

Theoretical Physics Developments for NICA

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1. The NICA White Paper (EPJA Topical Issue appears today!)

2. Selected Topics

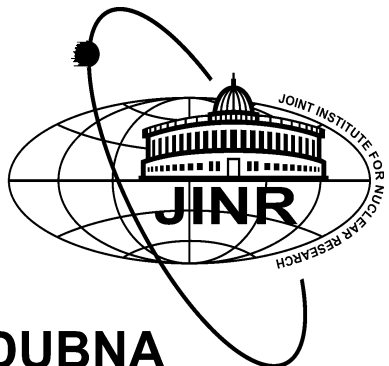
3. Event Simulation for NICA & FAIR: THESEUS

- Particlization and all that ...
- First results: Baryon stopping signal for a 1st order PT

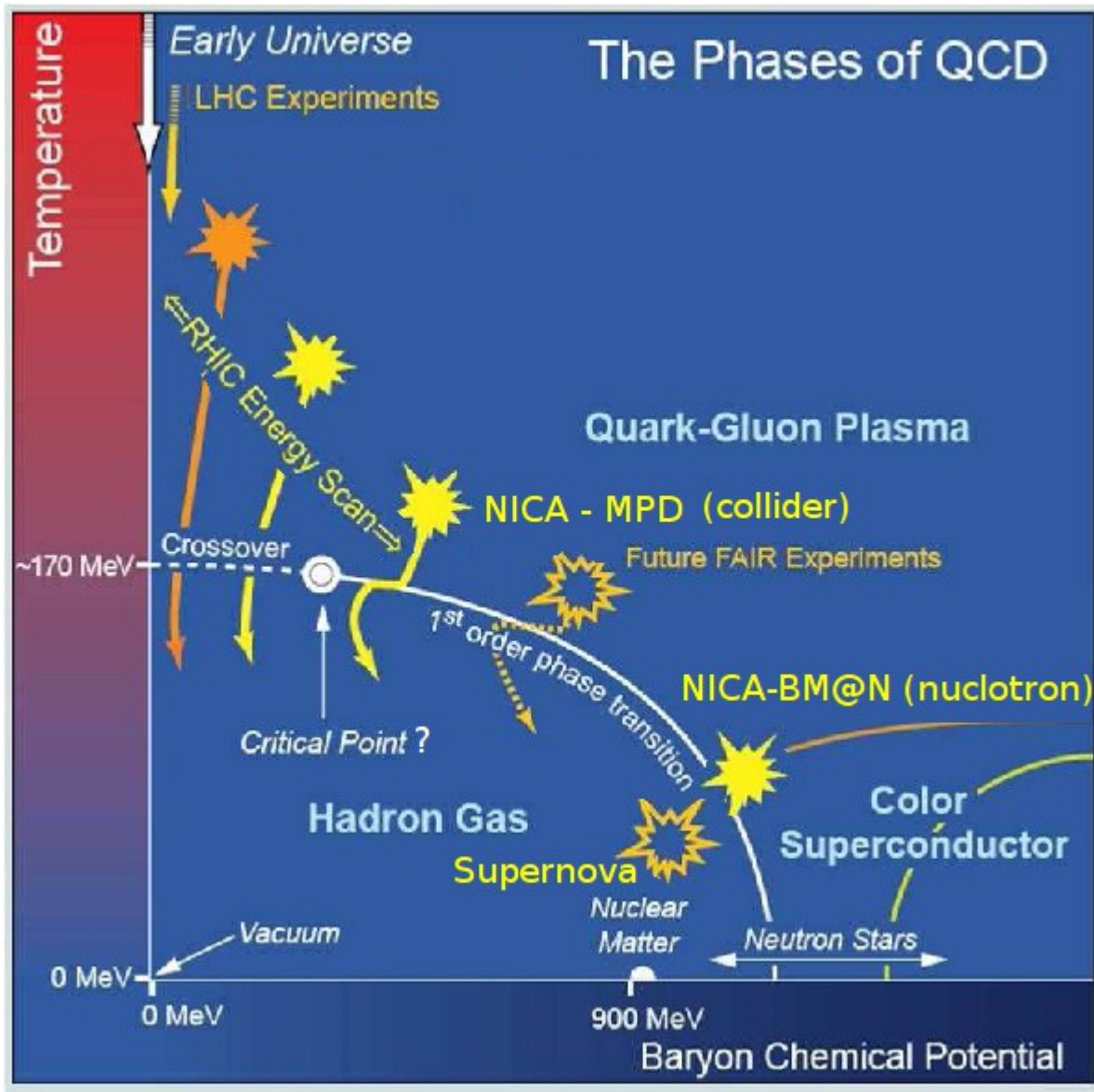
4. Further developments:

Flow, Detector response, new class of EoS ...

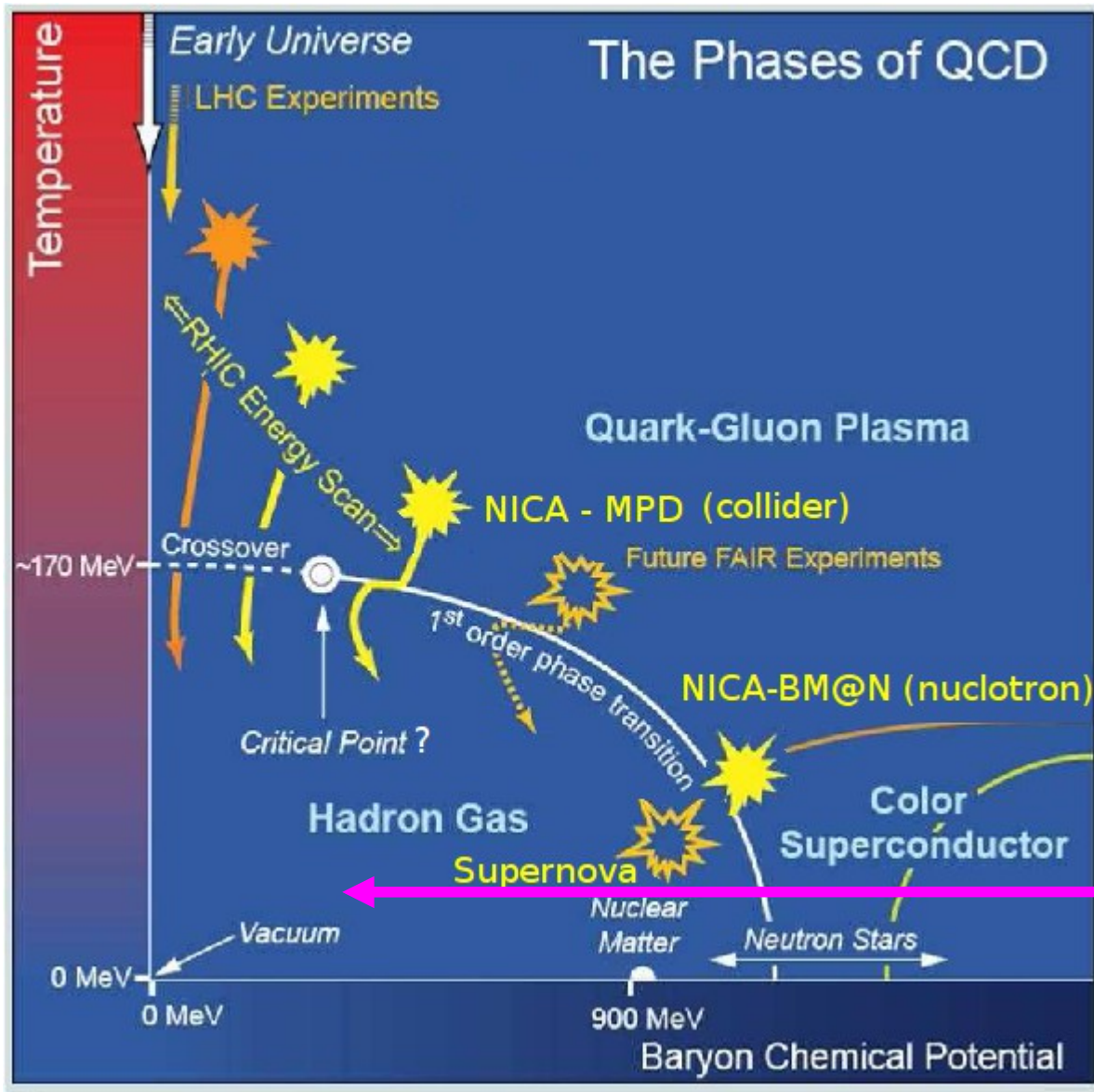
Reimei Workshop on “HI Program at J-PARC”, KEK Tokai, 08.-09.08.2016



The Goal: Theory of the QCD Phase Diagram



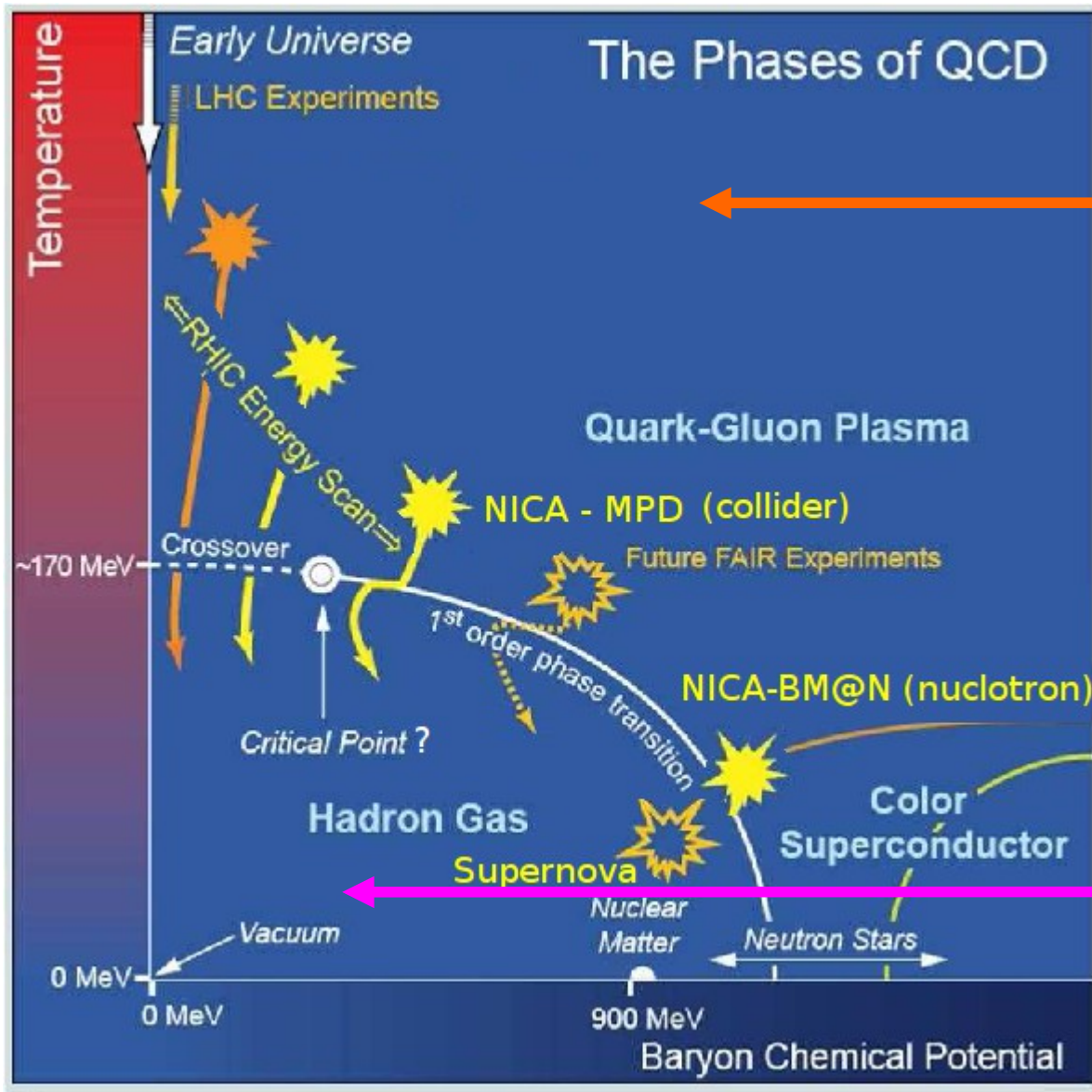
The Goal: Theory of the QCD Phase Diagram



Statistical Model of
Hadron Resonance Gas

Well established for
Description of chemical
freezeout

The Goal: Theory of the QCD Phase Diagram



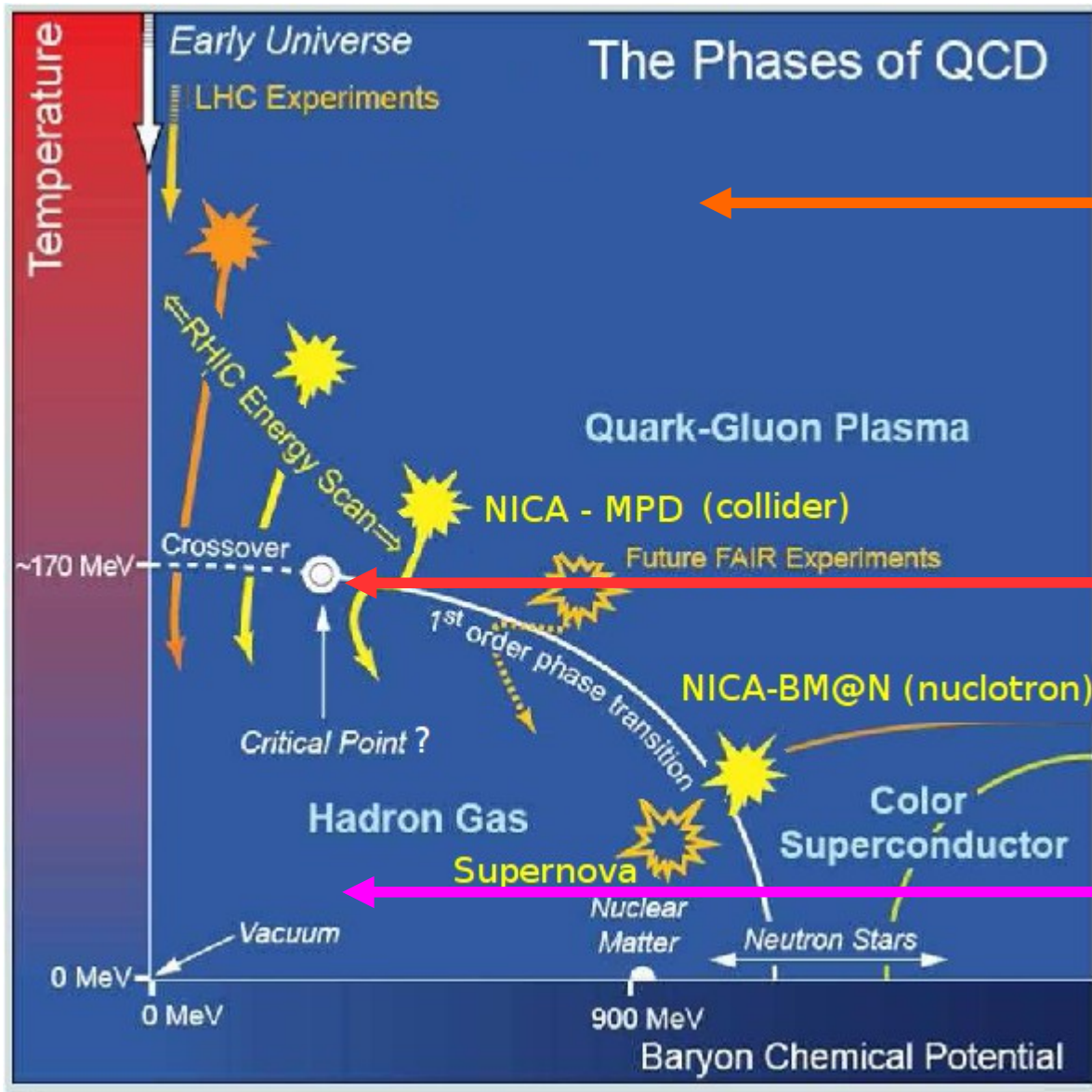
Perturbative QCD

Approximately selfconsistent
HTL resummation
($T > 2.5 T_c$, $\mu > 1500$ MeV)

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The Goal: Theory of the QCD Phase Diagram



Perturbative QCD

Approximately selfconsistent HTL resummation
($T > 2.5 T_c$, $\mu > 1500$ MeV)

QCD Phase transition(s)

Mott dissociation of hadrons,
Deconfinement, χ SR

Statistical Model of Hadron Resonance Gas

Well established for
Description of chemical
freezeout

Topical Issue on Exploring Strongly Interacting Matter at High Densities - NICA White Paper

edited by David Blaschke, Jörg Aichelin, Elena Bratkovskaya, Volker Friese, Marek Gazdzicki, Jørgen Randrup, Oleg Rogachevsky, Oleg Teryaev, Viacheslav Toneev



From: Three stages of the NICA accelerator complex by V. D. Kekelidze et al.

The NICA White Paper

TOPICS

- Phases of dense QCD matter and their possible realization
- Characteristic processes as indicators of phase transformations
- Estimates for events and event rates
- Comparison to other experiments
- Interdisciplinary aspects, e.g. astrophysical constraints for dense matter phases

Guest Editors

Jörg Aichelin (SUBATECH Nantes, France)
Elena Bratkovskaya (GSI Darmstadt & Goethe University Frankfurt, Germany)
Volker Friese (GSI Darmstadt, Germany)
Marek Gazdzicki (Goethe University Frankfurt, Germany & Jan Kochanowski Univ. Kielce, Poland)
Jørgen Randrup (LBNL Berkeley, California, USA)
Oleg Rogachevsky (JINR Dubna, Russia)
Oleg Teryaev (JINR Dubna, Russia)
Viacheslav Toneev (JINR Dubna, Russia)

Co-Editor

David Blaschke (University of Wroclaw, Poland & JINR Dubna & NRNU Moscow (MEPhI), Russia)

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1	Meshkov	Three stages of the NICA accelerator complex
2	Kekelidze	The multi-purpose detector (MPD) of the collider experiment
3	Kapishin	The fixed target experiment for studies of baryonic matter at the Nuklotron
4	Rogachevsky	Simulation software for the NICA experiments
5	Teryaev	Spin physics experiments at NICA-SPD with polarized proton and deuteron beams
General aspects		
6	Gazdzicki	Multi-purpose detector at the JINR NICA collider in the landscape of heavy-ion projects
7	Senger	Nuclear matter physics at NICA
8	Randrup	Exploring high-density baryonic matter: maximum freeze-out density
9	Bratkovskaya	Observations and open problems at NICA
10	Brodsky	Novel QCD physics at NICA
11	Klusek	Studying the interplay of strong and electromagnetic forces in heavy-ion collisions with NICA
Phases of QCD matter at high baryon density		
12	Fukushima	Strangeness as a probe to baryon-rich QCD matter at NICA
13	Voskresensky	Comments on manifestation of in-medium effects in heavy-ion collisions
14	DiToro	Probing the hadron-quark mixed phase at high isospin and beryon density. Sensitive observables
15	Fischer	Consequences of the simultaneous chiral symmetry breaking and deconfinement for the isospin symmetric phase diagram
16	Schmitt	From ultra-dense QCD to wards NICA densities: color-flavor locking and other color superconductors
17	Bugaev	Glueballs and vector mesons at NICA
18	Costa	Isentropic thermodynamics and scalar meson properties at finite temperature and density at NICA energies
19	Parganlija	Vacuum glueballs and in-medium vector mesons at NICA
20	Kunihiro	Combined chiral and diquark fluctuations along QCD critical line and enhanced
21	Contrera	Supporting the search for the CEP location with nonlocal PNJL models constrained by lattice QCD
22	Alvarez	Neutron star mass limit at $2M_{\odot}$ supports the existence of a CEP
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26	Tomasik	Observables of non-equilibrium phase transition
27	Ivanov	Baryon stopping in heavy-ion collisions at $E_{\text{Lab}} = 2\text{--}200$ AGeV
28	Wolschin	Baryon stopping probes deconfinement
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32	Botvina	Relativistic ion collisions as the source of hypernuclei
33	Uzikov	Search for scaling onset in exclusive reactions with the lightest nuclei
34	Roepke	Light cluster production at NICA

