Charge separation measurements in p+Au and A(B)+A collisions; Implications for characterization of the chiral magnetic effect

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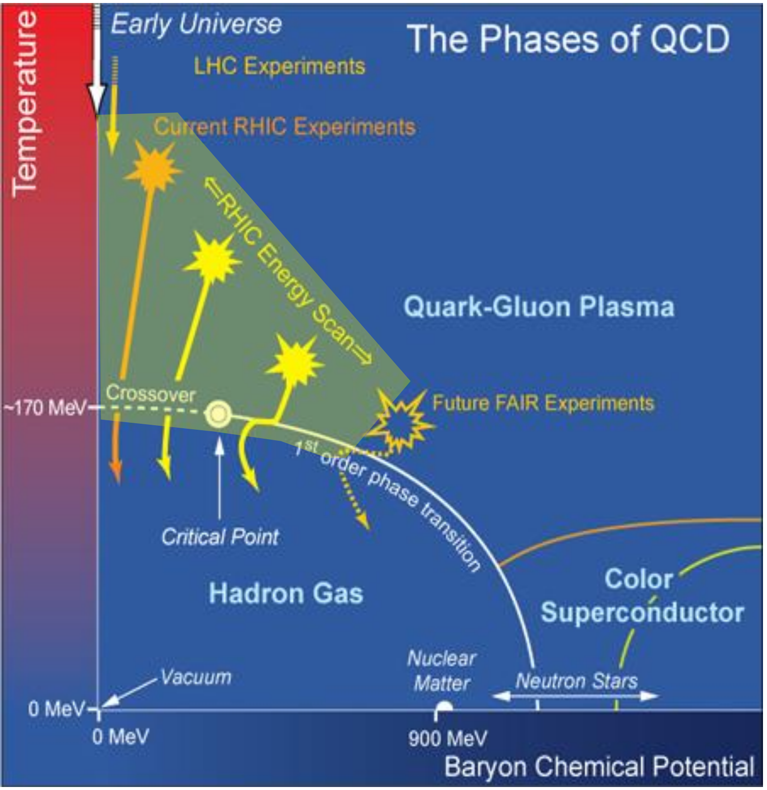
QCD Phase Diagram

Quantitative study of the QCD phase diagram is a current focus of our field



*Measurements spanning a large domain of the **(T, μ_B)-plane** are ongoing/slated at RHIC and other facilities*

Questions of interest:

- **Location of the essential *"landmarks"*?**
  - ✓ *Crossover region?*
  - ✓ *Critical Point (T^{cep}, μ_B^{cep})?*
    - ❖ *static critical exponents - ν, γ, δ?*
    - ❖ *dynamic critical exponent/s – z?*
  - ✓ *Coexistence regions?*
- ***Properties of the respective phases?***
  - ✓ *Thermodynamic properties?*
  - ✓ *Topological & Chiral properties*
  - ✓ *Transport properties?*
  - ✓ *Anomalous chiral transport?*
  - ✓ *etc*

All are required to fully chart the phase diagram

Subject of this talk

Comments about the CEP

Comment – I

Meaningful discussions about the location and character of the Critical End Point (CEP) must include Finite-size and/or Finite-time effects

Comment – II

The Generalized Finite-Size-Finite-Time Scaling form for χ is well known

$$\chi^{(i)}(\tau, t, L) \sim L^3 b^{i\delta\beta/\nu} \chi^{(i)}(\tau b^{1/\nu}, t b^{-z}, L^{-1} b)$$

$$\chi^{(i)} \sim L^{3+i\delta\beta/\nu} f_1(\tau L^{1/\nu}, R L^r)$$ FSS form

$$\chi^{(i)} = L^3 R^{-i\delta\beta/r\nu} f_2(\tau R^{-1/r\nu}, L^{-1} R^{-1/r})$$ FTS form

$V = L^3$, $\tau = \left(T - T^{\mathrm{cep}}\right) / T^{\mathrm{cep}}$

$r = z + 1/\nu$, $R =$ cooling rate $T_i \to T^{\mathrm{cep}}$

$\hat{\xi} =$ effective cor. length for FTE

If Finite-Size Effects Dominate

$\xi > \hat{\xi} > L \quad \dfrac{\chi^{(n)}}{\chi^{(m)}} = L^{(n-m)\delta\beta/\nu} f(\tau L^{1/\nu})$

If Finite-Time Effects Dominate

$$\xi > L > \hat{\xi}$$

$$\frac{\chi^{(n)}}{\chi^{(m)}} = L^{(n-m)\delta\beta/\nu} f(\tau L^{1/\nu})$$

$(n-m)\delta\beta/\nu \sim 0)$ and $\chi^{(i)} \sim L^3$.

- **Utilize Finite-Size-Finite-Time Scaling of susceptibility measurements for different sizes (L)**

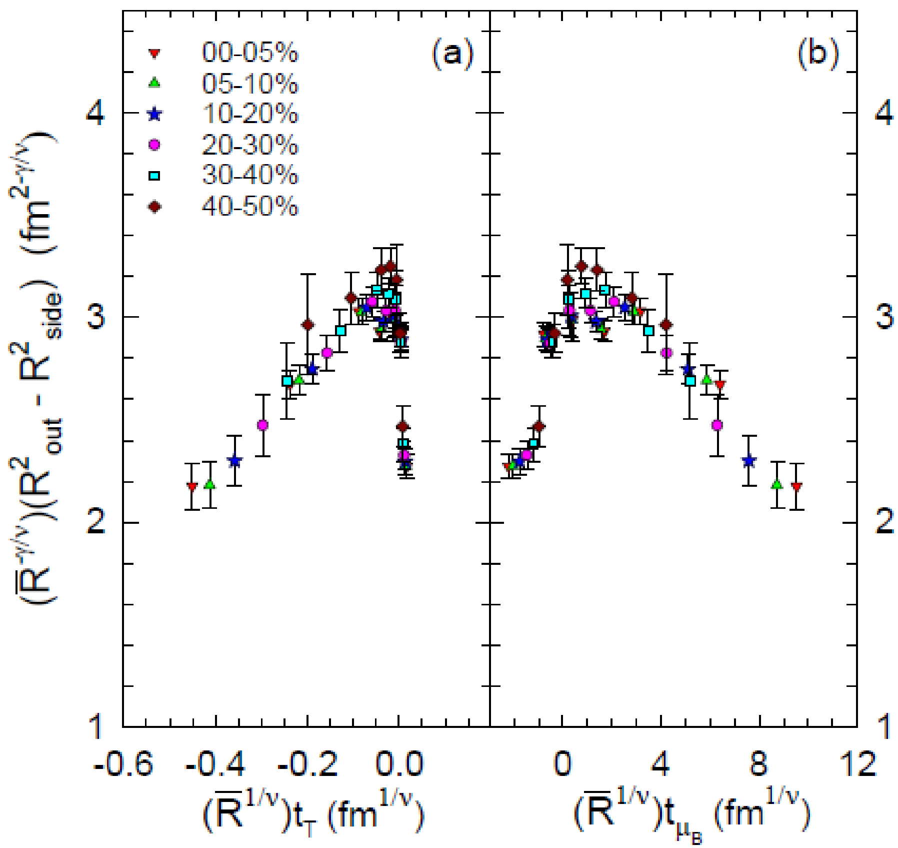
CEP estimate via finite-size scaling

$T^{cep} \sim 165$ MeV, $\mu_B^{cep} \sim 95$ MeV $(V \to \infty)$

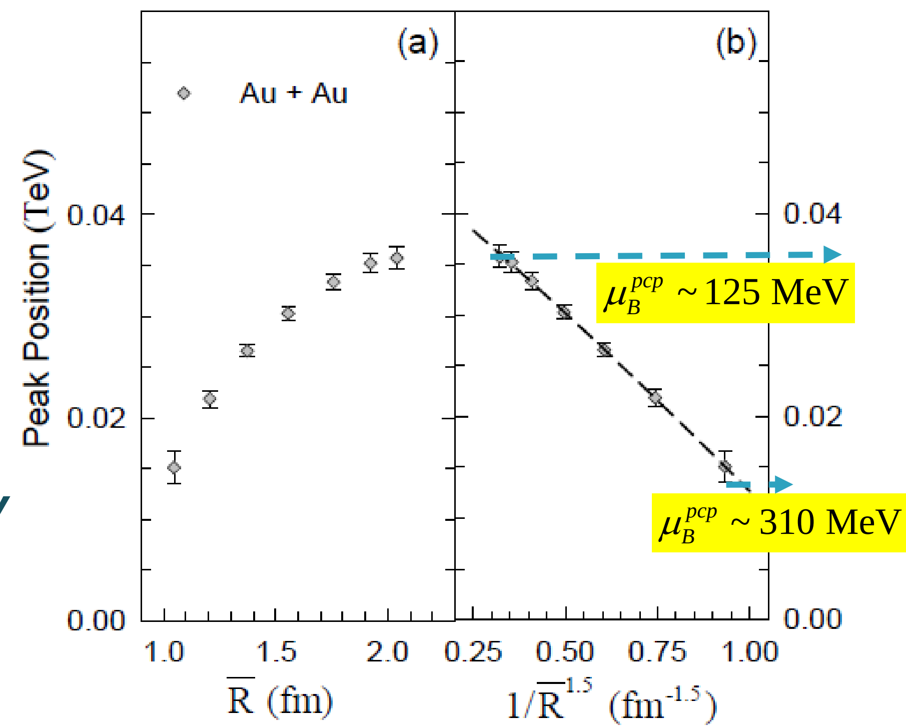
$\nu \sim 0.66$ $\gamma \sim 1.2$ $\delta \sim 4.8$

- ✓ ***2nd order phase transition***
- ✓ ***3D Ising Model (static) universality class for CEP***

RL - Phys.Rev.Lett. 114 (2015) no.14, 142301



****The pseudocritical point (PCP) has a strong volume dependence****



*****Scaling functions for proxy susceptibility (κ) validates the estimate for the location of the CEP and the (static) critical exponents → compressibility diverges*****

Finite-Size Effects shifts μ_B^{pcp} to much lager values

CEP estimate via Finite-Size-Finite-Time scaling

For an isothermal change

$$VdP = Nd\mu$$

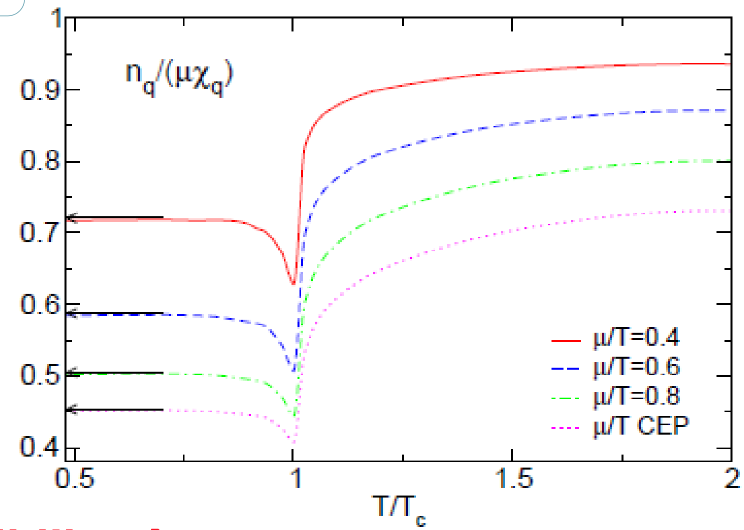
$$N\left(\frac{\partial \mu}{\partial N}\right)_{V,T} = V\left(\frac{\partial P}{\partial N}\right)_{V,T} = \frac{1}{\rho\kappa_T}$$

From partition function one obtains

$$\frac{1}{\langle N\rangle}\left(\frac{\partial\langle N\rangle}{\partial\beta\mu}\right) = \frac{\langle N^2\rangle - \langle N\rangle^2}{\langle N\rangle}$$

$$\kappa_T^{-1} \propto \frac{\langle N\rangle}{\langle N^2\rangle - \langle N\rangle^2} = \frac{C_1}{C_2}$$

