Exploring the EOS with heavy ion collisions at STAR

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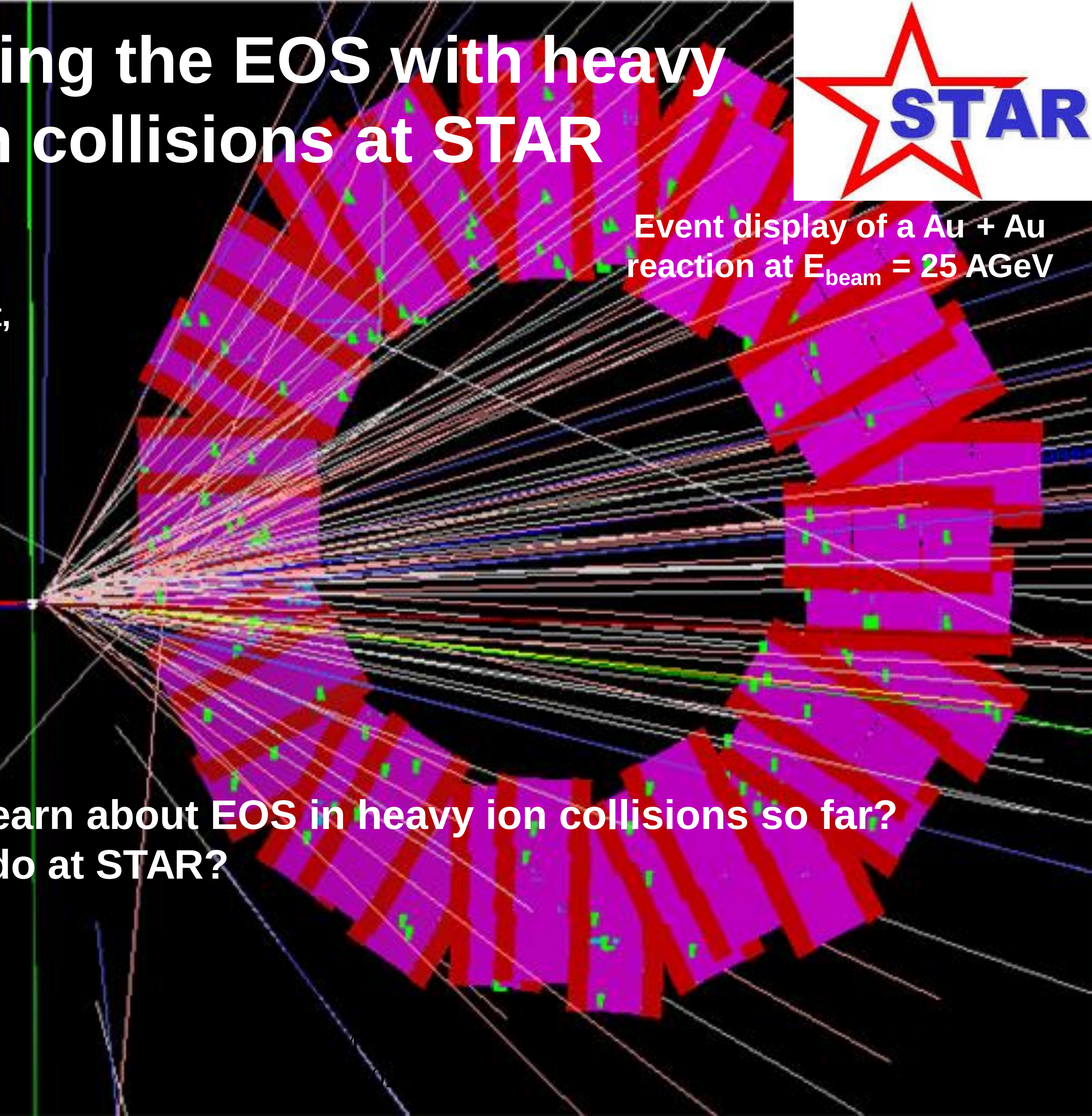


Event display of a Au + Au reaction at E_{beam} = 25 AGeV

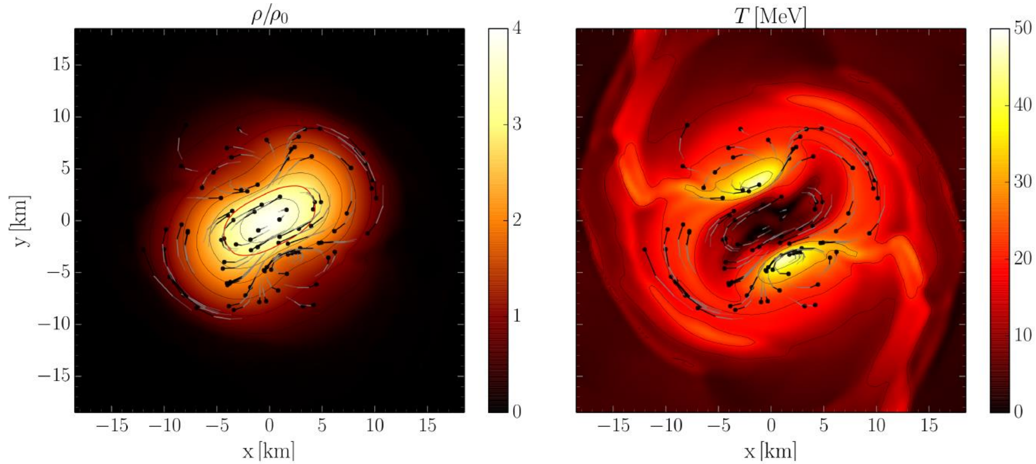
Outline

- Introduction
- What did we learn about EOS in heavy ion collisions so far?
- What can we do at STAR?
- Summary

