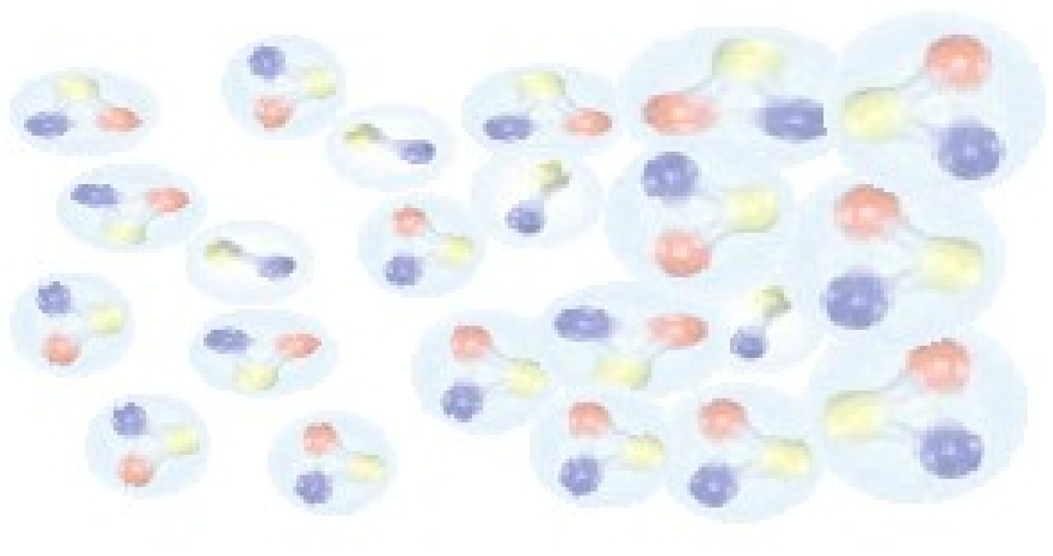
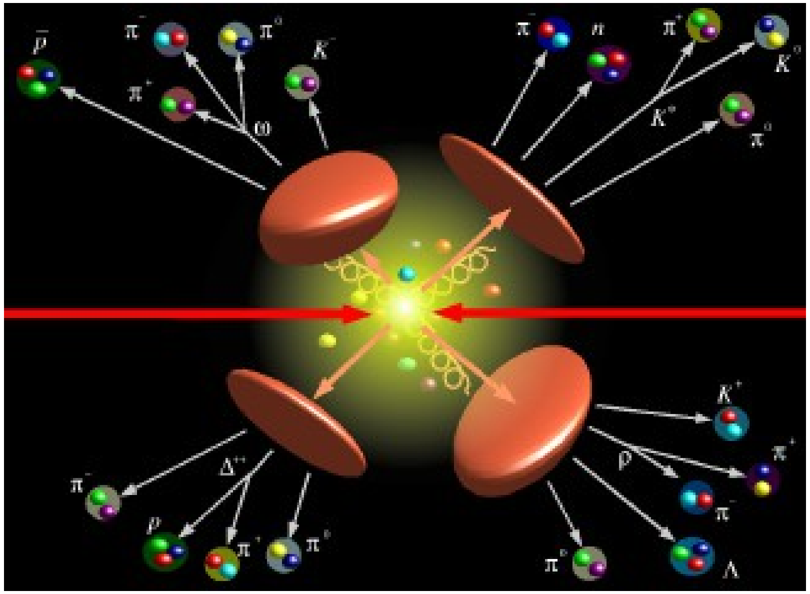
Robustness of baryon stopping signal for a PT

David Blaschke
University of Wroclaw, Poland & JINR Dubna, Russia





High-Density Matter Seminar, BLTP JINR Dubna, June 24, 2015

JOINT INSTITUTE FOR NUCLEAR RESEARCH
JINR
DUBNA

cost
EUROPEAN COOPERATION
IN SCIENCE AND TECHNOLOGY

NAVI

NARODOWE
CENTRUM
NAUKI

Uniwersytet
Wrocławski

HELMHOLTZ
ASSOCIATION

HIC for FAIR
Helmholtz International Center

Robustness of baryon stopping signal for a PT

David Blaschke
University of Wroclaw, Poland & JINR Dubna, Russia

1. **Introduction:**
   The baryon stopping signal for a 1st order phase transition
2. **Robustness: The dependence on experimental cuts**
   Based on arxiv:1504.03992 [with Yu. Ivanov]
3. **Further developments:**
   Particlization, Detector response, new class EoS, UrQMD

High-Density Matter Seminar, BLTP JINR Dubna, June 24, 2015

JINR DUBNA
cost EUROPEAN COOPERATION IN SCIENCE AND TECHNOLOGY
NARODOWE CENTRUM NAUKI
HELMHOLTZ ASSOCIATION
NAVI
Uniwersytet Wrocławski
HIC for FAIR Helmholtz International Center

Strategy towards event simulations testing PT signal

Two alternative approaches:

I) **Direct approach** based on transport codes:
Particle trajectories are followed;
Properties of the medium are encoded in propagators and cross sections
→ UrQMD (Aichelin et al.),
→ PHSD (Bratkovskaya, Cassing, et al.),
→ PHSD + SACA (Bratkovskaya, Aichelin, LeFevre, et al.)

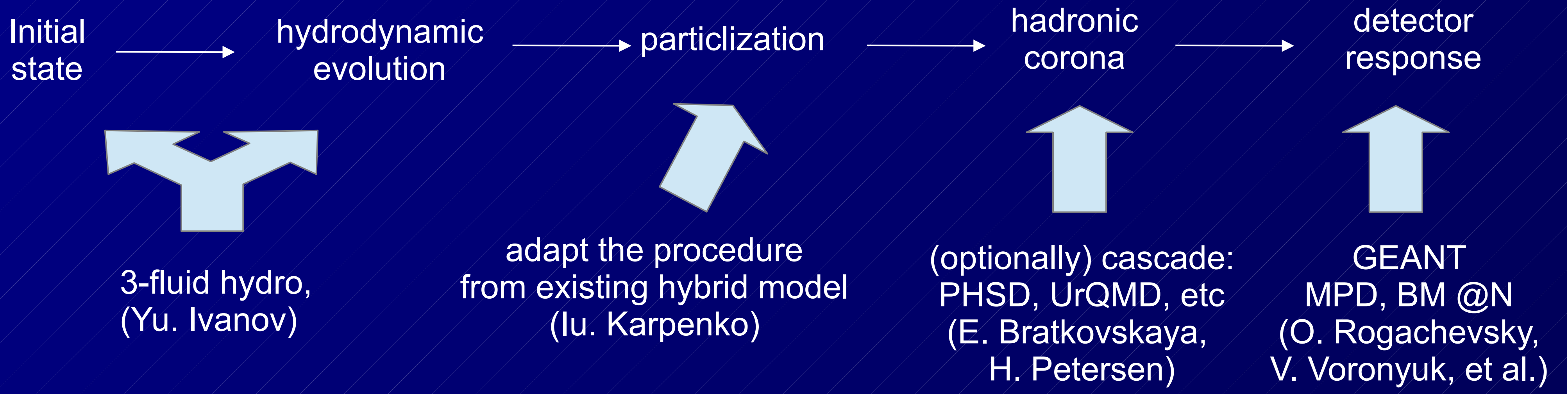
II) **Hybrid approach:**
Joins hydrodynamic evolution of a (multi-)fluid system described by an **EoS** with
Particle transport via a procedure called **"particlization"** (Karpenko)
Particularly suitable for studying effects of a strong phase transition in model EoS
a) Sandwich: UrQMD + hydro + hadronic cascade (H. Petersen et al.)
→ PT in hydro stage only
b) **3-fluid hydro**dynamics (Ivanov) + particlization (Karpenko)
→ PT in baryon stopping regime already!
(main difference to sandwich; appropriate for energy range of NICA / CBM)

Both approaches provide the inputs for the simulationof the **detector response**
(GEANT-MPD: Rogachevsky, Voronyuk, Batyuk, Wielanek, et al.)

Hydrodynamic modelling for NICA / FAIR

More complicated for lower energies:
→ baryon stopping effects,
→ finite baryon chemical potential,
→ EoS unknown from first principles
We want to simulate the effects of, and ultimately discriminate different EoS/PT types
The model has to be coupled to a detector response code to simulate detector events

taken from: MADAI.us



Initial state → hydrodynamic evolution → particlization → hadronic corona → detector response

3-fluid hydro,
(Yu. Ivanov)

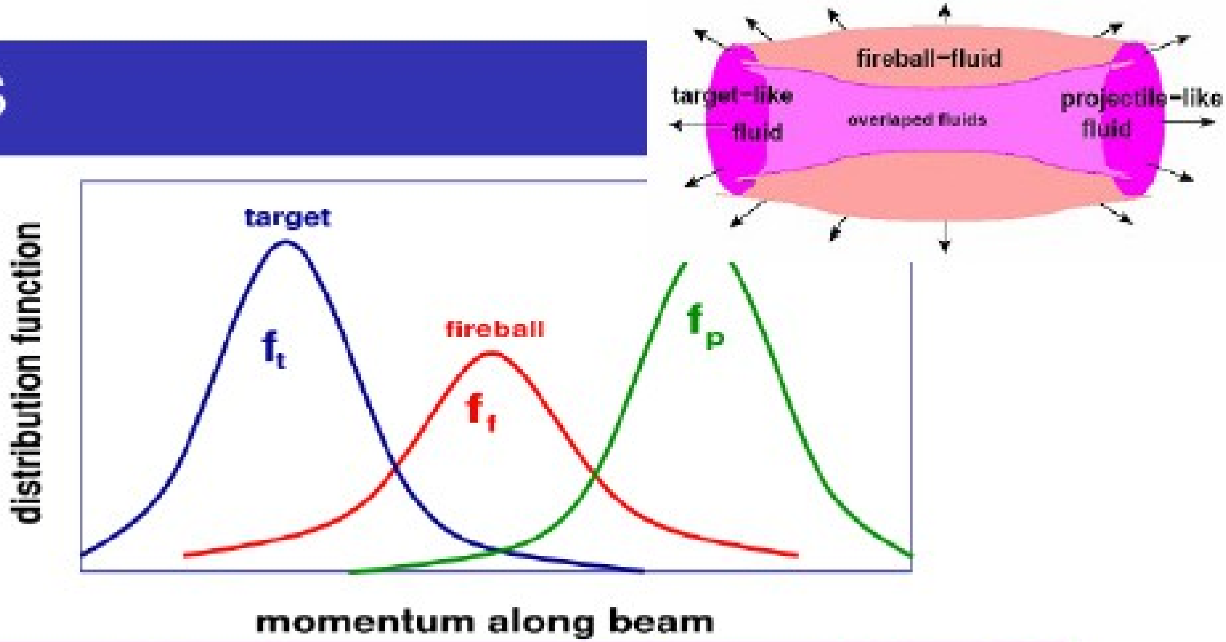
adapt the procedure
from existing hybrid model
(Iu. Karpenko)

(optionally) cascade:
PHSD, UrQMD, etc
(E. Bratkovskaya,
H. Petersen)

GEANT
MPD, BM @N
(O. Rogachevsky,
V. Voronyuk, et al.)

3-Fluid Dynamics

Produced particles populate mid-rapidity
$\Rightarrow$ fireball fluid



Target-like fluid: $\partial_\mu J_t^\mu = 0$ $\partial_\mu T_t^{\mu\nu} = -F_{tp}^\nu + F_{ft}^\nu$

Leading particles carry bar. charge exchange/emission

Projectile-like fluid: $\partial_\mu J_p^\mu = 0,$ $\partial_\mu T_p^{\mu\nu} = -F_{pt}^\nu + F_{fp}^\nu$

Fireball fluid: $J_f^\mu = 0,$ $\partial_\mu T_f^{\mu\nu} = F_{pt}^\nu + F_{tp}^\nu - F_{fp}^\nu - F_{ft}^\nu$

Baryon-free fluid Source term Exchange

The source term is delayed due to a formation time $\tau \sim 1$ fm/c

Total energy-momentum conservation:

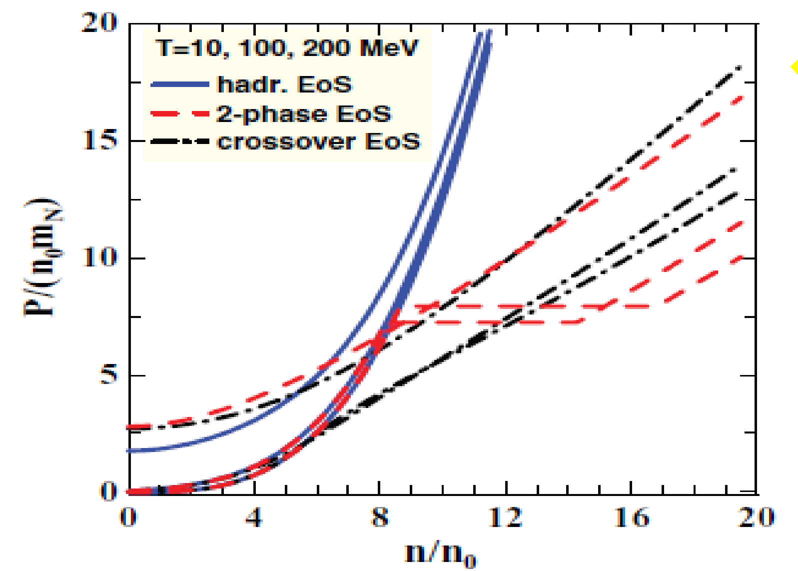
$$\partial_\mu (T_p^{\mu\nu} + T_t^{\mu\nu} + T_f^{\mu\nu}) = 0$$

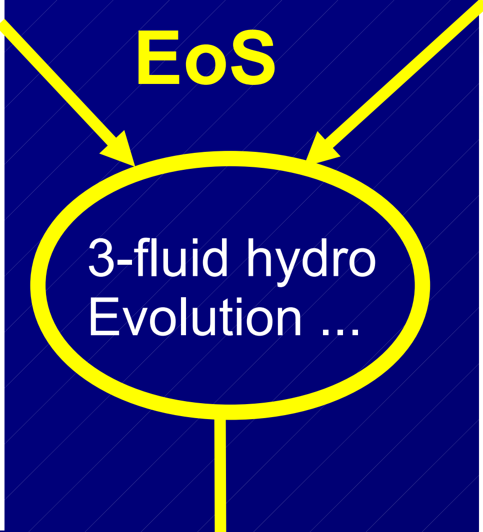
http://theory.gsi.de/~ivanov/mfd/

Yu.B. Ivanov, V.N. Russkikh and V.D. Toneev, Phys. Rev. C73, 044904 (2006)

