Experimental Exploration of QCD – Matter

Outline

QCD

Matter and phase transitions

QCD phase diagram

Nuclear liquid – gas phase transition

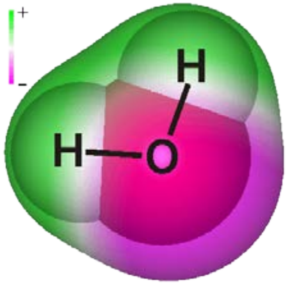
(s)QGP properties (LHC, RHIC)

Search for phase boundaries (STAR, SPS)

Outlook (FAIR)

Conclusion

QED – analog



QCD Lagrangian

$$
\begin{aligned}
\mathcal{L}_{QCD} &= -\frac{1}{4}F^{a}_{\mu\nu}F^{a\mu\nu} + \sum_{q}\overline{\psi}^{q}_{i}(i\gamma^{\mu}D_{\mu ij} - m_{q}\delta_{ij})\psi^{q}_{j} \cdot \\
F^{a}_{\mu\nu} &= \partial_{\mu}A^{a}_{\nu} - \partial_{\nu}A^{a}_{\mu} + g_{s}f^{abc}A^{b}_{\mu}A^{c}_{\nu} \\
D_{\mu ij} &= \delta_{ij}\partial_{\mu} - ig_{s}T^{a}_{ij}A^{a}_{\mu}
\end{aligned}
$$

where

- **g_s is the QCD coupling constant**
- **f^{abc} are the structure constants of SU(3): $[T^a,T^b] = i f^{abc} T^c$ (a,b,c = 1,…8)**
- **A_μ^a are the 8 *gluon* fields**
- **T_{ij}^a are 8 'colour matrices', i.e. generators of the SU(3) transformation acting on the fundamental (triplet) representation:**

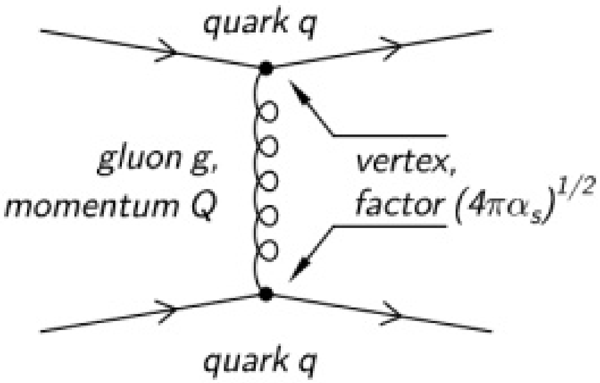
the QCD Lagrangian is invariant under local SU(3) transformations:

$$\psi \longrightarrow \exp\left(i\sum_{a=1}^{8}T^{a}\alpha^{a}(x)\right)\psi$$

$$A^{a}_{\mu} \longrightarrow A^{a}_{\mu} - \frac{1}{g_s}\partial_{\mu}\alpha^{a} - \sum_{b,c=1}^{8} f^{abc}\alpha^{b}A^{c}_{\mu}$$

Features of QCD

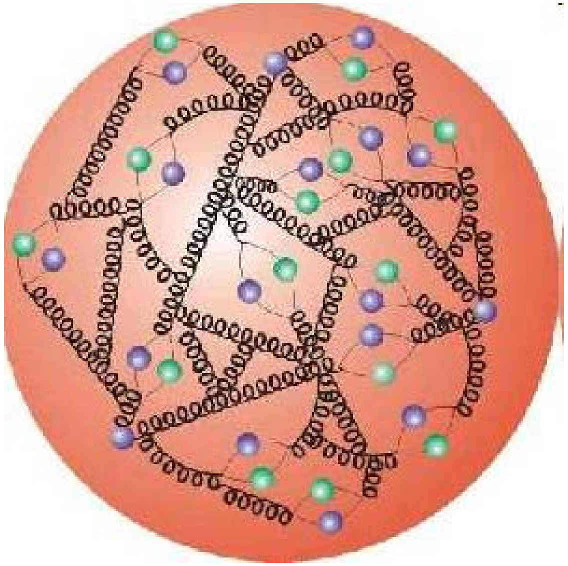
High energy behavior (large momentum transfers, small distances):
perturbative treatment possible



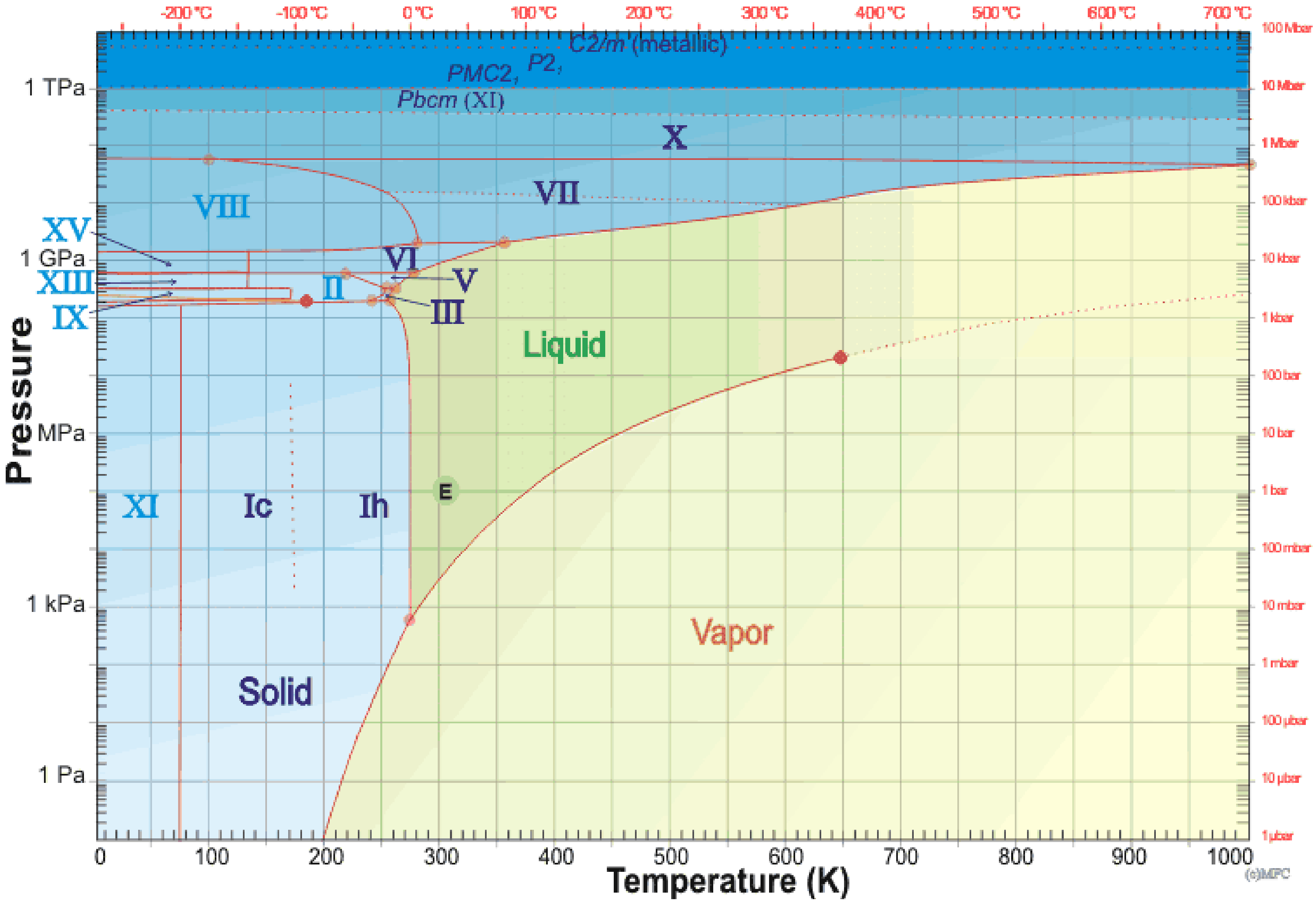
Low energy behavior (large distances)
non - perturbative treatment necessary

1) confinement

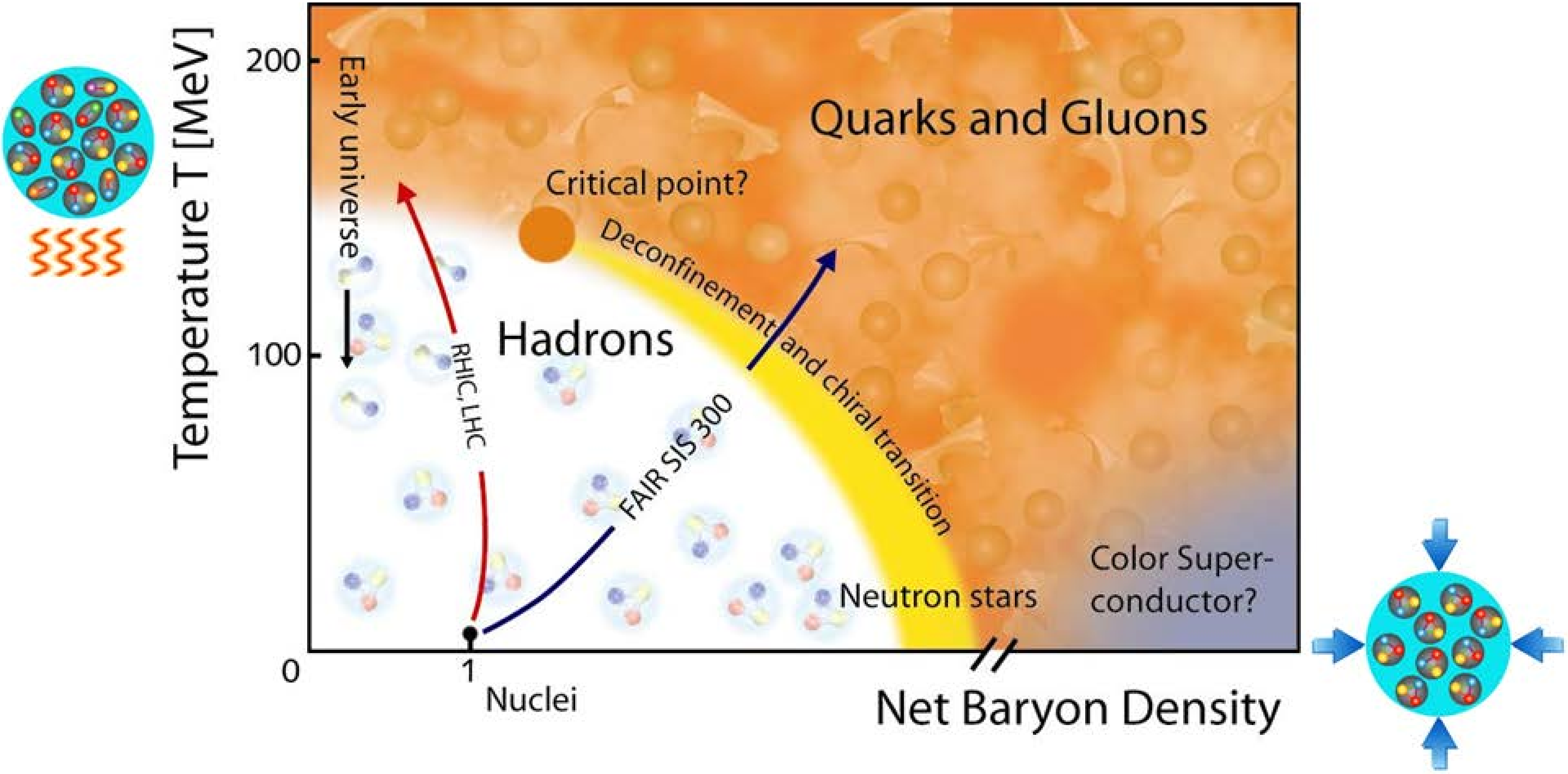
2) approximate chiral symmetry



Phase diagram of water



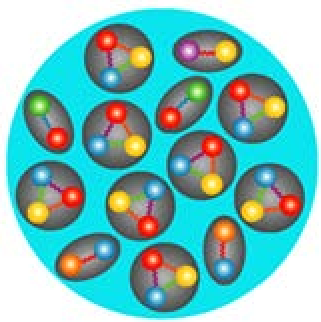
QCD phase diagram



Phases and phase transitions

Thermodynamic description: choice of proper variables:

Control parameters = external variables for reaction system
= independent variables in thermodynamic potential



Temperature T,
Volume V,
Particle number N

Helmholtz free energy F:

$$F = F(T, V, N)$$

$$dF = -SdT - PdV + \mu dN$$

Entropy S, pressure P and chemical potential μ are system properties.

Relation between state variables is called Equation – of – State (EOS), e.g.

$$P = P(\rho, T)$$

$$P = P(\varepsilon, T)$$

ρ – particle number density
ε – energy density

Phase boundary

Nature prefers phase with lowest free energy F.

Hadrons

F_1

Quarks & Gluons

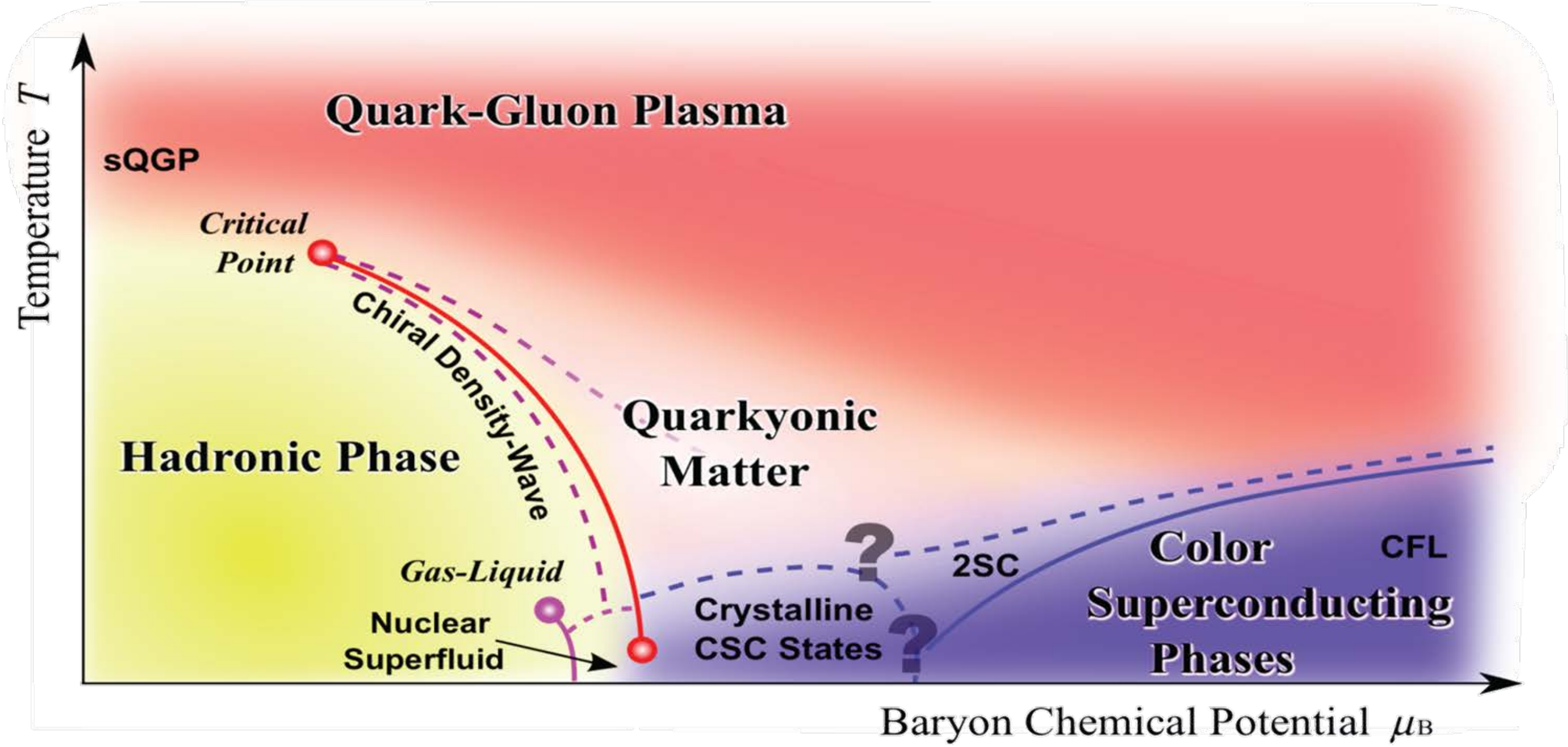
F_2

Phase equilibrium between 2 phases j=1,2:

$$dF\Big|_{T,V} = \sum_j \mu_j \, dN_j \overset{!}{=} 0 \quad \Rightarrow \quad \mu_1(\mathrm{P},T) = \mu_2(\mathrm{P},T)$$

QCD phase diagram

K. Fukushima, C. Sasaki, Prog.Part.Nucl.Phys. 72 (2013) 99



QCD – matter phases

History:

QGP concept
J.C. Collins, M.J. Perry, Phys. Rev. Lett. 34 (1975) 1373
N. Cabibbo, G. Parisi, Phys. Lett. B59 (1975) 67

Liquid – gas phase transition in nuclei
Theory
P.A. Siemens, Nature 305 (1983)
Experiments
(since ~1995)

New State of Matter (CERN 2000)

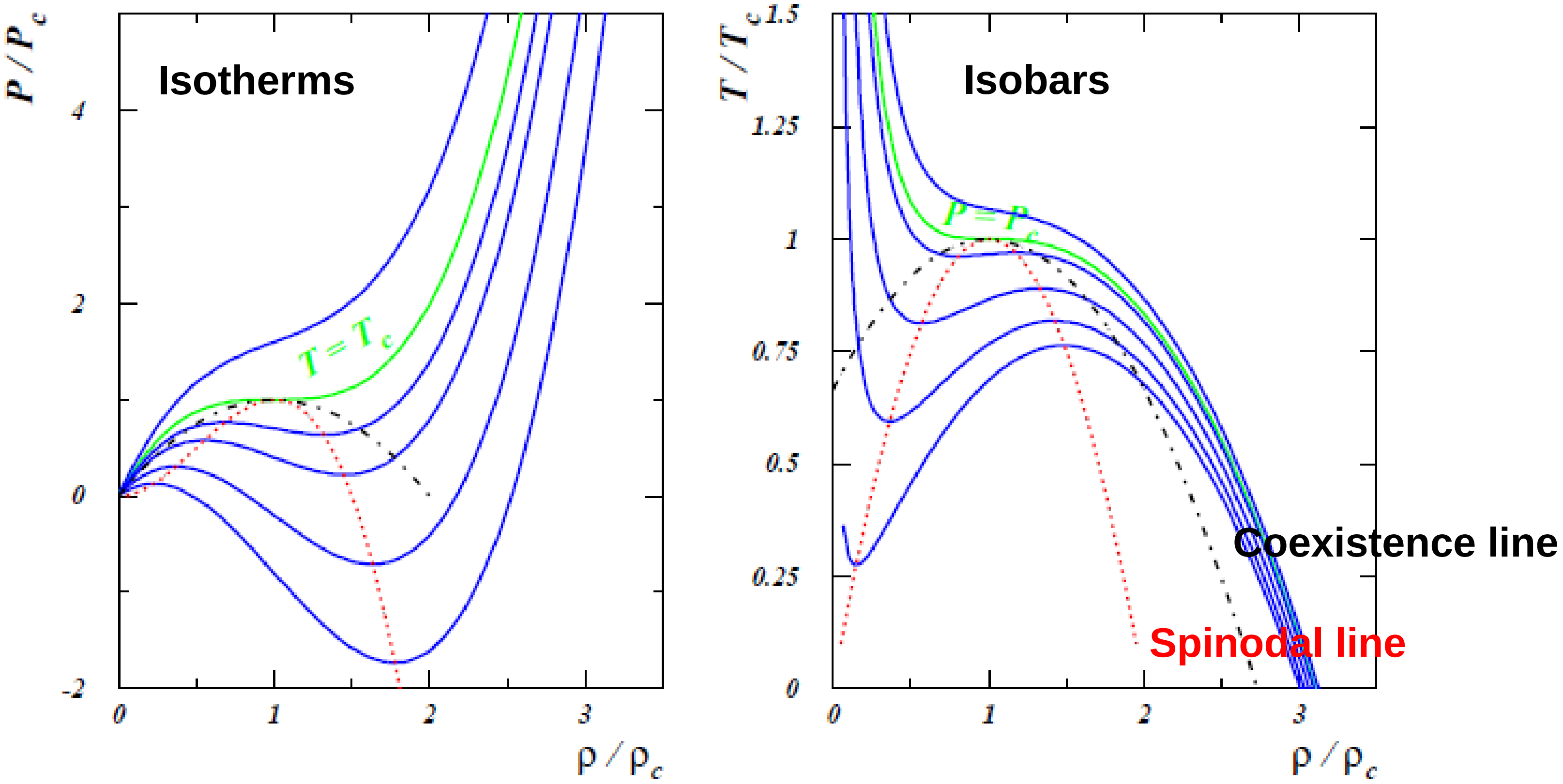
Perfect liquid (RHIC 2008)

Helpful conditions: **large long-lived systems!**

Nuclear liquid – gas - phase transition

Nuclei show properties of liquid -> ‘liquid – drop model’,
Bethe – Weizsäcker mass formula.

NN – potential very similar to Lennard – Jones – potential.

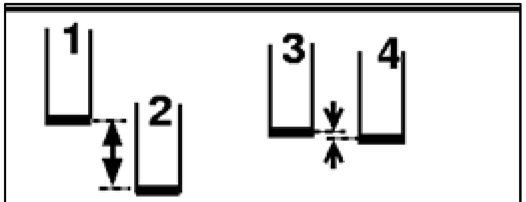


Recent review:

B. Borderie, M.F. Rivet,
“Nuclear multifragmentation and phase transition for hot nuclei”,
Progress in Particle and Nuclear Physics 61 (2008) 551-601

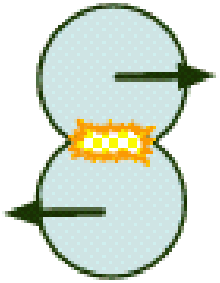
Caloric curve of nuclei

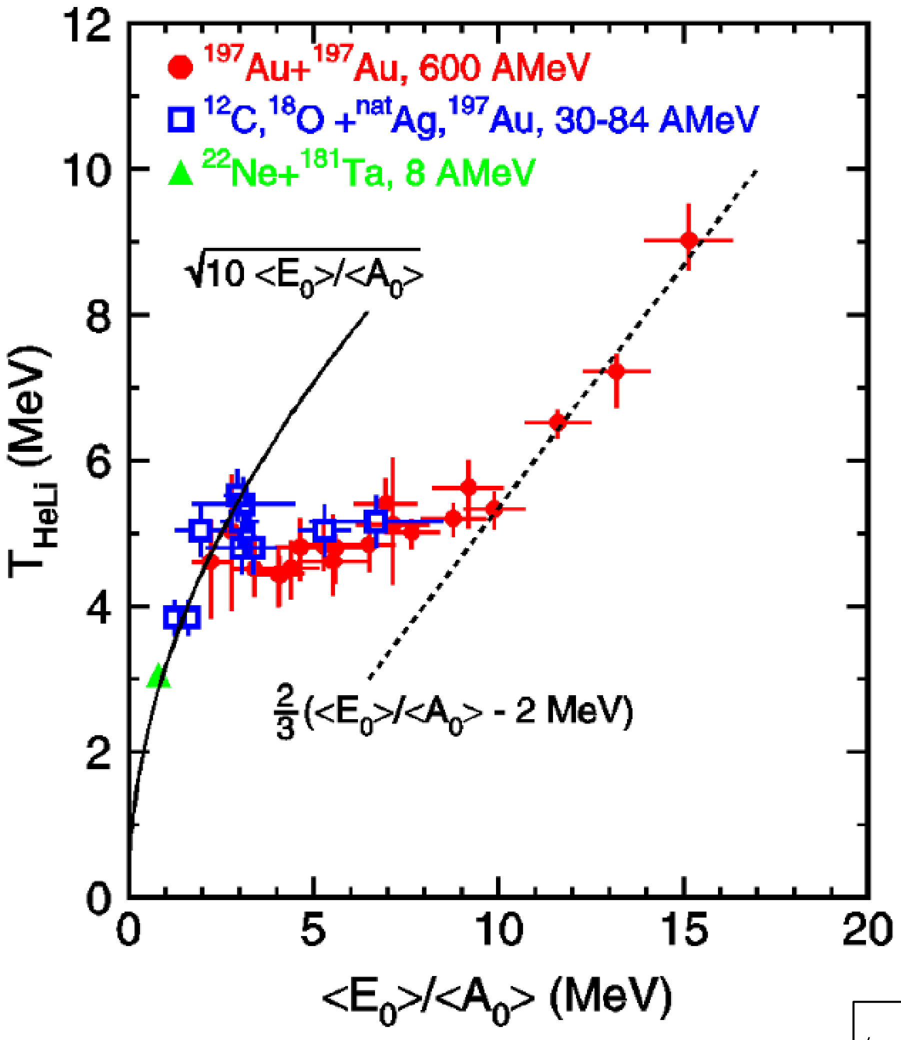
J. Pochodzalla et al. (ALADIN), PRL 75(1995) 1040



$$\ln \frac{Y_1/Y_2}{Y_3/Y_4} \sim (\Delta B_{12} - \Delta B_{34})/T$$

Peripheral
HI - collisions





temperature

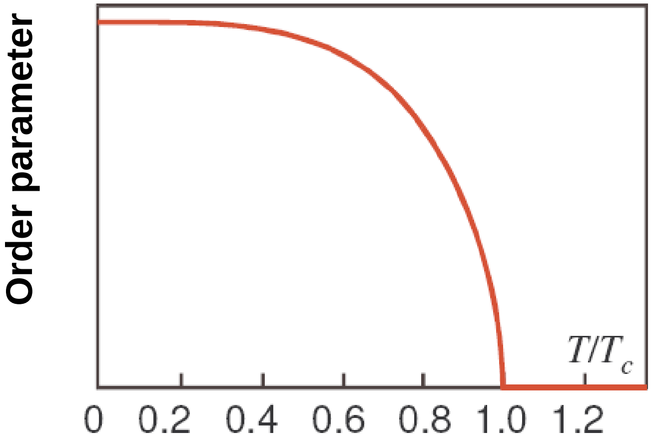
excitation energy of prefragment

$$\langle E_0\rangle = \left(\left\langle \sum_i m_i \right\rangle + \left\langle \sum_i K_i \right\rangle\right) - \left(\langle m_0\rangle + \langle K_0\rangle\right)$$

$$A_0 = \sum_i A_i$$

Description of phase transition

Phases are characterized by the presence of an order parameter that vanishes when going to a different phase.



Examples of order parameters:

Liquid gas – density difference of liquid to gaseous phase
Ferromagnet – spontaneous magnetisation
Superconductor – energy gap in electron excitation spectrum

Thermodynamic Potential (e.g. Free energy) is non analytic function of order parameter.

Ehrenfest's classification of phase transitions:
Phase transition of nth order = one of the nth – derivatives of the potential is discontinuous, while all derivatives of lower order are continuous.

Critical exponents

Close to a critical point the thermodynamic behaviour of physical systems is universal and depends within a universality class only on

$$t = \frac{T - T_C}{T_C}$$

Thermodynamic quantities show a power law behaviour:

Heat capacity: $C \sim |t|^{-\alpha}$

Order parameter: $M \sim |t|^{\beta}$

Susceptibility: $\chi \sim |t|^{-\gamma}$

Equation – of – state: $M \sim |H|^{\frac{1}{\delta}}$

Correlation length: $\xi \sim |t|^{-\nu}$

Griffiths universality hypothesis

R.B. Griffiths, PRL 24, 1479 (1970):

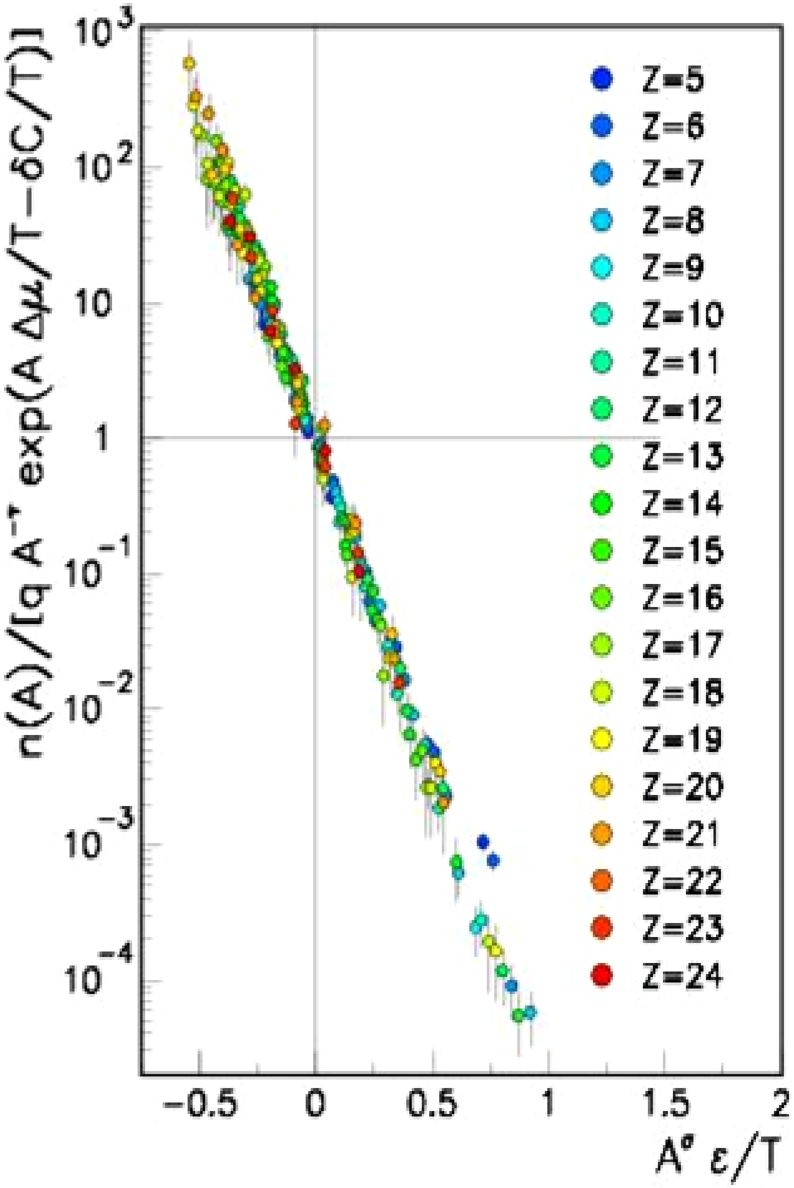
Critical exponents are universal and depend only on:

1) Dimension of the system
2) Range of the interaction
3) Spin dimensionality

Note: Only 2 of the critical exponents are independent.

