Strangeness Production

(with focus on FAIR energy range)

Outline

Part I

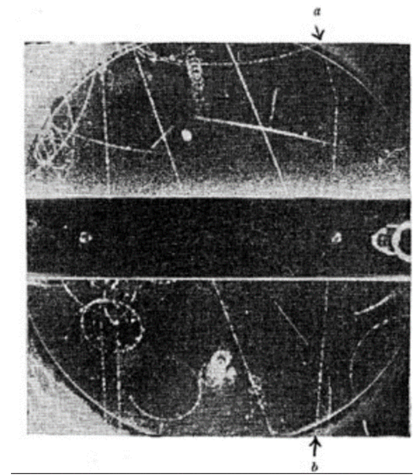
- History
- Quarkmodel
- Strange hadrons
- Strange particle yields in heavy ion collisions
- Strangeness enhancement
- The „horn“
- Thermal Model description
- Thermalization times
- Connection to phase transition
- Equation-of-state from subthreshold kaon production

Part II

- In medium modification of hadrons
- Connection to chiral symmetry of QCD
- Predictions of transport model (PHSD)
- Flow of kaons
- Hypernuclei
- Λ (1405)
- Deeply bound kaonic states

History

~ 1950 many V particles (~100):



kaon discovery

G.D. Rochester; C.C. Butler (1947). Nature. ***160*** *(4077): 855–857*

1953 Murray Gell – Mann, Abraham Pais, Kazuhiko Nishijima introduce „strangeness“

Descripton of „discovery“ process:

M. Gell-Mann. STRANGENESS. Journal de Physique Colloques, 1982, 43 (C8), pp.C8-395-C8-408. <10.1051/jphyscol:1982825>. <jpa-00222385>
https://hal.archives-ouvertes.fr/jpa-00222385

usually appears as a paradox. But a paradox is after all just one way of having your path blocked ; in art the blocking is manifested differently. Having filled your mind with the problem and the difficulty you may then find that in an odd moment while driving or shaving or while asleep and dreaming (as in the case of Kekulé and the benzene ring) or through a slip of the tongue as in this case one may suddenly find the path unblocked. Perhaps the solution comes, in the language of the psychoanalyst (a language that is not very popular in scientific circles today), from the precons-cious mind, the portion of our mind that is just out of awareness.

Quark model

Gell-Mann–Nishijima formula

$$Q = I_3 + \frac{1}{2}(B + S) = I_3 + \frac{1}{2}Y$$

Q – electric charge
I – Isospin
B – Baryon number
S – Strangeness
Y – Hypercharge

Key argument: Is reaction $n + n \rightarrow \Lambda + \Lambda$ possible ?

Conserved quantities in strong interactions:

Baryon number B, Strangeness S, Isospin I, I_3

S = - (n(s-quarks) – n(anti_s-quarks))

Flavour – SU(3)

Ansatz: mass of strange quark (~150 MeV) small on nucleon scale (1 GeV).
u,d,s approximately degenerate.

u,d,s – symmetry can be expressed by unitary matrix containing 9 complex numbers (with 18 real parameter):

$$\begin{pmatrix} u' \\ d' \\ s' \end{pmatrix} = \hat{U} \begin{pmatrix} u \\ d \\ s \end{pmatrix} = \begin{pmatrix} U_{11} & U_{12} & U_{13} \\ U_{21} & U_{22} & U_{23} \\ U_{31} & U_{32} & U_{33} \end{pmatrix} \begin{pmatrix} u \\ d \\ s \end{pmatrix}$$

9 parameters are fixed from unitarity. $\hat{U}^{+}\hat{U} = 1$

1 matrix is just the multiplication with complex phase.

The 8 remaining parameters have det U=1 and form the SU(3) symmetry group.

Generators are 8 Hermitian matrices: $\vec{T} = \frac{1}{2}\vec{\lambda}, \qquad \hat{U} = e^{i\vec{\alpha}\cdot\vec{T}}$

Gell – Mann Matrices λ_i

Flavor SU(3): Quark states

$$u = \begin{pmatrix} 1 \\ 0 \\ 0 \end{pmatrix}, \quad d = \begin{pmatrix} 0 \\ 1 \\ 0 \end{pmatrix}, \quad s = \begin{pmatrix} 0 \\ 0 \\ 1 \end{pmatrix}$$

$$u \leftrightarrow d \quad \lambda_1 = \begin{pmatrix} 0 & 1 & 0 \\ 1 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix} \quad \lambda_2 = \begin{pmatrix} 0 & -i & 0 \\ i & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix} \quad \lambda_3 = \begin{pmatrix} 1 & 0 & 0 \\ 0 & -1 & 0 \\ 0 & 0 & 0 \end{pmatrix}$$

$$u \leftrightarrow s \quad \lambda_4 = \begin{pmatrix} 0 & 0 & 1 \\ 0 & 0 & 0 \\ 1 & 0 & 0 \end{pmatrix} \quad \lambda_5 = \begin{pmatrix} 0 & 0 & -i \\ 0 & 0 & 0 \\ i & 0 & 0 \end{pmatrix}$$

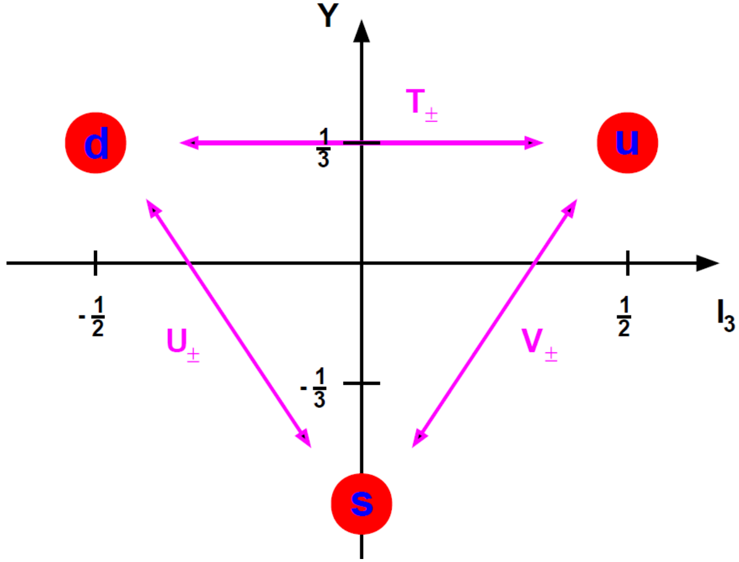
$$d \leftrightarrow s \quad \lambda_6 = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 1 \\ 0 & 1 & 0 \end{pmatrix} \quad \lambda_7 = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & -i \\ 0 & i & 0 \end{pmatrix}$$

$$\lambda_8 = \frac{1}{\sqrt{3}} \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & -2 \end{pmatrix}$$

$SU(3)_F$ – fundamental representations

Quarks:

$[3]$



Hypercharge Y:

Y = B + S

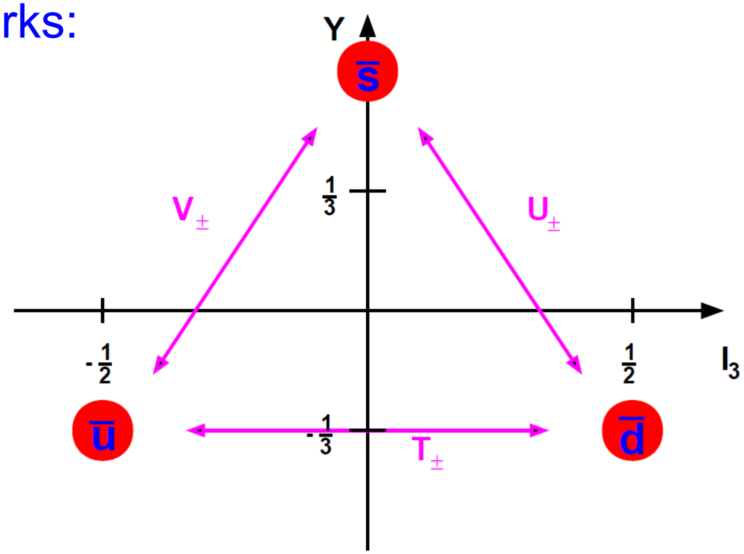
Baryon number B
Strangness number S

Charge Q:

Q= I_3 + Y/2
3. component of isospin I_3

Anti – Quarks:

$[\bar{3}]$



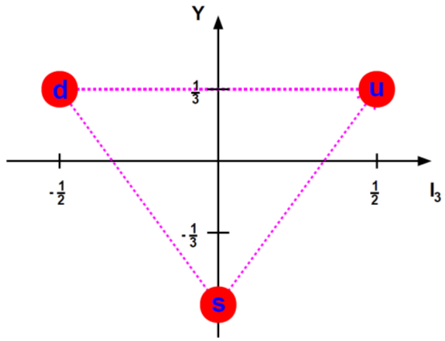
Ladder operators:

$$T_+ d = u, \quad T_- d = u$$
$$V_+ s = u, \quad V_- u = s$$
$$U_+ s = d, \quad U_- d = s$$

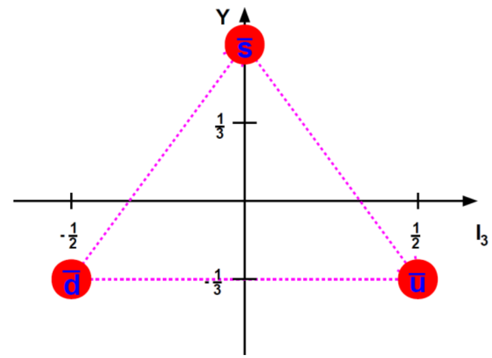
$$T_+ \bar{u} = -\bar{d}, \quad T_- \bar{d} = -\bar{u}$$
$$V_+ \bar{u} = -\bar{s}, \quad V_- \bar{s} = -\bar{u}$$
$$U_+ \bar{d} = -\bar{s}, \quad U_- \bar{s} = -\bar{d}$$

Light $SU(3)_F$ – (uds) – mesons

Quark – Anti-quark states:



$\otimes$



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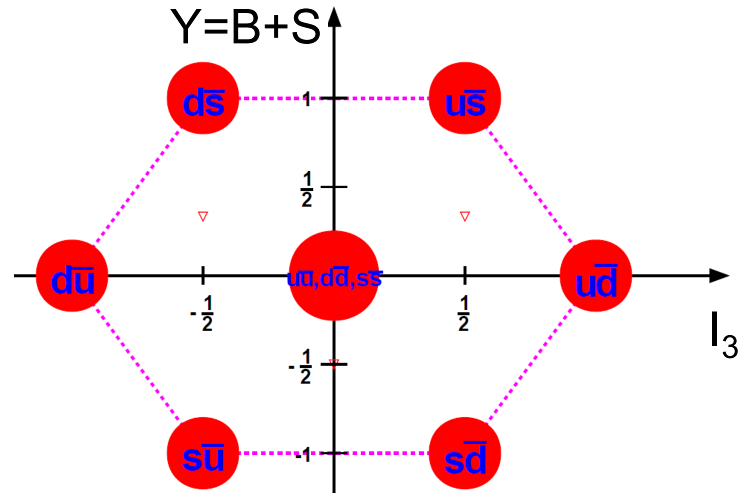


Construction of $SU(3)_F$ meson wave functions:

add conjugate (antiparticle) triplet to each point of fundamental (particle) triplet

[3]	$\otimes$	$[\bar{3}]$	=	[8]	$\oplus$	[1]
triplet		antitriplet		octet		singlet

3 states with $(Y,I_3)=(0,0)$:

1) fully symmetric state:

$$\{1\,|\,0,0\rangle\} = \frac{1}{\sqrt{3}}(|u\bar{u}\rangle + |d\bar{d}\rangle + |s\bar{s}\rangle) = |\eta'\rangle$$

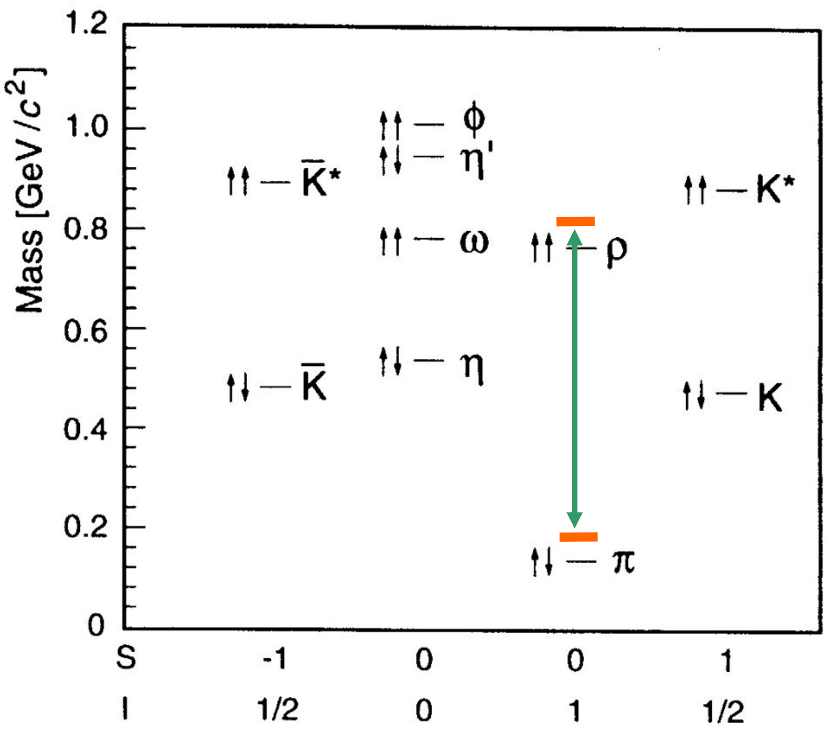
2) neutral pion:

$$\{8\,|\,1,0\rangle\} = \frac{1}{\sqrt{2}}(|u\bar{u}\rangle - |d\bar{d}\rangle) = |\pi^0\rangle$$

3) orthogonal state:

$$\{8\,|\,0,0\rangle\} = \frac{1}{\sqrt{6}}(|u\bar{u}\rangle + |d\bar{d}\rangle - 2\,|s\bar{s}\rangle) = |\eta\rangle$$

