Electromagnetic Fields in Heavy-Ion Collisions: Evolution, Photon Signals, and Initial Conditions

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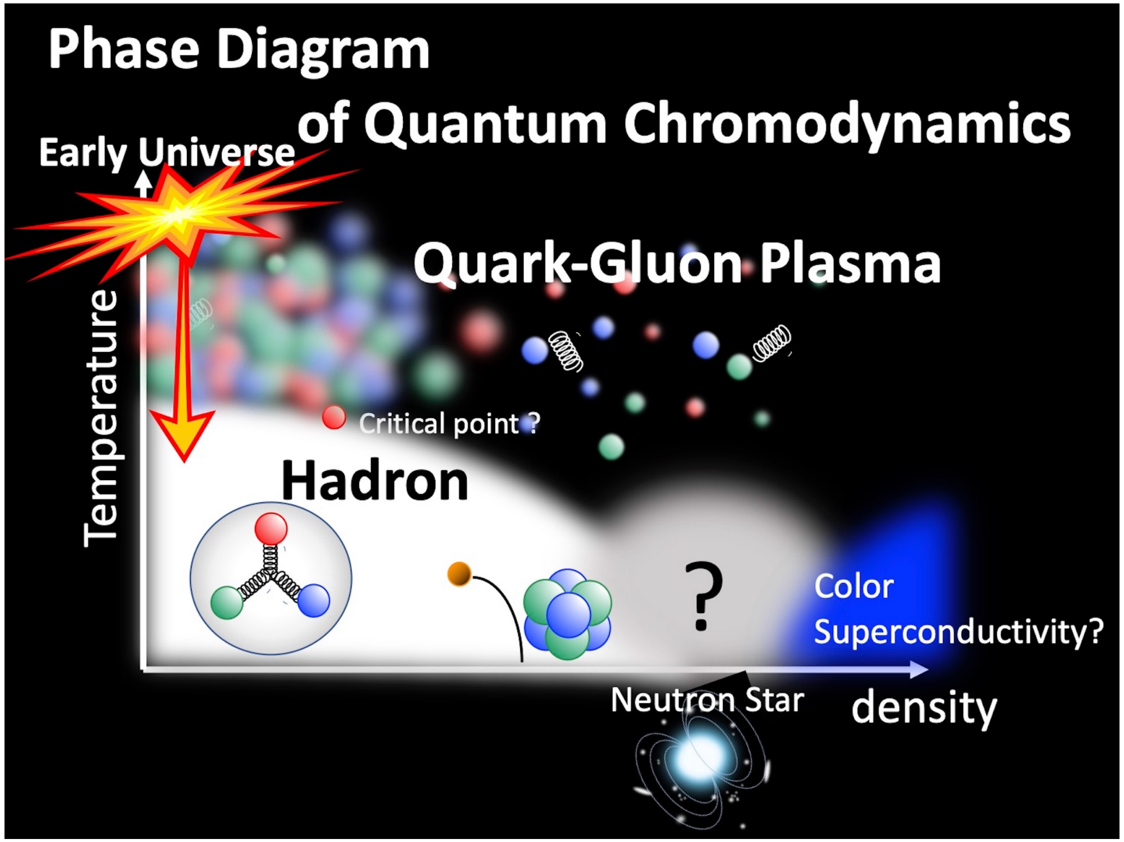
Contents

- Electromagnetic fields in high-energy heavy-ion collisions
- Relativistic resistive magnetohydrodynamics
  - Strong electromagnetic field after collisions
  - Construction of relativistic resistive magnetohydrodynamics
- Electric conductivity of QCD matter in heavy-ion Collisions
  - Charge dependent flow
  - Elliptic flow of photons
- Initial Conditions with electromagnetic fields
- Summary

Introduction

- High-Energy Heavy-Ion Collisions



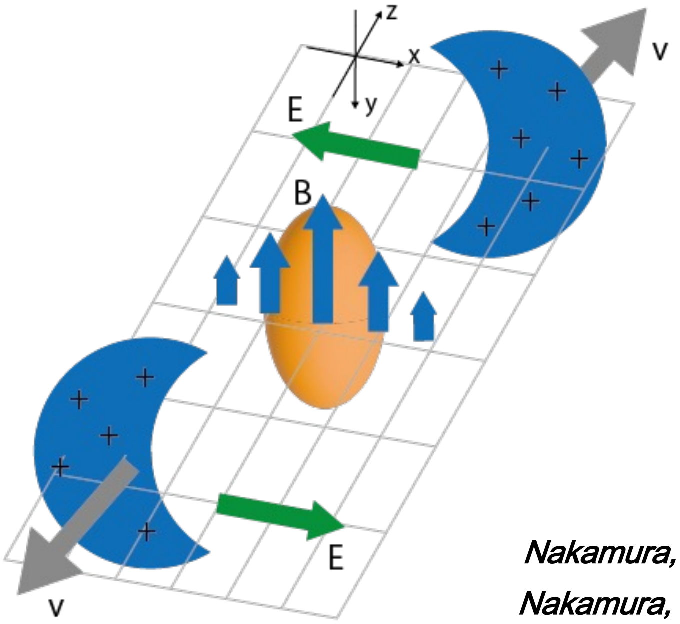
- QCD equation of state
- QGP structure
- The liquid QGP
- QCD critical point?
- Polarization & vorticity
- Thermalization
- Transport properties
- Jet showers
- Medium response

From slide by Berndt

Electromagnetic Fields?

Electromagnetic Fields in Heavy Ion Collisions ?

- Strong Electromagnetic fields and expansion? Observables?
  - Au + Au ($\sqrt{s_{NN}} = 200$ GeV) : 10^{14} T ~10 m_π^2
  - Pb + Pb ($\sqrt{s_{NN}} = 2.76$ TeV) : 10^{15} T



Nakamura, Miyoshi, C. N. and Takahashi, Phys. Rev. C 107, (2023) 014901

Nakamura, Miyoshi, C. N. and Takahashi, Eur.Phys.J.C 83 (2023) 3, 229.

Nakamura, Miyoshi, C. N. and Takahashi, Phys. Rev. C 107 (2023) 3, 034912

Benoit, Miyoshi, C. N., and Takahashi, Phys. Rev. C 112, 024911(2025)

Understanding of QGP Property

Charge conductivity of QGP from analysis of high-energy heavy-ion collisions

Physical property	Related Observables	Quantitative analysis
Charge conductivity	?	×
Shear viscosity	Azumithal anisotoropy v_n	○
Bulk viscosity	P_T distributions	○
Diffusion coefficient	Jet energy loss	○

Charge dependent directed flow

Asymmetic collisions → i.e., Hirono, Hongo, and Hirano, PRC 90, 021903 (2014).

