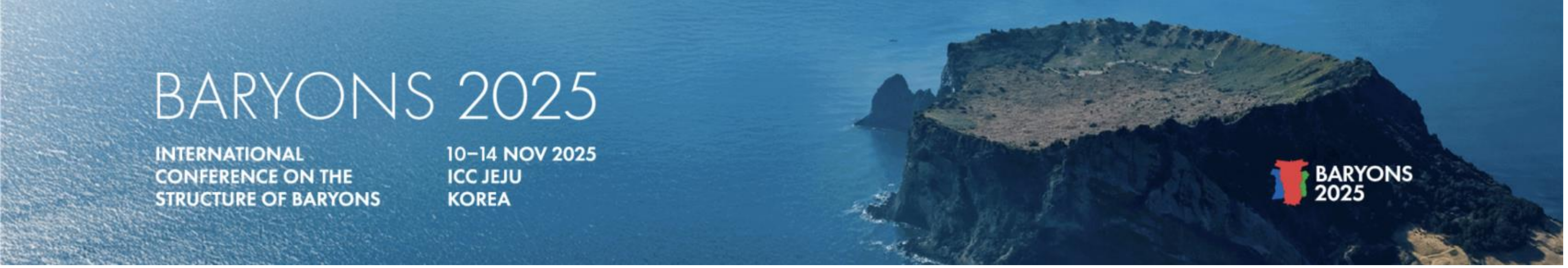


Hadron Production in High-Energy Heavy-Ion Collisions

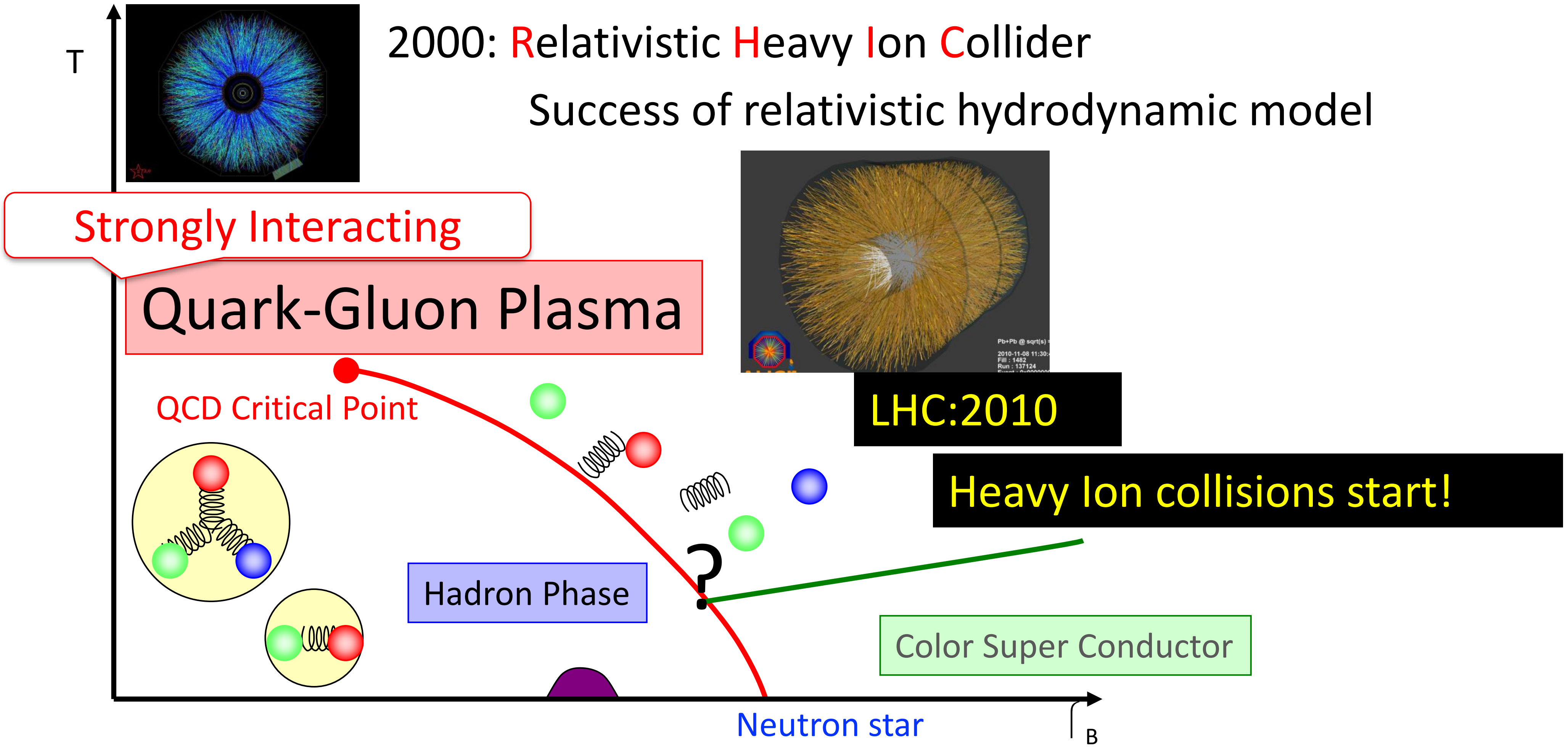
Department of physics, Hiroshima University
International Institute for Sustainability with Knotted Chiral Meta Matter／SKCM^2.
Hiroshima University
Kobayashi Maskawa Institute, Nagoya University

Chiho Nonaka

November 11, 2025@Baryons 2025, Jeju

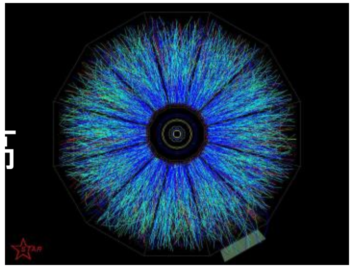
QCD Phase Diagram and High-Energy Heavy-Ion Collisions

- Quark-Gluon Plasma: State of Quarks and gluons at extreme conditions
  - Relativistic Heavy Ion Collisions

