Temperature Dependence of Transport Coefficients of QCD in High-Energy Heavy-Ion Collisions

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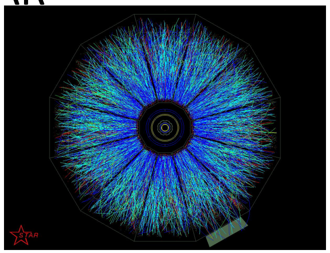
June 12, 2018@YKIS2018b Symposium

Quark-Gluon Plasma

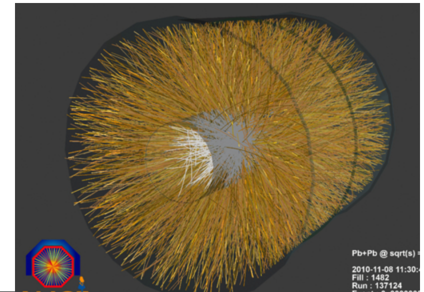
STAR



RHIC:2000

Strongly interacting QGP

- Relativistic hydrodynamics
- Recombination model
- Jet quenching
- Color Glass Condensate

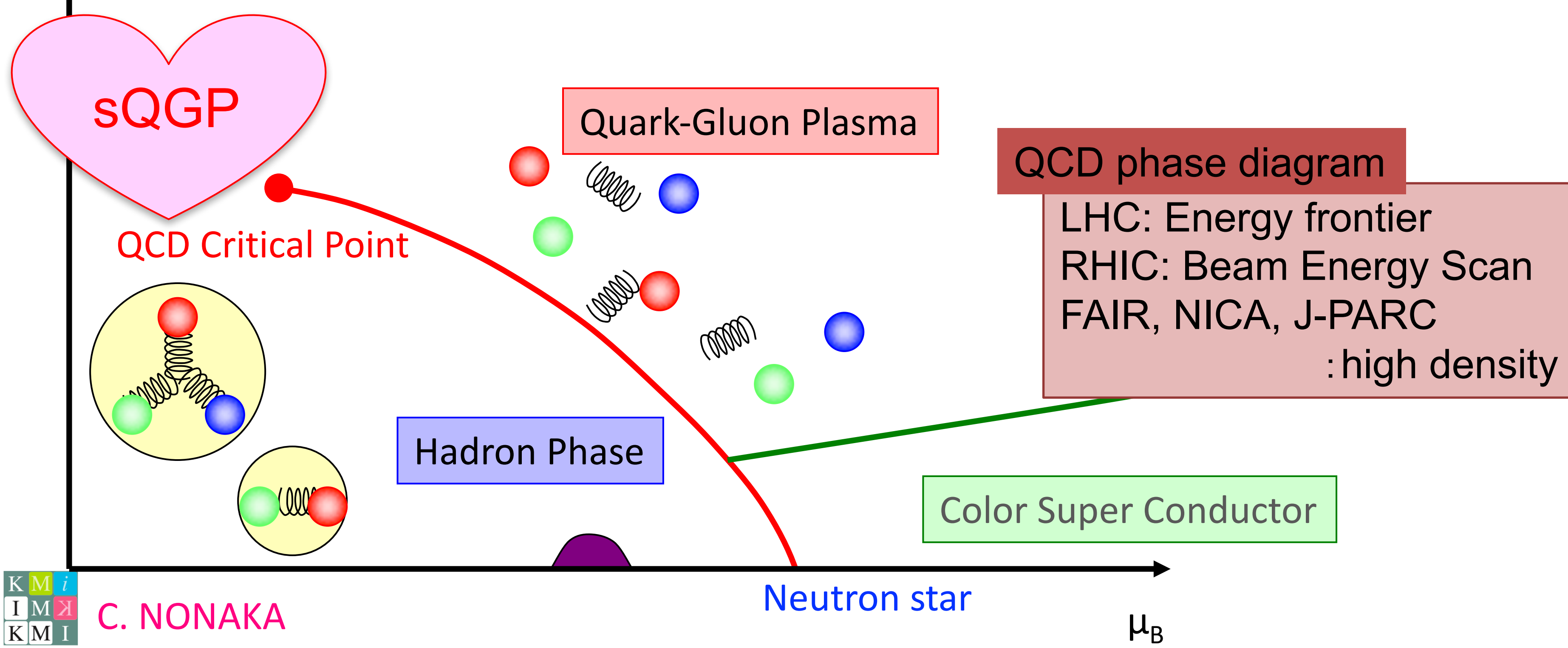


LHC:2010

Heavy Ion collisions start!

T

Heavy Ion Collisions：LHC,RHIC



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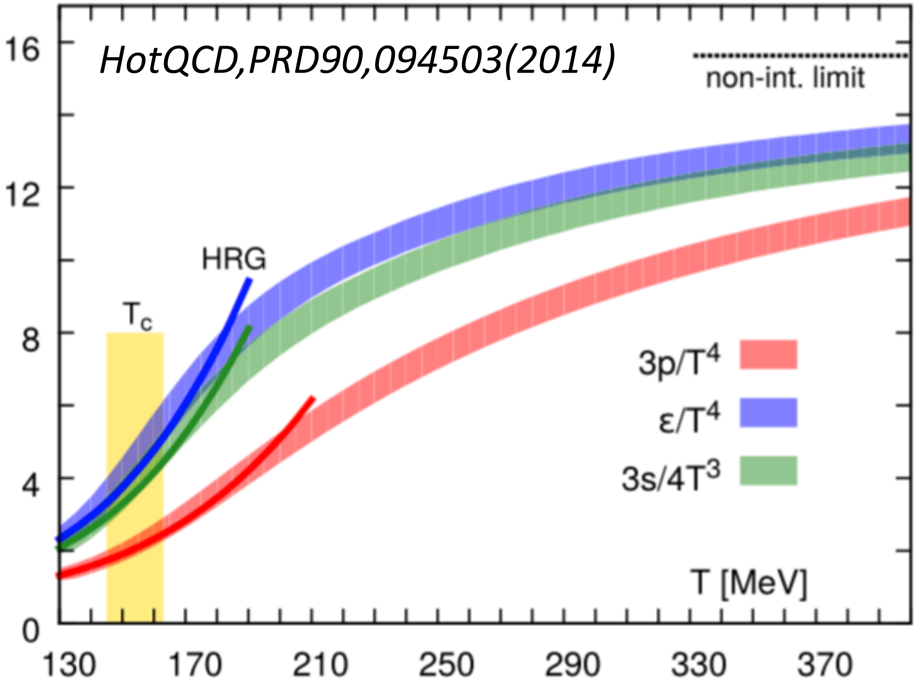
Property of QGP

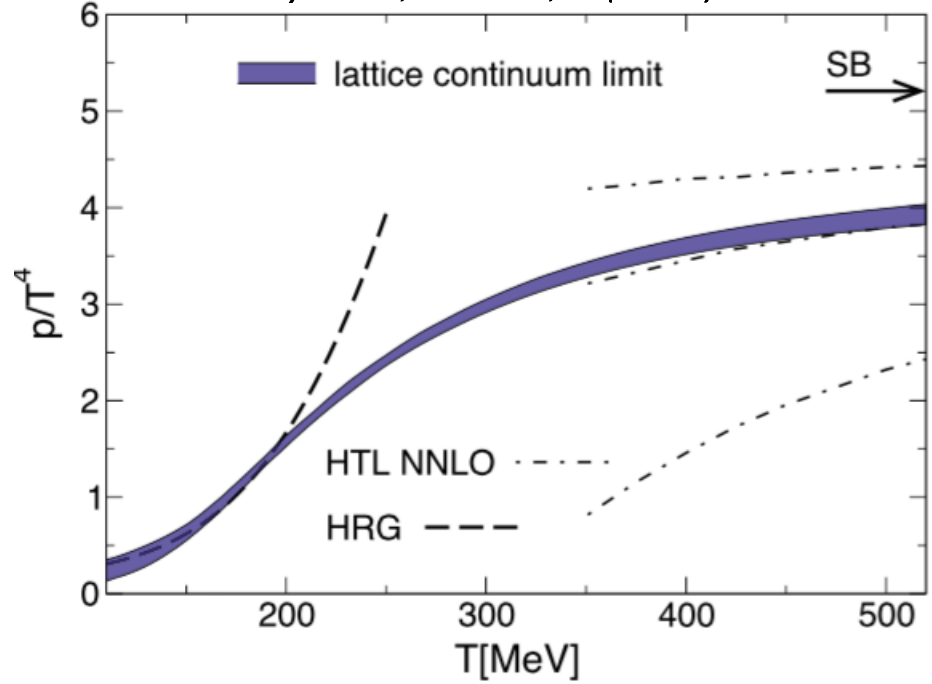
- Equation of State
  - Lattice QCD



(2+1) flavor, Highly improved staggered quark action
Nt=6,8,10,12,Ns=4Nt → continuum limit
Parametrization of EoS

$T_c \sim 155$ MeV

Borsanyi et al, PLB730,99(2014)



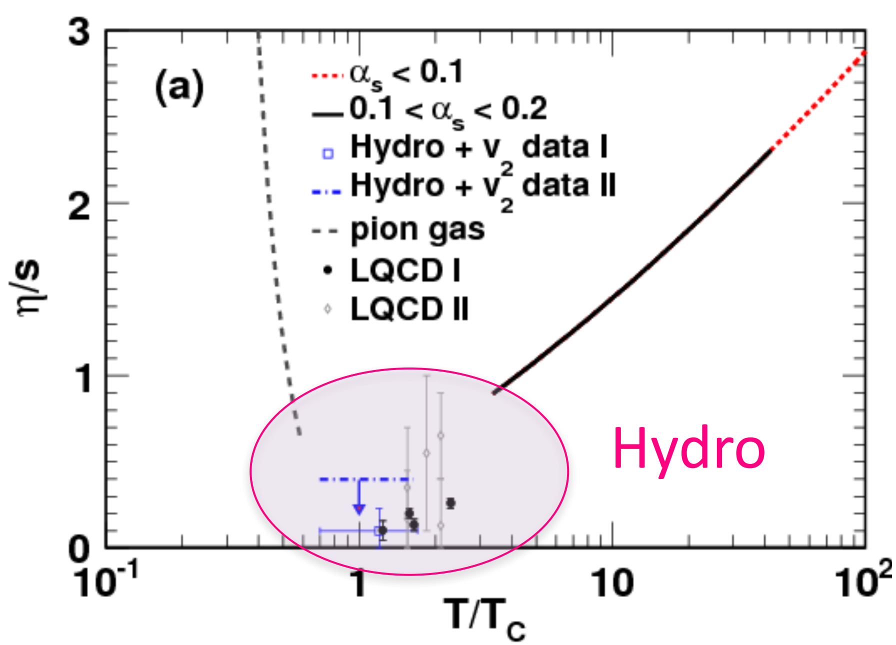
(2+1) flavor, Symanzik improved gauge and a stout- link improved staggered fermion action
Nt=6,8,10,12,16 → continuum limit
Parametrization of EoS

finite μ: sign problem

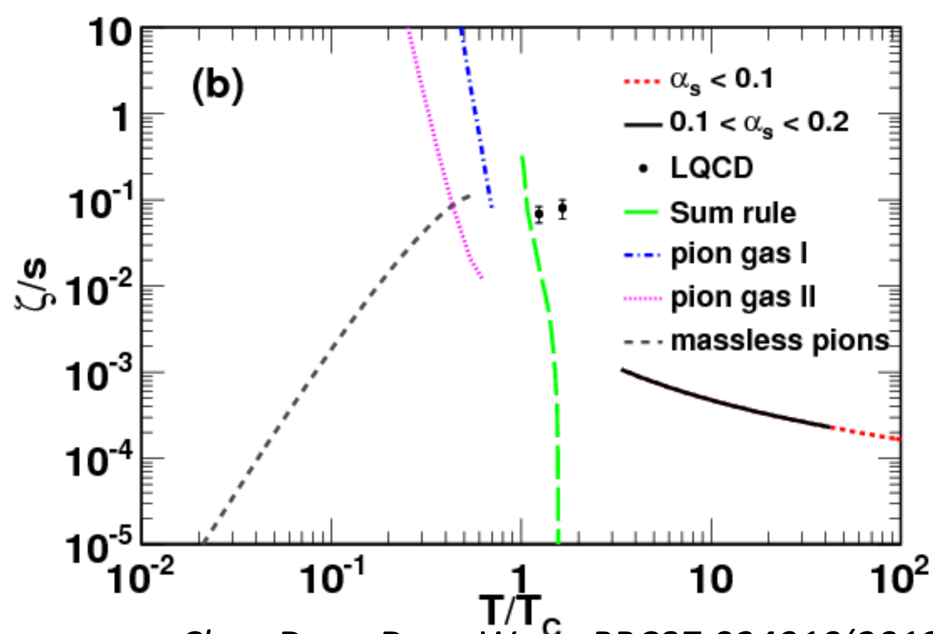
Property of QGP

- Current Status for transport coefficients

shear viscosity



bulk viscosity



Chen,Deng,Dong,Wang,PRC87,024910(2013)

