3-D Hydro + Cascade Model at RHIC

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Contents

- Introduction
- 3-D Hydrodynamic Model
  - Results (single particle spectra, elliptic flow)
- 3-D Hydro + Cascade Model
  - Results (single particle spectra, elliptic flow)
- Comparison between pure hydro and hydro + UrQMD
- Summary

Introduction

- Success of Ideal Hydrodynamic Models at RHIC

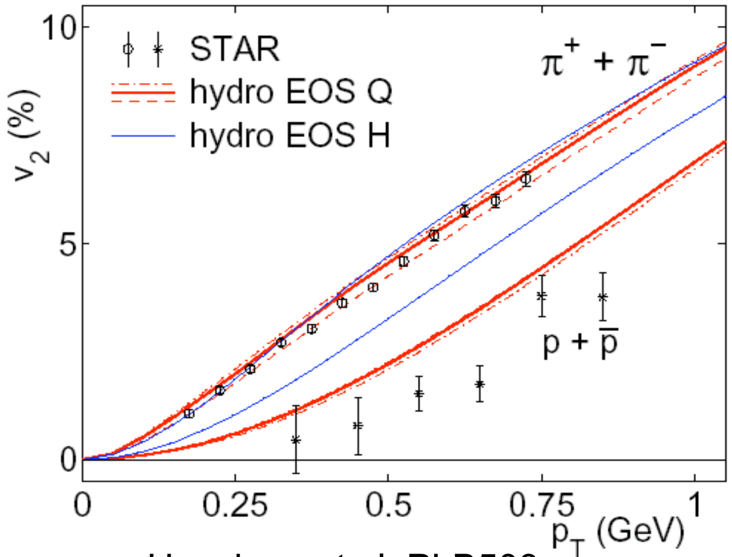
–Single particle spectra

P_T spectra up to ~ 2GeV

Huovinen, Kolb, Heinz, Hirano, Teaney, Shuryak, Hama, Morita, …….

– Strong Elliptic flow

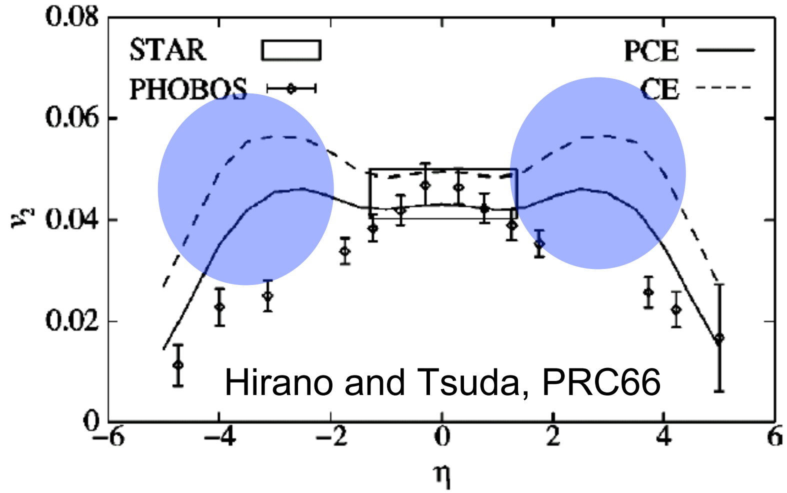
  • strong coupled QGP



Huovinen et.al, PLB503

However…

–Elliptic flow as a function of η



Hirano and Tsuda, PRC66

Discrepancy at large η:

•Insufficient thermalization?

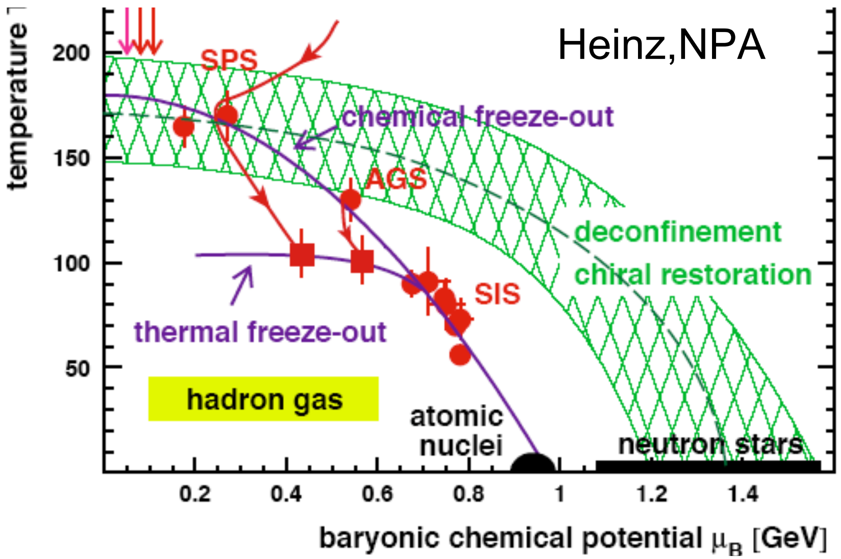
•Mean free path

•Viscosity effect?

→ ***Freezeout Process***

Freezeout process in Hydro

1. **Single freezeout temperature?**
   – Difference between chemical and thermal freezeout

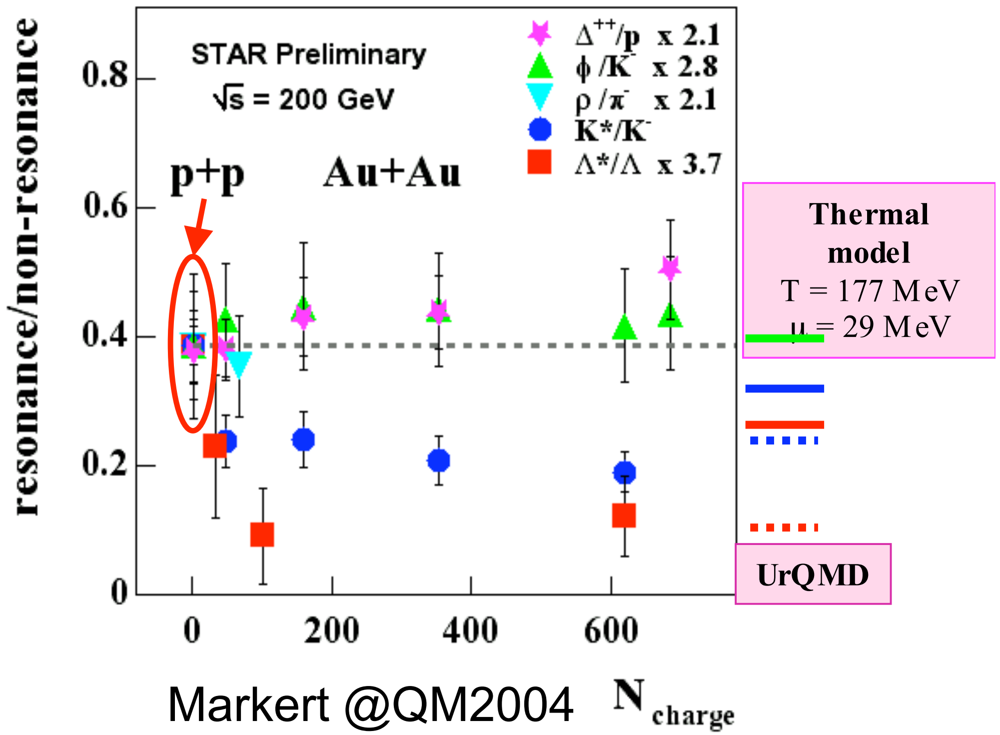


Possible solutions:

– Partial chemical equilibrium
  Hirano, Kolb, Rapp

– Hydro + Micro Model
  Bass, Dumitru, Teaney, Shuryak

2. **In UrQMD final state interactions are included correctly.**



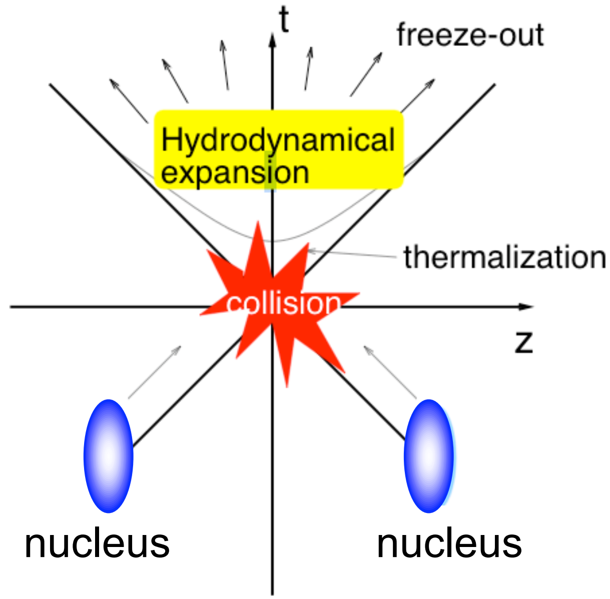
Markert @QM2004

⇨ 3D-Hydro + Cascade Model

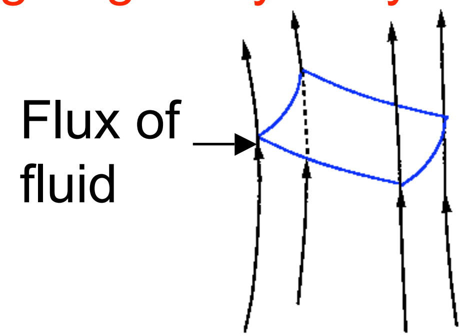
Step1. 3-D Hydro

3-D Hydrodynamic Model

- Hydrodynamic equation
  $$\partial_\mu T^{\mu\nu} = 0 \qquad T^{\mu\nu}$$: 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
- Algorithm
  - Focusing on the conservation law
  $$\partial_\mu (s(T,\mu)u^\mu) = 0,\ \partial_\mu (n_B(T,\mu)u^\mu) = 0$$



Lagrangian hydrodynamics



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 (pure hydro)

    τ_0=0.6 fm/c

    ε_{max}=43 GeV/fm^3, n_{Bmax}=0.15 fm^{-3}

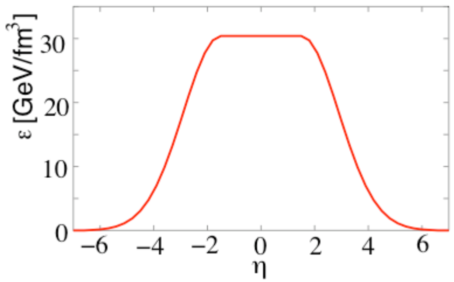
    η_0=0.5 σ_η=1.5
  - Flow

    $v_L=\eta$ (Bjorken's solution); v_T=0
- Equation of State
  - 1st order phase transition

    Bag Model + Exclude volume model
- Freezeout Temperature

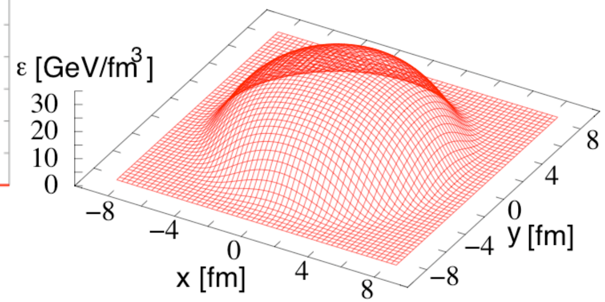
  T_f=110 [MeV]

$H(\eta)$:



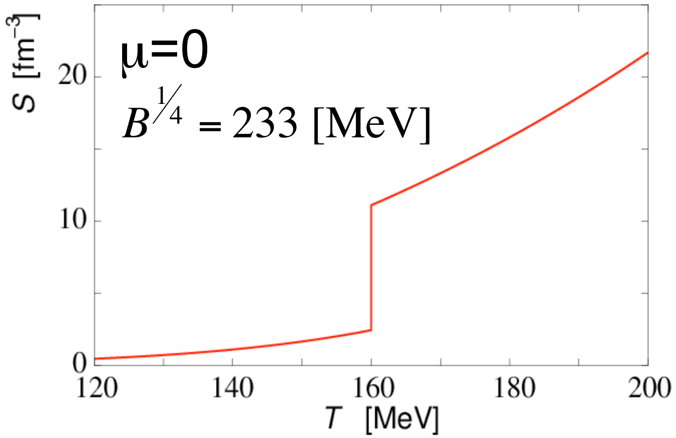
$W(x,y;b)$:

Wounded Nuclear Model



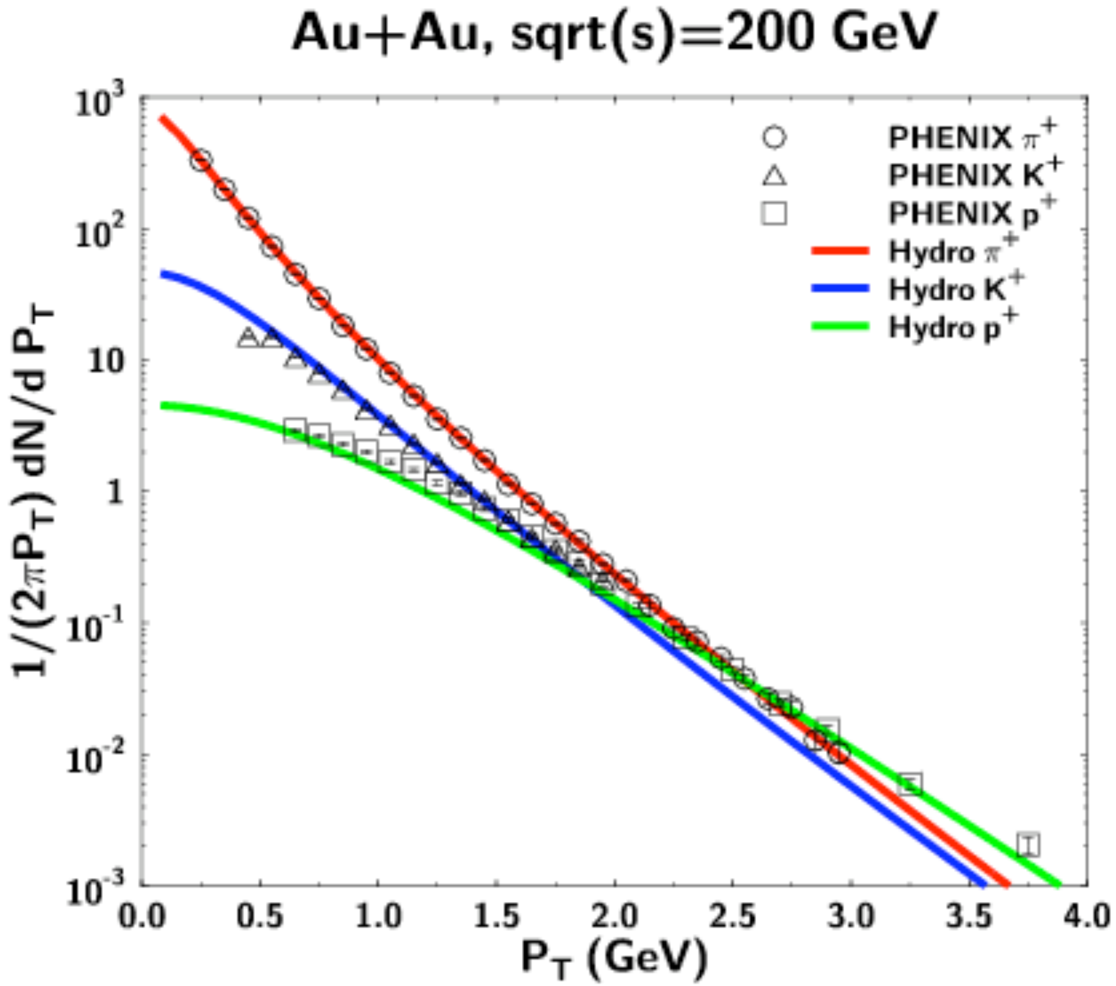
Different from hydo + UrQMD !

