Update on physics case and observables of the BM@N heavy-ion program

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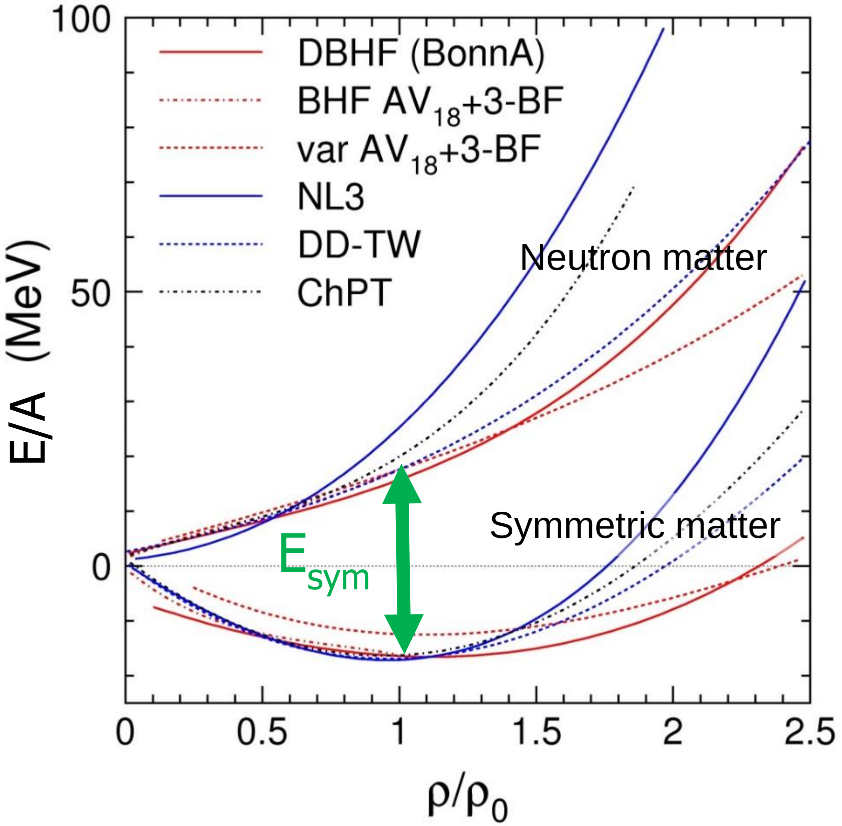
Outline:
- The heavy-ion physics program at BM@N:
  - Probing the equation-of-state of dense nuclear matter
  - Searching for quark degrees-of-freedom at high baryon densities
  - Exploring the strange dimension of the nuclear chart
- STAR fixed target results

7^{th} BM@N collaboration Meeting, JINR Dubna, April 19 -20, 2021

FAIR GSI
MEPhI
CREMLIN PLUS Connecting Russian and European Measures for Large-scale Research Infrastructures
BMBF German Russian Roadmap

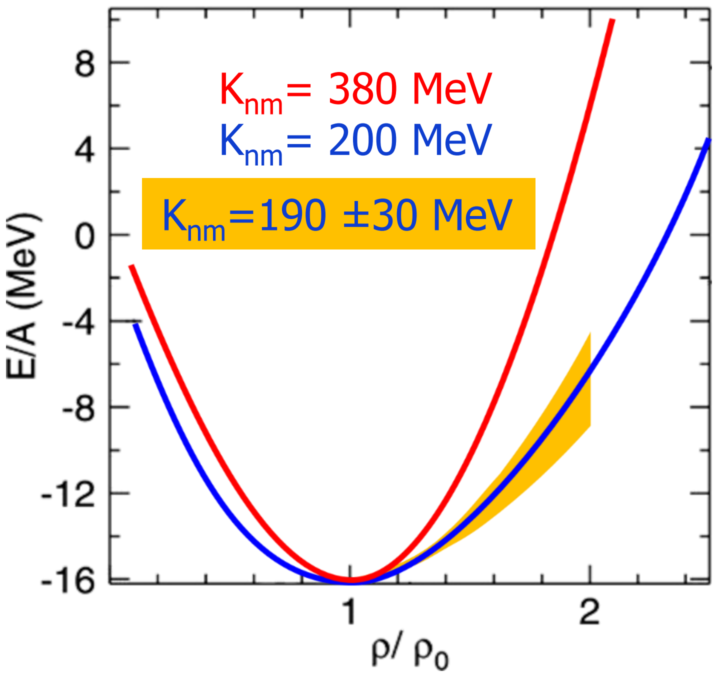
The nuclear matter equation-of-state up to 2 ρ_0



Nuclear incompressibility:
curvature $K_{nm} = 9\rho^2\ \delta^2(E/A)/\delta\rho^2$

Ch. Fuchs and H.H. Wolter, EPJA 30 (2006) 5

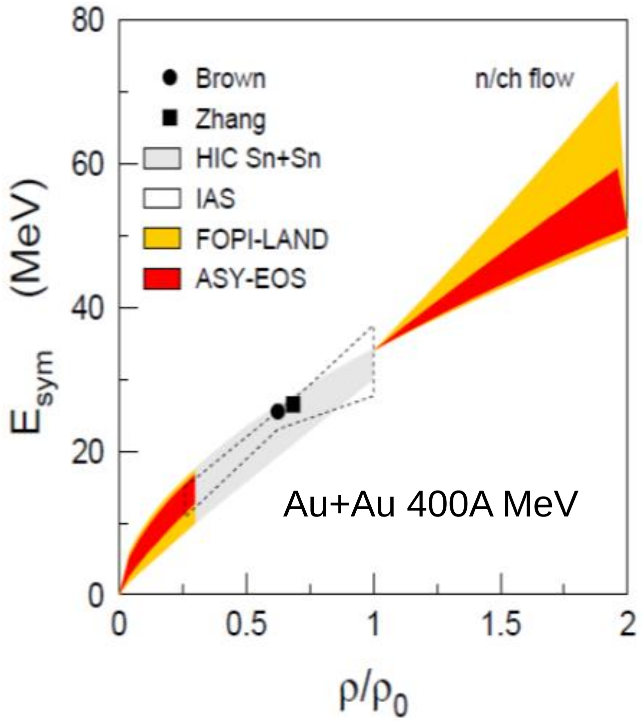
Symmetric matter



KaoS: Excitation function of kaon production in Au + Au collisions up to 1.5A GeV
C. Sturm et al., PRL 86 (2001) 39
C. Fuchs et al., PRL 86 (2001) 1974

FOPI: Excitation function of elliptic flow of protons and light fragments in Au + Au collisions up to 1.5A GeV
A. Le Fevre et al., Nucl. Phys. A945 (2016) 112

Symmetry energy

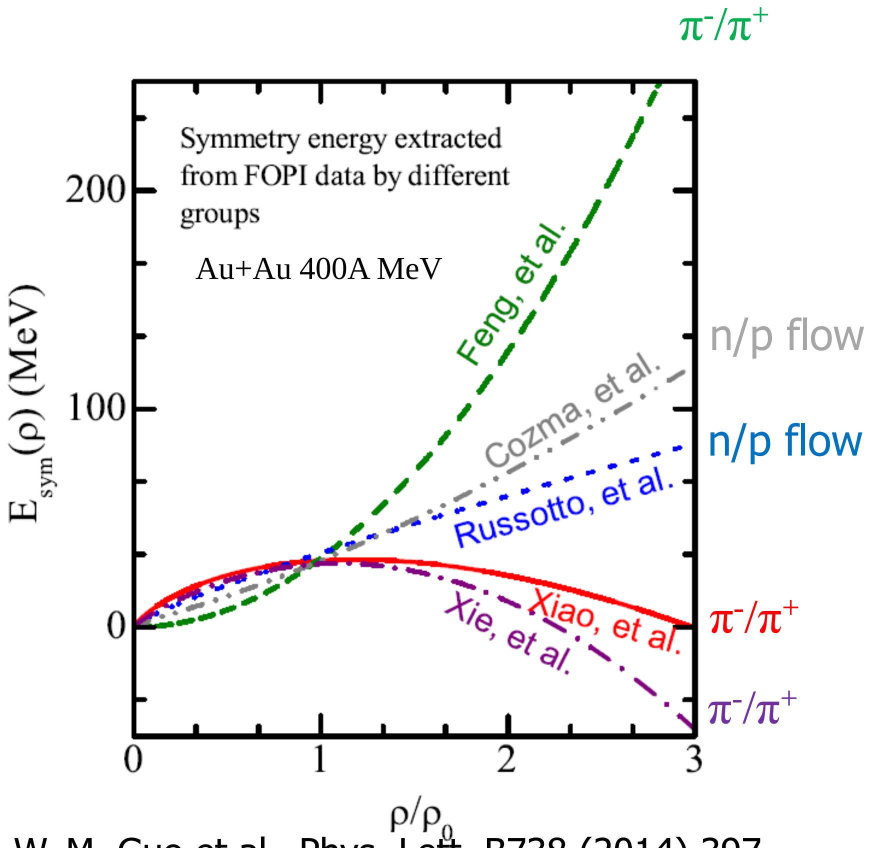


ASY-EOS: Elliptic flow of neutrons/charged particles

P. Russotto et al.,
Phys. Rev. C 94 (2016) 034608

The symmetry energy E_{sym} at high density

- Elliptic flow neutrons/protons
- Particles with opposite isospin ?

