Strangeness Production

(with focus on FAIR energy range)

Outline

Part I

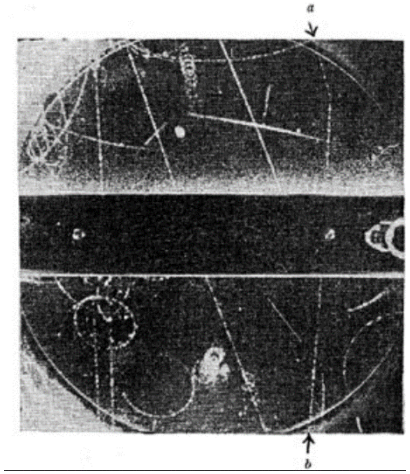
- History
- Quarkmodel
- Strange hadrons
- Strange particle yields in heavy ion collisions
- Strangeness enhancement
- The „horn“
- Thermal Model description
- Thermalization times
- Connection to phase transition
- Equation-of-state from subthreshold kaon production

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 preconscious 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

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

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

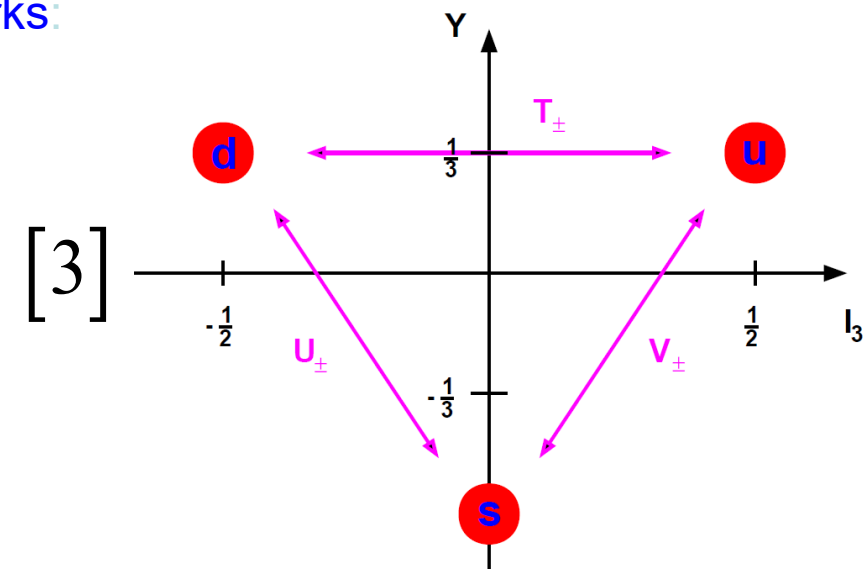
$$u \leftrightarrow s \quad \lambda_4 = \begin{pmatrix} 0 & 0 & 1 \\ 0 & 0 & 0 \\ 1 & 0 & 0 \end{pmatrix} \quad \lambda_5 = \begin{pmatrix} 0 & 0 & -i \\ 0 & 0 & 0 \\ i & 0 & 0 \end{pmatrix}$$

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

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

$SU(3)_F$ – fundamental representations

Quarks:



Hypercharge Y:

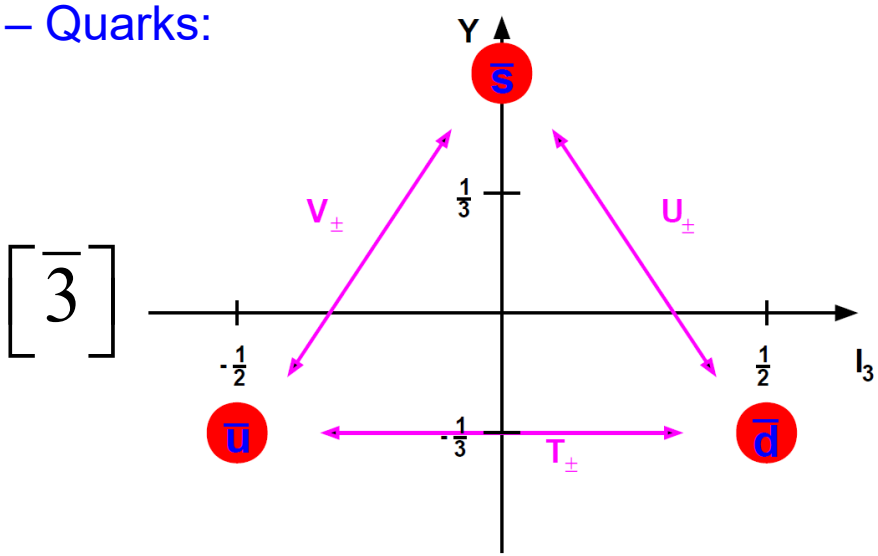
$Y = B + S$

Baryon number B
Strangness number S

Charge Q:

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

Anti – Quarks:



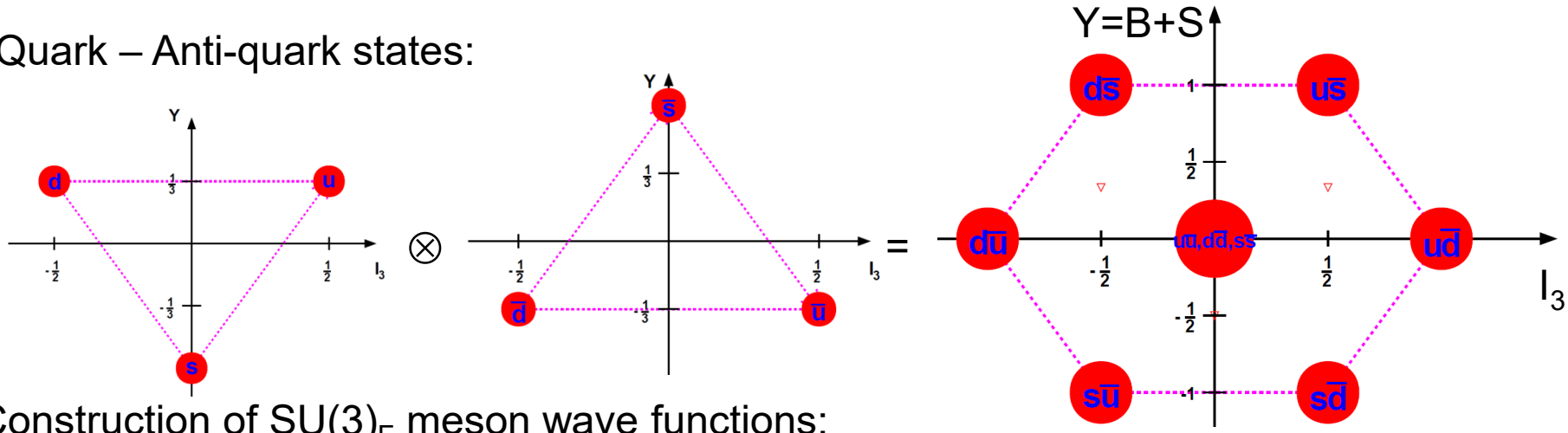
Ladder operators:

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

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

Light $SU(3)_F$ – (uds) – mesons

Quark – Anti-quark states:



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:

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

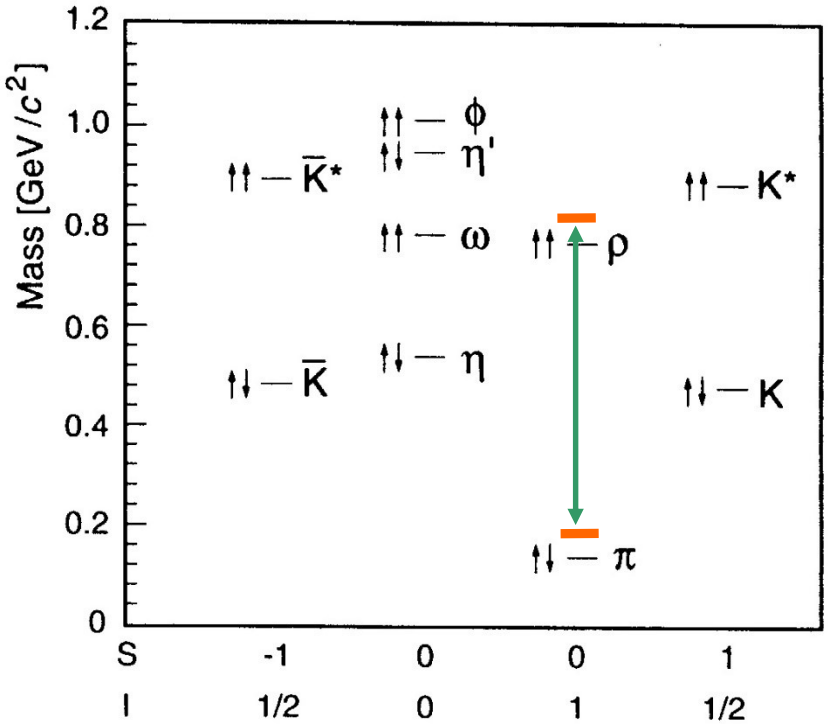
2) neutral pion:

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

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

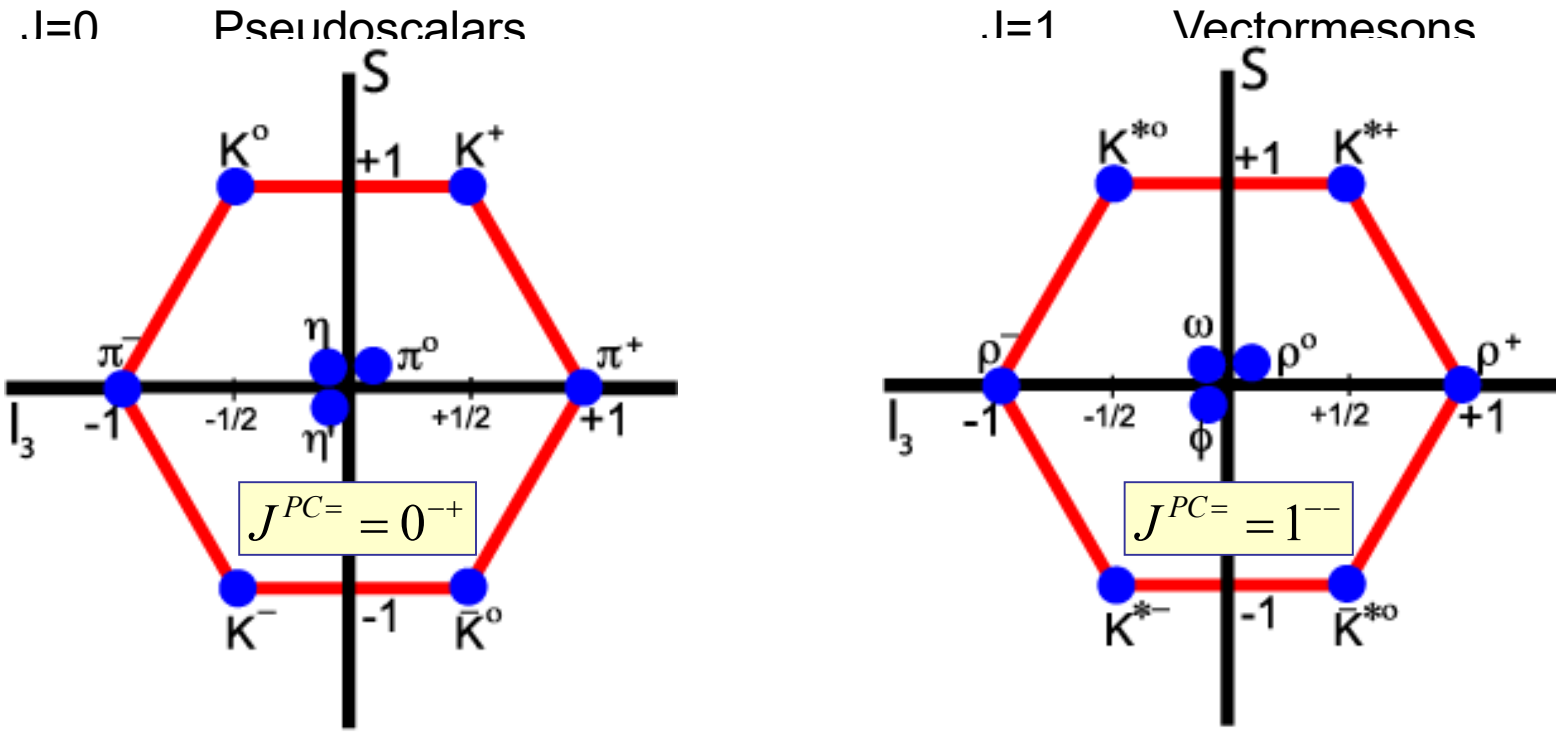
J = 0

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:



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
⇒ Exotic J^{PC}: 0^{--}, 0^{+-}, 1^{-+}, 2^{+-} ,…

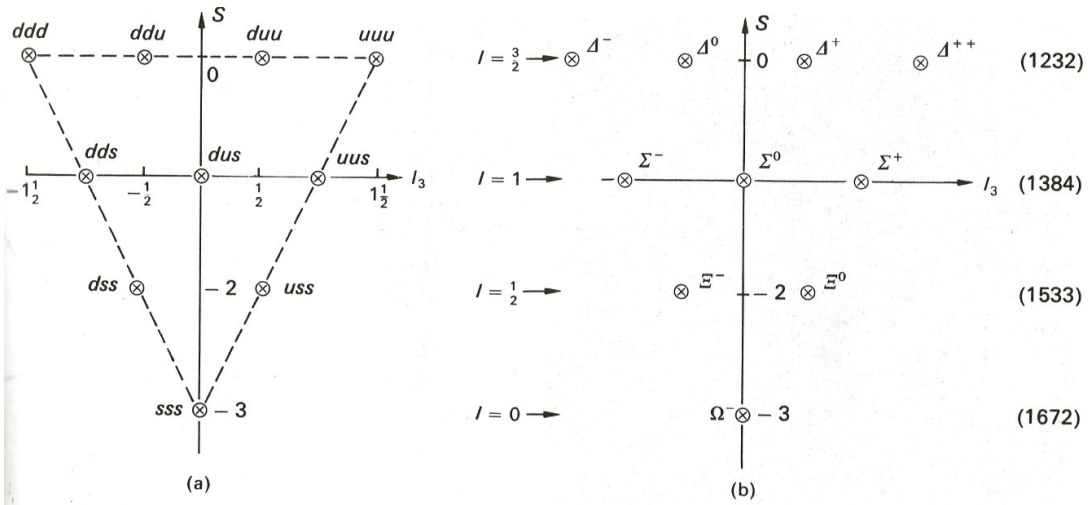
Exotic mesons can have these J^{PC} due to additional degrees of freedom.

The $SU(3)_F$ – baryon multiplets

Baryon decuplet: J=3/2

Mass (MeV)

(Figs.: Perkins)



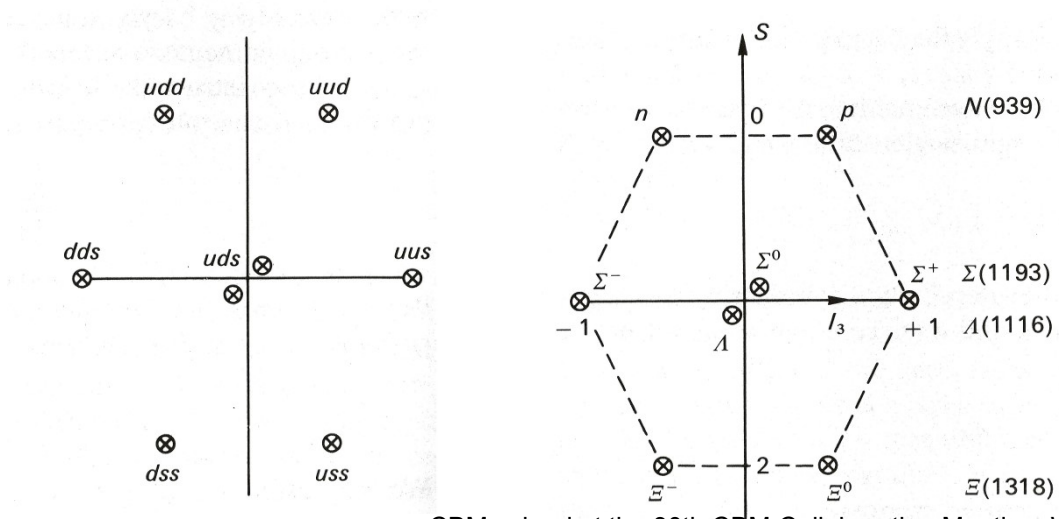
ΔM (MeV)

152

149

139

Baryon octet: J=1/2

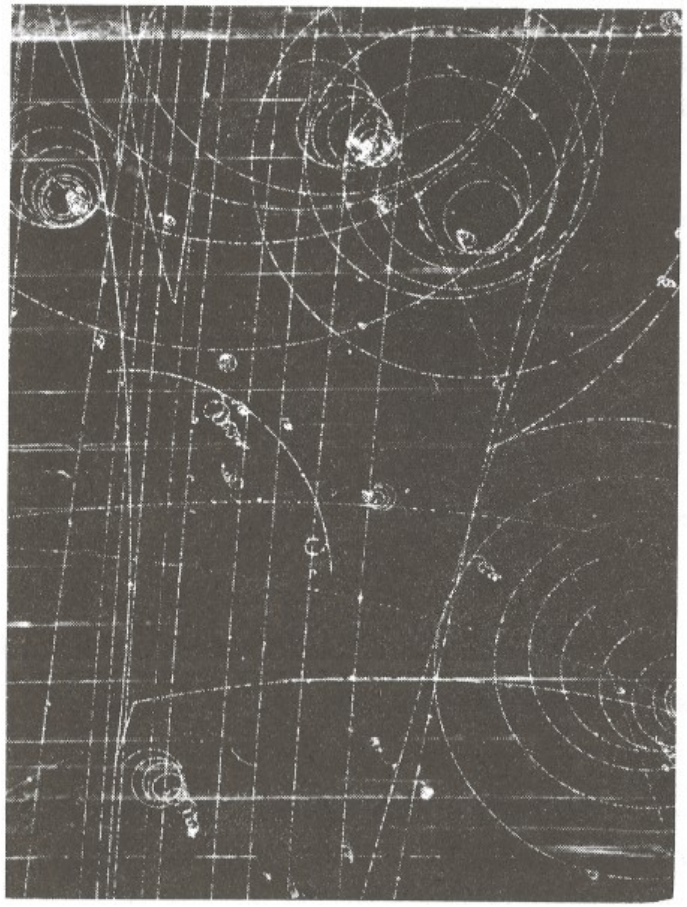


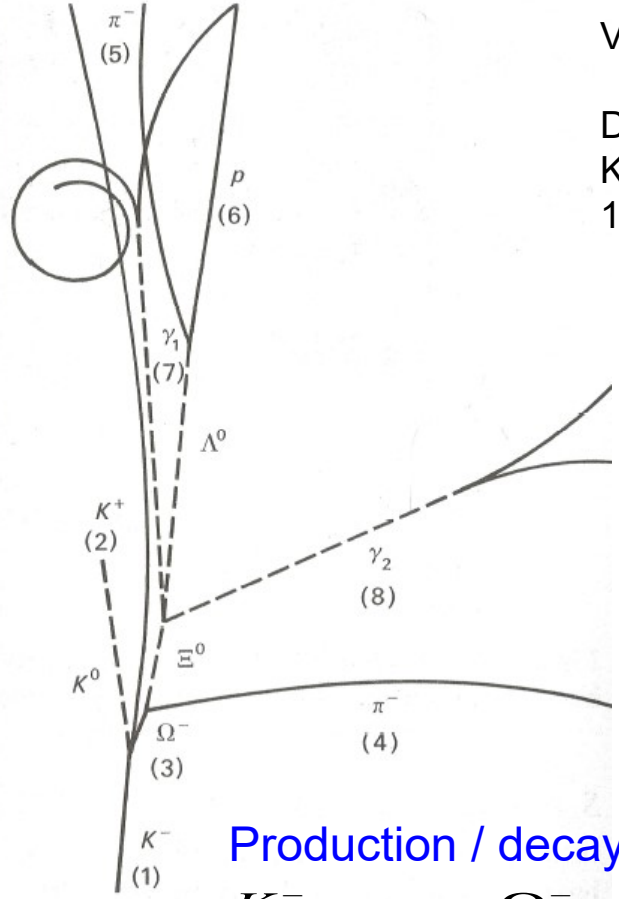
Historically:

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:

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

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

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

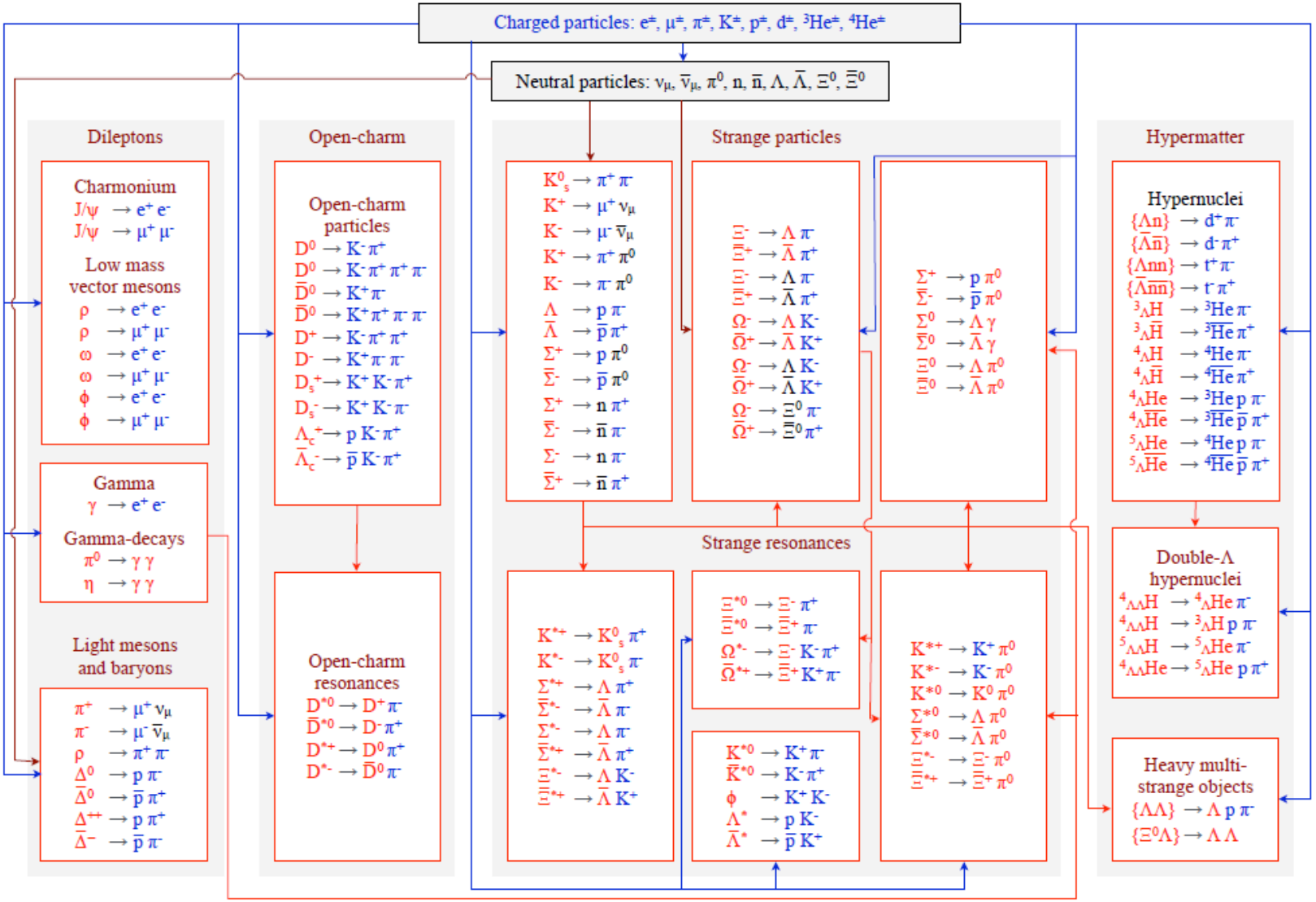
$$\Lambda^0 \rightarrow p + \pi^-$$

$$\pi^0 \rightarrow \gamma + \gamma$$

Groundstate strange hadrons decay by weak interaction
=> long lifetimes

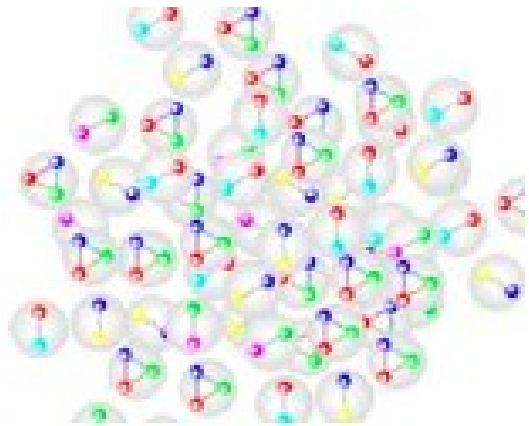
KF Particle Finder

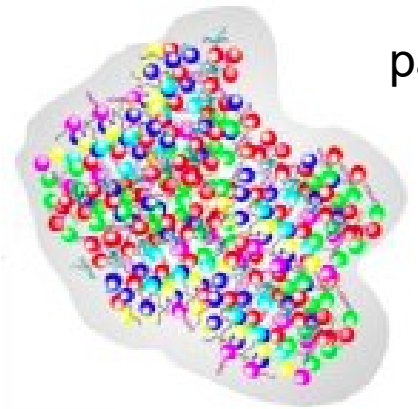
M. Zyzak et al. (CBM)



Strangeness as probe for QCD matter

hadronic



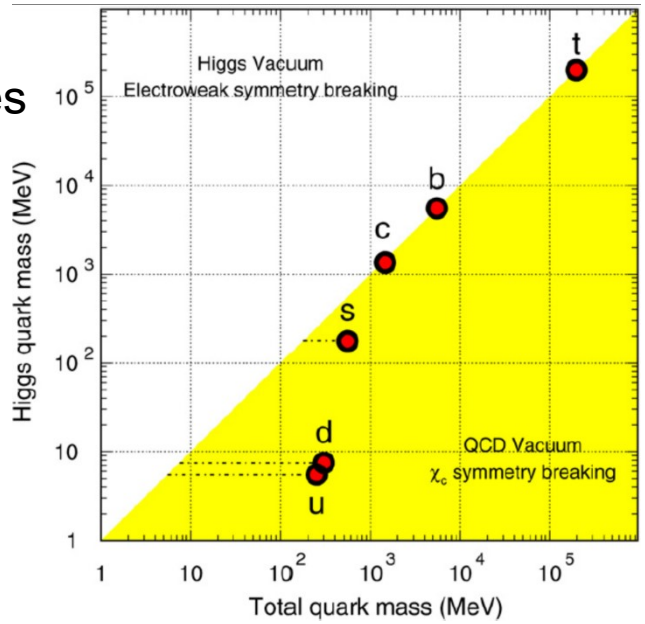


partonic

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:

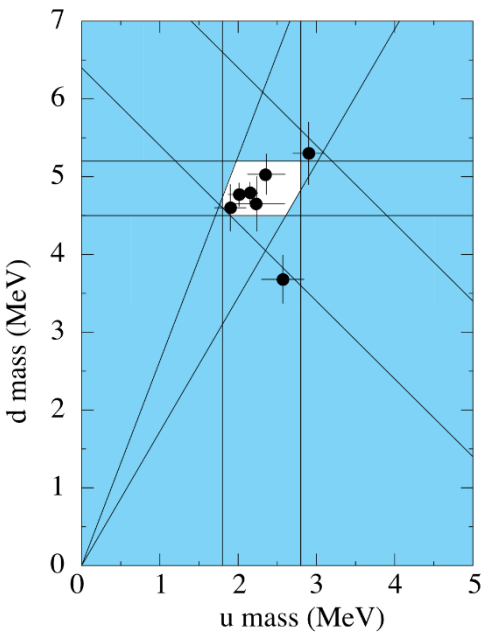
$$M_{hadron} = \sum_q m_q + \Delta M_J$$

