Effects of hadronic rescatterings in small system

Tetsufumi Hirano

Sophia Univ.

Ultra-RelatIvistiCH Heavy IoNZ 2016
18-20 July 2016, CERN

Contents

Ulrich’s paper triggered one of my first studies

ELSEVIER

Nuclear Physics A638 (1998) 357c–364c

NUCLEAR PHYSICS A

Hadronic Observables: Theoretical Highlights*

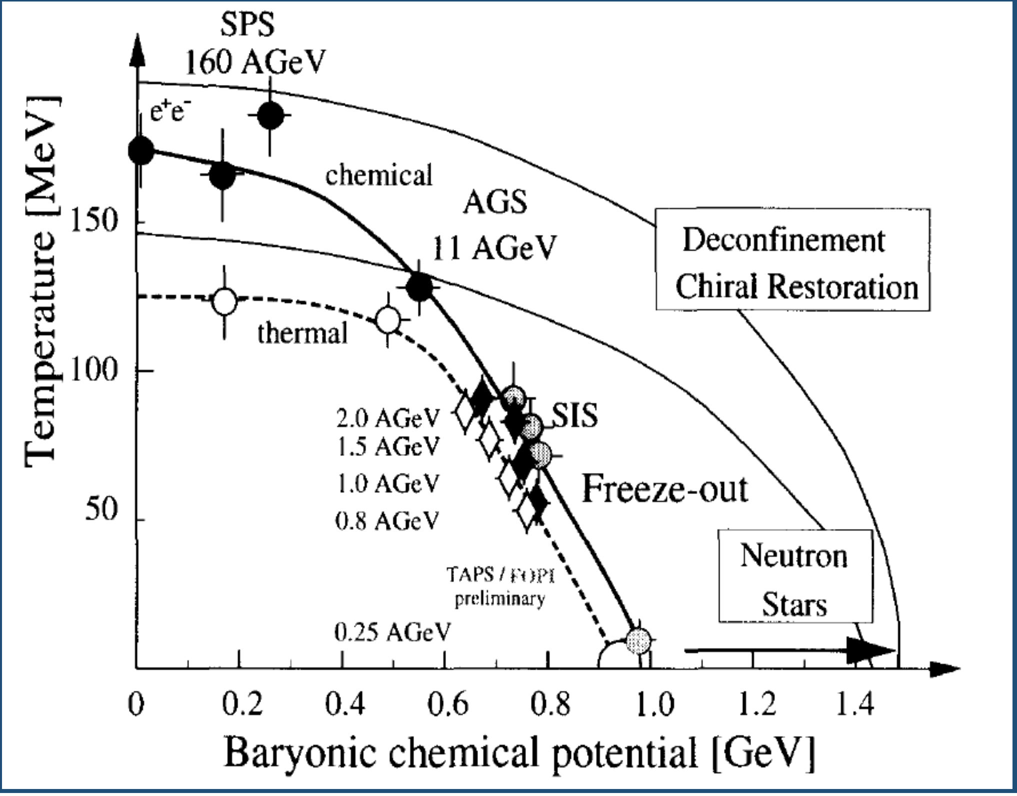
Ulrich Heinz

Inst. für Theoretische Physik, Universität Regensburg, D-93040 Regensburg, Germany

I present highlights from the parallel sessions on the theory of hadronic observables in e^+e^-, hadronic and nuclear reactions.

Proceedings of QM97 at Tsukuba
(My very first QM attendance)

$T_{ch\ f.o.} > T_{th\ f.o.}$



2.3. Rescattering – yes or no?

In his overview of the beam energy dependence of flow phenomena Ollitrault showed that all three types of flow appear in the data simultaneously, pointing to rescattering among the secondary hadrons as a common origin. The difference between the chemical and thermal freeze-out points in Fig. 1 suggests significant *elastic* rescattering between hadronization and decoupling, causing expansion and cooling of the momentum distributions. (Elastic collisions include resonance channels like $\pi+N\to\Delta\to\pi+N$ which do not change particle abundances.) While present SPS data are consistent with a common

Idea of partial chemical equilibrium in hydro

PHYSICAL REVIEW C **66**, 054905 (2002)

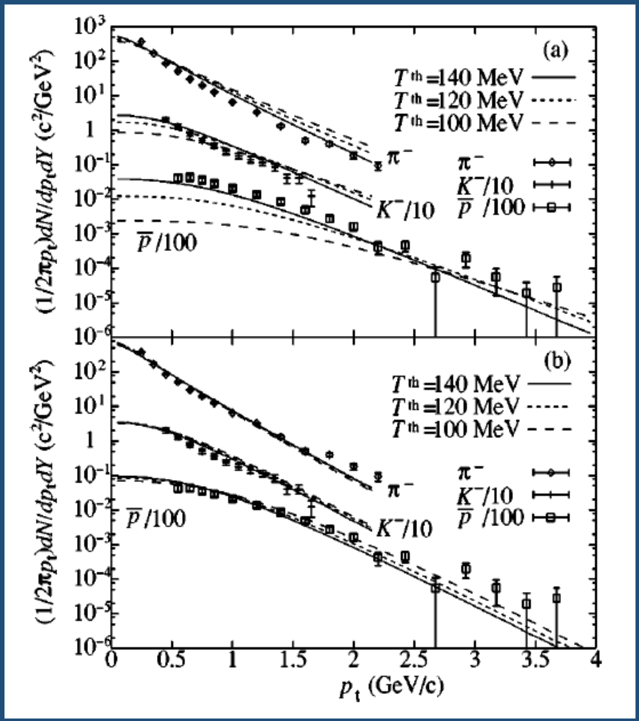
Collective flow and two-pion correlations from a relativistic hydrodynamic model with early chemical freeze-out

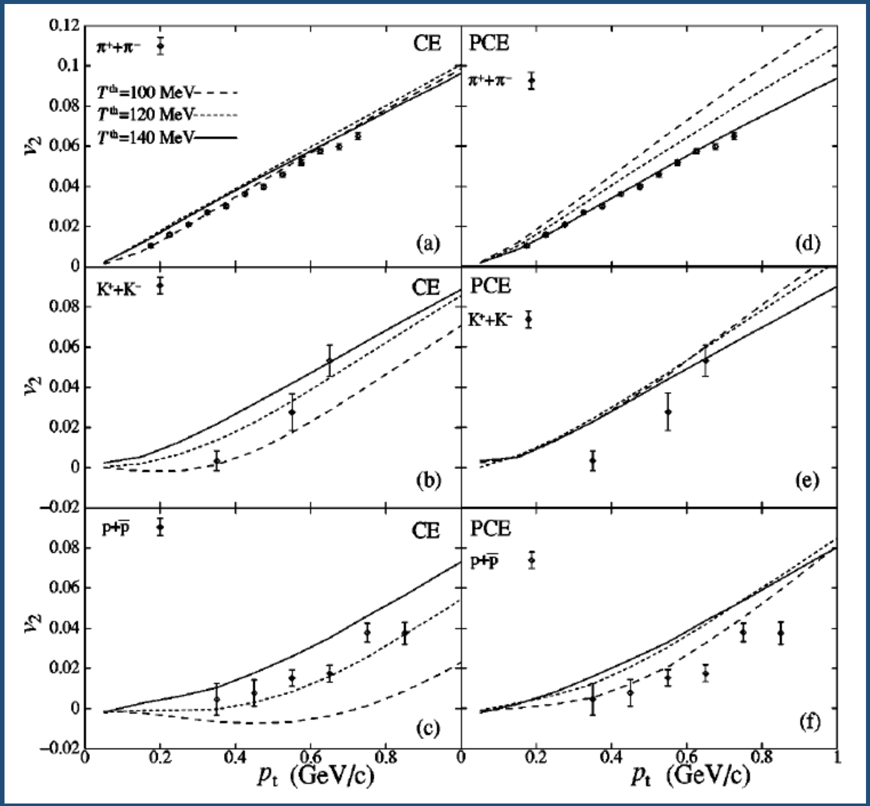
Tetsufumi Hirano[1,*] and Keiichi Tsuda[2]
[1]*Physics Department, University of Tokyo, Tokyo 113-0033, Japan*
[2]*Department of Physics, Waseda University, Tokyo 169-8555, Japan*
(Received 8 August 2002; published 27 November 2002)

Yield and slope of p_T spectra at once within hydro

Similar ideas:
D.Teaney (2002)
P.Kolb and R.Rapp (2003)
P.Huovinen (2008)

Slope of $v_2(p_T)$?





Upper: Chem. Eq.

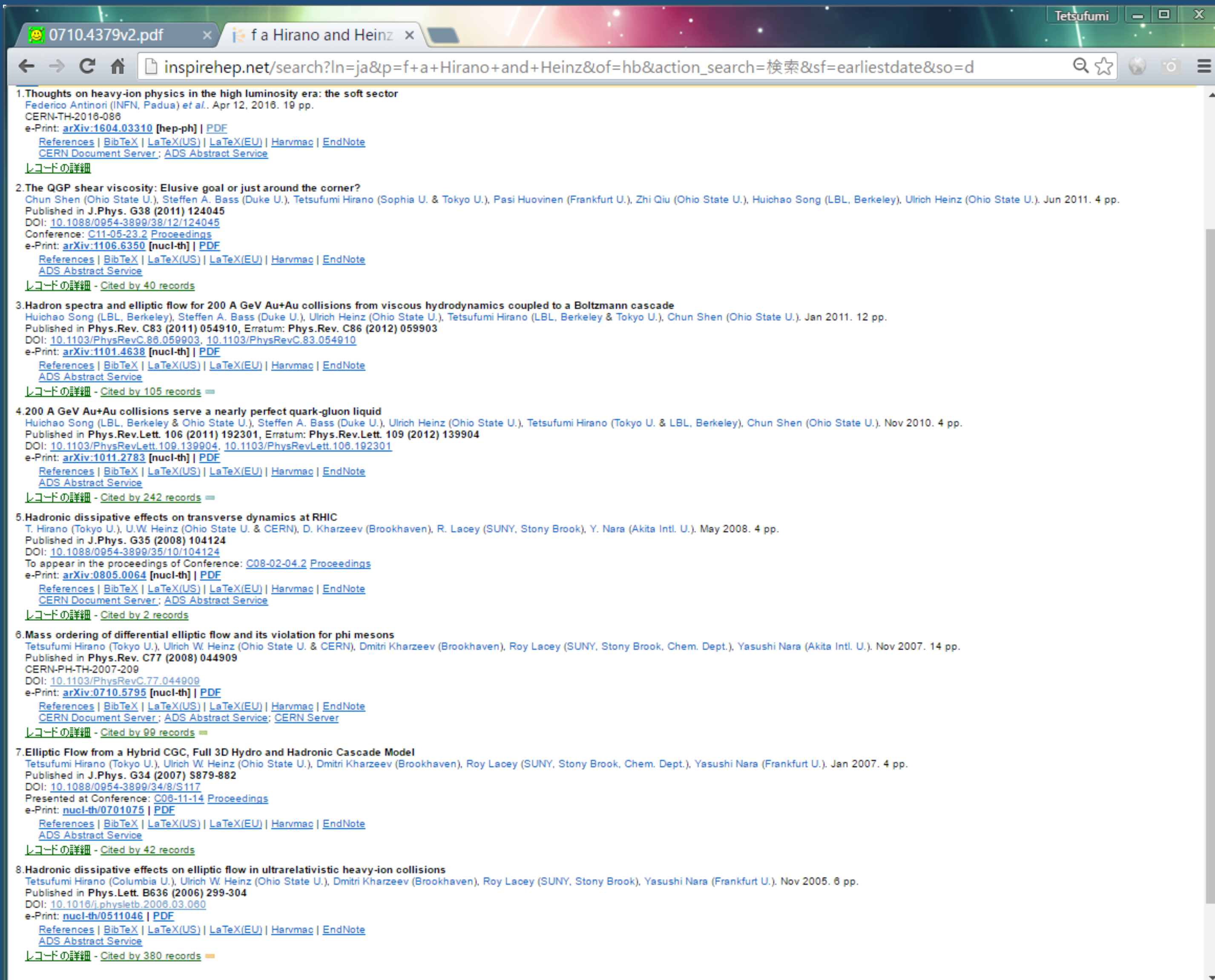
Lower: Partial Chem. Eq.

