Introduction to (selected) Physics at NICA

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0. Motivation: Astrophysics – Supernovae & BNS Mergers
1. The NICA White Paper [EPJA Topical Issue Vol. 52(8) (2016)]
2. Selected Topics
3. Event Simulation for NICA & FAIR: THESEUS
- Particlization and all that ...
- First results: Baryon stopping signal for a 1st order PT

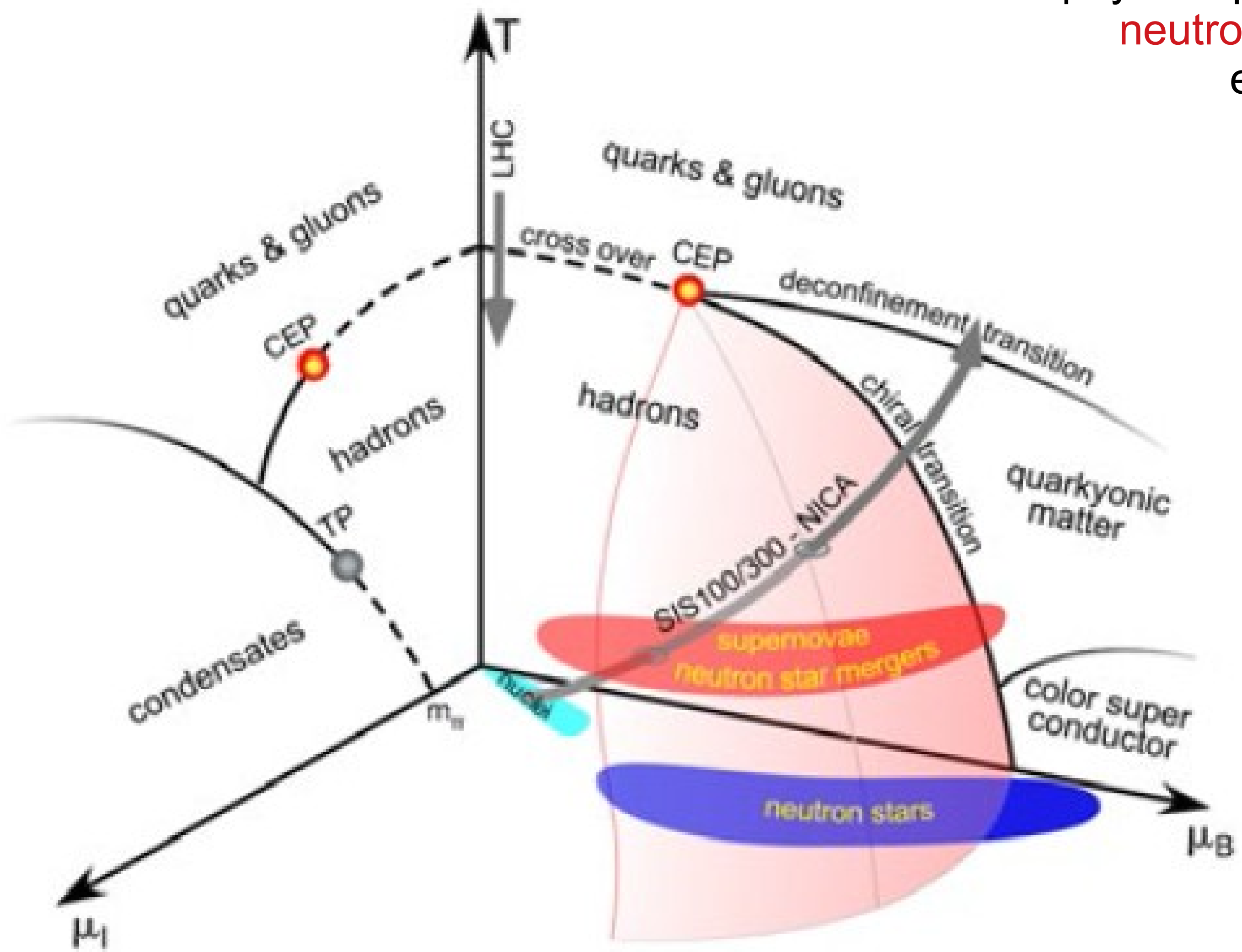
4. Further developments

3rd Collab. Meeting of BMaN and MPD at NICA, Dubna, 16.-17.04.2019

JINR DUBNA · MEPhI · Narodowe Centrum Nauki · Uniwersytet Wrocławski · COST European Cooperation in Science and Technology · HIC for FAIR Helmholtz International Center

The QCD Phase Diagram

Conjectured Phase Diagram highlighting the role of astrophysical phenomena like supernovae, neutron stars and their mergers for exploring the phase boundary Limiting the hadronic Matter phase.



New:

Evidence for strong Phase transition from Existence of exploding Massive blue supergiants (M~50 M_sun)

T. Fischer et al., Nature Astronomy 2 (2018) 960

From: “NuPECC Long Range Plan 2017”; http://www.nupecc.org

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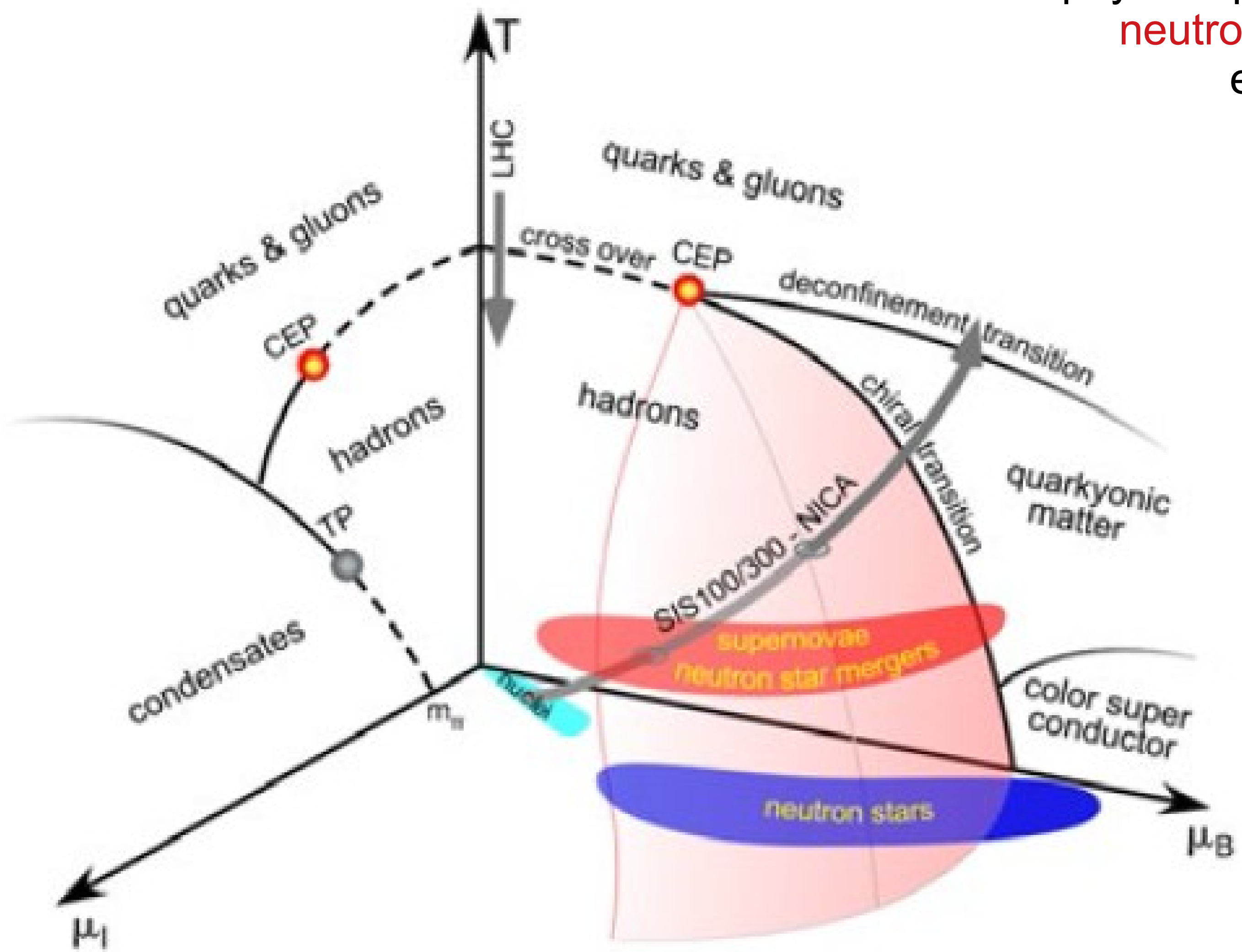

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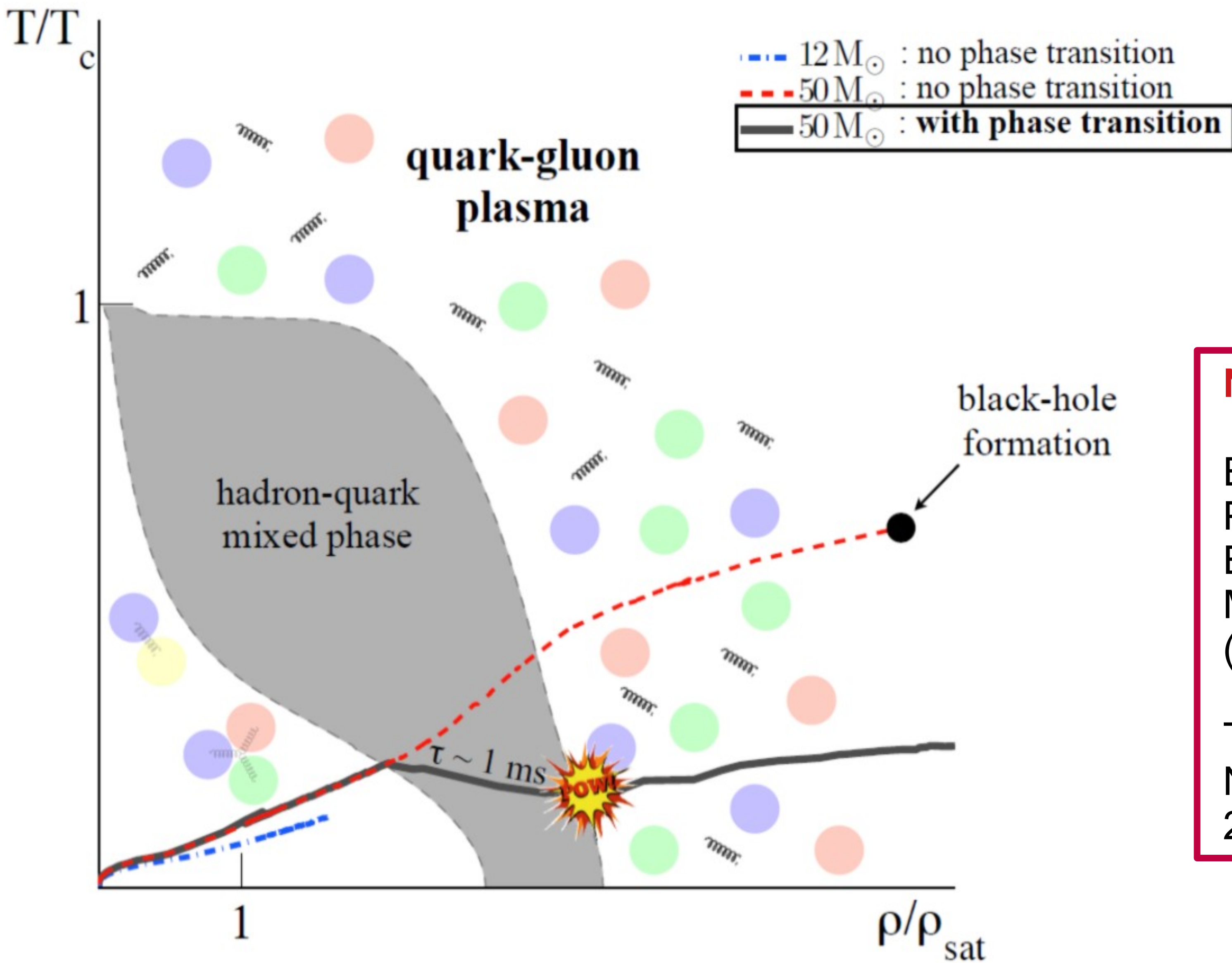
Phase diagram from relativistic density functional for hadronic (DD2F) & quark matter (SFM)



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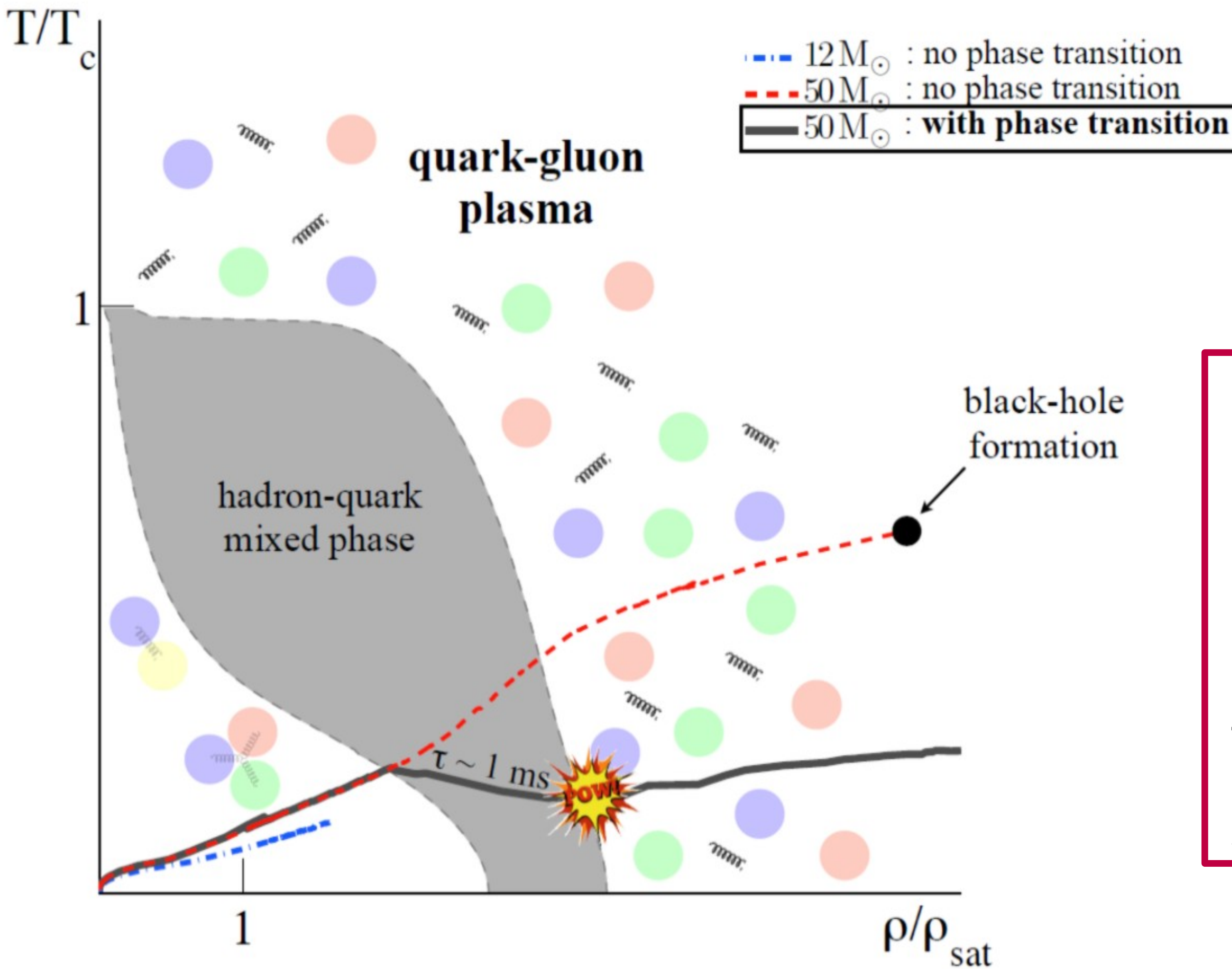

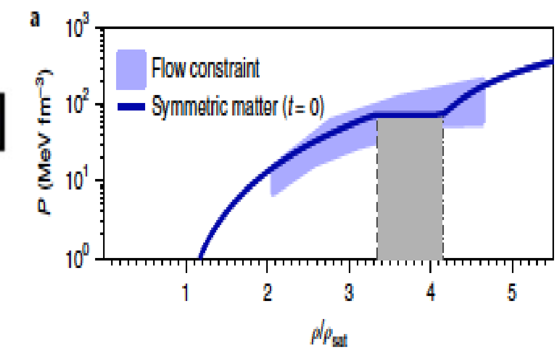

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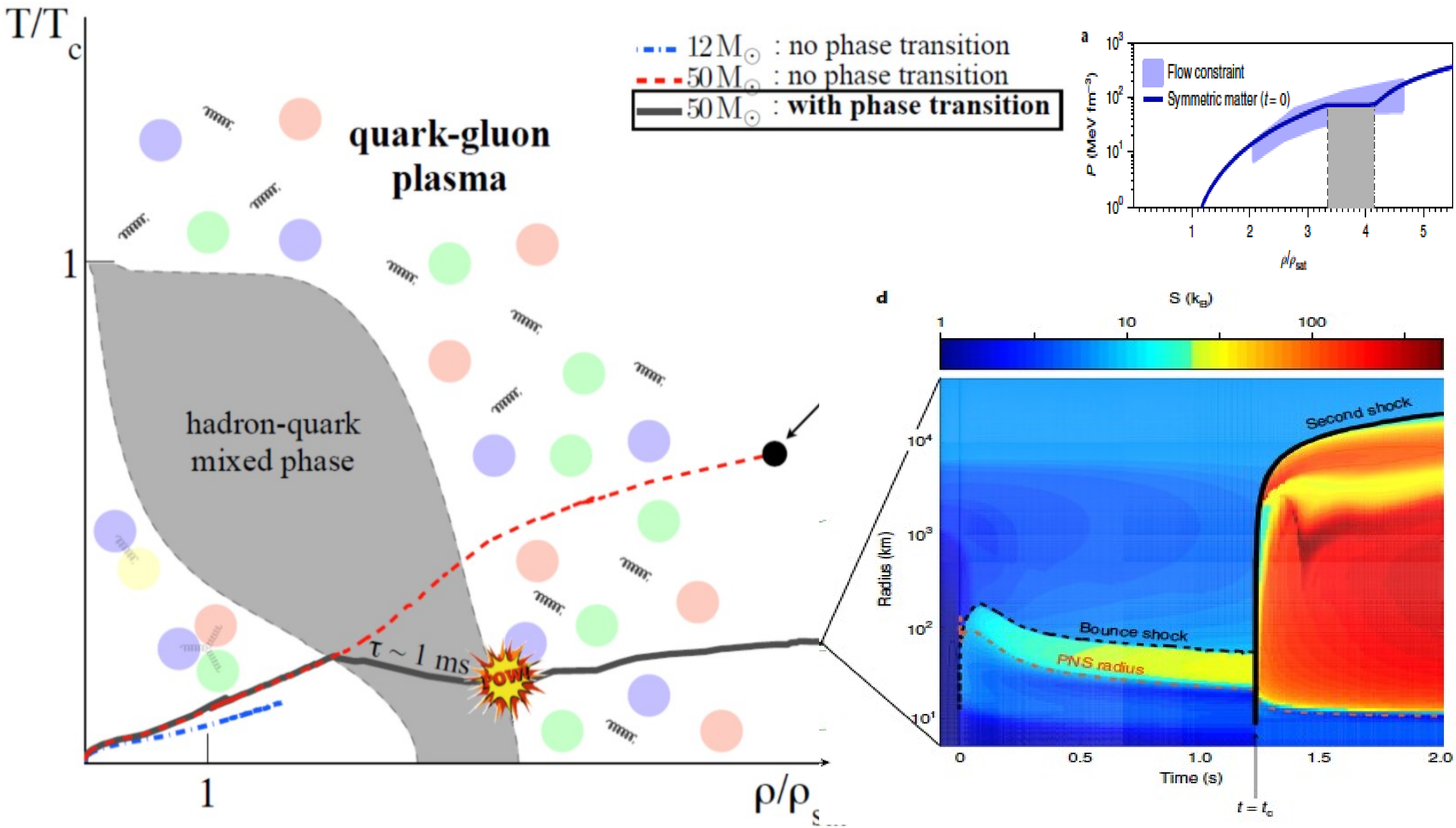
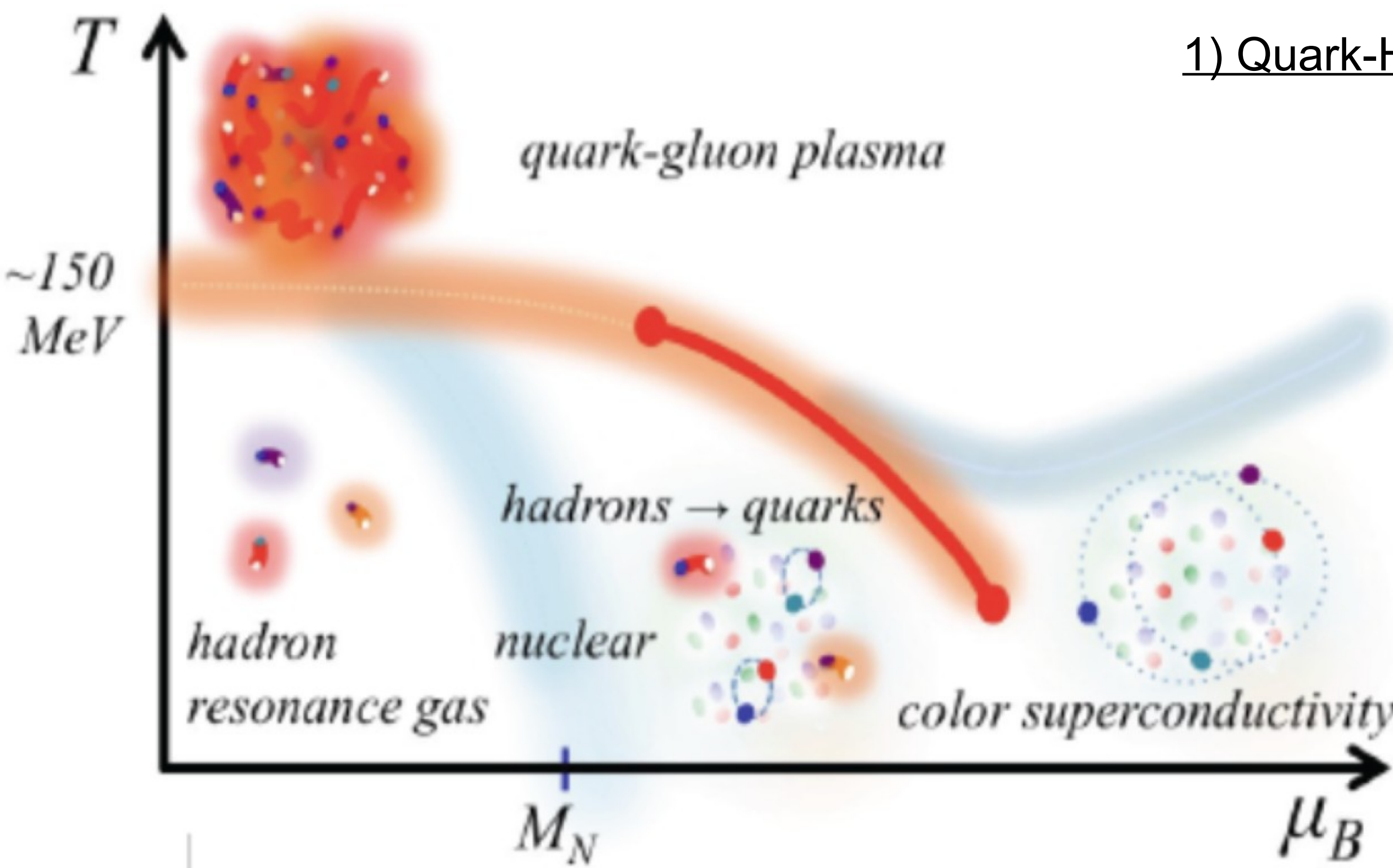


The QCD Phase Diagram

If the transition looks like a crossover – what can it mean ??



1) Quark-Hadron continuity (duality)

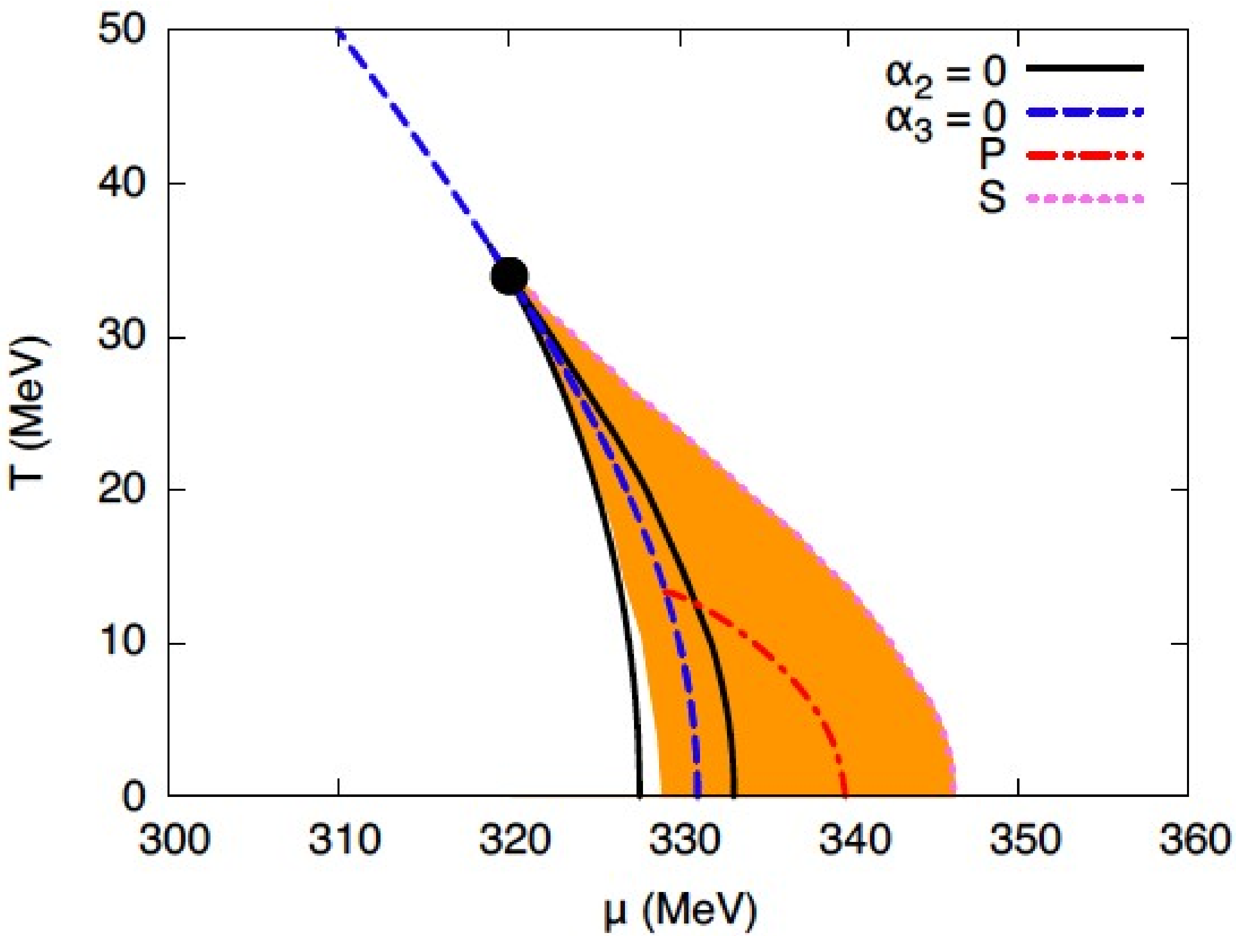
Schaefer – Wilczek
Wetterich
Baym – Hatsuda et al.

