Probing dense baryonic matter with strangeness

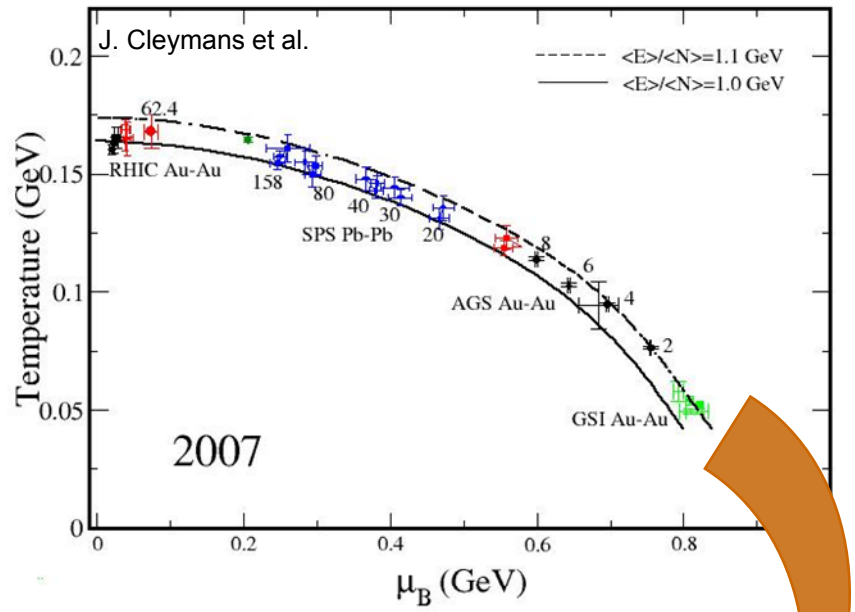
Motivation
- In - medium effects
- K^- N interaction

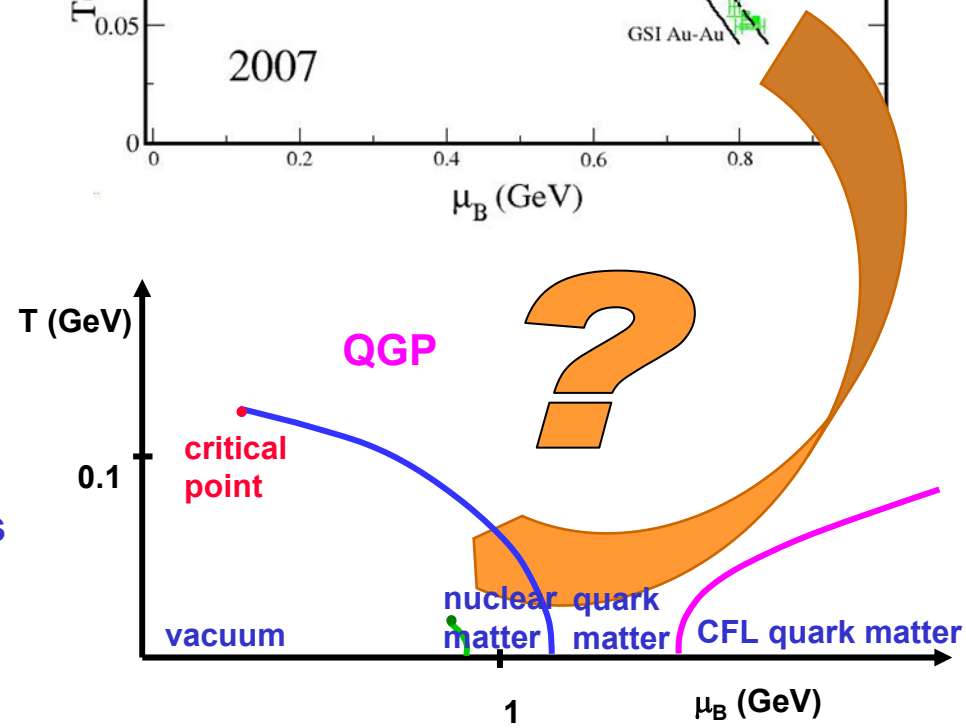
Kaons in Medium
- Inclusive K^0 – production in πA
- Kaon flow

Strange Resonances
- Excited hyperon $\Sigma^*(1385)$
- Mesons $K^*(895)$, $\phi(1020)$
- Thermalisation?

Kaonic bound states
- AY – model
- Kaonic cluster production in HI collisions
- Experimental evidence for kaonic clusters

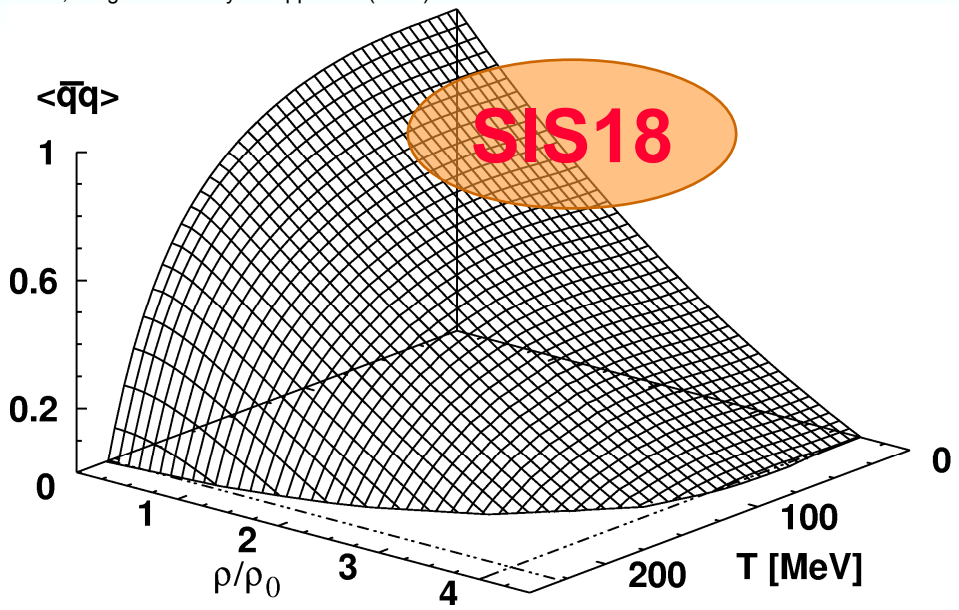
Summary/Conclusions





Hadrons in Medium

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



GOR – relation: $m_\pi^2 f_\pi^2 = - < m_q > \langle \bar{q} q \rangle$

In-medium effects in finite systems:

'Trivial'

- Fermi motion
- Pauli blocking
- Collisional broadening

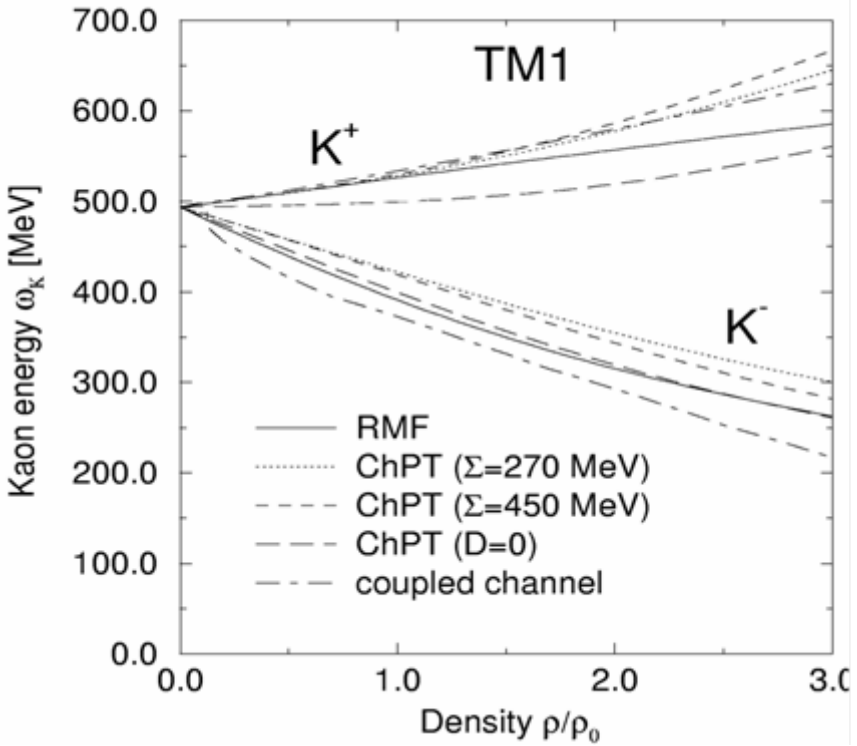
'Non-trivial'

- Partial restoration of chiral symmetry
- Meson – baryon coupling
- Bound states

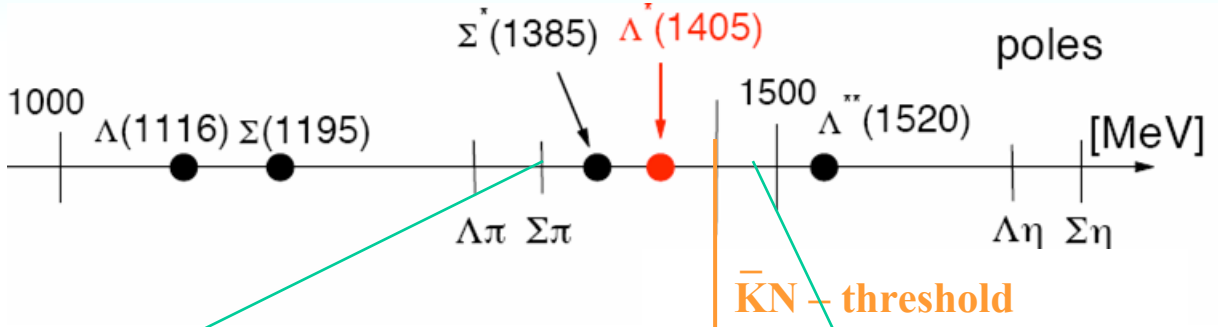
Modified properties of hadrons in dense baryonic matter?

