Chiral magnetic effect search in p+Au, d+Au and Au+Au collisions at RHIC

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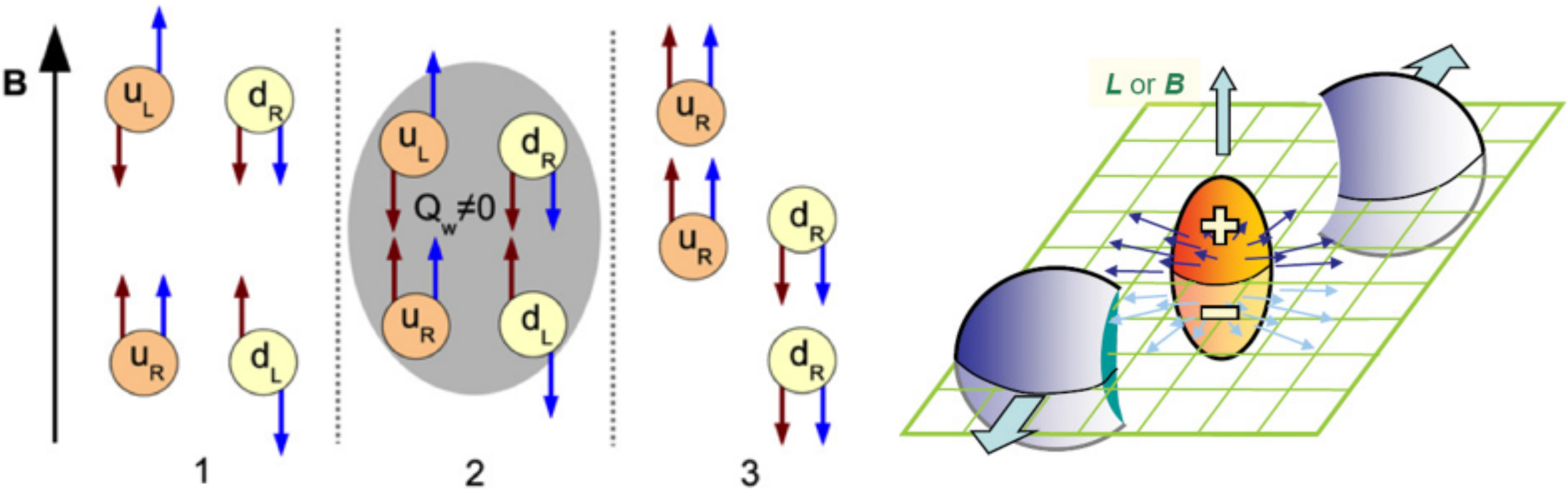
Outline

- Chiral Magnetic Effect (CME)
- CME in small systems
- RHIC-STAR experiment
- Results in p/d+A and A+A collisions
- Identification of backgrounds and possible CME
- Summary

Chiral Magnetic Effect (CME)

D. Kharzeev, etc. NPA 803, 227(2008)



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

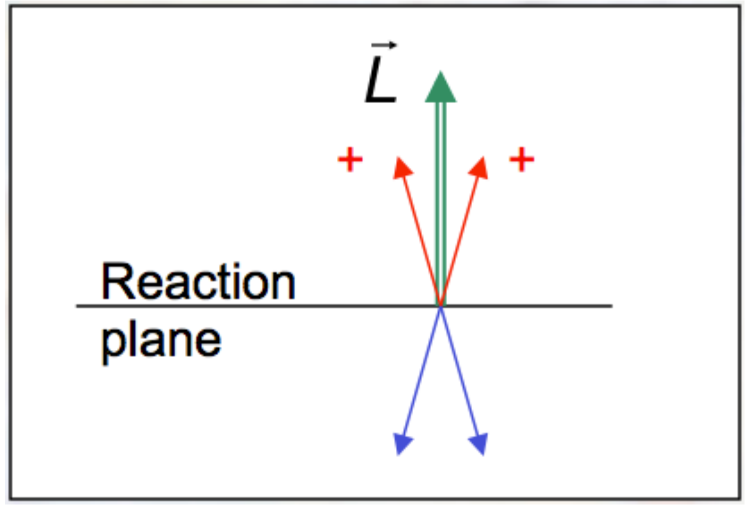
Configuration with non-zero topological charge (Q_w) converts left(right)-handed fermions to right(left)-handed fermions, generating electric current along B direction and leading to electric charge separation

Charged-Particle Azimuthal Correlations

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

Particle distribution effectively can be described by:

$$\frac{dN_\pm}{d\phi} \propto (1 + 2v_1\cos(\Delta\phi) + 2v_2\cos(2\Delta\phi) + \ldots + \\ + 2a_\pm \sin(\Delta\phi)), \quad (1)$$



slide from S. A. Voloshin

$a > 0$ preferential emission along the angular momentum, $a_+ = -a_-$.
The sign of Q_w **can vary** event to event and domain to domain -> one has to measure correlations, $\langle a_\alpha a_\beta \rangle$, P-even quantity (!) -- possibility of contribution from effects not related to P-violation

Predictions:

$a_+ = -a_-$

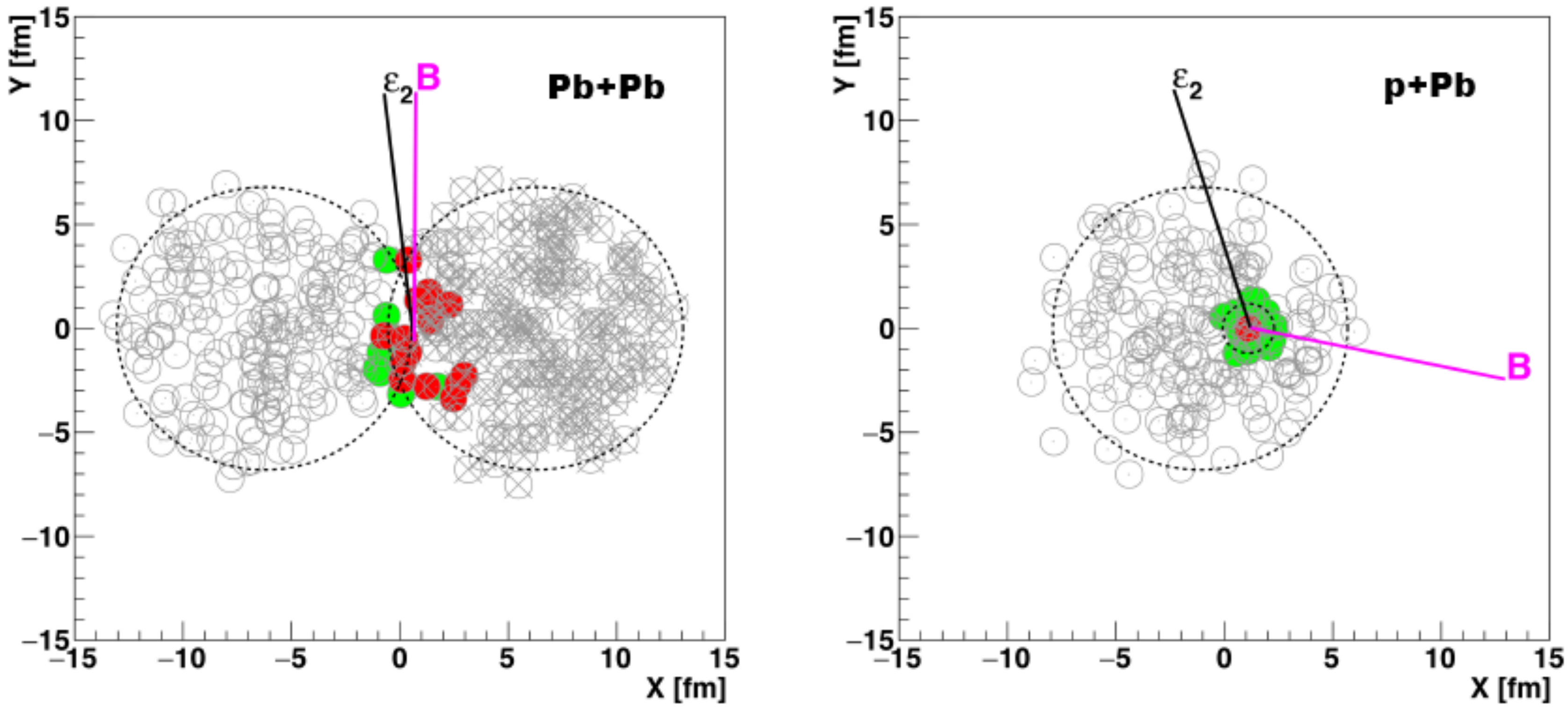
$a_+a_+ = a_-a_- = -a_+a_-$

$a \sim 10^{-2}$ for midcentral coll-ns

$$\langle\cos(\phi_\alpha + \phi_\beta - 2\Psi_{RP})\rangle = \\ = \langle\cos(\phi_\alpha - \Psi_{RP})\cos(\phi_\beta - \Psi_{RP})\rangle - \langle\sin(\phi_\alpha - \Psi_{RP})\sin(\phi_\beta - \Psi_{RP})\rangle \\ \approx (v_{1,\alpha}v_{1,\beta} - a_\alpha a_\beta)$$