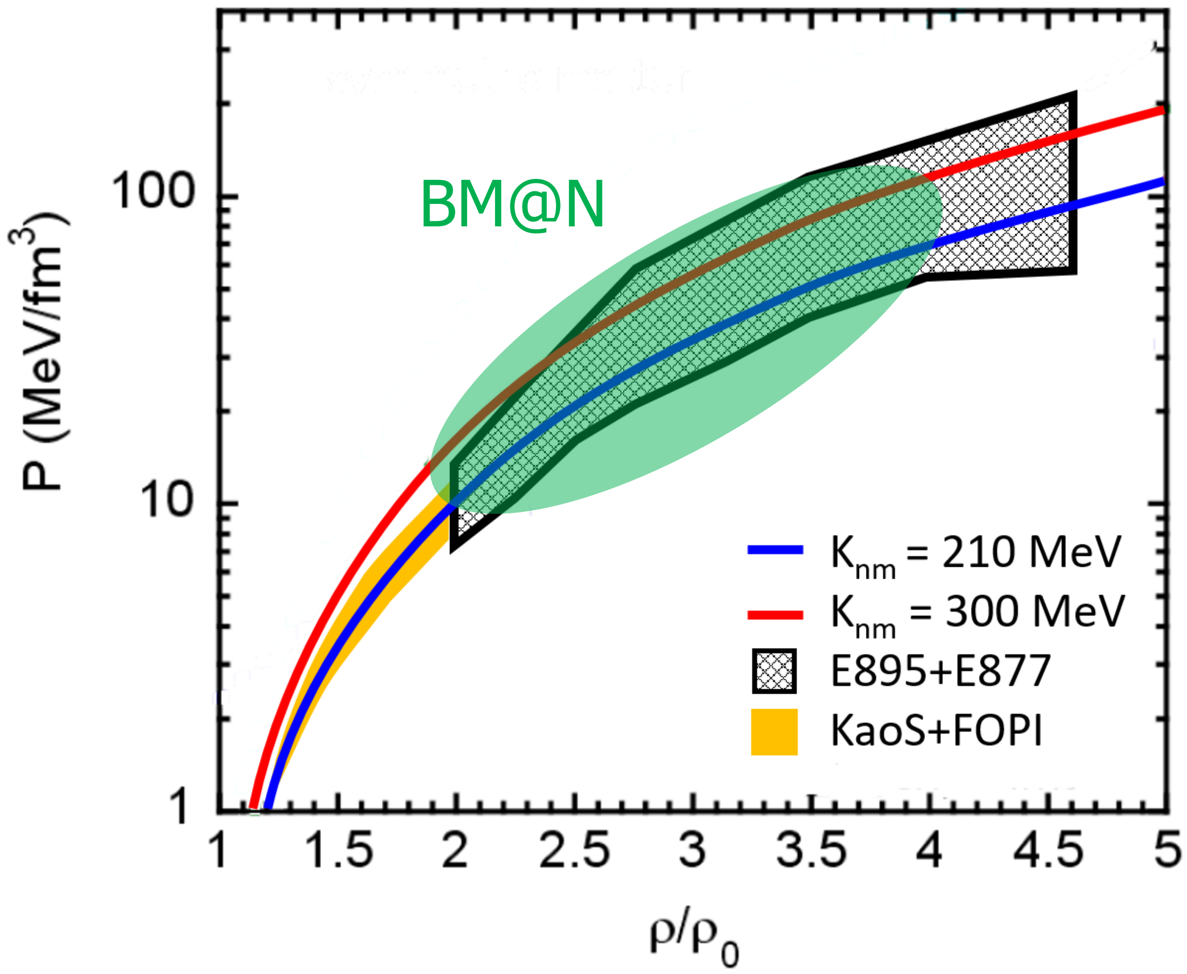


W.-M. Guo et al., Phys. Lett. B738 (2014) 397

I_3	particle	production	E_{thr} GeV	decay
+1	Σ^+(uus)	$pp \to \Sigma^+K^+n$ $pp \to \Sigma^+K^0p$ $pn \to \Sigma^+K^0n$	1.8	$\Sigma^+ \to p\pi^0$ $\Sigma^+ \to n\pi^+$
-1	Σ^-(dds)	$pn \to \Sigma^-K^+p$ $nn \to \Sigma^-K^+n$	1.8	$\Sigma^- \to n\pi^-$

I_3	particle	production	E_{thr} GeV	decay
+1	Σ^{*+}(uus)	$pp \to \Sigma^{*+}K^+n$ $pp \to \Sigma^{*+}K^0p$ $pn \to \Sigma^{*+}K^0n$	2.34	$\Sigma^{*+} \to \Lambda\pi^+$
-1	Σ^{*-}(dds)	$pn \to \Sigma^{*-}K^+p$ $nn \to \Sigma^{*-}K^+n$	2.34	$\Sigma^{*-} \to \Lambda\pi^-$

EOS of dense symmetric nuclear matter: The heavy-ion constraint



Grey area:

Data: transverse and elliptic proton flow (AGS)

E895: C. Pinkenburg et al., Phys. Rev. Lett. 83 (1999) 1295

E877: P. Braun-Munzinger et al., Nucl. Phys. A638 (1998) 3c

Theory:

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

Yellow area:

KaoS: Subthreshold K^+ production (GSI)

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

Theory: RQMD

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

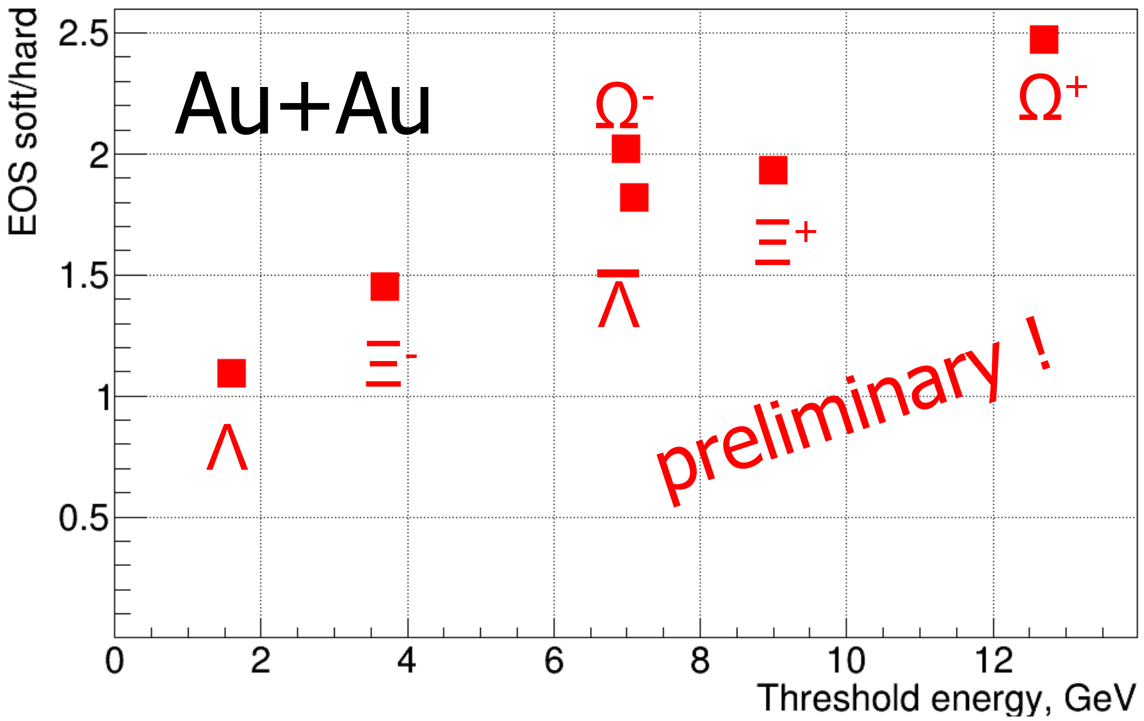
FOPI: Elliptic flow of protons and light fragments (GSI)

