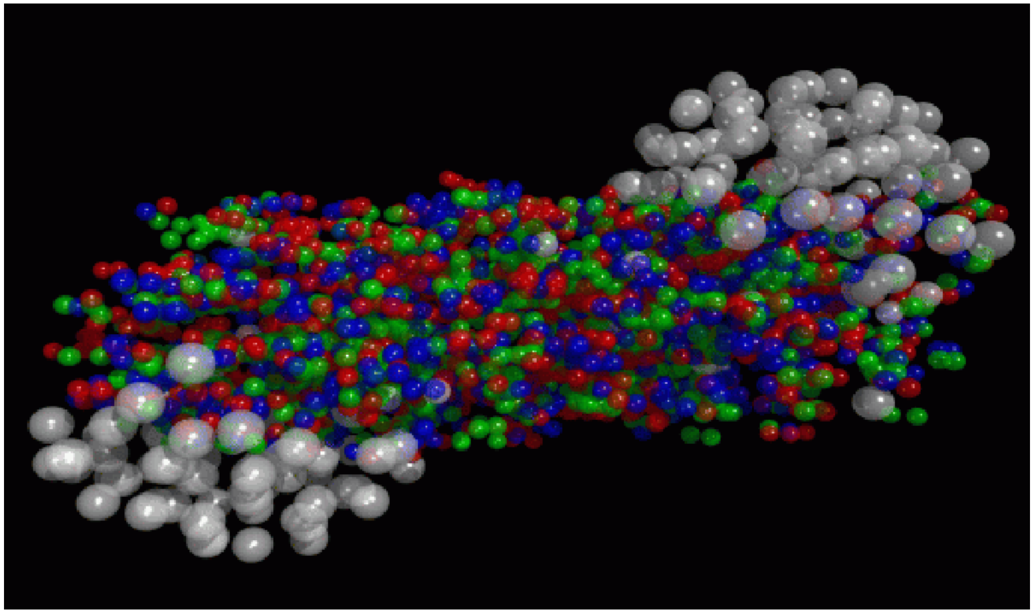
Search for the chiral magnetic effect in relativistic heavy-ion collisions

Jie Zhao
Purdue University

Relativistic heavy-ion collisions

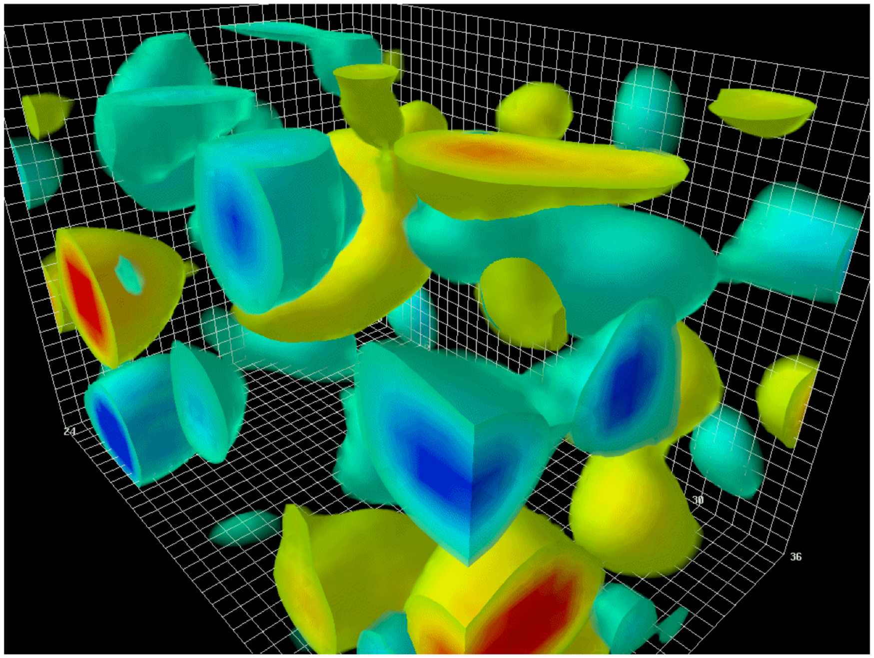


Quark-gluon plasma (QGP)

QCD vacuum

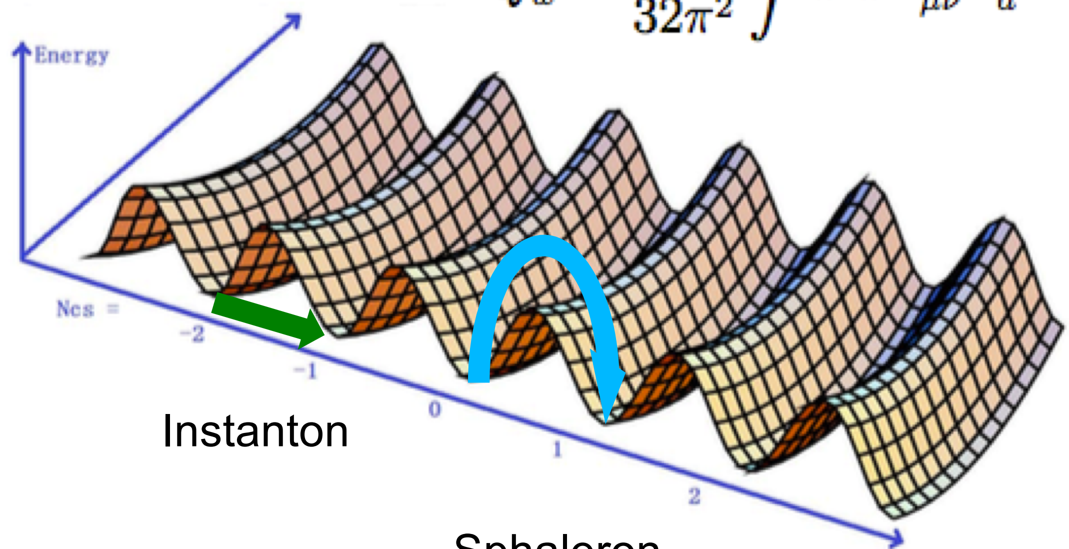
fluctuations of topological charge

$$Q_w = \frac{g^2}{32\pi^2}\int d^4x F^a_{\mu\nu}\tilde{F}^{\mu\nu}_a$$



The volume of the box is 2.4 x 2.4 x 3.6 fm

Derek Leinweber

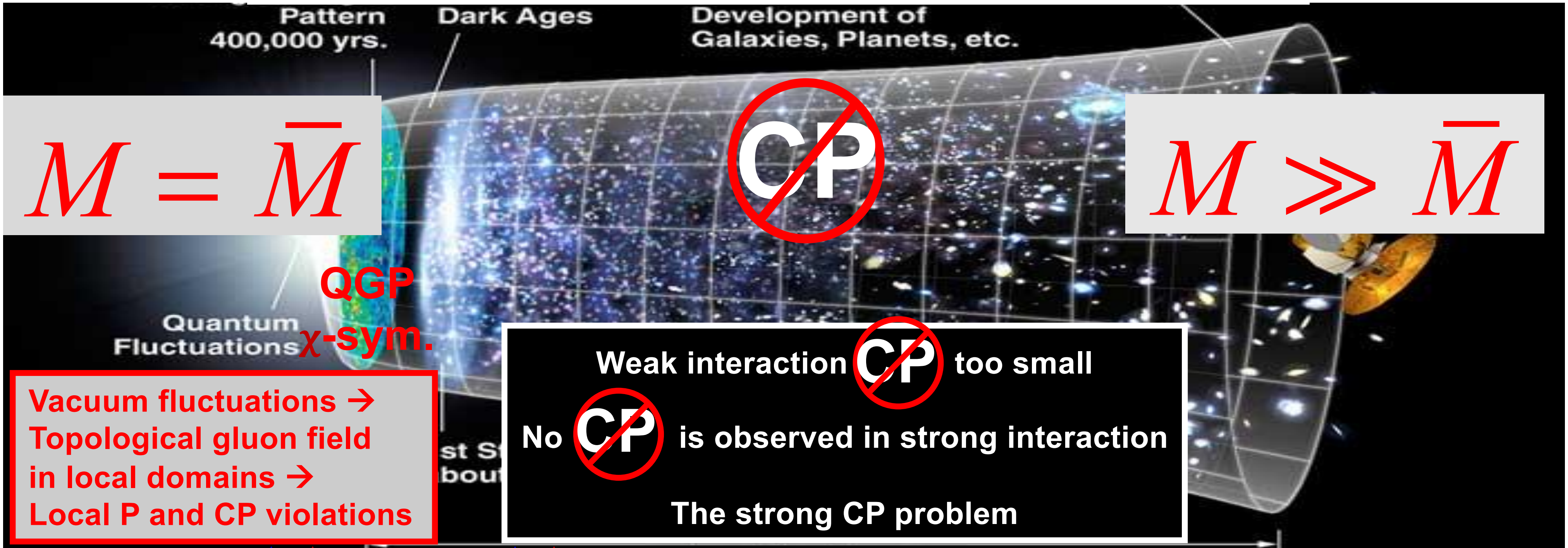


Dimitri Diakonov, Progress in Particle and Nuclear Physics, 51, 173-222, (2003)

- Transition between Quantum Chromodynamics (QCD) vacuum states by instanton/sphaleron mechanism
- Fluctuations of topological charge ($Q_w \propto N_L - N_R$) in QCD, "Winding number"
- Non-zero $Q_w \neq 0$ introduce chirality imbalance ($N_L \neq N_R$), **local $\mathcal{P}/\mathcal{CP}$ violation**

The strong CP problem

Kharzeev, Pisarski, Tytgat, PRL 81 (1998) 512; Kharzeev, et al. NPA 803 (2008) 227



$M = \bar{M}$

$M \gg \bar{M}$

CP

QGP

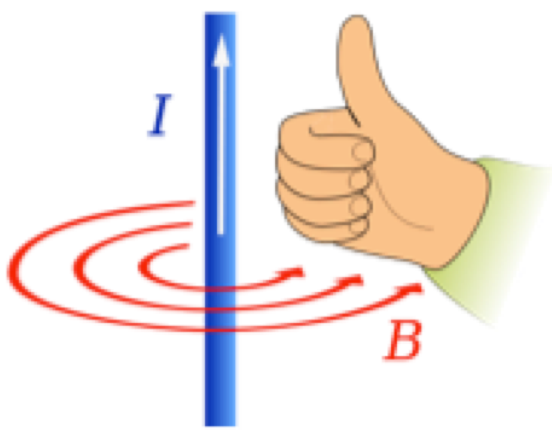
χ-sym.

Vacuum fluctuations → Topological gluon field in local domains → Local P and CP violations

Weak interaction CP too small

No CP is observed in strong interaction

The strong CP problem



- **Strong magnetic field**
- **Quark degree of freedom, χ-symmetry**
- **QCD vacuum fluctuations**
- **Topological gluon field, $Q_w \neq 0$.**
- **Local P, CP violations**