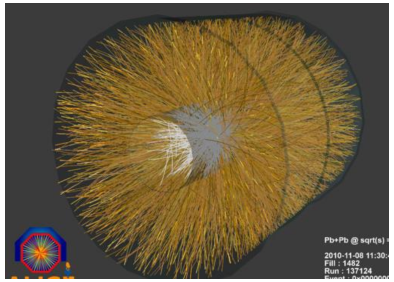


Heavy Ion Collisions

STAR@RHIC



ALICE@LHC



Au+Au(Beam Energy Scan)
7.7, 11.5, 19.8, 27, 39

p+p,
d+Au,He+Au
U+U, Au+Au,
200

RHIC

Pb+Pb
2760

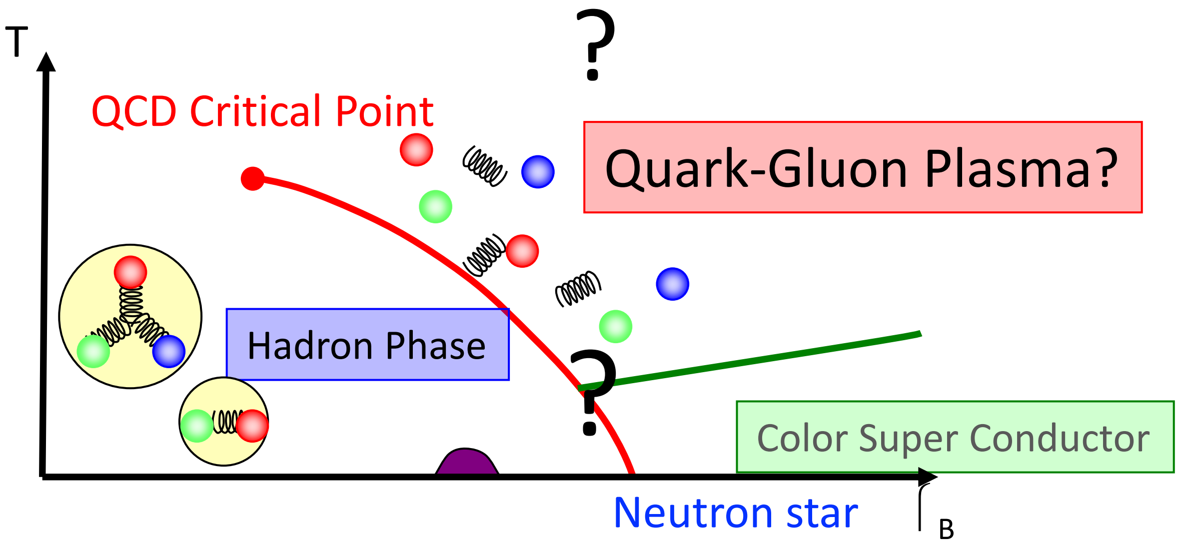
LHC

p+Pb
Pb+Pb
5020 5044

Xe+Xe
O+O, Ne+Ne
GeV

$\sqrt{s_{NN}}$

Wide region of QCD phase diagram



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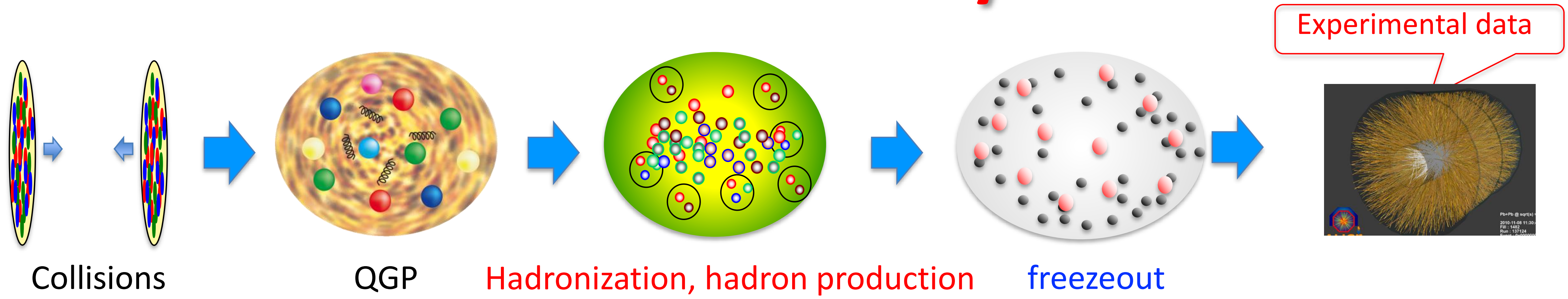
Hadron Production of Heavy Ion Collisions

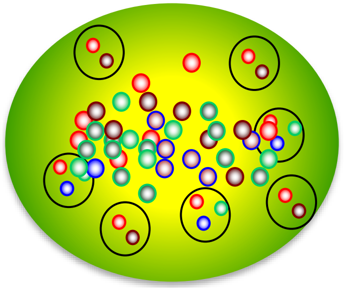


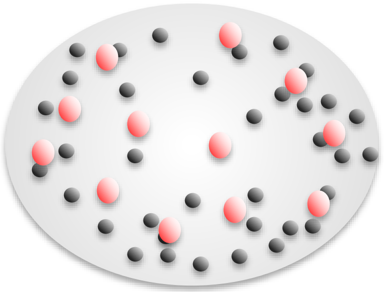
- Hadrons are the fingerprints of the QGP

  Comparison between experiments and theory
- Keys of hadron production
  - Production process: QCD equation of state, hadronization
  - Medium effects: chiral symmetry, QCD critical point
  - Final state interactions : freeze-out, resonance decay, hadron interaction

Hadron Production Process and Model

- Keys for hadron production
  - Production process: QCD equation of state, hadronization
  - Medium effects: chiral symmetry, QCD critical point
  - Final state interactions : freeze-out, resonance decay, hadron interaction





Hadronization ~ 155 MeV → Chemical freezeout → Final state interactions → Kinetic freezeout

Hadronization ~ 155 MeV
- Recombination
- Fragmentation

Chemical freezeout
- Statistical model
- Resonance gas model

Final state interactions
- Resonance decay

Kinetic freezeout
- P_T distributions
- Collective flow

Chiral and confinement-deconfinement phase transition, QCD critical point

In-medium modification

Hadron interactions

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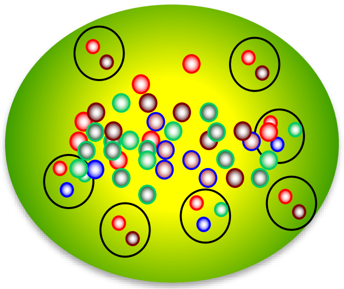
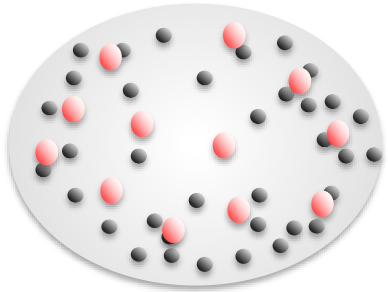
Observables





Hadronization ~ 155 MeV → Chemical freezeout → Final state interactions → Kinetic freezeout

- Recombination
- Fragmentation

- Statistical model
- Resonance gas model

- Resonance decay

- P_T distributions
- Collective flow

Chiral and confinement-deconfinement
phase transition , QCD critical point

In-medium modification

Collective flow

Hadron yield and ratio

Exotic hadrons, resonances
Light nuclei

structure

Spectral function in medium

Femtoscopy analysis

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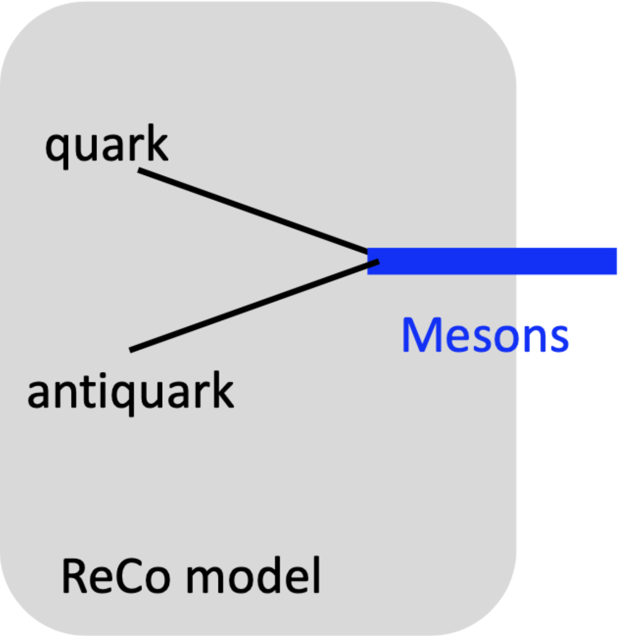
Recombination Model

