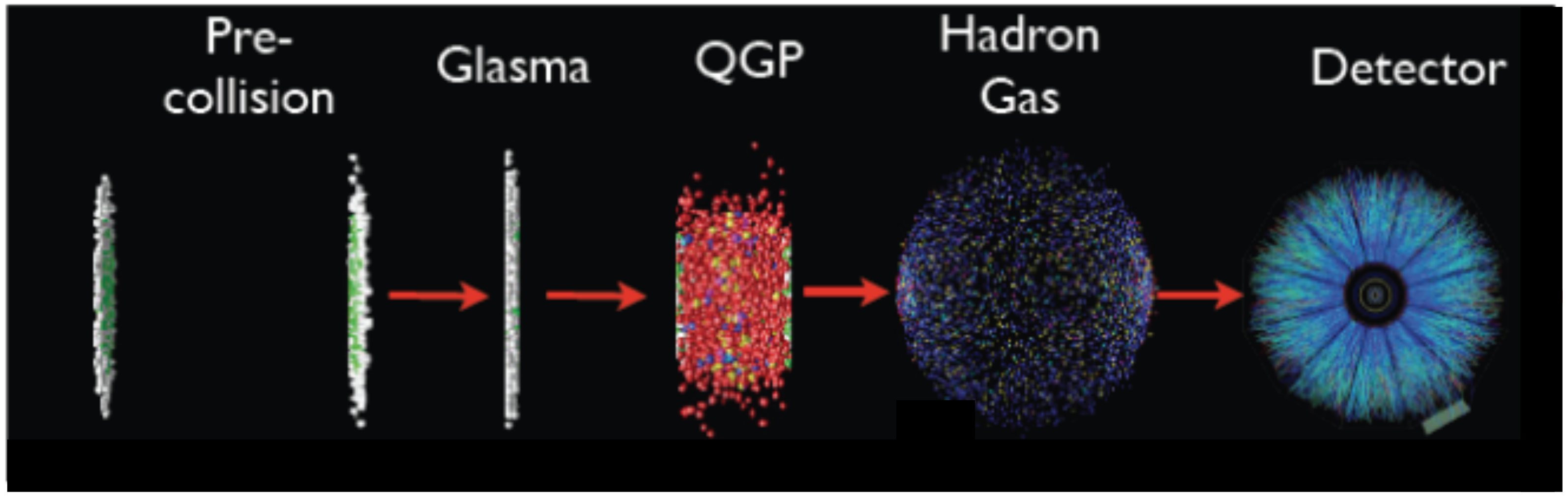
Chiral effects in relativistic heavy-ion collisions

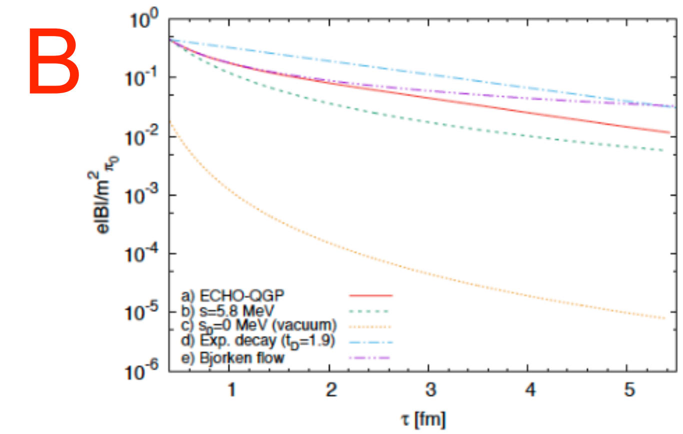
Guo-Liang Ma (马国亮)

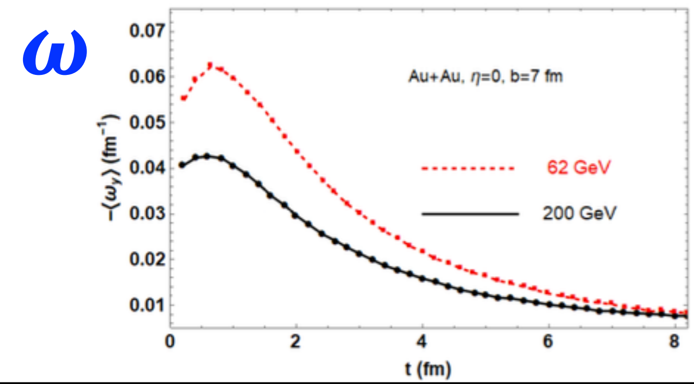
Outline

- Introduction
- AMPT results on CME
- AMPT results on isobaric collisions
- Summary

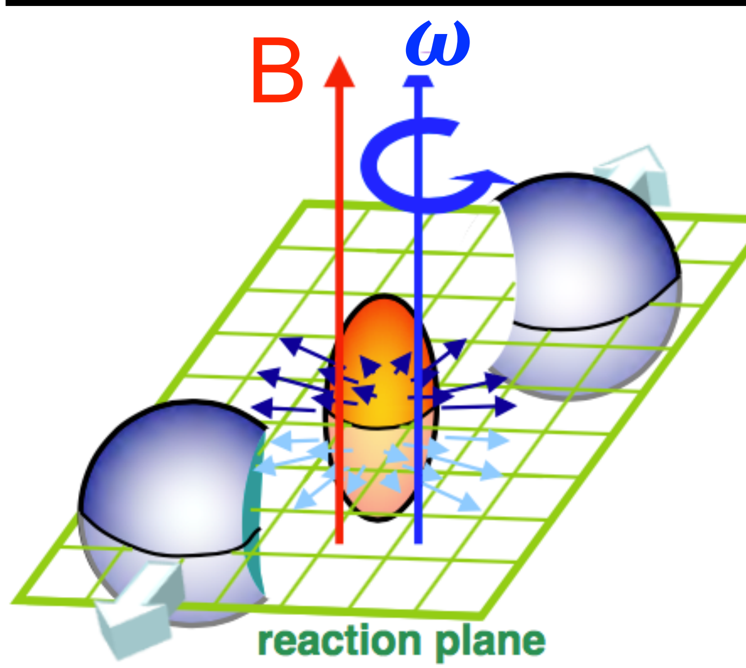
Chiral and Spin Effects in HIC







Chiral Magnetic Effect



Chiral Vortical Effect

Chiral Vortical Wave

Chiral Separation Effect

Chiral Magnetic Wave

Local Polarization

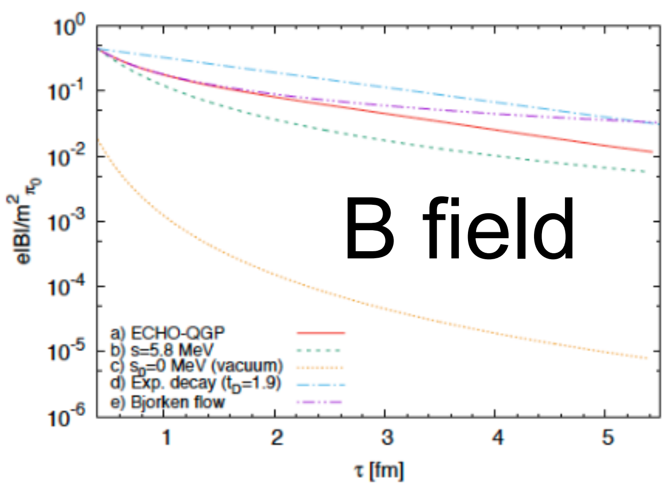
Global Polarization

Spin Alignment

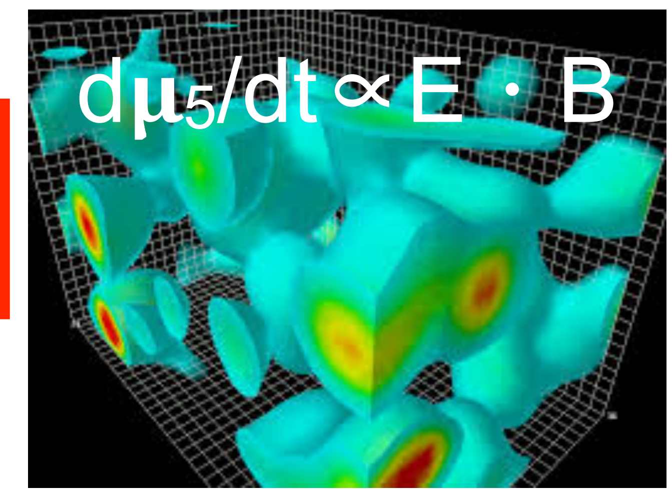
Chiral Magnetic Effect in HIC

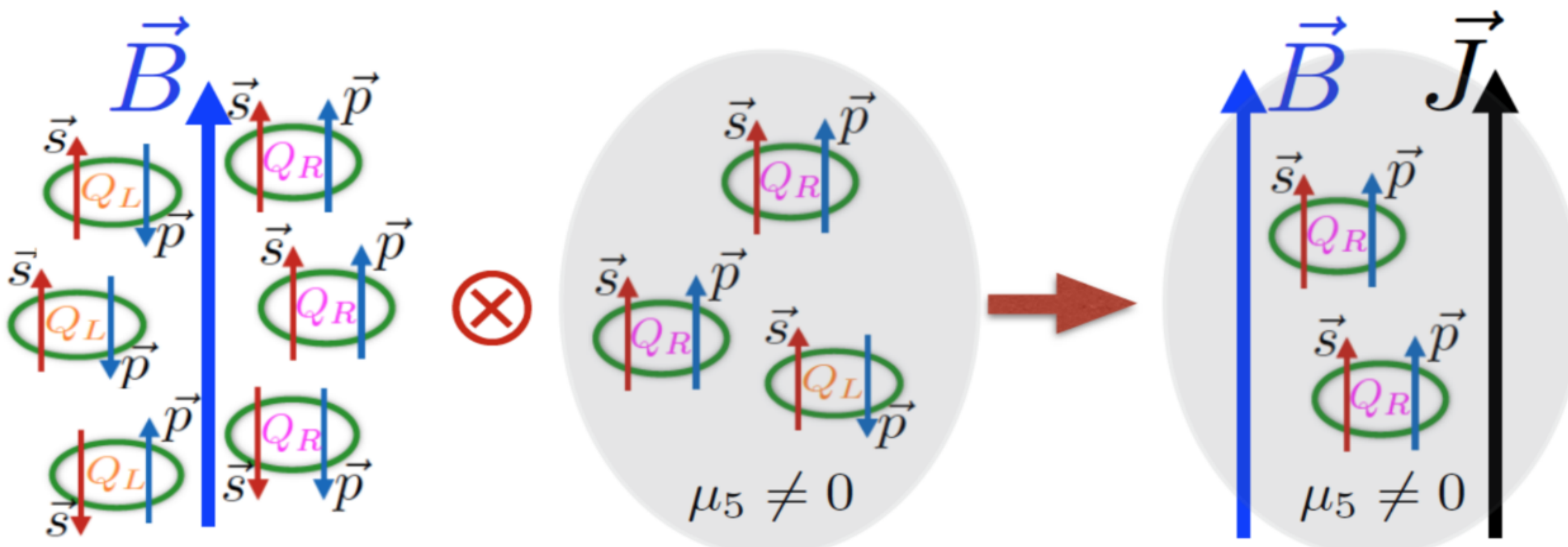
Chiral kinetic equation:

$$(1 + s\hbar B\cdot\Omega)\, n\cdot\partial^x f + \left[v^\mu + s\hbar(\widehat{p}\cdot\Omega)B^\mu + s\hbar\epsilon^{\mu\nu\rho\sigma}n_\rho E_\sigma\Omega_\nu\right]\bar{\partial}^x_\mu f + \left(\tilde{E}^\mu + \epsilon^{\mu\nu\alpha\beta}v_\nu n_\alpha B_\beta + s\hbar E\cdot B\Omega^\mu\right)\bar{\partial}^p_\mu f = C[f] \qquad (s=\pm,\ R \text{ or } L)$$