PCE spoils success of hydro!

Most people: Why is v_2 sensitive to final stage? Simply wrong!

It seemed to me Ulrich was at least interested in these results.

8 papers with Ulrich



0710.4379v2.pdf

f a Hirano and Heinz

Tetsufumi

inspirehep.net/search?ln=ja&p=f+a+Hirano+and+Heinz&of=hb&action_search=検索&sf=earliestdate&so=d

1.**Thoughts on heavy-ion physics in the high luminosity era: the soft sector**
Federico Antinori (INFN, Padua) *et al.*. Apr 12, 2016. 19 pp.
CERN-TH-2016-086
e-Print: arXiv:1604.03310 [hep-ph] | PDF
References | BibTeX | LaTeX(US) | LaTeX(EU) | Harvmac | EndNote
CERN Document Server ; ADS Abstract Service
レコードの詳細

2.**The QGP shear viscosity: Elusive goal or just around the corner?**
Chun Shen (Ohio State U.), Steffen A. Bass (Duke U.), Tetsufumi Hirano (Sophia U. & Tokyo U.), Pasi Huovinen (Frankfurt U.), Zhi Qiu (Ohio State U.), Huichao Song (LBL, Berkeley), Ulrich Heinz (Ohio State U.). Jun 2011. 4 pp.
Published in **J.Phys. G38 (2011) 124045**
DOI: 10.1088/0954-3899/38/12/124045
Conference: C11-05-23.2 Proceedings
e-Print: arXiv:1106.6350 [nucl-th] | PDF
References | BibTeX | LaTeX(US) | LaTeX(EU) | Harvmac | EndNote
ADS Abstract Service
レコードの詳細 - Cited by 40 records

3.**Hadron spectra and elliptic flow for 200 A GeV Au+Au collisions from viscous hydrodynamics coupled to a Boltzmann cascade**
Huichao Song (LBL, Berkeley), Steffen A. Bass (Duke U.), Ulrich Heinz (Ohio State U.), Tetsufumi Hirano (LBL, Berkeley & Tokyo U.), Chun Shen (Ohio State U.). Jan 2011. 12 pp.
Published in **Phys.Rev. C83 (2011) 054910**, Erratum: **Phys.Rev. C86 (2012) 059903**
DOI: 10.1103/PhysRevC.86.059903, 10.1103/PhysRevC.83.054910
e-Print: arXiv:1101.4638 [nucl-th] | PDF
References | BibTeX | LaTeX(US) | LaTeX(EU) | Harvmac | EndNote
ADS Abstract Service
レコードの詳細 - Cited by 105 records

4.**200 A GeV Au+Au collisions serve a nearly perfect quark-gluon liquid**
Huichao Song (LBL, Berkeley & Ohio State U.), Steffen A. Bass (Duke U.), Ulrich Heinz (Ohio State U.), Tetsufumi Hirano (Tokyo U. & LBL, Berkeley), Chun Shen (Ohio State U.). Nov 2010. 4 pp.
Published in **Phys.Rev.Lett. 106 (2011) 192301**, Erratum: **Phys.Rev.Lett. 109 (2012) 139904**
DOI: 10.1103/PhysRevLett.109.139904, 10.1103/PhysRevLett.106.192301
e-Print: arXiv:1011.2783 [nucl-th] | PDF
References | BibTeX | LaTeX(US) | LaTeX(EU) | Harvmac | EndNote
ADS Abstract Service
レコードの詳細 - Cited by 242 records

5.**Hadronic dissipative effects on transverse dynamics at RHIC**
T. Hirano (Tokyo U.), U.W. Heinz (Ohio State U. & CERN), D. Kharzeev (Brookhaven), R. Lacey (SUNY, Stony Brook), Y. Nara (Akita Intl. U.). May 2008. 4 pp.
Published in **J.Phys. G35 (2008) 104124**
DOI: 10.1088/0954-3899/35/10/104124
To appear in the proceedings of Conference: C08-02-04.2 Proceedings
e-Print: arXiv:0805.0064 [nucl-th] | PDF
References | BibTeX | LaTeX(US) | LaTeX(EU) | Harvmac | EndNote
CERN Document Server ; ADS Abstract Service
レコードの詳細 - Cited by 2 records

6.**Mass ordering of differential elliptic flow and its violation for phi mesons**
Tetsufumi Hirano (Tokyo U.), Ulrich W. Heinz (Ohio State U. & CERN), Dmitri Kharzeev (Brookhaven), Roy Lacey (SUNY, Stony Brook, Chem. Dept.), Yasushi Nara (Akita Intl. U.). Nov 2007. 14 pp.
Published in **Phys.Rev. C77 (2008) 044909**
CERN-PH-TH-2007-209
DOI: 10.1103/PhysRevC.77.044909
e-Print: arXiv:0710.5795 [nucl-th] | PDF
References | BibTeX | LaTeX(US) | LaTeX(EU) | Harvmac | EndNote
CERN Document Server ; ADS Abstract Service; CERN Server
レコードの詳細 - Cited by 99 records

7.**Elliptic Flow from a Hybrid CGC, Full 3D Hydro and Hadronic Cascade Model**
Tetsufumi Hirano (Tokyo U.), Ulrich W. Heinz (Ohio State U.), Dmitri Kharzeev (Brookhaven), Roy Lacey (SUNY, Stony Brook, Chem. Dept.), Yasushi Nara (Frankfurt U.). Jan 2007. 4 pp.
Published in **J.Phys. G34 (2007) S879-882**
DOI: 10.1088/0954-3899/34/8/S117
Presented at Conference: C06-11-14 Proceedings
e-Print: nucl-th/0701075 | PDF
References | BibTeX | LaTeX(US) | LaTeX(EU) | Harvmac | EndNote
ADS Abstract Service
レコードの詳細 - Cited by 42 records

8.**Hadronic dissipative effects on elliptic flow in ultrarelativistic heavy-ion collisions**
Tetsufumi Hirano (Columbia U.), Ulrich W. Heinz (Ohio State U.), Dmitri Kharzeev (Brookhaven), Roy Lacey (SUNY, Stony Brook), Yasushi Nara (Frankfurt U.). Nov 2005. 6 pp.
Published in **Phys.Lett. B636 (2006) 299-304**
DOI: 10.1016/j.physletb.2006.03.060
e-Print: nucl-th/0511046 | PDF
References | BibTeX | LaTeX(US) | LaTeX(EU) | Harvmac | EndNote
ADS Abstract Service
レコードの詳細 - Cited by 380 records

Very first full 3D hydro + cascade

ELSEVIER

Available online at www.sciencedirect.com

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Physics Letters B 636 (2006) 299–304

PHYSICS LETTERS B

www.elsevier.com/locate/physletb

Hadronic dissipative effects on elliptic flow in ultrarelativistic heavy-ion collisions

Tetsufumi Hirano [a,*], Ulrich Heinz [b], Dmitri Kharzeev [c], Roy Lacey [d], Yasushi Nara [e]

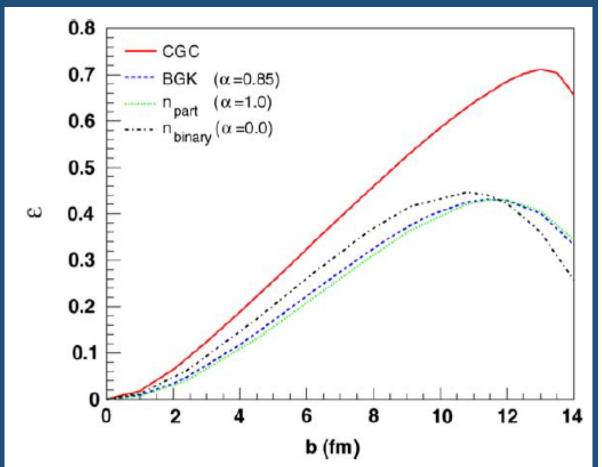
[a] *Department of Physics, Columbia University, 538 West 120th Street, New York, NY 10027, USA*
[b] *Department of Physics, Ohio State University, 191 West Woodruff Avenue, Columbus, OH 43210, USA*
[c] *Nuclear Theory Group, Physics Department, Brookhaven National Laboratory, Upton, NY 11973-5000, USA*
[d] *Department of Chemistry, SUNY Stony Brook, Stony Brook, NY 11794-3400, USA*
[e] *Institut für Theoretische Physik, J.W. Goethe-Universität, Max v. Laue Str. 1, D-60438 Frankfurt, Germany*

