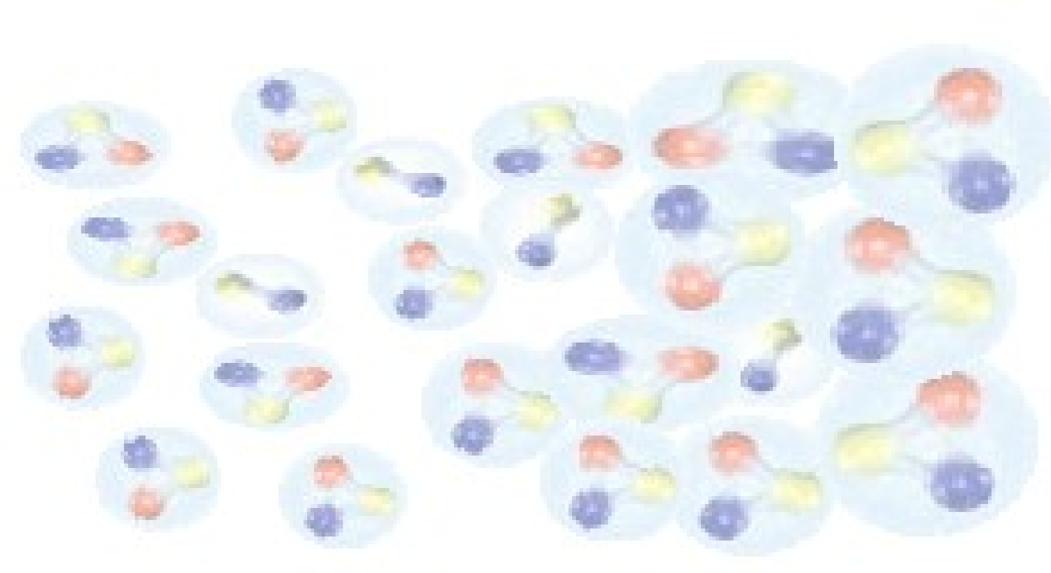
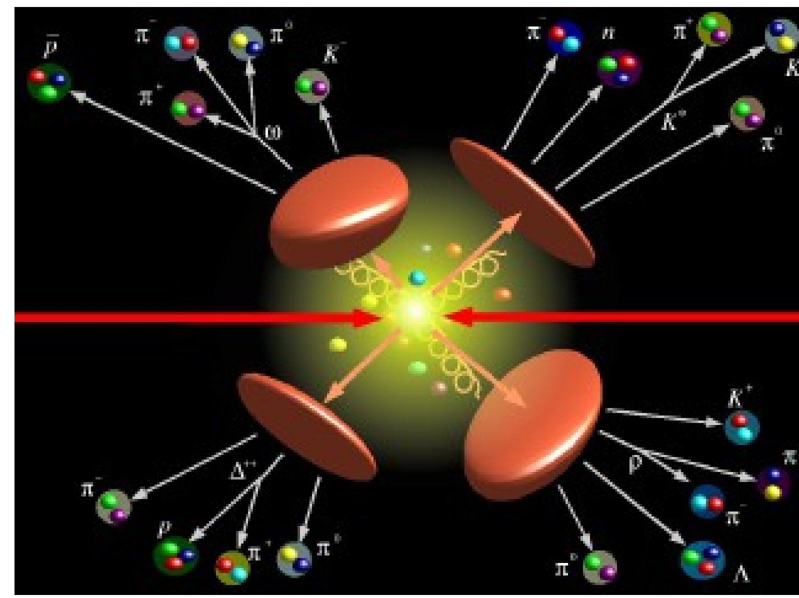
Baryon stopping signal for a Phase Transition in Heavy-Ion Collisions

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





Transport Theory Seminar, FIAS Frankfurt, November 11, 2015

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Baryon stopping signal for a Phase Transition in Heavy-Ion Collisions

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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, UrQMD, new class EoS

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

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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

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

3-fluid hydro, (Yu. Ivanov)

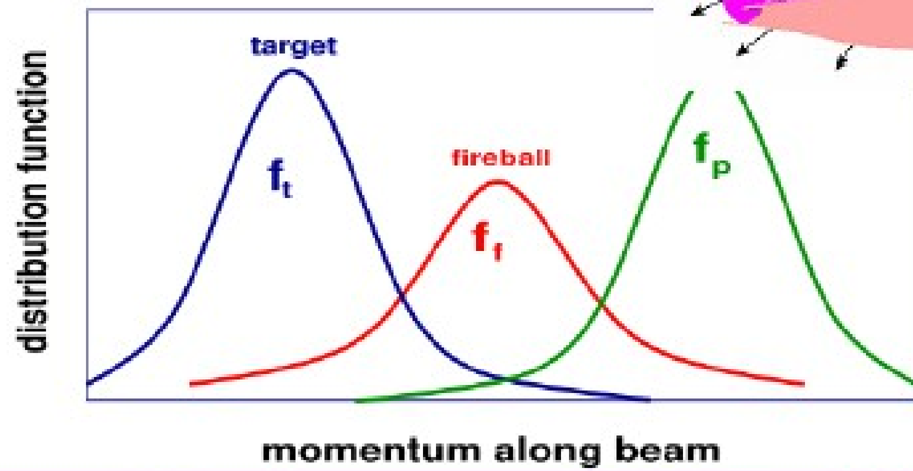
adapt the procedure from existing hybrid model (Iu. Karpenko)

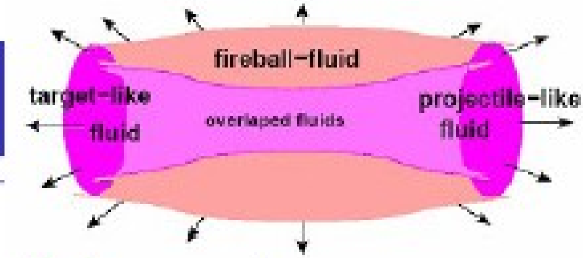
(optionally) cascade: PHSD, UrQMD, etc (E. Bratkovskaya, H. Petersen)

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

3-Fluid Dynamics

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





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

Leading particles carry bar. charge $\quad$ exchange/emission

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

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

Baryon-free fluid $\quad$ Source term $\quad$ Exchange

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

Total energy-momentum conservation:

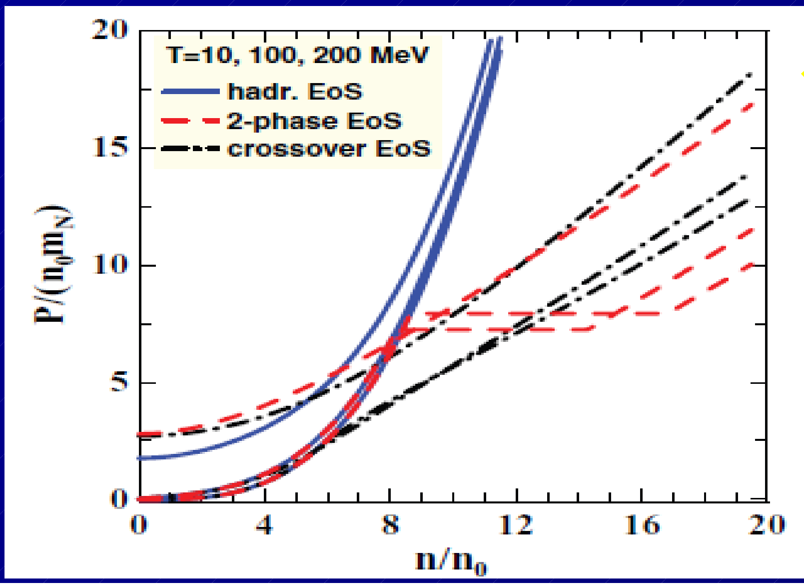
$$\partial_\mu (T_p^{\mu\nu} + T_t^{\mu\nu} + T_f^{\mu\nu}) = 0$$

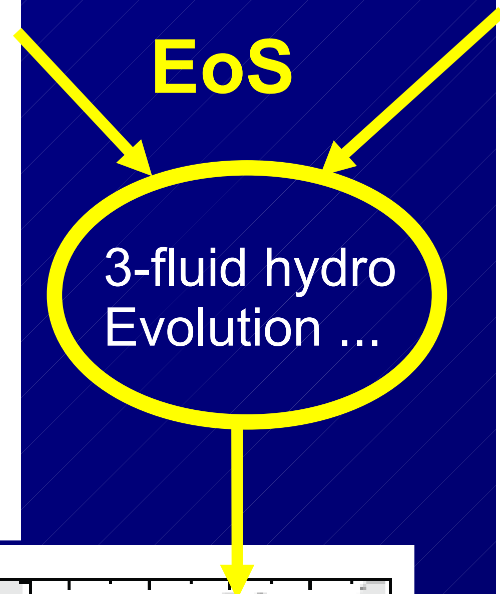
http://theory.gsi.de/~ivanov/mfd/

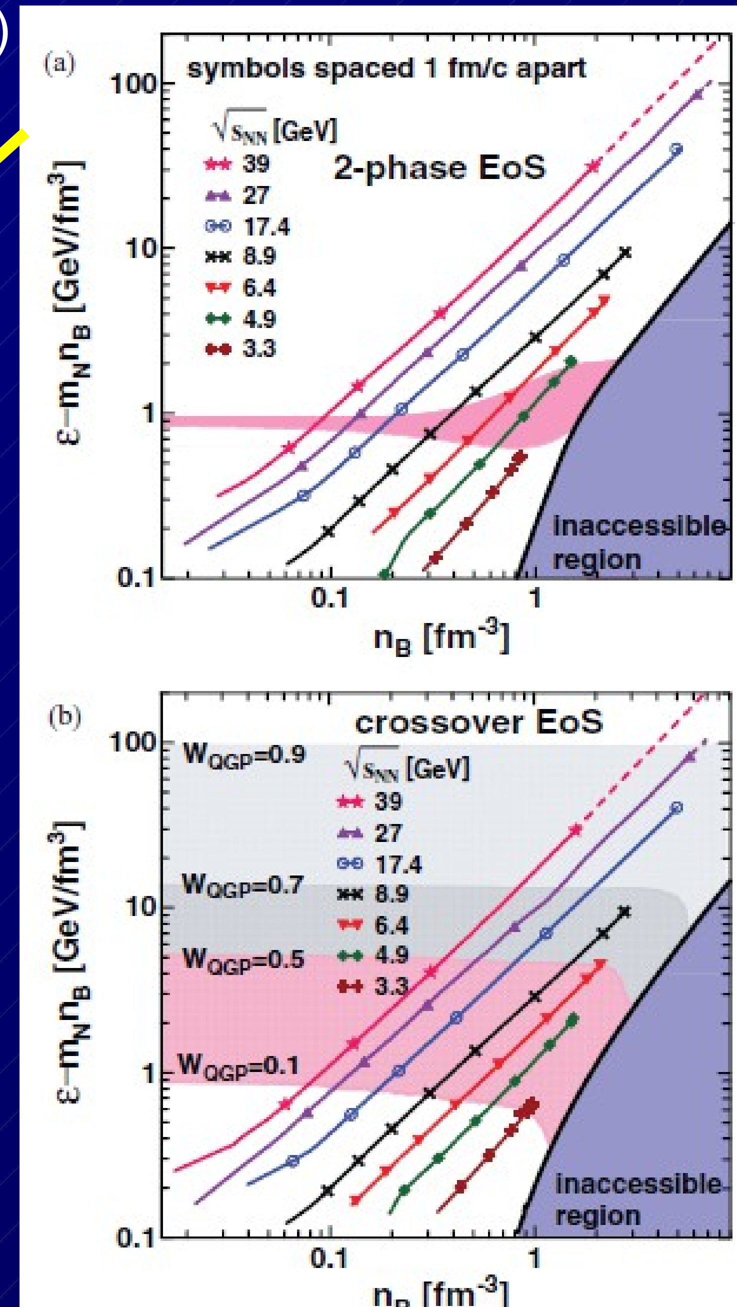
Yu.B. Ivanov, V.N. Russkikh and V.D. Toneev, Phys. Rev. C73, 044904 (2006)

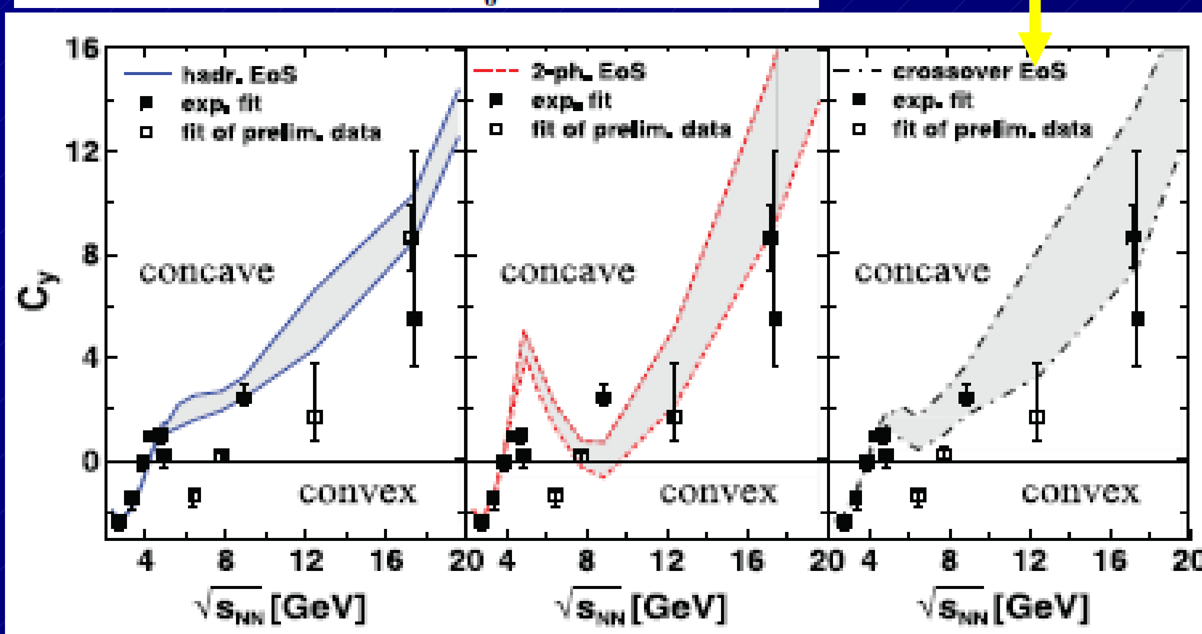
Net proton rapidity distribution – test case for a 1st order PT signal