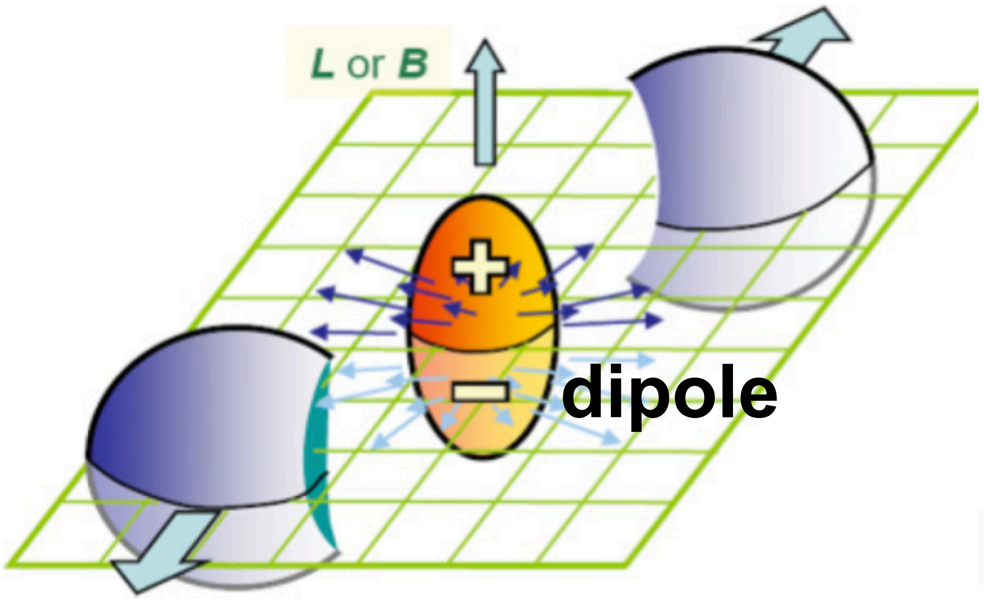


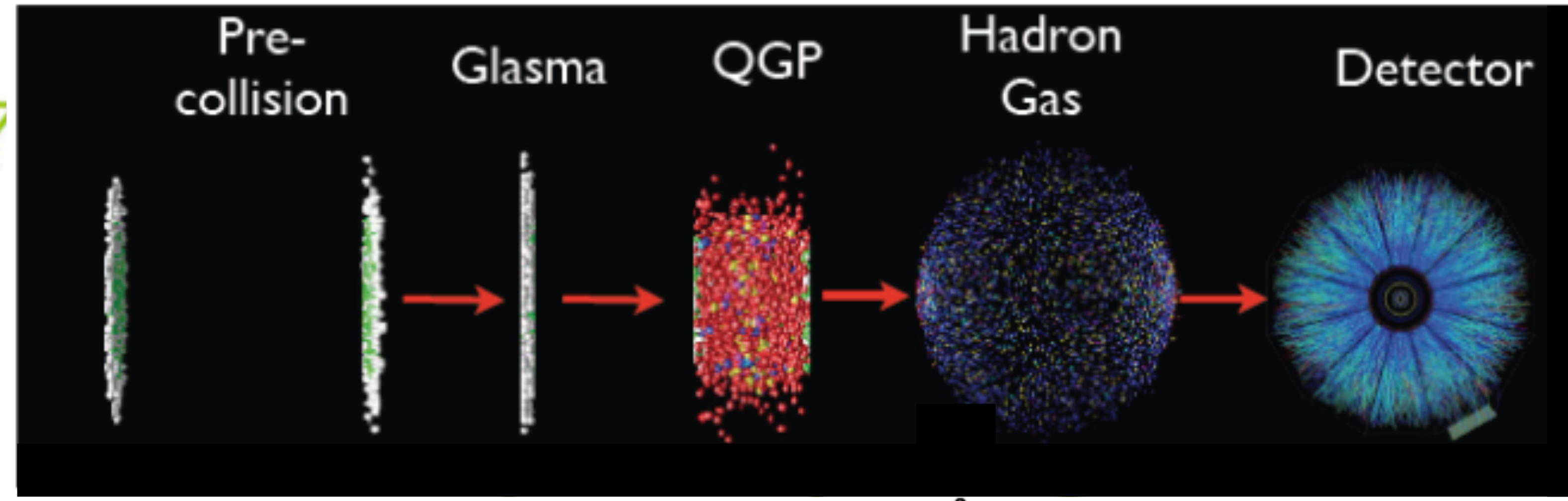
Chiral Magnetic Effect $\mathbf{J} = \frac{Qe}{2\pi^2}\mu_5\mathbf{B}$

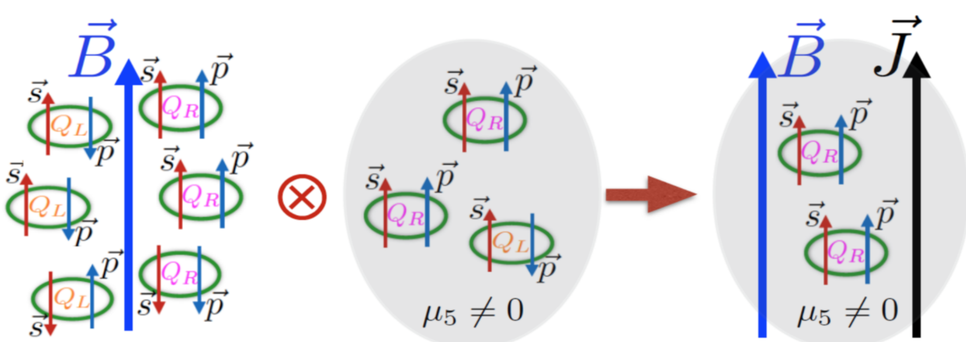


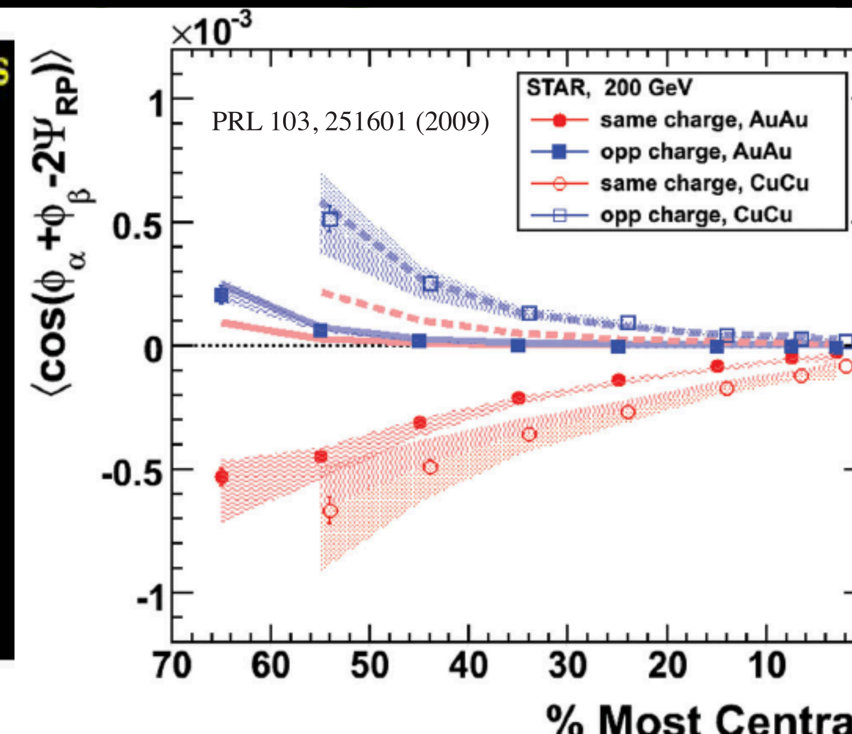


How to measure Chiral Magnetic Effect?









•STAR data on γ are consistent with the CME expectation => dipole charge separation.

$$\gamma = \langle\cos(\phi_\alpha + \phi_\beta - 2\Psi_{RP})\rangle$$
$$= [\langle v_{1,\alpha} v_{1,\beta}\rangle + B_{in}] - [\langle a_\alpha a_\beta\rangle + B_{out}]$$

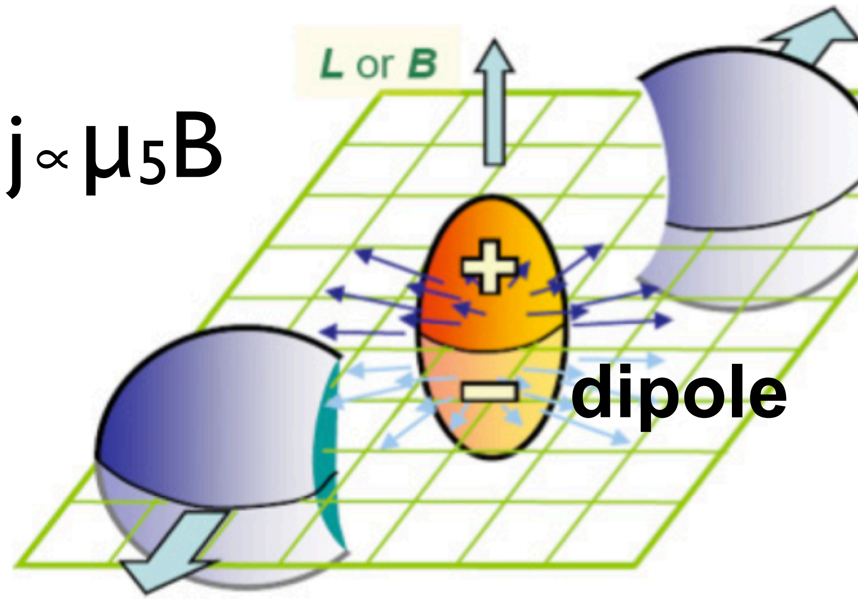
Non-flow/non-parity effects: largely cancel out

Directed flow: vanishes if measured in a symmetric rapidity range

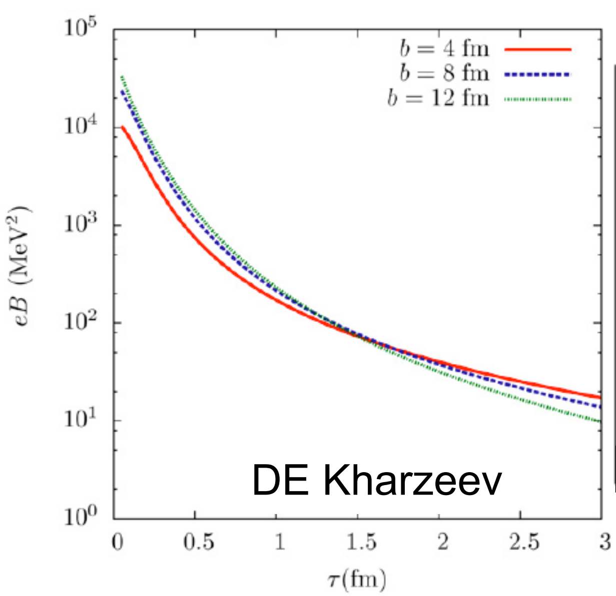
P-even quantity: sensitive to CME

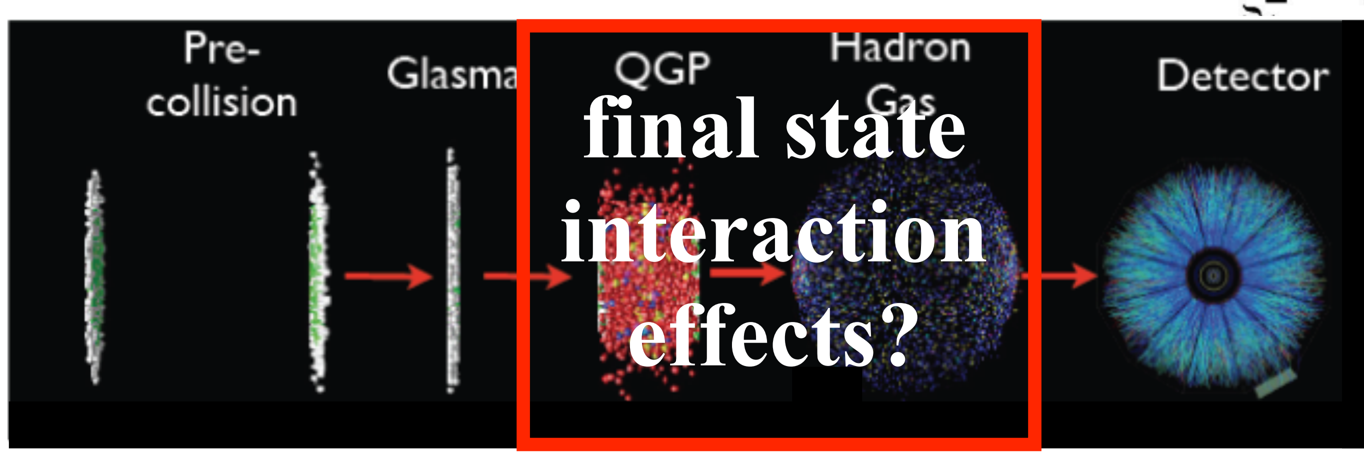
Can CME signal survive from final state interactions?

