重イオン衝突物理での ジェットの理解へむけて

Nagoya University

Chiho Nonaka

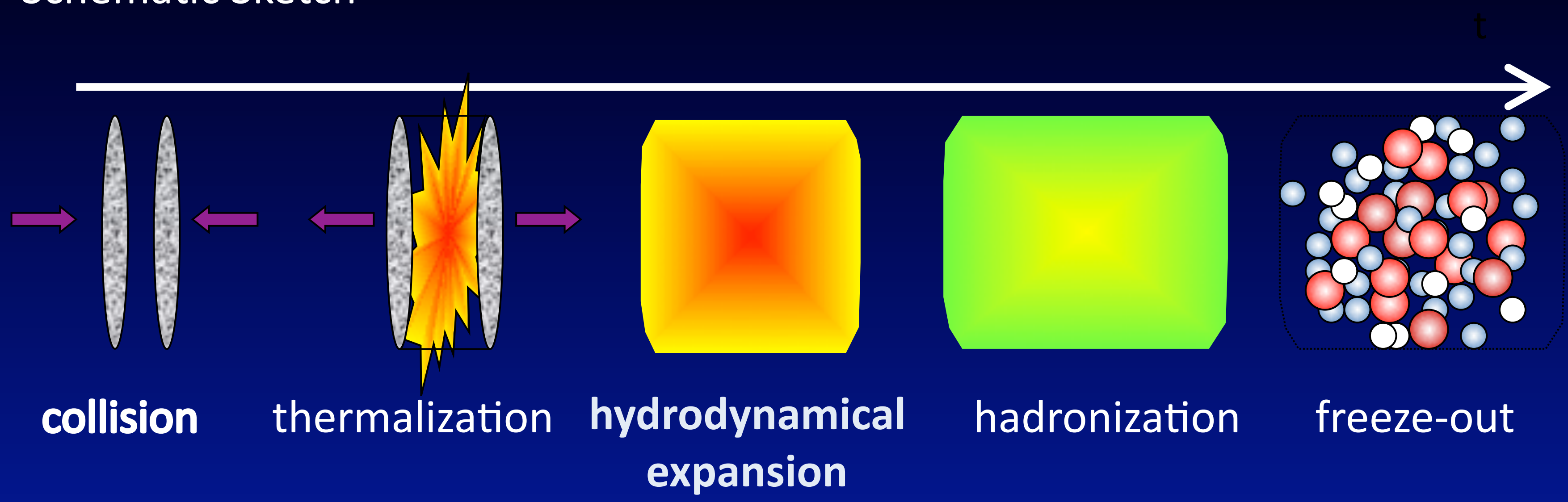
July 10, 2009@第６回Heavy Ion Pub

Jet Quenching

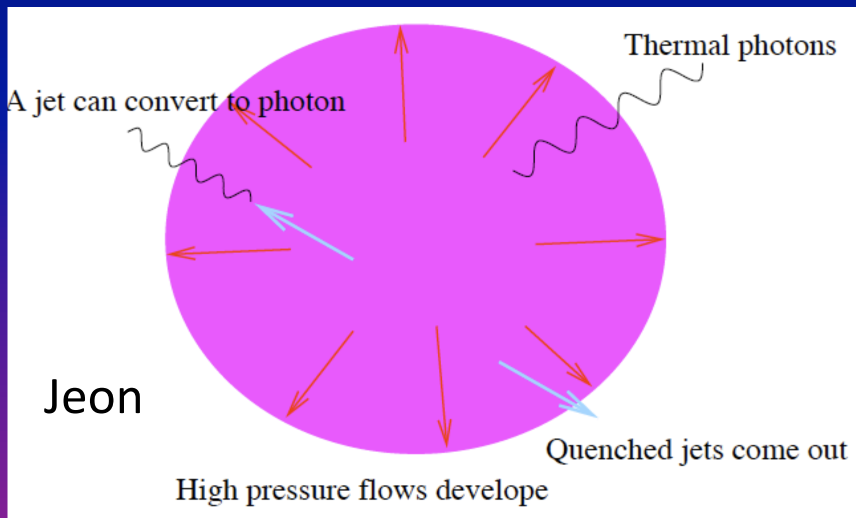
- 1990
  - Jet Quenching in lepton nucleus scattering, Gyulassy and Plumer
  - Jets in heavy ion collisions, X-N. Wang and Gyulassy
- RHIC
  - QM2001
  - Key issue
  - X-N.Wang
    - Event generators –Quo Vadis?
    - HIJING

Relativistic Heavy Ion Collisions

- Schematic Sketch



Dynamics of
Hot QCD matter



Jet quenching
mechamism

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Phenomena

- Nuclear modification factors
- Jets structure
  - Azimuthal angle
  - 3 particle correlations
  - $\Delta \eta$ and $\Delta \phi$

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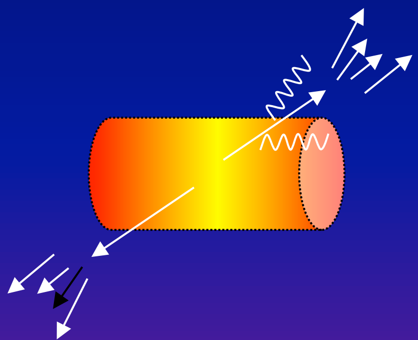
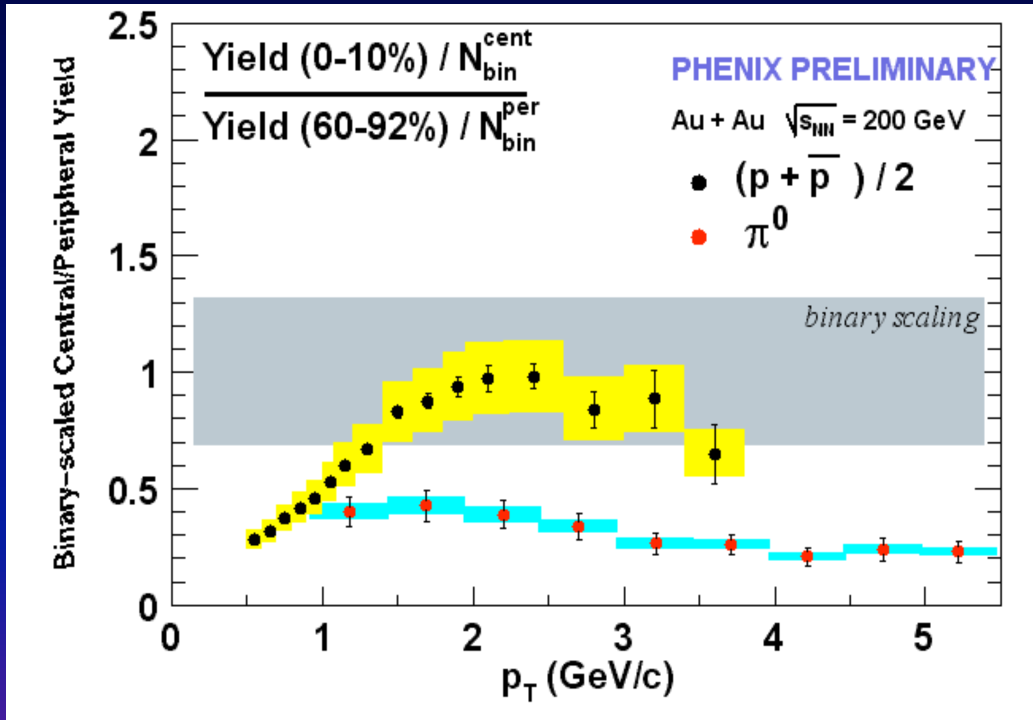


- hard scattering in medium
- jet quenching



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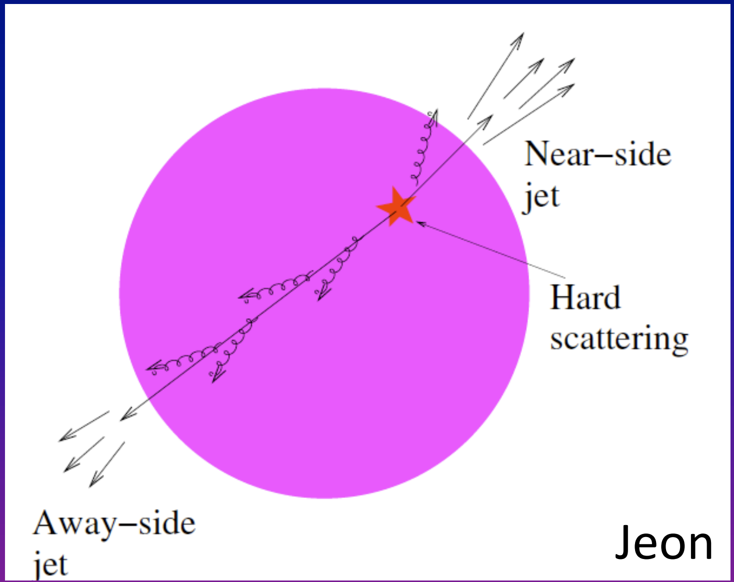