EOS(entropy density)



Results

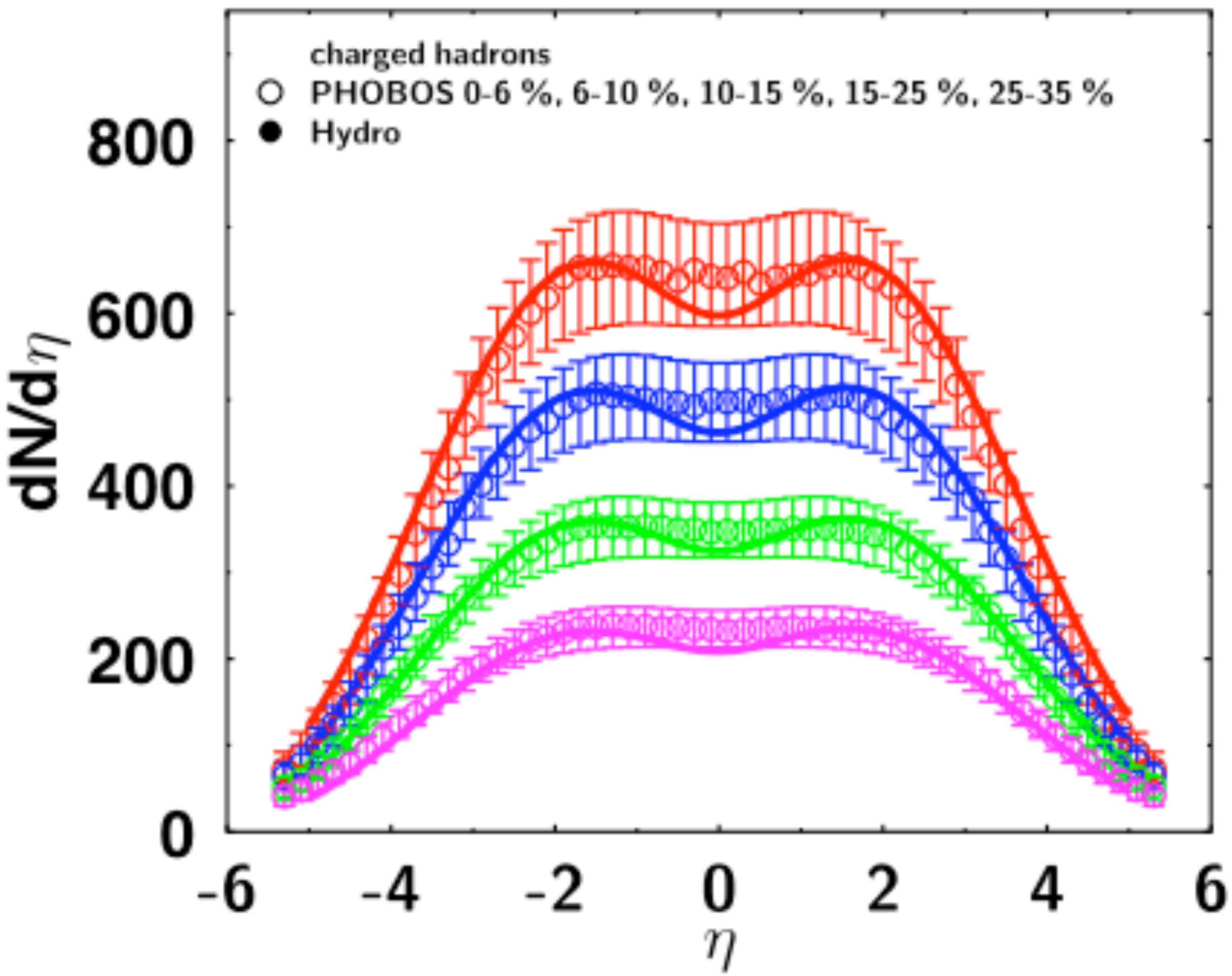
- P_T Spectra



T_f=110 MeV
Normalization of K and p: ratio at chemical at T_{chem}
Heinz and Kolb, hep-ph/0204061