Symmetric collisions

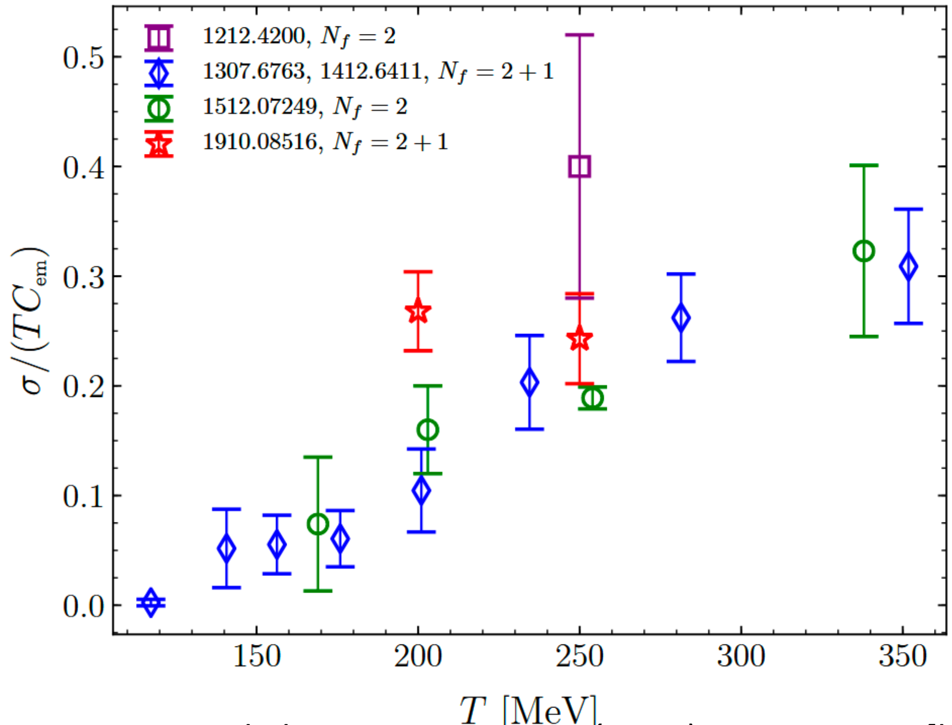
Proposed EM observables

Dileptons → i.e., Akamatsu, Hamagaki, Hatsuda, anf Hirano, PRC 85, 054903 (2012).

Photons → i.e., Sun and Yan, PRC 109, 034917 (2024).

Electric Conductivity of QCD Matter

- Study by Lattice QCD



Aarts, Nikolaev, EPJ.A 57, 118 (2021); 2008.12326 [hep-lat]

Electric Conductivity on the Lattice

$$\sigma = \frac{1}{6}\frac{\partial}{\omega}\left(\int d^4x e^{i\omega t}\langle[j_\mu^{em}(t,x), j_\mu^{em}(0,0)]\rangle\right)|_{\omega=0}$$

- Does not include external magnetic field effects
- Uses approximately realistic pion mass
- General agreement among results using a variety of methods and parameters

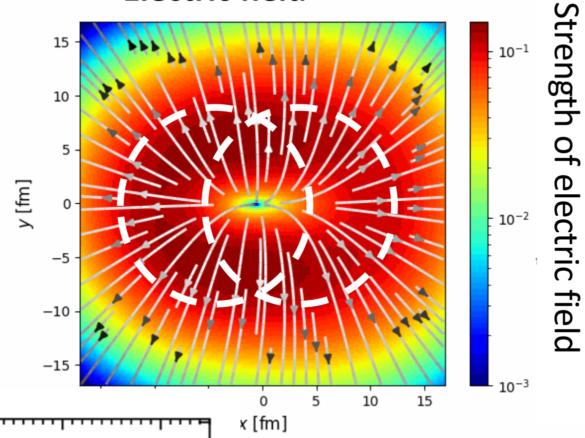
Electromagnetic Fields and Property of QGP

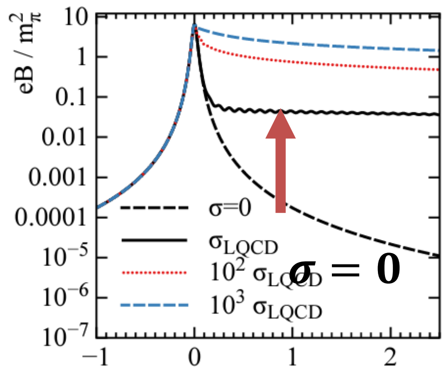
- Electric Conductivity
  - **Dissipation of electric field**
    - Ampere's law: $\partial_t \vec{E} - \nabla \times \vec{B} = -\vec{j}$

$\vec{B}$: magnetic field
$\vec{E}$: electric field

Ohm's law makes electric filed dissipate

➡Dissipated energy to fluid





L. McLerran and V. Skokov, Nucl. Phys. A 929 (2014) 184-190

  - **Charge is induced.**
    - Charge is induced by electric field.
    - Induced charge depends on charge conductivity
  - **Dissipation of magnetic field**

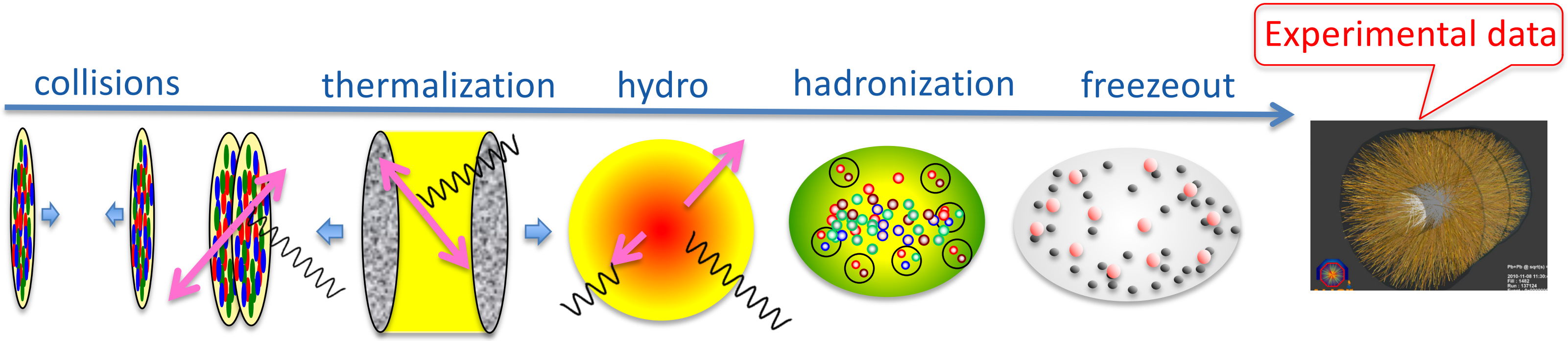
Charge conductivity of QGP

⬅ **dissipation of electromagnetic fields and charge distribution QGP**

Evolution:
Relativistic Resistive Magnetohydrodynamics

Relativistic Resistive Magneto-Hydrodynamics (RRMHD)

Nakamura, Miyoshi, C. N. and Takahashi, PRC107, no.1, 014901 (2023)



Initial conditions

Glauber model
+approximate solutions of Maxwell eq.

