CME and Related Measurements at STAR

Nu Xu

Many Thanks to Organizers

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Outline

1) Introduction

2) Measurements:
Search for CME, CMW, CVE

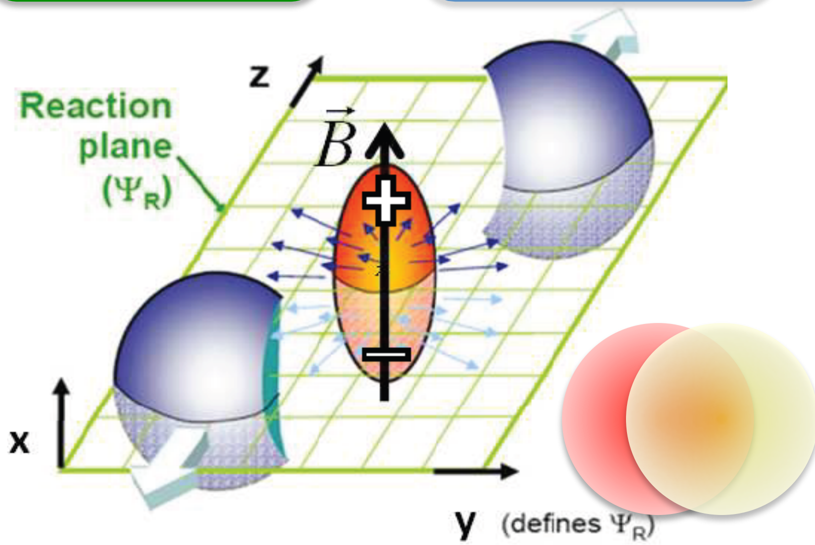
3) Future Measurements

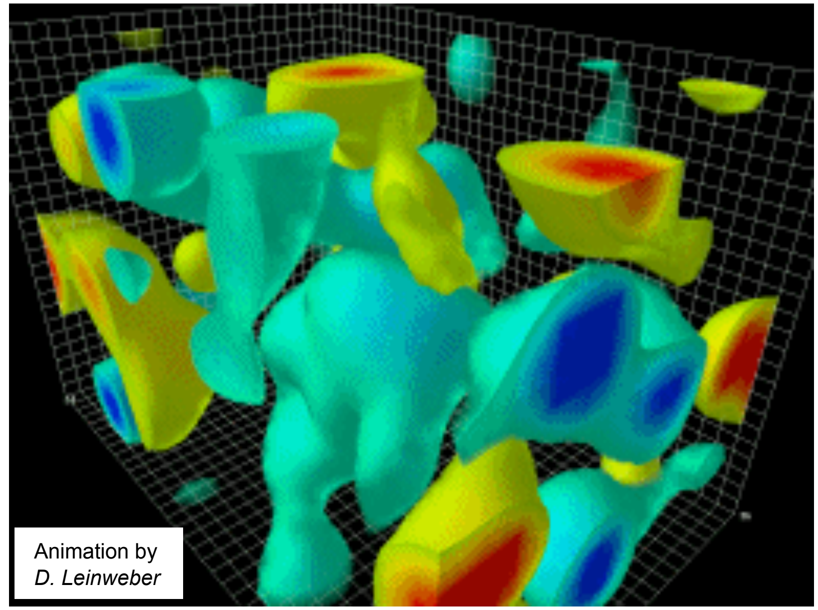
Study QCD Topological Structure

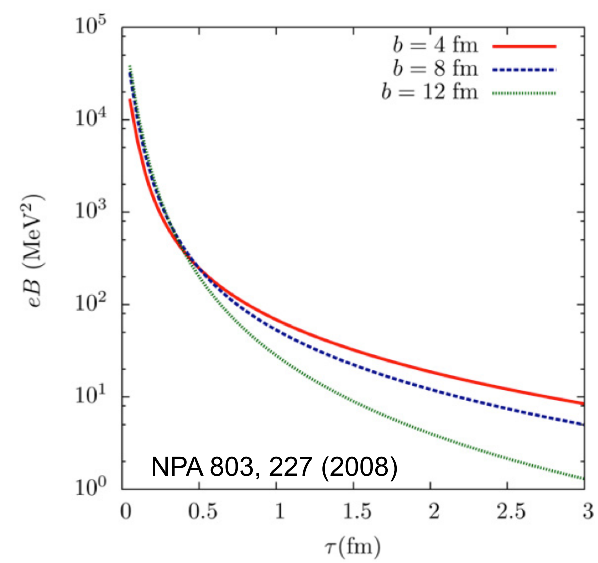
Hot/dense QCD Medium
Parity odd domains form

External Magnetic Field → Chiral magnetic effect (**CME**) (electric charge)

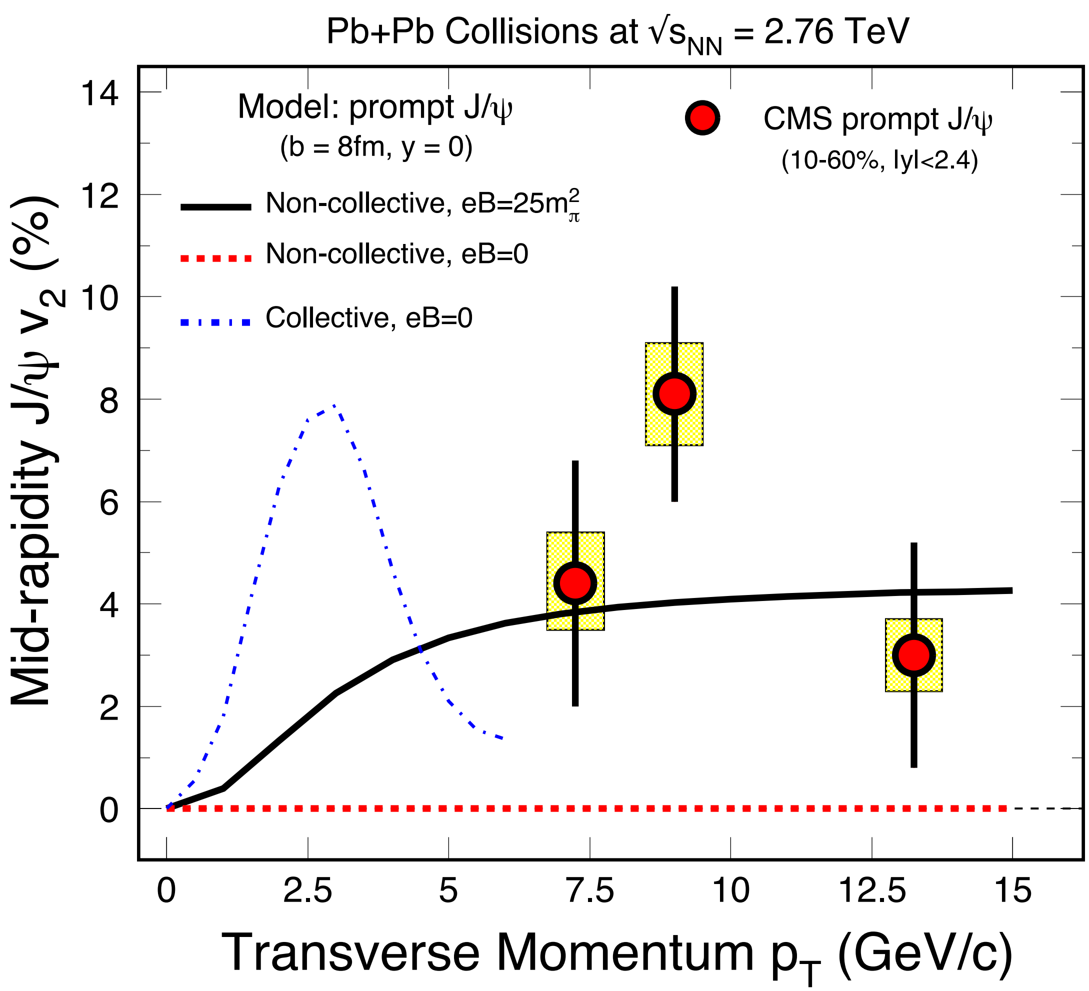
External Angular Momentum → Fluid Vorticity → Chiral vortical effect (**CVE**) (baryonic charge)







Initial B-Field



1) Very strong external magnetic filed at the beginning of the heavy-ion collisions

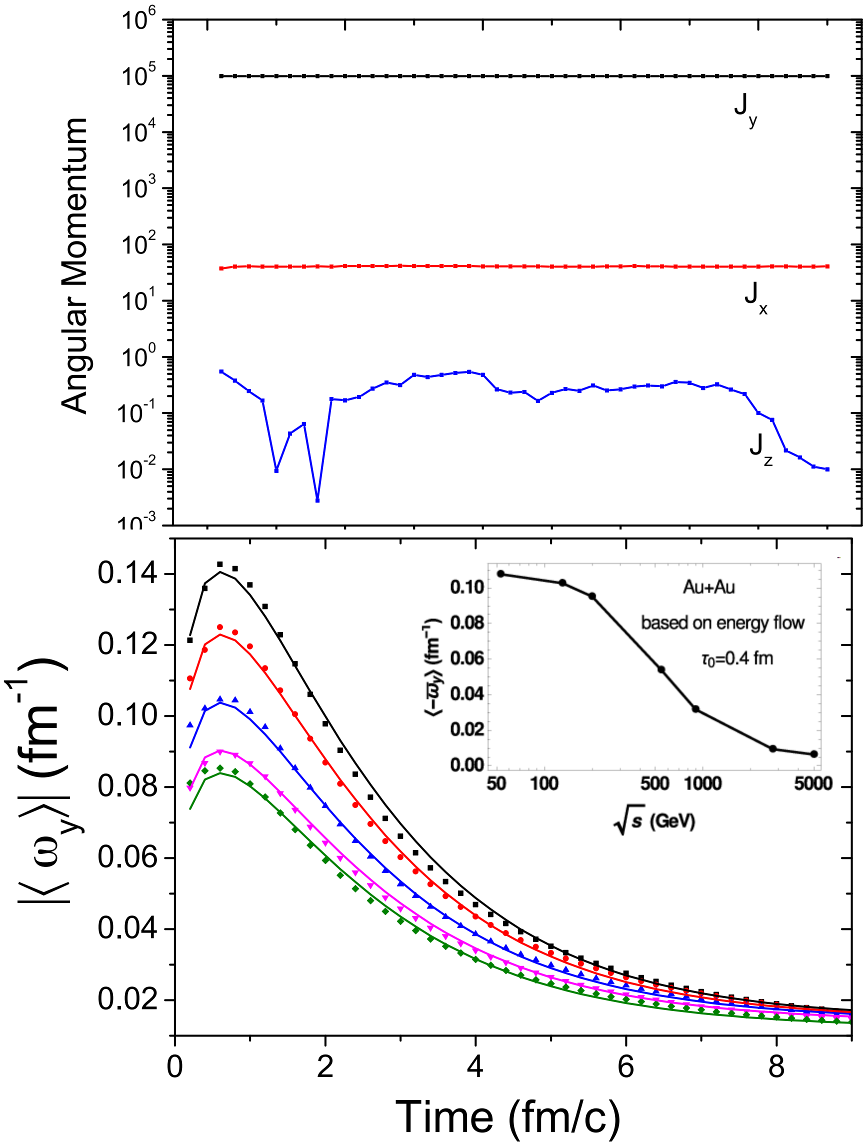
2) Early production of the high p_T quarkonia are sensitive to the initial field

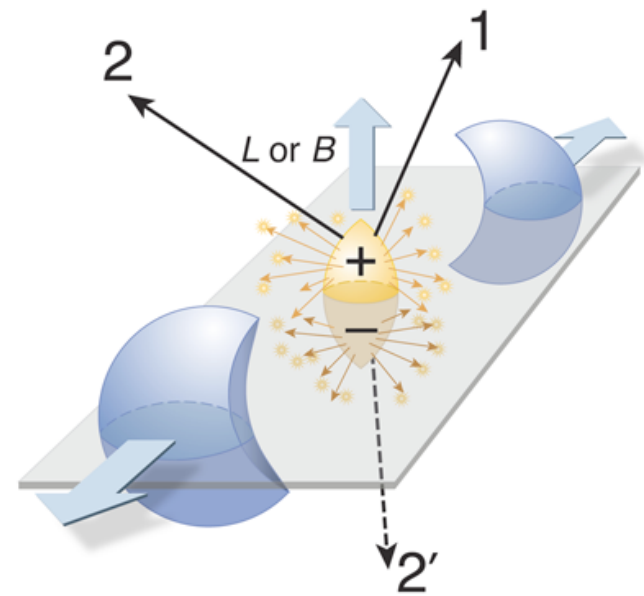
3) Measurements of the large p_{T}, non-collective v_2 of J/ψ, from Pb+ Pb collisions at LHC, seems consistent

4) Future tests:
   - Upsilon v_2 from LHC
   - Collectivity of J/ψ
   - J/ψ v_2 from RHIC