Interplay of:
Hadrons (ChSB) &
Quark pairing (CSC)

The QCD Phase Diagram

If the transition looks like a crossover – what can it mean ??

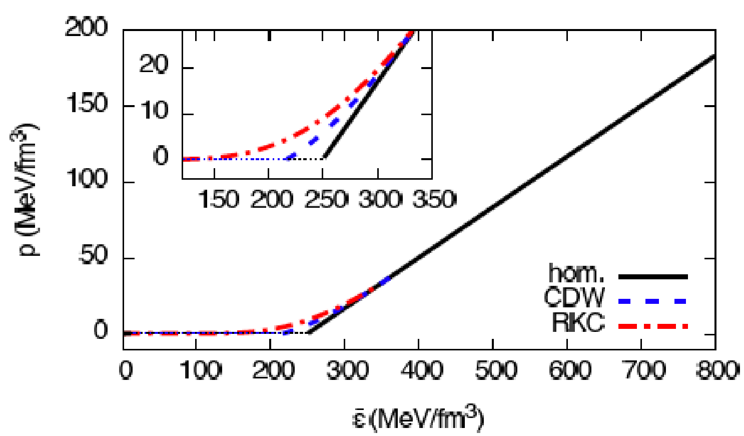
2) Inhomogeneous chiral condensates (ICC)



Buballa – Carignano
Arxiv:1809.10066

RKC – real kink crystal
CDW – chiral density wave

CEP → PLP
(Pseudo Lifshitz Point)



Buballa & Carignano, arxiv:1508.04361

The QCD Phase Diagram

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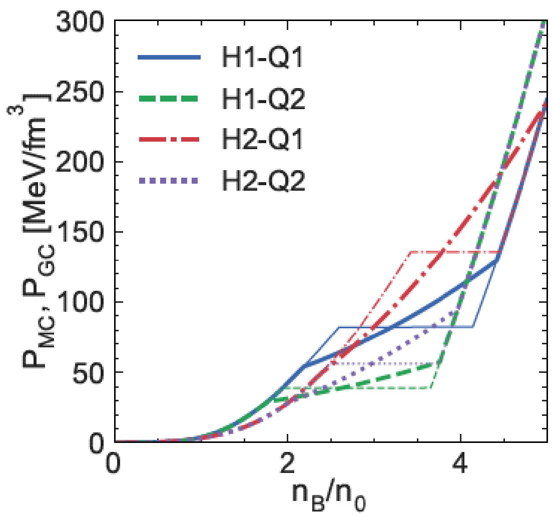
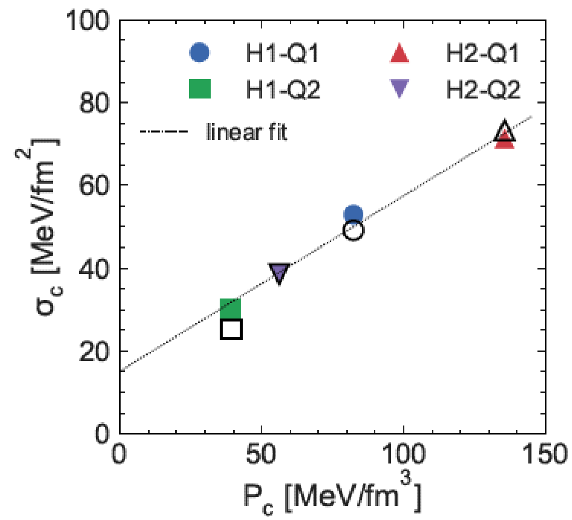


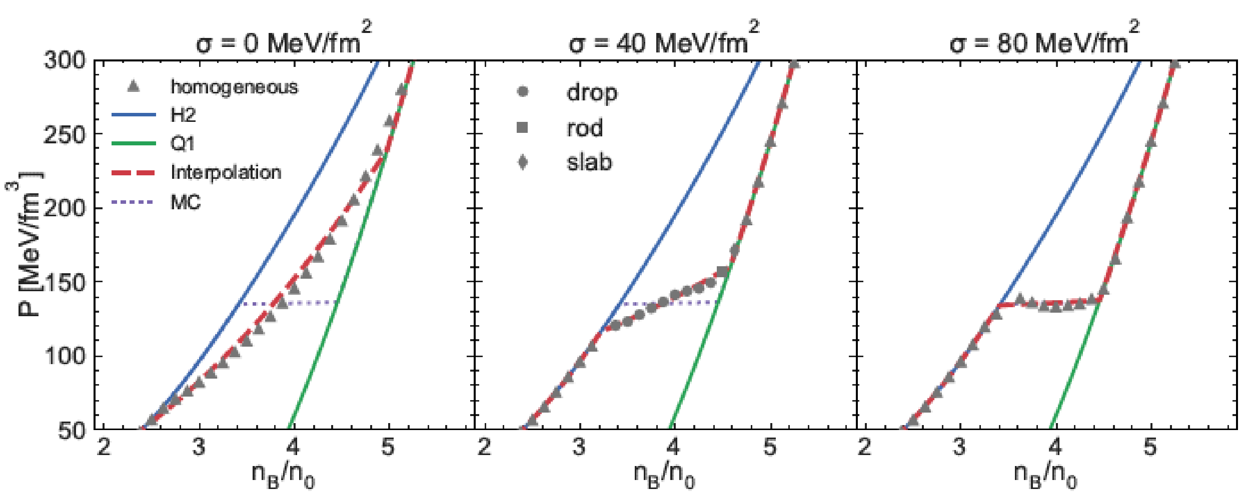


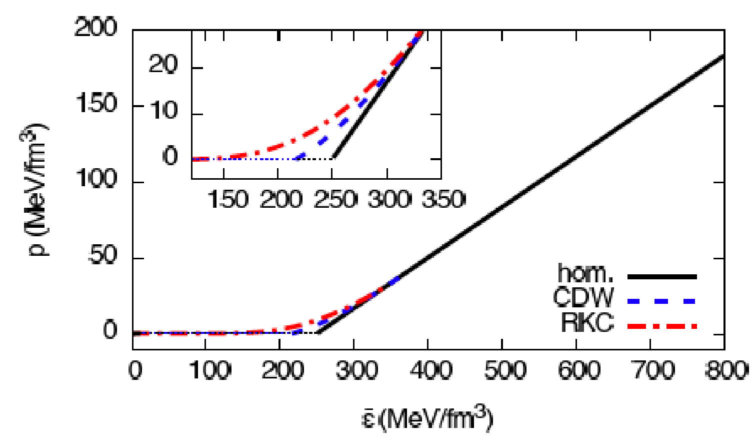
3) Structured mixed phase (pasta)

Yasutake et al.
Arxiv:1812.11889

surface tension effects:
sigma =0 : Gibbs construction
sigma > sigma_c : Maxwell constr.

Similarity with ICC



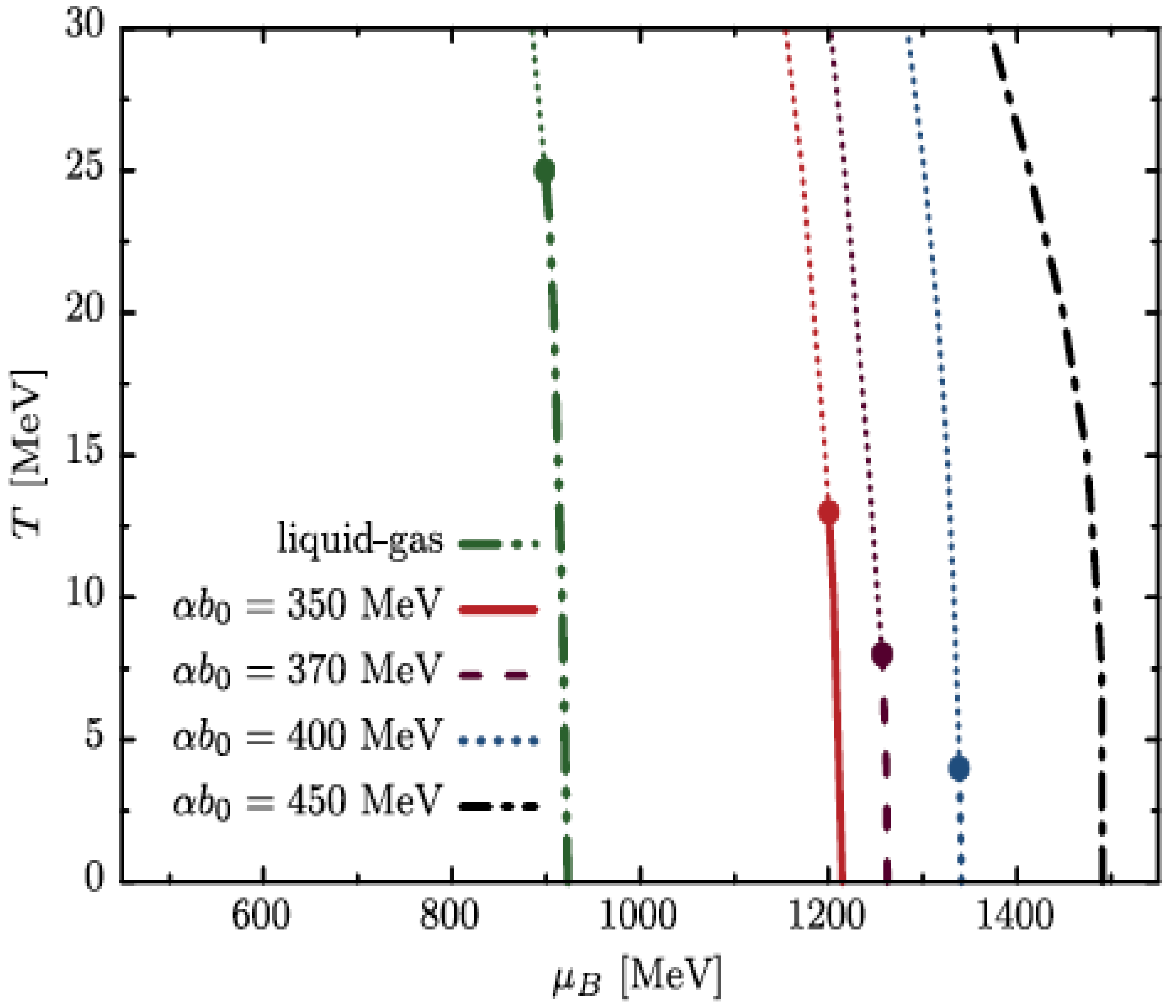


Buballa & Carignano, arxiv:1508.04361

The QCD Phase Diagram

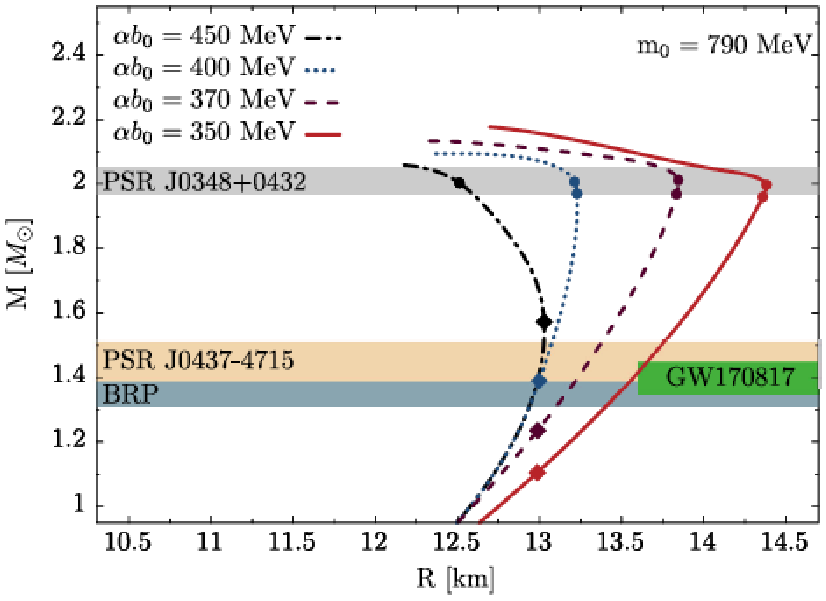
If the transition looks like a crossover – what can it mean ??

4) Parity doubling (equal mass for chiral partners)



Marczenko et al.
PRD 98 (2018) 103021
crossover or weak 1st order PT
Fulfills neutron star constraints

Purely hadronic matter!



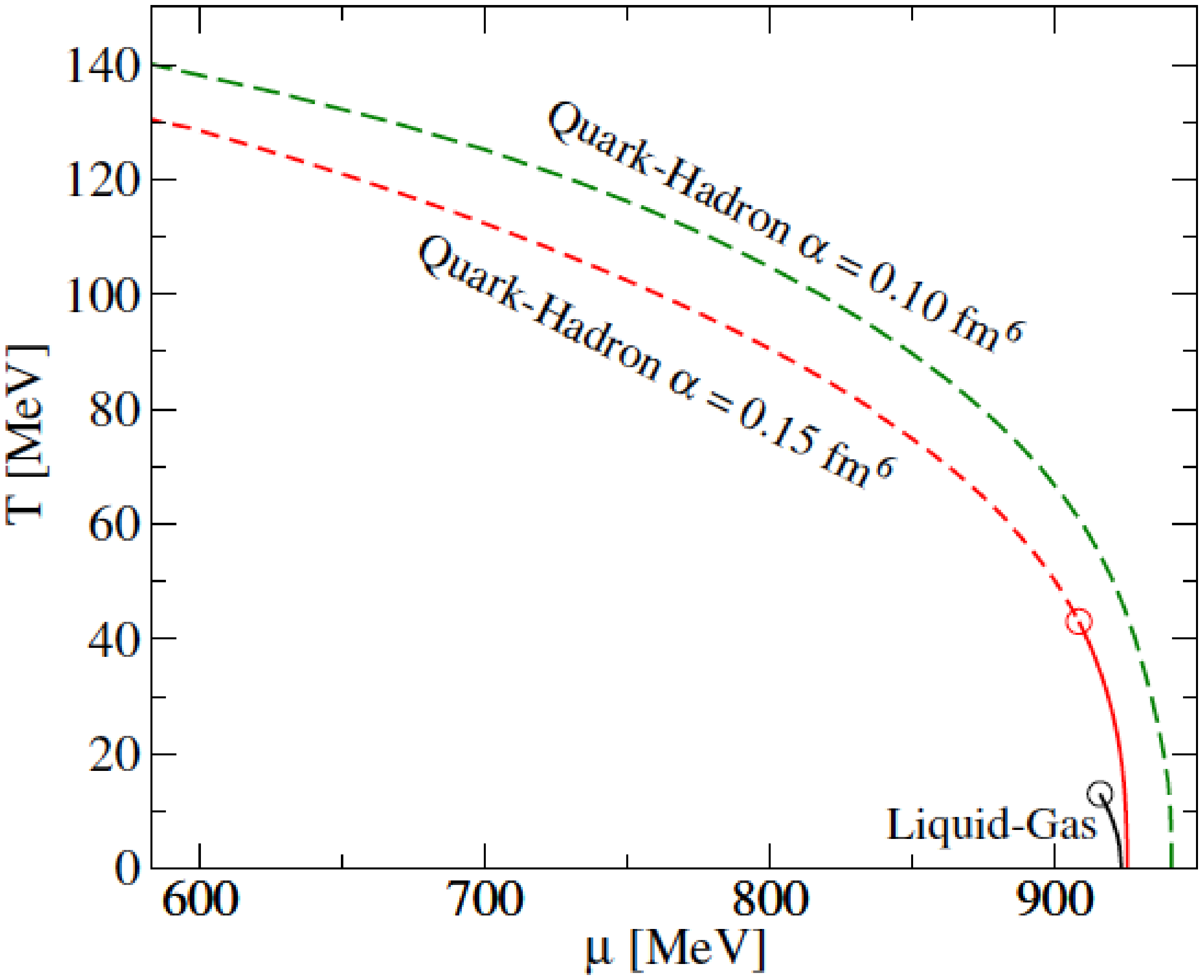
The QCD Phase Diagram

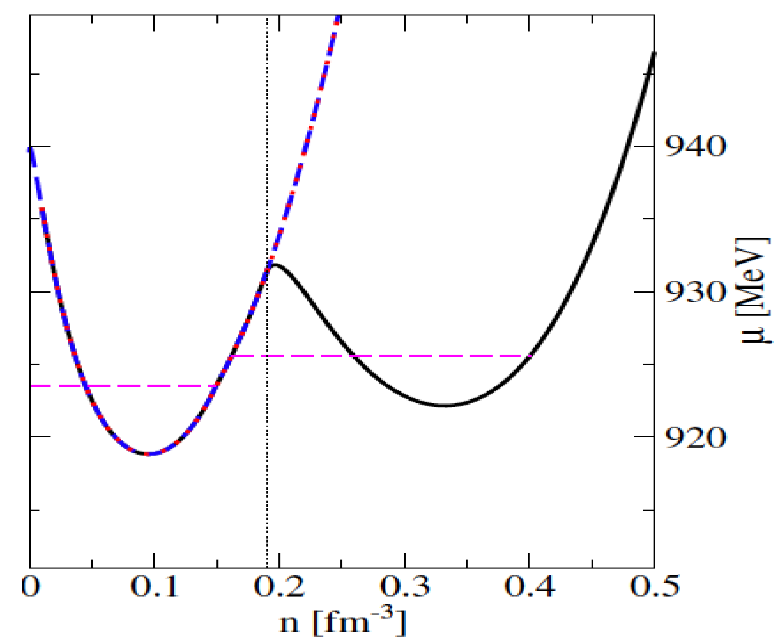
If the transition looks like a crossover – what can it mean ??

<u>5) Unified quark-hadron matter model</u>

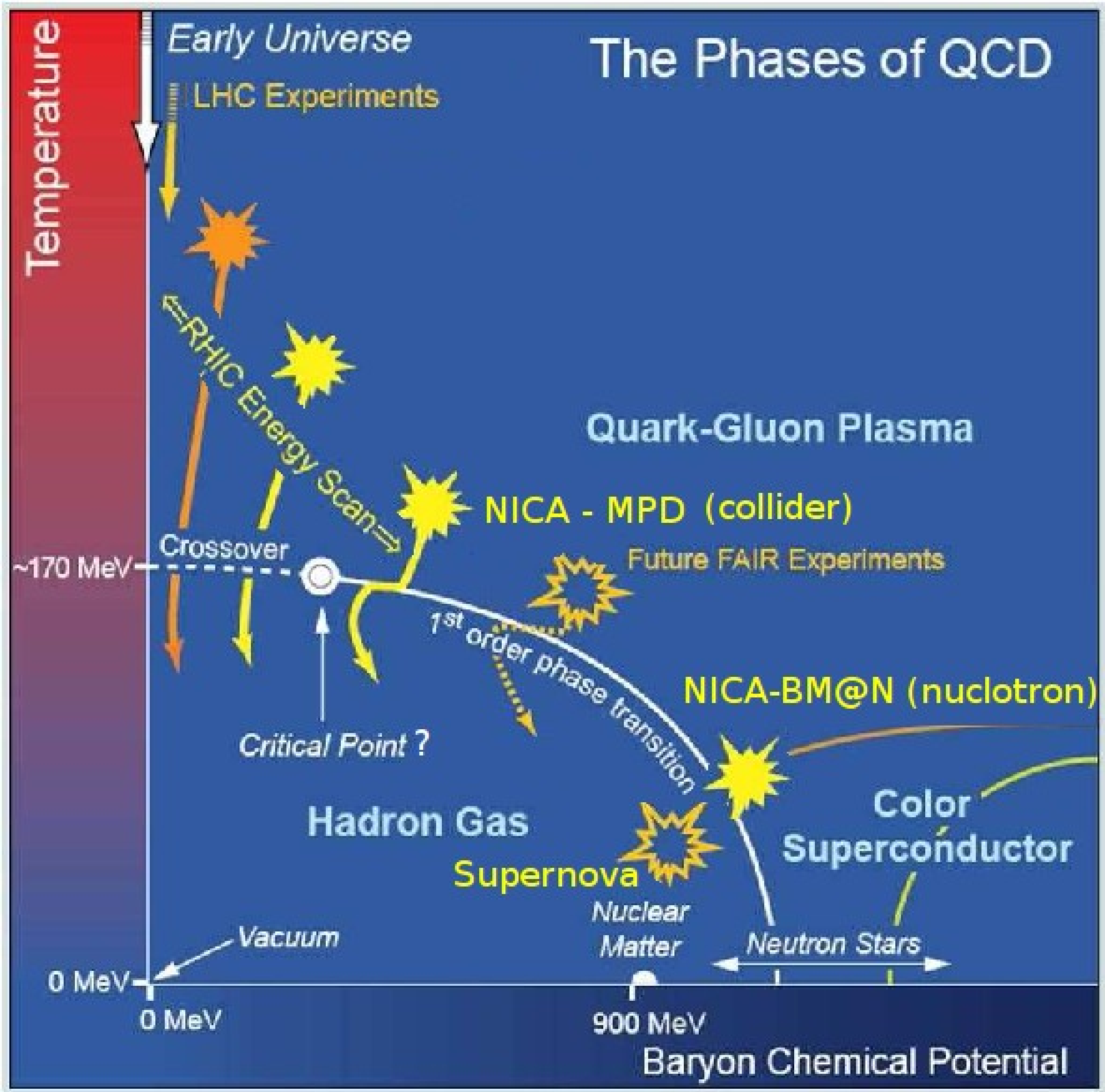
Bastian & Blaschke
Arxiv:1812.11766
crossover or 1st order PT + L-G

Mott transition for hadrons!





The Goal: Theory of the QCD Phase Diagram



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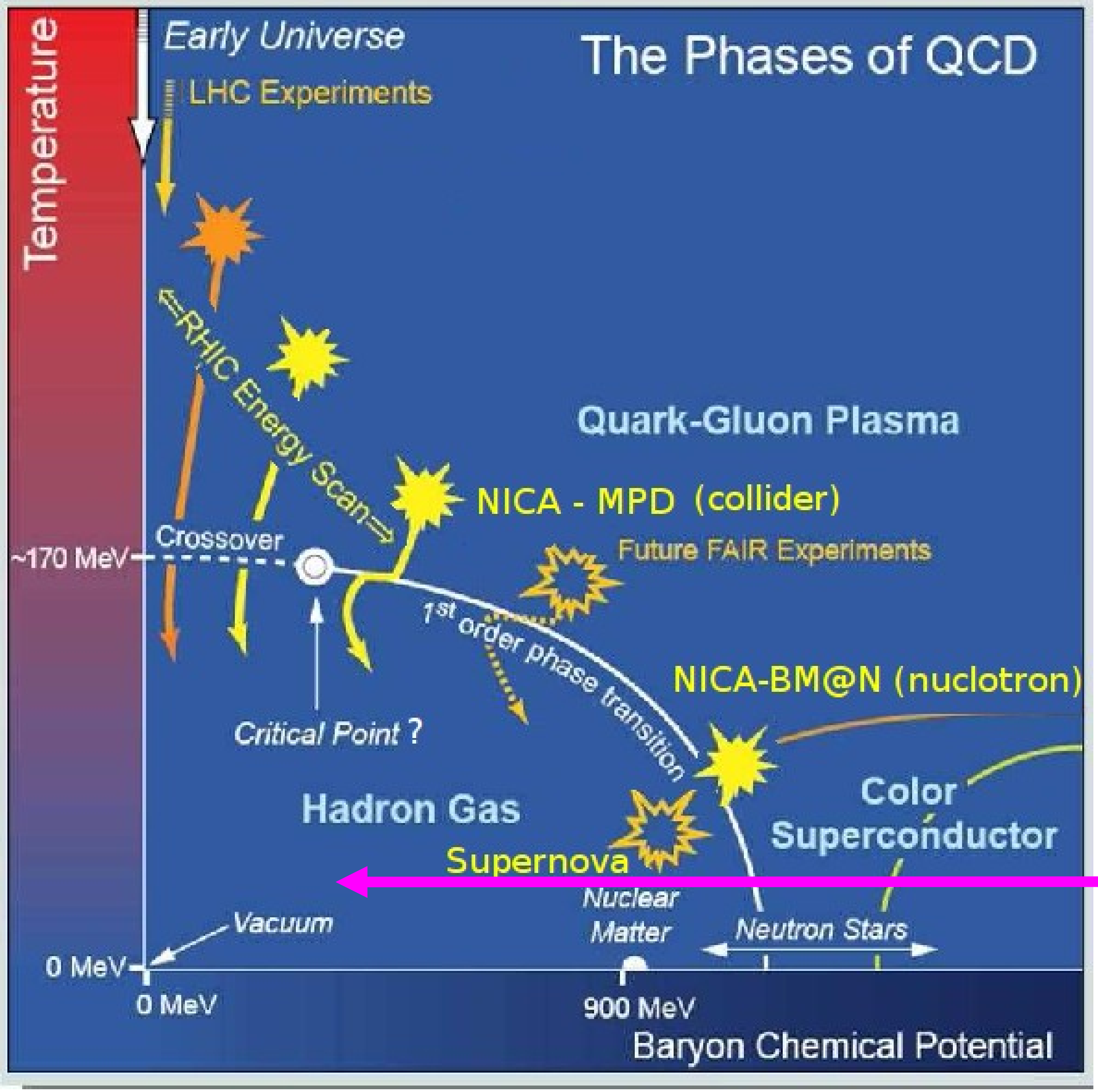
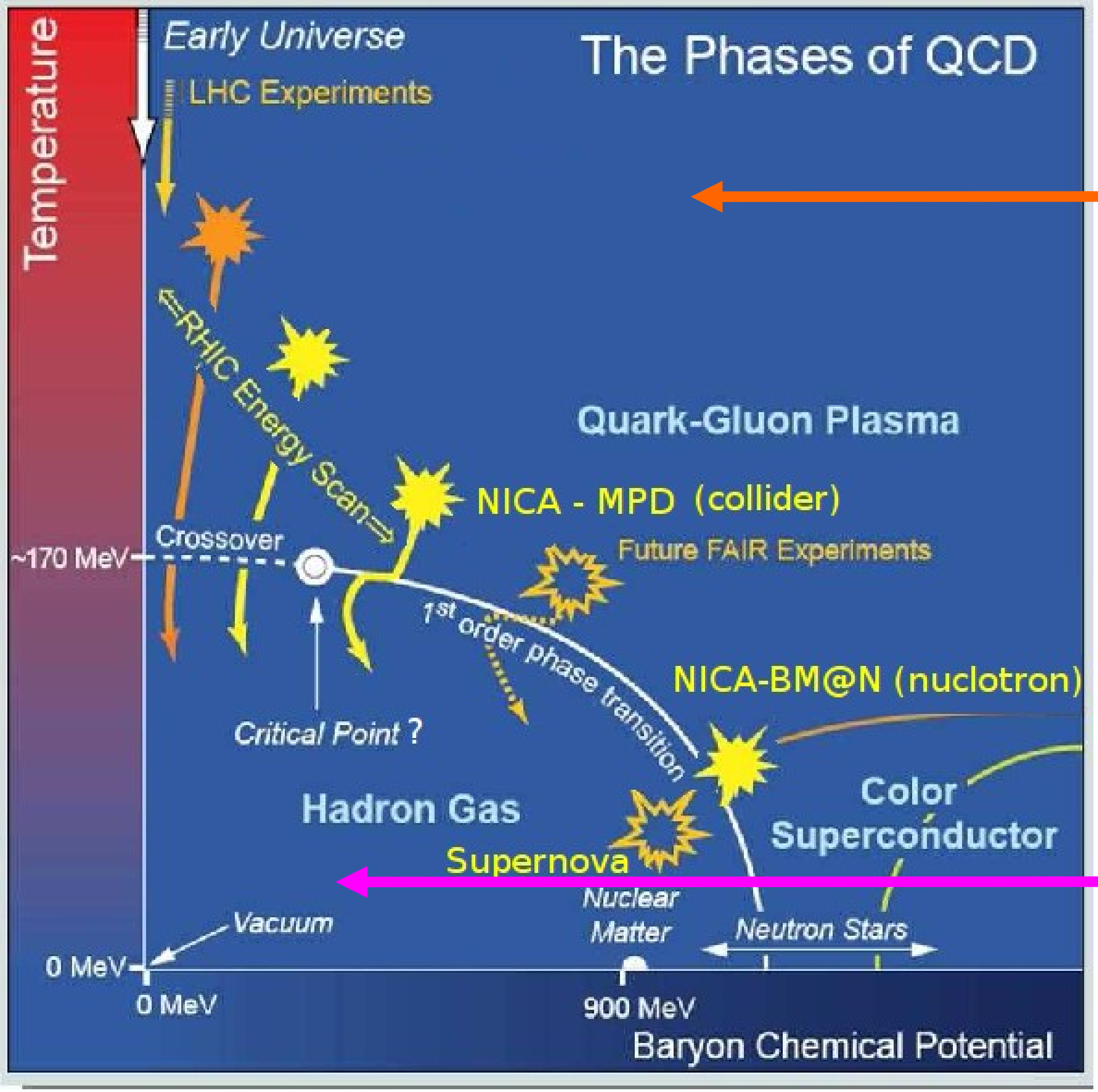


