Space-time Evolution of Bulk QCD Matter at RHIC

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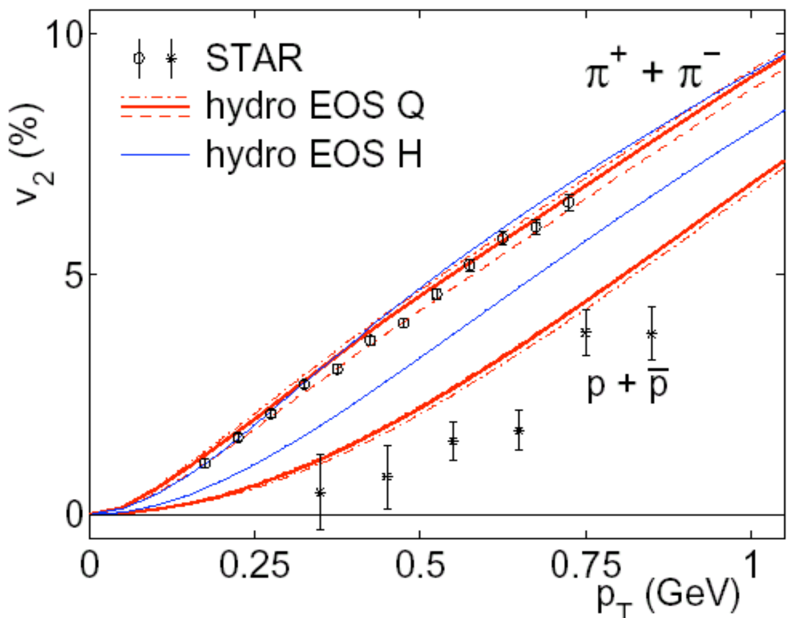
In collaboration with Steffen A. Bass (Duke University & RIKEN BNL)

June 7@RHIC AGS annual users' meeting

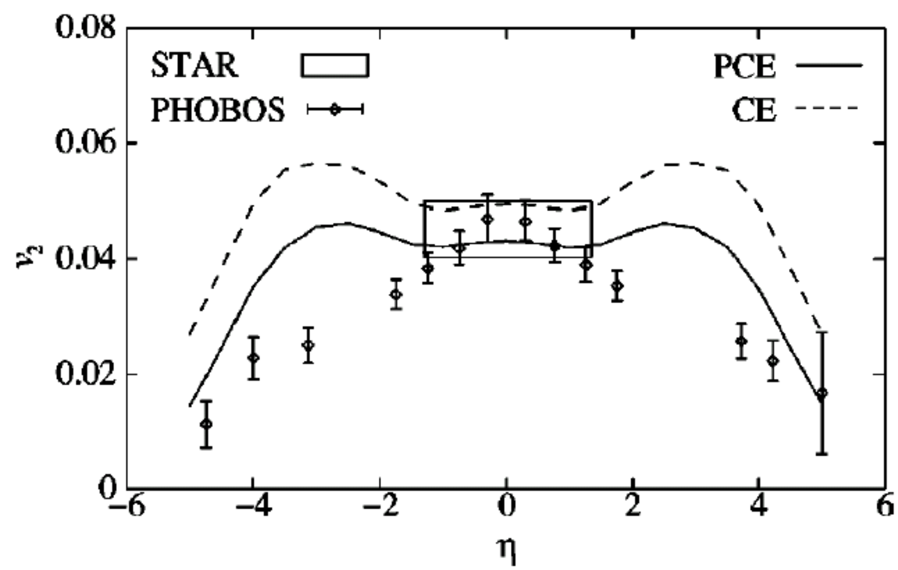
Hydrodynamic Models at RHIC

- Success of Perfect Hydrodynamic Models at RHIC
  - Single particle spectra
    Huovinen, Kolb, Heinz, Hirano, Teaney, Shuryak, Hama, Morita, …….
  - Strong elliptic flow
    Strong coupled (correlated) QGP



Huovinen et.al, PLB503 at mid rapidity

- However….
  – Elliptic flow vs. η



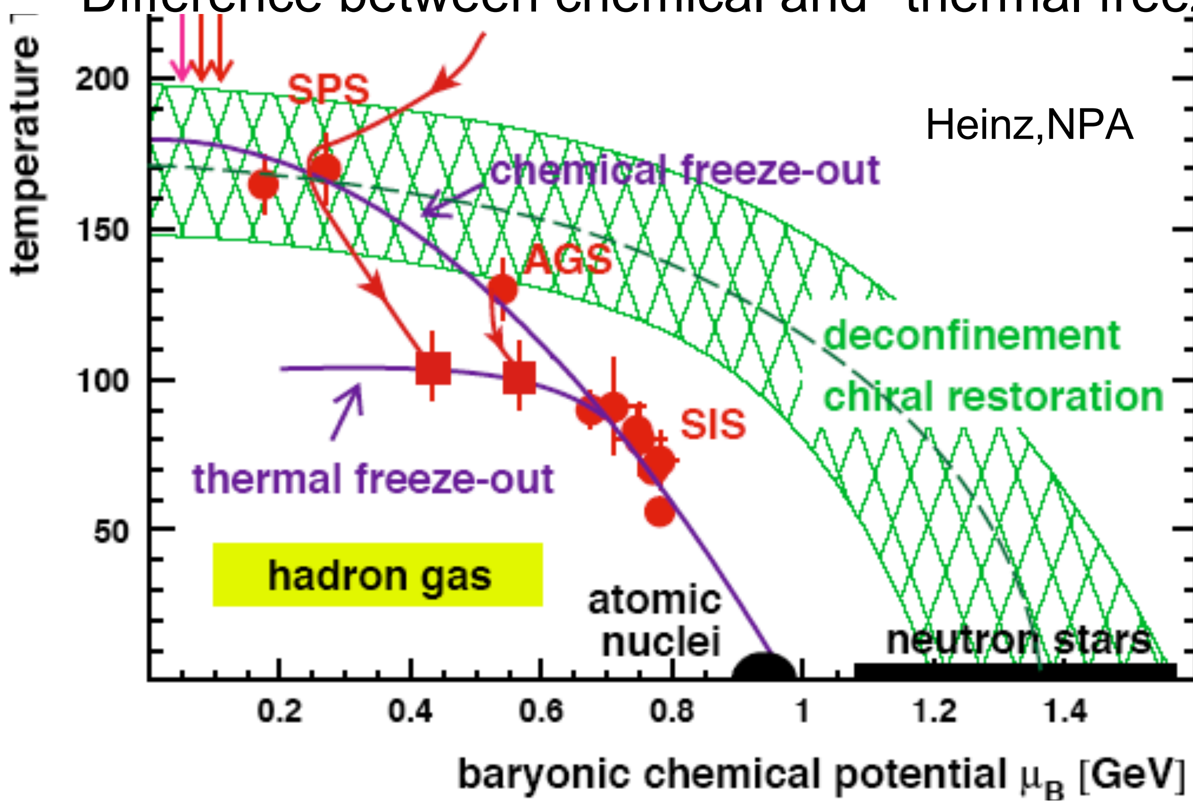
Hirano and Tsuda, PRC66

Discrepancy at large η:
•Insufficient thermalization?
•Viscosity effect?
•Simple freezeout process?

→ *•freezeout*
•viscosity

Freezeout process in Hydro

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



Heinz,NPA

- chemical freezeout
  statistical model
  T_{ch} ~170 MeV
  hadron ratio

- thermal freezeout
  hydro
  T_f ~ 110~140 MeV

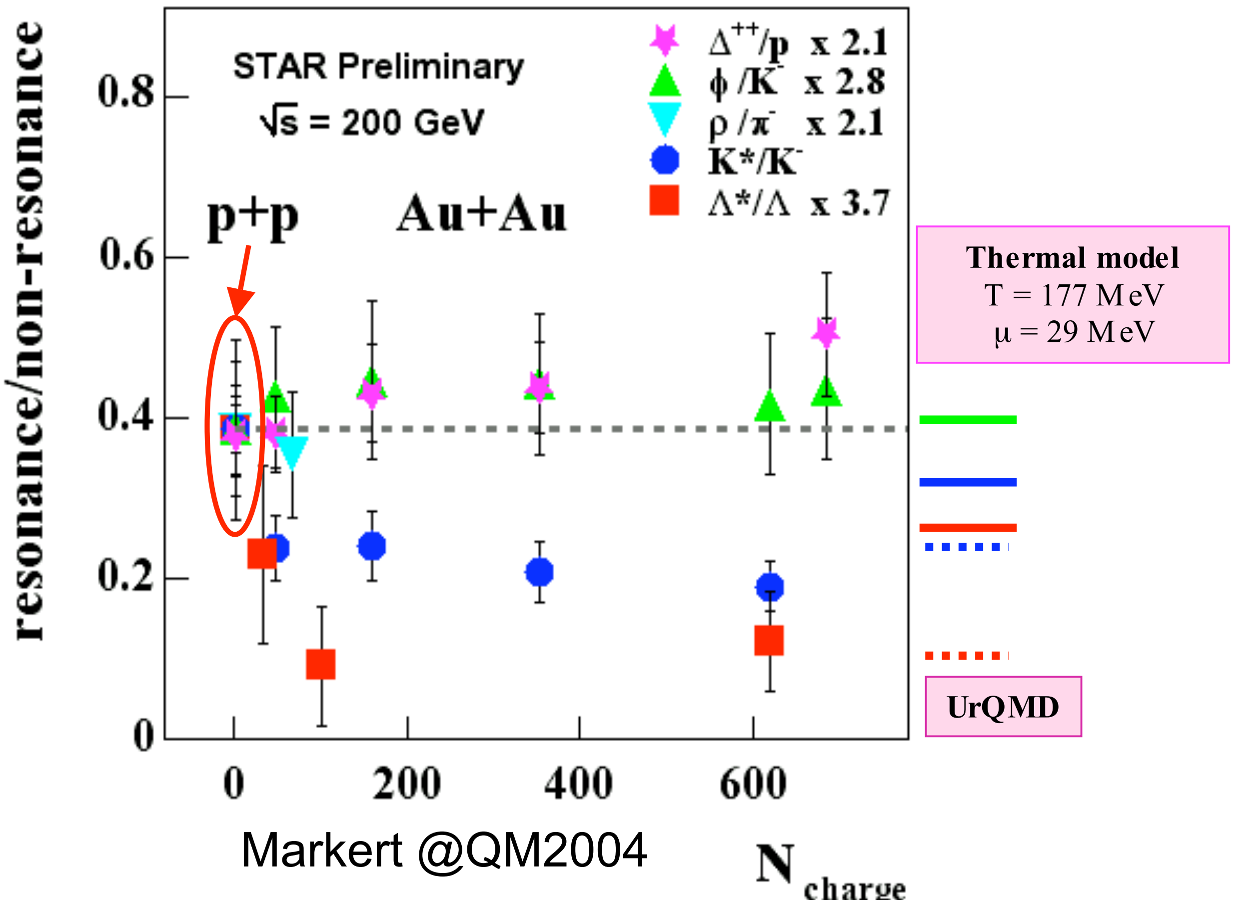
Possible solutions:

– Partial chemical equilibrium (PCE)
  Hirano, Kolb, Rapp

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

Final State Interactions

2. In UrQMD final state interactions are included correctly.



3D-Hydro +UrQMD

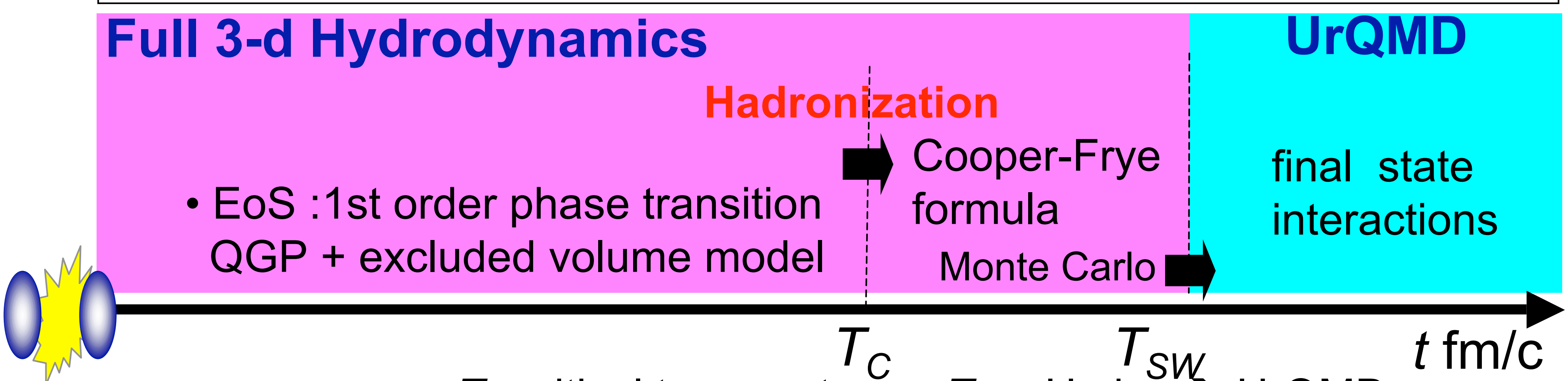
3D-Hydro + UrQMD Model

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

Key:

– Hadron phase: viscosity effect
– Freezeout process:
  - Chemical freezeout & thermal freezeout
  - Final state interactions

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



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

3-D Hydrodynamic Model

- Relativistic hydrodynamic equation

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

  – Baryon number conservation

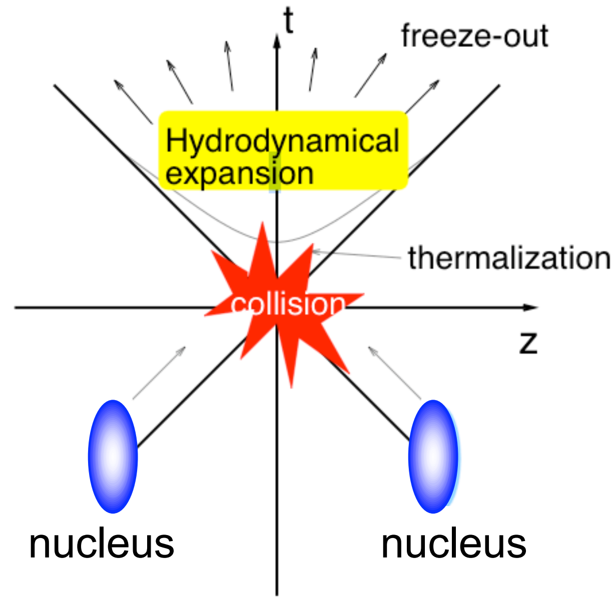
$$\partial_\mu (n_B(T,\mu)) = 0$$

- Coordinates

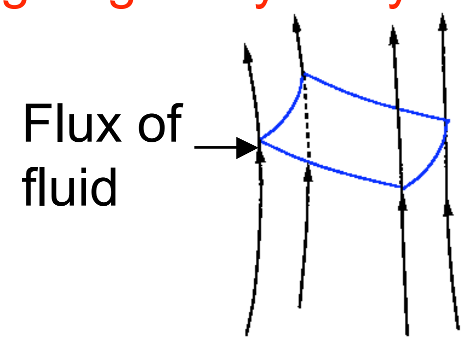
$$(\tau, x, y, \eta) : \tau = \sqrt{t^2 - z^2}, \eta = \tanh^{-1}\left(\frac{z}{t}\right)$$

- Lagrangian hydrodynamics
  – Tracing the adiabatic path of each volume element
  – Effects of phase transition on observables
  – Computational time
  – Easy application to LHC
- Algorithm
  – Focusing on the conservation law

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



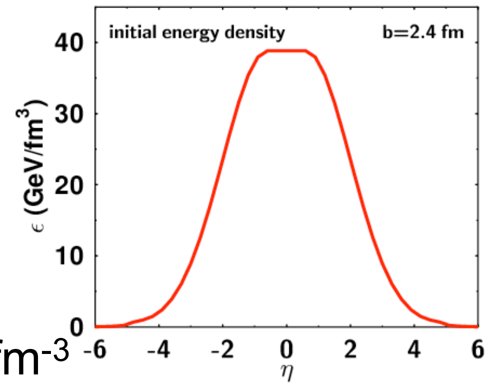
Lagrangian hydrodynamics



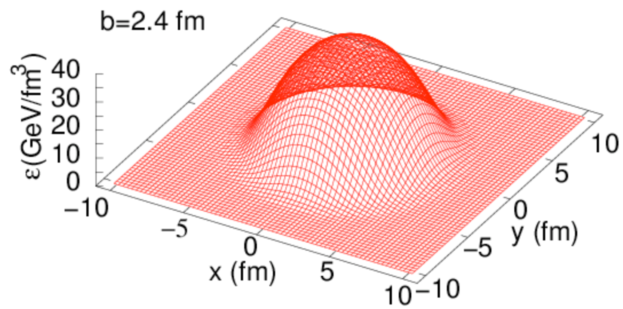
Parameters

- 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
    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
- Switching temperature
  T_{SW}=150 [MeV]

•longitudinal direction



•transverse plane

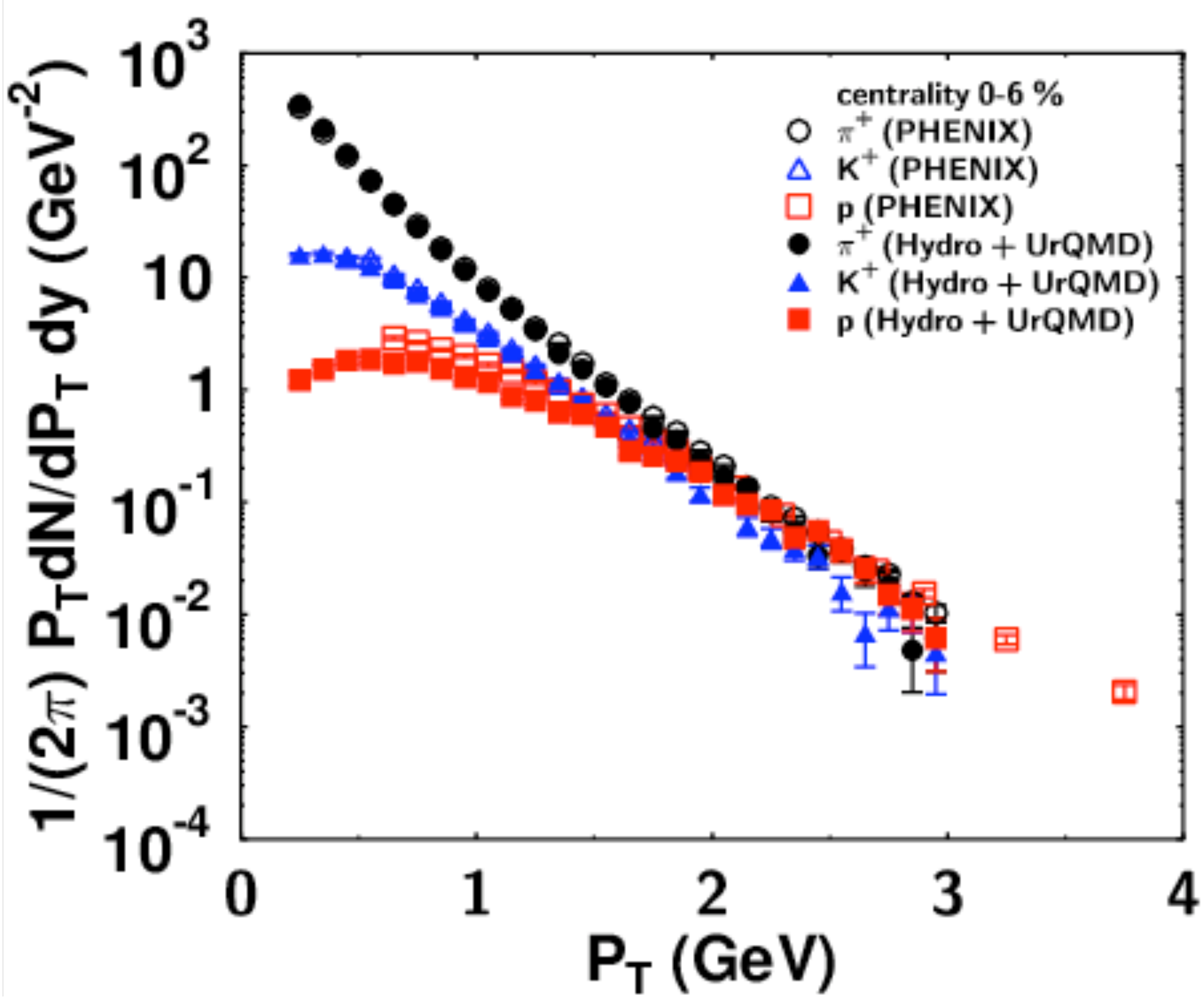


Different from Pure Hydro !