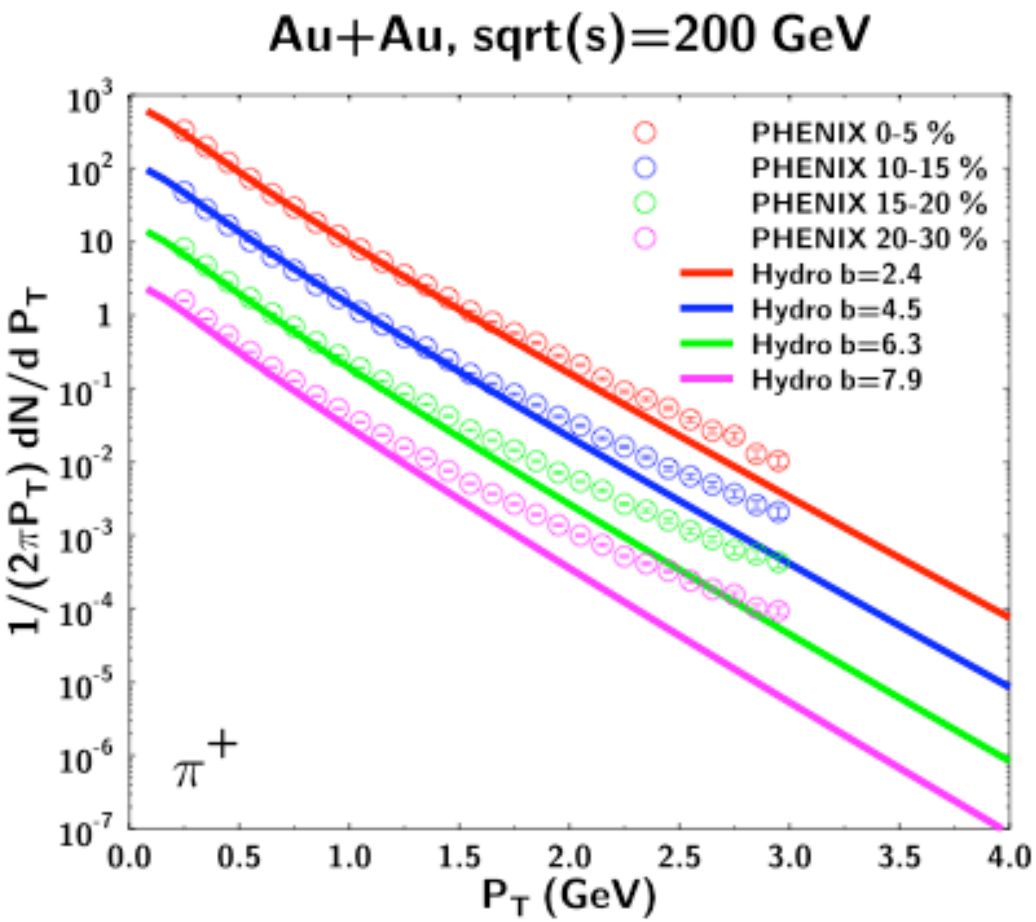
Results

- Impact parameter dependence of rapidity distribution



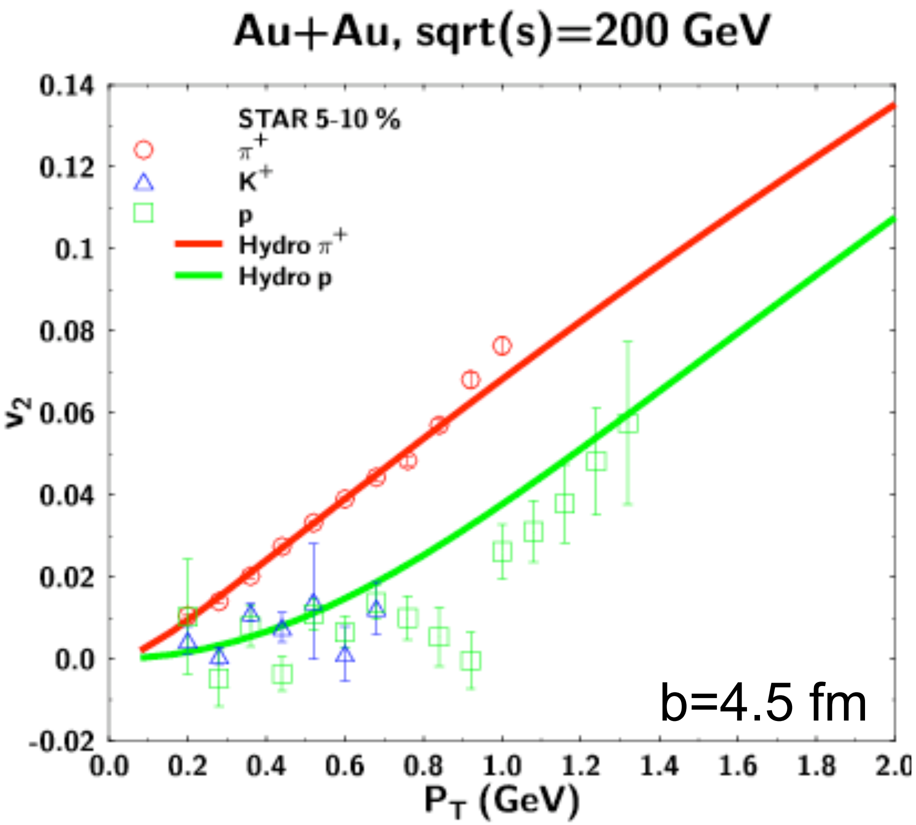
Results

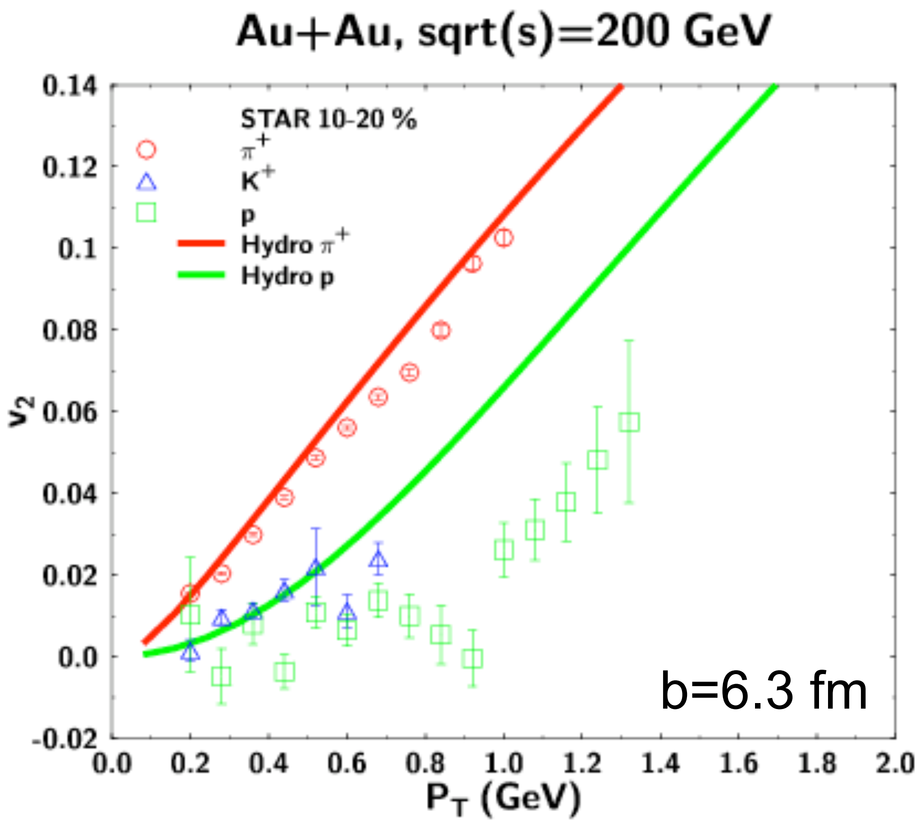
- Impact parameter dependence of P_T spectra



Results

- Elliptic Flow





•b=4.5 fm: consistent with experimental data

•b=6.3 fm: proton ➔ overestimate

Step2. 3-D Hydro + UrQMD

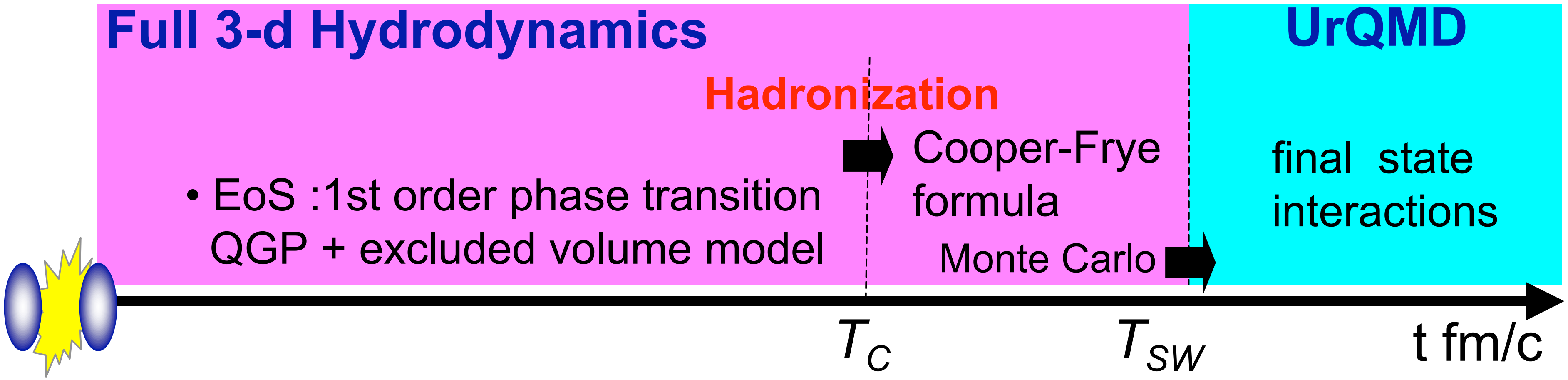
3D-Hydro + UrQMD Model

Bass and Dumitru, PRC61,064909(2000)
Teaney et al, nucl-th/0110037

Key:

- Hadron Phase: viscosity effect
- Freezeout process:
  - Chemical freezeout & thermal freezeout

➔3D-Hydro +UrQMD
  - Treatment of freeze-out is determined by mean free path.
  - Brake up thermalization: viscosity effect



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

Parameters

- Initial Conditions
  - Energy density

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

    $n_B(x,y,\eta) = n_{Bmax} W(x,y;b) H(\eta)$
  - Parameters (pure hydro)

    τ_0=0.6 fm/c

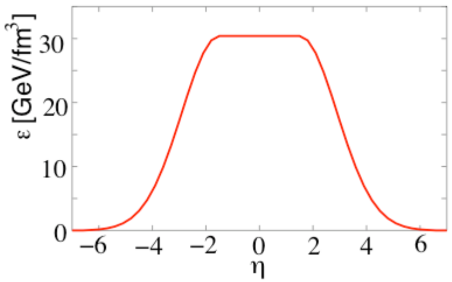
    ε_{max}=35 GeV/fm^3, n_{Bmax}=0.15 fm^{-3}

    η_0=0.5 σ_η=1.5
  - Flow

    $v_L=\eta$ (Bjorken's solution); $v_T=0$
- Switching temperature

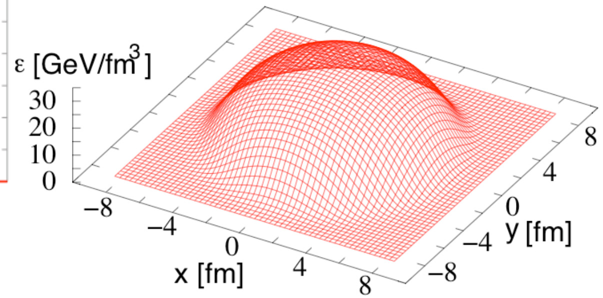
  T_f=150 [MeV]

$H(\eta)$:



$W(x,y;b)$:

Wounded Nuclear Model

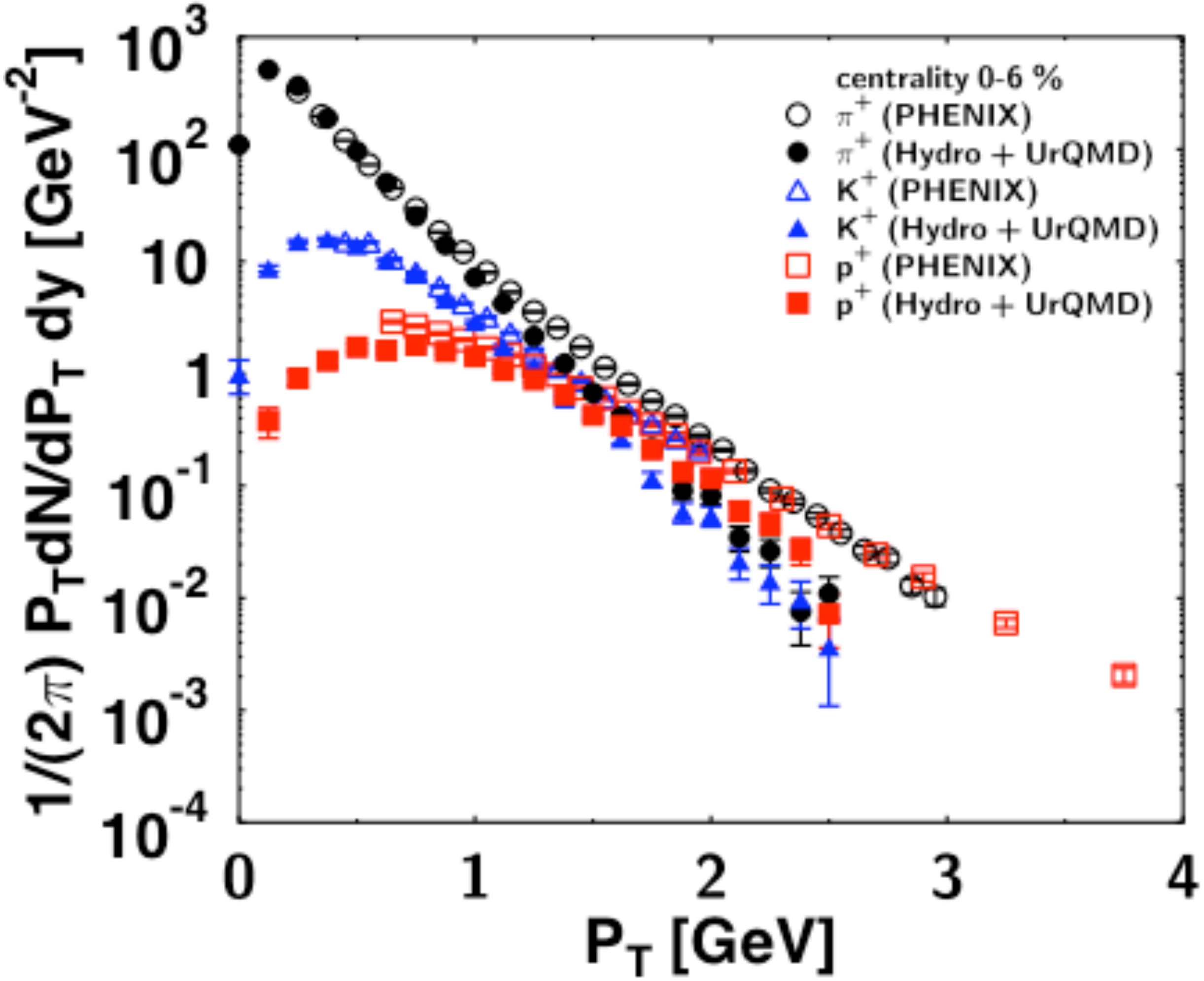


Different from Pure Hydro !

	hydro	Hydro+ UrQMD
τ_0(fm)	0.6	0.6
ε_{max}(GeV/fm^3)	43	35
n_{Bmax}(fm^{-3})	0.15	0.15
η_0,σ_η	0.5, 1.5	0.5, 1.5

