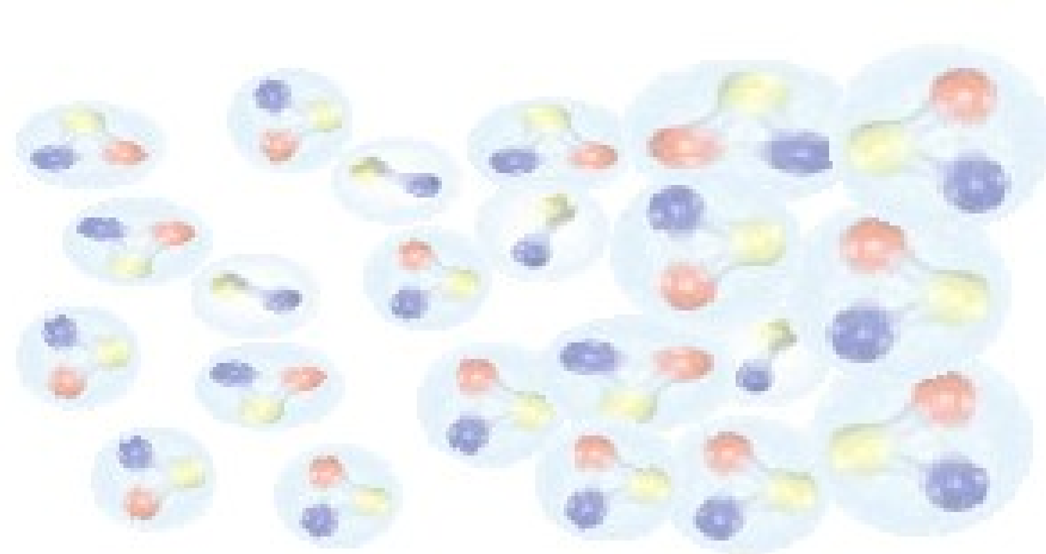
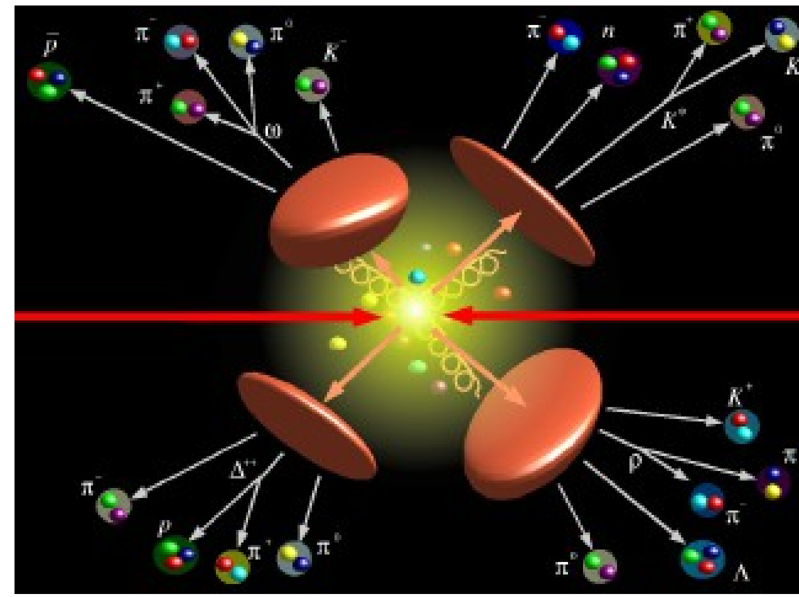
Boiling dense QCD – Theory and event simulation for collisions at NICA and FAIR energies

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





Association of Young Scientists and Specialists, JINR Dubna, 15.03.2016

DUBNA

NARODOWE CENTRUM NAUKI

EUROPEAN COOPERATION IN SCIENCE AND TECHNOLOGY

Uniwersytet Wrocławski

HIC for FAIR
Helmholtz International Center

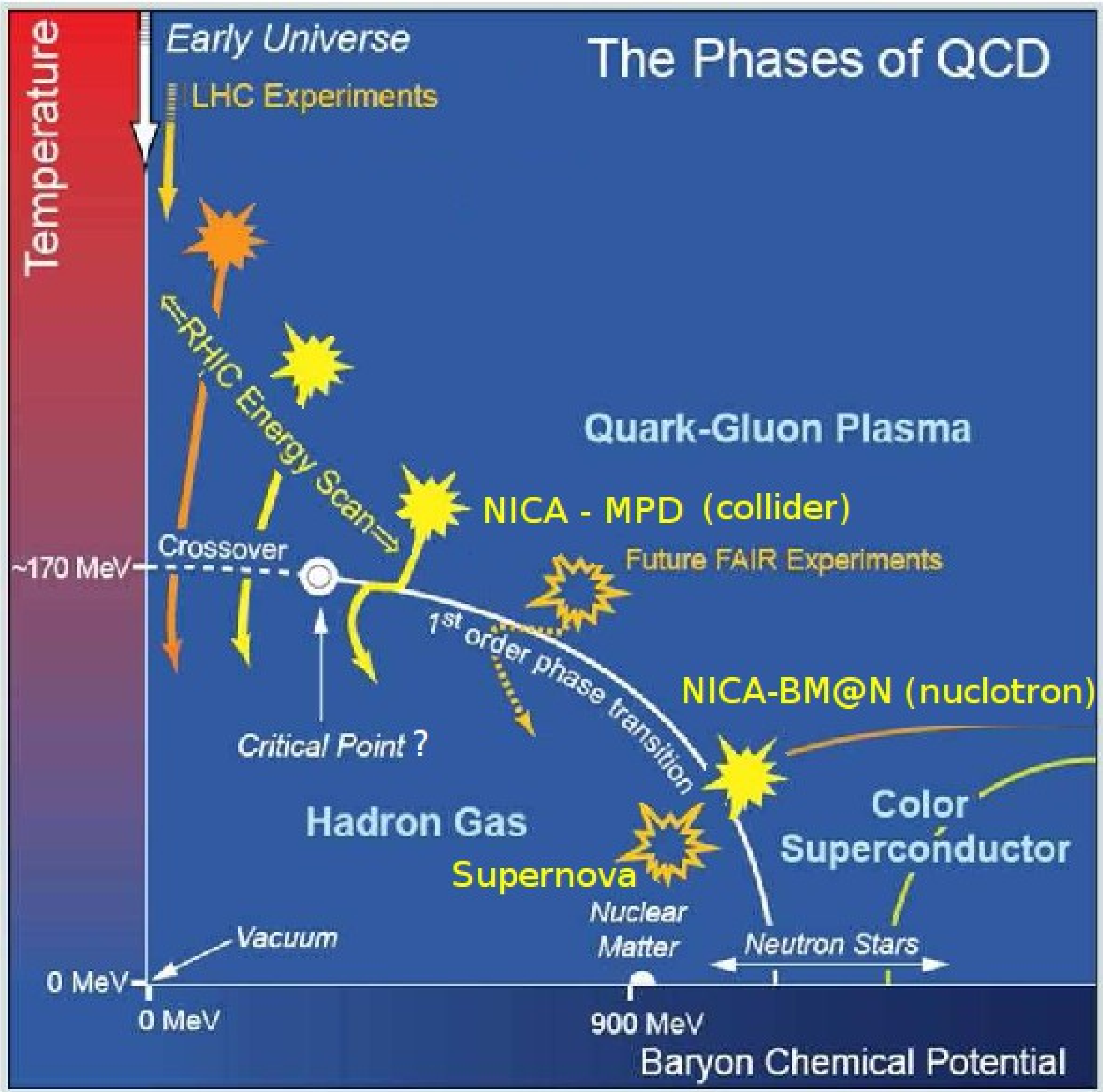
Boiling dense QCD – Theory and event simulation for collisions at NICA and FAIR energies

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

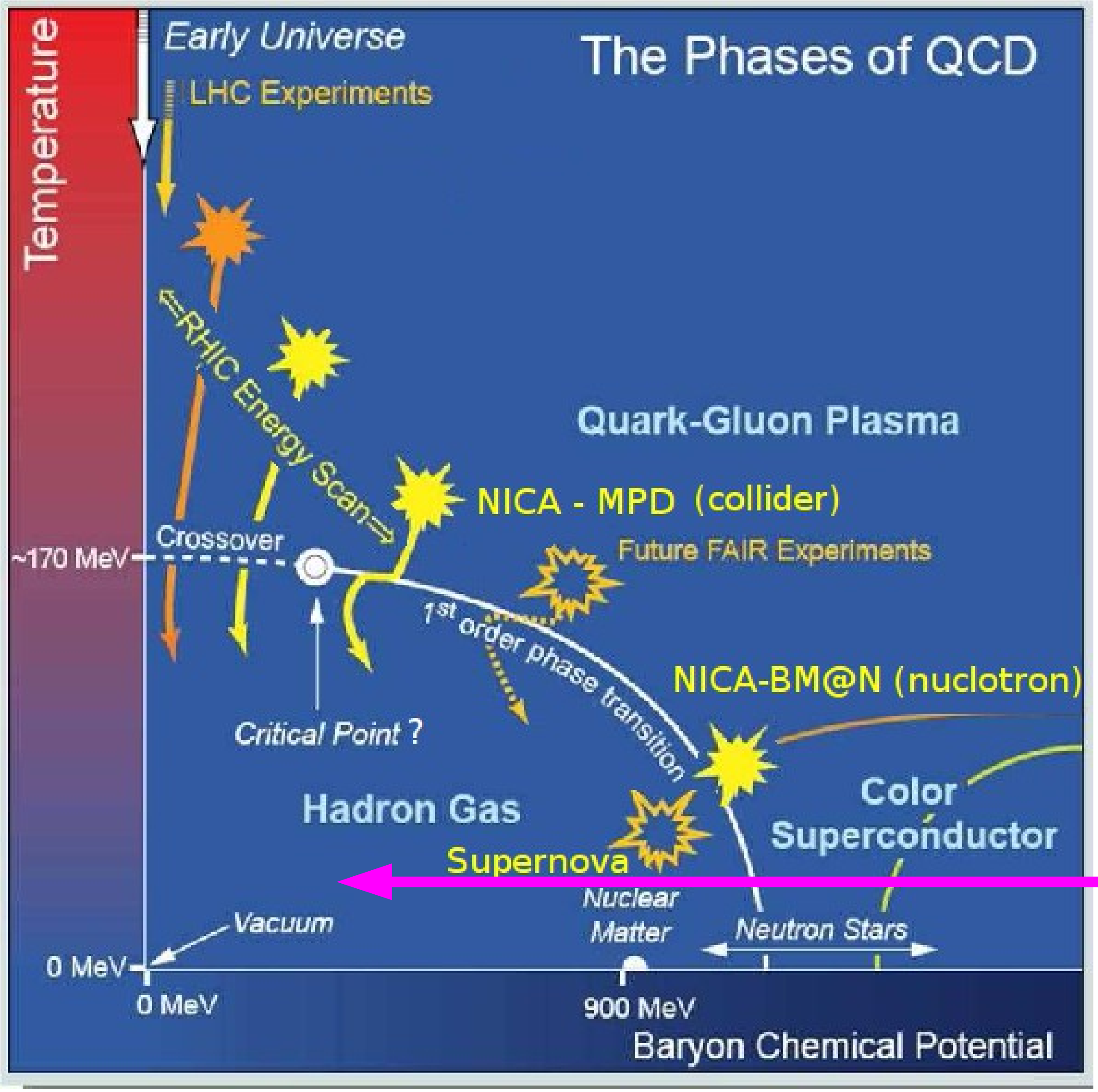
1. **Introduction: Theory of Selfconsistent Quark-Hadron EoS**
2. **THESCoN: Event Simulation for NICA & FAIR**
   A project with FIAS, MEPhI and JINR
3. **First results: Baryon stopping signal for a 1st order PT**
   Particlization and all that ...
4. **Further developments:**
   Flow, Detector response, new class of EoS **...**

Association of Young Scientists and Specialists, JINR Dubna, 15.03.2016

The Goal: Theory of the QCD Phase Diagram



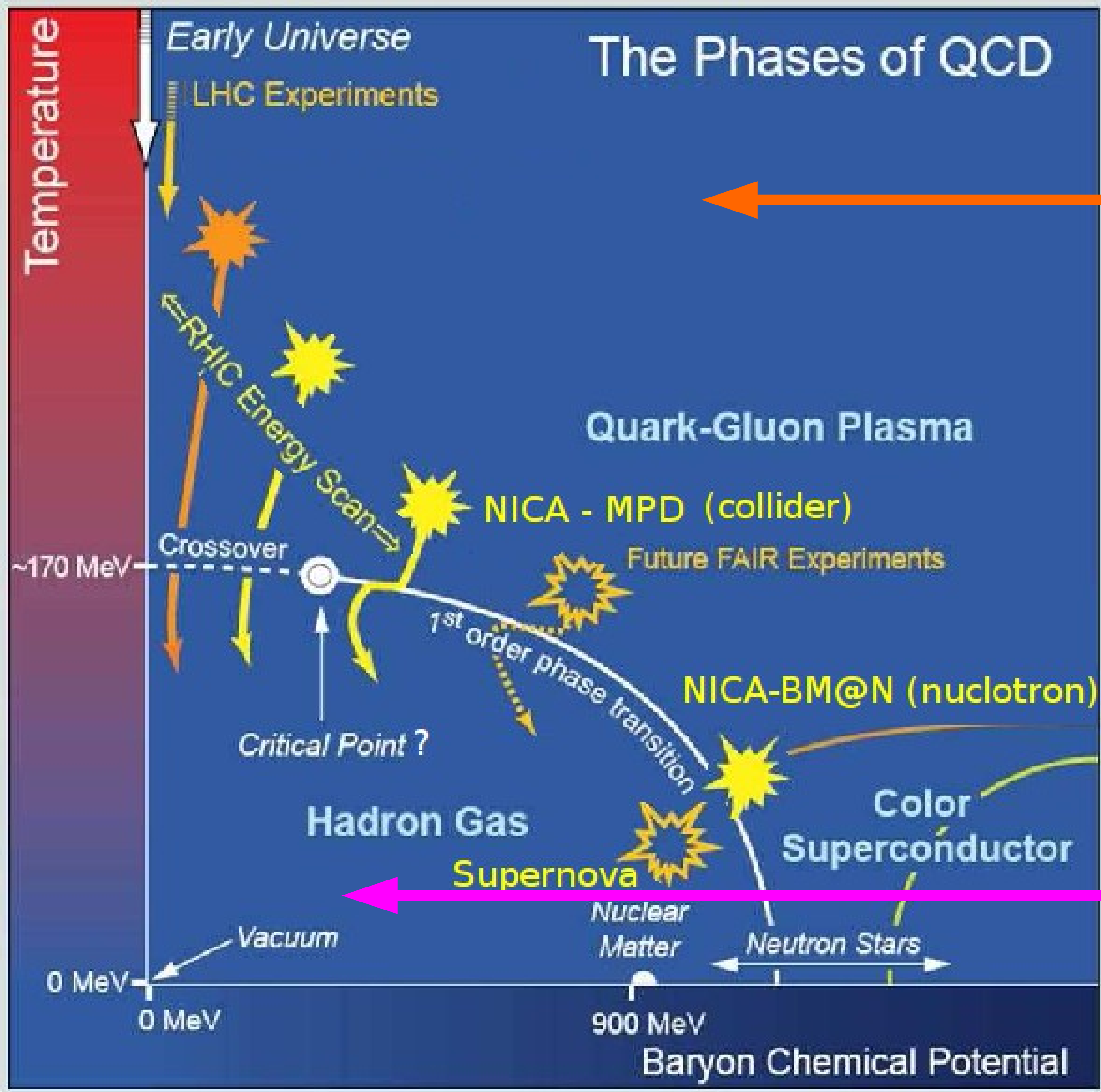
The Goal: Theory of the QCD Phase Diagram



Statistical Model of Hadron Resonance Gas

Well established for Description of chemical freezeout

The Goal: Theory of the QCD Phase Diagram



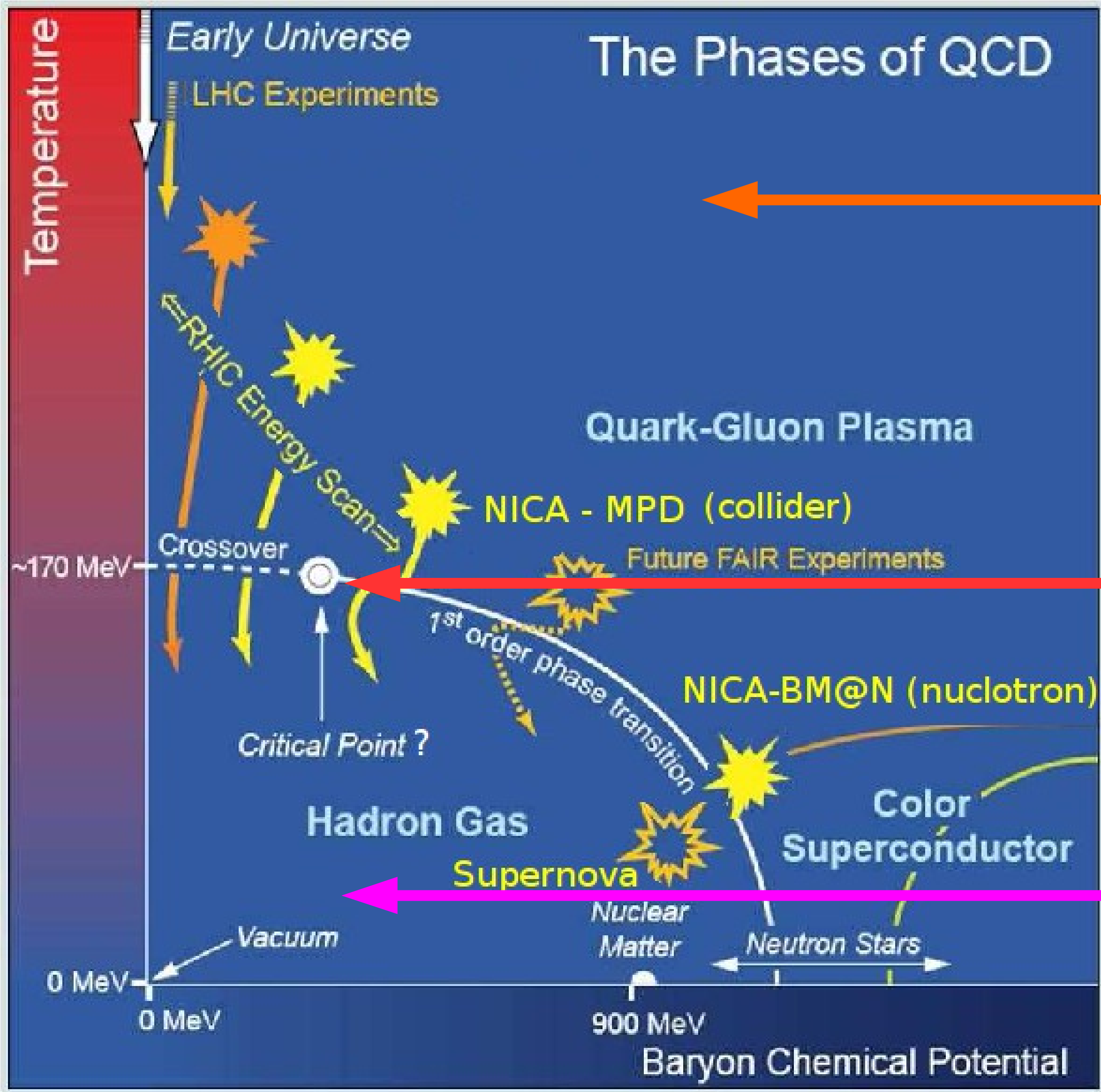
Perturbative QCD

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

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 , $\mu > 1500$ MeV)

QCD Phase transition(s)

Mott dissociation of hadrons, Deconfinement, χSR

Statistical Model of Hadron Resonance Gas

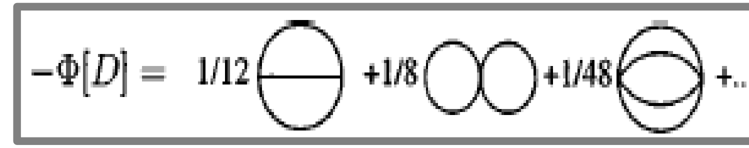
Well established for Description of chemical freezeout

Approximately selfconsistent HTL resumm. QCD

J.-P. Blaizot, E. Iancu, A. Rebhan, Phys. Rev. D 63 (2001) 065003

Skeleton expansion for thermodynamic potential and entropy

$$\beta\Omega[D] = -\log Z = \frac{1}{2}\mathrm{Tr}\log D^{-1} - \frac{1}{2}\mathrm{Tr}\,\Pi D + \Phi[D]$$



Inv. Temp: 1/T   trace in conf. Space   self-energy related to D

Dyson equation: $D^{-1} = D_0^{-1} + \Pi$ Free propagator Do is known

Essential property of Ω[D] is Stationarity under variation of D: δ Ω[D] / δ D = 0

This implies δ Φ[D] / δ D = 1/2 Π

Physical propagator and selfenergy are defined self-consistently !

Self-consistent approximations are defined by the choice of Φ

→ **Φ – derivable theories**

G. Baym, Phys. Rev. 127 (1962) 1391

Approximately selfconsistent HTL resumm. QCD

Matsubara summation:

$$\Omega/V = \int \frac{d^4k}{(2\pi)^4} n(\omega)[\mathrm{Im}\log(-\omega^2+k^2+\Pi) - \mathrm{Im}\,\Pi D] \ + T\Phi[D]/V$$

Analytic properties:

$$D(\omega,k) = \int_{-\infty}^{\infty} \frac{dk_0}{2\pi} \frac{\rho(k_0,k)}{k_0-\omega}, \qquad \mathrm{Im}\,D(\omega,k) \equiv \mathrm{Im}\,D(\omega+i\epsilon,k) = \frac{\rho(\omega,k)}{2}.$$

Thermodynamics from entropy density: $\mathcal{S} = -\partial(\Omega/V)/\partial T$

$$\mathcal{S} = -\int \frac{d^4k}{(2\pi)^4} \frac{\partial n(\omega)}{\partial T} \mathrm{Im}\log D^{-1}(\omega,k) \ + \int \frac{d^4k}{(2\pi)^4} \frac{\partial n(\omega)}{\partial T} \mathrm{Im}\,\Pi(\omega,k)\mathrm{Re}\,D(\omega,k) + \mathcal{S}'$$

$$\mathcal{S}' \equiv -\left.\frac{\partial(T\Phi/V)}{\partial T}\right|_D + \int \frac{d^4k}{(2\pi)^4} \frac{\partial n(\omega)}{\partial T} \mathrm{Re}\,\Pi\,\mathrm{Im}\,D \longrightarrow 0$$

for two-loop skeletons

Loosely speaking: S' accounts for residual interactions of "independent quasiparticles"

d/dω [Im log D^{-1} + Im Π Re D] = 2 Im [D Im(d/dω D*) Im Π = 2 $\sin^2\delta$ dδ/dω , for D = $|D|e^{i\delta}$

D. Blaschke, in preparation (2016)

Approximately selfconsistent HTL resumm. QCD

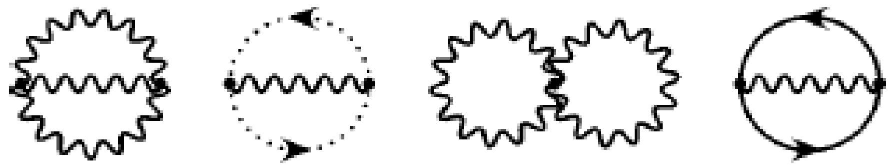
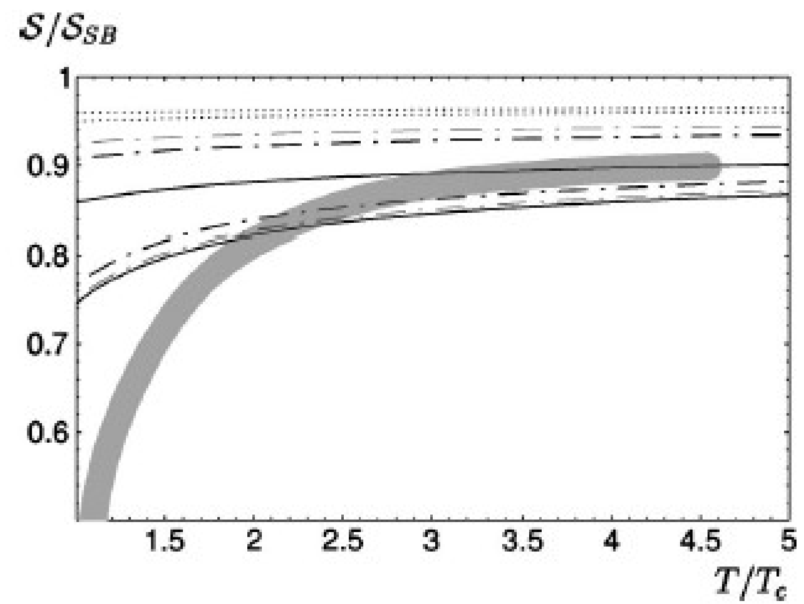


FIG. 3. Diagrams for Φ at 2-loop order in QCD. Wiggly, plain, and dotted lines refer respectively to gluons, quarks, and ghosts.



In ghost-free gauge, HTL resummed QCD thermodyn.

$$\mathcal{S}_2 = -\frac{g^2 N_g T}{48}\left\{\frac{4N+5N_f}{3}T^2 + \frac{3N_f}{\pi^2}\mu^2\right\},$$

$$\mathcal{N}_2 = -\frac{g^2 \mu N_g N_f}{16\pi^2}\left(T^2 + \frac{\mu^2}{\pi^2}\right),$$

$$P_2 = -\frac{g^2 N_g}{32}\left\{\frac{4N+5N_f}{18}T^4 + \frac{N_f}{\pi^2}\mu^2 T^2 + \frac{N_f}{2\pi^4}\mu^4\right\}$$

J.-P. Blaizot, E. Iancu, A. Rebhan, Phys. Rev. D 63 (2001) 065003

1. Cluster expansion in the 2PI formalism

- $\Phi-$ derivable approach to the grand canonical thermodynamic potential
  [Baym, Phys. Rev. 127 (1962) 139]

$$J = -\mathrm{Tr}\{\ln(-G_1)\} - \mathrm{Tr}\{\Sigma_1 G_1\} + \mathrm{Tr}\{\ln(-G_2)\} + \mathrm{Tr}\{\Sigma_2 G_2\} + \Phi[G_1, G_2]$$

with full propagators:
$G_1^{-1}(1,z) = z - E_1(p_1) - \Sigma_1(1,z)$; $G_2^{-1}(12,1'2',z) = z - E_1(p_1) - E_2(p_2) - \Sigma_2(12,1'2',z)$
and selfenergies

$$\Sigma_1(1,1') = \frac{\delta\Phi}{\delta G_1(1,1')}\,;\Sigma_2(12,1'2',z) = \frac{\delta\Phi}{\delta G_2^{-1}(12,1'2',z)}.$$

Because of stationarity equivalent to

$$n = -\frac{1}{\Omega}\frac{\partial J}{\partial\mu} = \frac{1}{\Omega}\sum_1 \int_{-\infty}^{\infty}\frac{d\omega}{\pi} f_1(\omega) S_1(1,\omega)\,,$$

(baryon number conservation)

- Generalization to A-nucleon clusters in nuclear matter

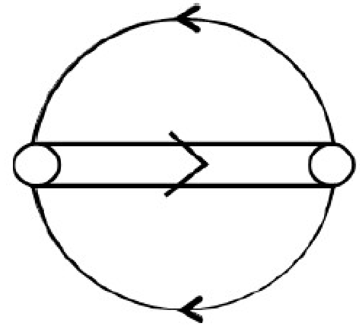
$$\Omega = \sum_A (-1)^A \left[\mathrm{Tr}\ln\left(-G_A^{-1}\right) + \mathrm{Tr}\left(\Sigma_A\, G_A\right)\right] + \Phi\,,$$

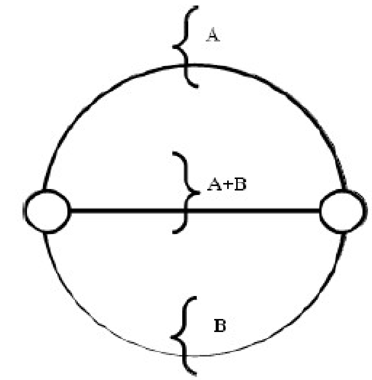
$$G_A^{-1} = G_A^{(0)-1} - \Sigma_A\,,\;\; \Sigma_A(1\dots A, 1'\dots A', z_A) = \frac{\delta\Phi}{\delta G_A(1\dots A, 1'\dots A', z_A)}\,.$$

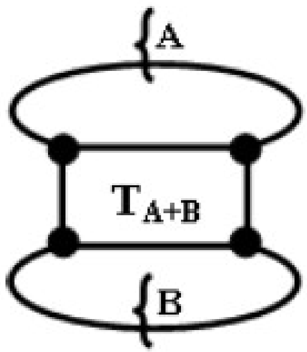
1. Cluster expansion in the 2PI formalism

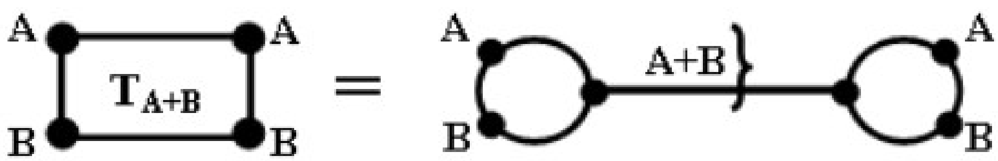
A) Choice of the Φ-functional:

- 2-particle irreducible diagrams
- closed 2-loop diagram involving
  3 cluster propagators (A, B, A+B)
  and 2 vertices
- equivalent to 1 T-matrix + 2 propagators









B) Ansatz for thermodynamic potential:

$$\Omega = \sum_A (-1)^A \left[\mathrm{Tr}\ln\left(-G_A^{-1}\right) + \mathrm{Tr}\left(\Sigma_A\, G_A\right)\right] + \sum_{A,B} \Phi[G_A, G_B, G_{A+B}]\;,$$

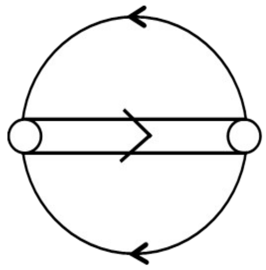
$$G_A^{-1} = G_A^{(0)^{-1}} - \Sigma_A\;,\;\; \Sigma_A(1\ldots A, 1'\ldots A', z_A) = \frac{\delta\Phi}{\delta G_A(1\ldots A, 1'\ldots A', z_A)}\;.$$

C) Check: conservation laws, e.g.:
(correspondence to GF formalism)

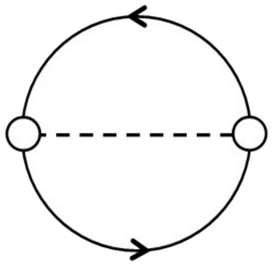
$$n = -\frac{1}{V}\frac{\partial\Omega}{\partial\mu} = \frac{1}{V}\sum_1 \int_{-\infty}^{\infty} \frac{d\omega}{\pi} f_1(\omega) A_1(1,\omega)$$

1. Cluster virial expansion in the 2PI formalism, Examples:

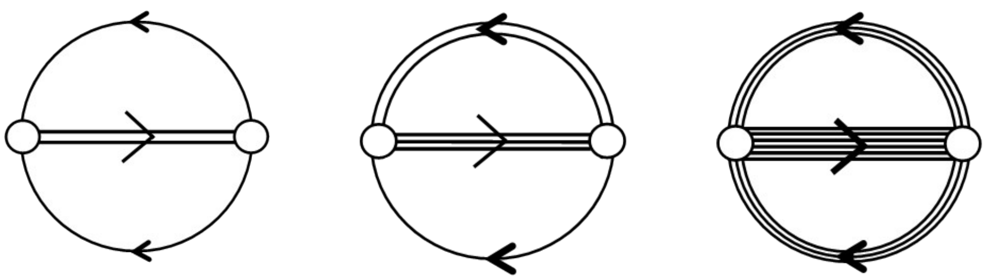
A) Deuterons in nuclear matter (check):



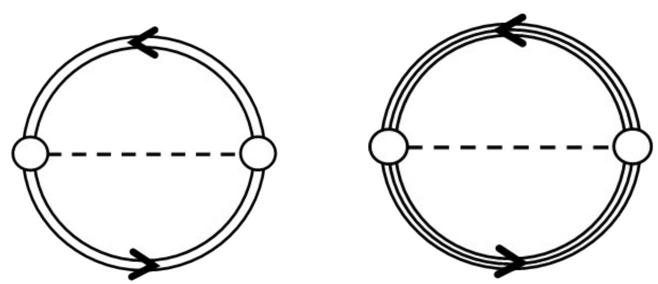
B) Mesons in quark matter:



C) Nucleons in quark matter:

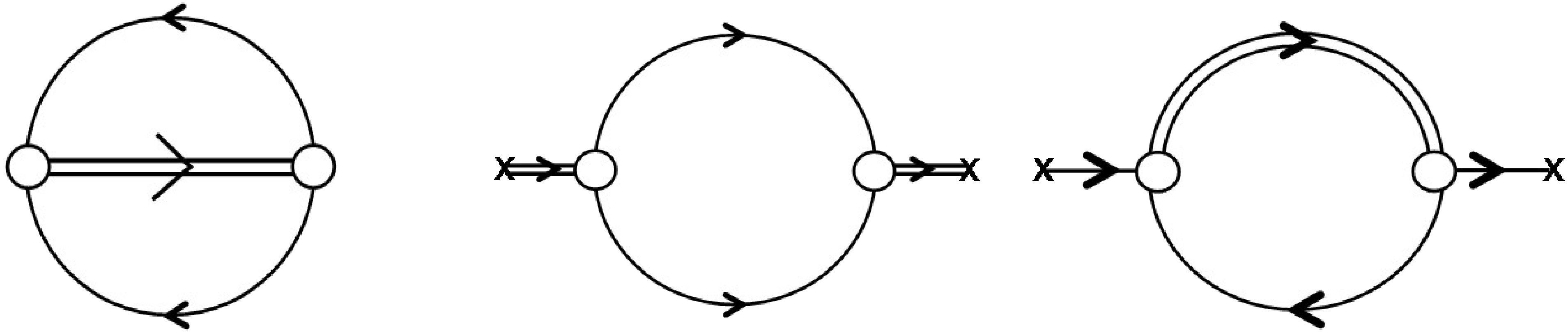


D) Nucleons and mesons (hadron resonance gas) in quark matter:

B) + C) + 

2. Example A: Deuterons in nuclear matter

Φ-functional deuteron selfenergy “Π” nucleon selfenergy



$T^{-1} = V^{-1} - \Pi$ Bethe-Salpeter equation for deuteron T-matrix, ladder approximation

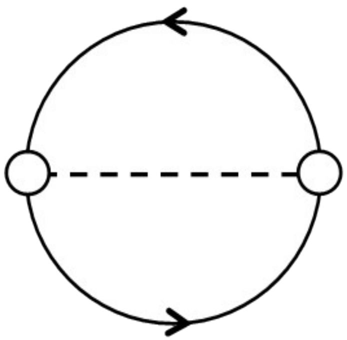
$$\Sigma(1,z) = \sum_2 \int \frac{d\omega}{2\pi} A(2,\omega) \left\{ f(\omega) V(12,12) - \int \frac{dE}{\pi} \Im T(12,12;E+i\eta) \frac{f(\omega)+g(E)}{E-z-\omega} \right\}$$

$$n(\mu,T) = n_{\rm free}(\mu,T) + 2n_{\rm corr}(\mu,T)\,, \quad n_{\rm sc} = \int \frac{dE}{2\pi} g(E) 2\sin^2\delta(E) \frac{d\delta(E)}{dE}\,.$$

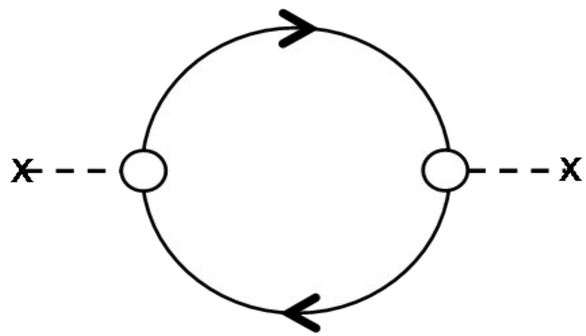
M. Schmidt, G. Roepke, H. Schulz: Ann. Phys. 202 (1990) 57

3. Example B: Mesons in quark matter

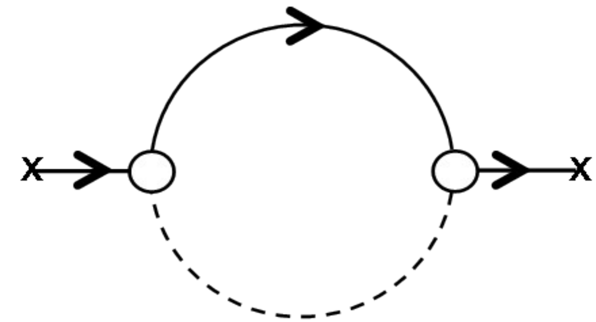
Φ-functional



Meson selfenergy (RPA)



Quark selfenergy



$$T_M^{-1}(q,\omega+i\eta)=G_S^{-1}-\Pi_M(q,\omega+i\eta)=|T_M(q,\omega)|^{-1}\mathrm{e}^{-i\delta_M(q,\omega)}\ , \quad \delta_M(q,\omega)=\arctan(\Im T_M/\Re T_M)$$

$$\Omega=\Omega_{\rm MF}+\Omega_M\ , \qquad \sigma_{\rm MF}=2N_fN_cG_S\int\frac{d^3p}{(2\pi)^3}\frac{m}{E_p}[1-f_-(E_p)-f_+(E_p)]\ ,$$

$$\Omega_{\rm MF}=\frac{\sigma_{\rm MF}^2}{4G_S}-2N_cN_f\int\frac{d^3p}{(2\pi)^3}\left[E_p+T\ln\left(1+\mathrm{e}^{-(E_p-\Sigma_+-\mu)/T}\right)+T\ln\left(1+\mathrm{e}^{-(E_p+\Sigma_-+\mu)/T}\right)\right]\ ,$$

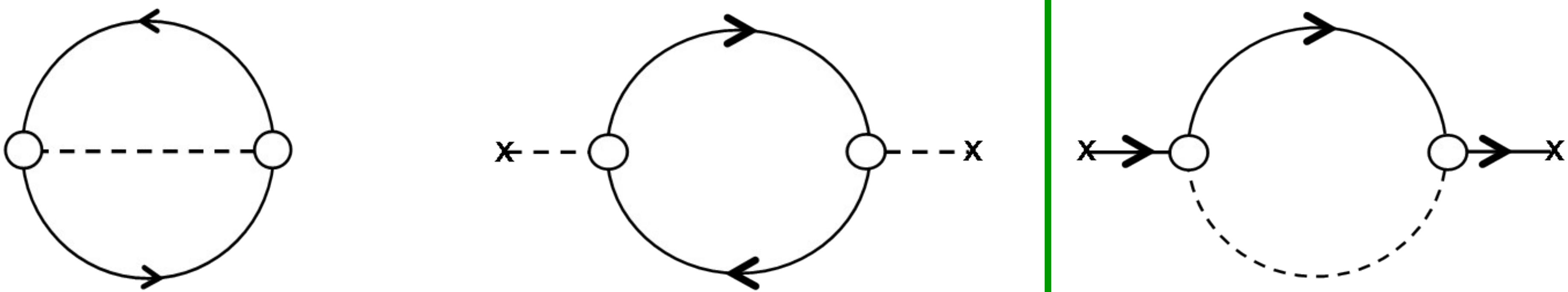
$$\Omega_M=d_M\int\frac{d^3k}{(2\pi)^3}\int\frac{d\omega}{2\pi}\left\{\omega+2T\ln\left[1-\mathrm{e}^{-\omega/T}\right]2\sin^2\delta_M(k,\omega)\,\frac{\delta_M(k,\omega)}{d\omega}\right\}\ ,$$

$$\Sigma_M(\mathbf{0},p_0)=d_M\int\frac{d^4q}{(2\pi)^4}\pi\rho_M(\mathbf{q},q_0)\left\{\frac{(\gamma_0+m/E_q)[1+g(q_0)-f_-(E_q)]}{q_0-p_0+E_q-\mu-i\eta}+\frac{(\gamma_0-m/E_q)[g(q_0)+f_+(E_q)]}{q_0-p_0-E_q-\mu-i\eta}\right\}\ ,$$

D. Blaschke, M. Buballa, A. Dubinin, G. Roepke, D. Zablocki: Ann. Phys. 348 (2014) 228
D. Blaschke, PoS Baldin ISHEPXXII (2015) 113; arxiv:1502.06279

3. Example B: Mesons in quark matter

Φ-functional | Meson selfenergy (RPA) | Quark selfenergy



$$T_M^{-1}(q,\omega+i\eta) = G_S^{-1} - \Pi_M(q,\omega+i\eta) = |T_M(q,\omega)|^{-1} \mathrm{e}^{-i\delta_M(q,\omega)} \,, \quad \delta_M(q,\omega) = \arctan(\Im T_M / \Re T_M)$$

$$\Omega = \Omega_{\rm MF} + \Omega_M \,, \qquad \sigma_{\rm MF} = 2N_f N_c G_S \int \frac{d^3p}{(2\pi)^3} \frac{m}{E_p} [1 - f_-(E_p) - f_+(E_p)] \,,$$

$$\Omega_{\rm MF} = \frac{\sigma_{\rm MF}^2}{4G_S} - 2N_c N_f \int \frac{d^3p}{(2\pi)^3} \left[E_p + T \ln\left(1 + \mathrm{e}^{-(E_p - \Sigma_+ - \mu)/T}\right) + T \ln\left(1 + \mathrm{e}^{-(E_p + \Sigma_- + \mu)/T}\right) \right] \,,$$

$$\Omega_M = d_M \int \frac{d^3k}{(2\pi)^3} \int \frac{d\omega}{2\pi} \left\{ \omega + 2T \ln\left[1 - \mathrm{e}^{-\omega/T}\right] \boxed{2\sin^2\delta_M(k,\omega)} \frac{\delta_M(k,\omega)}{d\omega} \right\} \,,$$

not yet !

$$\Sigma_M(0,p_0) = d_M \int \frac{d^4q}{(2\pi)^4} \pi \rho_M(\mathbf{q},q_0) \left\{ \frac{(\gamma_0 + m/E_q)[1 + g(q_0) - f_-(E_q)]}{q_0 - p_0 + E_q - \mu - i\eta} + \frac{(\gamma_0 - m/E_q)[g(q_0) + f_+(E_q)]}{q_0 - p_0 - E_q - \mu - i\eta} \right\} ,$$

D. Blaschke, M. Buballa, A. Dubinin, G. Roepke, D. Zablocki: Ann. Phys. 348 (2014) 228
D. Blaschke, PoS Baldin ISHEPXXII (2015) 113; arxiv:1502.06279