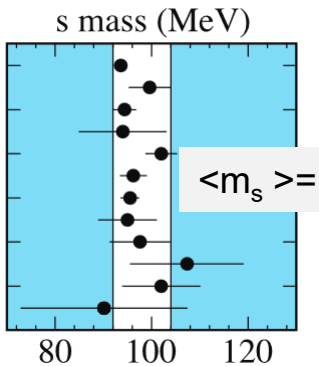
J – spin of hadron
(spin – spin interaction of quarks)

Result:

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

$$m_s \approx 483 MeV / c^2$$





$\langle m_s \rangle = (93.5 \pm 2)$ MeV

Experiments with Strangeness Measurements

GSI-SIS
FOPI, KAOS, HADES

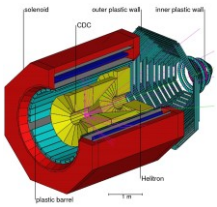
BNL-AGS
E866, E877, E891, E895, …

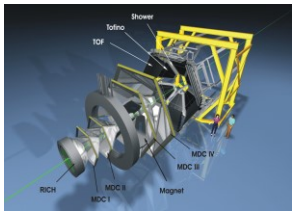
CERN-SPS (Pb beam)
WA97, NA44, NA45, NA50
NA49, NA57, NA61

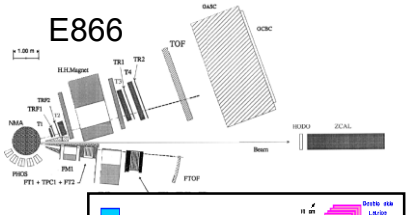
BNL-RHIC
STAR, PHENIX, BRAHMS

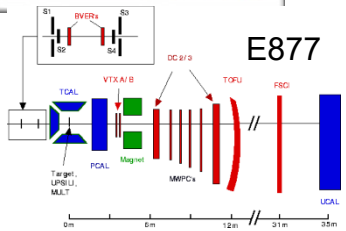
CERN-LHC
ALICE

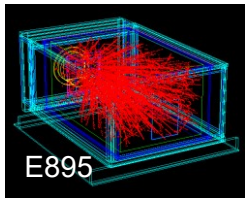
New low energy programs
CBM@FAIR, NICA

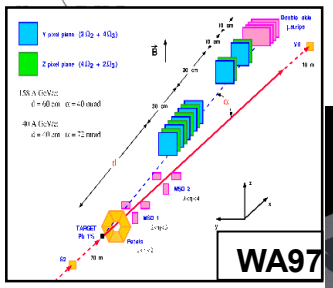


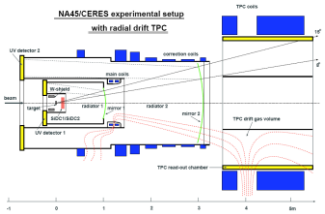


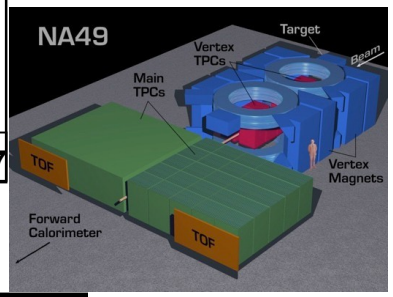


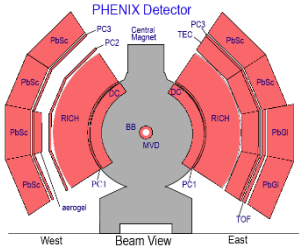


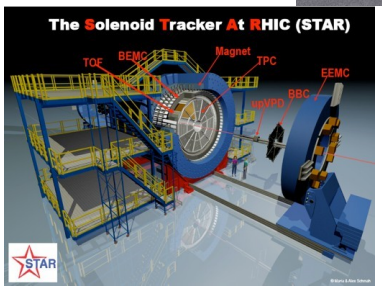


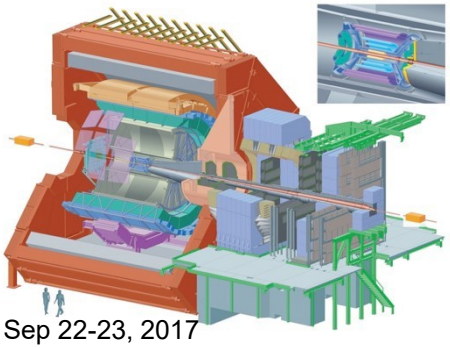








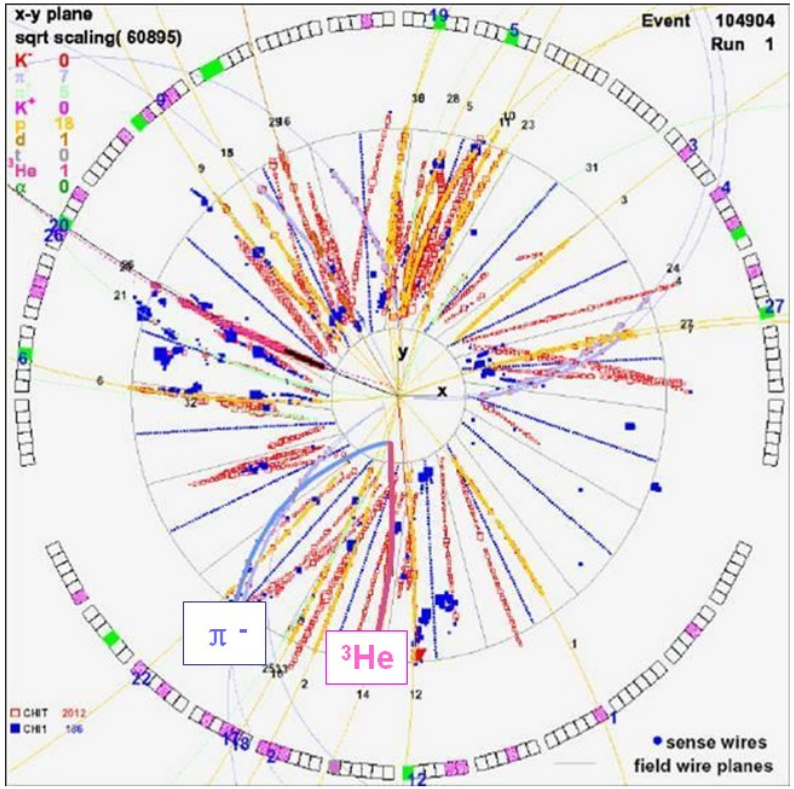


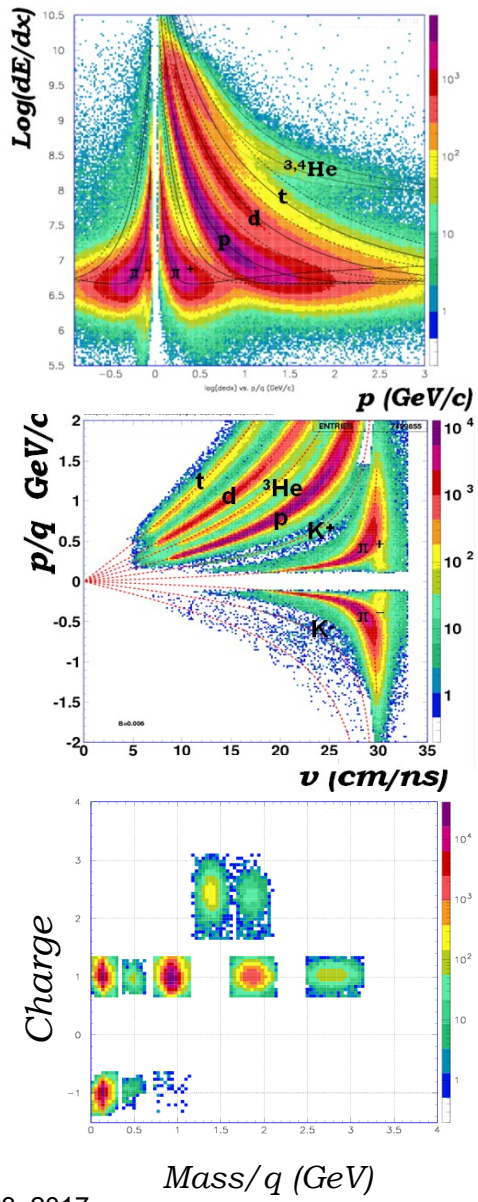


Strange particle reconstruction

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

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

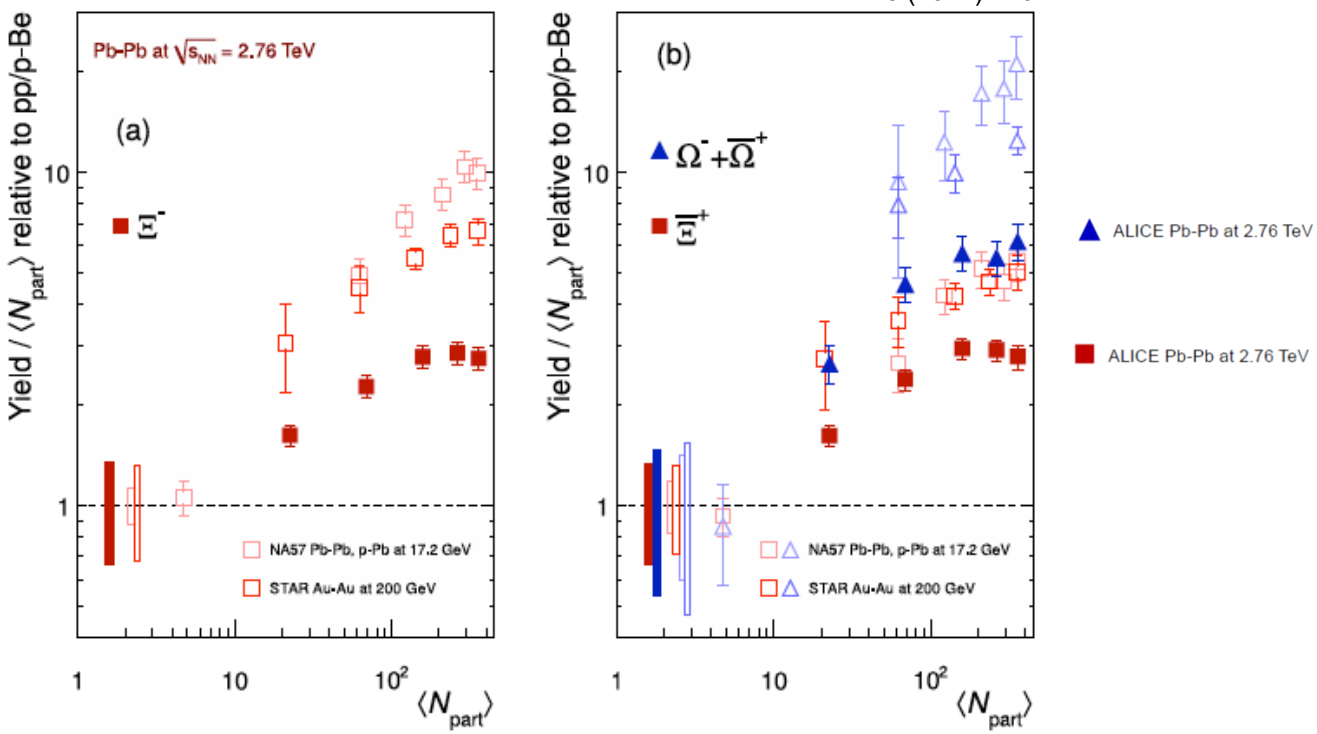




FOPI @ SIS18 of GSI
Ni+Ni @ 1.91AGeV
S325e (2008), ~ 60 M events

Strangeness production

ALICE
PLB **728** (2014) 216



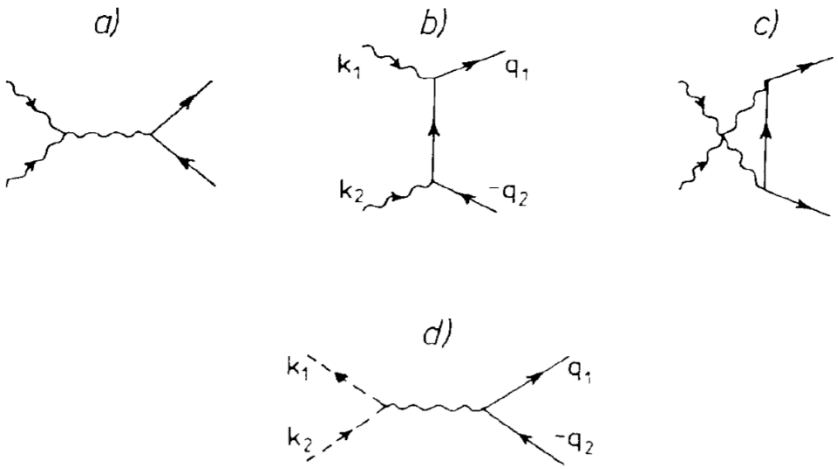
Enhancement factor: $E = \frac{2}{N_{part}} [\frac{dN}{dy}(Pb + Pb)\Big|_{y=0} / \frac{dN}{dy}(p + p)\Big|_{y=0}]$

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

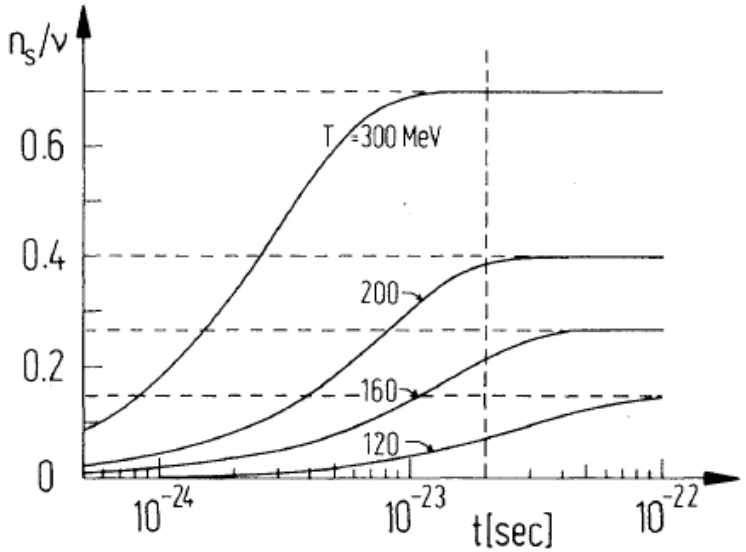
Strangeness enhancement as QGP signature

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

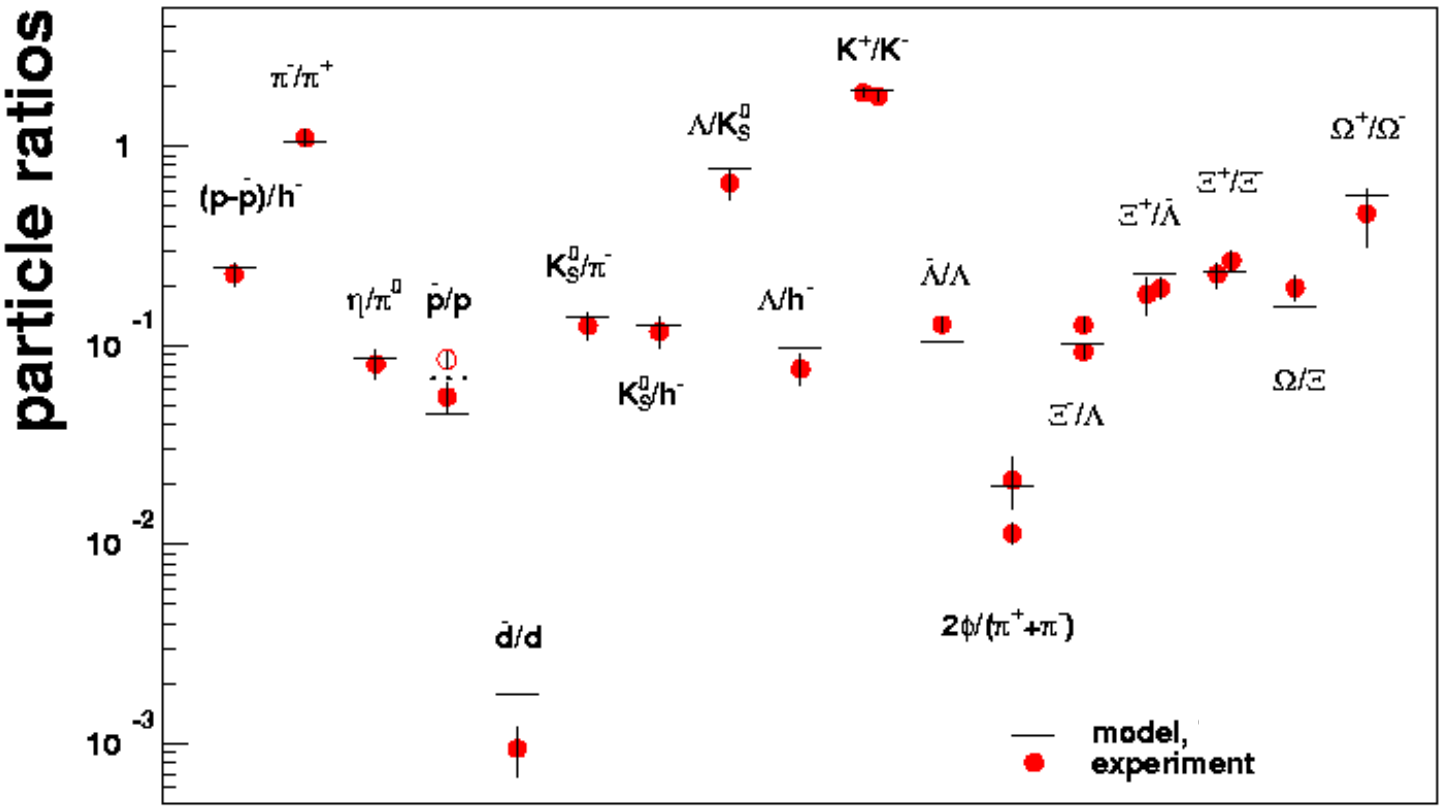
charge: $V\sum_i n_i I_{3,i} = \frac{Z-N}{2} \rightarrow \mu_{I_{3,i}}$

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]

Department of Physics, State University of New York at Stony Brook, Stony Brook, NY 11794 – 3800, USA

Interpretation in bag model:

1. order phase transition: latent heat

densities

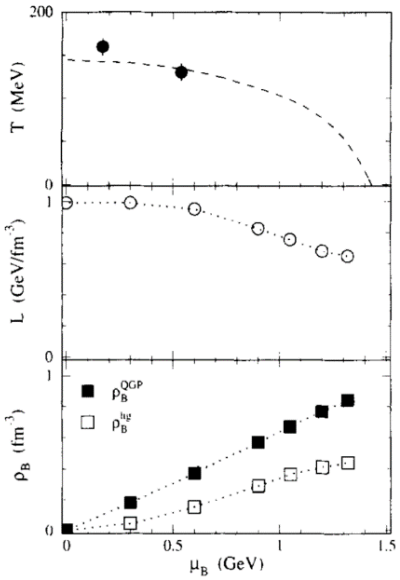


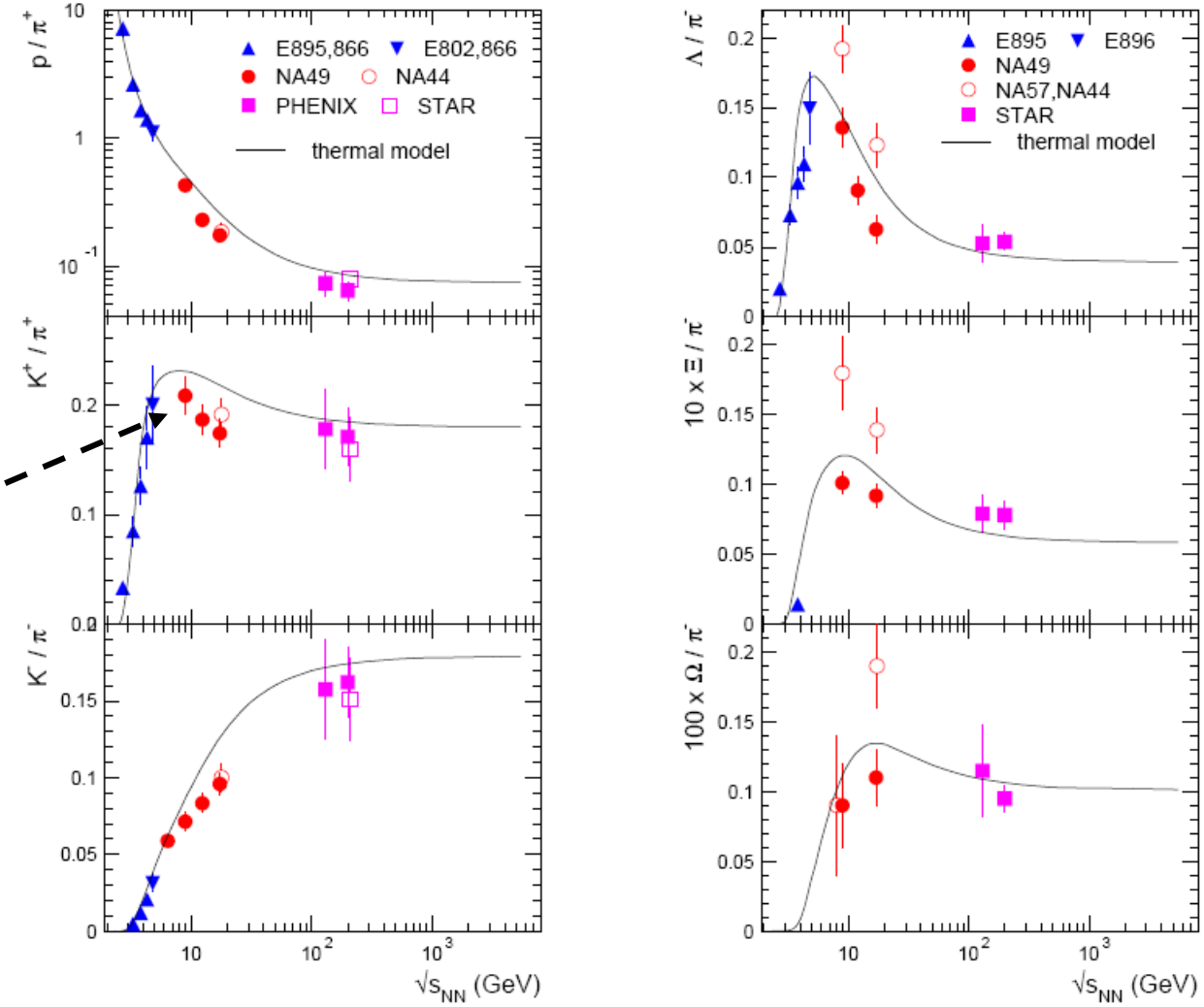
Fig. 3. Phase boundary between a hadron gas and a quark-gluon plasma (top) as function of temperature and baryon chemical potential together with the freeze-out points for Si(S) + Au(W,Pb) collisions at AGS [11] and SPS (present paper) energies. Latent heat of the phase transition (middle) and baryon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

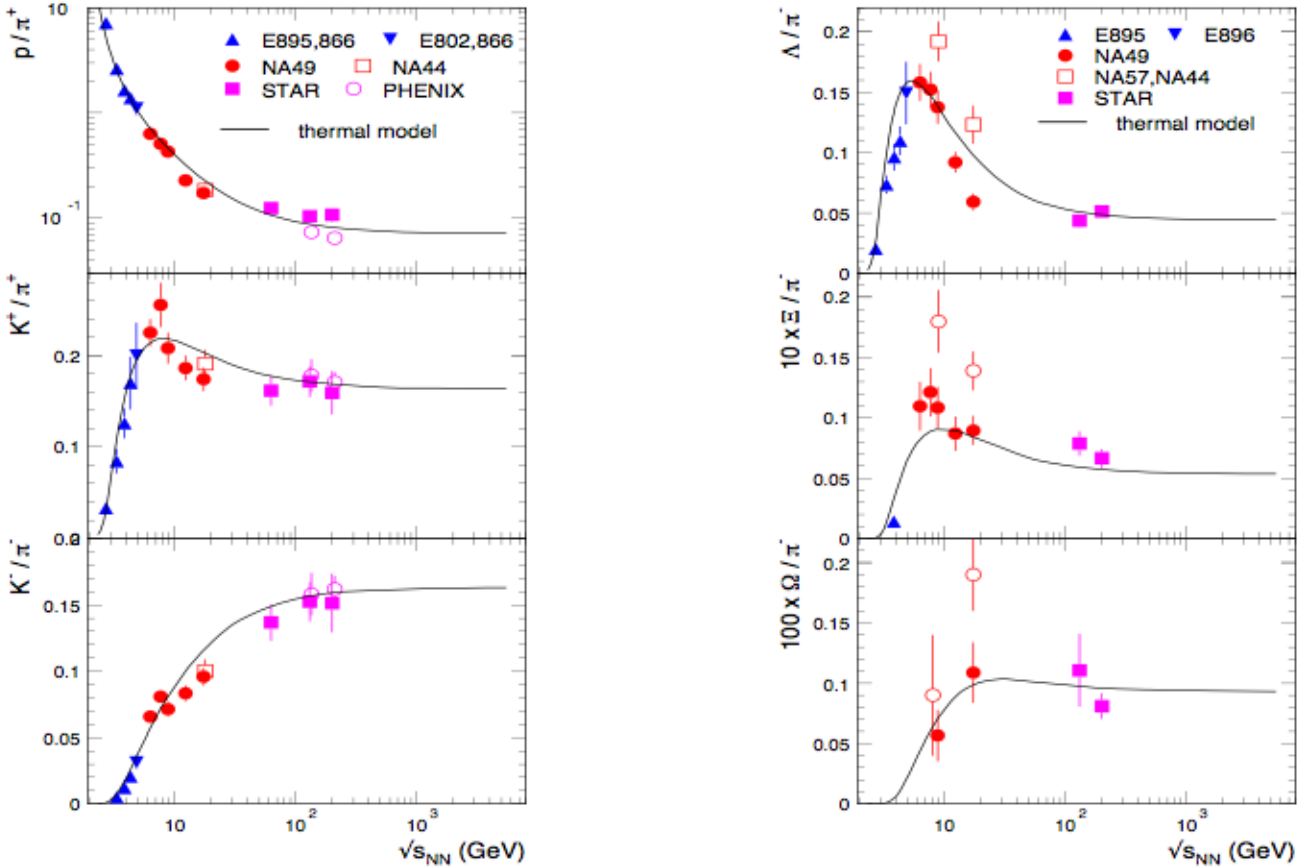
A. Andronic, P. Braun-Munzinger, J. Stachel, *Nucl. Phys. A 772 (2006) 167*

„horn“



Particle ratios revisited

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



Thermal model with extended resonance mass spectrum

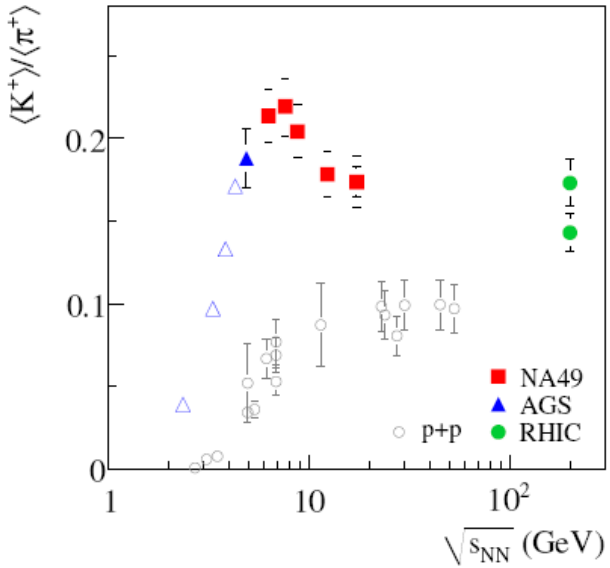
- high lying resonances (M > 2 GeV)
- sigma meson (M = 600 MeV)

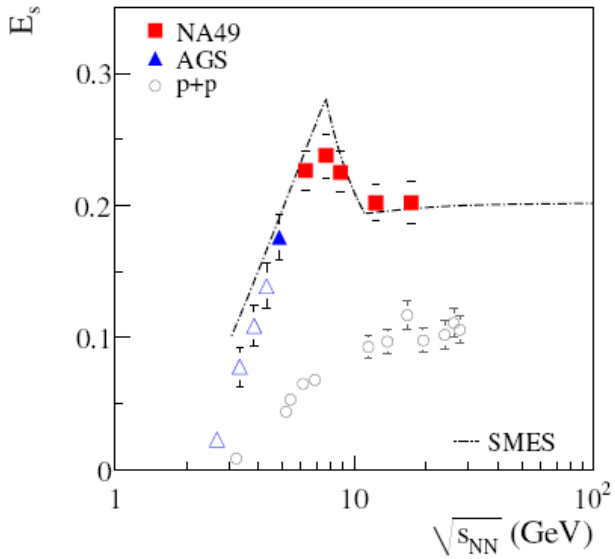
gross features very well.