Nuclear liquid - gas phase transition

M. D’Agostino et al., NPA 724, 455 (2003)



Fragment distribution

(Fisher droplet model 1967)

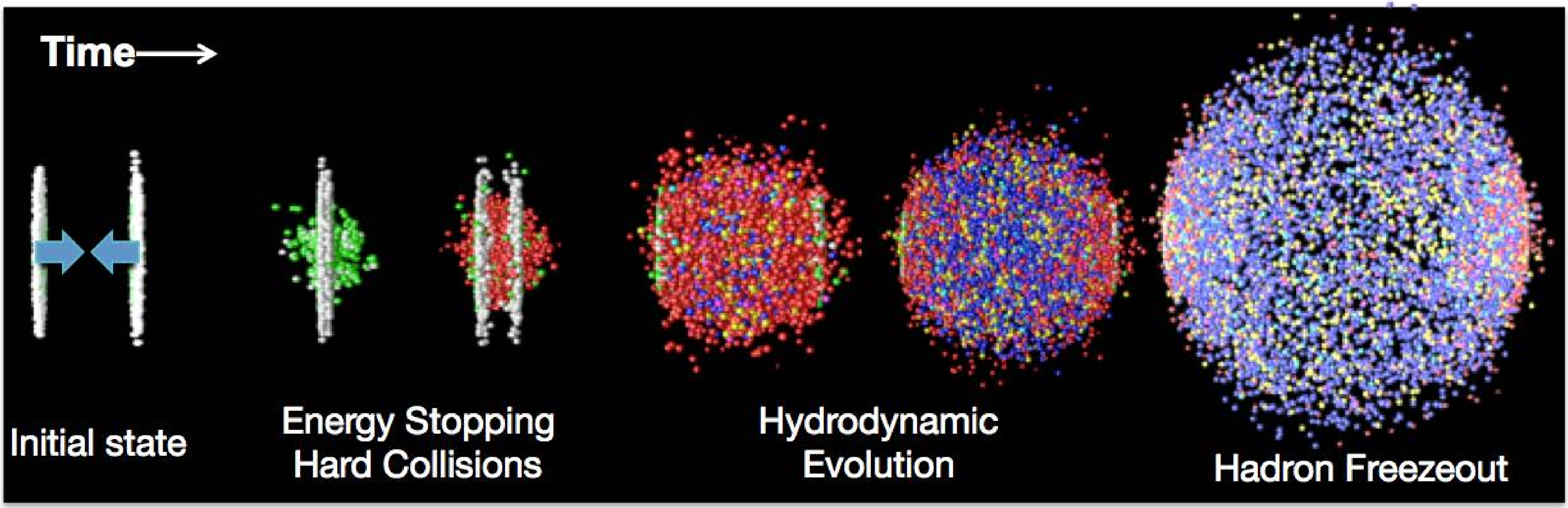
$$n_A = q_o A^{-\tau} \exp\left(\frac{-c_o \varepsilon A^\sigma}{T}\right)$$

$$\varepsilon = \frac{T_c - T}{T_c}$$

Universal critical exponents in the vicinity of the critical point:

	Au	**Liquid-Gas**
τ	2.1±0.1	2.196 ±0.024
σ	0.66±0.02	0.647 ±0.006

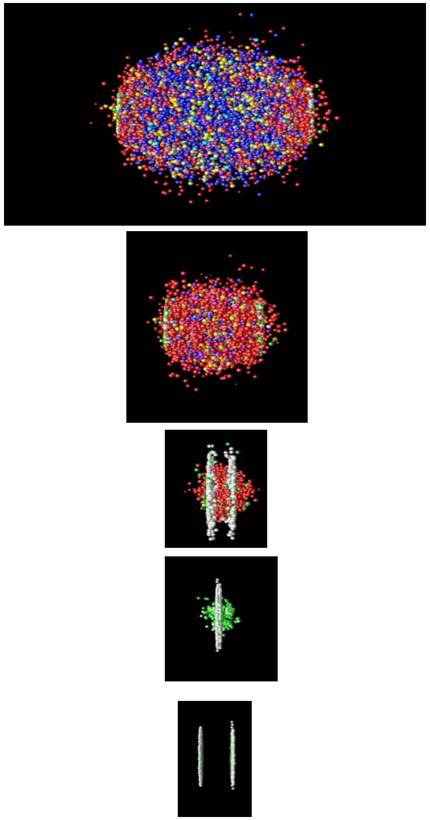
How to produce a phase of QCD matter ?

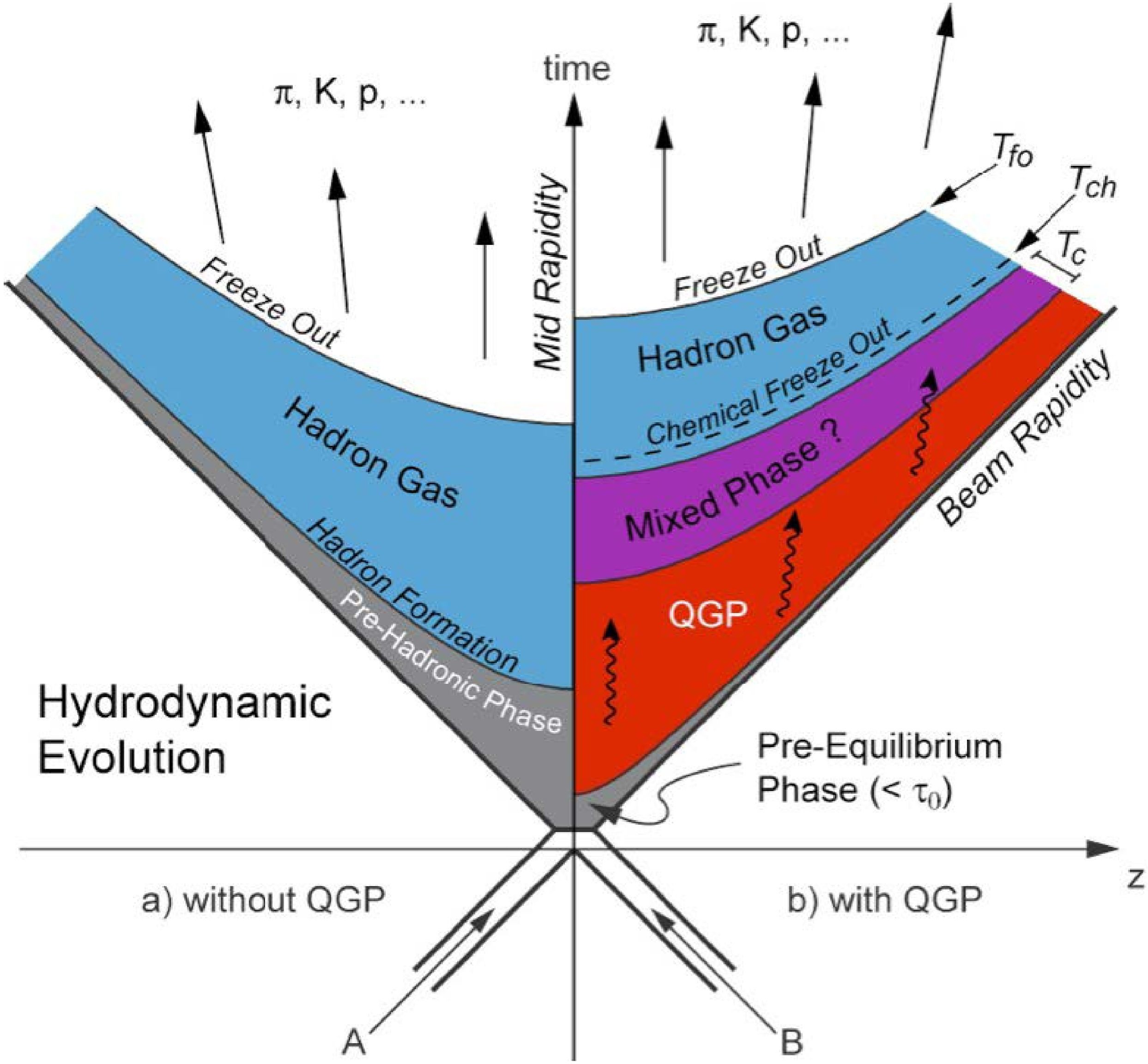


Dynamical Evolution

Thermalization ?

Relativistic Reaction Dynamics





Theory: Thermal model

Chemical thermal model:

P. Braun-Munzinger et al., arXiv:nucl-th/0304013

assume a common ‘surface’ at which all particles decouple (inelastic collisions stop)

Grand canonical formulation (i.e. energy and particle exchange with heat bath)

Partition function:

$$Z^{GC}\left(T,V,\mu_Q\right) = Tr\left[e^{-\beta\left(H - \sum_i \mu_{Q_i} Q_i\right)} \right]$$

Q_i = conserved quantum numbers (baryon number, strangeness, isospin, charm,…)

β= 1/T, T= Temperature

H = Hamiltonian of non-interacting hadron gas

Grand canonical potential J:

$$J\left(T,V,\mu_Q\right) = -T \ln Z^{GC}\left(T,V,\mu_Q\right)$$

$$F(T,V,N) = J\left(T,V,\mu_Q\right) + \sum_i \mu_{Q_i} N_i$$

Decomposition into individual hadronic species:

$$\ln Z^{GC}\left(T,V,\mu\right) = \sum_i \ln Z_i^{GC}\left(T,V,\mu\right)$$

Thermal model for particle production

P. Braun-Munzinger et al., arXiv:nucl-th/0304013

Chemical equilibrium concept.

Density of particle species i:

$$n_i(\mu,T) = \frac{N_i}{V} = -\frac{T}{V}\frac{\partial \ln Z_i}{\partial \mu_i} = \frac{g_i}{2\pi^2}\int \frac{p^2 dp}{e^{\frac{E_i-\mu_i}{T}} \pm 1}$$

$$\mu_i = \mu_B B_i + \mu_S S_i + \mu_{I_3} I_{3,i}$$

"+" for fermions, "-" for bosons
g_i – spin degeneracy factor

Chemical potentials μ_i are constrained by conservation of quantum numbers:

baryon number: $V\sum_i n_i B_i = Z + N \to V$

strangeness: $V\sum_i n_i S_i = 0 \to \mu_S$

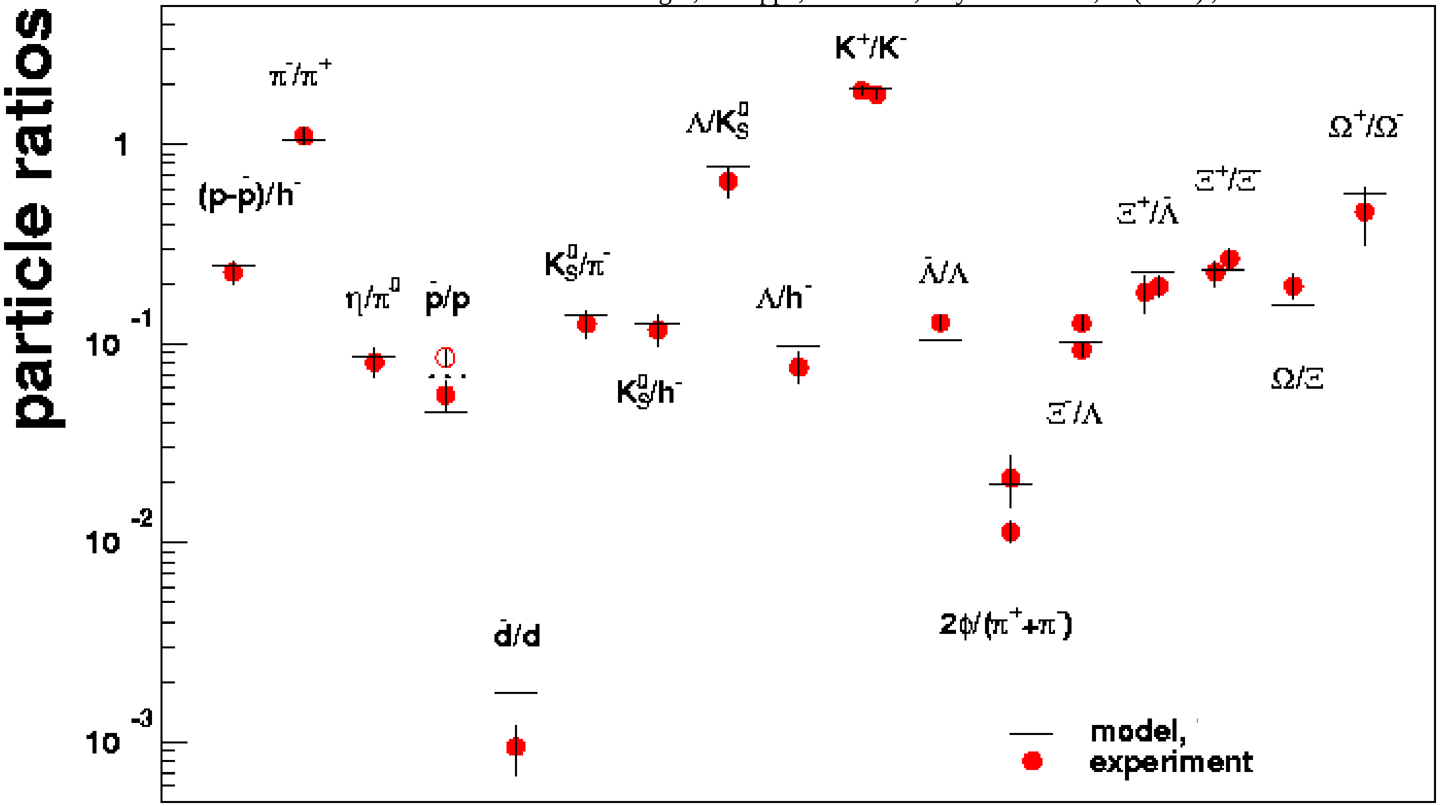
charge: $V\sum_i n_i I_{3,i} = \frac{Z-N}{2} \to \mu_{I_{3,i}}$

⇒

3 equations,
5 unknows
↓
2 free parameter

Chemical equilibrium

Example: SPS data, E_{beam}=158 AGeV, Pb+Pb



P. Braun-Munzinger, I. Heppe, J. Stachel, Phys.Lett.B465, 15(1999) , *nucl-th/9903010*

Model parameter:

$$T = 168 \pm 2.4 \text{ MeV}$$

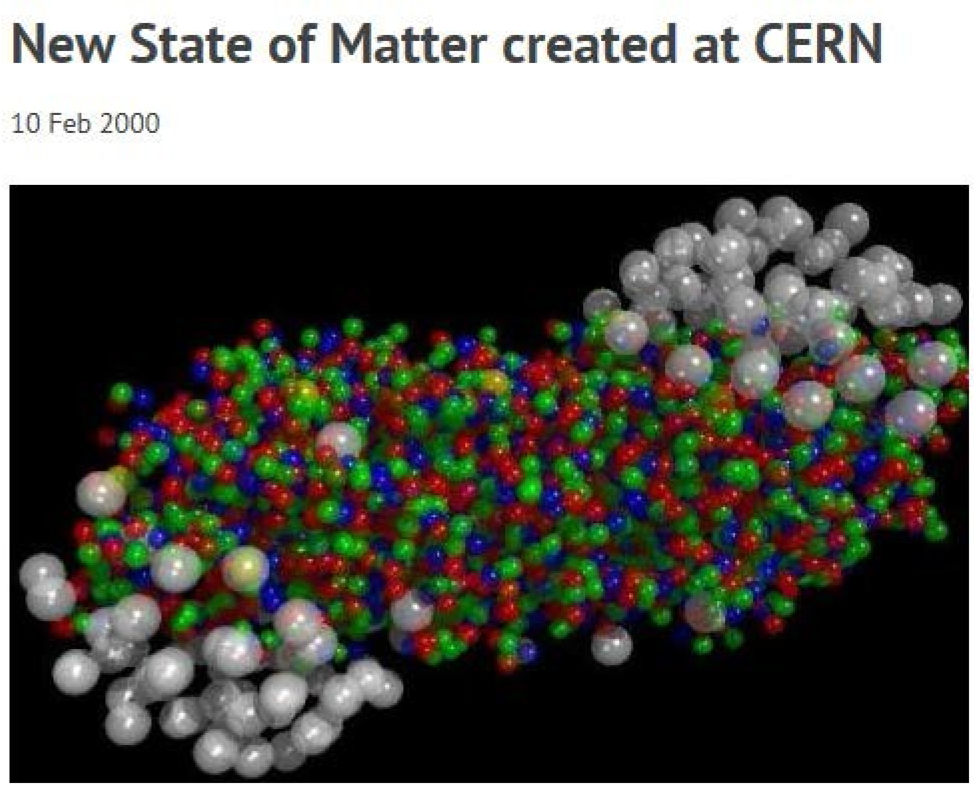
$$\mu_B = 266 \pm 5 \text{ MeV}$$

$$\mu_S = 71.1 \text{ MeV}$$

$$\mu_{I_3} = -5. \text{ MeV}$$

Note: volume is not needed for description of particle ratios.

Press release 2000



New State of Matter created at CERN

10 Feb 2000

http://press.web.cern.ch/press-releases/2000/02/new-state-matter-created-cern

Based on a (unpublished) 'common assessment' of results from ~ half dozen experiments

collected & published over the course of the SPS Pb program (1994 - 2000)

http://arxiv.org/abs/nucl-th/0002042v1

“The collected data from the experiments gives compelling evidence that a new state of matter has been created. This state of matter found in heavy ion collisions at the SPS features many of the characteristics of the theoretically predicted quark-gluon plasma.."

'.. a QGP-like state ..'

Signature of the “QGP” – phase

Thermodynamic behavior at freeze – out

Strangeness enhancement

J/Ψ – production

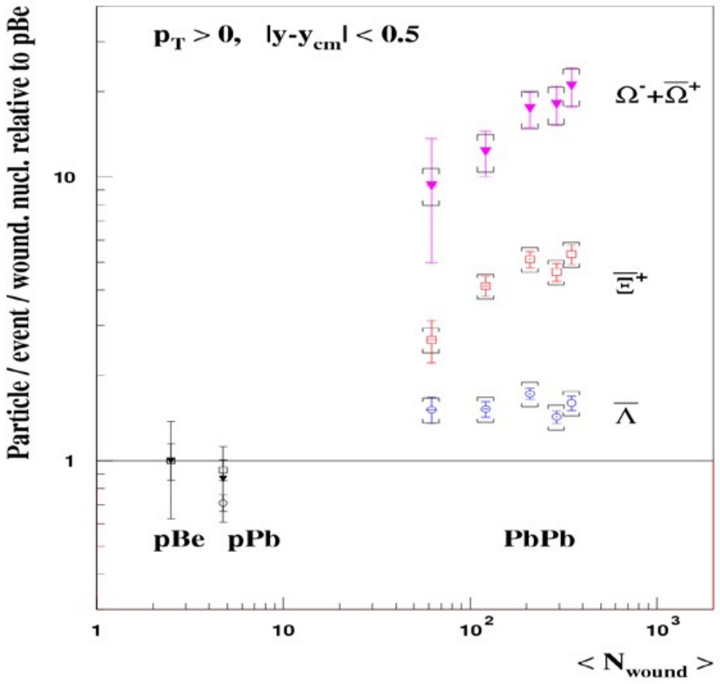
Low – mass dileptons

Partonic flow

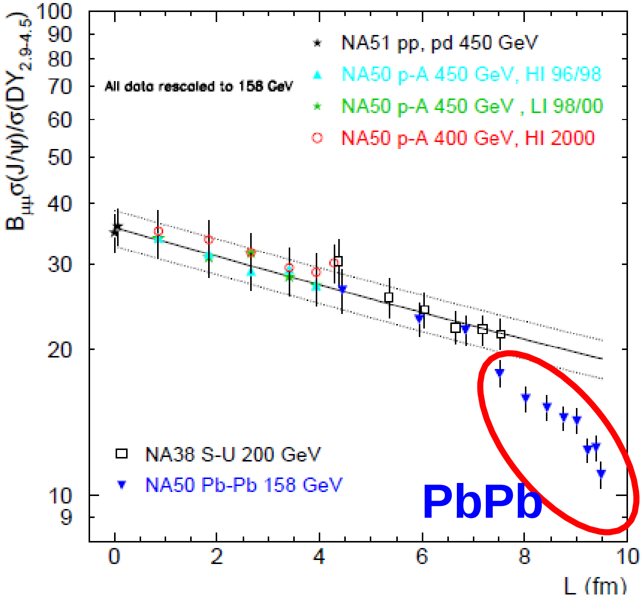
Jet – propagation in hot QCD – matter

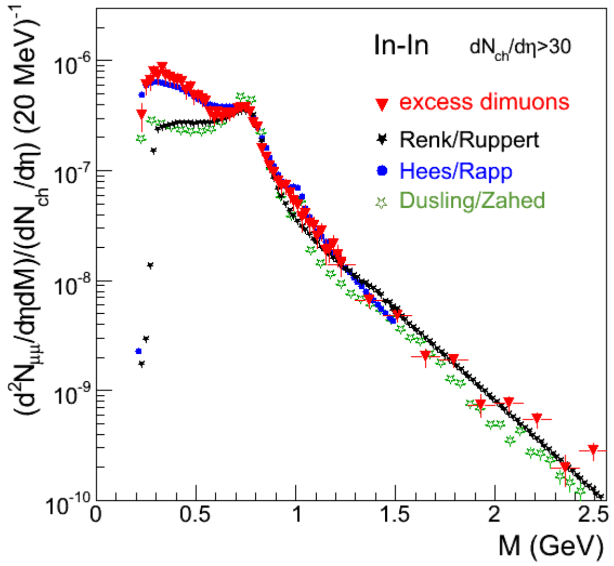
Main results from SPS

Strangeness enhancement



anomalous J/Y suppression

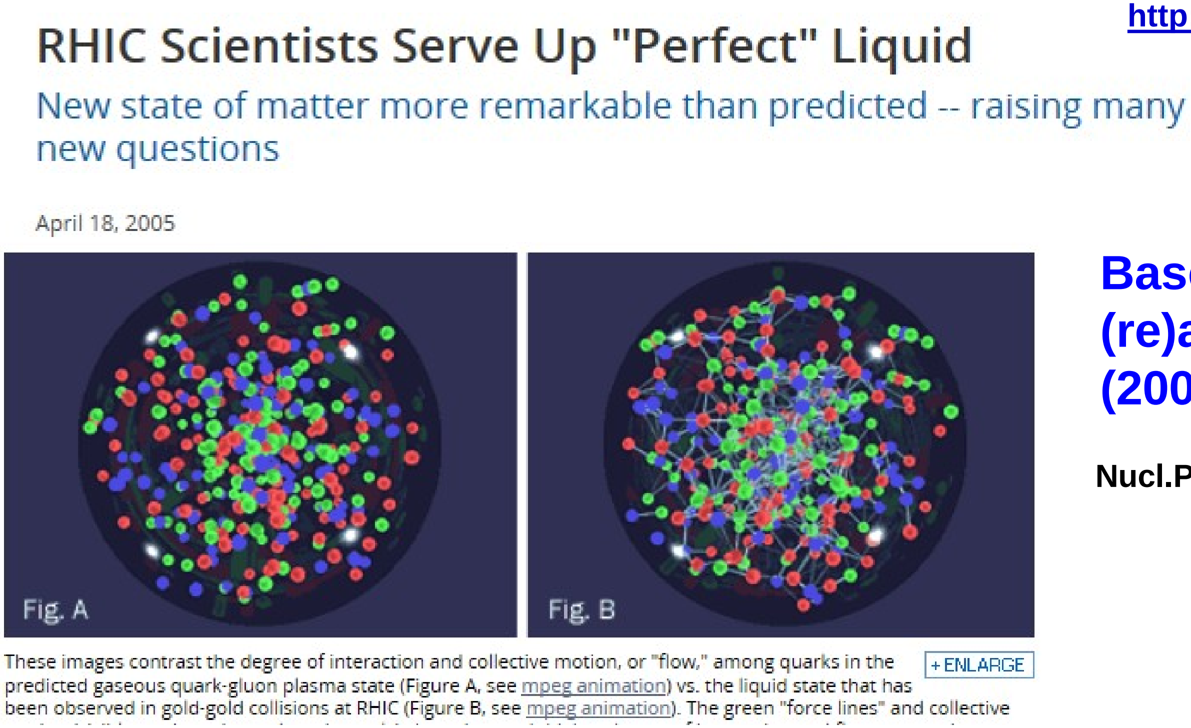




Enhancement of low mass lepton pairs

ρ – melting, chiral symmetry restoration

RHIC press release (2005)



RHIC Scientists Serve Up "Perfect" Liquid

New state of matter more remarkable than predicted -- raising many new questions

April 18, 2005

These images contrast the degree of interaction and collective motion, or "flow," among quarks in the predicted gaseous quark-gluon plasma state (Figure A, see mpeg animation) vs. the liquid state that has been observed in gold-gold collisions at RHIC (Figure B, see mpeg animation). The green "force lines" and collective

http://www.bnl.gov/newsroom/news.php?a=1303

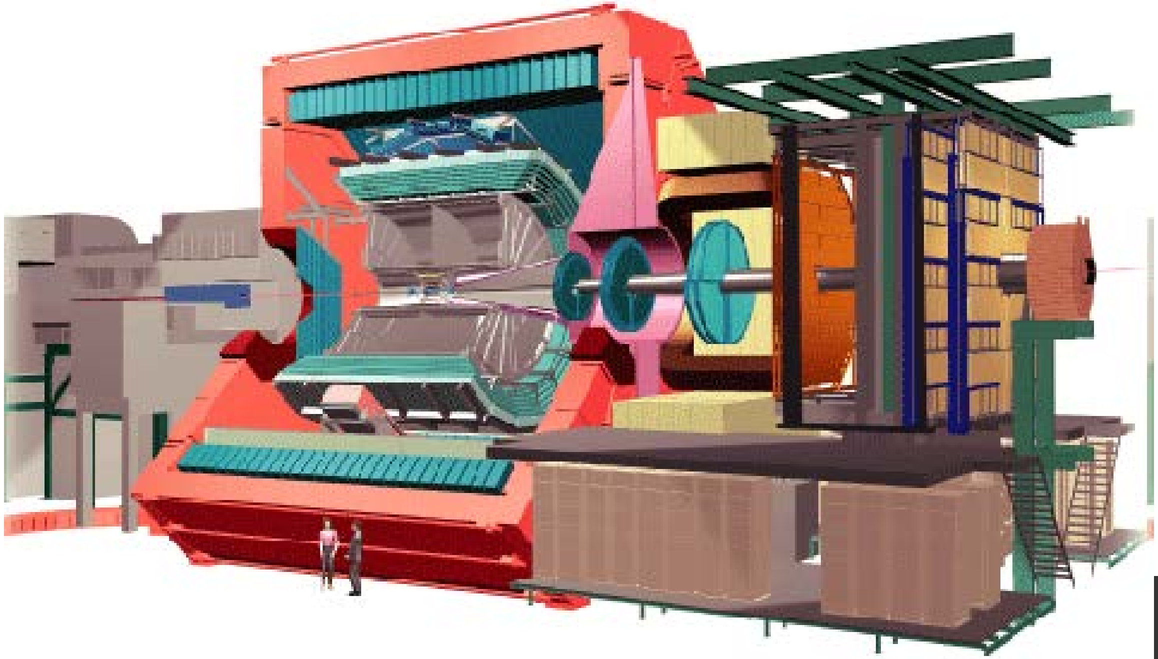
Based on a (published) comprehensive (re)analysis of the first years of RHIC (2000 - 2004)

Nucl.Phys.A757:1-284,2005

.. created a new state of hot, dense matter out of the quarks and gluons .., but it is a state quite different and even more remarkable than had been predicted.

sQGP: strongly interacting QGP

ALICE @ LHC

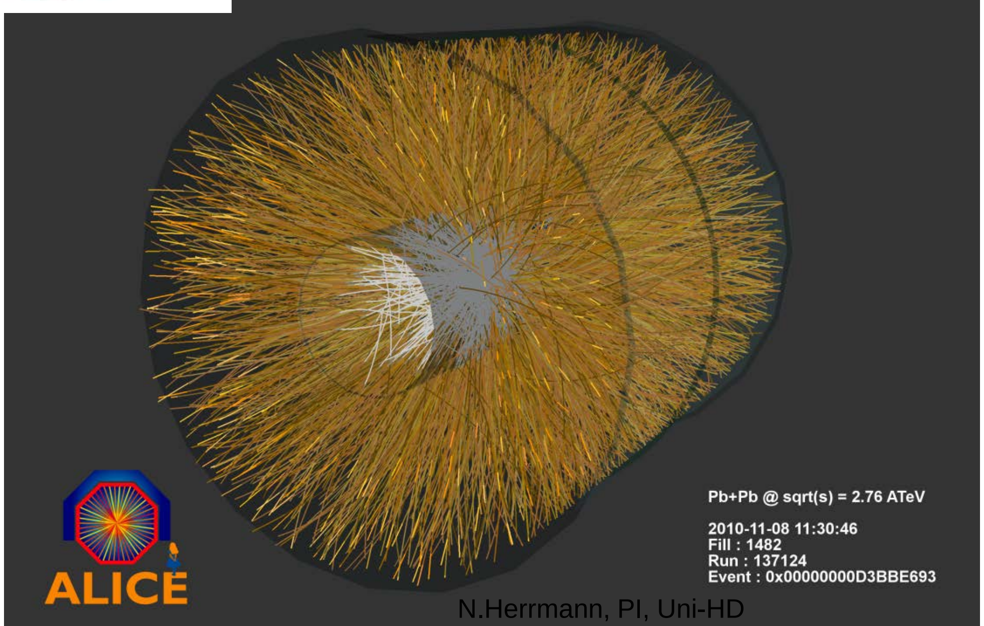


Pb+Pb collisions at LHC (2011)

$\sqrt{s}$ = 2.76 ATeV = 574 TeV

$R_{interaction}$ = 5 kHz

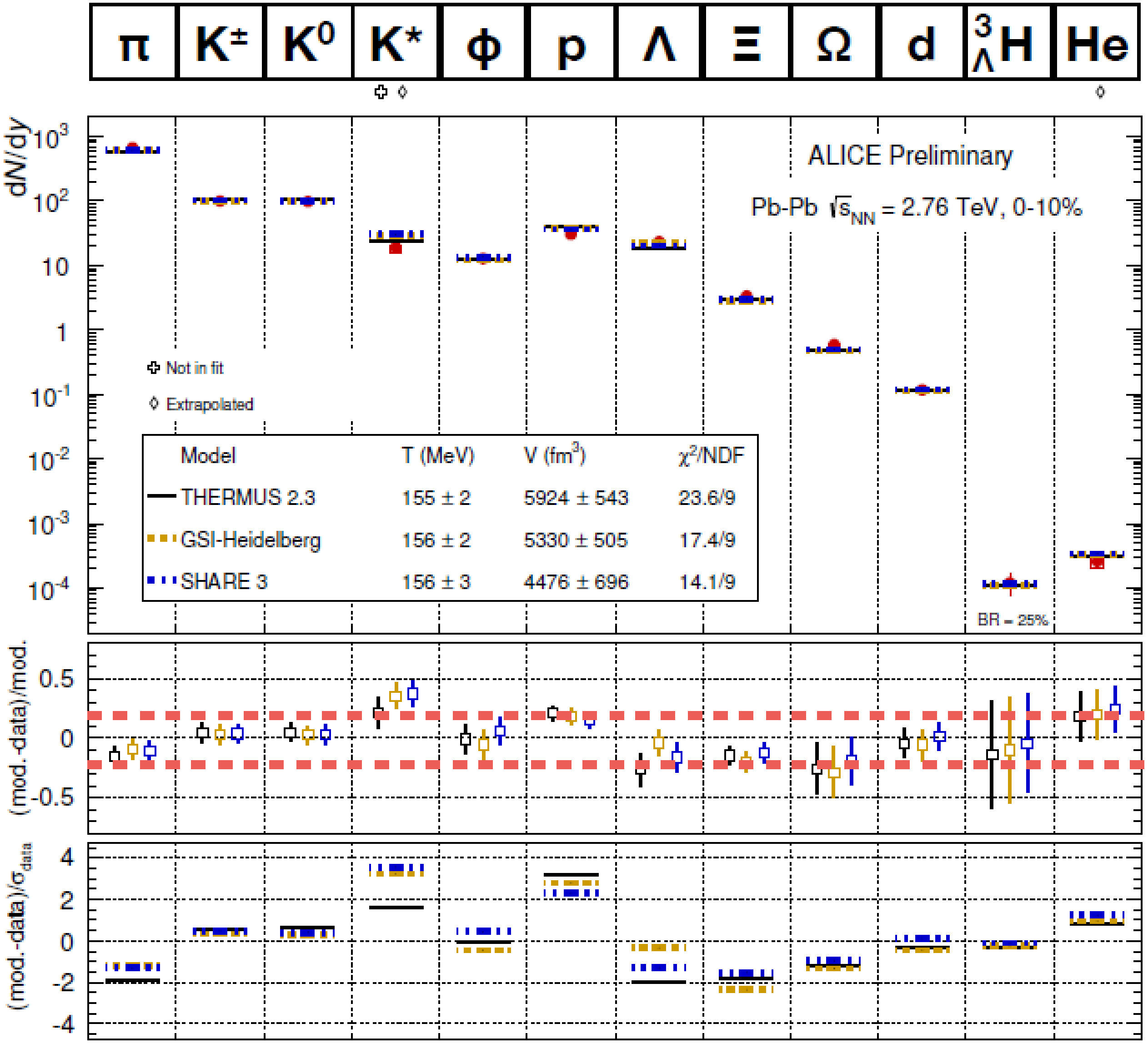
$N_{particles}$ < 20.000



Pb+Pb @ sqrt(s) = 2.76 ATeV

2010-11-08 11:30:46
Fill : 1482
Run : 137124
Event : 0x00000000D3BBE693

Particle Yields at LHC (ALICE)