- Shear viscosity takes the minimum around T_c. Cf. $\eta/s=1/4\pi$ AdS/CFT
- Hydrodynamic model
  constant η/s

- Bulk viscosity
  Temperature dependence is unclear.
- Hydrodynamic model
  vanishing

Detailed feature of shear and bulk viscosities

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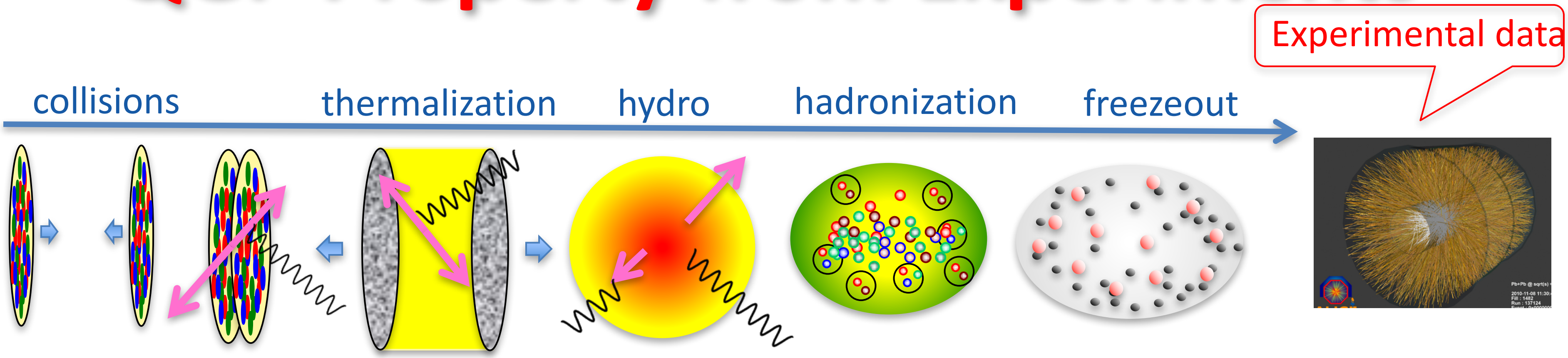
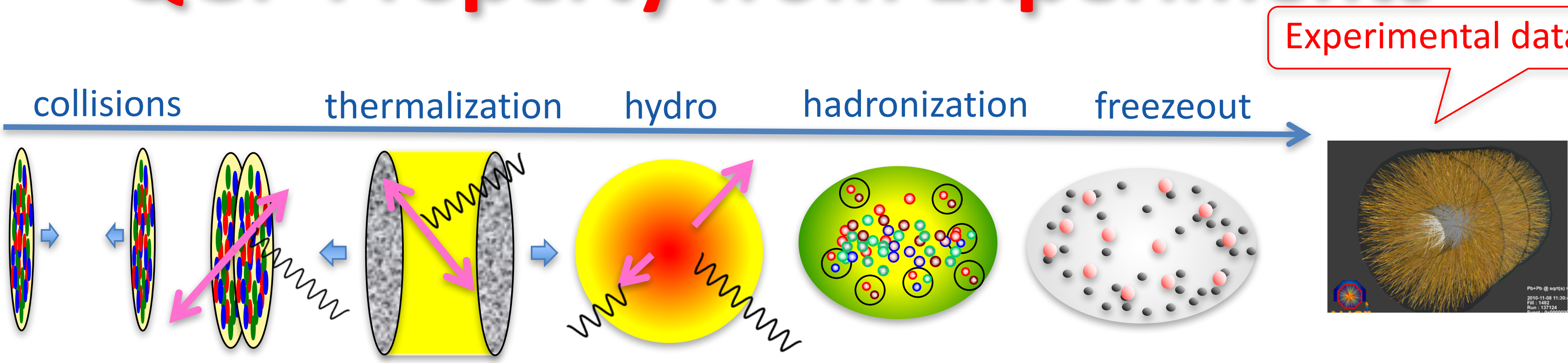
QGP Property from Experiments



Hydrodynamic Model

- One of successful phenomenological models
- Close relation to QGP bulk property
- Strong tools for understanding shear and bulk viscosities through experimental analyses

QGP Property from Experiments



Initial conditions	Hydrodynamics	Final state interactions
Fluctuations: Glauber, KLN, IP-Glasma…	QGP bulk property EoS: lattice QCD Shear and bulk viscosities	Hadron based event generator

Relativistic viscous hydrodynamic equation

$$\partial_\mu T^{\mu\nu} = 0$$

$$T^{\mu\nu} = (\epsilon + p)u^\mu u^\nu - pg^{\mu\nu} + \Delta T^{\mu\nu}$$

Denicol,Niemi,Molnar,Rischke, PRD85, 114047 (2012)
Denicol, Jeon, and Gale, Phys. Rev. C90, 024912 (2014)

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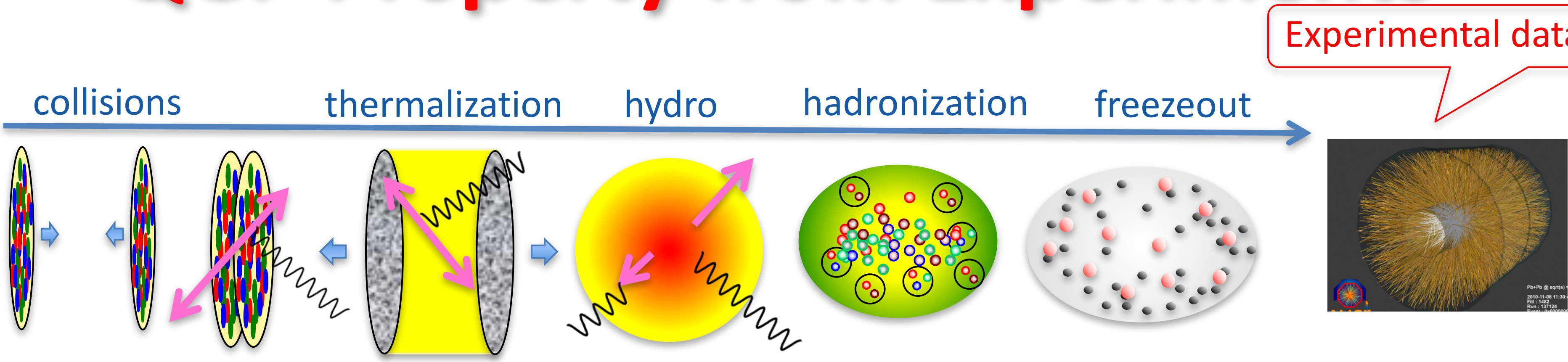
QGP Property from Experiments



Initial conditions

Fluctuations:
Glauber, KLN,
IP-Glasma...

Hydrodynamics

QGP bulk property
EoS: lattice QCD
Shear and bulk viscosities

New hydrodynamics code

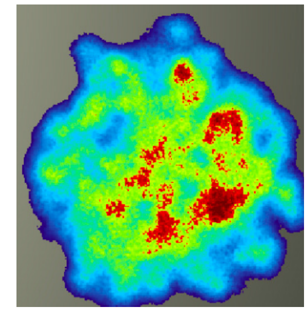
Final state interactions

Hadron based event generator

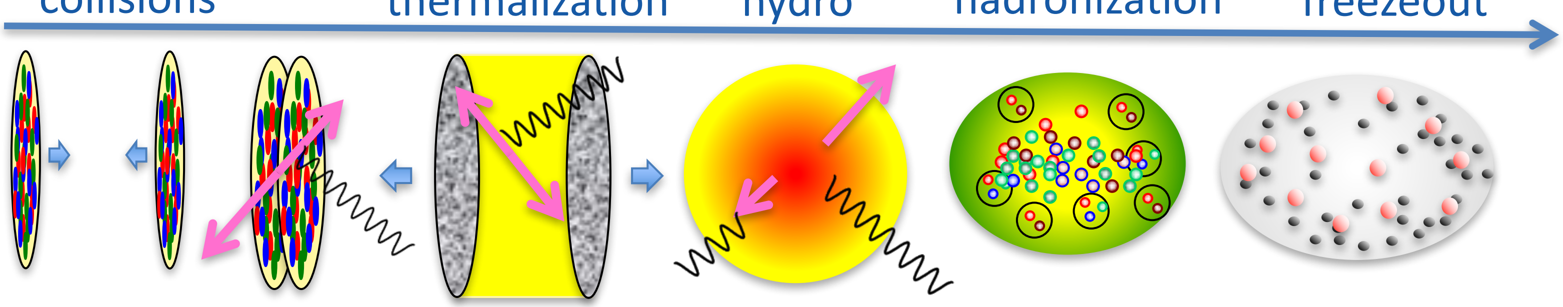
Akamatsu et al, JCP256,34(2014)
Okamoto, Akamatsu, Nonaka, EPJC76,579(2016)
Okamoto and Nonaka, EPJC77,383(2017)

Our Strategy

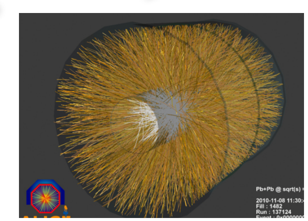
1. Development of new hydrodynamics code
   - Stable with small numerical dissipation
   - Shock wave
   - Strong expansion in longitudinal direction
   - Conservation property



2. Application to phenomenological analyses of LHC data
   - Description of space-time expansion after collisions



Experimental data



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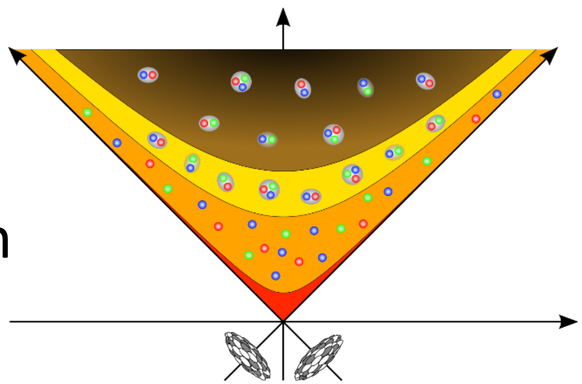

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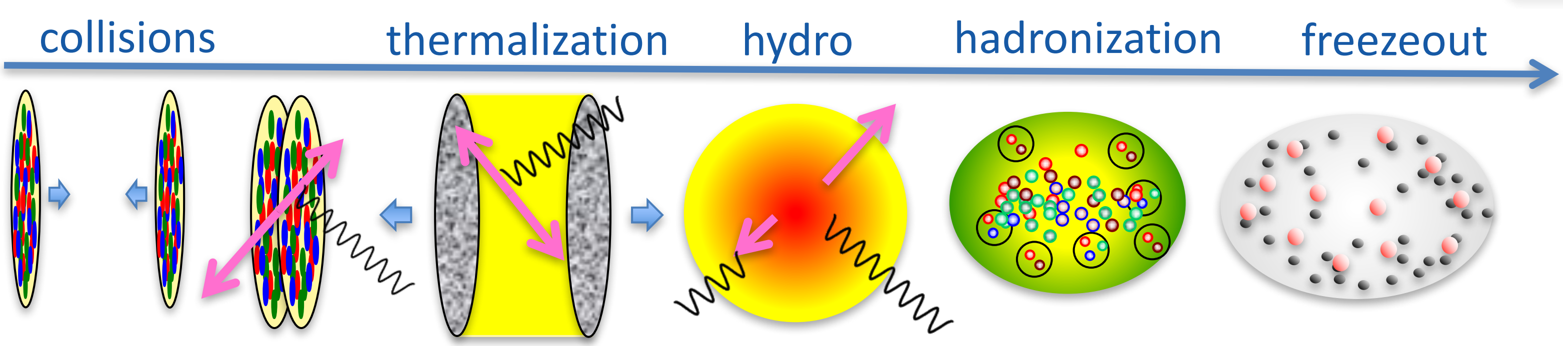
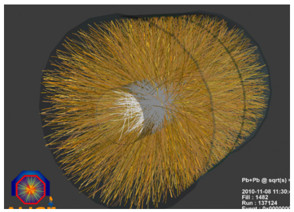
Experimental data





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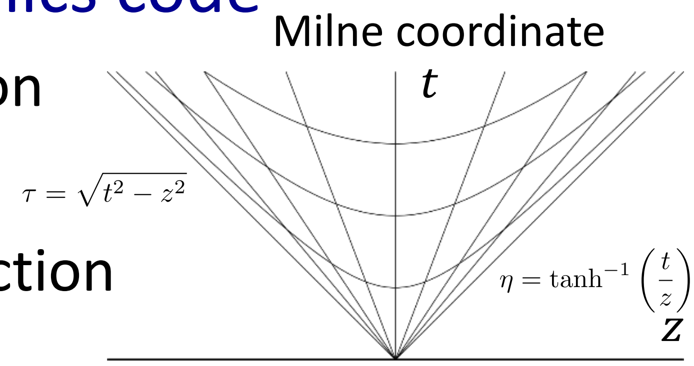

