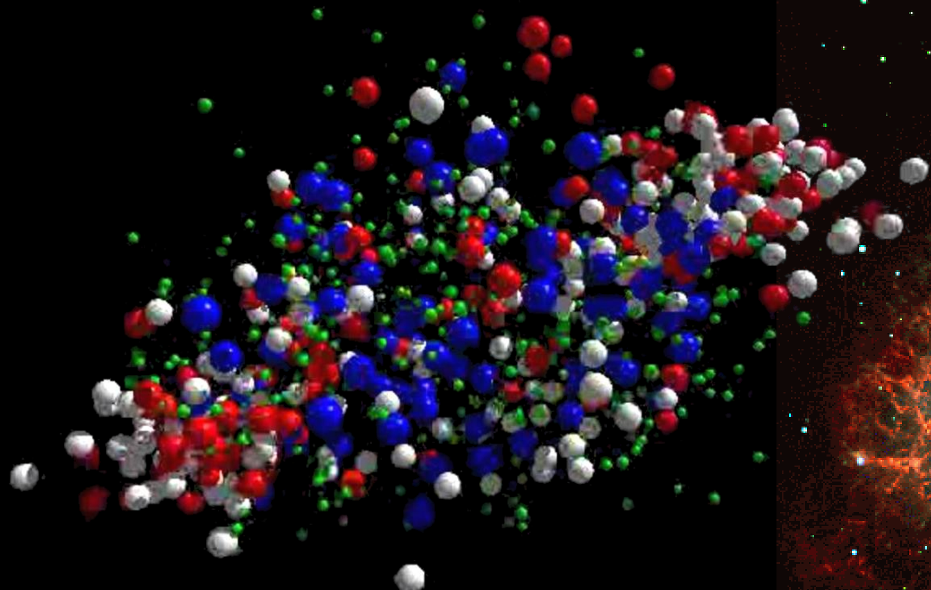
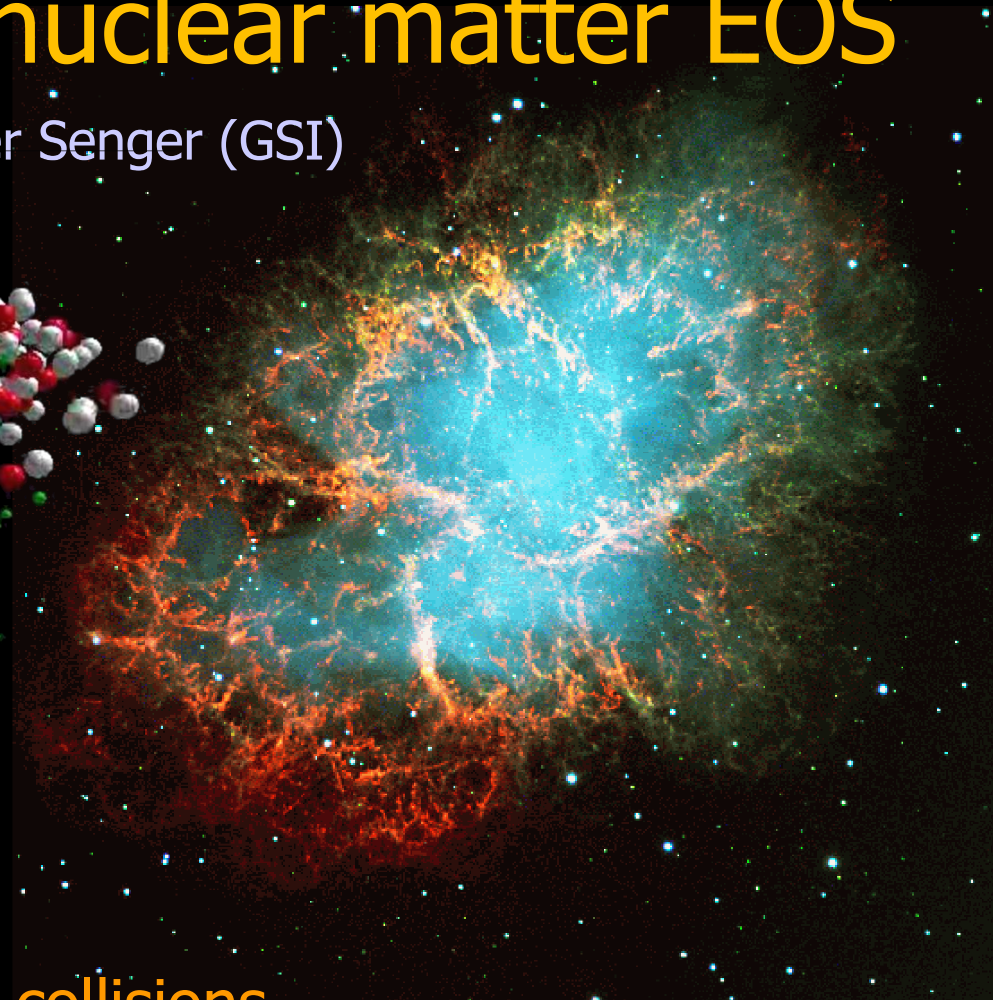
CBM and the nuclear matter EOS

Peter Senger (GSI)



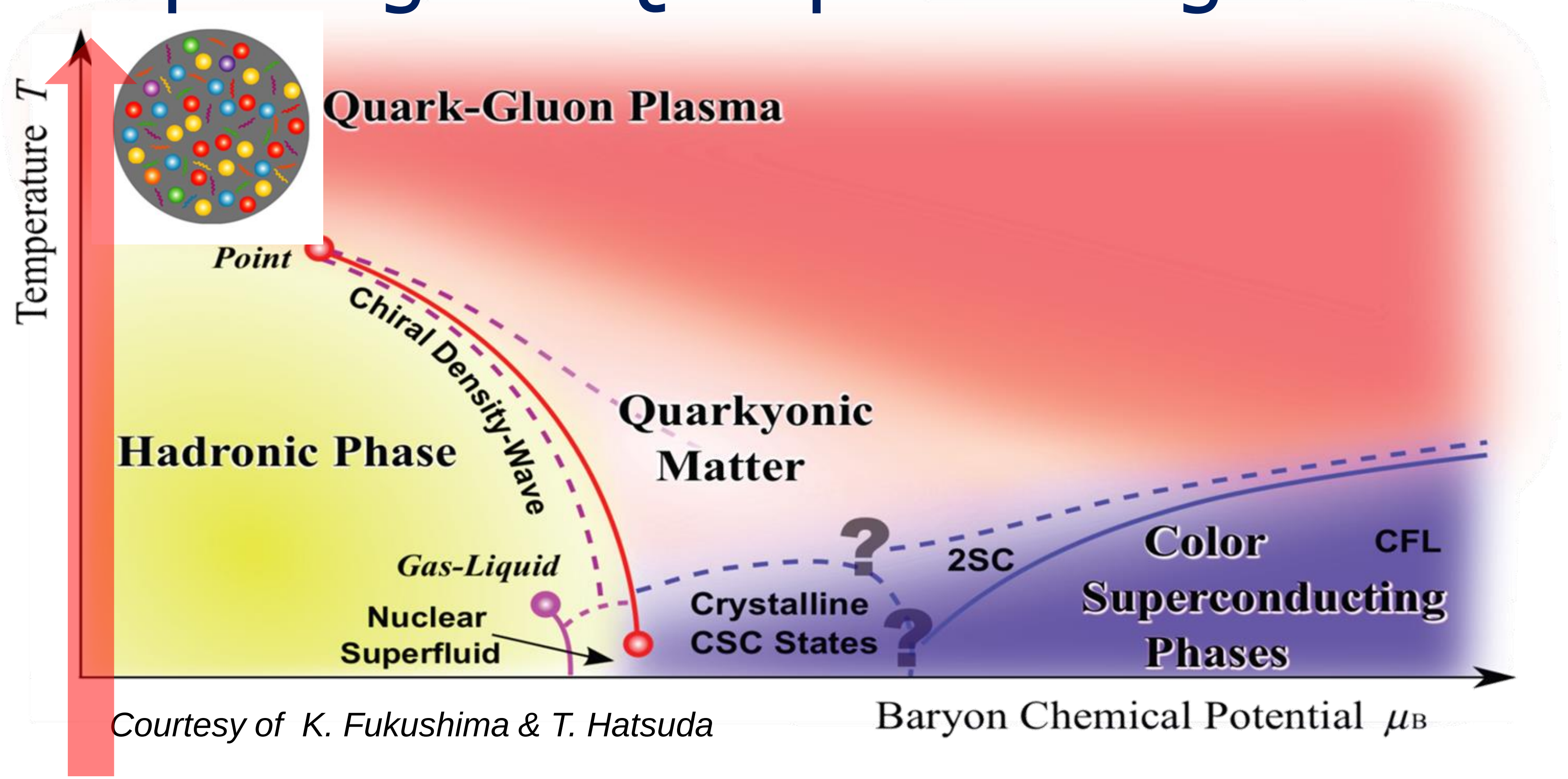


Outline:

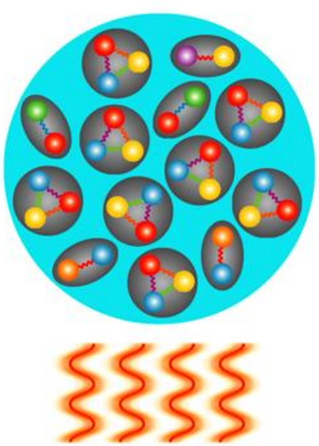
- EOS and heavy-ion collisions
- EOS of symmetric nuclear matter at $\rho < 3\ \rho_0$
- Observables sensitive to EOS at $\rho > 3\ \rho_0$?
- The CBM experiments and its performance

Hyperons in Nuclear Matter, GSI, July 22, 2015

Exploring the QCD phase diagram



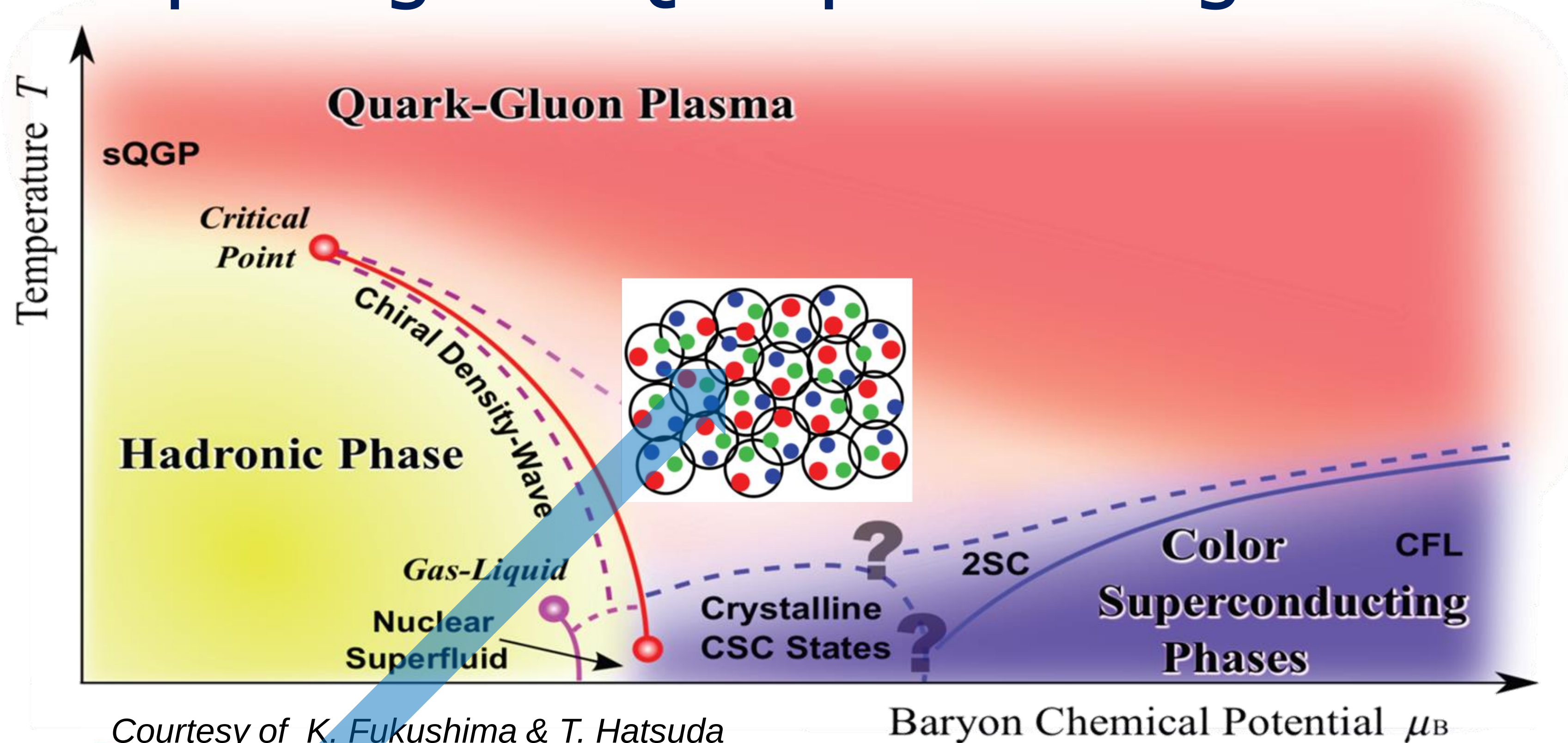
Courtesy of K. Fukushima & T. Hatsuda



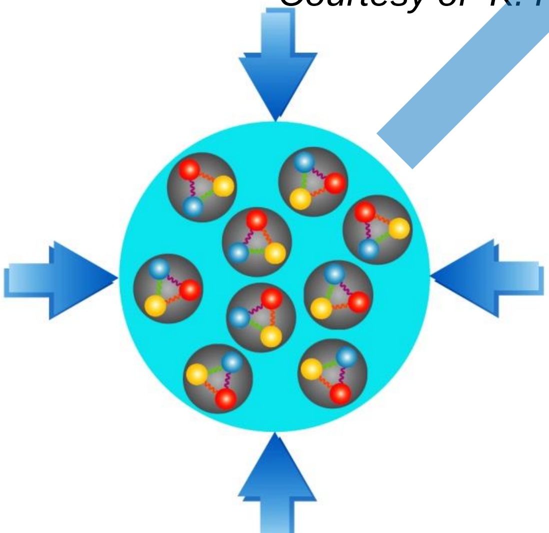
<u>At very high temperature:</u>

- N of baryons ≈ N of antibaryons
  Situation similar to early universe
- L-QCD finds crossover transition between
  hadronic matter and Quark-Gluon Plasma
- Precision experiments:
  ALICE, ATLAS, CMS at LHC, STAR, PHENIX at RHIC