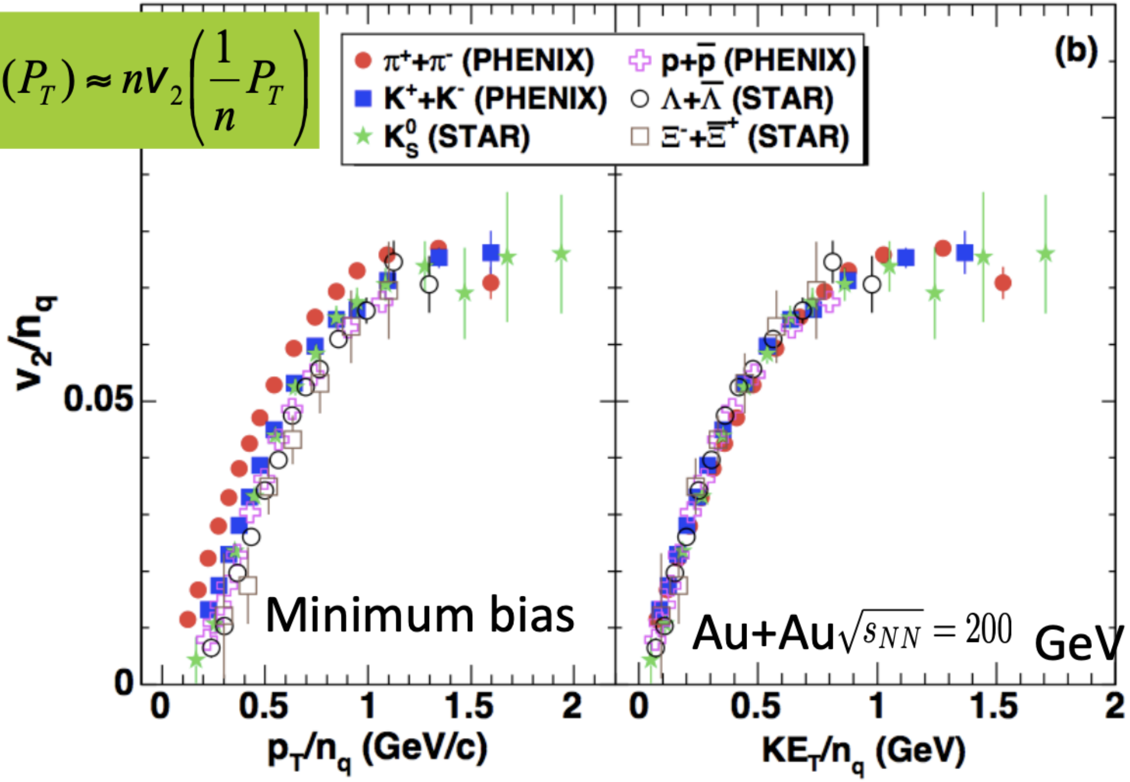
Fries, Mueller, CN and Bass, PRC68(2003)

- One of successful models



Ex: Quark number scaring

$$v_2^h(P_T) \approx n v_2\left(\frac{1}{n}P_T\right)$$



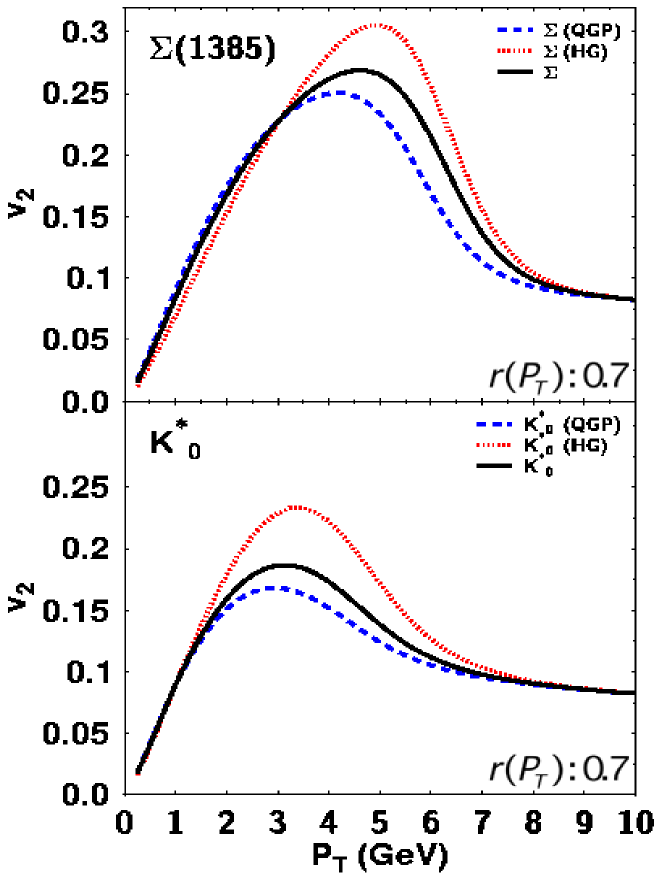
PHENIX,nucl-ex:0608033

- Baryon/Meson ratios
- Nuclear modification factors
- Quark number scaling in elliptic flow

➡ Radiative recombination, photon production

Fujii, Itakura, Miyachi, C, Phys. Rev. C 106, 034906 (2022)

Resonances and Exotic Hadrons



Phys.Rev.C 69 (2004) 031902

- QGP resonances:

  hadronizing QGP, no rescattering

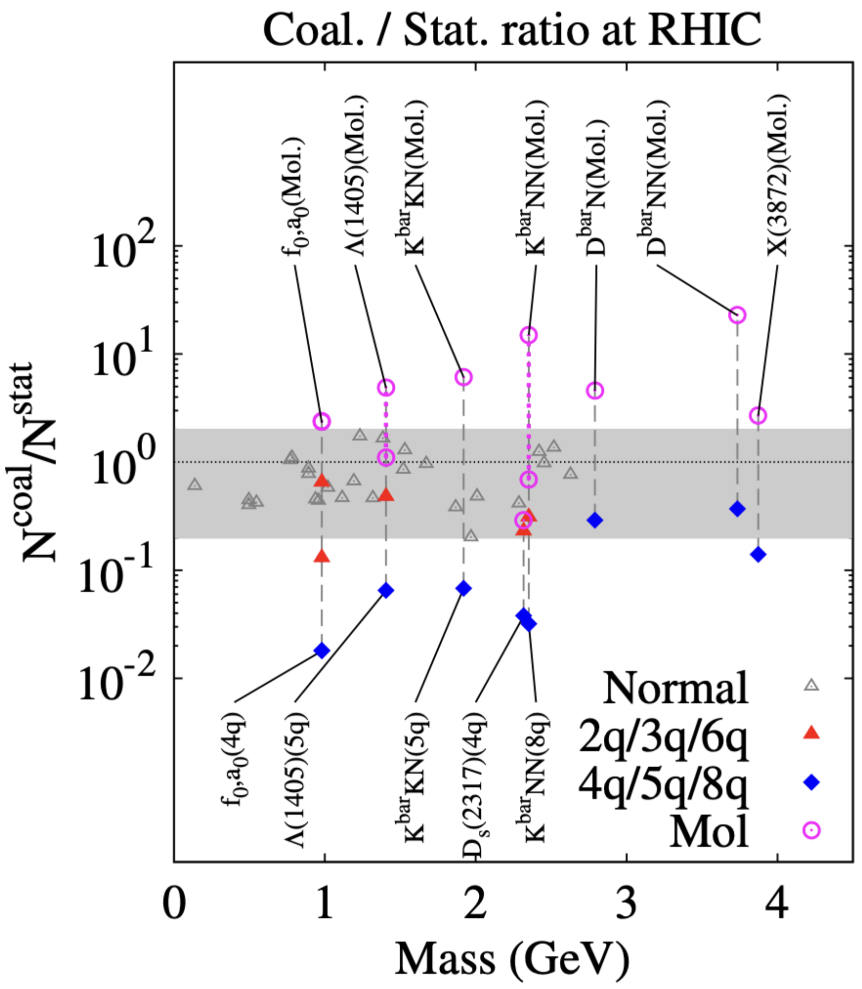
  K_0^* $d, \bar{s}$ quarks n=2 scaling

- HG resonances:

  hadron final stage, h-h rescattering

  K_0^* $K^+ + \pi^- \rightarrow K_0^*$ n=4 scaling

$$v_2^h(P_T) \approx n v_2\left(\frac{1}{n} P_T\right)$$



ExHIC collaboration, PRL 106, 212001 (2011)

Exotic Hadrons: Structure

PHYSICAL REVIEW LETTERS **126,** 012301 (2021)

Deciphering the Nature of X(3872) in Heavy Ion Collisions

Hui Zhang,[1,2,*] Jinfeng Liao,[3,†] Enke Wang,[1,2,‡] Qian Wang,[1,2,4,§] and Hongxi Xing[1,2,‖]

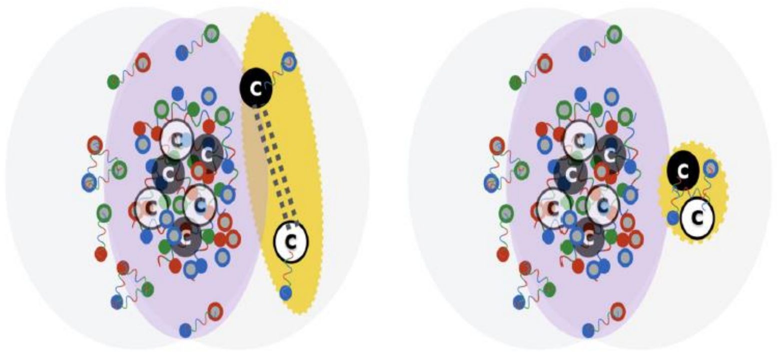
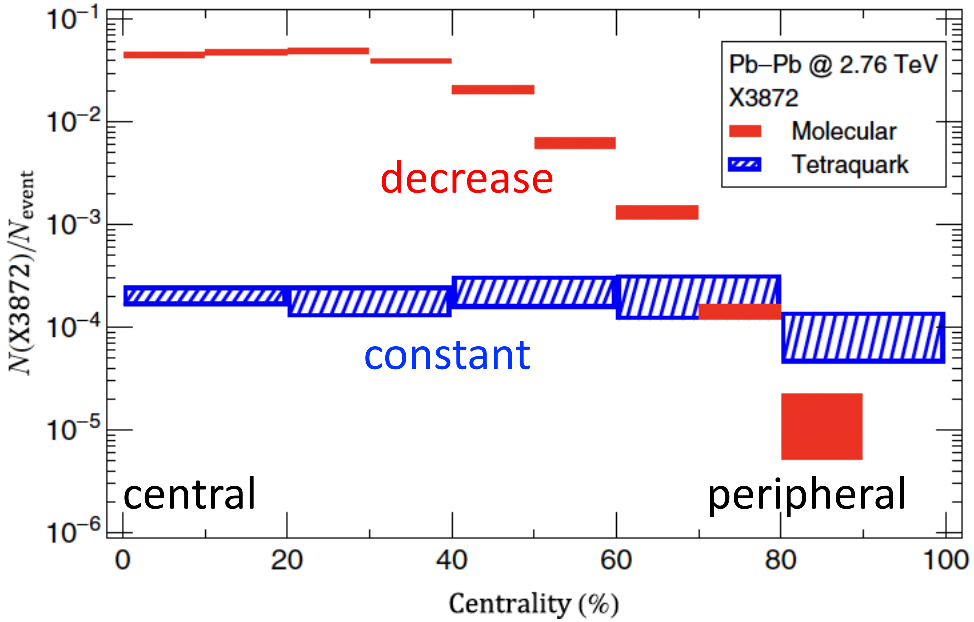


FIG. 1. Illustration of X(3872) production as hadronic molecule (left) or tetraquark (right) in heavy ion collisions.