Harmonic planes in small systems

CMS collaboration, PRL 118(2017)122301; R. Belmont and J.L. Nagle, arXiv:1610.07964v1

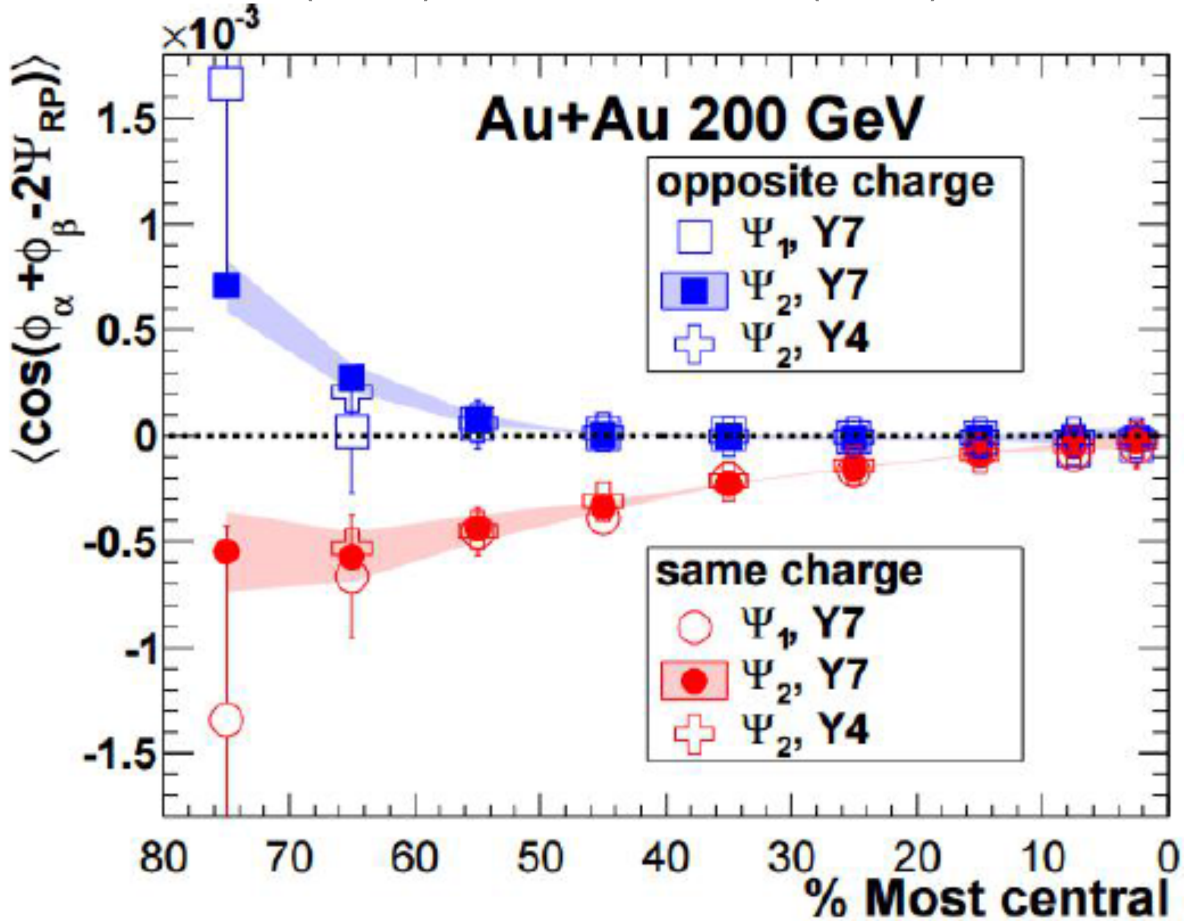


Ψ_2: second order event plane; Ψ_1: first order event plane

- Ψ_2 related to flow, related to -> flow background
- Ψ_1 related to the magnetic direction (B), useful for -> CME signal
- Ψ_1 and Ψ_2 correlated in A+A, signal and background entangled
- Ψ_1 and Ψ_2 not correlated in p+A, d+A, signal and background disentangled

Charge dependent signal at RHIC

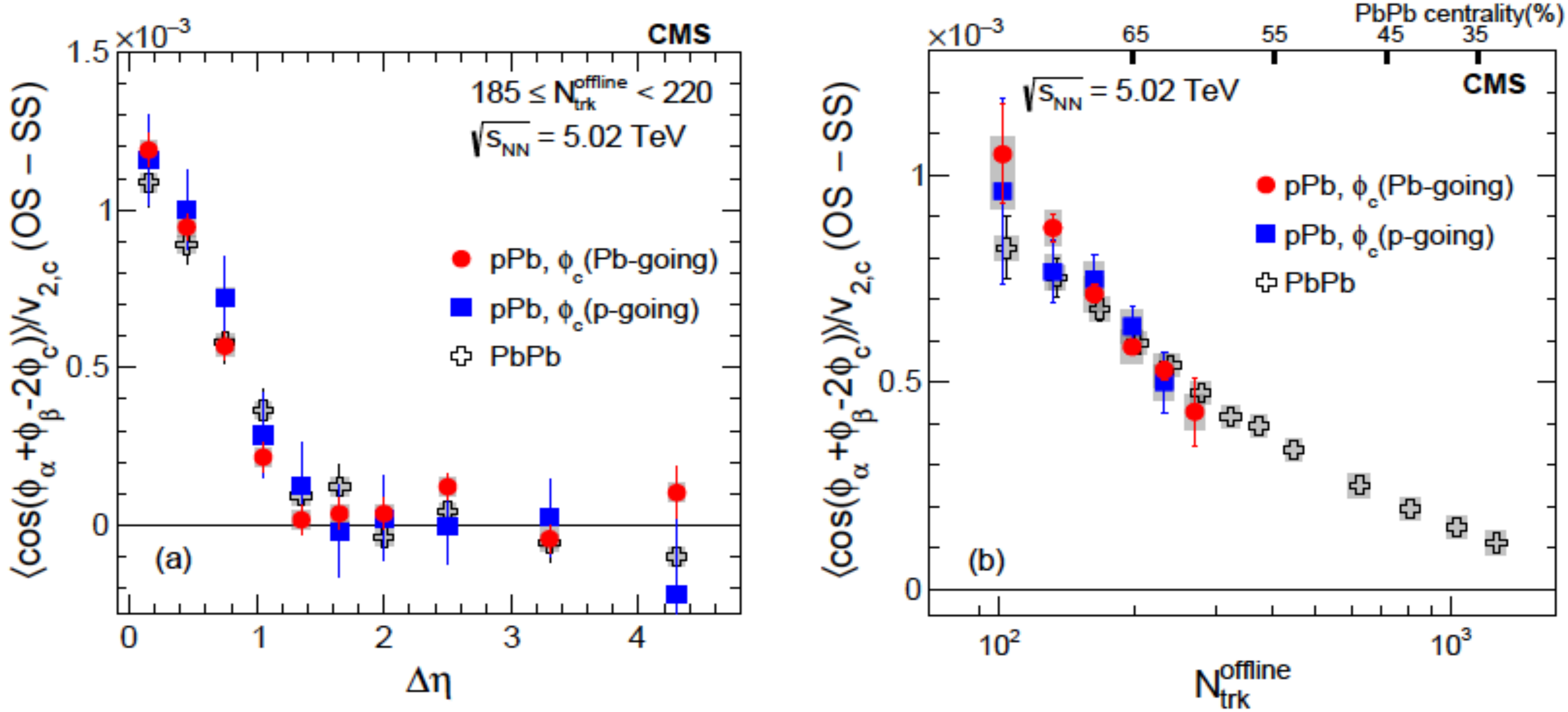
STAR collaboration, PRL 103(2009)251601; PRC 81(2010)54908; PRC 88 (2013) 64911