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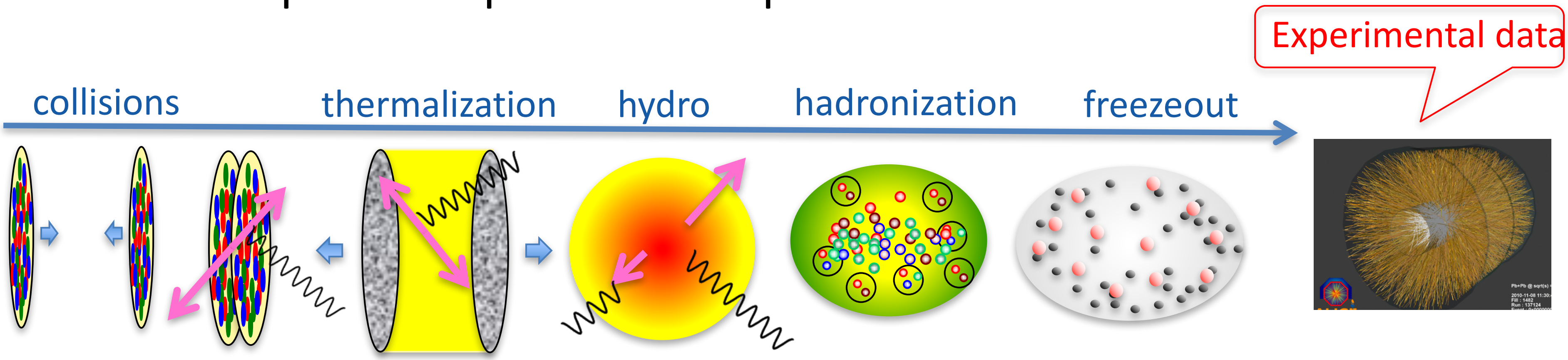

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1. Development of new hydrodynamics code
   - Stable with small numerical dissipation
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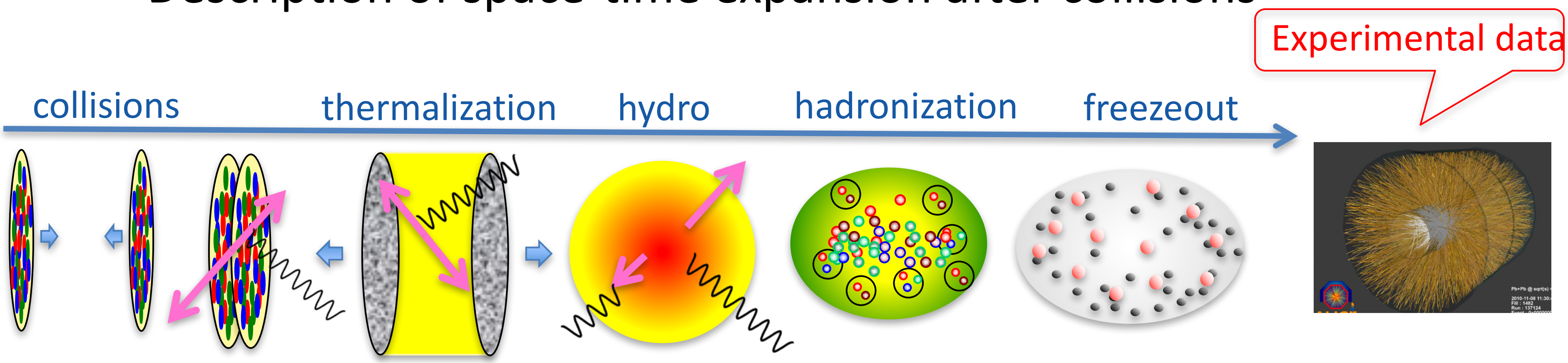
   - Strong expansion in longitudinal direction
   - Conservation property

   Riemann solver in Milne coordinates

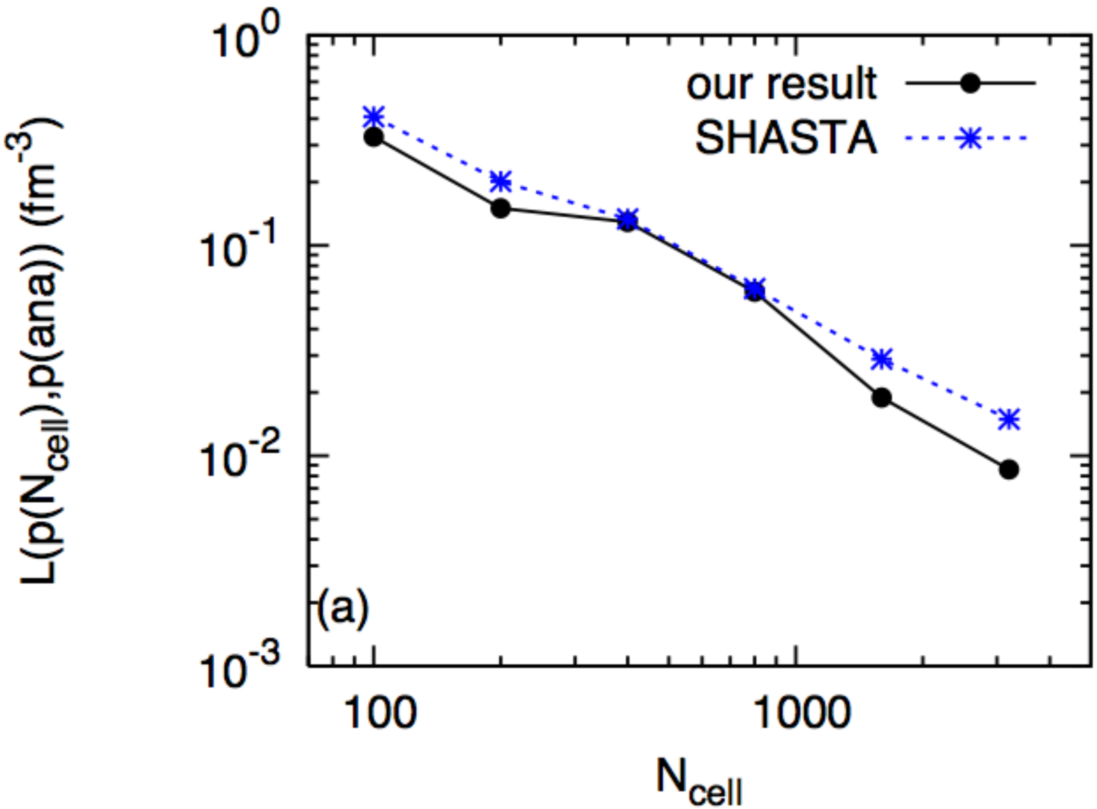
2. Application to phenomenological analyses of LHC data
   - Description of space-time expansion after collisions

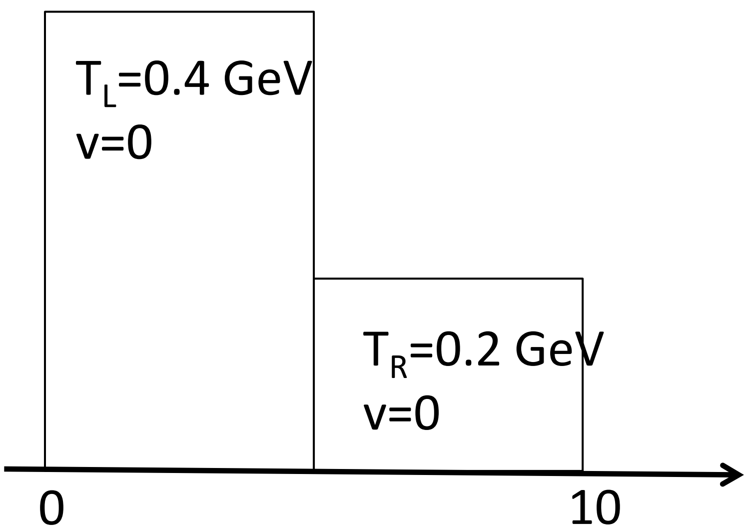


Small Numerical Dissipation

Akamatsu et al, JCP256,34(2014)

- Numerical dissipation: deviation from analytical solution





For analysis of heavy ion collisions

N_{cell}=100: dx=0.1 fm

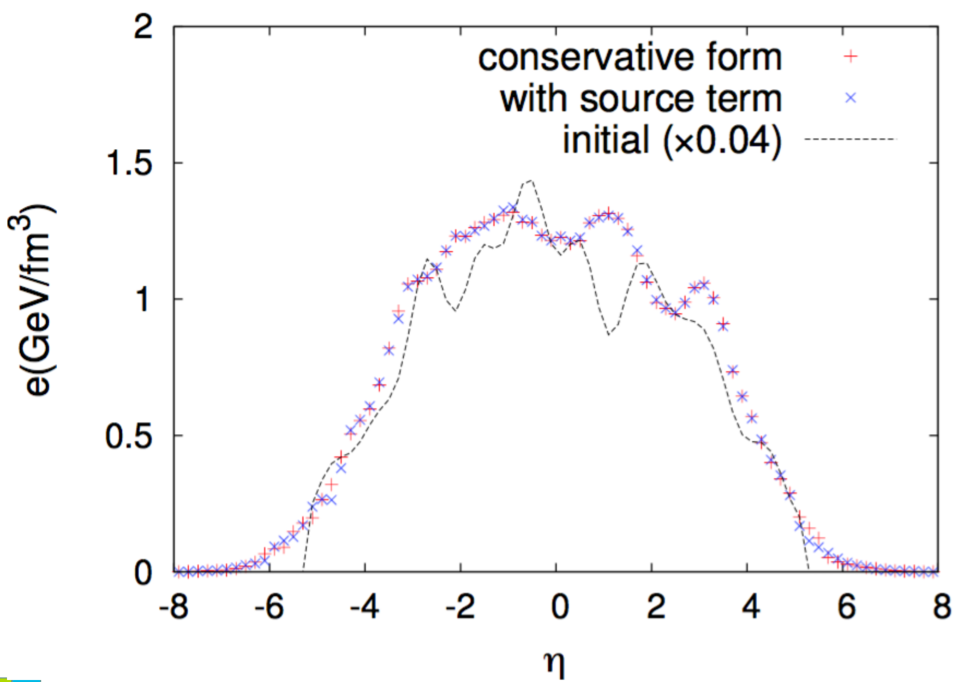
$$L(p(N_{\rm cell}), p({\rm anaytic})) = \sum_{i=1}^{N_{\rm cell}} |p(N_{\rm cell}) - p({\rm analytic})| \frac{\lambda}{N_{\rm cell}}$$

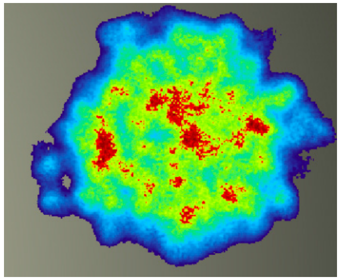
λ=10 fm

Numerical Tests in 1D

- ✓ Bjorken's scaling solutions
- ✓ Landau-Khalatnikov Solution (1D)
- ✓ Longitudinal fluctuations
- ✓ Conservation property