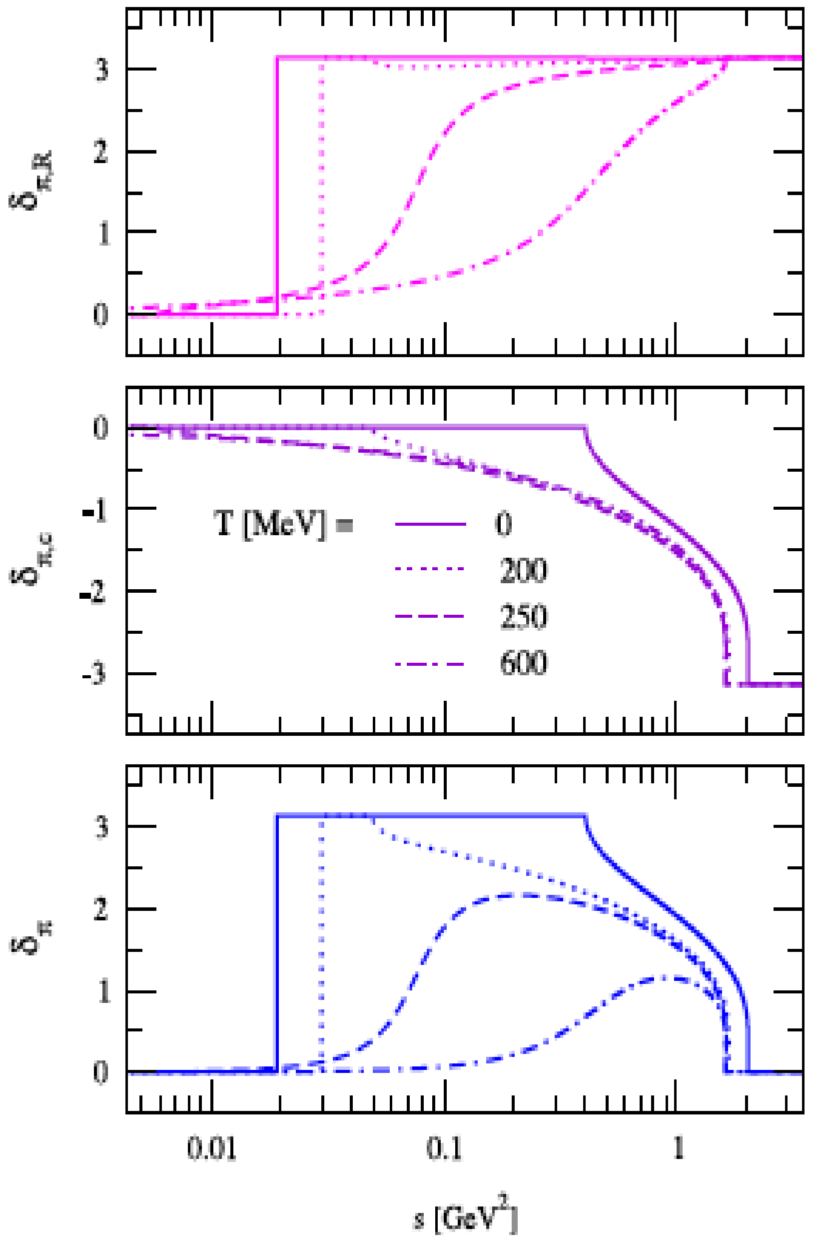
3. Example B: Mesons in quark matter

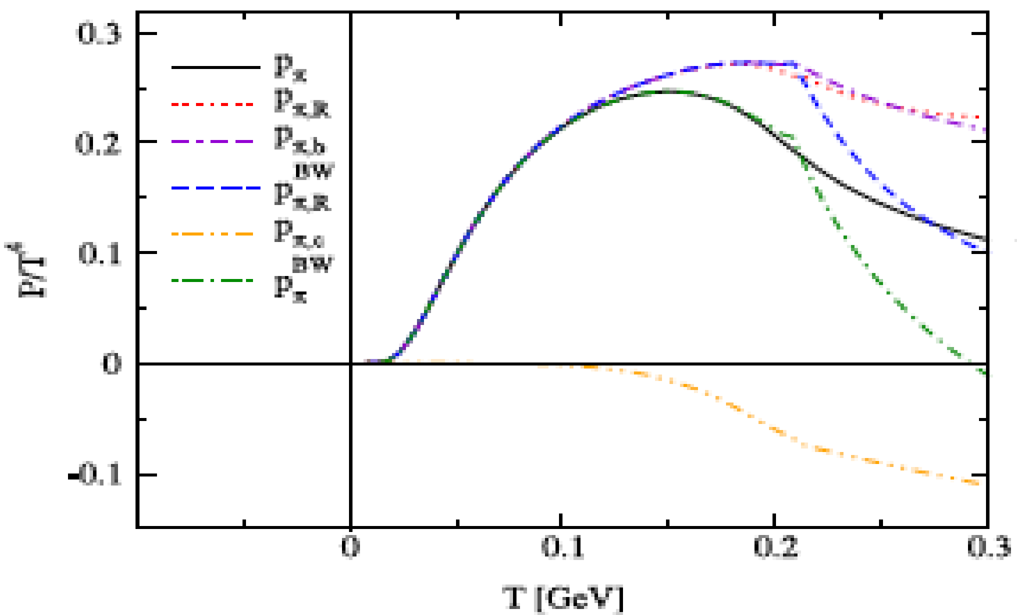
$$\Omega_X(T,\mu) = -d_X \int \frac{d^3q}{(2\pi)^3} \int_{-\infty}^{\infty} \frac{d\omega}{2\pi}\, n_X^-(\omega)\delta_X(\omega,\mathbf{q}),$$

$$\int_0^\infty d\omega \frac{1}{\pi}\frac{d\delta_X(\omega;T)}{d\omega} = 0 = \underbrace{\int_0^{\omega_{\rm thr}(T)} d\omega \frac{1}{\pi}\frac{d\delta_X(\omega;T)}{d\omega}}_{n_{B,X}(T)} + \underbrace{\frac{1}{\pi}\int_{\omega_{\rm thr}(T)}^{\infty} d\omega \frac{d\delta_X(\omega;T)}{d\omega}}_{\frac{1}{\pi}[\delta_X(\infty;T)-\delta_X(\omega_{\rm thr};T)]},$$

$$p_\pi(T) = -d_\pi T \int \frac{d^3q}{(2\pi)^3} \int_0^\infty \frac{d\omega}{\pi} \ln\left(1-e^{-\omega/T}\right) \frac{d\delta_\pi(\omega,\mathbf{q})}{d\omega}$$

$$\delta_\pi \doteq \delta_{\pi,c} + \delta_{\pi,R}$$





D. Blaschke, M. Buballa, A. Dubinin, G. Roepke, D. Zablocki: Ann. Phys. 348 (2014) 228

3. Example B*: Mesons+diquarks in quark matter

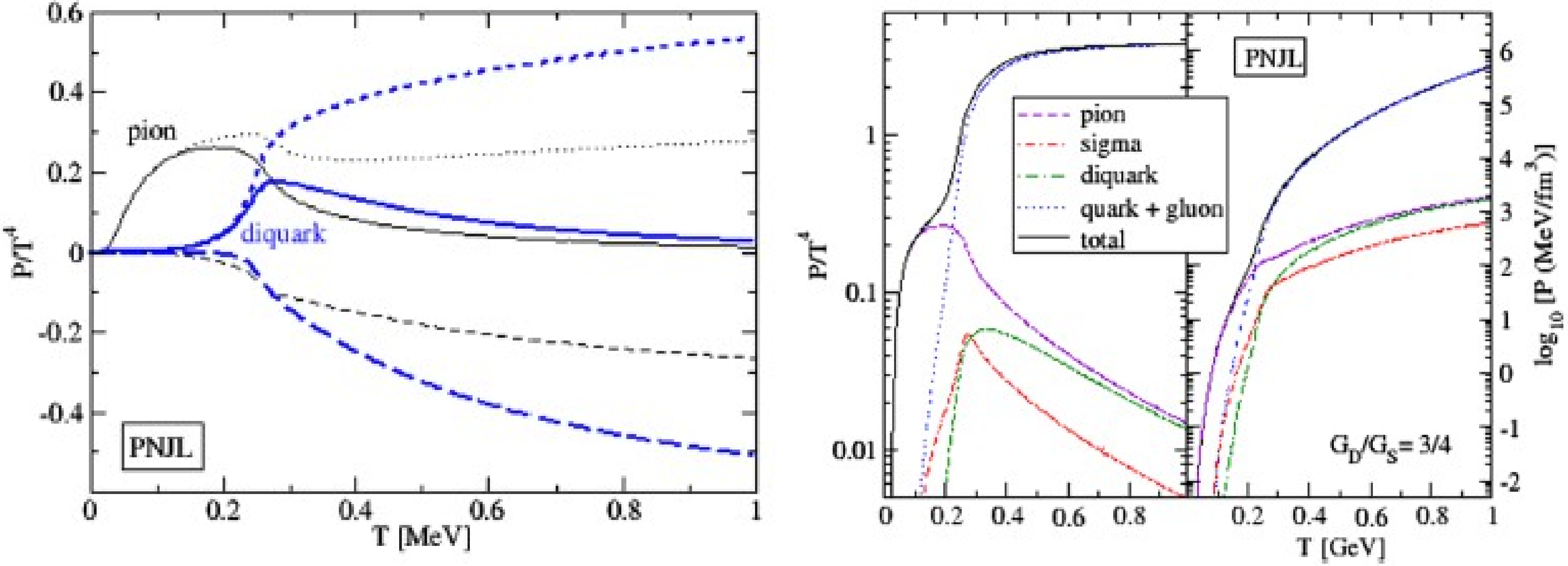
$$\Omega_Q = -\frac{2N_c N_f}{3}\int \frac{dp}{2\pi^2}\frac{p^4}{E_p}[f_\Phi^+(E_p) + f_{\bar\Phi}^-(E_p)],\;\; f_\Phi^+(E_p) = \frac{(\bar\Phi + 2\Phi Y)Y + Y^3}{1 + 3(\bar\Phi + \Phi Y)Y + Y^3},\;\; Y = \mathrm{e}^{-(E_p-\mu)/T}$$

$$X = \mathrm{e}^{-(\omega-2\mu)/T}$$

$$\Omega_D = -3\int \frac{d^3p}{(2\pi)^3}\int \frac{d\omega}{2\pi}[g_\Phi^+(\omega) + g_{\bar\Phi}^-(\omega)]\delta_D(\omega),\;\; g_\Phi^+(\omega) = \frac{(\Phi - 2\bar\Phi X)X + X^3}{1 - 3(\Phi - \bar\Phi X)X - X^3}$$

Suppression of colored states by Polyakov-loop Φ

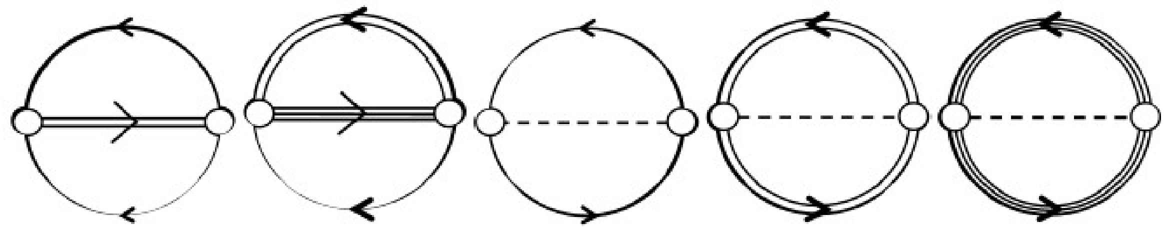
Confinement: Φ=0



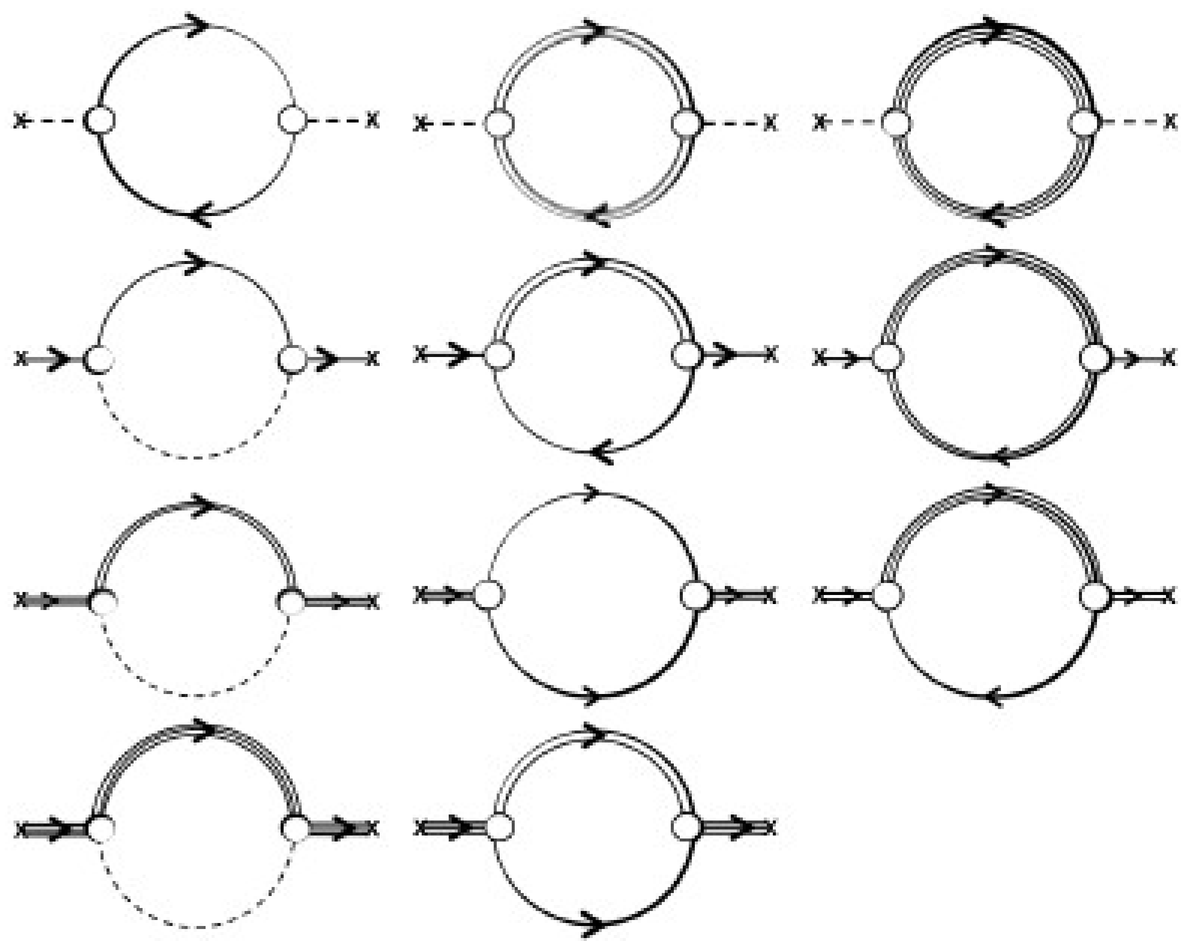
D. Blaschke, A. Dubinin, M. Buballa: Phys. Rev. D 91 (2015) 125040

3. Example C: Hadron resonance gas – toy model

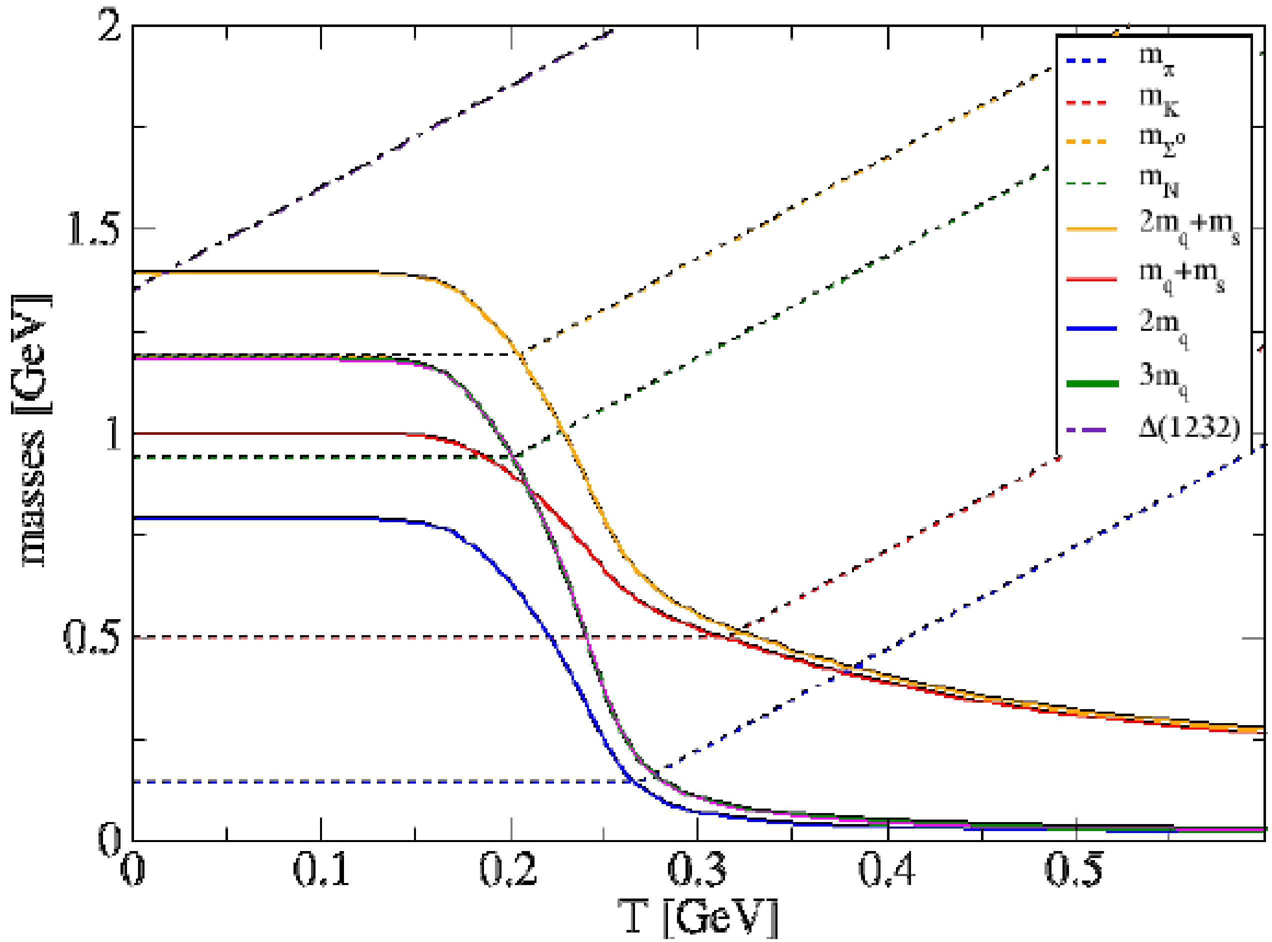
Φ-functional:



Selfenergies:



3. Example C: Hadron resonance gas – toy model

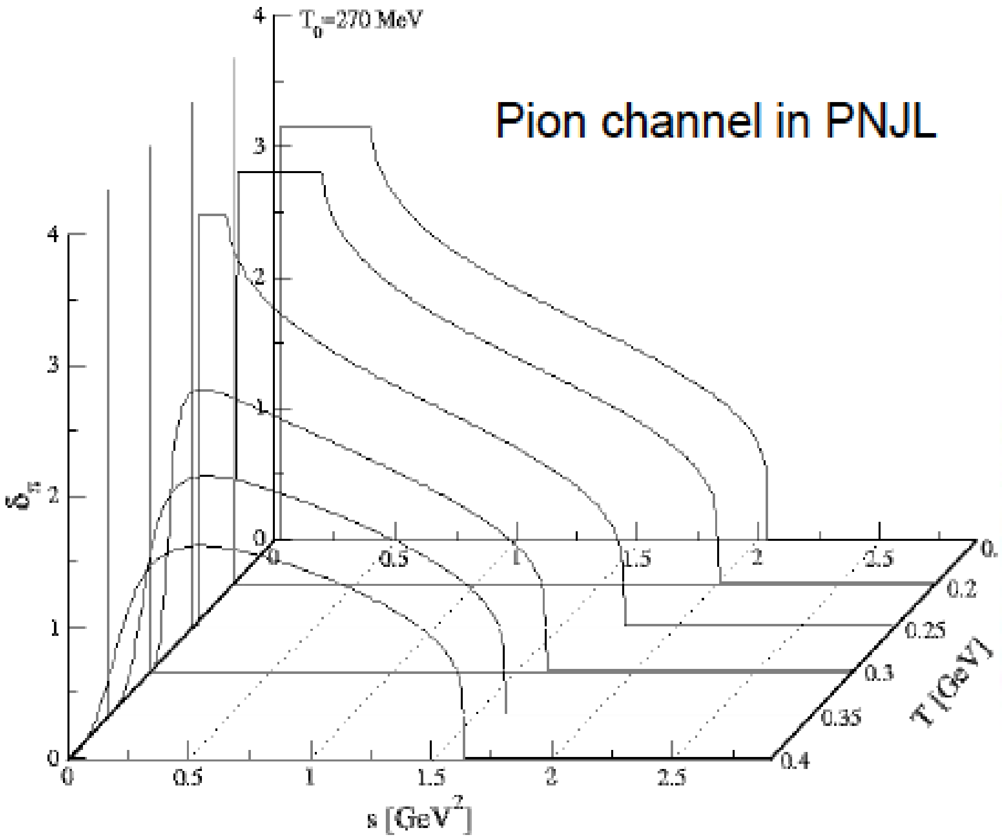


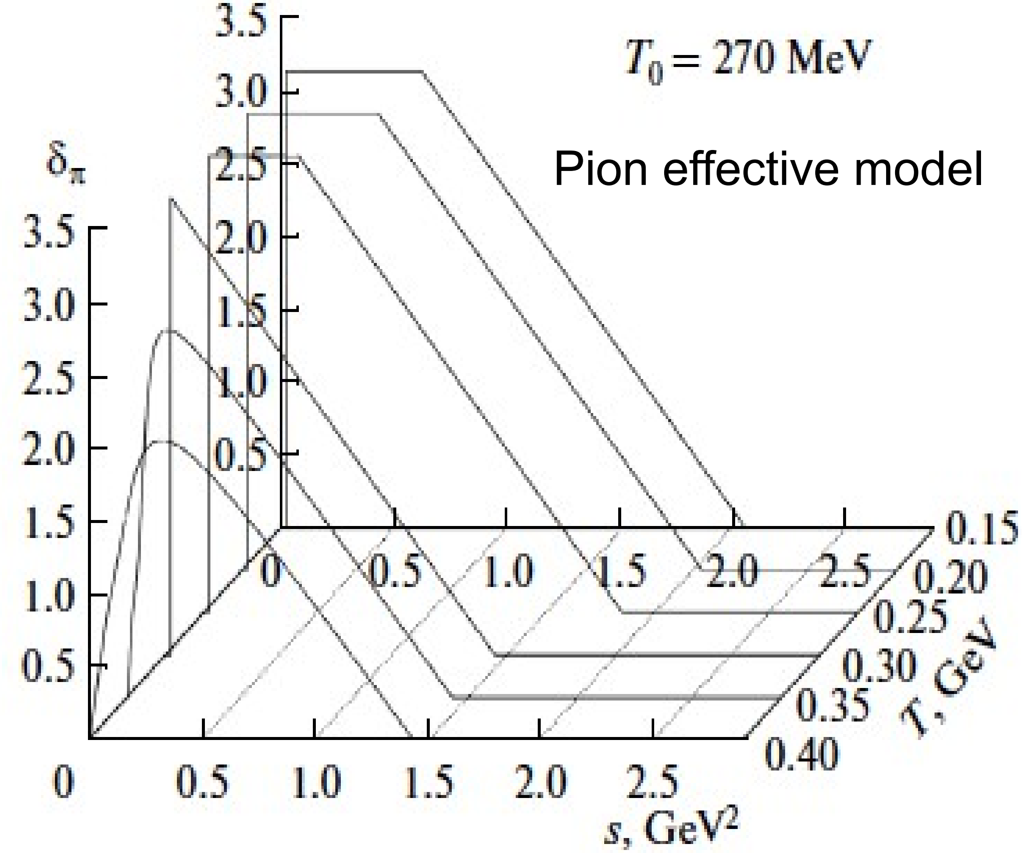
$$M_i(T) = M_i(0) + \Gamma_i(T) \quad ,$$
$$\Gamma_i(T) = a\,(T - T_{\rm Mott,i})\Theta(T - T_{\rm Mott,i})$$

$$M_i(T_{\rm Mott,i}) = m_{\rm thr,i}(T_{\rm Mott,i}) \ ,$$
$$m_{\rm thr,M}(T) = (2 - N_s)m(T) + N_s m_s(T)$$
$$m_{\rm thr,B}(T) = (3 - N_s)m(T) + N_s m_s(T)$$

D. Blaschke, A. Dubinin, L. Turko, Phys. Part. Lett. 46 (2015) 732

3. Example C: Hadron resonance gas – toy model



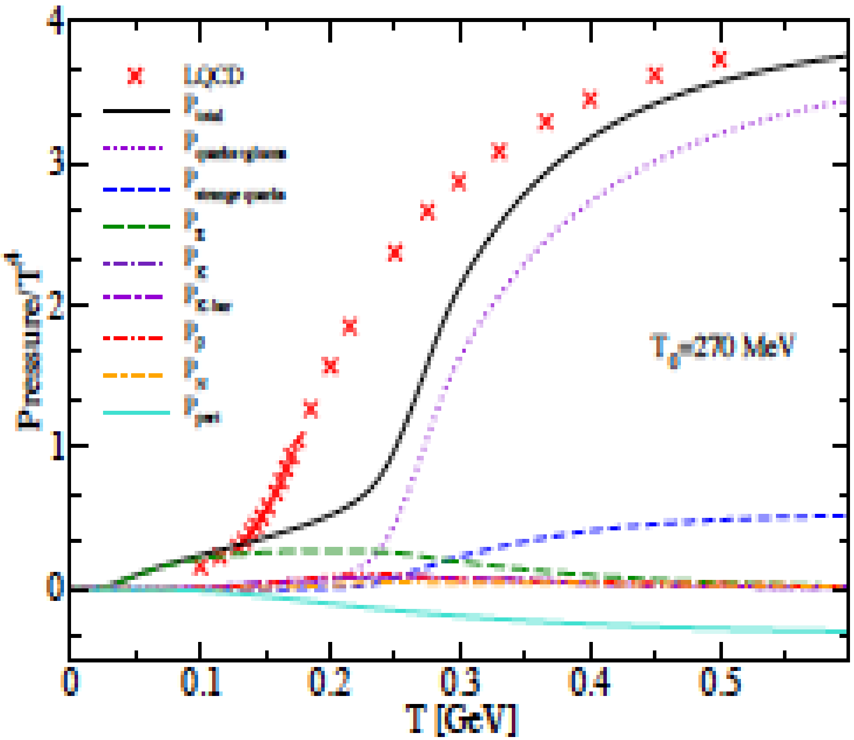


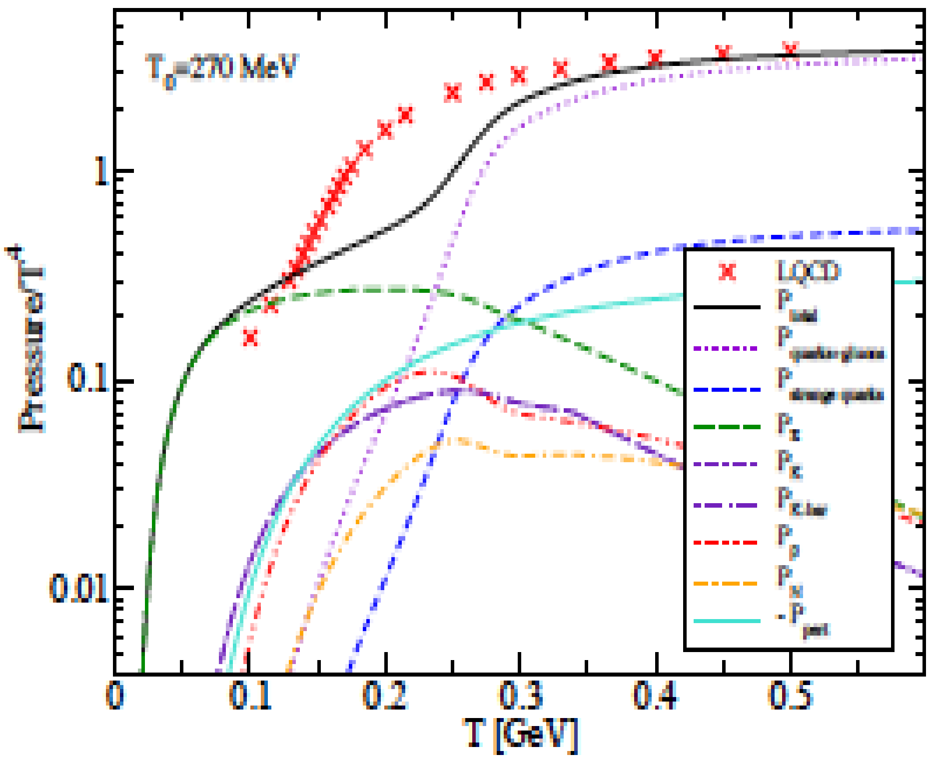
Effective model for in-medium hadron phase shifts

$$\delta_i(s;T) = \left[\frac{\pi}{2} + \arctan\left(\frac{s - M_i^2(T)}{M_i(T)\Gamma_i(T)}\right)\right]\left\{\Theta[m^2_{\rm thr,i} - s] + \Theta[s - m^2_{\rm thr,i}]\Theta[m^2_{\rm thr,i} + N_i^2\Lambda^2 - s]\left[\frac{m^2_{\rm thr,i} + N_i^2\Lambda^2 - s}{N_i^2\Lambda^2}\right]\right\} \quad (7)$$

D. Blaschke, A. Dubinin, L. Turko, Phys. Part. Lett. 46 (2015) 732

3. Example C: Hadron resonance gas – toy model



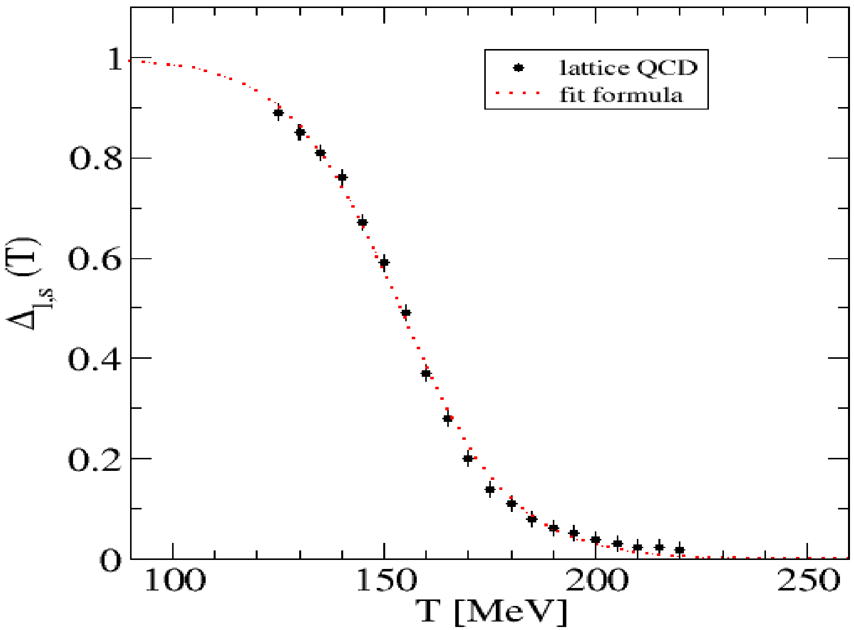


$$P_i(T) = d_i \int_0^\infty \frac{dpp^2}{2\pi^2} \int_0^\infty \frac{dM}{\pi} \frac{M}{\sqrt{p^2+M^2}} f_i(\sqrt{p^2+M^2}) \delta_i(M^2;T)$$

$$P_i(T) = \mp d_i \int_0^\infty \frac{dpp^2}{2\pi^2} \int_0^\infty dM\, T \ln(1 \mp e^{-\sqrt{p^2+M^2}/T}) \frac{1}{\pi} \frac{d\delta_i(M^2;T)}{dM}$$

$$P(T) = \sum_{i=M,B} P_i(T) + P_{\rm PNJL}(T) + P_{\rm pert}(T)$$

3. Example C: Mott HRG – improved toy model

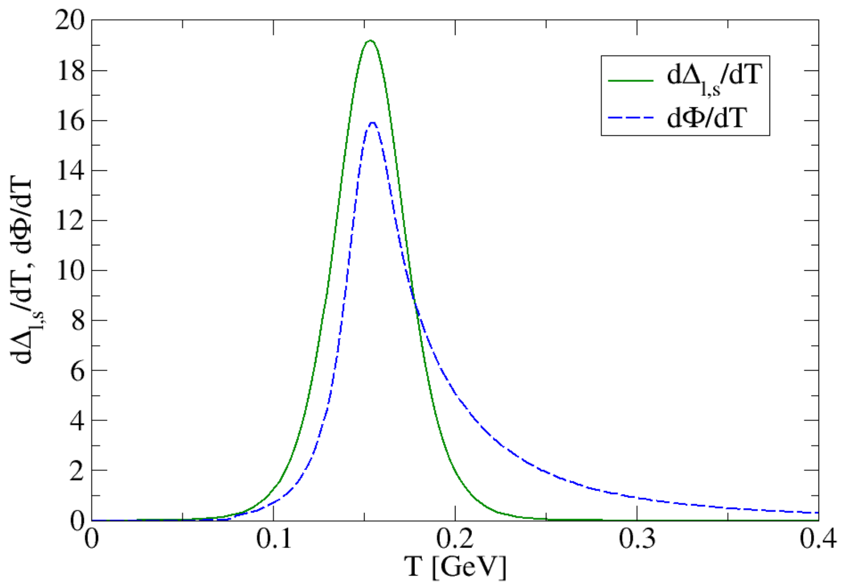


$$P_{\mathrm{PNJL}}(T) = P_{\mathrm{FG}}(T) + \mathcal{U}[\Phi;T] ,$$

$$P_{\mathrm{FG}}(T) = 4 \sum_{q=u,d,s} \int \frac{d^3p}{(2\pi)^3} T \ln\left[1 + 3\Phi(Y + Y^2) + Y^3\right]$$

$$Y(E_p) = \exp(-E_p/T)$$

$$\mathcal{U}[\Phi;T] = -\frac{a(T)}{2}\Phi^2 + b(T)\ln(1 - 6\Phi^2 + 8\Phi^3 - 3\Phi^4)$$



T-dependent quark masses from fit to LQCD

$$m(T) = [m(0) - m_0]\Delta_{l,s}(T) + m_0 ,$$

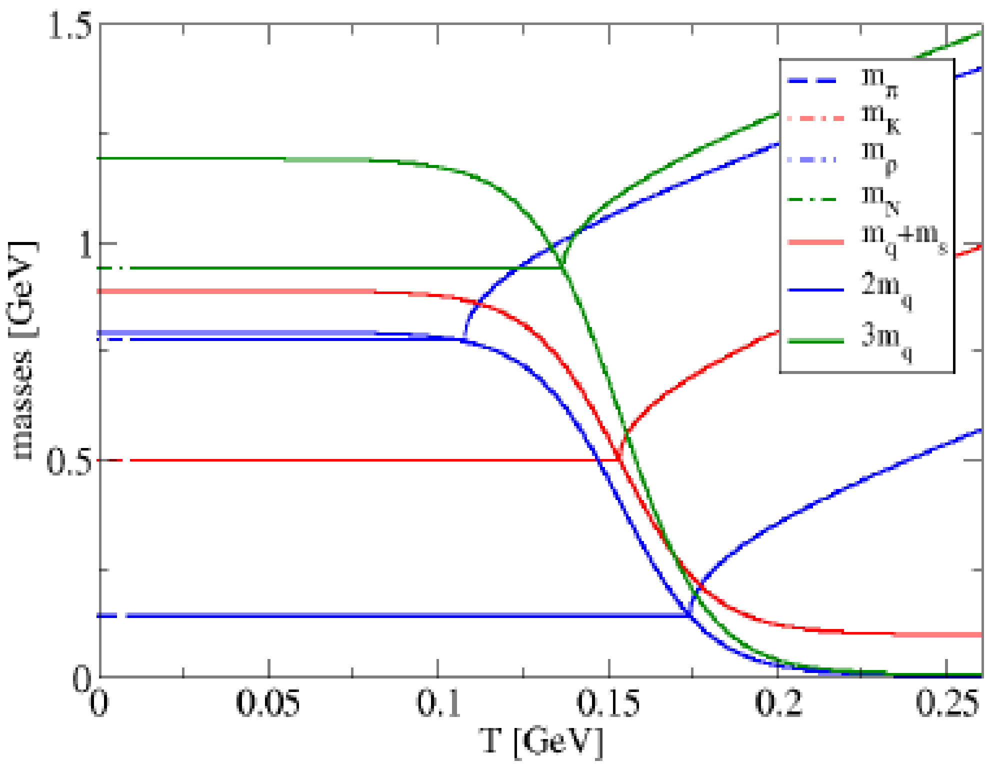
$$m_s(T) = m(T) + m_s - m_0 ,$$

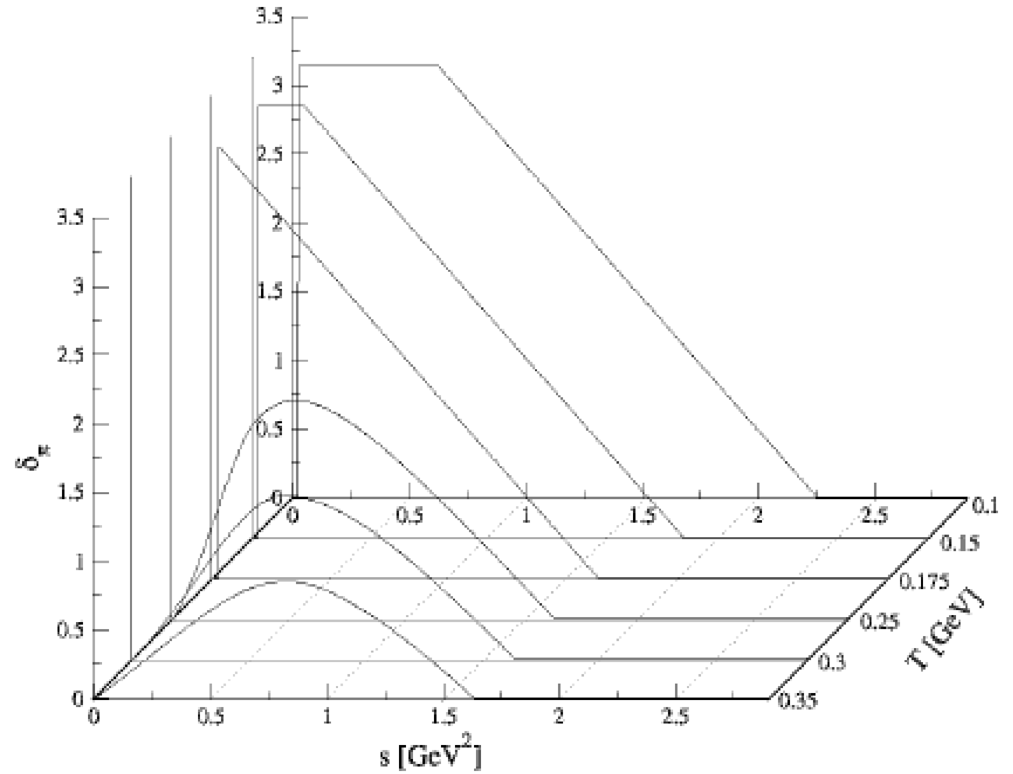
$$\Delta_{l,s}(T) = \frac{1}{2}\left[1 - \tanh\left(\frac{T - T_c}{\delta_T}\right)\right]$$

$T_c = 154$ MeV $\quad \delta_T = 26$ MeV

D. Blaschke, A. Dubinin, L. Turko, in prep. (2015)

3. Example C: Mott HRG – improved toy model





Hadrons + Mott effect

$$P_i(T) \;=\; \mp d_i \int_0^\infty \frac{dp\, p^2}{2\pi^2} \int_0^\infty dM\; T \ln\left(1 \mp \mathrm{e}^{-\sqrt{p^2+M^2}/T}\right) \frac{2}{\pi} \sin^2 \delta_i(M^2;T) \frac{d\delta_i(M^2;T)}{dM}$$

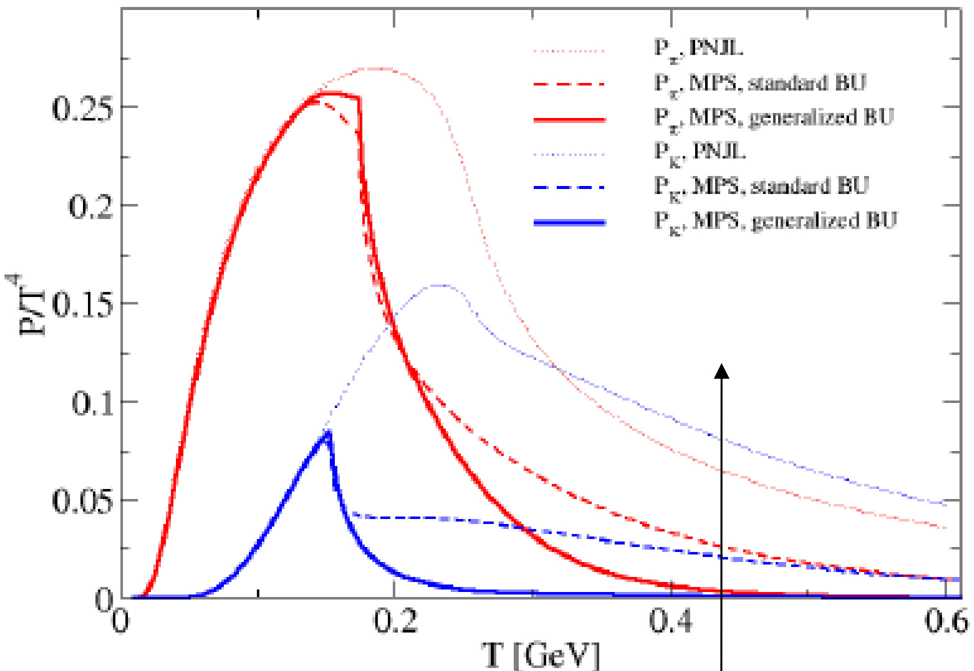
Quarks + rescattering effects

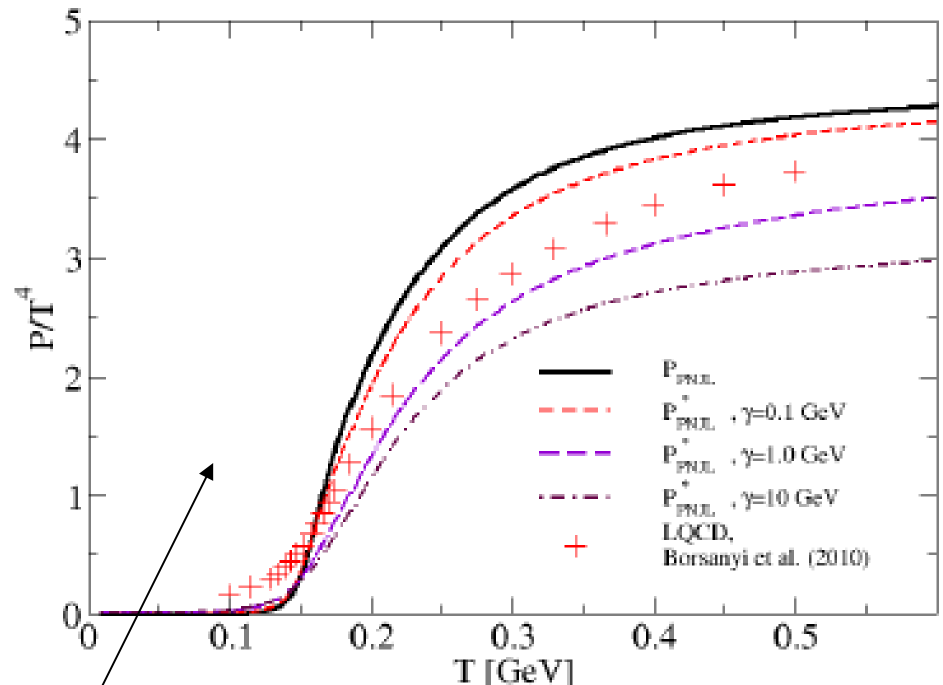
$$f_\Phi(\omega) \;=\; \frac{\Phi(1+2Y)Y + Y^3}{1 + 3\Phi(1+Y)Y + Y^3} \;,$$

$$P^*_{\rm FG}(T) = 4N_c \sum_{q=u,d,s} \int \frac{dp\, p^2}{2\pi^2} \int \frac{d\omega}{\pi} f_\Phi(\omega) \delta_q(\omega;\gamma),$$

$$\delta_q(\omega;\gamma) = \frac{\pi}{2} + \arctan\left[\frac{\omega - \sqrt{p^2+m_q^2}}{\gamma}\right]$$