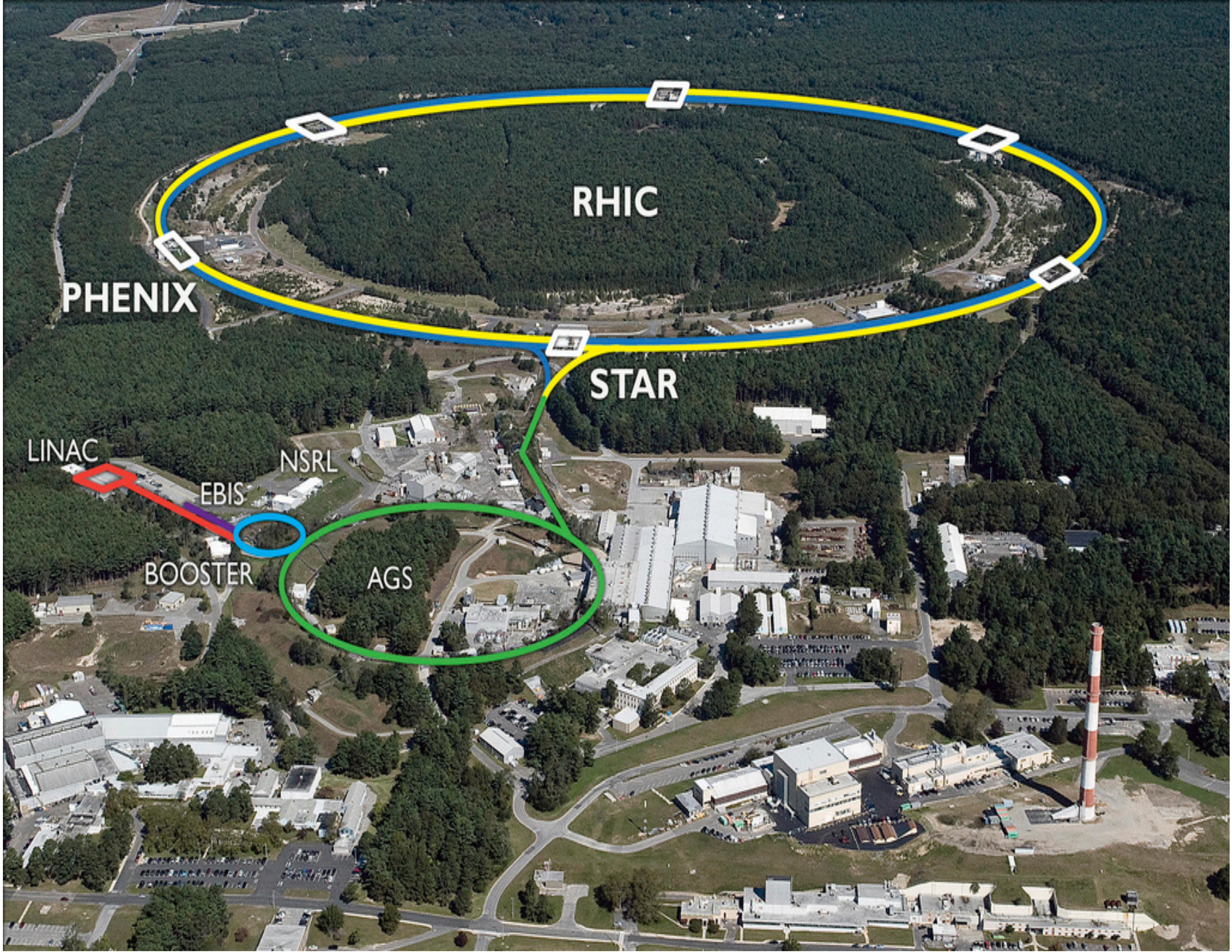
- ➢ Correlator indicates charge dependent signal
- ➢ Consistent between different years (2004 and 2007)
- ➢ Consistent with the 1st-order EP (from spectator neutron v_1)

Charge dependent signal by CMS

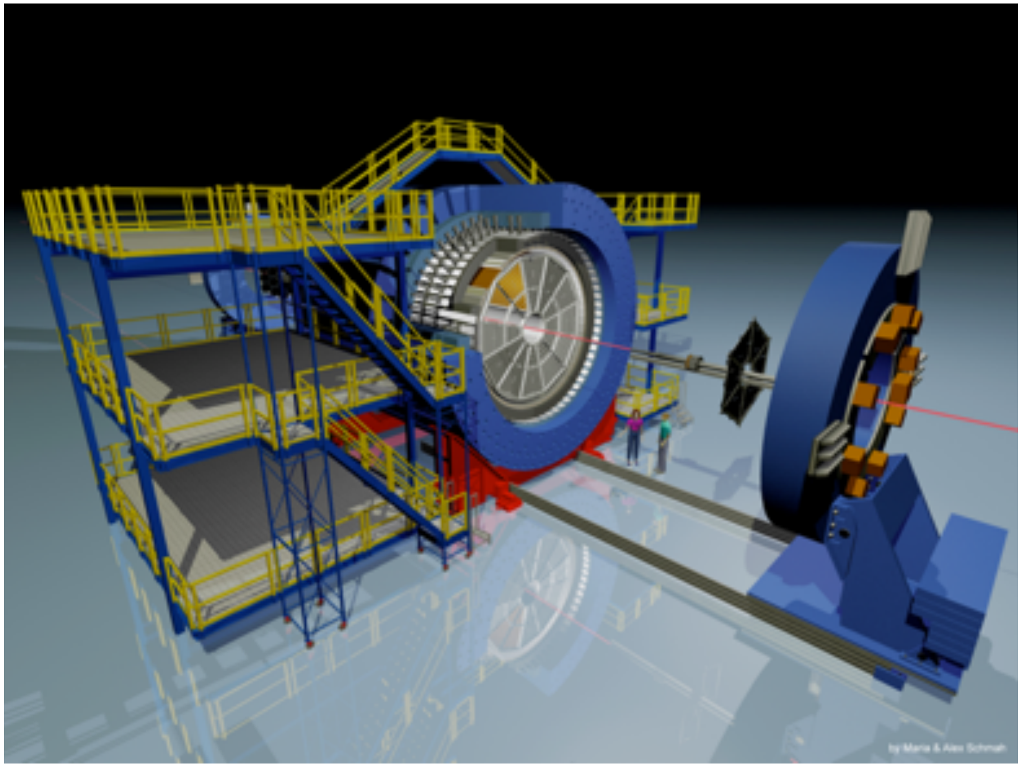
CMS collaboration, PRL 118(2017)122301

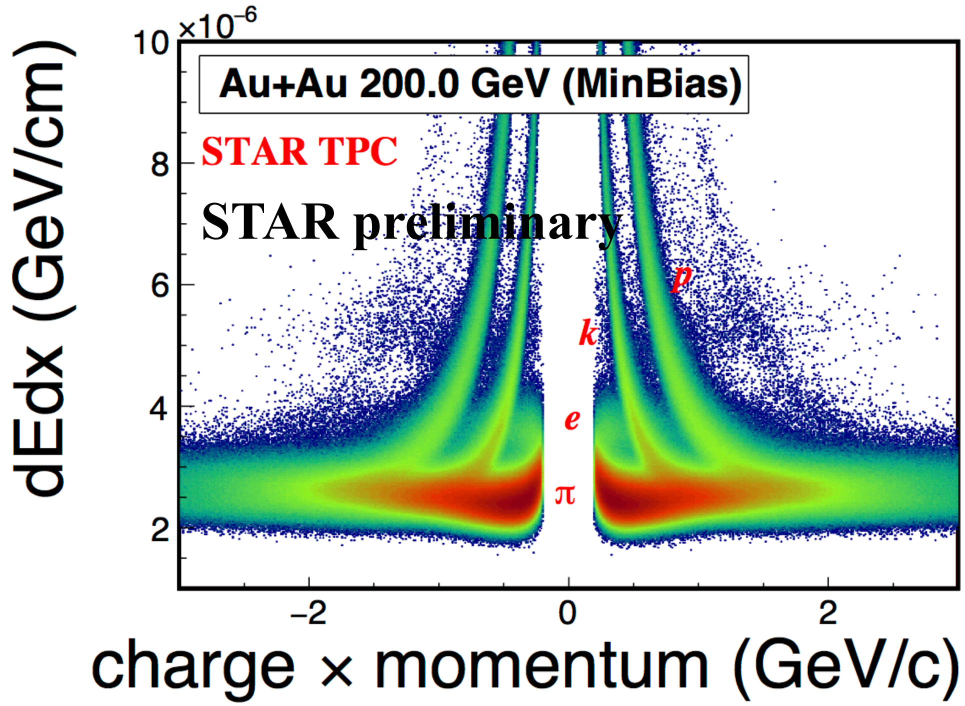


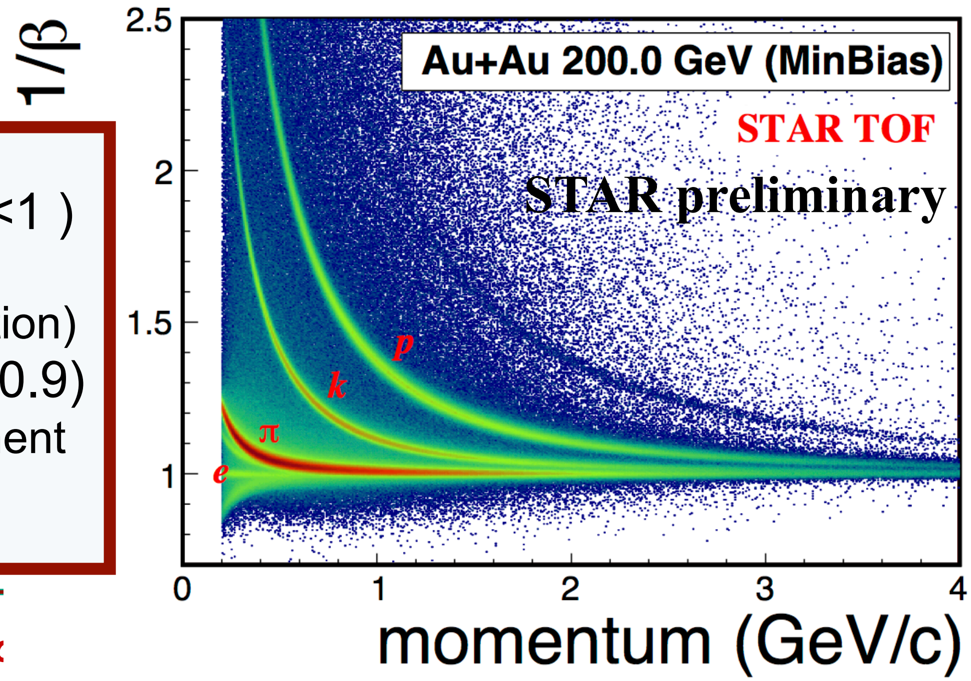
- "The observed signal as functions of multiplicity and η gap, are of similar magnitude in p+Pb and Pb+Pb collisions at the same multiplicities"
- "The results pose a challenge for the interpretation of charge-dependent azimuthal correlations in heavy-ion collisions in terms of the CME"
- There might be energy dependent difference, more studies at RHIC