L. McLerran and V. Skokov, 1305.0774
W.T. Deng and X.G. Huang, Phys. Rev. **C85**, 044907 (2012)
U. Gursoy, D. Kharzeev, K. Rajagopal, Phys. Rev. **C89**, 054905 (2014)
X.Y. Guo, P.F. Zhuang, *et al,* 1502.04407, Phys.Lett. **B751**, 215(2015)

Angular Momentum at RHIC



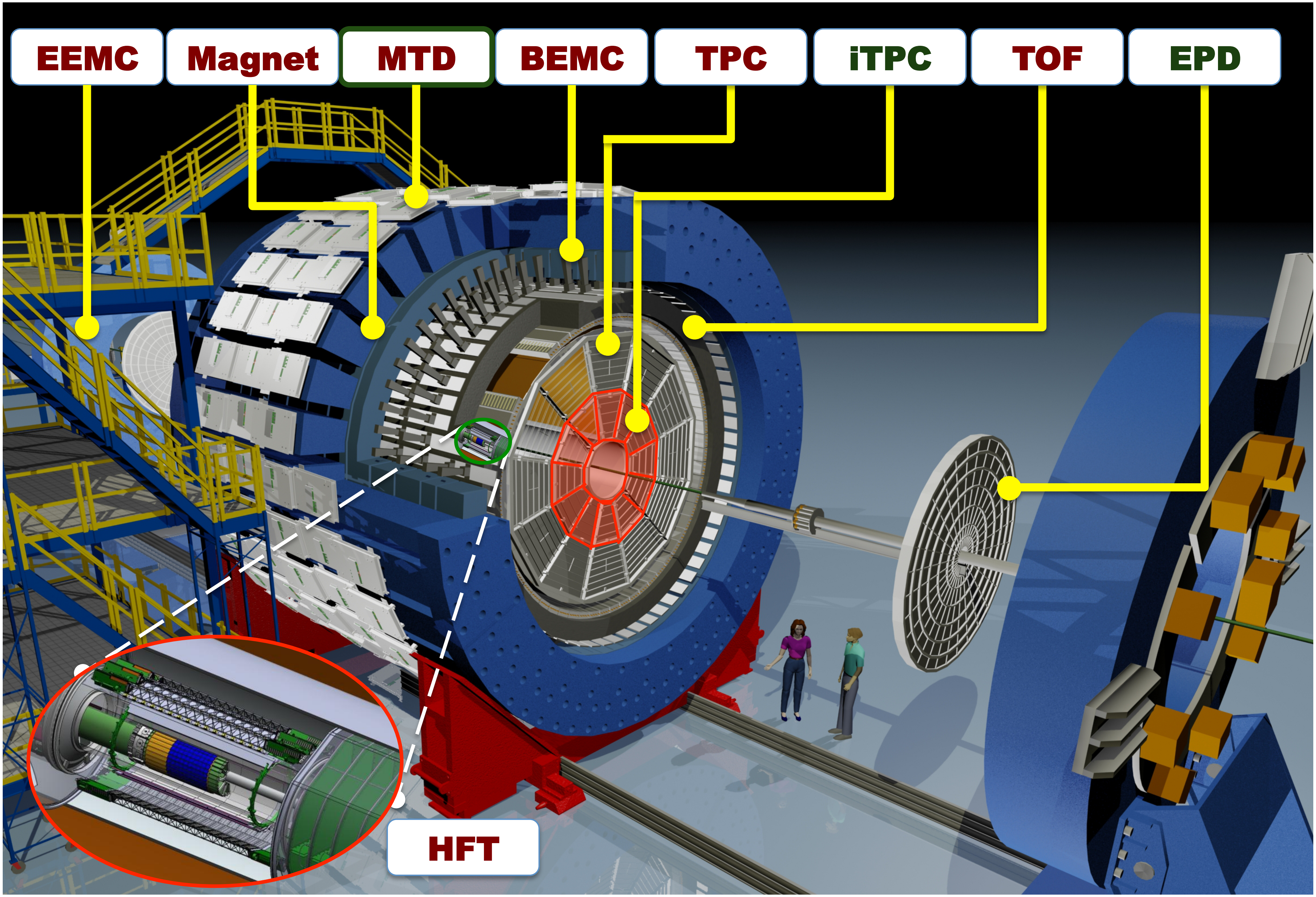


1) AMPT, Au+Au collisions, b = 7fm
2) Angular momenta conserved, no change as a function of time
3) Larger vorticity at lower collision energy
4) Mean lifetime:

$tau_{\omega} > tau_{Hydro} >> tau_B$

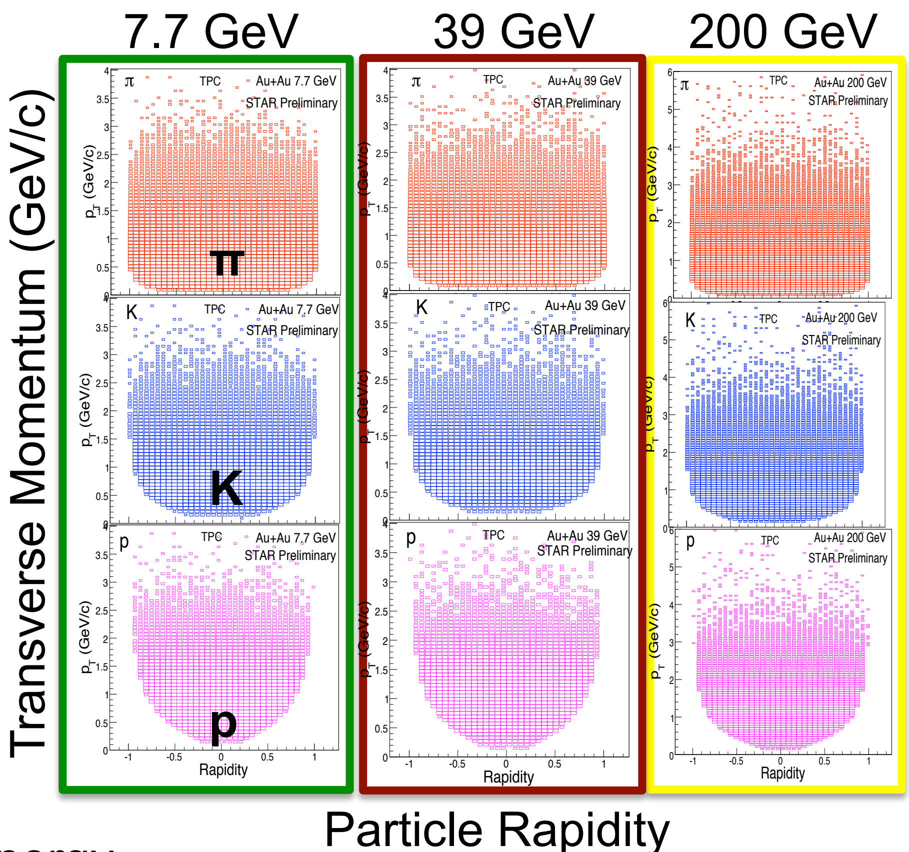
Y. Jiang, Z.W. Lin, J.F. Liao, 1602.06580
W. Deng and X. Huang, 2016

STAR Detector System and BES-II



Data Sets for BES-I Program

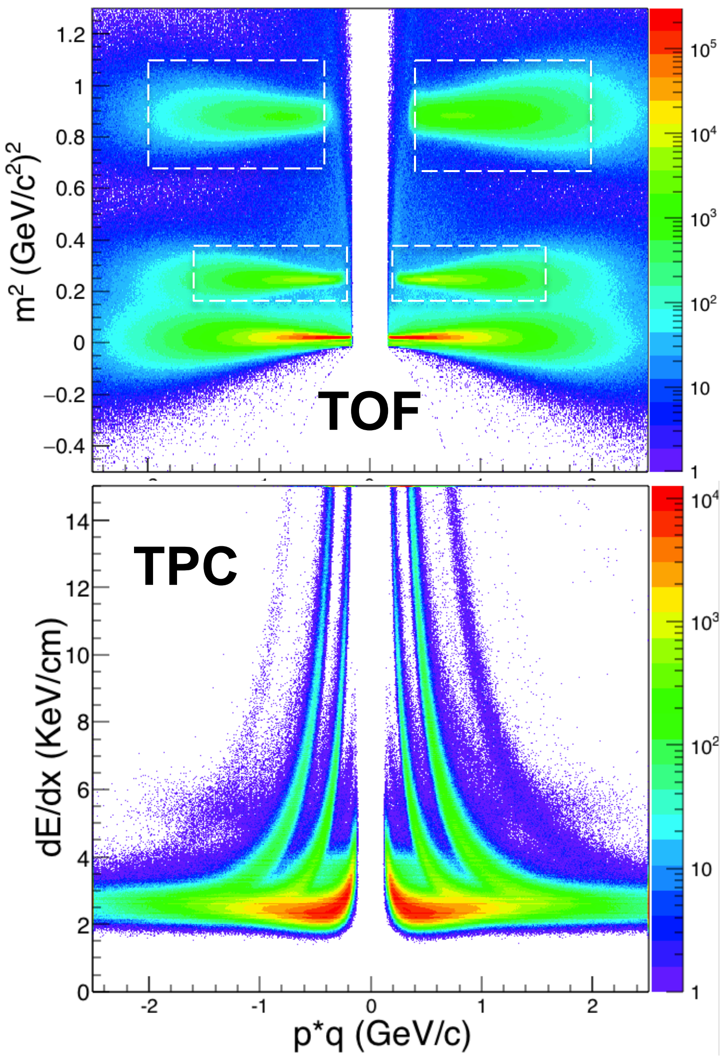
$\sqrt{s_{NN}}$ (GeV)	Events (10^6)	Year
200	350	2010
62.4	67	2010
39	39	2010
27	70	2011
19.6	36	2011
14.5	20	2014
11.5	12	2010
7.7	4	2010



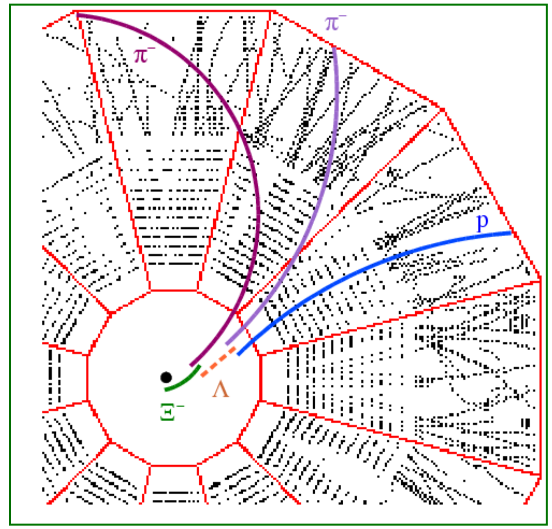
1) Largest data sets versus collision energy
2) STAR: Large and homogeneous acceptance, excellent particle identification capabilities. Especially important for fluctuation analysis

