The 5th Workshop on Chirality, Vorticity and Magnetic Field in Heavy Ion Collisions

Status of experimental searches for the chiral magnetic effect

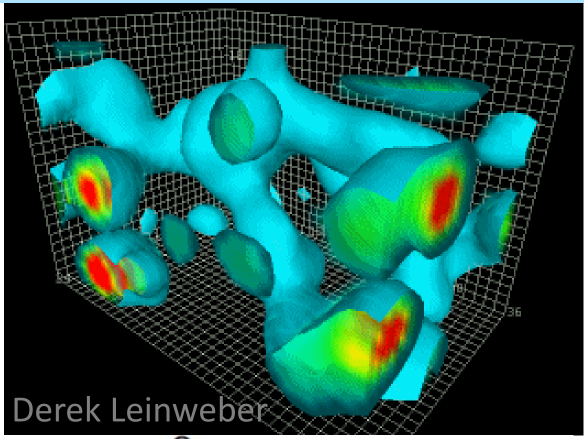
Fuqiang Wang（王福强）
Purdue University, Huzhou University

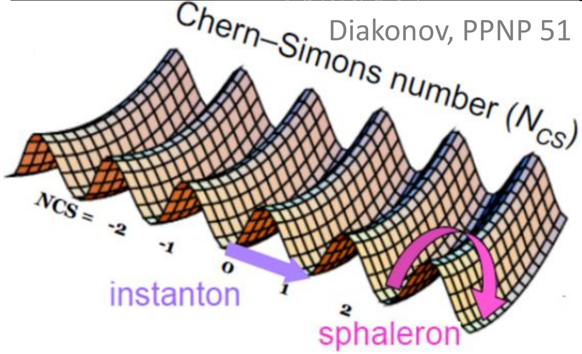
Outline

- Why is CME important?
- Background issue
- New progresses
- Summary

Why is CME important?

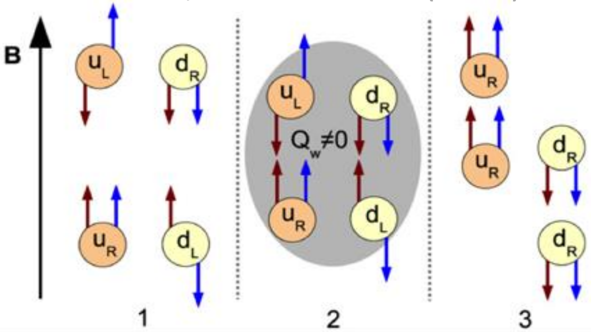
- **QCD vacuum fluctuations**
  - Non-zero topological charge gluon configuration
  - Chirality imbalance, quantum anomaly
  - Local P, CP violations
  - Strong CP problem, matter-antimatter asymmetry
- **Chira symmetry restoration**
  - Current quark degrees of freedom
- Strong magnetic field





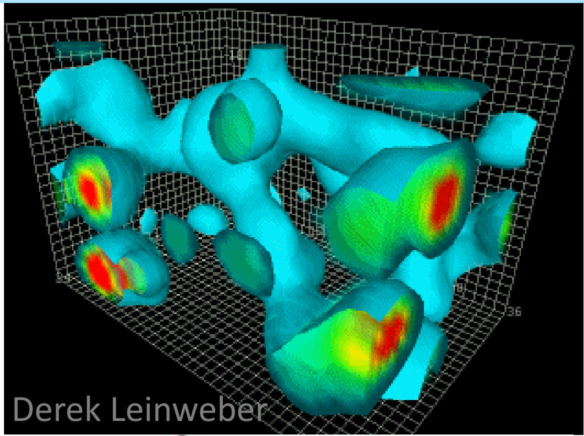
Diakonov, PPNP 51

Kharzeev, et al. NPA 803 (2008) 227

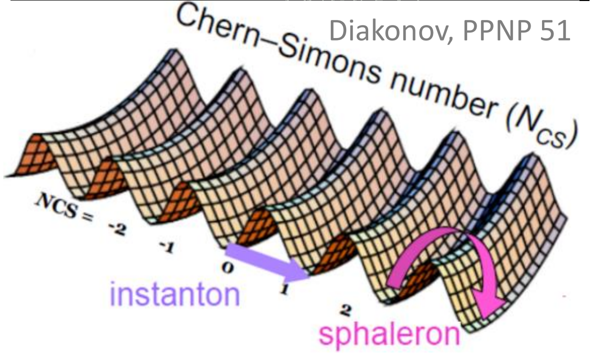


Why is CME important?

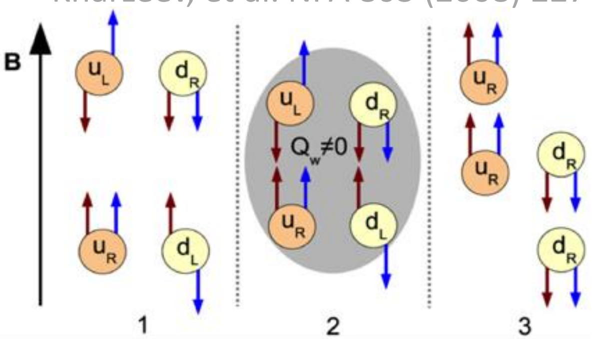
- **QCD vacuum fluctuations**
  - Non-zero topological charge gluon configuration
  - Chirality imbalance, quantum anomaly
  - Local P, CP violations
  - Strong CP problem, matter-antimatter asymmetry
- **Chira symmetry restoration**
  - Current quark degrees of freedom
- Strong magnetic field



Diakonov, PPNP 51



Kharzeev, et al. NPA 803 (2008) 227

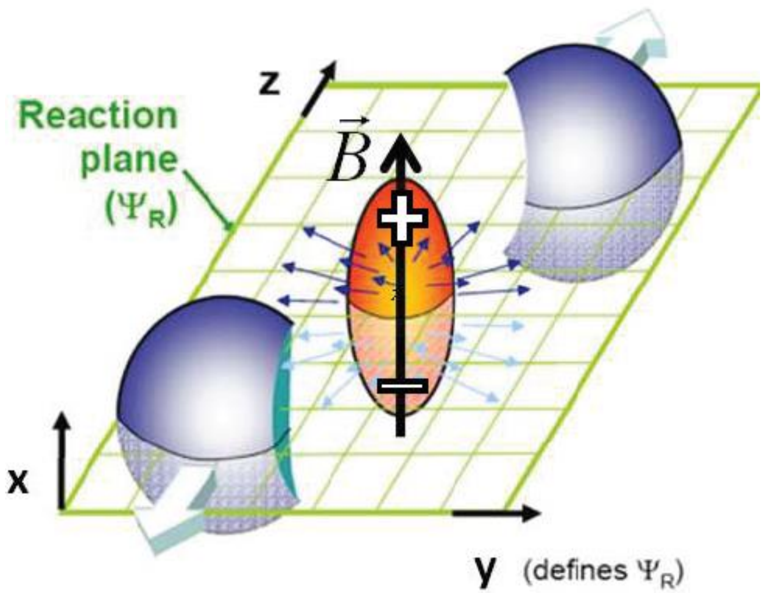


Message #1:

Extraordinary claims require extraordinary evidence.

Can you make your signal go away?

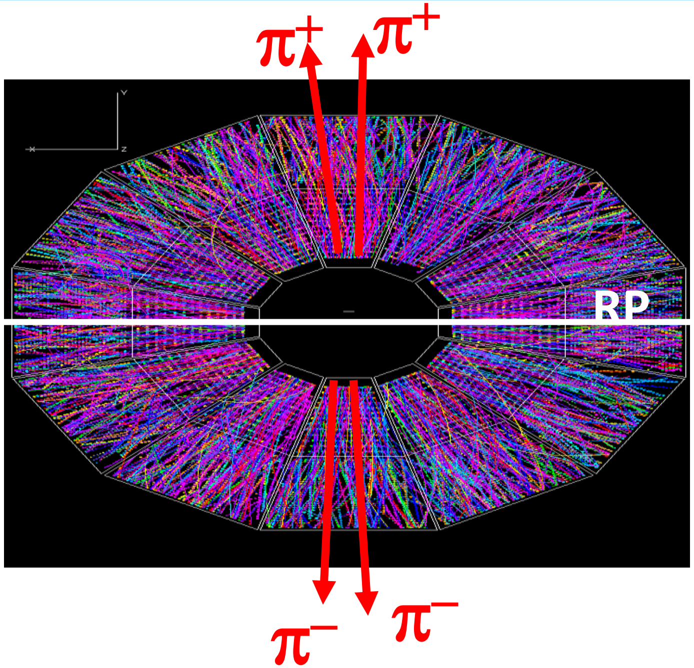
To measure CME: the γ observable

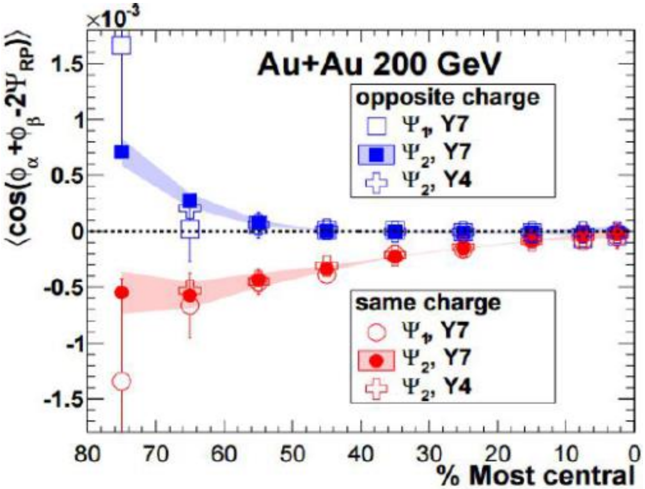


Voloshin, PRC 70 (2004) 057901

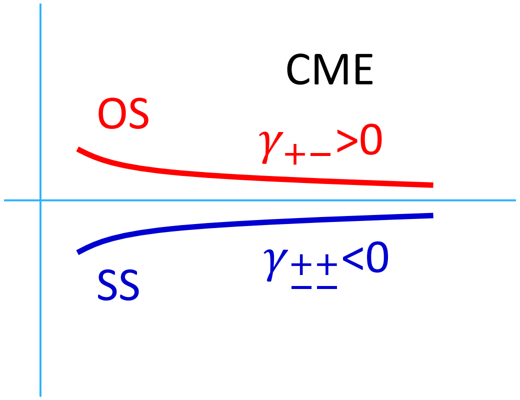
$$\gamma_{\alpha\beta} = \langle \cos(\varphi_\alpha + \varphi_\beta - 2\psi_{RP}) \rangle$$

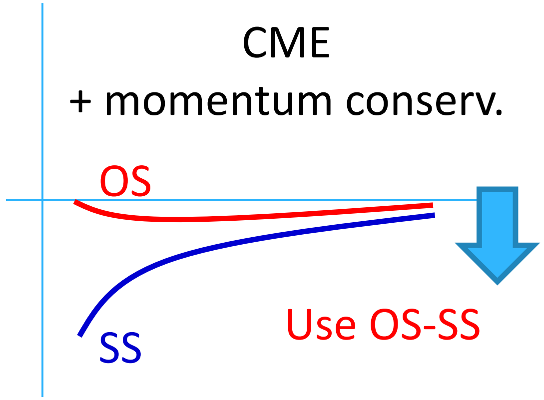
$\gamma_{+-}>0$; $\gamma_{\substack{++\\--}}<0$

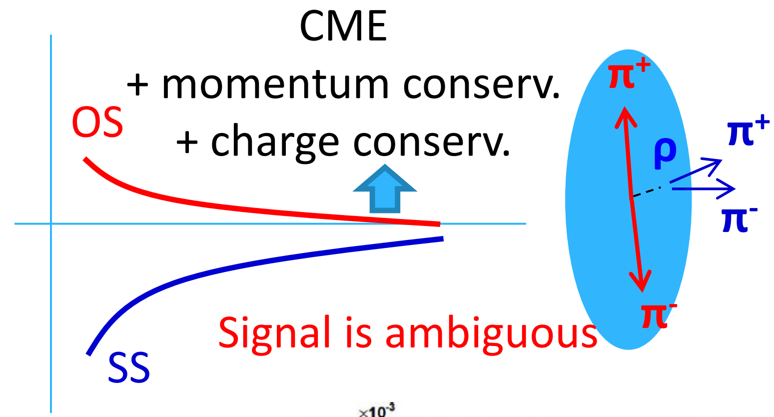




The Background Issue: It's big!