Chirality/helicity

$E = -\mu_s \cdot B, \ \mu_s \propto \frac{q \cdot s}{2m}$

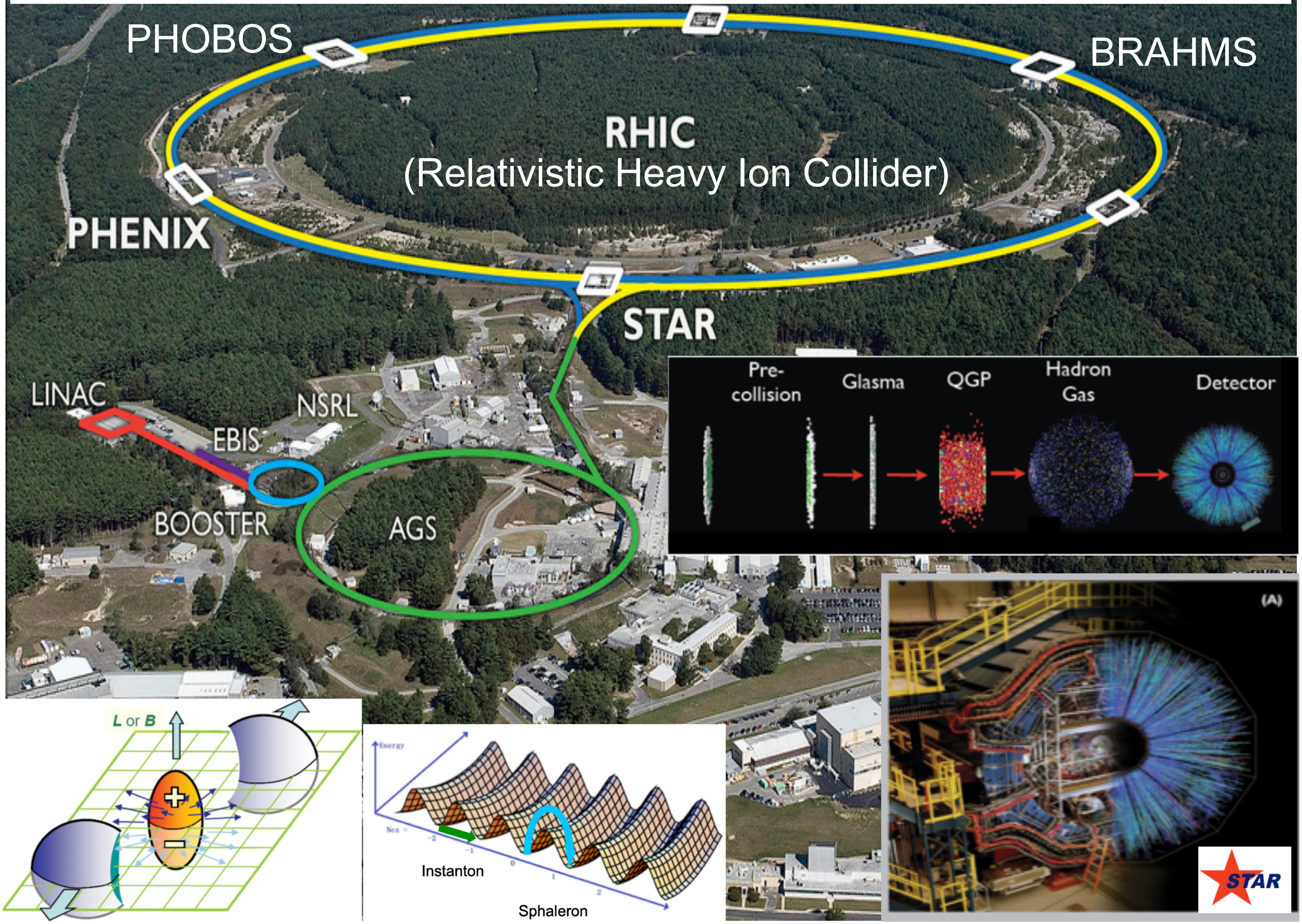
with $B \sim 10^{15}\,T$,

bare quark mass~3 MeV (app. χ-sym.),

$E \sim 1$ GeV

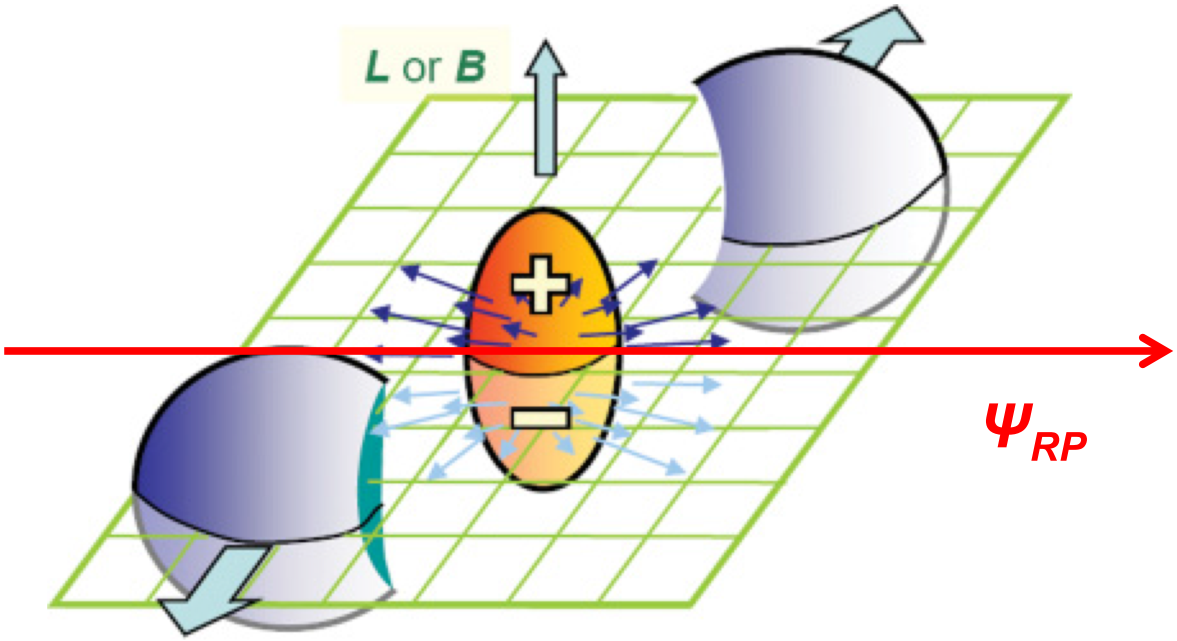
u: 2/3e; d: -1/3e, s=1/2

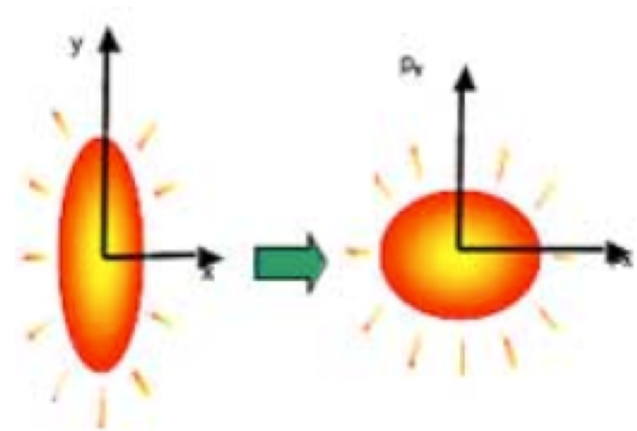
Heat up the QCD vacuum at RHIC



How to measure CME?

B. Alver *et al.* (PHOBOS) , PRL **98**, 242302 (2007).





$$\frac{dN}{d\varphi} \propto 1 + 2v_2 \cos(2\varphi - 2\psi_{RP})$$

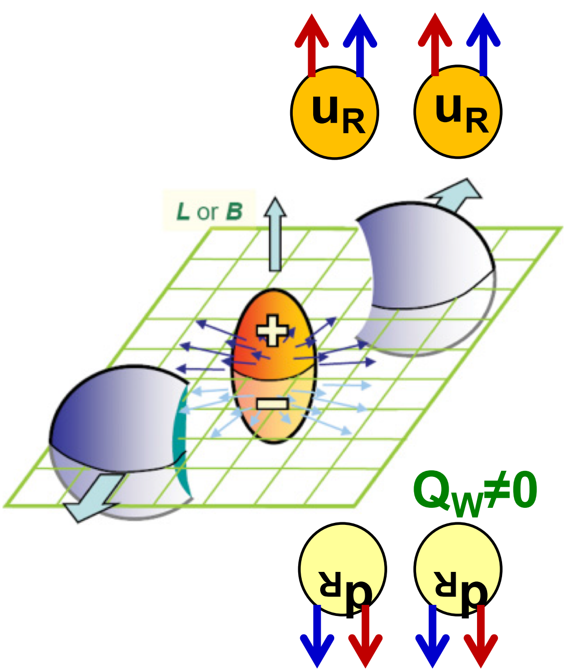
$$v_2 = \cos(2\varphi - 2\psi_{RP})$$

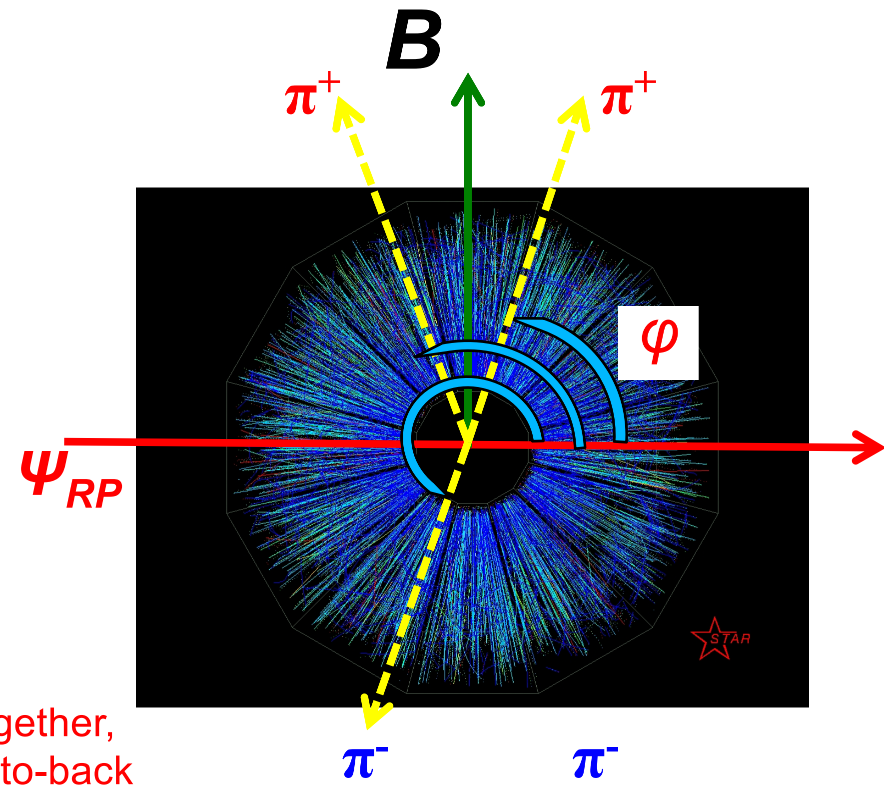
φ represents the azimuthal angle

- Direction correlated with the B direction ? *(Ψ_{RP} pre. to* **B***)*

How to measure CME?

S. A. Voloshin, Phys.Rev. C 70 (2004) 057901





same-sign (++/--) pairs go together,
opps.-sign (+-/-+) pairs back-to-back

The sign of Q_w **can vary** event to event and domain to domain ➔ one has to measure correlations

$$\gamma = \left\langle \cos(\varphi_\alpha + \varphi_\beta - 2\psi_{RP}) \right\rangle$$

$$\gamma^{+-} = \cos(\pi^+ + \pi^- - 0) = \cos(360°) = +1$$

$$\gamma^{++} = \cos(\pi^+ + \pi^+ - 0) = \cos(180°) = -1$$

$$\Delta\gamma = \gamma^{+-} - \gamma^{++/--} = 2 > 0$$

φ represents the azimuthal angle

α, β denote the charge of the particles, with combination of +-(-+), ++, --

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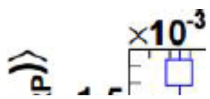
STAR, PRL 10



PHYSICAL REVIEW C 81, 054908 (2010)

Observation of charge-dependent azimuthal correlations and possible local strong parity violation in heavy-ion collisions

s,[16] B. D. Anderson,[17] D. Arkhipkin,[3] G. S. Averichev,[16] D. R. Beavis,[3] R. Bellwied,[49] F. Benedosso,[26] J. Bielcik,[10] J. Bielcikova,[11] B. Biritz,[6] L. C. Bland,[3] A. Bridgeman,[1] E. Bruna,[51] S. Bueltmann,[28] a Sánchez,[5] O. Catu,[51] D. Cebra,[5] R. Cendejas,[6] H. F. Chen,[37] J. H. Chen,[17] J. Y. Chen,[50] J. Cheng,[43] R. F. Clarke,[41] M. J. M. Codrington,[41] R. Corliss,[21] D. Das,[5] S. Dash,[12] M. Daugherity,[42] L. C. De Silva,[49] Souza,[7] L. Didenko,[3] P. Djawotho,[41] V. Dzhordzhadze,[3] Efimov,[16] Fatemi,[18] S. Ganti,[46] Grebenyuk,[20] Haag,[5] ffman,[21] P. Jacobs,[20] Kajimoto,[42] Kikola,[20]

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

B. Abelev *et al.**
(ALICE Collaboration)
(Received 5 July 2012; published 2 January 2013)

Measurements of charge-dependent azimuthal correlations with the ALICE detector at the LHC are reported for Pb-Pb collisions a
correlations in the pseudorapid
particle separation in pseudora
dependent separation relative t
dependence when compared to
standing the nature of the char

