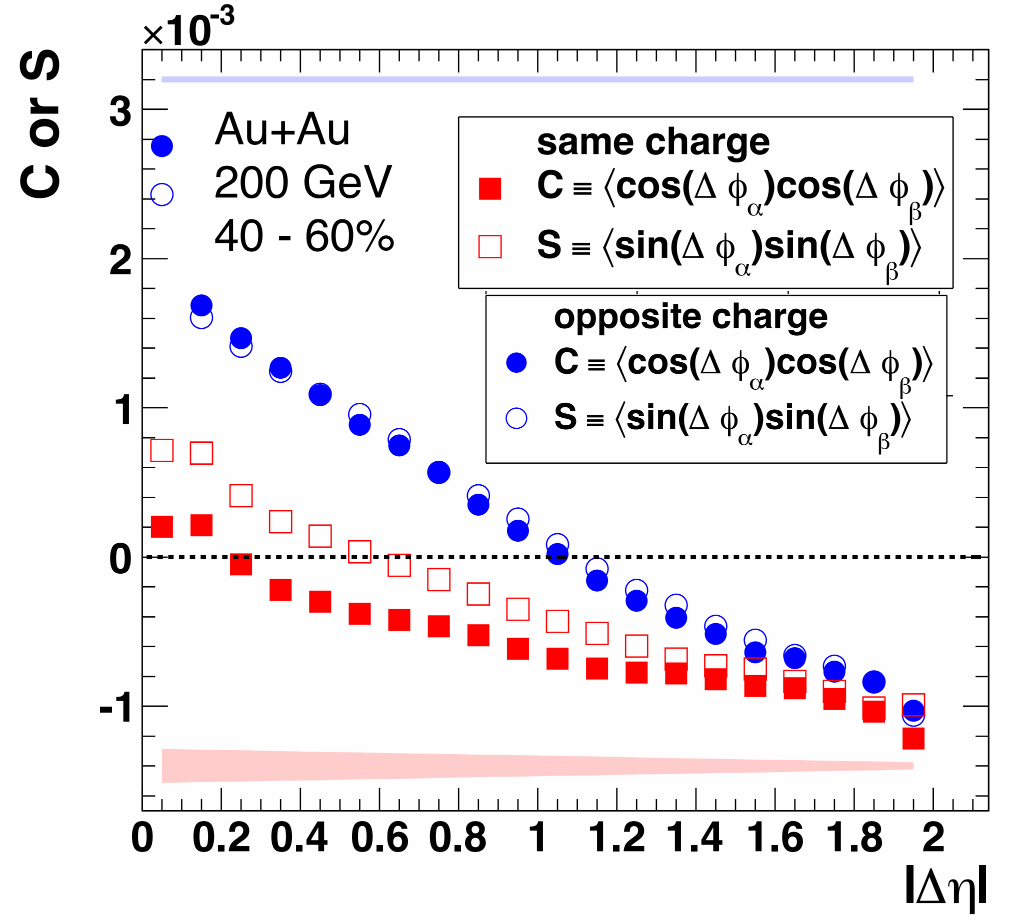
3-particle-correlator : $C_{112} = \langle \cos(\phi_\alpha + \phi_\beta - 2\phi_c)\rangle$

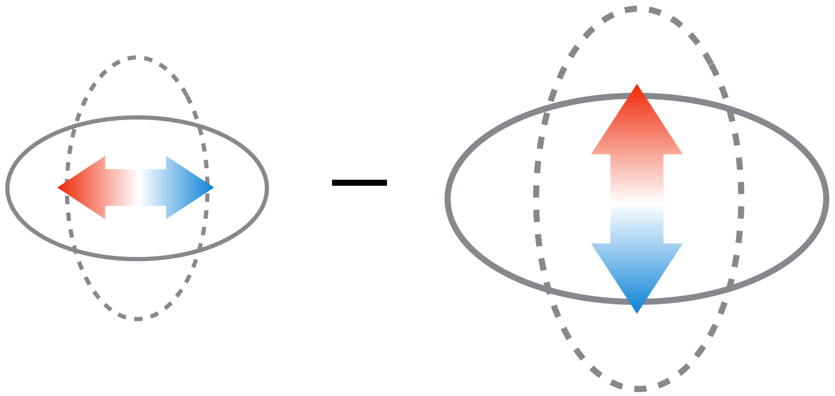
# Early measurements from STAR

## Early observation of charge separation in Au+Au 200 GeV

Adamczyk et al PRL 103, 251601 (2009), PRC 88 (2013) 6, 064911







Indication that pairs of same-charges preferably flow together & out-of plane

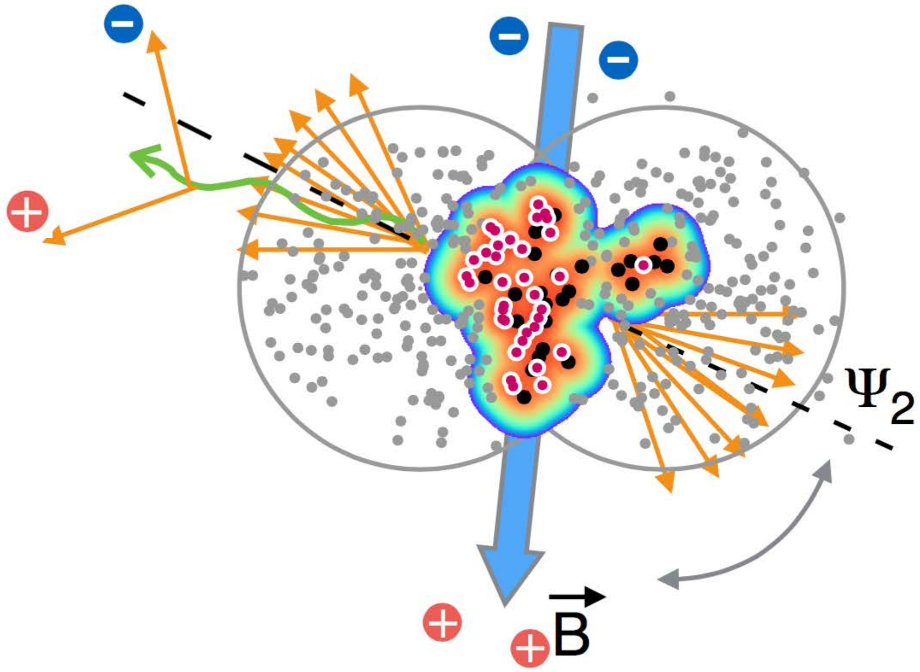
Weak preference for opposite charges

Multiple sources of background ?

# Sources of background

Background can contribute only in a very specific way

Sergei's γ-correlator :



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

$$= \langle \cos(\phi_\alpha - \Psi_{RP}) \cos(\phi_\beta - \Psi_{RP}) \rangle$$
$$- \langle \sin(\phi_\alpha - \Psi_{RP}) \sin(\phi_\beta - \Psi_{RP}) \rangle$$

$$= \quad [\langle v_{1,\alpha} v_{1,\beta} \rangle + B_{\mathrm{IN}}] - [\langle a_\alpha a_\beta \rangle + B_{\mathrm{OUT}}]$$

Directed flow (small at |η|<1)

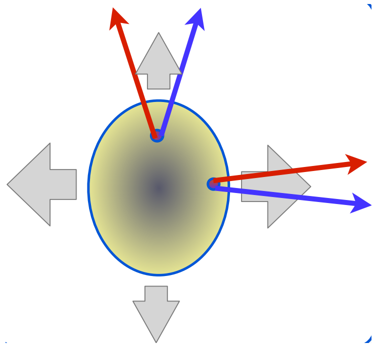
In-plane background

Interesting Signal

Out-of-plane background

(B<sub></sub>

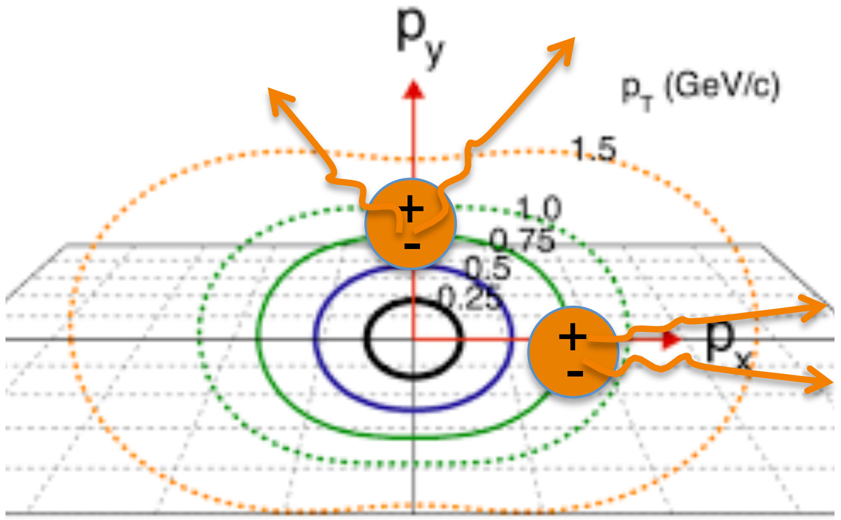
$(B_{IN}$ - $B_{OUT})$ ~ $v_2/N$
~ $v_2$ (anisotropy)
~ 1/ Multiplicity (random-walk)

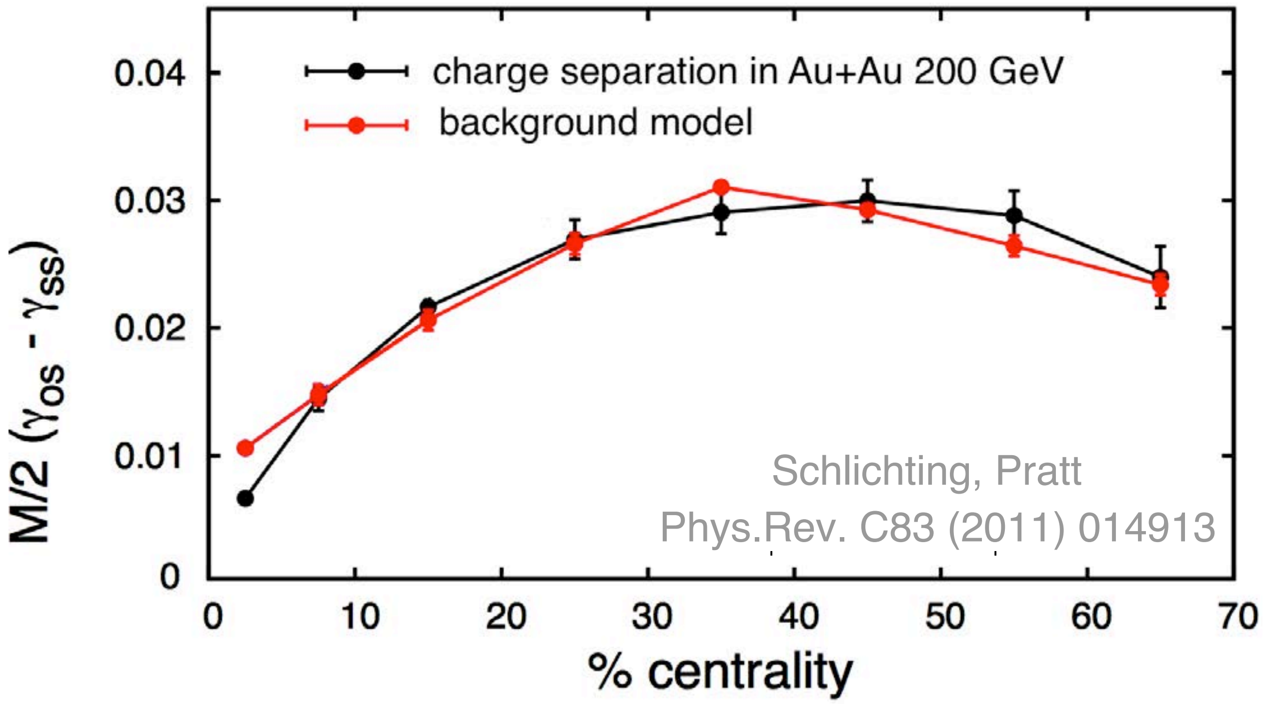


$$\gamma^{\alpha,\beta} = -\langle a_\alpha a_\beta \rangle + c\,\frac{v_2}{N}$$

# Background : Local charge conservation

LCC + radial + Flow → stronger correlation between in-plane opposite charge pairs predicted





Schlichting, Pratt
Phys.Rev. C83 (2011) 014913

$$\gamma^{\alpha,\beta} = -\langle a_\alpha a_\beta \rangle + c\ \frac{v_2}{N}$$

||

0

Local charge conservation :

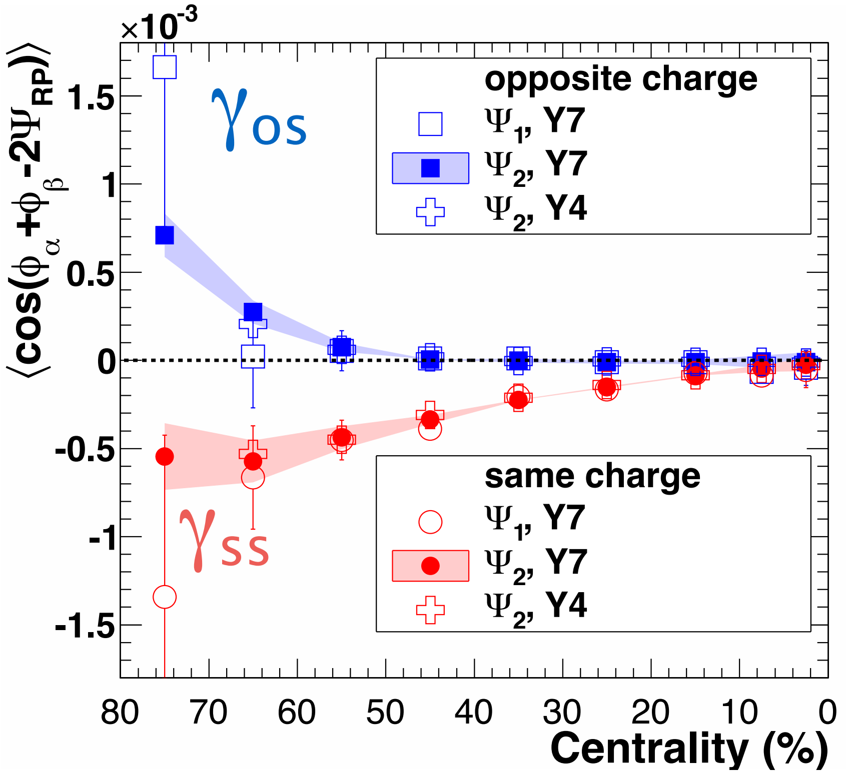
$$\left.\begin{array}{l} c > 0 \text{ if } \alpha \neq \beta \Rightarrow \gamma_{os} > 0 \\ c = 0 \text{ if } \alpha = \beta \Rightarrow \gamma_{ss} = 0 \end{array}\right\} \gamma_{os} - \gamma_{ss} > 0$$

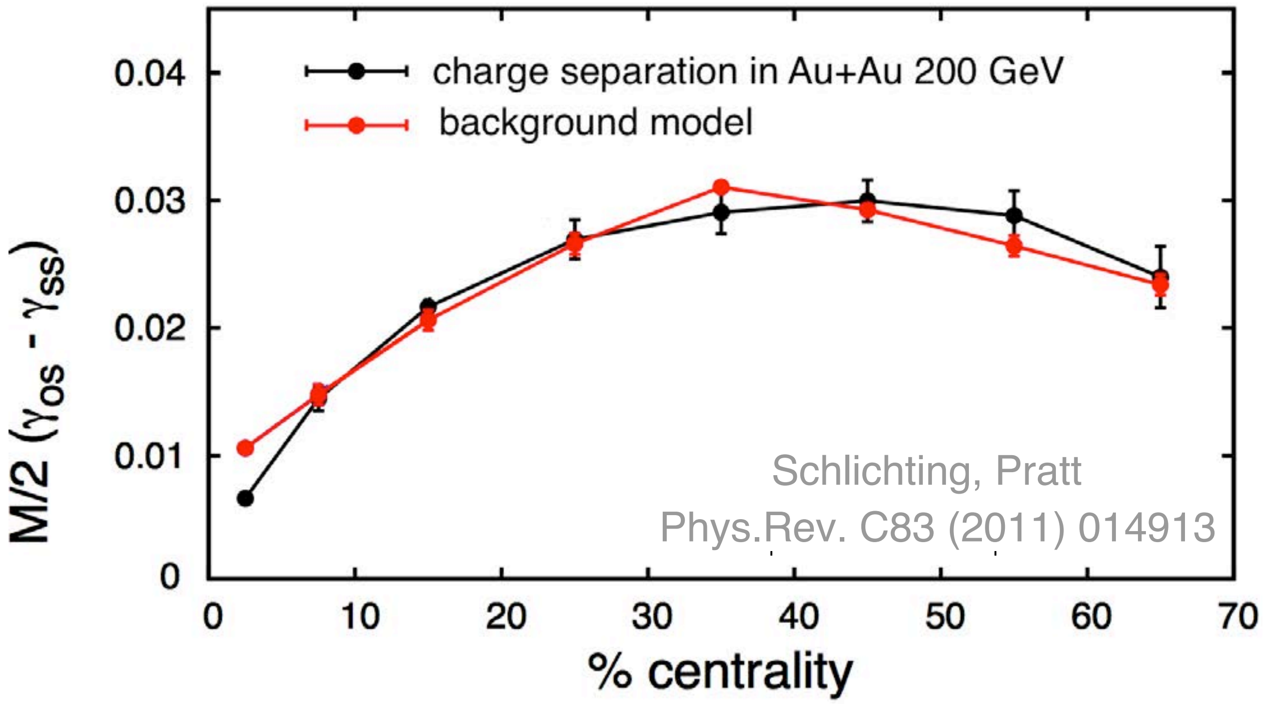
LCC explains $\Delta\gamma = (\gamma_{os} - \gamma_{ss})$ but not $\gamma_{os}$ & $\gamma_{ss}$ separately

Momentum conservation leads to negative $\gamma_{os}$ & $\gamma_{ss}$ but $\Delta\gamma$=0

# Background : Local charge conservation

Strong correlation between opposite charge pair
predicted by Blast Wave model : LCC + radial + Flow





Schlichting, Pratt
Phys.Rev. C83 (2011) 014913

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

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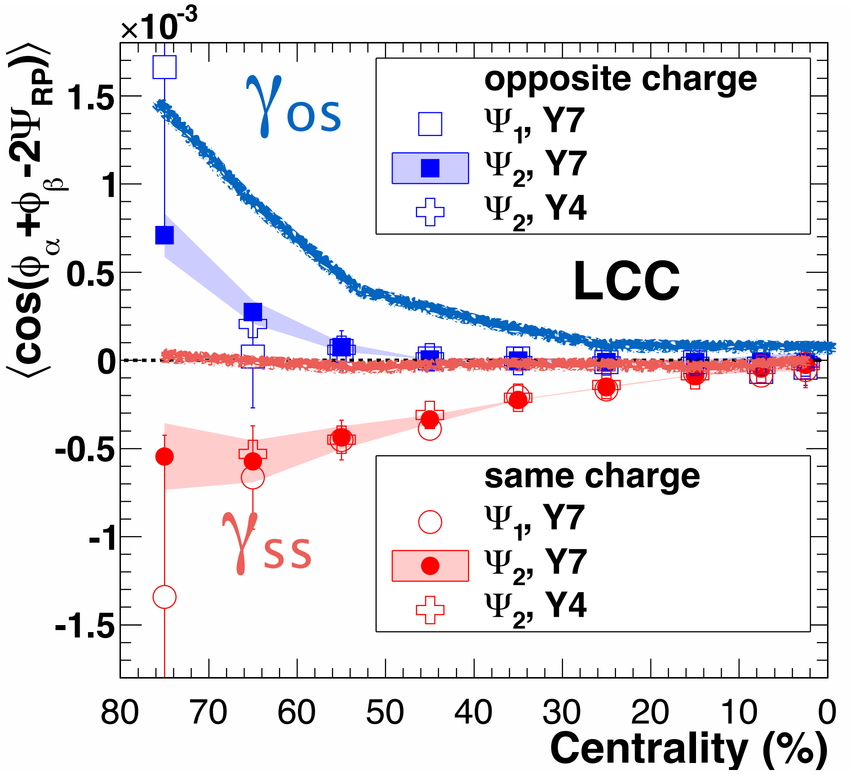

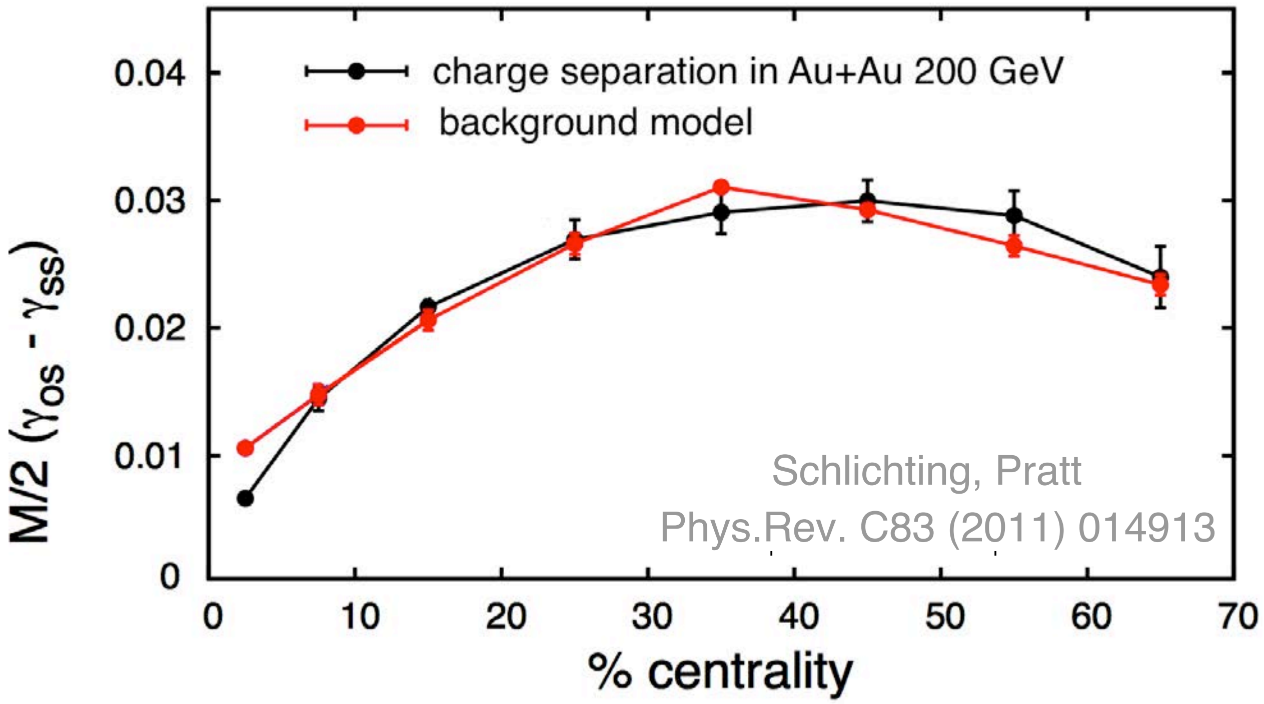

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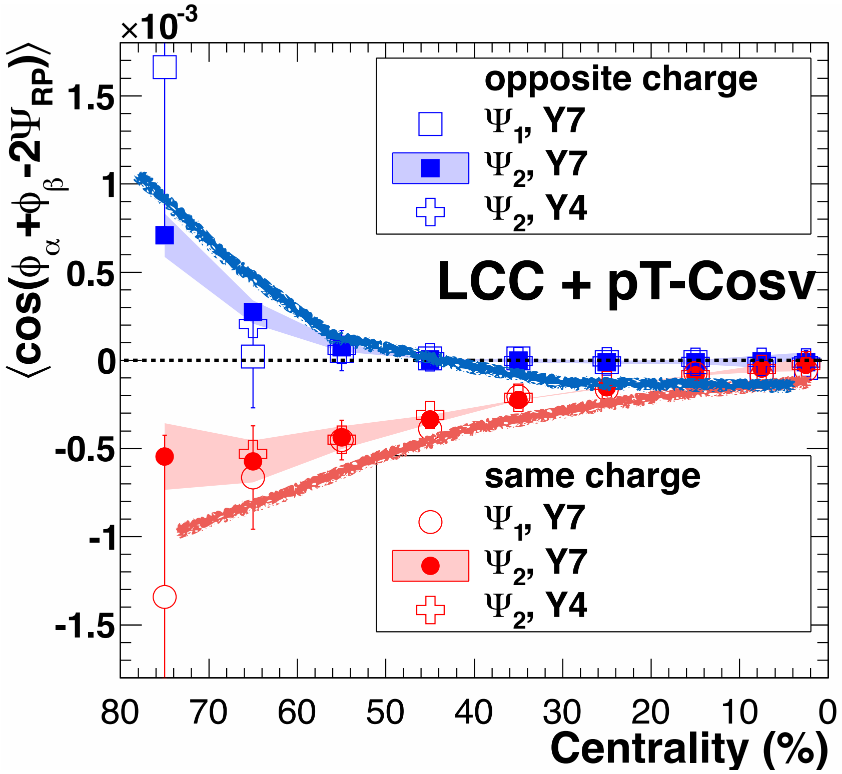

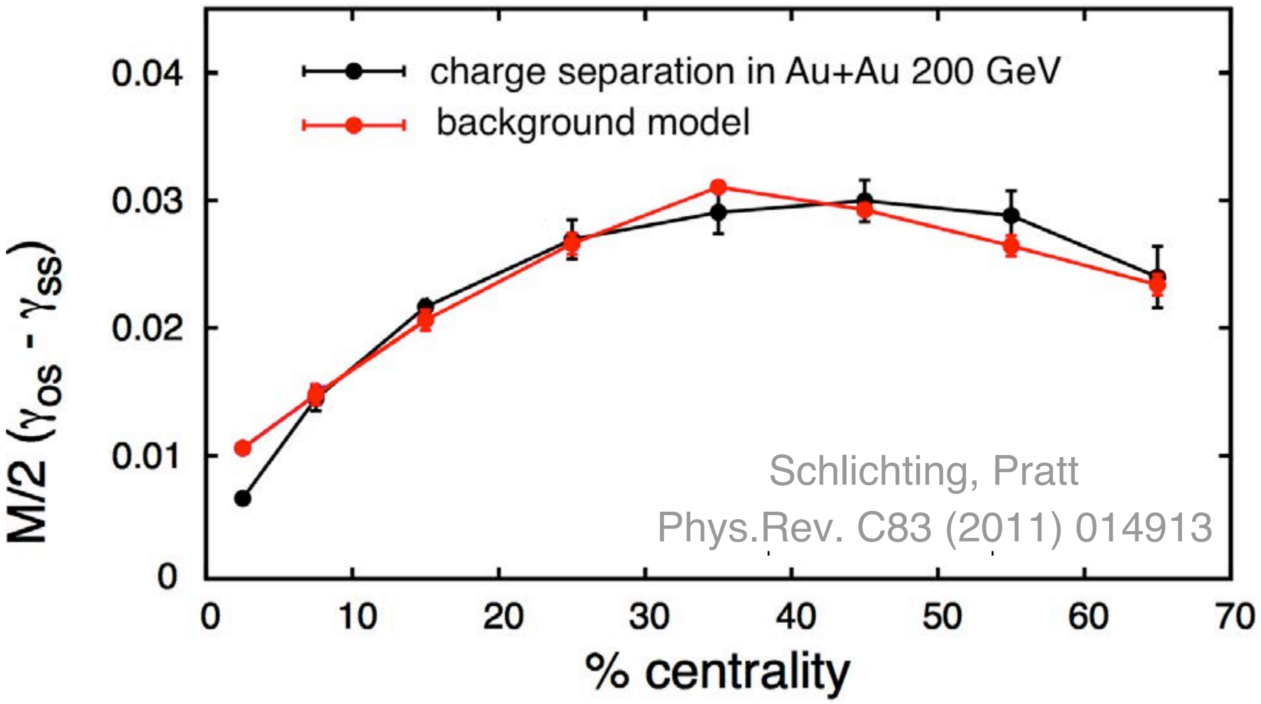

Pratt 1002.1758,
Pratt, Schlichting, Gavin1011.6053
Bzdak, Koch, Liao 1008.4919

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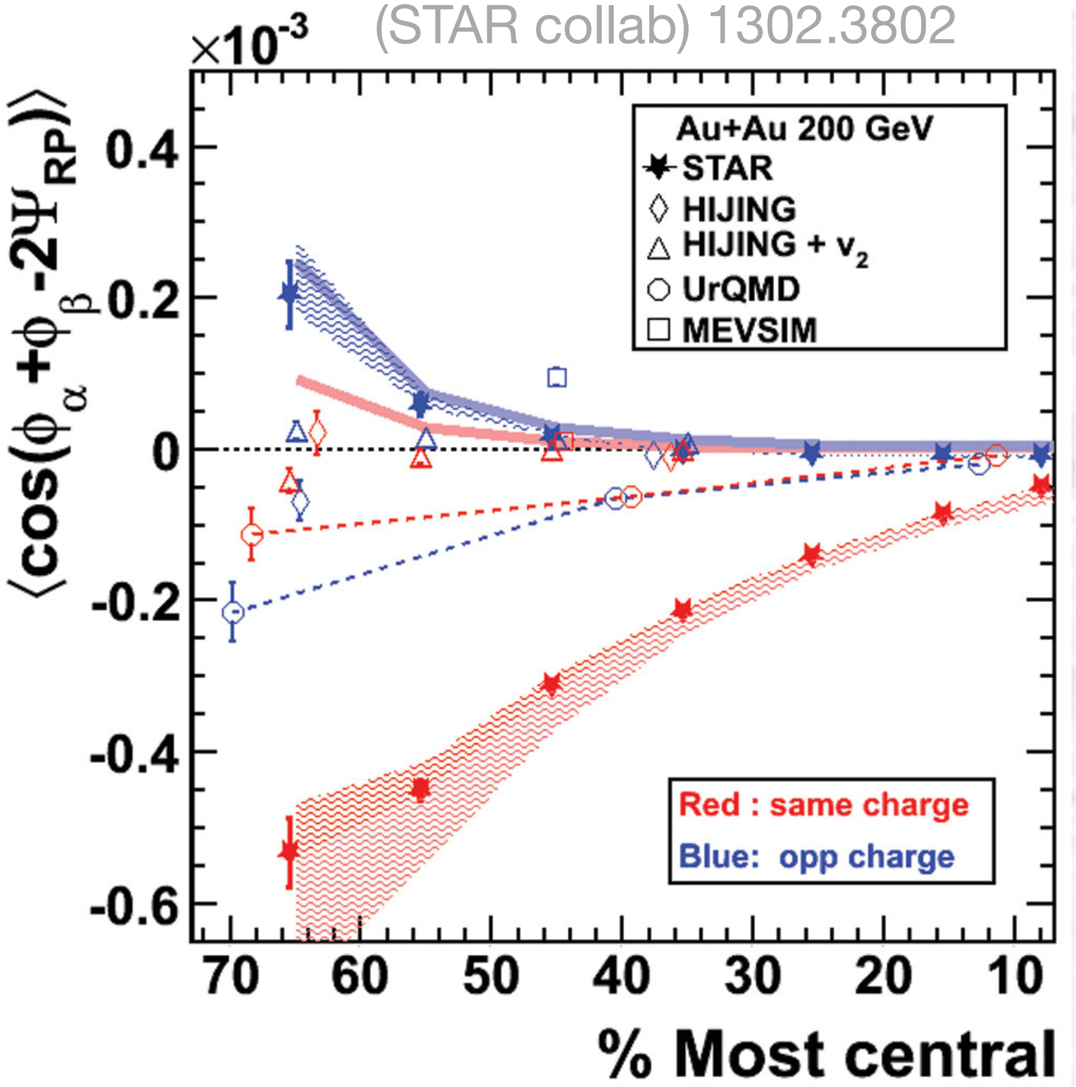
Momentum conservation will predict negative $\gamma_{os}$ & $\gamma_{ss}$ but $\Delta\gamma=0$