N.B.
at RHIC
√s=200 A GeV STAR
χ^2/ NDF~1

Petran et al, arXiv:1310.5108
Wheaton et al, Comput.Phys.Commun, 180 84
Andronic et al, PLB 673 142

Tension Thermal Model / Data

- **Incomplete hadron spectrum in the model**
  - **Affects feed-down and hence final abundances**

PRL 113, 072001 (2014)
arXiv:1405.7298

- **Inelastic interactions in the hadronic phase**
  - **May deplete baryons**

PRC 90, 054907 (2014)

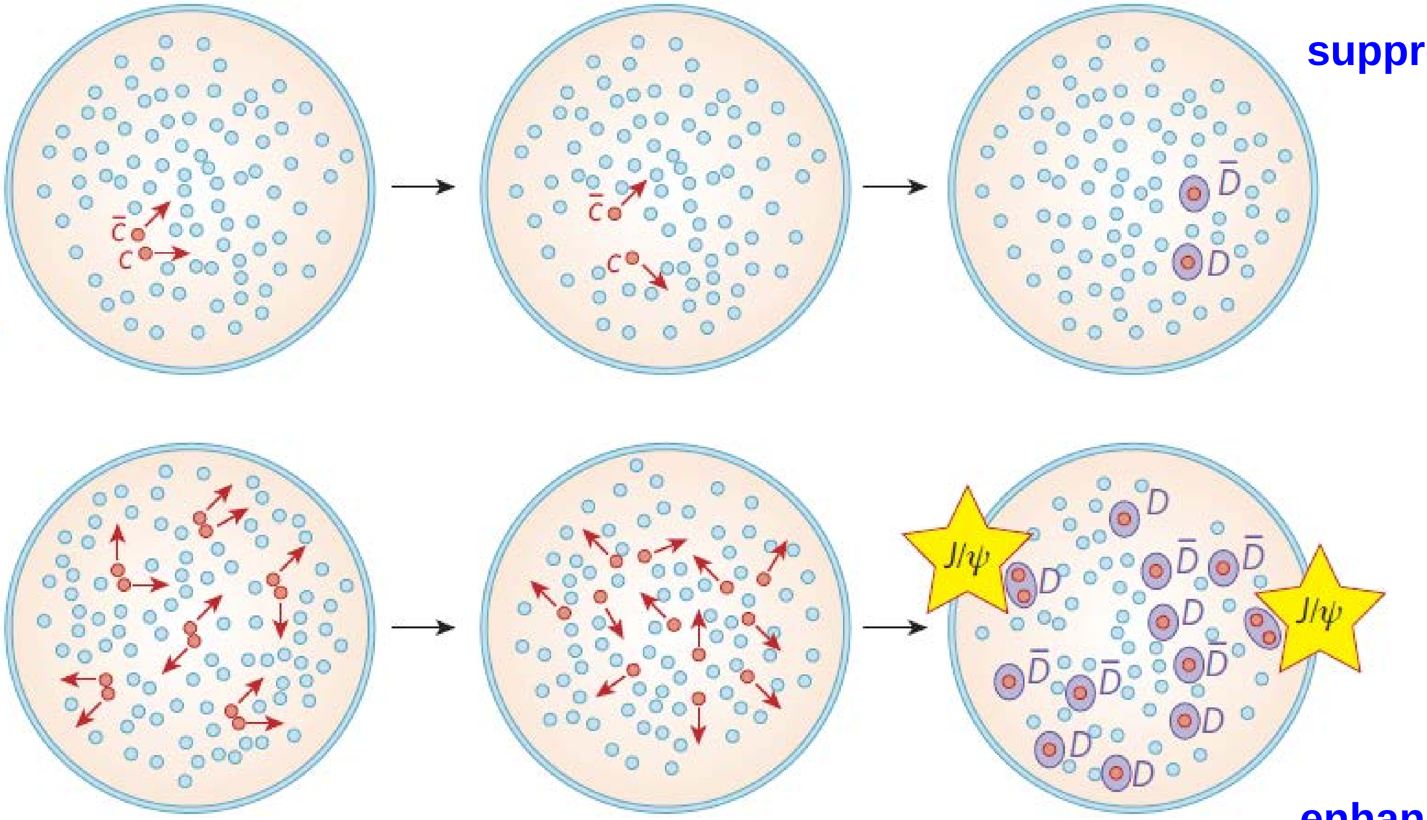
- **Flavor ordering at freeze-out**
  - **Different T preferred by *s* and *u-d***

PRL 111, 202302 (2013)

- **Non–equilibrium thermal model**
  - **reflects equilibrium in the preceding QGP phase**

PRC, 88, 021901 (2013)

J/Ψ – production in HIC



production **equilibration** **freeze-out**

“low” energy
SPS, RHIC

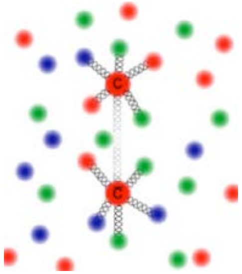
suppression

“high” energy
LHC

enhancement

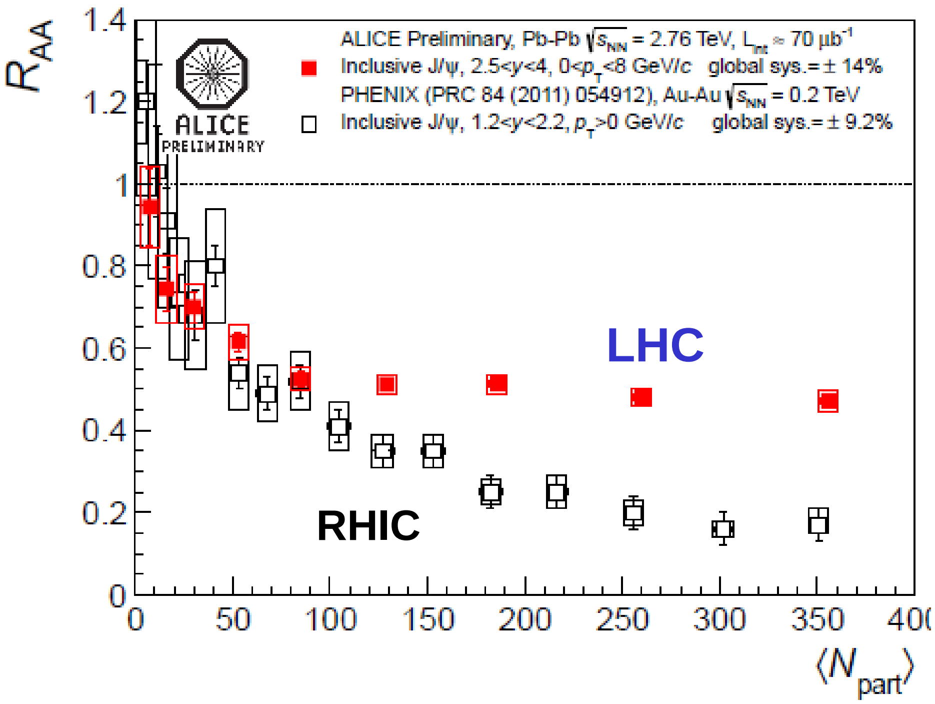
Debye – screening:

$$V(r) = -\frac{4}{3}\frac{\alpha_s}{r} e^{-\frac{r}{\lambda_D}}$$

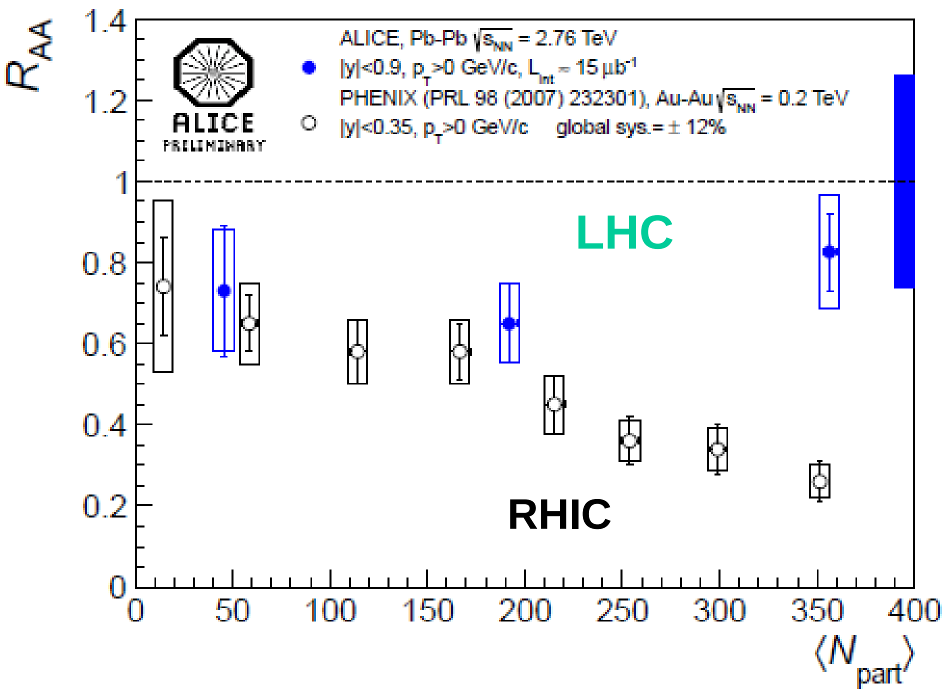


J/Ψ – production at LHC

Forward rapidity



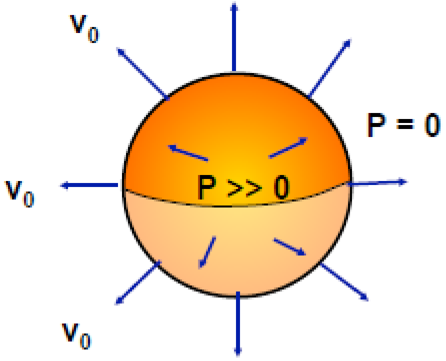
Central rapidity



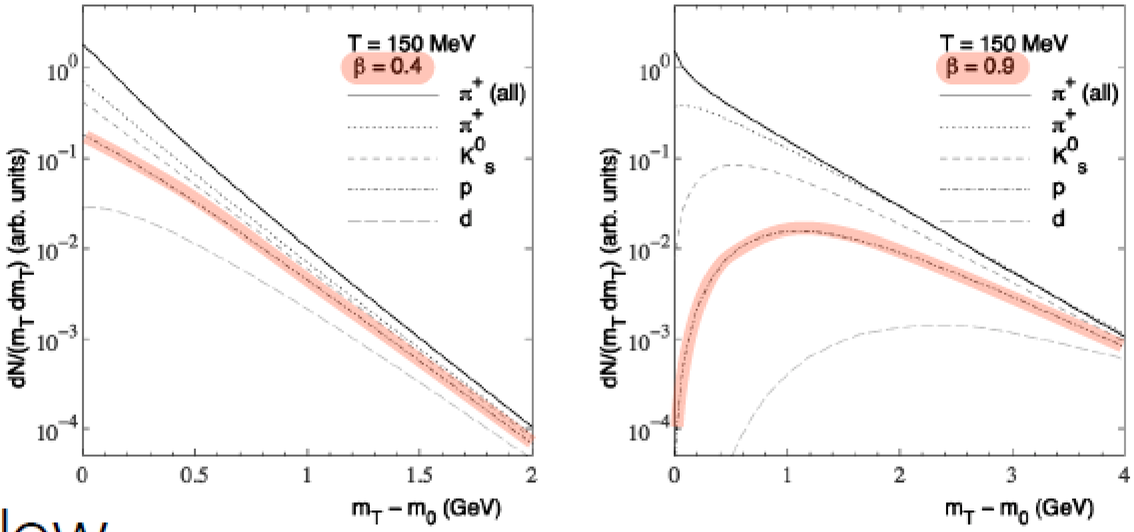
J/Ψ – suppression much less pronounced at LHC ($\sqrt{s_{NN}} = 2.76$ TeV)
as compared to RHIC ($\sqrt{s_{NN}} = 0.2$ TeV) .

Collective flow

Isotropic (radial) flow

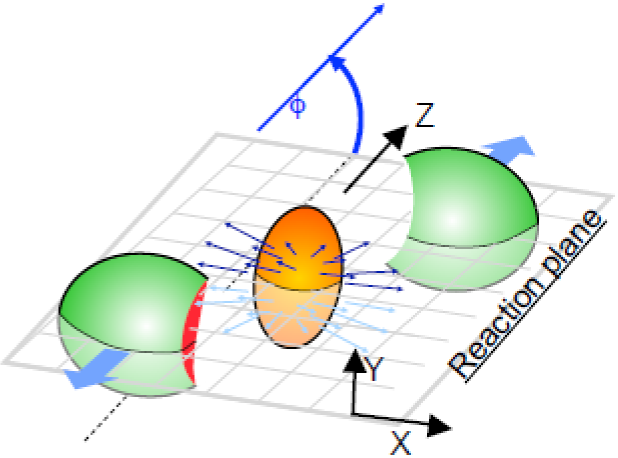


hep-ph/0407360

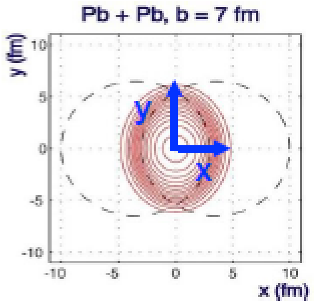


Anisotropic (elliptic) flow

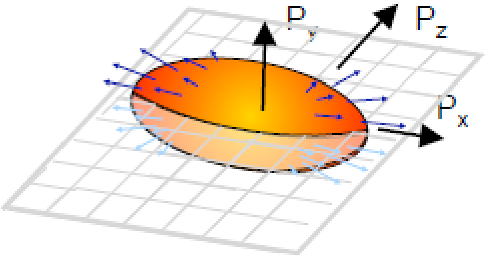
Spatial deformation



Azimuthal (ϕ) pressure gradients

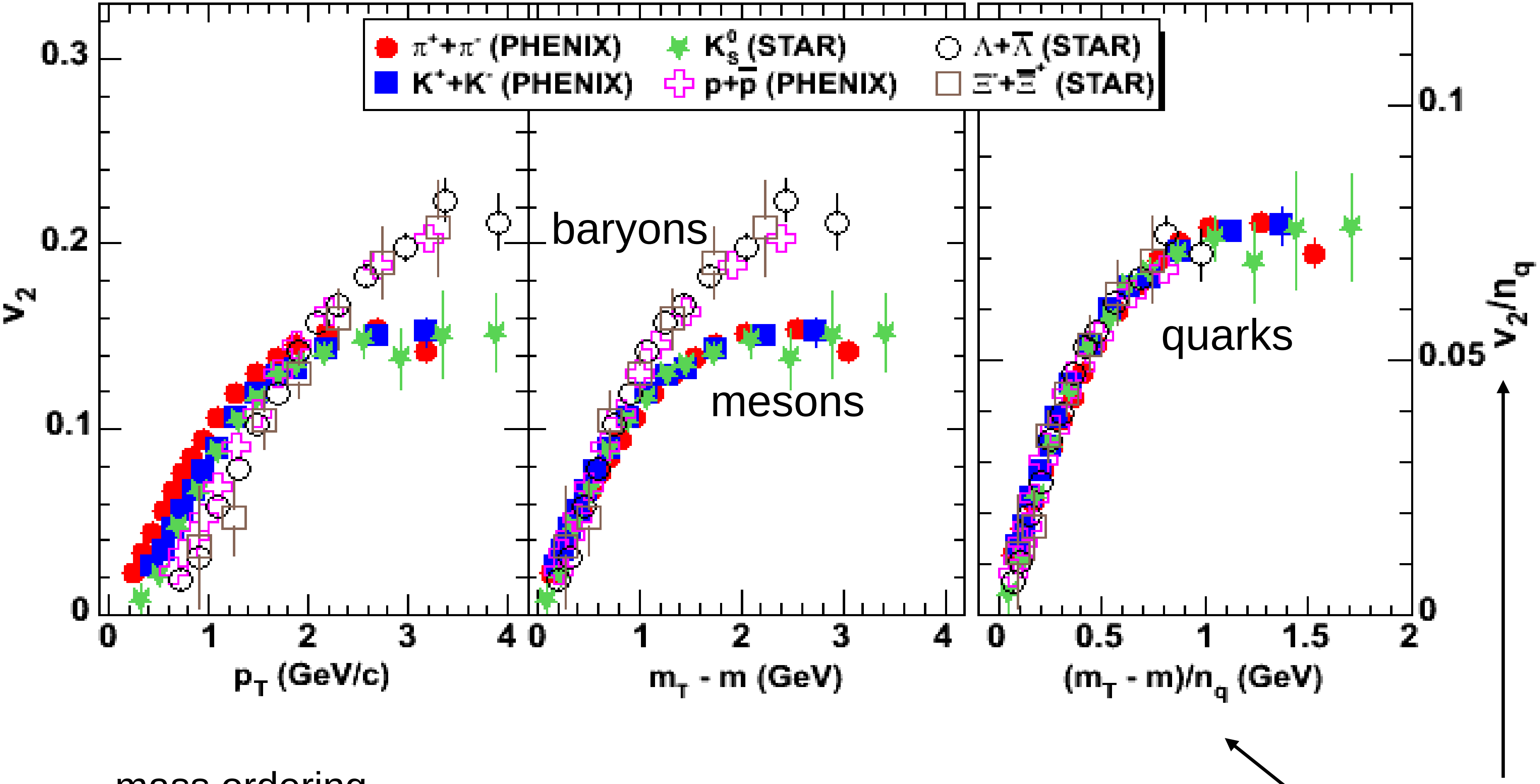


Anisotropic particle density



$$\frac{dN}{d\varphi} \propto 1 + 2v_1\cos[\varphi - \Psi_1] + 2v_2\cos[2(\varphi - \Psi_2)] + 2v_3\cos[3(\varphi - \Psi_3)] + ..$$

Scaling with Number of Quarks @ 200AGeV



mass ordering

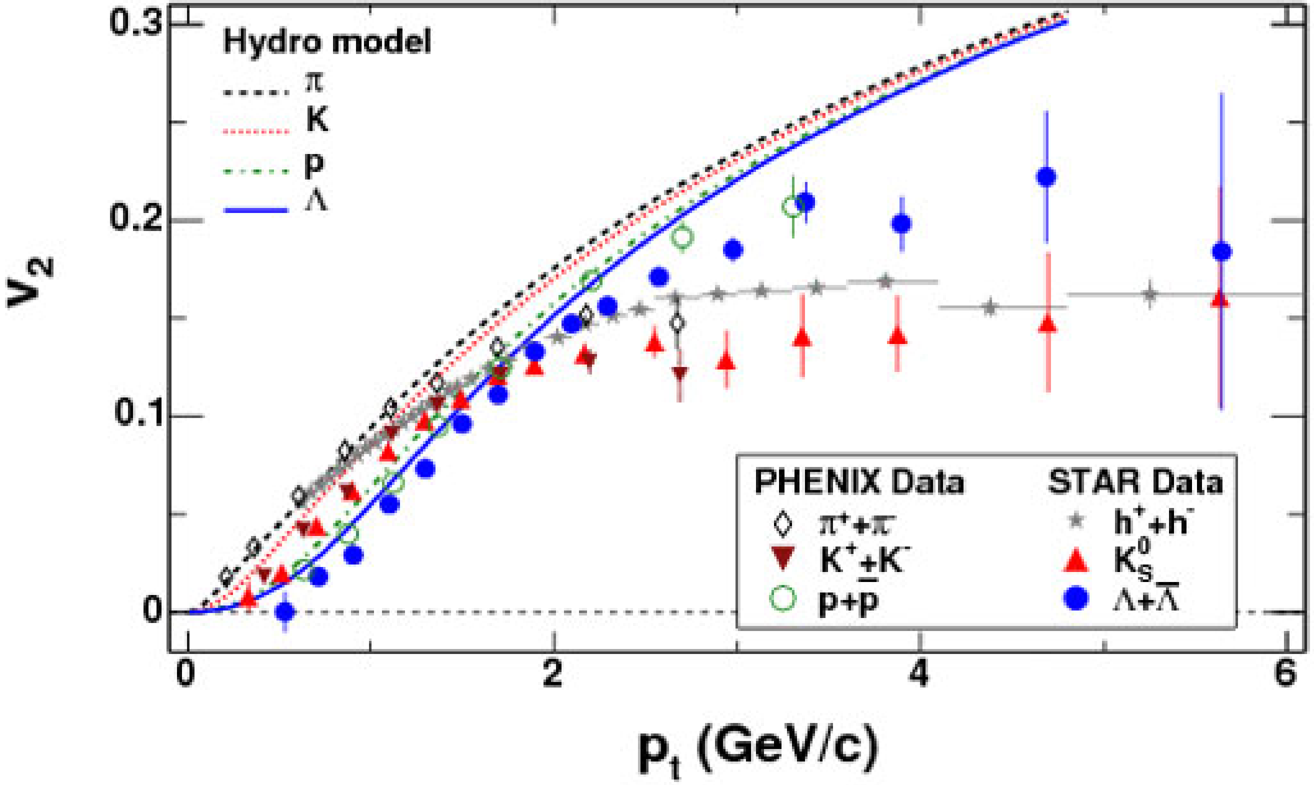
both axes scaled by number of constituent quarks

n_q = 2 for mesons
n_q = 3 for baryons

quarks have v_2 before hadronization

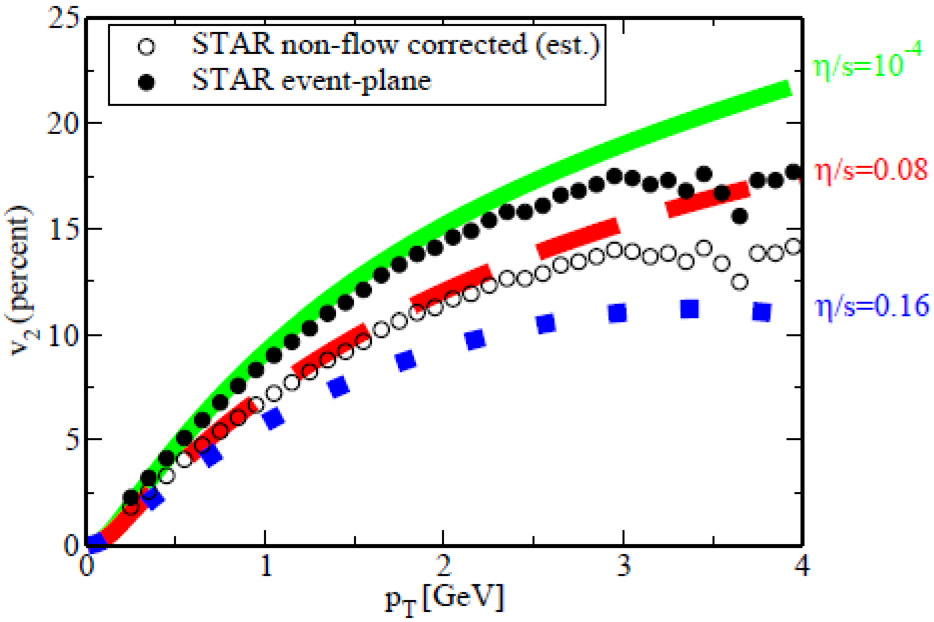
S. Voloshin, QM02, 379c (2003)
STAR, PRL **95**, 122301 (2005)   PHENIX, PRL **98**, 162301 (2007)

Hydrodynamical description of flow pattern



Perfect liquid

M.Luzum, P. Romatschke, arXiv:0804.4015



Hydrodynamics
local thermal equilibrium
mean free path << system size
succesfully describes flow data.

Magnitude of flow can be tuned by
viscosity / entropy density

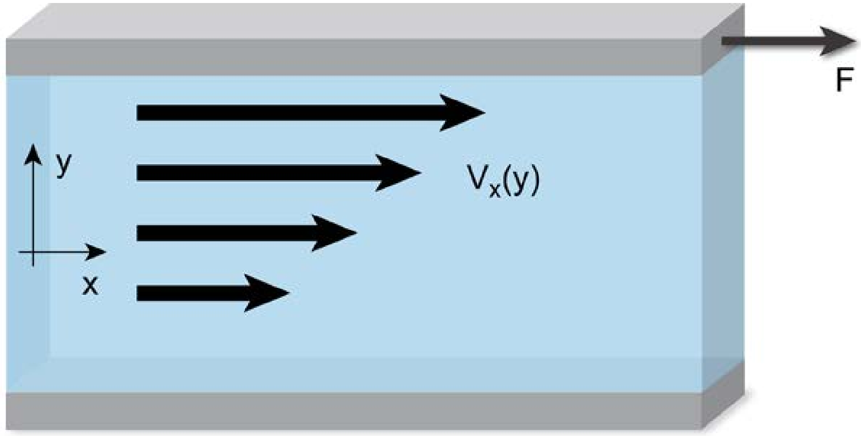
Extracted η/s – value is much smaller than for any other known substance:

at T_C:	**He**	**0.8**
	H_2O	**2.1**

Viscosity and fluidity

Shear viscosity η

T. Schäfer, Physics 2, 88 (2009)



Friction force / unit area:

$$\frac{F}{A} = \eta \nabla_y \mathrm{v}_x$$

	η(Pa . s)
LHe	$2 \cdot 10^{-15}$
sQGP	$5 \cdot 10^{+11}$

Fluidity ↔ large Reynold number

$$\mathrm{Re} = \left(\frac{mn}{\eta}\right) \mathrm{vL}$$

mass density m · n
length scale L

η / n has units of ħ,
n is not conserved in relativistic fluid,
however: with entropy density s and s / n ~ kB

$$\left(\frac{mn}{\eta}\right) \rightarrow \frac{\eta}{s}\left[\frac{\hbar}{k_B}\right]$$

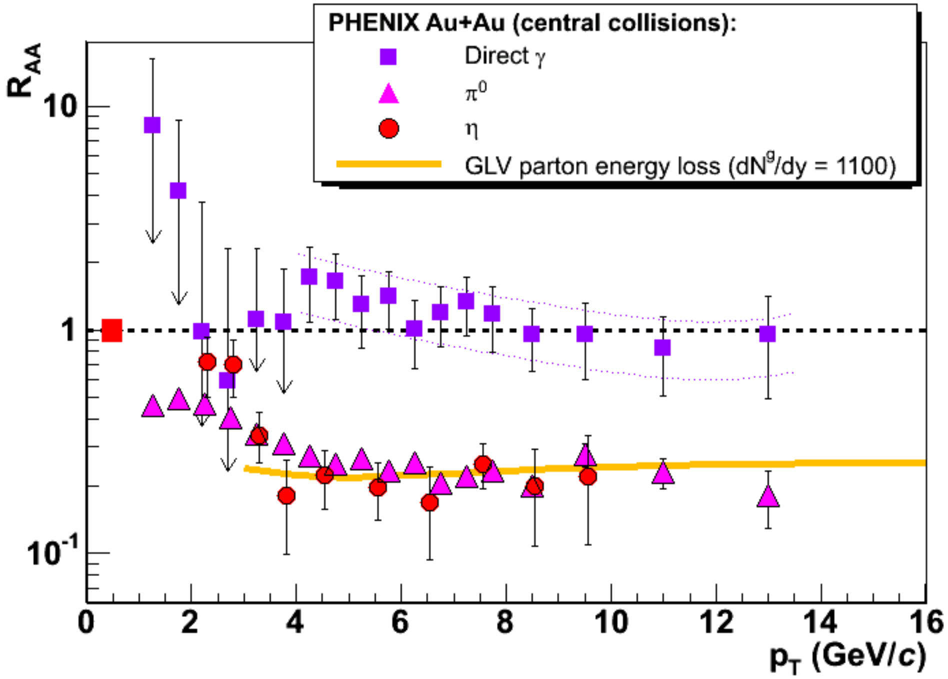
Nuclear modification factor R_{AA}

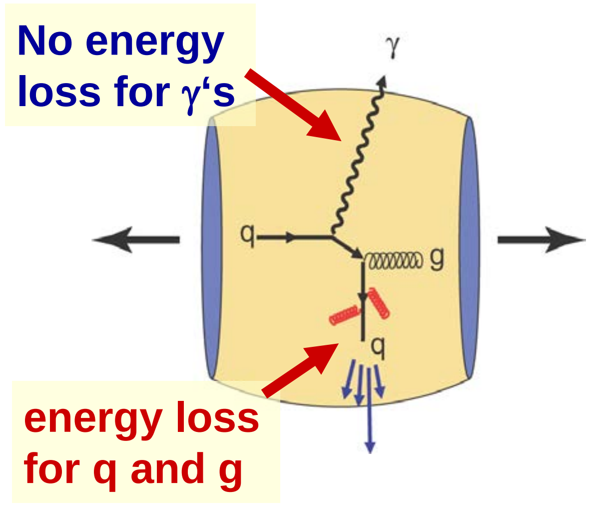
K. Reygers, QM2008

Compare data from heavy – ion reaction to scaled proton - proton data:

$$R_{AA} = \frac{\left.\frac{d\sigma}{dp_t}\right|_{A+A}}{N_{coll} \cdot \left.\frac{d\sigma}{dp_t}\right|_{p+p}}$$

“Jet – quenching”



