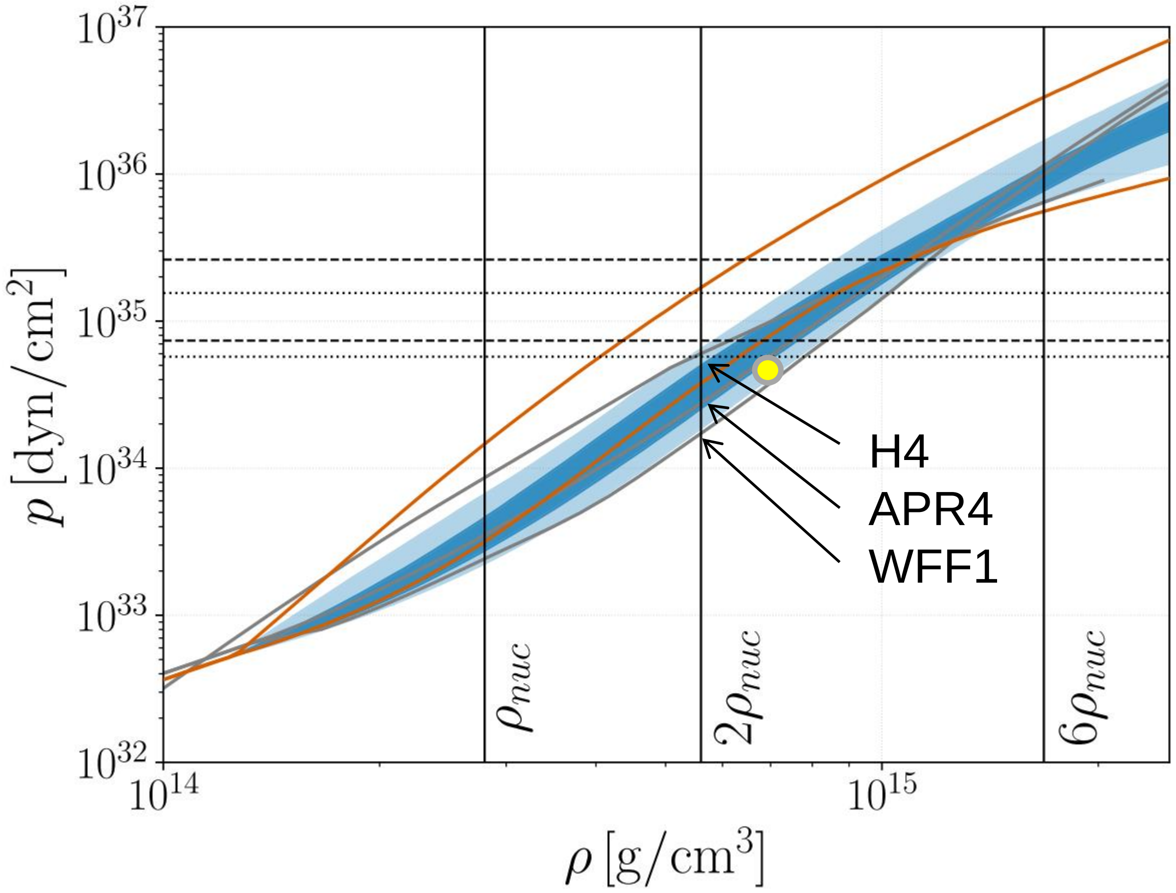
Discussion

Questions

1. Can HIC help constrain the EOS at NS core densities?
2. Signatures of phase transitions in QCD matter at large baryon densities?
3. What are suitable observables?

EOS from NSs



GW170817
arXiv:1805.11581v1

Central pressure:

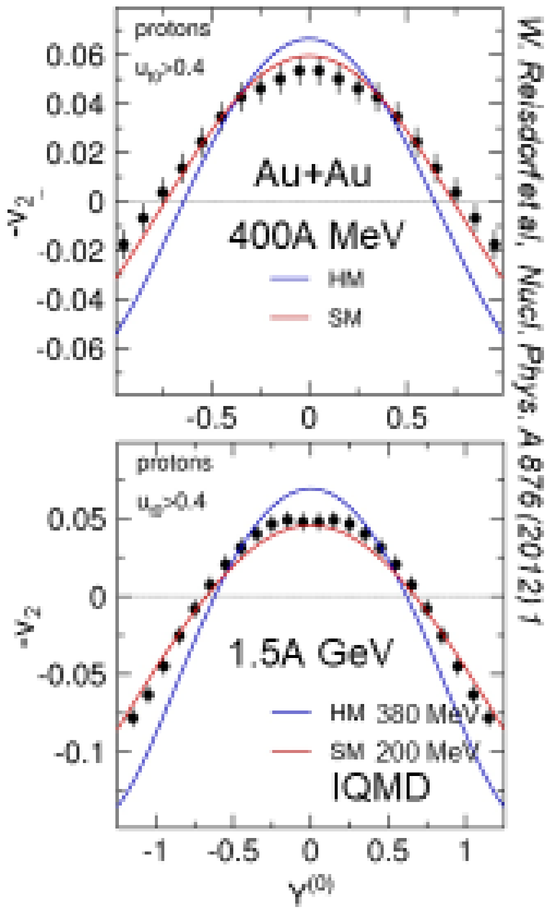
NS1
NS2

Core densities:
ρ_{core} = 2.5 – 2.7 ρ_{nuc}

“While terrestrial experiments are able to test and constrain the EOS at densities below the saturation density of nuclei $\rho_{nuc} = 2.8 \times 10^{14}$ g cm^{-3} (see e.g. [14–17] for a review), currently they cannot probe the extreme conditions in the core of NSs”

EOS determination in HIC

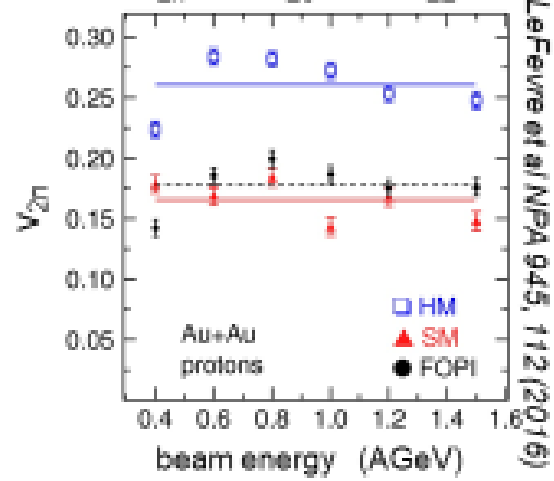
Elliptic flow at energies 0.25-1.5 AGeV



Parametrization of shape:

$$v_2(Y^{(0)}) = v_{20} + v_{22} \cdot Y^{(0)2}$$

$$v_{2n} = |v_{20}| + |v_{22}|$$

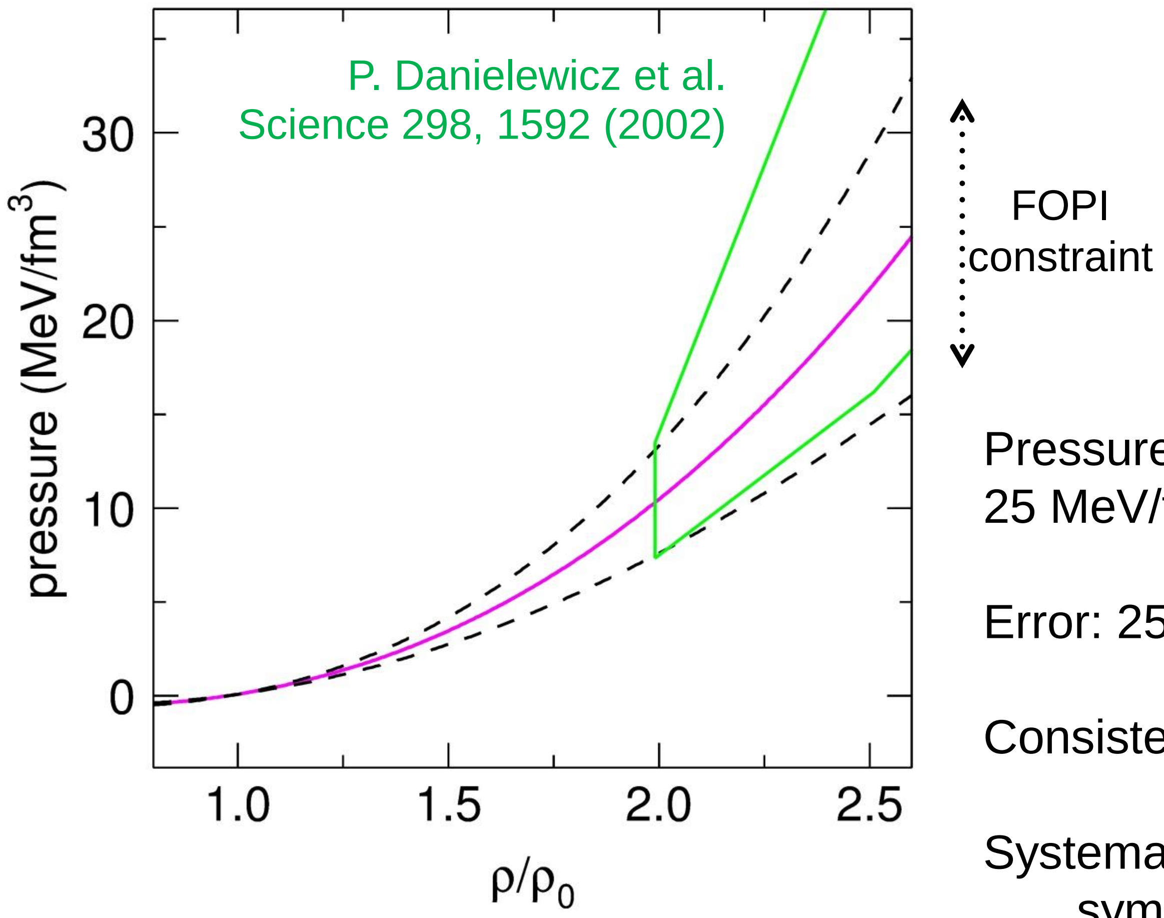


- sensitive to EOS over a large energy range
- $v_{2n}(E_{beam})$ varies by a factor ≈1.6 >> measured uncertainty (≈1.1)
- relevant density range $\rho \simeq (1-3)\,\rho_0$
- extracted compressibility K=190±30 MeV

Yvonne Leifels - EMMI RRTF Symposium 2018 14

EOS for symmetric nuclear matter from HIC

A. LeFevre et al NPA 945, 112 (2016)



Pressure at ρ = 2.5 ρ_0:
25 MeV/fm^3 = 4 x 10^{34} dyn/cm^2

Error: 25% ? - model dependence

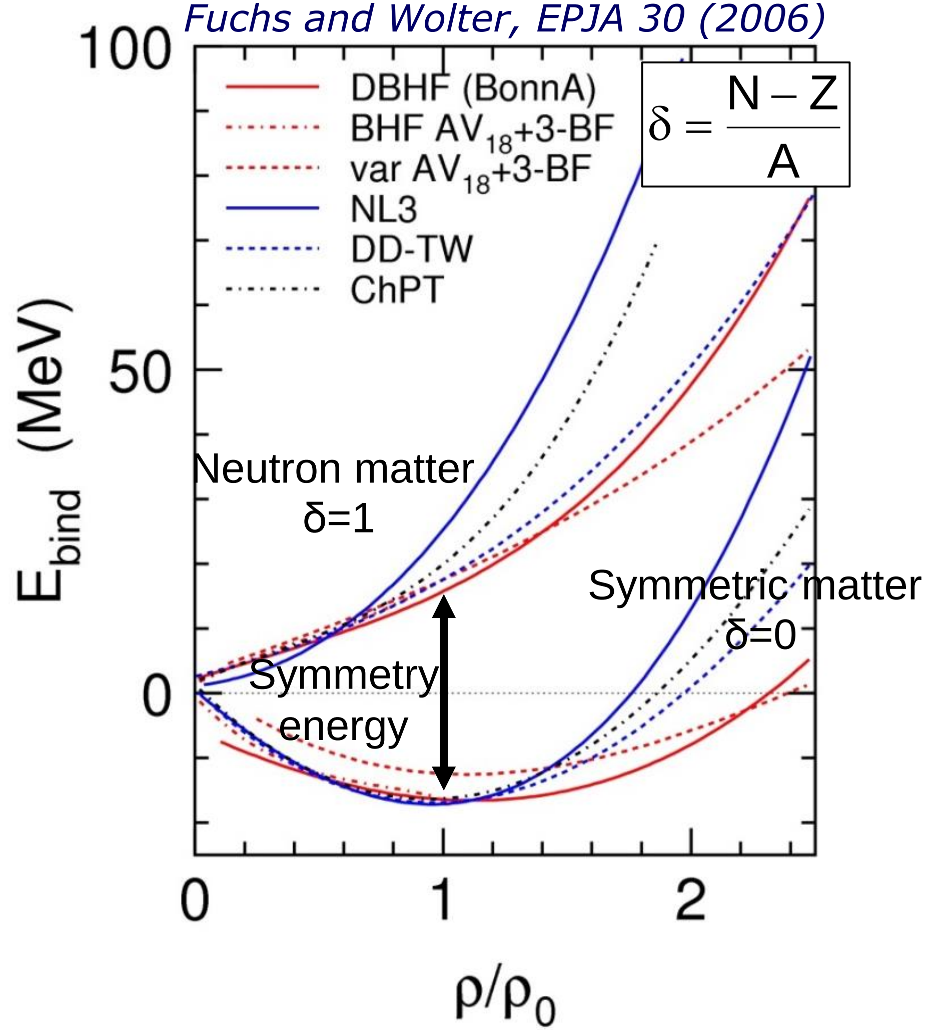
Consistent with APR4

Systematic uncertainty:
symmetry energy

Nuclear Physics EOS

- heavy ion reactions rapidly evolving, transient state
- influenced by
  - **nuclear matter equation of state**
    - momentum dependence
  - in-medium cross sections
    - Pauli blocking
  - in-medium characteristics of particles
    - effective masses/potentials, spectral functions
    - decay widths
- microscopic transport models needed
- convincing conclusions on basic nuclear properties imply a successful simulation:
  - of the full set of experimental observables
  - with the same code
  - using the same physical and technical parameters.