RHIC
PHENIX
STAR
LINAC
NSRL
EBIS
BOOSTER
AGS

STAR detector

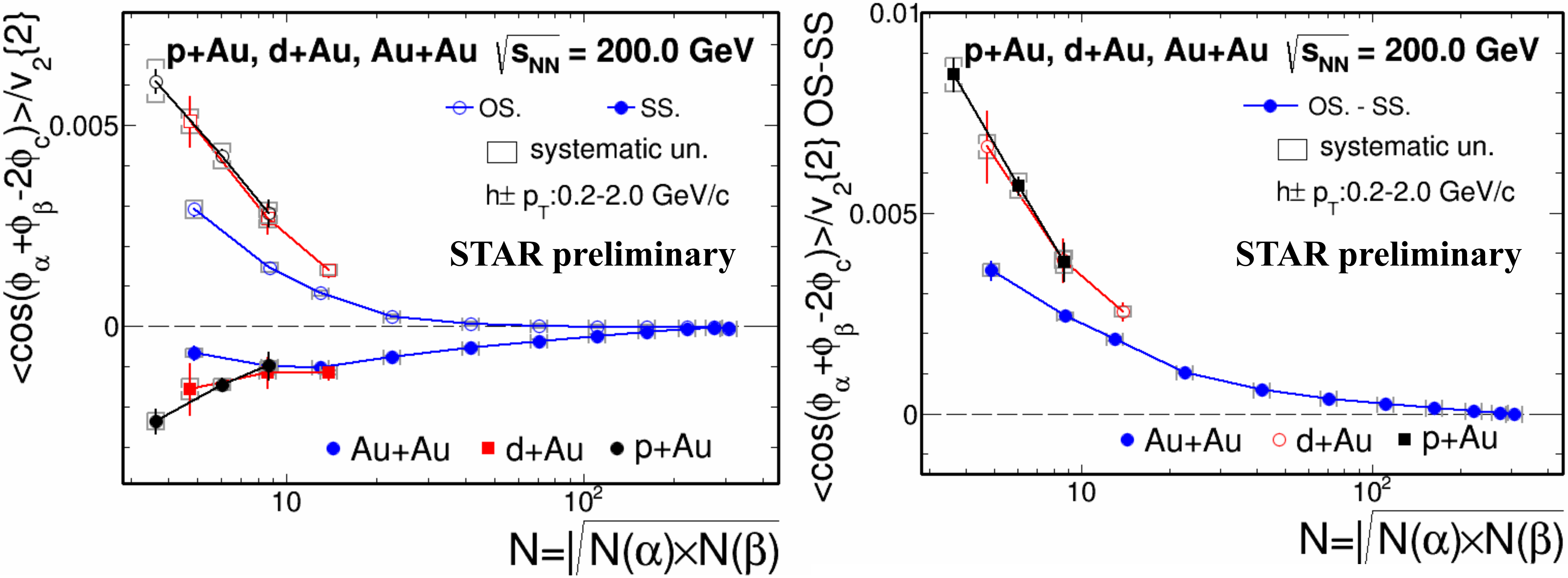






- **Time Projection Chamber** ($0<\phi<=2\pi$, $|\eta|<1$)
  Tracking – momentum
  Ionization energy loss – dE/dx (particle identification)
- **Time Of Flight detector** ($0<\phi<=2\pi$, $|\eta|<0.9$)
  Timing resolution <100ps - significant improvement for PID

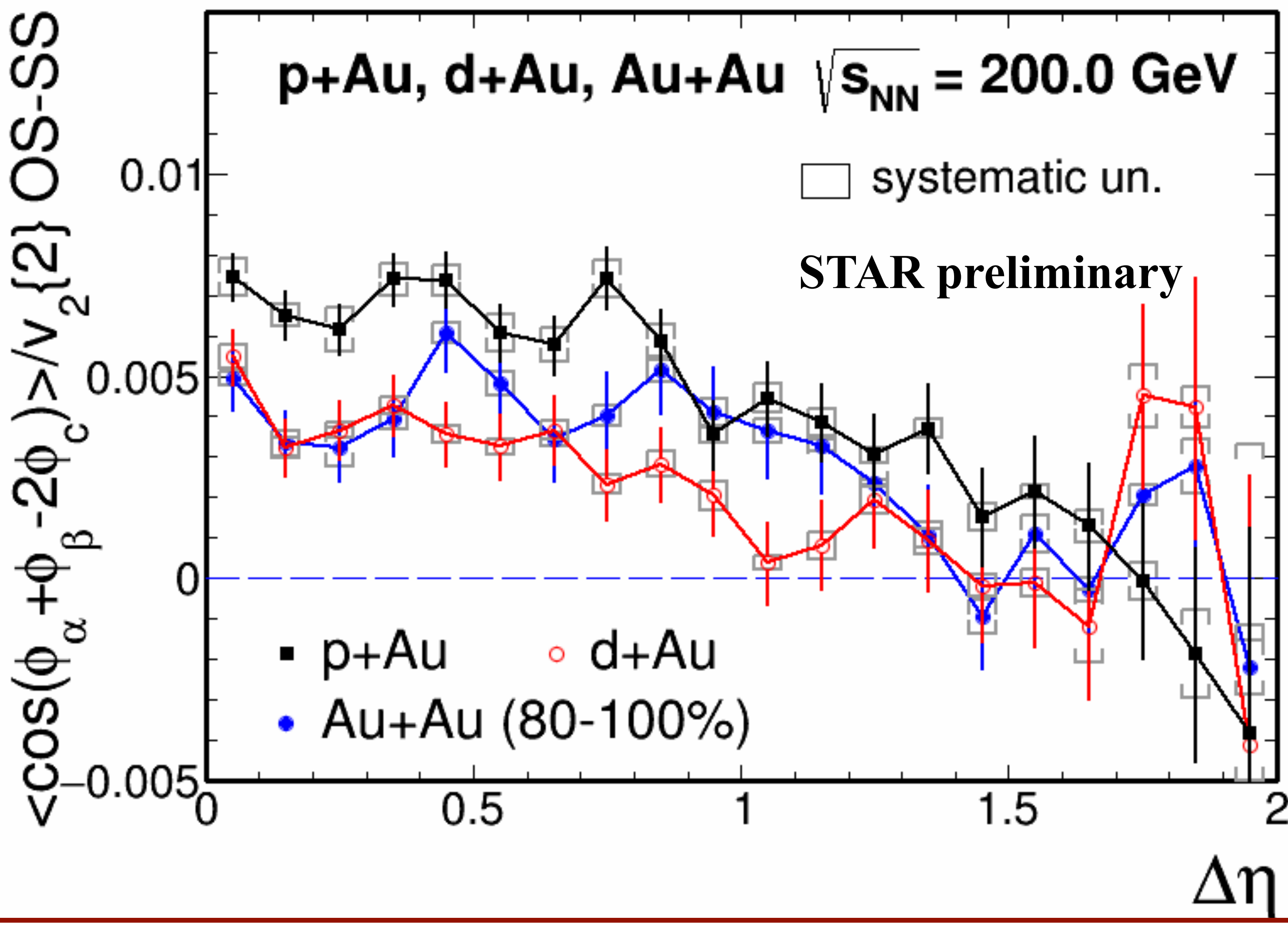
Multiplicity dependence in small systems



N(α/β) represents the charged(+/-) particle multiplicity used for the correlator

- Sizeable charge dependent signal in small system p+Au and d+Au collisions with respect to second order event plane Ψ_2
- $v_2\{2\}$ with η gap of 1.0