The light meson mass spectrum



J = 1

Mass difference ~ 600 MeV

J = 0

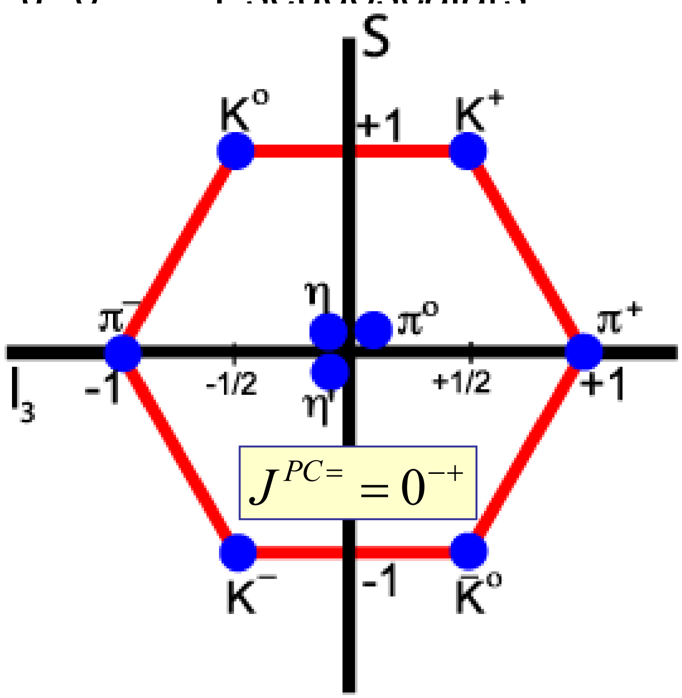
Mass splitting between pseudoscalar and vector mesons suggests color magnetic interaction:

$$\Delta M_J \propto \frac{\vec{\sigma}_q}{m_q} \cdot \frac{\vec{\sigma}_{\bar{q}}}{m_{\bar{q}}}$$

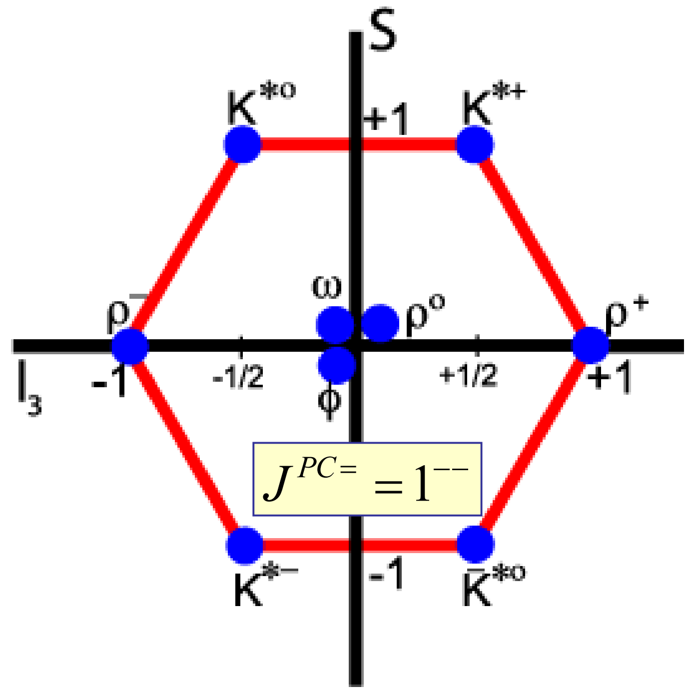
Light $SU(3)_F$ – (uds) – mesons

2 nonets exist due to spin with the same flavour wave functions:

J=0 Pseudoscalars



J=1 Vectormesons



Parity:

$$P = P(q)P(\bar{q})(-)^L = -(-)^L$$

Charge conjugation for neutral states:
(allowed Eigenvalues)

$$C = \underbrace{(-)}_{\text{interchange of fermions}} (-)^{S+1}(-)^L = (-)^{L+S}$$

Parity and C-parity are conserved in e.m. and strong interactions.

Quark model states

- For $q\bar{q}$ meson systems, let L to be the orbital angular momentum. The meson spin J is given by |L-S|<J<|L+S|, where S=0 (antiparallel quark spin) or S=1 (parallel quark spin)

- The parity P and charge parity C of the meson system can be expressed as: $P=(-1)^{L+1}$
  $C=(-1)^{L+S}$

S	0	1	0	1	1	1	0	…
L	0	0	1	1	1	1	2	…
J	0	1	1	0	1	2	2	…
J^{PC}	0^{-+}	1^{--}	1^{+-}	0^{++}	1^{++}	2^{++}	2^{-+}	…
$^{2S+1}L_J$	$^1S_0$	$^3S_1$	$^1P_1$	$^3P_0$	$^3P_1$	$^3P_2$	$^1D_2$	…

Not all combinations of quantum numbers are possible in quark model
$\Rightarrow$ Exotic J^{PC}: 0^{--}, 0^{+-}, 1^{-+}, 2^{+-} ,…

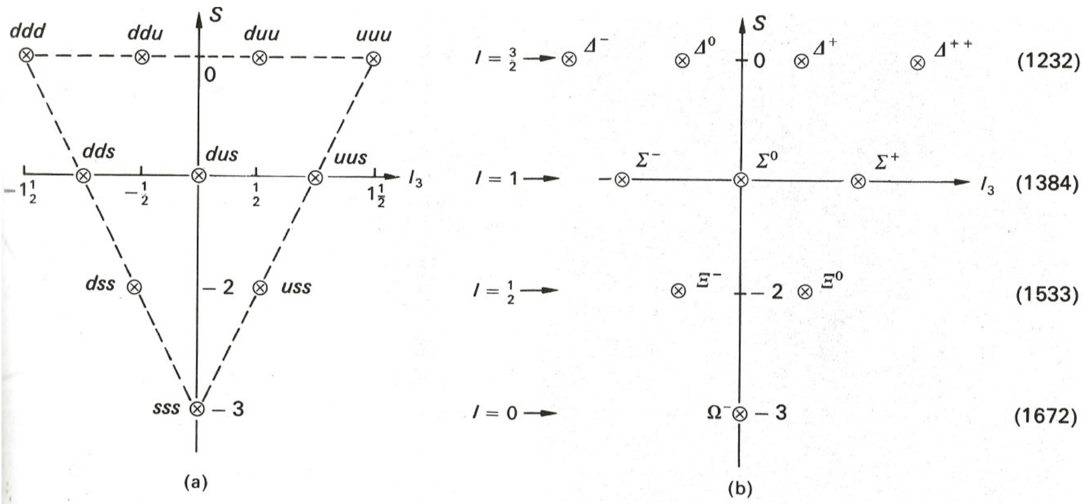
Exotic mesons can have these J^{PC} due to additional degrees of freedom.

The SU(3)$_F$ – baryon multiplets

Baryon decuplet: J=3/2

Mass (MeV)

(Figs.: Perkins)



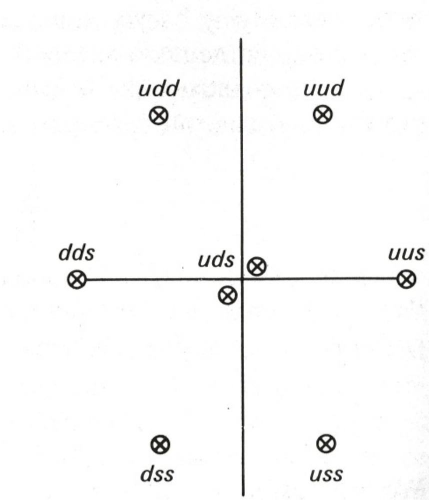
ΔM (MeV)

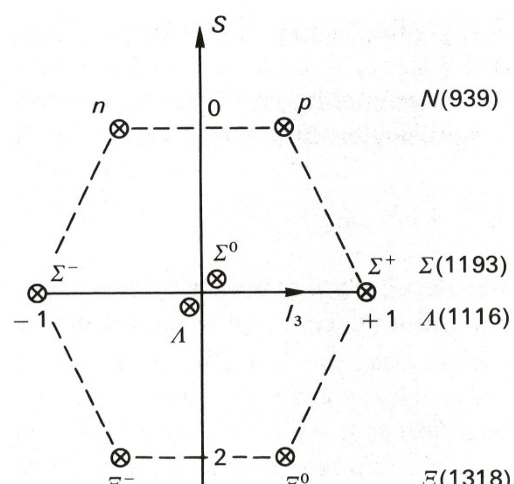
152

149

139

Baryon octet: J=1/2



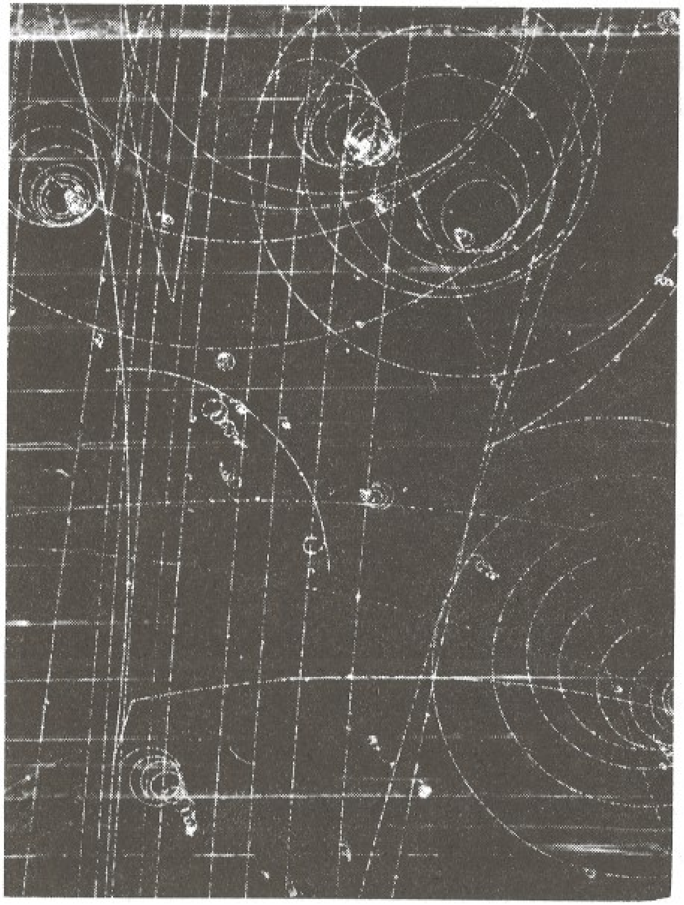


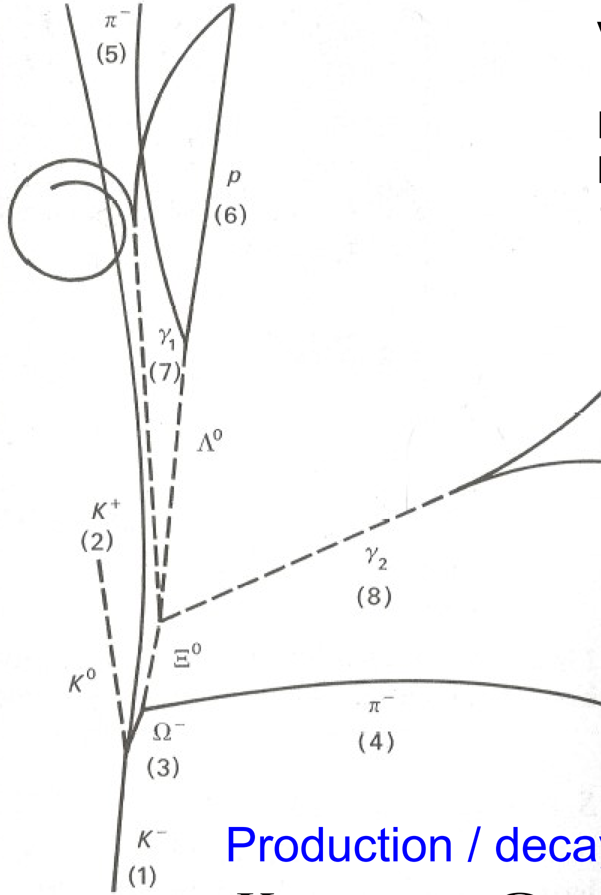
Historically:

Gell-Mann – Okubo mass formula

$$M = M_0 + M_1 Y + M_2 \left(I(I+1) - \frac{Y^2}{4} \right)$$

Ω^- - discovery





V. Barnes et al., PRL 12, 204 (1964)

Details:
K^- - beam, 5GeV, AGS @ BNL
100.000 bubble chamber pictures

Production / decay chain:

$$K^- + p \longrightarrow \Omega^- + K^0 + K^+$$

$$\Omega^- \longrightarrow \Xi^0 + \pi^-$$

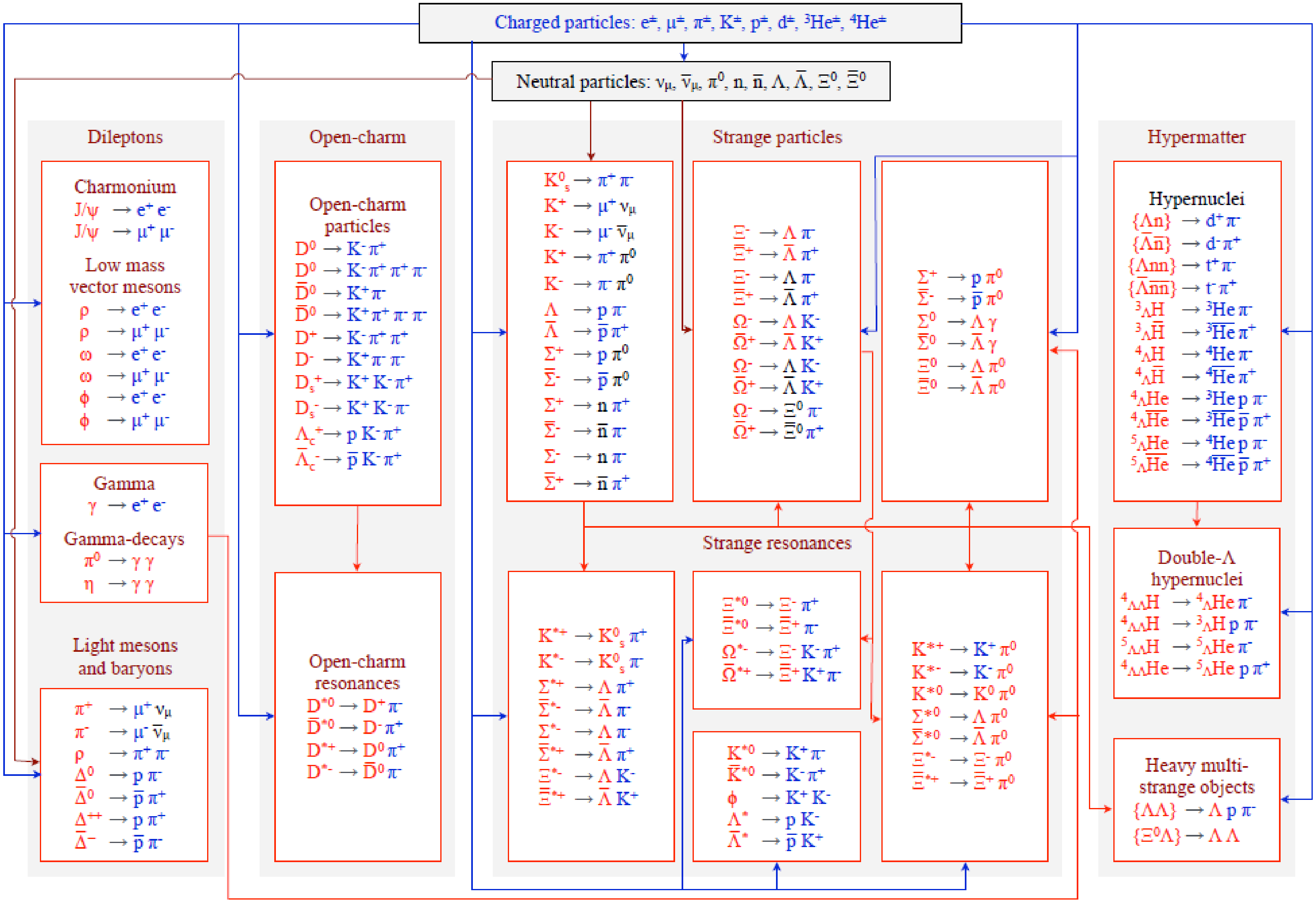
$$\Xi^0 \longrightarrow \Lambda^0 + \pi^0$$