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







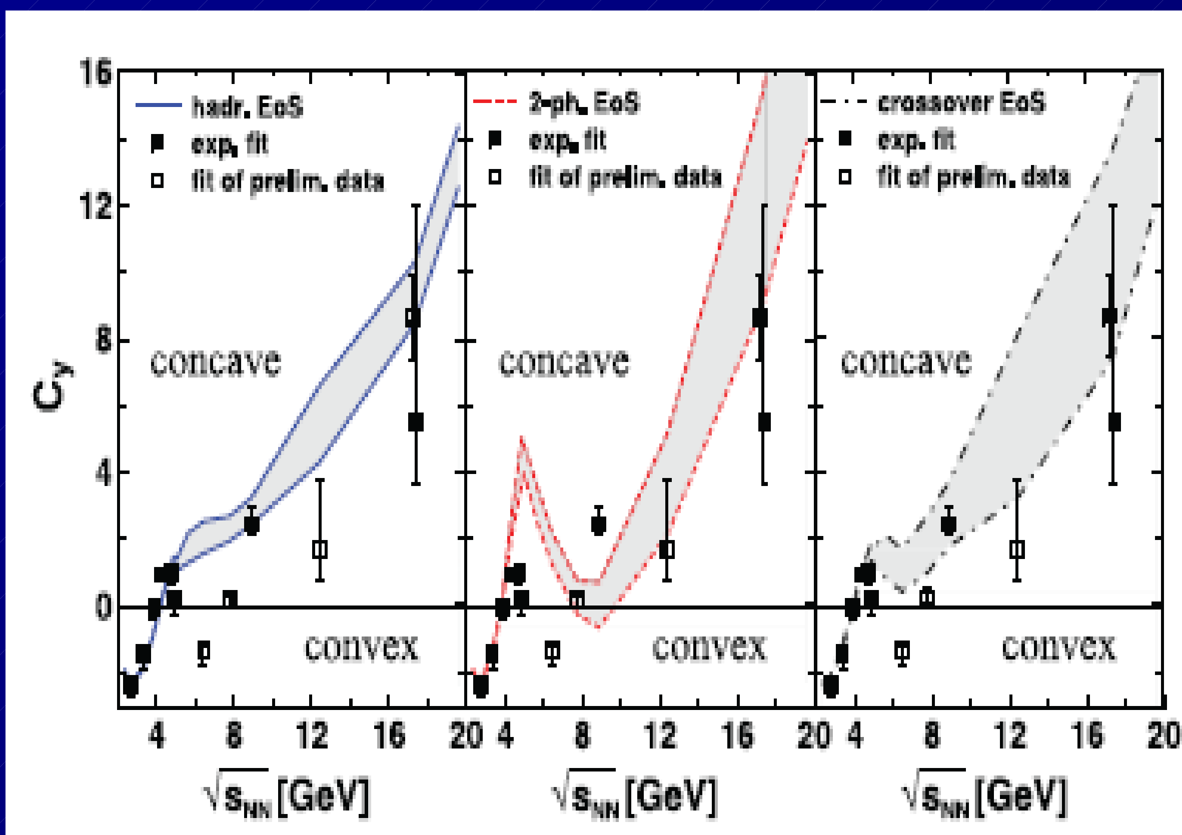


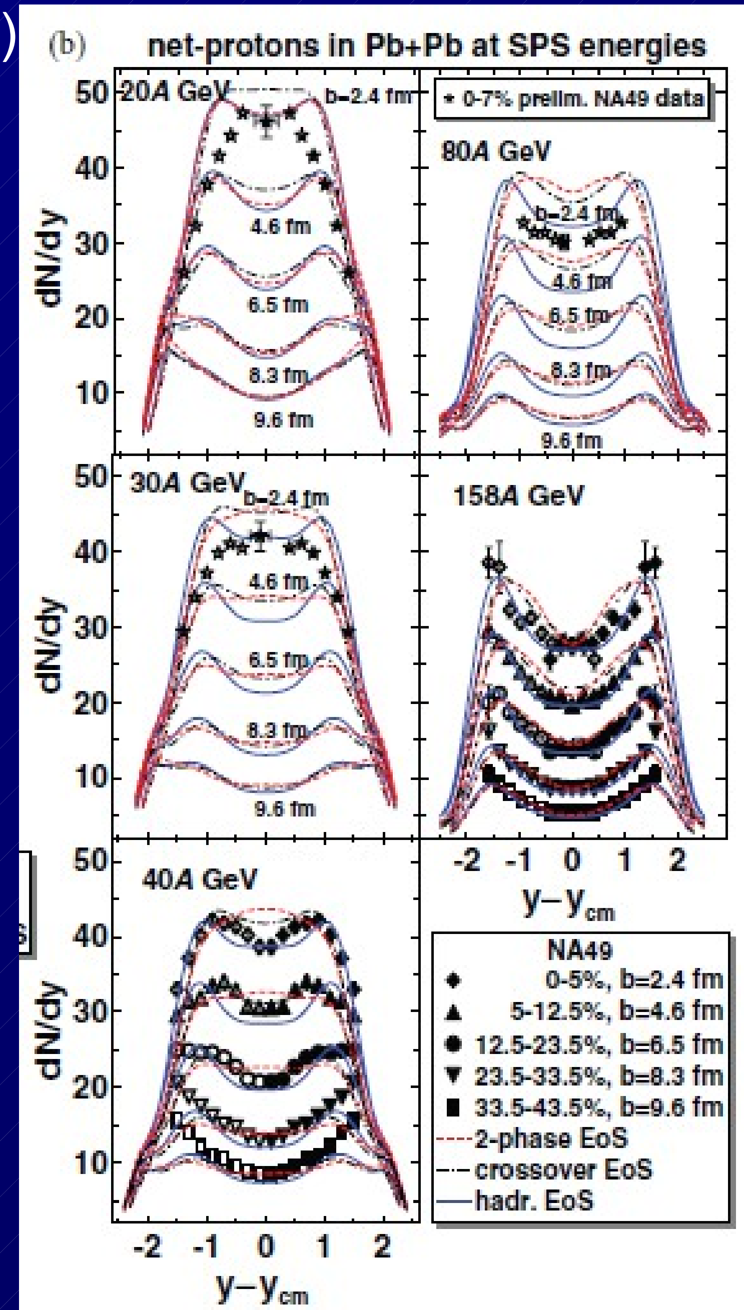
Net proton rapidity distribution – test case for a 1st order PT signal

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

$$C_y = \left(y_{\rm c.m.}^3 \frac{d^3N}{dy^3} \right)_{y=y_{\rm c.m.}} \Bigg/ \left(y_{\rm c.m.} \frac{dN}{dy} \right)_{y=y_{\rm c.m.}}$$

$$= (y_{\rm c.m.}/w_s)^2 (\sinh^2 y_s - w_s \cosh y_s).$$





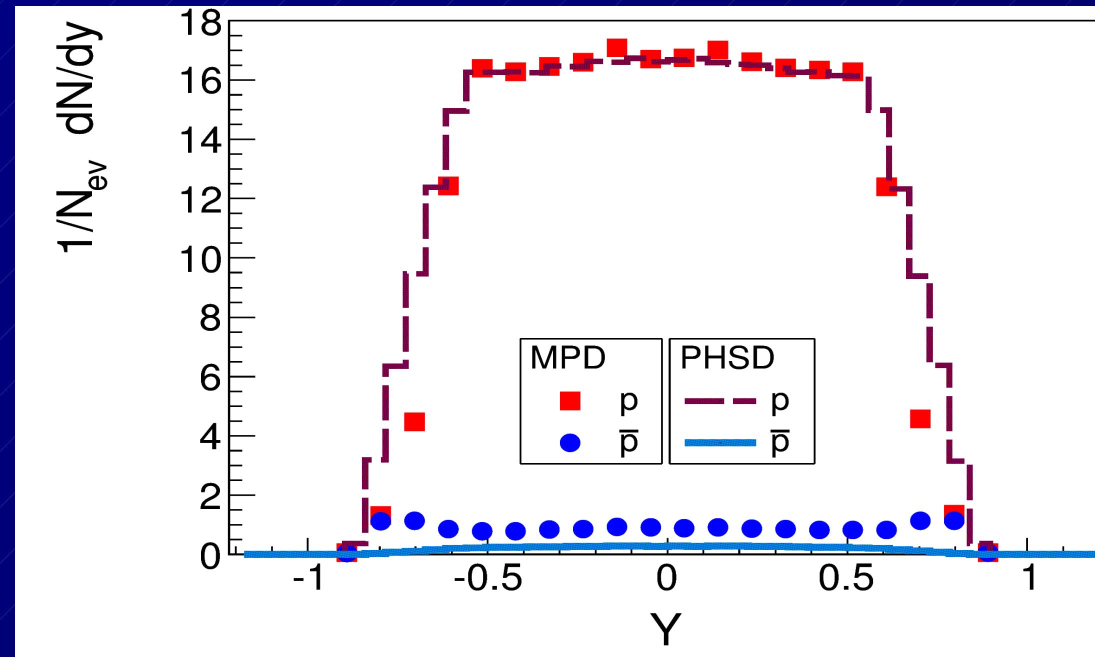
Net proton rapidity distribution – test case for a 1st order PT signal

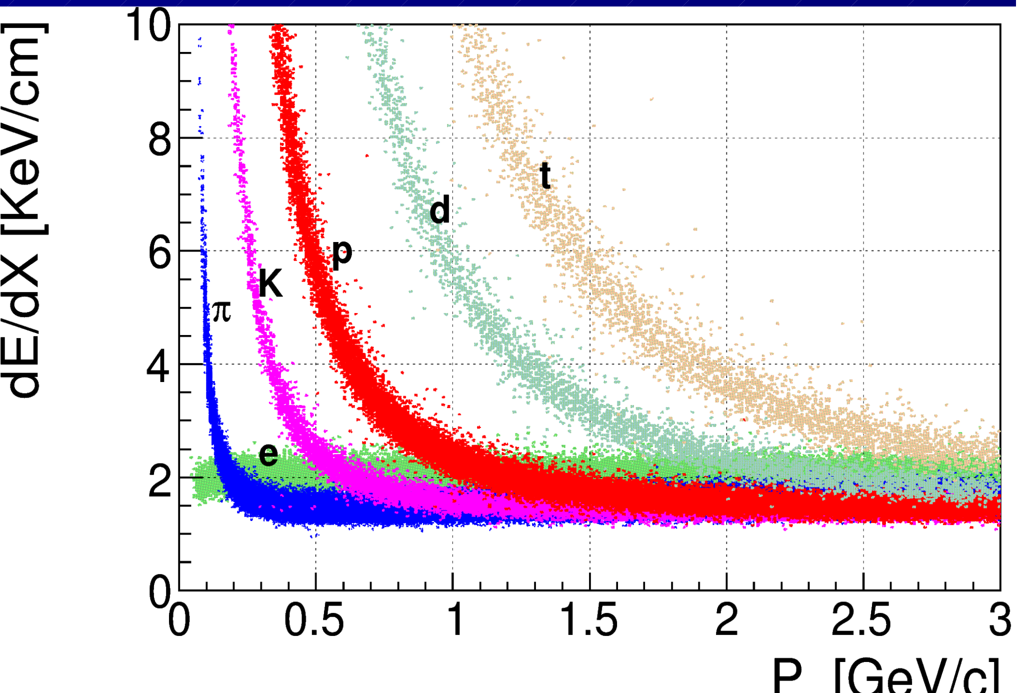
Event set:
40k AuAu @ √s_NN = 9 GeV [0-5%]
The most reliable region
|eta| < 1.2 ; 0.4 < p_t [GeV/c] < 0.8

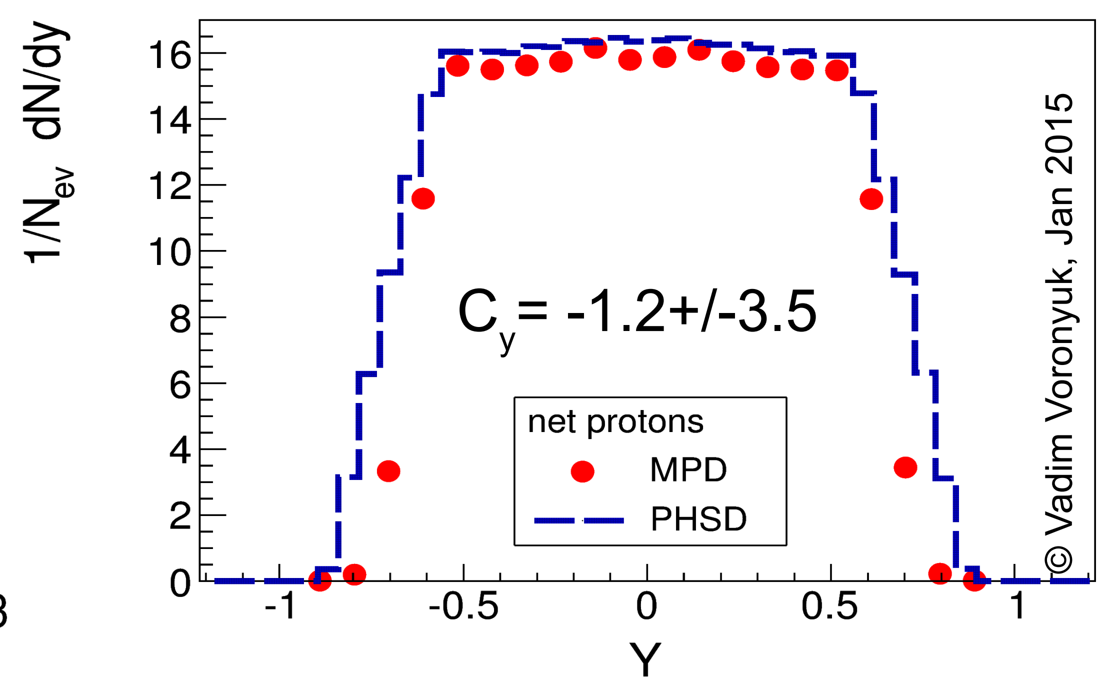
Result:
PHSD input → GEANT+MPD
detector reproduces the rapidity distribution !
(previous concerns not confirmed !!)

