三峡大学
CHINA THREE GORGES UNIVERSITY

Chiral Electromagnetic Current and Charge Separation in Relativistic Heavy-Ion Collisions

1. Introductions
2. The Magnetic Fields in Realtivistic HIC
3. Chiral Electromagnetic Current in Relativistic HIC
4. Charge Separation in Relativistic HIC

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Collab. with: X. Ai (艾鑫)， B.-X. Chen(陈帮祥)， Y. J. Mo（莫玉俊）, D. She（佘端） and Y. Zhong（钟洋）

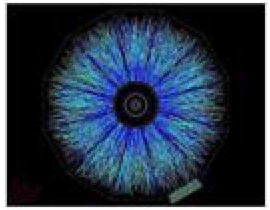
The 13th Workshop on QCD Phase Transitions and Relativistic HIC，Enshi，August 16-20, 2019

1. Introduction

D. Kharzeev, L. D. Mclerran, H. J. Warringa, NPA 803, 227 (2008)

Strong

Strong matter produced
in heavy ion collisions



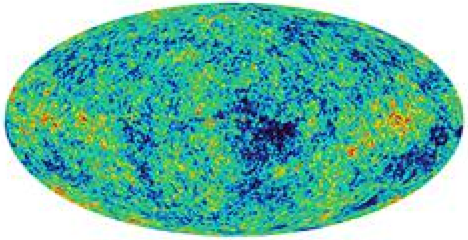
Topological charge changing transitions

induce difference between number of left- and right-handed fermions

Parity to be violated locally in microscopic domains in QCD at finite temperature

ElectroWeak Matter

Electroweak matter produced
in the early universe



Topological charge changing transitions

induce nonzero baryon + lepton number

Parity to be violated globally of weak interactions of the standard model

At high temperatures these transitions are unsuppressed (Sphalerons)
Manton ('83), Manton and Klinkhamer ('84), Mclerran and Shaposhnikov ('85)

How to observe topological charge changing transitions in hot quark matter?

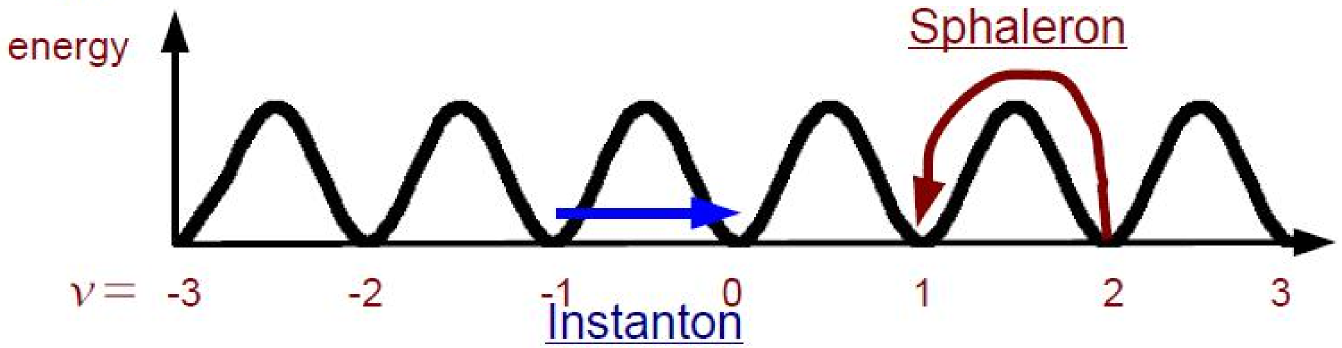
Kharzeev, Mclerran, Warringa, （‘08)

An asymmetry between matter and antimatter is observed
Kuzmin, Shaposhnikov ('85)

Instantons and Sphaleron

$$Q_w = \frac{g^2}{8\pi^2}\int d^4x\, \vec{E}_a \cdot \vec{B}_a = 0, \pm 1, \pm 2, \ldots.$$

Stable under smooth deformations
Change topological charge vacuum



Instantons: Configuration with finite action. **Tunneling through barrier**

Suppression of rate at T=0, 't Hooft ('76), Pisarski and Yaffe ('80)

Sphaleron: Configuration with finite energy. Go over barrier.

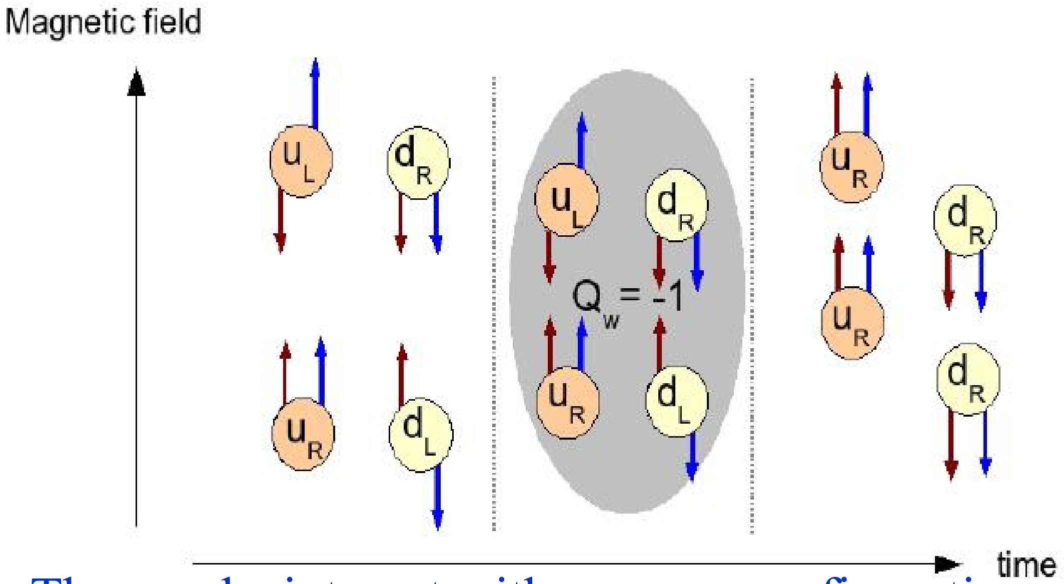
Only possible at finite temperature, rate not suppressed, look for it in QGP!

Manton ('83), Manton and Klinkhamer ('84), McLerran, Mottola and Shaposhnikov ('88)

$$\frac{dN_t^{\pm}}{d^3x\,dt} \sim 385\,\alpha_S^5 T^4$$

Bödeker, Moore and Rummukainen ('00), several transitions per fm^{-3} per fm/c

The Chiral Magnetic Effect (CME)



1. Due to very large magnetic field, the up and down quarks in the lowest landau level and can only move along the direction of the magnetic field. Initially there are as many left-handed as right-handed quarks.

2. The quarks interact with a gauge configuration with non-zero Q_w. Assuming $Q_w = -1$, this will convert a left-handed up/down quark into a right-handed up/down quark by reversing the direction of momentum.

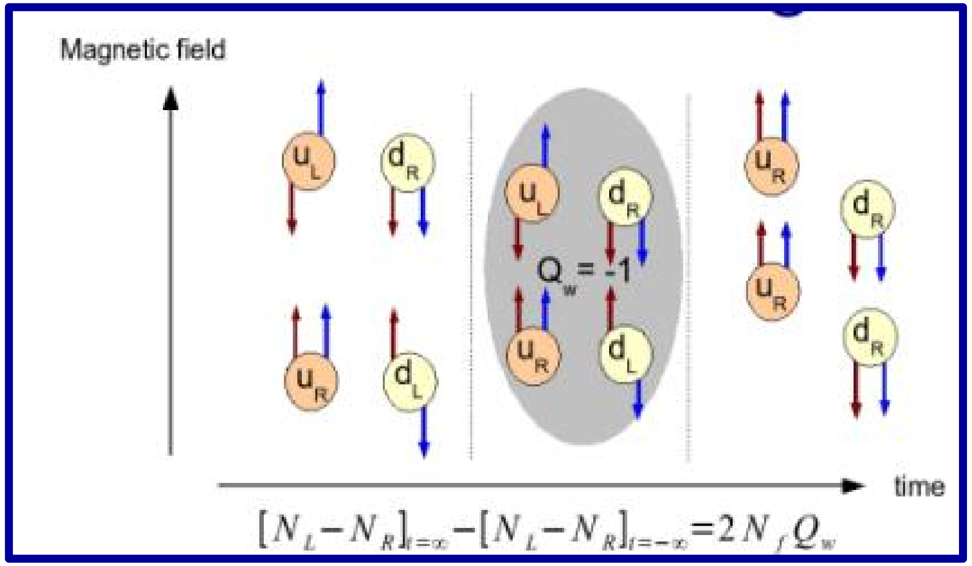
3. The right-handed up quarks will move upwards, the right-handed down quarks will move downwards. A charge of $q = 2e$ will be created between two sides of a plane perpendicular the magnetic fields

In finite volume this causes separation of positive from negative charge

In presence of magnetic field， this induces a chiral electromagnetic current

D. Kharzeev, L. D. Mclerran, H. J. Warringa, NPA 803, 227 (2008)

The Chiral Magnetic Effect



Charge difference:

$$Q = 2Q_w \sum_f |q_f|$$

Same sign for antiparticles!

Toplogical charge changing transitions induces chirality

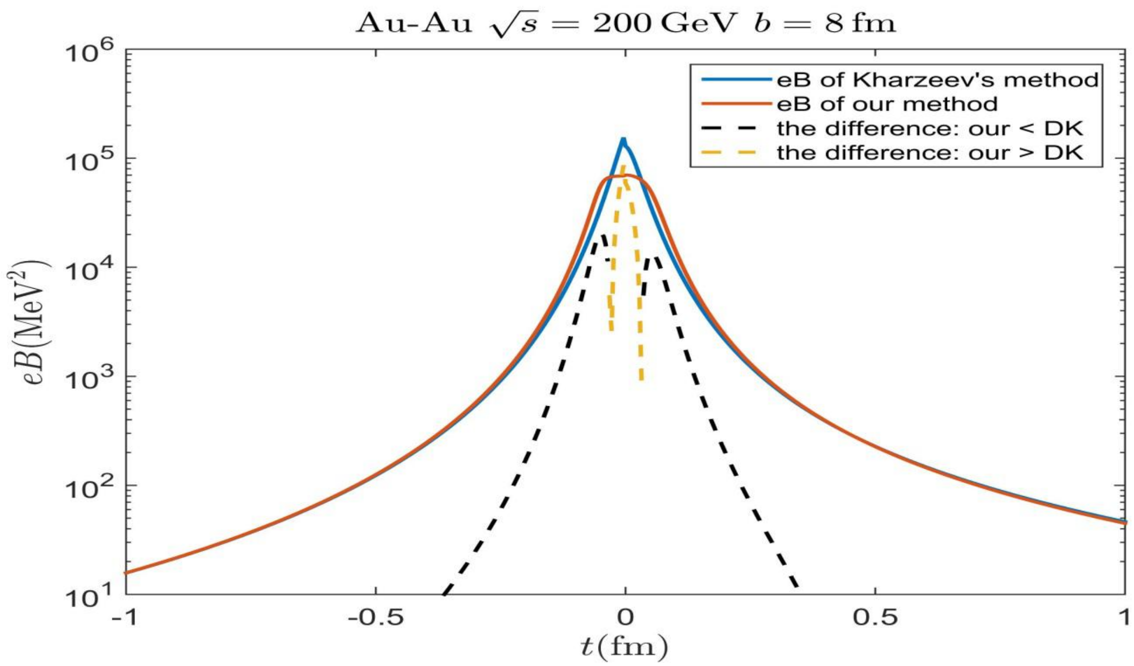
In finite volume this causes separation of positive from negative charge

Reasonable polarization of quarks requires: $e\,B \sim \frac{1}{\rho^2} \sim \alpha_s^2 T^2 \sim 10^3 - 10^4\ \mathrm{MeV}^2$