Neutron star merger and heavy ion collisions

GW170817

M. Hanauske et al., J. Phys.: Conf. Ser. 878 012031



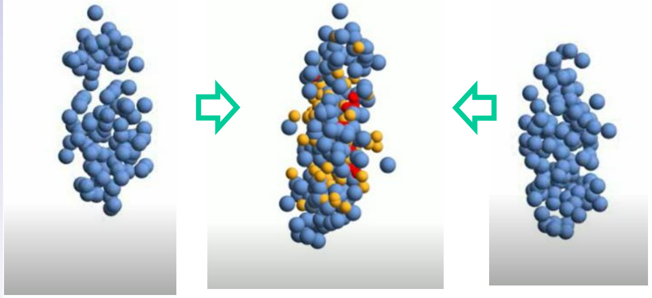
Neutron star merger

Temperature
T < 50 MeV

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

Reaction time
(GW170817)
T ~ 10 ms

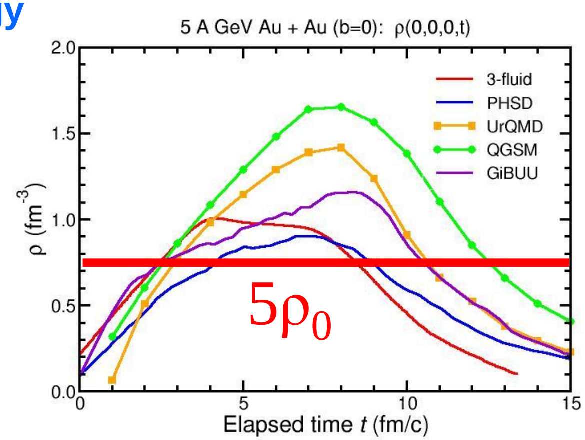
Heavy ion collisions at „low“ energy

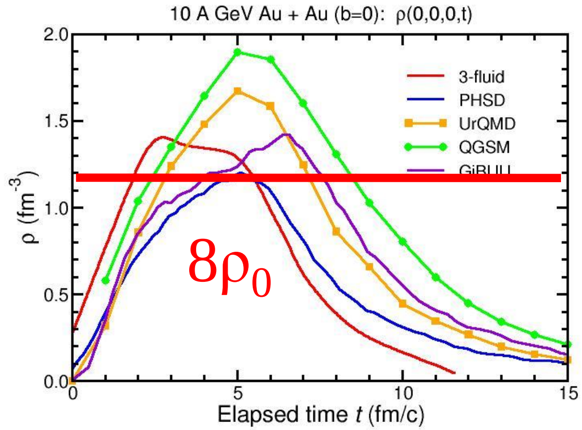


Temperature,
T < 120 MeV,

Density,
$\rho < 8\rho_0$,

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

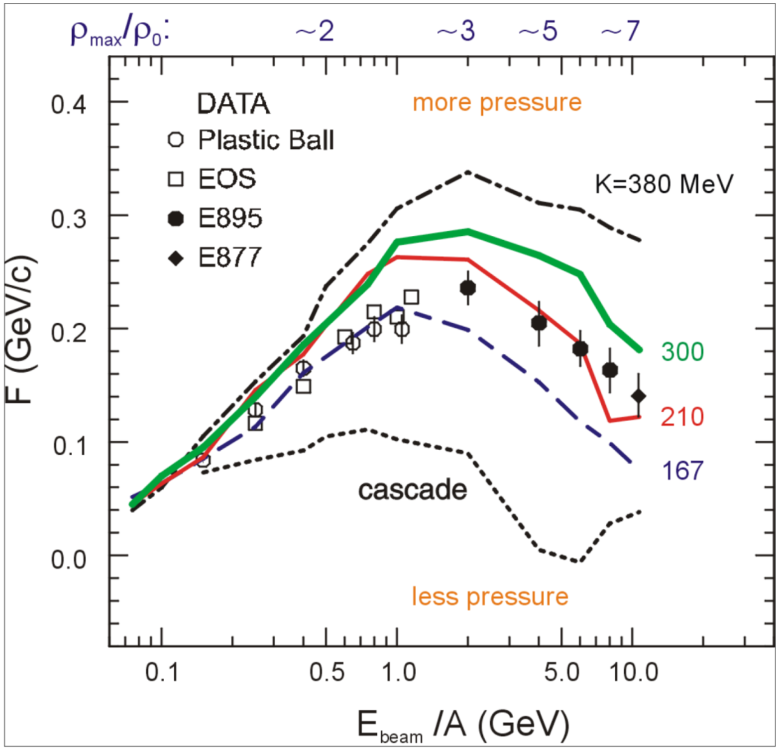


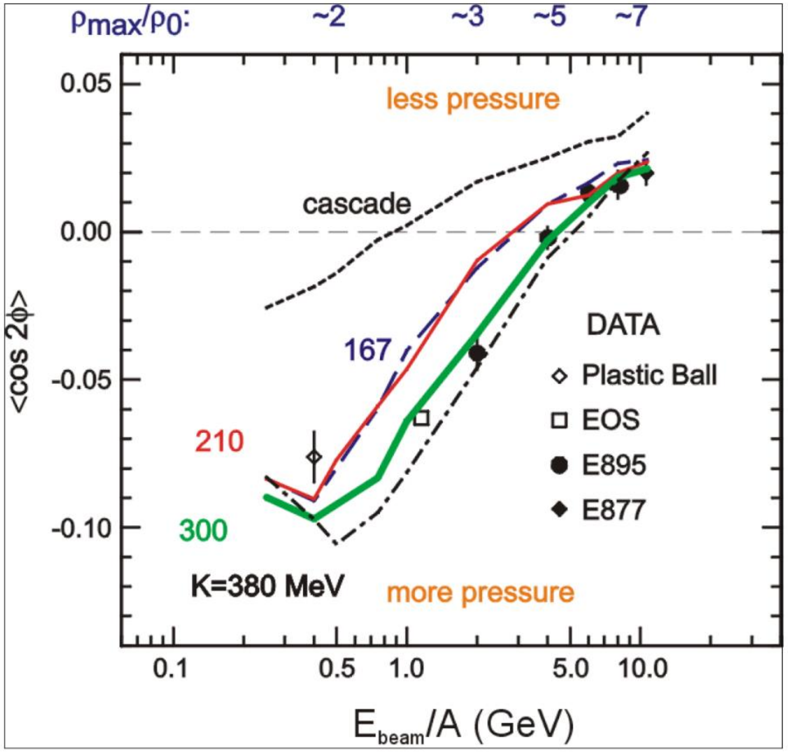


I.C. Arsene et al., Phys. Rev. C 75, 24902 (2007)