A. Le Fevre et al., Nucl. Phys. A945 (2016) 112

BM@N: collective flow, hyperon production

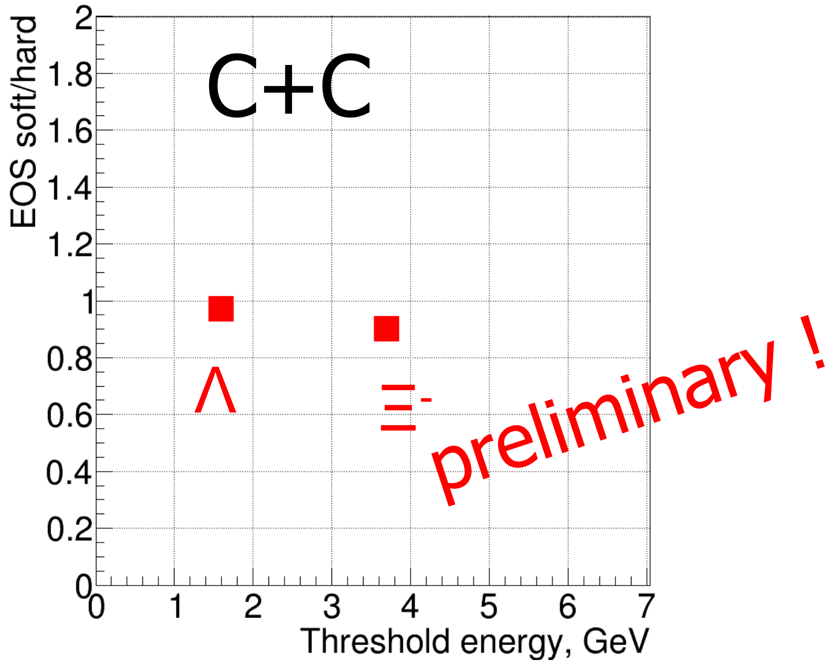
Multi-strange hyperons: promising observables for the EOS of symmetric matter at Nuclotron beam energies

Hyperon yield in heavy ion collisions at 4A GeV (BM@N energies):
soft EOS (K=240 MeV) / hard EOS (K=350) MeV



PHQMD: J. Aichelin et al., Phys. Rev. C 101 (2020) 044905

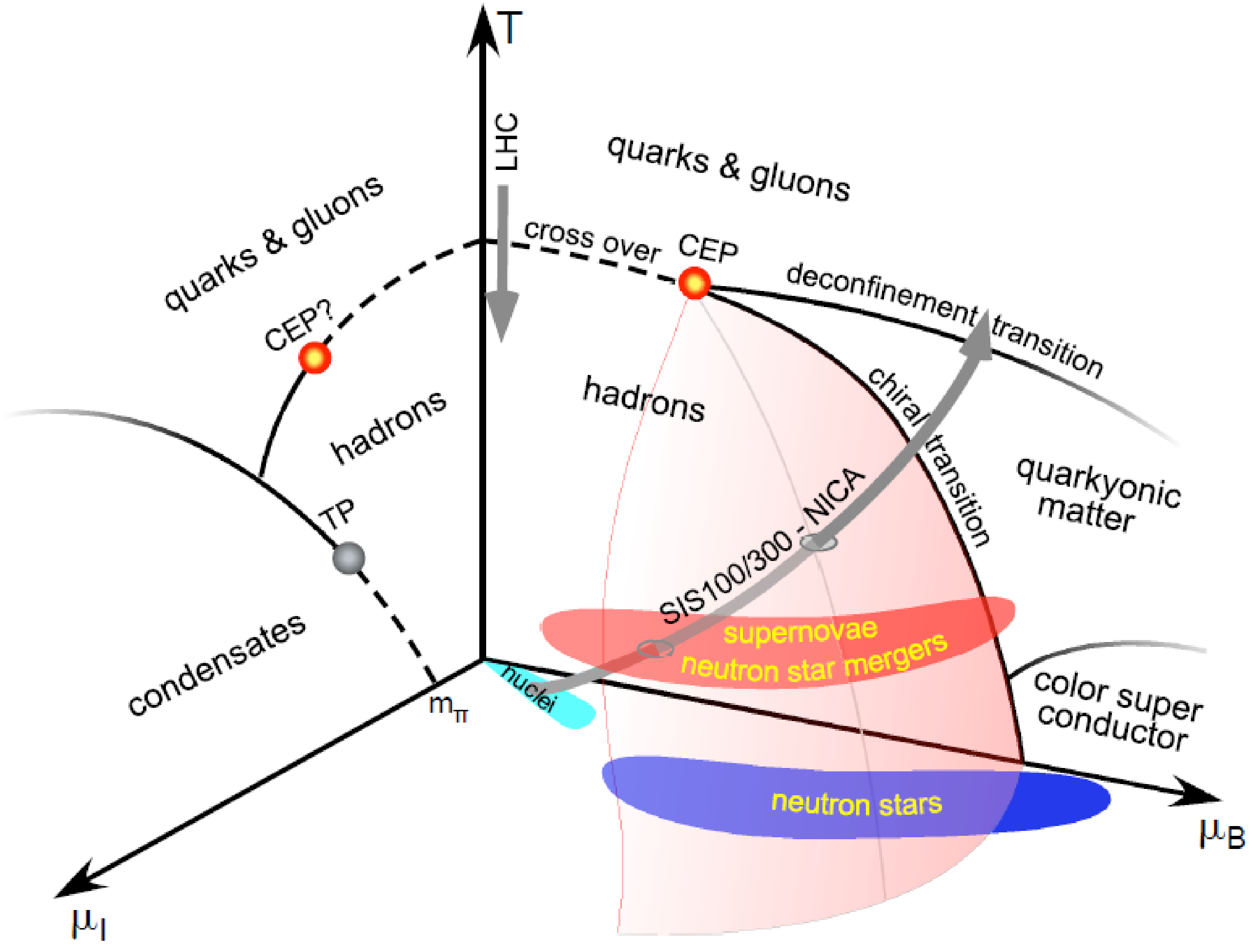
With crossover transition to quark matter above ε = 0.5 GeV/fm^3 (~ 3 ρ_0)



Reference measurement reduce:

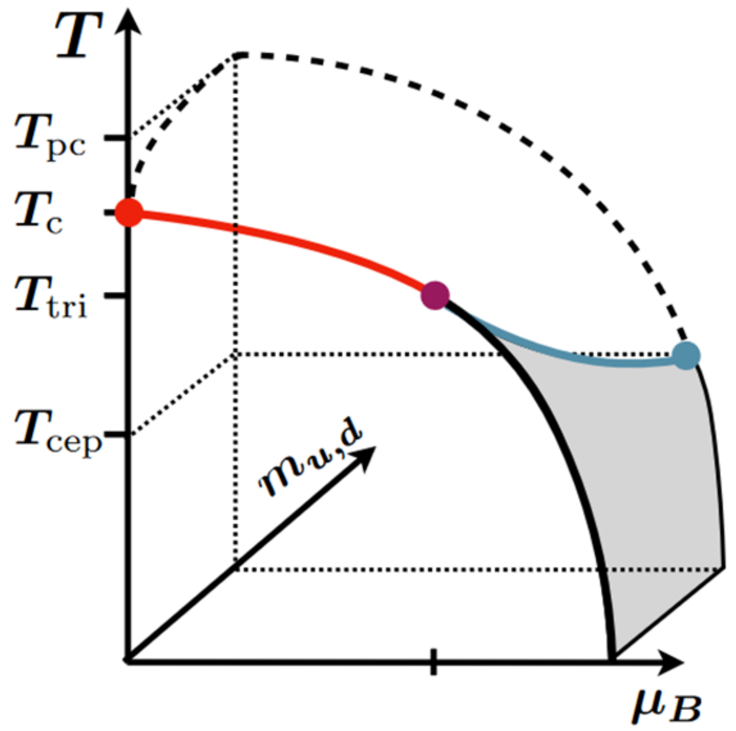
- systematic errors of experiment and theory
- contributions from SRC, in-medium cross sections, momentum-dependent interactions