3. Example C: Mott HRG – improved toy model

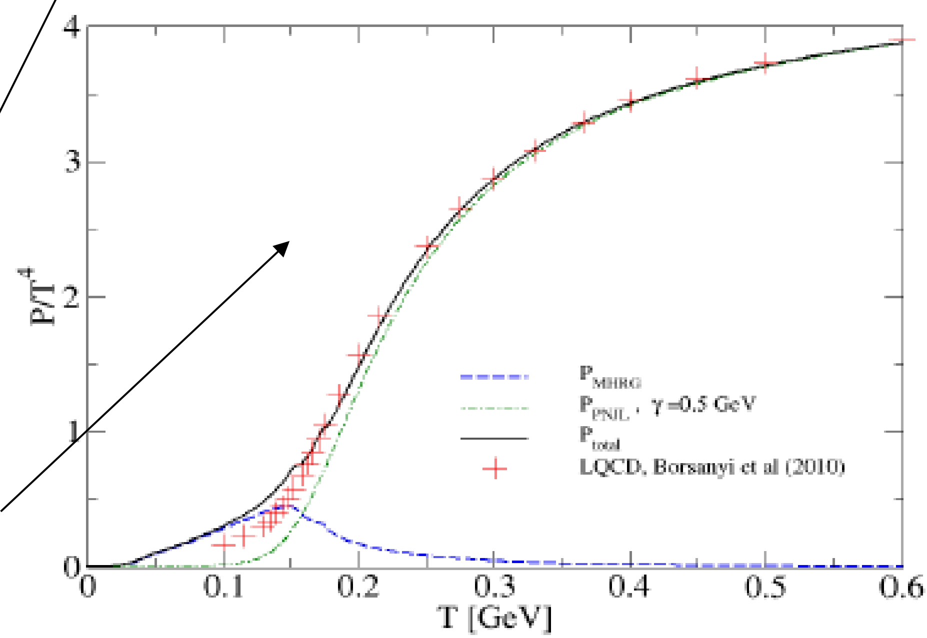




- Mott dissociation of hadrons (here pi, K) at the Chiral rstoration temperature T_c = 153 MeV

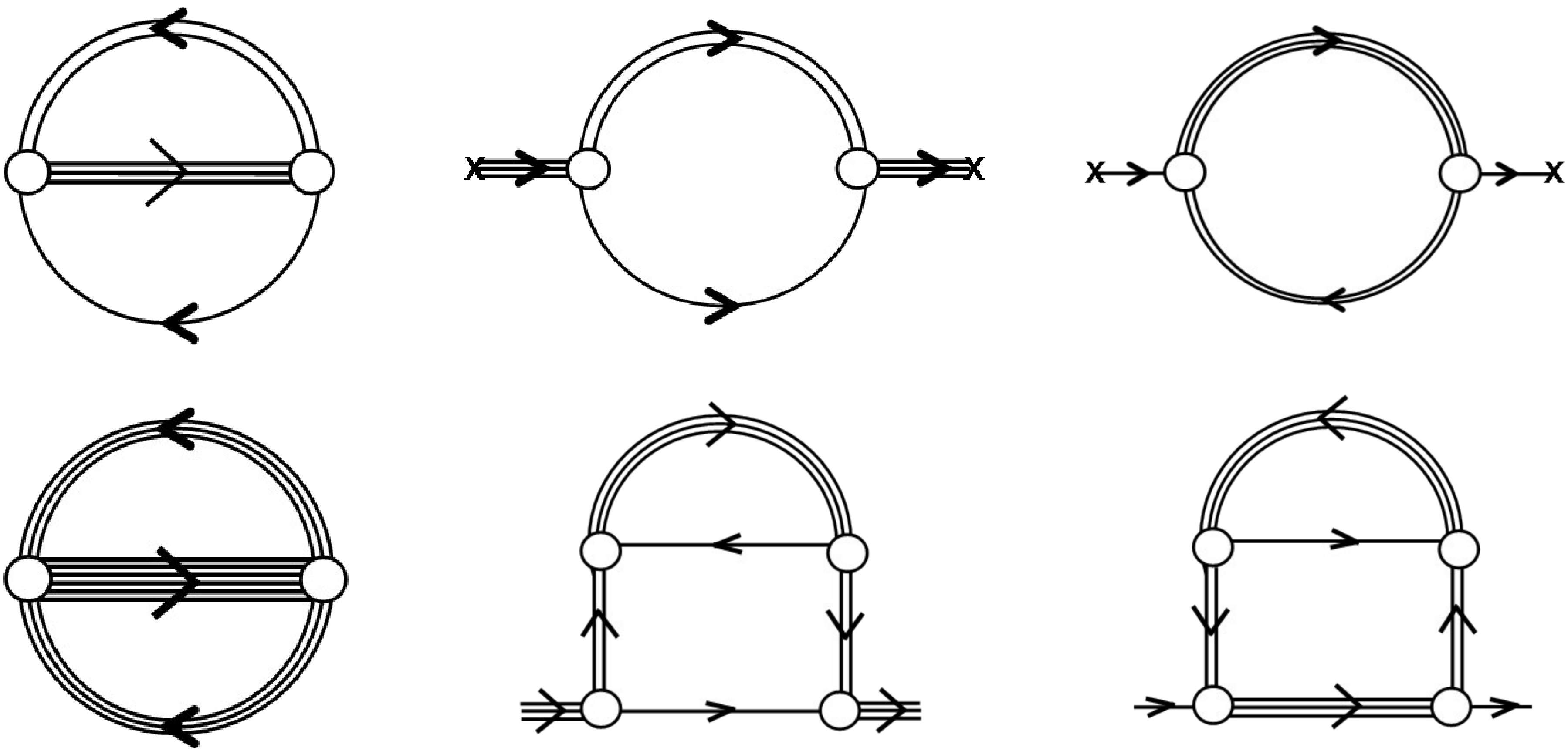
- Asymptotic behaviour of acled quark-gluon Pressure can be adjusted with rescattering Parameter gamma

- Very good correspondence between lattice QCD Thermodynamics and improved MHRG model; Hadronic and partonic contributions quantified

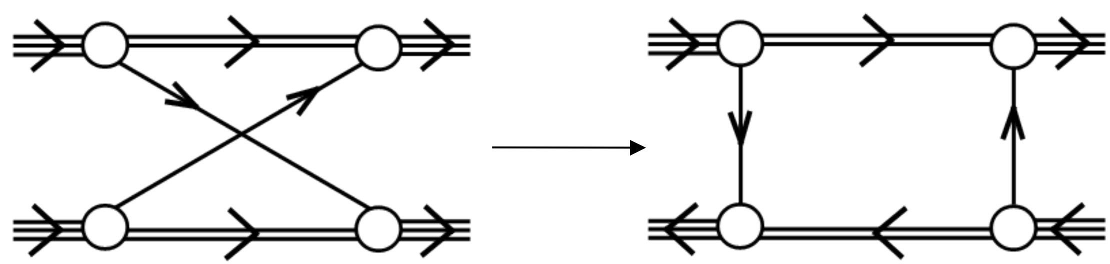


3. Example D: Nucleons in quark matter

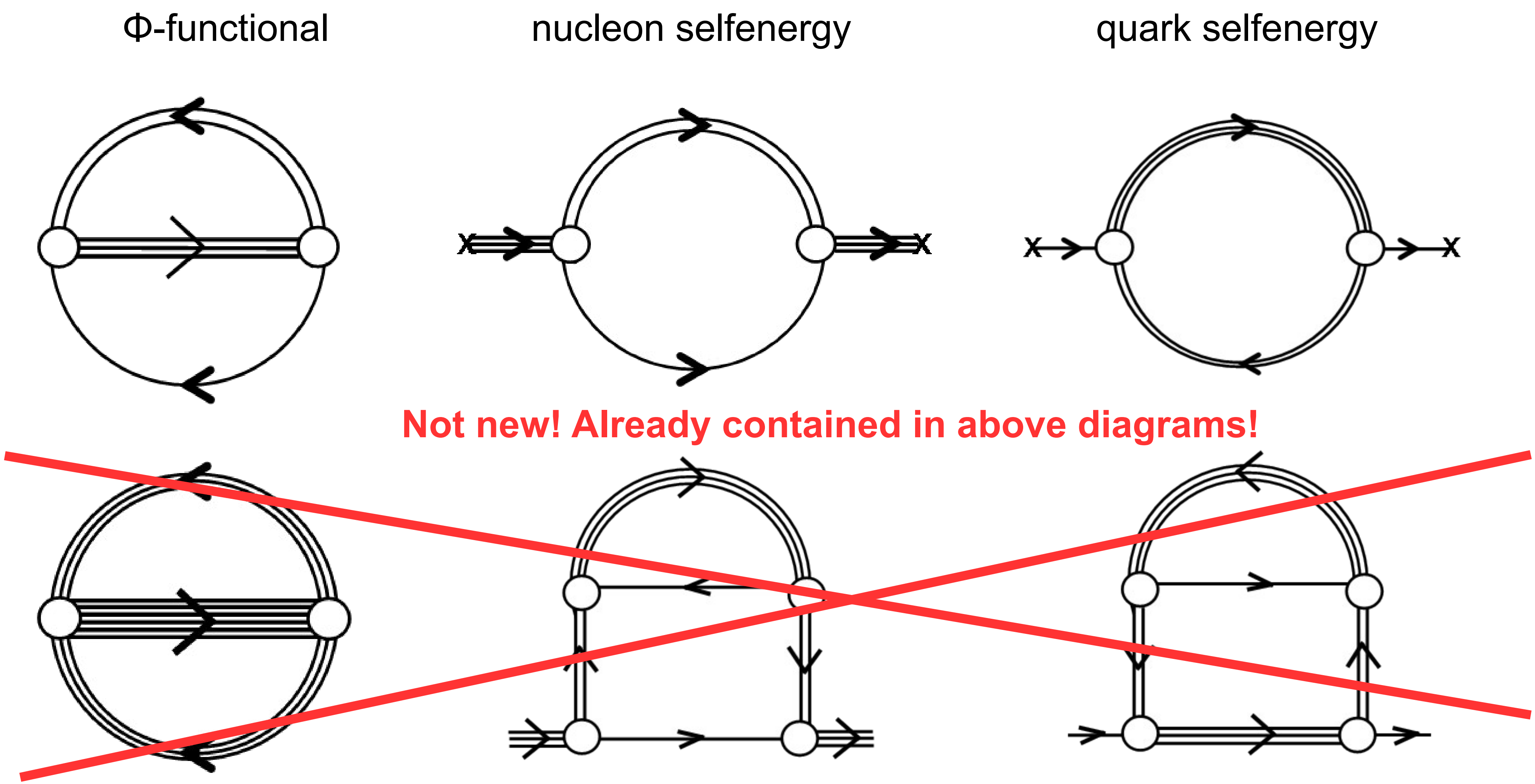
Φ-functional | nucleon selfenergy | quark selfenergy



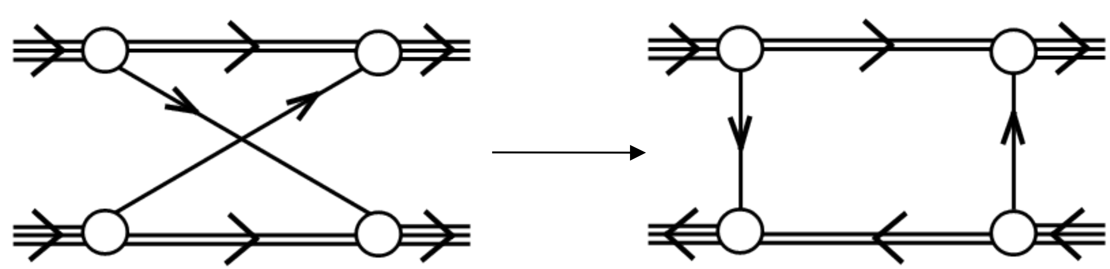
quark exchange interaction
between nucleons:



5. Example D: Nucleons in quark matter

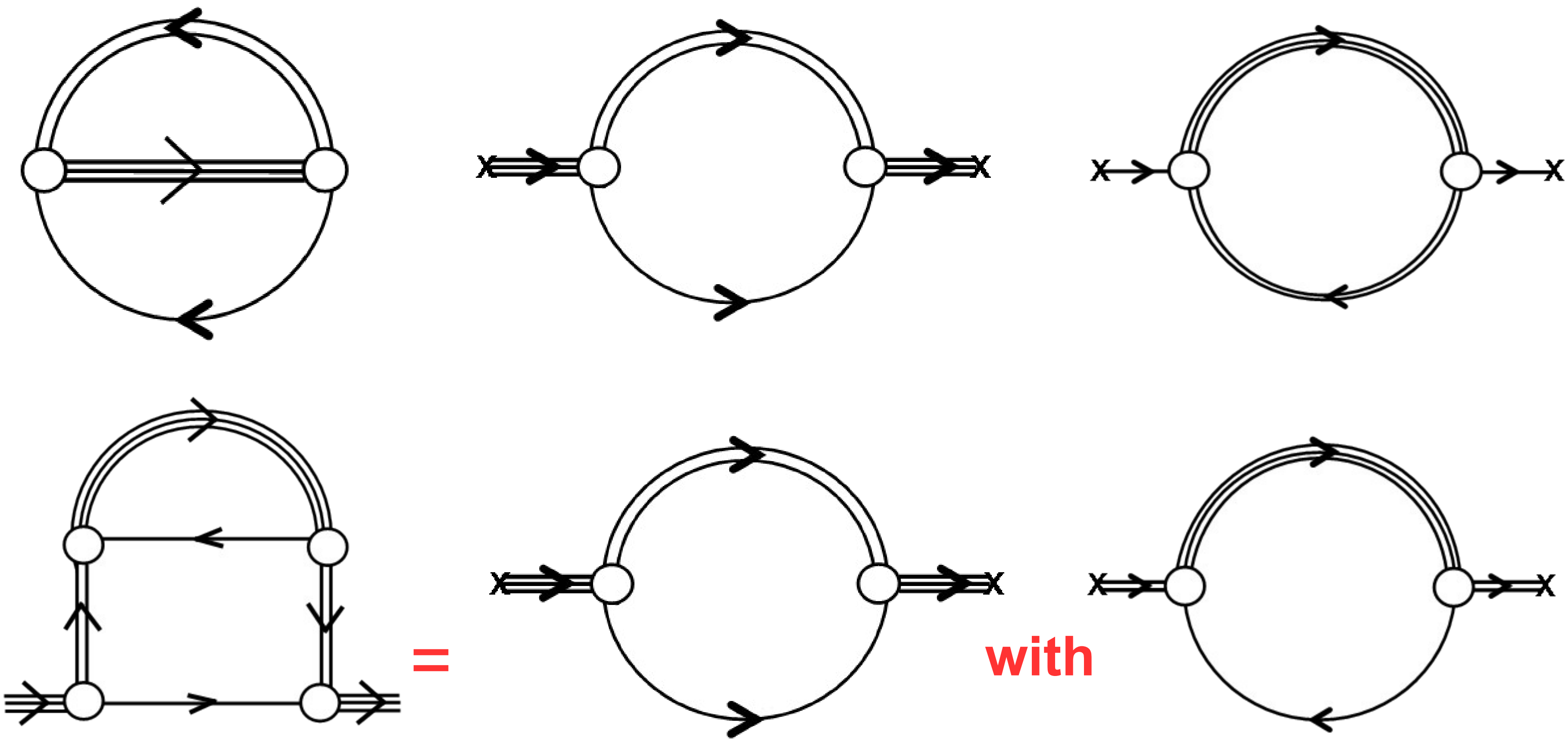


quark exchange interaction
between nucleons:

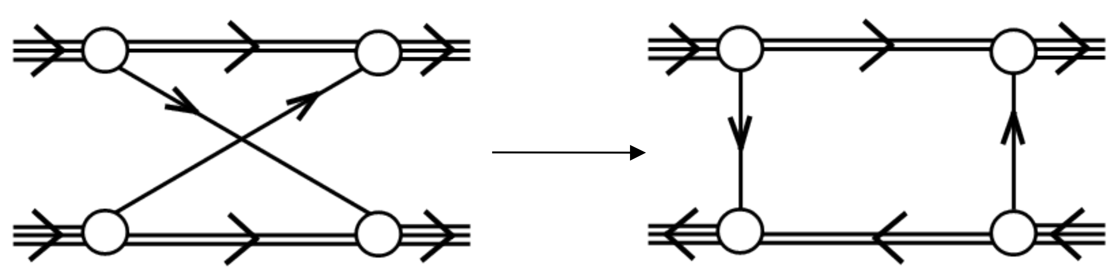


5. Example D: Nucleons in quark matter

Φ-functional　　nucleon selfenergy　　quark selfenergy



quark exchange interaction between nucleons:



Intermezzo: Structure of the baryon?

12-Apostle Church, Kars

Intermezzo: Structure of the baryon?

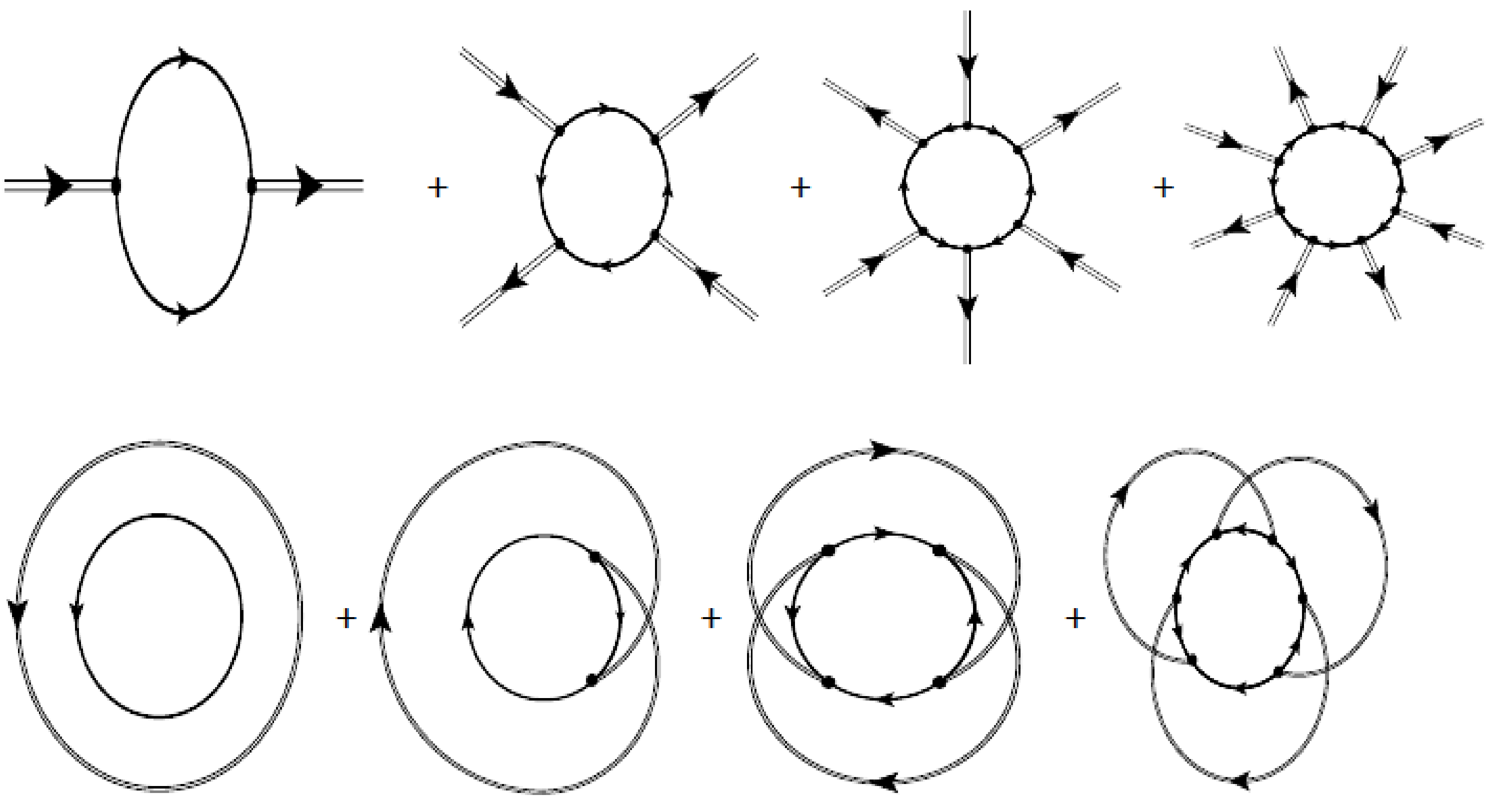
12-Apostle
Church,
Kars

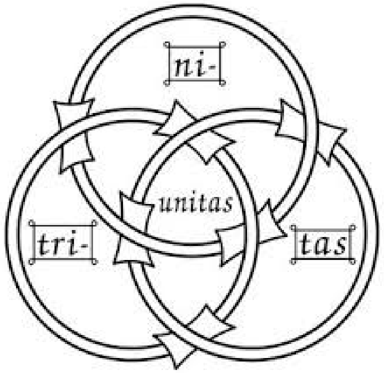
Intermezzo: Structure of the baryon?

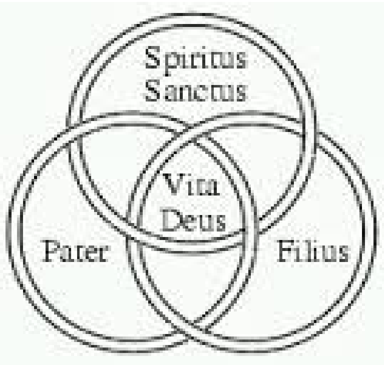
Borromean ? !!

$$Z_{\text{fluct}} = \int D\Delta^\dagger D\Delta D\phi \exp\{-\frac{|\Delta|^2}{4G_D} - \frac{\phi^2}{4G} - Tr\, lnS^{-1}[\Delta, \Delta^\dagger, \phi]\}$$

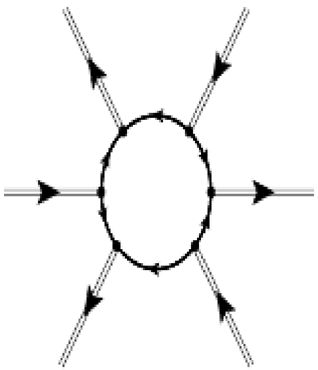
Cahill, Roberts, Prashifka: Aust. J. Phys. 42 (1989) 129, 161
Cahill, ibid, 171; Reinhardt: PLB 244 (1990) 316; Buck, Alkofer, Reinhardt: PLB 286 (1992) 29

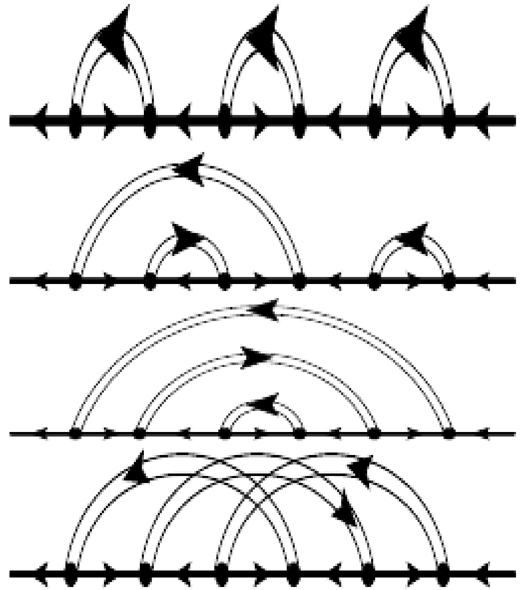


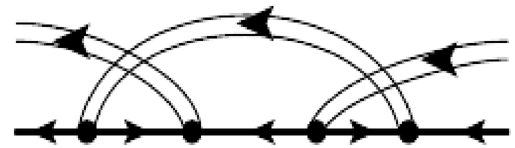


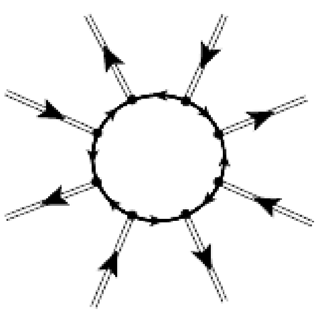


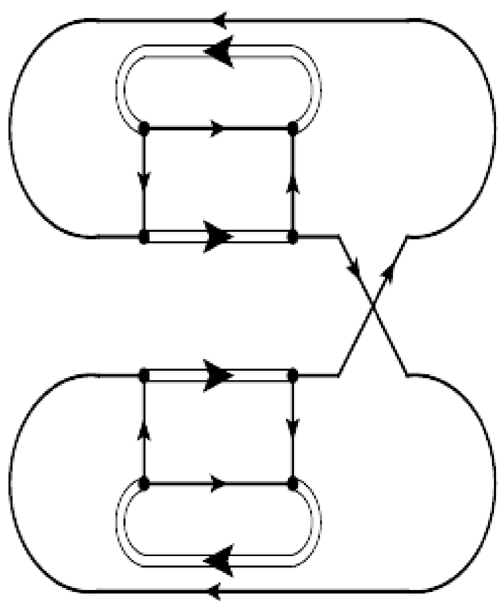
Intermezzo: Structure of the baryon?

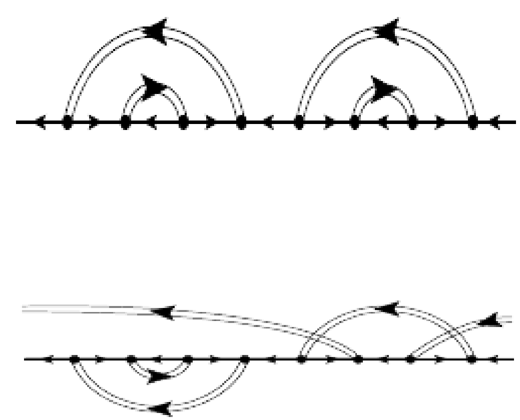




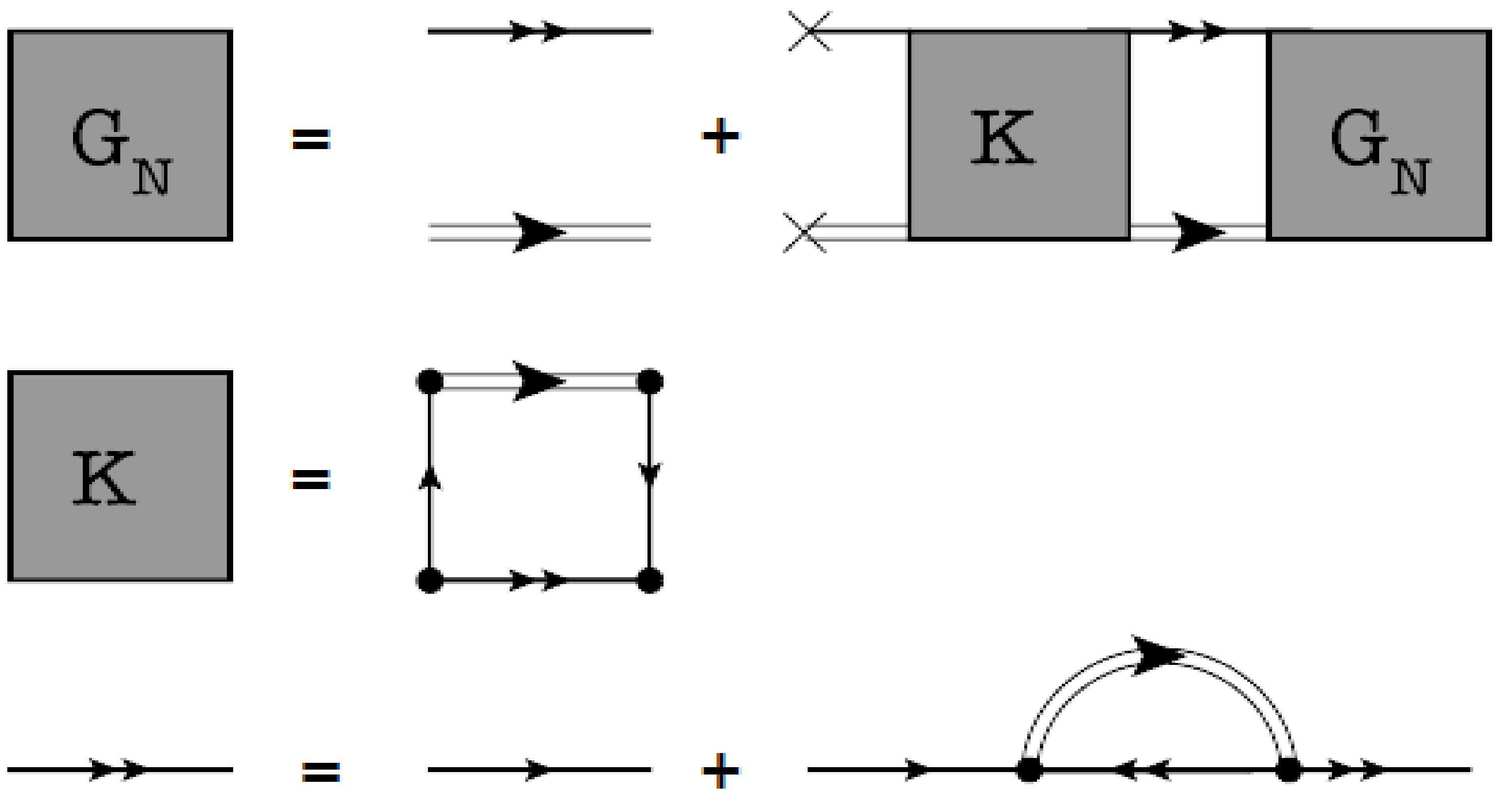








Intermezzo: Structure of the baryon?



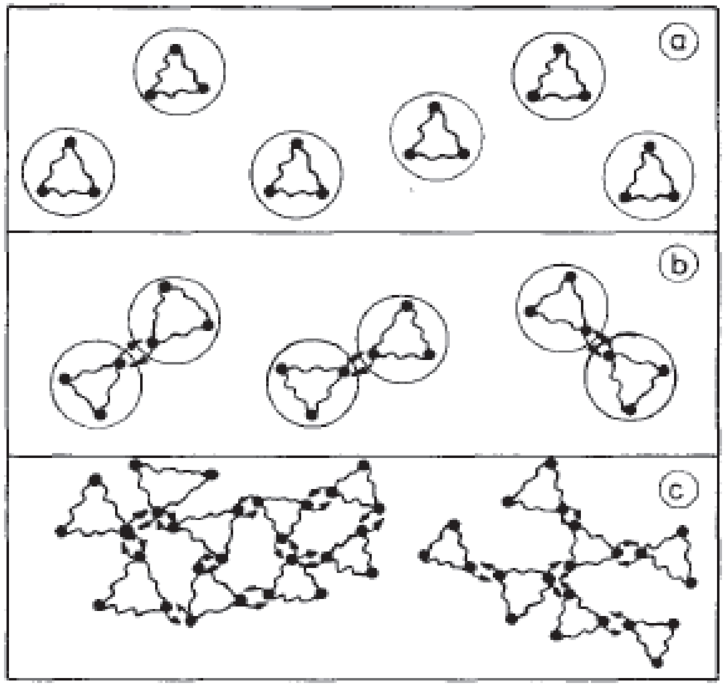
Generalized Bethe-Salpeter equation for the baryon

Dyson- Schwinger equation for the quarks ... important:

Bethe-Salpeter (RPA) equation for the diquark propagator must be consistent !

==> see the Phi- derivable approach !

4. Example C: Pauli blocking among baryons

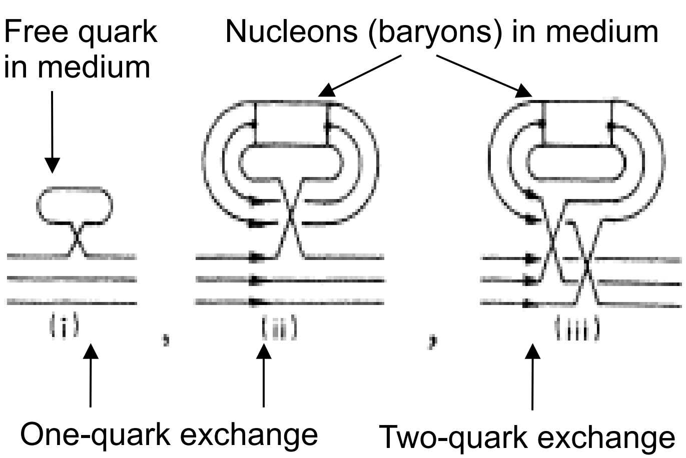


a) Low density: Fermi gas of nucleons (baryons)

b) ~ saturation: Quark exchange interaction and Pauli blocking among nucleons (baryons)

c) high density: Quark cluster matter (string-flip model ...)

Roepke & Schulz, Z. Phys. C 35, 379 (1987); Roepke, DB, Schulz, PRD 34, 3499 (1986)



Nucleon (baryon) self-energy --> Energy shift

$$\Delta E_{\nu P}^{\text{Pauli}} = \sum_{123} |\psi_{\nu P}(123)|^2 [E(1)+E(2)+E(3)-E_{\nu P}^0][f_{\alpha_1}(1)+f_{\alpha_2}(2)+f_{\alpha_3}(3)]$$
$$+\sum_{123}\sum_{456}\sum_{\nu' P'} \psi_{\nu P}^*(123)\psi_{\nu' P'}(456) f_3(E_{\nu' P'}^0)\{\delta_{36}\psi_{\nu P}(123)\psi_{\nu' P'}^*(456)-\psi_{\nu P}(453)\psi_{\nu' P'}^*(126)\}$$
$$\times [E(1)+E(2)+E(3)+E(4)+E(5)+E(6)-E_{\nu P}^0-E_{\nu' P'}^0]$$
$$=\Delta E_{\nu P}^{\text{Pauli,free}}+\Delta E_{\nu P}^{\text{Pauli,bound}} .$$

PHYSICAL REVIEW D VOLUME 34, NUMBER 11 1 DECEMBER 1986

Pauli quenching effects in a simple string model of quark/nuclear matter

G. Röpke and D. Blaschke
Department of Physics, Wilhelm-Pieck-Universtiy, 2500 Rostock, German Democratic Republic

H. Schulz
Central Institute for Nuclear Research, Rossendorf, 8051 Dresden, German Democratic Republic and The Niels Bohr Institute, 2100 Copenhagen, Denmark

(Received 16 December 1985)

4. Example C: Pauli blocking in NM - details

$$\Sigma_\nu(p, p_{Fn}, p_{Fp}) = \sum_{\nu'=\{n,p\}} \sum_{\alpha=1,2} C^{(\alpha)}_{\nu\nu'} W_\alpha(p_{F\nu'}, p)$$

$$W_\alpha(p_{F\nu'}, p) = \frac{\Omega}{2\pi^2} \int_0^{p_{F\nu'}} p'^2 \bar{V}^{(\alpha)}(p, p') dp';$$

$$\bar{V}^{(\alpha)}(p, p') = \frac{1}{2} \int_{-1}^{1} V^{(\alpha)}(\vec{p}, \vec{p}') dz;$$

$$V^{(\alpha)}(\vec{p}, \vec{p}') = \frac{V_0 b}{\Omega m} \left(\frac{15}{2} - \lambda_\alpha^2 (\vec{p} - \vec{p}')^2 \right) \exp(-\lambda_\alpha^2 (\vec{p} - \vec{p}')^2).$$

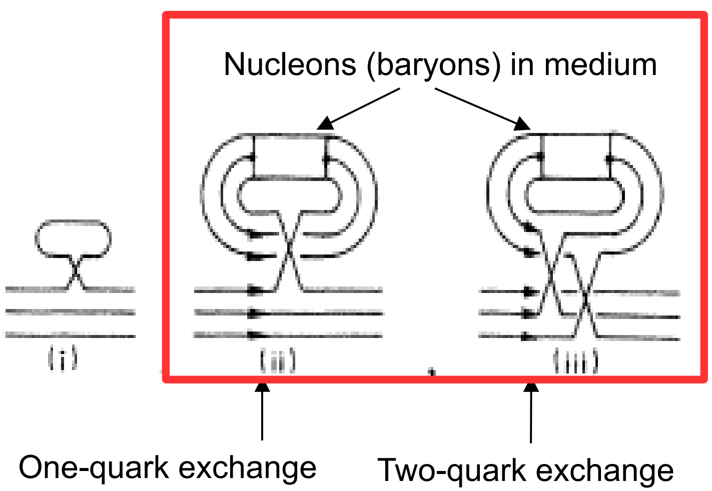
	$C^{(1)}_{n\ \nu}$	$C^{(2)}_{n\ \nu}$
neutron	$-\frac{96}{243}$	$\frac{10}{27}$
proton	$-\frac{28}{81}$	$\frac{8}{27}$

$$b^{-2} = \sqrt{3} m\omega$$

$$\omega = 178.425 \text{ MeV}$$

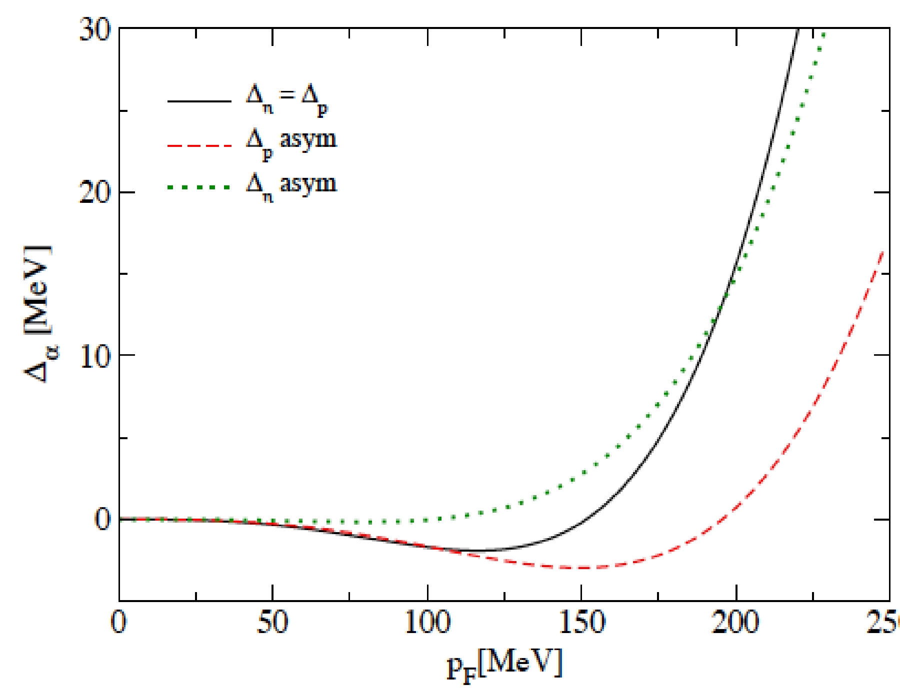
$$m = 350 \text{ MeV} \qquad b = 0.6 \text{ fm}$$

$$V_0 = \frac{9\sqrt{3}\pi^{3/2}}{2} \text{ and } \lambda_\alpha = \frac{b}{\sqrt{3}\alpha}.$$



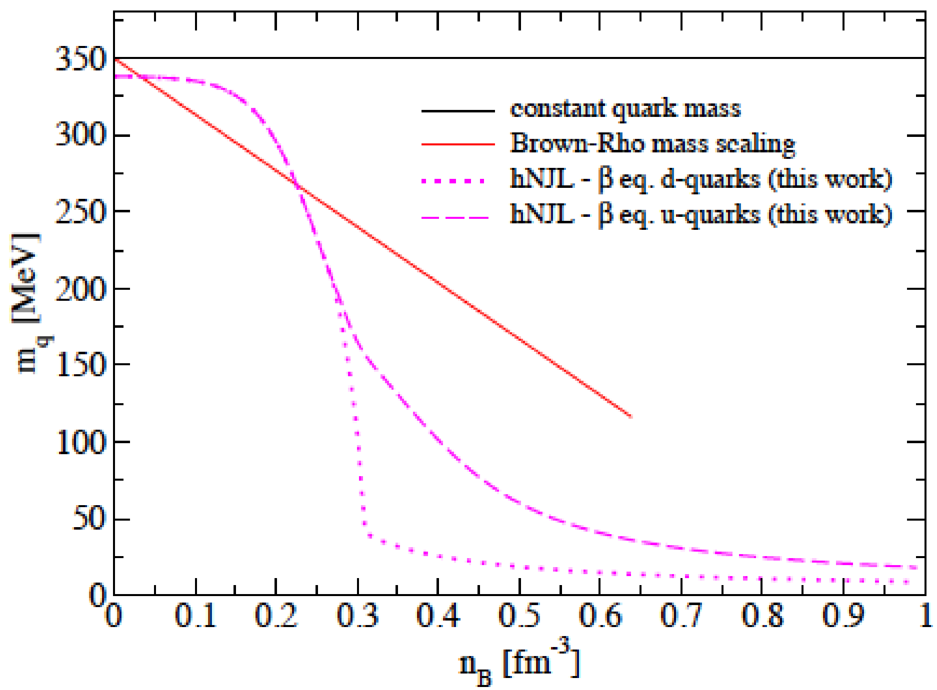
$$W_\alpha(p_{F\nu'}, p) = \frac{V_0 b}{32\pi^2 \lambda_\alpha^4 m} \{12\lambda_\alpha \sqrt{\pi} [\operatorname{erf}(\lambda_\alpha(p_{F\nu'} - p)) + \operatorname{erf}(\lambda_\alpha(p_{F\nu'} + p))]$$
$$+ \frac{1}{p} [(11 - 2\lambda_\alpha^2\, p_{F\nu'}(p_{F\nu'} + p))\, e^{-\lambda_\alpha^2 (p_{F\nu'} + p)^2}$$
$$+ (11 - 2\lambda_\alpha^2\, p_{F\nu'}(p_{F\nu'} - p))\, e^{-\lambda_\alpha^2 (p_{F\nu'} - p)^2}]\}$$

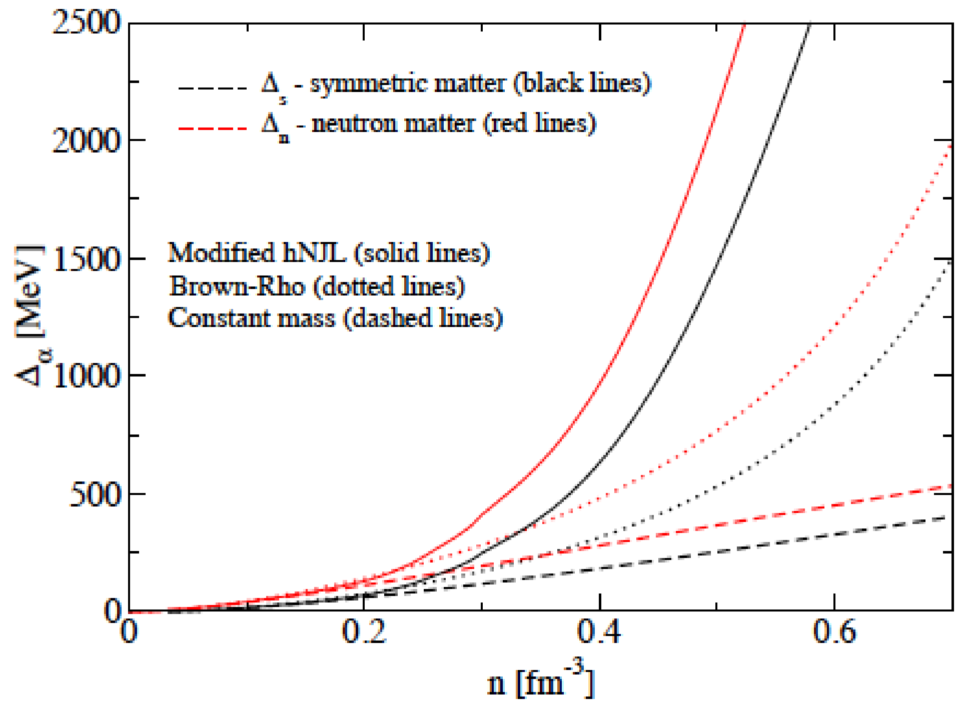
$$\Delta^{Pauli}_{\nu_A, P} = \frac{1}{24\sqrt{3\pi}} \frac{b}{m} \sum_{\nu'} [15 a_{\nu,\nu'} P_F(\nu')^3 + \frac{17}{12} b_{\nu,\nu'} b^2 (P^2 + P_F(\nu')^2) P_F(\nu')^3]$$



4. Example C: Pauli blocking in NM – details

New aspect: chiral restoration --> dropping quark mass





Increased baryon swelling at supersaturation densities:
--> dramatic enhancement of the Pauli repulsion !!