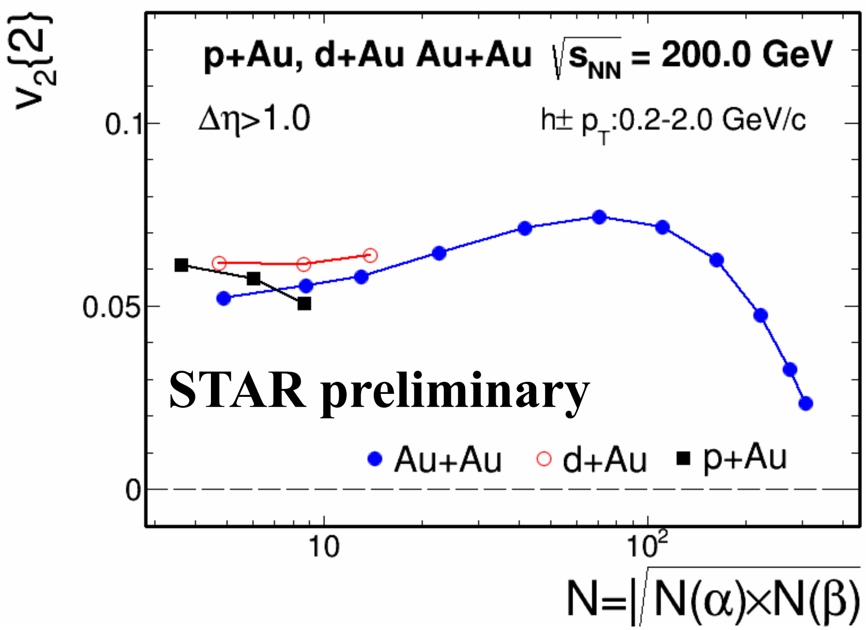
Rapidity-gap dependence in small systems

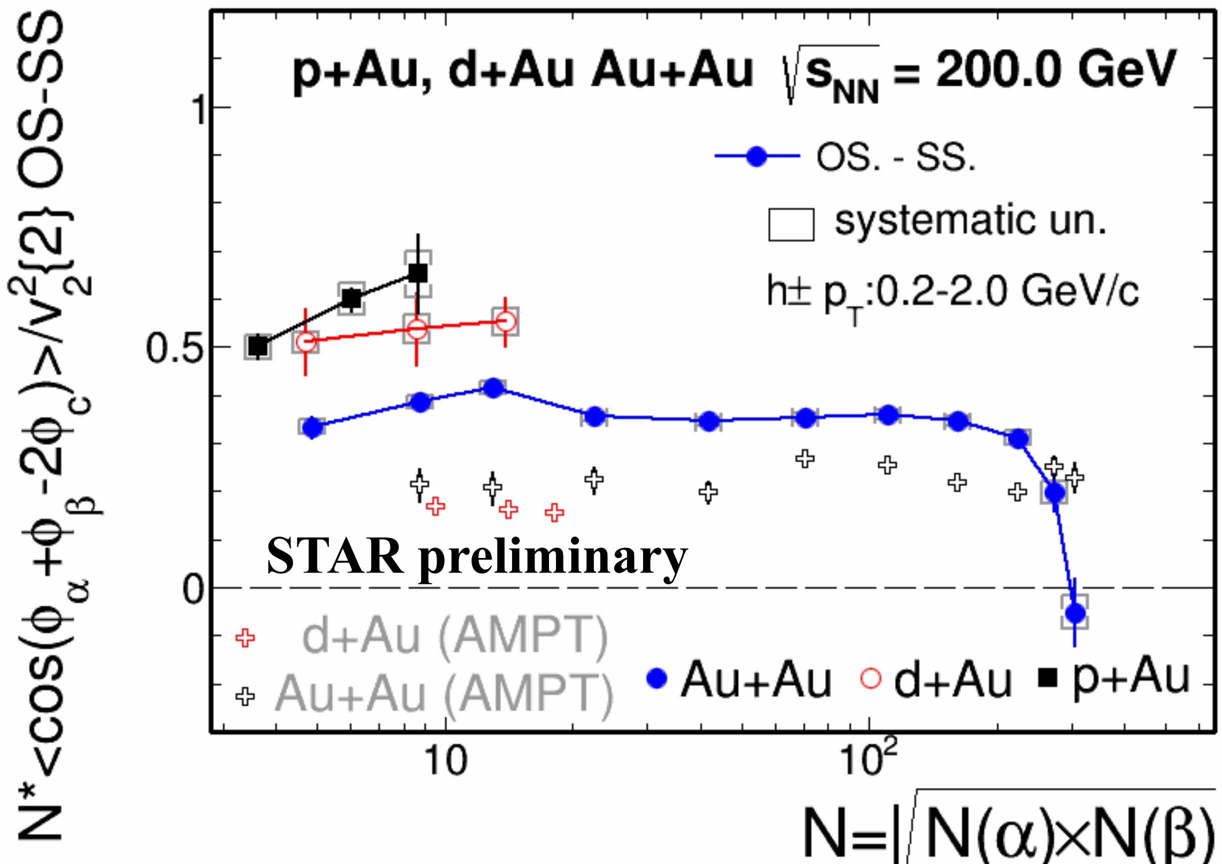


- ➢ Correlator as a function of the η gap between the two charged particles in p+Au, d+Au and peripheral Au+Au collisions
- ➢ Peripheral Au+Au data are similar to those of p+Au and d+Au

Multiplicity dependence

$v_2\{2\}$ with eta gap of 1.0





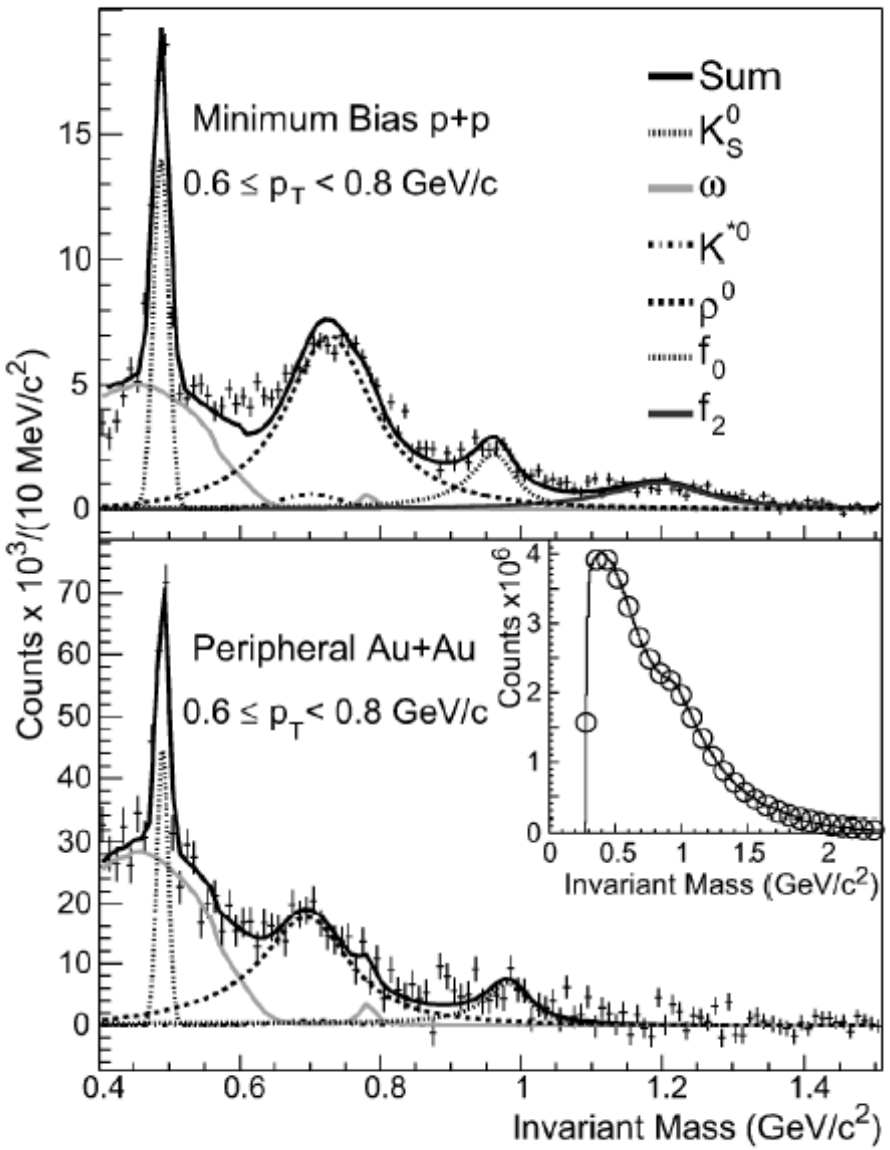
- Background expectation: N dilution, proportional to flow $v_2\{2\}$
- Right plot: if intrinsic particle pair-wise correlation is independent of N, background scenario would yield a constant as a function of N
- With topological charge sign fluctuations and magnetic field direction fluctuations, CME might yield different multiplicity dependence