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44	Tawfik	Analogy of QCD hadronization and Hawking-Unruh radiation at NICA
45	Okorokov	NICA-MPD: azimuthal and femtosopic particle correlations
46	Okorokov	NICA fixed target mode: soft jet studies in the relative 4-velocity space

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Strong magnetic fields		
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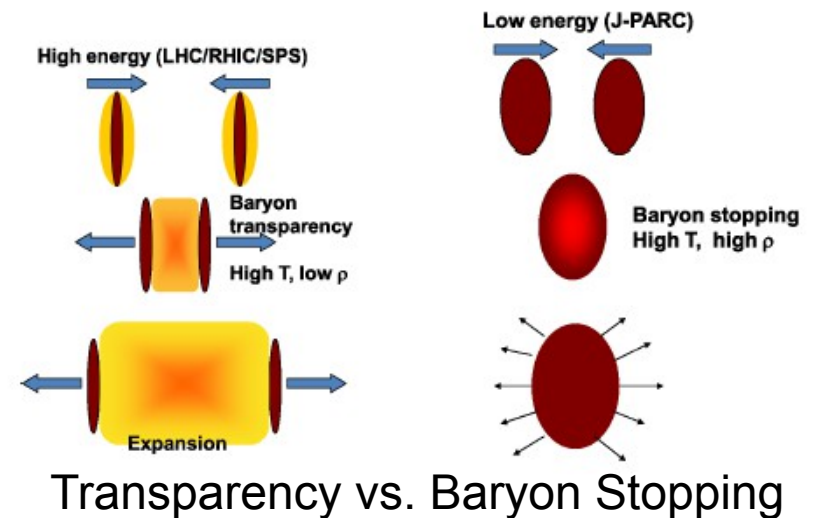
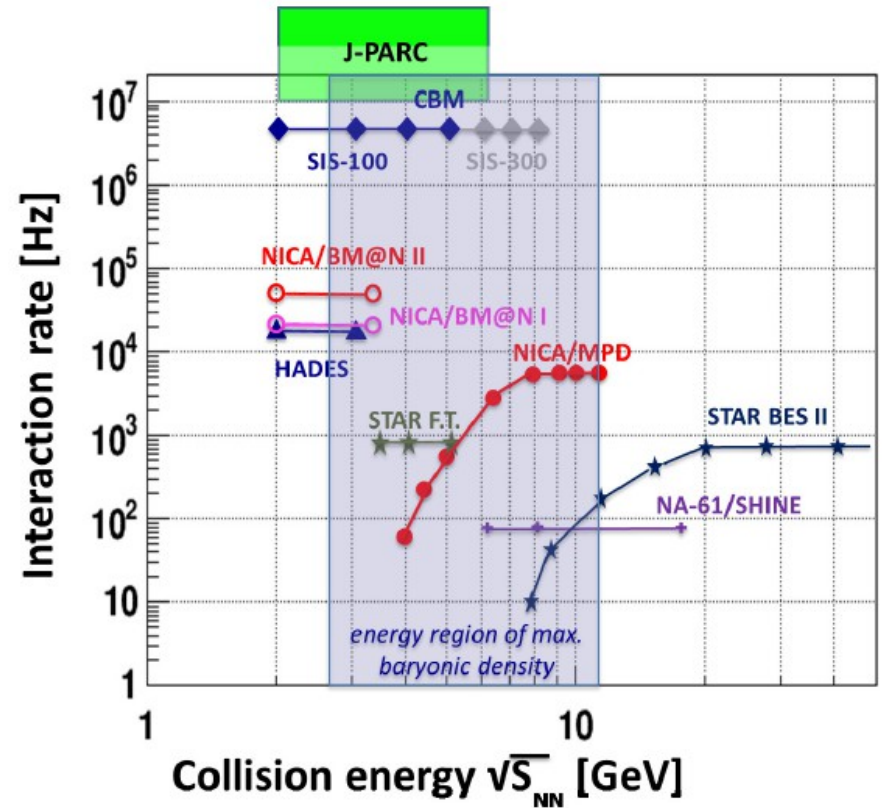
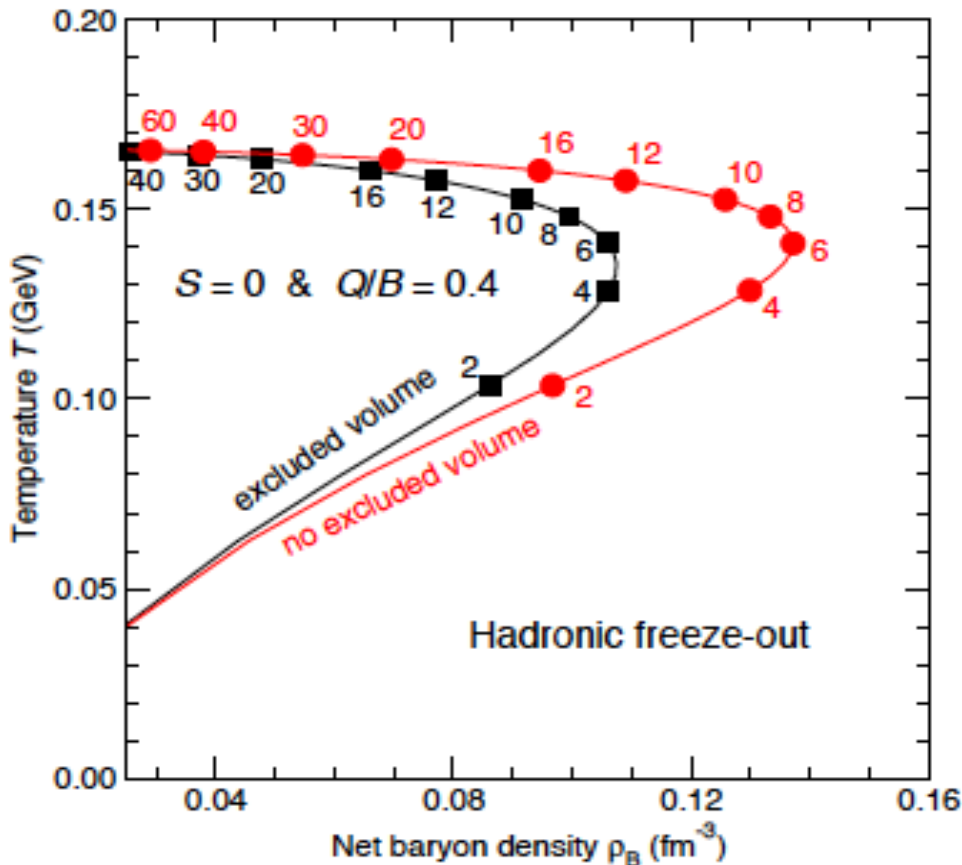
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What is special at NICA / FAIR / J-PARC energy?

#8: Exploring high-density baryonic matter: Maximum freeze-out density

Jørgen Randrup¹ and Jean Cleymans²

Highest baryon density at freeze-out for $s^{1/2} \sim 6$ GeV, slightly lowering with ex. volume



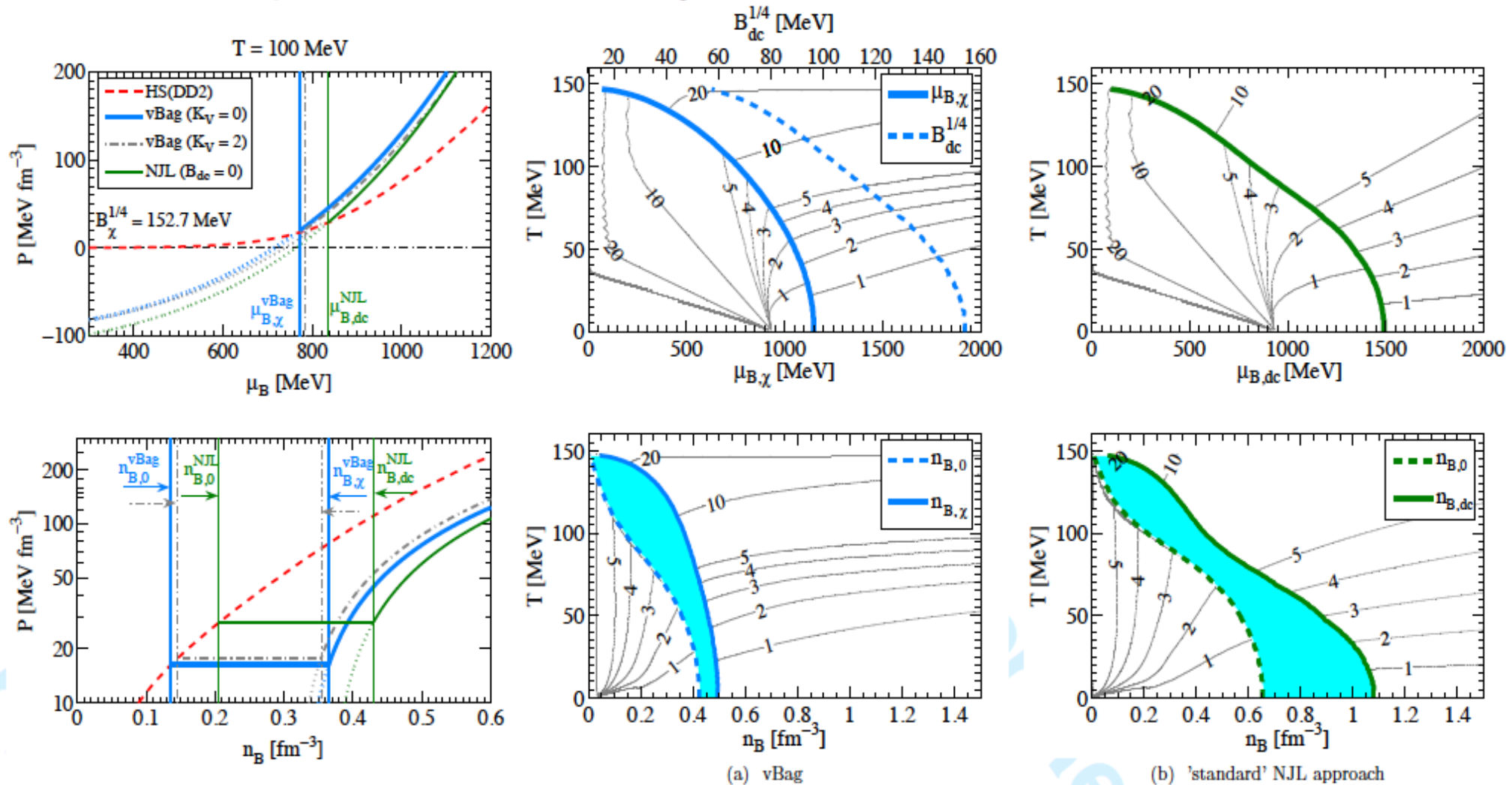
Transparency vs. Baryon Stopping

NICA White Paper – selected topics ...

Many ideas about the QCD phase diagram at finite baryon densities ... one of them:

#15 Consequences of simultaneous chiral symmetry breaking and deconfinement for the isospin symmetric phase diagram

Tobias Fischer^{1,a}, Thomas Klähn¹ and Matthias Hempel²

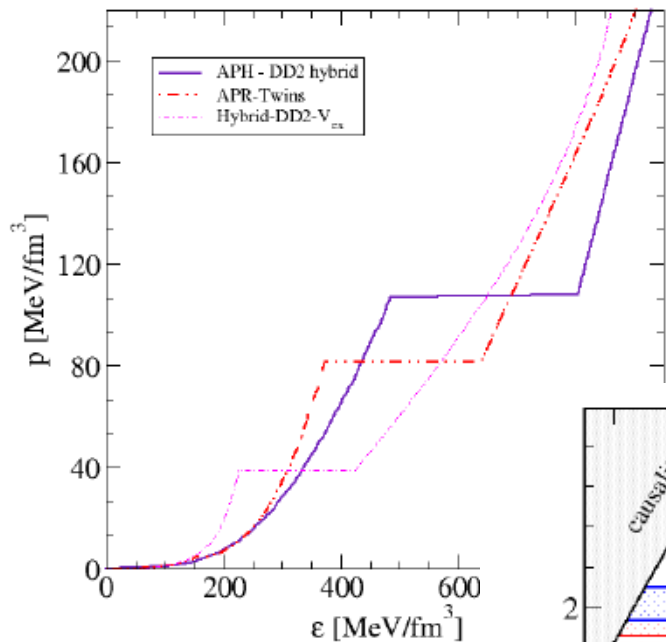


NICA White Paper – selected topics ...

Many cross-relations with astrophysics of compact stars! High-mass twin stars prove CEP !

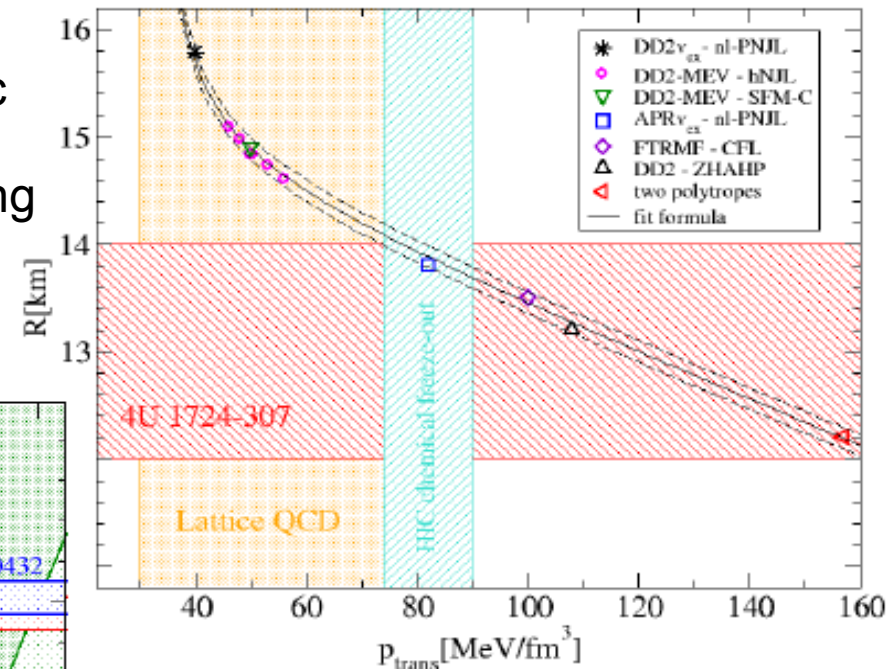
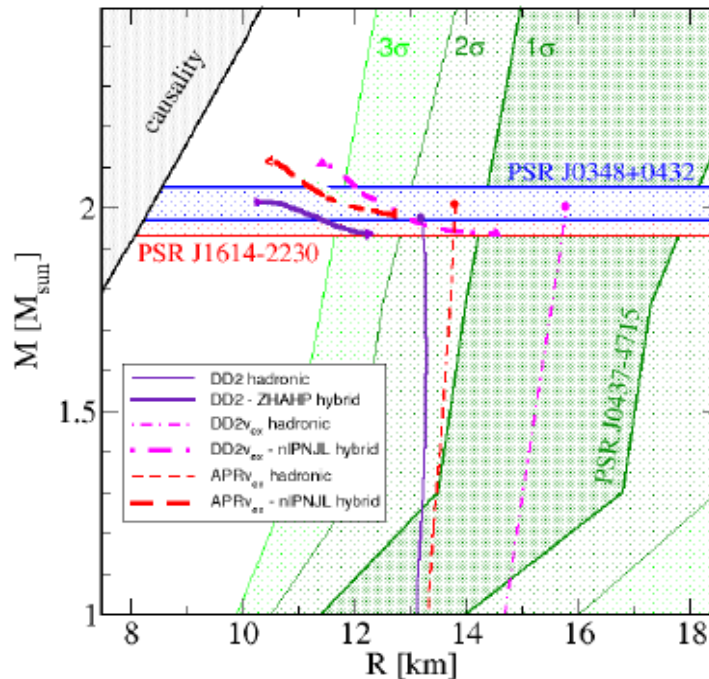
#22 Neutron star mass limit at $2M_{\odot}$ supports the existence of a CEP

D. Alvarez-Castillo^{1,a}, S. Benic^{2,b}, D. Blaschke^{1,3,4}, Sophia Han^{5,6}, and S. Typel⁷



Endpoint of hadronic
Neutron star config.
At $2M_{\text{sun}}$, then strong
Phase transition

Strong phase trans.
High-mass twin stars



Universal transition pressure ?

Petran & Rafelski, PRC 88, 021901

$$P_{\text{trans}} = 82 \pm 8 \text{ MeV/fm}^3$$

NICA White Paper – selected topics ...

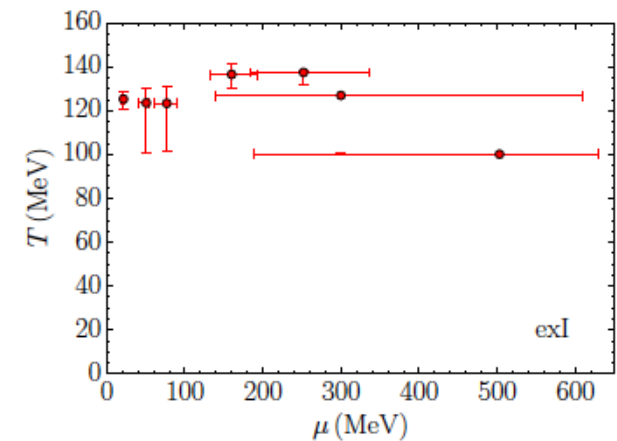
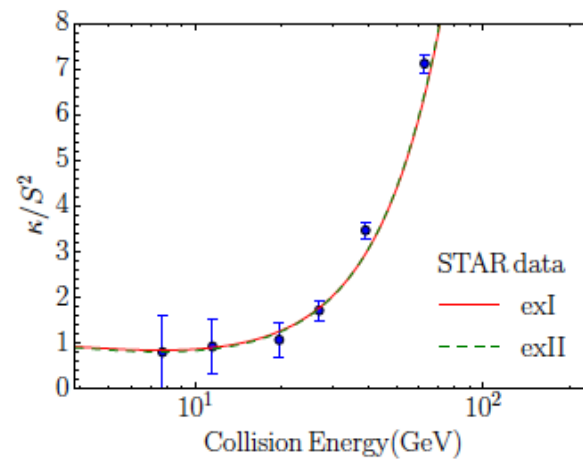
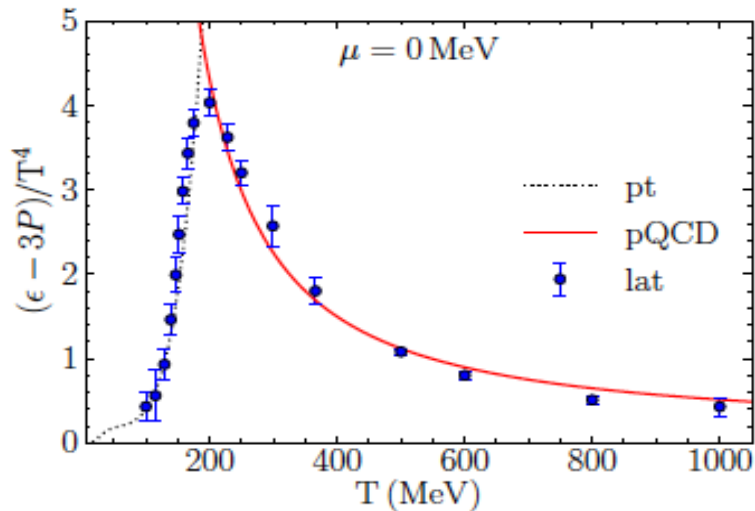
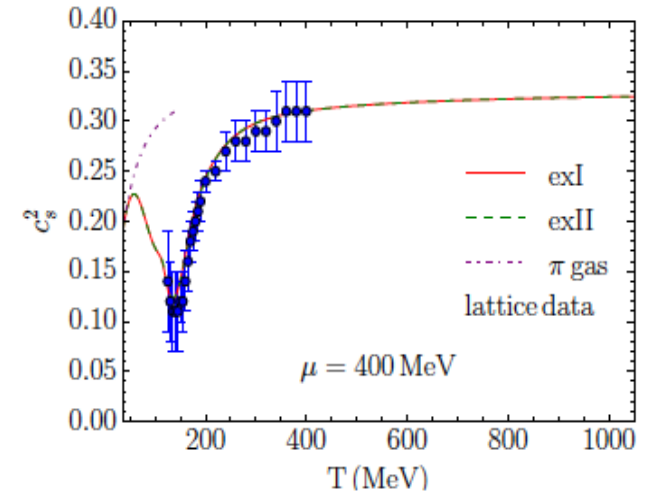
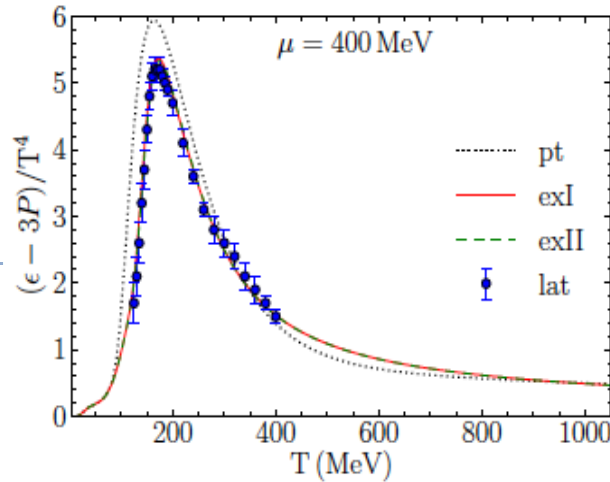
#41 Net Baryon Fluctuations from a Crossover Equation of State