DOI: 10.1103/PhysRevLett.110.01

PHYSICAL REVIEW C 88, 064911 (2013)

Fluctuations of charge separation perpendicular to the event plane and local parity violation in $\sqrt{s_{NN}} = 200$ GeV Au + Au collisions at the BNL Relativistic Heavy Ion Collider

L. Adamczyk,[1] J. K. Adkins,[23] G. Agakishiev,[21] M. M. Aggarwal,[34] Z. Ahammed,[53] I. Alekseev,[19] J. Alford,[22] C. D. Anson,[31] A. Aparin,[21] D. Arkhipkin,[4] E. Aschenauer,[4] G. S. Averichev,[21] J. Balewski,[26] A. Banerjee,[53] Z. Barnovska,[14] D. R. Beavis,[4] R. Bellwied,[49] M. J. Betancourt,[26] R. R. Betts,[10] A. Bhasin,[20] A. K. Bhati,[34] P. Bhattarai,[48] H. Bichsel,[55] J. Bielcik,[13] J. Bielcikova,[14] L. C. Bland,[4] I. G. Bordyuzhin,[19] W. Borowski,[45] J. Bouchet,[22] A. V. Brandin,[29] S. G. Brovko,[6] E. Bruna,[57] ez,[6] D. Cebra,[6] n,[44] J. Y. Chen,[9] Codrington,[48] R. Debbe,[4] Ding,[6] A. Dion,[4] L. G. Efimov,[21] J. Fedorisin,[21] D. Garand,[37] Guryn,[4] B. Haag,[6] A. Hirsch,[37] W. W. Jacobs,[18] A. Kesich,[6] W. Korsch,[23] M. Landgraf,[4] C. Li,[42] W. Li,[44] ngacre,[4] X. Luo,[9]

PRL 113, 052302 (2014) PHYSICAL REVIEW LETTERS week ending 1 AUGUST 2014

Beam-Energy Dependence of Charge Separation along the Magnetic Field in Au + Au Collisions at RHIC

L. Adamczyk,[1] J. K. Adkins,[23] G. Agakishiev,[21] M. M. Aggarwal,[35] Z. Ahammed,[53] I. Alekseev,[19] J. Alford,[22] C. D. Anson,[32] A. Aparin,[21] D. Arkhipkin,[4] E. C. Aschenauer,[4] G. S. Averichev,[21] A. Banerjee,[53] D. R. Beavis,[4] R. Bellwied,[49] A. Bhasin,[20] A. K. Bhati,[35] P. Bhattarai,[48] H. Bichsel,[55] J. Bielcik,[13] J. Bielcikova,[14] L. C. Bland,[4] I. G. Bordyuzhin,[19] W. Borowski,[45] J. Bouchet,[22] A. V. Brandin,[30] S. G. Brovko,[6] S. Bültmann,[33] I. Bunzarov,[21] T. P. Burton,[4] J. Butterworth,[41] H. Caines,[57] M. Calderón de la Barca Sánchez,[6] D. Cebra,[6] R. Cendejas,[36] M. C. Cervantes,[47] P. Chaloupka,[13] Z. Chang,[47] S. Chattopadhyay,[53] H. F. Chen,[42] J. H. Chen,[44] L. Chen,[9] J. Cheng,[50] M. Cherney,[12] A. Chikanian,[57] W. Christie,[4] J. Chwastowski,[11] M. J. M. Codrington,[48] G. Contin,[26] J. G. Cramer,[55] H. J. Crawford,[5] X. Cui,[42] S. Das,[16] A. Davila Leyva,[48] L. C. De Silva,[12] R. R. Debbe,[4] T. G. Dedovich,[21] J. Deng,[43] A. A. Derevschikov,[37] R. Derradi de Souza,[8] S. Dhamija,[18] B. di Ruzza,[4] L. Didenko,[4] C. Dilks,[36] F. Ding,[6] P. Djawotho,[47]

RHIC's collisions of heavy nuclei at nearly light speed are designed to re-create, on a tiny scale, the

Background?

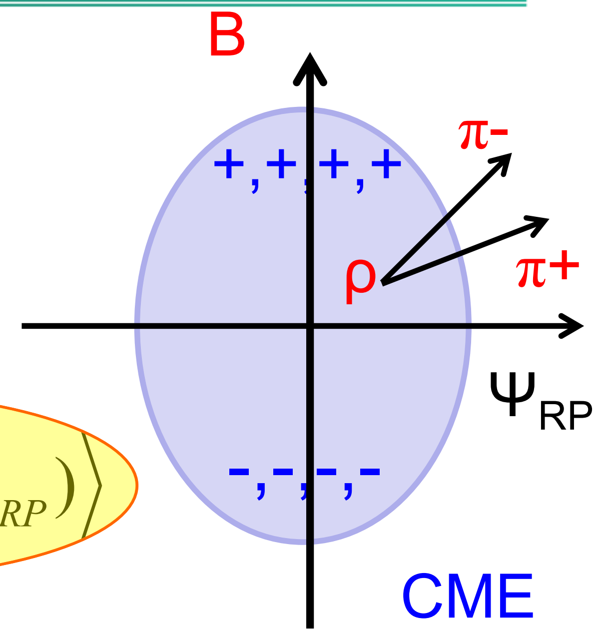
F. Wang 2009, A. Bzdak, V. Koch and J. Liao 2010,
S. Pratt, S. Schlichting 2010 …

$$\gamma = \left\langle \cos(\varphi_\alpha + \varphi_\beta - 2\psi_{RP}) \right\rangle$$

$$= \frac{N_{cluster}}{N_\alpha N_\beta} \left\langle \cos(\varphi_\alpha + \varphi_\beta - 2\varphi_{cluster}) \cos(2\varphi_{cluster} - 2\psi_{RP}) \right\rangle$$

two-particle correlation

v_2



$\gamma^{+-} = \cos(\pi^+ + \pi^- - 0) = \cos(360°) = +1$
$\Delta\gamma > 0$ CME

≈

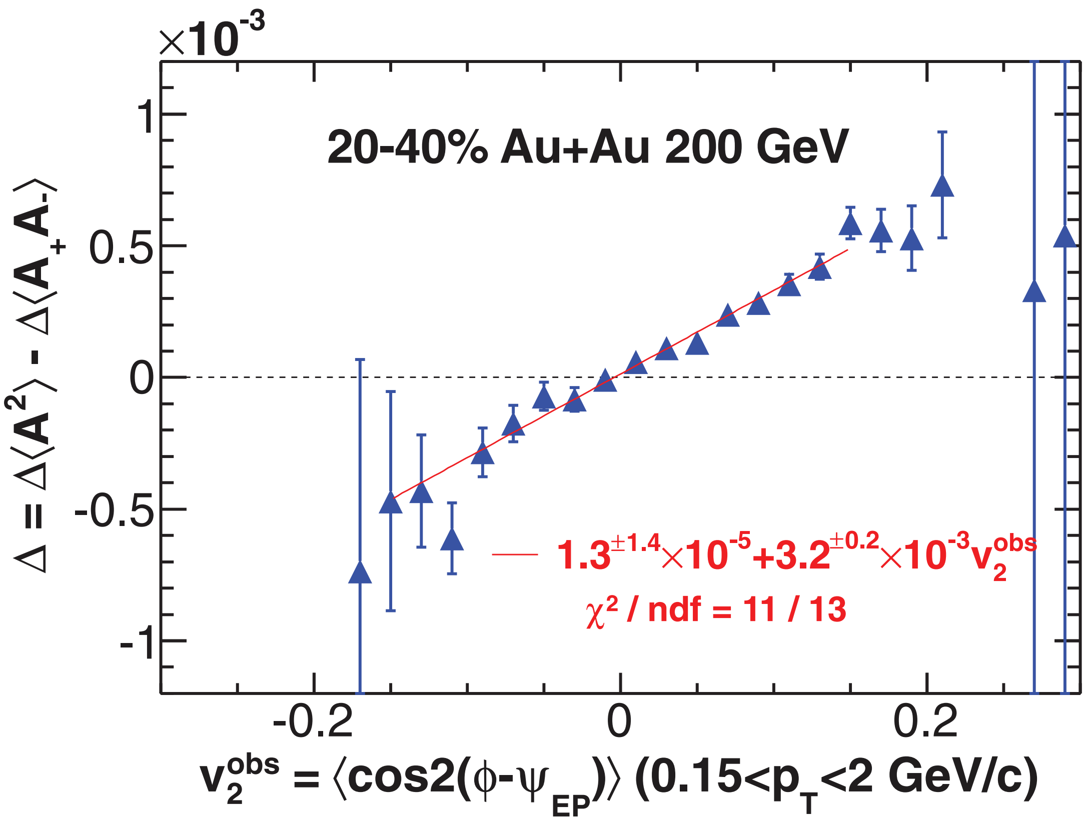
$\gamma^{+-} = \cos(\pi^+ + \pi^- - 0) = \cos(0°) = +1$
$\Delta\gamma > 0$ Decay BKG.

- Background from two-particle correlation coupled with v_2
- Remove background by selecting on $v_2=0$ (event shape)

Background issue, event-by-event v_2

STAR, PRC 89,044908 (2014)

Δ similar to $\Delta\gamma$

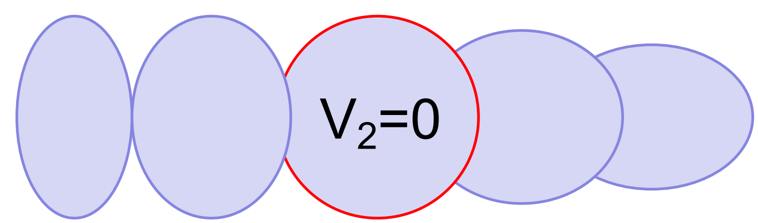


$$Q_n = \frac{1}{M}\sum_{j=1}^{N} w_j e^{in\phi_j} \,,$$

$$q_{n,\mathrm{EP}} = e^{in\psi_{\mathrm{EP}}} \,,$$

$$v_{n,\mathrm{ebye}} = Q_n^* q_{n,\mathrm{EP}} \,,$$

where $n = 2, 3$.

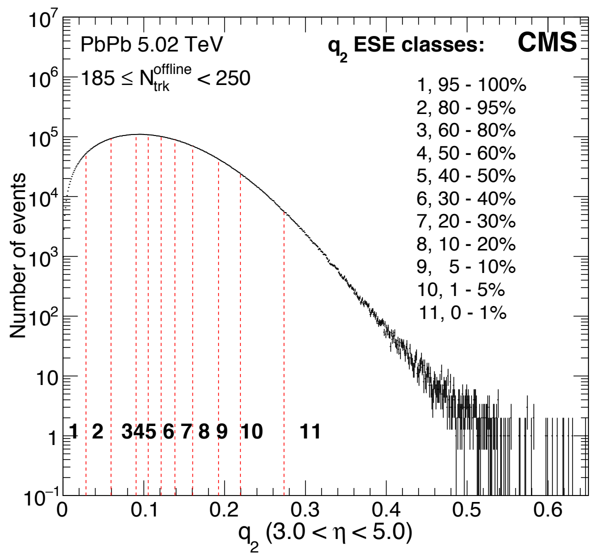


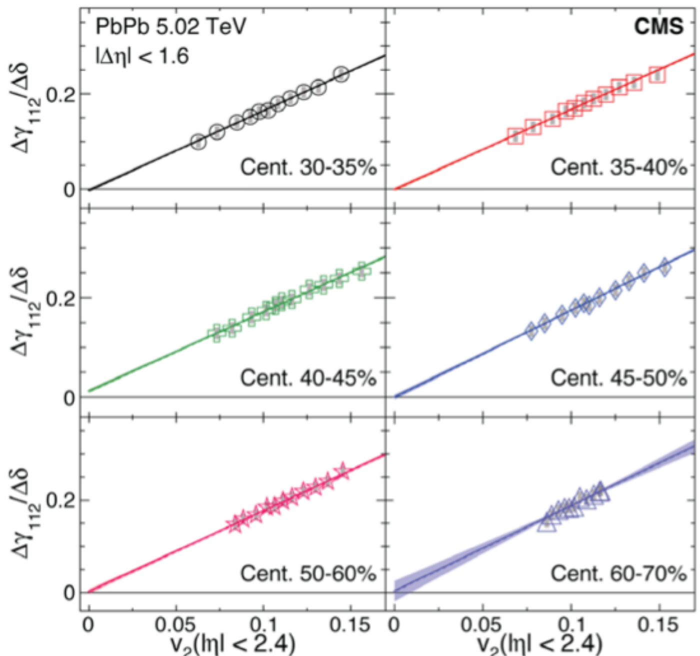
- Charge correlator linear as function of event-by-event v_2 (v_2^{obs} or $v_{2,ebye}$)
- suggests large v_2 background contributions
- By selecting the events with $v_2^{obs} = 0$, the correlator is largely reduced