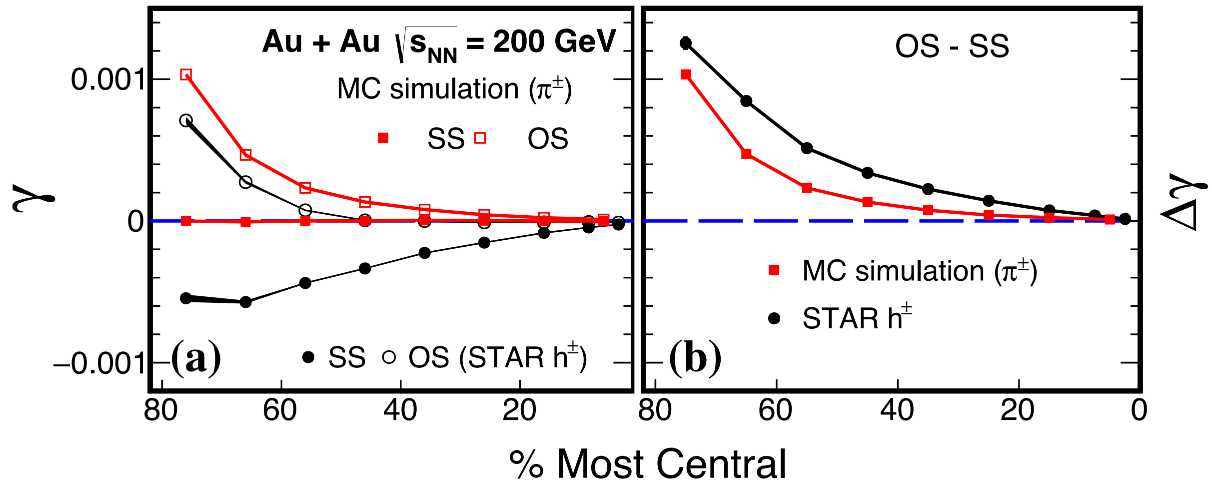
Identify the backgrounds

Resonance decay background

Fuqiang Wang, Jie Zhao, Phys.Rev.C 95,051901(R) (2017)

STAR, Phys.Rev.Lett.92,092301 (2004)





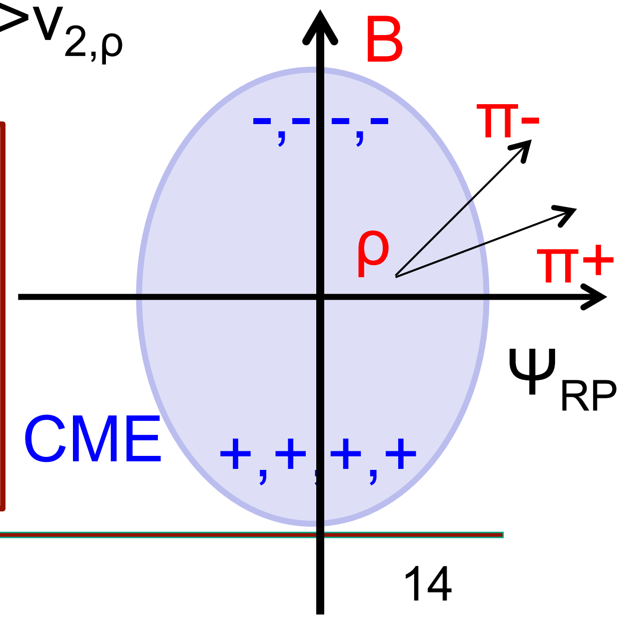
Resonance decay:

$\Delta\gamma = \cos(\alpha+\beta-2\Psi_{RP})$

$\propto \langle\cos(\alpha+\beta-2\phi_\rho)\rangle \cos2(\phi_\rho-\psi_{RP})$

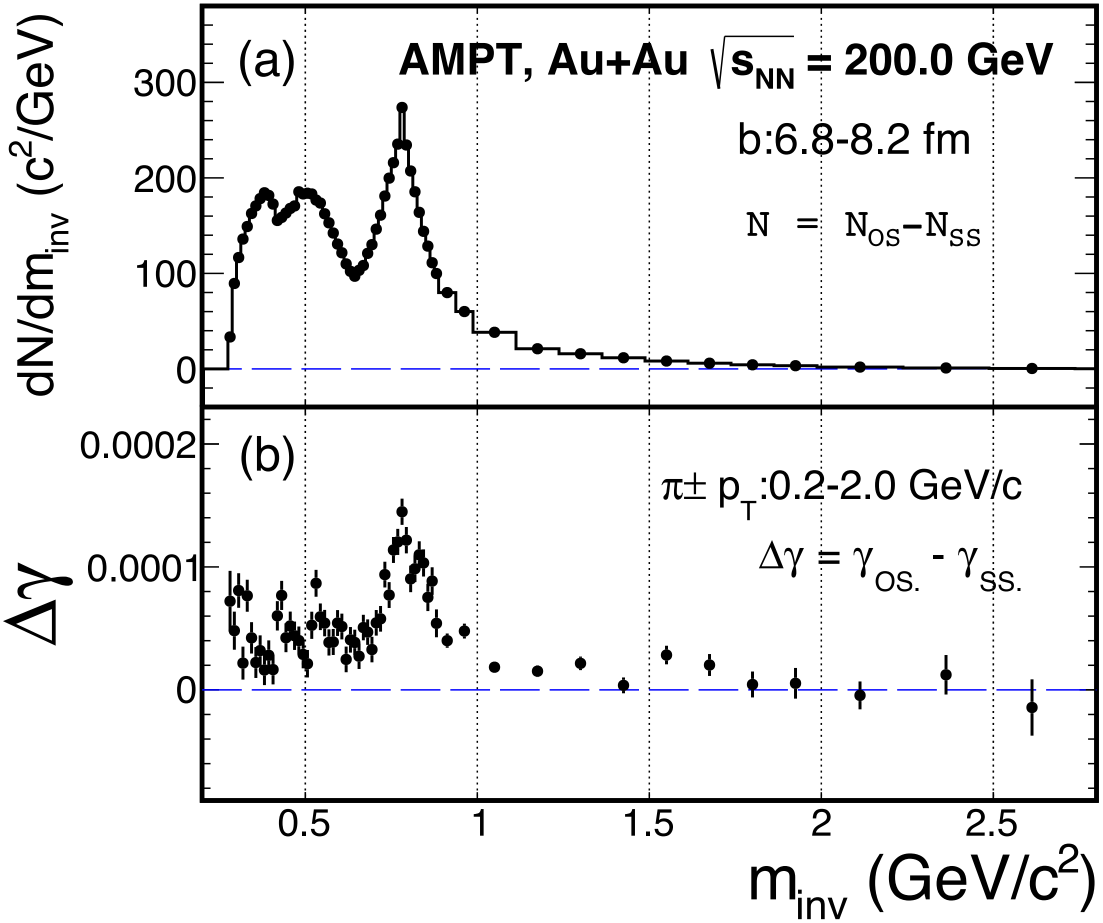
$\approx \langle\cos(\alpha+\beta-2\phi_\rho)\rangle v_{2,\rho}$

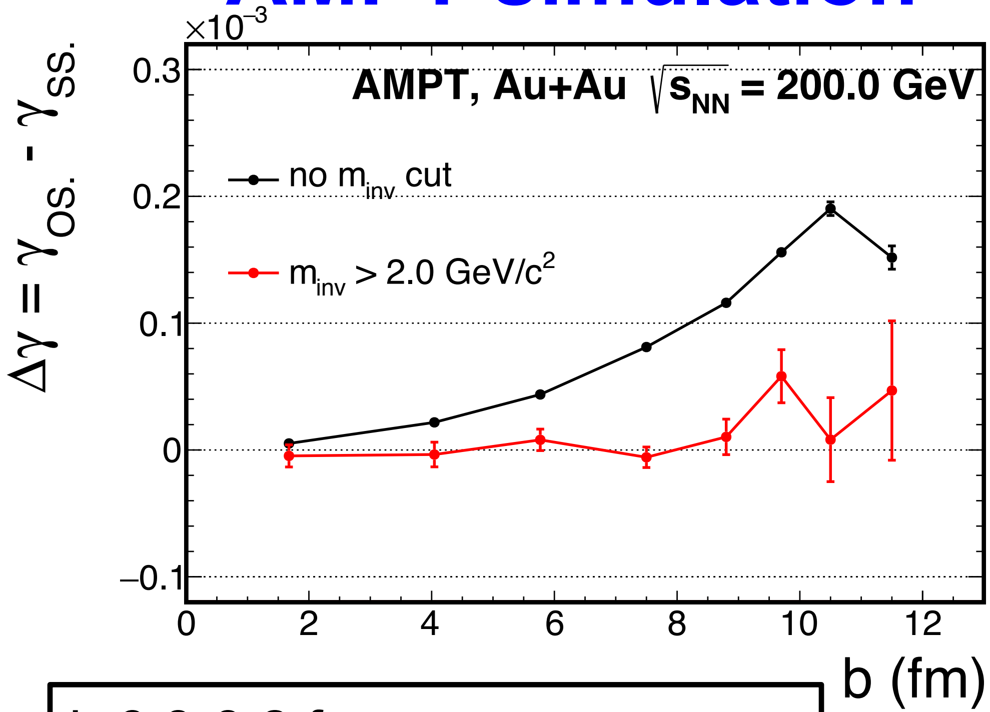
Resonance bkg.:
resonance decay coupled with v_2, will give a CME-like $\Delta\gamma$ signal



