Measurements of the Chiral Magnetic Effect with Background Isolation in 200 GeV Au+Au Collisions at STAR

Jie Zhao (for the STAR collaboration)

April 10 2019

Purdue University, West Lafayette

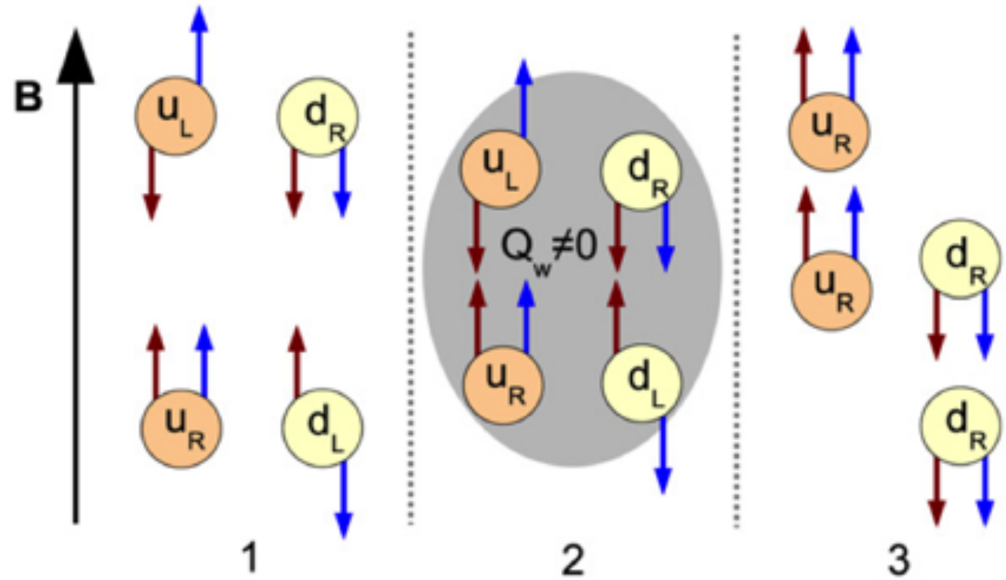
Outline

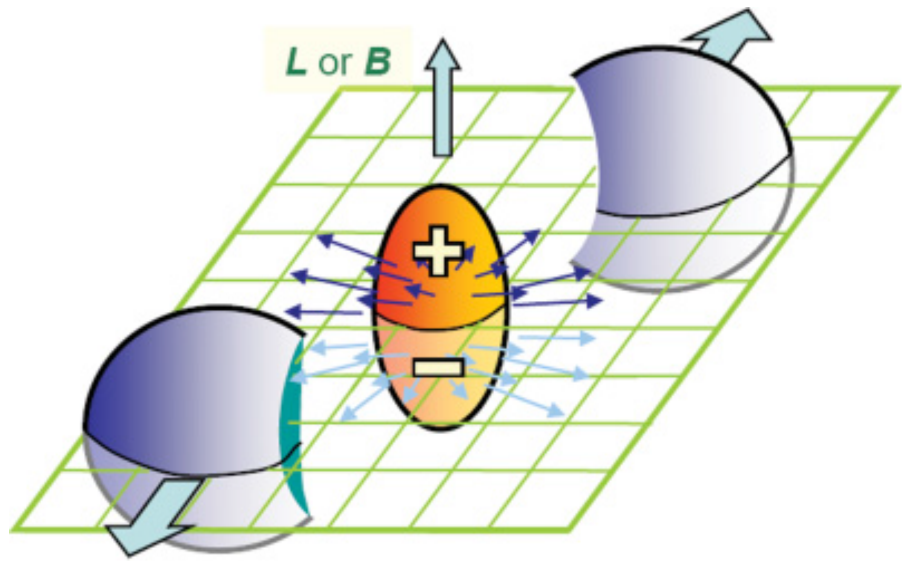
- **Chiral Magnetic Effect (CME)**
- **RHIC-STAR experiment**
- **Background issue**
- **Invariant mass dep. of the Δγ correlator**
- **Δγ with respect to Ψ_{RP} (ZDC) and Ψ_{PP} (TPC)**
- **Summary**

Ψ_{RP}: reaction plane ; Ψ_{PP}: participant plane

Chiral Magnetic Effect (CME)

Kharzeev, *et al*. NPA 803, 227 (2008)
Voloshin, PRC 70, 057901 (2004)