J. Kapusta¹, M. Albright^{1a}, and C. Young²

Hybrid crossover EoS with
Switching function and exvol.

$$S(T, \mu) = \exp\{-\theta(T, \mu)\}$$

$$\theta(T, \mu) = \left[\left(\frac{T}{T_0} \right)^n + \left(\frac{\mu}{3\pi T_0} \right)^n \right]^{-1}$$

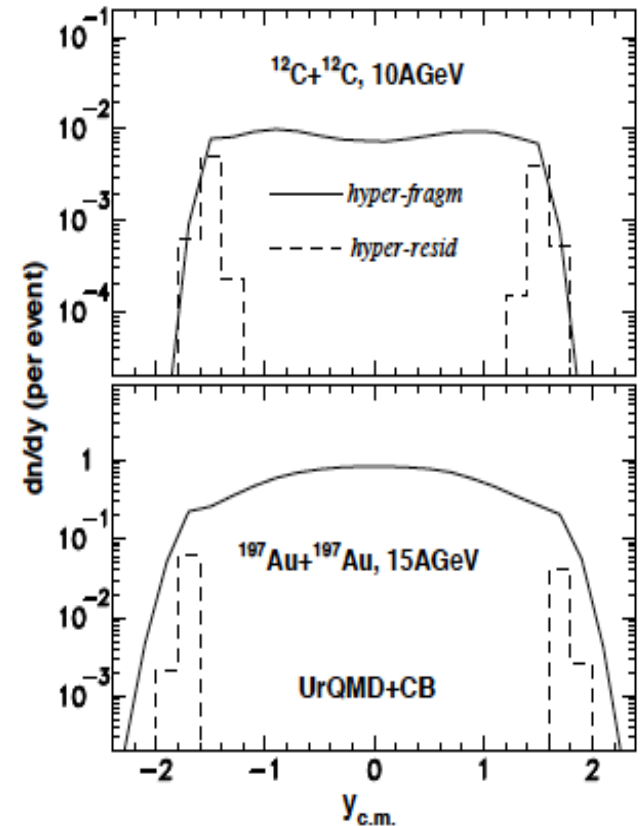
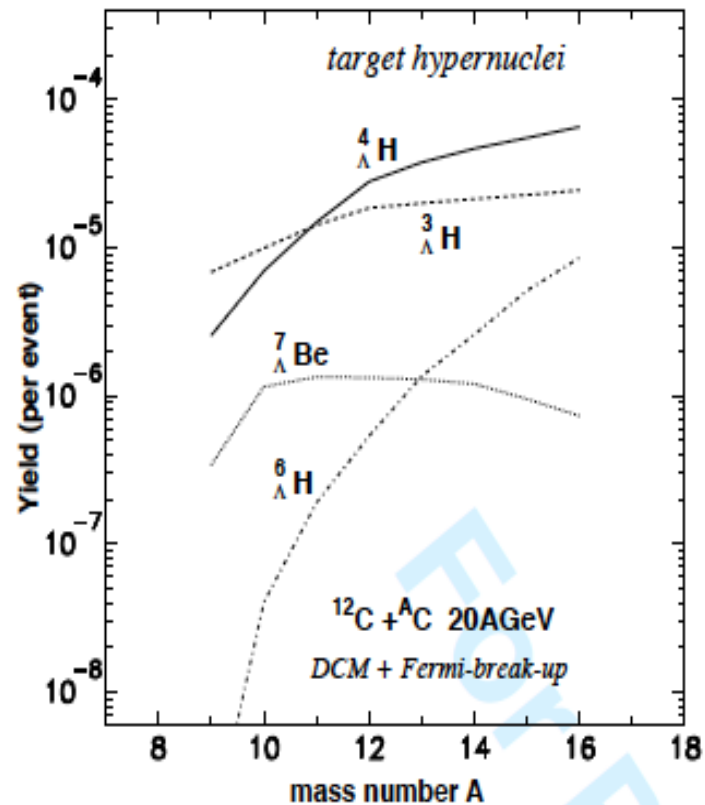
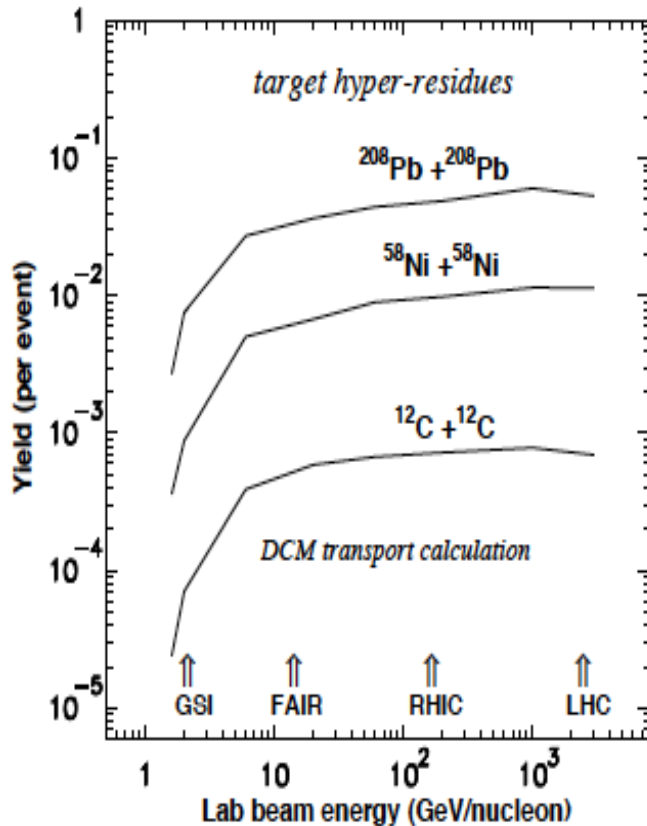


No evidence for a critical point in RHIC BES data.
But for lower energies – maybe!

NICA White Paper – selected topics ...

#32 Relativistic ion collisions as the source of hypernuclei.

A. S. Botvina^{1,2}, M. Bleicher¹, J. Pochodzalla^{3,4}, and J. Steinheimer¹



Dubna Cascade Model (DCM) prediction for hyper-residues production as a function of beam energy

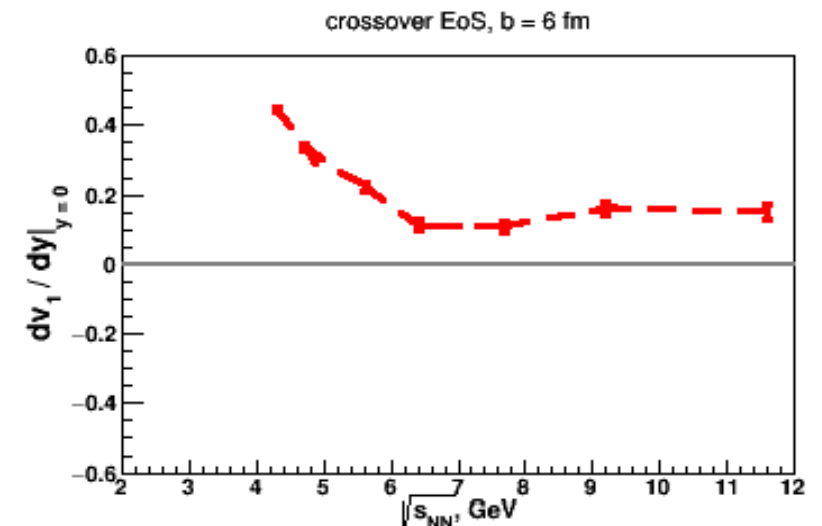
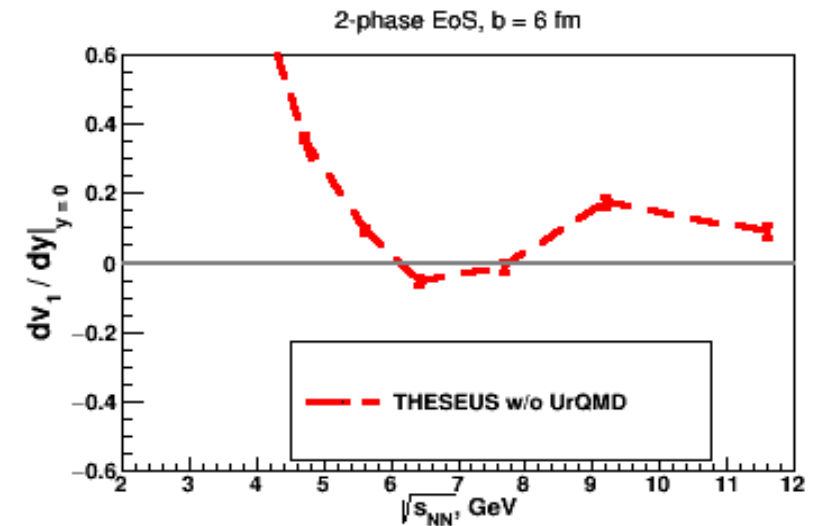
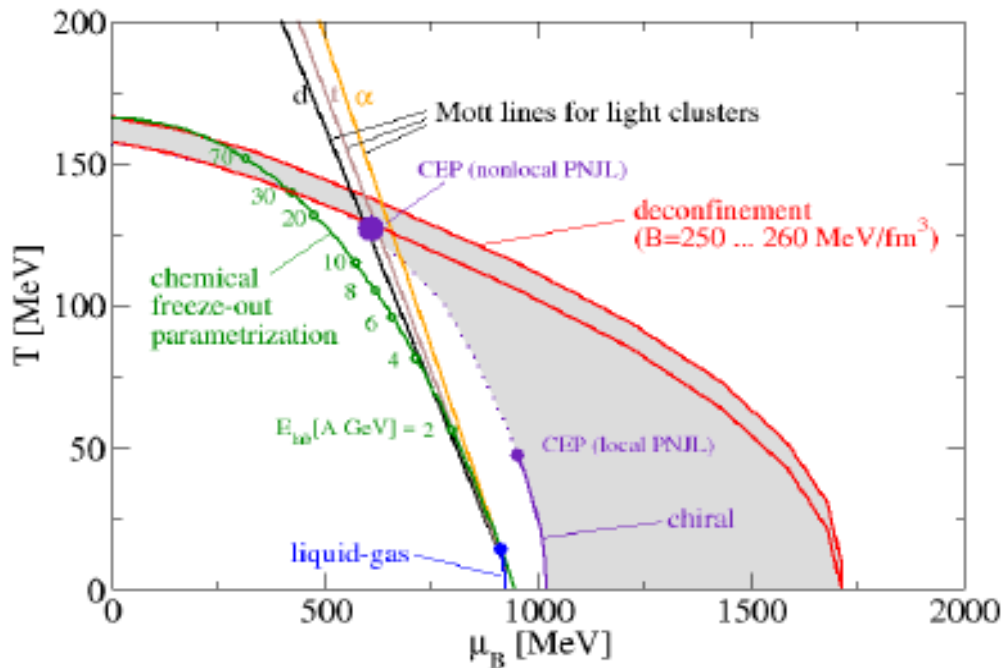
Yields of light hypernuclei from target residues in hybrid DCM Fermi breakup model (FBM) calculations at 20 AGeV

UrQMD plus coalescence of baryons (CB) model results For rapidity distributions of hyper fragments and residues

NICA White Paper – selected topics ...

#34 Light cluster production at NICA

N.-U. Bastian¹, P. Batyuk², D. Blaschke^{1,2,3}, P. Danielewicz⁴, Yu. B. Ivanov^{3,5}, Iu. Karpenko^{6,7}, G. Röpke^{3,8,a}, O. Rogachevsky², H. H. Wolter⁹



Danielewicz:
Flow of light clusters traces early pressure distribution, not affected by rescattering on pions and light hadrons

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 simulation of the **detector response** (GEANT-MPD: Rogachevsky, Merts, Batyuk, Wielanek, et al.)

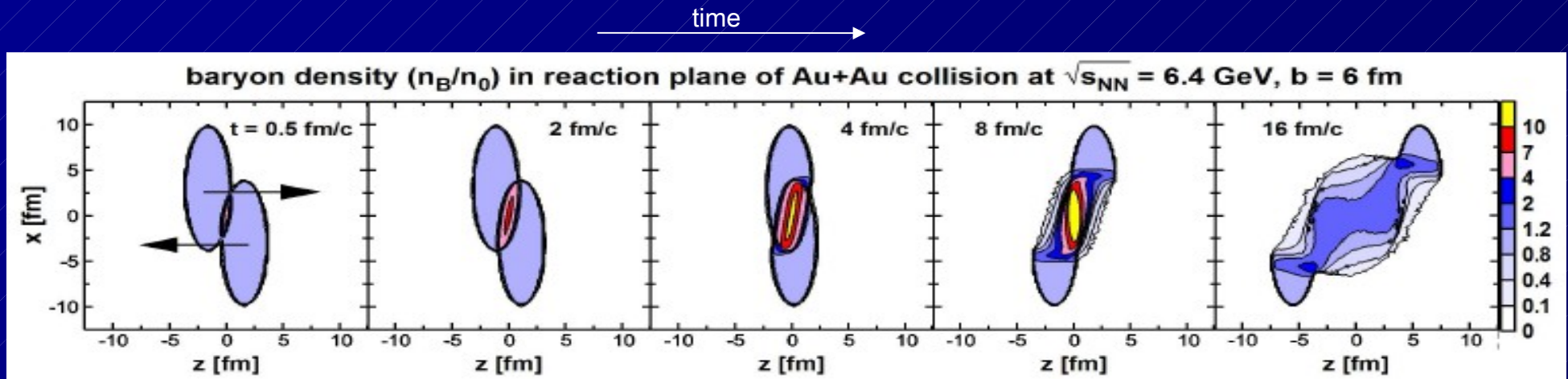
Hydrodynamic modelling for NICA / FAIR / J-PARC-HI

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



3-fluid hydro,
(Yu. Ivanov)

hydrodynamic evolution



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

particlization



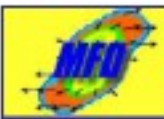
(optionally) cascade:
PHSD, UrQMD, etc
(E. Bratkovskaya,
H. Petersen)

hadronic
corona



GEANT
MPD, BM @N
(O. Rogachevsky,
P. Batyuk,
S. Merts, et al.)

detector
response



3-Fluid Dynamics

Baryon Stopping

JINR, 24.08.10

Model

Rapidity Density

Fit

Reduced curvature

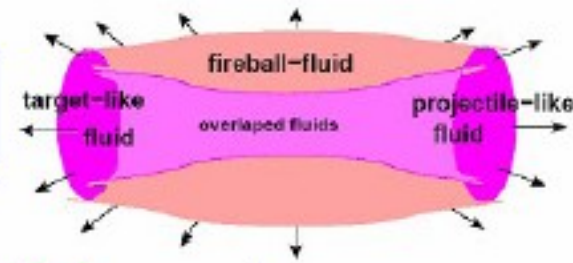
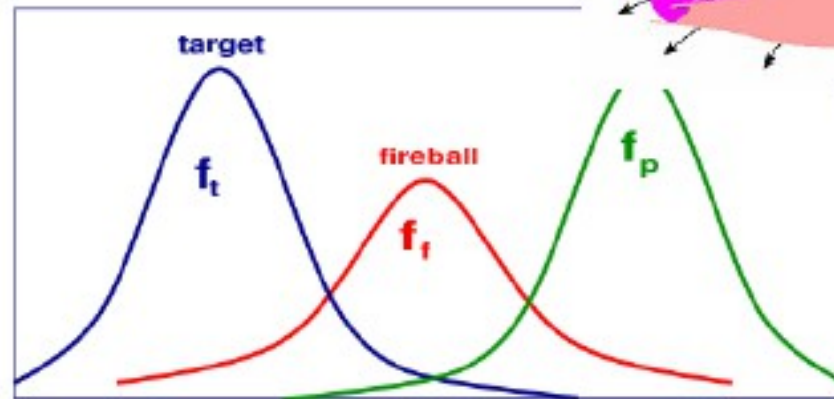
Trajectories

Crossover

Summary

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

distribution function



momentum along beam

Target-like fluid:

$$\partial_\mu J_t^\mu = 0$$

Leading particles carry bar. charge

$$\partial_\mu T_t^{\mu\nu} = -F_{tp}^\nu + F_{ft}^\nu$$

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:

$$J_f^\mu = 0,$$

Baryon-free fluid

$$\partial_\mu T_f^{\mu\nu} = F_{pt}^\nu + F_{tp}^\nu - F_{fp}^\nu - F_{ft}^\nu$$

Source term Exchange

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

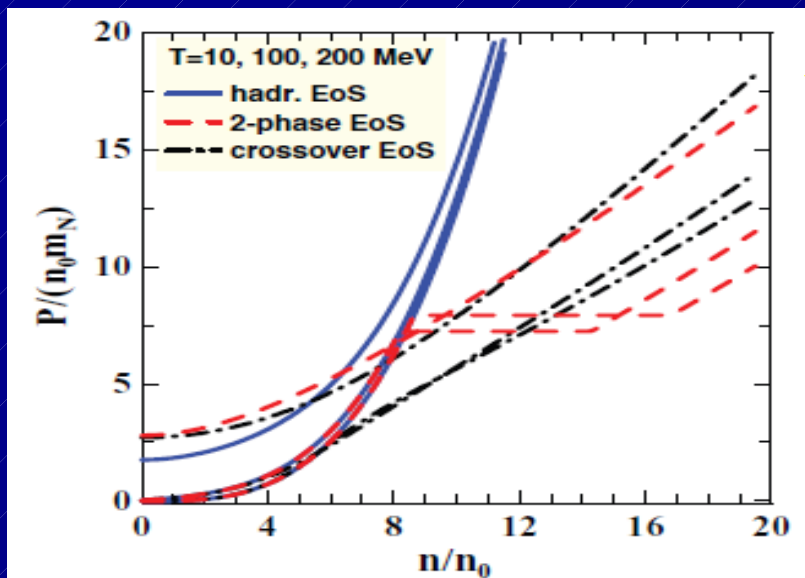
Total energy-momentum conservation:

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

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

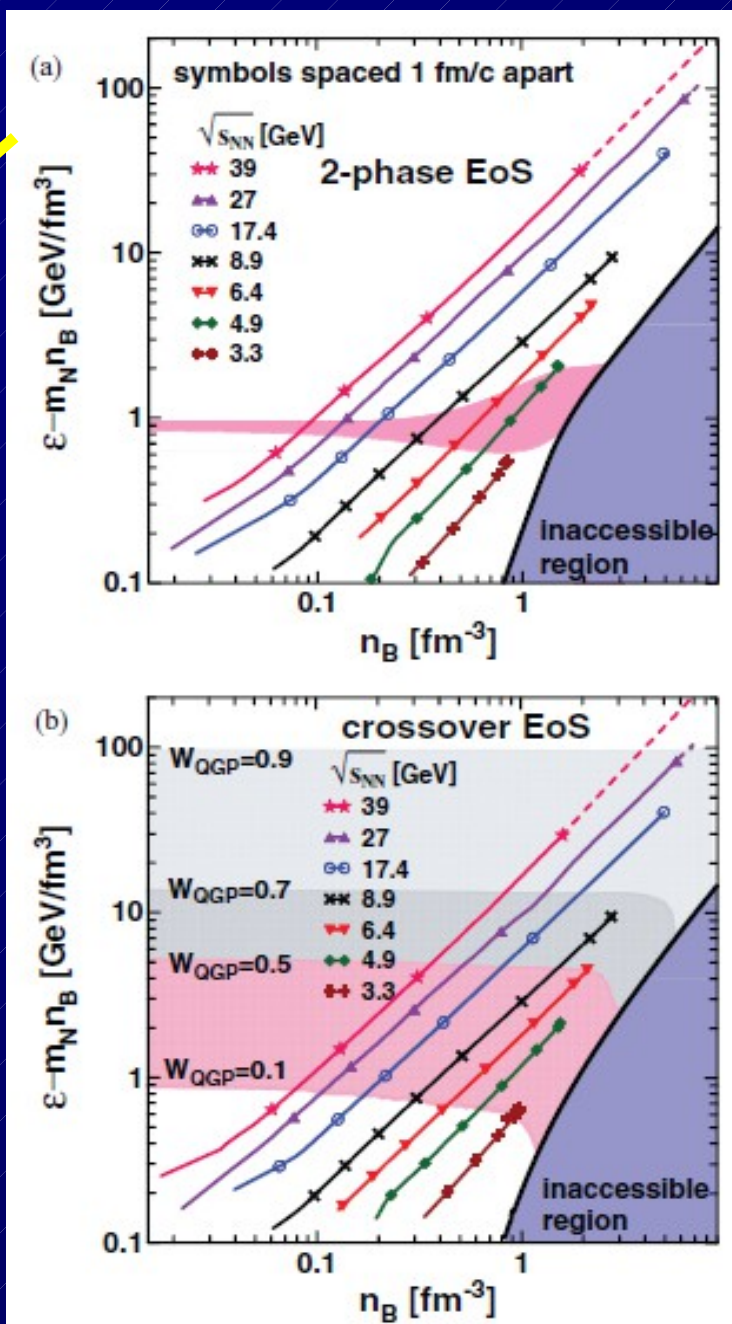
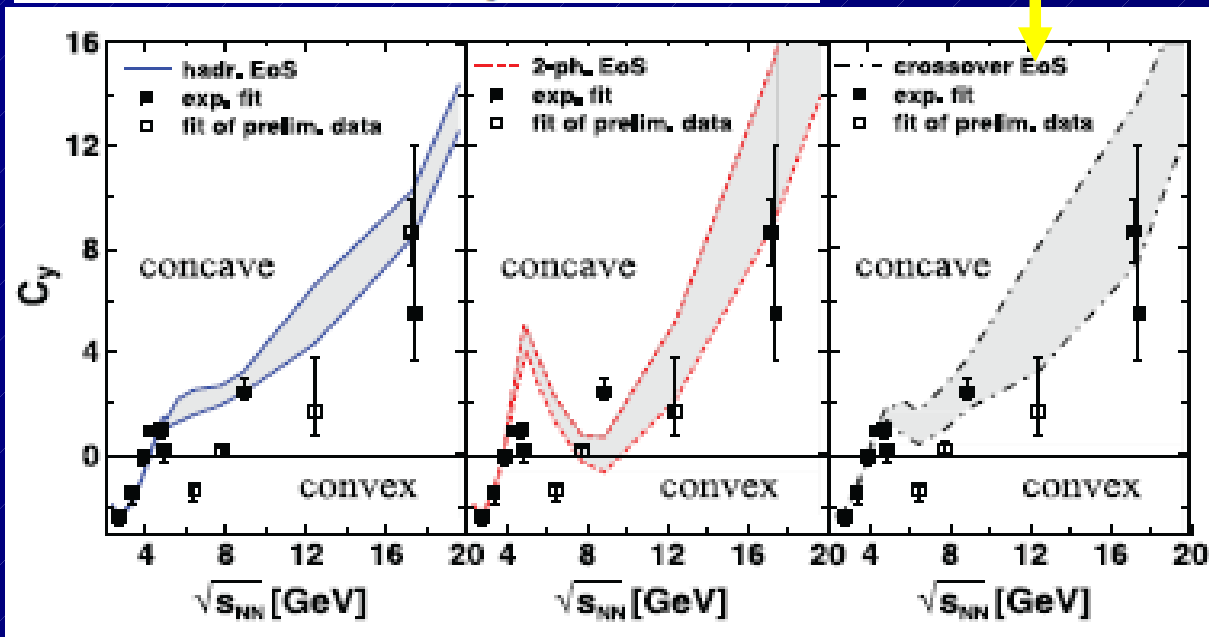
Net proton rapidity distribution – test case for a 1st order PT signal

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



EoS

3-fluid hydro Evolution ...

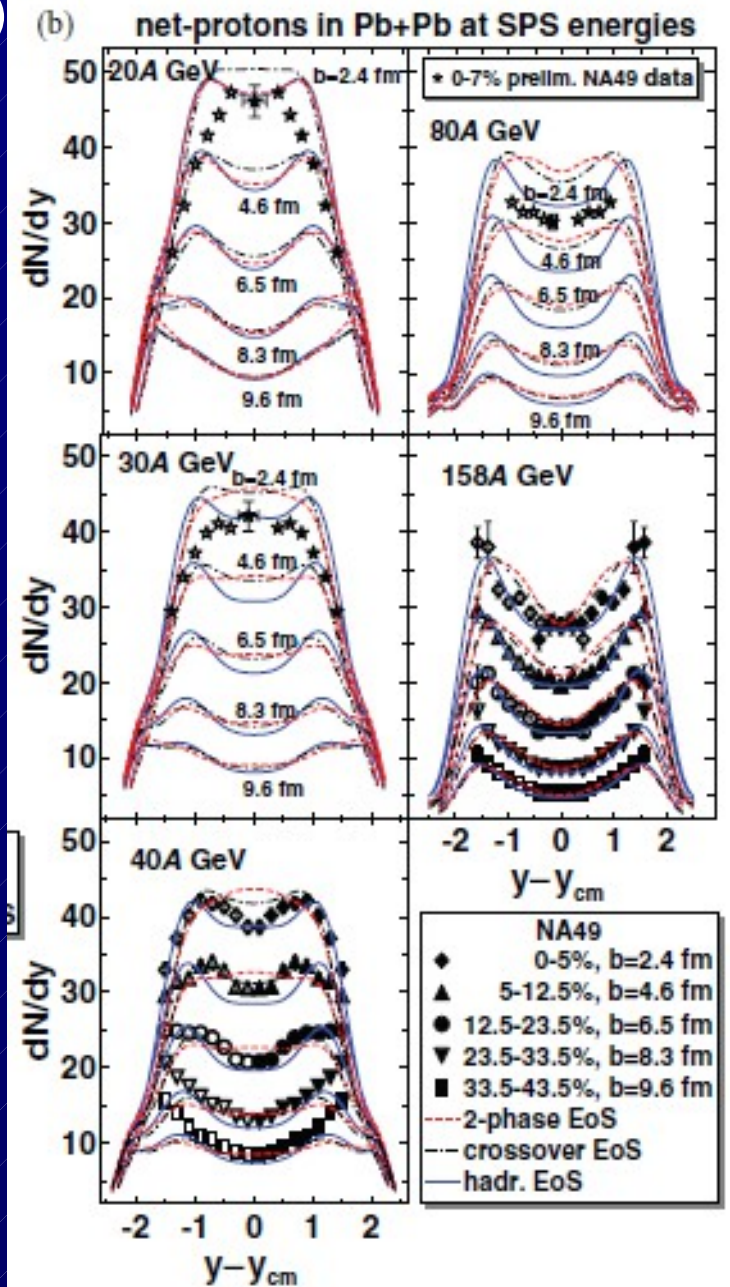
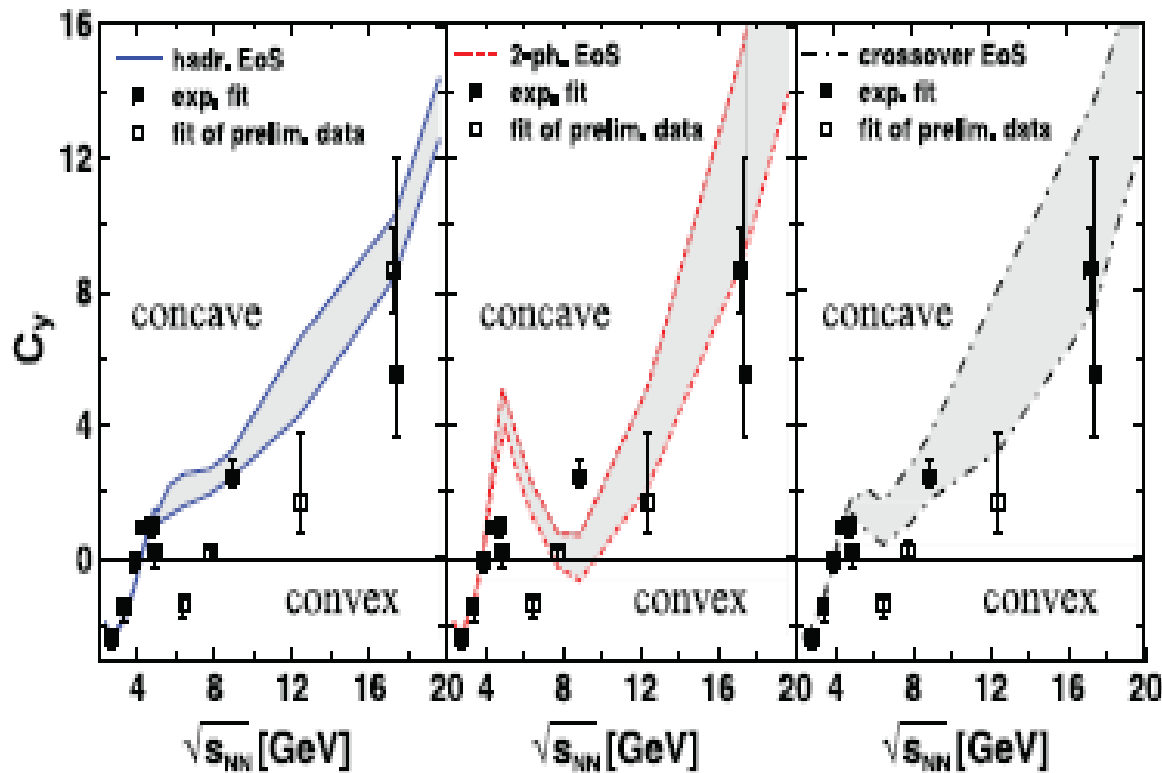


Net proton rapidity distribution – test case for a 1st order PT signal

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

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

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



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

Event set:

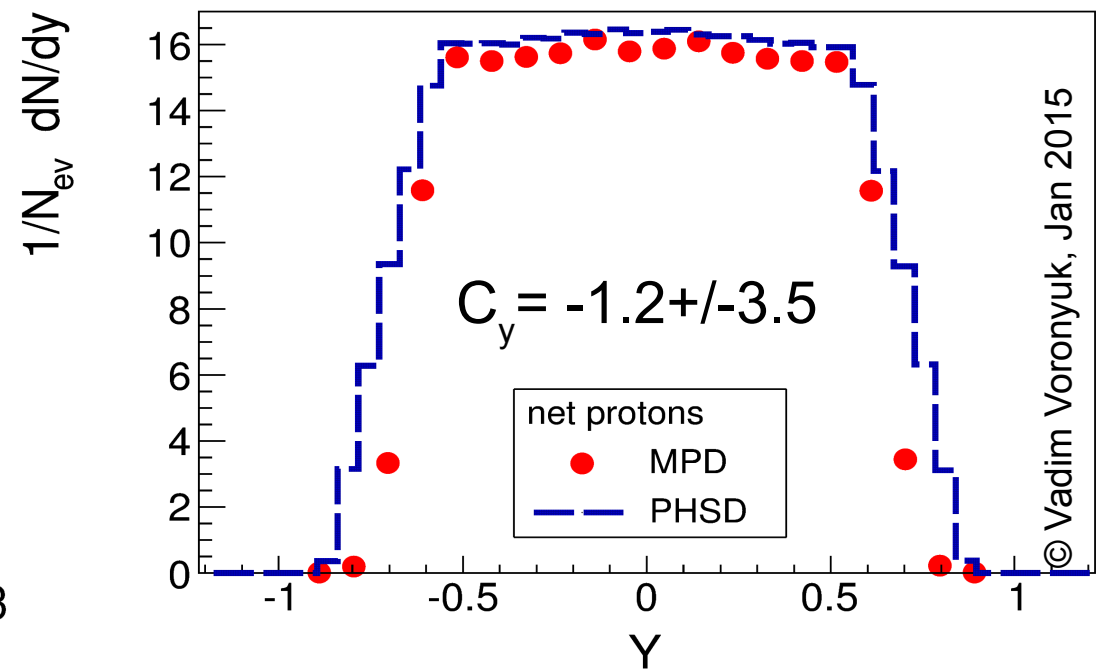
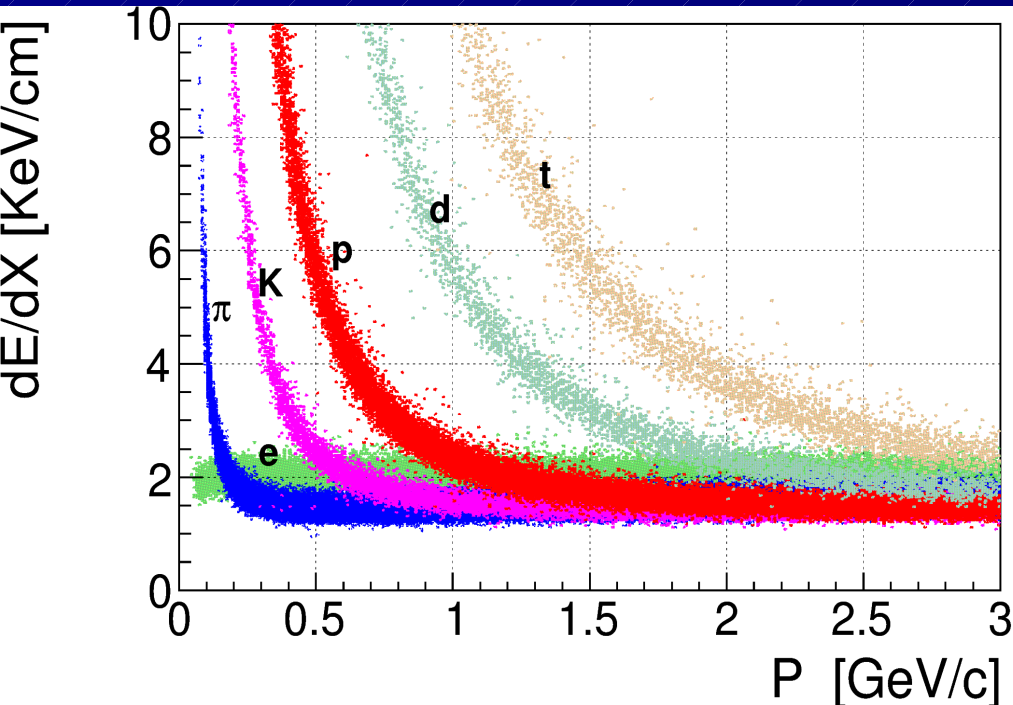
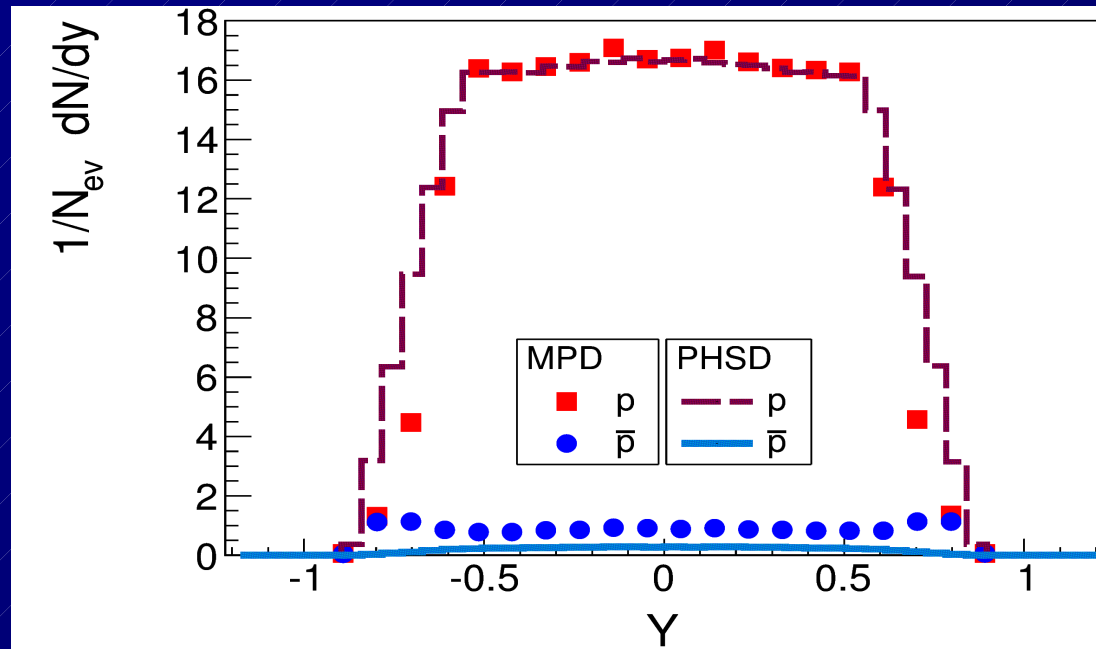
40k AuAu @ $\sqrt{s_{NN}} = 9$ GeV [0-5%]
 The most reliable region
 $|\eta| < 1.2$; $0.4 < p_t$ [GeV/c] < 0.8

Result:

PHSD input \rightarrow 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

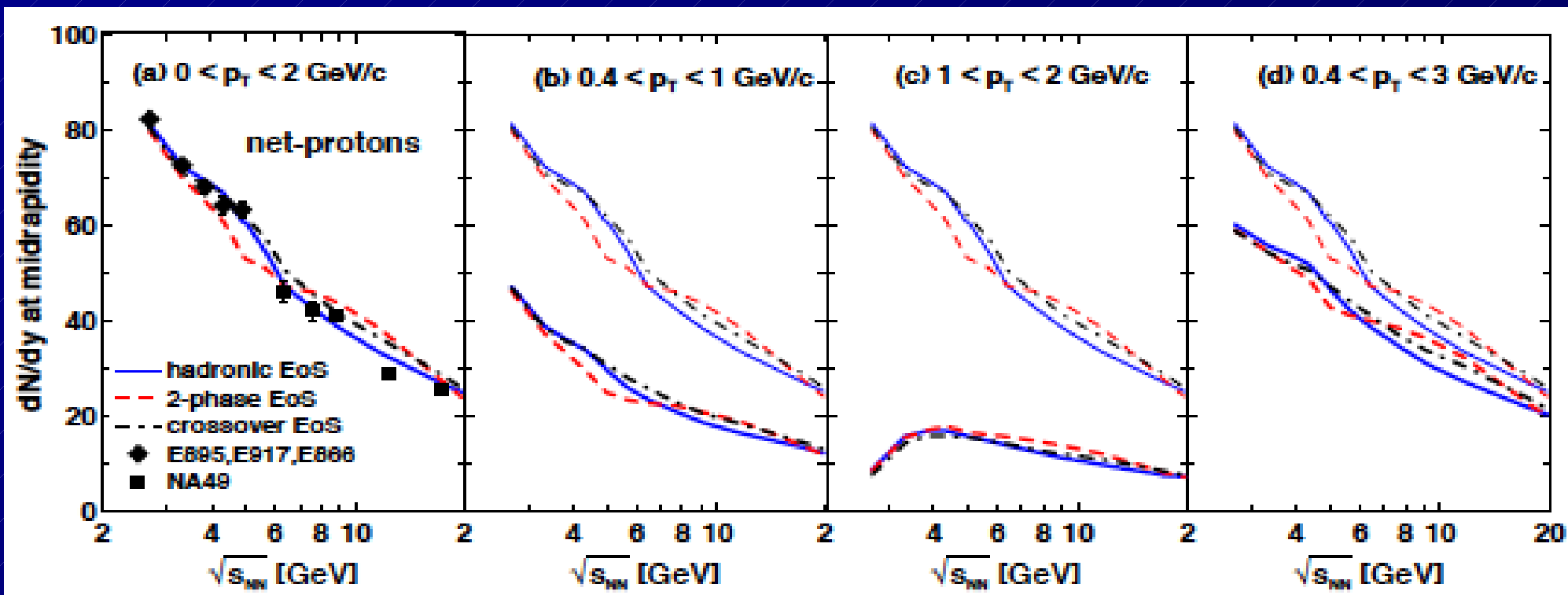
Investigation of p_T cuts:

Yu. Ivanov & D. Blaschke, arxiv:1504.03992

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

$$= (y_{\text{beam}}/w_s)^2 (\sinh^2 y_s - w_s \cosh y_s).$$

- i. $0 < p_T < 2 \text{ GeV}/c$ and a very unrestrictive constraint to the rapidity range $|y| < 0.7 y_{\text{beam}}$, where y_{beam} is the beam rapidity in the collider mode, which is practically equivalent to the full acceptance;
- ii. $0.4 < p_T < 1 \text{ GeV}/c$ and $|y| < 0.5$, the expected MPD acceptance [17];
- iii. $1 < p_T < 2 \text{ GeV}/c$ and $|y| < 0.5$, an acceptance range where low-momentum particles witnessing collective behaviour are largely eliminated;
- iv. $0.4 < p_T < 3 \text{ GeV}/c$ and $|y| < 0.5$, the range of the STAR acceptance [18].