Collectivity **Criticality** **Chirality**

Particle Identifications



Charged hadrons

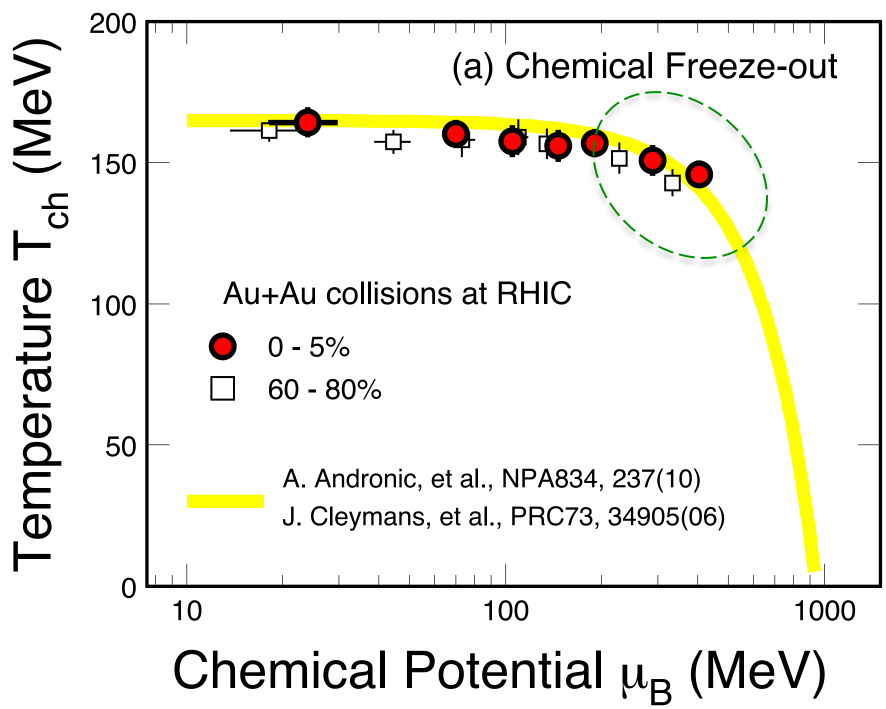


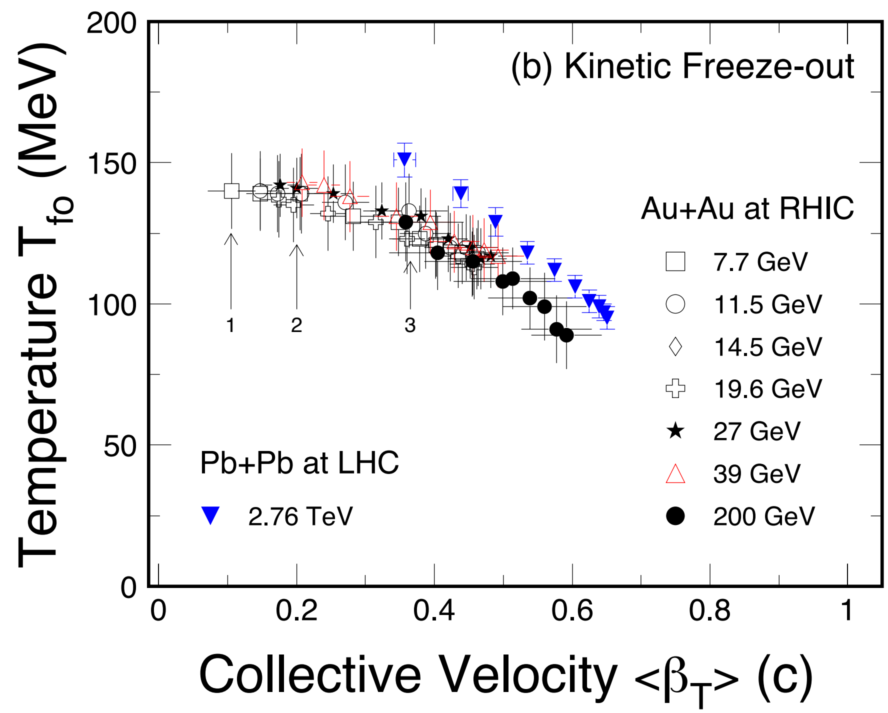
Hyperons & Hyper-nuclei

Hadron Acceptances at STAR:

particle	p_T (GeV/c)	y
$h^{\pm}$	$0.2 \le p_T \le 2.0$	$\lvert\eta\rvert \le 0.9$
protons	$0.4 \le p_T \le 2.0$	$\lvert y\rvert \le 0.5$
Kaons	$0.4 \le p_T \le 1.6$	$\lvert y\rvert \le 0.5$
pions	$0.2 \le p_T \le 1.6$	$\lvert y\rvert \le 0.5$
Λ	$0.5 \le p_T \le 5.0$	$\lvert y\rvert \le 1.0$
K_S	$0.2 \le p_T \le 2.0$	$\lvert y\rvert \le 1.0$

Bulk Properties at Freeze-out





Chemical Freeze-out:

(STAR covers: 20 < μ_B < 420 MeV)

- Weak temperature dependence
- Centrality dependence μ_B!

Kinetic Freeze-out:

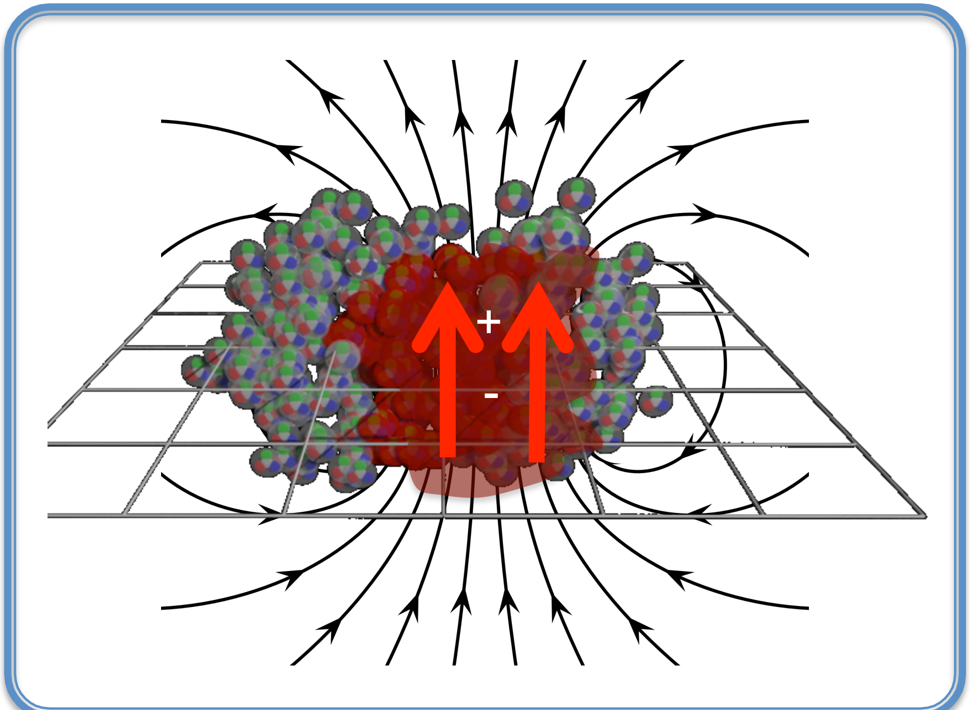
- Central collisions => lower value of T_{fo} and larger collectivity β_T
- Stronger collectivity at higher energy, even for peripheral collisions

ALICE: B.Abelev et al., PRL109, 252301(12); PRC88, 044910(2013).
STAR: J. Adams, et al., NPA757, 102(05); X.L. Zhu, NPA931, c1098(14); L. Kumar, NPA931, c1114(14)

Measurement: CME

Observable: The γ - Correlator

$$\gamma = \left\langle \cos\left(\phi_\alpha + \phi_\beta - 2\psi_{EP}\right)\right\rangle = \left[\left\langle v_{1,\alpha} v_{1,\beta}\right\rangle + b_{in}\right] - \left[\left\langle a_\alpha a_\beta \right\rangle + b_{out}\right]$$



Same for SS and OS pairs. Removed in Δγ

Sensitive to the separation signal

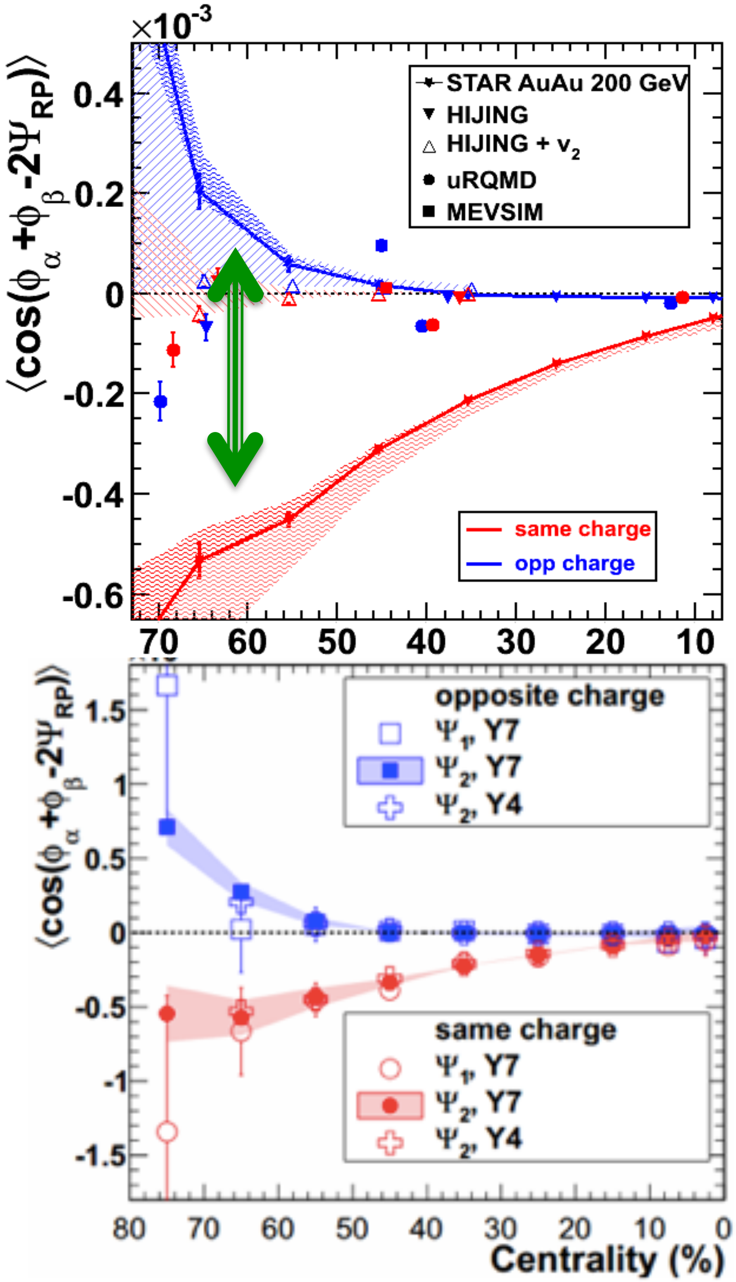
$$\gamma_{SS} = \left\langle \cos\left(\phi_\pm + \phi_\pm - 2\psi_{EP}\right)\right\rangle$$

$$\gamma_{OS} = \left\langle \cos\left(\phi_\pm + \phi_\mp - 2\psi_{EP}\right)\right\rangle$$

$$\Delta\gamma = \gamma_{OS} - \gamma_{SS}$$

S. Voloshin, Physical Review **C70** (2004) 057901

Charge Separation (CME)



1) At 200 GeV, OS&SS charged-hadron-pairs separation at non-central collisions

2) At peripheral collisions, OS pairs larger than 0: effects of flow, energy loss,…

3) Model calculations: HIJING(v_2) and UrQMD do not show the observed separation. Note: no event-plane reconstruction, as in data, in the model analysis.

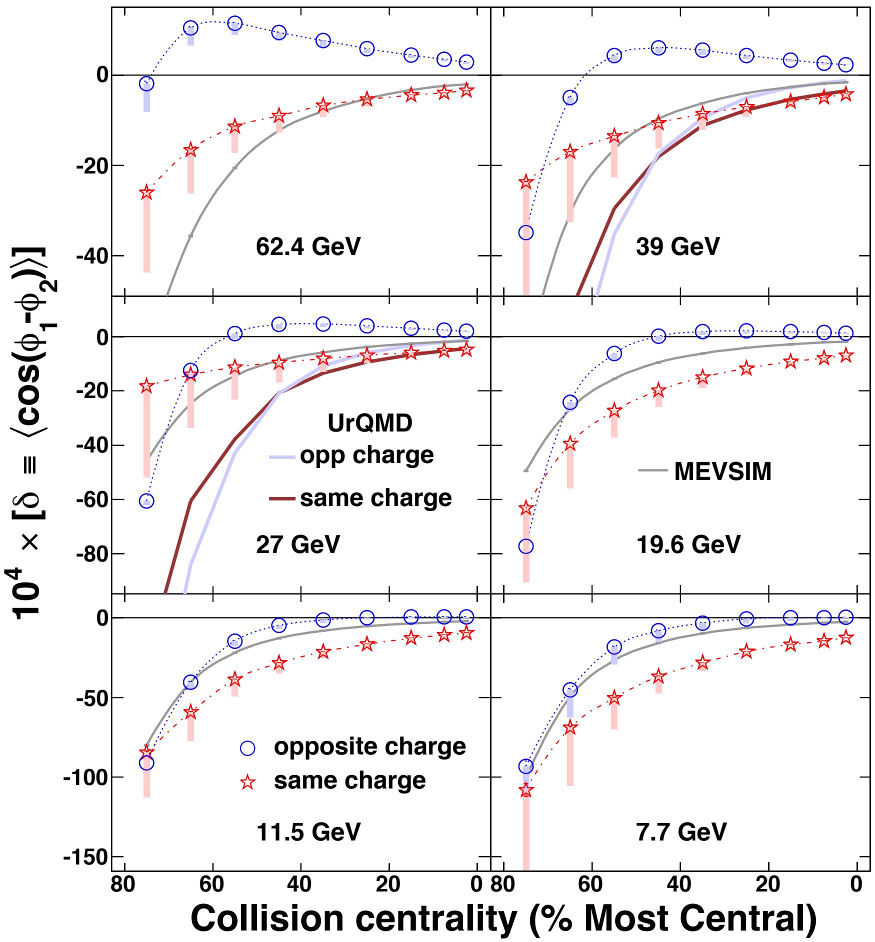
STAR: ***PRL103***, *251601(09); PRC**88**, 64911(13)*