D.B., H. Grigorian, G. Roepke: “Quark exchange effects in dense nuclear matter”, STSM 2014

4. Example C: Pauli blocking in NM – results

New EoS: Joining RMF (Linear Walecka) for pointlike baryons with chiral Pauli blocking

$$p = \frac{1}{4\pi^2}\sum_\nu \left[-E^*_\nu m^{*2}_\nu p_{F\nu} + \frac{2}{3}E^*_\nu p^3_{F\nu} + m^{*4}_\nu \log\left(\frac{E^*_\nu + p_{F\nu}}{m^*_\nu}\right)\right]$$

$$+ \frac{1}{2}\left(\frac{g_\omega}{m_\omega}\right)^2 n^2 - \frac{1}{2}\left(\frac{g_\sigma}{m_\sigma}\right)^2 n_s^2 + p_{ex};$$

$$\epsilon = \frac{1}{4\pi^2}\sum_\nu \left[2\,E^{*3}_\nu p_{F\nu} - E^*_\nu m^{*2}_\nu p_{F\nu} - m^{*4}_\nu \log\left(\frac{E^*_I + p_{F\nu}}{m^*_\nu}\right)\right]$$

$$+ \frac{1}{2}\left(\frac{g_\omega}{m_\omega}\right)^2 n^2 + \frac{1}{2}\left(\frac{g_\sigma}{m_\sigma}\right)^2 n_s^2 + \epsilon_{ex},$$

$$\mu_{ex,\nu} = \Delta_\nu(n,x) = \Sigma_\nu(p_{F,\nu}; p_{Fn,}, p_{Fp}),$$

$$\epsilon_{ex} = \sum_\nu \int_0^n dn'\{x\Delta_p(n',x) + (1-x)\Delta_n(n',x)\},$$

$$p_{ex} = \sum_\nu \mu_{ex,\nu}\, n_\nu - \epsilon_{ex},$$

$$n_{s,\nu} = \frac{m^*_\nu}{\pi^2}\left[E^*_\nu p_{F\nu} - m^{*2}_\nu \log\left(\frac{E^*_\nu + p_{F\nu}}{m^*_\nu}\right)\right],$$

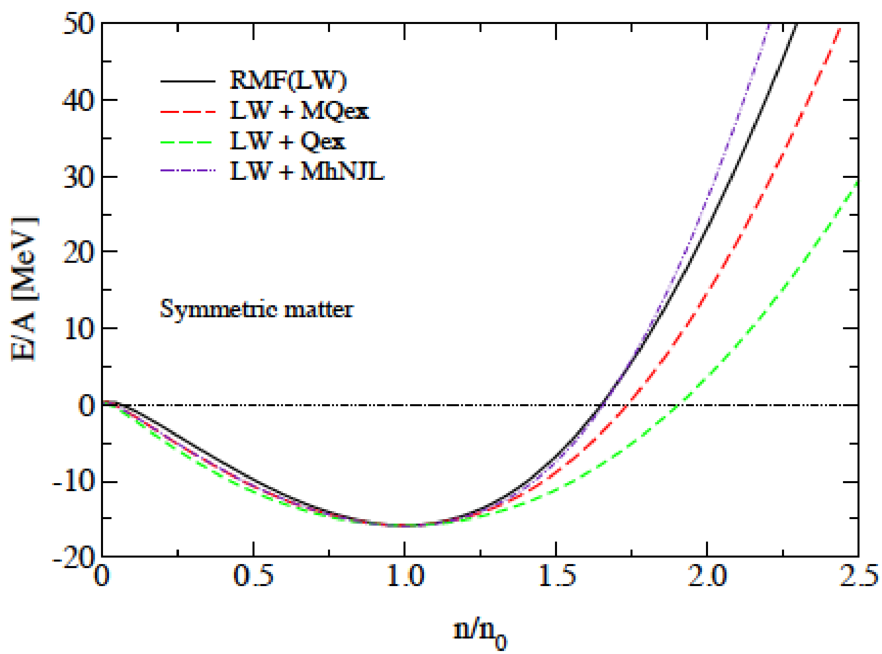
$$E^*_\nu = \sqrt{m^{*2}_\nu + p^2_{F\nu}}$$

$$n_\nu = \frac{p^3_{F\nu}}{3\pi^2},$$

$$m^*_\nu = m_\nu - \left(\frac{g_\sigma}{m_\sigma}\right)^2 n_{s,\nu},$$

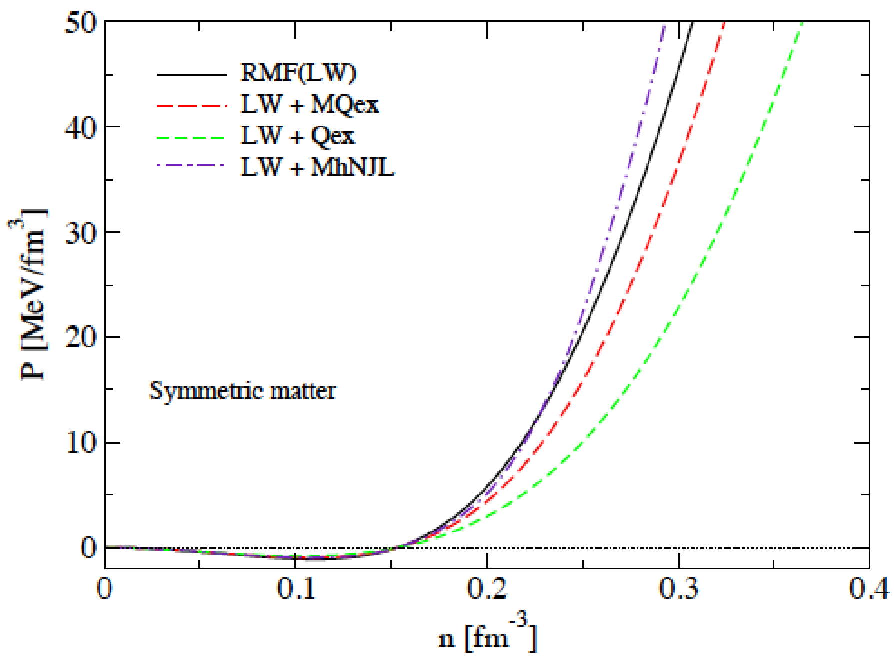
$$\mu_\nu = E^*_\nu + \left(\frac{g_\omega}{m_\omega}\right)^2 n_\nu + \mu_{ex,\nu}.$$

4. Example C: Pauli blocking in NM – results

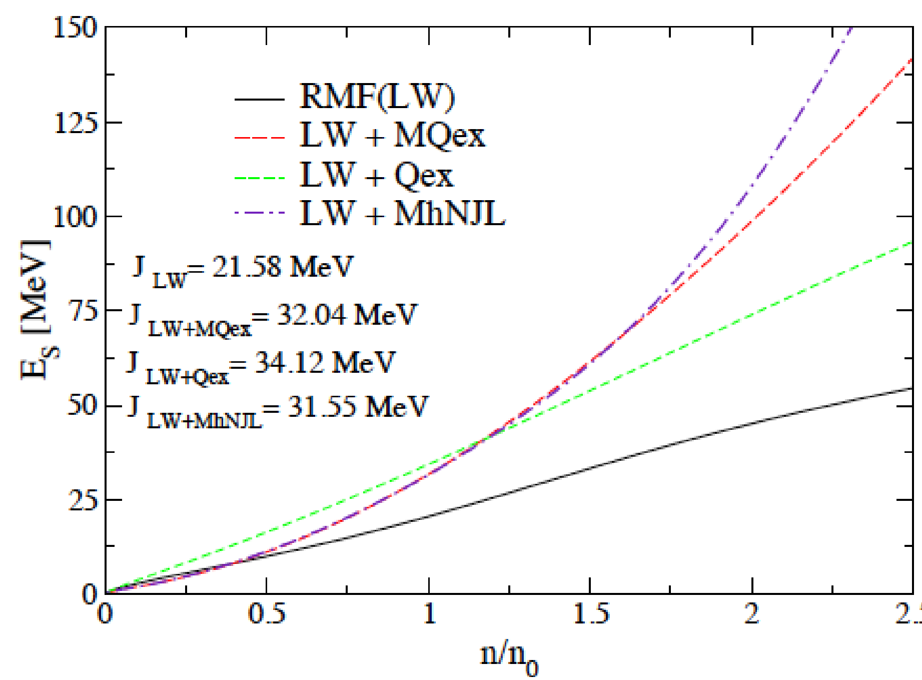


Parametrization: from saturation properties

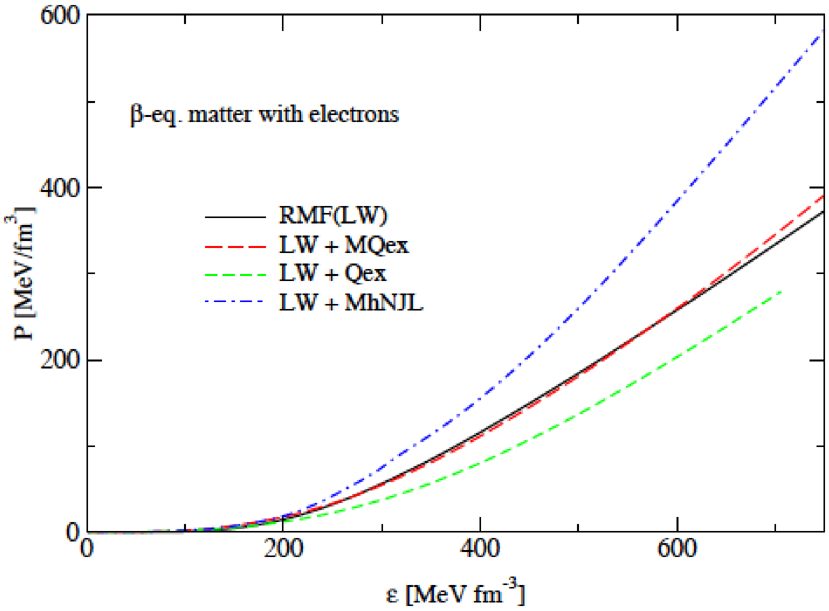
	$(g_\omega/m_\omega)^2$[fm^2]	$(g_\sigma/m_\sigma)^2$ [fm^2]
RMF (LW)	11.6582	15.2883
LW+Qex	6.11035	9.91197
LW+MQex	6.59170	13.29118
LW+MhNJL	9.25683	13.9474

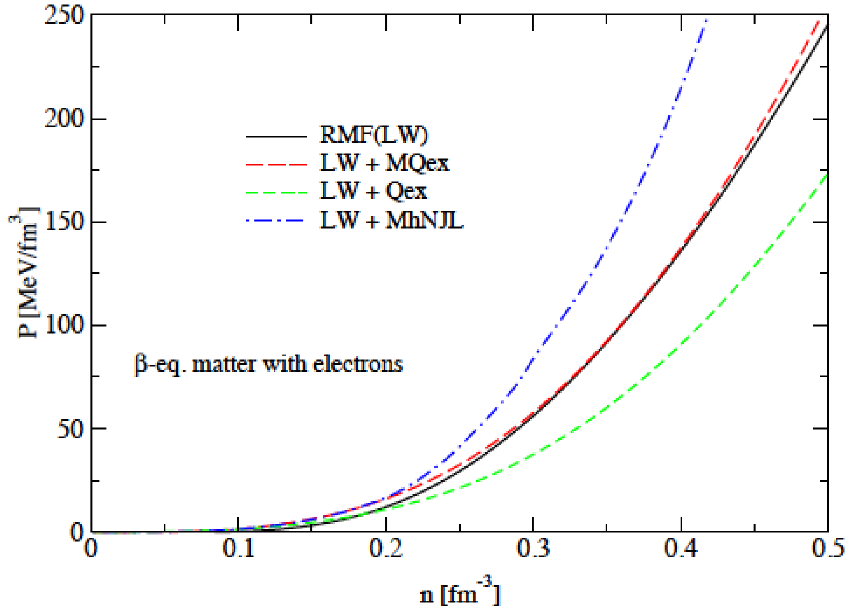


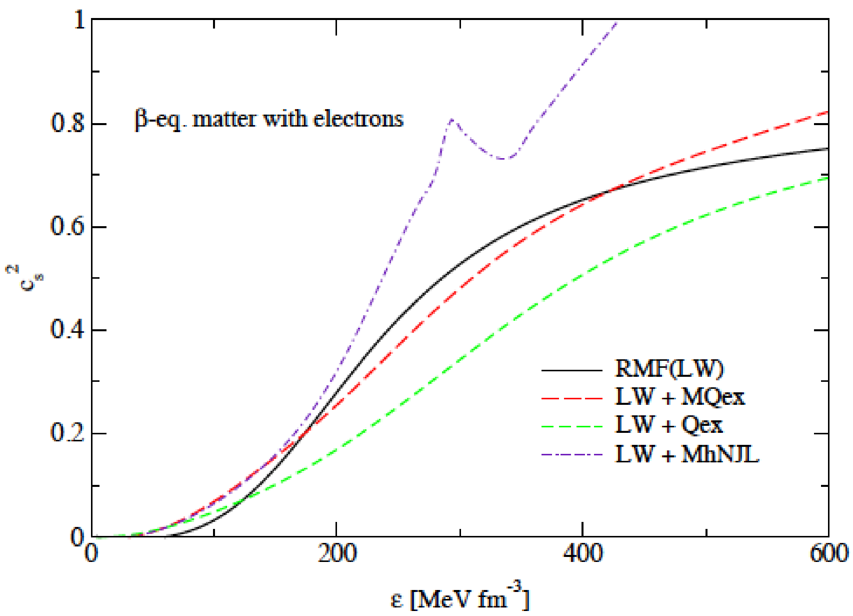
Prediction: symmetry energy

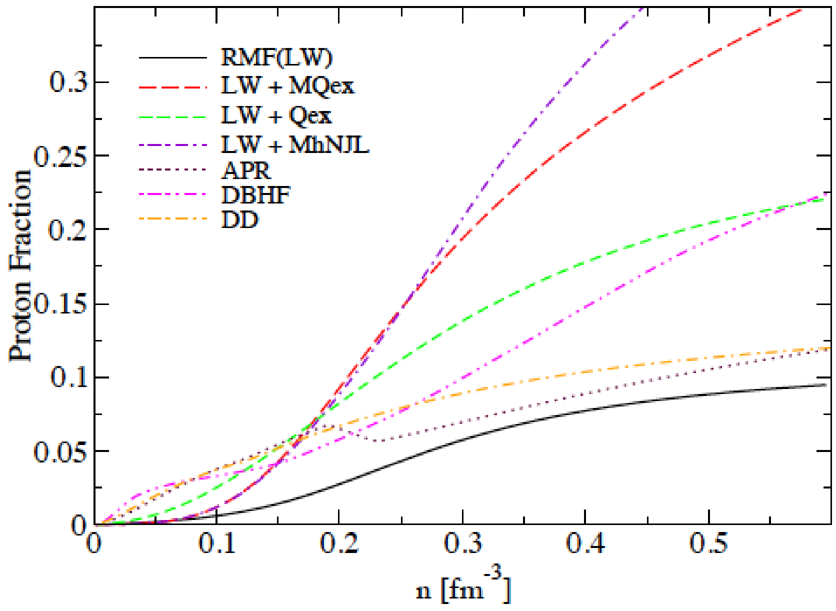


4. Example C: Pauli blocking in NM – results

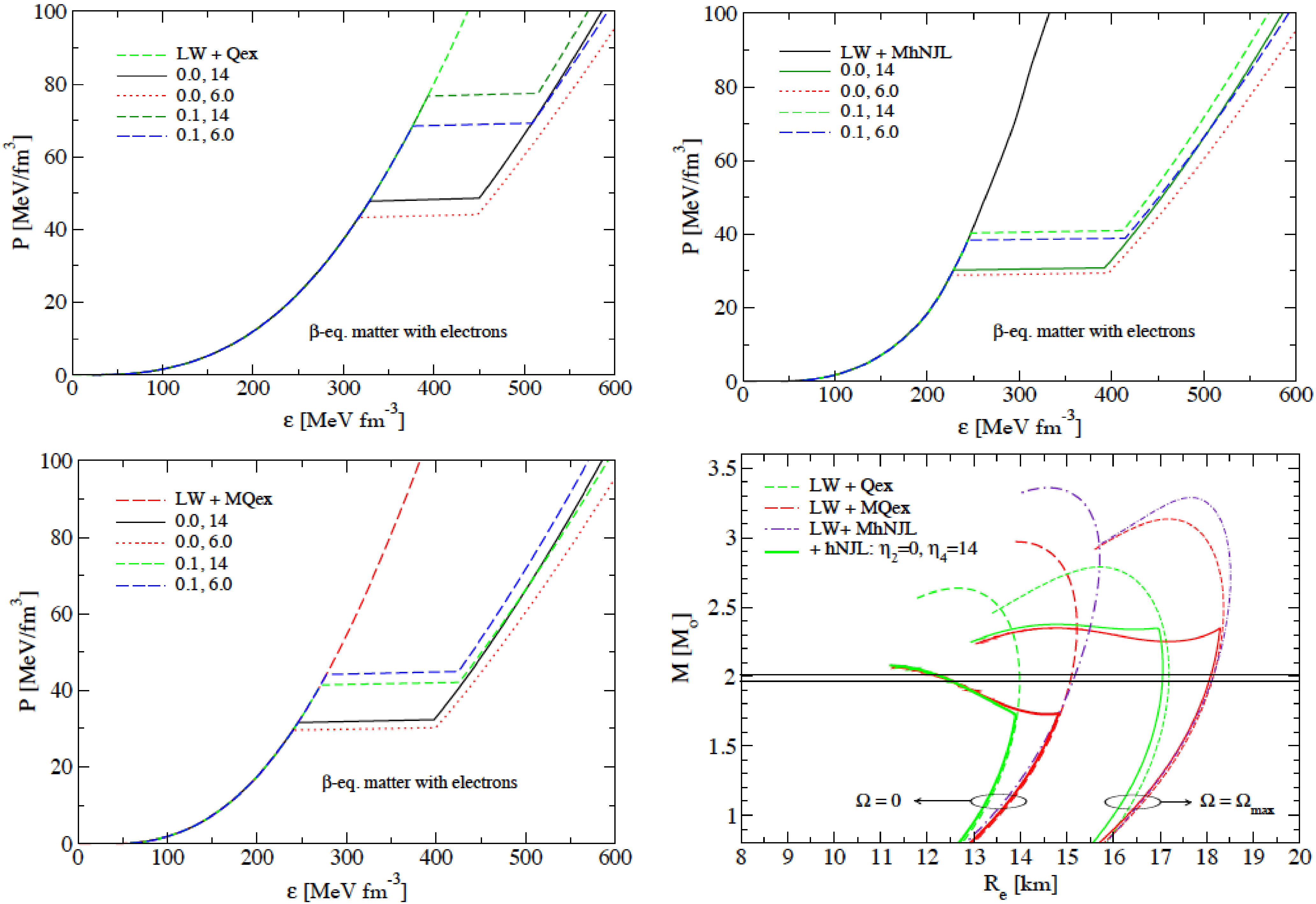








4. Example C: Pauli blocking in NM – results



4. Example C: Pauli blocking in NM – Summary

Pauli blocking selfenergy (cluster meanfield) calculable in potential models for baryon structure

Partial replacement of other short-range repulsion mechanisms (vector meson exchange)

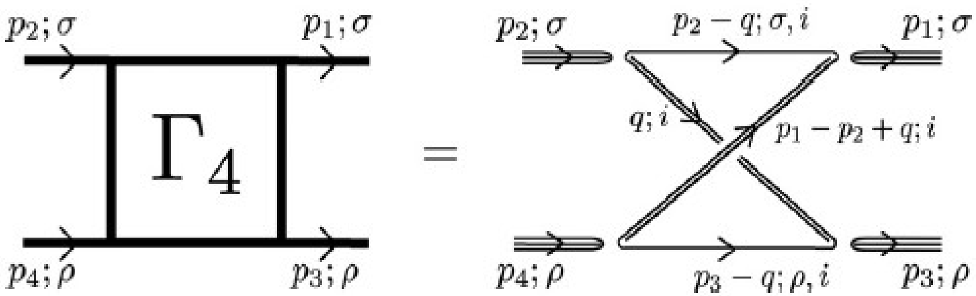
Modern aspects:
- onset of chiral symmetry restoration enhances nucleon swelling and Pauli blocking at high n
- quark exchange among baryons -> six-quark wavefunction -> “bag melting” -> deconfinement

Chiral stiffening of nuclear matter --> reduces onset density for deconfinement

Hybrid EoS:
Convenient generalization of RMF models,
Take care: eventually aspects of quark exchange already in density dependent vertices!

Other baryons:
- hyperons
- deltas
Again calculable, partially done in nonrelativistic quark exchange models, chiral effects not yet!

Relativistic generalization:
Box diagrams of quark-diquark model ...



K. Maeda, Ann. Phys. 326 (2011) 1032

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

Equations of state for T=0 nuclear matter:

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

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

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

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

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

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

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

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

Vector meanfield: $V_i \sim n_i$

4b. 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: $\mathcal{L}_{\mathrm{MF}} = \bar{q}(i\partial\!\!\!/ - M)q + \tilde{\mu}_q \bar{q}\gamma^0 q - U \,,$

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

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

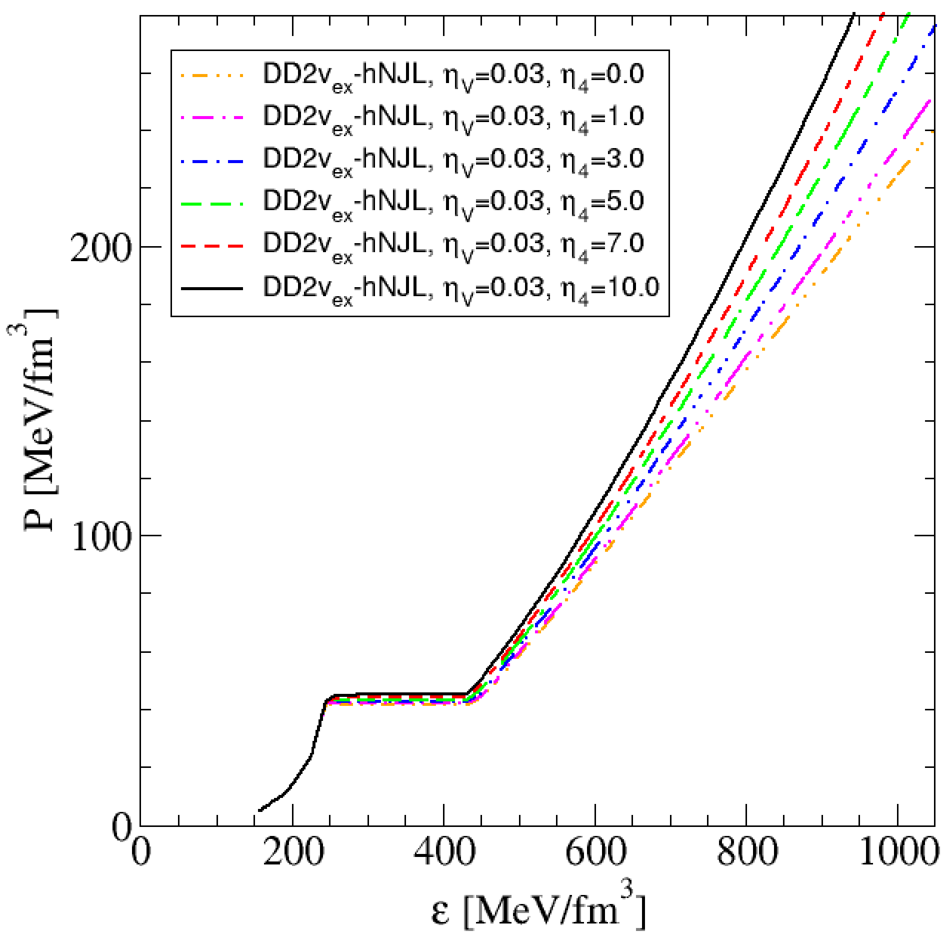
$$U = \frac{g_{20}}{\Lambda^2}\langle\bar{q}q\rangle^2 + 3\frac{g_{40}}{\Lambda^8}\langle\bar{q}q\rangle^4 - 3\frac{g_{22}}{\Lambda^8}\langle\bar{q}q\rangle^2\langle q^\dagger q\rangle^2 - \frac{g_{02}}{\Lambda^2}\langle q^\dagger q\rangle^2 - 3\frac{g_{04}}{\Lambda^8}\langle q^\dagger q\rangle^4 \,.$$

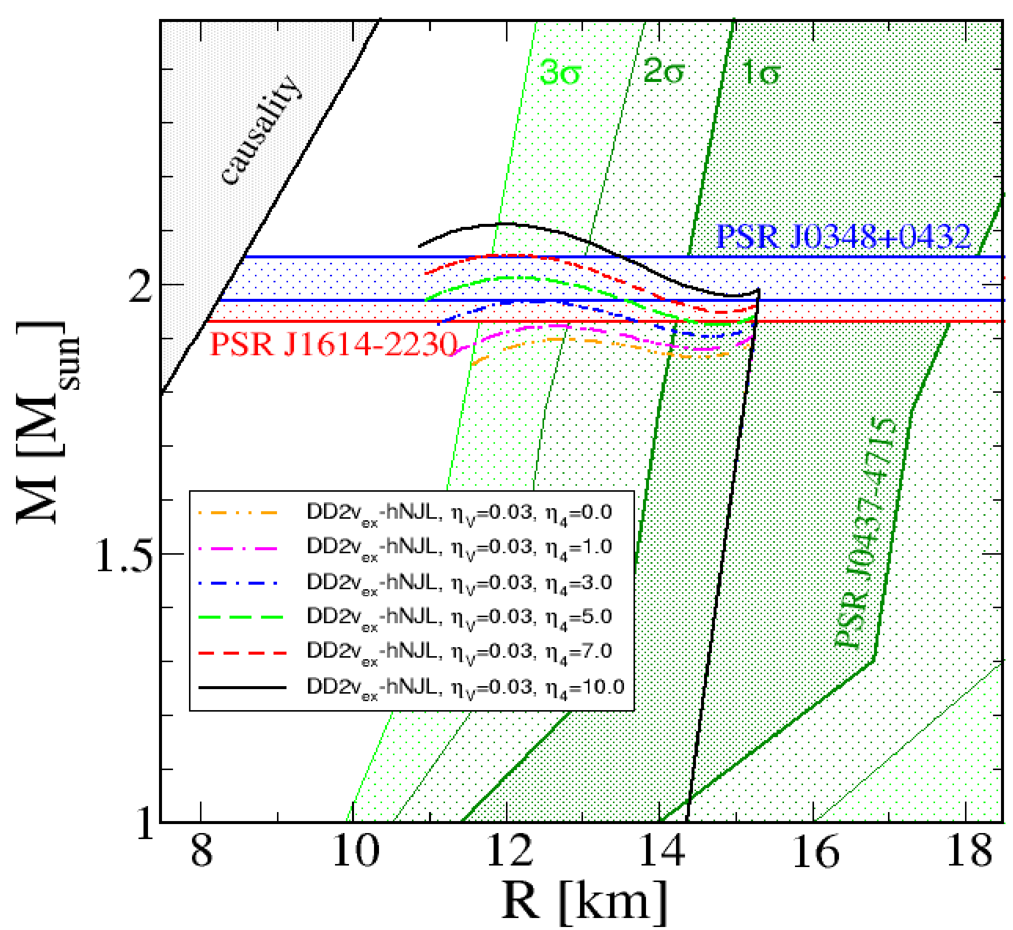
Thermodynamic Potential:

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

Result: high-mass twins ↔ 1st order PT

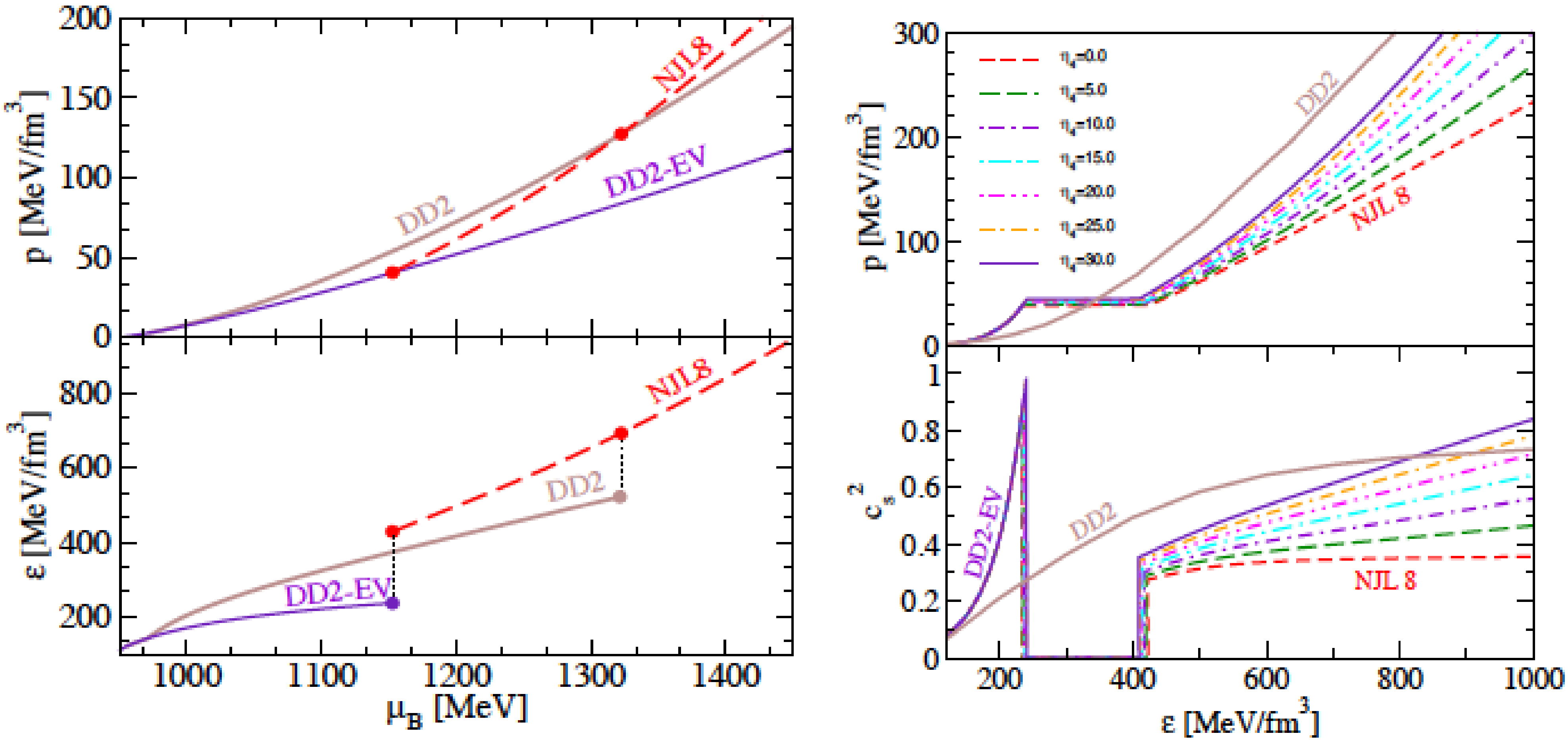
S. Benic, D. Blaschke, D. Alvarez-Castillo, T. Fischer, S. Typel, arxiv:1411.2856





Hybrid EoS supports M-R sequences with high-mass twin compact stars

4b. Stiff quark matter at high densities

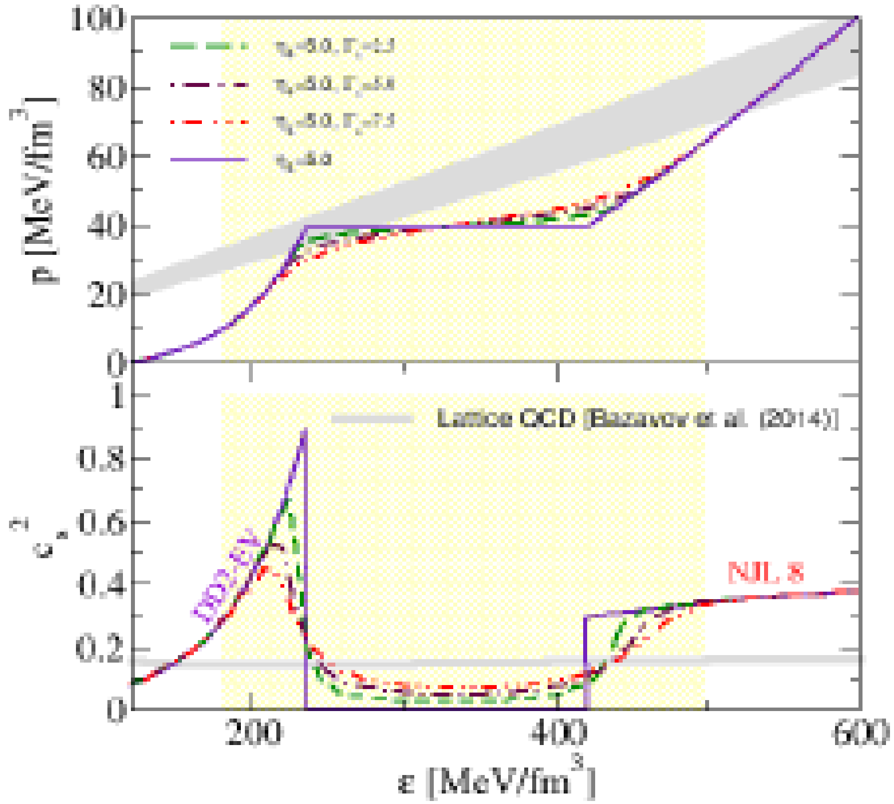


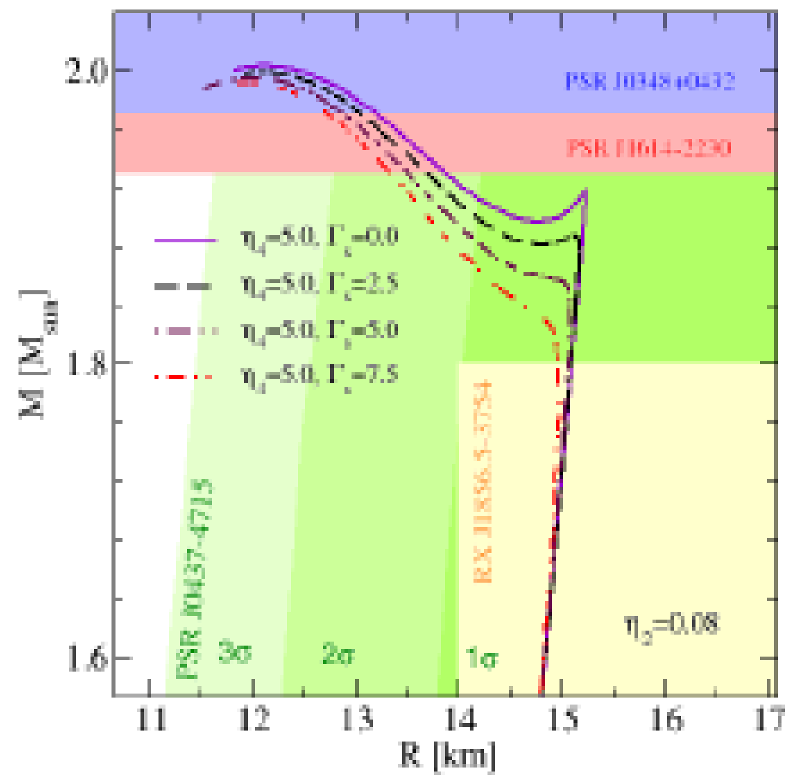
Here: Stiffening of dense hadronic matter by excluded volume in density-dependent RMF

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

4b. Stiff quark matter at high densities

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

4c. Rotation

- existence of 2 M_sun pulsars and possibility of high-mass twins raises question for their inner structure: (Q)uark or (N)ucleon core ??
  --> degenerate solutions
  --> transition from N to Q branch

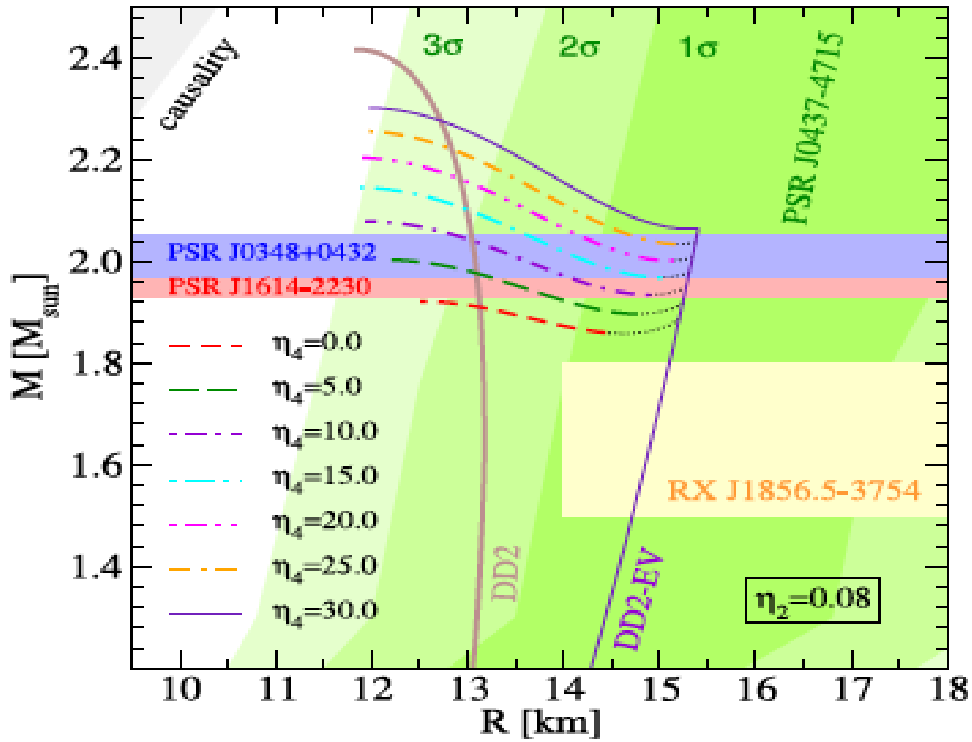
- PSR J1614-2230 is millisecond pulsar, period P = 3.41 ms, consider rotation !

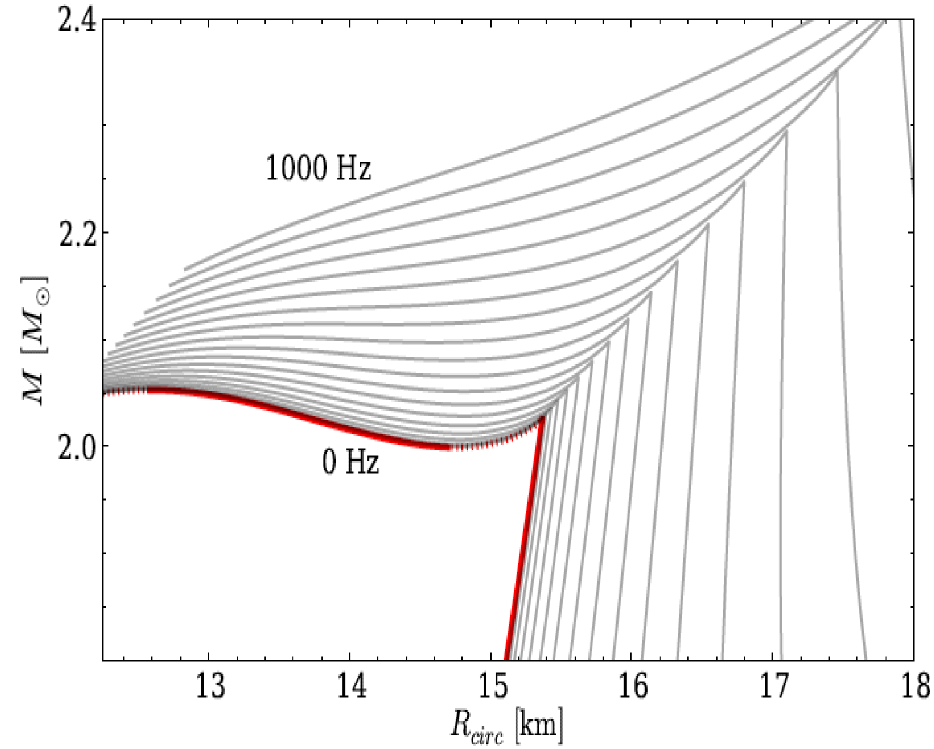
- transitions N --> Q must be considered for rotating configurations:
  --> how fast can they be?