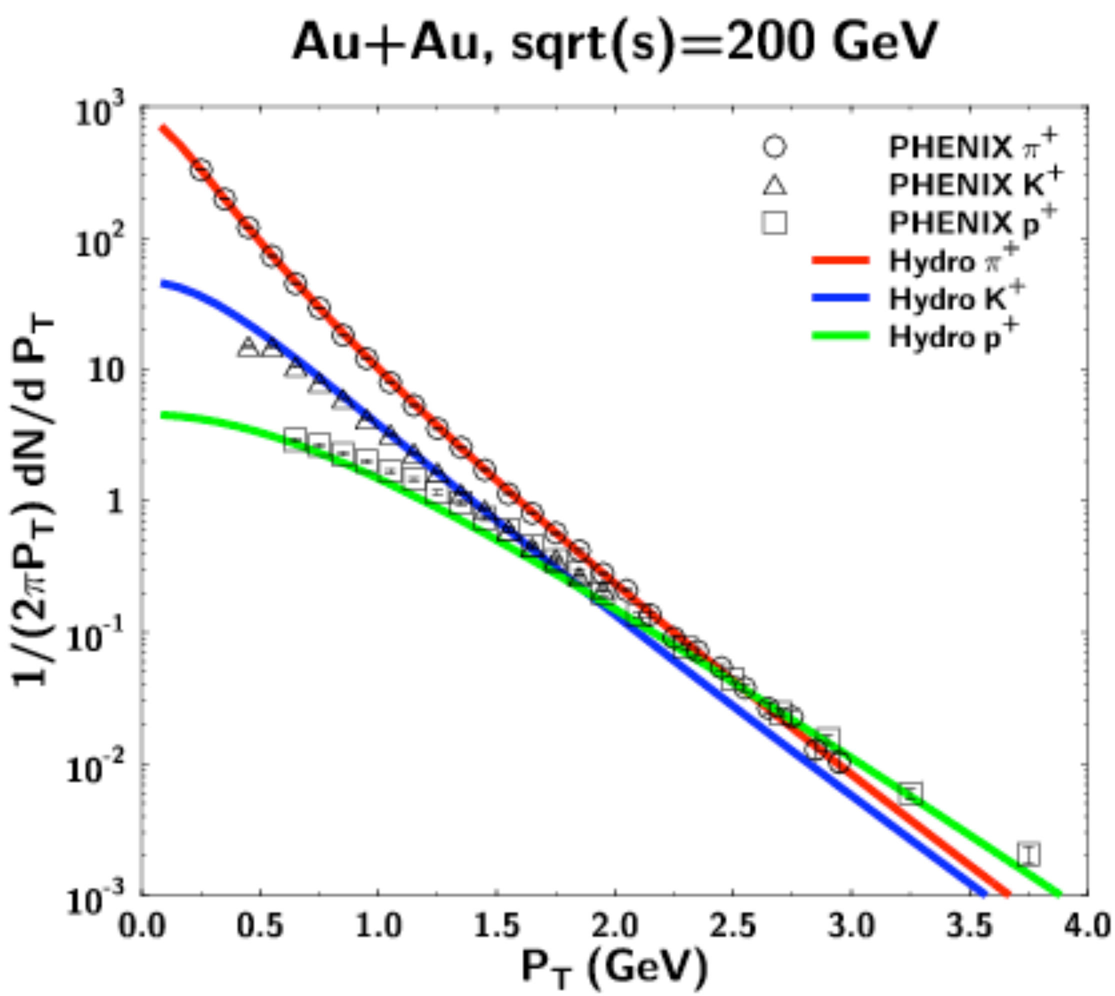
	hydro	Hydro+ UrQMD
τ_0(fm)	0.6	0.6
ε_{max}(GeV/fm^3)	55	40
n_{Bmax}(fm^{-3})	0.15	0.15
η_0,σ_η	0.5, 1.5	0.5, 1.5

P_T spectra

- P_T spectra at central collisions



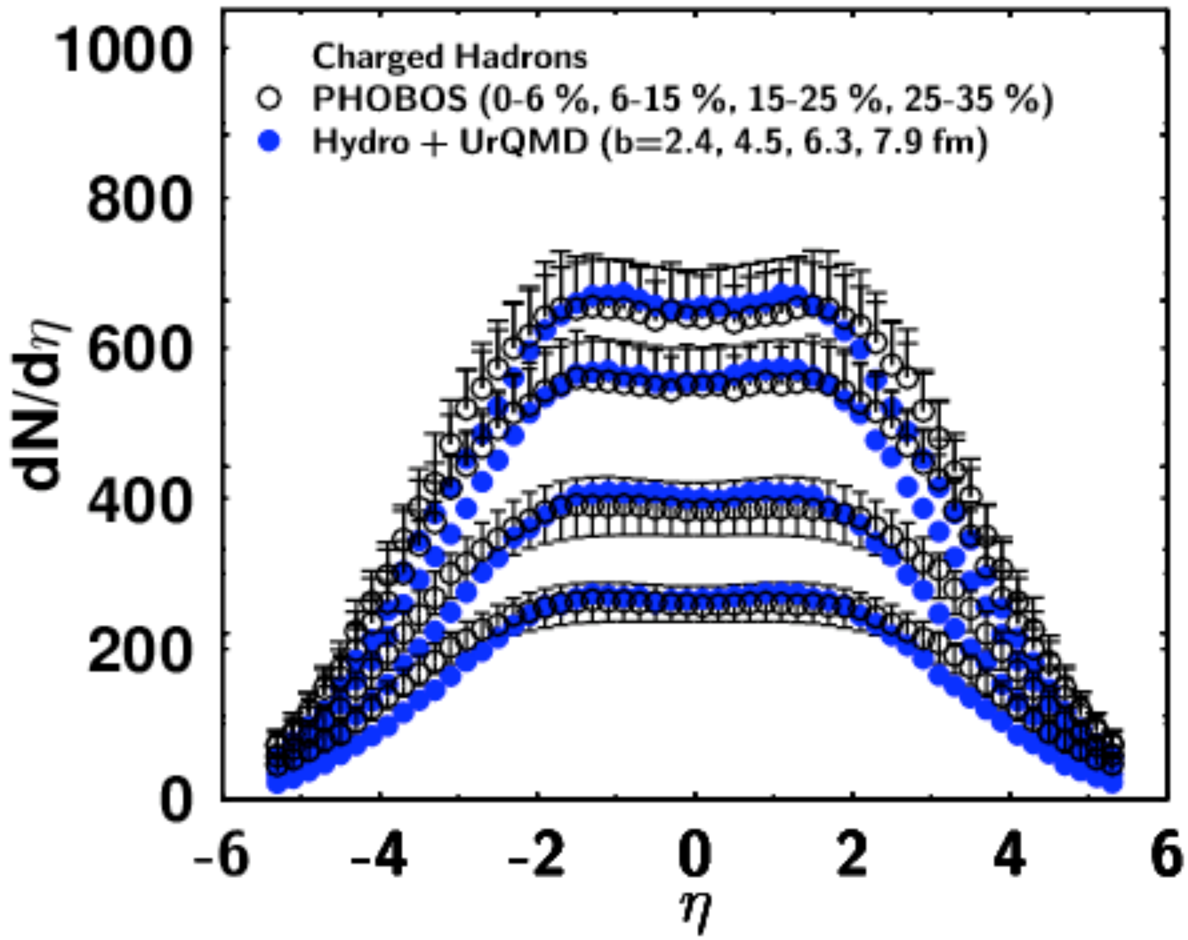
P_T Spectra (Pure Hydro)