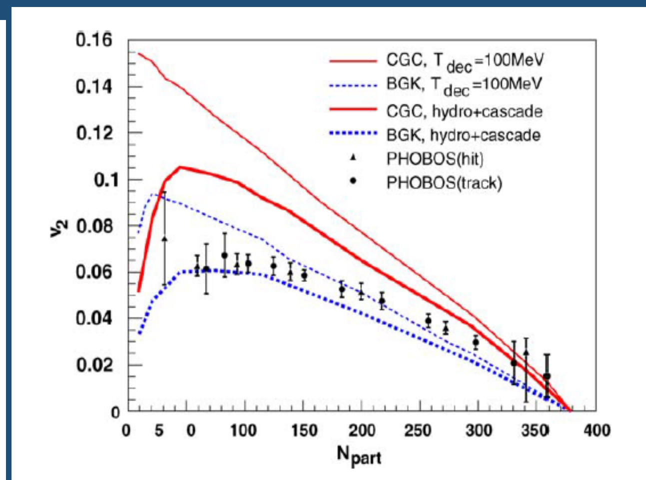
Received 17 November 2005; received in revised form 27 January 2006; accepted 27 March 2006

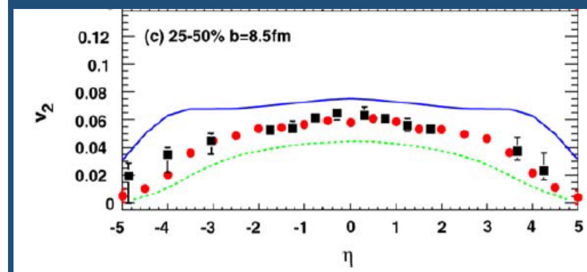
Available online 7 April 2006

Editor: J.-P. Blaizot

Main results







$\varepsilon_{2,\mathrm{CGC}} > \varepsilon_{2,\mathrm{Glauber}}$

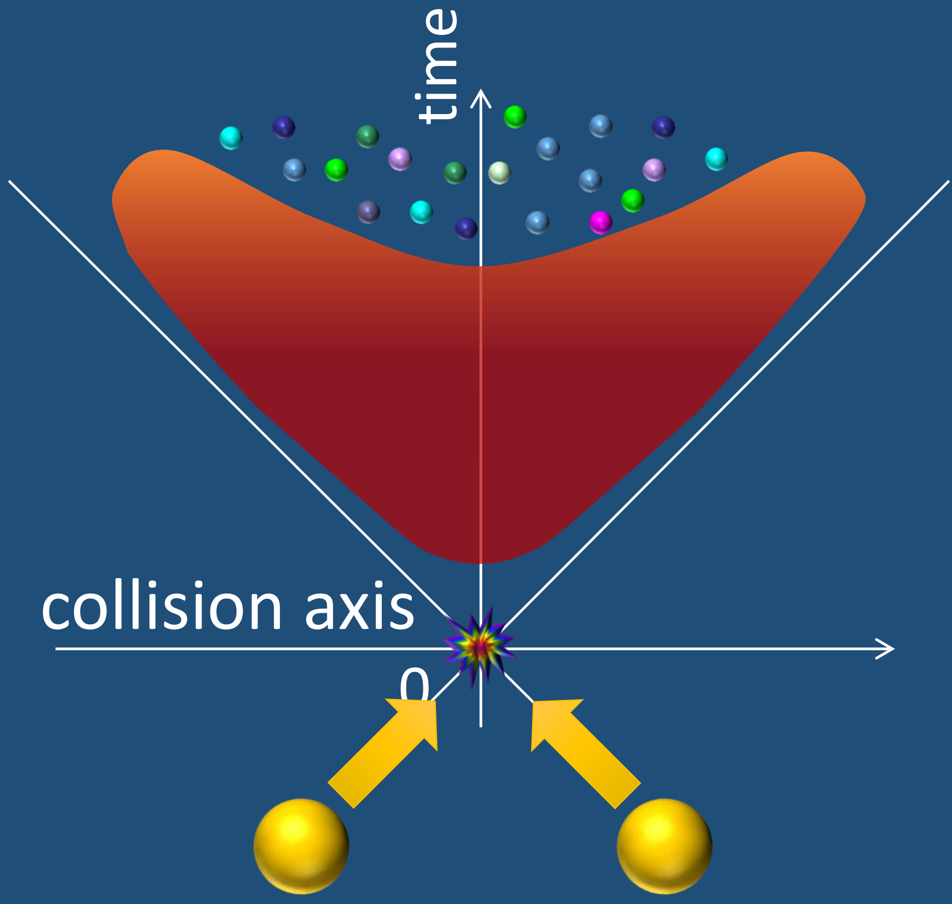
Initial condition: CGC vs. Glauber

v2(eta): Crucial roll played by hadronic rescatterings

These ideas survive in recent hydro analysis

Contents

Integrated dynamical model



<u>Hadronic cascade model</u>
Microscopic description of Hadron gases (JAM)

<u>Relativistic hydrodynamics</u>
Space-time evolution of QGP+hadronic fluids
Lattice EOS

<u>Monte-Carlo Glauber/KLN model</u>
Initial profile of matter

Hirano, Huovinen, Murase, Nara (2013)
Takeuchi, MHHN (2015)

Contents

Rapidity triangle/trapezoid of $(dN_{dAu}/deta)/(dN_{pp}/deta)$

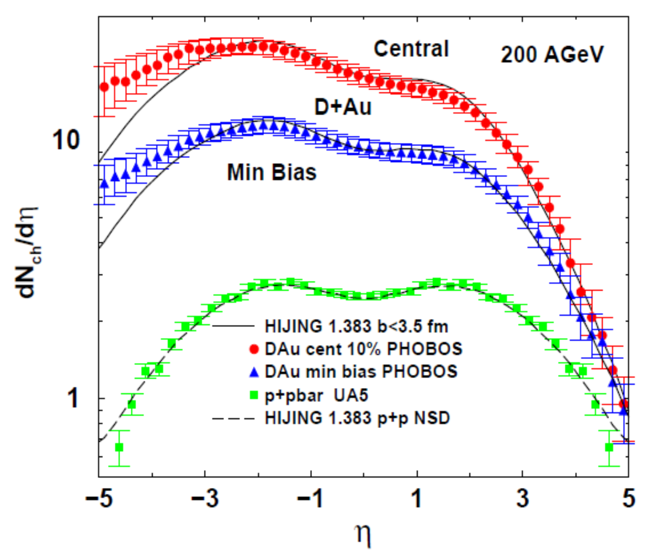


FIG. 2: Asymmetric pseudorapidity distributions of charged hadrons produced in $D+Au$ minimum bias and central 0-10% reactions at 200 AGeV from PHOBOS[12] are compared to $p+\bar{p}$ data from UA5[13]. The curves show predictions using the HIJING v1.383 code[14]. (In color online)

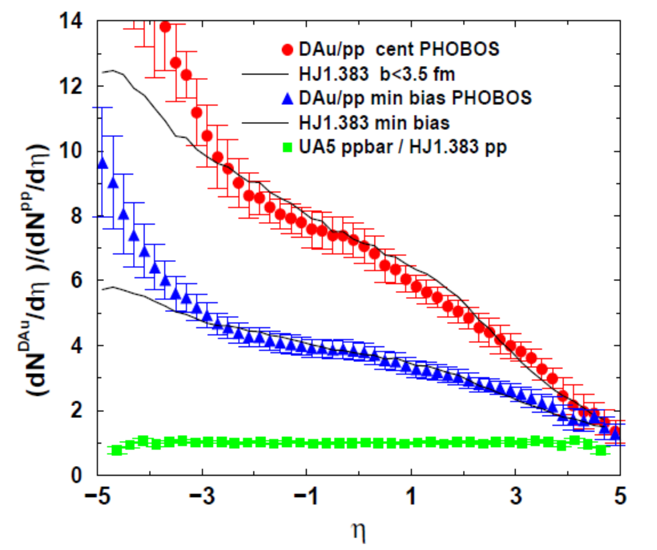
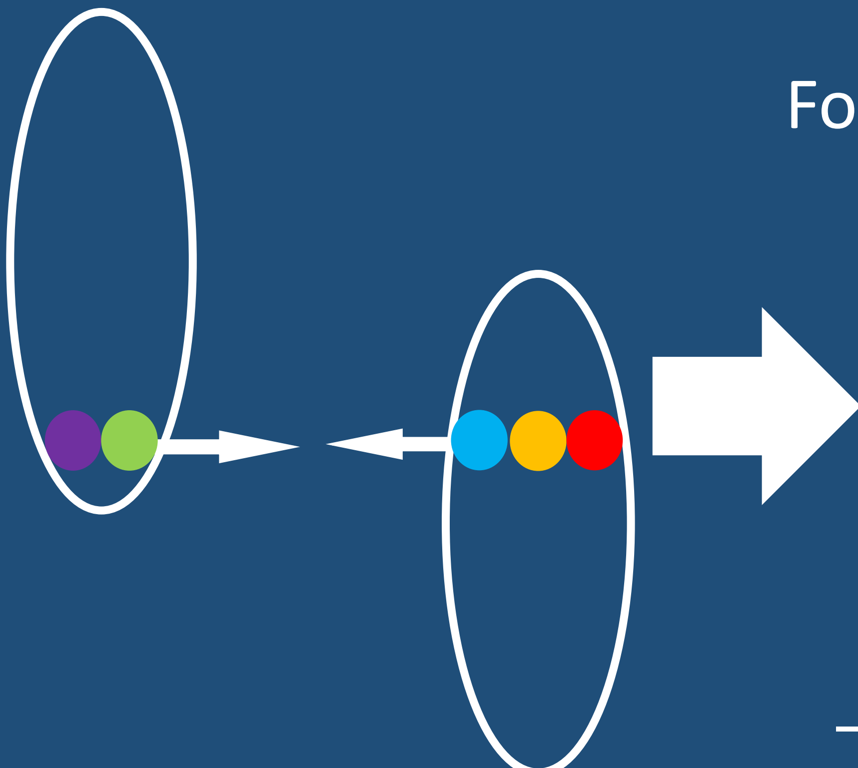


FIG. 1: The approximate triangular form of the ratio of the observed $D+Au$[12] charged particle pseudorapidity distributions to the dashed HIJING $p+p$ curve from Fig.1 are shown for two centrality cuts. The solid curves are predictions using HIJING 1.383 [14] for $D+Au/p+p$. The ratio of UA5 $p+\bar{p}$[13] data to the baseline HIJING p+p predictions are shown by filled squares. (In color online)