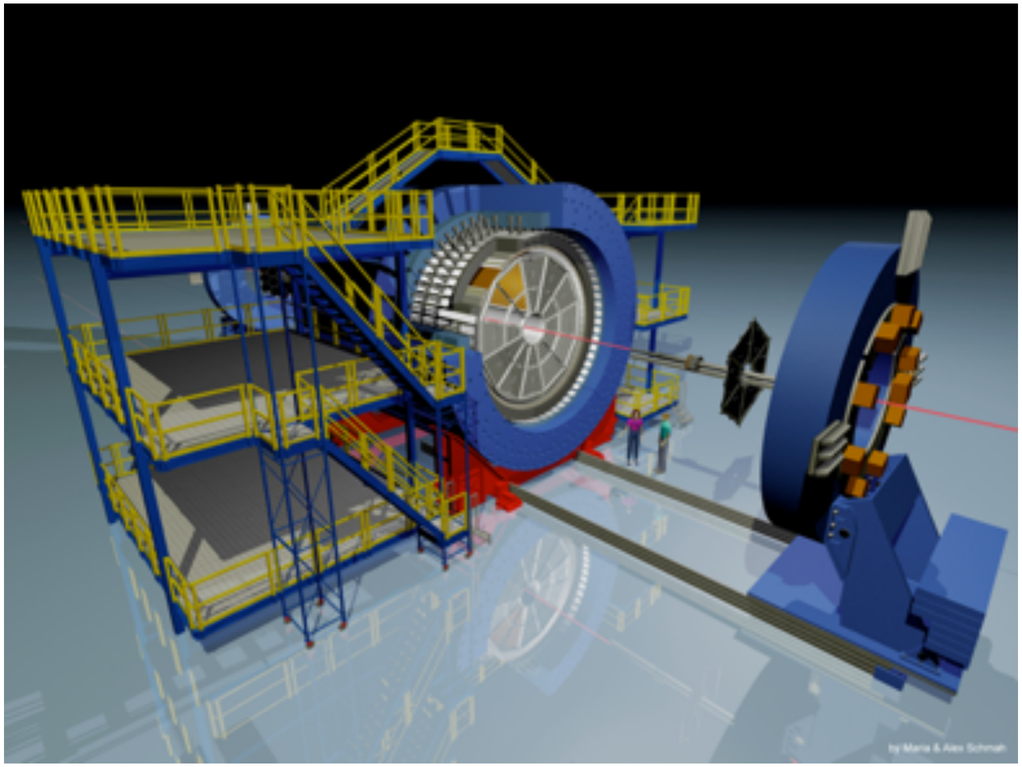


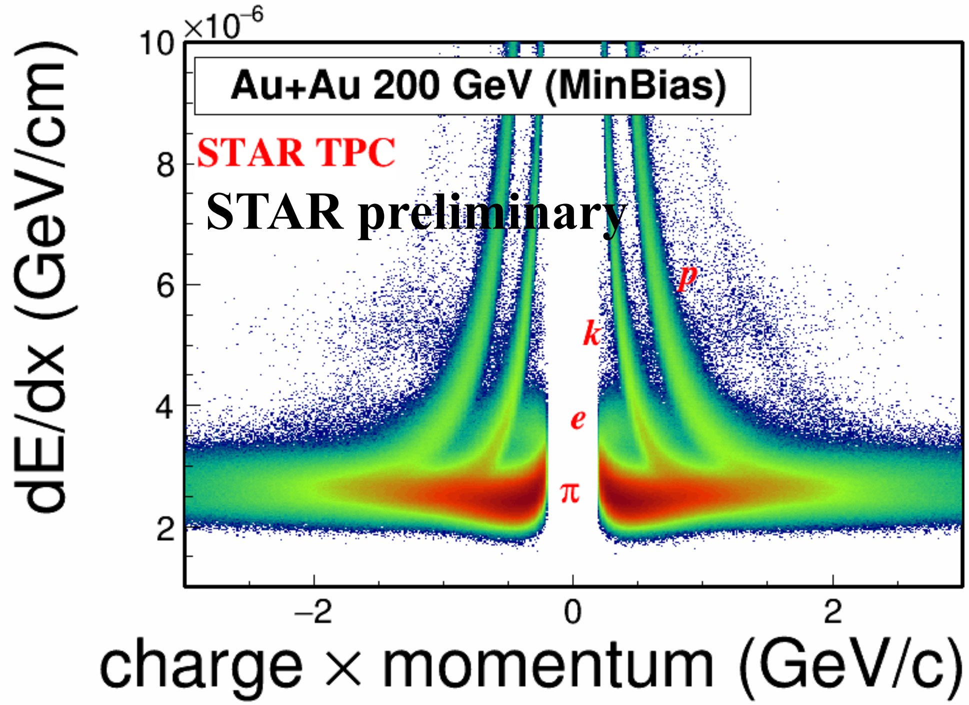


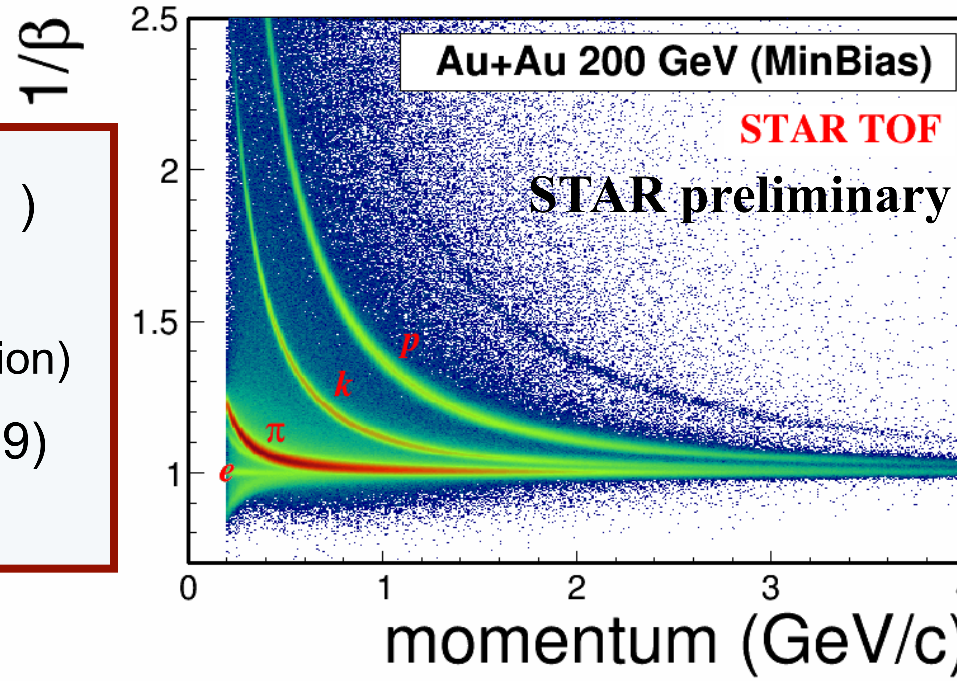
$j_V = \frac{N_c e}{2\pi^2}\mu_A B,$ ⟹ electric charge separation along the B field

- ➢ Gluon configuration with non-zero topological charge (Q_w) converts left (right)-handed fermions to right (left)-handed fermions, generating electric current along B direction and leading to electric charge separation
- ➢ Experimentally, $\gamma = \cos(\phi_\alpha + \phi_\beta - 2\psi_{RP})$ used to search for the CME

The STAR detector



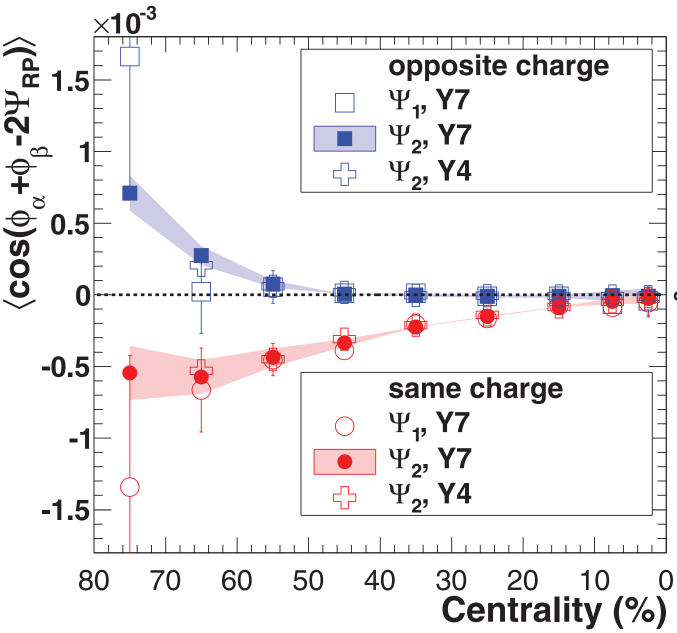


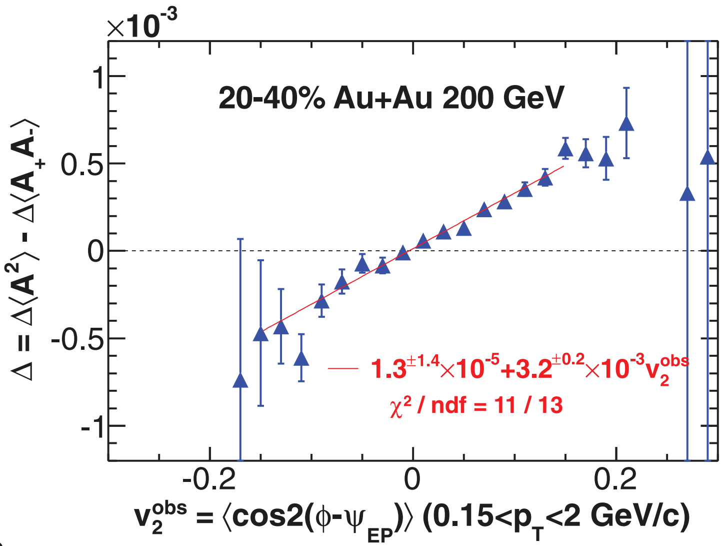


- **Time Projection Chamber** (ϕ=0-2π, |η|<1)
  - Tracking - momentum
  - Ionization energy loss - dE/dx (particle identification)
- **Time Of Flight detector** (ϕ=0-2π, |η|<0.9)
  - Timing resolution <100ps - PID improvement