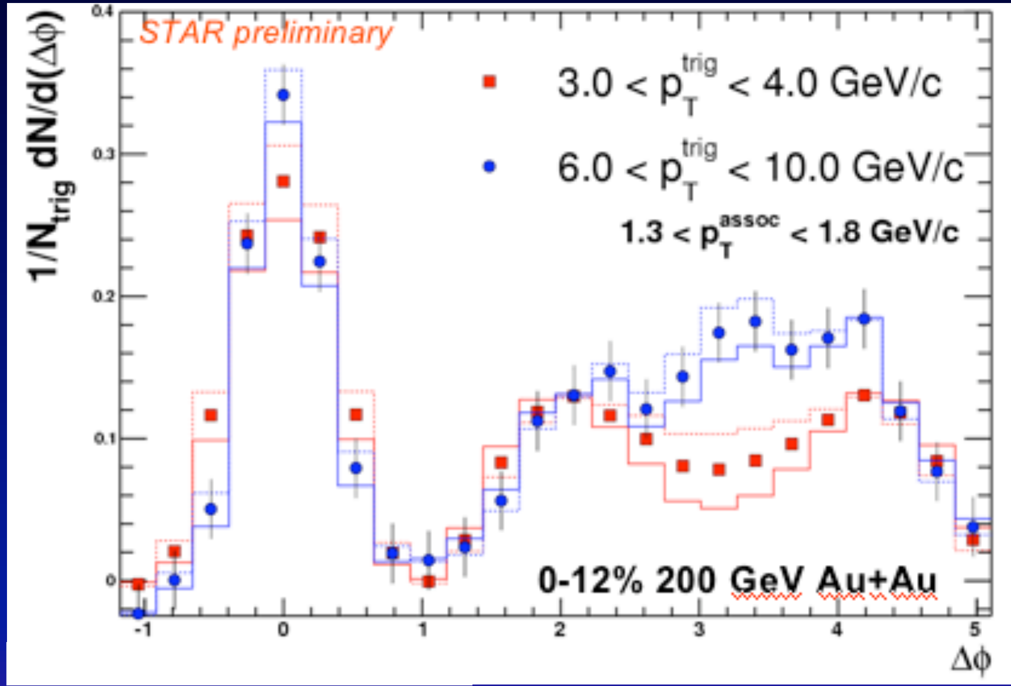

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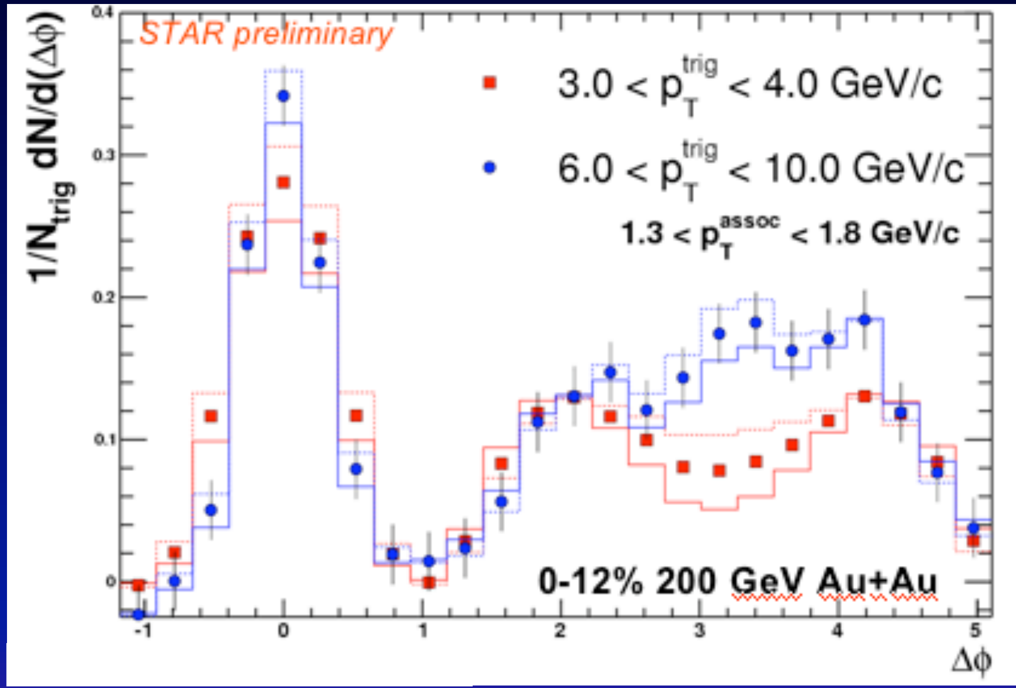
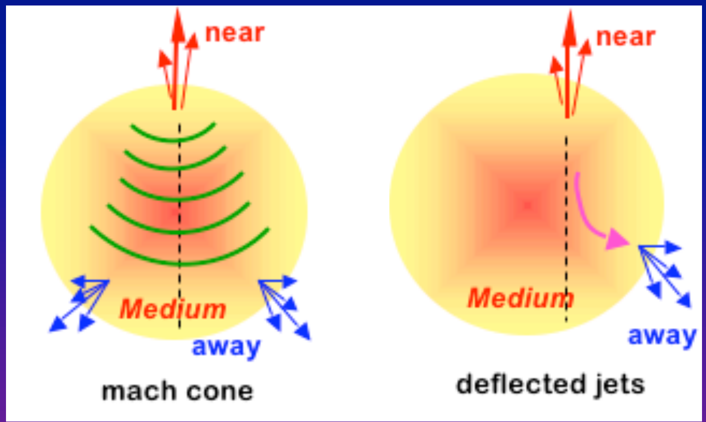
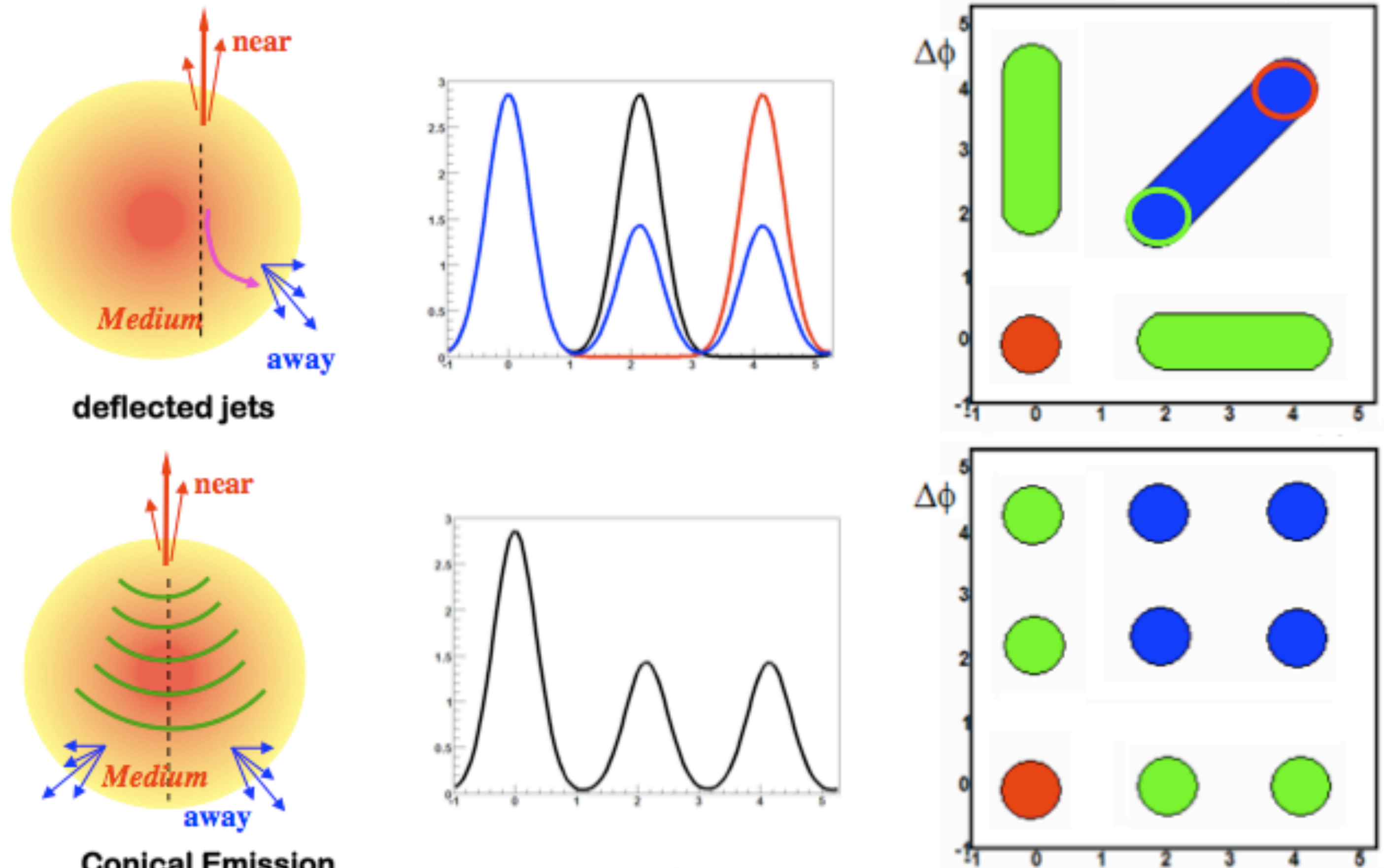




Azimuthal 3-Particle Correlations



From : Jason Glyndwr Ulery (QM 2008)

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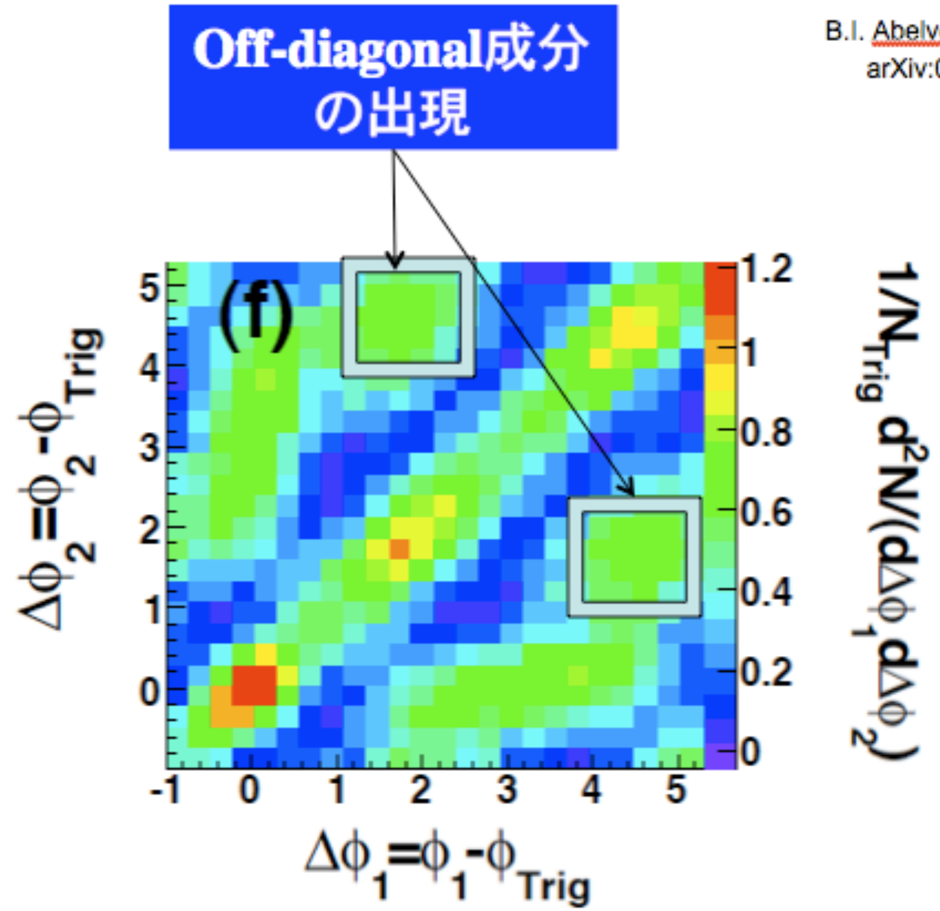
(f) Au+Au 0-12%



B.I. Abelve et al. (STAR),
arXiv:0805.0622v1

Trigger particle ($3 < p_T < 4$ GeV/c),
Associated particle ($1 < p_T < 2$ GeV/c) .

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Phenomena

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- ❖ Nuclear modification factors
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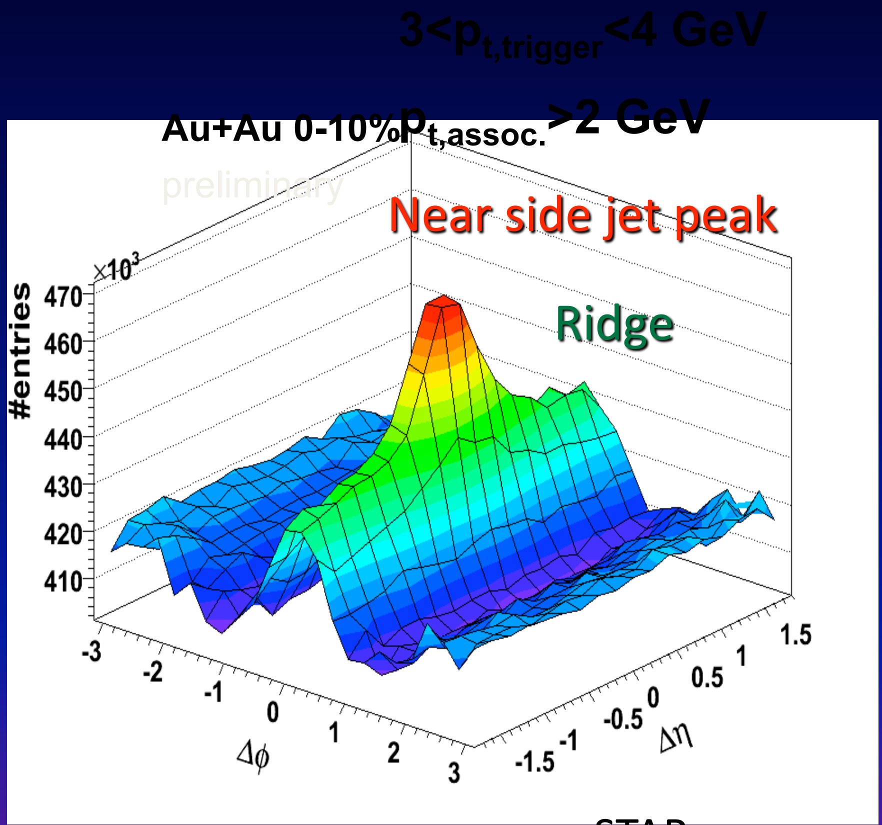
  - – Azimuthal angle
  - – 3 particle correlations
  - – $\Delta\,\eta$ and $\Delta\,\phi$: Ridge



STAR

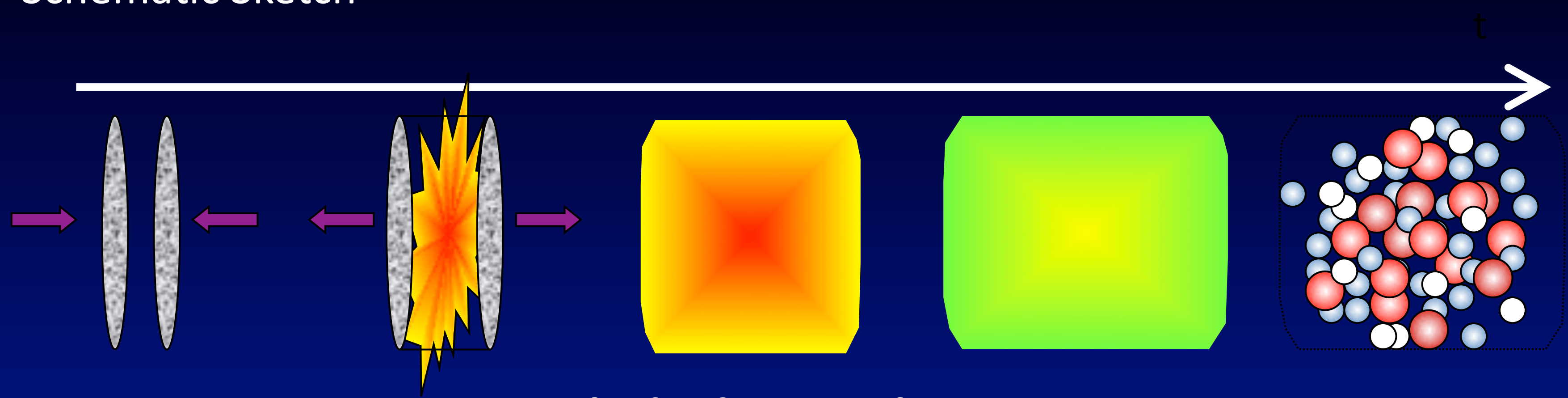
Phenomena

- Nuclear modification factors ☺
- Jets structure 😐
  - Azimuthal angle
  - 3 particle correlations
  - $\Delta\,\eta$ and $\Delta\,\phi$

Renk, Rupper, Nonaka, Bass, PRC75,031902(R),2007
Majumder, Nonaka, Bass, PRC76,041902(R),2007
Qin,Rupper,Turbide,Gale,Nonaka,Bass,PRC76,064907(2007)
Bass,Gale,Majumder,Nonaka,Qin,Renk,Ruppert, PRC79,024901(2009)