D. Kharzeev, **PLB633**, 260 (06)

D. Kharzeev, et al. **NPA803**, 227(08)

D. E. Kharzeev, J. Liao, S. A. Voloshin and G. Wang, Prog. Part. Nucl. Phys. 88, 1(2016)

Background



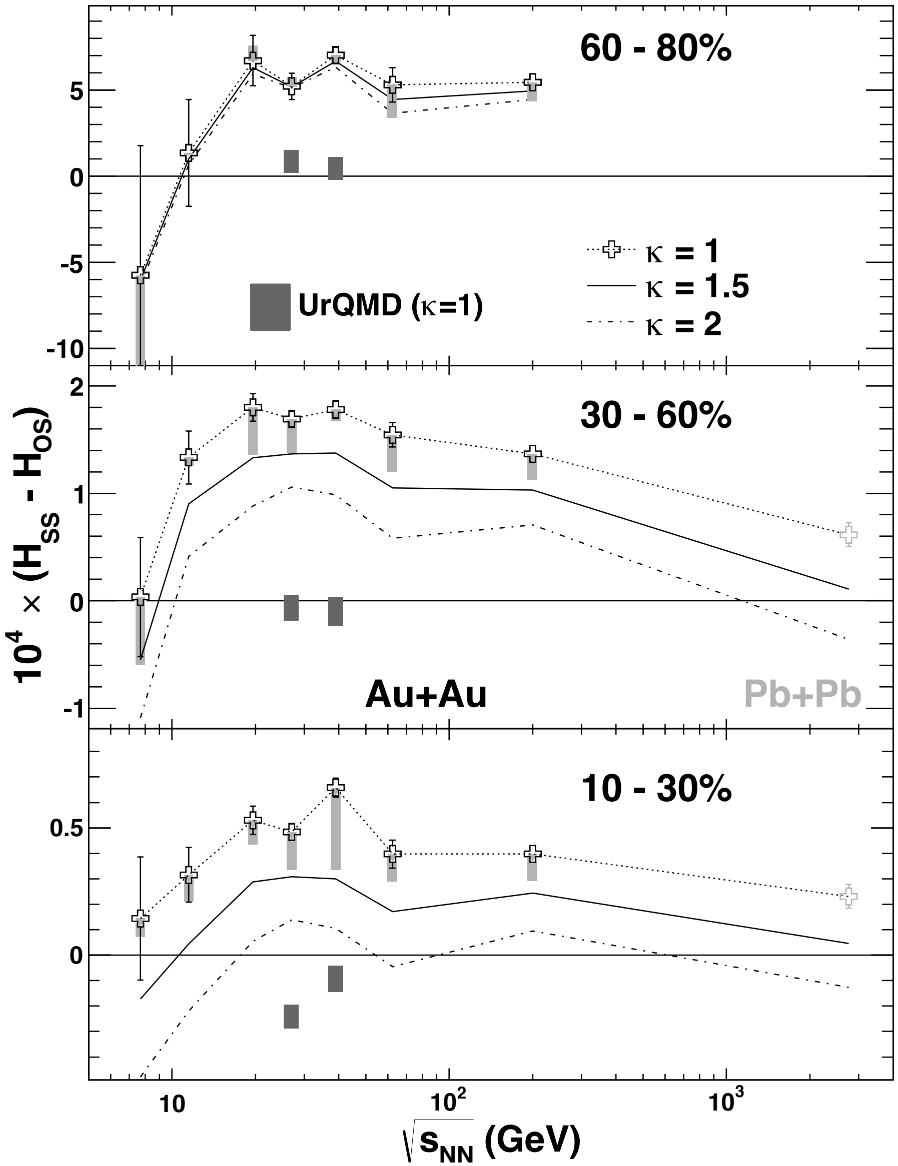
1) Two particle correlation, flow, contribute to the possible CME signal:

$$\delta = \left\langle \cos\left(\phi_\alpha - \phi_\beta\right)\right\rangle$$

2) $\delta_{OS} > \delta_{SS}$ strong charge conservation + flow contributions!

STAR: ***PRL103****, 251601(09);* ***PRL113****, 052302(14)*
D. Kharzeev, **PLB633**, 260 (06)
D. Kharzeev, et al. **NPA803**, 227(08)

Case I: Background Subtraction



Energy Dependence:

1) H-function removes the flow contributions:

$$H^{\kappa} = \frac{\kappa v_2 \delta - \gamma}{1 + \kappa v_2}$$

κ model dependent

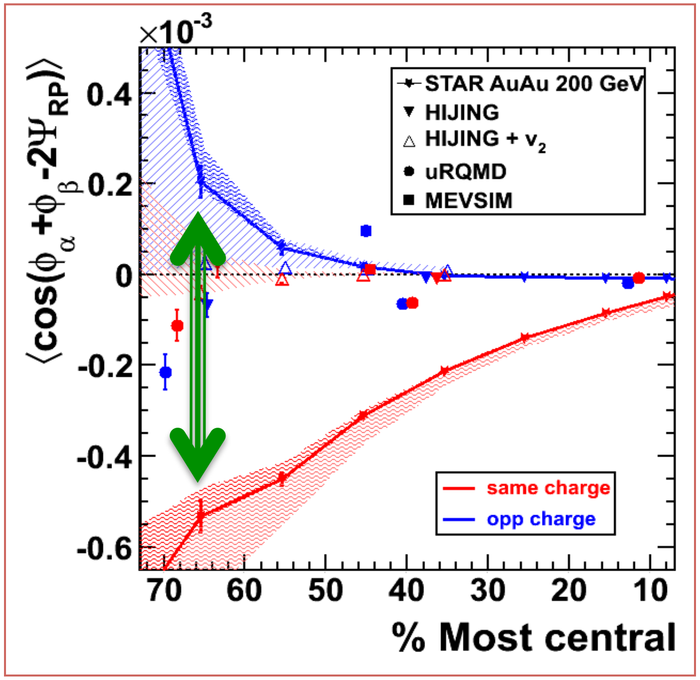
2) UrQMD model does not show the observed separation

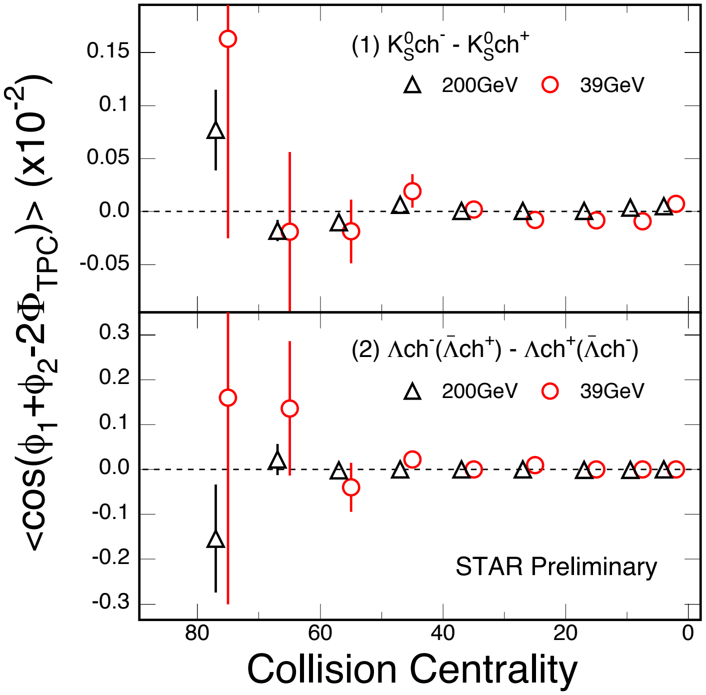
3) At low energy, no chiral symmetry restoration so any CME effect would vanish.

➔ hadronic interactions become dominant at $\sqrt{s_{NN}} \leq 11.5$ GeV

STAR: ***PRL103***, *251601(09);* ***PRL113***, *052302(14)*
ALICE: ***PRL110***, *012301(13)*
A. Bzdak, V. Koch and J.F. Liao, Lect. Notes Phys. ***871***, 503(13)

Charge Separation (**CME**)

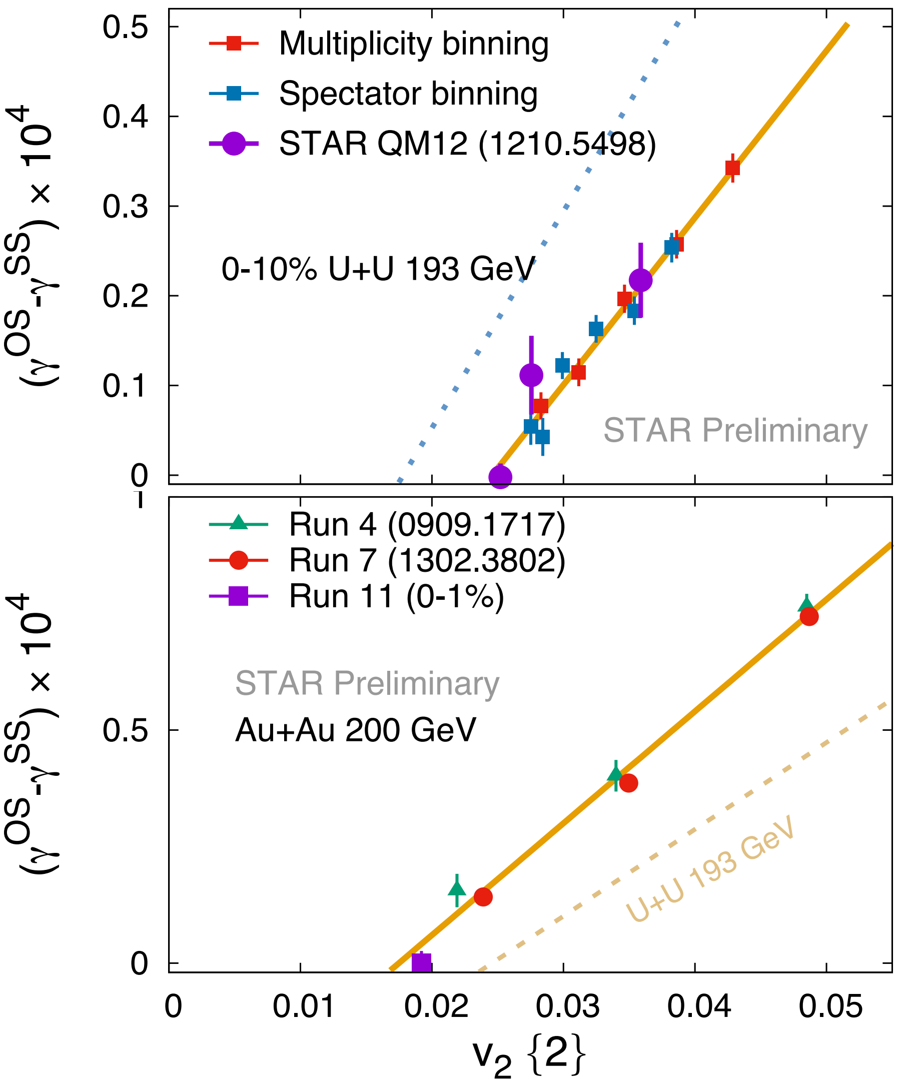


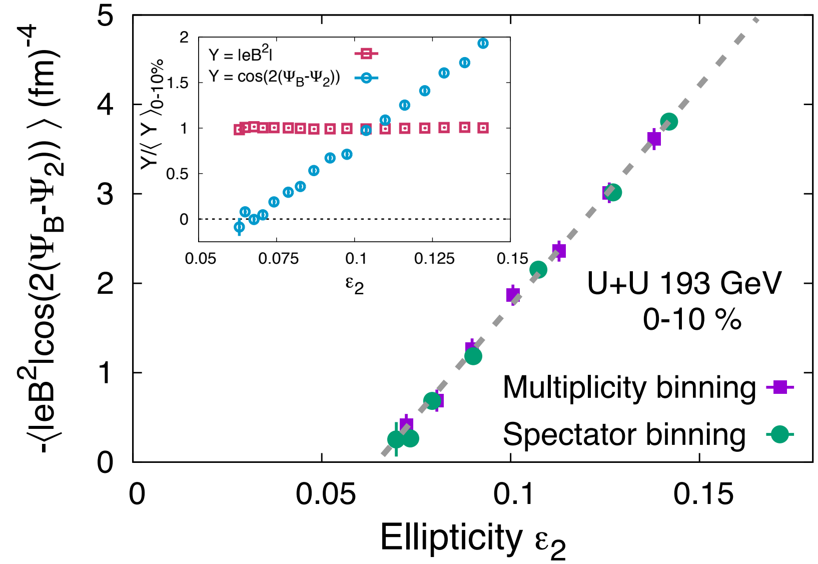


1) CME should disappear with neutral hadrons. Data of Ks-h and Λ-h show no effects.
2) Flow related background under study

STAR: ***PRL103**, 251601(09);* ***PRL113**, 052302(14); Q.Y. Shou, talk at QM2014*
D. Kharzeev, **PLB633**, 260 (06)
D. Kharzeev, et al. **NPA803**, 227(08)