M*(ρ)	(mass)
Γ* (ρ)	(width)
σ* (ρ)	(cross section)

in-medium kaon energy



$\bar{K}N$ – interaction

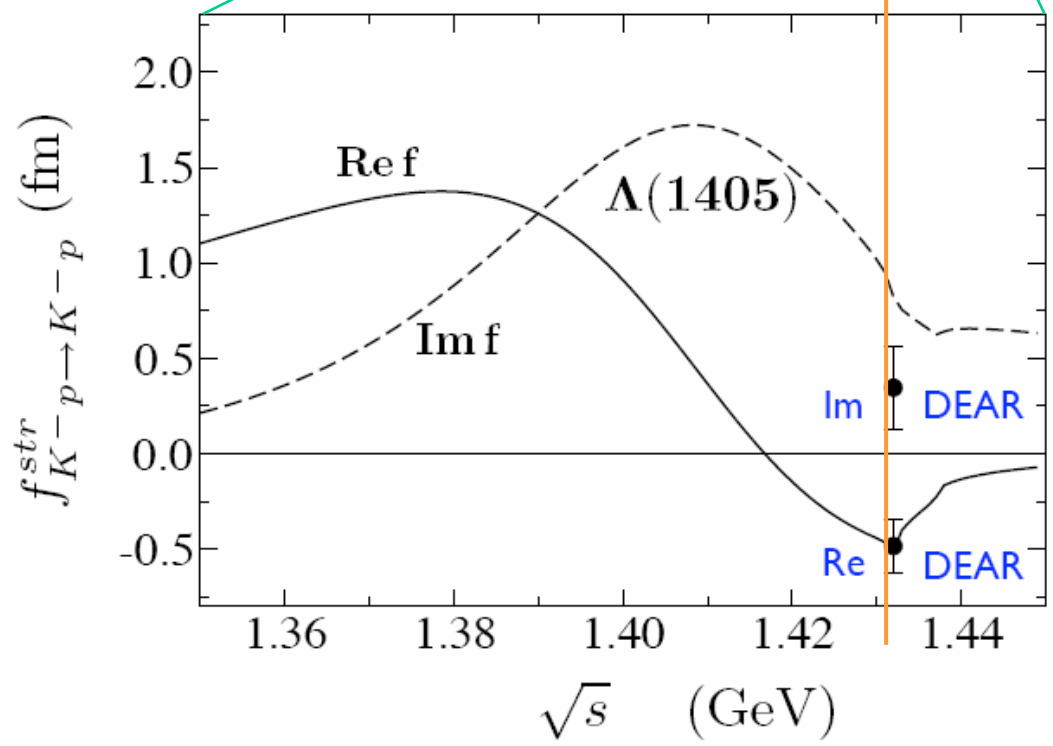


$\bar{K}N$ – threshold

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

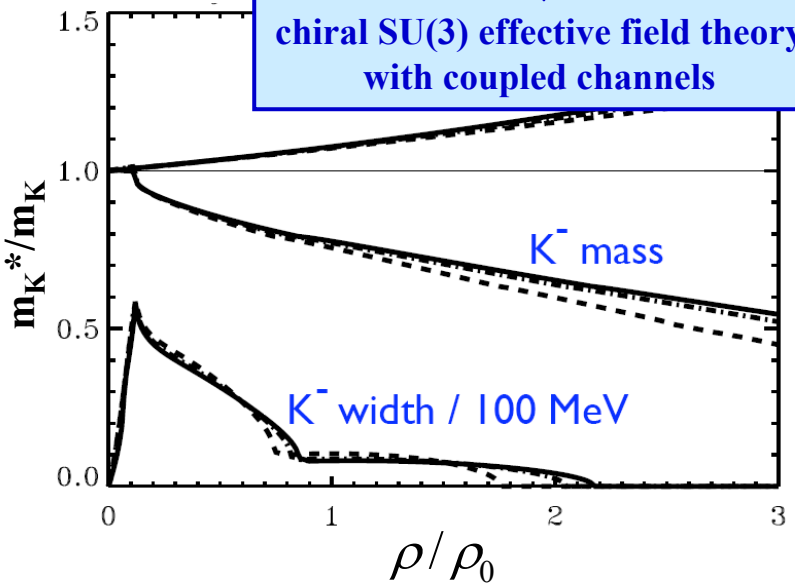
$\bar{K}$ – energy

Scattering amplitude f



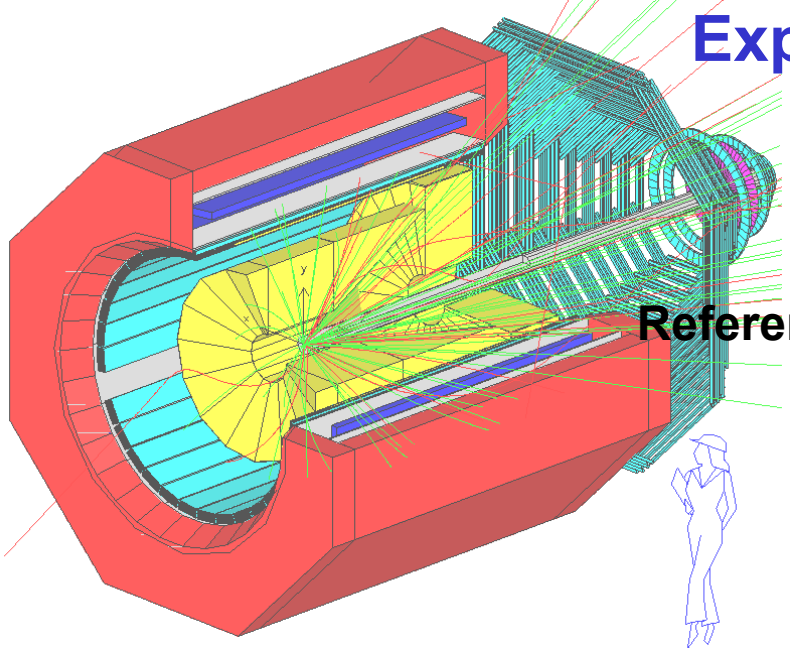
W.Weise et al.: PLB 379, 34 (1996), PRL 94, 213401 (2005)

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



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

Experimental program



Reference data from elementary reactions

K^0 , Λ production and phase space distributions in

π^- + C, Al, Cu, Sn, Pb @ 1.15 GeV/c, (S273, 2004)

K^0 , K^+, K^-, ϕ, Λ production in

π^- + LH_2, C, Pb @ 1.7 GeV/c, (S339, 2010)

Systematics of strangeness data from heavy-ion reactions

K^0 , K^+, K^-, ϕ, K^*, Λ, $\Sigma*(1385)$ production and kaon flow

Search for kaonic bound states

Ni + Ni	@ 1.93 AGeV,	(S261, 2003)
Al + Al	@ 1.91 AGeV,	(S297, 2005)
Ni + Ni	@ 1.91 AGeV,	(S325, 2008)
Ru+ Ru	@ 1.7 AGeV,	(S338, 2009)
Ni + Pb	@ 2 AGeV,	(S338, 2009)

Search for exotica in elementary reaction

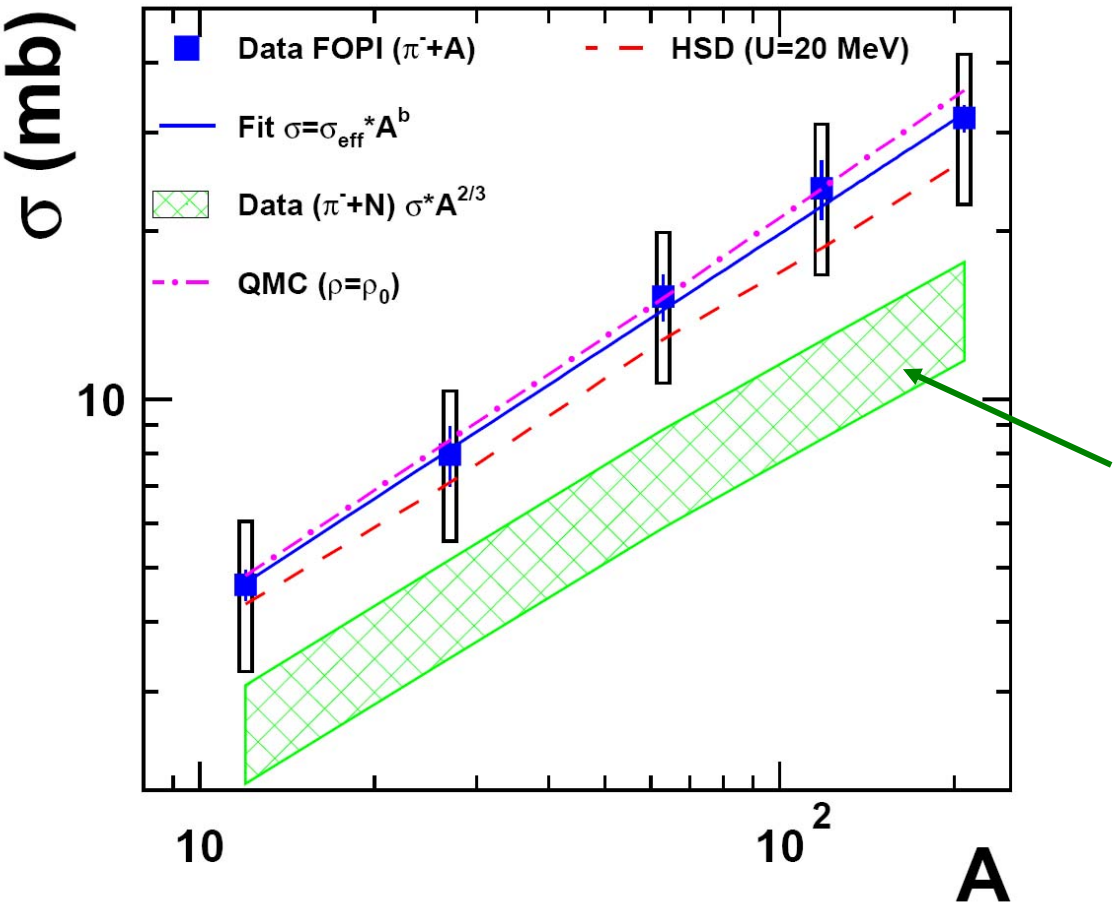
existance of ppK^- - bound state

p + p @ 3 GeV, (S349, 2009)

Evidence for in-medium effect at $\rho=\rho_0$

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

M.L. Benabderramahne et al. (FOPI) , submitted to PRL, arXiv:0807.3361



$$\sigma(\pi + A \rightarrow K^0 + X) = \sigma_0 A^{\alpha}$$

$$\sigma_0 = 0.87 \pm 0.13\,\mathrm{mb}$$

$$\alpha = 0.67 \pm 0.03$$

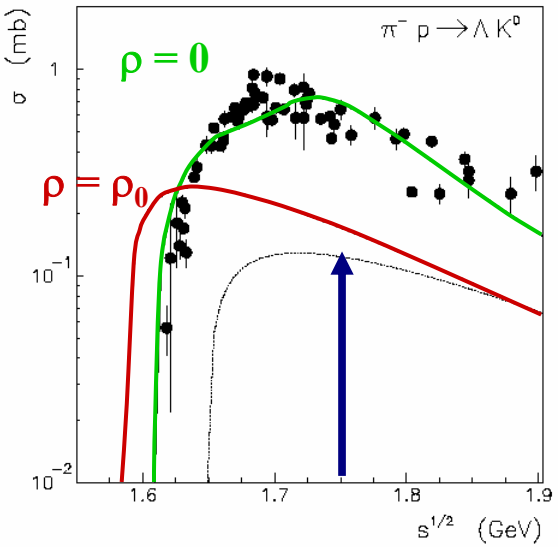
Expectation for vacuum cross section

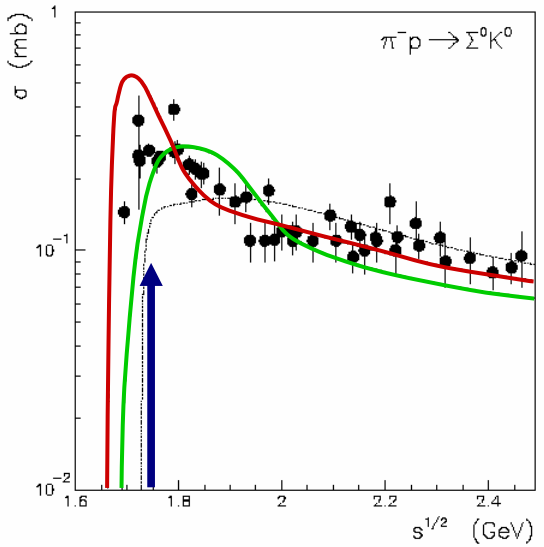
Enhanced K^0 – production on cold nuclei!