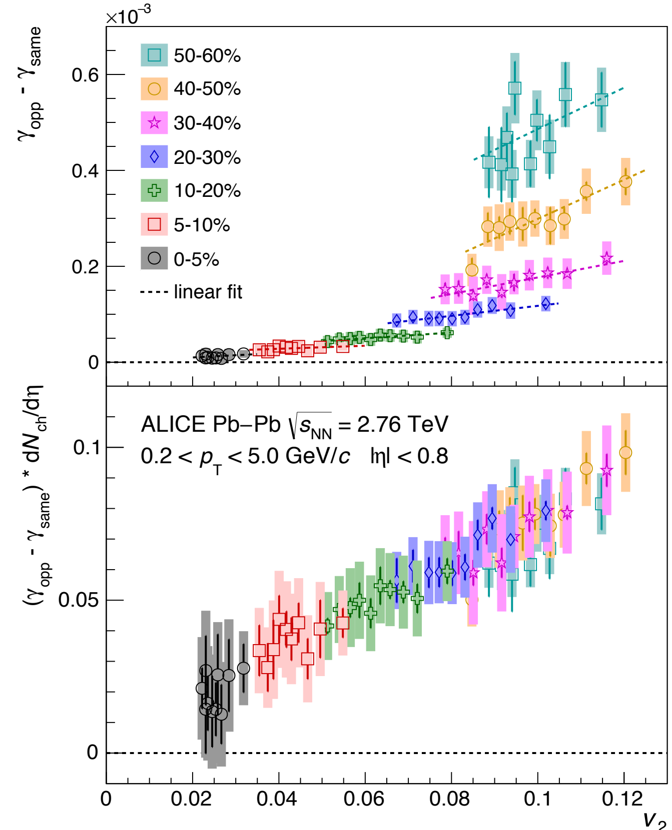
Event shape engineering (ESE)

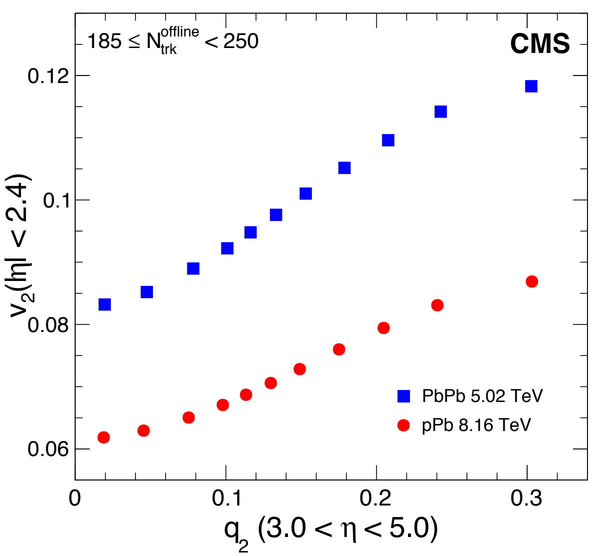
CMS, Phys.Rev. C97 (2018) no.4, 044912

ALICE, Phys.Lett. B777 (2018) 151-162









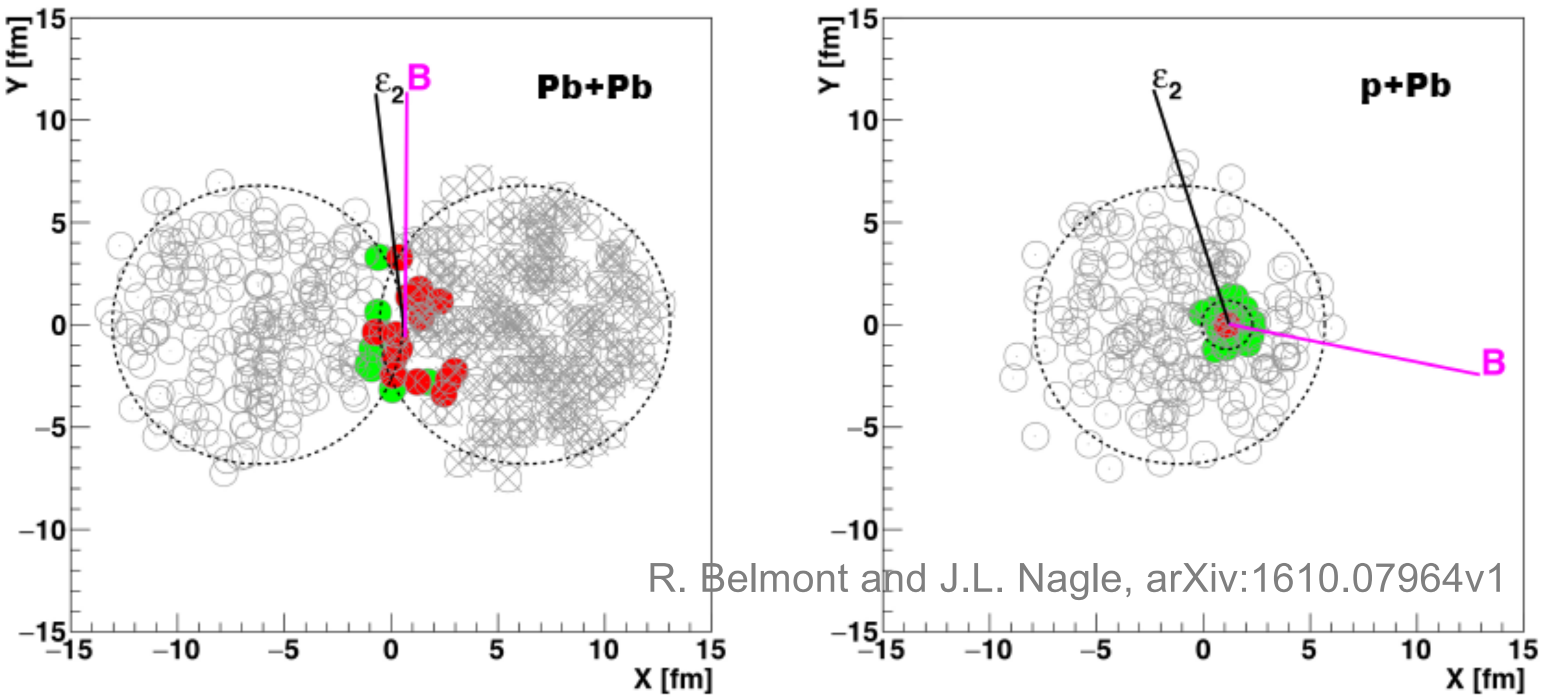
$$q_n = \sqrt{M}|Q_n| \quad \text{where } n = 2, 3\,,$$

$V_2=0$

- Select events of different shape (v_2) with the q_2 value using the ESE method
- Correlator largely depends on the v_2 (or q_2)

Small system

CMS, PRL 118(2017)122301;

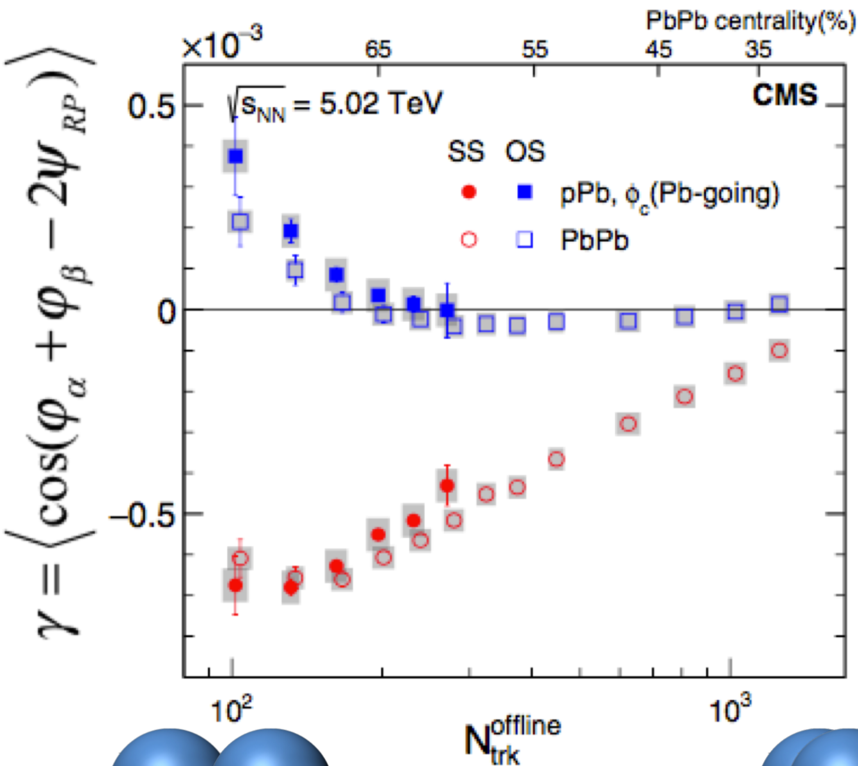


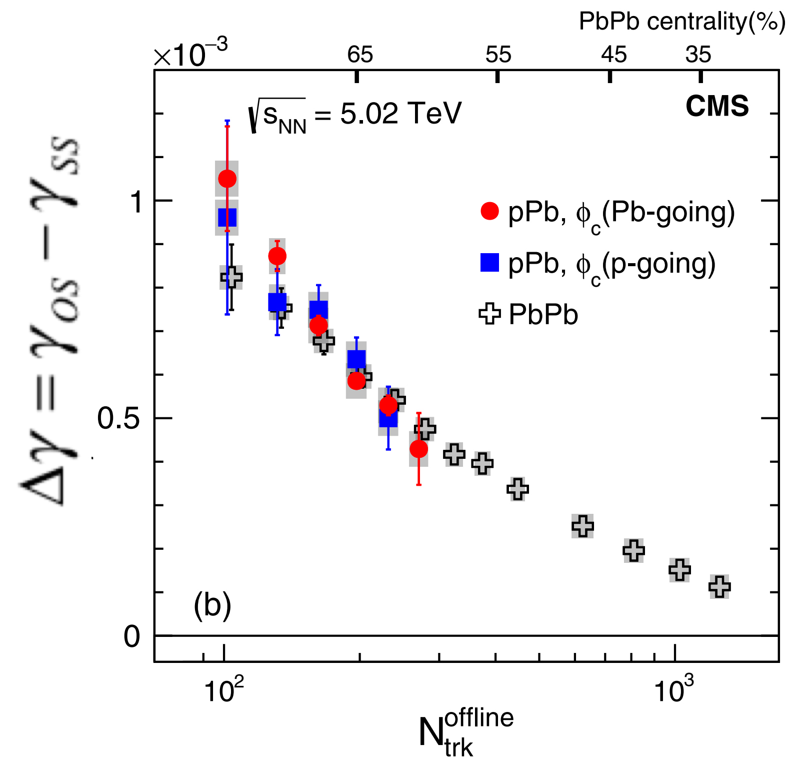
R. Belmont and J.L. Nagle, arXiv:1610.07964v1

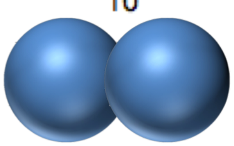
- ε_2 related to v_2, related to -> v_2 background
- the magnetic direction (B), related to -> CME signal
- ε_2 and B directions correlated in A+A, CME and background entangled
- ε_2 and B directions not correlated in p+A, d+A, CME and background disentangled