Exploring the QCD phase diagram



NUPECC Long Range Plan 2017

lQCD, F. Karsch, arXiv:1905.03936



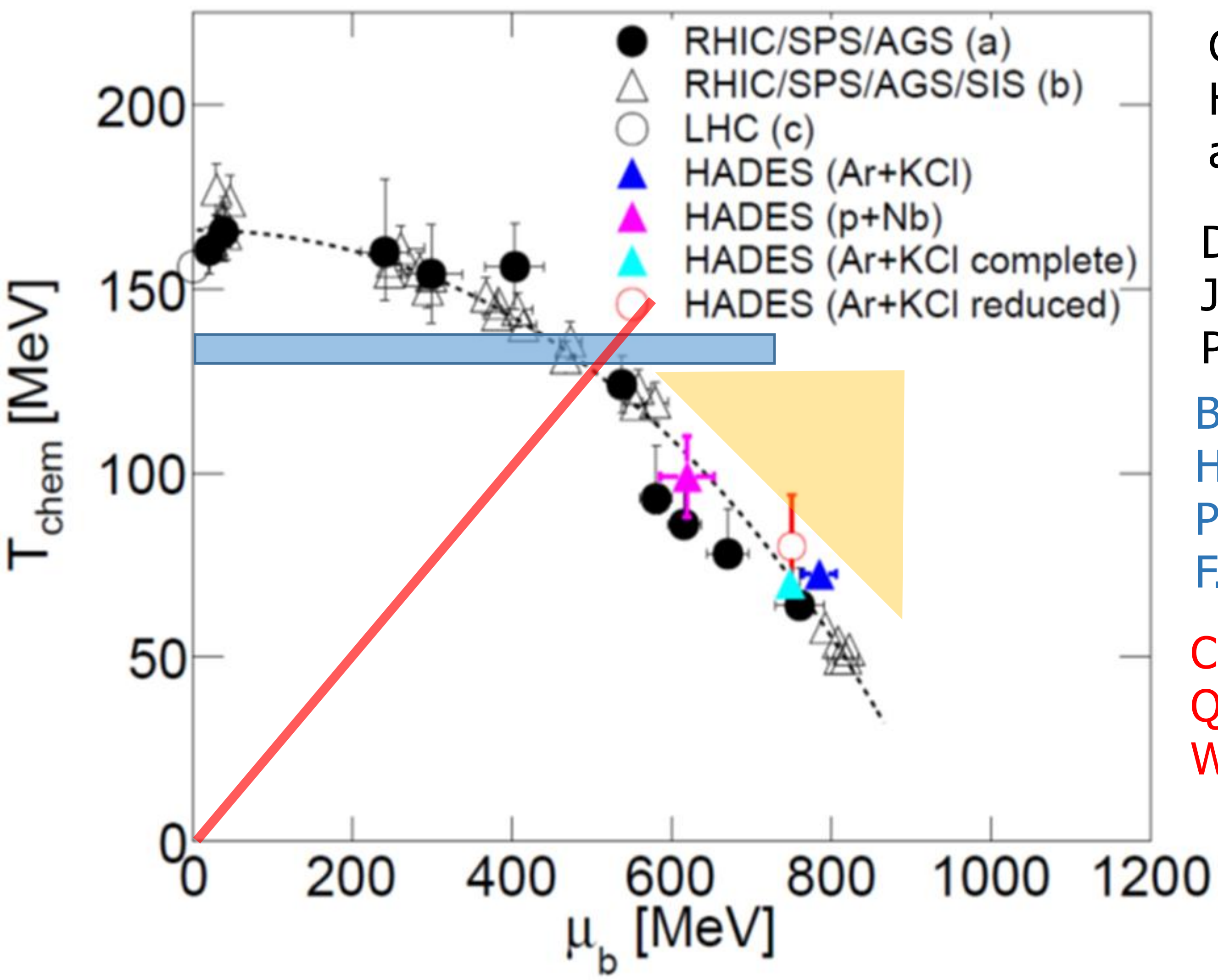
T_{pc}= 156.5 ± 1.5 MeV at $\mu_B = 0$

Chiral phase transition:

T^0_c = 132 + 3 – 6 MeV at $\mu_B = 0$

Conclusion: $T_{cep} < T^0_c$ “if it exists at all”

On the location of a possible critical endpoint



G. Agakishiev et al.,
HADES Collaboration
arXiv:1512.07070

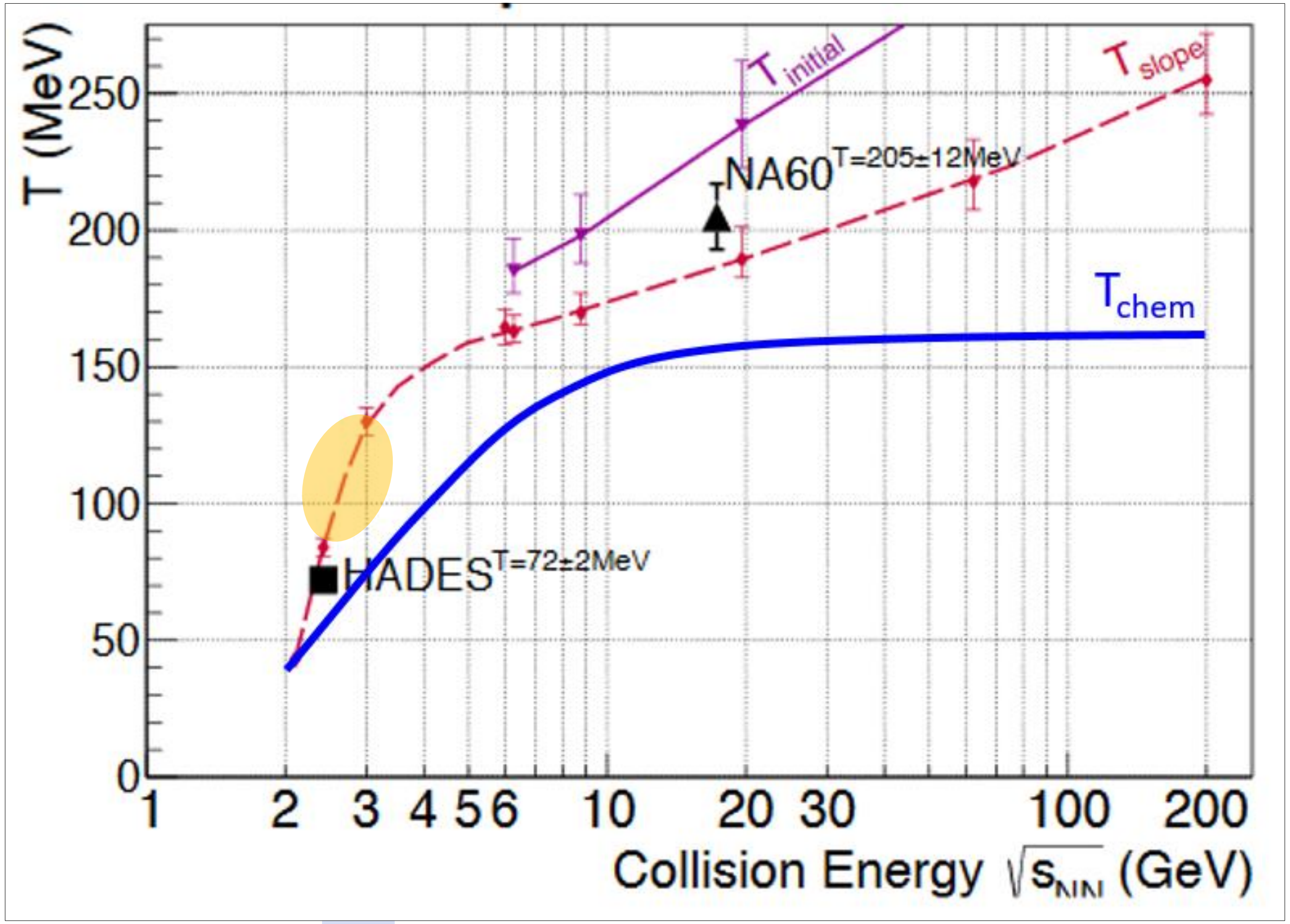
Dashed line: Freeze-out curve
J. Cleymans et al.,
Phys. Rev. C73 (2006) 034905