Nuclear incompressibility from collective proton flow

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



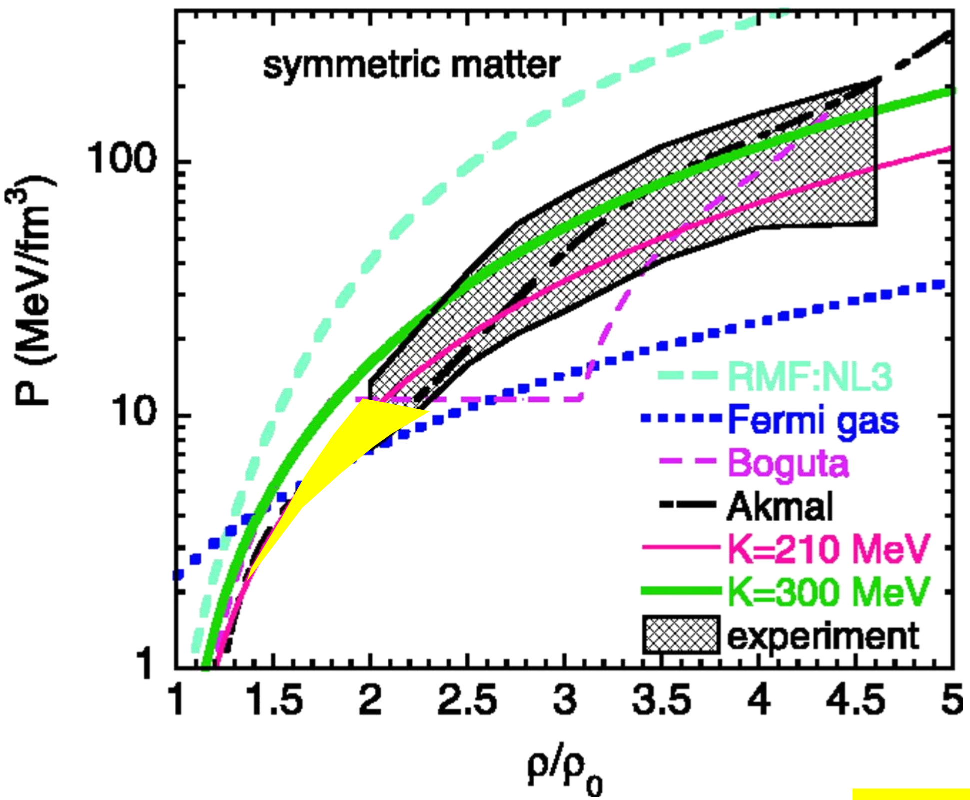


Directed flow v_1 predicts soft equation-of-state: $\kappa \leq 210$ MeV

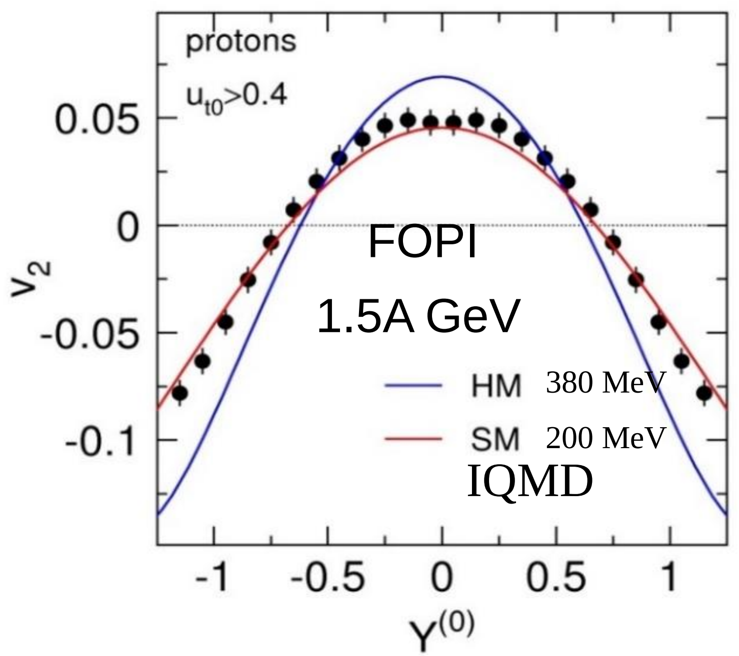
Elliptic flow v_2 predicts hard equation-of-state: $\kappa \geq 300$ MeV

Nuclear incompressibility from collective proton flow

P. Danielewicz et al., Science 298 (2002) 1592



W. Reisdorf et al.,Nucl. Phys. A 876 (2012) 1



Soft equation-of-state: κ ≤ 200 MeV

EOS from sub-threshold Kaon production

VOLUME 55, NUMBER 24 PHYSICAL REVIEW LETTERS 9 DECEMBER 1985

Subthreshold Kaon Production as a Probe of the Nuclear Equation of State

J. Aichelin and Che Ming Ko[a]

Joint Institute for Heavy Ion Research, Holifield Heavy Ion Research Facility, Oak Ridge, Tennessee 37831

(Received 11 June 1985; revised manuscript received 23 September 1985)

The production of kaons at subthreshold energies from heavy-ion collisions is sensitive to the nuclear equation of state. In the Boltzmann-Uehling-Uhlenbeck model, the number of produced kaons from central collisions between heavy nuclei at incident energies around 700 MeV/nucleon can vary by a factor of ~3, depending on the equation of state.

K yield at sub-threshold energies ~ density ~ compressibility→ **EOS**

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

Kaon production below threshold via sequential/multiple collisions involving nucleonic resonances. Multiple collisions enhanced at high densities, i.e. for a soft EOS

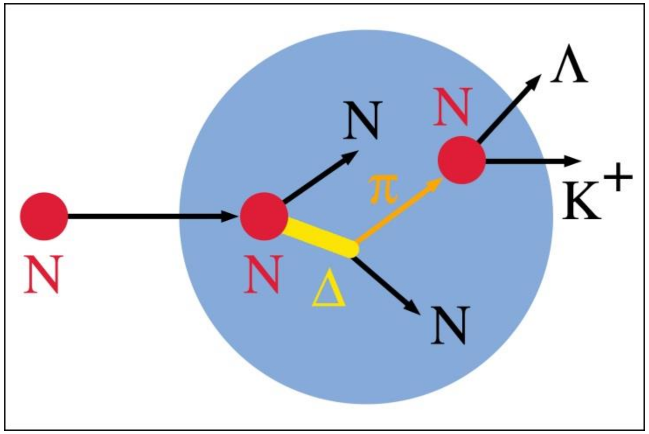
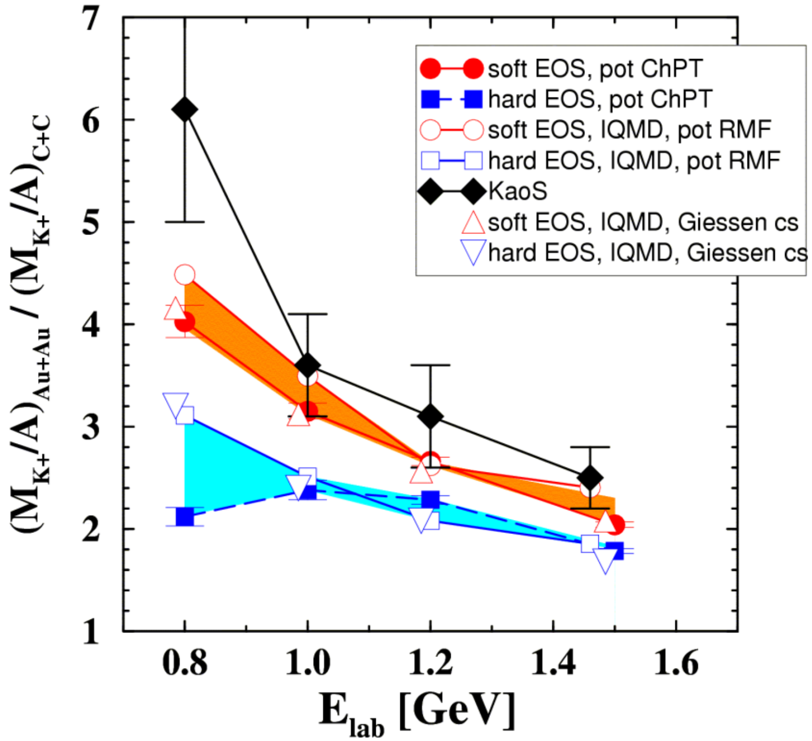
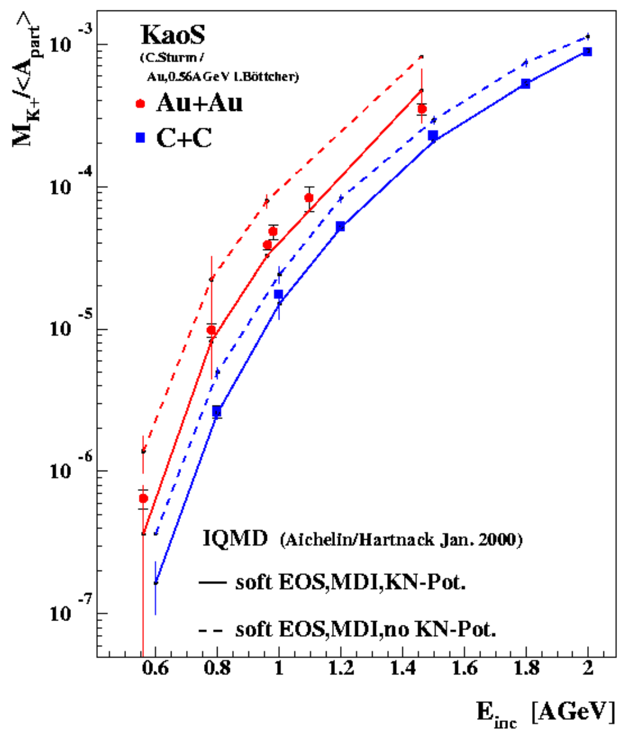