Identify resonance bkg. by invariant mass

AMPT simulation





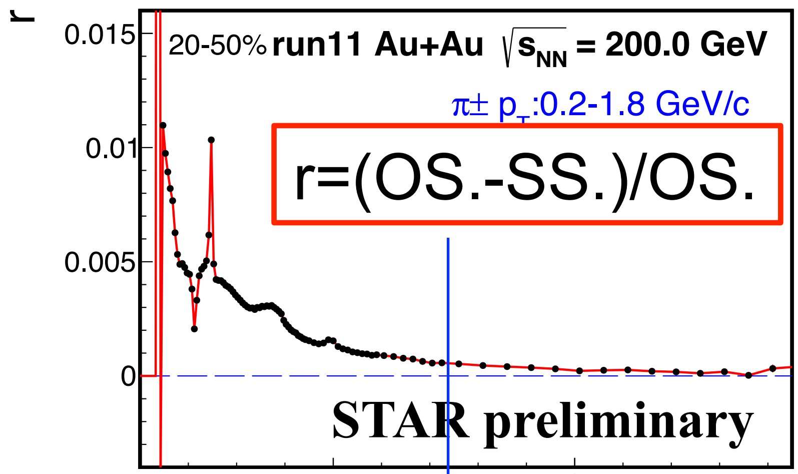
b:6.8-8.2 fm

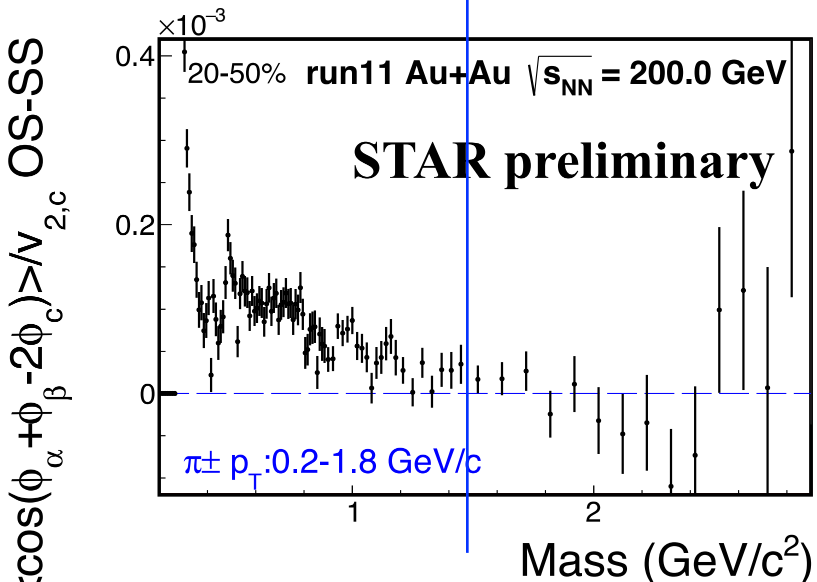
$\Delta\gamma$: $(81.2\pm1.2)\times10^{-6}$

$m>2$GeV/c^2: $(-5.8\pm8.1)\times10^{-6}$

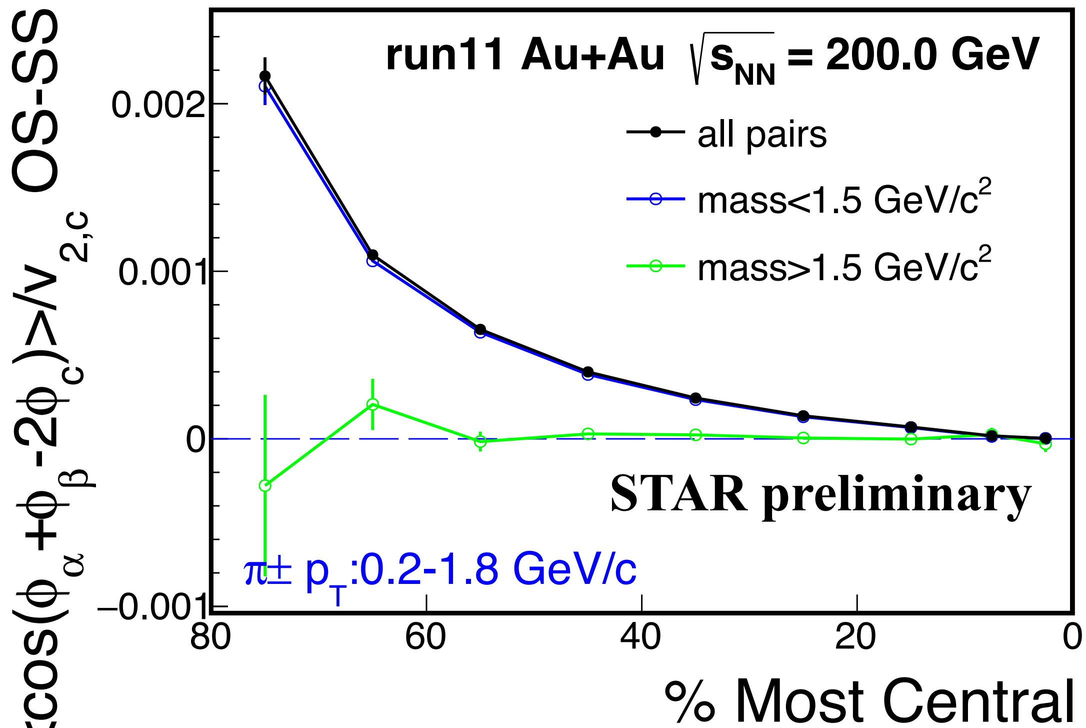
- AMPT has no CME, only background
- AMPT show resonance structure in Δγ as function of mass
- At large mass with smaller abundance difference between the unlike-sign and like-sign pairs, Δγ consistent with zero

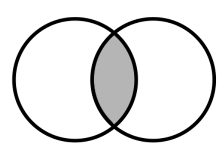
Identify resonance bkg. by invariant mass

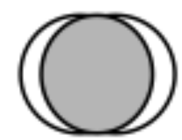




STAR data



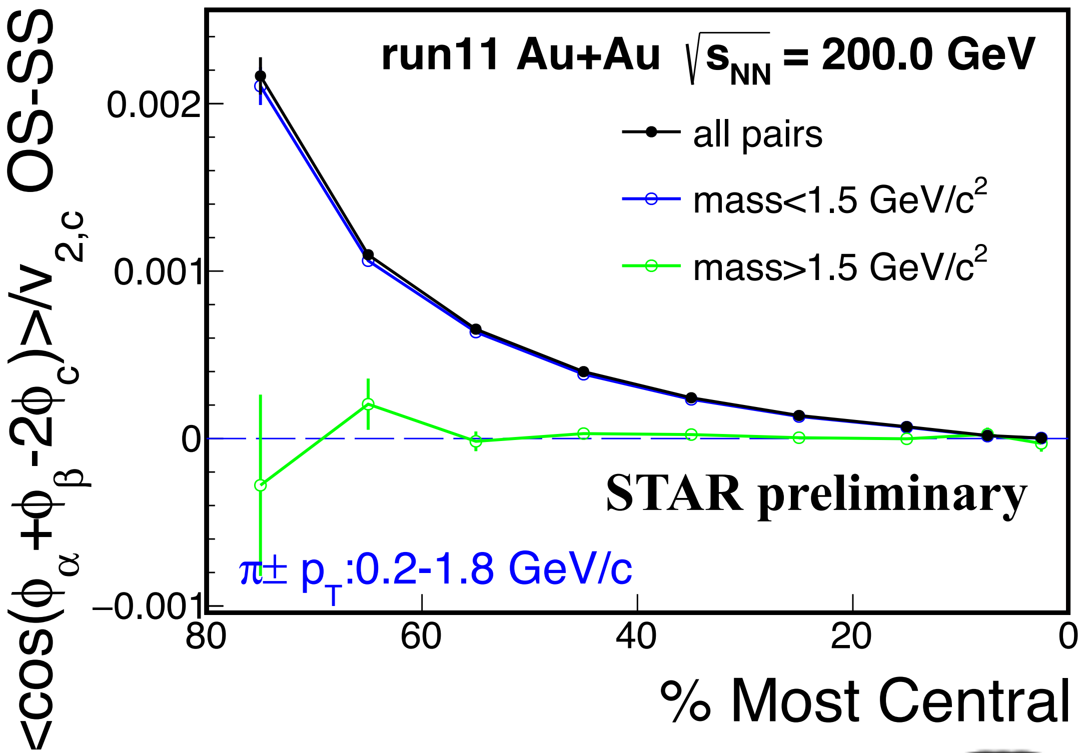




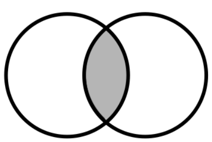
- Identify resonance background by the invariant mass
- Data show resonance structure in $\Delta\gamma$ as function of mass
- $\Delta\gamma$ decrease as r decrease with m increase, larger r -> larger res. contribution -> larger $\Delta\gamma$