K. Okamoto, Y. Akamatsu and CN, Eur. Phys. J. C76 (2016)579





fluctuations

Sum of violation of conservation

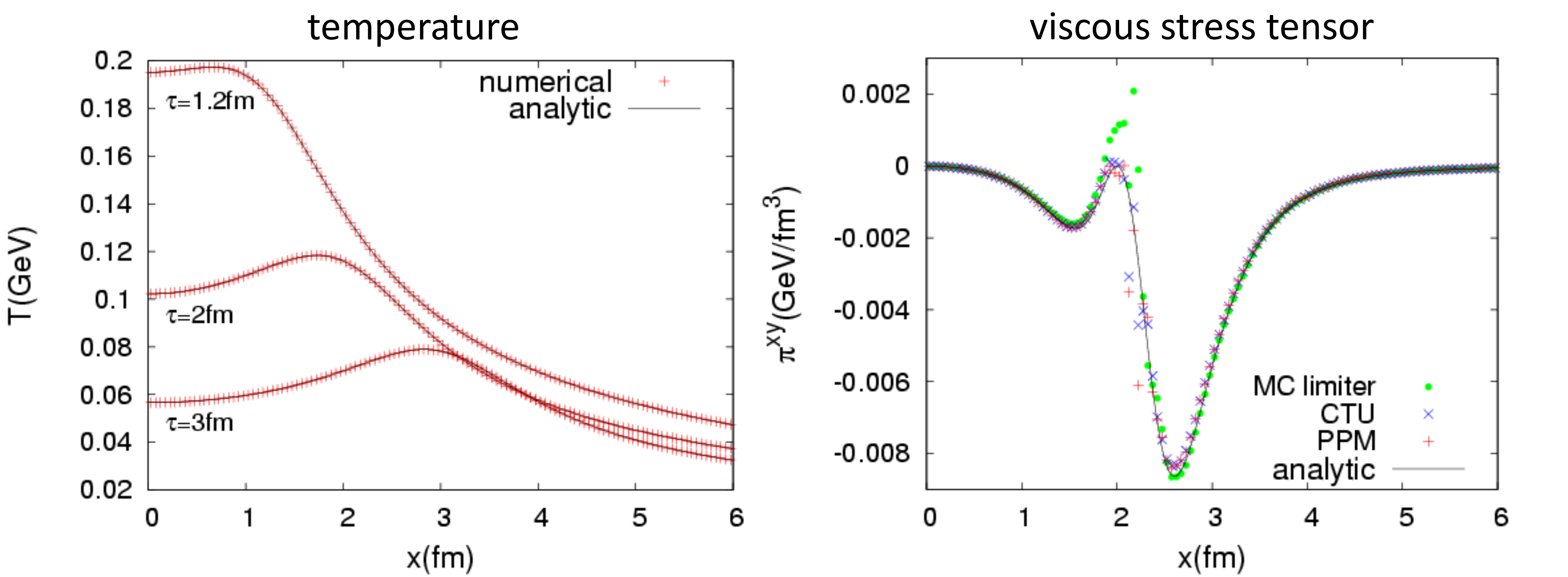
	ε_E	ε_M
conservative	1.38E-09	8.59E-09
with souce	1.27E-02	5.61E-02

Gubser Flow with Finite η/s

Okamoto and Nonaka, EPJC77,383(2017)

- Analytical solution
  - Bjorken flow + transverse expansion

Marrochio et al, PRC91,014903(2015)



Our computed results show good agreement with analytical solution.

Our Strategy

1. Development of new hydrodynamics code
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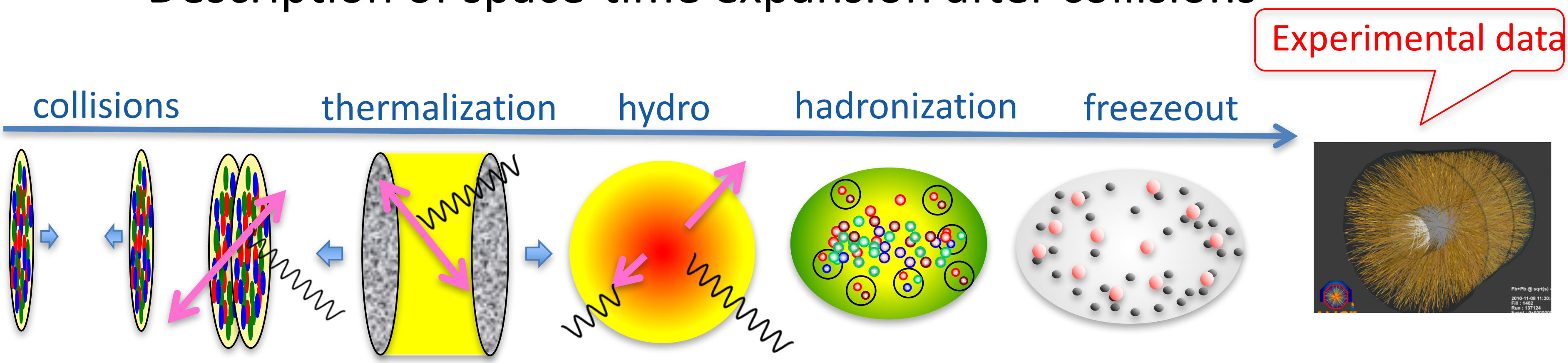
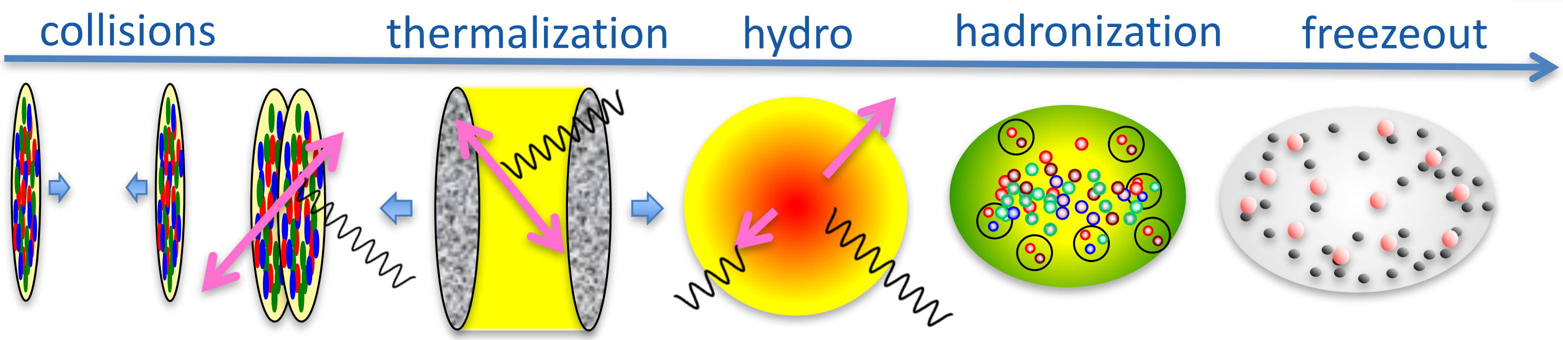
   Riemann solver in Milne coordinates

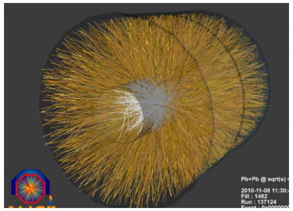
2. Application to phenomenological analyses of LHC data
   – Description of space-time expansion after collisions



Quantitative Analyses



Experimental data



Initial conditions

Fluctuations:
Glauber, KLN,
IP-Glasma…

TRENTO

Phenomenological model
Parametrization

Moreland et al.,PRC92,011901(2015)
Ke et al.,PRC96,044192(2017)

Hydrodynamics

QGP bulk property
EoS: lattice QCD
Shear and bulk viscosities

New hydrodynamics code

Final state interactions

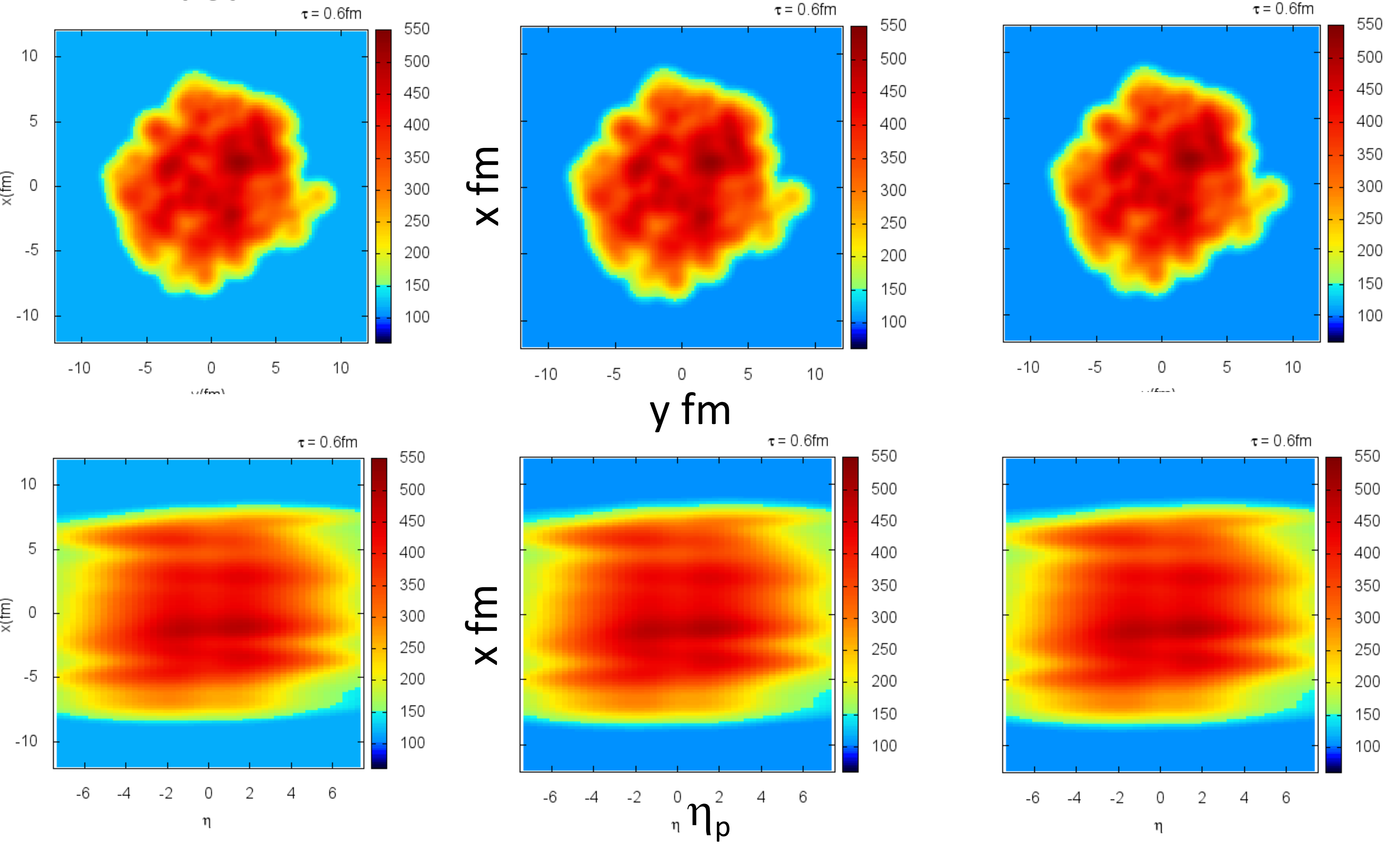
Hadron based event generator

UrQMD

Bass et al., Prog.Part.Nucl.Phys.(1998)
Bleicher et al., J.Phys.G25,1859(1999)

Time Evolution of Temperature

Ideal | **shear** | **shear+bulk**



Shear and Bulk Viscosities

shear viscosity

$$\eta/s = 0.17$$

shear + bulk viscosities

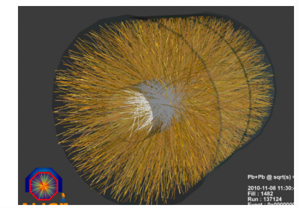
$$\eta/s = 0.17$$

$$\zeta = b\eta\left(\frac{1}{3} - c_s^2\right)^2 \quad b = 40$$

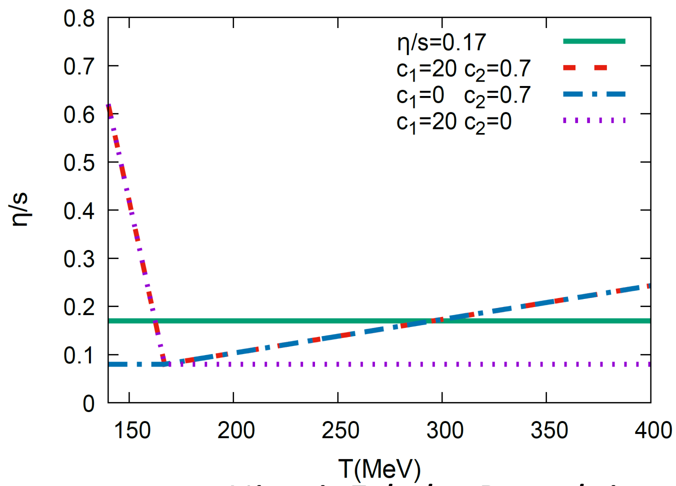
Molnar et al., PRC89,074010(2014)