Image: P. Senger

EOS from sub-threshold Kaon production

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

EOS from sub-threshold Kaon production

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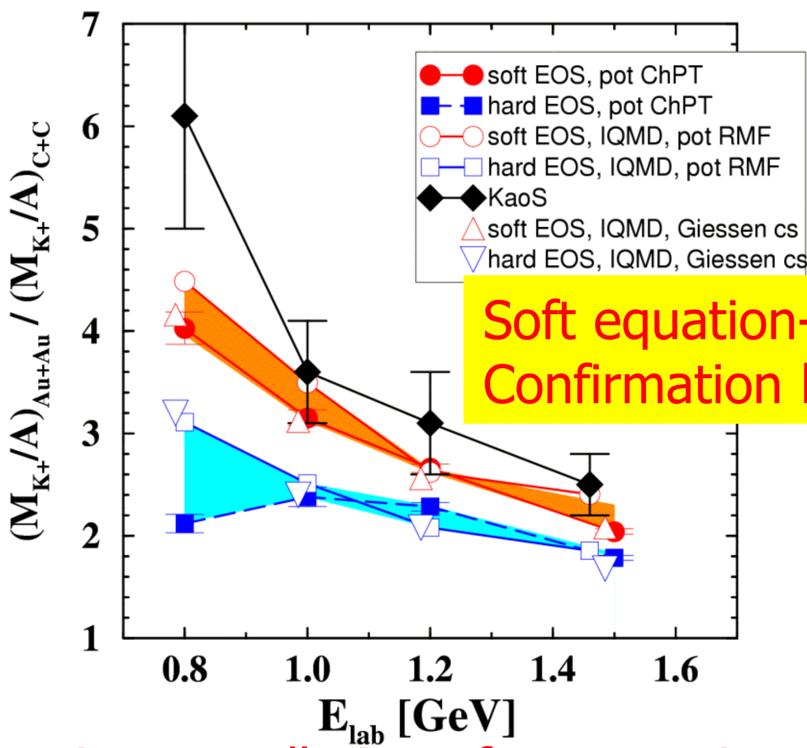
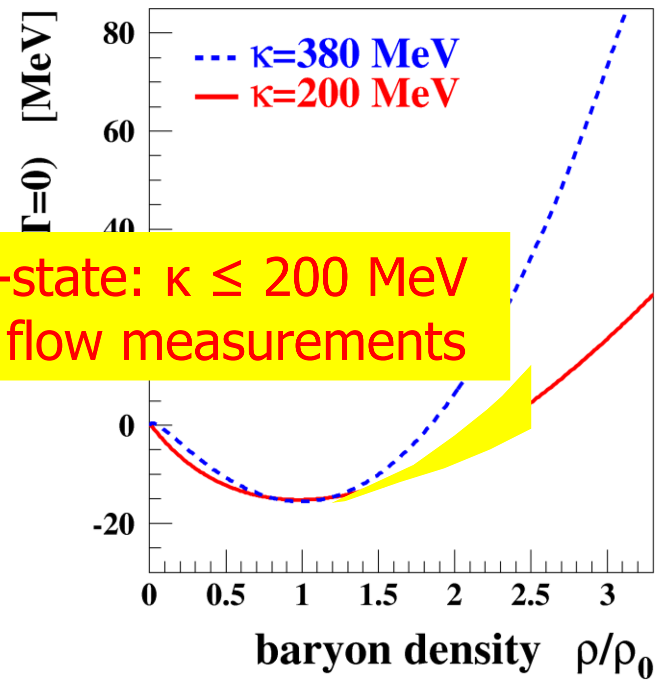




Soft equation-of-state: κ ≤ 200 MeV
Confirmation by flow measurements

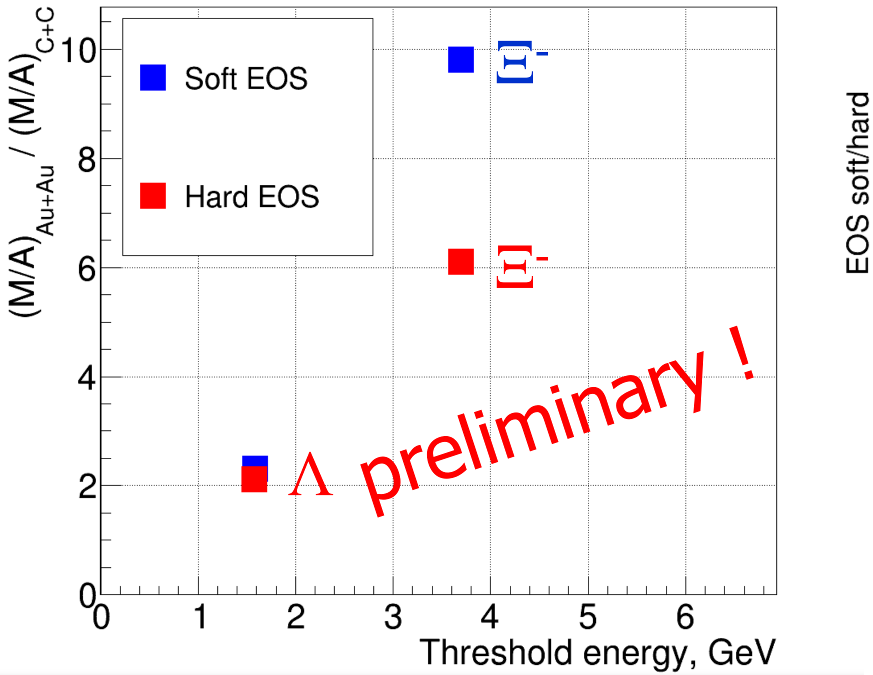
Au/C ratio: cancellation of systematic errors both in experiment and theory