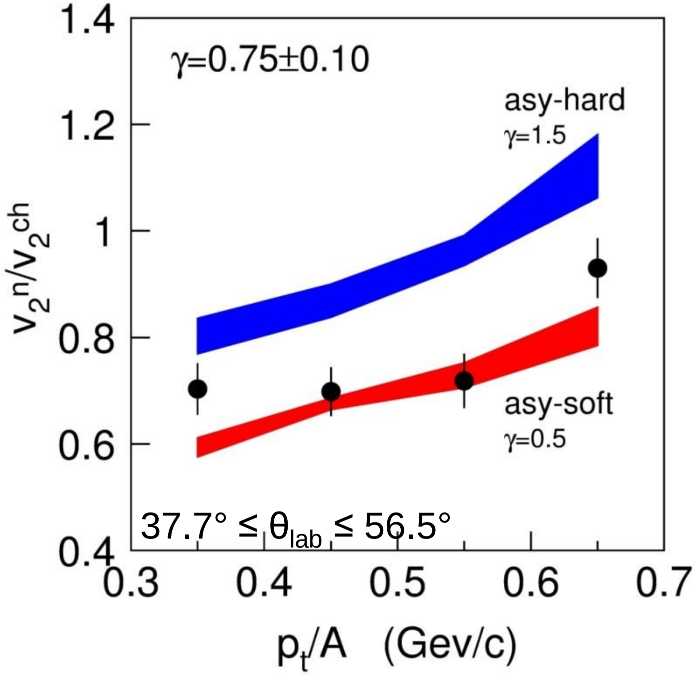
Fuchs and Wolter, EPJA 30 (2006)

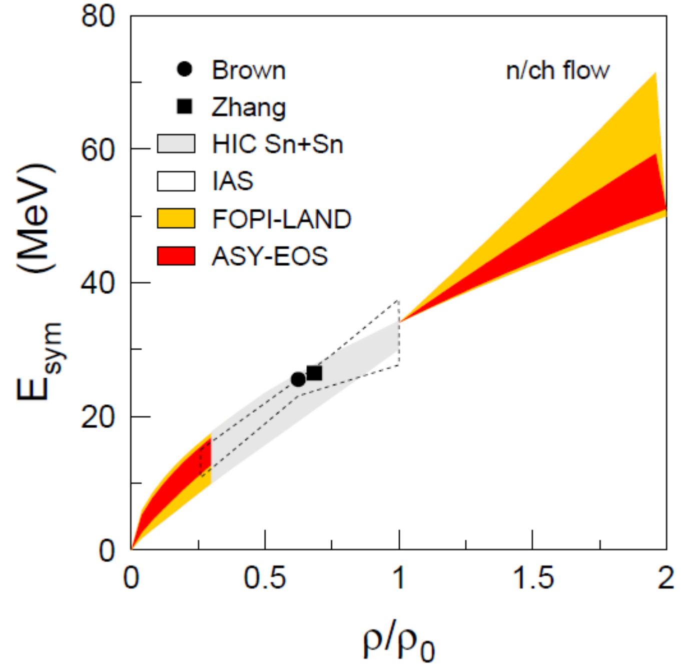


Symmetry energy from neutron/proton flow

for details see Y. Leifels, EMMI – RRTF symposium

P. Russotto et al., PRC 94, 034608 (2016)





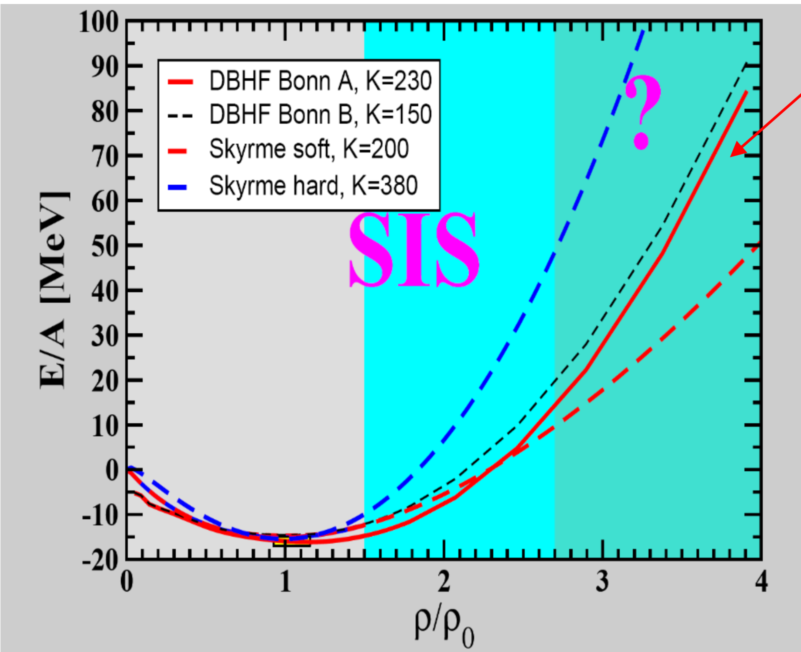
$E_{sym} = E_{sym}^{pot} + E_{sym}^{kin} = 22\text{MeV}\cdot(\rho/\rho_0)^{\gamma} + 12\text{MeV}\cdot(\rho/\rho_0)^{2/3}$

Density dependence: $\gamma = 0.72 \pm 0.19$

Pressure contribution at $\rho = \rho_0$: $p_0 = 3.4 \pm 0.7$ MeV/fm^3

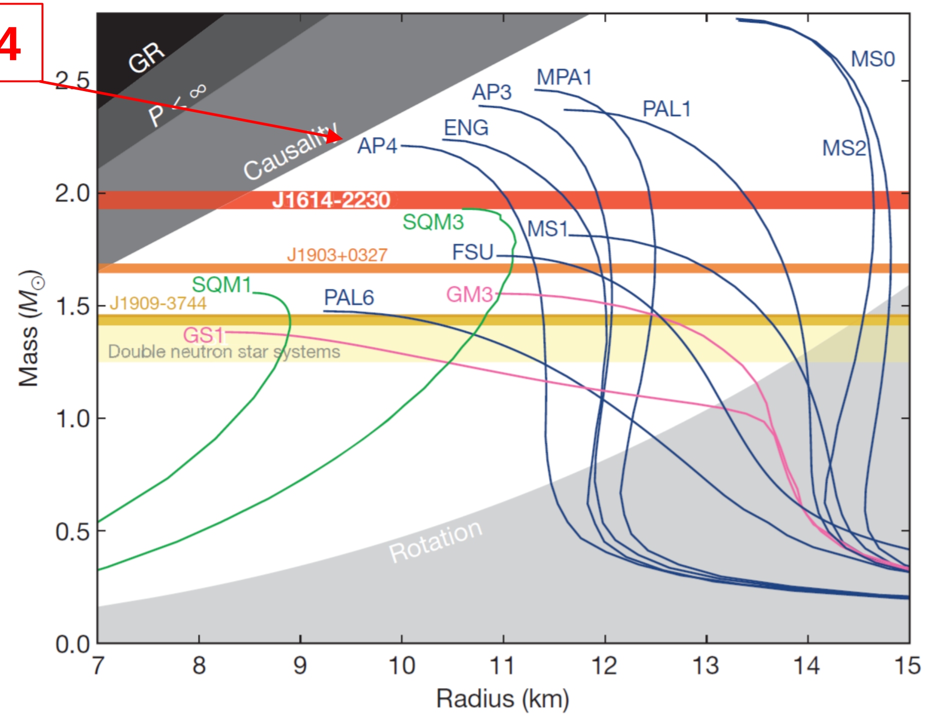
EOS at center of largest NSs ?

C. Fuchs,
Prog. Part. Nucl. Phys. 56 (2006) 1



AP4

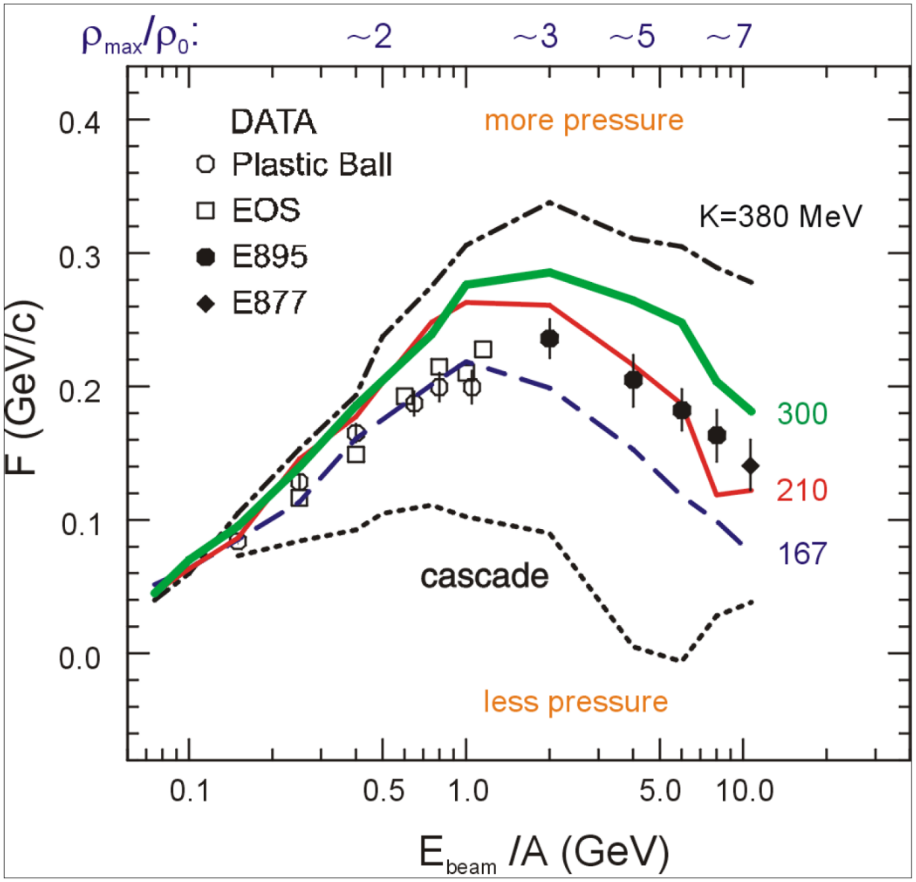
P.B. Demorest (2010)
doi:10.1038/nature09466

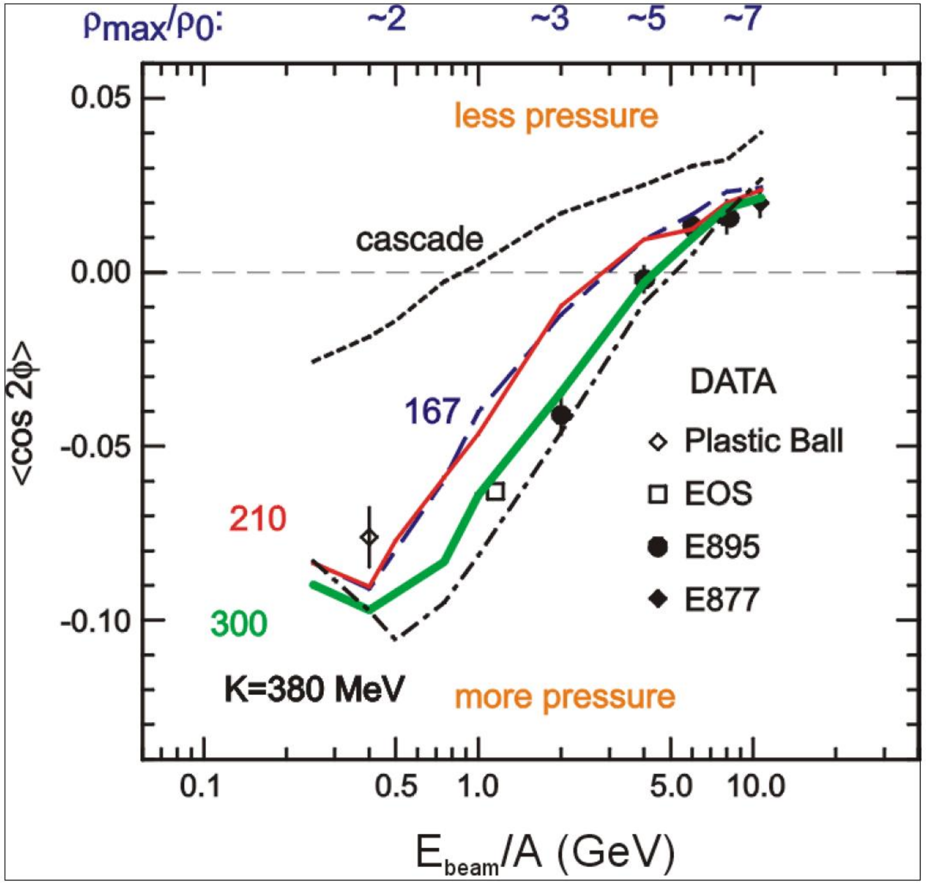


AP4 incomplete, strangeness DoF missing.