Hydrodynamics

Hydrodynamic eq. + Maxwell eq. + Ohm's law

$$\partial_\mu T^{\mu\nu} = F^{\nu\lambda} J_\lambda \qquad J^\mu = \sigma e^\mu$$

Relativistic Resistive Magneto-Hydrodynamics (RRMHD)

Nakamura, Miyoshi, C. N. and Takahashi, PRC107, no.1, 014901 (2023)

■RRMHD equation

- Conservation law＋Maxwell eq. ＋Ohm's law

$$\partial_\mu T^{\mu\nu} = F^{\nu\lambda} J_\lambda$$

$$J^\mu = J_c^\mu + q u^\mu$$

e: energy density
p: pressure
$p_{em} = (E^2 + B^2)/2$

$$\varepsilon = (e+p)\gamma^2 - p + p_{em}$$
$$m^i = (e+p)\gamma^2 v^i + \epsilon^{ijk} B_j E_k$$
$$\Pi^{ij} = (e+p)\gamma^2 v^i v^j + (p + p_{em}) g^{ij} - E^i E^j - B^i B^j$$

Energy Conservation

$$\partial_t \varepsilon + \nabla \cdot m = 0$$

Momentum conservation

$$\partial_t m^i + \nabla \cdot \Pi^i = 0$$

Faraday's law

$$\partial_t \vec{B} + \nabla \times \vec{E} = 0$$

Ohm's law

$$\vec{J} = q\vec{v} + \underbrace{\sigma\gamma[\vec{E} + \vec{v}\times\vec{B} - (\vec{v}\cdot\vec{E})\vec{v}]}_{=:\vec{J}_c}$$

Ampere's law

$$\partial_t \vec{E} - \nabla\times\vec{B} = -\vec{J} \quad \rightarrow \quad \partial_t \vec{E} - \nabla\times\vec{B} = q\vec{v}, \quad \partial_t \vec{E} = \vec{J}_c$$

operator splitting

- Integration with quasi-analytic solutions

$$\vec{E}_\perp = -\vec{v}\times\vec{B} + \left(E_\perp^0 + \vec{v}\times\vec{B}\right)\exp(-\sigma\gamma t)$$
$$\vec{E}_\parallel = E_\parallel^0 \exp(-\sigma t/\gamma)$$

Komissarov, Mon. Not. R. Astron. Soc. 382, 995-1004 (2007)

RRMHD Equation in Milne Coordinates

New

- Milne coordinates
  - **Expanding systems in the longitudinal direction (τ, x, y, η_s)**
    - Strong expansion in the longitudinal direction is effectively included.
    - Number of grid of fluid is saved.

$$\tau = \sqrt{t^2 - z^2}$$
$$\eta_s = \frac{1}{2}\ln\frac{t+z}{t-z}$$

RRMHD Equation

$$\partial_\tau(\tau U) + \partial_i(\tau F^i) = \tau S$$

$$U = \begin{pmatrix} D \\ m_j \\ \varepsilon \\ B^j \\ E^j \\ q \end{pmatrix}, \mathrm{F}^{\mathrm{i}} = \begin{pmatrix} Dv^i \\ \Pi^{ji} \\ m^i \\ \varepsilon^{jik}E_k \\ \varepsilon^{jik}B_k \\ J^i \end{pmatrix}, S = \begin{pmatrix} 0 \\ \frac{1}{2}T^{ik}\partial_j g_{ik} \\ -\frac{1}{2}T^{ik}\partial_0 g_{ik} \\ 0 \\ J_c^i \\ 0 \end{pmatrix}$$

The first RRMHD code in Milne coordinates

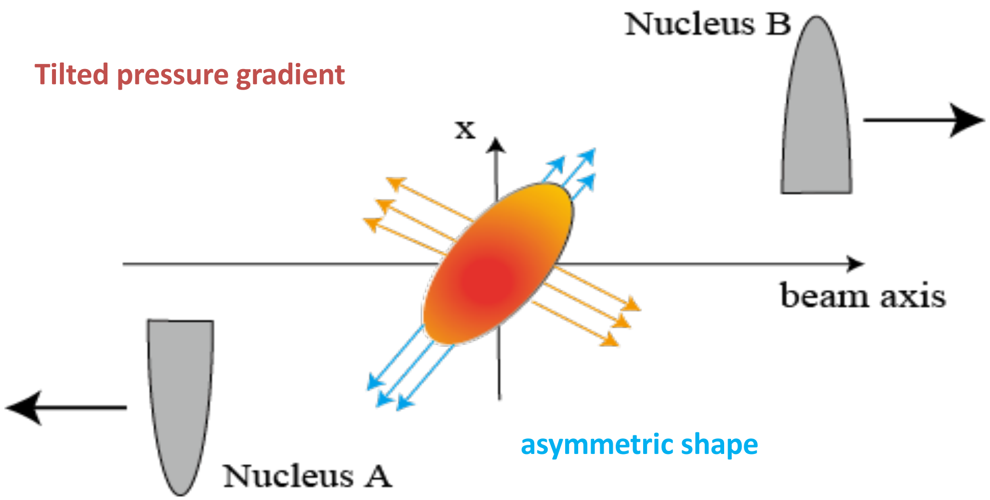
Initial Condition：QGP Medium

■ Tilted Glauber model

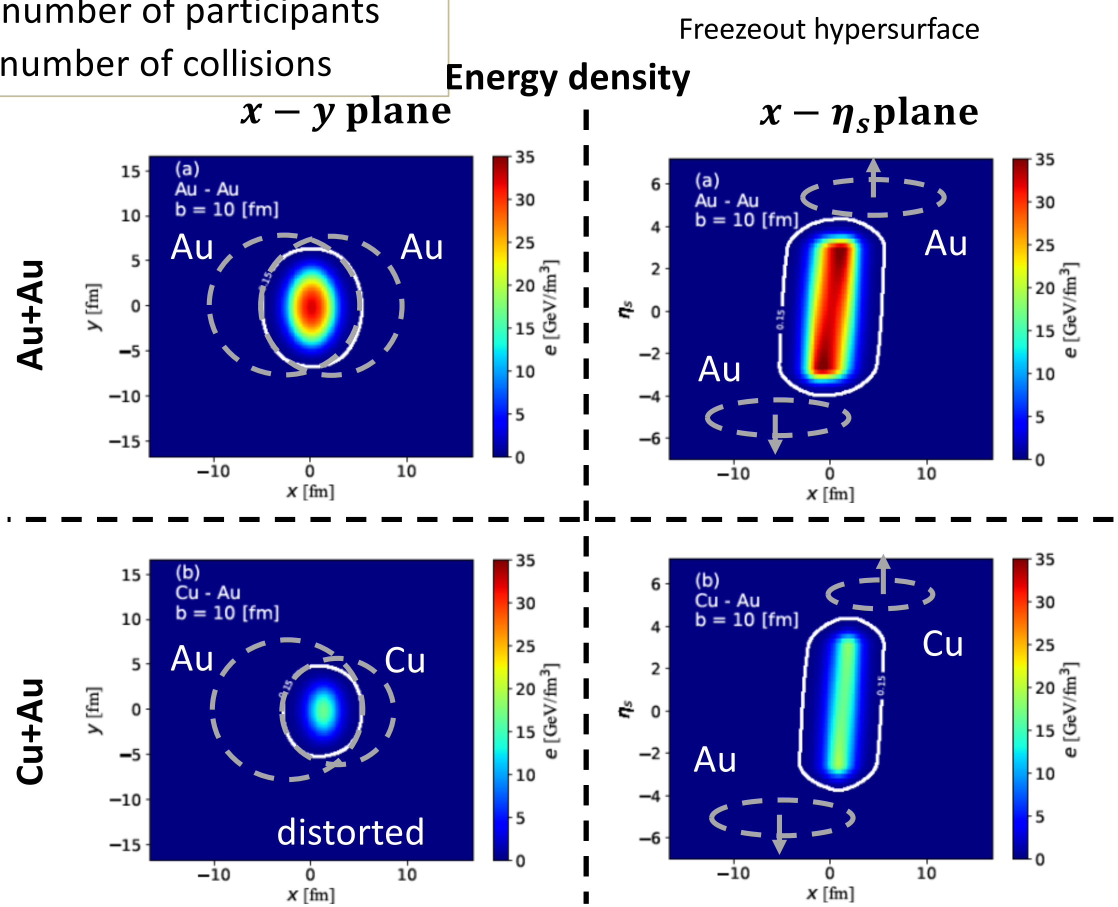
n_p : number of participants
n_c : number of collisions