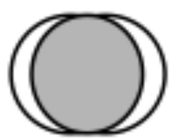
$\Delta\gamma$ traces r

Move away from resonance region



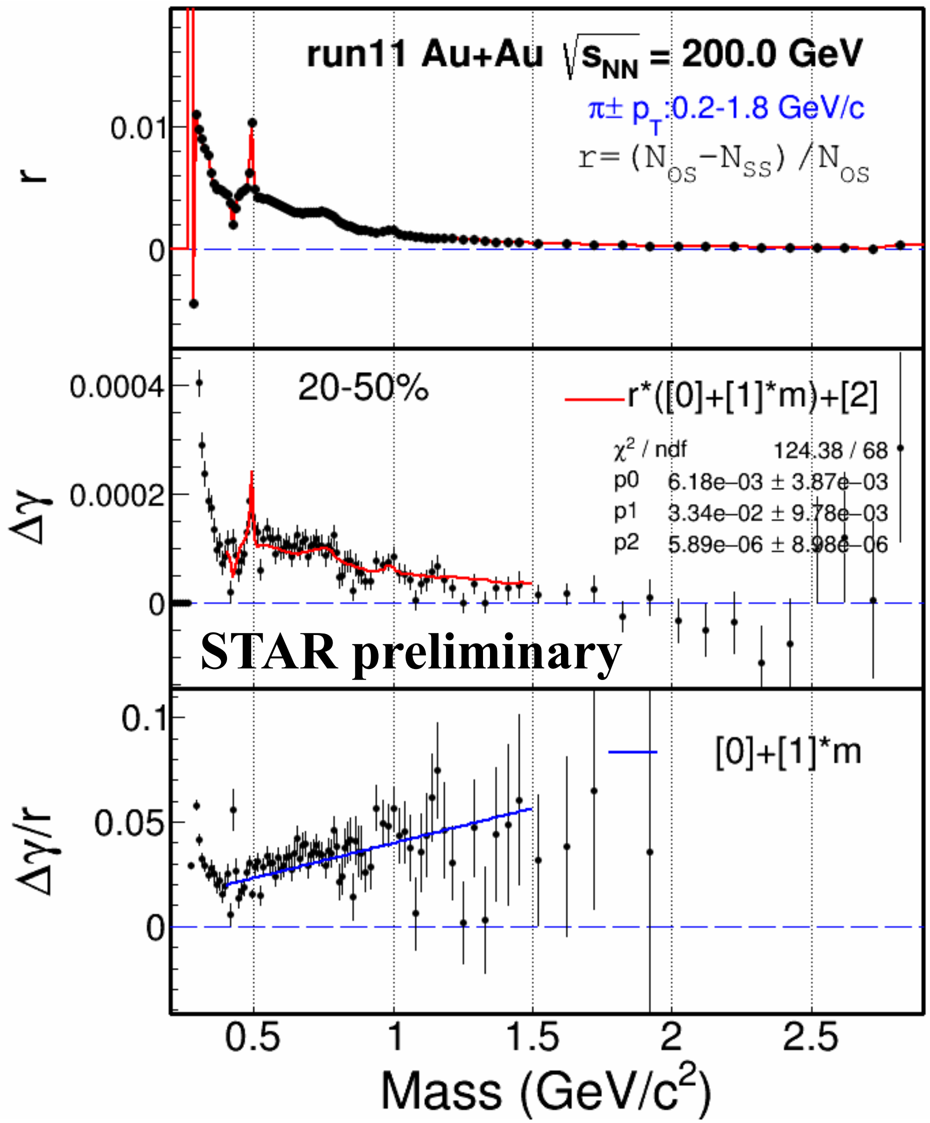
Centrality	All (A)	M>1.5 (B)	B/A
50-80%	(7.45±0.21)E-4	(1.3±5.7)E-5	(1.8±7.6)%
20-50%	(1.82±0.03)E-4	(7.7±9.0)E-6	(4.3±4.9)%
0-20%	(3.70±0.67)E-5	(1.4±1.8)E-5	(-3.8±49)%





- Negligible resonance contributions at large mass
- At m>1.5 GeV/c^2, $\Delta\gamma$ consistent with zero

Identify resonance bkg. and possible CME



- **Resonance bkg.:**

  $\Delta\gamma = \cos(\alpha+\beta-2\Psi_{RP})$

  $\propto \langle\cos(\alpha+\beta-2\phi_{res.})\rangle \cos 2(\phi_{res.}-\Psi_{RP})$

  $\approx \langle\cos(\alpha+\beta-2\phi_{res.})\rangle v_{2res.}$

- **Resonance bkg. + CME**

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

  $=r(m)*f(m)*v_{2res.} \quad +\text{CME}$

peaky smooth

different dep. on mass, viable way to distinguish

Data are fitted assuming constant CME, independent of mass

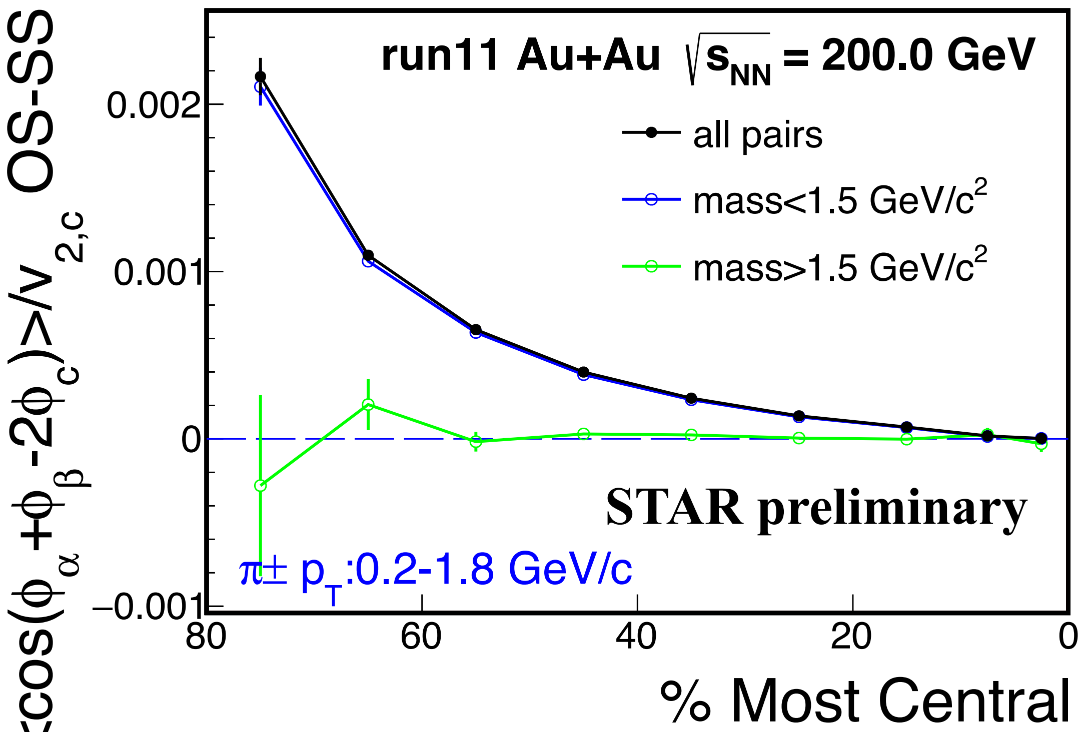
- In the current approach, the statistical error is dominant

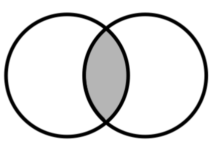
Summary

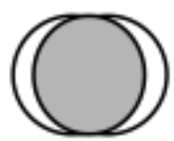
- With respect to Ψ_2: p+Au and d+Au charge dependent correlations are background. Peripheral Au+Au data are similar to that of p+Au and d+Au
- The scaled correlators from peripheral to mid-central Au+Au collisions are approximately constant over multiplicity. These data do not currently allow conclusive statements to be made regarding the presence of the CME
- Identify resonance bkg. by the **invariant mass**
- At $m>1.5$ GeV/c^2, $\Delta\gamma$ is consistent with zero within uncertainty
- Observation of resonance structure in $\Delta\gamma$ at $m<1.5$ GeV/c^2. Two component fit to isolate the possible CME from bkg.

backup

Move away from resonance region







Centrality	All (A)	M>1.5 (B)	B/A
70-80%	(2.17±0.11)E-3	(-0.3±0.5)E-3	(-13±25)%
60-70%	(1.10±0.03)E-3	(2.1±1.5)E-4	(19±14)%
50-60%	(6.53±0.13)E-4	(-1.7±5.9)E-5	(-2.5±9.0)%
40-50%	(4.00±0.06)E-4	(3.0±2.9)E-5	(7.4±7.1)%
30-40%	(2.43±0.03)E-4	(2.4±1.7)E-5	(10±7)%
20-30%	(1.38±0.03)E-4	(5±11)E-6	(3.6±8.2)%
10-20%	(7.08±0.32)E-5	(-0.2±1.4)E-5	(-2±20)%
5-10%	(1.8±0.91)E-5	(2.5±4.0)E-5	(139±223)%
0-5%	(0.28±1.00)E-5	(-2.9±4.9)E-5	(-1046±1777)%
50-80%	(7.45±0.21)E-4	(1.3±5.7)E-5	(1.8±7.6)%
20-50%	(1.82±0.03)E-4	(7.7±9.0)E-6	(4.3±4.9)%
0-20%	(3.70±0.67)E-5	(1.4±1.8)E-5	(-3.8±49)%

- Negligible resonance contributions at large mass
- At m>1.5 GeV/c^2, Δγ consistent with zero