***Stoki´c, et. al*, Phys.Lett.B673:192-196,2009**

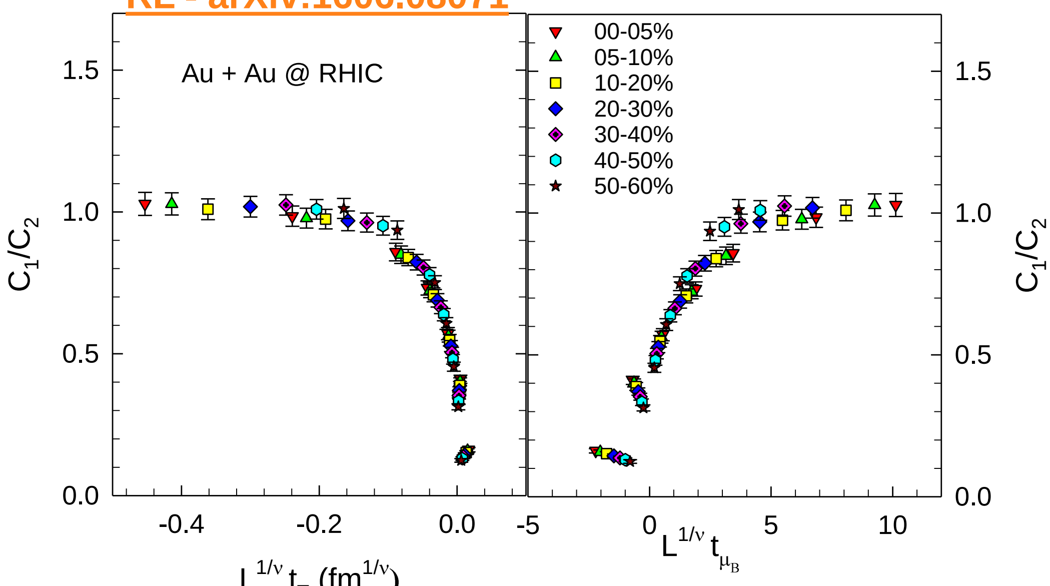


- **At the CEP the inverse compressibility → 0**
- **Scaling properties of fluctuations data can be leveraged.**

$$T^{cep} \sim 165 \text{ MeV}, \mu_B^{cep} \sim 95 \text{ MeV } (V \to \infty)$$

Use T^{cep}, μ_B^{cep}, and ν in conjunction with Finite-Size-Finite-Time scaling to obtain Scaling Function for C_1/C_2

RL - arXiv:1606.08071



Anomalous Transport in the QGP

Chiral Magnetic Effect

Electric Current — *Chiral Magnetic Conductivity* — *Chiral Chemical potential*

$$\vec{J}_Q = \sigma_5 \vec{B}$$

$$\sigma_5 = C_A \mu_5$$

$$C_A = Q^2 / (4\pi^2)$$

Kharzeev hep-ph/0406125

[Jiang et al., arXiv:1611.04586](https://arxiv.org/abs/1611.04586)

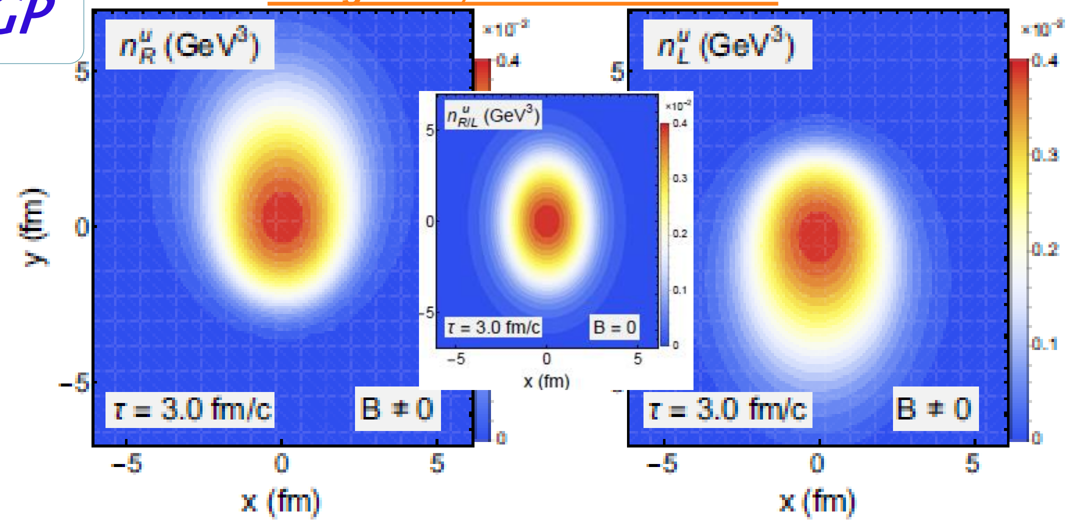


FIG. 1. Comparison of the evolution of the densities (n_R^u, n_L^u) for right-handed (left panel) and left-handed (right panel) u-flavor quarks at $\tau = 3.00$fm/c for a nonzero B field along the positive y-axis (i.e. perpendicular to the reaction plane). The figures, which show results from Anomalous Viscous Fluid Dynamics (AVFD) calculations, are taken from Ref. [8].

The Chiral Magnetic Effect (CME) results from anomalous chiral transport of the chiral fermions in the QGP, leading to the generation of an electric current $\vec{J}_Q$ *along the magnetic field* $\vec{B}$ *generated in the collision:*

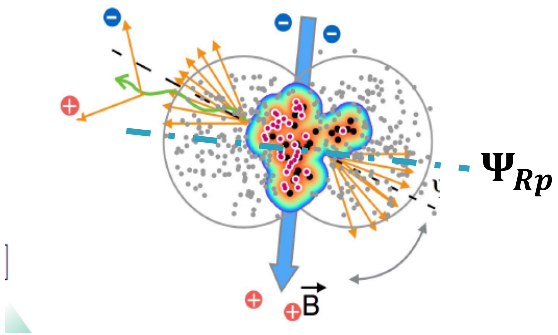
→ **Leads to charge separation about the event plane**

Charge separation leads to a dipole term in the azimuthal distribution of the produced charged hadrons:

$$\frac{dN^{ch}}{d\phi} \propto [1 \pm 2a_1^{ch} \sin\phi + ...]$$

Objective: identify & characterize this "dipole moment"

Gamma correlator & its Response

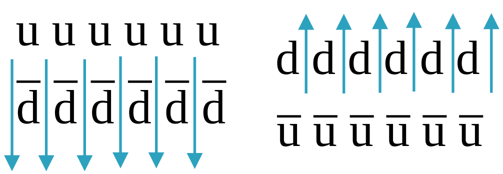


Voloshin, PRC 70 (2004) 057901

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

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

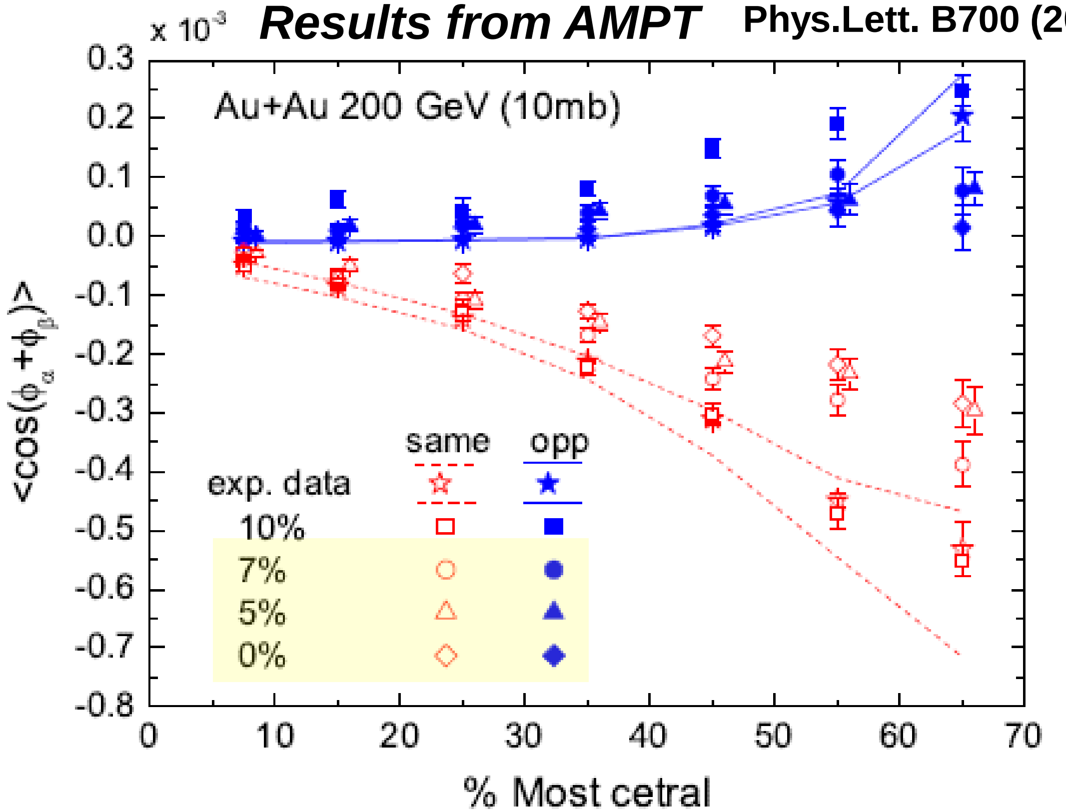
Input charge separation studied with AMPT



switch the p_y values of a fraction of each set

Ma, Zhang
Phys.Lett. B700 (2011) 39-43

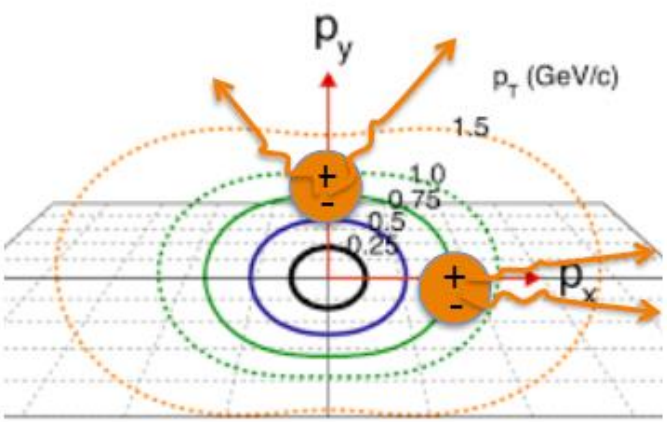
Results from AMPT



- **The Gamma Correlator's response is similar for signal and background**
  - ✓ **Background-driven correlations complicate CME-driven signal extraction?**

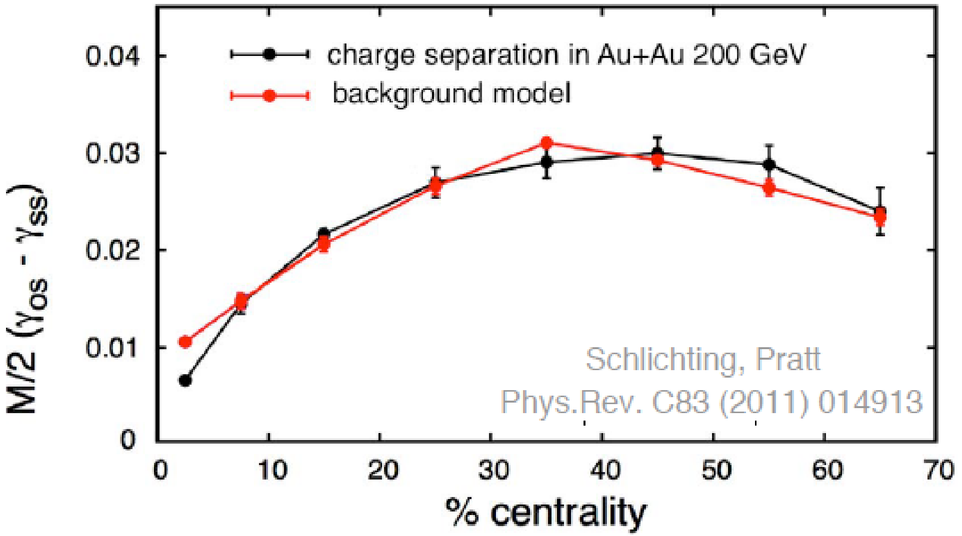
Gamma correlator status quo & measurements