$$\Lambda^0 \longrightarrow p + \pi^-$$

$$\pi^0 \longrightarrow \gamma + \gamma$$

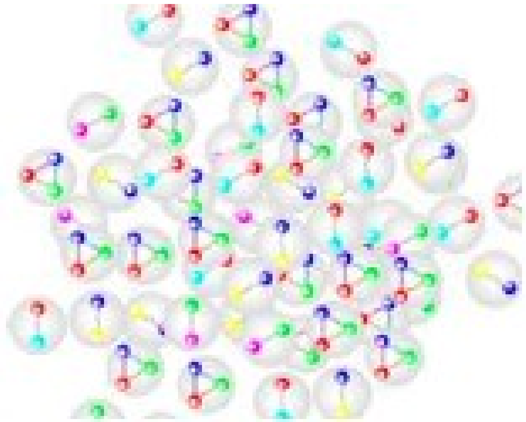
Groundstate strange hadrons decay by weak interaction
=> long lifetimes

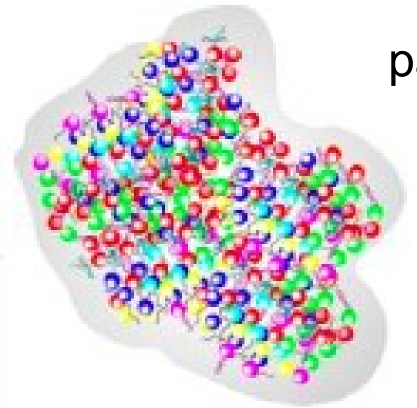
KF Particle Finder



Strangeness as probe for QCD matter

hadronic



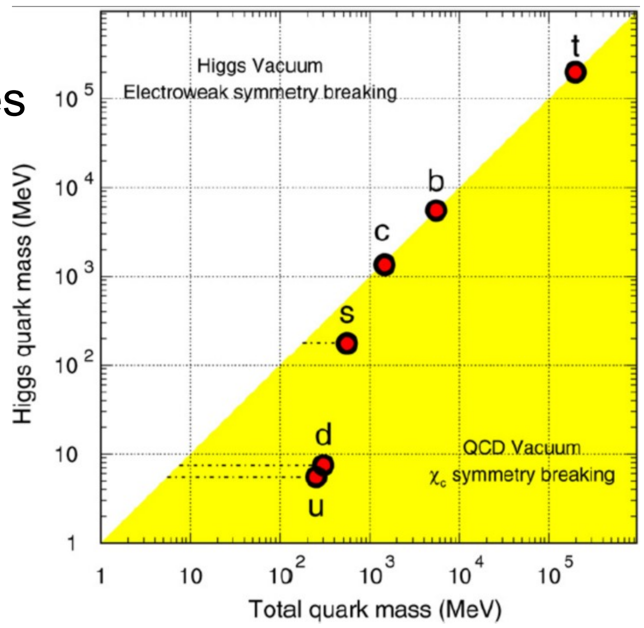


partonic

No strangeness in initial state

Strange hadrons offer a wide variety of mass scales
probing different energy scales

Strange quarks probe chiral symmetry

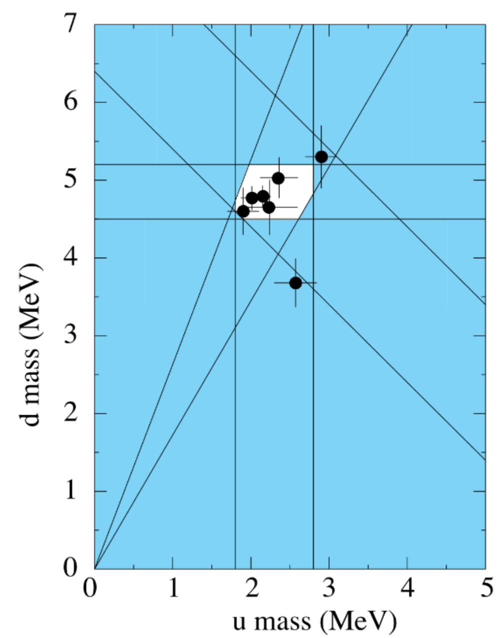


Quark masses

Static picture of hadrons
constituent quark masses

dynamic picture
current quark masses

http://pdg.lbl.gov/2017/reviews/rpp2016-rev-quark-masses.pdf

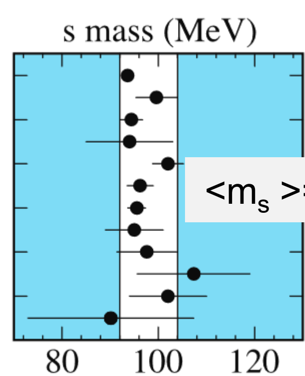


Ansatz: $$M_{hadron} = \sum_q m_q + \Delta M_J$$

J – spin of hadron
(spin – spin interaction of quarks)

Result:

$$m_{u,d} \approx 310 MeV / c^2$$
$$m_s \approx 483 MeV / c^2$$



$<m_s> = (93.5 \pm 2)$ MeV

Experiments with Strangeness Measurements

GSI-SIS
FOPI, KAOS, HADES

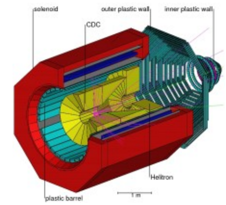
BNL-AGS
E866, E877, E891, E895, …

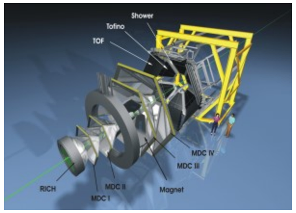
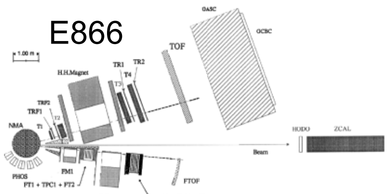
CERN-SPS (Pb beam)
WA97, NA44, NA45, NA50
NA49, NA57, NA61

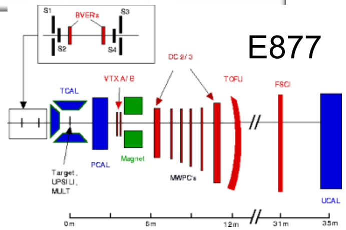
BNL-RHIC
STAR, PHENIX, BRAHMS

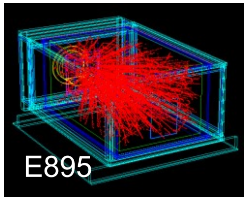
CERN-LHC
ALICE

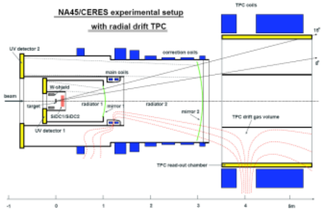
New low energy programs
CBM@FAIR, NICA

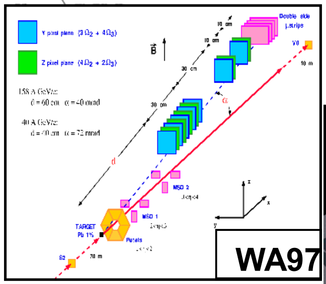


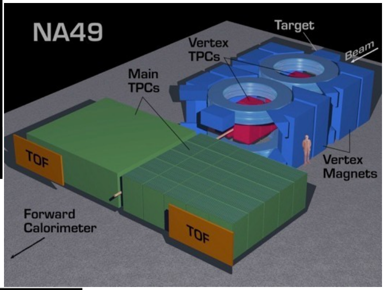



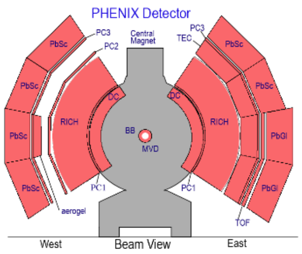


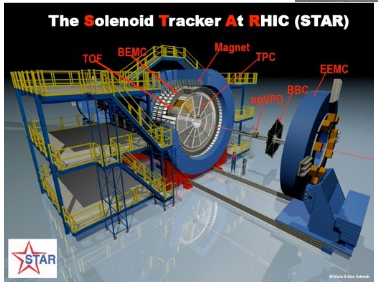


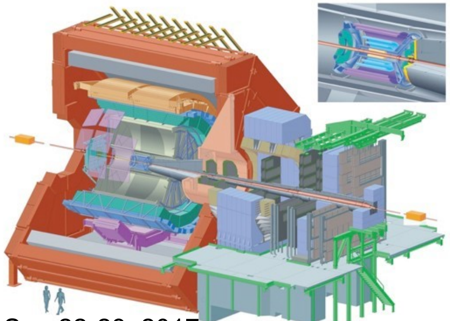








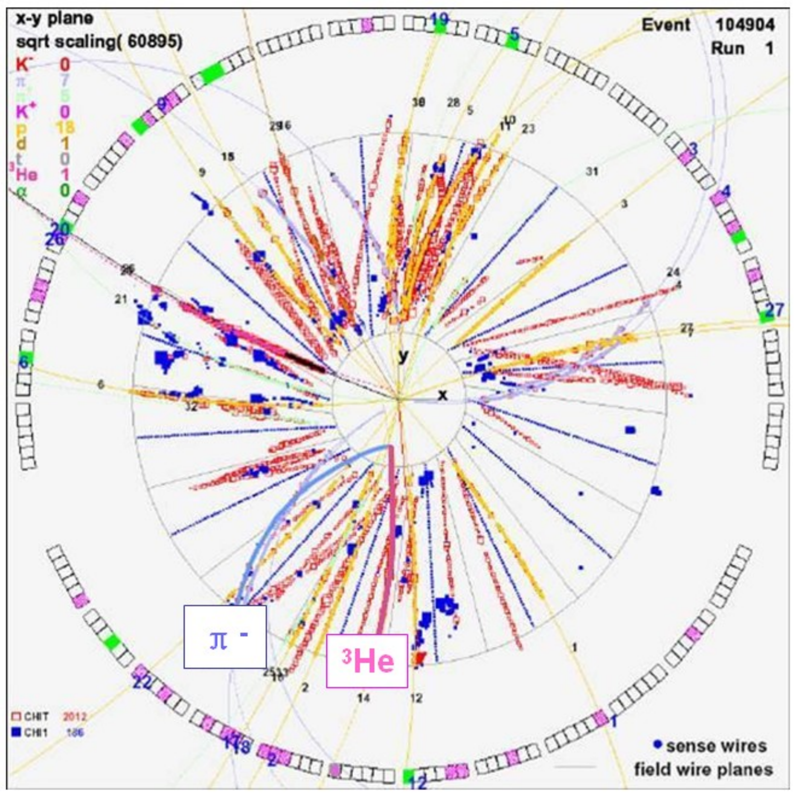


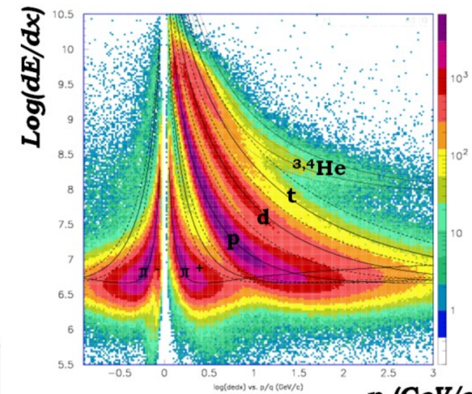


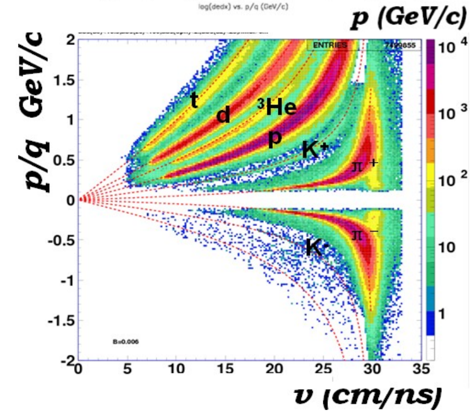
Strange particle reconstruction

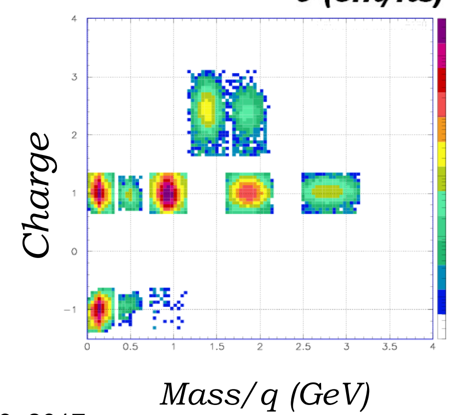
Particle identification,
coverage of phase space,
spectral shapes,
extrapolation to uncovered regions,
…