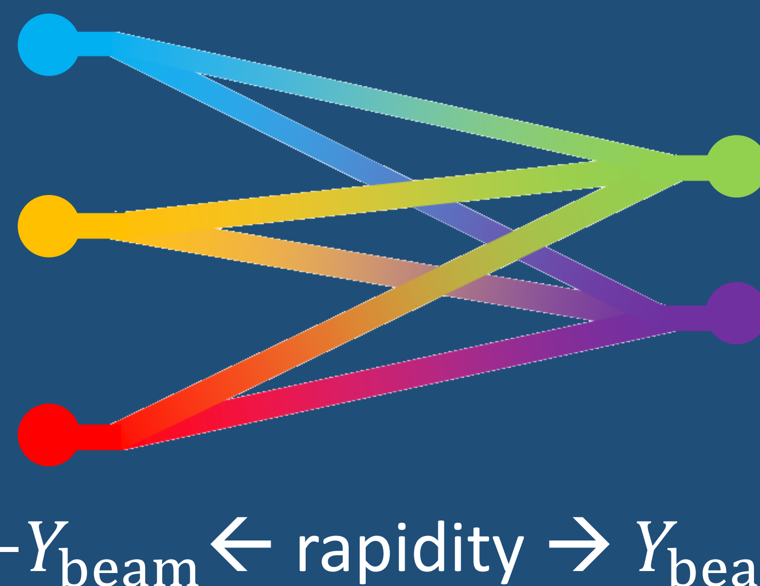
Figures from
Adil and Gyulassy (2005)

Original BGK: Brodsky, Gunion, Kuhn (1977)

Modified BGK model



Formation of hadronic strings

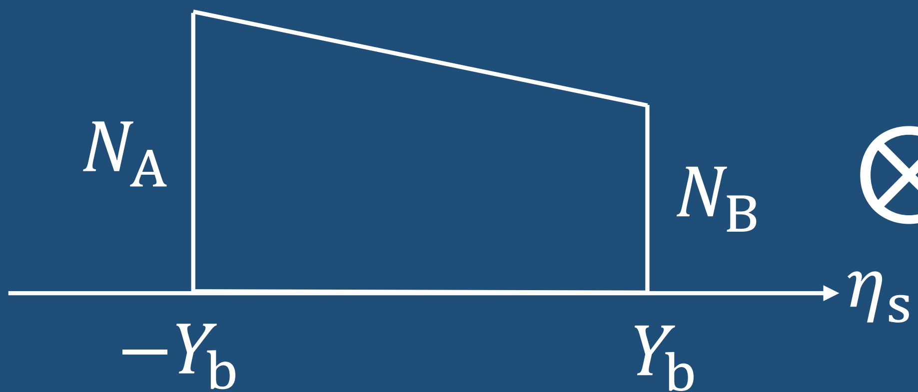


Number of participants from MC-Glauber model

Parametrization of entropy density dist.

Rapidity dependence of initial entropy density

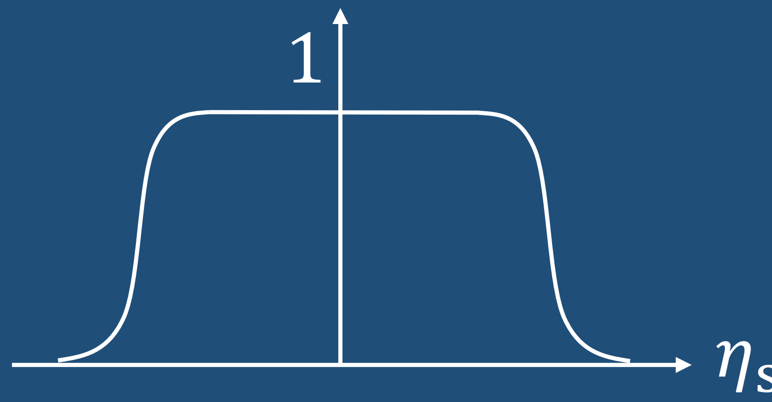
$s_0(\tau_0, \eta_s, x_\perp) \propto$



Rapidity triangle/trapezoid

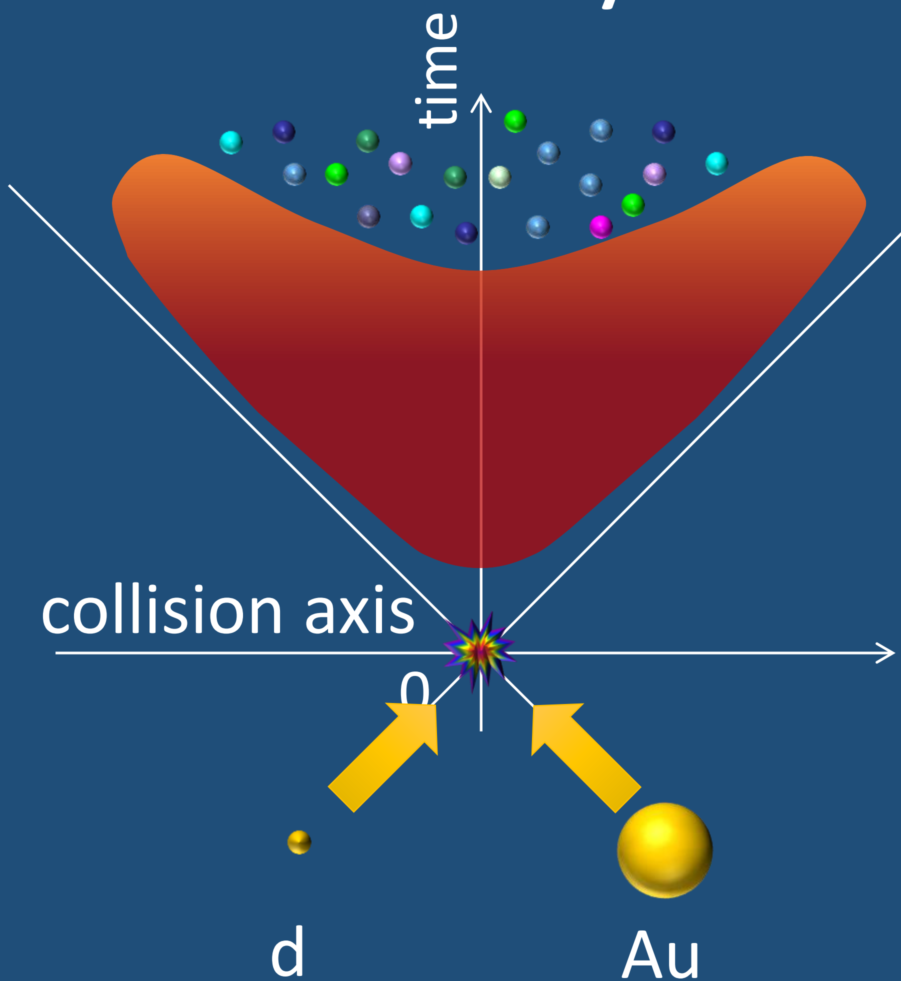
$\otimes$

$f^{pp}(\eta_s)$



Rapidity profile in pp collisions
→ Boost inv. near midrapidity

Integrated dynamical model for small systems



<u>Hadronic cascade model</u>
Microscopic description of Hadron gases

<u>Relativistic hydrodynamics</u>
Space-time evolution of QGP+hadronic fluids

<u>Monte-Carlo Glauber + modified BGK + PYTHIA</u>
Initial profile of matter

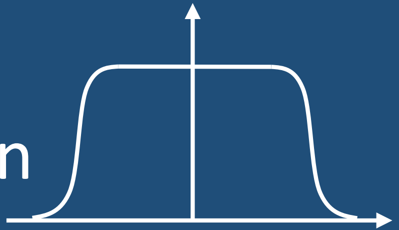
NEW

Kawaguchi, Murase, Hirano (work in progress)

New version of Modified BGK Model

Issues in $f^{pp}(\eta_s)$

- No multiplicity fluctuation
  - Multiplicity does not fluctuate in pp collisions.
- No longitudinal fluctuation
  - Smooth profile in longitudinal direction



➡ PYTHIA8.1

Multiplicity fluctuation even in pp collisions

Fluctuation of longitudinal matter profile

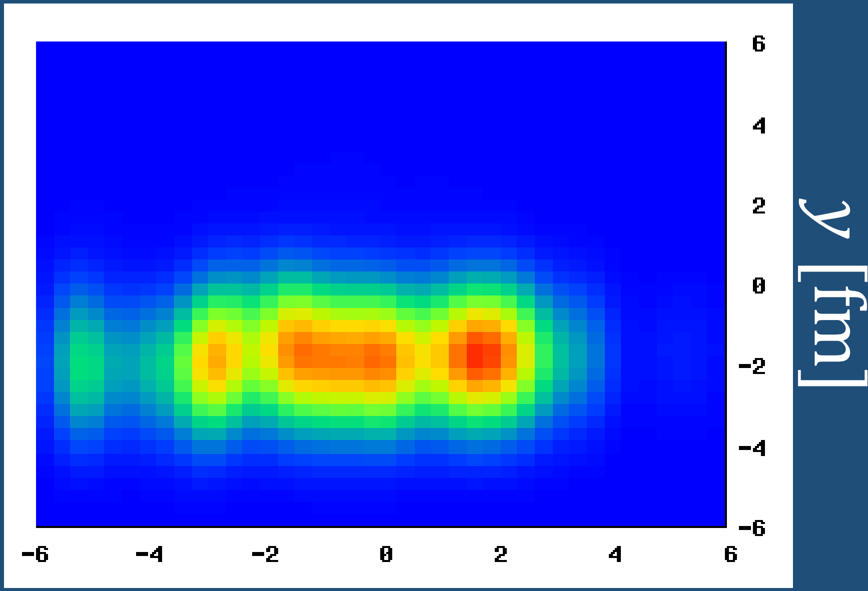
→New baseline initial condition based on Glauber picture

Contents

1. My early career and collaboration with Ulrich
2. Integrated dynamical model
3. Initial longitudinal structure
4. Results in d+Au
5. Hydro + mini-jet model
6. Summary