Net proton rapidity distribution – test case for a 1st order PT signal

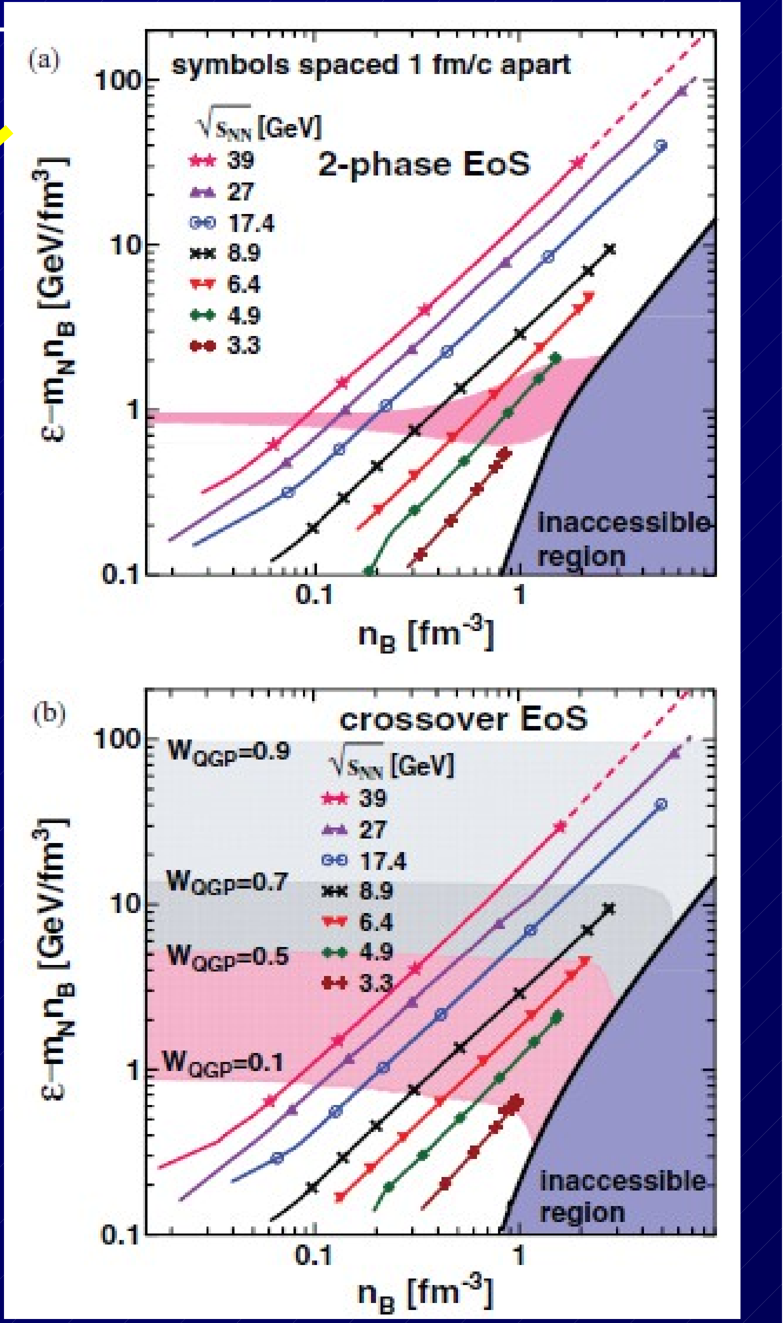
Theory: Yu.B. Ivanov, Phys. Rev. C 87, 064904 (2013) -

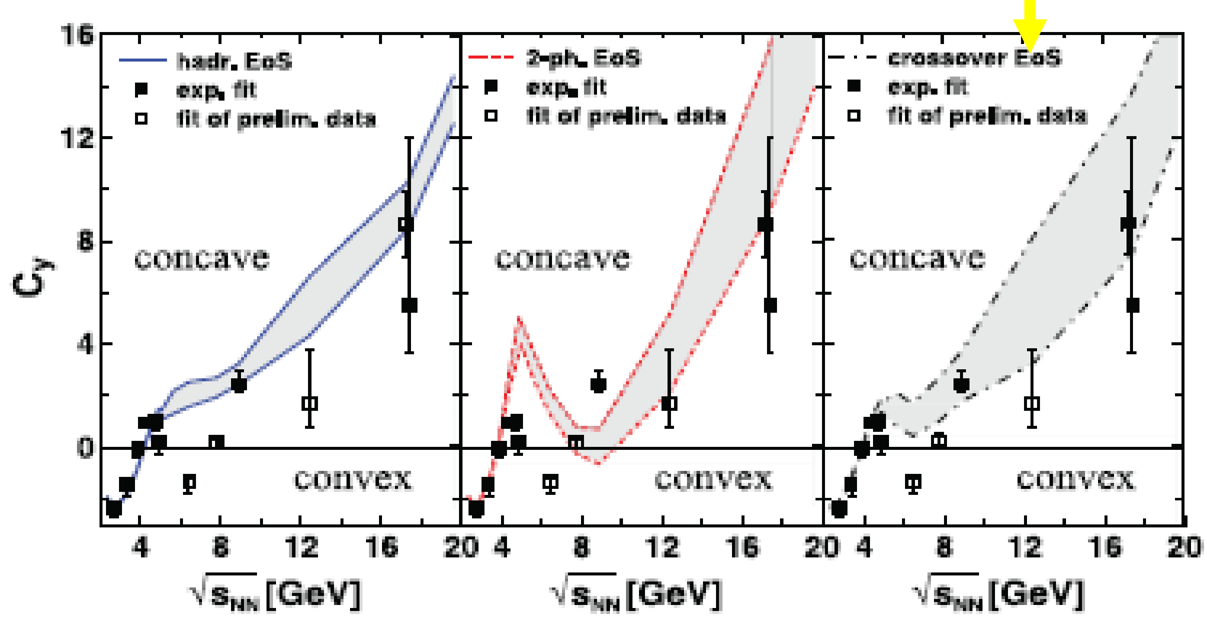




EoS

3-fluid hydro Evolution ...

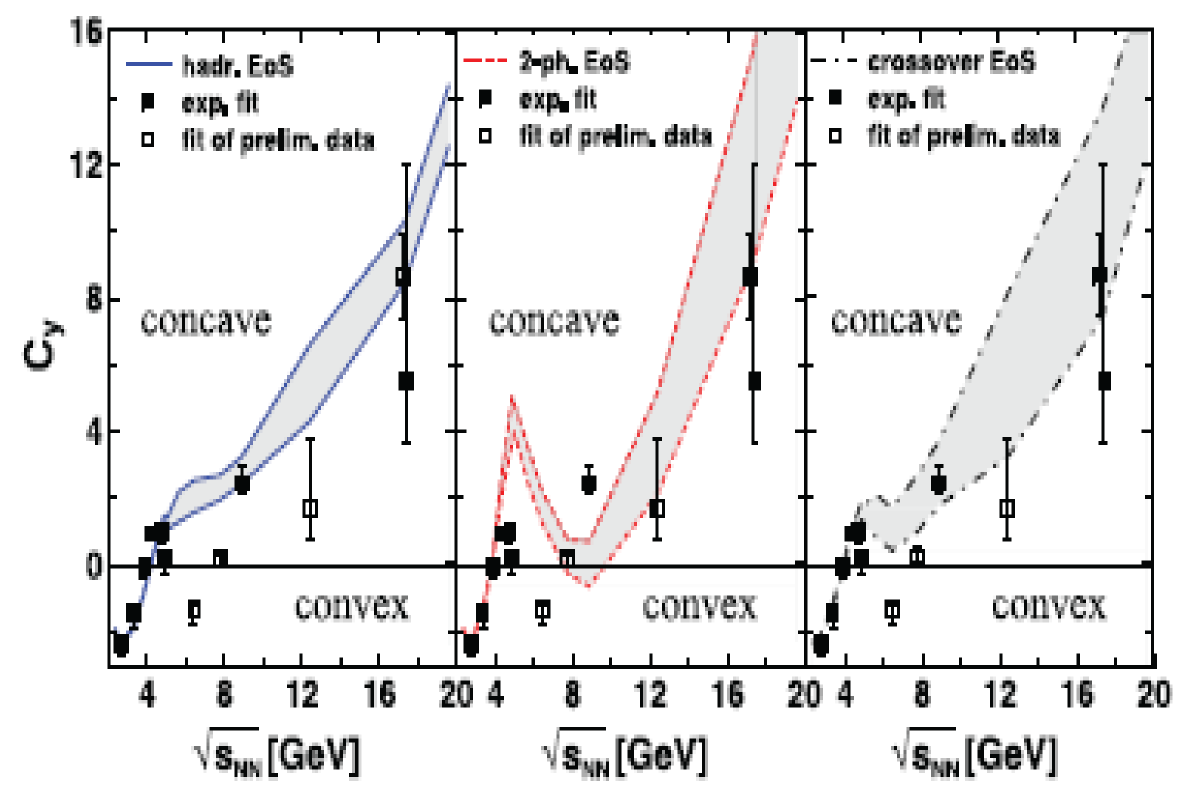


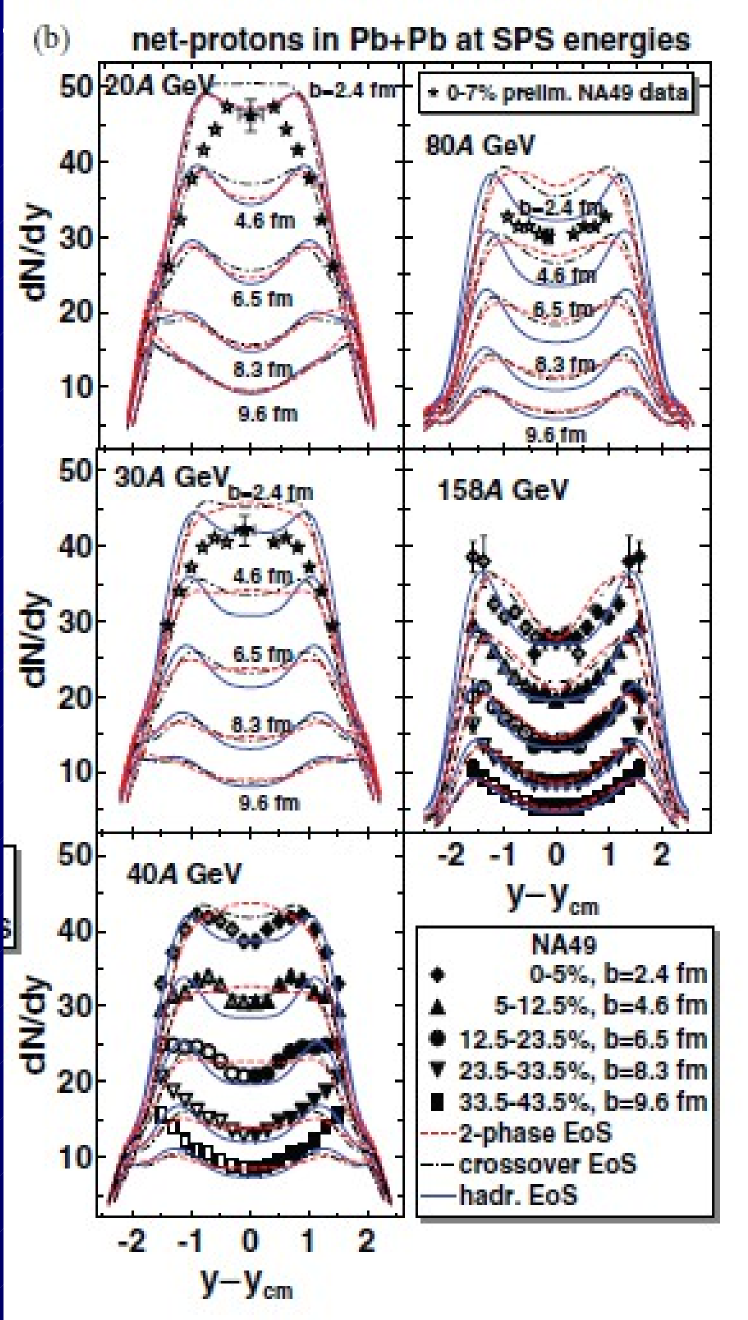


Net proton rapidity distribution – test case for a 1st order PT signal

Theory: Yu.B. Ivanov, Phys. Rev. C 87, 064904 (2013)

$$C_y = \left(y_{\rm c.m.}^3 \frac{d^3N}{dy^3}\right)_{y=y_{\rm c.m.}} \Big/ \left(y_{\rm c.m.} \frac{dN}{dy}\right)_{y=y_{\rm c.m.}}$$
$$= (y_{\rm c.m.}/w_s)^2(\sinh^2 y_s - w_s \cosh y_s).$$





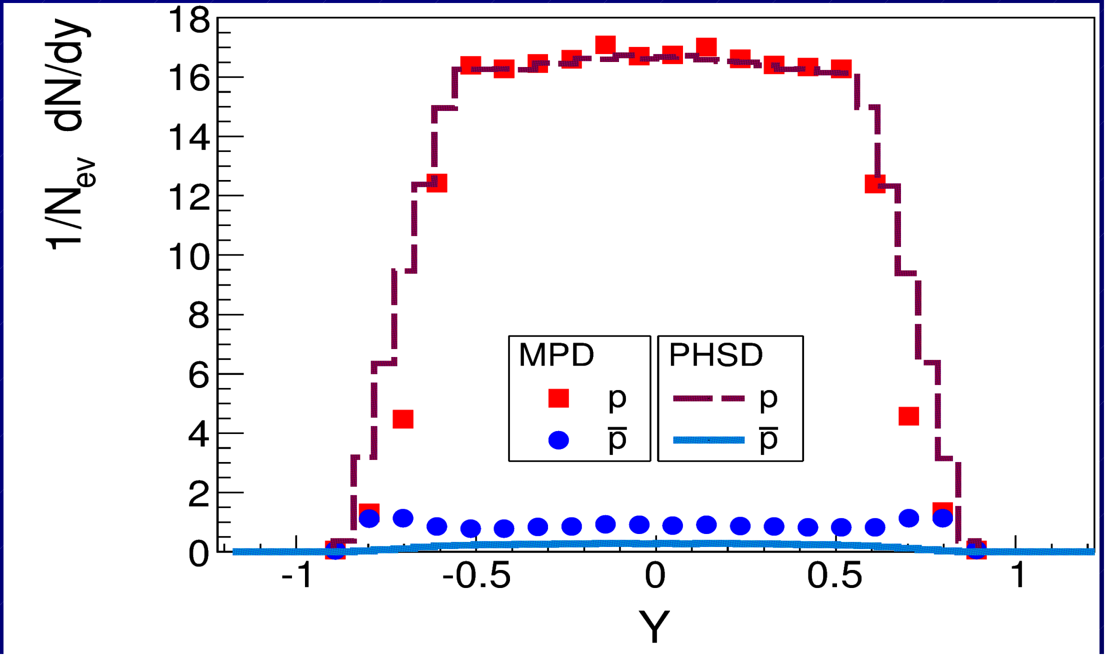
Net proton rapidity distribution – test case for a 1st order PT signal

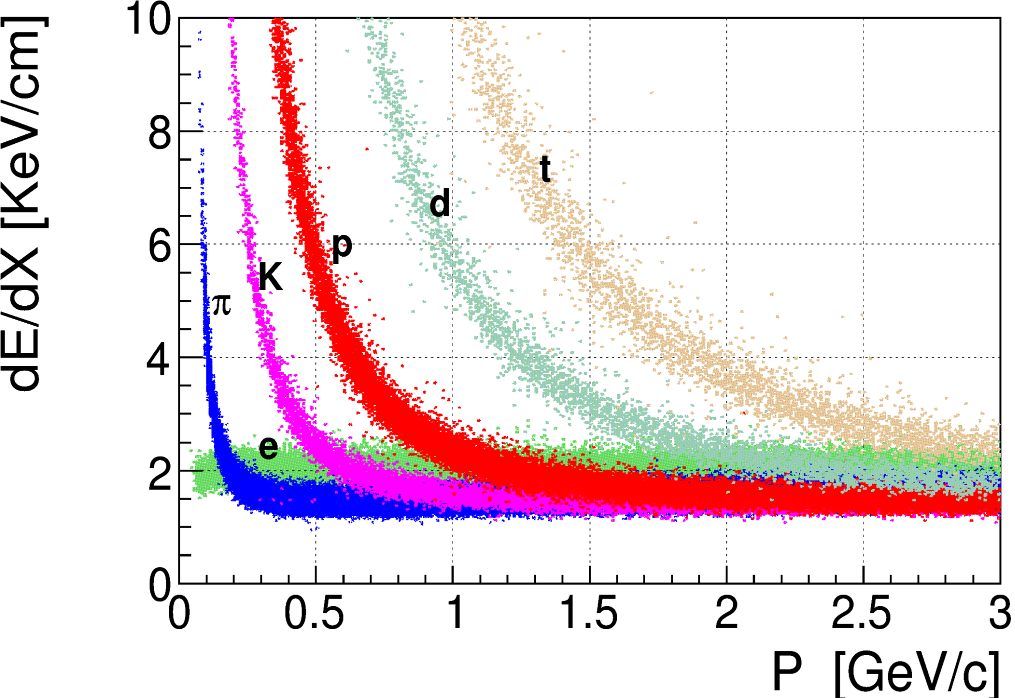
Event set:
40k AuAu @ √s_NN = 9 GeV [0-5%]
The most reliable region
|eta| < 1.2 ; 0.4 < p_t [GeV/c] < 0.8

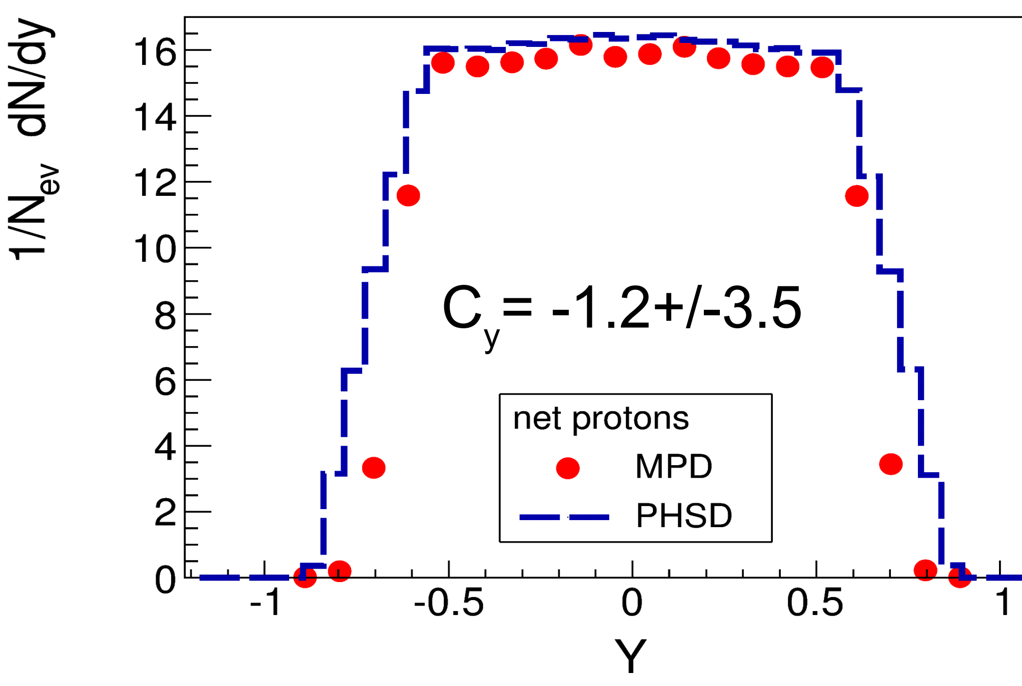
Result:
PHSD input → GEANT+MPD
detector reproduces the rapidity distribution !
(previous concerns not confirmed !!)