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

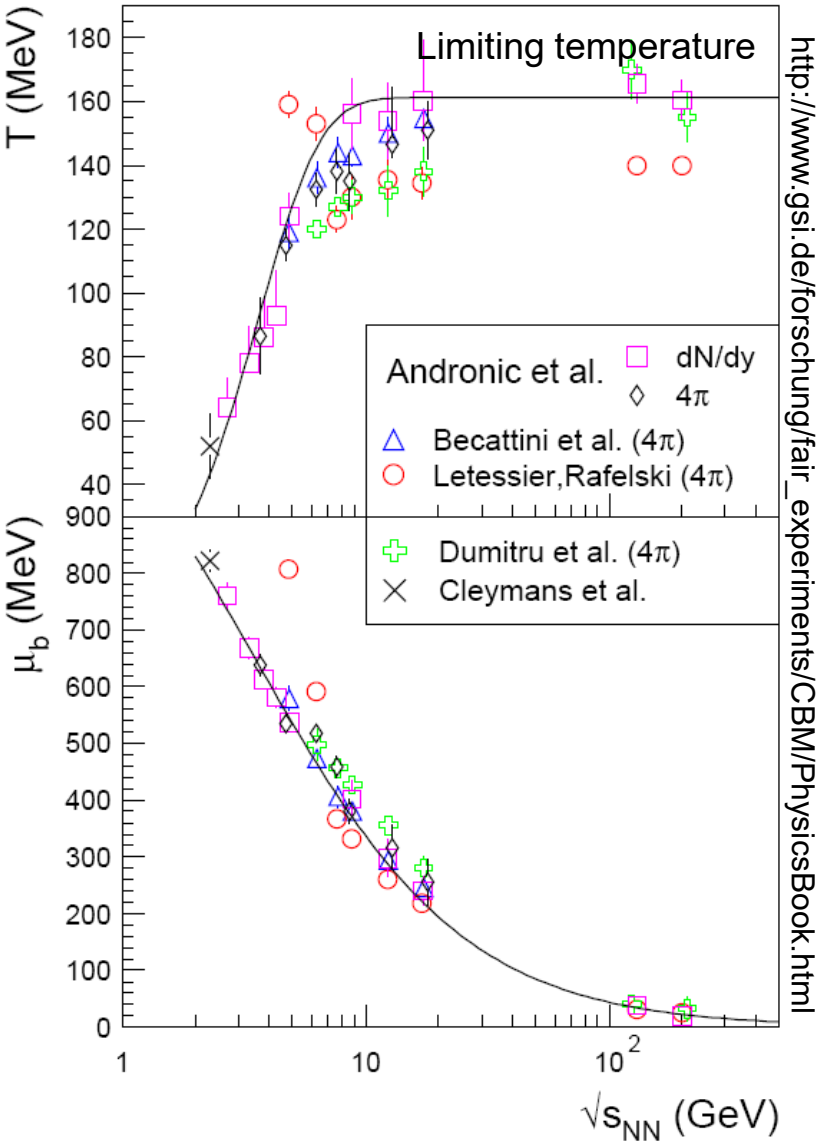




Large entropy production beyond threshold energy

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.

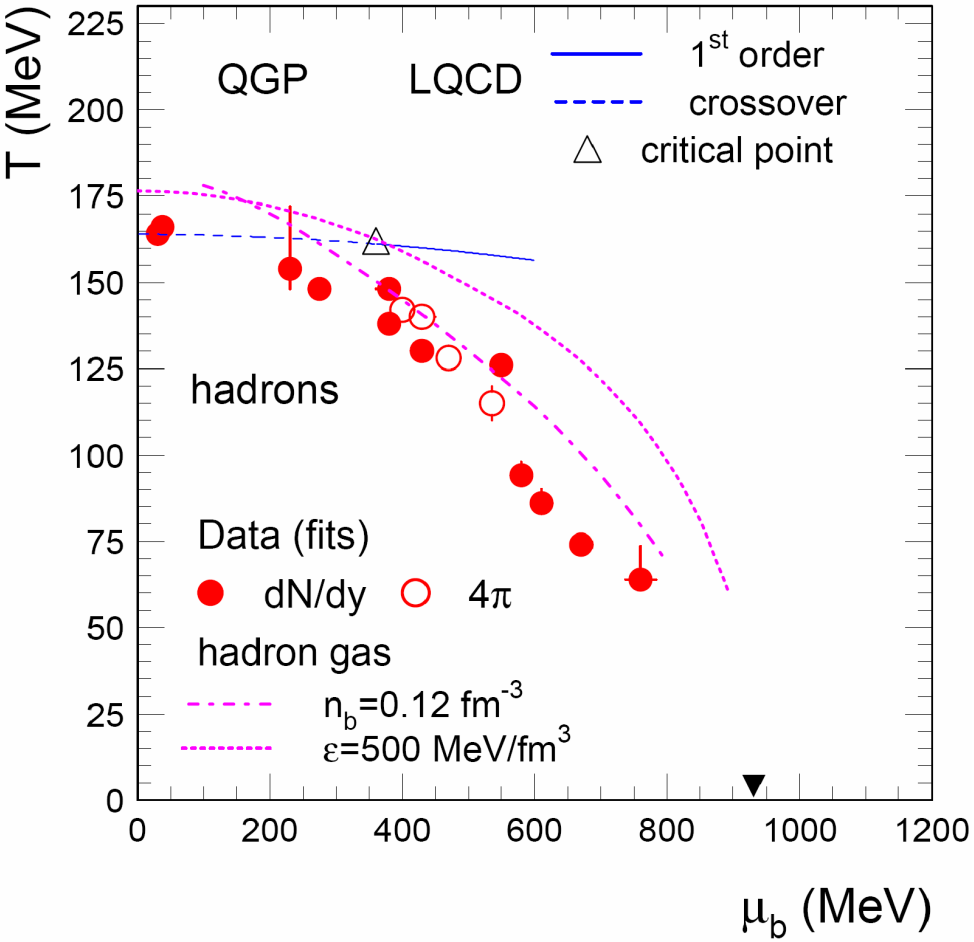
Excitation function of particle production



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

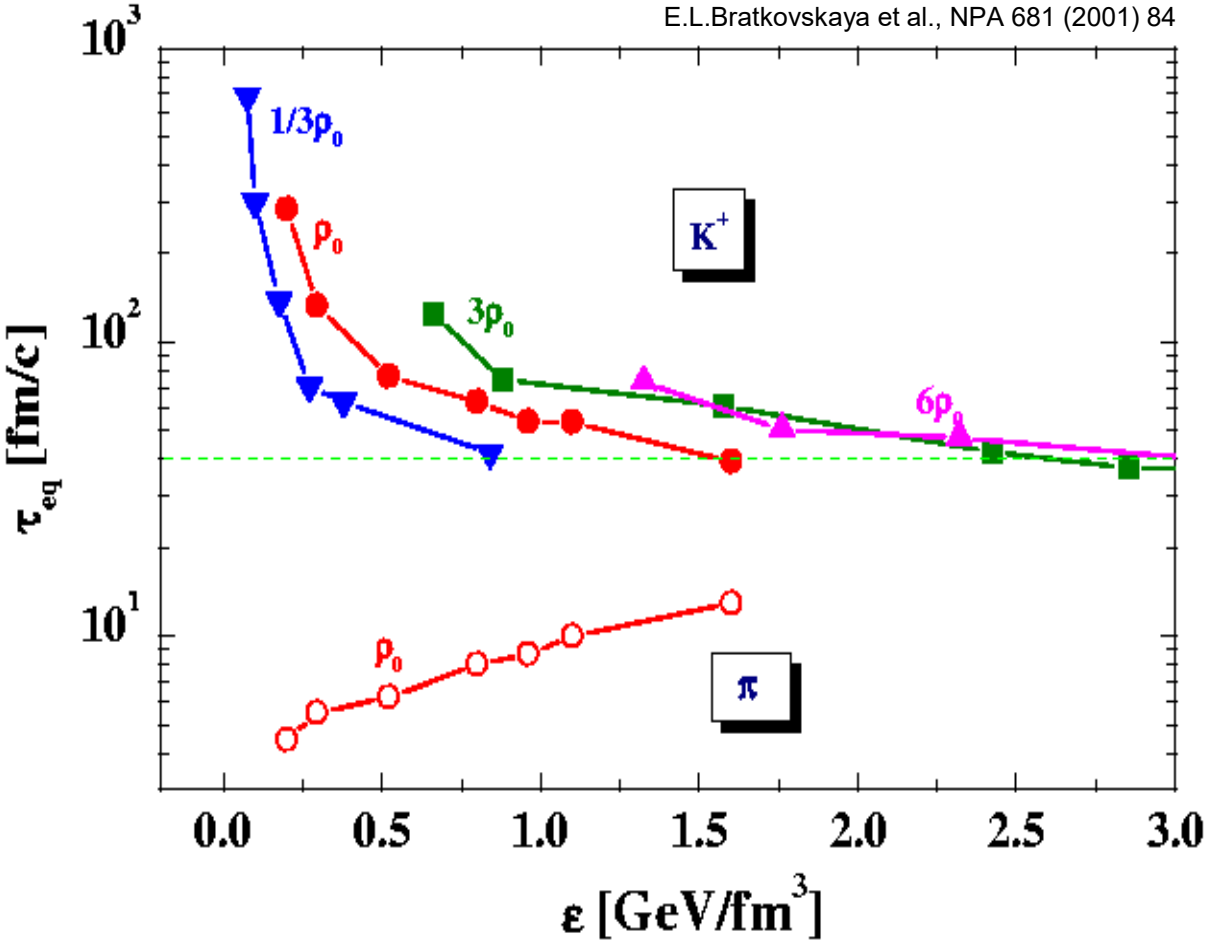
time between collisions $$\tau = \lambda / c = 1.5\,fm / c$$

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

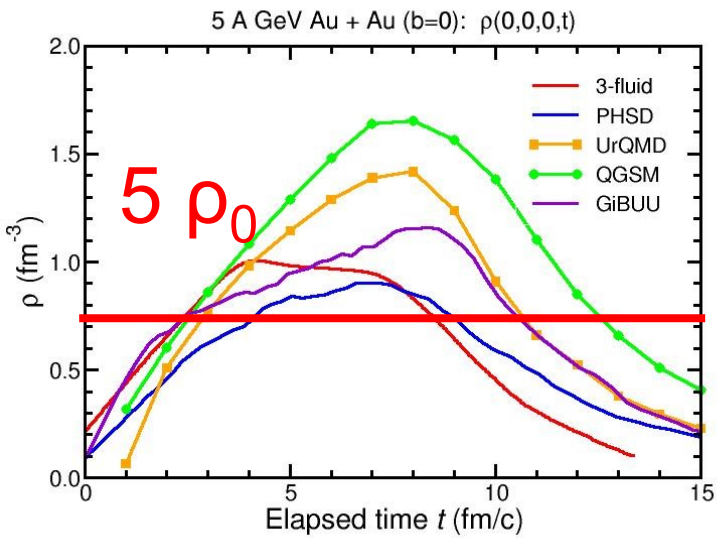


Even the lightest strange particle (K^+) needs at least 40 fm/c to equilibrate.

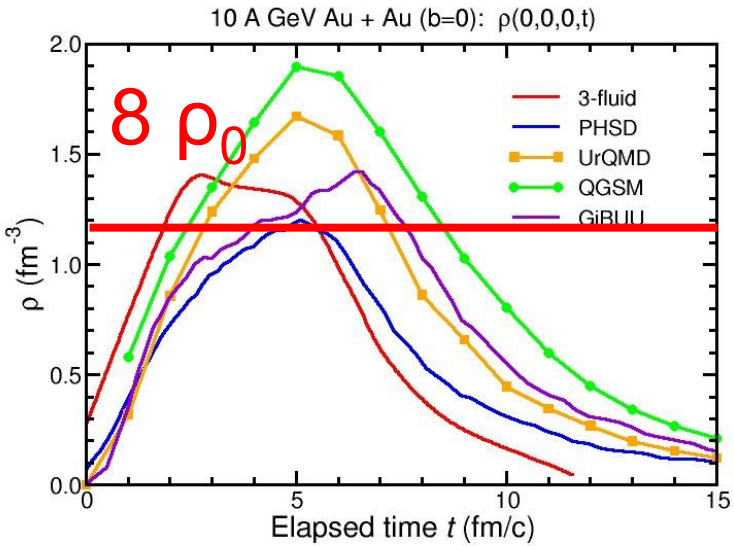
Baryon densities in central Au+Au collisions

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

5 A GeV

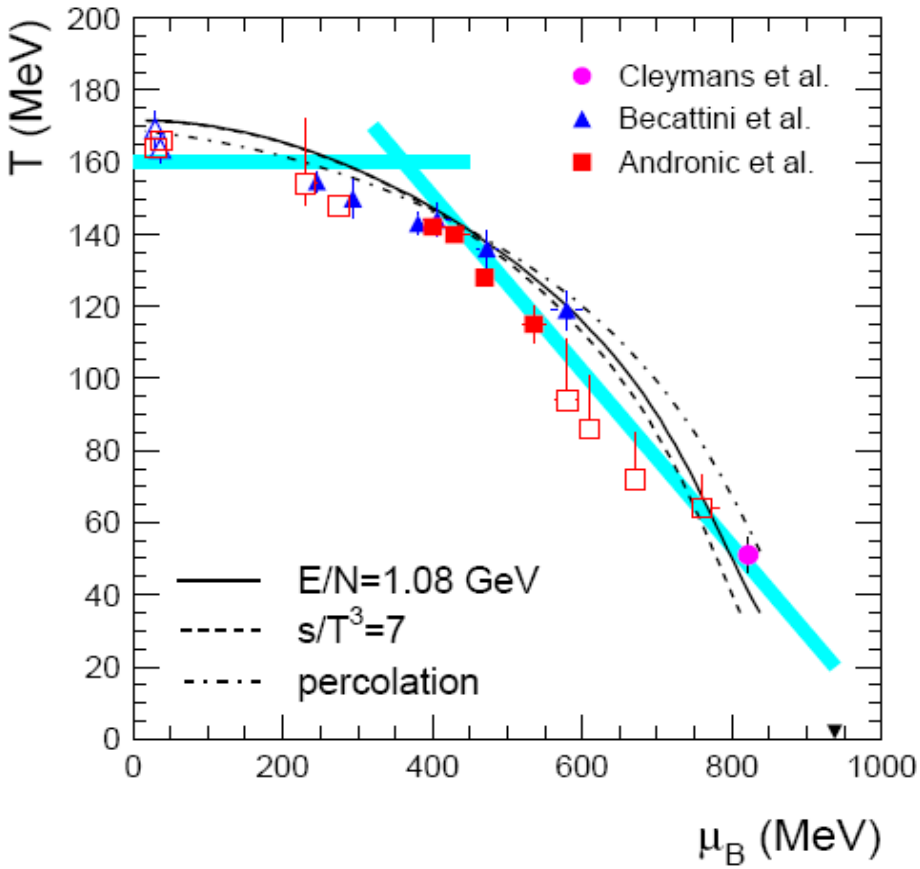


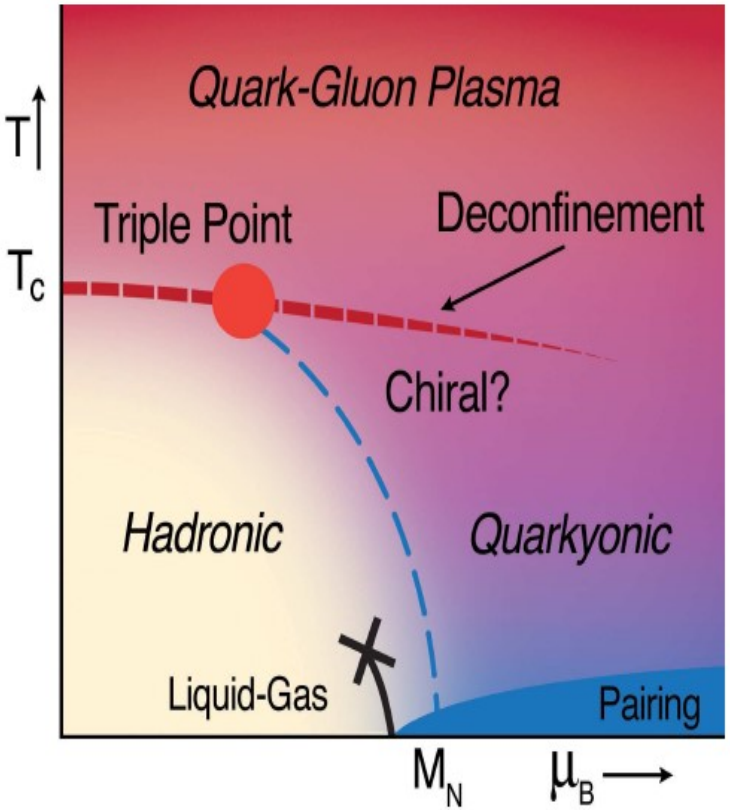
10 A GeV



Chemical Freeze-out phase diagram

A. Andronic et al., arXiv:0911.4806



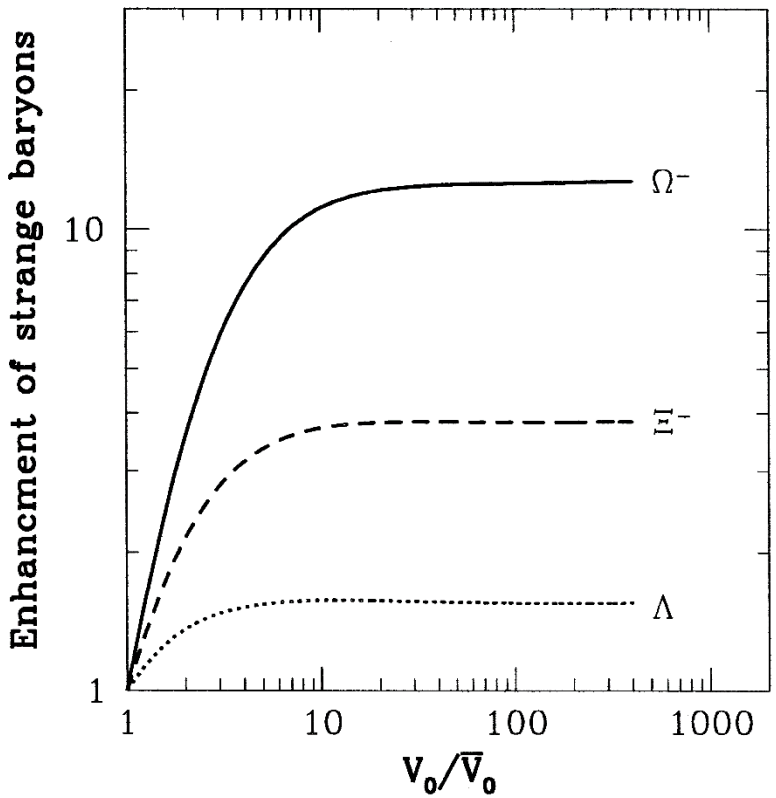


Speculation about the existence of a 1.order phase transition because of apparent thermal equilibrium.

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)

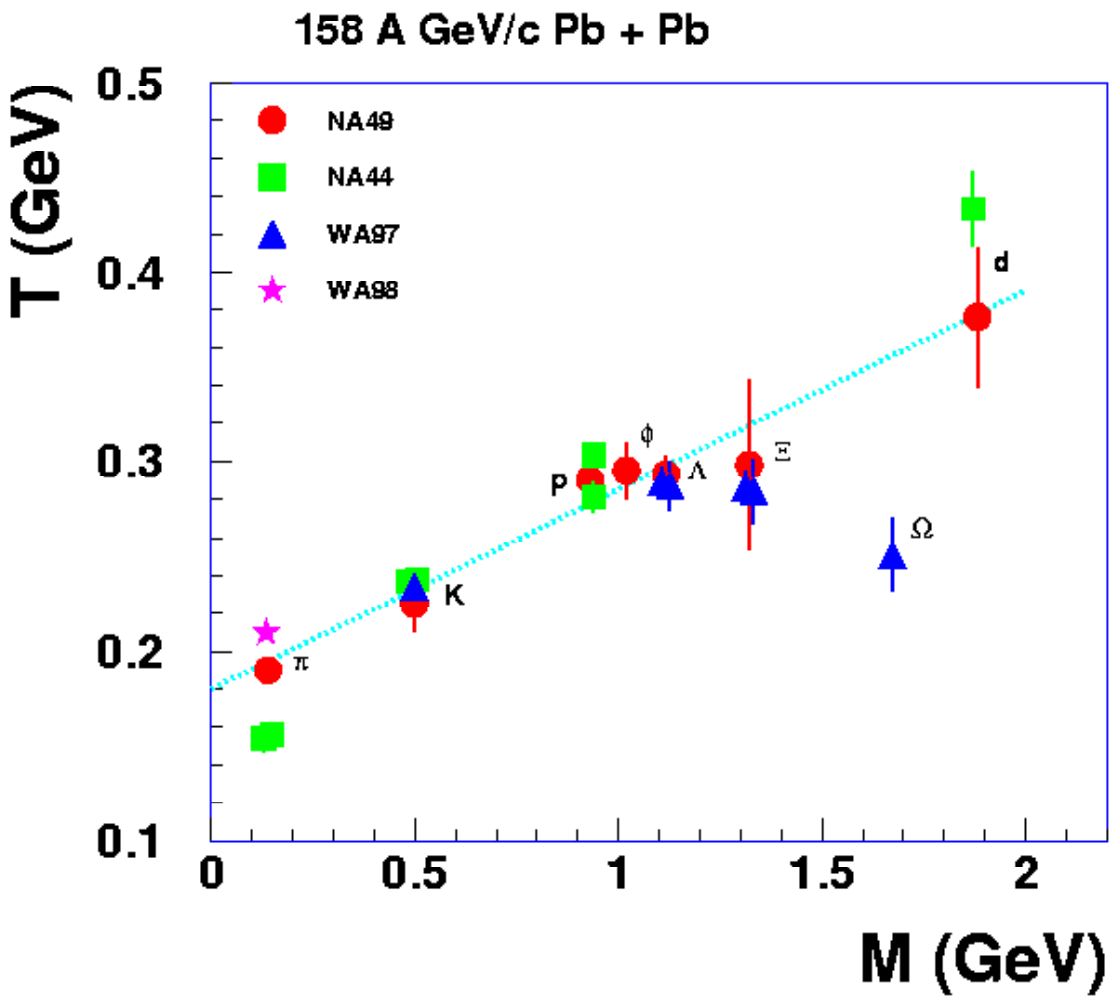
Result:
Particle numbers of strange particle in canonical (C) and grand canonical (GC) approach are related:

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

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

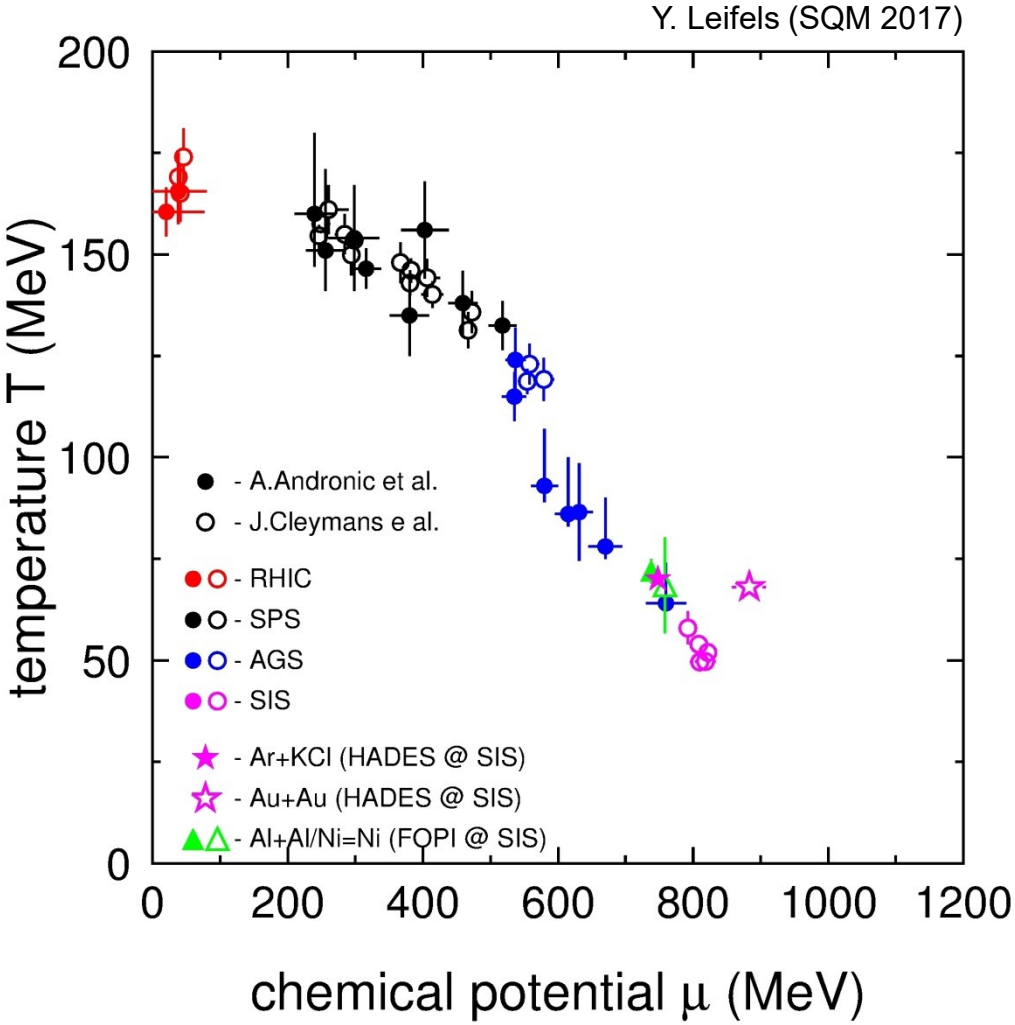
Conclusion: strangeness is in equilibium over the whole energy range !?
Needs consistency checks!

Transverse expansion



Slopes are proportional to mass except for multiple strange particles.

Collection of SHM freeze-out data



High energies:
grandcanonical ensemble

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

Equilibrium achieved in small systems?

Equilibrium as signature for phase transition?

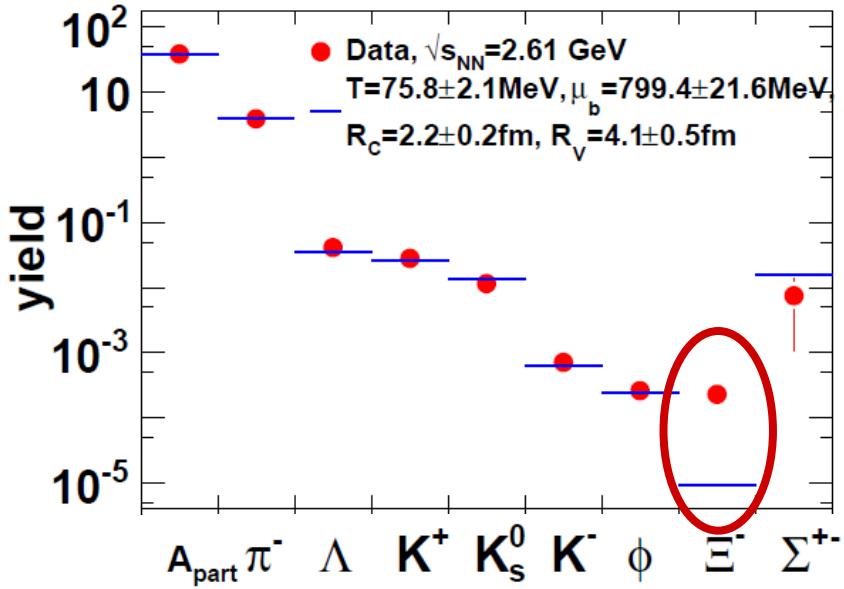
Freeze-out line at large baryon densities
as phase boundary to quarkyonic matter ?