Excitation function of collective flow

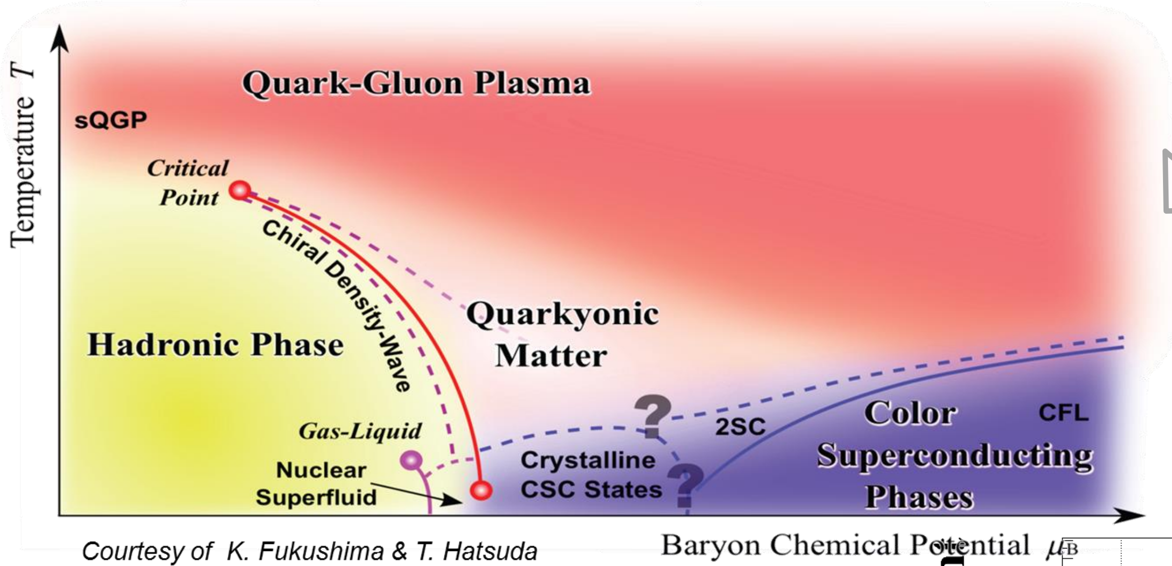
P. Danielewicz, R. Lacey, W.G. Lynch, Science 298 (2002) 1592





Large sensitivity for high densities in the (lower) AGS/SIS100 beam energy range.

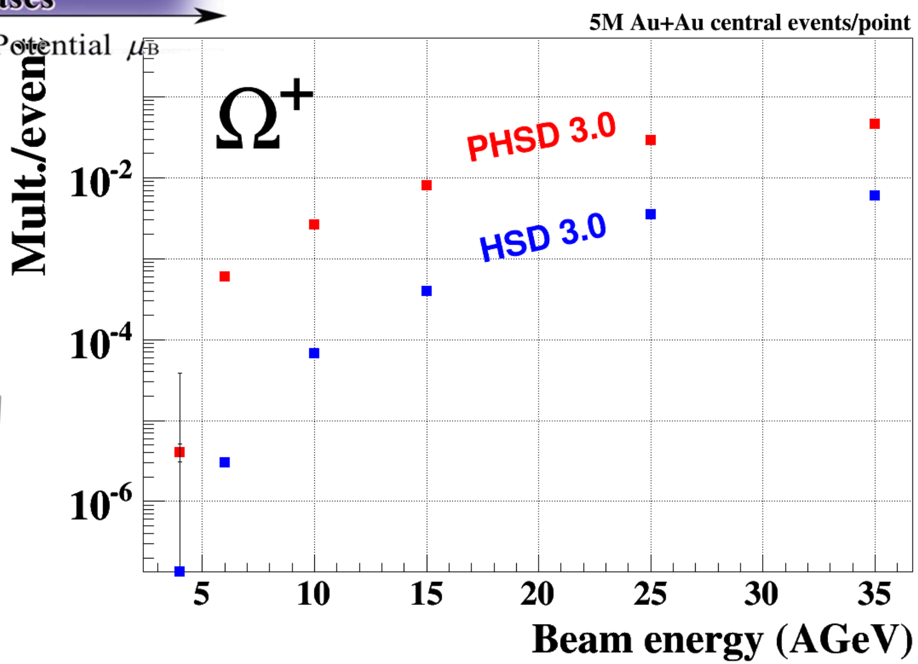
Phases of QCD matter ?



Courtesy of K. Fukushima & T. Hatsuda

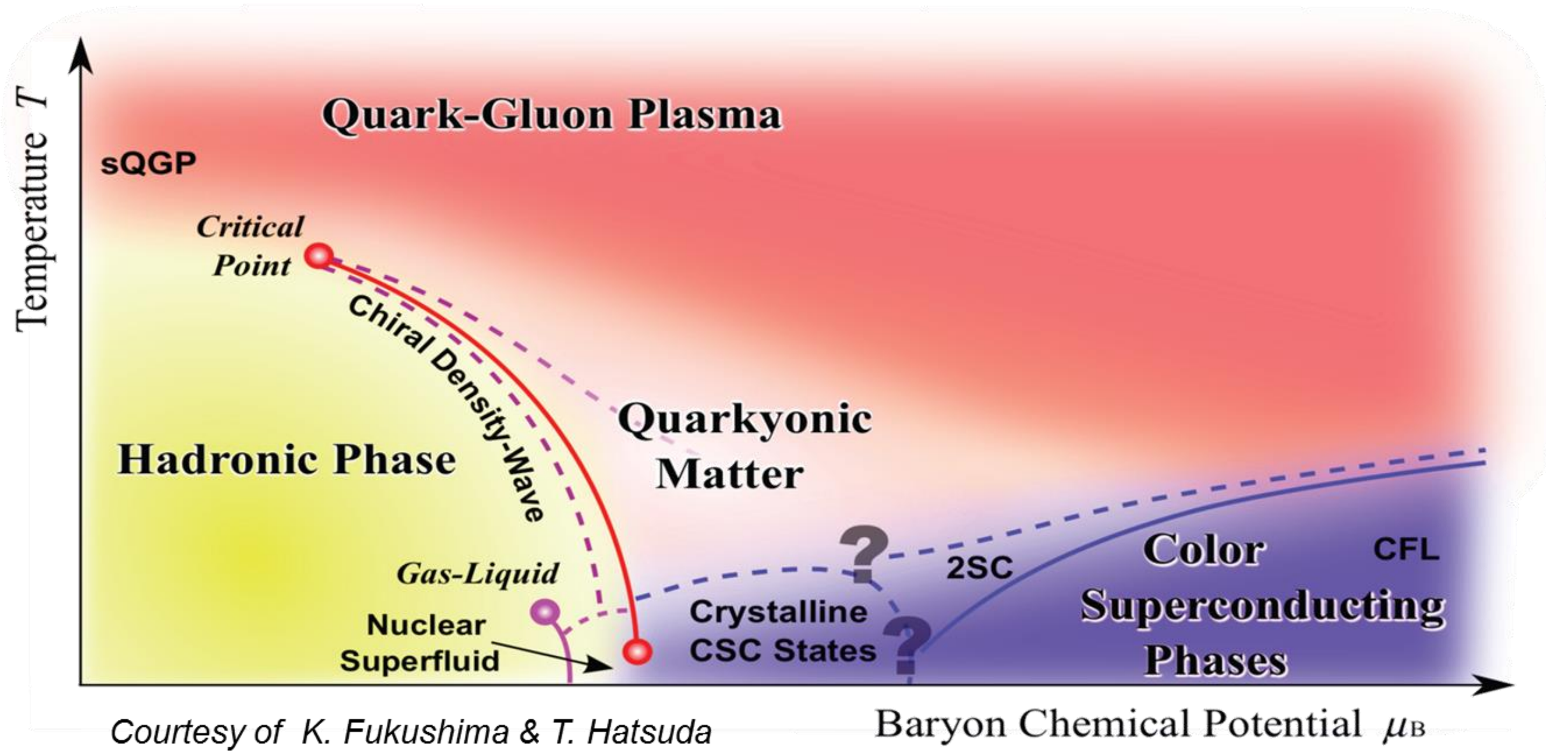
?

I. Vassiliev, CBM, priv. com., PHSD predictions



?

CBM – Goals

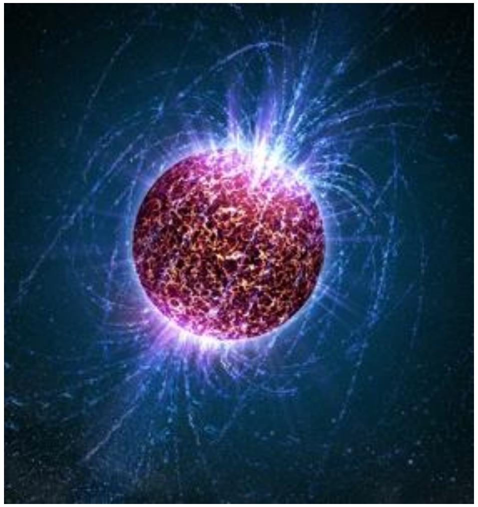


Courtesy of K. Fukushima & T. Hatsuda

Mission:

Systematically explore QCD matter at large baryon densities with high accuracy and rare probes.