(angular momentum J and baryon mass should be conserved simultaneously)

- similar scenario as fast radio bursts (Falcke-Rezzolla, 2013) or braking index (Glendenning-Pei-Weber, 1997)

M. Bejger, D.B., work in preparation (2015)





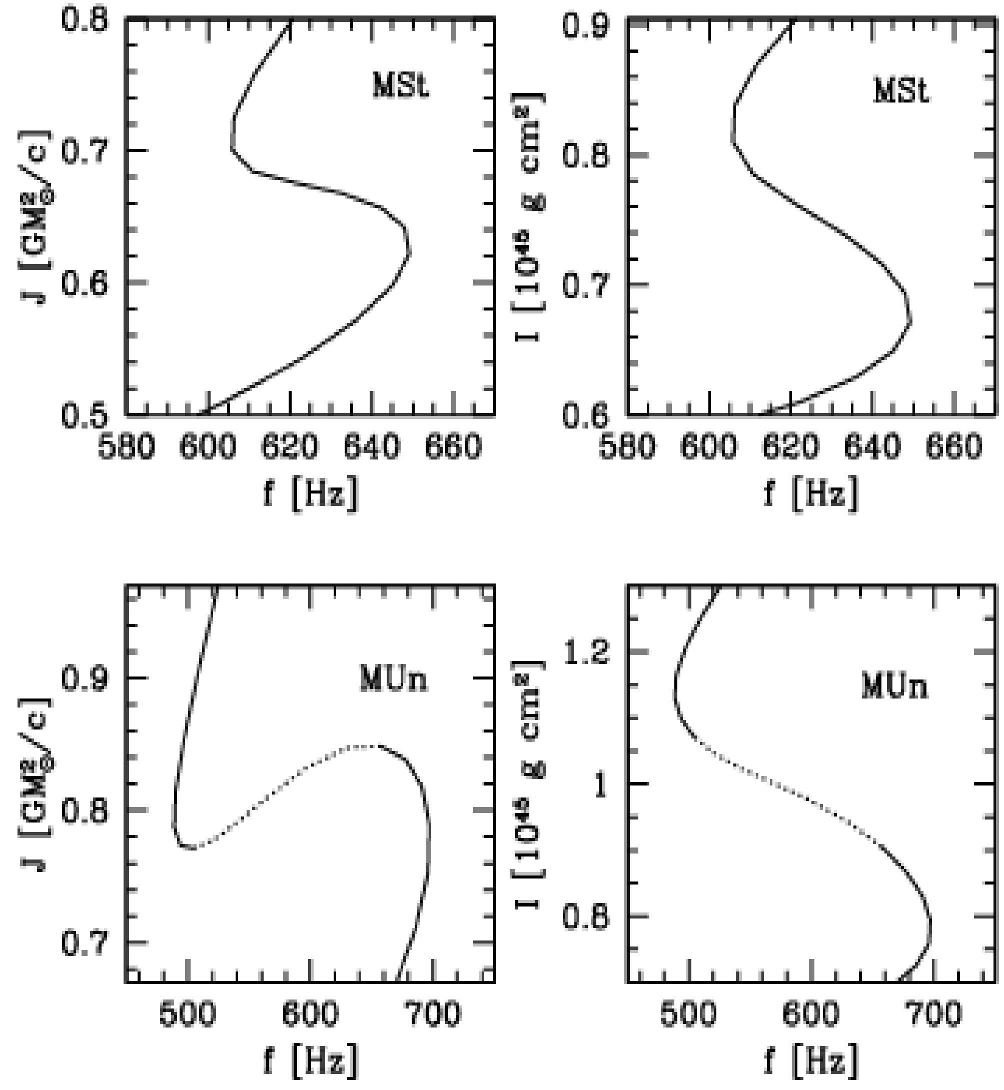
4c. Rotation and stability

- ⋆ Back-bending is connected to the existence of a minimum of M_b along $f = const.$ sequence,
- ⋆ *Change in stability* corresponds to extremum of M or M_b at fixed J:

$$\left(\frac{\partial M}{\partial \lambda_c}\right)_J = 0, \quad \left(\frac{\partial M_b}{\partial \lambda_c}\right)_J = 0,$$

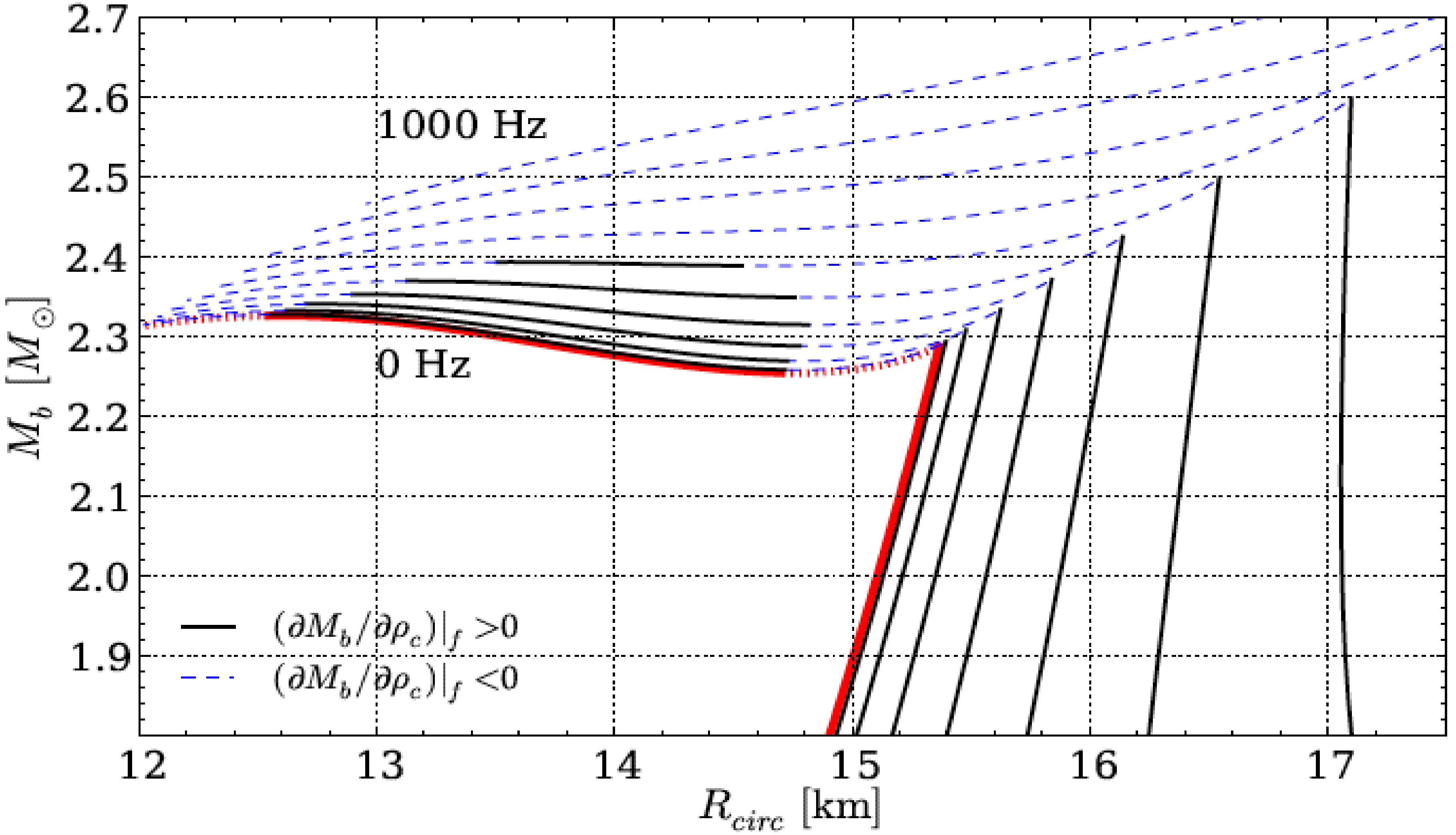
or to extremum of J at fixed either M or M_b:

$$\left(\frac{\partial J}{\partial \lambda_c}\right)_M = 0, \quad \left(\frac{\partial J}{\partial \lambda_c}\right)_{M_b} = 0.$$



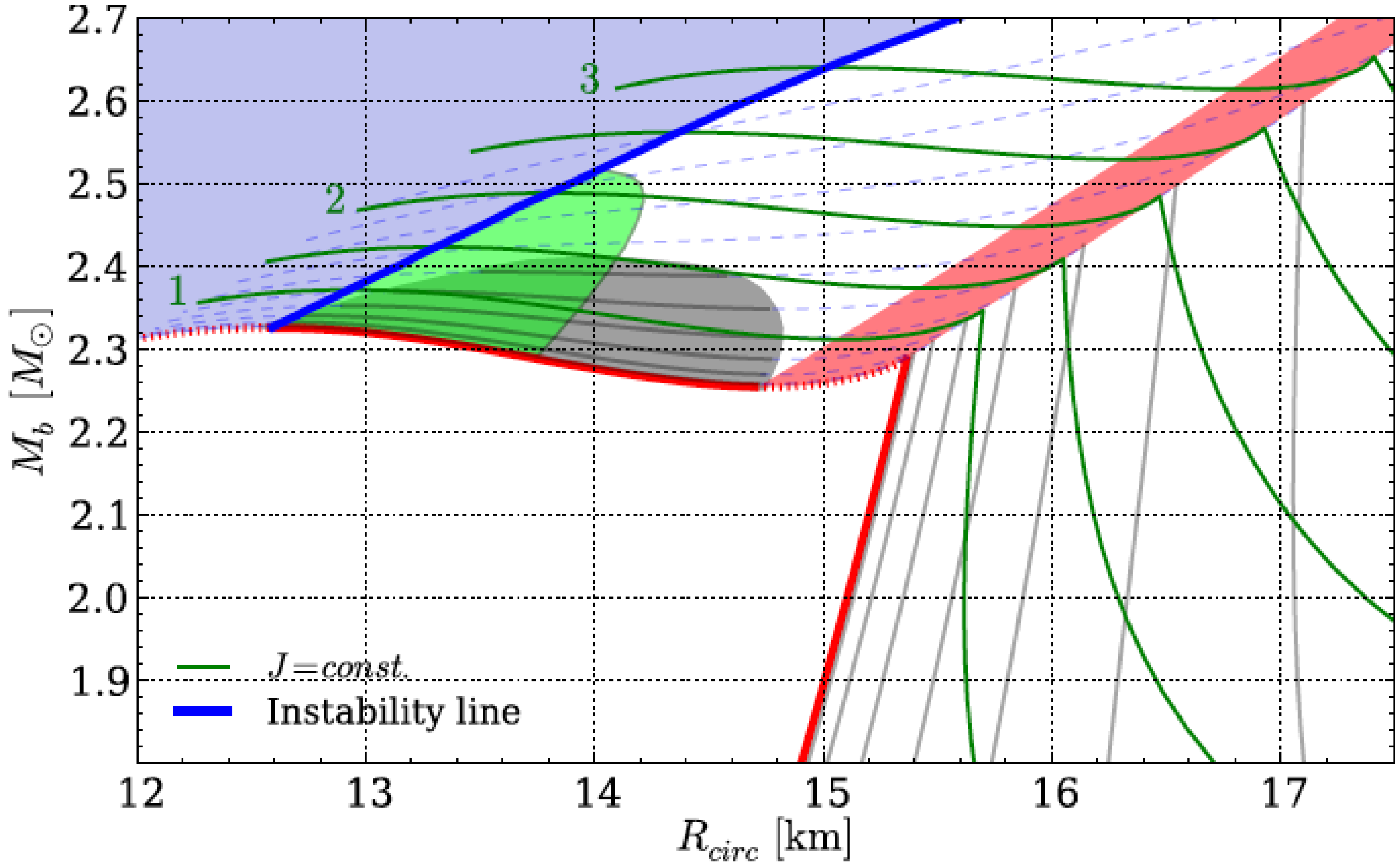
Zdunik, Bejger, Haensel, Gourgoulhon, A&A 450 (2006) 747

4c. Rotation and stability



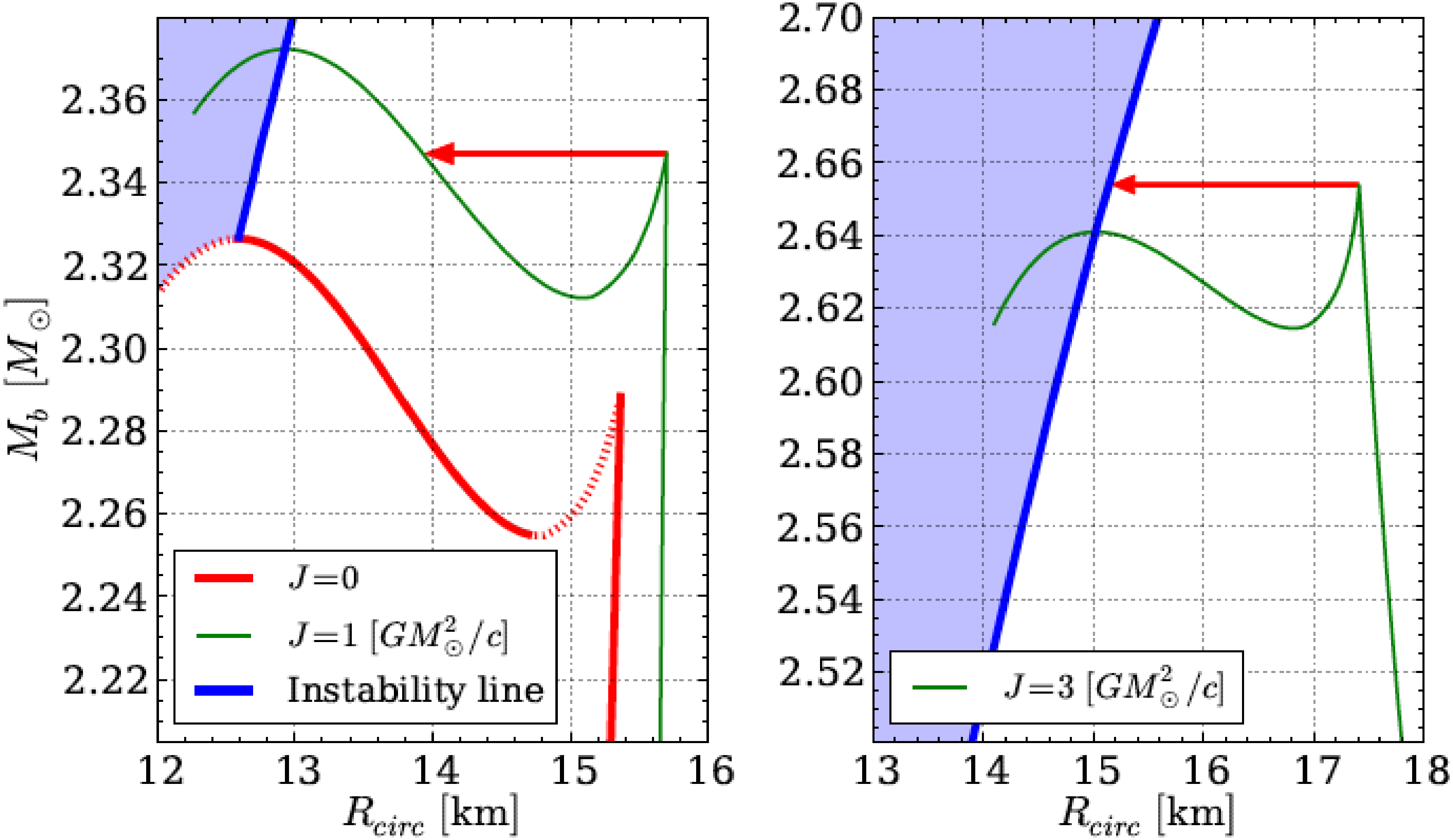
Large regions of backbending phenomenon
(NS spins up while losing angular momentum due to the dense matter EoS)

4c. Rotation and stability



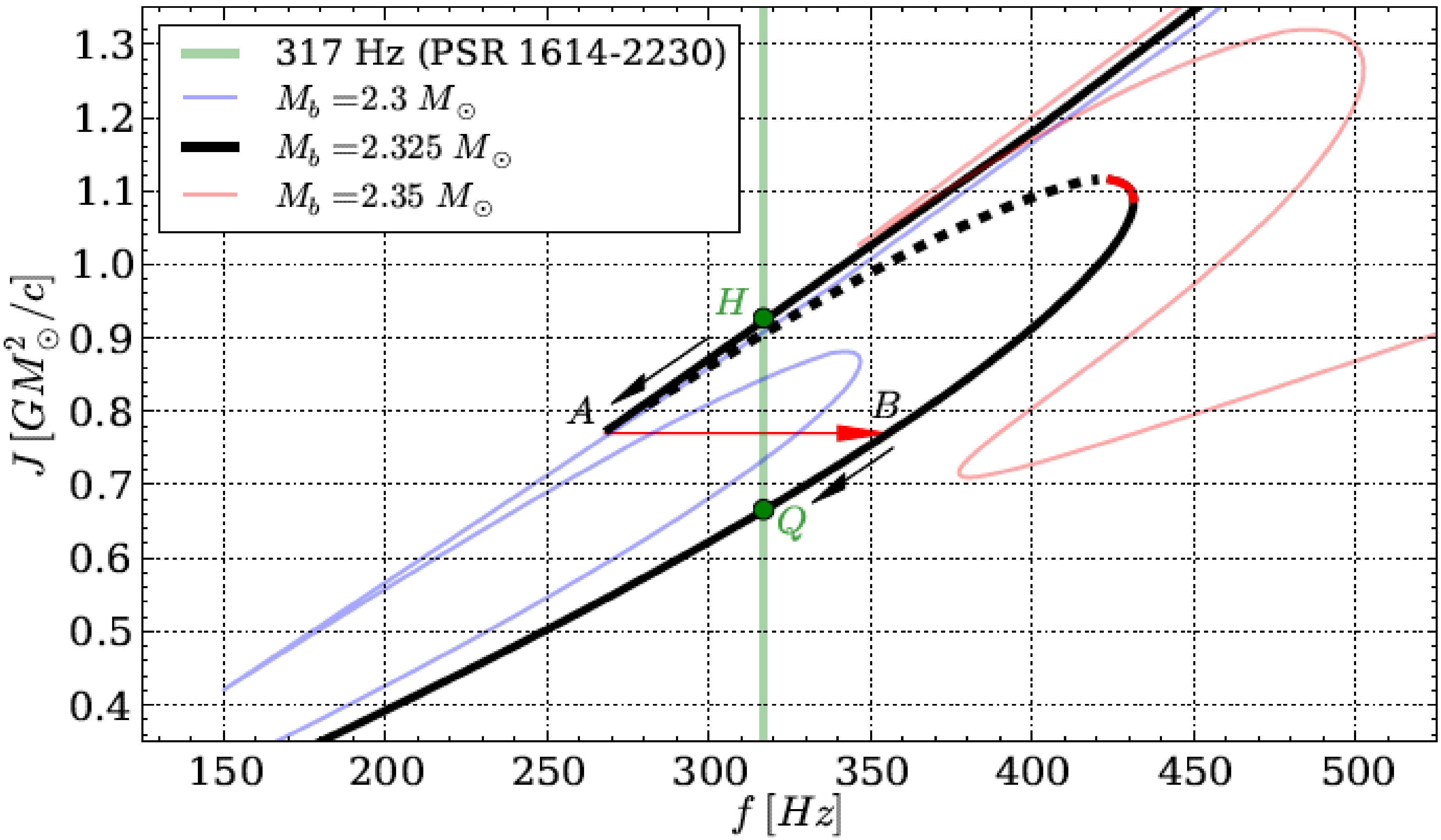
Red region - strong phase-transition instability,
Blue region - unstable w.r.t axisymmetric oscillations,
Grey region - no back-bending,
Green region - stable twin branch reached after the mini-collapse from the tip of $J = const.$ curve, along $M_b = const.$

4c. Rotation and stability



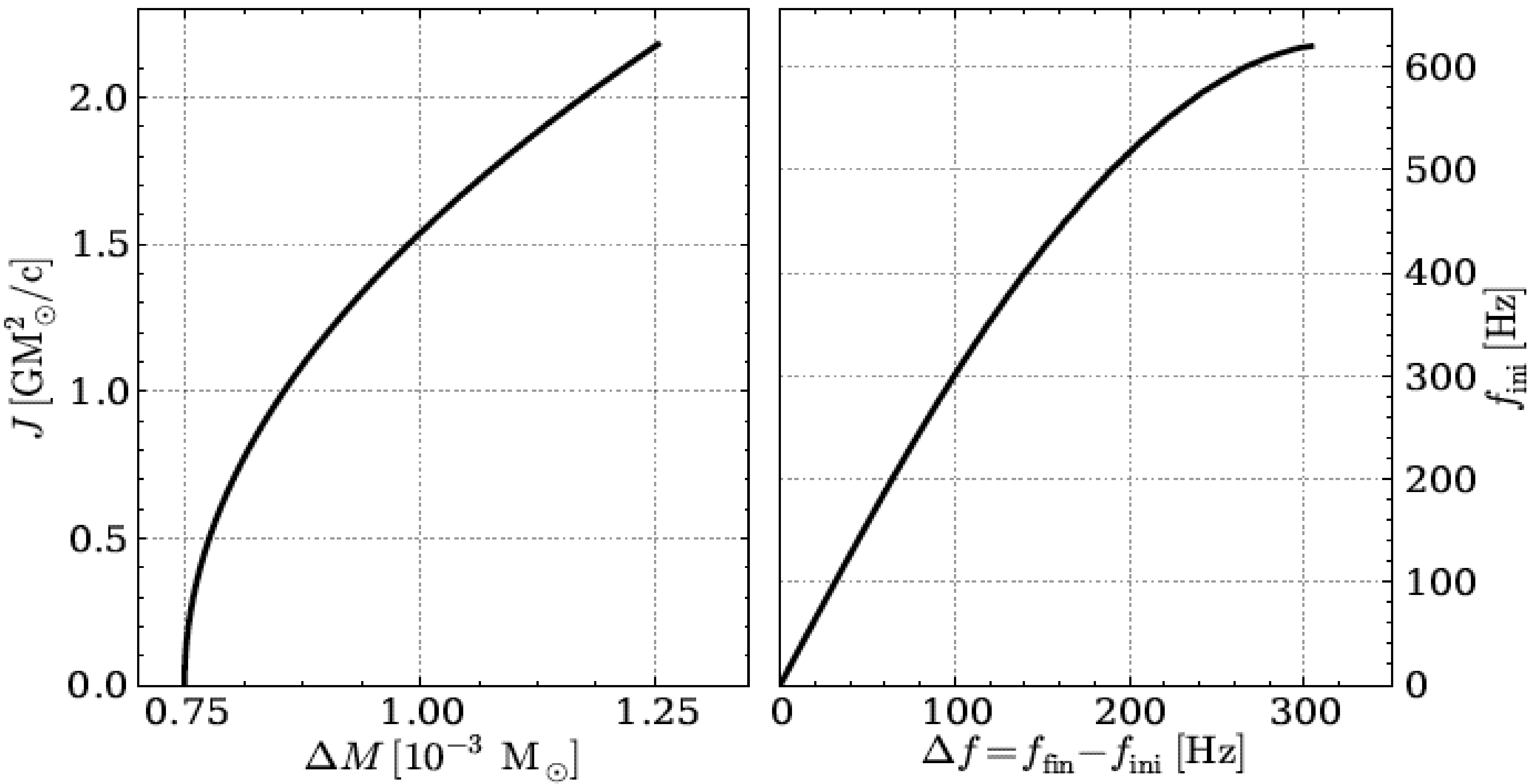
Stars with too much angular momentum *e.g., spun-up by accretion* end up in the instability.

4c. Constraints from mass and frequency



For NSs with measured gravitational mass *M* and frequency - possibility to put limits on M_b, *J*, moment of inertia *I*, core EOS composition etc.

4c. Energy release and spin-up (glitch)



Left panel: energy release (difference in the gravitational mass) vs *J* of the configuration entering the strong phase-transition instability.
Right panel: spin-up Δf (difference between the final and initial spin frequency) against the spin frequency of the initial configuration.

4c. Rotation - summary

This type of instability EOS provides a ”natural” explanation for:

- ⋆ Lack of back-bending in radiopulsar timing,
- ⋆ Spin frequency cut-off at some moderate (but >716 Hz) frequency,
- ⋆ Falcke & Rezzolla Fast Radio Burst (FRB) engine
  - ⋆ catastrophic mini-collapse to the second branch (or to a black hole),
  - ⋆ massive rearrangement of the magnetic field → energy emission.

Astrophysical predictions:

- ⋆ Way to constraint on M_b, J, I, core EOS etc.,
- ⋆ Specific shape of NS-BH mass function (no mass gap?)
- → population of massive, low B-field NSs (radio-dead?),
- → population of massive, high B-field NSs (collapse enhances the field?),
- ⋆ Characteristic burst-like signature in GW emission during the mini-collapse.

4d. New Bayesian Analysis scheme

ISSN 1742-6588

JOURNAL OF PHYSICS: CONFERENCE SERIES

The open access journal for conferences

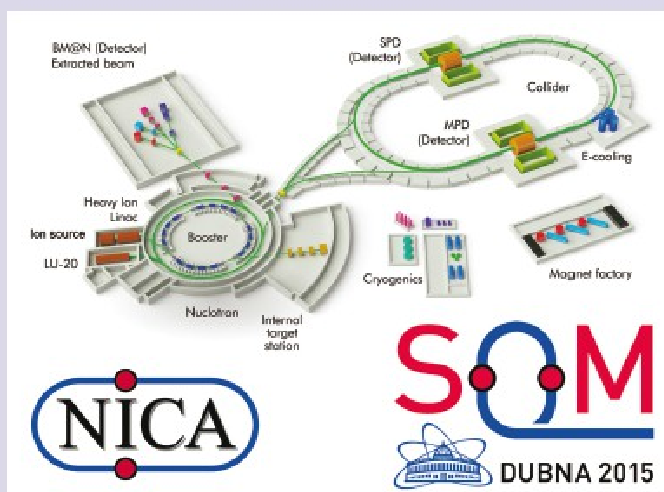
15th International Conference on Strangeness in Quark Matter (SQM2015)

Dubna, Russia
6–11 July 2015

Editors: David E. Alvarez-Castillo, David Blaschke, Vladimir Kekelidze, Victor Matveev and Alexander Sorin

Volume 668 2016

jpcs.iop.org



IOP Publishing

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

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

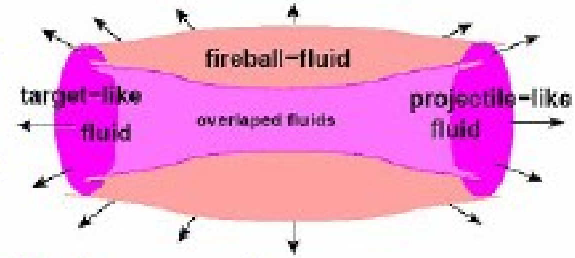
3-fluid hydro, (Yu. Ivanov)

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

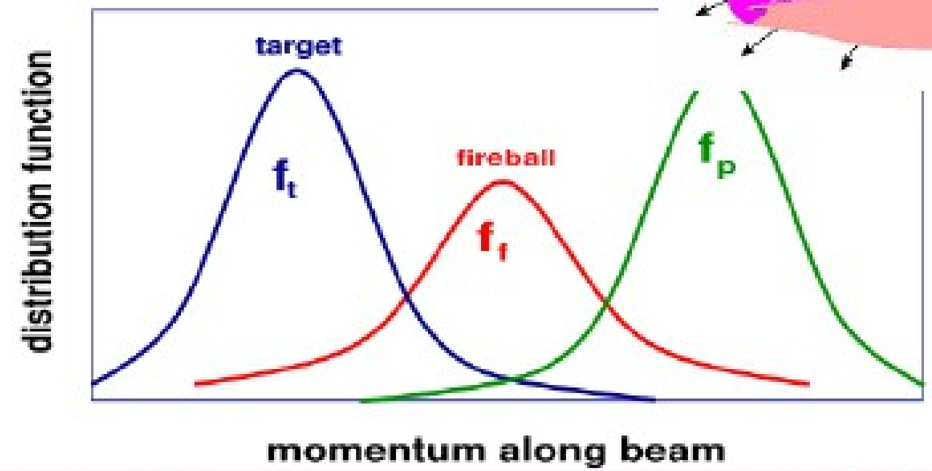
(optionally) cascade: PHSD, UrQMD, etc (E. Bratkovskaya, H. Petersen)

GEANT MPD, BM @N (O. Rogachevsky, P. Batyuk, S. Merts, 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 — 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 — Source term — Exchange

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

Total energy-momentum conservation:

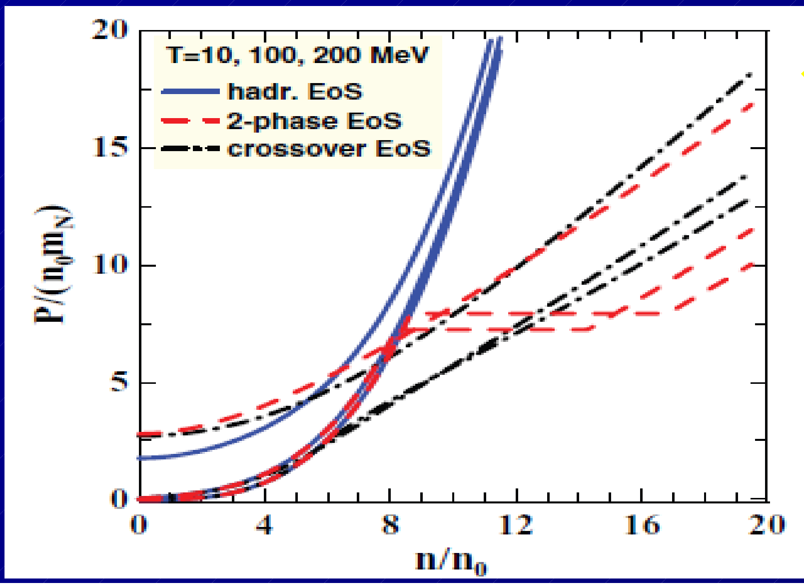
$$\partial_\mu (T_p^{\mu\nu} + T_t^{\mu\nu} + T_f^{\mu\nu}) = 0$$

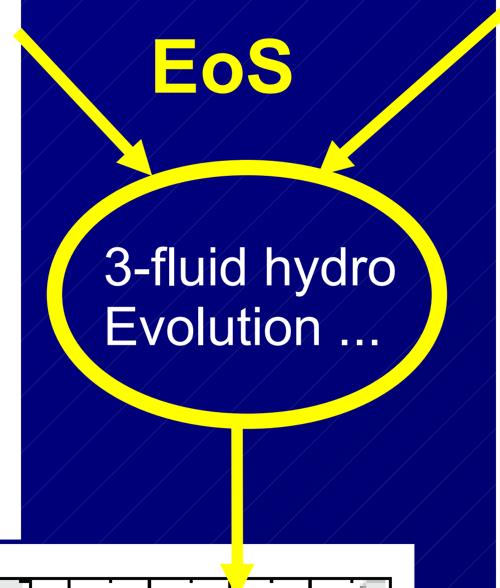
http://theory.gsi.de/~ivanov/mfd/

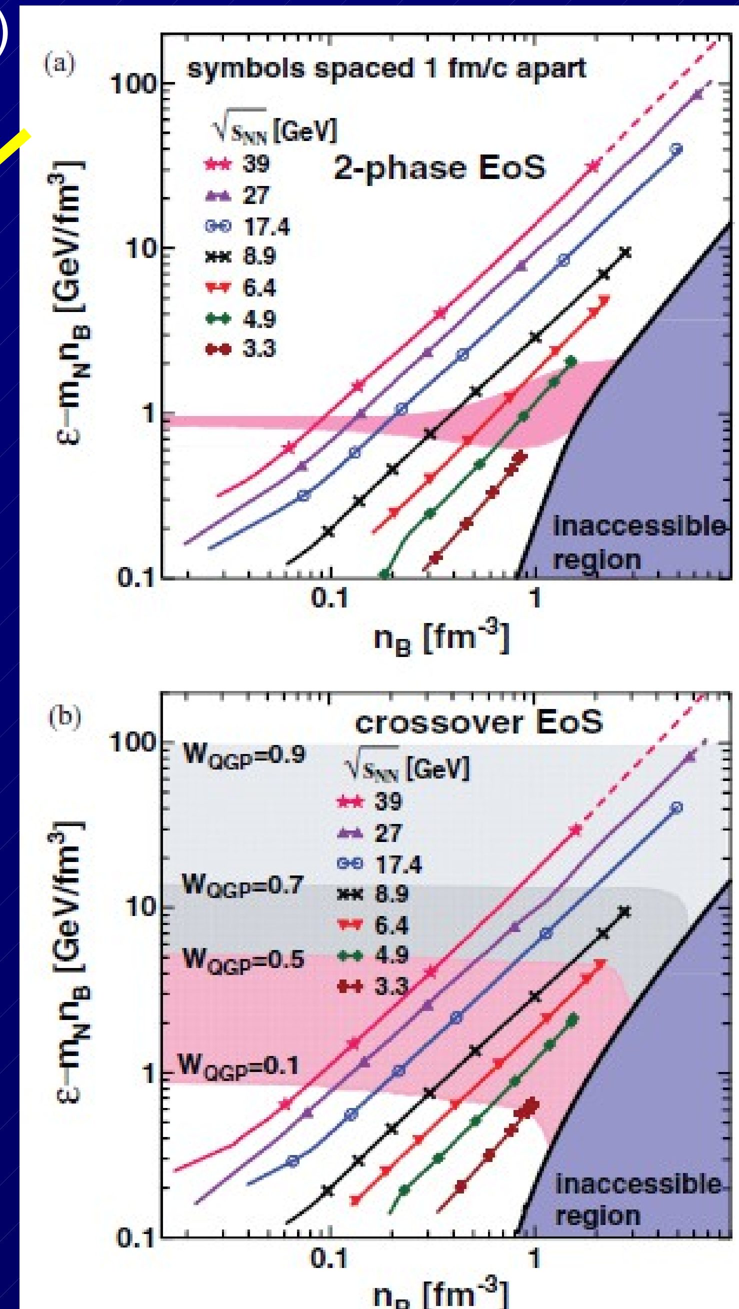
Yu.B. Ivanov, V.N. Russkikh and V.D. Toneev, Phys. Rev. C73, 044904 (2006)

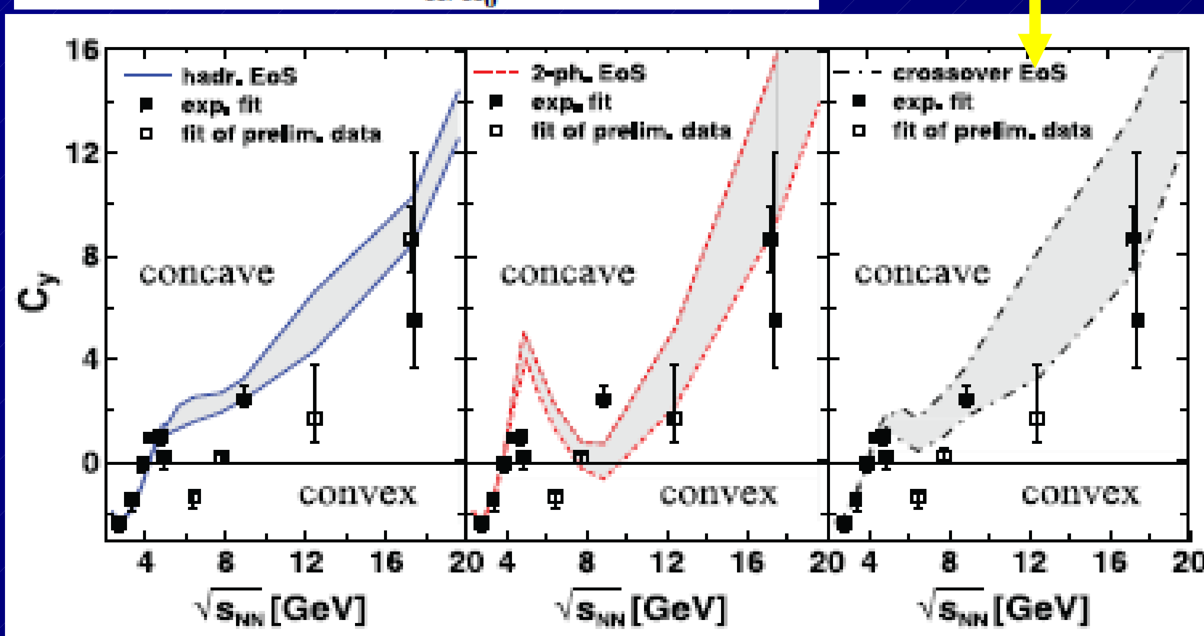
Net proton rapidity distribution – test case for a 1st order PT signal

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





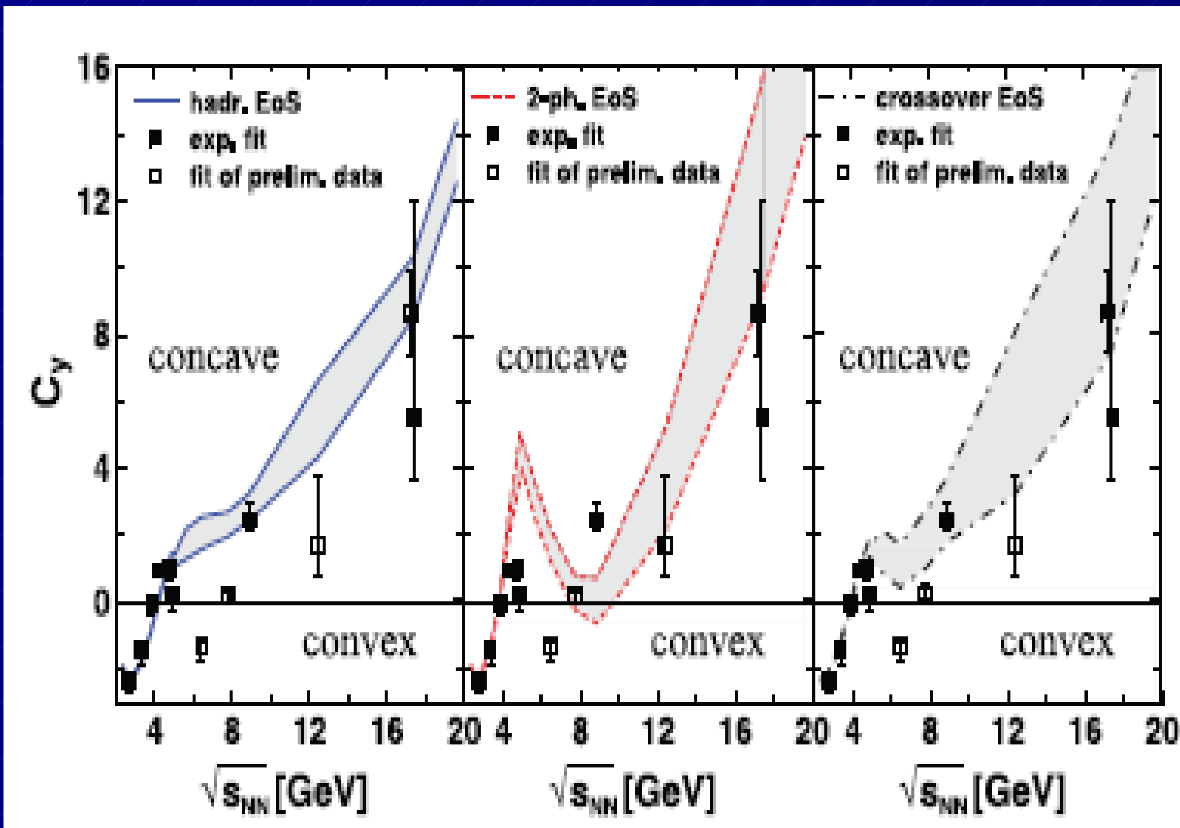


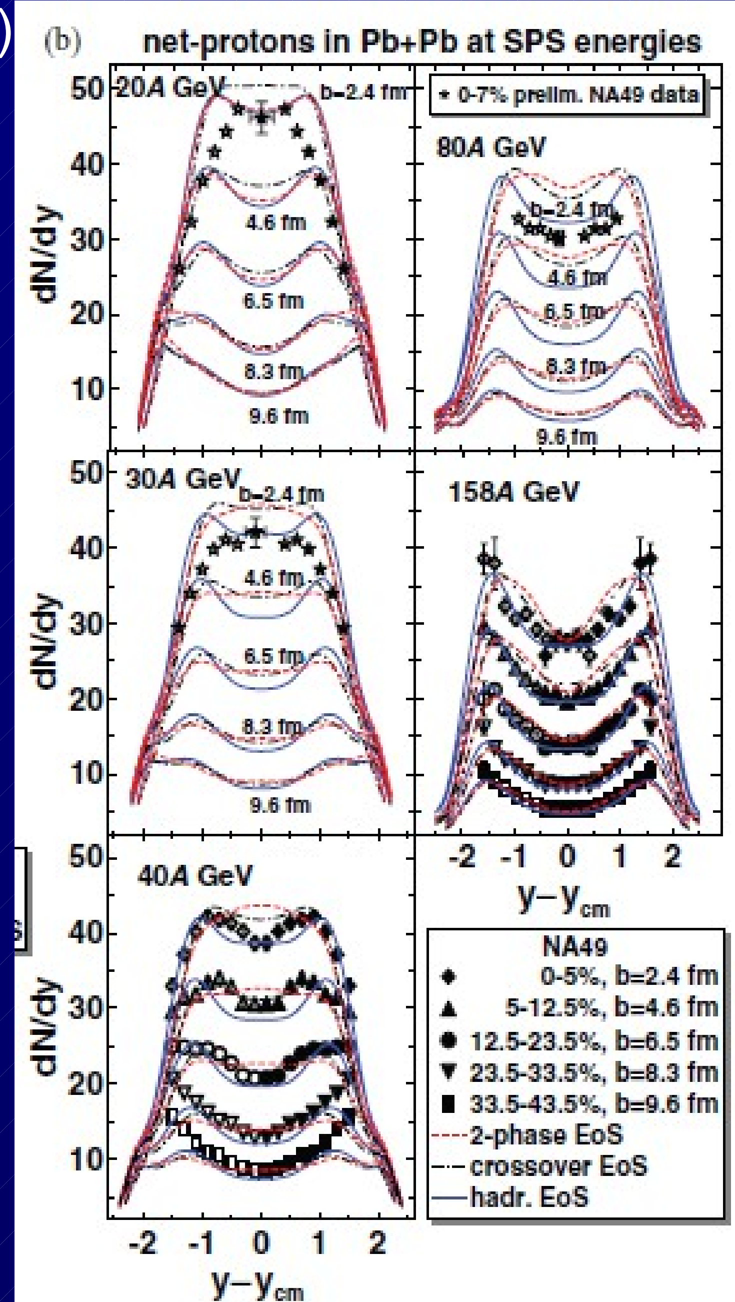


Net proton rapidity distribution – test case for a 1st order PT signal

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

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





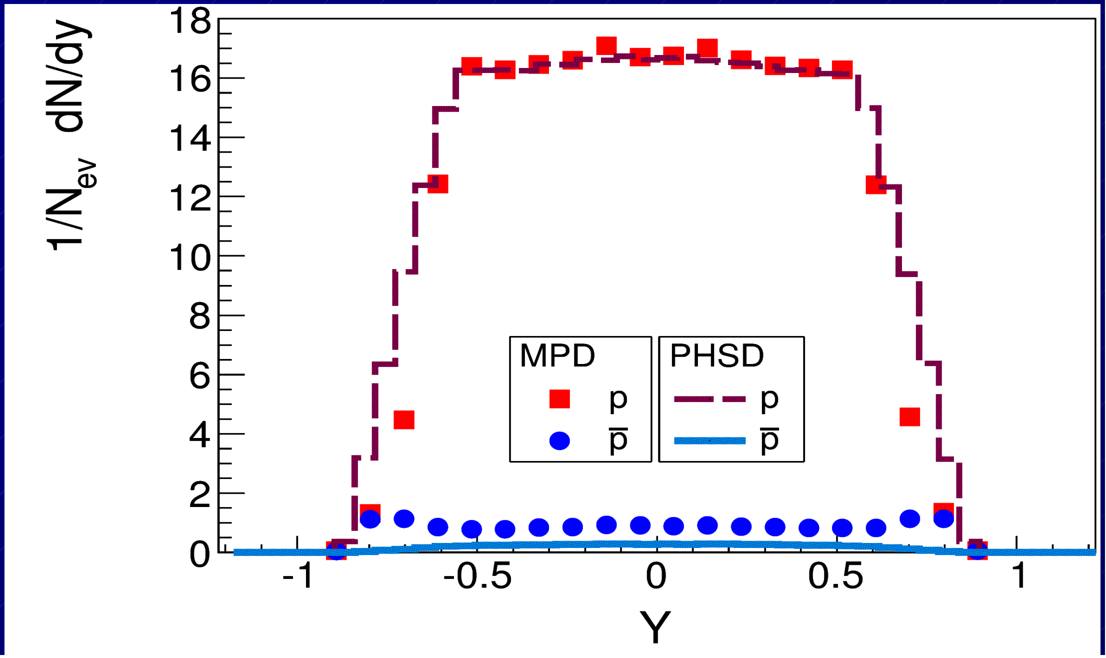
Net proton rapidity distribution – test case for a 1st order PT signal

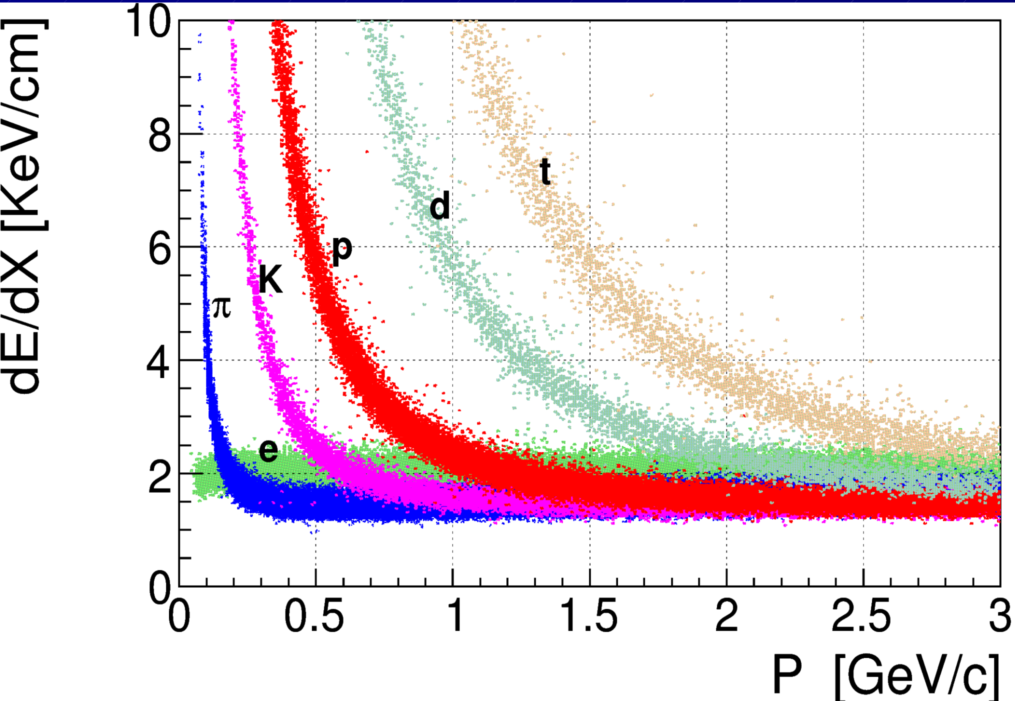
Event set:
40k AuAu @ √s_NN = 9 GeV [0-5%]
The most reliable region
|eta| < 1.2 ; 0.4 < p_t [GeV/c] < 0.8

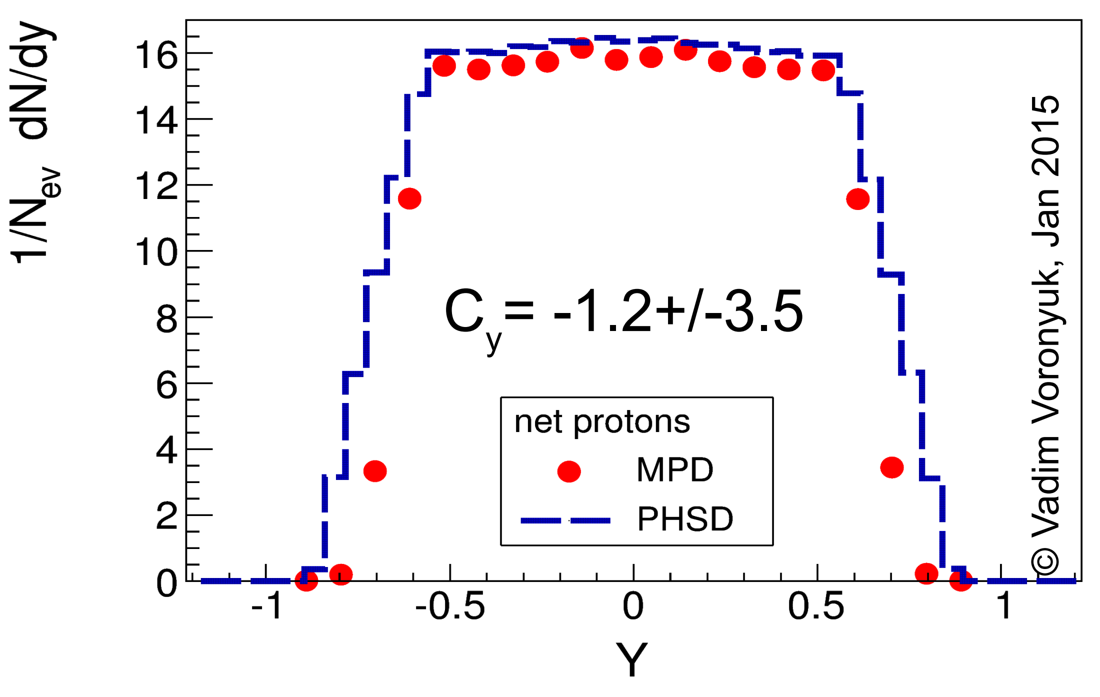
Result:
PHSD input → GEANT+MPD
detector reproduces the rapidity distribution !
(previous concerns not confirmed !!)