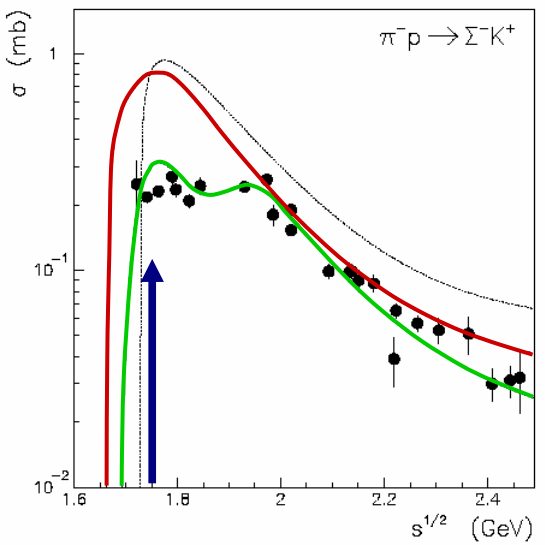
Pion induced strangeness production

QMC – Quark-Meson Coupling Model + Resonance model,
(infinite nuclear matter)

K. Saito, K. Tsushima, A.W. Thomas, hep-ph/0506314





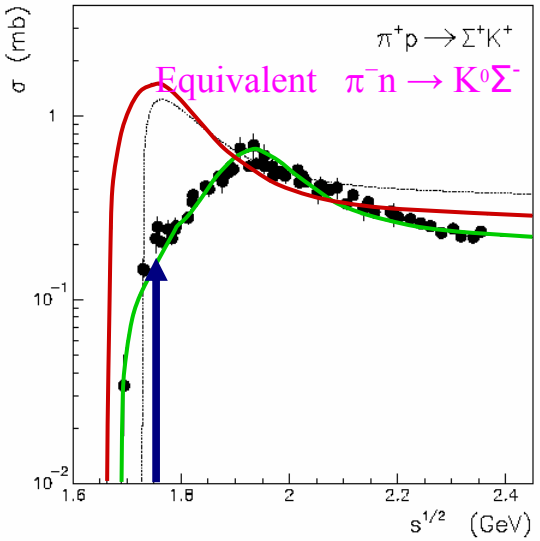


Strangeness production in π^-A reactions:

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

$\pi^- + n \rightarrow \Sigma^- + K^0$
$\pi^- + p \rightarrow \Sigma^- + K^+$

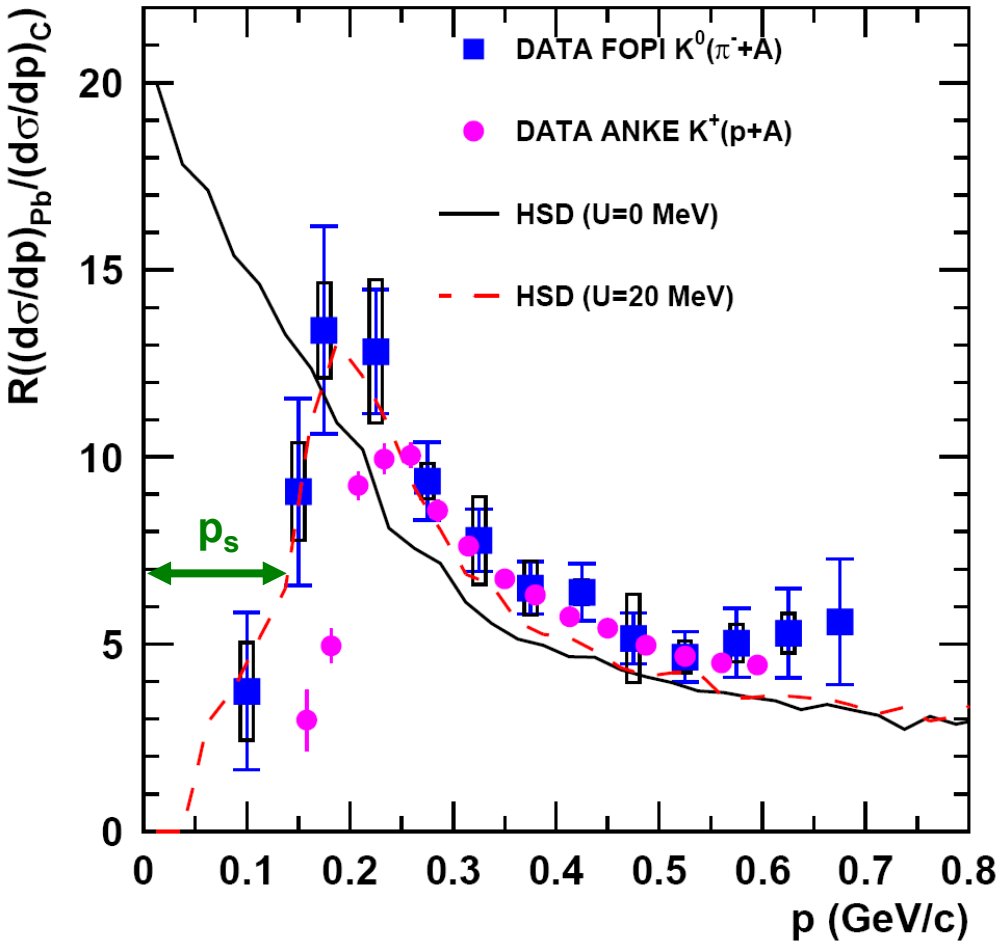
All channels have different density dependence.



Resonance model can be tested by exclusive measurements and by analysing all reaction channels, i.e. K^0, K^+, K^-, Φ and Λ
(new data needed)

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

Ratio of momentum distributions:



M.L. Benabderramahne, PhD thesis, Heidelberg (2007), arXiv:0807.3361

Anke data @ COSY

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

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

Model interpretation with RBUU

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

Model independent analysis:

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

Potential depth: $U(K^0) = +20$ (+/- 5) MeV consistent with heavy-ion data on K^+,
Accuracy (only) statistics limited,
Method applicable to determine isospin dependence of KN – potential (e.g. π^- + ^{X}Sn).

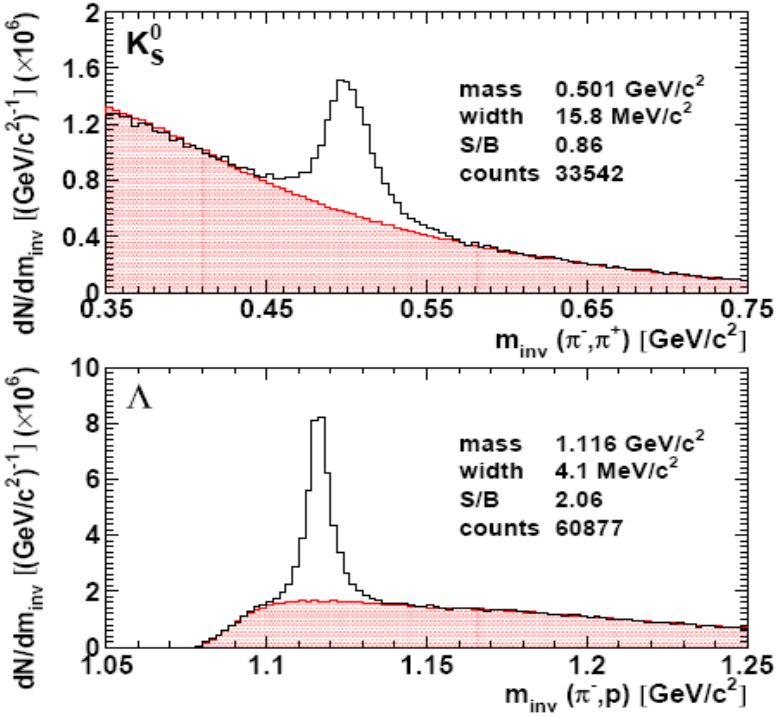
K^0 and Λ measurements in HI - reactions

M. Merschmeyer et al. (FOPI), PRC 76, 024906 (2007),
nucl-ex/0703036

Reconstruction of secondary vertices

~ 60k (100k) Λ in Ni (Al)

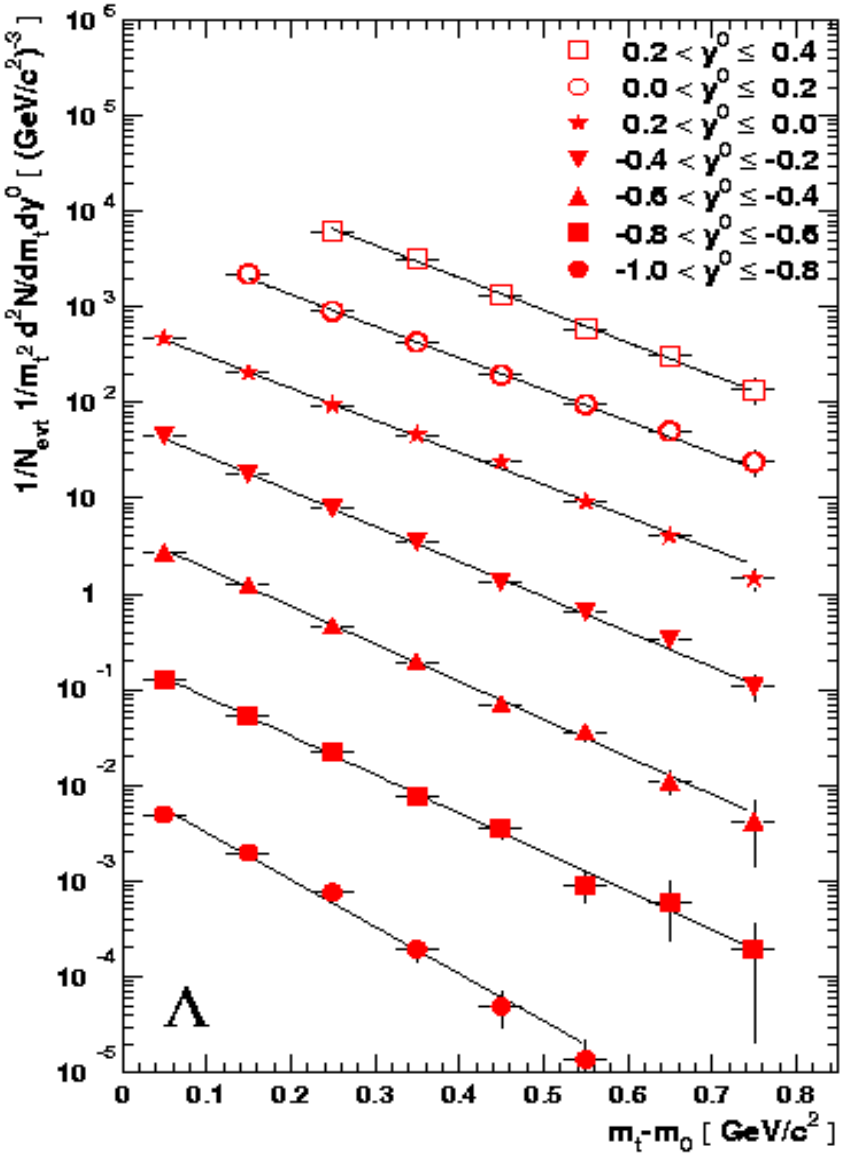
~ 30k (60k) K^0 in Ni (Al)



Typical detection probability

$$P_{\det} = P_{prod} \cdot \varepsilon \approx 10^{-1} \cdot 10^{-2} = 10^{-3}$$