$$_{\Lambda}t \rightarrow {}^{3}He + \pi^{-}$$





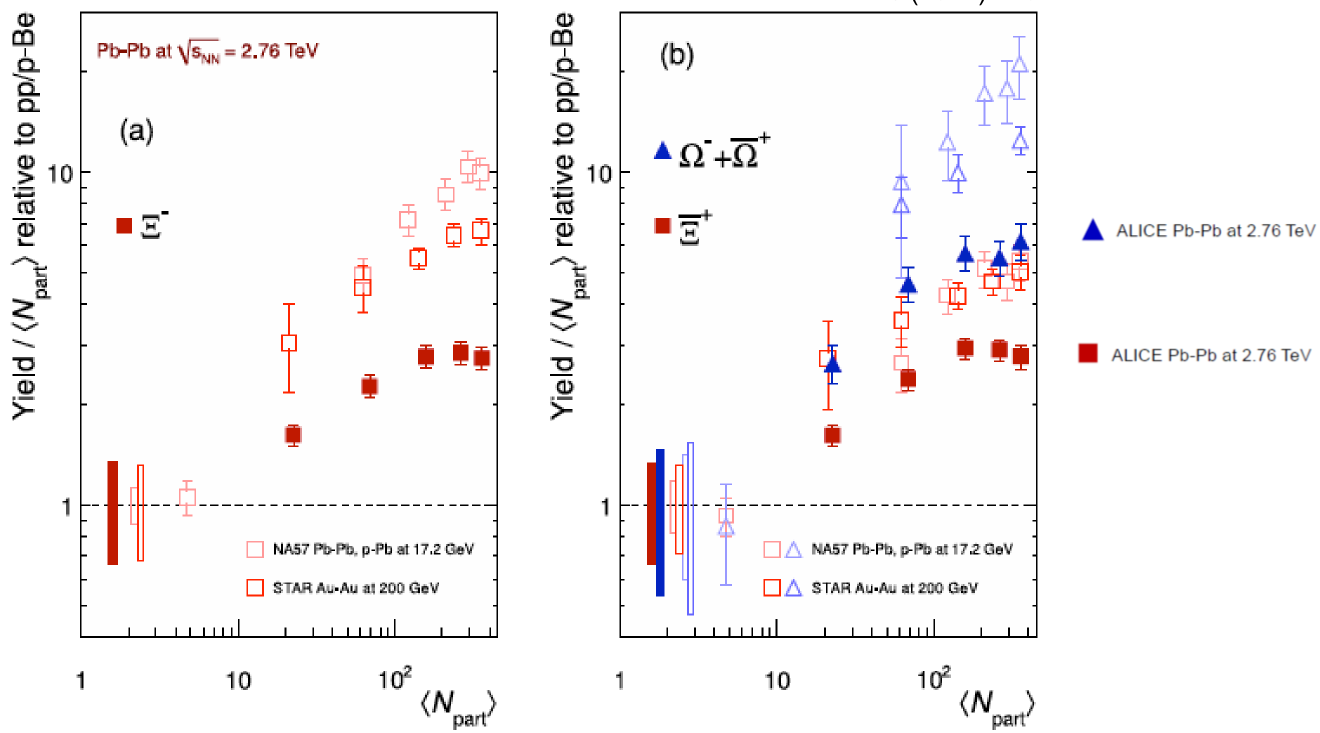




FOPI @ SIS18 of GSI
Ni+Ni @ 1.91AGeV
S325e (2008), ~ 60 M events

Strangeness production

ALICE
PLB **728** (2014) 216



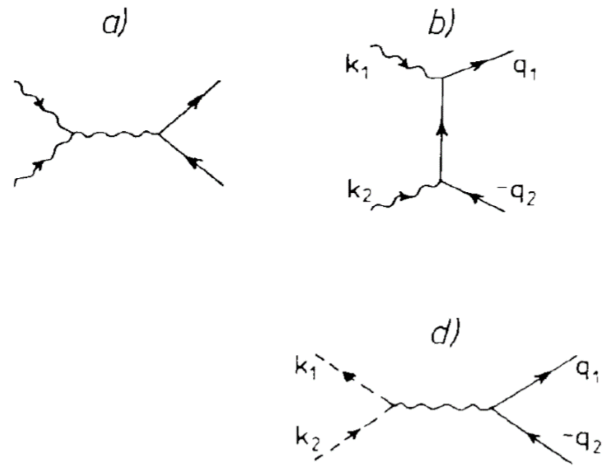
Enhancement factor: $E = \frac{2}{N_{part}} \left[\frac{dN}{dy}(Pb+Pb)\Big|_{y=0} \Big/ \frac{dN}{dy}(p+p)\Big|_{y=0} \right]$

Enhancement factor for Ω:	SPS	20
(in central collisions)	RHIC	12
	LHC	6

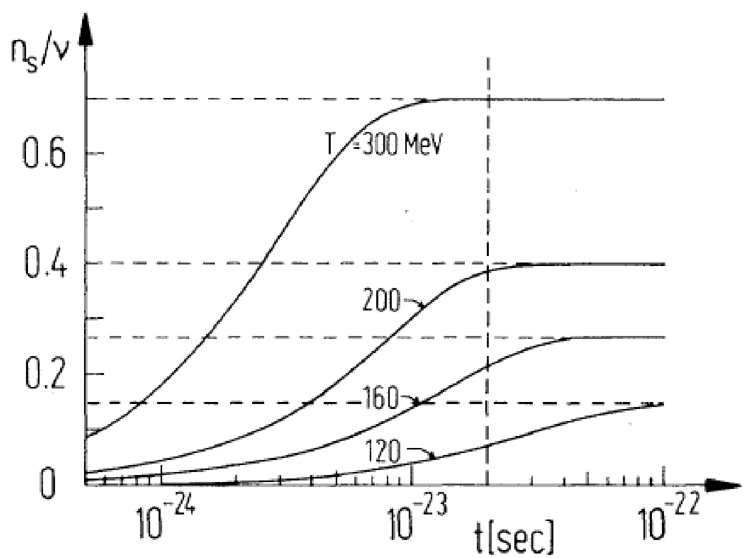
Strangeness enhancement as QGP signature

P. Koch, B. Müller, J. Rafelski, Phys. Rep. 142 (1986) 167

Elementary production processes:



Strangeness fraction



Relaxation of s-Quarks
in a QGP within few fm/c
≈ lifetime of the fireball

Expectation:
More strangeness production in A+A relative to p+p if QGP was formed

Statistical Hadronization Model (Thermal model)

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

Chemical thermal model:

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:

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

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

β= 1/T, T= Temperature

H = Hamiltonian of non-interacting hadron gas

Decomposition into individual hadronic species:

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

Thermal model for particle production

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

Chemical equilibrium concept.

Density of particle species i:

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

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

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

Chemical potentials μ_i are constrained by conservation of quantum numbers:

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

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

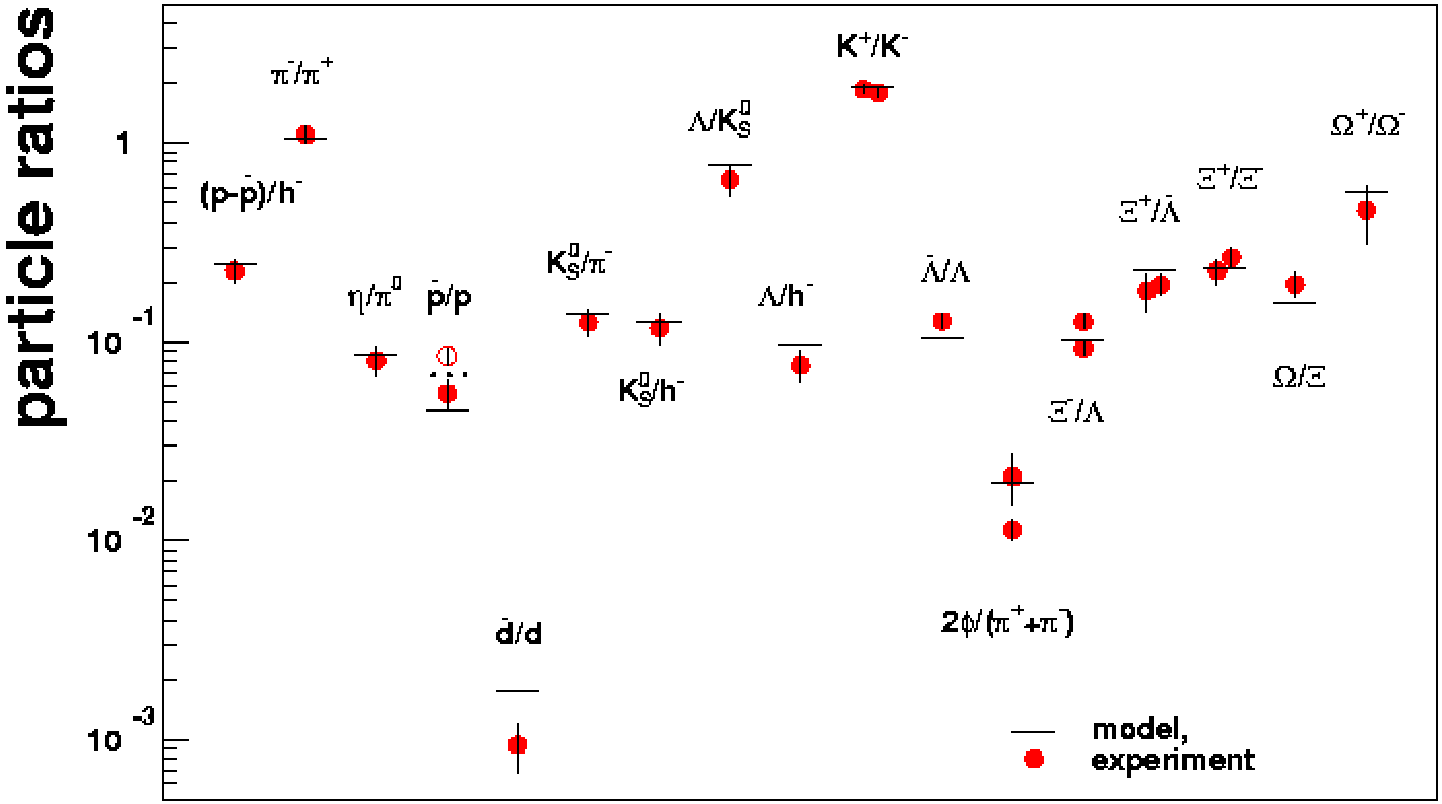
charge: $V\sum_i n_i I_{3,i} = \frac{Z-N}{2} \rightarrow \mu_{I_{3,i}}$

⇒ 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.

First application of SHM to freeze-out data

4 January 1996

PHYSICS LETTERS B

ELSEVIER

Physics Letters B 365 (1996) 1–6

Thermal and hadrochemical equilibration in nucleus-nucleus collisions at the SPS

P. Braun-Munzinger, J. Stachel, J.P. Wessels, N. Xu [1]

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Interpretation in bag model:

1. order phase transition: latent heat

densities

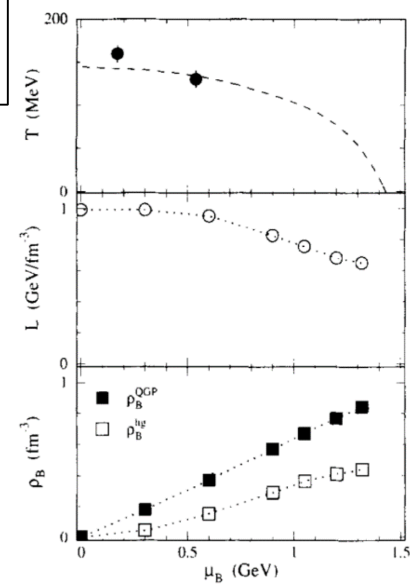
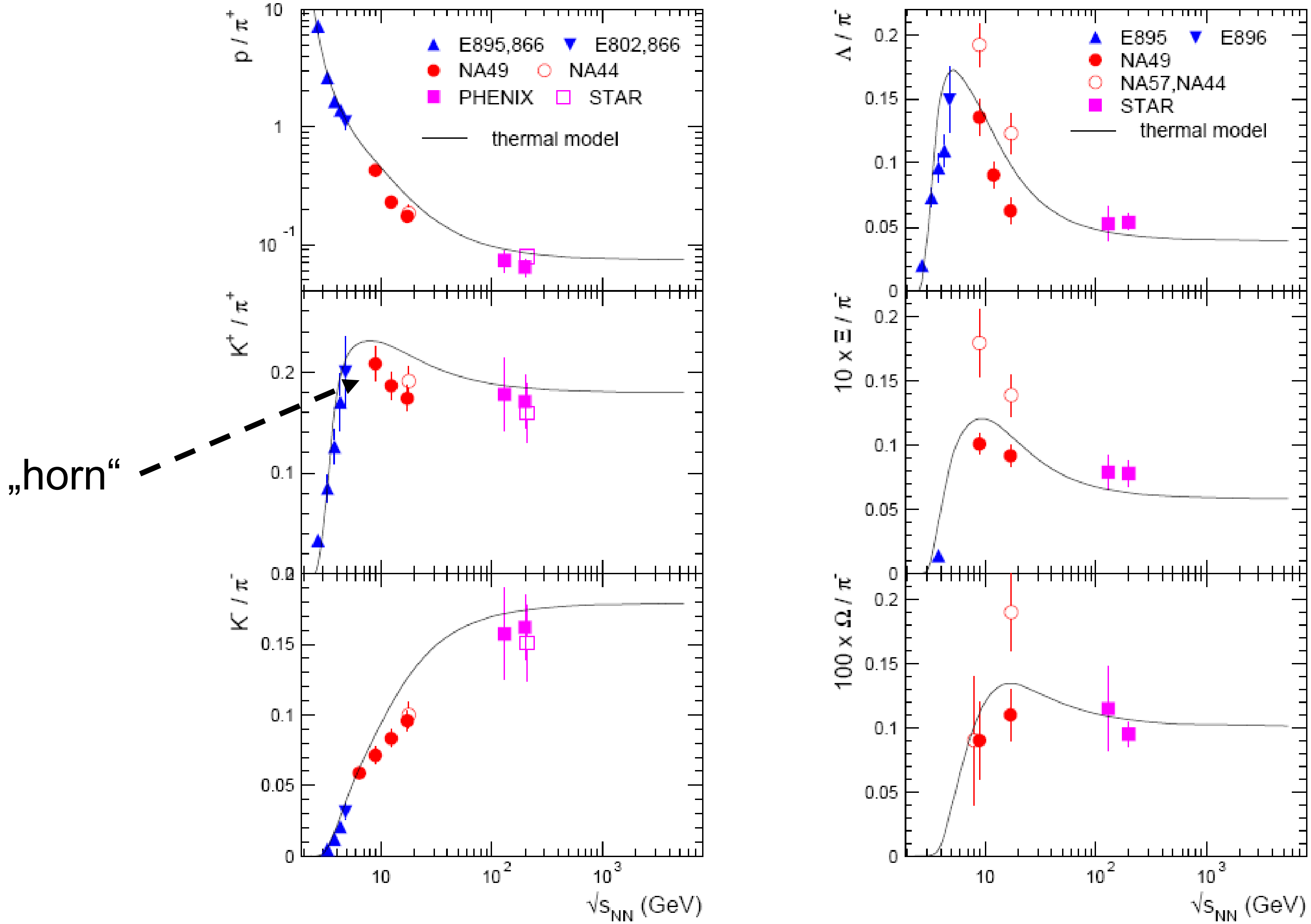


Fig. 3. Phase boundary between a hadron gas and a quark-gluon plasma (top) as function of temperature and baryon chemical potential together with the freeze-out points for Si(S) + Au(W,Pb) collisions at AGS [11] and SPS (present paper) energies. Latent heat of the phase transition (middle) and baryon density in the hadron and quark-gluon phase at the phase boundary (bottom).