Relativistic Heavy Ion Collisions

- Schematic Sketch



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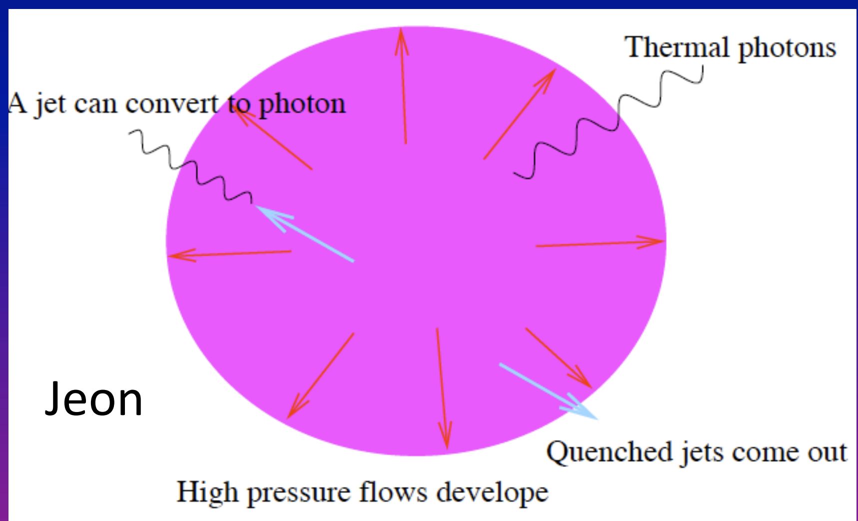

Jet quenching
mechamism

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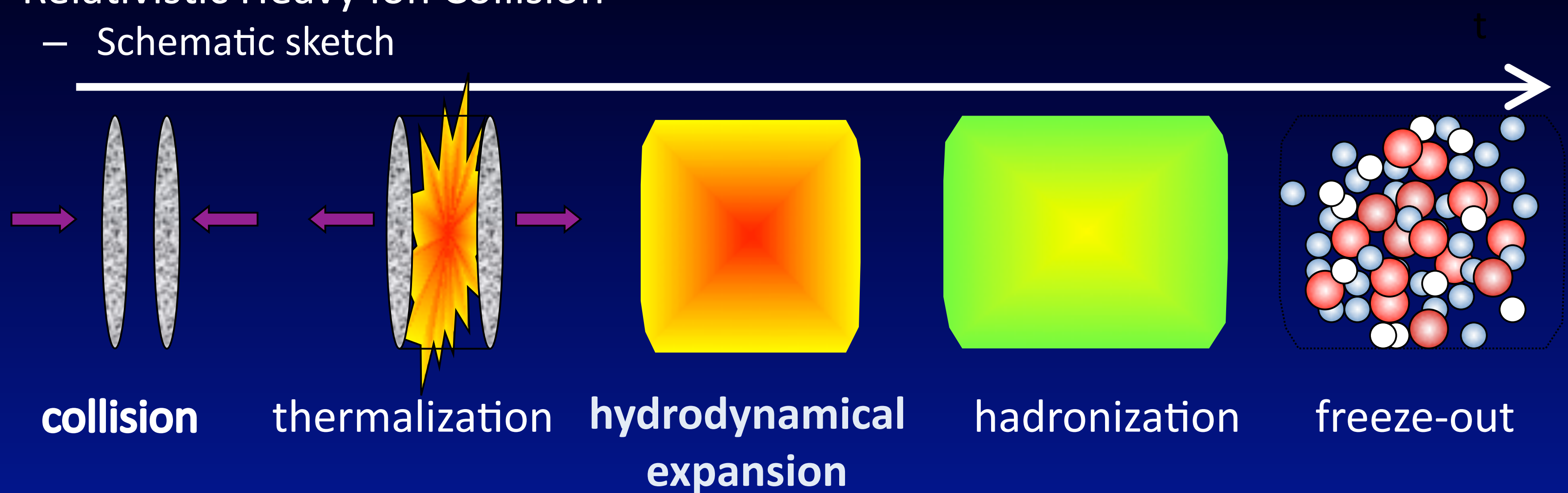
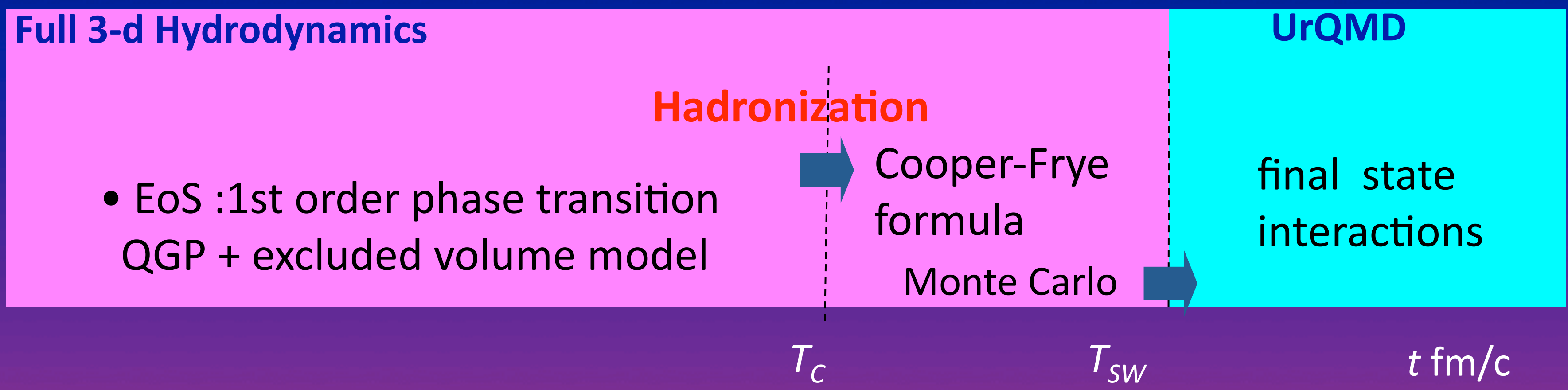
3D Hydro + UrQMD

- Relativistic Heavy Ion Collision
  - Schematic sketch



◉ 3D Hydro + UrQMD



T_C:critical temperature > T_{SW}: Hydro ➔ UrQMD

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3-D Hydrodynamic Model

❖ Relativistic hydrodynamic equation

$$\partial_\mu T^{\mu\nu} = 0 \qquad T^{\mu\nu}: \text{energy momentum tensor}$$

– Baryon number conservation

$$\partial_\mu (n_B(T,\mu)) = 0$$

❖ Coordinates

$$(\tau, x, y, \eta) : \tau = \sqrt{t^2 - z^2}, \eta = \tanh^{-1}\left(\frac{z}{t}\right)$$

❖ Lagrangian hydrodynamics

– Tracing the adiabatic path of each volume element

– Effects of phase transition on observables

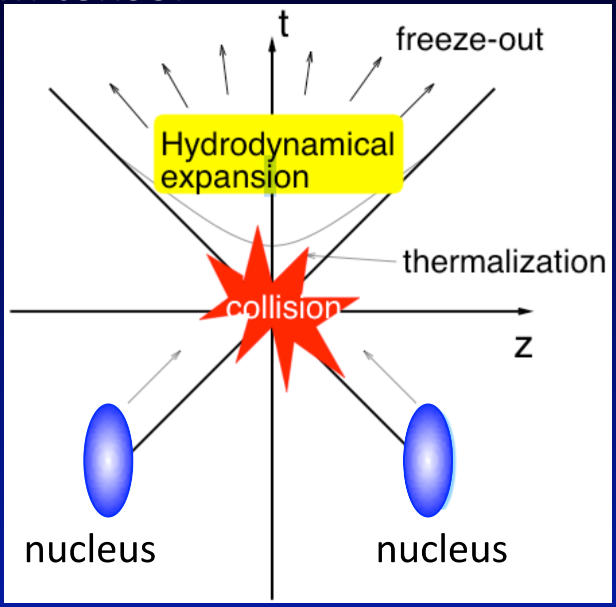
– Computational time

– Easy application to LHC

❖ Algorithm

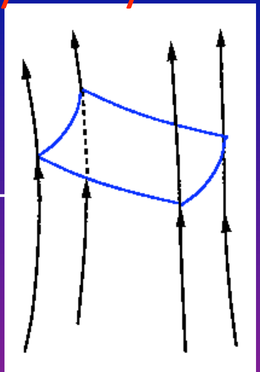
– Base on the conservation law

$$\partial_\mu (s(T,\mu)u^\mu) = 0,\ \partial_\mu (n_B(T,\mu)u^\mu) = 0$$



Lagrangian hydrodynamics

Flux of fluid



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Parameters

- Initial Conditions
  - Energy density

$$\varepsilon(x,y,\eta) = \varepsilon_{\max} W(x,y;b) H(\eta)$$

  - Baryon number density

$$n_B(x,y,\eta) = n_{B\max} W(x,y;b) H(\eta)$$

  - Parameters

τ_0=0.6 fm/c

ε_{max}=55 GeV/fm^3, n_{Bmax}=0.15 fm^{-3}

η_0=0.5 σ_η=1.5

  - Flow

v_L=η (Bjorken's solution); v_T=0

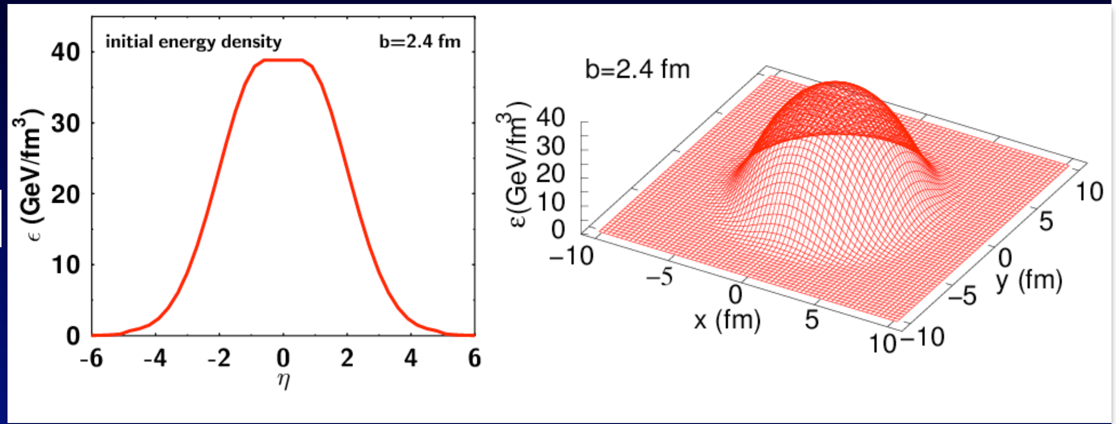
- Equation of State

  1st order phase transition, T_c=160 MeV

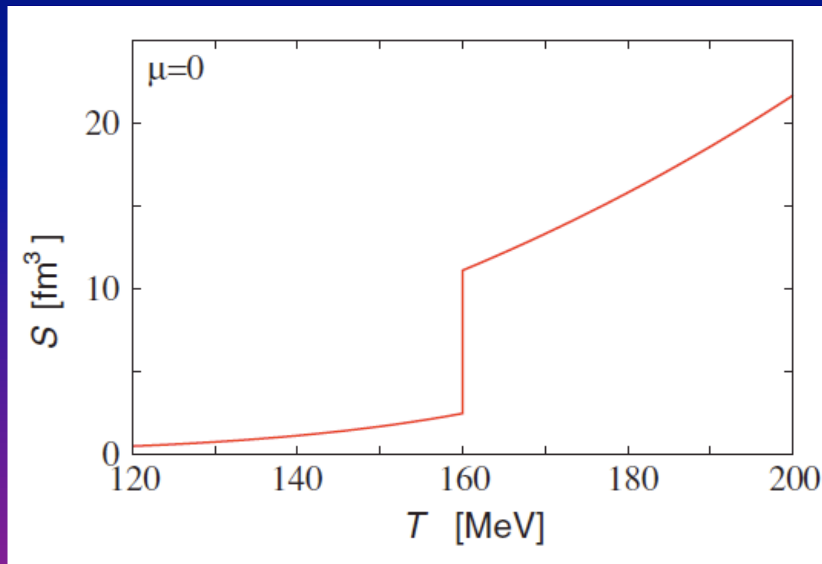
- Switching temperature

  T_{SW}=150 [MeV]