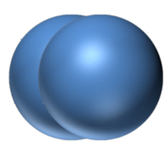
Small systems, a milestone

CMS, PRL 118(2017)122301





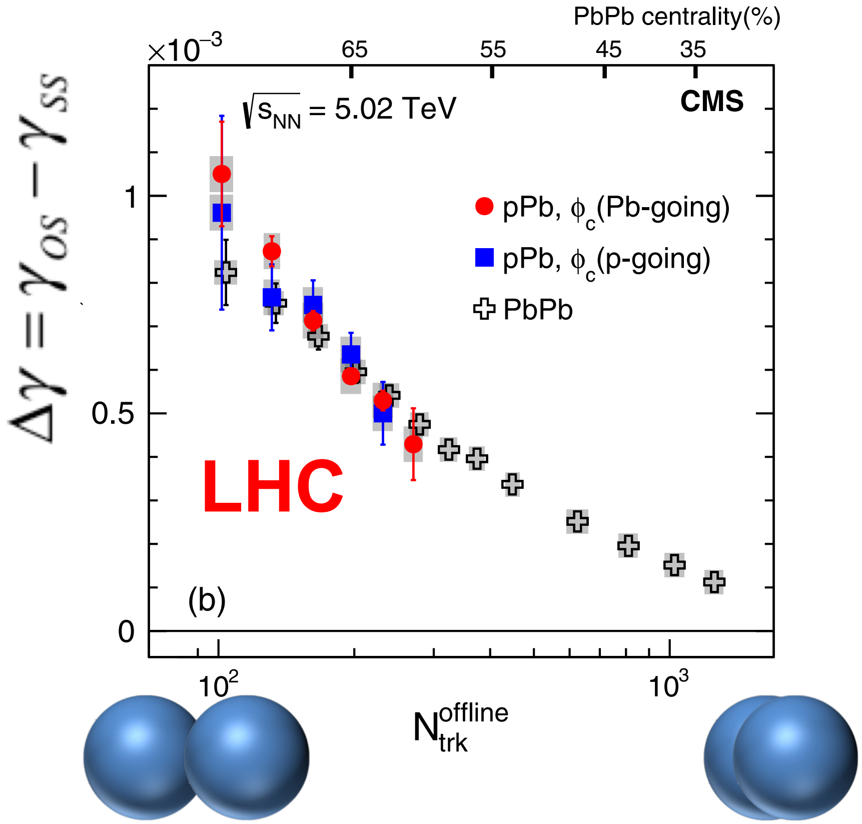




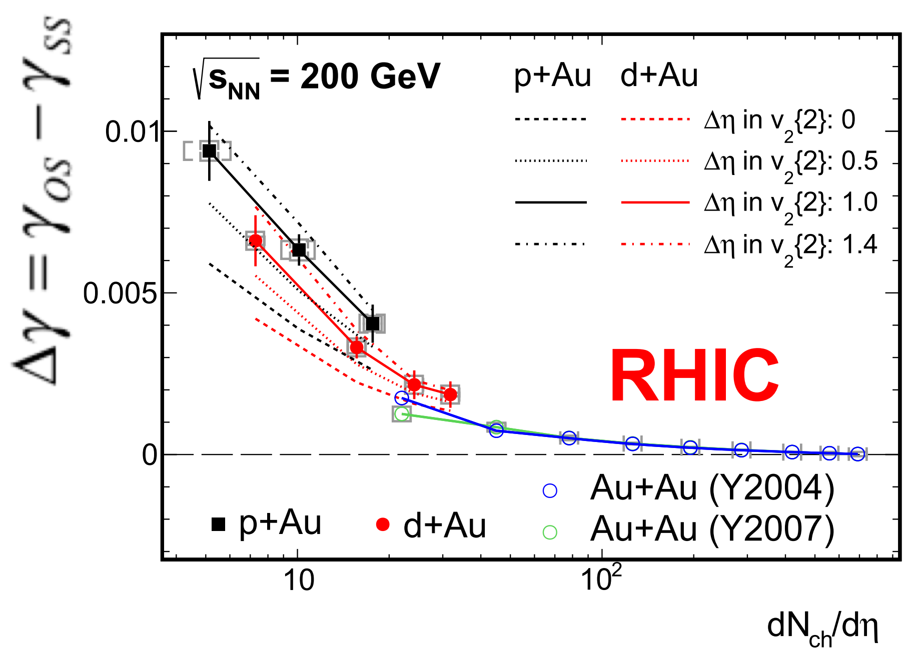
- p+Pb ≈ Pb+Pb at the same multiplicities (N_{trk}^{offine}) at LHC
- Major challenge to the CME interpretation in heavy-ion collisions

Small systems, a milestone

CMS, PRL 118(2017)122301



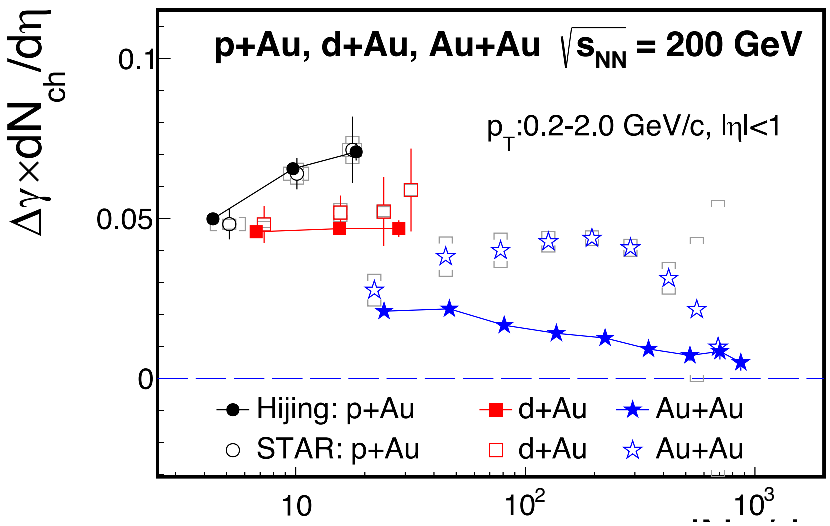
STAR, PLB 798 (2019) 134975

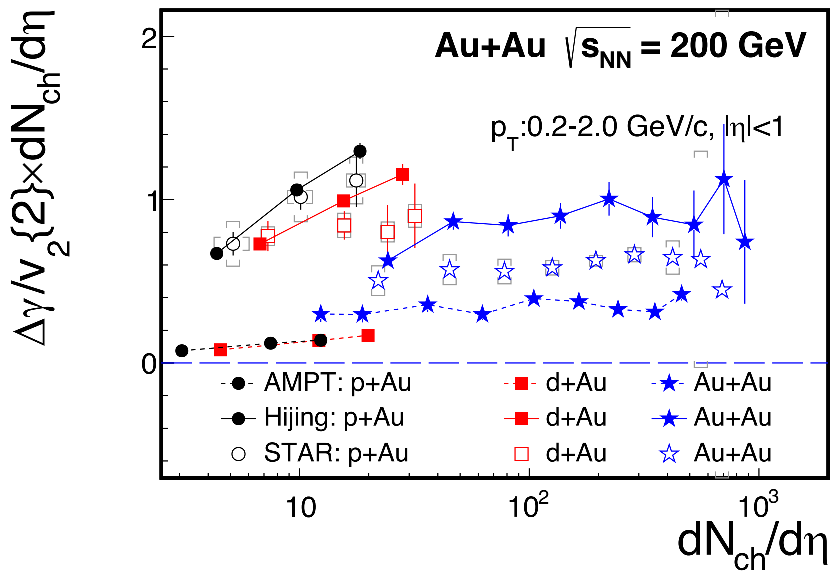


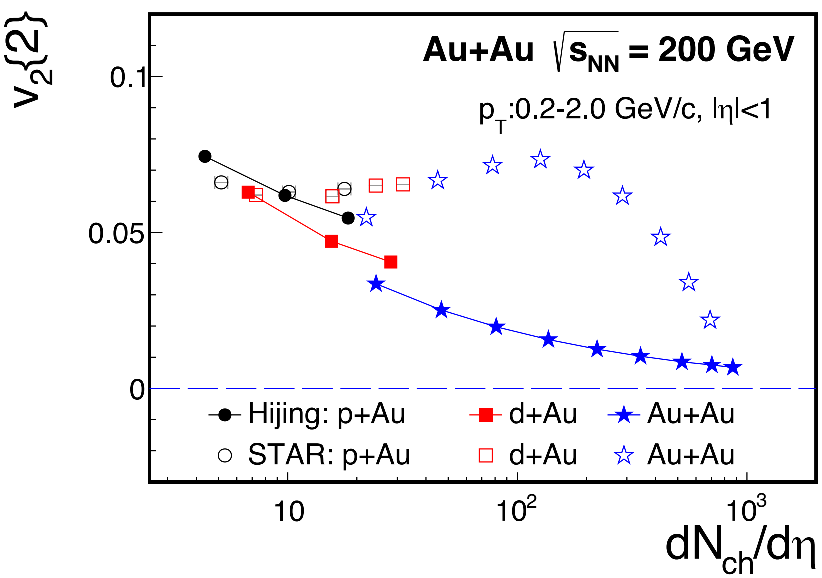
- p+Pb ≈ Pb+Pb at the same multiplicities (N_{trk}^{offine}) at LHC
- Major challenge to the CME interpretation in heavy-ion collisions
- p/d+A ≈ A+A, RHIC ≈ LHC

Why model can not reproduce data ?

J. Zhao, Y. Feng, H. Li, F. Wang arXiv:1912.00299







- Early conclusions:
  Δγ, model < data in A+A, suggests CME
- p/d+A, Hijing ~ data, AMPT < data CME?
- Hijing < data in A+A, due to small v_2 in Hijing
- Scaled Hijing ~ or > data, depends on details, like, rescattering, resonance yield…

- Early measurements dominated by background
- How to measure the background-free CME signal?
- Two novel methods:

  1, Exploiting invariant mass dependence of $\Delta\gamma$

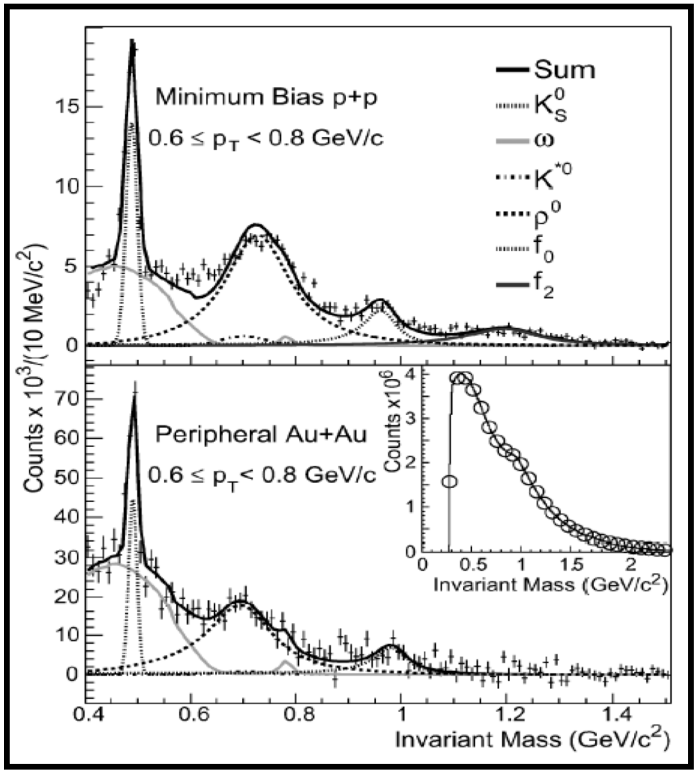
  2, $\Delta\gamma$ with respect to Ψ_{RP} and Ψ_{PP}

J. Zhao, F. Wang, Progress in Particle and Nuclear Physics 107 (2019) 200-236
J. Zhao, H. Li, F. Wang, Eur. Phys. J. C (2019) 79:168
H-J Xu, J. Zhao, X. Wang, H. Li, Z. Lin, C. Shen and F. Wang, CPC 42 (2018) 084103
H-J Xu, X. Wang, H. Li, J. Zhao, Z. Lin, C. Shen and F. Wang, PRL 121 (2018) 022301

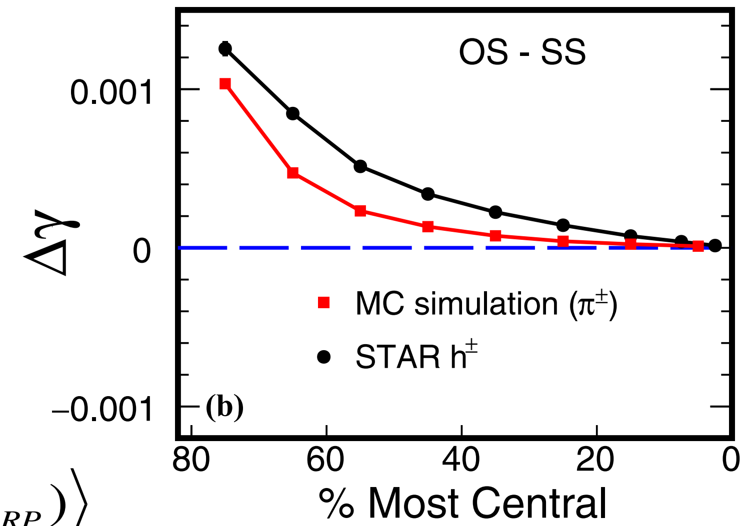
Resonance decay background

STAR, PRL 92,092301 (2004)

F. Wang, J. Zhao, PRC 95,051901(R) (2017)
STAR, PRL103,251601 (2009)



+ v_2 →



$$\left\langle \cos(\phi_\alpha + \phi_\beta - 2\psi_{RP}) \right\rangle$$
$$= \left\langle \cos(\phi_\alpha + \phi_\beta - 2\phi_{reso.} + 2\phi_{reso.} - 2\psi_{RP}) \right\rangle$$
$$\approx \left\langle \cos(\phi_\alpha + \phi_\beta - 2\phi_{reso.} \right\rangle \times v_{2,\,reso}$$

invariant mass of the π+π pair, $m_{inv} = \sqrt{(E^2 - p^2)}$

- ➢ Resonance background: resonance decay + v_2 ➔ CME-like Δγ
- ➢ Can we remove/isolate the background?