Strange particles are crucial to constrain fit parameters

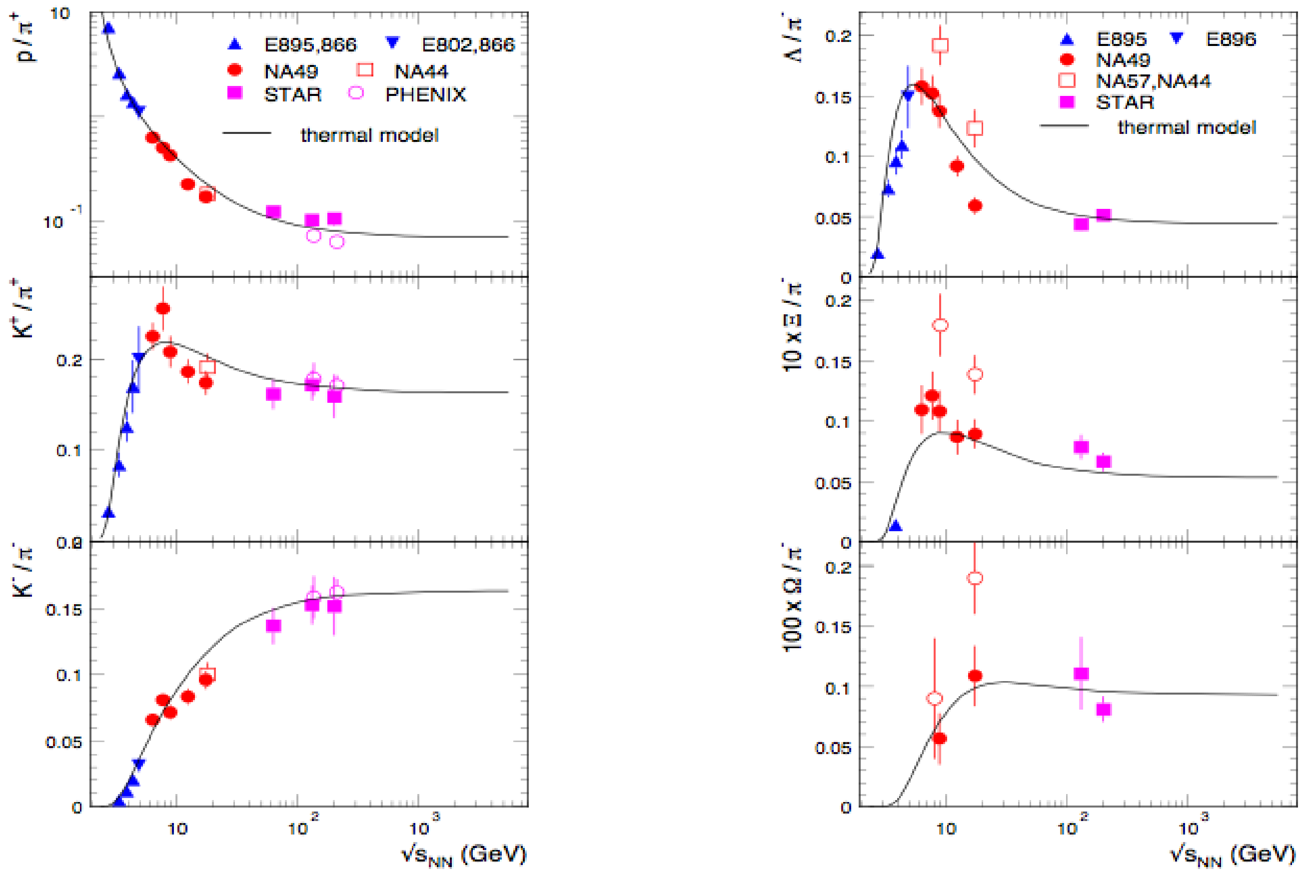
Excitation function of particle ratios

A. Andronic, P. Braun-Munzinger, J. Stachel, *Nucl. Phys. A 772 (2006) 167*



Particle ratios revisited

A. Andronic, P. Braun-Munzinger, J. Stachel, Phys. Lett. B 673 (2009) 142



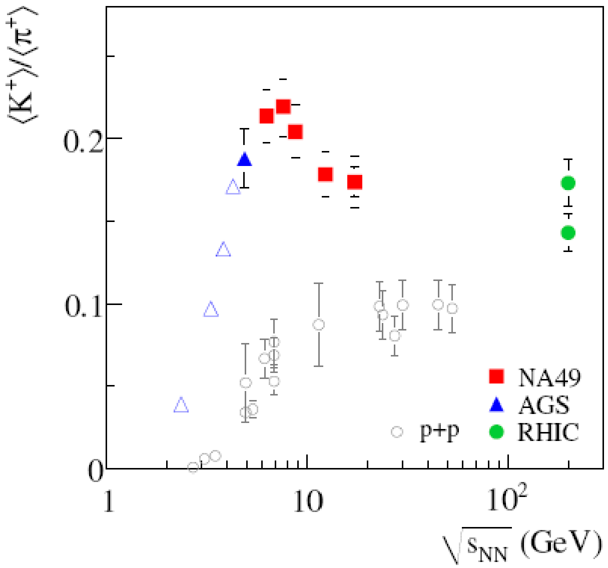
Thermal model with extended resonance mass spectrum

- high lying resonances (M > 2 GeV)
- sigma meson (M = 600 MeV)

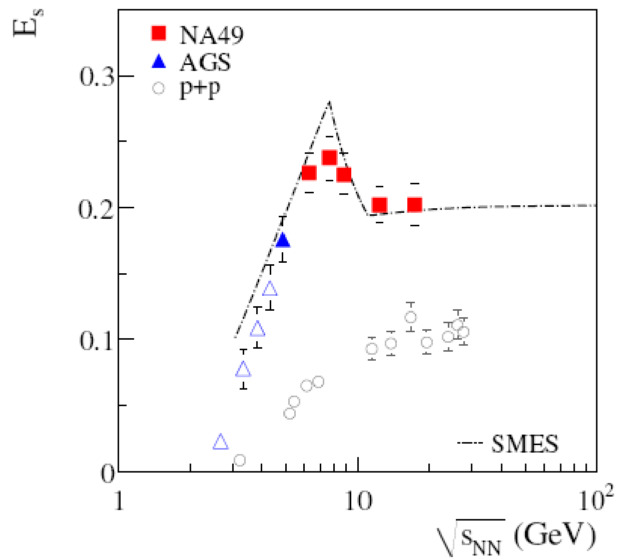
gross features very well.

Statistical Model for Early Stage (SMES)

Gadzicki Acta Phys Pol, B, 35,187(2004);
Gorenstein JPG,28,1623(2002)



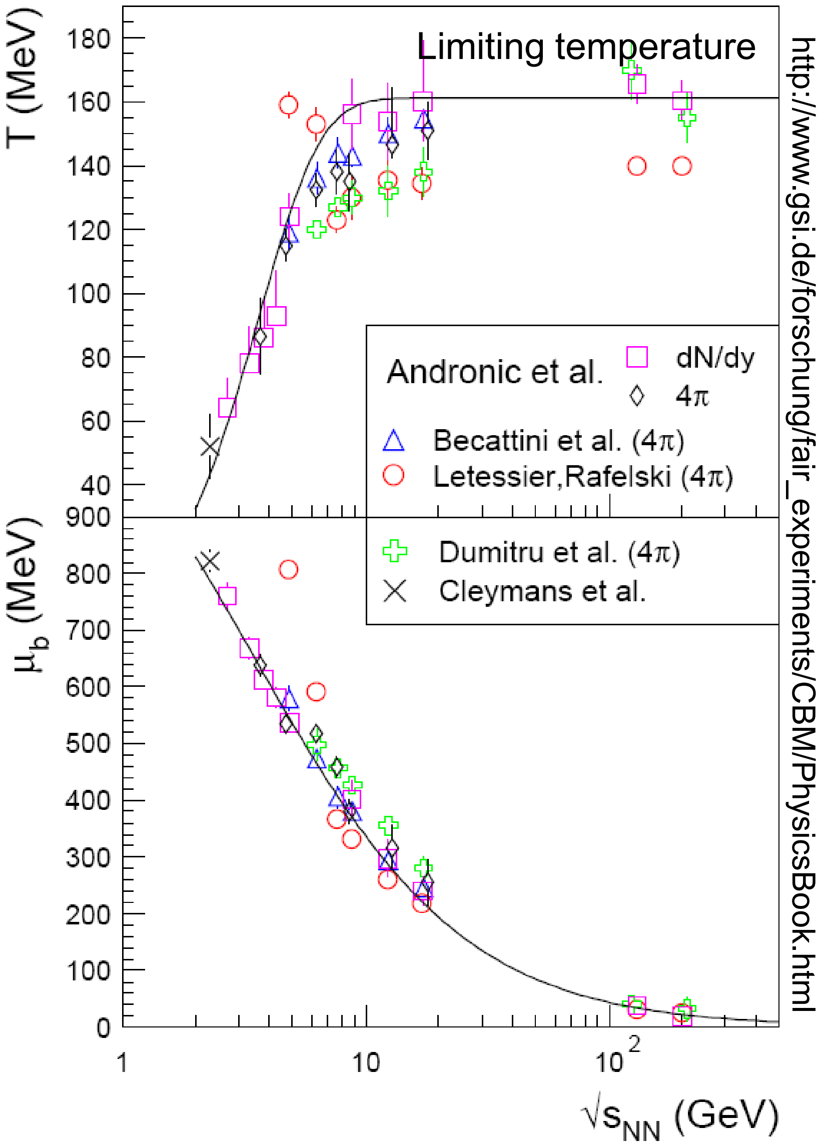
E_s=Ratio of strangeness to entropy



Large entropy production beyond threshold energy

In the SMES the role of strangeness is different. This is because statistical production of particles is postulated and therefore also strange particles are assumed to be produced in equilibrium. Consequently possible secondary processes do not modify its value. At $T = T_c$ the strangeness density is lower in the QGP than in confined matter. Thus, a suppression of strangeness production is expected to occur when crossing the transition energy range from below. The low level of strangeness production in N+N interactions as compared to the higher strangeness yield per participant nucleon in central A+A collisions (called strangeness enhancement) can be understood as mostly due to the effect of strict strangeness conservation (canonical suppression) imposed on the strange and anti-strange degrees of freedom [32]. This constraint has an important effect for small statistical systems such as the confined matter in the early stage of N+N collisions.

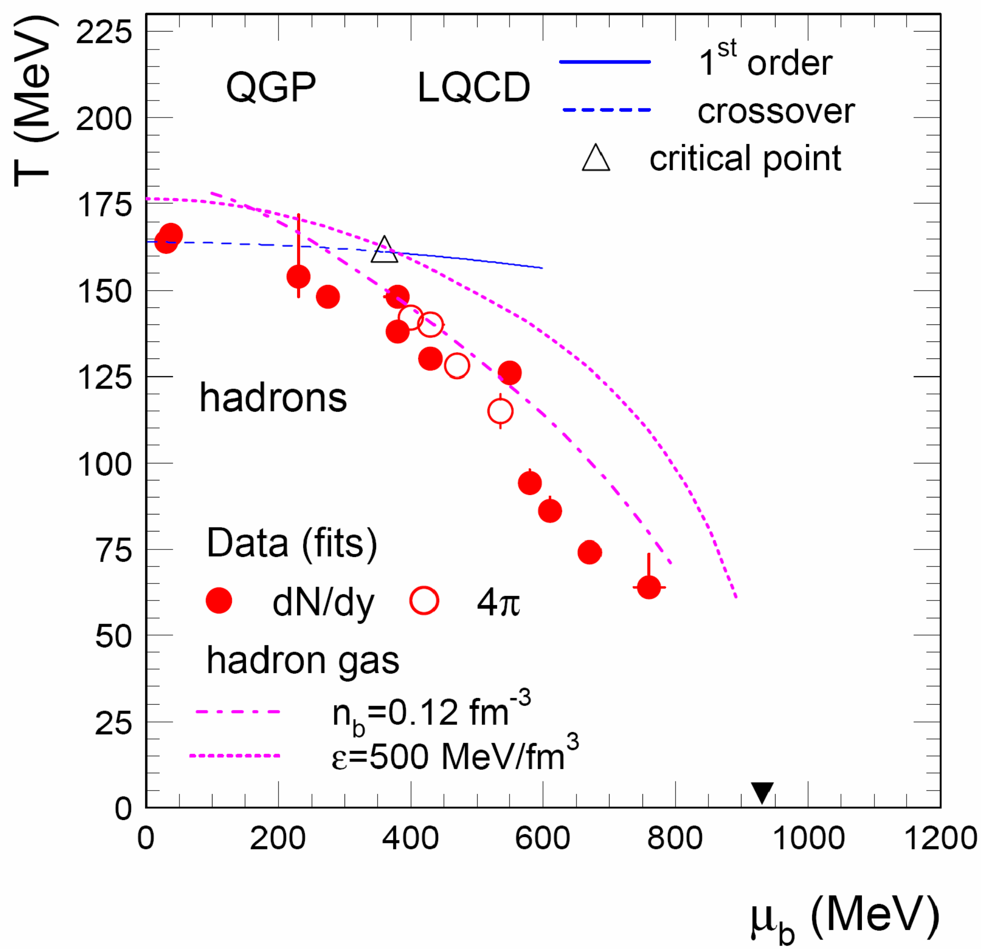
Excitation function of particle production



- Fit works at all energies from SIS to LHC
- T and μ_b evolve monotonically with $\sqrt{s_{NN}}$
- T saturates at $\sqrt{s_{NN}} = 10$ GeV: T_{lim}=160 MeV