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

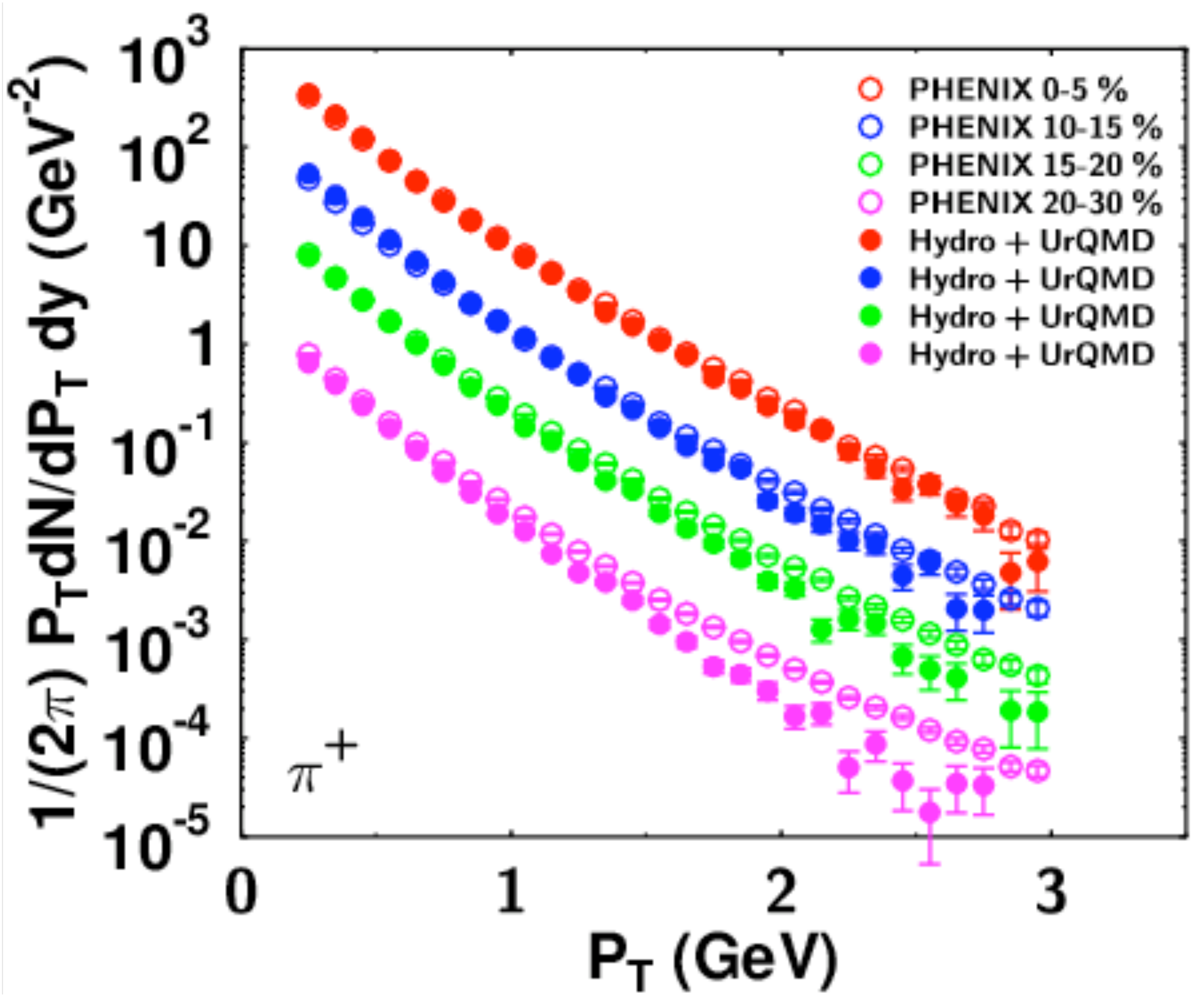
Rapidity Distribution

- Impact parameter dependence of rapidity distributions



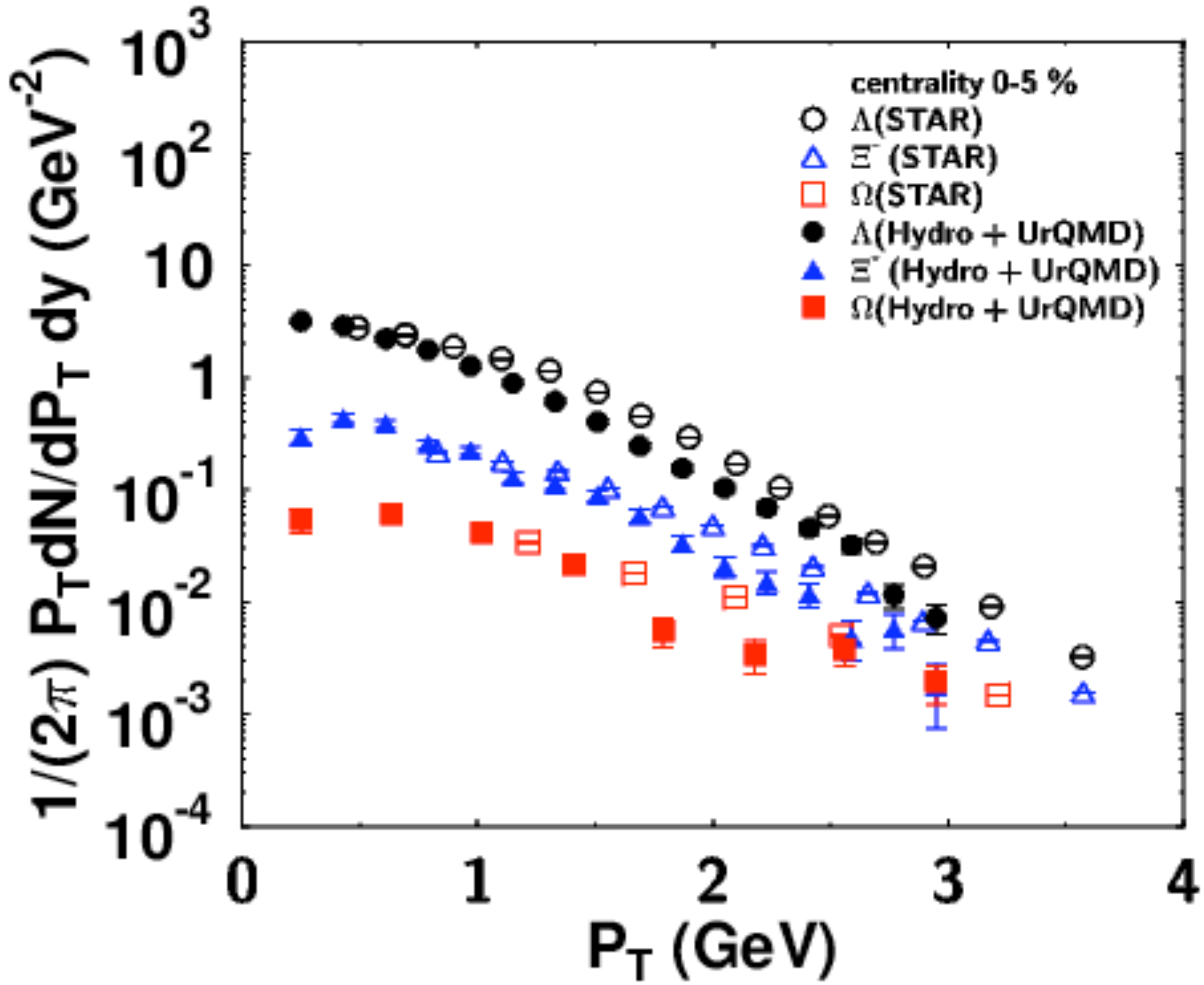
Centrality Dependence

- Impact parameter dependence of P_T



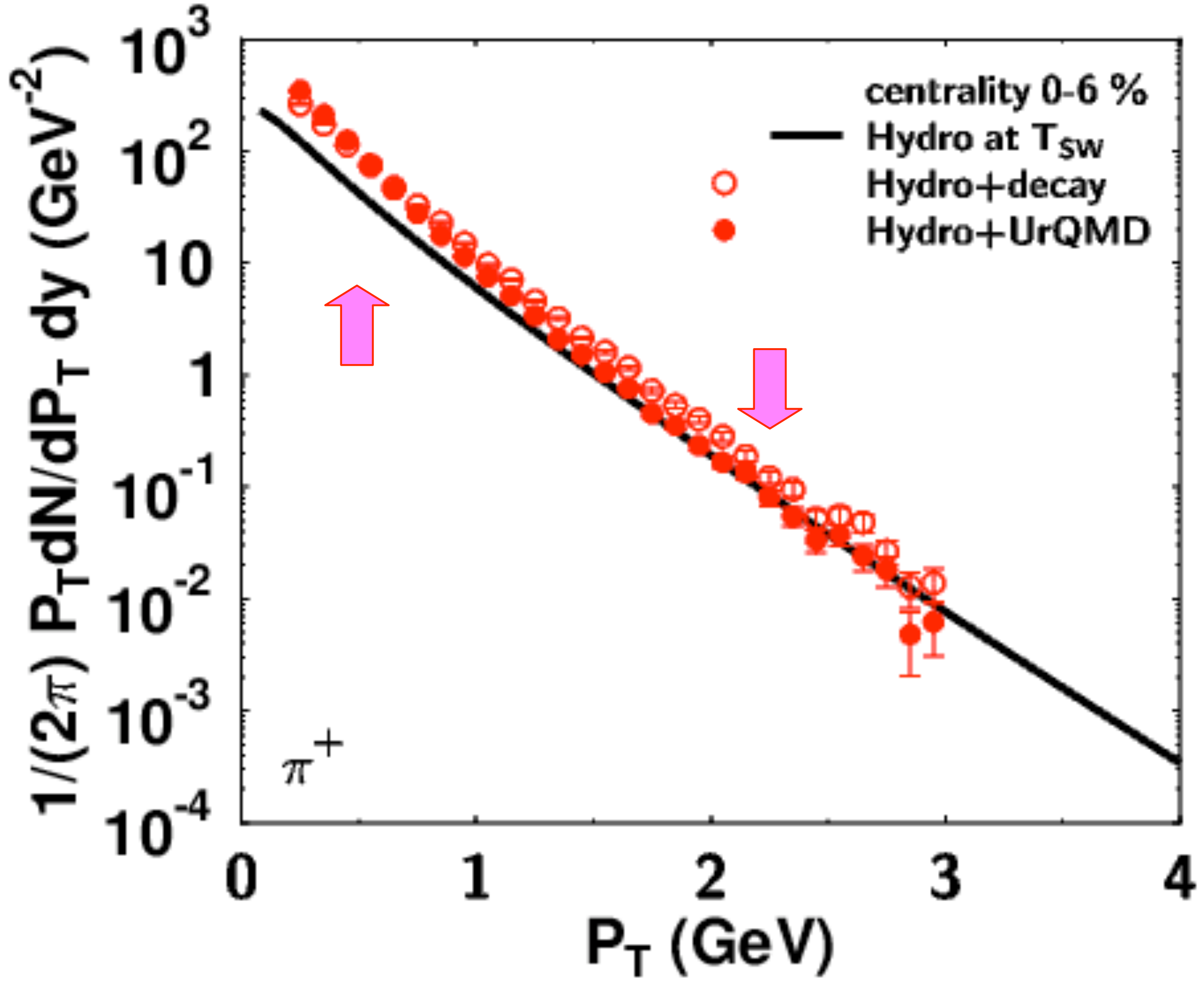
P_T Spectra for Strange Particles

Normalization is perfect!