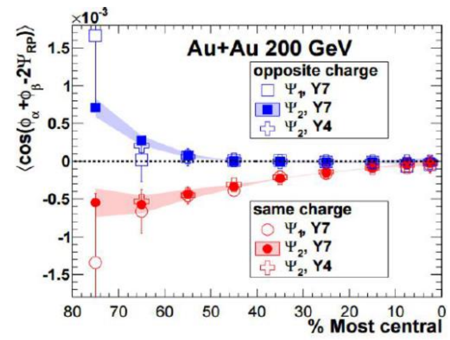




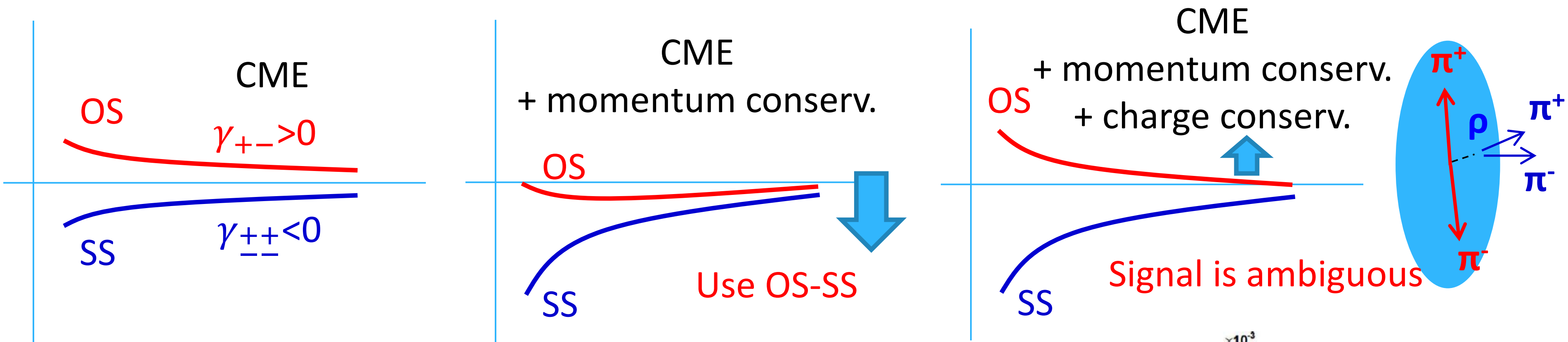
Voloshin, PRC 70 (2004) 057901 (magnitude underestimated by x10-100)

$$\gamma_{\alpha\beta} = \langle\cos(\varphi_\alpha + \varphi_\beta - 2\psi_{RP})\rangle = \langle\cos[(\varphi_\alpha + \varphi_\beta - 2\varphi_{clust.}) + 2(\varphi_{clust.} - \psi_{RP})]\rangle$$
$$= \frac{N_{clust.}}{N_\pi^2}\langle\cos(\varphi_\alpha + \varphi_\beta - 2\varphi_{clust.})\rangle v_{2,clust.}$$

Background: nonflow coupled with flow $\propto v_{2,\rho} / N$

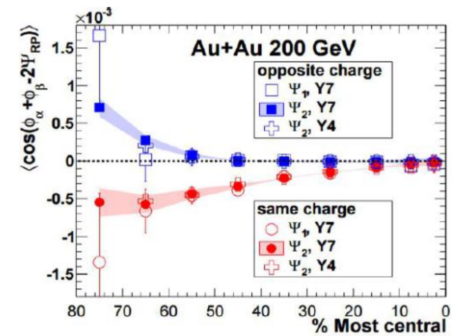


The Background Issue: It's big!



Voloshin, PRC 70 (2004) 057901 (magnitude underestimated by x10-100)

$$\gamma_{\alpha\beta} = \langle\cos(\varphi_\alpha + \varphi_\beta - 2\psi_{RP})\rangle = \langle\cos[(\varphi_\alpha + \varphi_\beta - 2\varphi_{clust.}) + 2(\varphi_{clust.} - \psi_{RP})]\rangle$$
$$= \frac{N_{clust.}}{N_\pi^2}\langle\cos(\varphi_\alpha + \varphi_\beta - 2\varphi_{clust.})\rangle v_{2,clust.}$$

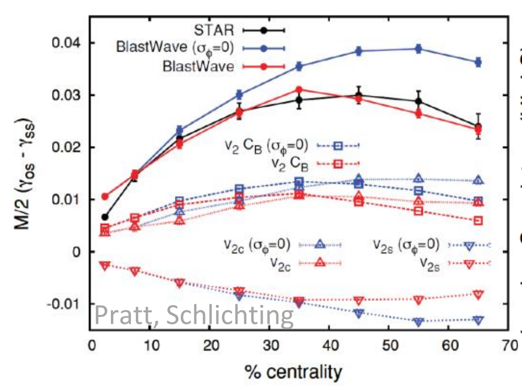


Background: nonflow coupled with flow $\propto v_{2,\rho} / N$

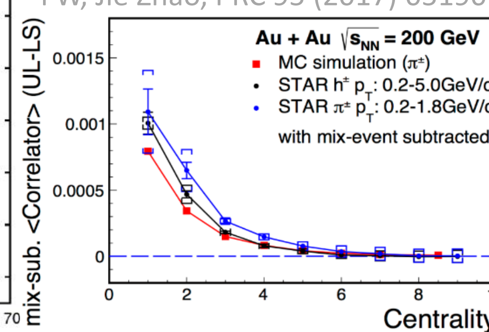
FW 2009, Bzdak, Koch, Liao 2010, Pratt, Schlichting 2010,

$$\frac{N_{clust.}}{N_\pi^2}\langle\cos(\varphi_\alpha + \varphi_\beta - 2\varphi_{clust.})\rangle v_{2,clust.}$$

$20/100^2*0.65 \sim 10^{-3}$ 0.1



FW, Jie Zhao, PRC 95 (2017) 051901



Handling background

- When background is small
  - Can be a bit sloppy in background estimation.
    Imprecision can be afforded by systematic uncertainty.
  - Can be somewhat model-dependent (theo. syst. uncertainties)

- **When background is large**
  - Have to cleanly remove background
  - Extreme care should be taken.
    Small error in background can result in big mistake in signal.
  - Should not rely on theory/model
    (unless theory is very precise)
  - Better be data-driven, often
    involving new observables and
    methods.

Handling background

- When background is small
  - Can be a bit sloppy in background estimation.
    Imprecision can be afforded by systematic uncertainty.
  - Can be somewhat model-dependent (theo. syst. uncertainties)

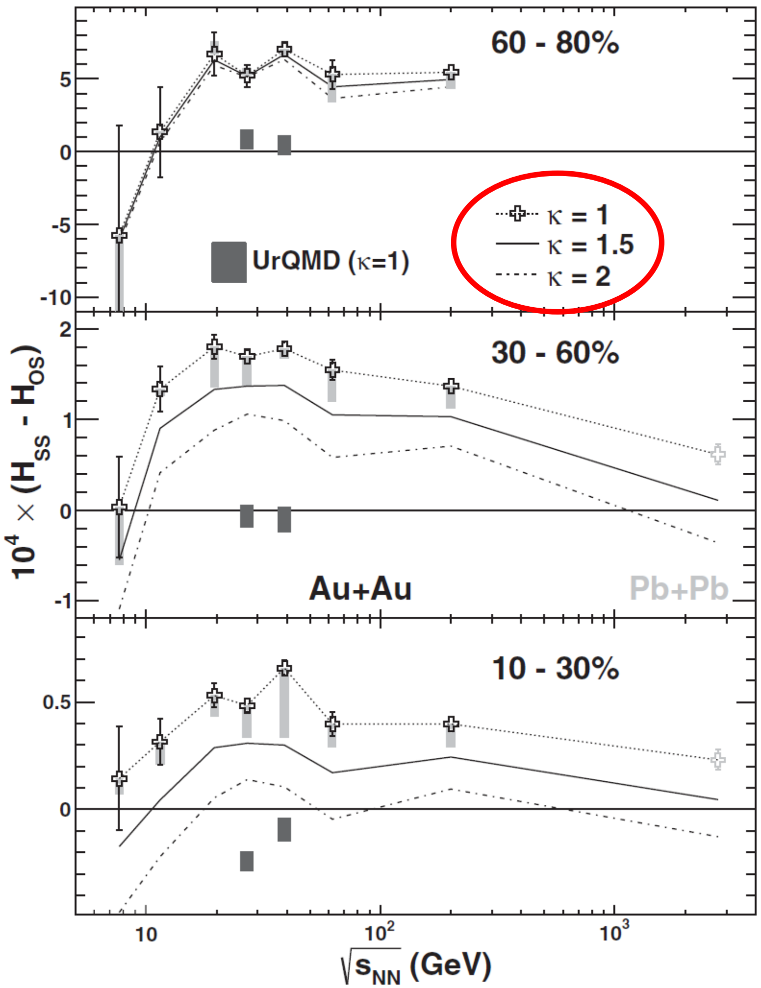
- **When background is large**
  - Have to cleanly remove background
  - Extreme care should be taken.
    Small error in background can result in big mistake in signal.
  - Should not rely on theory/model (unless theory is very precise)
  - Better be data-driven, often involving new observables and methods.

Message #2:

Be cautious, and be persistent!

The infamous κ parameter

$$\gamma \equiv \langle \cos(\phi_\alpha + \phi_\beta - 2\psi_{RP}) \rangle = \langle \cos(\phi_\alpha - \phi_\beta) \rangle \cdot \langle \cos 2(\phi_\beta - \psi_{RP}) \rangle = v_2 \delta \; *\kappa$$



STAR, PRL 113 (2014) 052302

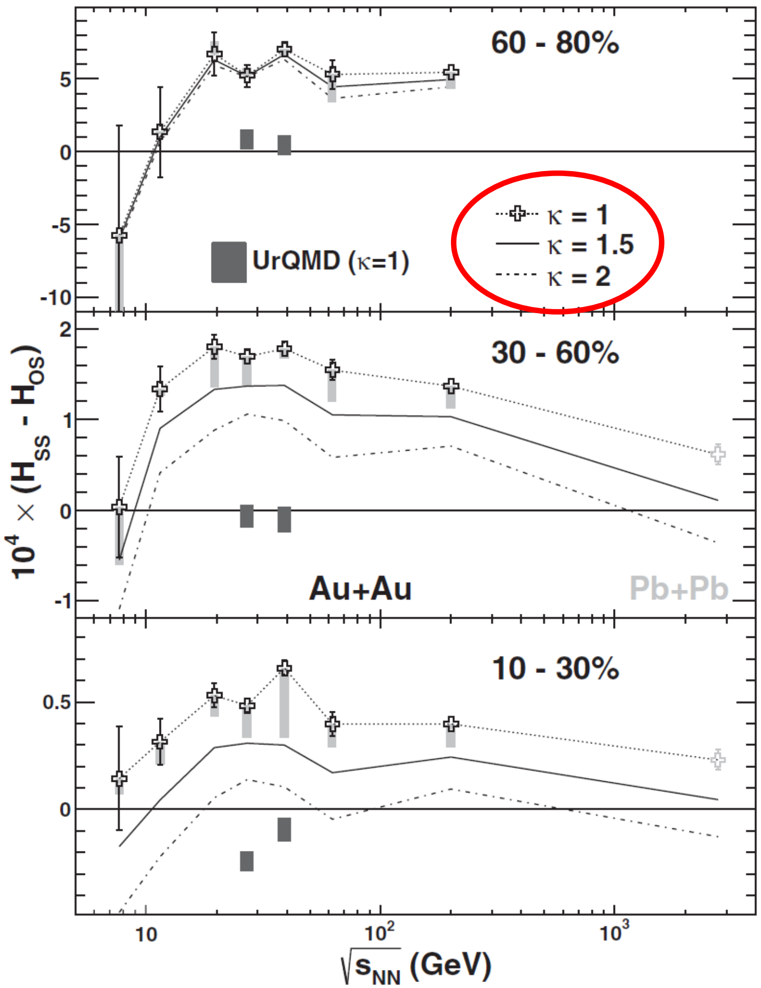
$$\Delta\gamma = \kappa v_2 \Delta F - \Delta H \,,$$
$$\Delta\delta = \Delta F + \Delta H \,.$$

$$\Delta H \approx \Delta\gamma - \kappa v_2 \delta$$

- κ=1 is a misconception
- Background size assumed!
- No new info beyond the original Δγ measurement. Over-sold.