Local charge conservation is an especially important background



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

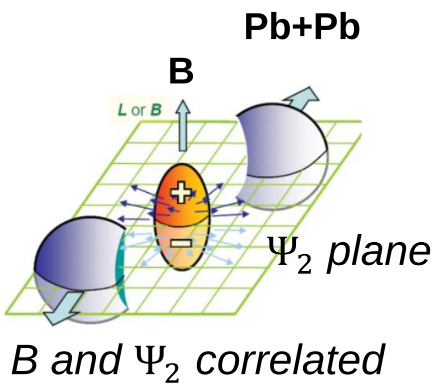
$$\langle a_\alpha a_\beta \rangle = 0$$

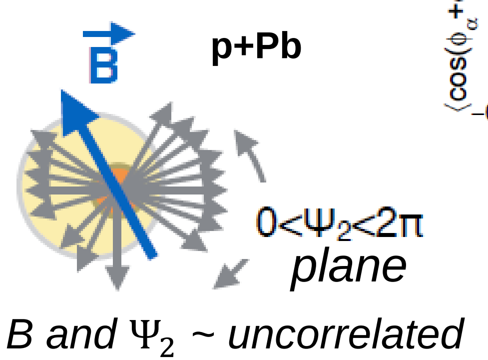


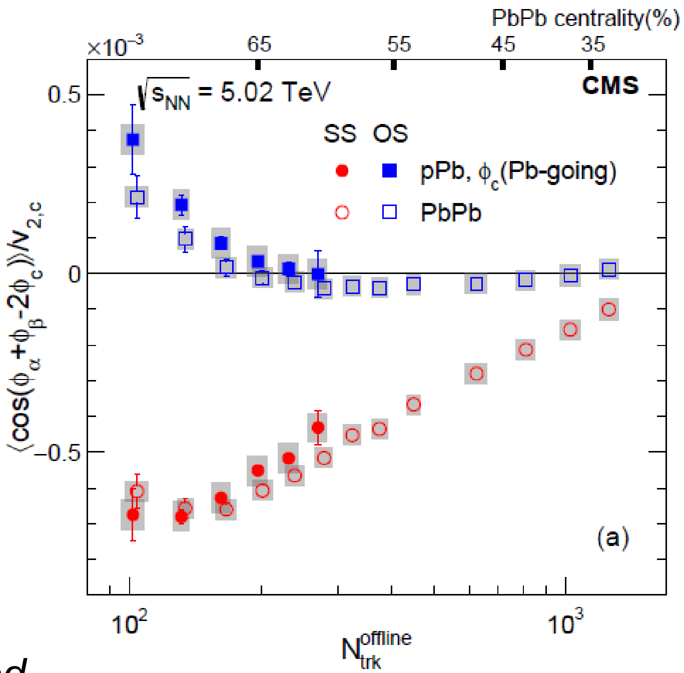
- **Background-driven correlations can account for a <u>part</u>, or <u>all</u> of the observed charge separation signal?**

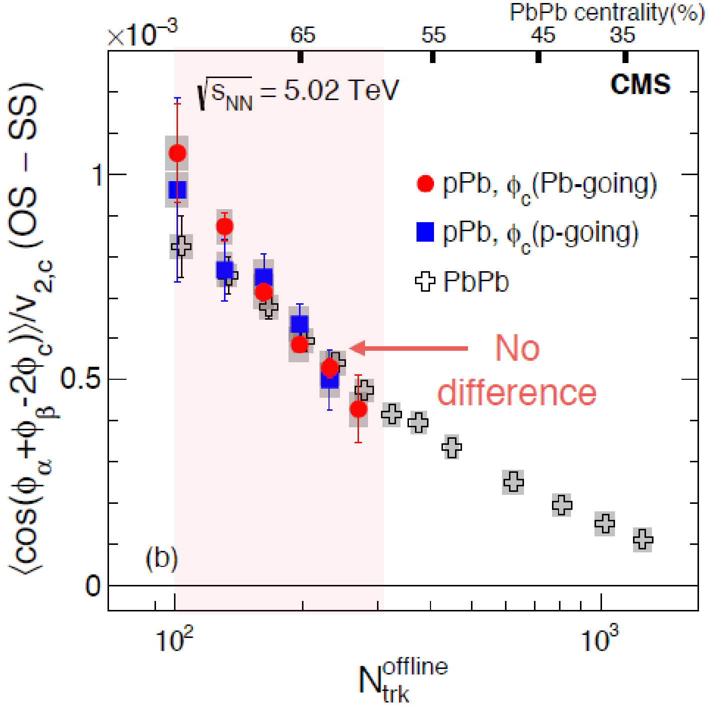
Gamma correlator status quo & measurements

Recent CMS measurements for p+Pb and Pb+Pb at the LHC gives cause for pause!









- **The magnitudes of the scaled correlators for p+Pb and Pb+Pb are not expected to be the same**

→ **"Reduced" magnetic field strength for p+Pb?**

→ **Large dispersion of the B-field about Ψ_2 in p+Pb**

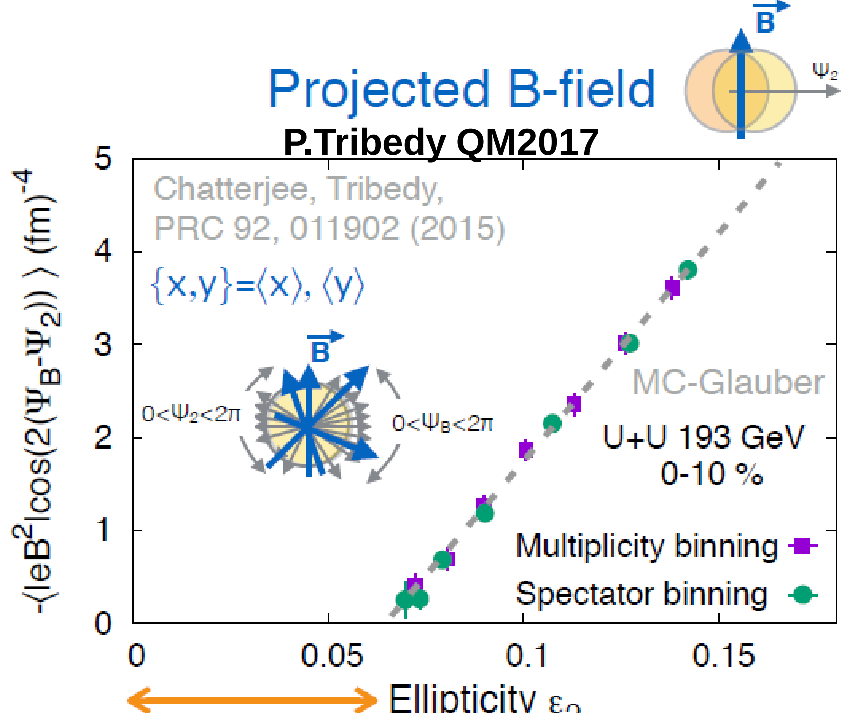
Separating signal from Background

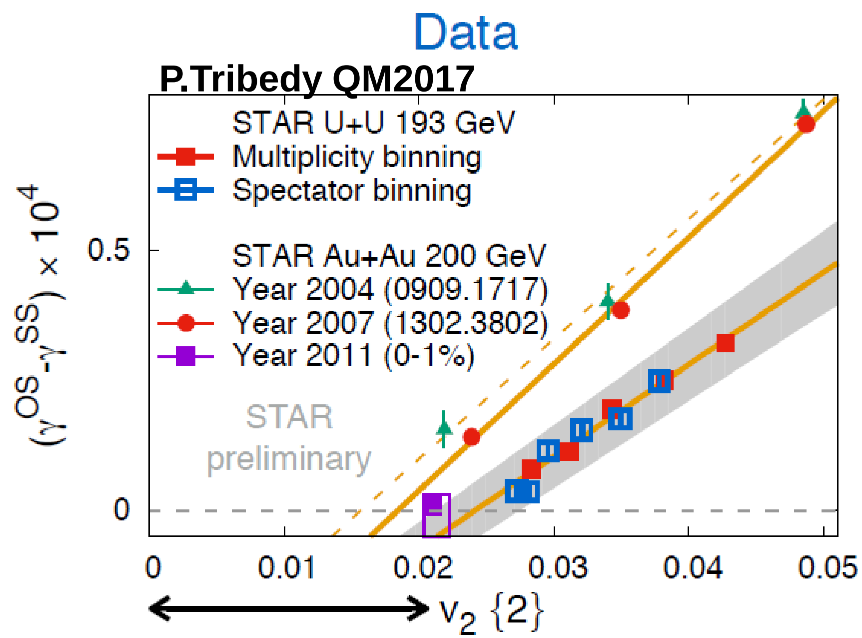
Techniques which can reliably suppress or separate background contributions from the desired CME-driven signal → underway

Gamma correlator Measurements
focused on ``clever" subtraction techniques

<u>**Ongoing strategy**</u>

- *vary the background for a fixed signal*
- *vary the signal for fixed background*





- Data trend compatible with expectation from projected B-field

Separating signal from Background

<u>Complimentary approach:</u>

✓ *Focus on new measurements with an “improved” correlator which can distinguish between signal and background*

➢ A charge-sensitive in-event correlator is used to search for, and characterize CME-driven charge separation

"New" Correlator

A Multi-particle charge-sensitive in-event correlator is used to measure charge separation (ΔS) relative to the Ψ_2 *plane!*

$$C_p(\Delta S) = \frac{N_{\text{real}}(\Delta S)}{N_{\text{shuffled}}(\Delta S)}$$

N. N. Ajitanand, et al., Phys. Rev. C 83, 011901(R) (2011).

The Numerator is the distribution over events, of the event-by-event averaged ΔS

charged hadrons ($h^{\mp}$)

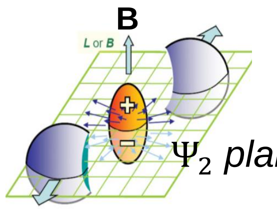
$n = \# h^{-}$

$p = \# h^{+}$

$$\Delta\varphi = \phi - \Psi_2$$

$$\langle S_p^{h+} \rangle = \frac{\sum_1^p \sin(\Delta\varphi_+)}{p} \qquad \langle S_n^{h-} \rangle = \frac{\sum_1^n \sin(\Delta\varphi_-)}{n}$$

$$\Delta S = \langle S_p^{h+} \rangle - \langle S_n^{h-} \rangle$$



$N_{\text{shuffled}}(\Delta S)$ → **Random shuffling of [only] the charges within an event**

Numerator → *carries charge separation response*

Denominator → *carries the "null" or charge averaged response*

A second multi-particle correlator $C_p^{\perp}(\Delta S)$ is similarly constructed for $\Psi_2 + \pi/2$, for which contributions from CME-driven charge asymmetry vanish.