Exploring the QCD phase diagram



Courtesy of K. Fukushima & T. Hatsuda



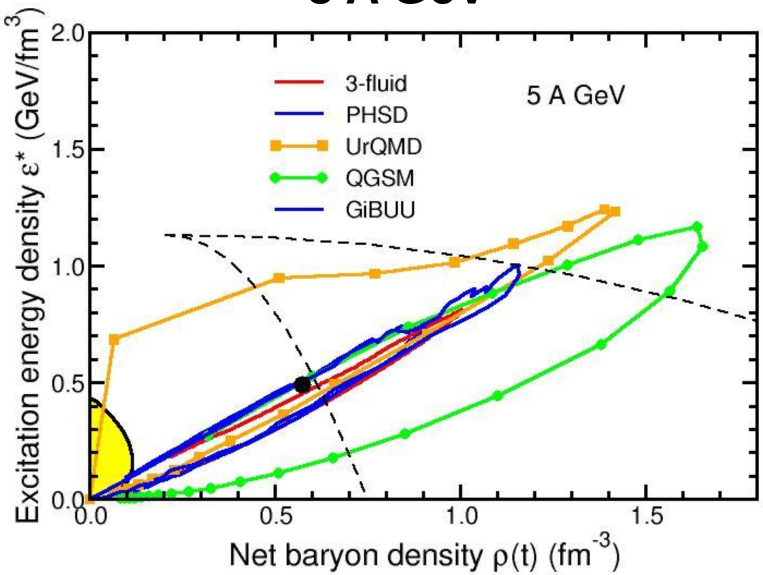
At high baryon density:

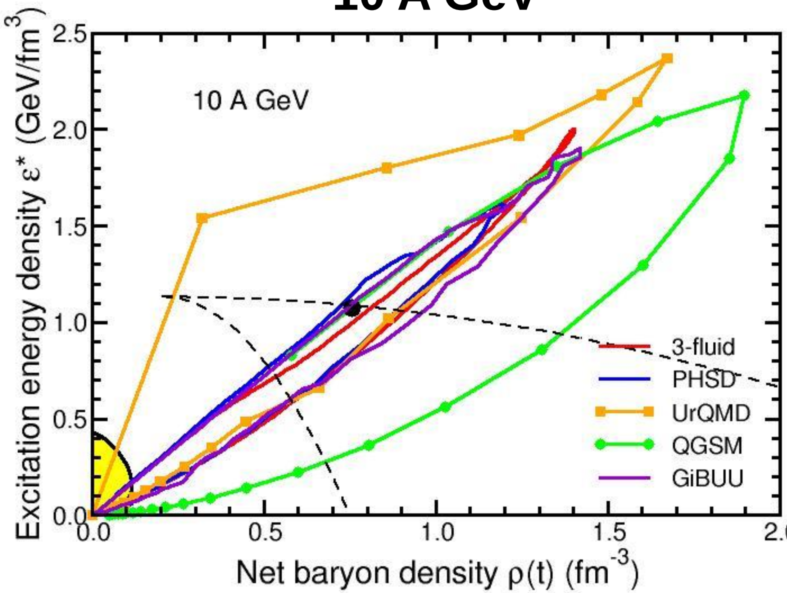
- N of baryons >> N of antibaryons
  Densities like in neutron star cores
- L-QCD not (yet) applicable
- Models predict first order phase transition with mixed or exotic phases
- Experiments: BES at RHIC, NA61 at CERN SPS, CBM at FAIR, NICA at JINR

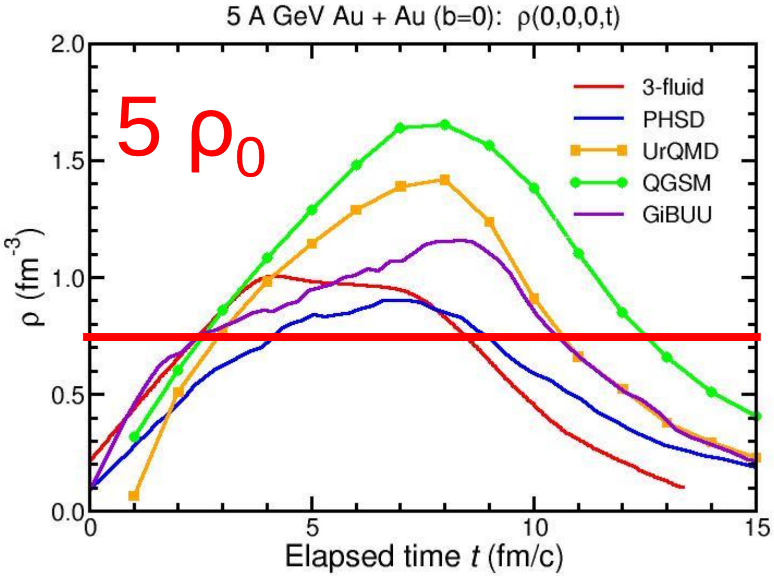
Baryon densities in central Au+Au collisions

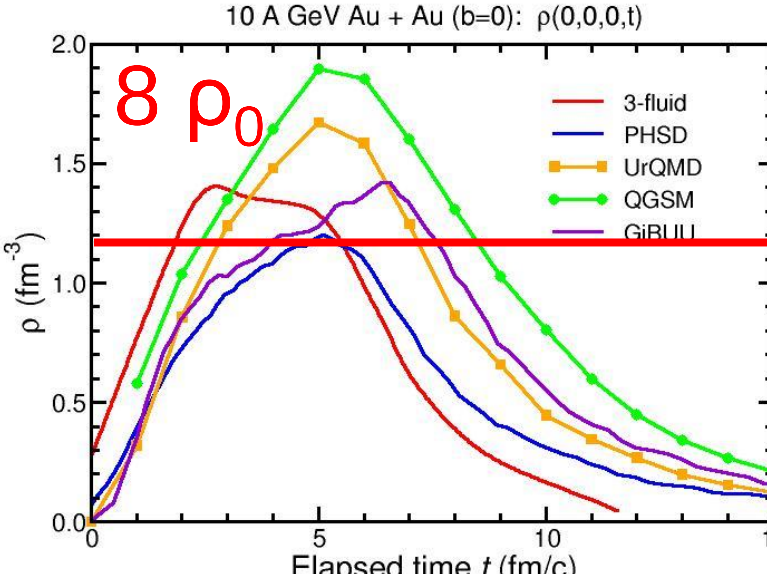
I.C. Arsene et al., Phys. Rev. C 75, 24902 (2007), V. D. Toneev et al., Eur. Phys. J. C32 (2003) 399

5 A GeV **10 A GeV**





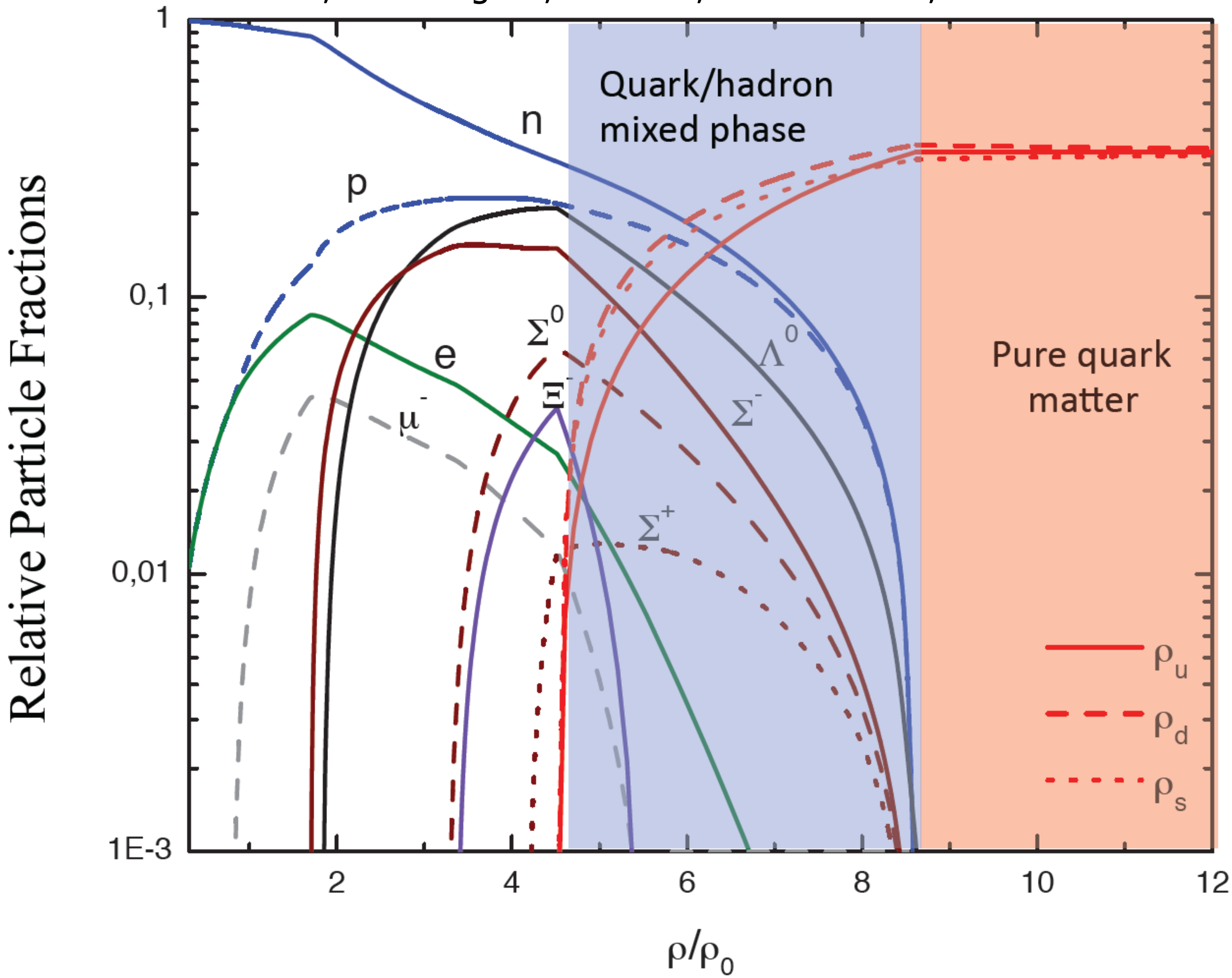




Quark matter in massive neutron stars?

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

M. Orsaria, H. Rodrigues, F. Weber, G.A. Contrera, arXiv:1308.1657



The equation-of-state of (symmetric) nuclear matter

Equation of state:

$P = \delta E/\delta V\,\big|_{T=const}$

$V = A/\rho$

$\delta V/\,\delta\rho = -\,A/\rho^2$

$P = \rho^2\;\delta(E/A)/\delta\rho\,\big|_{T=const}$

T=0: $E/A = 1/\rho \int U(\rho)d\rho$

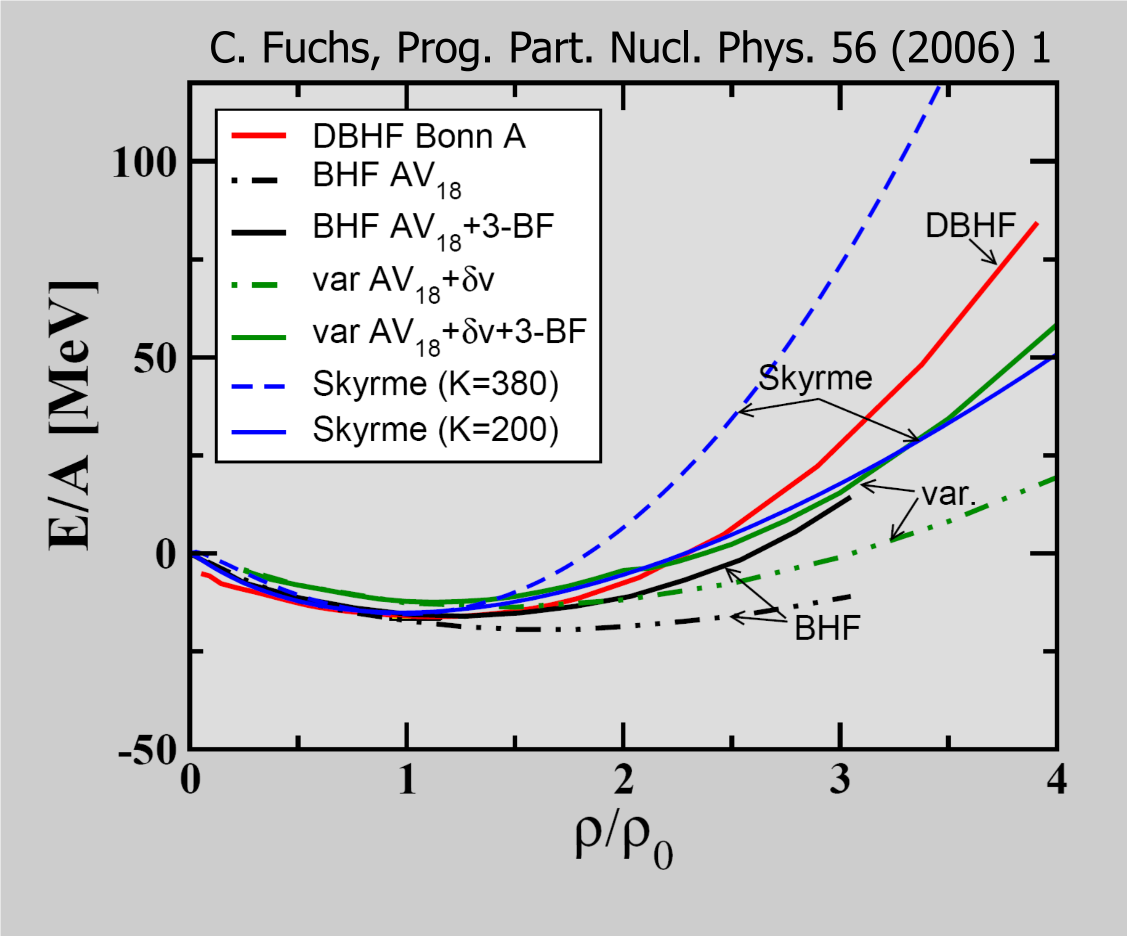
Effective NN-potential:

$U(\rho) = \alpha\rho + \beta\rho^{\gamma}$

$E/A(\rho_o) = -16$ MeV

- $\delta(E/A)(\rho_o)/\delta\rho = 0$
- Compressibility:

$\kappa = 9\rho^2\;\delta^2(E/A)/\;\delta\rho^2$



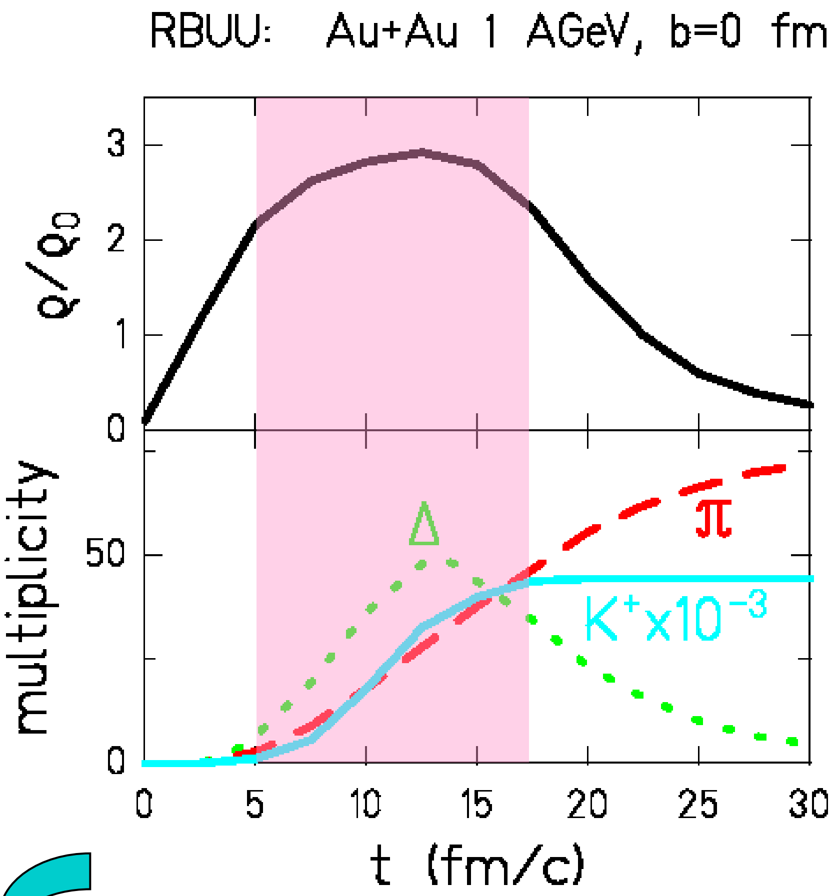
κ = 200 MeV: "soft" EOS

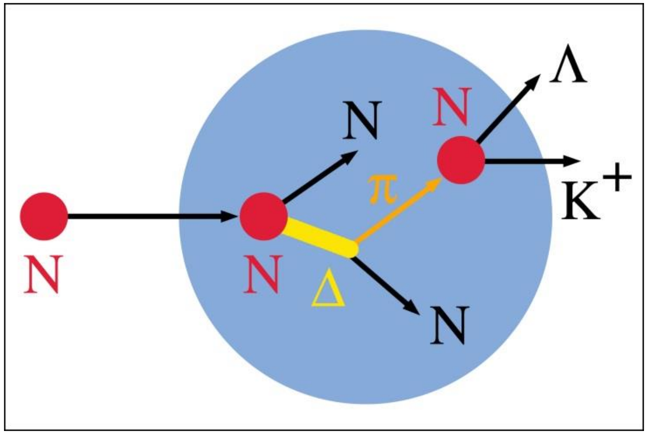
κ = 380 MeV: "stiff" EOS

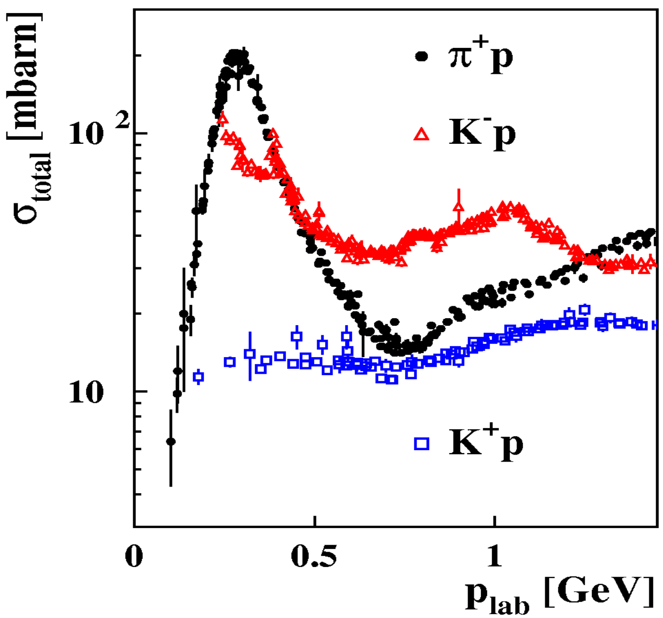
The equation-of-state of (symmetric) nuclear matter

Observable: Kaon production in Au+Au collisions at 1 AGeV

$pp \rightarrow K^+ \Lambda p \quad (E_{thres} = 1.6\ GeV)$







K+ mesons probe high densities

K+ mesons scatter elastically only

Probing the nuclear equation-of-state ($\rho = 1 - 3\ \rho_0$) by K^+ meson production in C+C and Au+Au collisions

Idea: K^+ yield $\propto$ baryon density $\rho \propto$ compressibility κ

Transport model (RBUU)

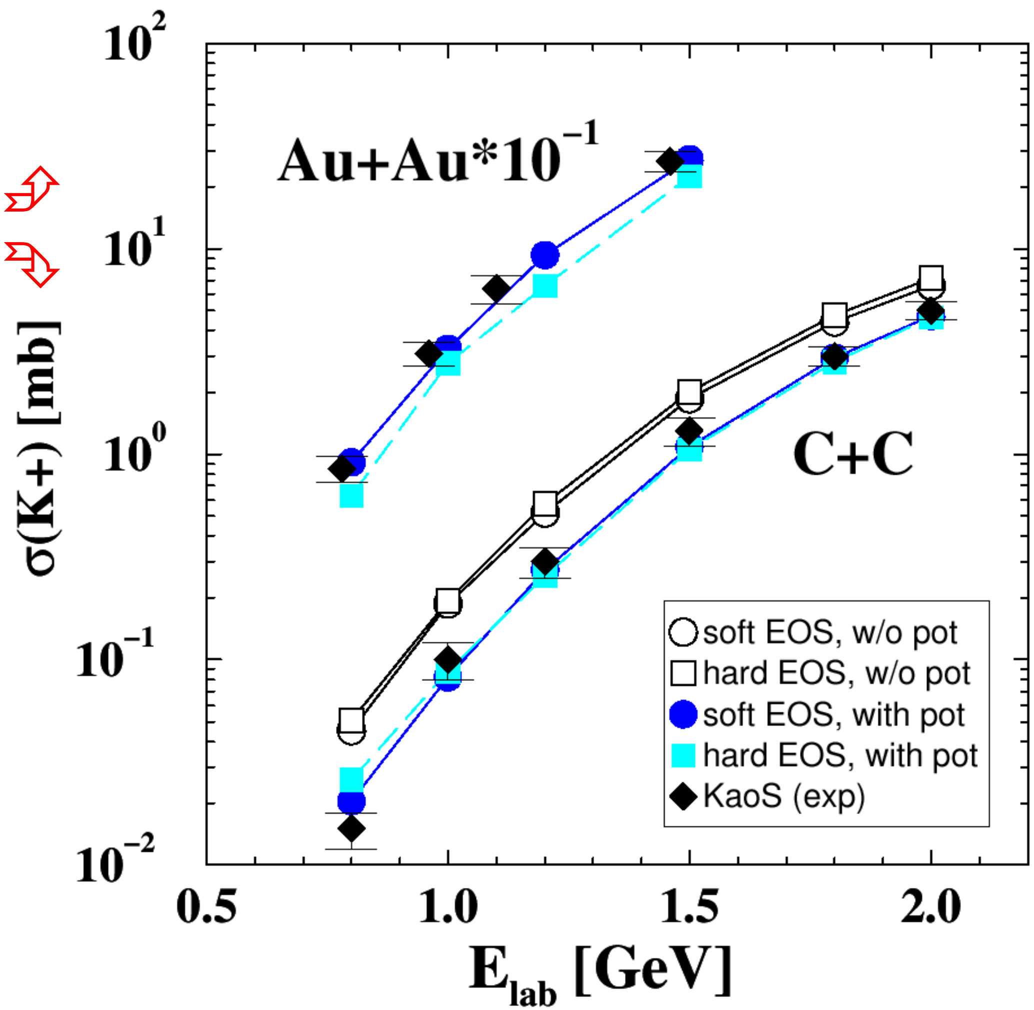
Au+Au at 1 AGeV:

κ = 200 MeV ⇨ $\rho_{max} \approx 2.9\ \rho_0$ ⇨ K^+ ⇧

κ = 380 MeV ⇨ $\rho_{max} \approx 2.4\ \rho_0$ ⇨ K^+ ⇩

Reference system C+C:

K^+ yield not sensitive to EOS



Experiment:

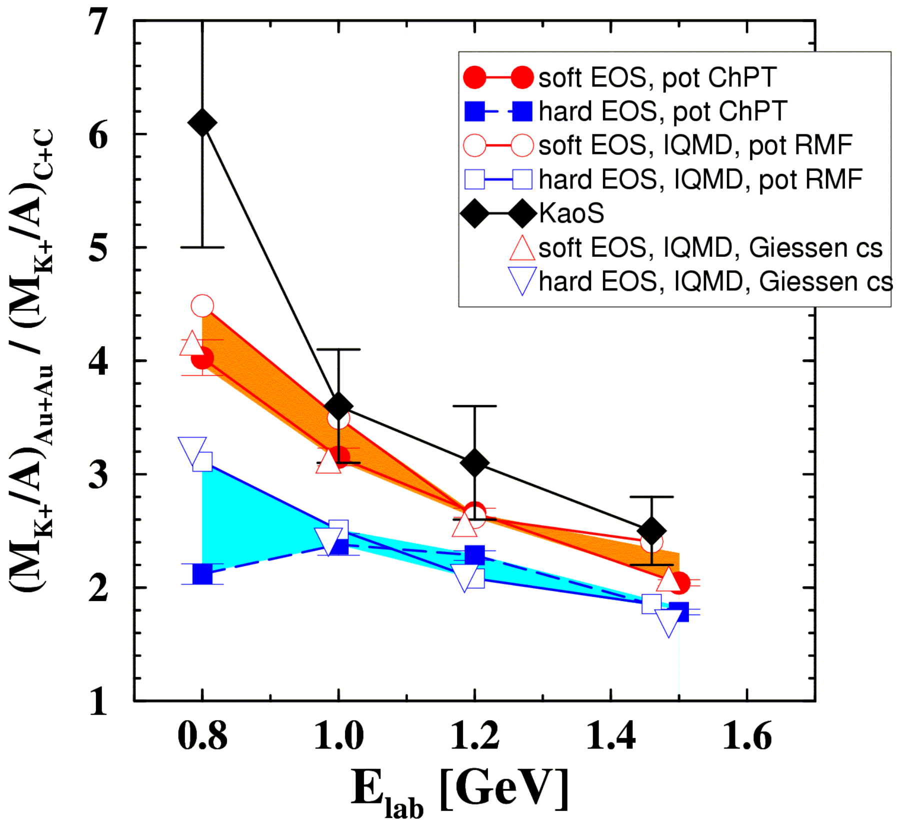
C. Sturm et al., (KaoS Collaboration), Phys. Rev. Lett. 86 (2001) 39

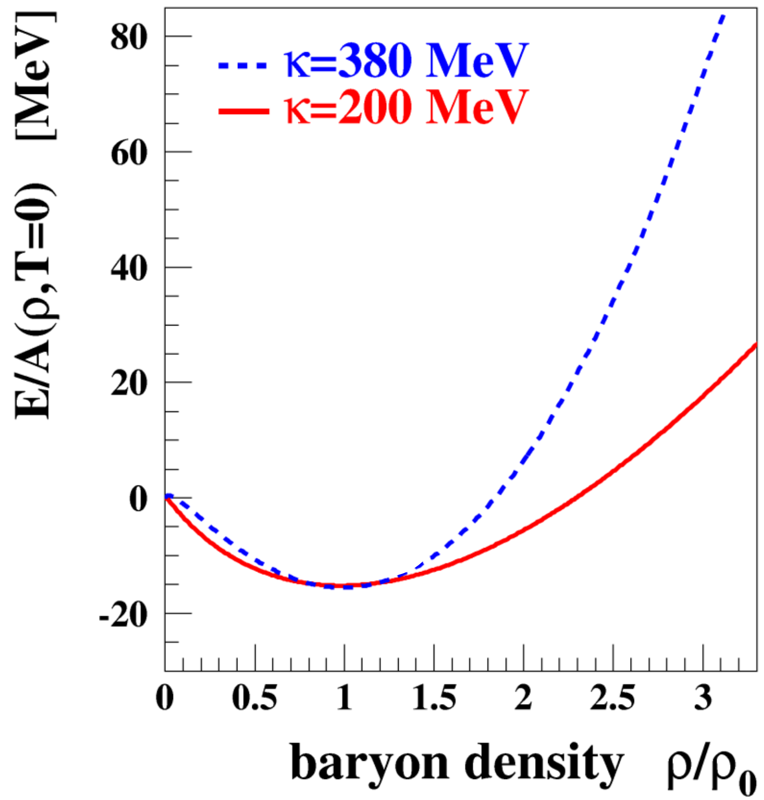
Theory:

Ch. Fuchs et al., Phys. Rev. Lett. 86 (2001) 1974

The compressibility of (symmetric) nuclear matter

Experiment: C. Sturm et al., (KaoS Collaboration) Phys. Rev. Lett. 86 (2001) 39
Theory: QMD Ch. Fuchs et al., Phys. Rev. Lett. 86 (2001) 1974
IQMD Ch. Hartnack, J. Aichelin, J. Phys. G 28 (2002) 1649