Dense Baryonic Matter



Neutron stars

Temperature
$T < 20$ MeV

Density
$\rho < 10\ \rho_0$

Lifetime
T ~ infinity

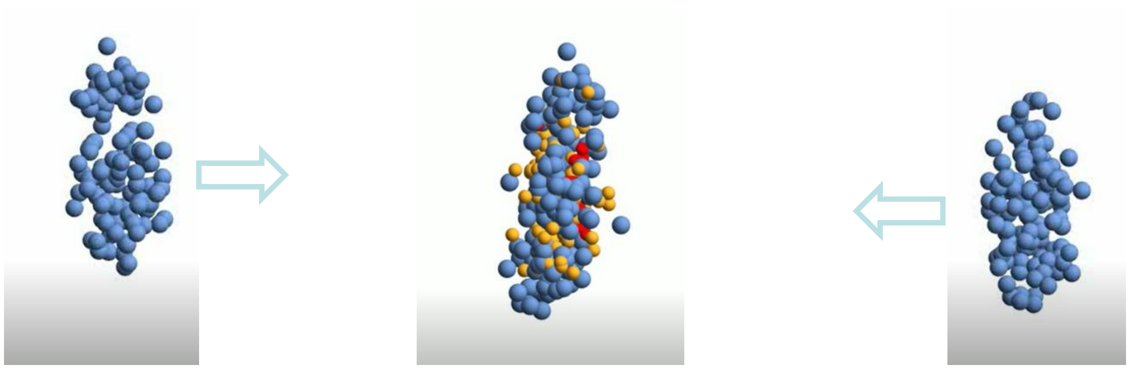
Neutron star merger

Temperature
$T < 70$ MeV

Density
$\rho < 2 - 6\ \rho_0$

Reaction time
(GW170817)
T ~ 10 ms

Heavy ion collisions at SIS100



Compressed Baryonic Matter

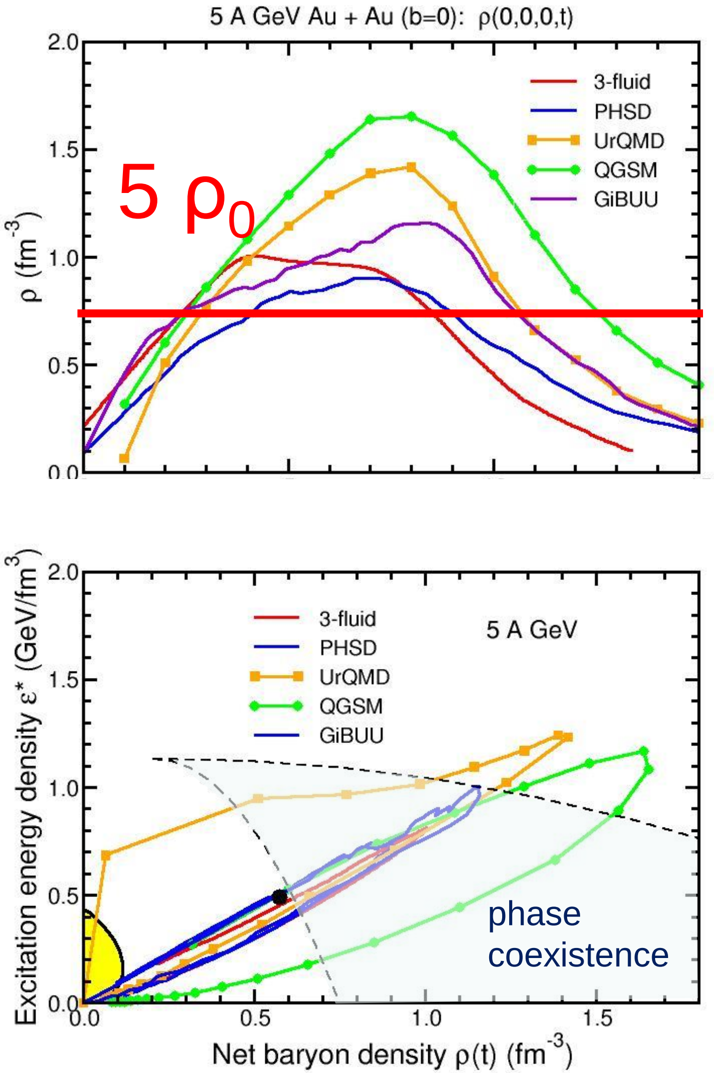
Temperature
$T < 120$ MeV

Density
$\rho < 8\rho_0$

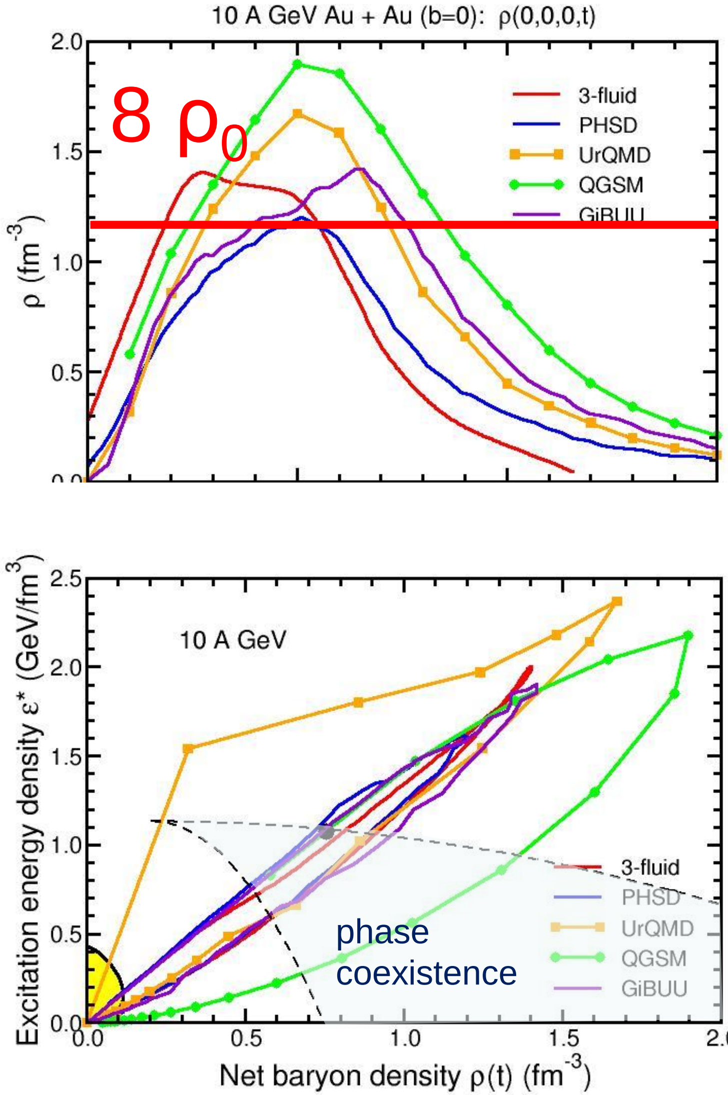
Reaction time
$t \sim 10^{-23}$ s

Baryon densities in central Au+Au collisions

5 A GeV



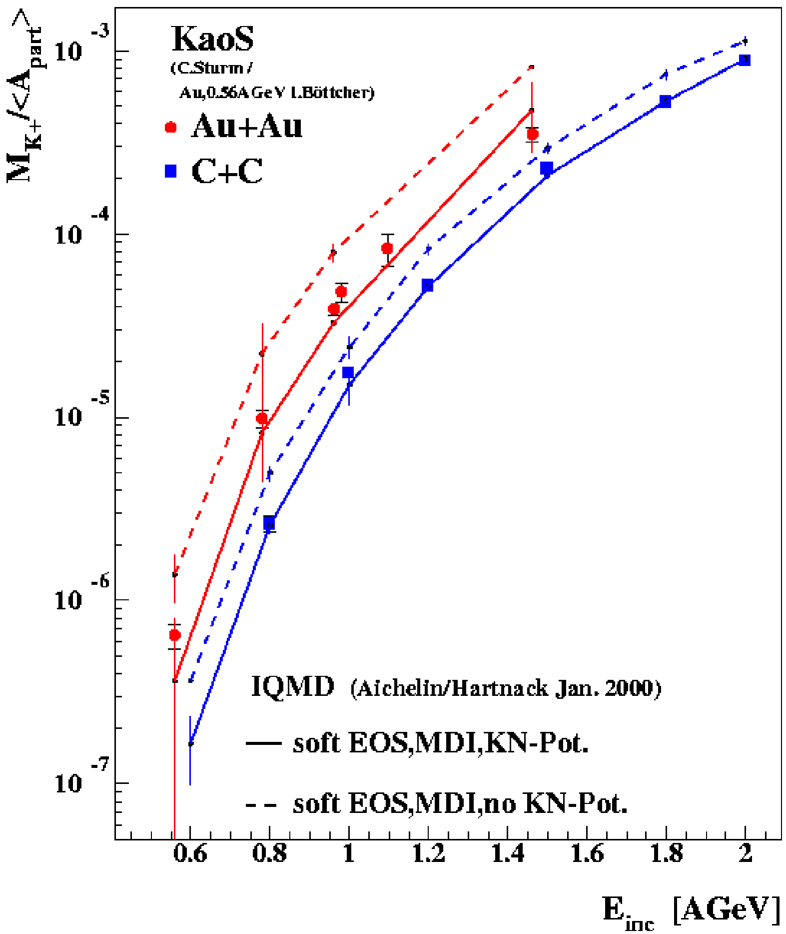
10 A GeV



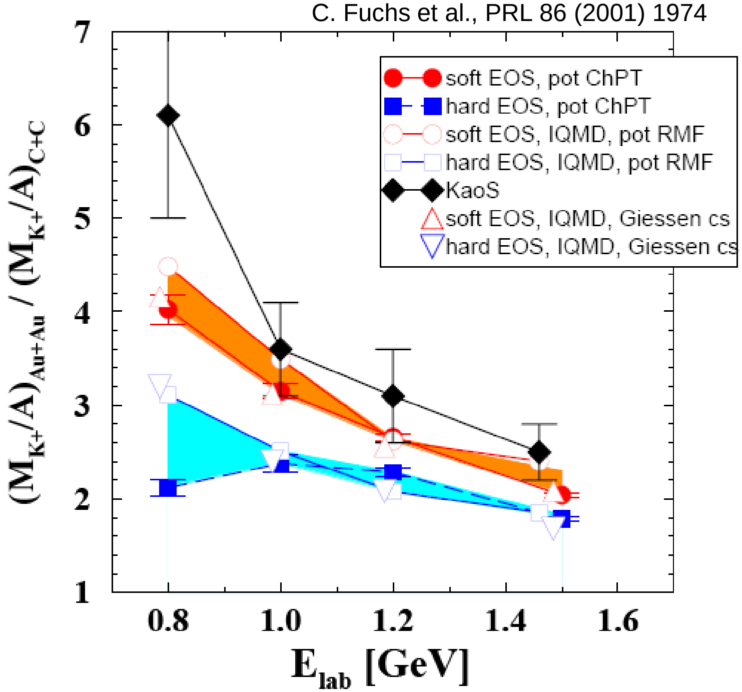
I.C. Arsene et al., Phys. Rev. C 75, 24902 (2007)

Reminder: Subthreshold Kaon – measurements (KAOS at SIS18)

C.Sturm et al. (KaoS), PRL 86 (2001) 39



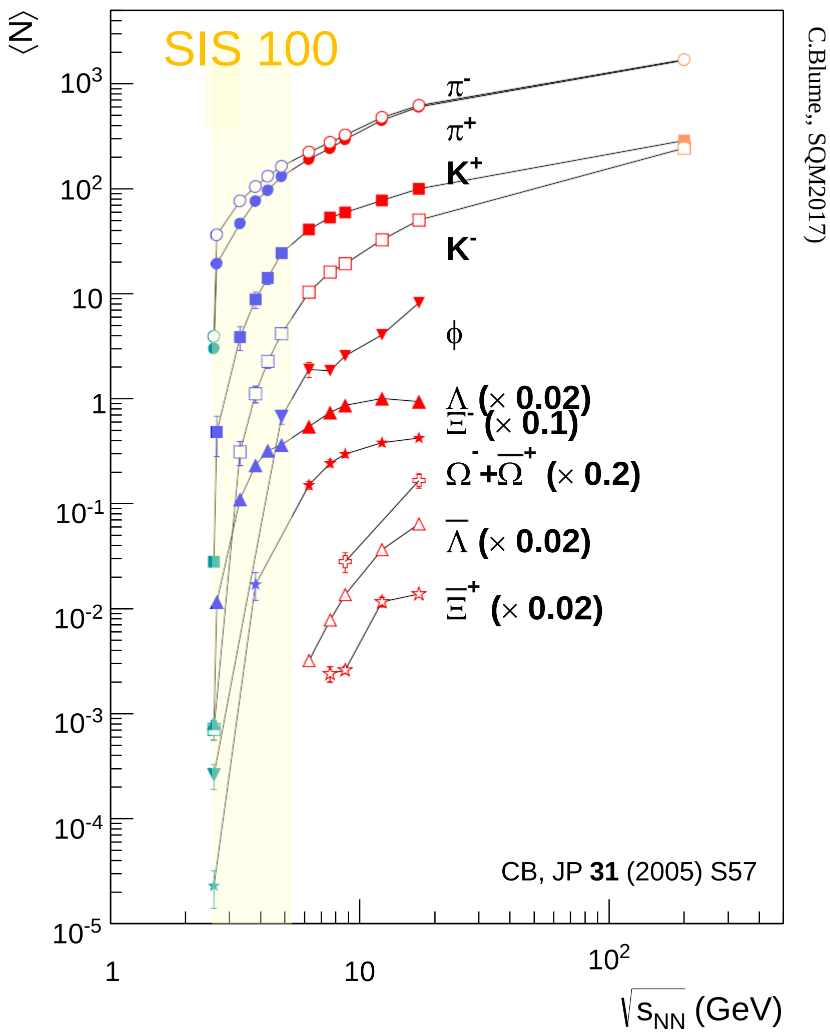
C. Fuchs et al., PRL 86 (2001) 1974



Strong sensitivity to Equation Of State
due to multistep production
(formation of nucleon resonances)
=> soft EOS (K=200 MeV)

Final state particle abundance

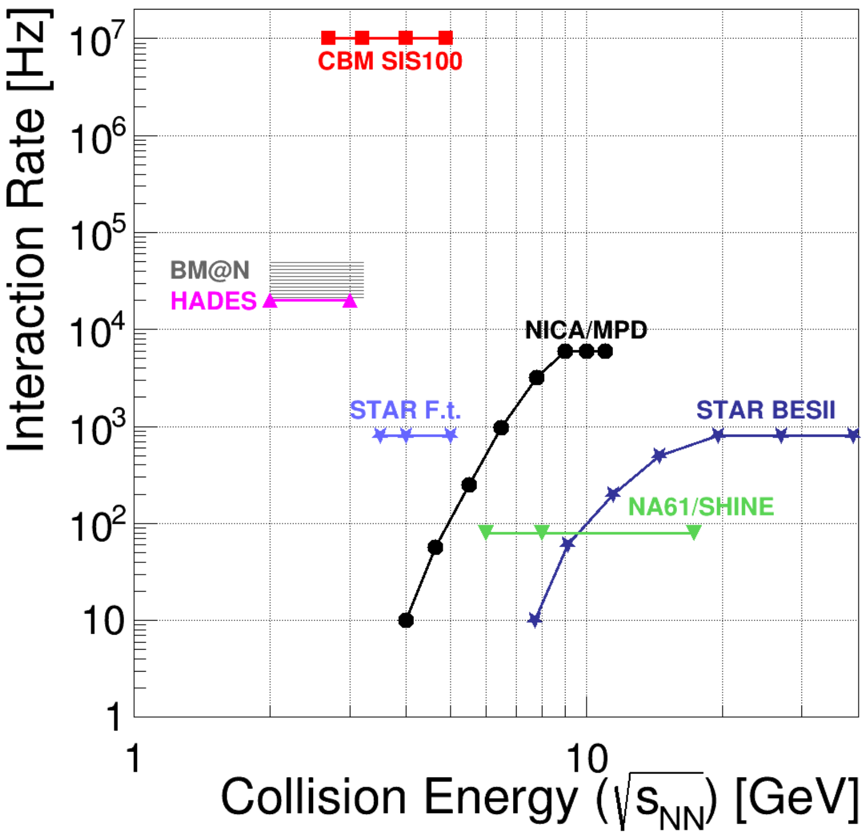
Particle yields from central Au + Au collisions



Strange and charmed particle production thresholds in pp - collisions

reaction	$\sqrt{s}$ **(GeV)**	T_{lab}**(GeV)**
$pp \rightarrow K^+\Lambda p$	2.548	1.6
$pp \rightarrow K^+K^-pp$	2.864	2.5
$pp \rightarrow K^+K^+\Xi^-p$	3.247	3.7
$pp \rightarrow K^+K^+K^+\Omega^-n$	4.092	7.0
$pp \rightarrow \Lambda\bar{\Lambda}pp$	4.108	7.1
$pp \rightarrow \Xi^-\bar{\Xi}^+pp$	4.520	9.0
$pp \rightarrow \Omega^-\bar{\Omega}^+pp$	5.222	12.7
$pp \rightarrow J/\Psi\, pp$	4.973	12.2