Background Dominated

The shape and magnitude of the correlator,

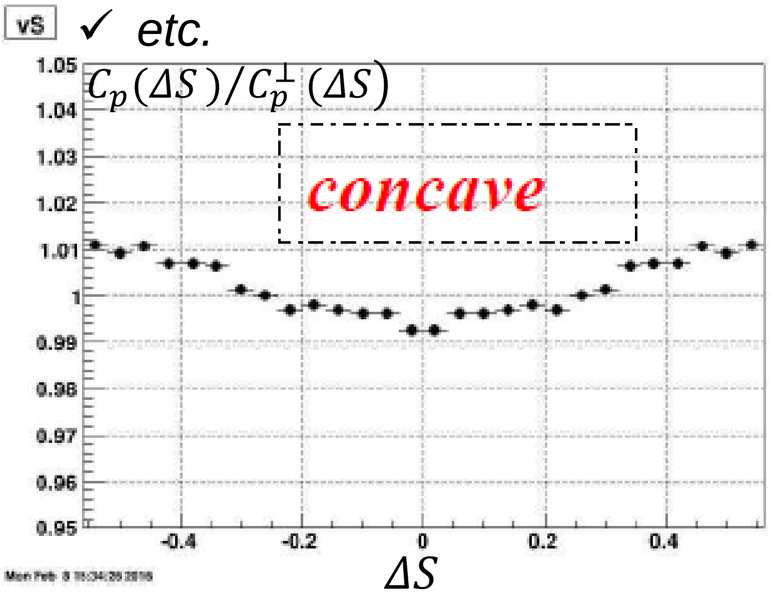
$$R(\Delta S) = C_p(\Delta S) / C_p^{\perp}(\Delta S)$$

is used to identify and characterize charge separation

New Correlator Response

$$R(\Delta S) = C_p(\Delta S) / C_p^{\perp}(\Delta S)$$

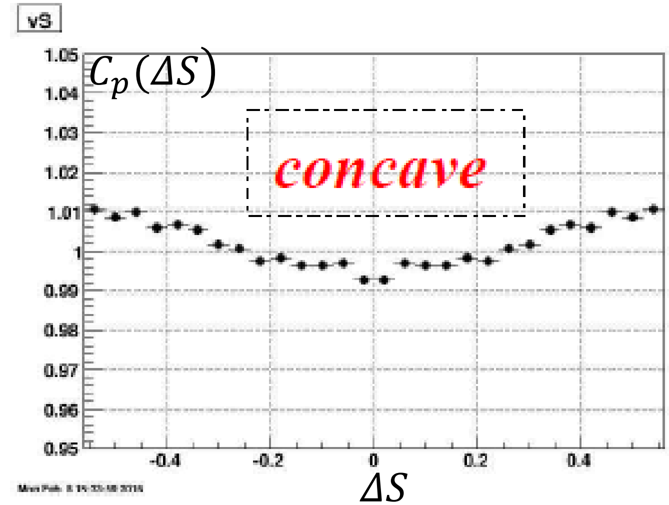
- **Is "concave-shaped" for CME-driven charge separation**
- **Is flat or "convex-shaped" for all known non-CME related backgrounds of interest**
  - ✓ *collective flow,*
  - ✓ *momentum conservation,*
  - ✓ *local charge conservation*
  - ✓ *etc.*

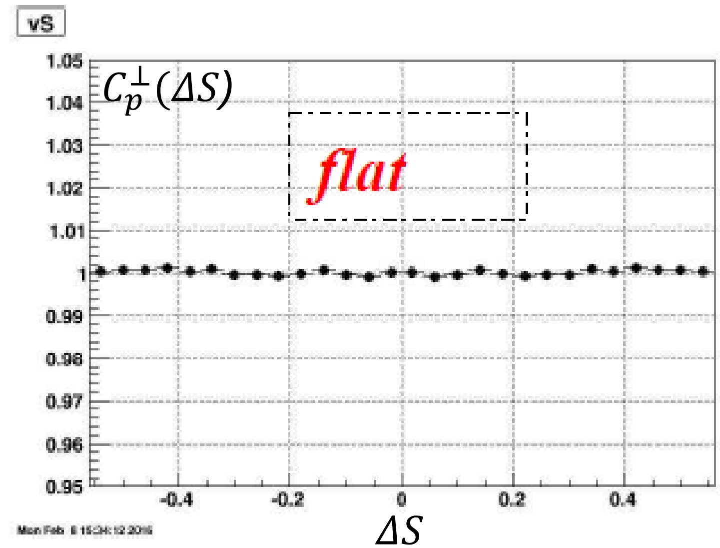


- **"Concave-shaped" response for input charge separation validated**

Toy **model** ***with***

- ✓ **Flow**
- ▪ **No resonance decay**
- ✓ **Charge separation (a_1>0)**

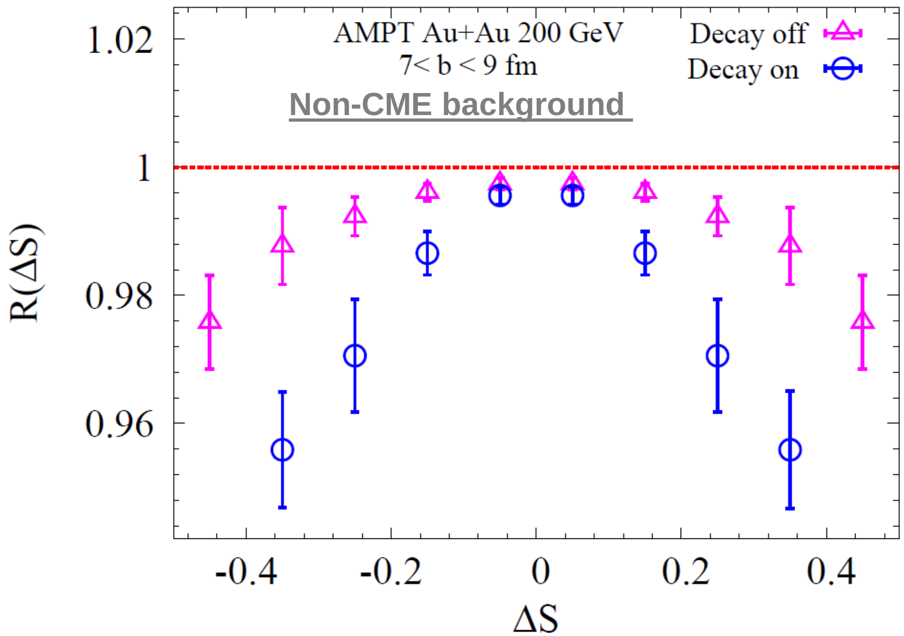




New Correlator Response

$$R(\Delta S) = C_p(\Delta S) / C_p^{\perp}(\Delta S)$$

- **Is "concave-shaped" for CME-driven charge separation**
- **Is flat or "convex-shaped" for all known non-CME related backgrounds**

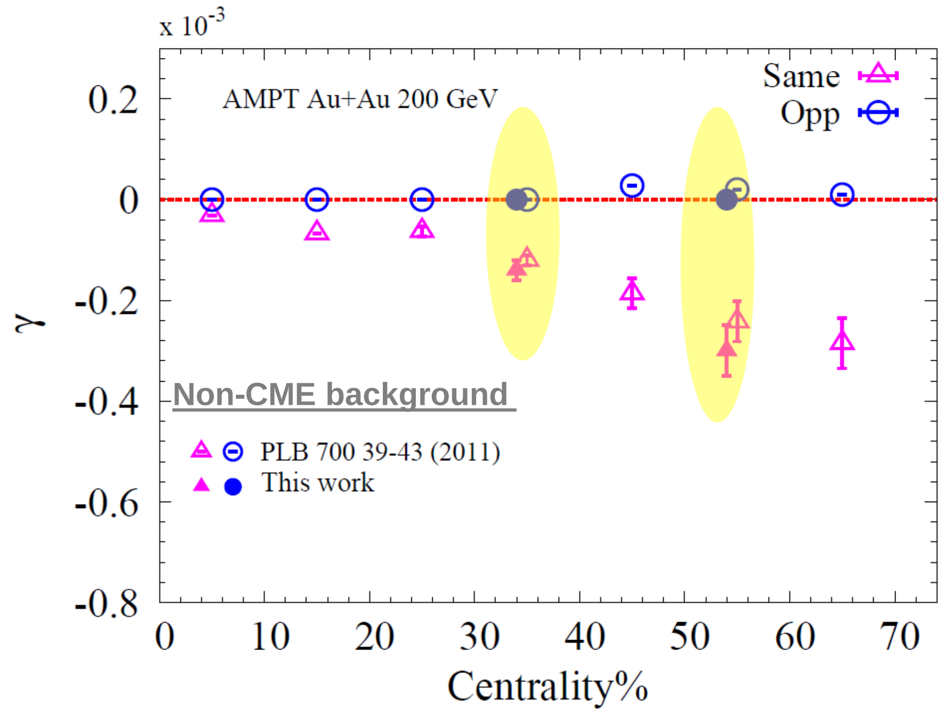


- **Non-CME convex-shaped background validated**

***AMPT* model**

- ✓ **Flow**
- ✓ **Resonance decay**
- ▪ **Charge separation (a_1=0)**

Gamma correlator Results from AMPT

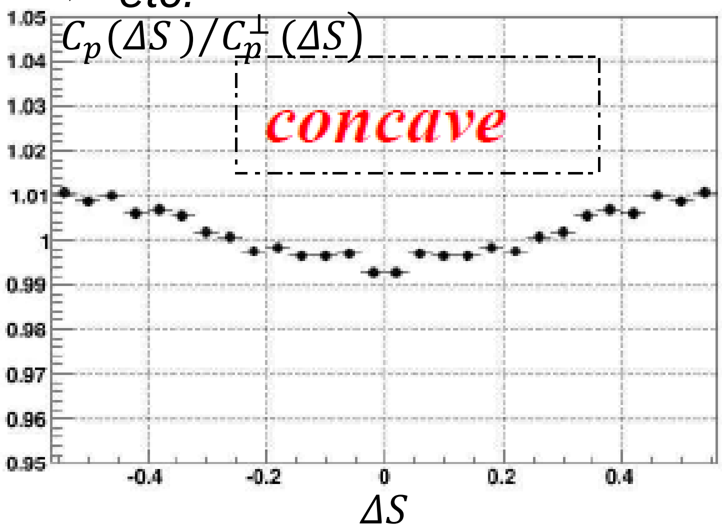


- **Gamma correlator's response contrasts with that for $R(\Delta S)$**

New Correlator Response

$$R(\Delta S) = C_p(\Delta S) / C_p^{\perp}(\Delta S)$$

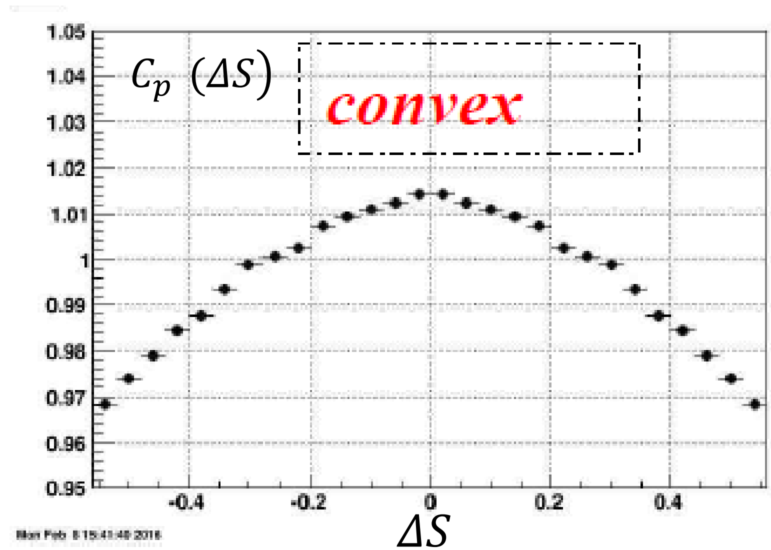
- Is "concave-shaped" for CME-driven charge separation
- Is flat or "convex-shaped" for all known non-CME related backgrounds of interest
  - ✓ *collective flow,*
  - ✓ *momentum conservation,*
  - ✓ *local charge conservation*
  - ✓ *etc.*