The infamous κ parameter

$$\gamma \equiv \langle\cos(\phi_\alpha + \phi_\beta - 2\psi_{\rm RP})\rangle = \langle\cos(\phi_\alpha - \phi_\beta)\rangle \cdot \langle\cos 2(\phi_\beta - \psi_{\rm RP})\rangle = v_2\delta \; *\kappa$$



STAR, PRL 113 (2014) 052302

$$\Delta\gamma = \kappa v_2 \Delta F - \Delta H\,,$$
$$\Delta\delta = \Delta F + \Delta H\,.$$

$$\Delta H \approx \Delta\gamma - \kappa v_2 \delta$$

- κ=1 is a misconception
- Background size assumed!
- No new info beyond the original Δγ measurement. Over-sold.

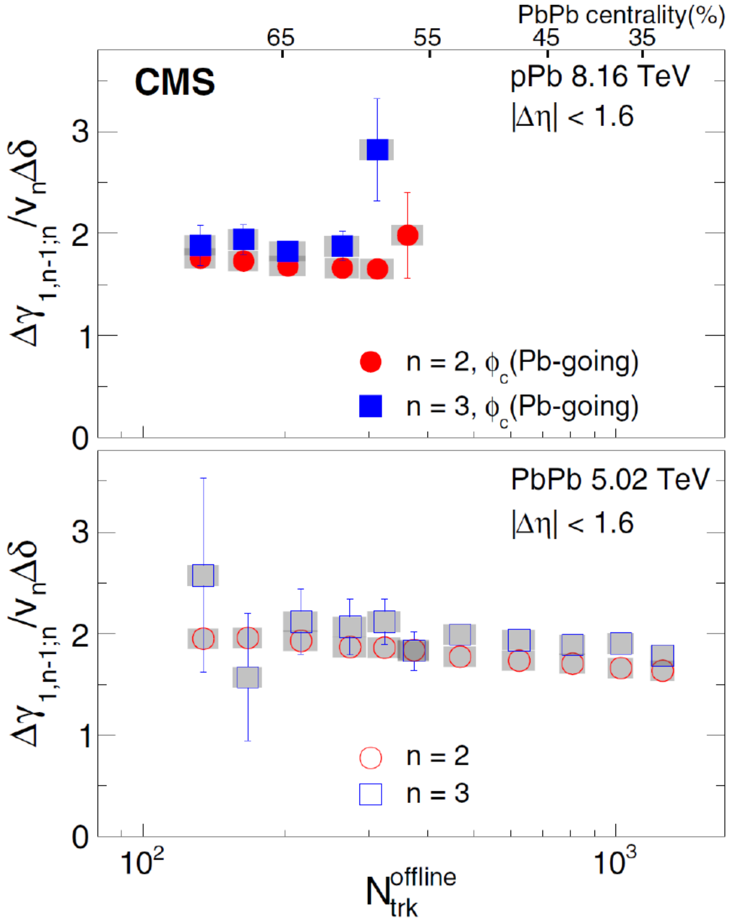
Message #3:

Be courageous, but be rigorous!

CMS clarification

$$\gamma \equiv \langle \cos(\phi_\alpha + \phi_\beta - 2\psi_{RP}) \rangle = \langle \cos(\phi_\alpha - \phi_\beta) \rangle \cdot \langle \cos 2(\phi_\beta - \psi_{RP}) \rangle = v_2 \delta \; *\kappa$$

$$\gamma = \langle \cos[(\varphi_\alpha + \varphi_\beta - 2\varphi_{clust.}) + 2(\varphi_{clust.} - \psi_{RP})] \rangle = \frac{N_{clust.}}{N_\pi^2} \langle \cos(\varphi_\alpha + \varphi_\beta - 2\varphi_{clust.}) \rangle v_{2,clust.}$$



$$\kappa_2 \equiv \kappa = \frac{\langle \cos(\phi_\alpha + \phi_\beta - 2\phi_{clust.}) \rangle}{\langle \cos(\phi_\alpha - \phi_\beta) \rangle_{clust.}} \cdot \frac{v_{2,clust.}}{v_2}$$

$$\kappa_3 = \frac{\langle \cos(\phi_\alpha + 2\phi_\beta - 3\phi_{clust.}) \rangle}{\langle \cos(\phi_\alpha - \phi_\beta) \rangle_{clust.}} \cdot \frac{v_{3,clust.}}{v_3}$$

$\kappa_2 = \kappa_3$ accidental?

To eliminate background

$$\text{Background } \Delta\gamma = \frac{N_\rho}{N_\alpha N_\beta} \left\langle \cos(\varphi_\alpha + \varphi_\beta - 2\varphi_{clus}) \right\rangle v_{2,clus}$$

Make v_2 zero…

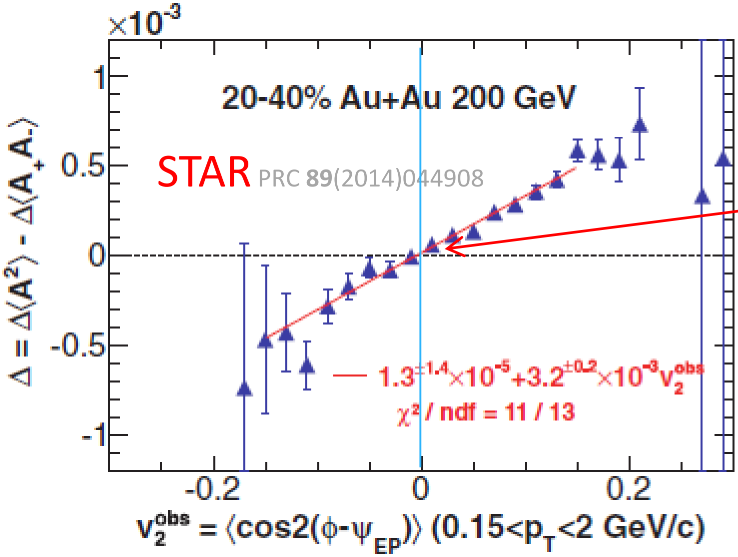
PHYSICAL REVIEW C 89, 044908 (2014)

Measurement of charge multiplicity asymmetry correlations in high-energy nucleus-nucleus collisions at $\sqrt{s_{NN}} = 200$ GeV

STAR

Make v_2 "zero" – EbyE technique

Here Δ is similar to $\cos(\alpha+\beta-2\psi)$ correlator

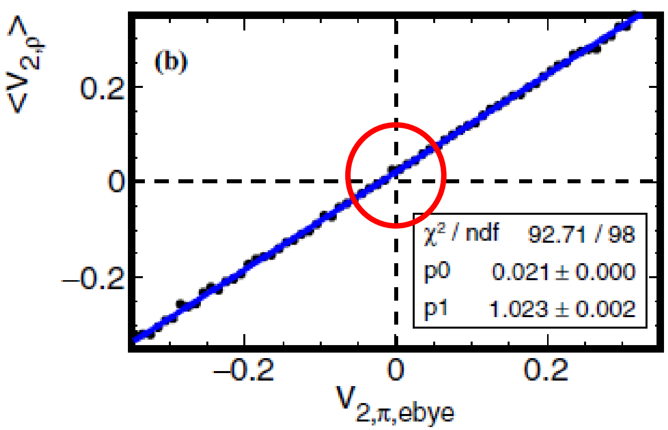


STAR PRC **89** (2014) 044908

Event-by-event v_2 technique

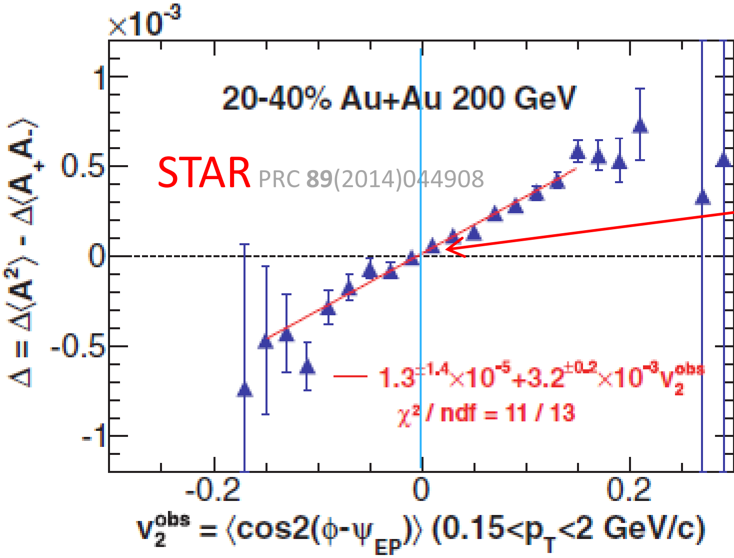
Still has residual background, because background ~ $v_{2,\rho}$ not $v_{2,\pi}$

FW, Jie Zhao, PRC 95 (2017) 051901(R)