CBM – Strategy

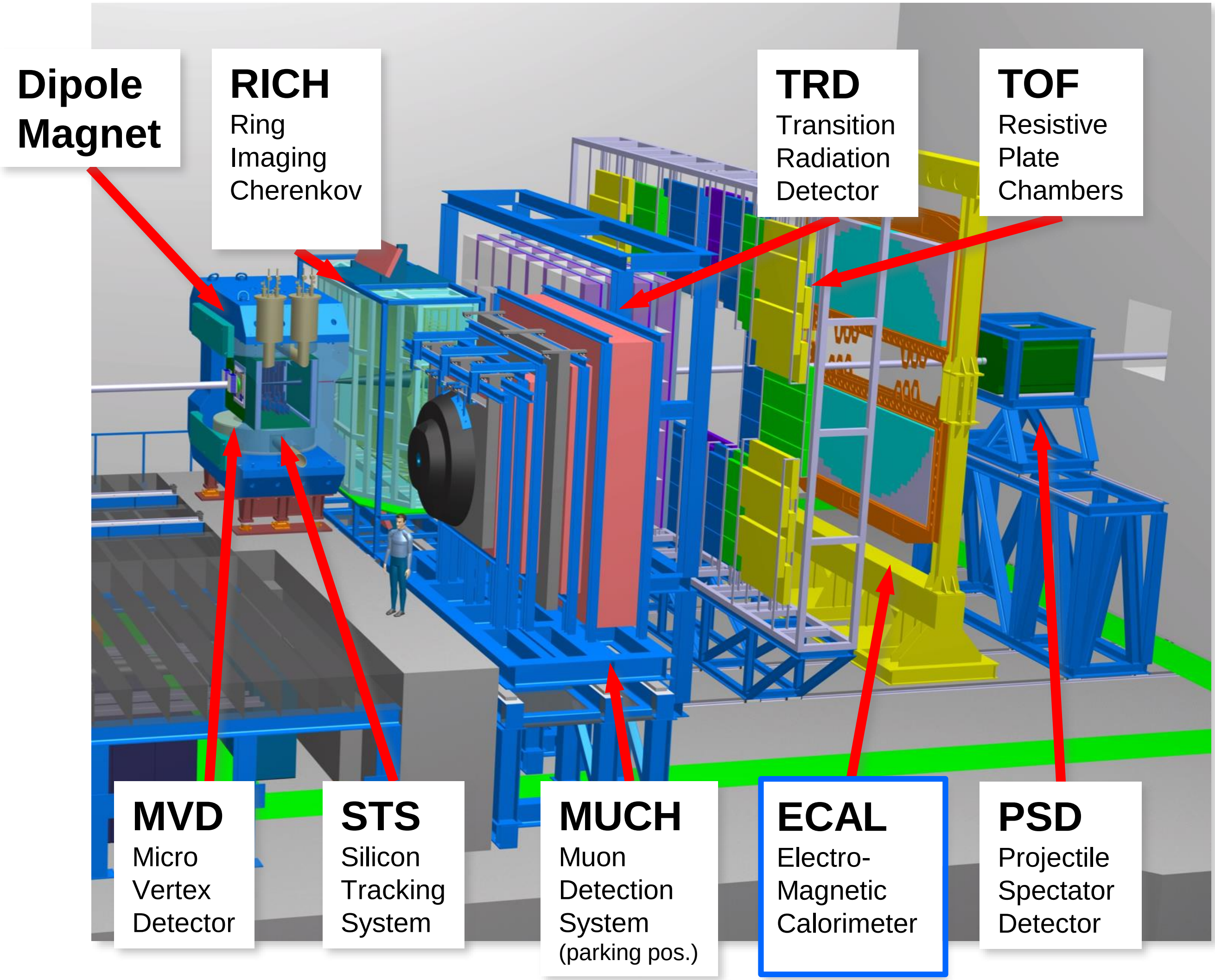


Exploration of QCD phase diagram as international effort:

NA61	@ SPS / CERN
BM@N	@ Nuclotron/JINR
STAR (F.t.)	@ RHIC/BNL
MPD	@ NICA / JINR

CBM's unique feature
High statistics measurement of rare probes

CBM experimental setup (day-1)



- Tracking acceptance: $2^o < \theta_{lab} < 25^o$
- Free streaming DAQ
- R_{int} = 10 MHz (Au+Au)

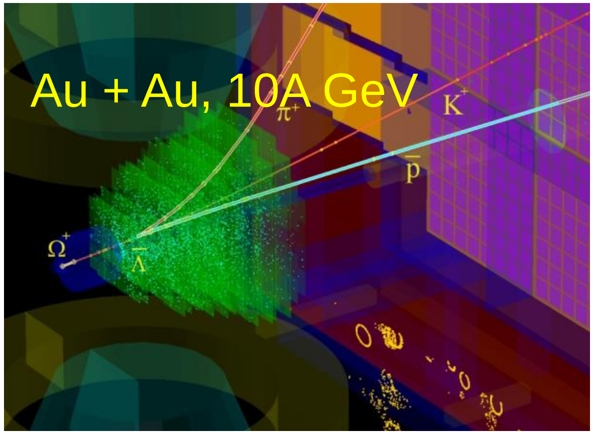
  $R_{int} \approx 0.5$ MHz
  full bandwith:
  Det. – Entry nodes
  reduced bandwidth
  Entry nodes – Comp. farm

  with
  R_{int} (MVD)=0.1 MHz
- Software based event selection

Day-1 setup = MSV setup – Compute Performance - ECAL
Phase-1 = Day1 with full Compute Performance + ECAL

Day-1 funding:
~ 90% secured

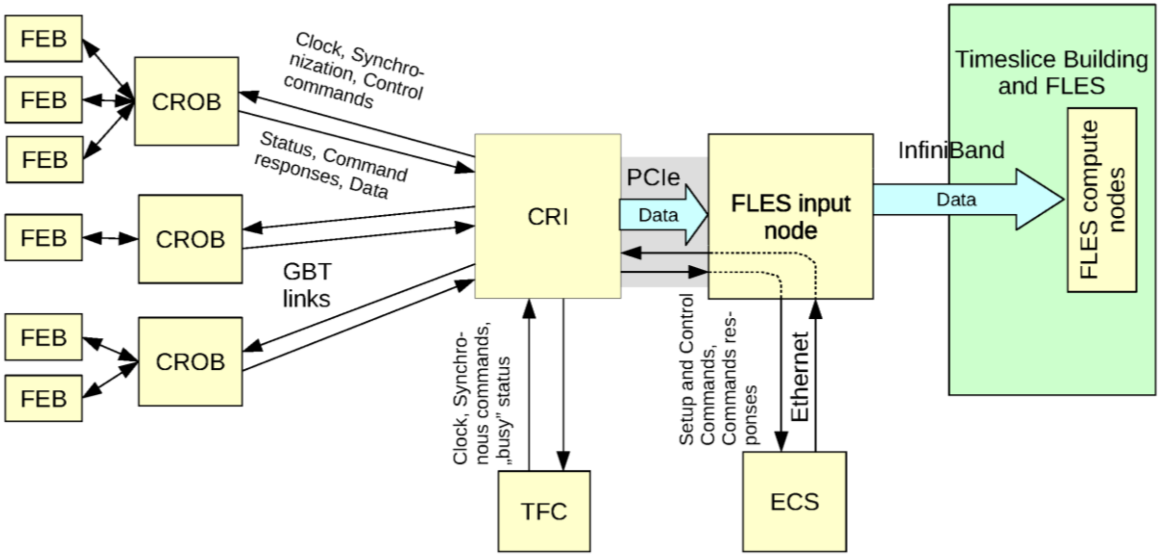
CBM data processing system



Reaction rate Au + Au:

10^7 collisions per second

Data rate: ~ 1 TB/s

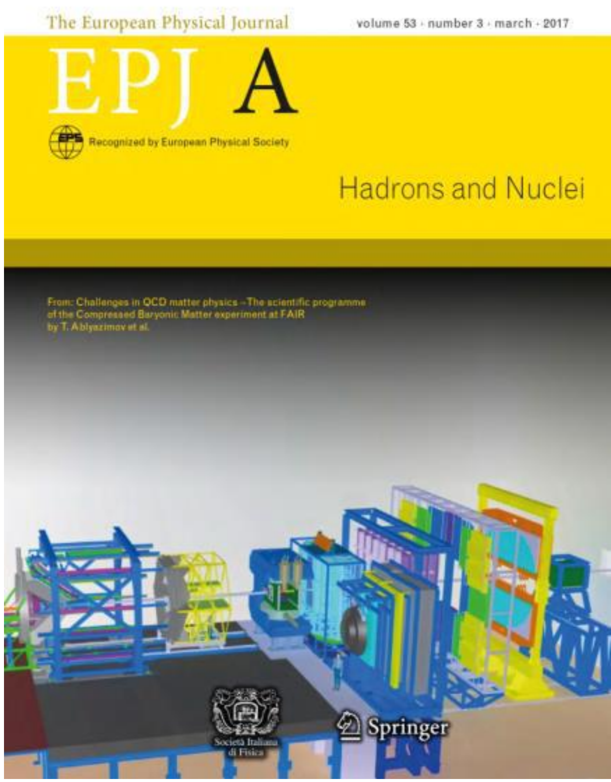


Main features:

- radiation tolerant detectors and front-end electronics
- free streaming (triggerless) data with time stamps,
- software based event selection

CBM physics and observables

Eur.Phys.J. A53 (2017) 60



QCD equation-of-state

- collective flow of identified particles
- particle production at threshold energies

Phase transition

- excitation function of hyperons
- excitation function of LM lepton pairs

Critical point

- event-by-event fluctuations of conserved quantities

Chiral symmetry restoration at large ρ_B

- in-medium modifications of hadrons
- dileptons at intermediate invariant masses

Strange matter

- (double-) lambda hypernuclei
- Search for meta-stable objects (e.g. strange dibaryons)

Heavy flavour in cold and dense matter

- excitation function of charm production

→ V. Friese

Observables: Strangeness and Dileptons

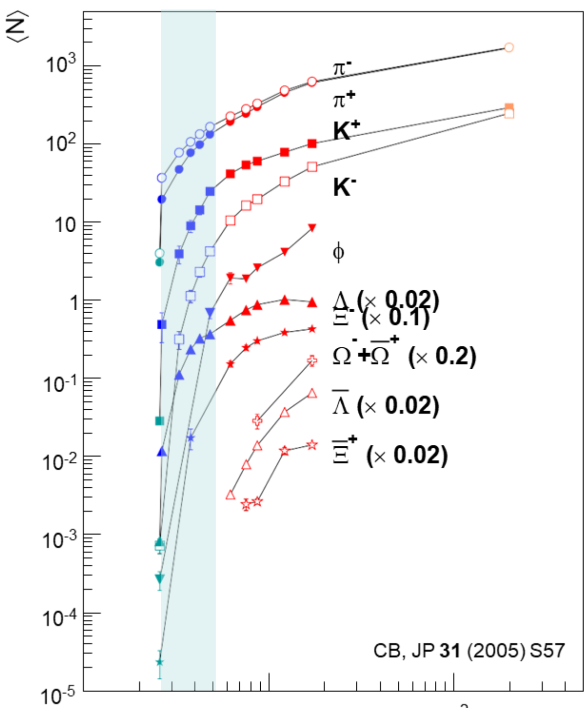
Excitation function of yields and phase-space distributions of

multi-strange hyperons and

lepton pairs in AA (C+C, Au+Au) collisions from 2-11 A GeV.