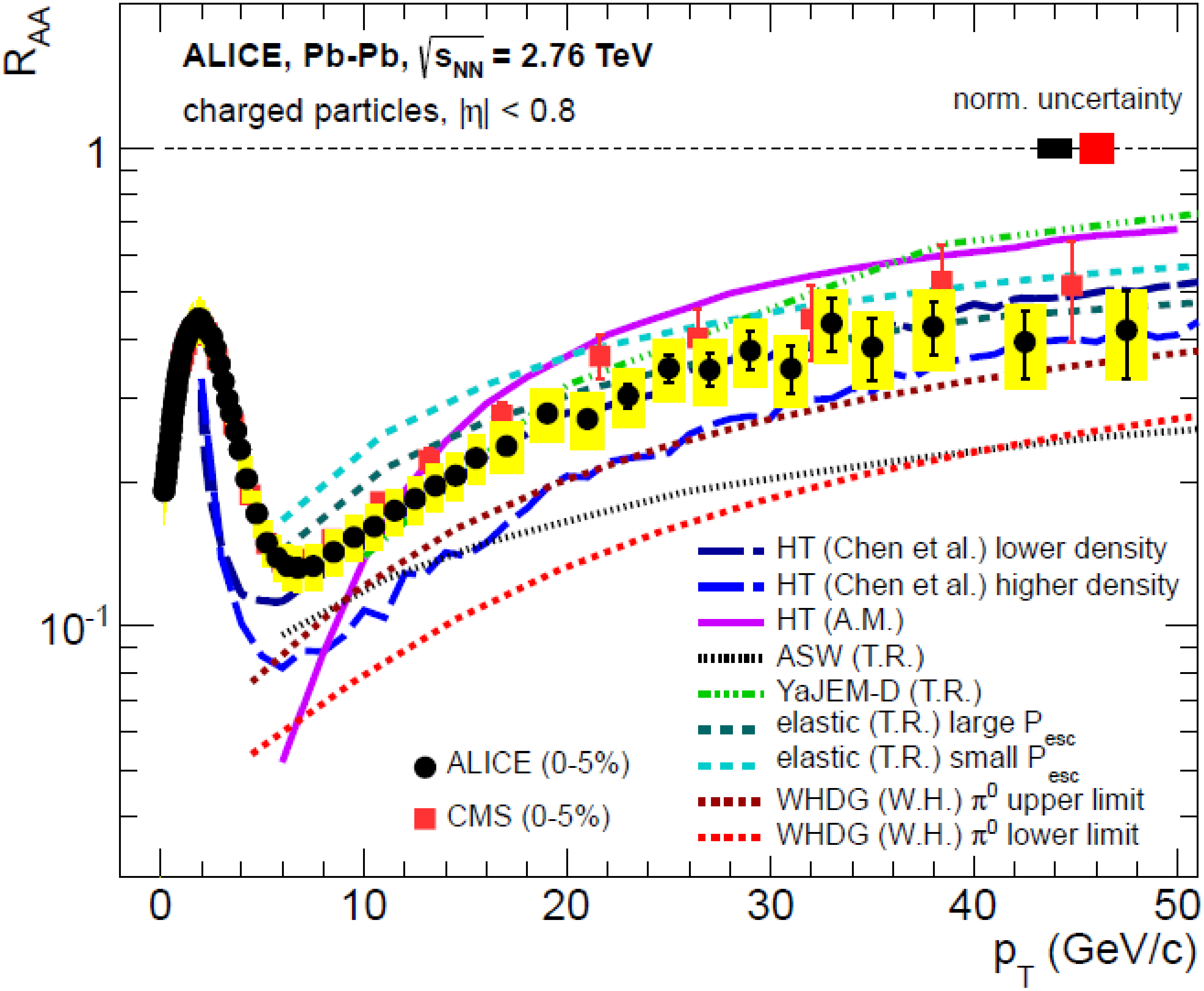


No energy loss for γ‘s

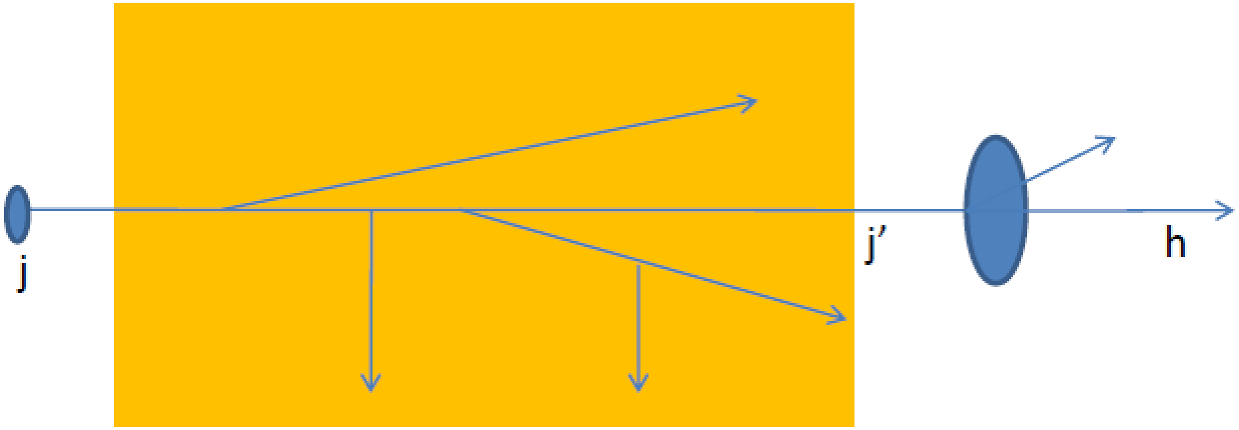
energy loss for q and g

Jet quenching at the LHC

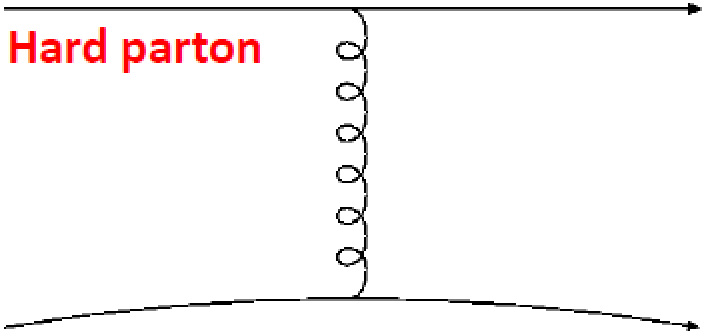
ALICE, arXiv:1208.2711
PLB 720, 52



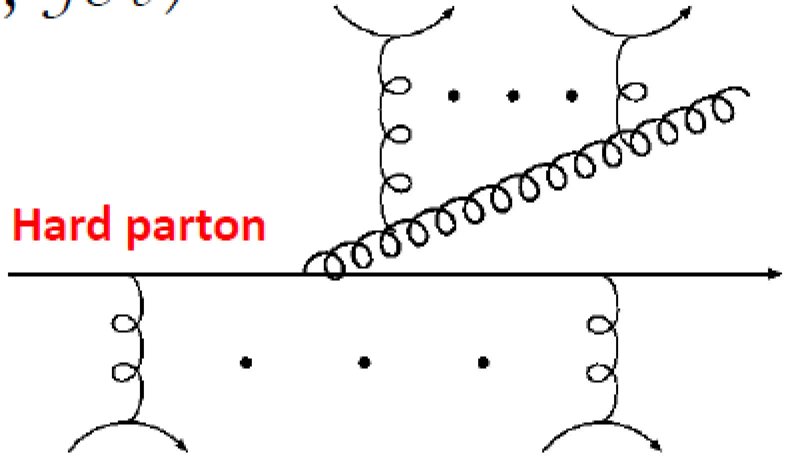
Energy loss of partons in QGP



$$P_{j \to j'}(medium,\ jet)$$

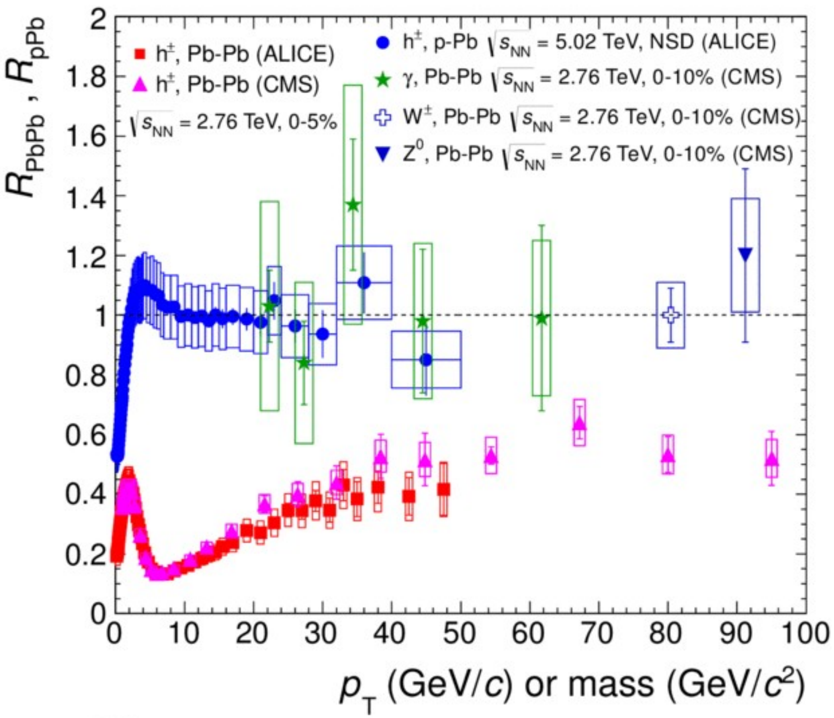


Elastic (collisional)

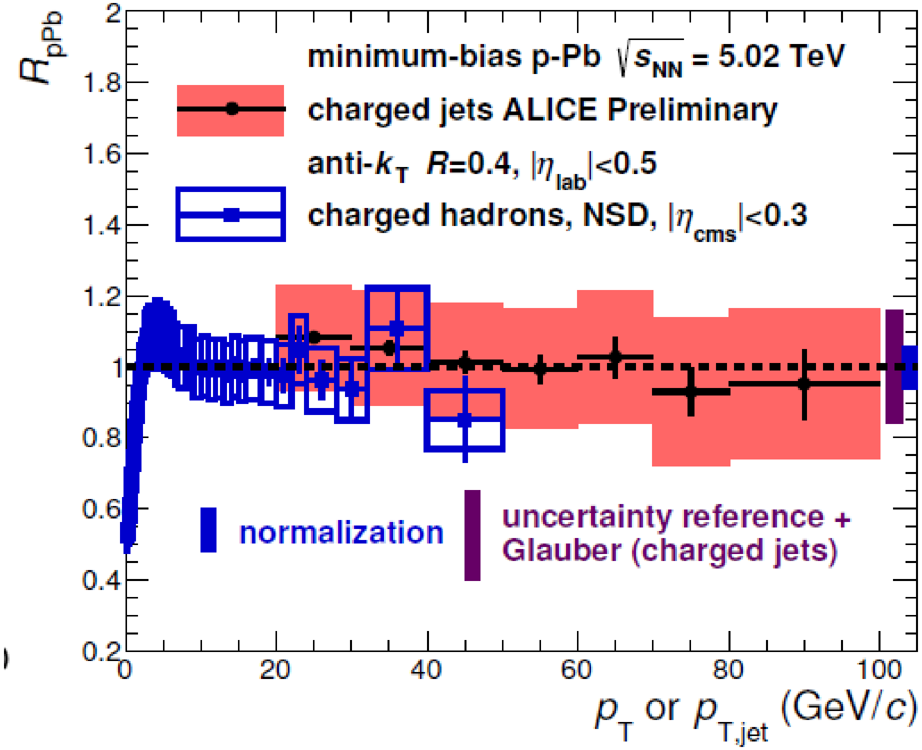


Inelastic (radiative)

Control experiment: p + Pb



ALI-PUB-75263

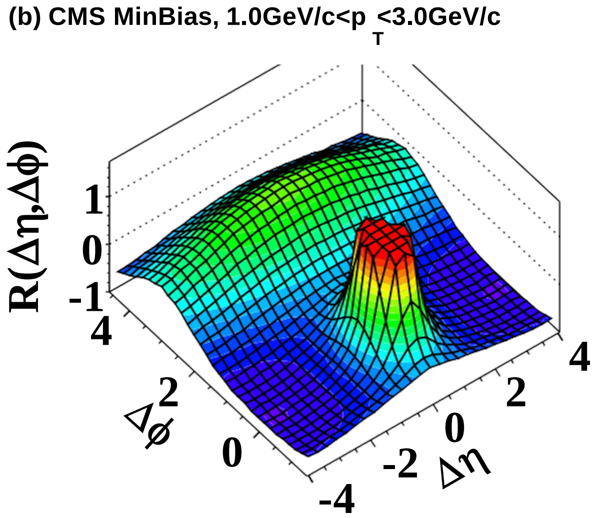


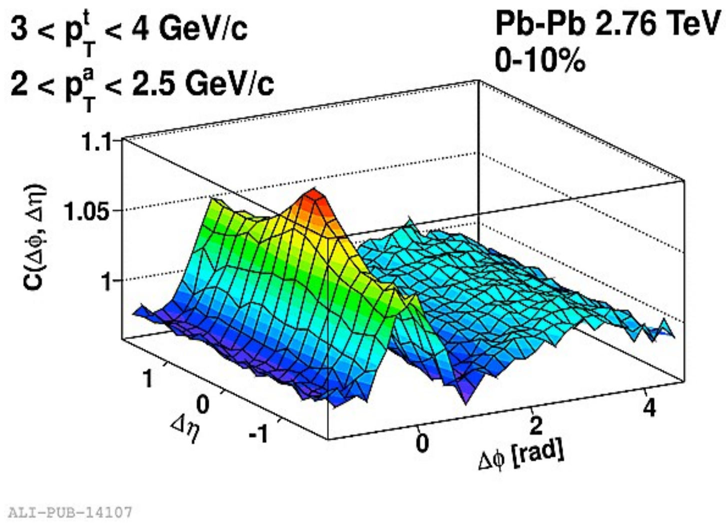
ALI-PREL-80555

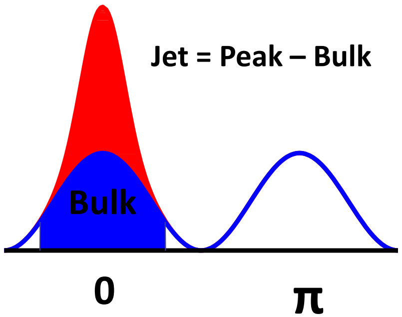
2 – particle correlation functions

pp

AA

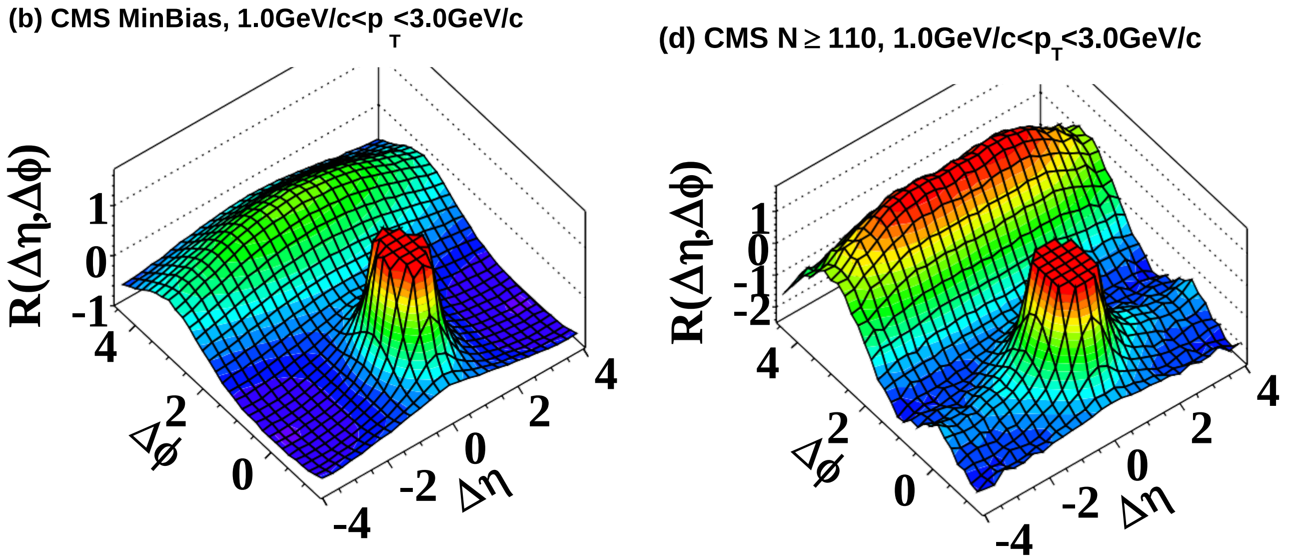




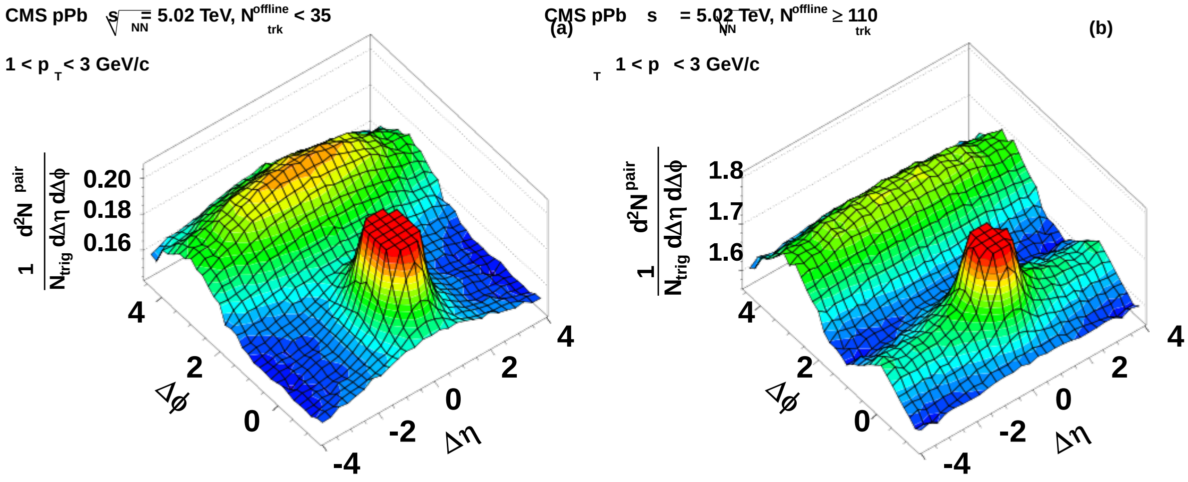


LHC discovery

JHEP 1009:091,2010
arXiv:1009.4122



PLB 718 (2013)
arXiv:1210.5482

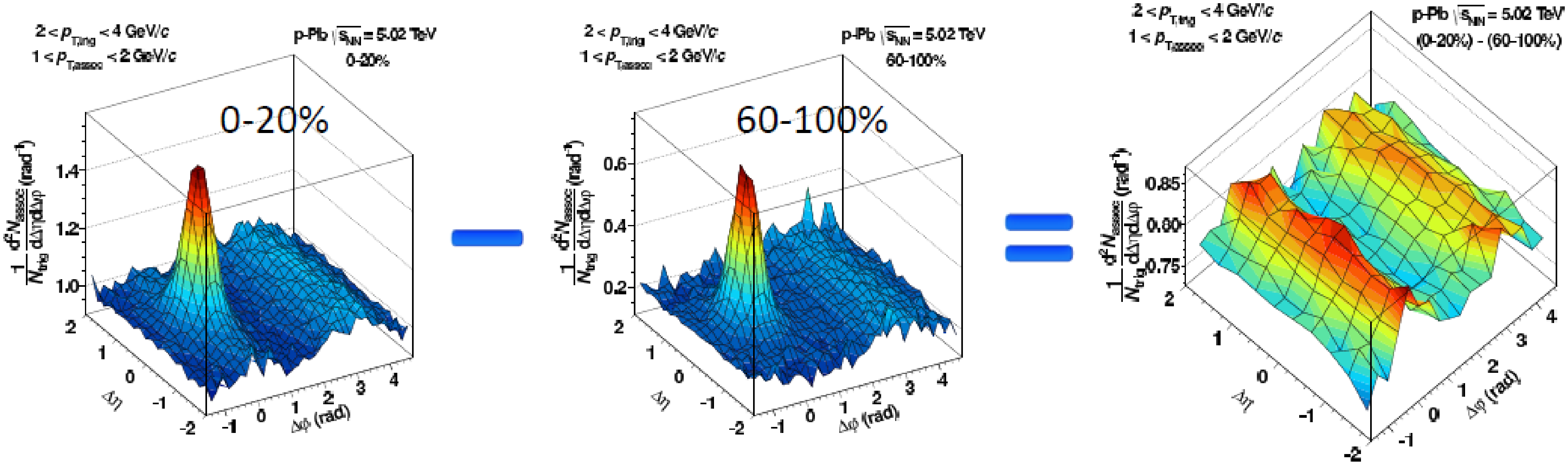


Nearside ridge structure in high multiplicity pp and pPb events !

Double ridge structure in pPb

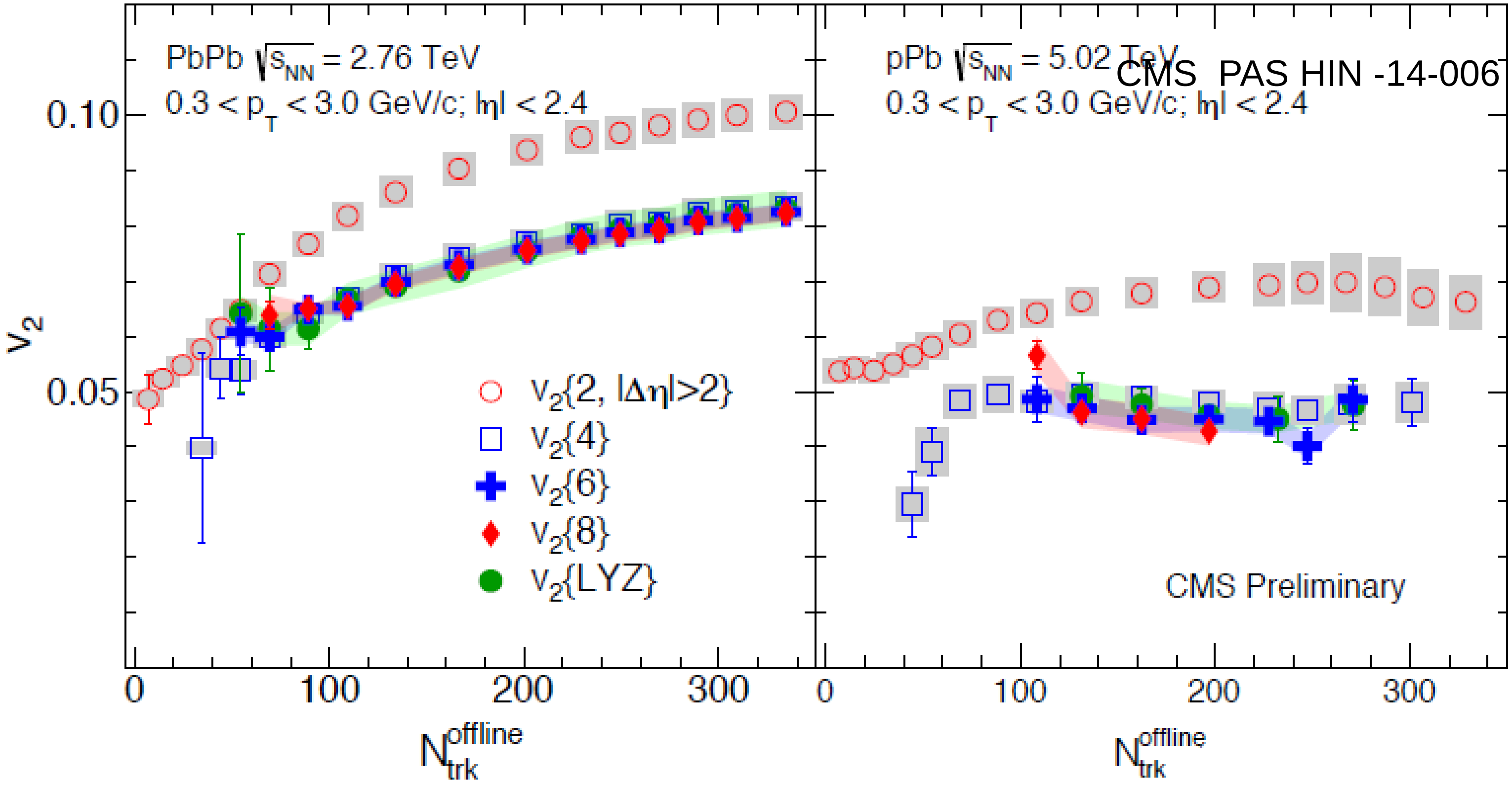
Subtraction of 2 – particle correlations
measured in high – multiplicity and low – multiplicity events

PLB 719 (2013)
arXiv:1212.2001



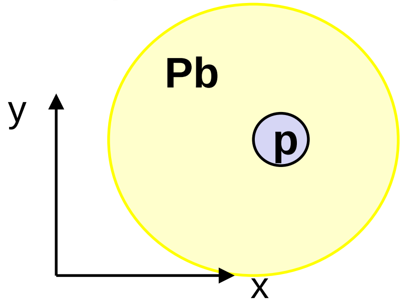
Multiparticle correlations in pPb

Higher order cumulants remove all non – flow effects.



CMS PAS HIN -14-006

Collective behavior in pPb observed, also at RHIC (STAR & PHENIX).
Where does it come from?



Back to phase transitions …

Chiral symmetry of QCD

Decomposition of states (spinors)

$$\psi = \psi_R + \psi_L = \tfrac{1}{2}\left(1+\gamma^5\right)\psi + \tfrac{1}{2}\left(1-\gamma^5\right)\psi$$

Decomposition of currents:

$$\begin{aligned} j = \overline{\psi}\gamma^\mu\psi &= \left(\overline{\psi}_R + \overline{\psi}_L\right)\gamma^\mu\left(\psi_R + \psi_L\right) \\ &= \left(\overline{\psi}_R\gamma^\mu\psi_R + \overline{\psi}_R\gamma^\mu\psi_L + \overline{\psi}_L\gamma^\mu\psi_R + \overline{\psi}_L\gamma^\mu\psi_L\right) \\ &= \left(\overline{\psi}_R\gamma^\mu\psi_R + \overline{\psi}_L\gamma^\mu\psi_L\right) \end{aligned}$$

u,d,s – quarks are massless on QCD – scale (1GeV).

Consequences for QCD with massless quarks:

Dirac equation:

$$\left(i\gamma^\mu\partial_\mu - m \right)\psi = 0 \rightarrow i\gamma^\mu\partial_\mu\psi = 0$$

Interaction with vector field conserves chirality (→ QED):

$$i\gamma^\mu D_\mu\psi_L = 0$$

$$i\gamma^\mu D_\mu\psi_R = 0$$

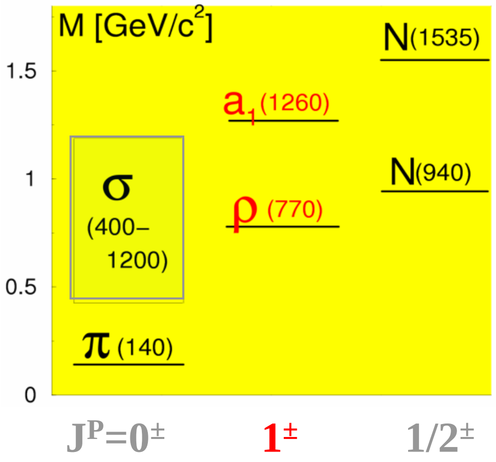
L and R handed states do not interact.

New Symmetry group:

$$SU(3)_L \times SU(3)_R$$

Current quark mass breaks this symmetry explicitly.

Spontaneous chiral symmetry breaking



Exact chiral symmetry:

all hadrons should exist in 2 degenerate parity states!

Parity operator P = γ^0:

$$P_R = \tfrac{1}{2}\left(1+\gamma^5\right)$$
$$P_L = \tfrac{1}{2}\left(1-\gamma^5\right)$$

$$P\,|\,q_R> = |\,q_L>$$
$$P\,|\,q_L> = |\,q_R>$$

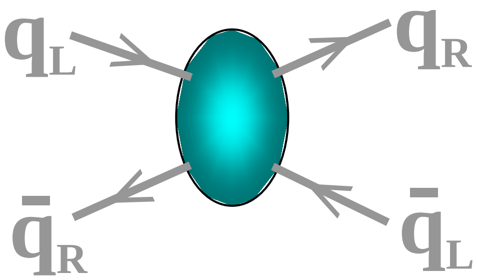
Construct: $$|\psi_\pm> = \frac{1}{\sqrt{2}}\left(|\,q_R> \pm |\,q_L>\right)$$

$$P\,|\,\psi_+> = +|\,\psi_+>$$
$$P\,|\,\psi_-> = -|\,\psi_->$$

These 2 states should have the same energy / mass.
This feature is not observed in nature,
Mass difference between chiral partners much larger than current quark mass difference

⇒chiral symmetry is spontaneously broken.

$$\langle\bar{q}q\rangle = \langle\bar{q}_L q_R + \bar{q}_R q_L\rangle \neq 0$$

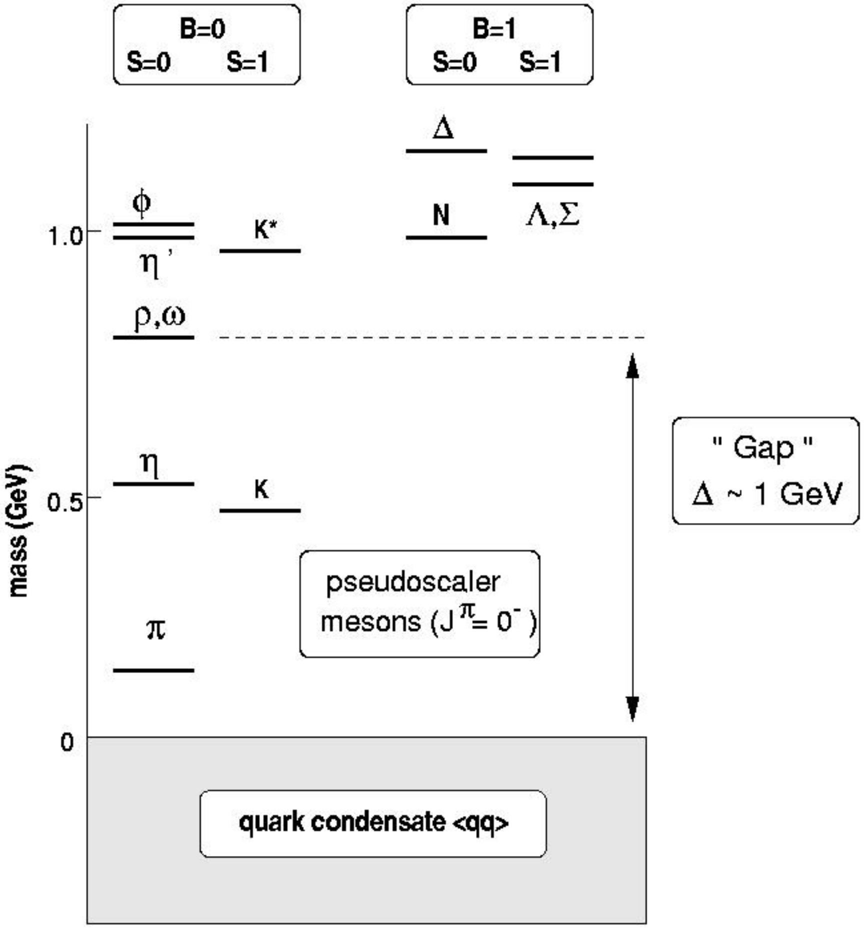


Analogy: magnetism ↔ QCD

Heisenberg magnet (rotationally invariant): $H_{\mathrm{int}} = g\sum_{i\neq j}\vec{s}_i\cdot\vec{s}_j$	**QCD in chiral limit (m_q=0)**
Excitation modes: spin waves = magnons **Excitation spectrum is gapless.** (infinetely long wavelength corresponds to rotation of whole matter block, rotation without external field does not cost energy)	**Hadrons in QCD vacuum** **Massless Goldstone bosons**
Ground state characterized by macroscopic magnetisation M $\vec{M} = \langle\vec{s}_i\rangle$	**Quark condensate <q$\bar{q}$>** $\langle\bar{q}q\rangle \approx -(240\,\mathrm{MeV})^3 \times N_f$
M is modified by external magnetic field B: $H_{\mathrm{int}} = g\sum_{i\neq j}\vec{s}_i\cdot\vec{s}_j + \vec{B}\cdot\sum_i\vec{s}_i$ **B breaks rotational invariance explicitely.**	**Current masses break chiral symmetry of QCD - Lagrangian explicitely**
Due to presence of B is excitation spectrum no longer gapless.	**Goldstone bosons acquire mass (→Pseudoscalar mesons, Gell-Mann Oaks Renner relation)**
M=M(T), M vanishes above critical temperature. **Rotational symmetry is restored.**	**A phase transition to chirally symmetric state exists.**
M is the order parameter of phase transition.	**<q$\bar{q}$> is order parameter.**

Consequences of Spontaneous Chiral Symmetry Breaking

1) All hadrons have well defined parity,
   chiral J^P doublets not observed.