Matter Profile in d+Au Collision

Longitudinal profile $(x = 0)$

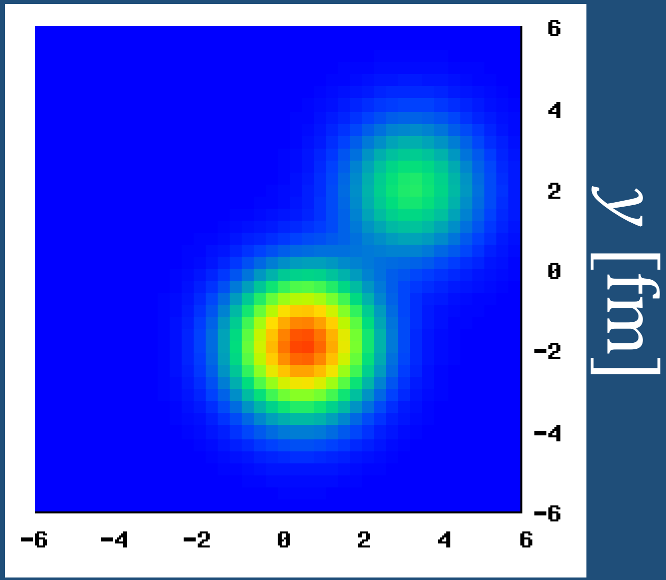


Au-going side

η_s

d-going side

Transverse profile $(\eta_s = 0)$

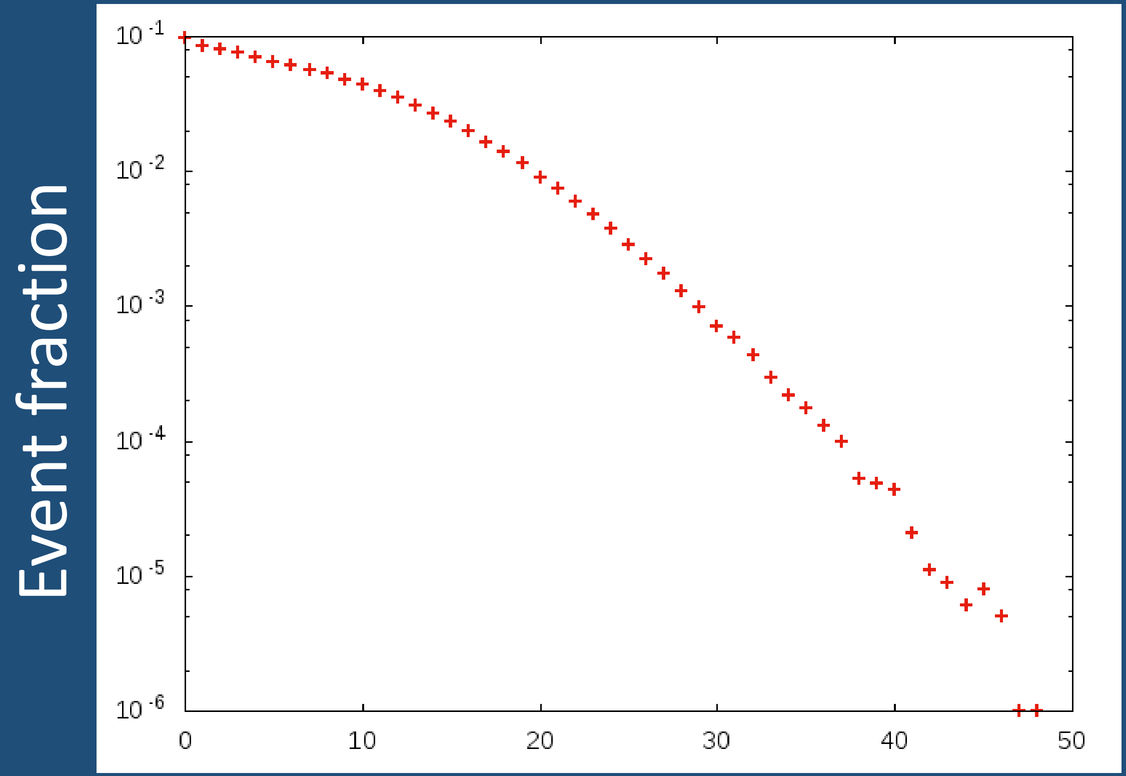


x [fm]

Smearing parameters

$$\delta_x = \delta_y = 0.3\ [\text{fm}], \delta_{\eta_s} = 0.3$$

Multiplicity distribution in d+Au collisions

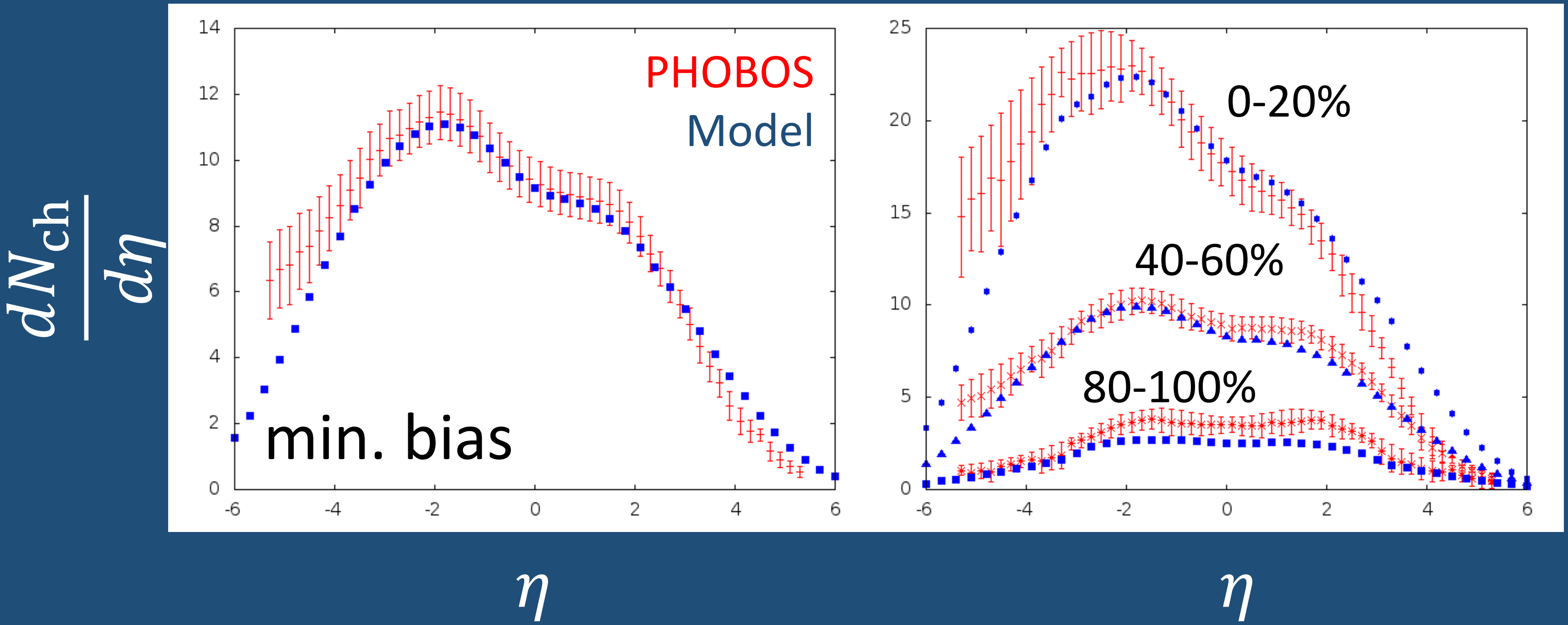


$N_{\mathrm{ch}}(-3.9 < \eta < -3.0)$

Au-going side

Utilize for centrality cut

Pseudorapidity distribution in d+Au collisions

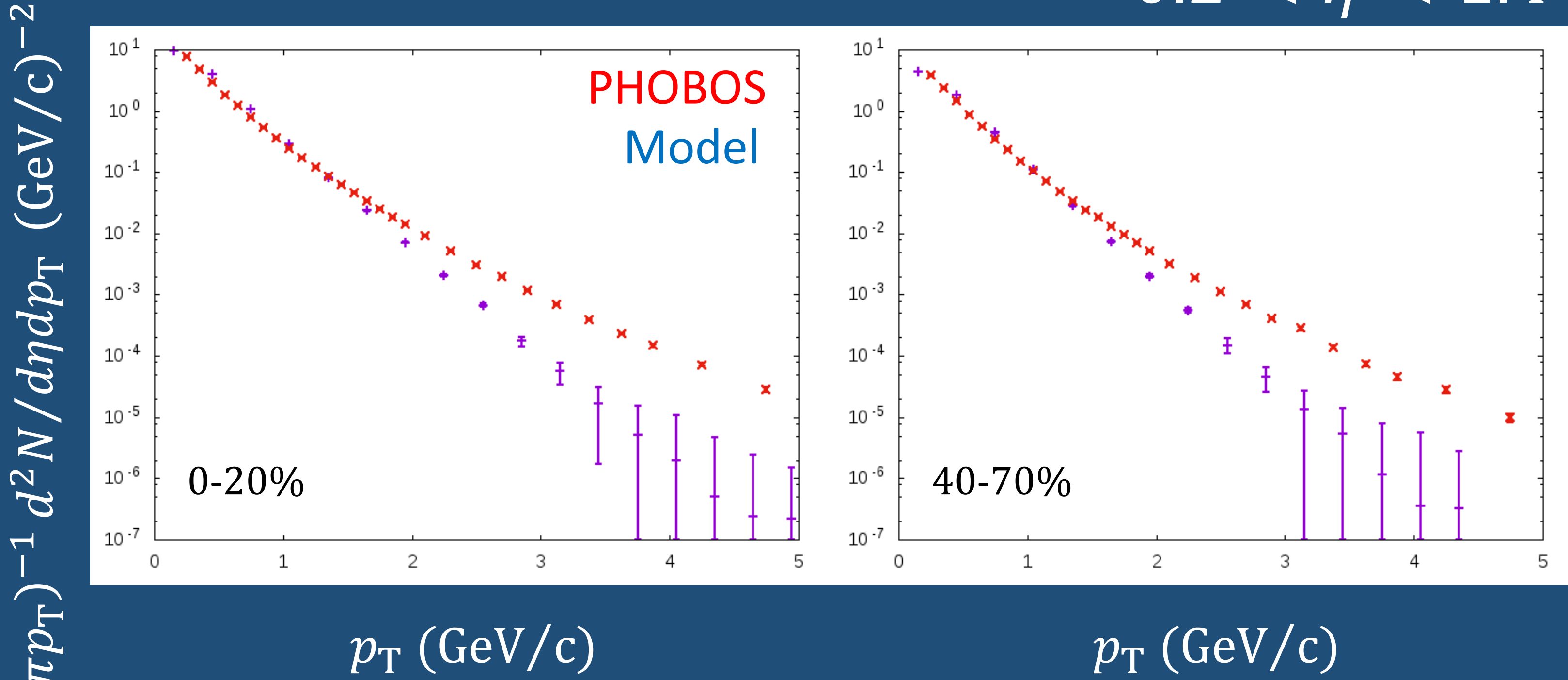


Reasonable description of pseudorapidity and centrality dependences in d+Au collisions