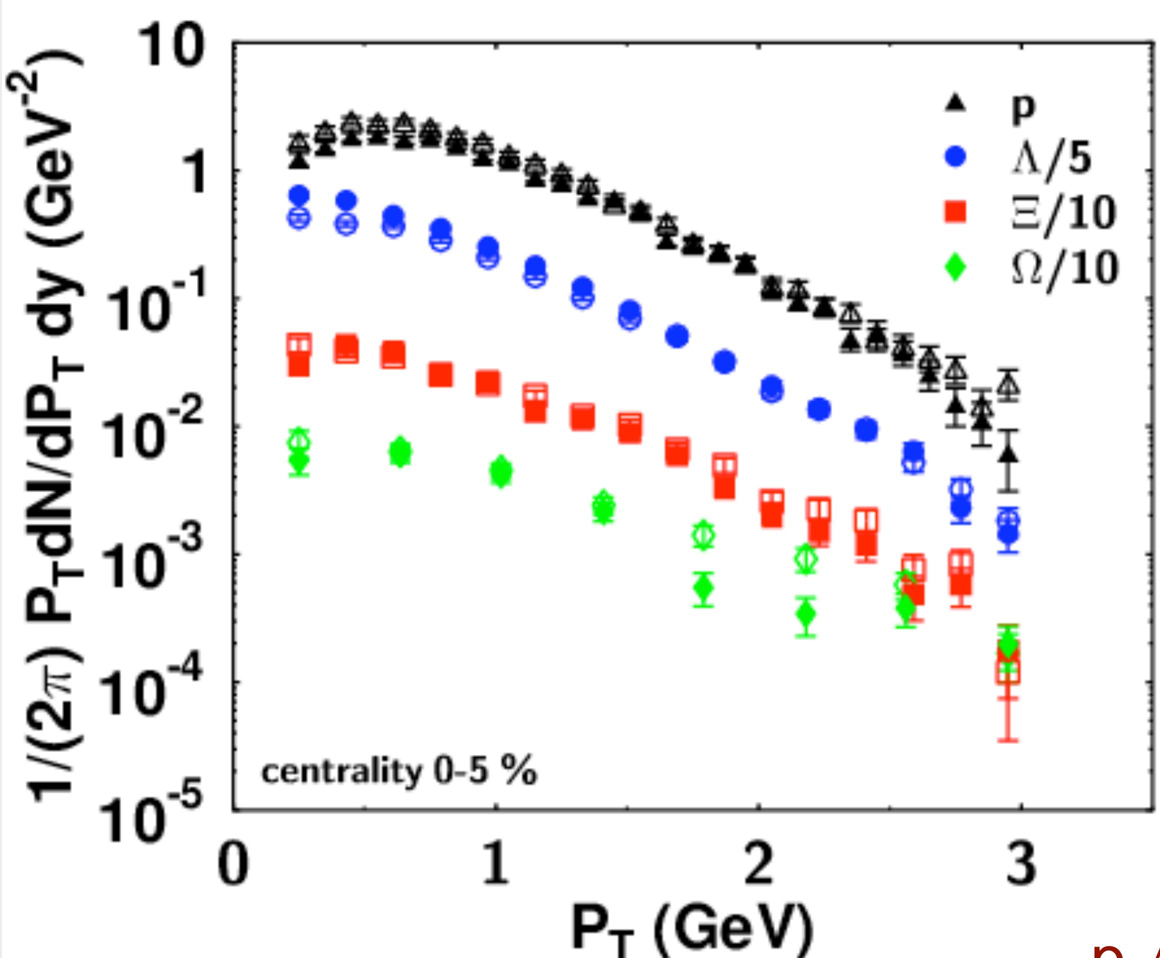
Reaction Dynamics

- At mid rapidity



•Slope becomes steeper

Final State Interactions

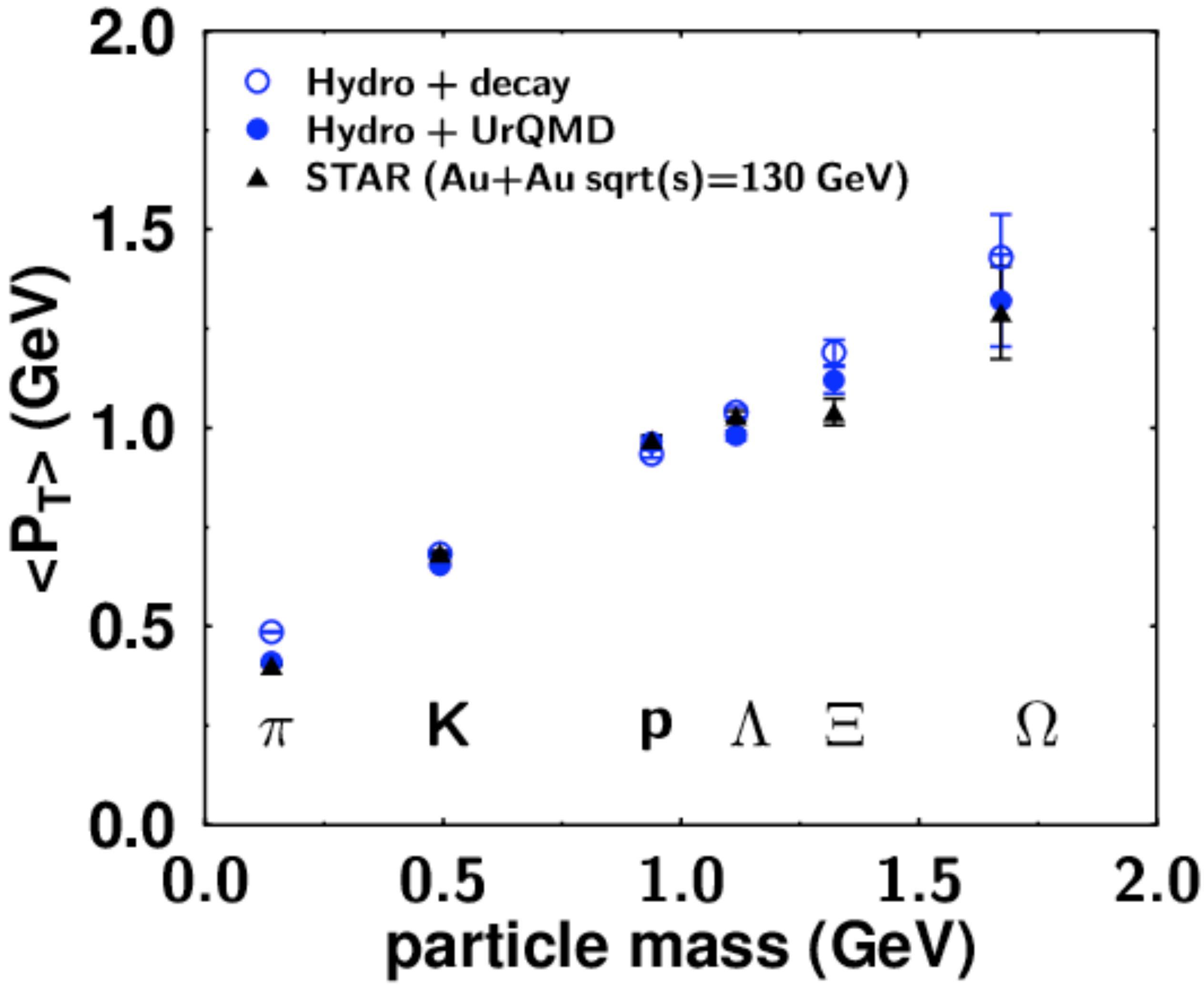


p,Λ : flatter, pion wind

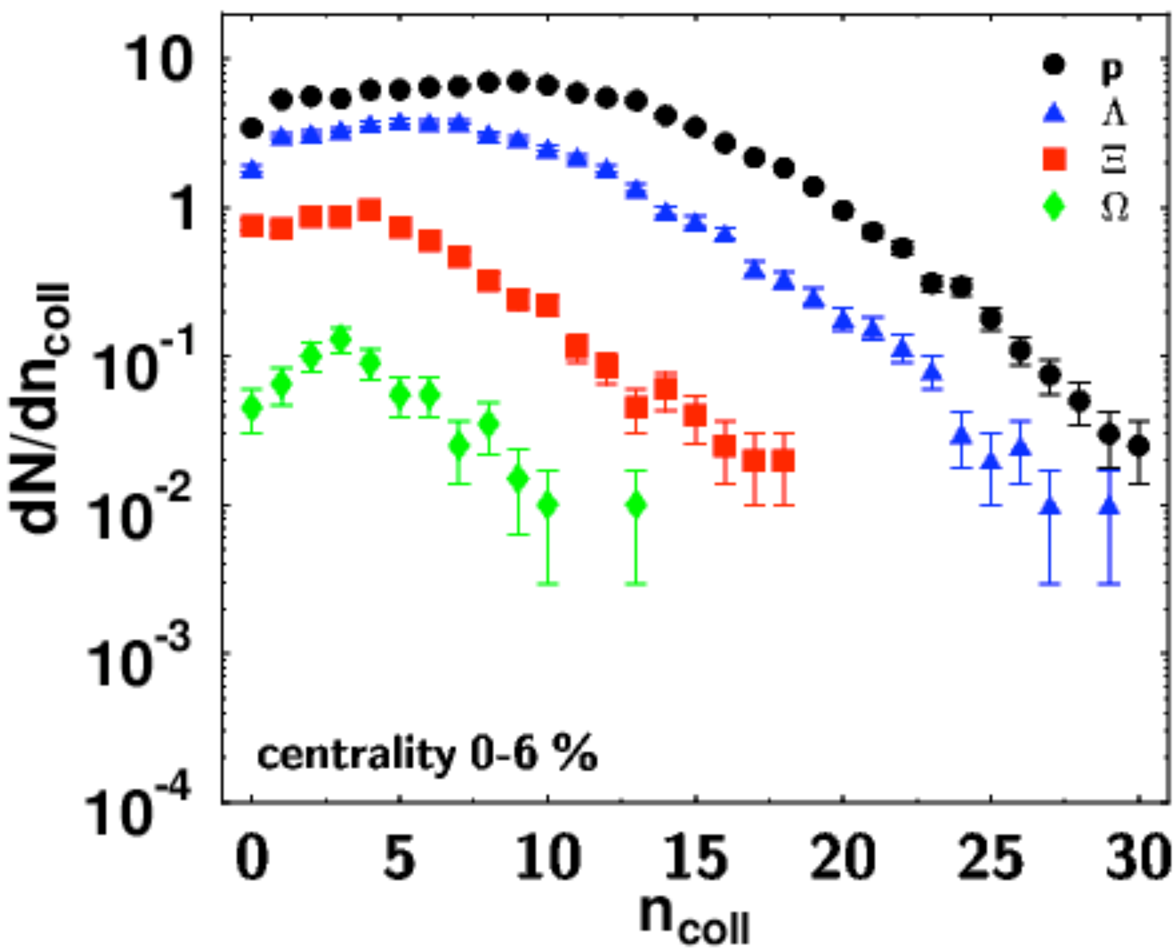