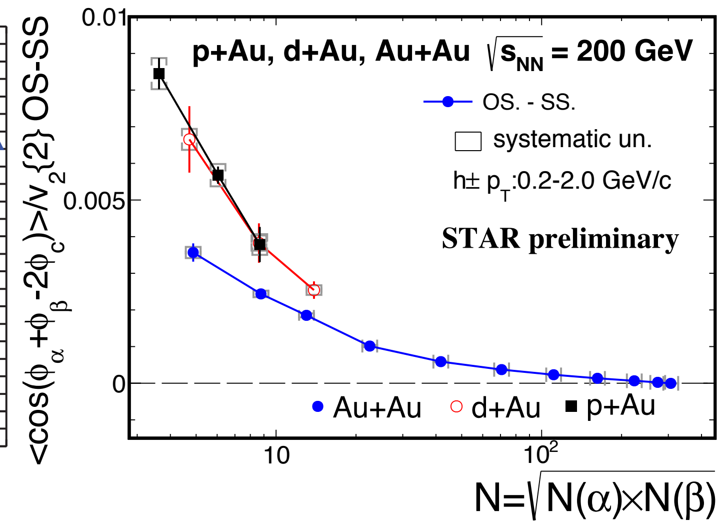
Background issue

STAR, PRL 103,251601 (2009); PRC 81,54908 (2010); PRC 88,64911 (2013)





STAR, PRC 89,044908 (2014)



Jie Zhao (STAR), ISMD2017

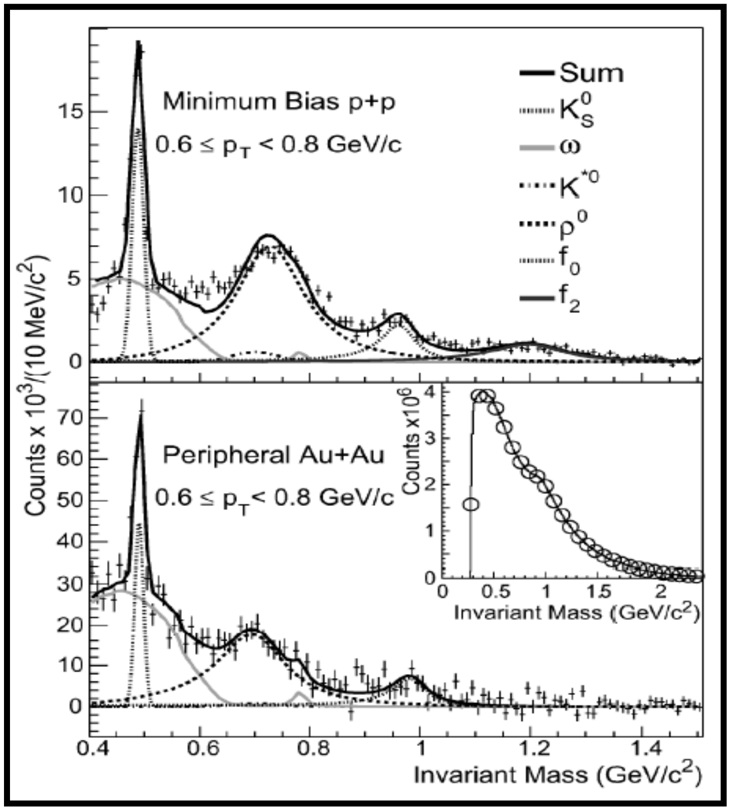
ϕ_α, ϕ_β, ϕ_c are the azimuthal angles of the charged particles measure by STAR TPC

- $\Delta\gamma = \gamma_{OS} - \gamma_{SS}$ correlator consistent with CME expectation
- Recent measurements of charge correlations suggest dominant, if not all, background contribution
- What is the background?

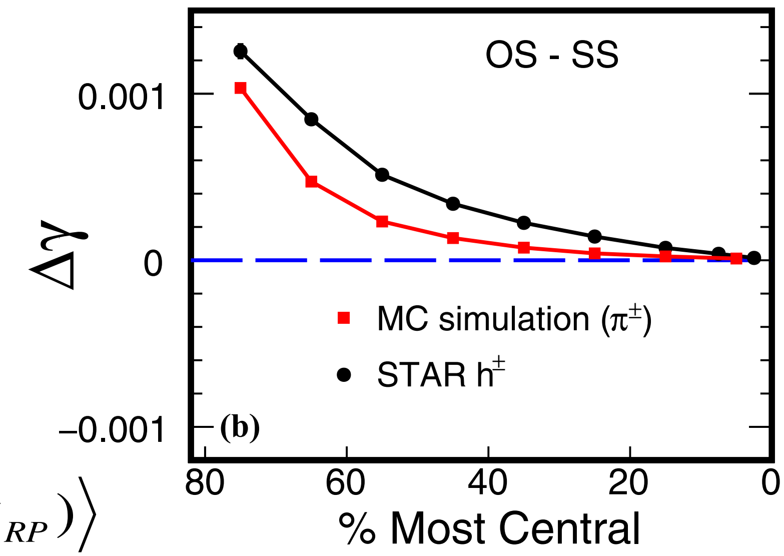
Resonance decay background

STAR, PRL 92,092301 (2004)

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



+ v_2 →



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

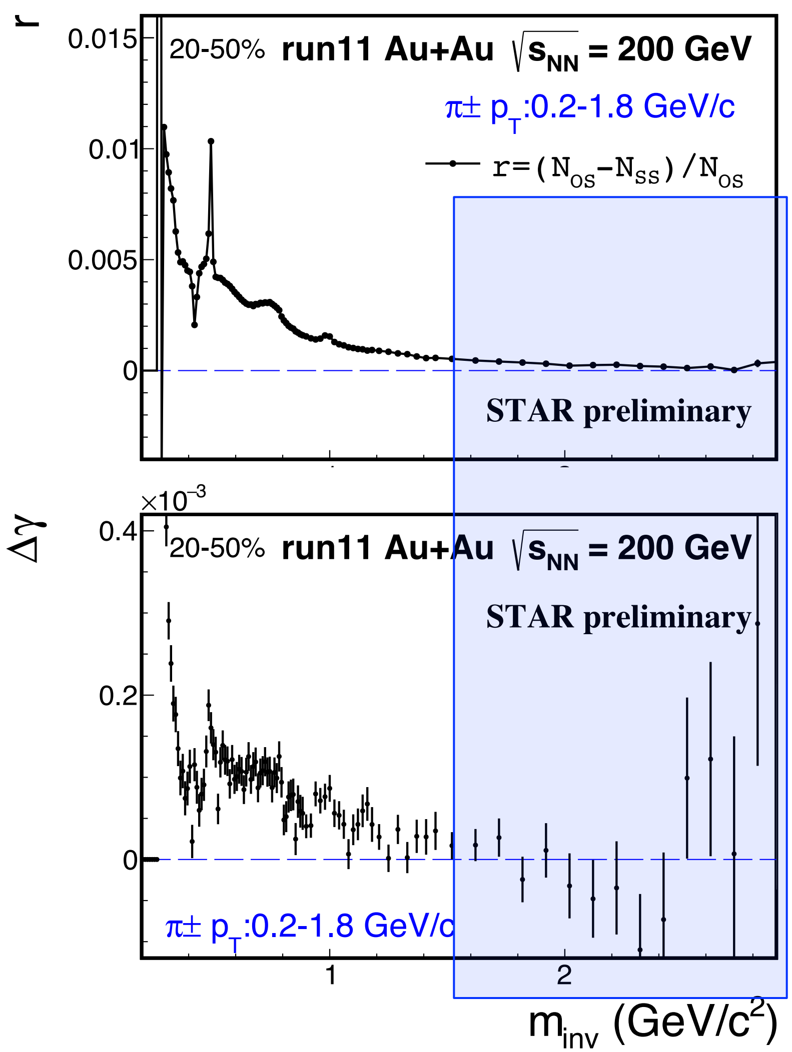
$$= \langle \cos(\phi_\alpha + \phi_\beta - 2\phi_{reso.} + 2\phi_{reso.} - 2\psi_{RP}) \rangle$$

$$\approx \langle \cos(\phi_\alpha + \phi_\beta - 2\phi_{reso.} \rangle \times v_{2,\,reso.}$$