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

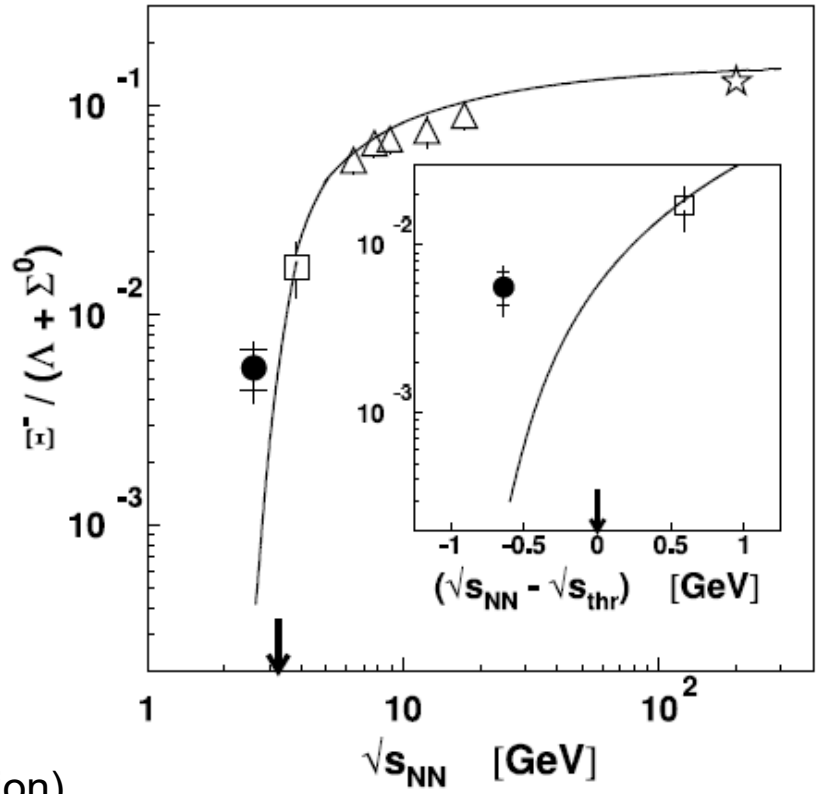
HADES: Sub-threshold Ξ^- - production

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)



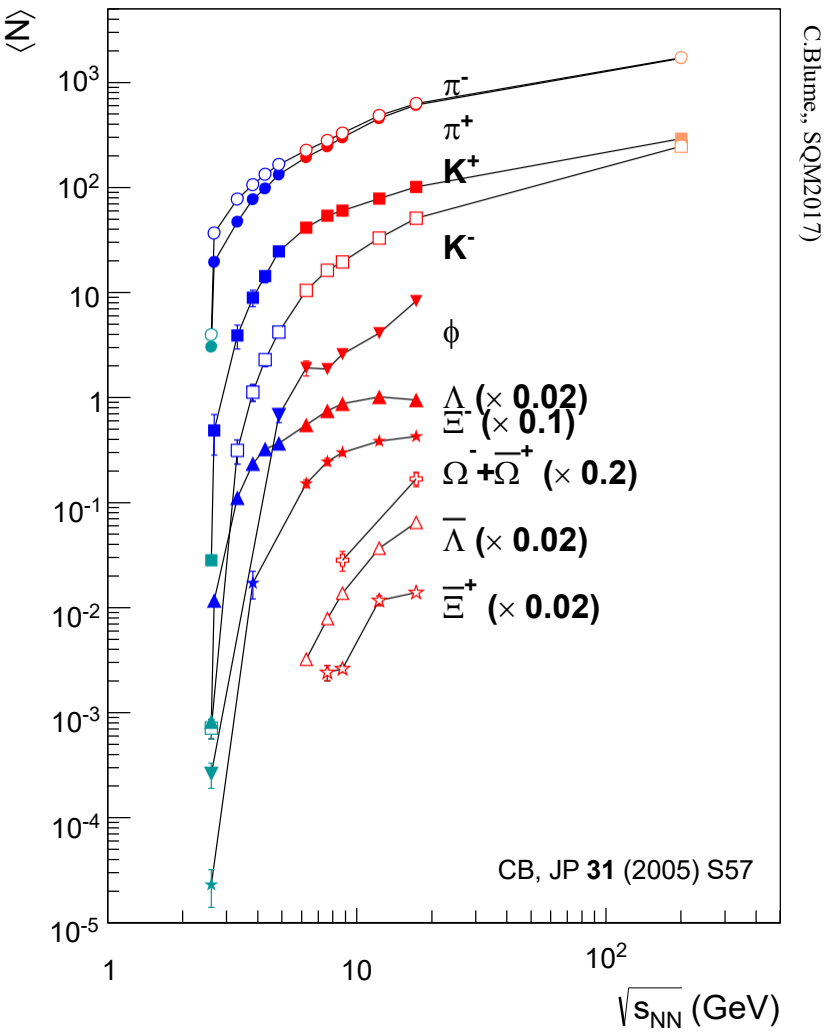
Enhancement factor: ∞ (deep subthreshold production)

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

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

Final state particle abundance

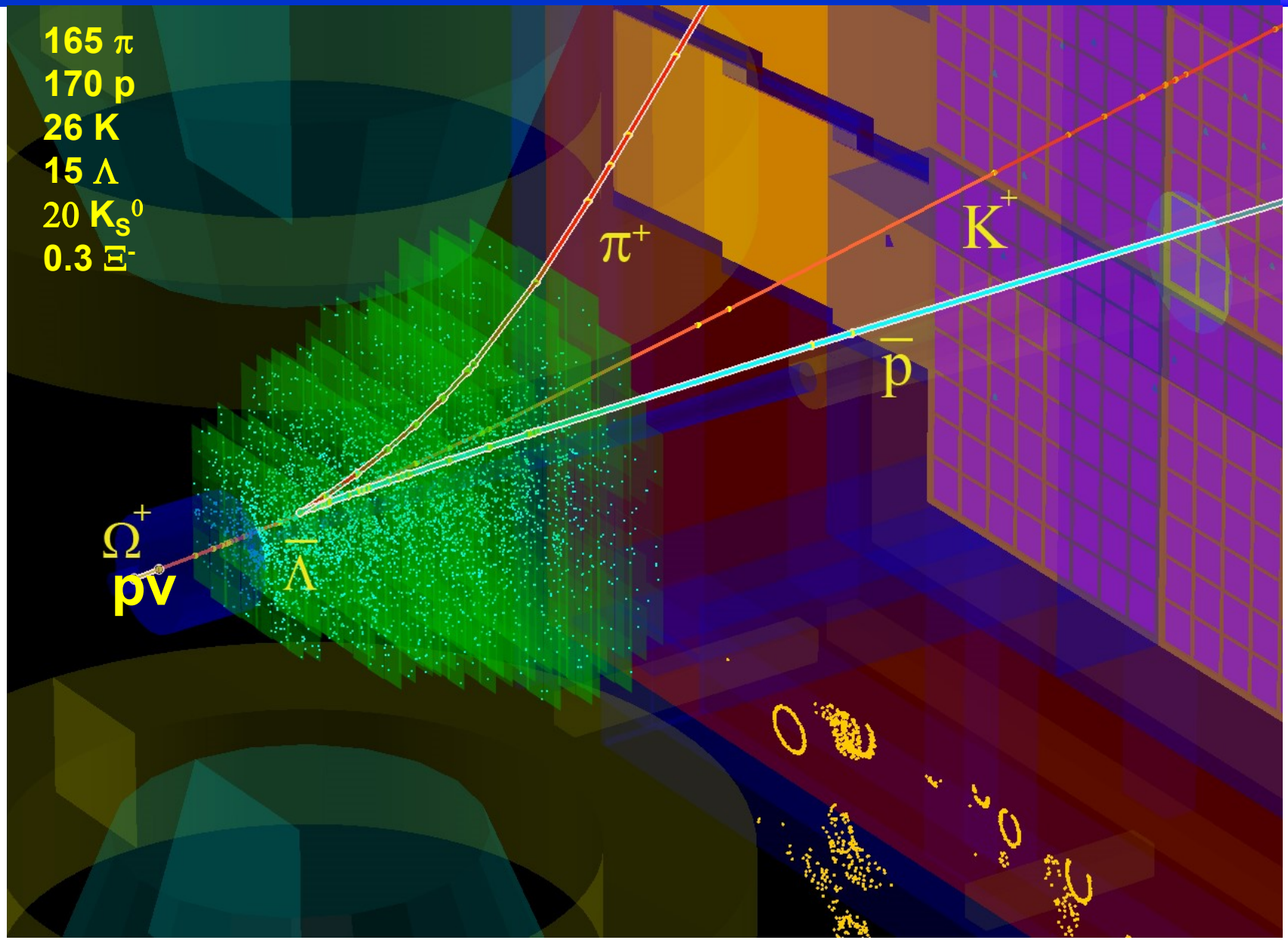
Particle yields from central Au + Au collisions



Strange and charmed particle production thresholds in pp - collisions

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

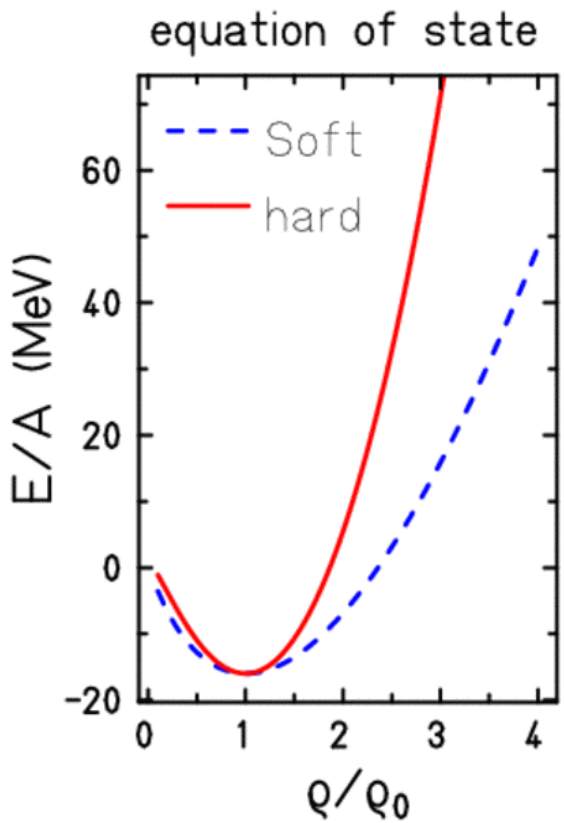
Subthreshold Kaon Production as a Probe of the Nuclear Equation of State

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.

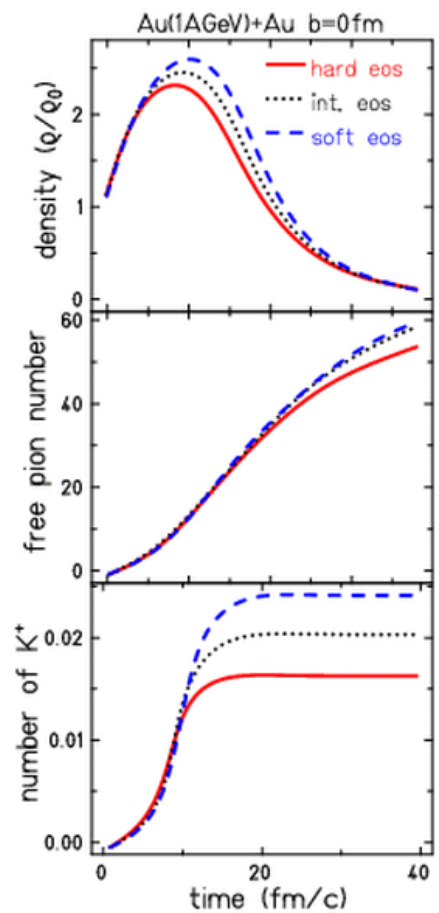


Transport model (IQMD) →

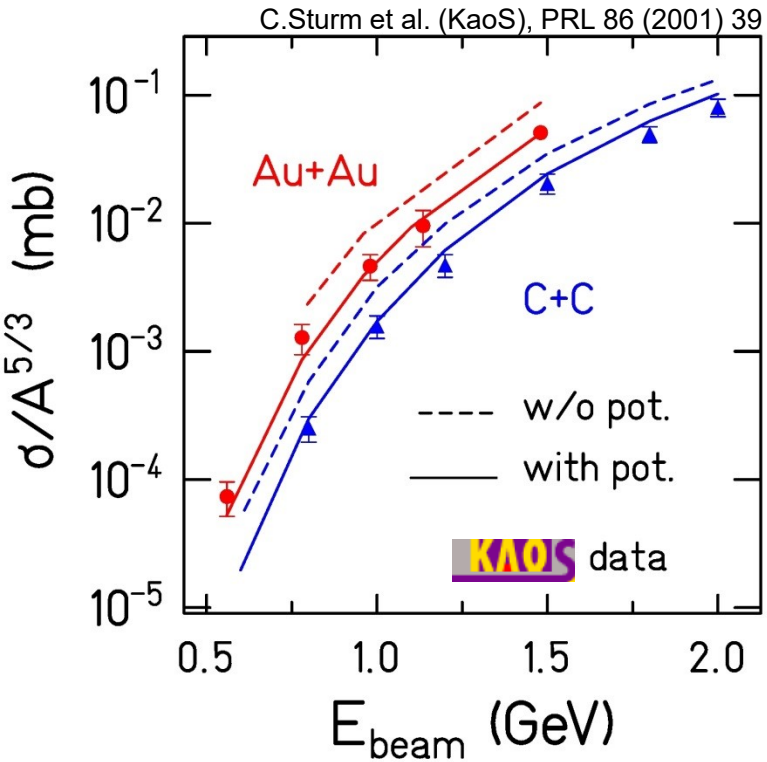
Softer EOS
⇒ larger densities
⇒ stronger resonance population
⇒ more NΔ collisions
⇒ more collisions above production threshold:

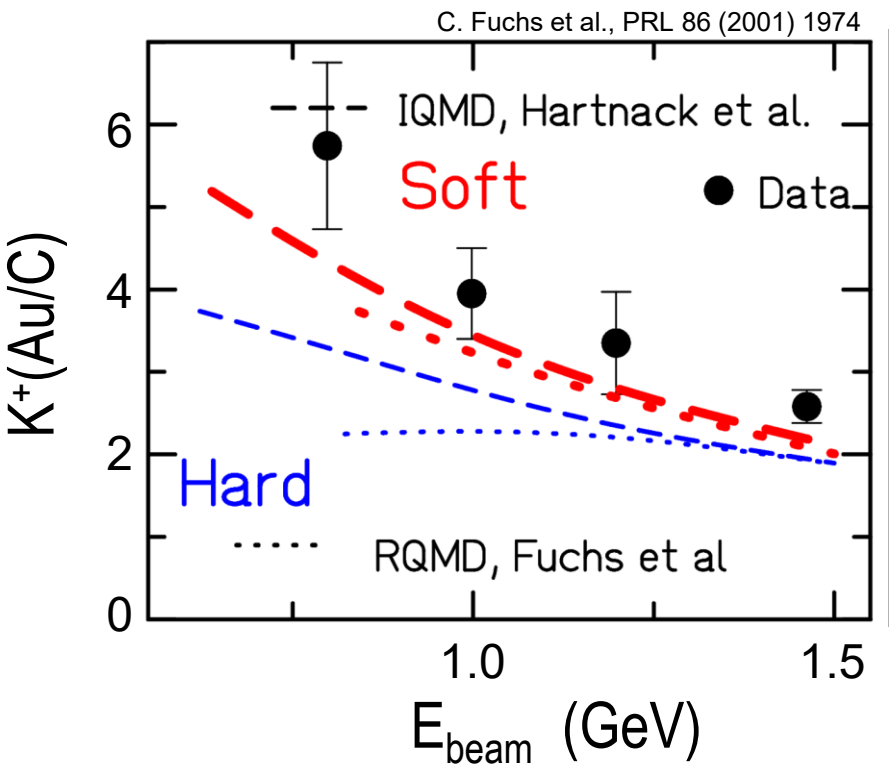
$N\Delta \rightarrow NK\Lambda$
$\Delta\Delta \rightarrow NK\Lambda$
(associated production)

C. Hartnack (IQMD)



Kaon production



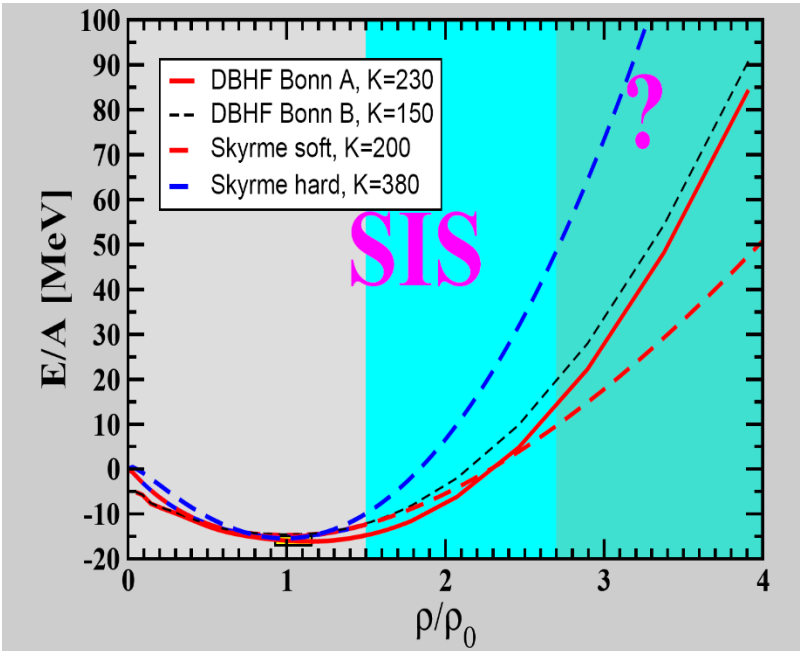


Sub-threshold kaon production

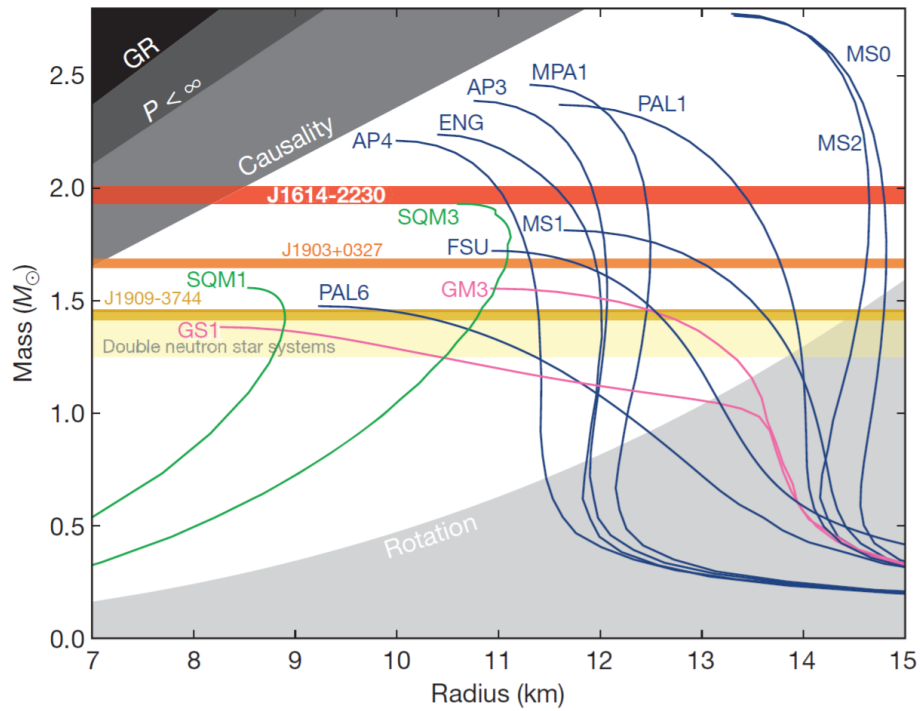
- multi-step processes, using resonances/pions as intermediate energy storage
  - strongly dependent on density
- sensitive to the stiffness of the nuclear matter equation of state
- EOS is soft up to densities $\varrho \leq 2.5\ \varrho_0$

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.

Chiral symmetry of QCD

Decomposition of states (spinors) $\psi = \psi_R + \psi_L = \frac{1}{2}\left(1+\gamma^5\right)\psi + \frac{1}{2}\left(1-\gamma^5\right)\psi$

Decomposition of currents:

$$\begin{aligned} j = \overline{\psi}\gamma^\mu\psi &= \left(\overline{\psi}_R + \overline{\psi}_L\right)\gamma^\mu\left(\psi_R + \psi_L\right) \\ &= \left(\overline{\psi}_R\gamma^\mu\psi_R + \overline{\psi}_R\gamma^\mu\psi_L + \overline{\psi}_L\gamma^\mu\psi_R + \overline{\psi}_L\gamma^\mu\psi_L\right) \\ &= \left(\overline{\psi}_R\gamma^\mu\psi_R + \overline{\psi}_L\gamma^\mu\psi_L\right) \end{aligned}$$

u,d,s – quarks are massless on QCD – scale (1 GeV).

Consequences for QCD with massless quarks:

Dirac equation: $\left(i\gamma^\mu\partial_\mu - m \right)\psi = 0 \rightarrow i\gamma^\mu\partial_\mu\psi = 0$

Interaction with vector field conserves chirality (→ QED):

$$i\gamma^\mu D_\mu\psi_L = 0$$

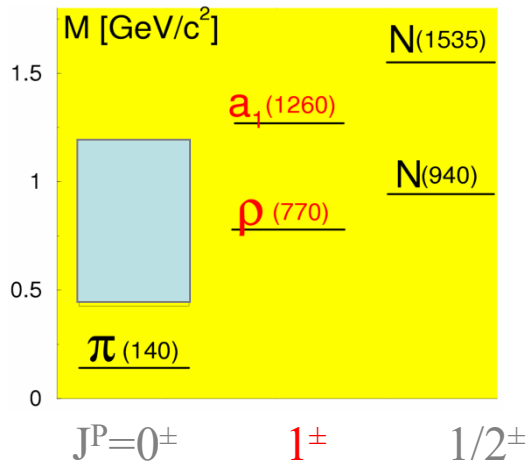
$$i\gamma^\mu D_\mu\psi_R = 0$$

L and R handed states do not interact.

New Symmetry group: $SU(3)_L \times SU(3)_R$

Current quark mass breaks this symmetry explicitely.

Chiral symmetry breaking in QCD



Exact chiral symmetry:

all hadrons should exist in 2 degenerate parity states!

Parity operator P = γ^0:

$$P|q_R> = |q_L>$$

$$P|q_L> = |q_R>$$

Construct: $$|\psi_\pm> = \frac{1}{\sqrt{2}}\left(|q_R> \pm |q_L>\right)$$

$$P|\psi_+> = +|\psi_+>$$

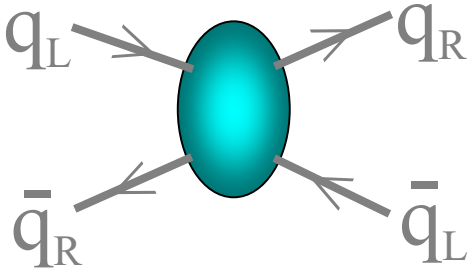
$$P|\psi_-> = -|\psi_->$$

These 2 states should have the same mass.
This feature is not observed in nature,
mass difference between chiral partners much larger than current quark mass differenc

$\Rightarrow$chiral symmetry is spontaneously broken.

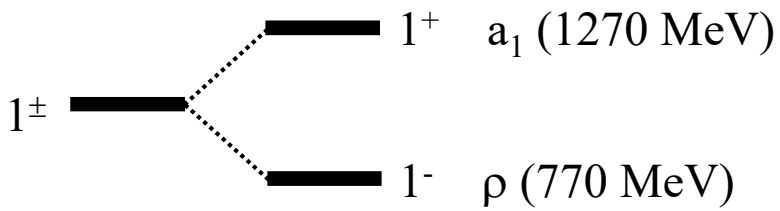
Chiral condensate fills QCD vacuum:

$$\langle \bar{q}q \rangle = \langle \bar{q}_L q_R + \bar{q}_R q_L \rangle \neq 0$$



Consequences of Spontaneous Chiral Symmetry Breaking

1) All hadrons have well defined parity,
chiral J^P doublets not observed.



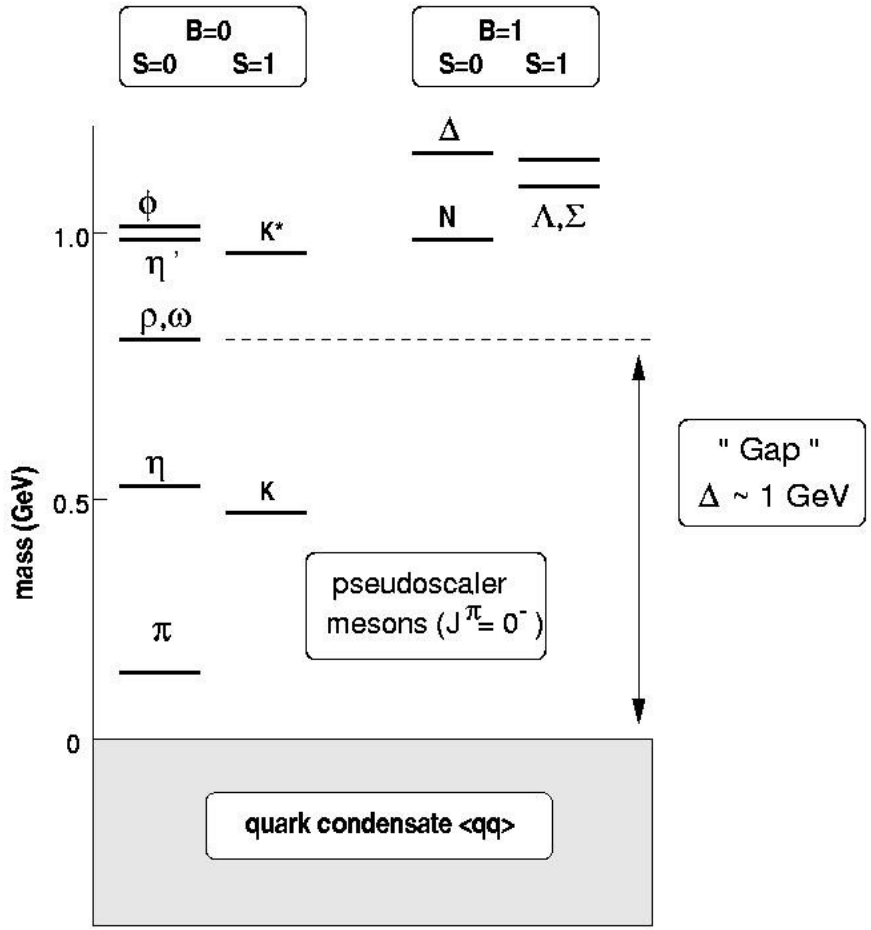
2) Chiral symmetry spontaneously broken,
vacuum is filled with qq – condensate.

3) Goldstone theorem:
Any spontaneously broken continous symmetry generates a massless boson (→ Goldstone bosons).