Blue area: T_c^0 = 132+3−6 MeV at $\mu_B = 0$
H. T. Ding et al., HotQCD Collaboration
Phys. Rev. Lett. 2019 123 062002
F. Karsch, arXiv:1905.03936

CEP at $\mu_b/T > 4$ (red line) predicted by
QCD-assisted low-energy effective field theory
W. Fu et al., arXiv:2101.06035

Region of the critical endpoint ?

On the location of a possible critical endpoint



BM@N   Region of the critical endpoint ?

T_{slope}:
Dilepton invariant mass spectrum (1–2 GeV/c^2) calculated with a transport model+coarse graining.
T. Galatyuk et al., Eur. Phys. J. A 52 (2016) 131
R. Rapp and H. v. Hess, PLB 753 (2016) 586

T_{chem}:
Freeze-out at ⟨E⟩/⟨N⟩ = 1 GeV
J.Cleymans et al. 2006 Phys. Rev. C73, 034905

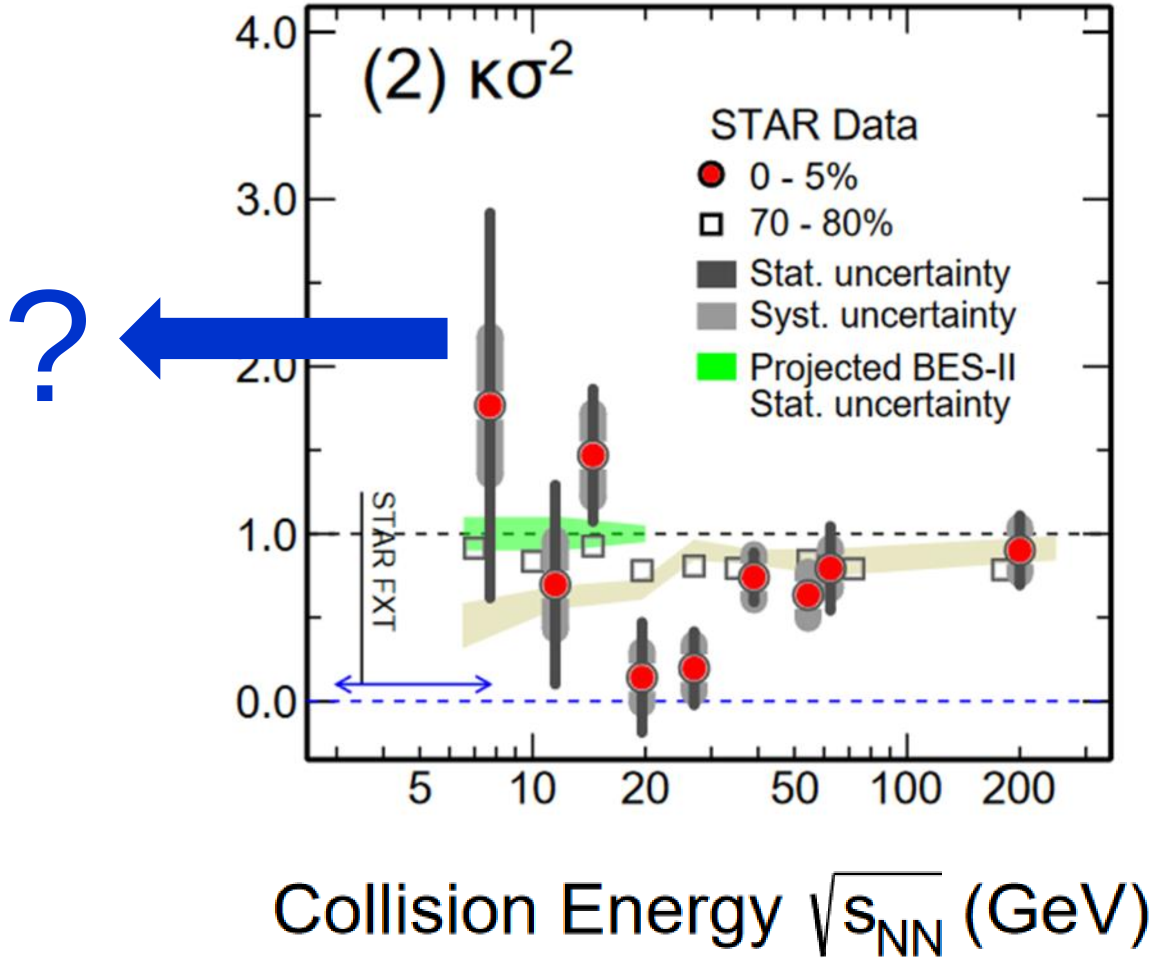
NA60:
H. Specht, AIP Conf. Proc. 1322 (2010) 160

HADES:
J. Adamczewski-Musch et al.
Nature Physics 15 (2019) 1040

$T_c^0 = 132+3-6$ MeV at $\mu_B = 0$
H.T.Ding et al., Phys. Rev. Lett. 123 (2019) 062002

Searching for the critical endpoint of the 1st order phase transition

Ratio of 4th/2nd moment of (net)-proton multiplicity distribution



STAR collaboration,
arXiv:2001.02852

Searching the onset of chemical equilibration of $\Xi^{\pm}$ and $\Omega^{\pm}$ hyperons

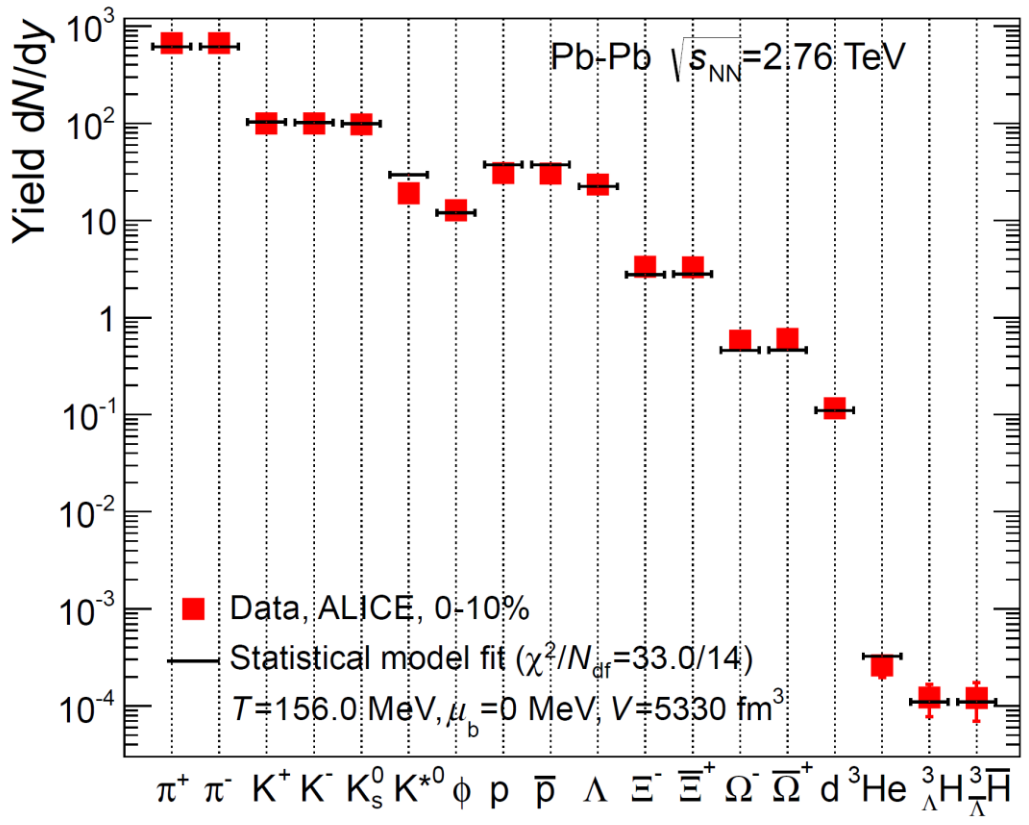
Observation at high energies: Multi-strange hyperons Ξ^-, Ξ^+, Ω^-, Ω^+ in chemical equilibrium! Why?