2) Chiral symmetry spontaneously broken,
   vacuum is filled with $q\bar{q}$ – condensate.

3) Goldstone theorem:
   Any spontaneously broken continous
   symmetry generates a massless boson
   (→ Goldstone bosons).

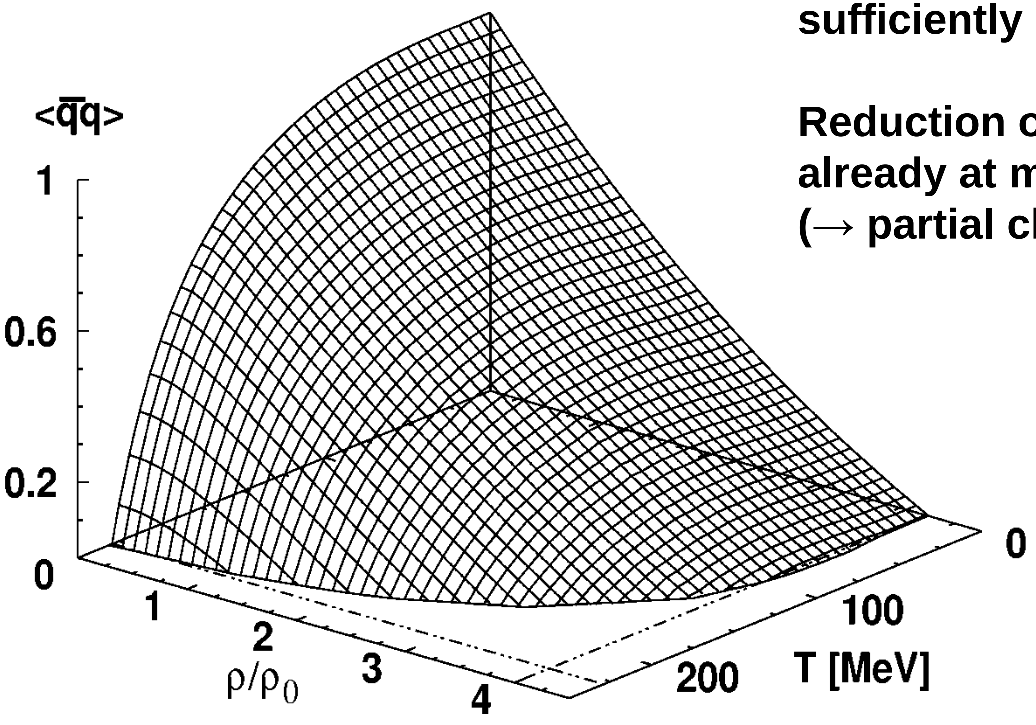
4) Characteristic mass scale of hadrons

   1 GeV mass gap to quark condensate

   pseudoscalar mesons are
   Pseudo - Goldstone bosons:
   π, η, and K

Chiral symmetry restoration of QCD

Chiral Condensate



W.Weise, Prog. Theor. Phys. Suppl. 149 (2003) 1
initially: S.Klimt et al.., PLB 249, 386 (1990)

Chiral symmetry should be restored at sufficiently high temperatures and baryon densities.

Reduction of vacuum value should be visible already at moderate densities
(→ partial chiral symmetry restoration)

Symmetry breaking pattern of Chiral Symmetry of QCD

Gell-Mann-Oaks-Renner Relation:

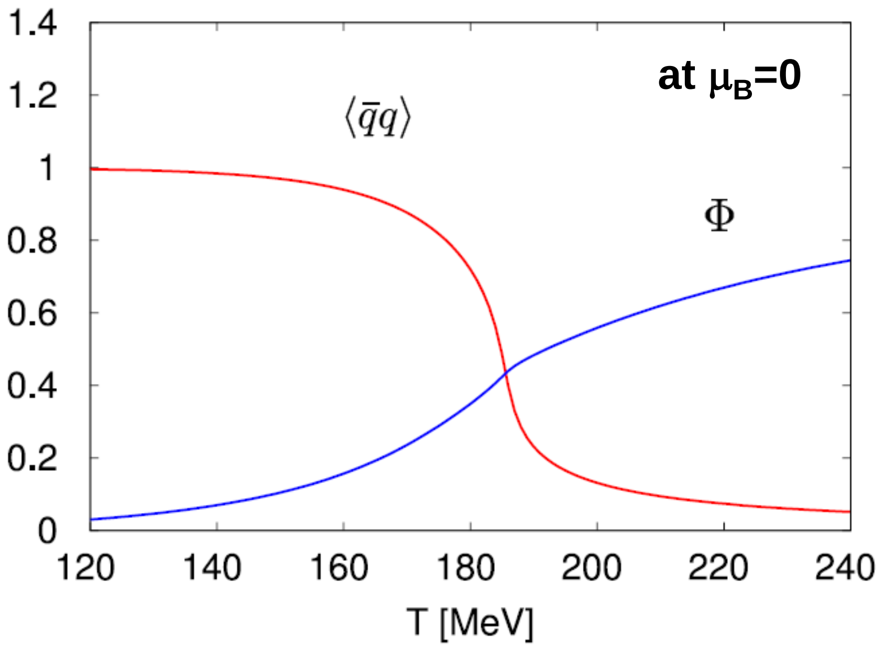
$$m_\pi^2 f_\pi^2 = -\frac{1}{2}\left(m_u + m_d\right)\left\langle \bar{u}u + \bar{d}d \right\rangle + O\left(m_u^2\right)$$

$$m_K^2 f_K^2 = -\frac{1}{2}\left(m_u + m_s\right)\left\langle \bar{u}u + \bar{s}s \right\rangle + O\left(m_s^2\right)$$

spontaneous symmetry breaking

explicit symmetry breaking

Order parameters in QCD



Order parameters:

chiral symmetry: Quark condensate $\langle\bar{q}q\rangle$

deconfinement: Polyakov loop $\Phi \sim e^{-\beta F_q}$

with β=1/T, F_q = free energy of free quark

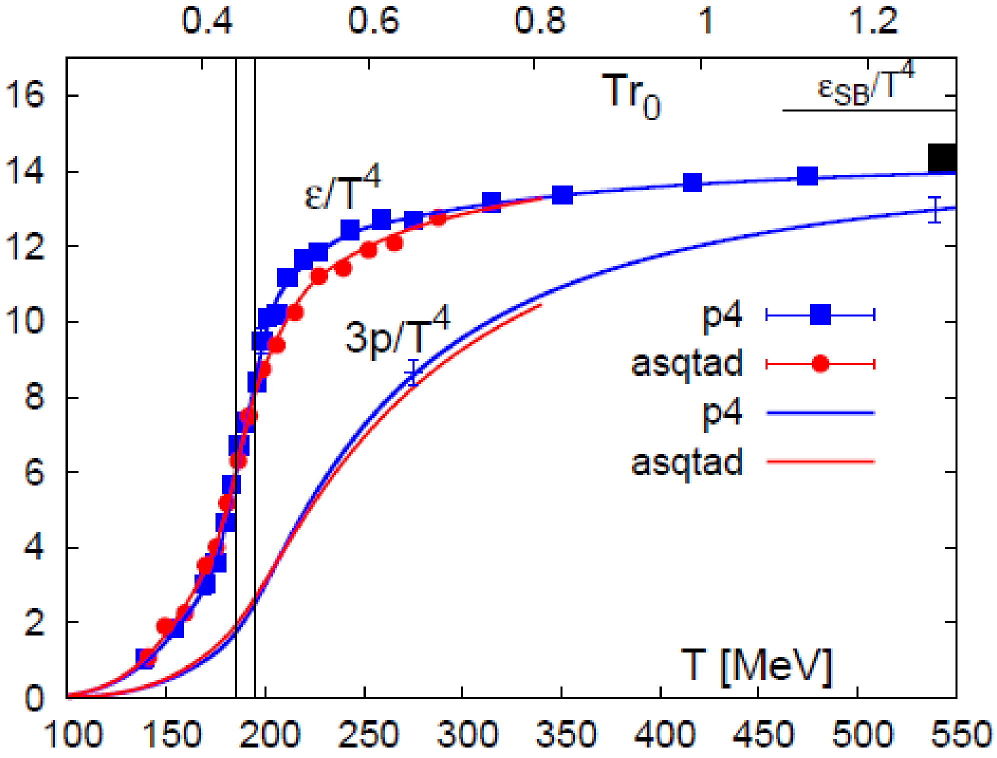
Chiral and Polyakov loop order parameters show transition at the same temperature.

Lattice – QCD

Lattice QCD equation – of – state

Owe Philipsen, arXiv:1207.5999 [hep-lat]

Calculations for μ_B=0:



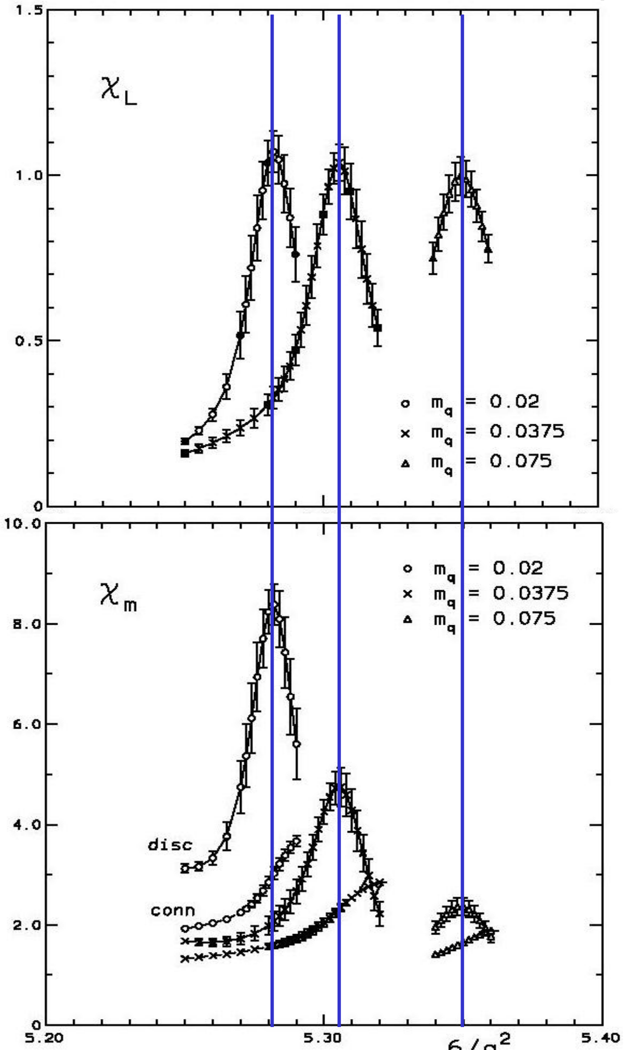
jump in energy density: T_C ~ 170 MeV, ε_C ~ 0.7 GeV/fm^3

The QCD phase transition

Polyakov loop response function

chiral susceptibility

different quark mass m_q



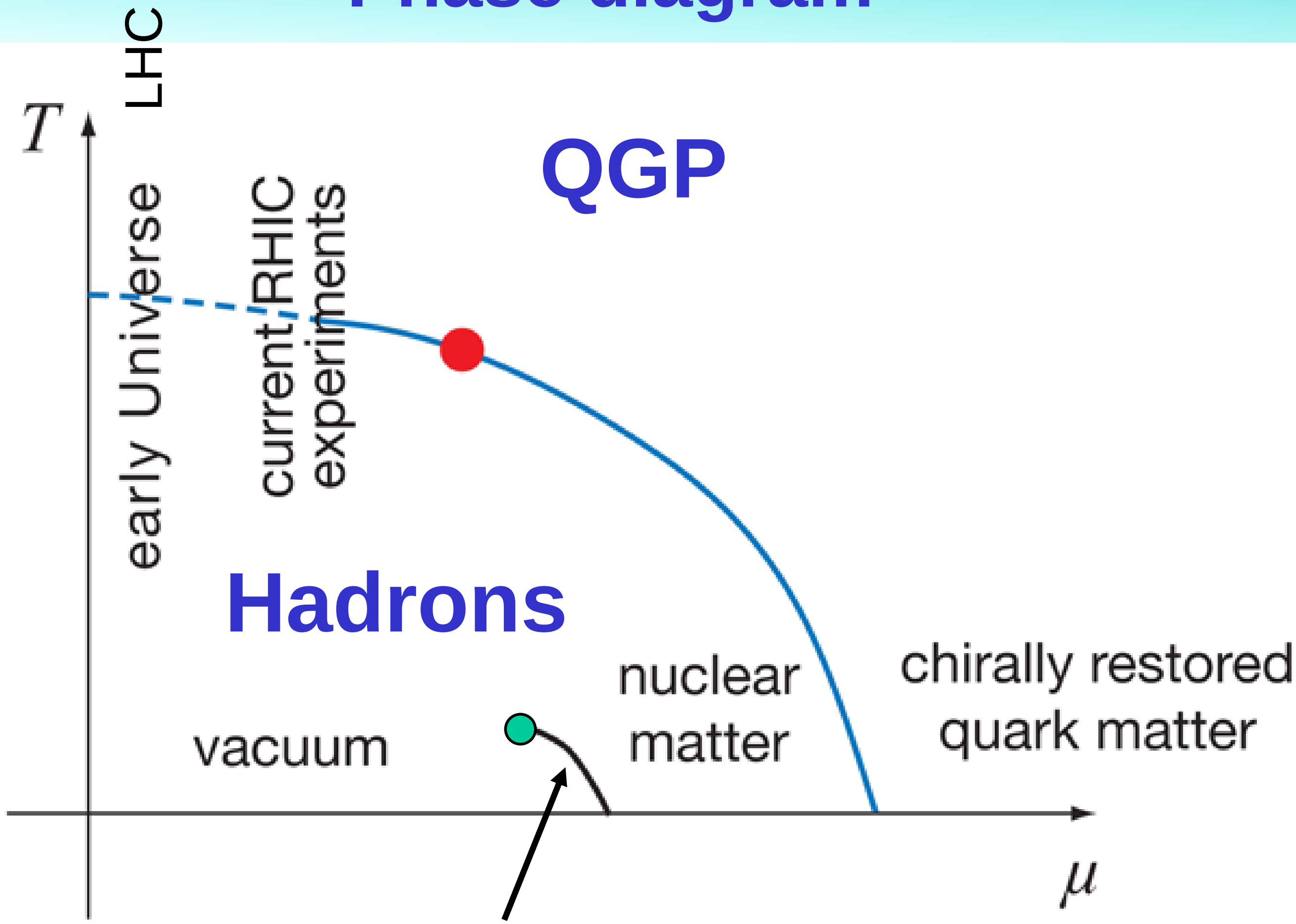
temperature

deconfinement

chiral symmetry restoration

Susceptibilities not divergent
-> rapid cross over

Phase diagram



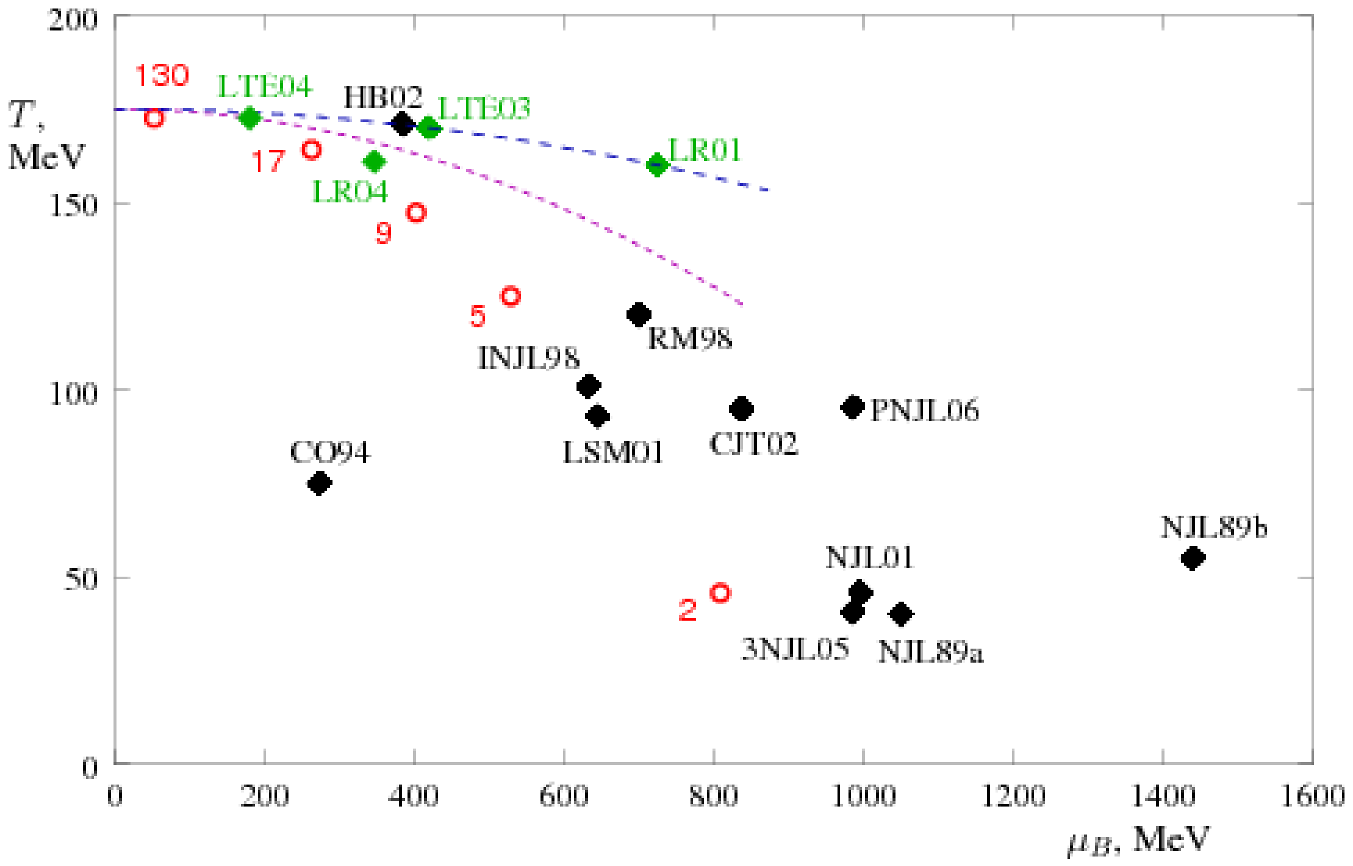
Liquid – gas phase transition

Lattice QCD applicable,
deconfinement & χ PT coincide

No firm predictions available
From L-QCD for μ>0,
→QCD – inspired models

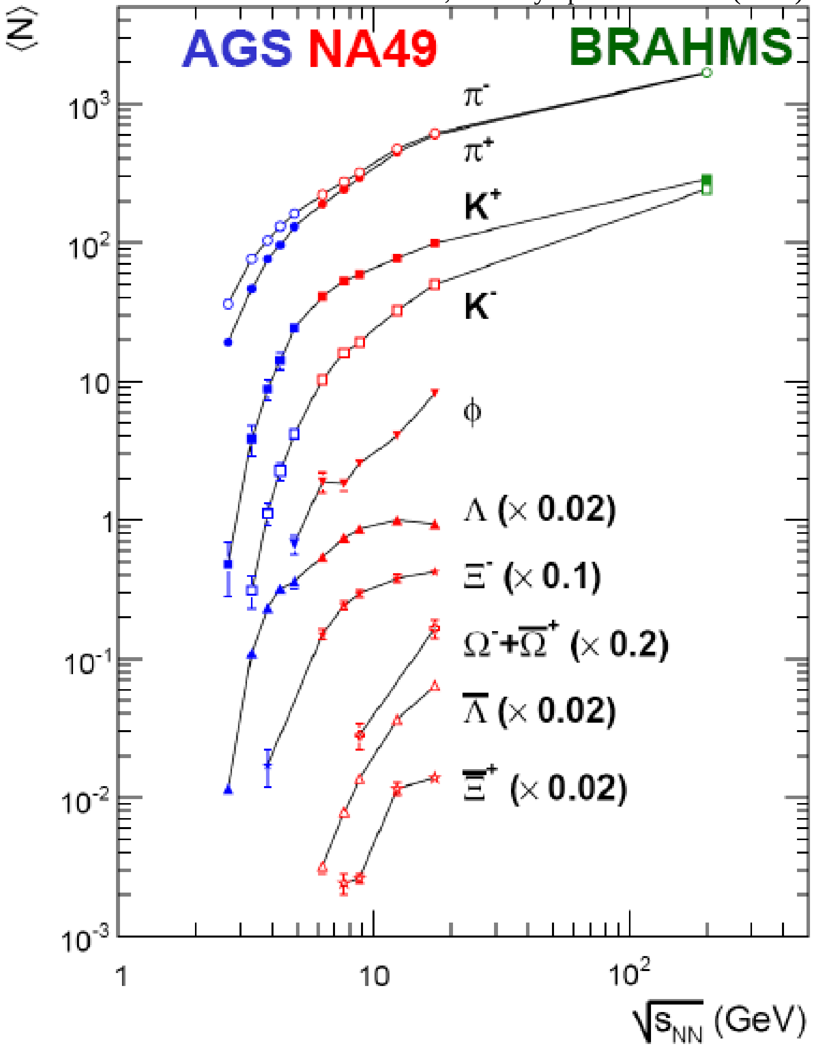
Location of the critical point

M.A. Stephanov, hep-lat/0701002



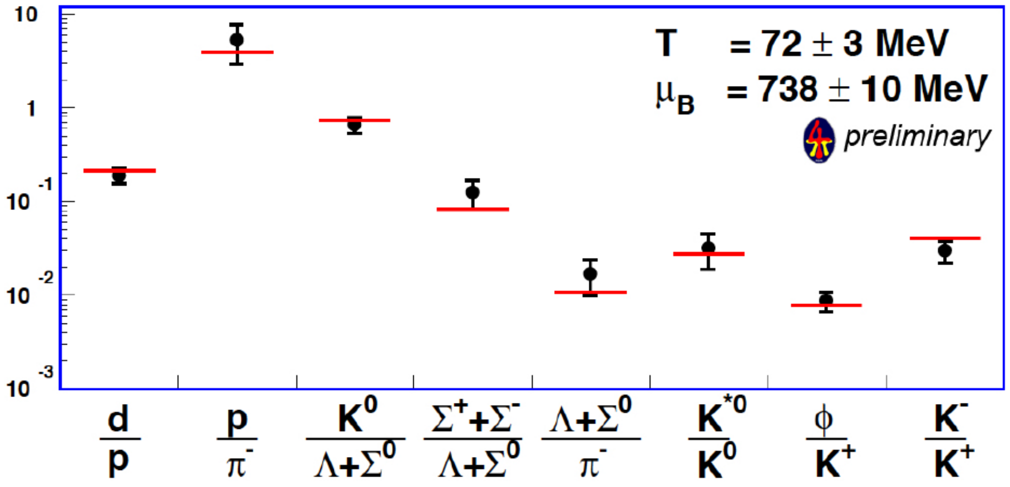
Excitation function of particle production

Central Au+Au collisions, 4π yields

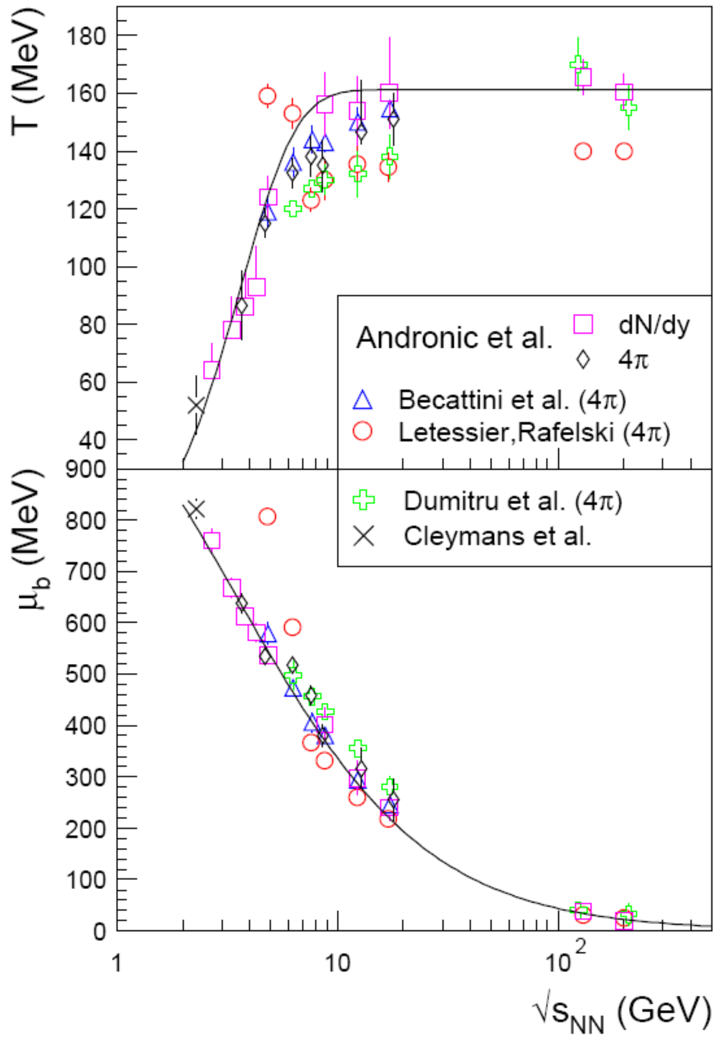


C.Blume, CBM symposium HZDR (2011)

Low energies (SIS18): **light systems only**
e.g. Al + Al at 1.91 AGeV



Excitation function of particle production



Limiting temperature

T = 161 ± 4 MeV

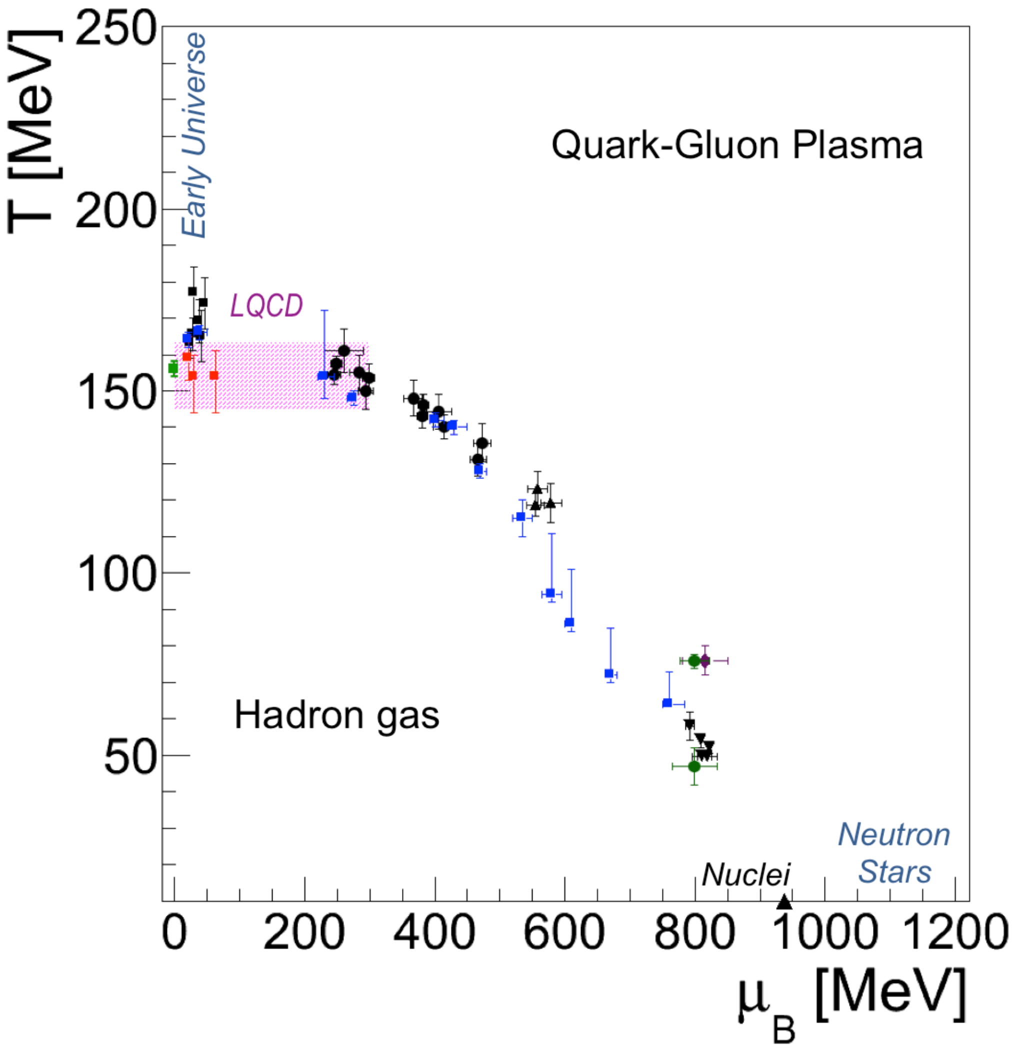
Note:

Limiting temperature first predicted by

Hagedorn’s bootstrap model (1965)

Chemical Freeze-out data

T. Galatyuk (HADES, CBM)



Errors include systematic errors (when given).

Data sources:

SHM : J. Cleymans: PRC 73 (2006) 034905,
A. Andronic PLB 673 (2009) 142
ALICE : J. Stachel, arXiv:1311.4662
STAR : PRC 79 (2009) 034909
HADES : NPA 931 (2014)
FOPI : PRC 76 (2007) 052203
Lattice : $T_c(\mu_B) = 154(9)\ [1-0.0006(7)\mu_B^2]$ MeV

At lower energies canonical ensemble has to be used.

Equilibrium yields as signature for phase transition?