4) Characteristic mass scale of hadrons

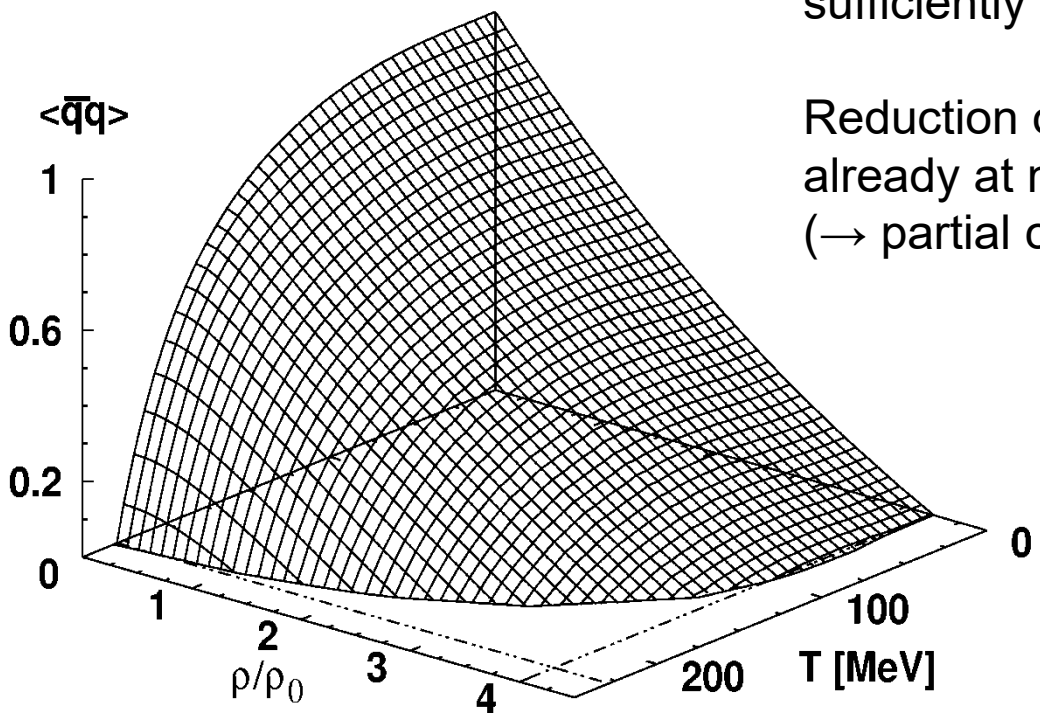
1 GeV mass gap to quark condensate

except pseudoscalar mesons that are the Goldstone bosons:
π, η, and K



Chiral symmetry restoration of QCD

Chiral Condensate



W.Weise, Prog. Theor. Phys. Suppl. 149 (2003) 1

initially: S.Klimt et al.., PLB 249, 386 (1990)

f_π, f_K – pion,kaon weak decay constants.

Chiral symmetry should be restored at sufficiently high temperatures and baryon densities.

Reduction of vacuum value should be visible already at moderate densities
(→ partial chiral symmetry restoration)

Symmetry breaking pattern of Chiral Symmetry of QCD

Gell-Mann-Oaks-Renner Relation:

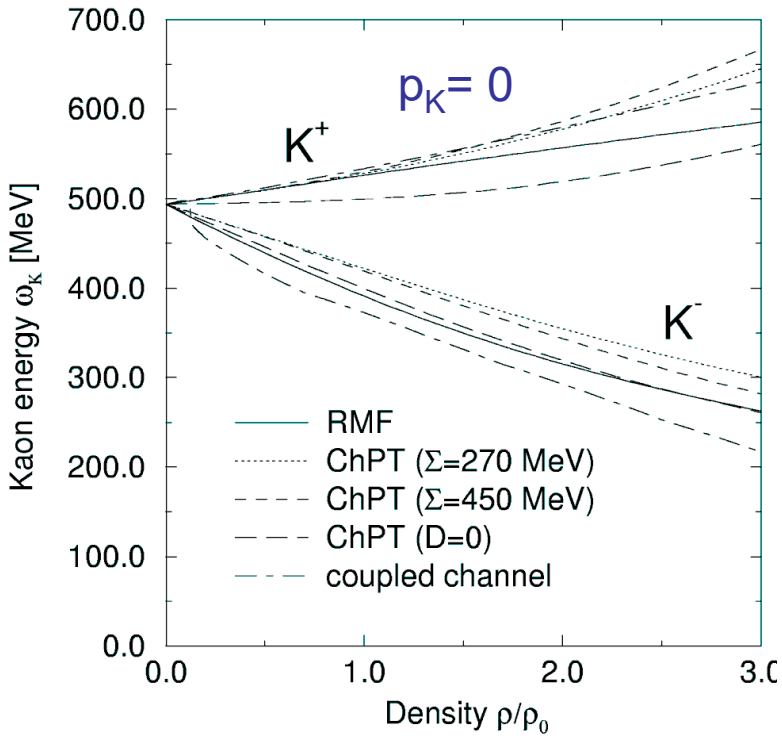
$$m_\pi^2 f_\pi^2 = -\frac{1}{2}(m_u + m_d)\langle \bar{u}u + \bar{d}d \rangle + O(m_u^2)$$

$$m_K^2 f_K^2 = -\frac{1}{2}(m_u + m_s)\langle \bar{u}u + \bar{s}s \rangle + O(m_s^2)$$

spontaneous symmetry breaking

explicit symmetry breaking

Kaon in-medium energy



D.B. Kaplan, A.E. Nelson,
Phys. Lett. B 175 (1986) 57

G.E Brown, C.H. Lee, M. Rho,
V. Thorsson,
Nucl. Phys. A 567 (1994) 937

T. Waas, N. Kaiser, W. Weise,
Phys. Lett. B 379 (1996) 34

J. Schaffner-Bielich,
J. Bondorf, I. Mishustin ,
Nucl. Phys. A 625 (1997) 325

G.Mao et al.,
Phys.Rev. C59 (1999) 3381

Note: In – medium energy at vanishing momentum is an effective mass.
Effective meson masses modified due to the presence of the baryonic medium.

Kaon in-medium energy:

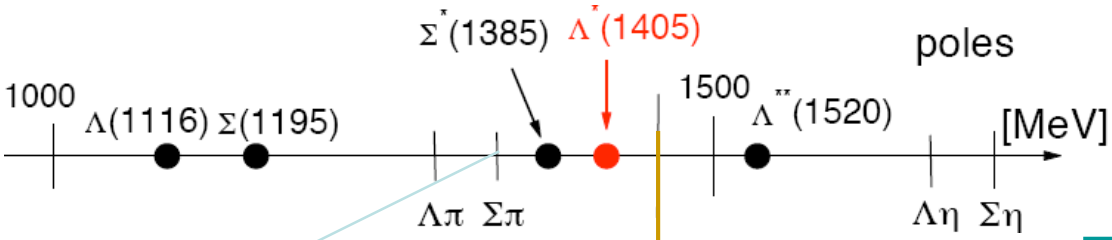
$$\omega_{K^\pm}(\vec{p},\rho_N) = \left(m_K^{*2} + \vec{p}^{\,2}\right)^{\frac{1}{2}} = U_S \pm U_V + \left(m_K^2 + \vec{p}^{\,2}\right)^{\frac{1}{2}}$$

in mean field approx.:

$$\omega_{K^\pm}(\vec{p},\rho_B) = \left(m_K^2 + \vec{p}^{\,2} - \frac{\Sigma_{KN}}{f_K^2}\rho_s + \left(\frac{3}{8}\frac{\rho_B}{f_K^2}\right)^2\right)^{\frac{1}{2}} \pm \frac{3}{8}\frac{\rho_B}{f_K^2}$$

scalar vector (baryon) density

$\bar{K}N$ – interaction



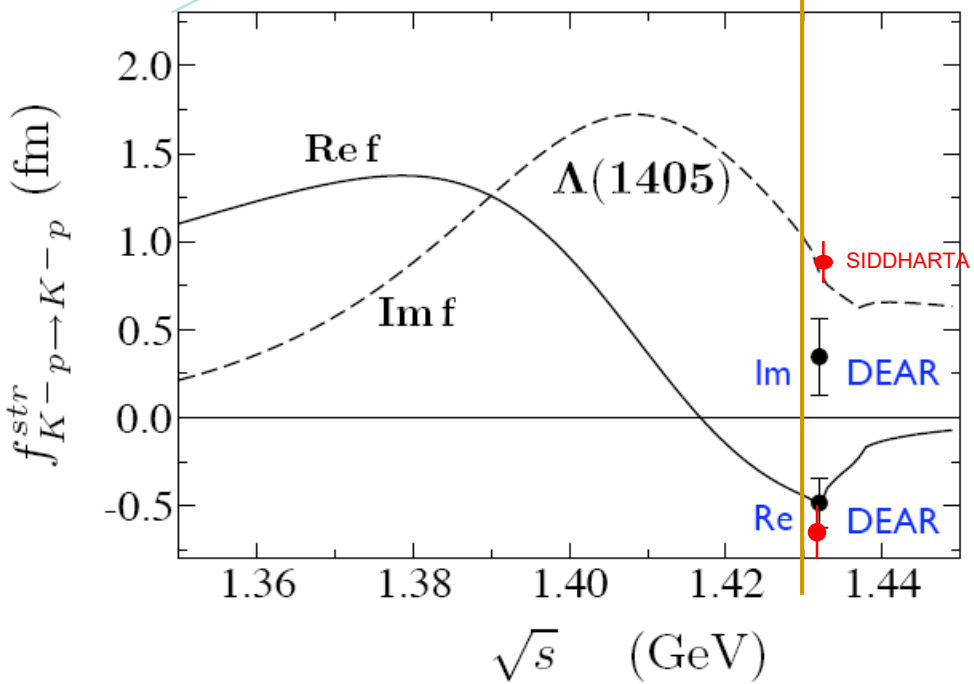
$$\sqrt{s} = \omega + m_N$$

$\bar{K}$ – energy

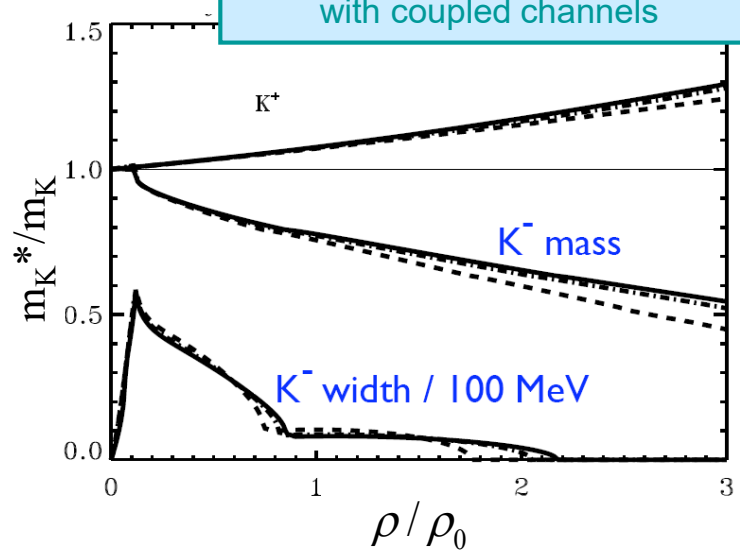
$\bar{K}N$ – threshold

due to presence of resonances
↓
non – perturbative problem
↓
chiral SU(3) effective field theory with coupled channels

Scattering amplitude f



W.Weise et al.: PLB 379, 34 (1996), PRL 94, 213401 (2005)



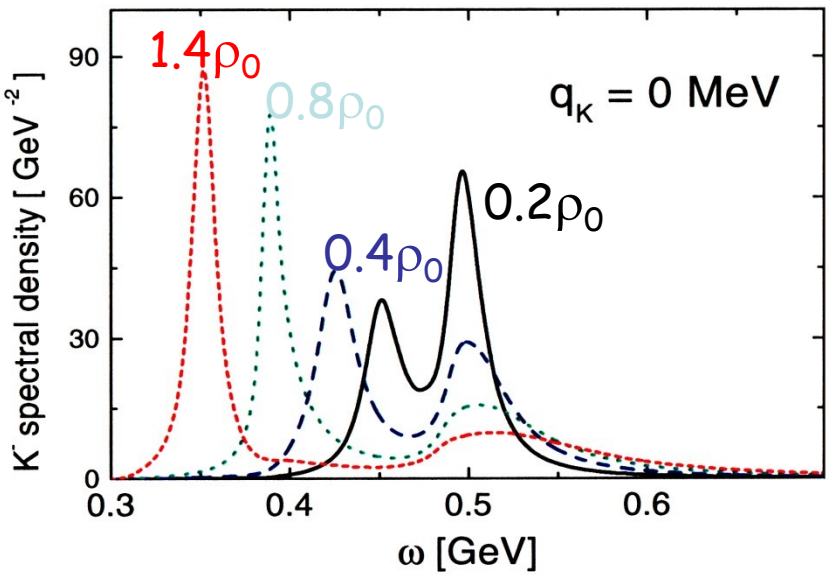
$\bar{K}N$ – interaction is attractive at finite densities, but strength (depth of potential) is unclear

Experimental signatures: flow of kaons
bound baryonic states, resonances

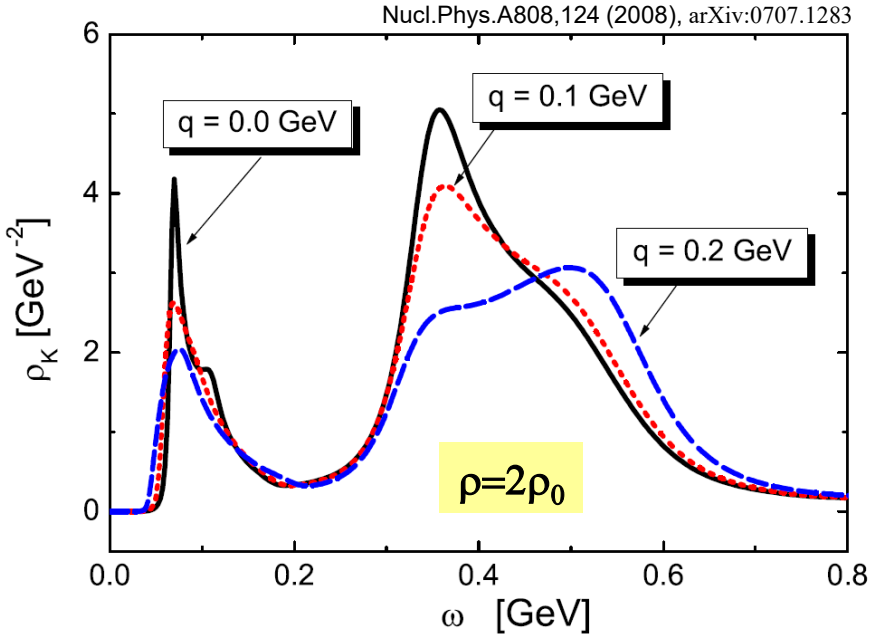
Antikaons in hadronic matter

spectral function of antikaons in dense matter

Coupled channel calculation
M.F.M. Lutz, Phys. Lett. B426 (1998) 12



M.F.M. Lutz et al.,
Nucl.Phys.A808,124 (2008), arXiv:0707.1283



$$\omega_{K^\pm}(p,\rho) = \left(m^{*2} + p^2\right)^{\frac{1}{2}} = U + \left(m_K^2 + p^2\right)^{\frac{1}{2}}$$

effective mass **Kaon potential**

~~**Production:**~~
~~**P ~ exp (-m*/T)**~~
~~**→ K-yields**~~

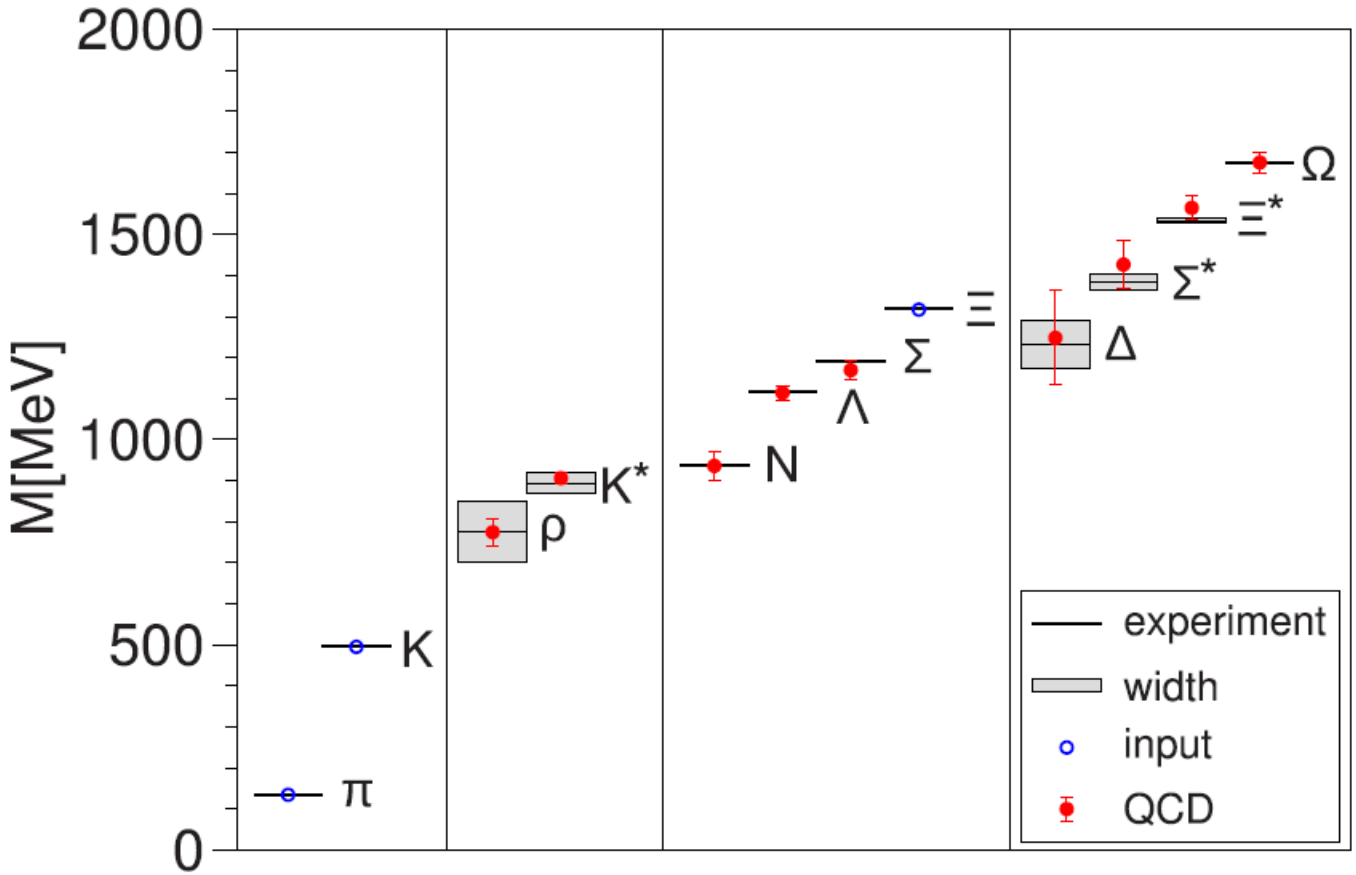
Propagation:
F=-∇U
→ K-flow

Bound states:
B = $\Sigma_i m_i - \Sigma_i m_i^*$
→ Search for Λ+X states

Hadron masses from LQCD

S. Dürr et al., Science 322, 1224 (2008)
Ab Initio Determination of Light Hadron Masses

Fig. 3. The light hadron spectrum of QCD. Horizontal lines and bands are the experimental values with their decay widths. Our results are shown by solid circles. Vertical error bars represent our combined statistical (SEM) and systematic error estimates. π, K, and Ξ have no error bars, because they are used to set the light quark mass, the strange quark mass and the overall scale, respectively.



Differential flow

Measurement of phase space distributions and differential flow offers additional information on

Equation – of – State (EOS)

In – medium modifications of hadron masses (CSR)

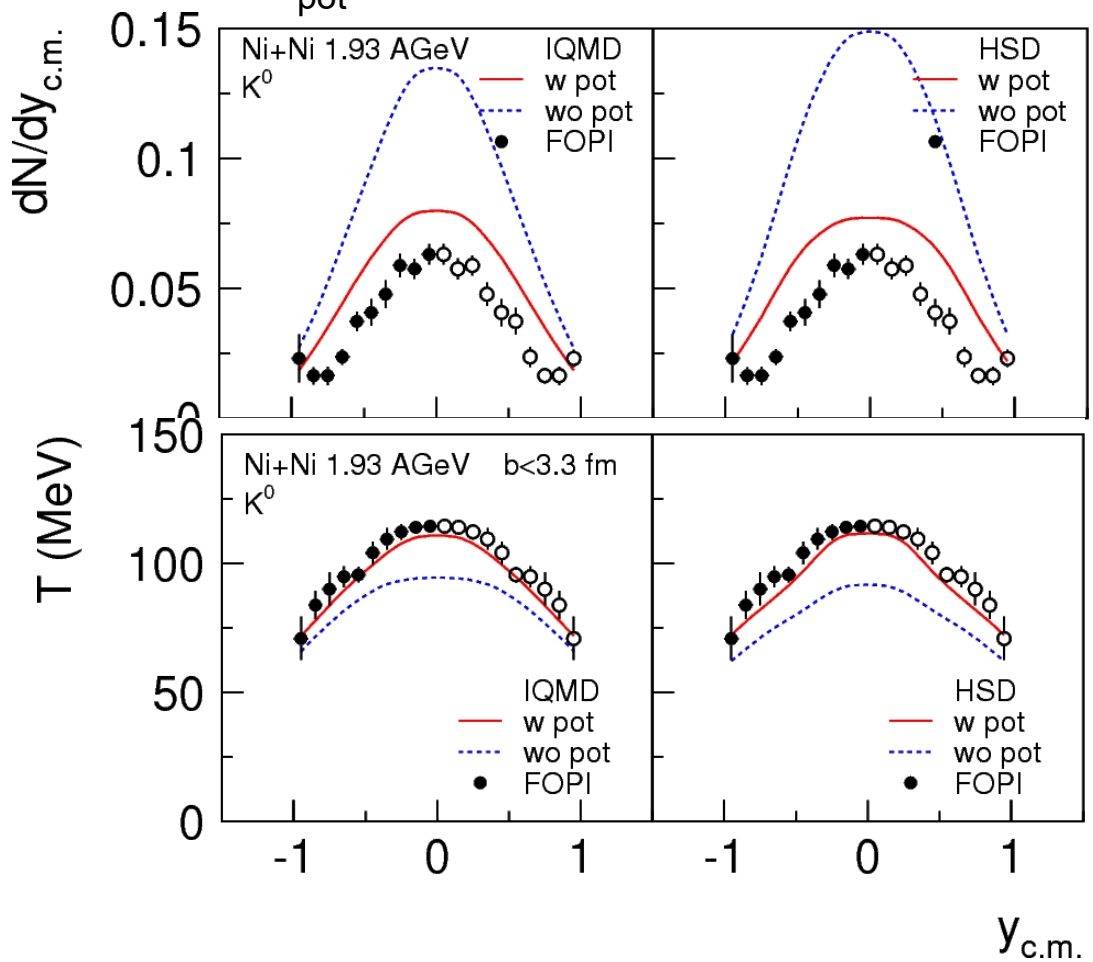
Large data samples required for rare probes (e.g. K^- at SIS18 energies).

Comparison to transport model calculation necessary.
Model dependence needs to be controlled.

FOPI Ni+Ni data

C. Hartnack, H. Oeschler, Y. Leifels, E.L. Bratkovskaya, J. Aichelin, Phys.Rept. 510 (2012) 119-200
Y. Leifels, 2016

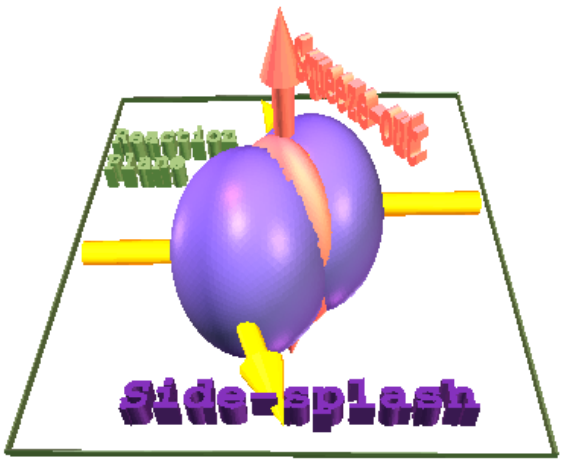
KN U_{pot} = 40 MeV both IQMD and HSD



X. Lopez
M. Merschmeyer

All spectra, yields reasonably well described by HSD and IQMD

Fourier Expansion of Azimutal Distributions



Phase space distribution with respect to reaction plane Φ_R

$$\varphi' := \varphi - \Phi_R$$

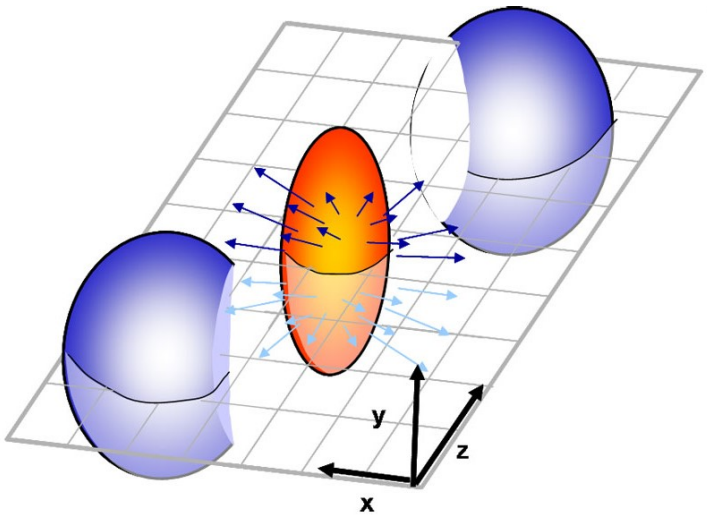
$$\frac{d^3N}{p_t dp_t dy d\varphi'} \propto (1 + 2v_1 \cos(\varphi') + 2v_2 \cos(2\varphi') + \ldots)$$

Fourier expansion coefficients

$$v_1 = \left\langle \frac{p_x}{p_t} \right\rangle$$ sideflow

$$v_2 = \left\langle \frac{p_x^2 - p_y^2}{p_x^2 + p_y^2} \right\rangle$$ elliptic flow

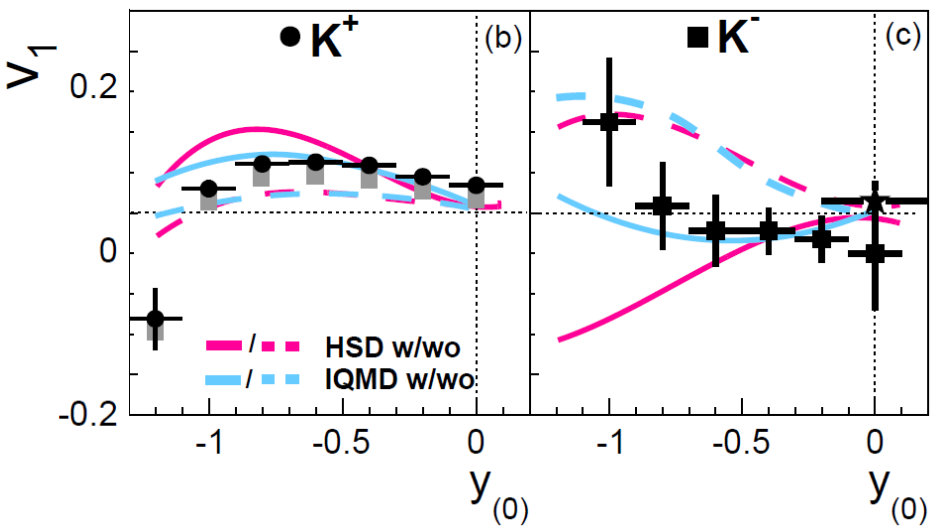
Transition energy: E_{beam} = 4A GeV

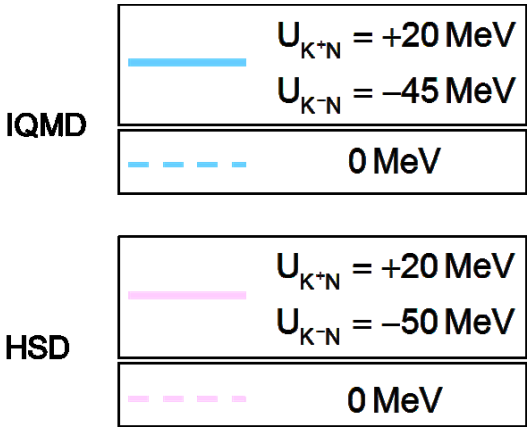


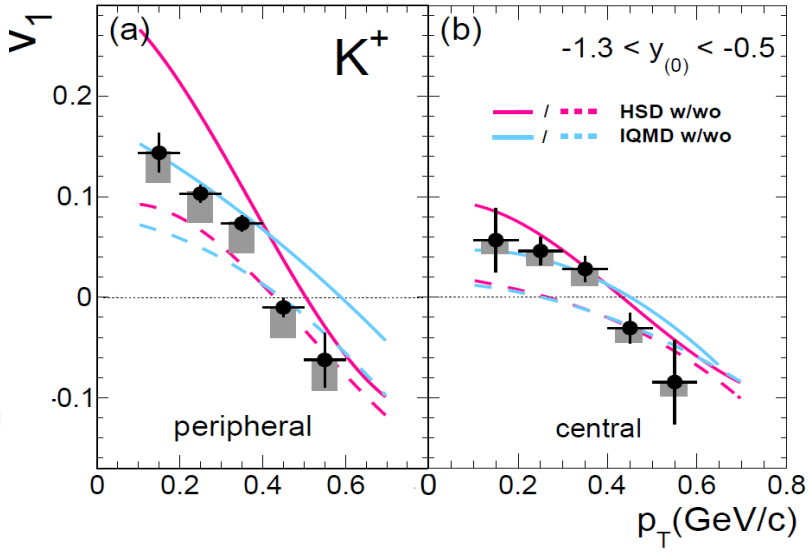
S. Voloshin, Y. Zhang, *hep-ph/9407082*
J.Y. Ollitrault, *nucl-ex/9711003*