To eliminate background

$$\gamma = \left\langle \cos(\varphi_\alpha + \varphi_\beta - 2\psi_{RP}) \right\rangle$$

$$= \frac{N_{cluster}}{N_\alpha N_\beta} \left\langle \cos(\varphi_\alpha + \varphi_\beta - 2\varphi_{cluster}) \cos(2\varphi_{cluster} - 2\psi_{RP}) \right\rangle$$

Resonance decay … v_2

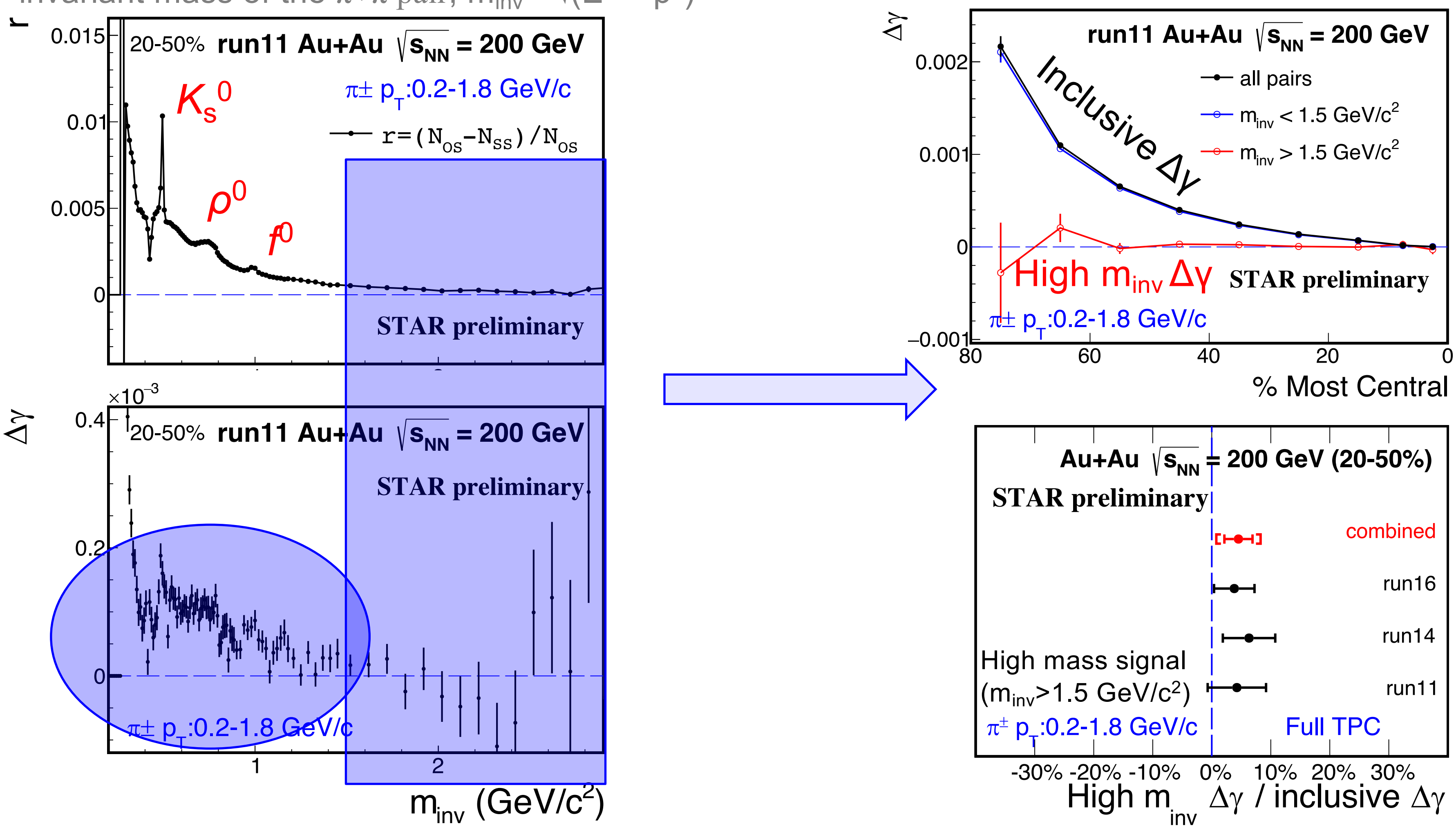
Get rid of resonances, or utilize them…

Identify the backgrounds by invariant mass of α+β pairs

J. Zhao, H. Li, F. Wang, Eur. Phys. J. C (2019) 79:168
H. Li, J. Zhao, F. Wang, NPA 982 (2019) 563–566

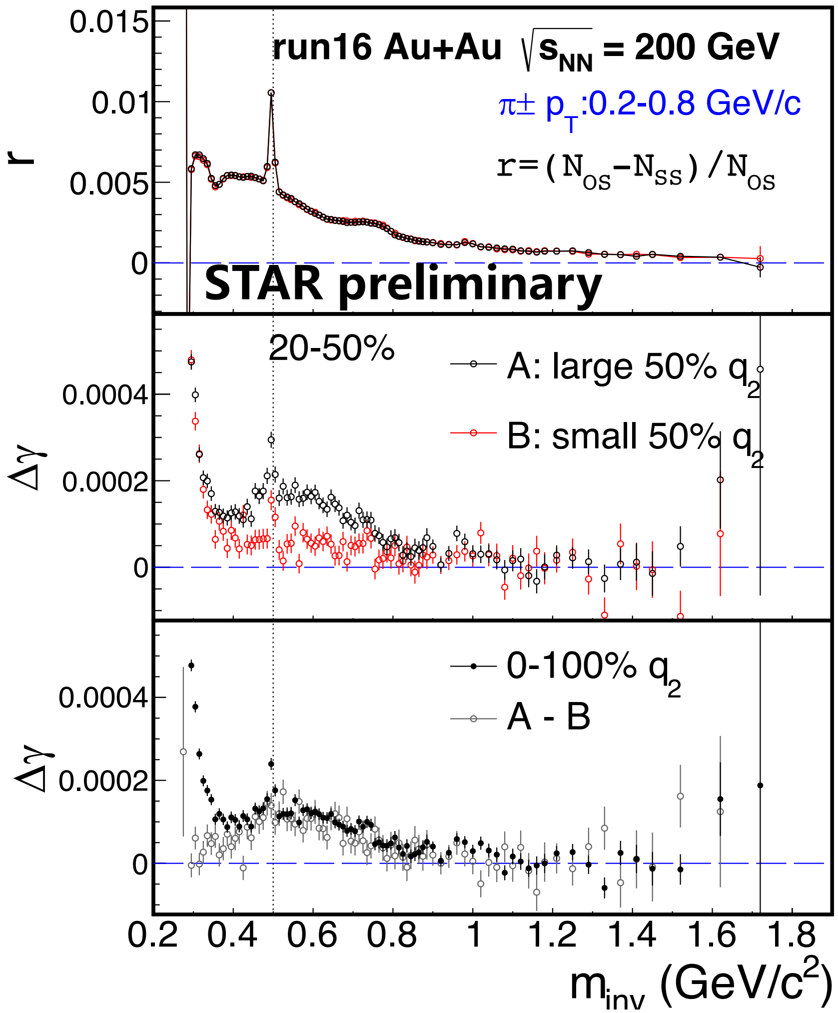
Identify the background

invariant mass of the π+π pair, $m_{inv} = \sqrt{(E^2 - p^2)}$



- Data show resonance structure in Δγ vs. invariant mass (m_{inv})
- At high m_{inv}, possible CME signal is (5±2±4)% of the early measurements

Isolate the CME from background



$$\frac{N_{cluster}}{N_\alpha N_\beta}\langle \cos(\varphi_\alpha+\varphi_\beta-2\varphi_{cluster})\cos(2\varphi_{cluster}-2\psi_{RP})\rangle$$

vary v_2

$\Delta\gamma(m) = r(m)*\cos(\alpha+\beta-2\phi_{reso.})*v_{2,reso.}$ + CME

Background shape

ESE select events with diff. v_2 by q_2 class (A, B)

Background shape: $\mathbf{\Delta\gamma_A - \Delta\gamma_B}$

Fit $\Delta\gamma = k*(\Delta\gamma_A-\Delta\gamma_B)$ + CME

J. Zhao, H. Li, F. Wang, Eur. Phys. J. C (2019) 79:168

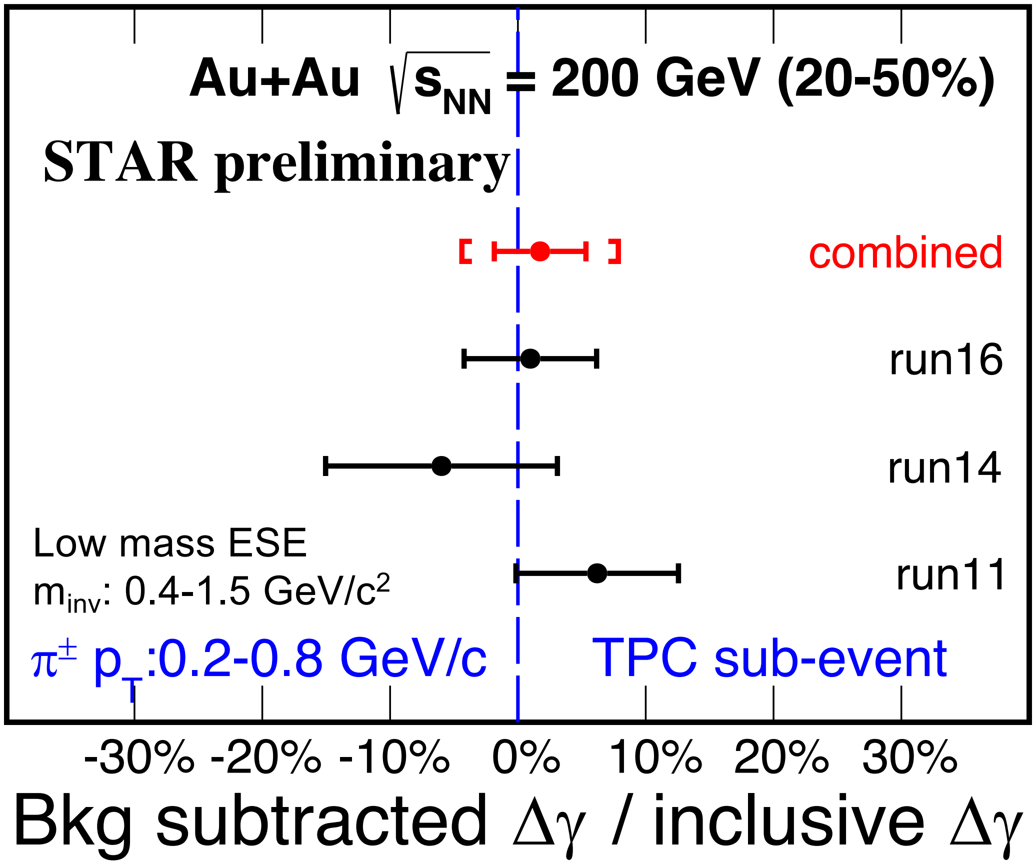
J. Zhao. Int. J. Mod. Phys., A33(13):1830010, 2018