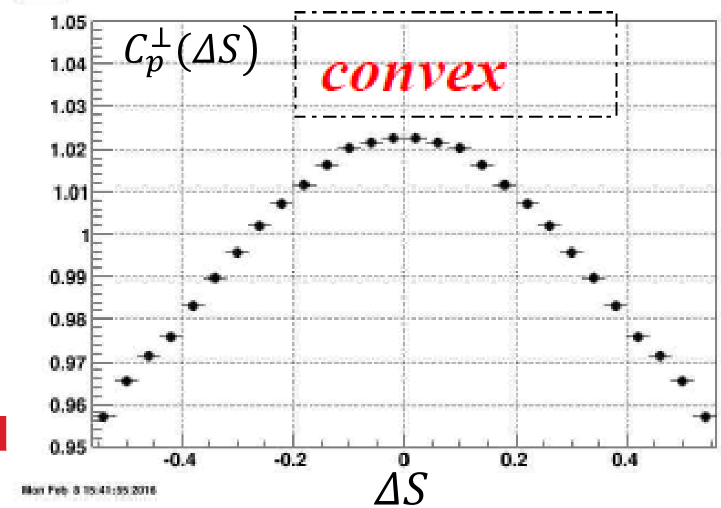


- "Concave-shaped" response validates charge separation input in the presence of sizeable background

Toy **model** ***with***

- ✓ Flow
- ✓ Resonance decay
- ✓ Charge separation (a_1>0)





Signal Quantification

- **Data driven simulation, which takes account of the respective correlations due to anisotropic flow, resonance decays, local charge conservation, etc., can be used to quantify the magnitudes of the charge separation signals**

  - ***Sampling distribution***

$$N(\Delta\varphi) = N_0[(1+2v_2\cos(2\Delta\varphi)+2v_3\cos(3\Delta\varphi)+2v_4\cos(4\Delta\varphi)+2a_1^{ch}\sin(\Delta\varphi)]$$

v_n obtained from data $\Delta\varphi = \phi - \Psi_2$

Strength of input charge separation signal

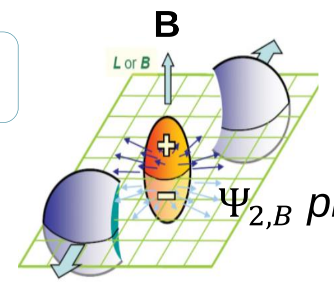
  - ***Constraints for***
    - ✓ Relative abundance of resonances
    - ✓ Local charge conservation
    - ✓ Etc.

- ***Anomalous Viscous Fluid Dynamics calculations***
  - ✓ Requisite set of constraints included

****Detailed extractions of a_1^{ch} currently underway****

Signal Quantification & trends

Charge separation amplitude



$\Psi_{2,B}$ *planes*

$$\frac{dN^{ch}}{d\phi} \propto [1 \pm 2a_1^{ch} \sin\phi + ...]$$

Ψ_B *and* Ψ_2 *correlated*

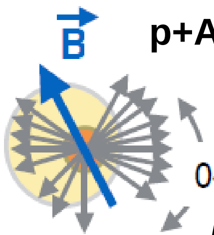
Relation to Gamma Correlator

$$a_1^{ch} \propto \mu_5 \vec{B}$$

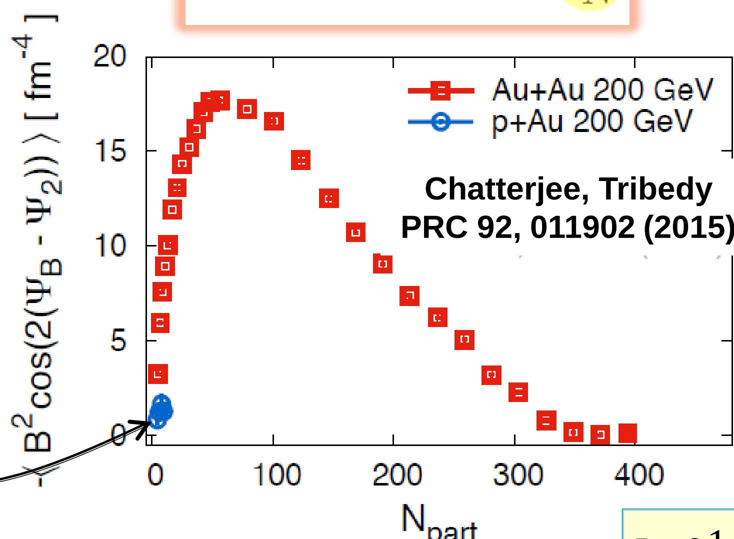
$$a_1^{ch} \propto \mu_5 \vec{B} \implies \langle a_\alpha a_\beta \rangle \propto |\vec{B}|^2 \implies \langle B^2 \cos(2(\Psi_B - \Psi_2)) \rangle$$

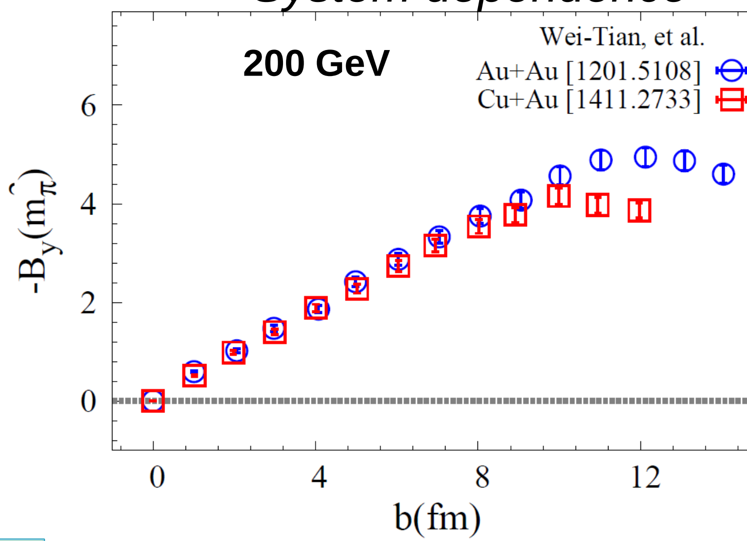
$$\gamma^{\alpha,\beta} = -\langle a_\alpha a_\beta \rangle + c\,\frac{v_2}{N}$$

System dependence



Ψ_B *and* Ψ_2
~
uncorrelated





$\tau_B \propto 1/\sqrt{s}$

$B \propto \sqrt{s}$

→ *Little if any, dependence on* $\sqrt{s}$

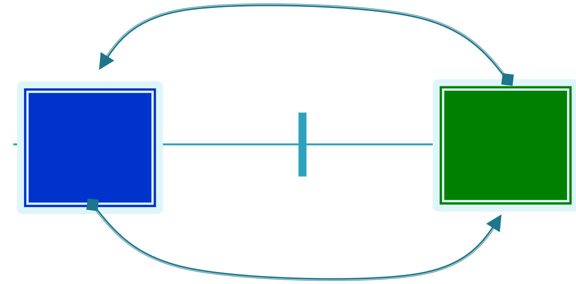
➤ **Characteristic $\sqrt{s}$, centrality and system dependence Expected for "background-free" signal?**

Measurements

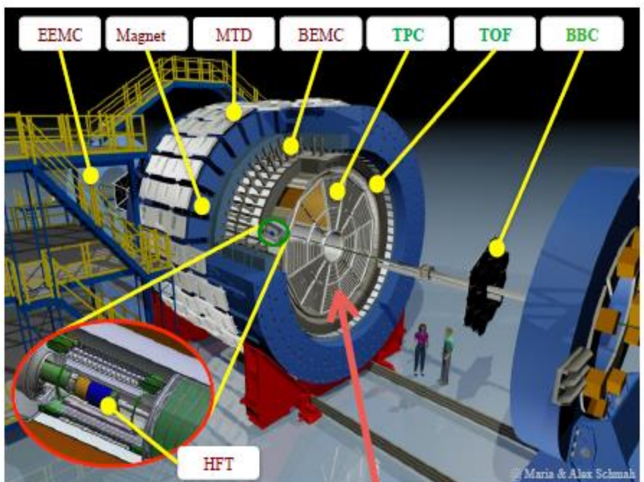
<u>*Data sets studied:*</u>

U+U 193 GeV
Au+Au *7.7* – 200 GeV
Cu+Au 200 GeV
p+Au 200 GeV

<u>*Analysis*</u>



STAR Detector



Time-Projection Chamber
(used for this analysis)

Charged hadrons with 0.2 < p_T < 2.0 GeV/c used to construct ;

Ψ_{2E} *(East) for particles with* **0.1 < η < 1.0**
Ψ_{2W} *(West) for particles with* ***−1.0 < η < −0.1***

For p+Au, Ψ_2 for the Au going side is used

Evaluate $R(\Delta S) = C_p(\Delta S) / C_p^{\perp}(\Delta S)$

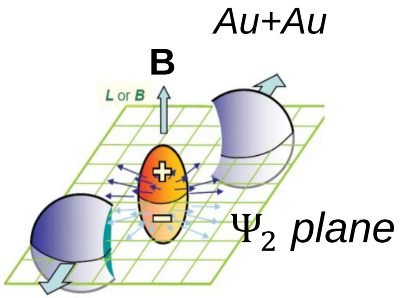
for charged hadrons with 0.35 < pT < 2.0 GeV/c,

Ψ_{2W} *(West) for particles in the range* **0.1 < η < 1.0**
Ψ_{2E} *(East) for particles in the range* ***−1.0 < η < −0.1***

- ✓ *Avoids auto-correlations,*
- ✓ *Suppress possible short-range non-flow correlations*

Results

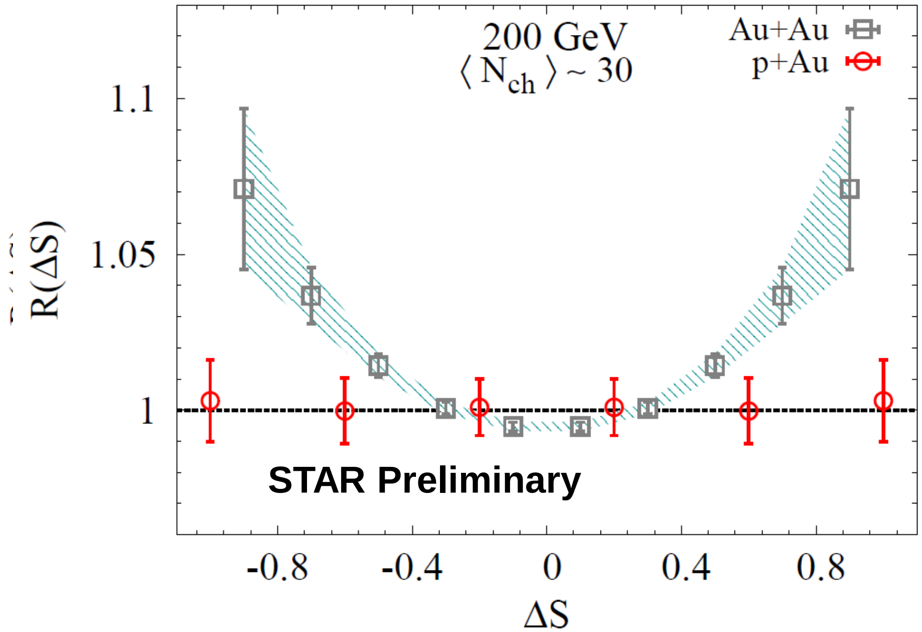
System dependence - Au+Au vs. p+Au Collisions