- Energy density is scaled by n_p and n_c
- Tilted distribution in the longitudinal direction

For directed flow v_1



Bozek, et al, Phys. Rev. C 81, 054902(2010)



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Initial Condition : Electromagnetic Fields

Tuchin, Phys.Rev.C88,024911(2013)

■Asymptotic solution of Maxwell eq.

➢ **Electromagnetic filed made by point charge moving in the longitudinal axis**

- **Proton distribution in nucleus : uniform sphere**
- **Constant charge conductivity (σ =0.023 fm^{-1})**

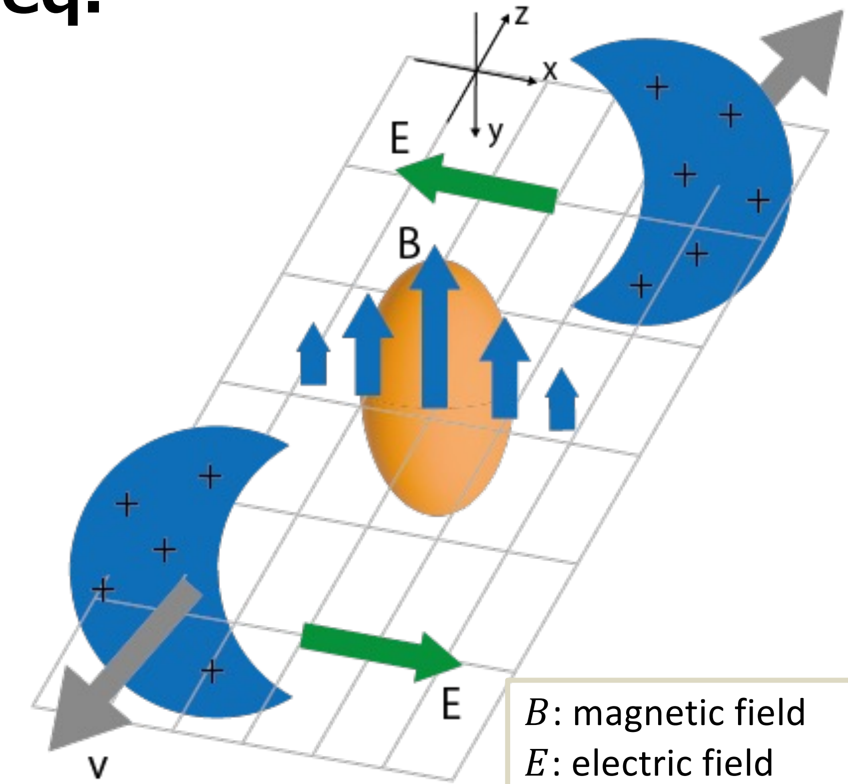
$$\nabla \cdot \boldsymbol{B} = 0\,, \quad \nabla \times \boldsymbol{E} = -\frac{\partial \boldsymbol{B}}{\partial t}\,,$$

$$\nabla \cdot \boldsymbol{D} = e\delta(z - vt)\delta(\boldsymbol{b})\,,$$

$$\nabla \times \boldsymbol{H} = \frac{\partial \boldsymbol{D}}{\partial t} + \sigma \boldsymbol{E} + ev\hat{z}\delta(z - vt)\delta(\boldsymbol{b})$$

Integration of the asymptotic solutions over

the charge distribution inside of nucleus



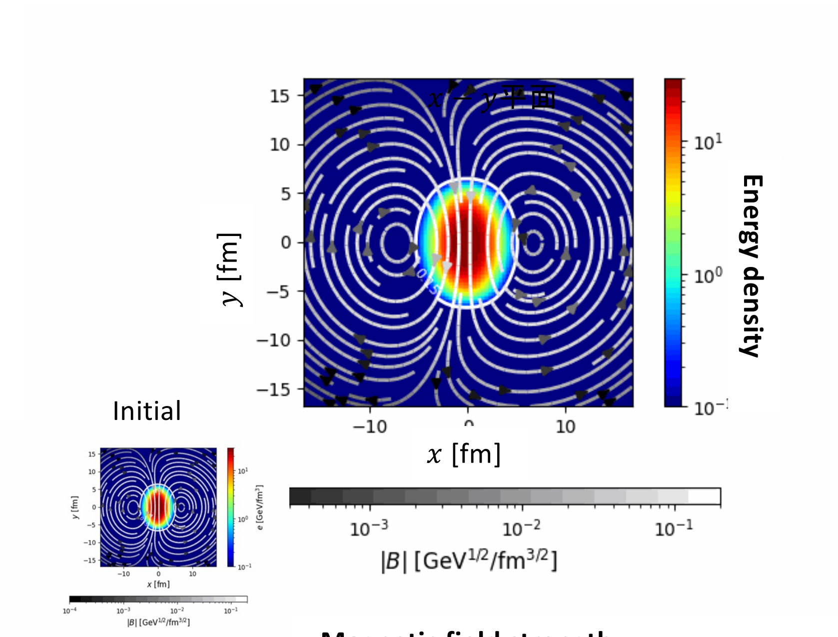
B: magnetic field
E: electric field
v: velocity of heavy ion

Space-time Evolution

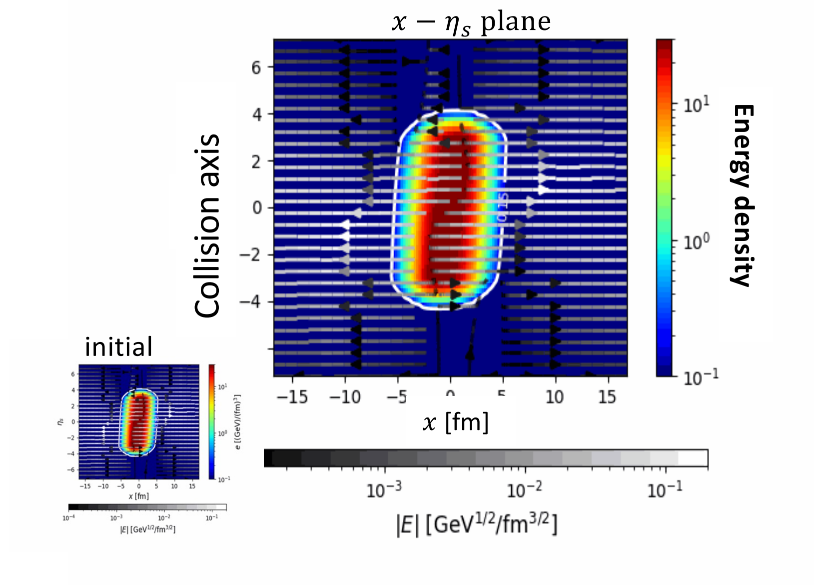
Nakamura, Miyoshi, C. N. and Takahashi, PRC 107, no.1, 014901 (2023)