Phase diagram with freeze-out data

A. Andronic et al., Phys. Lett. B 673 (2009).



Fit results

- depend on input data (4π - dN / dy)
- point to low density of hadron gas
- have substantial errors at large μ_b

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 μb = 4 · 10^{-2} fm^2

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

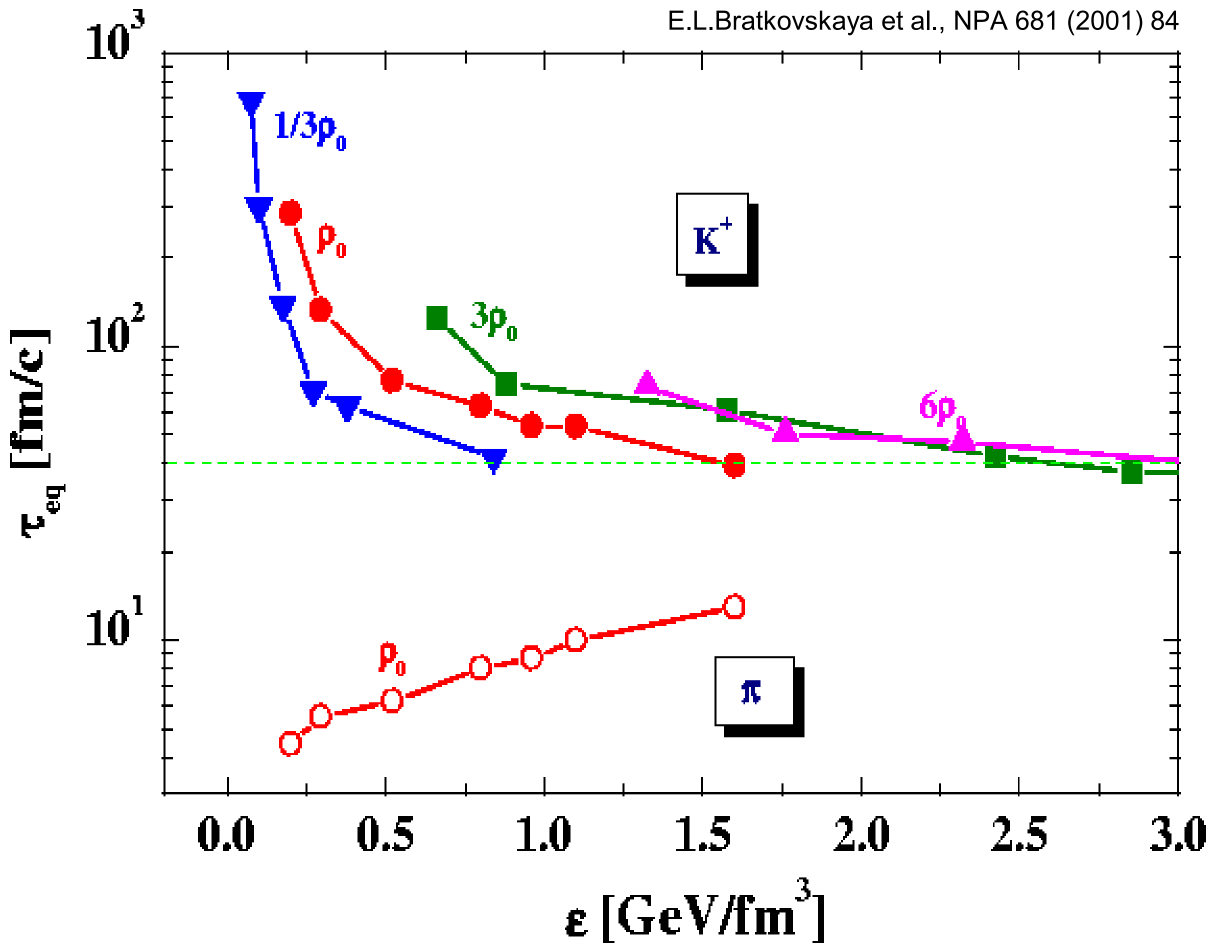
time between collisions $$\tau = \lambda / c = 1.5\, fm / c$$

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

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

Chemical equilibration in transport models

Equilibration times in hadronic matter

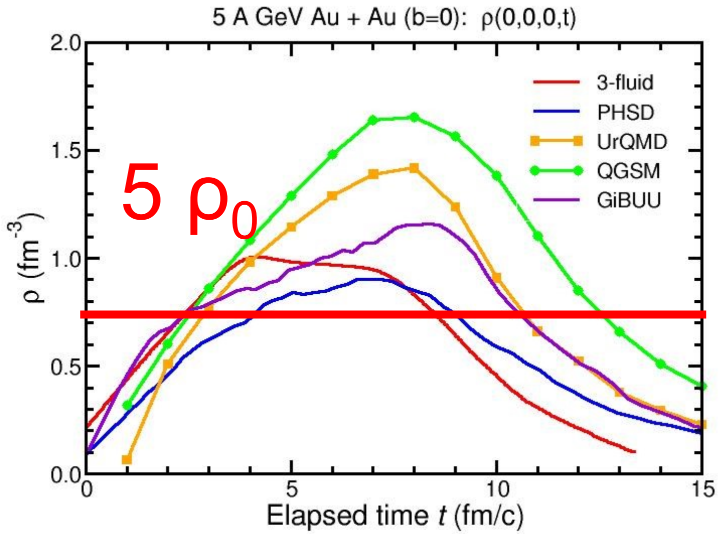


Even the lightest strange particle (K^+) needs at least 40 fm/c to equilibrate.

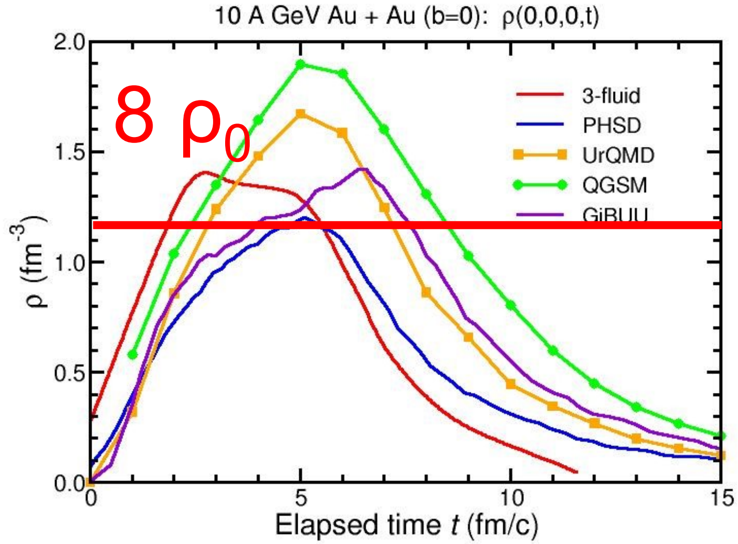
Baryon densities in central Au+Au collisions

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

5 A GeV

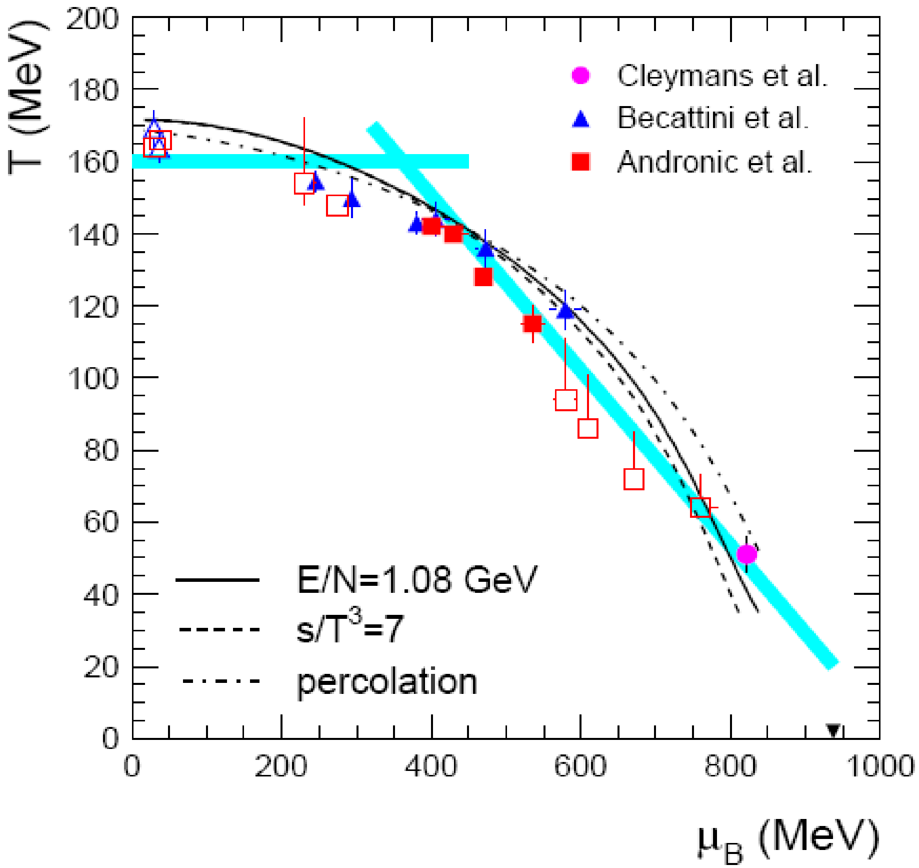


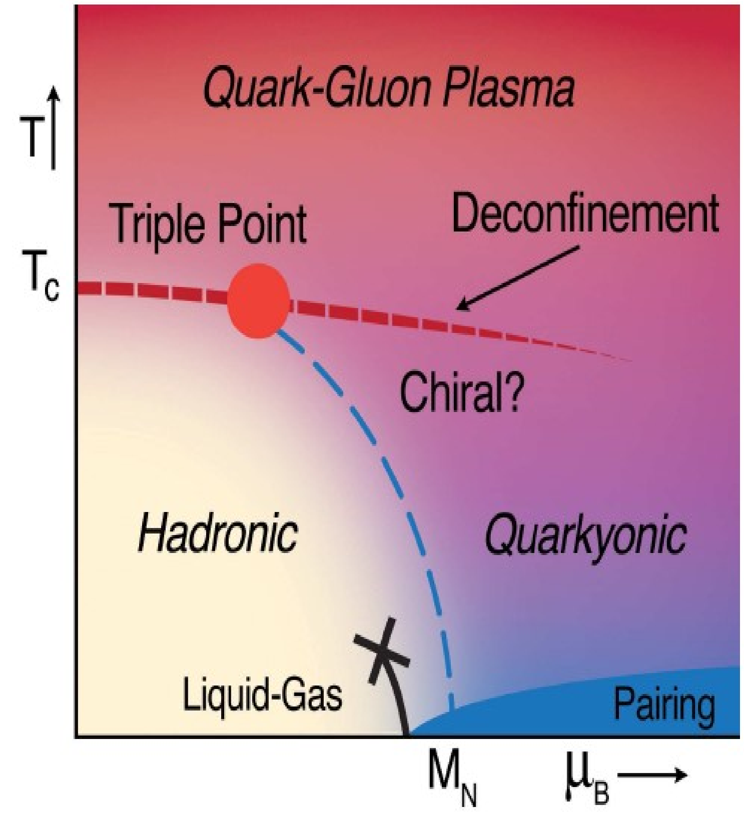
10 A GeV



Chemical Freeze-out phase diagram

A. Andronic et al., arXiv:0911.4806



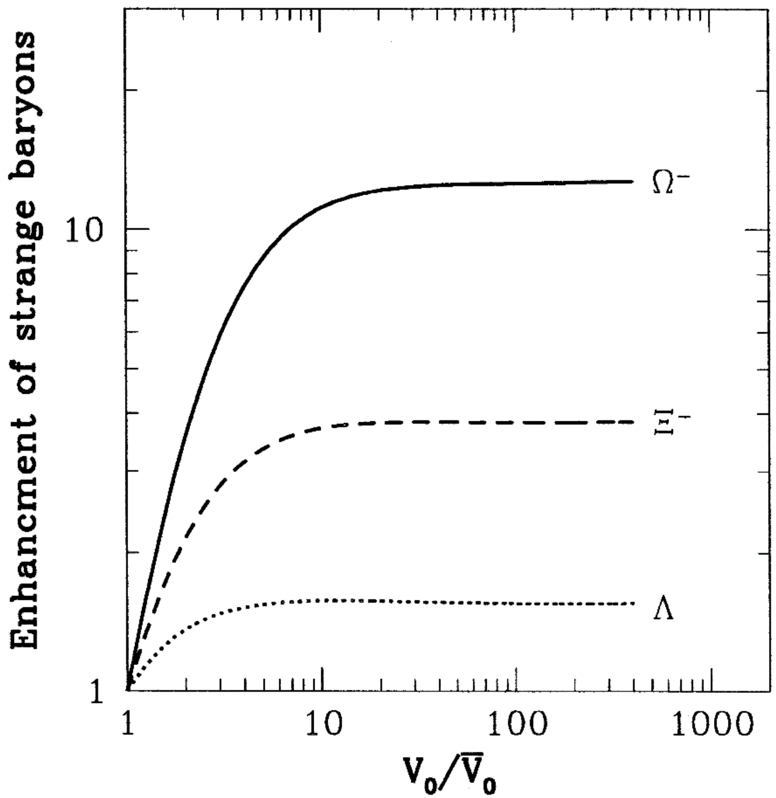


Speculation about the existence of a 1.order phase transition because of apparent thermal equilibrium.