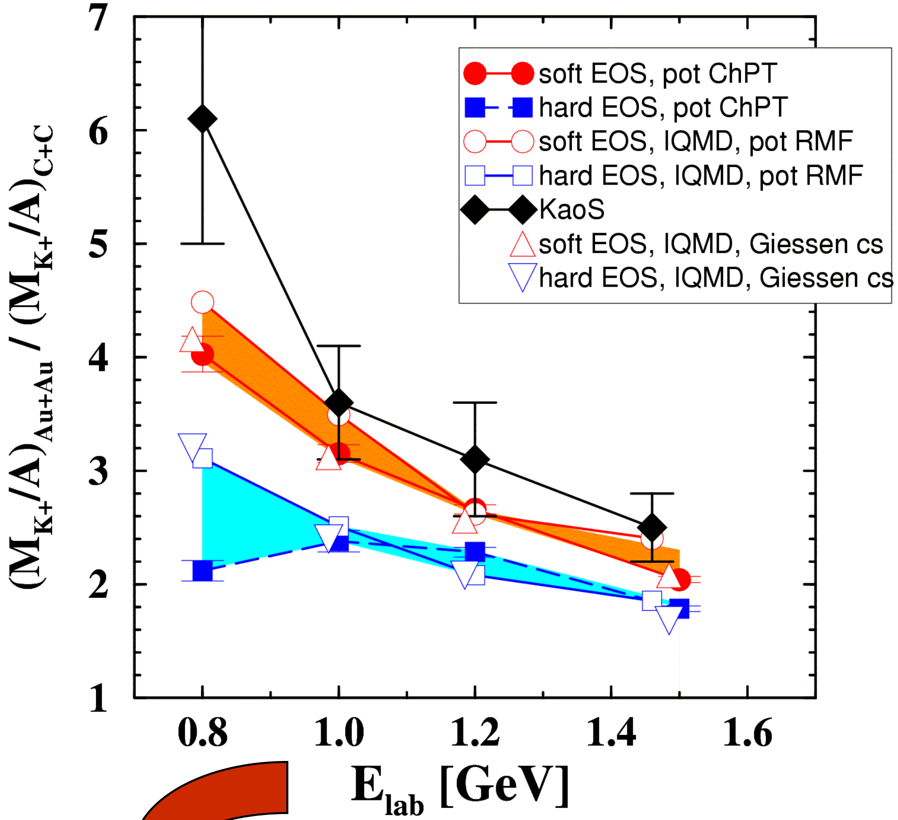


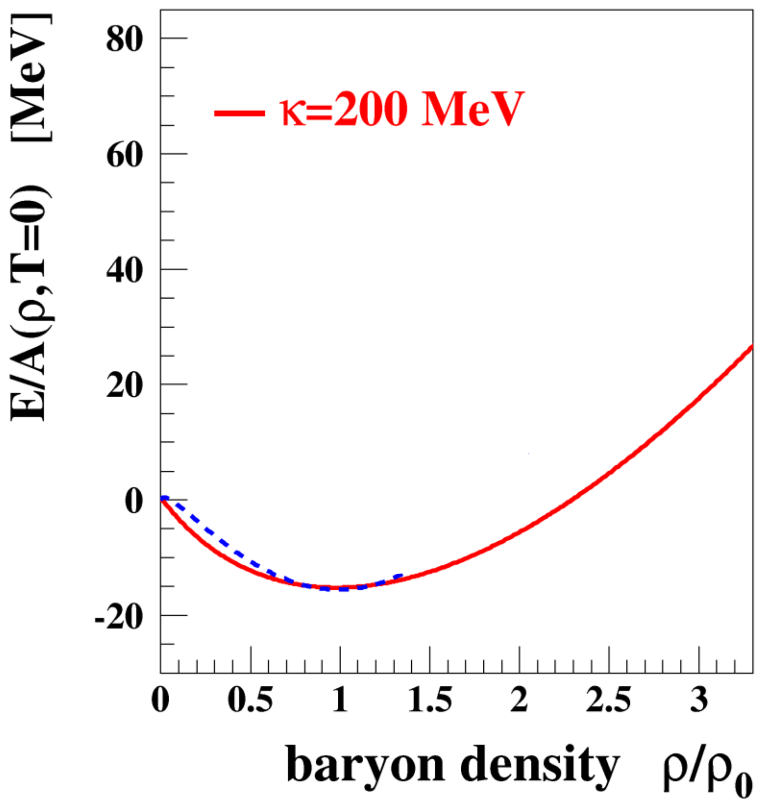


Au/C ratio: cancellation of systematic errors both in experiment and theory

The compressibility of (symmetric) nuclear matter

Experiment: C. Sturm et al., (KaoS Collaboration) Phys. Rev. Lett. 86 (2001) 39
Theory: QMD Ch. Fuchs et al., Phys. Rev. Lett. 86 (2001) 1974
IQMD Ch. Hartnack, J. Aichelin, J. Phys. G 28 (2002) 1649

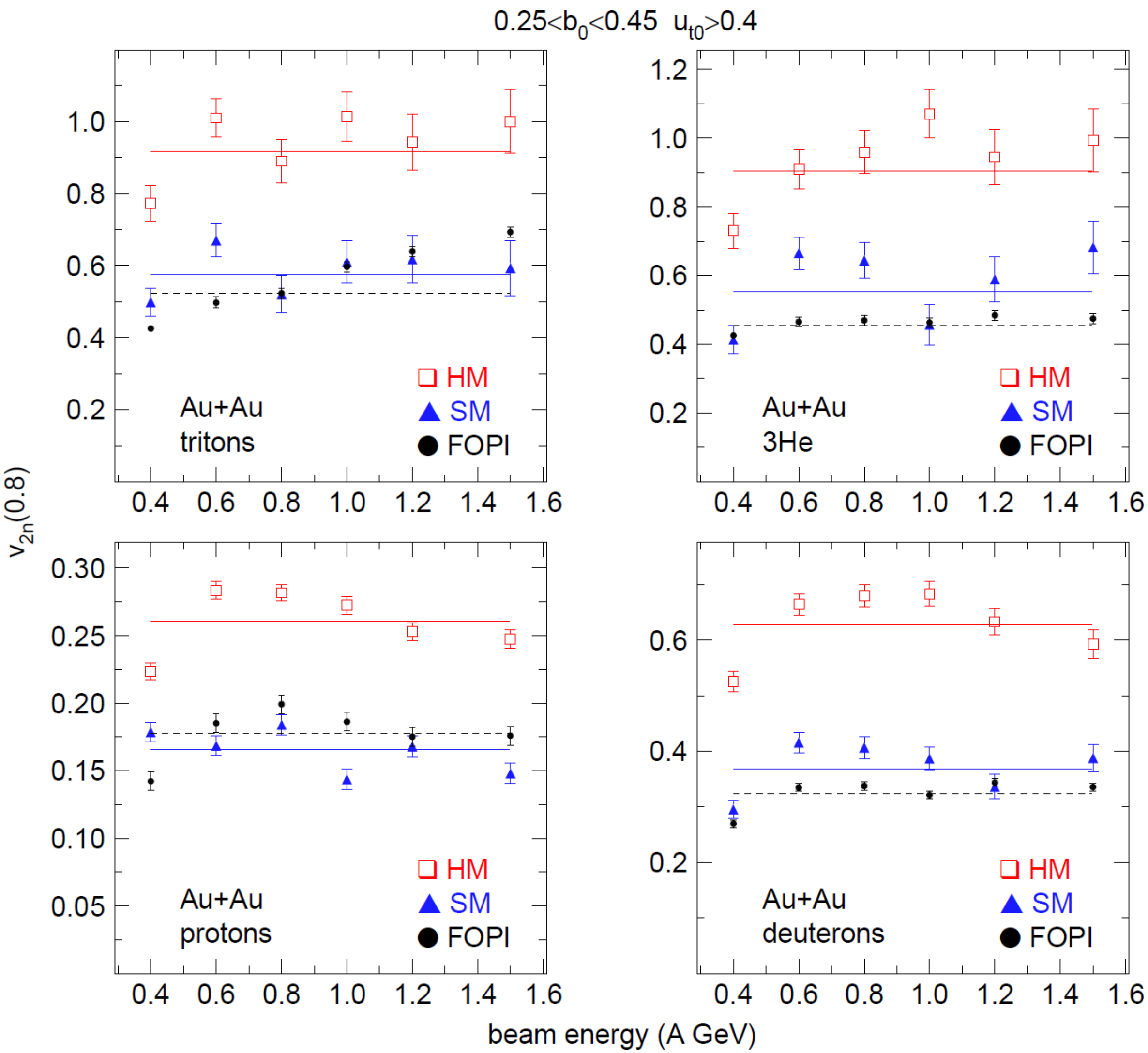


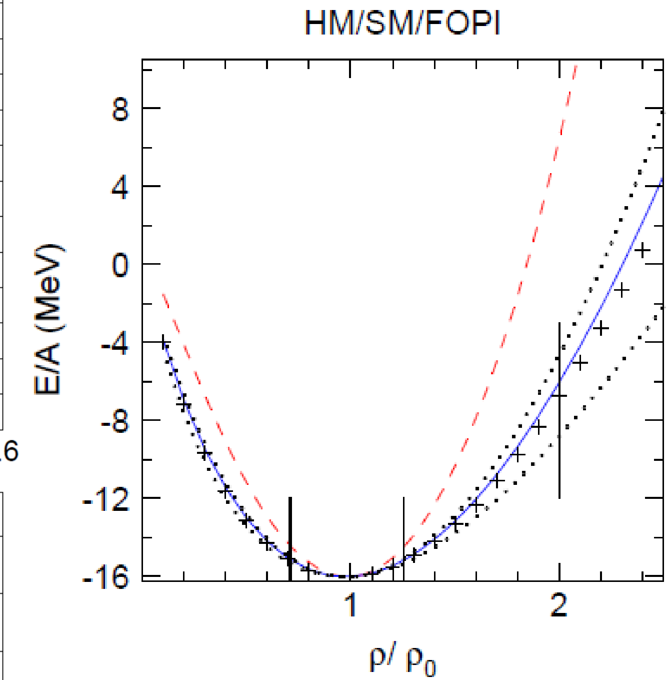


soft equation-of-state: κ ≤ 200 MeV

EOS from the elliptic flow of fragments in Au+Au collisions

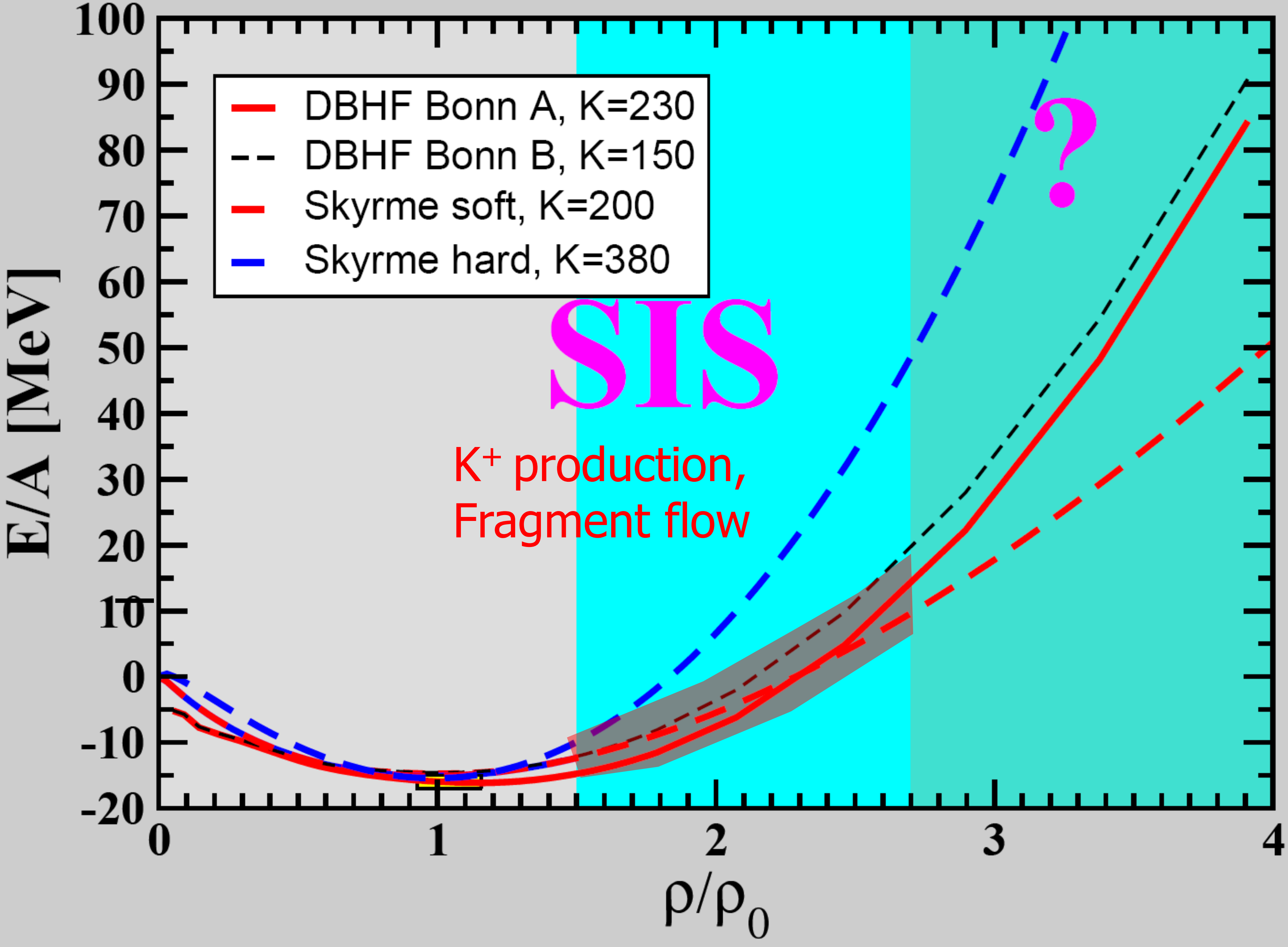
W. Reisdorf for the FOPI Collaboration, arXiv:1307.4210