Ξ,Ω: small cross section

$\langle P_T \rangle$ vs mass

- At mid rapidity

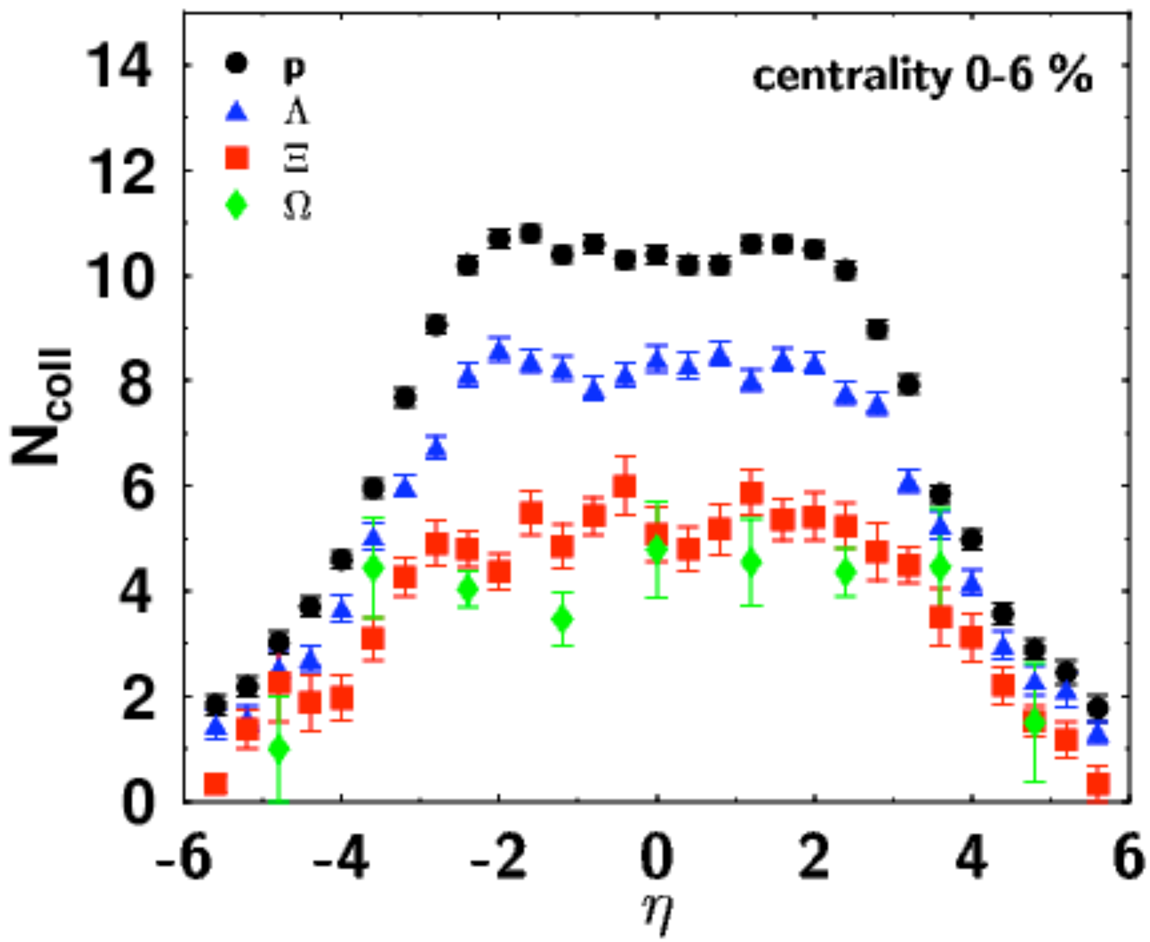


Distribution of # of Collisions



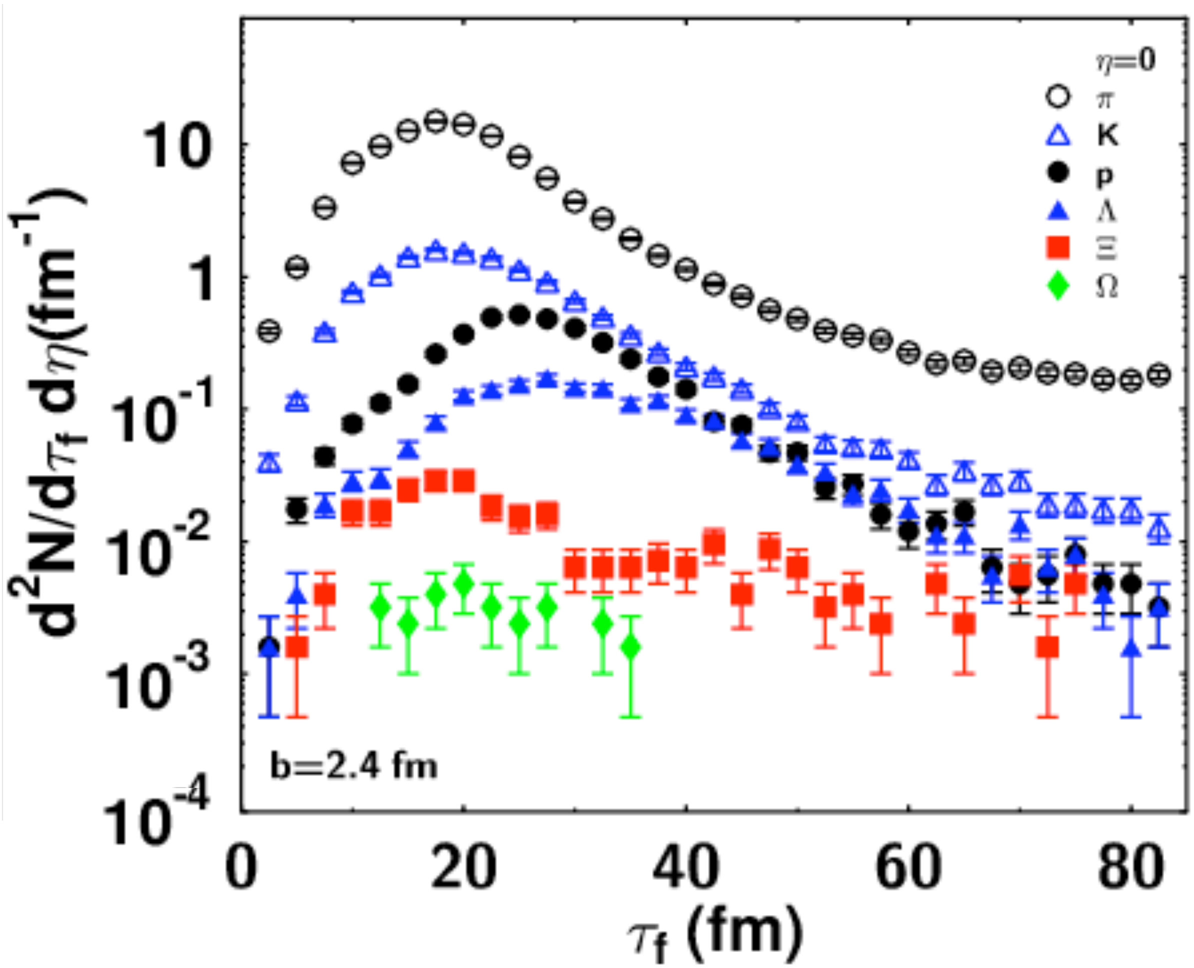
- p, Λ broad
  p ~ 10 times, Λ ~ 7 times
- Ξ, Ω small cross section