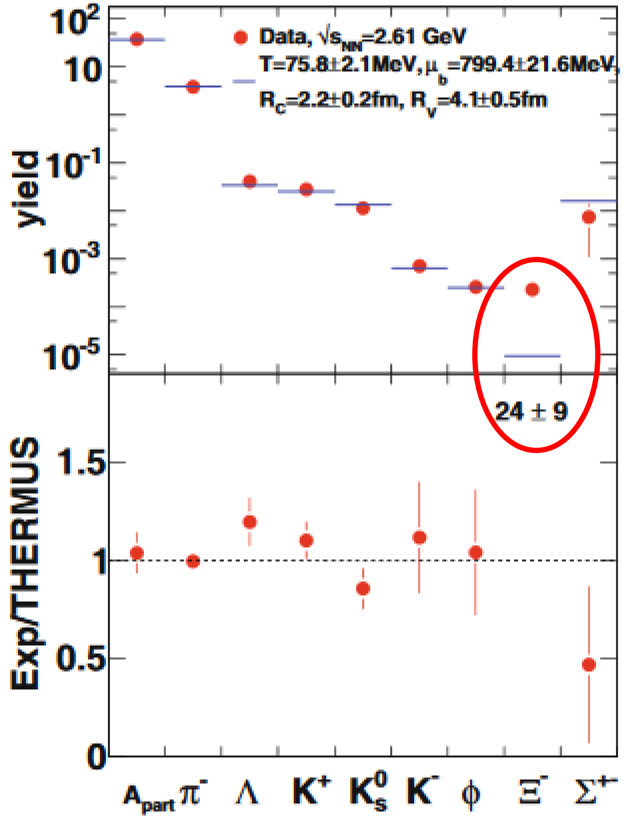
Hyperon-nucleon cross section too small to reach equilibrium in hadronic phase

Explanation: Equilibrium reached by multiple collisions in high density at phase transition

(P. Braun-Munzinger, J. Stachel, C. Wetterich, Phys. Lett. B 2004, 596, 61)

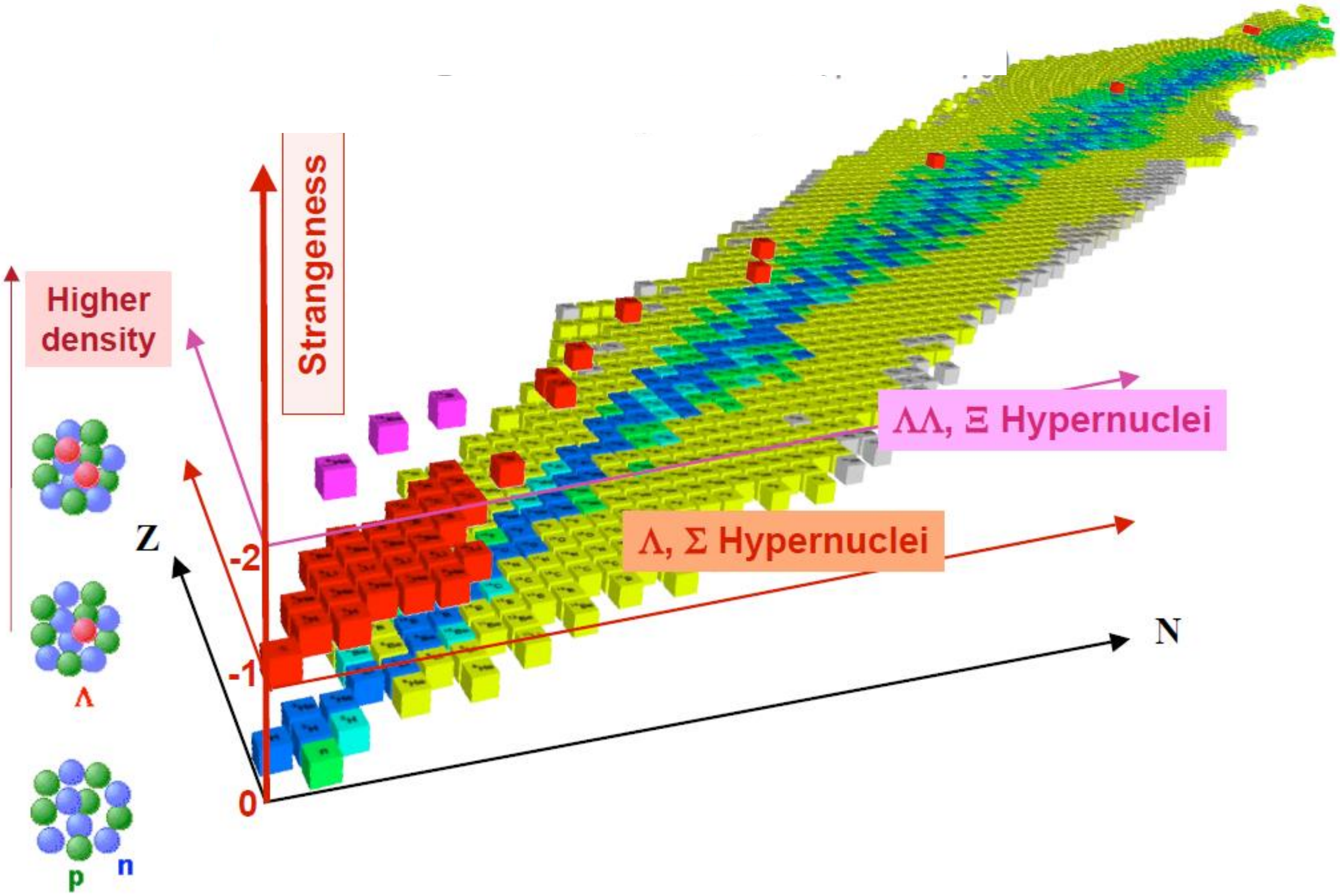
A. Andronic et al., Jour. Phys. G38 (2011)