•longitudinal direction •transverse plane



•Entropy density as a function of T



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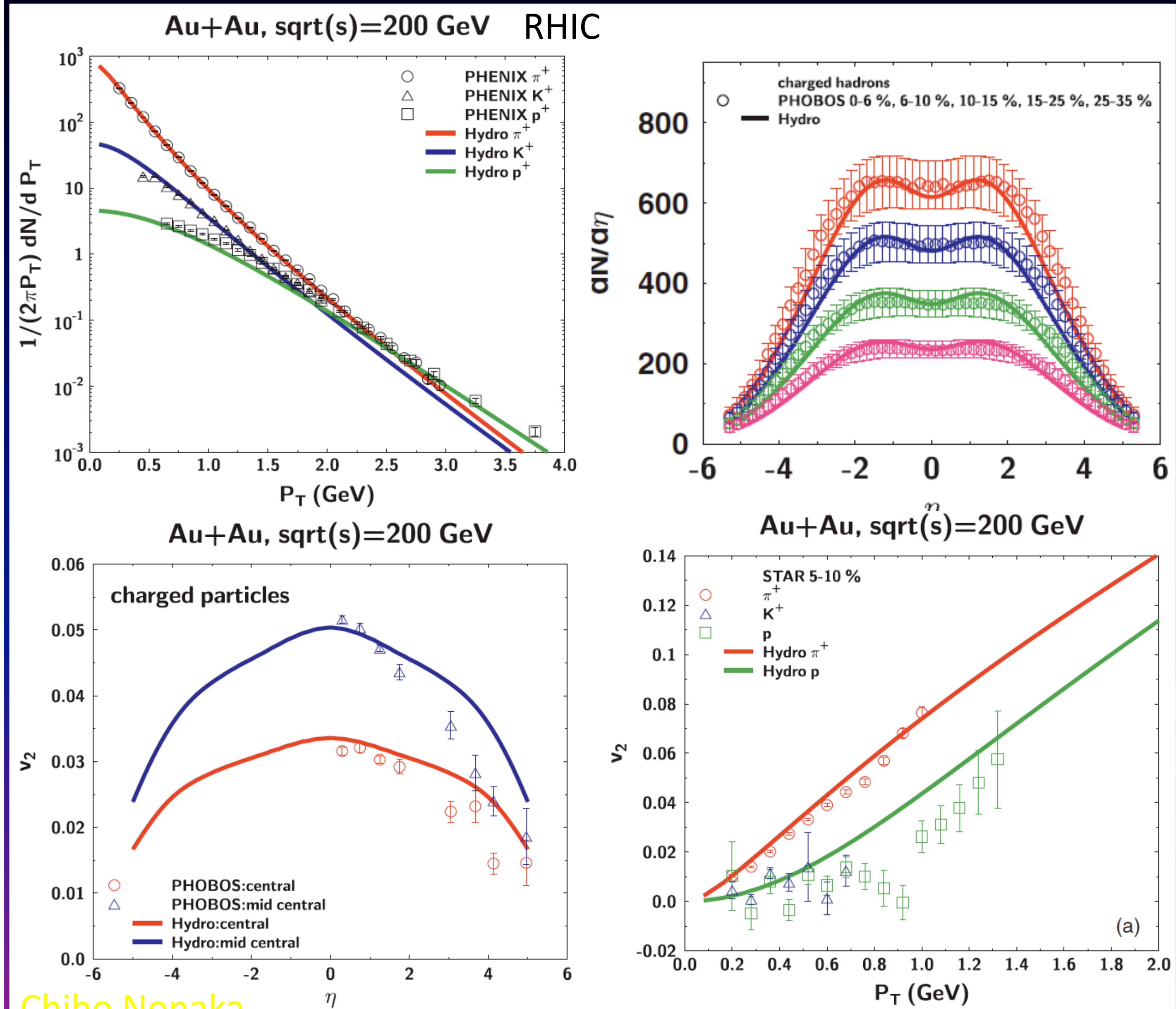
3D Ideal Hydrodynamic Model



- Chemical equilibrium freezeout
- Final state interactions are neglected.

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Parameters

- Initial Conditions
  - Energy density

$$\varepsilon(x,y,\eta) = \varepsilon_{\max} W(x,y;b) H(\eta)$$

  - Baryon number density

$$n_B(x,y,\eta) = n_{B\max} W(x,y;b) H(\eta)$$

  - Parameters

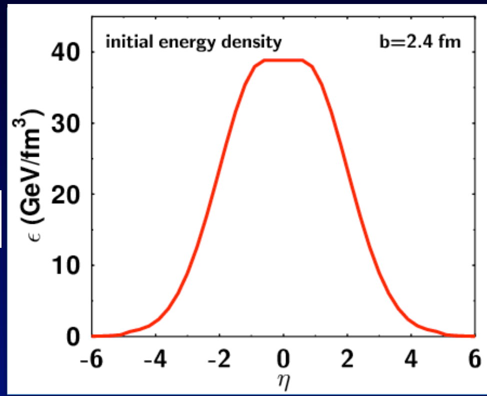
τ_0=0.6 fm/c
ε_{max}=40 GeV/fm^3, n_{Bmax}=0.15 fm^{-3}
η_0=0.5 σ_η=1.5

  - Flow

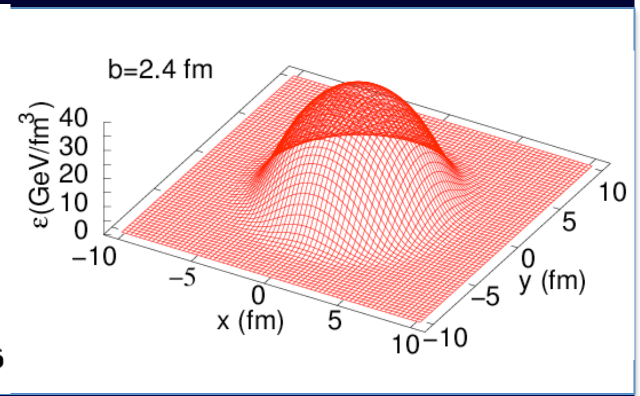
v_L=η (Bjorken's solution); v_T=0

- Equation of State
  1st order phase transition, T_c=160 MeV
- Switching temperature
  T_{SW}=150 [MeV]

•longitudinal direction



•transverse plane



	hydro	Hydro+ UrQMD
τ_0(fm)	0.6	0.6
ε_{max}(GeV/fm^3)	55	40
n_{Bmax}(fm^{-3})	0.15	0.15
η_0,σ_η	0.5, 1.5	0.5, 1.5

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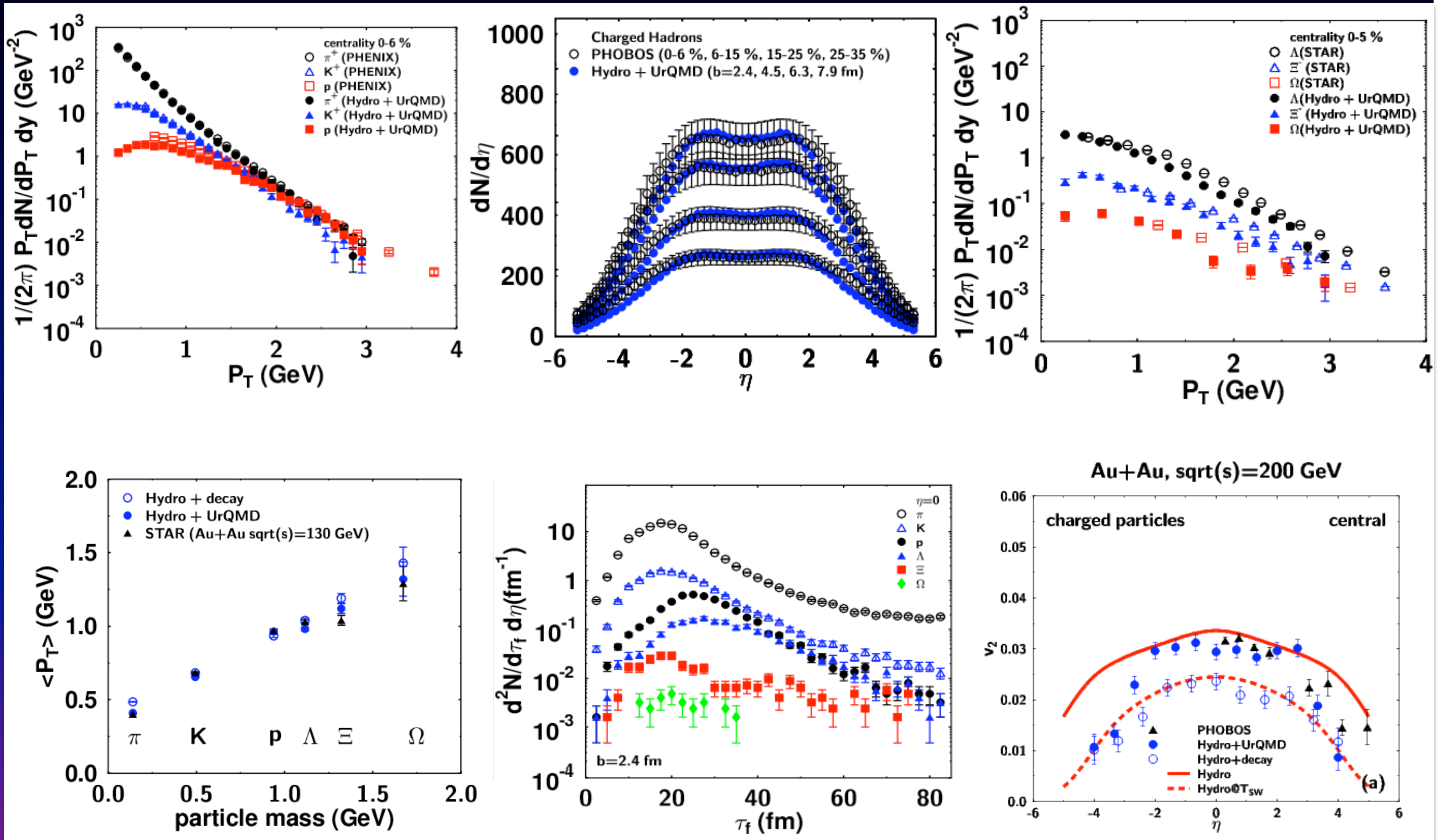
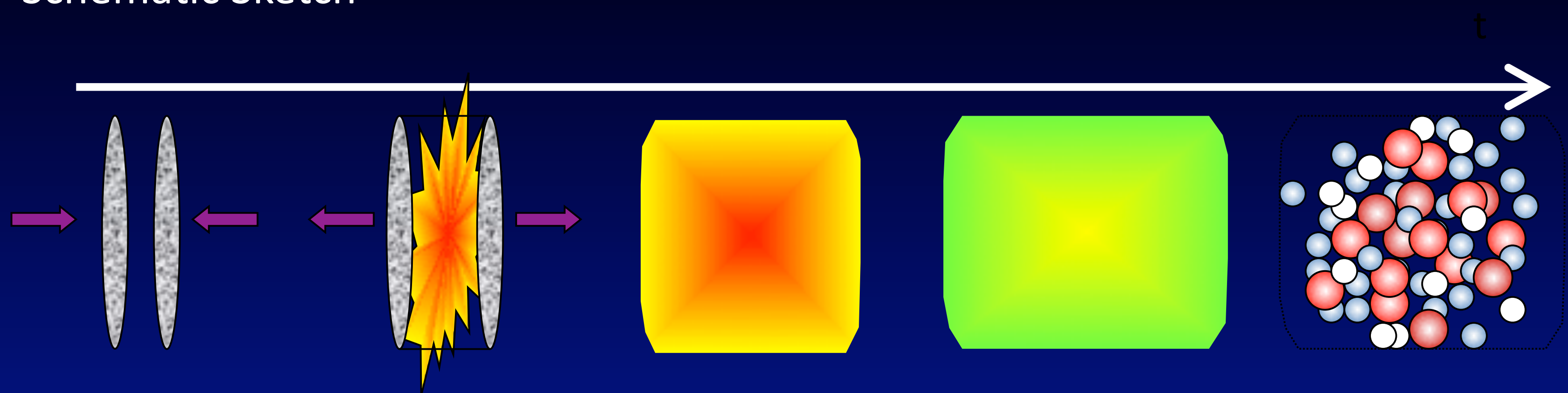
3D Ideal Hydro+UrQMD



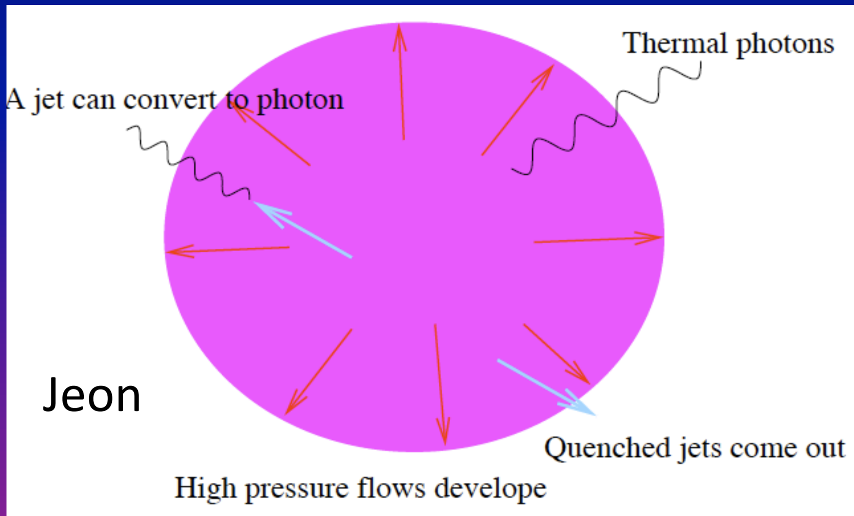
Relativistic Heavy Ion Collisions

- Schematic Sketch



collision thermalization **hydrodynamical expansion** hadronization freeze-out

Dynamics of
Hot QCD matter



Jet quenching
mechamism

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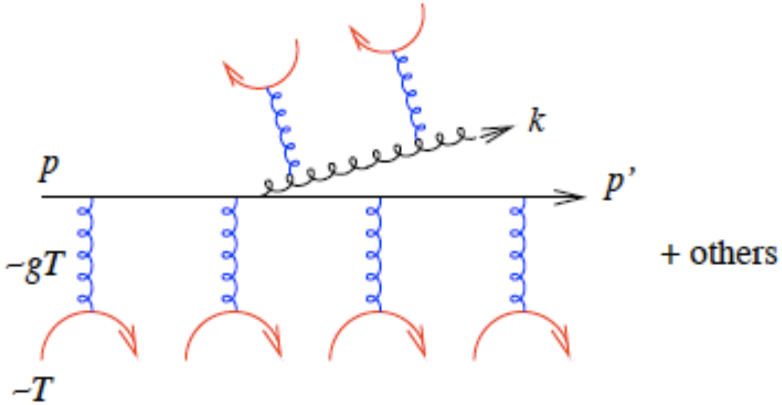
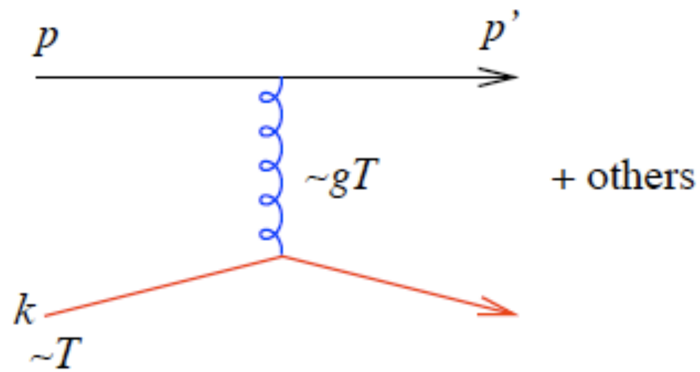
Energy Loss

- QGP makes jets lose energy
  - Radiational (Inelastic)



  - Elastic

QGP?