Statistical Model of Hadron Resonance Gas

Well established for Description of chemical freezeout

The Goal: Theory of the QCD Phase Diagram



Perturbative QCD

Approximately selfconsistent HTL resummation
(T > 2.5 Tc , μ > 1500 MeV)

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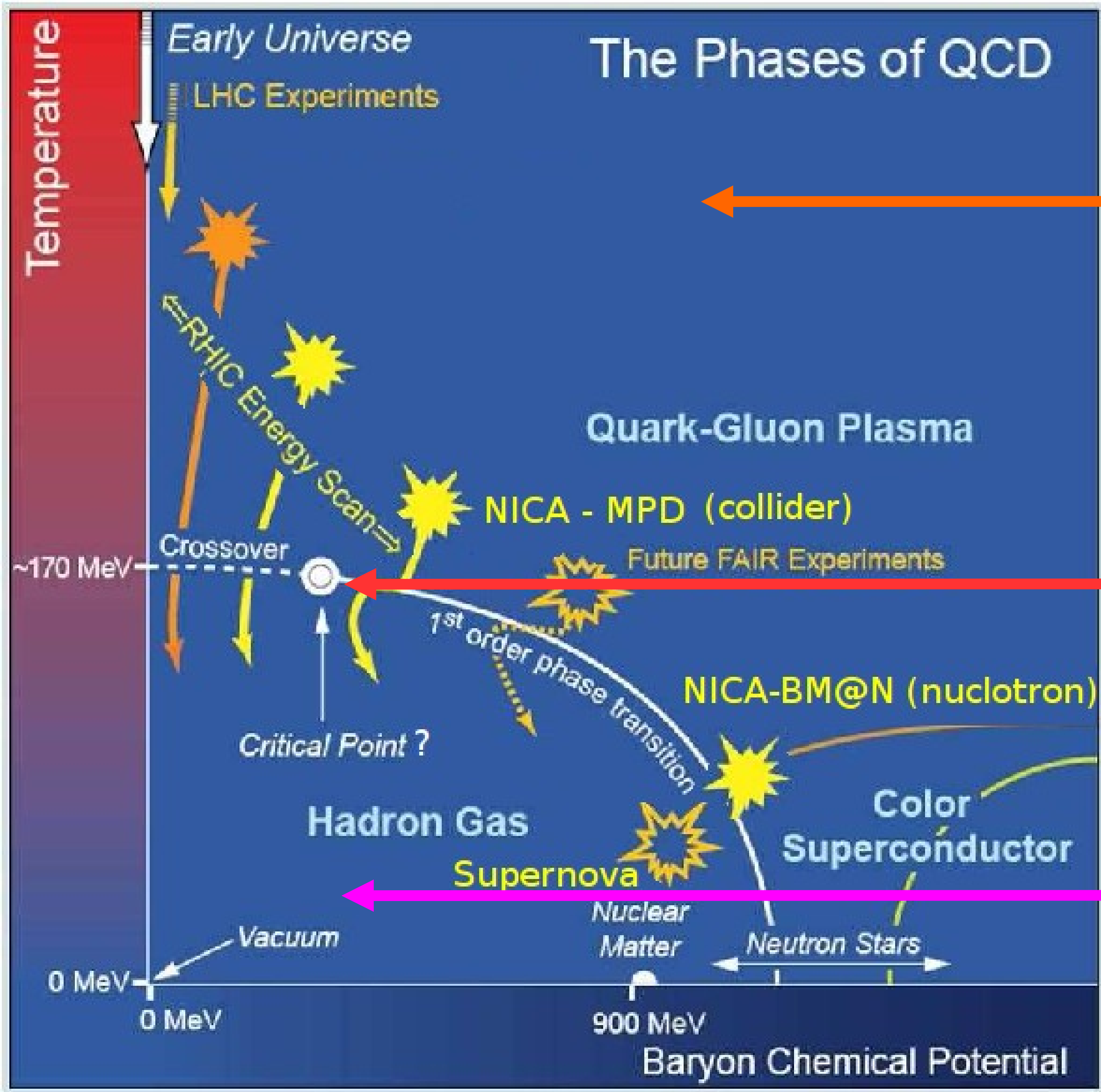


Perturbative QCD

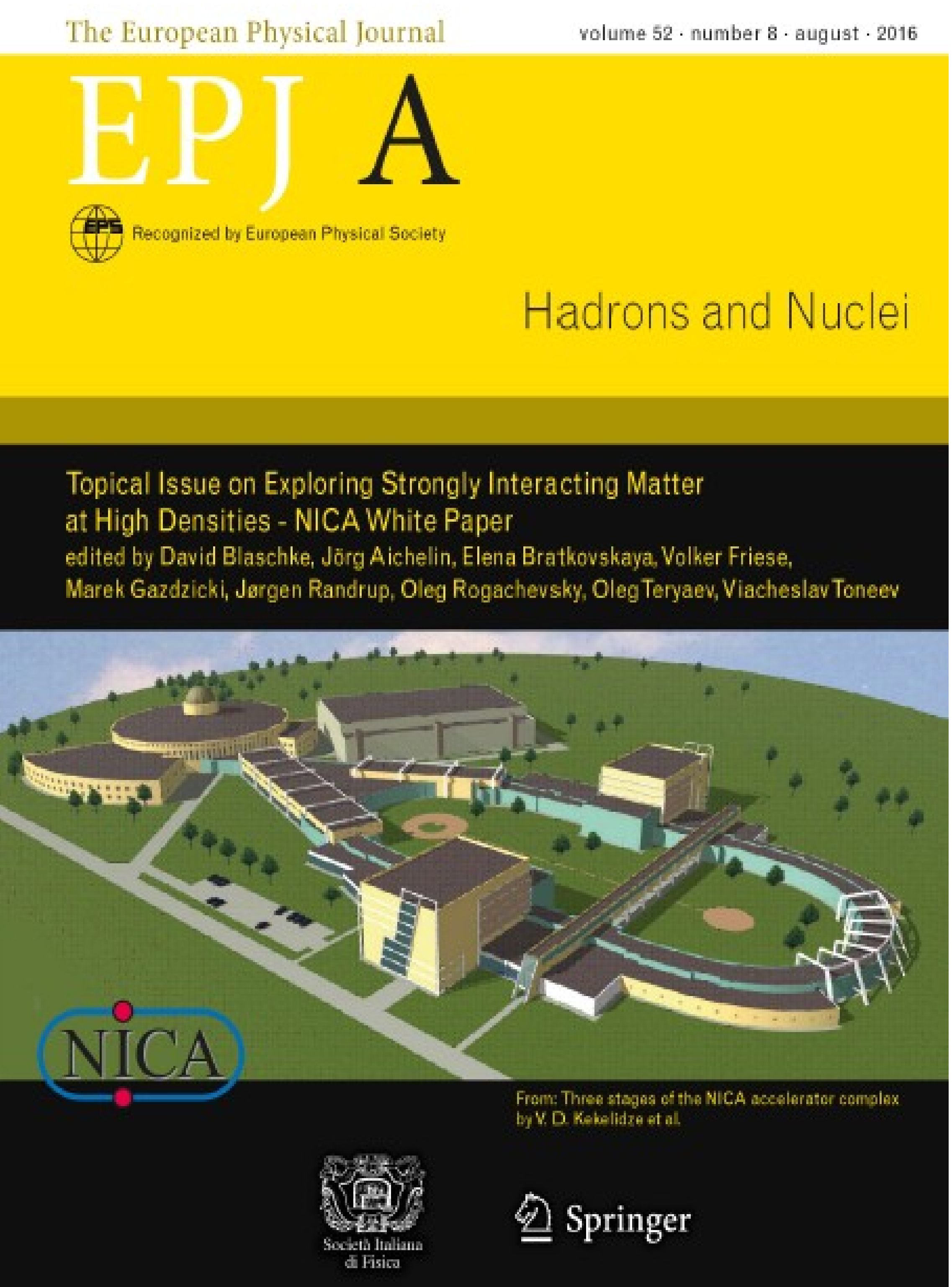
Approximately selfconsistent HTL resummation ($T > 2.5\ T_c$, $\mu > 1500$ MeV)

QCD Phase transition(s)

Mott dissociation of hadrons, Deconfinement, χSR

Statistical Model of Hadron Resonance Gas

Well established for Description of chemical freezeout



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)

http://epja.epj.org/component/list/?task=topic

NICA White Paper – Table of Contents (I)

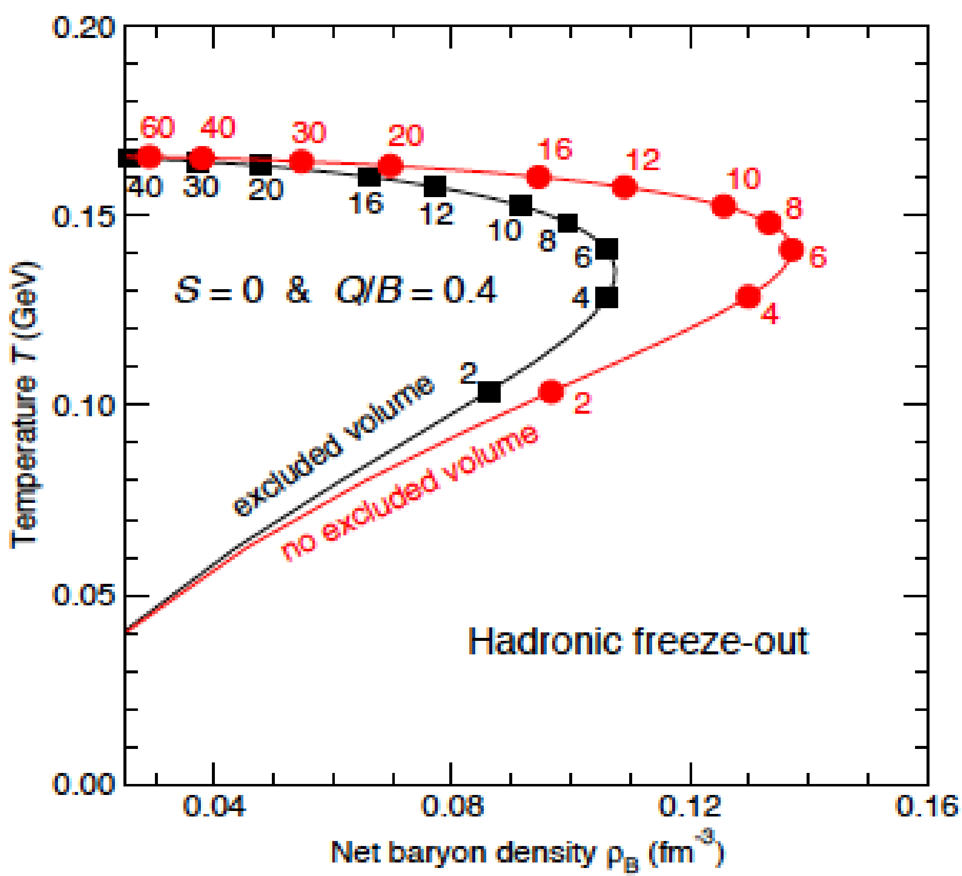
NICA White Paper – Table of Contents (II)

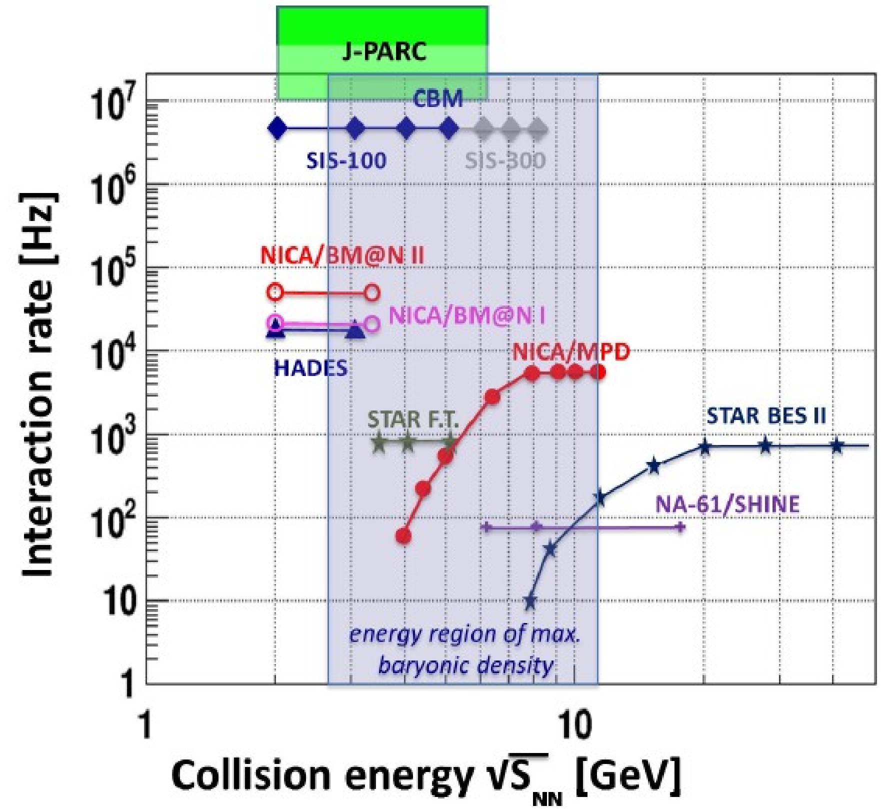
What is special at NICA / FAIR / J-PARC energy?

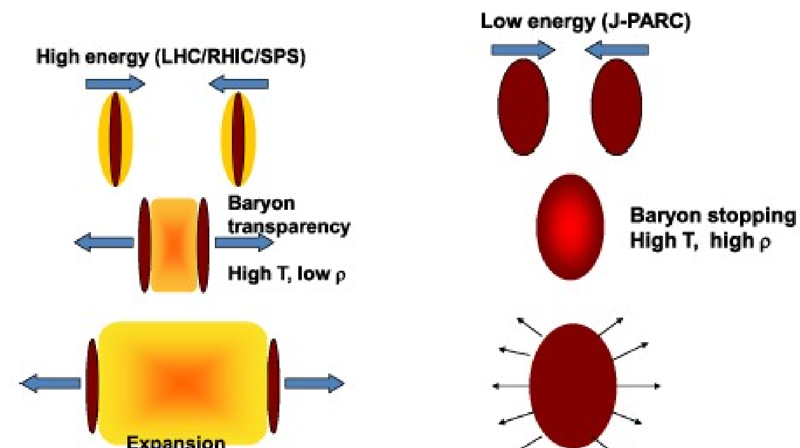
#8: Exploring high-density baryonic matter: Maximum freeze-out density

Jørgen Randrup[1] and Jean Cleymans[2]

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







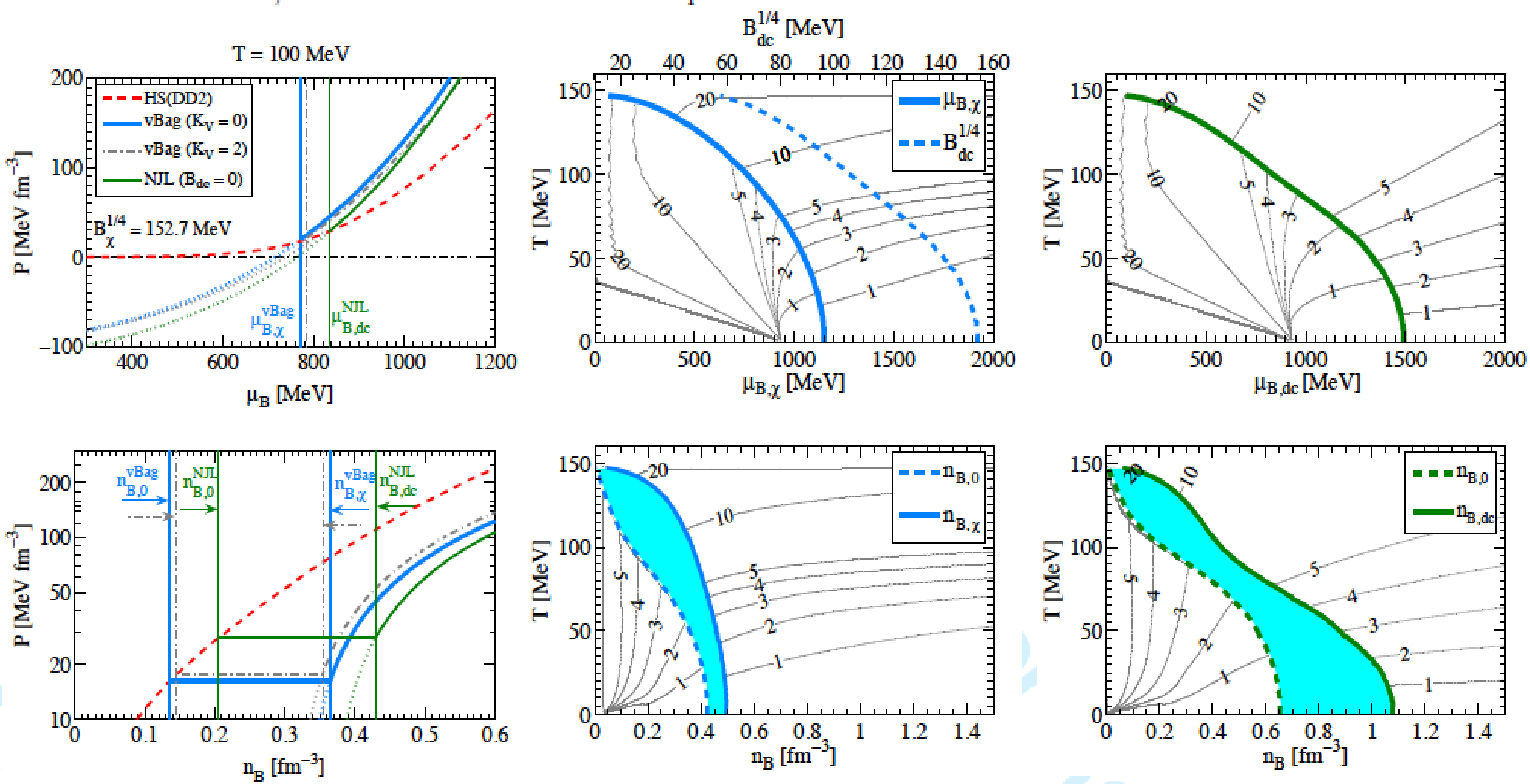
Transparency vs. Baryon Stopping

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 Klähn[1] and Matthias Hempel[2]



(a) vBag

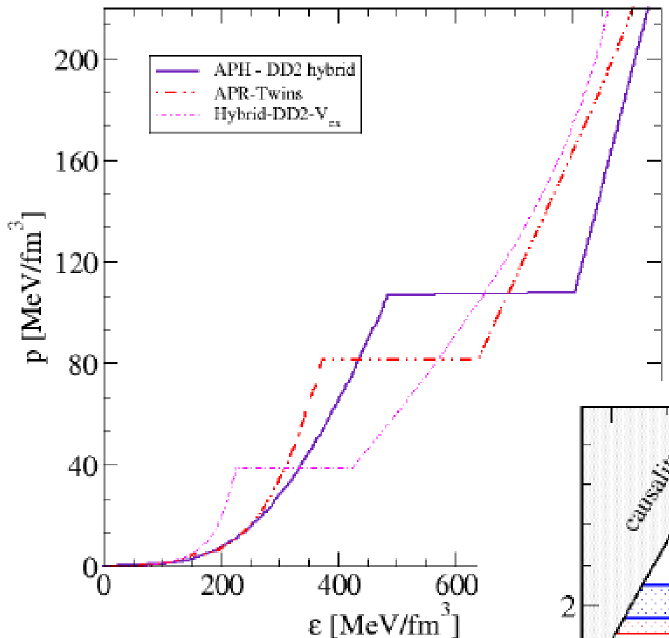
(b) 'standard' NJL approach

NICA White Paper – selected topics ...

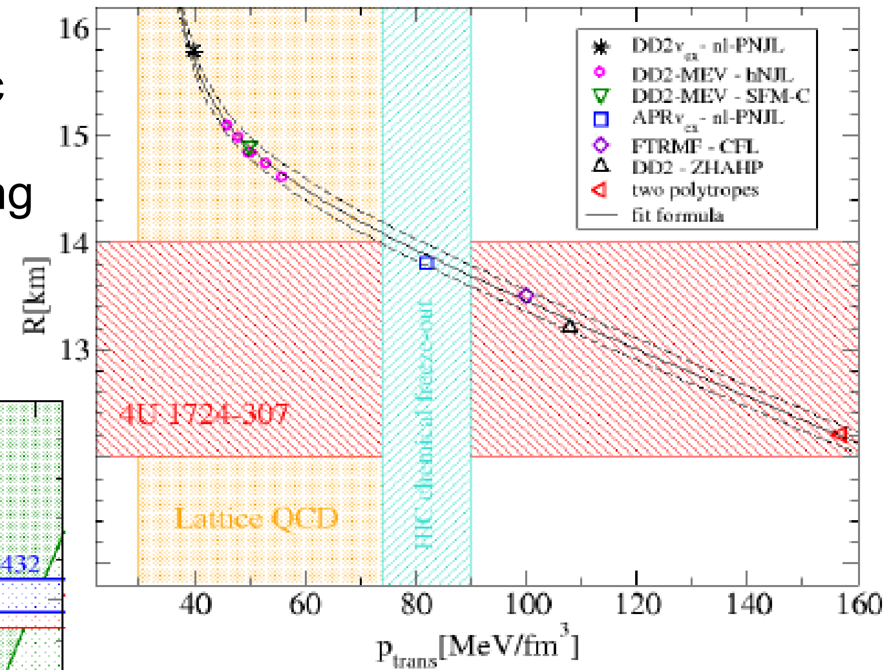
Many cross-relations with astrophysics of compact stars! High-mass twin stars prove CEP !

#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. Typel[7]

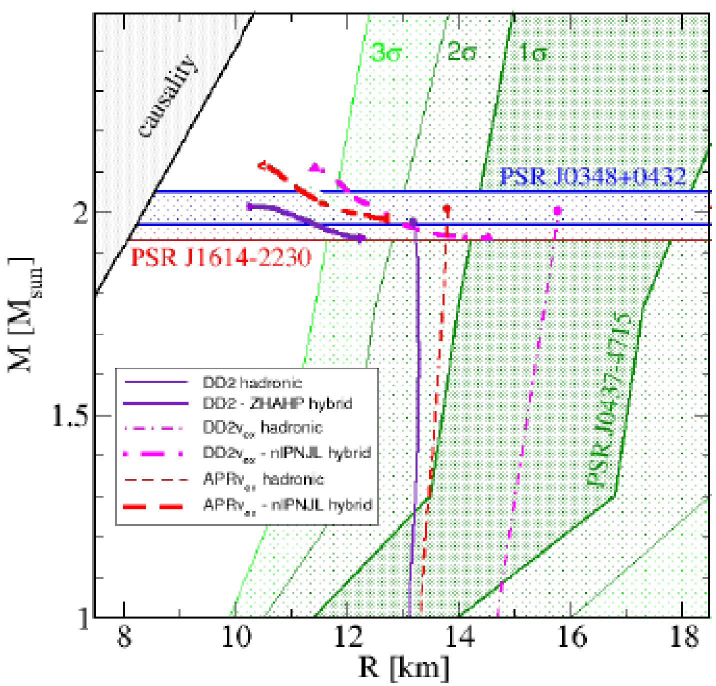


Endpoint of hadronic Neutron star config. At 2Msun, then strong Phase transition



Strong phase trans.

High-mass twin stars



Universal transition pressure ?

Petran & Rafelski, PRC 88, 021901

P_{trans} = 82 +/- 8 MeV/fm^3

NICA White Paper – selected topics ...