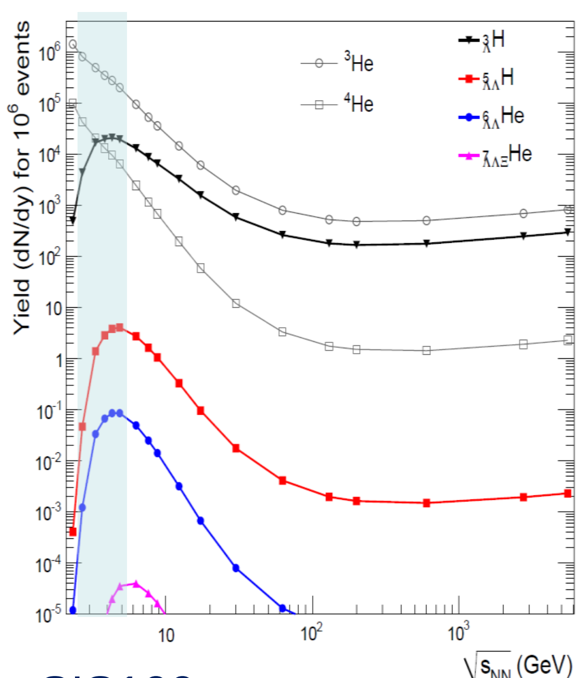
Search for hypernuclei (no data available in this energy range).

multi-strange hyperons



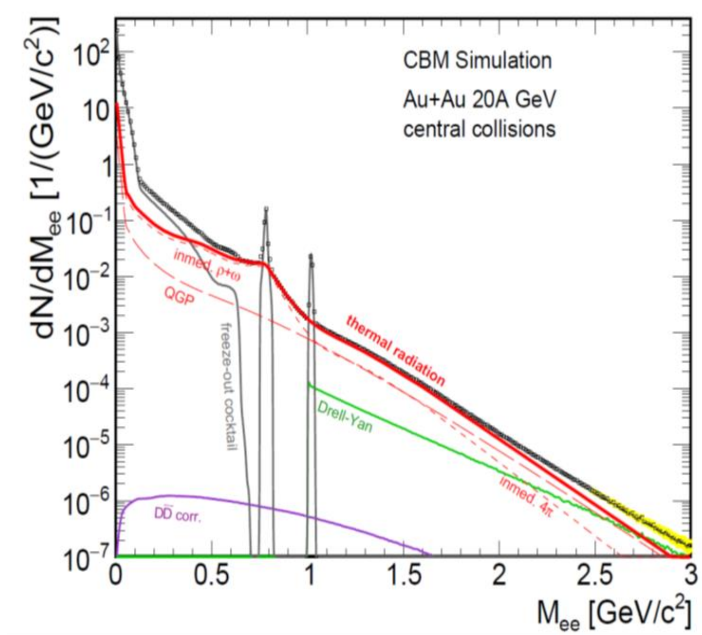
SIS100

hypernuclei



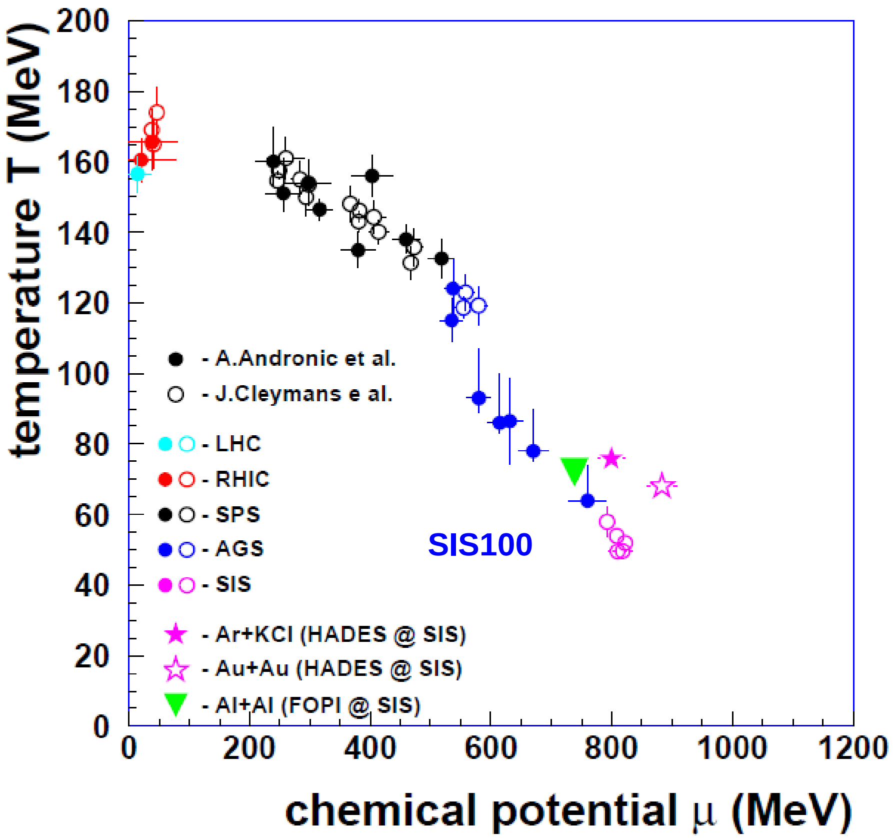
SIS100

dilepton invariant mass



Chemical Freeze-out data

Analyses in framework of
Statistical Hadronisation Model



High energies:
grandcanonical ensemble

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

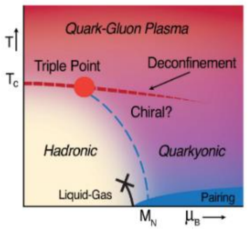
$$\mu_i = \mu_B B_i + \mu_S S_i + \mu_{I_3} I_{3,i}$$

Lower energies / small systems:
canonical ensemble,
strangeness suppression factor γ_S

Equilibrium achieved in small systems?

Equilibrium as signature for phase transition?

Freeze-out line at large baryon densities
as phase boundary to quarkyonic matter ?

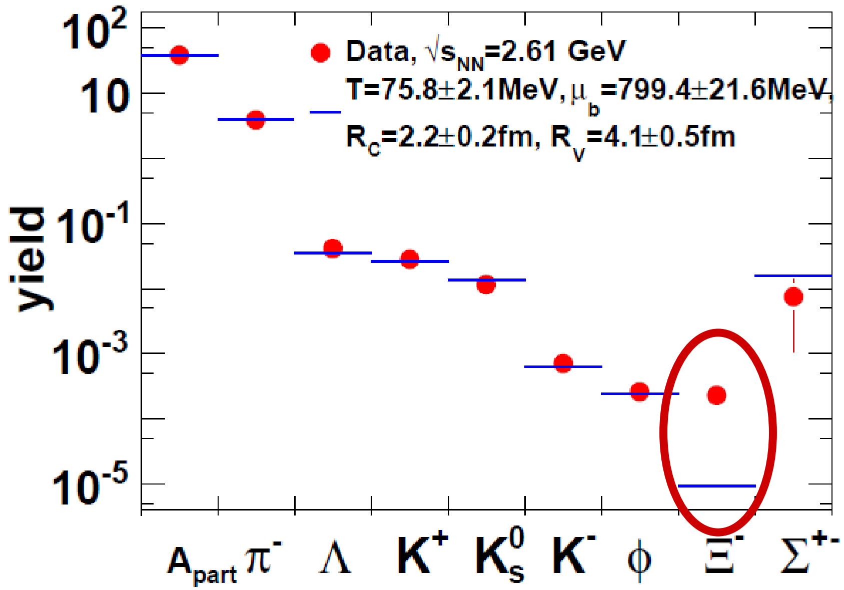


A. Andronic et al.,
Nucl. Phys. A837 (2010) 65

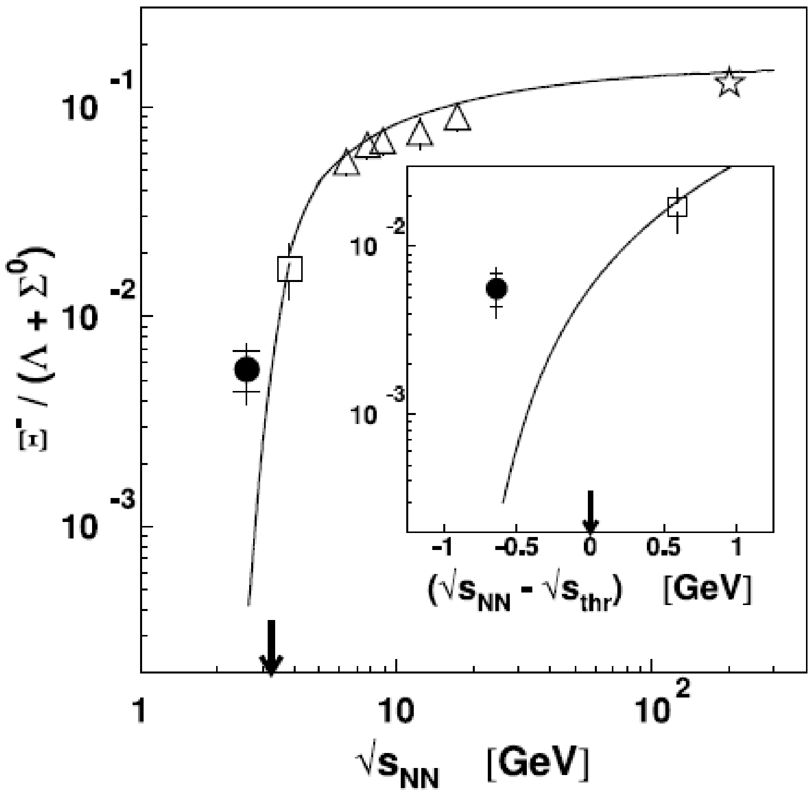
HADES: Sub-threshold Ξ^- - production

Ar+KCl reactions at 1.76A GeV

- Ξ^- yield by appr. factor 25 higher than thermal yield



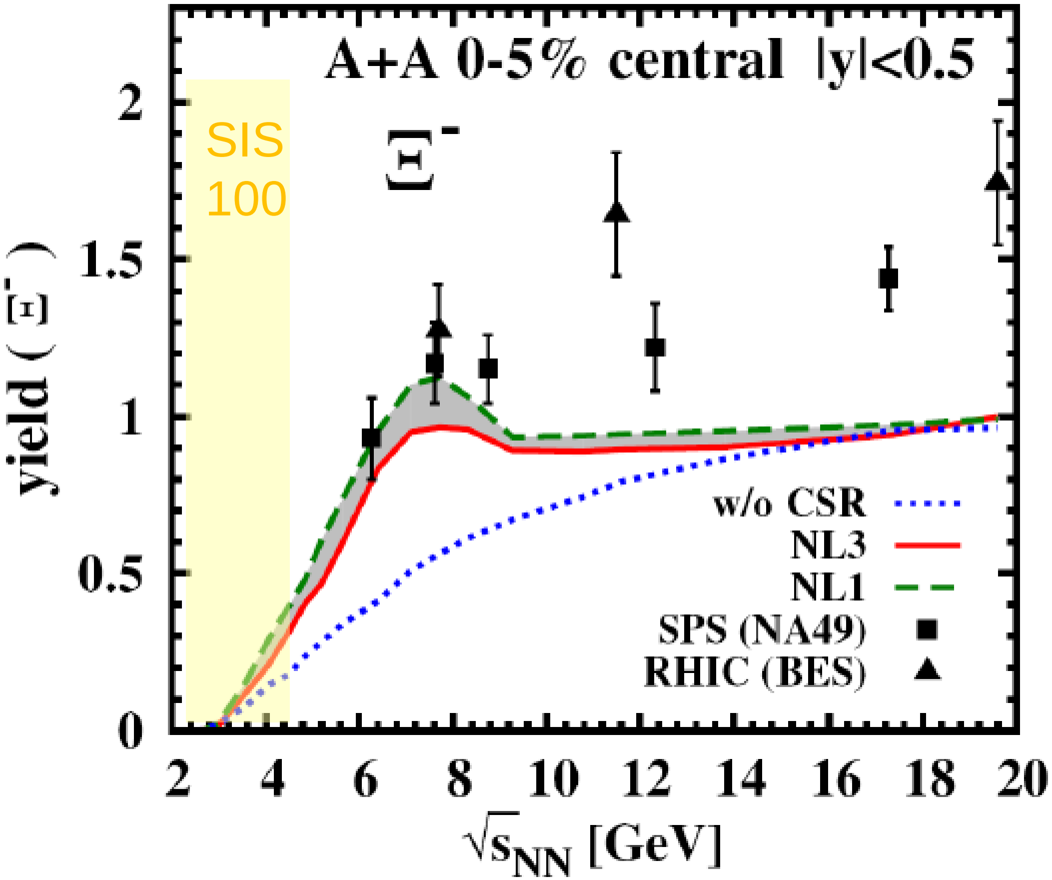
G. Agakishiev et al. (HADES), PRL103, 132301, (2009)



Hyperons as probes of dense matter

PHSD interpretation of Ξ^- - production

A. Palmese et al. Phys.Rev. C94 (2016) no.4, 044912



Predicted sensitivities
of production yields:

strong dependence on
Chiral Symmetry Restoration (CSR)

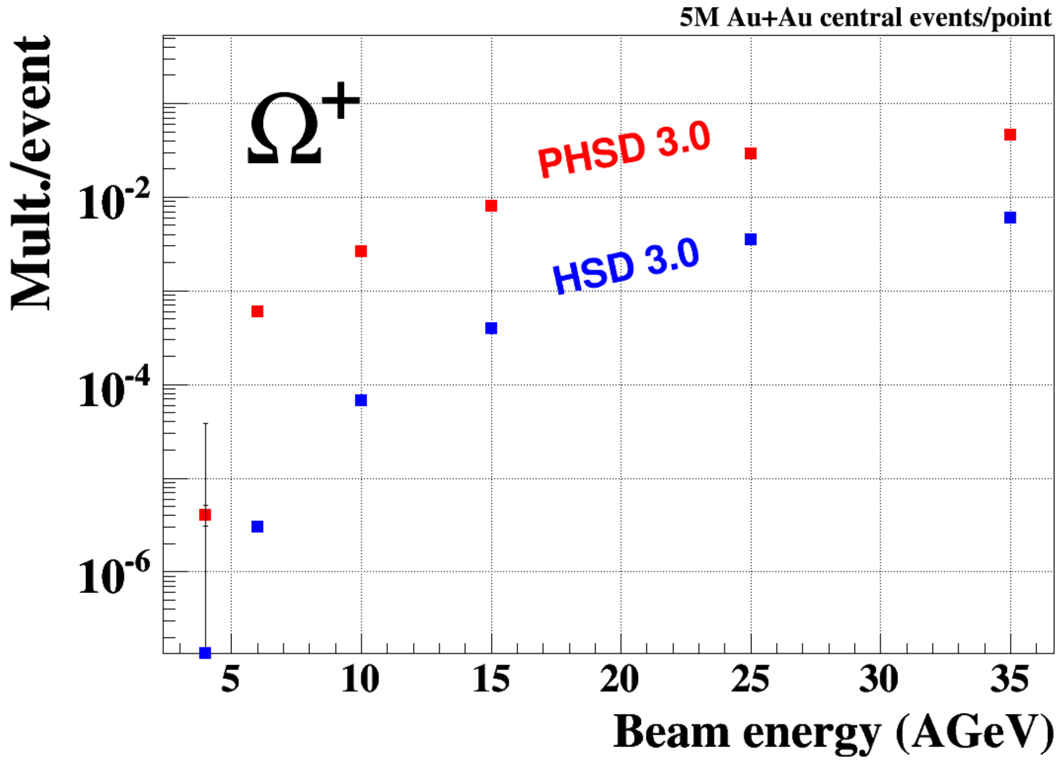
Measurable dependence on
Equation of State (NL1, NL3)