PHOBOS, PRC83, 024913 (2011)

p_T spectra of charged hadrons

$0.2 < \eta < 1.4$

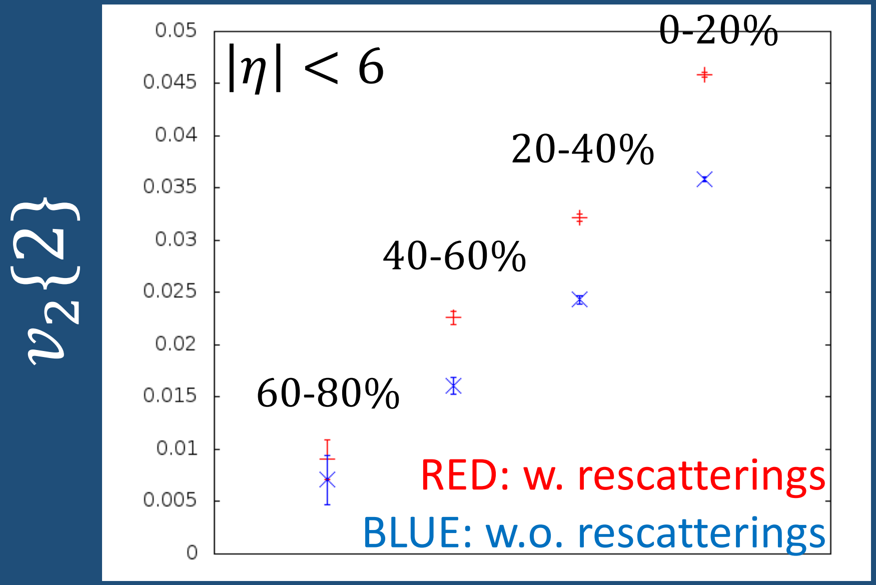


Low p_T well described by this model

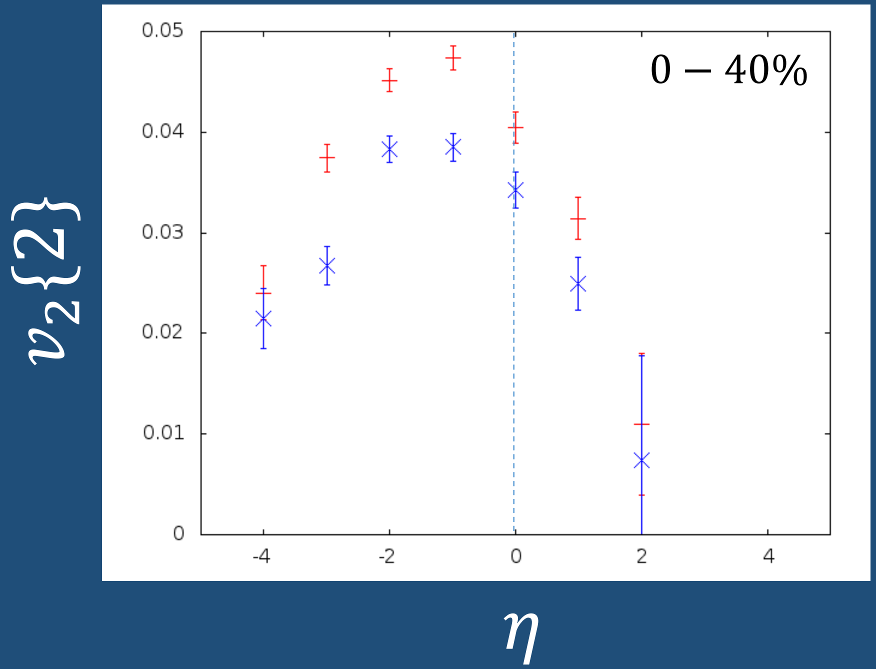
PHOBOS, PRL91, 072302 (2003)

Effects of hadronic rescatterings on v_2 in d+Au collisions

Centrality dependence



Pseudorapidity dependence

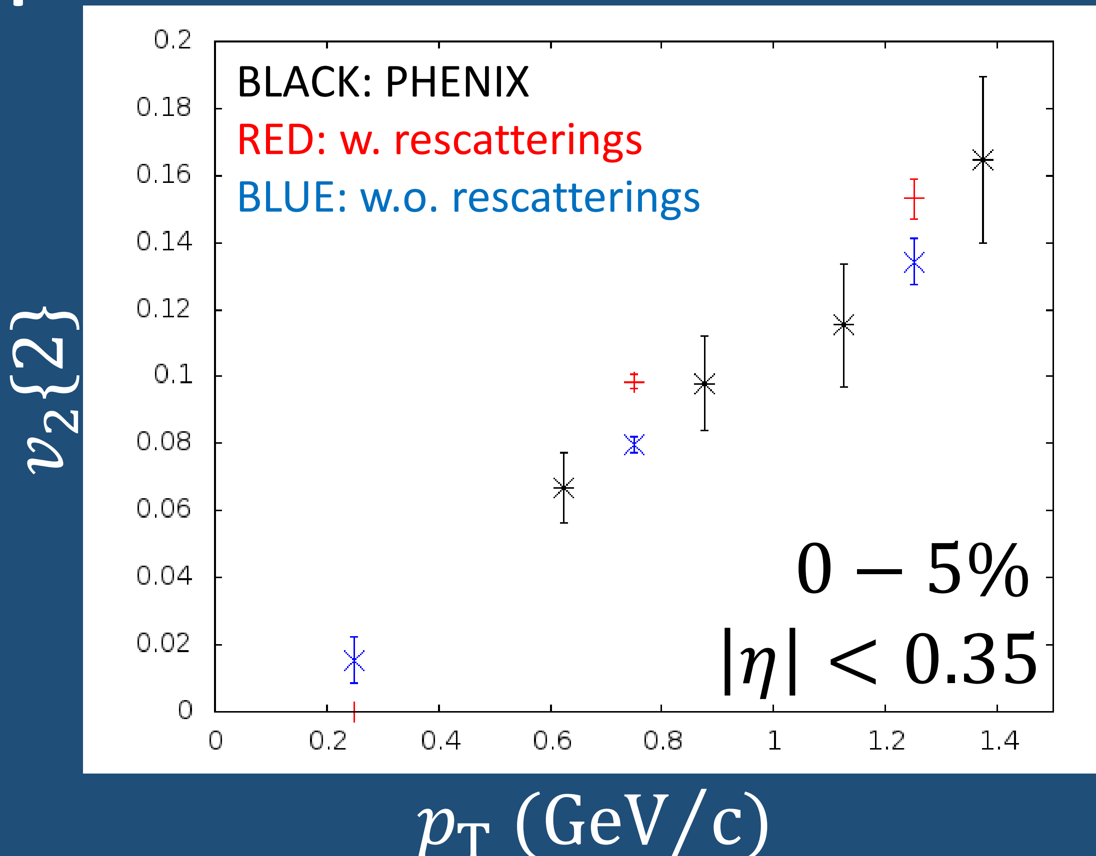


~80% of total v_2 from fluid-dynamical stage

→ Similar to AA collisions

PHENIX, PRL114, 192301 (2015)

Comparison with PHENIX data



Not significant effects of rescatterings on $v_2(p_{\mathrm{T}})$ slope

→Partly canceled by increase of mean p_{T}

Analysis of $v_2\{\mathrm{EP}\}$: work in progress

Contents

New source of higher harmonics?

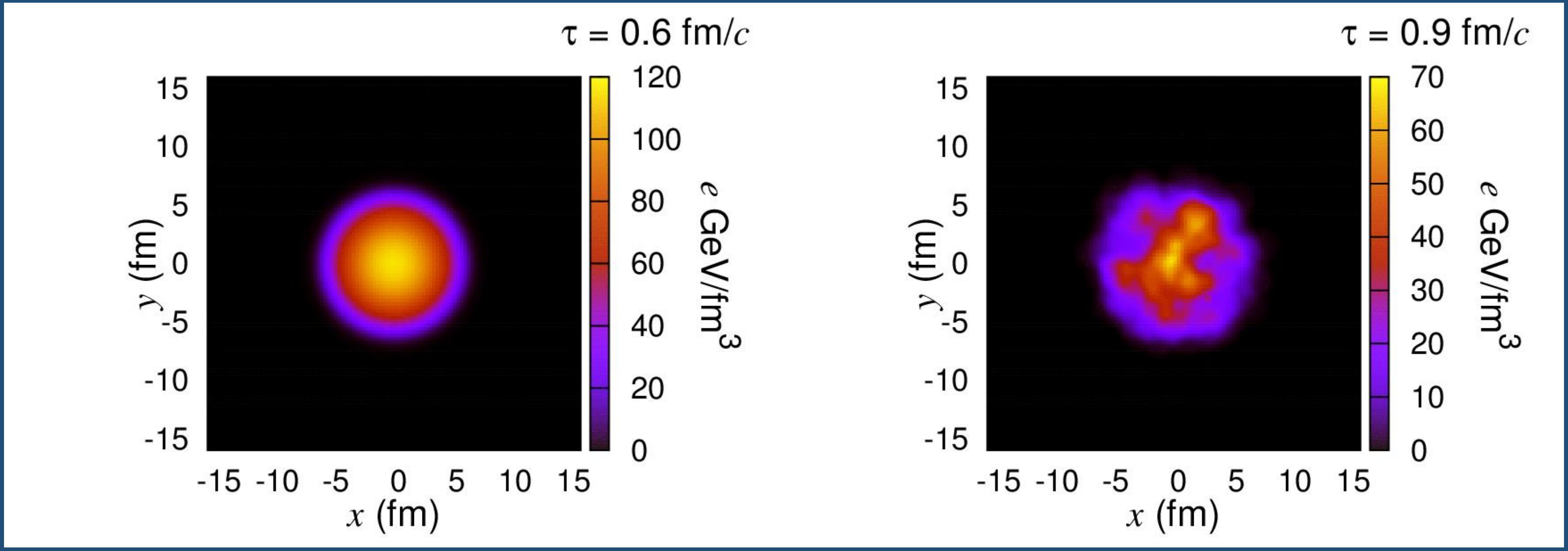
Fluctuations appear everywhere!