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

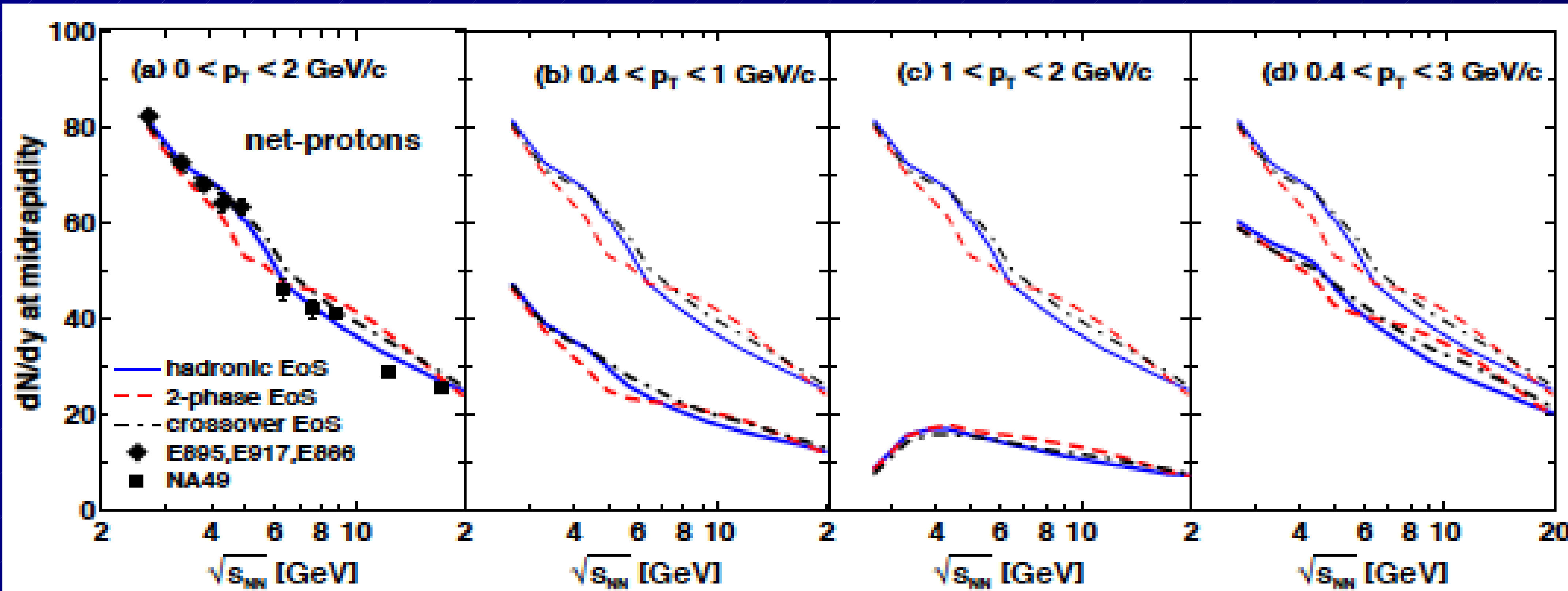
$$C_y = \left(y_{\rm beam}^3 \frac{d^3N}{dy^3} \right)_{y=0} \Big/ \left(y_{\rm beam} \frac{dN}{dy} \right)_{y=0} = (y_{\rm beam}/w_s)^2 \left(\sinh^2 y_s - w_s \cosh y_s \right) .$$

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

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Yu. Ivanov & D. B., PRC 92, 024916 (2015)

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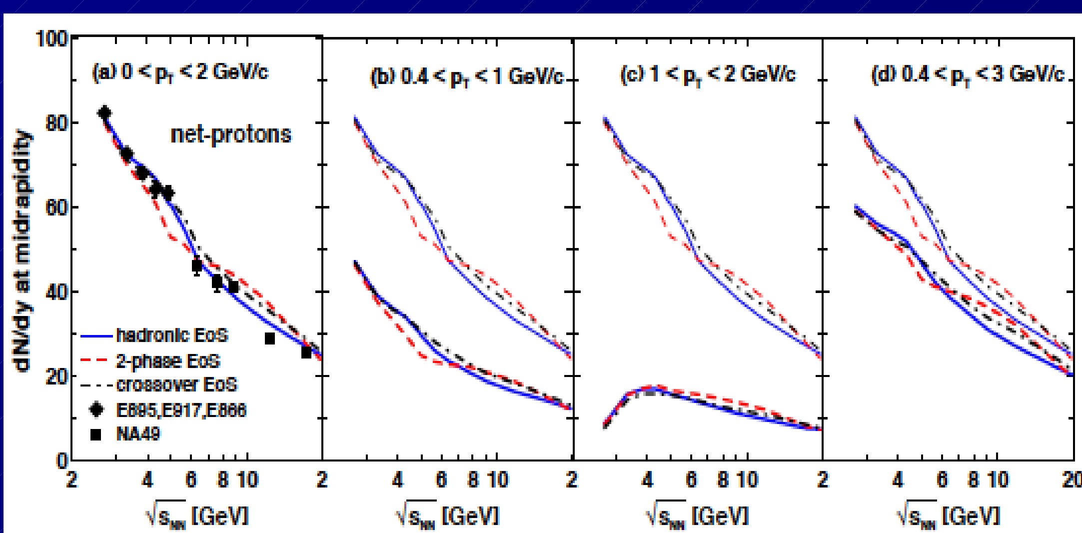
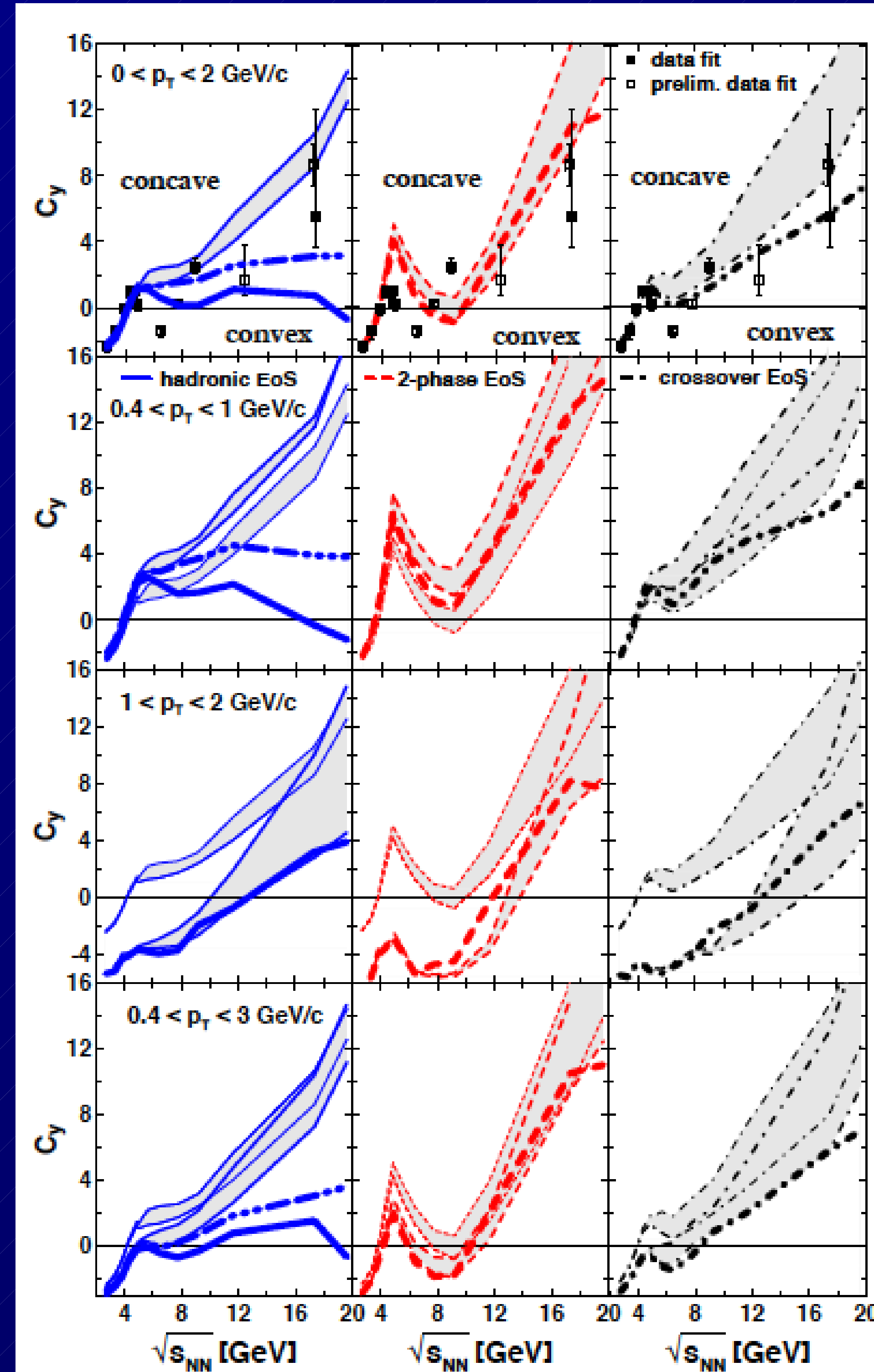
- "wiggle" formed in the nonequilibrium compresion stage of the collision, where p_T only in 3FH
- robust against serious p_T cuts
- at high p_T (1 - 2 GeV/c) in convex region
- at low p_T (0.2 - 1 GeV/c) in concave region
- required accuracy in C_y determination: $\Delta C_y < 2$





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

Investigation of p_T cuts:

Yu. Ivanov & D. Blaschke, arxiv:1504.03992

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

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

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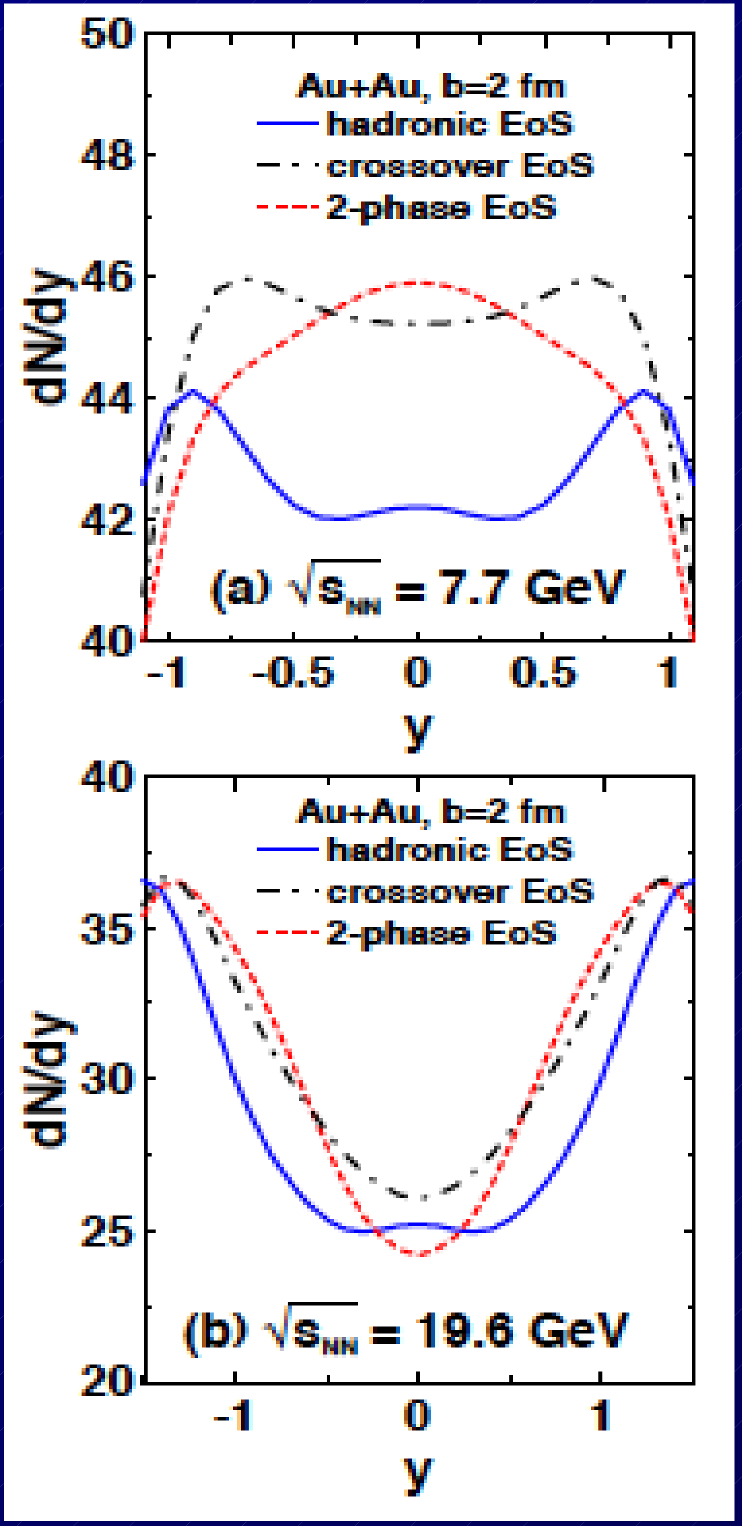


3+1D viscous hydro-cascade model (Yu. Karpenko, FIAS)

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

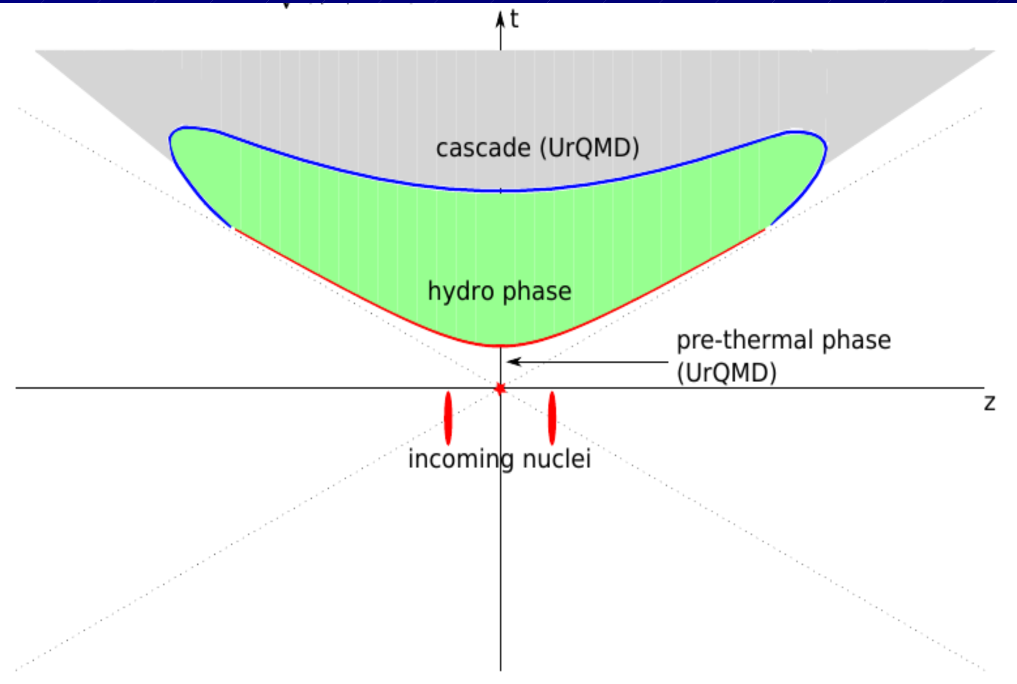
Cascade-hydro-cascade approach:

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

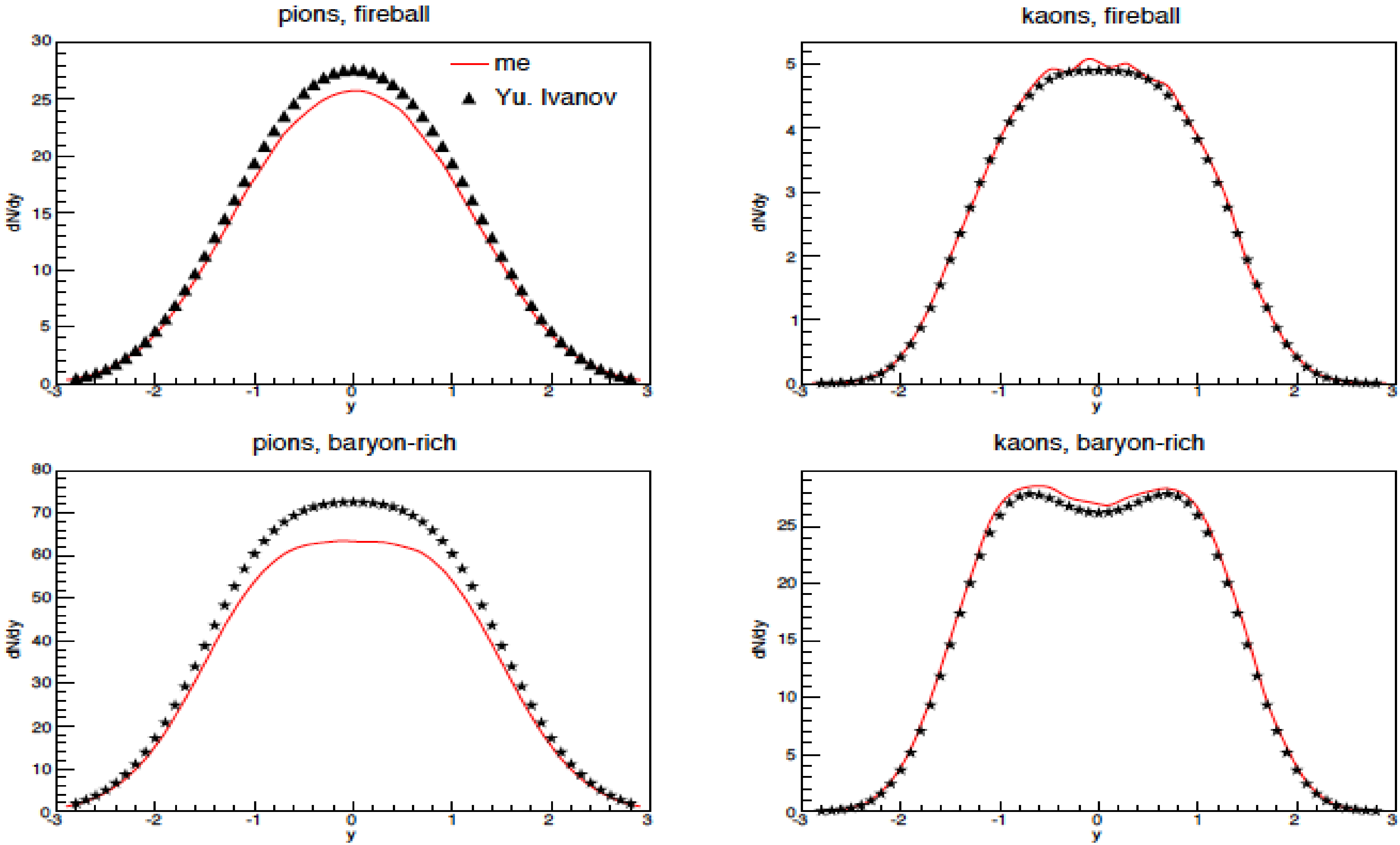
- Chiral model
  - coupled to Polyakov loop to include the deconfinement phase transition
  - good agreement with lattice QCD data at $\mu_B = 0$, also applicable at finite baryon densities
  - (current version) has crossover type PT between hadron and quark-gluon phase at all μ_B
- Hadron resonance 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 1^{st} 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

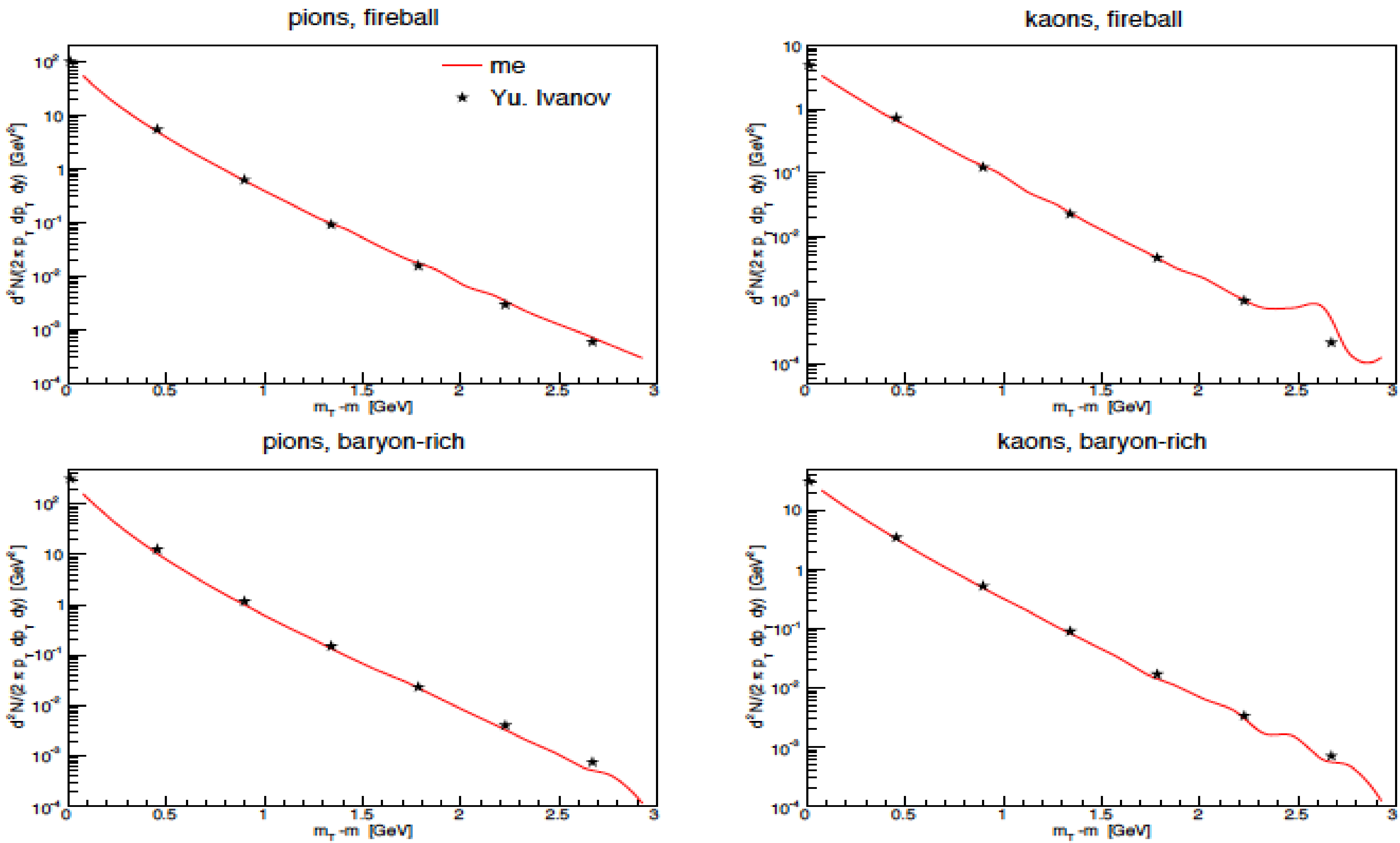
Rapidity distribution



Preview: Particlization of 3-fl uid Hydrodynamics model

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

P_T / m_T distribution



Baryon stopping signal for first order phase transition ?

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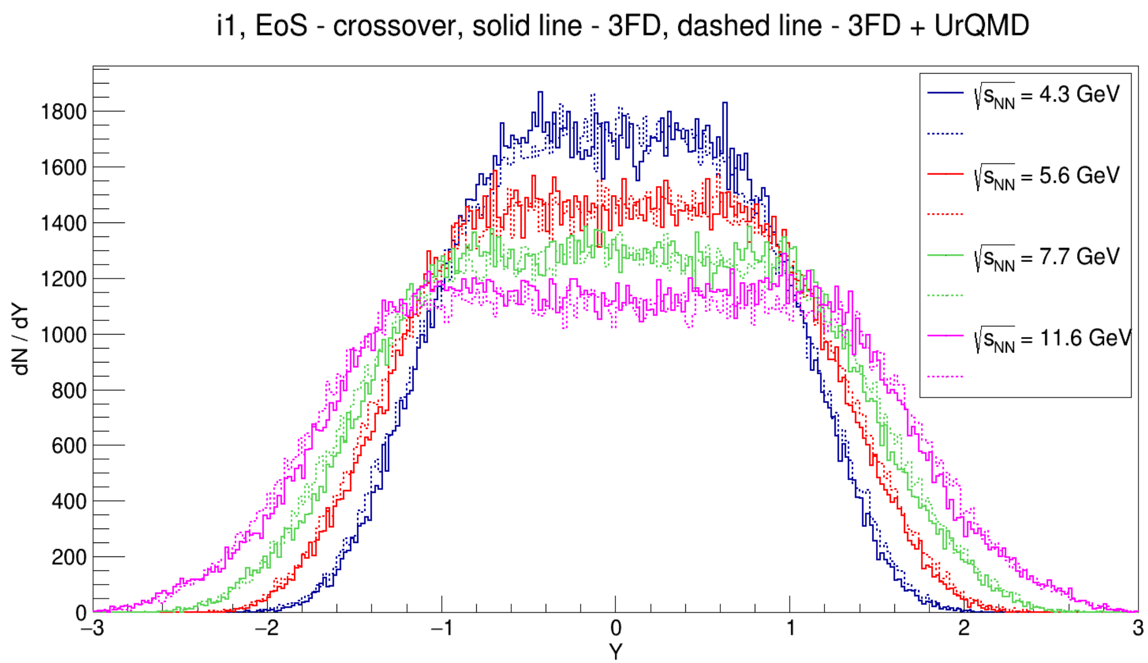
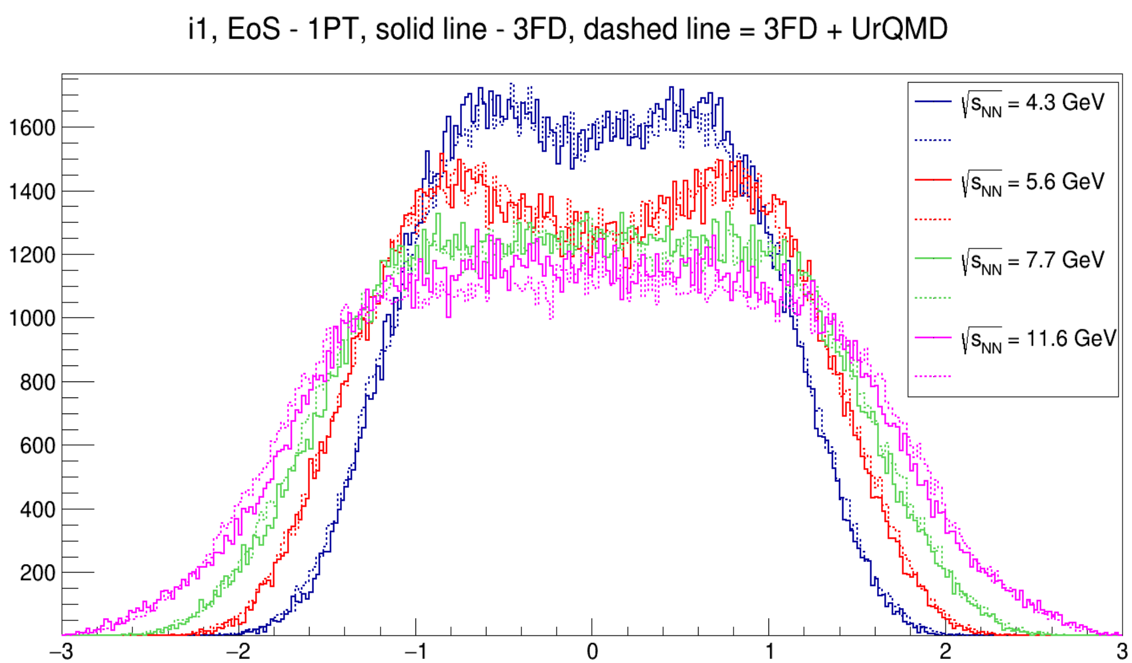


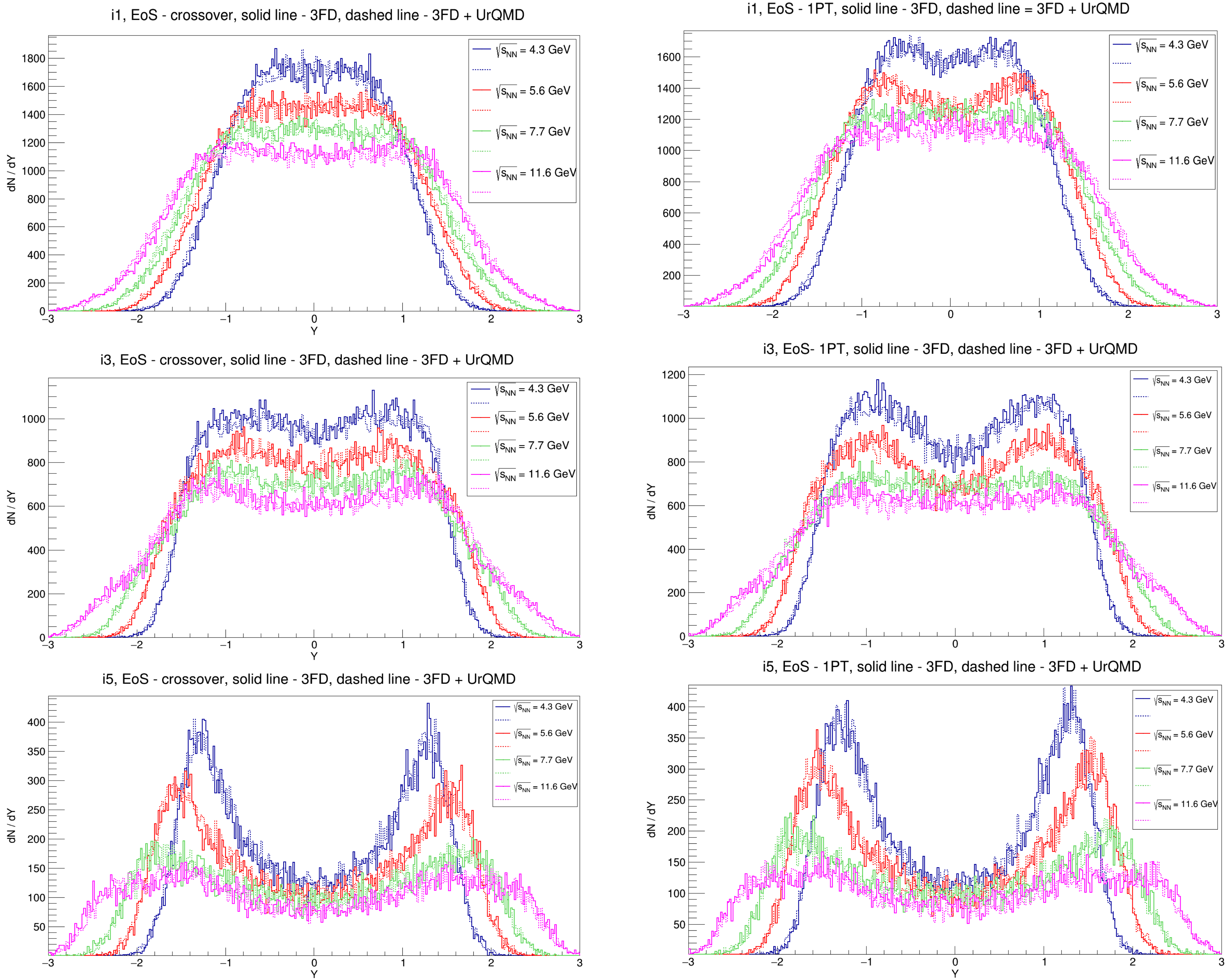
EoS: Crossover

Impact parameter: b=2 fm



EoS: First order PT

Impact parameter: b=2 fm


i1, EoS - crossover, solid line - 3FD, dashed line - 3FD + UrQMD
i1, EoS - 1PT, solid line - 3FD, dashed line = 3FD + UrQMD
i3, EoS - crossover, solid line - 3FD, dashed line - 3FD + UrQMD
i3, EoS- 1PT, solid line - 3FD, dashed line - 3FD + UrQMD
i5, EoS - crossover, solid line - 3FD, dashed line - 3FD + UrQMD
i5, EoS - 1PT, solid line - 3FD, dashed line - 3FD + UrQMD
$\sqrt{s_{NN}}$ = 4.3 GeV
$\sqrt{s_{NN}}$ = 5.6 GeV
$\sqrt{s_{NN}}$ = 7.7 GeV
$\sqrt{s_{NN}}$ = 11.6 GeV
dN / dY
Y