Equilibration times in hadronic matter

Naïve estimate:

3 collisions needed for equilibration (result from kinetic theory)

hadronic cross section: σ**=40 mb = 4 fm**^{2}

strangeness production cross section: σ**=400** μ**b = 4 10**$^{-2}$ **fm**^{2}

mean free path

$$\lambda = \frac{1}{n\sigma} = \frac{1}{0.17\, fm^{-3} \cdot 4\, fm^2} = 1.5\, fm$$

time between collisions

$$\tau = \lambda / c = 1.5\, fm / c$$

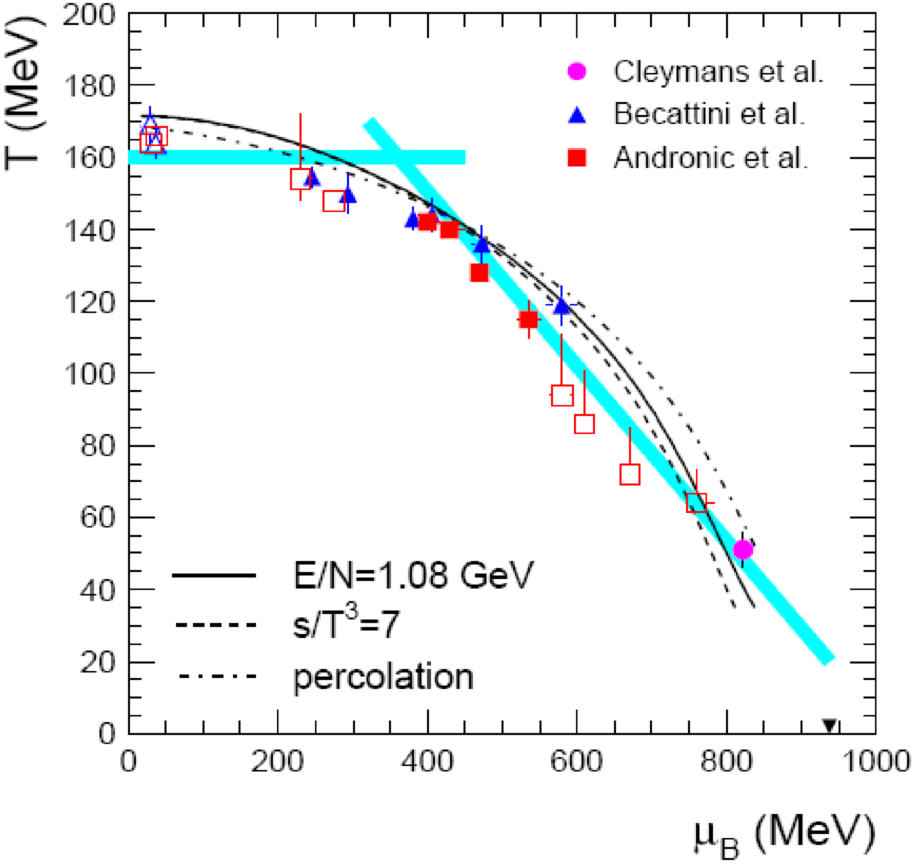
minimal equilibration time

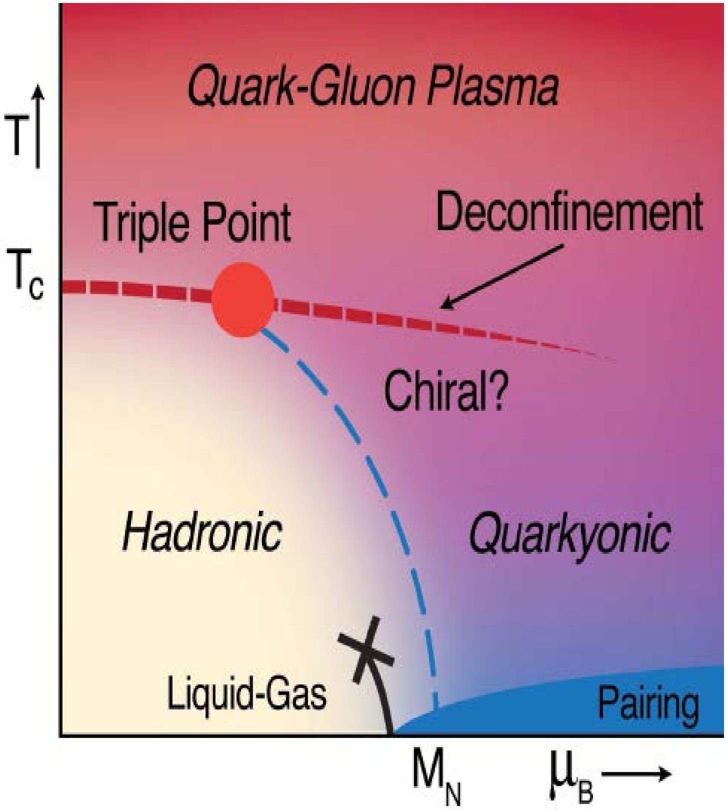
$$\tau_{eq}^{pion} = 4.5\, fm / c$$

$$\tau_{eq}^{strangeness} = 450\, fm / c$$

Chemical Freeze-out

A. Andronic et al., arXiv:0911.4806

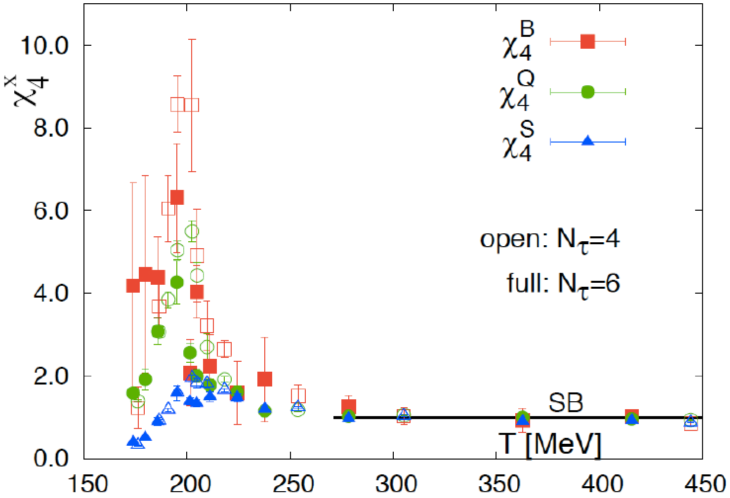


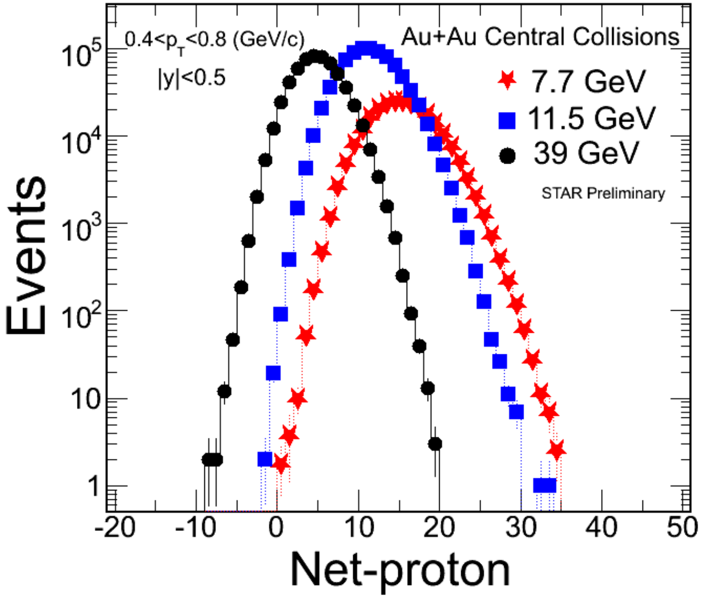


Speculation about the existence of a 1.order phase transition because of apparent thermal equilibrium.

Quarkyonic matter – confined objects with color - interaction

Higher Moments of Yield Distributions





1) Higher moments of conserved quantum numbers: ***Q, S, B***, in high-energy nuclear collisions

2) Sensitive to critical point (ξ correlation length):

$$\left\langle (\delta N)^2 \right\rangle \approx \xi^2, \quad \left\langle (\delta N)^3 \right\rangle \approx \xi^{4.5}, \quad \left\langle (\delta N)^4 \right\rangle \approx \xi^7$$

3) Direct comparison with calculations at any order:

$$S\sigma \approx \frac{\chi_B^3}{\chi_B^2}, \qquad \kappa\sigma^2 \approx \frac{\chi_B^4}{\chi_B^2}$$

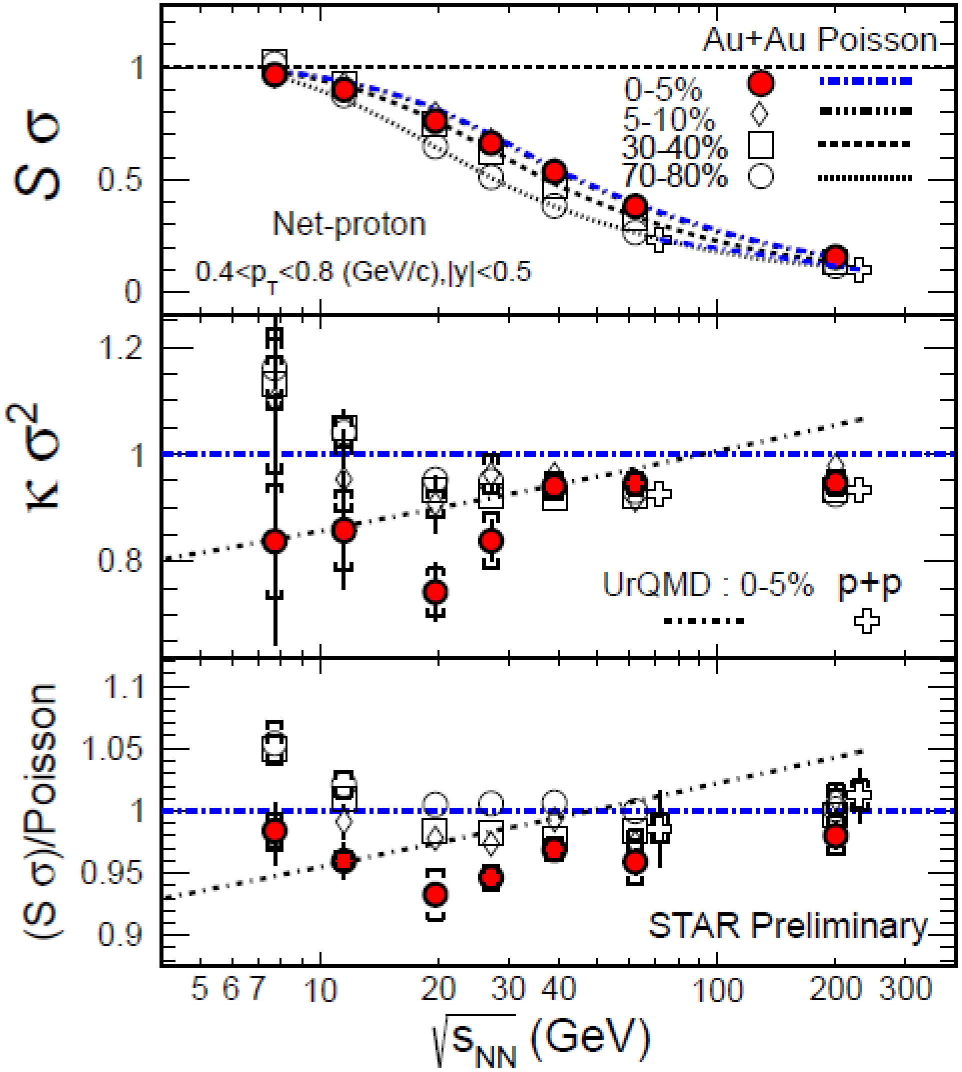
References:

- STAR: *PRL*105, 22303(10); *ibid*, 032302(14)
- M. Stephanov: *PRL*102, 032301(09) // R.V. Gavai and S. Gupta, *PLB696*, 459(11) // F. Karsch et al, *PLB695*, 136(11) // S.Ejiri et al, PLB633, 275(06)
- A. Bazavov et al., PRL109, 192302(12) // S. Borsanyi et al., PRL111, 062005(13) // V. Skokov et al., PRC88, 034901(13)

Beam energy scan (STAR)

Xiaofeng Luo et al. (STAR), Nucl.Phys.A904 – 905 (2013) 911

Net – baryon number



Higher order moments of $N_{p-\bar{p}}$

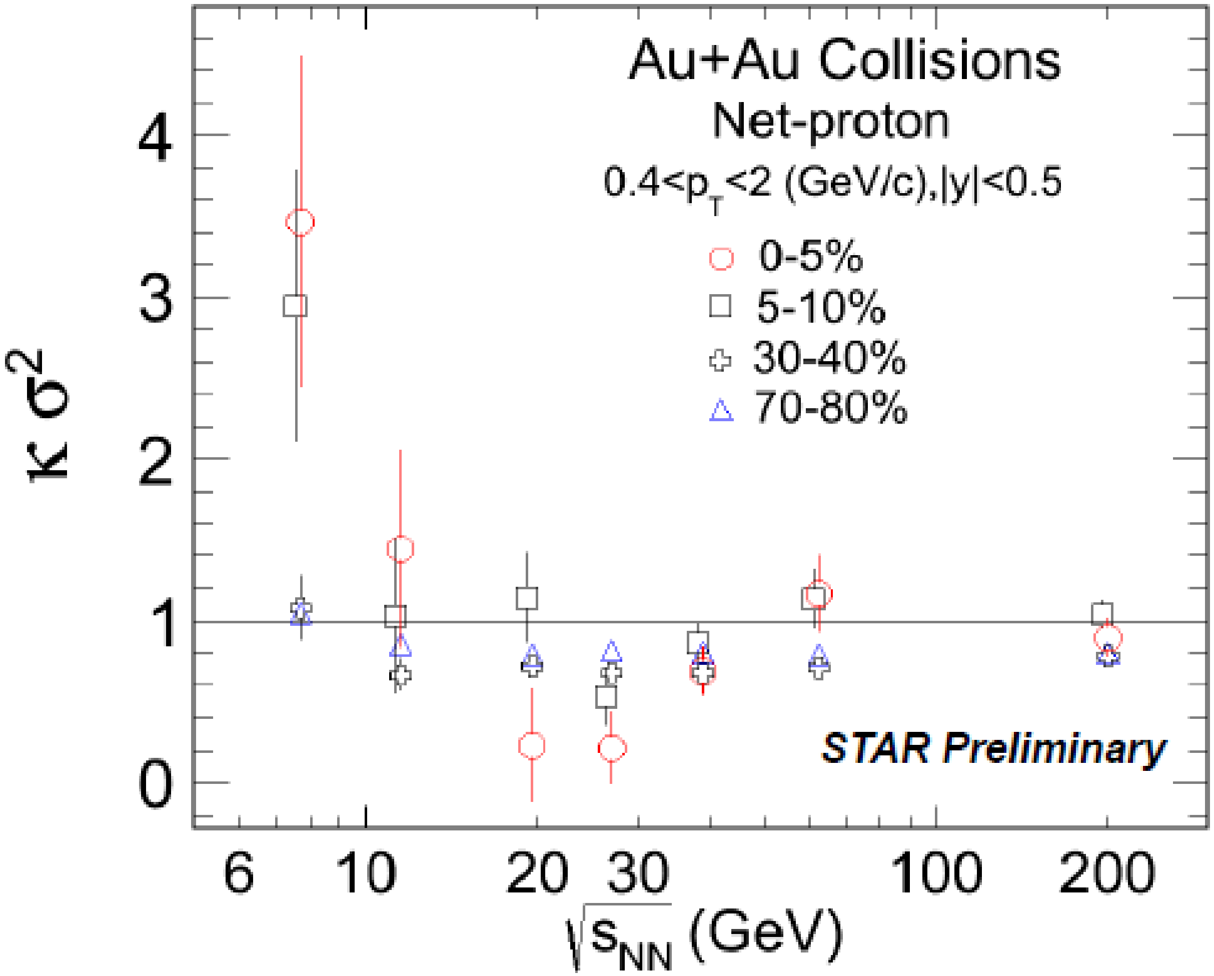
Skewness S

$$S = \frac{\left\langle \left(N_{p-\bar{p}} - \left\langle N_{p-\bar{p}} \right\rangle \right)^3 \right\rangle}{\left\langle \left(N_{p-\bar{p}} - \left\langle N_{p-\bar{p}} \right\rangle \right)^2 \right\rangle^{\frac{3}{2}}}$$

Kurtosis κ

$$\kappa = \frac{\left\langle \left(N_{p-\bar{p}} - \left\langle N_{p-\bar{p}} \right\rangle \right)^4 \right\rangle}{\left\langle \left(N_{p-\bar{p}} - \left\langle N_{p-\bar{p}} \right\rangle \right)^2 \right\rangle^{2}}$$

Excitation function of fluctuation

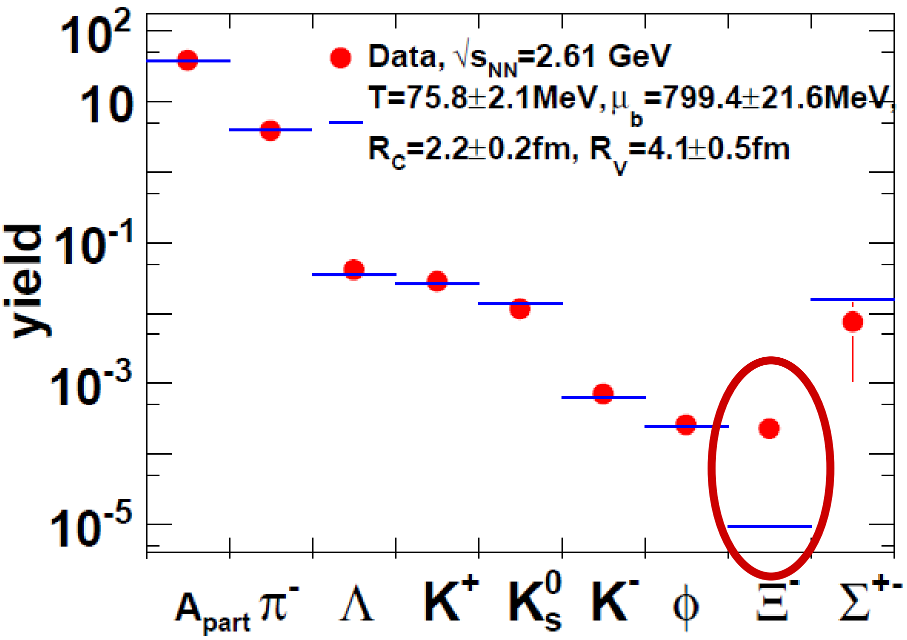


HADES: Sub-threshold Ξ^- production

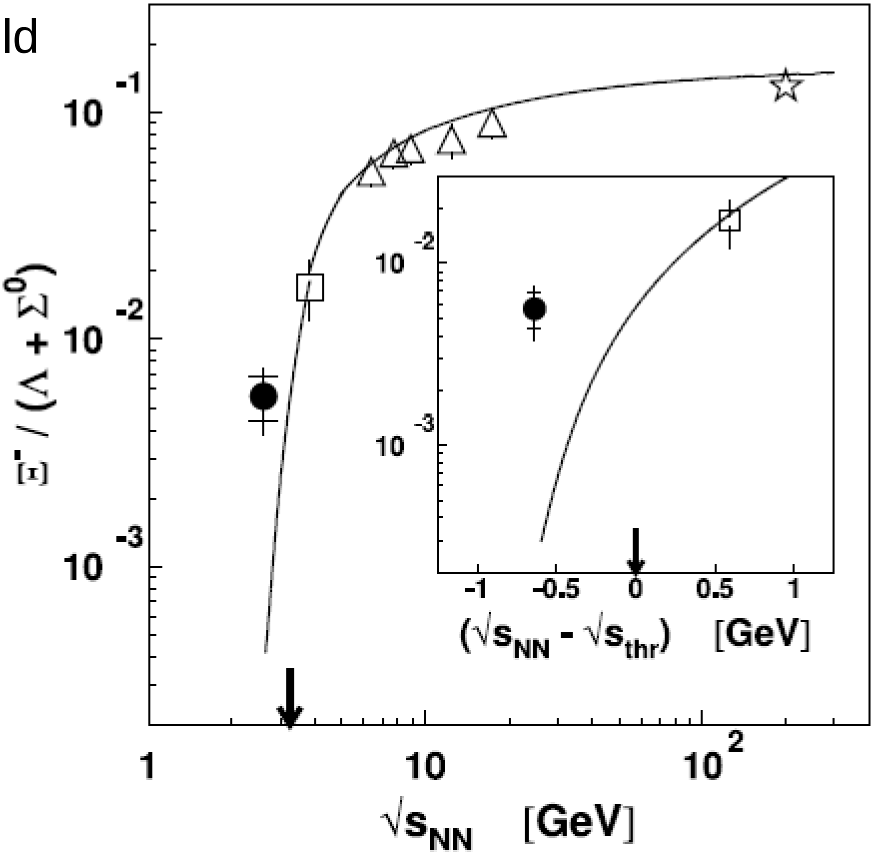
Ar+KCl reactions at 1.76A GeV

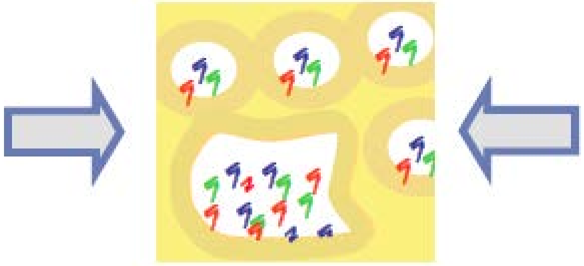
- Ξ^- yield by appr. factor 25 higher than thermal yield
- strangeness exchange reactions like

$\bar{K}Y \rightarrow \pi\ \Xi$ (Y=Λ,Σ) ?



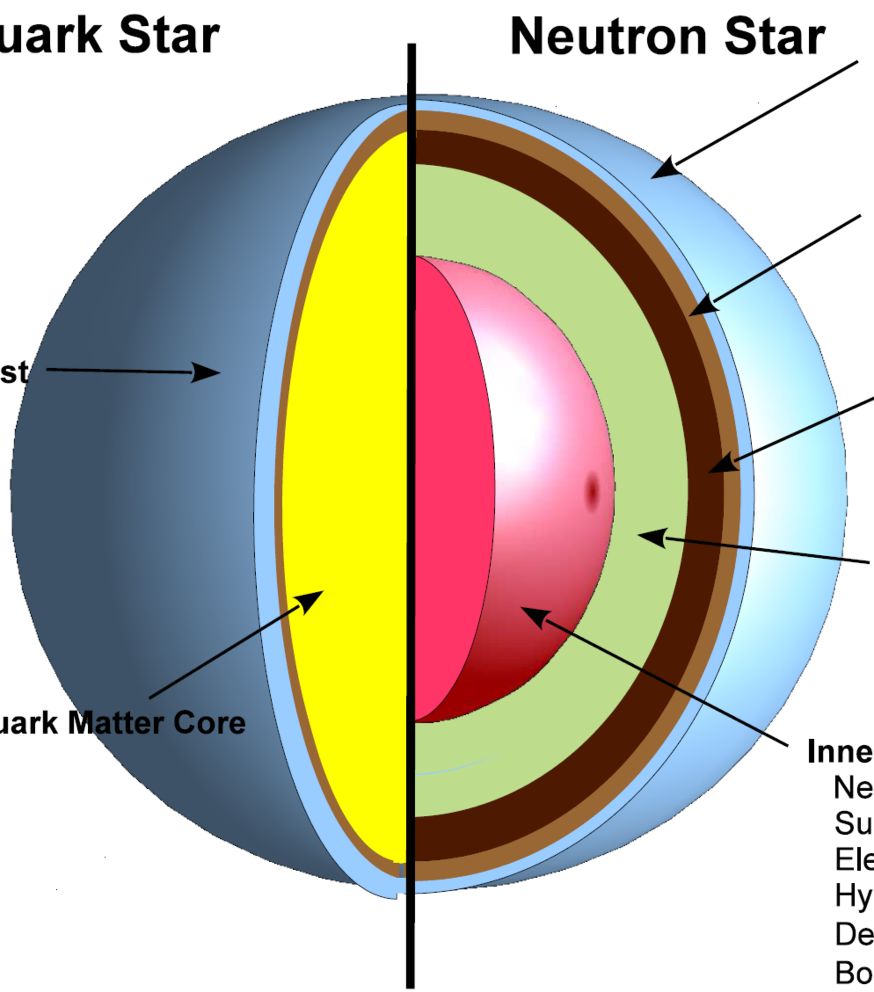
G. Agakishiev et al. (HADES), PRL103, 132301, (2009)





trapping of strange quarks in bubbles ?

The structure of neutron stars



Surface:
Hydrogen/Helium plasma
Iron nuclei

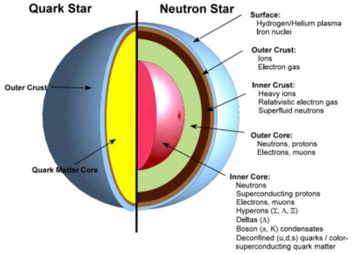
Outer Crust:
Ions
Electron gas

Inner Crust:
Heavy ions
Relativistic electron gas
Superfluid neutrons

Outer Core:
Neutrons, protons
Electrons, muons

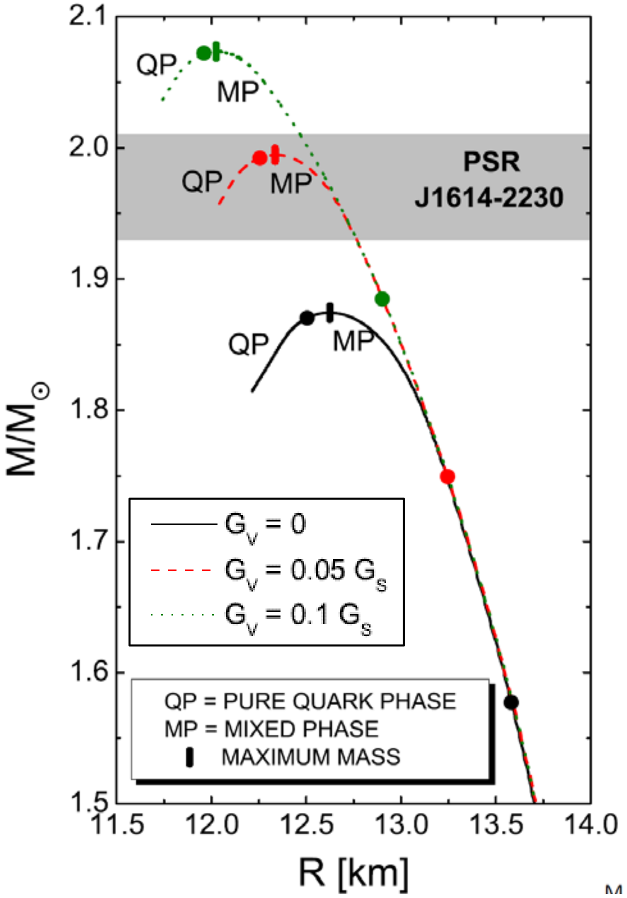
Inner Core:
Neutrons
Superconducting protons
Electrons, muons
Hyperons (Σ, Λ, Ξ)
Deltas (Δ)
Boson (π, K) condensates
Deconfined (u,d,s) quarks / color-superconducting quark matter

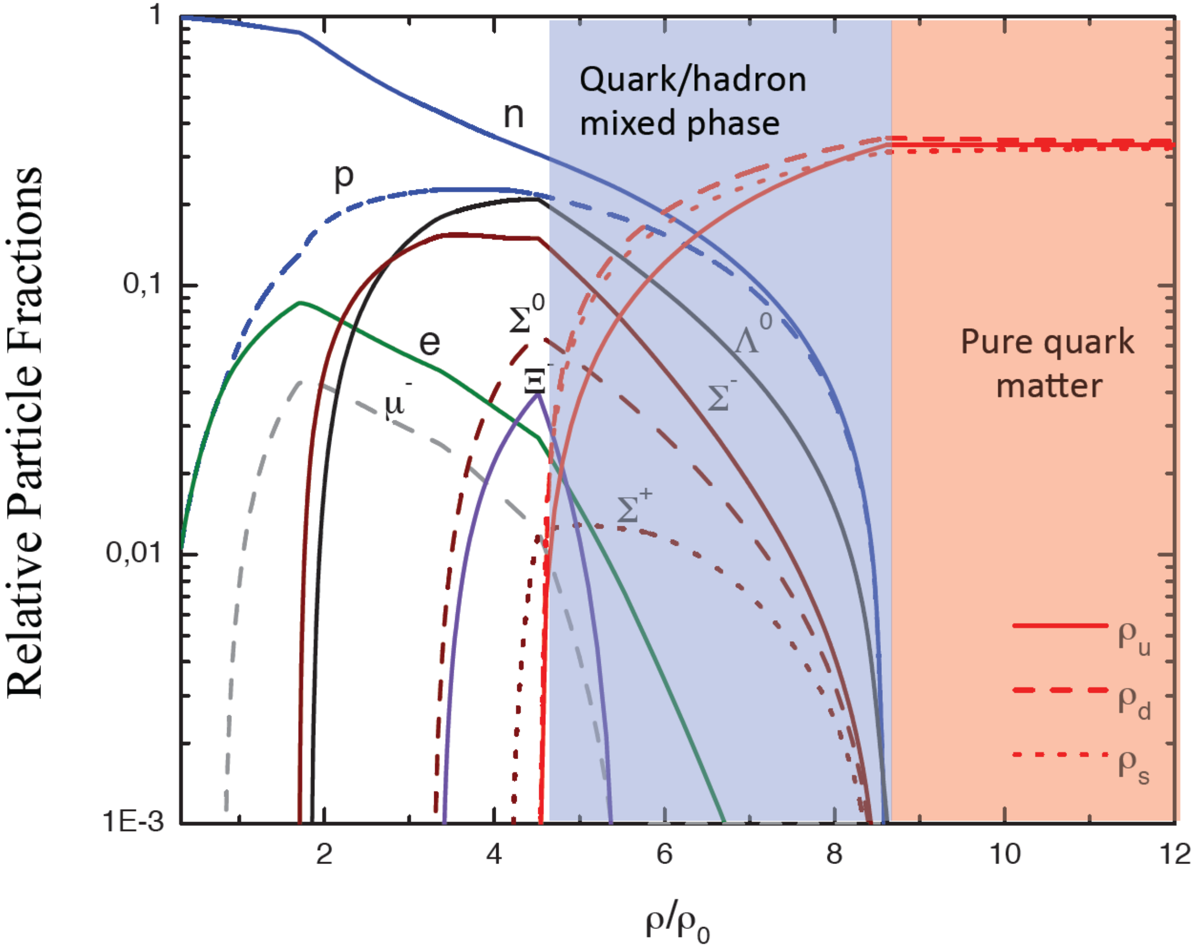
Equation – of – State of neutron stars



Equation-of-state: Non-local SU(3) NJL with vector coupling

M. Orsaria, H. Rodrigues, F. Weber, Phys.Rev. D87 (2013) 023001

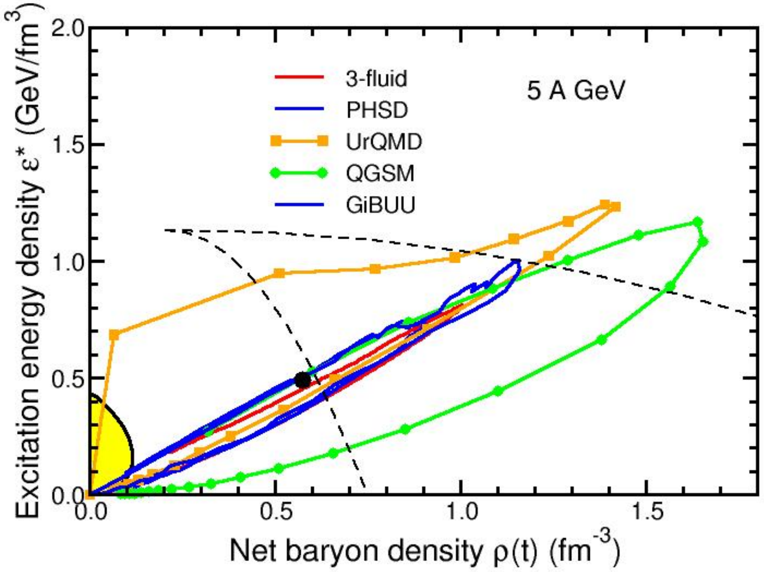




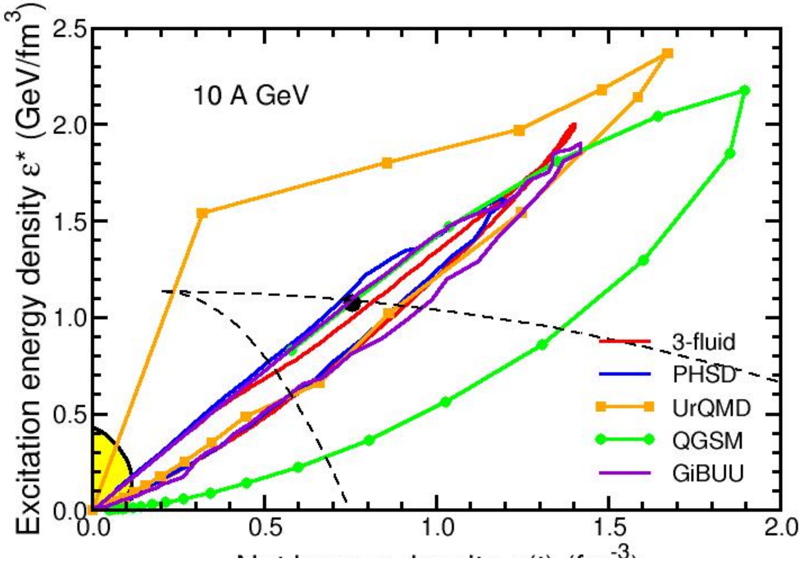
Baryon density in HI - collisions

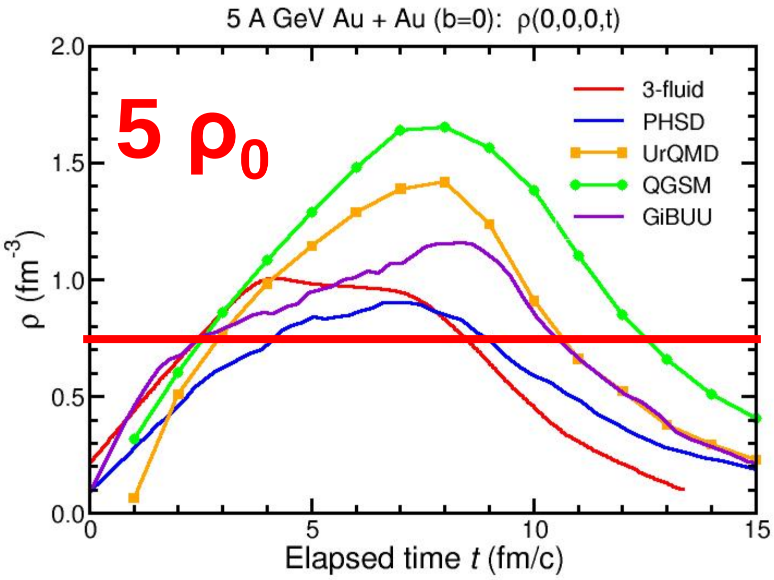
I.C. Arsene et al., Phys. Rev. C 75, 24902 (2007)