Au+Au collision system

First calculation in HIC with RRMHD code



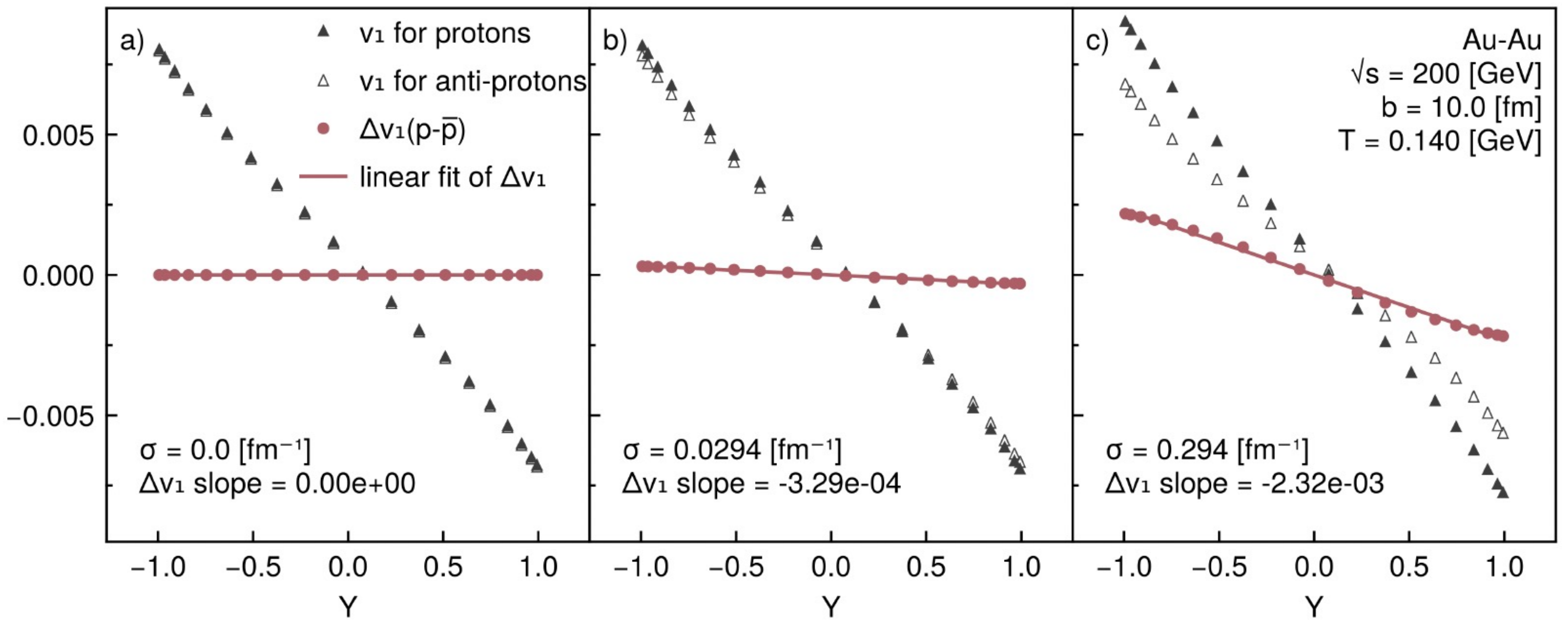
Magnetic field strength



Electric field strength

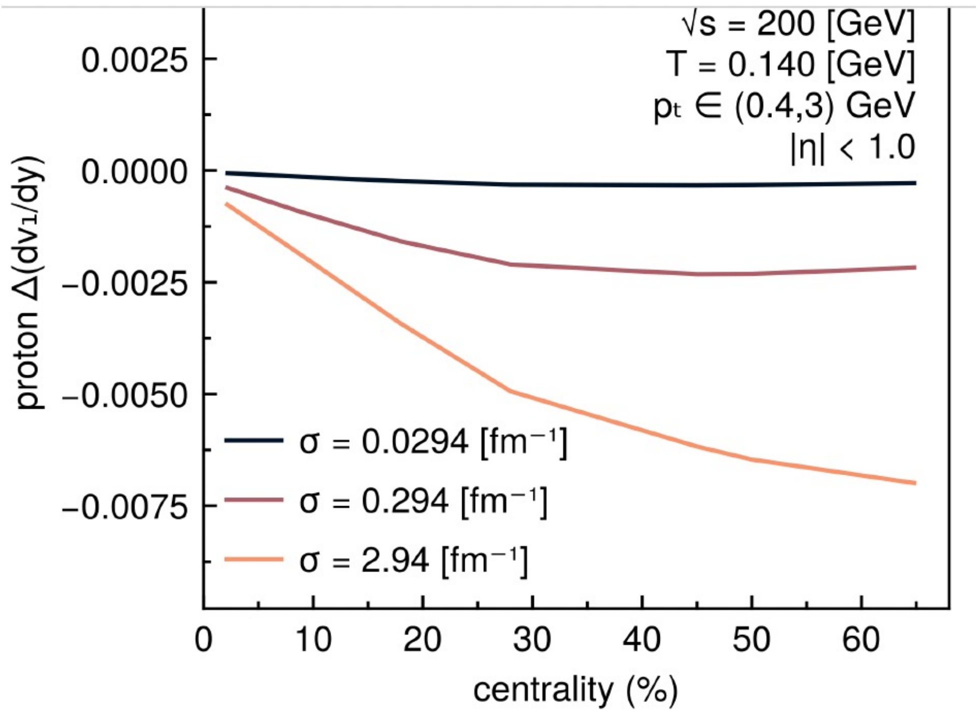
Analysis of Heavy Ion Collisions

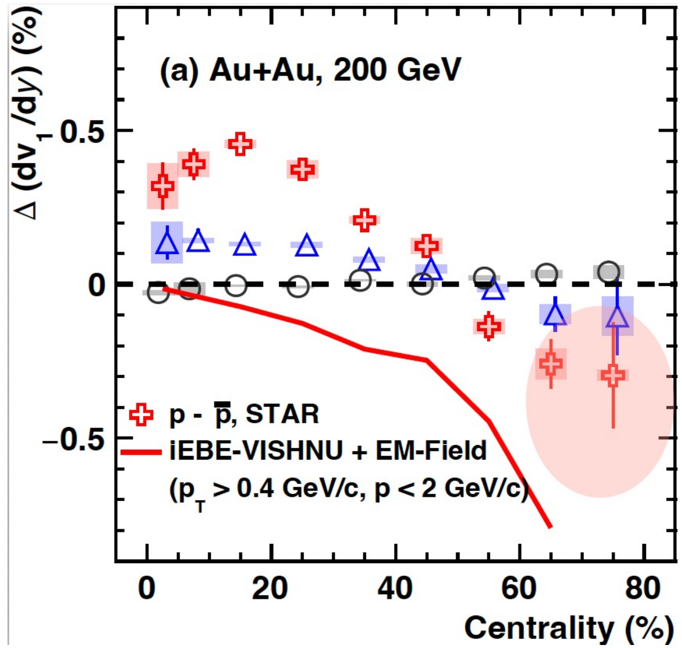
Charge Dependent Directed Flow



Benoit, Miyoshi, C. N., and Takahashi, Phys. Rev. C 112, 024911(2025)