Ultra-central Au+Au and U+U Collisions

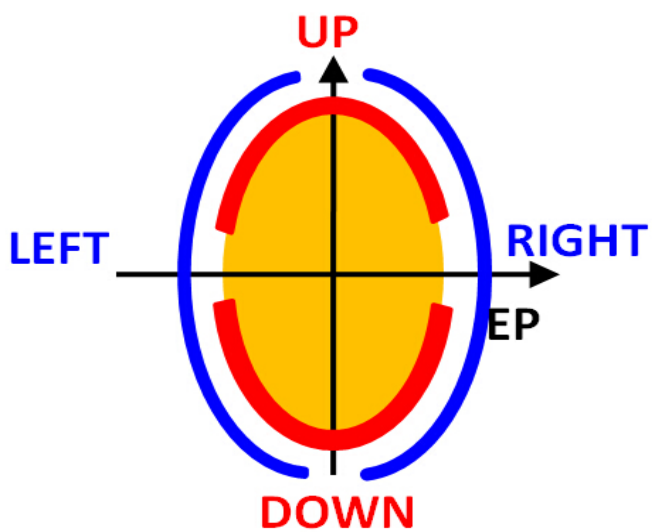




In ultra-central collisions, both in Au+Au and U+U, **Δϒ = 0 at finite value of v_2**

P. Tribedy, "Chirality Workshop", UCLA, 2016
Chatterjee, Tribedy, PR**C92** (2015), 011902

Case II: Background Subtraction



$$A_{\pm,UD} = \frac{N_{\pm,up} - N_{\pm,down}}{N_{\pm,up} + N_{\pm,down}}$$

$$A_{\pm,LR} = \frac{N_{\pm,left} - N_{\pm,right}}{N_{\pm,left} + N_{\pm,right}}$$

Dynamical Variance:

$$\delta\langle A_{UD}^2\rangle = \left(\delta\langle A_{+,UD}^2\rangle + \delta\langle A_{-,UD}^2\rangle\right)/2$$

$$\delta\langle A_{LR}^2\rangle = \left(\delta\langle A_{+,LR}^2\rangle + \delta\langle A_{-,LR}^2\rangle\right)/2$$

Covariance:

$$\delta\langle A_+A_-\rangle_{UD} = \langle A_+A_-\rangle_{UD} - \langle A_+A_-\rangle_{UD,mix}$$

$$\delta\langle A_+A_-\rangle_{LR} = \langle A_+A_-\rangle_{LR} - \langle A_+A_-\rangle_{LR,mix}$$

$$\Delta\langle A^2\rangle = \delta\langle A_{UD}^2\rangle - \delta\langle A_{LR}^2\rangle$$

$$\Delta\langle A_+A_-\rangle = \delta\langle A_+A_-\rangle_{UD} - \delta\langle A_+A_-\rangle_{LR}$$

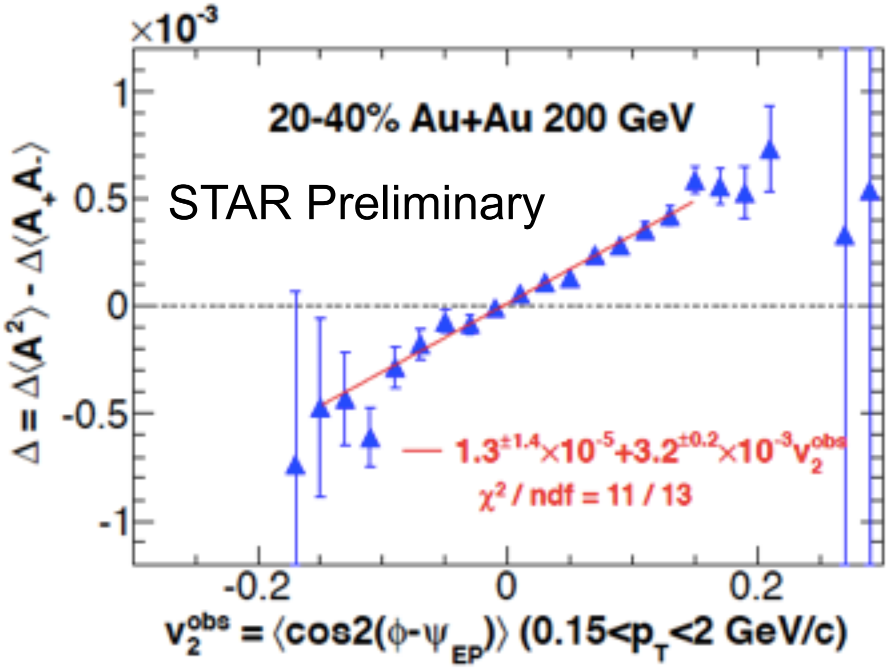
Charge separation:

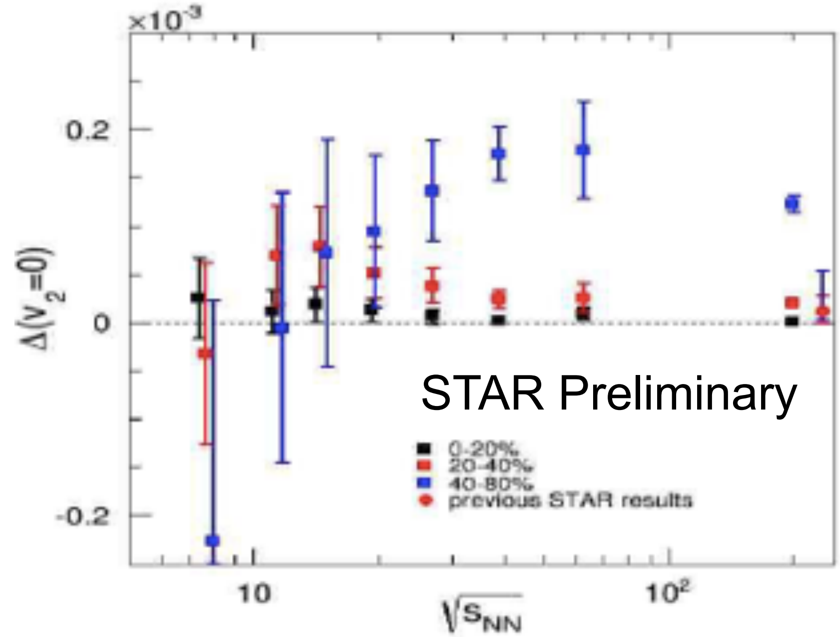
$$\Delta = \Delta\langle A^2\rangle - \Delta\langle A_+A_-\rangle$$

$\Delta > 0$ implies charge separation, if associated backgrounds are understood.

Bzdak, Koch and Liao, PR**C81**, 031901(10)
F. Wang, PR**C81**, 064002(10)

Background Subtraction III (Event shape)

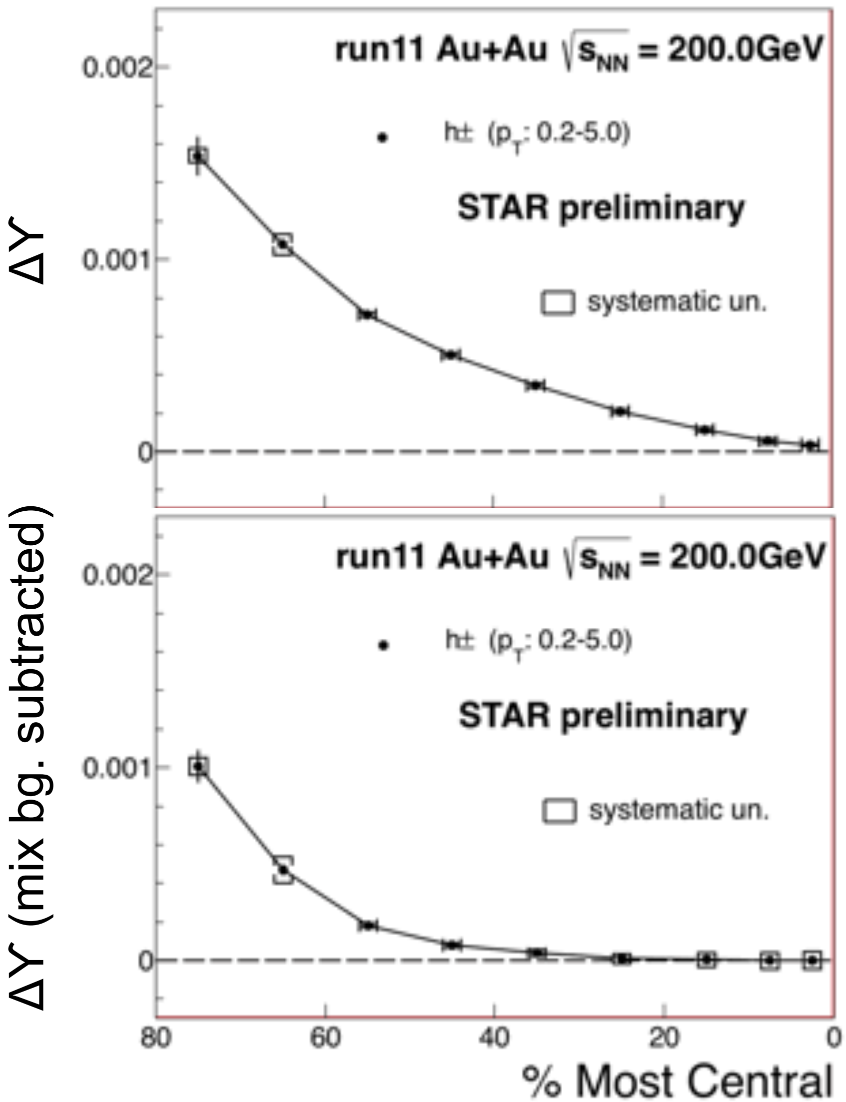


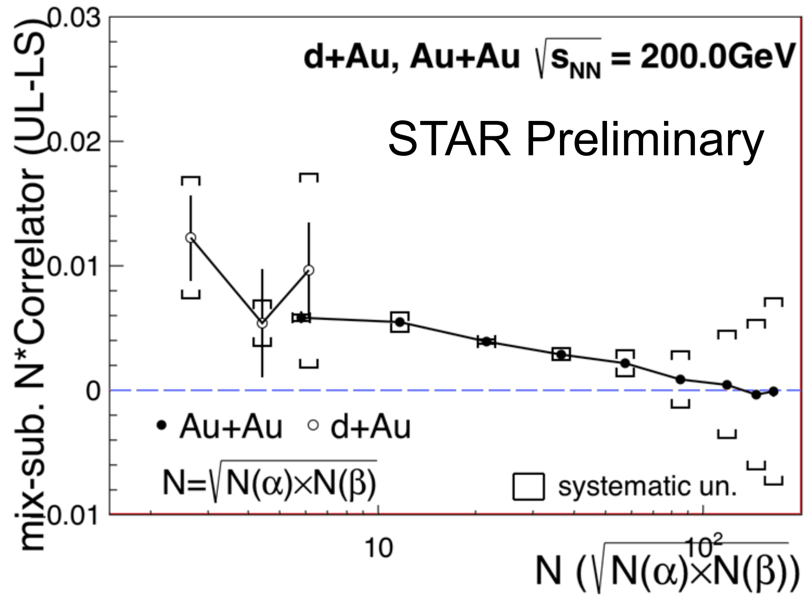


1) At $<v_2^{obs}> = 0$, finite strength of separation Δ observed!
2) Caveats: (i) not all flow related bg. removed, i.g. resonance decays. (ii) Event-plane resolution corrections*

E. Wen, L. Wen, G. Wang, arXiv: 1608.03205

Subtraction II (mixed-event)

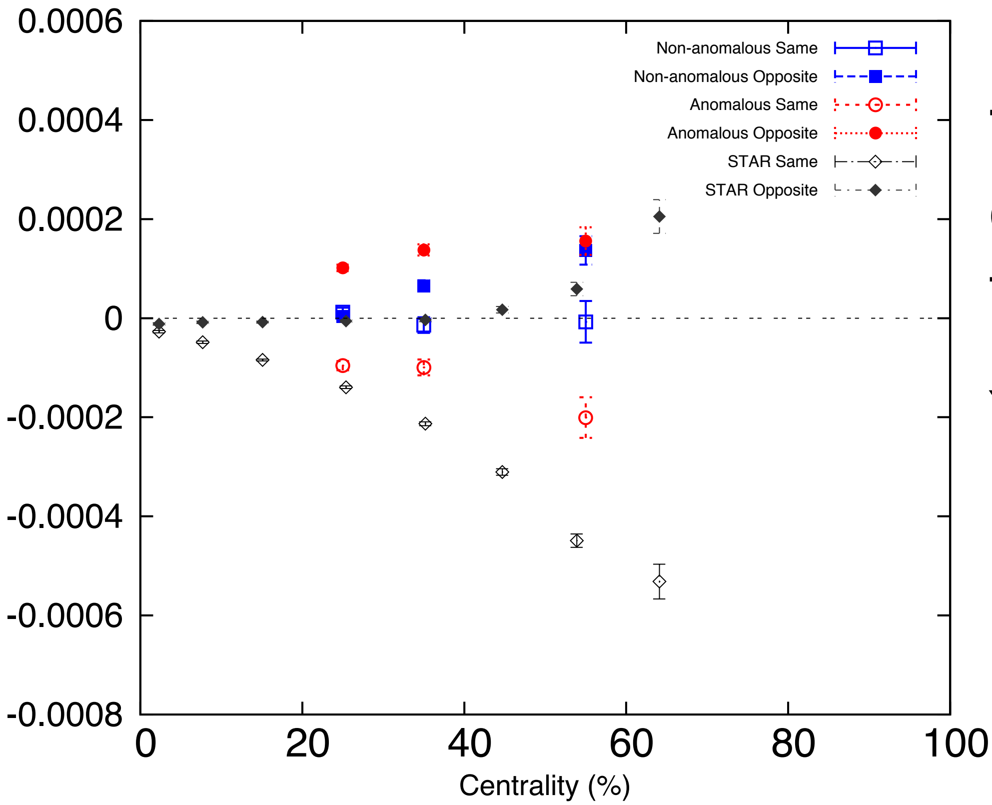




1) Mixed-event subtraction method. *Not all flow related bg. subtracted.*
2) Centrality dependence similar to previous approach in 200GeV Au+Au collisions
3) 200GeV **d+Au results fit to the multiplicity trend.** High statistics data for d+Au and p+Au are coming