Transverse mass spectra



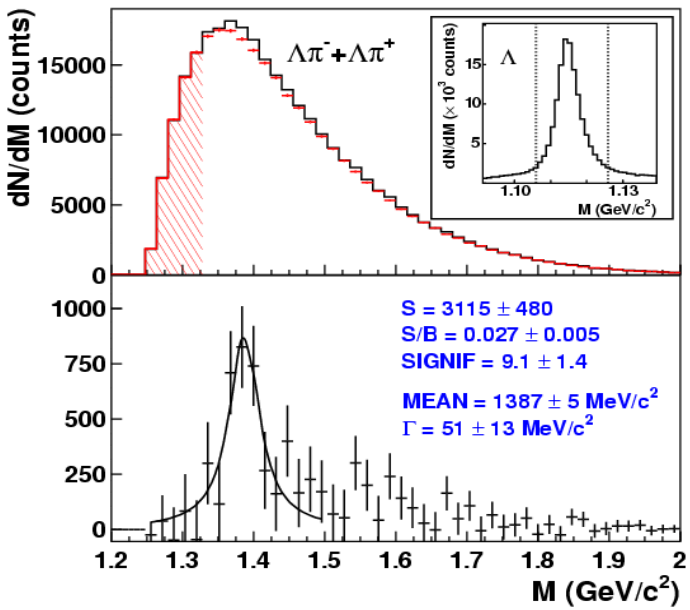
Reconstruction of short lived resonances in HI collisions

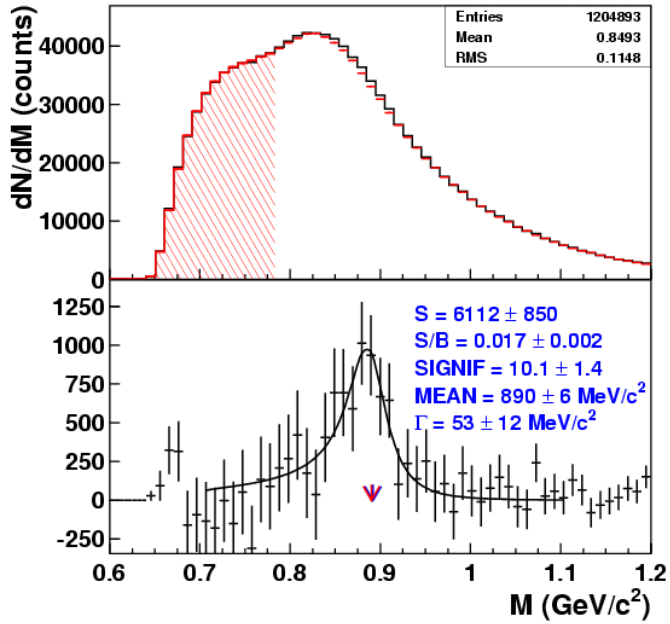
$\Sigma^*(1385)$ subthreshold production,
X. Lopez et al. (FOPI), PRC 76, 052203(R) (2007)

$\Sigma^* \rightarrow \Lambda + \pi \quad (88 \pm 2\%)$
$\rightarrow p + \pi^- + \pi$
$\Gamma = 39.4$ MeV
$c\tau = 5$ fm

$K^* \rightarrow K + \pi \quad (88 \pm 2\%)$
$\Gamma = 50.7$ MeV
$c\tau = 4$ fm

Exp. Conditions:
Al+Al at 1.92 AGeV,
21 d running (Aug 2005)
$5 \cdot 10^8$ recorded events
10 TByte raw data



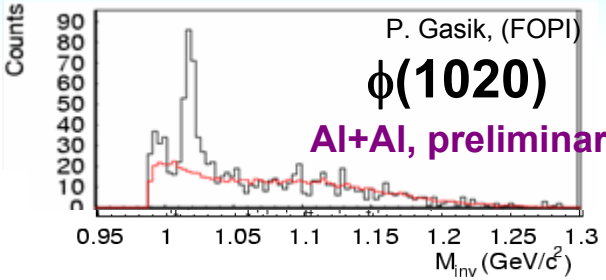


$$P_{\mathrm{det}} \approx 10^{-5}$$

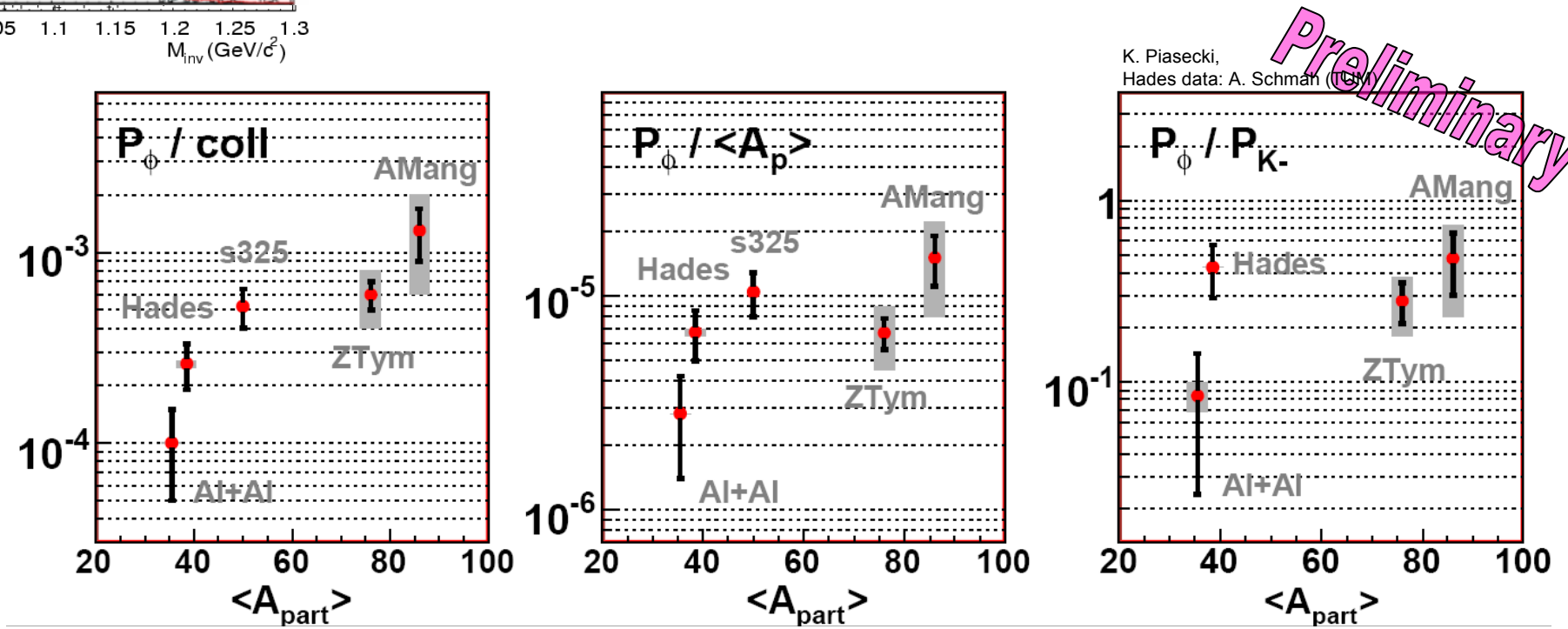
FOPIs reconstruction method and background construction works for wide resonances.

Masses and widths consistent with PDG values.

Φ – meson production systematics



$$P_{\mathrm{det}} \approx 10^{-6}$$



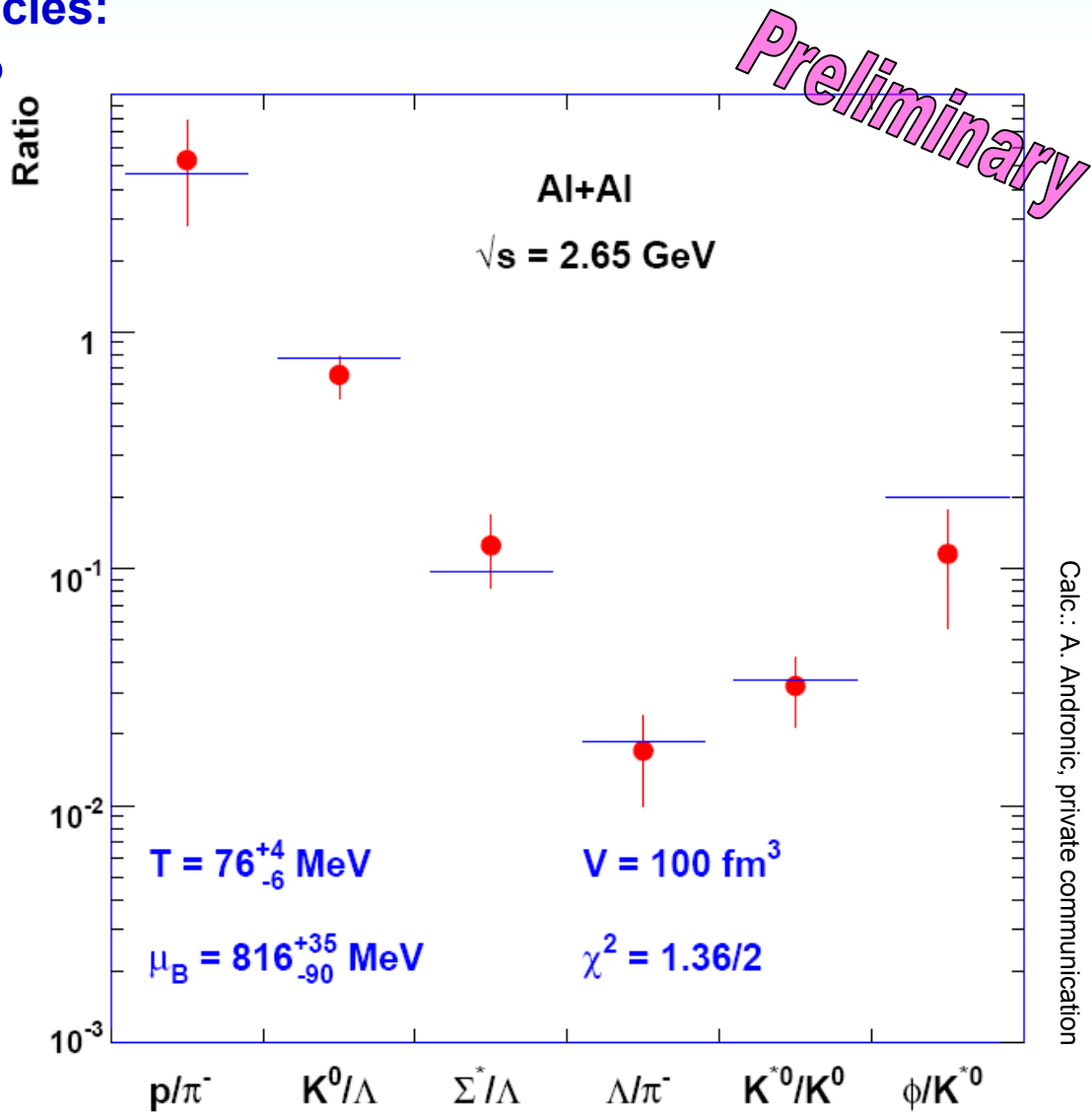
Available data still rather scarce.

Large Φ/K⁻ - ratio seems to be confirmed (A.Mangiarotti et al. (FOPI), NPA 714, 89 (2003) **)**
15% - 20% of all K⁻ are produced via the ϕ - meson and will not see any attractive K⁻ - potential.

Necessary to extend studies to larger size systems.