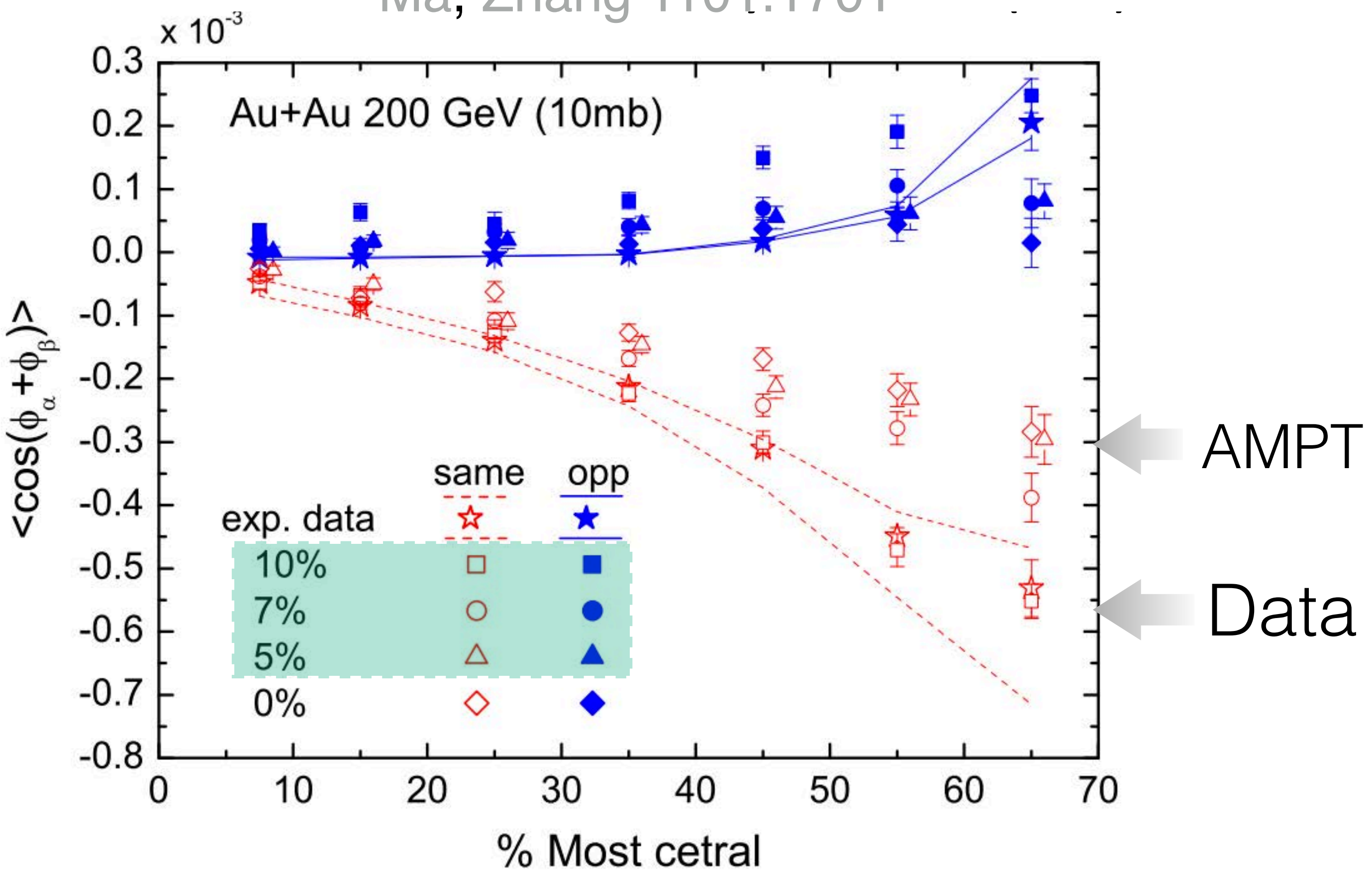
# Background : Model comparison

$$\gamma^{\alpha,\beta} = -\langle a_\alpha a_\beta \rangle + \boxed{c\ \frac{v_2}{N}}$$

Adamczyk *et. al.*
(STAR collab) 1302.3802



Ma, Zhang 1101.1701

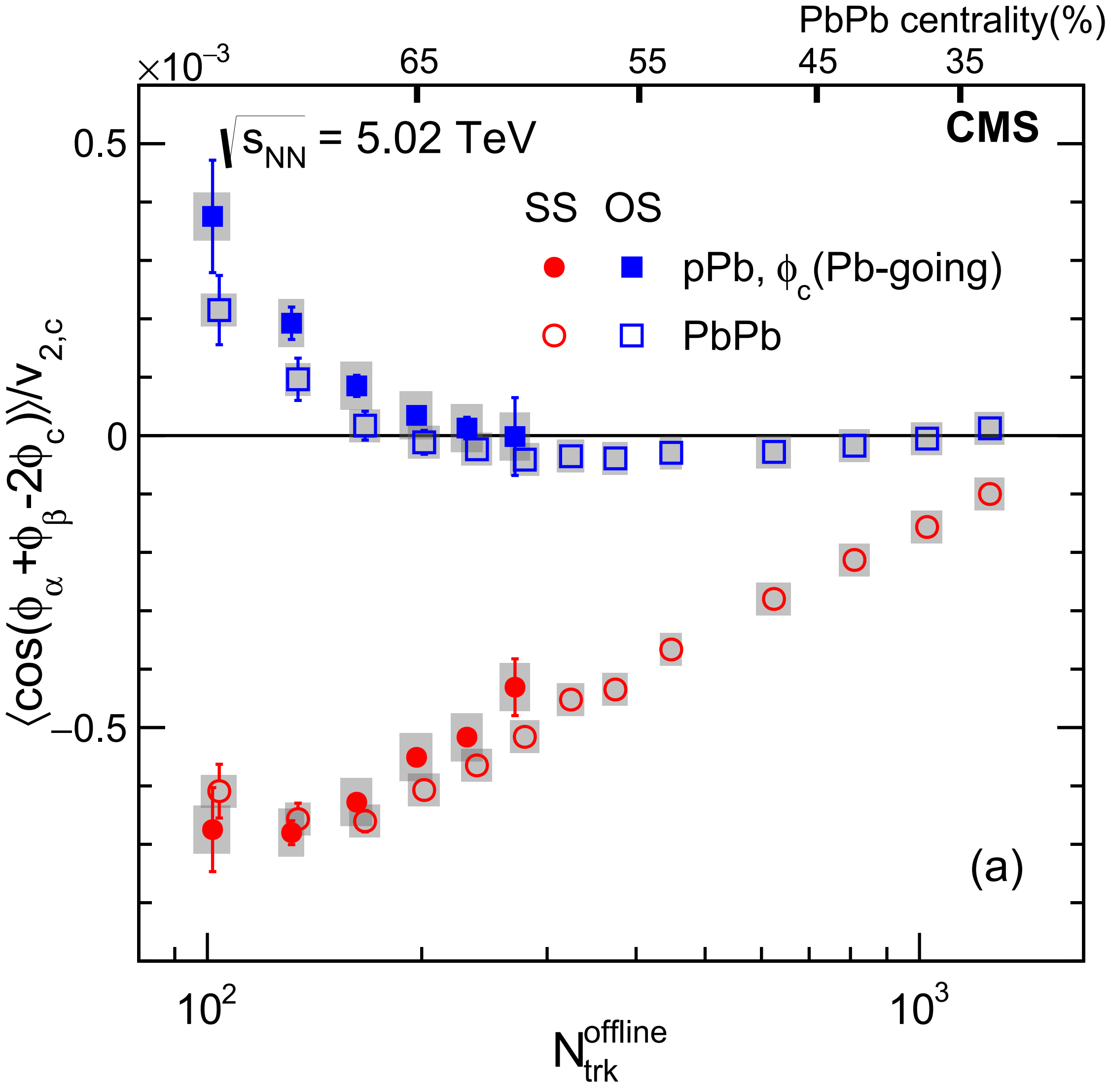


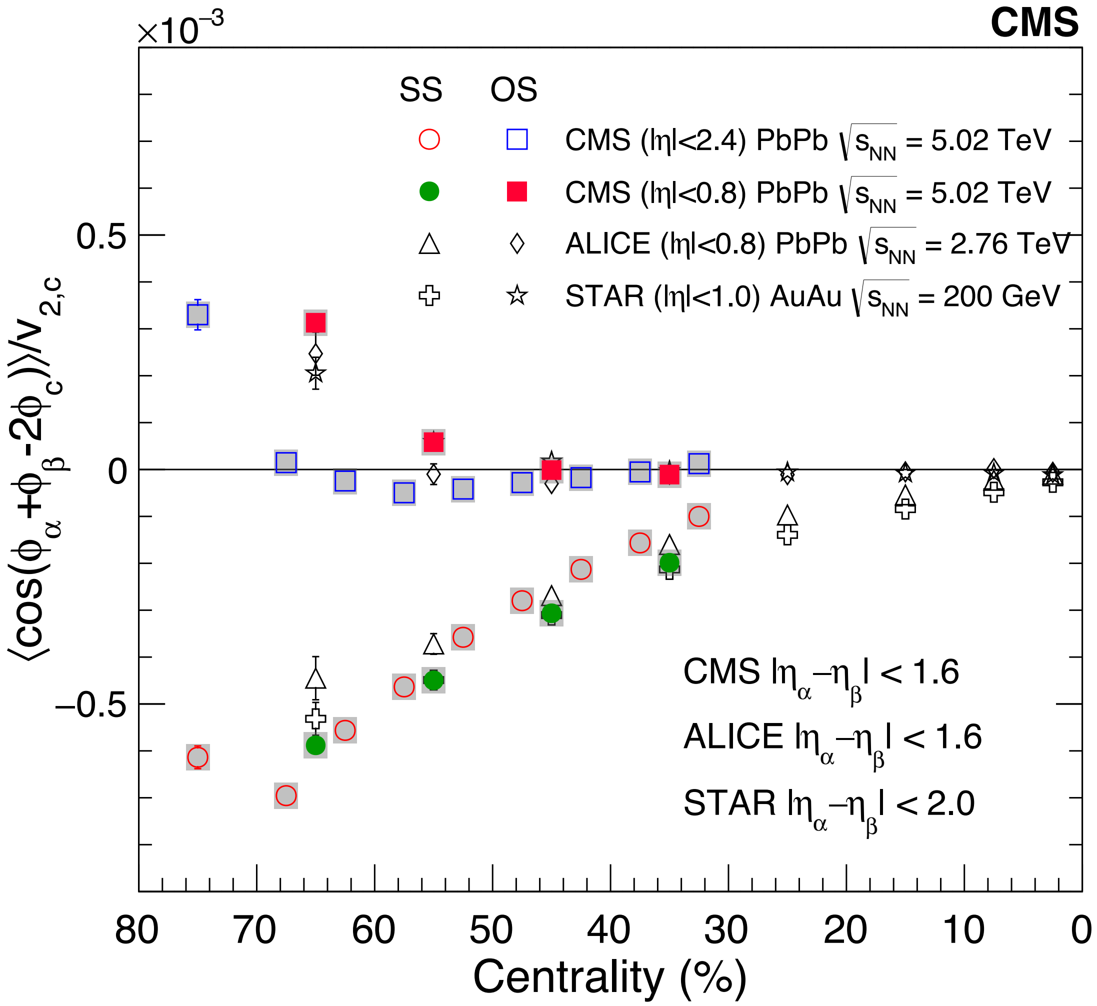
No (single) event generator can describe all aspects of the data

Some of the qualitative features can be explained

# Background : p+A collisions

New measurements at the LHC → new puzzles





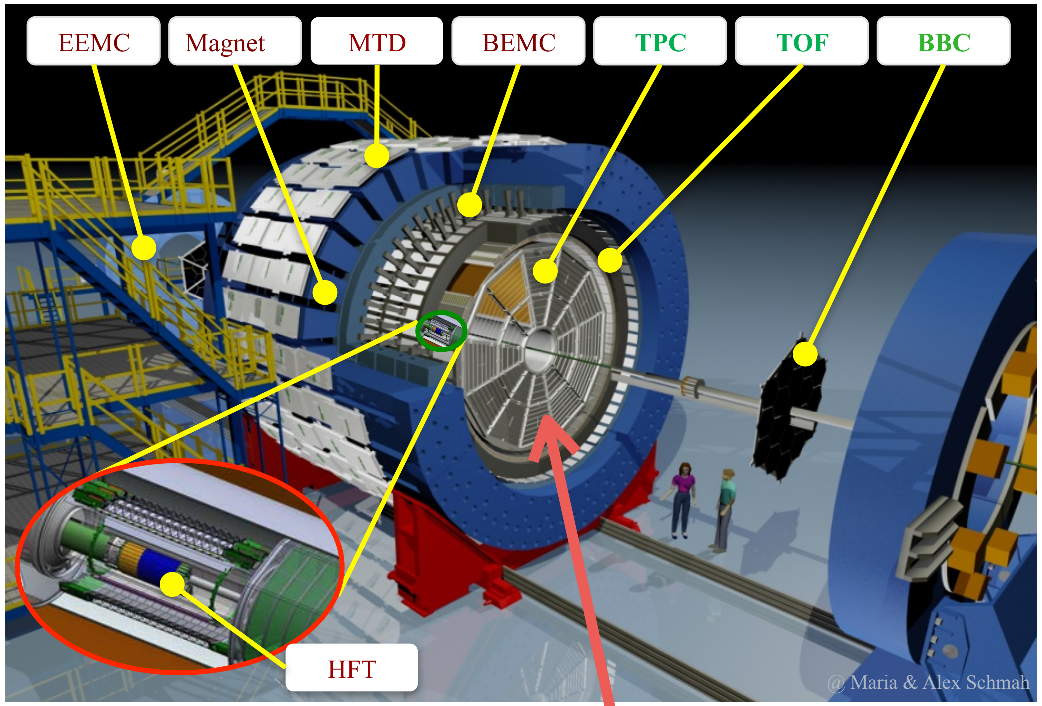
**arXiv:1610.00263**

Surprising similarity between p+Pb & Pb+Pb and between RHIC & LHC

“Challenge to CME” ?

# Recent measurements from STAR

STAR Detector



Time-Projection Chamber
(used for this analysis)

**Data Set :**

U+U 193 GeV (2012),
Au+Au 200 GeV (2011),
p+Au 200 GeV (2015)

**Acceptance :** $0<\phi<2\pi$, $|\eta|<1$,
$p_T > 0.2$ GeV/c

**Centrality :**

Time Projection Chamber
Zero Degree Calorimeter

**Observables :**

Voloshin, PRC 70 (2004) 057901

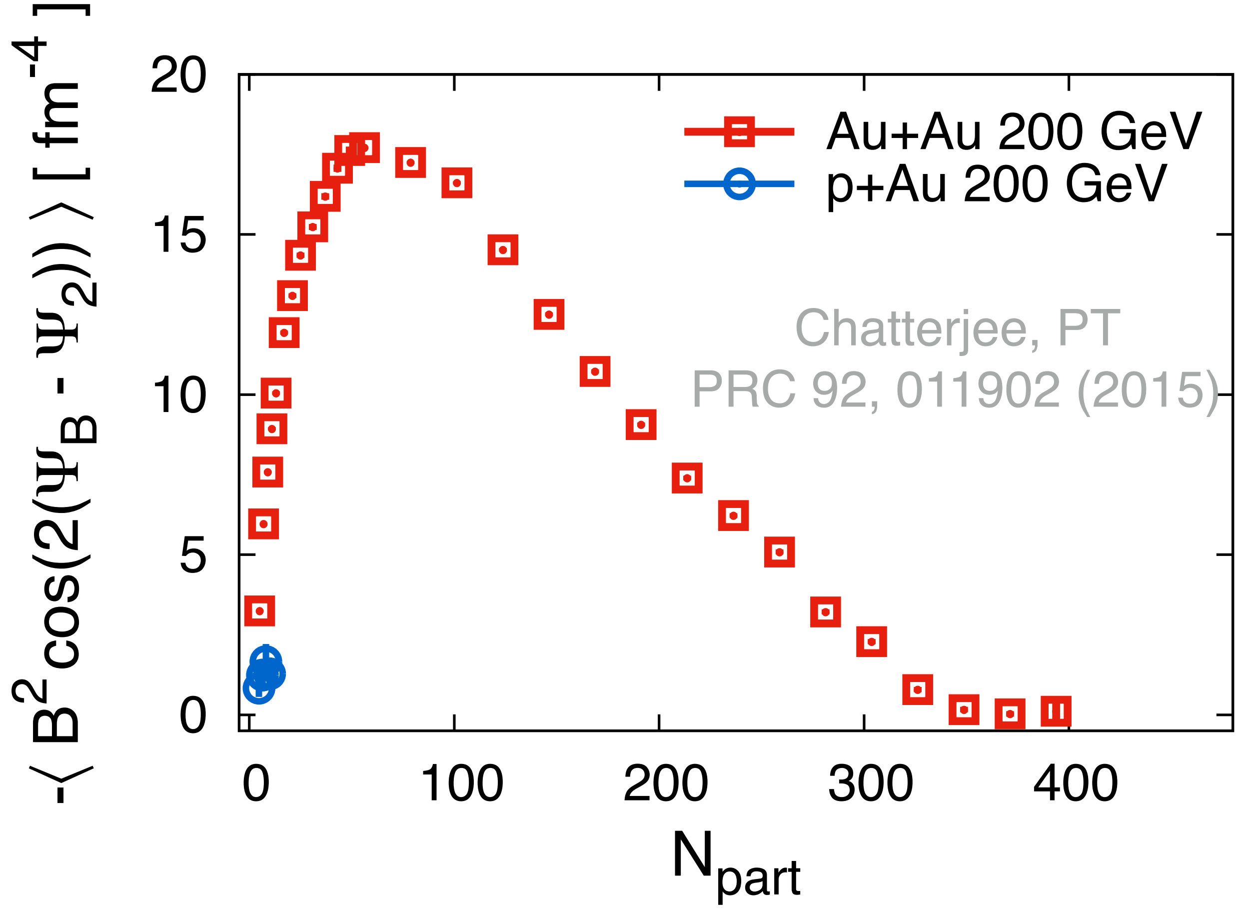
Three particle correlator : $C_{112} = \langle \cos(\phi_1 + \phi_2 - 2\phi_3) \rangle$

LPV correlator : $\gamma^{a,b} \sim \dfrac{\langle \cos((\phi_1^a + \phi_2^b - 2\phi_3)) \rangle}{v_2\{2\}}$ , $v_2\{2\}^2 = \langle \cos(2(\phi_1 - \phi_2)) \rangle$

# Revisit : Magnetic field in HICs

Quantity of interest is the projection of B on $\Psi_2$

$$a_{\pm} \propto \mu_5 \vec{B} \implies \langle a_\alpha a_\beta \rangle \propto |\vec{B}|^2 \implies \langle B^2 \cos(2(\Psi_B - \Psi_2)) \rangle$$



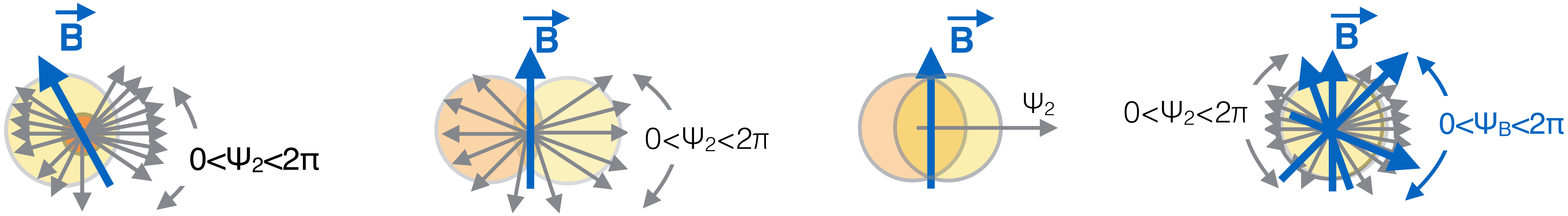
Chatterjee, PT
PRC 92, 011902 (2015)

Projected
B-field

$$\langle B^2 \cos(2(\Psi_B - \Psi_2)) \rangle$$

Observable

$$\langle \cos(\phi_\alpha + \phi_\beta - 2\Psi_{RP}) \rangle$$



p+A

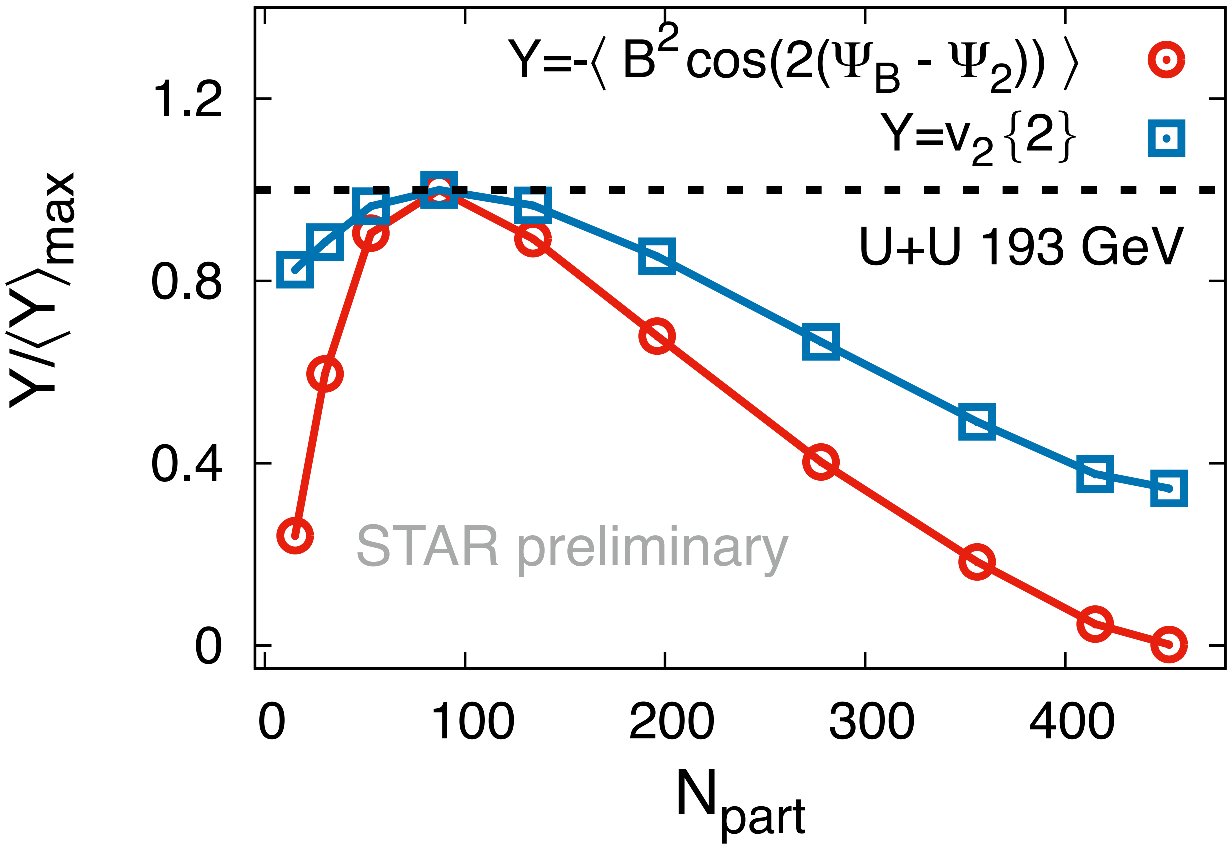
peripheral

mid-central

central

# Why background removal is difficult ?

v2 → STAR data, B-field → Chatterjee, PT, PRC 92, 011902 (2015)



$$\gamma^{\alpha,\beta} = -\langle a_\alpha a_\beta \rangle + c\,\frac{v_2}{N}$$

B-field driven
(Signal)

flow driven
(Background)

The centrality dependence of signal & background is similar

Attempts to reduce flow also reduces the ability to resolve the direction of event plane and therefore the direction of projected B-field

Disentangling the effects driven by B-field and flow is challenging

# How to deal with this problem

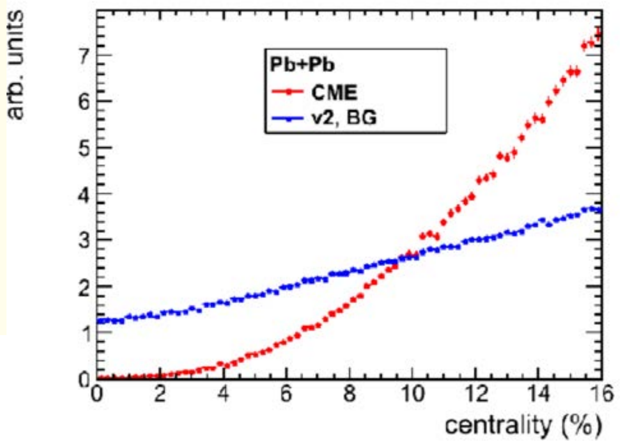
## A list provided by Sergei Voloshin during QM 2017

- Beam energy scan II (signal should disappear at lower energies)
- Vary magnetic field keeping the same flow (isobar collisions)
- Higher harmonic correlators (+ differential)
- Event Shape Engineering (increase/decrease background)
- Correlations with identified particles (e.g. for the next bullet)
- Cross-correlation of different observables, CME X CMW X CVE) (both in experiment and theory)
- U+U (body-body vs tip-tip ??)
- Very central collisions ( Signal ~0, BG>0)
- Small system collision (??)

- Studies of EM fields
- Improving the phenomenology

- Try a new observable

Chatterjee, PT
PRC 92, 011902 (2015)
fig : Voloshin



https://indico.cern.ch/event/433345/contributions/2345400/attachments/1407180/2150703/voloshin_CAEs_v2.pdf

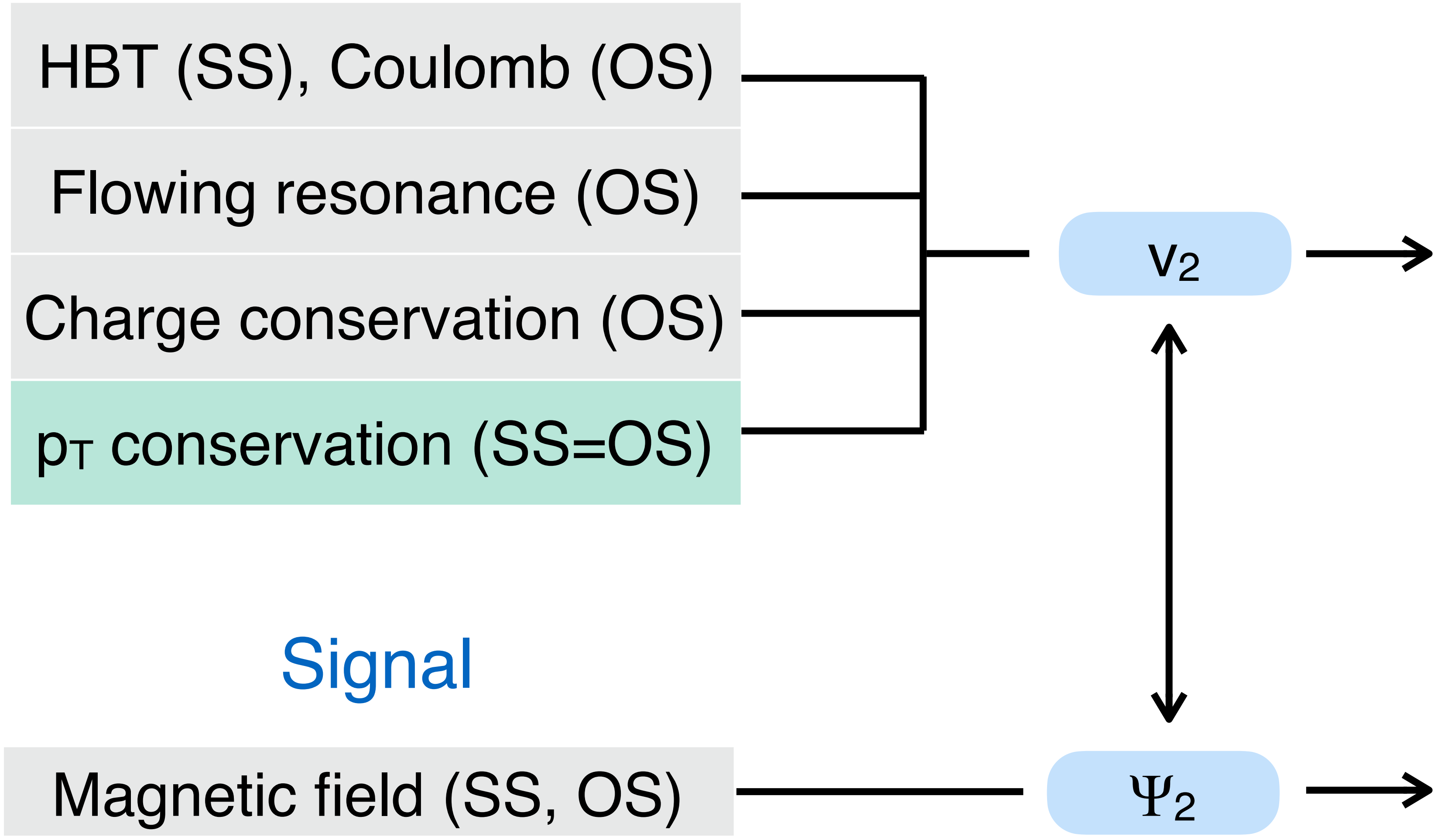
# Signal & Backgrounds of charge separation

## Charge separation (central-events)

$$\gamma^{\alpha,\beta} = \langle \cos(\phi_\alpha + \phi_\beta - 2\Psi_2) \rangle = -\langle a_\alpha a_\beta \rangle + c\frac{v_2}{N}$$

$$\Delta\gamma = \gamma^{OS} - \gamma^{SS} = \left\langle \sum_{\alpha,\beta} -a_\alpha a_\beta \right\rangle + c\,\frac{v_2}{N}$$

## Backgrounds



HBT (SS), Coulomb (OS)

Flowing resonance (OS)

Charge conservation (OS)

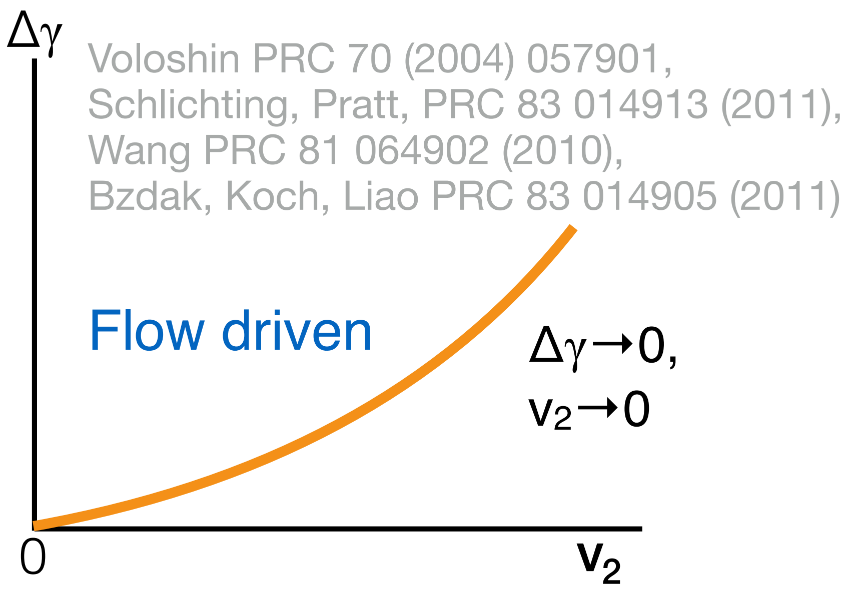
$p_T$ conservation (SS=OS)

$v_2$

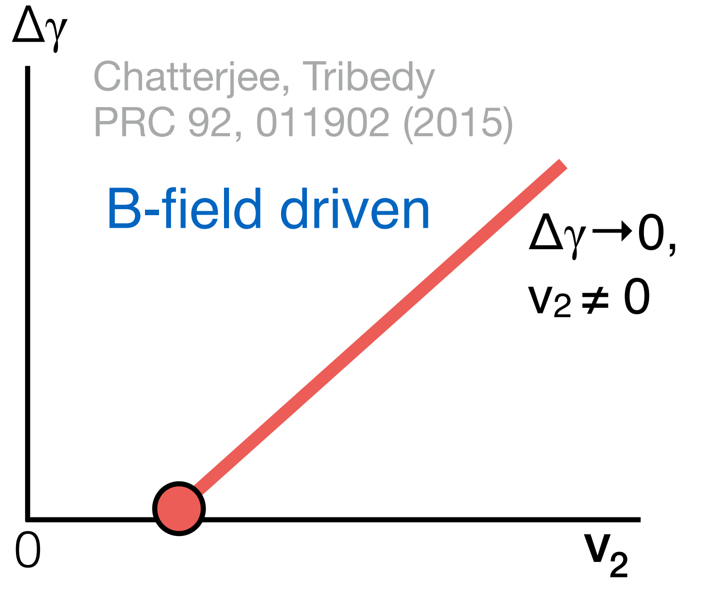
## Signal

Magnetic field (SS, OS)