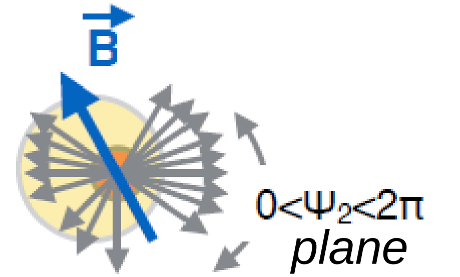


Ψ_B *and* Ψ_2 *correlated*

$$a_1^{ch} \propto \mu_5 \vec{B}$$

$$\frac{dN^{ch}}{d\phi} \propto [1 \pm 2a_1^{ch} \sin\phi + ...]$$





Ψ_B *and* Ψ_2 *~ uncorrelated*

- **A decidedly "concave-shaped" distribution for peripheral Au+Au collisions**
  - ✓ ***Indication for a CME-driven charge separation contribution in these collisions***

- **In contrast, an essentially flat distribution for p+Au**
  - ❖ **Validates the absence of significant charge separation signal in these collisions**
    - ✓ *"reduced magnetic field strength"*
    - ✓ *random B-field orientations*

Results

$a_1^{ch} \propto \mu_5 \vec{B}$

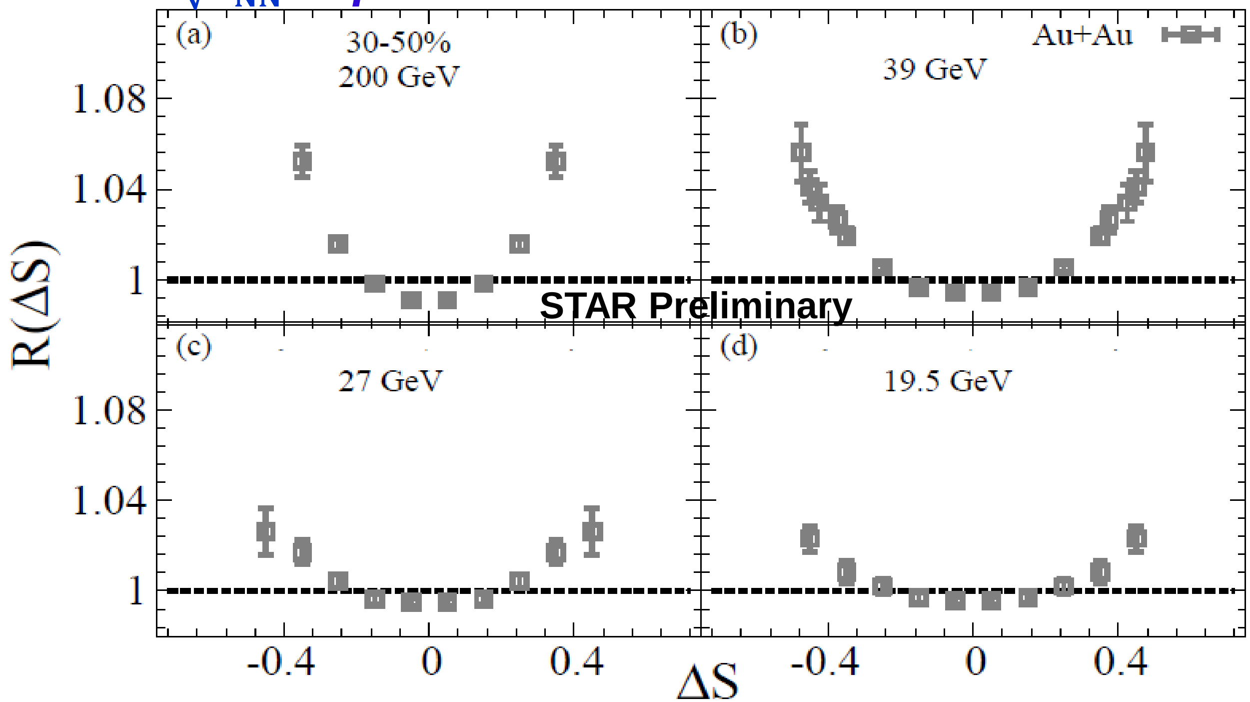
$$\frac{dN^{ch}}{d\phi} \propto [1 \pm 2a_1^{ch} \sin\phi + ...]$$

- ✓ a_1^{ch} *quantifies the magnitude of the signal*

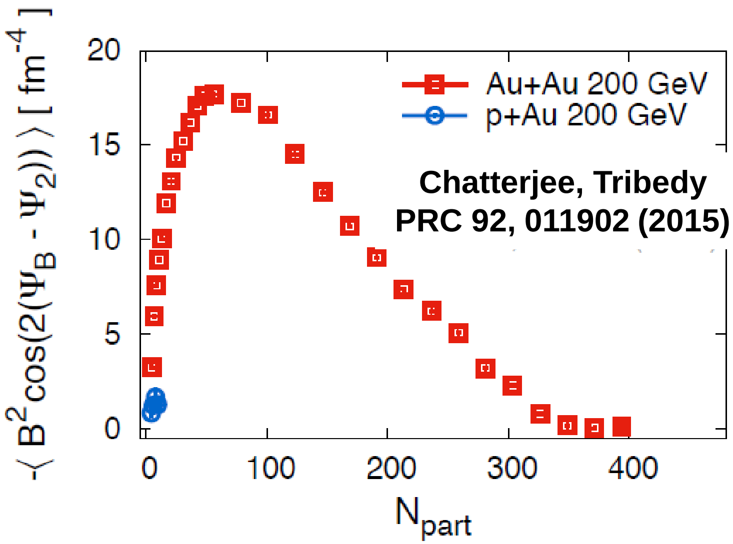
$\tau \propto 1/\sqrt{s}$

$B \propto \sqrt{s}$

$\sqrt{s_{NN}}$ dependence – Au+Au Collisions

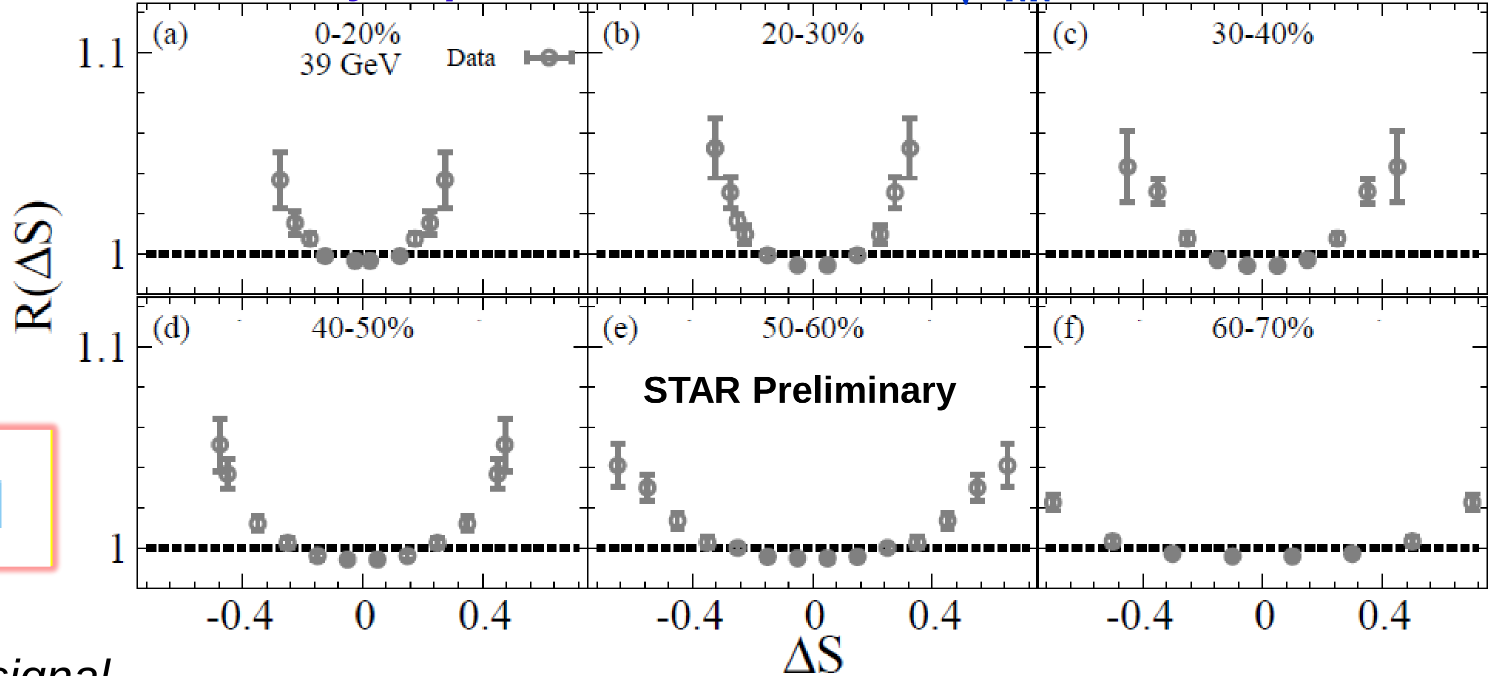


- **Concave-shaped distributions validate CME-driven charge separation in Au+Au collisions at each beam energy**
  - ✓ ***Signal variation consistent with expectation***
- **Indications for <u>weak $\sqrt{s}$ dependence</u> of the charge separation signal!**



Results

Centrality dependence – Au+Au @ $\sqrt{s_{NN}}$ = 39 GeV

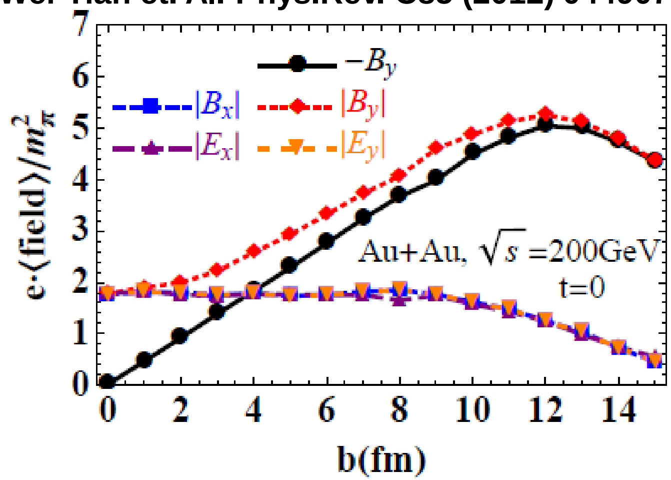


$a_1^{ch} \propto \mu_5 \vec{B}$

$$\frac{dN^{ch}}{d\phi} \propto [1 \pm 2a_1^{ch} \sin\phi + ...]$$

a_1^{ch} *quantifies the magnitude of the signal*

Wei-Tian et. Al. Phys.Rev. C85 (2012) 044907



- ***Indications for a CME-driven charge separation contribution across centrality***
- ***More detailed a_1^{ch} extractions underway***