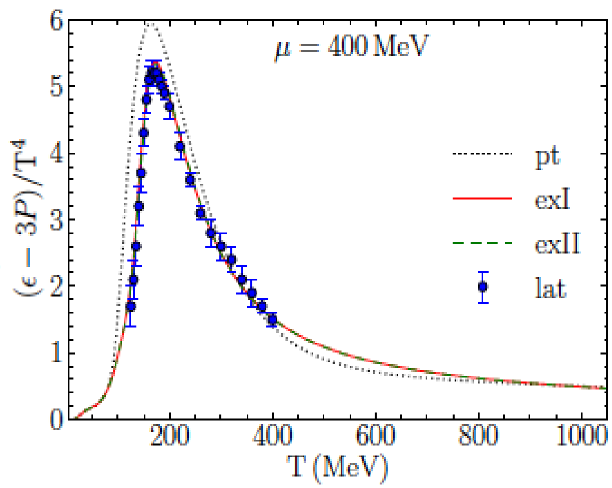
#41 Net Baryon Fluctuations from a Crossover Equation of State

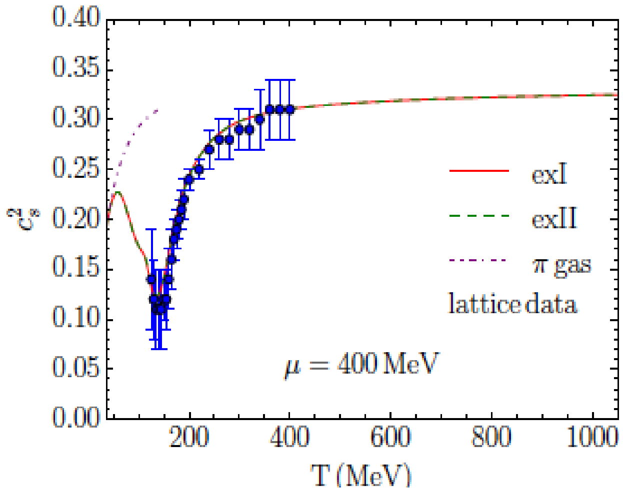
J. Kapusta[1], M. Albright[1a], and C. Young[2]

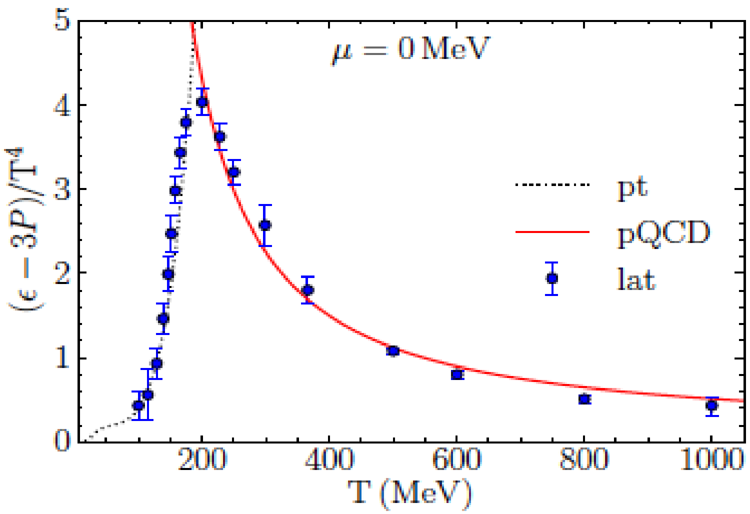
Hybrid crossover EoS with
Switching function and exvol.

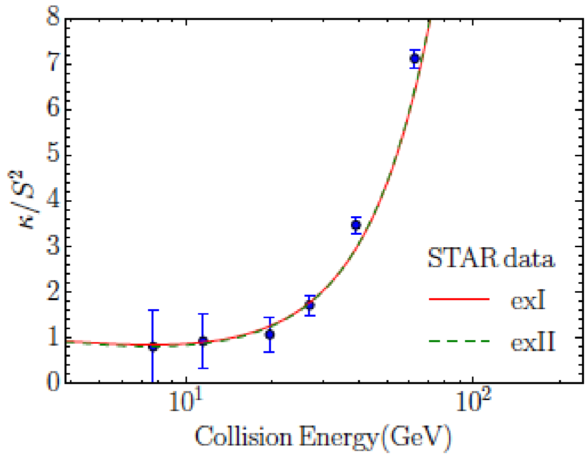
$$S(T,\mu) = \exp\{-\theta(T,\mu)\}$$

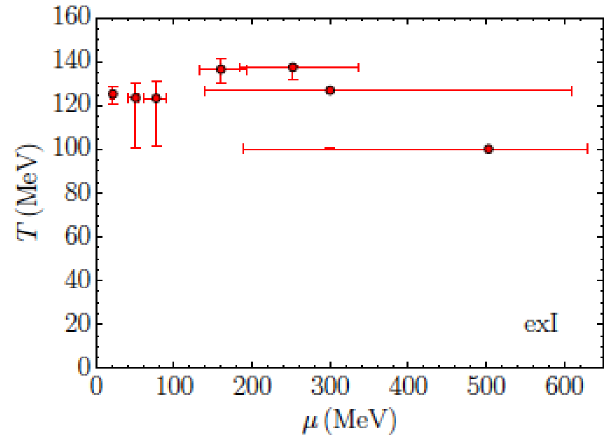
$$\theta(T,\mu) = \left[\left(\frac{T}{T_0}\right)^n + \left(\frac{\mu}{3\pi T_0}\right)^n\right]^{-1}$$









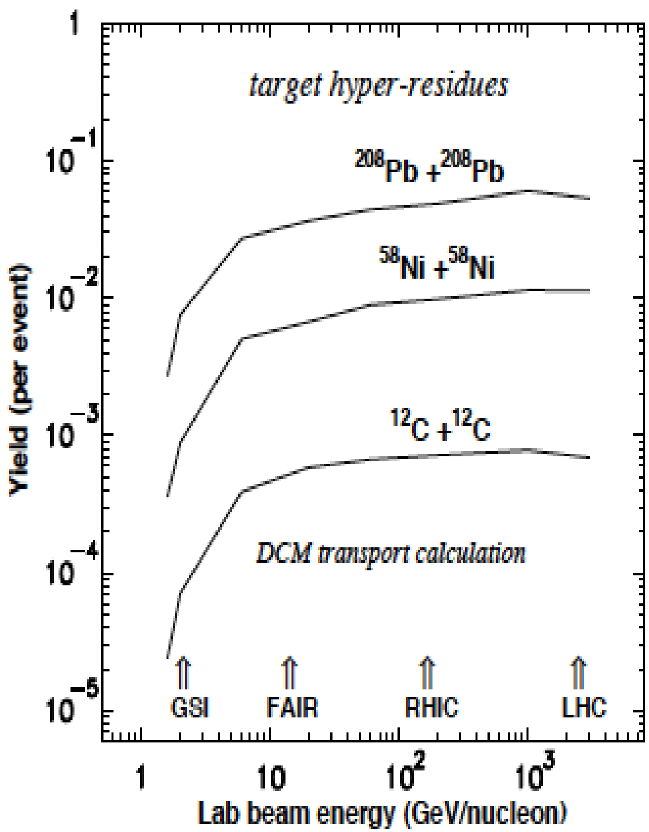


No evidence for a critical point in RHIC BES data.
But for lower energies – maybe!

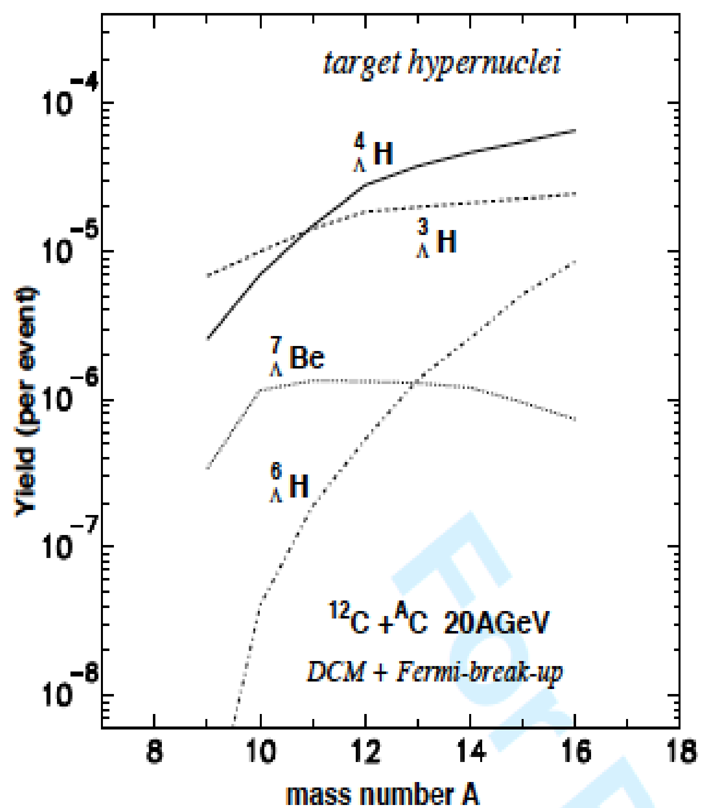
NICA White Paper – selected topics ...

#32 Relativistic ion collisions as the source of hypernuclei

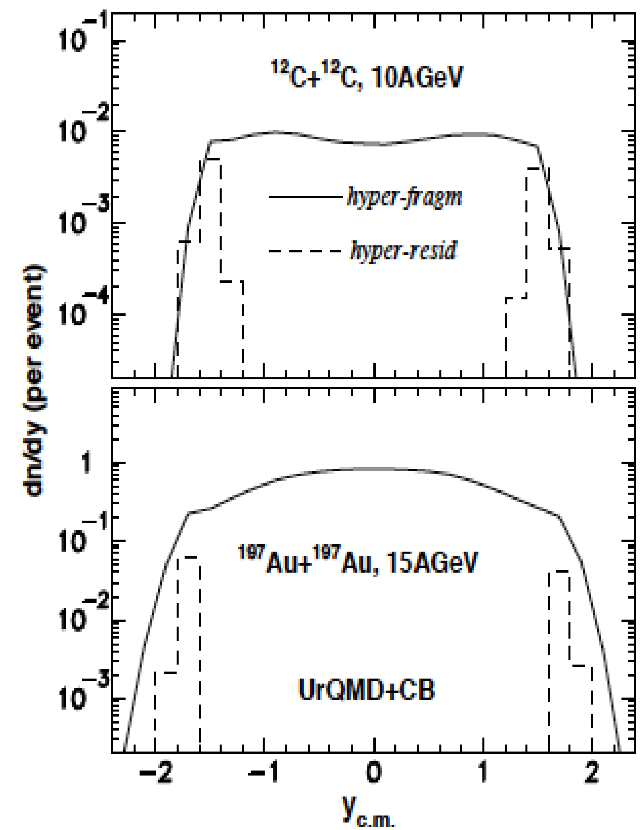
A. S. Botvina[1,2], M. Bleicher[1], J. Pochodzalla[3,4], and J. Steinheimer[1]



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

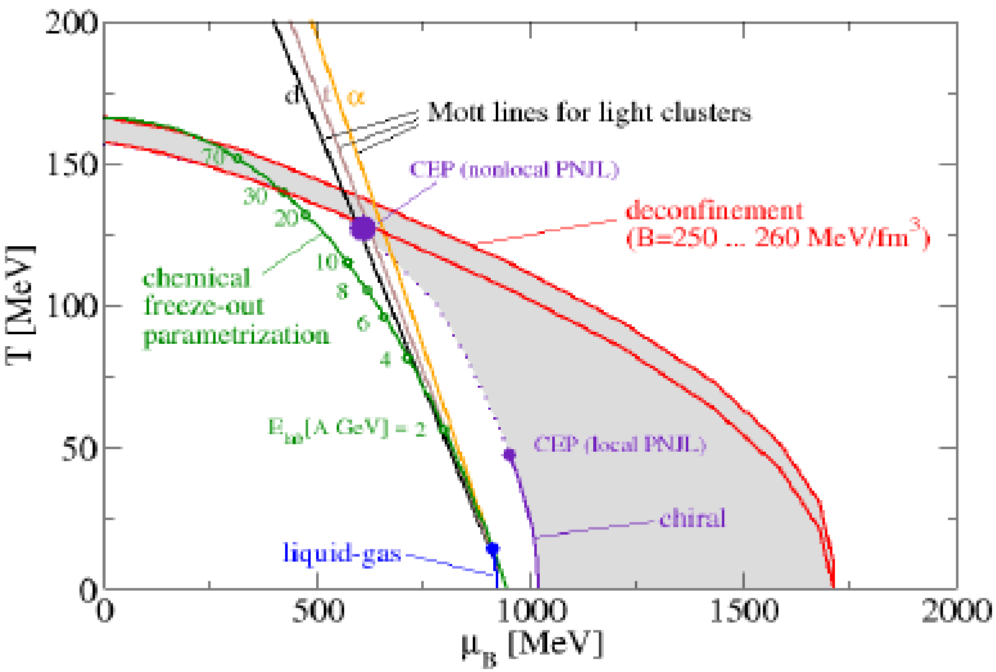


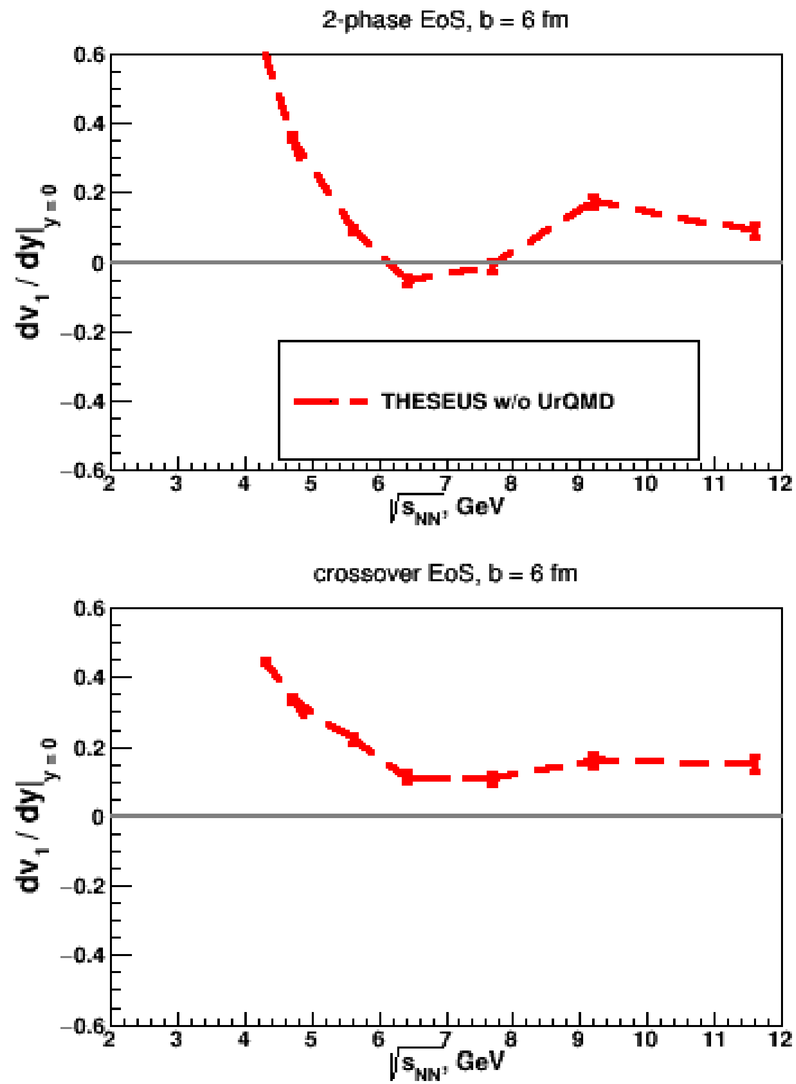
UrQMD plus coalescence of baryons (CB) model results For rapidity distributions of hyper fragments and residues

NICA White Paper – selected topics ...

#34 Light cluster production at NICA

N.-U. Bastian[1], P. Batyuk[2], D. Blaschke[1,2,3], P. Danielewicz[4], Yu. B. Ivanov[3,5], Iu. Karpenko[6,7], G. Röpke[3,8,a], O. Rogachevsky[2], H. H. Wolter[9]





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

Three-fluid Hydrodynamics based Event Simulator Extended by UrQMD final State interactions (THESEUS)

P. Batyuk, D. Blaschke, M. Bleicher, Yu. Ivanov, Iu. Karpenko, S. Merts, M. Nahrgang, H. Petersen, O. Rogachevsky,
Arxiv:1608.00965
(Dubna-Wroclaw-Frankfurt-Moscow-Florence-Nantes collab.)

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.)

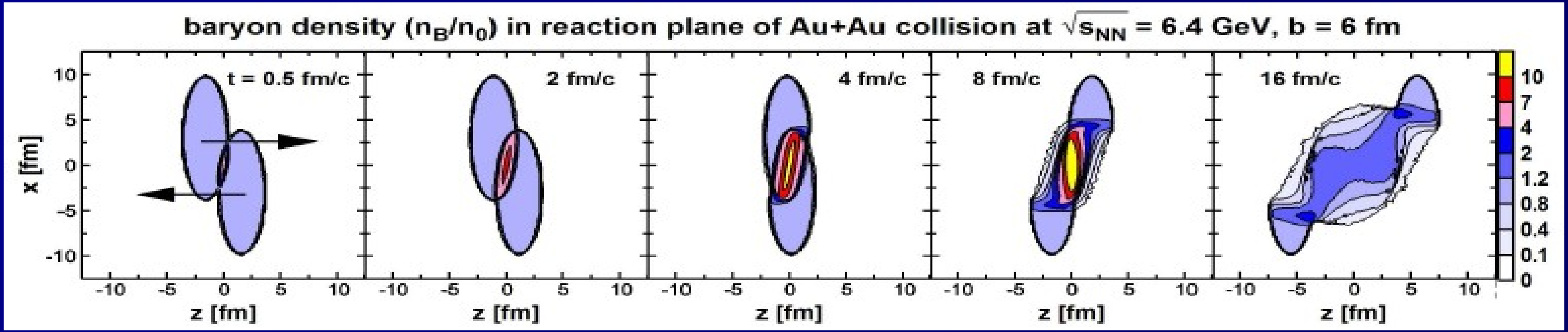
II) **Hybrid approach:**
Joins hydrodynamic evolution of a (multi-)fluid system described by an **EoS** with
Particle transport via a procedure called **"particlization"** (Karpenko)
Particularly suitable for studying effects of a strong phase transition in model EoS
a) Sandwich: UrQMD + hydro + hadronic 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

time →



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

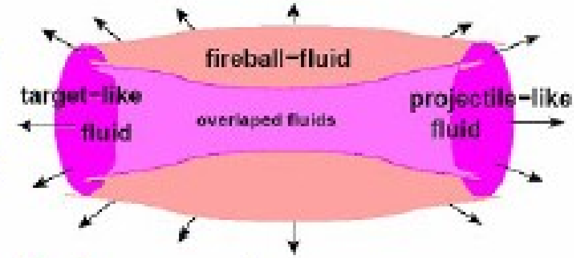
3-fluid hydro, (Yu. Ivanov)

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

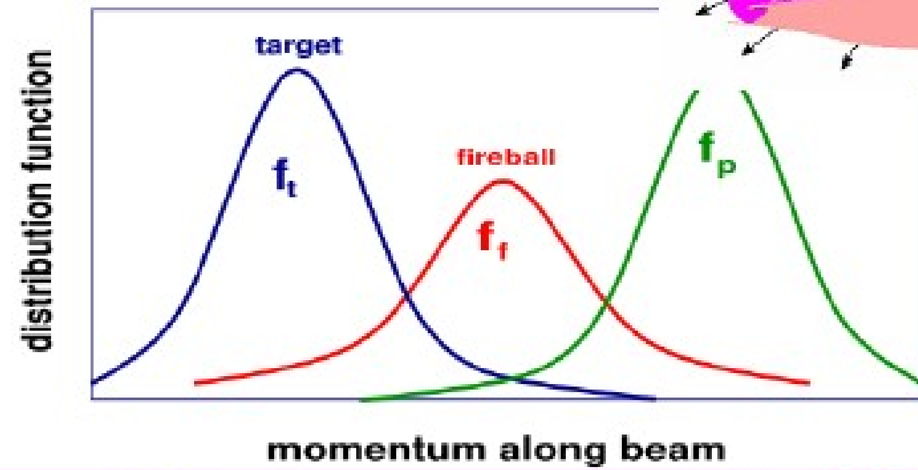
(optionally) cascade: PHSD, UrQMD, etc (E. Bratkovskaya, H. Petersen)

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

3-Fluid Dynamics



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



Target-like fluid: $\partial_\mu J^\mu_t = 0$ $\quad$ $\partial_\mu T^{\mu\nu}_t = -F^\nu_{tp} + F^\nu_{ft}$

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

Projectile-like fluid: $\partial_\mu J^\mu_p = 0,$ $\quad$ $\partial_\mu T^{\mu\nu}_p = -F^\nu_{pt} + F^\nu_{fp}$

Fireball fluid: $J^\mu_f = 0,$ $\quad$ $\partial_\mu T^{\mu\nu}_f = F^\nu_{pt} + F^\nu_{tp} - F^\nu_{fp} - F^\nu_{ft}$

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:

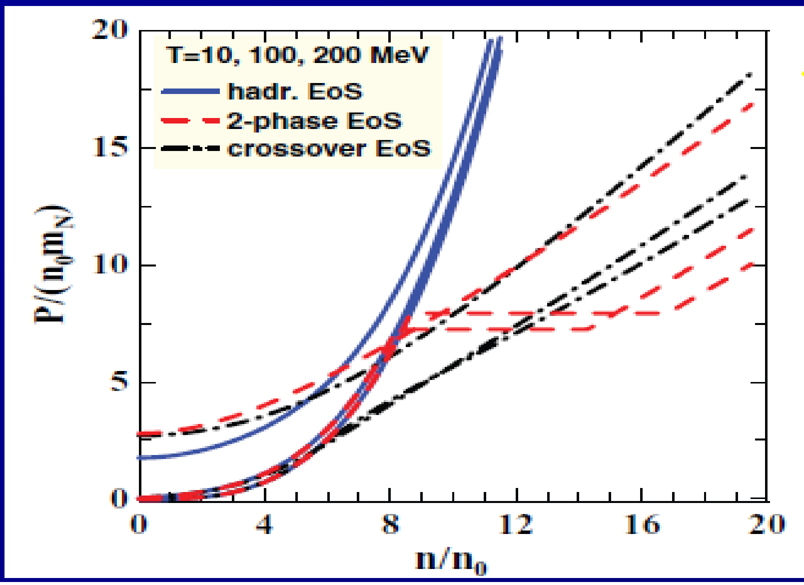
$$\partial_\mu (T^{\mu\nu}_p + T^{\mu\nu}_t + T^{\mu\nu}_f) = 0$$

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

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

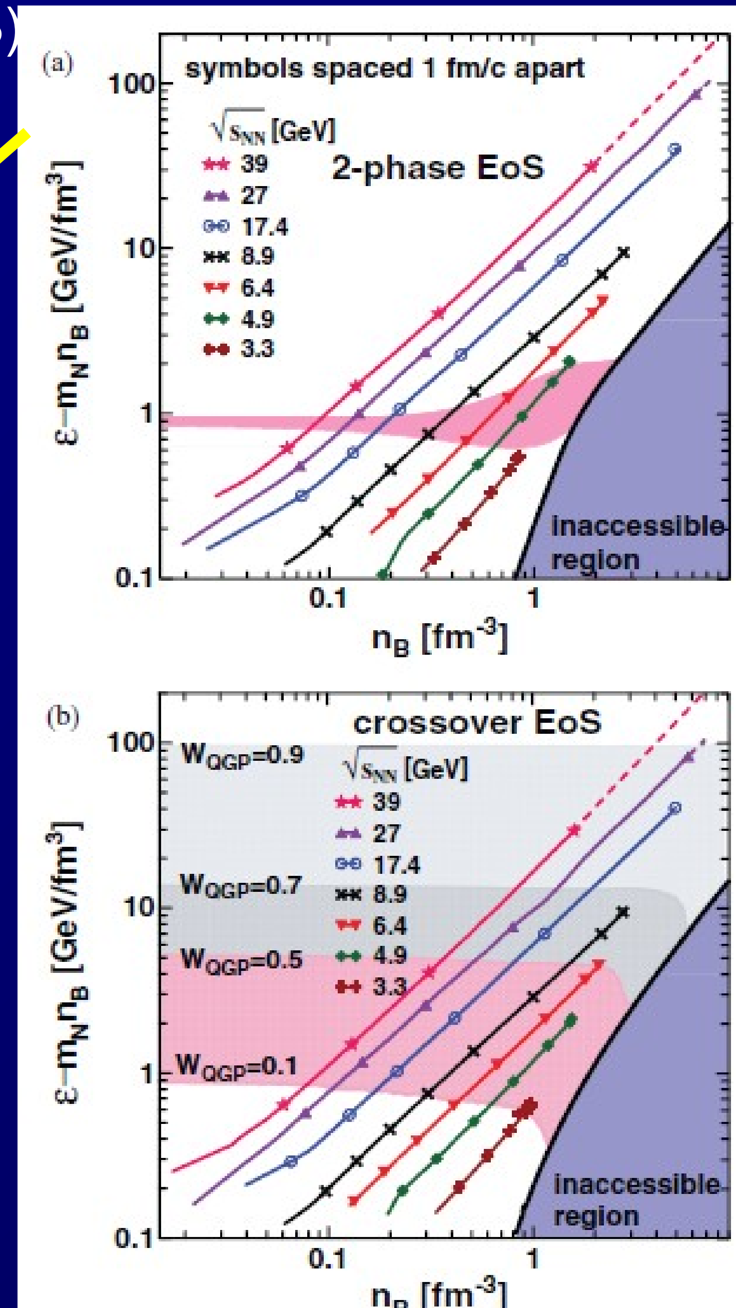
Net proton rapidity distribution – test case for a 1st order PT signal

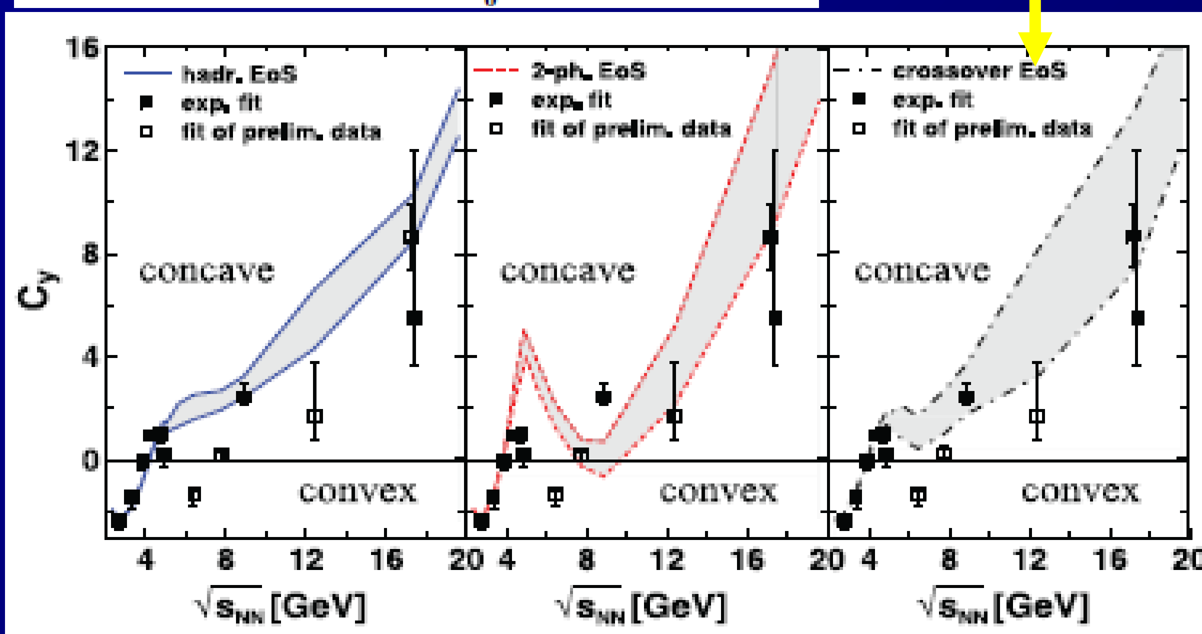
Theory: Yu.B. Ivanov, Phys. Rev. C 87, 064904 (2013)



EoS

3-fluid hydro Evolution ...