Make v_2 "zero" – EbyE technique

Here Δ is similar to $\cos(\alpha+\beta-2\psi)$ correlator

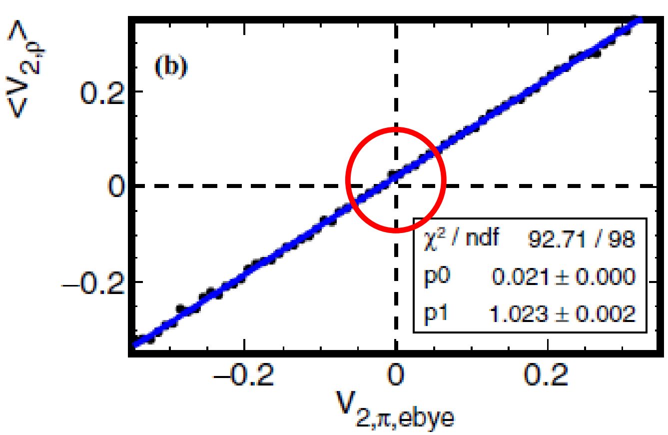


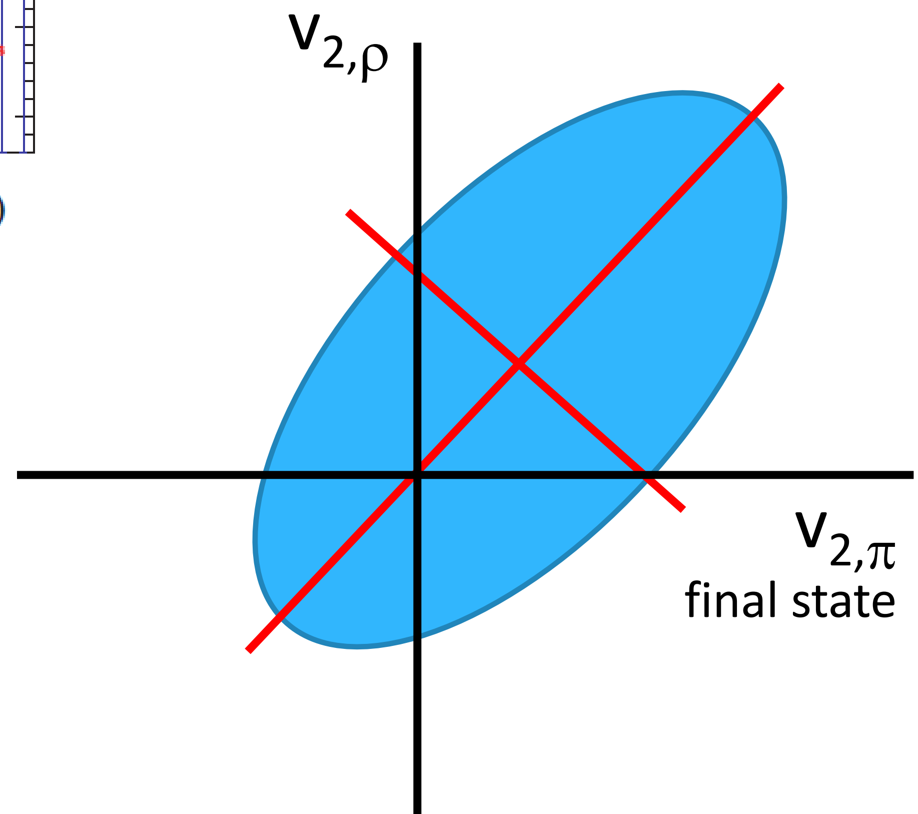
STAR PRC **89** (2014) 044908

Event-by-event v_2 technique

Still has residual background, because background ~ $v_{2,\rho}$ not $v_{2,\pi}$

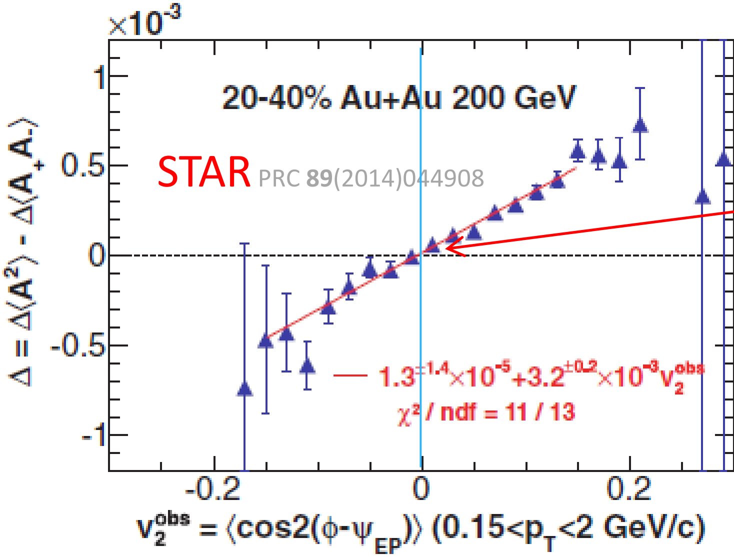
FW, Jie Zhao, PRC 95 (2017) 051901(R)



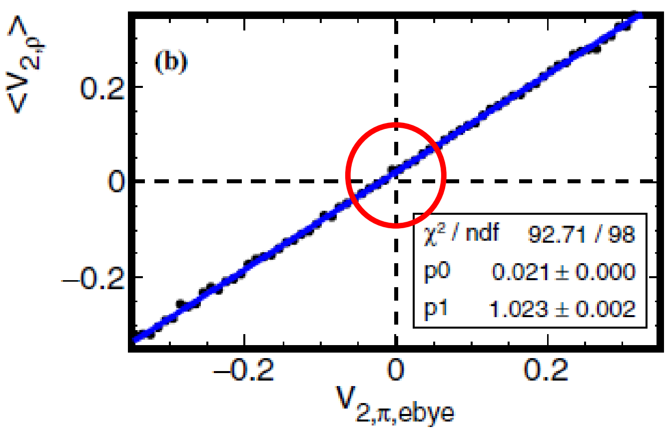


Make v_2 "zero" – EbyE technique

Here Δ is similar to $\cos(\alpha+\beta-2\psi)$ correlator



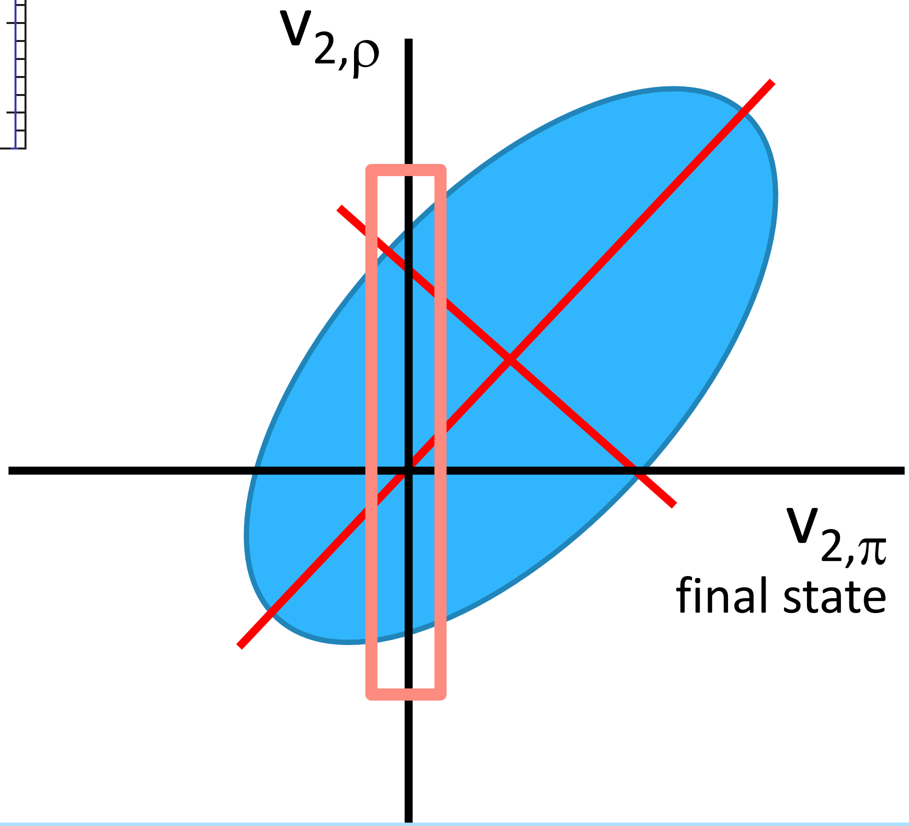
STAR PRC **89** (2014) 044908



Event-by-event v_2 technique

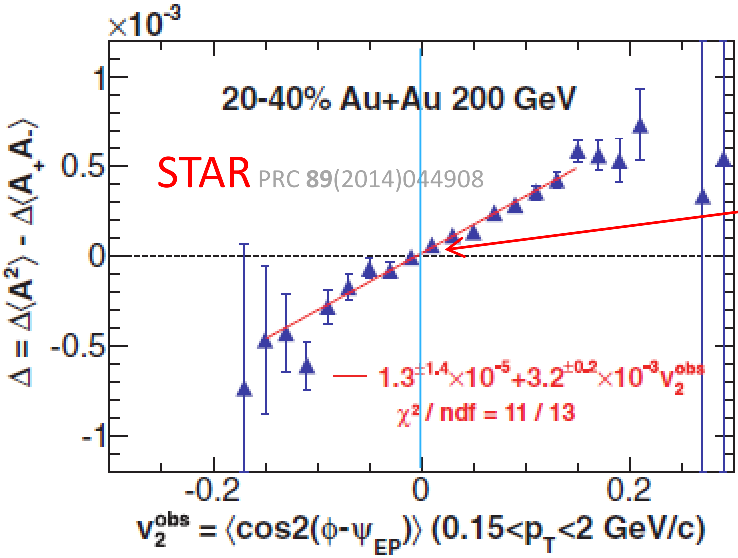
Still has residual background, because background ~ $v_{2,\rho}$ not $v_{2,\pi}$

FW, Jie Zhao, PRC 95 (2017) 051901(R)



Make v_2 "zero" – EbyE technique

Here Δ is similar to $\cos(\alpha+\beta-2\psi)$ correlator

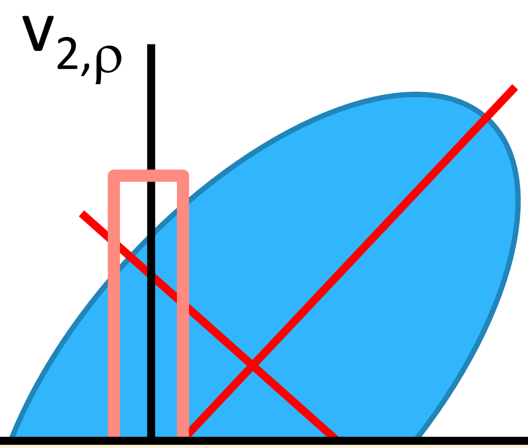


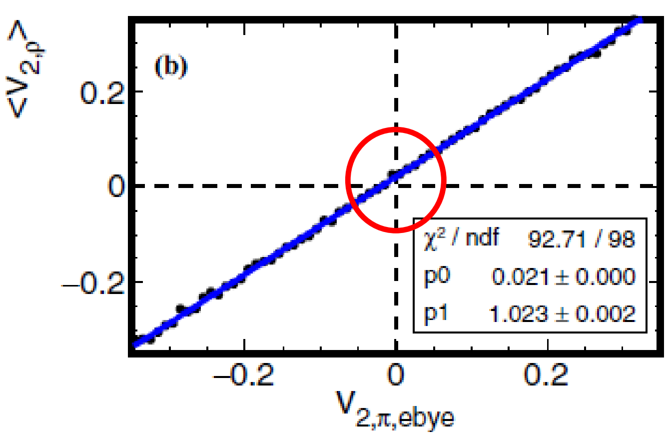
STAR PRC **89** (2014) 044908

Event-by-event v_2 technique

Still has residual background, because background ~ $v_{2,\rho}$ not $v_{2,\pi}$

FW, Jie Zhao, PRC 95 (2017) 051901(R)





Message #4:

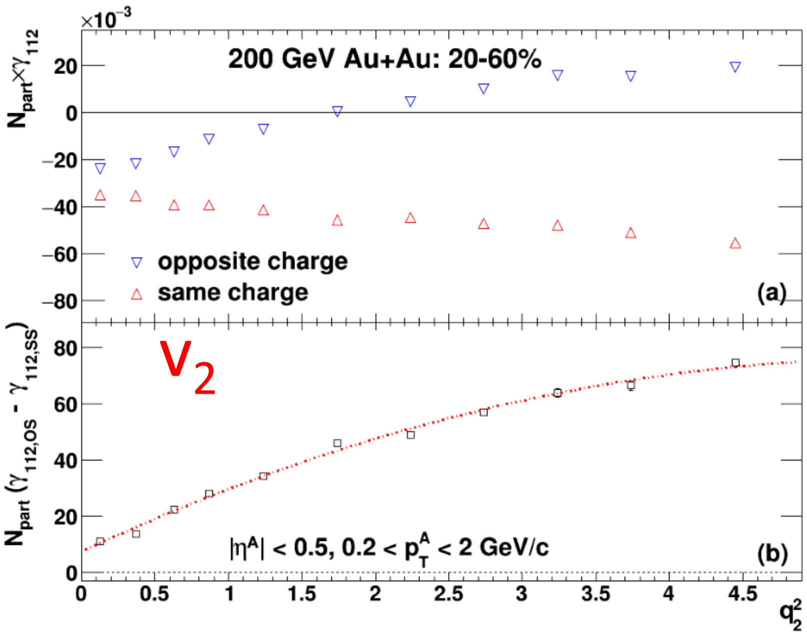
Be self-critical!

Sciences often progress thru self-denials.