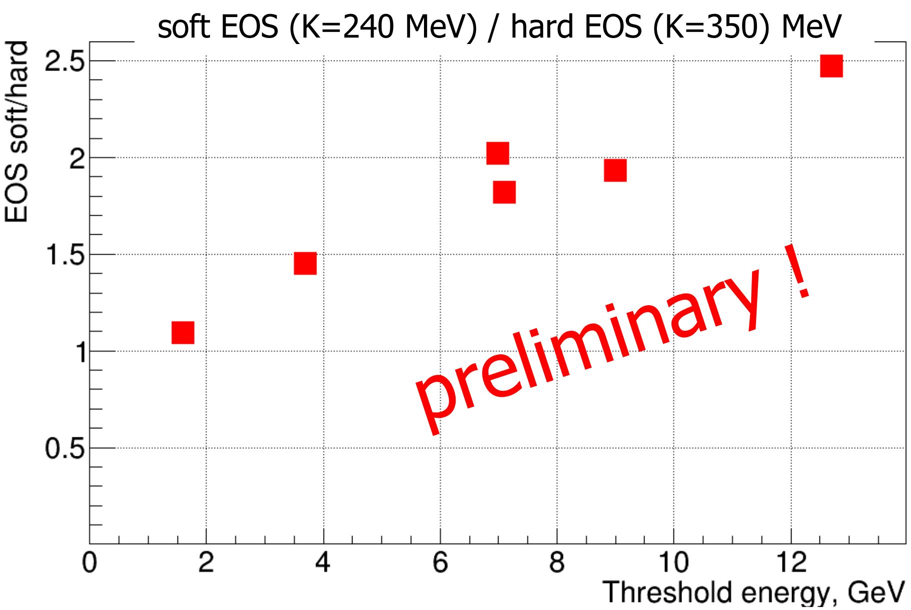
P. Senger, XLVIII International Workshop on Gross Properties of Nuclei and Nuclear Excitations – Nuclear equation of state and neutron stars

Multi-strange hyperons…

… a promising observables for the EOS of symmetric matter

Hyperon yield ratio for Au+Au/C+C at 4A GeV





P. Senger:
PHQMD calculations , J. Aichelin, E. Bratkovskaya, V. Kireyeu et al.

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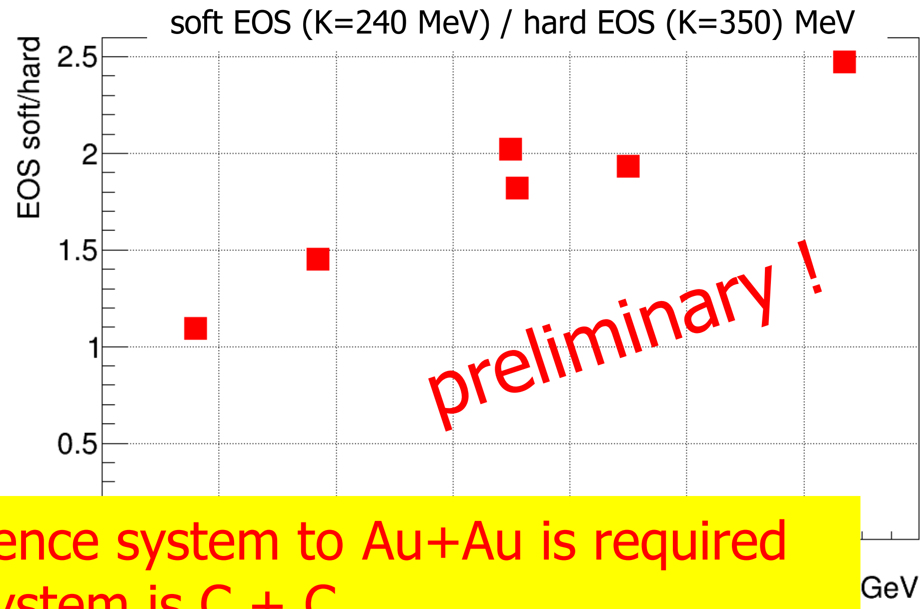
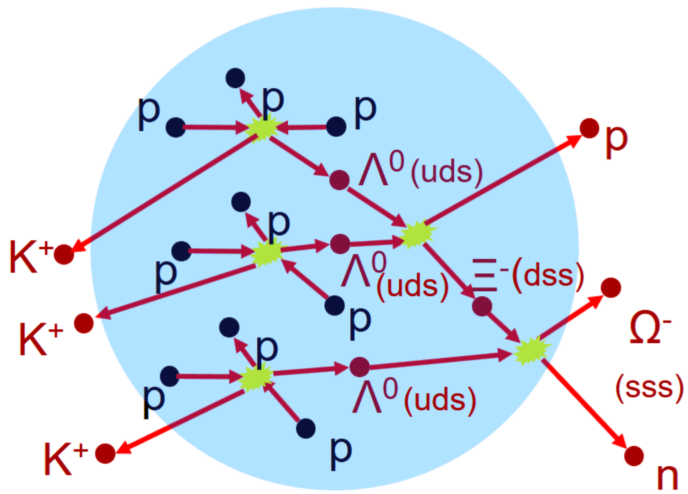


For this measurements a reference system to Au+Au is required
proposed system is C + C

PHQMD calculations , J. Aichelin, E. Bratkovskaya, V. Kireyeu et al.
P. Senger: (priv. com.)

Production threshold of multi-strange hyperons

Hyperon production via multiple collisions



$pp \rightarrow K^+p\Lambda^0$

$pp \rightarrow K^+p\Lambda^0$ → $\Lambda^0\Lambda^0 \rightarrow \Xi^- p$

$pp \rightarrow K^+p\Lambda^0$ → $\Lambda^0 \Xi^- \rightarrow \Omega^- n$

P. Senger, K, Agarval

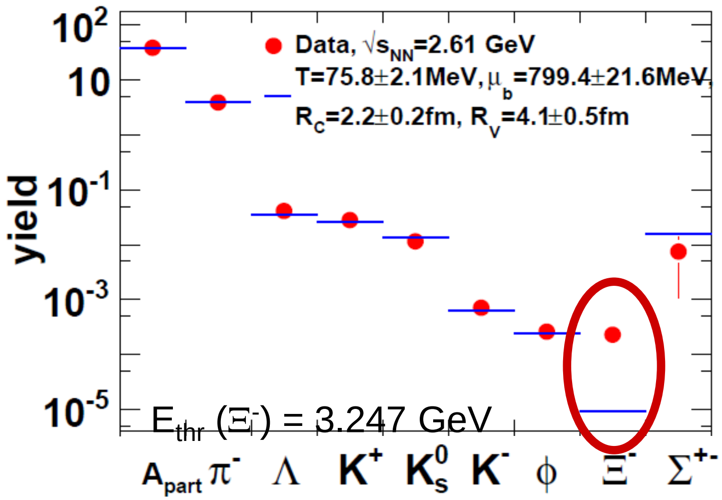
Strange and charmed particle production thresholds in pp - collisions