- Resonance background: resonance decay + v_2 ➔ CME-like Δγ
- Can we remove/isolate the background?
- Exploiting invariant mass dependence of Δγ
- Δγ with respect to Ψ_{RP} and Ψ_{PP}

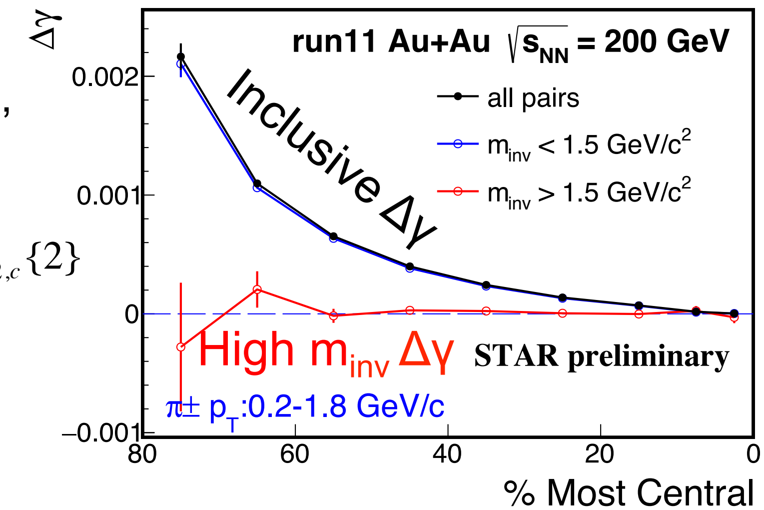
J. Zhao, *et al*, Eur. Phys. J. C (2019) 79:168
H.-J. Xu, *et al*, CPC 42 (2018) 084103

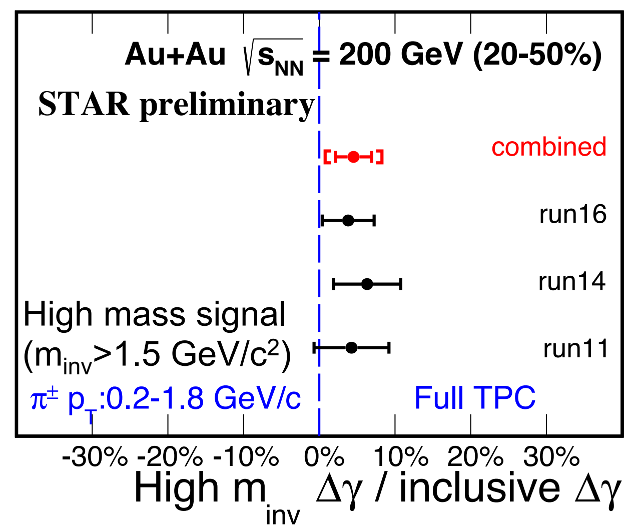
Identify resonance Bkg by $m_{inv}(\pi^+\pi^-)$



Full TPC acc. (|η|<1),
pion PID by TOF

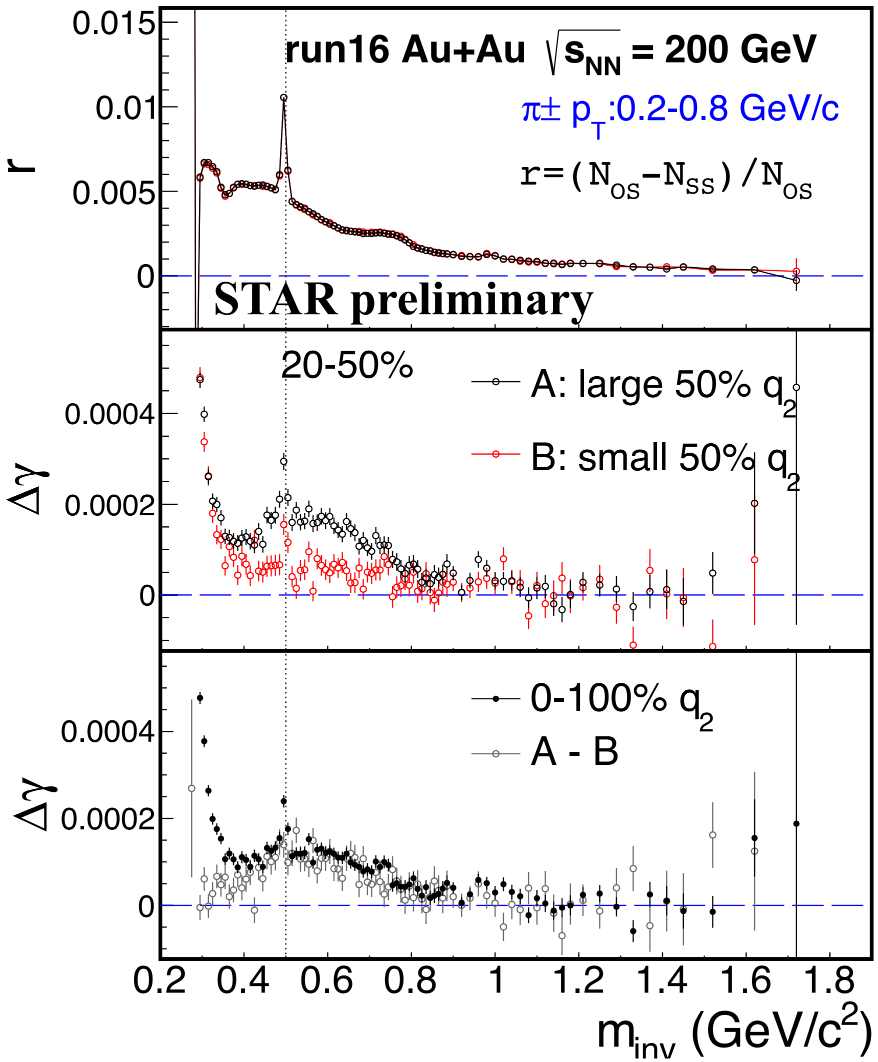
$$\gamma = \cos(\phi_\alpha + \phi_\beta - 2\phi_c) / v_{2,c}\{2\}$$