$\Psi_2$



Voloshin PRC 70 (2004) 057901,
Schlichting, Pratt, PRC 83 014913 (2011),
Wang PRC 81 064902 (2010),
Bzdak, Koch, Liao PRC 83 014905 (2011)



Chatterjee, Tribedy
PRC 92, 011902 (2015)

## Possible strategy : look for $\Delta\gamma \rightarrow 0$, $v_2 \neq 0$

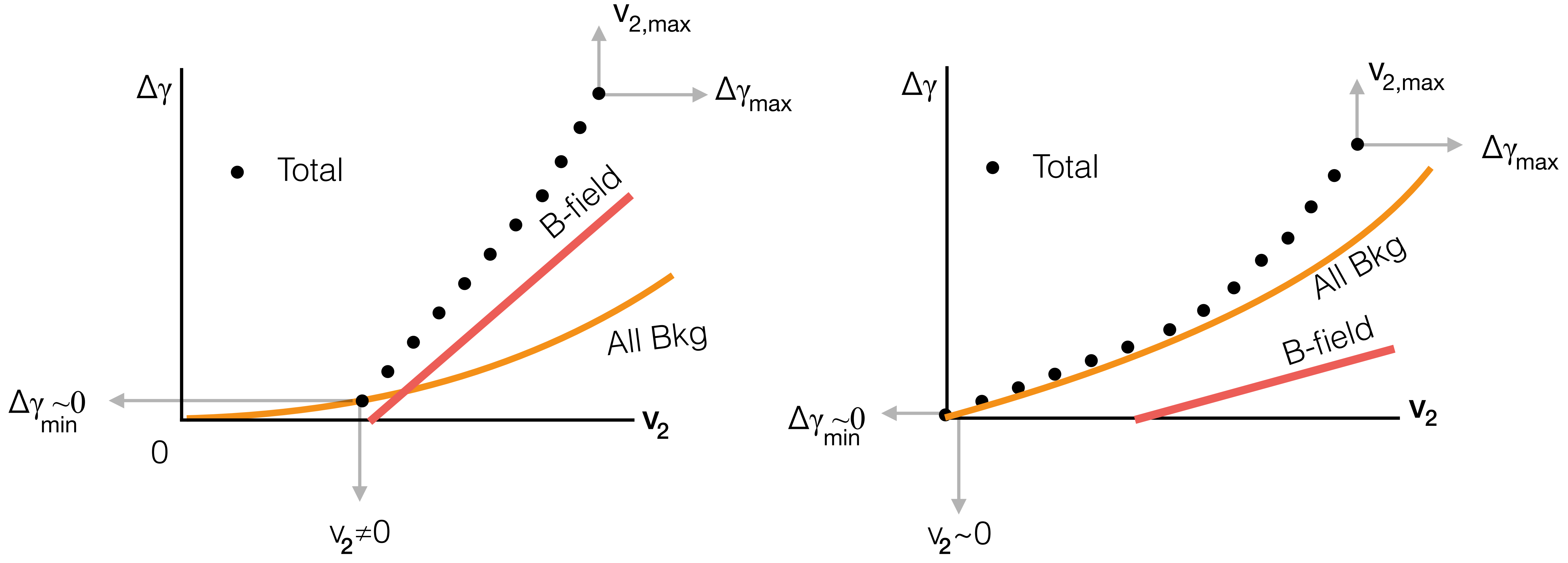
# Two possible scenarios

Measurements in central-events may help disentangle the two effects

$$\Delta\gamma = \gamma^{OS} - \gamma^{SS} = \left\langle \sum_{\alpha,\beta} -a_\alpha a_\beta \right\rangle + c\,\frac{v_2}{N}$$

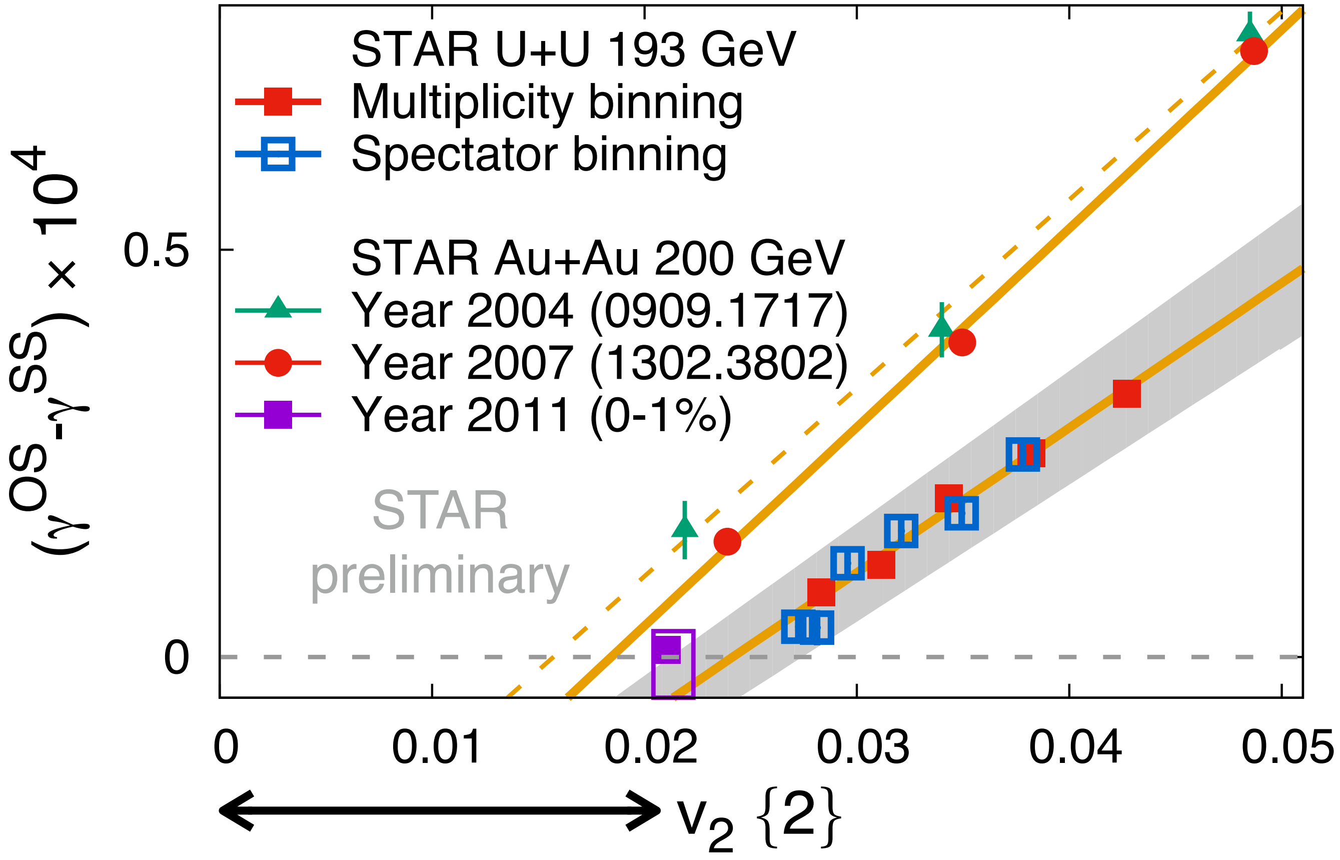
If B-field dominates

If Background dominates

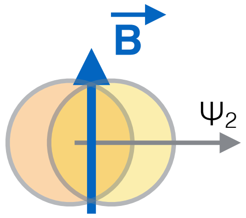


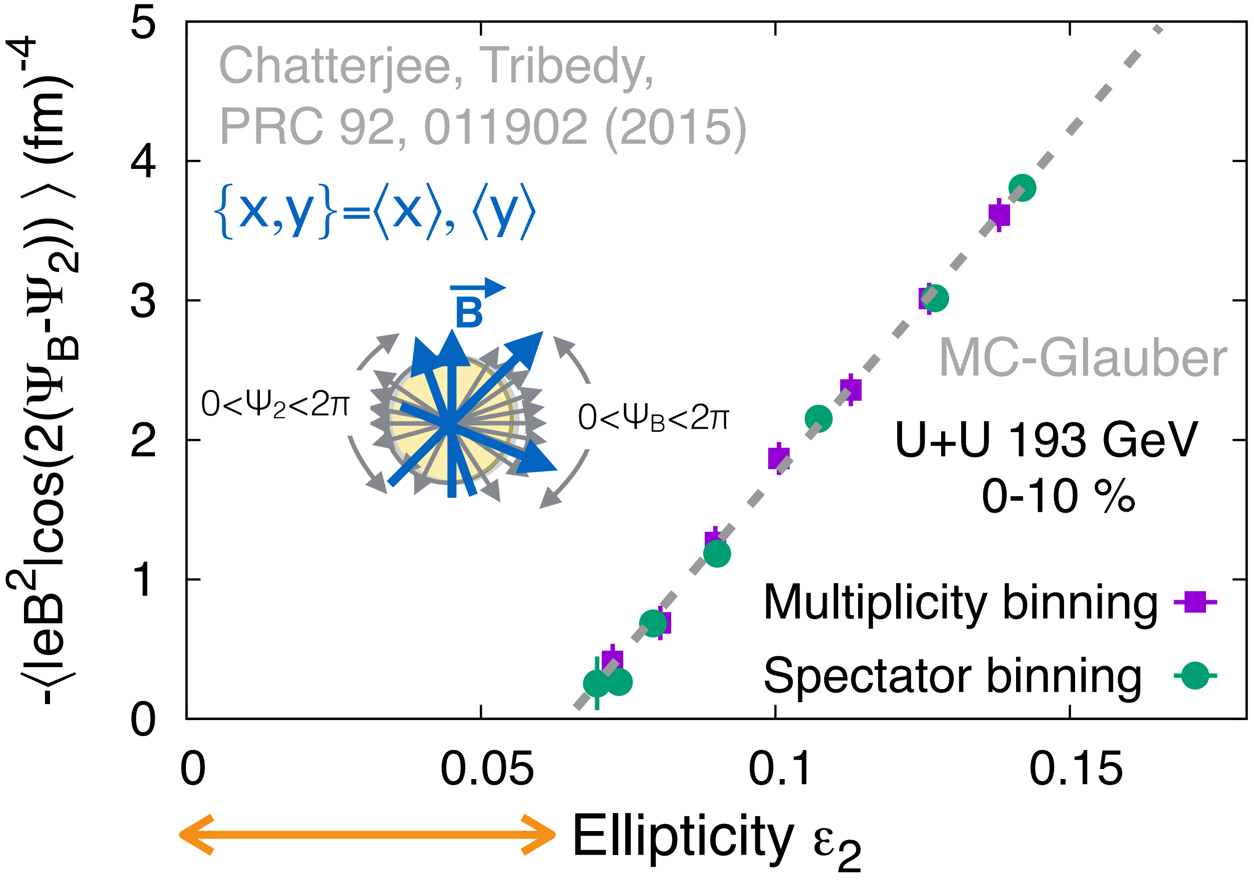
# Central and Ultra-central Collisions

Data



Projected B-field



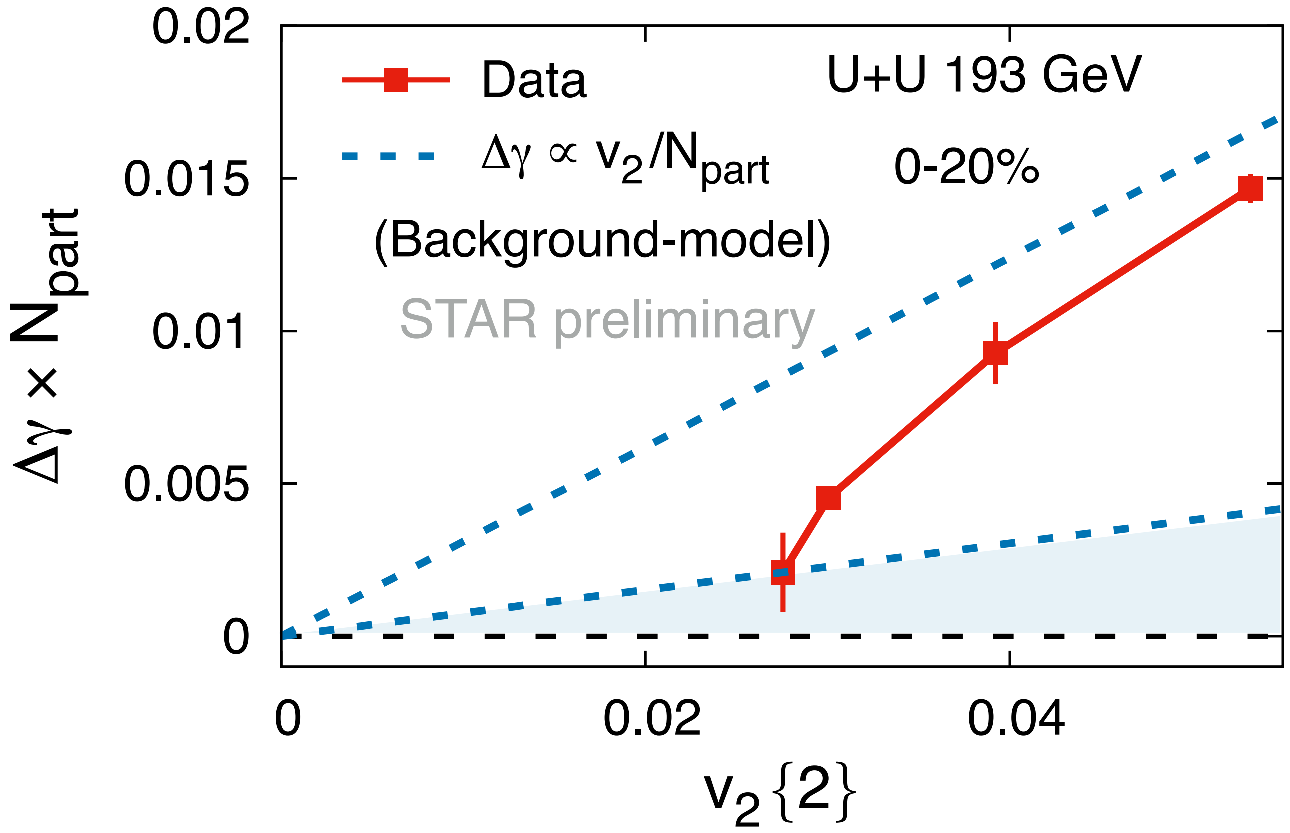


Projected B-field vs $\varepsilon_2$ can provide a natural explanation to the data

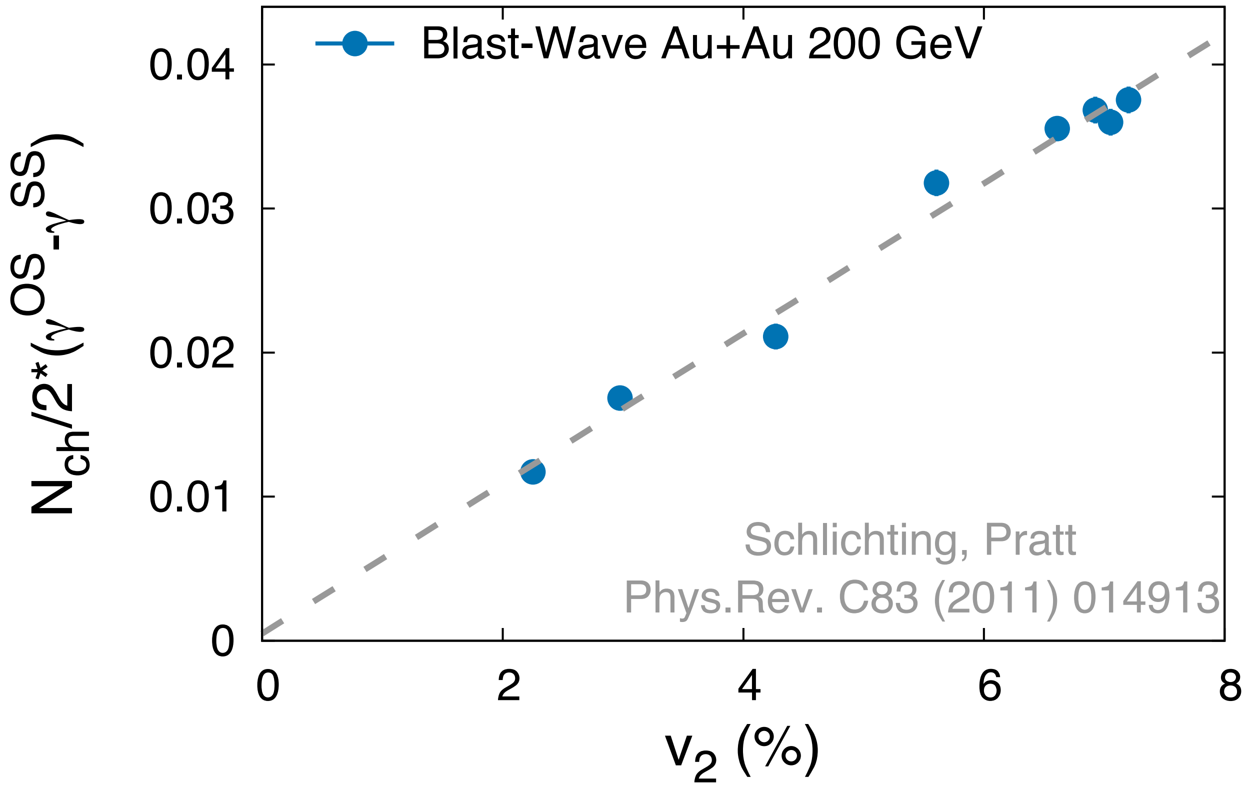
More theory inputs needed to see if a background model can explain data

# Central and Ultra-central Collisions

Data



Local charge conservation



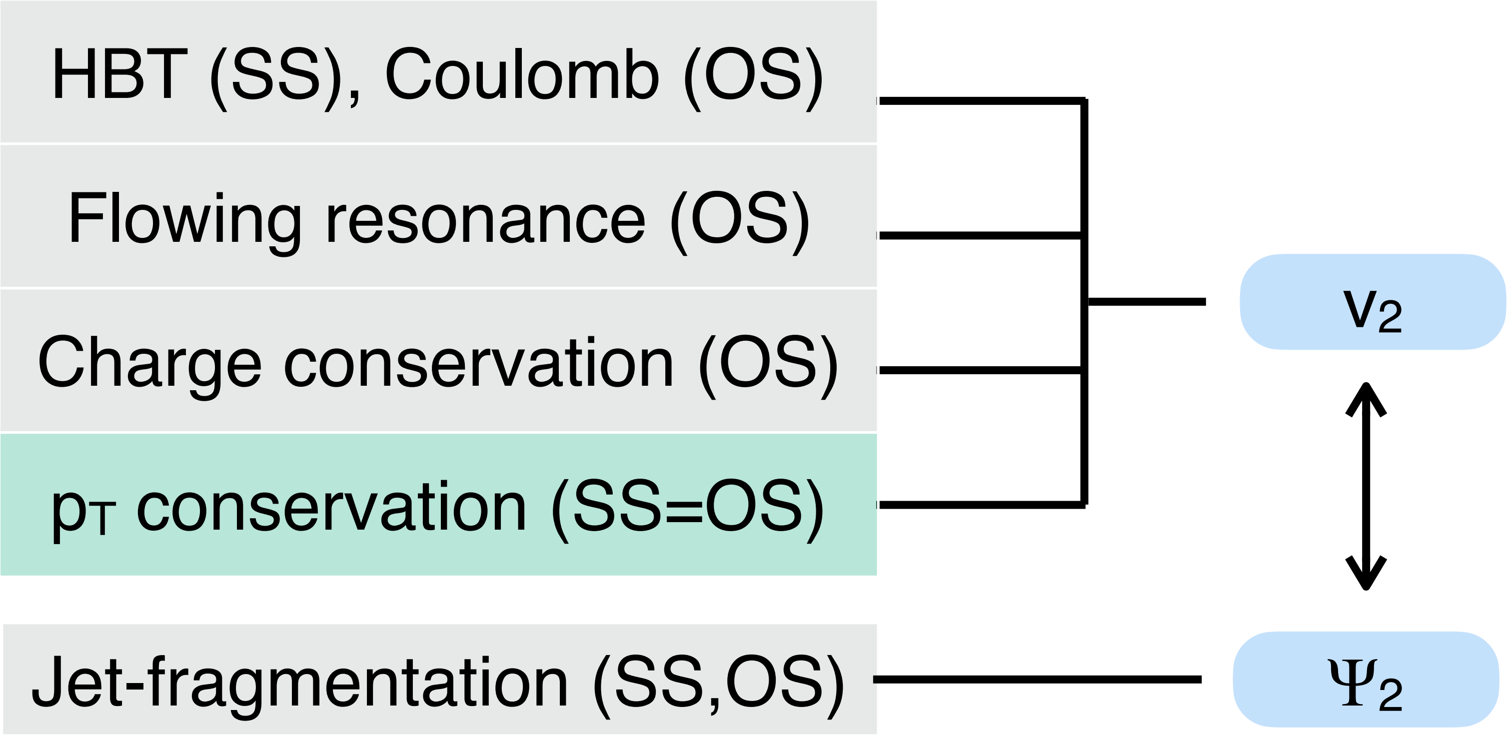
$$(\Delta\gamma)^{LCC} = \gamma^{OS} - \gamma^{SS} = c\,\frac{v_2}{N}$$

Highly constrained

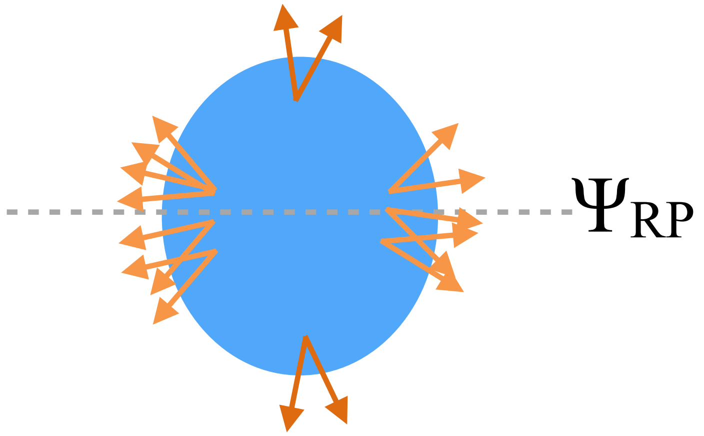
# Peripheral collisions in A+A

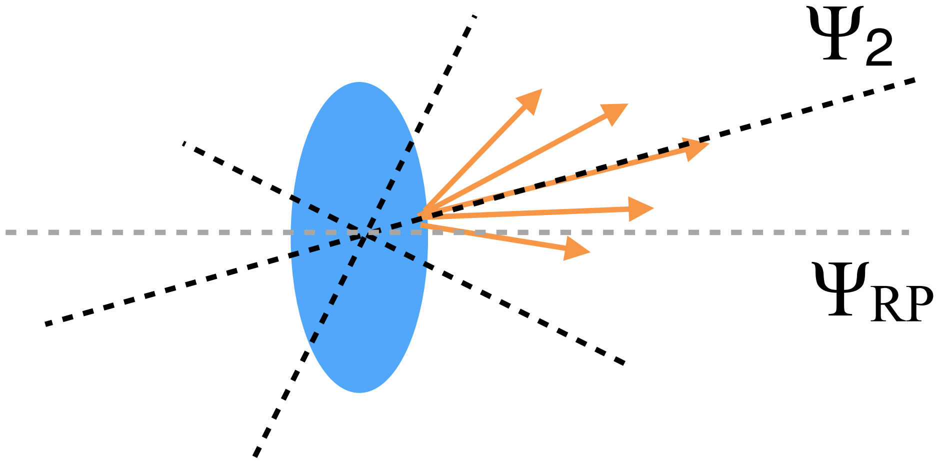
However complicated background effects
may arise in peripheral events

Backgrounds



Central A+A : Δη,Δϕ∼0 emission + $v_2$ modulation, jets are mostly quenched

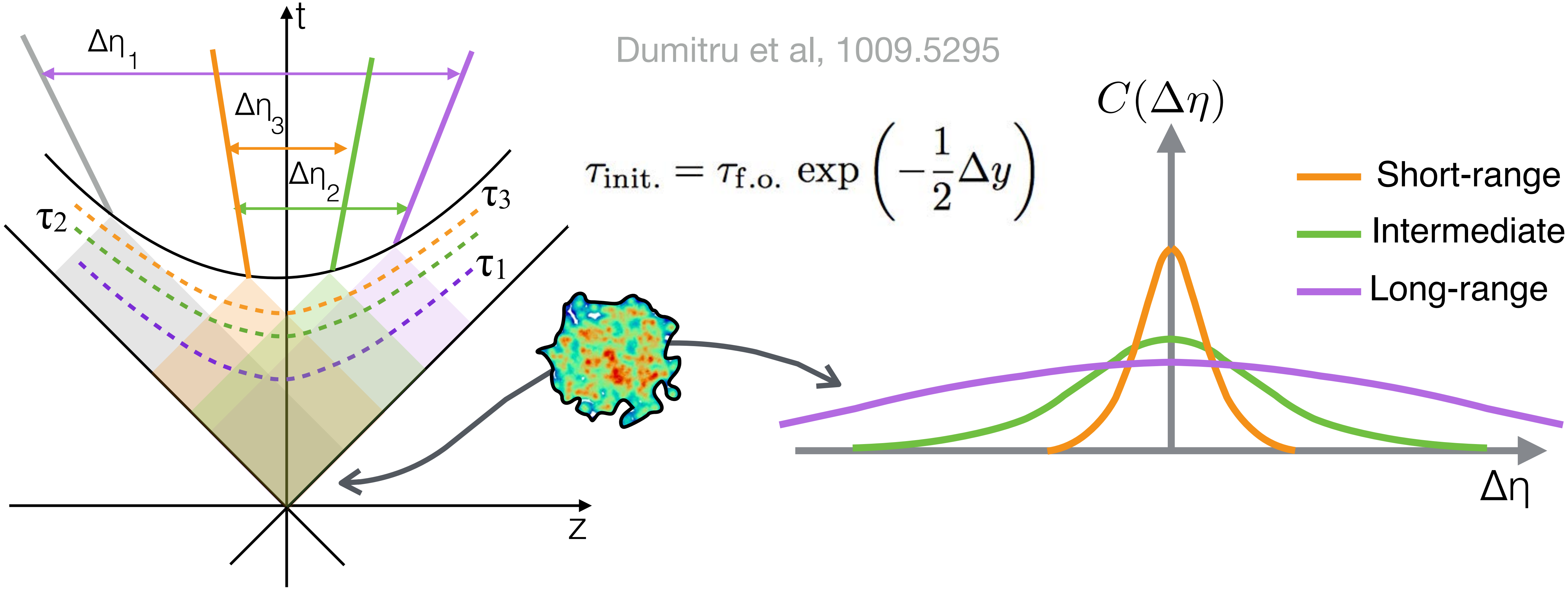




Peripheral A+A :
Jet-fragmentation → Jets define the $\Psi_2$

# A new approach to reduce background

Early time effects→ should be long-range in $\Delta\eta$



Dumitru et al, 1009.5295

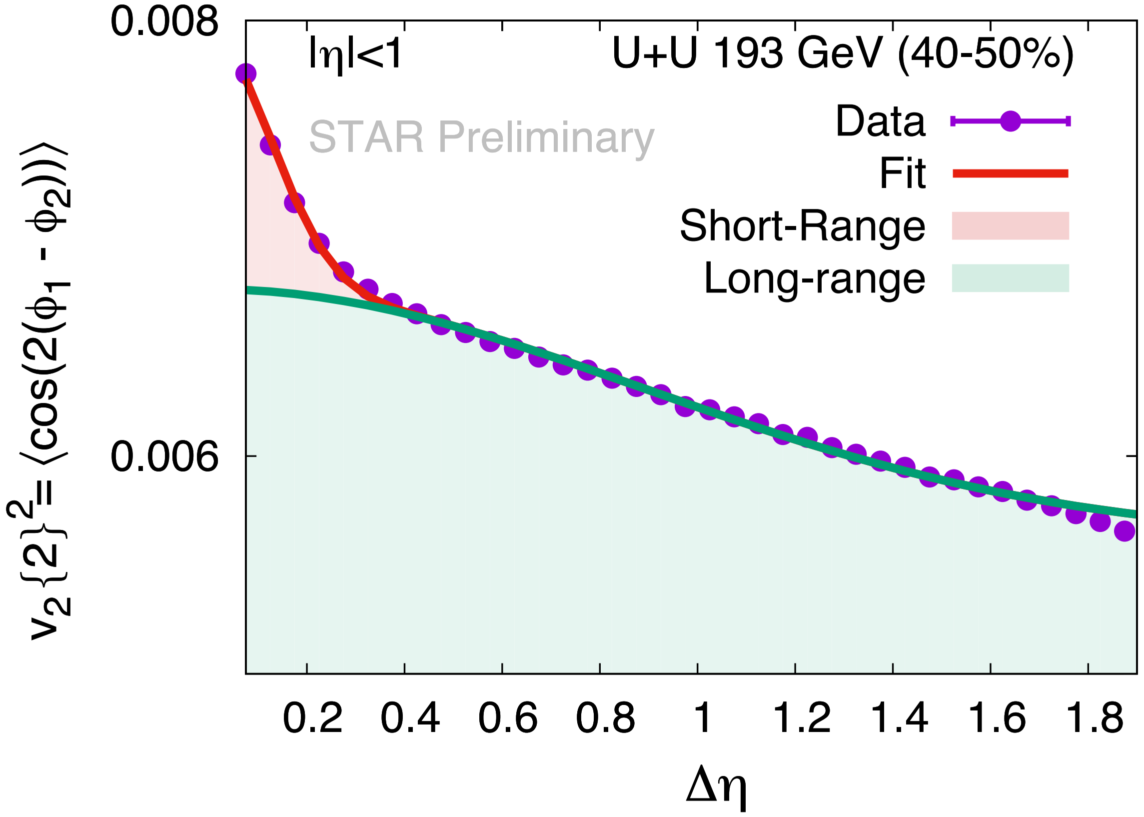
$$\tau_{\rm init.} = \tau_{\rm f.o.}\ \exp\left(-\frac{1}{2}\Delta y\right)$$

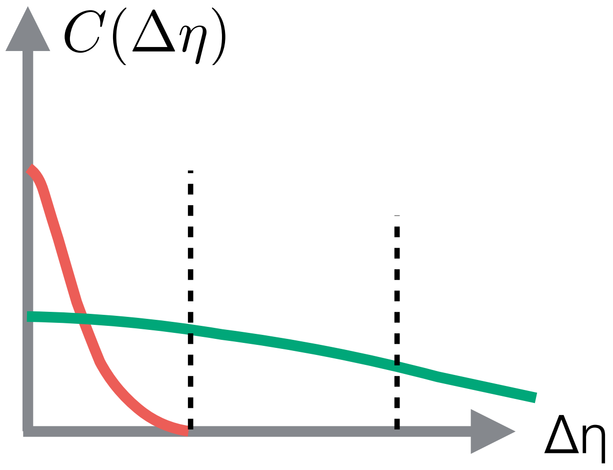
Differential measurement of correlation in Δη may be a key to disentangle signal and background