Particle yields at freeze-out

5 independent ratios with 4 strange particles:
p, π^-, K^0, ($\Lambda+\Sigma^0$), $K^{*0}(892)$ and $\Sigma^{*\pm}(1385)$, ϕ
in Al+Al @ 1.9 AGeV



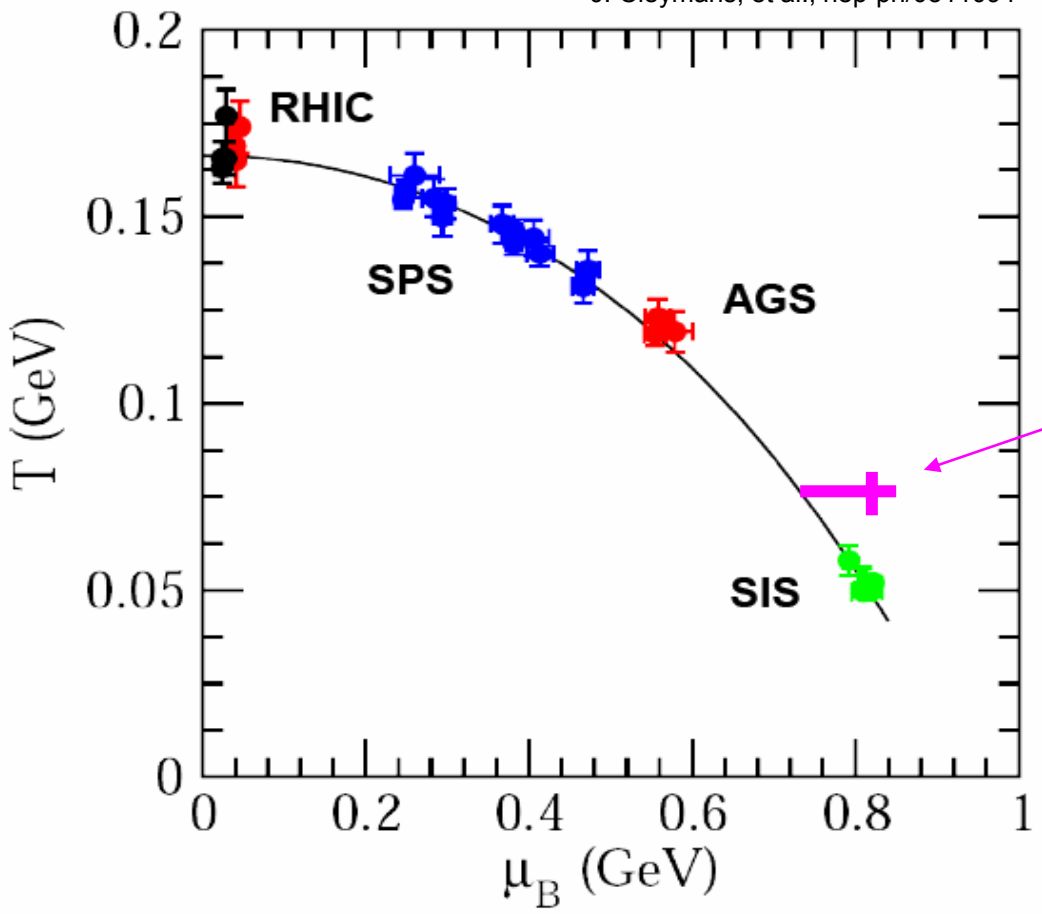
Comparison to statistical model:

- canonical ensemble (γ_s = 1)

Equilibrium picture works surprizingly well for Al+Al with γ_s=1 !

Freeze-out points in phase diagram

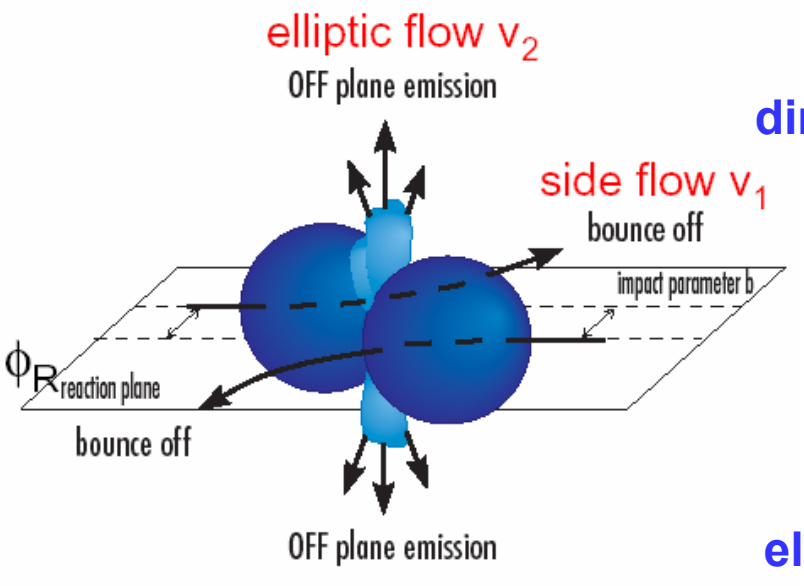
J. Cleymans, et al., hep-ph/0511094



Al + Al @ 1.9 AGeV

Chemical equilibrium seems to be achieved even in Al+Al.
Equilibration mechanism not understood yet in transport.
T(Al + Al) > T(Au + Au).
In-medium effects need to be extracted from other observables.

Kaon – flow measurements

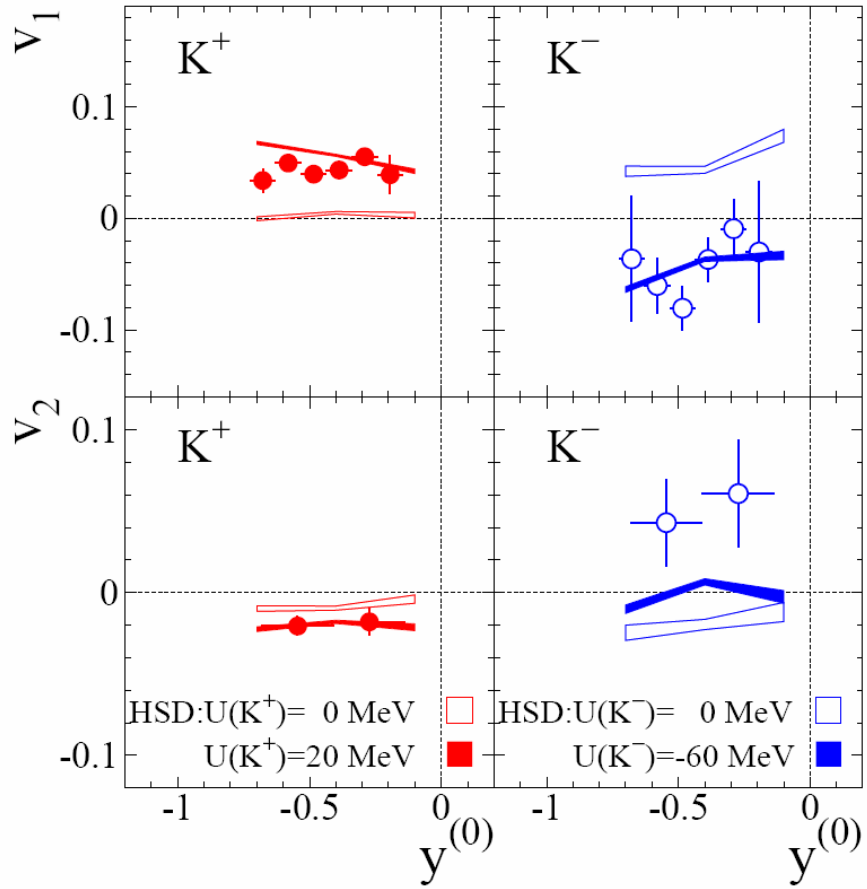


directed flow:

elliptic flow:

Ni+Ni @ 1.93 AGeV

Y.J.Kim (FOPI)



Sensitivity of flow to depth of kaon potential: $U(K^+) = +20$ MeV, $U(K^-) < -60$ MeV

For K^- no consistent description yet by transport models.

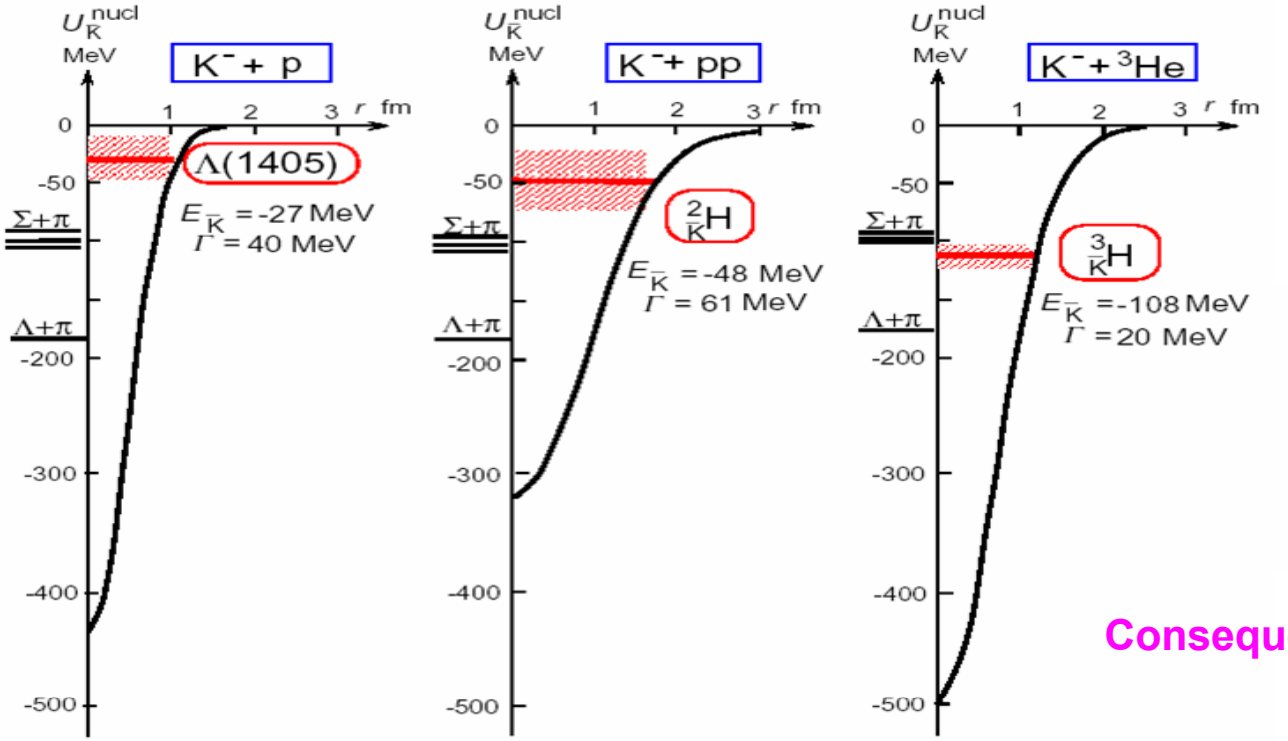
HSD – E. Bratkovskaya et al. (Frankfurt, Giessen)

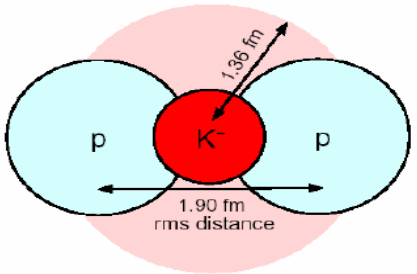
IQMD – C. Hartnack et al. (Nantes)

Phenomenological $\bar{K}N$ - potential

$\bar{K}N$ interaction is strongly attractive ! $\Lambda(1405)$ is (K^-p) bound state.