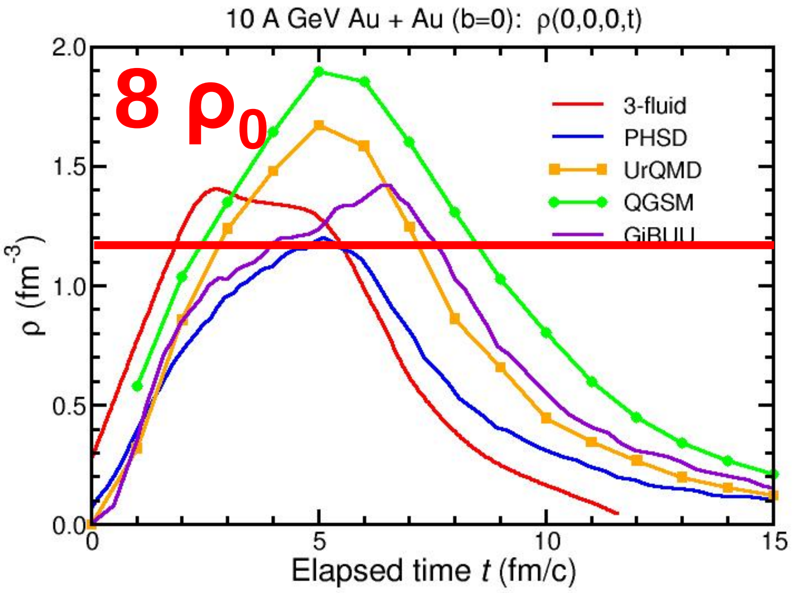
5 A GeV



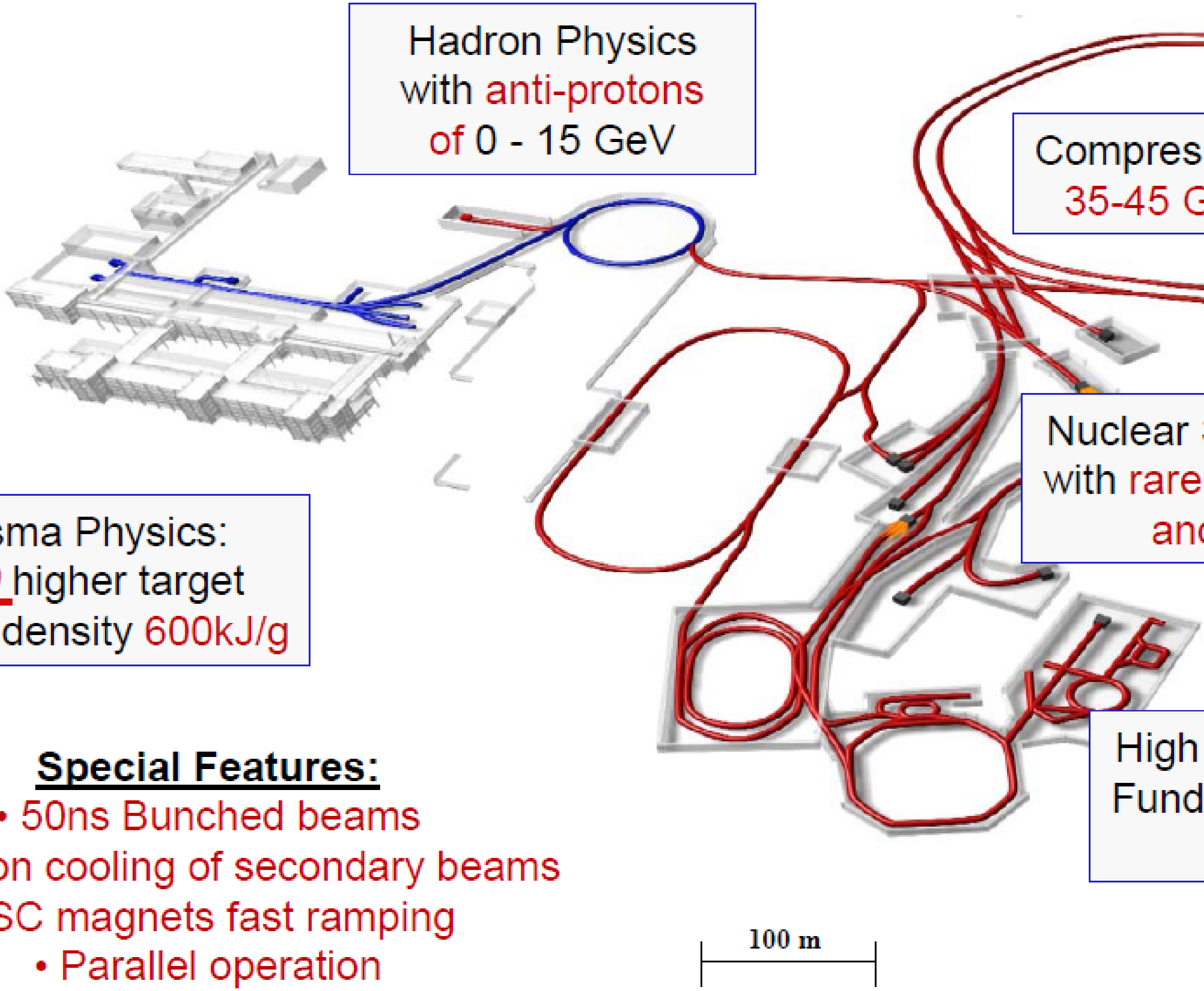
10 A GeV







FAIR project (since 2001)



Hadron Physics
with anti-protons
of 0 - 15 GeV

Compressed Baryonic Matter with
35-45 GeV/u HI beams, ***x1000***

Nuclear Structure & Astrophysics
with rare isotope beams, ***x10 000***
and excellent cooling

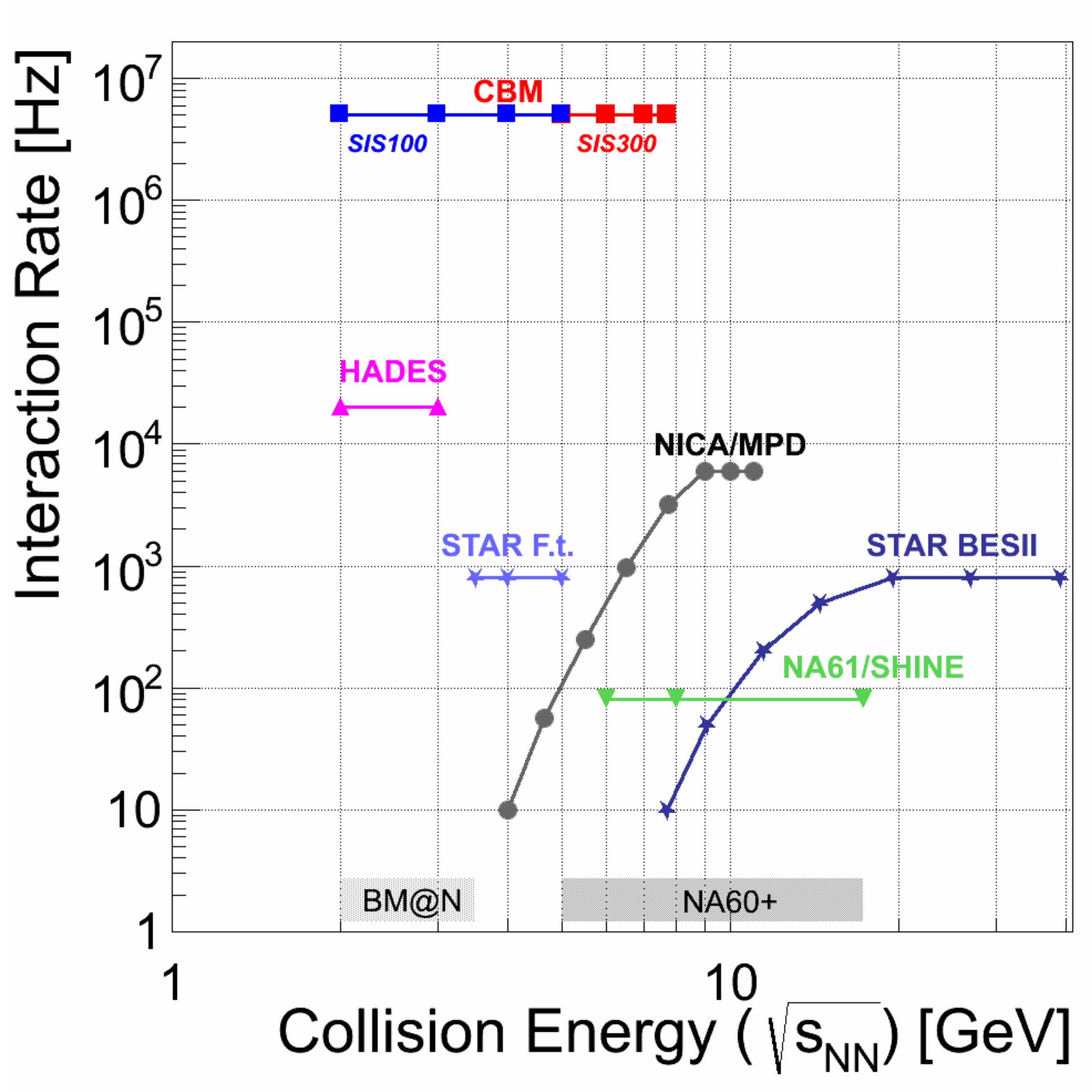
Plasma Physics:
x600 higher target
energy density 600kJ/g

High EM Field (HI)
Fundamental Studies (HI & $\bar{p}$)
Applications (HI)

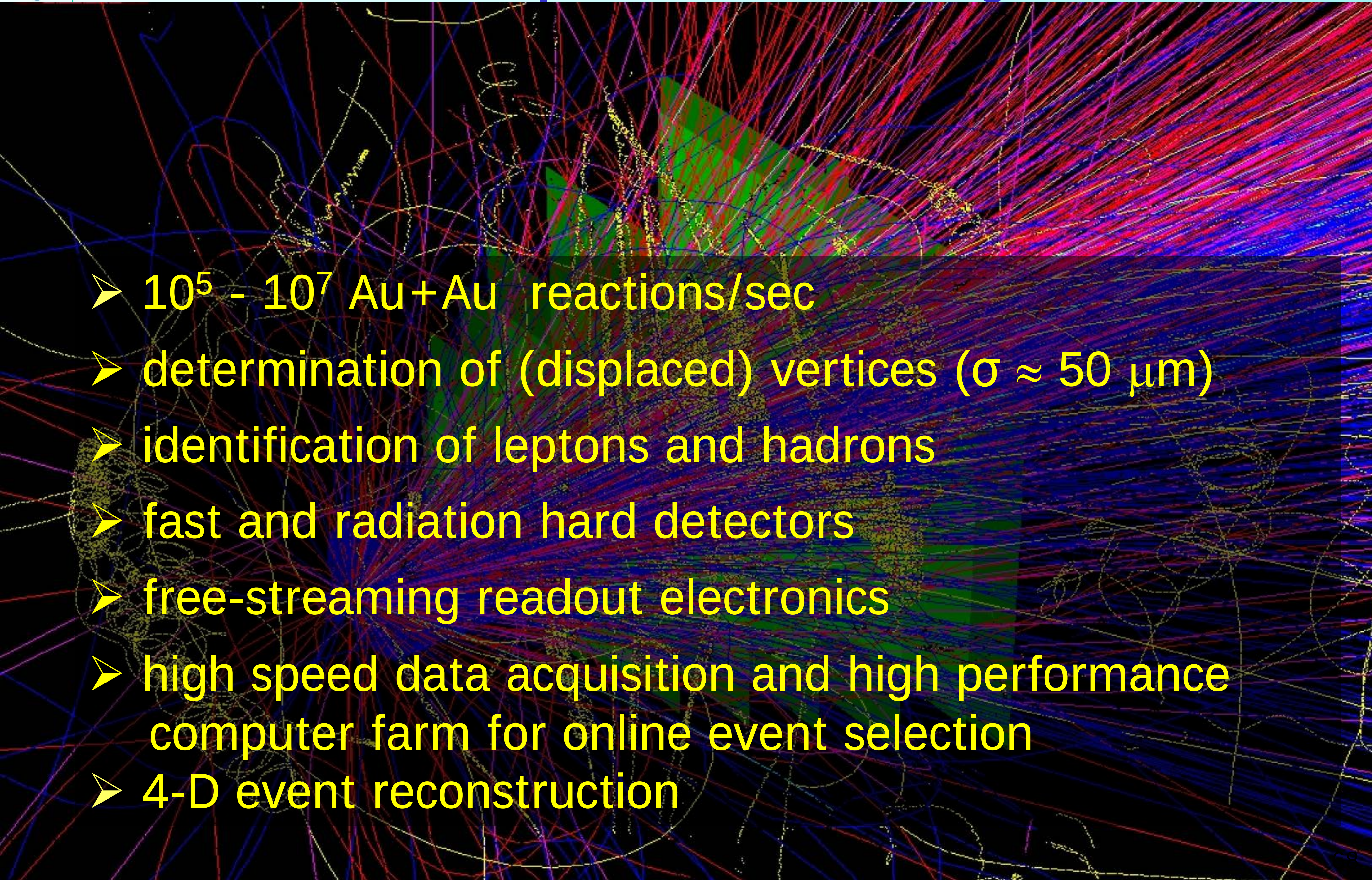
Special Features:

- 50ns Bunched beams
- Electron cooling of secondary beams
- SC magnets fast ramping
- Parallel operation

Experiments exploring dense QCD matter



CBM – Experimental Challenges



- 10^5 - 10^7 Au+Au reactions/sec
- determination of (displaced) vertices ($\sigma \approx 50$ μm)
- identification of leptons and hadrons
- fast and radiation hard detectors
- free-streaming readout electronics
- high speed data acquisition and high performance computer farm for online event selection
- 4-D event reconstruction

CBM – Detector Concept

Different detector setups for muon & electron measurements:

0) Core elements

- dipole magnet
- STS – silicon tracking system
- PSD – projectile spectator detector
- TOF – MRPC time-of-flight detector
- DAQ – data acquisition
- FLES – first level event selection

1) Muon setup

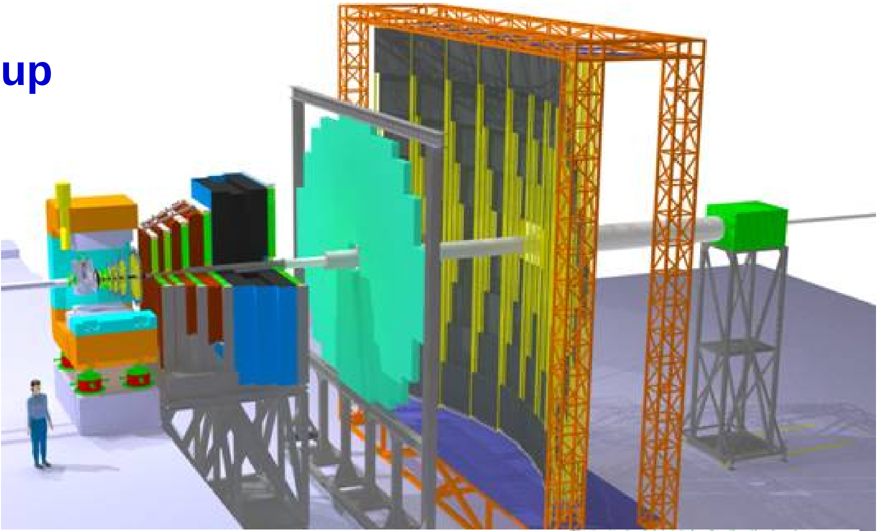
- MUCH – Muon detection system
  (active absorber)
- TRD – tracking station

2) Electron/Hadron setup

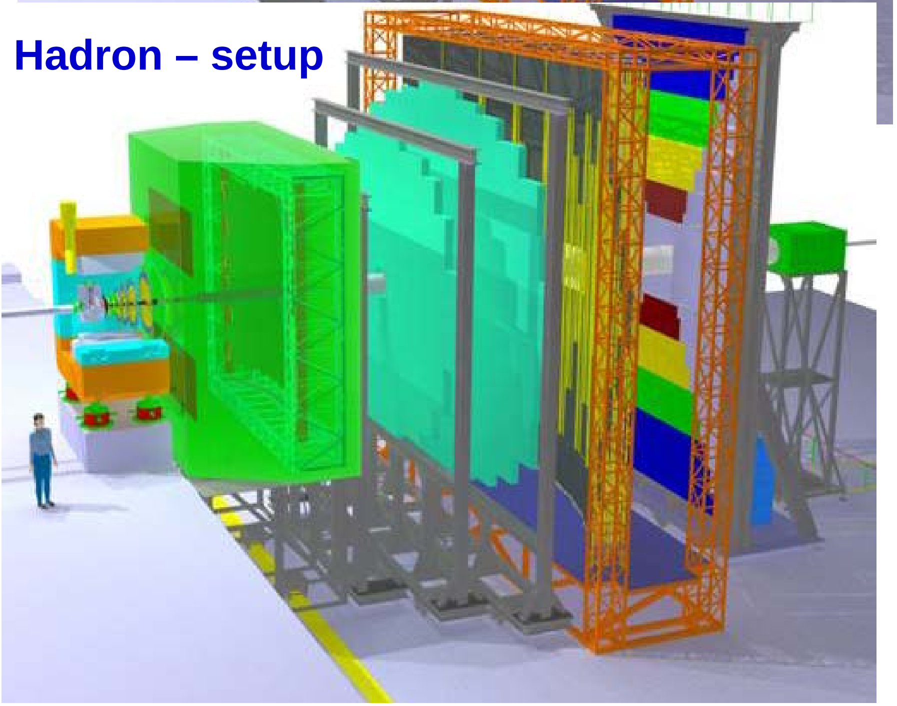
- MVD – Micro vertex detector
- TRD – Transistion radidation detector
- ECAL – Electromagnetic calorimeter

All core components designed with self triggered FEE and free running DAQ for 10 MHz interaction rate.

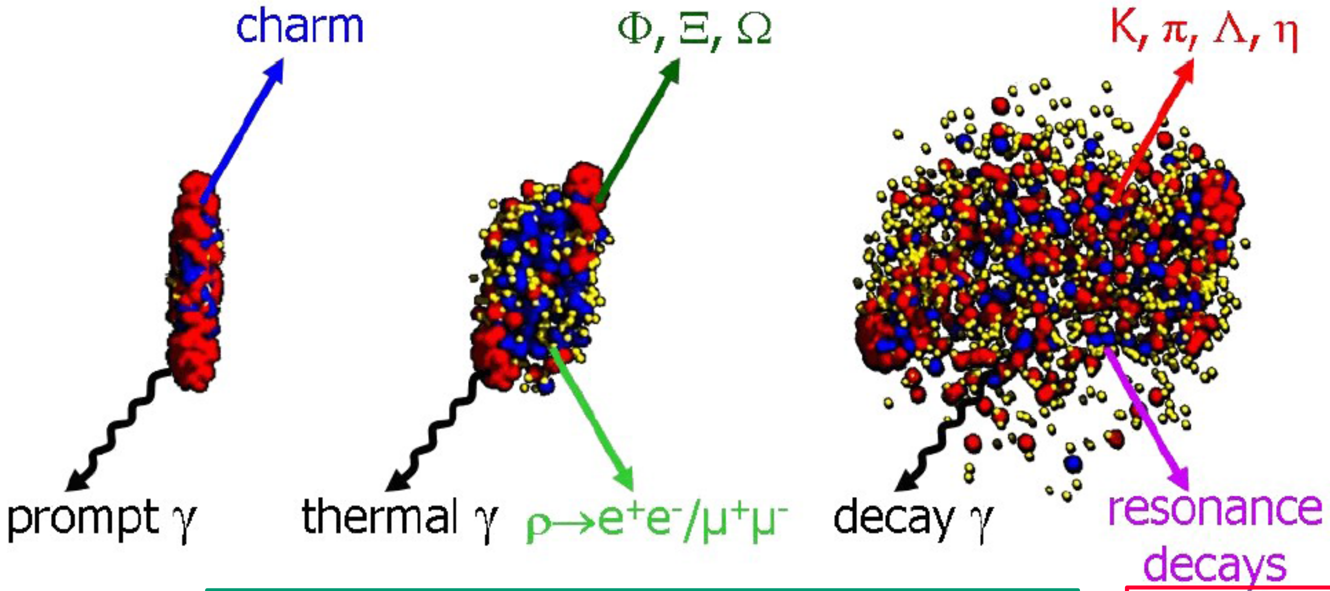
1) Muon – setup



2) Electron + Hadron – setup



Observables in HI – collisions



Hard probes
(initial state)

Penetrating probes
(integrate over collision history)

Relicts
(produced in dense phase,
sub – NN – threshold processes
are sensitive to medium properties)

Freeze-out
(final state particles)

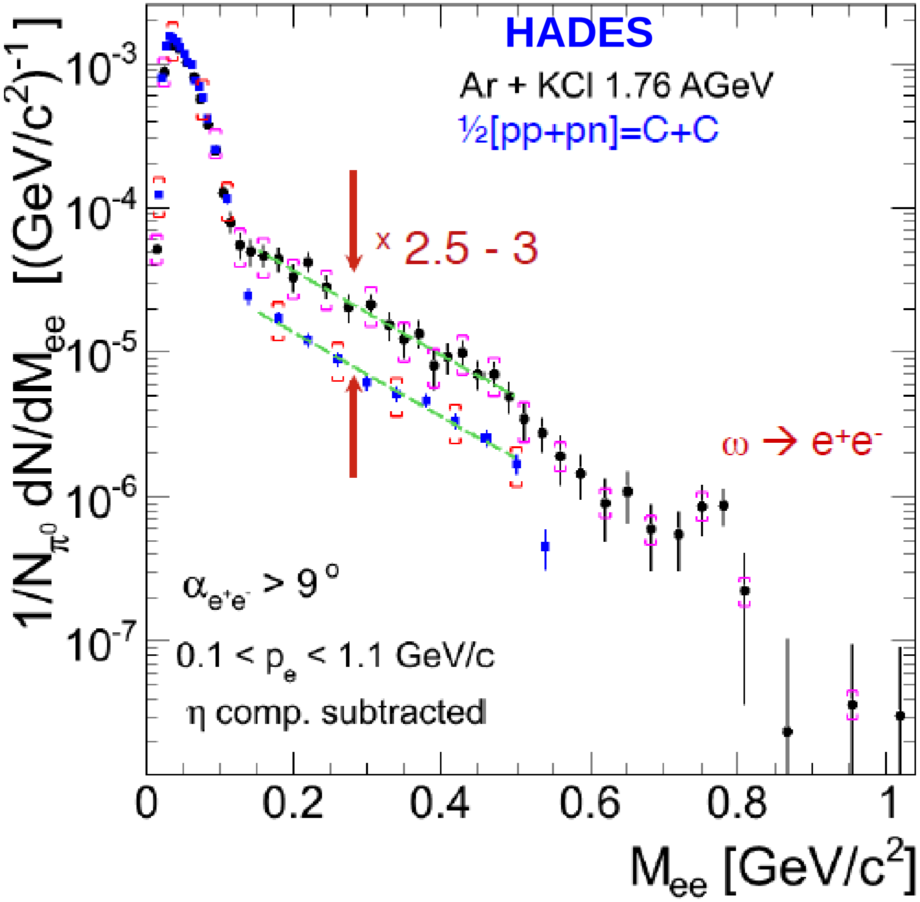
Thermalized (?) hadrons

Direct multi-strange hyperon production:

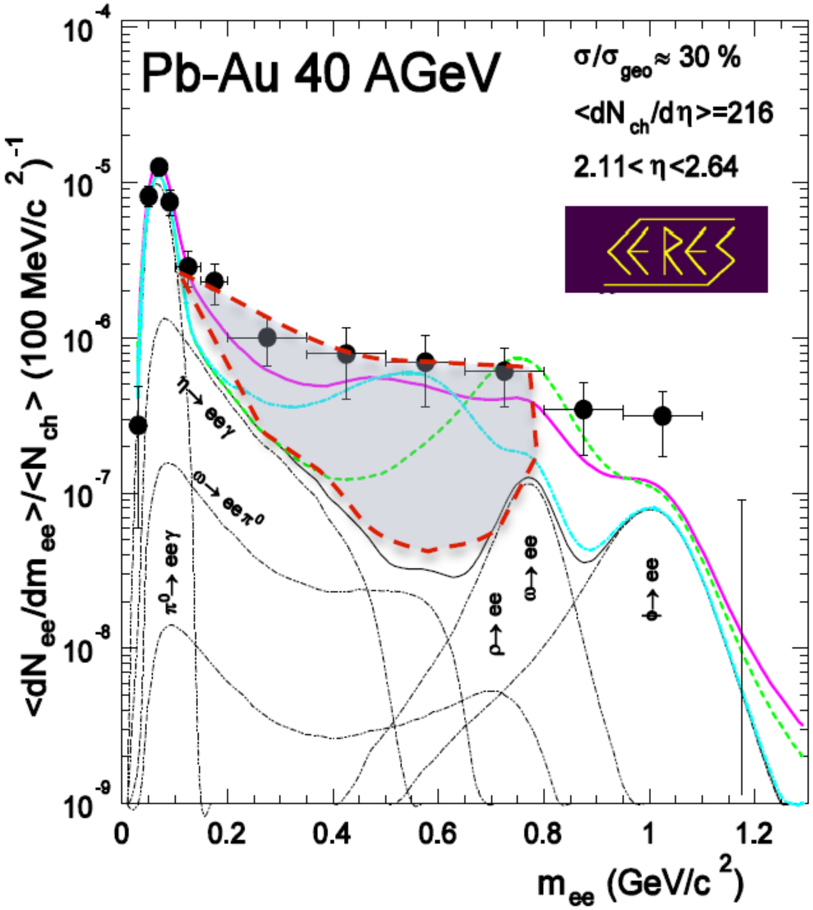
$pp \rightarrow \Xi^- K^+ K^+ p \quad (E_{thr} = 3.7\ \mathrm{GeV})$
$pp \rightarrow \Omega^- K^+ K^+ K^0 p \quad (E_{thr} = 7.0\ \mathrm{GeV})$

In – medium properties of light vector mesons

G. Agakishiev et al., Phys. Rev. C 84 (2011) 014902



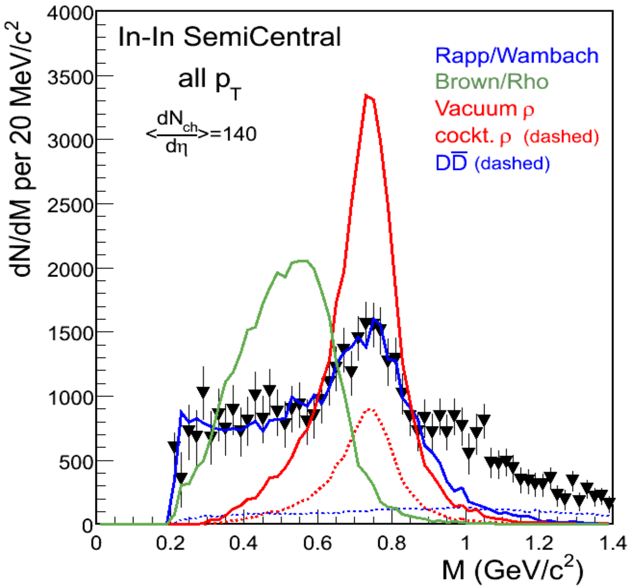
D. Adamova et al., Phys. Rev. Lett. 91 (2003) 042301

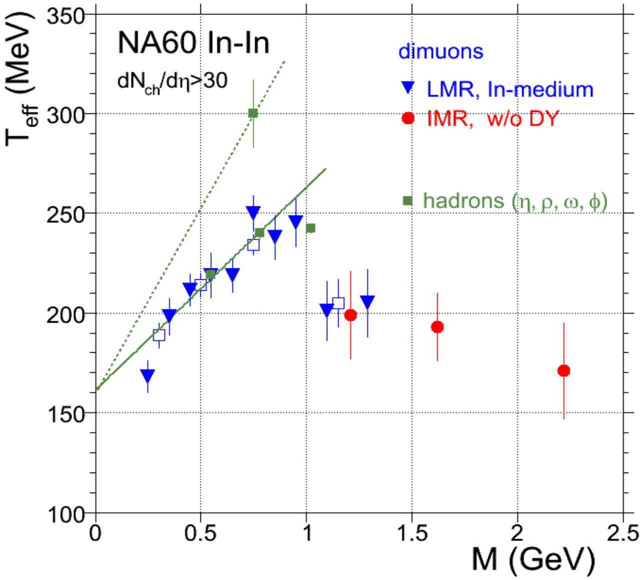


No data available in SIS100 / SIS300 energy range

Phase transition observables (?)