J. Zhao, Z. Tu, F. Wang, NPR 2018, 35 (3): 225-242.

➢ Obtain the Bkg Δγ m_{inv} shape by event shape engineering (ESE)

Isolate the CME from background

J. Zhao (for the STAR collaboration), NPA 982 (2019) 535–538

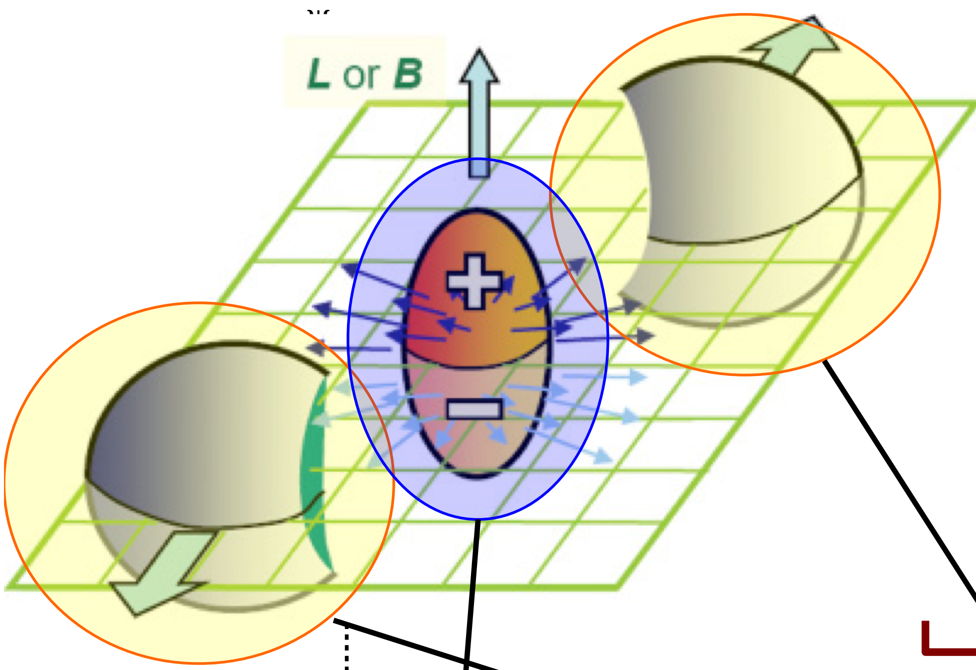


- possible CME signal is (2±4±6)% of the inclusive $\Delta\gamma$ measurements from this method

Ψ_{PP} & Ψ_{RP} to solve Bkg & CME

H-J Xu, J. Zhao, X. Wang, H. Li, Z. Lin, C. Shen and F. Wang, CPC 42 (2018) 084103
H-J Xu, X. Wang, H. Li, J. Zhao, Z. Lin, C. Shen and F. Wang, PRL 121 (2018) 022301

B. Alver *et al.* (PHOBOS) , PRL **98**, 242302 (2007).



Ψ_{PP} maximizes v_2,

➔ v_2 background

Ψ_{RP} maximizes the magnetic field (B),

➔ CME signal

Ψ_{PP} and Ψ_{RP} are correlated, but not identical due to geometry fluctuations

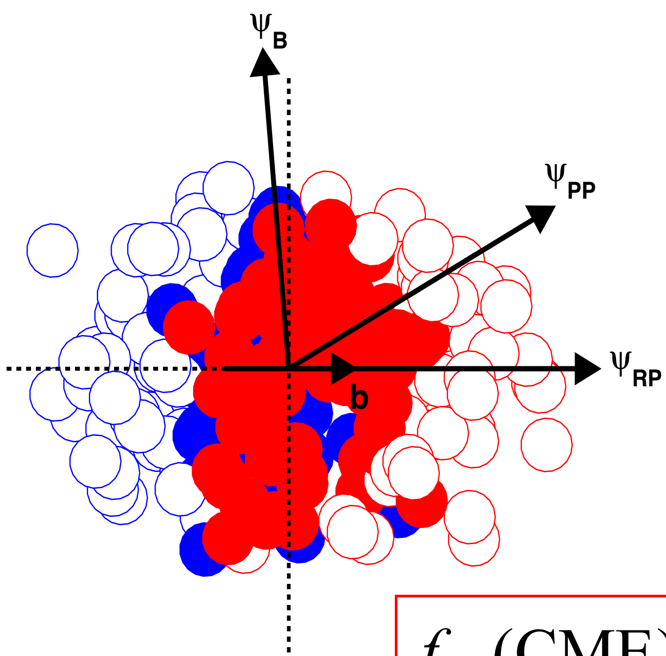
$$a \equiv \langle \cos 2(\psi_{PP} - \psi_{RP}) \rangle$$

- Δγ w.r.t. TPC Ψ_{EP} (proxy of Ψ_{PP}) and ZDC Ψ_1 (proxy of Ψ_{RP}) contain different fractions of CME and Bkg

Ψ_{PP} & Ψ_{RP} to solve Bkg & CME

- Ψ_{PP} maximizes flow, ➔ flow background
- Ψ_{RP} maximizes the magnetic field (B), ➔ CME signal
- Ψ_{PP} and Ψ_{RP} are correlated, but not identical due to geometry fluctuations
- $\Delta\gamma$ w.r.t. TPC Ψ_{EP} (proxy of Ψ_{PP}) and ZDC Ψ_1 (proxy of Ψ_{RP}) contain different fractions of CME and Bkg

H-J. Xu, *et al*, CPC 42 (2018) 084103, arXiv:1710.07265



$$\Delta\gamma\{\psi_{TPC}\} = \text{CME}\{\psi_{TPC}\} + \text{Bkg}\{\psi_{TPC}\}$$

$$\Delta\gamma\{\psi_{ZDC}\} = \text{CME}\{\psi_{ZDC}\} + \text{Bkg}\{\psi_{ZDC}\}$$

Two-component assumption

$$\text{CME}\{\psi_{TPC}\} = a * \text{CME}\{\psi_{ZDC}\},\ \text{Bkg}\{\psi_{ZDC}\} = a * \text{Bkg}\{\psi_{TPC}\}$$

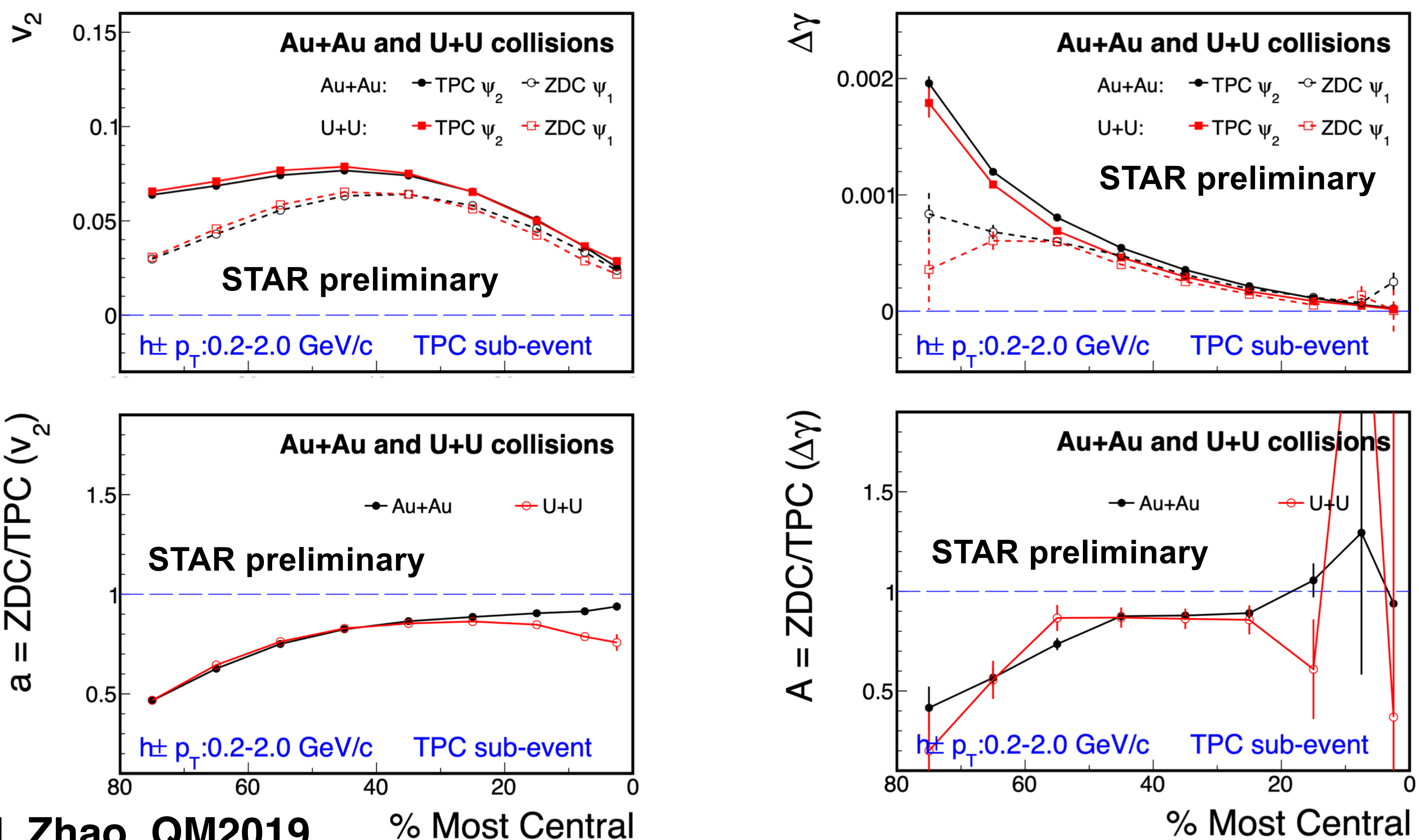
assume Bkg $\propto v_2$

$$a = v_2\{\psi_{ZDC}\} / v_2\{\psi_{TPC}\},\ A = \Delta\gamma\{\psi_{ZDC}\} / \Delta\gamma\{\psi_{TPC}\}$$

Both are experimental measurements

$$f_{EP}(\text{CME}) = \text{CME}\{\psi_{TPC}\} / \Delta\gamma\{\psi_{TPC}\} = (A/a - 1)/(1/a^2 - 1)$$

$\Delta\gamma_{112}$ w.r.t. Ψ_{PP} & Ψ_{RP} in U+U & Au+Au



J. Zhao, QM2019

- Data indicate difference in v_2 between central U+U and Au+Au
- “a” and “A” similar trend and magnitude, indicate bkg. dominant

Au+Au 27 GeV with EPD Ψ_{PP} & Ψ_{RP}

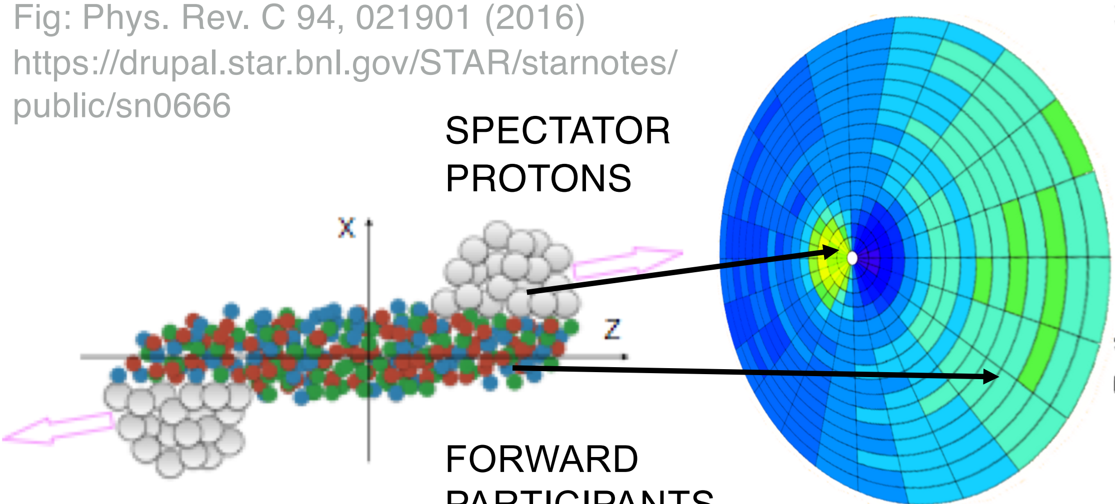
STAR Event Plane detector acceptance: **2.1<|η|<5.1**