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

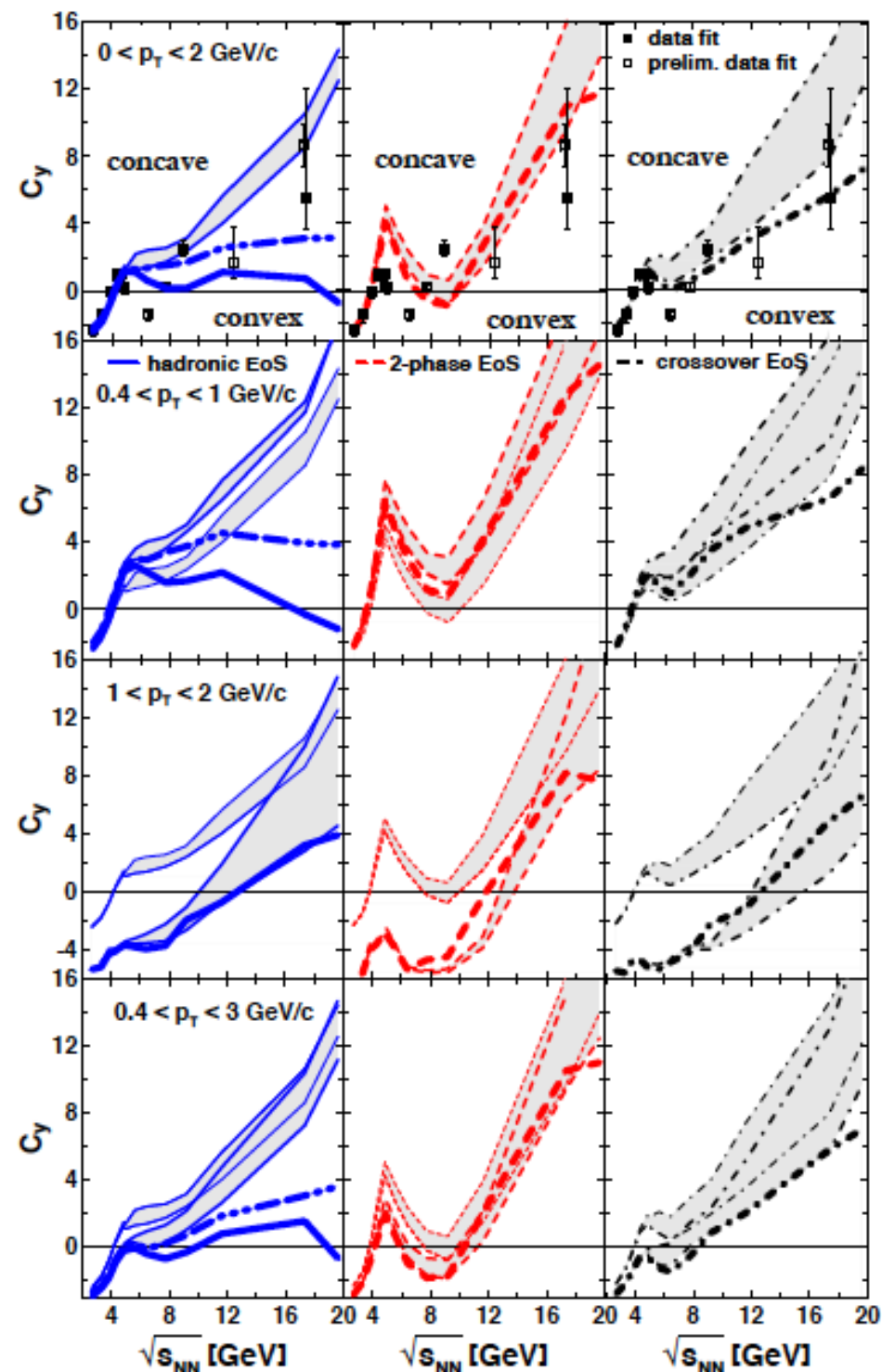
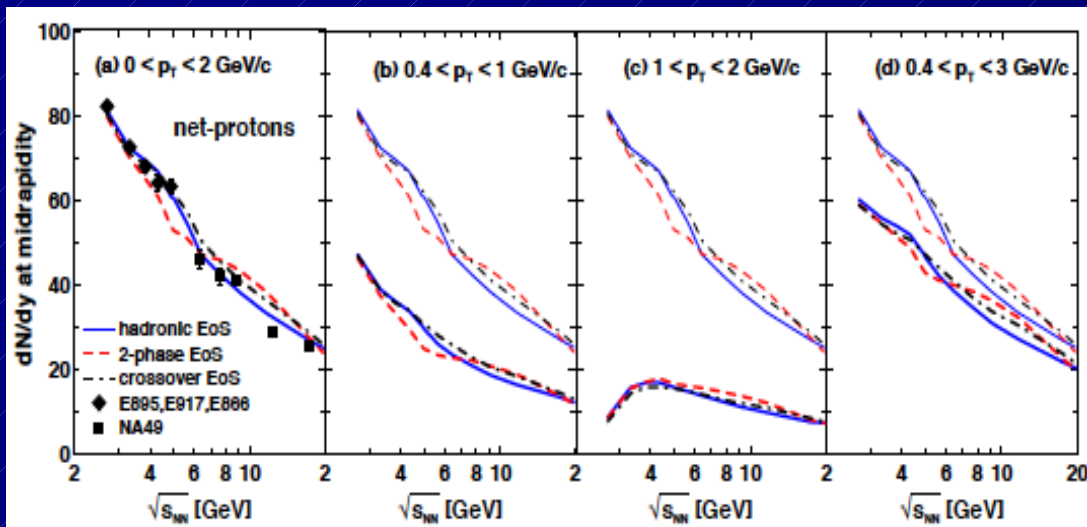
Investigation of p_T cuts:

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

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

$$= (y_{\text{beam}}/w_s)^2 (\sinh^2 y_s - w_s \cosh y_s)$$

- “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

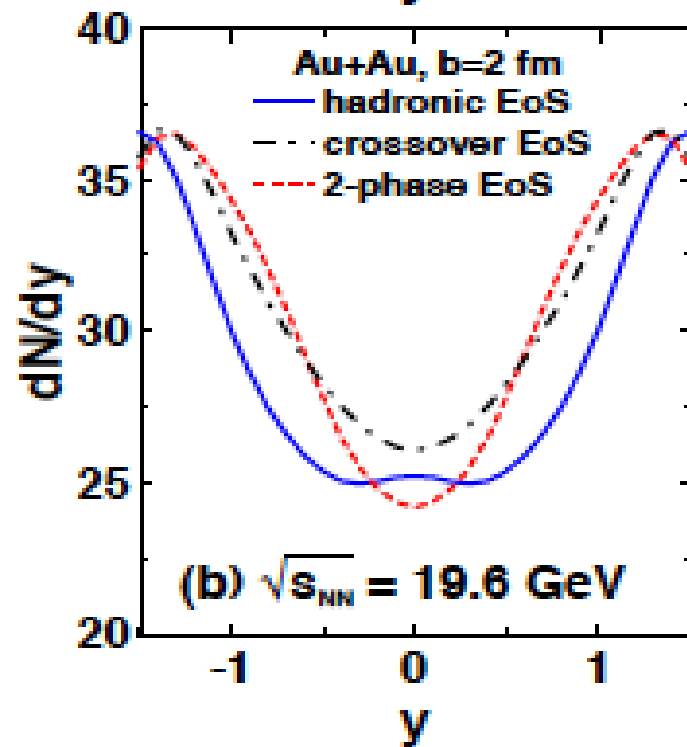
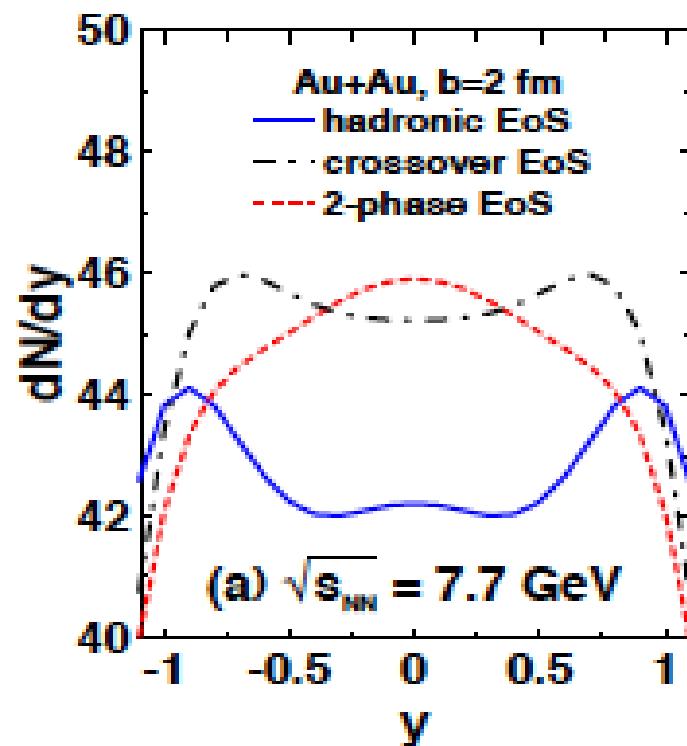
Investigation of p_T cuts:

Yu. Ivanov & D. Blaschke, arxiv:1504.03992

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

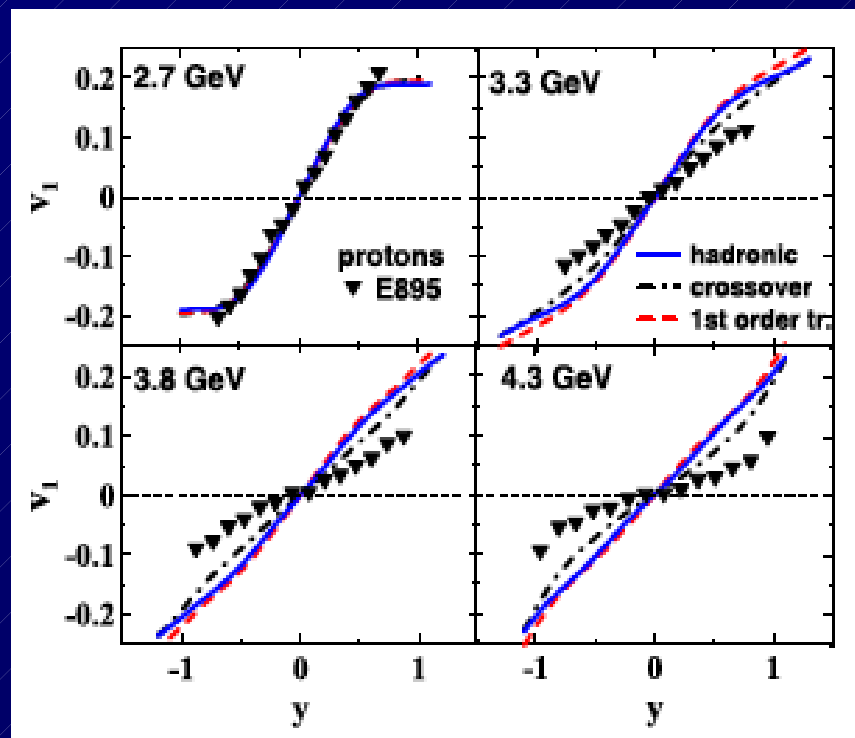
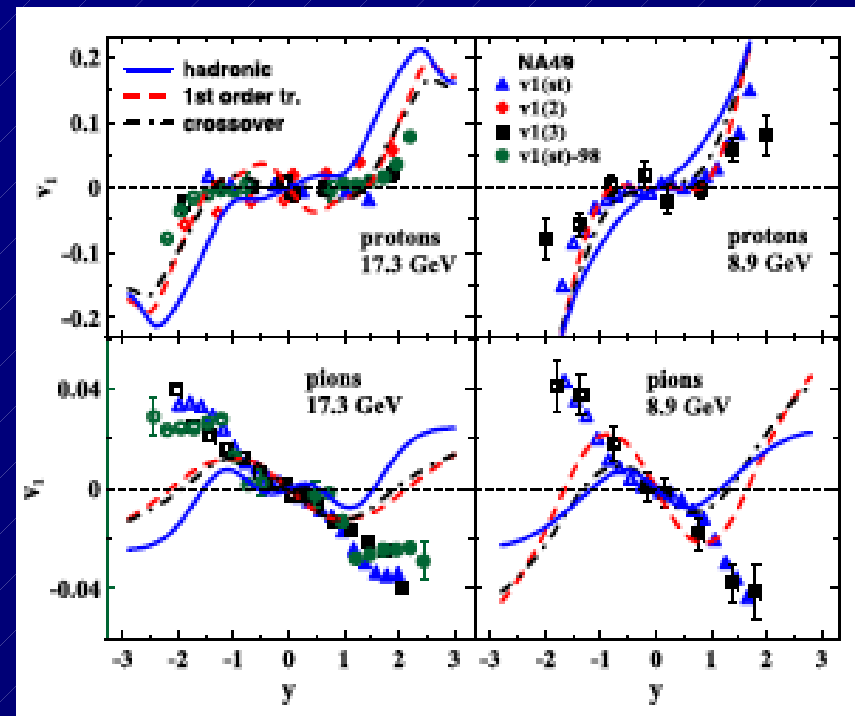
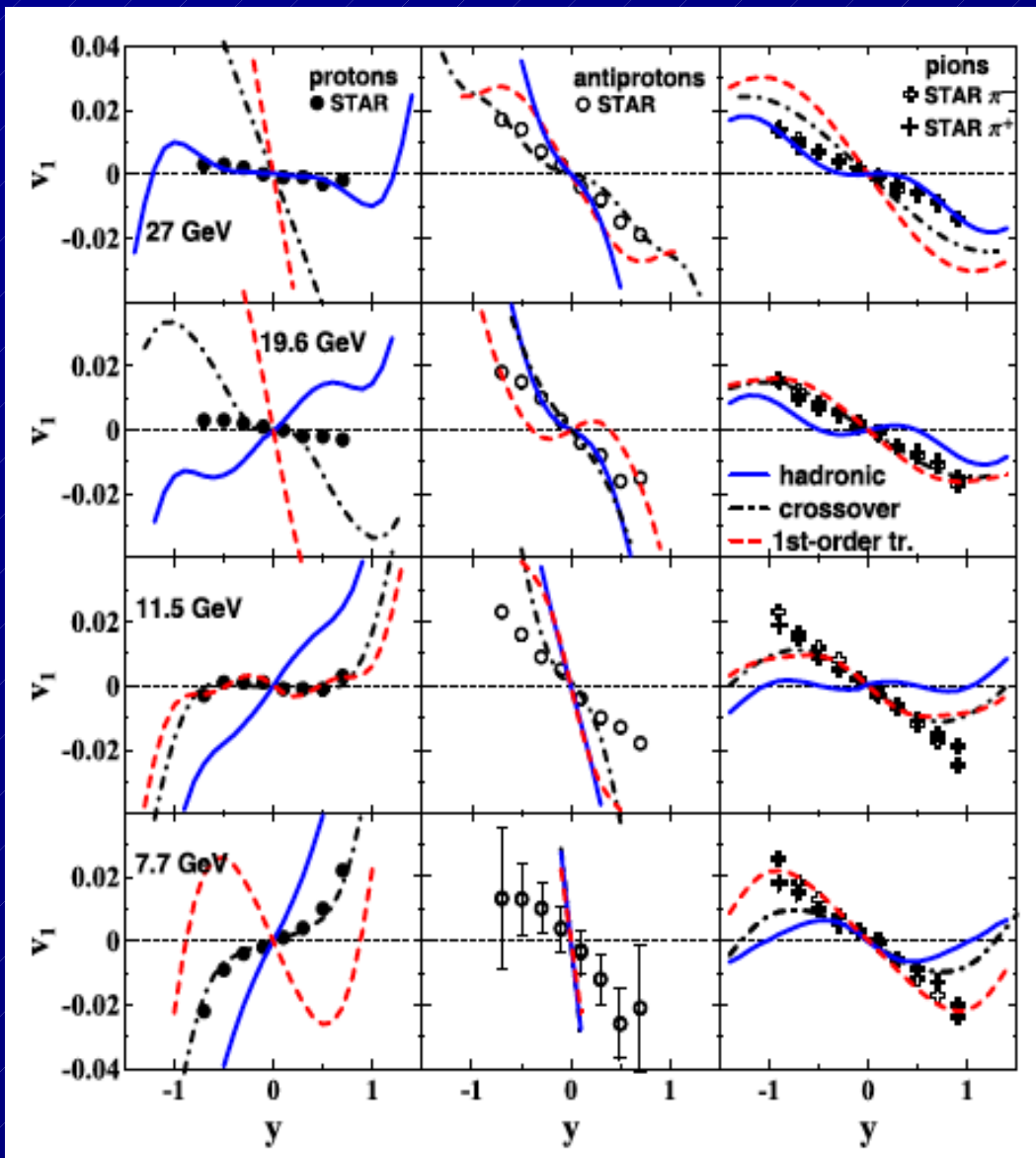
$$C_y = \left(y_{\text{beam}}^3 \frac{d^3 N}{dy^3} \right)_{y=0} / \left(y_{\text{beam}} \frac{dN}{dy} \right)_{y=0} = (y_{\text{beam}}/w_s)^2 (\sinh^2 y_s - w_s \cosh y_s).$$

- “wiggle” formed in the nonequilibrium compression stage of the collision, where p_T **only in 3FH**
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- required accuracy in C_y determination: $\Delta C_y < 2$



Directed flow indicates a cross-over Deconfinement transition ...