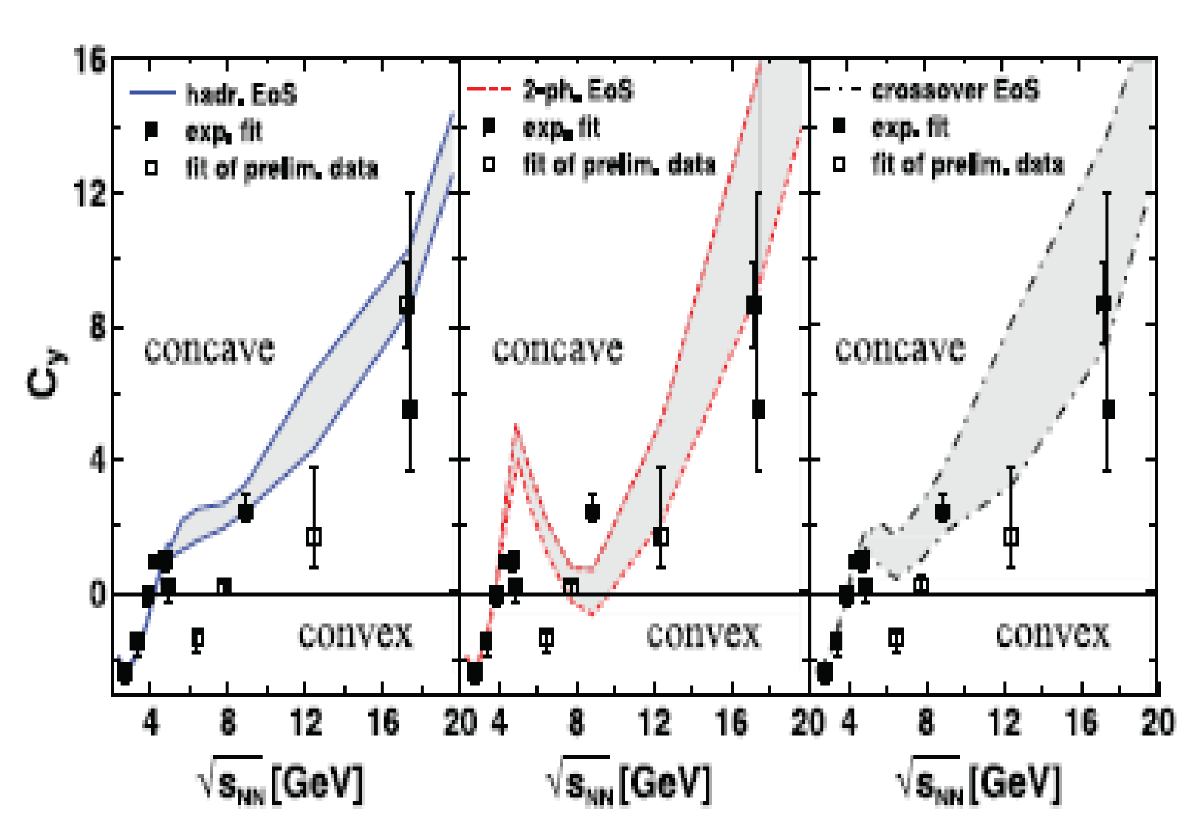


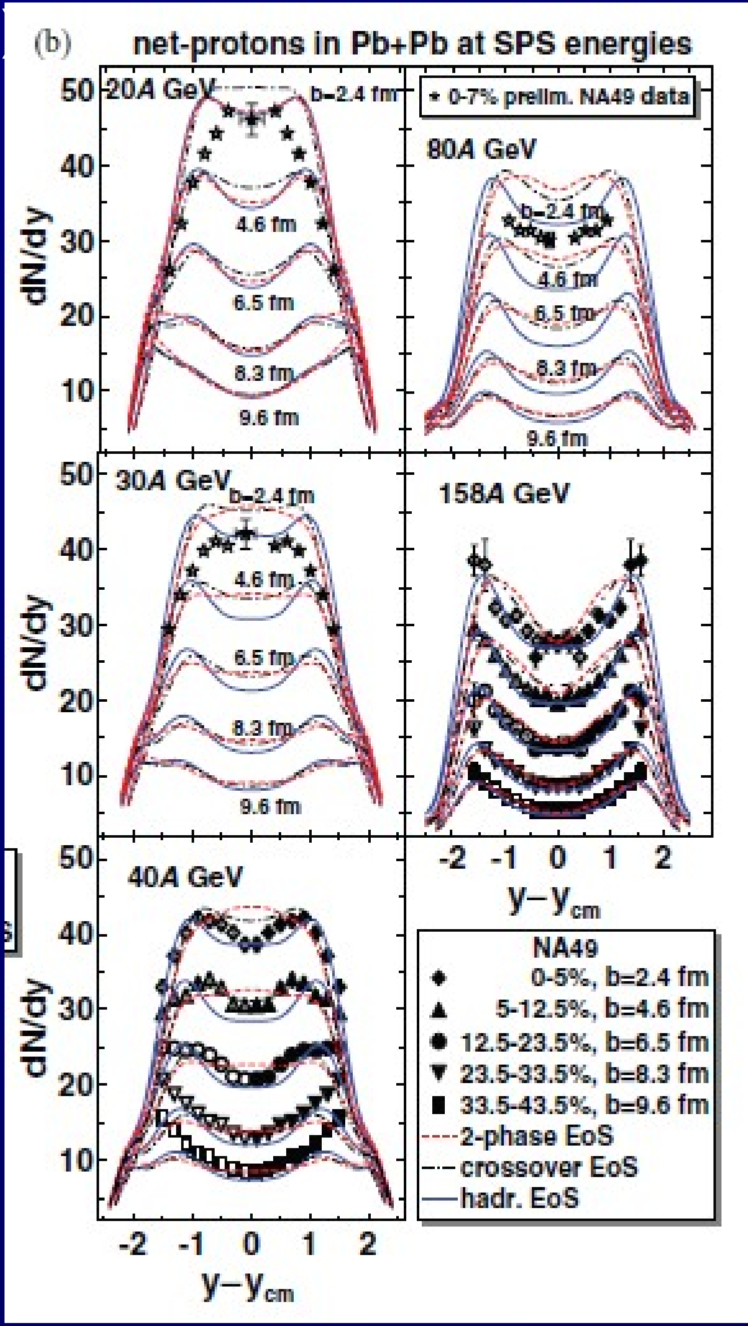
Net proton rapidity distribution – test case for a 1st order PT signal

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

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

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





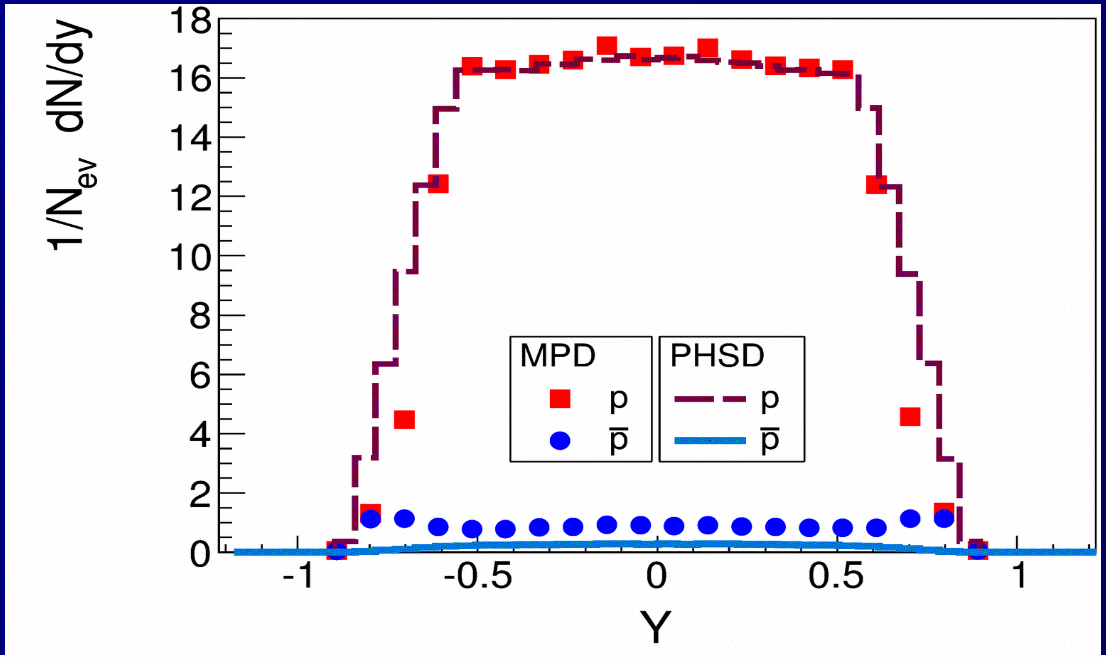
Net proton rapidity distribution – test case for a 1st order PT signal

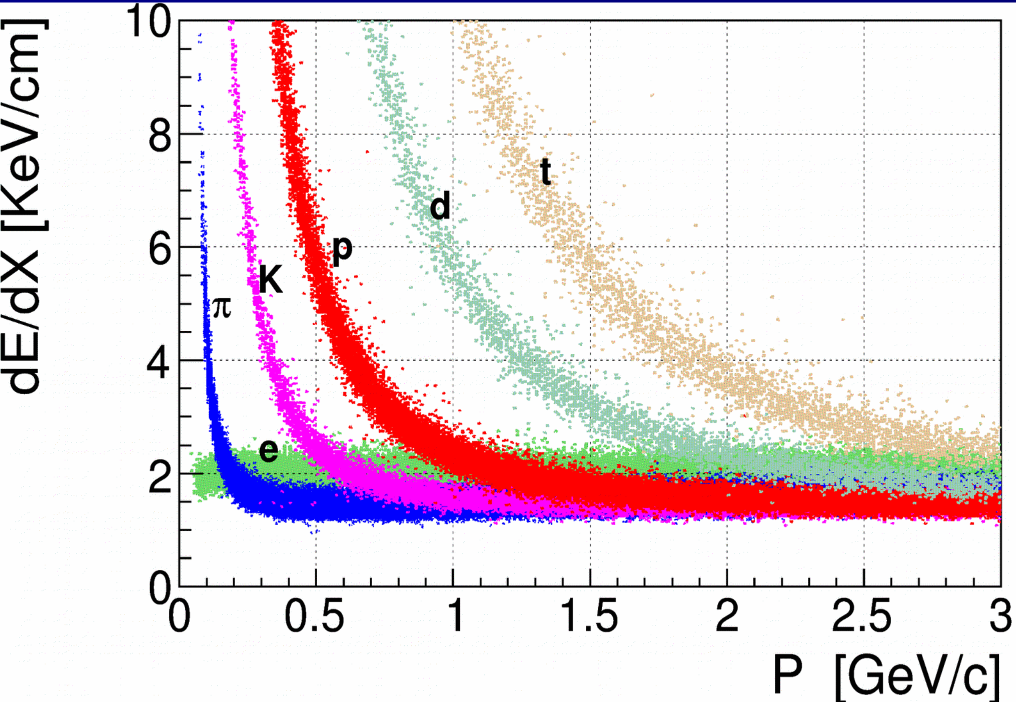
Event set:
40k AuAu @ √s_NN = 9 GeV [0-5%]
The most reliable region
|eta| < 1.2 ; 0.4 < p_t [GeV/c] < 0.8

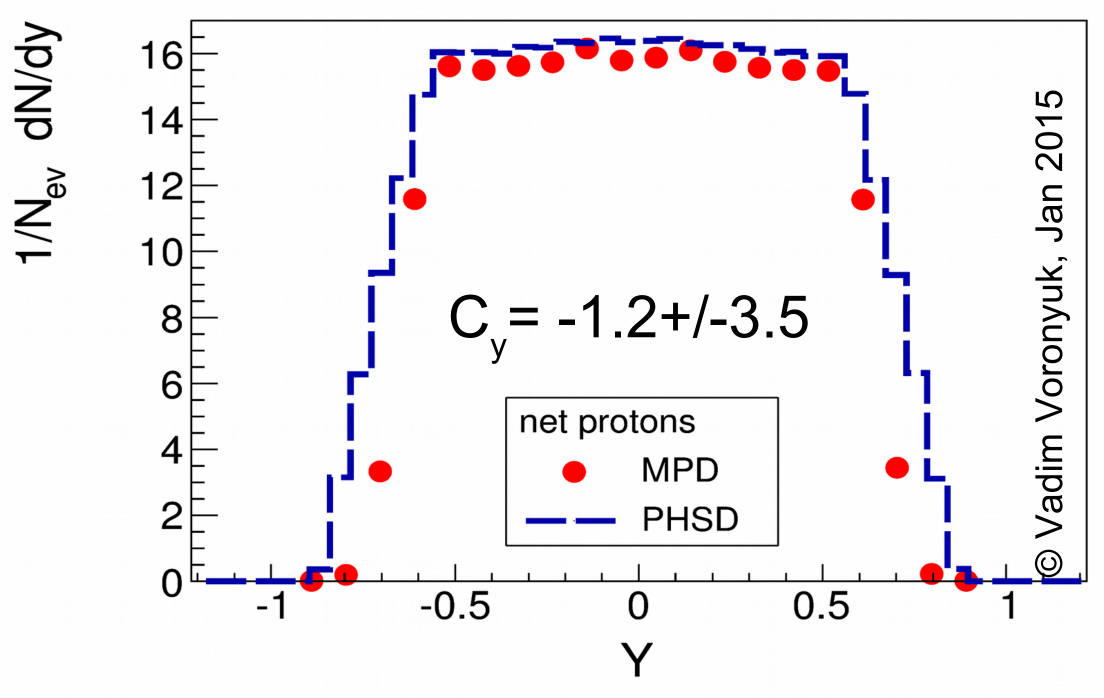
Result:
PHSD input → GEANT+MPD
detector reproduces the rapidity distribution !
(previous concerns not confirmed !!)

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

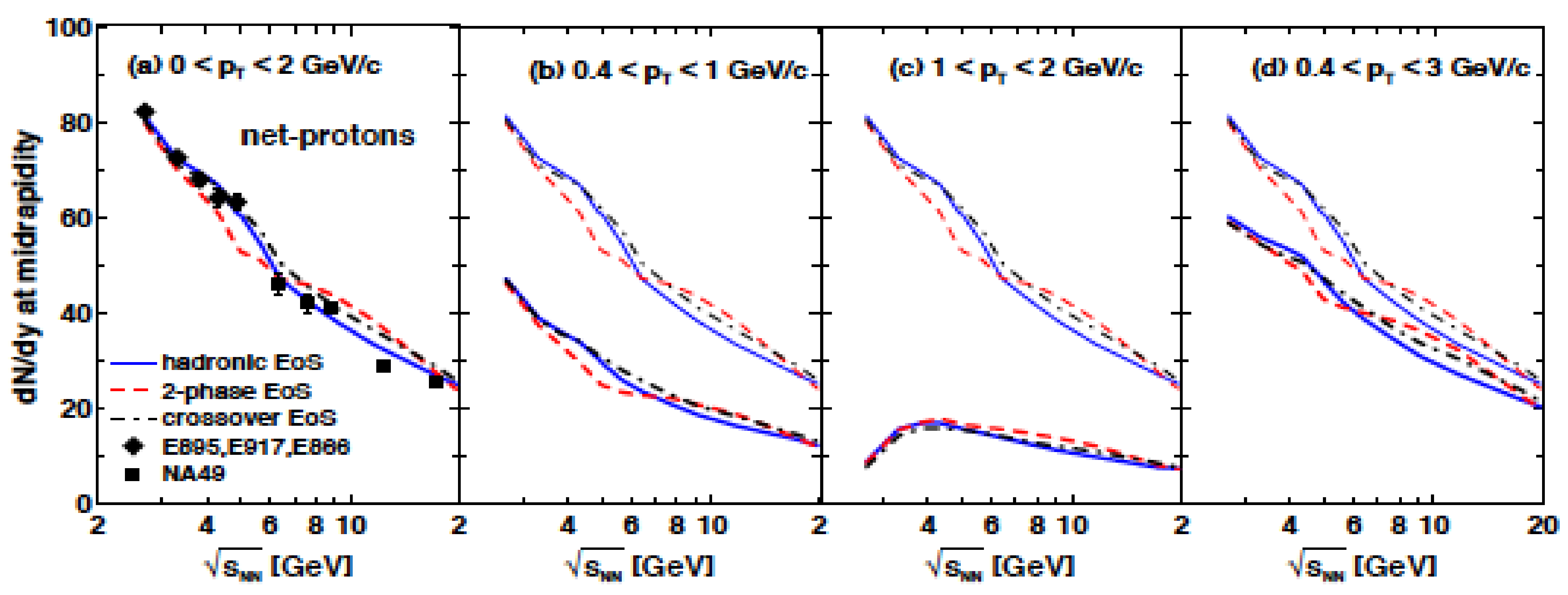
$$C_y = \left(y_{\rm beam}^3 \frac{d^3N}{dy^3} \right)_{y=0} \Big/ \left(y_{\rm beam} \frac{dN}{dy} \right)_{y=0} = (y_{\rm beam}/w_s)^2 \left(\sinh^2 y_s - w_s \cosh y_s \right) .$$

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. B., PRC 92, 024916 (2015)

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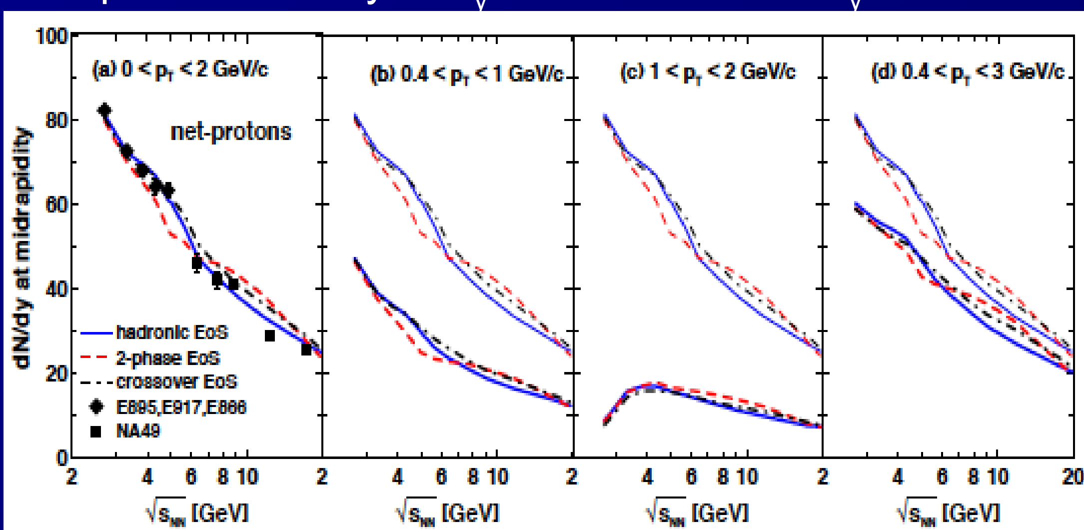
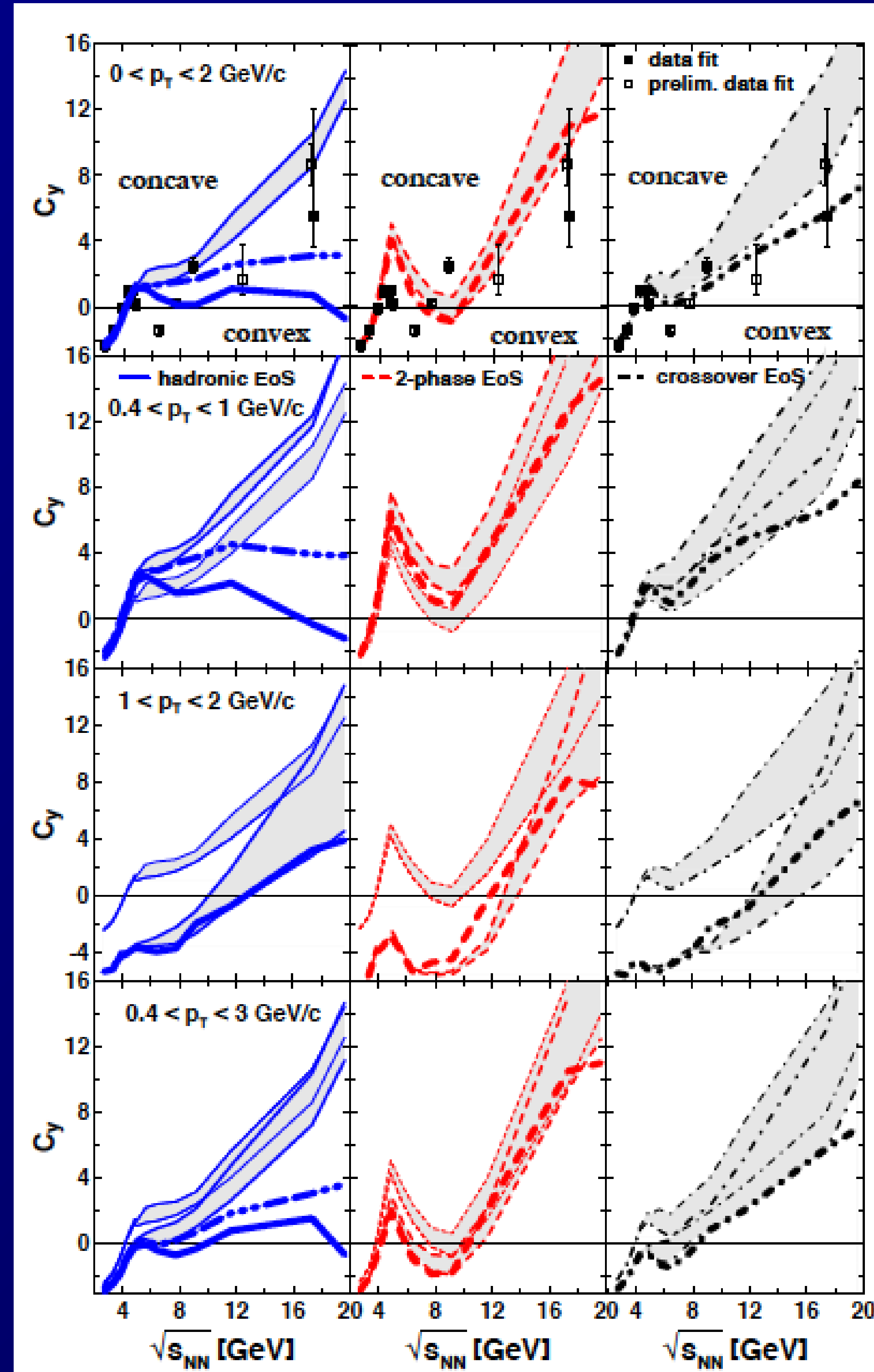
- “wiggle” formed in the nonequilibrium compression stage of the collision, where p_T only in 3FH
- robust against serious p_T cuts
- at high p_T (1 - 2 GeV/c) in convex region
- at low p_T (0.2 - 1 GeV/c) in concave region
- required accuracy in C_y determination: $\Delta C_y < 2$





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

Investigation of p_T cuts:

Yu. Ivanov & D. Blaschke, arxiv:1504.03992

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

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

- "wiggle" formed in the nonequilibrium compression stage of the collision, where p_T only in 3FH
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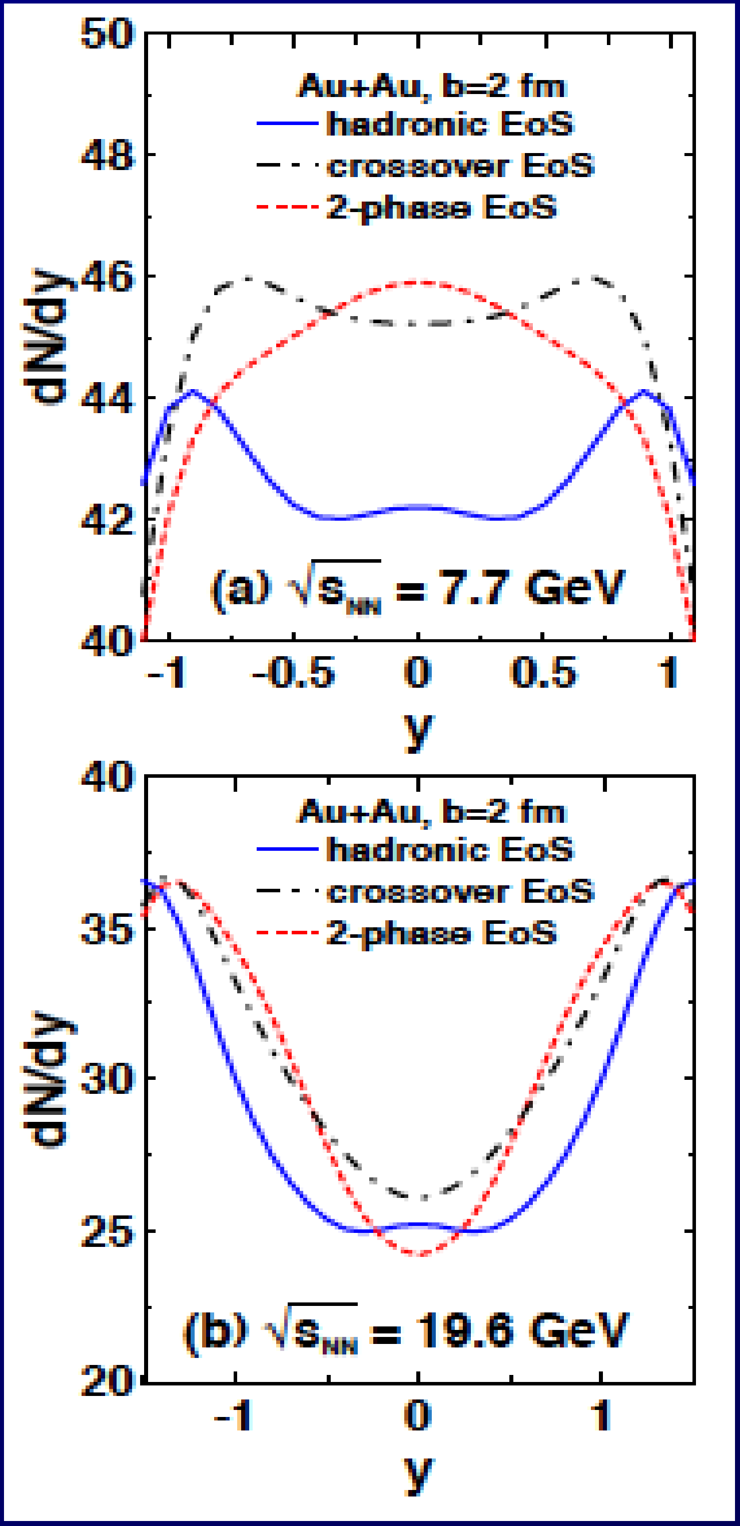
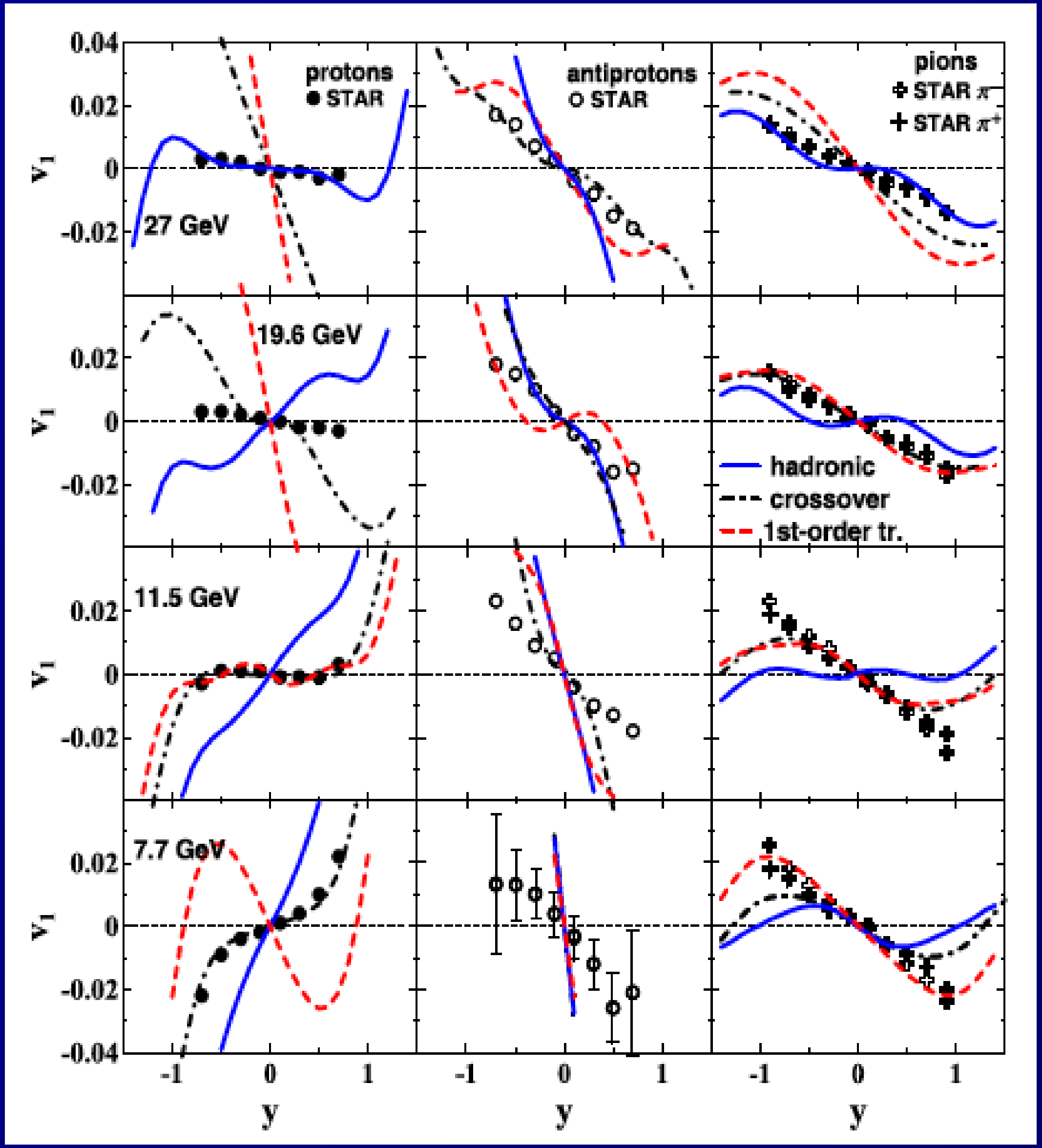
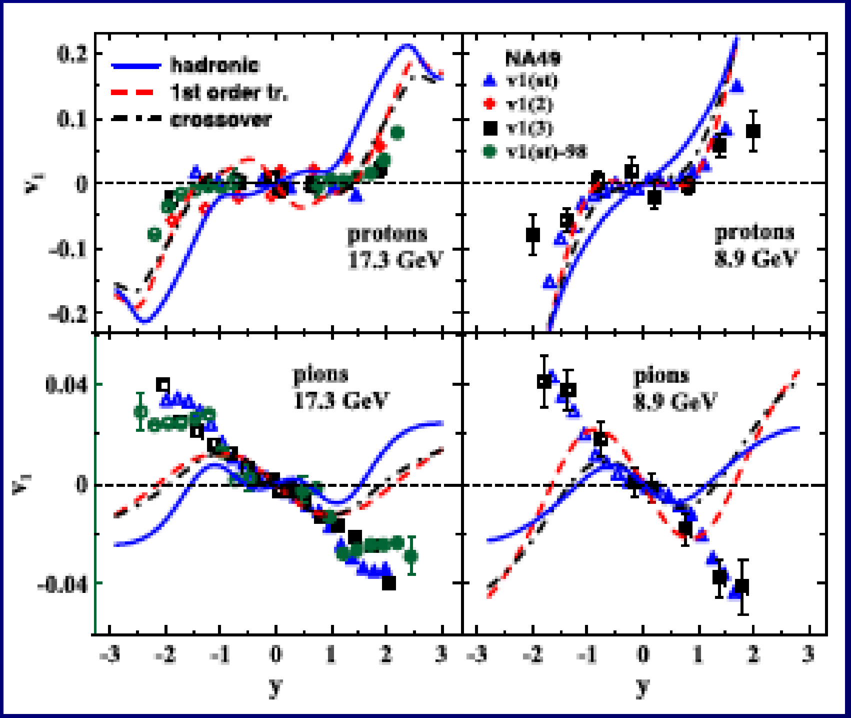
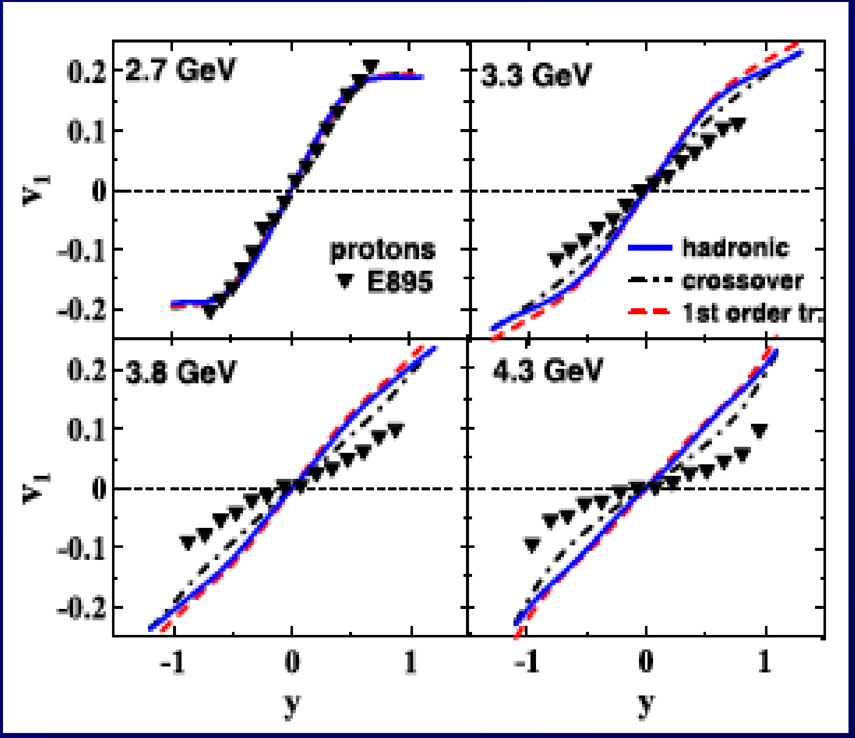


Directed flow indicates a cross-over Deconfinement transition …

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

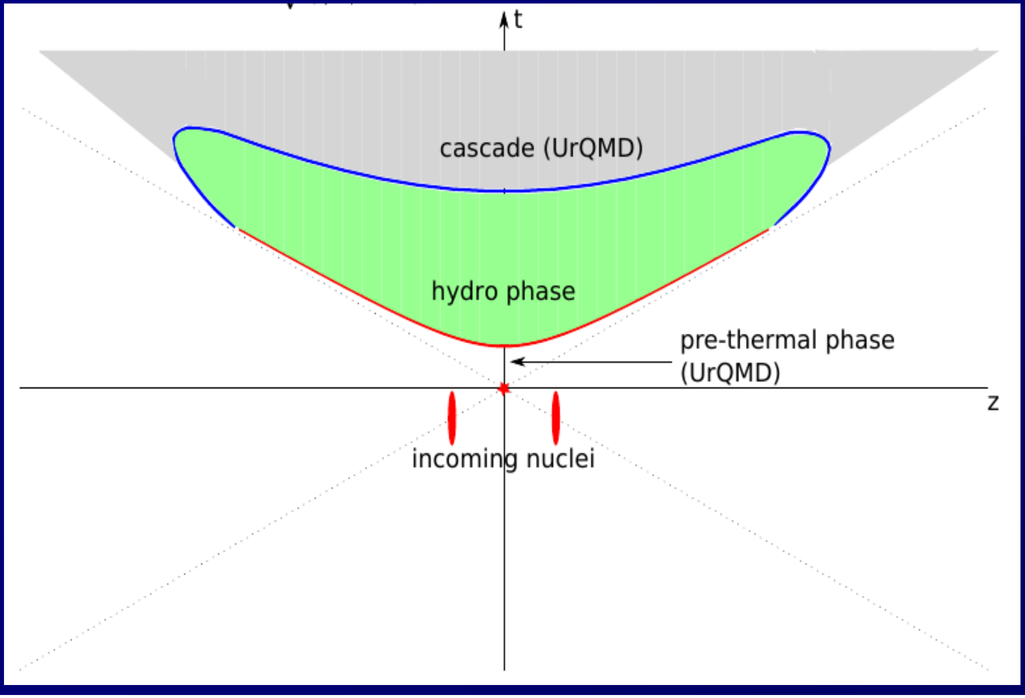






3+1D viscous hydro-cascade model (Yu. Karpenko, FIAS)

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→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

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

Equations of state for hydrodynamic phase

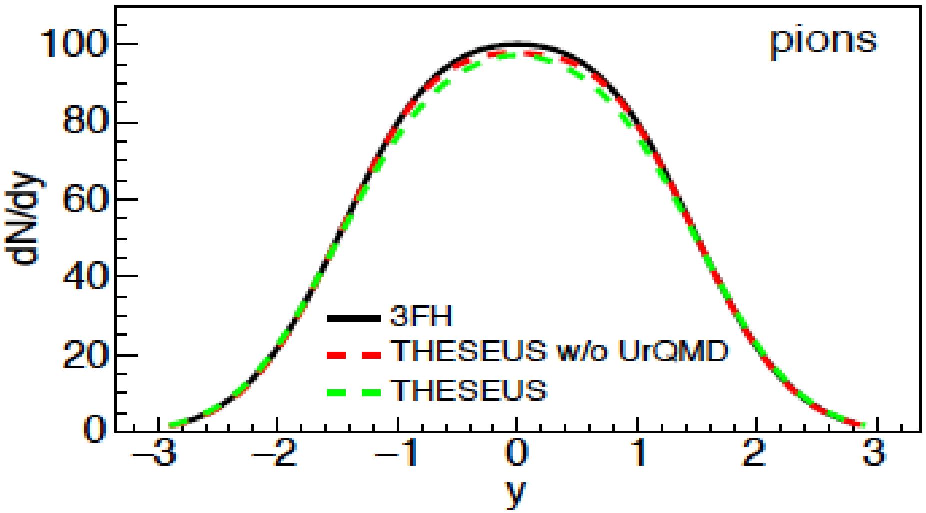
- Chiral model
  - coupled to Polyakov loop to include the deconfinement phase transition
  - good agreement with lattice QCD data at $\mu_B = 0$, also applicable at finite baryon densities
  - (current version) has crossover type PT between hadron and quark-gluon phase at all μ_B
- Hadron resonance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

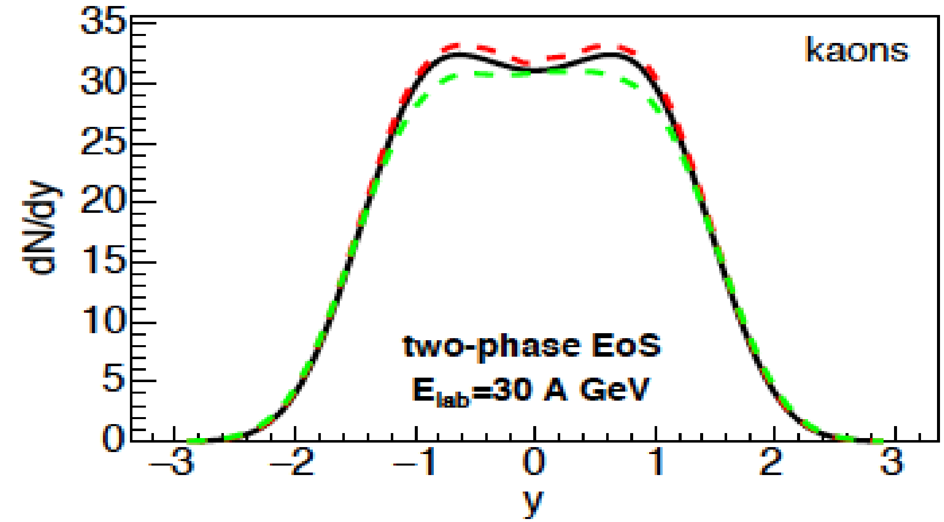
J. Steinheimer, S. Schramm and H. Stocker, J. Phys. G 38, 035001 (2011); P.F. Kolb, J. Sollfrank, and U. Heinz, Phys.Rev. C 62, 054909 (2000).

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

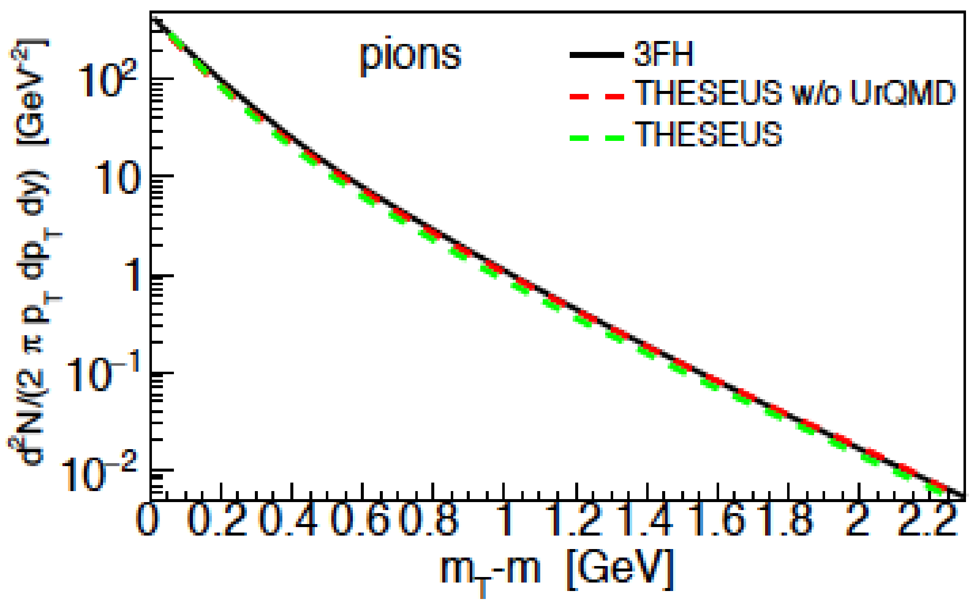
P. Batyuk, D.B., M. Bleicher, Yu. Ivanov, et al., arxiv:1608.00965

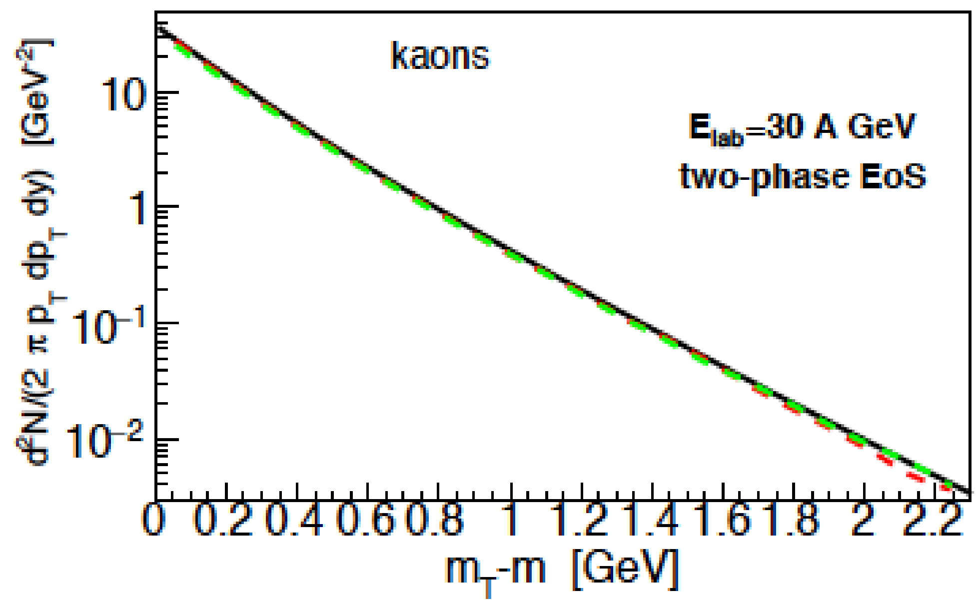
Rapidity distribution



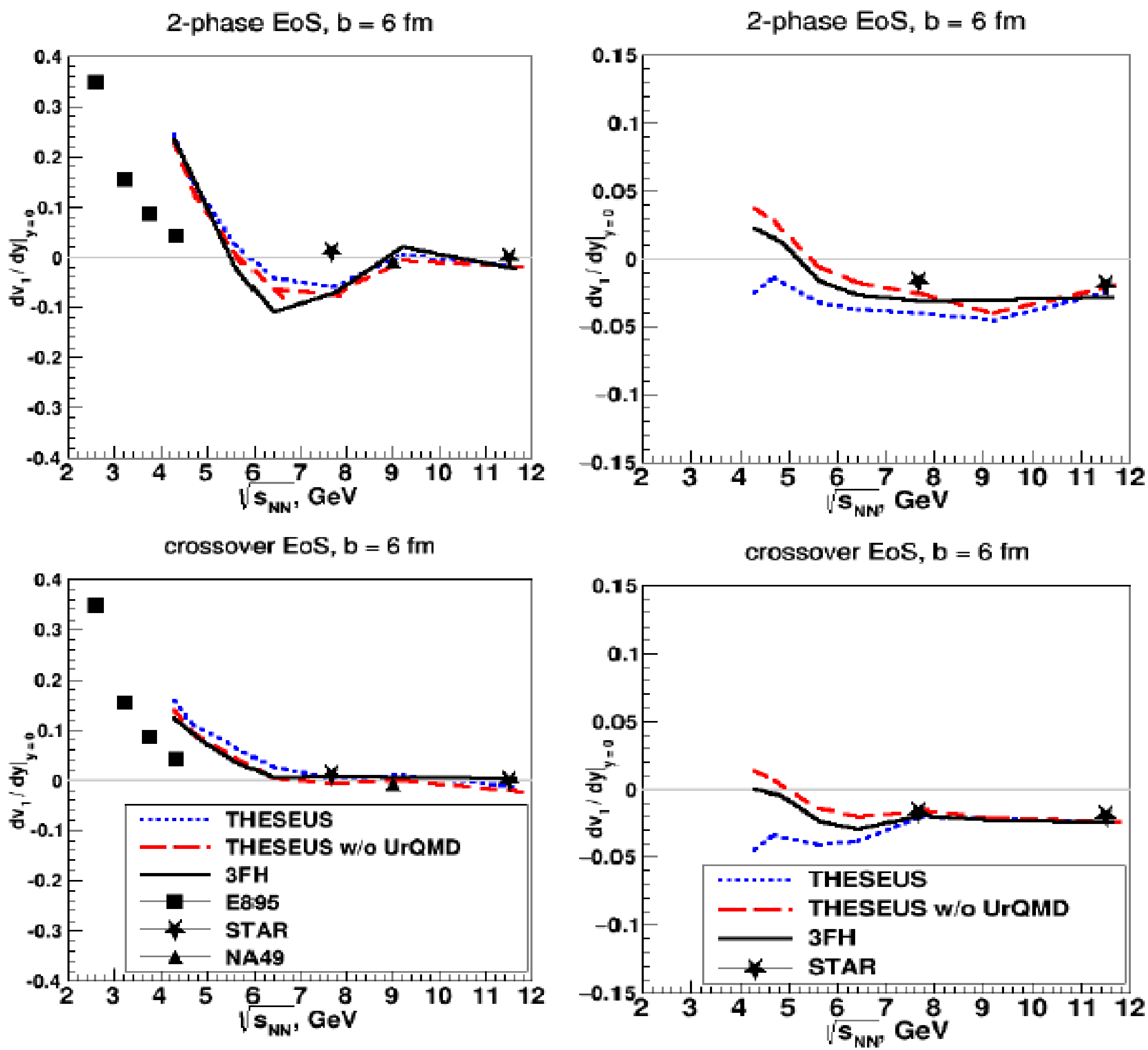


P_T / m_T distribution





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



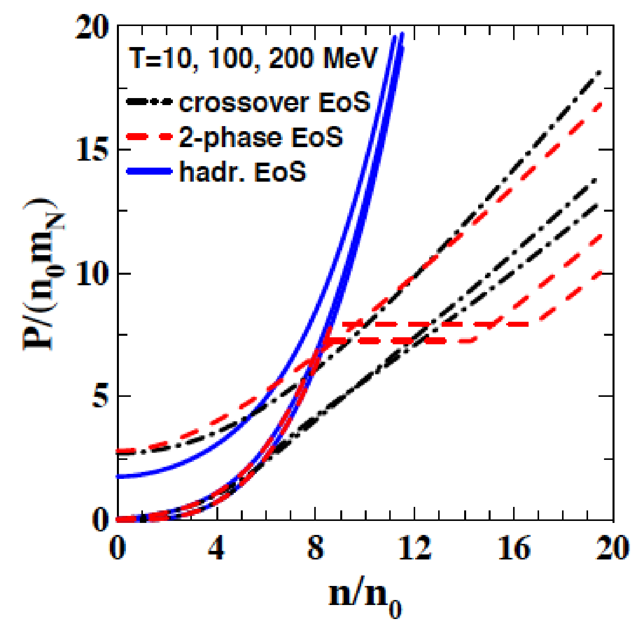
Slope of directed flow

Protons (left)
Pions (right)

First-order PT (upper)
Crossover (lower)

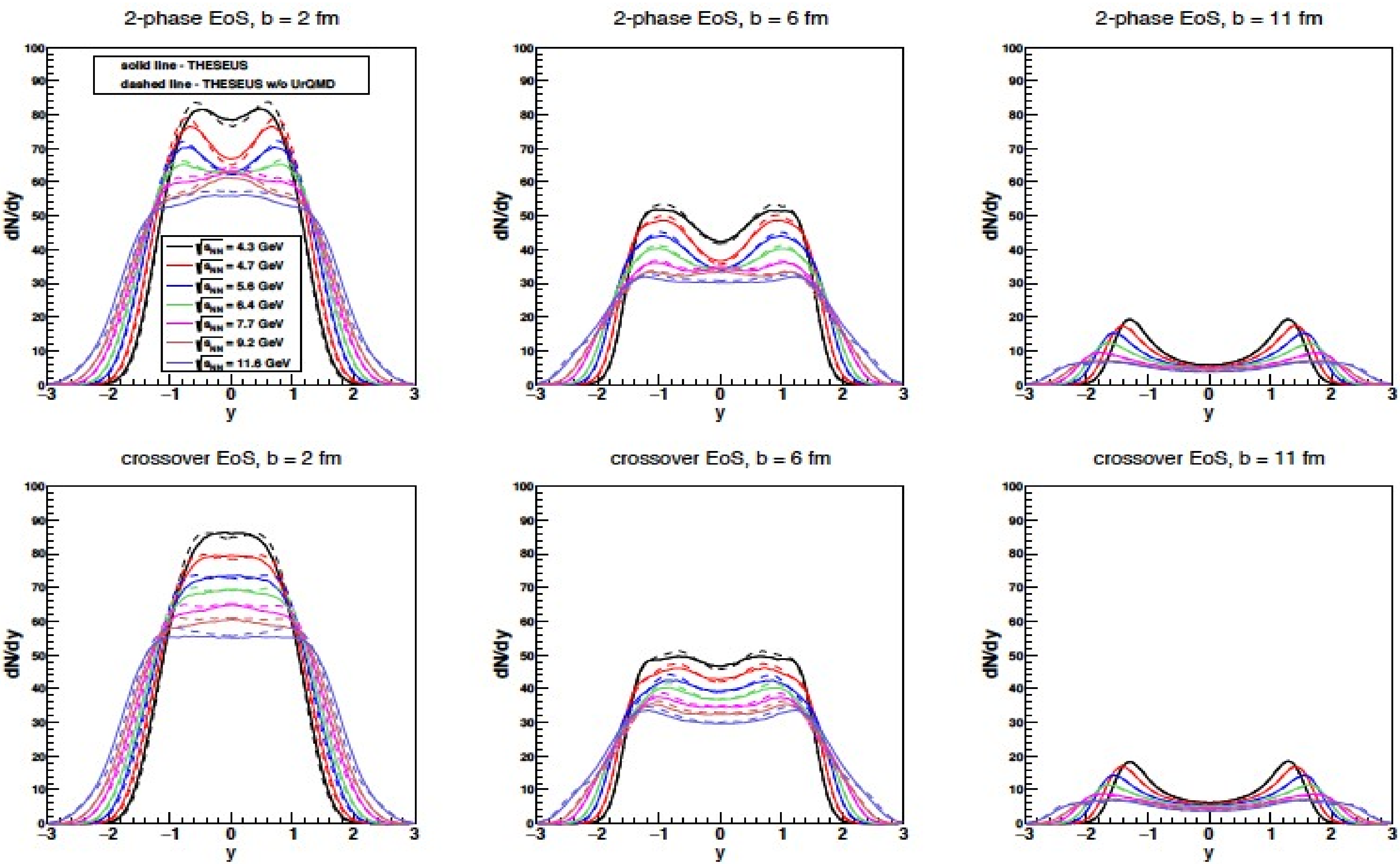
$\sqrt{s_{NN}}$ [GeV]	4.3	4.7	5.6	6.4	7.7	9.2	11.6
E_{lab} [A GeV]	8	10	15	20	30	43	70

arxiv:1608.00965



Baryon stopping signal for first order phase transition ?