# Structure of the correlations in Δη

## Two-particle correlation

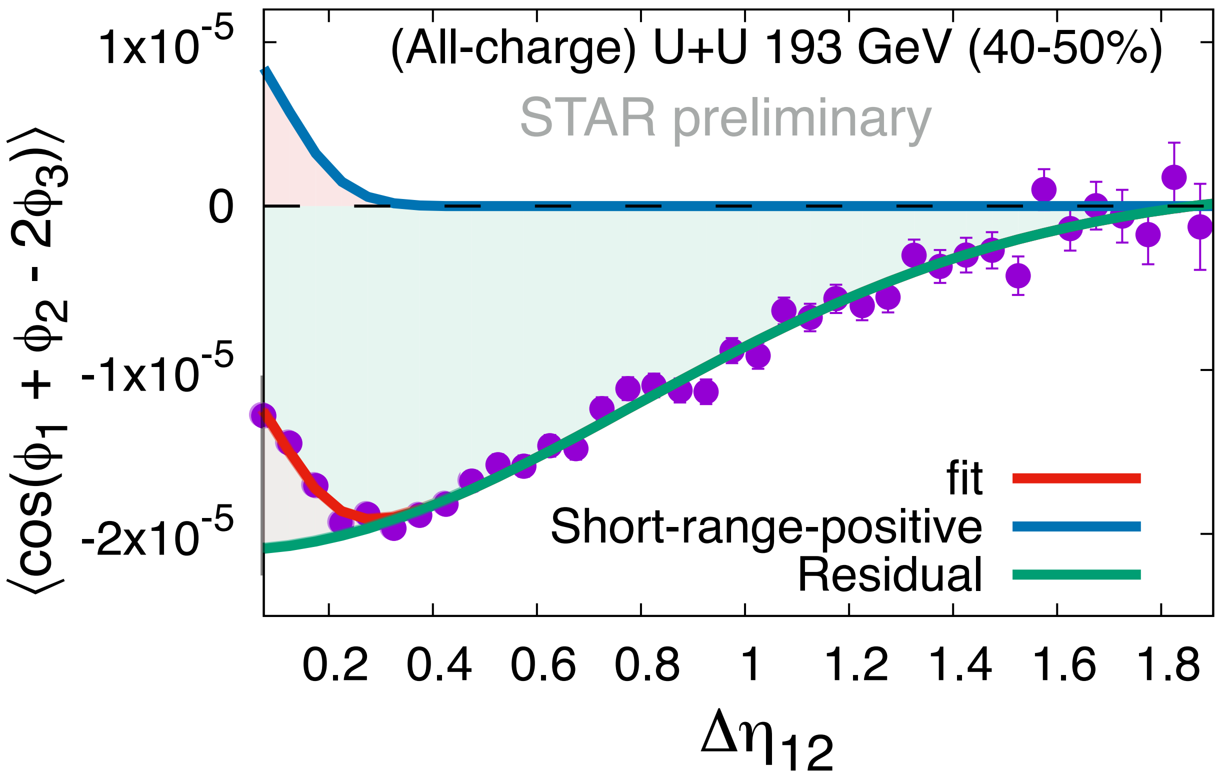
(elliptic flow $v_2$)

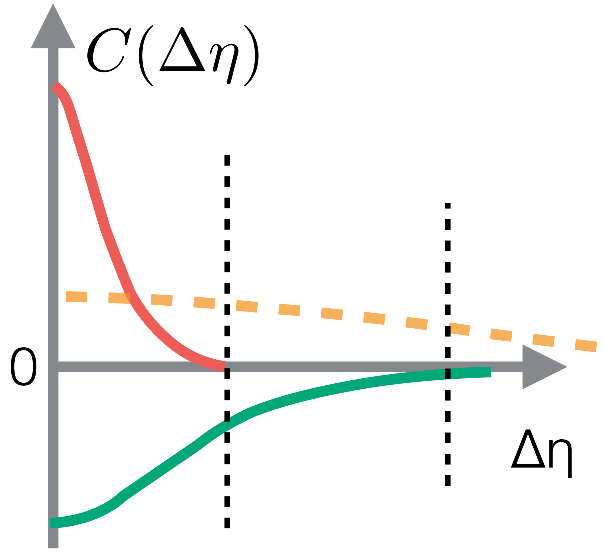




## Three-particle correlation

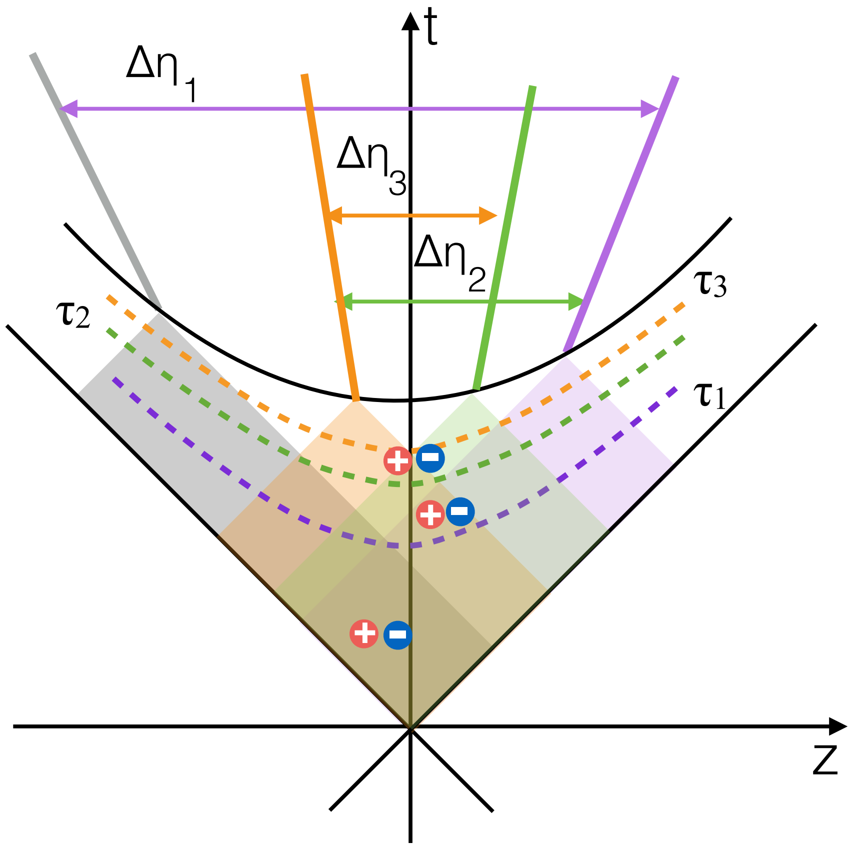
(numerator of $\gamma^{\alpha\beta}$ )

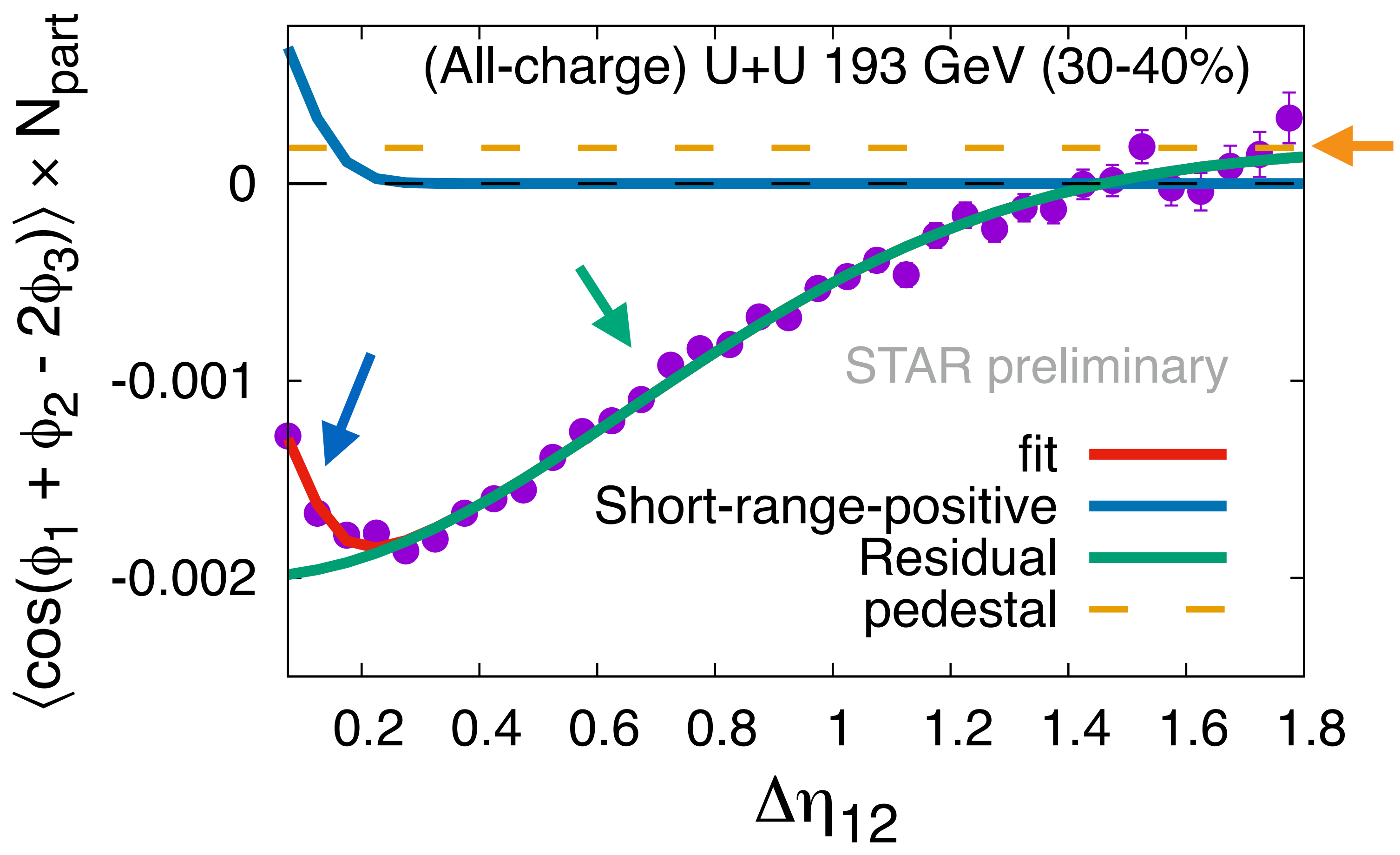




# A new approach to reduce background

Search of early time charge separation → should be long-range in $\Delta\eta$

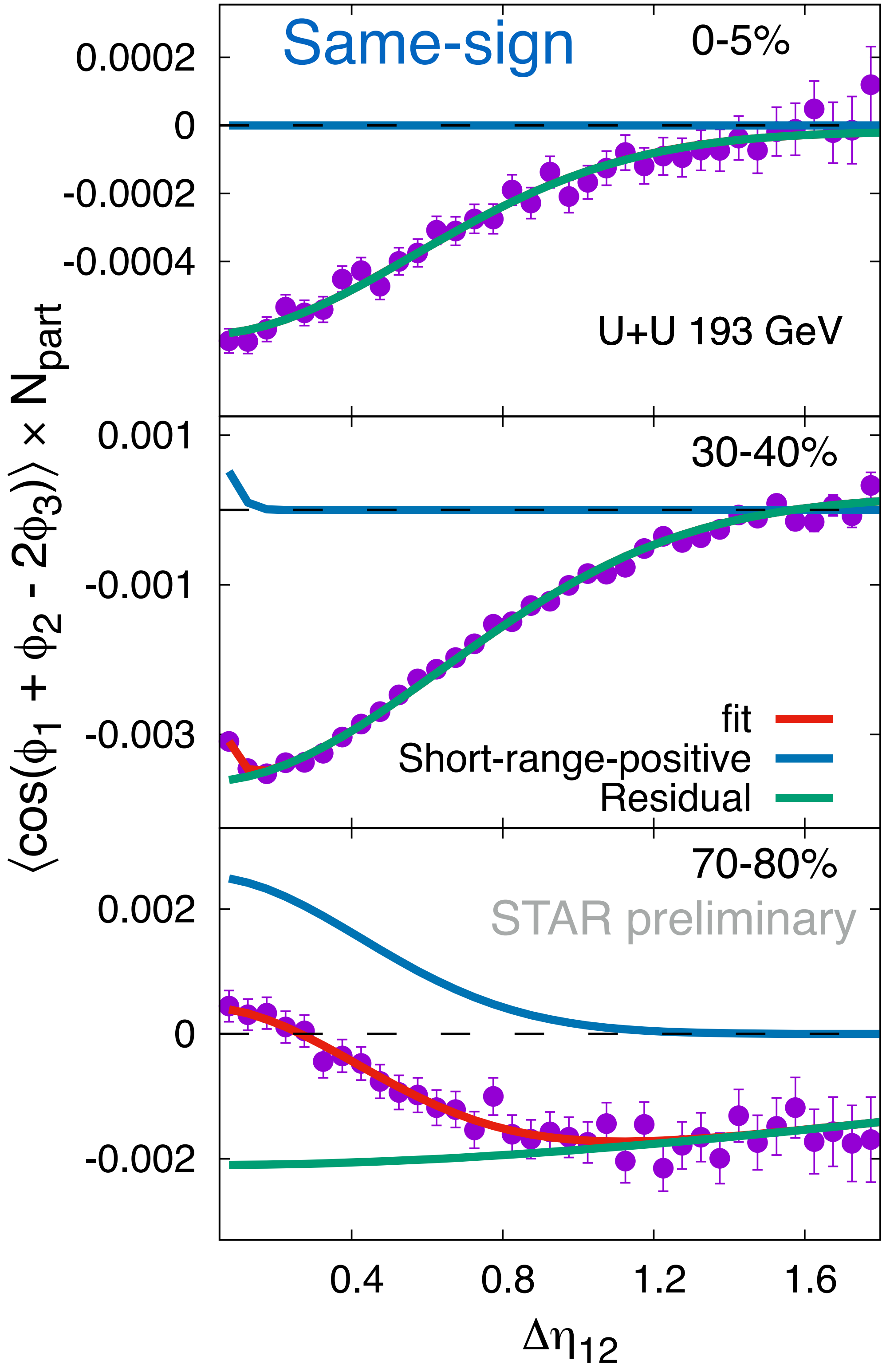




Short-range limit : $\Delta\phi \to 0, \Delta\eta \to 0 : C_{112} = \langle \cos(\phi_1(\eta_1) + \phi_2(\eta_2) - 2\phi_3) \rangle \geq 0$

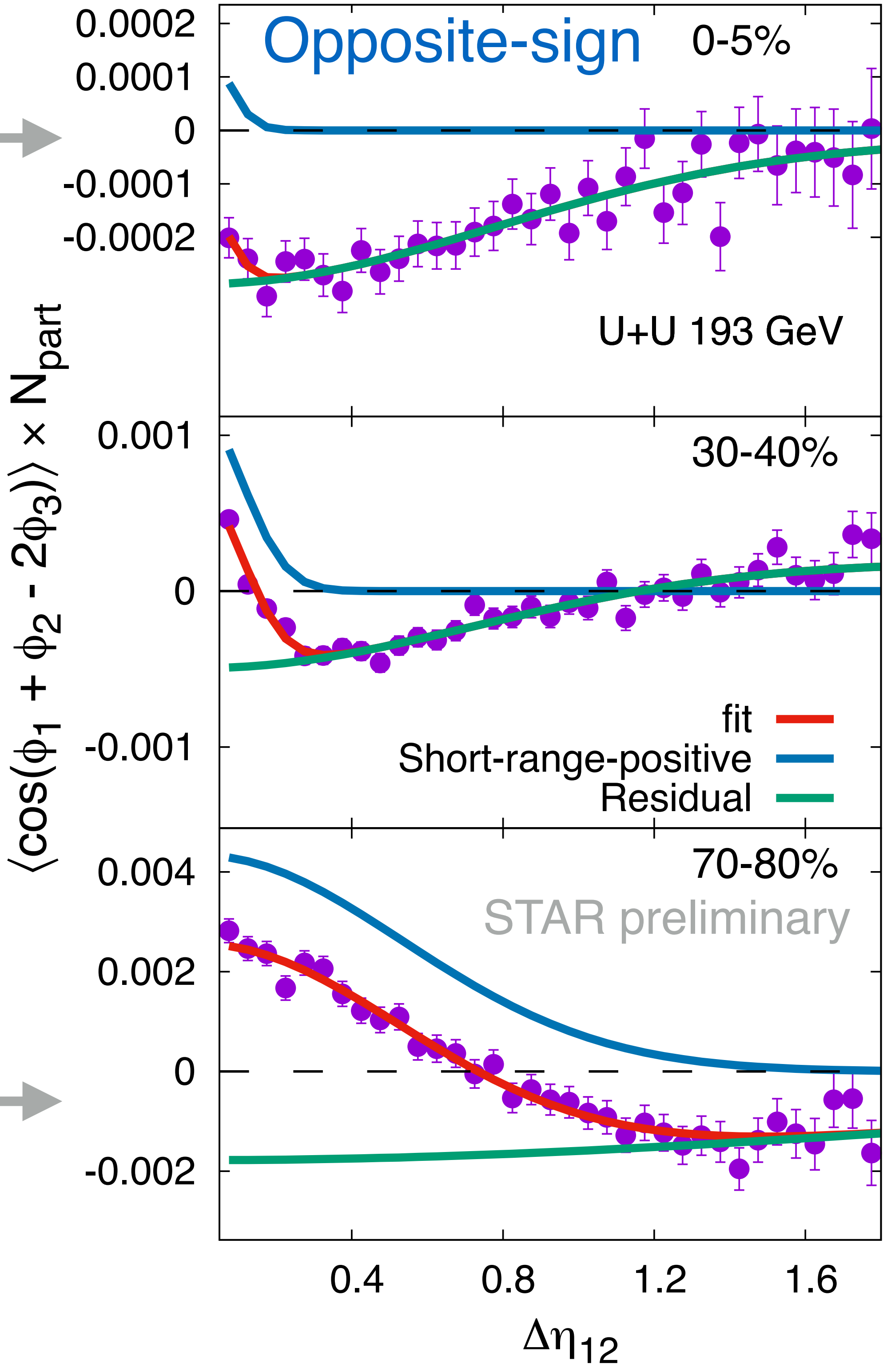
$$C_{112}(\Delta\eta_{12}) = \underbrace{A^{+}_{SR} e^{-(\Delta\eta)^2/2\sigma^2_{SR}}}_{\text{Short-range-positive}} \underbrace{- A^{-}_{IR} e^{-(\Delta\eta)^2/2\sigma^2_{IR}} + \boxed{A_{LR}}}_{\text{Residual}} \longrightarrow \text{Pedestal}$$

# Comparison between A+A centralities



Central

Peripheral

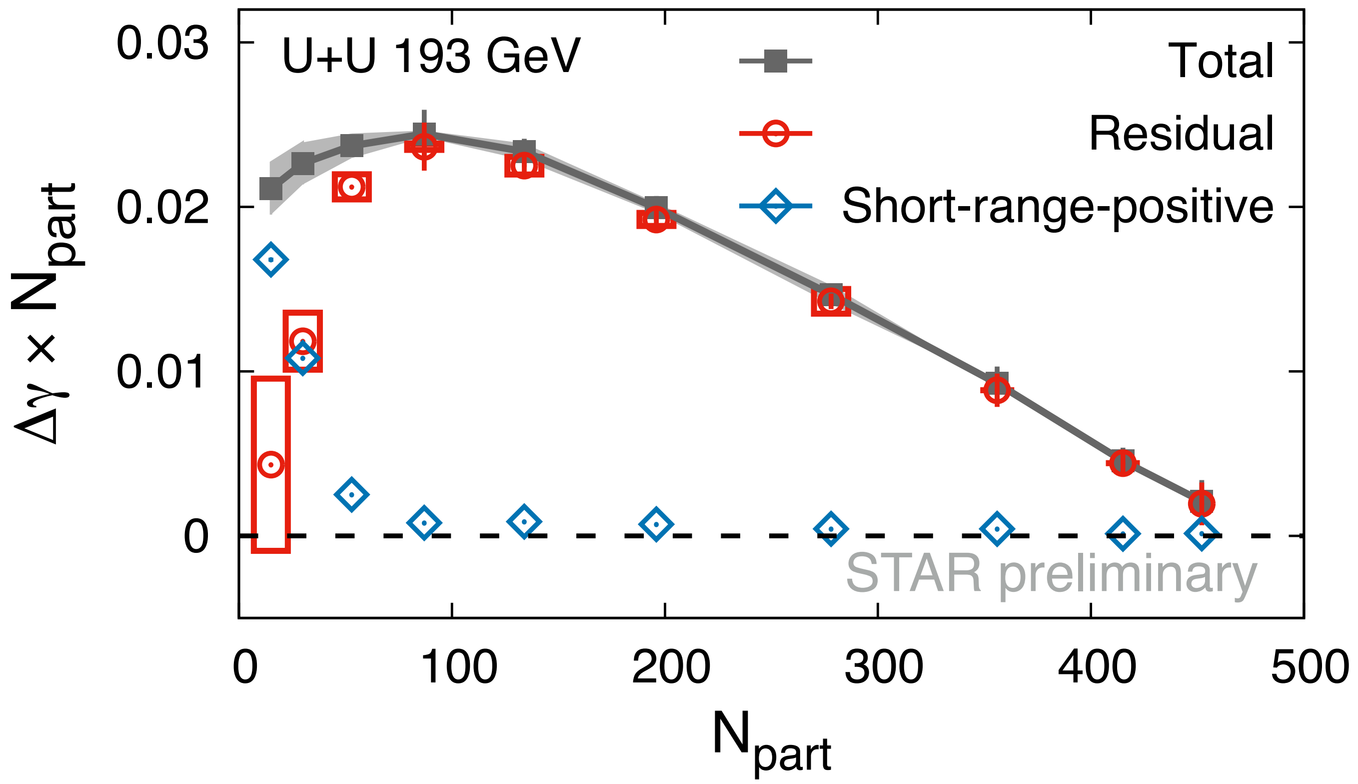


Very different structures in central and peripheral events

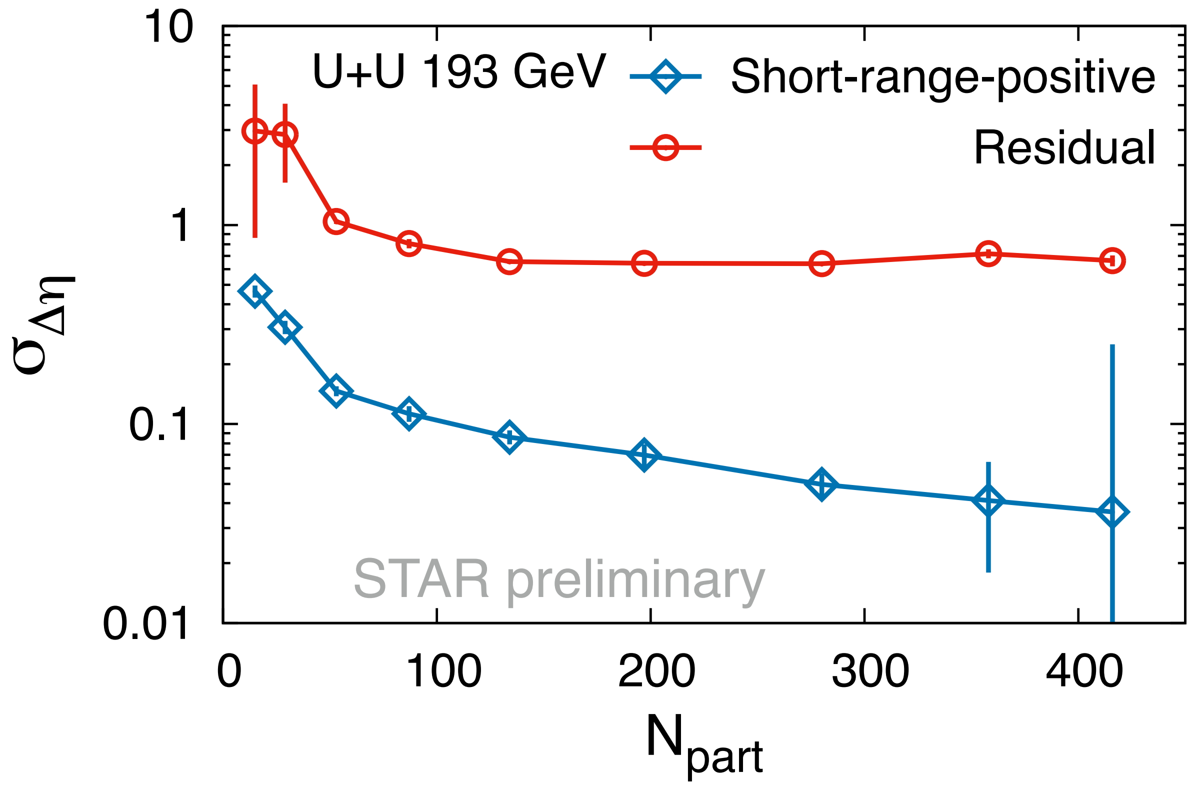
# Centrality dependence of charge separation

Charge separation has a narrow and wide Δη component

Magnitudes of different components



Widths of different components



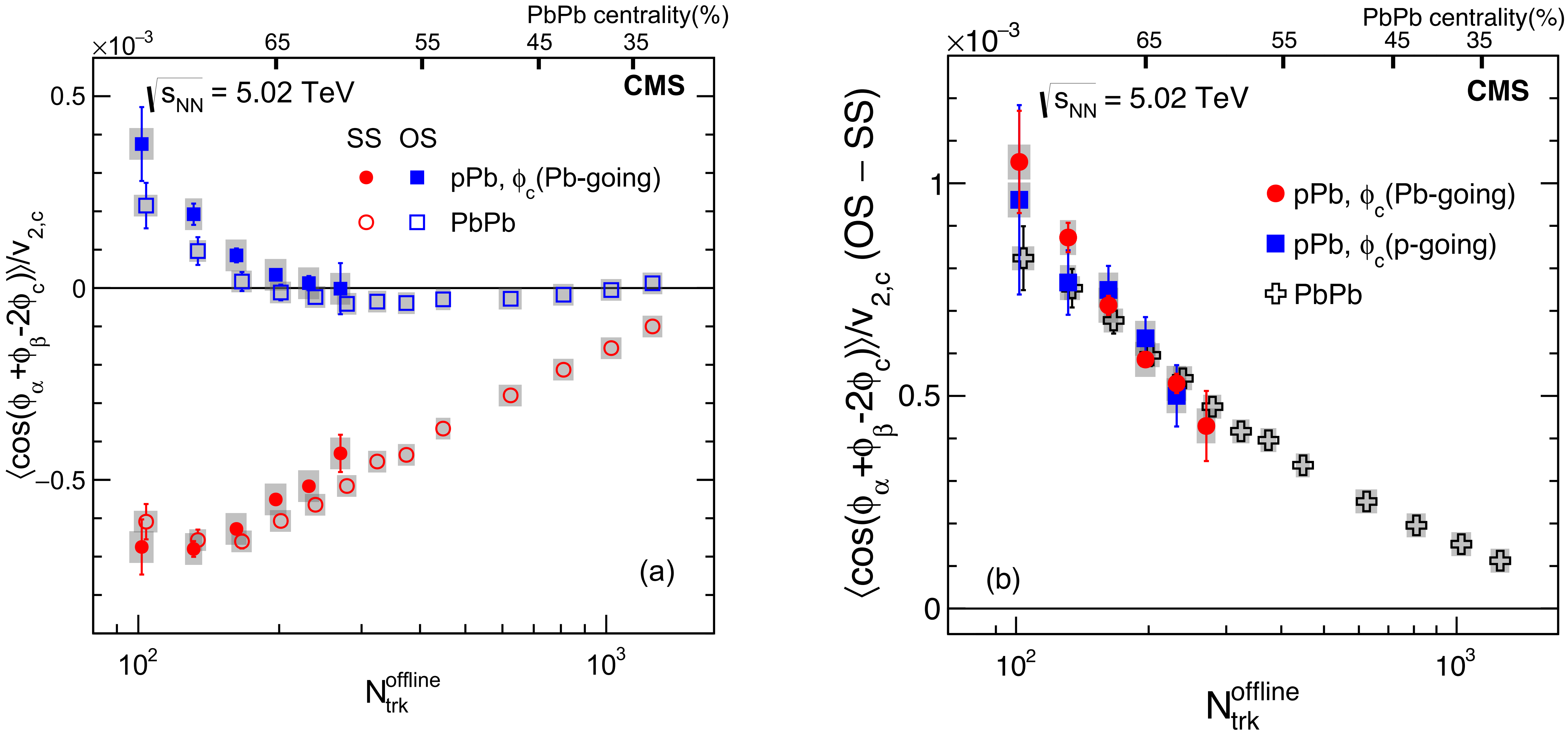
Wider Δη component (Short-range-positive)→ 0 for small & large $N_{part}$

The narrow Δη component (Residual) grows at small $N_{part}$

# CMS measurements in p+Pb collisions

What does this mean ?

$$\gamma^{\alpha,\beta} = \langle \cos(\phi_\alpha + \phi_\beta - 2\Psi_2) \rangle = -\langle a_\alpha a_\beta \rangle + c\frac{v_2}{N}$$



PRL 118 (2017) 122301

Interpretations by CMS :

$\Delta\gamma$ (OS-SS) agree between systems

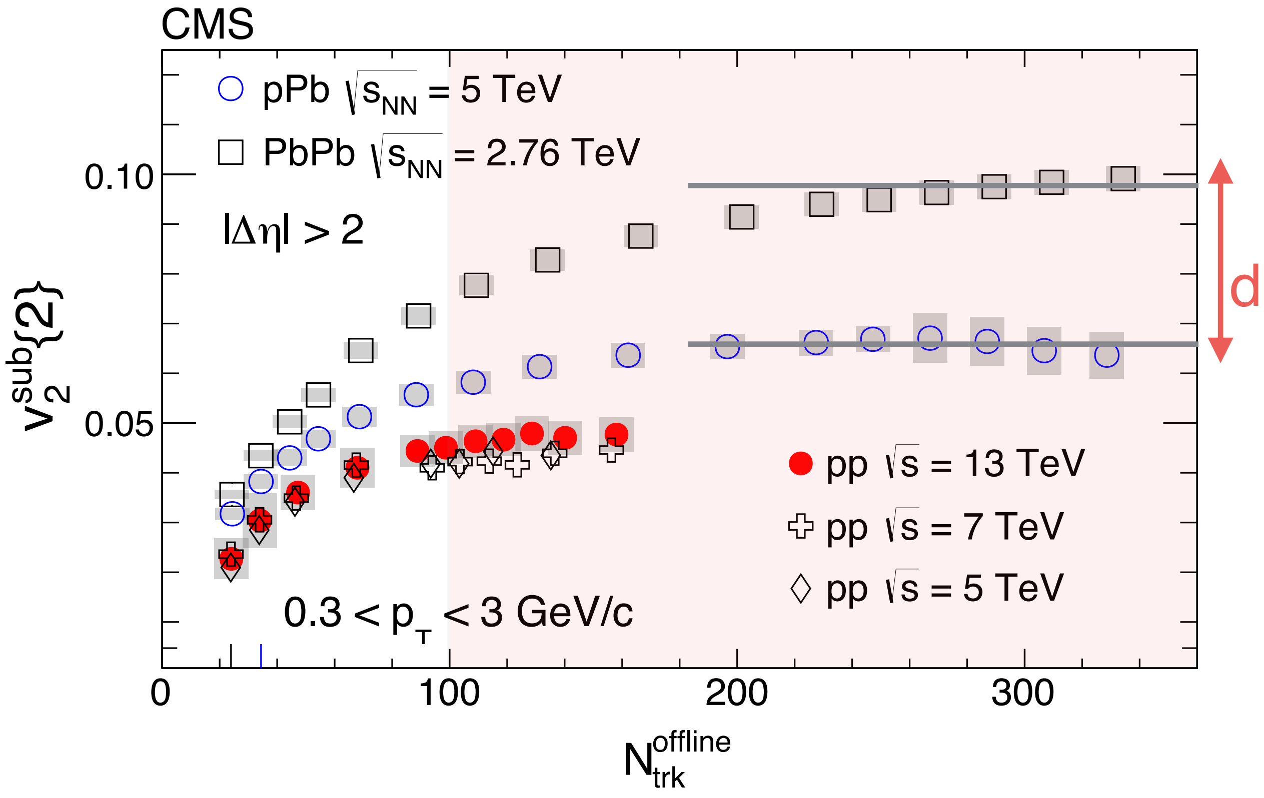
The $\gamma$ seems have no sensitivity to the CME signal $\gamma^{\alpha,\beta} \propto \frac{v_2}{N}$