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:

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

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

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

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

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

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

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

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

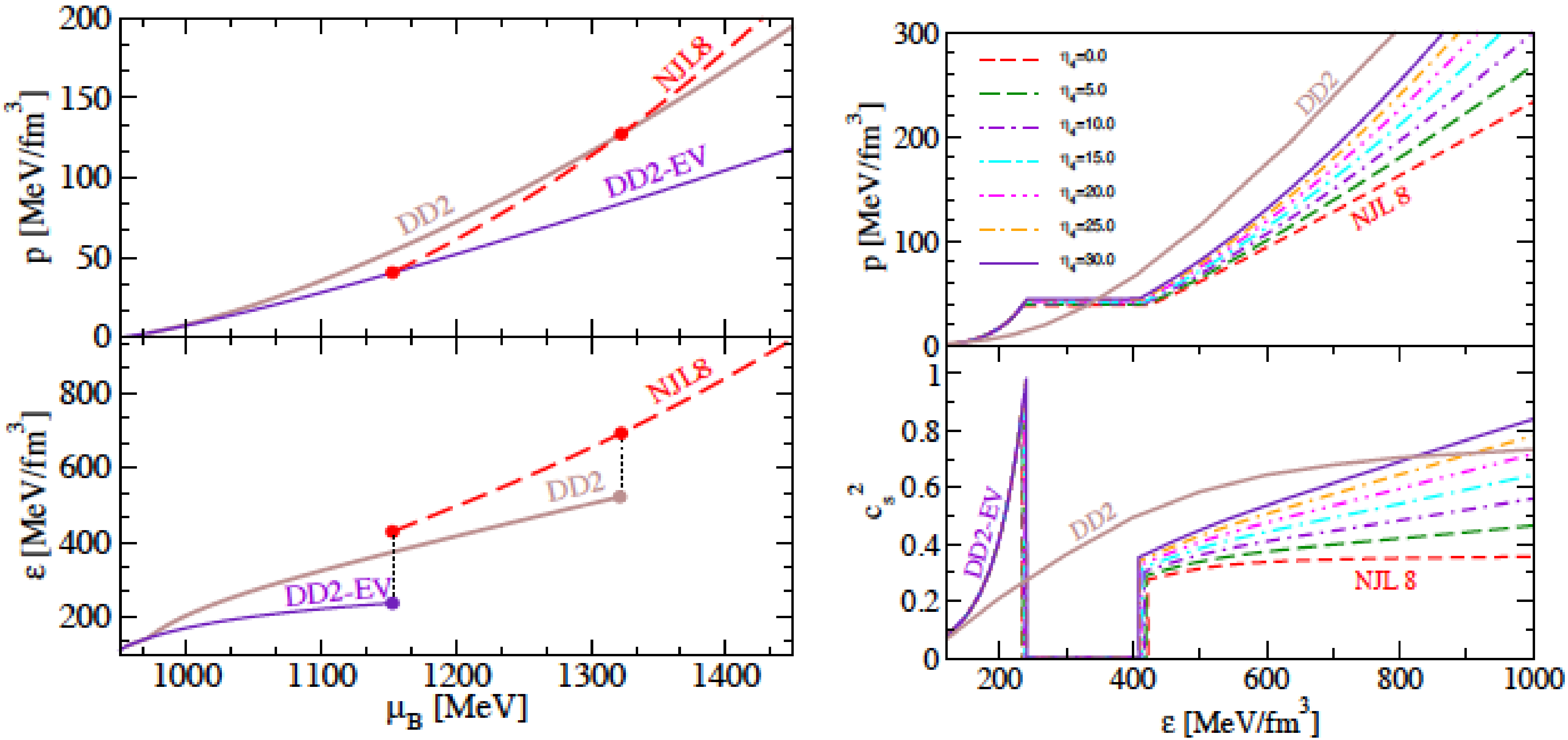
$$\tilde{\mu}_q = \mu_q - 2\frac{g_{02}}{\Lambda^2}\langle q^\dagger q\rangle - 4\frac{g_{04}}{\Lambda^8}\langle q^\dagger q\rangle^3 - 2\frac{g_{22}}{\Lambda^8}\langle\bar{q}q\rangle^2\langle q^\dagger q\rangle \,,$$

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

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

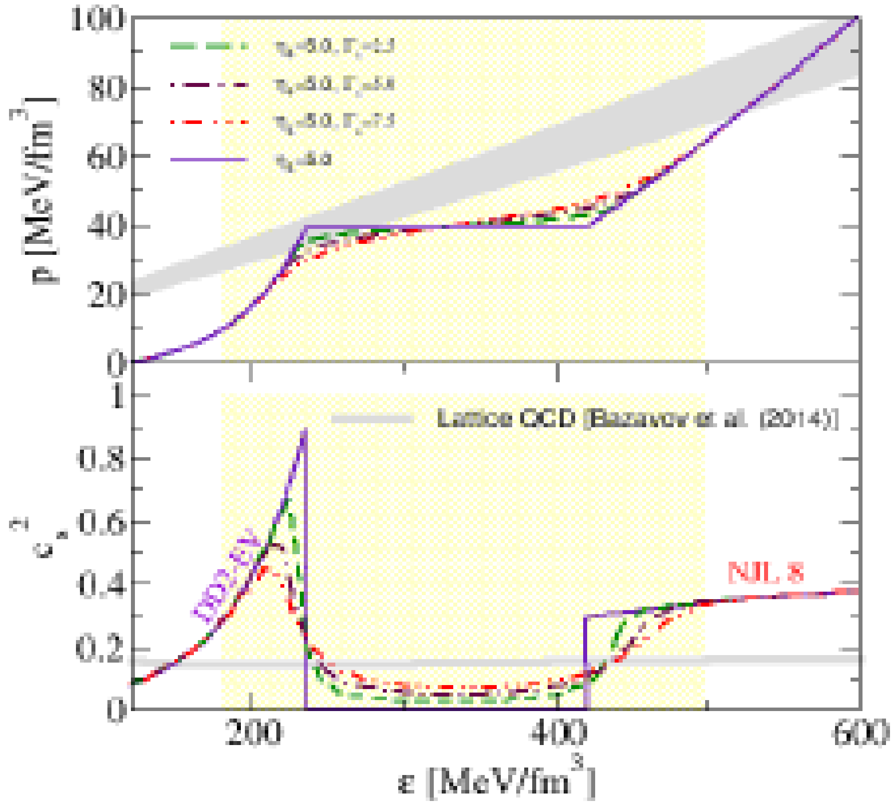


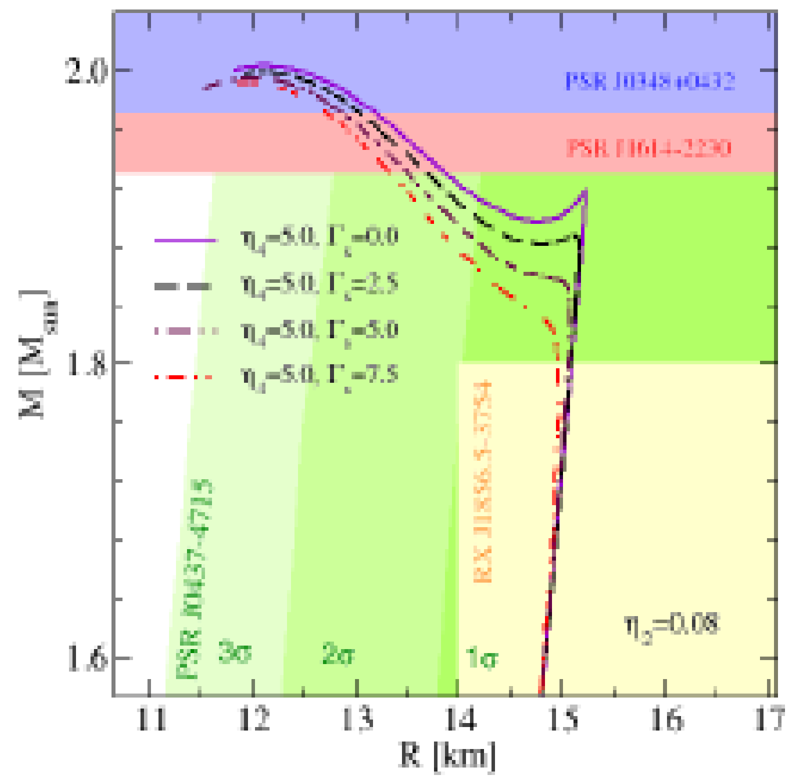
Here: Stiffening of dense hadronic matter by excluded volume in density-dependent RMF
Stiffening of dense quark matter by higher order quark vector current interactions (η_4)

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")

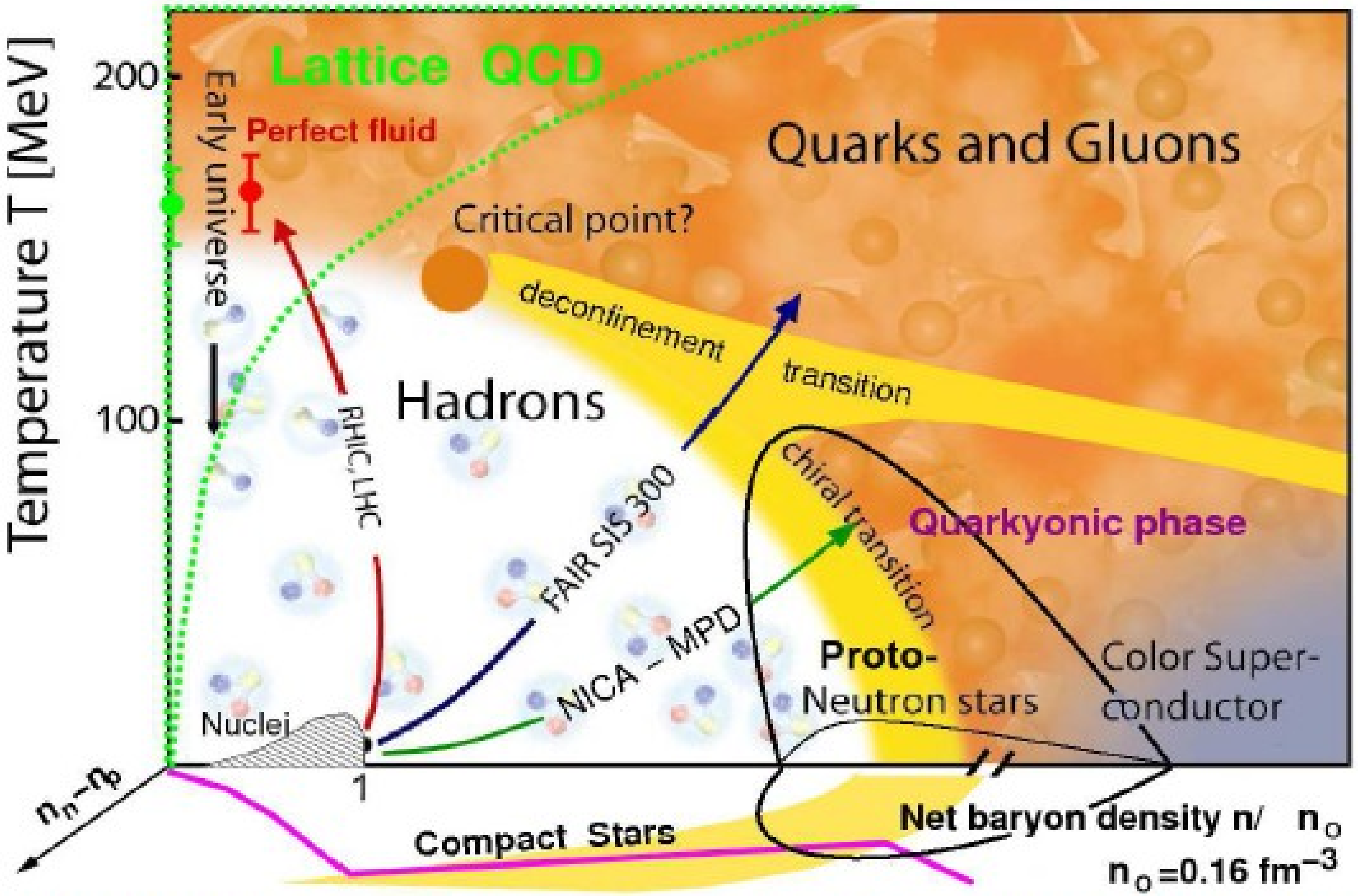




High-mass Twins relatively robust against "smoothing" the Maxwell transition construction

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

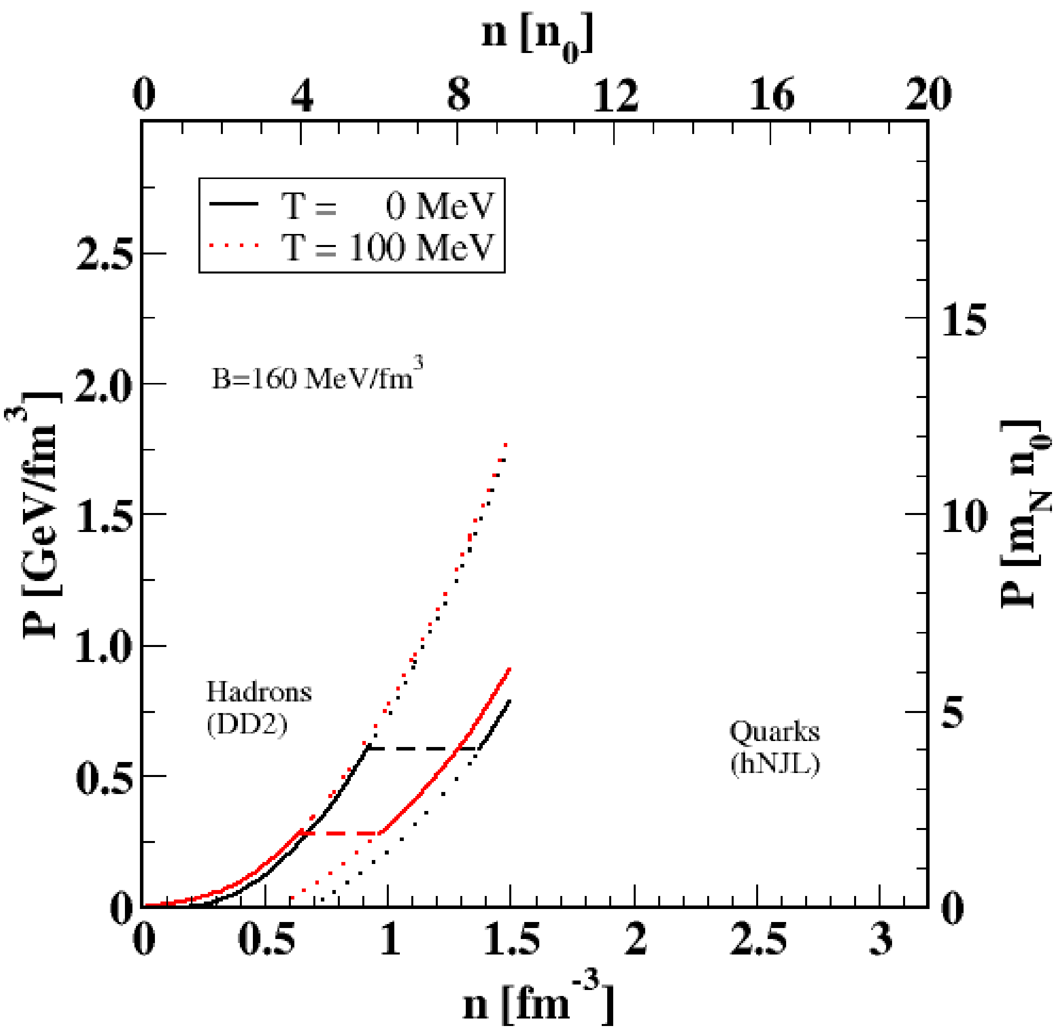
Support a CEP in QCD phase diagram with Astrophysics?