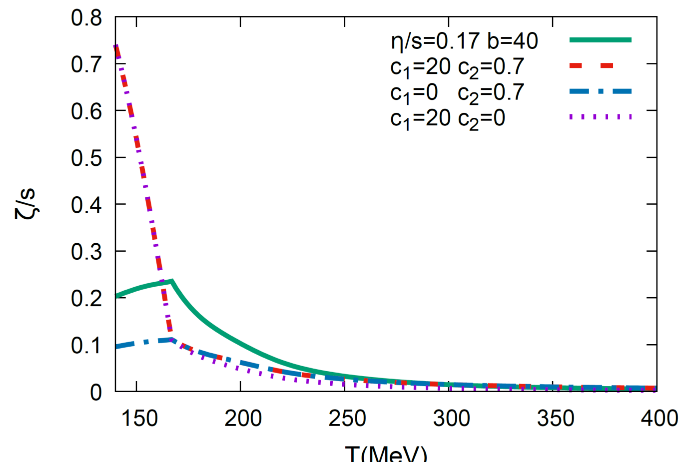
ALICE Pb+Pb $\sqrt{s_{NN}} = 2.76$ TeV, LHC

- √ Rapidity distributions
  central collision: parameter fixing
- √ P_T distributions
- √ Mean P_T
- √ Collective flow v_2, v_3



temperature dependent shear + bulk viscosities

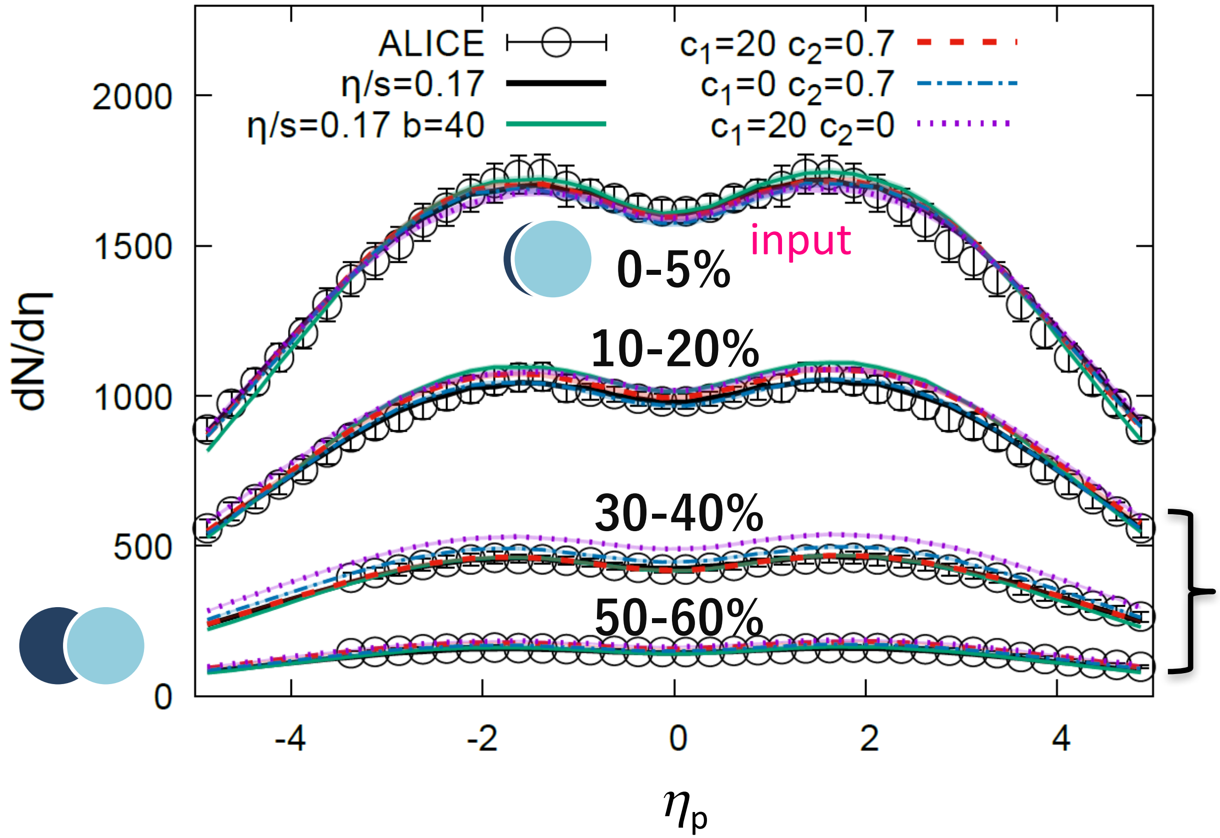




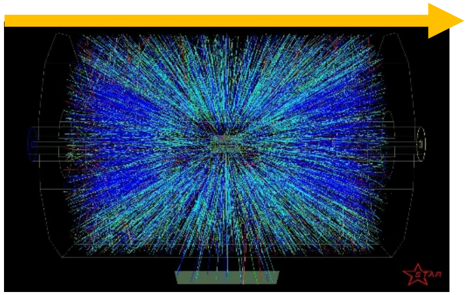
Niemi, Eskola, Paatelainen, PRC93, 024907(2016)

Denicol, Monnai, Schenke, PRL 116, 212301 (2016)

Rapidity Distributions



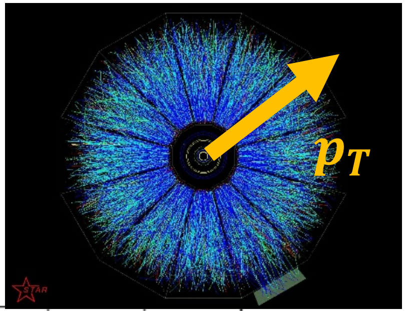
pseudorapidity η_p



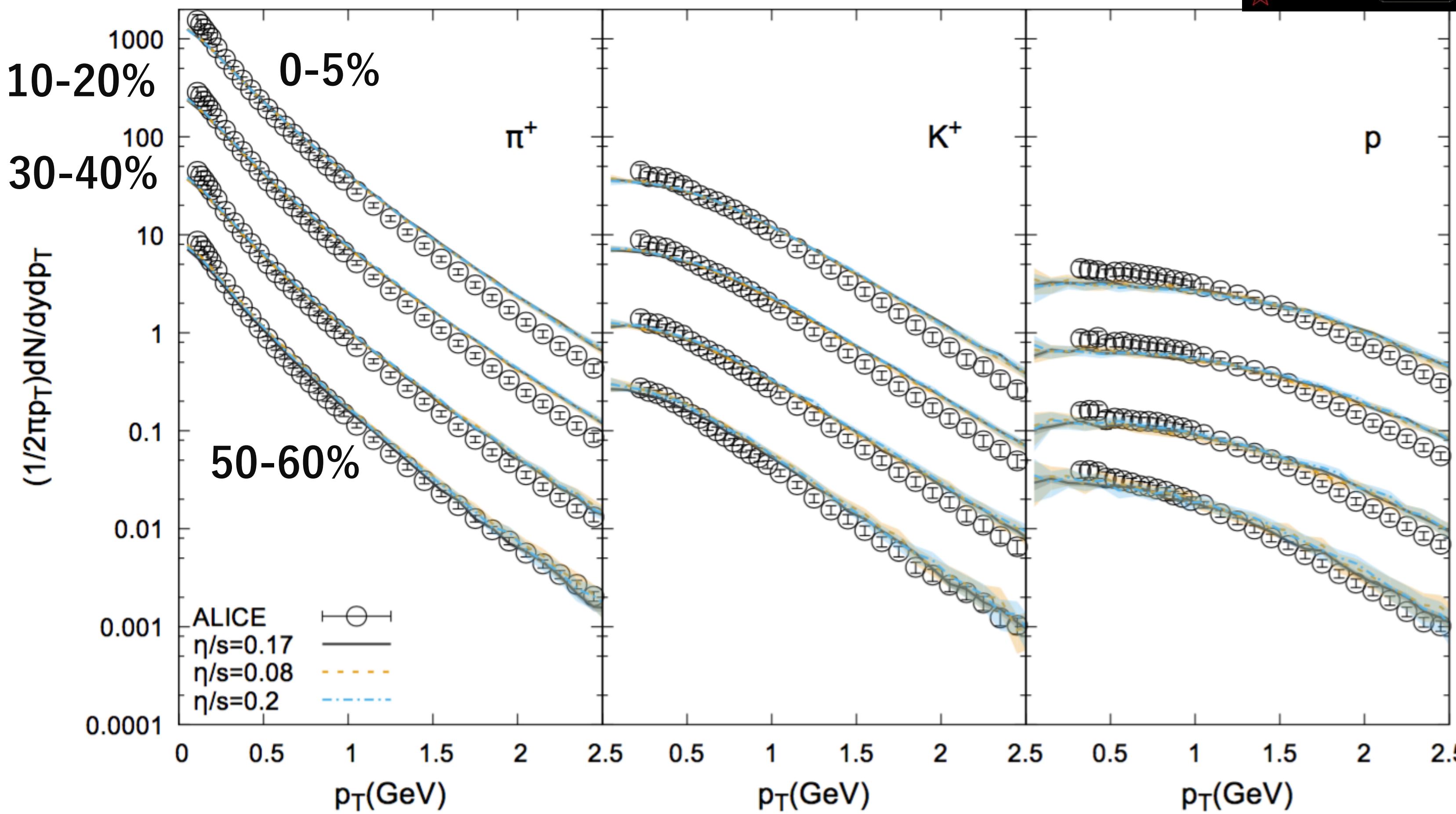
colission axis

- Parameters in initial condition TRENTO are fixed from comparison with experimental data at 0-5 % centrality.

η/s dependence



- p_T spectra



P_T spectra do not depend on η/s.

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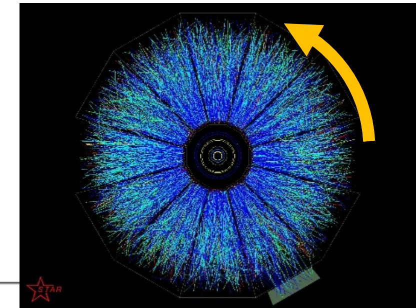
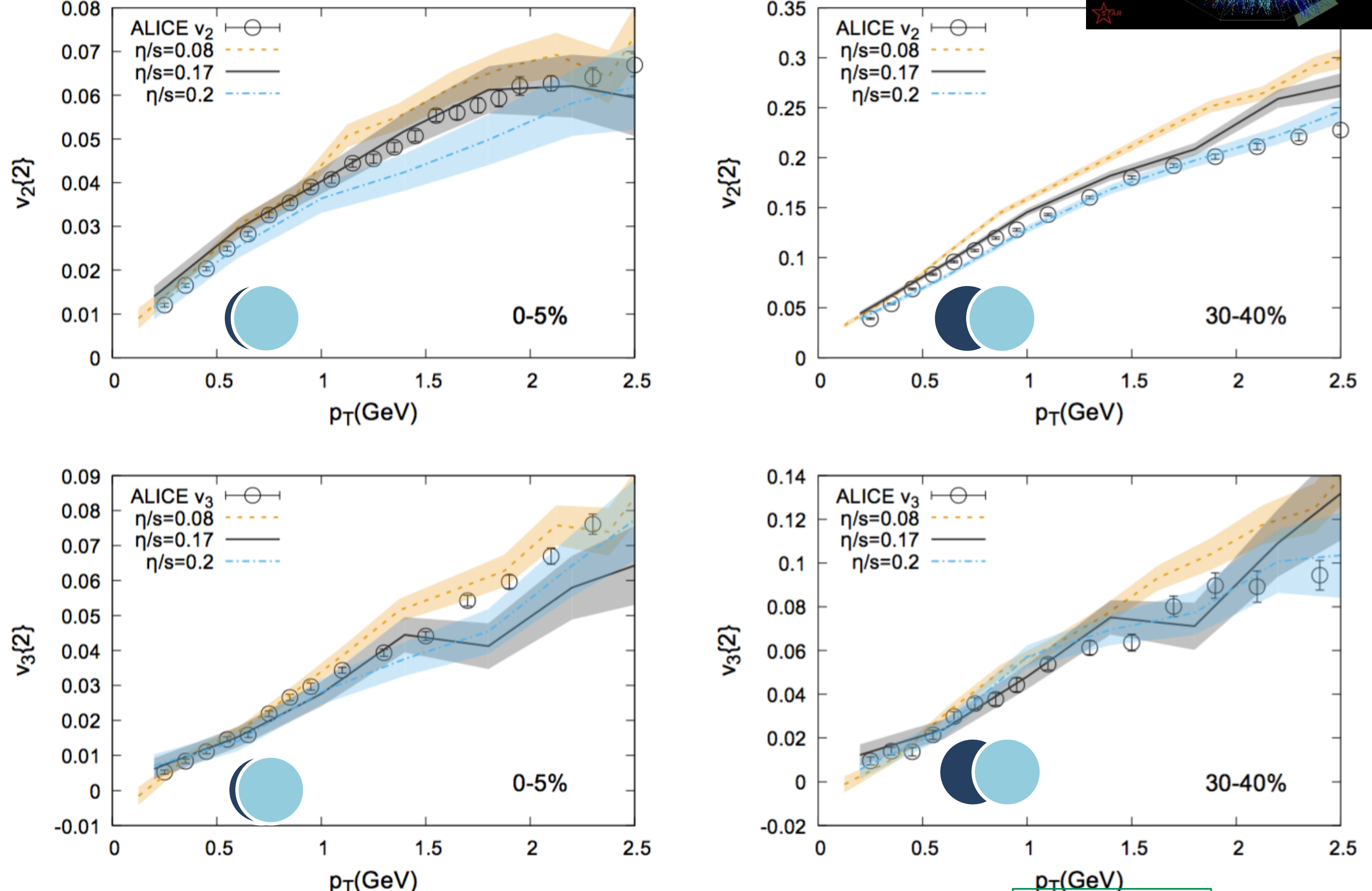
η/s dependence