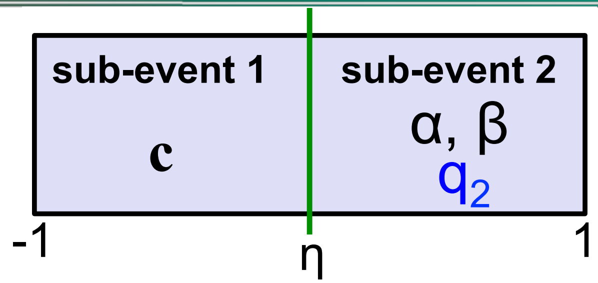


- Data show resonance structure in Δγ as function of invariant mass (m_{inv})
- At high m_{inv} >1.5 GeV/c², Δγ is (5±2±4)% of the inclusive Δγ in 200 GeV Au+Au 20-50%
- Systematic uncertainty currently estimated by run differences and different ways of combining runs (combine the Δγ first or the fractions directly)

Bkg shape by event shape engineering



Fit range m_{inv} from 0.4 to 1.5 GeV/c^2



$$\gamma = \cos(\phi_\alpha + \phi_\beta - 2\phi_c)/v_{2,c}\{2\}$$

$$\vec{q}_2 = \frac{1}{N}\sum(\cos 2\phi, \sin 2\phi)$$

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

Bkg Δγ mass shape

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

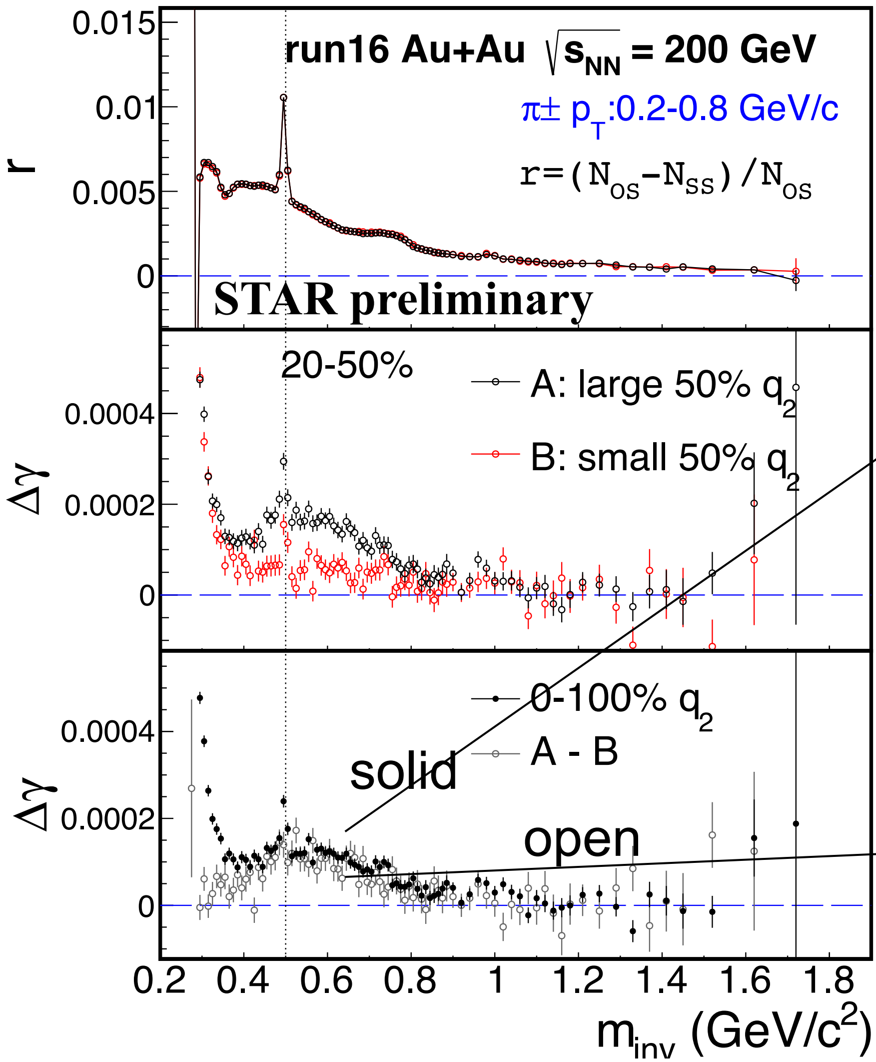
Bkg Δγ mass shape: $\Delta\gamma_A$-$\Delta\gamma_B$

CME the same for events from different q_2 classes

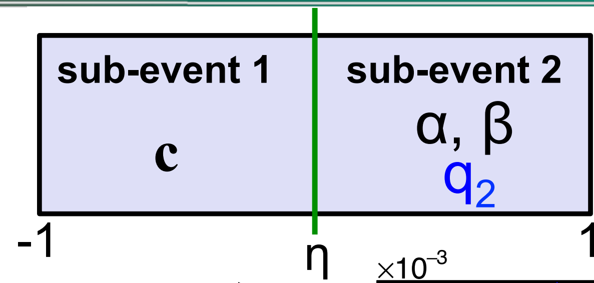
Fit $\Delta\gamma = k^*(\Delta\gamma_A-\Delta\gamma_B)$ + CME

- TPC sub-event, one side for ESE (other side for ref.), pion PID by TPC dE/dx
- Obtain the Bkg Δγ m_{inv} shape by event shape engineering (ESE)