Signal:

$$C_y = \left(y_{cm}^3 \frac{d^3 N}{dy^3} \right)_{y=0} / \left(y_{cm} \frac{dN}{dy} \right)_{y=0}$$



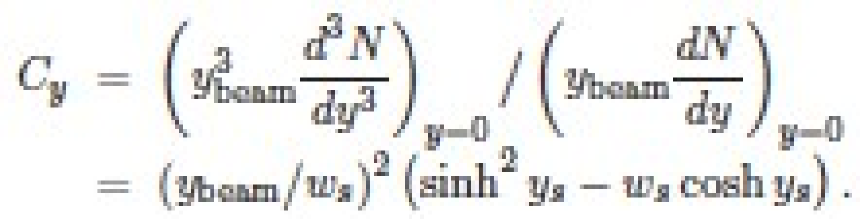




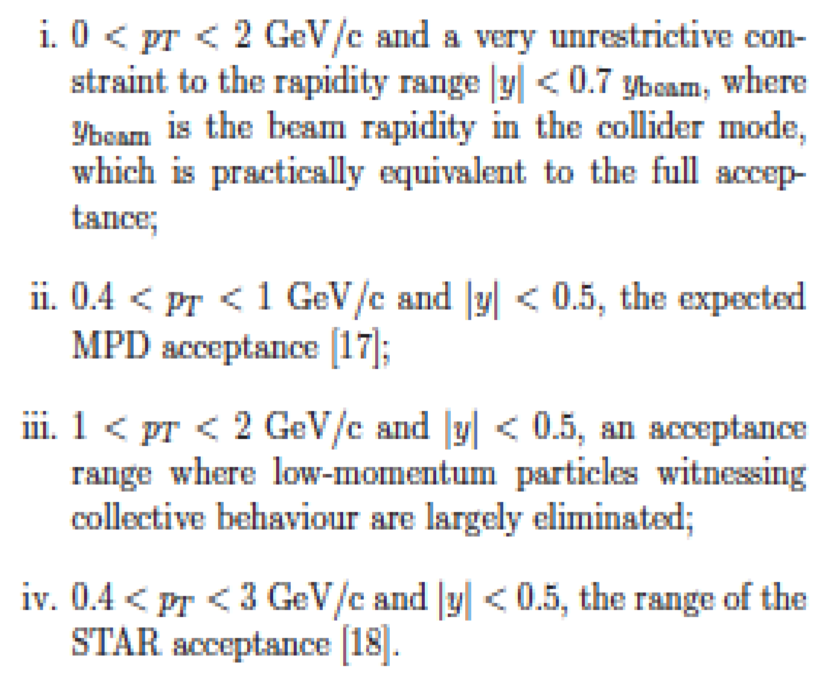
Net proton rapidity distribution – test case for a 1st order PT signal

Investigation of p_T cuts:

Yu. Ivanov & D. Blaschke, arxiv:1504.03992



$$C_y = \left(y_{\rm beam}^3 \frac{d^3N}{dy^3}\right)_{y=0} \Big/ \left(y_{\rm beam} \frac{dN}{dy}\right)_{y=0} = (y_{\rm beam}/w_s)^2 \left(\sinh^2 y_s - w_s \cosh y_s\right).$$

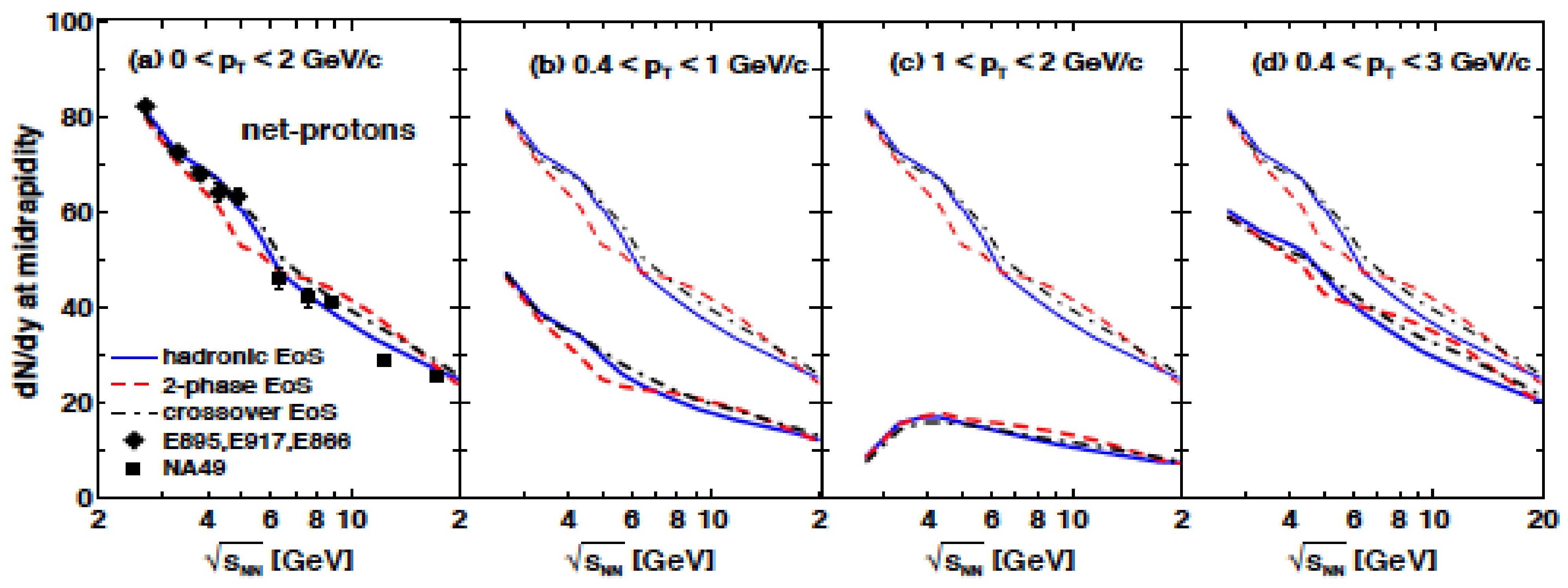


i. $0 < p_T < 2$ GeV/c and a very unrestrictive constraint to the rapidity range $|y| < 0.7\, y_{\rm beam}$, where $y_{\rm beam}$ is the beam rapidity in the collider mode, which is practically equivalent to the full acceptance;

ii. $0.4 < p_T < 1$ GeV/c and $|y| < 0.5$, the expected MPD acceptance [17];

iii. $1 < p_T < 2$ GeV/c and $|y| < 0.5$, an acceptance range where low-momentum particles witnessing collective behaviour are largely eliminated;

iv. $0.4 < p_T < 3$ GeV/c and $|y| < 0.5$, the range of the STAR acceptance [18].



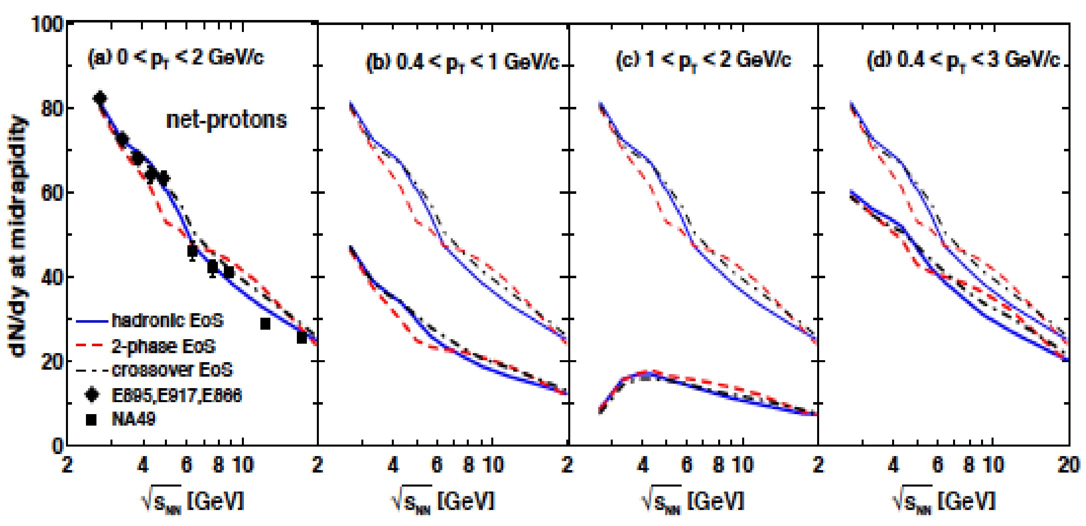
Net proton rapidity distribution – test case for a 1st order PT signal

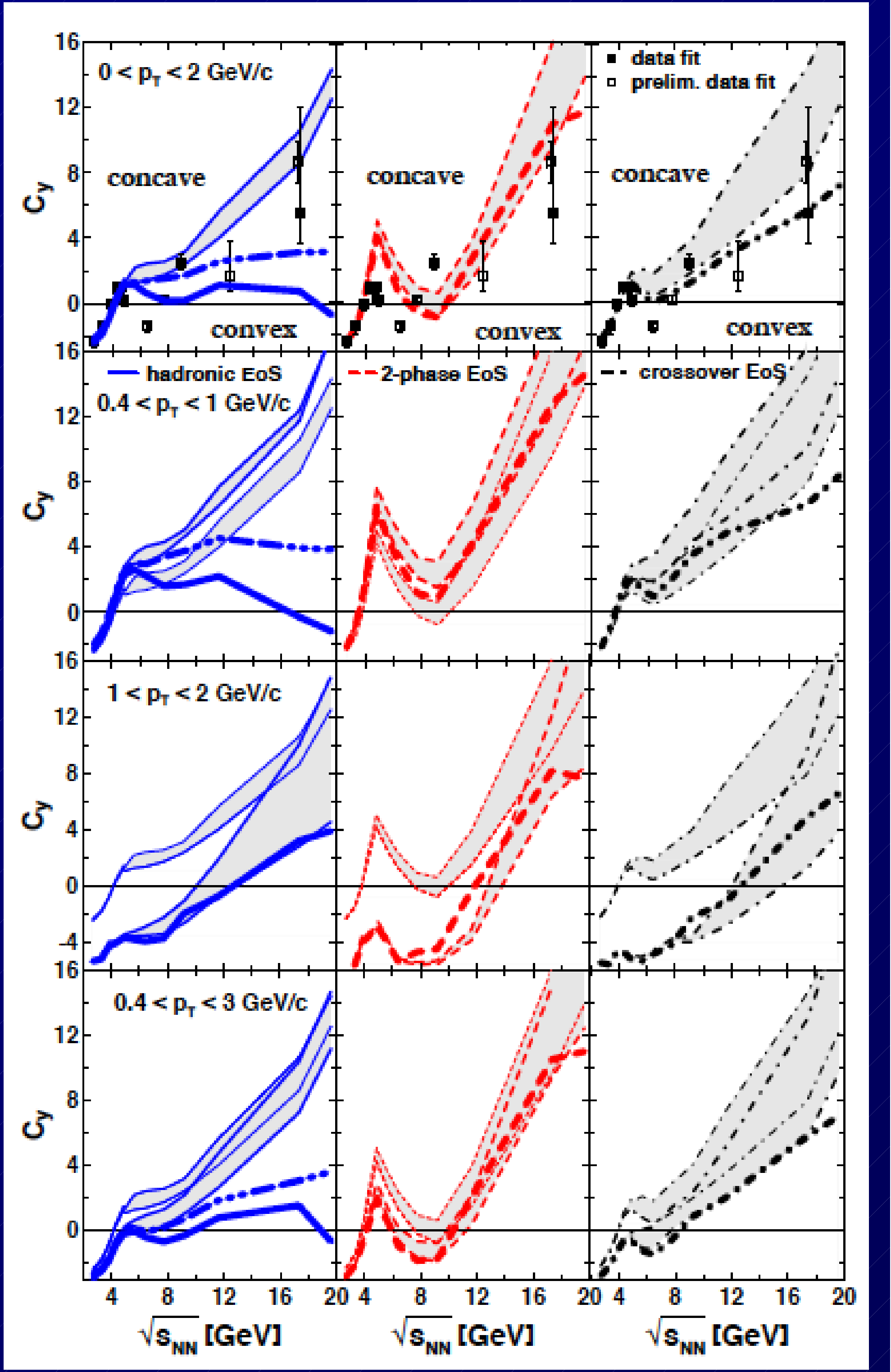
Investigation of p_T cuts:

Yu. Ivanov & D. Blaschke, arxiv:1504.03992

$$C_y = \left(y_{\mathrm{beam}}^3 \frac{d^3N}{dy^3}\right)_{y=0} \Big/ \left(y_{\mathrm{beam}} \frac{dN}{dy}\right)_{y=0} = (y_{\mathrm{beam}}/w_s)^2 \left(\sinh^2 y_s - w_s \cosh y_s\right).$$

- “wiggle” formed in the nonequilibrium compression stage of the collision, where p_T only in 3FH
- robust against serious p_T cuts
- at high p_T (1 - 2 GeV/c) in convex region
- at low p_T (0.2 - 1 GeV/c) in concave region
- required accuracy in C_y determination: $\Delta C_y < 2$