- Collective Flows



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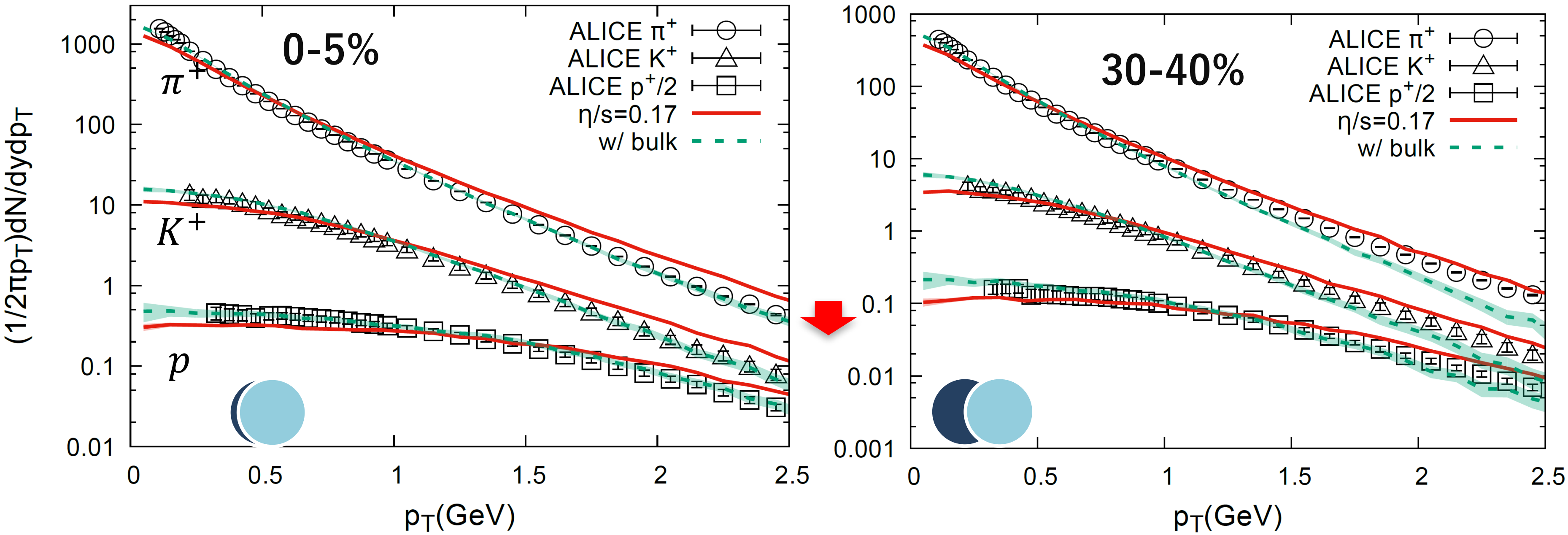
v_2 and v_3 are smaller at larger η/s. → $\eta/s=0.17$

Effect of Bulk Viscosity

- Shear + Bulk viscosities $\zeta = b\eta\left(\frac{1}{3} - c_s^2\right)^2$



Bulk viscosity reduces the transverse expansion.
-> Slope of P_T spectra becomes steep.
-> Close to ALICE data.

Finite bulk viscosity

KMI

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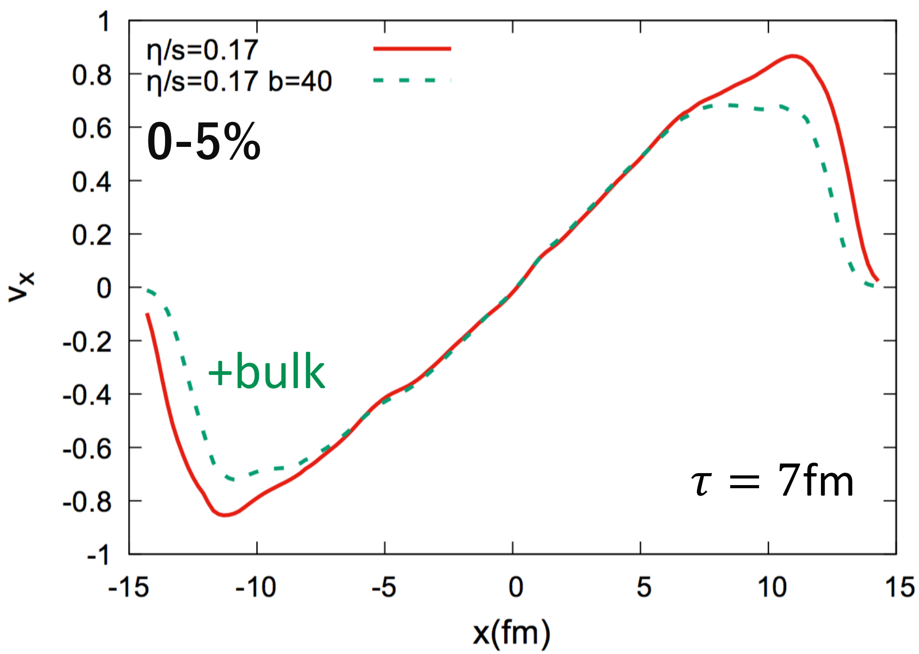
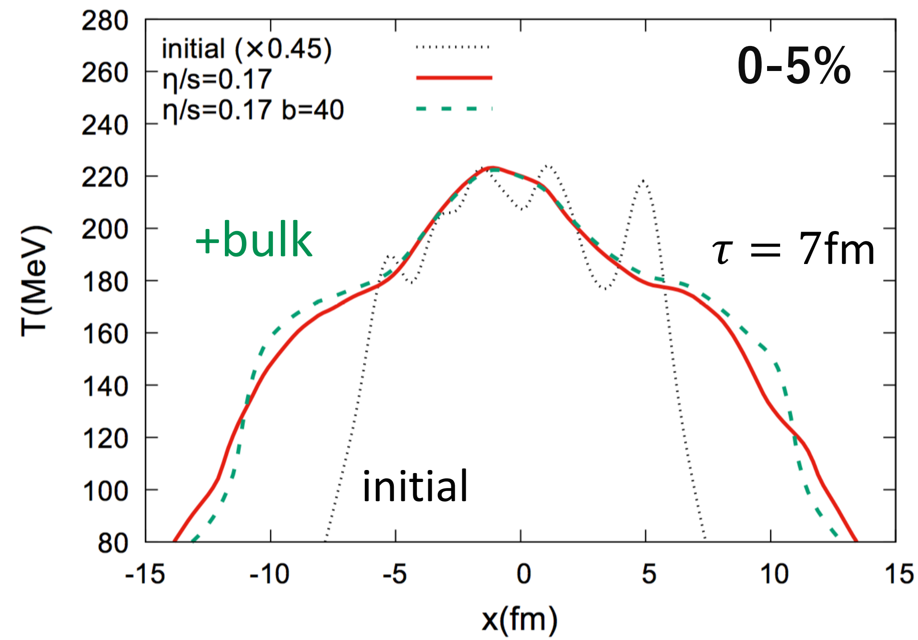
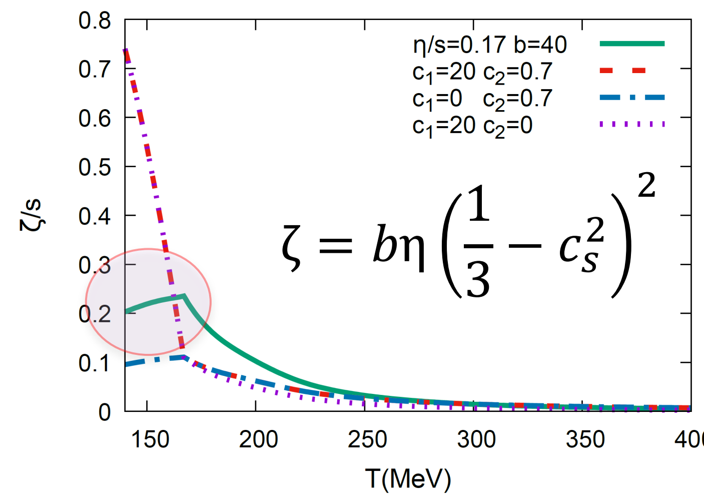
Effect on Expansion





Bulk viscosity is large below 200 MeV.
-> Its effect appears around T_c ~160 MeV.
-> Expansion rate decreases in lower temperature region.
-> Volume elements of fluid remain around T_c temperature longer.



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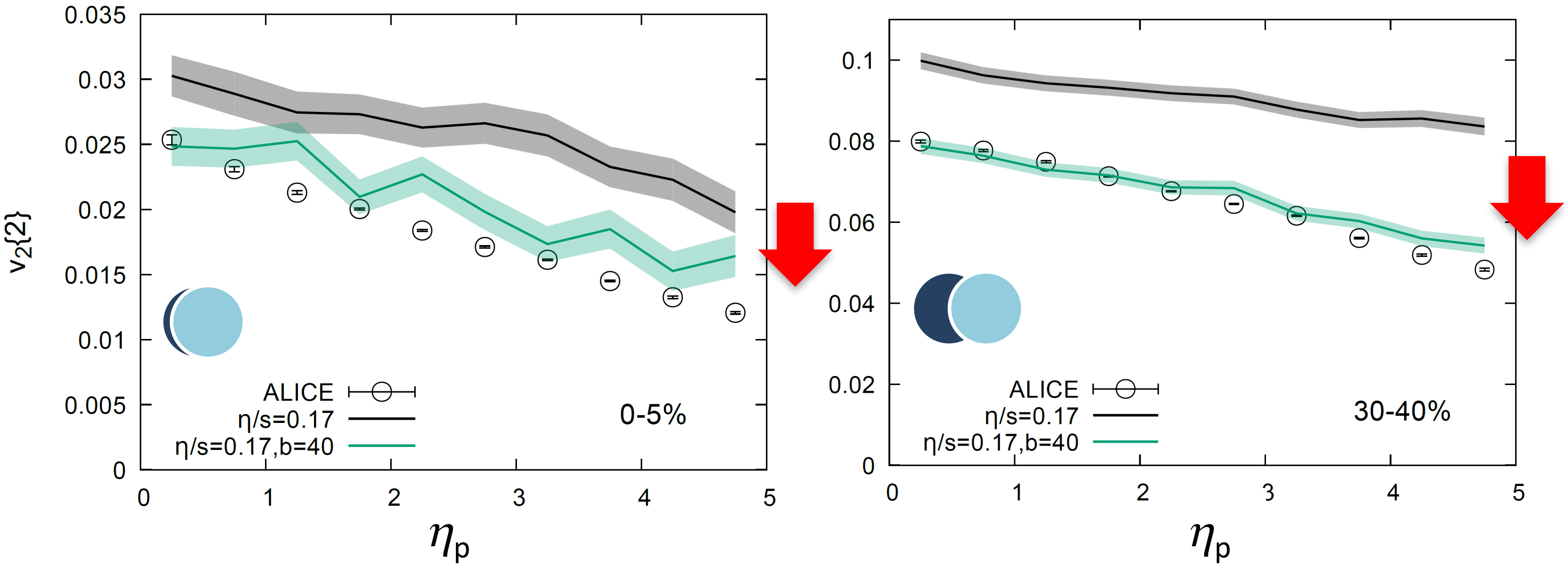
Effect on Collective Flow