Bkg shape by event shape engineering

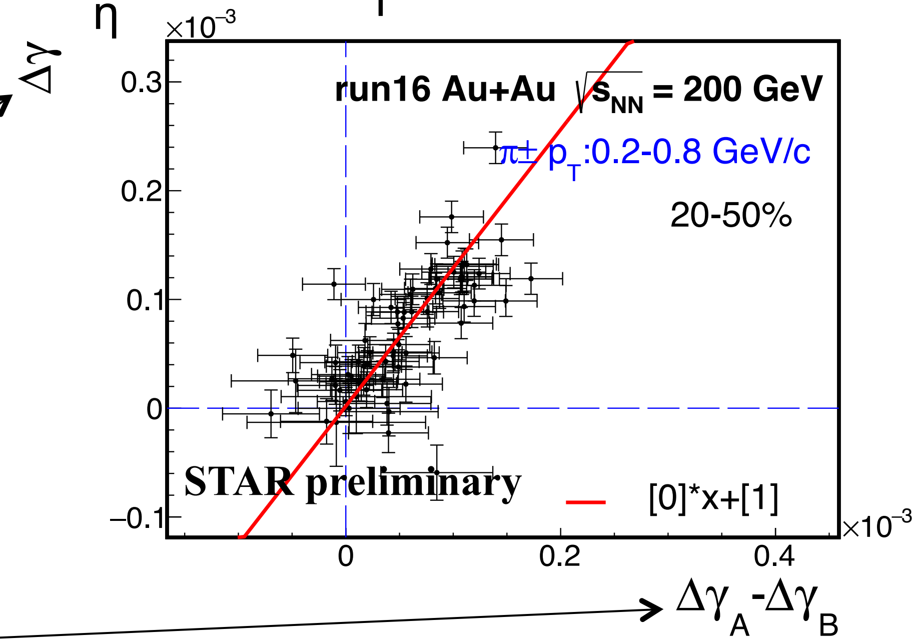


Fit range m_{inv} from 0.4 to 1.5 GeV/c^2



$$\gamma = \cos(\phi_\alpha + \phi_\beta - 2\phi_c)/v_{2,c}\{2\}$$

$$\vec{q}_2 = \frac{1}{N}\sum(\cos 2\phi, \sin 2\phi)$$



Bkg Δγ mass shape: **$\Delta\gamma_A$-$\Delta\gamma_B$**

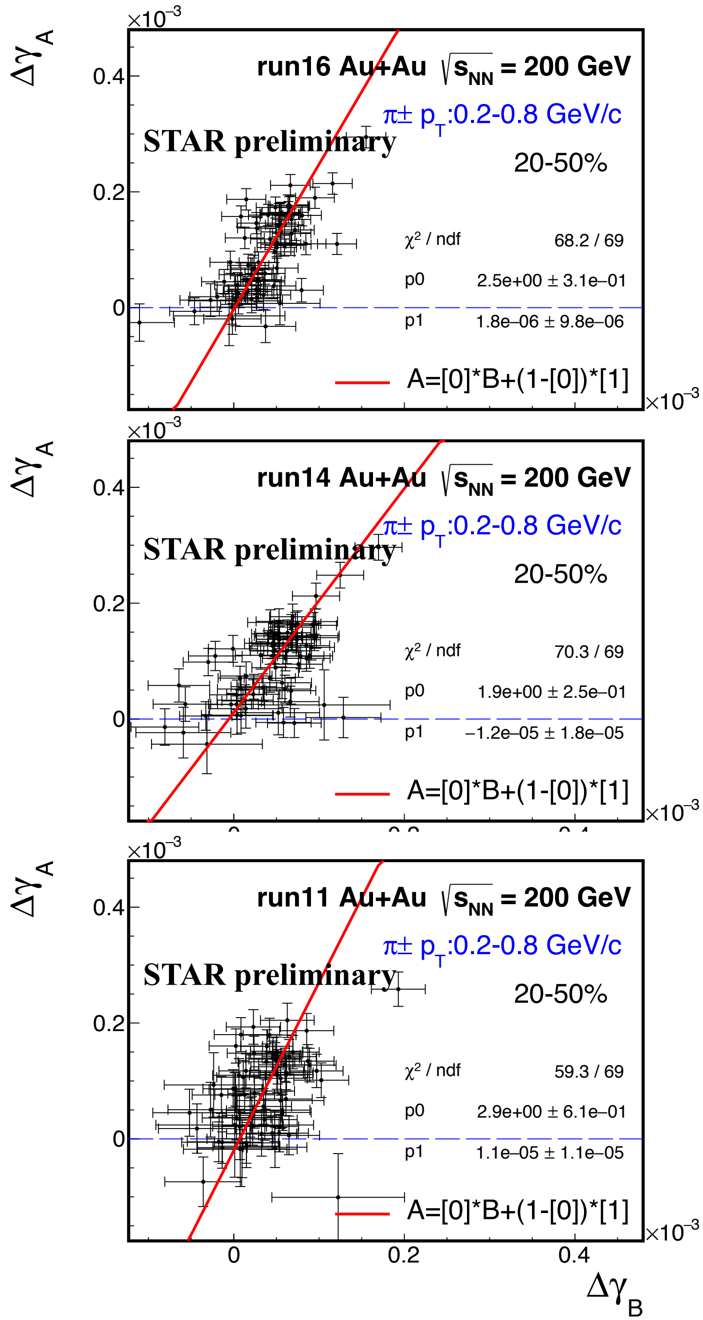
$\Delta\gamma = k^*(\Delta\gamma_A-\Delta\gamma_B)$ + CME

To properly handle errors, fit $\Delta\gamma_A$ vs. $\Delta\gamma_B$ with

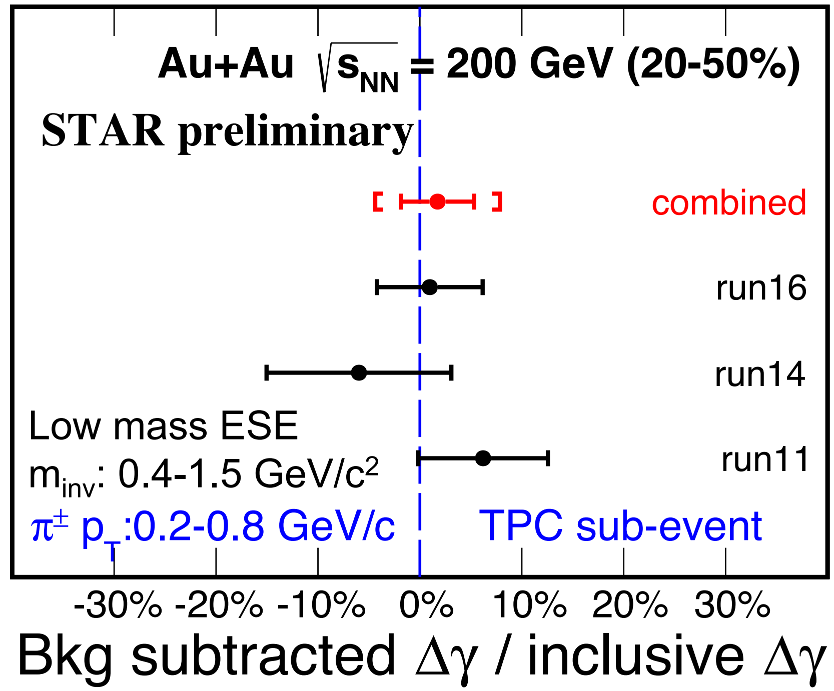
$\Delta\gamma_A=b^*\Delta\gamma_B+(1-b)^*$CME

- TPC sub-event, one side for ESE (other side for ref.), pion PID by TPC dE/dx
- Obtain the Bkg Δγ m_{inv} shape by event shape engineering (ESE)

Bkg + CME fit at low invariant mass



$\Delta\gamma_A = b*\Delta\gamma_B + (1-b)*CME$

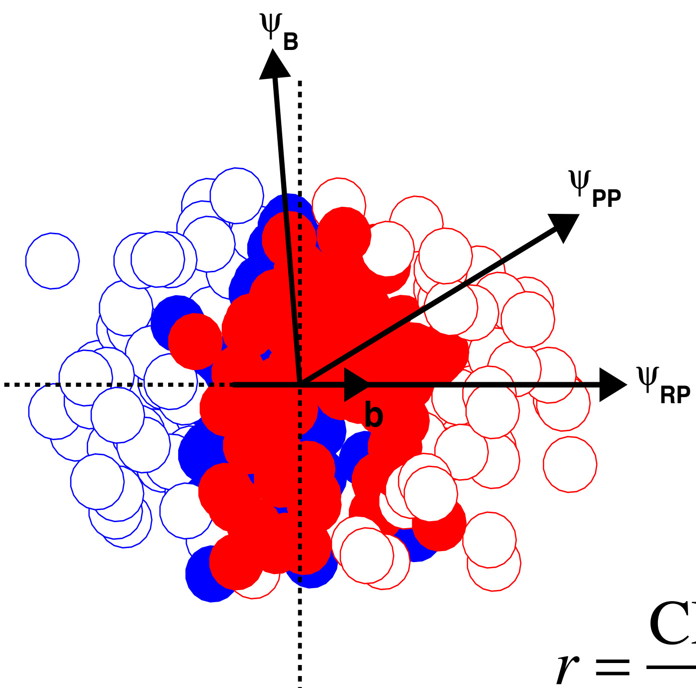


- Bkg subtracted Δγ / inclusive Δγ: (2±4±6)% in 200 GeV 20-50% Au+Au

Use Ψ_{PP} and Ψ_{RP} to solve Bkg and 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