Net proton rapidity distribution – test case for a 1st order PT signal

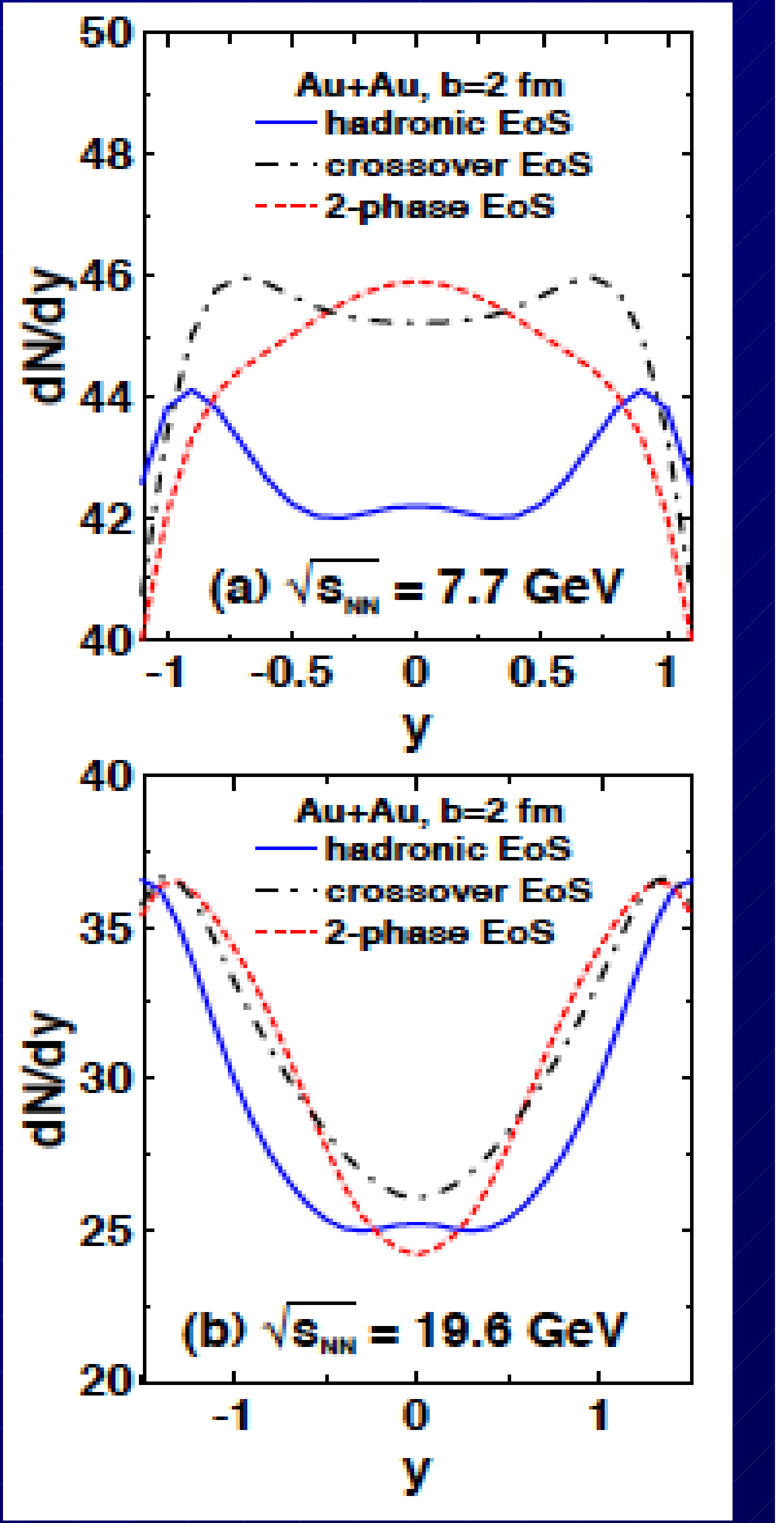
Investigation of p_T cuts:

Yu. Ivanov & D. Blaschke, arxiv:1504.03992

$$\frac{dN}{dy} = a\left(\exp\{-(1/w_s)\cosh(y-y_s)\} + \exp\{-(1/w_s)\cosh(y+y_s)\}\right),$$

$$\begin{aligned} C_y &= \left(y_{\mathrm{beam}}^3 \frac{d^3N}{dy^3}\right)_{y=0} \Big/ \left(y_{\mathrm{beam}} \frac{dN}{dy}\right)_{y=0} \\ &= (y_{\mathrm{beam}}/w_s)^2 \left(\sinh^2 y_s - w_s \cosh y_s\right). \end{aligned}$$

- “wiggle” formed in the nonequilibrium compression stage of the collision, where p_T only in 3FH
- robust against serious p_T cuts
- at high p_T (1 - 2 GeV/c) in convex region
- at low p_T (0.2 - 1 GeV/c) in concave region
- required accuracy in C_y determination: $\Delta C_y < 2$



3+1D viscous hydro-cascade model (Yu. Karpenko, FIAS)

3+1D viscous hydro+cascade model was applied for A+A collisions at RHIC Beam Energy Scan energies ($\sqrt{s}$ = 7.7 − 39 GeV), and for SPS energy points

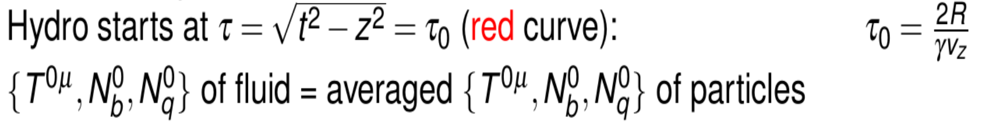
Cascade-hydro-cascade approach:

Initial state: UrQMD cascade

S.A. Bass et al., Prog. Part. Nucl. Phys. 41 255-369, 1998

Hydrodynamic phase: numerical 3+1D hydro solution via original relativistic viscous hydro code

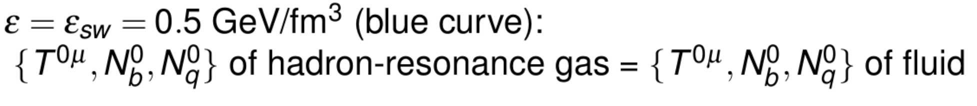
Iu. Karpenko, P. Huovinen, M. Bleicher, arXiv:1312.4160



Hydro starts at $\tau = \sqrt{t^2 - z^2} = \tau_0$ (red curve): $\tau_0 = \frac{2R}{\gamma v_z}$

$\{T^{0\mu}, N_b^0, N_q^0\}$ of fluid = averaged $\{T^{0\mu}, N_b^0, N_q^0\}$ of particles

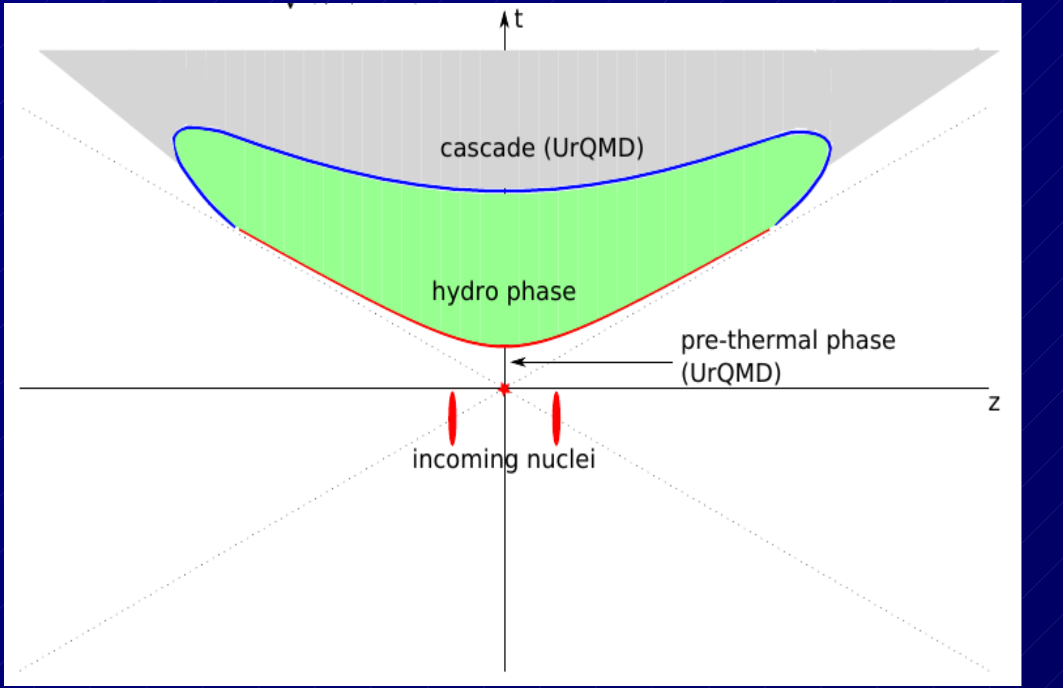
Fluid→particle transition

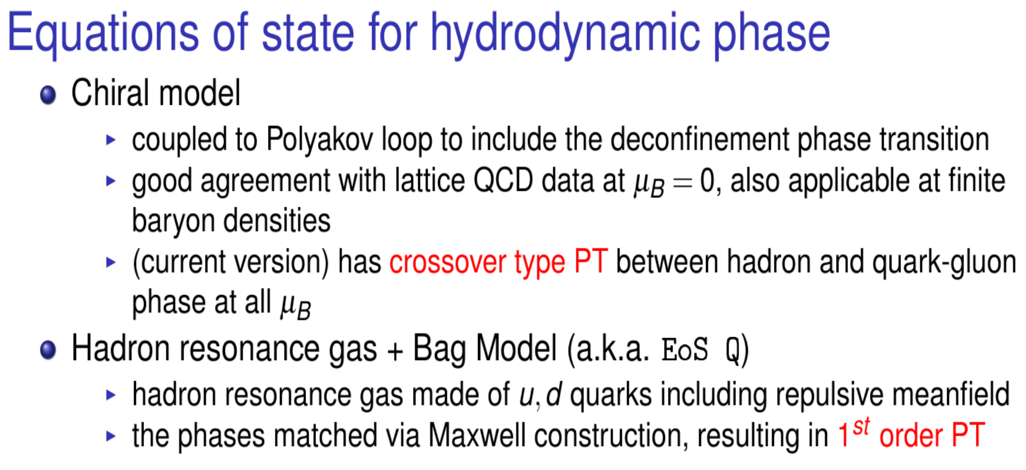


$\varepsilon = \varepsilon_{sw} = 0.5$ GeV/fm^3 (blue curve):

$\{T^{0\mu}, N_b^0, N_q^0\}$ of hadron-resonance gas = $\{T^{0\mu}, N_b^0, N_q^0\}$ of fluid

Hadronic cascade: UrQMD





Equations of state for hydrodynamic phase

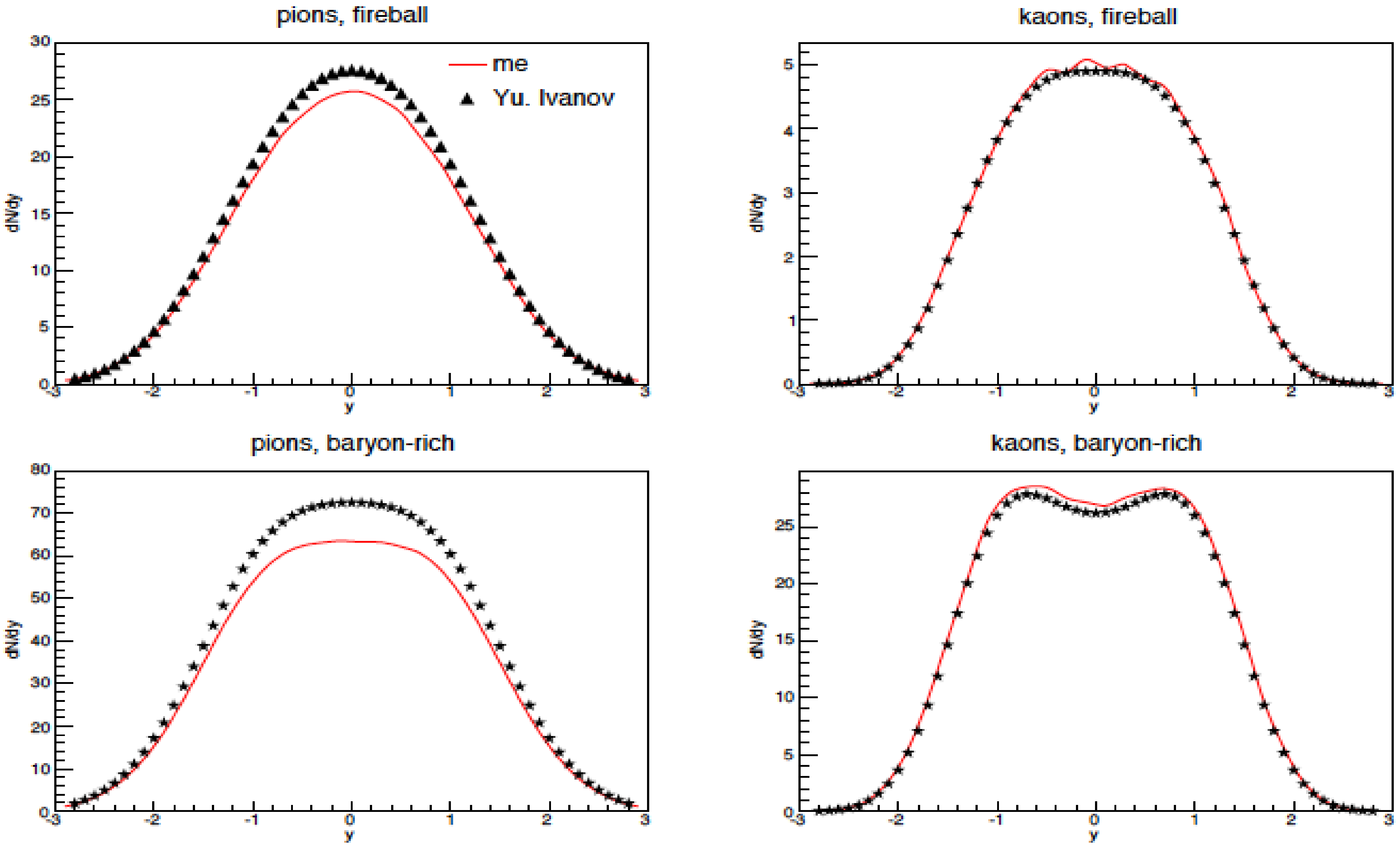
- Chiral model
  - coupled to Polyakov loop to include the deconfinement phase transition
  - good agreement with lattice QCD data at $\mu_B = 0$, also applicable at finite baryon densities
  - (current version) has crossover type PT between hadron and quark-gluon phase at all μ_B
- Hadron resonance gas + Bag Model (a.k.a. `EoS Q`)
  - hadron resonance gas made of u, d quarks including repulsive meanfield
  - the phases matched via Maxwell construction, resulting in 1st order PT

J. Steinheimer, S. Schramm and H. Stocker, J. Phys. G 38, 035001 (2011);
P.F. Kolb, J. Sollfrank, and U. Heinz, Phys.Rev. C 62, 054909 (2000).