Charge Dependent Flow





Benoit, Miyoshi, C. N., and Takahashi, Phys. Rev. C 112, 024911(2025)

Caveat:

- No baryon current
- Initial condition
- EoS
- Final state interactions

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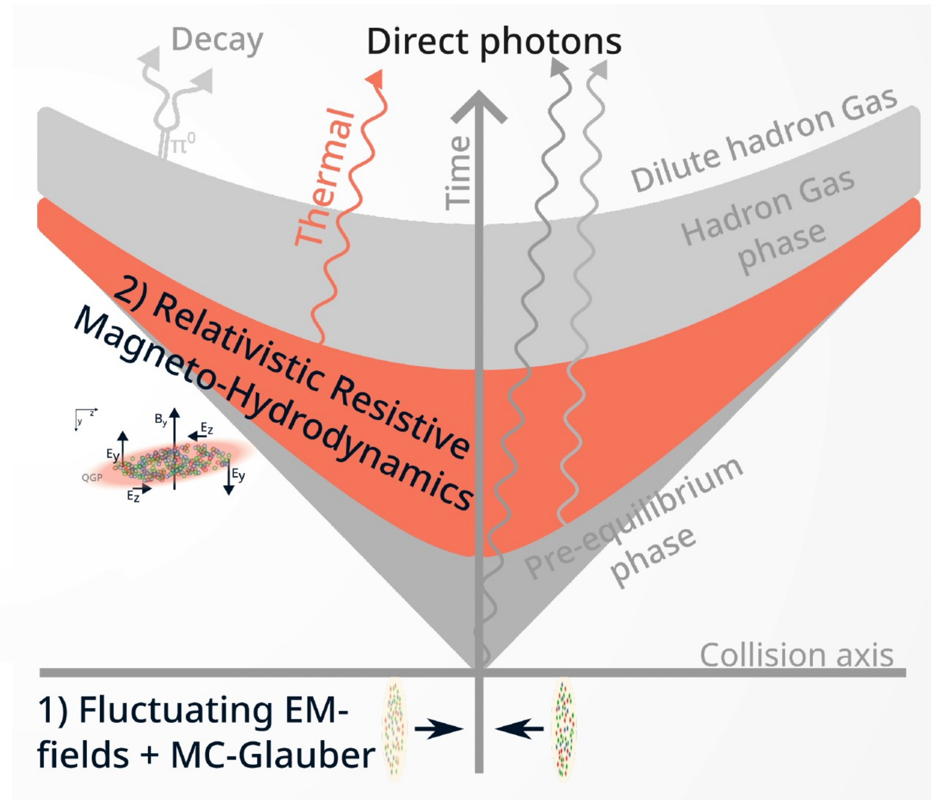
Photon

Snapshot of the EM fields

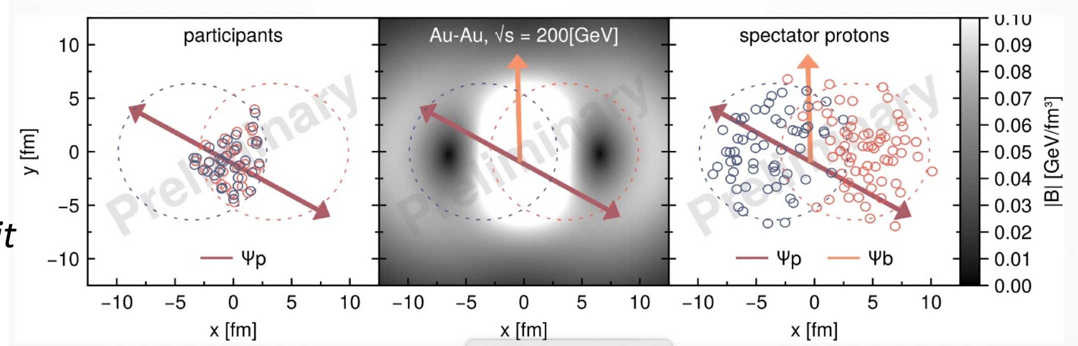
Nicholas J. Benoit, Takahiro Miyoshi, CN, Hiroyuki Takahashi

Photon



- A photon carries information from the early stages through to the final stage
- It is affected by EM field.

- P_T spectra and elliptic flow of photon
- Including event by event fluctuations in initial conditions
- Consider the direction of the lab frame EM fields



By courtesy of Benoit

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Electromagnetic Dissipation for QGP Photon

- Electromagnetic fields inside QGP
  - The fluid + EM field contributions from hydrodynamics
  - All of those values can be calculated self-consistently using relativistic resistive magneto-hydrodynamics (RRHMD)

Temperature and four velocity

conductivity

$$\delta f^{(1)}_{a,EM}(X,k) = -\frac{-f_{a,eq}(1-f_{a,eq})}{T\chi_{el}k^{\mu}u_{\mu}} e\sigma Q_a e^{\mu} k_{\mu}$$

Electric susceptibility of QGP

$$\chi_{a,el} = -\frac{1}{3}\int \frac{d\vec{p}}{(2\pi)^3 E_p}(p^{\sigma}p^{\nu}\Delta_{\sigma\nu})\frac{-f_{a,eq}(1-f_{a,eq})}{p^{\mu}u_{\mu}}$$

Spacetime dependent EM fields in QGP medium

$$e^{\mu} = (\gamma v_k E^k, \gamma E^i + \gamma \epsilon^{ijk} v_j B_k)$$

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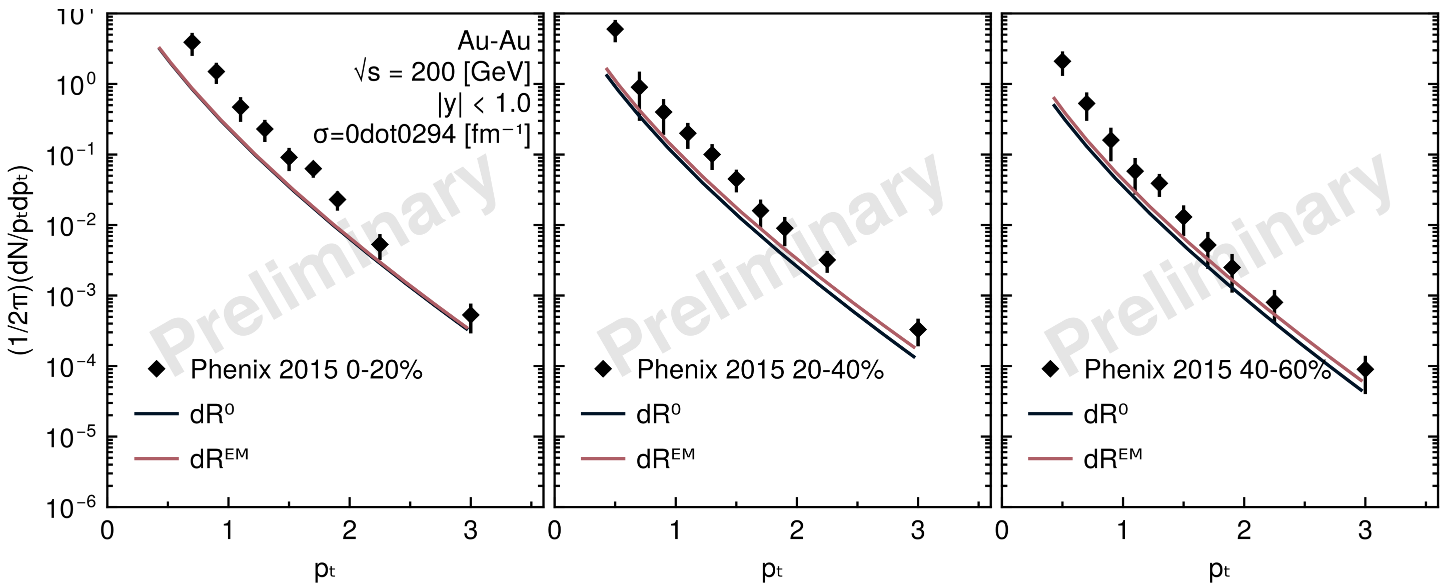
P_T Spectra of Photon