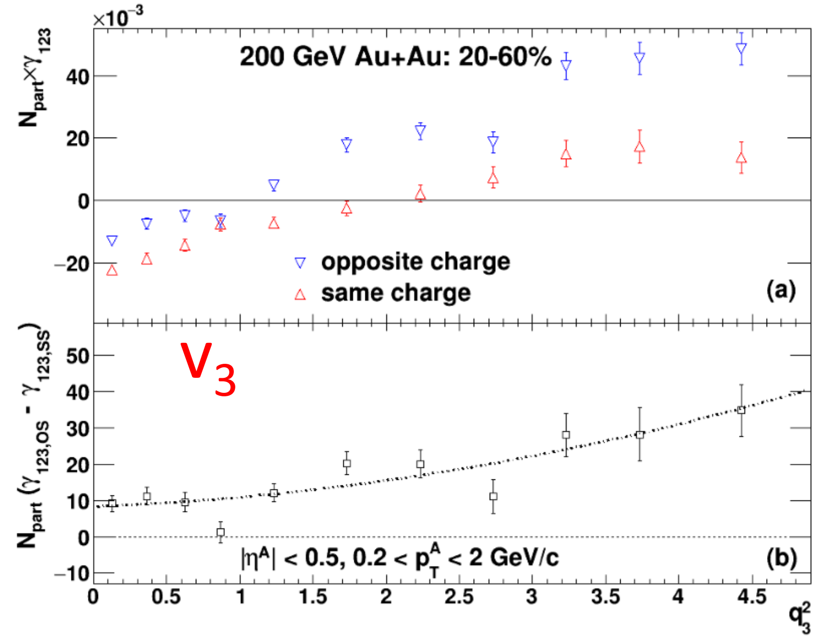
Event-by-event q^2 technique

Wen, Bryon, Wen, Wang, CPC 42 (2018) 014001

Similar to event-by-event v2 technique



Intercept = $(7.51 \pm 0.75)*10^{-3}$

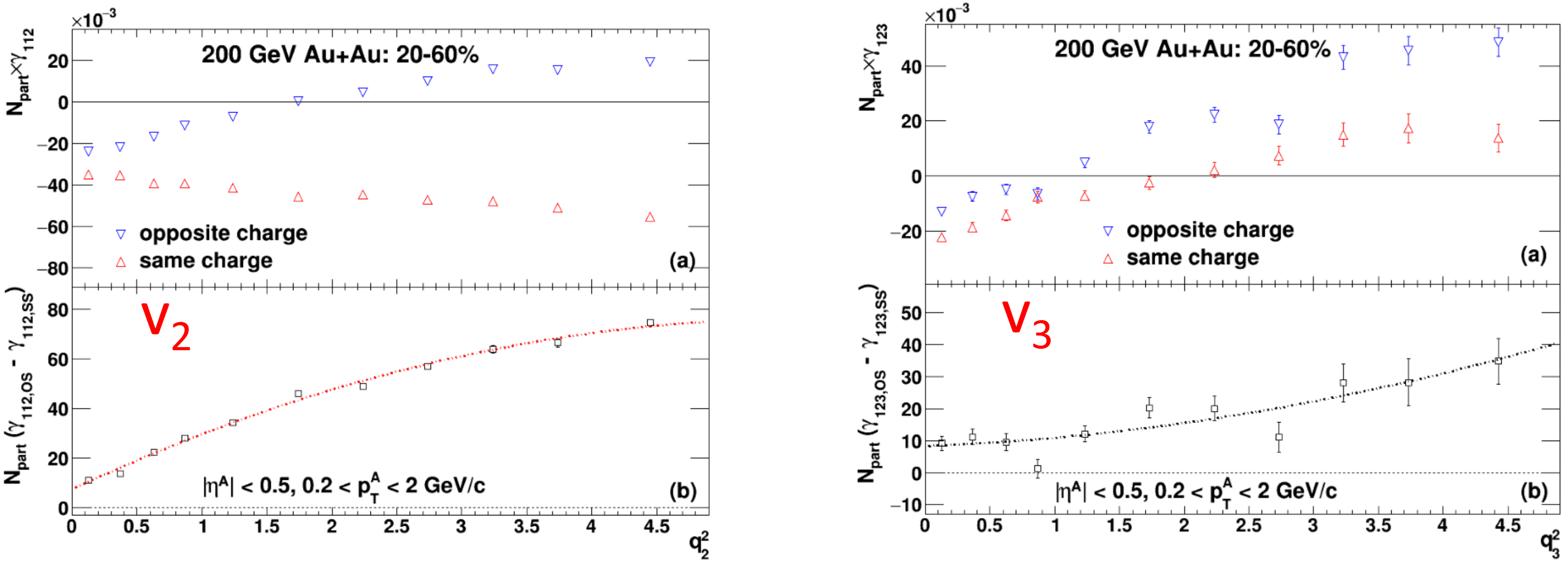


Intercept = $(8.32 \pm 1.92)*10^{-3}$

Event-by-event q^2 technique

Wen, Bryon, Wen, Wang, CPC 42 (2018) 014001

Similar to event-by-event v2 technique



Intercept = $(7.51 \pm 0.75)*10^{-3}$

Intercept = $(8.32 \pm 1.92)*10^{-3}$

Message #5:

Be conservative. Make claims only after having exhausted all mundane physics.

To eliminate background

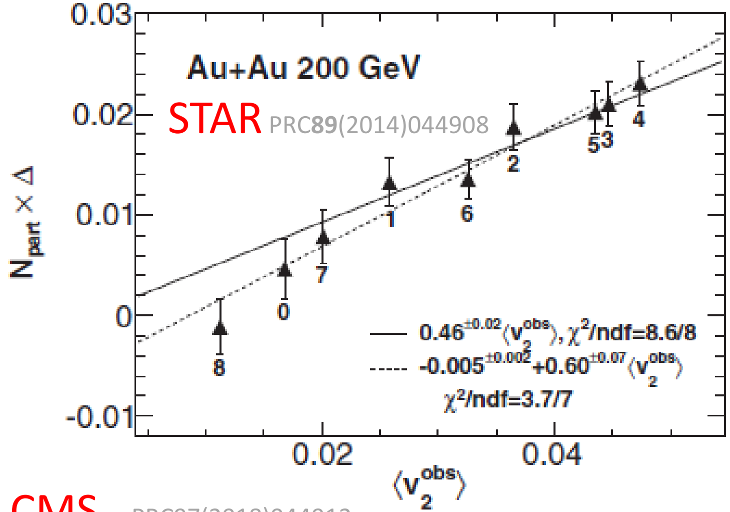
Three methods on the market that I think are hopeful to eliminate the backgrounds…