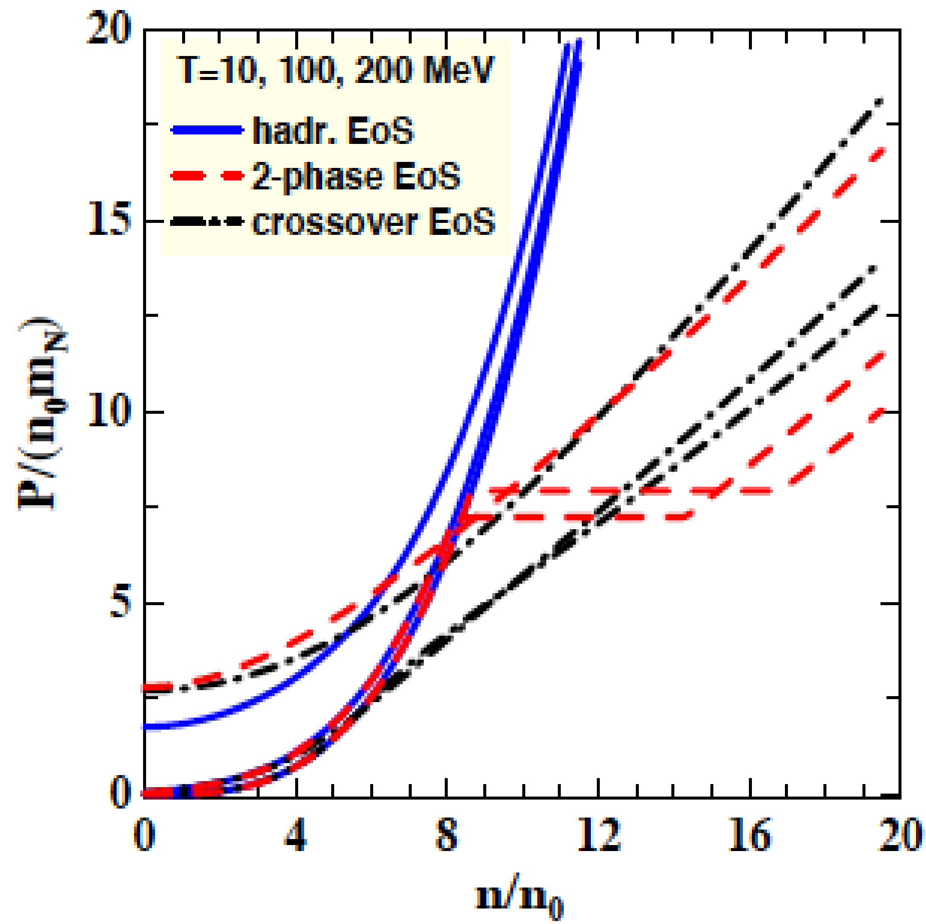


NICA White Paper, http://theor.jinr.ru/twiki-cgi/view/NICA/WebHome

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

Comparison 2-phase EoS

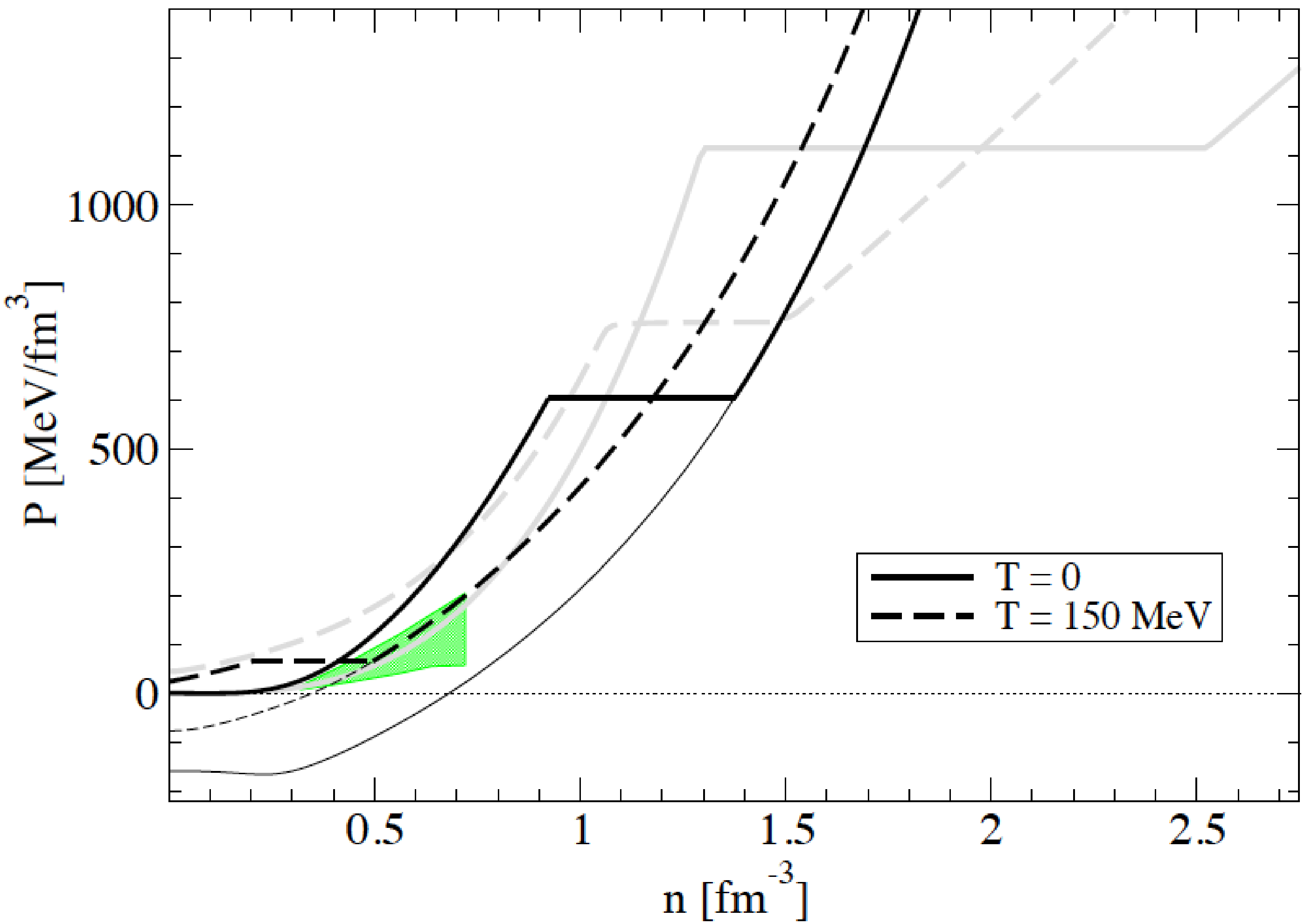




N.-U. Bastian, D. Blaschke (S. Benic, S. Typel), In progress (2015)

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

Comparison 2-phase EoS



Grey: Ivanov (2010)

Black: DD2 vs. HNJLb

B=160 MeV/fm^3

N.-U. Bastian, D. Blaschke, Proceedings SQM (2015)

Summary / Outlook:

- Baryon stopping signal ("wiggle") remains a robust signal for 1^{st} 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 !

- UrQMD "afterburner" works too !

- Detector simulation in progress

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

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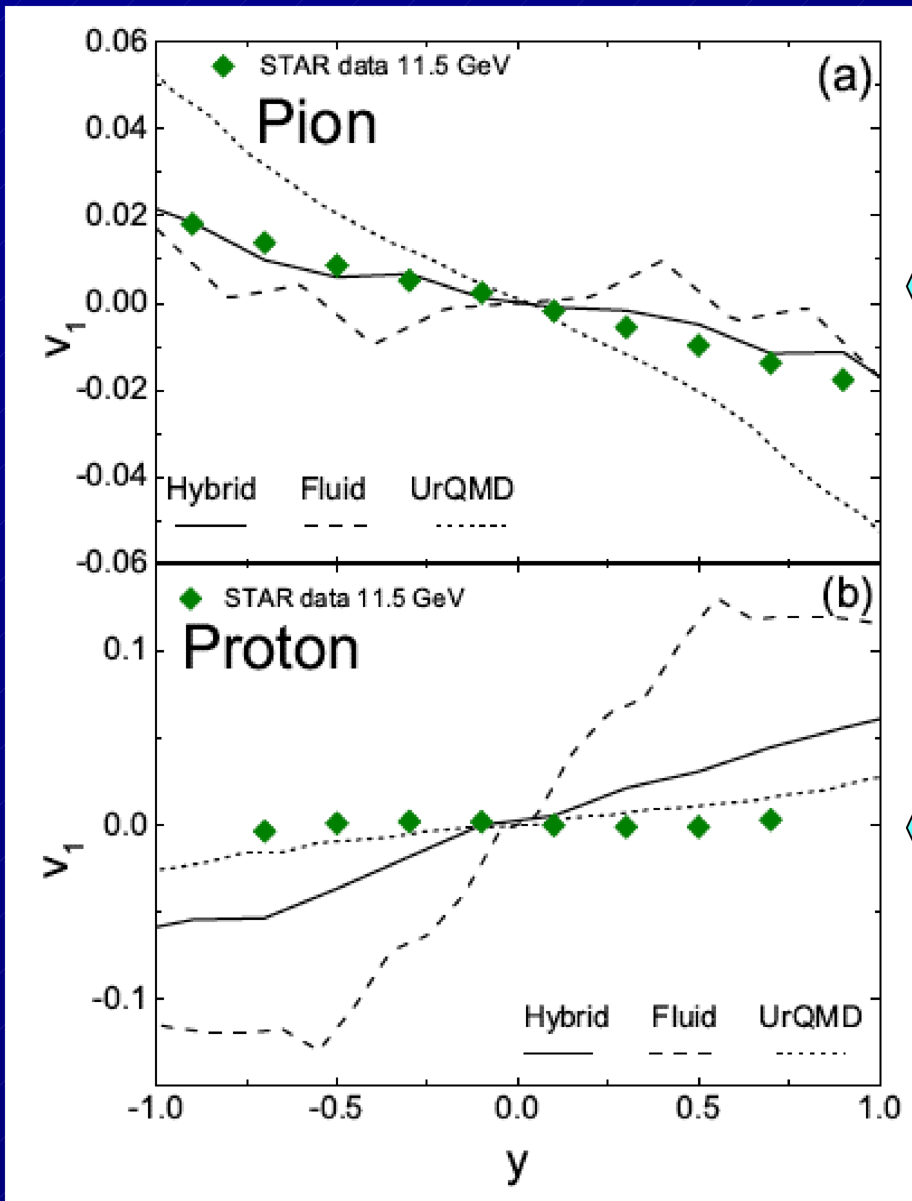
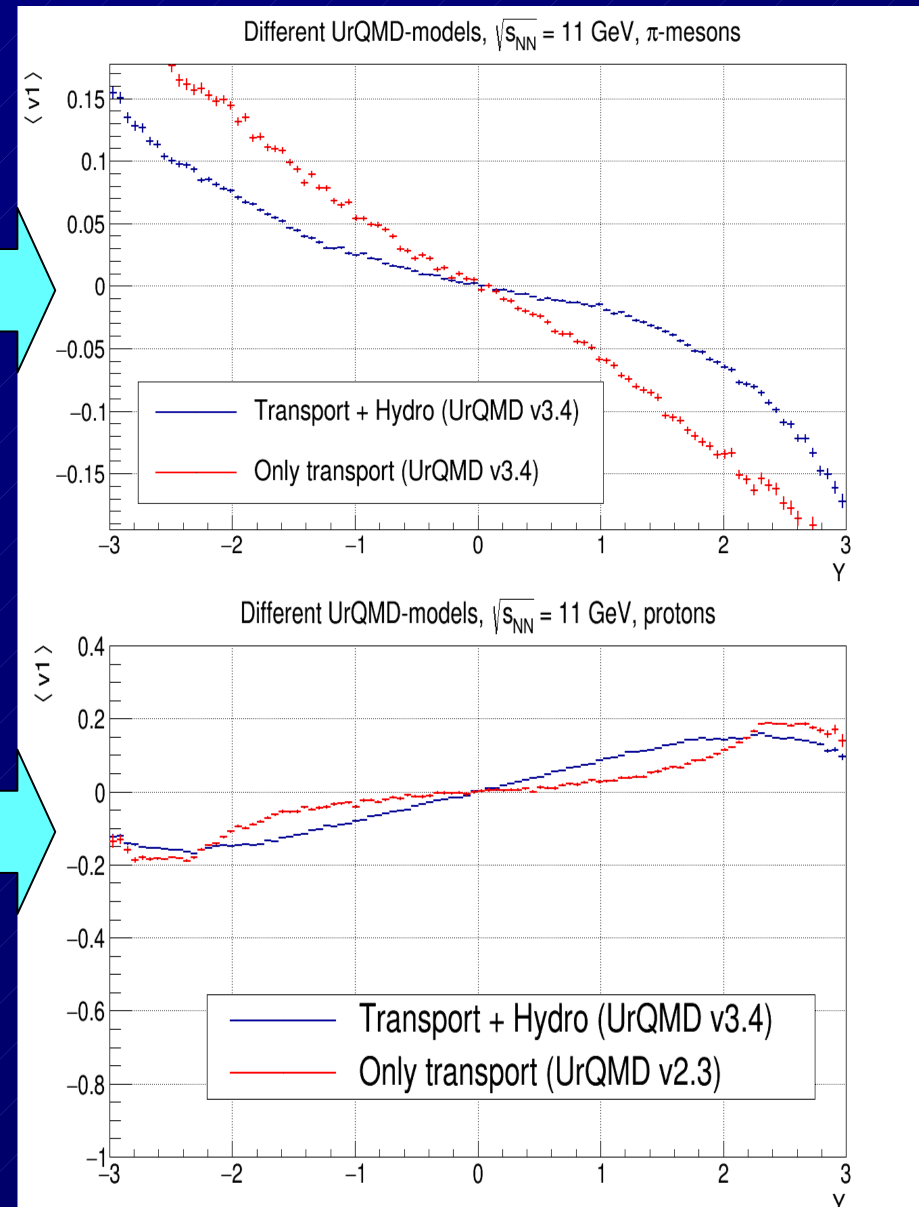
Additional Slides

Further results of test simulations – flow observables

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



Reproduced !