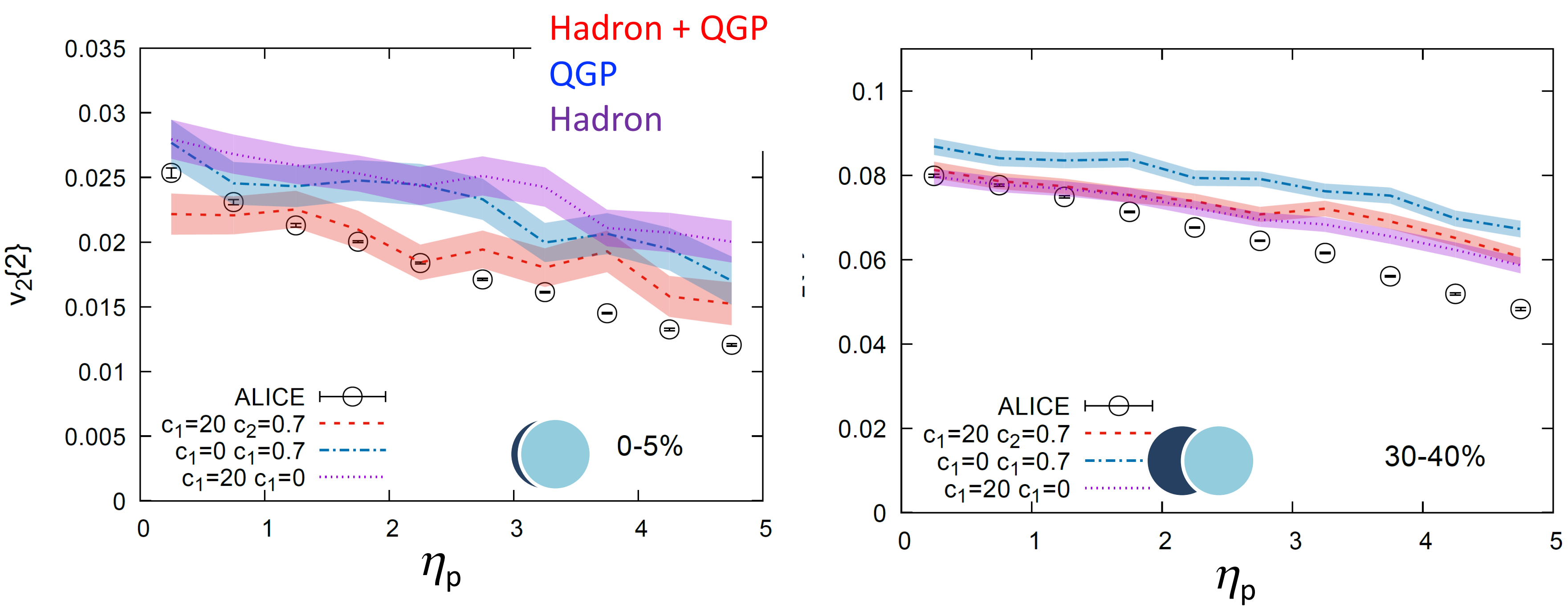
- Collective flow as a function of η_p

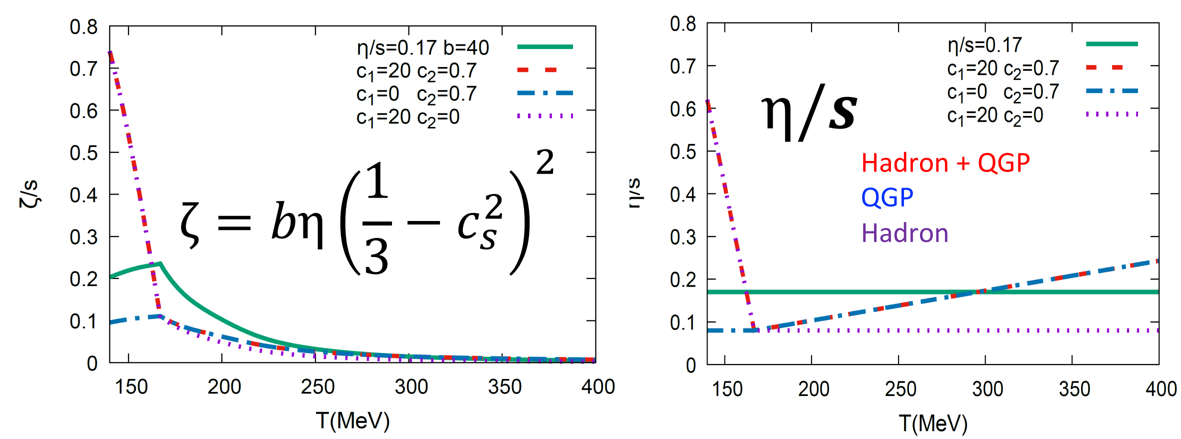


- (3+1)-d calculation
- v_n with bulk viscosity is much closer to the ALICE data: amplitude and slope
- Effect of bulk viscosity at forward rapidity is large.

Finite bulk viscosity

Temperature Dependent η/s





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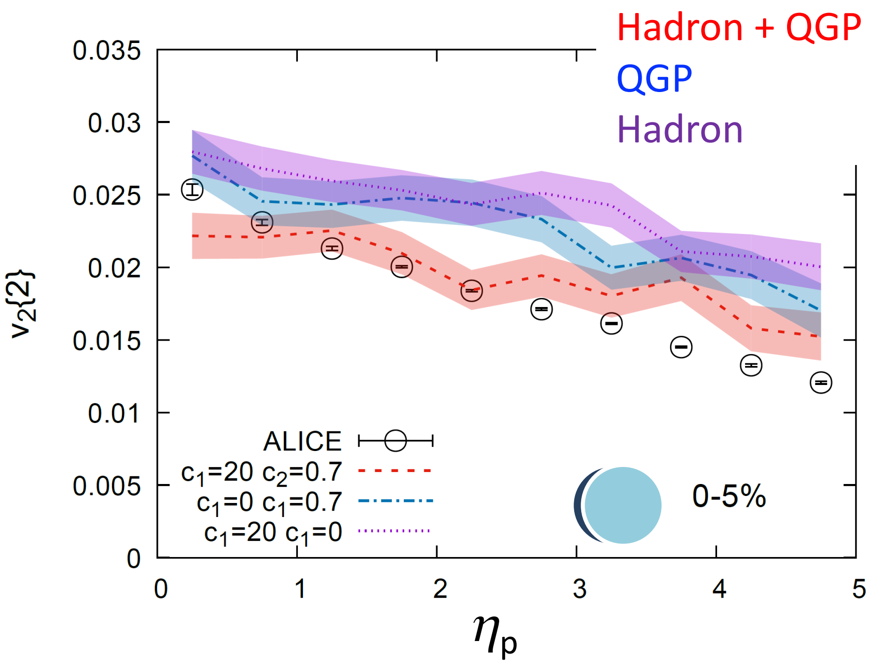

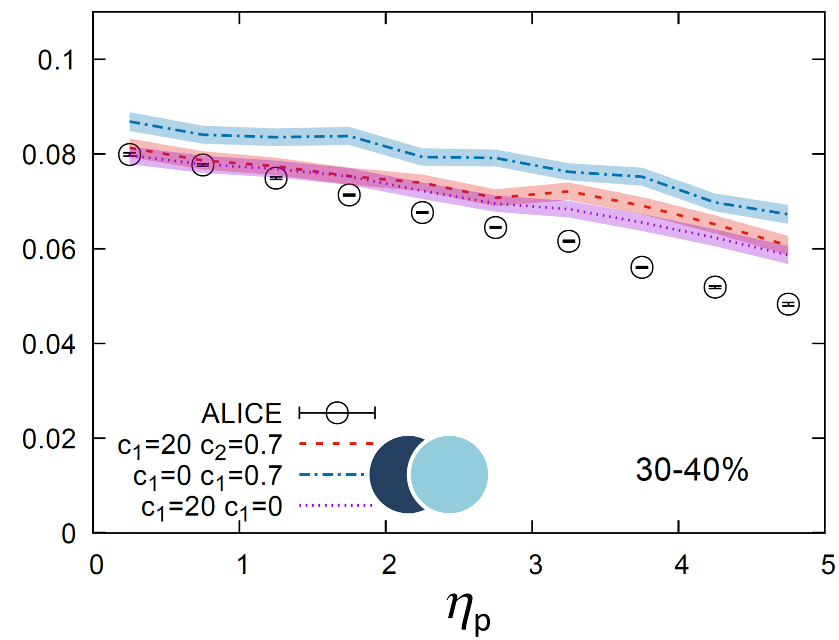

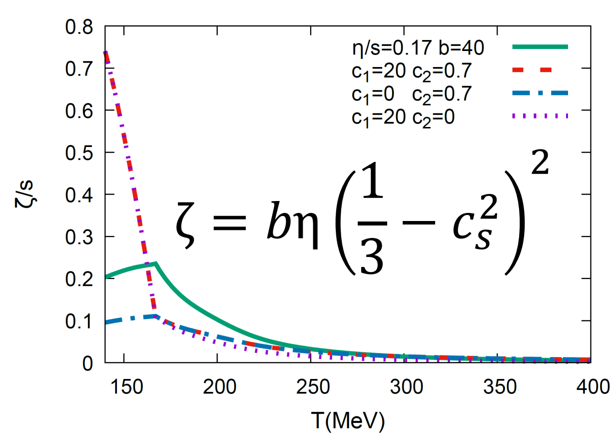

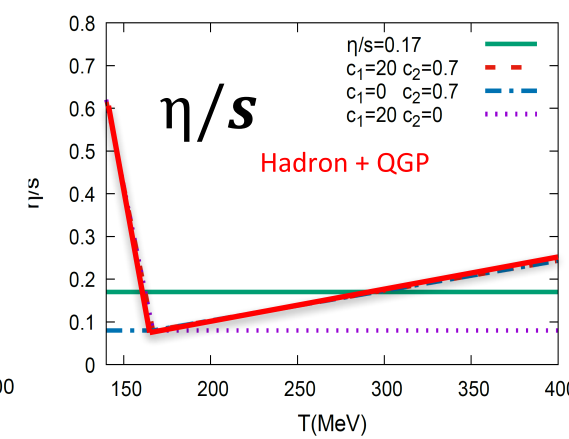

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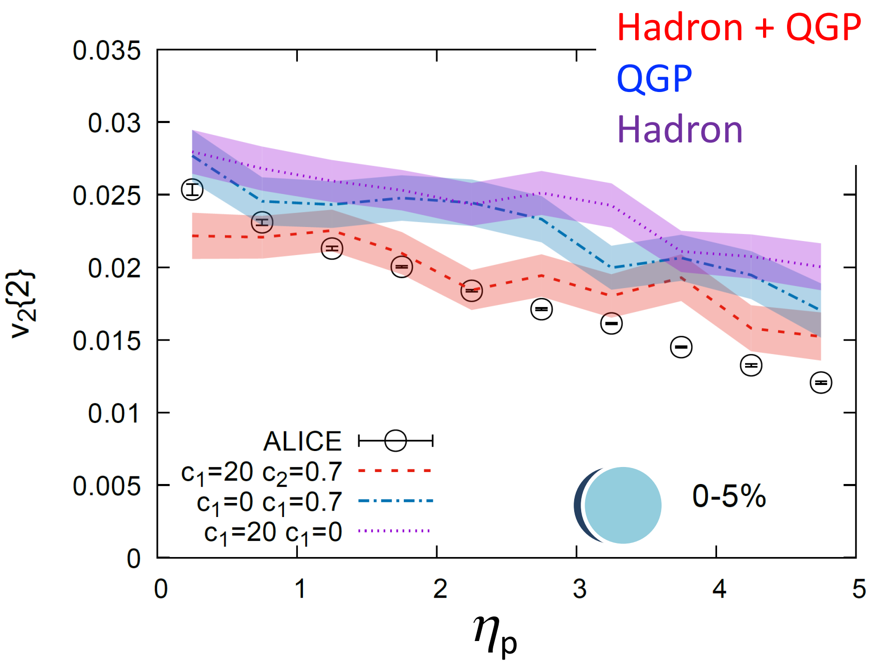
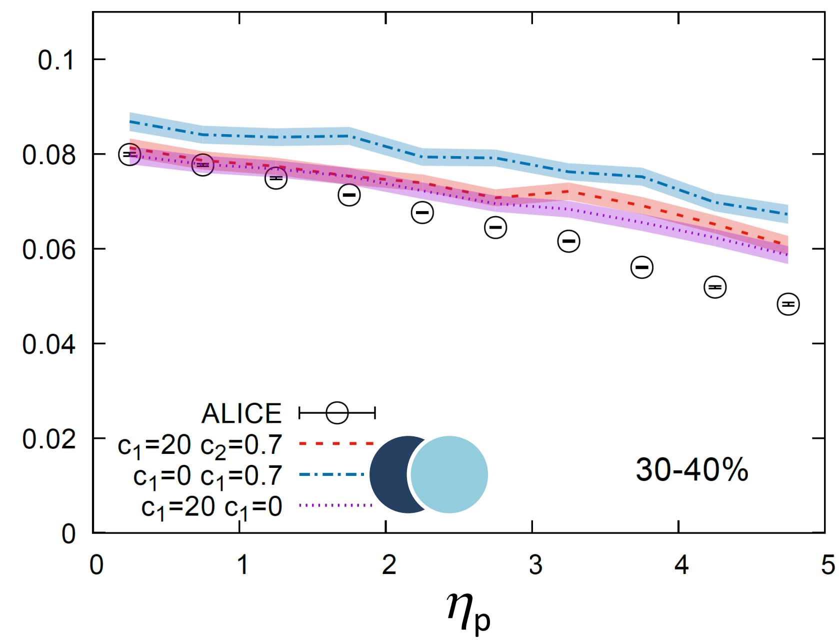
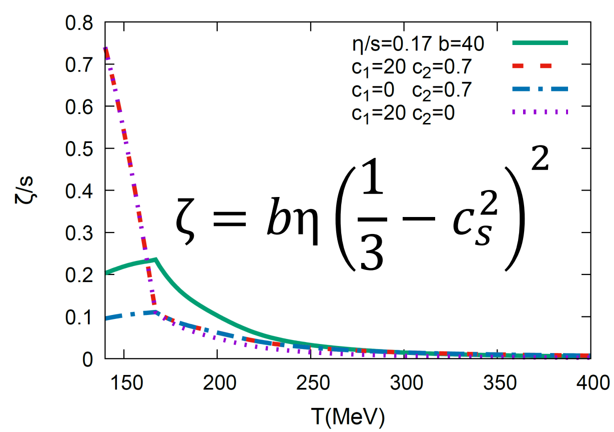
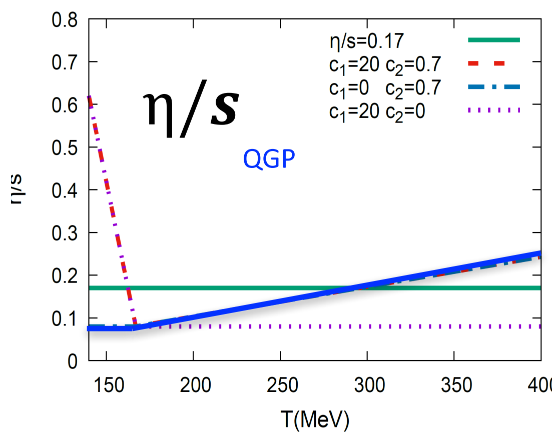
Temperature Dependent η/s