Directed flow of Kaons in Ni+Ni at 1.91 AGeV

V. Zinyuk et al., PRC 90 (2014) 05210



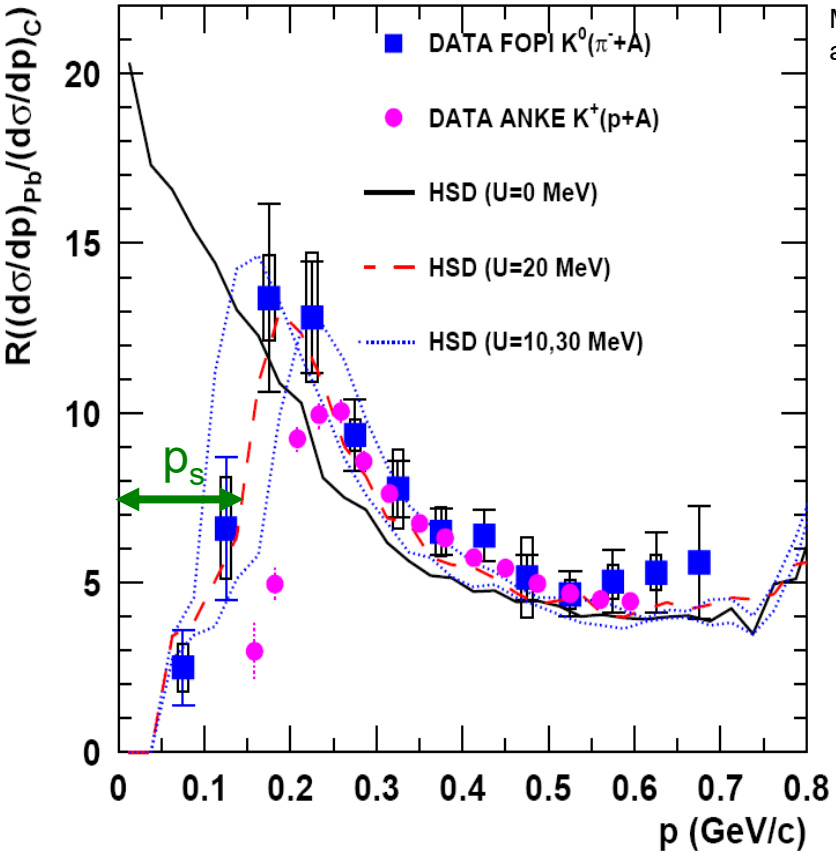




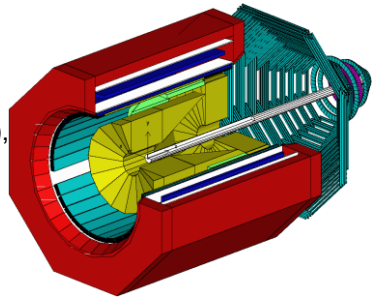
- K^- description in models
  - IQMD: quasi particle, chiral perturbation theory
  - HSD: off-shell, coupled channel G-Matrix approach
- moderate sensitivity to potential of K^+
- data for K^- slightly better described with potential
  - but large experimental error bars, need of more statistics
  - recent COSY results: $U_{K\text{-}N} \approx$ -60 MeV
    E. Paryev et al., arXiv: 1505.01992v1

K^0 – production in π^- + A reactions at 1.15 GeV/c

Ratio of momentum distributions:



M.L. Benabderramahne et al., PRL 102, 182501 (2009), arXiv:0807.3361



Anke data @ COSY

M. Büscher et al., *EPJ*, A22, 301 (2004)

$p + p \rightarrow K^+ + X$ at 2.5 GeV

Model comparison with HSD

(Hadron String Dynamics, W. Cassing, E. Bratkovskaya et al.)

$U(K^+) = +20$ MeV

Model independent analysis:

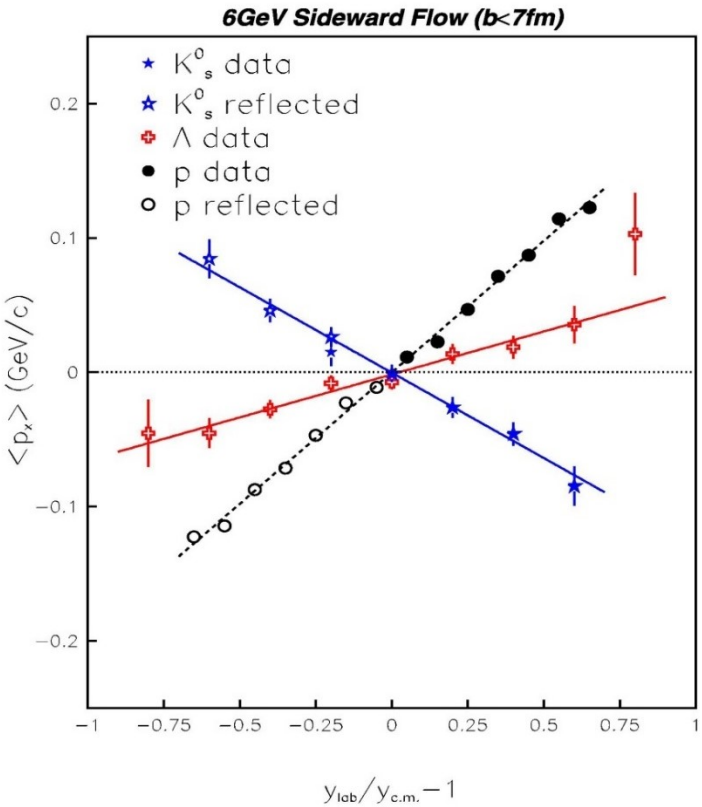
$$U_K = \frac{p_s^2}{2m_K} = \frac{(140\text{MeV})^2}{2 \cdot 498\text{MeV}} = 20\text{MeV}$$

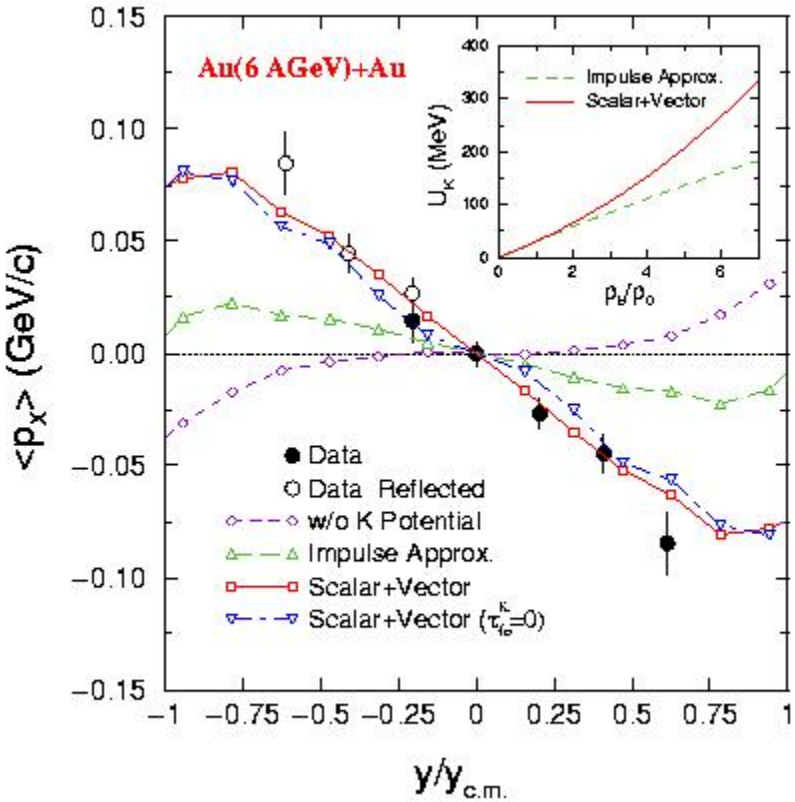
Neutral kaons in heavy nuclei are experiencing a repulsive potential.
Potential depth: $U(K^0) = +20$ (+/- 5) MeV (consistent with heavy-ion data on K^+)
Accuracy of measurement is (only) limited by statistics.

AGS: K^0 – flow

Data: P. Chung et al. (E895), PRL85, 940 (2000)

Theo: S. Pal et al., Phys.Rev.C62:061903, (2000)





Kaon flow as barometer in HI collisions?
Calibrate probe by systematic measurements

- centrality
- system size
- incident energy

How to get further?

Need for dynamical model that addresses the full set of problems

dynamics of heavy ion collisions
equilibration times
chiral symmetry restoration
deconfinement transition

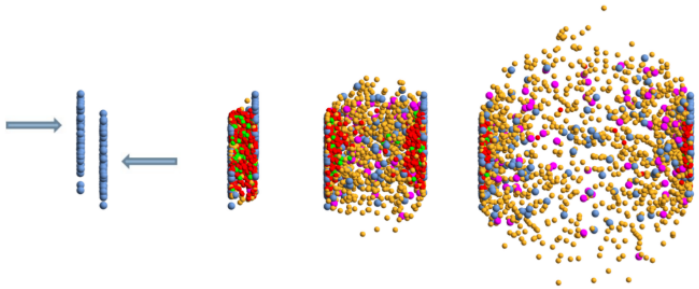
Parton Hadron String Dynamics?
https://fias.uni-frankfurt.de/~phsd-project/PHSD/index1.html

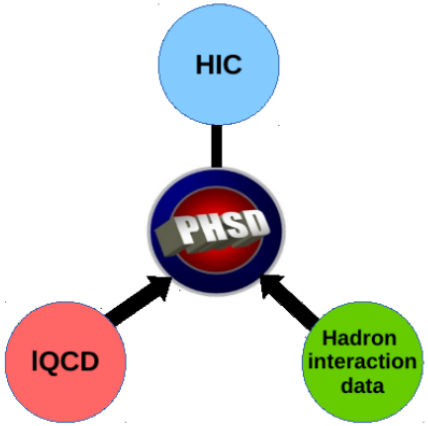
(see also talk of P. Moreau during last (29th) CBM student week)

PHSD advertisement

A. Palmese talk, Erice 2016, from PHSD page

- Dynamical many-body transport approach.
- Consistently describes the full time evolution in HIC.
- Explicit parton-parton interactions, explicit phase transition from hadronic to partonic degrees of freedom.





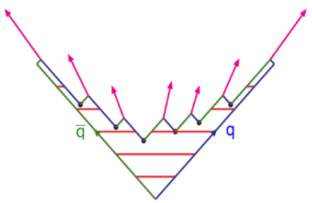
- Model applicable out of equilibrium and in agreement with the lattice results in equilibrium as well as with the nuclear physics input.
- Transport theory: off-shell transport equations in phase-space representation based on Kadanoff-Baym equations for the partonic and hadronic phase.

W.Cassing, E.Bratkovskaya, PRC 78 (2008) 034919; NPA831 (2009) 215; W.Cassing, EPJ ST 168 (2009) 3.

PHSD ingredients

A. Palmese talk, Erice 2016, from PHSD page

- **String formation** in primary NN Collisions.
- **String decays** to pre-hadrons (baryons and mesons).



- Formation of a **QGP state** if $\epsilon > \epsilon_C \approx 0.5\,\mathrm{GeVfm}^{-3}$.
- Dissolution of newly produced secondary hadrons into **massive colored quarks/antiquarks** and **mean-field energy** U_q:

$$B \to qqq\,(\bar{q}\bar{q}\bar{q}) \qquad M \to q\bar{q} \qquad + \quad U_q.$$

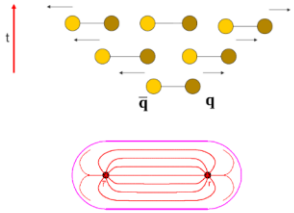
- **DQPM** defines the properties (masses and widths) of partons and mean-field potential at a given local energy density ϵ.
- **EoS**: crossover at $\mu_q = 0$ from Lattice QCD fitted by DQPM.

In PHSD the flavor chemistry of the final hadrons is mainly defined by the **LUND string model**.

According to the **Schwinger-formula**, the probability to form a massive $s\bar{s}$ pair in a string-decay is suppressed in comparison to light flavor pair ($u\bar{u}$, $d\bar{d}$):

$$\frac{P(s\bar{s})}{P(u\bar{u})} = \frac{P(s\bar{s})}{P(d\bar{d})} = \gamma_s = \exp\left(-\pi\frac{m_s^2 - m_{u,d}^2}{2\kappa}\right)$$

with $\kappa \approx 0.176\,\mathrm{GeV}^2$ and $m_{u,d,s}$ as constituent ('dressed') masses due to the coupling to the vacuum.



In **vacuum** (e.g. p+p collisions) the dressing of the bare quark masses follows:

$$m_q^V = m_q^0 - g_s\langle\bar{q}q\rangle_V,$$

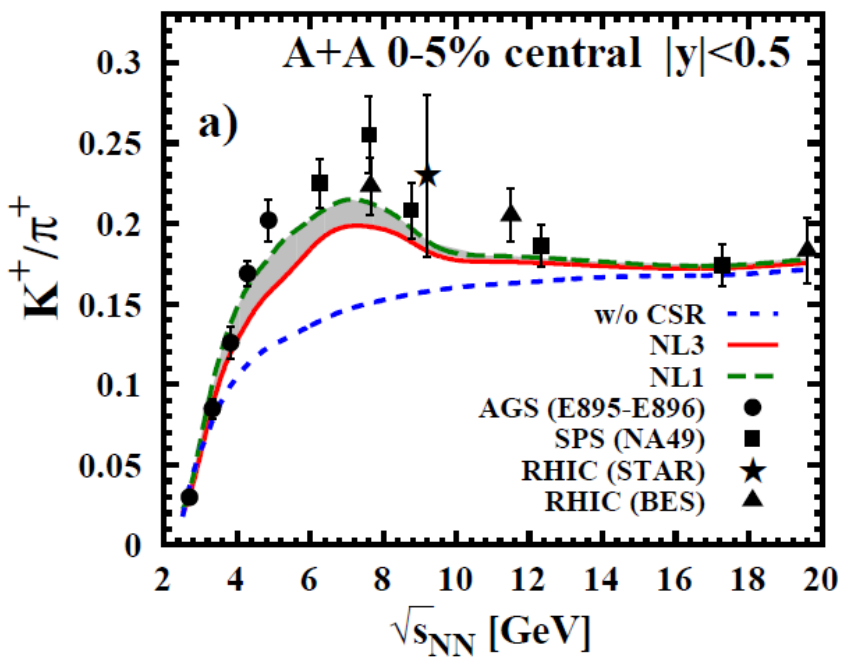
with $m_{u,d}^0 \approx 7\,\mathrm{MeV}$, $m_s^0 \approx 100\,\mathrm{MeV}$ and $\langle\bar{q}q\rangle_V \approx -3.2\,\mathrm{fm}^{-3}$.

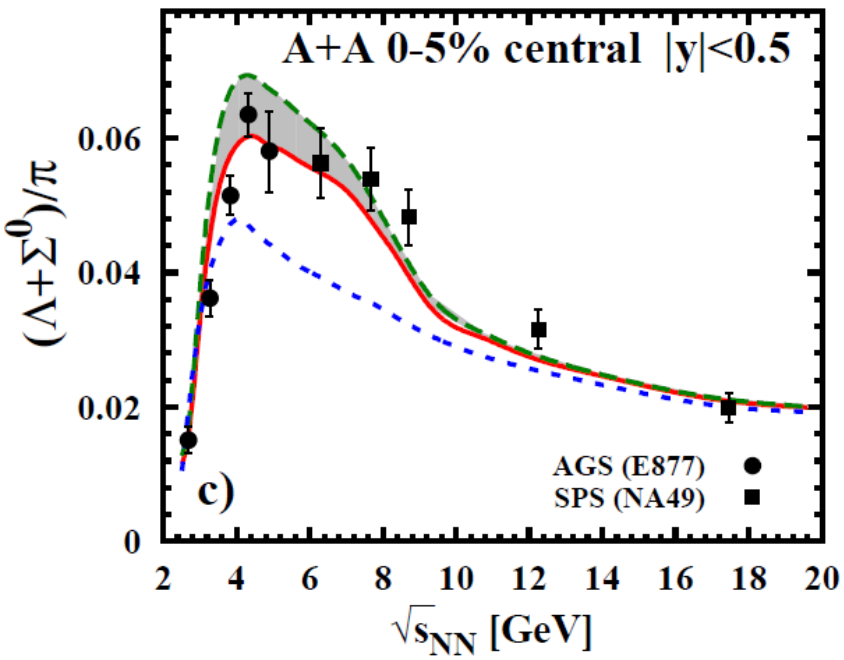
In **medium** (e.g. A+A collisions) the dressing of the bare quark masses follows:

$$m_q^* = m_q^0 - g_s\langle\bar{q}q\rangle,$$
$$= m_q^0 + (m_q^V - m_q^0)\frac{\langle\bar{q}q\rangle}{\langle\bar{q}q\rangle_V}.$$

PHSD view of strange particle yields

W. Cassing et al. Phys.Rev. C93 (2016) 014902
A. Palmese et al. Phys.Rev. C94 (2016) 044912



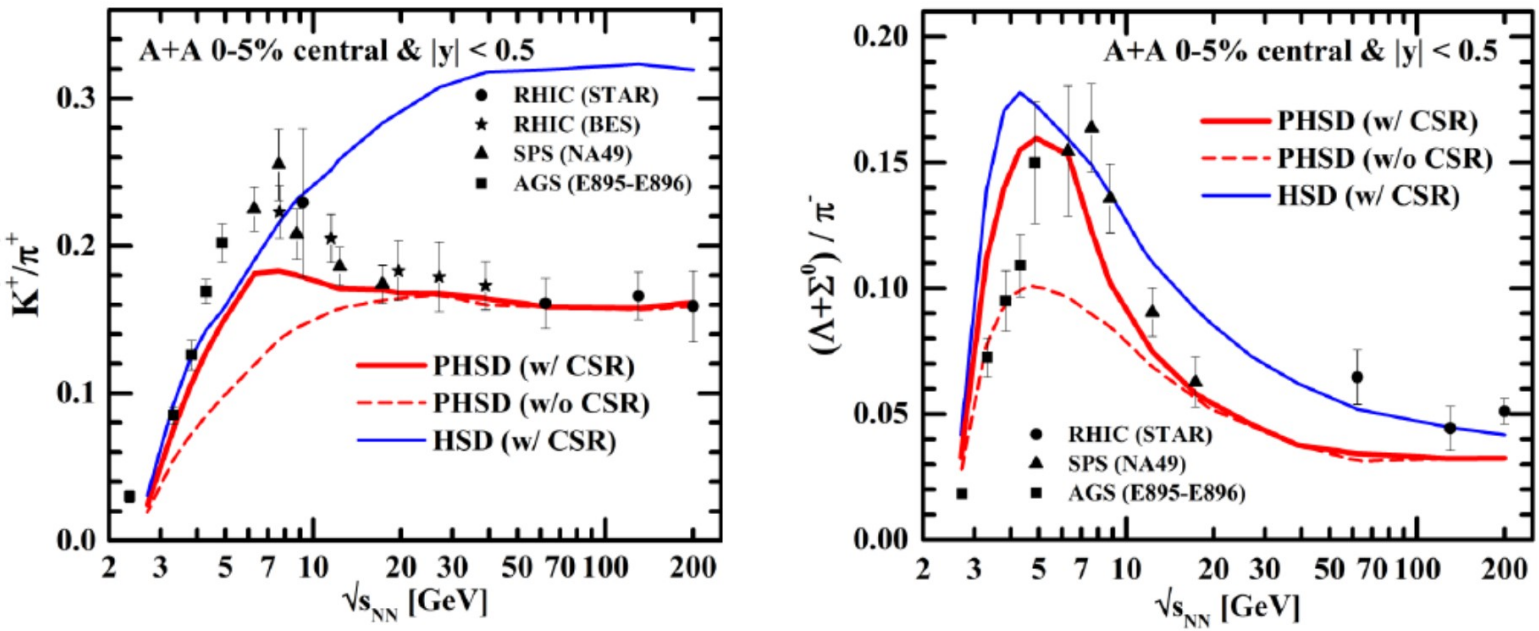


- Reproduction of „horn“ by Chiral Symmetry Restoration (CSR) in hadronic system
- Yield ratio weakly sensitive to EOS (NL1, NL3)

Origin of the „horn“ in PQCD

A. Palmese talk, Erice 2016

We observe a rise in the ratio K^+/π^+ at low $\sqrt{s_{NN}}$ related to **Chiral Symmetry Restoration (CSR)** and then a drop due to the appearance of a **deconfined partonic medium**. ➜ A **"horn"**-structure emerges.

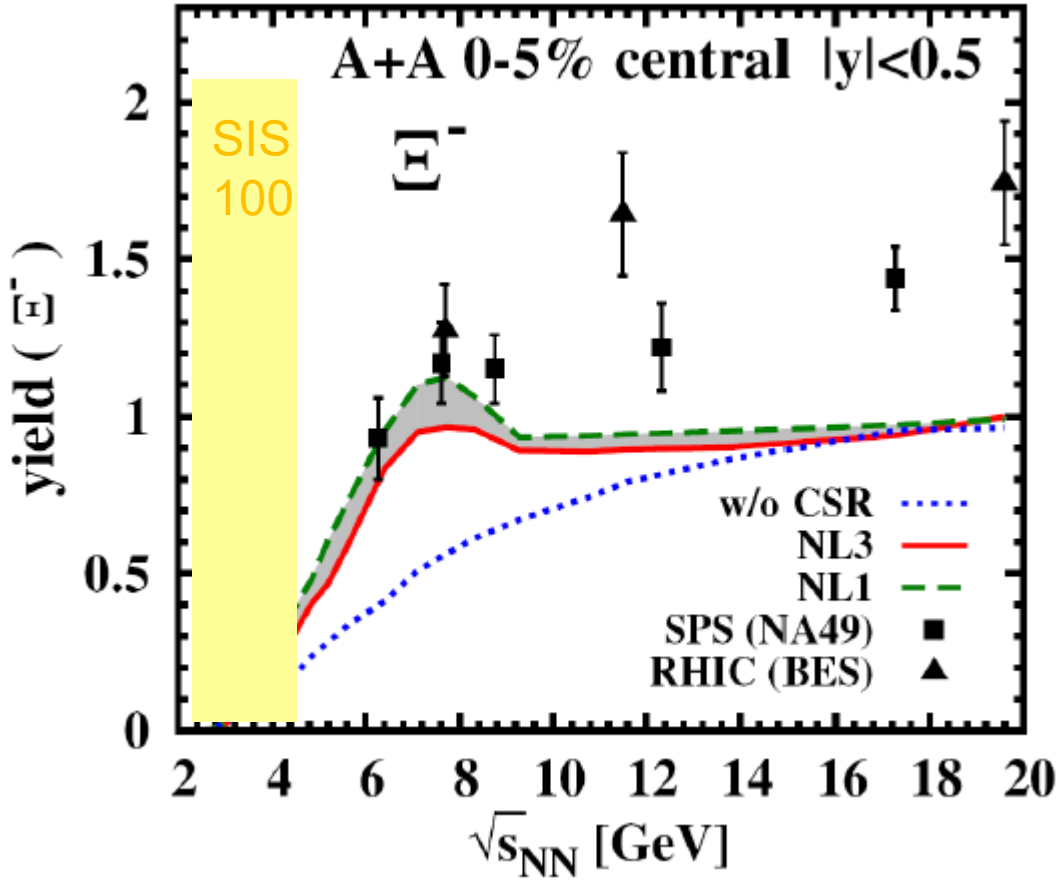


W. Cassing, A. P., P. Moreau, E.L. Bratkovskaya, Phys. Rev. C93 (2016) 014902.

Hyperons as probes of dense matter

PHSD interpretation of Ξ^- -production

A. Palmese et al. Phys.Rev. C94 (2016) 044912



Predicted sensitivities of production yields:

strong dependence on Chiral Symmetry Restoration (CSR)

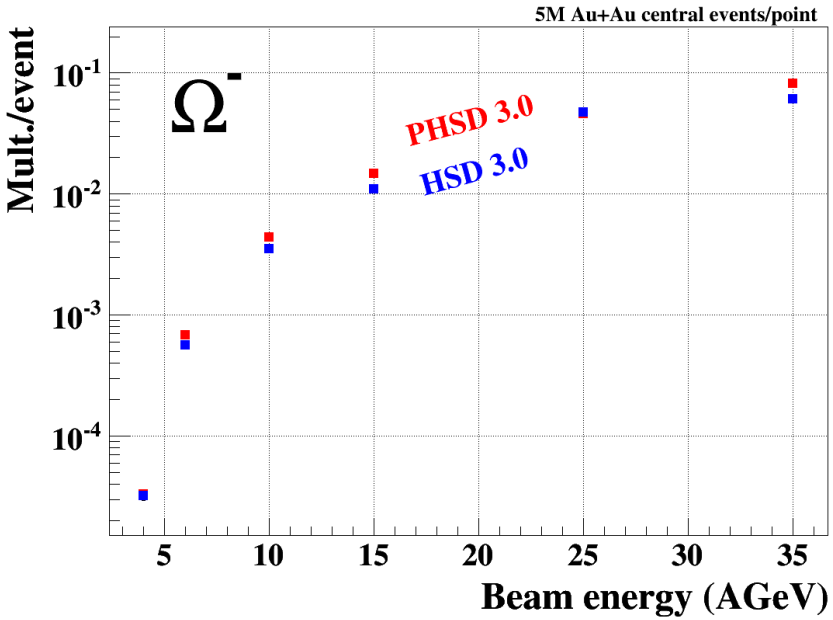
Measurable dependence on Equation of State (NL1, NL3)

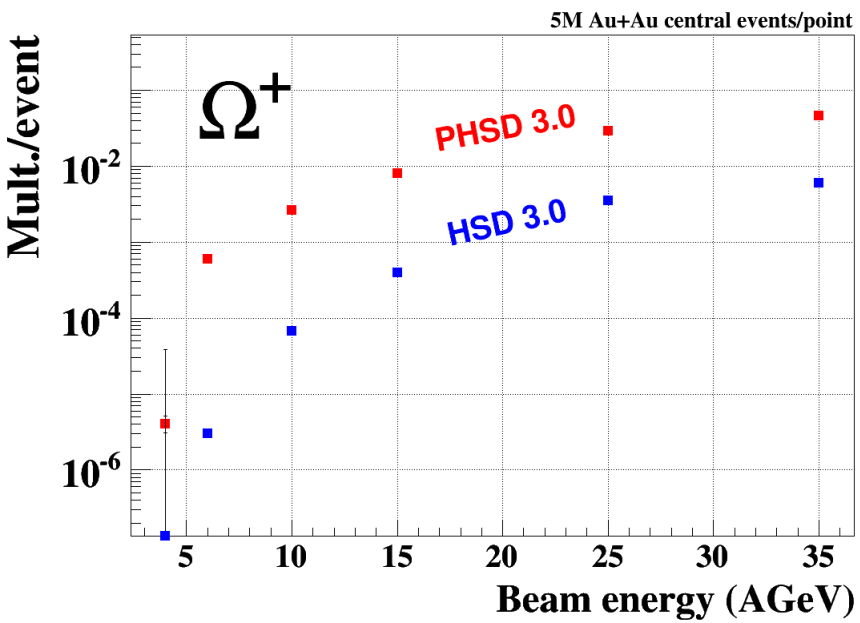
Higher energy data are missed !