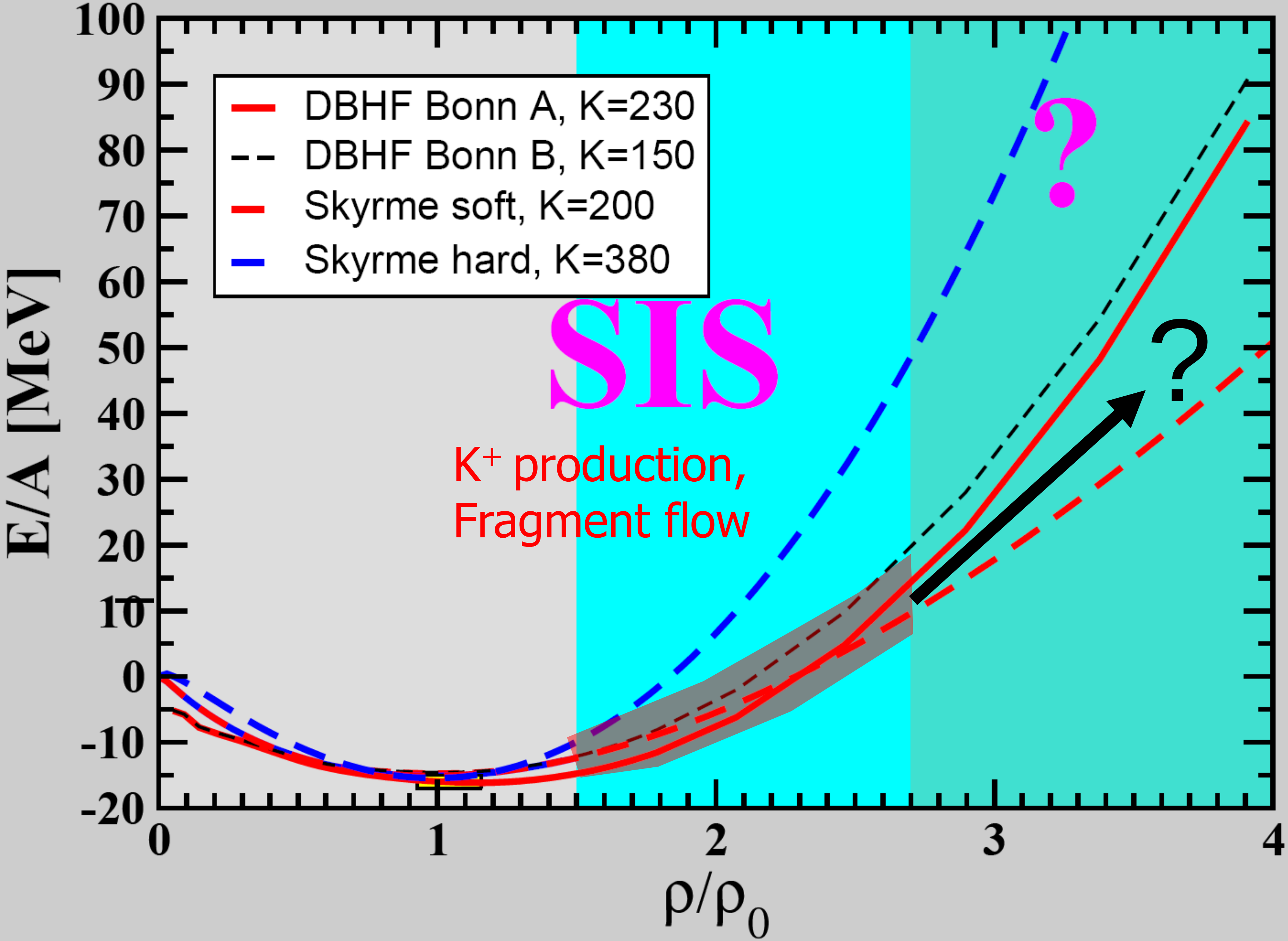


A. Le Fevre et al., FOPI collaboration
arXiv:1501.02546

nuclear matter EOS

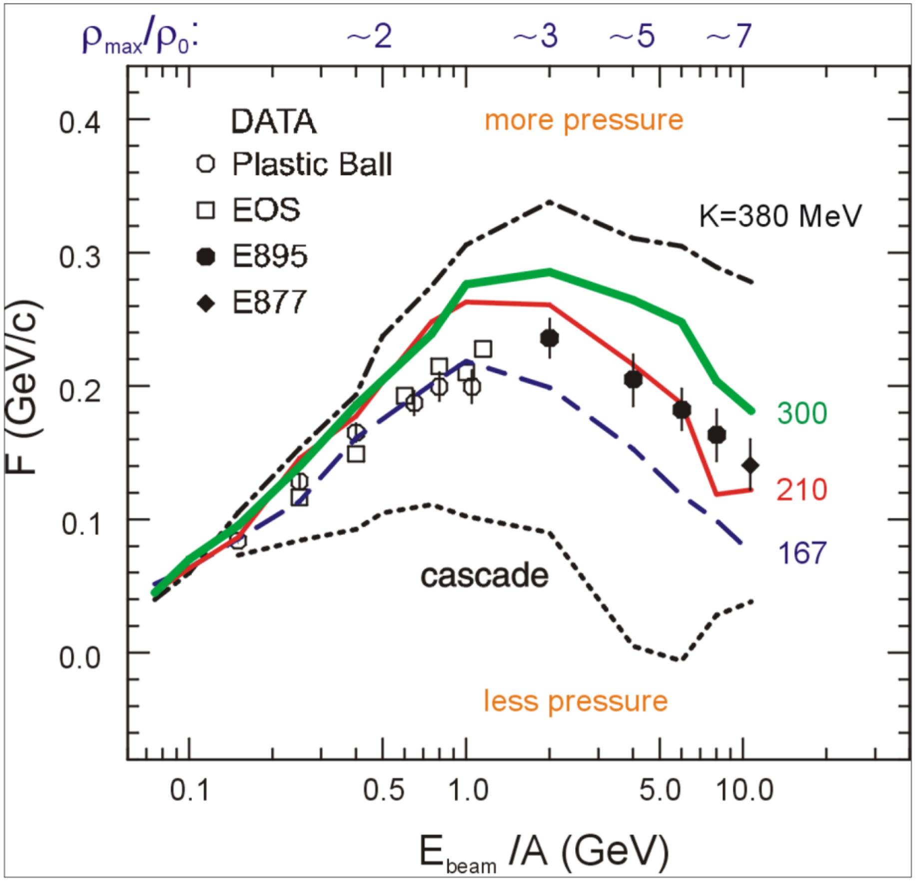


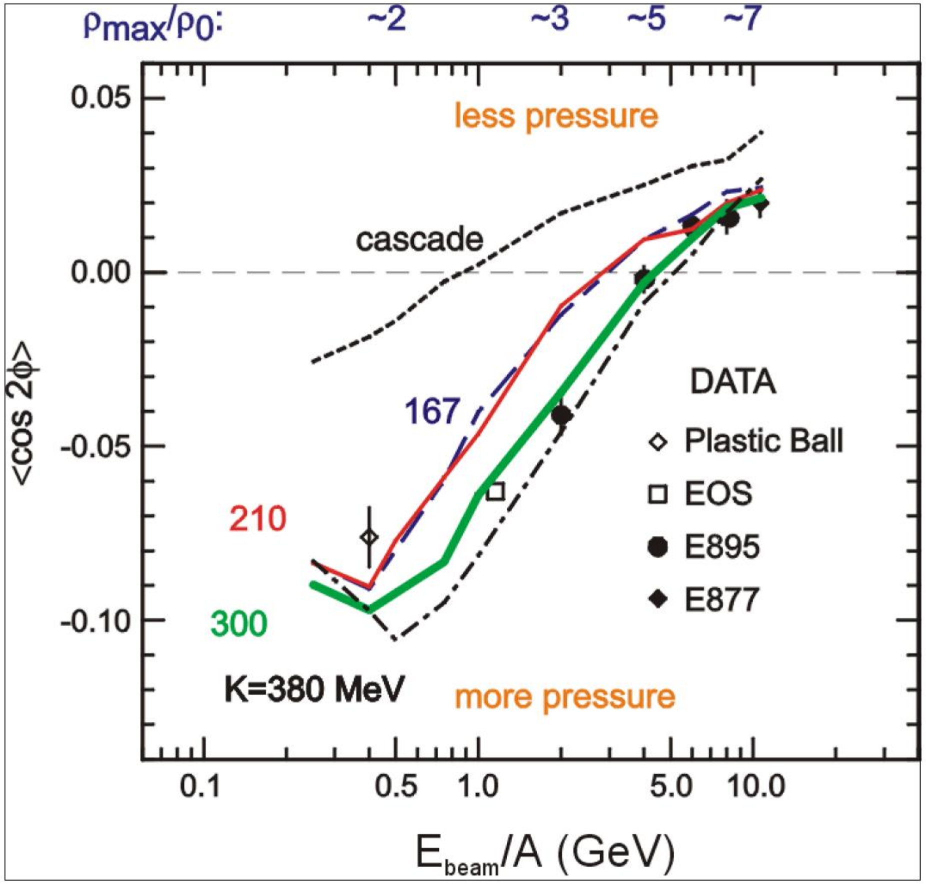
nuclear matter EOS



EOS from collective flow of protons

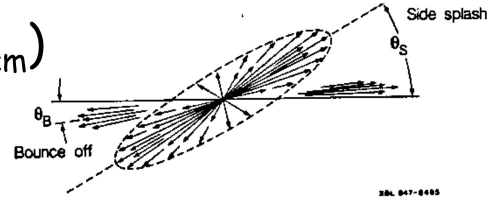
P. Danielewicz, R. Lacey, W.G. Lynch, Science 298 (2002) 1592



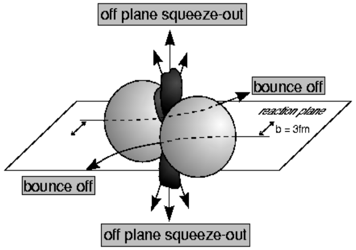


Transverse in-plane flow:

$F = d(p_x/A)/d(y/y_{cm})$



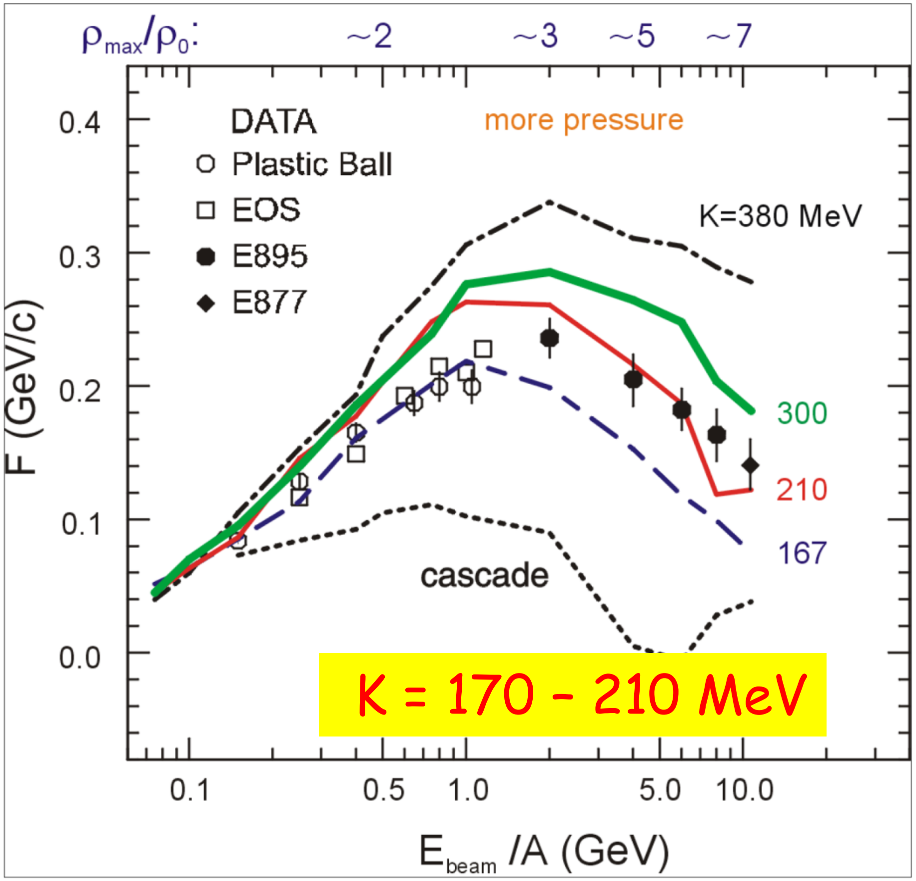
Elliptic flow:

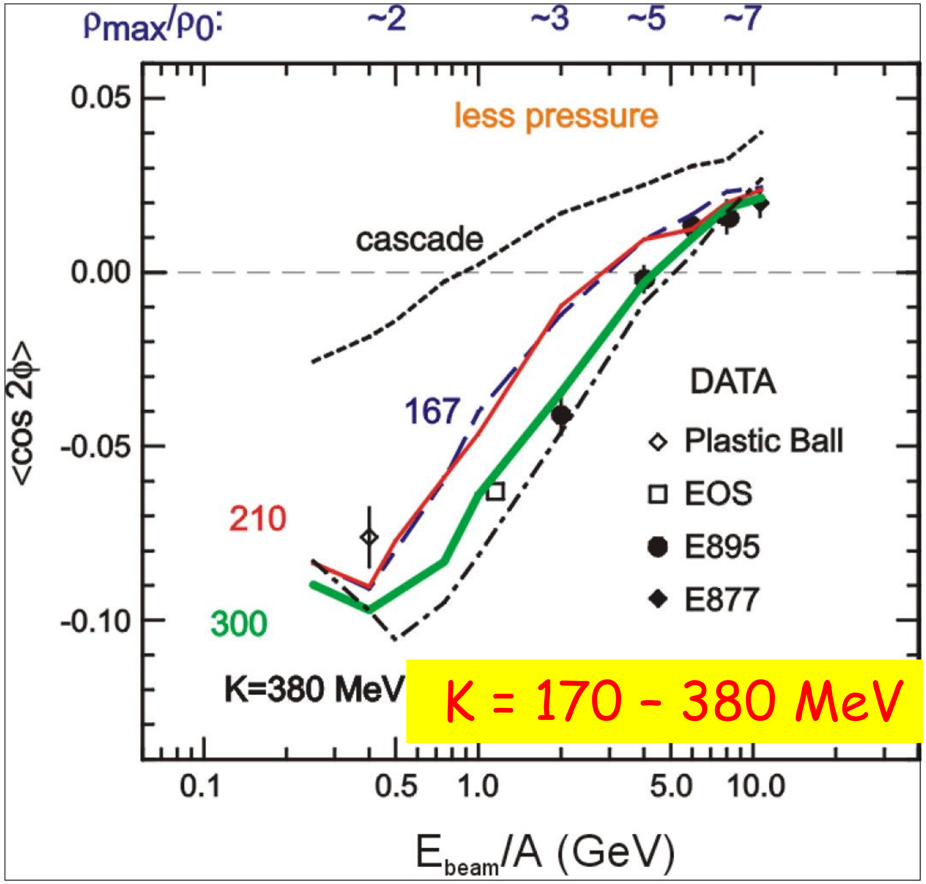


$dN/d\Phi \propto (1 + 2v_1 \cos\Phi + 2v_2 \cos 2\Phi)$

EOS from collective flow of protons

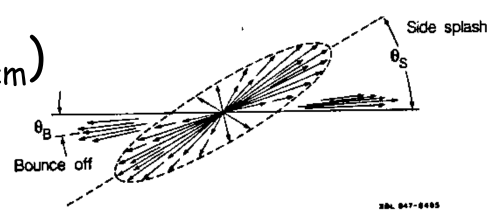
P. Danielewicz, R. Lacey, W.G. Lynch, Science 298 (2002) 1592



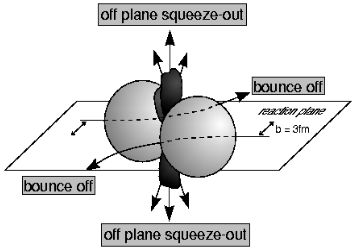


Transverse in-plane flow:

$F = d(p_x/A)/d(y/y_{cm})$



Elliptic flow:



$dN/d\Phi \propto (1 + 2v_1 \cos\Phi + 2v_2 \cos 2\Phi)$

The equation-of-state of symmetric nuclear matter at neutron star core densities

Observable: multistrange hyperon production at (sub)threshold energies

<u>Direct multi-strange hyperon production:</u>

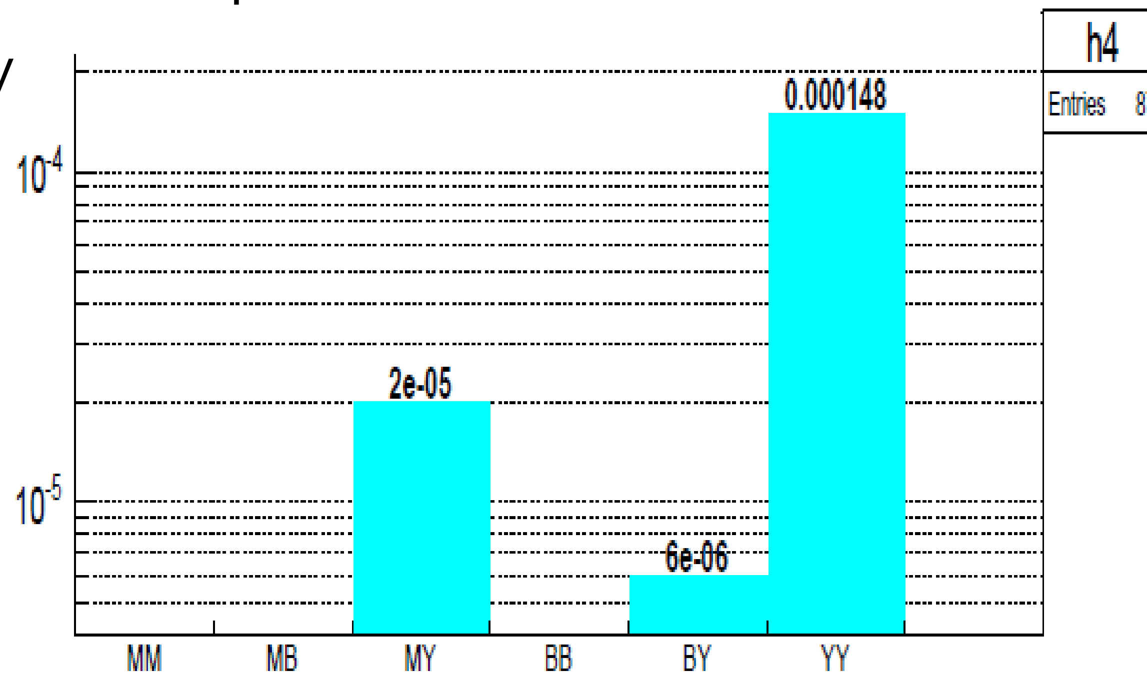
$pp \to \Xi^- K^+K^+p$ (E_{thr} = 3.7 GeV)
$pp \to \Omega^- K^+K^+K^0p$ (E_{thr} = 7.0 GeV)
$pp \to \bar{\Lambda}^0\Lambda^0\, pp$ (E_{thr} = 7.1 GeV)
$pp \to \Xi^+ \Xi^-\, pp$ (E_{thr} = 9.0 GeV)
$pp \to \Omega^+ \Omega^-\, pp$ (E_{thr} = 12.7 GeV

<u>Hyperon production via multiple strangeness exchange reactions:</u>

Hyperons (s quarks):
1. $pp \to K^+\Lambda^0 p$, $pp \to K^+K^- pp$,
2. $p\Lambda^0 \to K^+ \Xi^- p$, $\pi\Lambda^0 \to K^+ \Xi^- \pi$,
3. $\Lambda^0\Lambda^0 \to \Xi^- p$, $\Lambda^0 K^- \to \Xi^- \pi^0$
4. $\Lambda^0 \Xi^- \to \Omega^- n$, $\Xi^- K^- \to \Omega^- \pi^-$

Antihyperons (anti-s quarks):
1. $\bar{\Lambda}^0 K^+ \to \Xi^+ \pi^0$,
2. $\Xi^+ K^+ \to \Omega^+ \pi^+$.