- Au+Au $\sqrt{s_{\rm NN}} = 200$ GeV
  - Set normalization of initial conditions from charge π rapidity distribution

σ=0.0294 fm^{-1}

T~ 220 MeV (lattice QCD)



- EM fields create mild increase in photon yield
- Larger pt (~ 3 GeV) has greater increase

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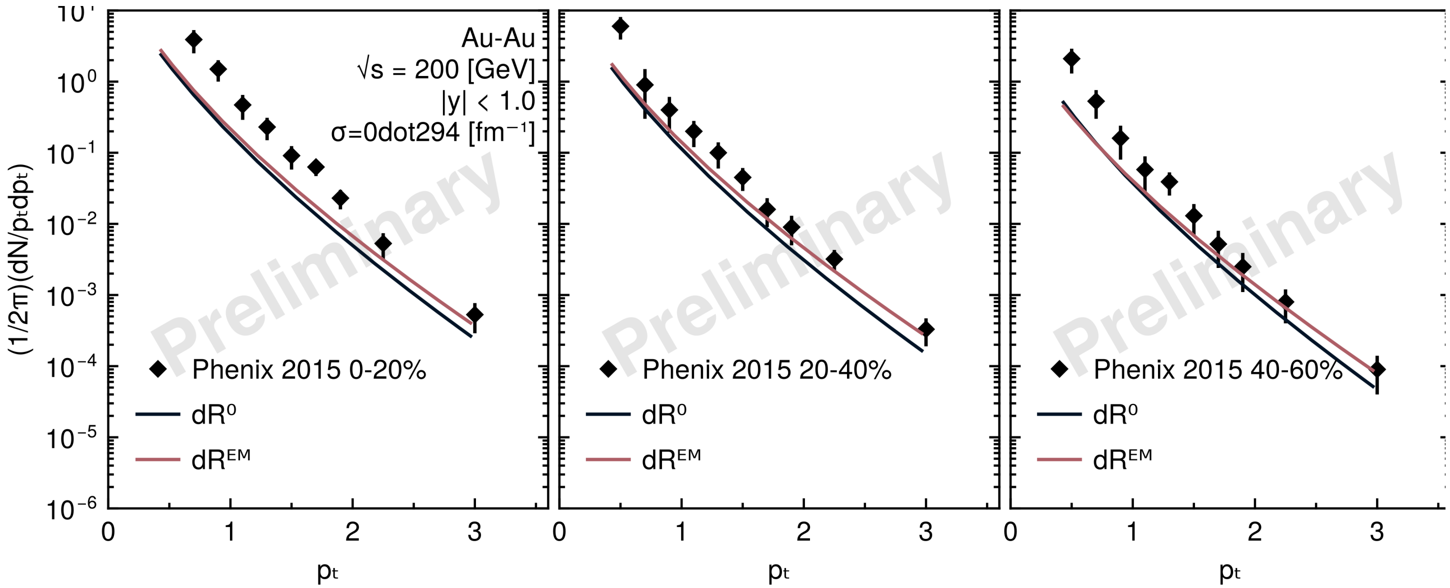
P_T Spectra of Photon

- Au+Au $\sqrt{s_{NN}} = 200$ GeV
  - Set normalization of initial conditions from charge π rapidity distribution

    σ=0.294 fm^{-1}

    T~ 340 MeV (lattice QCD)



- EM fields create mild increase in photon yield
- Larger pt (~ 3 GeV) has greater increase
- O(10) larger QGP conductivity σ increases the higher Pt yield

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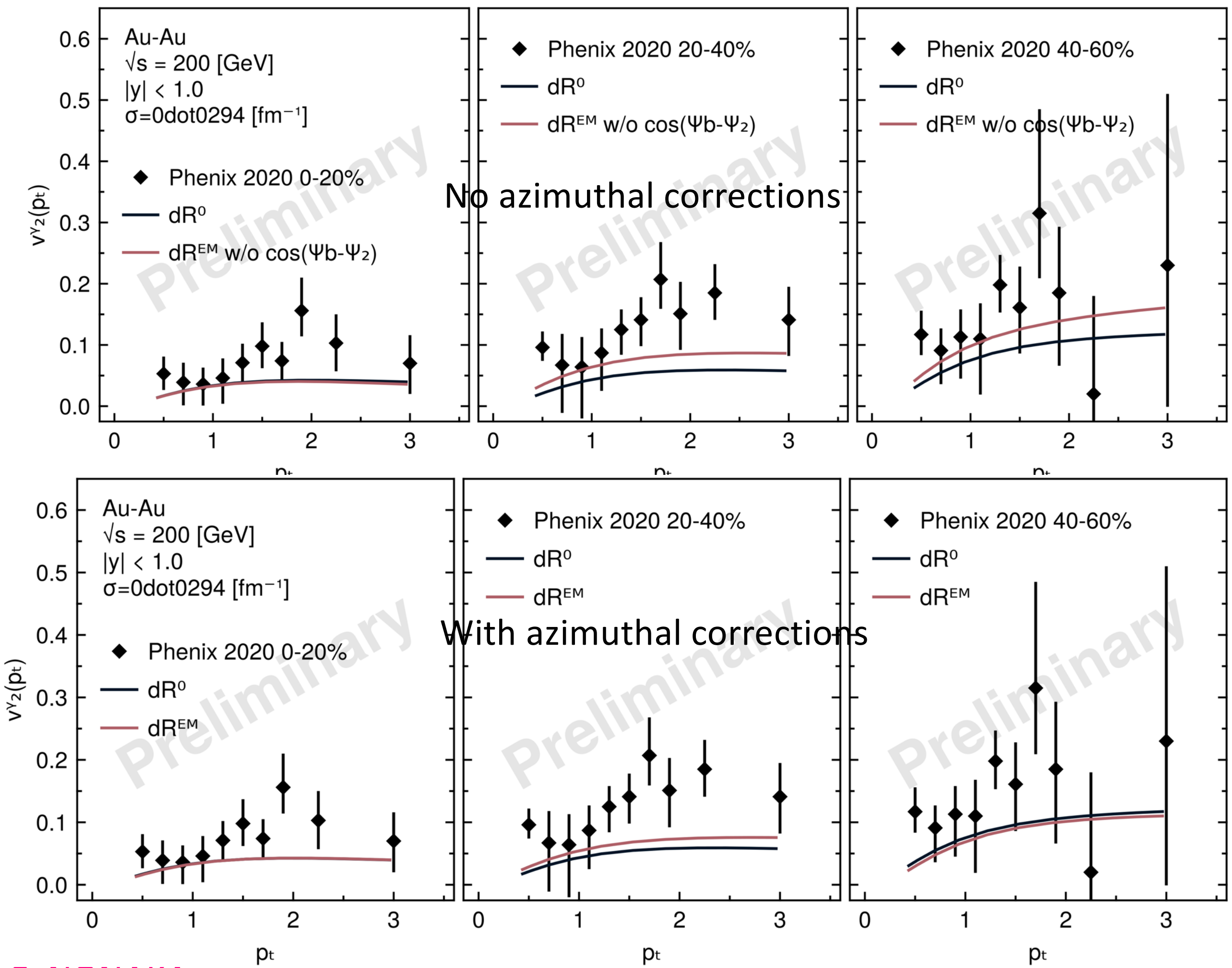
Elliptic Flow of Photon