HADES:
Ar + KCl 1.76 A GeV
G. Agakishiev et al.,
Eur. Phys. J. A 47 (2011) 21

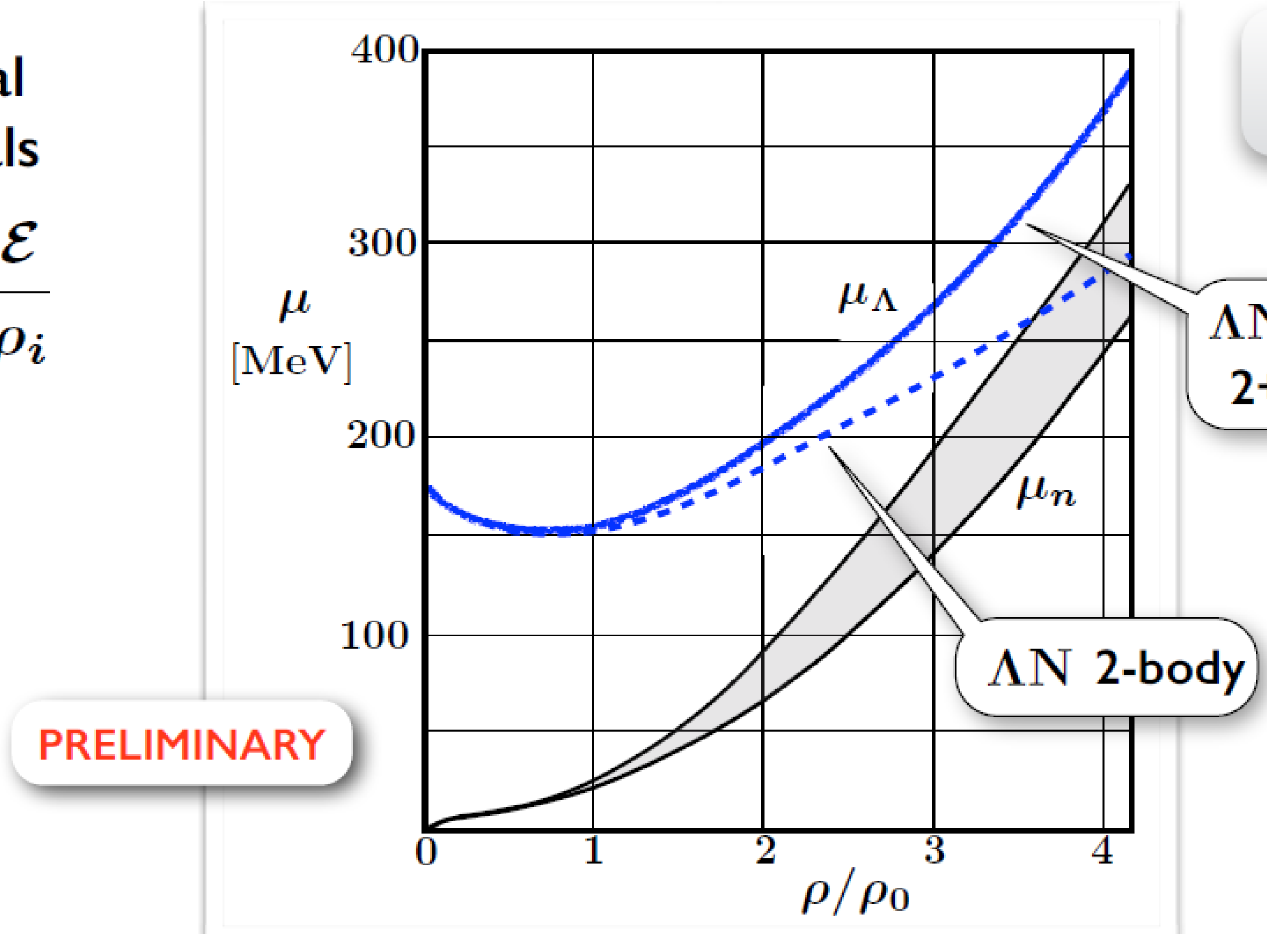
The strange dimension of the nuclear chart



Hypernuclei as laboratory for the study of ΛN, ΛNN, and ΛΛN interactions to unravel the hyperon puzzle in neutron stars

chemical potentials

$$\mu_i = \frac{\partial \mathcal{E}}{\partial \rho_i}$$



$$\mu_\Lambda = \mu_n$$

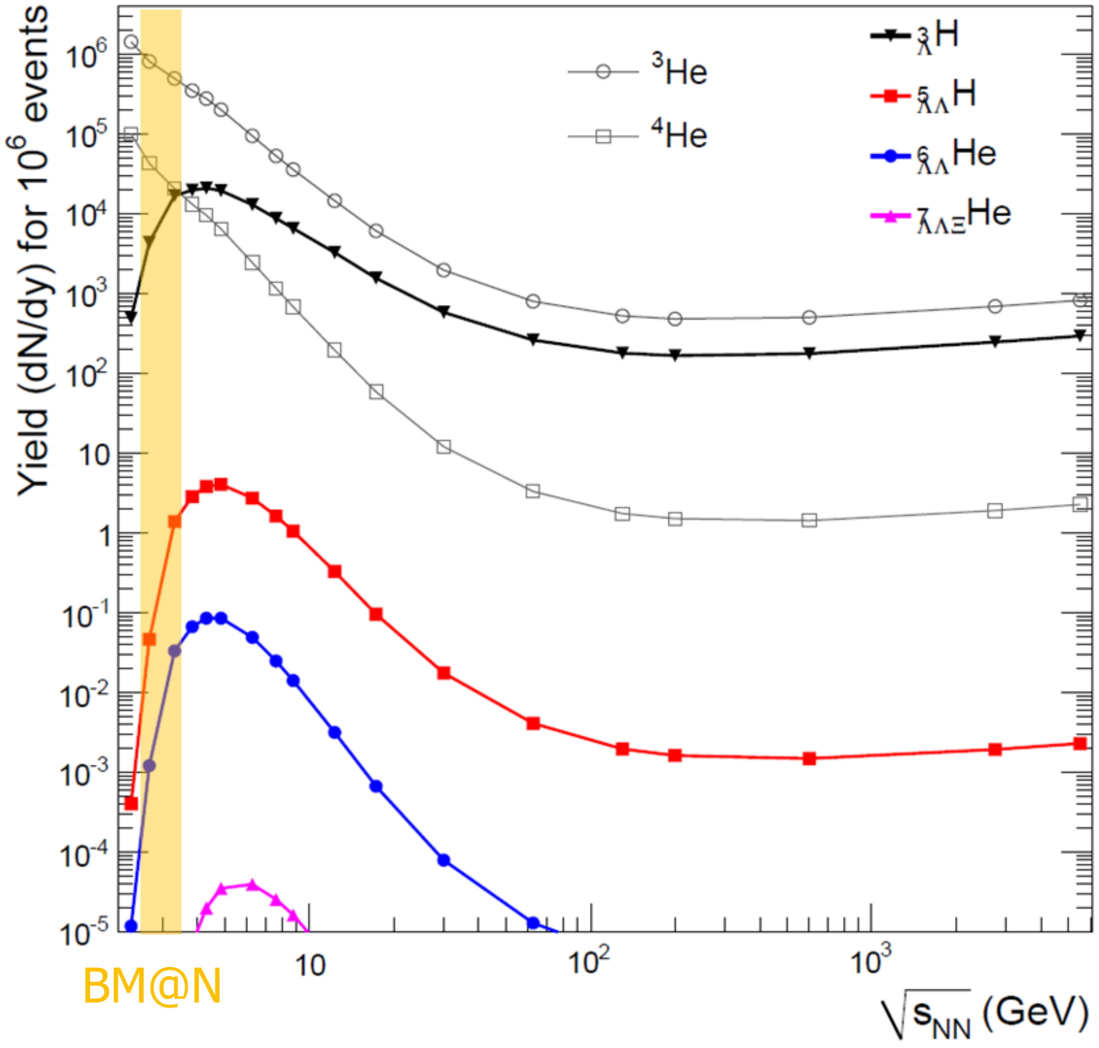
Both the chemical potentials of nucleons μ_n and hyperons μ_Λ increase with increasing baryon density.

If $\mu_n > \mu_\Lambda$, neutrons decay into hyperons, the EOS softens, and prevents the existence of massive neutron stars.

Measure ΛN, ΛNN, and ΛΛN interactions !

W. Weise, arXiv:1905.03955v1, to appear in JPS Conf. Proc
(Lambda single particle potential in neutron star matter from Chiral SU(3) EFT interactions)

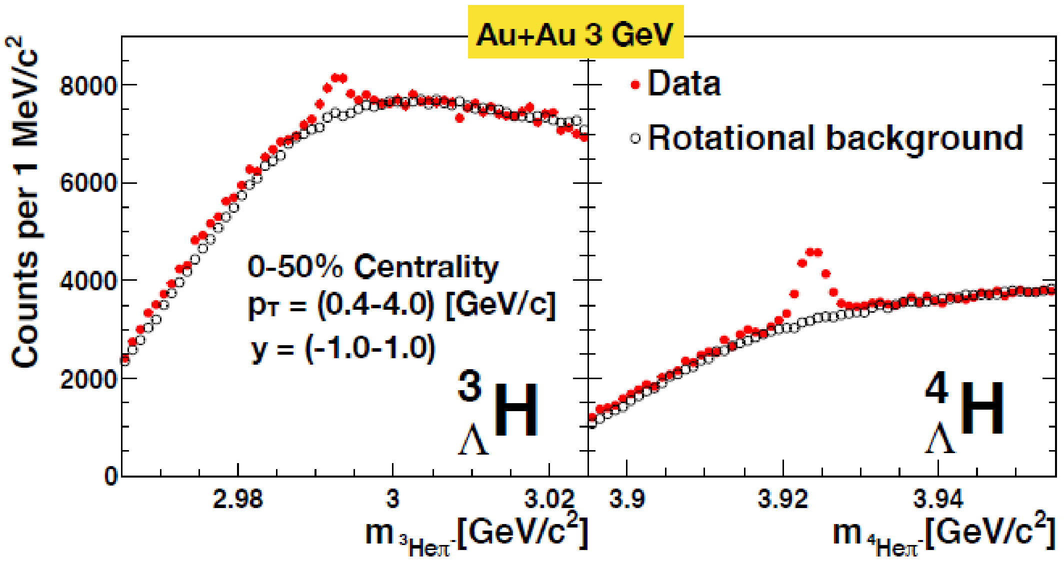
Hypernuclei production in heavy-ion collisions