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

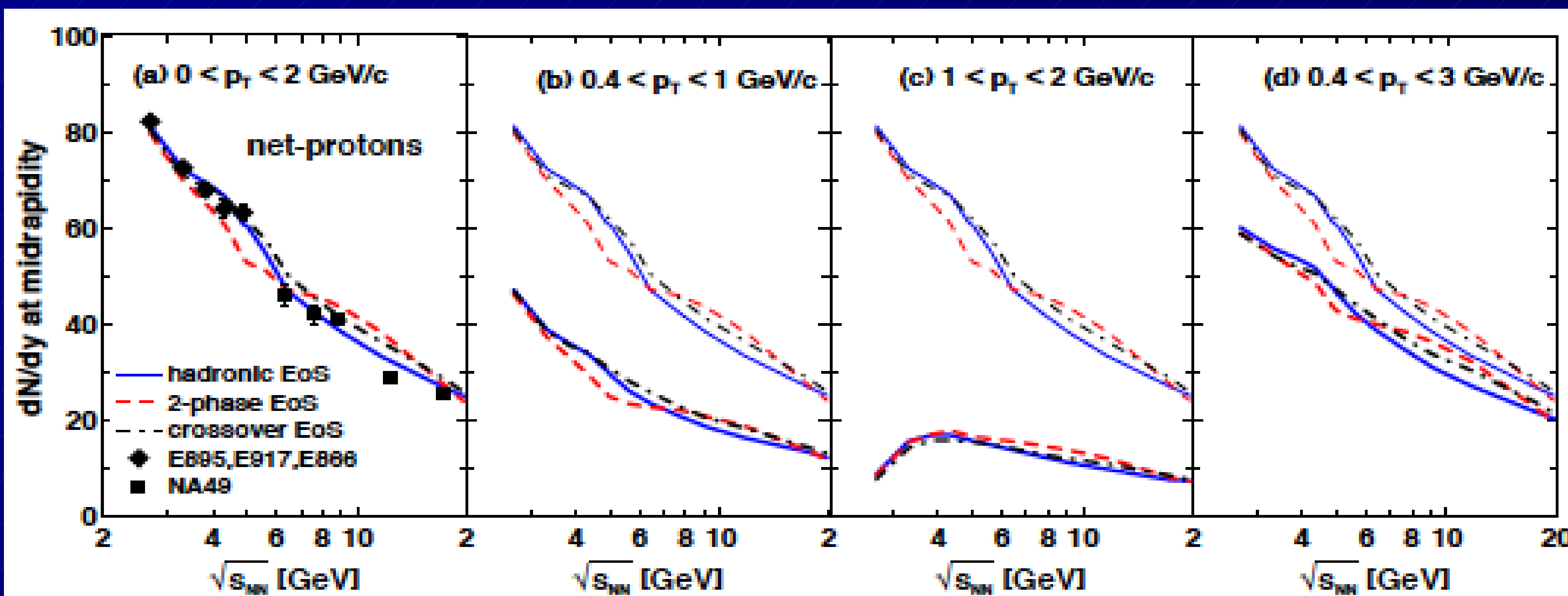
$$C_y = \left(y_{\rm beam}^3 \frac{d^3N}{dy^3} \right)_{y=0} \Big/ \left(y_{\rm beam} \frac{dN}{dy} \right)_{y=0}$$
$$= (y_{\rm beam}/w_s)^2 \left(\sinh^2 y_s - w_s \cosh y_s \right) .$$

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].



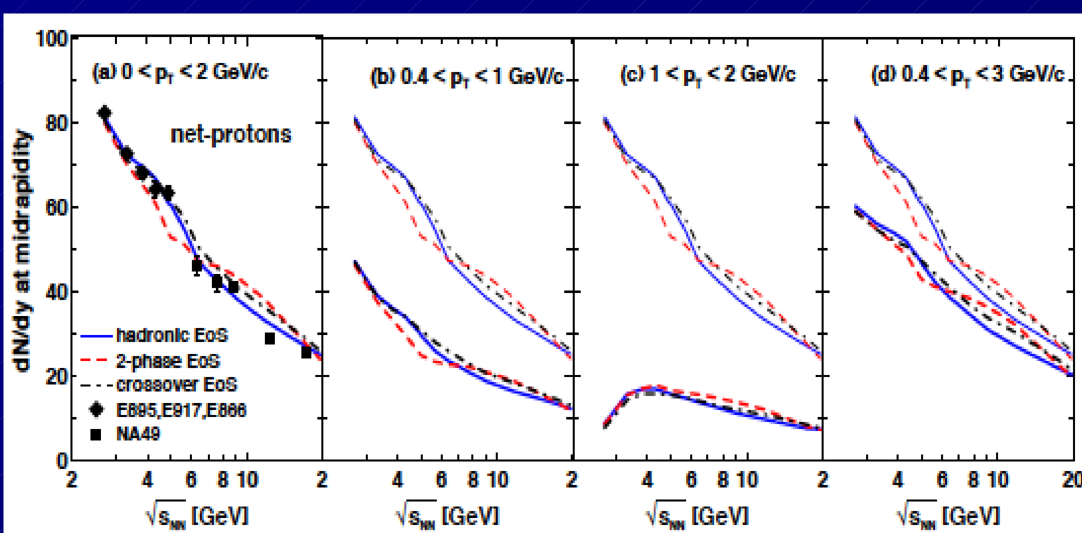
Net proton rapidity distribution – test case for a 1st order PT signal

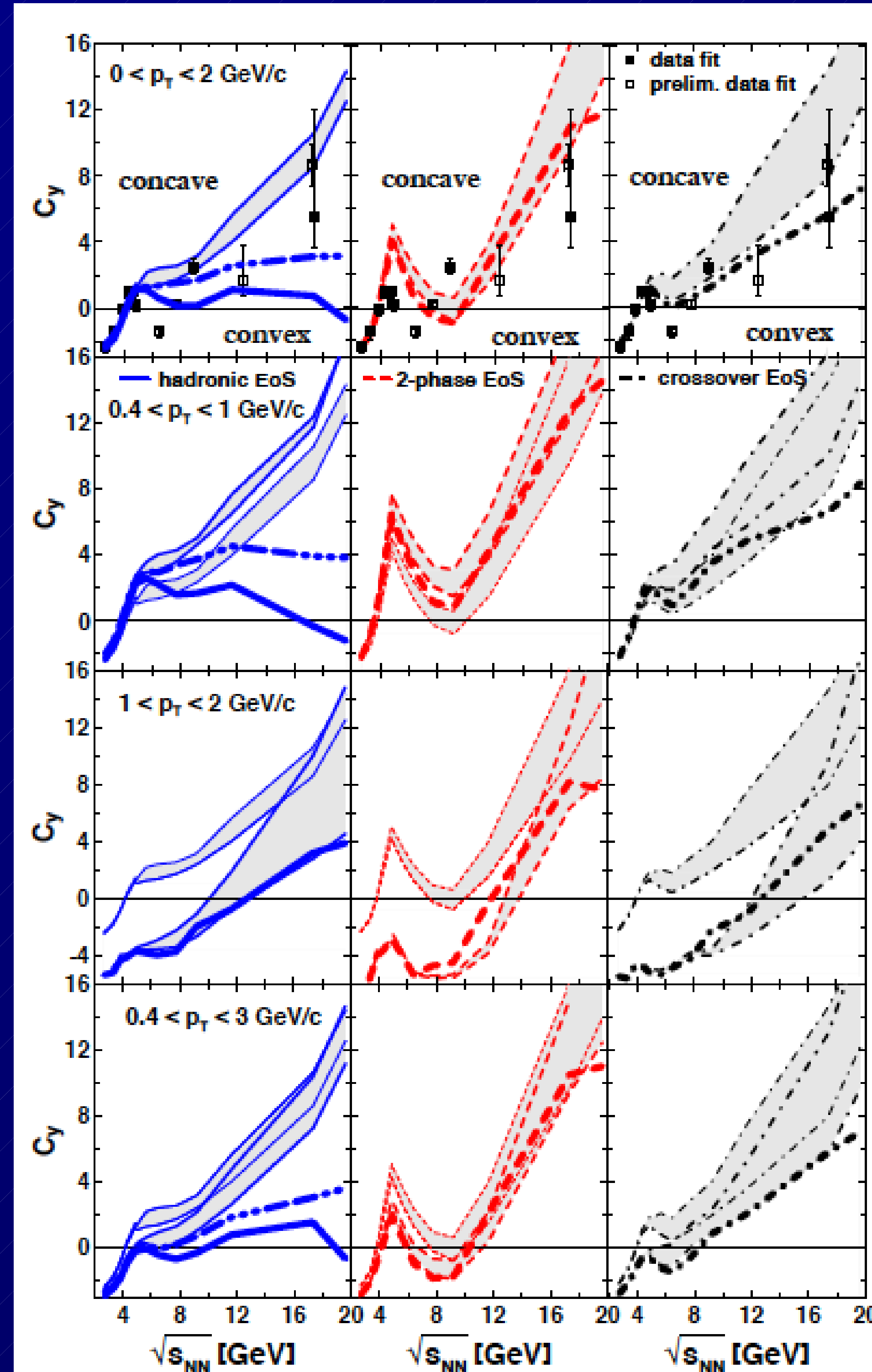
Investigation of p_T cuts:

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

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

- "wiggle" formed in the nonequilibrium 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: $\Delta C_y < 2$





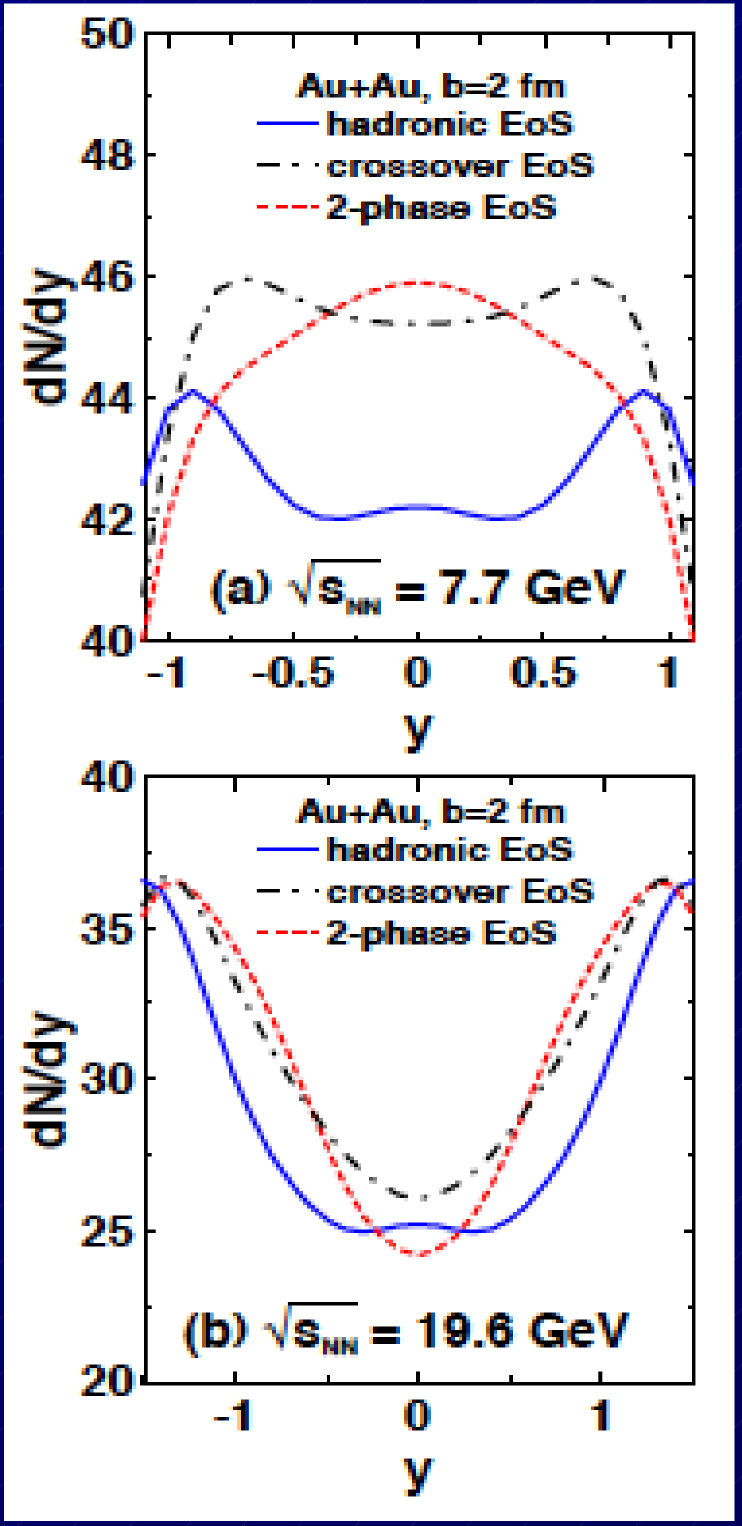
Net proton rapidity distribution – test case for a 1st order PT signal

Investigation of p_T cuts:

Yu. Ivanov & D. Blaschke, arxiv:1504.03992

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

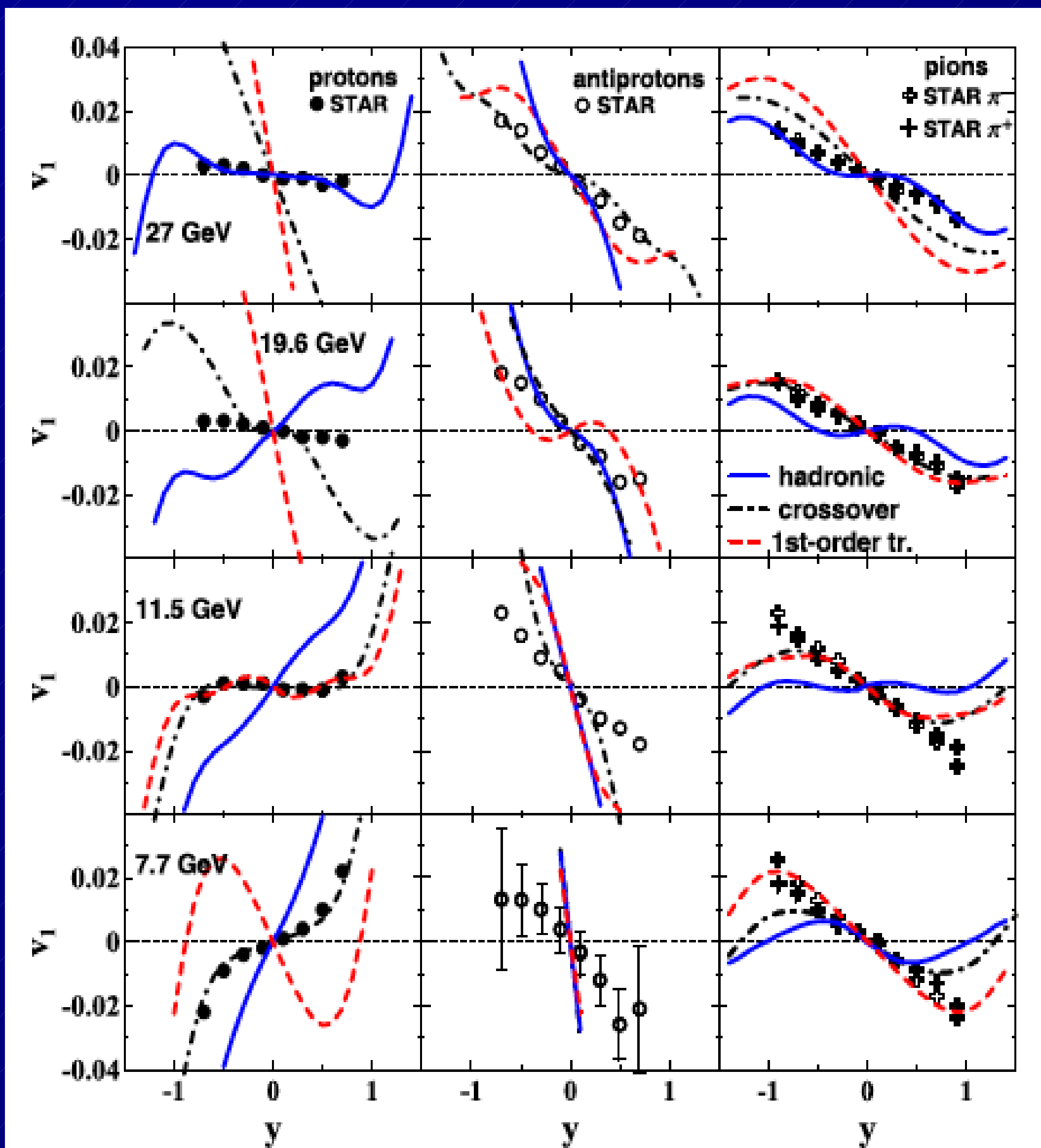
$$C_y = \left(y_{\rm beam}^3 \frac{d^3N}{dy^3}\right)_{y=0} \Big/ \left(y_{\rm beam}\frac{dN}{dy}\right)_{y=0} = (y_{\rm beam}/w_s)^2\left(\sinh^2 y_s - w_s \cosh y_s\right).$$

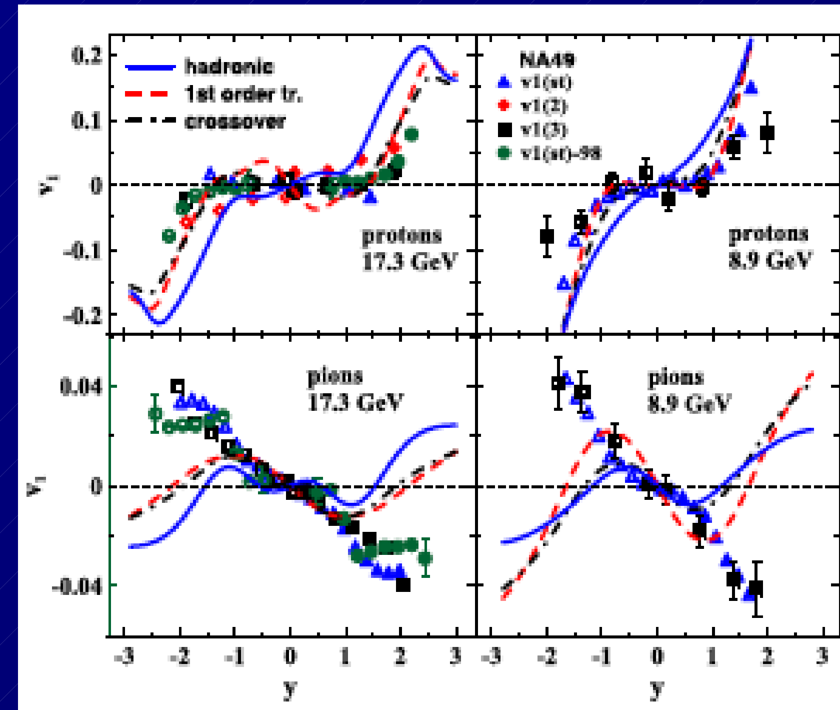


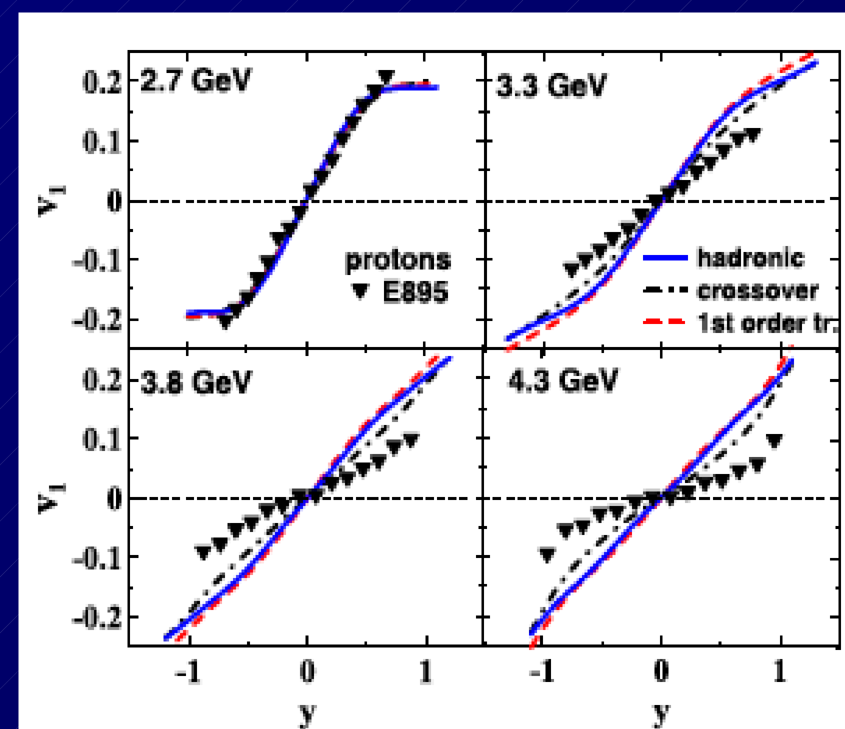
- “wiggle” formed in the nonequilibrium compression stage of the collision, where p_T only in 3FH
- robust against serious p_T cuts
- at high p_T (1 - 2 GeV/c) in convex region
- at low p_T (0.2 - 1 GeV/c) in concave region
- required accuracy in C_y determination: $\Delta C_y < 2$

Directed flow indicates a cross-over Deconfinement transition …

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

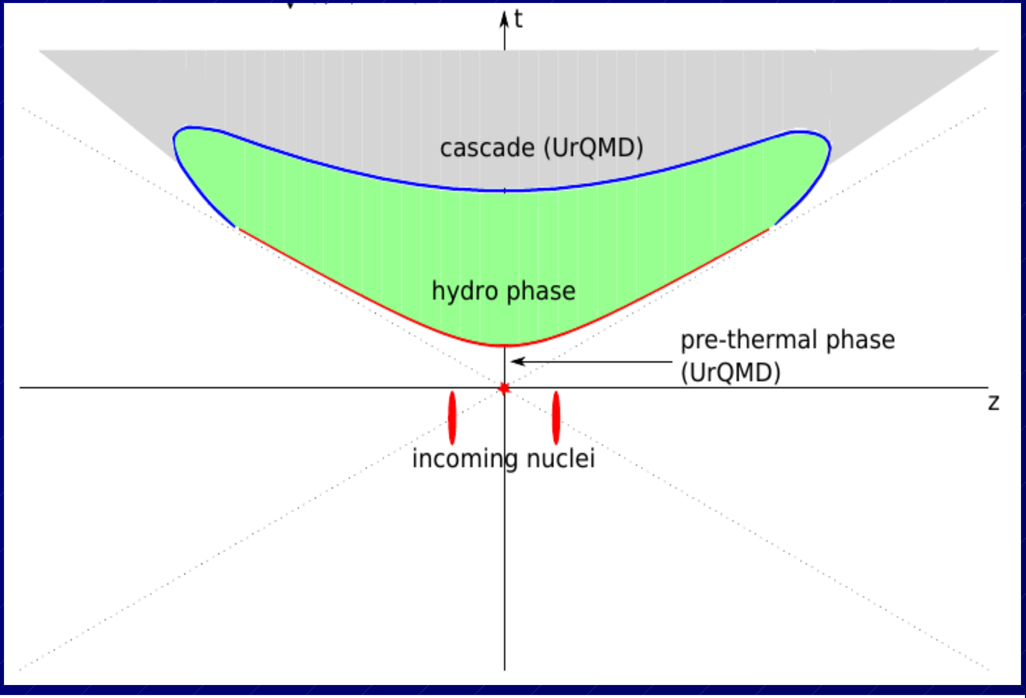






3+1D viscous hydro-cascade model (Yu. Karpenko, FIAS)

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

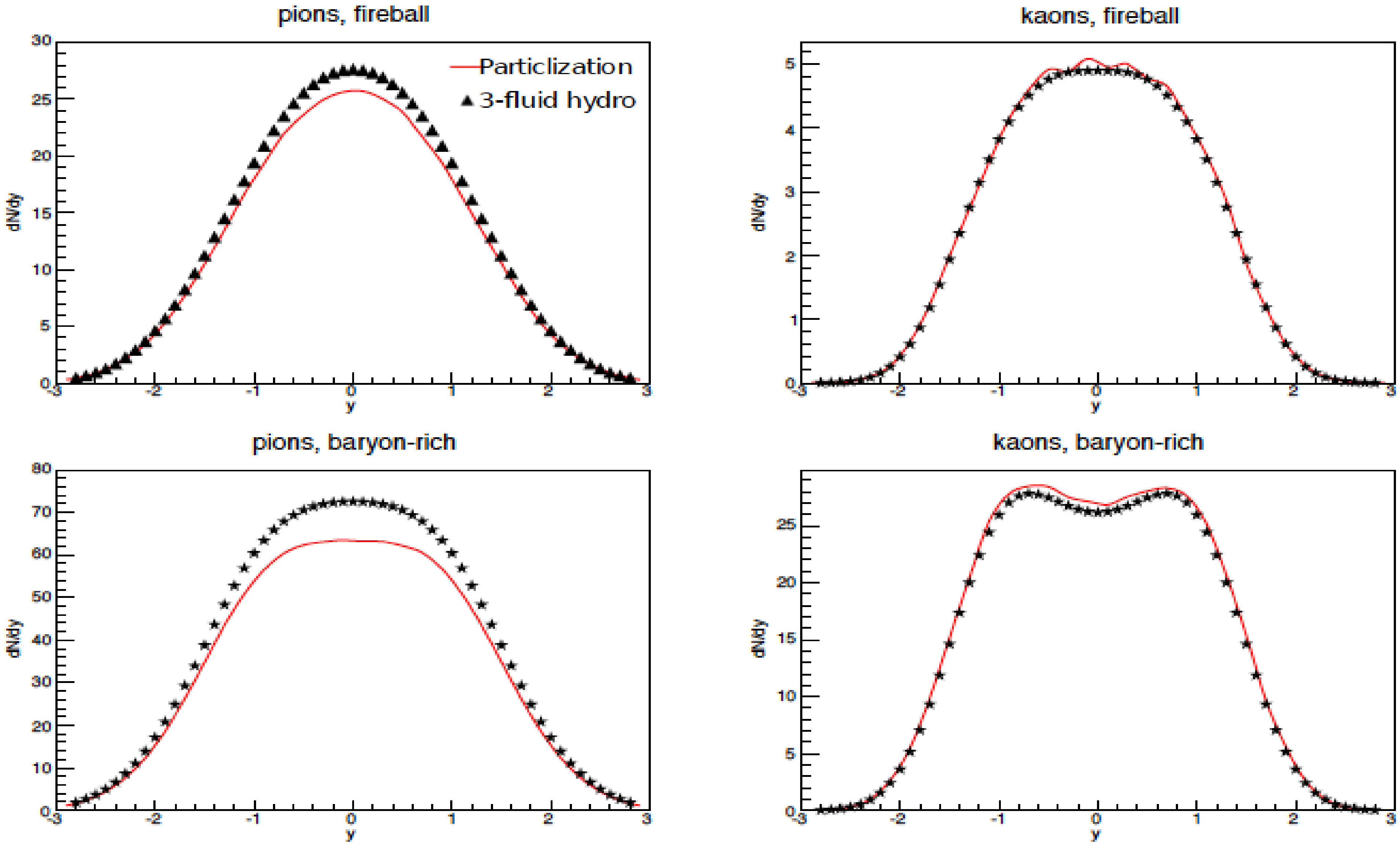
- Chiral model
  - coupled to Polyakov loop to include the deconfinement phase transition
  - good agreement with lattice QCD data at $\mu_B = 0$, also applicable at finite baryon densities
  - (current version) has crossover type PT between hadron and quark-gluon phase at all μ_B
- Hadron resonance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

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

Preview: Particlization of 3-fluid Hydrodynamics model

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

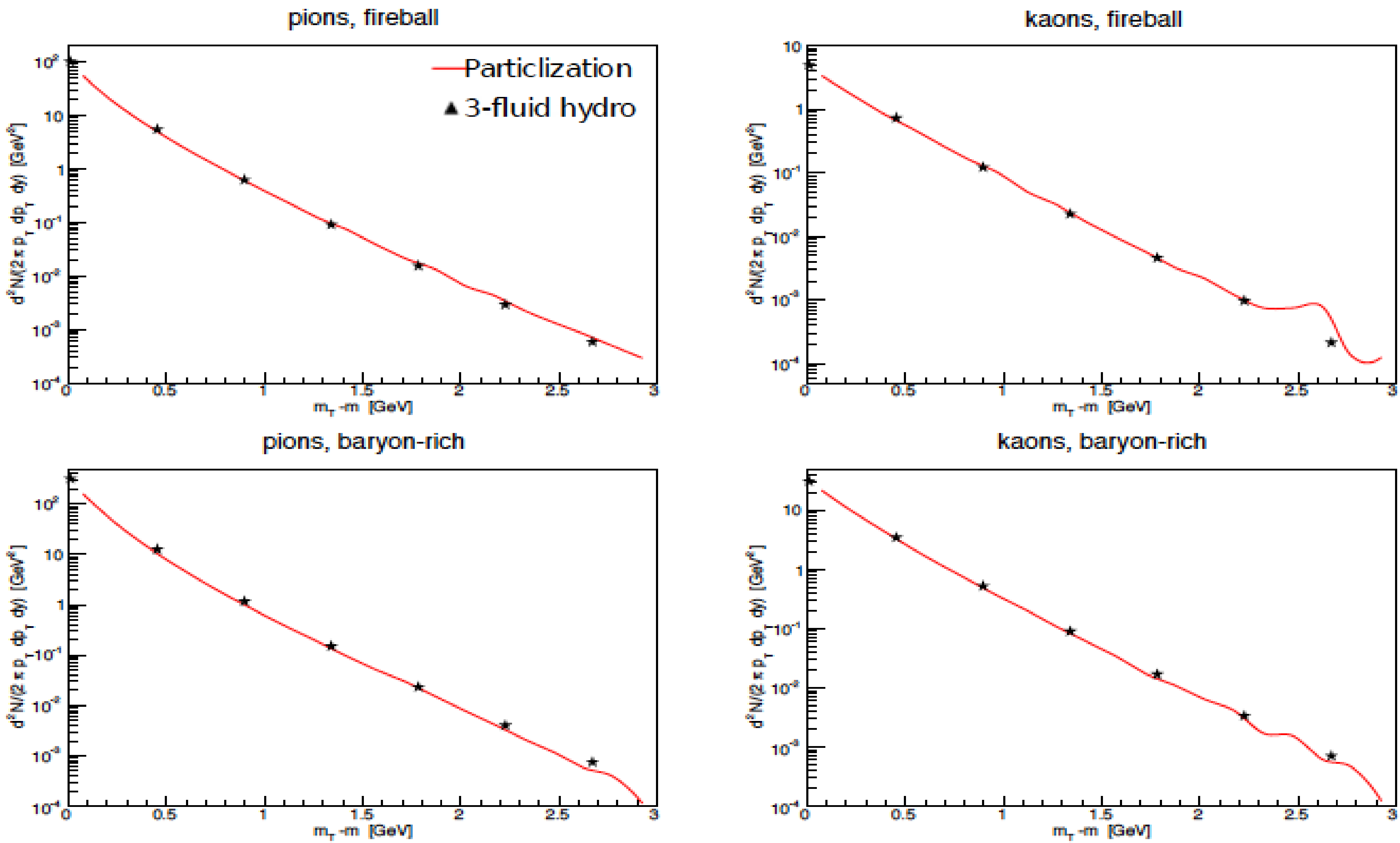
Rapidity distribution



Preview: Particlization of 3-f uid Hydrodynamics model

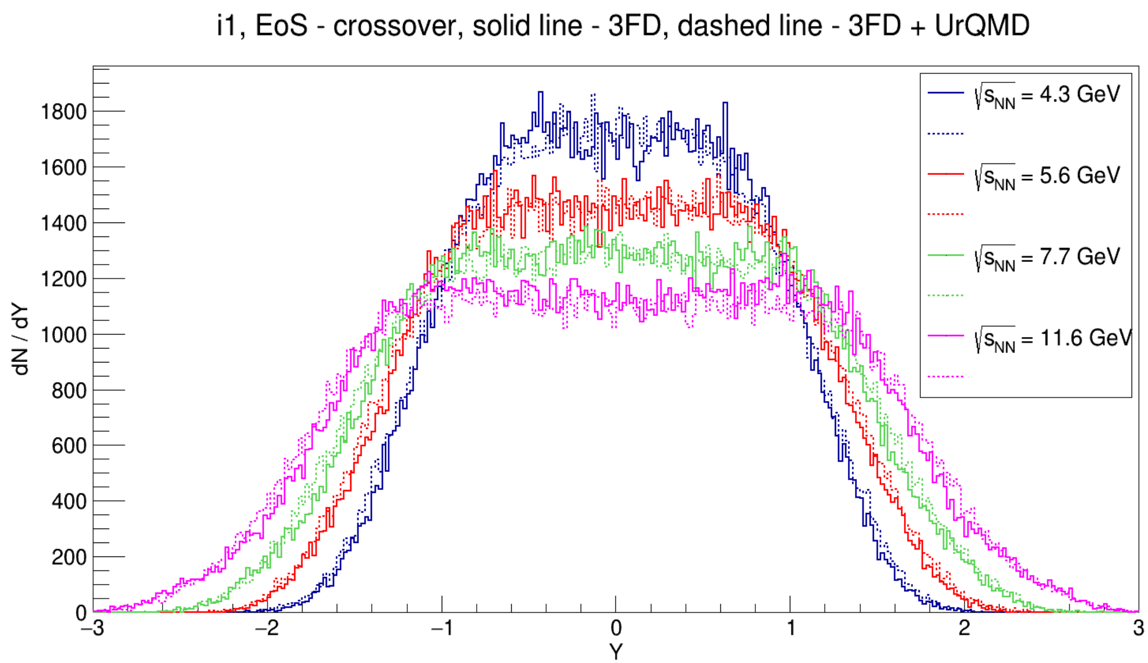
Yu. Karpenko & Yu. Ivanov: May 2014 - May 2015

P_T / m_T distribution



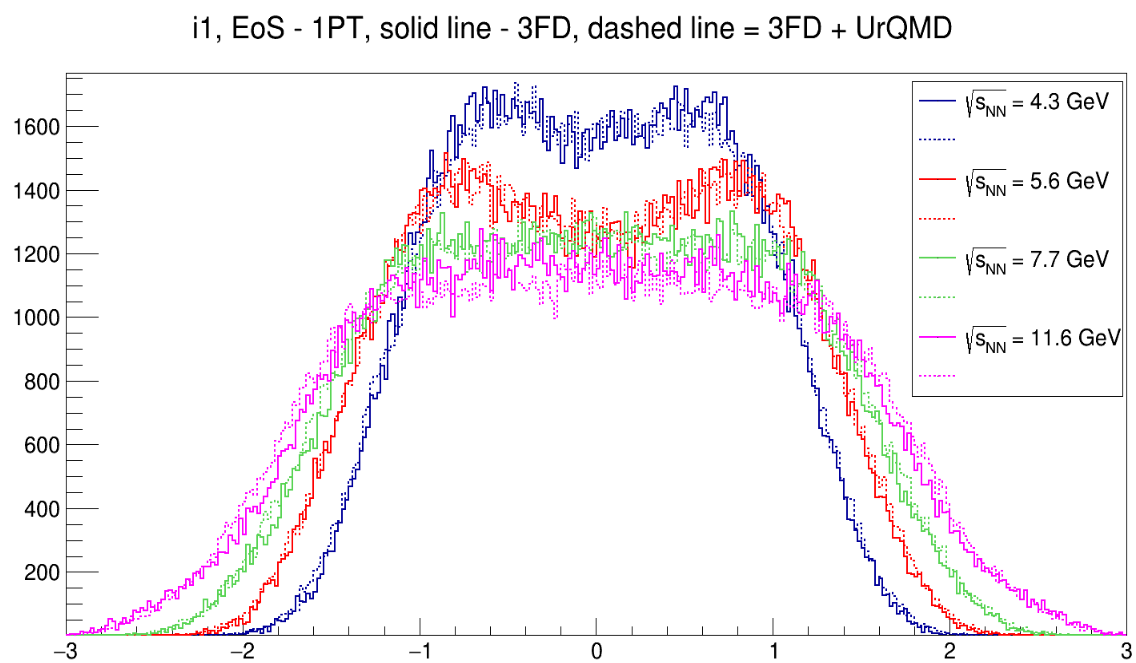
Baryon stopping signal for first order phase transition ?

Baryon stopping signal for first order phase transition ?



EoS: Crossover

Impact parameter: b=2 fm



EoS: First order PT

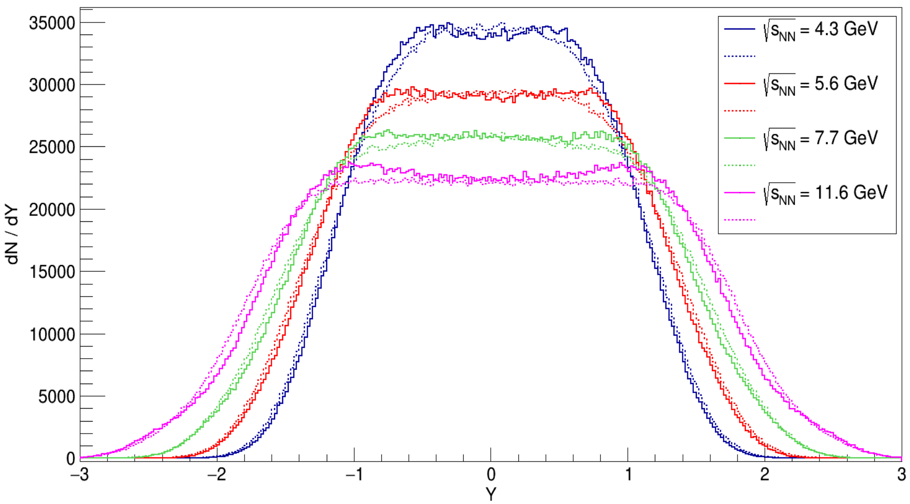
Impact parameter: b=2 fm

Baryon stopping signal for first order phase transition ?