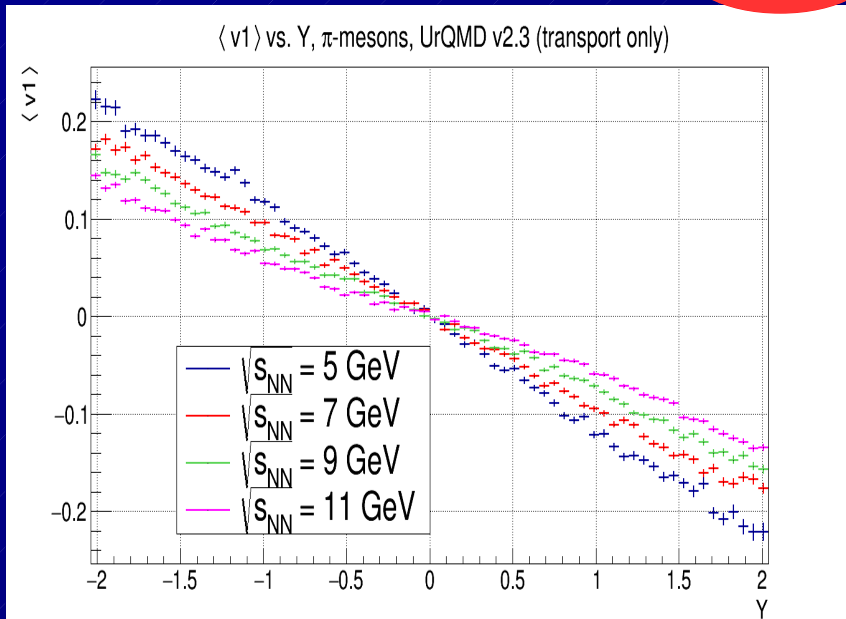


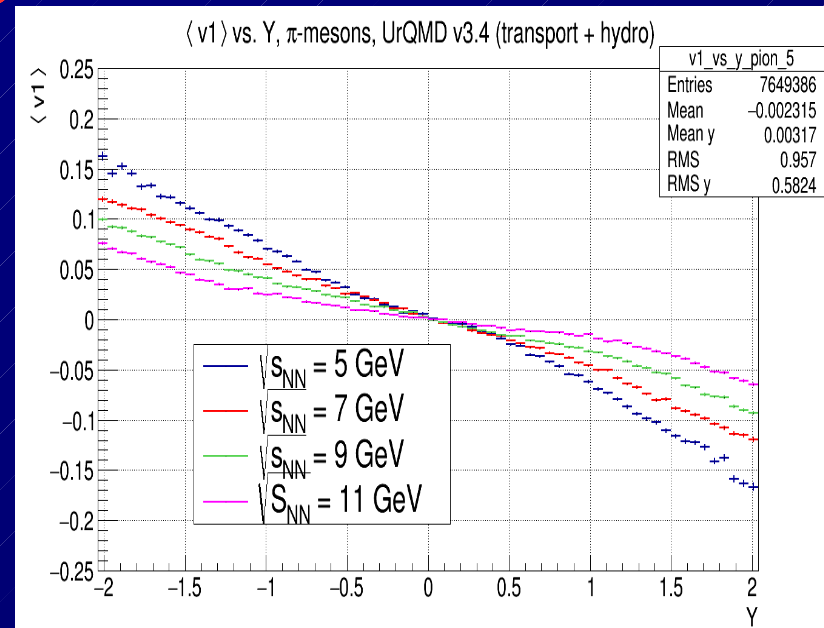
UrQMD + hydro (1st order PT) – H. Petersen

Further results of test simulations – flow observables

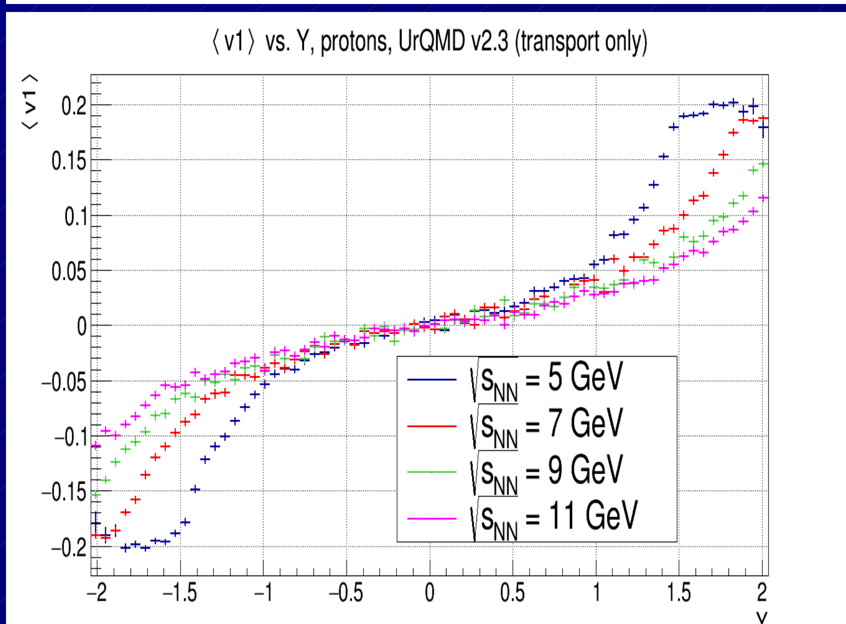
NICA energy scan: **UrQMD** $\langle v_1 \rangle$ UrQMD + hydro (1st order PT)

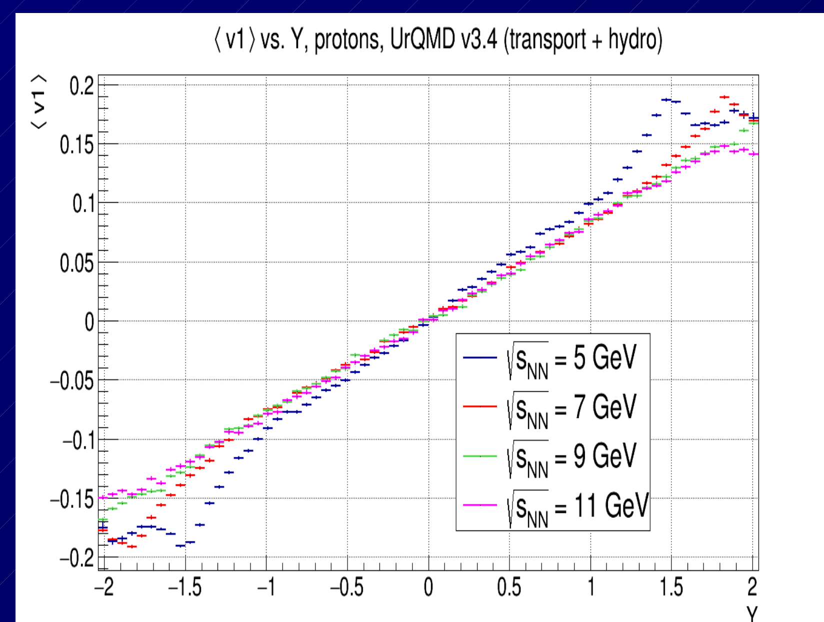
Pions





Protons

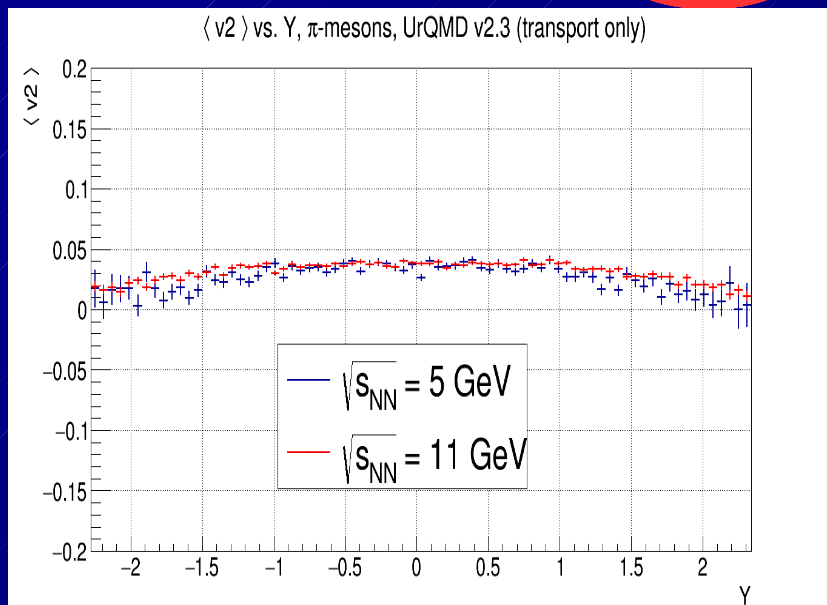


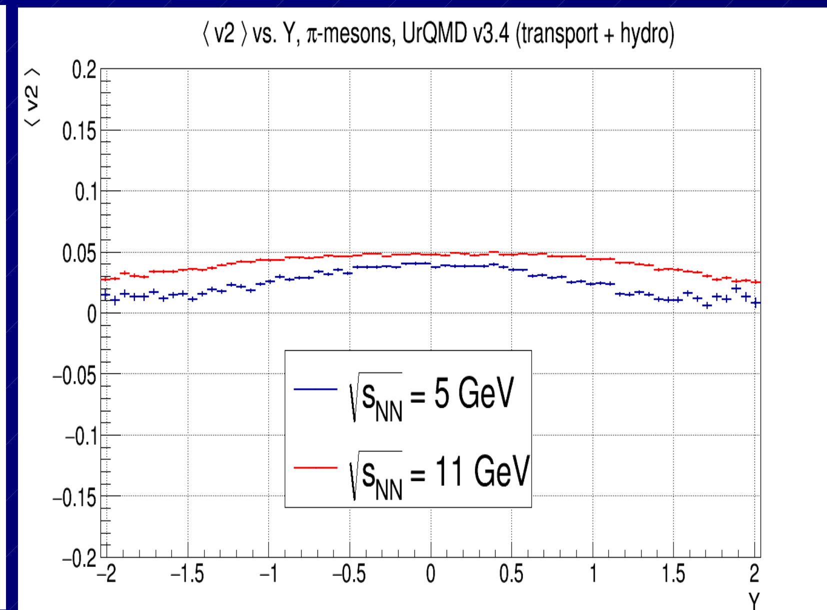


Further results of test simulations – flow observables

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

Pions





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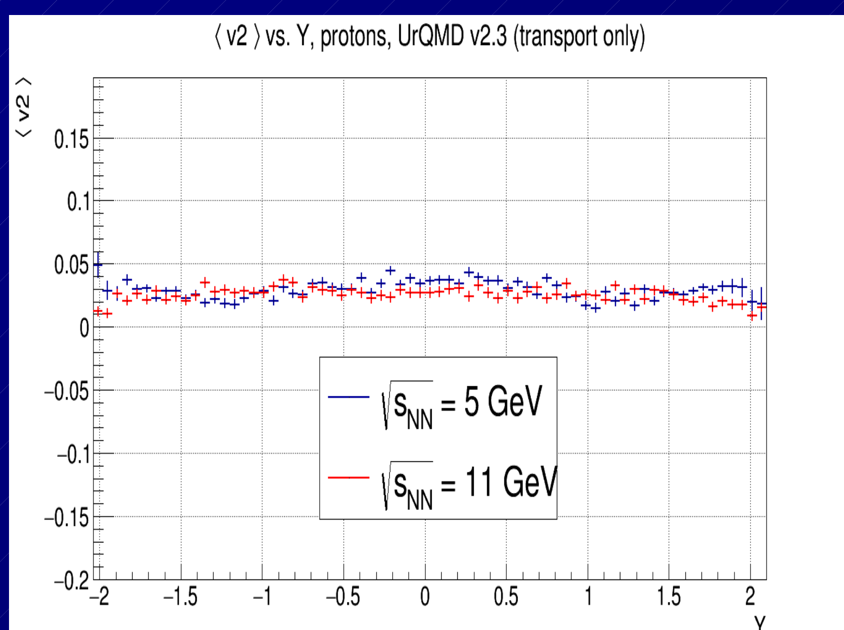
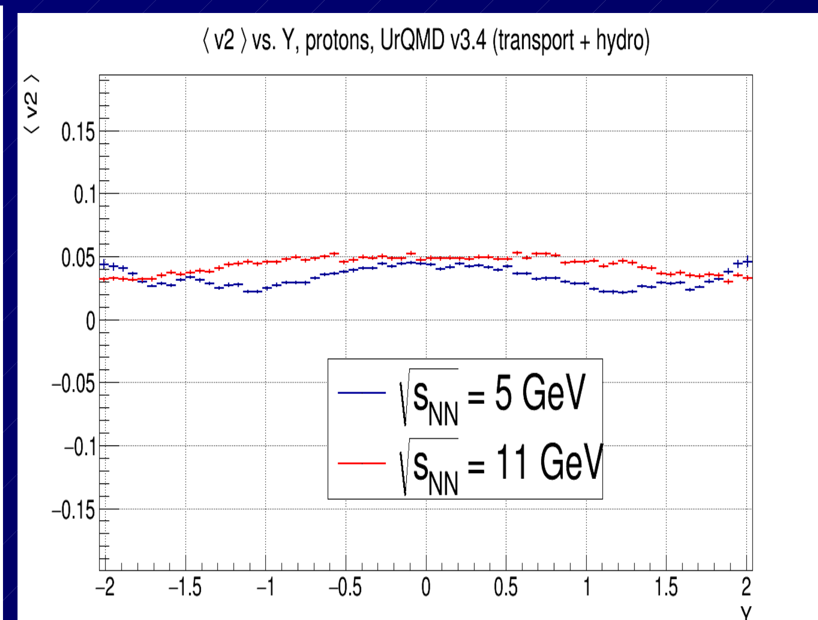
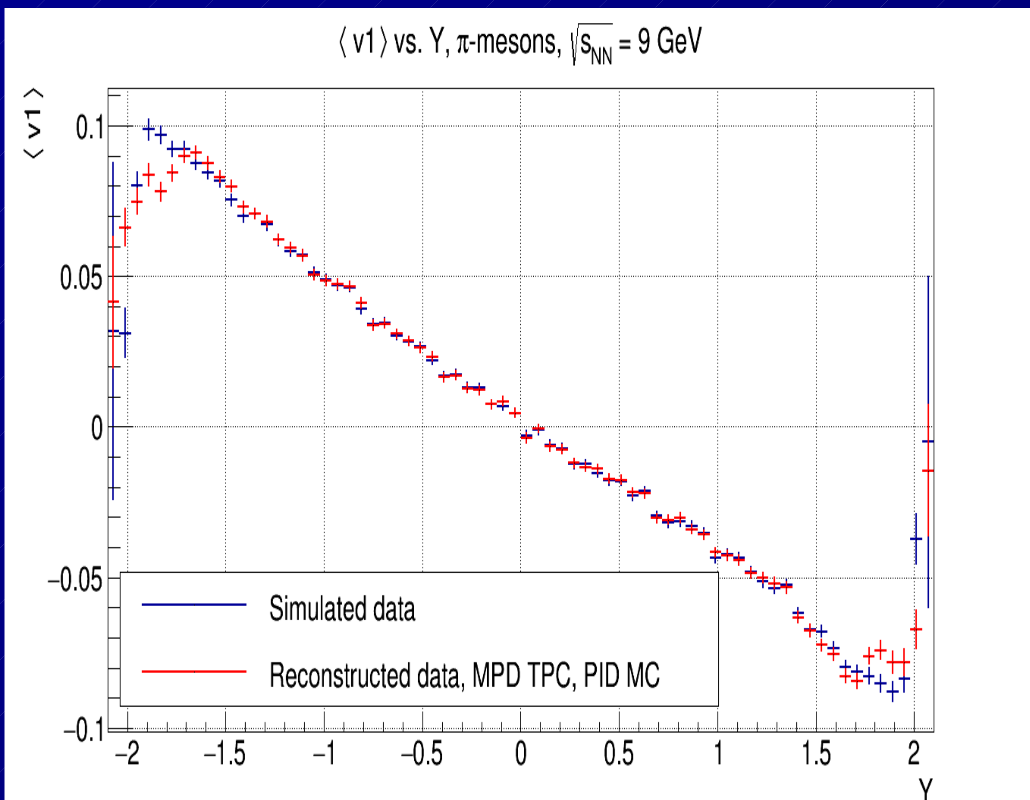
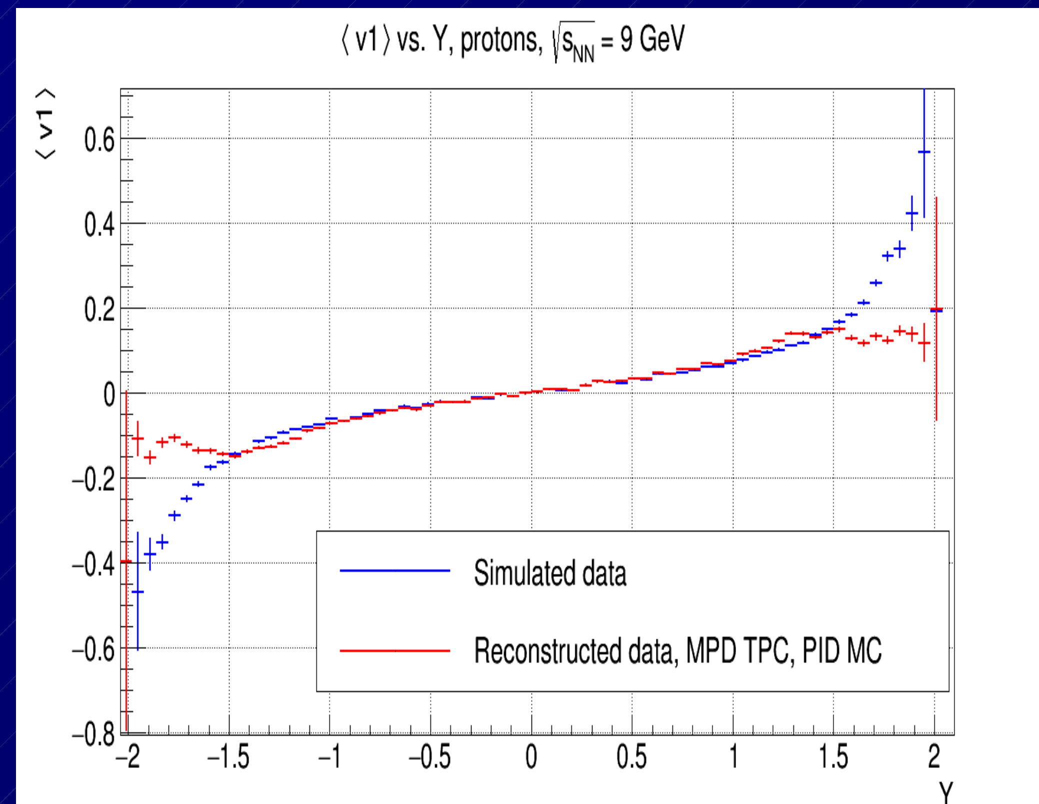