H.-J. Xu, et al, CPC 42 (2018) 084103



$\Delta\gamma$ 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

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

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

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

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

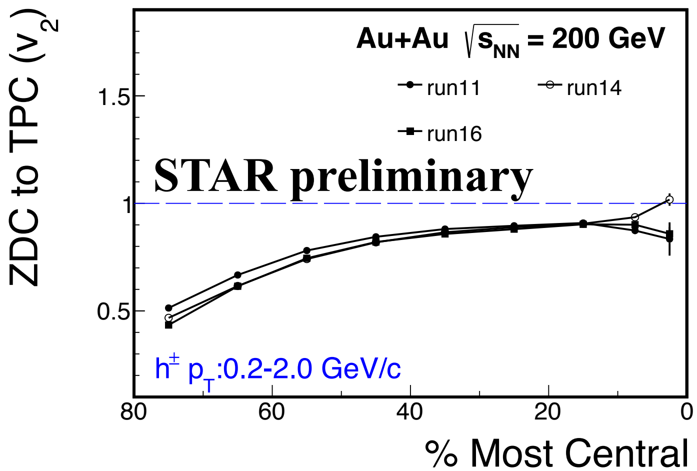
Both are experimental measurements

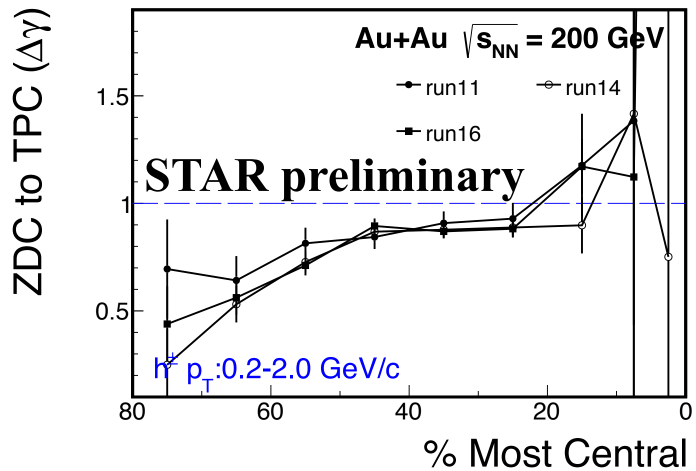
$$r = \frac{\mathrm{CME}\{\psi_{ZDC}\}}{\mathrm{Bkg}\{\psi_{TPC}\}} = \left(\frac{a-1}{a+1} - \frac{A-1}{A+1}\right) \Big/ \left(\frac{a-1}{a+1} + \frac{A-1}{A+1}\right) = \frac{A-a}{1-Aa}$$

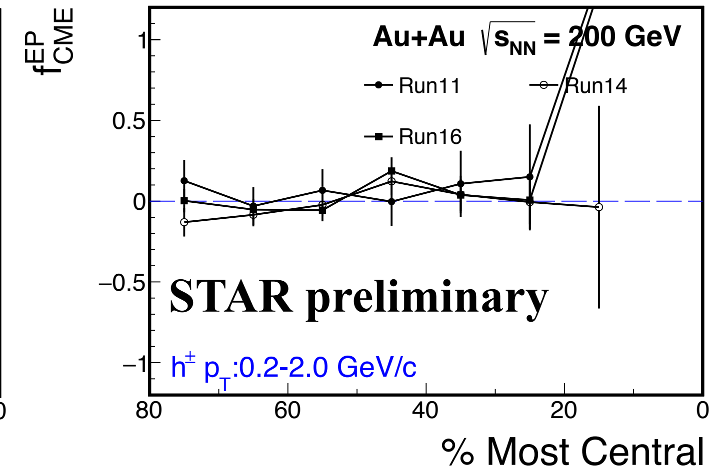
$$f_{EP}(\mathrm{CME}) = \mathrm{CME}\{\psi_{TPC}\} / \Delta\gamma\{\psi_{TPC}\} = r/(r+1/a) = (A/a-1)/(1/a^2-1)$$

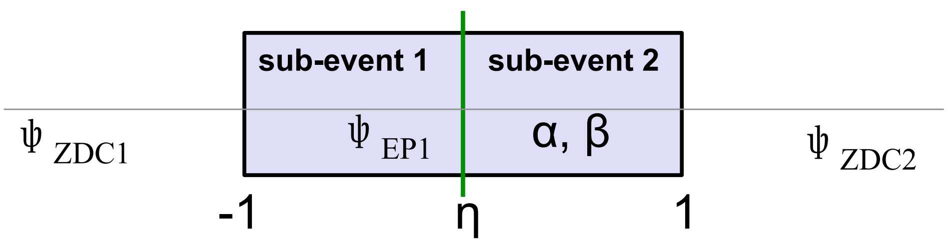
$\Delta\gamma$ with respect to Ψ_{PP} and Ψ_{RP}

TPC sub-event (east and west) method to reduce non-flow effects









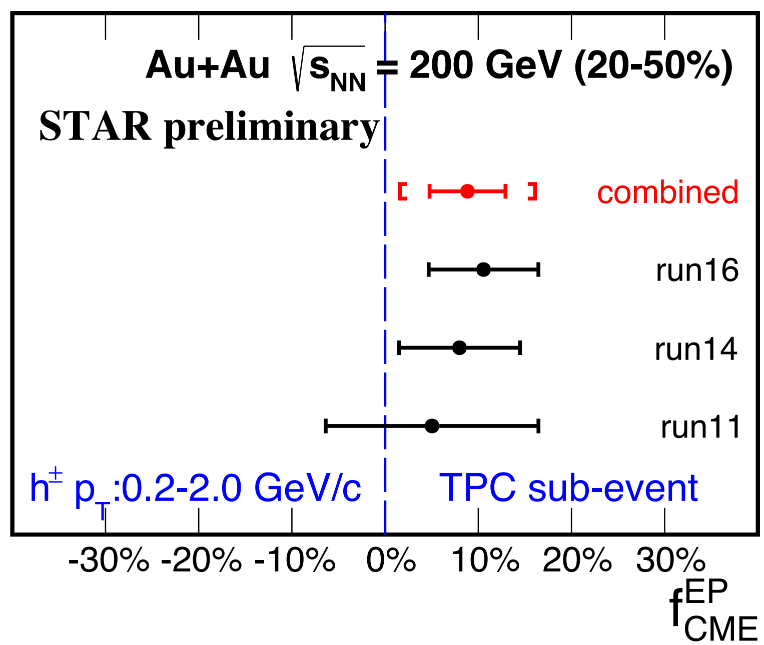
$\gamma = \cos(\phi_\alpha+\phi_\beta-2\psi)/R$, $v_2= \cos(2\phi -2\psi)/R$

$\Psi= \Psi_{PP}$ or Ψ_{RP}, R the corresponding resolution

Ψ_{PP} from TPC ψ_{EP1} ($-1<\eta<-0.075$) or ψ_{EP2} ($0.075<\eta<1$)