D. Kharzeev, L. D. Mclerran, H. J. Warringa, NPA 803, 227 (2008)

2. Magnetic Field in HIC

Consider the thickness of the Lorentz contraction of the collision nuclear in the Z directions



KMW's model --**pancake approximation($z \to 0$)**, **we consider the thinkness in the z direction**

RHIC@BNL

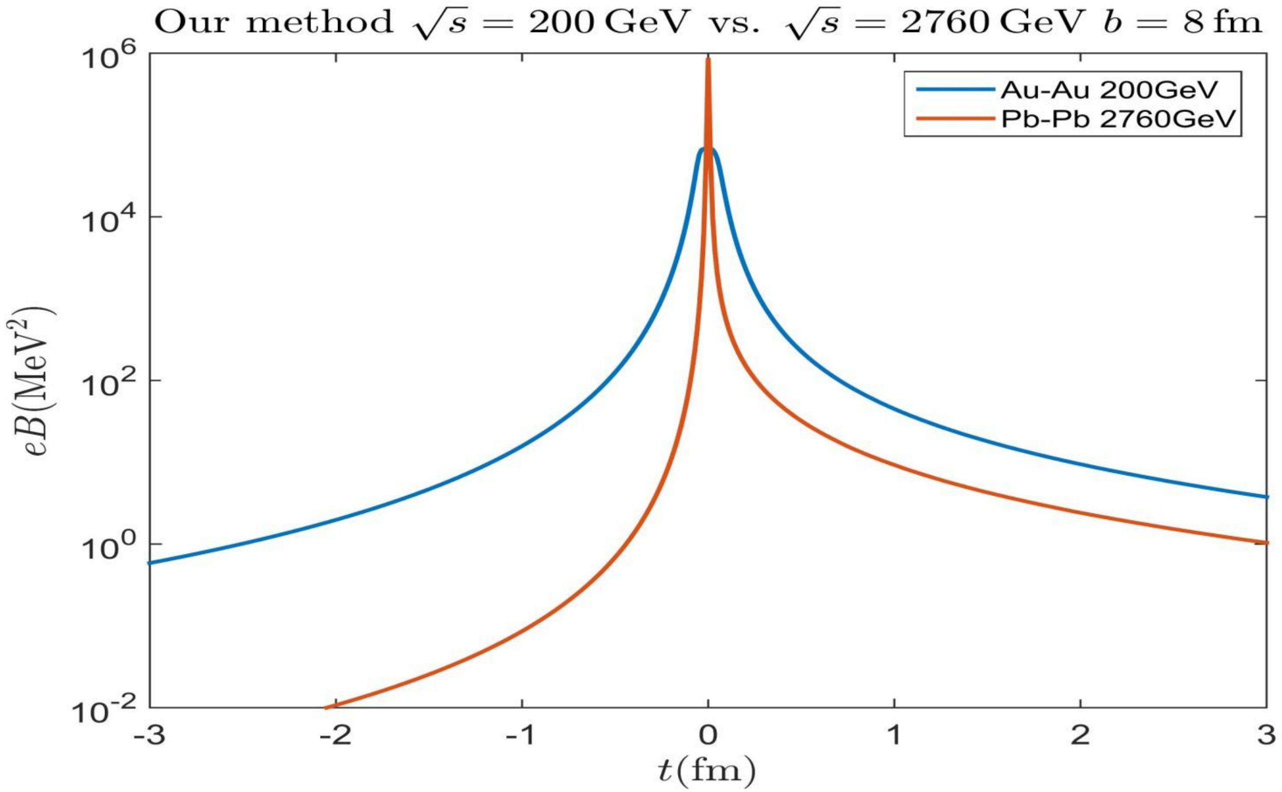
$$eB(\tau = 0.2\,\mathrm{fm}) = 10^3 \sim 10^4\ \mathrm{MeV}^2 \sim 10^{17}\,\mathrm{G}$$

Reasonable polarization of quarks requires: $eB \sim 1/\rho^2 \sim 10^3$ - $10^4\,\mathrm{MeV}^2$

Y. -J. Mo, S. -Q. Feng and Y. -F. Shi, Phys. Rev. C 024901 (2013);
Y. Zhong, C.-B. Yang, X. Cai and S. -Q. Feng , Adv. High Energy Phys. 2014 (2014) 193039

D. Kharzeev, L. D. Mclerran, H. J. Warringa, NPA 803, 227 (2008)

Comparison of Magnetic fields of RHIC with LHC



At LHC, magnetic fields falls off rapidly with time than that at RHIC, Chiral Magnetic Effect Is early time dynamics

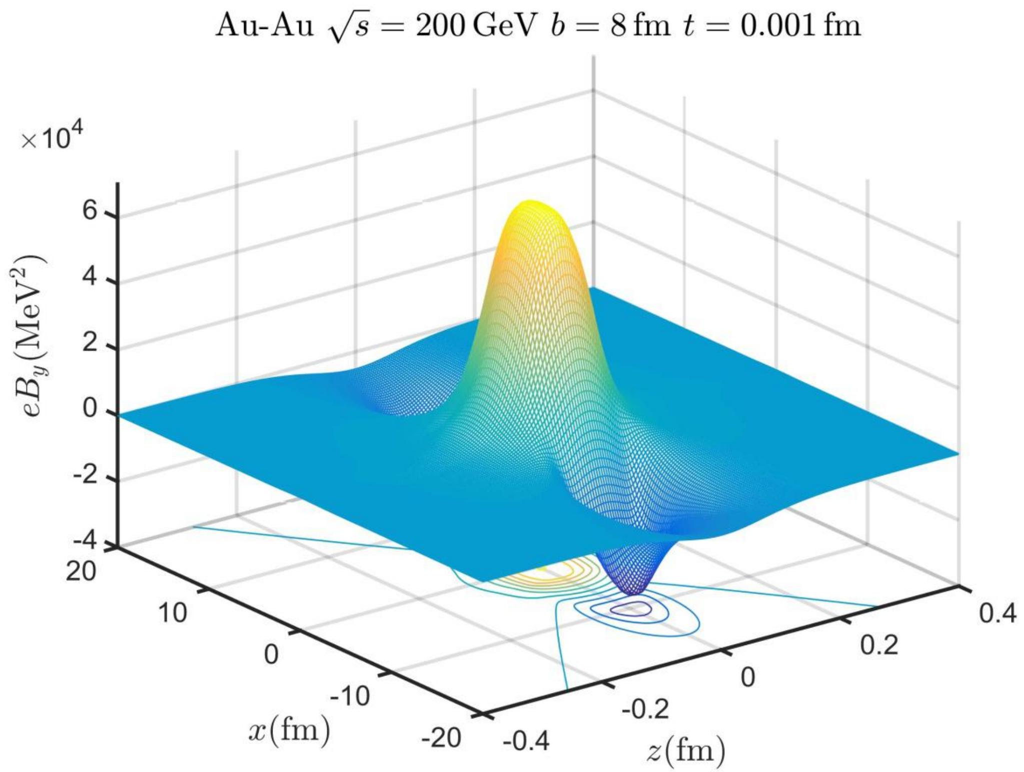
$$eB(\tau = 0.2\mathrm{fm}) = 10^{3} \sim 10^{4}\,\mathrm{MeV}^{2} \sim 10^{17}\,\mathrm{G} \qquad (200\mathrm{GeV})$$

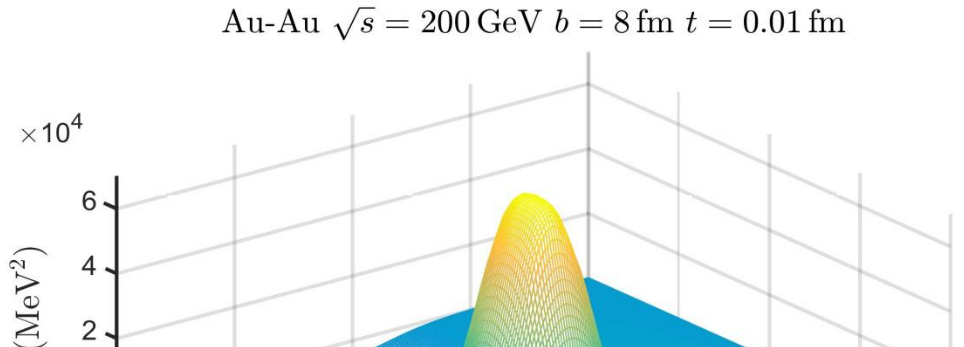
$$eB(\tau = 0.2\mathrm{fm}) = 10^{2} \sim 10^{3}\,\mathrm{MeV}^{2} \sim 10^{16}\,\mathrm{G} \qquad (2760\mathrm{GeV})$$

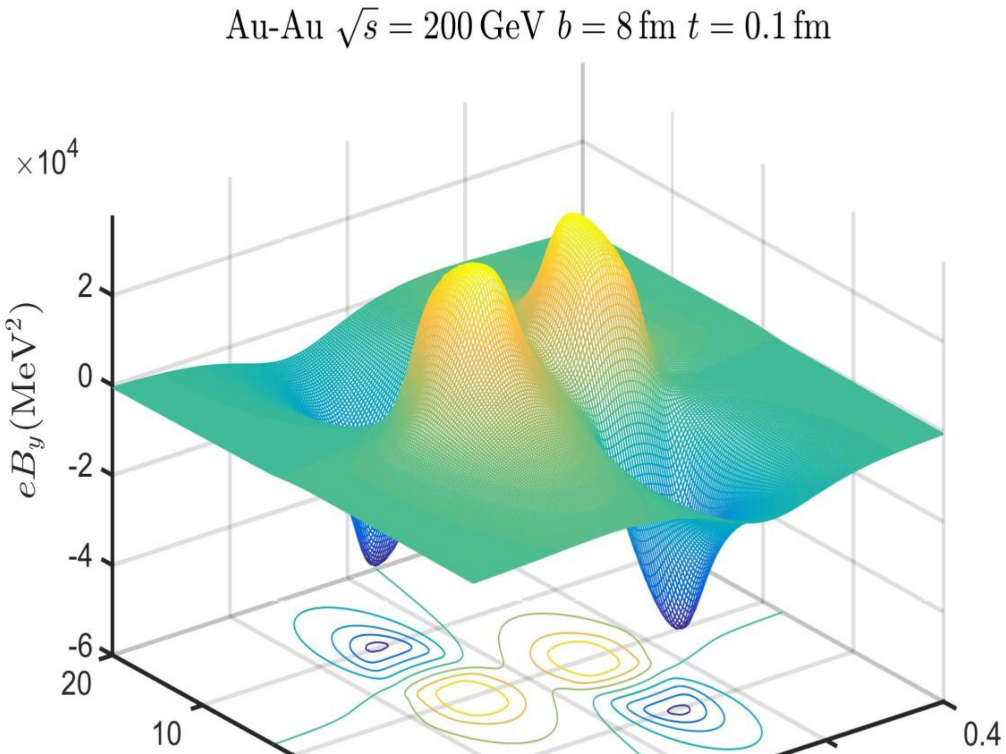
Low energy quarks which are produced in early stages will be polarized in the direction perpendicular to reaction plane

Y. -J. Mo, S. -Q. Feng and Y. -F. Shi, Phys. Rev. C 024901 (2013);
Y. Zhong, C. -B. Yang, X. Cai and S. -Q. Feng , Adv. High Energy Phys. 2014 (2014) 193039