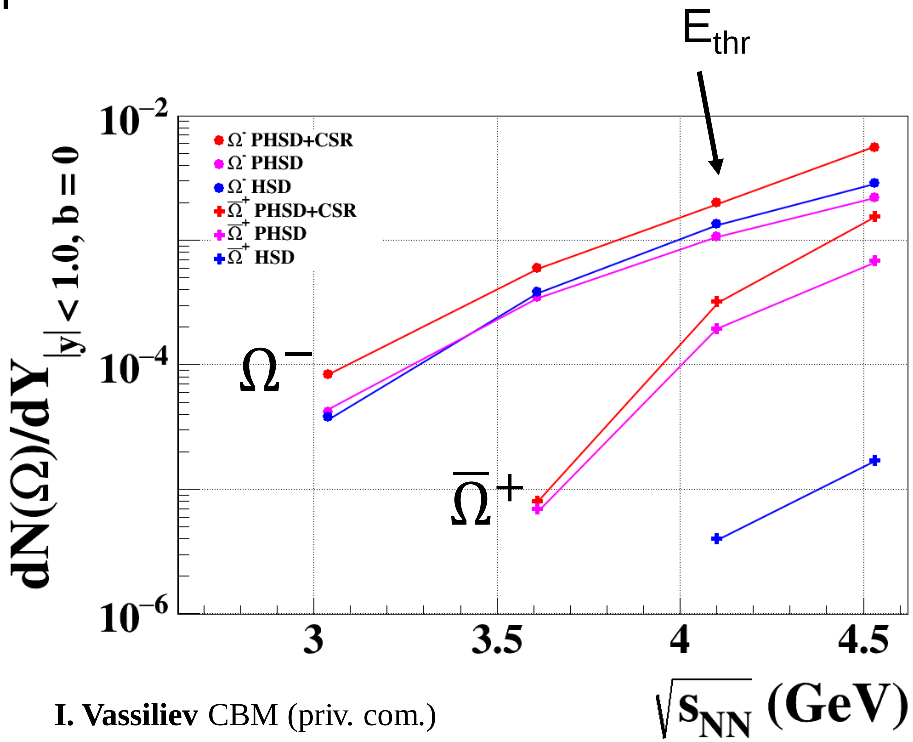
reaction	$\sqrt{s}$ (GeV)	T_{lab}(GeV)
$pp \rightarrow K^+\Lambda p$	2.548	1.6
$pp \rightarrow K^+K^-pp$	2.864	2.5
$pp \rightarrow K^+K^+\Xi^-p$	3.247	3.7
$pp \rightarrow K^+K^+K^+\Omega^-n$	4.092	7.0
$pp \rightarrow \Lambda\bar{\Lambda}pp$	4.108	7.1
$pp \rightarrow \Xi^-\bar{\Xi}^+pp$	4.520	9.0
$pp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

N. Herrmann (priv. com)

Production yields

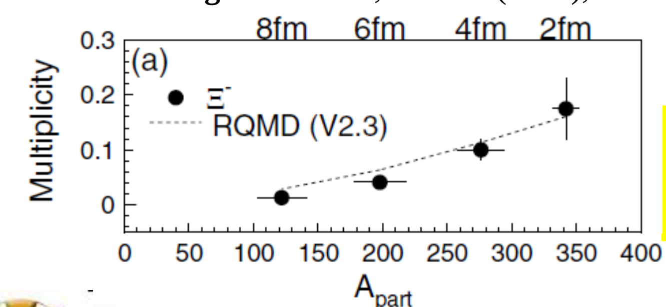
HADES sub-threshold Ξ⁻-production
Ar+KCl reactions at 1.76A GeV





E895: Ξ⁻-production Au+Au 6 GeV

P. Chung et al. E895 , PRL 91 (2003), 202301



I. Vassiliev CBM (priv. com.)

PHSD W. Cassing, E. Bratkovskaya et al., Phys.Rev. C93 (2016), 014902

At threshold energies production yield of multi-strange hyperons is in the order of 10^{-2} - 10^{-3}

BES II program ++

STAR BESII program

Collider Energy	Fixed-Target Energy	Single beam AGeV	Center-of-mass Rapidity	μ_B (MeV)
62.4	7.7	30.3	2.10	420
39	6.2	18.6	1.87	487
27	5.2	12.6	1.68	541
19.6	4.5	8.9	1.52	589
14.5	3.9	6.3	1.37	633
11.5	3.5	4.8	1.25	666
9.1	3.2	3.6	1.13	699
7.7	3.0	2.9	1.05	721

2019
2020

Daniel Cebra

Collider energy	Single beam AGeV	E_{kin} AGeV	Fixed-target Energy
62,4	31,2	30,262	7,76
39	19,5	18,562	6,19
27	13,5	12,562	5,20
25	12,5	11,562	5,02
23	11,5	10,562	4,83
19,6	9,8	8,862	4,49
17,6	8,8	7,862	4,27
16	8	7,062	4,09
14,5	7,25	6,312	3,92
13,5	6,75	5,812	3,80
11,5	5,75	4,812	3,54
9,1	4,55	3,612	3,21
8,4	4,2	3,262	3,10
7,7	3,85	2,912	3,00

$\Omega^+\Omega^-$
E_{thr}=5.22 GeV

$\Xi^+\Xi^-$
E_{thr}=4.52 GeV

Ω^-
E_{thr}=4.09 GeV

Ξ^-
E_{thr}=3.247 GeV

We propose to measure more points at FXT mode

BES II program ++

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$\Xi^+\Xi^-$
E_{thr}=4.52 GeV

Ω^-
E_{thr}=4.09 GeV

Ξ^-
E_{thr}=3.247 GeV

Estimated beam time request

For Au+Au: (2021/22)

yield x efficiency x interaction rate

10^{-2} (10^{-3}) x 10^{-2} x 10^{3} = 10k (1k)/day

FAZIT: 1 day for each energy should be sufficient

For C+C: (2023++)