Distribution of # of Collisions



- plateau
  $-3 < \eta < 3$
- flavor difference

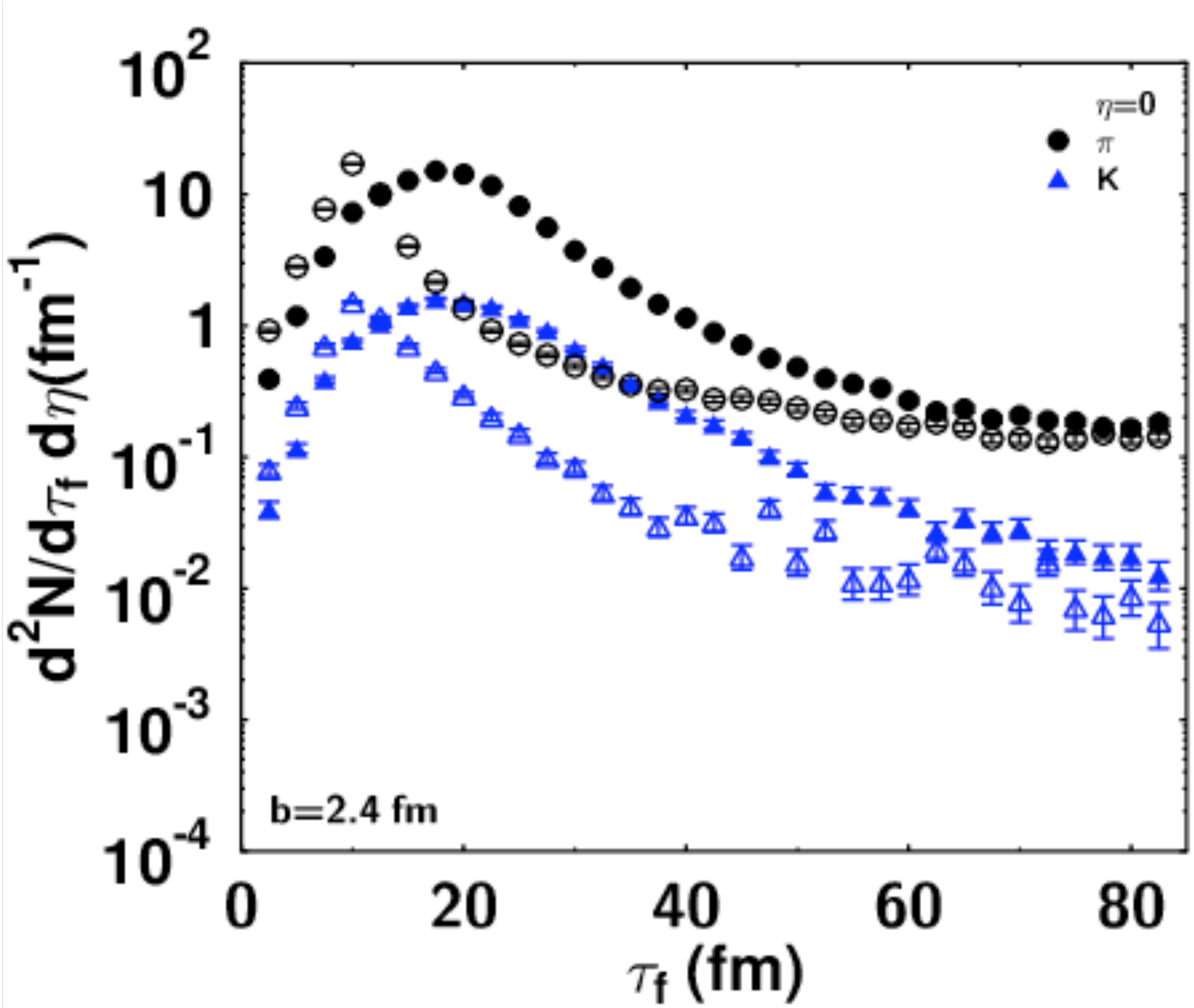
τ_f Distribution



- π, K: peak ~ 19 fm
- p, Λ: peak ~ 22 fm
- Multistrange particles small

•Species dependence
•Broad distribution

τ_f Distribution of M

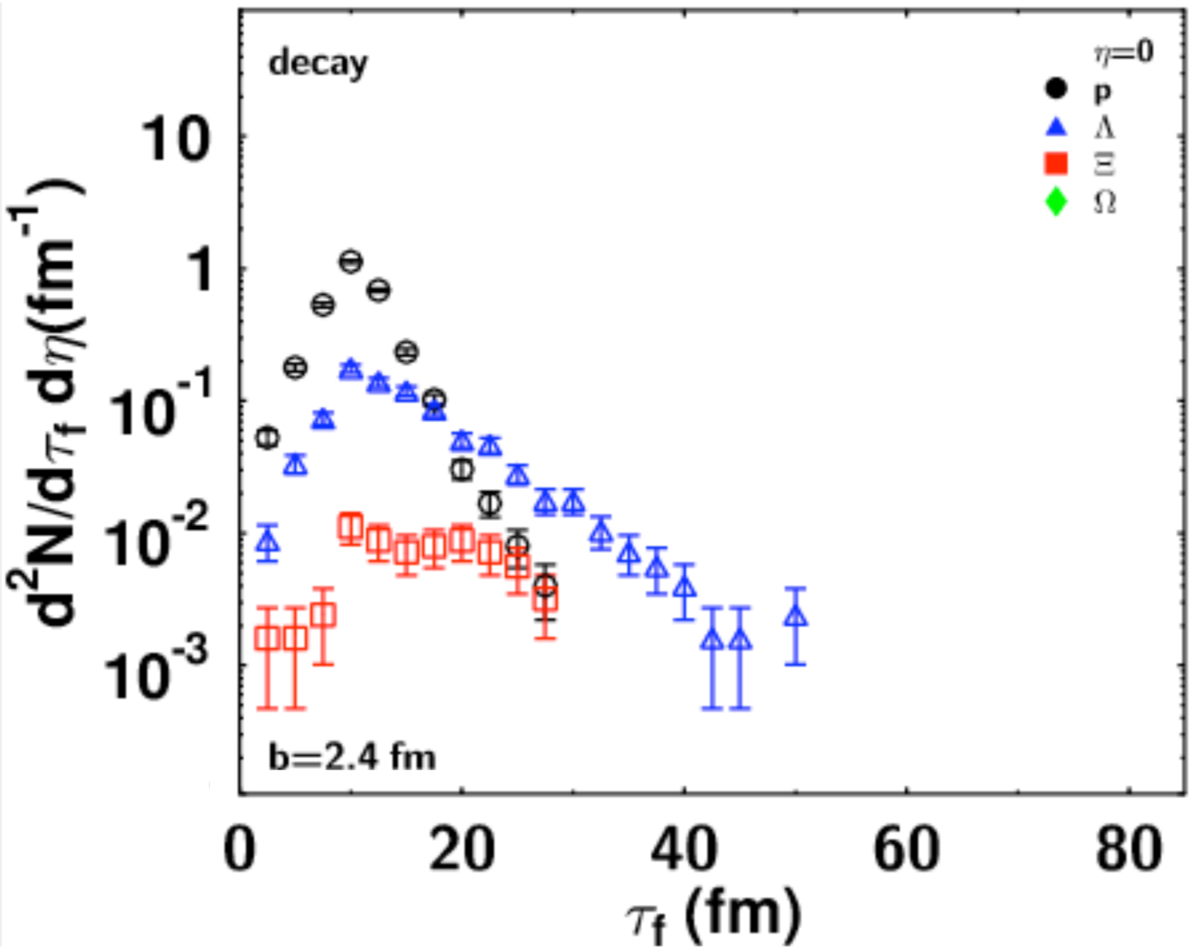


•Final state interactions

↓

Duration of freezeout process

τ_f Distribution of B

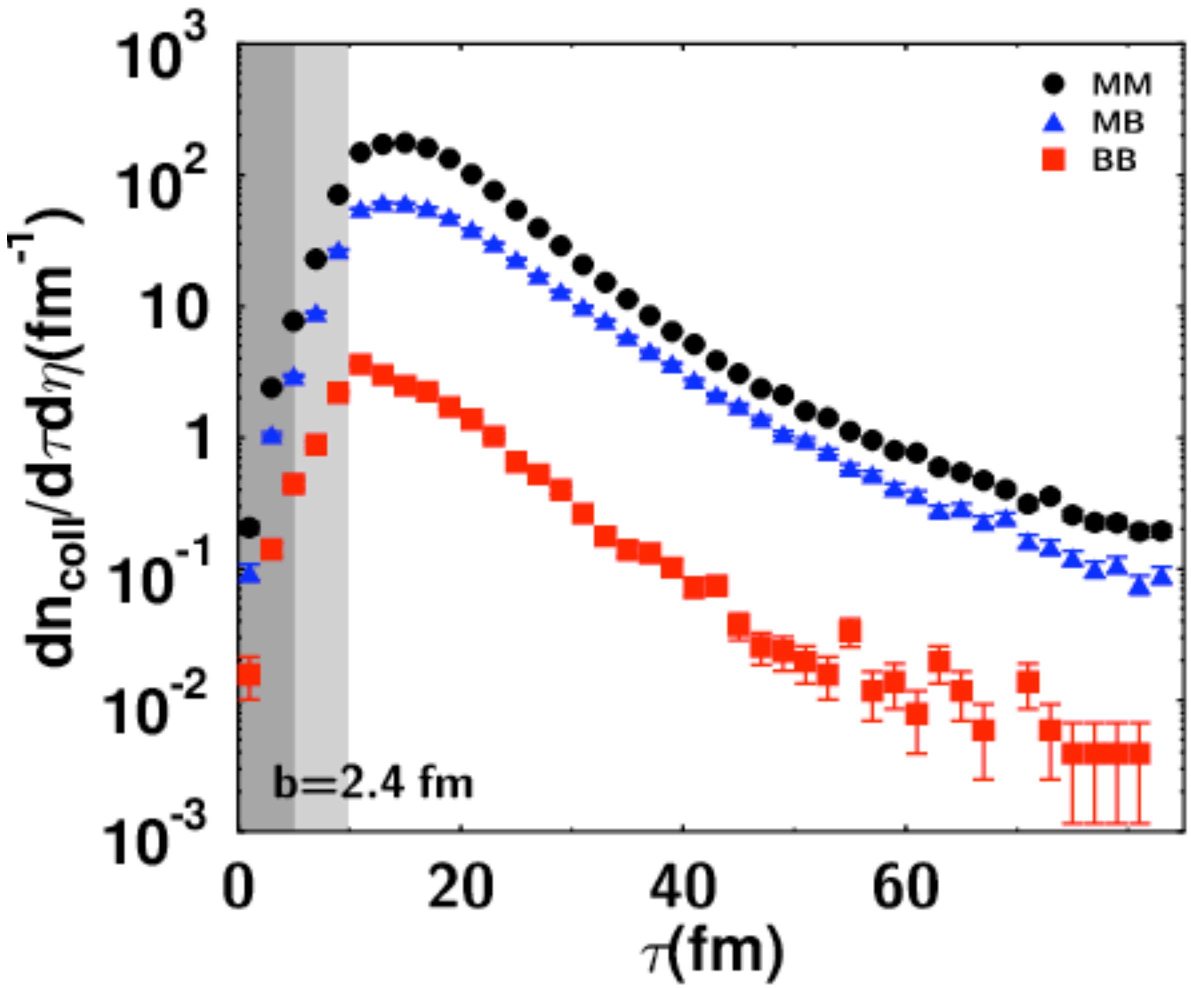


•Final state interactions

↓

Duration of freezeout process

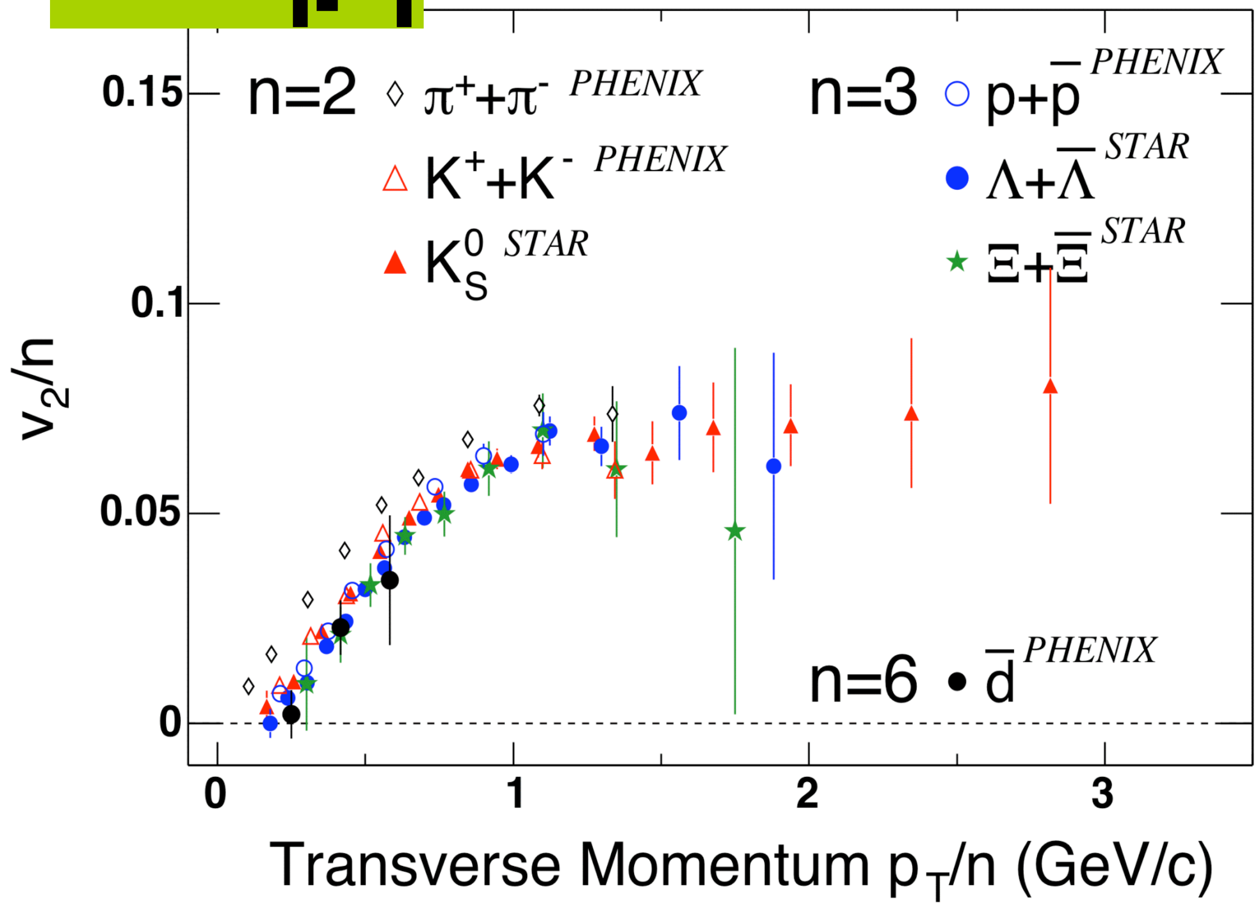
Collision Rate



- MM is dominant.

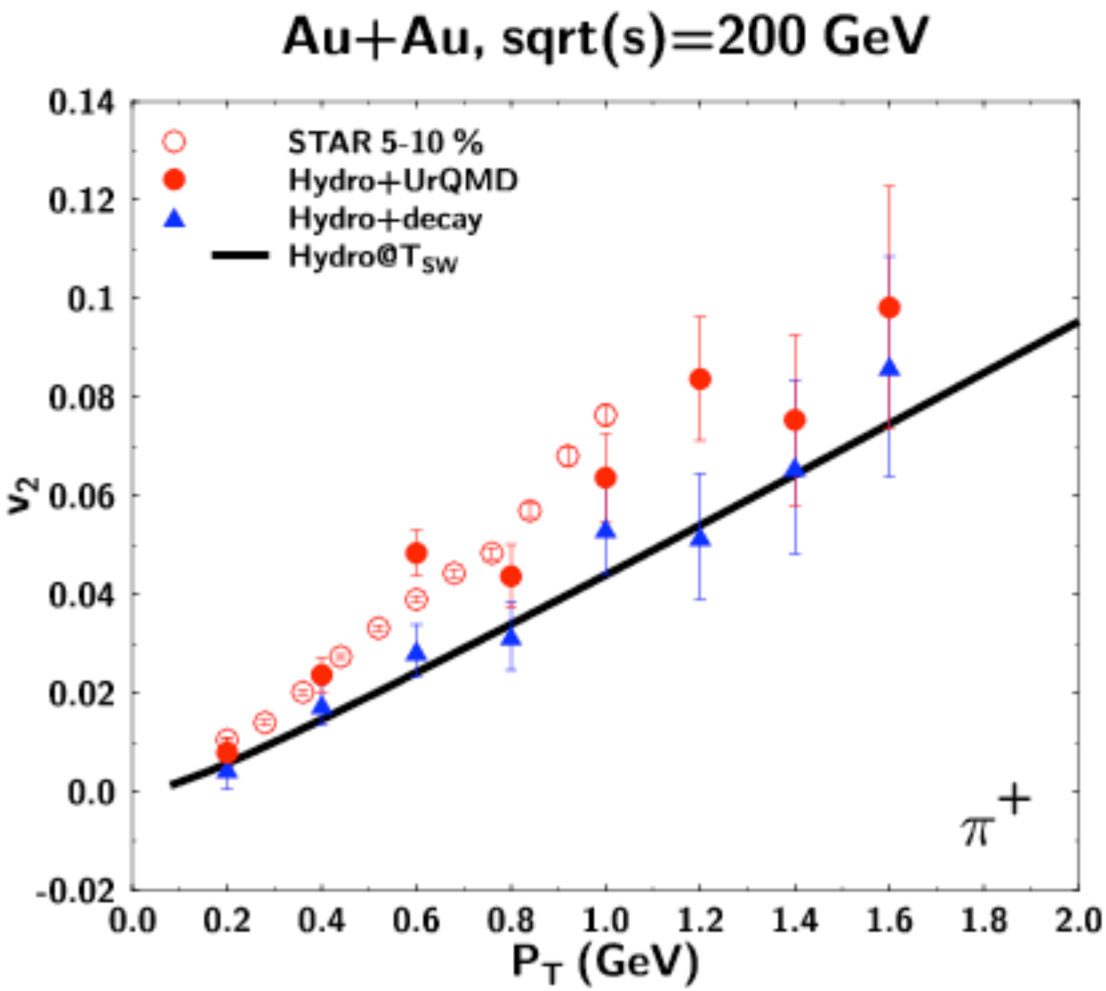
v_2 in hadron phase ?

- Quark number scaling of v_2