Ivanov & Soldatov, Phys. Rev. C 91 (2015)



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

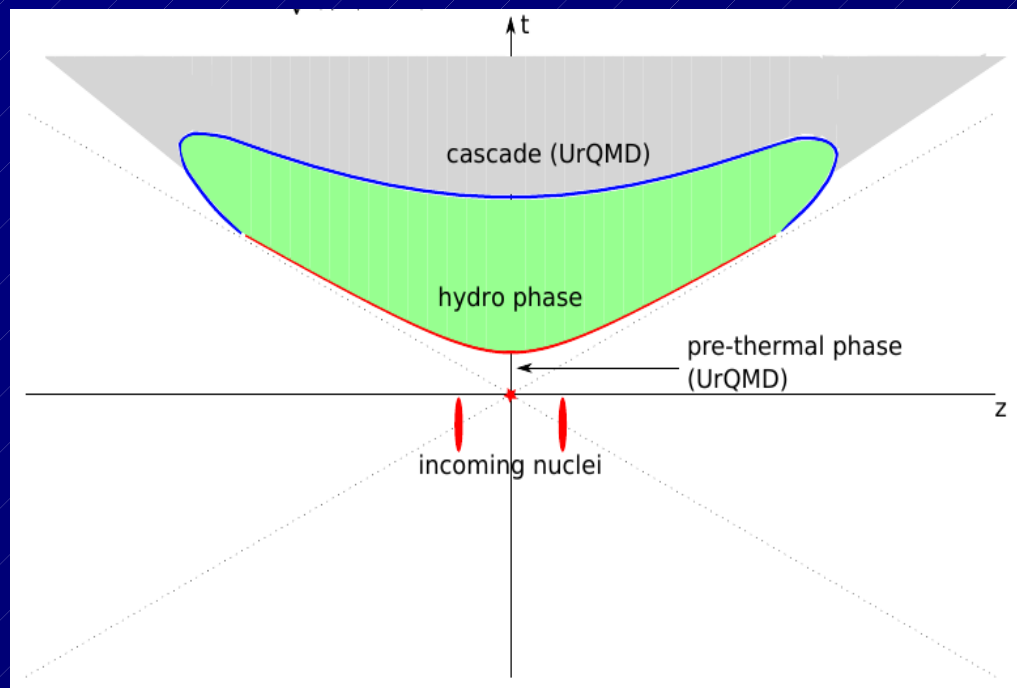
Fluid \rightarrow particle transition

$\varepsilon = \varepsilon_{SW} = 0.5 \text{ GeV/fm}^3$ (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

P. Huovinen, H. Petersen: "Particlization in hybrid models", Eur. Phys. J. A48 (2012) 171; arxiv:1206.3371



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)

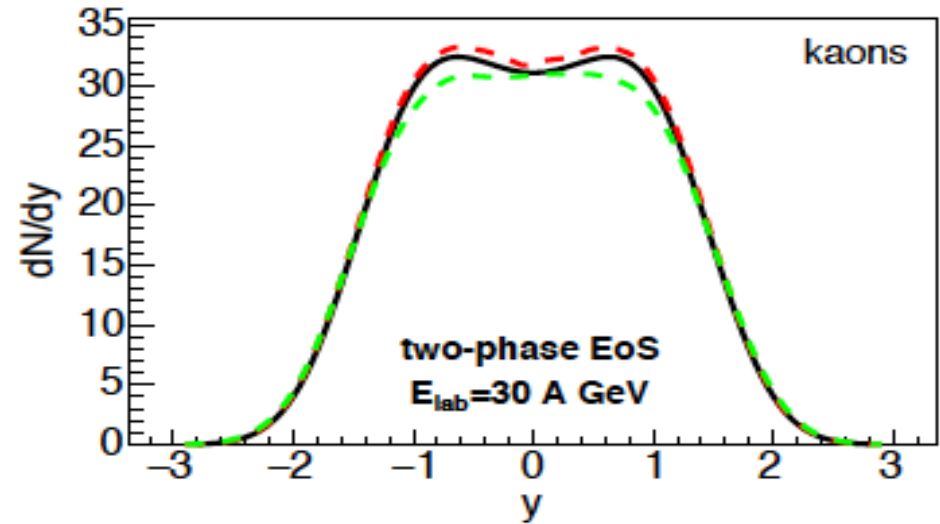
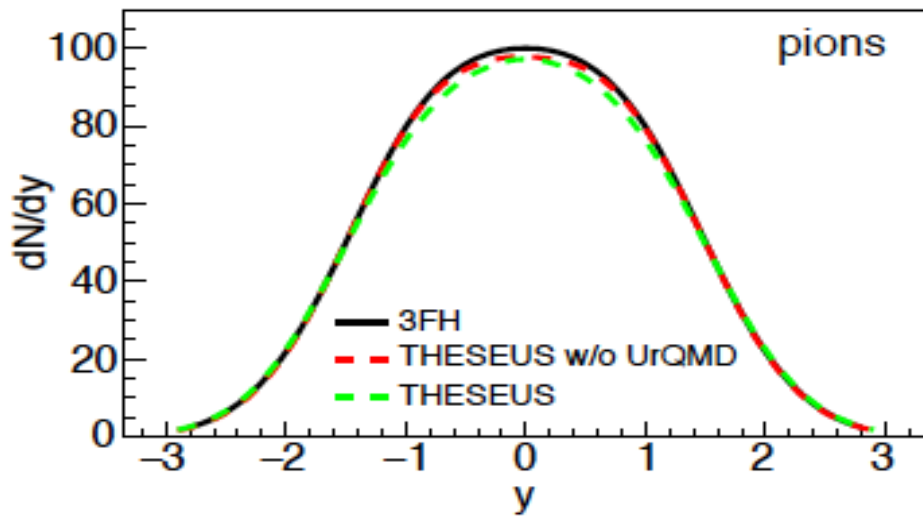
- ▶ hadron resonance gas made of u, d quarks including repulsive meanfield
- ▶ the phases matched via Maxwell construction, resulting in **1st order PT**

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).

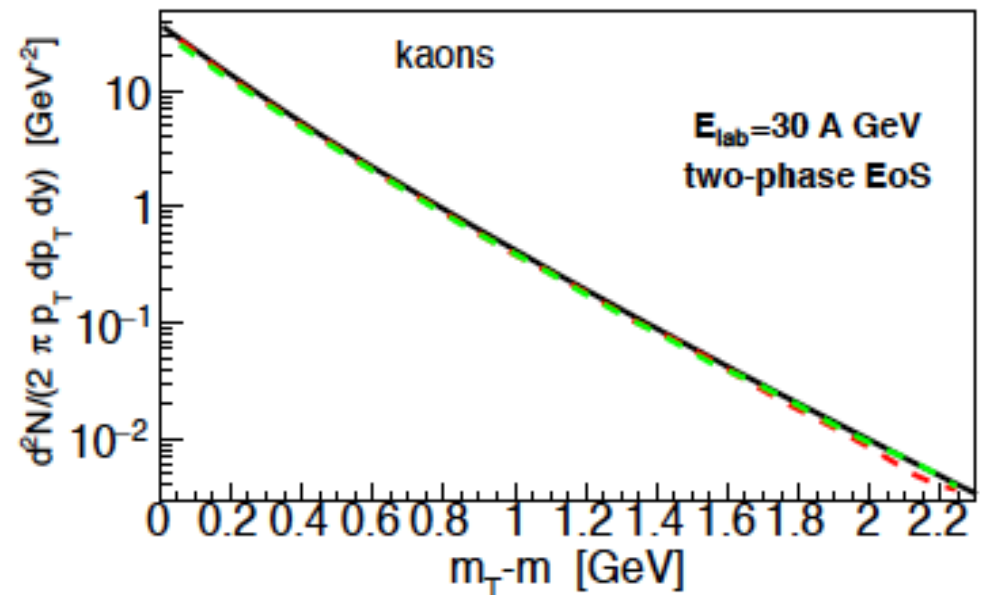
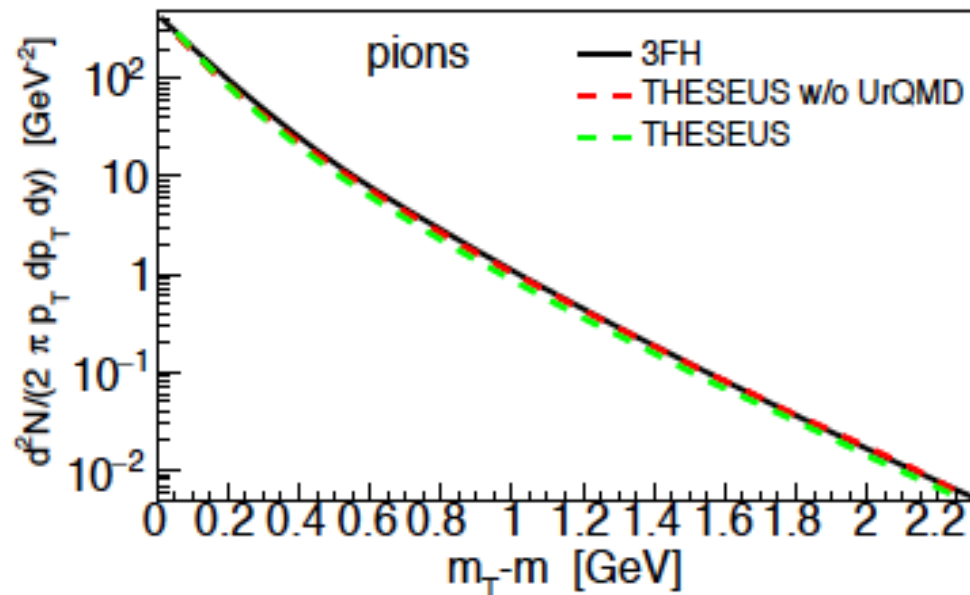
THESEUS: Particlization of 3-fluid Hydro + UrQMD casc.

P. Batyuk, D.B., M. Bleicher, Yu. Ivanov, et al., arxiv:1608.00965

Rapidity distribution

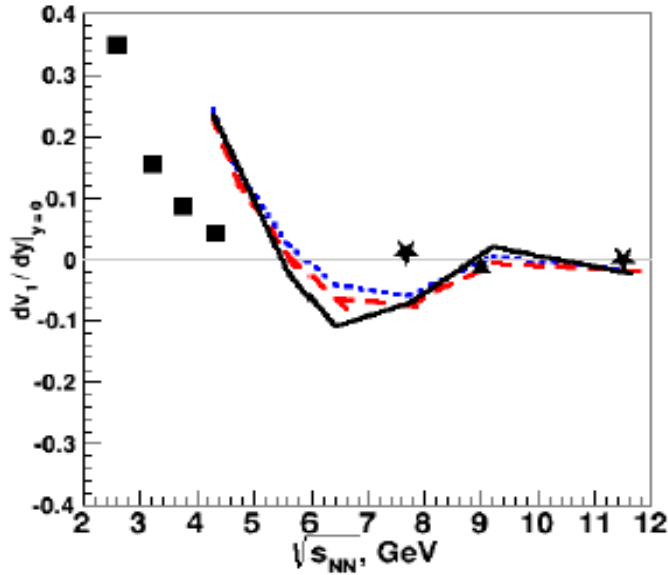


P_T / m_T distribution

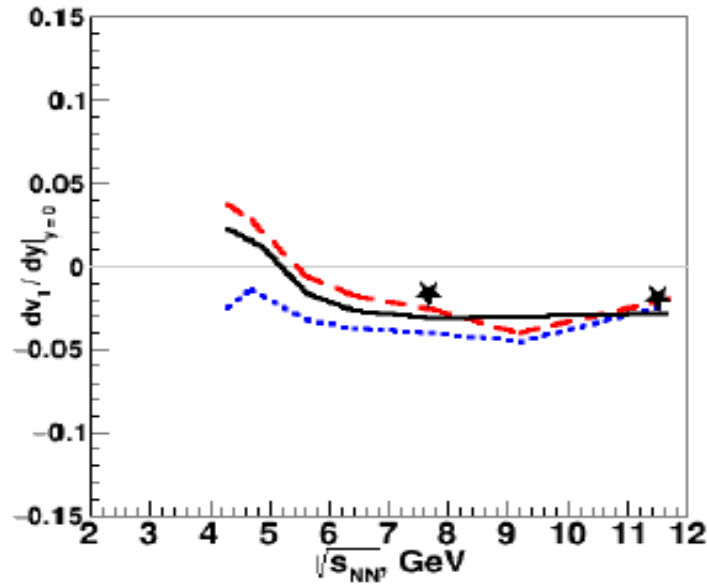


THESEUS: Particlization of 3-fluid Hydro + UrQMD casc.

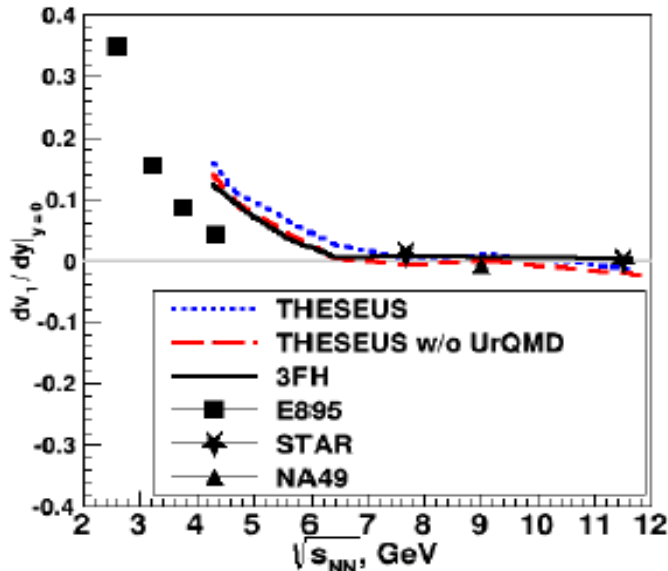
2-phase EoS, b = 6 fm



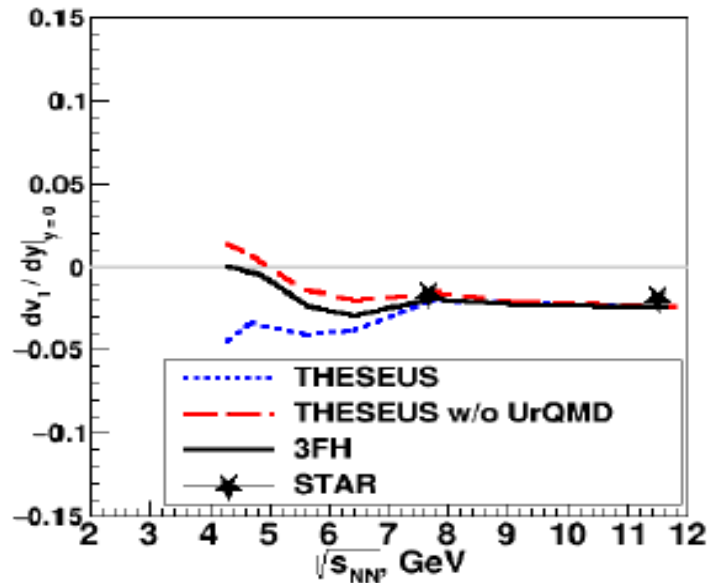
2-phase EoS, b = 6 fm



crossover EoS, b = 6 fm



crossover EoS, b = 6 fm



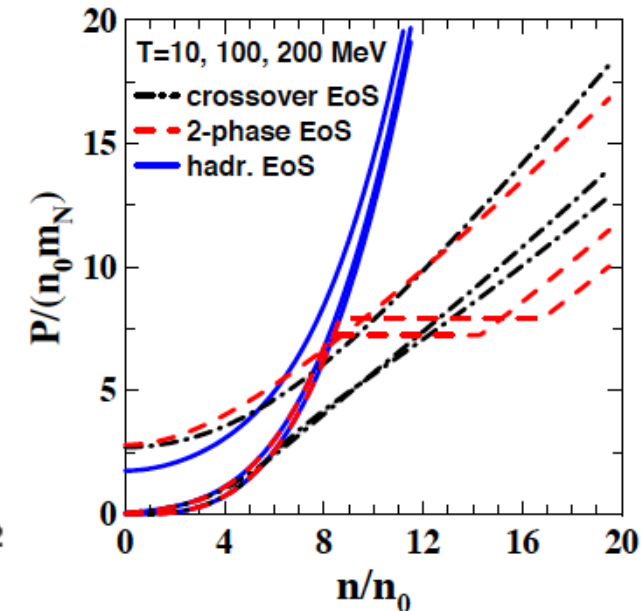
Slope of directed flow

Protons (left)
Pions (right)

First-order PT (upper)
Crossover (lower)

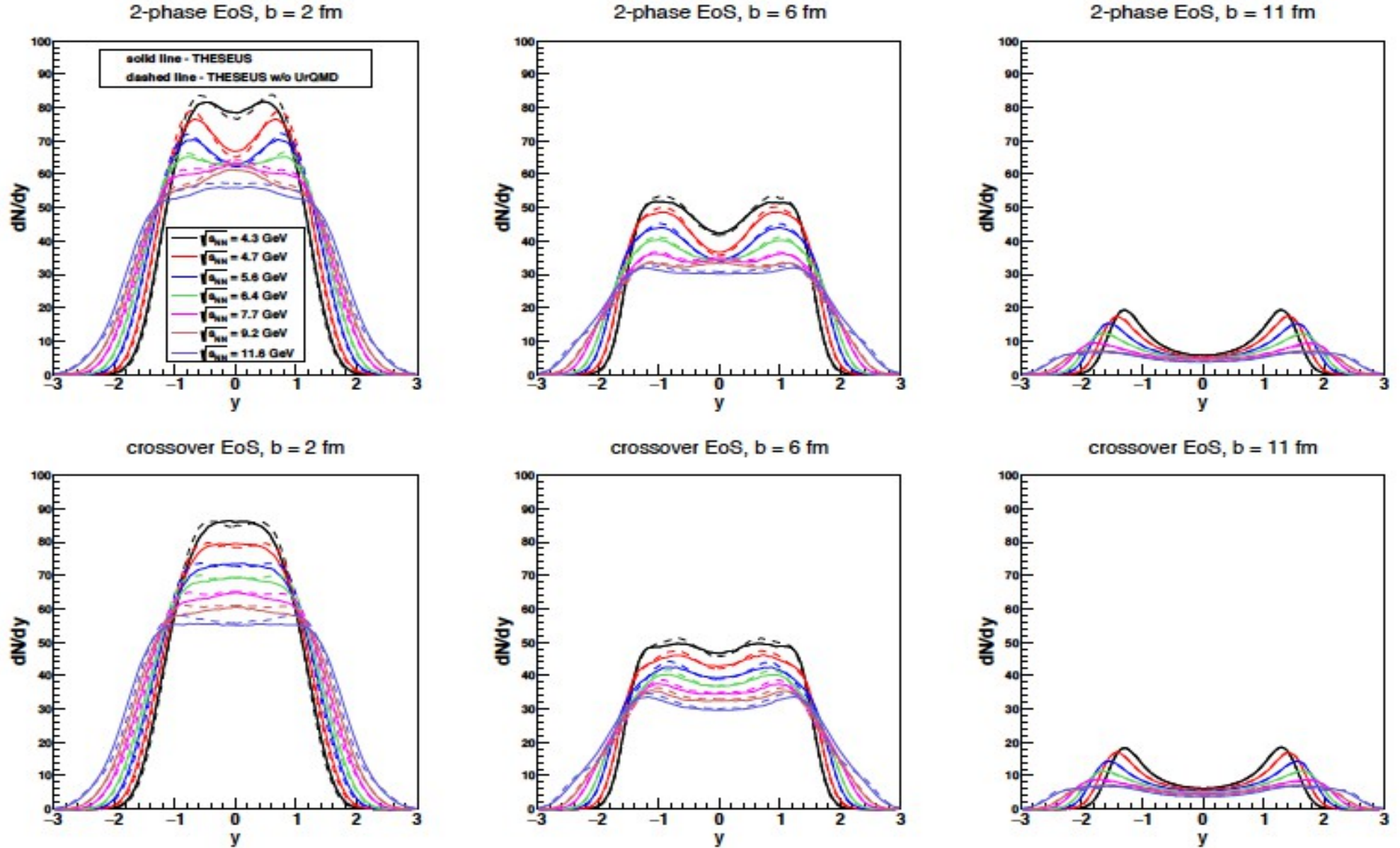
$\sqrt{s_{NN}}$ [GeV]	4.3	4.7	5.6	6.4	7.7	9.2	11.6
E_{lab} [A GeV]	8	10	15	20	30	43	70

arxiv:1608.00965

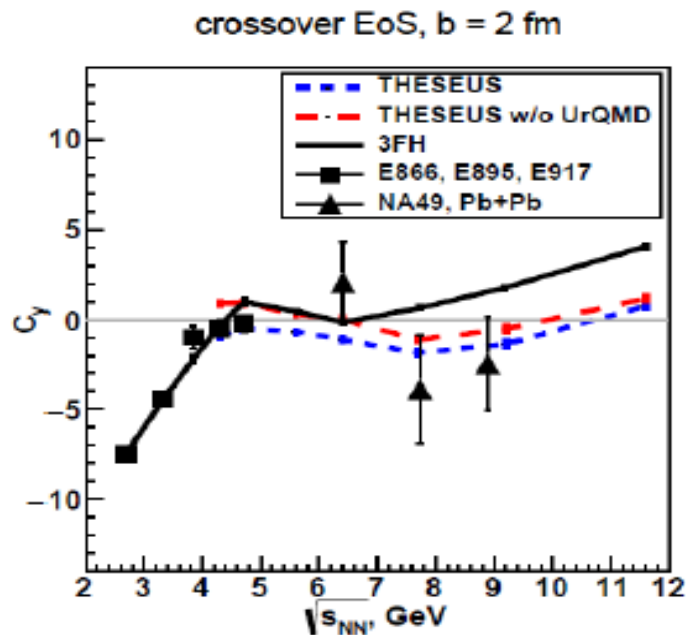
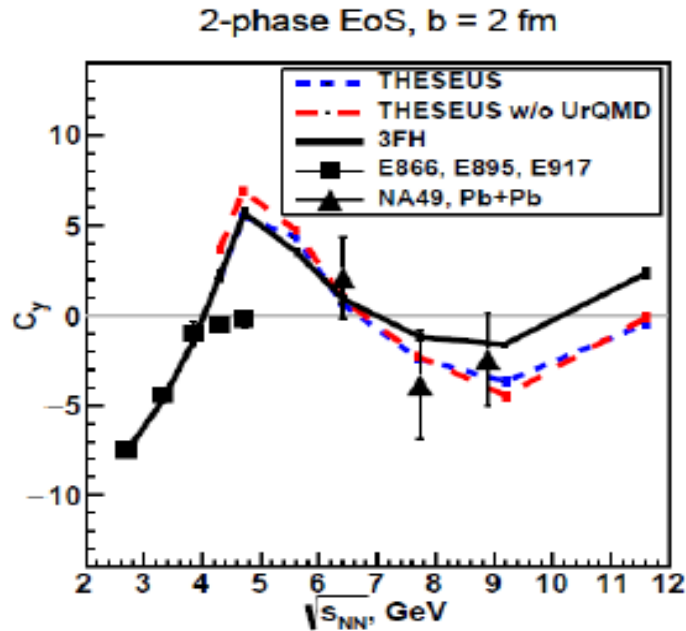


Baryon stopping signal for first order phase transition ?