Jeon@Nagoya

Application of Hydro

- Interactions between jets and medium
  - Medium ← Hydrodynamic Model
- Systematic Comparison of Jet Energy-Loss Scheme
  - BDMPS/ASW: path integral approach to the opacity expansion
  - Higher Twist (HT)
  - Arnold-Moor-Yaffe (AMY) : finite temperature field theory approach
  - GLV: reaction operator approach to the opacity expansion

soft sector : Hydro

Hirano and Nara, PRC69,034908(2004)

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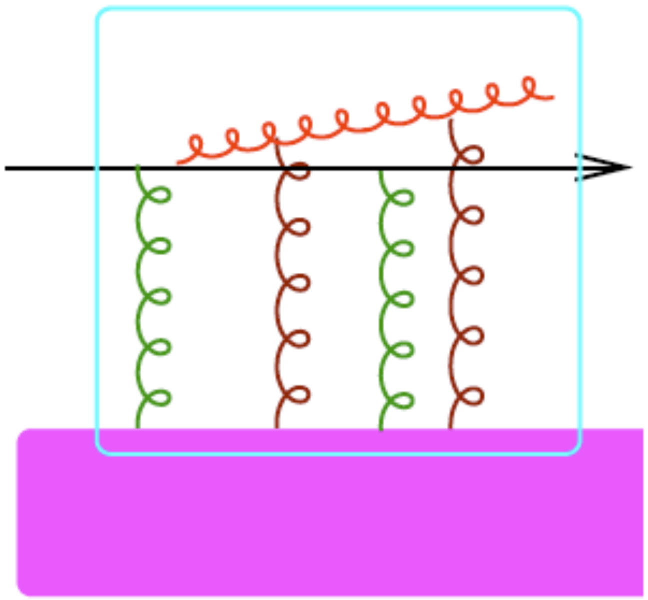
Calculation Scheme



First calculate the *local* radiation rate $\frac{dN_g}{d\omega dt}$

The magenta box:

Jeon@QM2009

- QGP medium characterized by T, g_s – AMY, DGLV
- Static medium characterized by μ, l_{mfp} – BDMPS-Z, GLV, AWS, ...
- General nuclear medium with short color correlation – HT

Hadron Production

$$\frac{d^2\sigma^h}{dyd^2p_T} = \frac{1}{\pi}\int dx_a \int dx_b G_a^A(x_a) G_b^B(x_b) \frac{d\sigma_{ab\to cX}}{d\hat{t}} \frac{\tilde{D}_c(z)}{z}$$

same initial state

G（x）: parton distribution function: CTEQ5

Vacuum fragmentation functions: KKP, AKP

different in each energy loss scheme : ASW, HT, AMY

$\tilde{D}_c(z)$: medium modified fragmentation function

Energy Loss in Medium

❖ Information of medium: thermodynamic values, velocity

🡐 Hydrodynamic Models

❖ Transport coefficients in each energy loss scheme

– BDMPS/ASW

$$\hat{q}(\xi) = K \cdot 2 \cdot \varepsilon^{\frac{3}{4}}(\xi)$$

ξ: trajectory of jets

– Higher Twist

$$\hat{q}(\vec{r},\tau) = q_0 \frac{\gamma(\vec{r},\tau)T^3(\vec{r},\tau)}{T_0^3}\left[R_{QGP}(\vec{r},\tau) + c_{HG}(1 - R_{QGP}(\vec{r},\tau))\right]$$

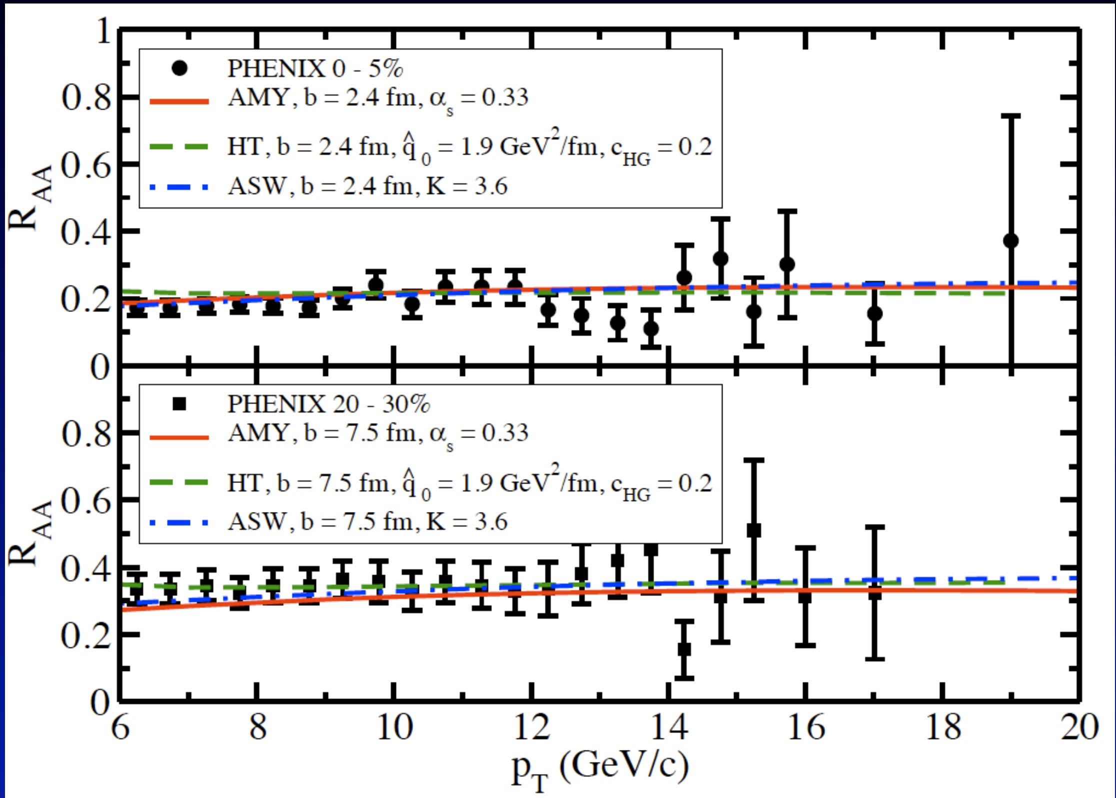
R_{QGP}: ratio of QGP phase

q_O at initial time(0.6 fm/c), c_{HG} hadron phase

– AMY: α_s

$$\hat{q}(\vec{r},\tau) = \frac{C_A g^2 T(\vec{r},\tau) m_D^2}{2\pi} \ln \frac{q_\perp^{\max}}{m_D}$$

Nuclear Modification Factors



- Predictions:
  P_T dependence,
  centrality dependence
- Very small difference
  More sophisticated observables are needed.

Parameters: fixed in central collisions

ASW	HT	AMY
K=3.5	q_0=1.9 GeV^2/fm	α_s=0.33

Scaling with the Medium

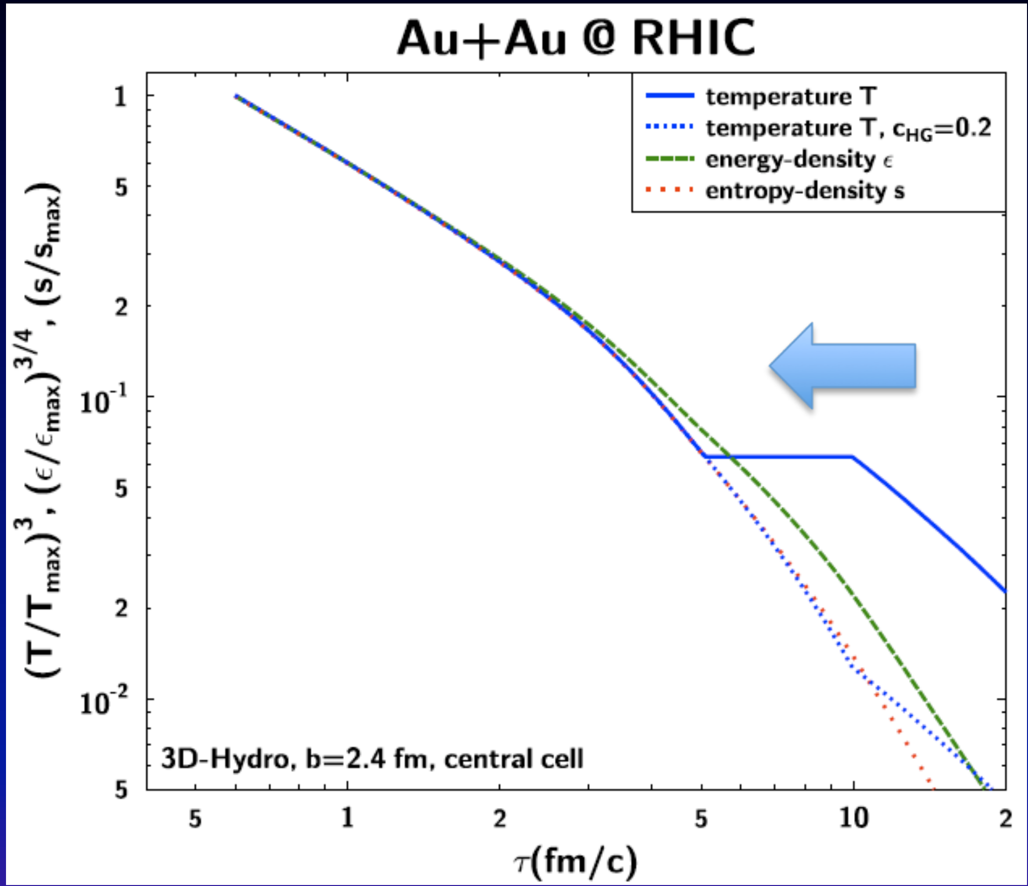
Possible choices of scaling

$$\hat{q} \sim T^3 \qquad \hat{q} \sim \varepsilon^{3/4} \qquad \hat{q} \sim s$$

T ε, s: Information of medium
Hydrodynamic model &
Equation of states

- Bjorken expansion with Ideal QGP
  - -Identical results
- Hydro with realistic equation of state
  - -different time dependence

realistic dynamical model,
proper medium scaling



- Choice of c_{HG}=0.2 mimics scaling with entropy density

PRC79,024901(2009)

Quantitative Comparison

$$\hat{q}(\xi) = \hat{q}_0 \cdot \Gamma(\xi)$$

ξ: trajectory of jets in medium

$$\Gamma = \left(\frac{T}{T_0}\right)^3, \left(\frac{\epsilon}{\epsilon_0}\right)^{3/4}, \left(\frac{s}{s_0}\right)$$

$\hat{q}_0$:initial maximum value

$\hat{q}(\vec{r},\tau)$ scales as	ASW $\hat{q}_0$	HT $\hat{q}_0$	AMY $\hat{q}_0$
$T(\vec{r},\tau)$	10 $\mathrm{GeV}^2/\mathrm{fm}$	2.3 $\mathrm{GeV}^2/\mathrm{fm}$	4.1 $\mathrm{GeV}^2/\mathrm{fm}$
$\epsilon^{3/4}(\vec{r},\tau)$	18.5 $\mathrm{GeV}^2/\mathrm{fm}$	4.5 $\mathrm{GeV}^2/\mathrm{fm}$	
$s(\vec{r},\tau)$		4.3 $\mathrm{GeV}^2/\mathrm{fm}$	