Prediction of (Anti)Omega – producttion

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

I. Vassiliev, CBM, private communication



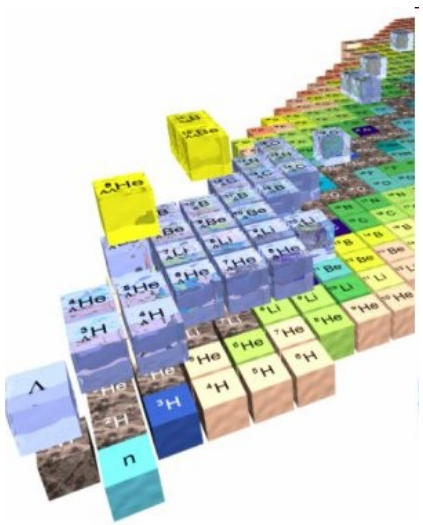


Large sensitivity to partonic degrees of freedom in SIS100 energy range with antihyperons (deconfinement phase transition in PHSD)

Mapping out the phase structure requires systematic differential measurements (i.e. flow for different systemsizes at various centralities)

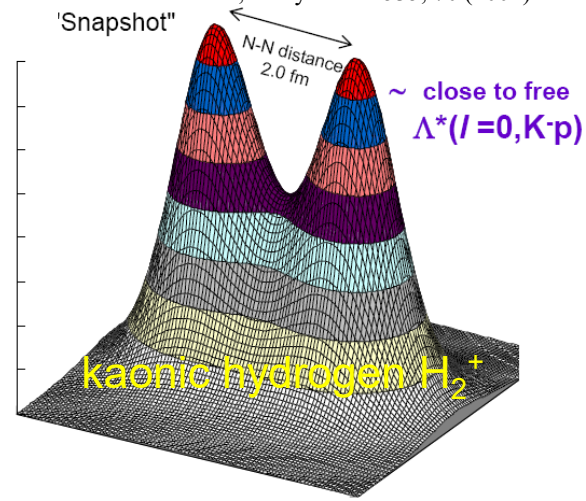
Relicts of high density phase(?)

Hypernuclei



Kaonic molecules

T.Yamazaki and Y. Akaishi, Phys. Rev. C76 (2007) 045201
Y. Akaishi, T.Yamazaki, Phys.Rev.C65, 044005 (2002)
T.Yamazaki and Y. Akaishi, Phys.Lett.B535, 70 (2002)



$$\Psi = \phi_a + \phi_b$$

Decay by weak interaction

Production in HI – collisions!
Recently: STAR, ALICE

Double strange hypernuclei??

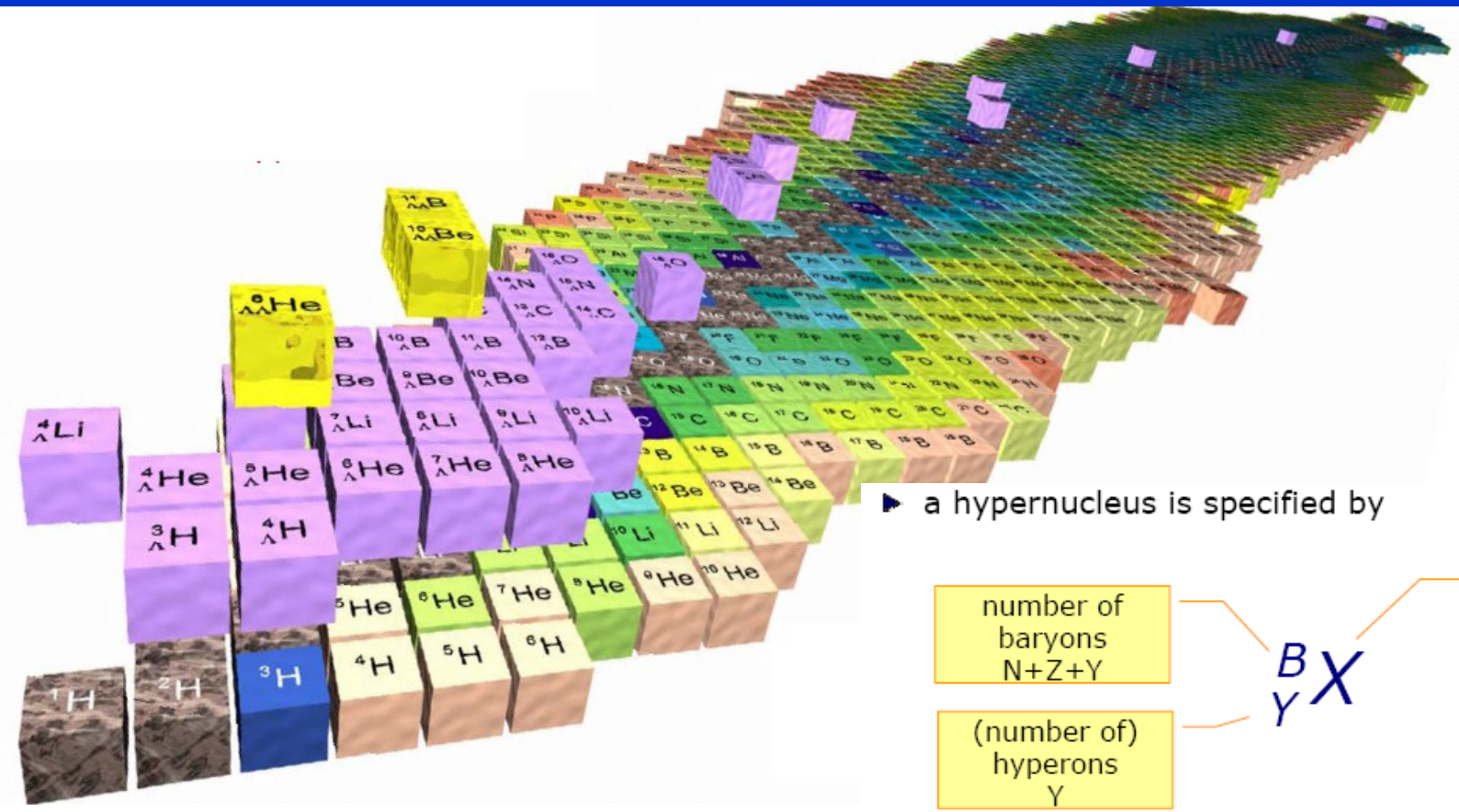
Decay by strong interaction

(pΛ*) = (ppK-): $(ppK^-) \rightarrow \Lambda + p$

FINUDA M=2255±9 MeV, Γ=64±14 MeV
DISTO M=2265±2 MeV, Γ=118±8 MeV

Heavier clusters, e.g.: $(ppnK^-) \rightarrow \Lambda + d$

Hypernuclei



- a hypernucleus is specified by

number of baryons N+Z+Y

(number of) hyperons Y

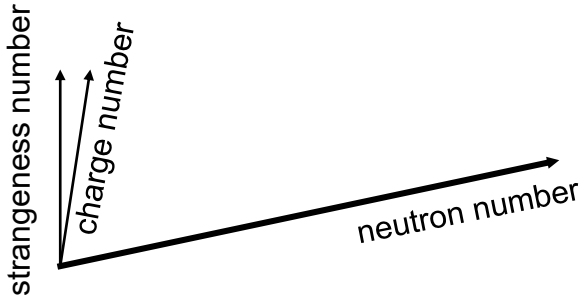
$$ {}^{B}_{Y}X $$

element = total charge (not number of protons)

- examples:

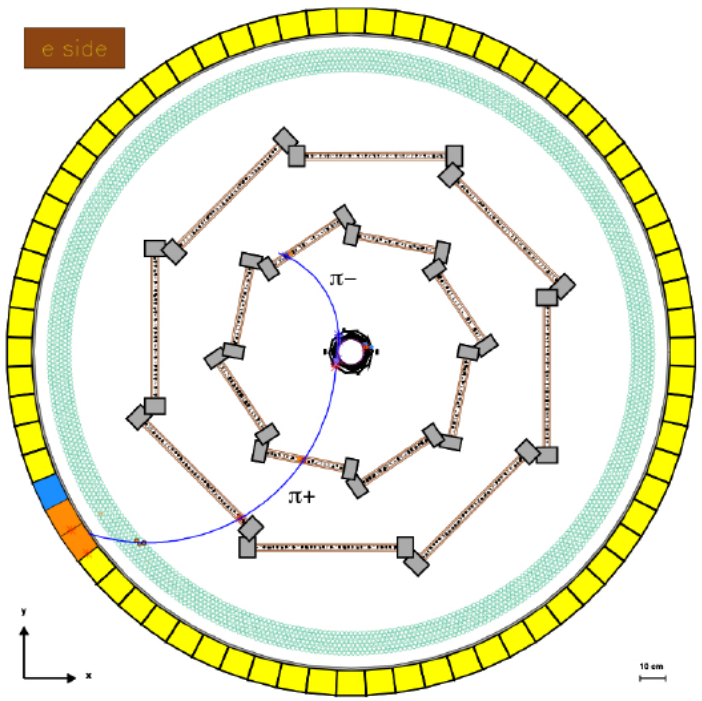
$$ {}^{10}_{\Lambda\Lambda}Be \rightarrow \begin{cases} Be \rightarrow \text{4 protons} \\ \Lambda\Lambda \rightarrow \text{2 lambdas} \\ 10 \rightarrow \text{10-4-2=4 neutrons} \end{cases} $$

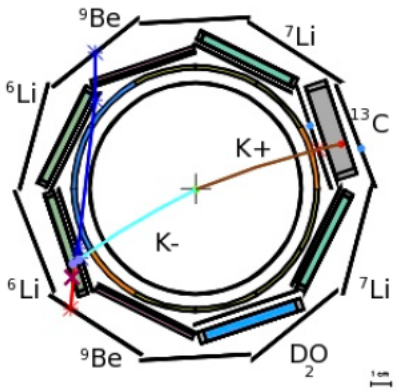
$$ {}^{4}_{\Sigma}He \rightarrow \begin{cases} 1p + 2n + 1\Sigma^{+} \\ 2p + 1n + 1\Sigma^{0} \\ 3p + 0n + 1\Sigma^{-} \end{cases} \quad \text{indistinguishable} $$



$_{\Lambda}^{6}$H measurement by FINUDA @ Daphne

M. Agnello et al., Phys.Rev.Lett. 108 (2012) 042501





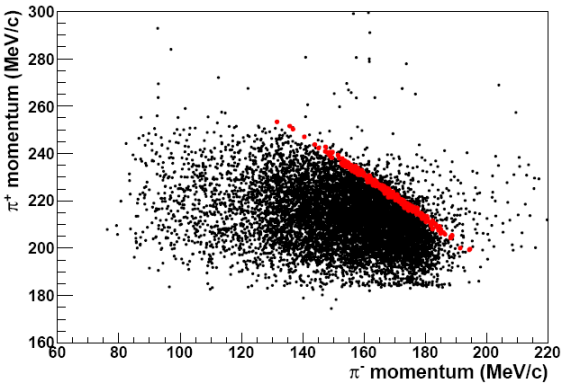
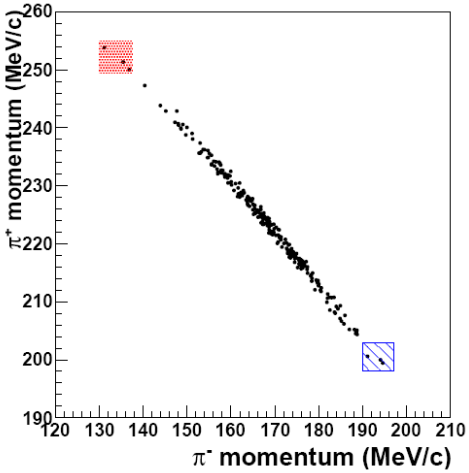


Fig. 7. Left: front view of one of the $^{6}_{\Lambda}$H candidate events reconstructed by FINUDA where a (π^+, π^-) pair emerges from a ^{6}Li target and crosses the spectrometer. Right: expanded view of the target region for the same event where the K^- track stops in a ^{6}Li target.

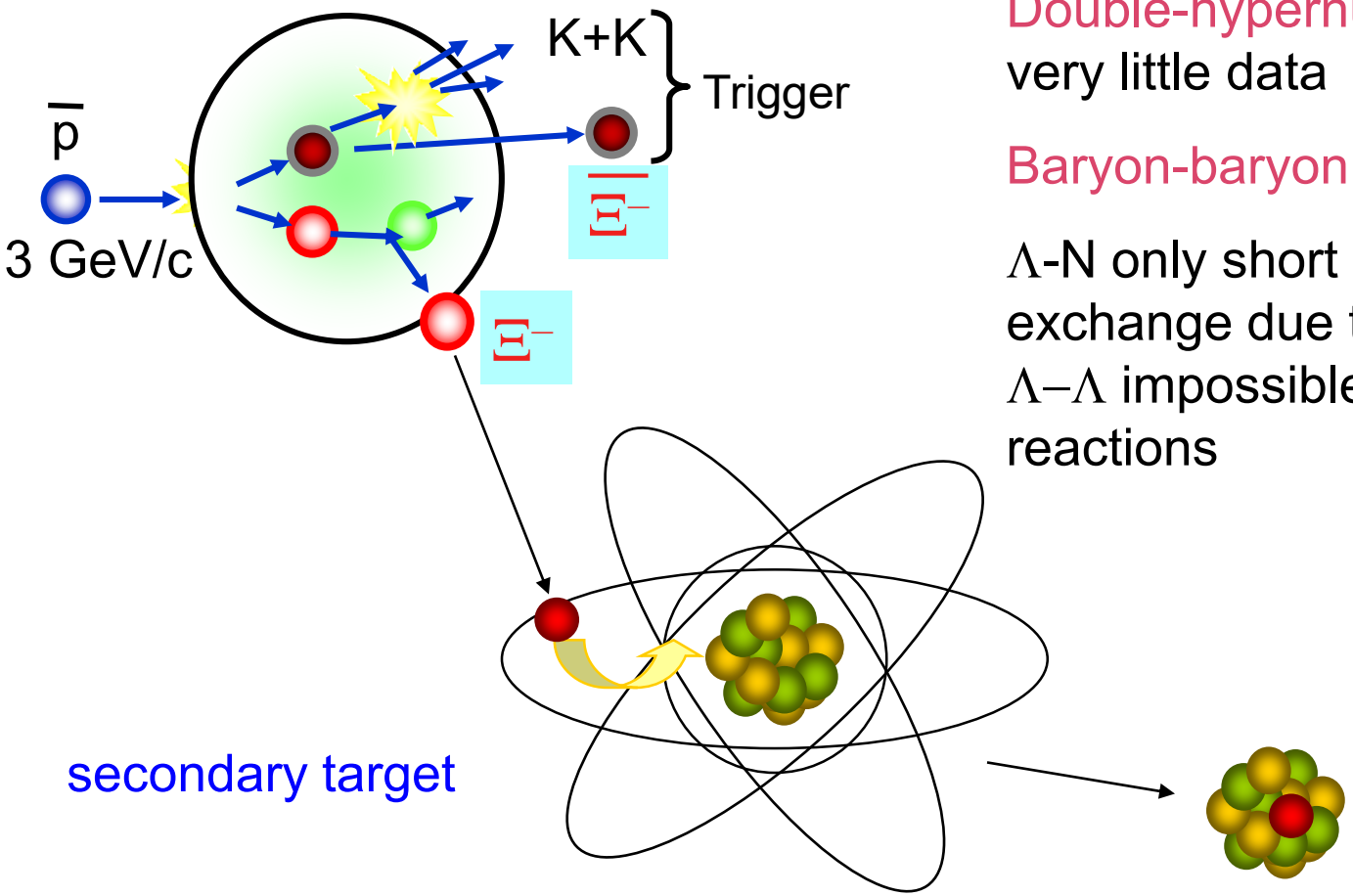
$$K^-_{\text{stop}} + {}^{6}\text{Li} \rightarrow {}^{6}_{\Lambda}\text{H} + \pi^+ \quad (p_{\pi^+} \sim 252 \text{ MeV/c}).$$

$${}^{6}_{\Lambda}\text{H} \rightarrow {}^{6}\text{He} + \pi^- \quad (p_{\pi^-} \sim 130 - 140 \text{ MeV/c}).$$



Double Λ-Hypernuclei production (PANDA)

Hypernuclei open a 3rd dimension (strangeness) in the nuclear chart



Double-hypernuclei:
very little data

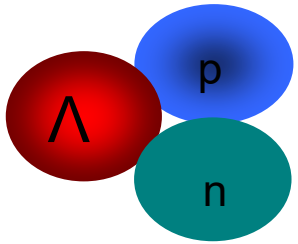
Baryon-baryon interactions:

Λ-N only short ranged (no 1π exchange due to isospin)
Λ–Λ impossible in scattering reactions

$\Xi^-(dss)\ p(uud) \Rightarrow \Lambda(uds)\ \Lambda(uds)$

Hypertritons in HI reactions

$${}^{3}_{\Lambda}H(n+p+\Lambda)$$



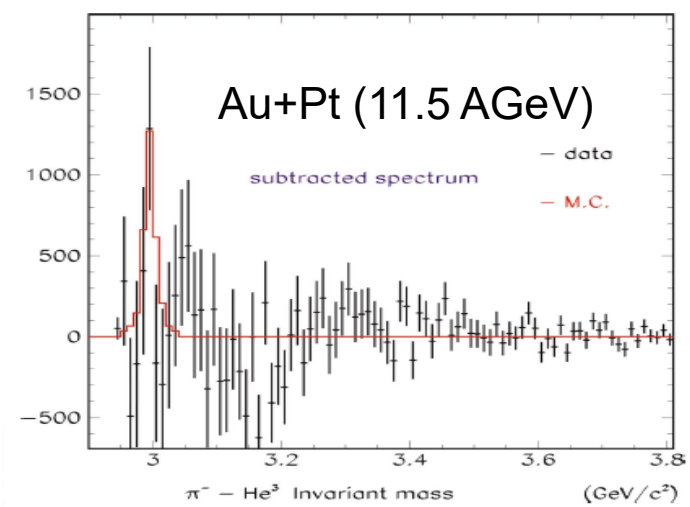
(B_Λ: 0.13±0.05 MeV)

M. Juric et al. Nucl. Phys. B 52 (1973), p. 1

Weak mesonic decay	B.R.
${}^{3}_{\Lambda}H \rightarrow {}^{3}He + \pi^-$	~25%
${}^{3}_{\Lambda}H \rightarrow d + p + \pi^-$	~50%

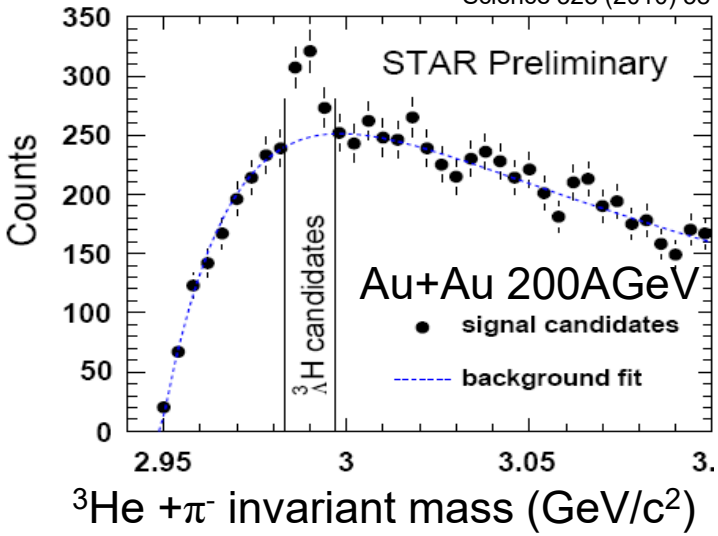
M.Derrick et al. PRD,1,66 (1970);
H.Kamada et al. PRC57,1595 (1998);

T.A.Armstrong et al. (E864 collaboration). PRC70, 024902(2004)



Signal at 2σ level
1.35 10^9 central collisions

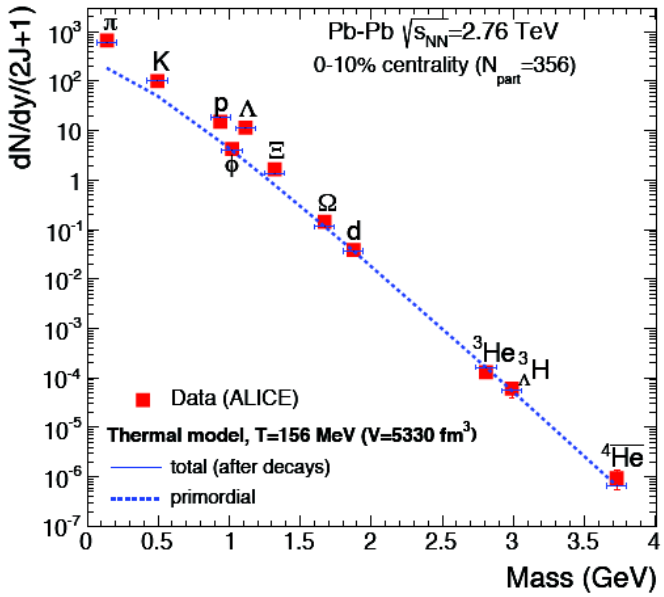
B.I. Abelev et al. (Star – collaboration) arXiv:1003.2030 [nucl-ex], Science 328 (2010) 58



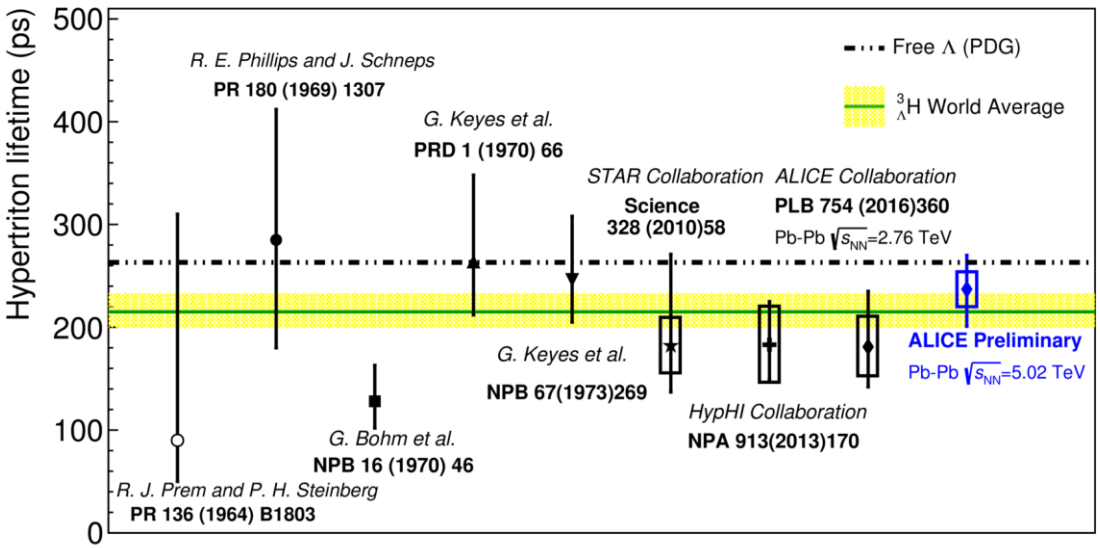
Signal at 5.5σ level, 157 candidates
110 · 10^6 central collisions

ALICE results

PBM, SQM 2016



M. Puccio (Alice), SQM2017



ALI-PREL-130195

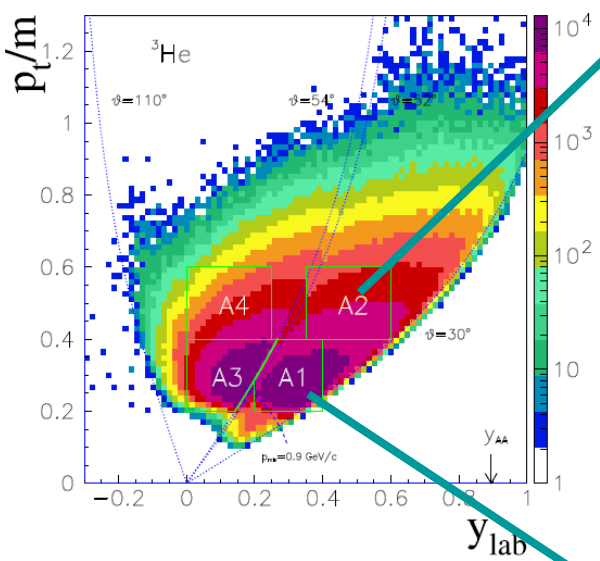
- Hypernucleus production can be described by SHM
- Lifetime of hypertriton compatible with free Λ lifetime

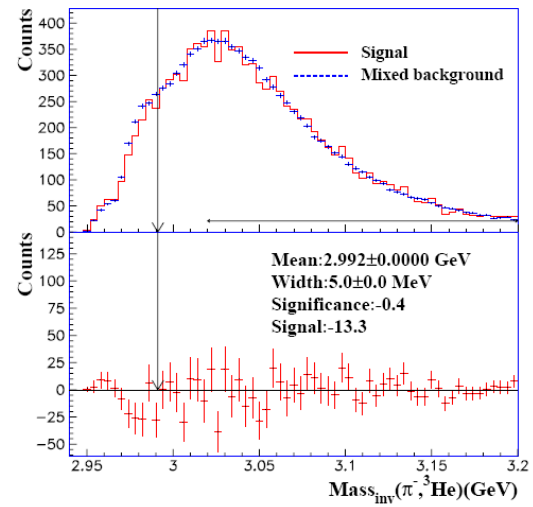
Hypertriton production in Ni+Ni at 2 AGeV

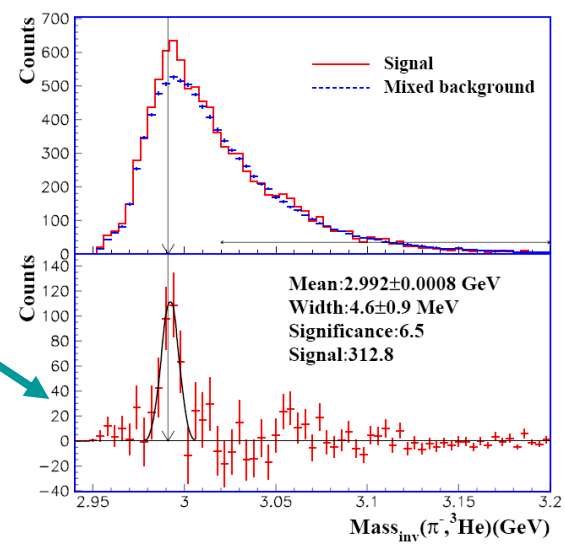
$$ {}_{\Lambda}t \rightarrow {}^{3}He + \pi^{-} $$

50 M events,

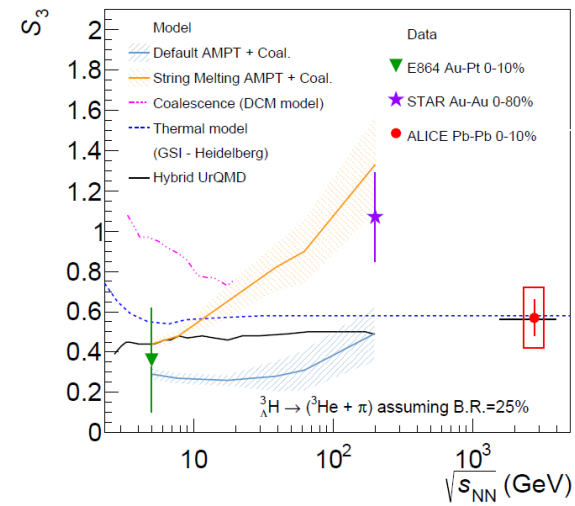
$\sigma_{triggered} = 0.5 \cdot \sigma_{reaction}$