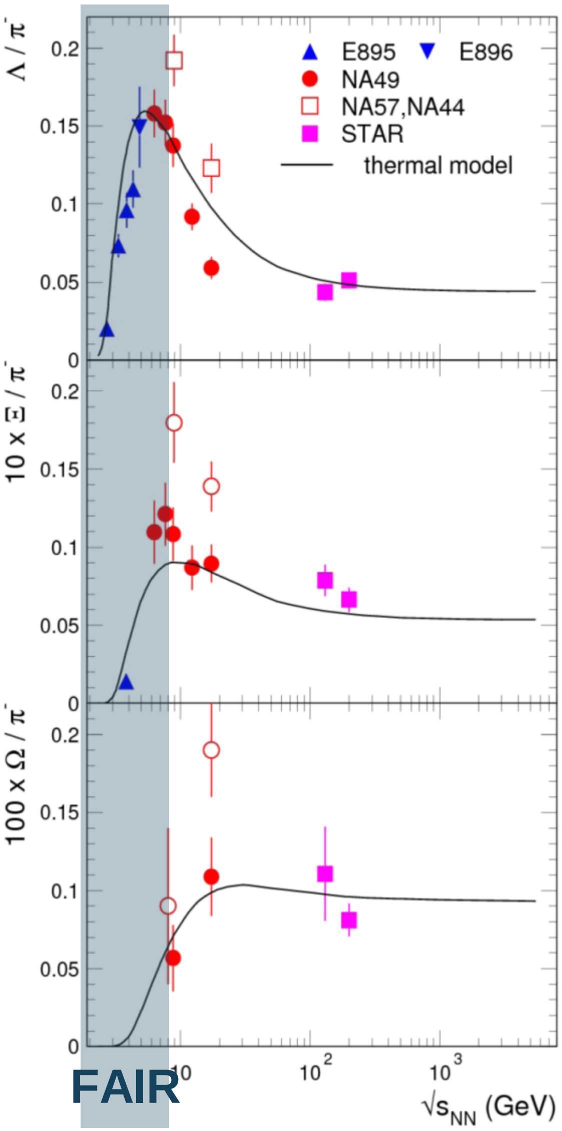
Ω^- production in 4 A GeV Au+Au



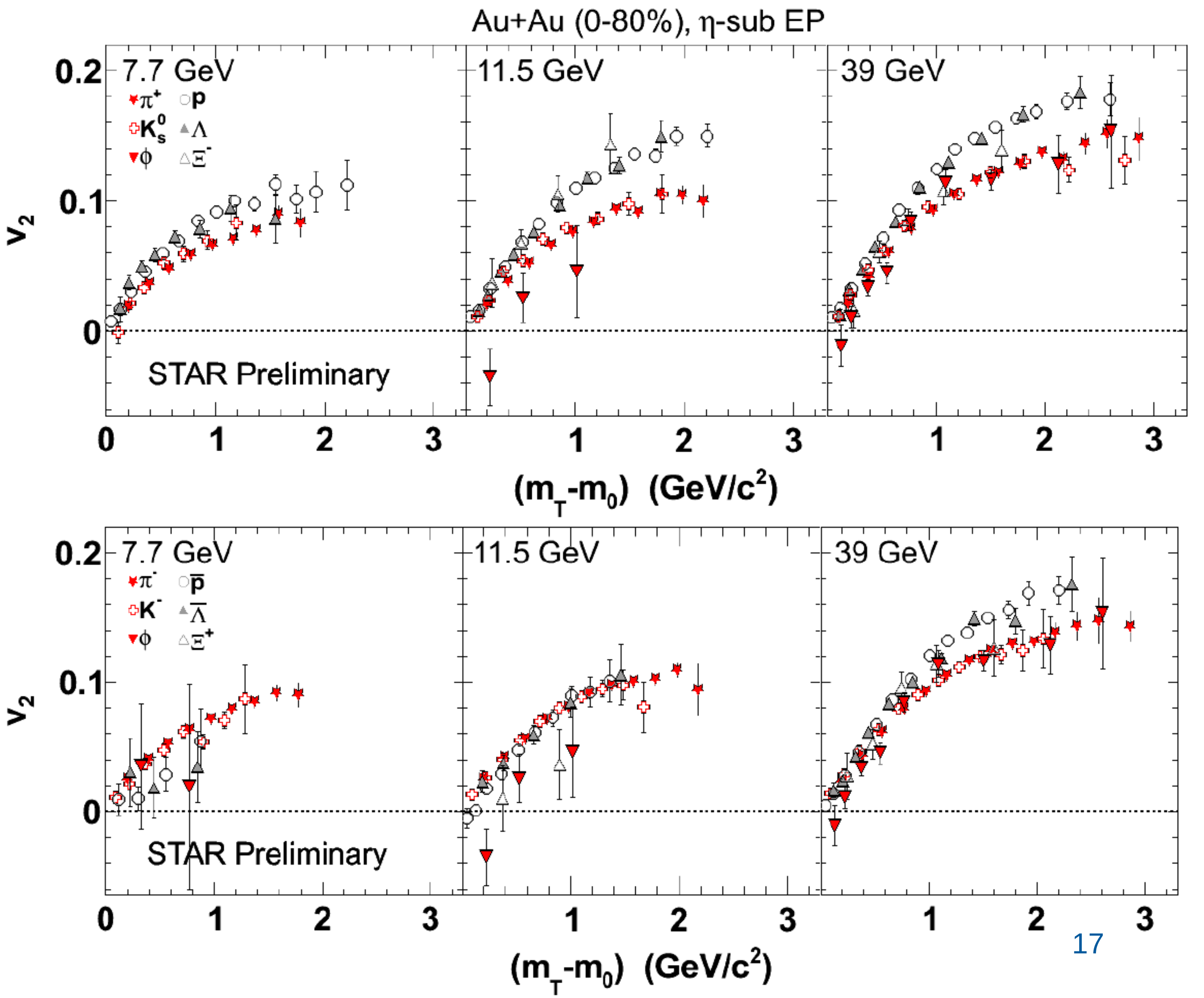
HYPQGSM calculations , K. Gudima et al.

Strangeness
Data situation

Pb+Pb, Au+Au (central)



RHIC beam energy scan

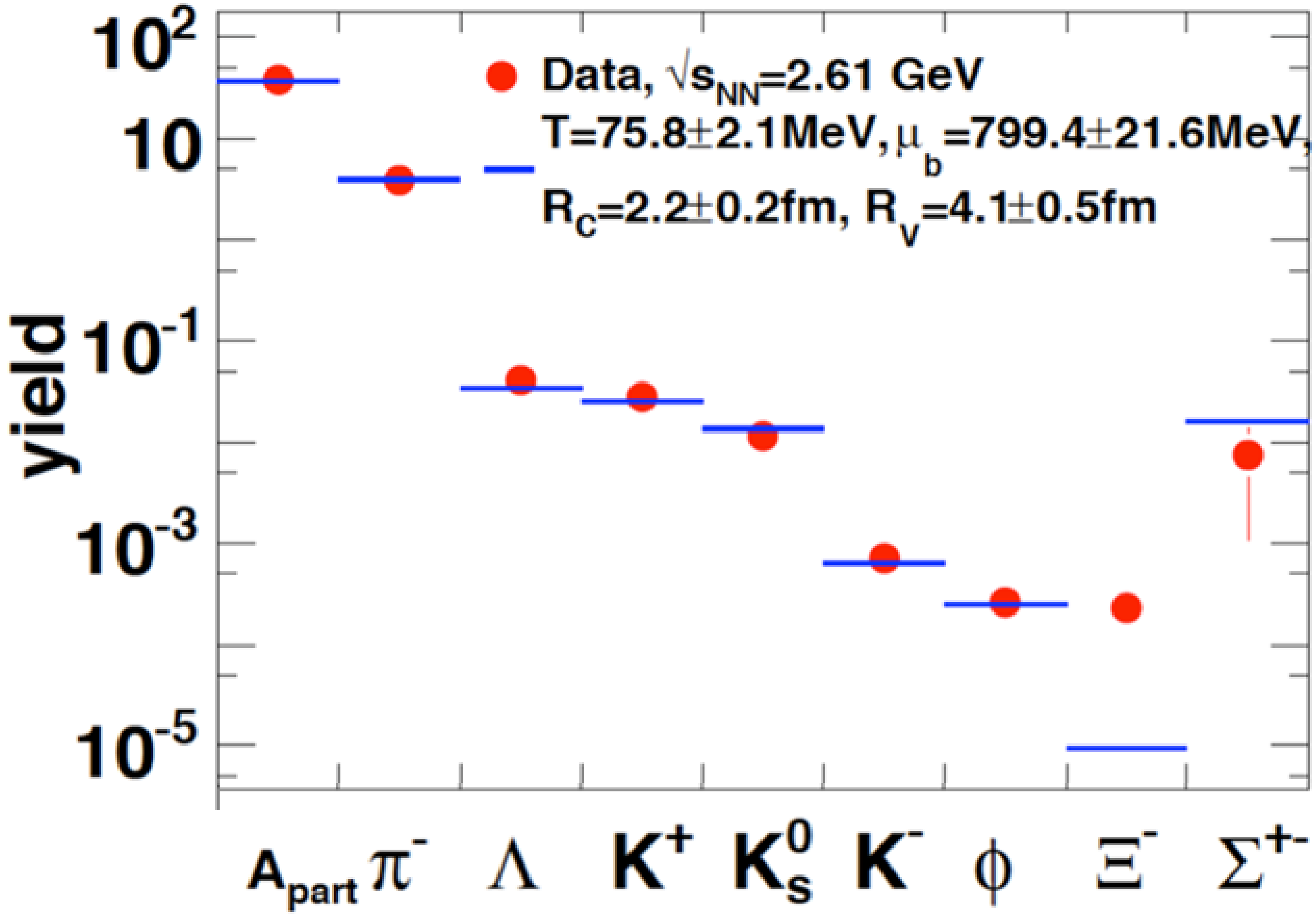


Strangeness

Data situation

HADES: Ar + KCl 1.76 A GeV

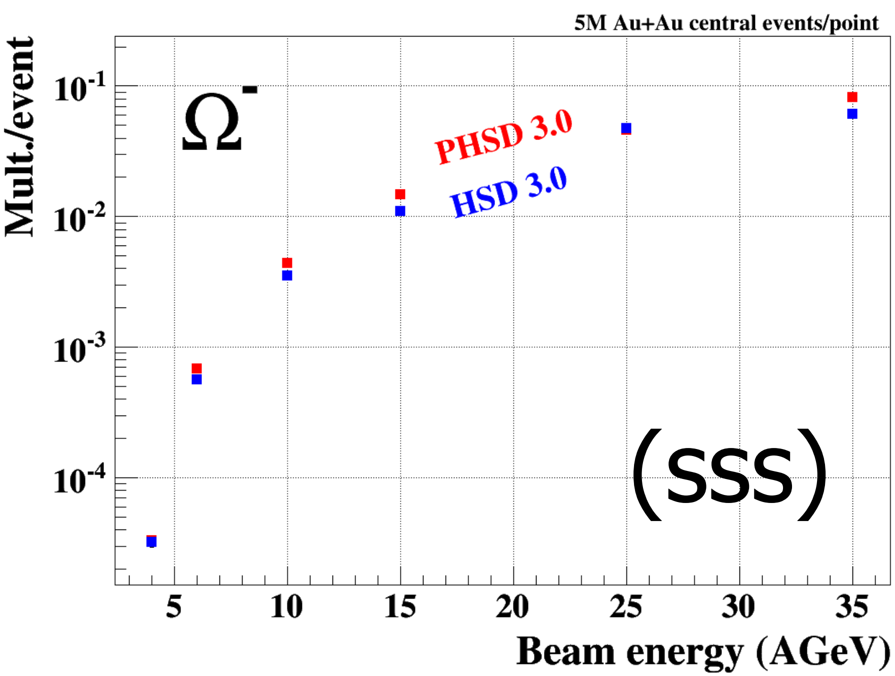
Phys. Rev. Lett. 103 (2009) 132301

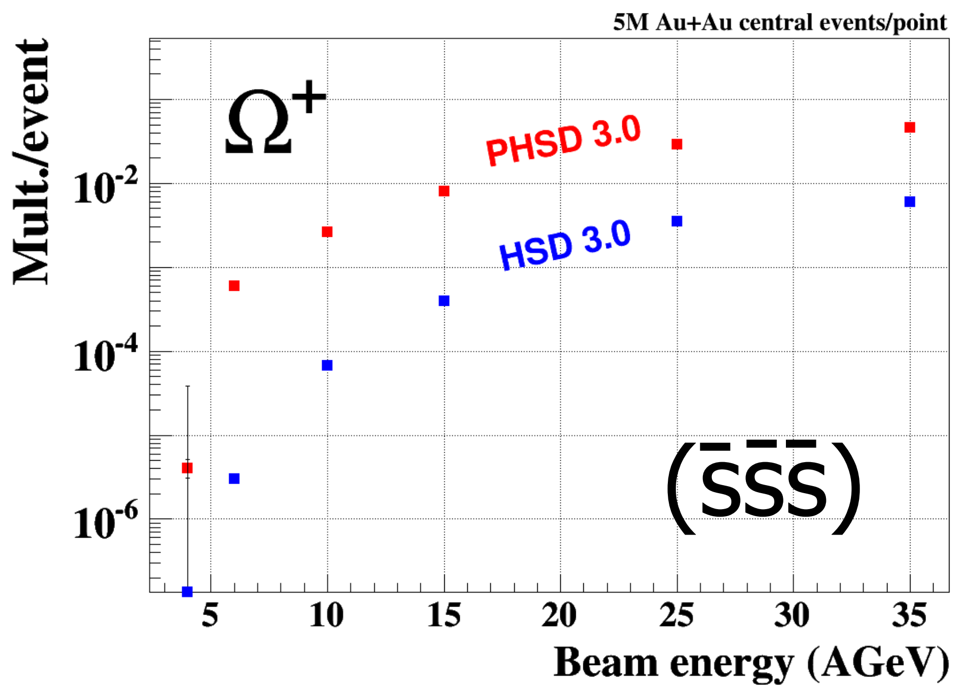


Strangeness

Multistrange (anti-)hyperon production in HSD and PHSD transport codes at FAIR energies