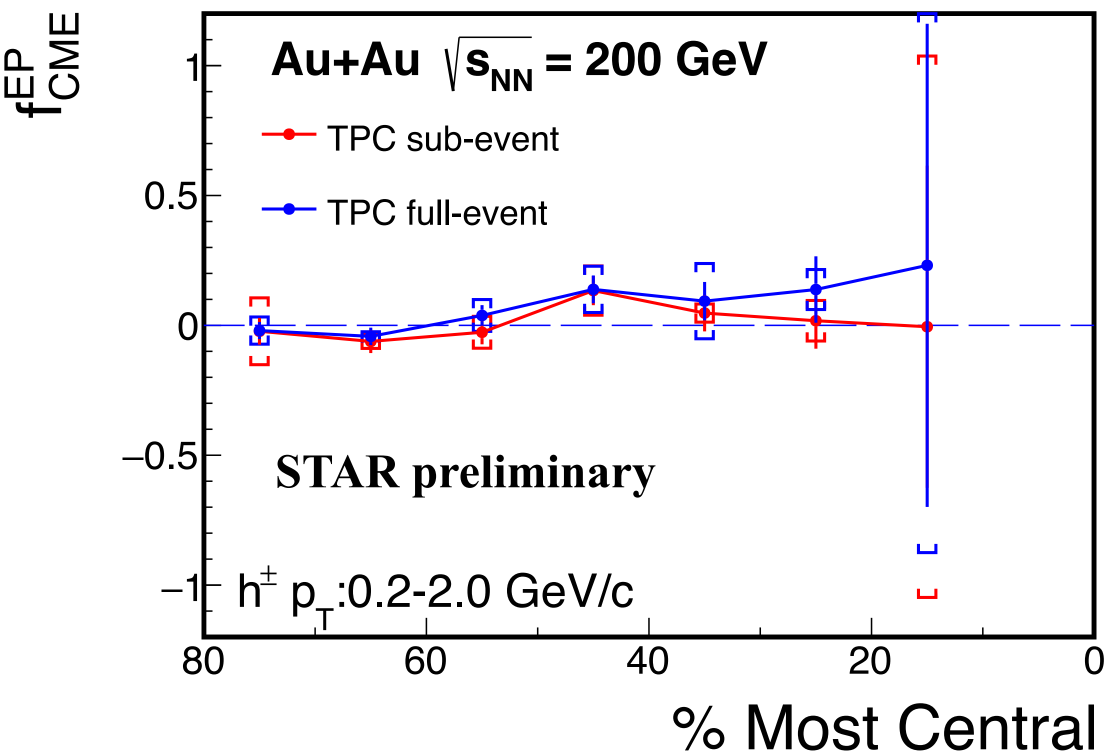
Ψ_{RP} from combined ZDC ψ_{zdc1} and ψ_{zdc2}

Poskanzer, Voloshin, PRC 58, 3 (1998);
STAR, PRC 86, 054908 (2012)



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

nevertheless also look at full TPC acceptance



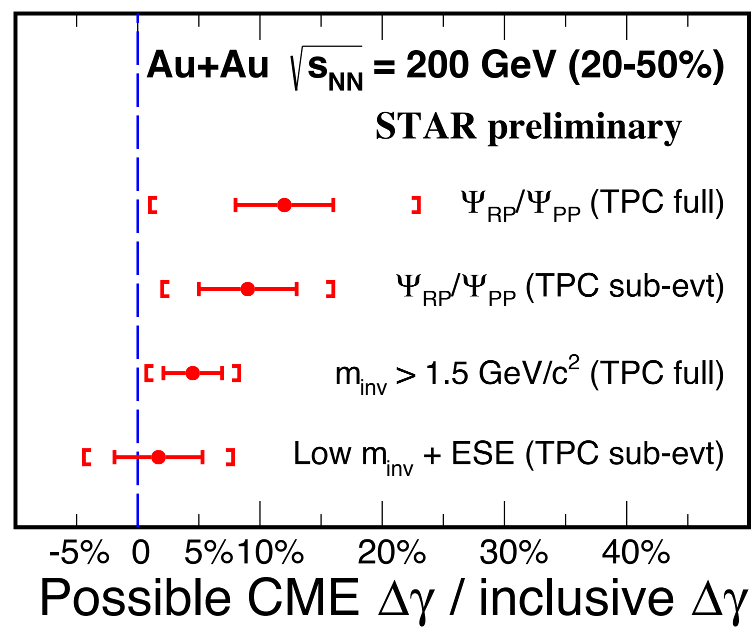
CME (EP) fraction	**20-50% centrality**
TPC sub-event	(9±4±7)%
TPC full-event	(12±4±11)%

- CME fractions are (9±4±7)% and (12±4±11)% from TPC sub-event and TPC full-event methods in 200 GeV 20-50% Au+Au collisions, respectively

Summary

- Identify resonance Bkg by $\pi\pi$ invariant mass.
  Observation of resonance structure in $\Delta\gamma$ at m_{inv}<1.5 GeV/c^2.
  Isolate the possible CME from Bkg by invariant mass + ESE.
- $\Delta\gamma$ with respect to Ψ_{PP} and Ψ_{RP}, isolate possible CME from Bkg

Year	Minbias events
Run11	~0.5B
Run14	~0.8B
Run16	~1.2B



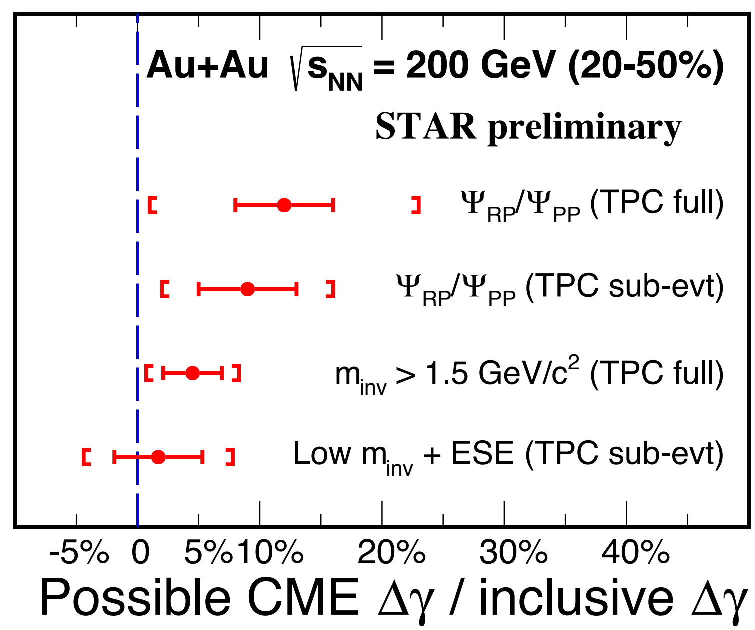
- These data-driven estimates indicate that:
  possible CME signal is small in $\Delta\gamma$, within 1-2σ from zero with the current precision

Summary

- Identify resonance Bkg by ππ invariant mass.
  Observation of resonance structure in Δγ at m_{inv}<1.5 GeV/c^2.
  Isolate the possible CME from Bkg by invariant mass + ESE.
- Δγ with respect to Ψ_{PP} and Ψ_{RP}, isolate possible CME from Bkg

Year	Minbias events
Run11	~0.5B
Run14	~0.8B
Run16	~1.2B

- More Au+Au data (+isobar)
- Consider ZDC upgrades for Ψ_{RP}



- These data-driven estimates indicate that:
  possible CME signal is small in Δγ, within 1-2σ from zero with the current precision