Size difference

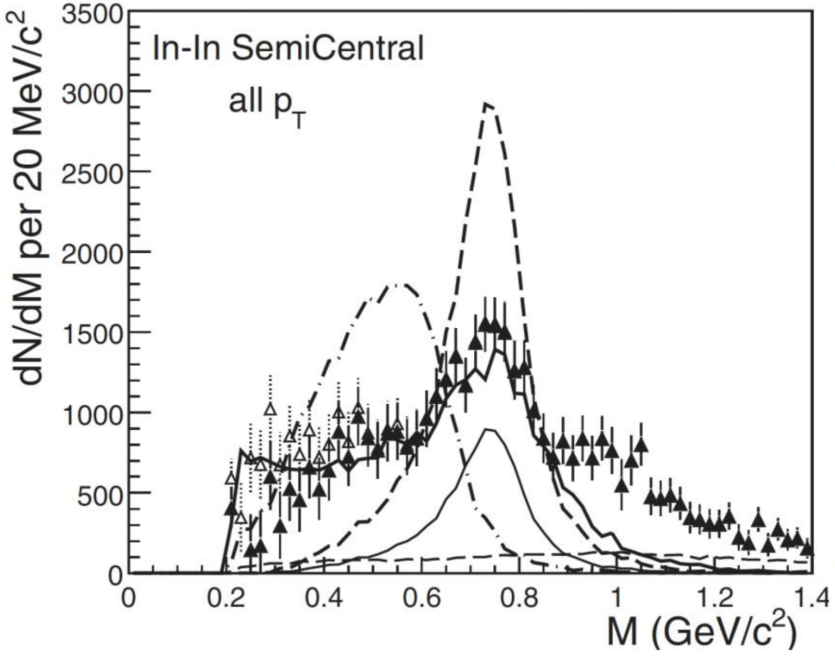


AMPT (A Multi Phase Transport) Model

Particle distribution, collective flow

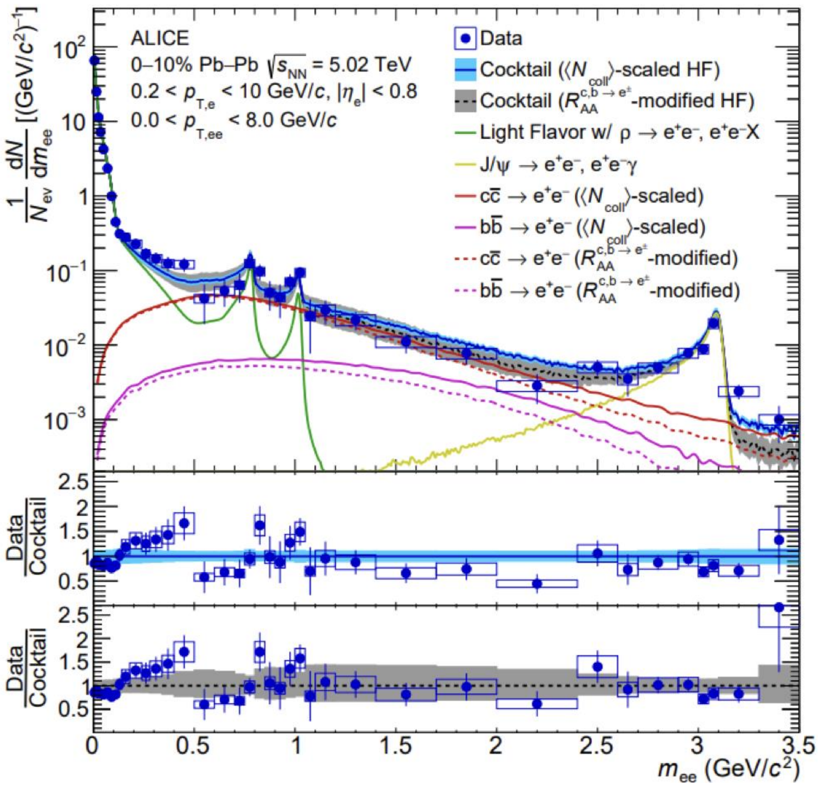
Hadron Properties in Medium

- Hadron properties in medium probed by dilepton invariant mass spectra
  - Lepton emitted at all stages of a heavy-ion collision



NA60, Phys.Rev.Lett

ρ spectral function : broadening



ALICE, 2308.16704

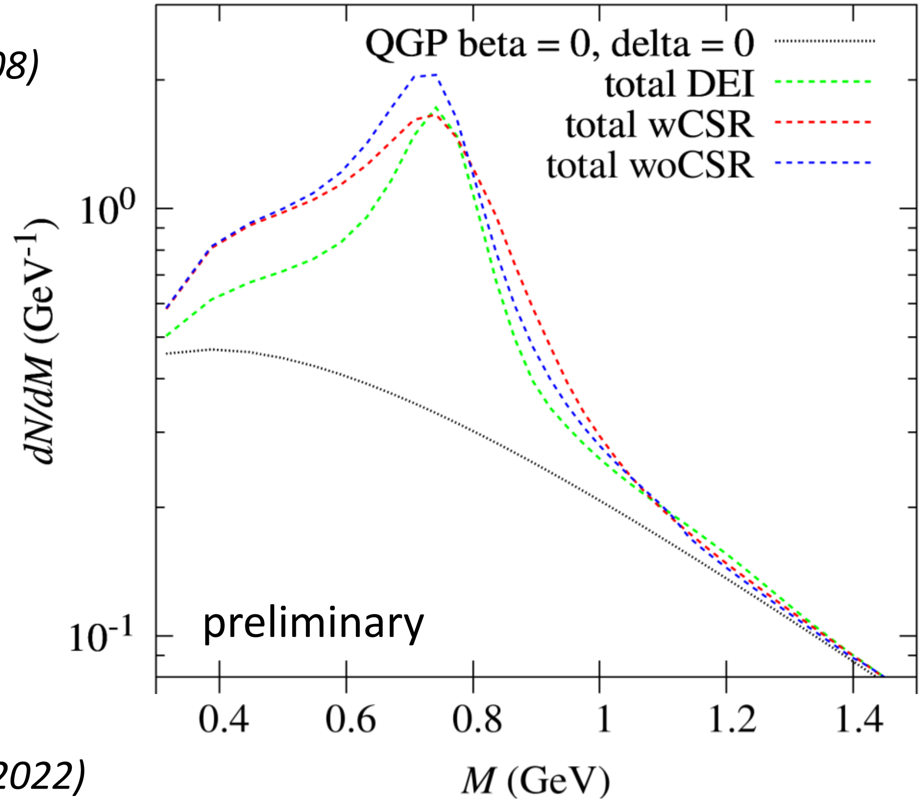
Dilepton production rate

$$\frac{dR_{\rm had}}{d^4q}(q;T) = \frac{\alpha_{\rm EM}^2}{\pi^3 M^2}\frac{{\rm Im}G_V(q;T)}{e^{q_0/T}-1}$$

G_V: vector-current correlation

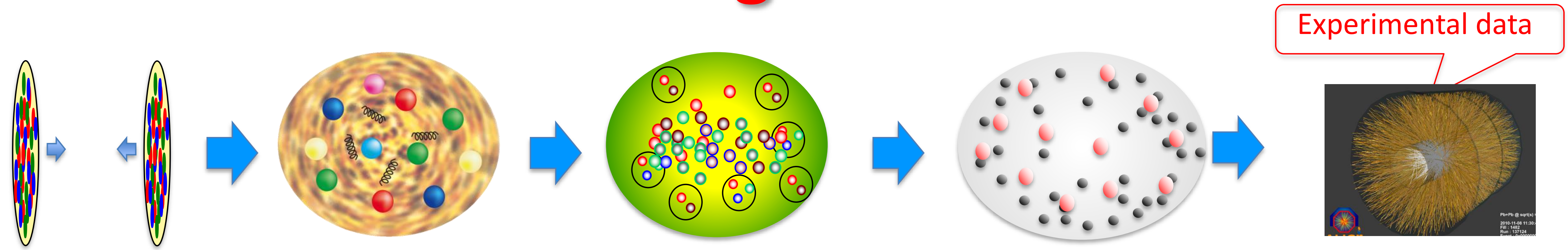
Dilepton Invariant Mass Distribution

- Chiral symmetry restoration from ρ-a_1 mixing
- Spectral functions *Harada, et al., Phys. Rev D 78, 114003 (2008)*
  - With chiral symmetry restoration: dropping a_1 mass
  - Without chiral symmetry restoration:
    constant ρ, a_1 mass
  - DEI: low-temperature mixing theorem
    maximal mixing, no mass degeneration
- Medium
  - (3+1) d relativistic viscous hydrodynamics
    $\eta/s(T)$, $\zeta/s(T)$ *Okamoto, CN, Phys. Rev. C 98, 054906 (2018)*
    Fujii, Itakura, Miyachi, C, Phys. Rev. C 106, 034906 (2022)
- Signal: not so large
  T_c dependence in connection between production rate from QGP and that of hadron



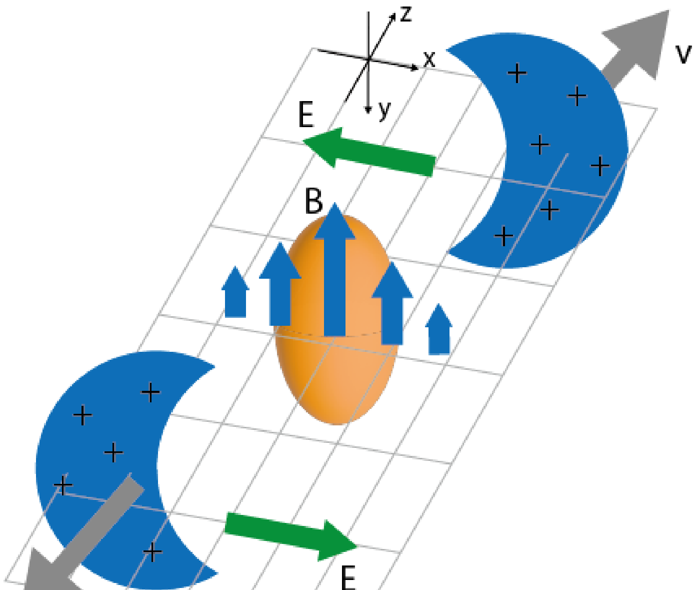
Sakai, Harada, CN, Sasaki, Shigaki, Yano, In preparation