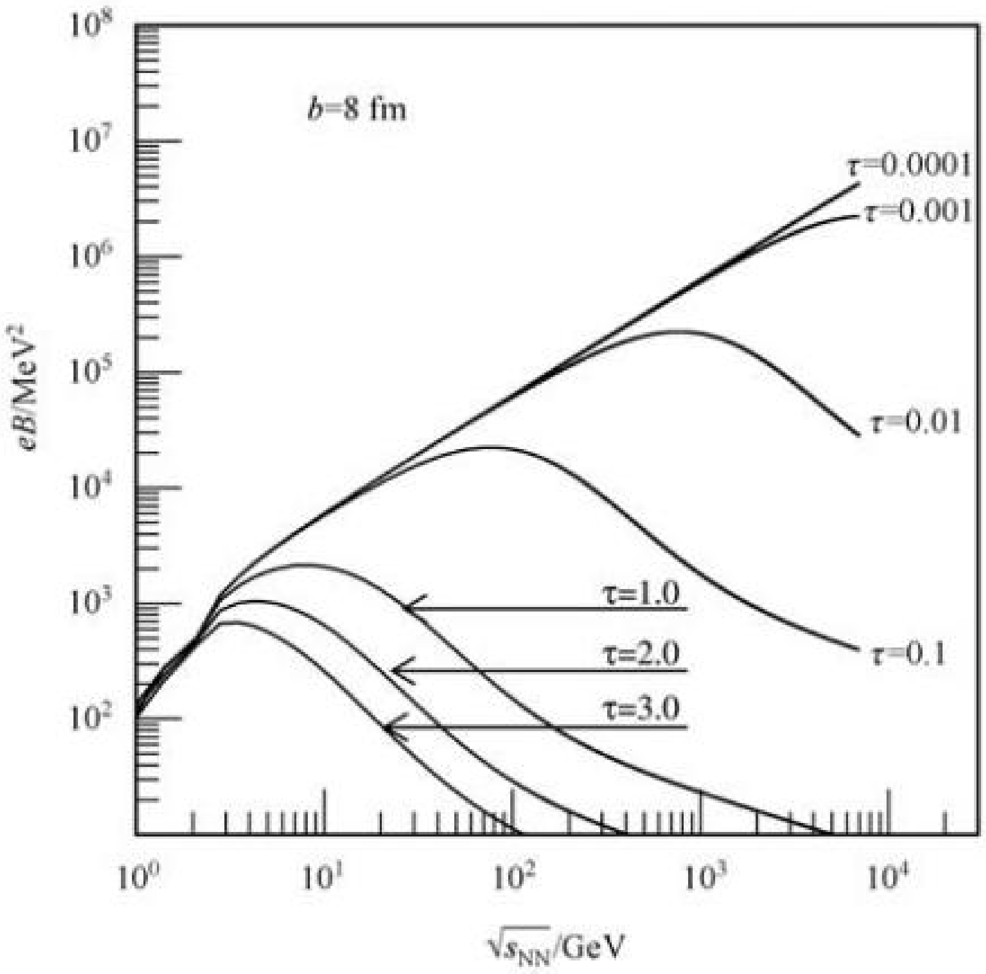
Magnetic field distributes with space and time





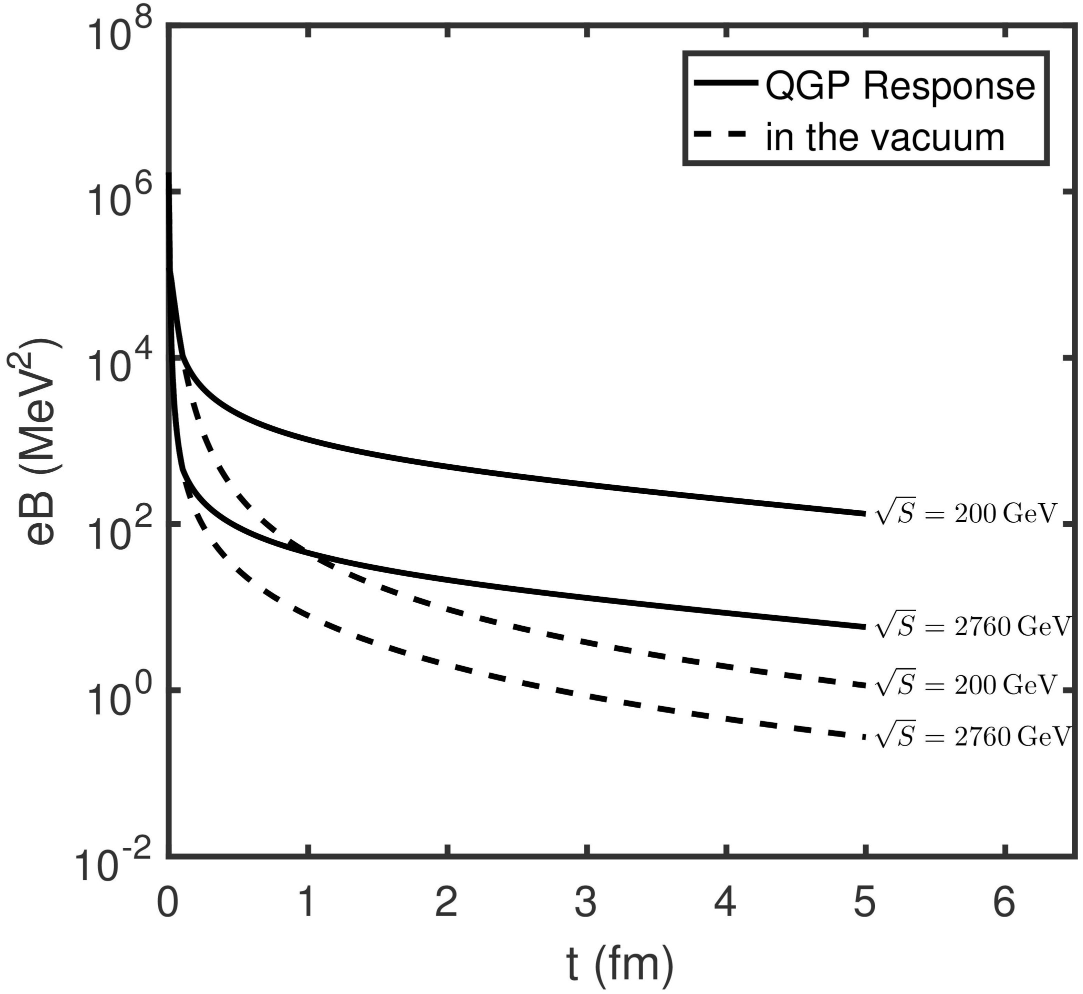


Magnetic fields change with collision energy at different time



Y. Zhong, C.-B. Yang, X. Cai and S. -Q. Feng , Adv. High Energy Phys. 2014 (2014) 193039

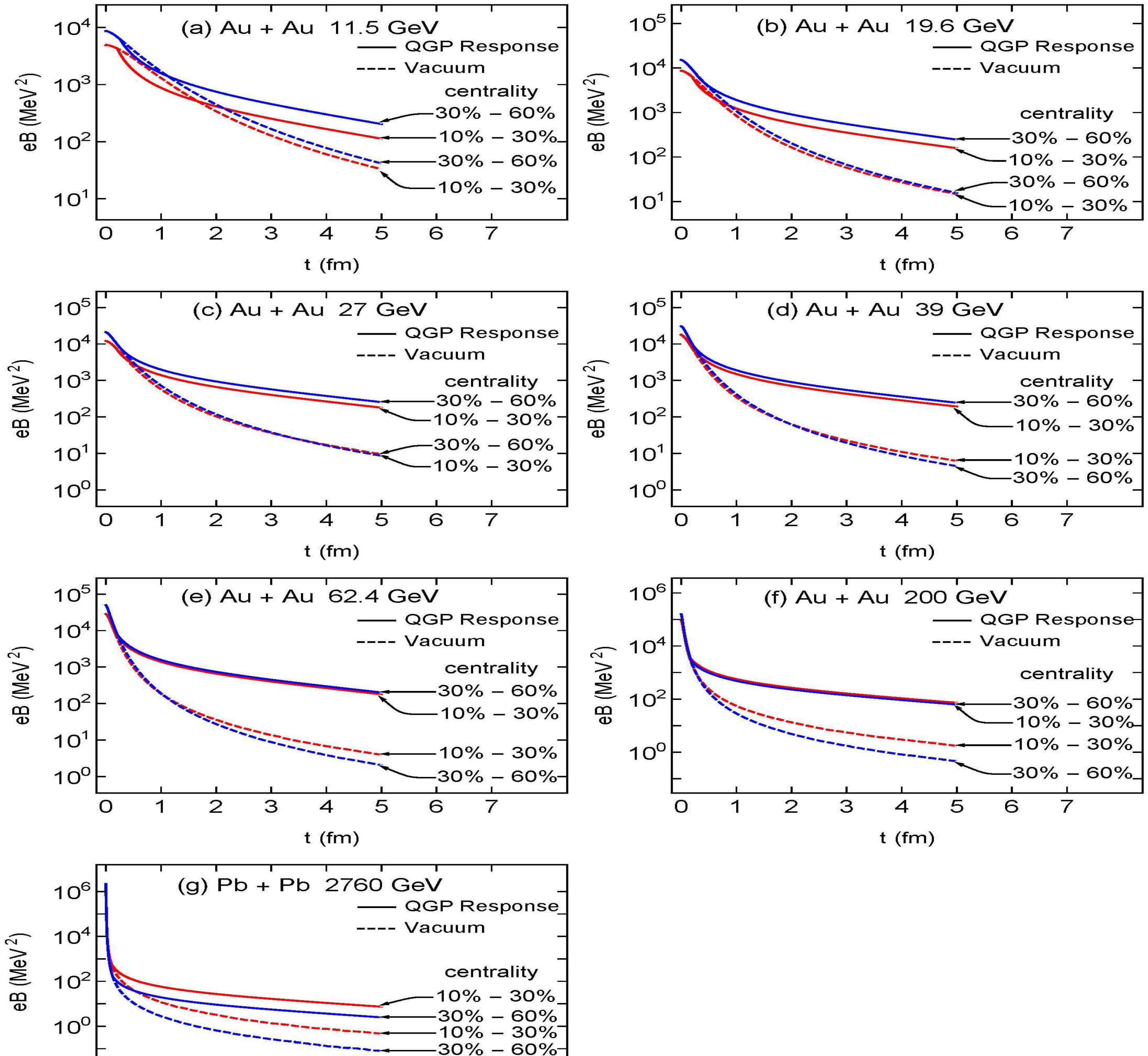
Consider the response of QGP in relativistic heavy-ion collisions



Coupled Maxwell +hydro: W. T. Deng, and X. G. Huang, Phys. Rev. C 85, 044907 (2012).