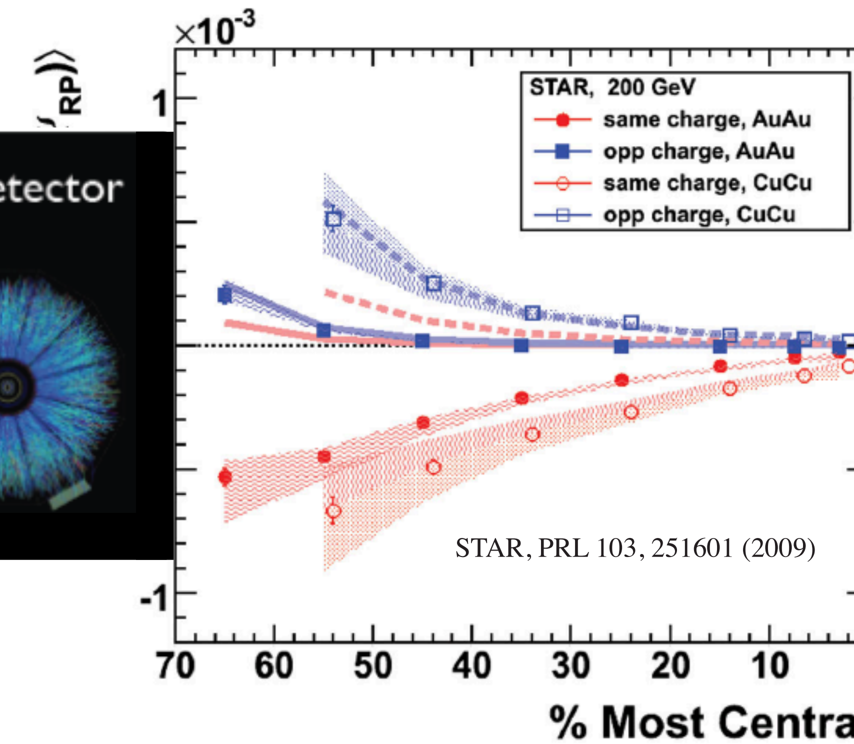
$j \propto \mu_5 B$



$$(1+s\hbar B\cdot\Omega)\, n\cdot\partial^x f + \left[v^\mu + s\hbar(\hat{p}\cdot\Omega)B^\mu + s\hbar\epsilon^{\mu\nu\rho\sigma}n_\rho E_\sigma\Omega_\nu\right]\bar{\partial}^x_\mu f + \left(\tilde{E}^\mu + \epsilon^{\mu\nu\alpha\beta}v_\nu n_\alpha B_\beta + s\hbar E\cdot B\,\Omega^\mu\right)\bar{\partial}^p_\mu f = C[f]$$

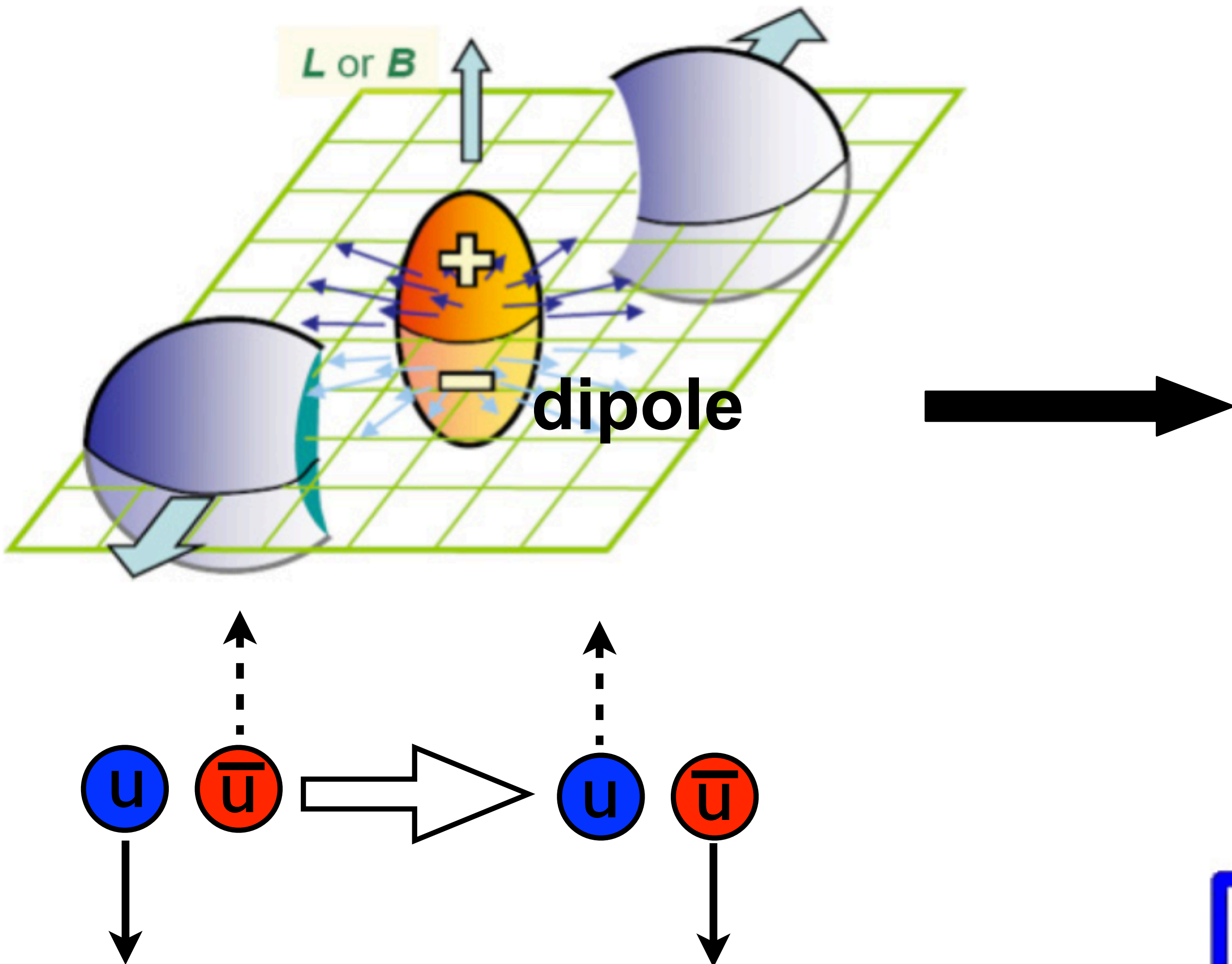






- The lifetime of B field is short. →The CME is an initial effect.
- Final state interaction effects on the CME could be important.