Canonical strangeness suppression

Braun-Munzinger, Redlich, Stachel, nucl-th/0304013v1

S. Hamieh, K. Redlich und A. Tounsi,
Phys. Lett. B 486 (2000) 61



Small systems:
local conservation of strangeness
(needs canonical ensemble:
N, V fixed, energy can vary)

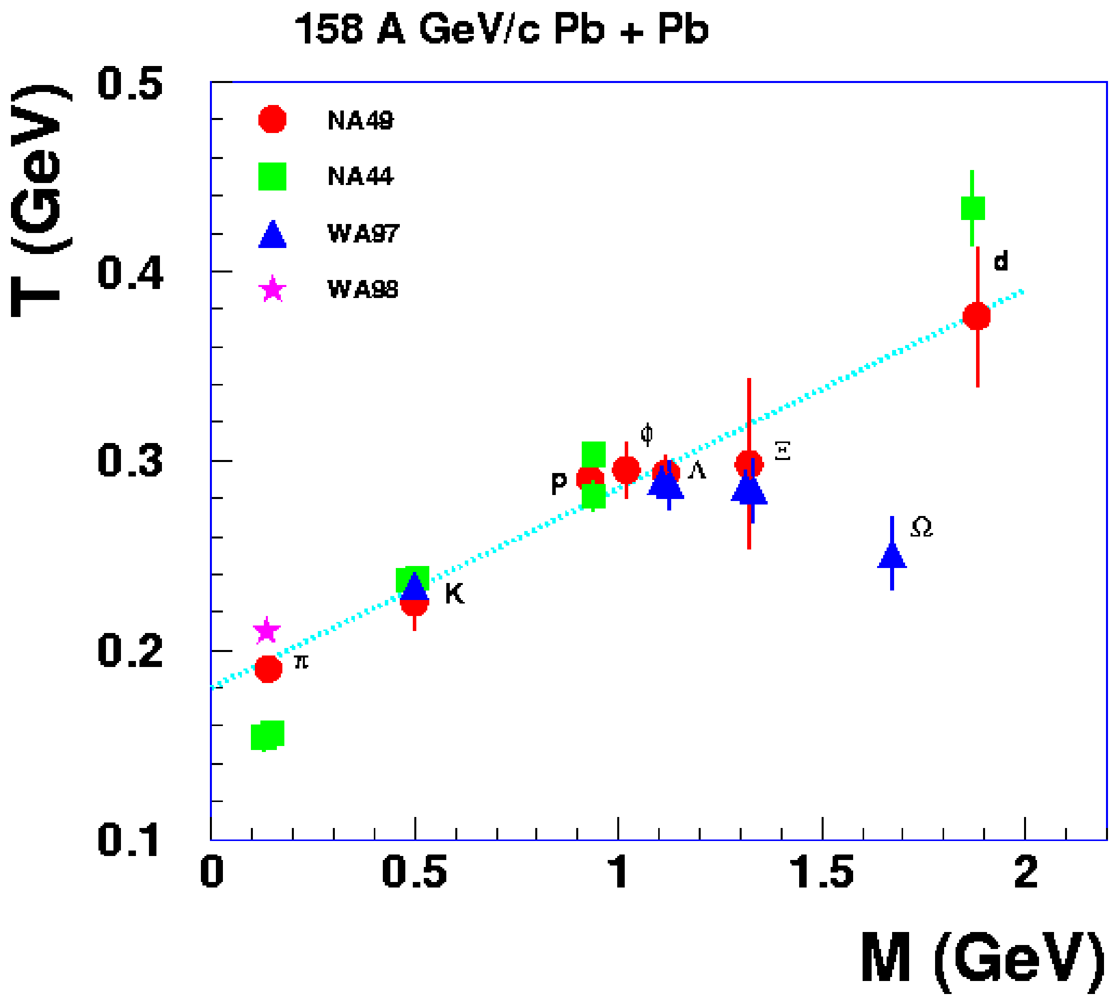
Result:
Particle numbers of strange particle in canonical (C) and grand canonical (GC) approach are related:

$$n_{|S|}^{C} = n_{|S|}^{GC} \cdot F\left(n_{|S|}^{GC} \cdot V\right)$$

F is a ratio of modified Bessel functions,
V is correlation volume

Conclusion: strangeness is in equilibium over the whole energy range !?
Needs consistency checks!

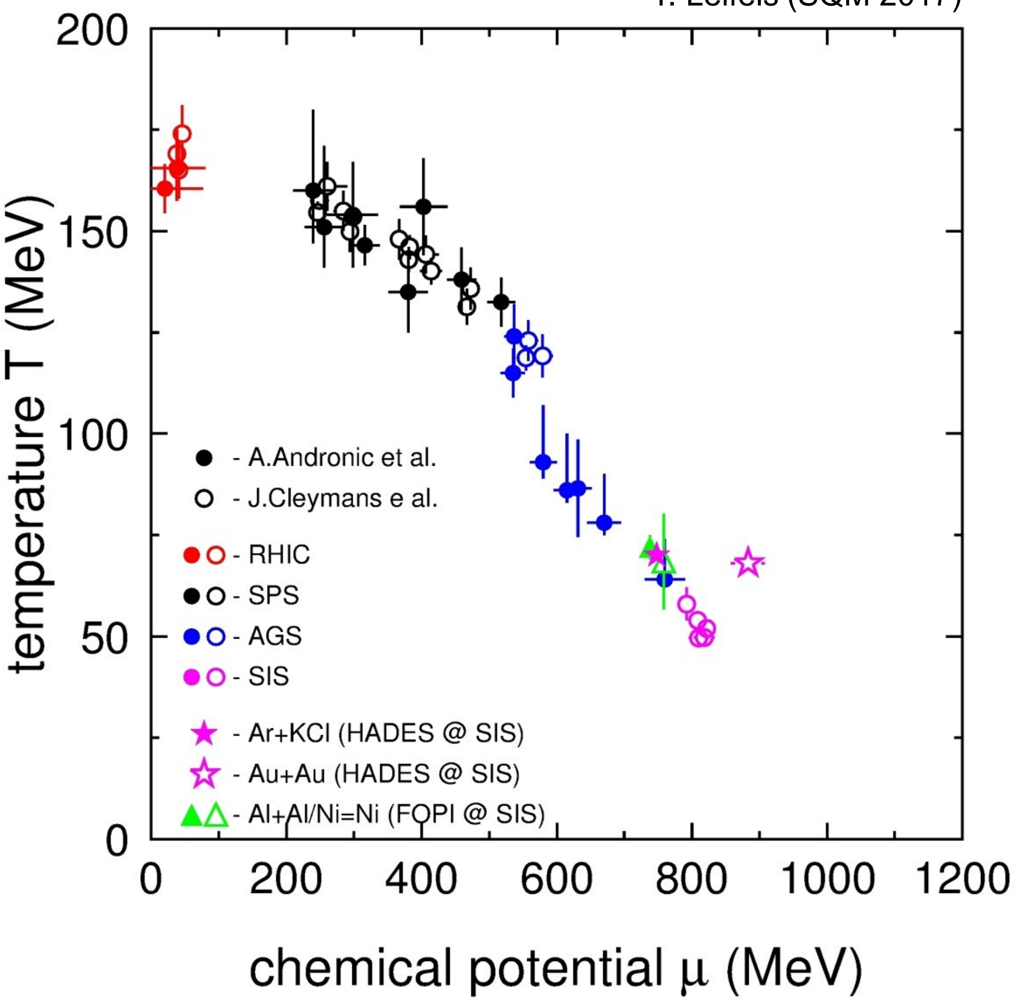
Transverse expansion



Slopes are proportional to mass except for multiple strange particles.

Collection of SHM freeze-out data

Y. Leifels (SQM 2017)



High energies:
grandcanonical ensemble

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

Equilibrium achieved in small systems?

Equilibrium as signature for phase transition?

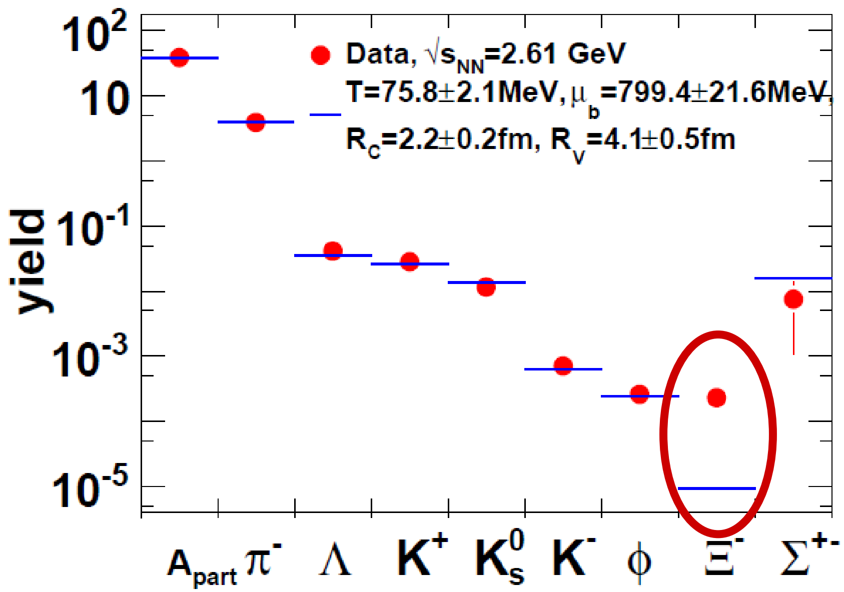
Freeze-out line at large baryon densities
as phase boundary to quarkyonic matter ?

FOPI analysis: K. Piasecki et al., Phys.Rev. C94 (2016)
Thermus V2.3,
Wheaton & Cleymans Comp. Phys. Comm. 180 (2009)

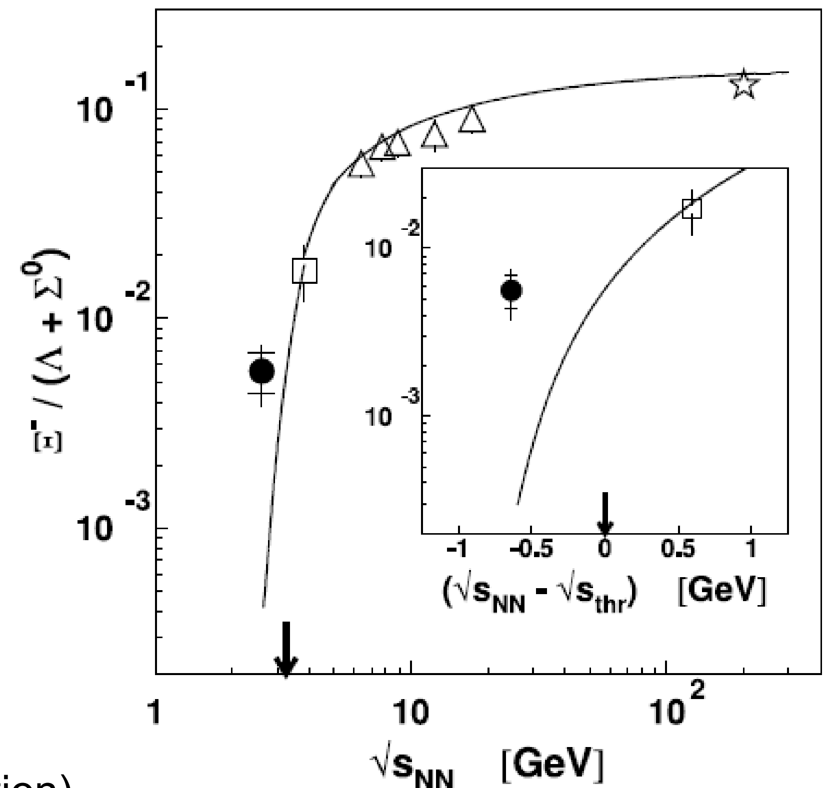
HADES: Sub-threshold Ξ^- - production

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)



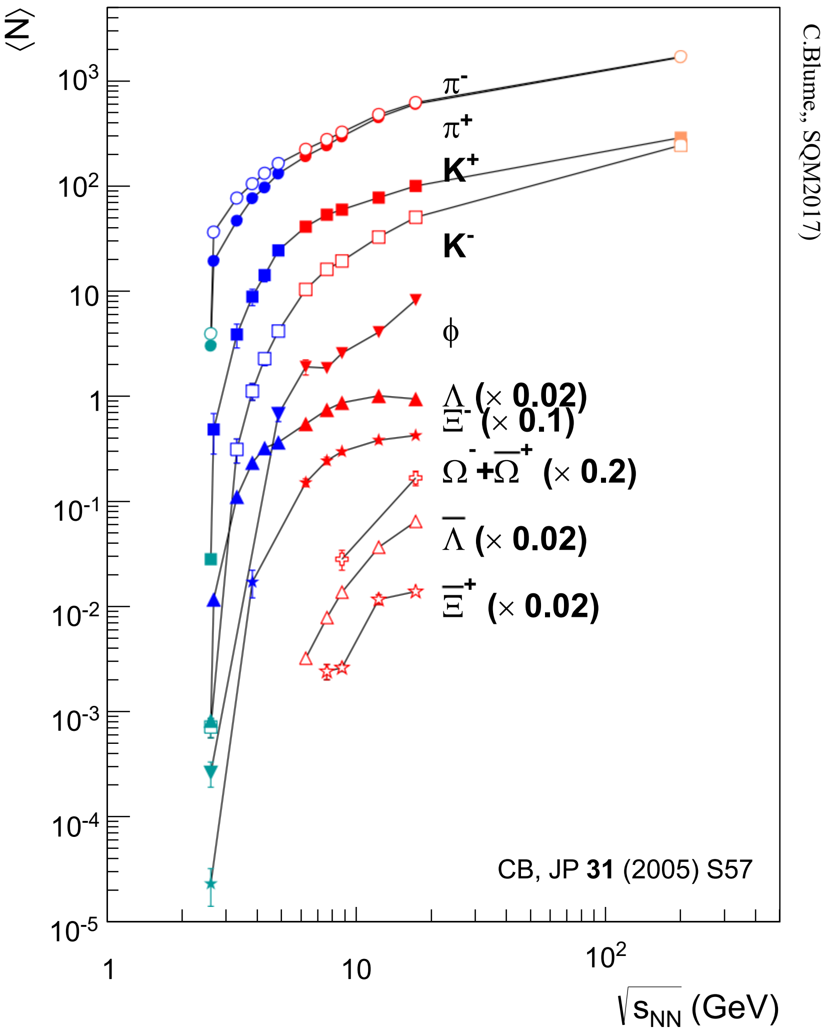
Enhancement factor: ∞ (deep subthreshold production)

Note: yield can be reproduced by microscopic models (e.g. UrQMD)
tuning branching ratios of heavy resonances (Steinheimer, Bleicher, arXiv: 1503.07305) :

$$N + \phi \leftrightarrow N^*(1990,2080,2190,2220,2250) \longrightarrow \Xi K K$$