S. Zhang et al., Phys. Lett. B684, 224 (2010), ALICE, Phys. Lett. B 754 (2016) 360



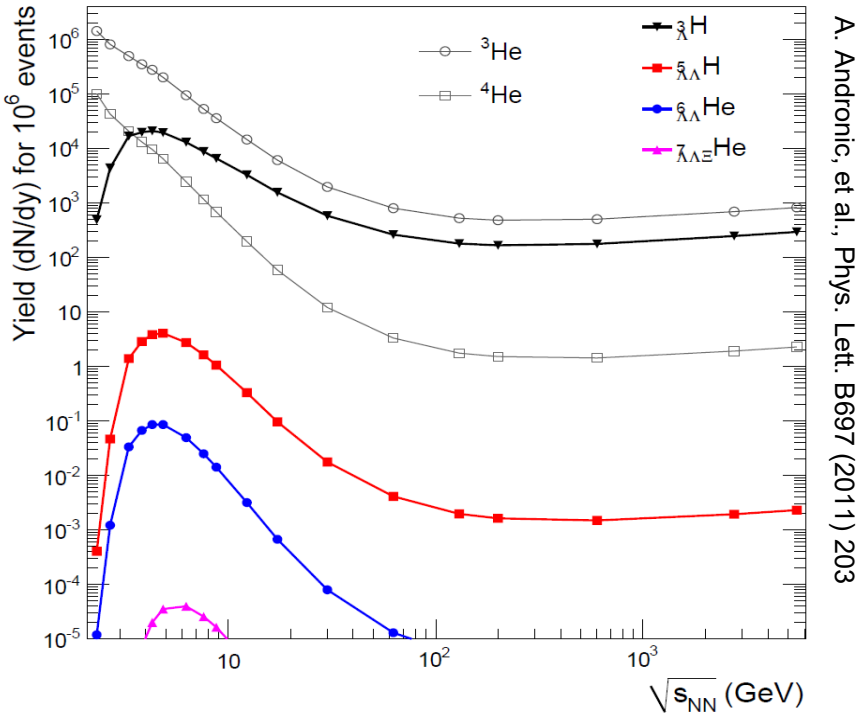
	Region A1	Region A2
${}_{\Lambda}t/{}^{3}He$	0.029 +/- 0.002	<0.003 +/- 0.002
Λ/p	0.0020 +/- 0.0005	0.0028 +/- 0.0005
${}_{\Lambda}t/{}^{3}He$ / Λ/p	10 +/- 3	< 0.95 +/- 0.6

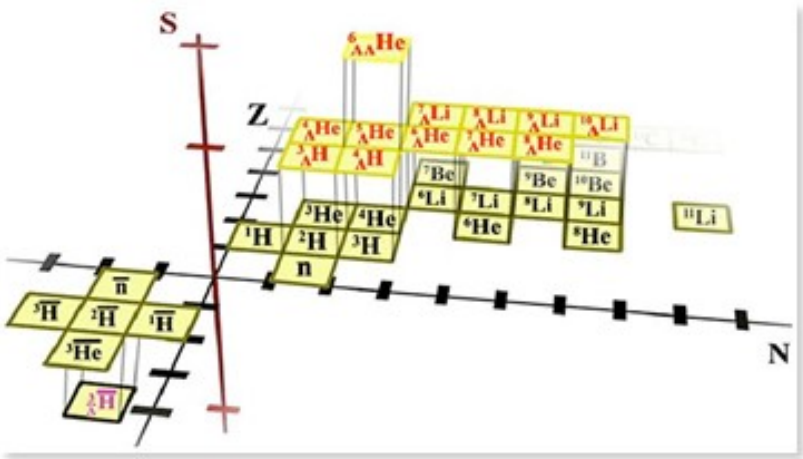
Excess over combinatorial background only in Phase space region A1

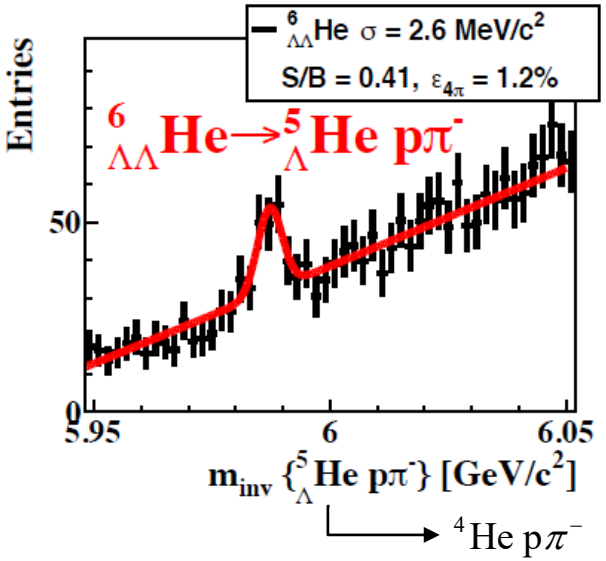
Y.P. Zhang, PhD thesis, Heidelberg 2013 (unpublished)

CBM@SIS 100 - Hypernuclei

Thermal model prediction







Simulation:
Au+Au collisions at 10 AGeV,
Background scaled to 10^{12} central events,
TOF PID

~ 7 days of running at max. luminosity

Double hypernuclei – NAGARA event

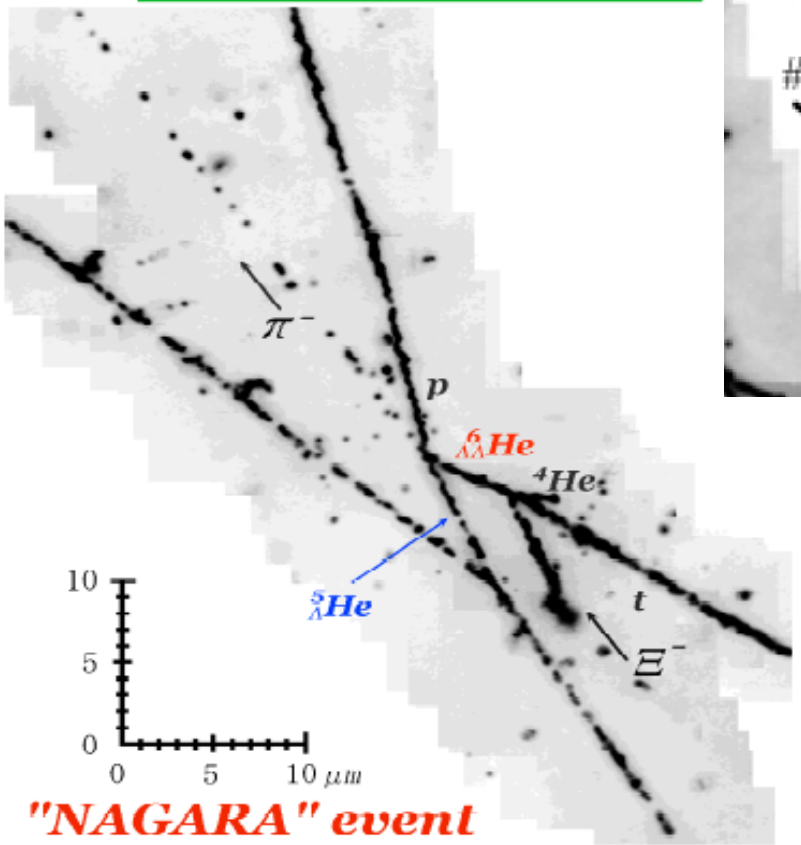
http://www.phys.ed.gifu-u.ac.jp/Topics/NAGARA-e.htm

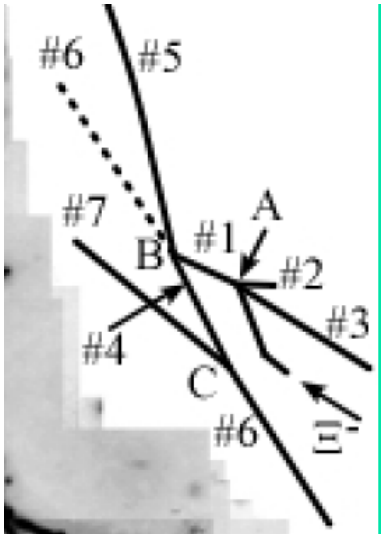
Oct. 20. 2001

${}^{6}_{\Lambda\Lambda}$He double-hypernucleus

Unique interpretation!!

$$\Xi^- + {}^{12}C \longrightarrow {}^{6}_{\Lambda\Lambda}Hc + {}^{4}Hc + t$$
$${}^{6}_{\Lambda\Lambda}He \longrightarrow {}^{5}_{\Lambda}He + p + \pi^-$$





"NAGARA" event

presented by E373(KEK-PS) on Jan.2001

Track data (lengths, angles and PID)

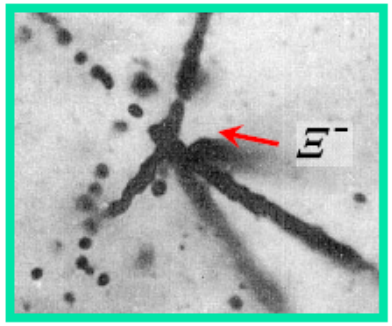
point	track#	length [μm]	θ [degree]	ϕ [degree]	
A	#1	8.1 ± 0.3	44.9 ± 2.0	337.5 ± 1.8	double-hypernucleus
	#2	3.2 ± 0.4	57.7 ± 5.2	174.9 ± 2.9	
	#3	88.6 ± 0.5	156.2 ± 0.5	143.0 ± 1.0	
B	#4	9.1 ± 0.3	77.7 ± 1.6	115.9 ± 0.8	single-hypernucleus
	#5	82.1 ± 0.6	122.8 ± 1.0	284.2 ± 0.7	stopped in base
	#6	13697	81.0 ± 0.5	305.5 ± 0.2	π^-
C	#7	742.6 ± 0.6	138.5 ± 0.2	322.1 ± 0.3	stopped in D-Block
	#8	5868 ± 20	52.2 ± 1.2	123.7 ± 0.7	scattered before stopping

World double – Λ – hypernuclei

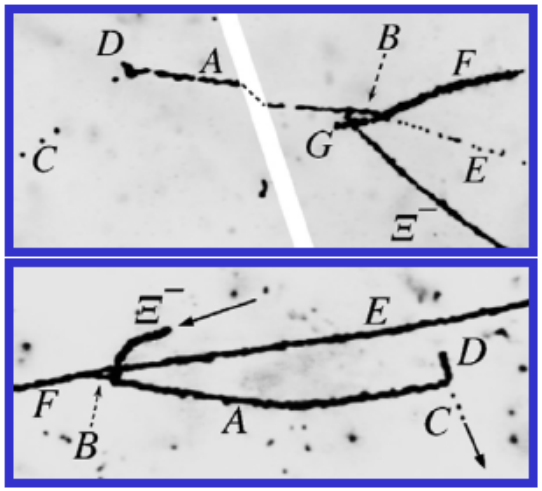
http://fb19.hiskp.uni-bonn.de/fb19-sessions/m/Thursday/NakazawaFB19.pdf

KEK-E176

in ~80 Ξ^- stops



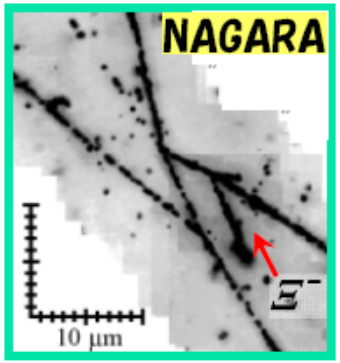
Twin HY. to refer to BΞ^-

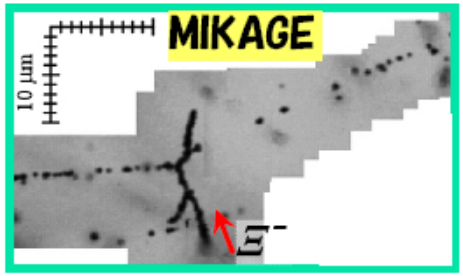


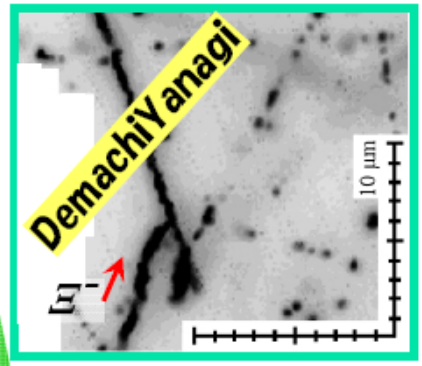
S.Aoki et al., NP. A828 (2009) 191-232

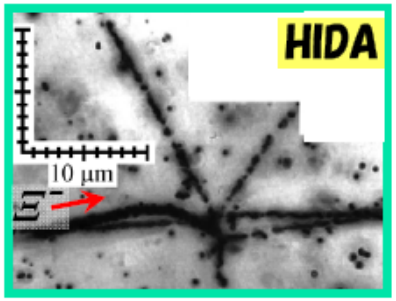
KEK-E373

~2×10^4 Ξ^- tracks (followed) → ~ 10^3 Ξ^- stops



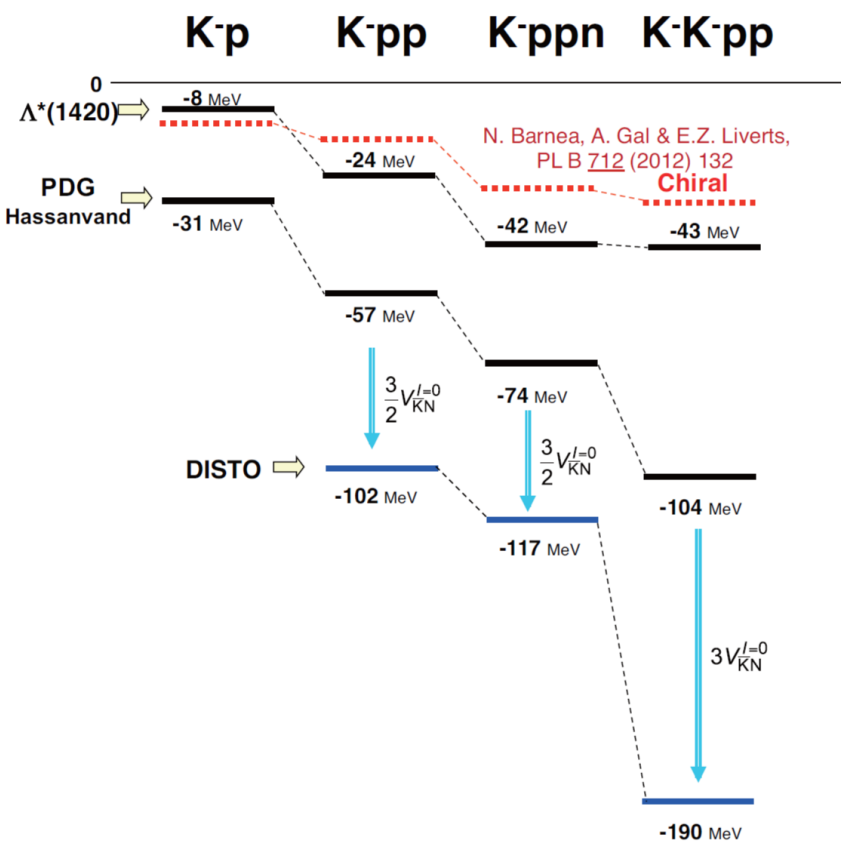






High-density kaonic-proton matter

T. Yamazaki, Y. Akaishi, arXiv:1610.01249
S. Maeda, Y. Akaishi, T. Yamazaki, JPS Conf.Proc. 17 (2017) 082007, arXiv:1610.02150



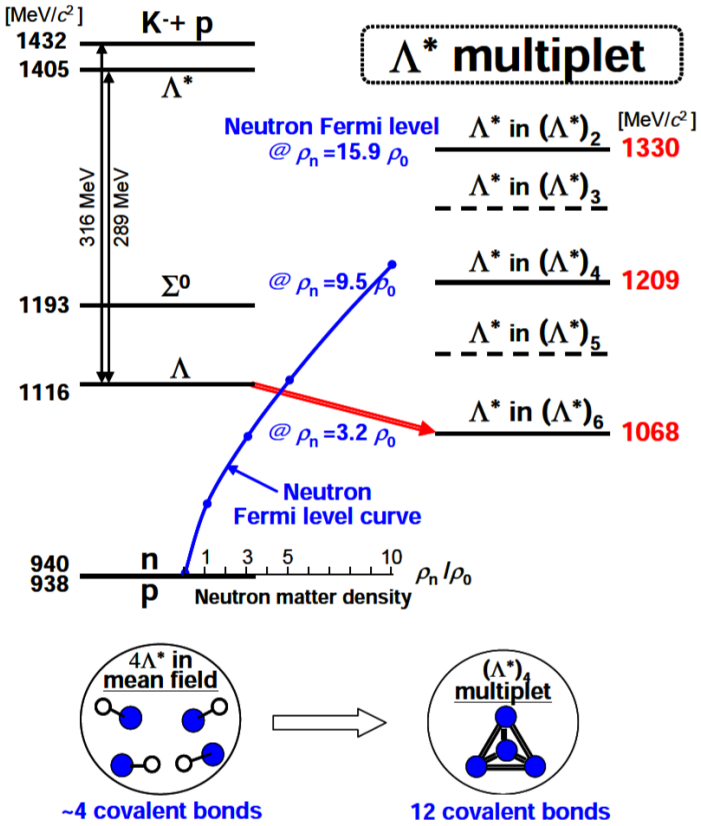
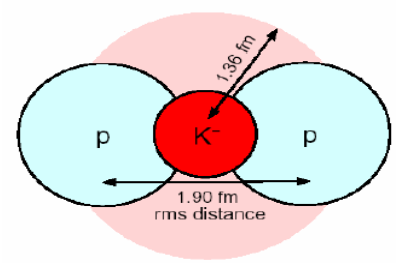


FIG. 2: Predicted energy levels of $\Lambda^* = K^- p$ in Λ^* multiplets calculated by a variational method [20]. The corresponding nuclear densities and neutron Fermi levels are also shown, indicating that the Λ^* in the $(\Lambda^*)_6$ cannot decay to a neutron in neutron matter at 3.2 times the normal density ρ_0.

Λd – correlations

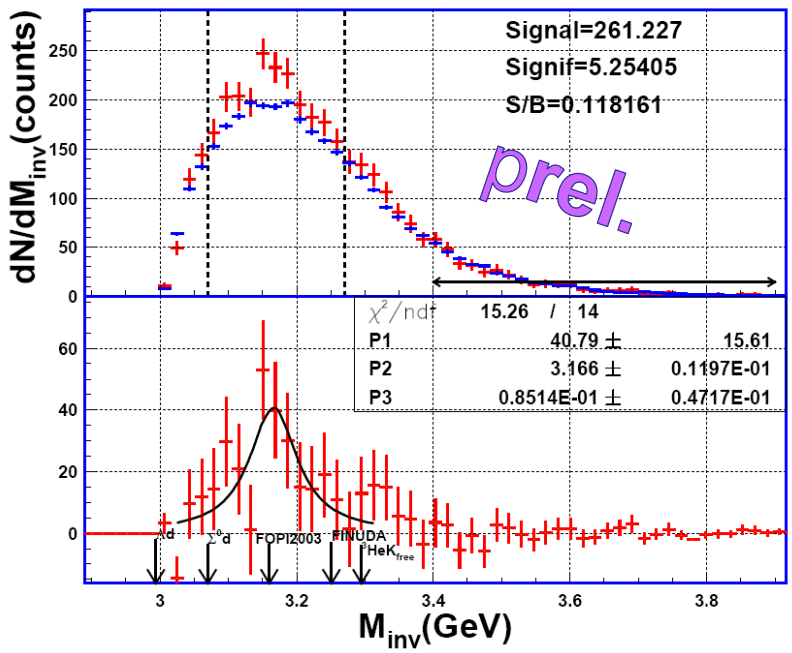
Deeply bound kaonic clusters

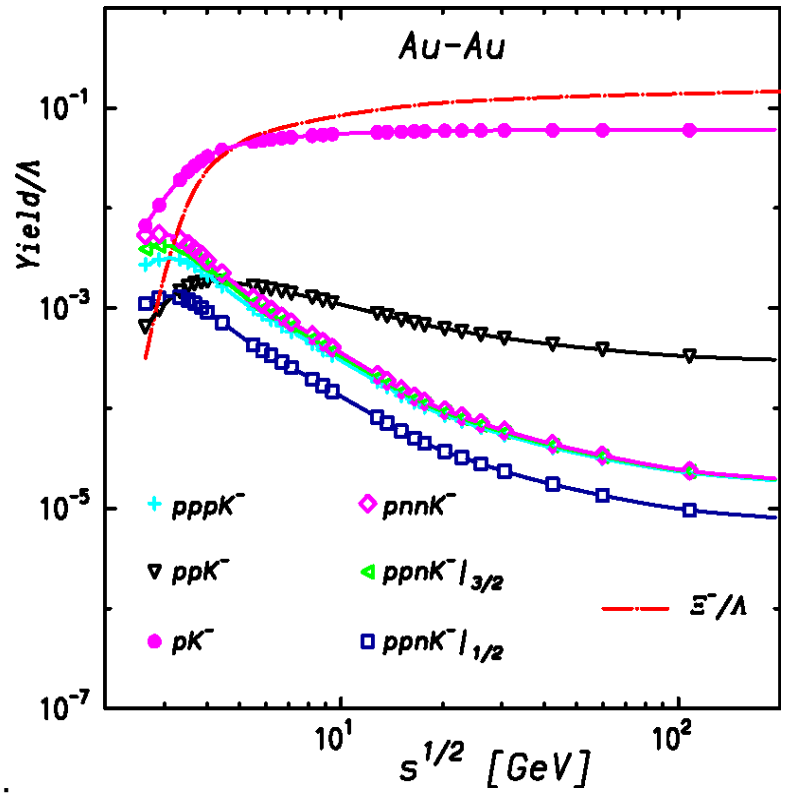
T.Yamazaki and Y. Akaishi, Phys.Lett.B535, 70 (2002)



$$(ppnK^-) \rightarrow \Lambda + d$$

Ni+Ni at 1.91 AGeV (FOPI, 2008))





A.Andronic, PBM, K. Redlich (2005), nucl-th/0506083

Observations:

non – thermal phase space population

non – monotonous centrality dependence

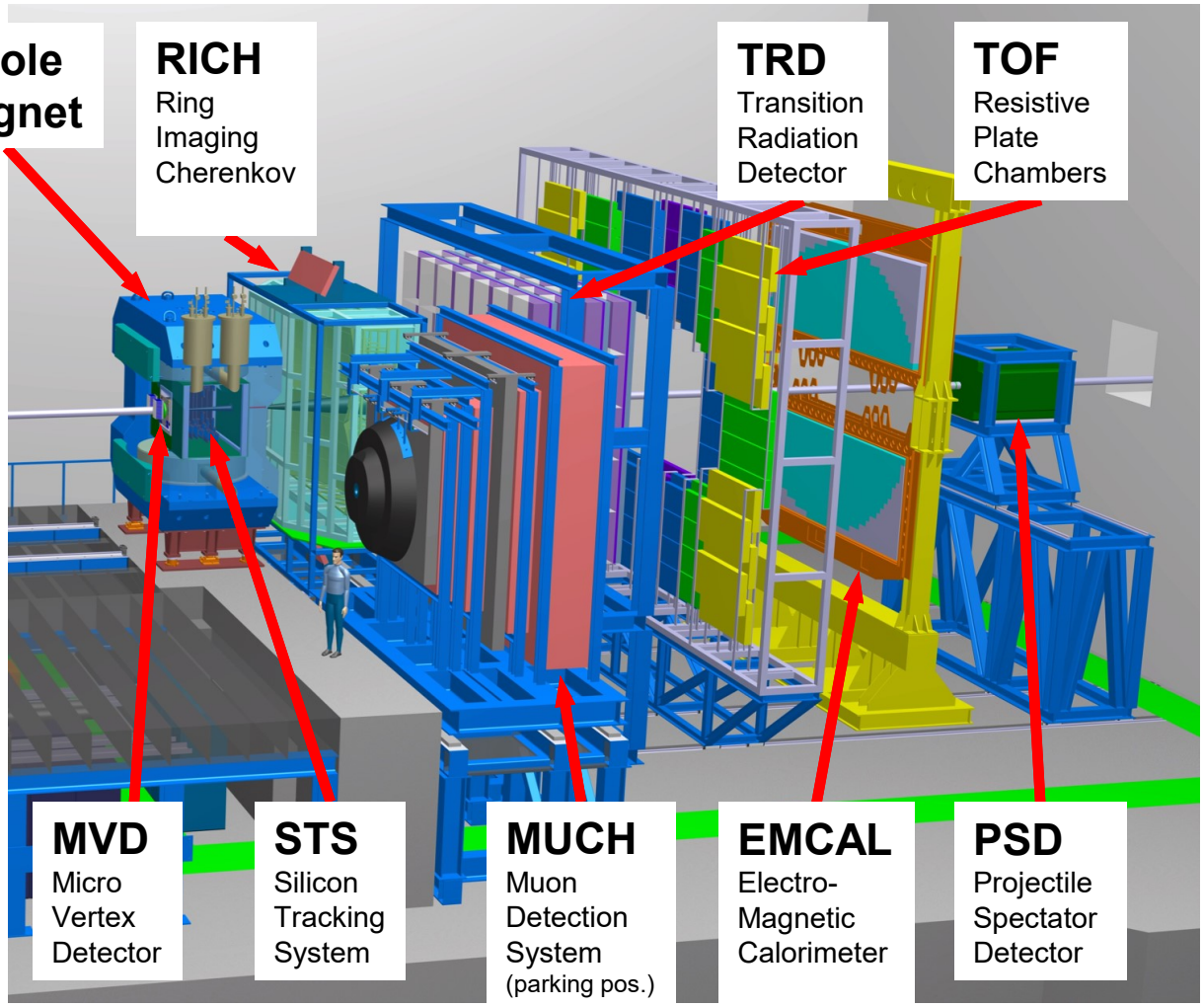
non – trivial mixed event bkgd determination

Statistics: currently: 10^8 events

necessary: 10^{10} events

syst. studies: 10^{12} events

CBM Experimental Setup



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

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

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

Expected particle yields for CBM

Y. Vassiliev, 29th CBM CM, 2017

Event generator: URQMD + thermal source for hypernuclei

Particle (mass MeV/c^2)	Multi-plicity 6 AGeV	Multi-plicity 10 AGeV	decay mode	BR	ε (%)	yield (s^{-1}) 6AGeV	yield (s^{-1}) 10AGeV	yield in 10 weeks 6AGeV	yield in 10 weeks 10 AGeV	IR MHz
Λ (1115)	$4.6\cdot10^{-4}$	0.034	$p\pi^+$	0.64	11	1.1	81.3	$6.6\cdot10^{6}$	$2.2\cdot10^{8}$	**10**
Ξ^- (1321)	0.054	0.222	$\Lambda\pi^-$	1	6	$3.2\cdot10^{3}$	$1.3\cdot10^{4}$	$1.9\cdot10^{10}$	$7.8\cdot10^{10}$	**10**
Ξ^+ (1321)	$3.0\cdot10^{-5}$	$5.4\cdot10^{-4}$	$\Lambda\pi^+$	1	3.3	$9.9\cdot10^{-1}$	17.8	$5.9\cdot10^{6}$	$1.1\cdot10^{8}$	**10**
Ω^- (1672)	$5.8\cdot10^{-4}$	$5.6\cdot10^{-3}$	ΛK^-	0.68	5	17	164	$1.0\cdot10^{8}$	$9.6\cdot10^{8}$	**10**
Ω^+ (1672)	-	$7\cdot10^{-5}$	ΛK^+	0.68	3	-	0.86	0	$5.2\cdot10^{6}$	**10**
${}^{3}_{\Lambda}H$ (2993)	$4.2\cdot10^{-2}$	$3.8\cdot10^{-2}$	${}^{3}He\pi^-$	0.25	19.2	$2\cdot10^{3}$	$1.8\cdot10^{3}$	$1.2\cdot10^{10}$	$1.1\cdot10^{10}$	**10**
${}^{4}_{\Lambda}He$ (3930)	$2.4\cdot10^{-3}$	$1.9\cdot10^{-3}$	${}^{3}Hep\pi^-$	0.32	14.7	110	87	$6.6\cdot10^{8}$	$5.2\cdot10^{8}$	**10**

- Results obtained with 4D (time based) simulation
- Particle yields allow for differential analysis
- Lifetime determination of hypernuclei possible