I. Vassiliev, E. Bratkovskaya, preliminary results

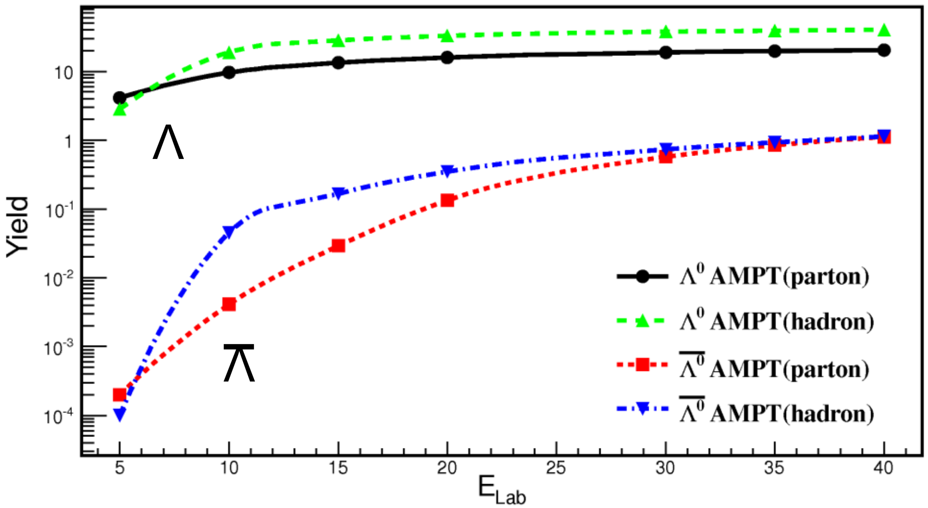




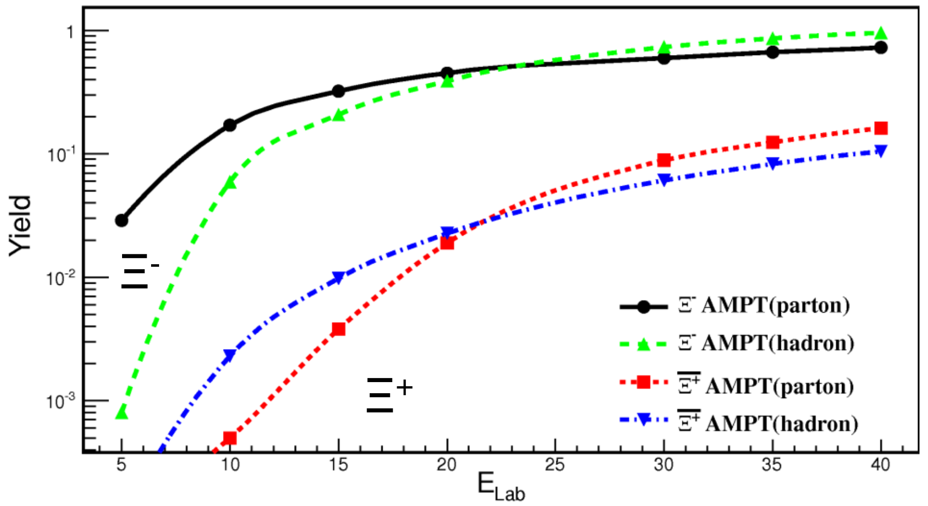
HSD: Hadronic transport code
PHSD:Hadronic transport code with partonic phase (ε > 1 GeV/fm^3)

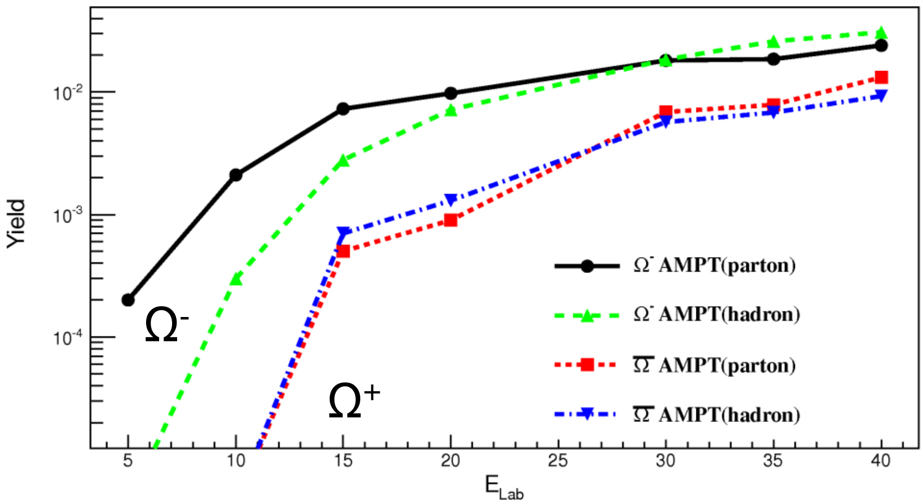
Production of (anti-)hyperons in hadronic and partonic matter

Simulations using the AMPT code of C.M. Ko, Texas A&M Univ.



http://personal.ecu.edu/linz/ampt/ampt-v1.26t1-v2.26t1.zip (9/2012)

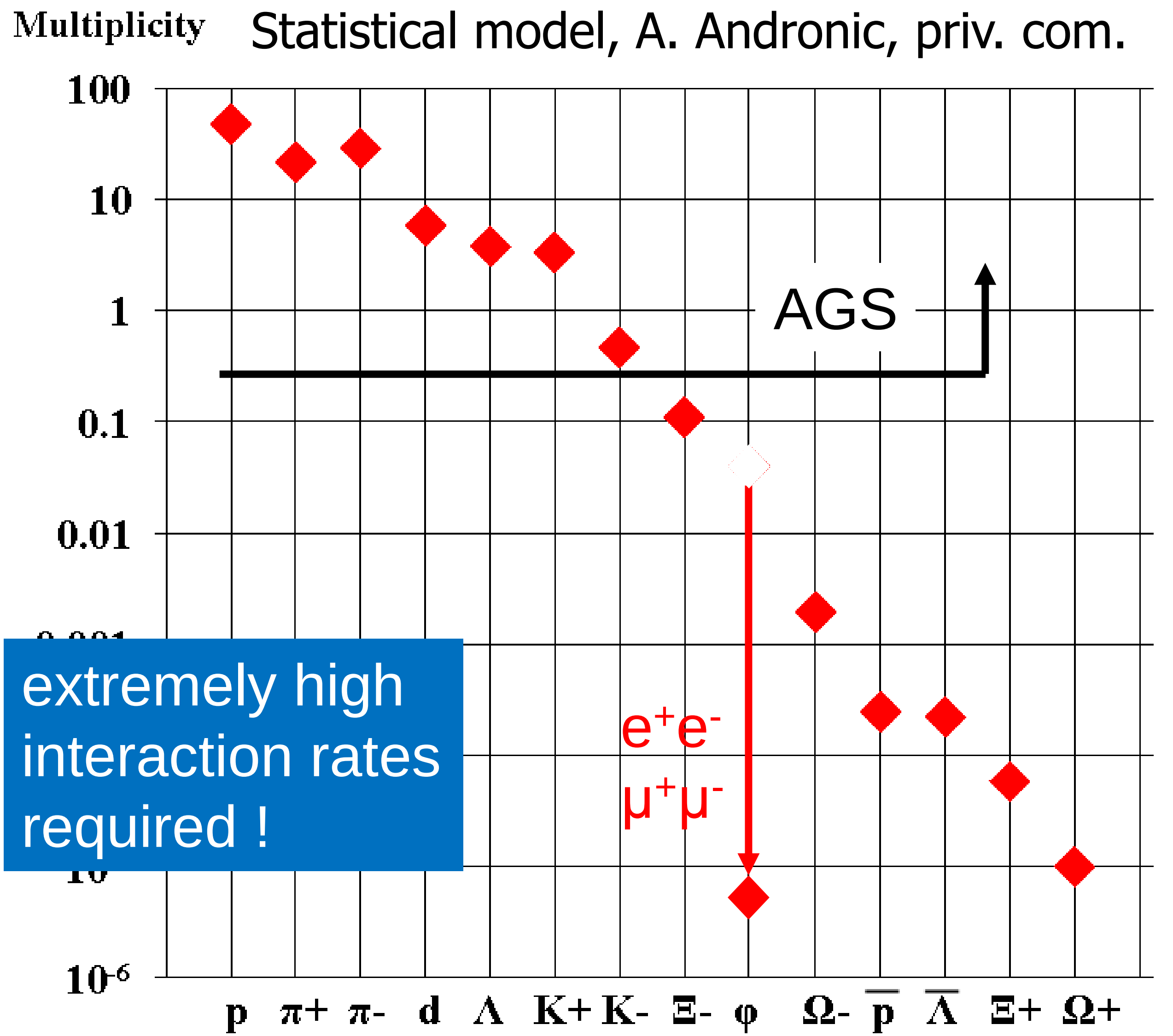




Experimental challenges

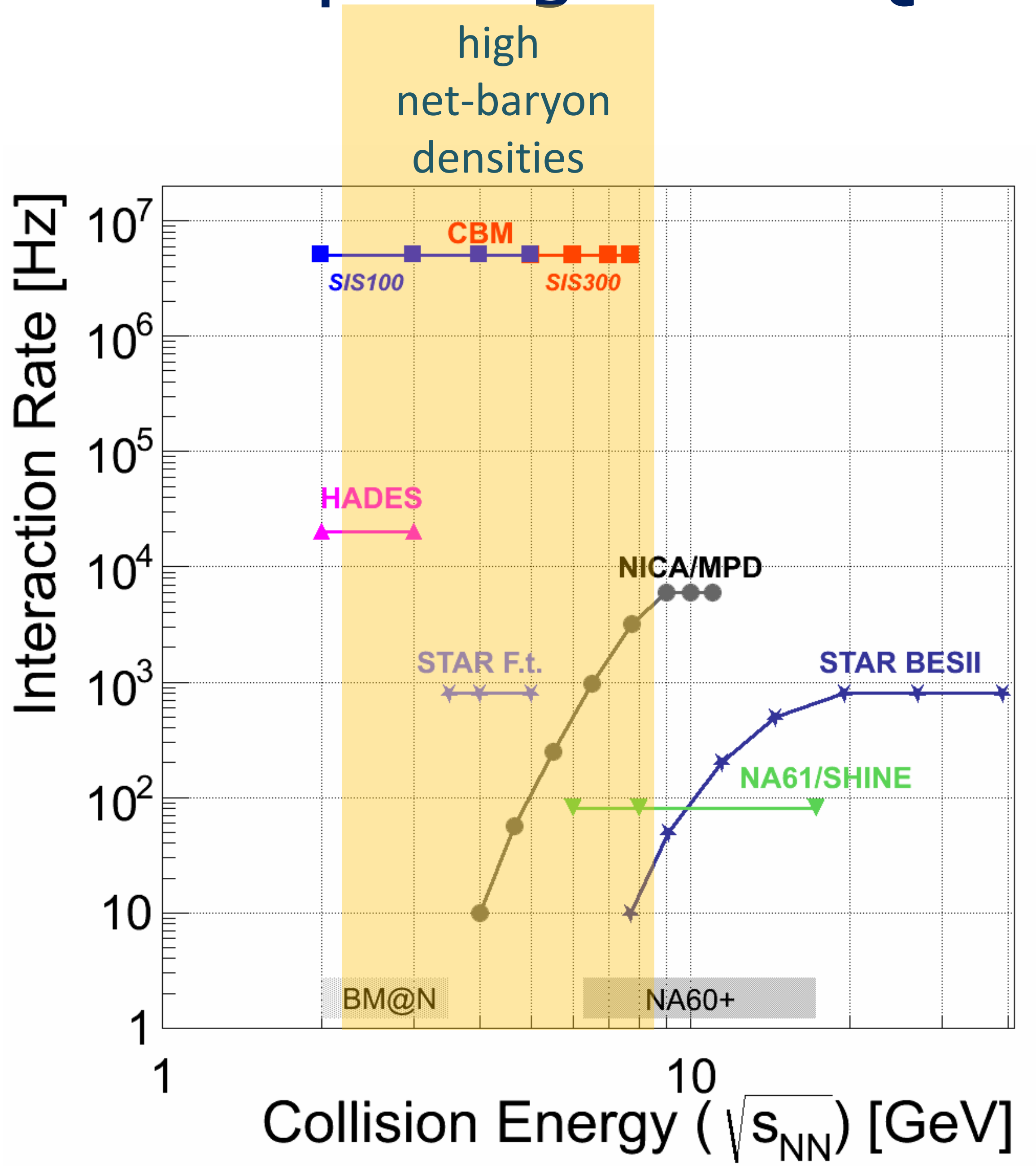
Particle yields in central Au+Au 4 A GeV

Statistical model, A. Andronic, priv. com.



extremely high interaction rates required !