Preview: Particlization of 3-fluid Hydrodynamics model

Yu. Karpenko & Yu. Ivanov: May 2014 - May 2015

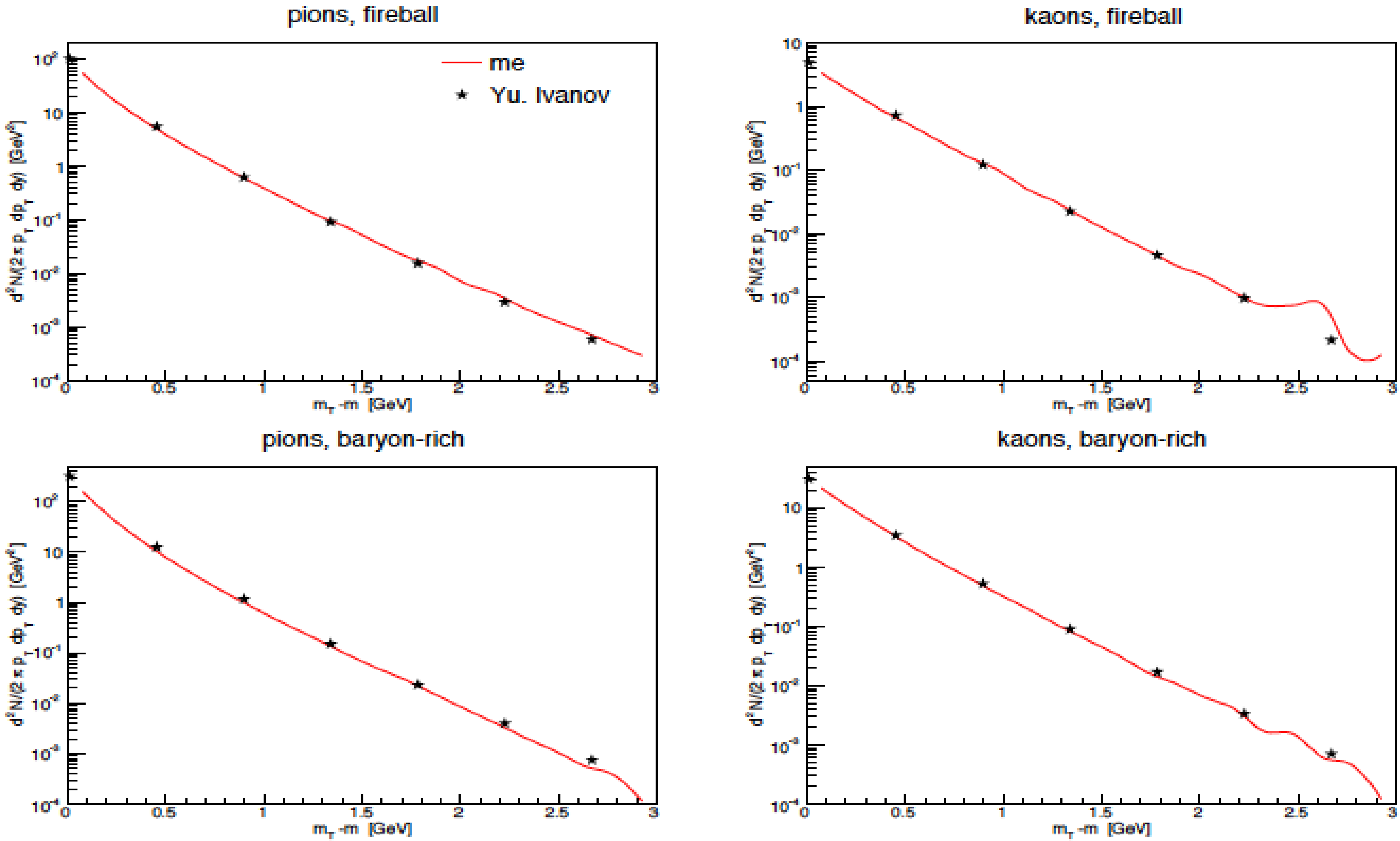
Rapidity distribution



Preview: Particlization of 3-fluid Hydrodynamics model

Yu. Karpenko & Yu. Ivanov: May 2014 - May 2015

P_T / m_T distribution



Further developments:

- Hadron rescattering in UrQMD (Hannah Petersen)
- MPD Detector simulation (Oleg Rogachevsky et al.)
- New 2-phase EoS (David Blaschke et al.)

A new class of 2-phase EoS: Motivation from Astrophysics

Modern 2-phase EoS in Astrophysics of Compact Stars

1. Pauli blocking effect → Excluded volume

Well known from modeling dissociation of clusters in the supernova EoS:

- excluded volume: Lattimer-Swesty (1991), Shen-Toki-Oyematsu-Sumiyoshi (1996), ...
- Pauli blocking: Roepke-Grigo-Sumiyoshi-Shen (2003), Typel et al. PRC 81 (2010)
- excl. Vol. vs. Pauli blocking: Hempel, Schaffner-Bielich, Typel, Roepke PRC 84 (2011)

Here: nucleons as quark clusters with finite size --> excluded volume effect !

Available volume fraction:

$$\Phi = V_{\rm av}/V = 1 - v \sum_{i=n,p} n_i, \quad v = \frac{1}{2}\frac{4\pi}{3}(2r_{\rm nuc})^3 = 4V_{\rm nuc}$$

Equations of state for T=0 nuclear matter:

$$p_{\rm tot}(\mu_{\rm n},\mu_{\rm p}) = \frac{1}{\Phi}\sum_{i=n,p} p_i + p_{\rm mes},$$

$$\varepsilon_{\rm tot}(\mu_{\rm n},\mu_{\rm p}) = -p_{\rm tot} + \sum_{i=\rm n,p} \mu_i n_i,$$

$$p_i = \frac{1}{4}\left(E_i n_i - m_i^* n_i^{(s)}\right),$$

$$n_i = \frac{\Phi}{3\pi^3} k_i^3,$$

$$n_i^{(s)} = \frac{\Phi m_i^*}{2\pi^2}\left[E_i k_i - (m_i^*)^2 \ln\frac{k_i + E_i}{m_i^*}\right],$$

$$E_i = \sqrt{k_i^2 + (m_i^*)^2} = \mu_i - V_i - \frac{v}{\Phi}\sum_{j=\rm p,n} p_j,$$

Effective mass: $m_i^* = m_i - S_i.$

Scalar meanfield: $S_i \sim n_i^{(s)}$

Vector meanfield: $V_i \sim n_i$

Modern 2-phase EoS in Astrophysics of Compact Stars

2. Stiff quark matter at high densities

S. Benic, Eur. Phys. J. A 50, 111 (2014)

$$\mathcal{L} = \bar{q}(i\partial\!\!\!/ - m)q + \mu_q \bar{q}\gamma^0 q + \mathcal{L}_4 + \mathcal{L}_8\ , \quad \mathcal{L}_4 = \frac{g_{20}}{\Lambda^2}[(\bar{q}q)^2 + (\bar{q}i\gamma_5\tau q)^2] - \frac{g_{02}}{\Lambda^2}(\bar{q}\gamma_\mu q)^2\ ,$$

$$\mathcal{L}_8 = \frac{g_{40}}{\Lambda^8}[(\bar{q}q)^2 + (\bar{q}i\gamma_5\tau q)^2]^2 - \frac{g_{04}}{\Lambda^8}(\bar{q}\gamma_\mu q)^4 - \frac{g_{22}}{\Lambda^8}(\bar{q}\gamma_\mu q)^2[(\bar{q}q)^2 + (\bar{q}i\gamma_5\tau q)^2]$$

Meanfield approximation: $\mathcal{L}_{\mathrm{MF}} = \bar{q}(i\partial\!\!\!/ - M)q + \tilde{\mu}_q \bar{q}\gamma^0 q - U\ ,$

$$M = m + 2\frac{g_{20}}{\Lambda^2}\langle\bar{q}q\rangle + 4\frac{g_{40}}{\Lambda^8}\langle\bar{q}q\rangle^3 - 2\frac{g_{22}}{\Lambda^8}\langle\bar{q}q\rangle\langle q^\dagger q\rangle^2\ ,$$

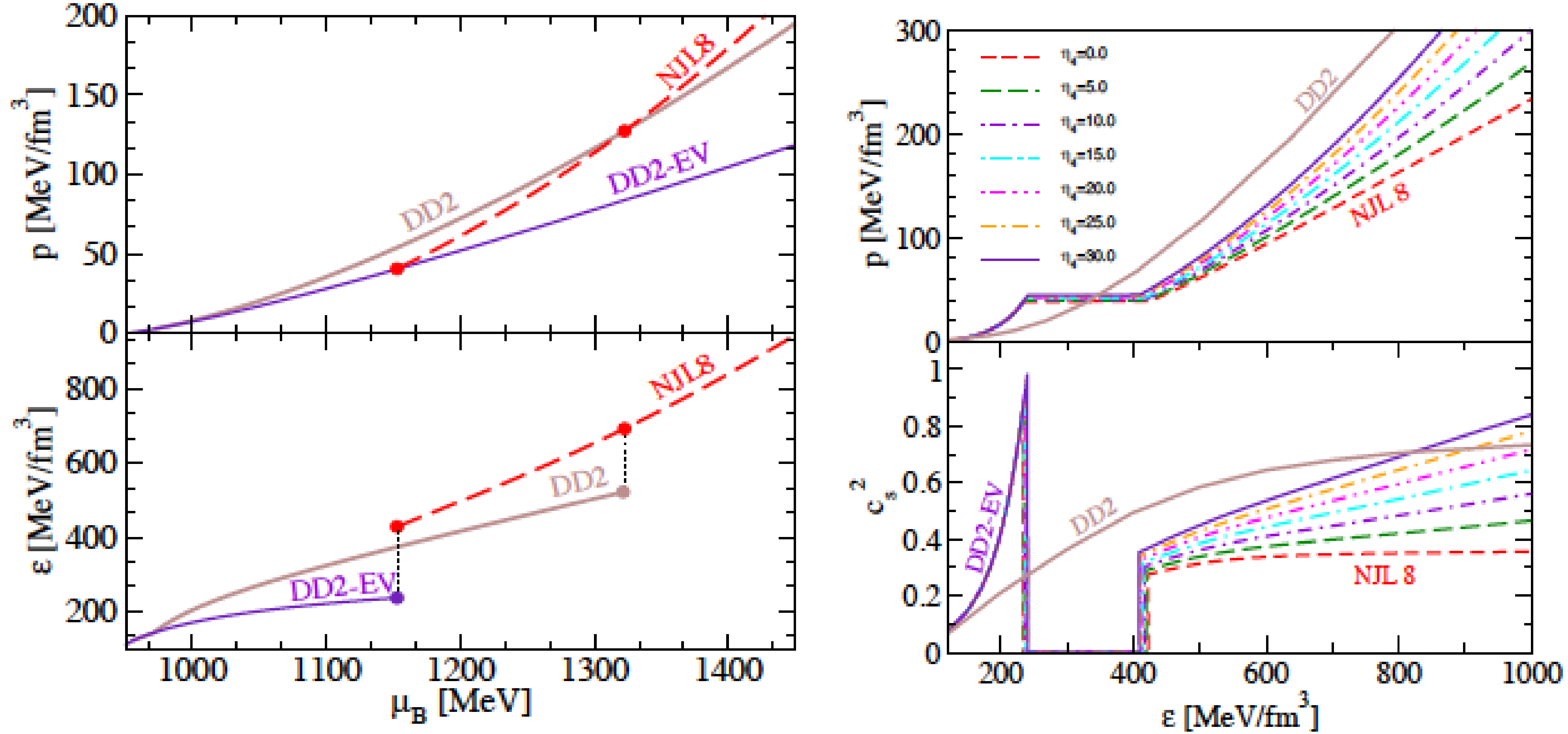
$$\tilde{\mu}_q = \mu_q - 2\frac{g_{02}}{\Lambda^2}\langle q^\dagger q\rangle - 4\frac{g_{04}}{\Lambda^8}\langle q^\dagger q\rangle^3 - 2\frac{g_{22}}{\Lambda^8}\langle\bar{q}q\rangle^2\langle q^\dagger q\rangle\ ,$$

$$U = \frac{g_{20}}{\Lambda^2}\langle\bar{q}q\rangle^2 + 3\frac{g_{40}}{\Lambda^8}\langle\bar{q}q\rangle^4 - 3\frac{g_{22}}{\Lambda^8}\langle\bar{q}q\rangle^2\langle q^\dagger q\rangle^2 - \frac{g_{02}}{\Lambda^2}\langle q^\dagger q\rangle^2 - 3\frac{g_{04}}{\Lambda^8}\langle q^\dagger q\rangle^4\ .$$

Thermodynamic Potential:

$$\Omega = U - 2N_f N_c \int \frac{d^3p}{(2\pi)^3}\left\{E + T\log[1 + e^{-\beta(E-\tilde{\mu}_q)}] + T\log[1 + e^{-\beta(E+\tilde{\mu}_q)}]\right\} + \Omega_0$$

Modern 2-phase EoS in Astrophysics of Compact Stars

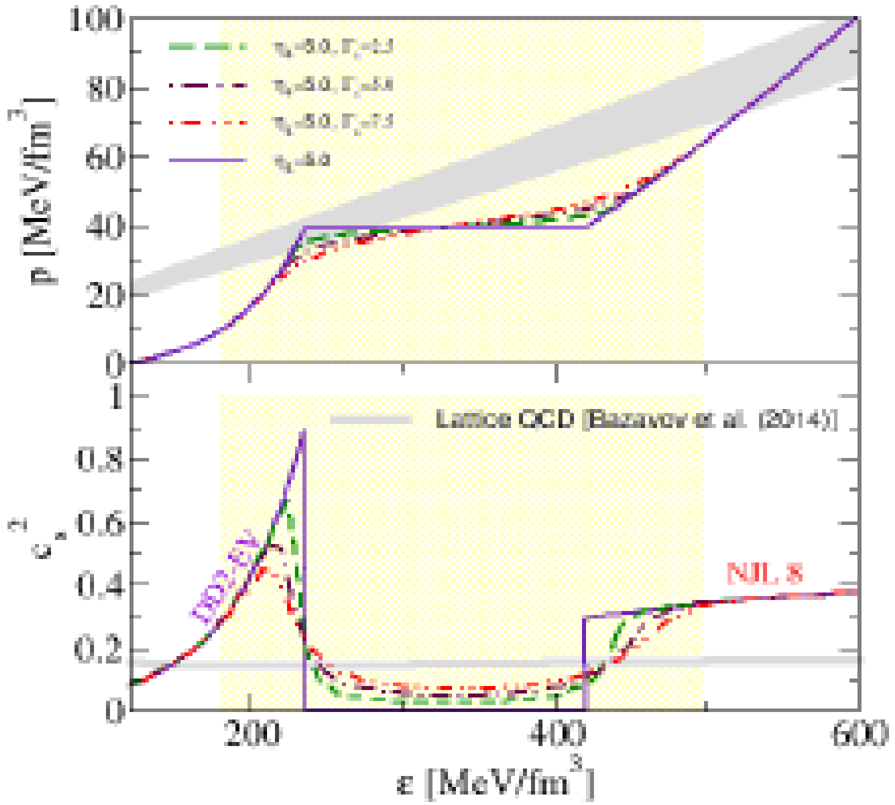


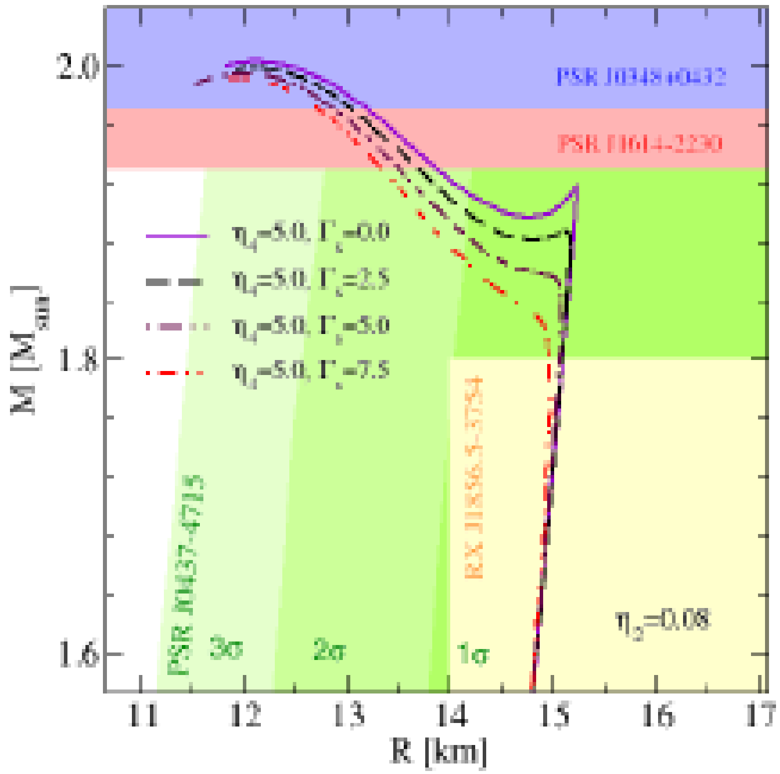
Here: Stiffening of dense hadronic matter by excluded volume in density-dependent RMF
Stiffening of dense quark matter by higher order quark vector current interactions (η_4)

S. Benic, D.B., D. Alvarez-Castillo, T. Fischer, S. Typel, A&A 577, A40 (2015) - STSM 2014

Modern 2-phase EoS in Astrophysics of Compact Stars

Estimate effects of structures in the phase transition region (“pasta”)