-BDMPS/ASW

$$\hat{q}(\xi) = K \cdot 2 \cdot \varepsilon^{\frac{3}{4}}(\xi)$$

-Higher Twist

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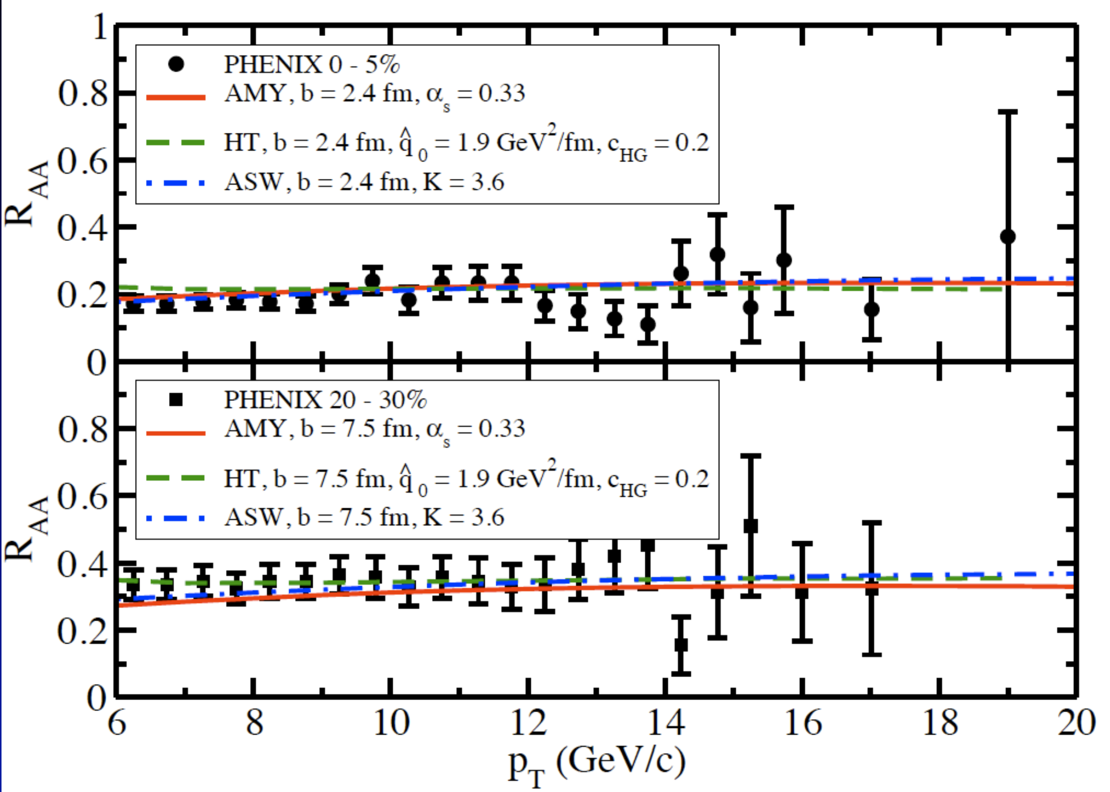
Nuclear Modification Factors



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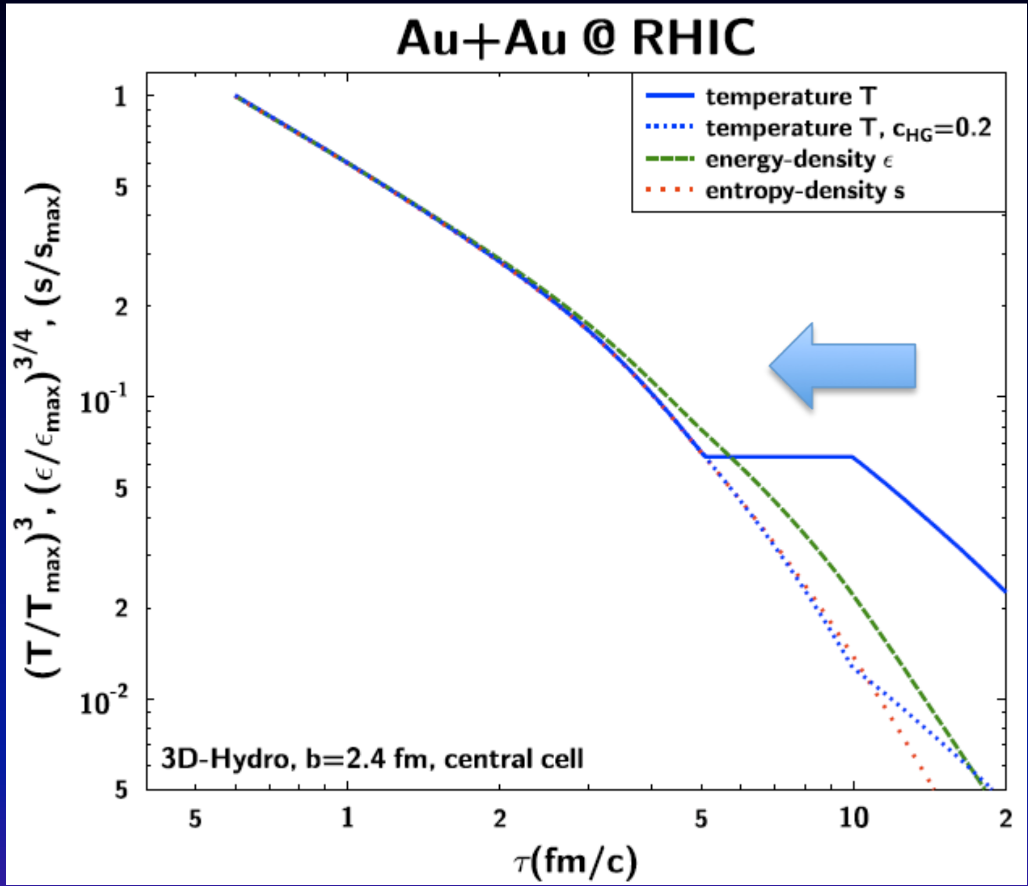

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PRC79,024901(2009)

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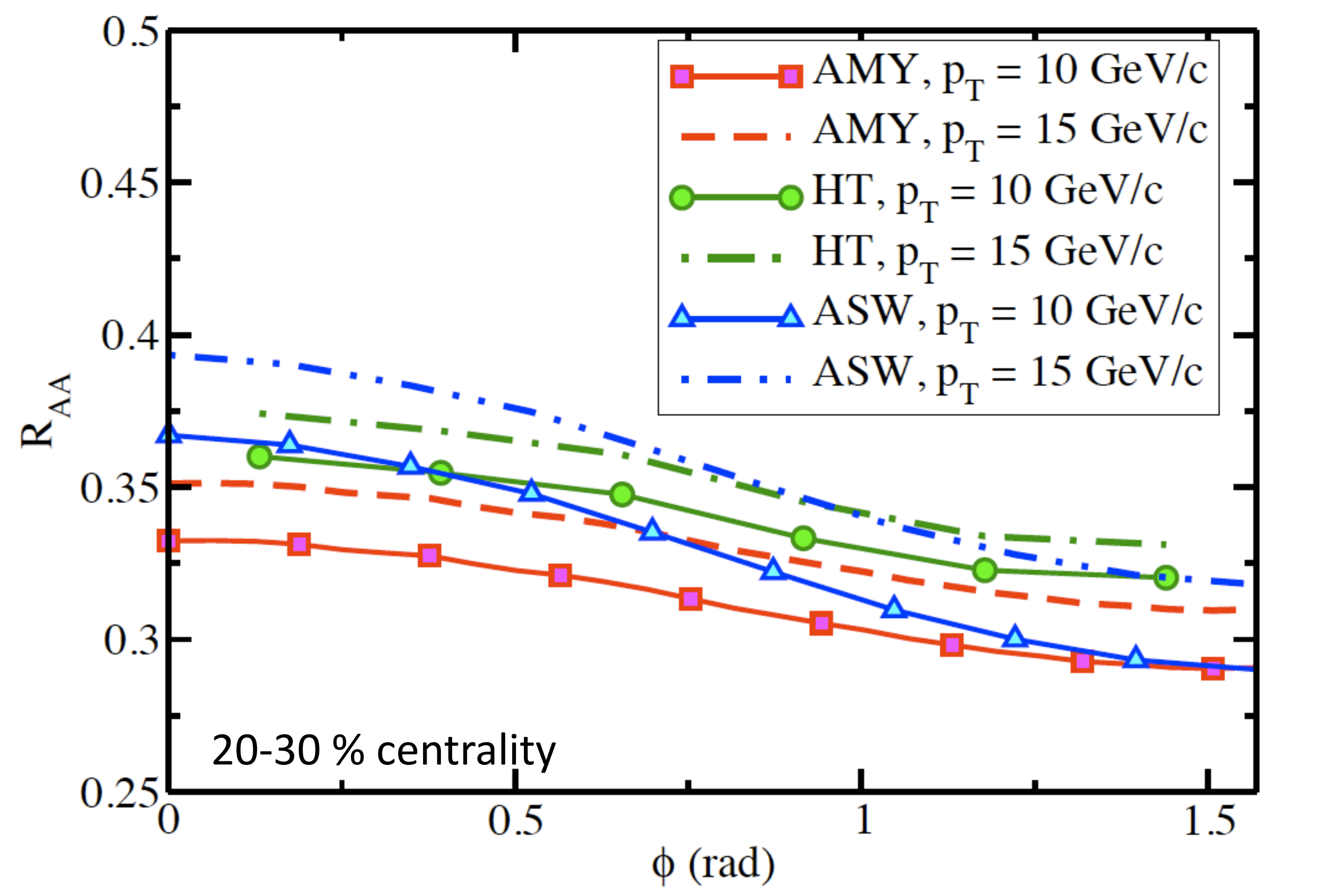
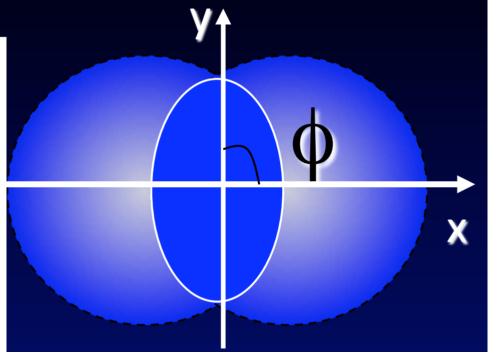
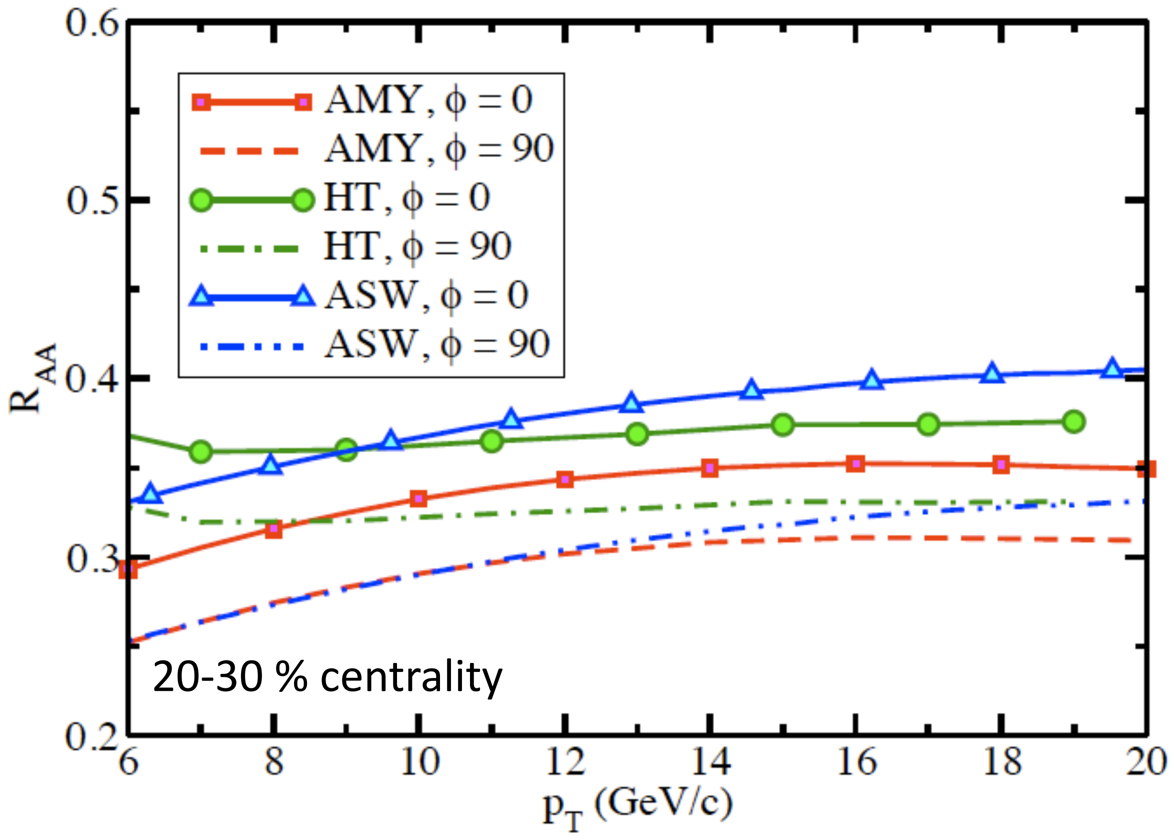
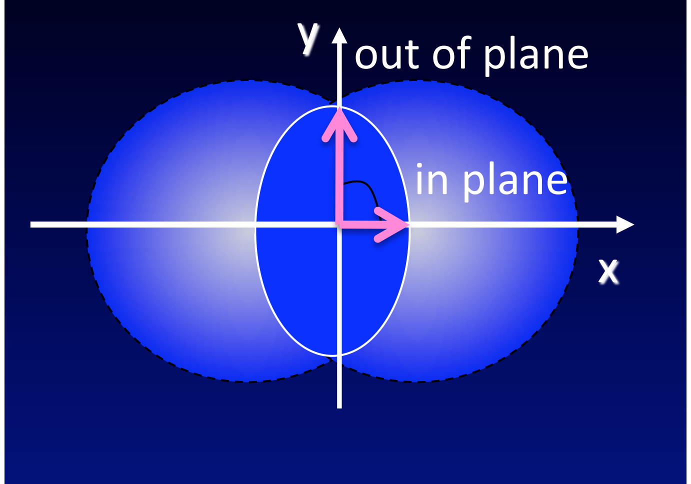
Azimuthal angle dependence