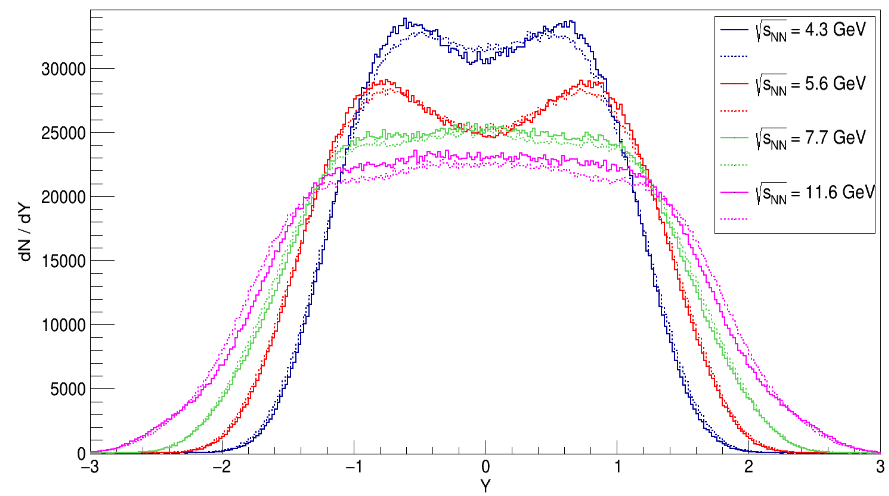
EoS: Crossover

EoS: First order PT

b = 2 fm, EoS - crossover, 3FD (solid line) , 3FD + UrQMD (dashed line)

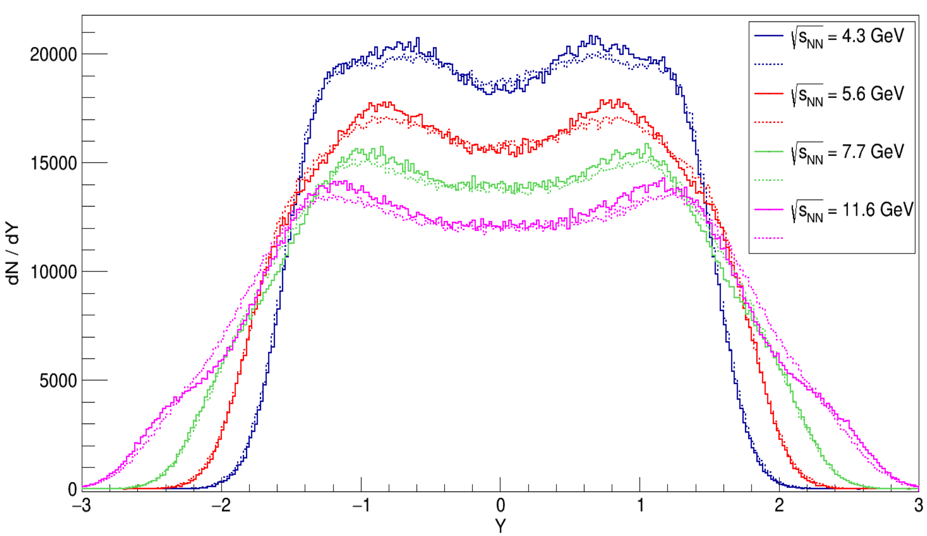


b = 2 fm, EoS - 1PT, 3FD (solid line), 3FD+ UrQMD (dashed line)

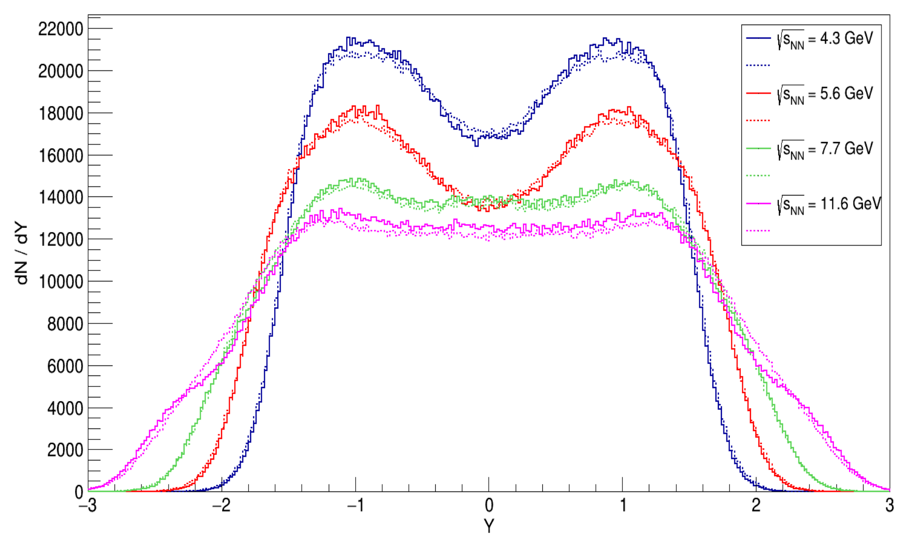


i1:
b=2 fm

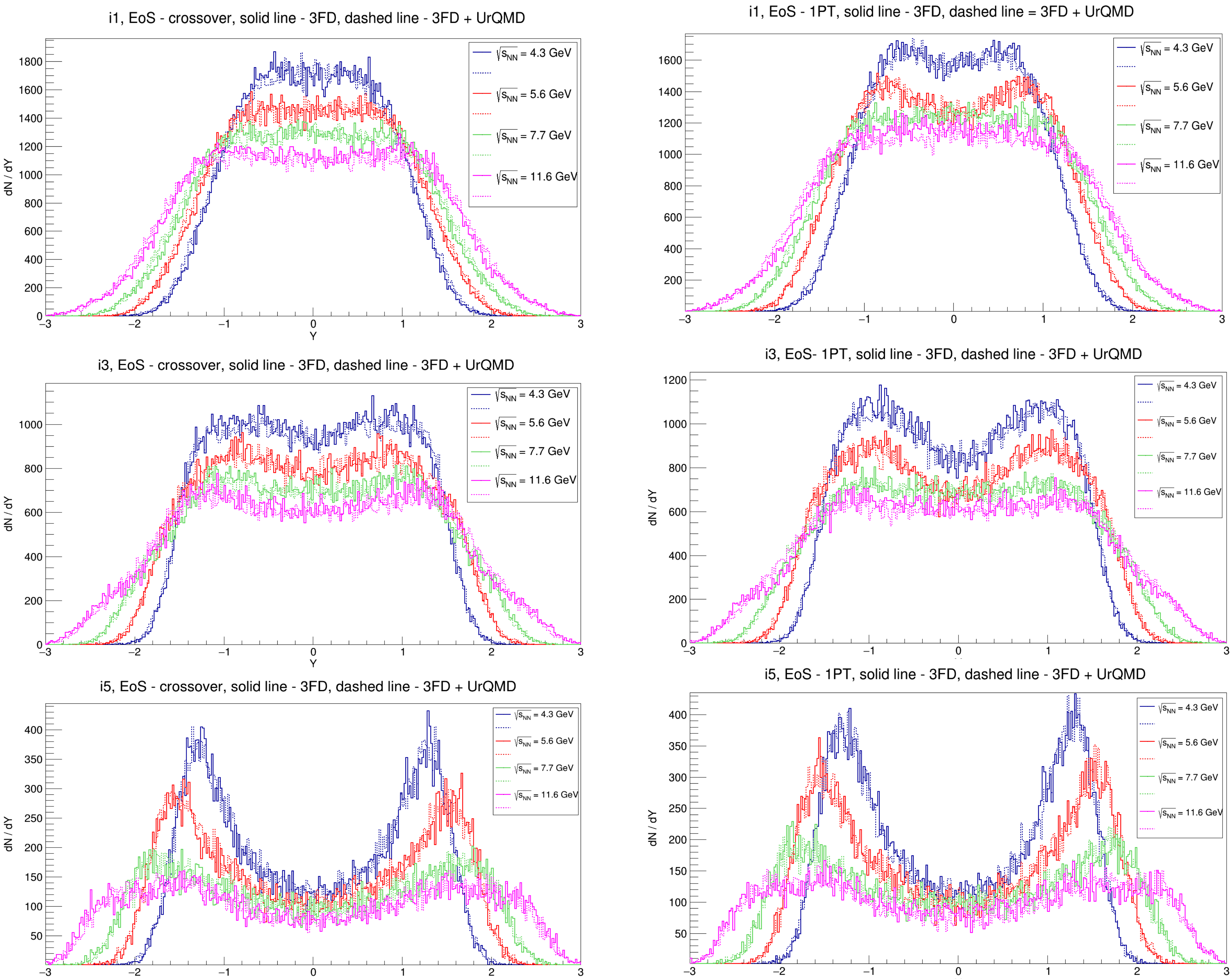
b = 6 fm, EoS - crossover, 3FD (solid line), 3FD + UrQMD (dashed line)



b = 6 fm, EoS - 1PT, 3FD (solid line), 3FD + UrQMD (dashed line)

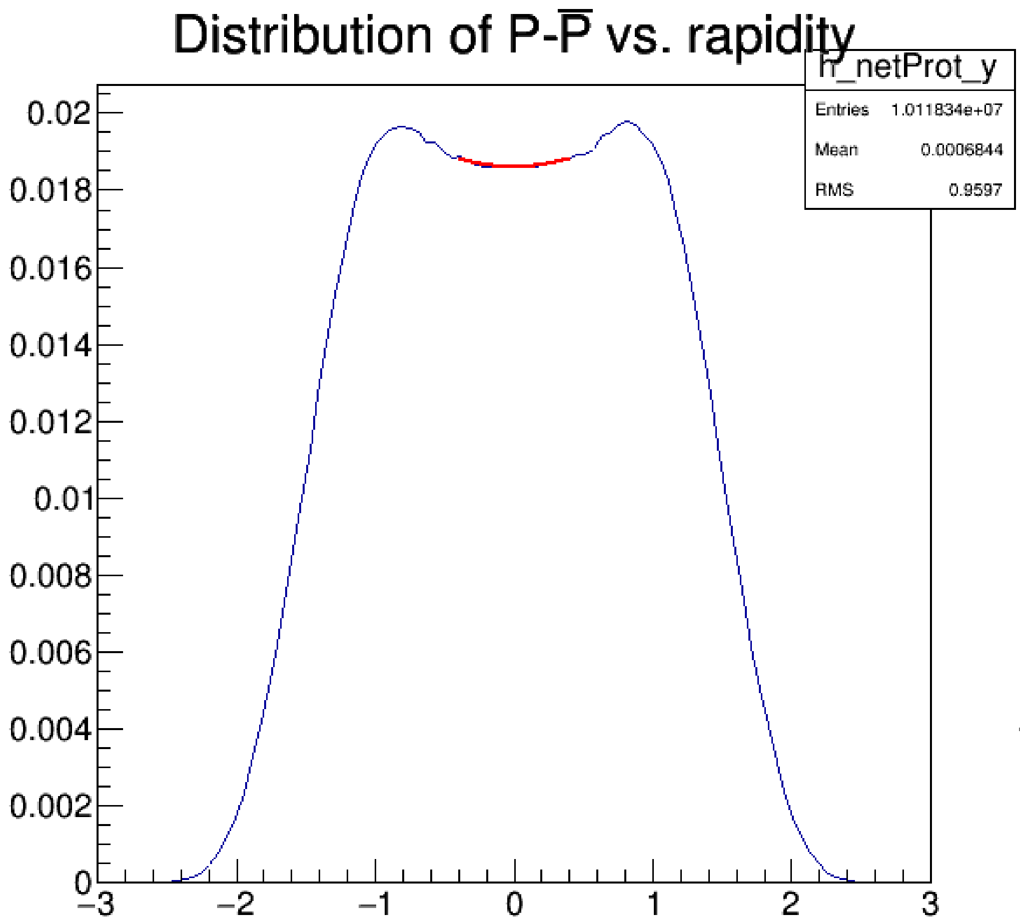


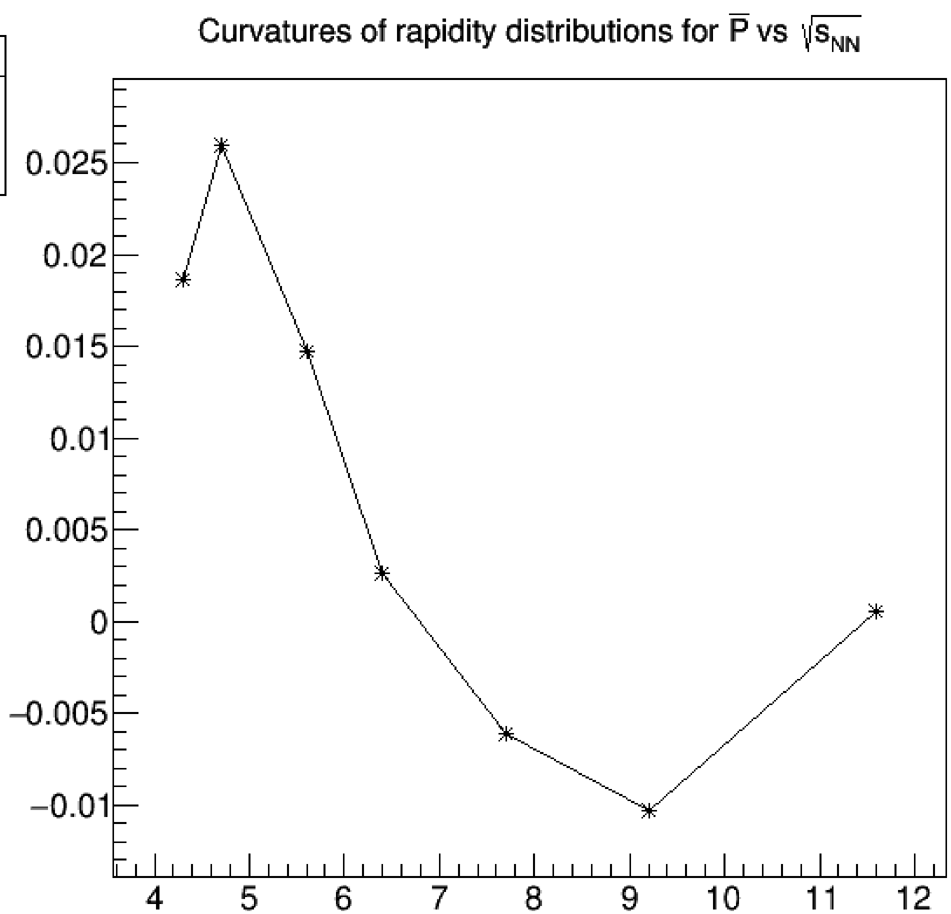
i3:
b=6 fm



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

Baryon stopping signal: extract the curvature at midrapidity !

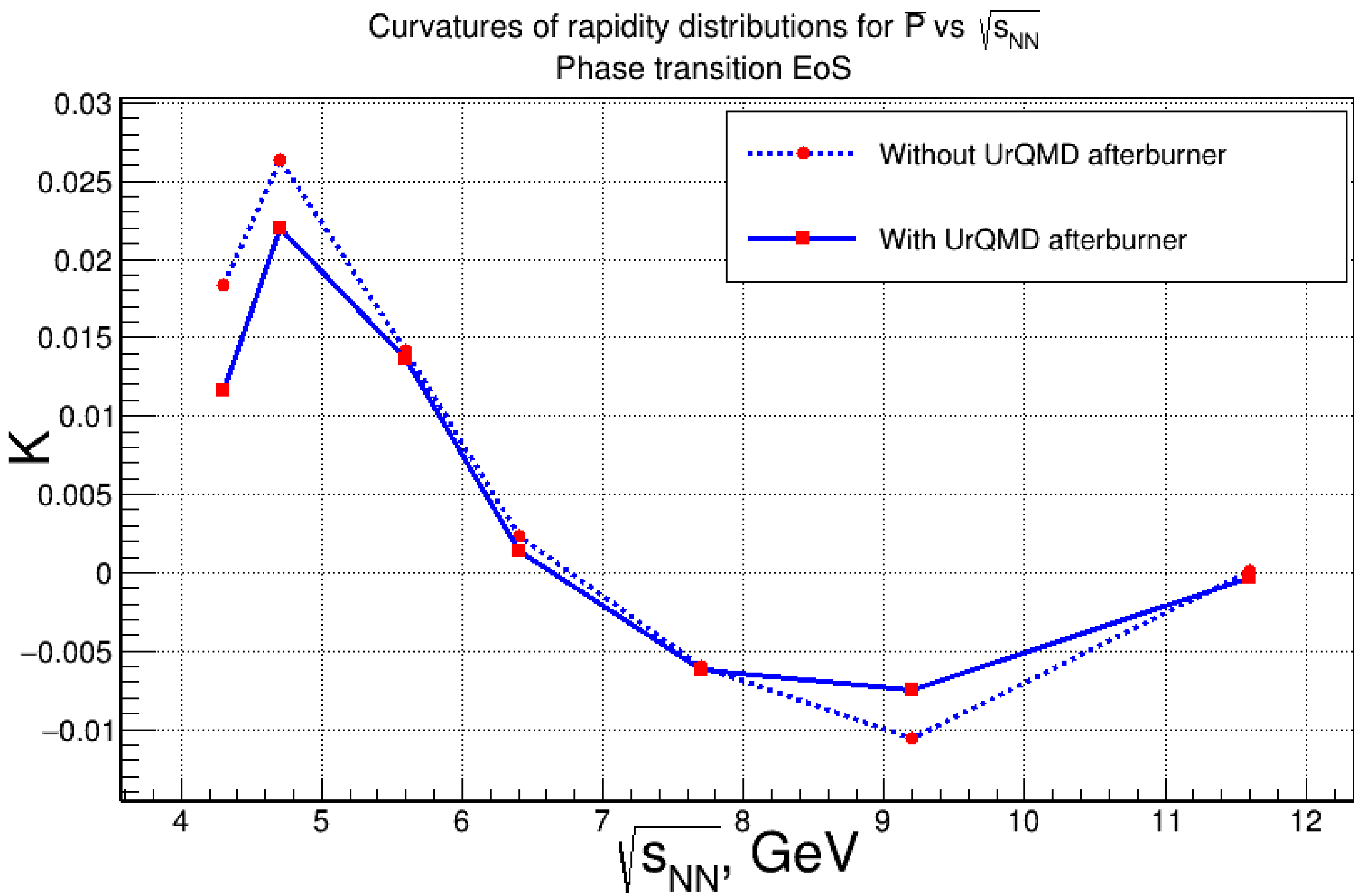




"Wiggle" in the excitation function (energy scan) confirmed !

Particlization of 3FH works satisfactorily → join with UrQMD "afterburner"

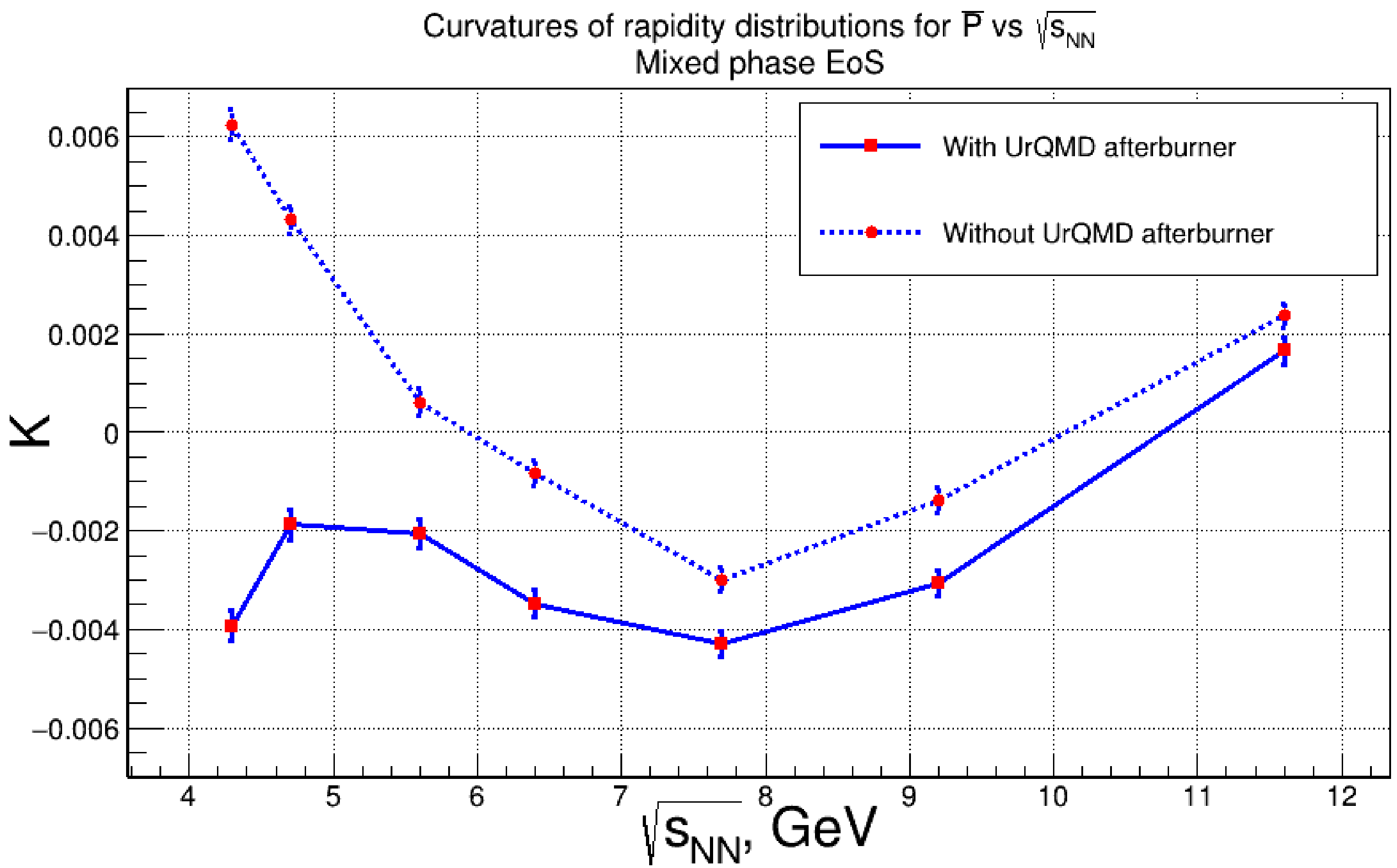
Baryon stopping signal: effect of UrQMD afterburner !



"Wiggle" in the excitation function (energy scan) confirmed !

UrQMD afterburner almost no effect on the "wiggle" for the 2PT EoS

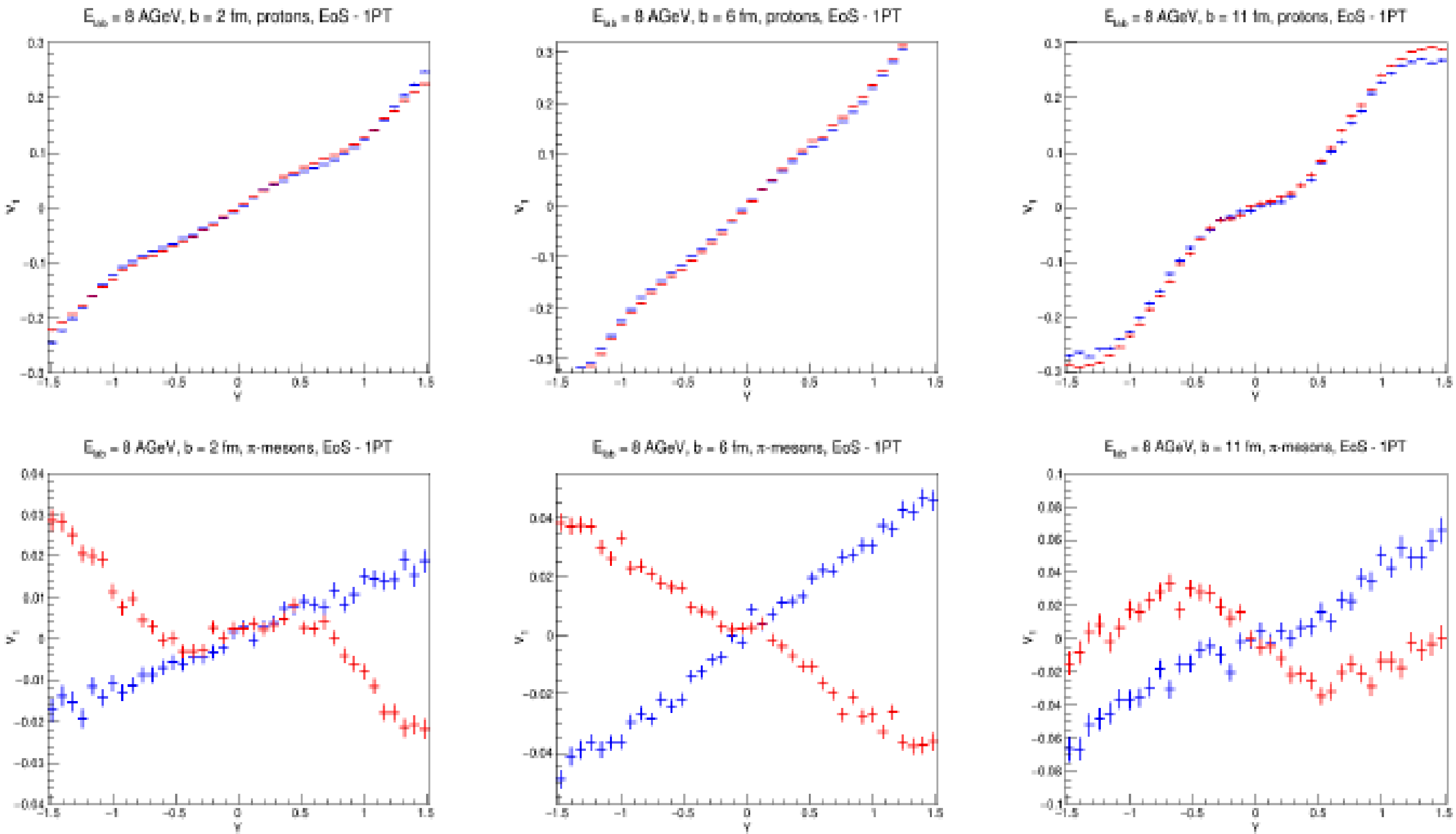
Baryon stopping signal: effect of EoS & UrQMD afterburner !



"Wiggle" in the excitation function (energy scan) confirmed !

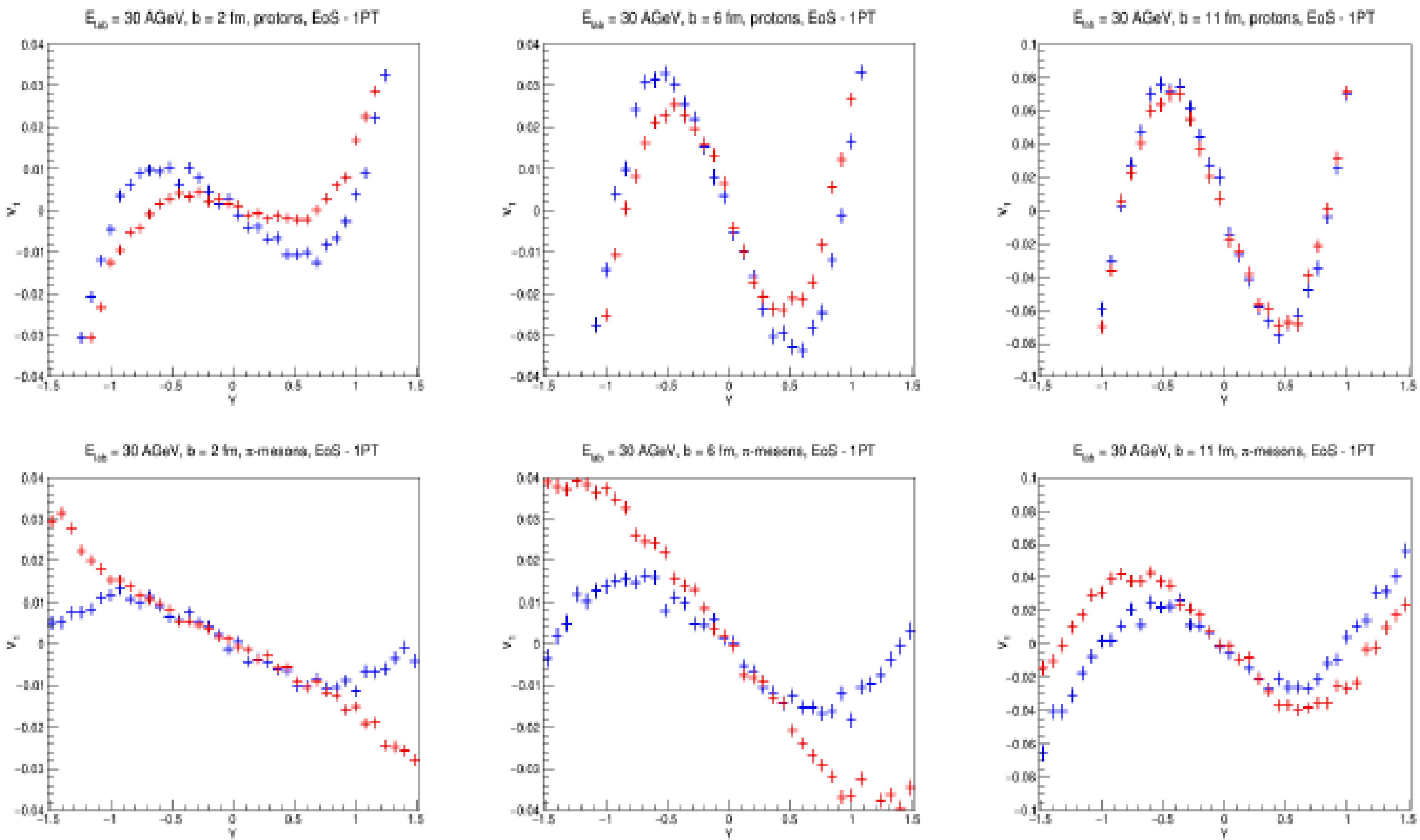
UrQMD afterburner smoothens the "wiggle" for the crossover EoS !

What about flow? First results (v1) ….   E_lab = 8 AGeV



Blocking of pions by hadronic rescattering (red plusses), upper w/o UrQMD !

What about flow? First results(v1) …. E_lab = 30 AGeV



Antiflow of protons → pions follow !

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

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

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

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

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

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

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

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

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

Vector meanfield: $V_i \sim n_i$

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

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

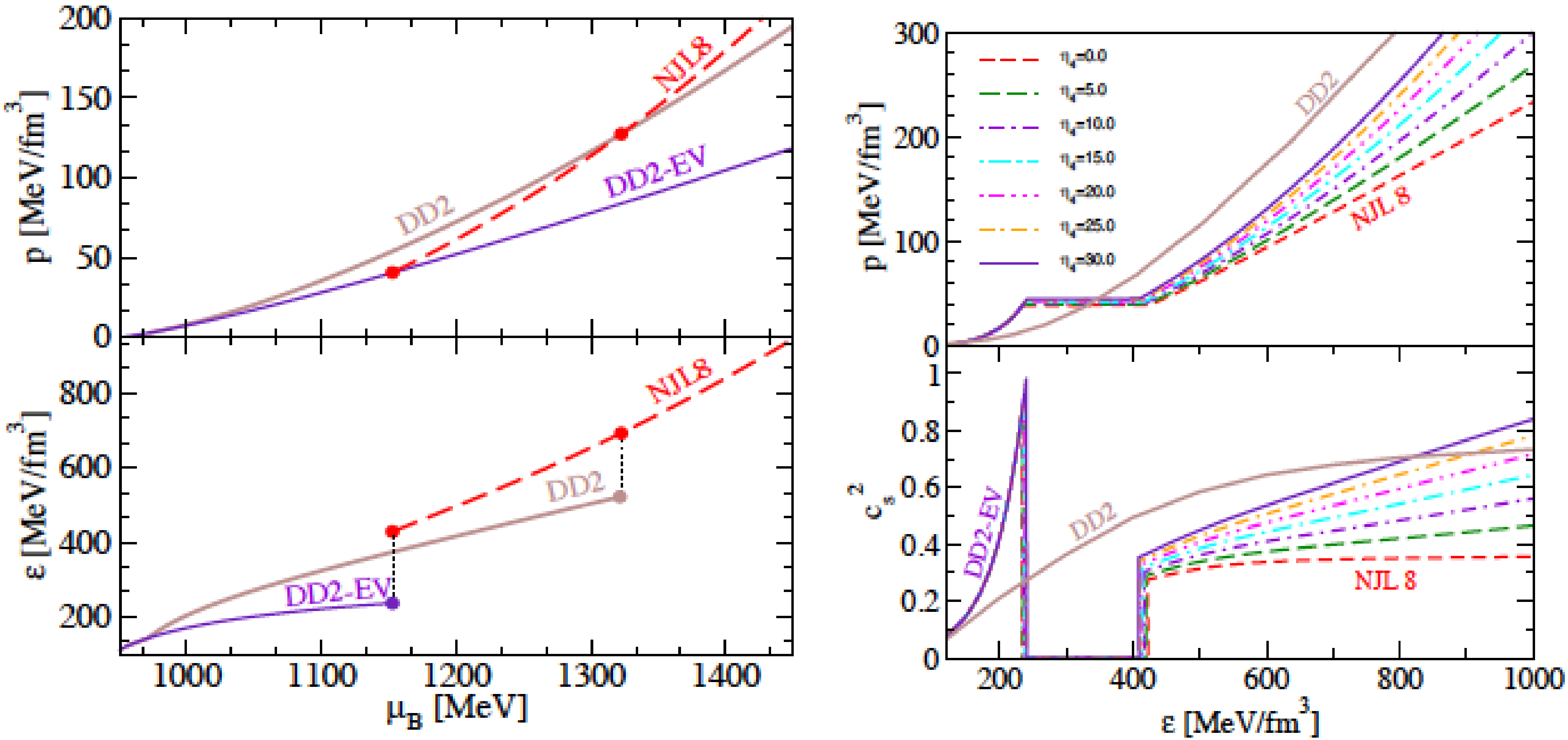
$$\tilde{\mu}_q = \mu_q - 2\frac{g_{02}}{\Lambda^2}\langle q^\dagger q\rangle - 4\frac{g_{04}}{\Lambda^8}\langle q^\dagger q\rangle^3 - 2\frac{g_{22}}{\Lambda^8}\langle\bar{q}q\rangle^2\langle q^\dagger q\rangle \,,$$

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

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

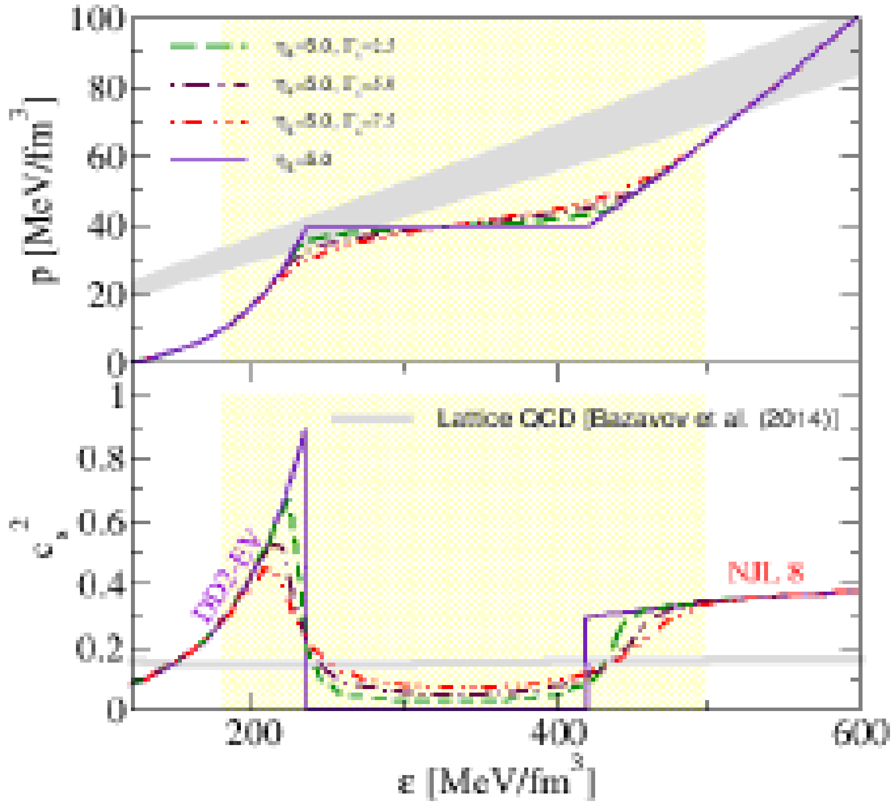


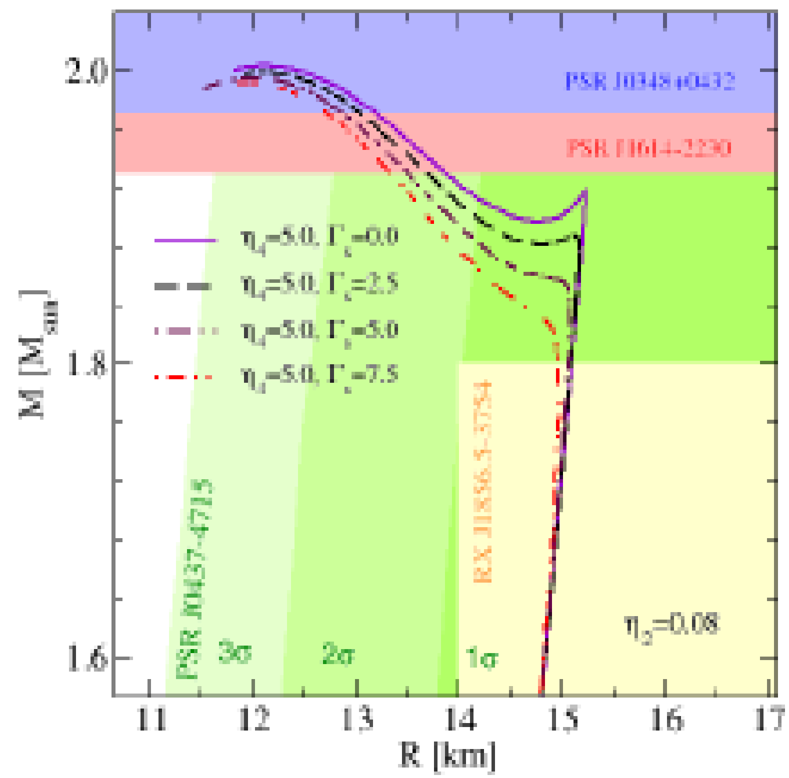
Here: Stiffening of dense hadronic matter by excluded volume in density-dependent RMF
Stiffening of dense quark matter by higher order quark vector current interactions (η_4)

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”)

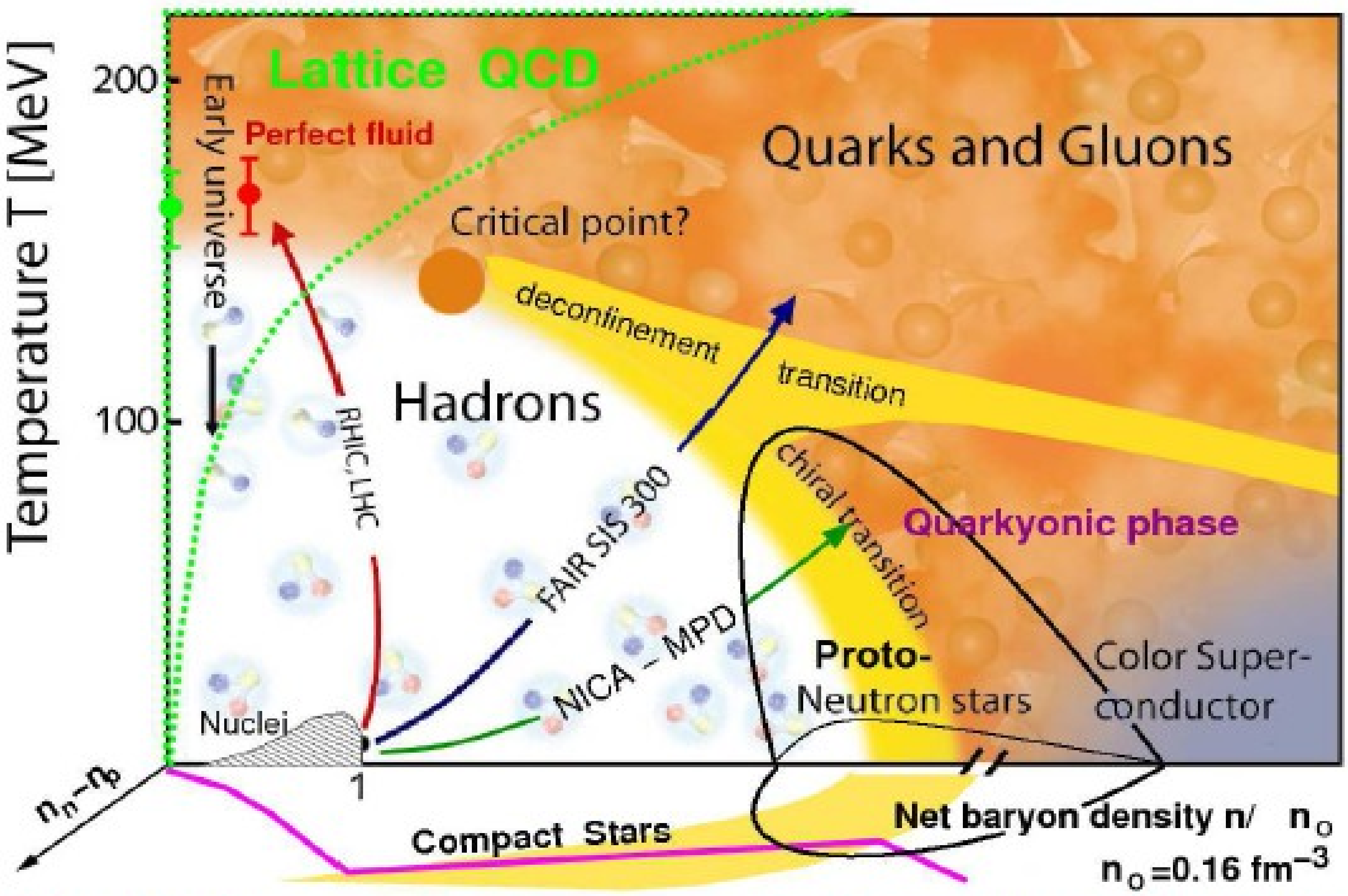




High-mass Twins relatively robust against “smoothing” the Maxwell transition construction

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

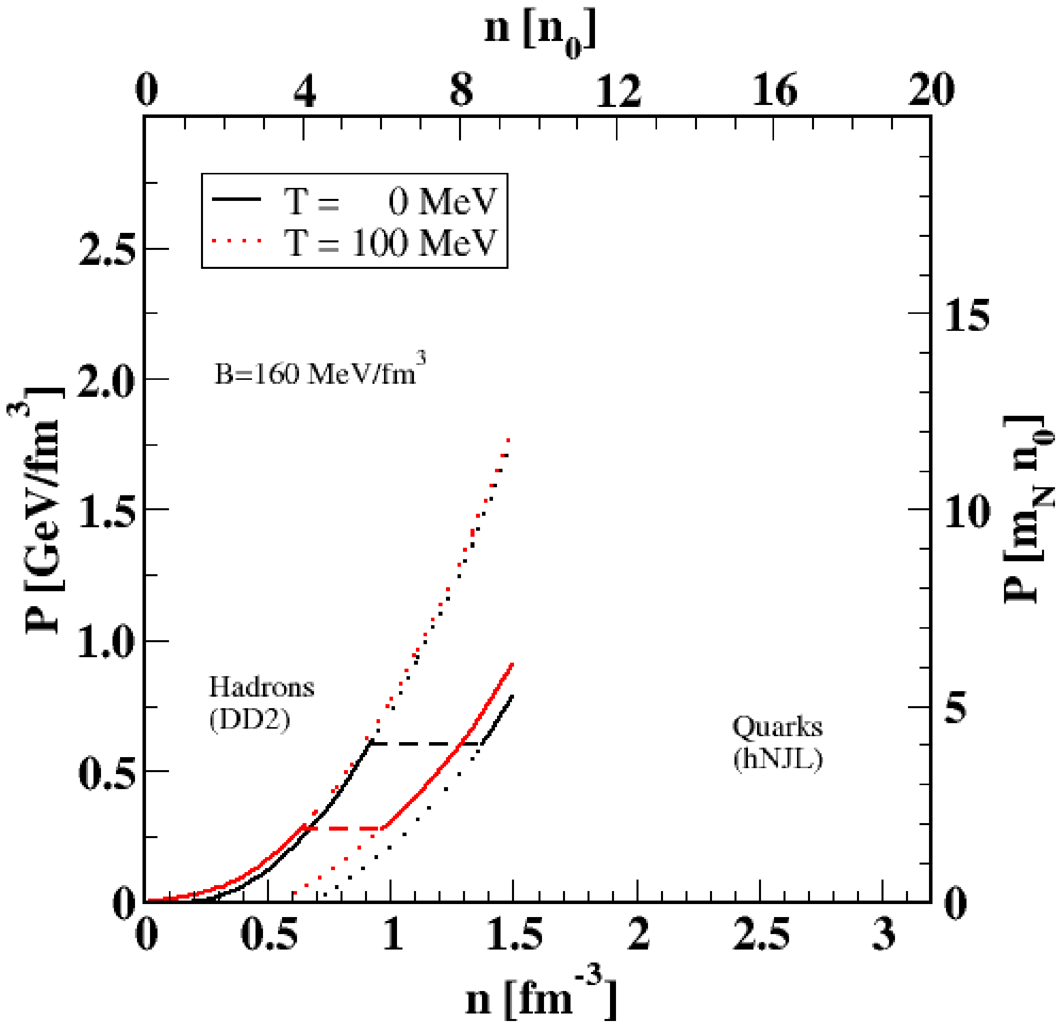
Support a CEP in QCD phase diagram with Astrophysics?