Estimate: yield Au+Au ≈ 100 C+C

yield x efficiency x interaction rate

10^{-4} (10^{-5}) x 10^{-2} x 10^{4} = 1k (0.1k)/day

FAZIT: about 10 days for each energy

Summary

- STAR is the optimal place to study the EOS at high baryon densities in near future
- We propose sub-threshold production measurement of multi-strange hyperons
- A substantial fraction of the needed measurements are already done (FXT BES II)
- For more robust results additional intermediate FXT energy points are needed (program for 2021/22)
- Measurement with light reference system needed (we propose C + C) (program for 2023++)

eTOF timeline

✓ December 2015	submit the physics proposal to GSI and BNL for approval
✓ Summer 2016	shipping a real size module to BNL and installing it on the east side pole of STAR
✓ Feb. 2017	1st system integration test with one module by participating in the Run17 beam time in STAR
✓ Fall 2017	shipping and installation of one sector
✓ Feb. 2018	2nd system integration test with one sector by participating in the Run18 beam time in STAR
✓ Sep. - Oct. 2018	shipping all 36 modules including infrastructure (gas system, LV-, HV-power supply) to BNL
✓ Oct. - Nov. 2018	Installation and commissioning
✓ Feb. 2019	Start of the BES II campaign
➢ Summer 2021++(+)	Decommissioning and shipping of all modules including infrastructure to FAIR

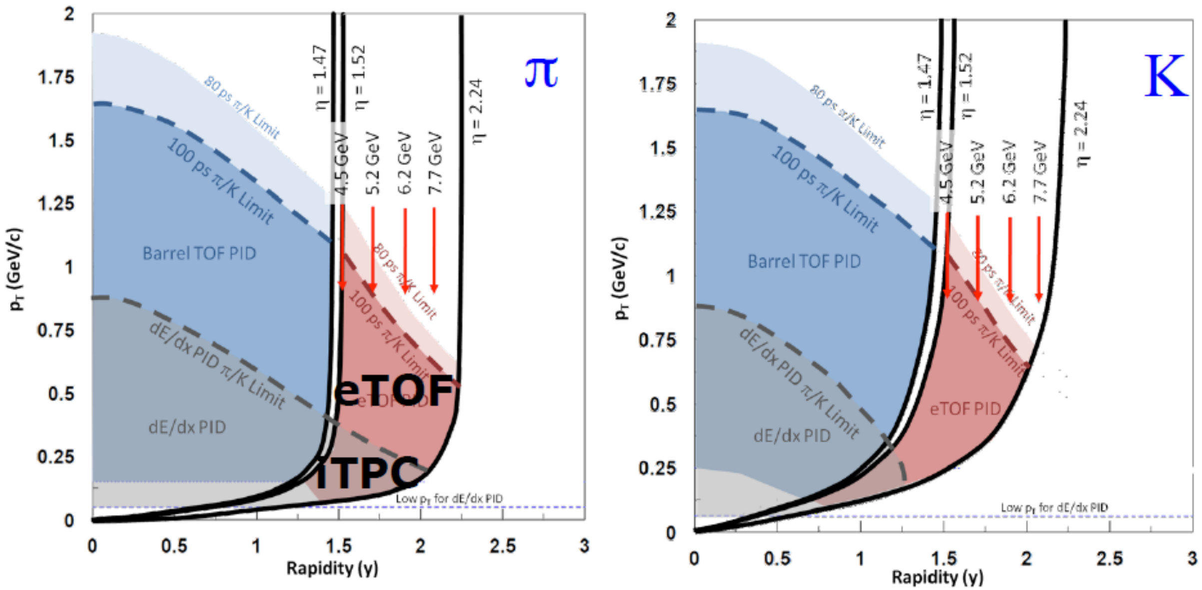
Backup Slides

BES II program

Daniel Cebra

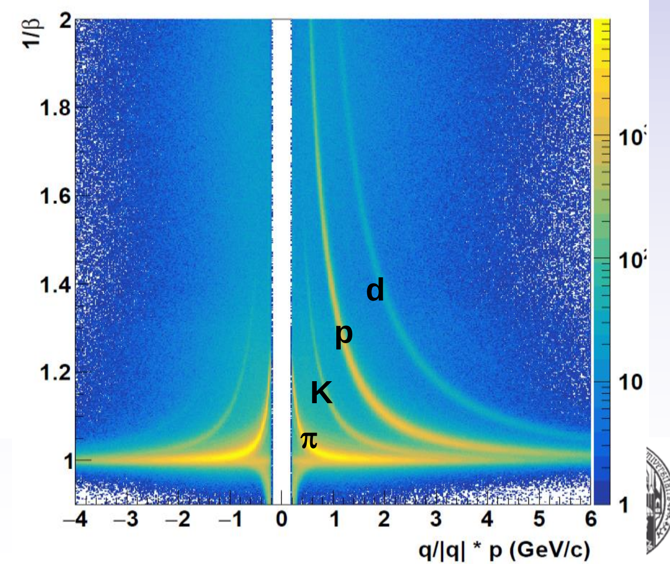
	Collision Energies (GeV):	7.7	9.1	11.5	14.5	19.6
	Chemical Potential (MeV):	**420**	**370**	**315**	**260**	**205**
	Observables	Millions of Events Needed				
QGP	R_{CP} up to p_T 4.5 GeV	NA	NA	160	92	22
QGP	Elliptic Flow of ϕ meson (v_2)	100	150	200	300	400
QGP	Local Parity Violation (CME)	50	50	50	50	50
1st P.T.	Directed Flow studies (v_1)	50	75	100	100	200
1st P.T.	asHBT (proton-proton)	35	40	50	65	80
C.P.	net-proton kurtosis ($\kappa\sigma^2$)	80	100	120	200	400
EM Probes	Dileptons	100	160	230	300	400
	Number of Events	**100**	**160**	**230**	**300**	**400**
	Weeks of Beams	**12**	**9.5**	**5.0**	**5.5**	**4.5**

Acceptance in fixed target mode



- eTOF is essential for fix target program for $\sqrt{s}$ > 4.5 GeV
- It covers mid-rapidity region for higher $\sqrt{s}$ energies
- π/K separation up to 2.5 GeV/c (current status)