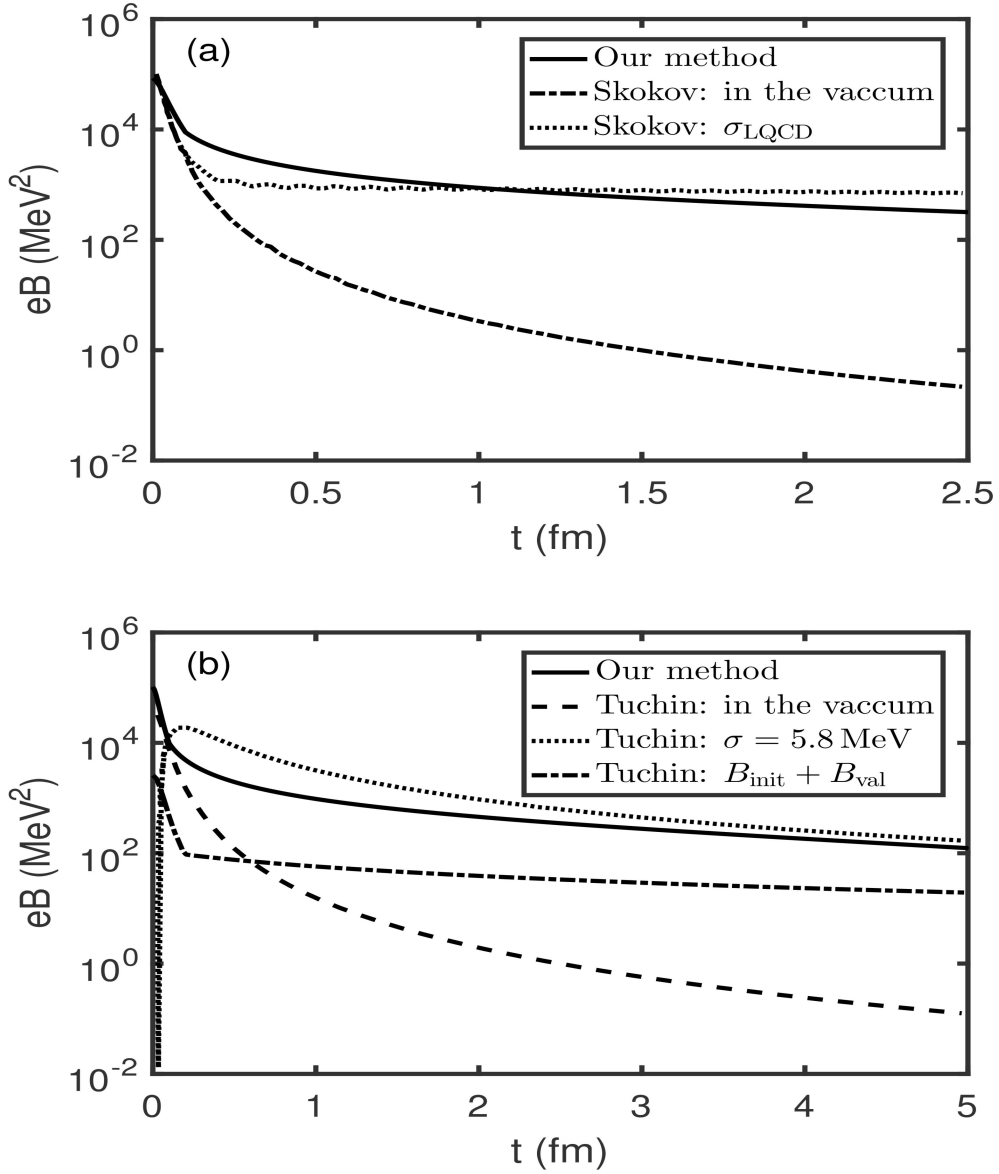
D. She, S. -Q. Feng, et al., European Physical Journal A 54: 48 (2018)

Magnetic field by considering the response of QGP



B.-X.Chen and S.-Q. Feng, in preparation

Comparison with other group calculation results



1. L. McLerran, V. Skokov, Nucl. Phys. A929, 184 (2014).

2. K. Tuchin, Phys. Rev. C 93, 014905 (2016).

D. She, S. -Q. Feng, et al., European Physical Journal A 54 : 48 (2018)

3. Chiral Electromagnetic Current

Based on: D. She, S. -Q. Feng, et al., European Physical Journal A 54:48 (2018)

Chiral Magnetic Conductivity (CMC)

The induced vector current can be calculated using the Kubo formula. This formula is provided by using first order in the time-dependent perturbation:

$$< j^{\mu}(x) >= \int d^4x' \Pi_R^{\mu\nu}(x,x')A_\nu(x')$$

Where $j^{\mu}(x) = e\bar{\psi}(x)\gamma^{\mu}\psi(x)$, and the retarded response function is given by

$$\Pi_{\mathrm{R}}^{\mu\nu}(x,x') = i\langle[j^{\mu}(x), j^{\nu}(x')]\rangle\theta(t-t').$$

Select vector field: $A_x = A_z = 0,\ A = A_y$

Then: $B_z = \partial_x A_y(x)$

The induced vector current in the magnetic field direction:

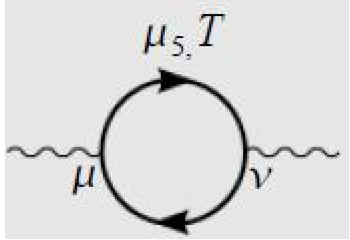
$$\langle j_z(x)\rangle = \sigma_\chi(p)\widetilde{B}_z(p)e^{-ipx} \qquad \sigma_\chi(p) = \frac{1}{ip^1}\widetilde{\Pi}_R^{23}(p) = \frac{1}{2ip^i}\widetilde{\Pi}_R^{jk}(p)\varepsilon^{ijk}$$

Chiral magnetic conductivity(CMC):

$$\sigma_\chi(p) = \frac{1}{ip^i}G_R^i(p) \qquad G_R^i(p) = \frac{1}{2}\varepsilon^{ijk}\widetilde{\Pi}_R^{jk}(p)$$

Retarded Correlator

Retarded correlator can be given by Euclidean correlator:



$$G_R^i(p_0, \boldsymbol{p}) = G_E^i(\omega_n, \boldsymbol{p})|_{i\omega_n \to p_0 + i\epsilon}$$

At very high temperatures， Euclidean correlator:

$$G_E^i(P) = \frac{e^2}{2\beta} \sum_{\tilde{\omega}_m} \int \frac{d^3 q}{(2\pi)^3} \epsilon^{ijk} \operatorname{tr}[\gamma^k S(Q) \gamma^j S(P+Q)]$$

The bare fermion propagator as a function of Euclidean momentum Q in the presence of a chiral chemical potential

$$S(Q) = \frac{1}{i\gamma^0(\tilde{\omega}_m - i\mu - i\mu_5\gamma^5) - \boldsymbol{\gamma} \cdot \boldsymbol{q}},$$

From fermion propagator and chirality projection operators, the integrand function can be written:

$$G_R^i(p) = \frac{ie^2}{16\pi^2} \frac{p^i}{p} \frac{p^2 - p_0^2}{p^2} \int_0^\infty dq f(q) \sum_{t=\pm} (2q + tp_0) \times log[\frac{(p_0 + i\varepsilon + tq)^2 - (q+p)^2}{(p_0 + i\varepsilon + tq)^2 - (q-p)^2}]$$

$$f(q) \equiv \sum_{s=\pm} s[\tilde{n}(q - \mu_s) - \tilde{n}(q + \mu_s)]$$

Real and Imaginary Part of CMC

At zero temperature:

$$\sigma''_\chi(\omega) = \frac{e^2}{3\pi}\omega\delta(\omega)\mu_5 - \frac{e^2\omega^2}{96\pi}\sum_{s,t=\pm} st\delta(\omega/2 + t\mu_s)$$

For large temperature:

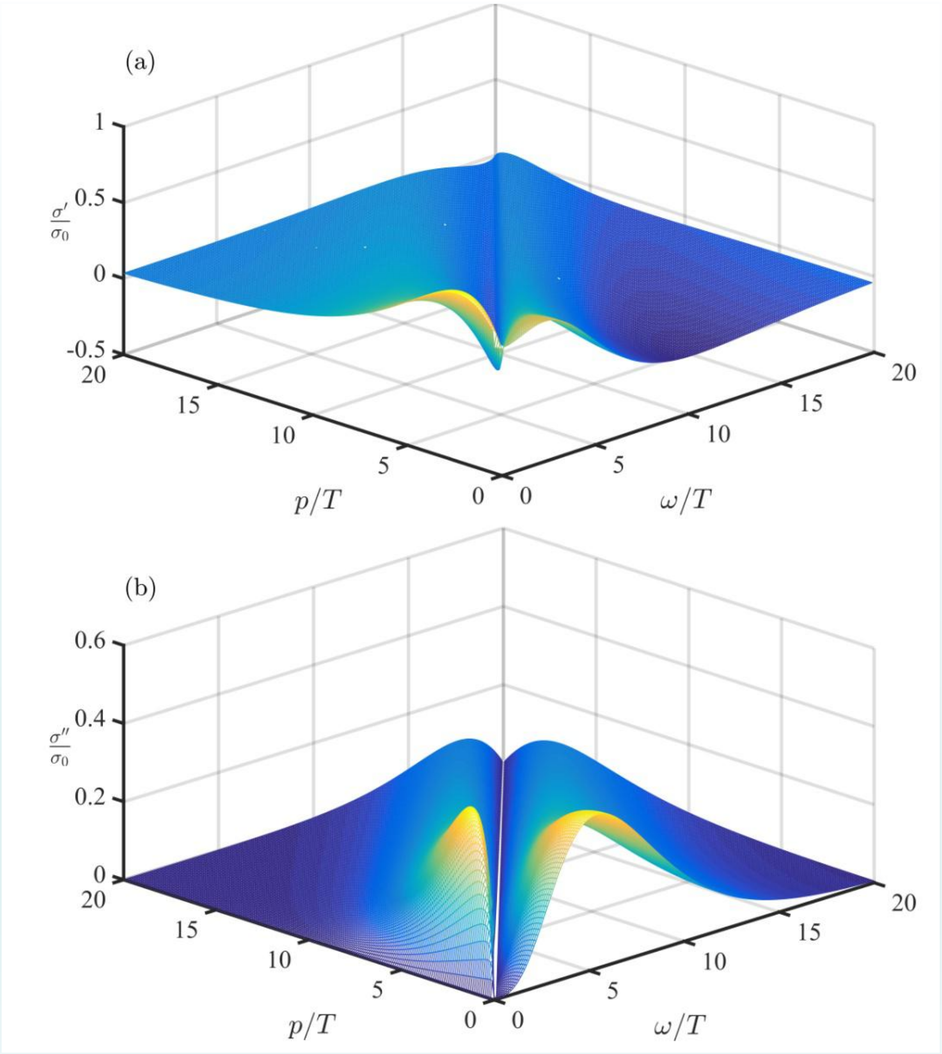
$$\sigma''_\chi(\omega) = \frac{e^2}{3\pi}\omega\delta(\omega)\mu_5 + \frac{e^2\omega|\omega|}{24\pi T^2}\tilde{n}(|\omega|/2)^3 \times [e^{|\omega|/T} - e^{|\omega|/(2T)}]\mu_5.$$

By Kramers-Kroning realtion:

$$\sigma'_\chi(\omega) = \frac{1}{\pi}\mathcal{P}\int_{-\infty}^{\infty} dq_0 \frac{\sigma''_\chi(q_0)}{q_0 - \omega},$$

$$\sigma''_\chi(\omega) = -\frac{1}{\pi}\mathcal{P}\int_{-\infty}^{\infty} dq_0 \frac{\sigma'_\chi(q_0)}{q_0 - \omega}.$$