- Initial state fluctuations
  - Fluctuations of transverse position of nucleons in colliding nuclei
  - Multiplicity fluctuations
- Hydrodynamic fluctuations
  - Thermal noises
  - Critical fluctuations
- Disturbance by (mini-)jet propagation

Schulk, Tomášik(2014)

Jet propagation in γ-jet event

Full 3D ideal hydrodynamics
+ energy-momentum deposition by a parton



Smooth profile case

Bumpy profile case

Without linearization

Chaudhuri, Heinz (2006), Betz, Noronha, Torrieri, Gyulassy, Rischke (2010), Tachibana, Hirano (2014, 2016), …

Movies: Courtesy of Y. Tachibana

Many mini-jet propagation

$\mathrm{Pb} + \mathrm{Pb}\ 2.76\ \mathrm{TeV}$

$b = 0\ \mathrm{fm}$

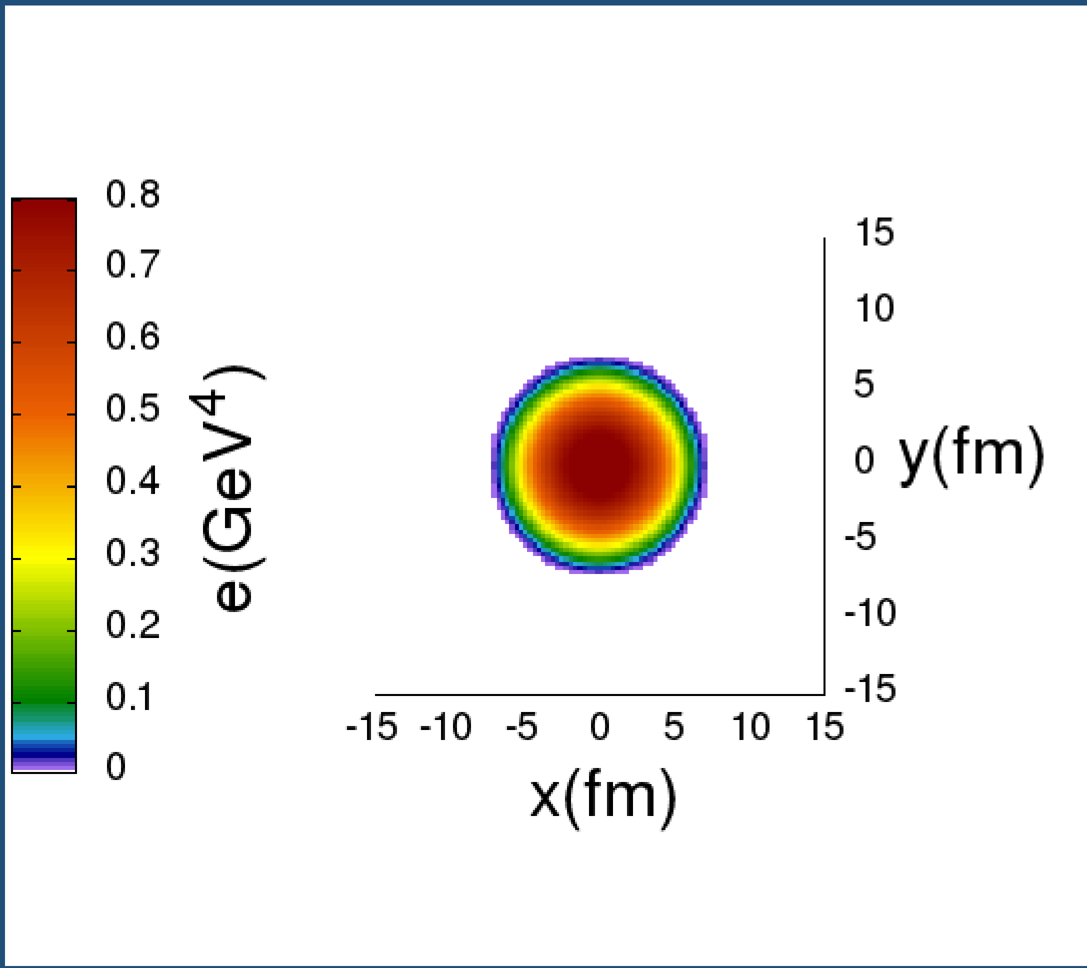
N_{coll}: 1983, N_{part}: 411

# of mini-jet ($p_{\mathrm{T}} > 2\mathrm{GeV}$): ~600 (at midrapidity)

Smooth initial condition (optical Glauber)

→ Bumpy freezeout hypersuface

→ Higher harmonics?



Okai, Tachibana, Hirano (work in progress)

Contents

Summary

Happy 60^{th} Birthday to Ulrich!

Effects of hadronic rescatterings (Calibration of a lens to look at the QGP) investigated together with Ulrich must be always important in high-energy nuclear collisions towards extracting transport properties of the QGP

Photos taken in
QM2015 at Kobe
To successful
QM2017 at Chicago!

Backups

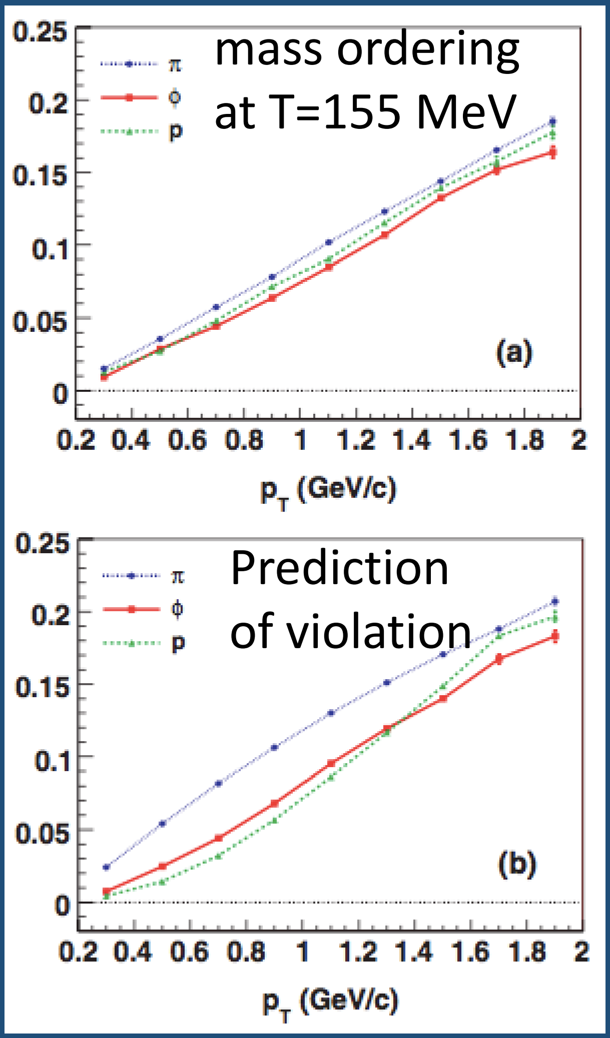
Violation of mass ordering in $v_2(p_T)$

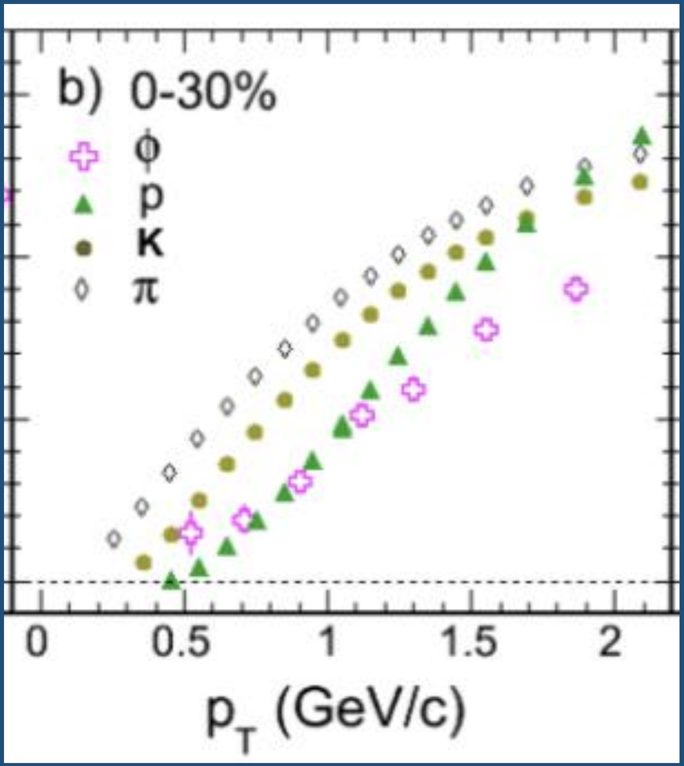
PHYSICAL REVIEW C **77**, 044909 (2008)

Mass ordering of differential elliptic flow and its violation for ϕ mesons

Tetsufumi Hirano,[1,*] Ulrich Heinz,[2,3] Dmitri Kharzeev,[4] Roy Lacey,[5] and Yasushi Nara[6]
[1]*Department of Physics, The University of Tokyo, Tokyo 113-0033, Japan*
[2]*Department of Physics, The Ohio State University, Columbus, Ohio 43210, USA*
[3]*CERN, Physics Department, Theory Division, CH-1211 Geneva 23, Switzerland*
[4]*Nuclear Theory Group, Physics Department, Brookhaven National Laboratory, Upton, New York 11973-5000, USA*
[5]*Department of Chemistry, SUNY Stony Brook, Stony Brook, New York 11794-3400, USA*
[6]*Akita International University, 193-2 Okutsubakidai, Yuwa-Tsubakigawa, Akita 010-1211, Japan*
(Received 31 October 2007; published 28 April 2008)

Observed!