F. Wang and J. Zhao, 1608.06610
STAR: ISMD2016

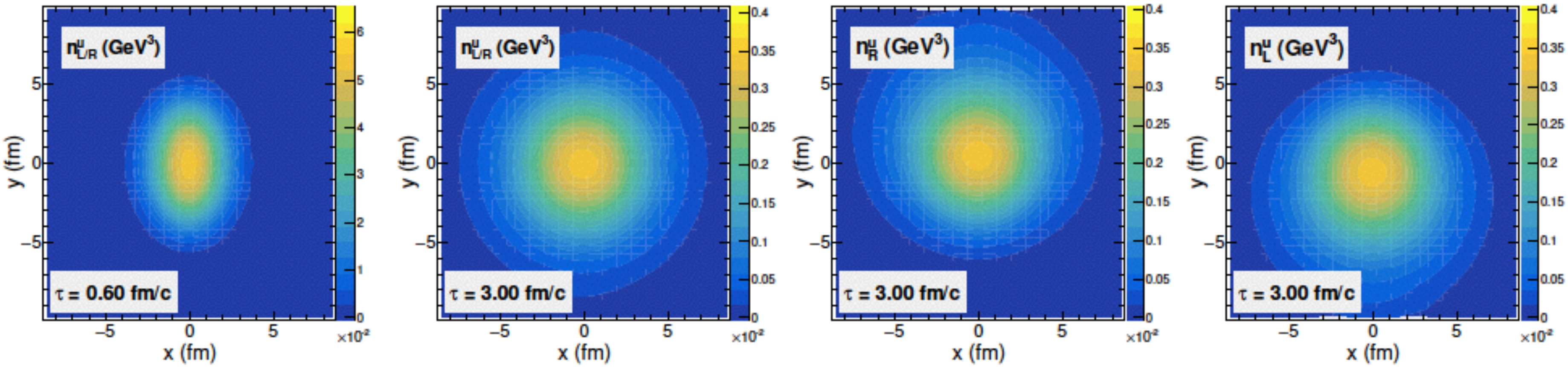
The chiral magnetic effect in heavy-ion collisions from event-by-event anomalous hydrodynamics

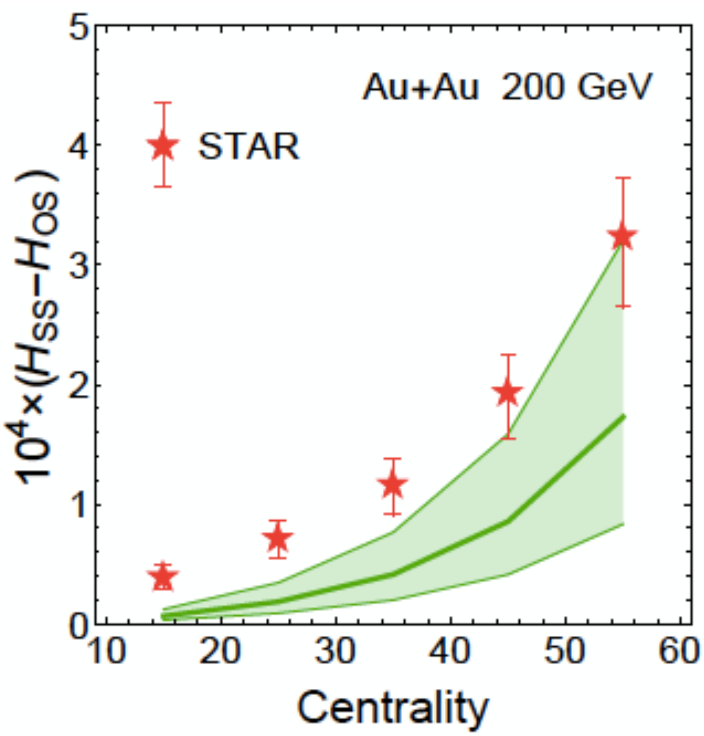


The magneto-hydrodynamic calculations predicted the trend qualitatively

Y. Hirono, T. Hirano, D. Kharzeev, 1412.0311

Quantitative CME from Anomalous-Viscous Fluid Dynamics





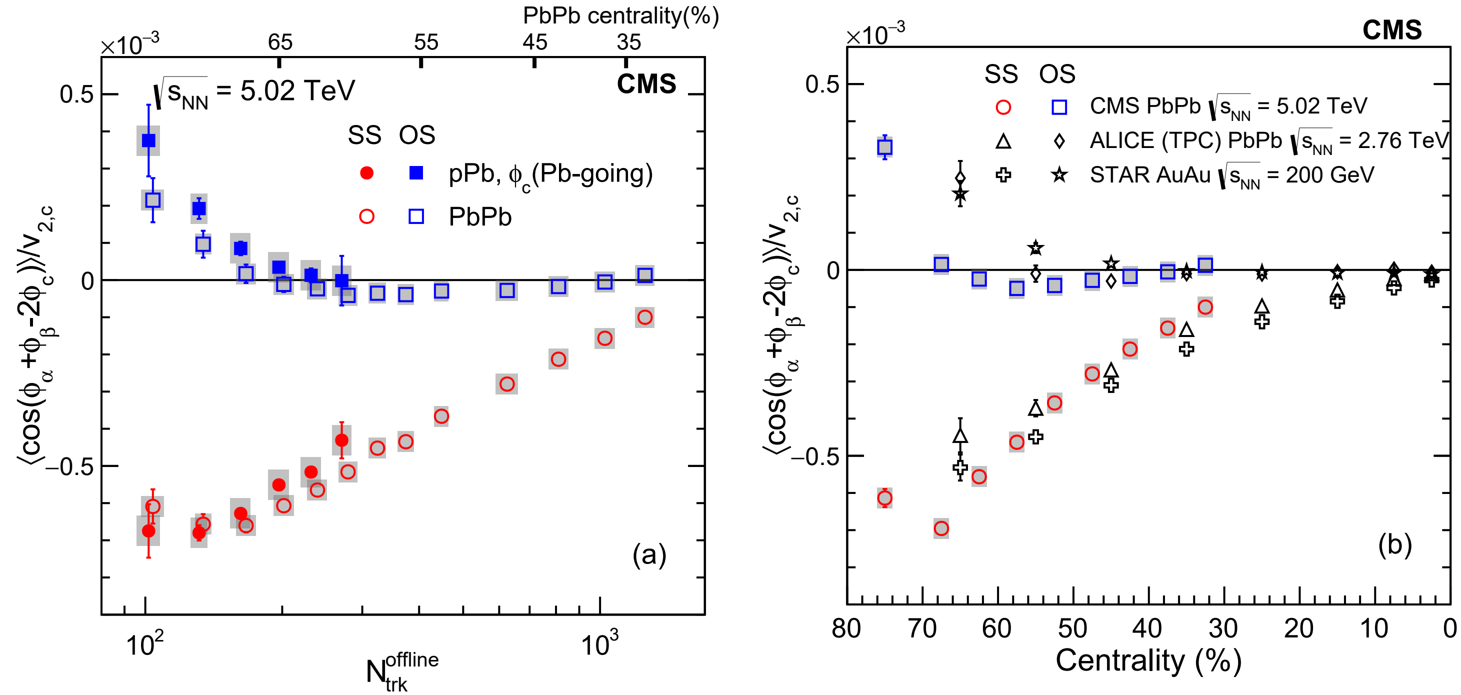
1)"With realistic initial axial charge density and short magnetic lifetime, data could be described"

2) Predictions for strangeness

3) In light of CMS results, more discussions needed

Jinfeng Liao's Talk

CMS CME Results arXiv: 1610.00263



1) $\sqrt{s_{NN}}$ = 5.02 TeV Pb+Pb and p+Pb collisions

2) Charged hadrons, $|\eta|<2.4$, $0.2 < p_T < 3$ GeV/c

3) For event-plane determination, hadrons are from $4.4 < |\eta| < 5.0$

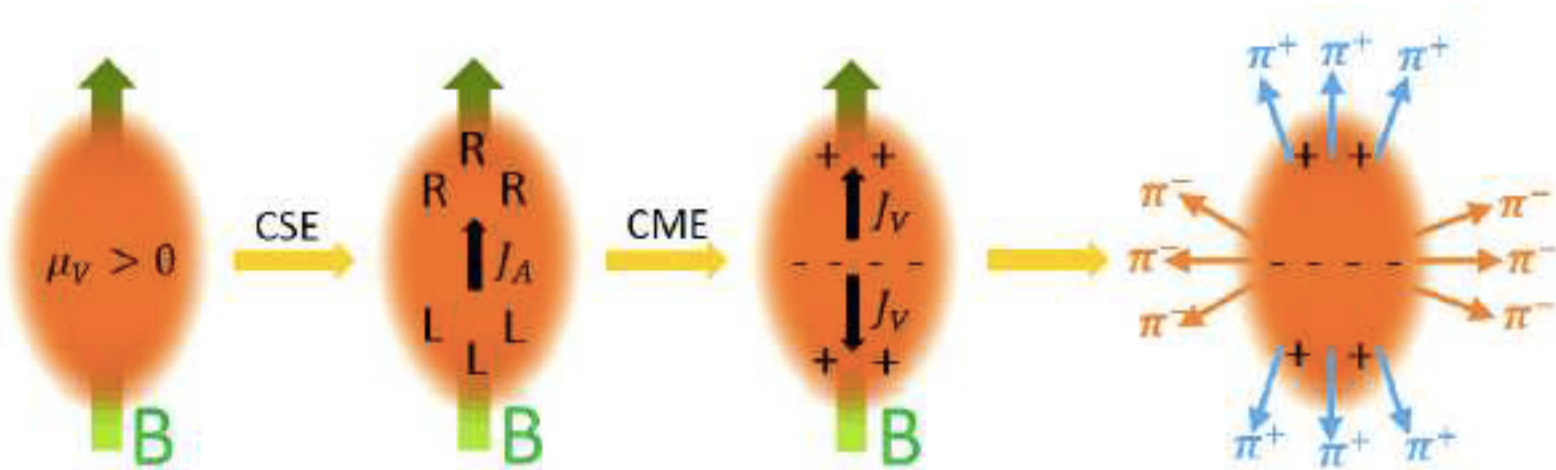
4) Similar centrality dependence of p+Pb and Pb+Pb data at LHC