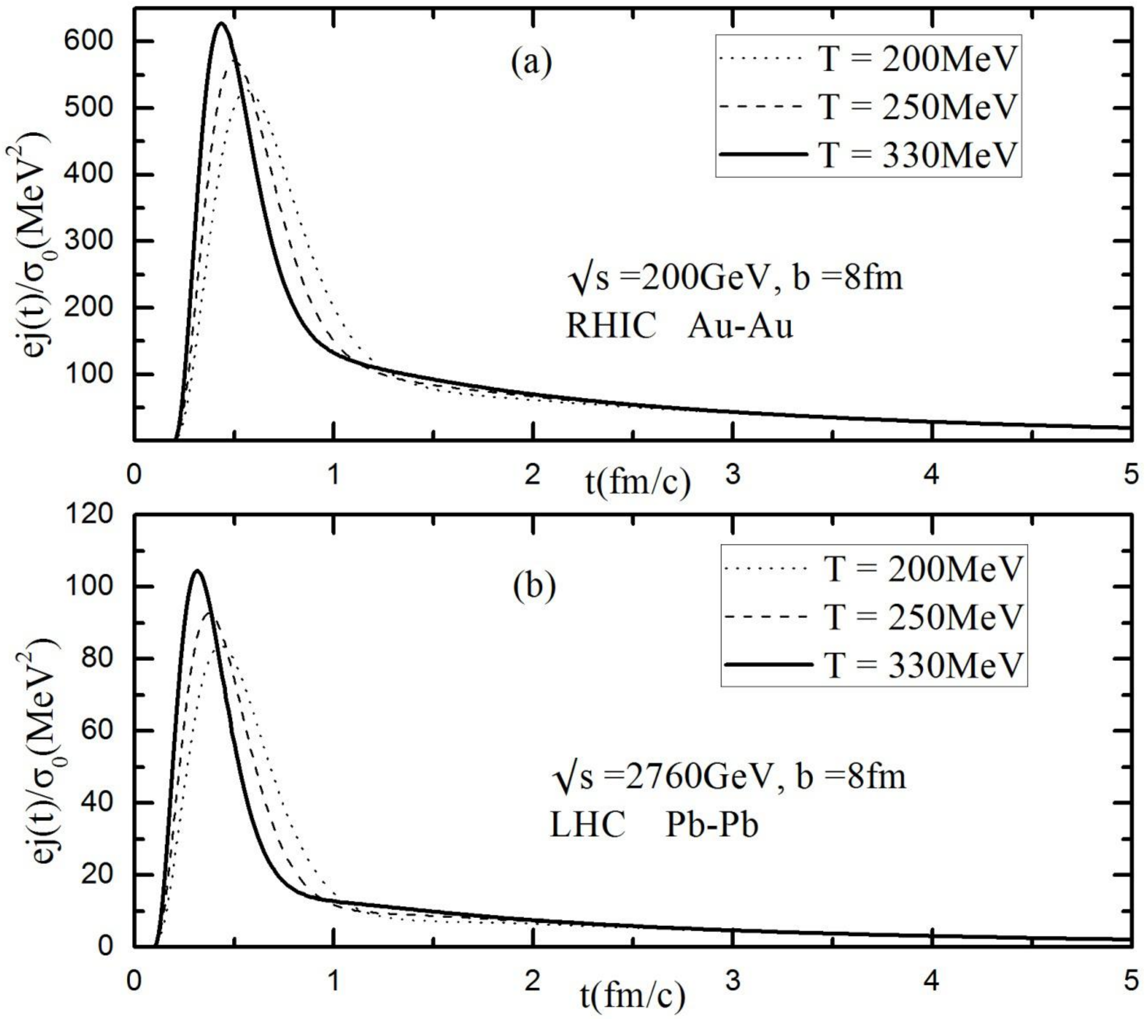
Frequency and momentum dependence of the chiral magnetic conductivity



$\mu = 10\text{MeV},\ \mu_5 = 1\text{MeV},\ T = 200\text{MeV}$

D. She, S. -Q. Feng, et al., European Physical Journal A 54:48 (2018)

Chiral Electromagnetic Current (CEC) in different temperatures

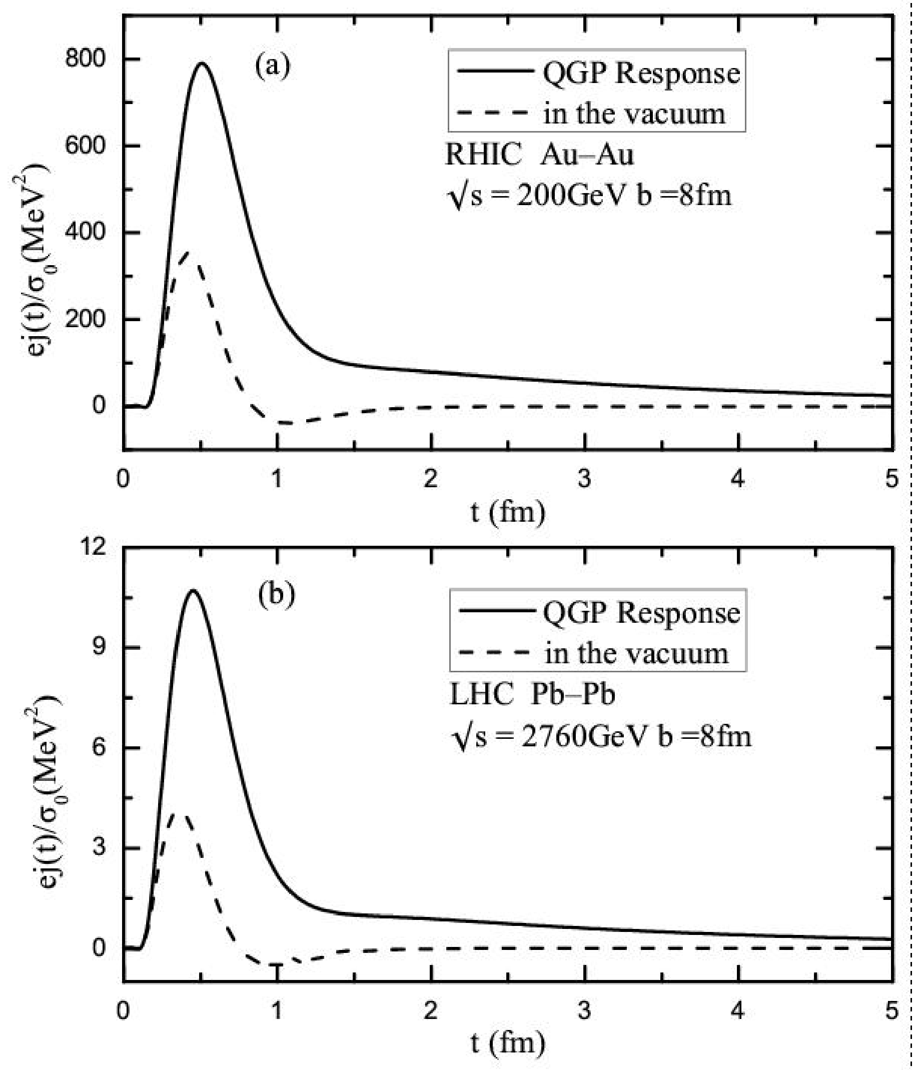


$$j(t) = \int_0^\infty \frac{d\omega}{\pi}[\sigma'(\omega)\cos(\omega t) + \sigma''(\omega)\sin(\omega t)]\tilde{B}(\omega).$$

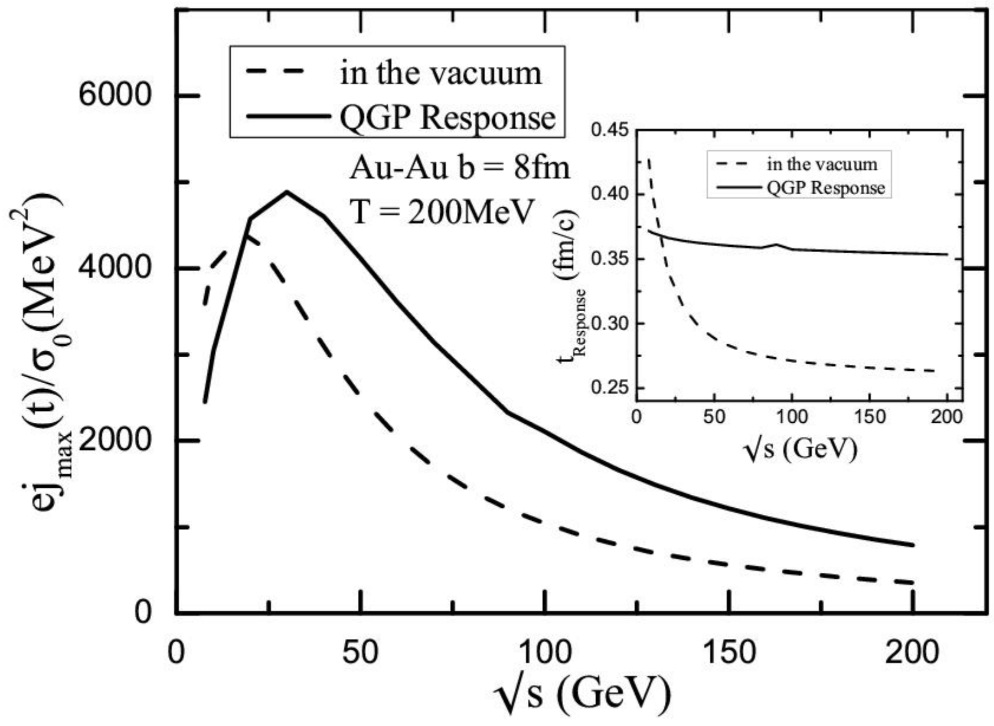
$$\tilde{B}(\omega) = \int_{-\infty}^{\infty} dt e^{i\omega t} B(t).$$

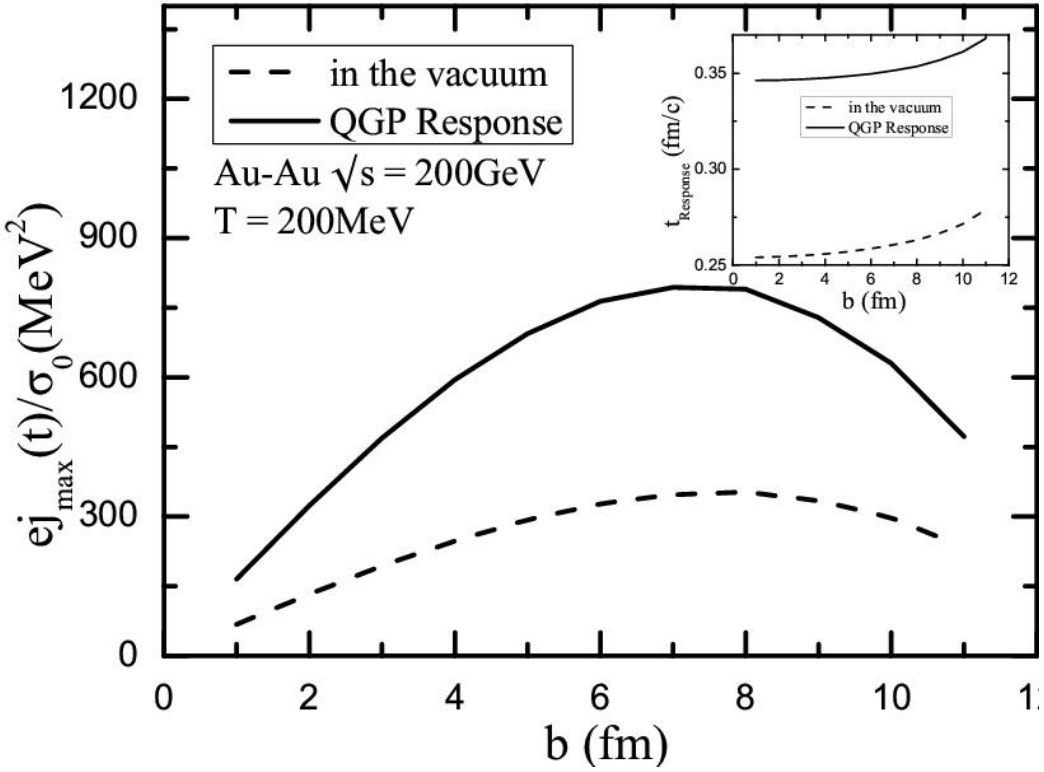
D. She, S. -Q. Feng, et al., European Physical Journal A 54:48 (2018)