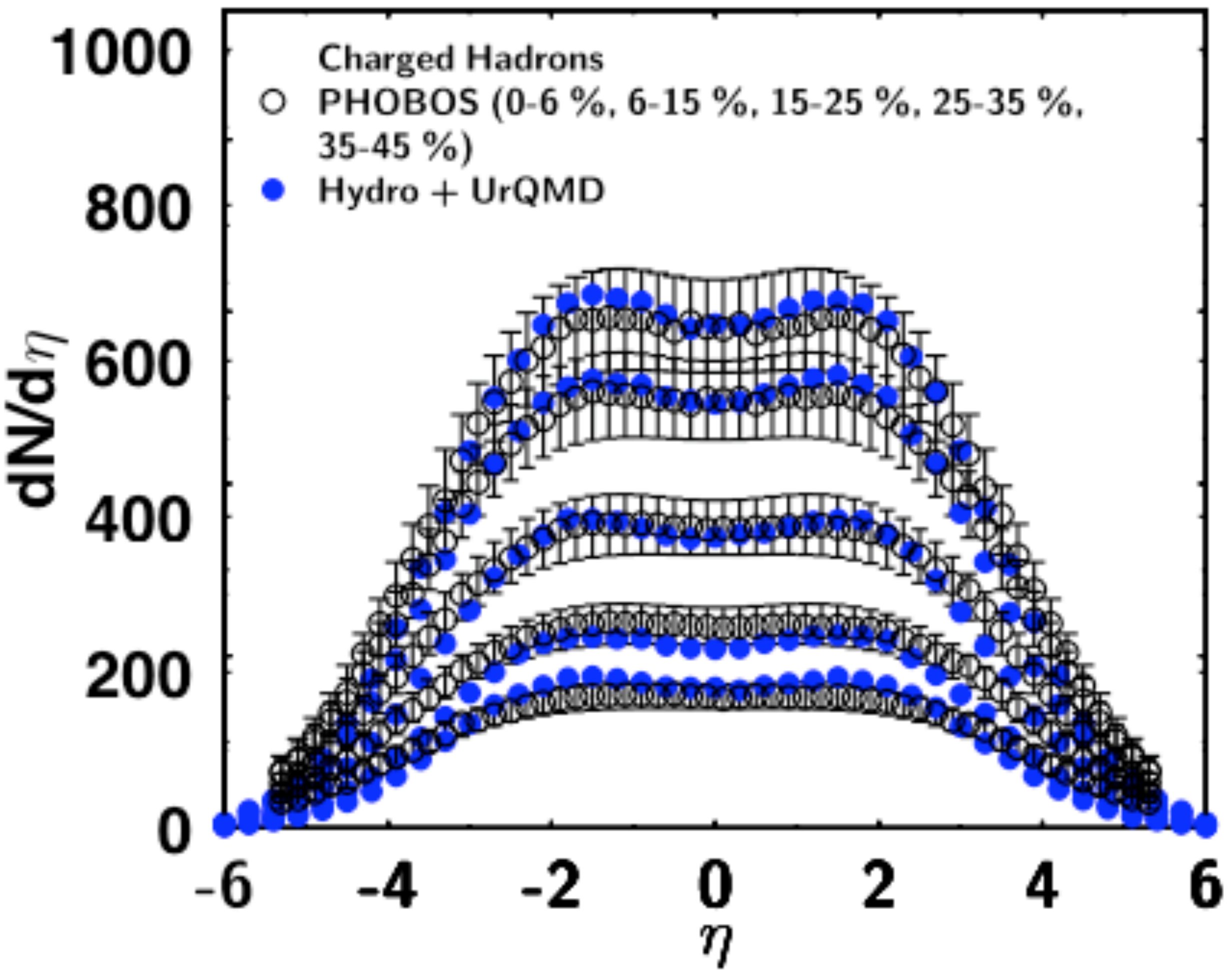
Results

- P_T spectra at central collisions



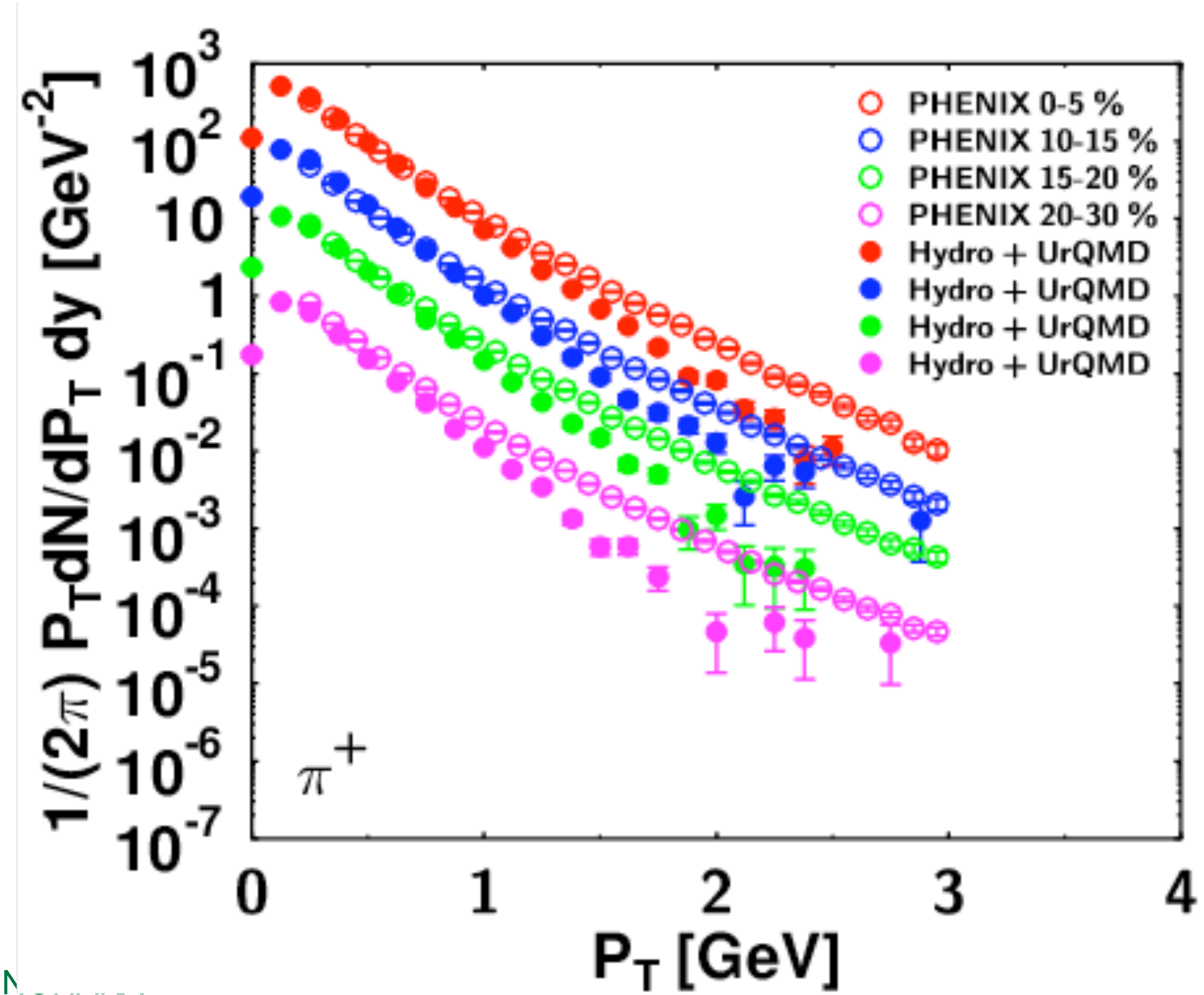
Results

- Impact parameter dependence of rapidity distributions



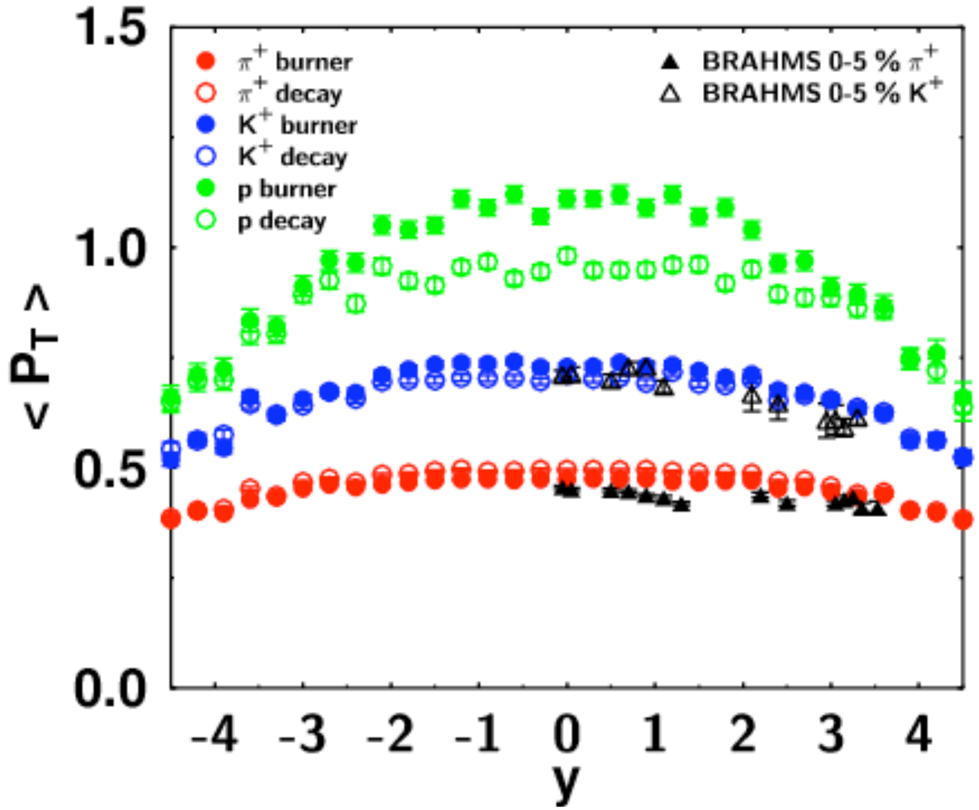
Results

- Impact parameter dependence of P_T



Reaction Dynamics in UrQMD I

- Hadron Interactions

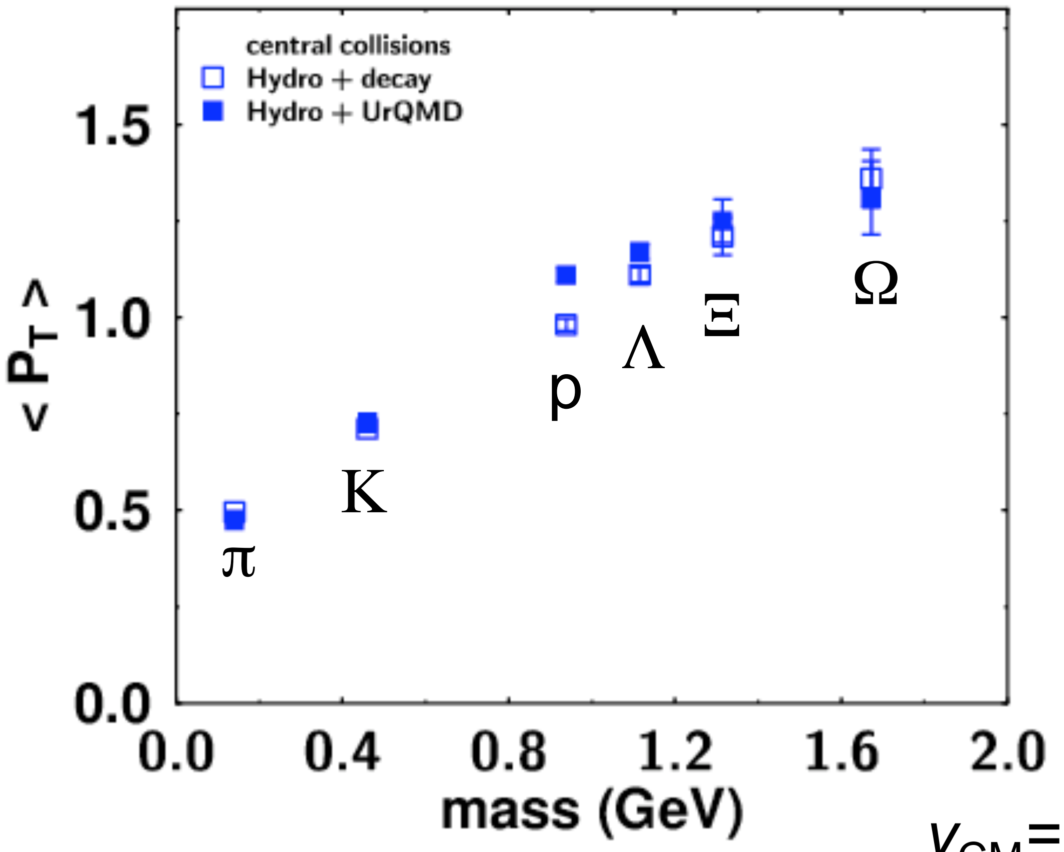


Pion wind

- π decrease
- K,p increase
- protons earn large P_T

Reaction Dynamics in UrQMD II

- $<P_T>$ vs mass



$y_{CM}=0$

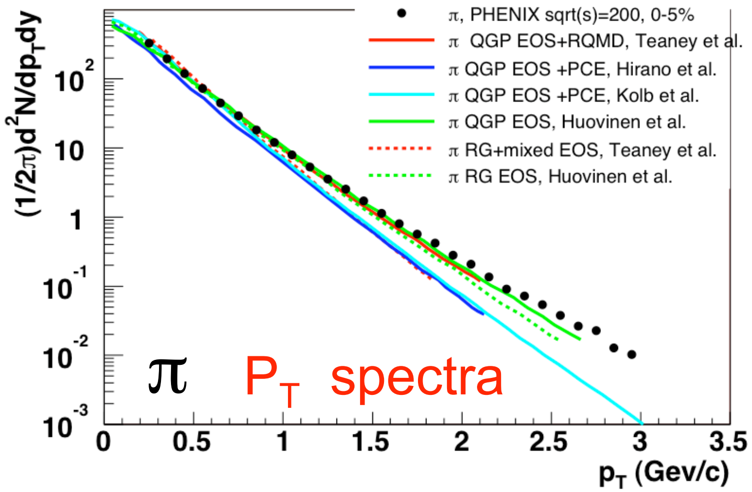
Summary

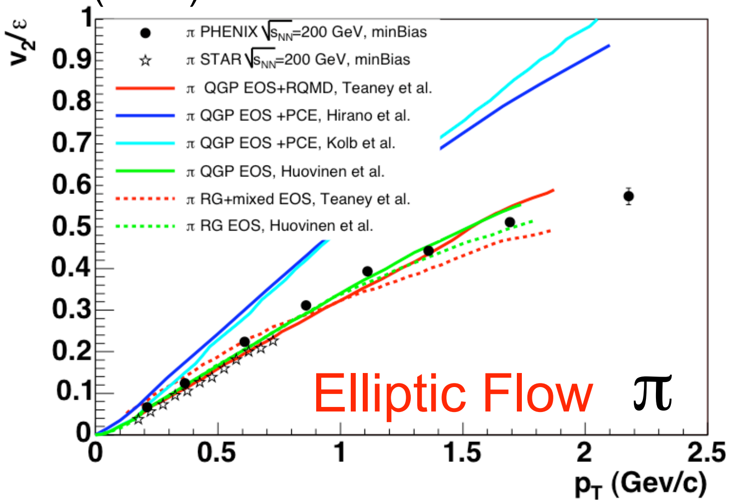
- 3-D Hydrodynamic Model
  - Single particle distribution
    - Centrality dependence
  - Elliptic flow
  - Low T_f : ✔single spectra, elliptic flow, ✖hadron ratios
    - ➔Necessity of improvement of freezeout process in Hydro
- 3-D Hydro + UrQMD
  - Single particle distribution
    - Centrality dependence
  - Different initial conditions from pure Hydro
  - Hadron ratios 🡐Switching temperature from Hydro to UrQMD
  - Reaction dynamics in UrQMD
- Work in progress
  - Elliptic Flow by Hydro + UrQMD
  - EoS dependence: ex. lattice QCD
  - Initial conditions: parametrization?
  - Switching temperature
  - HBT ?