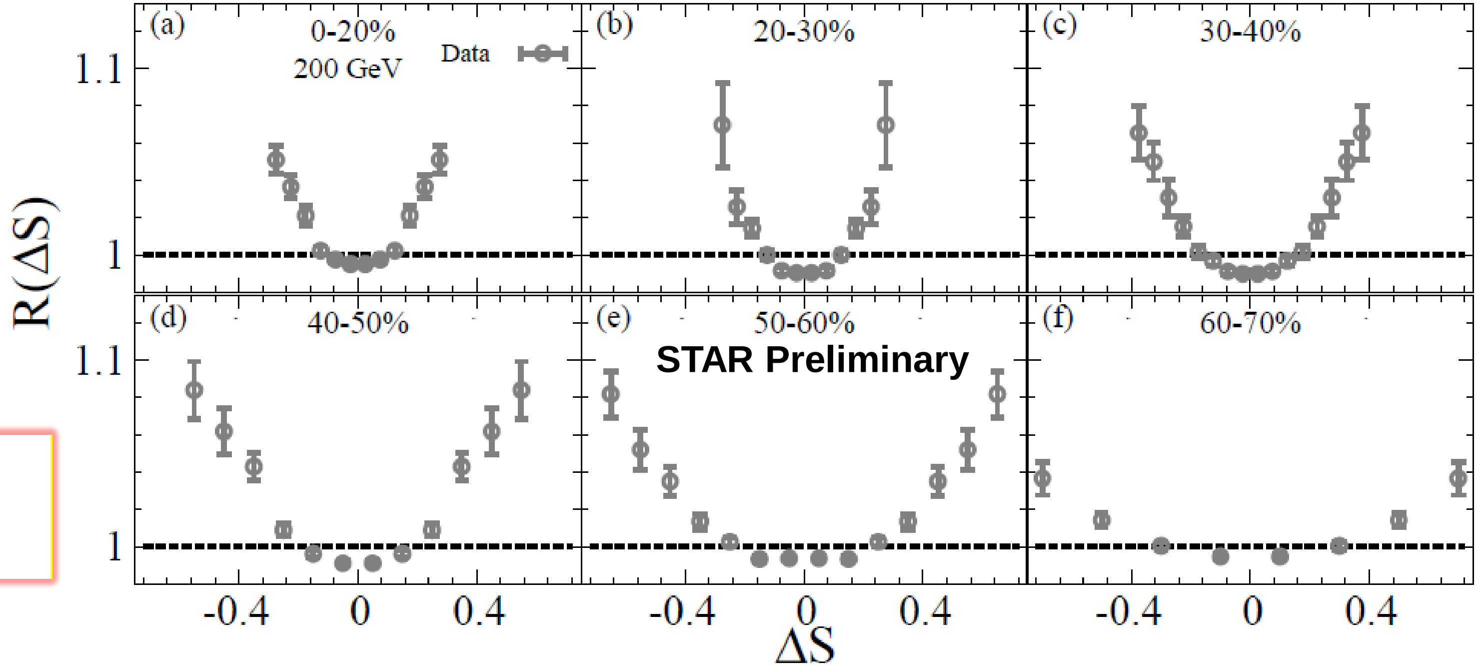
➢ **Centrality dependence of a_1^{ch} expected to follow the trend of the magnetic field**

Results

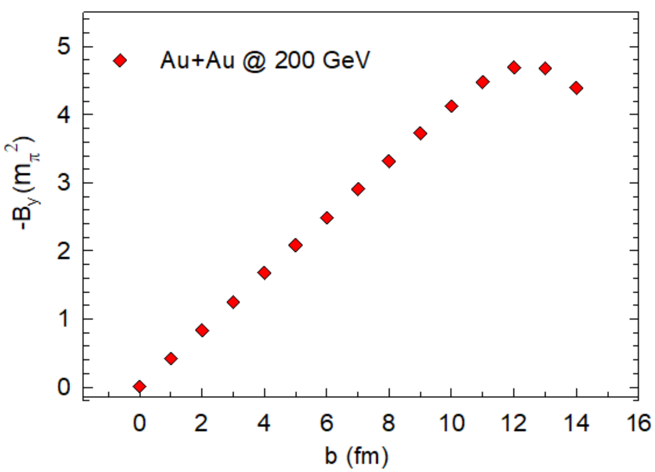
Centrality dependence – Au+Au @ $\sqrt{s_{NN}}$= 200 GeV

$a_1^{ch} \propto \mu_5 \vec{B}$

$$\frac{dN^{ch}}{d\phi} \propto [1 \pm 2a_1^{ch} \sin\phi + ...]$$



- ✓ ***Indications for a CME-driven charge separation contribution across centrality***
- ✓ ***More detailed a_1^{ch} extractions underway***



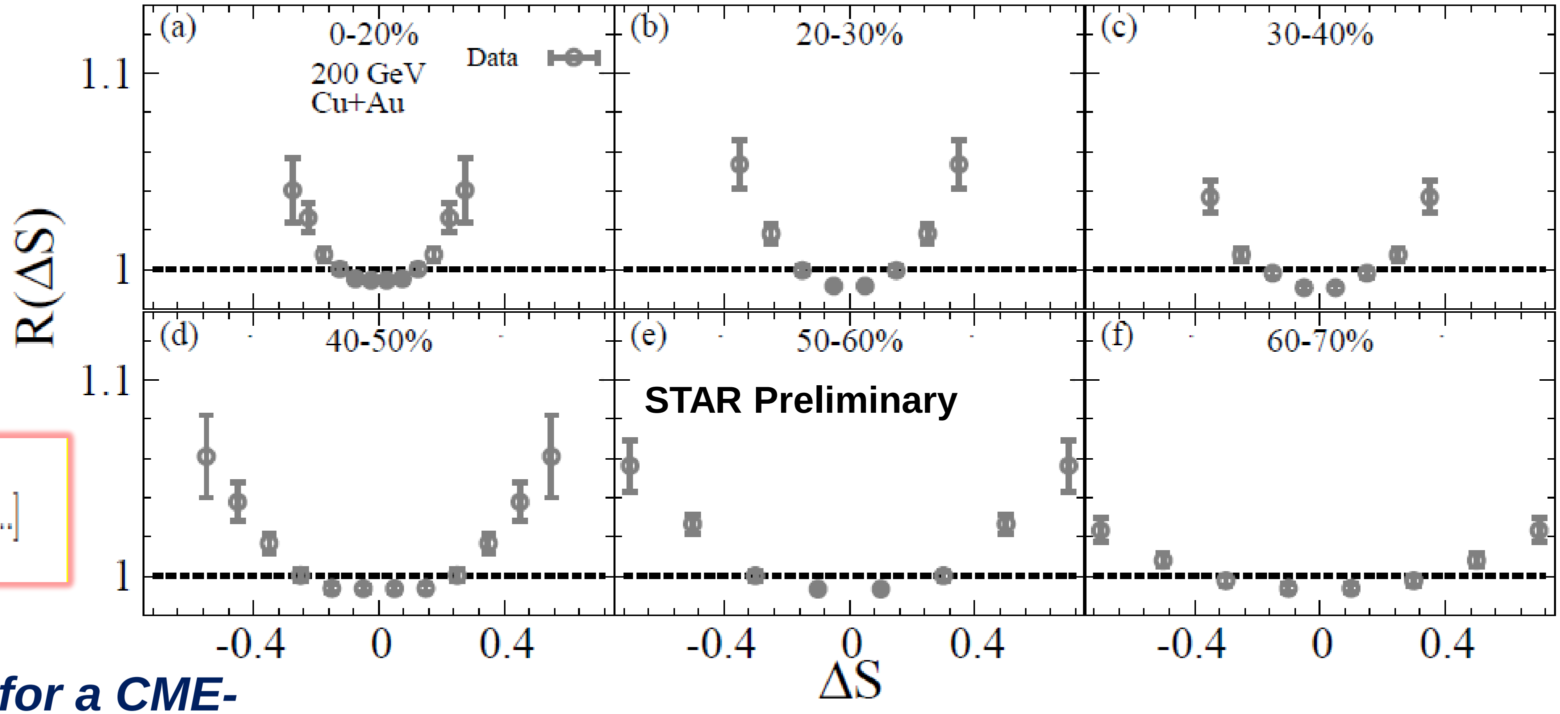
$\tau \propto 1/\sqrt{s}$

$B \propto \sqrt{s}$

➢ **Similar centrality dependent charge separation pattern expected for $\sqrt{s}$ = 200 GeV?**

Results

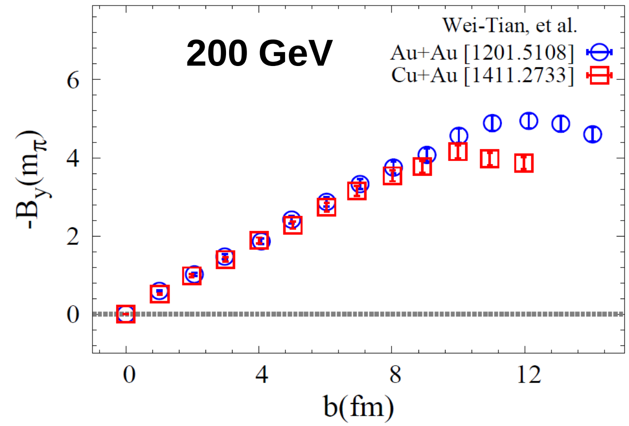
Centrality dependence – Cu+Au @ $\sqrt{s_{NN}}$=200 GeV



$a_1^{ch} \propto \mu_5 \vec{B}$

$$\frac{dN^{ch}}{d\phi} \propto [1 \pm 2a_1^{ch} \sin\phi + ...]$$

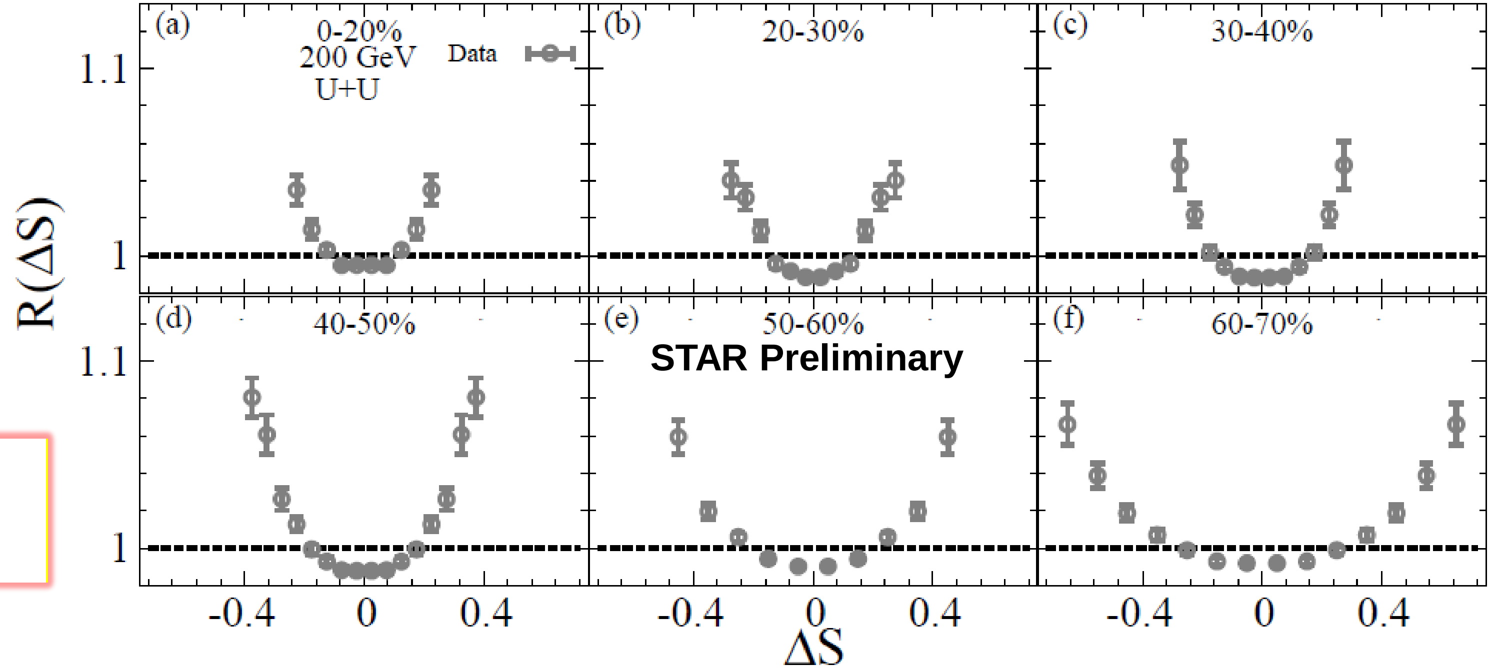
- ✓ *Indications for a CME-driven charge separation contribution across centrality*
- ✓ *More detailed a_1^{ch} extractions underway*



➢ **Similar magnitude and centrality dependence expected for a_1^{ch} for Cu+Au @ $\sqrt{s_{NN}}$ = 200 GeV?**