Comparison by QGP response with in the vacuum



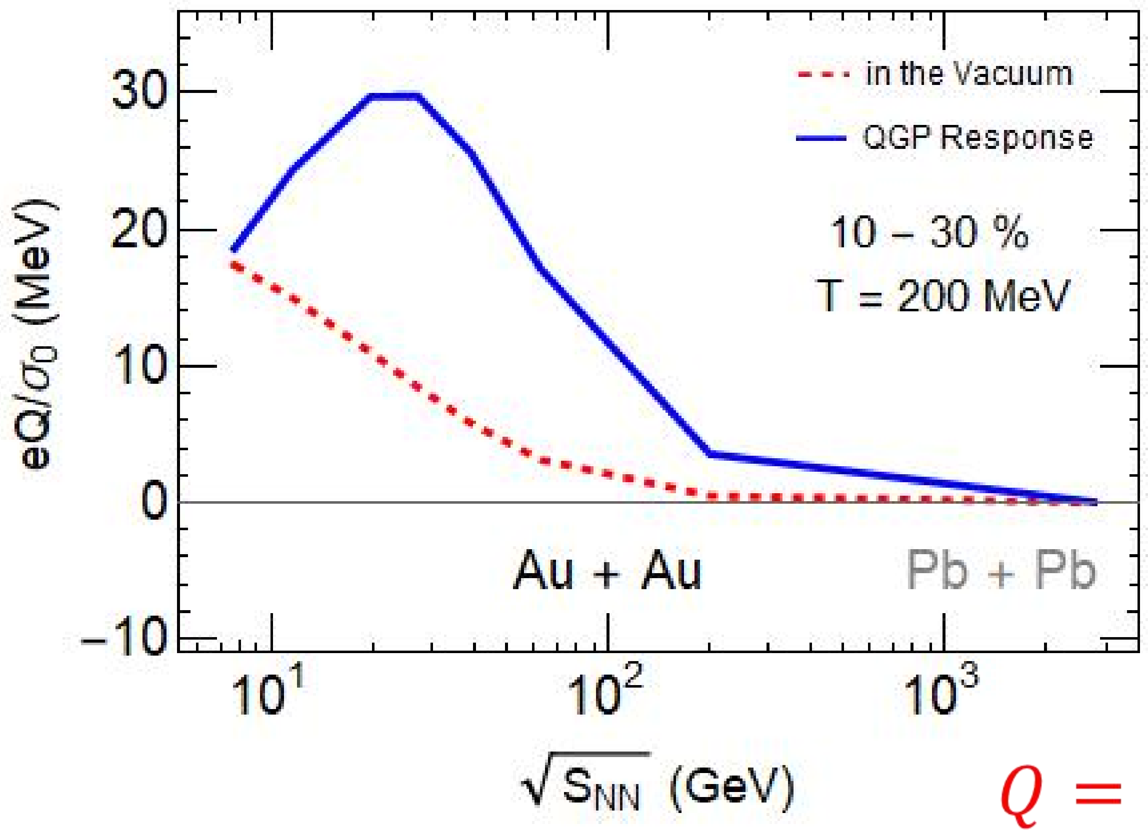
Maximum Chiral Electromagnetic Current (CEC) on energy and impact parameter



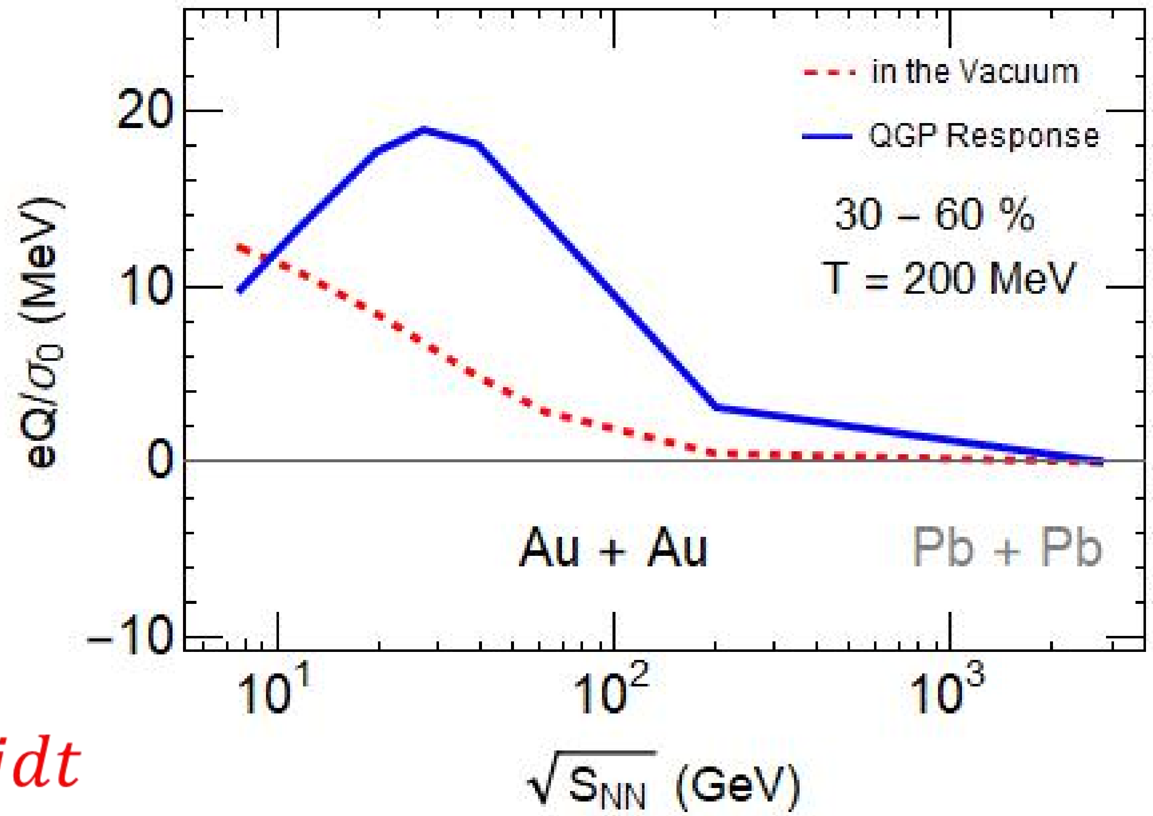


D. She, S. -Q. Feng, et al., European Physical Journal A 54:48 (2018)

Chiral electromagnetic charge with different centrality



$$Q = \int j dt$$



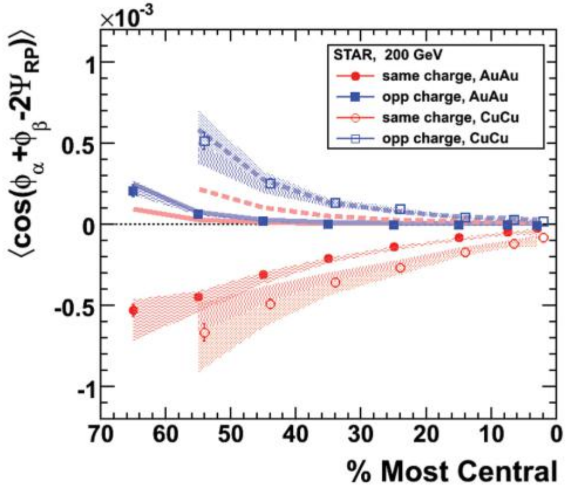
4. Charge Separation features in Relativistic HIC

Based on: S.-Q. Feng, X. Ai et al., Chinese Physics, C 42 054102 (2018)

CME Signal at RHIC

Selected for a Viewpoint in *Physics*
PRL **103,** 251601 (2009) PHYSICAL REVIEW LETTERS week ending 18 DECEMBER 200

Azimuthal Charged-Particle Correlations and Possible Local Strong Parity Violation

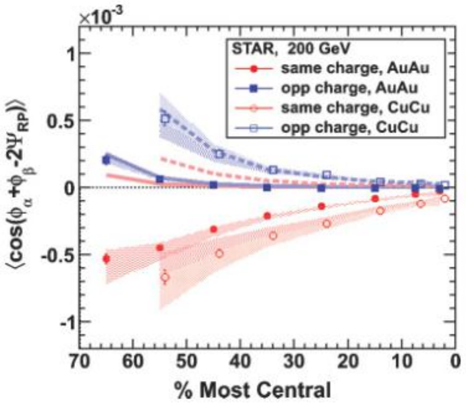


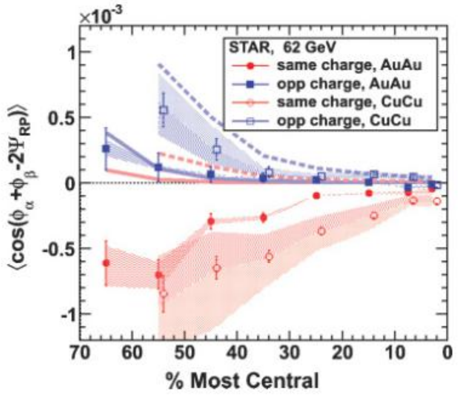
(STAR Collaboration)

PHYSICAL REVIEW C **81**, 054908 (2010)

Observation of charge-dependent azimuthal correlations and possible local strong parity violation in heavy-ion collisions

(STAR Collaboration)





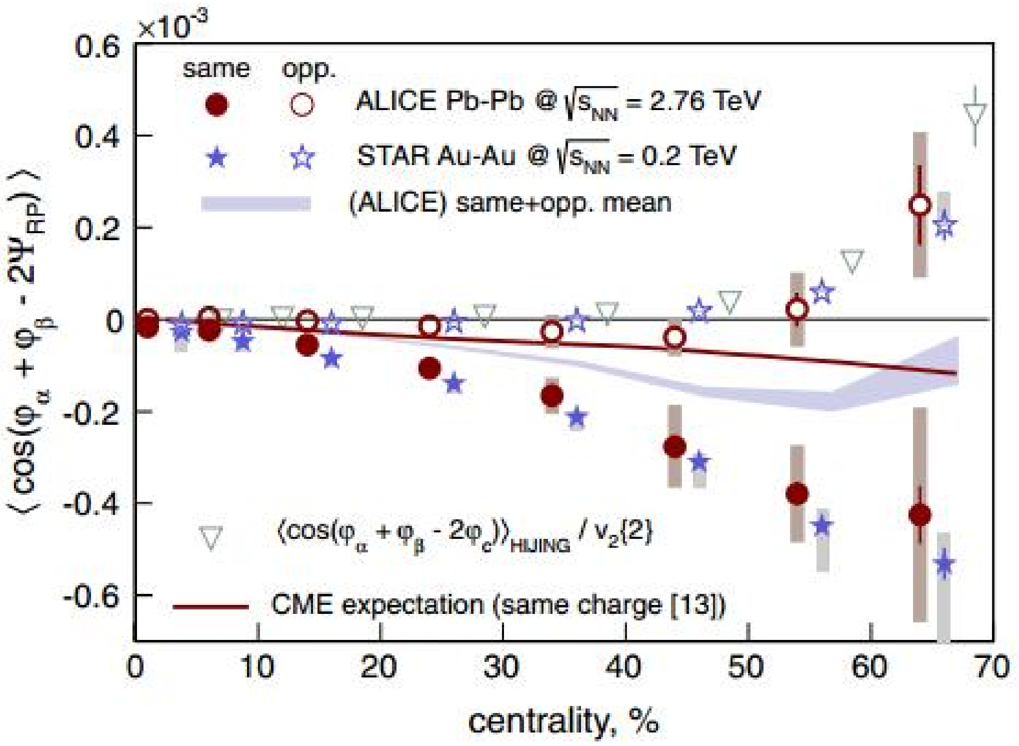
CME Signal at LHC

PRL 110, 012301 (2013) PHYSICAL REVIEW LETTERS week ending 4 JANUARY 2013

Charge separation relative to the reaction plane in Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV

B. Abelev *et al.**
(ALICE Collaboration)

(Received 5 July 2012; published 2 January 2013)