# CMS measurements in p+Pb collisions

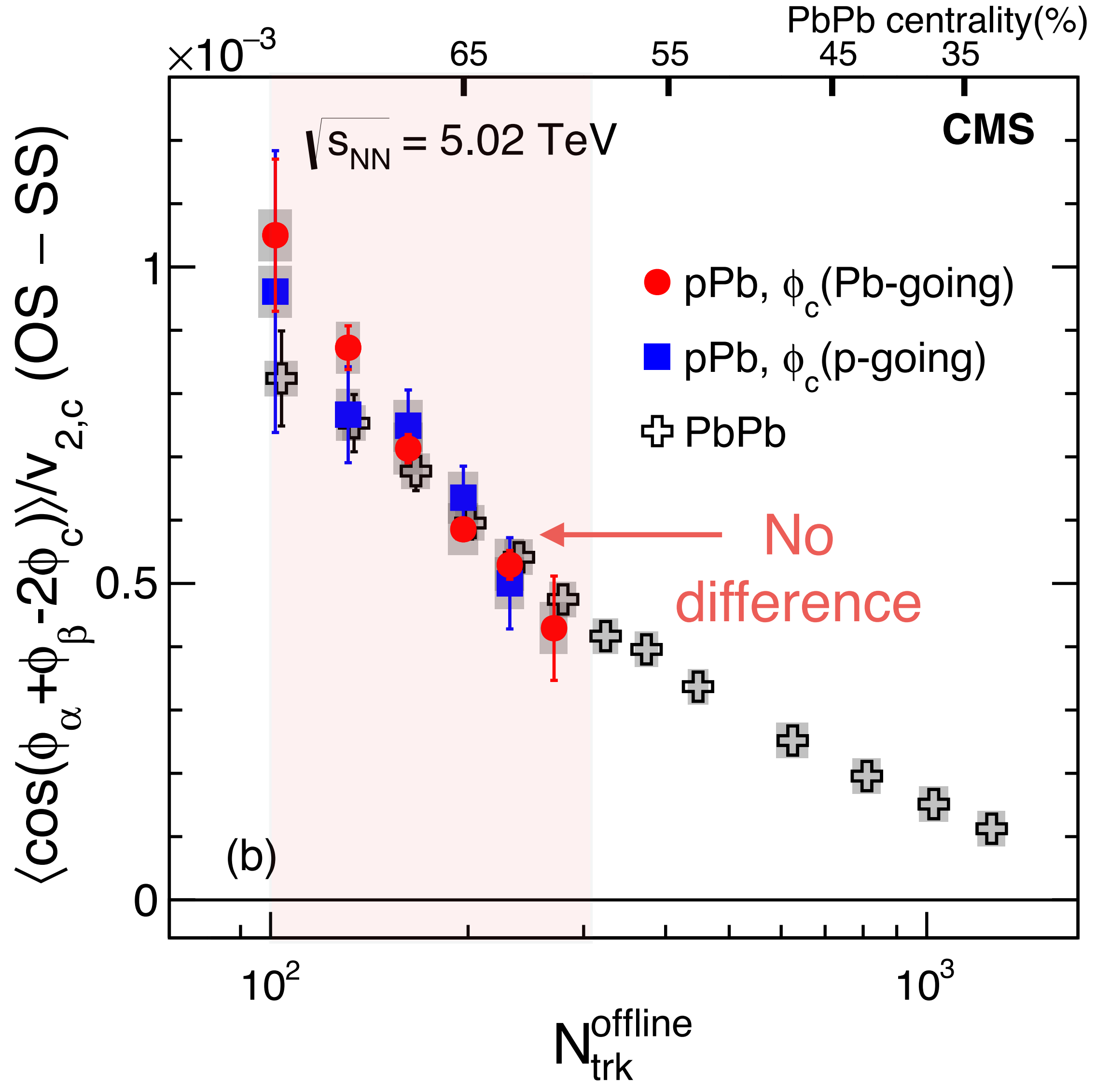
Puzzling feature of CMS data

$$\gamma^{\alpha,\beta} = \langle\cos(\phi_\alpha + \phi_\beta - 2\Psi_2)\rangle = -\xcancel{\langle a_\alpha a_\beta\rangle} + c\frac{v_2}{N}$$

Estimates of $c\frac{v_2}{N}$



40% difference



No difference

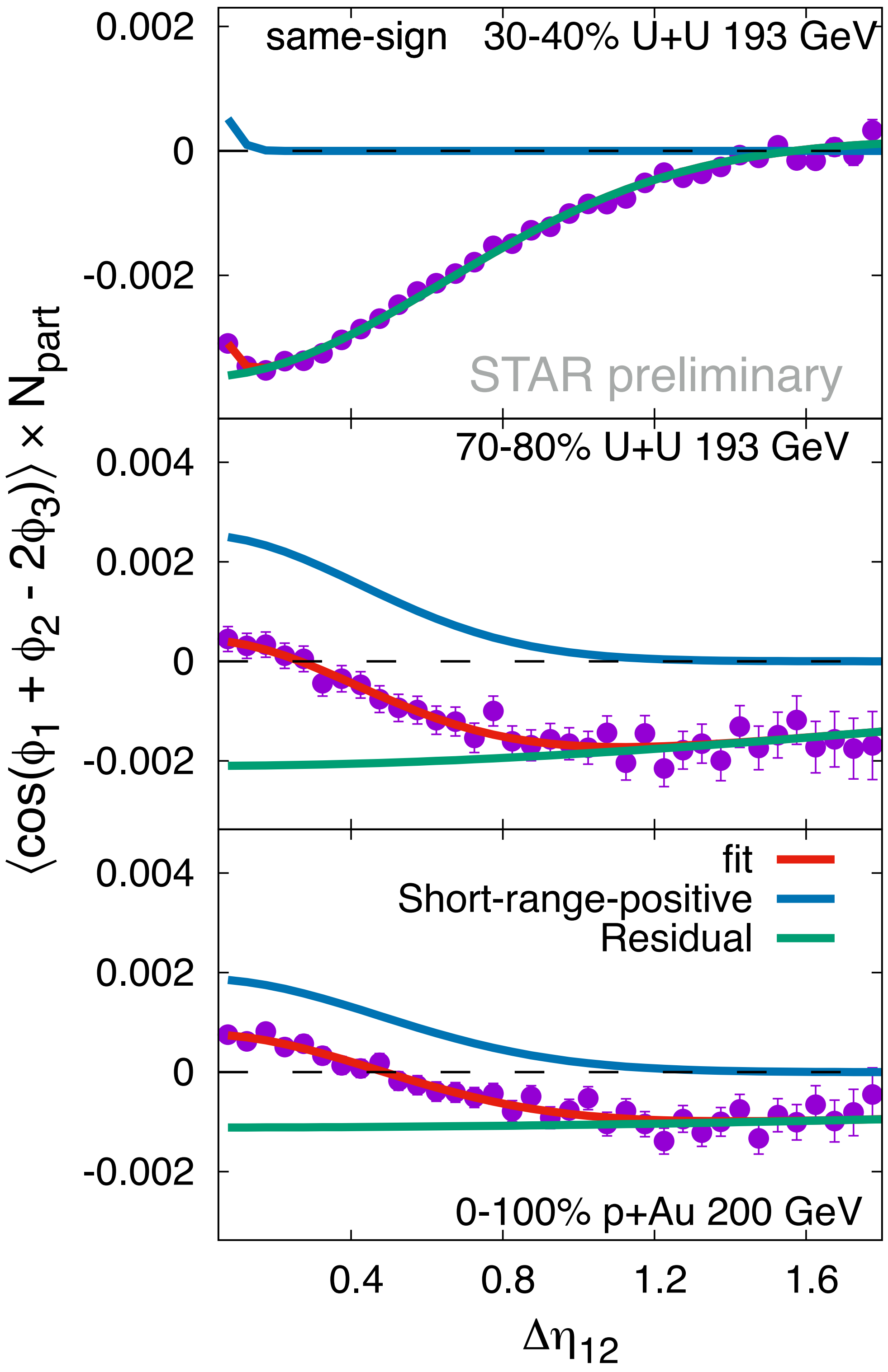
Puzzle :

If $\frac{v_2}{N}$ changes by 40% between systems, why $\gamma^{\alpha,\beta} \propto \frac{v_2}{N}$ is still same ?

p+Pb data challenge both signal and background interpretations ?

# STAR measurements of p+A vs A+A

## Same-sign



Central

A+A

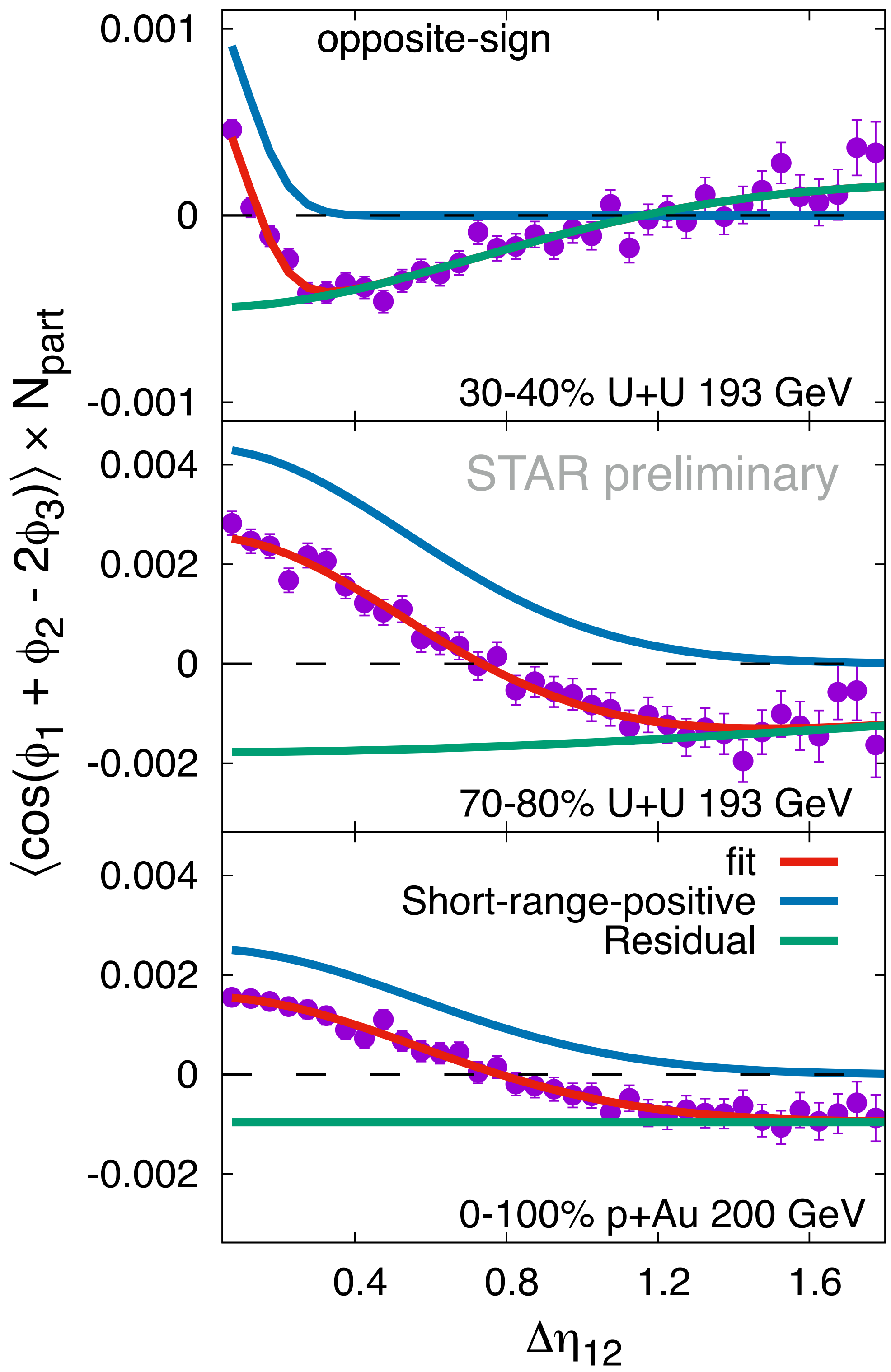
Peripheral

A+A

Min-bias

p+A

## Opposite-sign

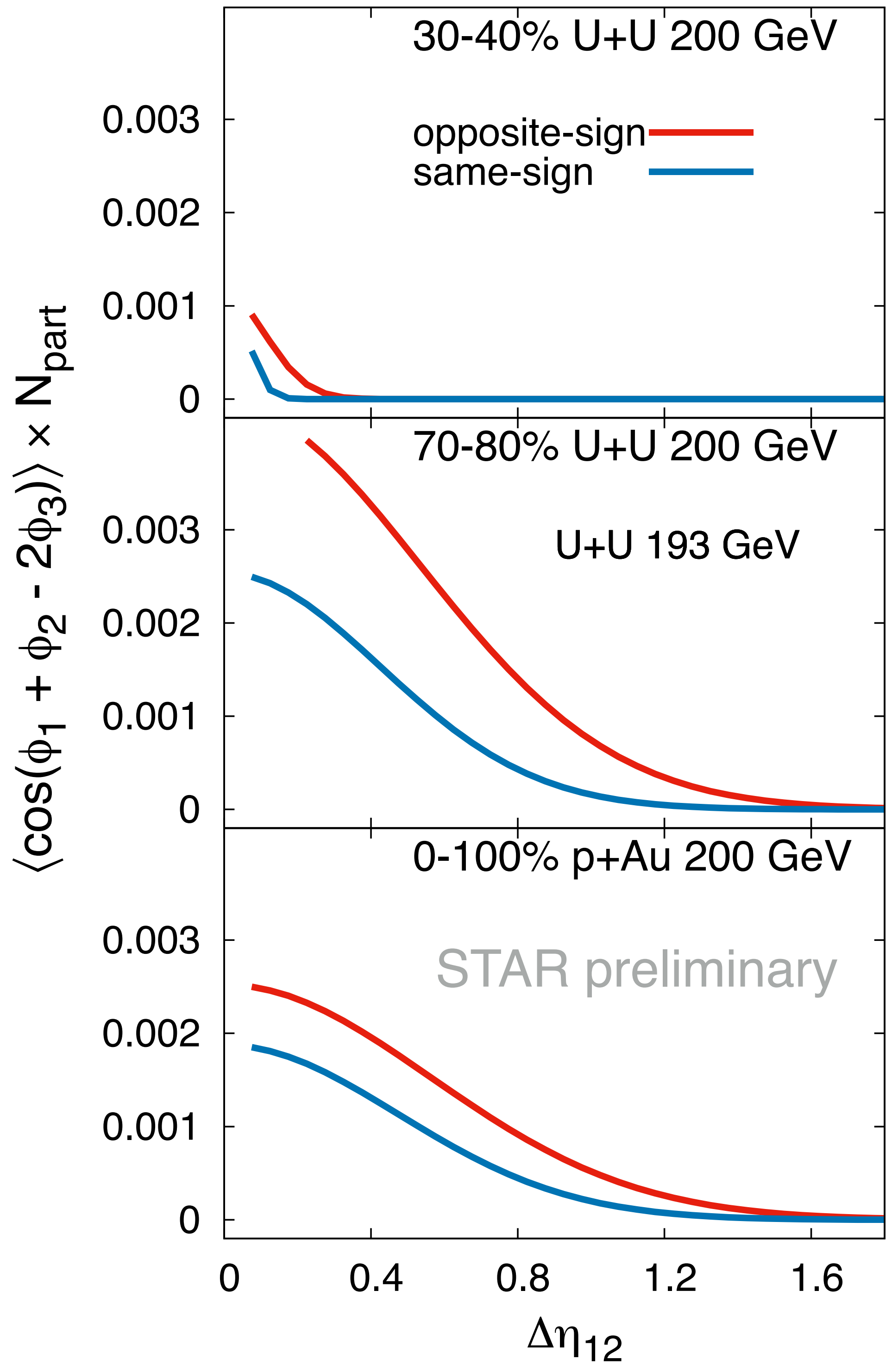


p+Au → similar to peripheral A+A, different from central A+A

# Comparison between p+A & peripheral A+A

Short-range-positive (Narrow Δη)

Residual (Wider Δη)