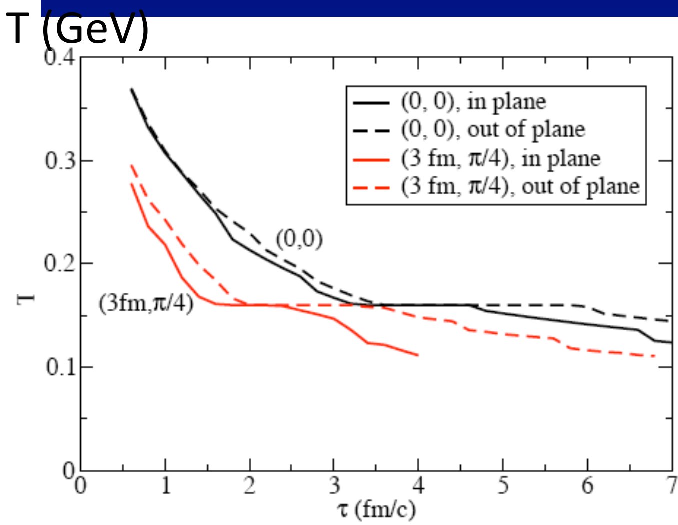


R_{AA} for In/Out of plane





Temperature profile in 3D hydro



- AMY & HT: same azimuthal spread, but difference in magnitude

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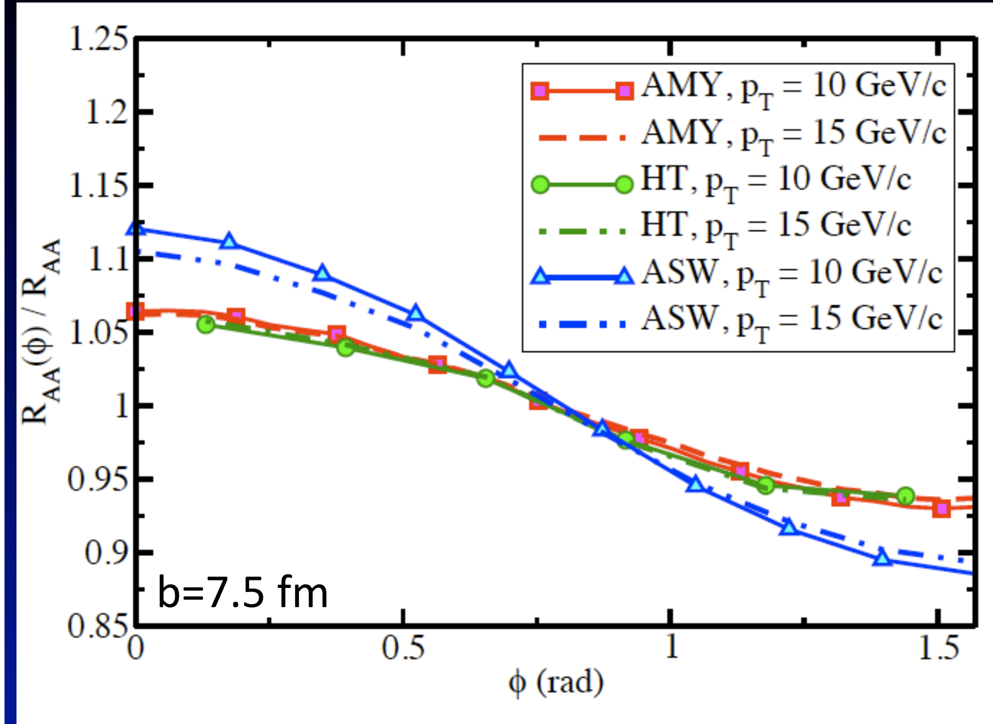
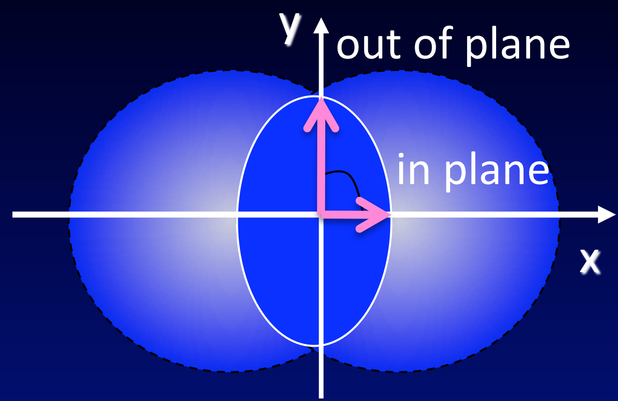
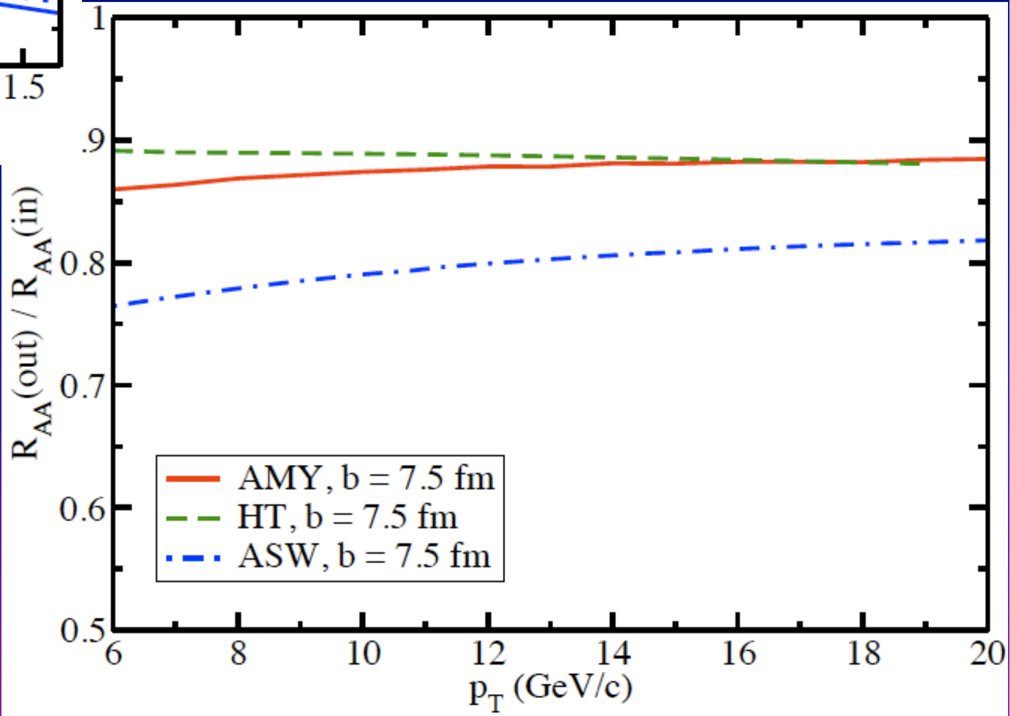
Azimuthal Spread

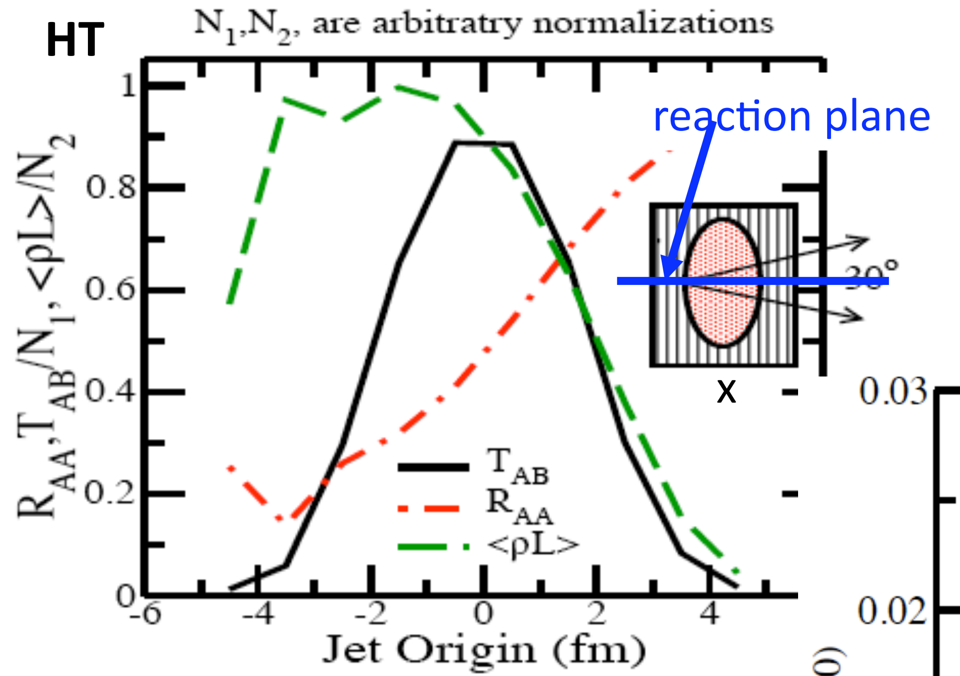






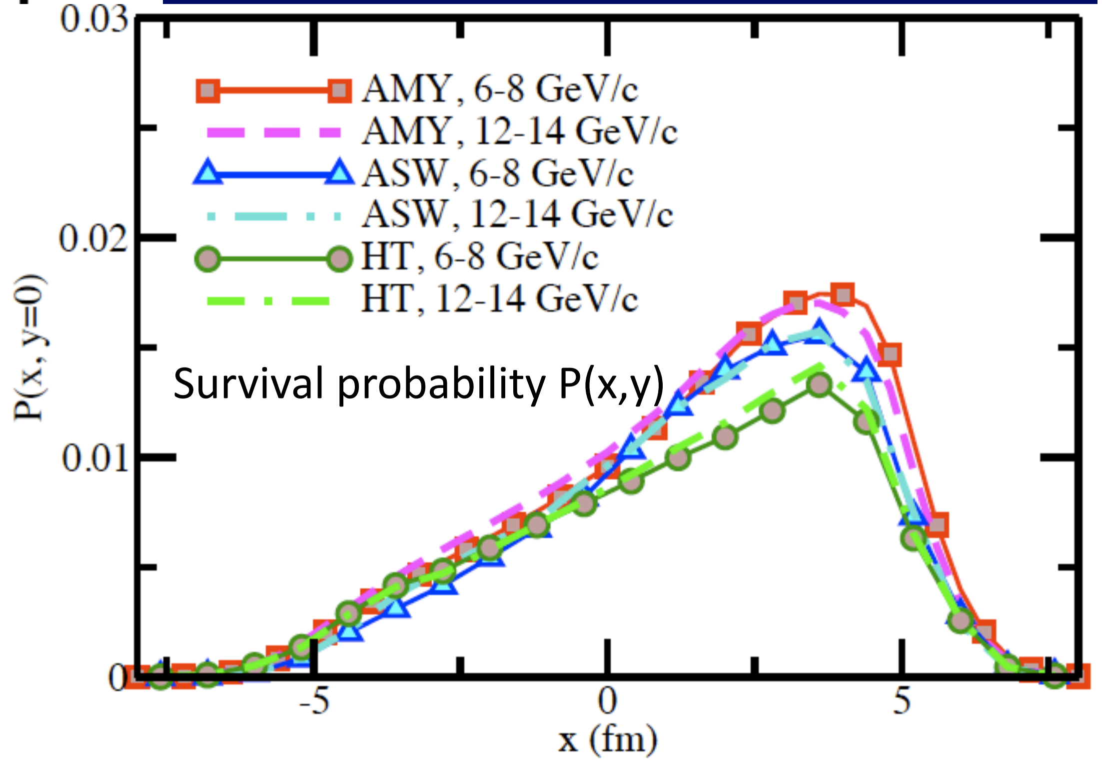
- ASW shows a significantly stronger azimuthal dependence of R_{AA} than AMY & HT

Nuclear Modification Factor



R_{AA} is anticorrelated with <ρL>

•Three approaches agree with each other
➔Same suppression factor



Summary

❖ Soft sector: 3D Hydro + UrQMD Model

– Success at RHIC: P_T spectra, rapidity distribution, elliptic flow

❖ Jets in medium

– Jet quenching mechanisms: BDMPS /ASW, higher twist and AMY

– Nuclear modification factors

  • Transport coefficients

TECHQM

- https://wiki.bnl.gov/TECHQM/index.php/Main_Page

TECHQM

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TECHQM:About

TECHQM: Theory-Experiment Collaboration for Hot QCD Matter [edit]

The goal of TECHQM is to further the understanding of hot QCD matter through detailed, quantitative analysis of heavy ion collision experimental data and theory, together with the dynamical modeling which connects them.