Final state particle abundance

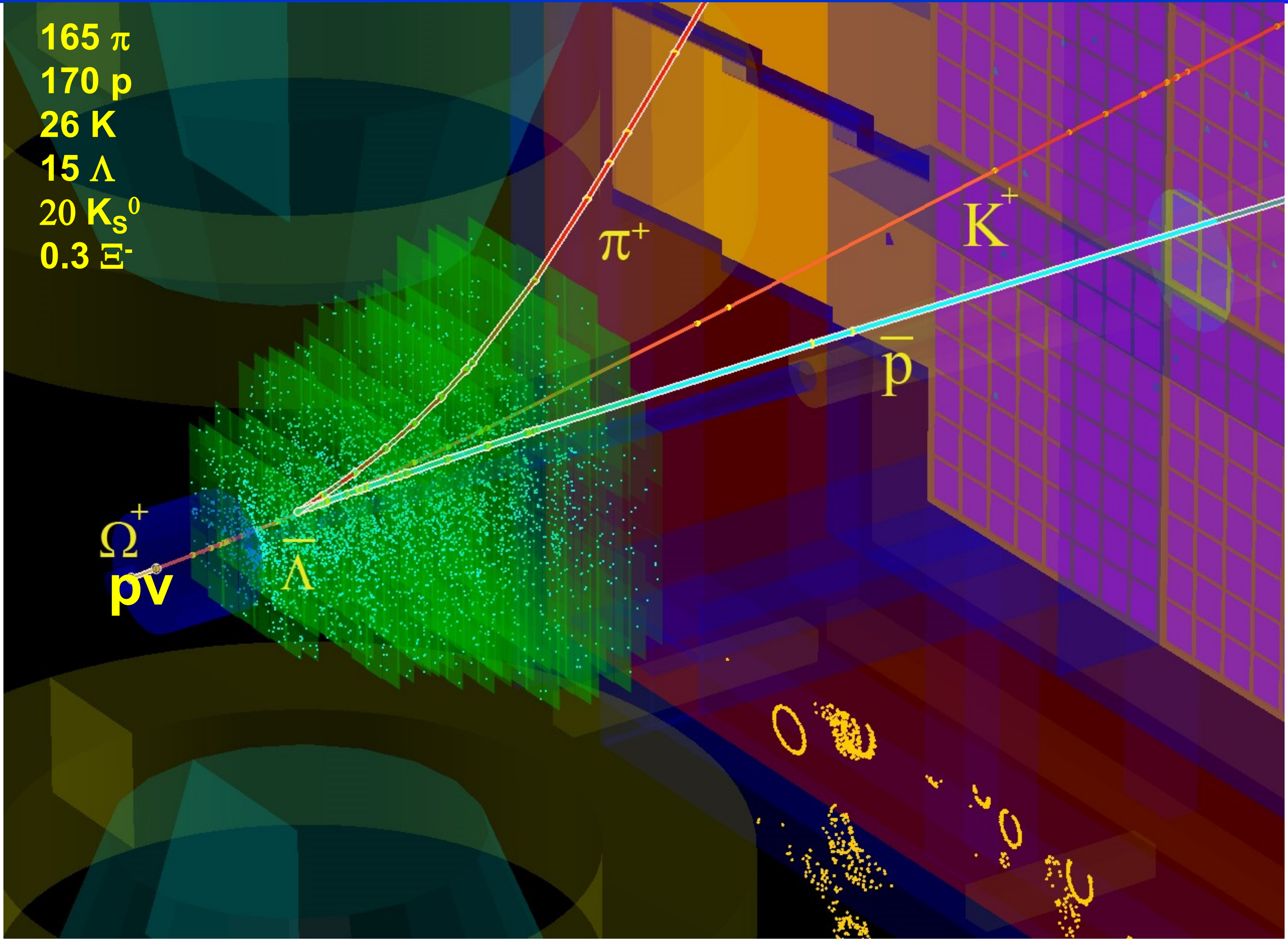
Particle yields from central Au + Au collisions



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

KF Particle Finder with ToF track ID: Au+Au @ 10AGeV SIS100



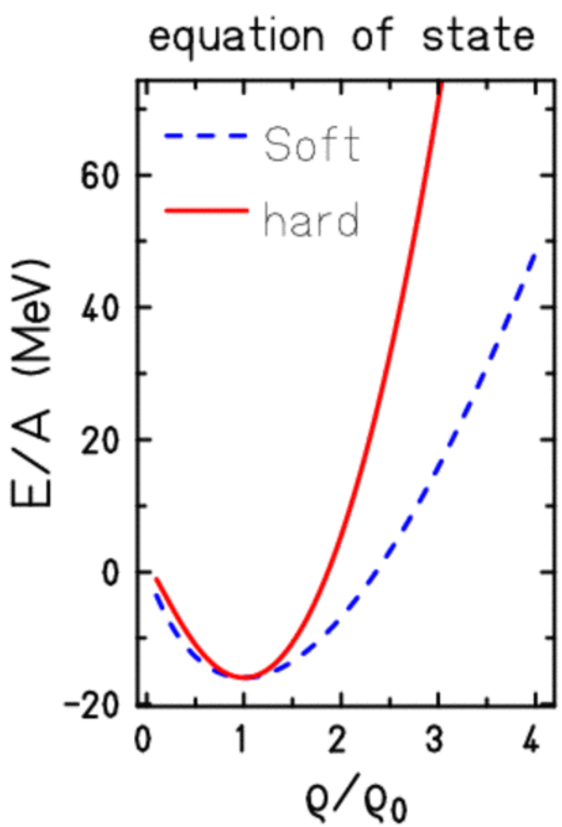
Matter effects on strangeness production

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.

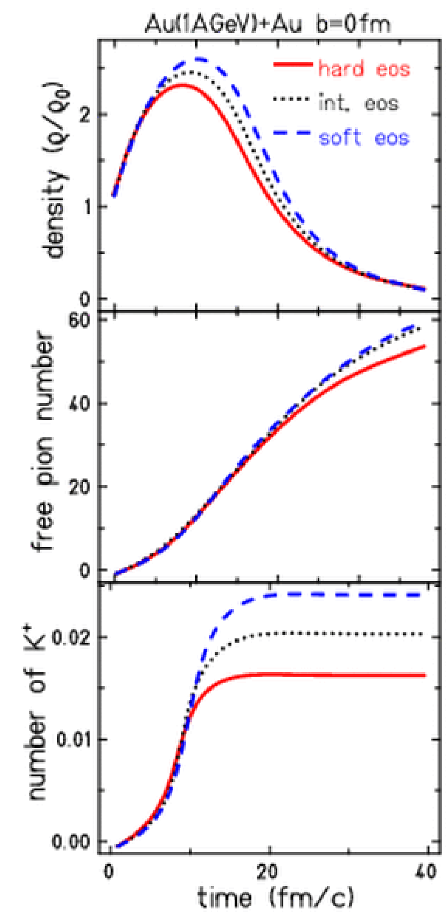


Transport model (IQMD)

Softer EOS
⇒ larger densities
⇒ stronger resonance population
⇒ more NΔ collisions
⇒ more collisions above production threshold:

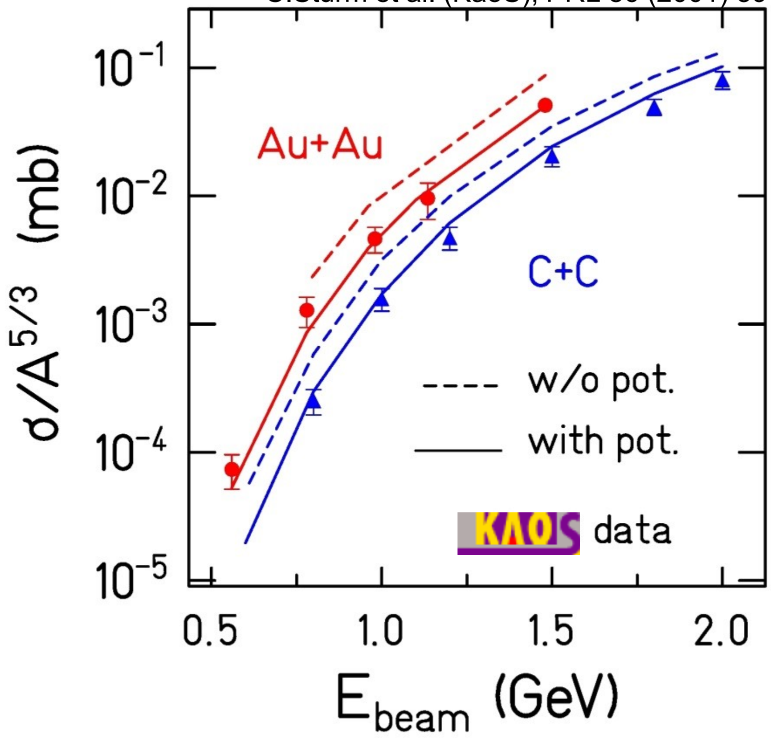
$$N\Delta \rightarrow NK\Lambda$$
$$\Delta\Delta \rightarrow NK\Lambda$$
(associated production)

C. Hartnack (IQMD)

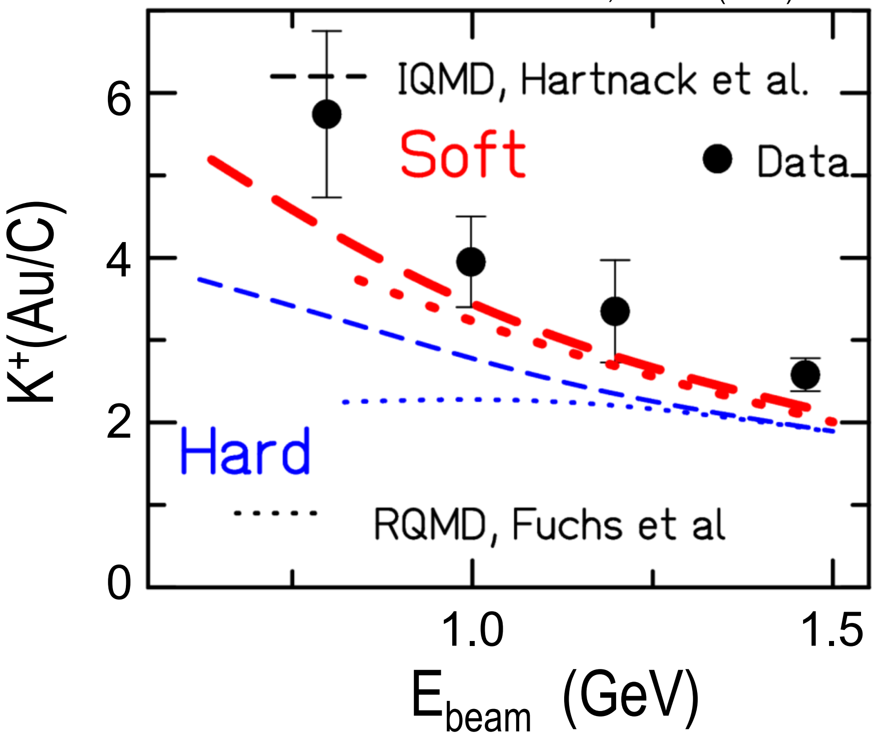


Kaon production

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



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

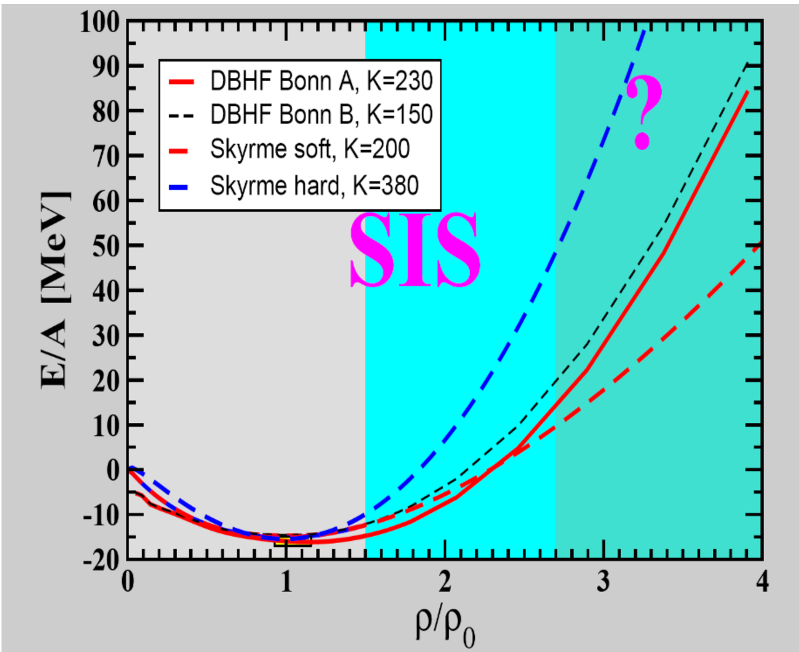


Sub-threshold kaon production

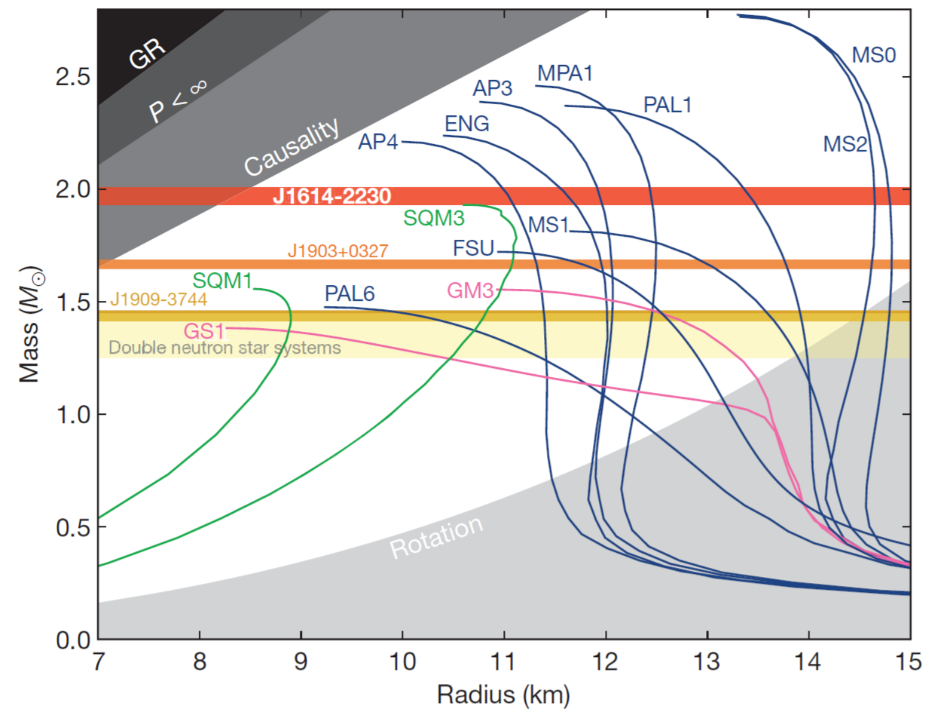
- multi-step processes, using resonances/pions as intermediate energy storage
  - strongly dependent on density
- sensitive to the stiffness of the nuclear matter equation of state
- EOS is soft up to densities $\varrho \leq 2.5\ \varrho_0$

Astrophysical constraints on the EOS

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.

Stiffening must occur in the range of densities up to 4 ρ_0.