Baryon stopping signal for first order phase transition ?



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

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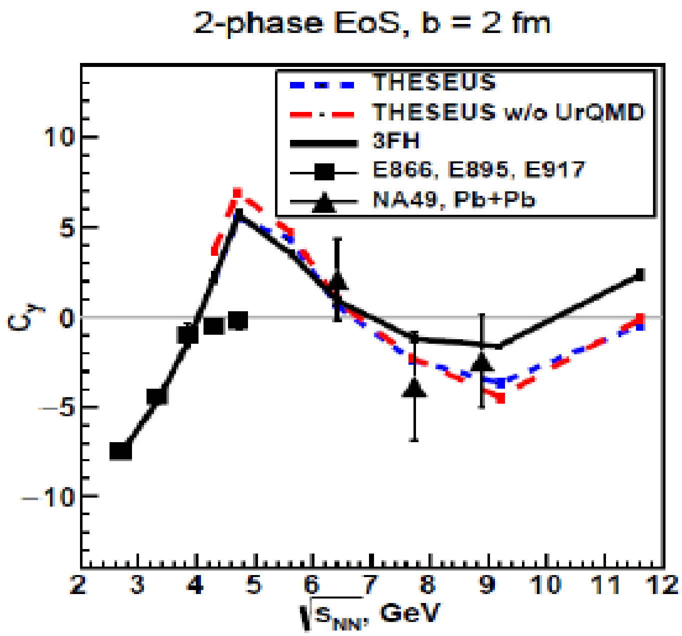
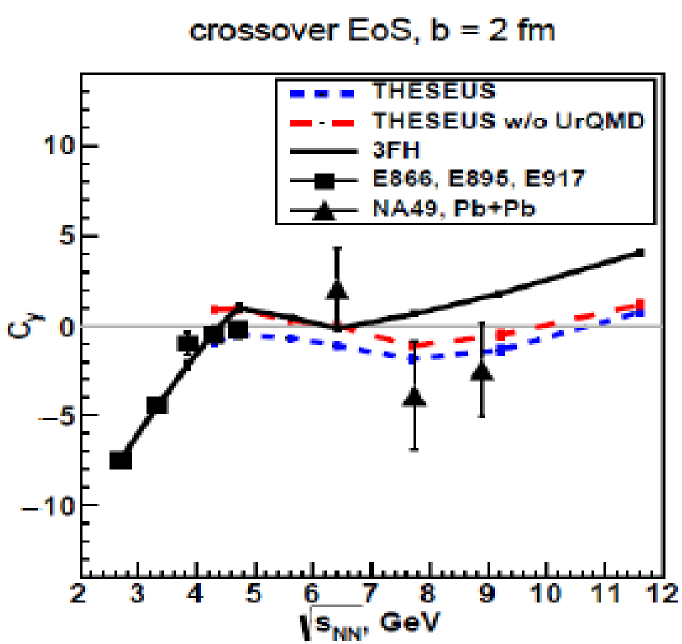


Energy scan of the curvature Cy of the net proton Rapidity distribution at central rapidity y_{cm}

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

Reduced curvature calculated for a parabolic fit

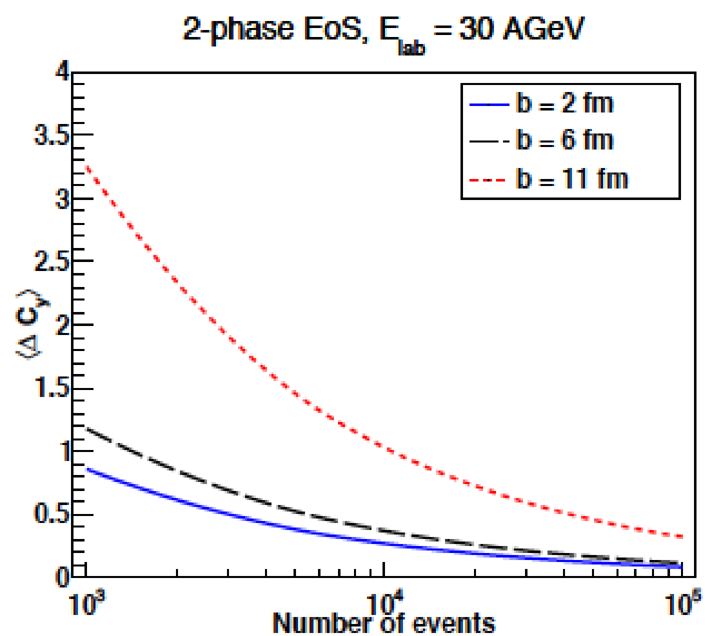
$$\check{P}_2(y) = ay^2 + by + c \longrightarrow C_y = y_{\rm beam}^2 2a/c$$



Statistical error

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

depends on number of events →



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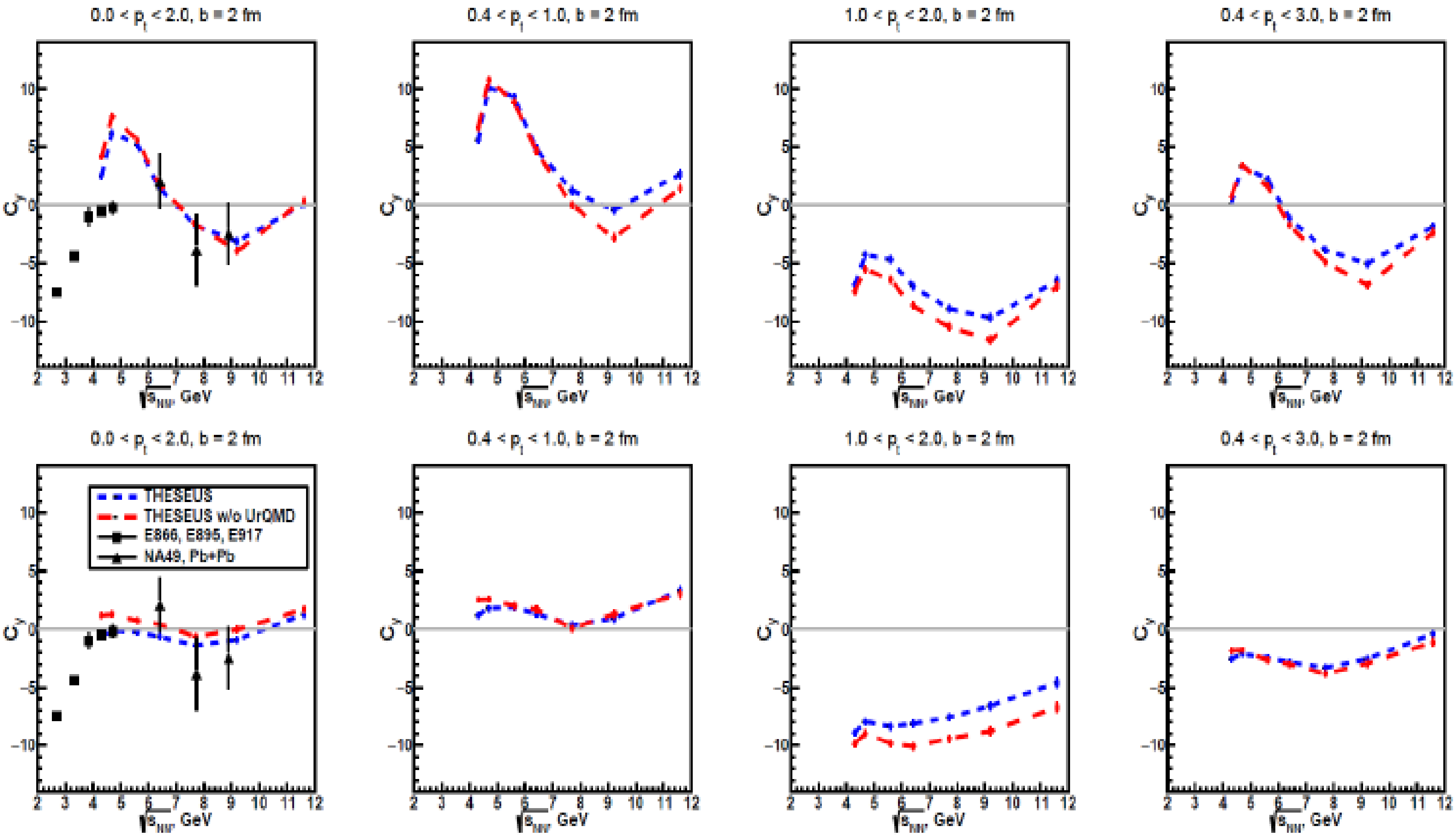

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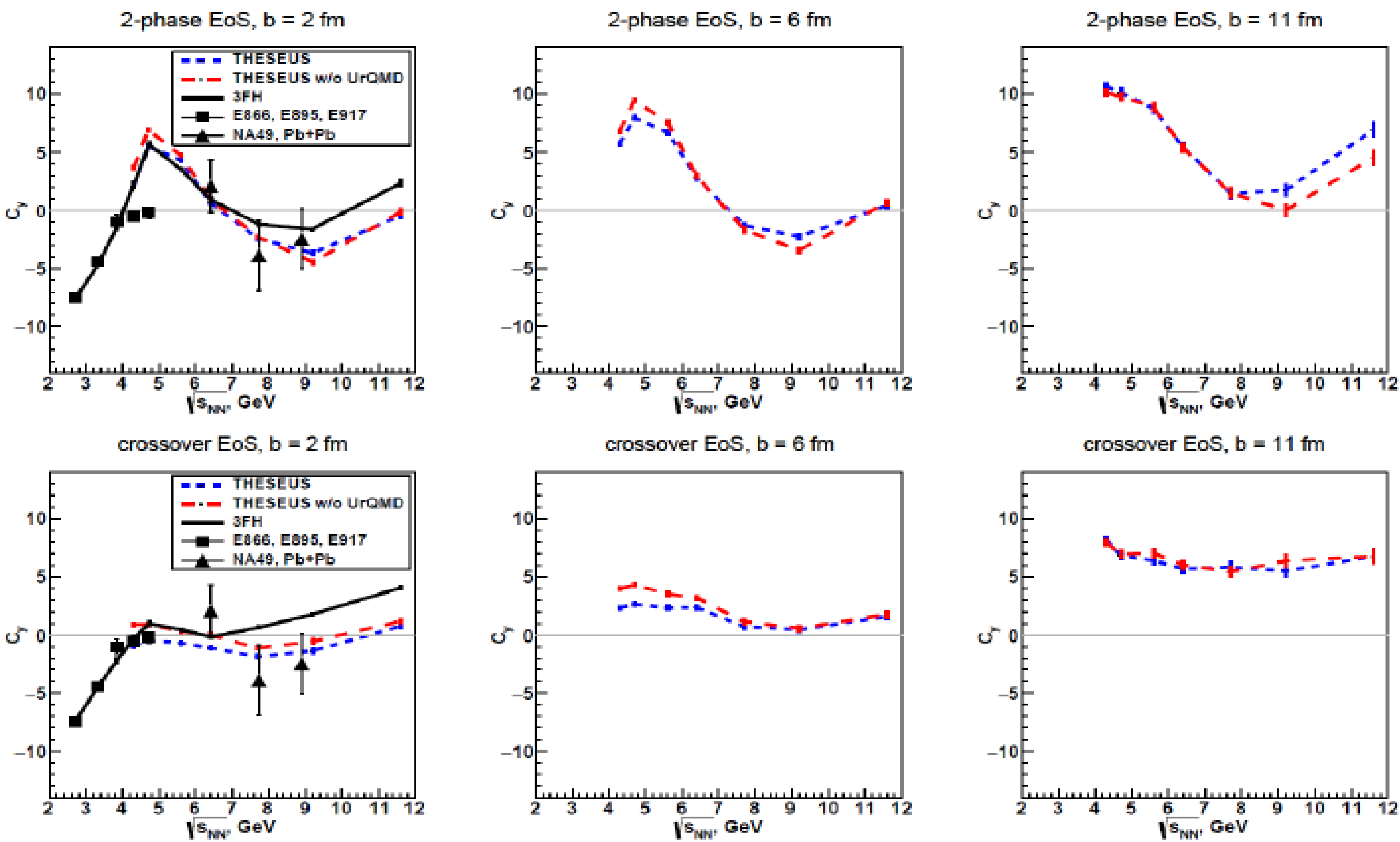
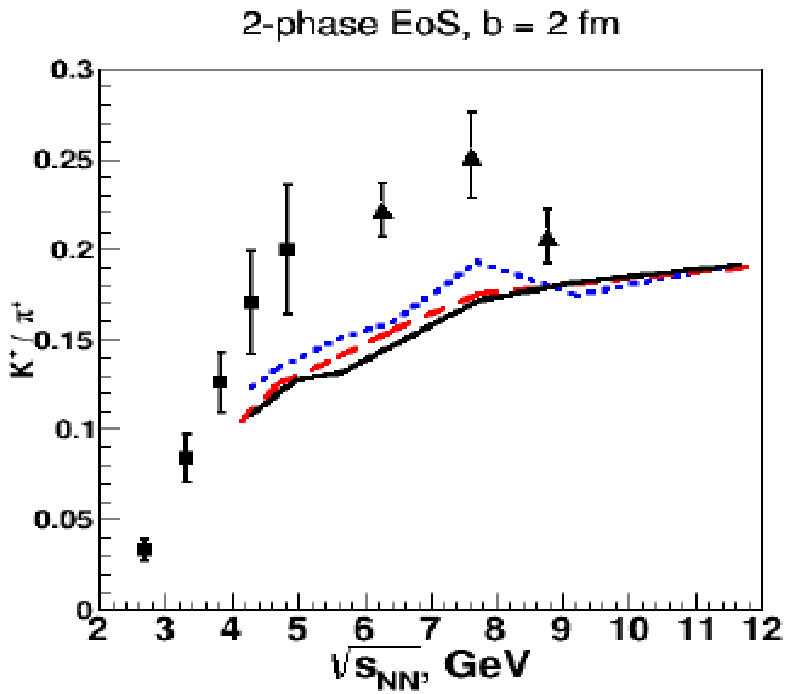


P. Batyuk, D.B., M. Bleicher, Yu. Ivanov, Iu. Karpenko, M. Nahrgang et al., arxiv:1608.00965

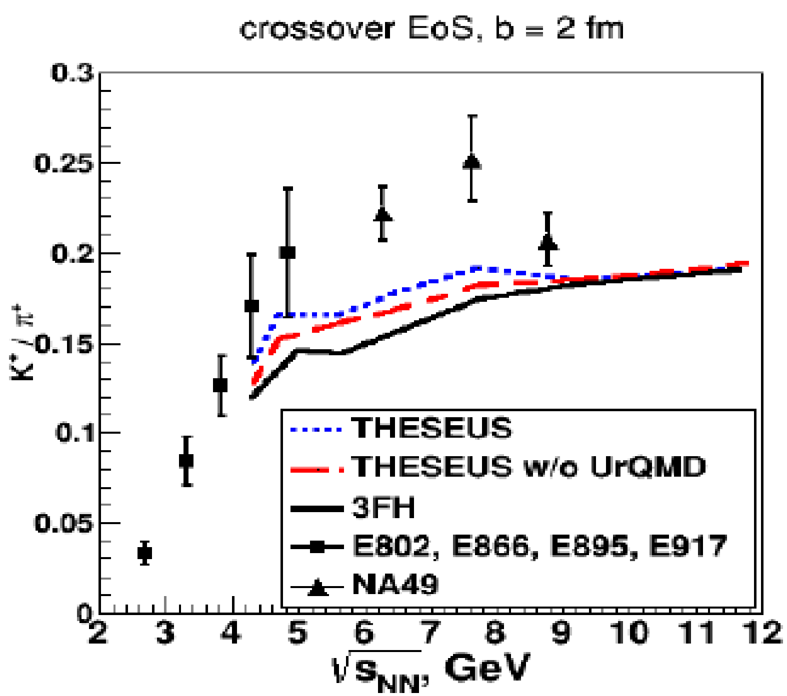
What about K+/π+ (Marek's horn) in THESEUS ?



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

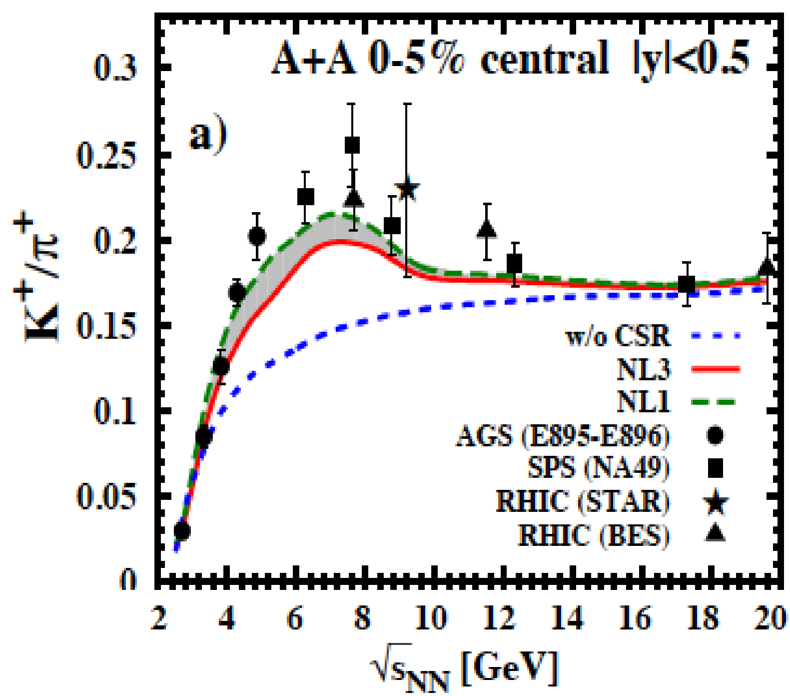
--> some key element still missing in the program

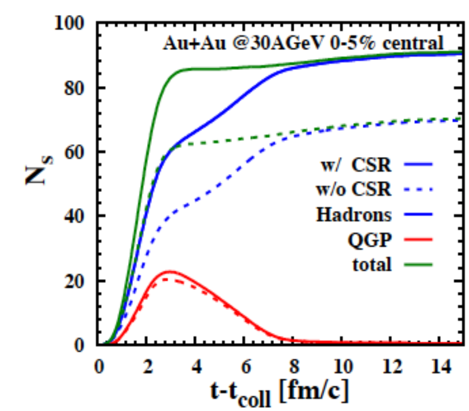
P. Batyuk, D.B., M. Bleicher et al., arxiv:1608.00965



Recent new development in PHSD

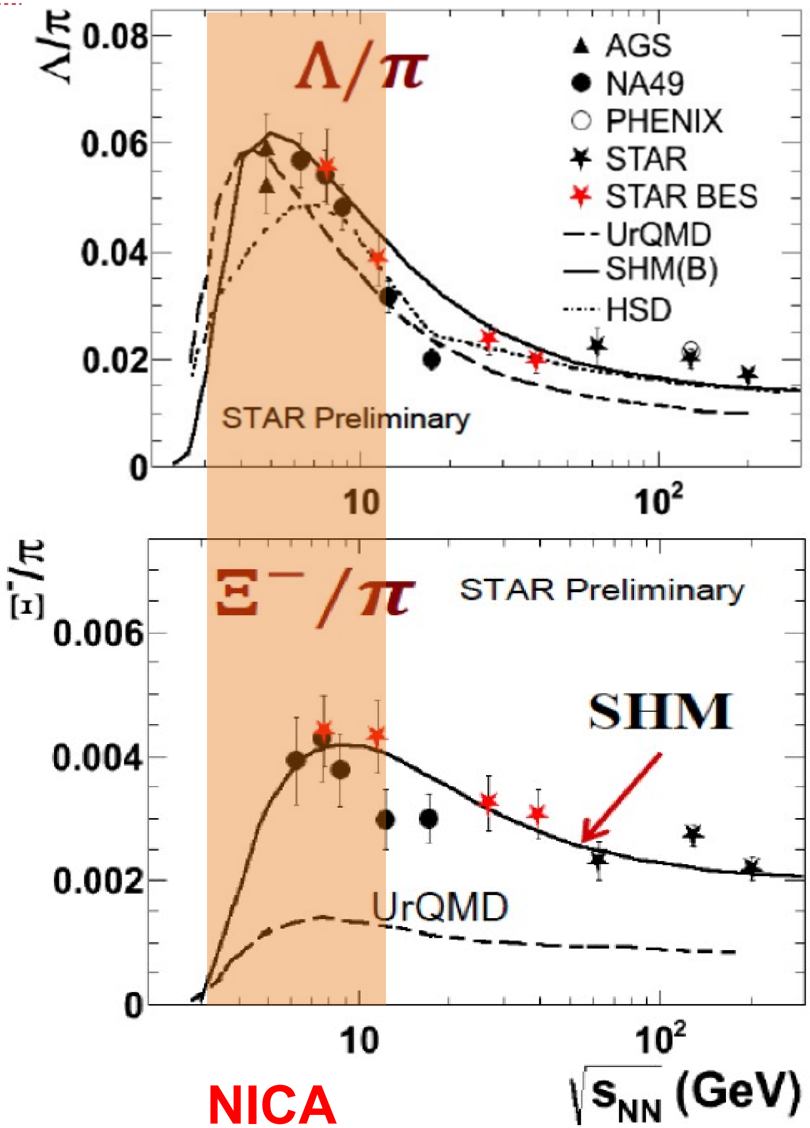
Chiral symmetry restoration in HIC at intermediate ..."
A. Palmese et al., arxiv: 1607.04073





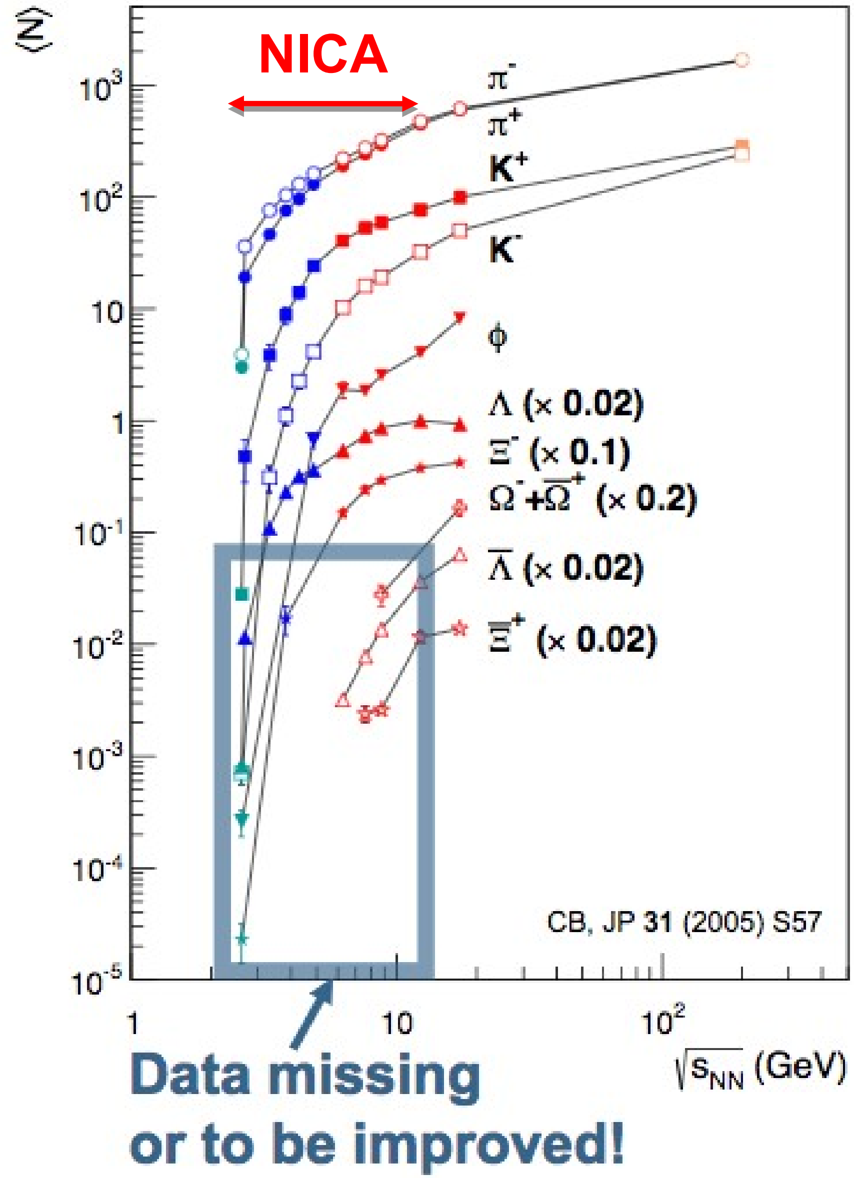
Strange particle number increase by CSR

Strange baryon to pion ratios



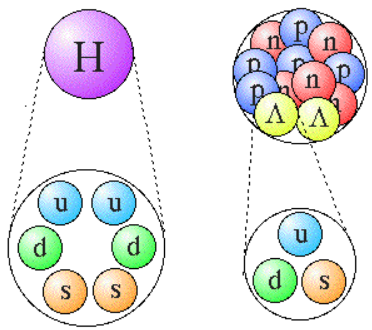
D. Tlusty, SQM-2017

Total yields



C. Blume, SQM-2017

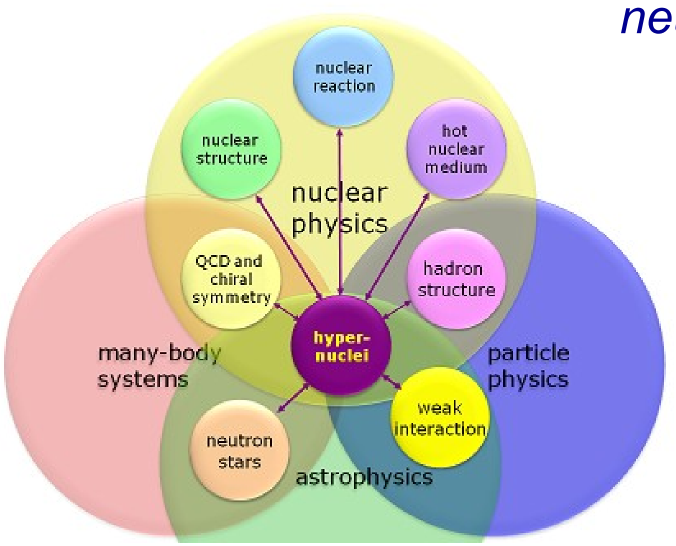
Hypernuclei

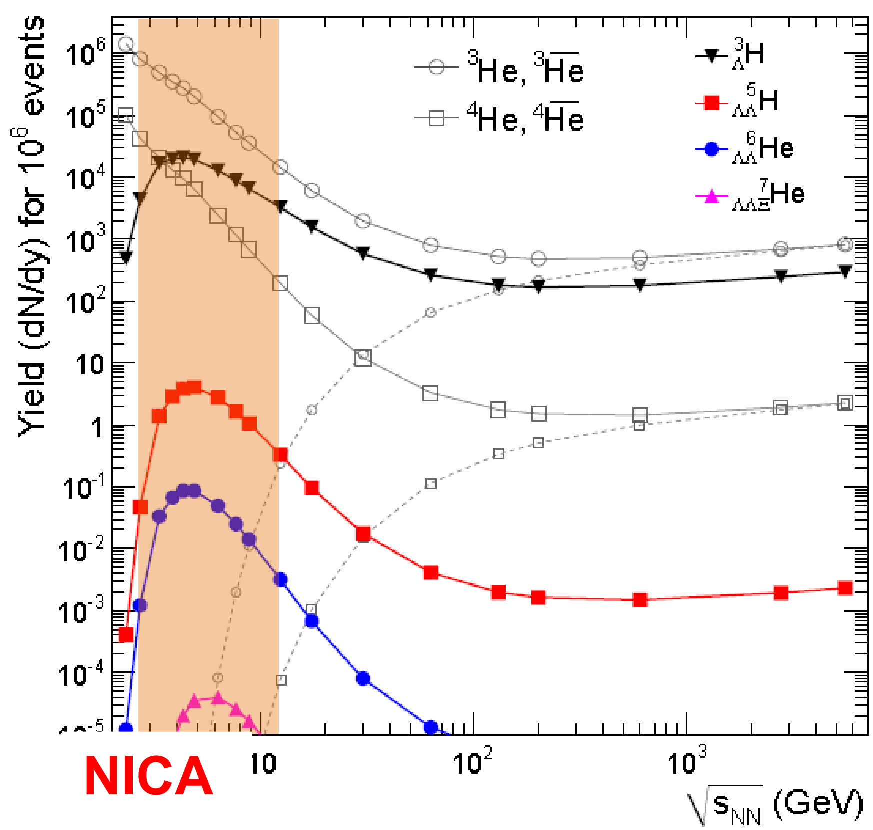


Hypernuclei provides unique opportunity to study the strange particle-nucleus interaction in a many-body environment.