(I) The AMPT model with CME



$f\% = (N^+_{upward} - N^+_{downward})/(N^+_{upward} + N^+_{downward})$

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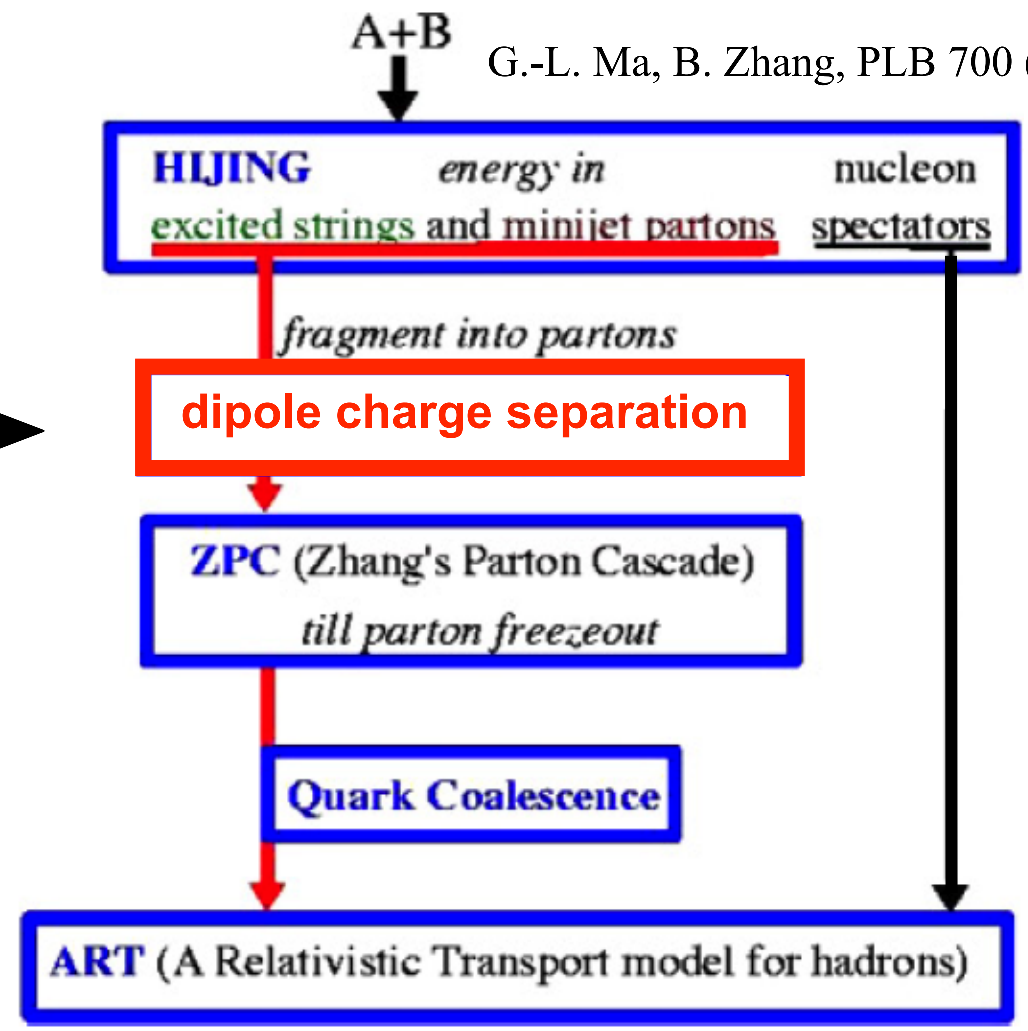
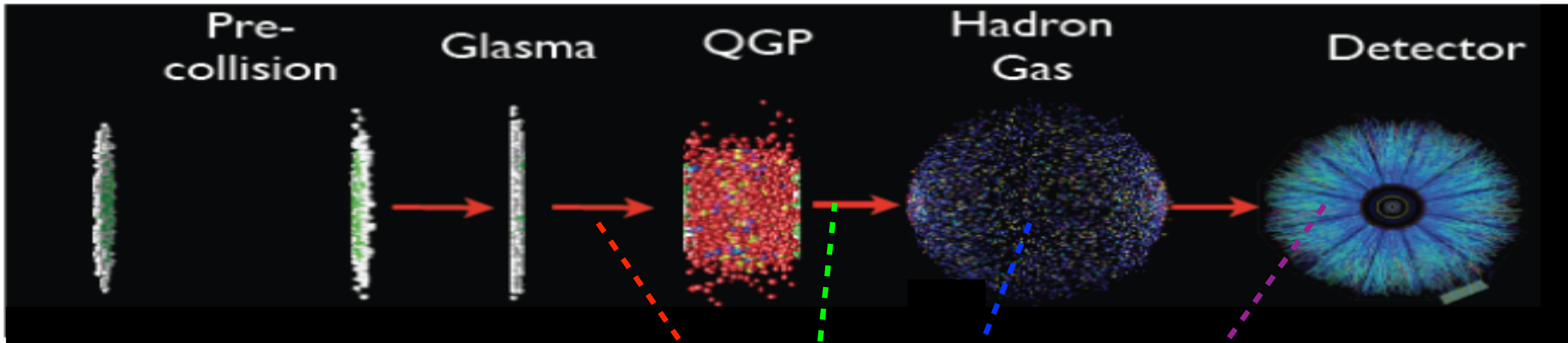
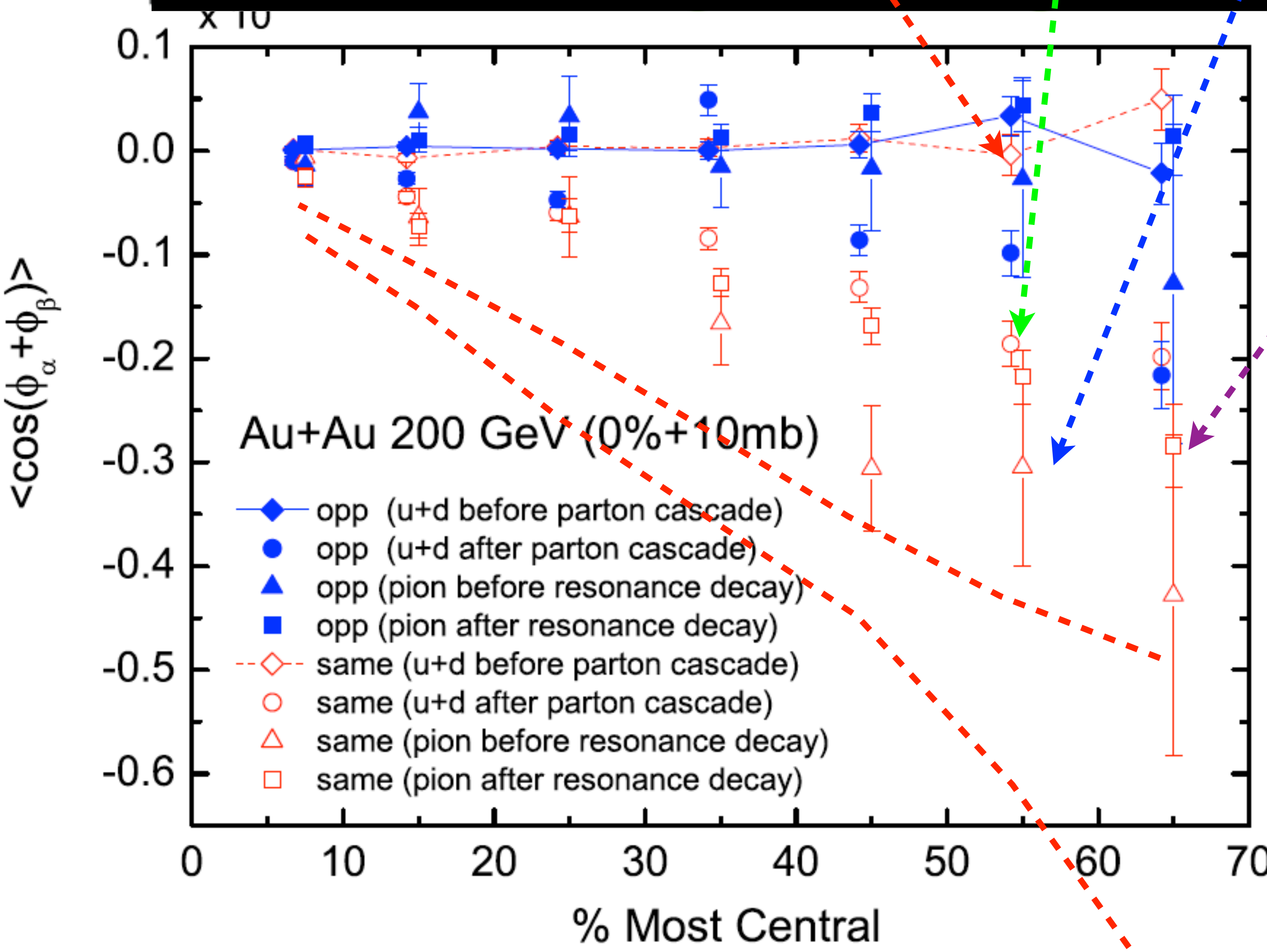


- We include initial dipole charge separation mechanism into AMPT model.
- We focus on final state effects on the charge separation, including parton cascade, hadronization, resonance decays after B and E vanish quickly.

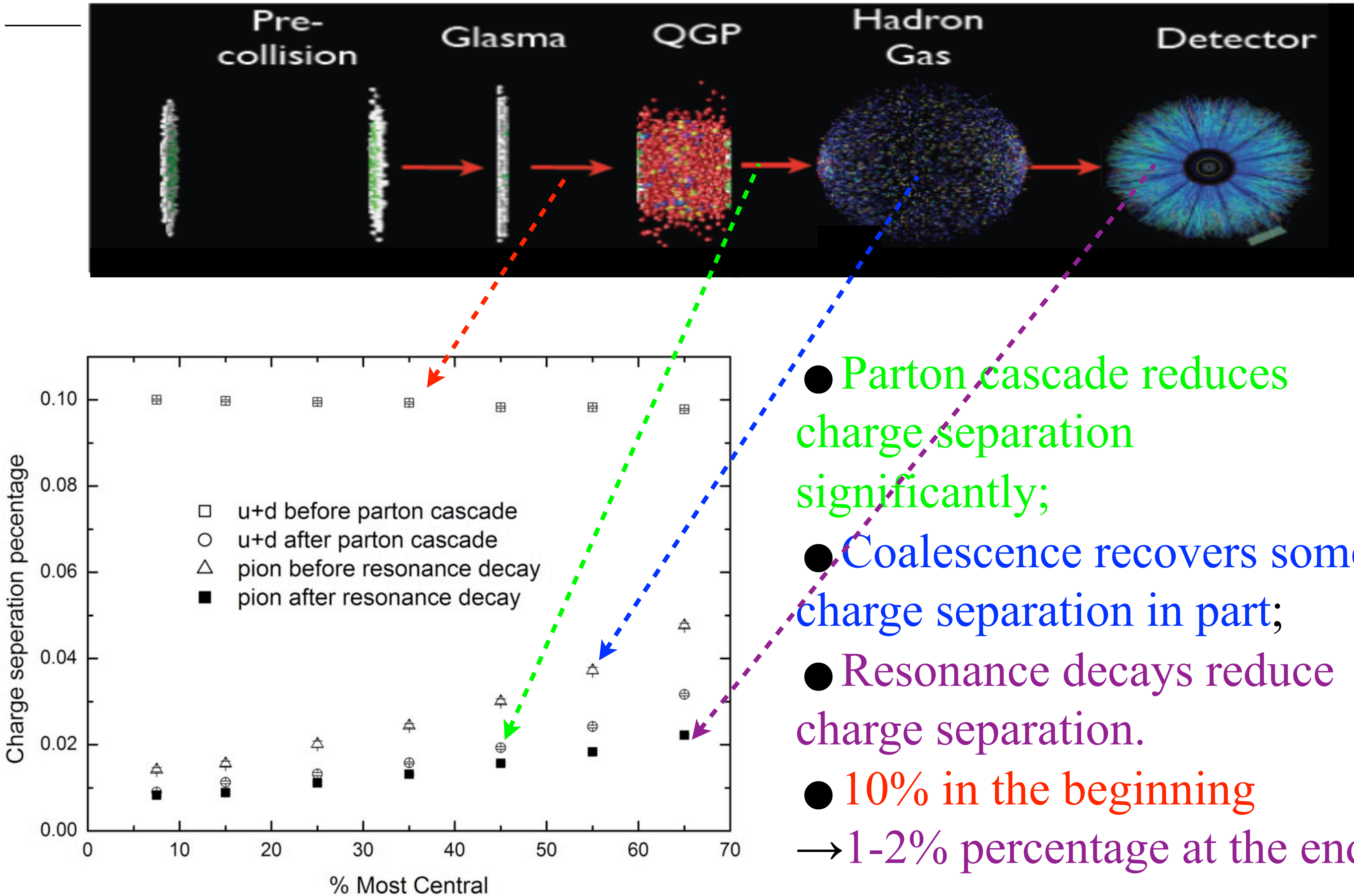
The Background from original AMPT





- Opp-charge and same-charge are consistent with zero initially.(diamond)
- being negative through parton cascae due to Flow+TMC.(circle)
- Coalesce enhances same-charge and reduce opp-charge. (triangle)
- Resonance decays reduce signal. (square)

Final state interaction effects on the CME



- Parton cascade reduces charge separation significantly;
- Coalescence recovers some charge separation in part;
- Resonance decays reduce charge separation.
- 10% in the beginning →1-2% percentage at the end.