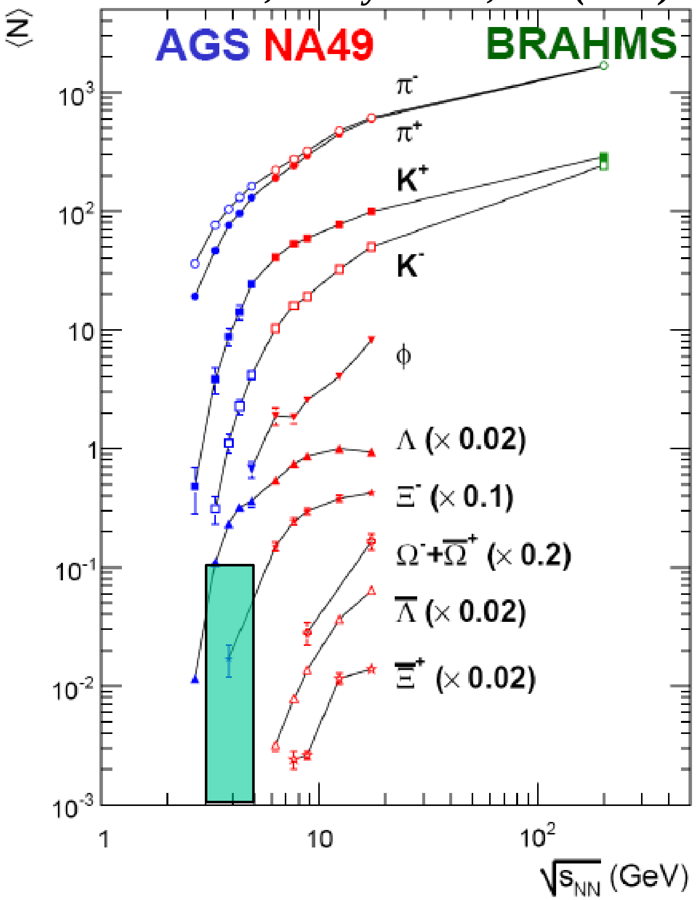
iTPC + eTOF: 1.52 < η < 2.24

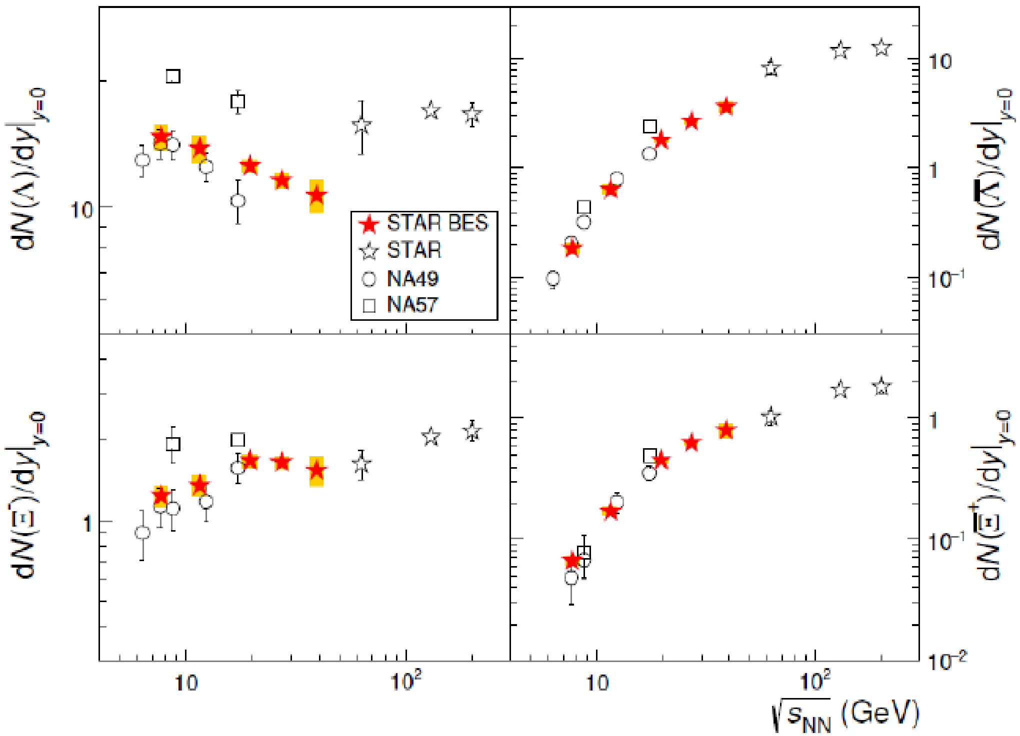


Acceptance in fixed target mode

Particle yield ratios from central Au + Au collisions

C. Blume, J. Phys. G 31, S57 (2005)

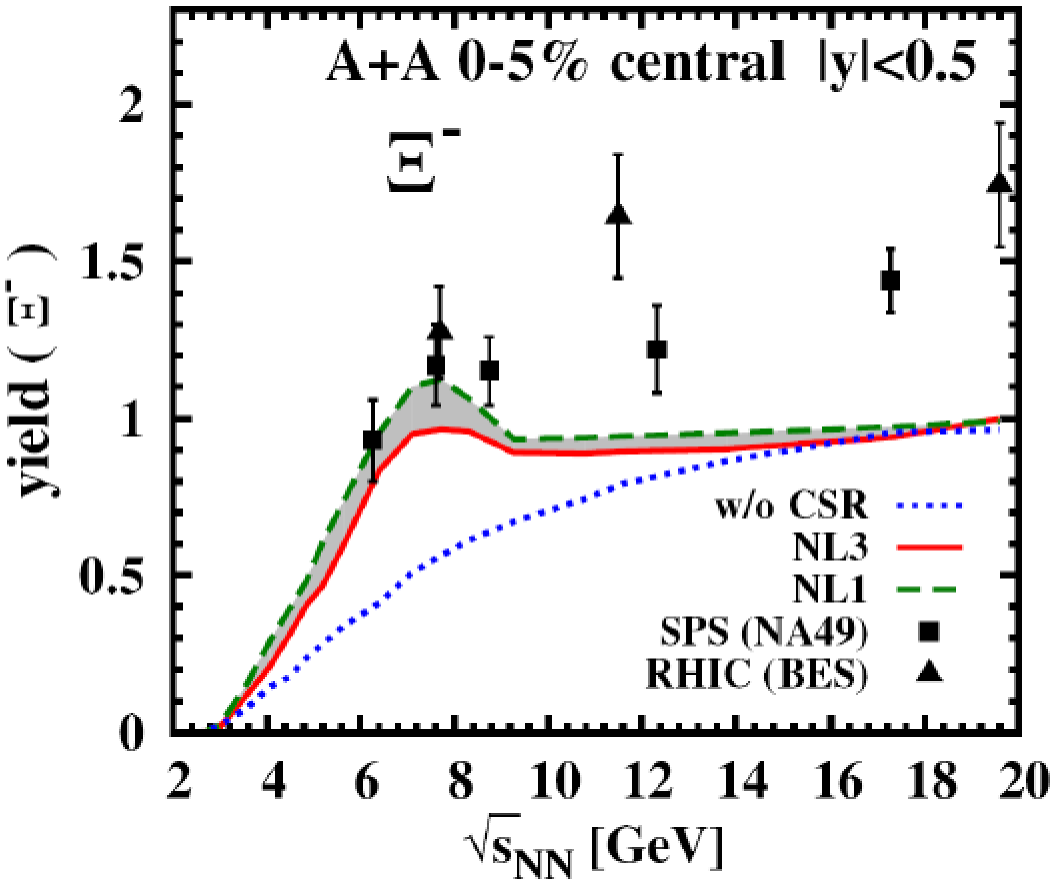




Multi-strange hyperons

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)
- Ξ^- production threshold in pp $\sqrt{s}$ = 3,247 GeV

$$pp \rightarrow K^+K^+\Xi^-p$$

Alternative explanation (URQMD): Tuned resonance parameter

J. Steinheimer, M. Bleicher, J.Phys. G43 (2016), 015104