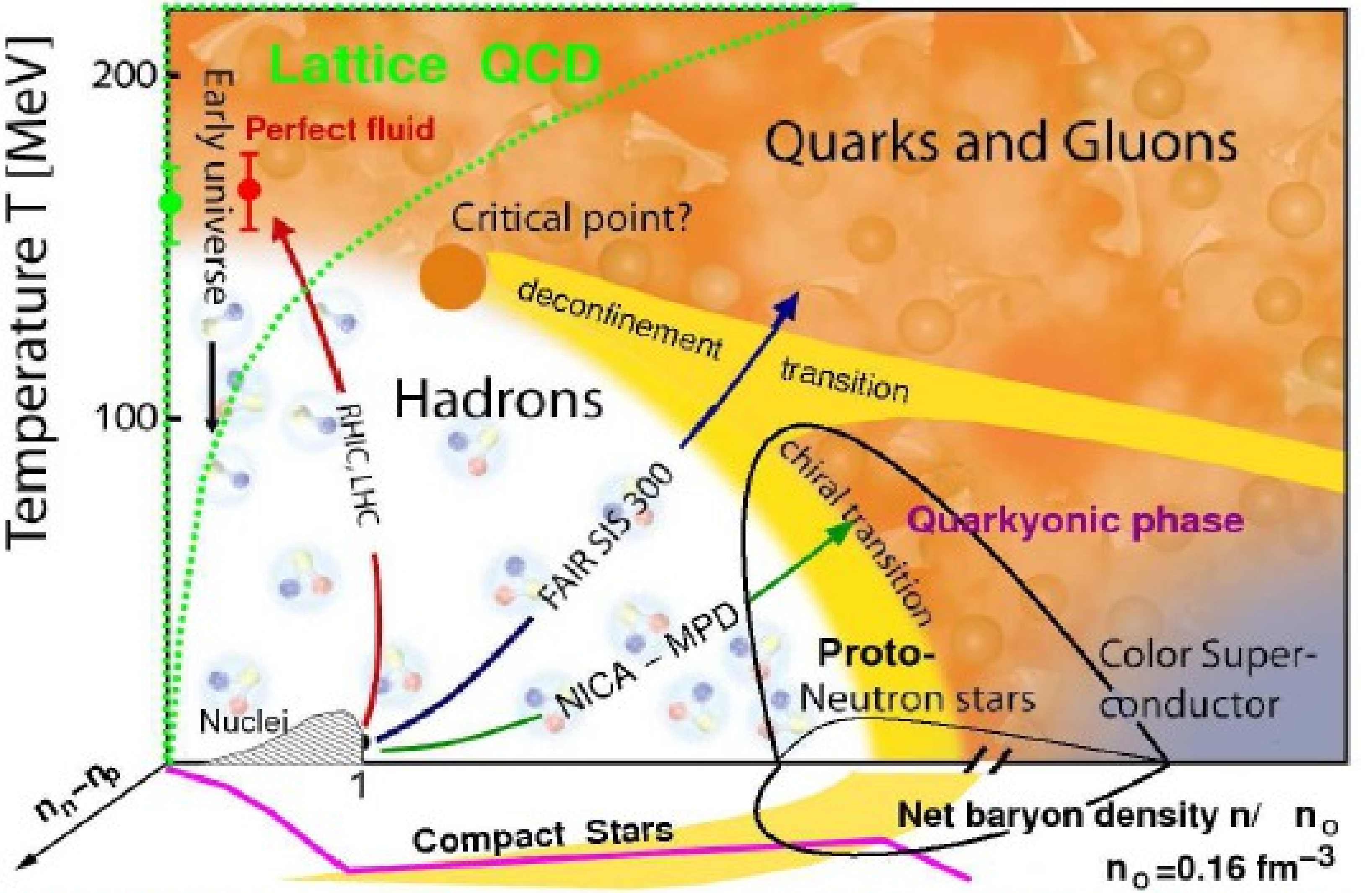




High-mass Twins relatively robust against “smoothing” the Maxwell transition construction

D. Alvarez-Castillo, D.B., arxiv:1412.8463

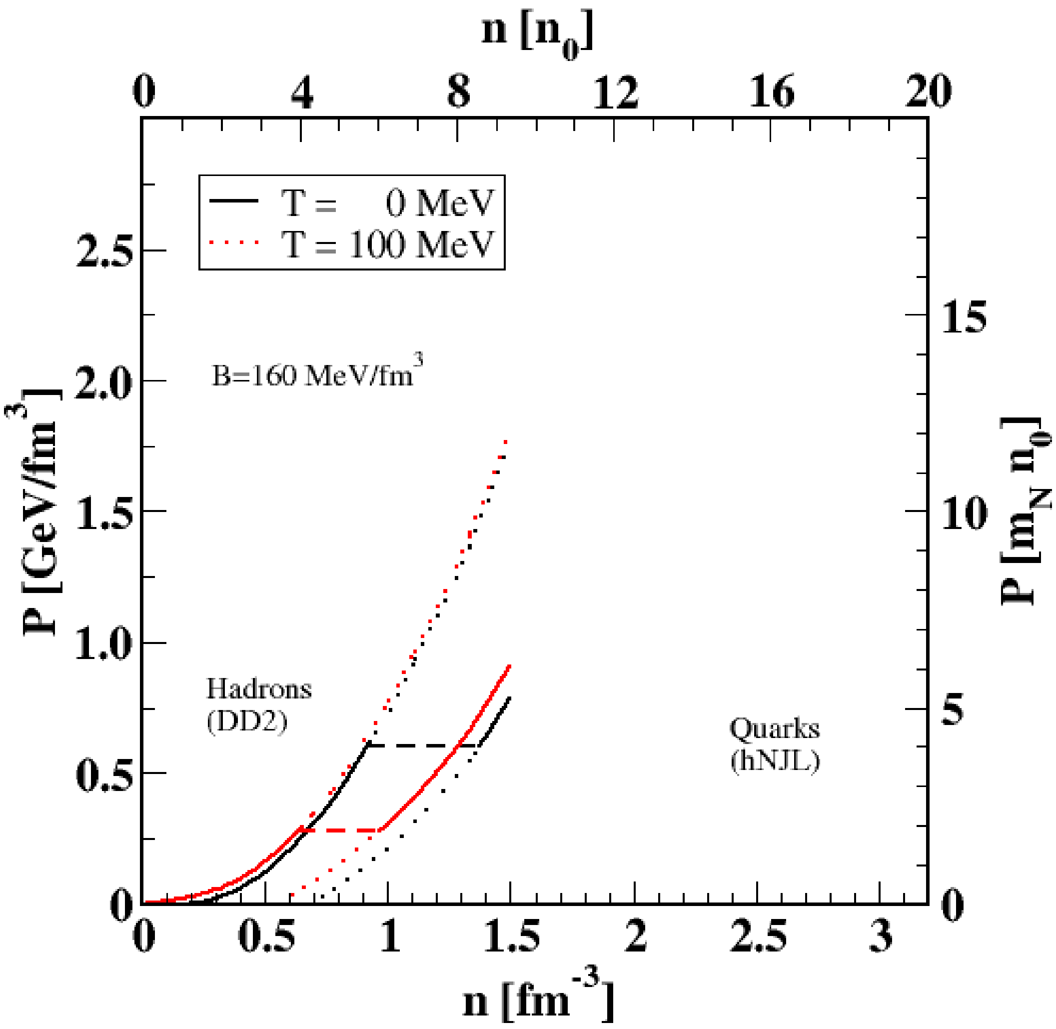
Support a CEP in QCD phase diagram with Astrophysics?

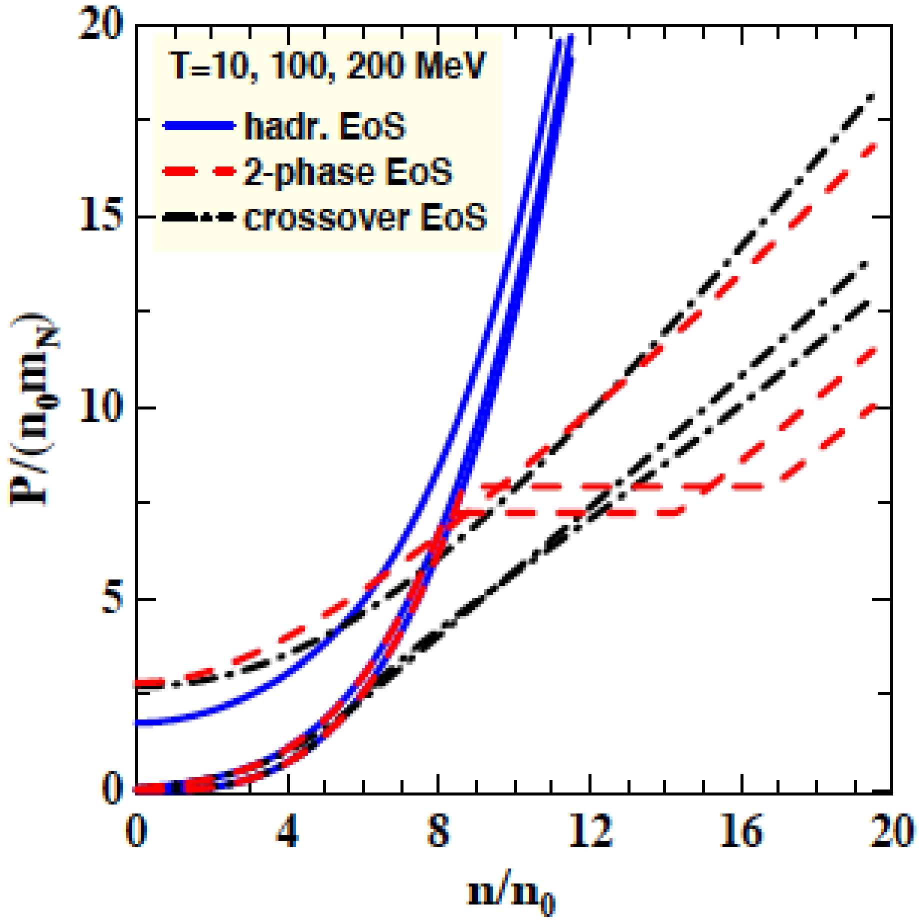


NICA White Paper, http://theor.jinr.ru/twiki-cgi/view/NICA/WebHome

Crossover at finite T (Lattice QCD) + First order at zero T (Astrophysics) = Critical endpoint exists!

Comparison 2-phase EoS





N.-U. Bastian, D. Blaschke (S. Benic, S. Typel),
In progress (2015)

A. Khvorostukhin et al. EPJC 48 (2006) 531
Yu. Ivanov, D. Blaschke, arxiv:1504.03992

Summary / Outlook:

- Baryon stopping signal (“wiggle”) remains a robust signal for 1st order PT also under severe cuts in transverse momentum !

- Discrimination between hadronic phase and crossover transition ambiguous

- Position of the “wiggle” in the beam energy scan is EoS dependent – new EoS ?!

- Particlization of 3-Fluid Hydrodynamics model works !

- Detector simulation in progress

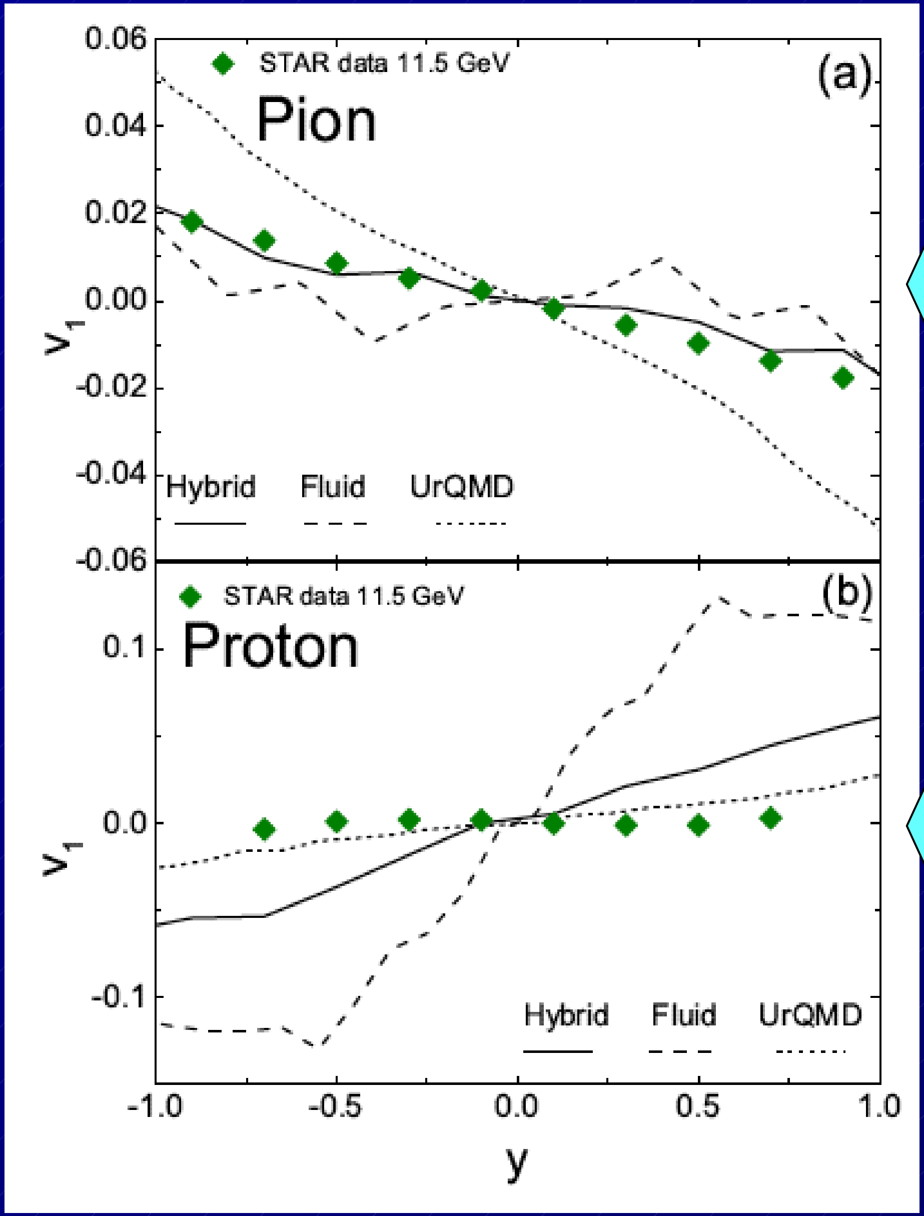
- UrQMD “afterburner” in progress

- Systematic study of modern 2-phase EoS (Bayesian analysis) in progress

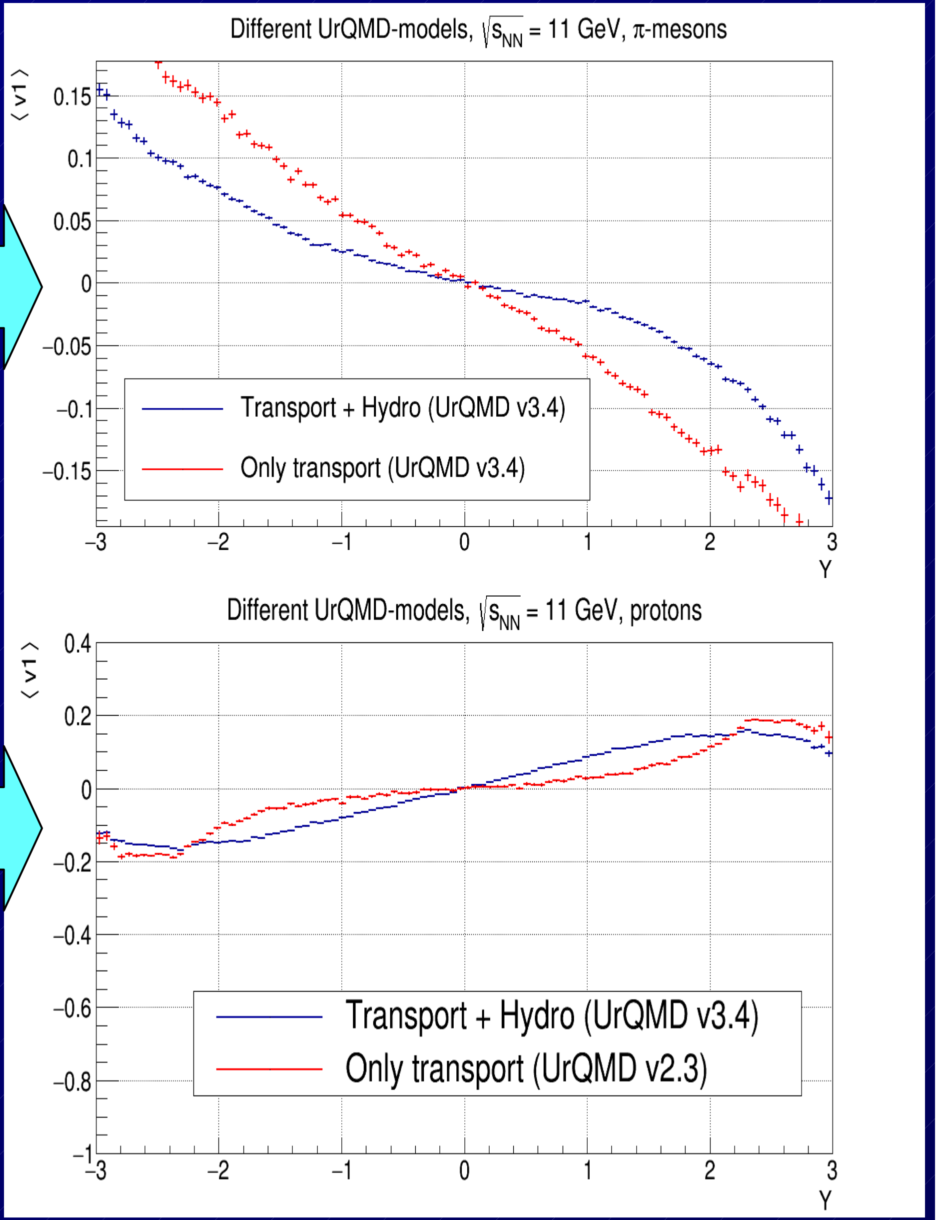
Additional Slides

Further results of test simulations – flow observables

J. Steinheimer et al., Phys. Rev. C89 (2014) 054913



Reproduced !