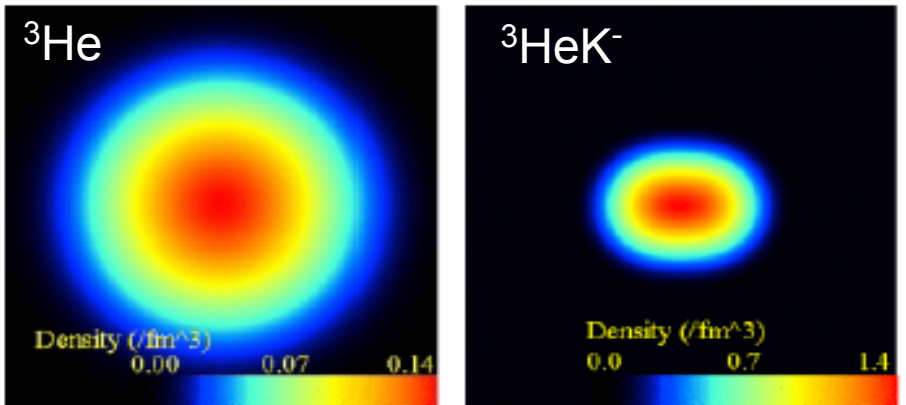
Y. Akaishi, T.Yamazaki, Phys.Rev.C65, 044005 (2002)
T.Yamazaki and Y. Akaishi, Phys.Lett.B535, 70 (2002)





Consequence of strong attraction: Shrinking!

A.Dote et al., PRC70,044313(2004)

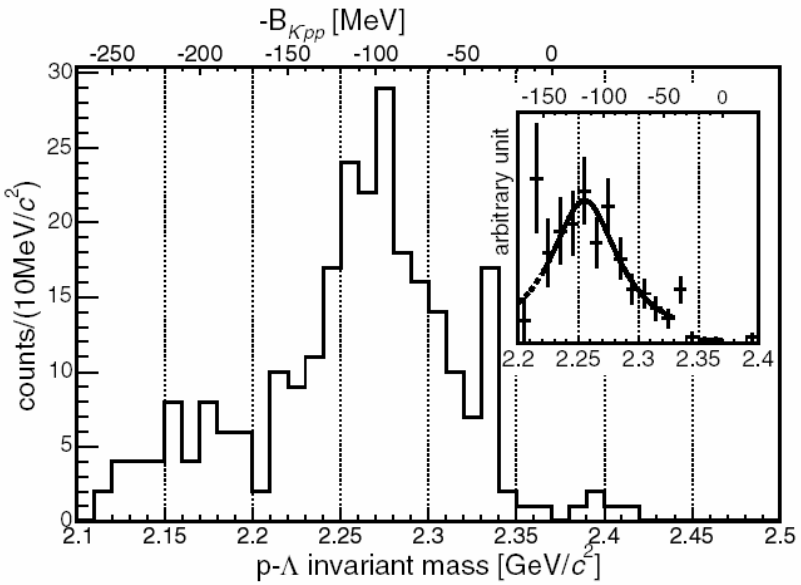


AY- potential designed to:

- describe scattering length of free KN scattering
- X-ray shifts of kaonic hydrogen atom
- mean and width of $\Lambda(1405)$

Evidence for $(ppK^-)_{bound}$ by FINUDA @ DaΦne

M. Agnello et al., PRL 94, 212303 (2005)



$$e^+e^- \rightarrow \Phi \rightarrow K^+K^-$$

$$K^- + A \rightarrow (ppK^-) + X \rightarrow \Lambda + p + X$$

(invariant mass spectroscopy)

Production probability:

P·BR = 0.1% per stopped K^-

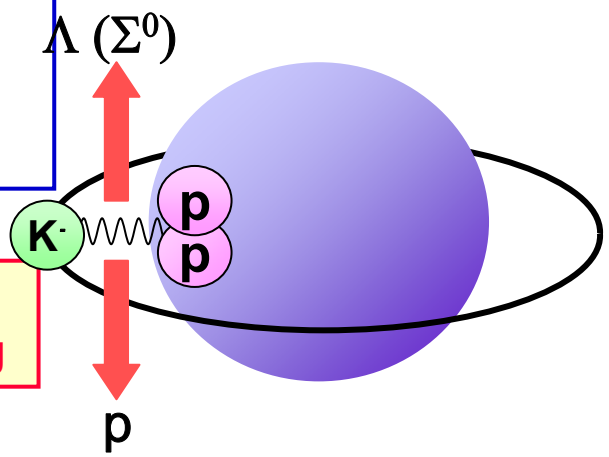
Peak parameter:

$M = 2.255 \pm 0.009$ GeV

$\Gamma = 67^{+14+2}_{-11-3}$ MeV

Controversial interpretation:
2N absorption + rescattering

V.K. Magas, E. Oset, et al., nucl-th/0601013



Bound state predictions for ppK^-:

Author	Ref.	Mean (GeV)	Width (MeV)
Akaishi, Yamazaki	PRC65, 044005 (2002)	2.322	61
Dote, Weise	nucl-th/0701050	2.310	100
N.V. Shevchenko et al.	PRL 98, 082301 (2007)	~2.310	~100

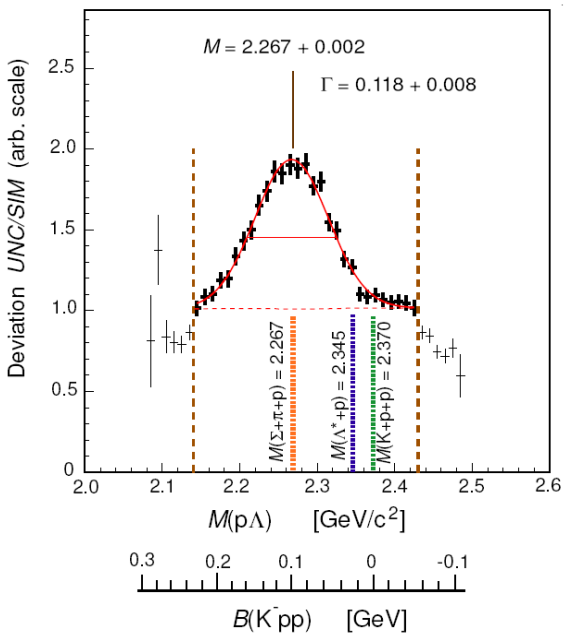
New data on $(ppK^-)_{bound}$

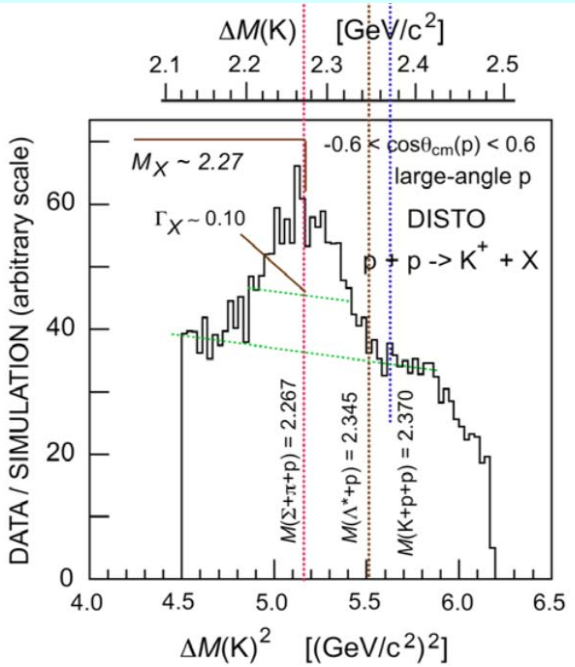
T. Yamazaki, et al.
Exa2008, Vienna, last week:
(reanalysis of old DISTO data)

$p + p \rightarrow K^+ + X \rightarrow K^+ + \Lambda + p$ at 2.85GeV

Production probability:
$X / \Lambda = 0.1$
Peak parameter:

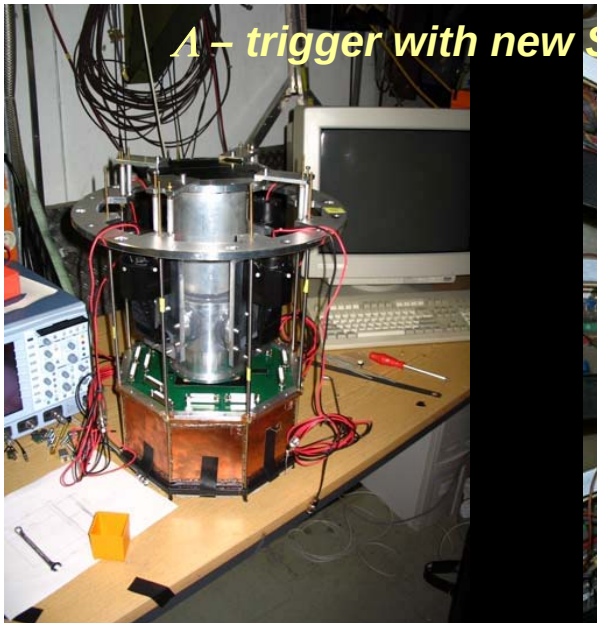
$$M = 2.265 \pm 0.002\ \text{GeV}$$
$$\Gamma = 118 \pm 0.008\ \text{MeV}$$

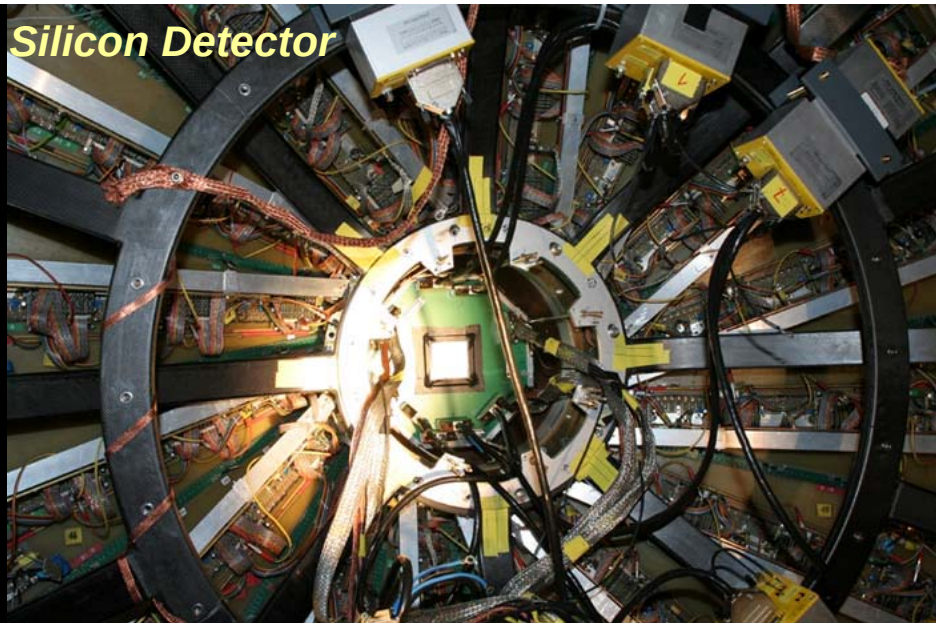




FOPI pp - program:
L. Fabbietti (TUM)