Backup

Hydrodynamic Models

Au + Au $\sqrt{s_{NN}} = 200$ GeV PHENIX:Nucl.Phys. A757 (2005) 184



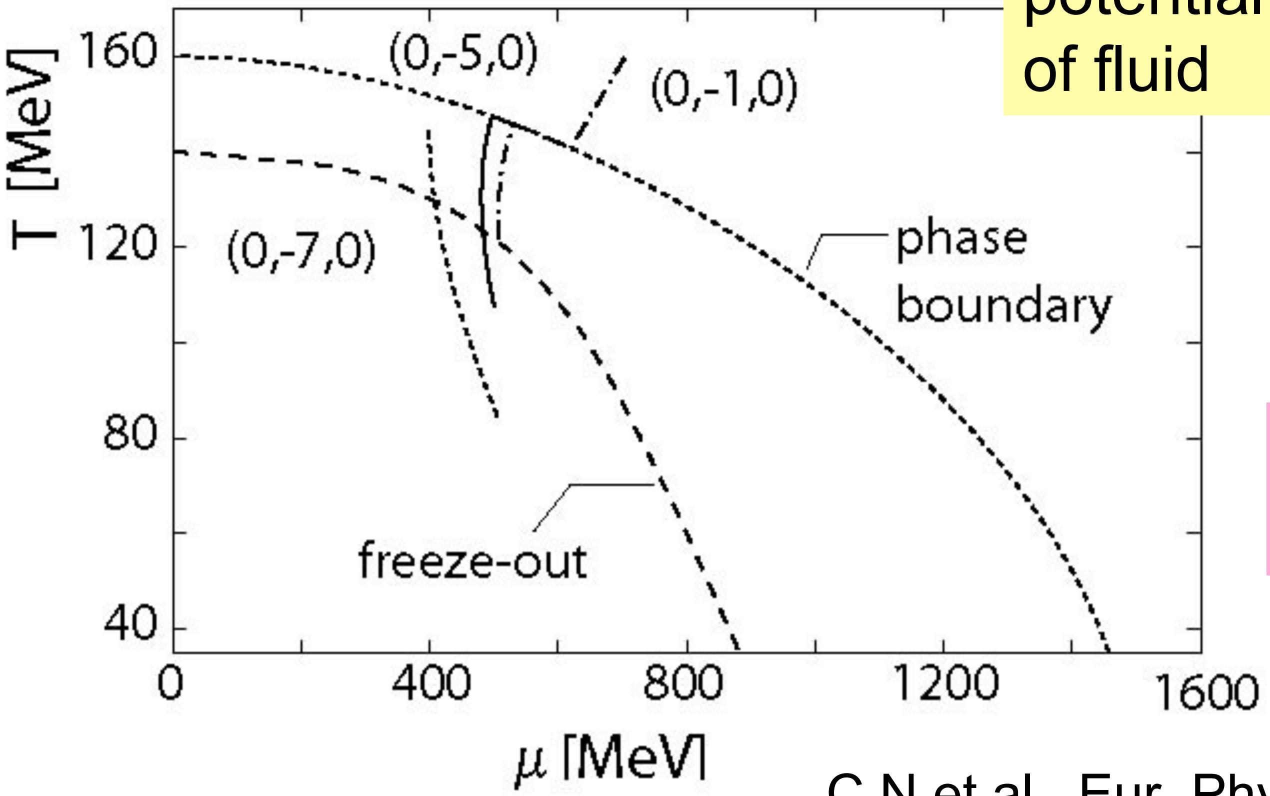


Ref.	Initial Conditions: Initial Cond. ε(GeV/fm³)or s(fm⁻³)	τ_0 (fm/c)	EoS: Latent heat (GeV/fm³)	Freeze-out: Hadronic stage	T_f (MeV)
[1]	23(ε)(eWN)	0.6	1.15	Full equil.	120
[2]	110(s)(0.75sWN+0.25sBC)	0.6	1.15	Partial chemical equil.	100
[3]	35(ε)(eBC)	0.6	1.7	Partial chemical equil.	100,120,140
[4]	16.7(ε)(sWN)	1.0	0.8	RQMD	100

[1]Huovinen et.al., PLB(130) [2]Kolb et.al. PRC, [3]Hirano et.al.PRC(130), [4]Teaney et al.

Trajectories on the Phase Diagram

- Lagrangian hydrodynamics



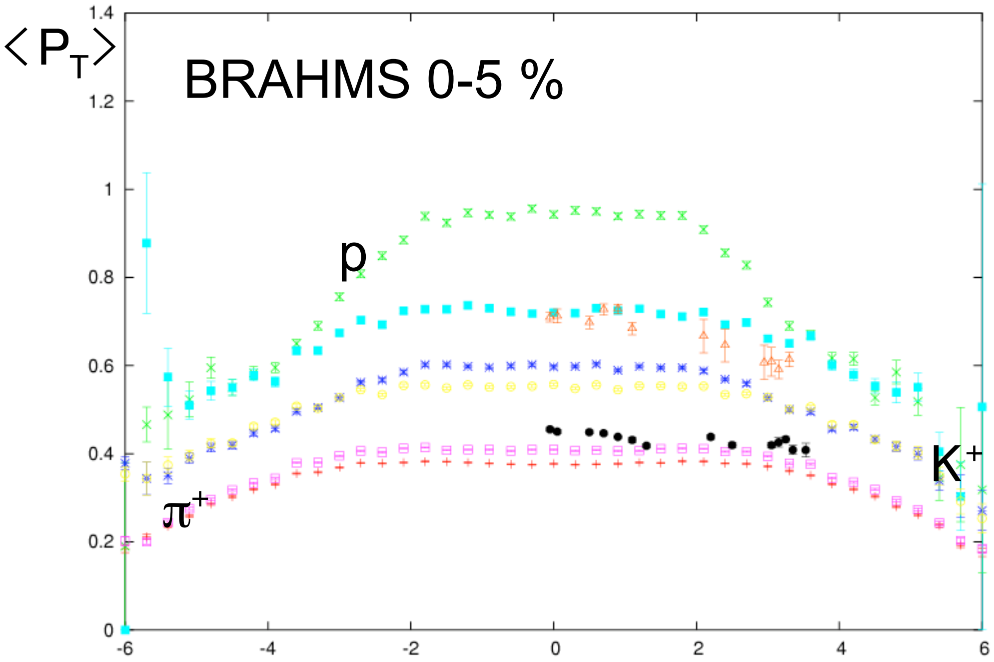
temperature and chemical potential of volume element of fluid

effect of phase transition

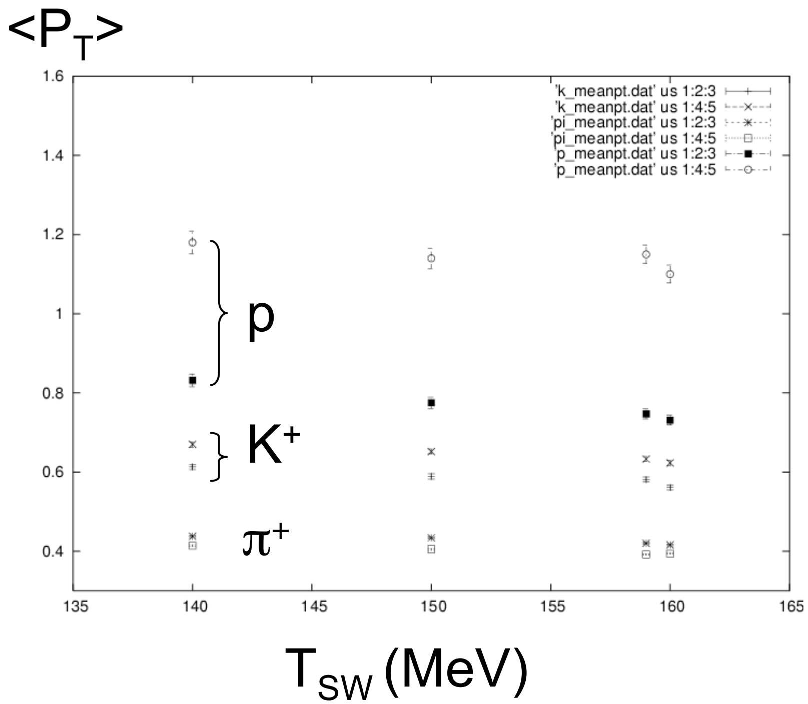
C.N et al., Eur. Phys.J C17,663(2000)