1. Event-shape engineering
2. Invariant mass
3. RP vs. PP comparison

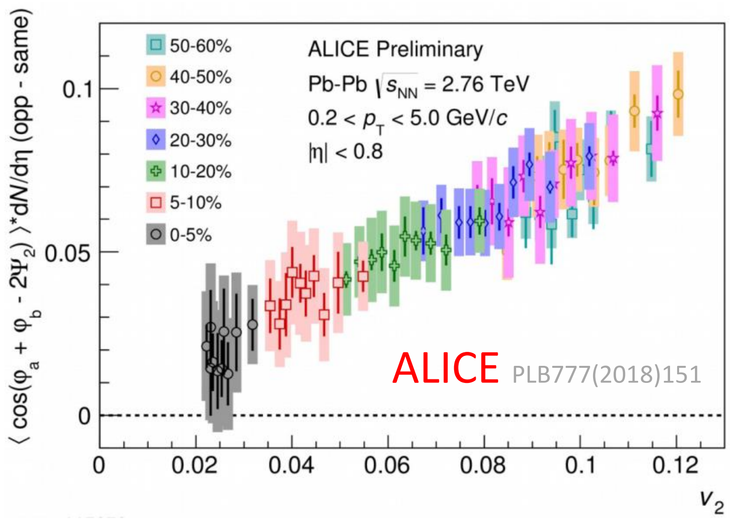
1) Event-shape-engineering technique

Here Δ is similar to cos(α+β−2ψ) correlator

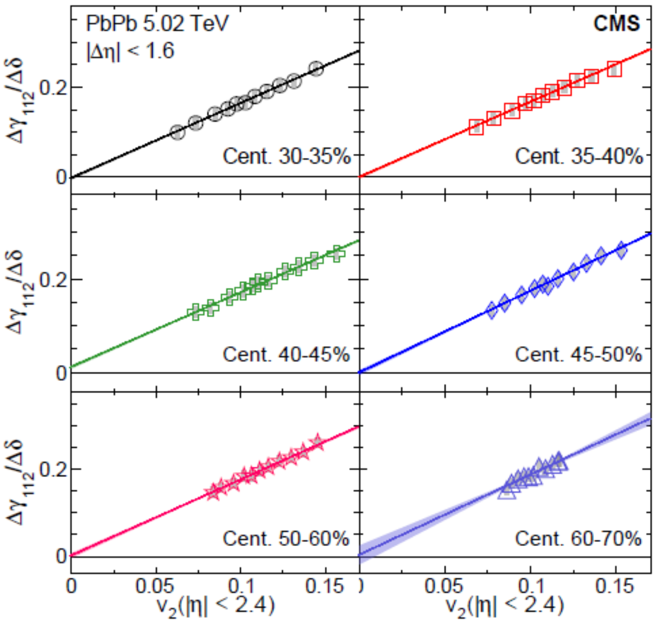
STAR PRC89(2014)044908



ALICE PLB777(2018)151



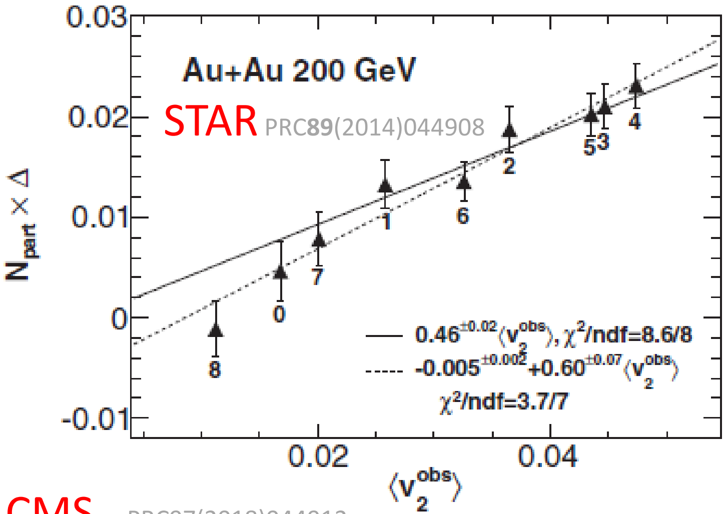
CMS PRC97(2018)044912

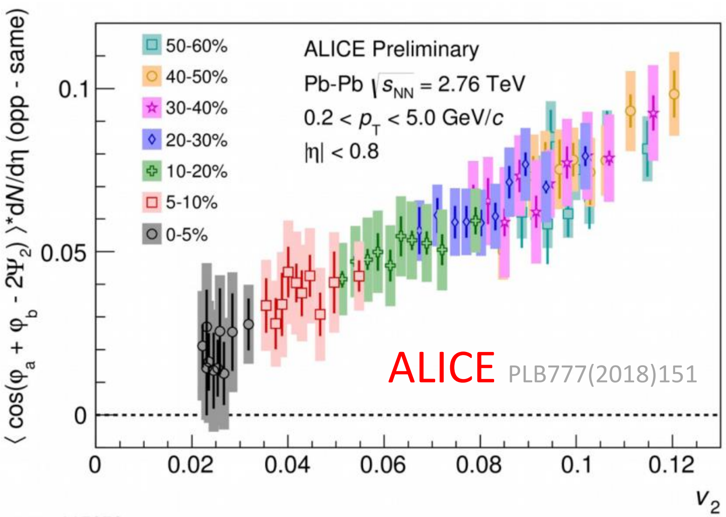


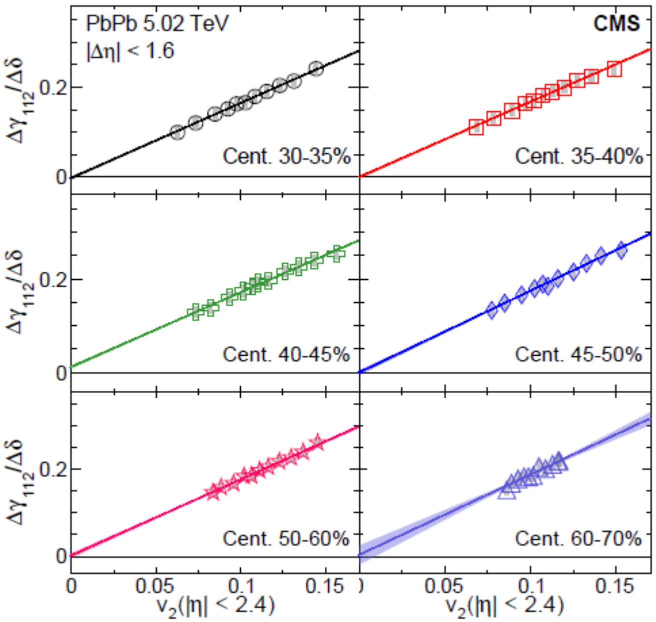
ESE displaced from α, β phase space

1) Event-shape-engineering technique

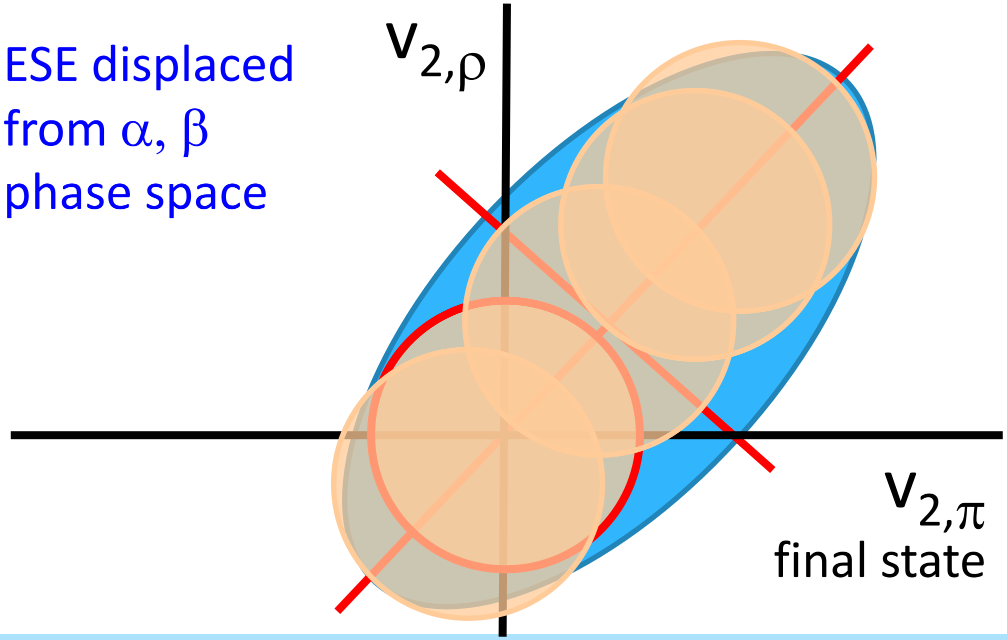
Here Δ is similar to cos(α+β−2ψ) correlator







ESE displaced from α, β phase space



2) The invariant mass method

$$\text{Background } \Delta\gamma = \frac{N_\rho}{N_\alpha N_\beta}\left\langle \cos(\varphi_\alpha + \varphi_\beta - 2\varphi_{clus}) \right\rangle v_{2,clus}$$

Get rid of resonances, or utilize them…

Identify the backgrounds by invariant mass

Eur. Phys. J. C (2019) 79:168
https://doi.org/10.1140/epjc/s10052-019-6671-1

THE EUROPEAN PHYSICAL JOURNAL C

Check for updates

Regular Article - Theoretical Physics

Isolating the chiral magnetic effect from backgrounds by pair invariant mass

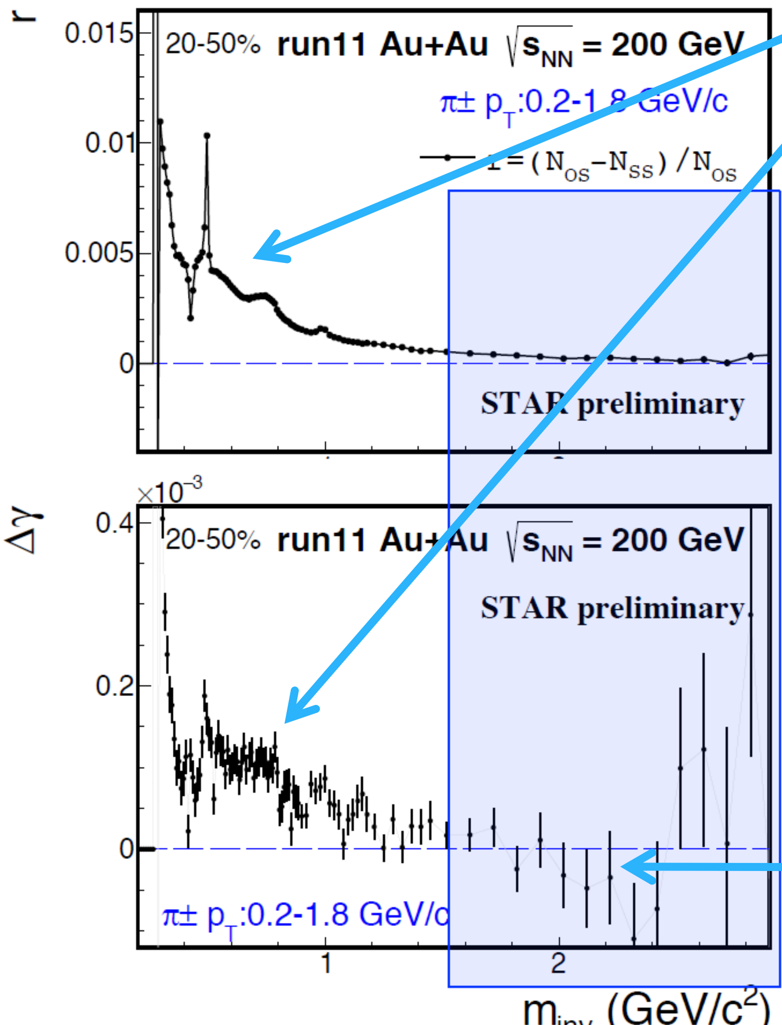
Jie Zhao[1,a], **Hanlin Li**[1,2], **Fuqiang Wang**[1,3,b]

arXiv:1705.05410

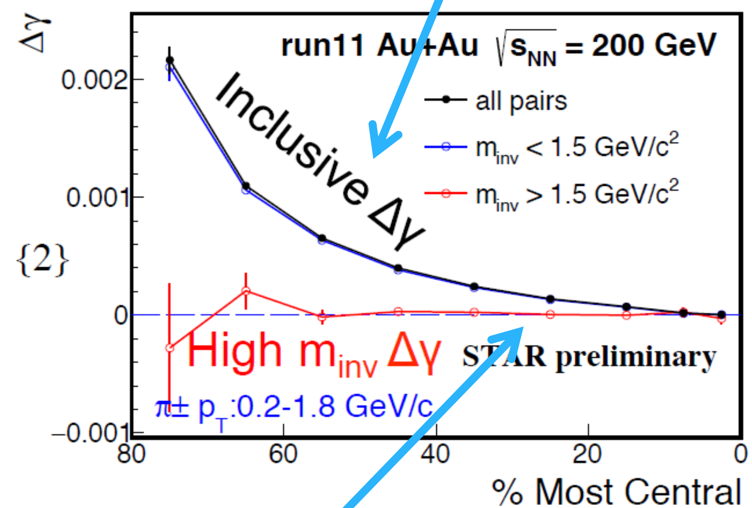
Get away from resonances

Jie Zhao (STAR) Quark Matter 2018, arXiv:1807.09925

Resonance structure in $\Delta\gamma$ as function of m_{inv}

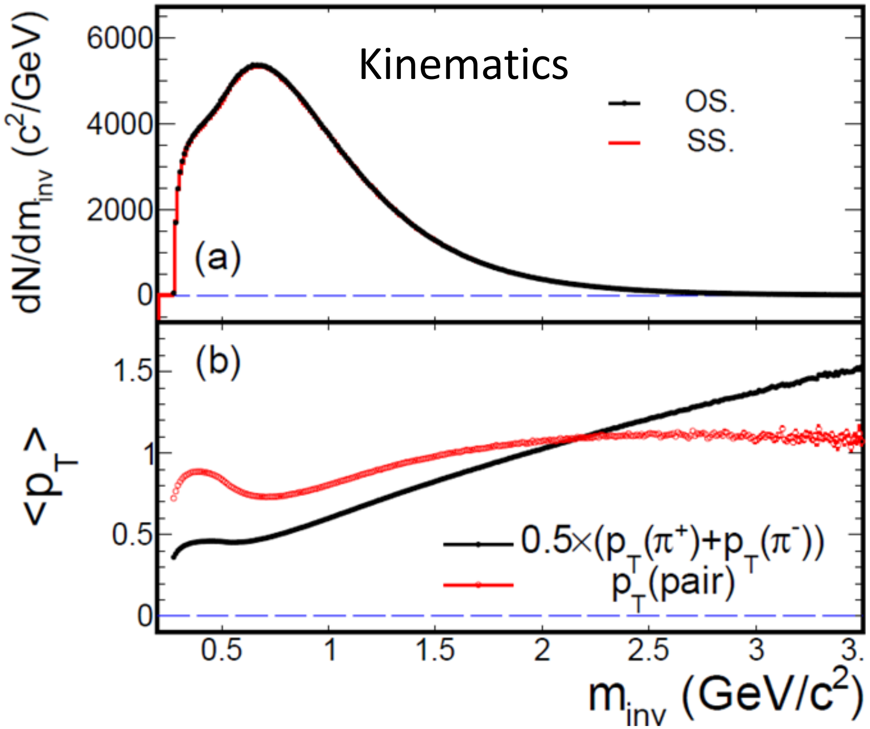


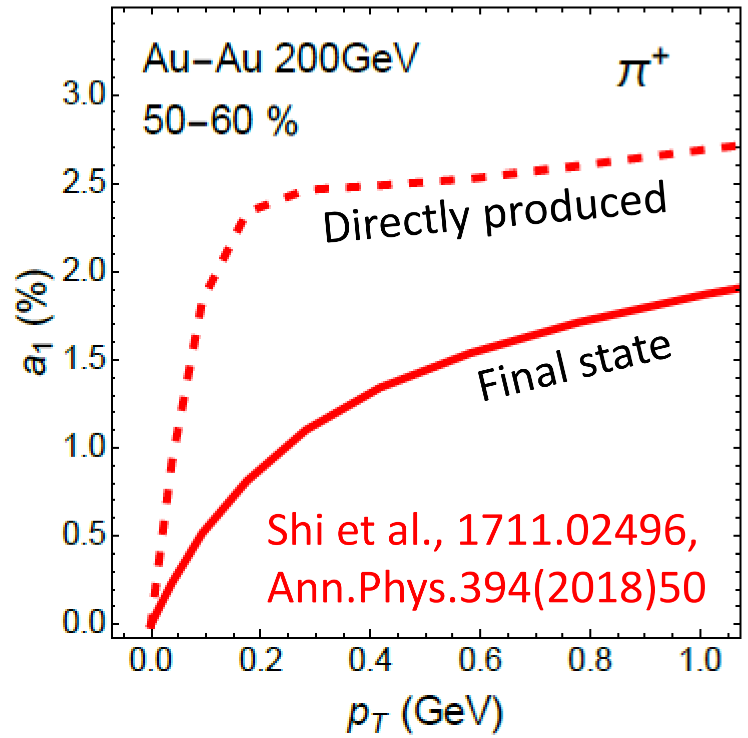
Major background



High mass $\Delta\gamma$: $(4.5 \pm 2.5)\%$

Can CME survive to high mass?