Calculate the charge separations between both sides of reaction plane

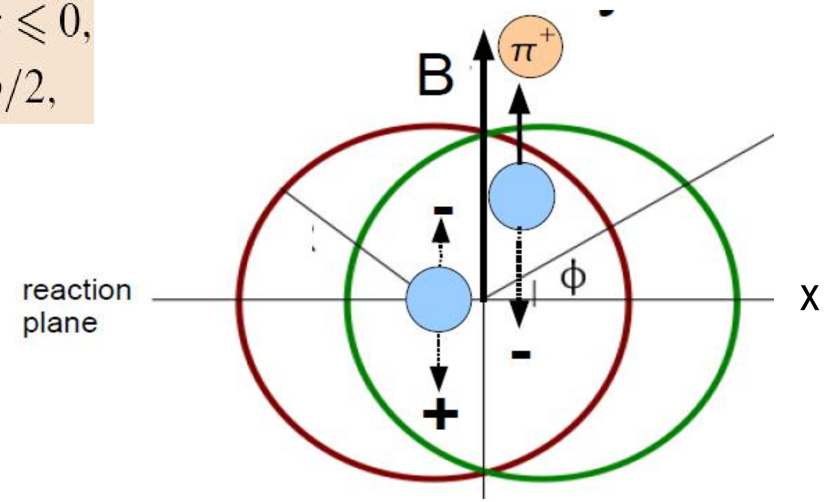
$$\langle \Delta_{\pm}^2 \rangle = 2\kappa\alpha_s \left[\sum_f q_f^2\right]^2 \int_{V_\perp} d^2x_\perp \left[\left(\xi_-(x_\perp)\right)^2 + \left(\xi_+(x_\perp)\right)^2\right] \int d\eta \int_{\tau_i}^{\tau_f} d\tau\, \tau[eB(\tau,\eta,x_\perp)]^2$$

$$\langle \Delta_+ \Delta_- \rangle = -4\kappa\alpha_s \left[\sum_f q_f^2\right]^2 \int_{V_\perp} d^2x_\perp \xi_-(x_\perp)\xi_+(x_\perp) \int d\eta \int_{\tau_i}^{\tau_f} d\tau\, \tau[eB(\tau,\eta,x_\perp)]^2$$

$$\xi_{\pm}(x_\perp) = \exp\left(-\left|y_{\pm}(x) - y\right|/\lambda\right)$$

$$y_+(x) = -y_-(x) = \begin{cases} \sqrt{R^2 - (x-b/2)^2} & -R + b/2 \leqslant x \leqslant 0, \\ \sqrt{R^2 - (x+b/2)^2} & 0 \leqslant x \leqslant R - b/2, \end{cases}$$

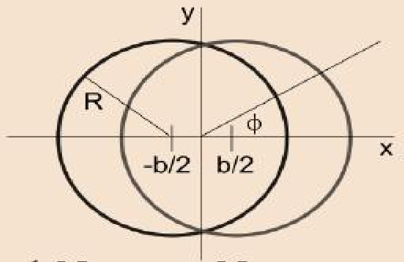
The Chiral Magnetic Effect is a near the surface effect



Calculate the charge separations between both sides of reaction plane

$$a_{++} = a_{--} = \frac{1}{N_{\pm}^2}\frac{\pi^2}{16}\langle \Delta_{\pm}^2 \rangle,$$

$$a_{+-} = a_{-+} = \frac{1}{N_+ N_-}\frac{\pi^2}{16}\langle \Delta_+ \Delta_- \rangle$$



ϕ : angle between particle and reaction plane

$$\frac{dN_{\pm}}{d\phi} = \frac{N_{\pm}}{2\pi} + a_{\pm}\sin\phi + v_2\cos 2\phi + \ldots.$$

Average over many equivalent events (to cancel statistical fluctuations) can give us

$\langle a_+^2 \rangle \sim \langle \Delta_+^2 \rangle$ Pref. emission positive on one side

$\langle a_-^2 \rangle \sim \langle \Delta_-^2 \rangle$ Pref. emission negative on one side

$\langle a_+ a_- \rangle \sim \langle \Delta_+ \Delta_- \rangle$ Correlations between positive on one and negative on other side

PRL 113, 052302 (2014) PHYSICAL REVIEW LETTERS week ending 1 AUGUST 2014

Beam-Energy Dependence of Charge Separation along the Magnetic Field in Au + Au Collisions at RHIC

three particle correlator γ, two particle correlator δ,

$$\gamma \equiv \langle \cos(\phi_1 + \phi_2 - 2\Psi_{RP}) \rangle = \kappa v_2 F - H,$$

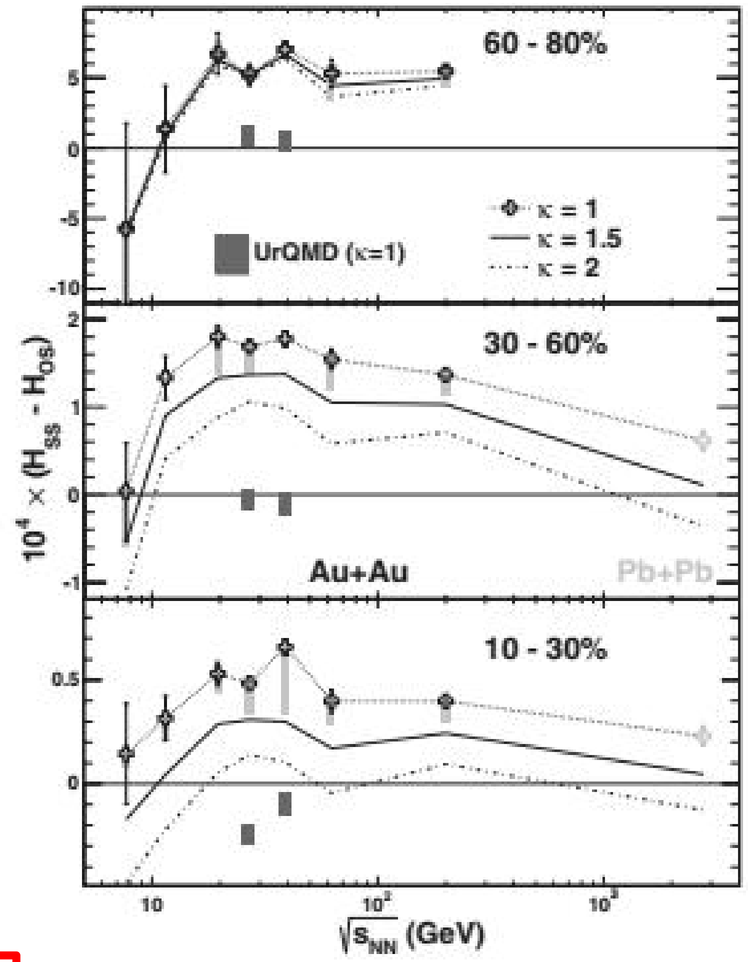
$$\delta \equiv \langle \cos(\phi_1 - \phi_2) \rangle = F + H,$$

where, H and F represent signal from CME and background, F mainly comes from elliptic flow.