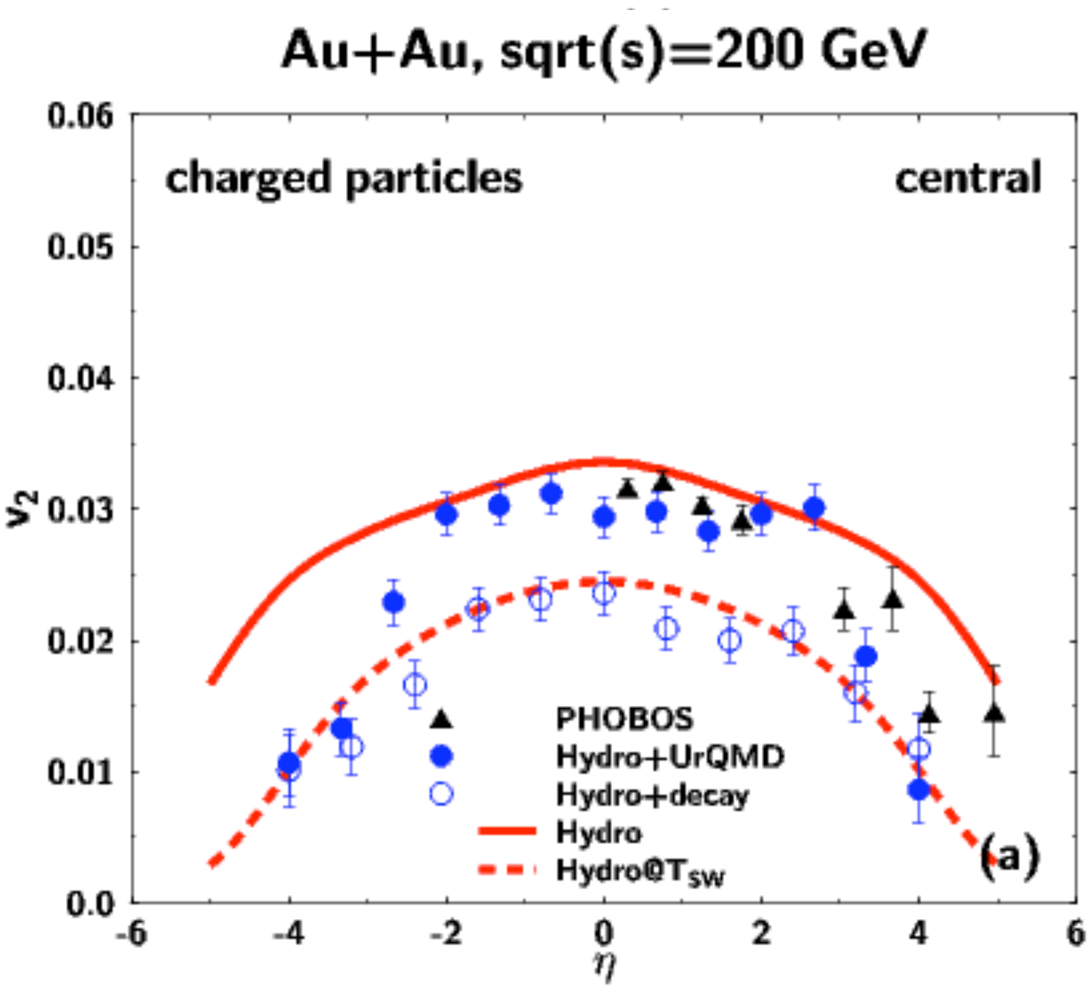


v_2: early stage of expansion

Reaction Dynamics in v_2 I



Reaction Dynamics in v_2 II



- Hydro+decay ~ Hydro@T_{SW}
- v_2 grows in hadron phase a bit.
- v_2 builds up in QGP phase.

Summary

- We present the 3-D hydrodynamic +cascade model
- 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
  - Elliptic flow
  - Different initial conditions from pure Hydro
  - Hadron ratios ←Switching temperature from Hydro to UrQMD
  - Reaction dynamics in UrQMD
    - Ξ,Ω:small cross section, v_2:improvement at forward/backward η
- Work in progress
  - EoS dependence: ex. lattice QCD
  - Switching temperature dependence