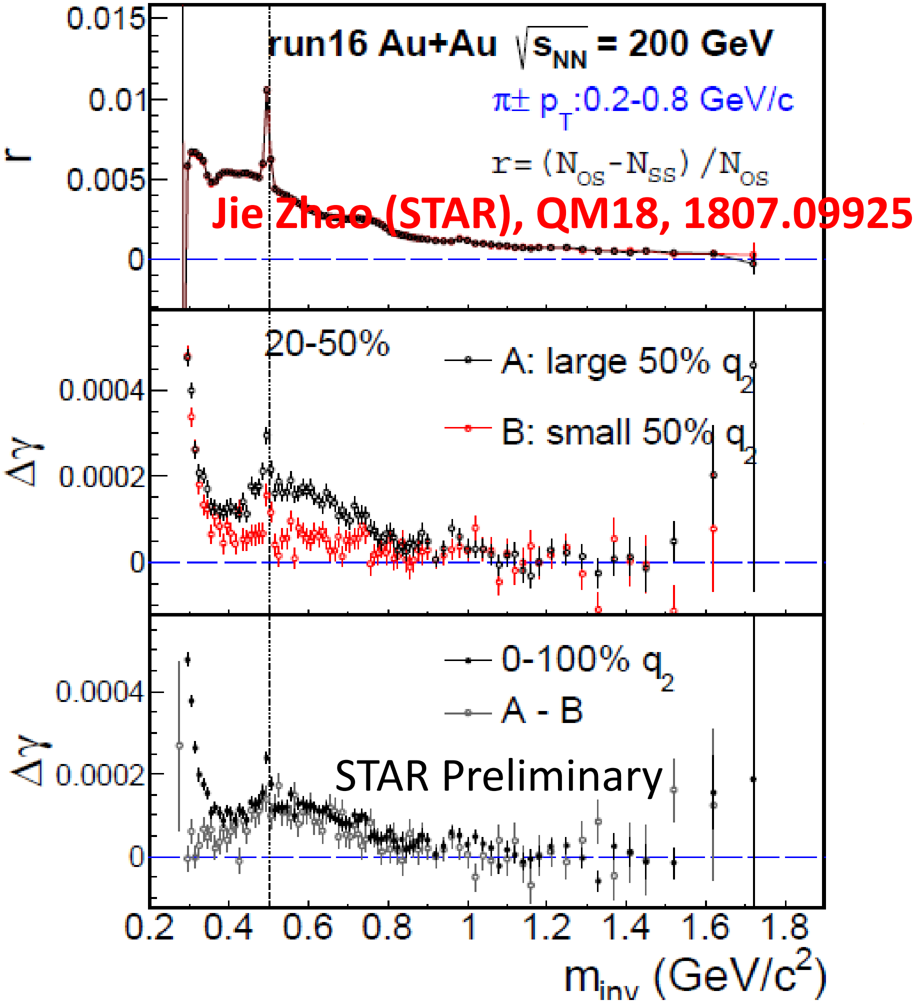




- $m_{inv} > 2$ GeV/c^2 contains appreciable low p_T pions
- CME signal may not be limited only to low p_T
- High mass should still contain CME

Indulge into the resonance region

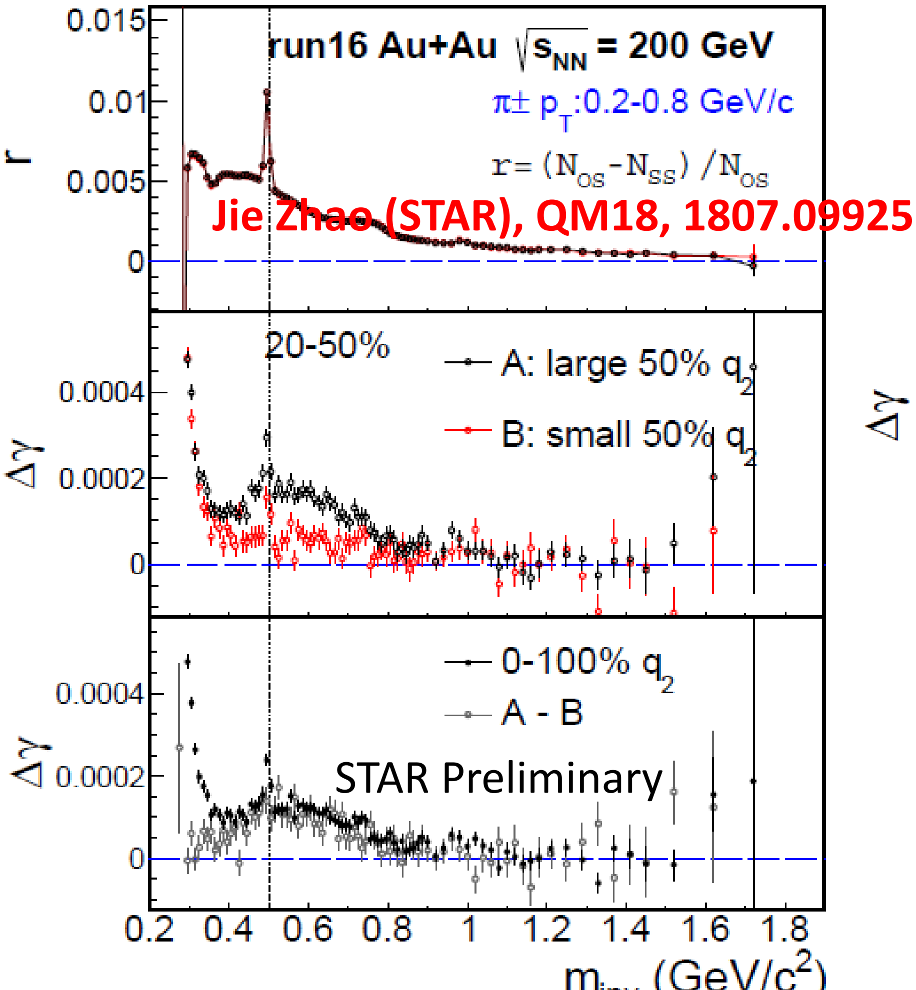
$$\frac{N_\rho}{N_\alpha N_\beta}\left\langle \cos(\varphi_\alpha + \varphi_\beta - 2\varphi_{clus})\right\rangle \times v_{2,clus}$$



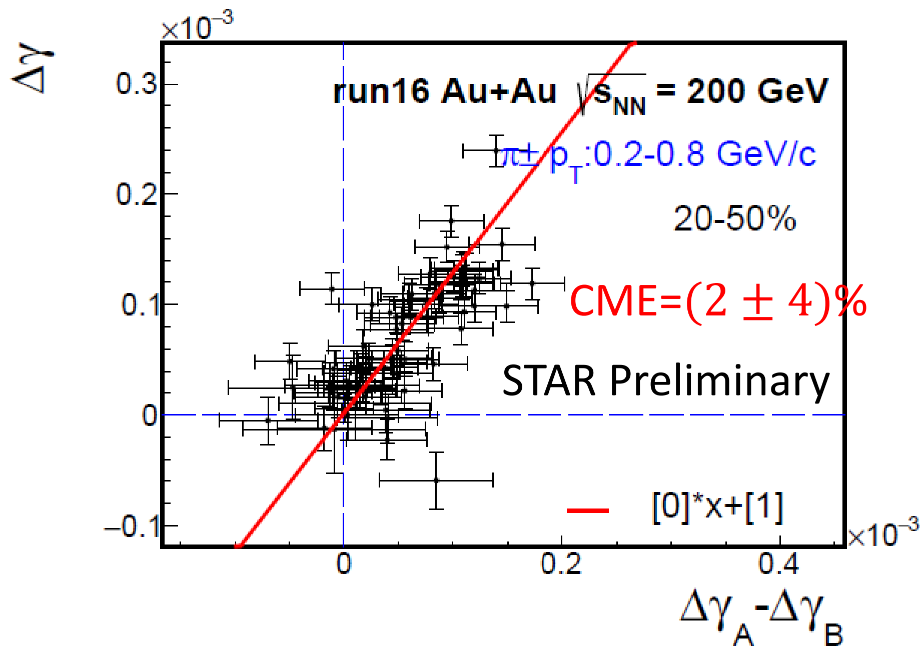
- ESE q_2 selects different v_2, but does not bias spectators or magnetic field
- $\Delta\gamma_A - \Delta\gamma_B$ represents background shape
- Fit $\Delta\gamma$ = k*(Bkg shape) + CME

Indulge into the resonance region

$$\frac{N_\rho}{N_\alpha N_\beta}\left\langle \cos(\varphi_\alpha + \varphi_\beta - 2\varphi_{clus}) \right\rangle \times v_{2,clus}$$



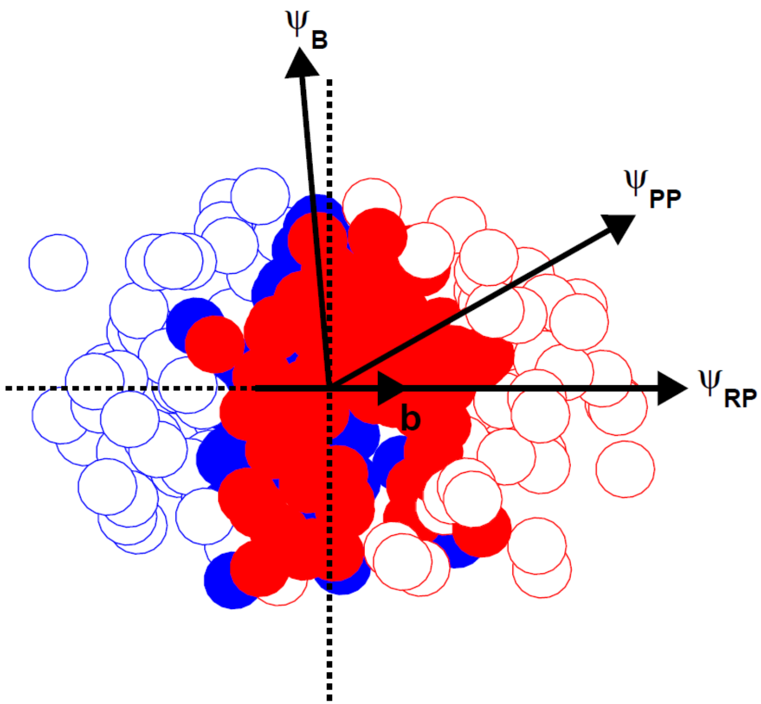
- ESE q_2 selects different v_2, but does not bias spectators or magnetic field
- $\Delta\gamma_A - \Delta\gamma_B$ represents background shape
- Fit $\Delta\gamma$ = k*(Bkg shape) + CME
- **Fit does not assume $\Delta\gamma \propto v_2$, but only dependent of v_2**
- Fit assumes constant CME. Fit χ^2/ndf tells whether it's a good assumption

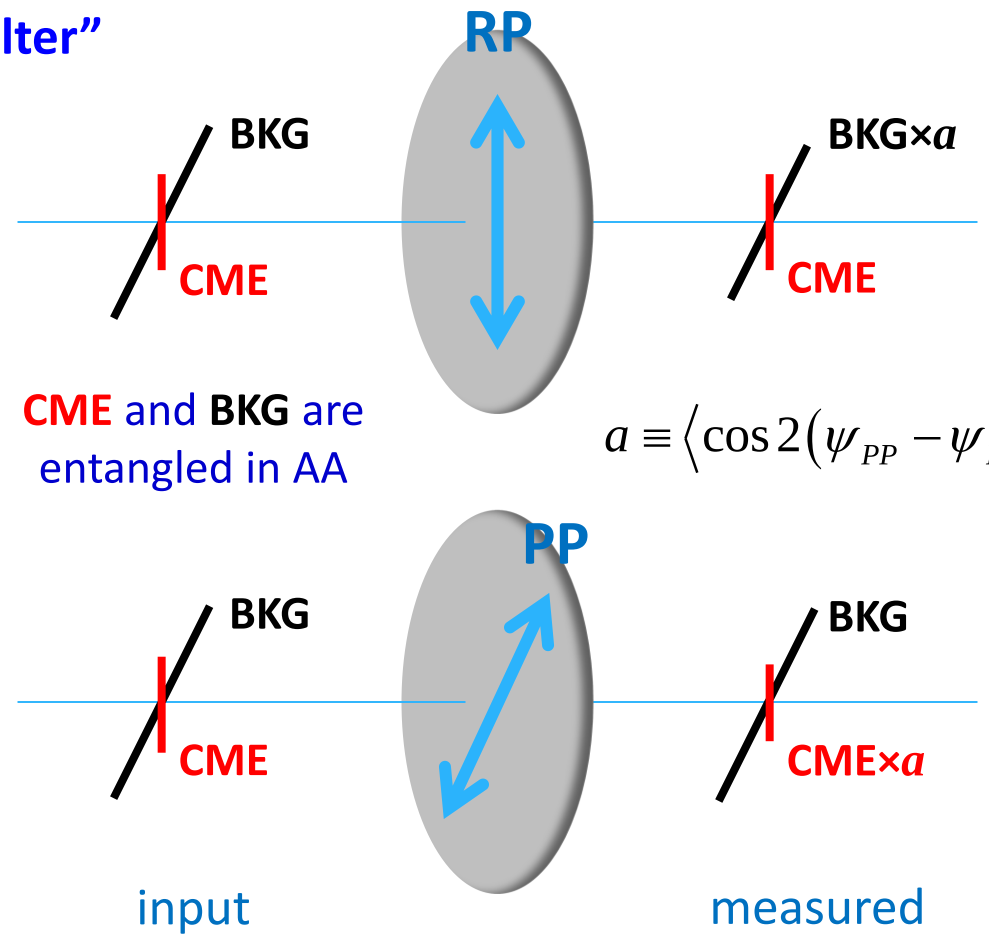


3) RP vs PP comparison measurement

H. Xu, J. Zhao, X. Wang, H. Li, Z.-W. Lin, C. Shen, F. Wang, CPC 42 (2018) 084103, arXiv:1710.07265

Intra-event "CME-v_2 Filter"