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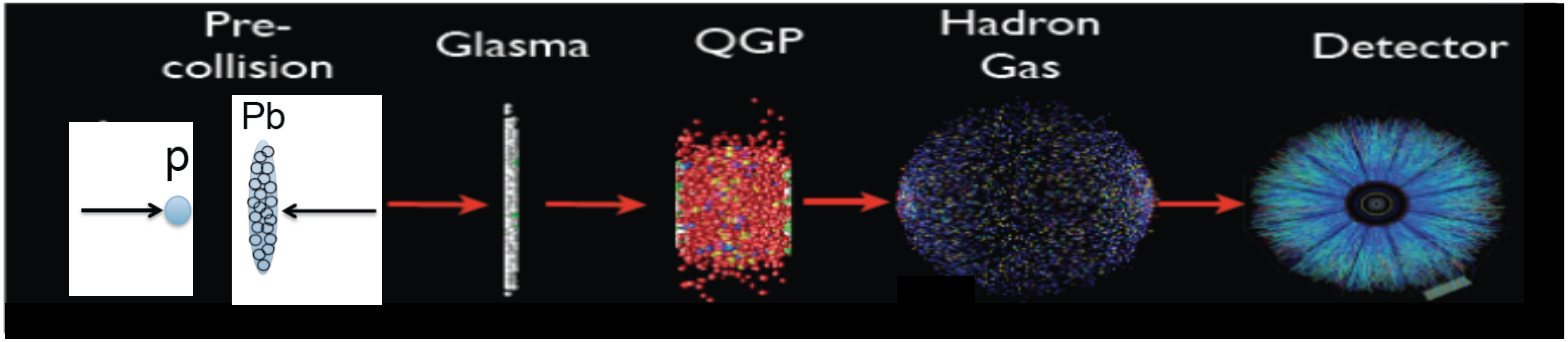
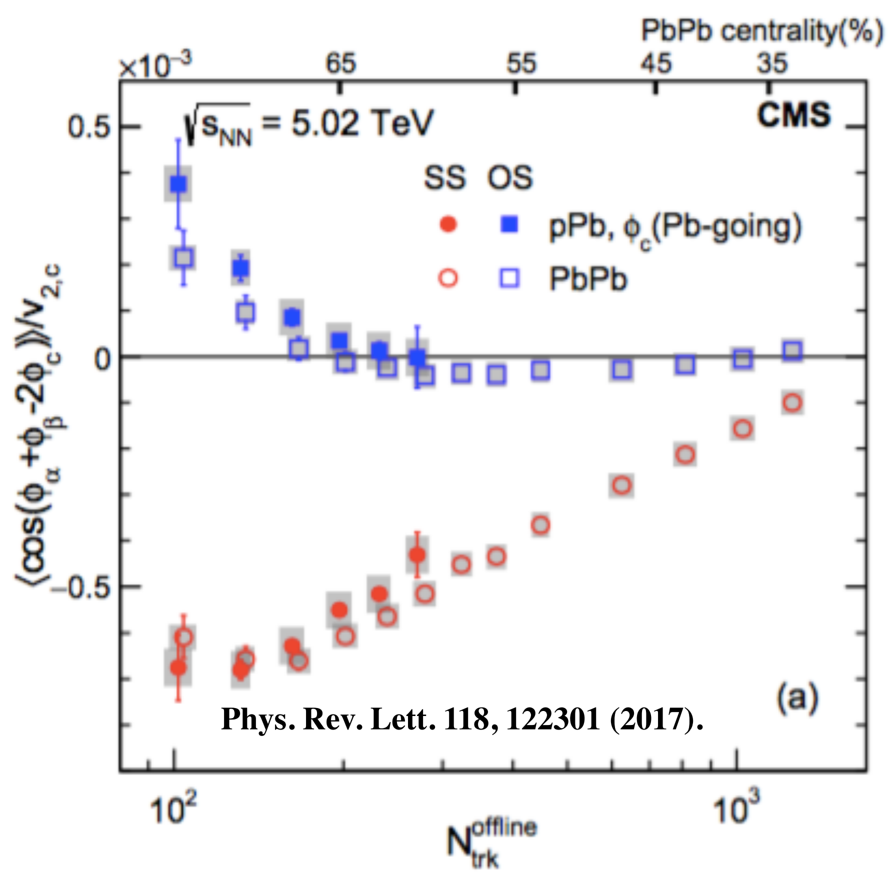
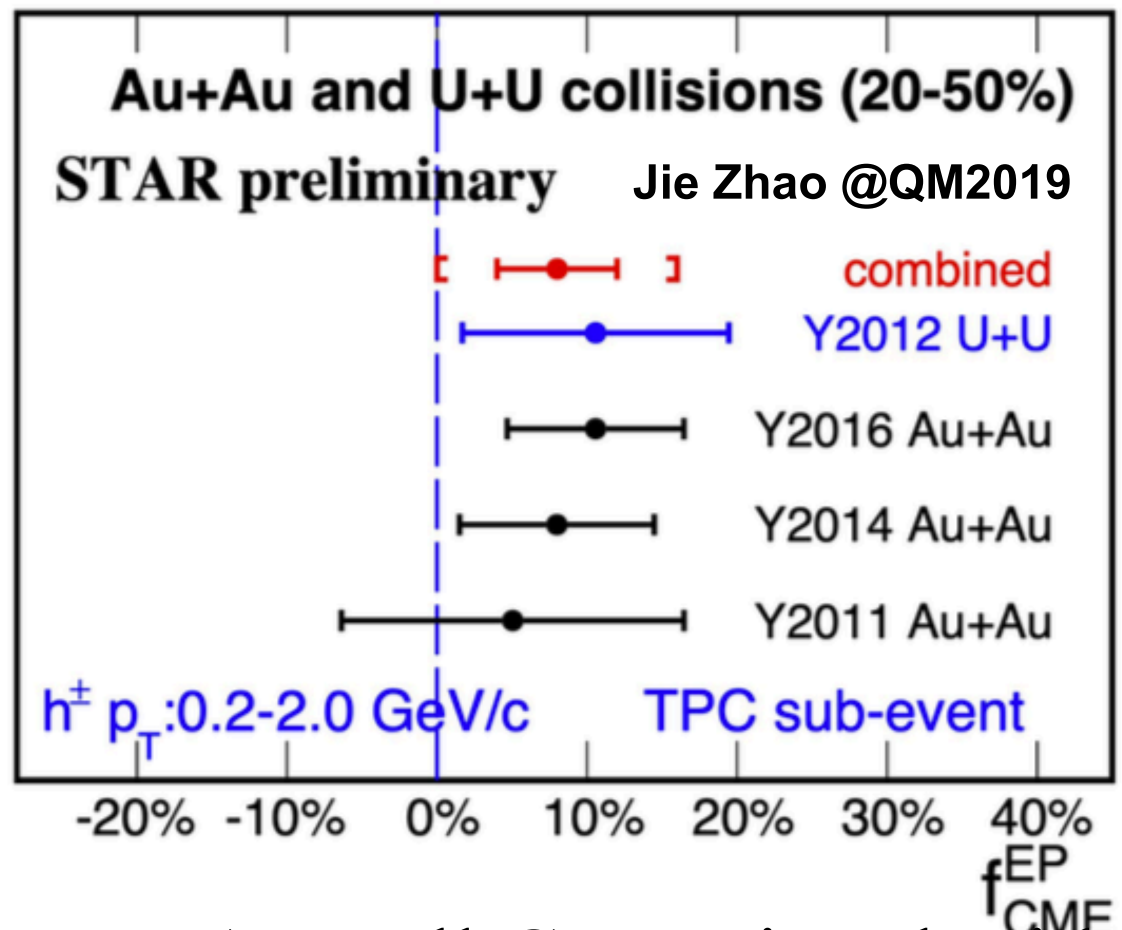
CME vs Background

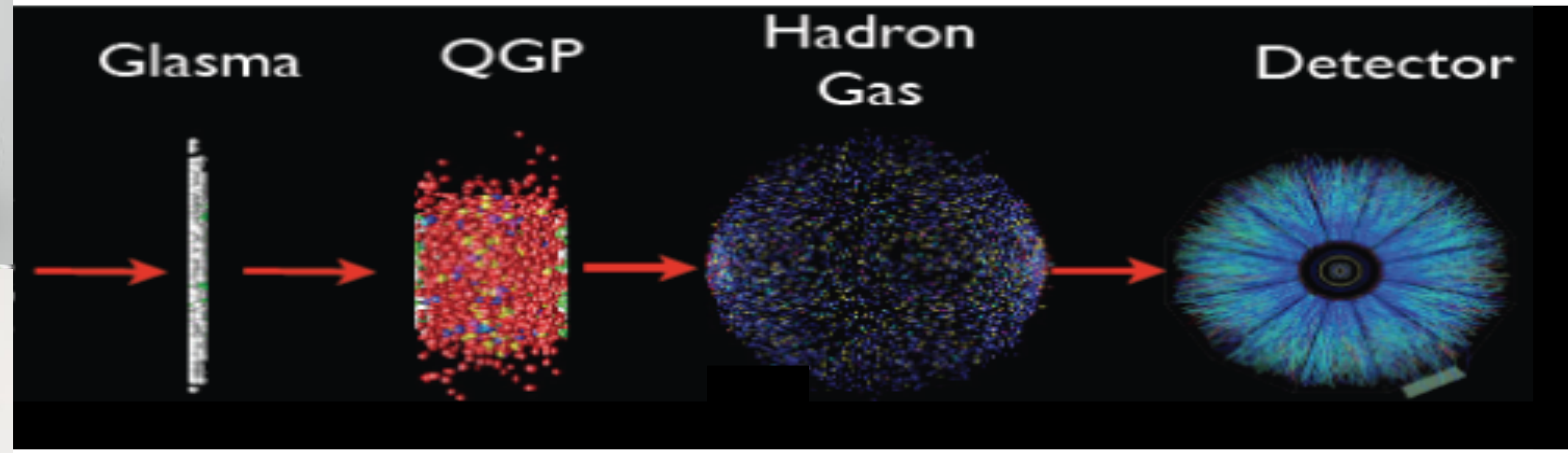




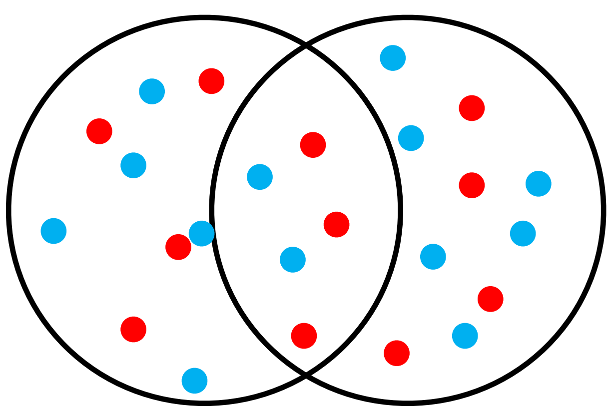


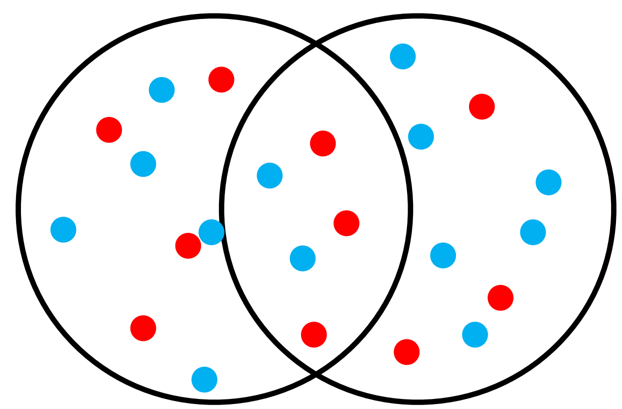
- Small systems results on CME=>A small CME signal with large backgrounds in large systems?

(II) CME in isobar exp.



$$\mathbf{J} = \frac{Qe}{2\pi^2}\mu_5 \mathbf{B}$$





${}^{96}_{44}\mathrm{Ru} + {}^{96}_{44}\mathrm{Ru}$ ${}^{96}_{40}\mathrm{Zr} + {}^{96}_{40}\mathrm{Zr}$

Identical nucleon number → Identical background

Different proton number → Different magnetic field

Geometry Configuration of Isobaric Collisions

Woods-Saxon form of spatial distribution of nucleons:

$$\rho(r,\theta) = \rho_0/(1 + exp((r - R_0 - \beta_2 R_0 Y_2^0(\theta))/a))$$

Case 1	R_0	a	β_2	β_4
Ru96	5.13	0.46	0.13	0.00
Zr96	5.06	0.46	0.06	0.00
Case 2	**R_0**	**a**	**β_2**	**β_4**
Ru96	5.13	0.46	0.03	0.00
Zr96	5.06	0.46	0.18	0.00

Relative ratio (RR): $R_Q = \frac{2(Q^{Ru} - Q^{Zr})}{Q^{Ru} + Q^{Zr}}$

e.g. for case 1, $R_{\beta_2} = \frac{2(0.13-0.06)}{0.13+0.06} = 0.33$; for case 2, $R_{\beta_2} = \frac{2(0.03-0.18)}{0.03+0.18} = -1.43$

Q can represent $|B|$, $\cos 2(\Psi_B - \Psi_2)$, $B^2 \cos 2(\Psi_B - \Psi_2)$, $\cos 2(\Psi_B - \Psi_2^{SP})$ and $B^2 \cos 2(\Psi_B - \Psi_2^{SP})$.