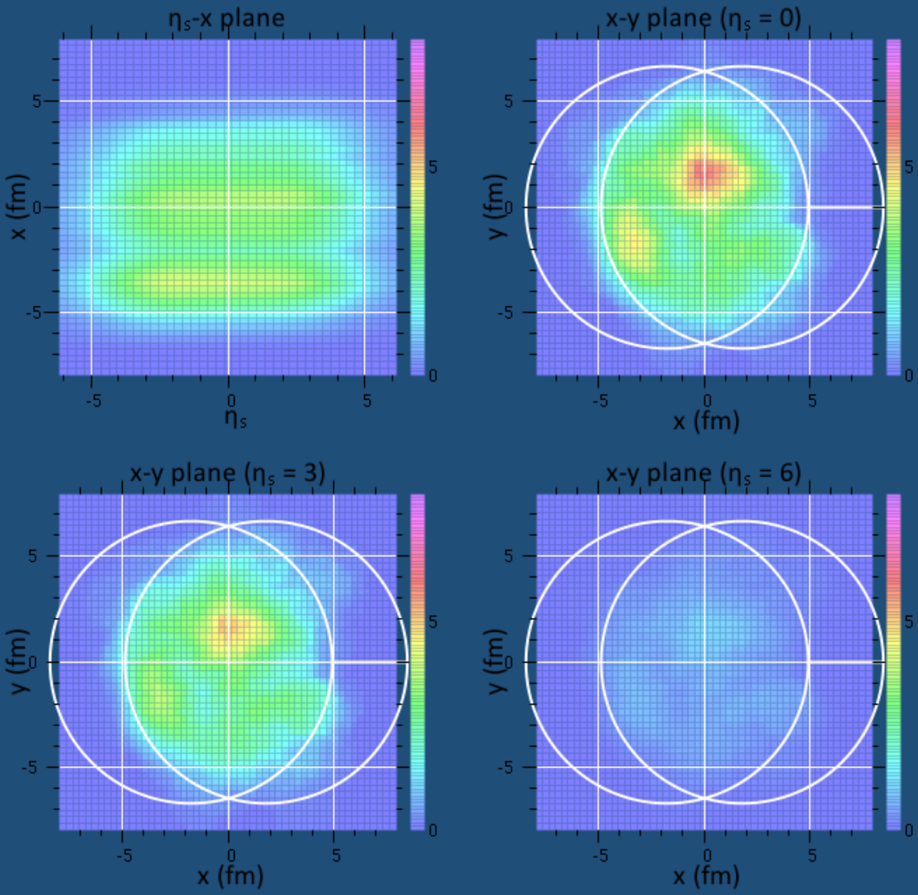




Md. Nasim [STAR Collaboration], Nucl. Phys. A 904-905 (2013) 413c

Quantitatively?

MC-Glauber to hydro



Initial time: $\tau_0 = 0.6\ \mathrm{fm}$

Soft/hard fraction: $\alpha = 0.18$

+ overall normalization

+ rapidity shape in pp

Entropy density

⇓

The other thermodynamic variables through equation of state

One example of initial condition

Relativistic hydrodynamics

Hydrodynamic equations

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

$$T^{\mu\nu} = (e+p)u^\mu u^\nu - p g^{\mu\nu}$$

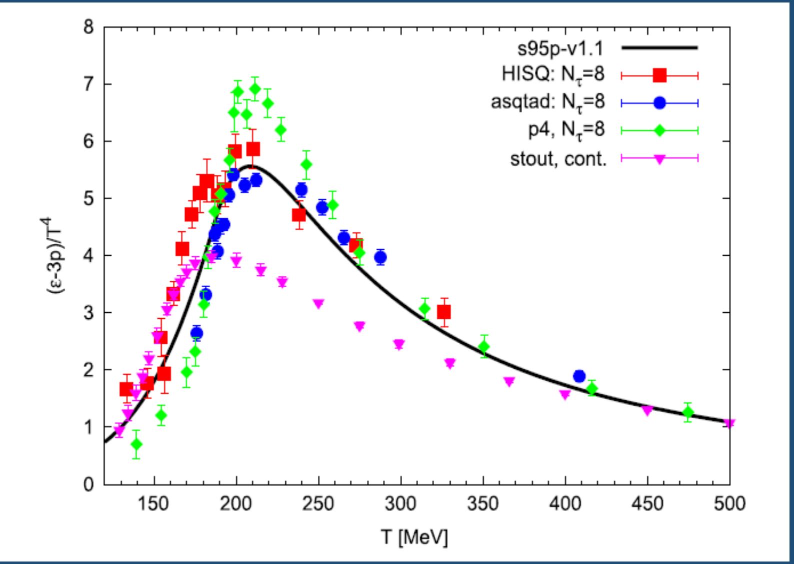
e: energy density

p: pressure

u^μ: four flow velocity

*No dissipation in this study

Equation of state



High T

→ Lattice result (hot QCD)

Low T

→ Hadron resonance gas

See also, P.Huovinen and P.Petreczky, NPA837, 26 (2010)

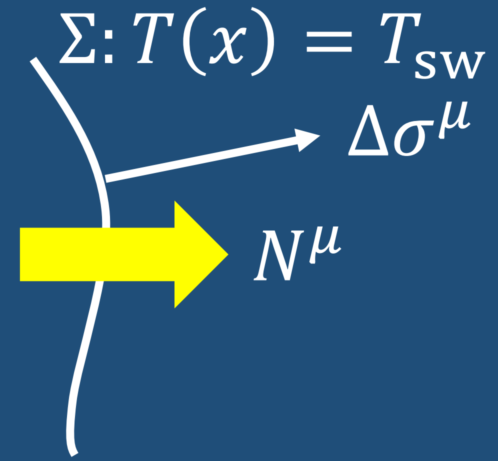
Hydro to cascade

One-particle distribution from a fluid element

F.Cooper, G.Frye (1974)

$$E\frac{d^3\Delta N}{d^3k} = \frac{g}{(2\pi)^3}\frac{k\cdot\Delta\sigma}{\exp[k\cdot u/T_{\mathrm{sw}}]\pm 1}$$

$$T_{\mathrm{sw}} = 155\ \mathrm{MeV}$$



Thermal dist. in switching hypersurface Σ boosted by fluid velocity u^μ

Output from hydro as initial condition for cascade

Hadronic cascade model (JAM)

Incoherent convolution of hadron-hadron scattering and resonance decays

Some remarks on strangeness sector

- $\bar{K}N$ and KN incoming channel

$$\bar{K}N \to \pi Y, \bar{K}N \to Y^*, KN \to K^*N$$

*Inverse process through detailed balance

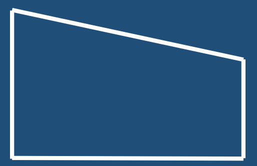
- Other processes → Additive quark model

$$\sigma_{\text{tot}} = \sigma_{NN} \frac{n_1}{3} \frac{n_2}{3} \left(1 - 0.4 \frac{n_{s1}}{n_1}\right) \left(1 - 0.4 \frac{n_{s2}}{n_2}\right)$$

See also, Y.Nara *et al*., PRC61, 024901 (2000),
TH and Y.Nara, PTEP 01A203 (2012).

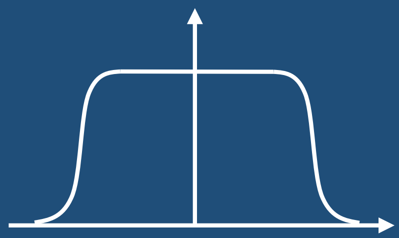
Some details of initial conditions in longitudinal direction

$$s_0(\tau_0, \eta_s, x_\perp) = \frac{dS}{\tau_0 d\eta_s d^2 x_\perp}$$



$$= \frac{C}{\tau_0} f^{pp}(\eta_s) \left[\frac{1-\alpha}{2} \underbrace{\left(\frac{Y_b - \eta_s}{Y_b} \rho_A(x_\perp) + \frac{Y_b + \eta_s}{Y_b} \rho_B(x_\perp) \right)}_{\text{Triangle/Trapezoid}} + \alpha \rho_{coll}(x_\perp) \right]$$

$$f^{pp}(\eta_s) = \exp\left[-\theta(|\eta_s| - \Delta\eta) \frac{(|\eta_s| - \Delta\eta)^2}{\sigma_\eta^2} \right]$$



RHIC energy:

$C = 15.0, \alpha = 0.18, \tau_0 = 0.6\ \text{fm}, \Delta\eta = 1.3, \sigma_\eta = 2.1$

Rejection sampling

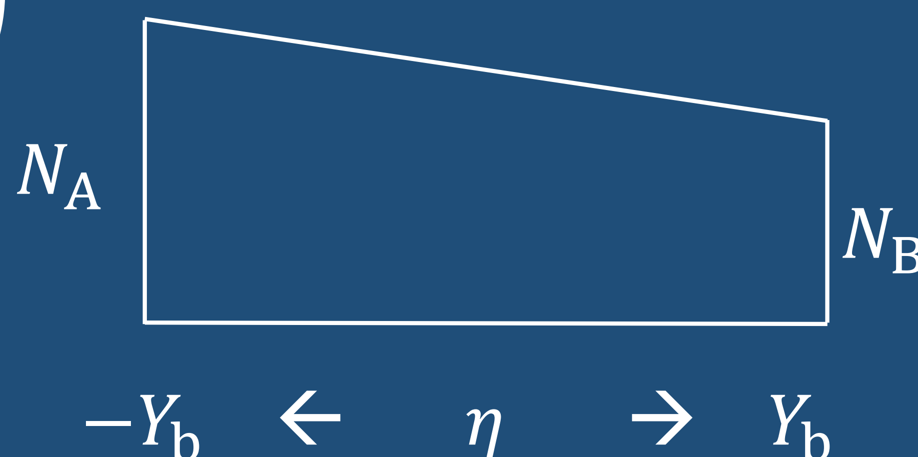
One AA event
→ $N_A \times N_B$ PYTHIA events

Weight in one PYTHIA event

$$w(\eta) = \frac{1}{2}\left(\frac{Y_\mathrm{b}+\eta}{Y_\mathrm{b}}\frac{1}{N_\mathrm{A}} + \frac{Y_\mathrm{b}-\eta}{Y_\mathrm{b}}\frac{1}{N_\mathrm{B}}\right)$$

$$N_\mathrm{A} N_\mathrm{B} w(\eta) = \begin{cases} N_\mathrm{A}\ (\eta = -Y_\mathrm{b}) \\ N_\mathrm{B}\ (\eta = Y_\mathrm{b}) \end{cases}$$

$N_A \times N_B$ strings



p_T dependent option in rejection sampling

$$w(\eta, p_\mathrm{T}) = w(\eta) \times \frac{1}{2}\left(1 - \tanh\frac{p_\mathrm{T} - p_\mathrm{T0}}{\Delta p_\mathrm{T}}\right) + 1 \times \frac{1}{2}\left(1 + \tanh\frac{p_\mathrm{T} - p_\mathrm{T0}}{\Delta p_\mathrm{T}}\right)$$