The complex, dynamic nature of a heavy ion collision dictates the need for extensive theoretical modeling as the bridge between experimental observations and underlying properties of the hot QCD Matter. While good progress has been made in this area, providing essential support for interpretation of RHIC data on flow and jet quenching, there are still significant conceptual and modeling uncertainties which limit the accuracy with which conclusions can be drawn about the properties of QCD matter.

In the view of the TECHQM working group, elucidation and reduction of these uncertainties requires coherent, sustained, collaborative effort of experts in all stages of a heavy ion collision. A collaborative effort of theorists and experimentalists, aimed at systematic validation of different approaches to the modeling of heavy ion collisions, will be able to go significantly beyond the scope achievable by individual research groups, which usually concentrate on the development of models for specific collision stages. This is not an issue for the RHIC or LHC communities in isolation in our view, full understanding of the physics at both facilities will require a unified approach, to compare and contrast their results within common calculational frameworks.

The first TECHQM meeting was a held at Brookhaven National Laboratory, May 6-7, 2008: http://www.bnl.gov/techqm/default.asp

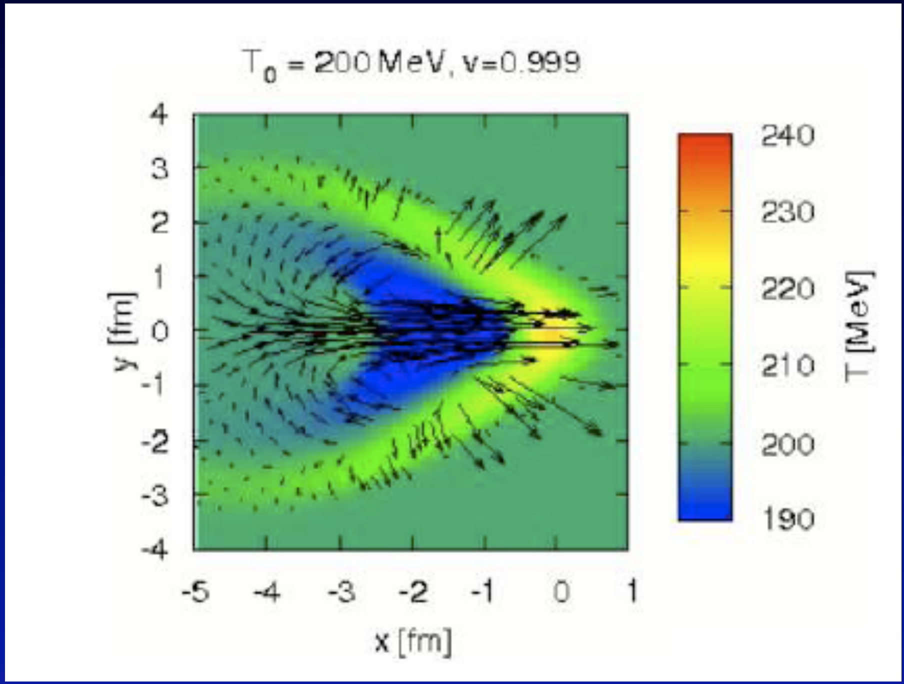
Working Groups: partonic energy loss
bulk evolution

Event Generators

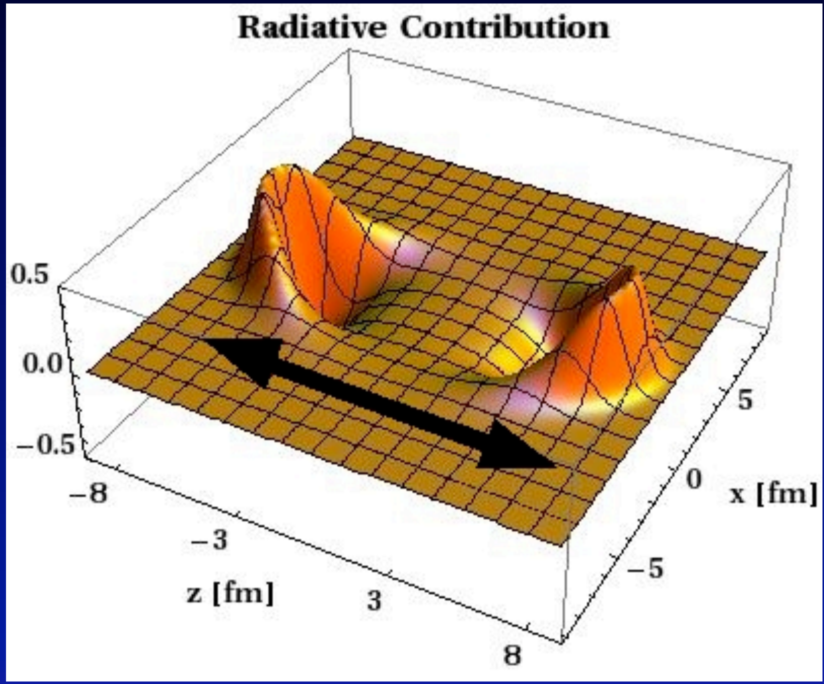
- YaJEM – T. Renk, Tues.Plenary
  (Yet another Jet Energy loss Model
- JEWEL – Zapp, Ingelman, Rothsman, Stachel, Wiedemann – K.C. Zapp, Tues.1A
  (Jet Evolution With Energy Loss
- Q-PYTHIA – Armesto, Salgado, Cunqueiro, Corcella – C. Salgado, Tues.2A
- PQM – Dainese, Loizides, Paić
  (Parton Quenching Model)
- PYQUEN/HYDJET – Lokhtin, Petrushanko, Snigirev, Teplov, Mailinina, Arsene, Tywoniuk
- MARTINI – McGill-AMY
  (Modular Algorithm for Relativistic Treatment of Heavy IoN Interactions)

Mach Cone

❖ Interactions between medium and jets



B.Betz et al. 0812.4401



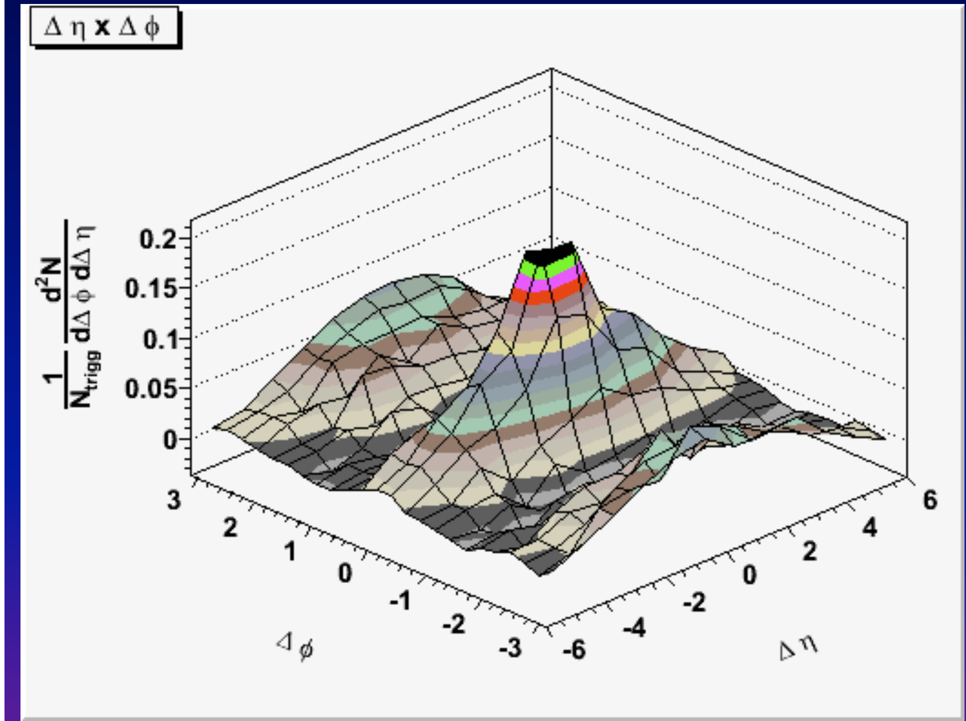
Neufeld and Mueller 0902.2950

AdS/CFT

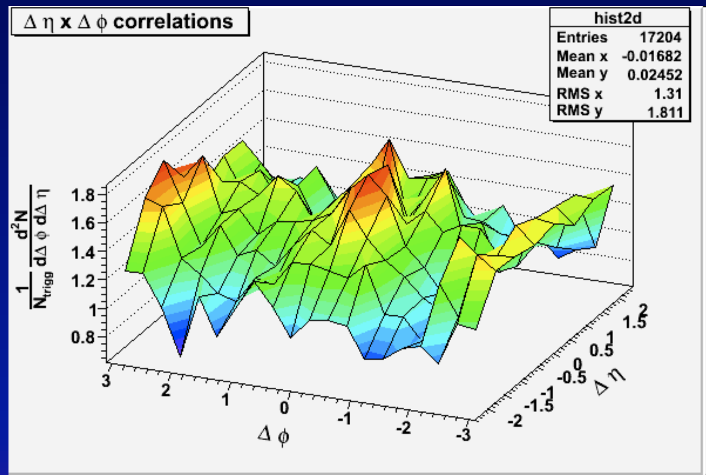
Possible Solution to Ridge

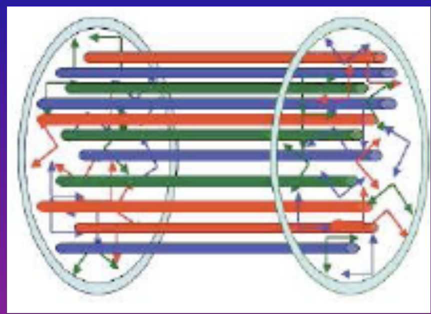
❖ Brazil group

Initial conditions Nexus → Hydro SPheRIO → Hadonization Cooper-Frye



Averaged initial conditions





Flux tube

+

fluctuations

Challenge

Theory:

- Towards quantitative calculations
  - Dynamical model
  - Jet quenching mechanism

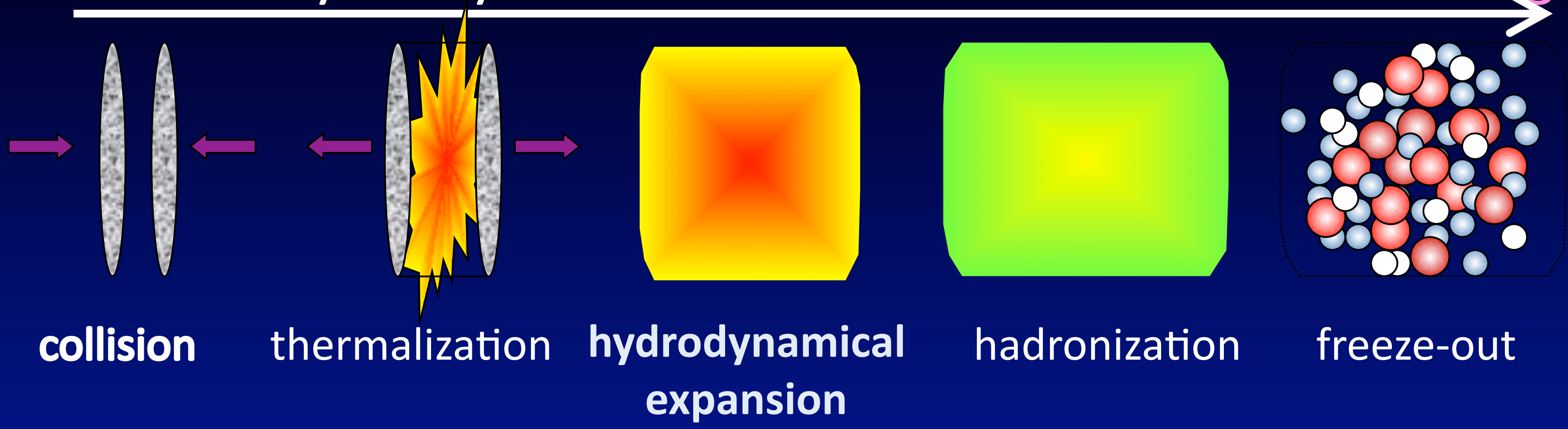
Phenomena:

- Azimuthal angle distribution

  Esumi-san's talk!
  - Reaction plane dependence?
  - Elliptic flow?
- Collisions energy dependence?

Toward More Realistic Dynamical Model

- Based on hydrodynamic models: Multi Module Modeling



Initial Conditions

- Event by event fluctuation
  - elliptic flow vs N_{part}
    - Hirano and Nara
  - Ridge
    - Brazil group

Hydrodynamics

- Viscosity
  - shear, bulk
- Equation of state
  - QCD critical point?

Freezeout process

- Hadronization –Recombination
- Final state interactions

Chiho Nonaka