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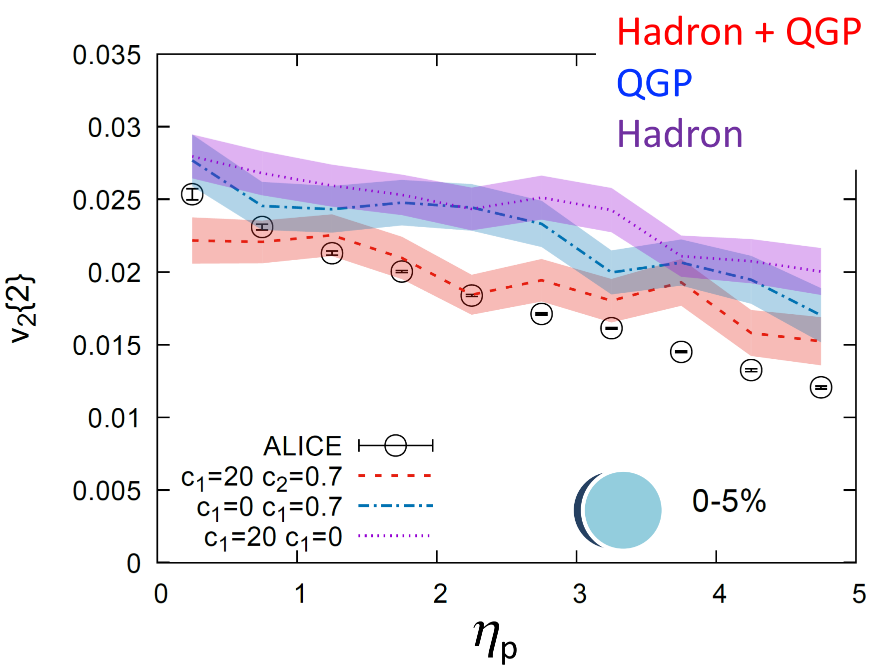
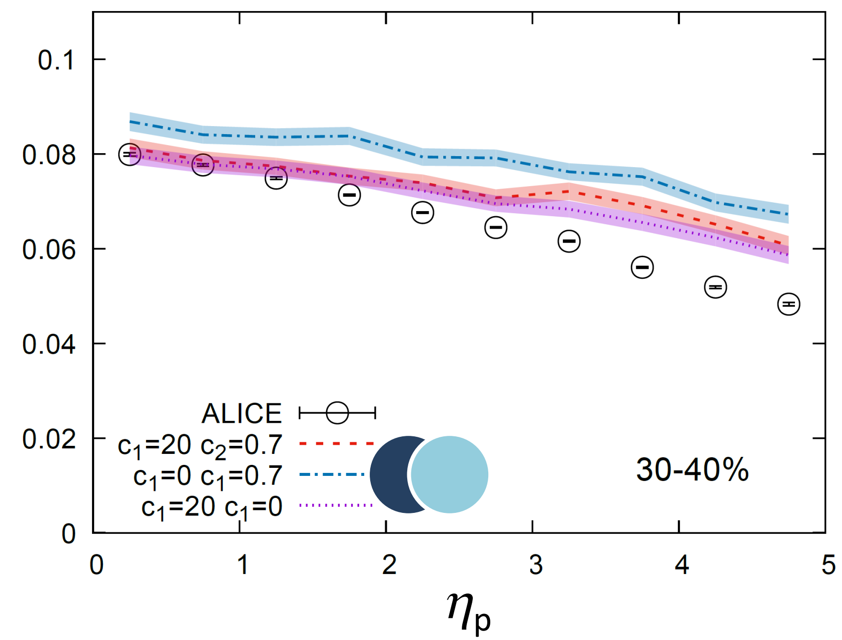
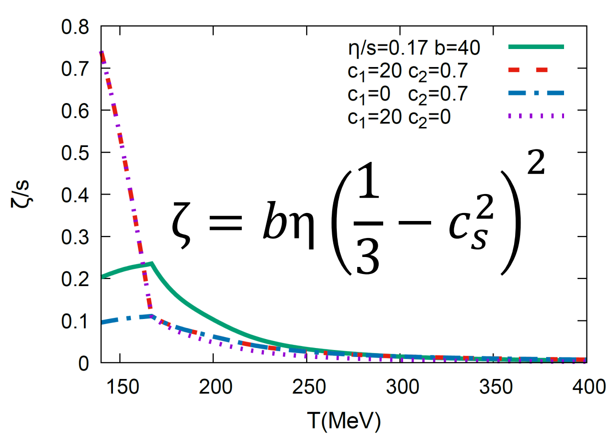
Temperature Dependent η/s







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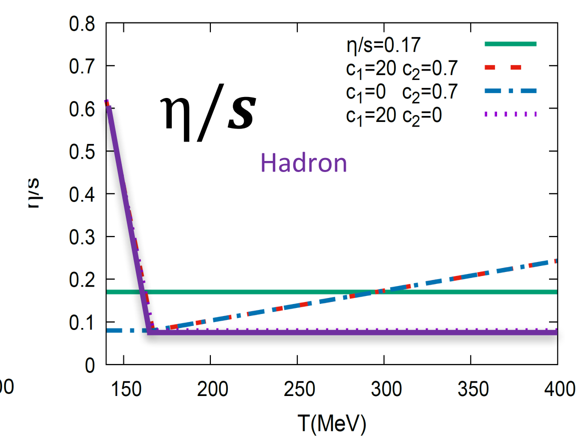
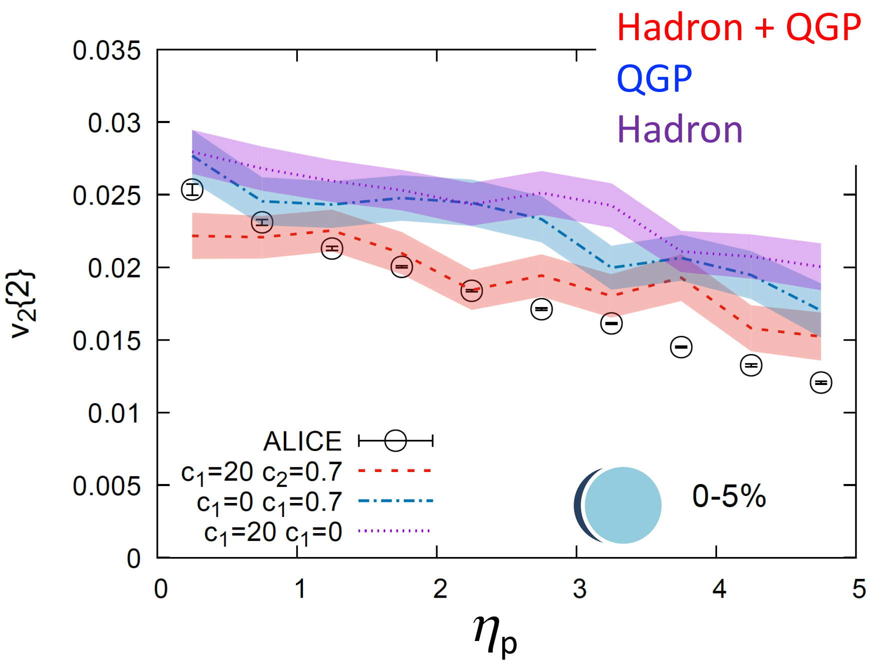
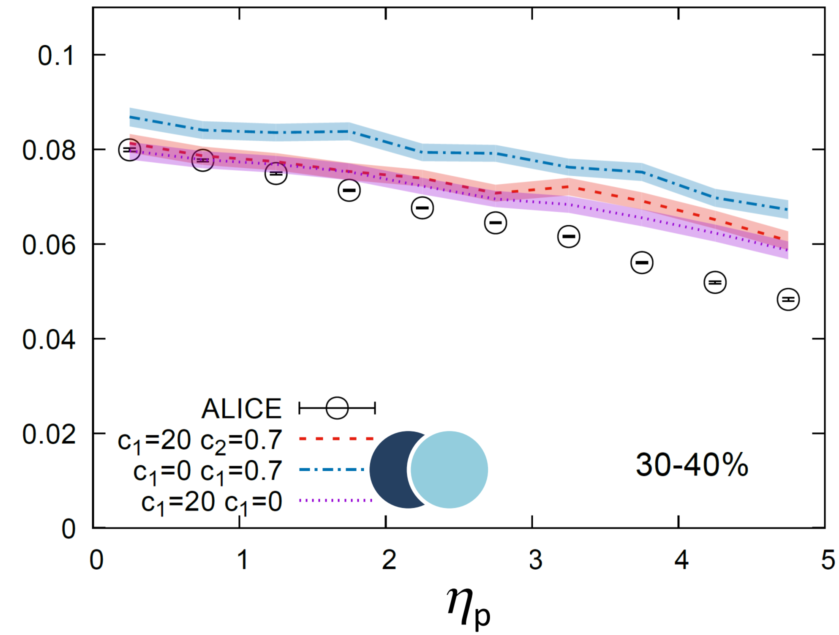


Temperature Dependent η/s



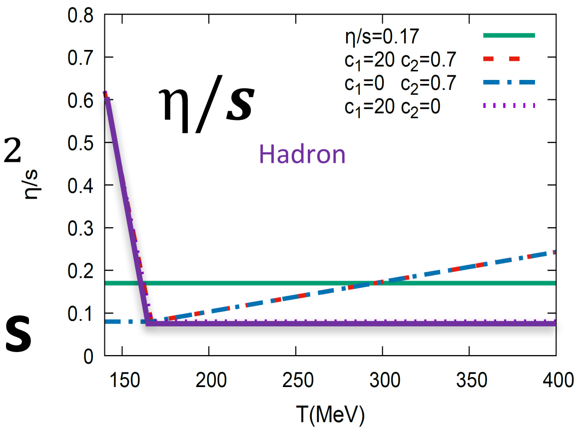


- 0-5 % centrality

  η/s of QGP and hadron phases is important.
- 30-40 % centrality

  η/s of hadron phase is dominant.

$$\zeta = b\eta\left(\frac{1}{3} - c_s^2\right)^2$$



Central dependence of $v_2(\eta_p)$ reveals temperature dependence of η/s.

C. NONAKA

Summary

Understanding QGP bulk property

- New relativistic viscous hydrodynamics code
  - Stable with small numerical dissipation
  - Phenomenological model: TRENTO — Hydro — UrQMD
  - Quantitative analyses

Quantitative analyses

Akamatsu et al, JCP256,34(2014)
Okamoto, Akamatsu, Nonaka, EPJC76,579(2016)
Okamoto and Nonaka, EPJC77,383(2017)
Okamoto and Nonaka, arXiv:1712.00923

- QGP bulk property
  - Shear and bulk viscosity
  - Finite bulk viscosity, central dependence of $v_2(\eta_p)$

Bayesian analyses, deep learning: Bass, Bernhard, Moreland, Pang….

- Future works
  - Two particle correlations（HBT）
  - Electromagnetic probes