Electromagnetic Fields



Collisions QGP Hadronization, hadron production freezeout

- Strong Electromagnetic field ?
  - 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



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

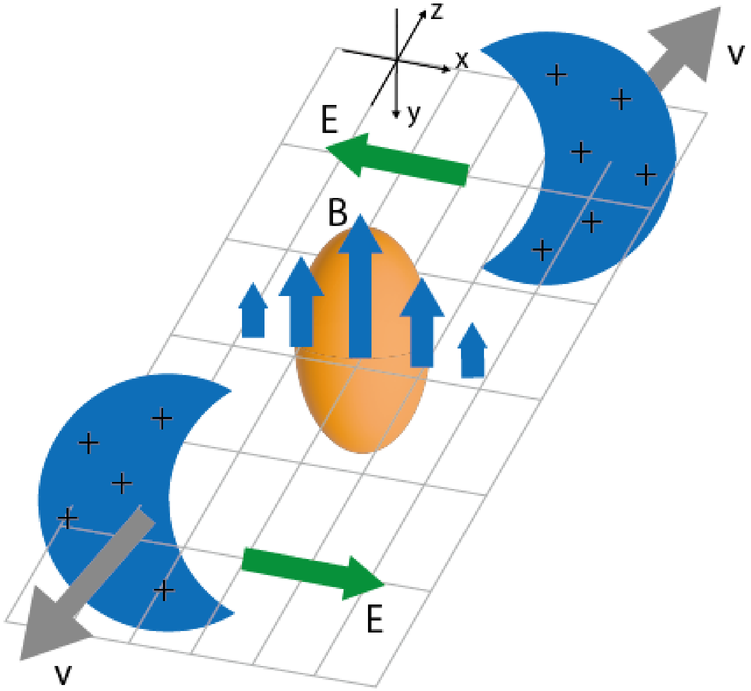
Nakamura, Miyoshi, C. N. and Takahashi, Phys. Rev. C 107, (2023) 014901

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

Electromagnetic Fields in Heavy Ion Collisions ?

- Strong Electromagnetic field ?
  - 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



- Conservation law

$$\boxed{\nabla_\mu T^{\mu\nu} = 0}$$

$$\boxed{\nabla_\mu T_m^{\mu\nu} = -J_\mu F^{\mu\nu}}$$

matter EM field

$$T^{\mu\nu} = T_m^{\mu\nu} + T_f^{\mu\nu}$$

$$T_f^{\mu\nu} = F^{\mu\lambda}F_\lambda^\nu - \frac{1}{4}g^{\mu\nu}F^{\lambda\kappa}F_{\lambda\kappa};$$

Maxwell eq. $\nabla_\mu F^{\mu\nu} = -J^\nu$

- Ohm's law *Blackman and Field, PRL71,3481(1993)*

$$J^\mu = \sigma F^{\mu\nu}u^\nu + qu^\mu$$

Electrical conductivity

$$q = -J^\mu u_\mu$$

Initial Condition of Electromagnetic Fields

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

■Asymptotic solution of Maxwell eq.

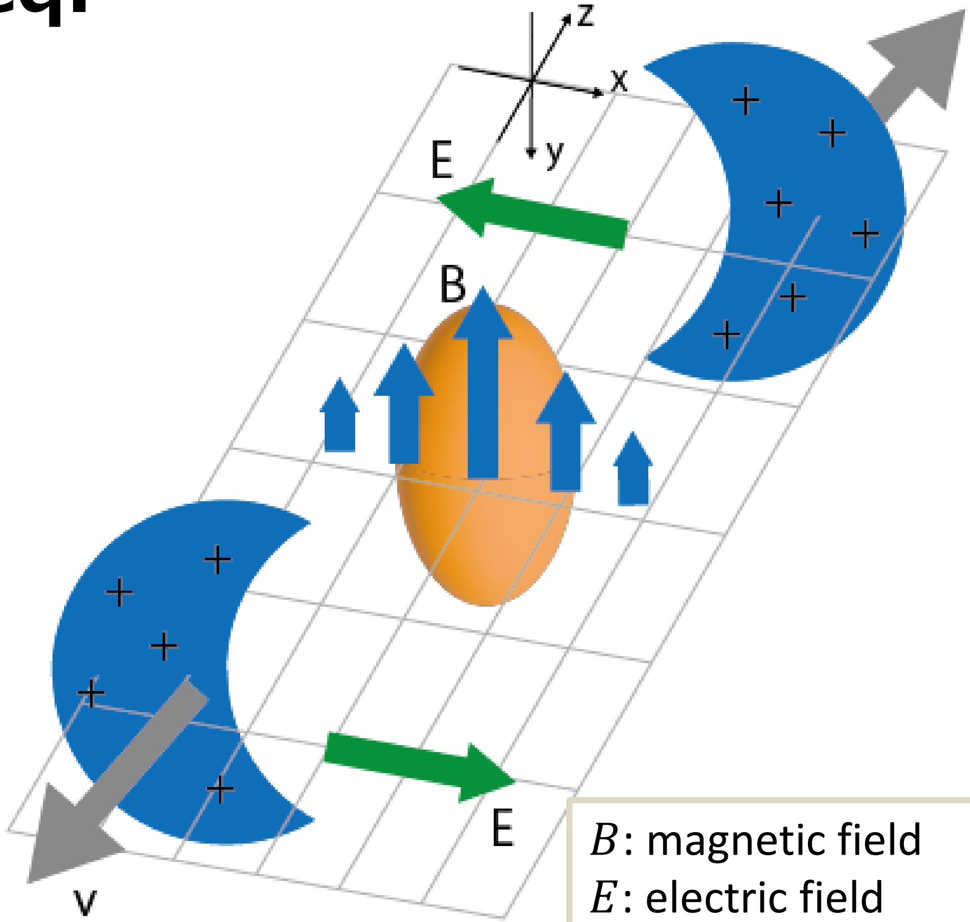
➢Electromagnetic field made by point charge moving in the longitudinal axis

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

$$\boxed{\begin{aligned} &\nabla\cdot\boldsymbol{B}=0\,, \quad \nabla\times\boldsymbol{E}=-\frac{\partial\boldsymbol{B}}{\partial t}\,, \\ &\nabla\cdot\boldsymbol{D}=e\delta(z-vt)\delta(\boldsymbol{b})\,, \\ &\nabla\times\boldsymbol{H}=\frac{\partial\boldsymbol{D}}{\partial t}+\sigma\boldsymbol{E}+ev\hat{z}\delta(z-vt)\delta(\boldsymbol{b}) \end{aligned}}$$