Central

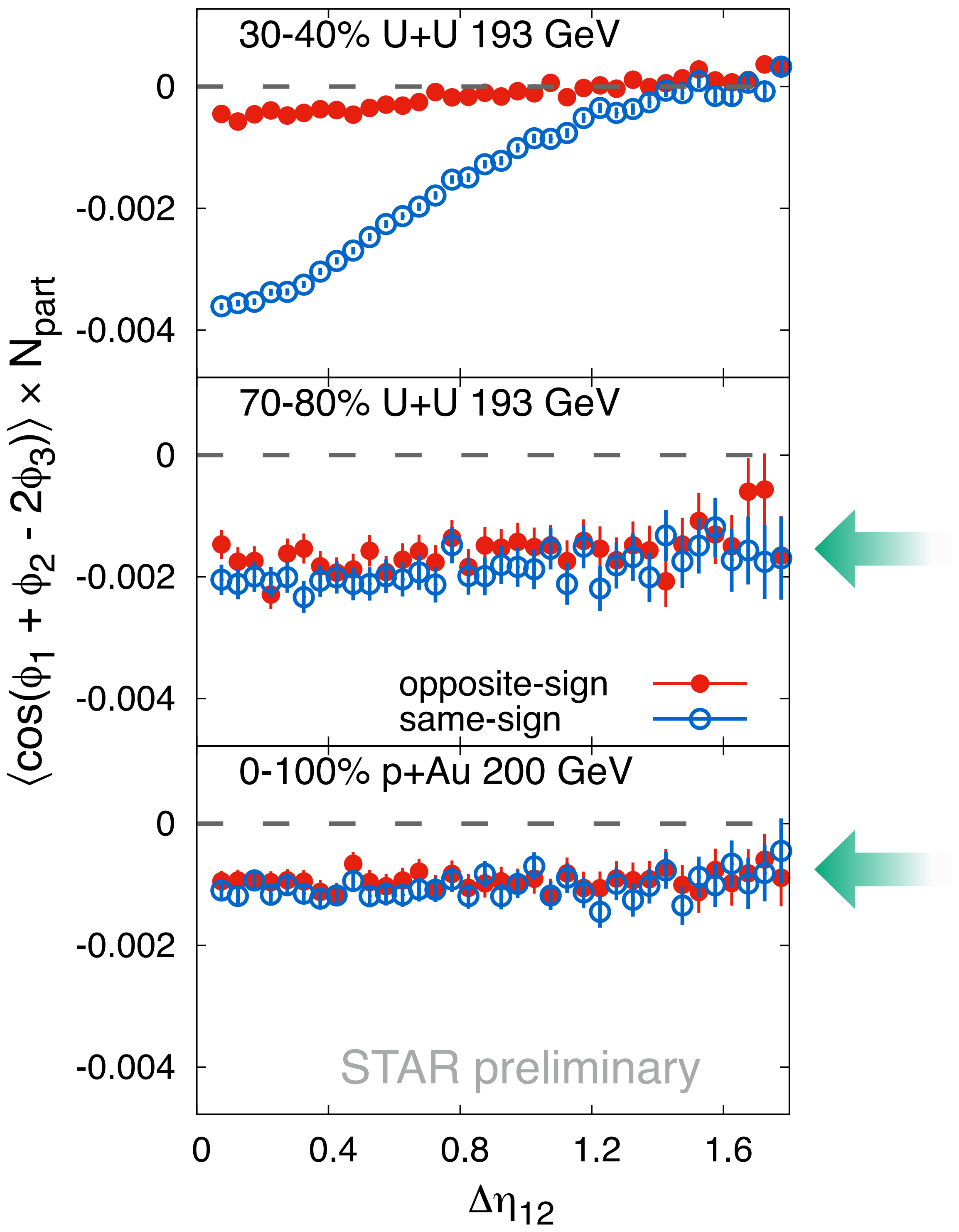
A+A

Peripheral

A+A

Min-bias

p+A

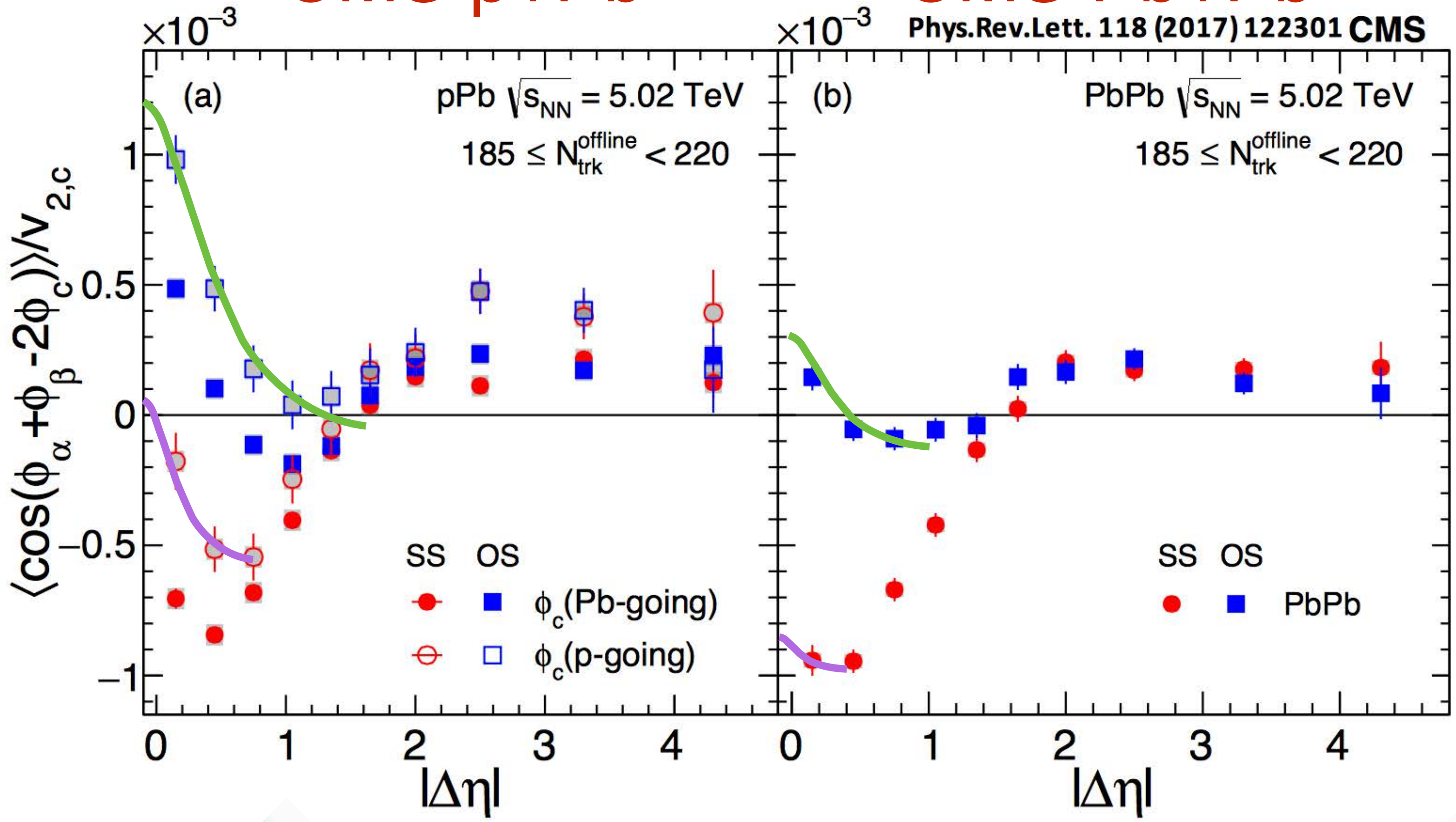


p+A & peripheral A+A → dominated by short-range correlations

# Comparison between p+A and A+A

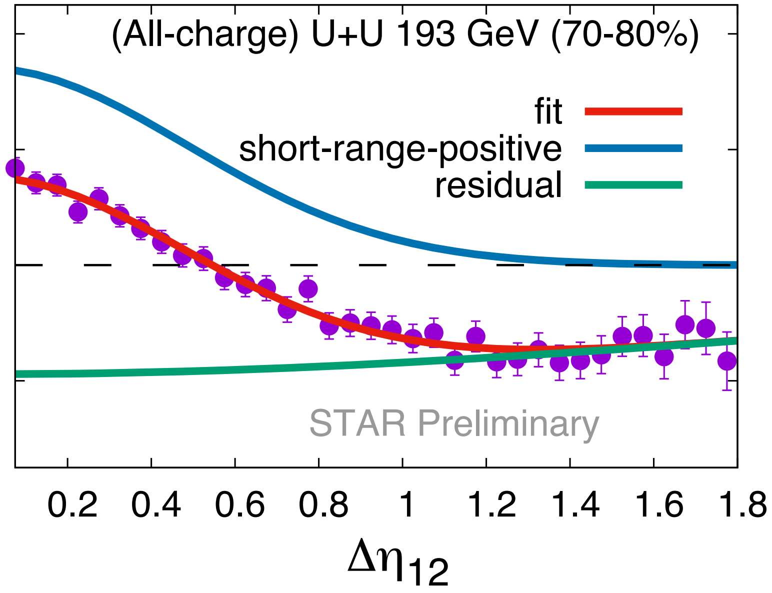
CMS p+Pb

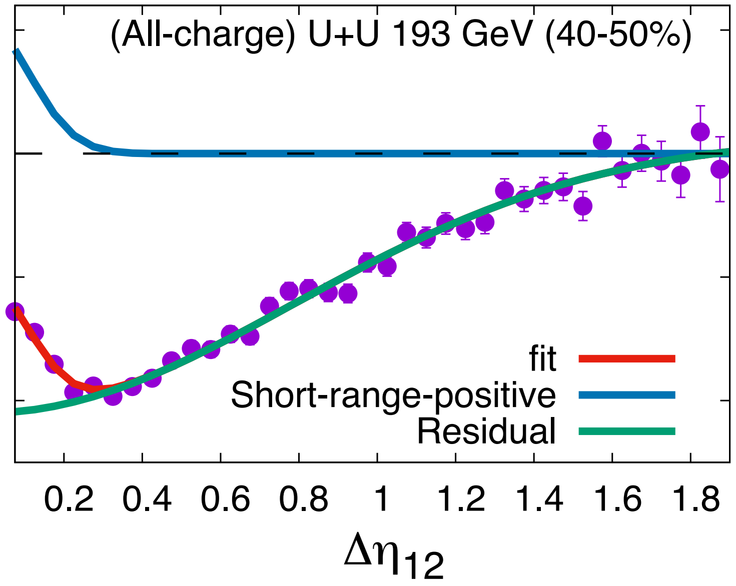
CMS Pb+Pb



Dominance of short-range correlations also in LHC data

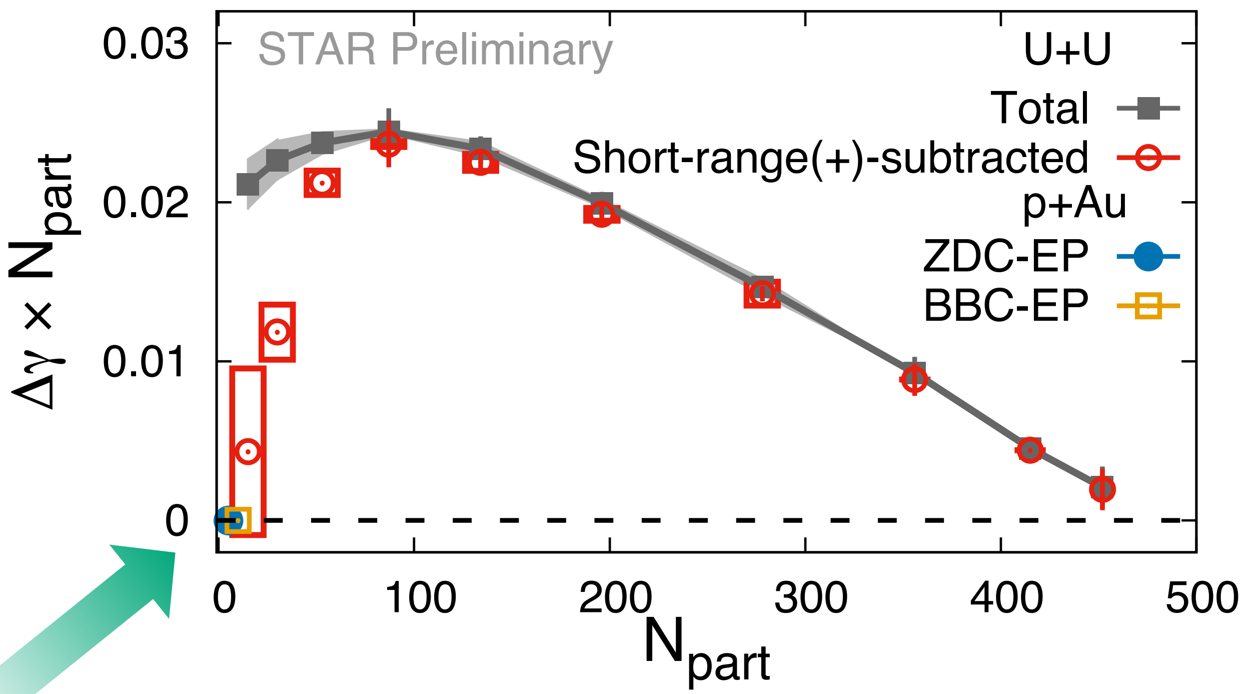
p+Pb looks different than Pb+Pb

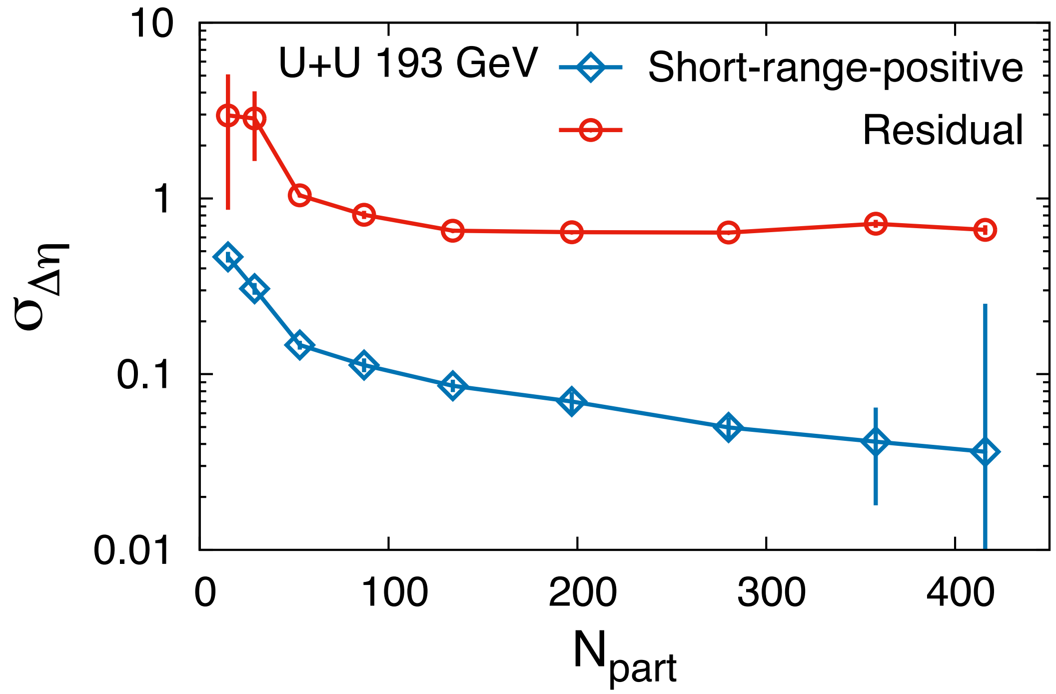




# Summary of STAR results in A+A & p+A

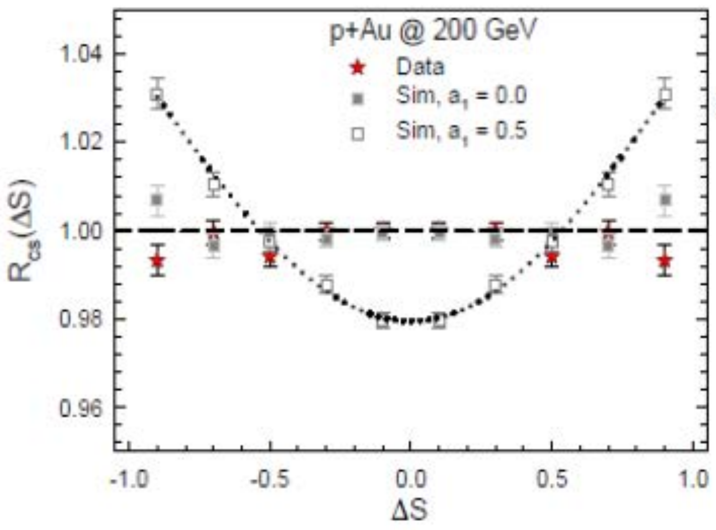
P. Soerensen QM 2017





Independent analysis also confirm vanishing signal in p+Au

Lacey, Ajitanand QM2017 poster

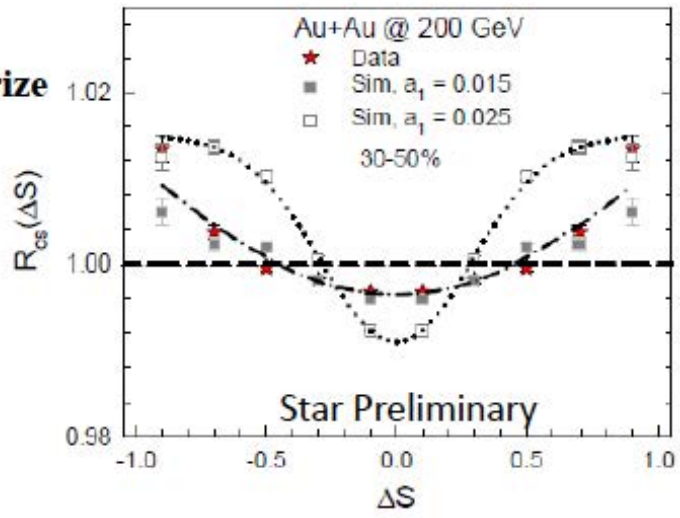


## Results

- $a_1^{ch}$ **is used to characterize the magnitude of the CME signal**

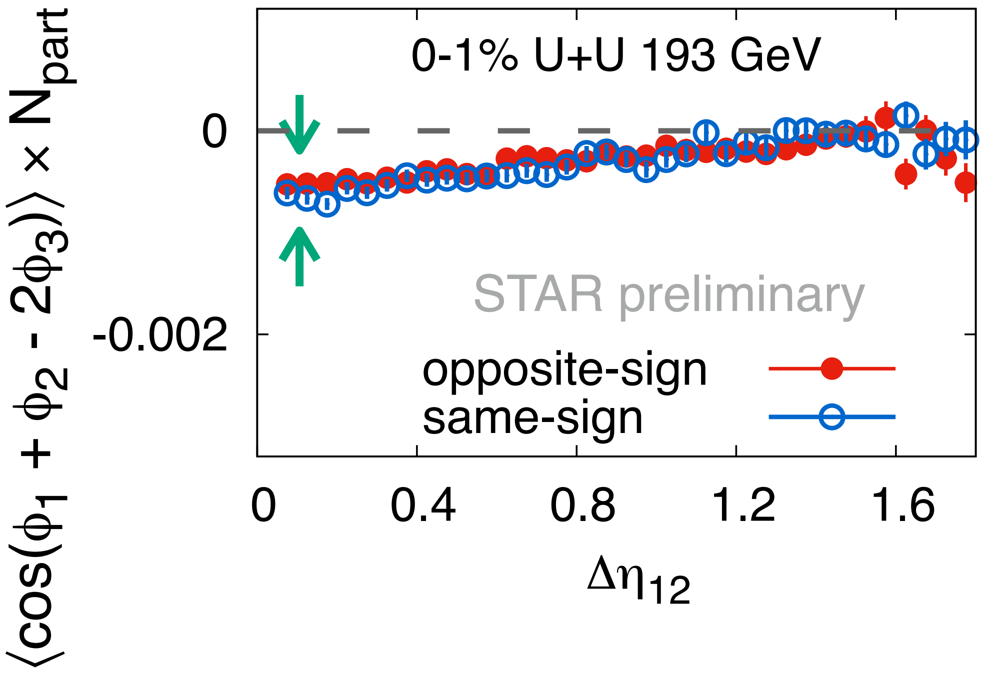
$a_1 \sim 0.0\%$ *for* $p + Au$

$a_1 \sim 1.0\%$ *for* $Au + Au$

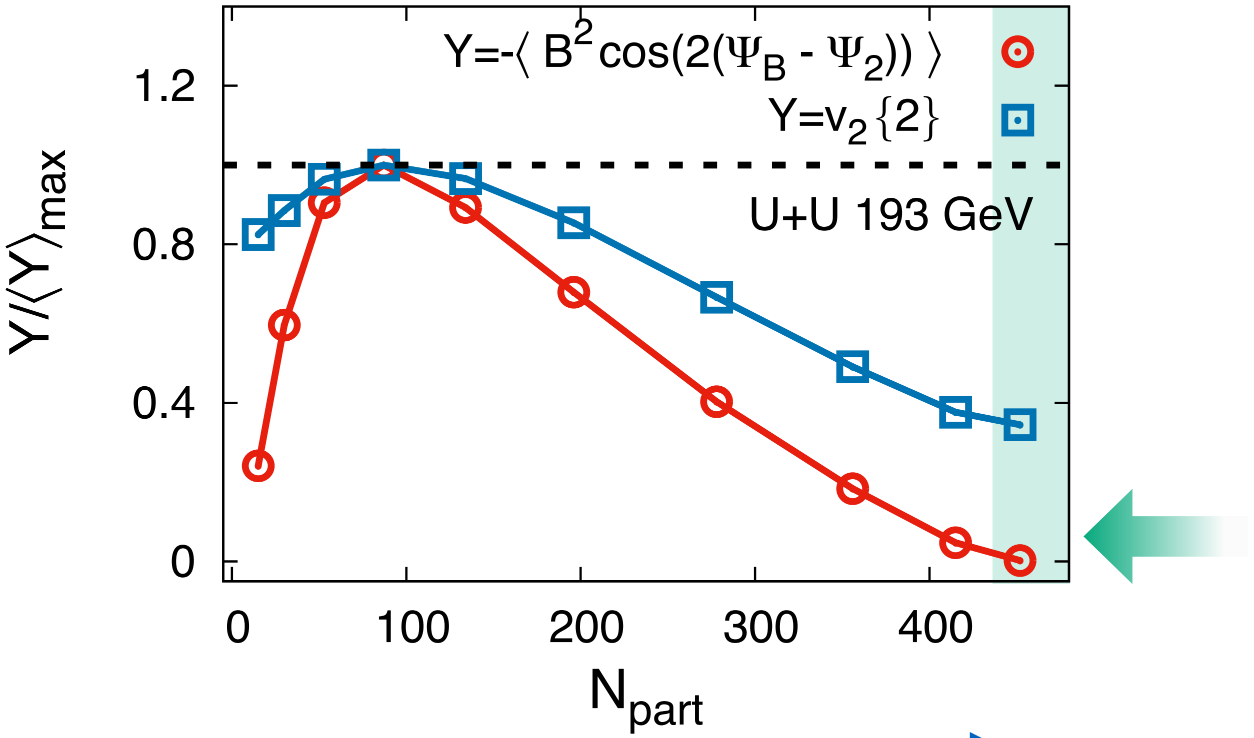


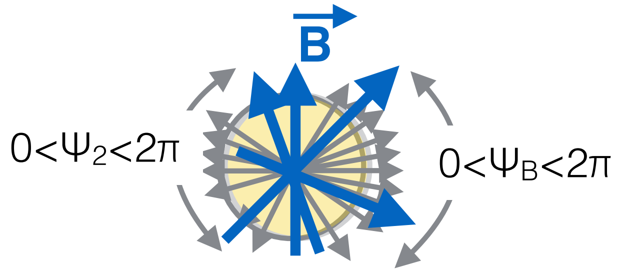
# Summary of STAR results in A+A & p+A

## Data (wide Δη component)



## Projected B-field in A+A

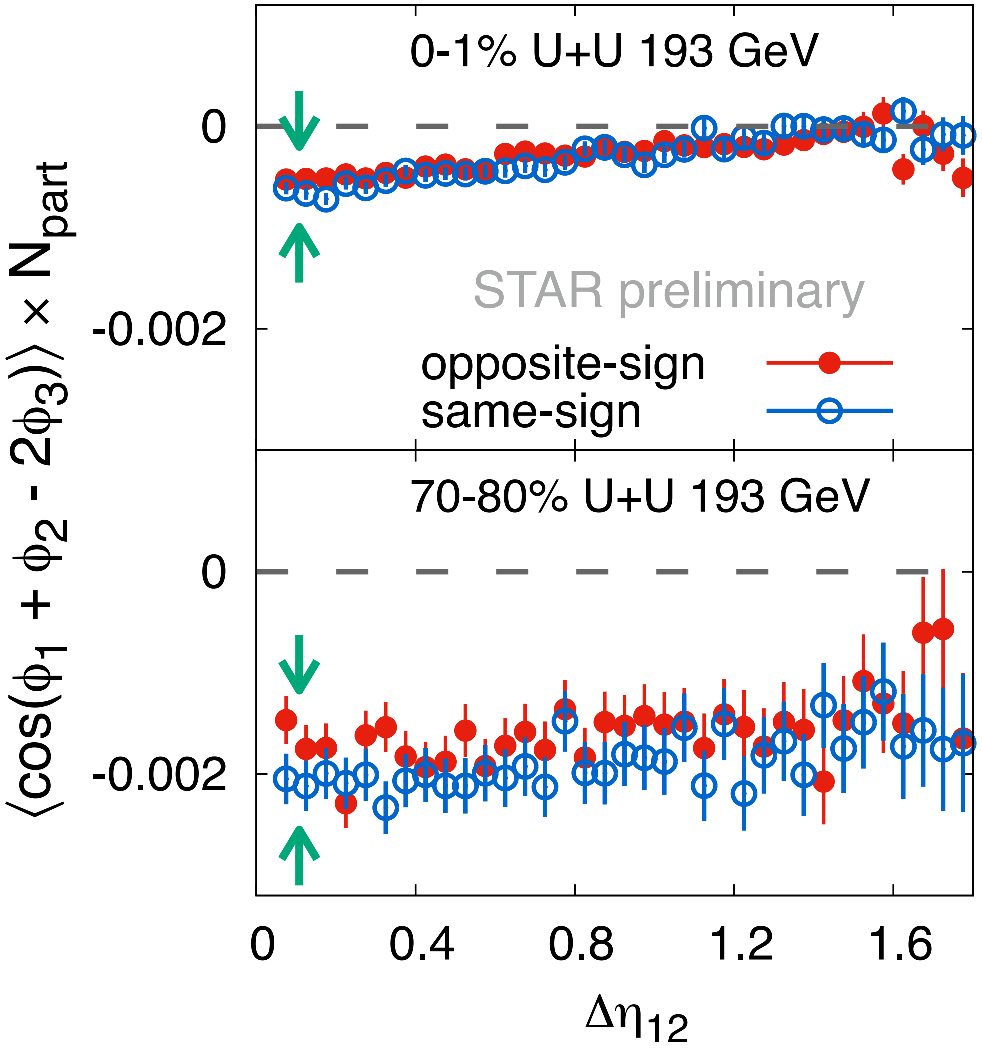




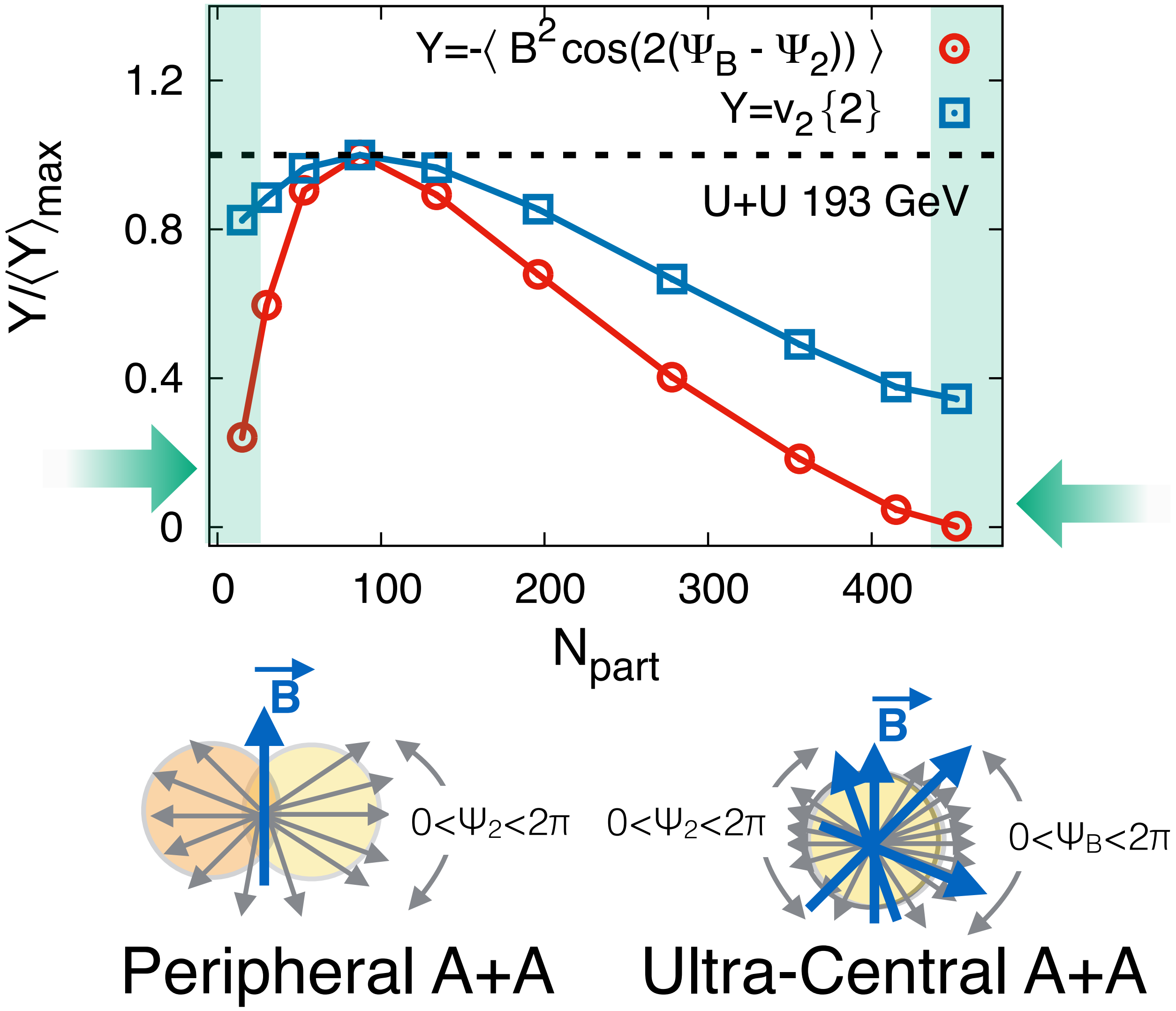
Ultra-Central A+A

# Summary of results in A+A and p+A

## Data (wide Δη component)

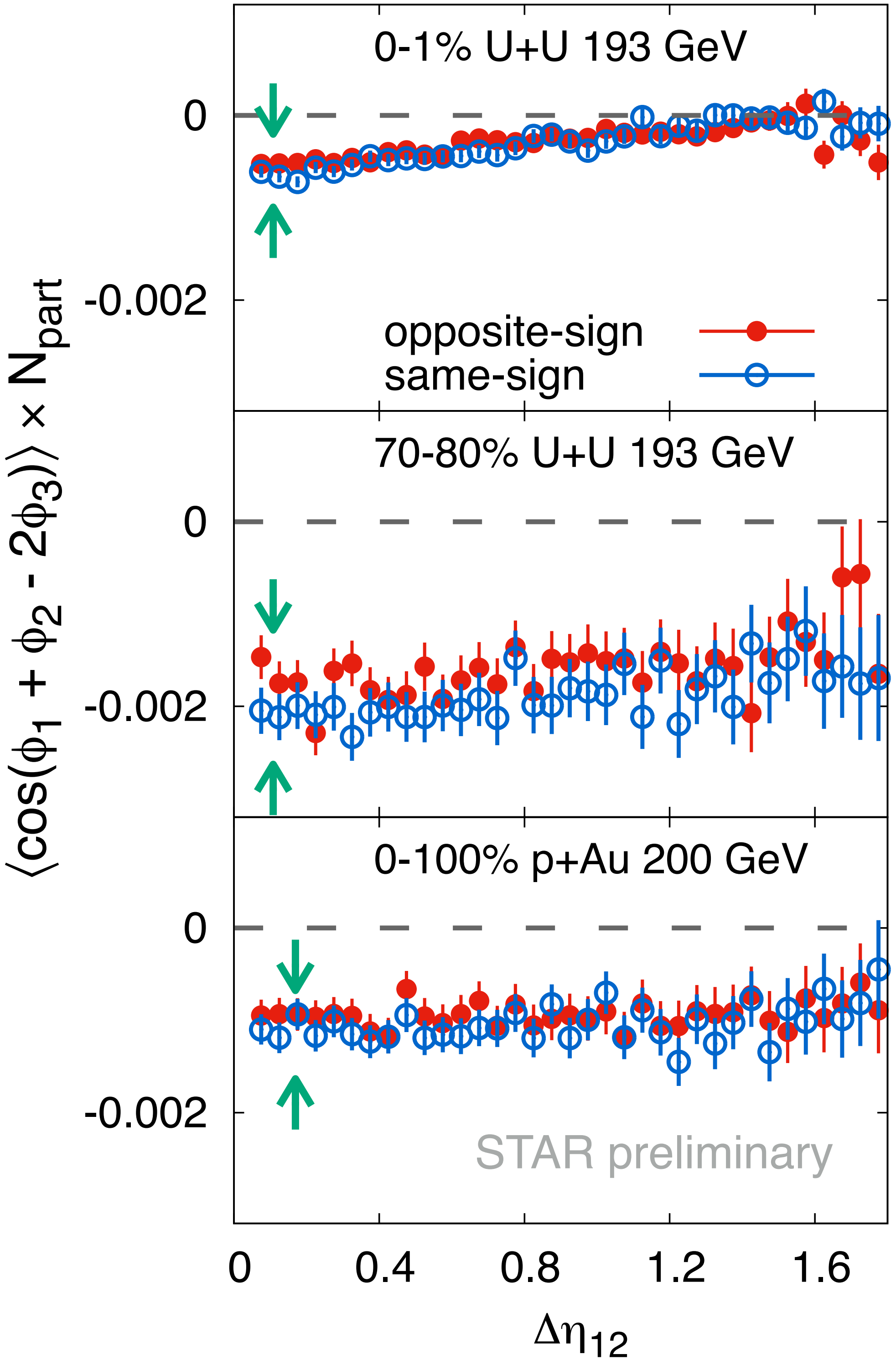


## Projected B-field in A+A

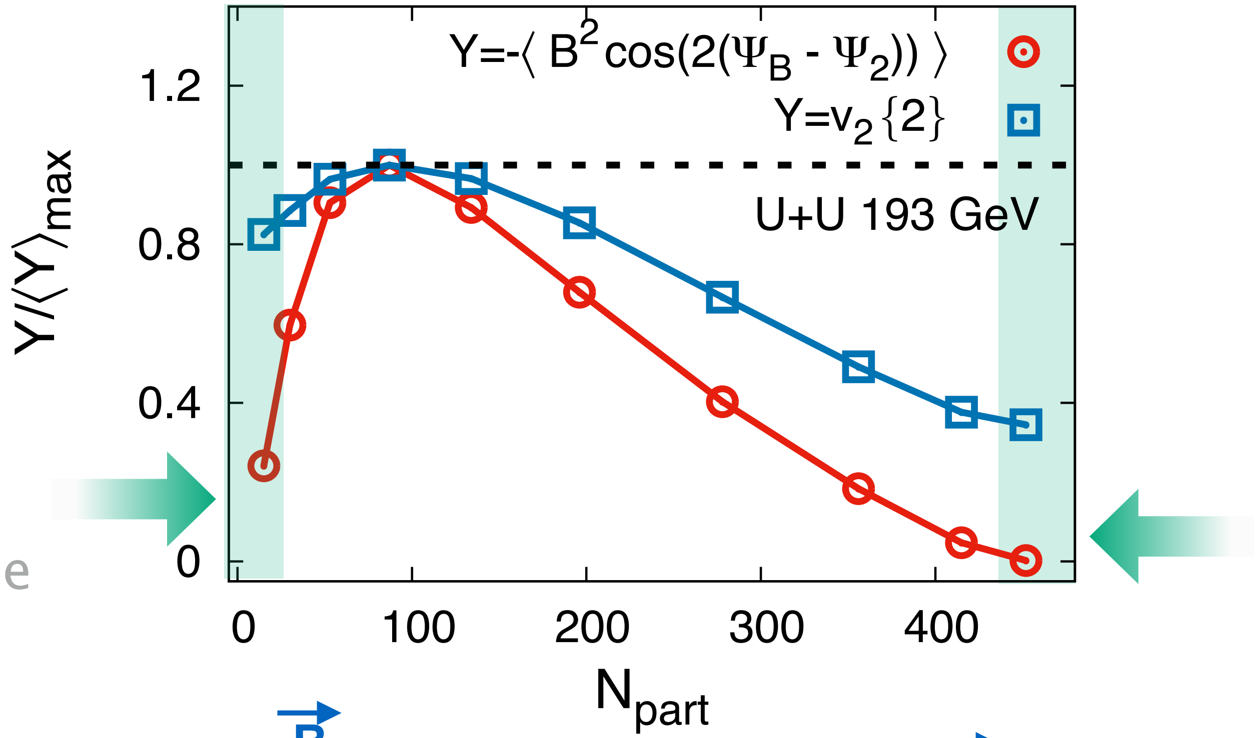


# Summary of results in A+A and p+A

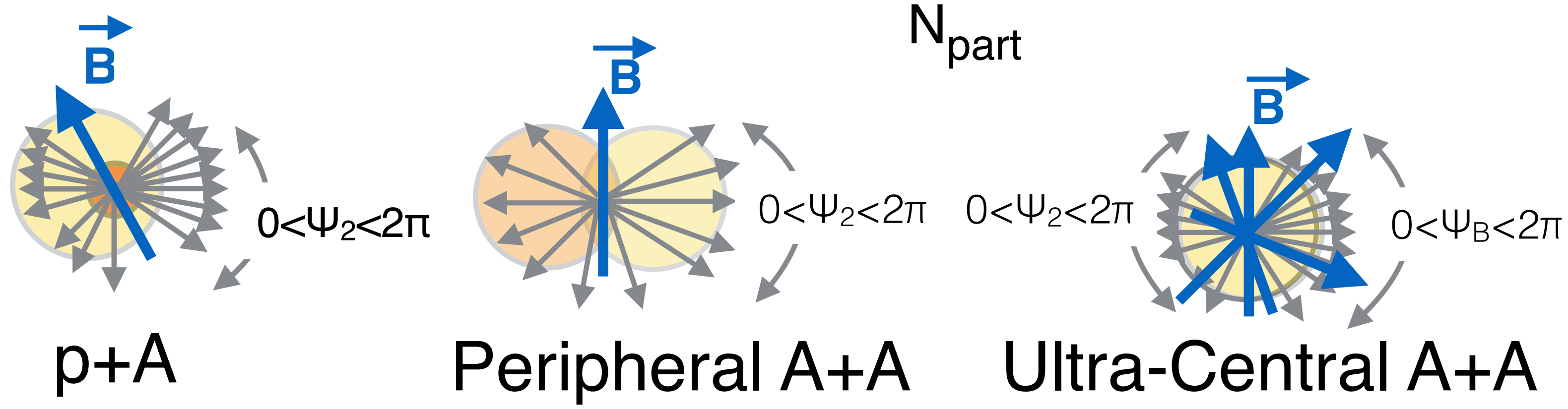
## Data (wide Δη component)



## Projected B-field in A+A

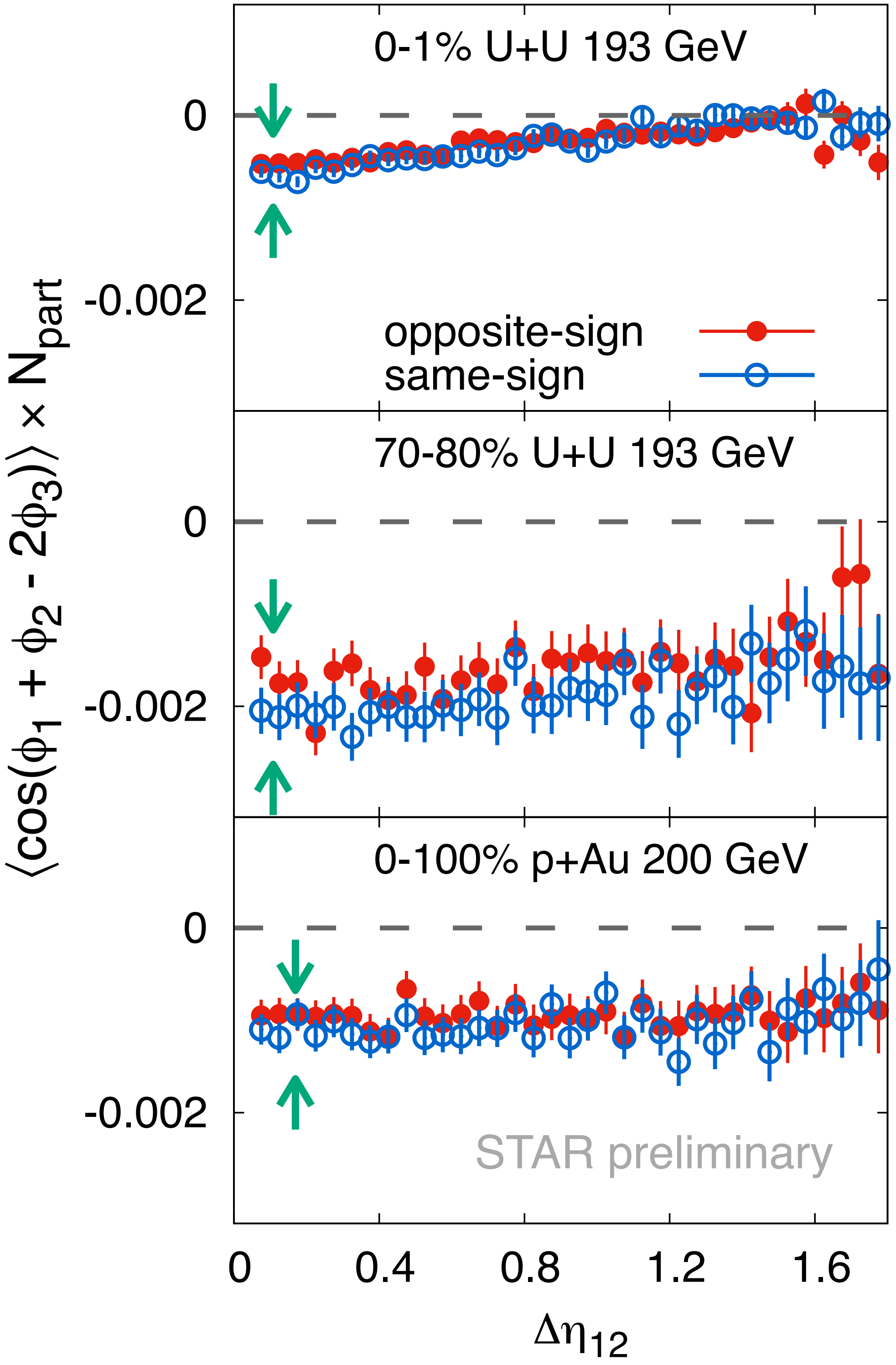


Belmont, Nagle
1610.07964

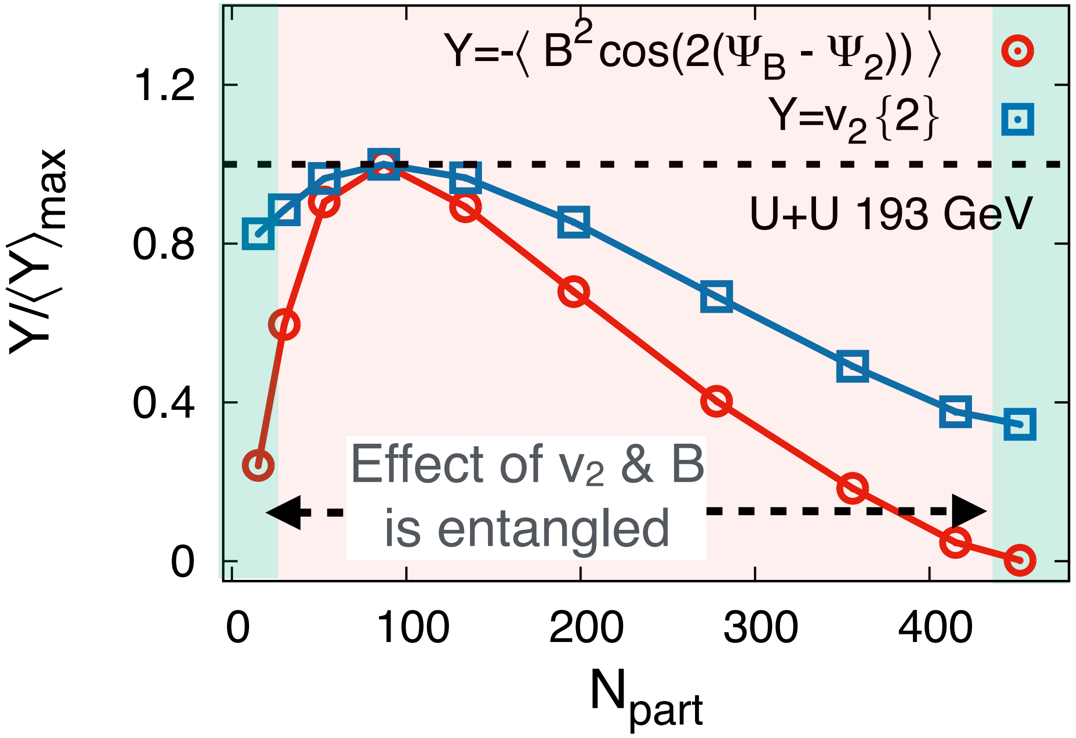


# Summary of results in A+A and p+A

## Data (wide Δη component)



## Projected B-field in A+A



Wider Δη component of charge separation vanishes when projected B→0, $v_2 \neq 0$

(Naive background model $\Delta\gamma \sim v_2/N$ can not explain this)

# Outlook for isobar collisions at RHIC

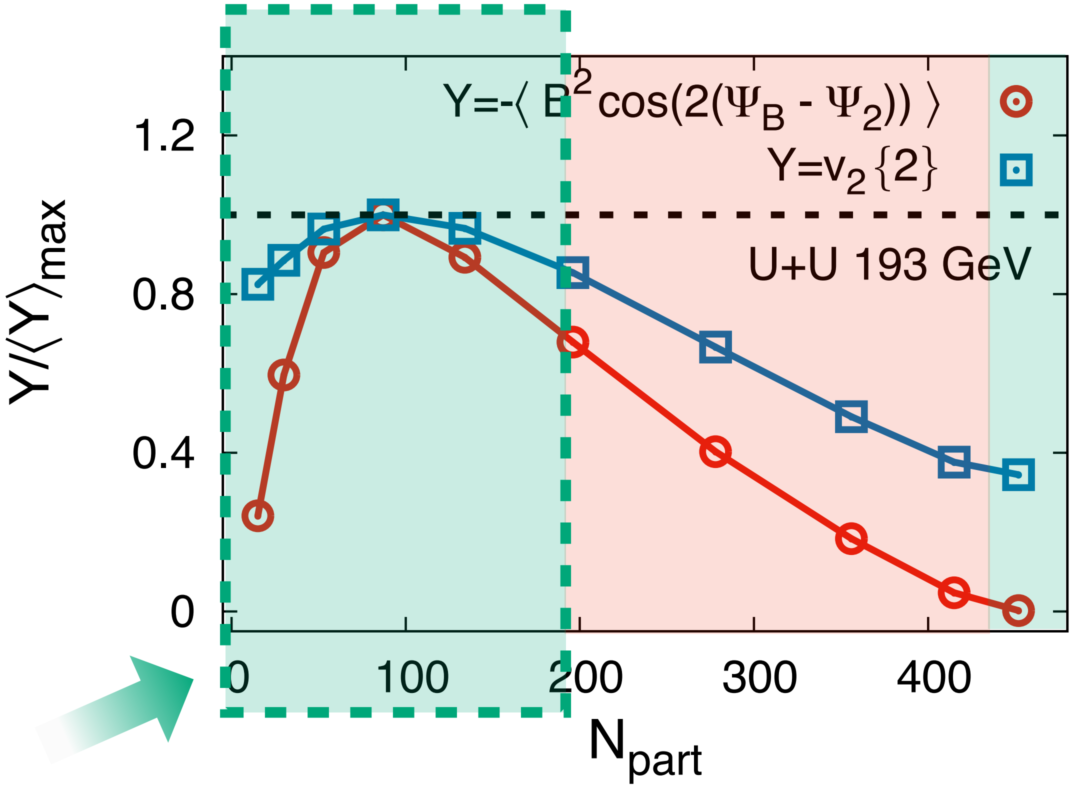
The idea is to change B-field without changing background