5) No clear energy dependence from RHIC to LHC

Measurement: CMW

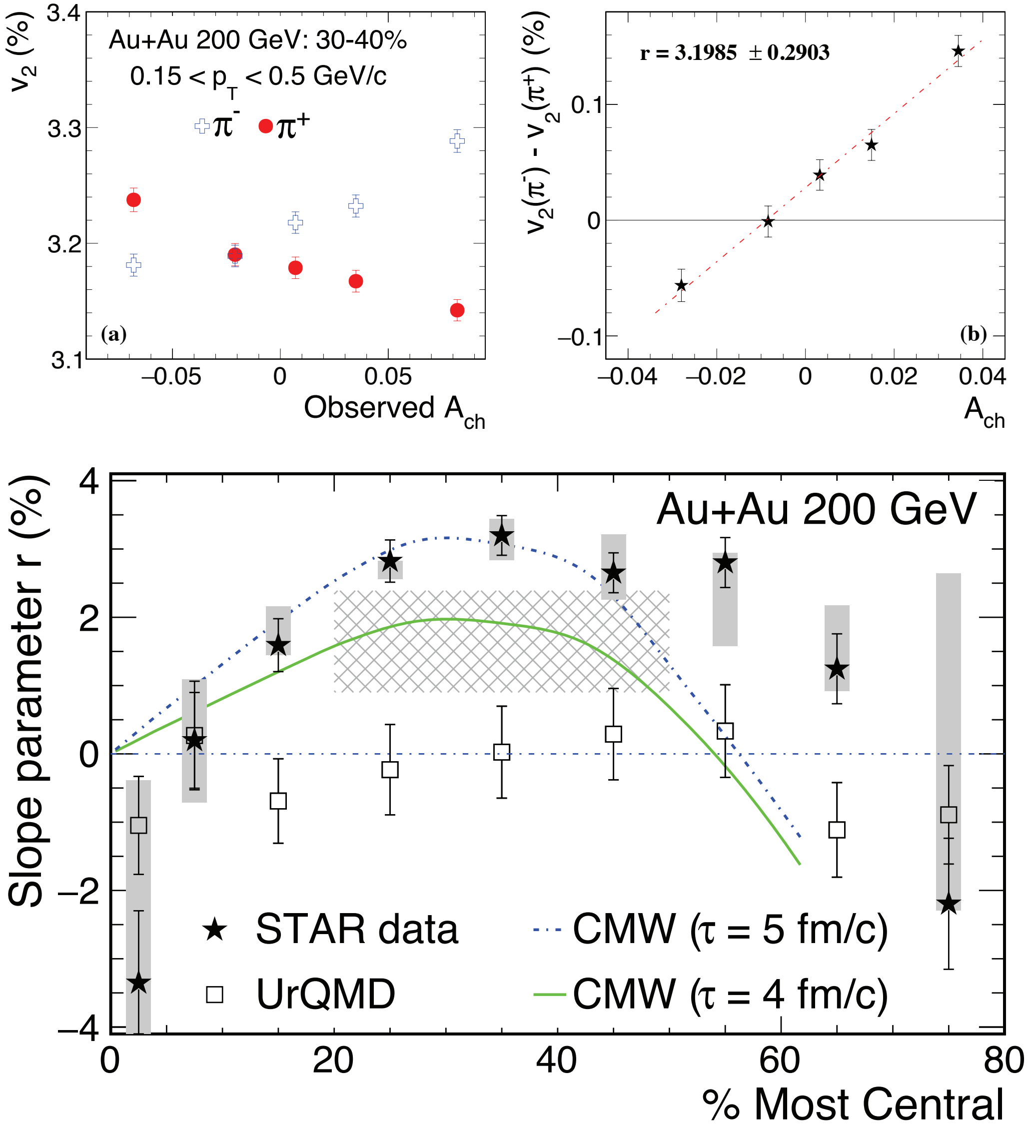
D. E. Kharzeev, J. Liao, S. A. Voloshin and G. Wang, Prog. Part. Nucl. Phys. **88**, 1(2016).

Chiral Magnetic Wave (CMW)



Y. Bumier, D.E. Kharzeev, J. Liao, H.-U. Yee, PRL, **107**, 052303(2011)
D. E. Kharzeev, J. Liao, S. A. Voloshin and G. Wang, Prog. Part. Nucl. Phys. **88**, 1(2016).

Chiral Magnetic Wave (CMW)

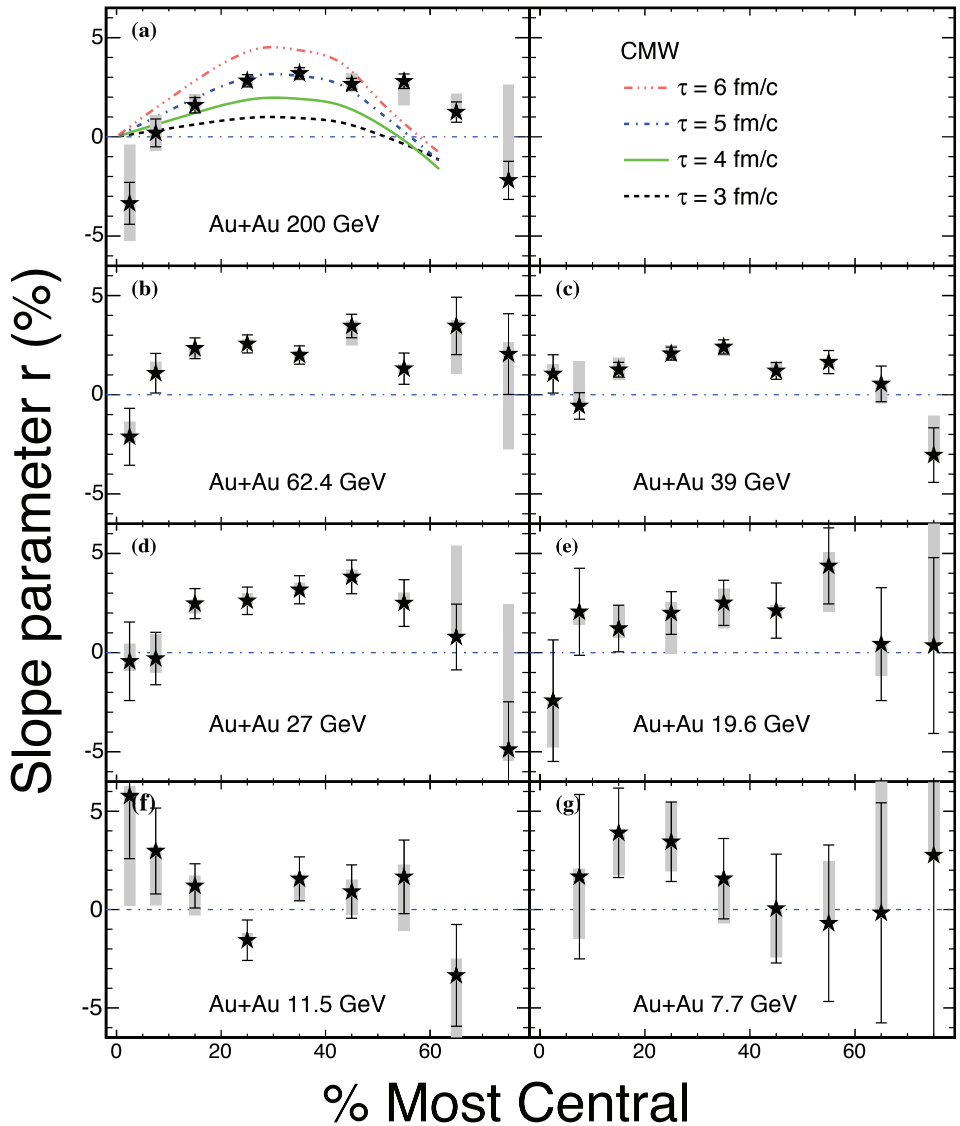


200GeV Au+Au collisions

1) CMW signal: the slope of the pion Δv_2 as a function of the charged multiplicity
2) The centrality dependence of the slopes observed. Model estimates with CMW are consistent with data
3) UrQMD results are not consistent

- STAR: *PRL**114**, 252302(2015)*
- Bumier, Kharzeev, Liao, Yee, *PRL**107***, 052303(2011)
- Kharzeev, Liao, Voloshin and G. Wang, *Prog. Part. Nucl. Phys.* ***88***, 1(2016).

Chiral Magnetic Wave (CMW)

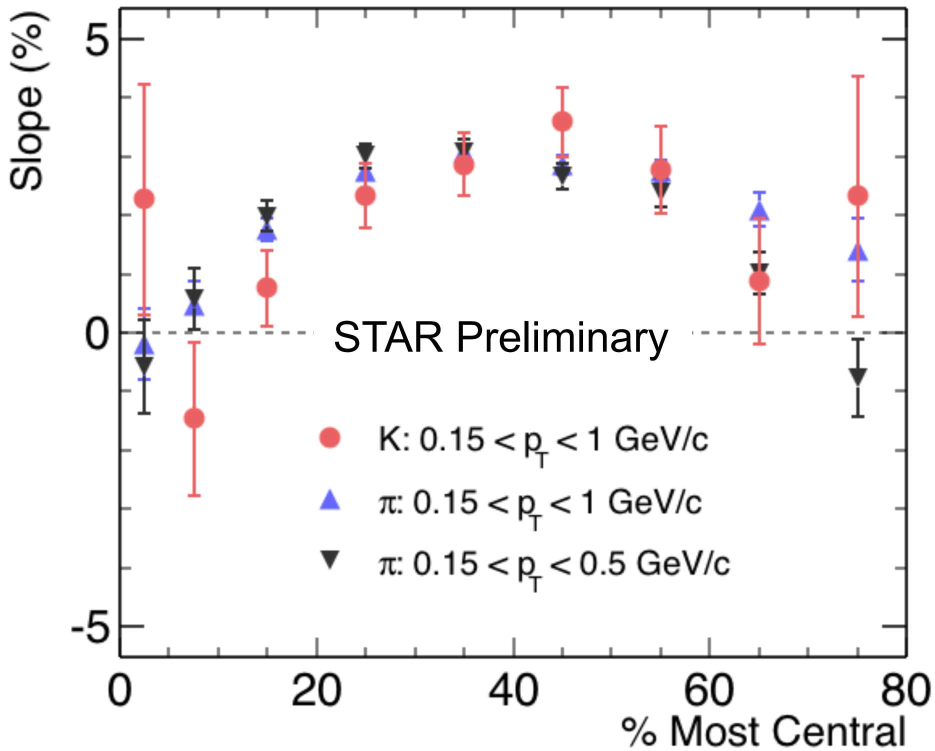


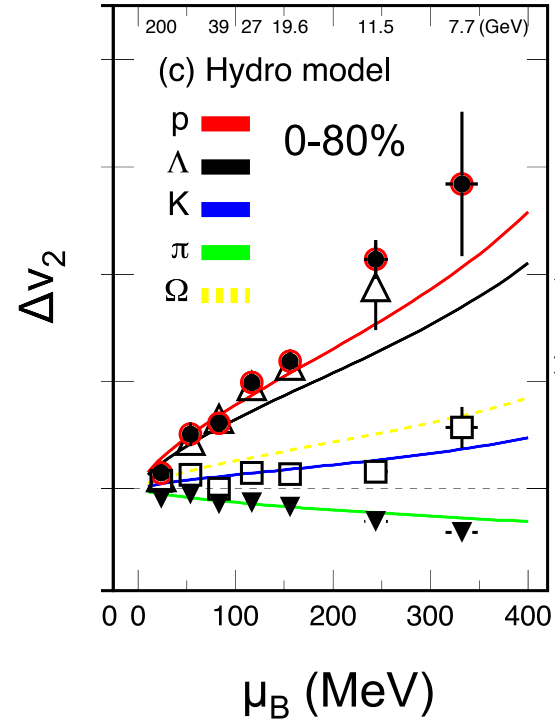
Collision energy dependence:

1) CMW signal: the slope of the pion Δv_2 as a function of the charged multiplicity
2) Large error bars in lower energy results, but consistent with 200GeV results
3) No model results explain the observation qualitatively

- STAR: *PRL**114**, 252302(2015)*
- Bumier, Kharzeev, Liao, Yee, *PRL**107***, 052303(2011)
- Kharzeev, Liao, Voloshin and G. Wang, *Prog. Part. Nucl. Phys.* ***88***, 1(2016).

200 GeV Au+Au Collisions Kaon Δv_2





1) Similar centrality dependence of the slope parameter r for pions. No strong p_T dependence for pions.
2) HMX-Hydro-model reproduced Δv_2 for pion and Kaon: Δv_2 proportional to viscosity η and chemical potential μ_B and the pion slope parameter r_π, **no need of CME!**
3) But, predicted an opposite sign for Kaon slope parameter $\mathbf{r_K \sim -\mu_B}$

Y. Hatta, A. Monnai and B.W. Xiao, NP***A974***, 155(16); PR***D92***, 114010(15)

Measurement: CVE

Global Alignment in AA Collisions at RHIC

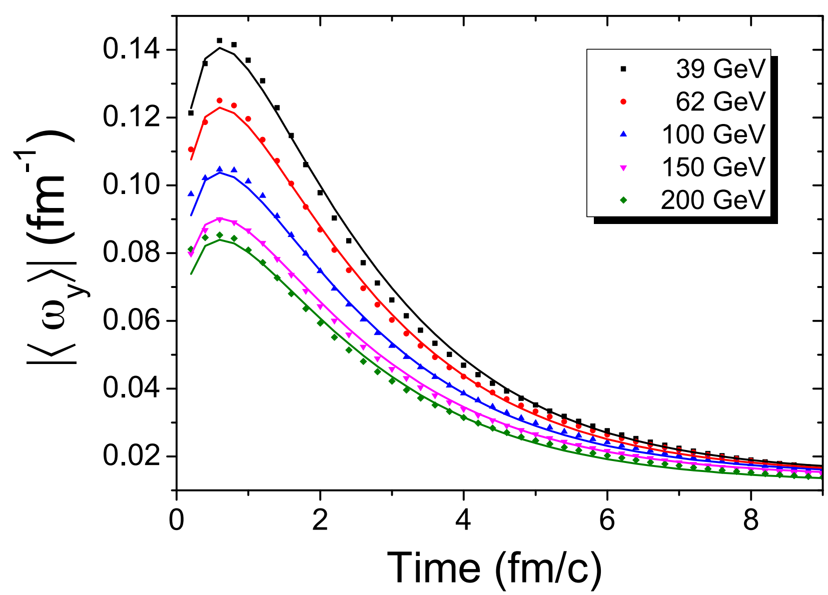
Isaac's Talk

1) Finite positive alignment with total angular momentum/ **Isaac Upsal's talk**
2) At lower energy, the effect is stronger ➔ larger vorticity at lower collision energy
3) New observable for studying underlying dynamics. Important for the search of CVE in high-energy nuclear collisions