Including the azimuthal fluctuations

- The elliptical flow is not always increased by EM fields (depends on centrality)
- Suggests the geometry of the EM can be probed, but effects become smaller.

Photons can carry a local snapshot of the EM fields (Magnetometer)
possibility to constrain field lifetime
(the electric conductivity σ of the QGP)

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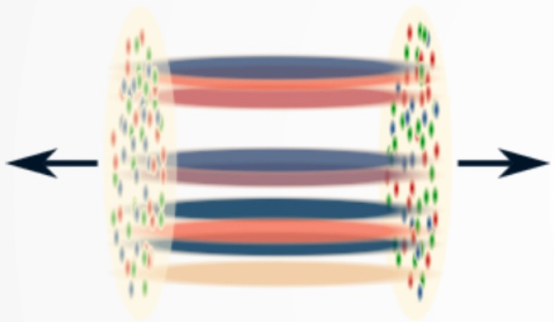
Initial Conditions

Nicholas J. Benoit and Hidetoshi Taya

Quark Pair Production from Initial Strong Color Fields

Model framework

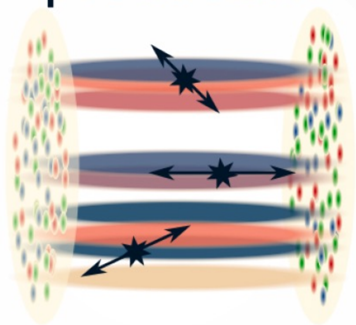
CGC + Glasma



Impact parameter dependent
MV Model (CGC)

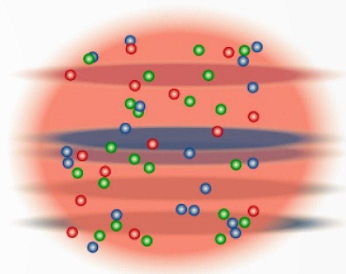
Real-time lattice 2+1D glasma
(Classical Yang-Mills solver)

Schwinger pair production



Schwinger formula for pair
production from color E&B
fields (Poisson sampler)

Wong equations with spin

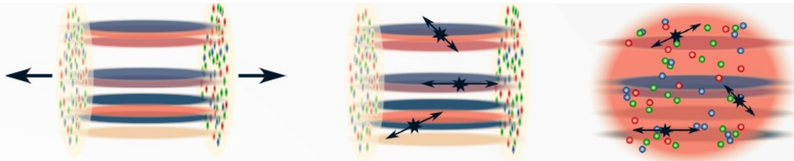


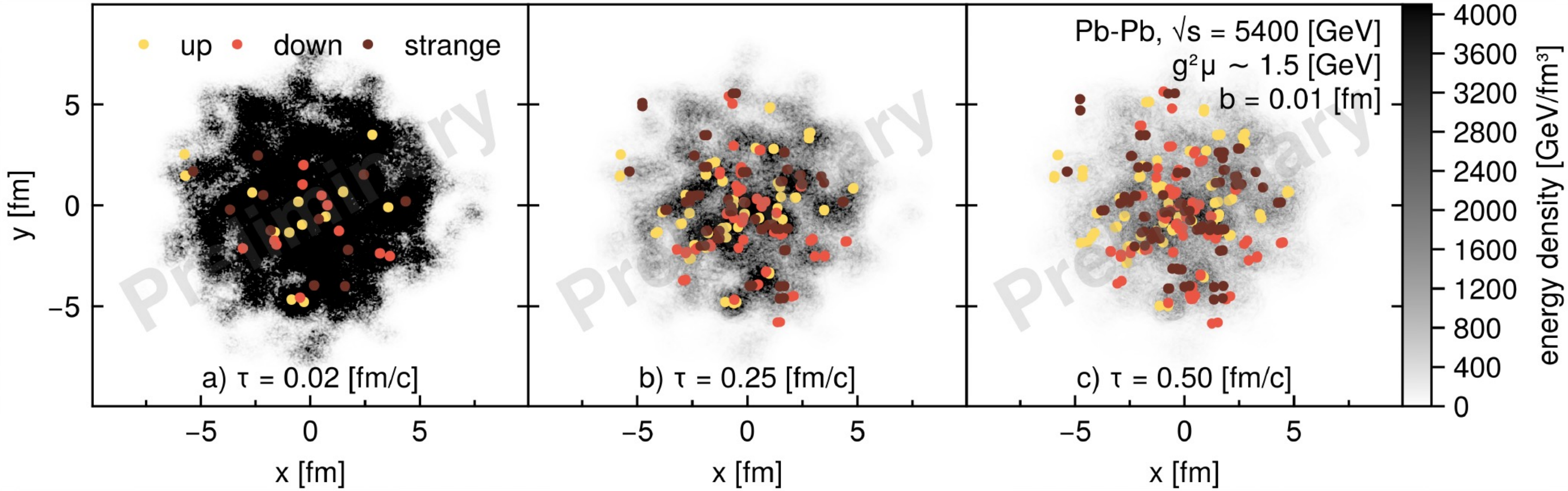
Colored particle-in-cell for
quark time evolution
(Wong equations + spin)

Final time Gaussian
smoothing on particles for
connecting to QGP

By courtesy of Benoit

Putting it all together





Our model simulates the real-time dynamics and non-perturbative production of particles from the glasma

By courtesy of Benoit

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Summary

Electromagnetic Fields and QGP properties in High-Energy Heavy-Ion Collisions

- Relativistic Resistive Magnetohydrodynamics (RRMHD)
  - Coupled hydrodynamics + Maxwell equations + Ohm's law
  - Implemented in expanding Milne coordinates
- Key results
  - EM fields modify charge-dependent directed flow
  - Photon production is slightly enhanced
  - Possible constraint on QGP conductivity and EM fileds lifetime
- Initial conditions
  - Towards getting more realistic EM fields in initial stage