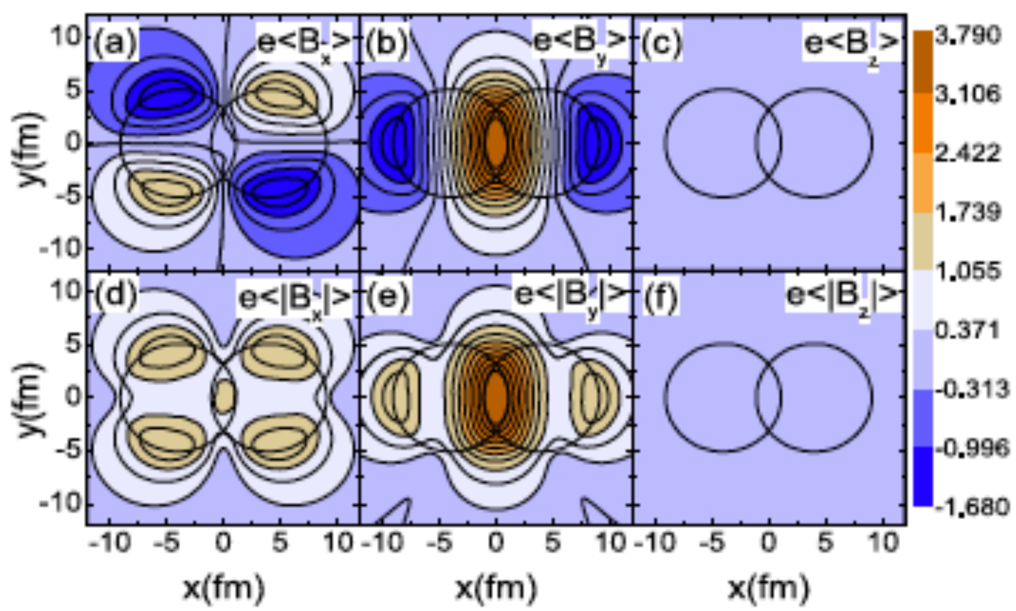
Spatial Distributions of Electromagnetic Fields

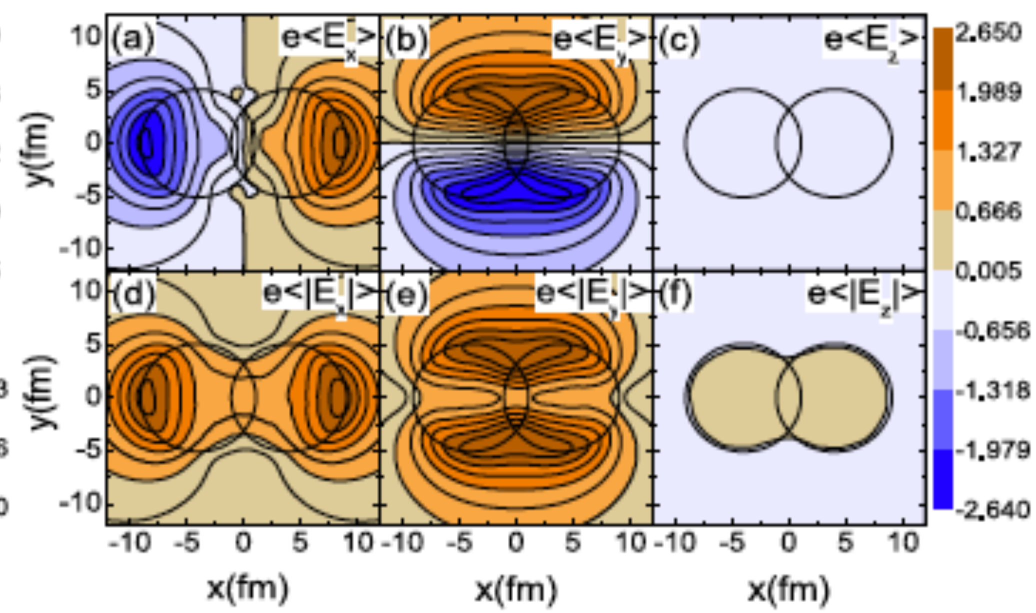
From Lienard-Wiechert potential:

$$e\mathbf{E}(t,\mathbf{r}) = \frac{e^2}{4\pi}\sum_n Z_n \frac{\mathbf{R}_n - R_n \mathbf{v}_n}{(R_n - \mathbf{R}_n \cdot \mathbf{v}_n)^3}(1 - v_n^2),$$

$$e\mathbf{B}(t,\mathbf{r}) = \frac{e^2}{4\pi}\sum_n Z_n \frac{\mathbf{v}_n \times \mathbf{R}_n}{(R_n - \mathbf{R}_n \cdot \mathbf{v}_n)^3}(1 - v_n^2),$$

b = 8 fm



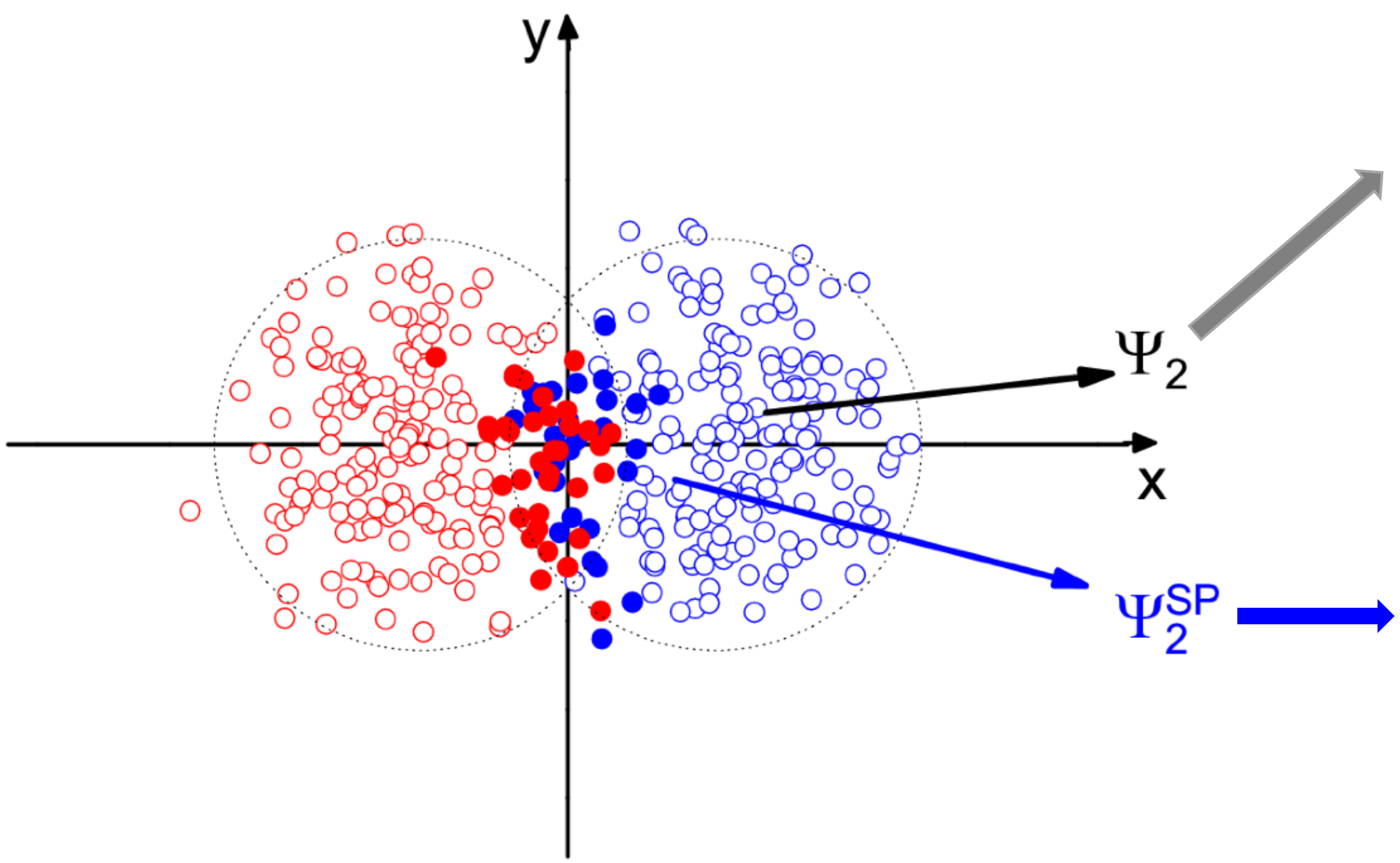


The distributions of RuRu collisions for case 1.

$\mathbf{r} = (0,0,0)$ & $\mathrm{t} = 0$

Charge separation signal: $\Delta\gamma \propto \langle B^2 \cos 2(\Psi_B - \Psi_{EP}) \rangle$

Calculation Method of Ψ_2 & Ψ_2^{SP}



In model,

$$\Psi_2 = \frac{1}{2}[arctan\frac{\langle r_p^2 sin(2\phi_p)\rangle}{\langle r_p^2 cos(2\phi_p)\rangle} + \pi]$$

X. L. Zhao, Y. G. Ma, G. L. Ma, PRC 97, 024910 (2018)

Ψ_2 is participant plane which is constructed by initial geometry of partons.

$$\Psi_2^{SP} = \frac{1}{2}arctan\frac{\langle r_s^2 sin(2\phi_s)\rangle}{\langle r_s^2 cos(2\phi_s)\rangle}$$

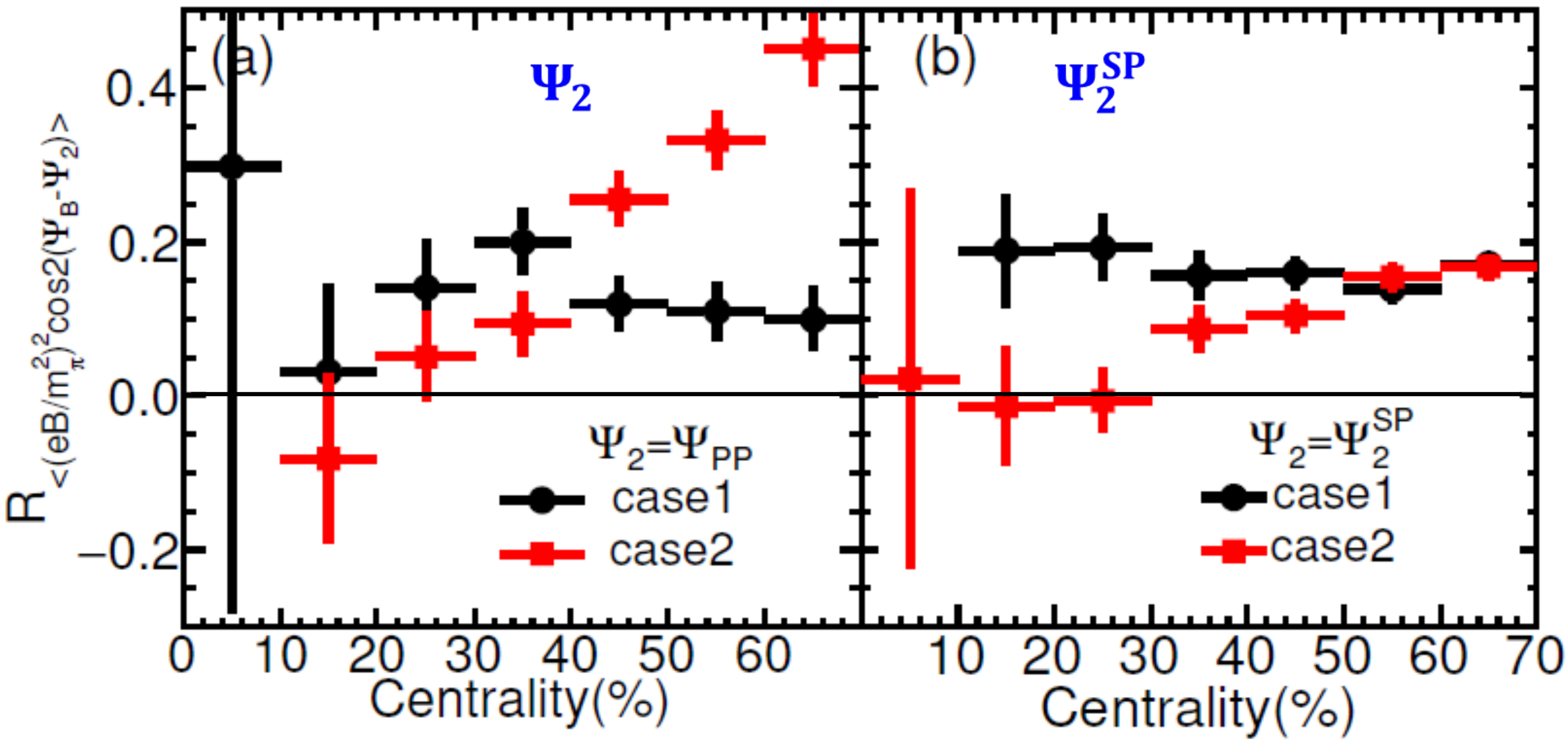
Sandeep Chatterjee *et al,* PRC 92, 011902(R) (2015)

Ψ_2^{SP} is spectator plane which is constructed by spectator neutrons from one projectile.