production enhanced at high baryon densities (NICA)

On the astrophysical scale the appearance of hyperons in the dense core of a neutron star has been a subject of extensive studies since the early days of neutron star research





A. Andronic et al., Phys. Lett. B697 (2011) 203

Conclusions

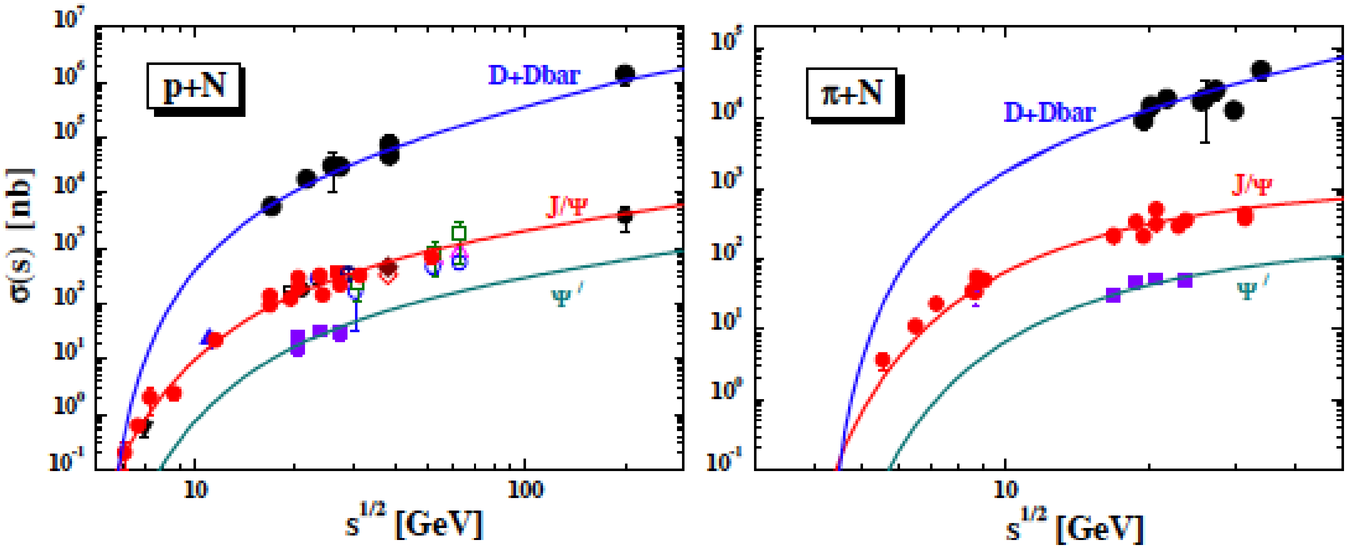
1. Light flavors and Hypernuclei: Spectra and Yields/ratios

2. Correlations & Fluctuations: Collective flow for hadrons; Femtoscopy

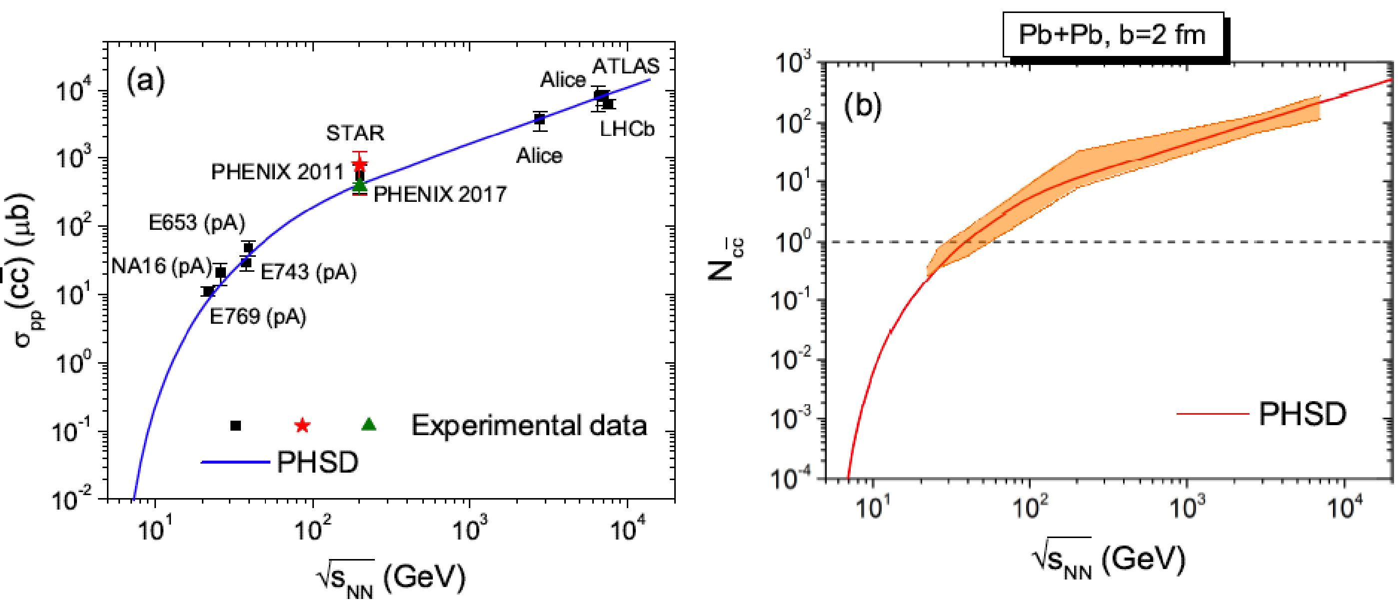
3. Electromagnetic probes: In-medium spectral properties – Mott effect for hadrons?

4. Heavy flavors: Charm at threshold in MPD – or even subthreshold?

Heavy Flavours ?



Linnyuk, Bratkovskaya, Cassing, Arxiv:0808.1505



Song, Cassing, Moreau, Bratkovskaya Arxiv:1803.02698

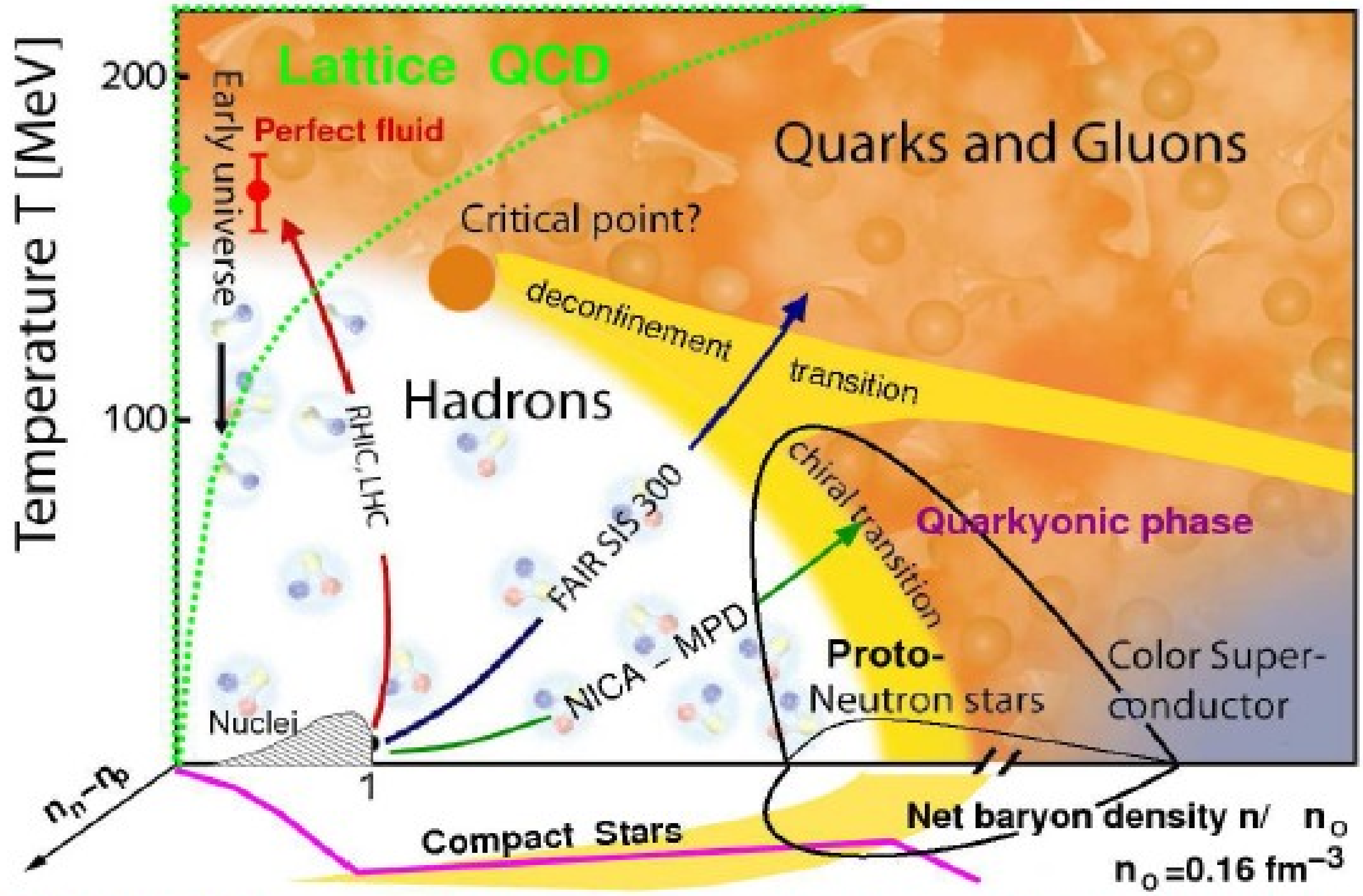
Further developments:

- MPD Detector simulation (Oleg Rogachevsky et al.)

- New 2-phase EoS (Wroclaw group: Bastian)

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

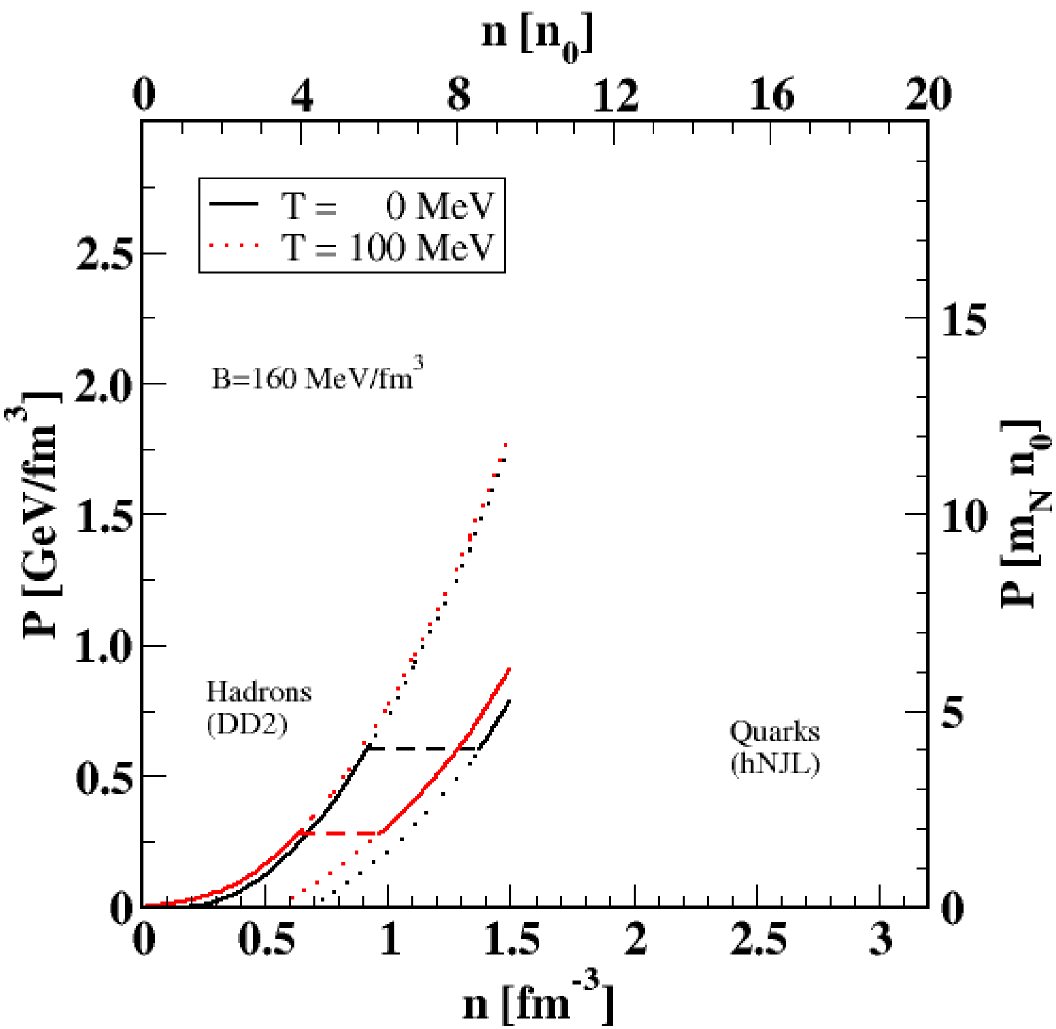
Support a CEP in QCD phase diagram with Astrophysics?

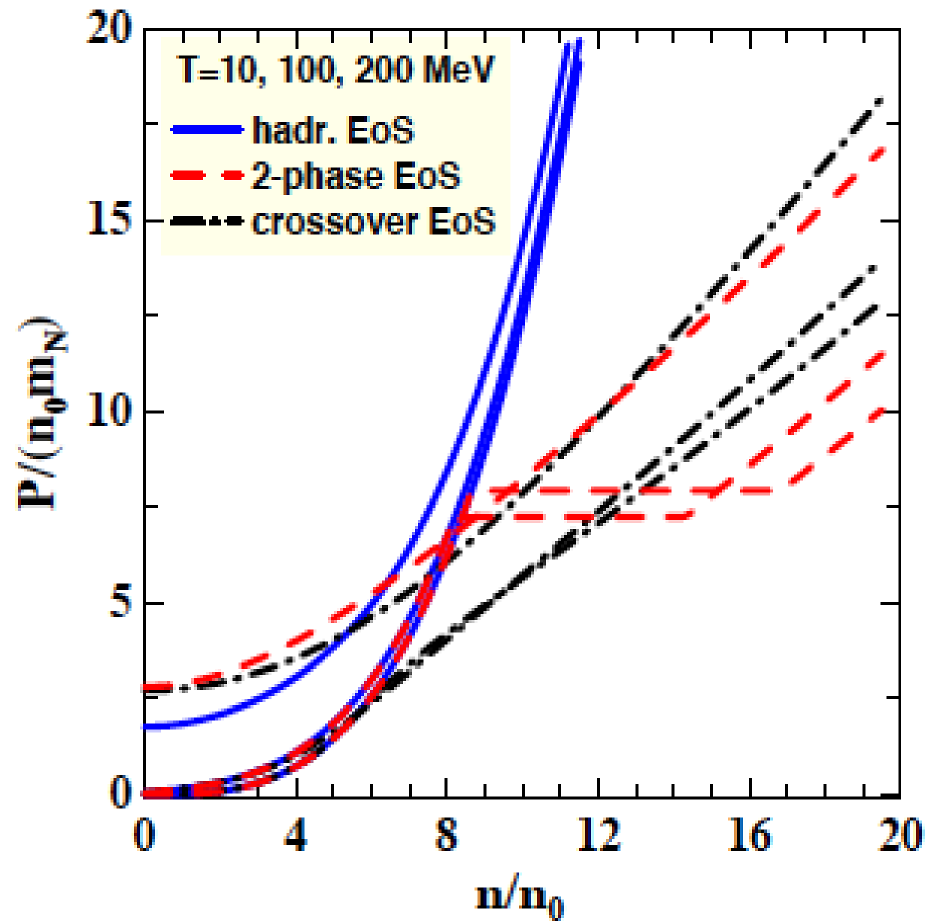


NICA White Paper, http://theor.jinr.ru/twiki-cgi/view/NICA/WebHome

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

Comparison 2-phase EoS

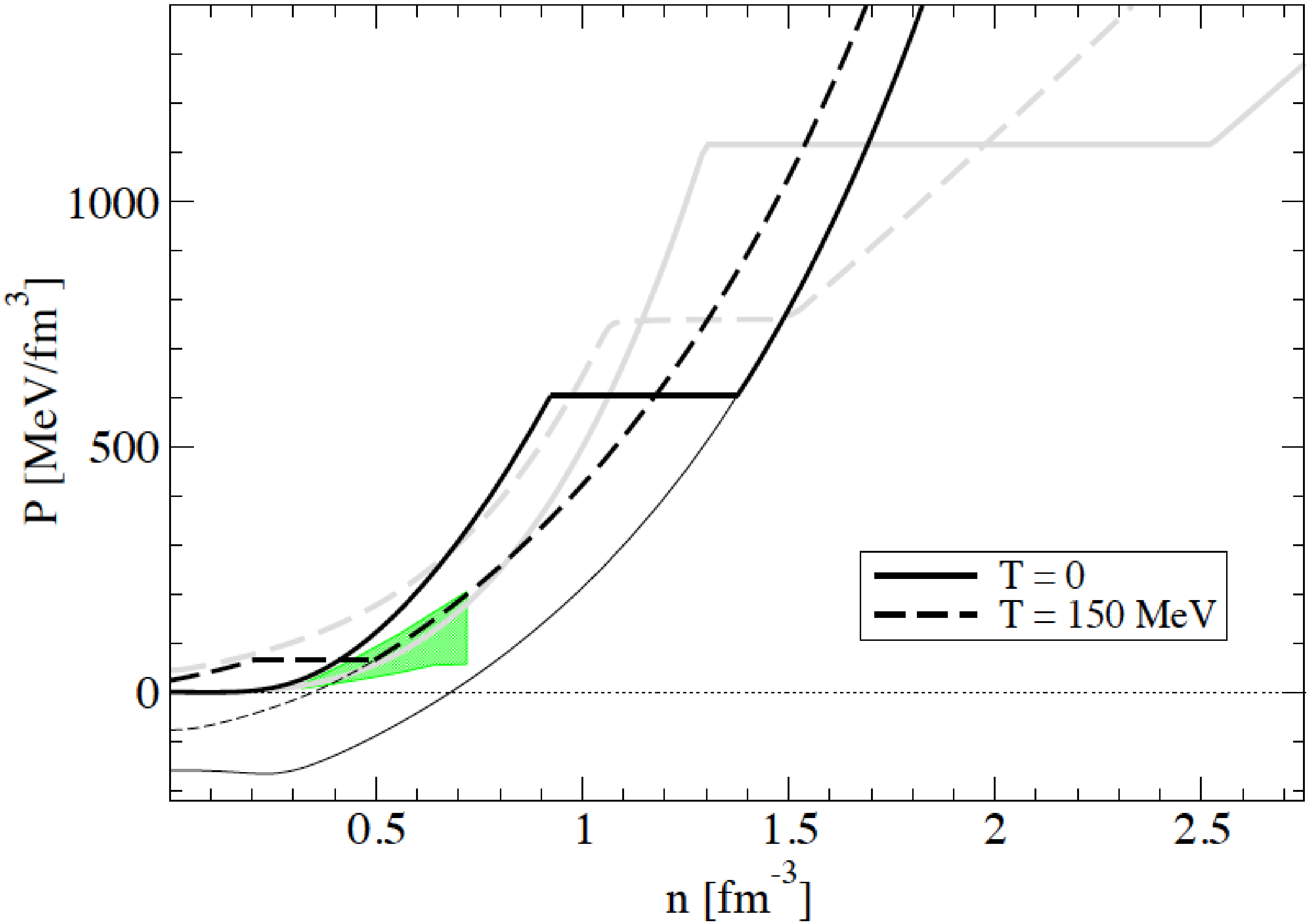




N.-U. Bastian, D. Blaschke (S. Benic, S. Typel), In progress (2016)

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/fm^3

N.-U. Bastian, D. Blaschke, in: Proceedings SQM-2015, JPCS **668** (2016) 012042

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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ift.uni.wroc.pl/~cpod2016

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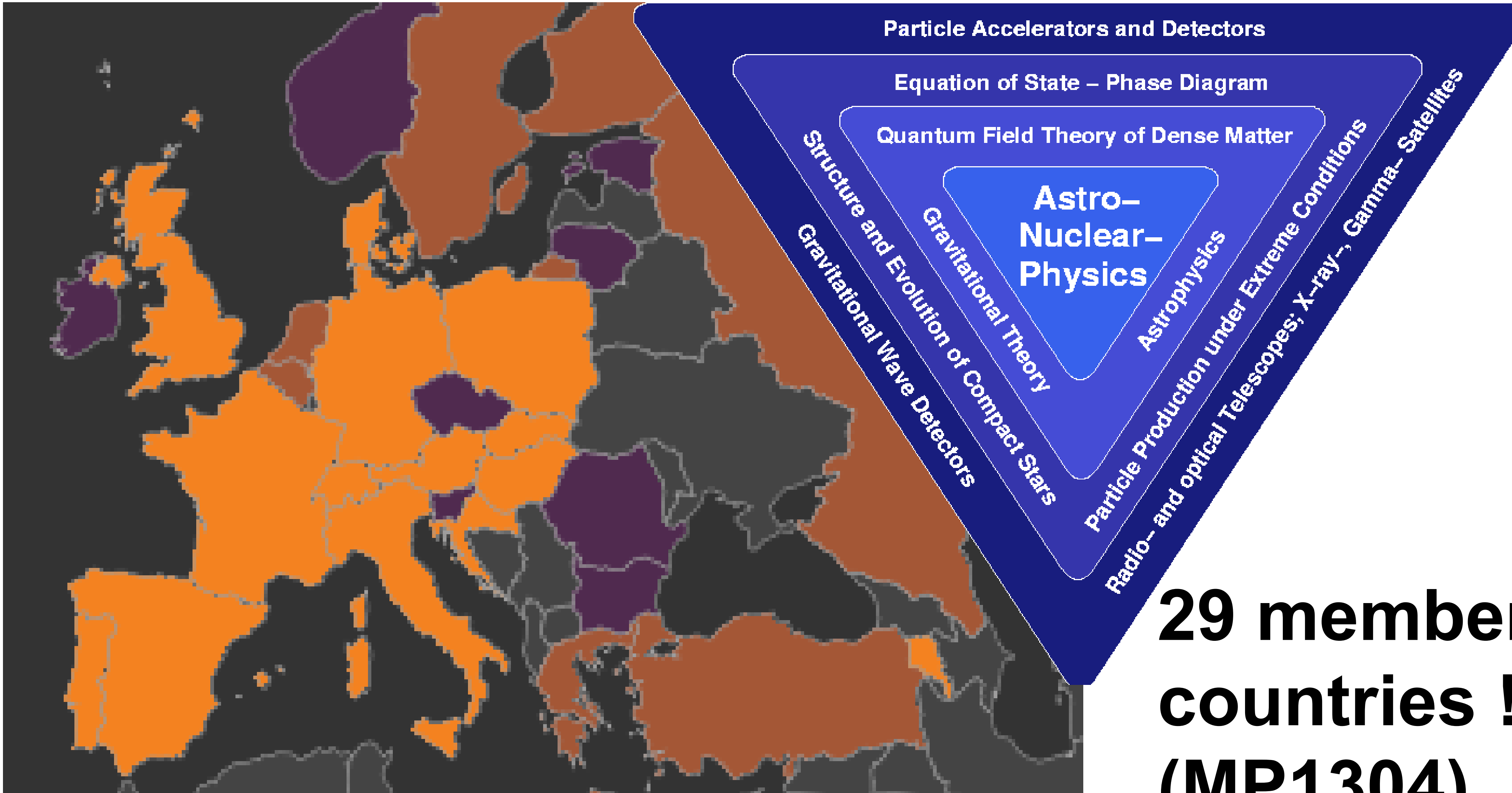

29 member countries !! (MP1304)

New comp star **!**

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IN SCIENCE AND TECHNOLOGY

Kick-off: Brussels, November 25, 2013

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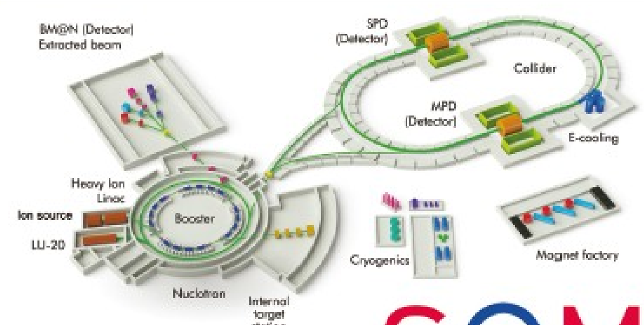

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