Integration of the asymptotic solutions over

the charge distribution inside of nucleus



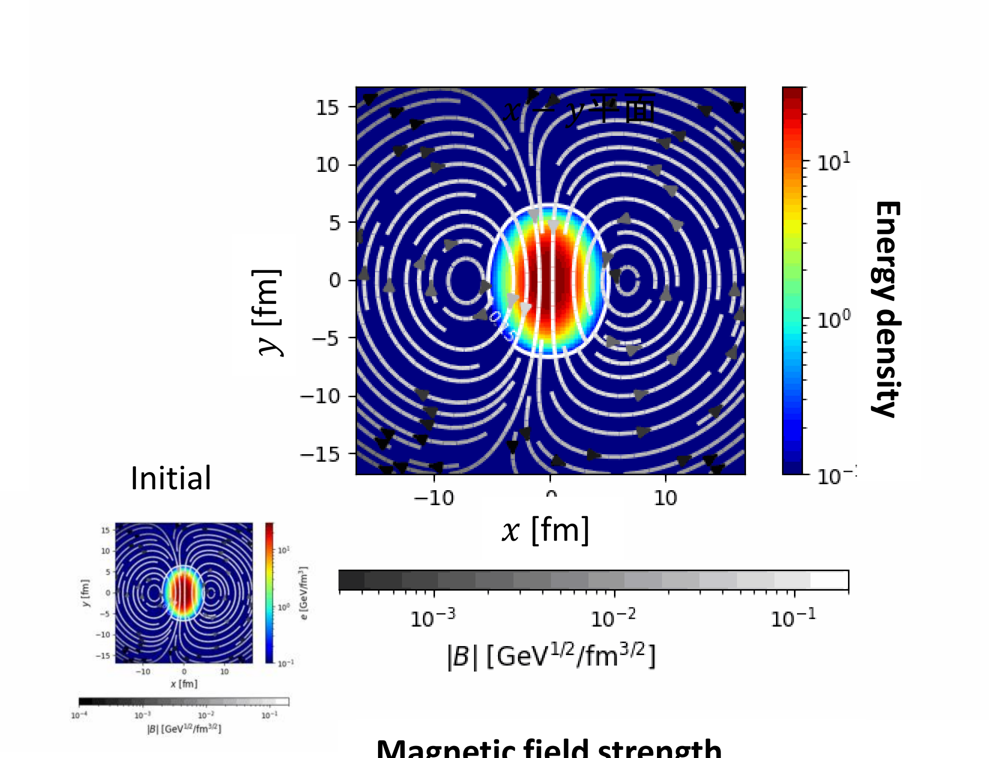
B: magnetic field
E: electric field
v: velocity of heavy ion

Space-time Evolution

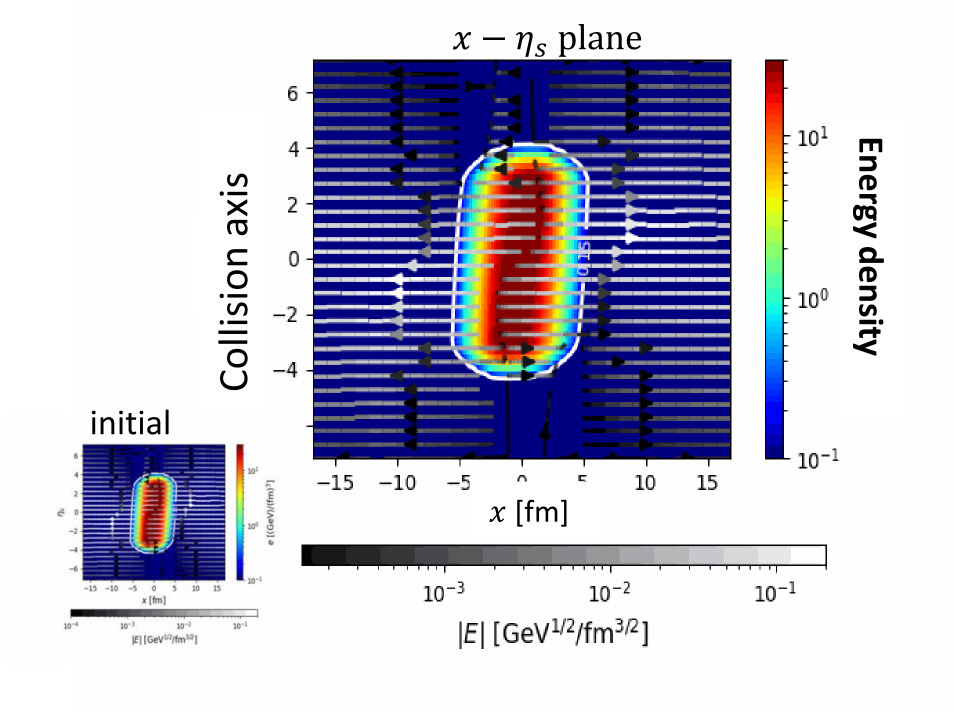
Nakamura, Miyoshi, CN and Takahashi, PRC 107, no.1, 014901 (2023)