In experiment, Ψ_2 is the 2nd-harmonic event plane measured by the TPC, and Ψ_2^{SP} is assessed by spectator neutrons measured by ZDC.

Jie Zhao *et al*, arXiv:1807.05083; Hao-Jie Xu *et al*, arXiv:1710.07265; Sergei A. Voloshin, arXiv:1805.05300

Ψ_2 VS Ψ_2^{SP}



- For case 1, RR of $B^2\cos2(\Psi_B-\Psi_2)$ and $B^2\cos2(\Psi_B-\Psi_2^{SP})$ are similar.
- For case 2, RR of Ψ_2 is larger than RR of Ψ_2^{SP}.
- Ψ_2^{SP} is expected to reflect much cleaner information about the CME signal.

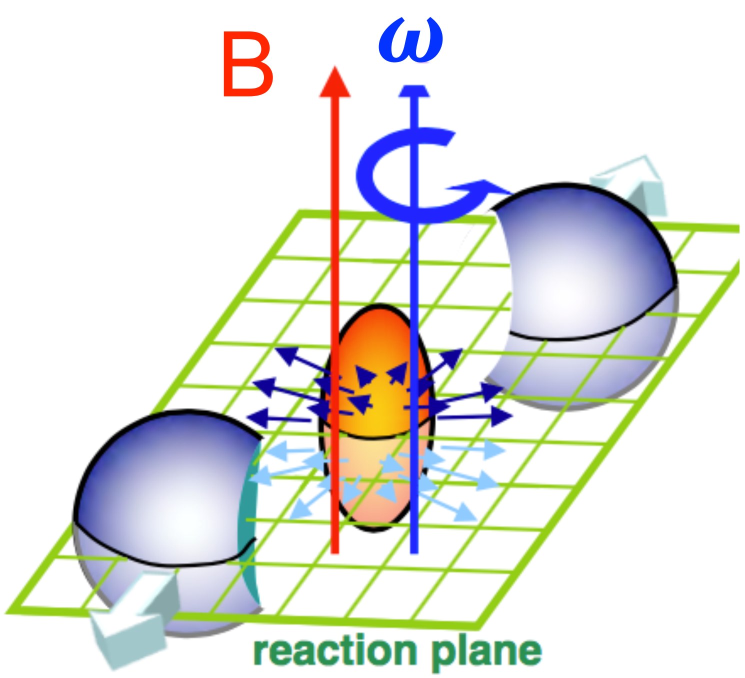
Xin-Li Zhao, Guo-Liang Ma, Yu-Gang Ma, Phys. Rev. C 99, 034903 (2019)

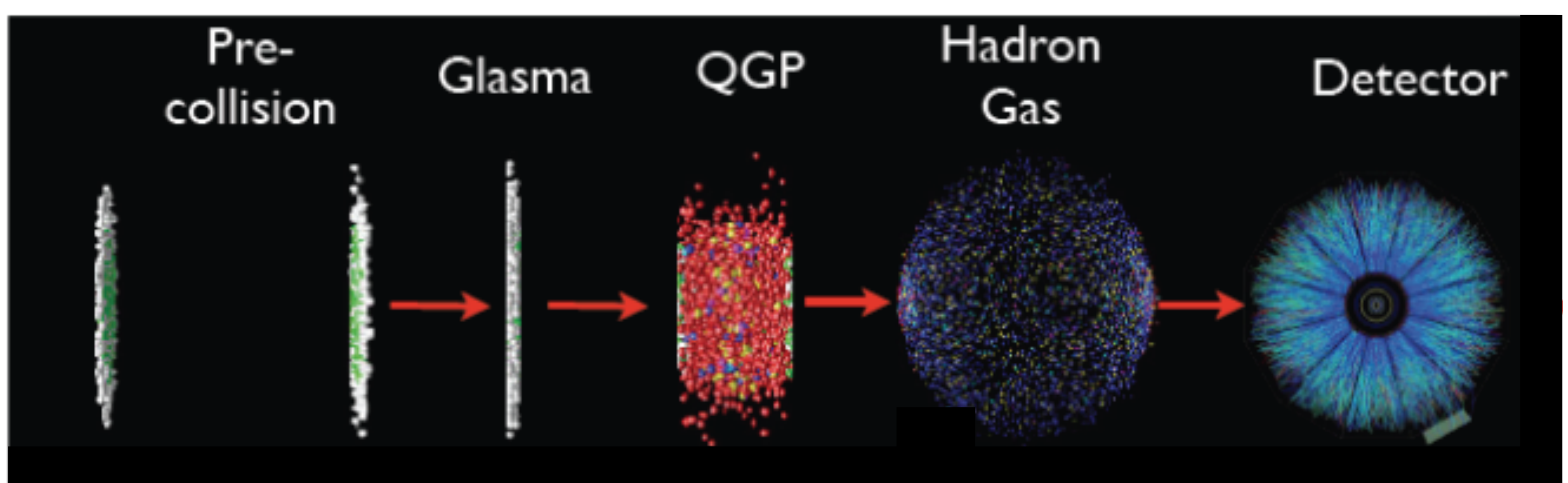
Summary

Chiral Magnetic Effect: $\mathbf{J} = \frac{Qe}{2\pi^2}\mu_5\mathbf{B}$

● **Final state interactions** significantly reduce the CME signal. The final CME observable is dominated by backgrounds.

● **The CME signal difference between isobaric collisions** can survive from final state interactions, which could be observed with enough statistics.





Thanks for your attention!

Back up

AMPT results on the CME obs. $\gamma=\langle\cos(\varphi_\alpha+\varphi_\beta)\rangle$

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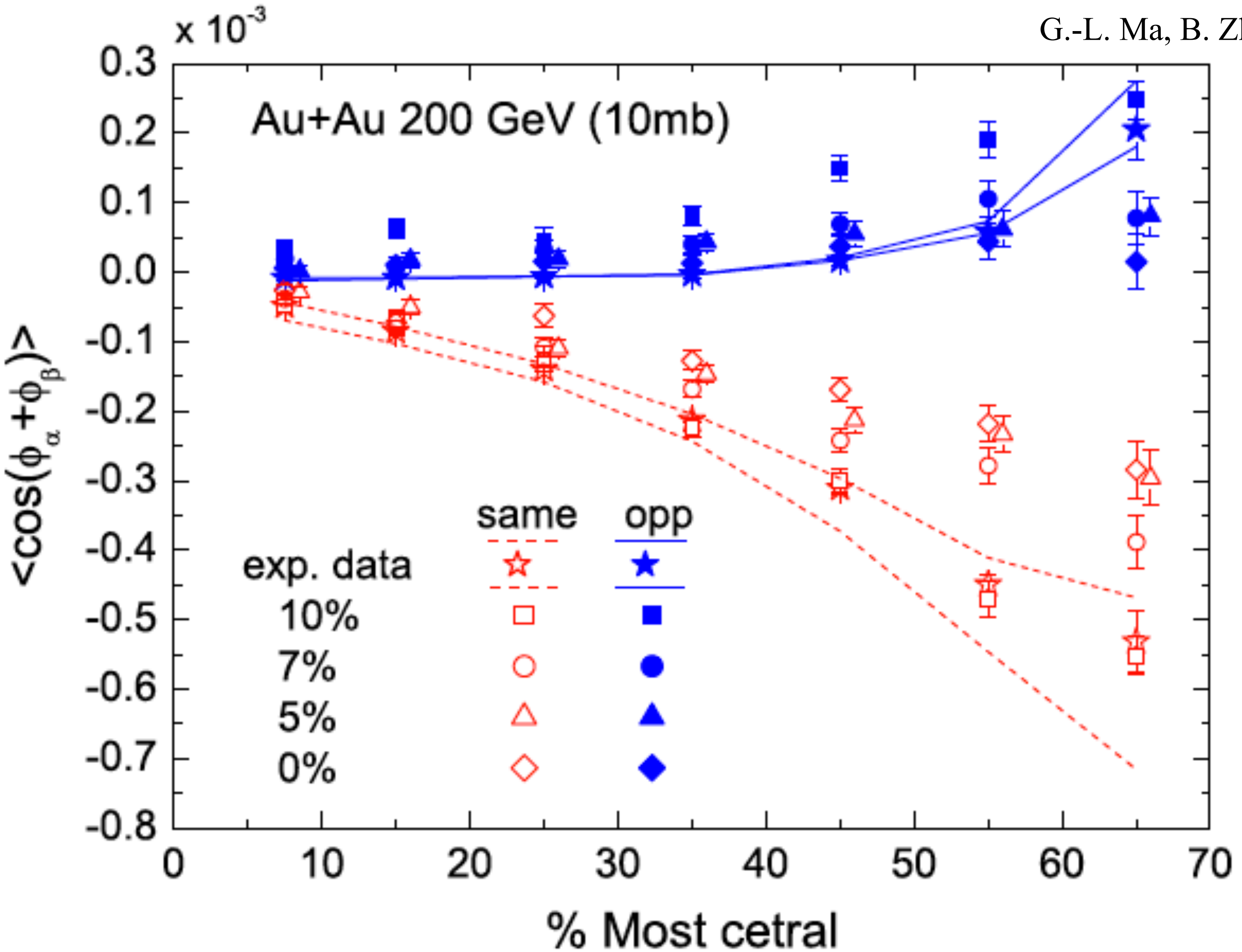
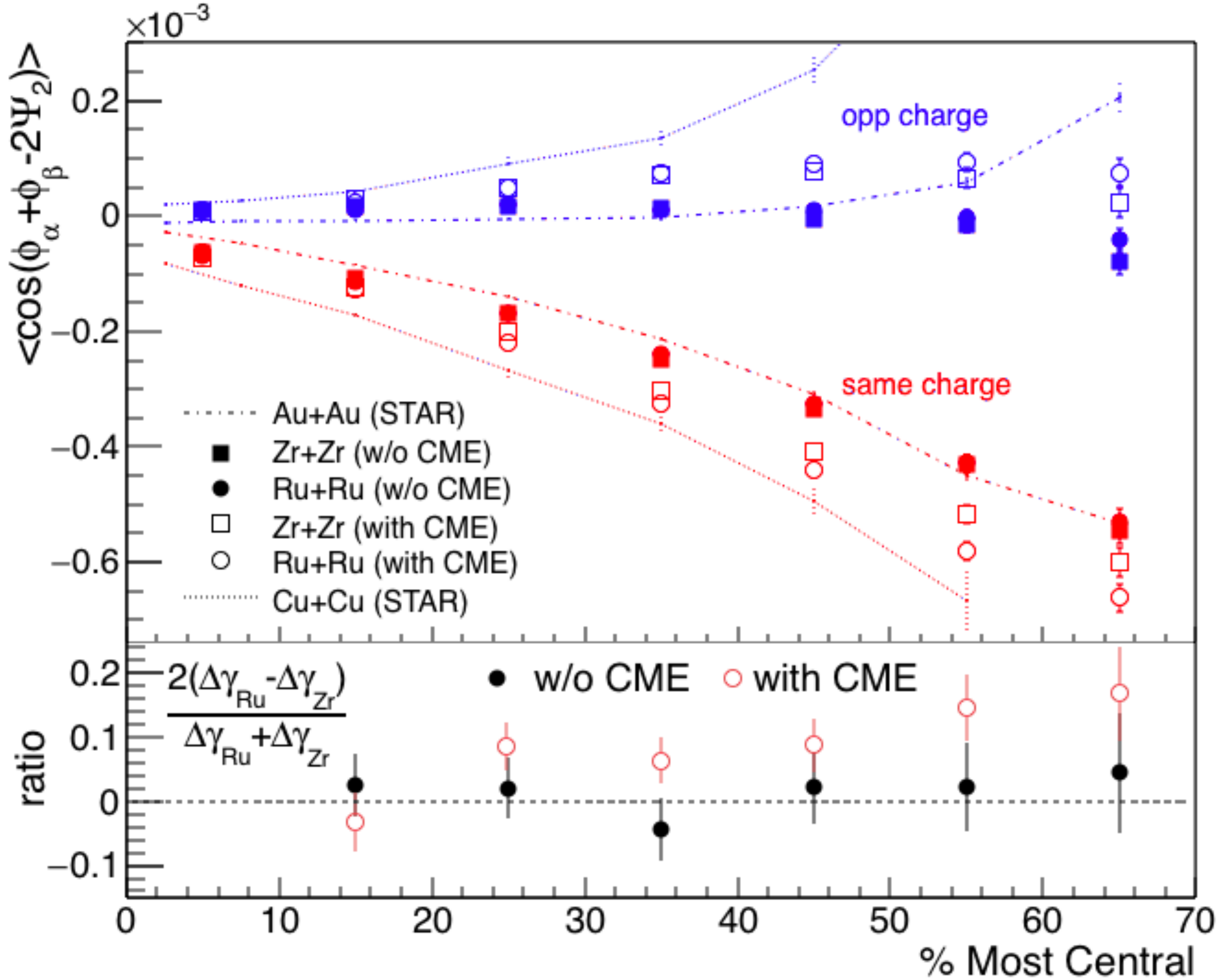