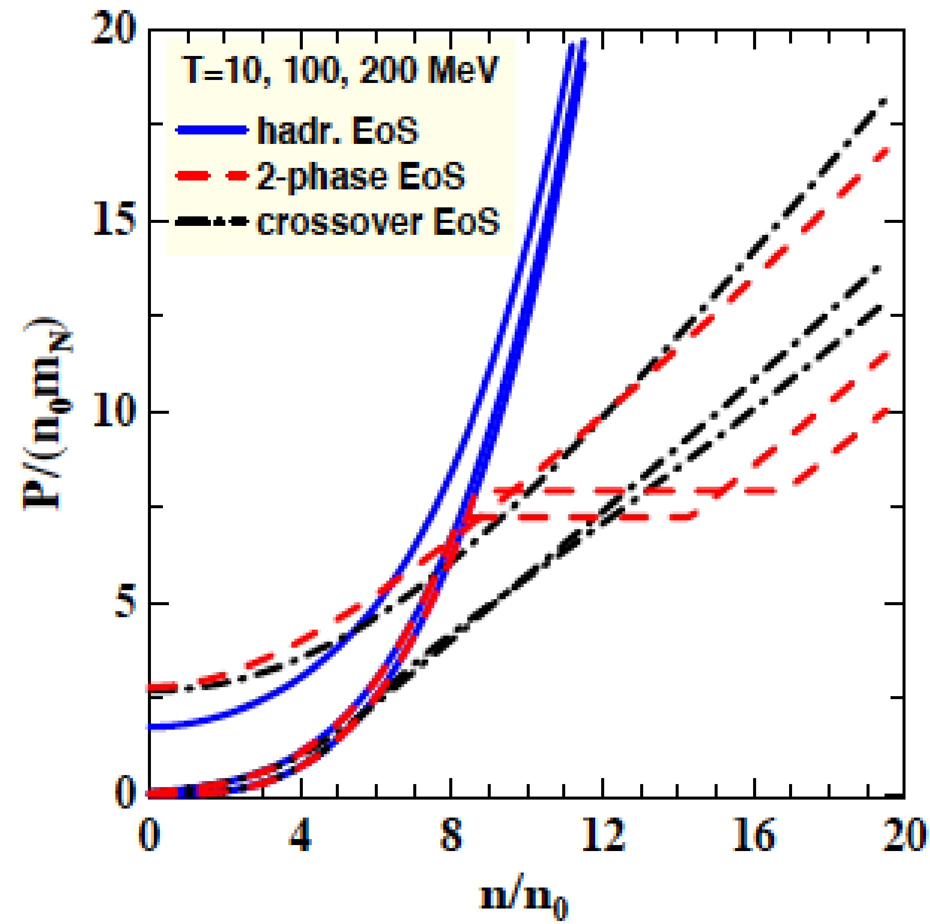
NICA White Paper, http://theor.jinr.ru/twiki-cgi/view/NICA/WebHome

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

Comparison 2-phase EoS

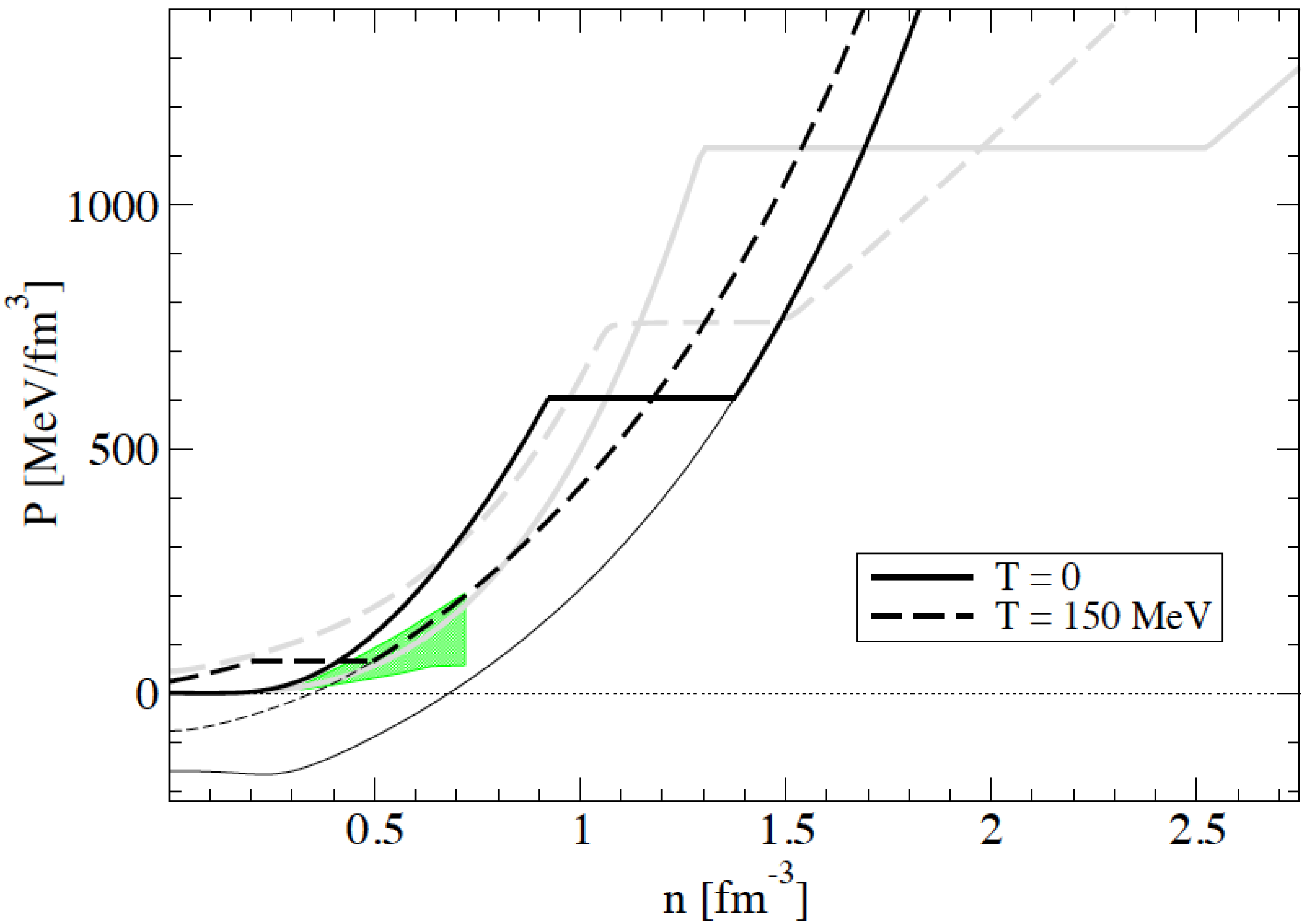


N.-U. Bastian, D. Blaschke (S. Benic, S. Typel), In progress (2015)



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 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

CPOD

Critical Point and Onset of Deconfinement 2016

and

Working Group Meeting of COST Action MP1304

Wrocław, Poland

May 30th - June 4th, 2016

Int. Advisory Comm.

F. Becattini (Florence
D. Blaschke (Dubna)
Xin Dong (Berkeley)
M. Gaździcki (Frankfurt)
L. McLerran (Upton)
E. Laermann (Bielefeld)
J. Mitchell (Upton)
K. Rajagopal (Boston)
J. Randrup (Berkeley)
D. Röhrich (Bergen)
P. Senger (Darmstadt)
P. Seyboth (Munich)
E. Shuryak (Stony Brook)
A. Sorin (Dubna)
M Stephanov (Chicago)
J. Stroth (Genf)
Nu Xu (Berkeley)
Dacui Zhou (Wuhan)

Organization Comm.

D. Blaschke (Wroclaw)
J. Margueron (Lyon)
K. Redlich (Wroclaw)
L. Turko (Wroclaw)
C. Sasaki (Wroclaw)

Local Org. Comm.

T. Fischer (Wroclaw)
T. Klähn (Wroclaw)
Pok Man Lo (Wroclaw)
M. Marczenko (Wroclaw)
M. Naskręt (Wroclaw)

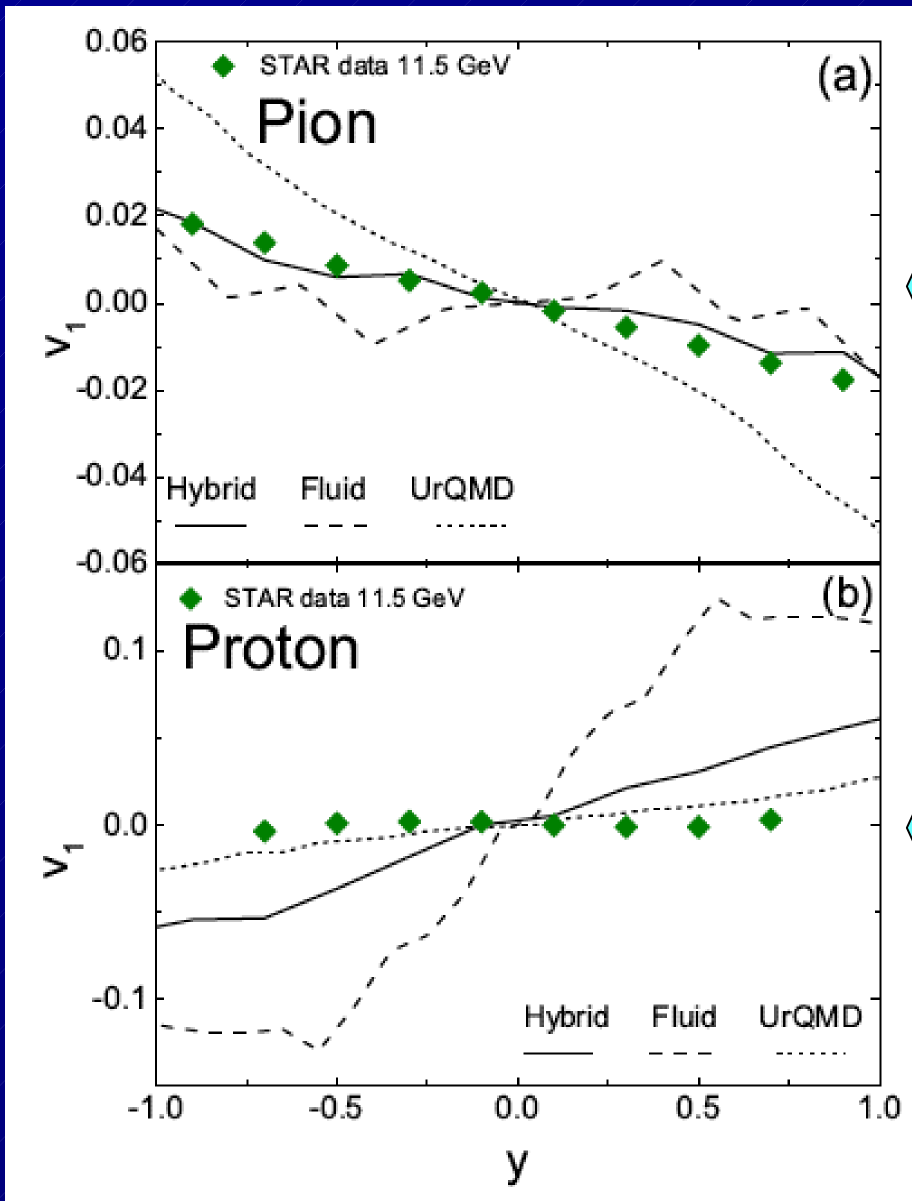
Website: ift.uni.wroc.pl/~cpod2016

Email: cpod2016@ift.uni.wroc.pl

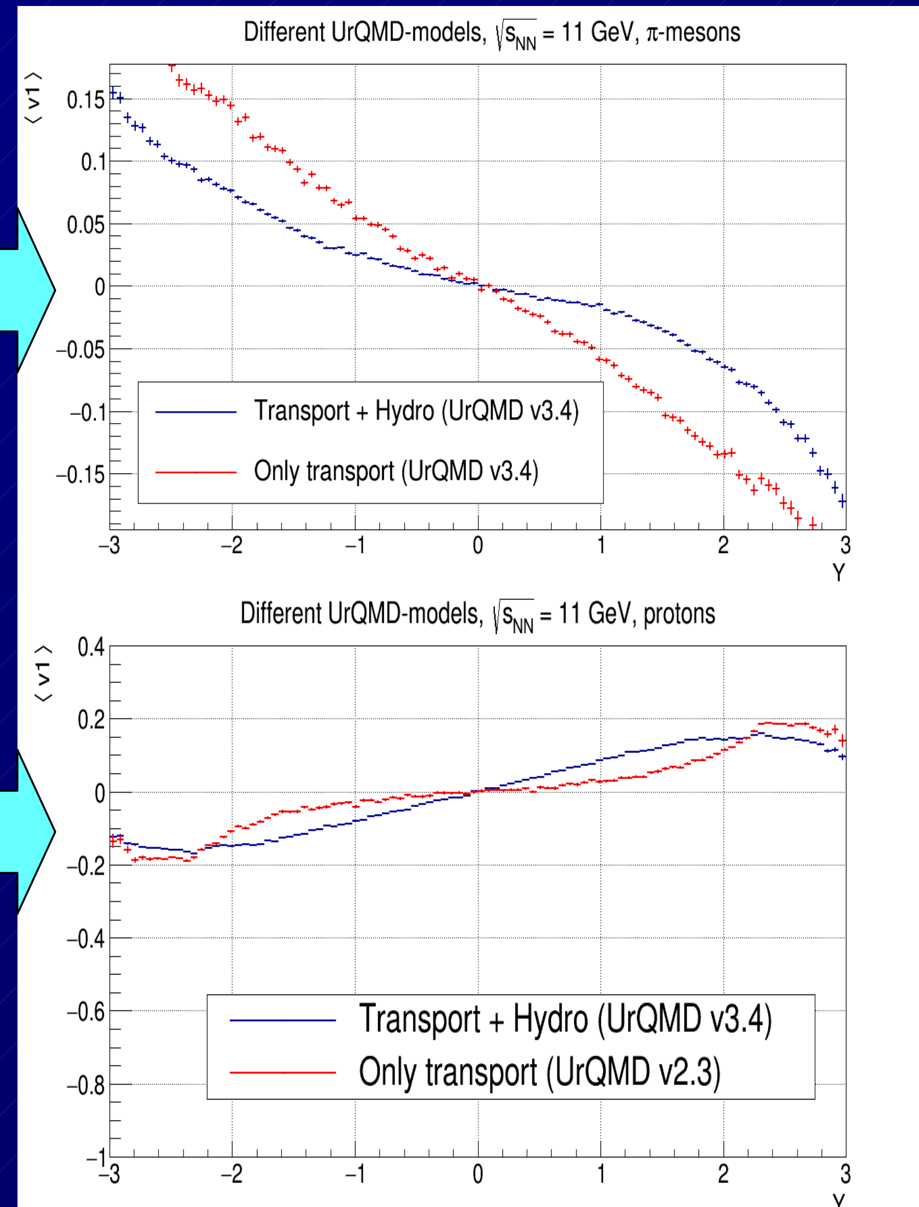
Additional Slides

Further results of test simulations – flow observables

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



Reproduced !



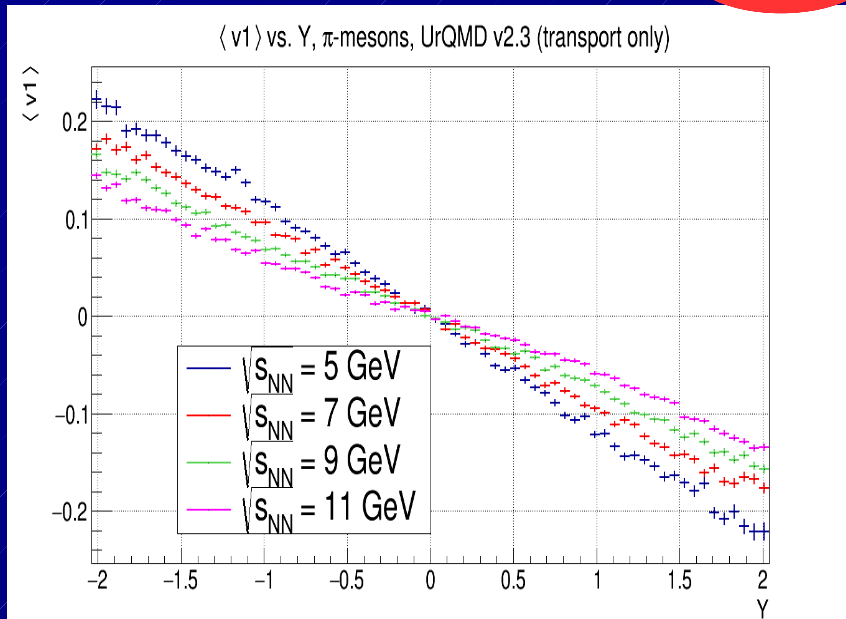
UrQMD + hydro (1st order PT) – H. Petersen

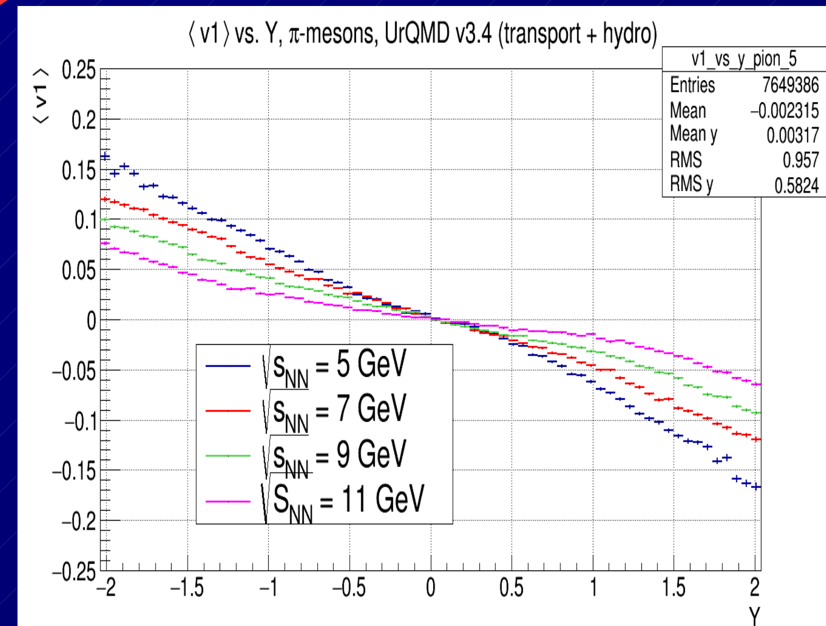
© Pavel Batyuk, Jan 2015

Further results of test simulations – flow observables

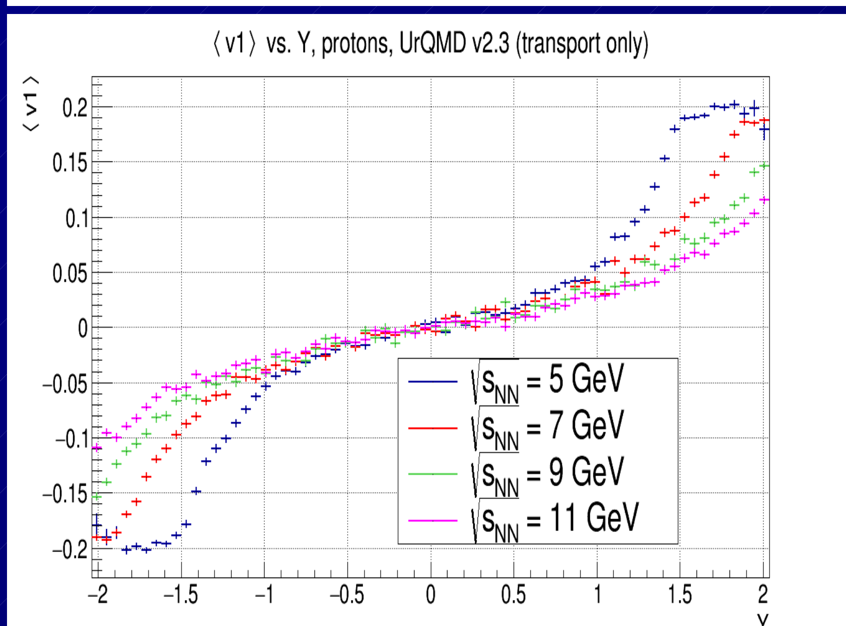
NICA energy scan: **UrQMD** **$\langle v_1 \rangle$** UrQMD + hydro (1[st] order PT)

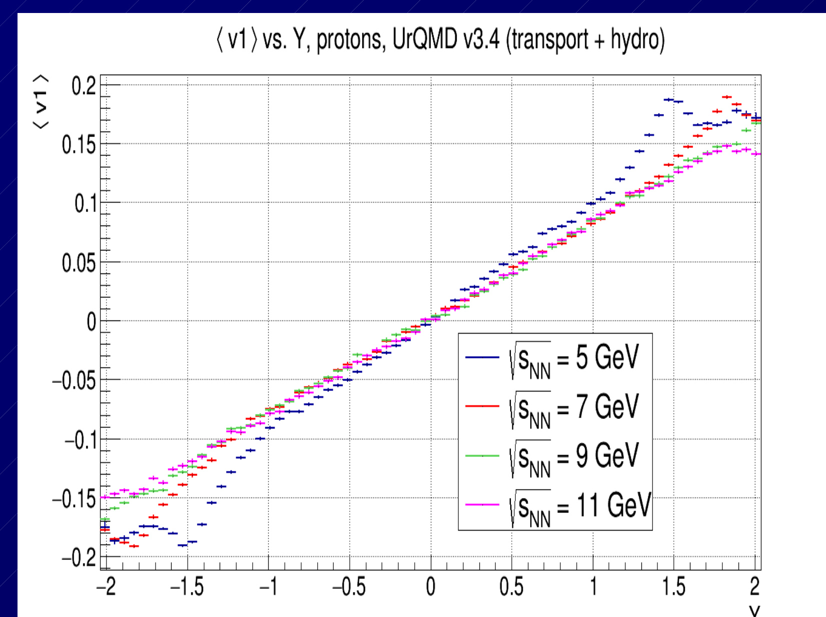
Pions





Protons



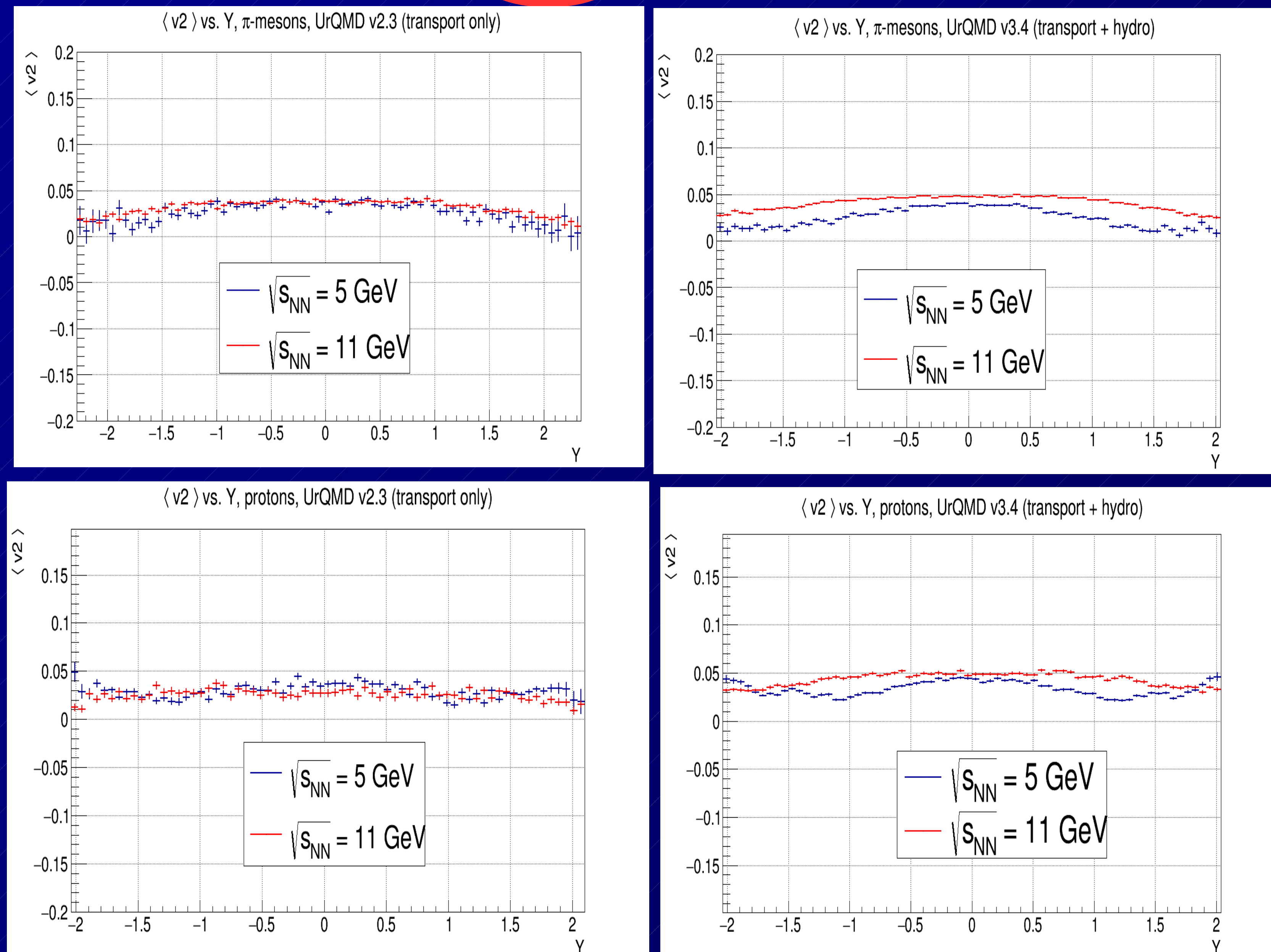


Further results of test simulations – flow observables

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

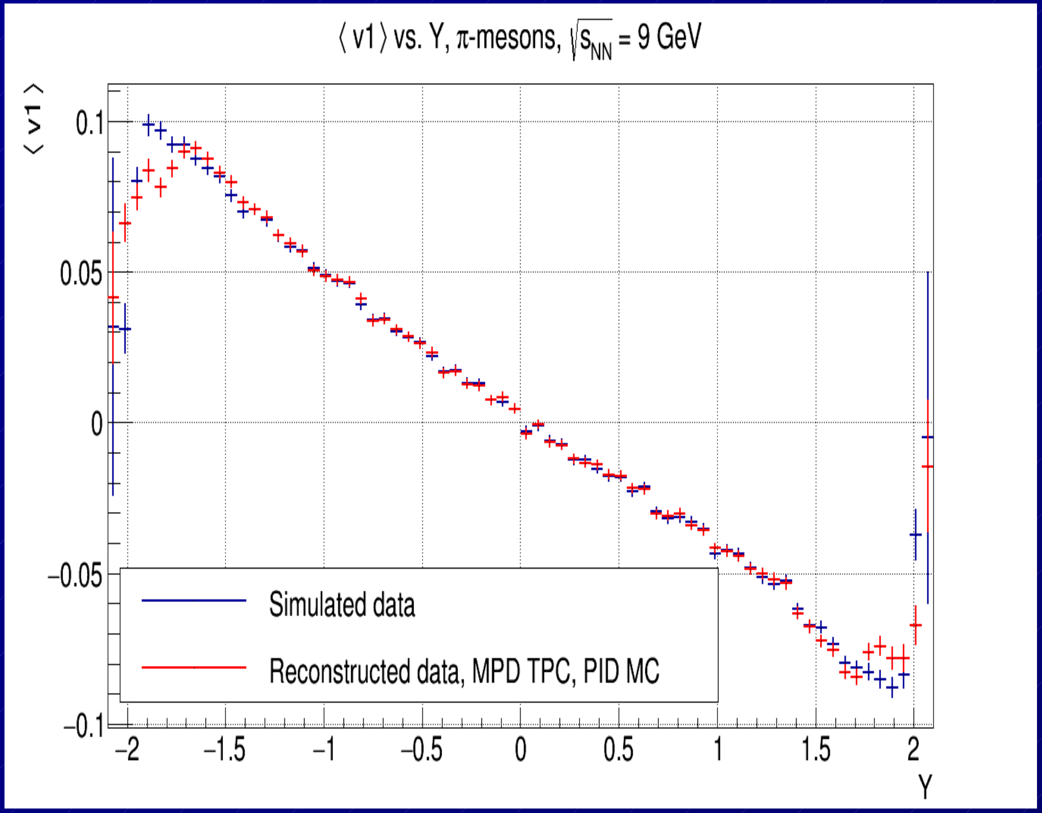
Pions

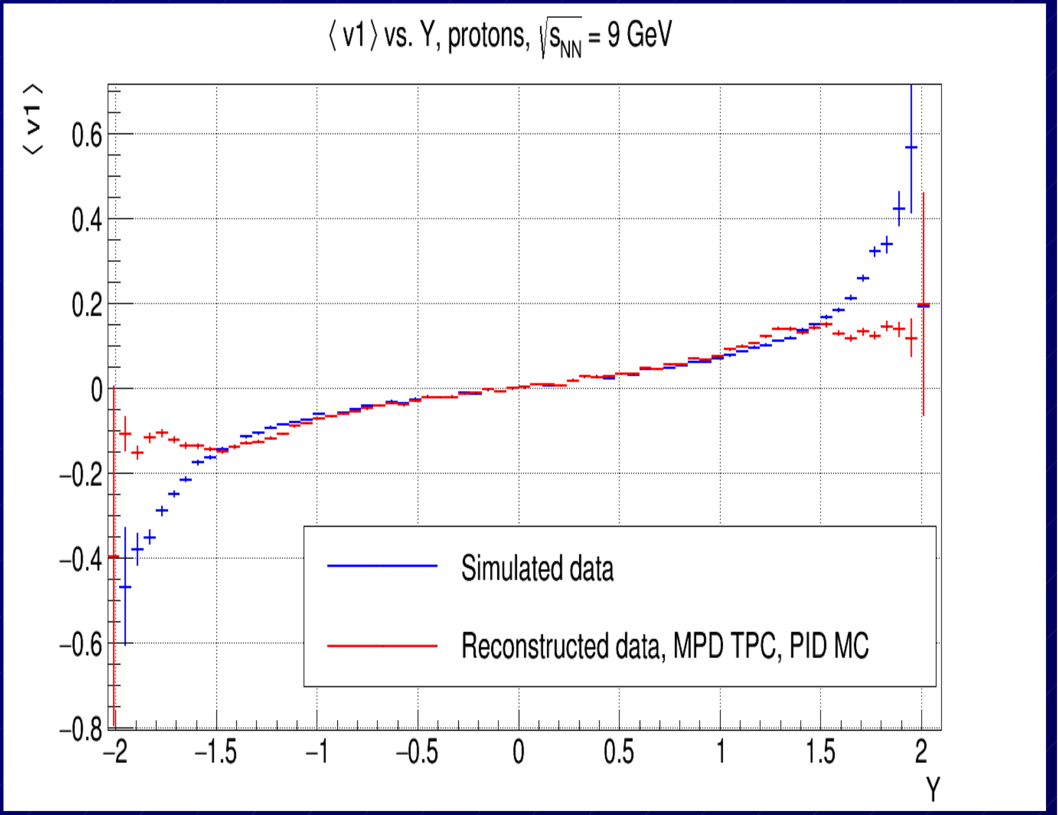
Protons



Further results of test simulations – flow observables

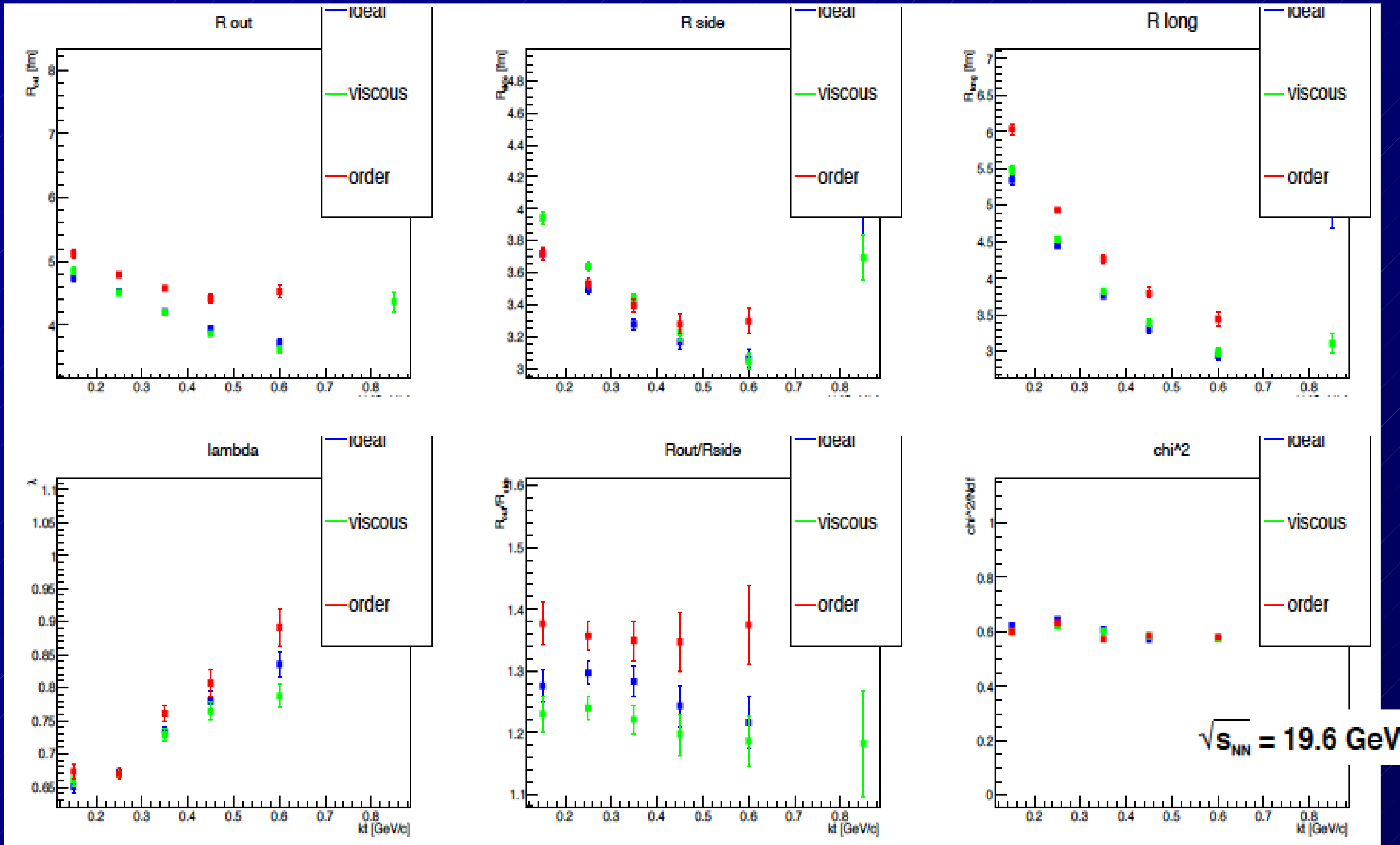
Detector Simulation with GEANT : Excellent reproduction of simulation results !



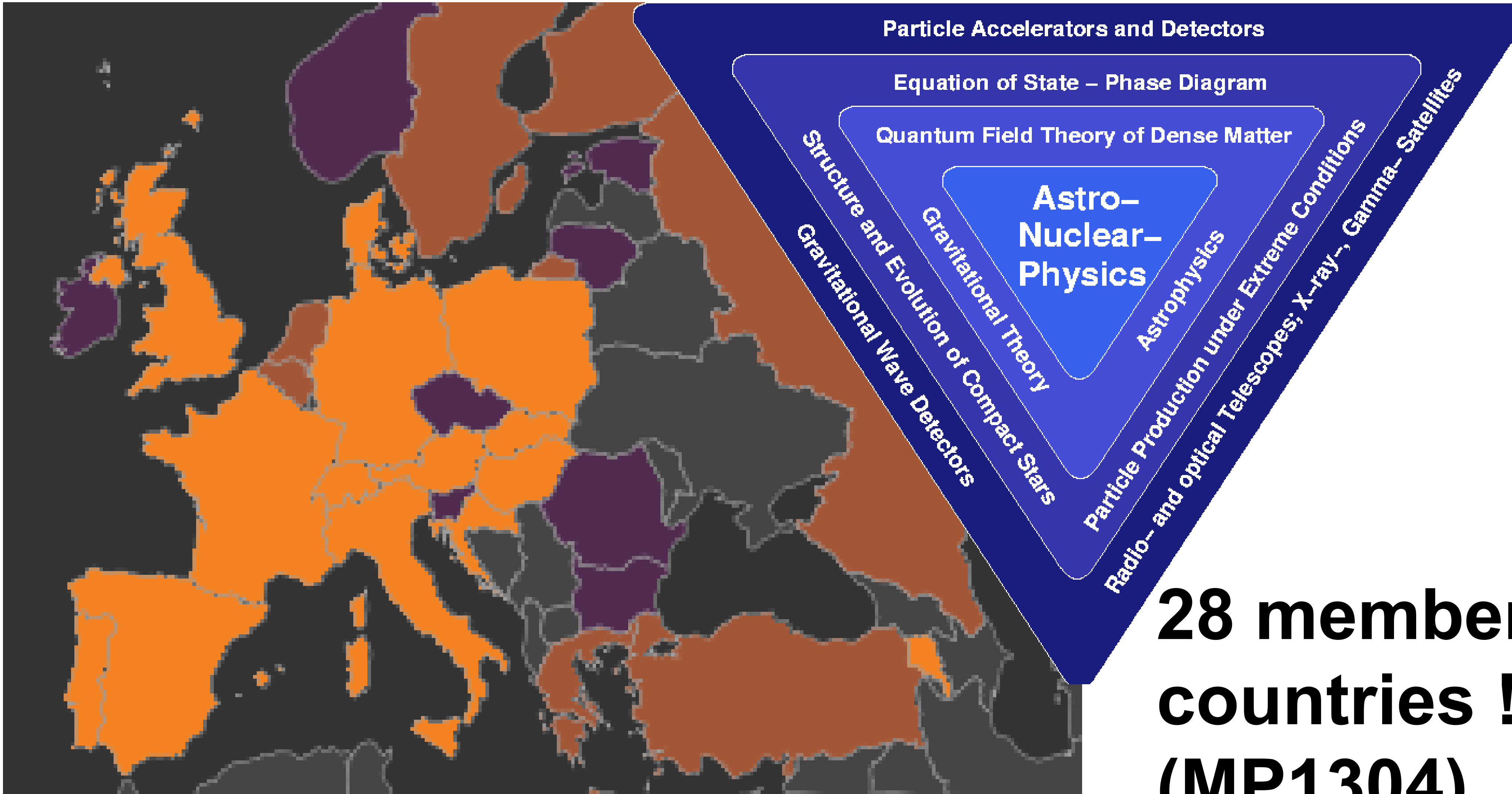


UrQMD + hydro (1st order PT) – H. Petersen

Further results of test simulations – HBT radii



Hydro+kinetic model (Karpenko)



28 member countries !! (MP1304)

New compstar !

EUROPEAN COOPERATION
IN SCIENCE AND TECHNOLOGY

Kick-off: Brussels, November 25, 2013

Critical Point and Onset of Deconfinement 2016

and

Working Group Meeting of COST Action MP1304

Wrocław, Poland

May 30th - June 4th, 2016

Website:

ift.uni.wroc.pl/~cpod2016

Email:

cpod2016@ift.uni.wroc.pl

POLSKA AKADEMIA NAUK

International advisory cor

Francesco Becattini (Florence)
David Blaschke (Wrocław and Dub
Xin Dong (Berkeley)
Marek Gaździcki (Frankfurt)
Larry McLerran (Upton)
Edwin Laermann (Bielefeld)
Jeffery Mitchell (Upton)
Krishna Rajagopal (Boston)
Jorgen Randrup (Berkeley)
Dieter Röhrich (Bergen)
Peter Senger (Darmstadt)
Peter Seyboth (Munich)
Edward Shuryak (Stony Brook)
Alexander Sorin (Dubna)
Misha Stephanov (Chicago)
Joachim Stroth (Genf)
Nu Xu (Berkeley)
Daicui Zhou (Wuhan)

Organization committee:

David Blaschke (Wrocław and Dul
Jérôme Margueron (Lyon)
Krzysztof Redlich (Wrocław)
Ludwik Turko (Wrocław)

Local organization comm

Tobias Fischer (Wrocław)
Thomas Klaehn (Wrocław)
Pok Man Lo (Wrocław)
Michał Marczenko (Wrocław)
Michał Naskręt (Wrocław)
Chihiro Sasaki (Wrocław)