Hydro vs. Hydro + UrQMD

- Hadron Interactions



- π decrease
- K,p increase
- proton earn large P_T



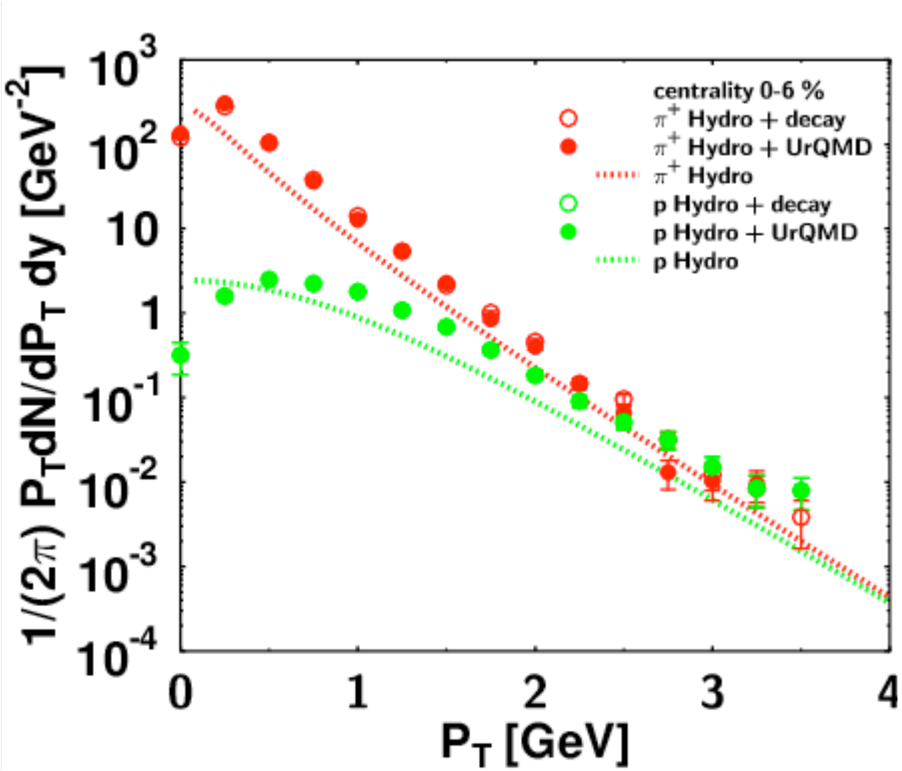
- <P_T> increases as T_{SW} increases

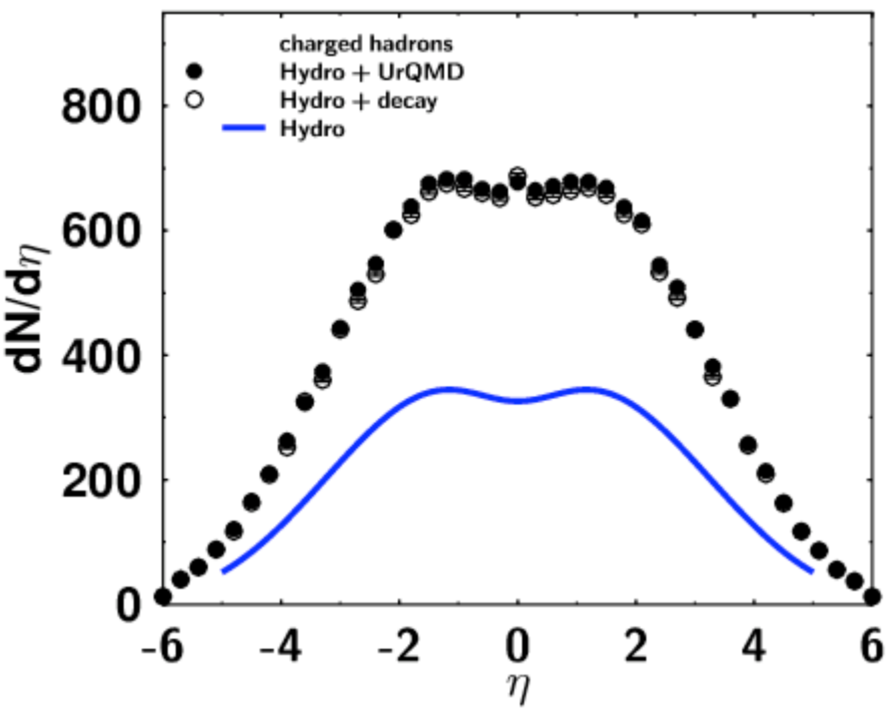
Hydro + UrQMD

- Large <P_T> ⇒ Low v_2

(hadron interactions)

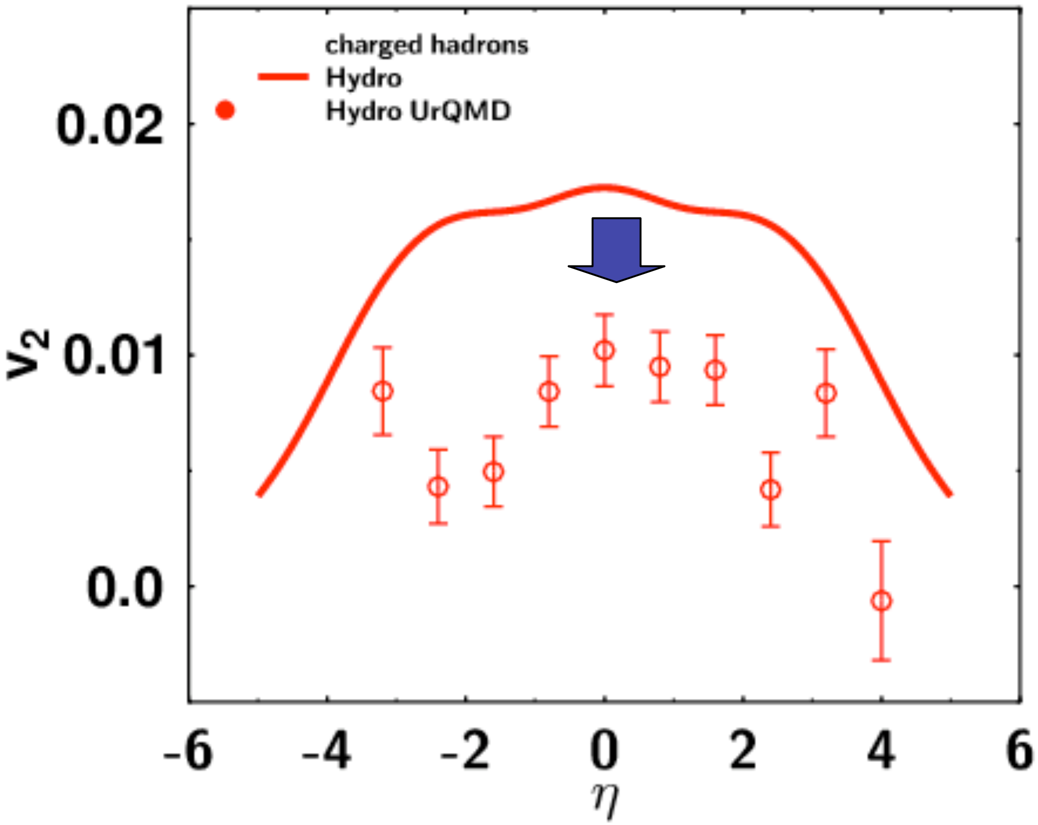
Hydro vs Hydro+ UrQMD





Elliptic Flow

- Hadron Interaction reduces elliptic flow



- Switching temperature T_{sw}=150 MeV