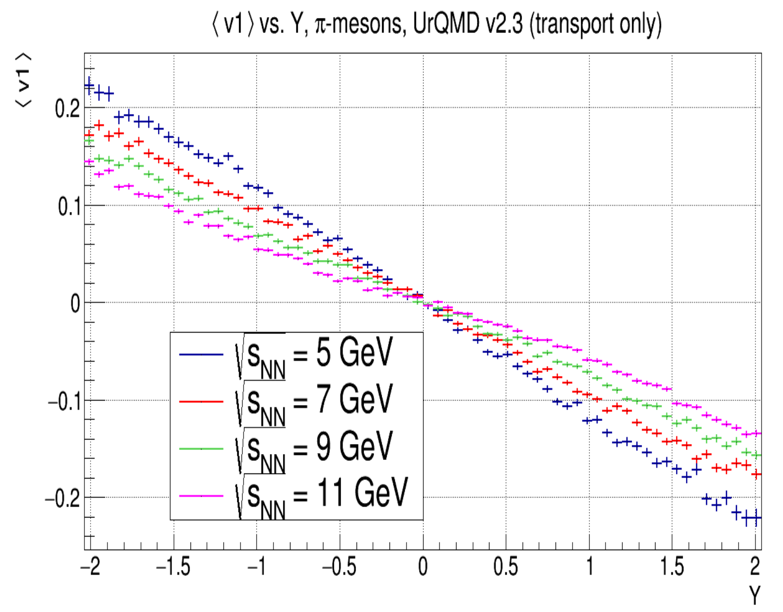
UrQMD + hydro (1st order PT) – H. Petersen

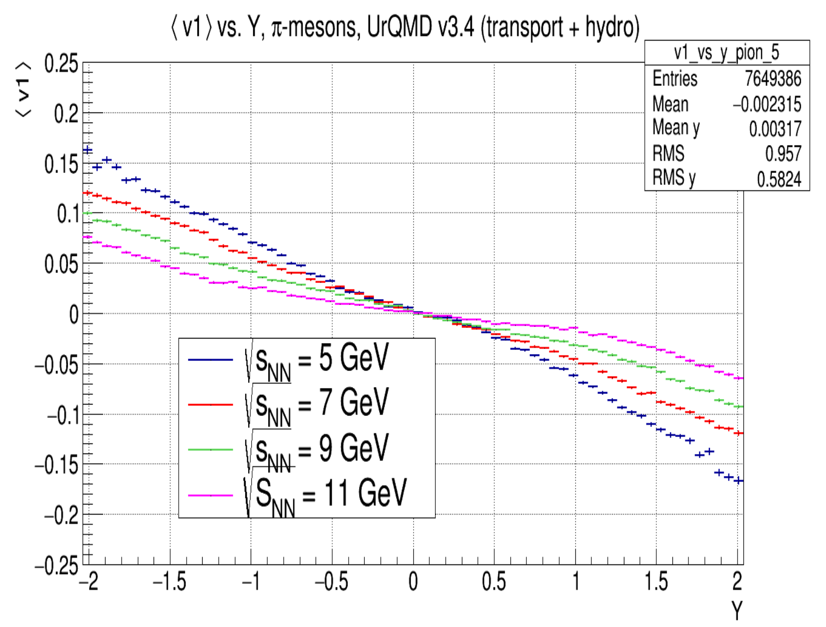
© Pavel Batyuk, Jan 2015

Further results of test simulations – flow observables

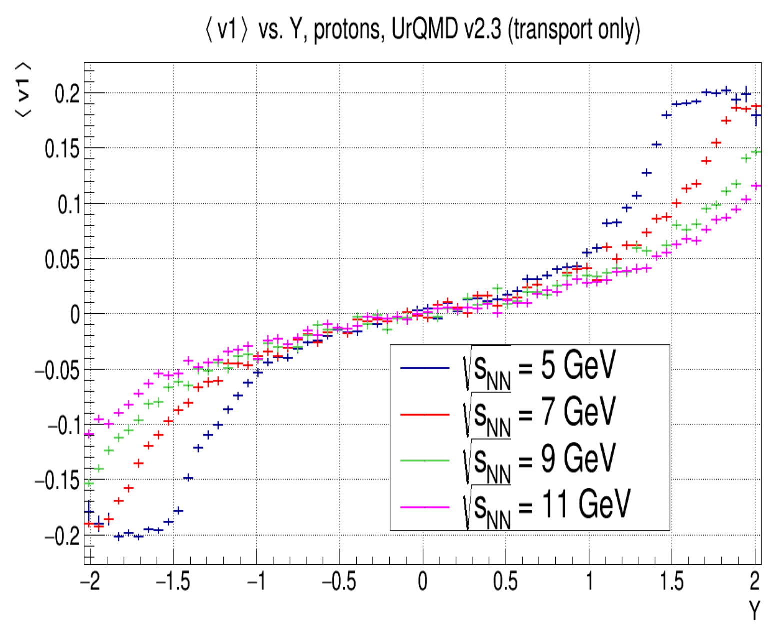
NICA energy scan: **UrQMD** **$\langle v_1 \rangle$** UrQMD + hydro (1st order PT)

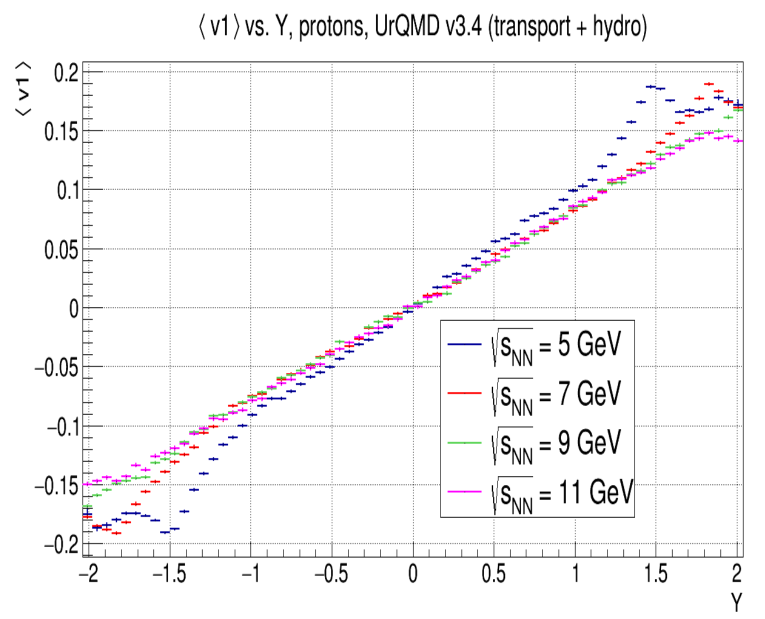
Pions





Protons

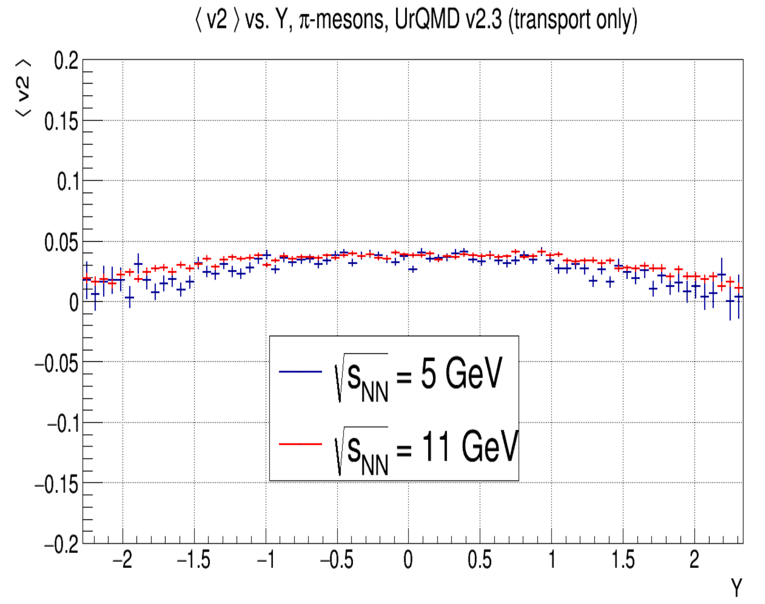


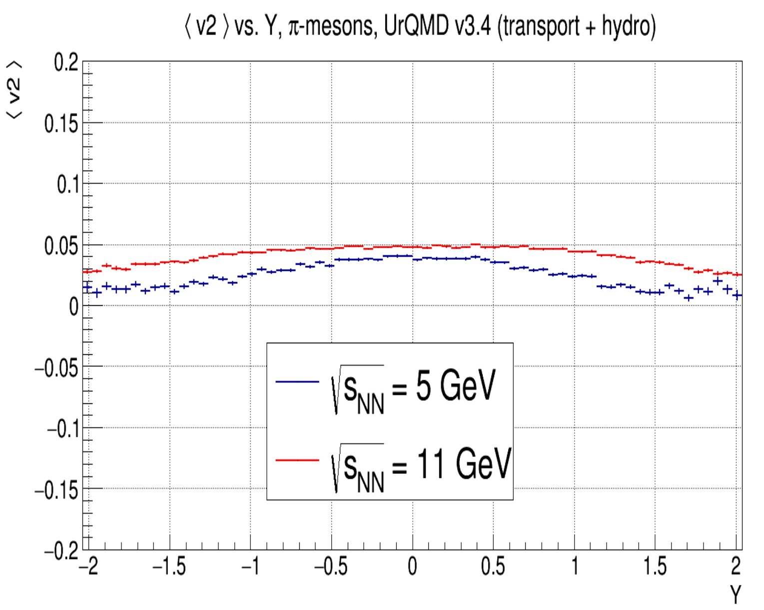


Further results of test simulations – flow observables

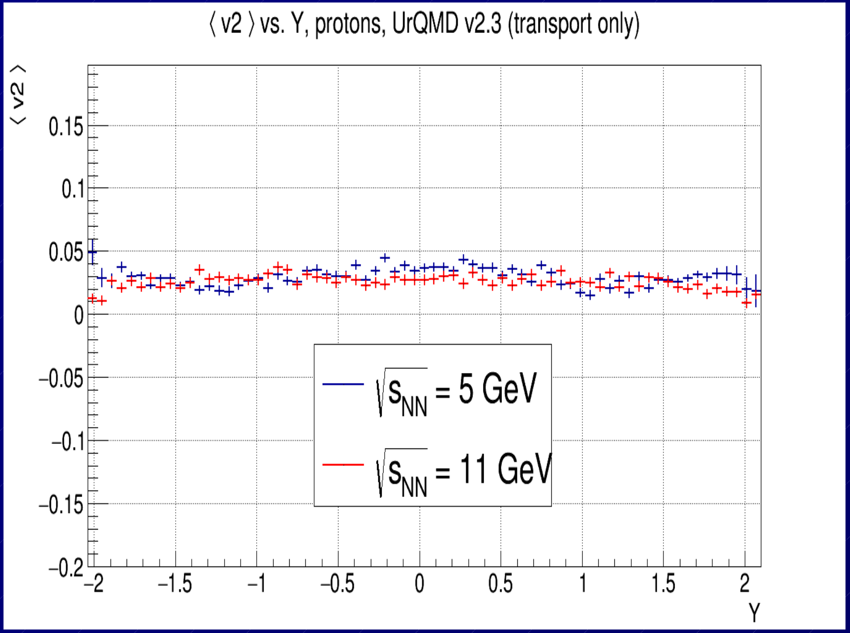
NICA energy scan: UrQMD $\langle v_2 \rangle$ UrQMD + hydro (1st order PT)

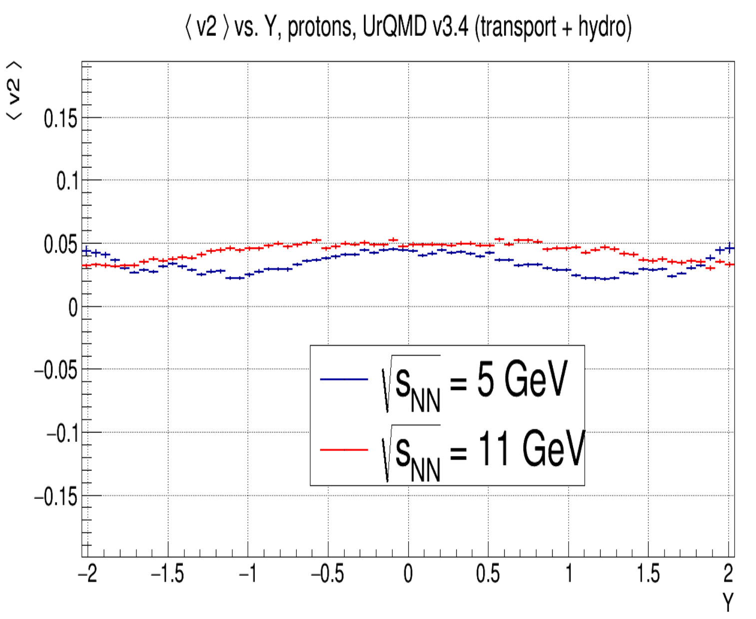
Pions


⟨ v2 ⟩ vs. Y, π-mesons, UrQMD v2.3 (transport only)


⟨ v2 ⟩ vs. Y, π-mesons, UrQMD v3.4 (transport + hydro)