Results

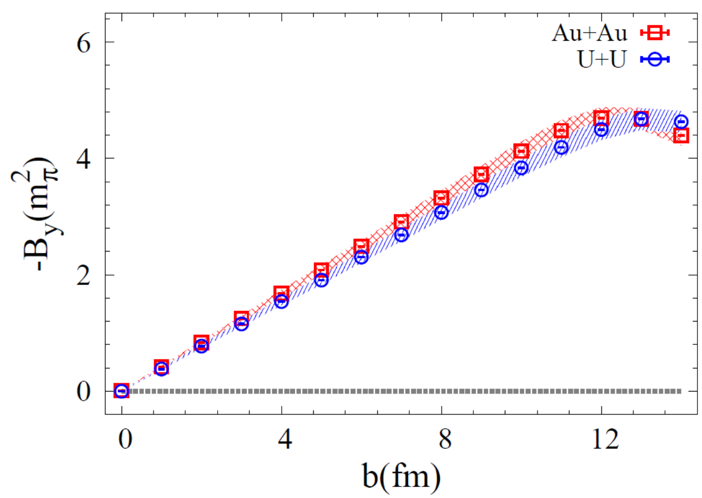
Centrality dependence – U+U @ $\sqrt{s_{NN}}$ = 193 GeV



$$a_1^{ch} \propto \mu_5 \vec{B}$$

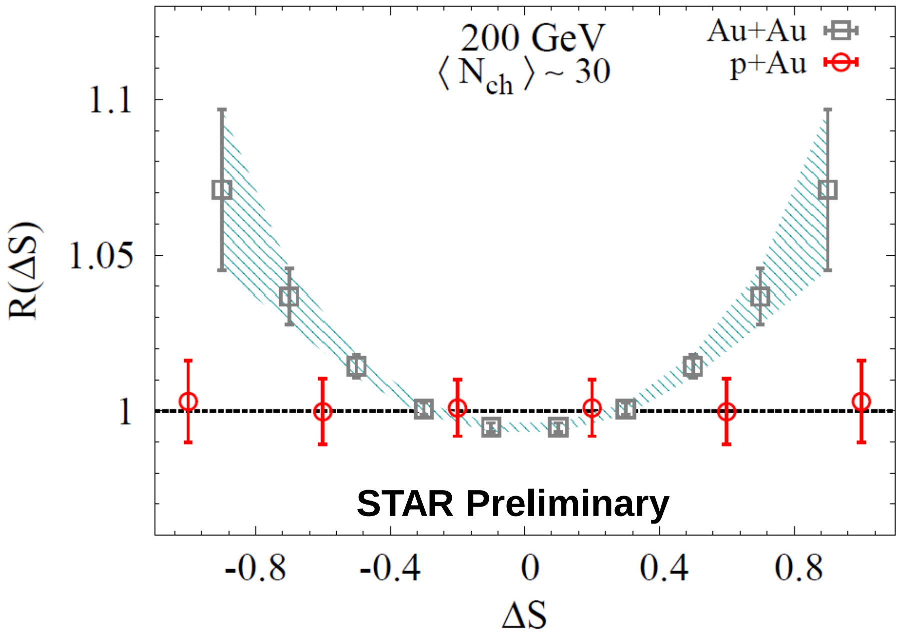
$$\frac{dN^{ch}}{d\phi} \propto [1 \pm 2a_1^{ch} \sin\phi + ...]$$

- ✓ ***Indications for a CME-driven charge separation contribution across centrality***
- ✓ ***More detailed a_1^{ch} extractions underway***



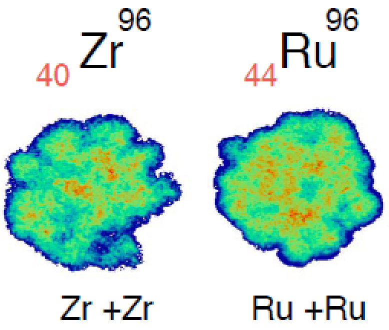
➢ **Similar centrality dependence but smaller magnitudes for a_1^{ch} for $U+U$?**

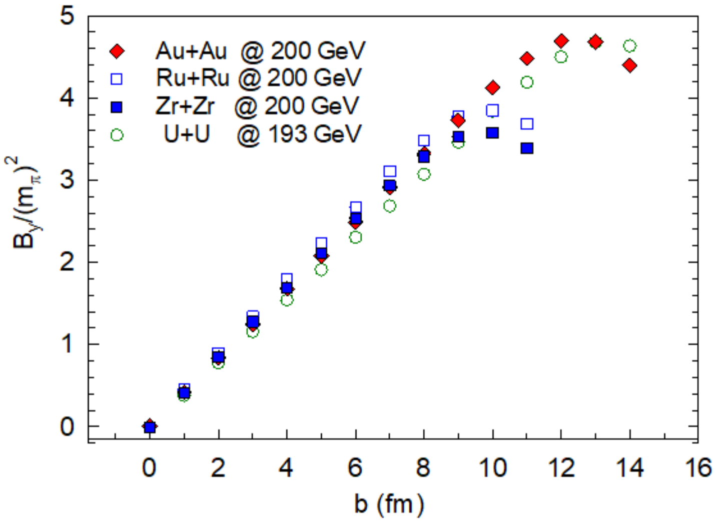
Near-term Horizon



Isobars

Future Run (2018)





- **p+A measurements used as an important bench mark for identification of CME-driven charge separation in A(B)+A collis*ions → this work !!***

- **Refined extractions of a_1^{ch} - underway**
- **Further leveraging of the system dependence of charge separation is planned for the near term**

Summary

- *New charge-sensitive correlator $R_{cs}(\Delta S)$ used to to perform charge separation measurements for charged hadrons in p+Au and A(B)+A collisions*
  - ✓ *This correlator gives distinct responses for CME-driven charge separation and non-CME background*
  - ✓ *well suited for identification and characterization of CME-driven charge separation.*

- *For A(B)+A collisions, $R_{cs}(\Delta S)$ shows a characteristic concave shape, indicative of a non-zero CME-driven charge separation signal.*
  - ✓ *In contrast, the measurements for p+Au collisions show an approximately flat distribution consistent with the "reduced" magnetic field strength and random B-field orientations generated in these collisions.*

- **CME-driven charge separation signal obtained as a function of centrality for several systems and beam energies.**
  - ✓ **The measured dependencies on centrality, system and $\sqrt{s}$ can provide crucial insights on CME-driven charge separation**

End

The Blessings of Finite-Size

γ and ν

critical exponents

$$\chi_T^{\max}(V) \sim L^{\gamma/\nu},$$

$$\delta T(V) \sim L^{-\frac{1}{\nu}},$$

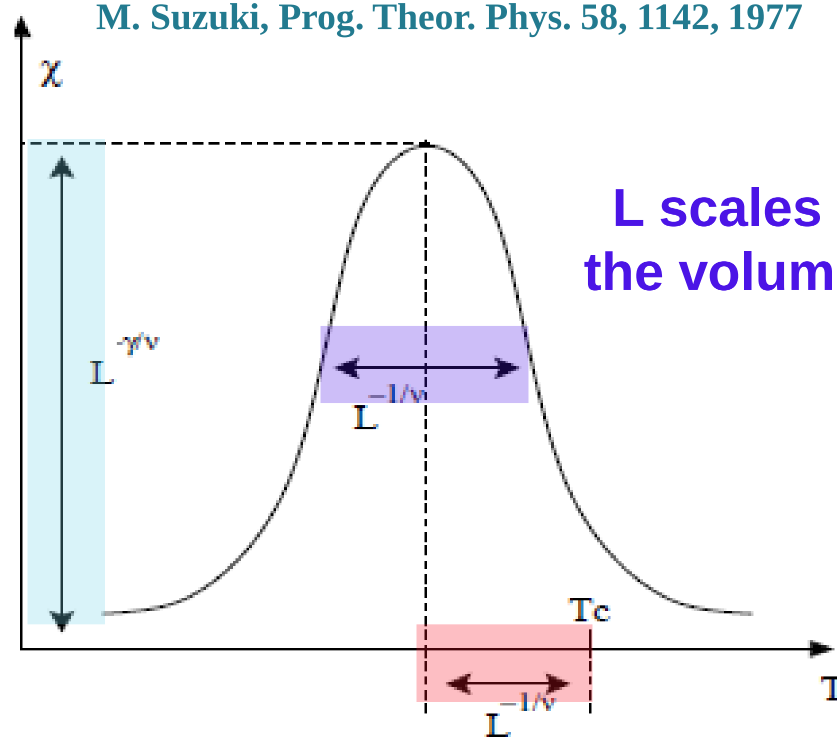
$$\tau_T(V) \sim T^{\text{cep}}(V) - T^{\text{cep}}(\infty) \sim L^{-\frac{1}{\nu}},$$

Consider measurements of the susceptibility (κ_T) for different lengths ($L = V^{1/3}$)

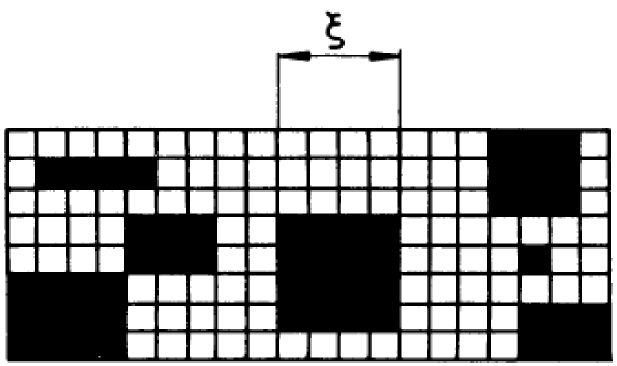
$$\chi(T,L) = L^{\gamma/\nu} P_\chi(tL^{1/\nu}) \qquad t = (T - T_c)/T_c$$

M. Suzuki, Prog. Theor. Phys. 58, 1142, 1977

Finite-size effects lead to specific dependencies of the peak heights, widths & positions on L



L scales the volume



b) T close to Tc

$$\xi \sim |T - T_c|^{-\nu} \leq L$$

✓ **The scaling of these dependencies give access to the CEP's location, critical exponents and a non-singular scaling function.**

Interferometry as a susceptibility proxy

Hung, Shuryak, PRL. 75,4003 (95)
T. **Csörgő**. and B. Lörstad, PRC54 (1996) 1390-1403
Chapman, Scotto, Heinz, PRL.74.4400 (95)
Makhlin, Sinyukov, ZPC.39.69 (88)

The radii of the "fireball" encode space-time information for the reaction dynamics

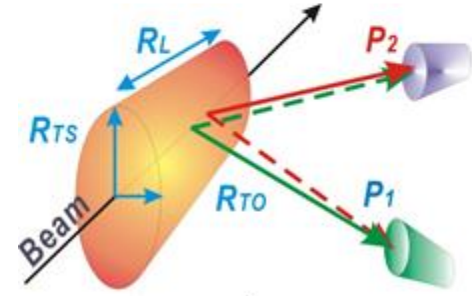
$$R^2_{side} = \frac{R^2_{geo}}{1+\frac{m_T}{T}\beta_T^2}$$

$$R^2_{out} = \frac{R^2_{geo}}{1+\frac{m_T}{T}\beta_T^2} + \beta_T^2(\Delta\tau)^2$$

emission duration

$$R^2_{long} \approx \frac{T}{m_T}\tau^2$$

emission lifetime



$$c_s^2 = \frac{1}{\rho\kappa}$$

The divergence of the susceptibility κ

- ✓ *"softens" the sound speed c_s*
- ✓ *extends the emission duration*

(R^2_{out} - R^2_{side}) sensitive to the κ

(R_{side} - R_{init})/ R_{long} sensitive to c_s

Specific non-monotonic patterns expected as a function of $\sqrt{s_{NN}}$

- **A maximum for (R^2_{out} - R^2_{side})**
- ***A minimum for*** **(R_{side} - $R_{initial}$)/R_{long}**