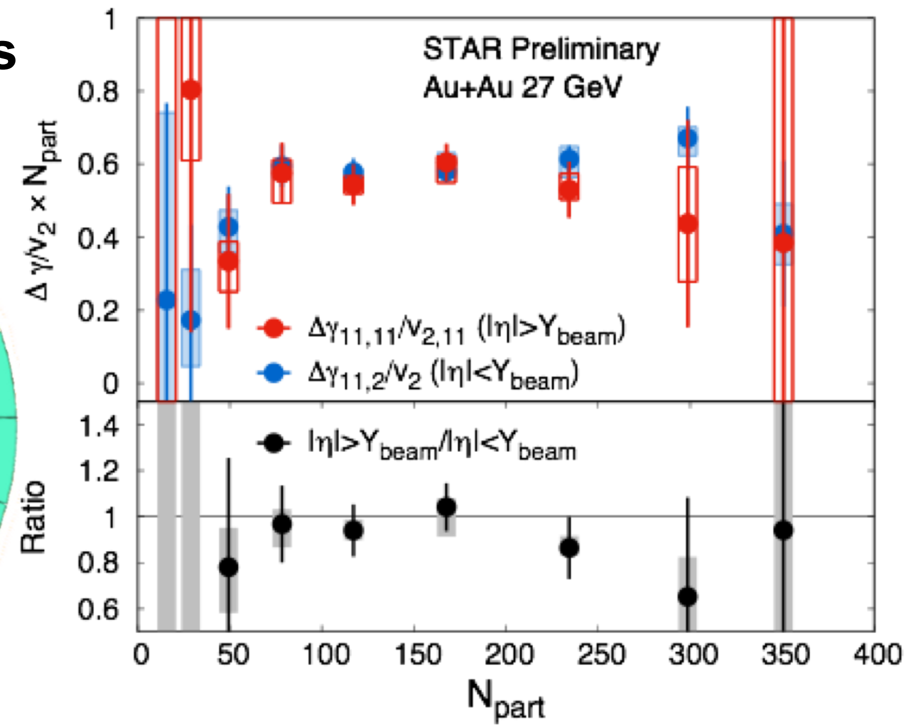
Beam rapidity for Au+Au 27 GeV, $\mathbf{Y_{beam}}$ **=3.4**

EPD detects both participants & spectators

S. Choudhury, QM2019

Fig: Phys. Rev. C 94, 021901 (2016)
https://drupal.star.bnl.gov/STAR/starnotes/public/sn0666





w.r.t. planes of the produced particles $|\eta|<Y_{beam}$

$$\gamma^{\alpha,\beta}_{1,1,2}(\mathrm{TPC}-\mathrm{EPD}^{\mathrm{outer}}) = \left\langle \cos(\phi^\alpha_a + \phi^\beta_b - 2\Psi_2^{|\eta|<Y_{beam}}) \right\rangle$$

w.r.t. planes of the spectator protons $|\eta|>Y_{beam}$

$$\gamma^{\alpha,\beta}_{1,1,1,1}(\mathrm{TPC}-\mathrm{EPD}^{\mathrm{inner}}) = \left\langle \cos(\phi^\alpha_a + \phi^\beta_b - \Psi_1^{\eta>Y_{beam}} - \Psi_1^{-\eta<-Y_{beam}}) \right\rangle$$

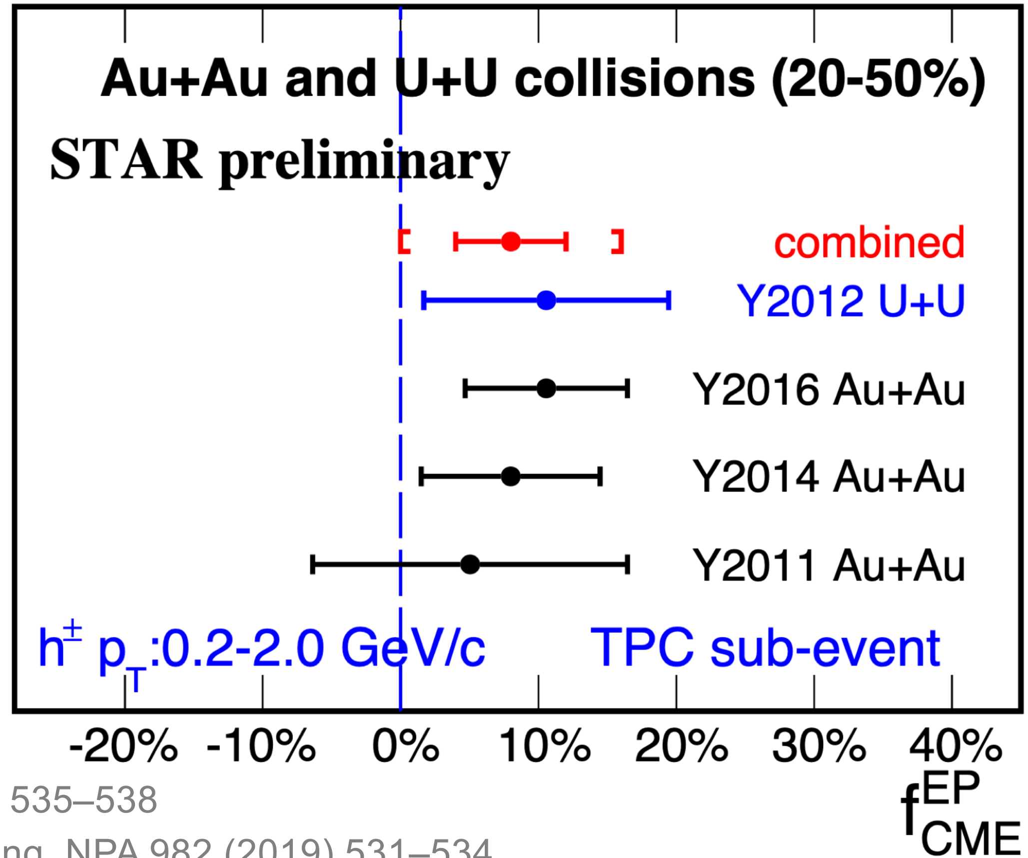
> Unique way to search for CME using EPD for both Ψ_{PP} and Ψ_{RP}
> Ratio ~1 with large uncertainity, indicating CME fraction consistent with zero. More quantitative result in progress

CME fraction by Ψ_{PP} & Ψ_{RP} in U+U & Au+Au

J. Zhao, QM2019

$$a = v_2\{\psi_{ZDC}\} / v_2\{\psi_{TPC}\}$$
$$A = \Delta\gamma\{\psi_{ZDC}\} / \Delta\gamma\{\psi_{TPC}\}$$

$$f_{EP}(\text{CME})$$
$$= \text{CME}\{\psi_{TPC}\} / \Delta\gamma\{\psi_{TPC}\}$$
$$= (A/a - 1)/(1/a^2 - 1)$$



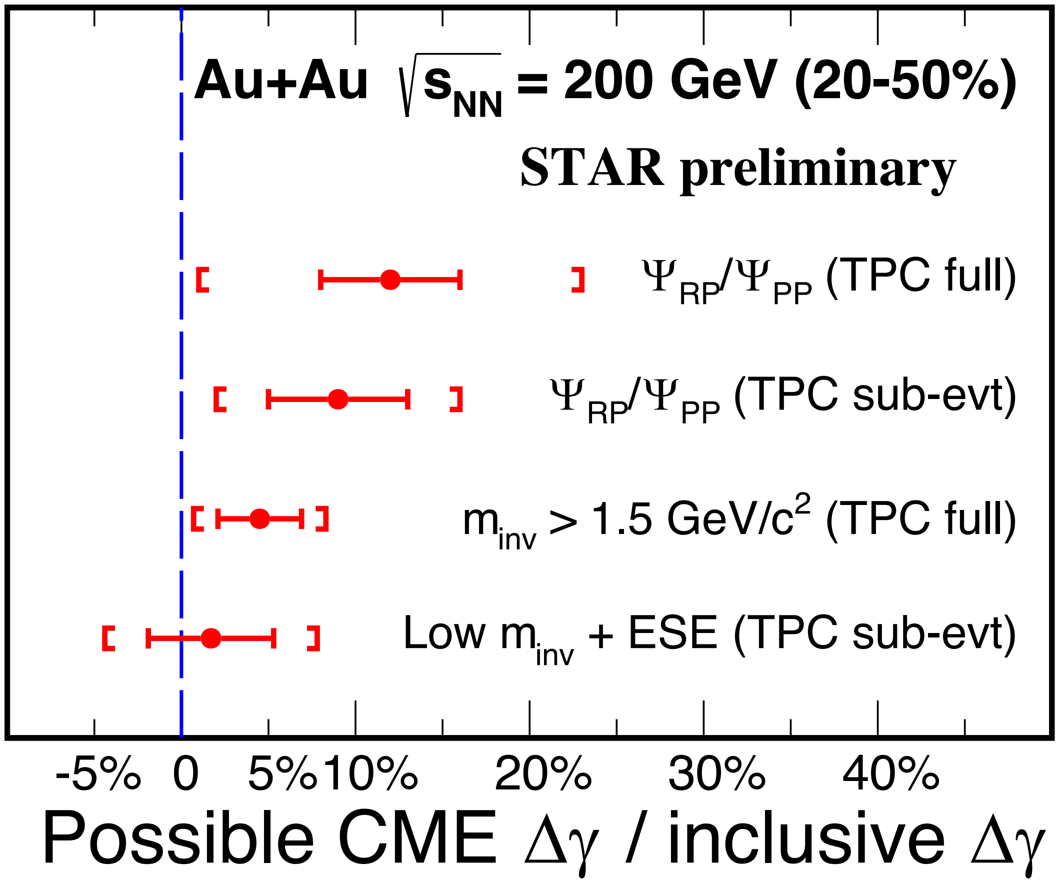
J. Zhao (for the STAR collaboration), NPA 982 (2019) 535–538

H. Xu, J. Zhao, X. Wang, H. Li, Z. Lin, C. Shen, F. Wang, NPA 982 (2019) 531–534

- CME fractions are extracted with Δγ using Ψ_{PP}/Ψ_{RP} in U+U and Au+Au: the combined result is (8±4±8)%, previous results (9±4±7)%
- Systematic uncertainties assessed by track quality cuts and η gap

Our current measurements

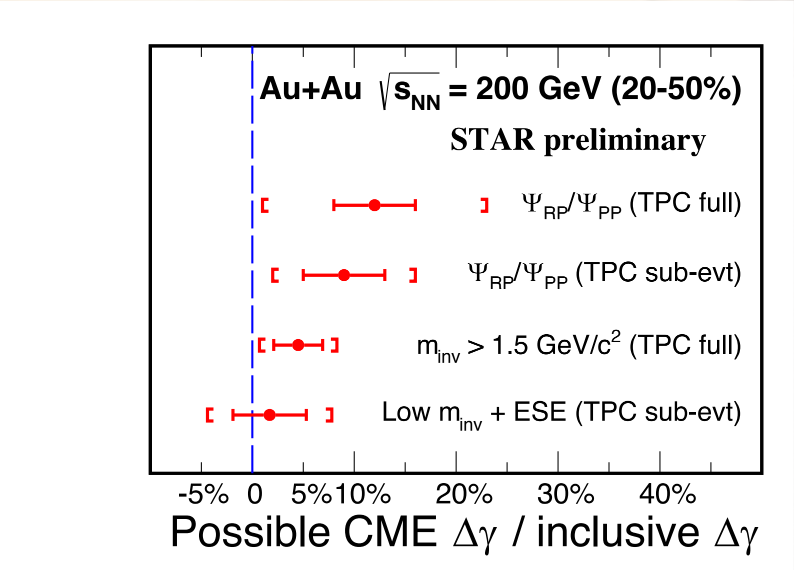
J. Zhao (for the STAR collaboration), NPA 982 (2019) 535–538



- possible CME signal is 5-10% of the early measurements, with1-2σ significance

Summary

- The Chiral Magnetic Effect (CME) is extremely important in QCD
- Early measurements dominated by background
- Novel methods to measure the background-free CME signal, precision improved ~10



The possible CME signal ~5-10% of the early measurements, with 1-2σ significance

J. Zhao, F. Wang, Progress in Particle and Nuclear Physics 107 (2019) 200-236

- In future, more Au+Au data, possible ZDC upgrades for Ψ_{RP}

Back up