Au+Au collision system

First calculation in HIC with RRMHD code



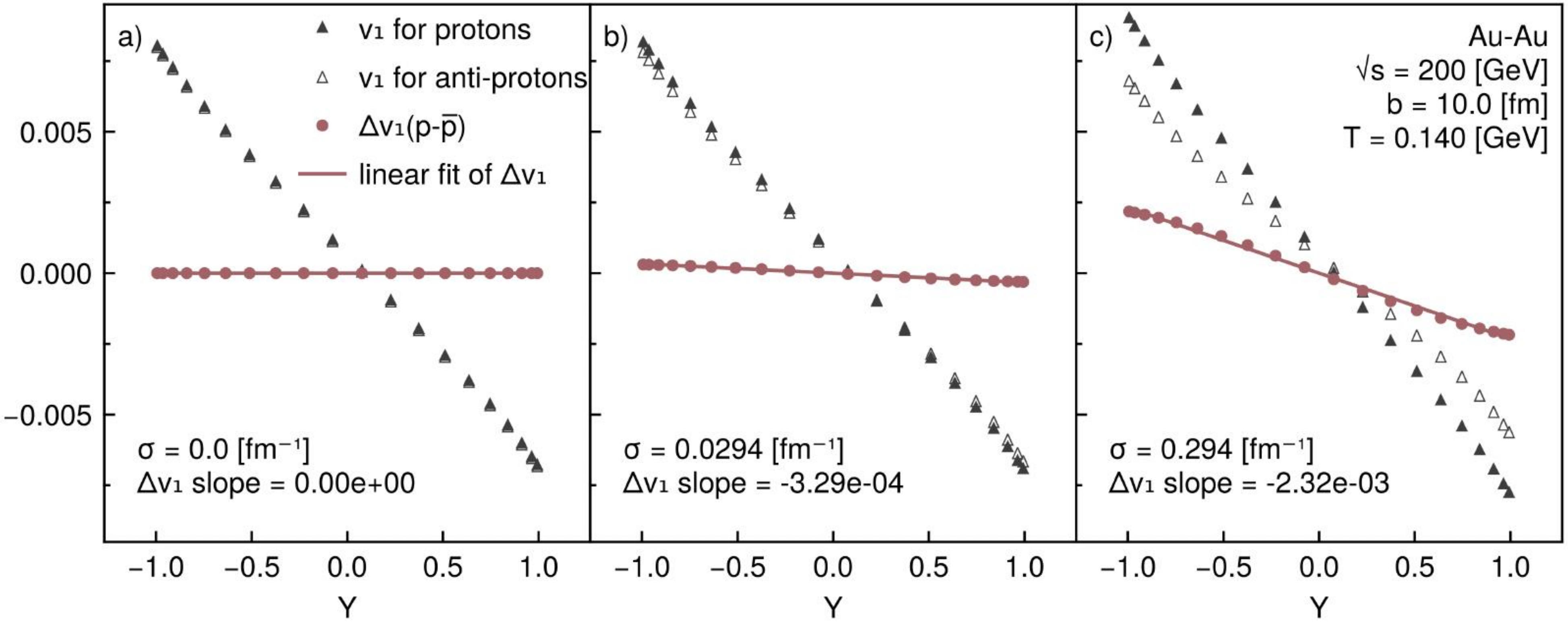
Magnetic field strength



Electric field strength

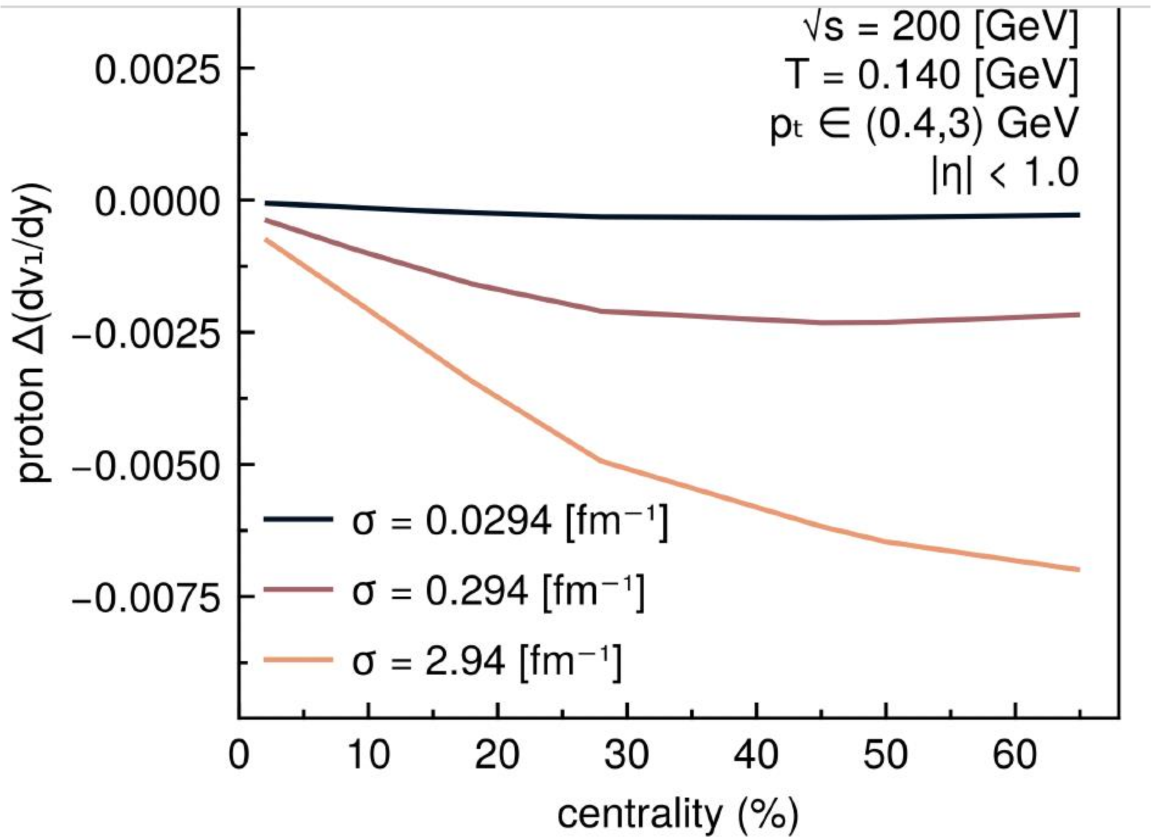
Analysis of Heavy Ion Collisions

Charge Dependent Directed Flow

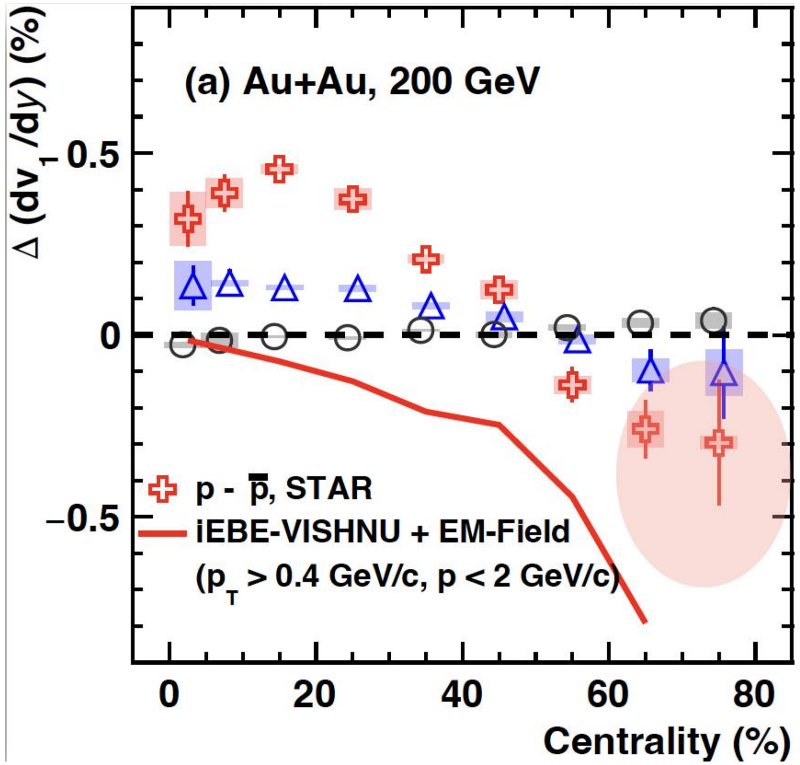


Benoit, Miyoshi, C. N., and Takahashi, Phys. Rev.C 112, (2025) 024911

Charge Dependent Flow



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



Caveat:

No baryon current
Initial condition
EoS
Final state interactions

Electromagnetic Probes
photon puzzle

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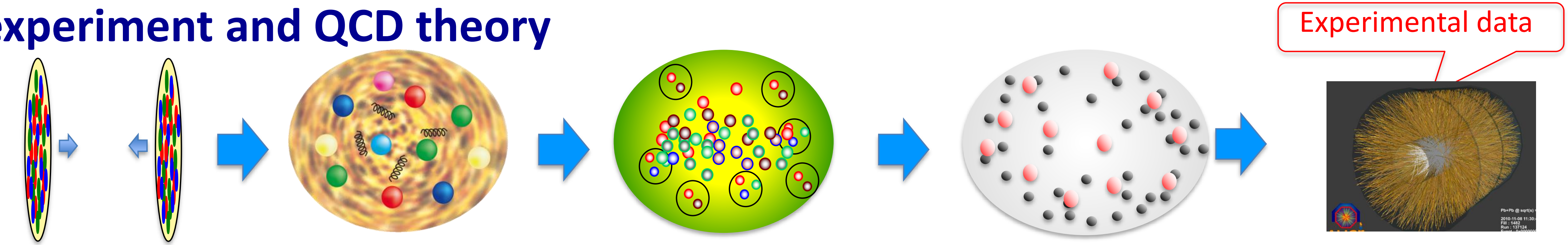
Summary

Hadron production in high-energy heavy-ion collisions: bridge between experiment and QCD theory



- Key to explore feature of QGP, QCD phase transition, QCD critical point hadronization mechanisms
  - Resonances, exotic hadrons and light nuclei: hadronization dynamics and critical phenomena
  - Electromagnetic probes (dileptons, photons) : in-medium spectral properties of hadrons
  - Existence of strong EM fields, charge dependent flow
  - Femtoscopy: hadron-hadron interaction, hadronic correlations in the late stage.