Y. Jiang, Z.W. Lin, J.F. Liao, 1602.06580

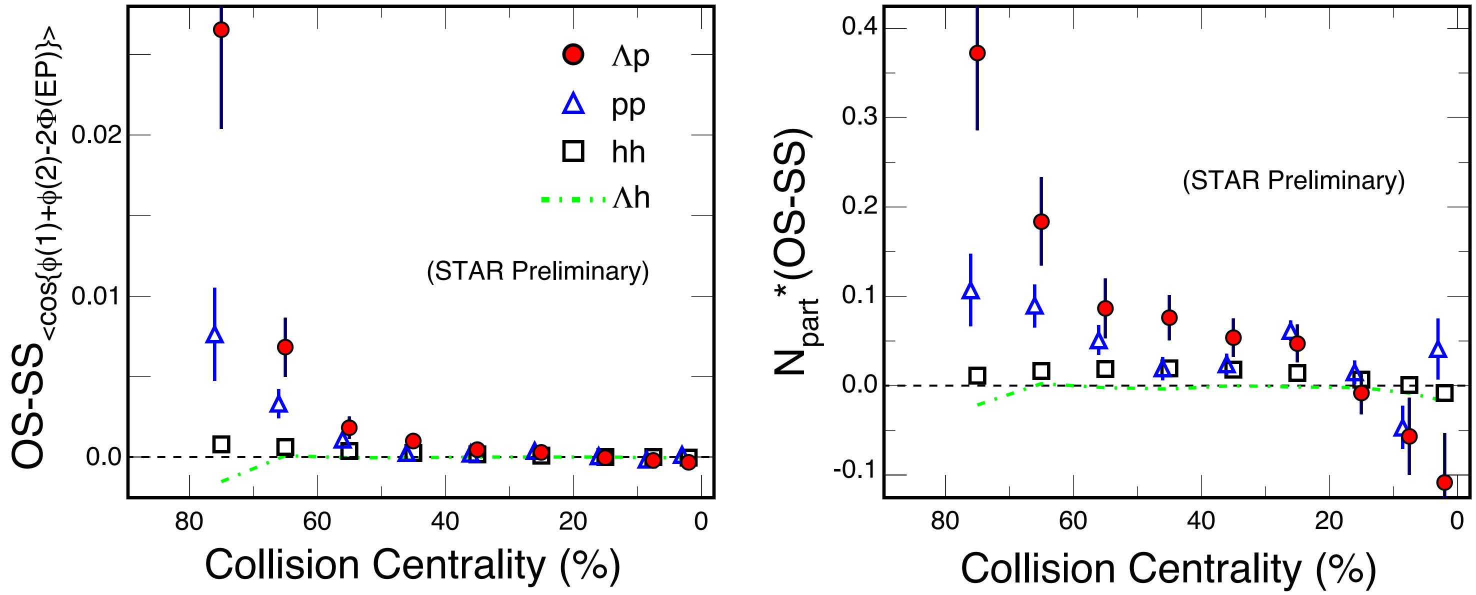
1) AMPT, Au+Au collisions, b = 7fm
2) Larger vorticity at lower collision energy
3) Mean lifetime:

tau_{ω} > tau_{Hydro} >> tau_B



Baryon-Charge Separation (CVE)

$\sqrt{s_{NN}}$ = 200GeV Au+Au Collisions



1) The values of $\Delta\gamma$, in pp and Λp, are non-zero, ***baryon charge separation***, as expected from the CVE

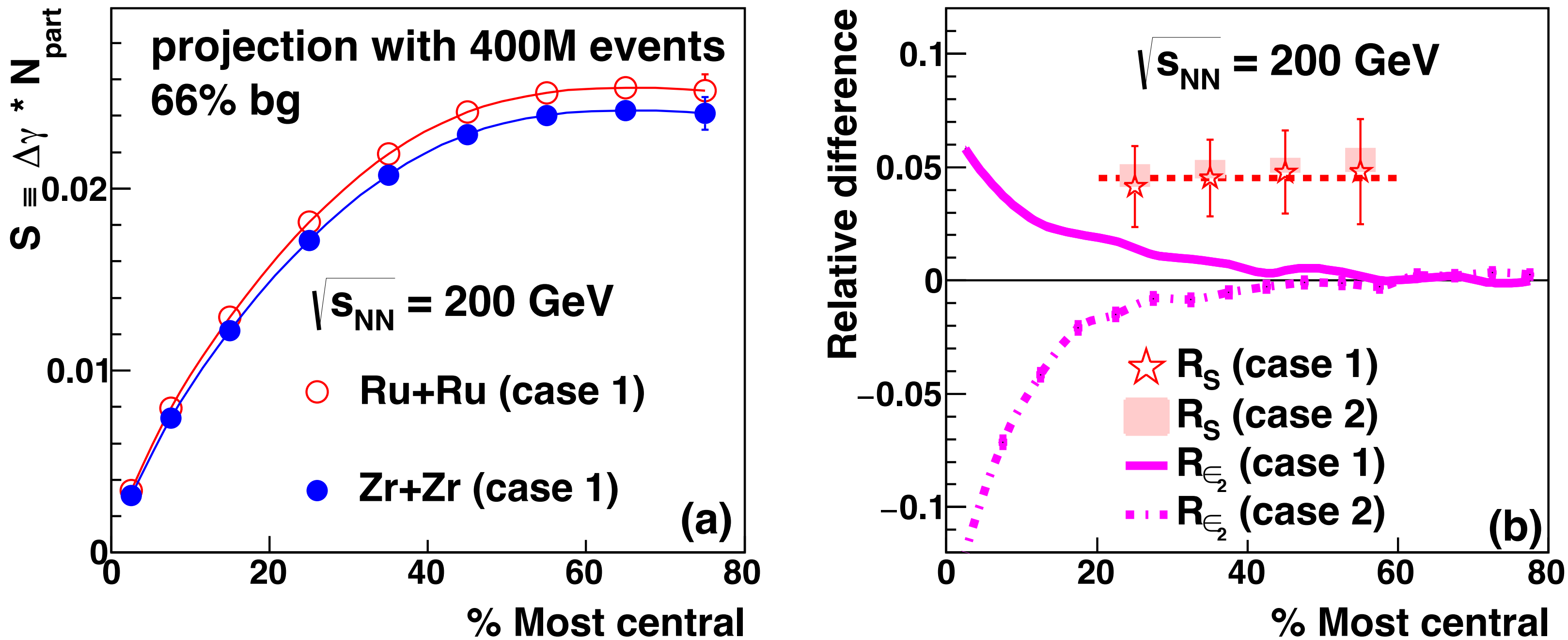
2) The Λh does not show any separation effect, consistent with CVE

3) Note: $\Delta\gamma(pp) < \Delta\gamma(\Lambda p)$???

STAR: F. Zhao, QM2014 Proceedings **NPA931**, 746(14) ; L.W. Wen, “Chiral Workshop”, UCLA, 2016
Kharzeev, Son, **PRL106**, 062301(11); Kharzeev. **PLB633**, 260 (06); Kharzeev, et al. **NPA803**, 227(08)

Future Measurements

2018: 200 GeV **Isobaric** Collisions



A=96	$_{44}$Ru + $_{44}$Ru vs. $_{40}$Zr + $_{40}$Zr
CME	>
CMW	>
CVE	= $\mu_e << \mu_B$
Flow	=

RHIC Run18 Plan: 200 GeV Collisions

- $_{44}$Ru+$_{44}$Ru, MB, 1.2B events
- $_{40}$Zr + $_{40}$Zr, MB, 1.2B events

ΔH(Ru)/ΔH(Zr) > 5σ (30-60%)

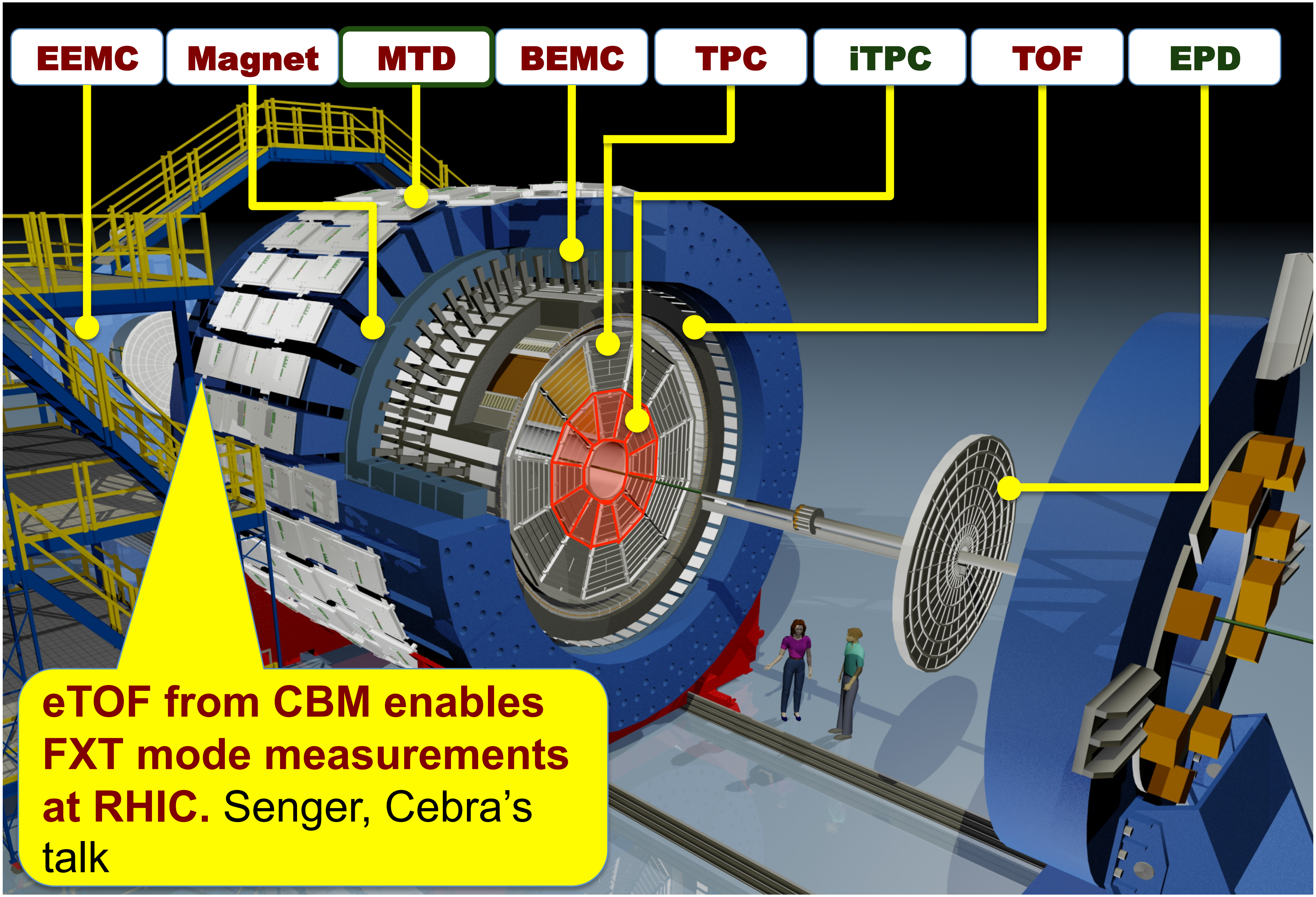
V. Sokokov et al., 1608.00982

2019-2020: BES II at RHIC

$\sqrt{s_{NN}}$ (GeV)	Events (10^6)	**BES II / BES I**	**Weeks**	μ_B (MeV)	T_{CH} (MeV)
200	350	2010		25	166
62.4	67	2010		73	165
39	39	2010		112	164
27	70	2011		156	162
19.6	**400** / 36	**2019-20** / 2011	**3**	206	160
14.5	**300** / 20	**2019-20** / 2014	**2.5**	264	156
11.5	**230** / 12	**2019-20** / 2010	**5**	315	152
9.2	**160** / 0.3	**2019-20** / 2008	**9.5**	355	140
7.7	**100** / 4	**2019-20** / 2010	**14**	420	140

Precision measurements that map the QCD phase diagram **$200 < \mu_B < 420$MeV**

STAR Detector System and BES-II



Summary

1) Both charged and identified hadron pairs, with the three-particle correlator Δγ, are used for the search of charge- and baryon-charge-separation.

2) Finite separation signals in h-h, (π-π, π-K), p-p, p-Λ pairs observed at mid-central Au+Au collisions.

3) Strong flow contributions to Δγ. More background studies are underway.

4) 2018: 200GeV isobaric collisions Ru vs. Zr: Ultimate answer!?

5) 2019-2020 BES-II: $7.7 \le \sqrt{s_{NN}} \le 19.6$ GeV ($420 \ge \mu_B \ge 200$ MeV). Factors of 10-20 more statistics:

Precision measurements