Alternative explanation (URQMD):
Tuned resonance parameter
J. Steinheimer, M. Bleicher, J.Phys. G43 (2016), 015104

Antihyperon – production

Prediction of PHSD transport model
(E. Bratkovskaya, W. Cassing)

I. Vassiliev, CBM, private communication

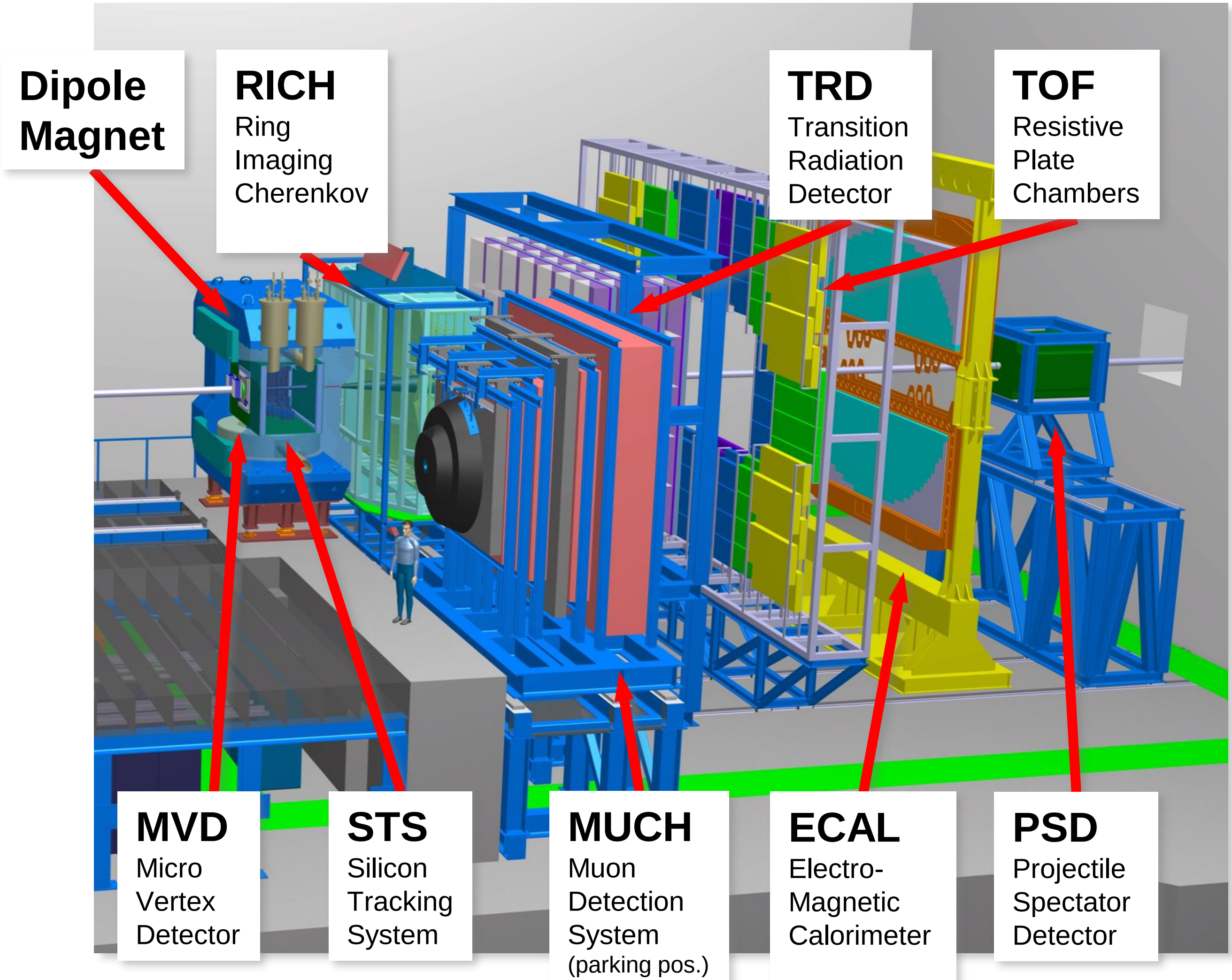


Large sensitivity to

partonic degrees of freedom
in SIS100 energy range
(deconfinement phase transition)

Mapping out the phase structure
requires systematic measurements.

CBM experimental setup (MSV)



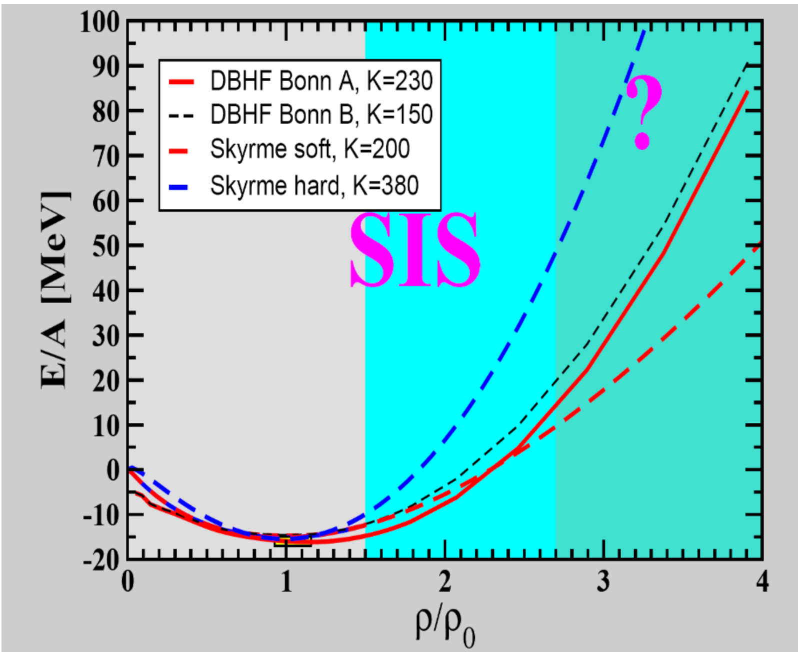
- Tracking acceptance: $2^o < \theta_{lab} < 25^o$
- Free streaming DAQ

  R_{int} = 10 MHz (Au+Au)

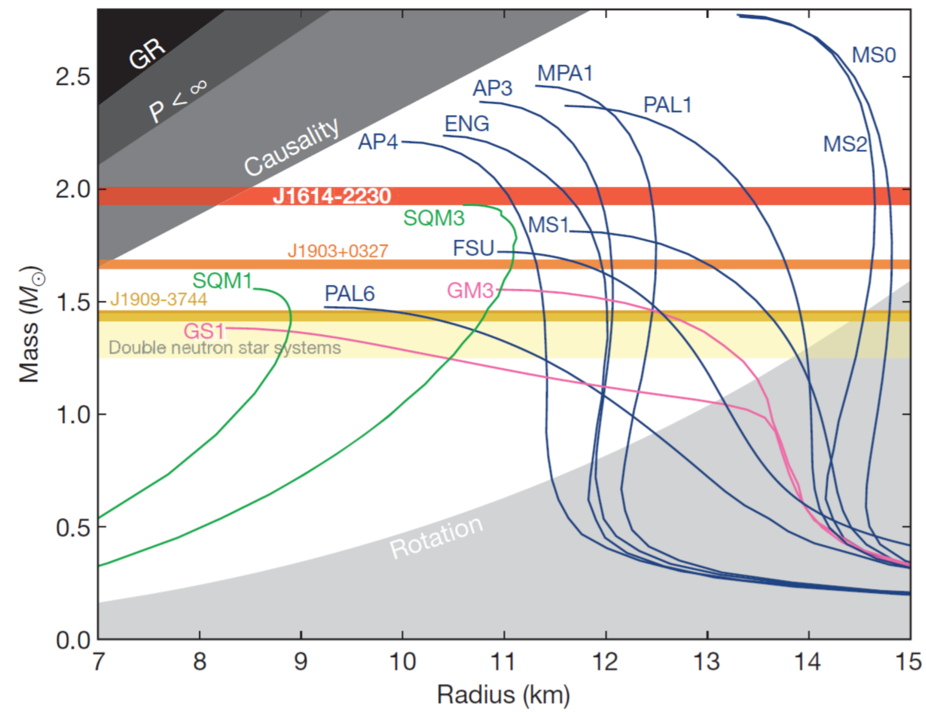
  with
  R_{int} (MVD) = 0.1 MHz
- Software based event selection

Equation of State & Neutron stars

C. Fuchs,
Prog. Part. Nucl. Phys. 56 (2006) 1



P.B. Demorest (2010)
doi:10.1038/nature09466



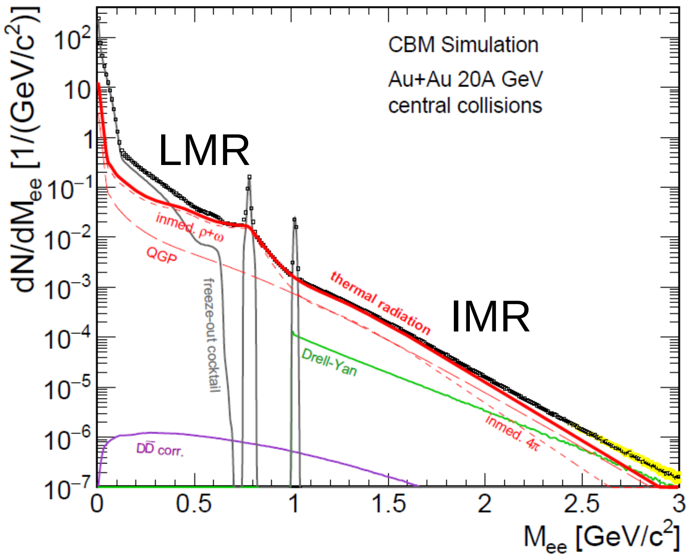
Soft EOS (Skyrme, K = 200 MeV) is not repulsive enough to allow for a neutron star with 2 solar masses.

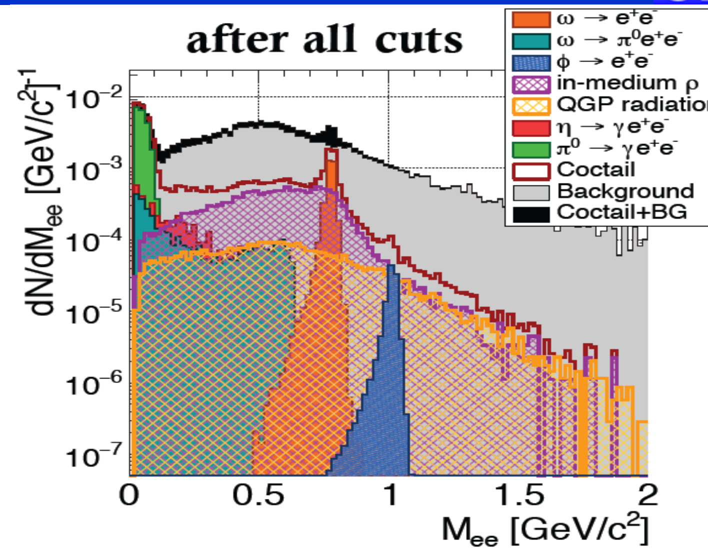
DBHF BONN A corresponds to AP4, however, does not contain strange baryons.

Stiffening of EOS must occur in the range of densities up to 4 ρ_0 (SIS100 energy range).