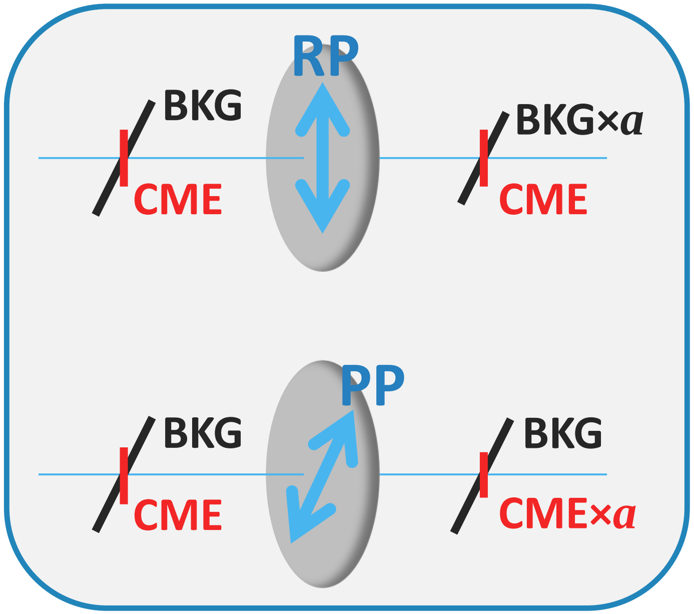


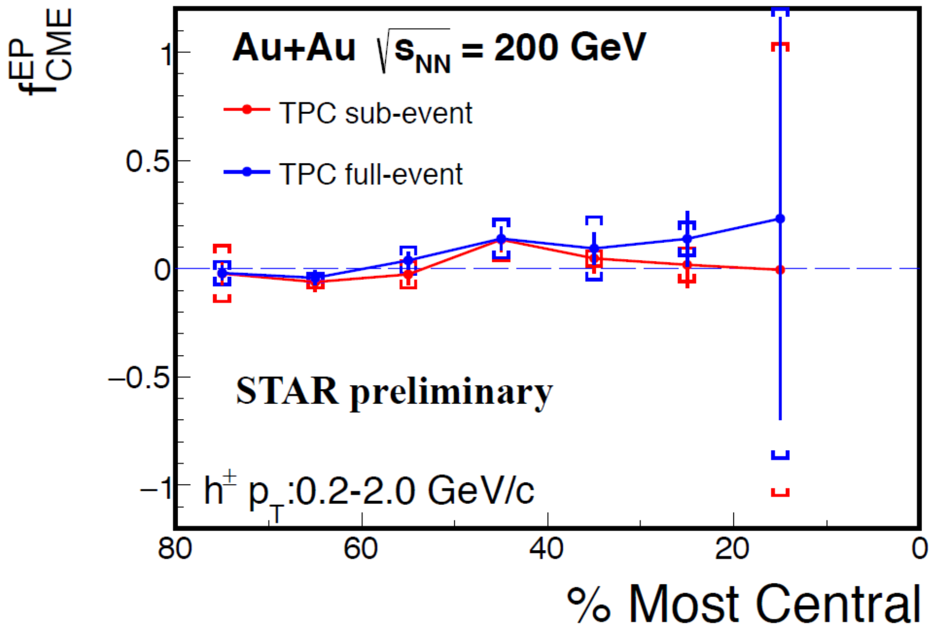


$$a \equiv \langle \cos 2(\psi_{PP} - \psi_{RP}) \rangle$$

SAME EVENT

"CME-v_2 Filter" results from STAR

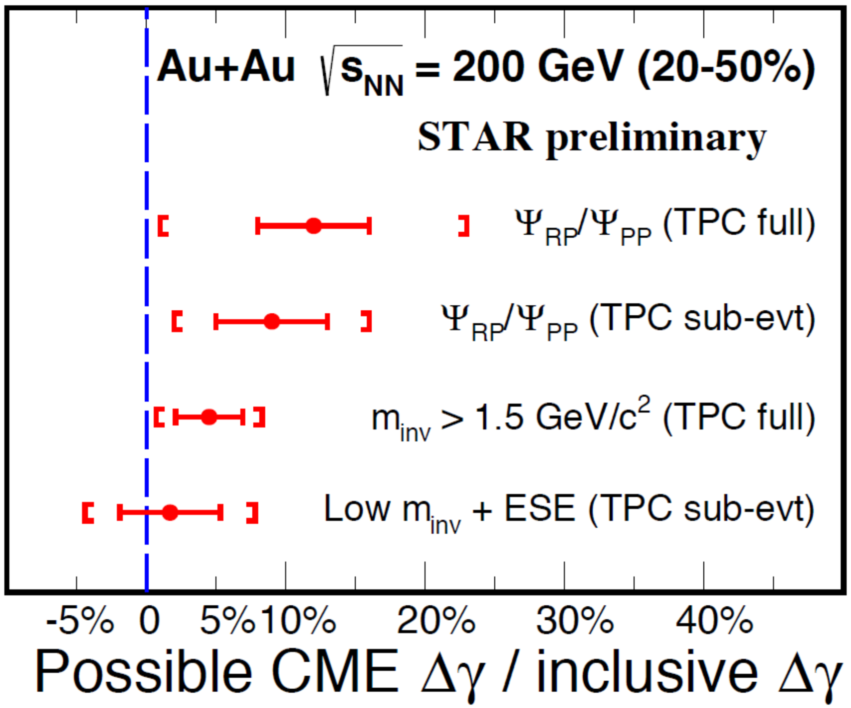


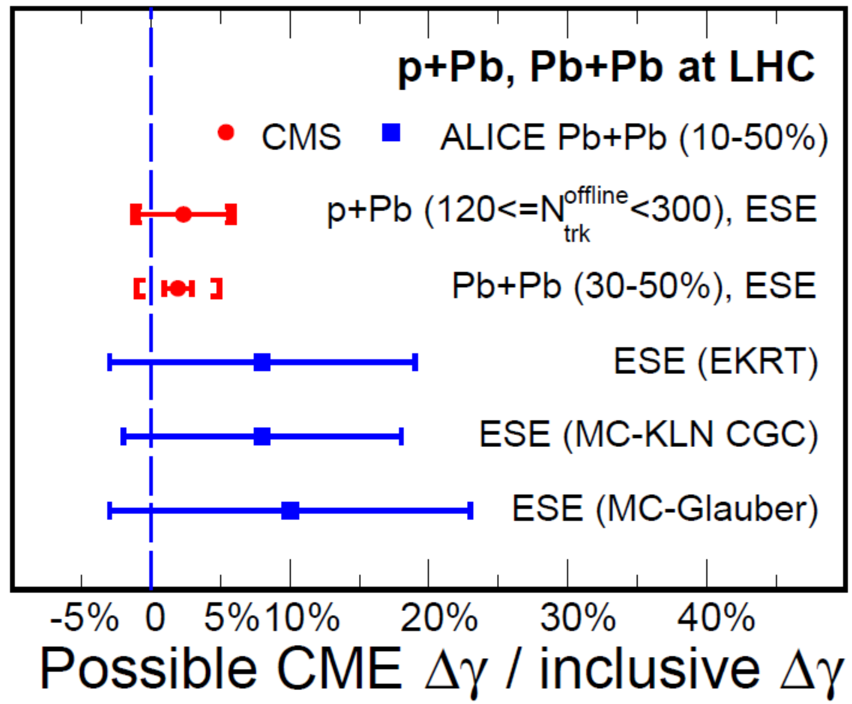


CME (EP) fraction	20-50% centrality
TPC sub-event	(9±4±7)%
TPC full-event	(12±4±11)%

Summary of Possible CME Signal

Jie Zhao (STAR) Quark Matter 2018
arXiv:1807.09925



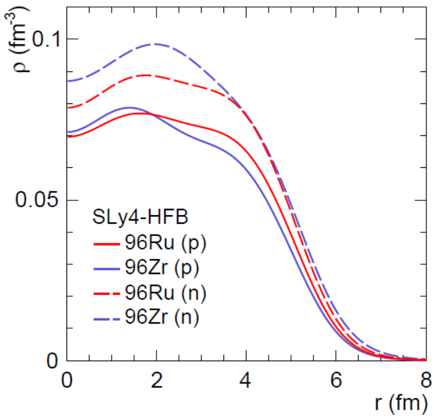


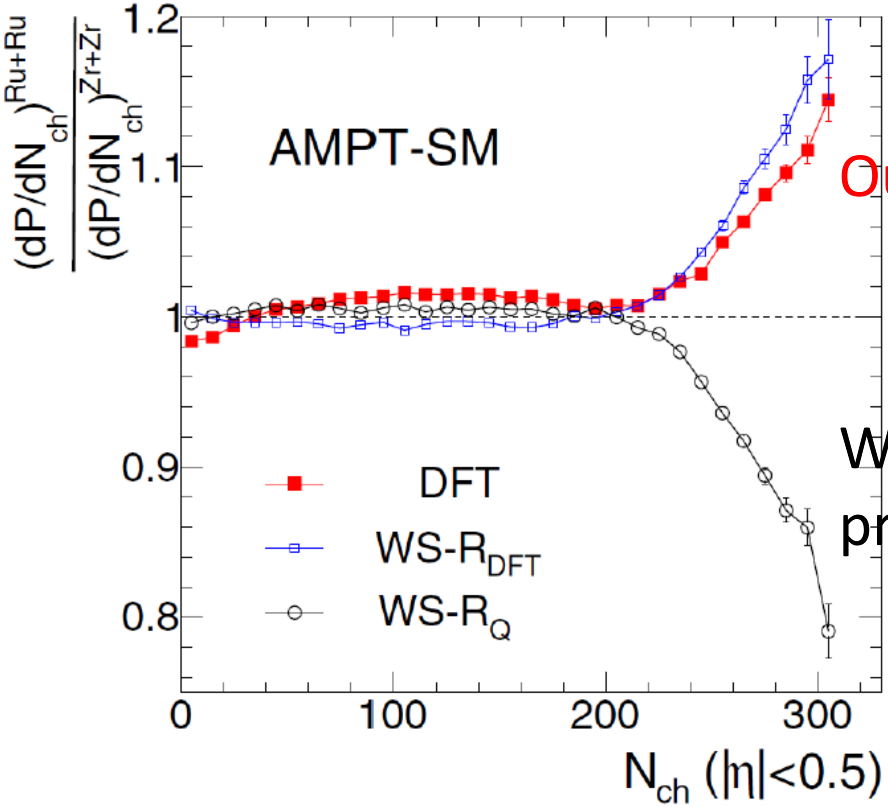
- **Major physics backgrounds**
- **Possible CME signal ~ a few %, 1-2σ from zero.**

A day-1 prediction for isobar

Haojie Xu et al. PRL 121 (2018) 022301
Haojie Xu et al. CPC 42 (2018) 084103
Hanlin Li et al. PRC 98 (2018) 054907

Multiplicity sensitive to nuclear structure





Our prediction

Woods-Saxon prediction

Summary

- Background dominate in $\Delta\gamma$.
  Rigorous treatment of background is critical.
- Three viable methods so far:
  - Event-shape engineering
  - Invariant mass
  - RP vs. PP comparison
- Possible CME signal is small, a few % of $\Delta\gamma$, 1-2σ from zero.

Summary

- Background dominate in $\Delta\gamma$.
  Rigorous treatment of background is critical.
- Three viable methods so far:
  - Event-shape engineering
  - Invariant mass
  - RP vs. PP comparison
- Possible CME signal is small, a few % of $\Delta\gamma$, 1-2σ from zero.

Disclaimer:

CME is not observed ≠ CME is nonexistent