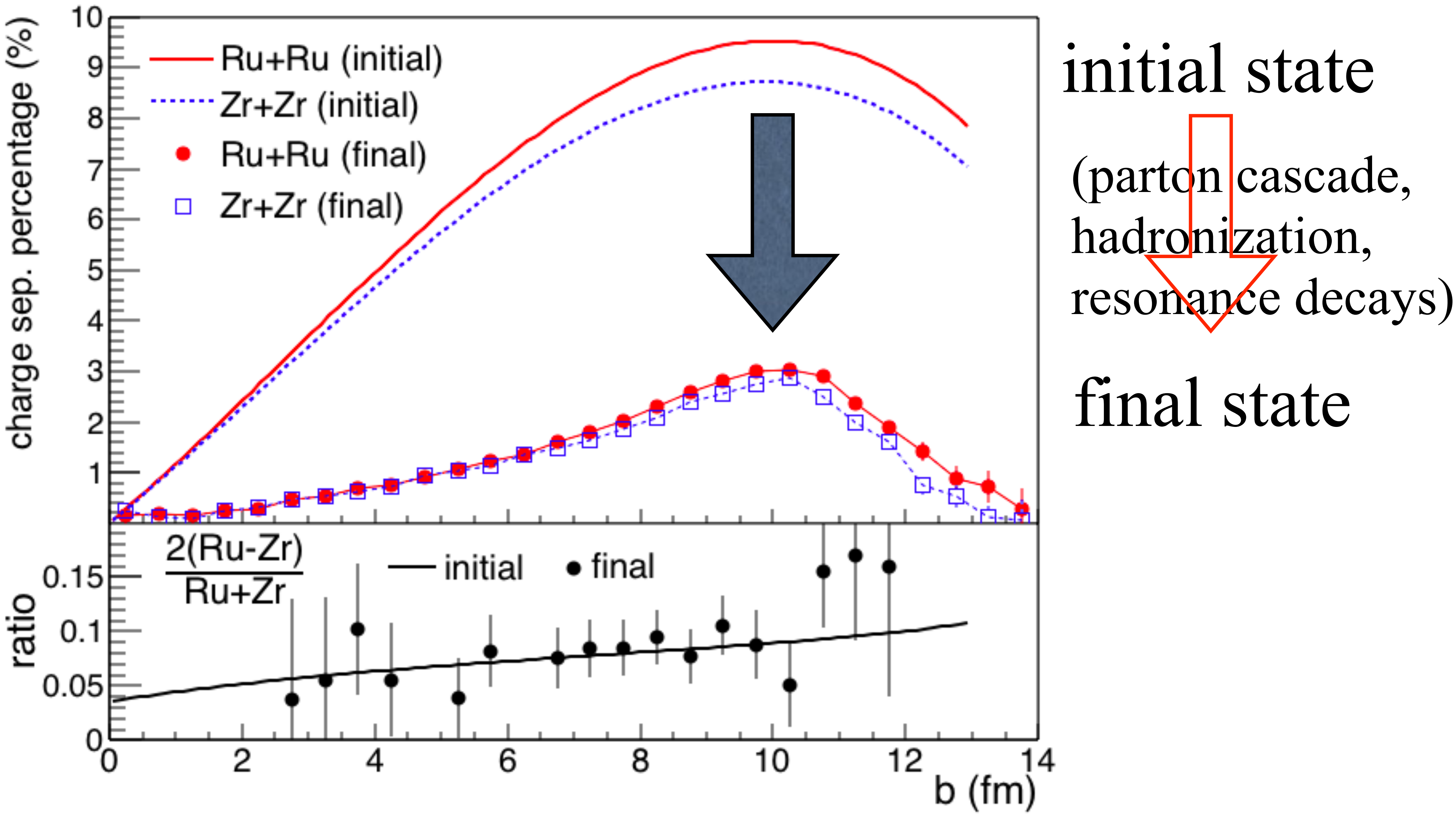
- Original AMPT (0%) underestimates exp. data, ~2/3.
- 10% initial charge separation can describe same-charge data.

CME effect in isobar collisions



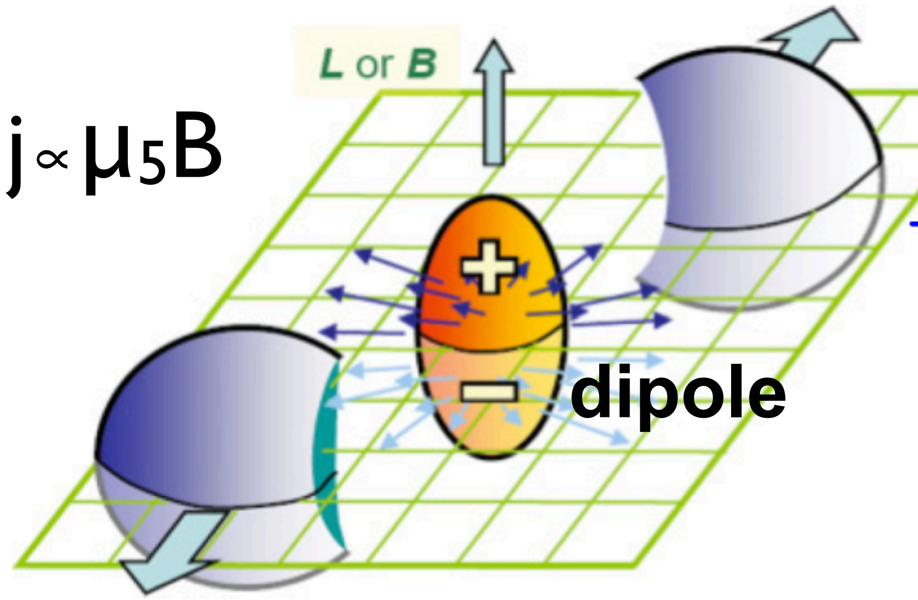
- **If w/o CME(solid symbol),** the signals are almost same between Ru+Ru and Zr+Zr from the regular AMPT model.
- **If with CME (open symbol),** the magnitudes of signals increase, the difference between Ru+Ru and Zr+Zr appears ~10%.

Final interaction effect in isobar collisions



- Final state interactions reduce imported charge separations.
- The relative ratio of charge separation percentage is kept, same as <B_y> ratio.
- Ones could observe the CME signal difference even after strong final state interactions, if with enough statistics.

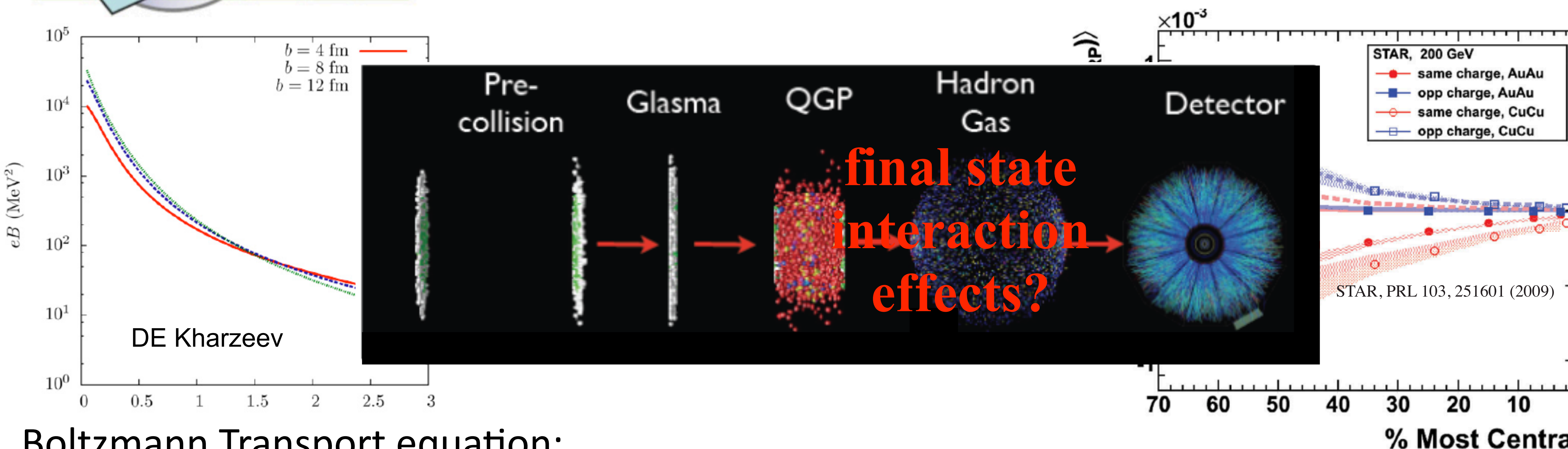
From CKE to BTE



$j \propto \mu_5 B$

Chiral kinetic equation:

$$(1 + s\hbar B\cdot\Omega)\, n\cdot\partial^x f + \left[v^\mu + s\hbar(\hat{\bar{p}}\cdot\Omega)B^\mu + s\hbar\epsilon^{\mu\nu\rho\sigma}n_\rho E_\sigma \Omega_\nu\right]\bar{\partial}^x_\mu f + \left(\tilde{E}^\mu + \epsilon^{\mu\nu\alpha\beta}v_\nu n_\alpha B_\beta + s\hbar E\cdot B\Omega^\mu\right)\bar{\partial}^p_\mu f = C[f]$$



Boltzmann Transport equation:

$$\left\{\partial_t + \dot{\mathbf{x}}\cdot\vec{\nabla}_{\mathbf{x}} + \dot{\mathbf{p}}\cdot\vec{\nabla}_{\mathbf{p}}\right\} f^{(c)}(t,\mathbf{x},\mathbf{p}) = C[f^{(c)}]\,,$$

$$\dot{\mathbf{x}} = \mathbf{v} = \vec{\nabla}_{\mathbf{p}} E_{\mathbf{p}}\,,\quad \dot{\mathbf{p}} = q\,(\mathbf{E} + \mathbf{v}\times\mathbf{B}) = 0$$

$$\frac{d\sigma_{gg}}{dt} = \frac{9\pi\alpha_s^2}{2s^2}\left(3 - \frac{ut}{s^2} - \frac{us}{t^2} - \frac{st}{u^2}\right)$$