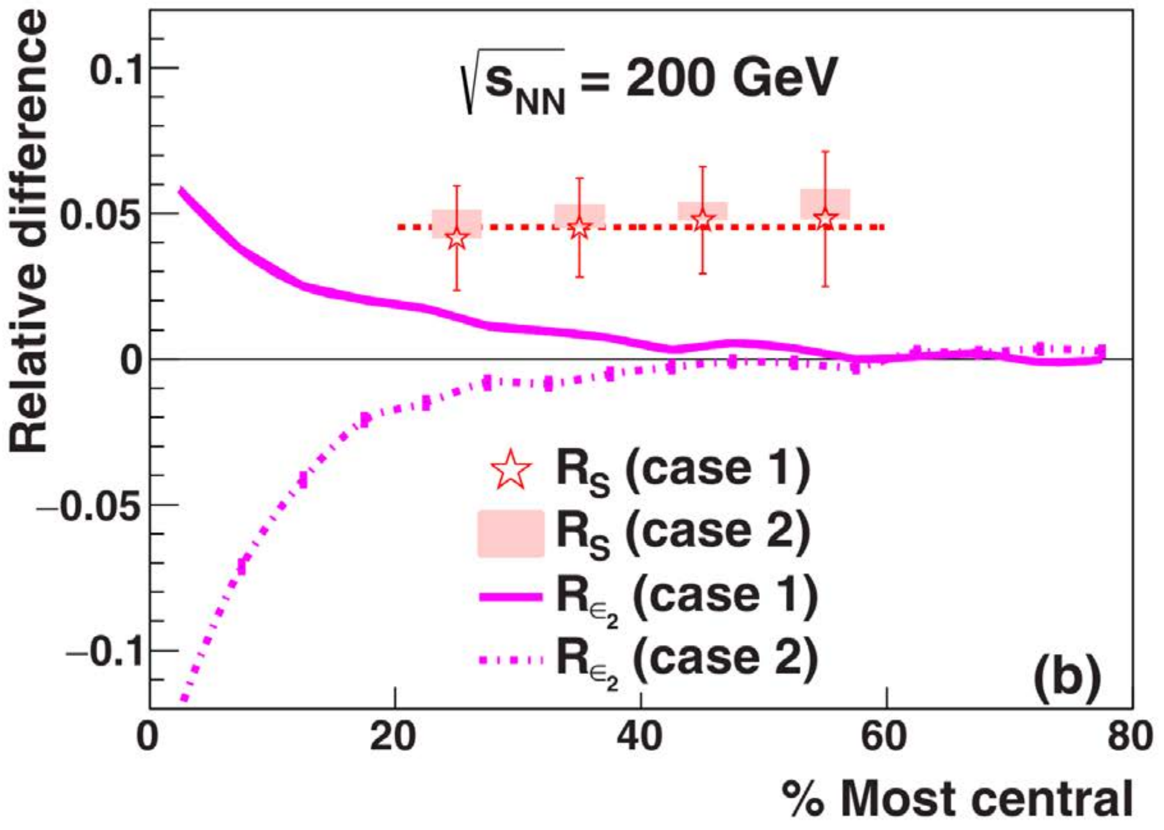
$${}^{96}_{44}\mathrm{Ru} + {}^{96}_{44}\mathrm{Ru} \xleftrightarrow[\sqrt{s}\,=200\ \mathrm{GeV}]{} {}^{96}_{40}\mathrm{Zr} + {}^{96}_{40}\mathrm{Zr}$$

Different B-field with same flow background is expected

1.2 B events can provide about 5σ confidence of signal/bkg

Gang Wang, QCD Chirality workshop '2016, Deng et al PRC 94, 041901 (2016), Skokov et al, 1608.00982



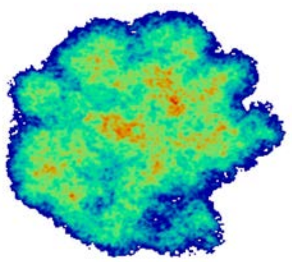


# What else can be done ?

## Isobars

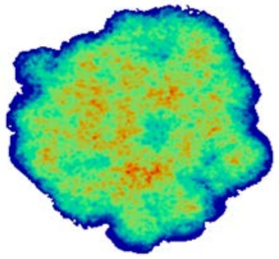
Future Run (2018)

$^{96}_{40}\text{Zr}$



Zr +Zr

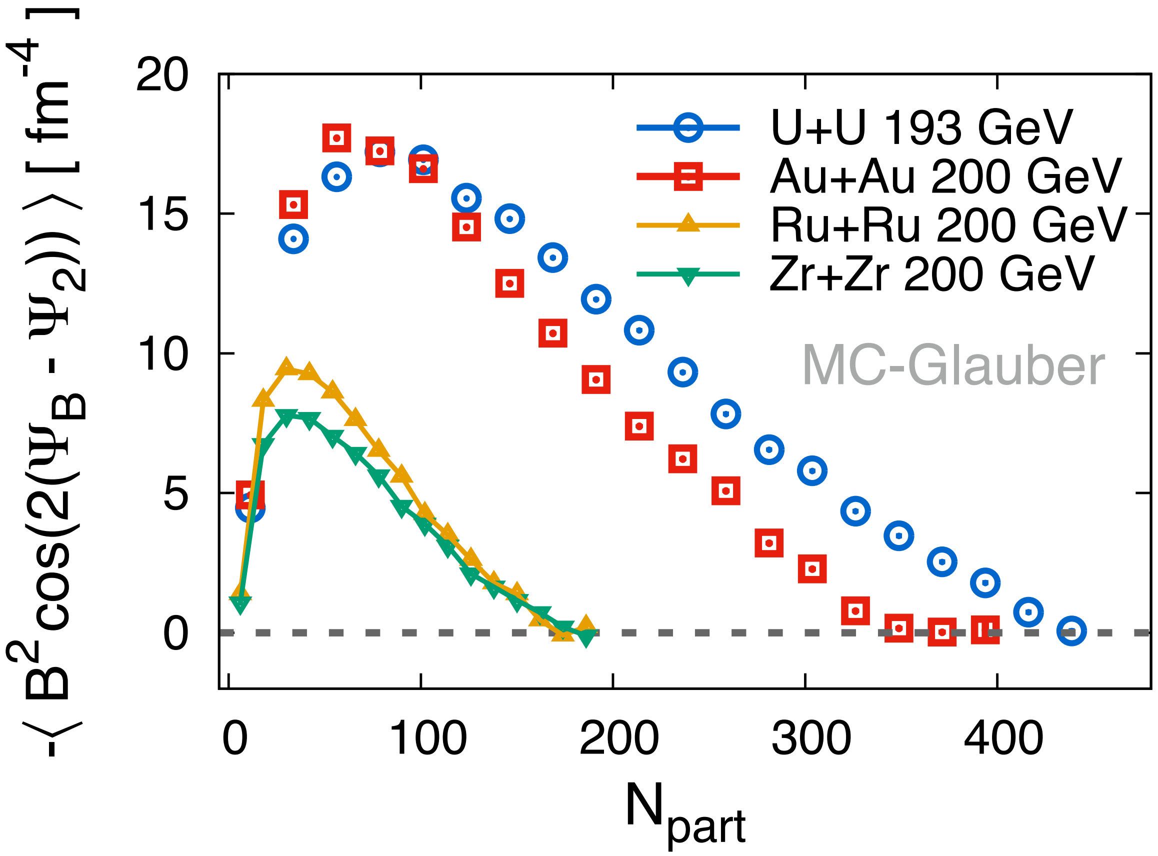
$^{96}_{44}\text{Ru}$



Ru +Ru

Single (b=0) collision in IP-Glasma model,

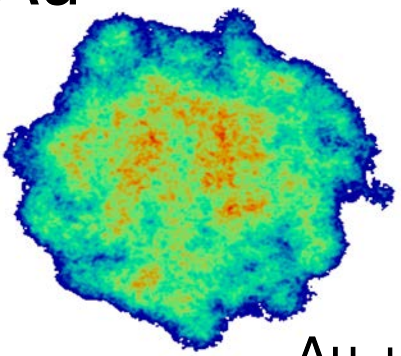
Ru, Zr parameters : Deng et al PRC 94,041901 (2016)



## Au+Au , U+U

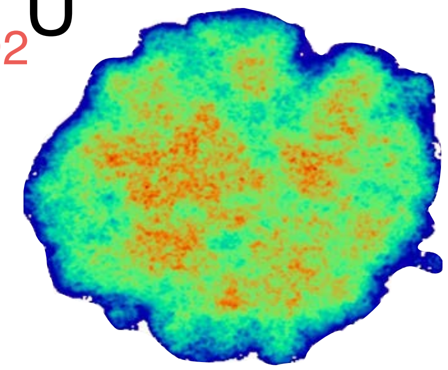
Measurements exist

$^{197}_{79}\text{Au}$



Au +Au

$^{238}_{92}\text{U}$



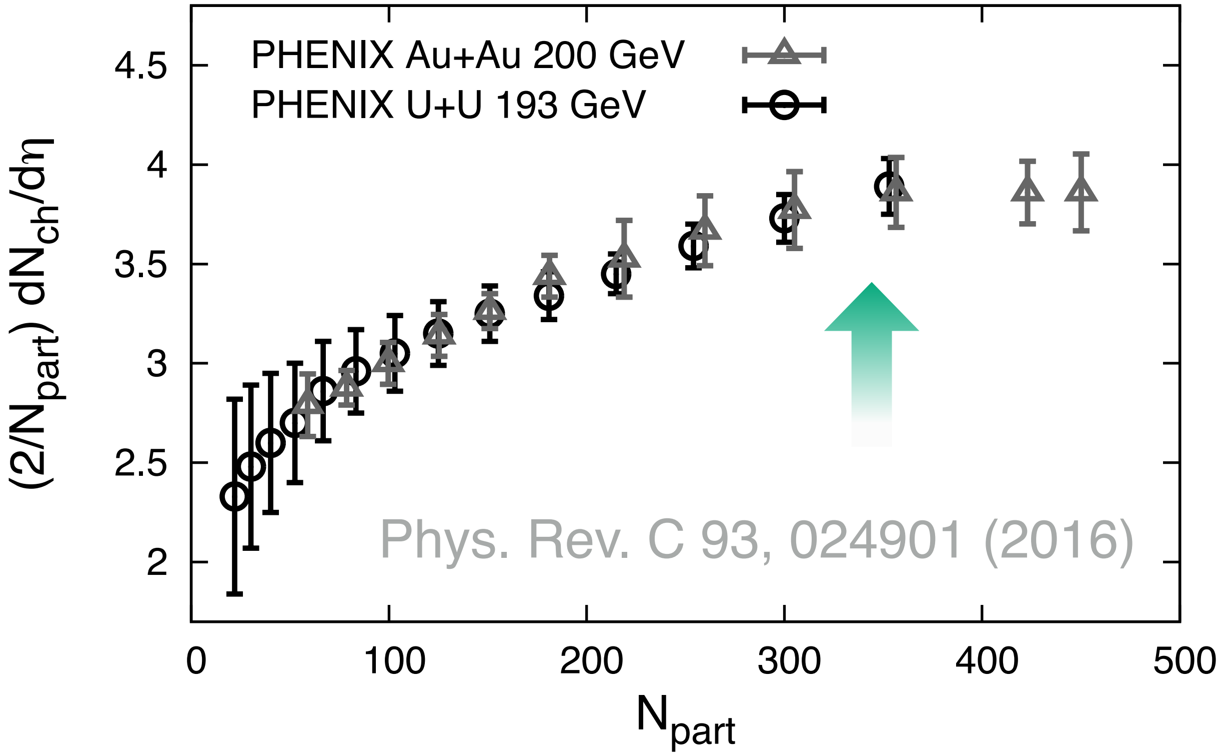
U+U

Change in Z by 13
Large difference in B-field ?

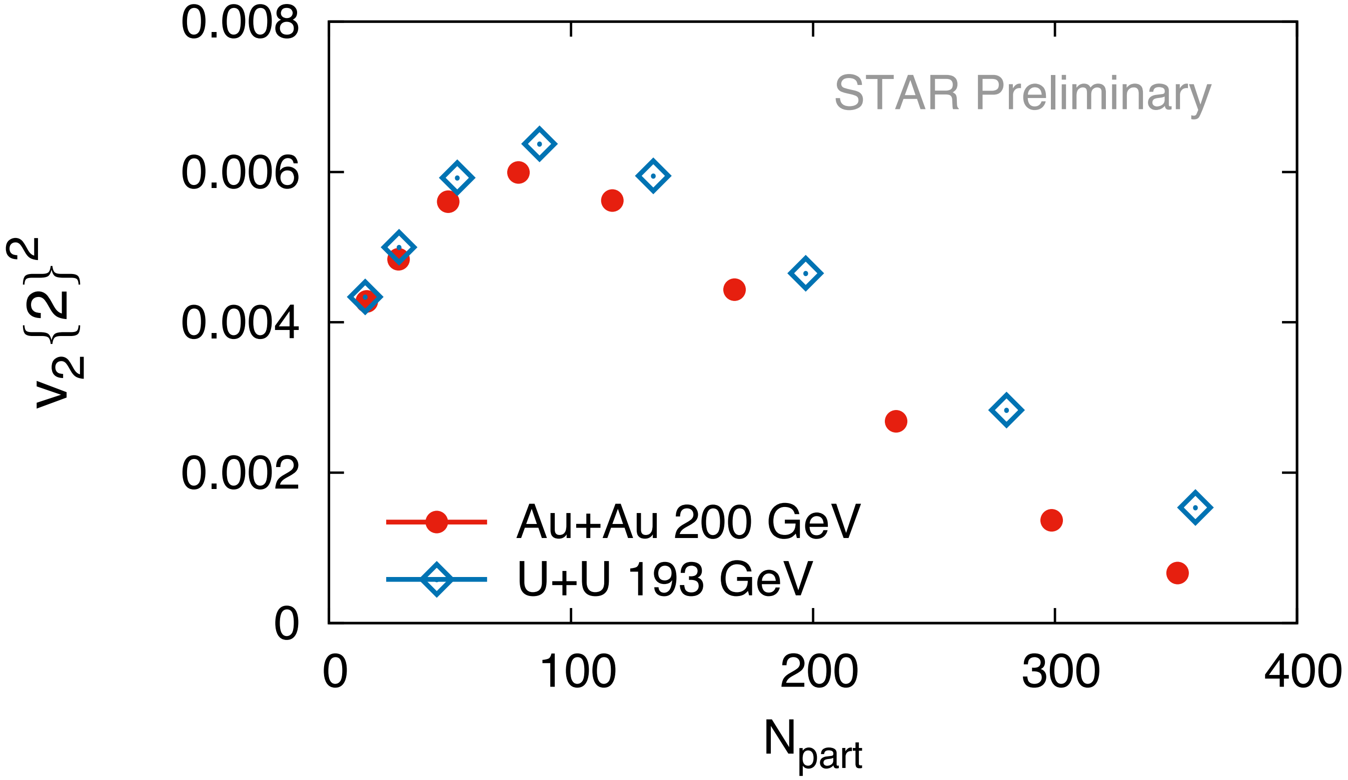
# Multiplicity and flow in Au+Au & U+U

Background expectation is under control : $\Delta\gamma_{\text{Background}} \approx \frac{v_2\{2\}}{N}$

Multiplicity per $N_{part}$



Measured flow

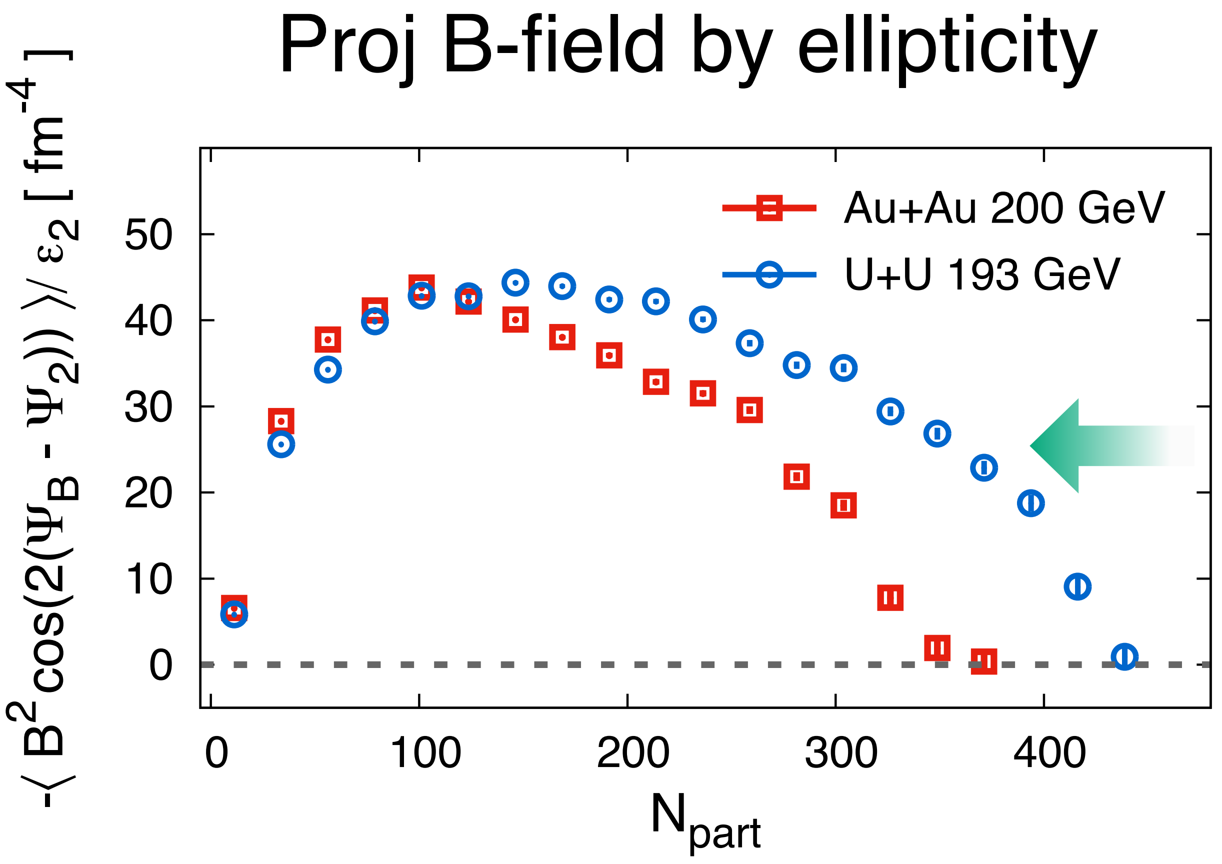


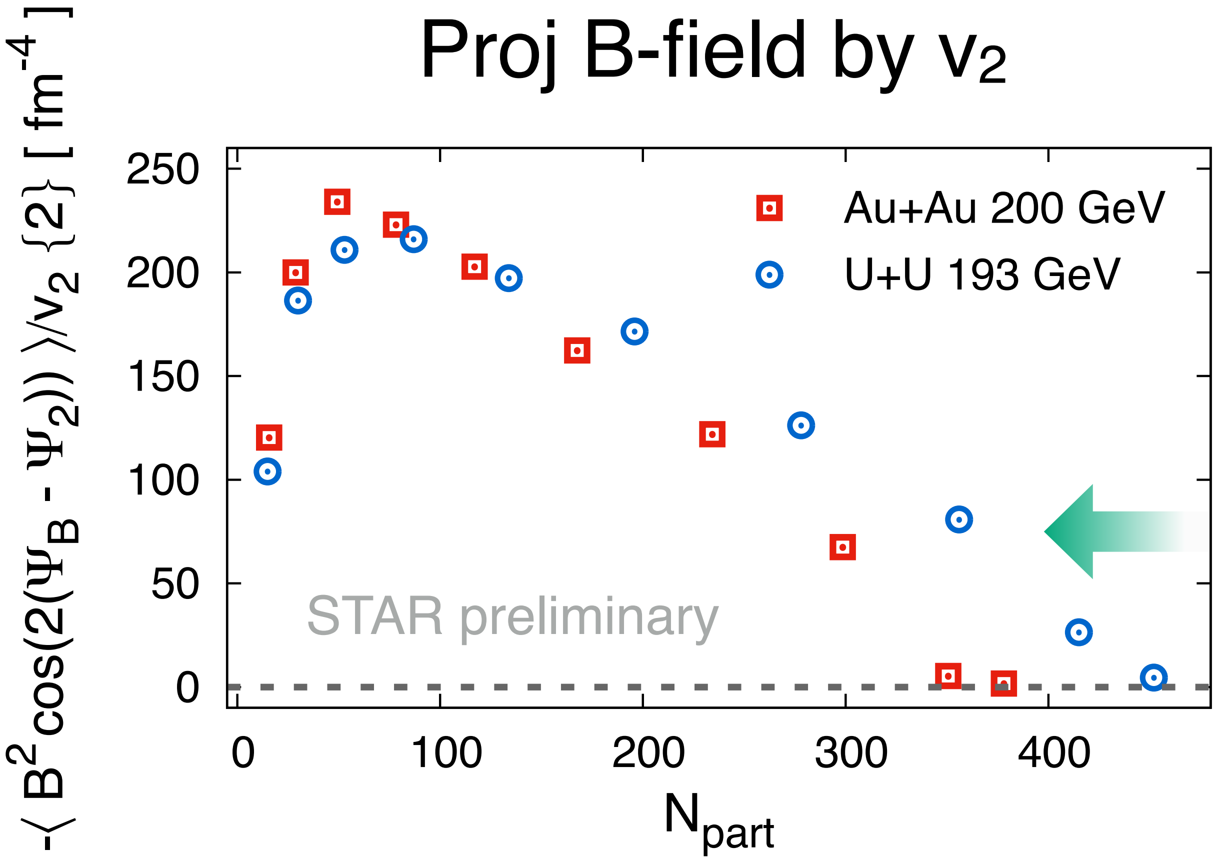
At the same $N_{part}$ multiplicity dN/dη per participant is similar

$v_2\{2\}$ measurement with very small uncertainties available

# Projected B-field differs in central collisions

One needs to take care of shape difference between Au+Au & U+U


Proj B-field by ellipticity

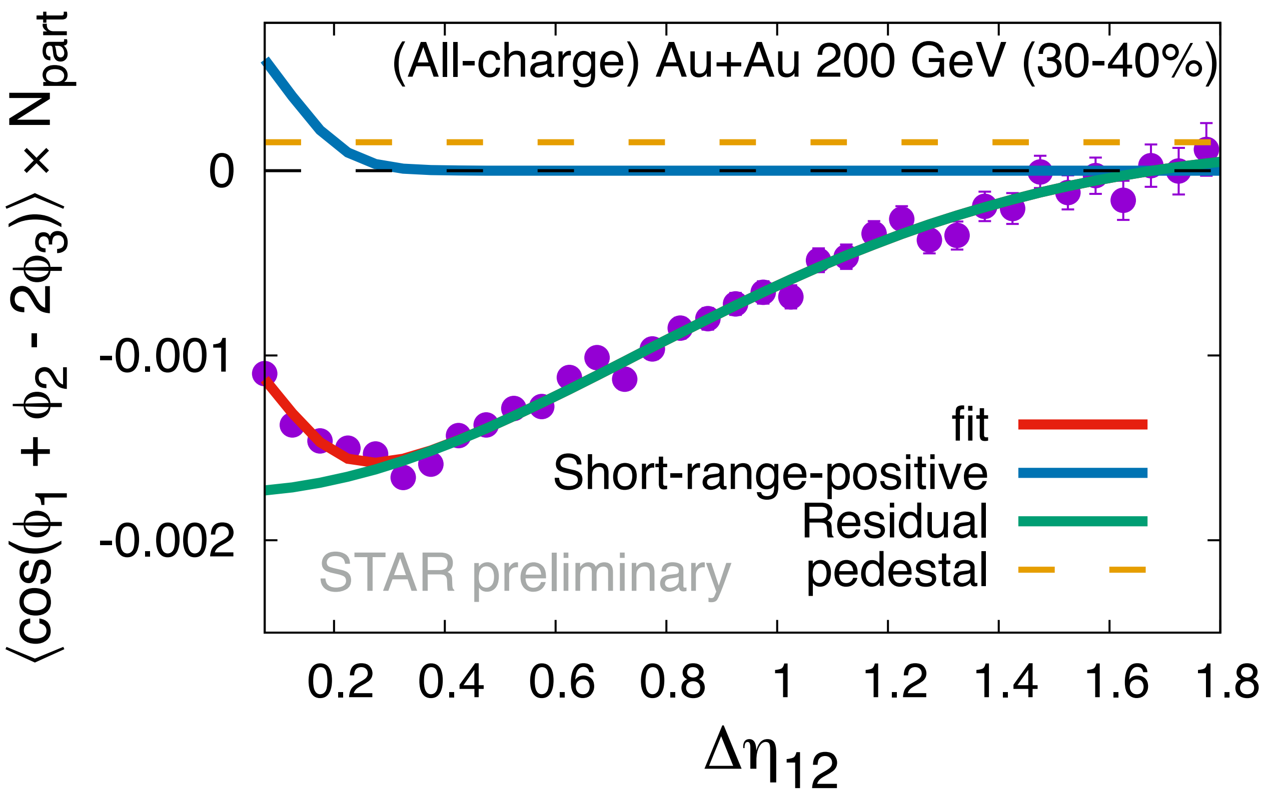

Proj B-field by $v_2$

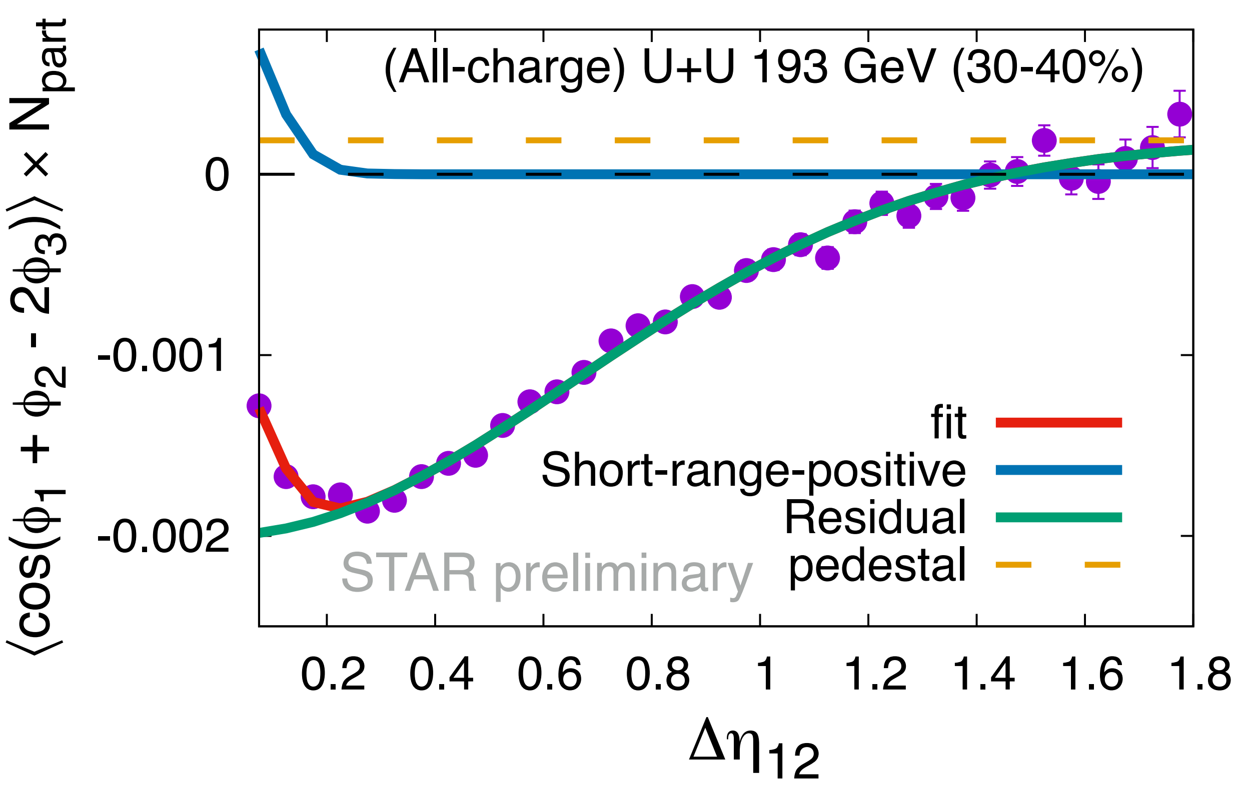
At same $N_{part}$ projected B-field differs when scaled by $\varepsilon_2$ or $v_2$

Larger B-field per eccentricity in U+U than Au+Au at large $N_{part}$

Motivation : Qualitatively similar scenario as isobar collisions

# Comparison between Au+Au and U+U


Au+Au


U+U

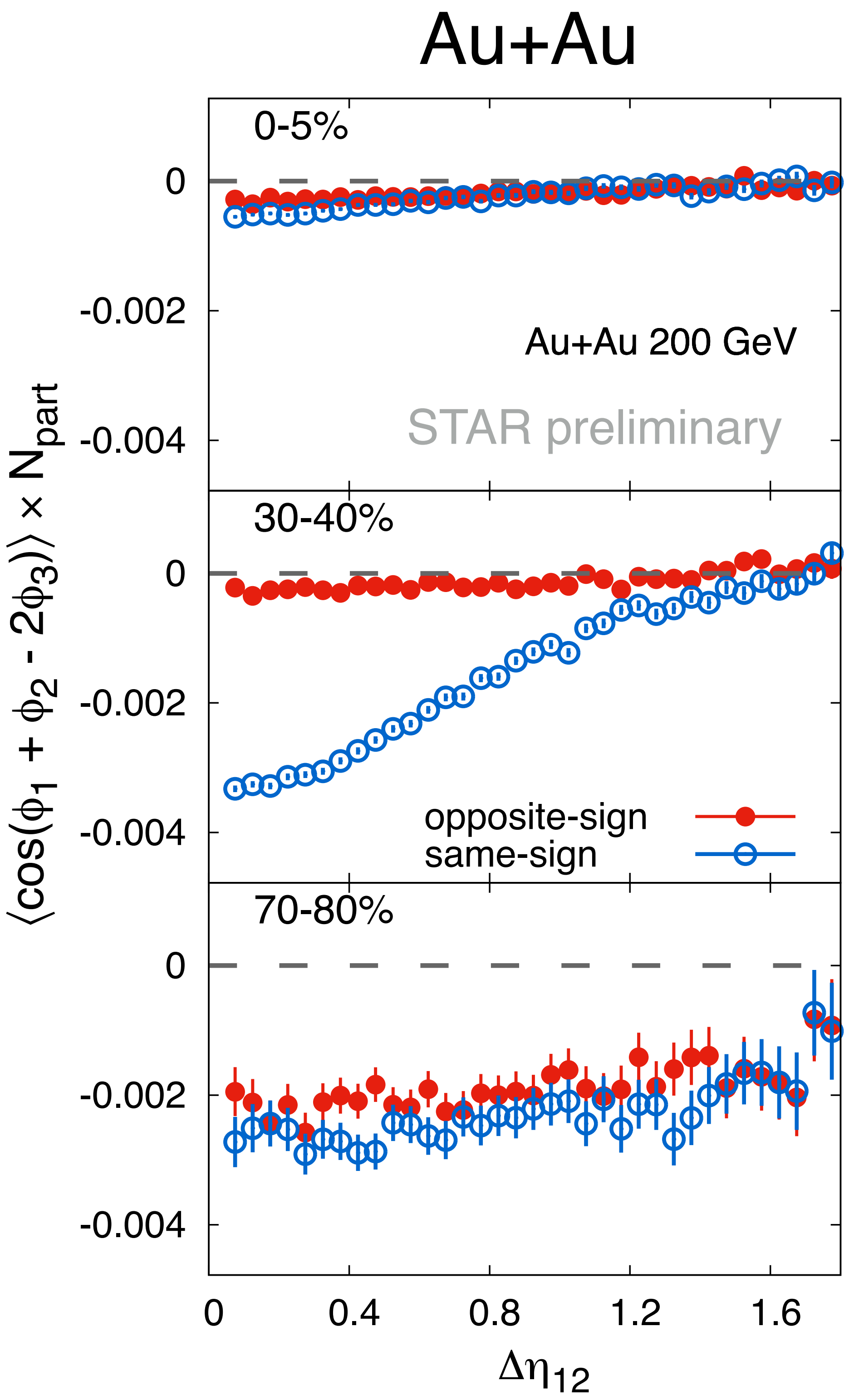
Perform three component fit to remove fragmentation, HBT-like peak