R. Arnaldi et al. (NA60), PRL 100 (2008) 022302





NA60

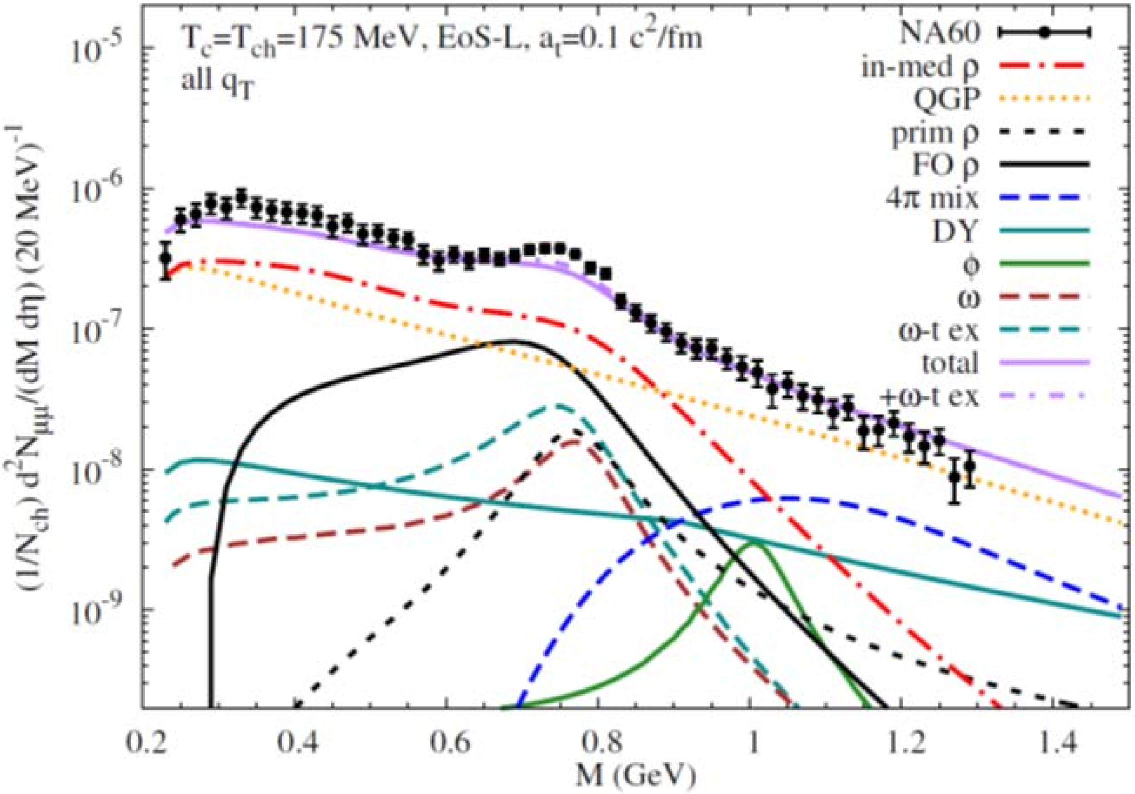
In + In collisions at 158 AGeV (SPS)

Clean measurement of ρ – meson spectral function.

Slope parameter of transverse momentum spectra in agreement with hadrons up to M ~ 1 GeV

Spectra above 1 GeV are conjectured to originate from partonic source

Theoretical interpretation of Dilepton Spectrum



Experiment:
R. Arnaldi et al. [NA60 Coll.],
Phys. Rev. Lett. 96, (2006) 162302,
Theory:
R. Rapp, J. Wambach and H. van Hees, in
arXiv:0901.3289 hep-ph

Signatures:

In – medium modification of hadrons

in 1 – 2 GeV range:

temperature of source

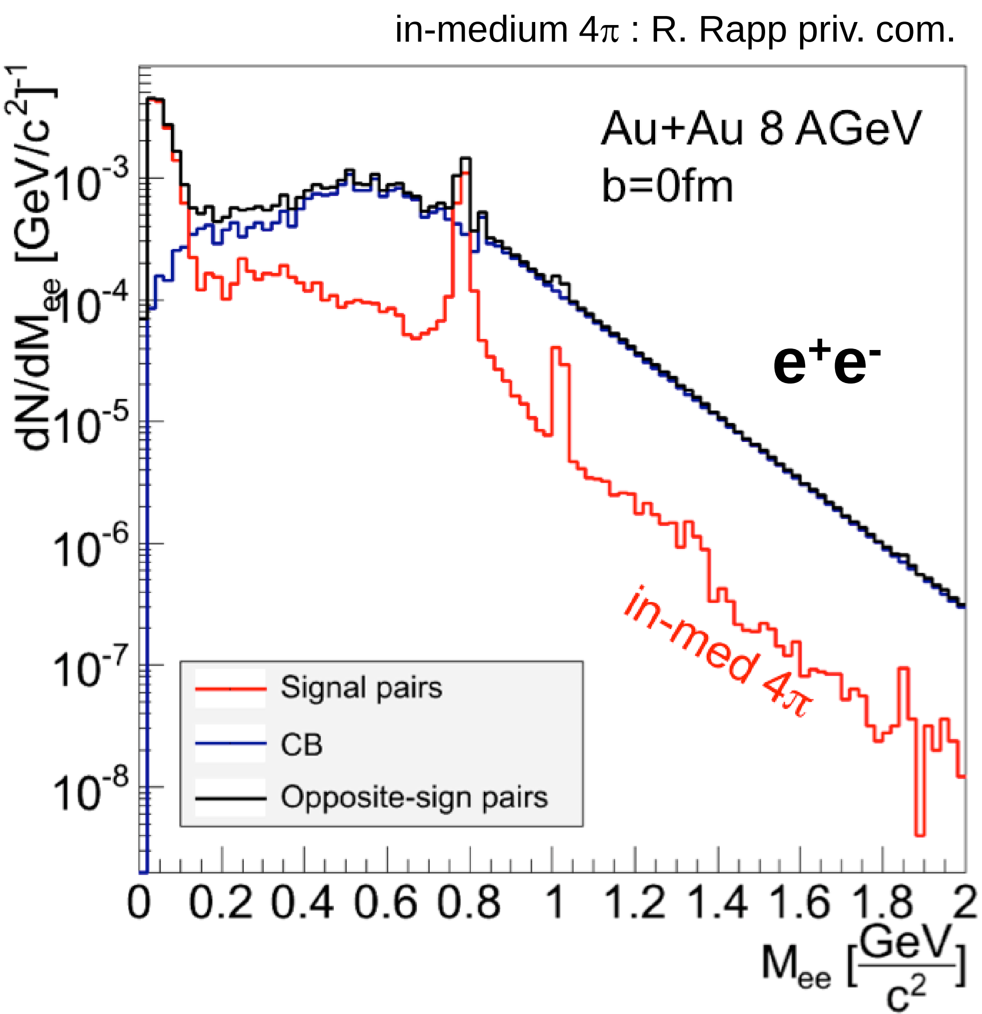
ρ – a_1 mixing
(chiral symmetry restoration)

Exploring restoration of chiral symmetry

At SIS100 beam energies:

M_{inv} between 1 and 2 GeV/c^2 dominated by in-medium 4π
$\rightarrow$ ρ-a_1 chiral mixing

in-medium 4π : R. Rapp priv. com.

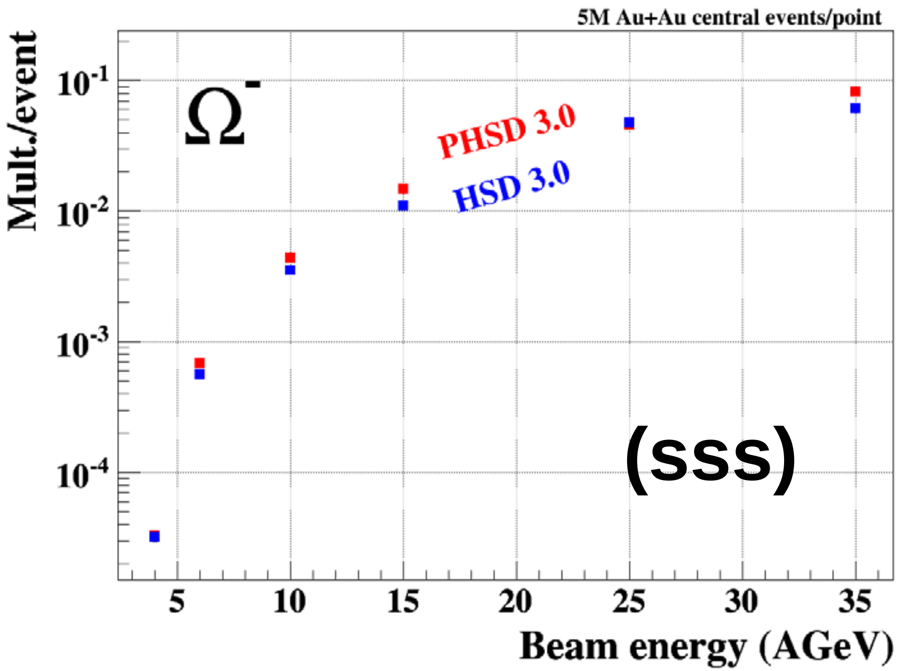


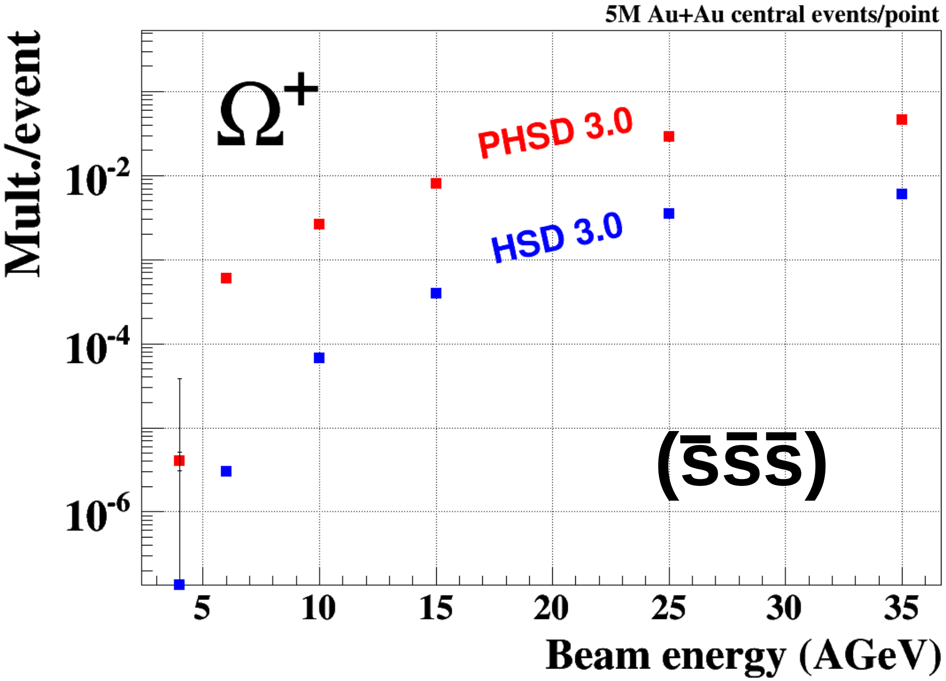
Correlated charm, Drell-Yan and QGP contributions decrease with decreasing beam energy

SIS100 energy range is well suited to search for signals for chiral symmetry restoration

Strangeness

I. Vassiliev, E. Bratkovskaya (preliminary)



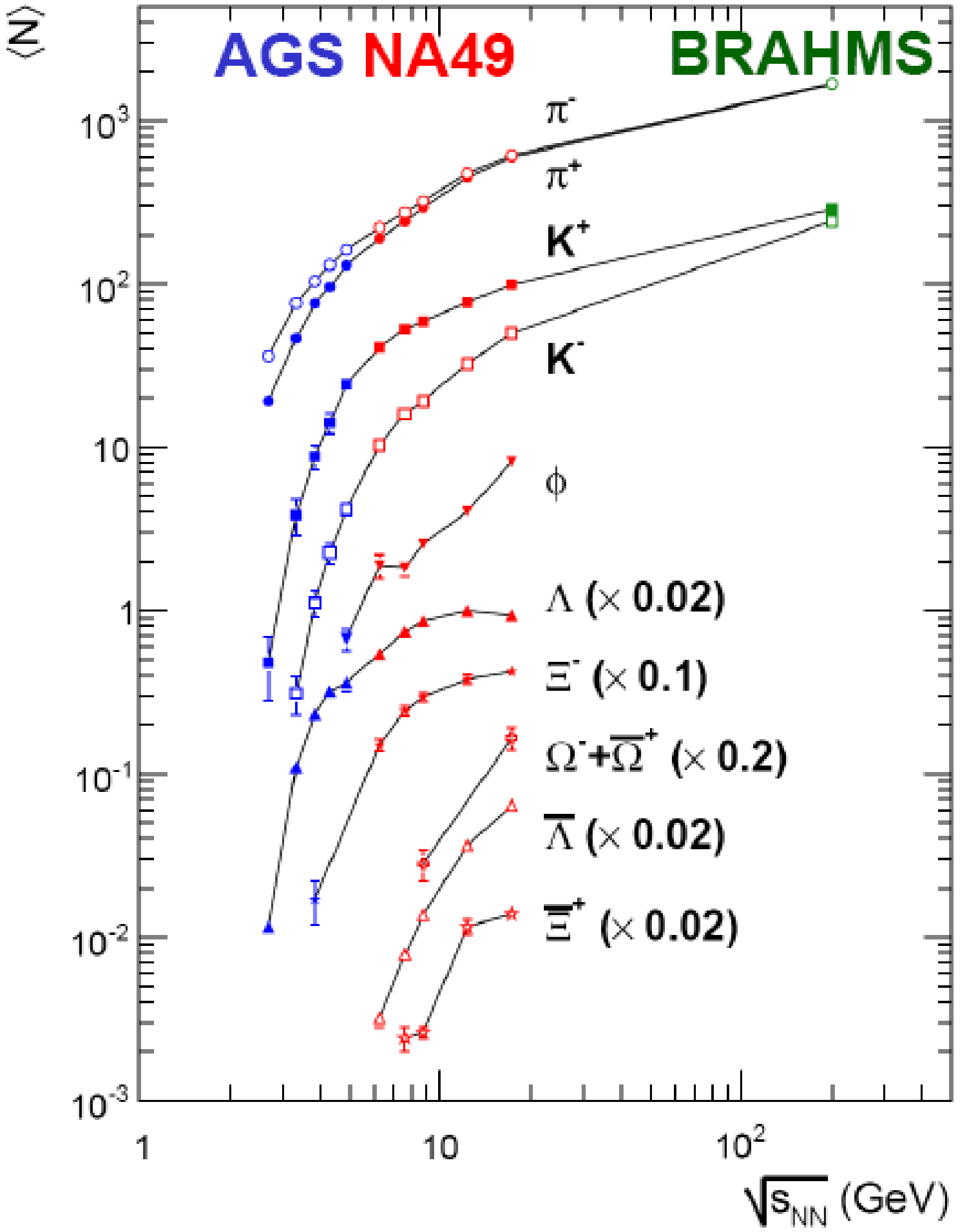


HSD: Hadronic transport code

PHSD: Hadronic transport code with partonic phase ($\varepsilon > 1$ GeV/fm^3)

Excitation function of particle production

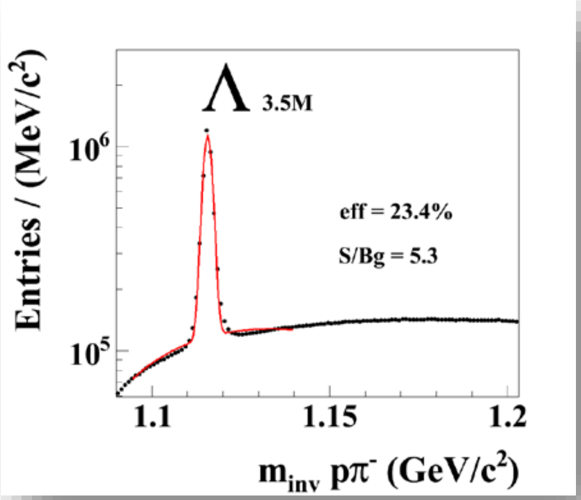
Central Au+Au collisions (4π yields)

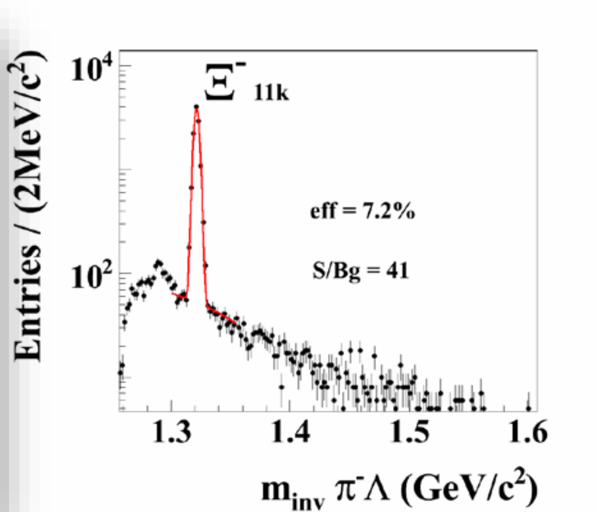


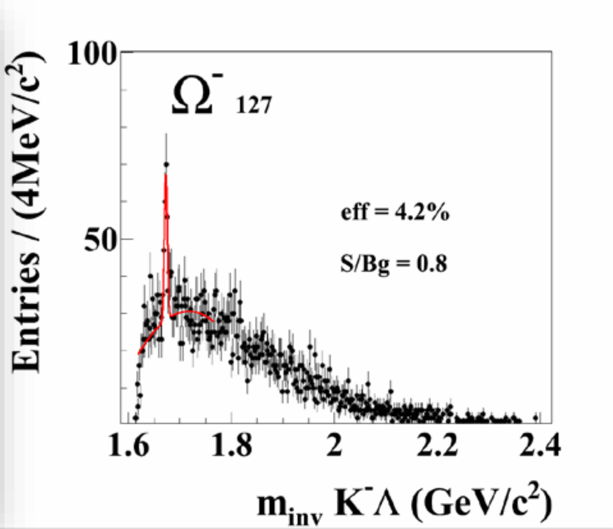
C.Blume, CBM symposium HZDR (2011)

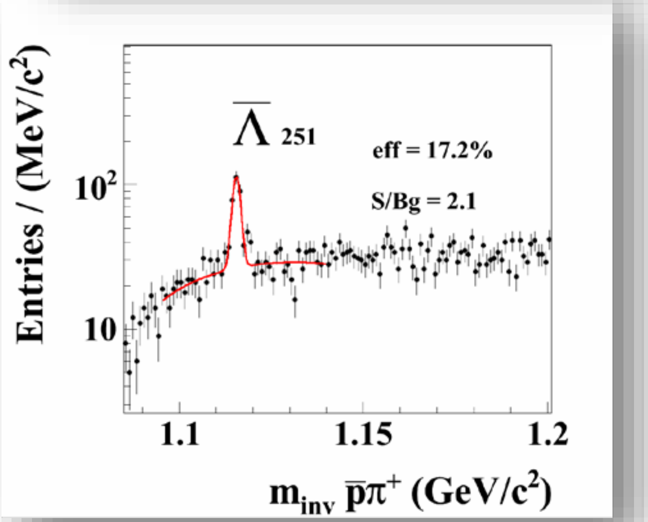
Au + Au at 8 AGeV, 10^6 central events

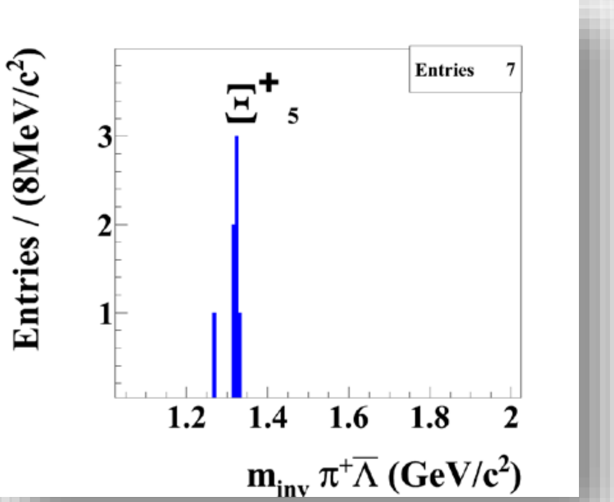
Hyperon yields in CBM

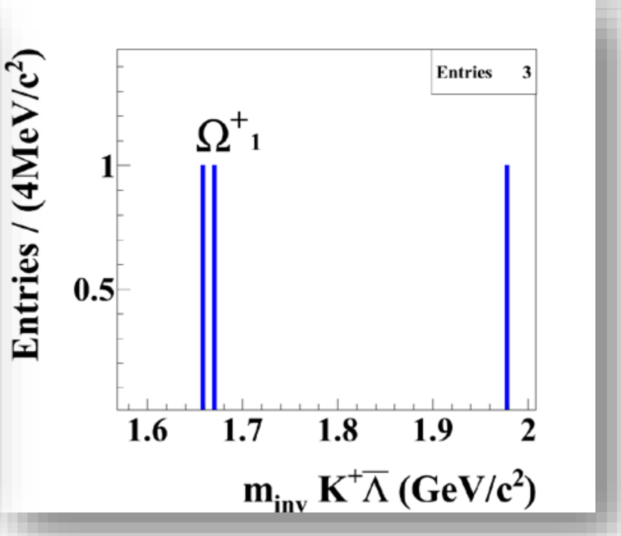












Hyperons rates in CBM

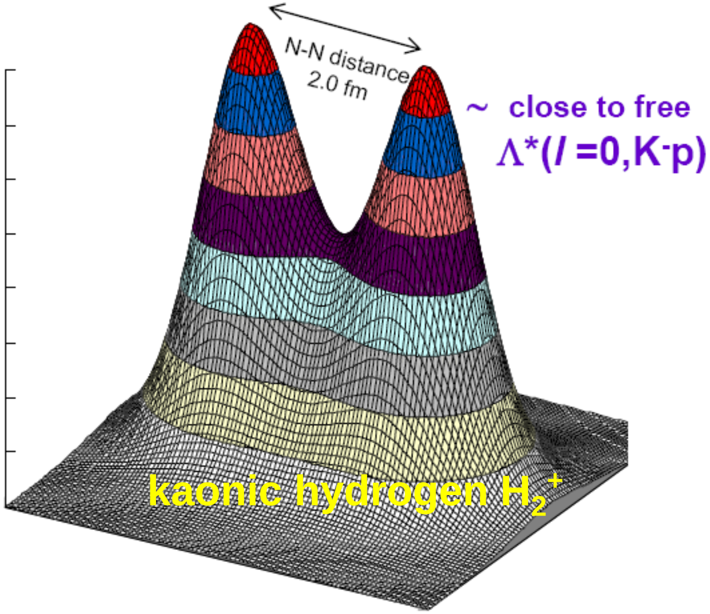
- Expected reconstructed yields for 4 weeks/energy min. bias Au+Au with 10^7 beam ions/s (100 kHz events/s):

A GeV	Λ	$\bar{\Lambda}$	Ξ^-	Ξ^+	Ω^-	Ω^+
4	$8.1\cdot10^{10}$	$3.0\cdot10^{5}$	$6.6\cdot10^{7}$	$6.0\cdot10^{4}$	$3.6\cdot10^{5}$	$1.2\cdot10^{3}$
6	$1.6\cdot10^{11}$	$5.0\cdot10^{6}$	$3.4\cdot10^{8}$	$1.8\cdot10^{5}$	$2.4\cdot10^{6}$	$1.2\cdot10^{4}$
8	$2.1\cdot10^{11}$	$1.5\cdot10^{7}$	$6.6\cdot10^{8}$	$3.0\cdot10^{5}$	$7.6\cdot10^{6}$	$6.0\cdot10^{4}$
10	$2.4\cdot10^{11}$	$3.8\cdot10^{7}$	$9.6\cdot10^{8}$	$2.0\cdot10^{6}$	$1.3\cdot10^{7}$	$1.5\cdot10^{5}$

Strange baryon bound states

Kaonic molecules

T.Yamazaki and Y. Akaishi, Phys. Rev. C76 (2007) 045201
Y. Akaishi, T.Yamazaki, Phys.Rev.C65, 044005 (2002)
T.Yamazaki and Y. Akaishi, Phys.Lett.B535, 70 (2002)



$$\Psi = \phi_a + \phi_b$$

Decay by strong interaction

(ppK^-): $$(ppK^-) \rightarrow \Lambda + p$$

FINDUA **M=2255±9 MeV, Γ=64±14 MeV**
DISTO **M=2265±2 MeV, Γ=118±8 MeV**

Heavier clusters, e.g.: $$(ppnK^-) \rightarrow \Lambda + d$$

Hypernuclei

Decay by weak interaction

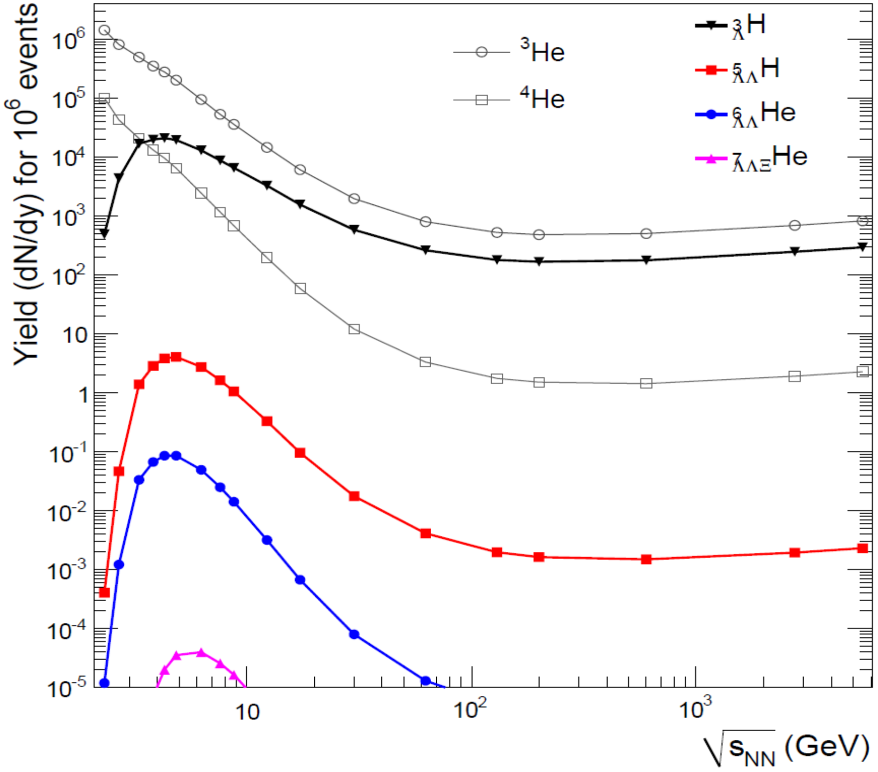
Production in HI – collisions?
Recently: STAR, ALICE

Double strange hypernuclei?

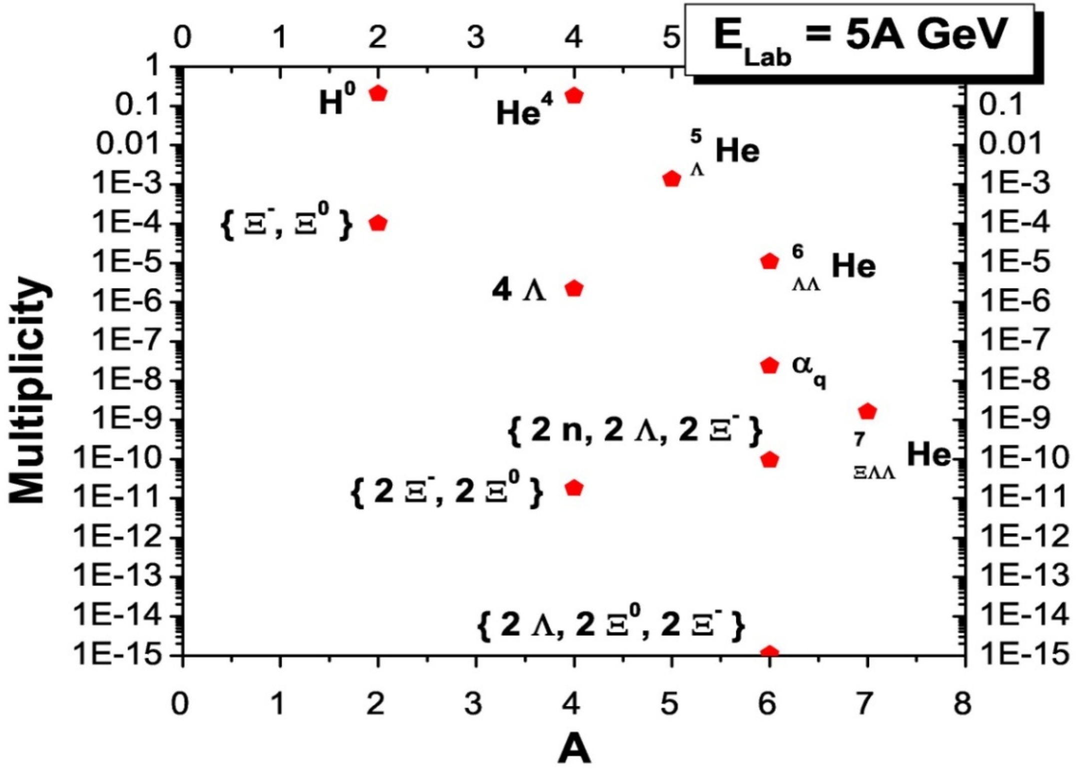
Strange baryonic bound states

- **Single and double strange hypernuclei in heavy ion collisions**
- **Search for strange matter in the form of strange dibaryons and heavy multi-strange short-lived objects.**

A. Andronic, P. Braun-Munzinger, J. Stachel, H. Stöcker, Phys. Lett. B697 (2011) 203



H. Stöcker et al., Nucl. Phys. A 827 (2009) 624c



Conclusion

Future: exploring the QCD phase structure with rare probes