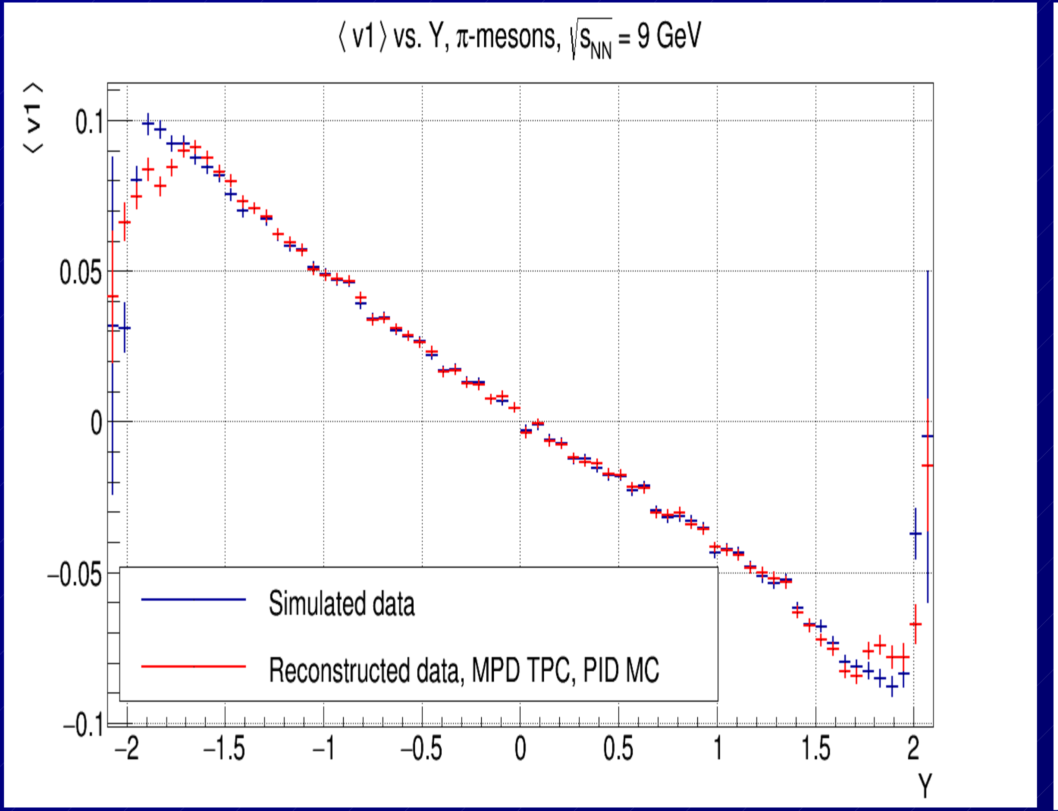
Protons

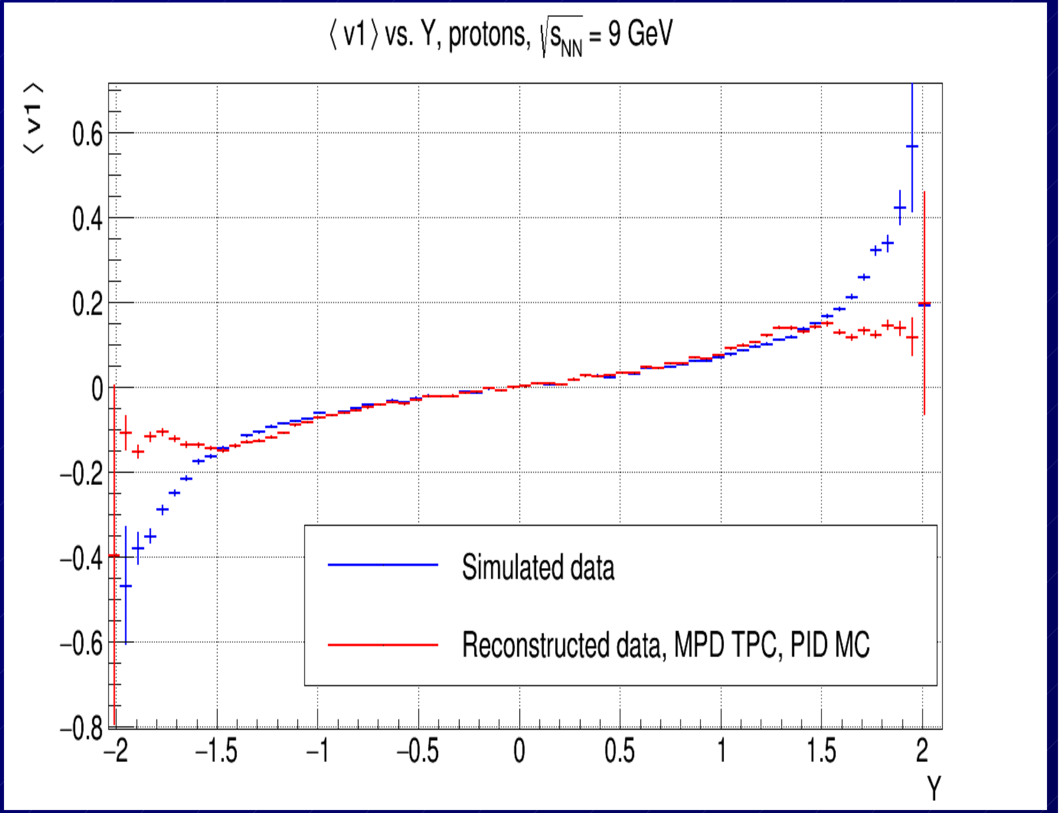

⟨ v2 ⟩ vs. Y, protons, UrQMD v2.3 (transport only)


⟨ v2 ⟩ vs. Y, protons, UrQMD v3.4 (transport + hydro)

Further results of test simulations – flow observables

Detector Simulation with GEANT : Excellent reproduction of simulation results !

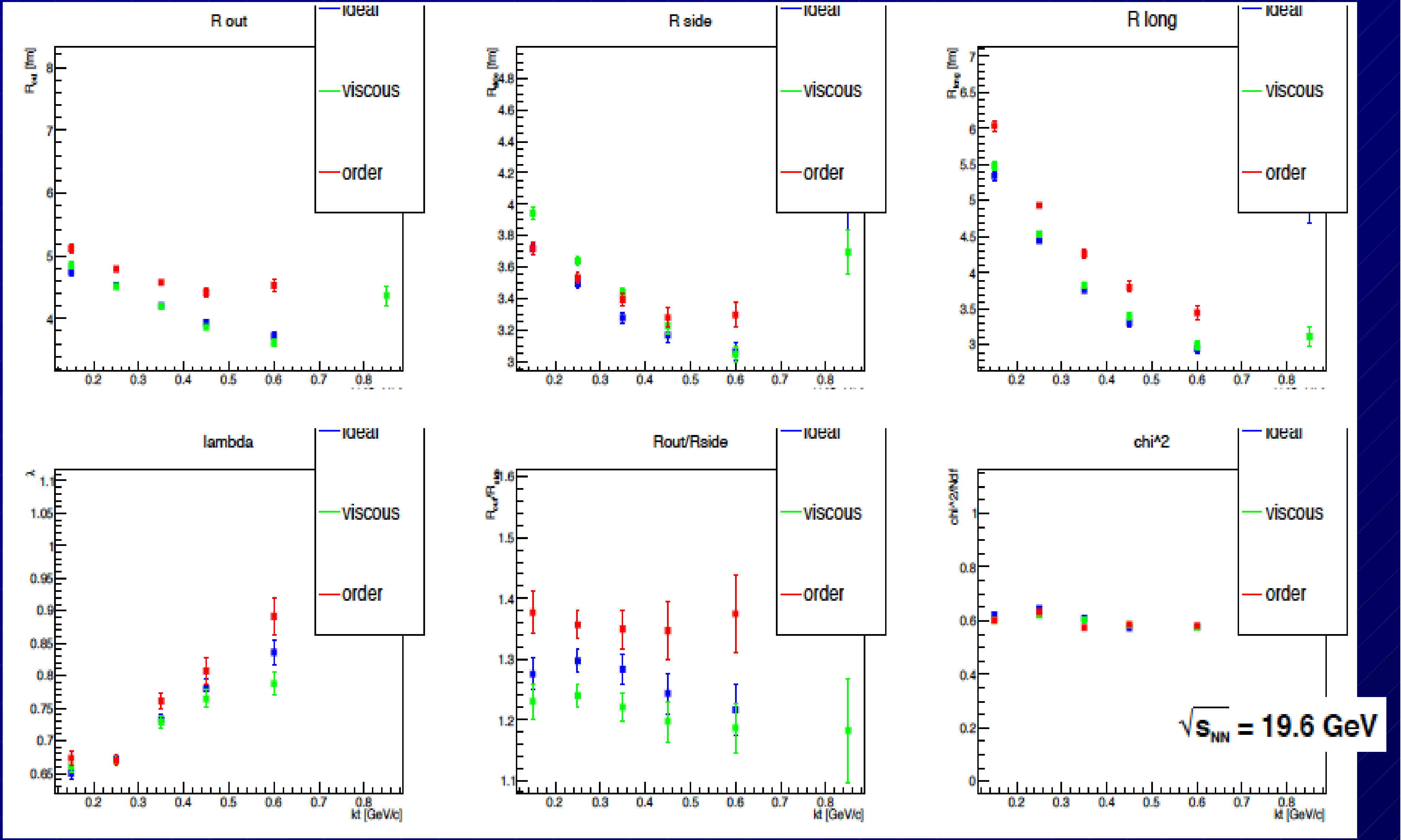

⟨v1⟩ vs. Y, π-mesons, $\sqrt{s_{NN}} = 9$ GeV


⟨v1⟩ vs. Y, protons, $\sqrt{s_{NN}} = 9$ GeV

UrQMD + hydro (1st order PT) – H. Petersen

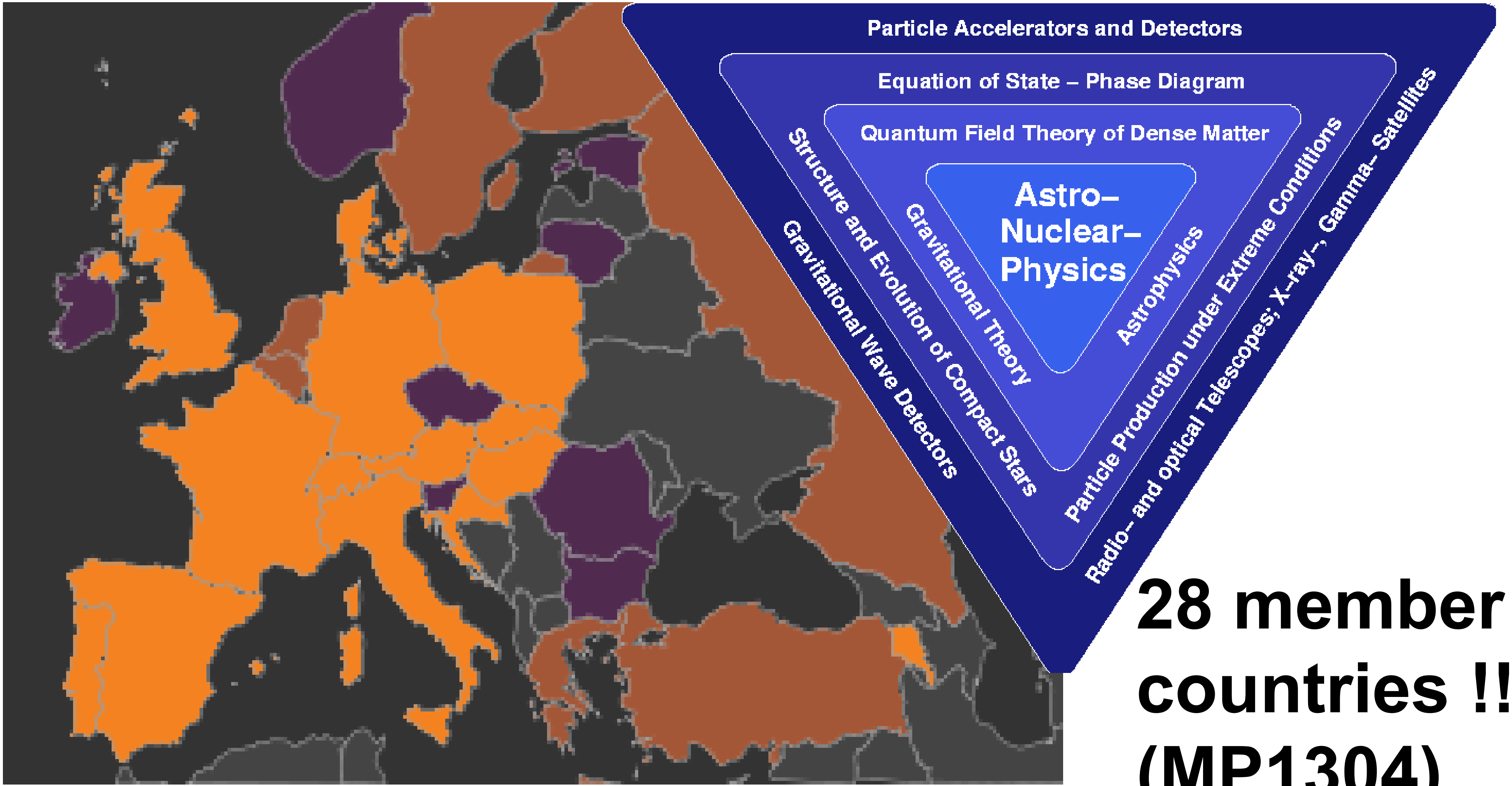
© Pavel Batyuk, Jan 2015

Further results of test simulations – HBT radii



Hydro+kinetic model (Karpenko)

© Daniel Wielanek (Warsaw), Jan 2015



Particle Accelerators and Detectors

Equation of State – Phase Diagram

Quantum Field Theory of Dense Matter

Astro–Nuclear–Physics

Gravitational Theory

Astrophysics

Structure and Evolution of Compact Stars

Particle Production under Extreme Conditions

Gravitational Wave Detectors

Radio– and optical Telescopes; X–ray–, Gamma– Satellites

28 member countries !!
(MP1304)

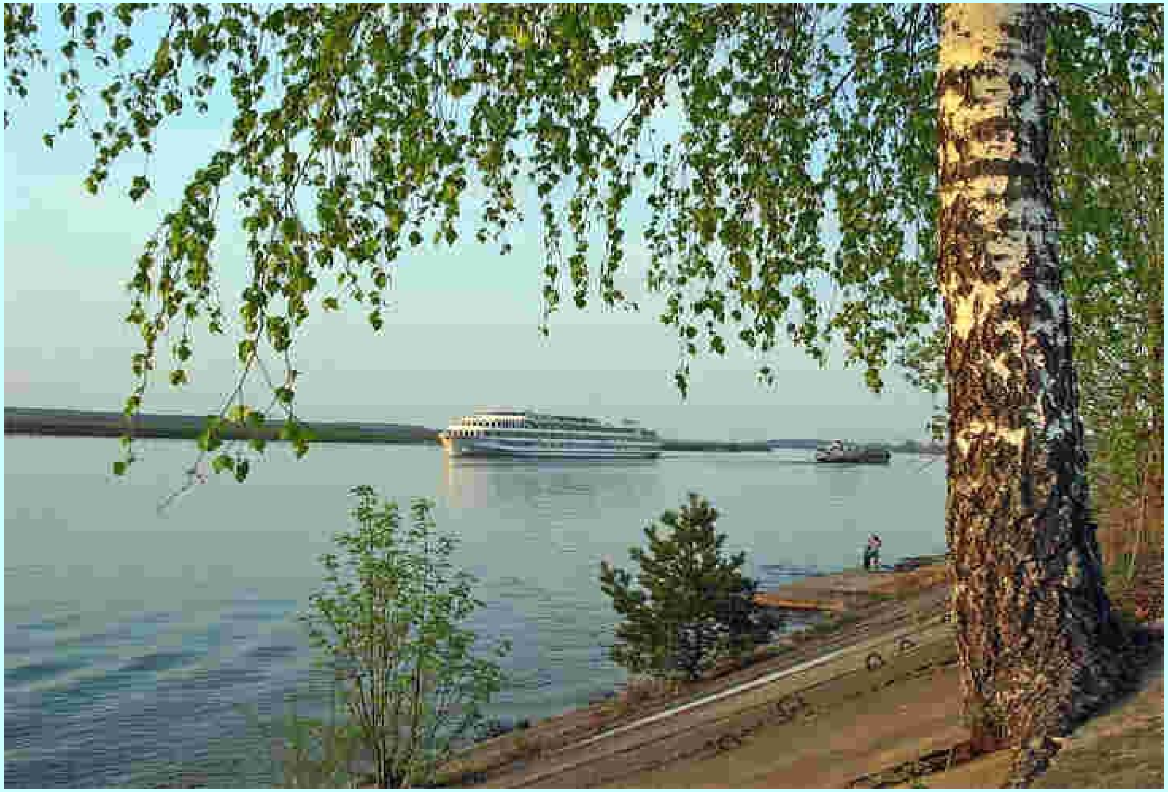
New compstar **!**

cost
EUROPEAN COOPERATION
IN SCIENCE AND TECHNOLOGY

Kick-off: Brussels, November 25, 2013

Strangeness in Quark Matter 2015

Dubna, 6.-11. July 2015



Official Logo:

SQM

DUBNA 2015

Email: sqm@jinr.ru
Website: http://sqm.jinr.ru

Satellite Meetings:

Summer School “Dense Matter”, Dubna, June 29 – July 11, 2015
Roundtable “Physics at NICA”, Dubna, 5. July 2015