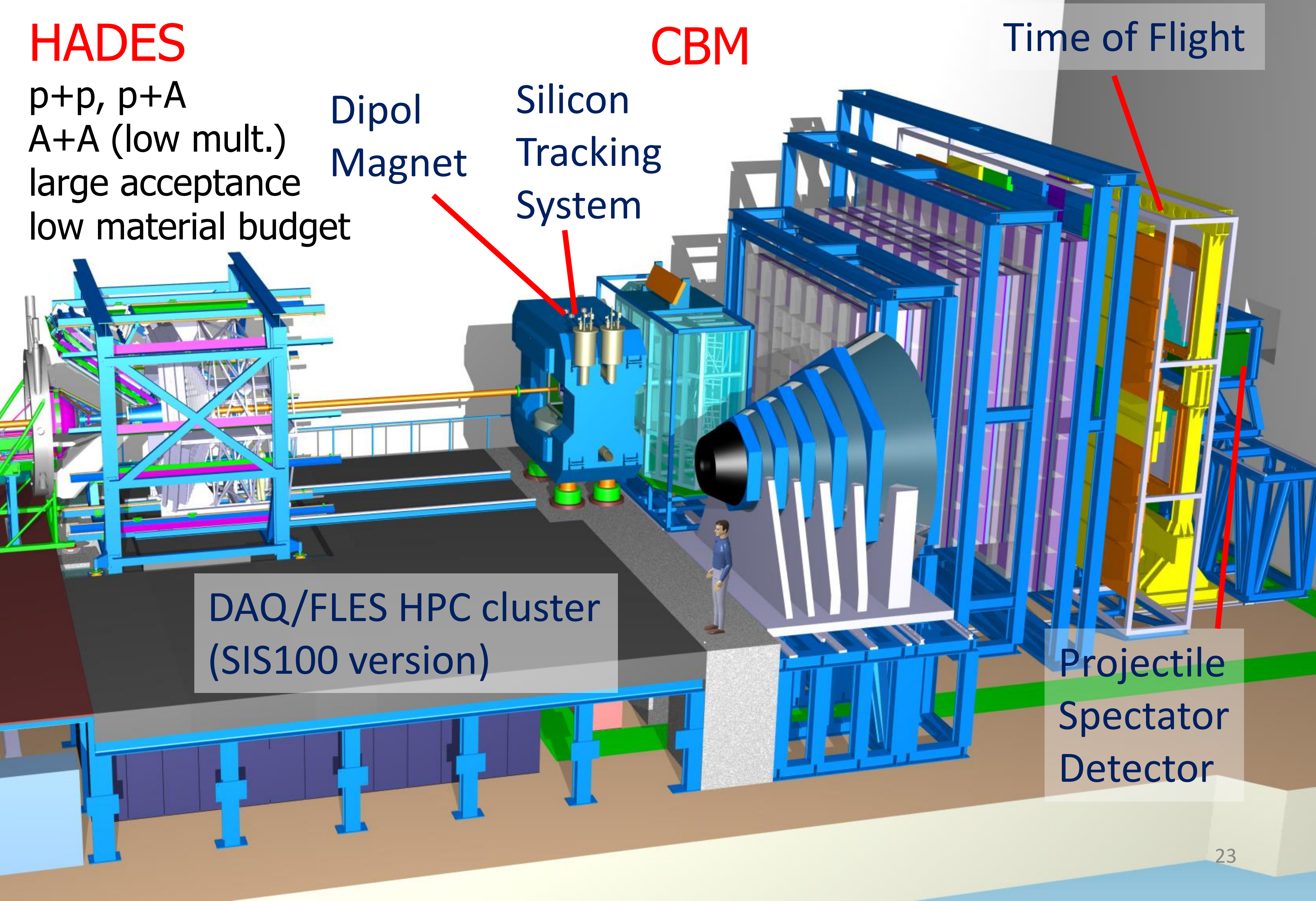
Experiments exploring dense QCD matter



Experimental requirements

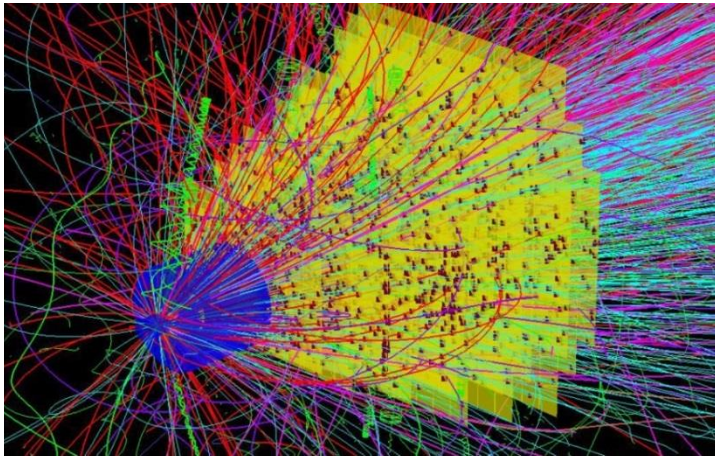
HADES

p+p, p+A
A+A (low mult.)
large acceptance
low material budget

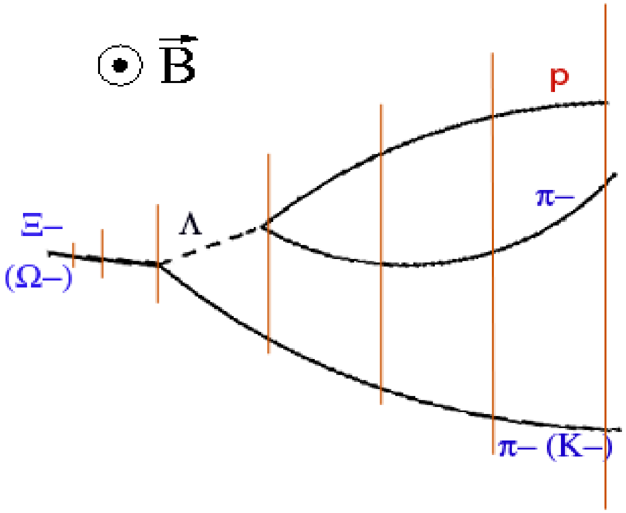


Simulations

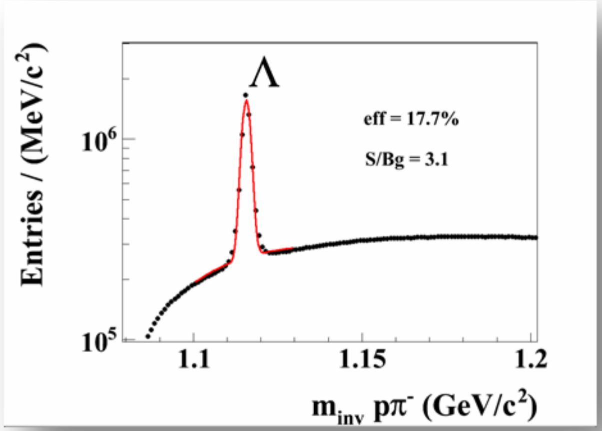
Event generators UrQMD 3.3
Transport code GEANT3, FLUKA
Realistic detector geometries, material budget and detector response

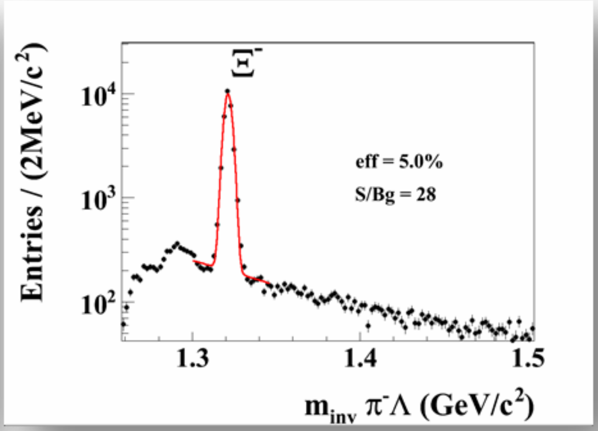


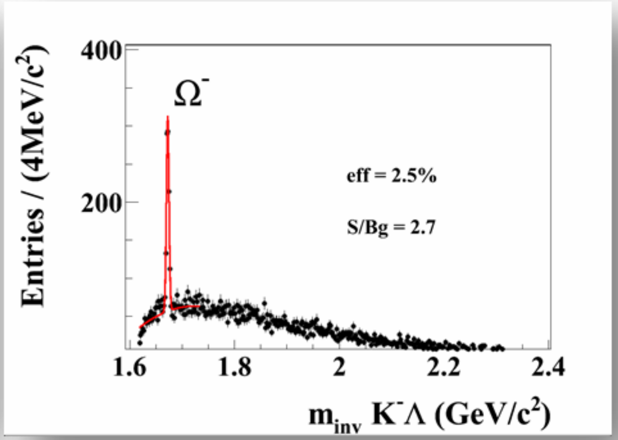
reconstruction →



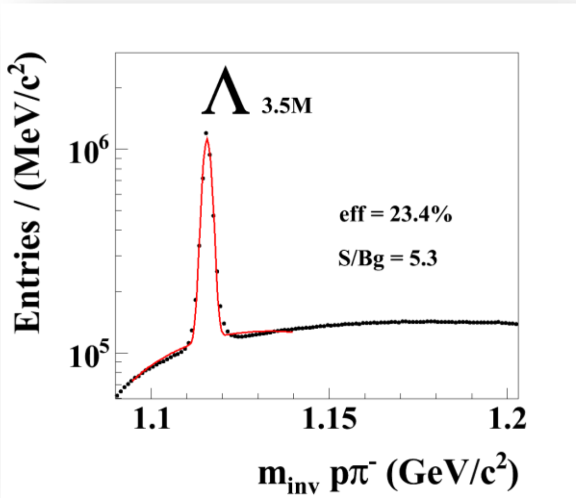
Au+Au 25 A GeV:
Ω^-/event = 1/1000

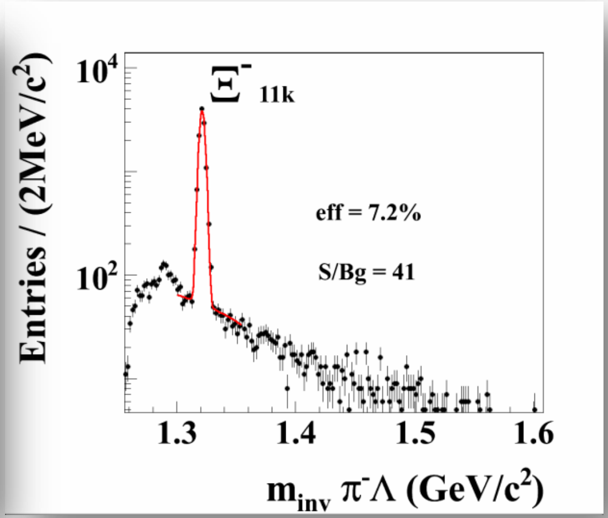


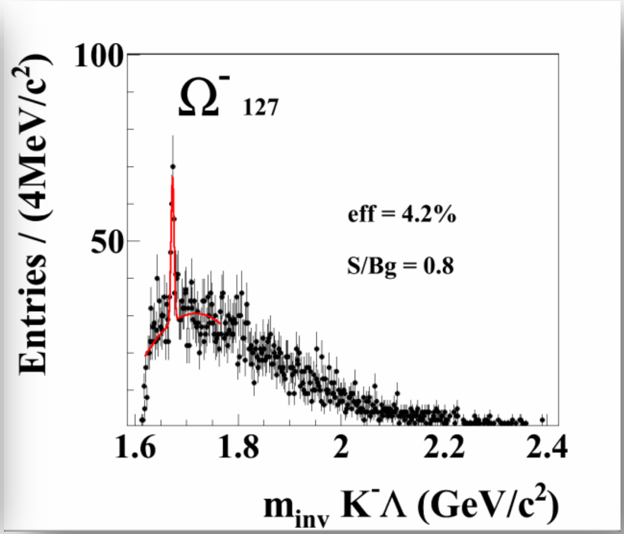


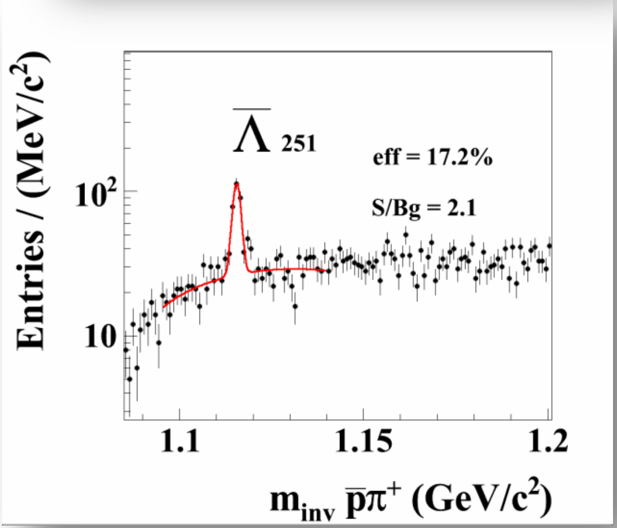


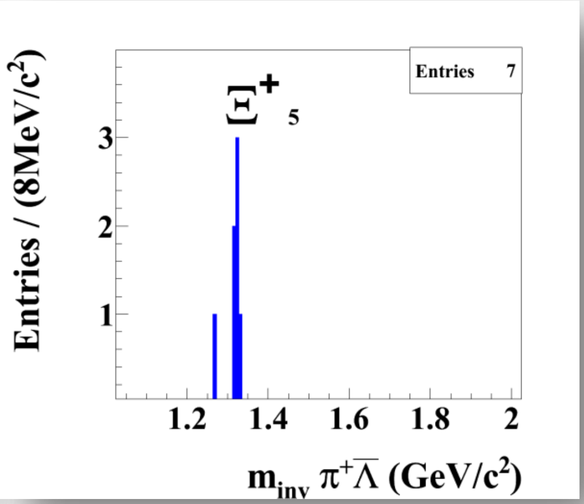
Au+Au 8 AGeV 1M central events

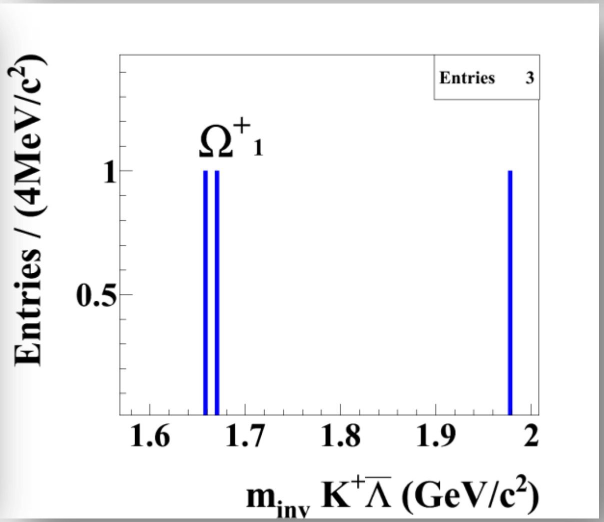












Hyperons in CBM

- Au+Au, C+C at 4 energies (4, 6, 8, 10 A GeV)
- 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	$2.4\cdot10^{11}$	$3.8\cdot10^7$	$9.6\cdot10^8$	$2.0\cdot10^6$	$1.3\cdot10^7$	$1.5\cdot10^5$

- In addition kaons and resonances (K^*,Λ^*,Σ^*,Ξ^*)

Conclusions

CBM will provide data on:

- strangeness production
- collective flow of identified particles
- dilepton production

with unprecedented statistics in heavy-ion collisions at beam energies from 3 - 14 A GeV (Au beam up to 11 A GeV)

Questions

- Are the yield, flow, spectra of multi-strange (anti-) hyperons sensitive to the dense phase of the collision ?
- Is collective flow at high beam energies sensitive to the EOS?
- Which transport/hybrid codes are suited to extract information on the nuclear EOS from observables in high-energy collisions ?
- How to disentangle effects of EOS and phase transition?