Dileptons as probes for dense matter (Day 1)

[R. Rapp, H. v.Hees, PLB 753 (2016) 586]



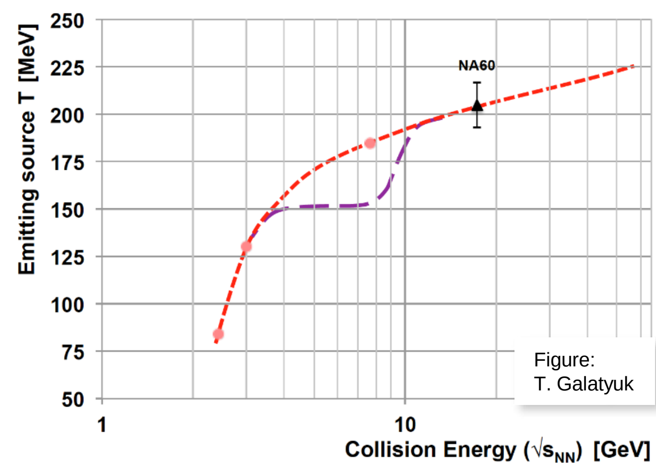


- 1M Au+Au (b=0 fm), 8A GeV
- IMR: S/B > 1/100
- Statistical accuracy of 10% requires ~1 week of beamtime

LMR: ρ – chiral symmetry restoration
fireball space – time extension

IMR: access to fireball temperature
ρ-a_1 chiral mixing

Measurement program:
e.g. excitation function of IMR – slope
full performance, uses MVD (100 kHz)

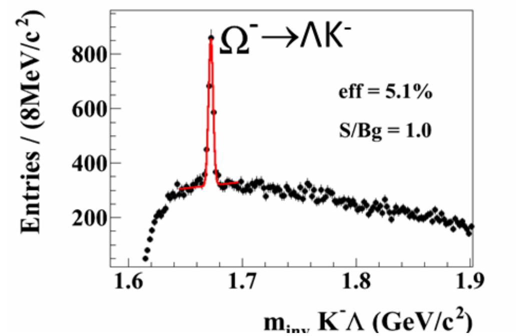


CBM Day 1 – further unique measurements

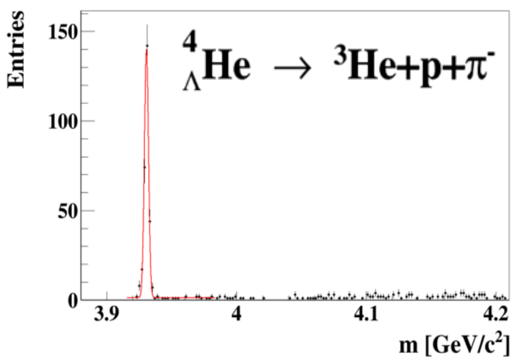
Hyperon measurements:

Au+Au at 10A GeV, ε_{duty} = 50%, R=100kHz

Particle	Multi-plicity	BR	ε (%)	yield (s^{-1})	yield in 1 week
Ω^- (1672)	$5.6\cdot10^{-3}$	0.68	5	1.64	$5\cdot10^{5}$
$^{4}_{\Lambda}He$ (3930)	$1.9\cdot10^{-3}$	0.32	14.7	0.87	$3\cdot10^{5}$



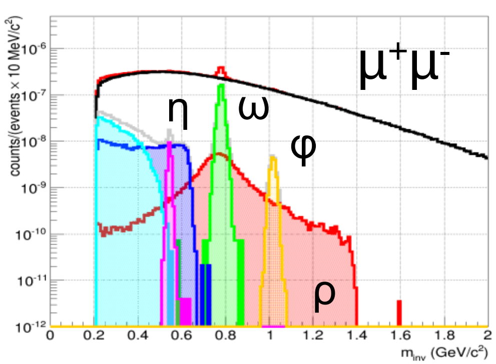
Hypernuclei measurement:



Di-Muon

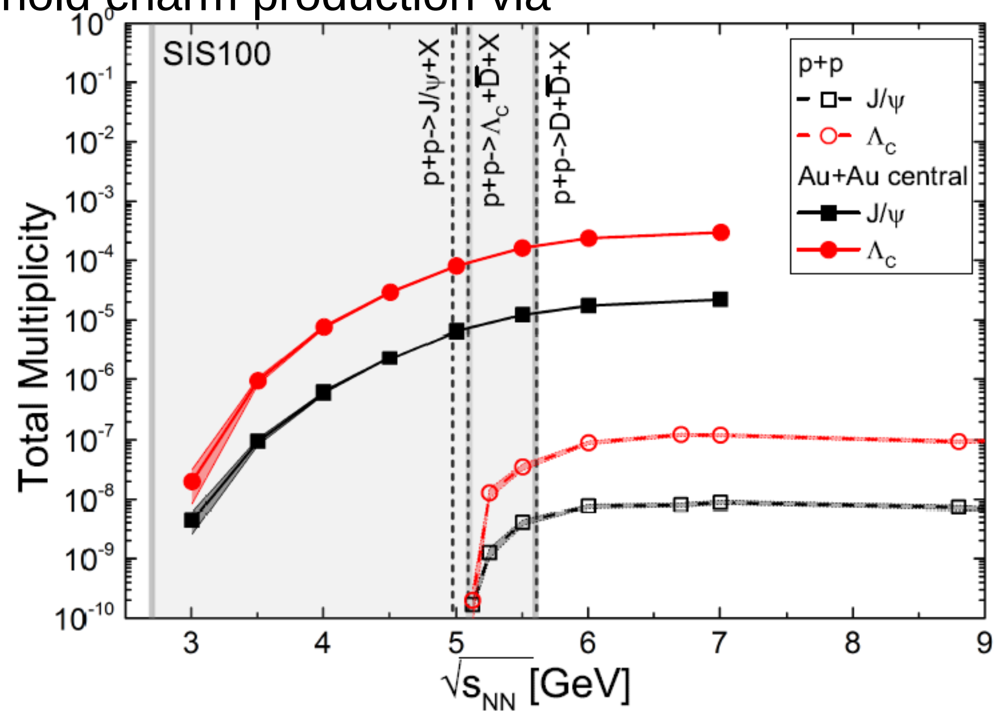
LM measurement at 8A GeV

complementary measurement to e^+e^- with different systematic errors



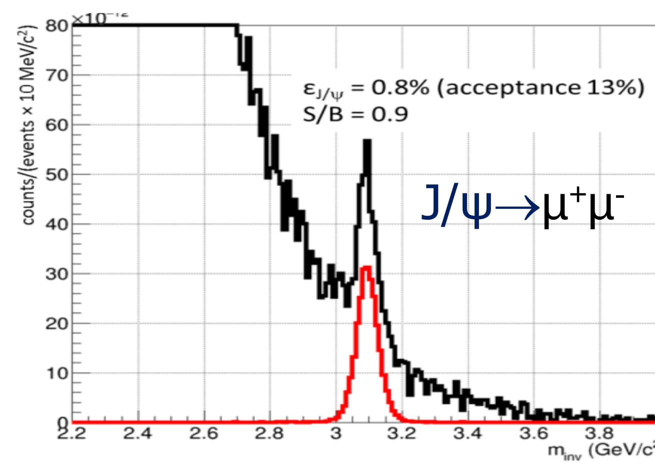
Indian contribution: Muon Detector and Physics

UrQMD calculation including subthreshold charm production via
$N^* \rightarrow \Lambda_c + D$ and $N^* \rightarrow N + J/\psi$



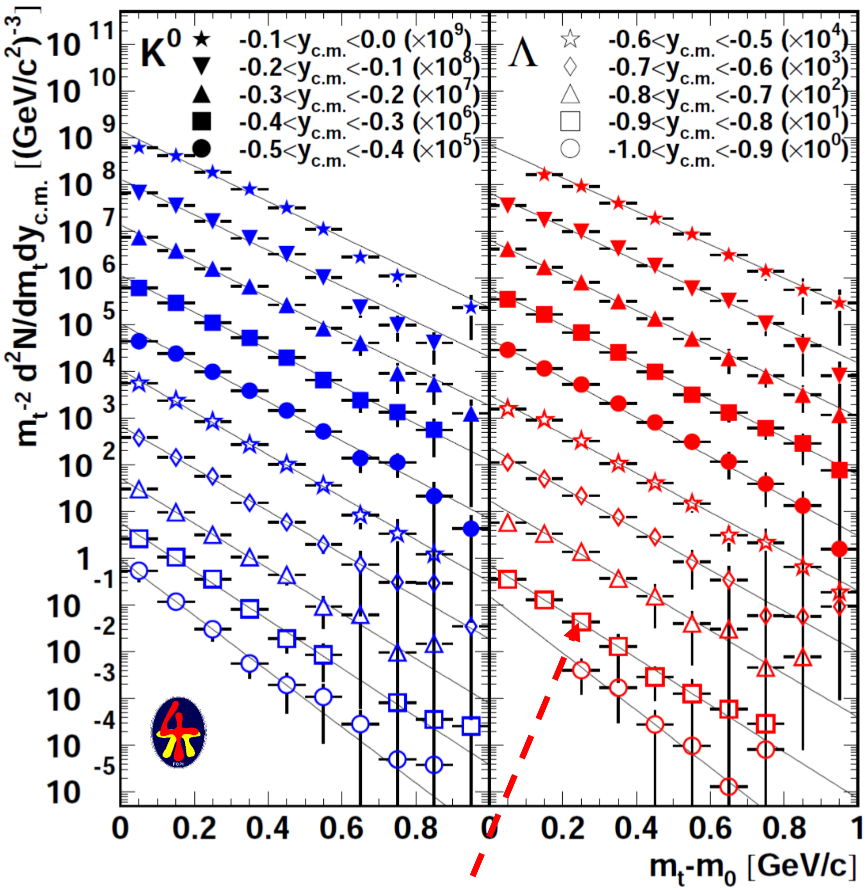
Di-muons in central Au+Au collisions at 10A GeV (J/ψ)

HSD prediction:
300 J/Ψ per week
at 10 MHz



Reference data for Λ – production

M. Merschmeyer et al. (FOPI), PRC 76, 024906 (2007)



midrapidity

Reaction:

^{58}Ni + ^{58}Ni at 1.93 AGeV

Centrality:

350 mb (most central)

$$\frac{\sigma_{cen}}{\sigma_{geo}} \leq 0.13$$

Data taking period:

17.1.2003 – 3.2.2003

Statistics:

~ 60.000 reconstructed Λ

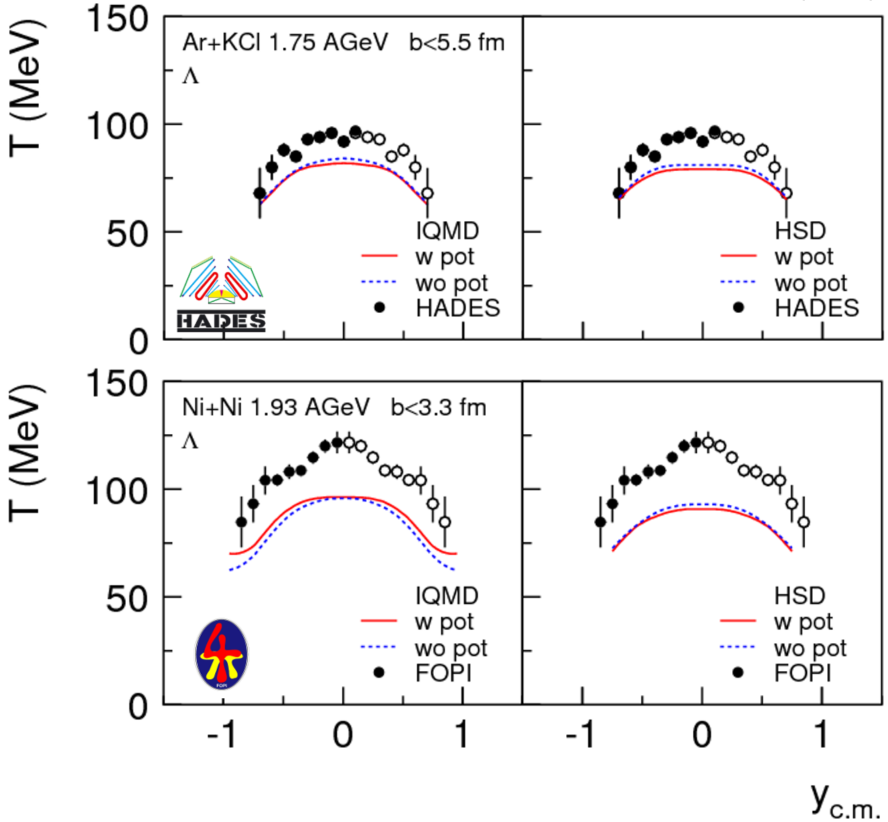
Derived quantities:

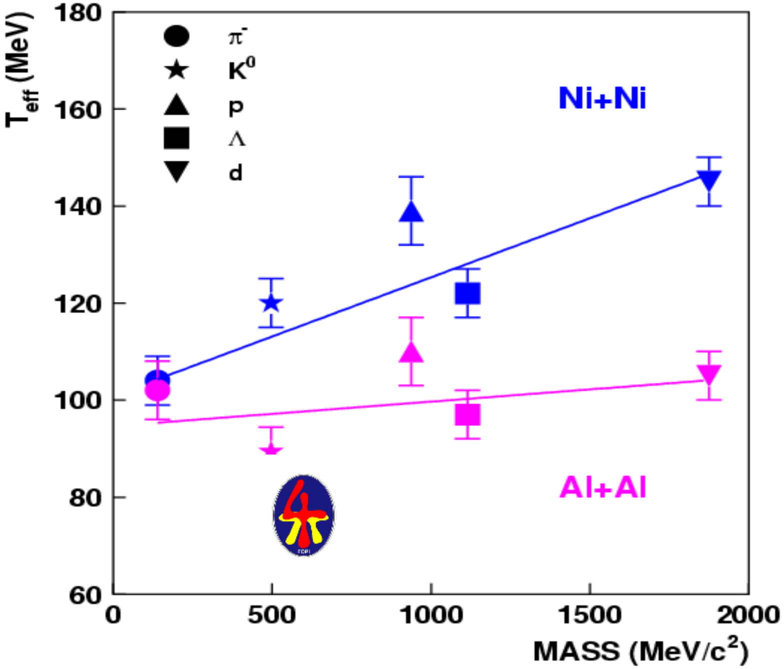
slope parameter

integrated yield

Physics of the benchmark observable

C. Hartnack et al. PR 510 (2012)





Λ - slope parameter:

- smaller than proton
- not explained by transport models
- reason unclear:
  - rescattering cross section
  - repulsive potential