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

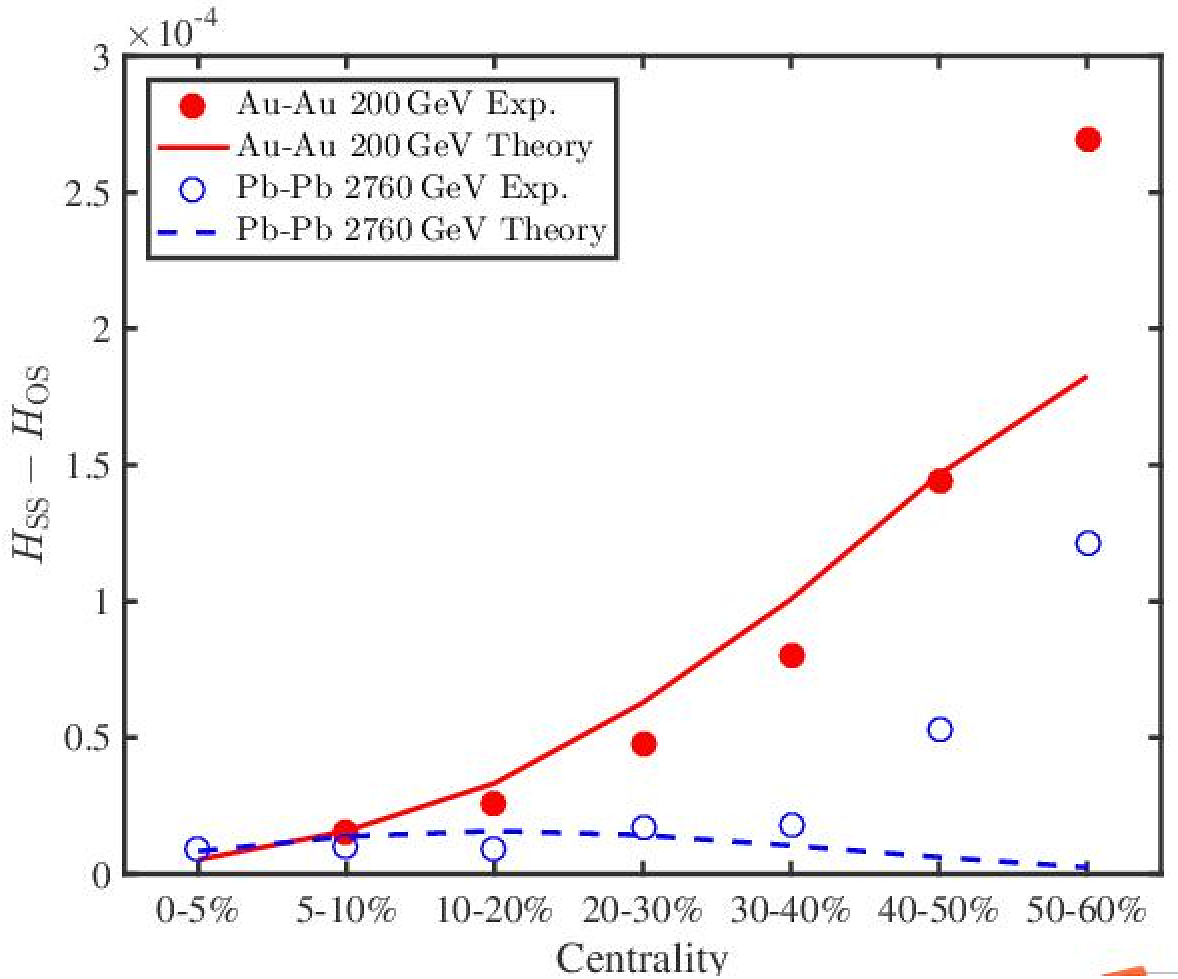
Star's (14) used: H_{SS}, H_{OS}

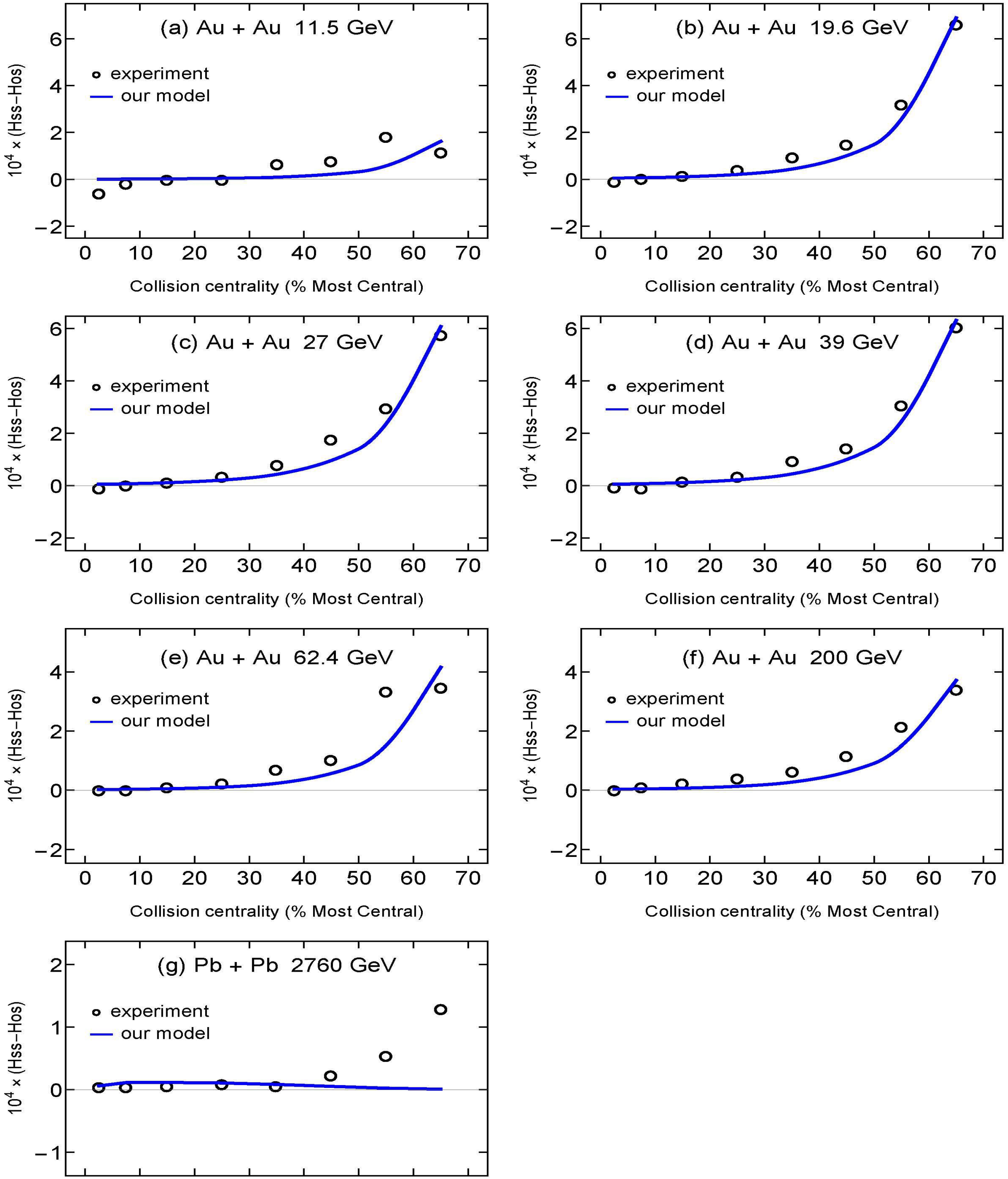
can subtract non-flow background



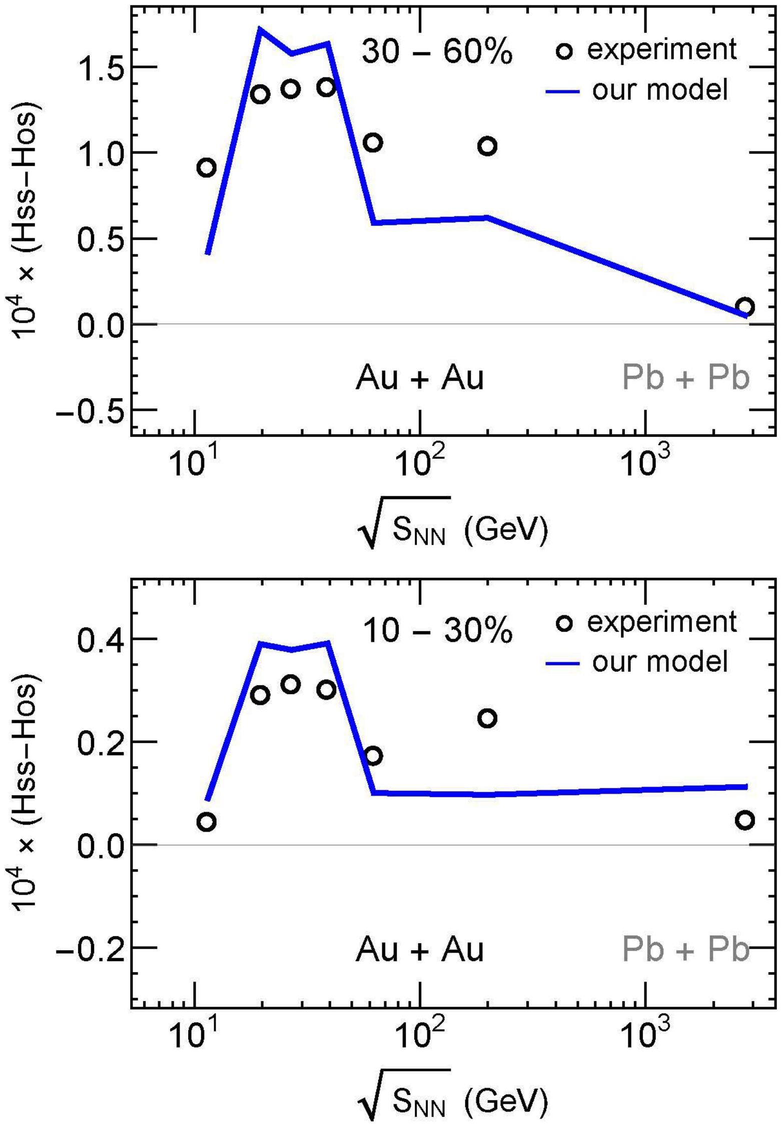
A. Bzdak, V. Koch, and J. Liao, Phys. Rev. C 83, 014905 (2011).
A. Bzdak, V. Koch, and J. Liao, Lect. Notes Phys. 871, 503 (2013).

Fit with experimental data



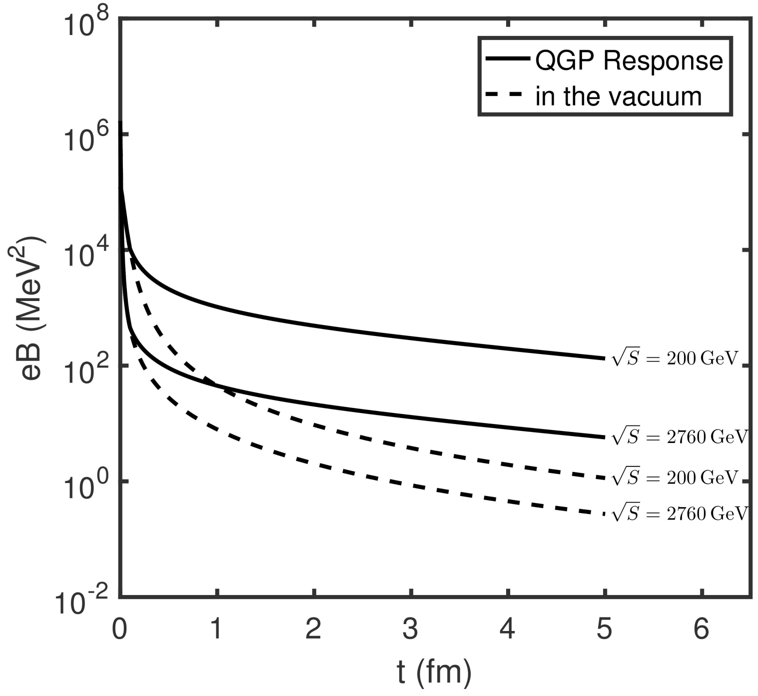


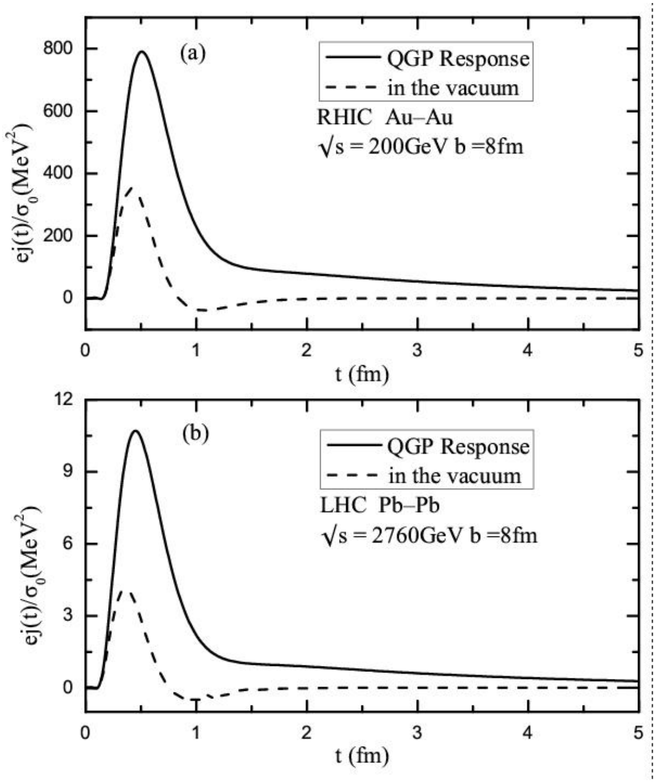
B.-X.Chen and S.-Q. Feng, in preparation

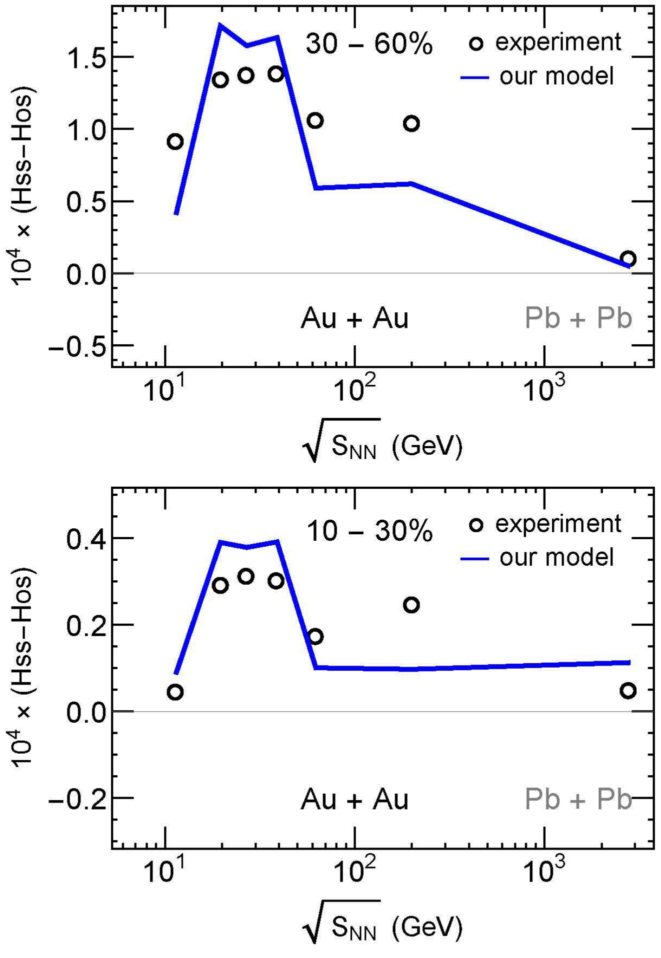


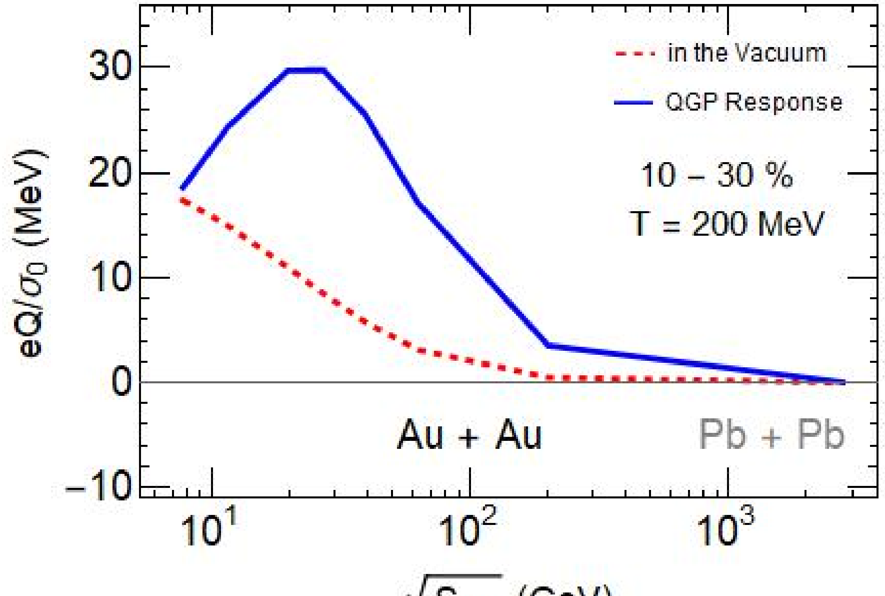
B.-X.Chen and S.-Q. Feng, in preparation

Summary and Conclusions









Thank your attentions