Baryon stopping signal for first order phase transition ?



Baryon stopping signal for first order phase transition ?



Energy scan of the curvature C_y of the net proton
 Rapidity distribution at central rapidity y_{cm}

$$C_y = y_{cm}^2 (d^3 N_{net-p} / dy^3) / (dN_{net-p} / dy)$$

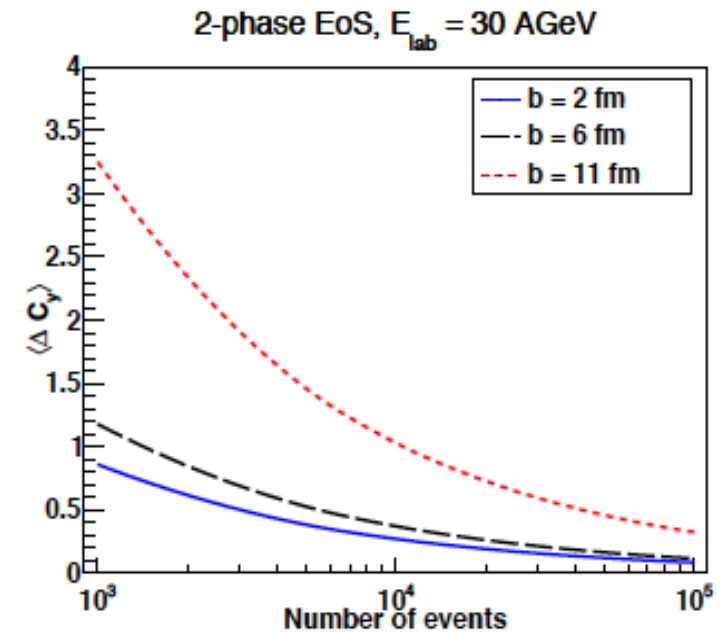
Reduced curvature calculated for a parabolic fit

$$\tilde{P}_2(y) = ay^2 + by + c \longrightarrow C_y = y_{beam}^2 2a/c$$

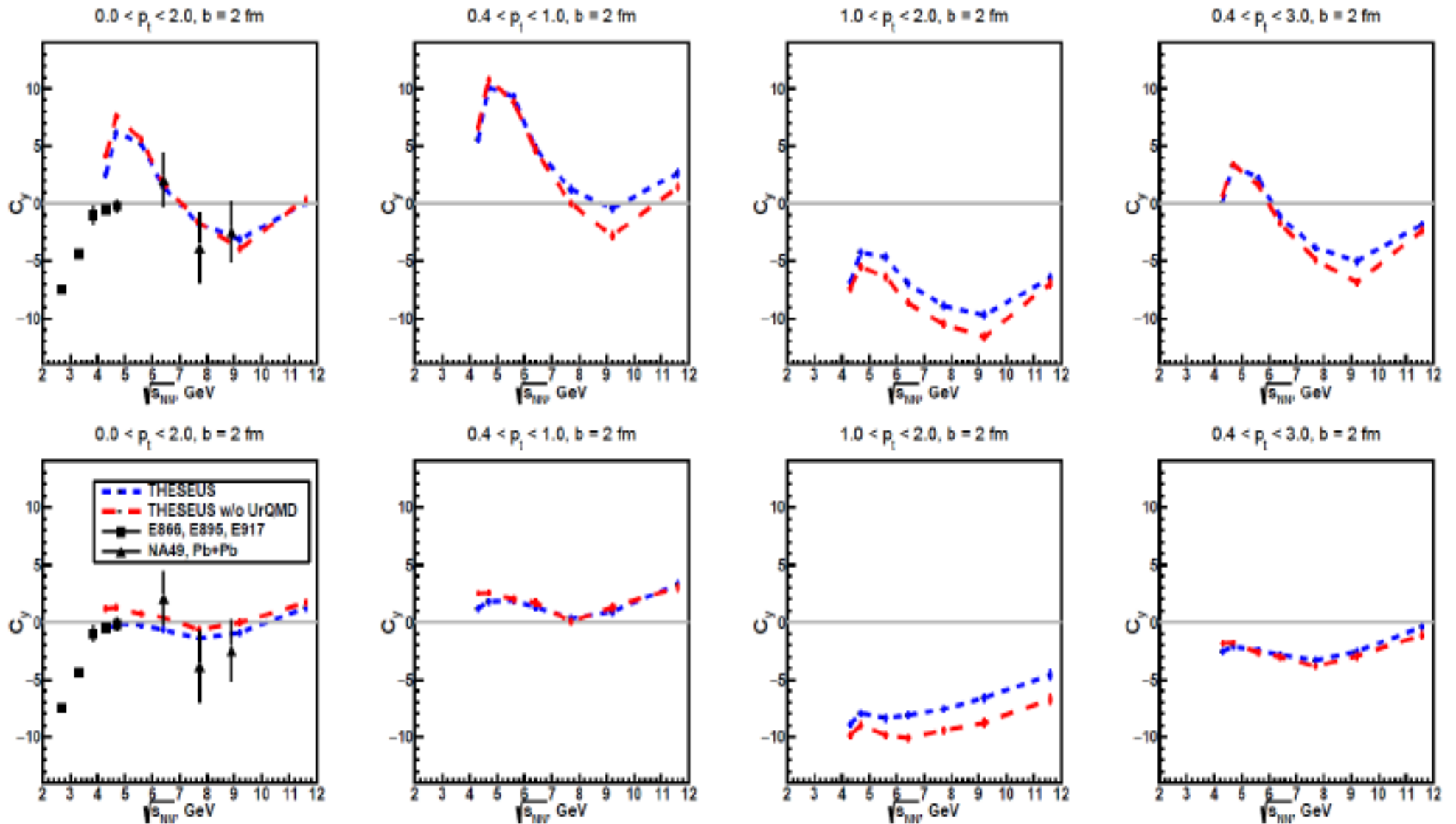
Statistical error

$$\Delta C_y = \frac{2y_{beam}^2}{c} \sqrt{(\Delta a)^2 + \frac{a^2}{c^2} (\Delta c)^2},$$

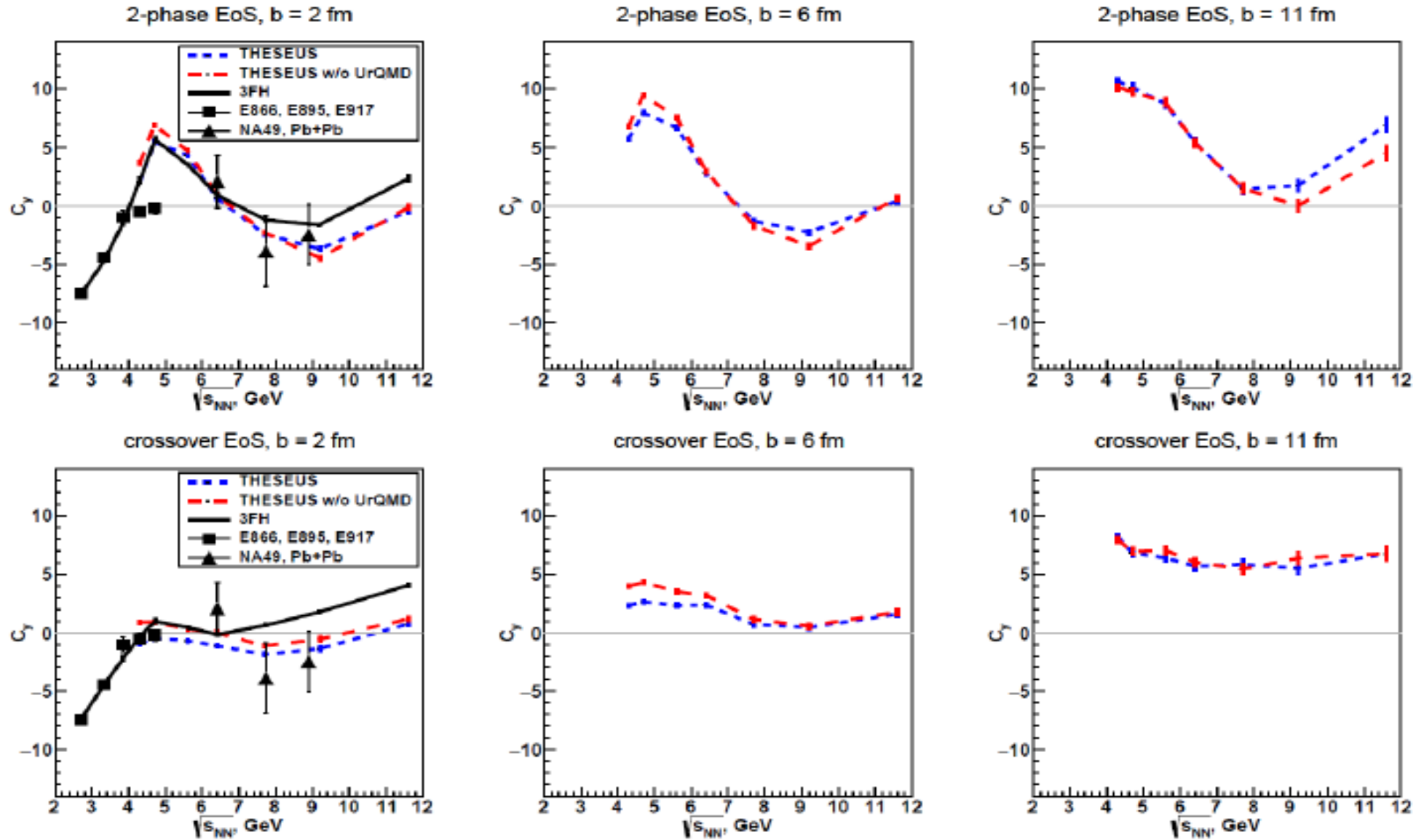
depends on number
 of events



Baryon stopping signal for first order phase transition ?

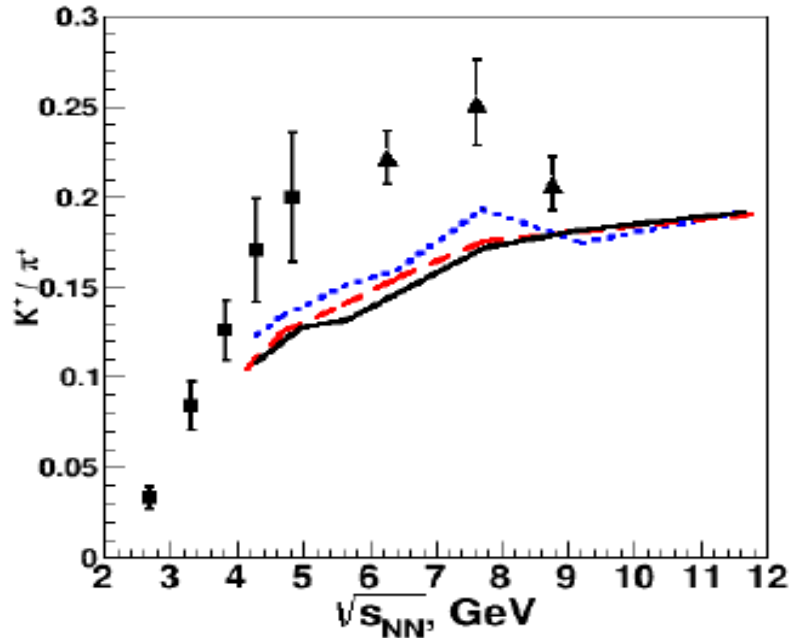


Baryon stopping signal for first order phase transition ?



What about K^+/π^+ (Marek's horn) in THESEUS ?

2-phase EoS, $b = 2$ fm



THESEUS simulation reproduces 3FH result, Thus it has the same discrepancy with experiment

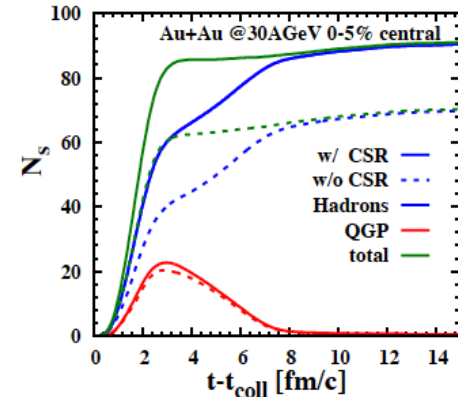
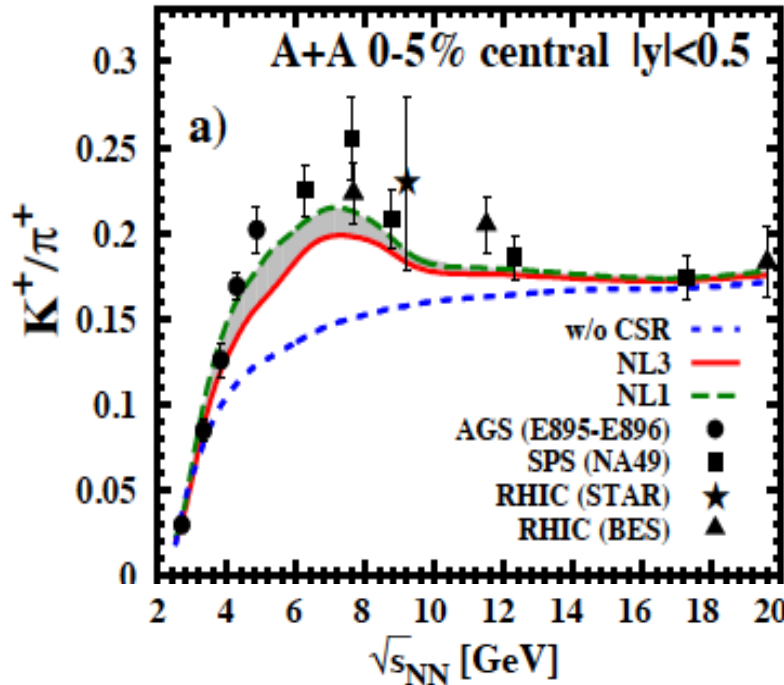
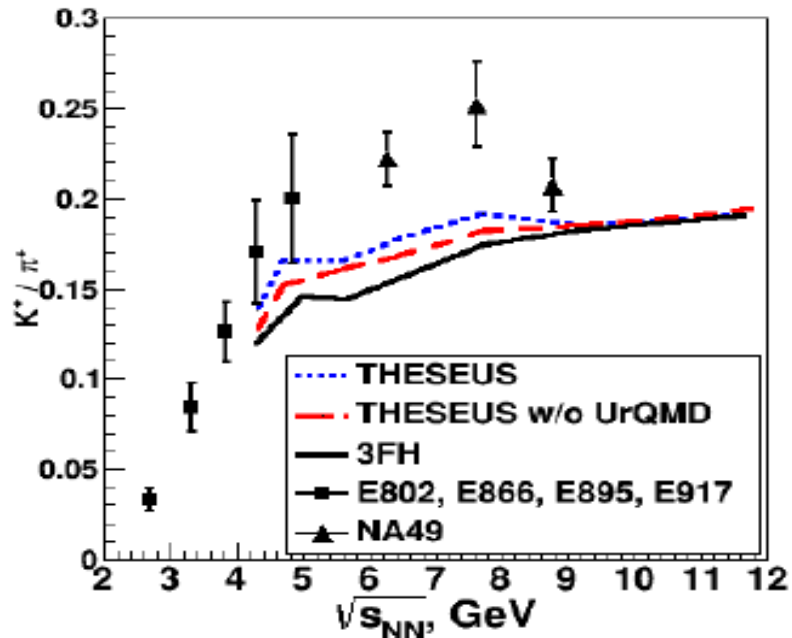
--> some key element still missing in the program

P. Batyuk, D.B., M. Bleicher et al., arxiv:1608.00965

Recent new development in PHSD

Chiral symmetry restoration in HIC at intermediate ...
A. Palmese et al., arxiv: 1607.04073

crossover EoS, $b = 2$ fm



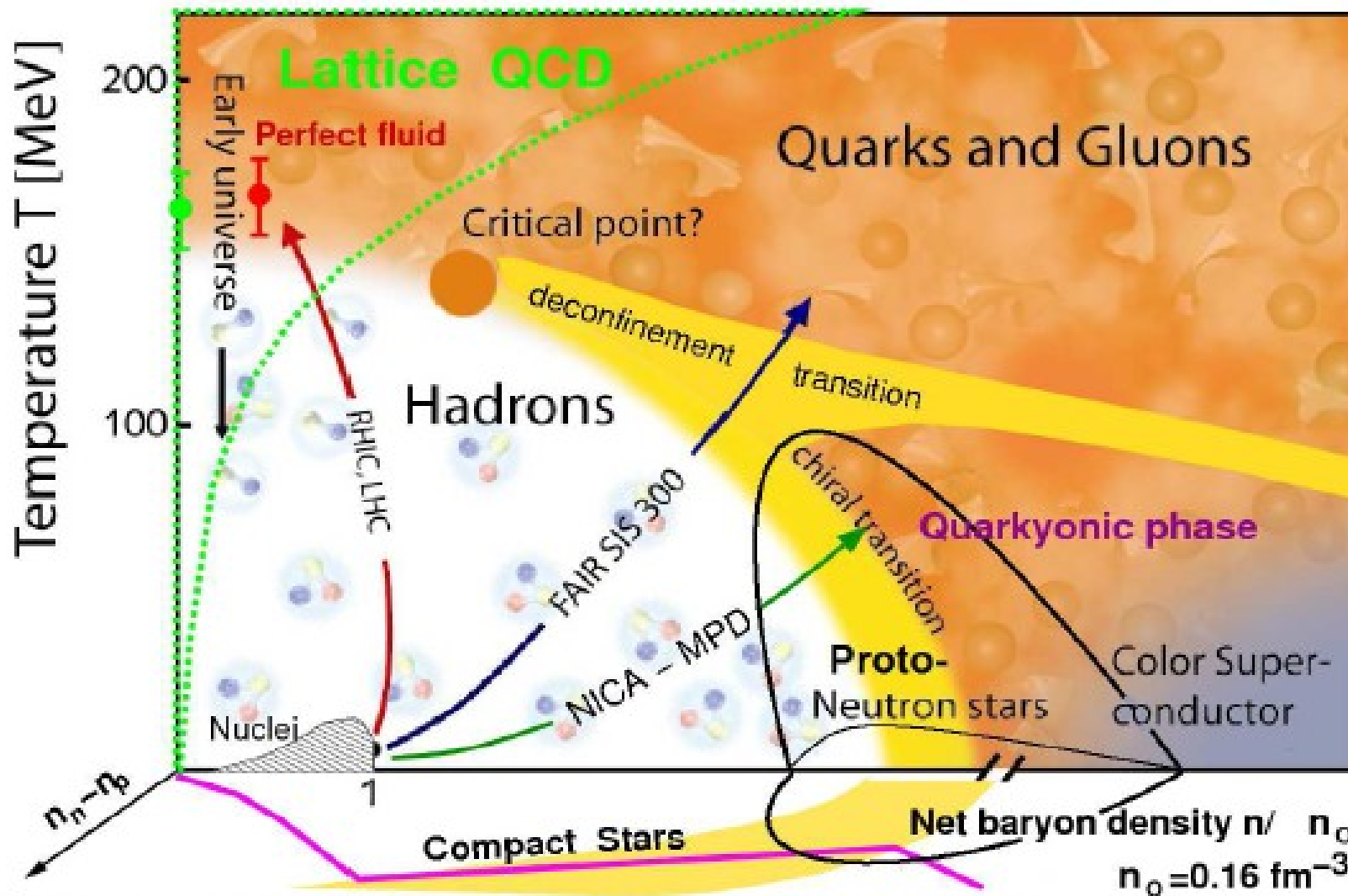
Strange particle number increase by CSR

Further developments:

- MPD Detector simulation (Oleg Rogachevsky et al.)**
- New 2-phase EoS (Wroclaw group, see talk Bastian)**

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

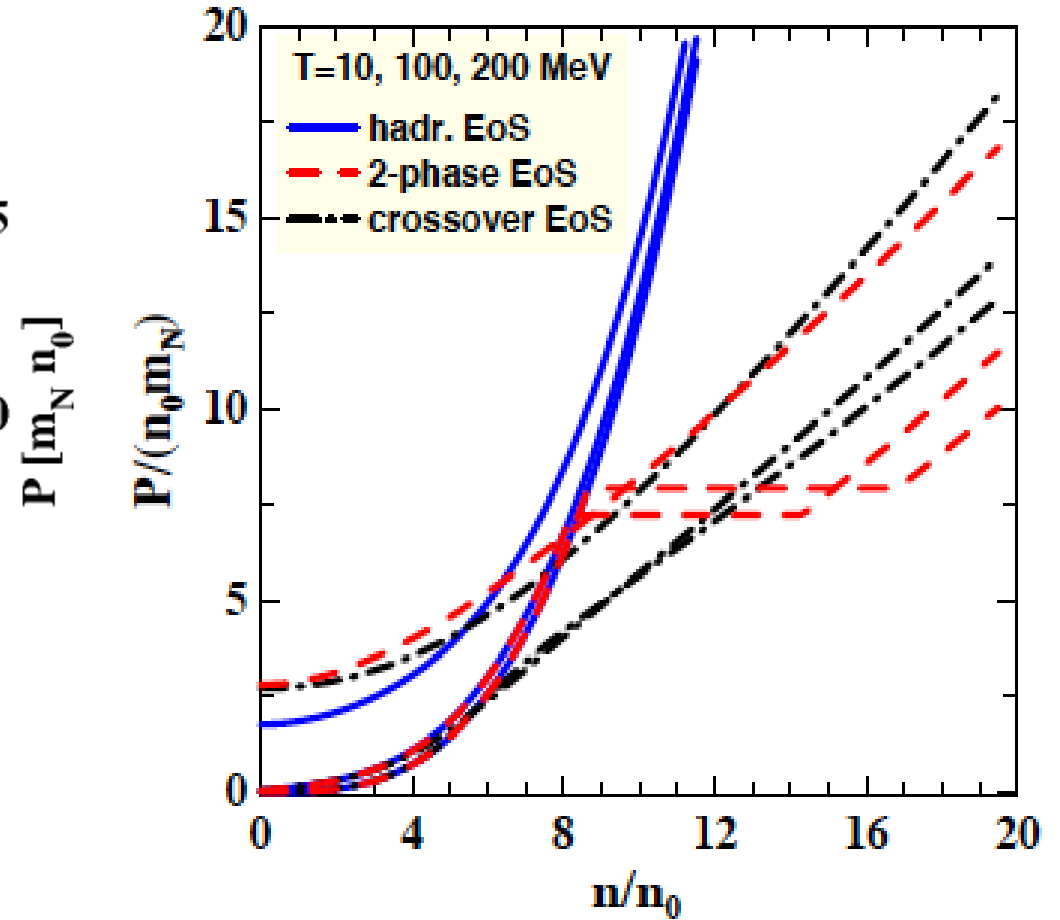
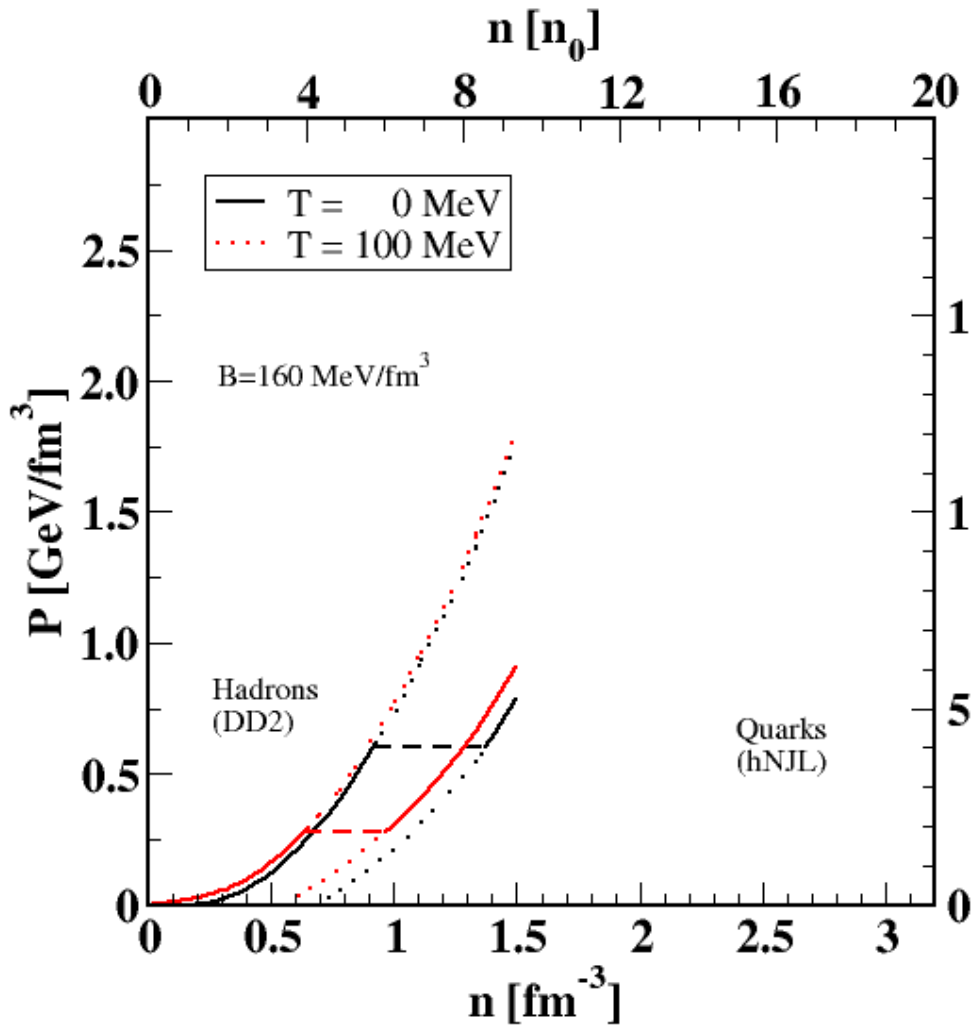
Support a CEP in QCD phase diagram with Astrophysics?



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!

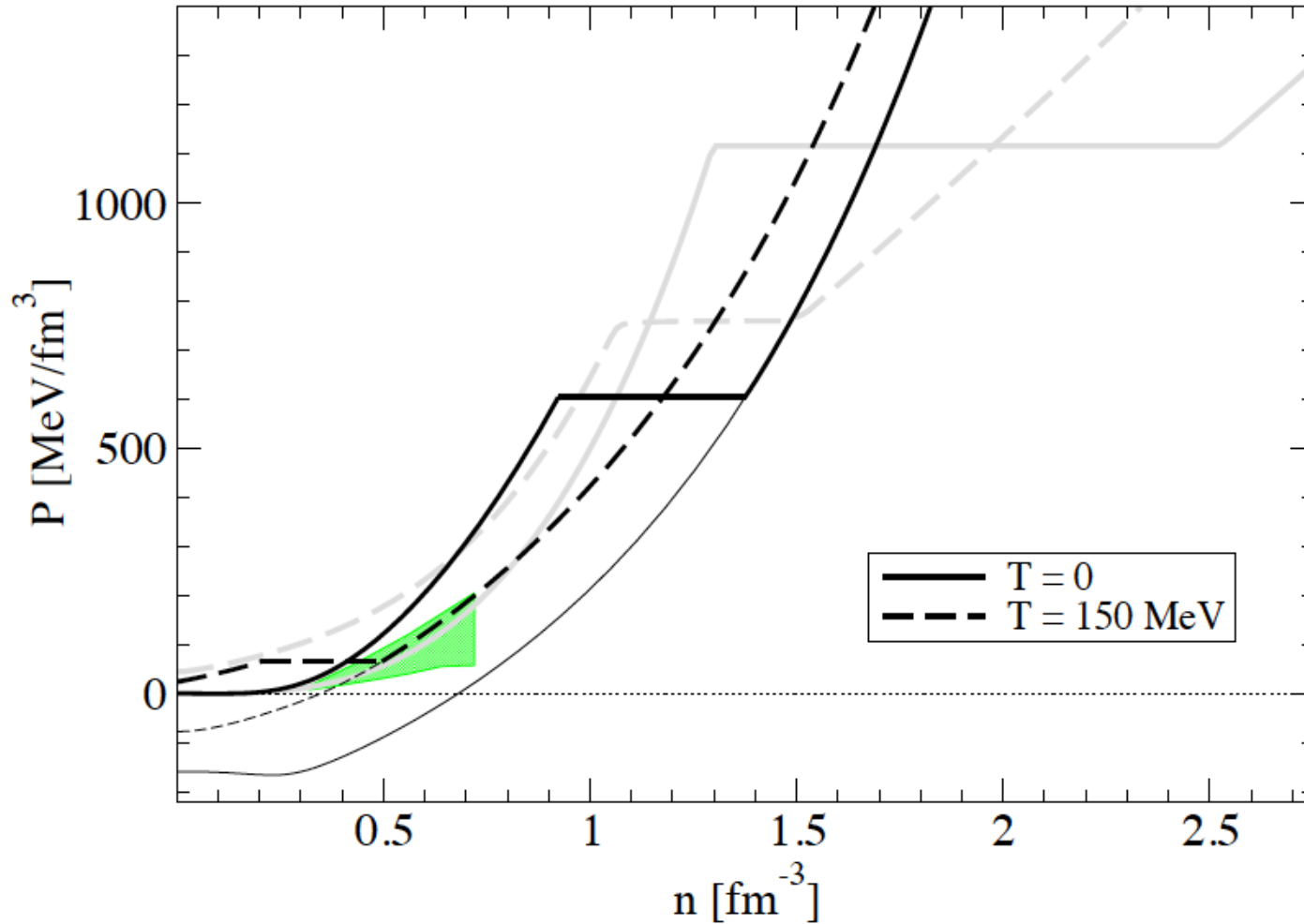
Comparison 2-phase EoS



N.-U. Bastian, D. Blaschke (S. Benic, S. Typel),
In progress (2016)

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/fm³

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 !
- UrQMD “afterburner” works too !

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



Critical Point and Onset of Deconfinement 2016

and

Working Group Meeting of COST Action MP1304

Wrocław, Poland

May 30th - June 4th, 2016



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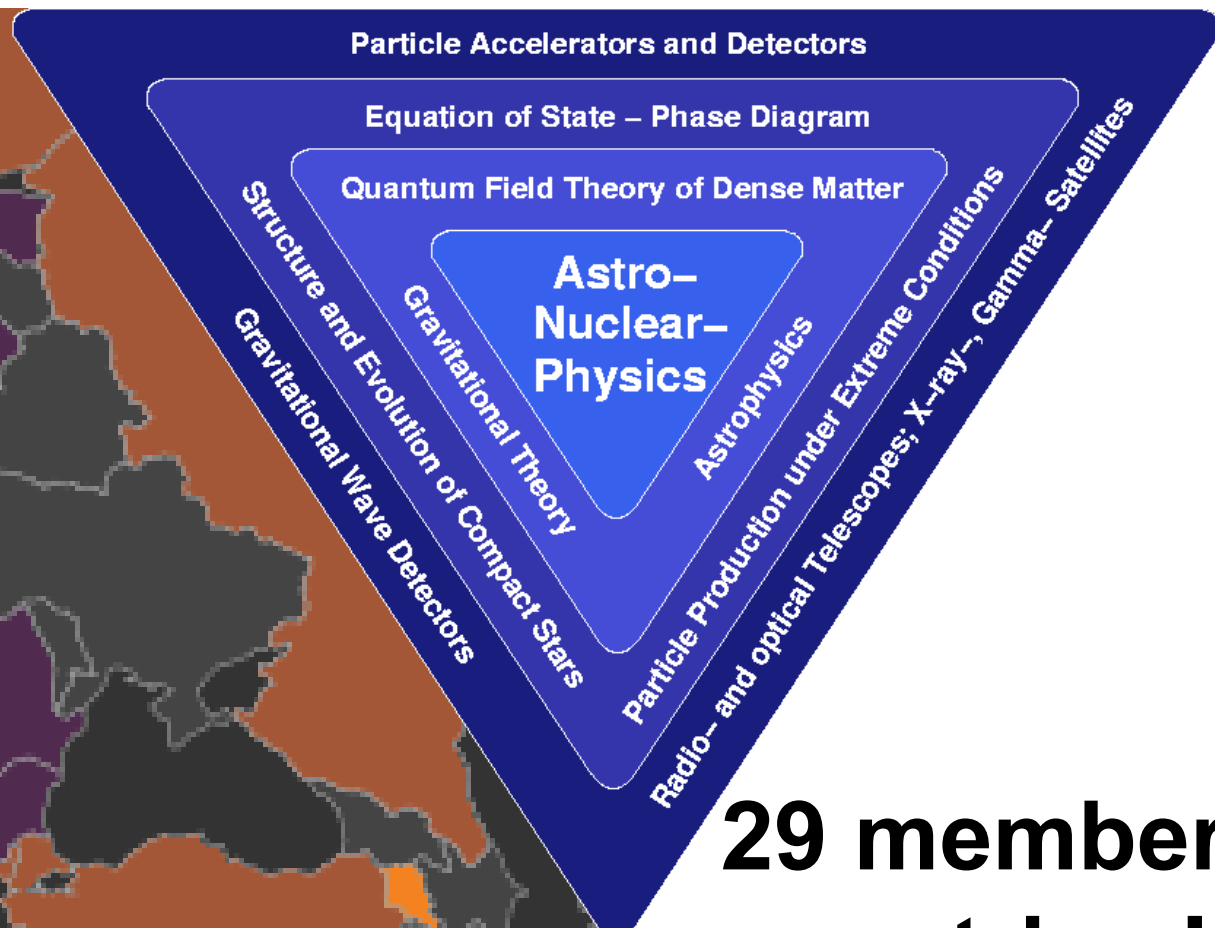
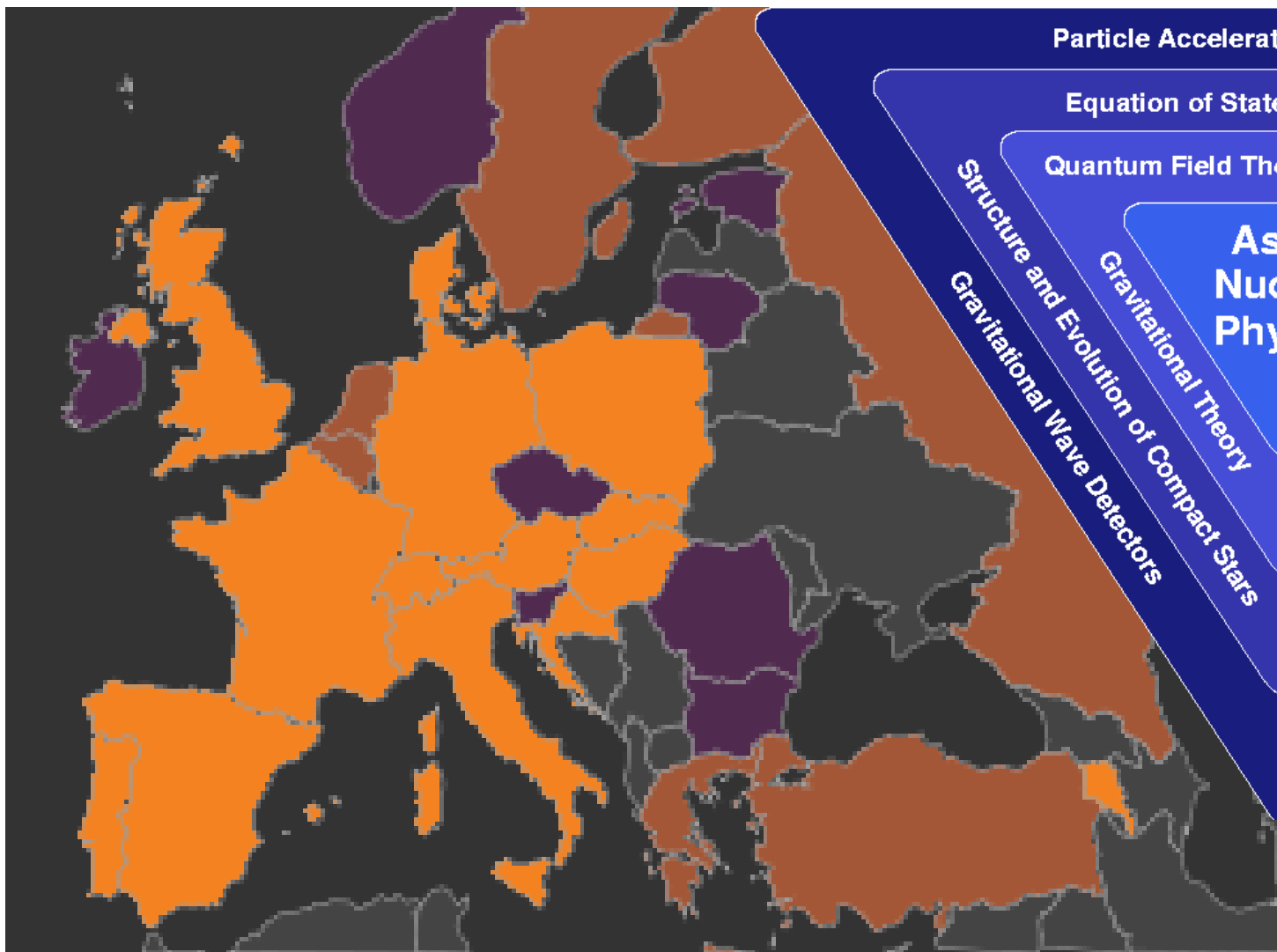


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(MP1304)**

New



Kick-off: Brussels, November 25, 2013

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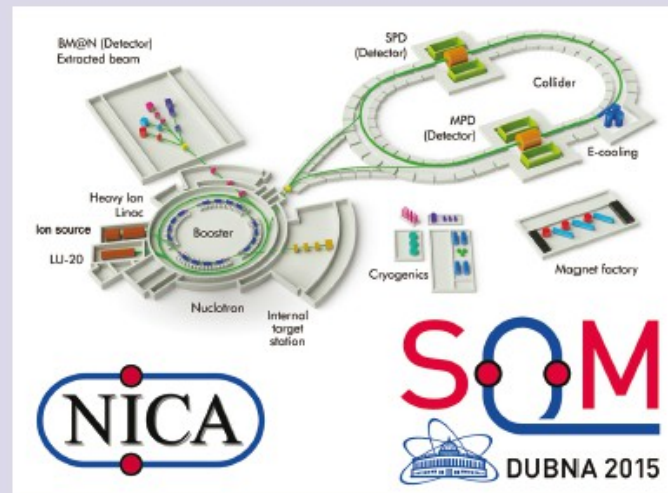
15th International Conference on Strangeness in Quark Matter (SQM2015)

Dubna, Russia
6–11 July 2015

Editors: David E. Alvarez-Castillo, David Blaschke, Vladimir Kekelidze,
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