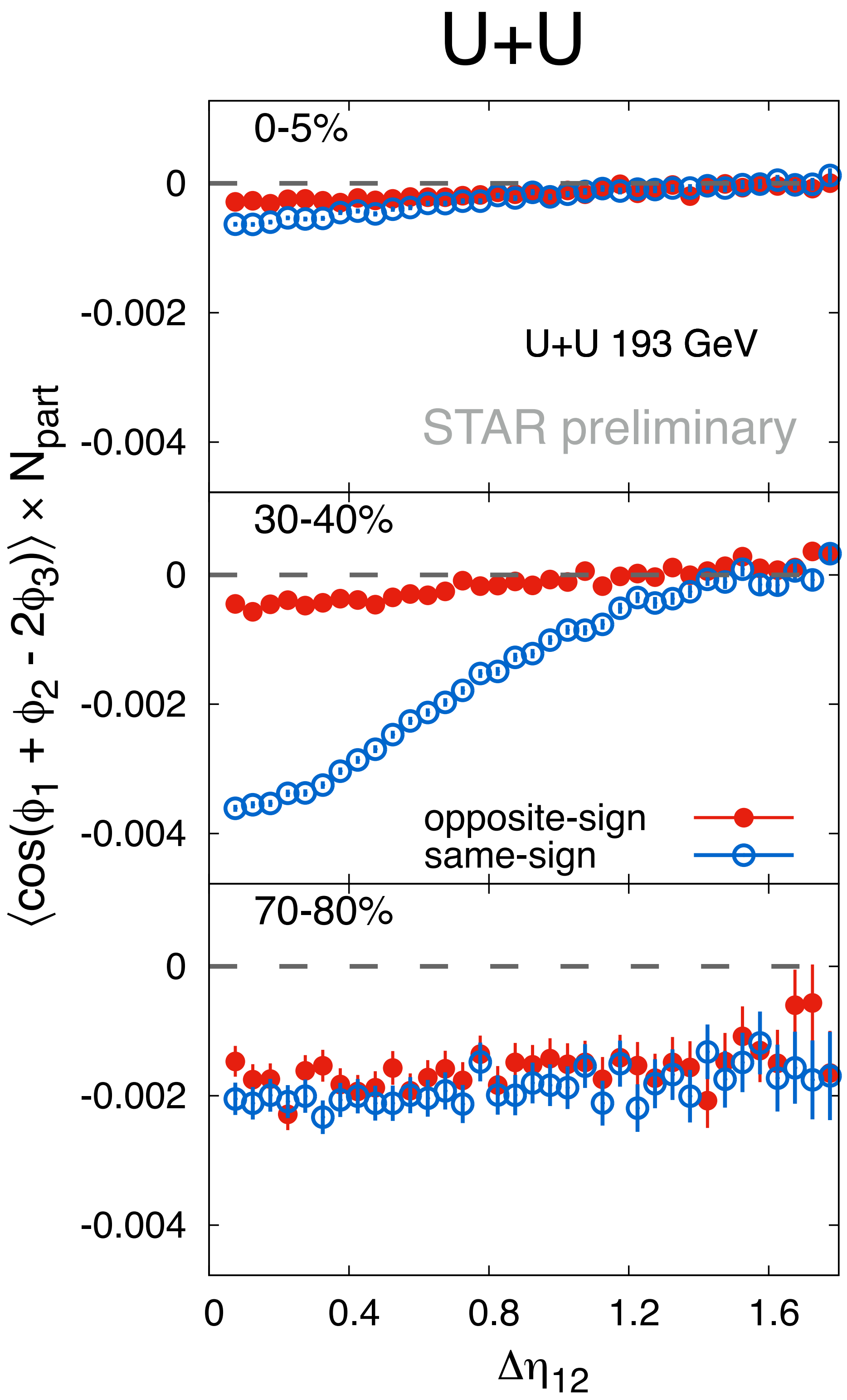
$$C_{112}(\Delta\eta_{12}) = \boxed{A^{+}_{SR}\, e^{-(\Delta\eta)^2/2\sigma^2_{SR}}} - \boxed{A^{-}_{IR}\, e^{-(\Delta\eta)^2/2\sigma^2_{IR}} + \boxed{A_{LR}}} \rightarrow \text{Pedestal}$$

Short-range-positive

Residual

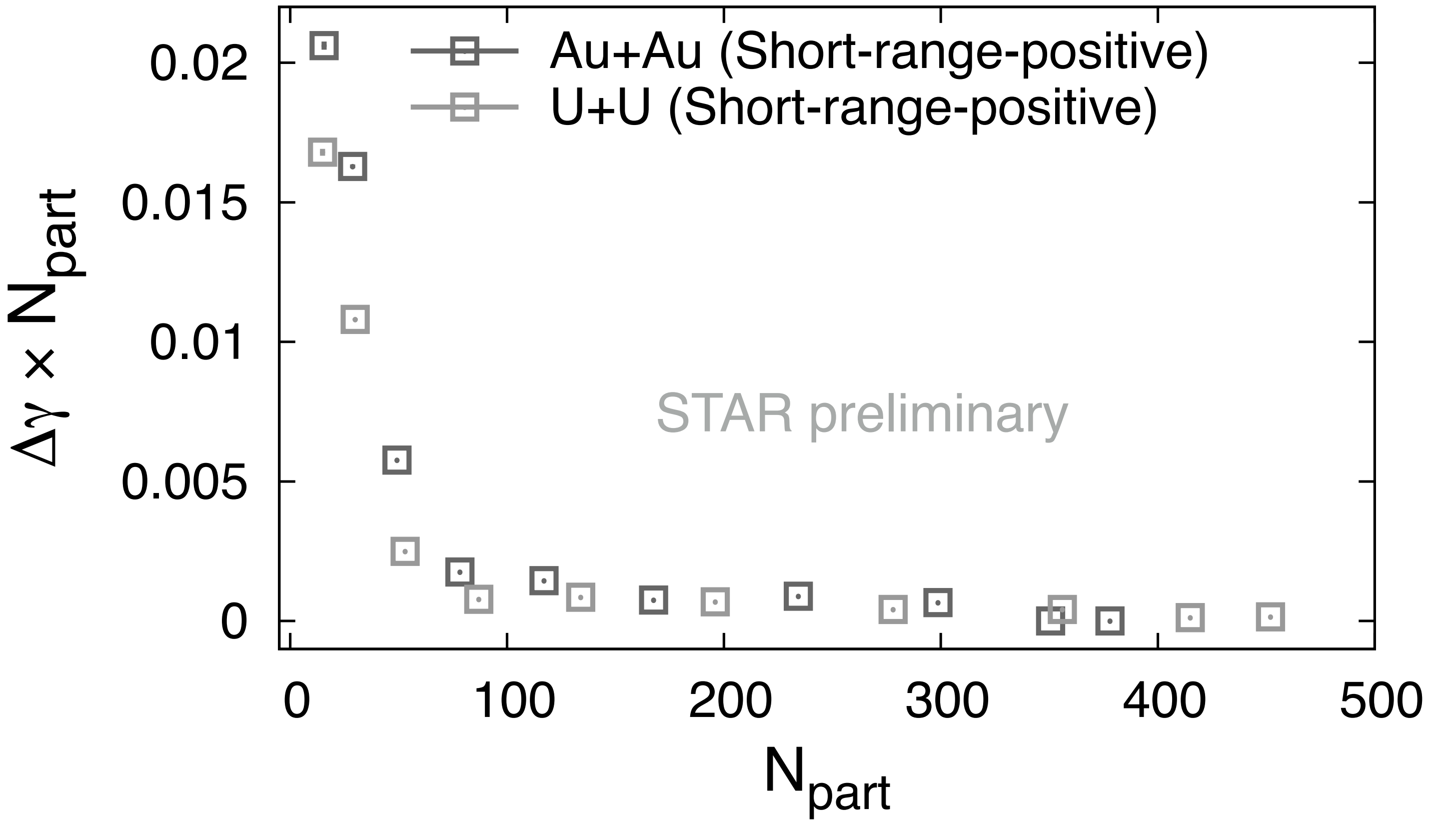
# Residual components





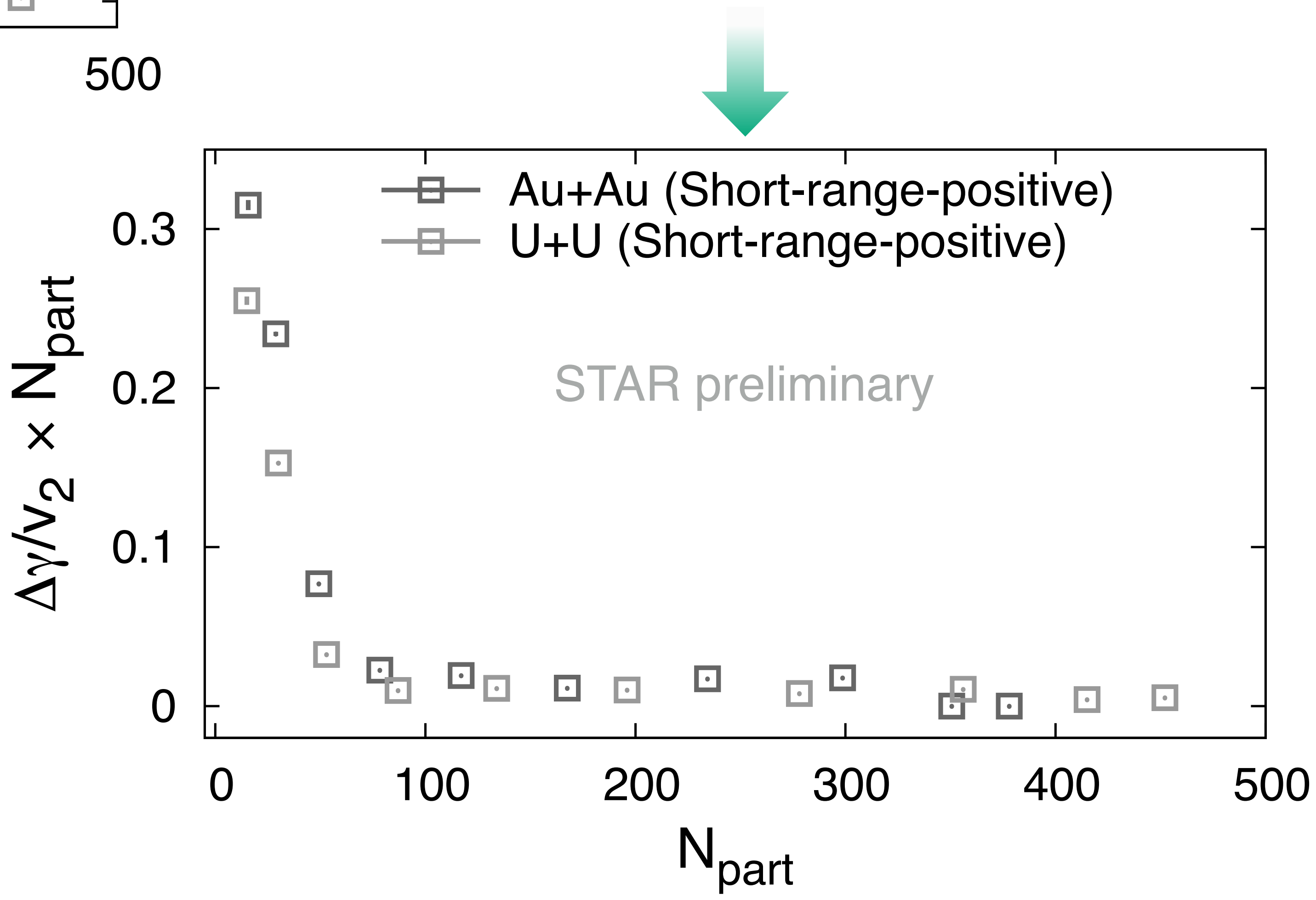
Relative pseudo-rapidity dependence looks similar

# Short range-positive (narrow Δη) component



Scaled by $N_{part}$

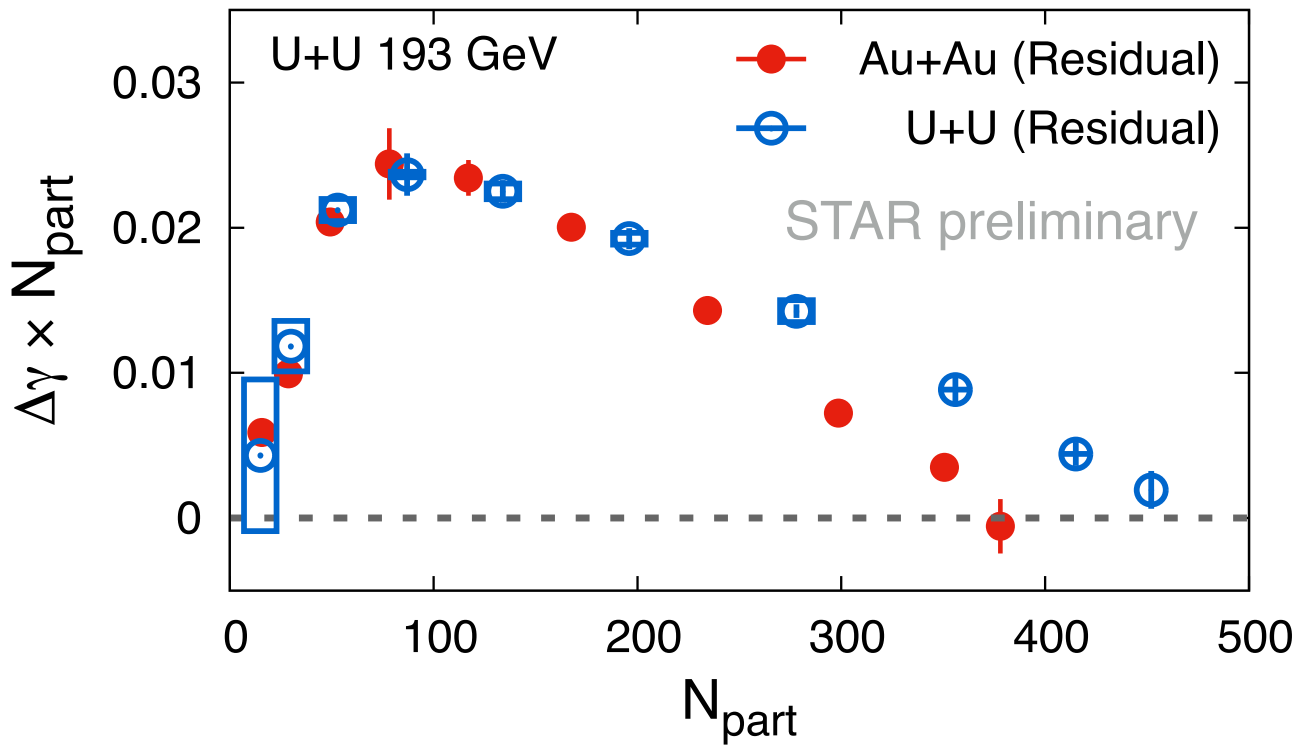
Scaled by $N_{part}/v_2$



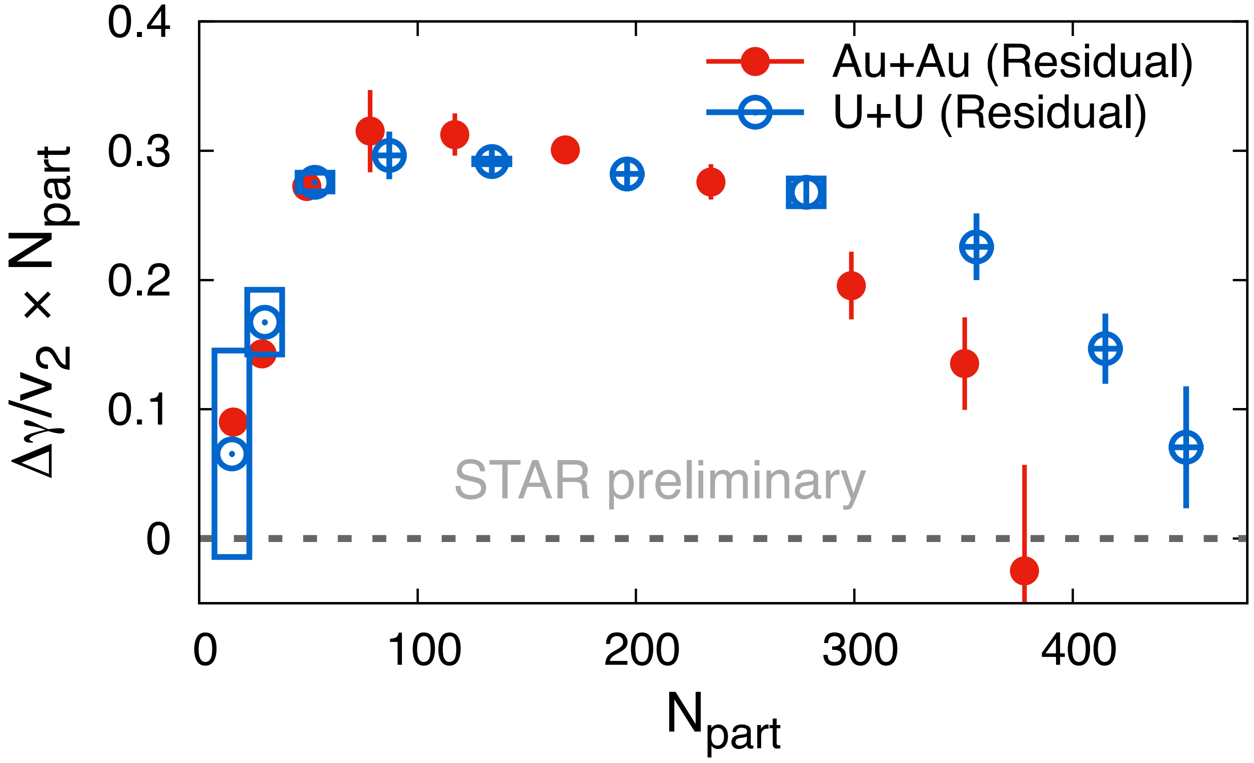
No strong system dependence for short-range-positive component is observed

# Residual (wide Δη) components

scaled by $N_{part}$



scaled by $N_{part}$ /$v_2$



Au+Au is lower than U+U at large $N_{part}$

$$\Delta\gamma_{\text{Background}} \approx \frac{v_2\{2\}}{N}$$

In a pure background scenario this plot should be flat & universal

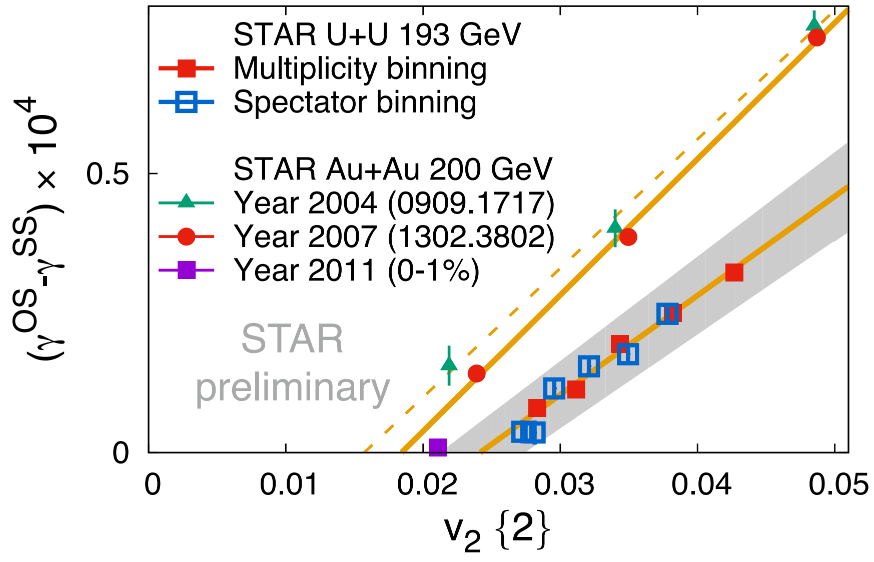
System dependence → not explained by naive background model

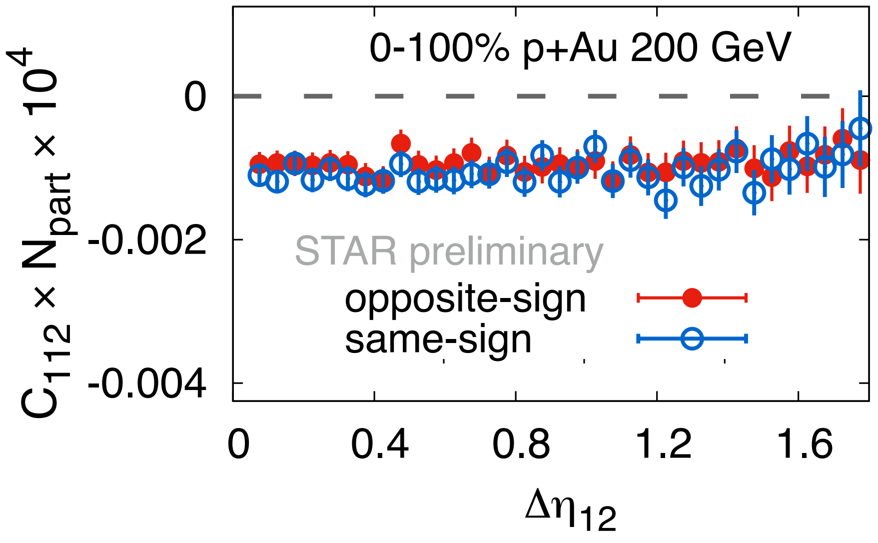
# Summary

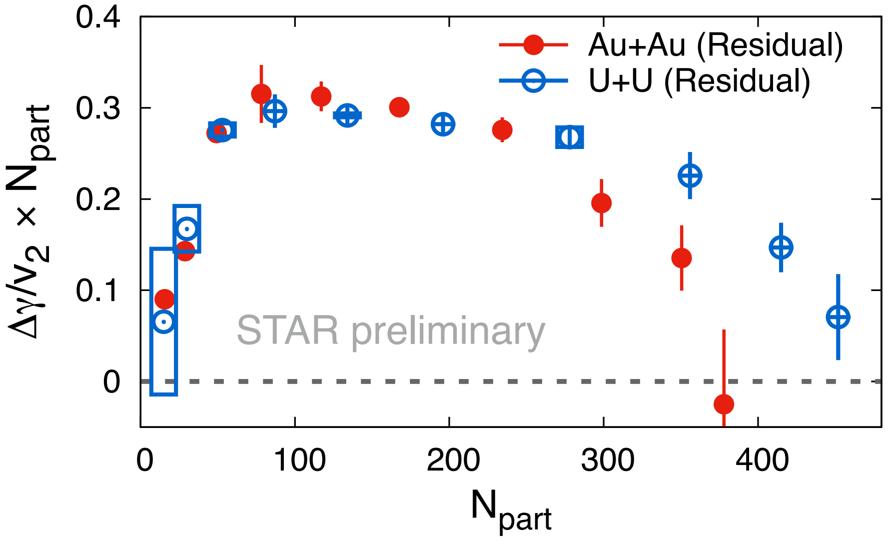
- Ultra-central U+U and Au+Au show $\Delta\gamma \sim 0$, $v_2 \neq 0$
- Short-range-positive component ($A_{SR}$) subtracted charge separation vanishes in central & peripheral A+A and in p+A collisions
- Comparison between Au+Au and U+U show difference in central events at same $N_{part}$

Several similarities of charge separation with projected B-field is observed in contrast to naive background ($\sim v_2/N$) expectation. Theoretical inputs needed to see if sophisticated background model calculations can explain these observations.

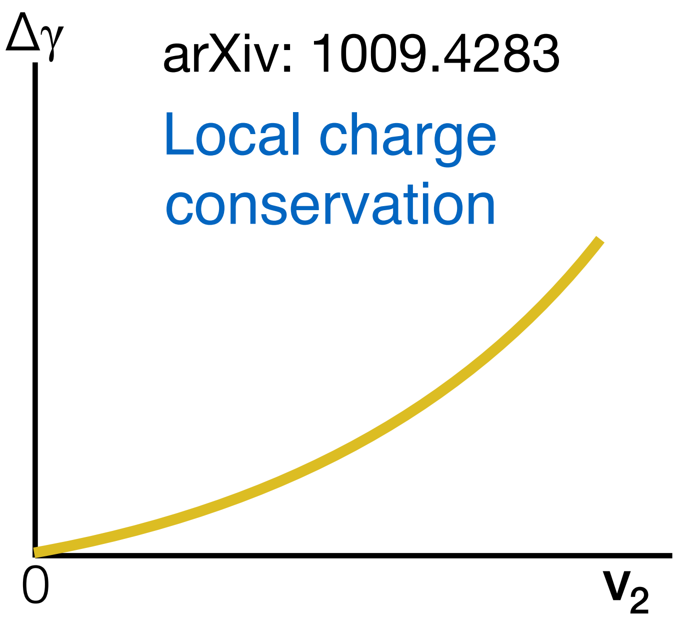
Future Isobar collisions at RHIC will provide more stringent test to disentangle background vs B-field driven charge separation.



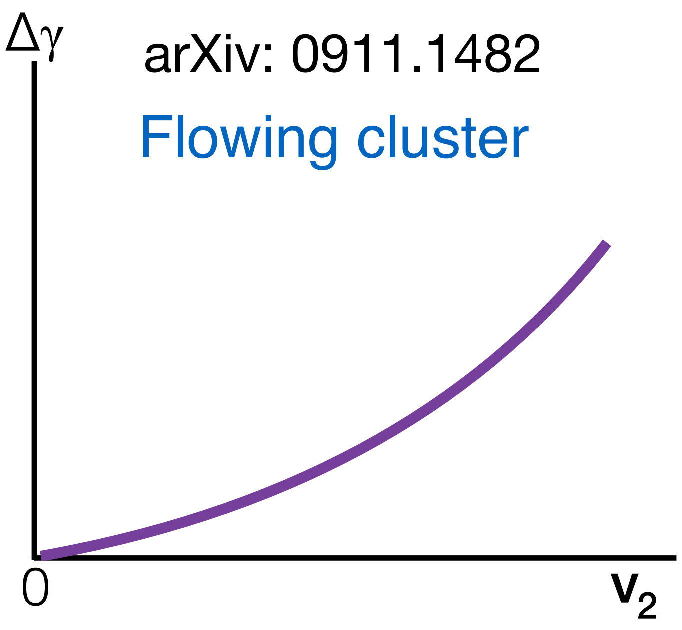




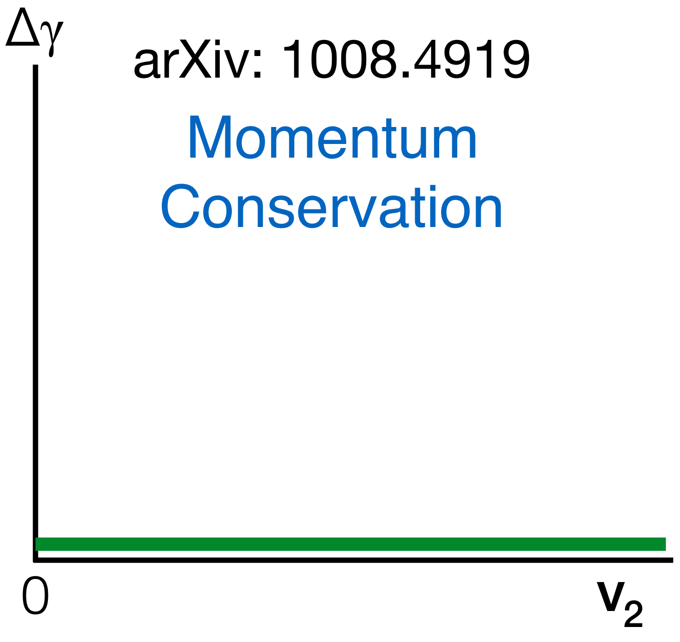
# Backup


arXiv: 1009.4283

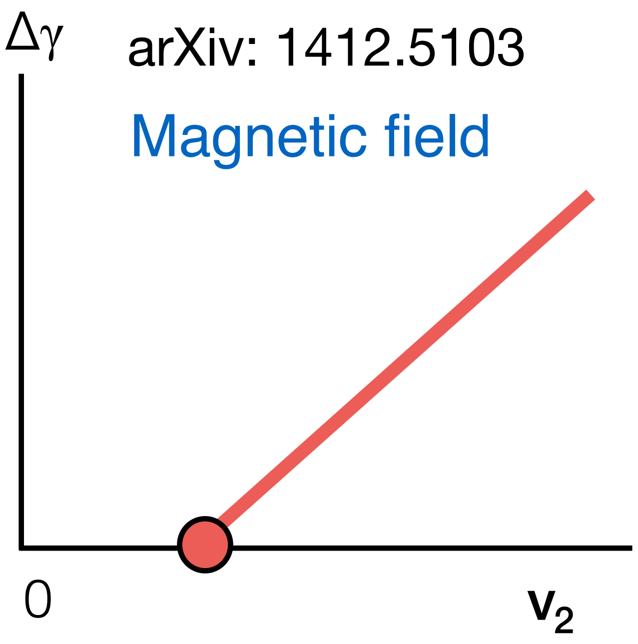
Local charge conservation


arXiv: 0911.1482

Flowing cluster


arXiv: 1008.4919

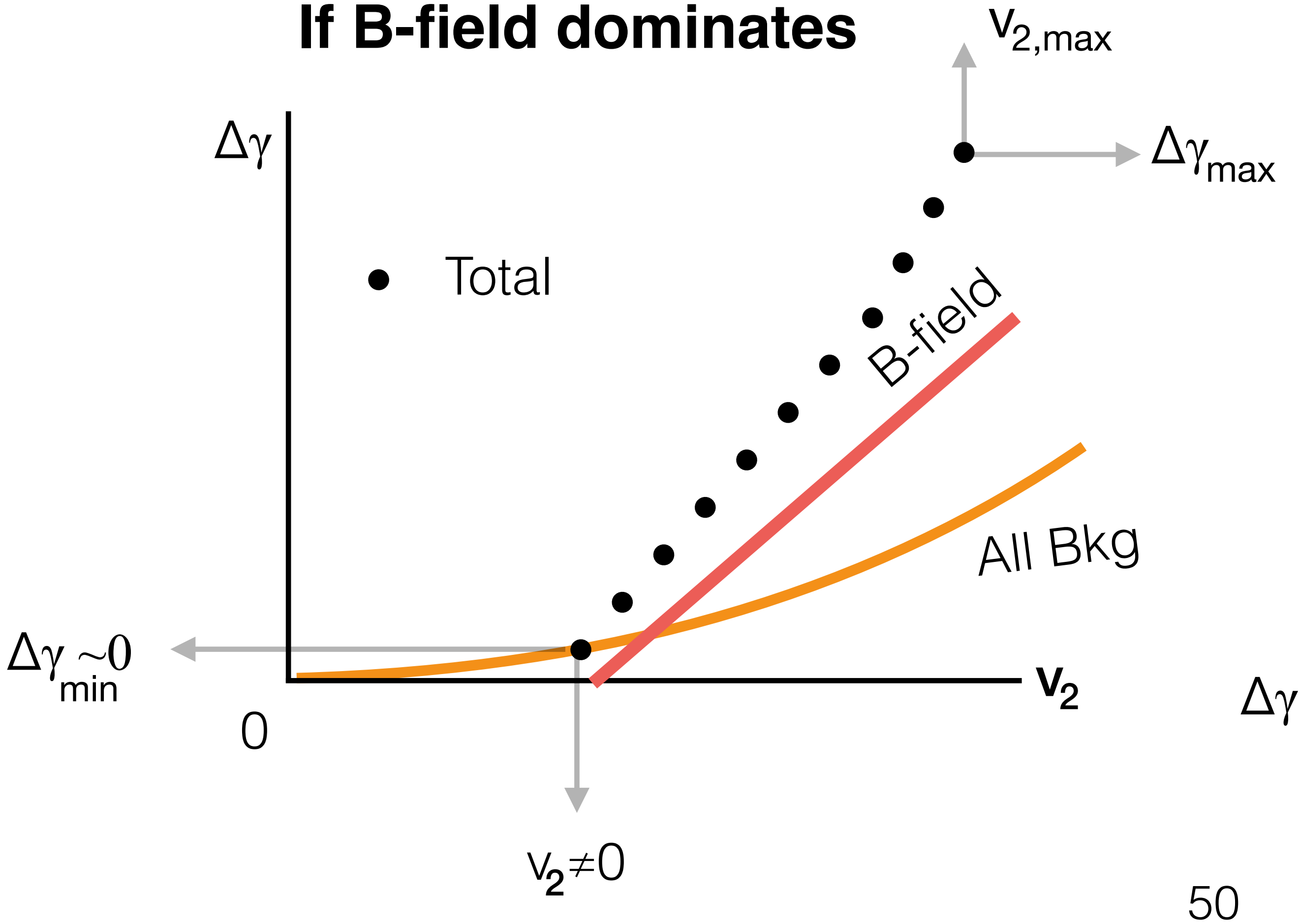
Momentum Conservation


arXiv: 1412.5103

Magnetic field

# Ultimately boils down to two scenarios

**If B-field dominates**



**If Background dominates**