Statistical Hadronization Model: A. Andronic et al., Phys. Lett. B697 (2011) 203

Hypernuclei results of STAR at $\sqrt{s_{NN}}$= 3 GeV ($^{3}_{\Lambda}$H, $^{4}_{\Lambda}$H)

(= 2.9A GeV)

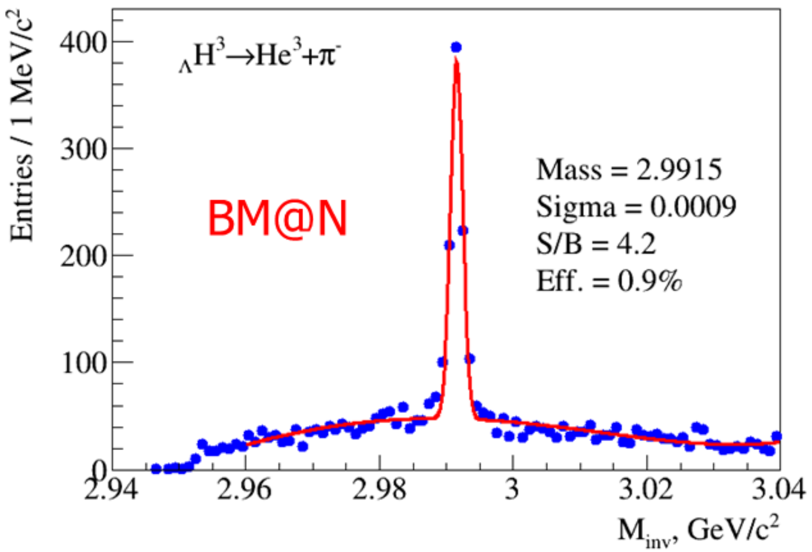


- Decay channels

$$^{3}_{\Lambda}\mathrm{H} \rightarrow {}^{3}\mathrm{He} + \pi \quad (B.R. \approx 25\%)$$

~2900 candidates

PRC57(1998)1595



➤ Lifetimes

$$^{3}_{\Lambda}\mathrm{H}: \tau = 232.1 \pm 29.2(\mathrm{stat}) \pm 36.7(\mathrm{syst})[\mathrm{ps}]$$

$$^{4}_{\Lambda}\mathrm{H}: \tau = 218.3 \pm 7.5(\mathrm{stat}) \pm 11.8(\mathrm{syst})[\mathrm{ps}]$$

➤ Spectra

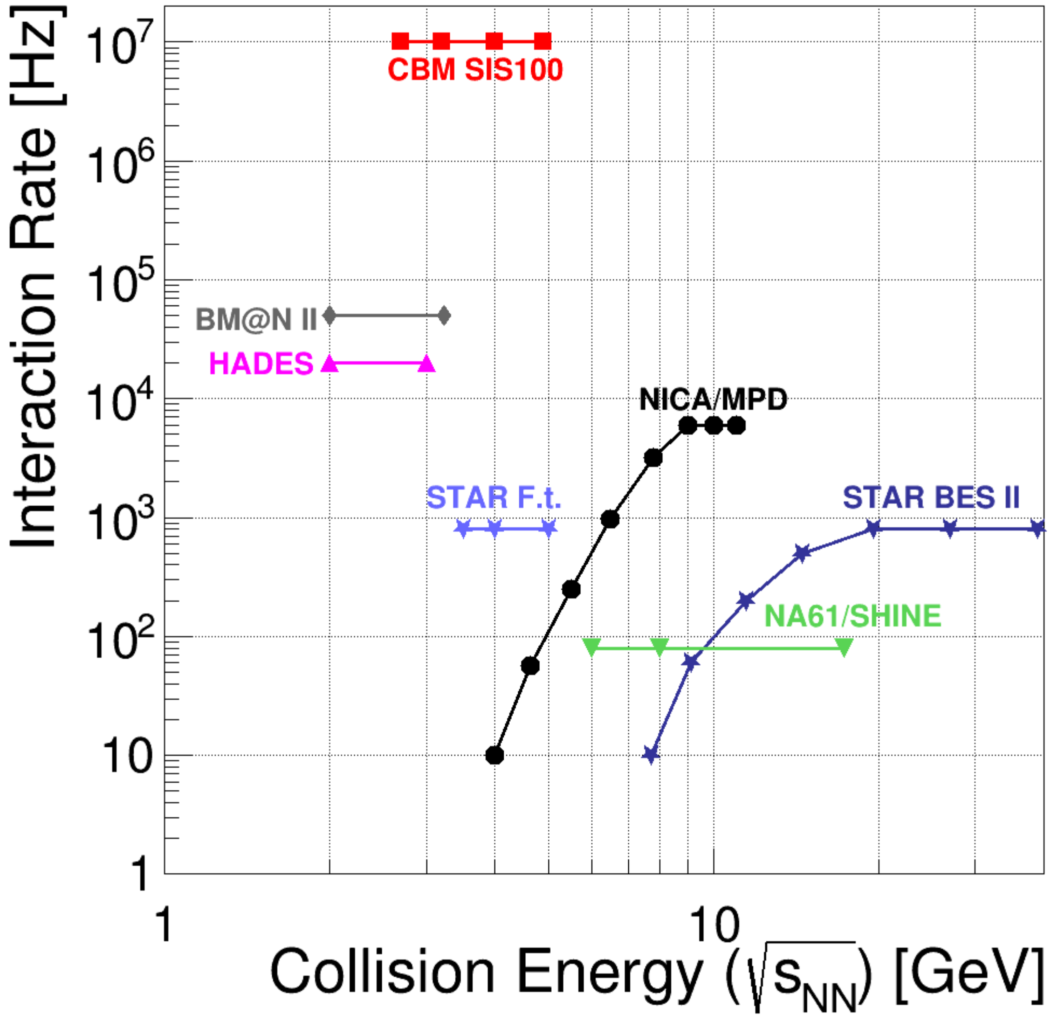
➤ Rapidity distribution

➤ Yields confirm thermal model

➤ Collective flow

https://indico.cern.ch/event/985460/contributions/4264621/attachments/2207903/3744847/cpod20210302v10.pdf

Rate capability of heavy-ion experiments (running and under construction)



T. Ablyasimov et al., (CBM Collaboration)
Eur. Phys. J. A 53 (2017) 60

Conclusions

1. BM@N energy range is very promising (EOS, CEP, hypernuclei)
2. Sensitive probes have to be measured multi-differential (p_T, y, Θ) and as function of beam energy (2 – 4 GeV/u)

- EOS for high-density symmetric matter:
  - Collective flow of protons and light fragments in Au+Au collisions: Centrality, event plane, identification of fragments
  - Ξ^- and Ω^- hyperons: Yields, spectra, p_T vs. y from Au+Au and C+C collisions
- Symmetry energy at high baryon densities:
  - Particles with opposite isospin $I_3=\pm1$: Σ^{*+}(uus)/Σ^{*-}(dds)
- Hypernuclei: Yields, lifetimes, masses of (${}^{3}_{\Lambda}H$, ${}^{4}_{\Lambda}H$), ${}^{5}_{\Lambda}H$, ${}^{4}_{\Lambda}He$, ${}^{5}_{\Lambda}He$, … (${}^{5}_{\Lambda\Lambda}H$, ${}^{4}_{\Lambda\Lambda}He$?)
- Quark degrees-of-freedom:
  - Critical endpoint: higher order moments of the proton multiplicity distribution
  - Deconfinement: chemical equilibration of Ξ^-, Ω^- (EOS observables)