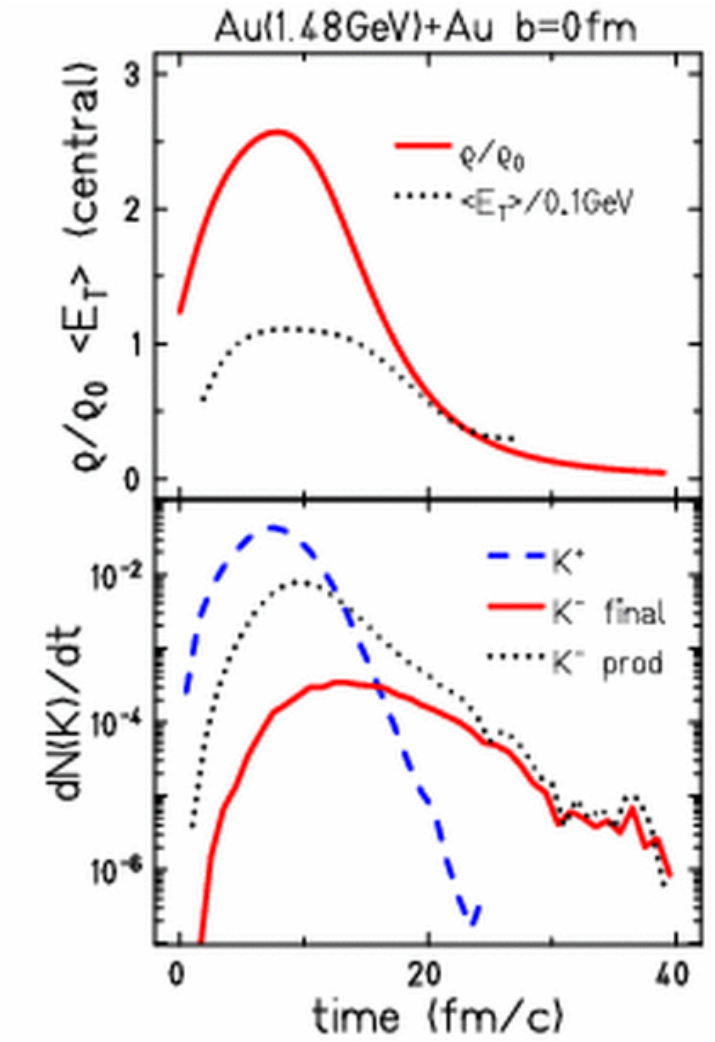
production run planned
for 2009





Antikaon Cluster Production in HI collisions

IQMD, C.Hartnack, Nantes



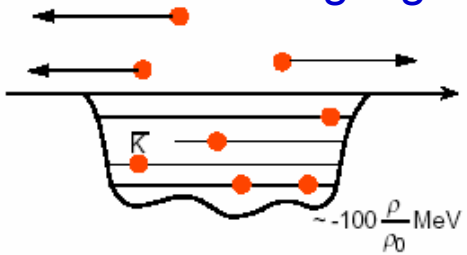
Central density in HI collisions from transport model calculations:

$\rho_{max}=2\text{-}3 \cdot \rho_0$

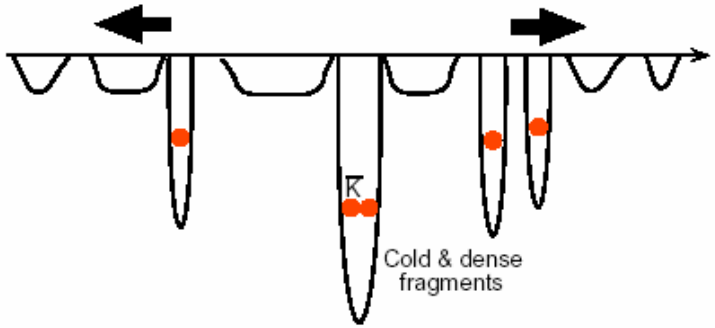
Possible mechanism for cluster formation:

T.Yamazaki et al., NPA738,168 (2004)

1) Kaon production during high density phase

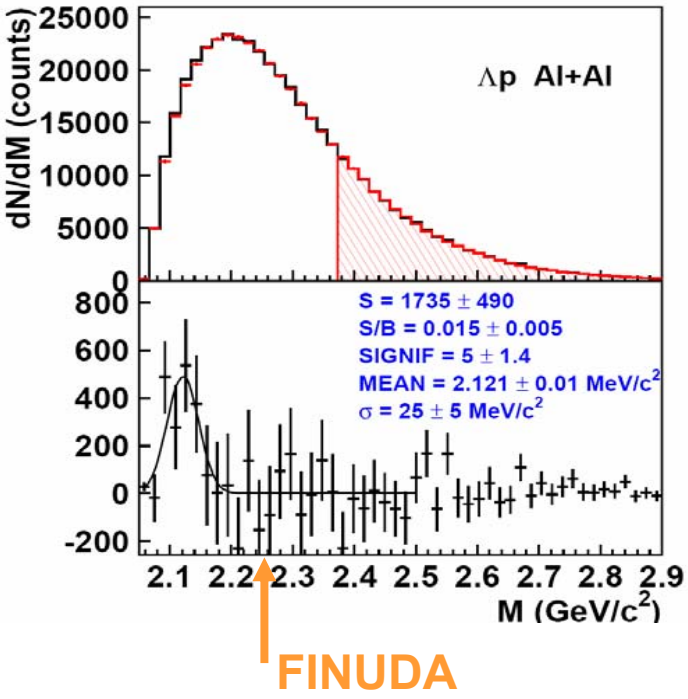


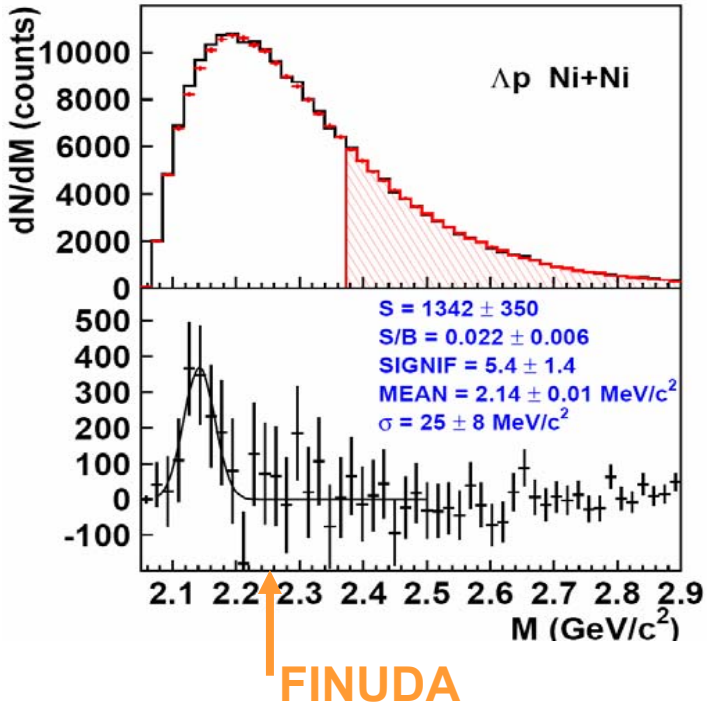
2) capture of K^- in deep trapping centers



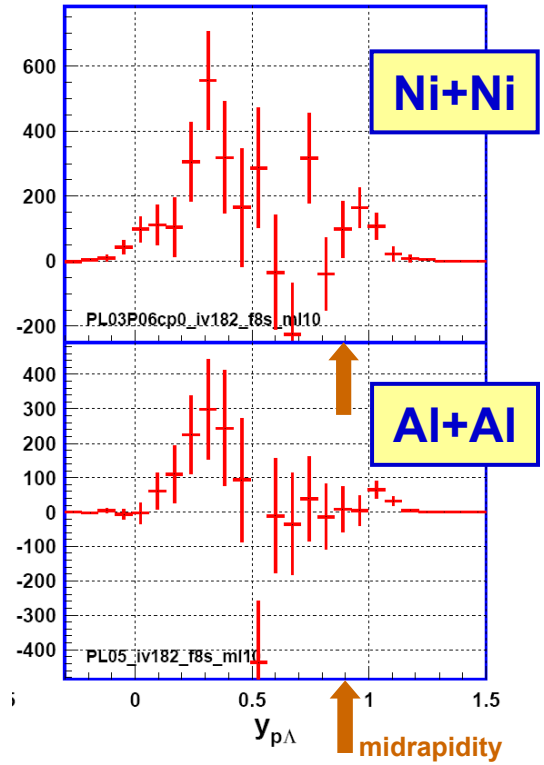
Search for ppK$^-$

Λp – invariant mass





Rapidity distribution

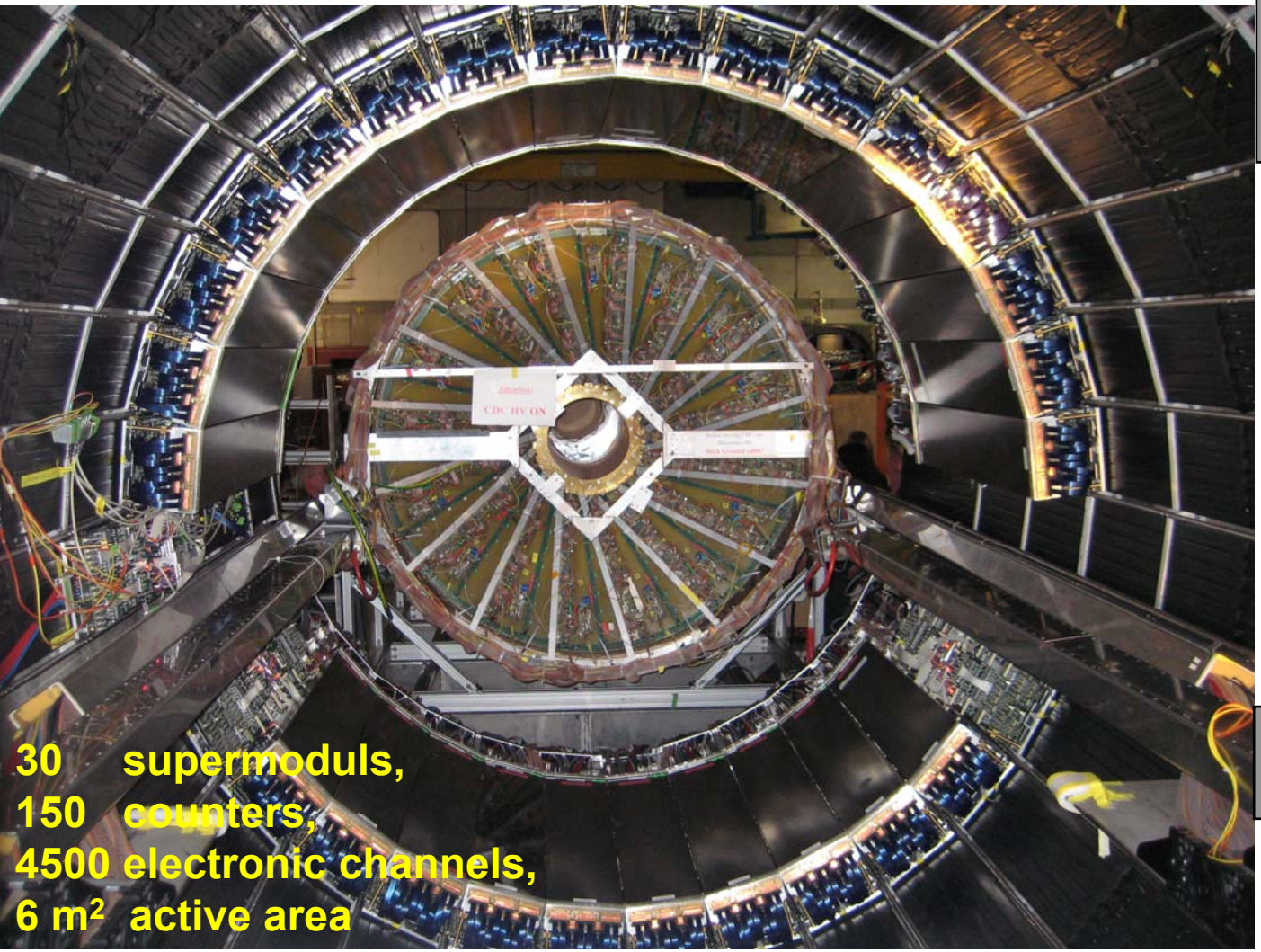


Excess observed in Ni+Ni and Al+Al with statistical significance of ~ 5.
Yield located in spectator/fireball interface region (like non-strange clusters).
Peak position in variance with FINUDA result.