Further results of test simulations – flow observables

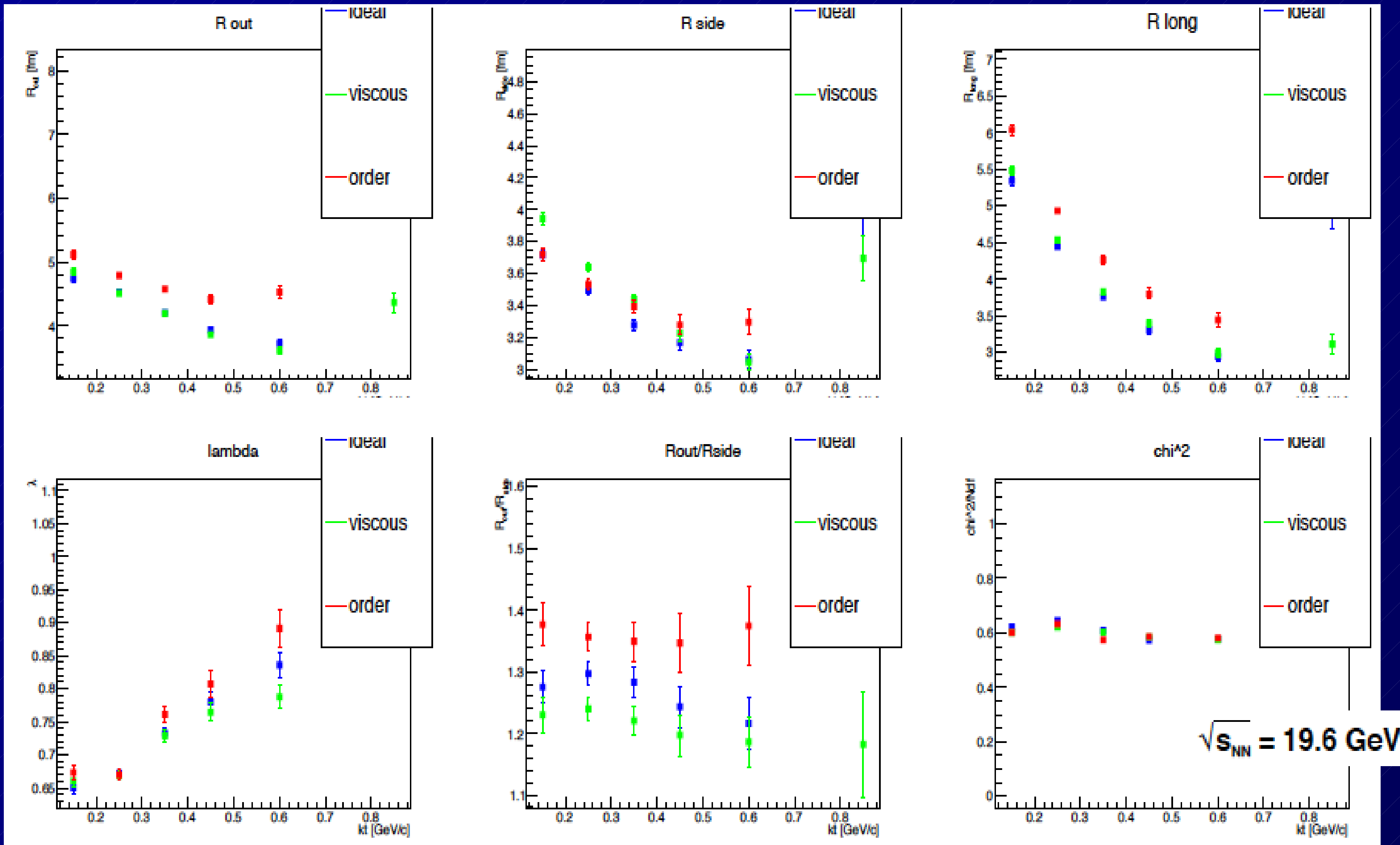
Detector Simulation with GEANT : Excellent reproduction of simulation results !



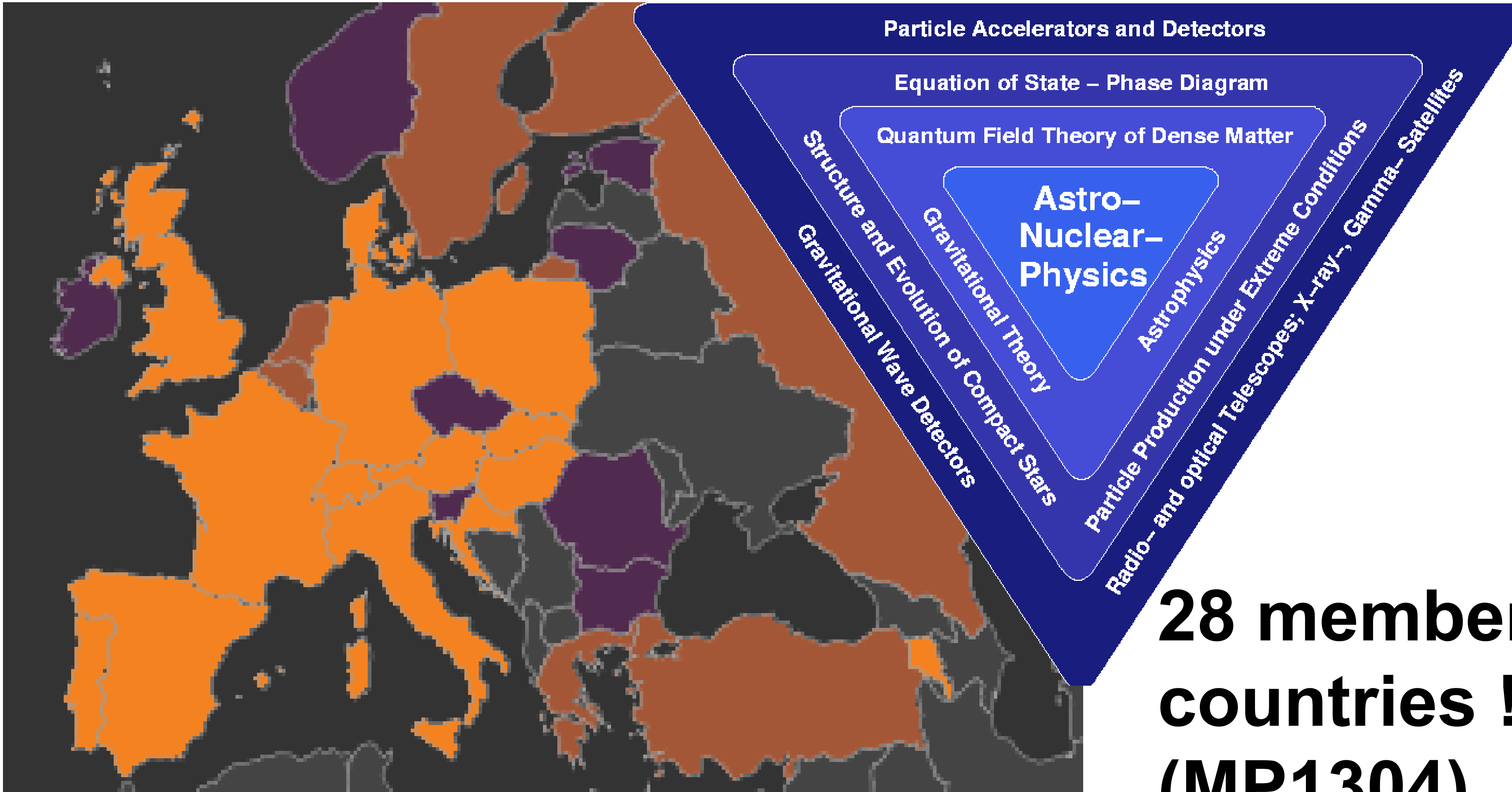


UrQMD + hydro (1^{st} order PT) – H. Petersen

Further results of test simulations – HBT radii



Hydro+kinetic model (Karpenko)



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Critical Point and Onset of Deconfinement

CPOD 2016

University of Wroclaw, Poland

May 30th – June 3rd, 2016

Scientific Topics:

- Critical Point
- Phase transitions in hot and dense matter
- Deconfinement and chiral symmetry restoration
- Hadronization and chemical freeze-out
- Compact Stars
- Future facilities, detectors and methods

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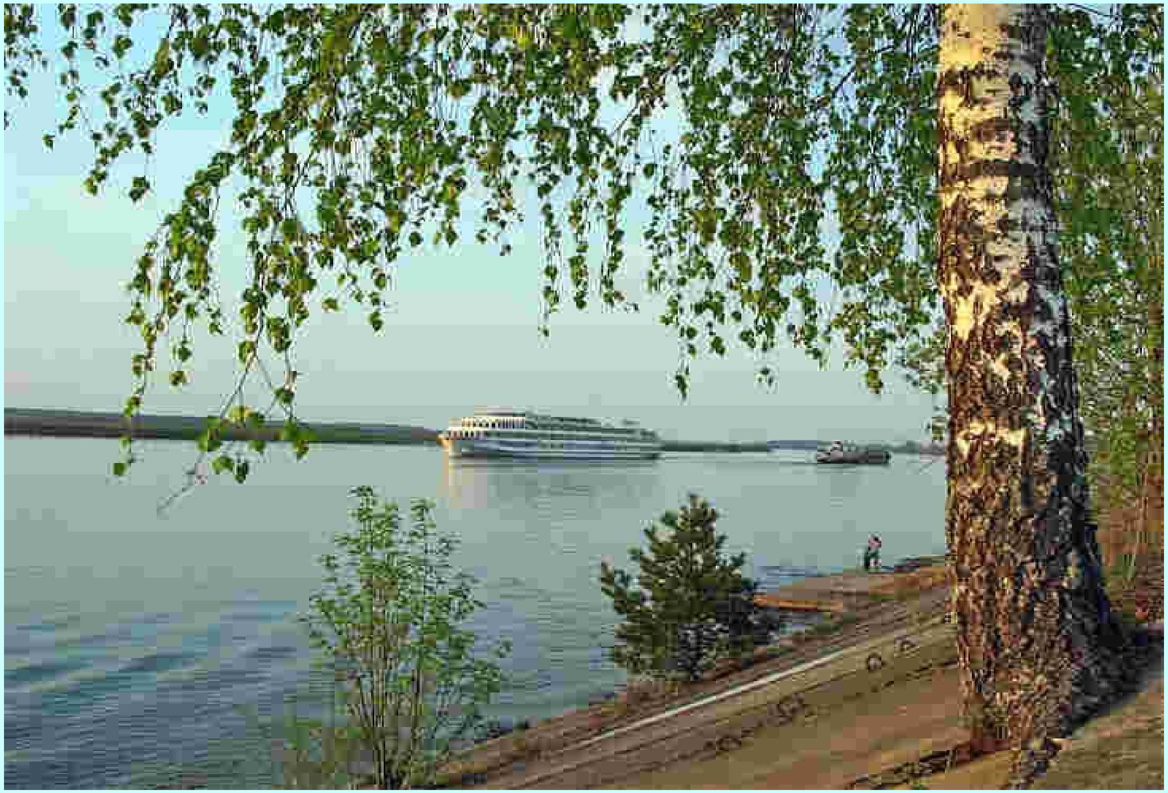
Strangeness in Quark Matter 2015

Dubna, 6.-11. July 2015



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Satellite Meetings:

Summer School “Dense Matter”, Dubna, June 29 – July 11, 2015

Roundtable “Physics at NICA”, Dubna, 5. July 2015