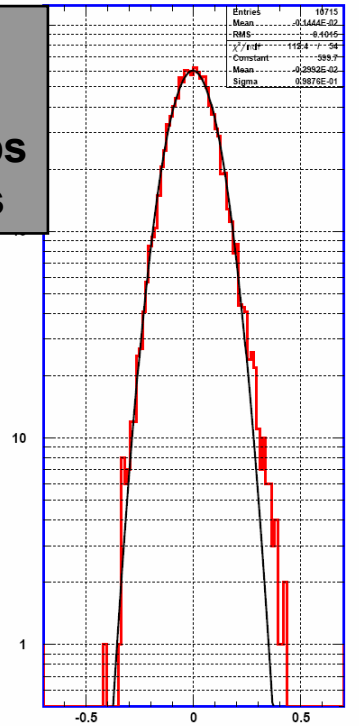
Possible interpretation: ΣN – bound state H(2129)
Object seen in $K^- + d \rightarrow \Lambda p \pi^-$ (O. Braun et al., NPB 124,45 (1977))

Final round of experiments in 2008 - 2010 with improved PID

New MMRPC TOF Barrel

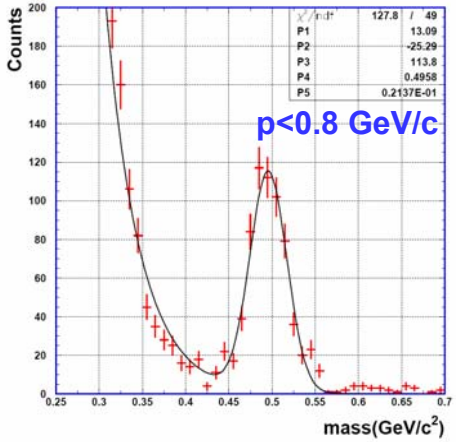


Performance:
(Oct. 2007)
σ_{system} ~ 100 ps
σ_{RPC} ~ 65 ps



$\Delta t = t_{meas} - t_{exp}$ (ns)

K^- - PID:
S/B > 10



September 2003

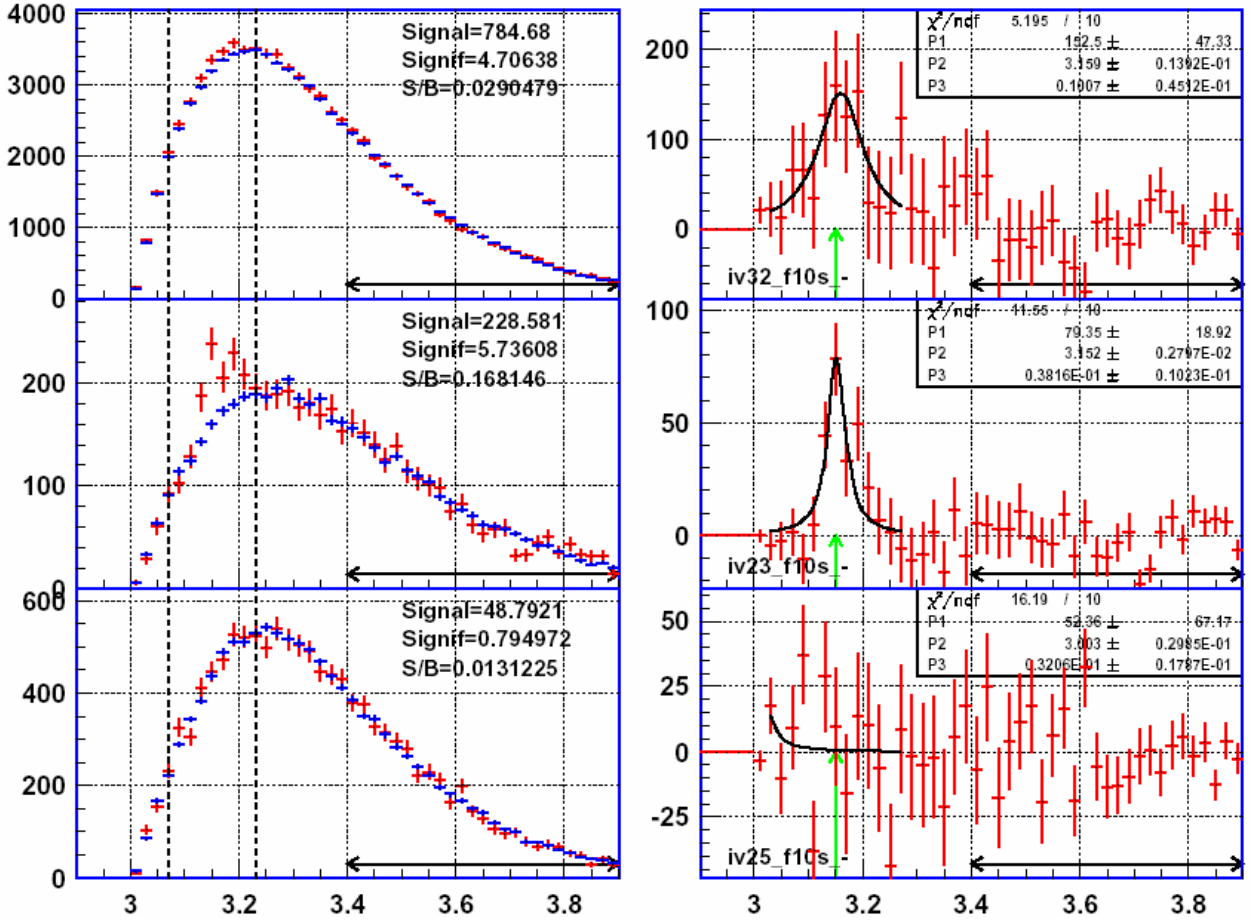
* described in proceedings EXA05, Vienna (2005)

Λd – Correlation Signal in Ni + Ni

Subevents rotated
Vertex shifted
Lambda Cut "s"

Possible decay channel:

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



M_{inv} (Λ+d) (GeV)

Data

additional cuts:

$|\Delta\phi|>30^0$

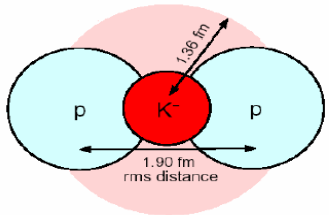
$y_{pair} < 0.65$

Signal-MC

Background-MC

d-Cuts:

HM3MIN	
D03MAX	
PT3MIN	
PT3MAX	
Sdxy3max	
M3LOW	1,7
M3HIGH	
DML	
DPHL3MIN	30
YDLMAX	0,65
PTDLMIN	
PTDLMAX	
CCNT	<10
BM3MIN	
	F10

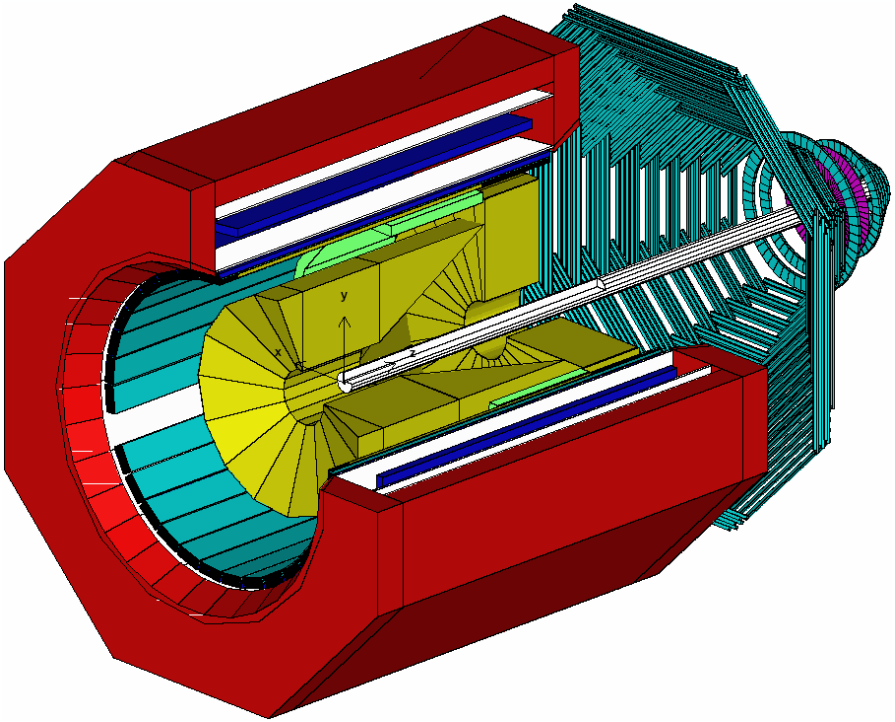


Properties: (?)

M ≈ M(KEK) = 3.14 GeV

Γ >> 20 MeV > Γ(KEK)

Strange baryon program with FOPI @ GSI



IPNE Bucharest, Romania
CRIP/KFKI Budapest, Hungary
LPC Clermont-Ferrand, France
GSI Darmstadt, Germany
FZ Rossendorf, Germany
Univ. of Warsaw, Poland
IMP Lanzhou, China
TUM, Munich, Germany
+ P. Kienle (TUM), T.Yamazaki(RIKEN)

ITEP Moscow, Russia
Kurchatov Institute Moscow, Russia
Korea University, Seoul, Korea
IReS Strasbourg, France
Univ. of Heidelberg, Germany
RBI Zagreb, Croatia
SMI Vienna, Austria

A. Andronic, R. Averbeck, Z. Basrak, N. Bastid, M.L. Benabderramahne, P. Bühler, R. Caplar, M. Cargnelli, M. Ciobanu, P. Crochet, I. Deppner, P. Dupieux, M. Dzelalija, L. Fabbietti, F. Fu, P. Gasik, O. Hartmann, N. Herrmann, K.D. Hildenbrand, B. Hong, T.I. Kang, J. Keskemeti, Y.J. Kim, M. Kis, M. Kirejczyk, P. Koczon, M. Korolija, R. Kotte, A. Lebedev, K.S. Lee, Y. Leifels, X. Lopez, J. Marton, M. Merschmeyer, D. Moisa, M. Petrovici, K. Piasecki, F. Rami, V. Ramillien, A. Reischl, W. Reisdorf, M.S. Ryu, A. Schüttauf, Z. Seres, B. Sikora, K.S. Sim, V. Simion, K. Siwek-Wilczynska, K. Suzuki, Z. Tyminski, K. Wisniewski, Z. Xiao, H.S. Xu, J.T. Yang, I. Yushmanov, A. Zhilin, Y. Zhang, J. Zmeskal

Program:

Strangeness in

HI collision

pion induced reactions

proton-proton collisions

Summary / Conclusion

Strangeness production close to threshold is still far from being understood.

New data from FOPI at SIS18

- Inclusive K^0 production in πA
  - sensitivity to in-medium cross sections and Kaon potential at $\rho=\rho_0$
- Short lived strange resonances: ϕ, K*(892), Σ*(1395)
  (for the first time below NN – threshold)
  - chemical equilibrium in Al + Al @ 1.9 AGeV ?
- Flow of charged kaons under the same experimental condition
  - K^- - potential is attractive, magnitude is unclear
- Evidence for strange di-baryon production ($H1^+$)
  - cluster formation not yet understood

Search for multi-baryonic strange clusters ongoing

- Structures seen in Λp (Λd) final states in diff. reactions
  - confirmation of peak position and width under diff. experimental absolutely necessary

Serious theoretical effort necessary to interpret available and coming data.

Strange hadrons, especially strange multi-baryonic clusters, are an exiting possibility towards the properties of cold dense baryonic matter and non-perturbative QCD.

Strangeness physics from 2 – 10 AGeV must be revisited! ⇒ CBM @ SIS100