Subthreshold K^+ production and the nuclear equation-of-state

Dense Baryonic Matter in the Cosmos and in the Laboratory
EMMI-Workshop@Tübingen
October 2012

Introduction

brief survey

In-medium properties of Kaons - important for *transport models*

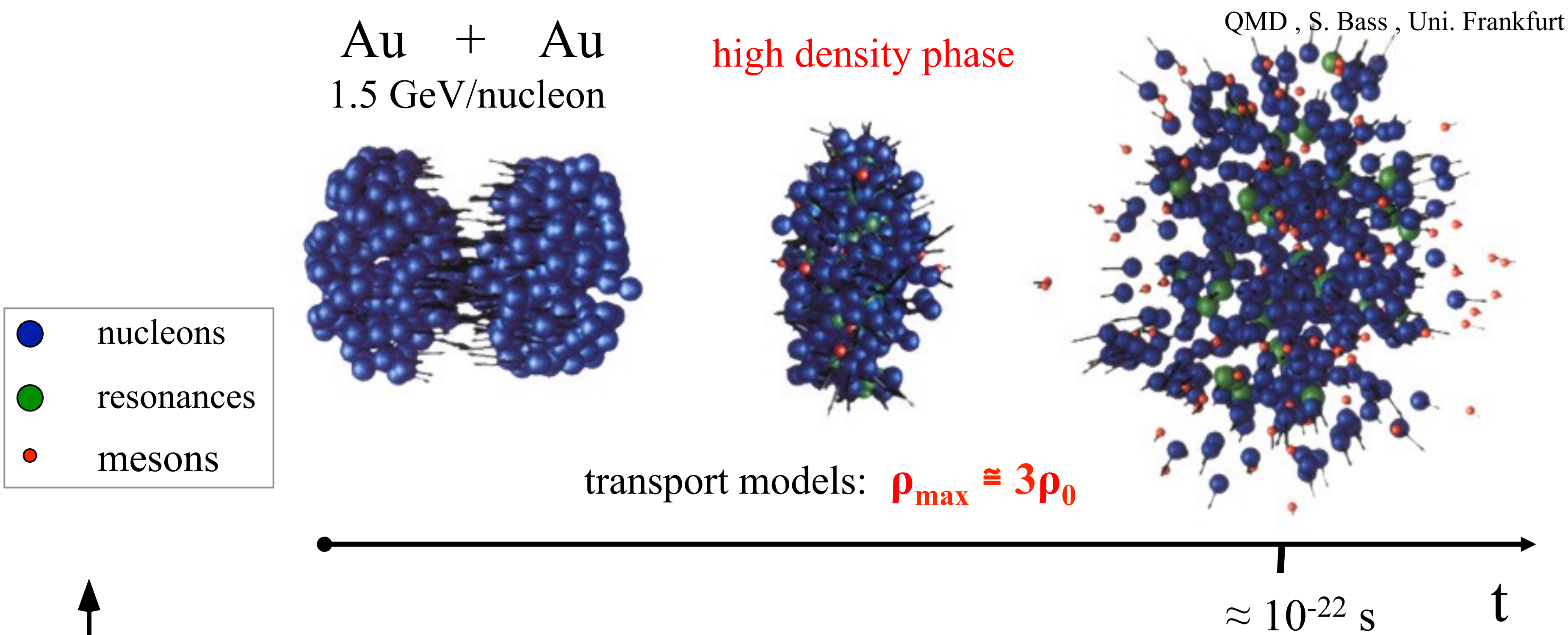
The Nuclear Equation-of-State

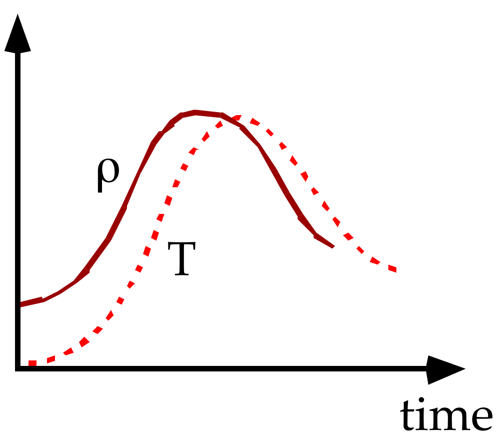
at saturation density ρ_0

at higher baryon densities

To investigate high baryon densities in the **laboratory** :

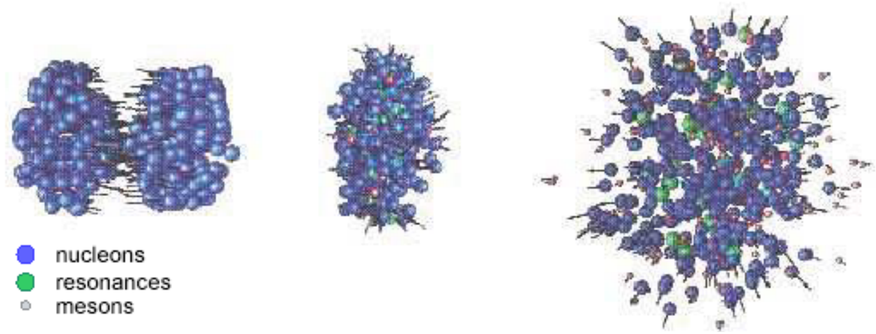
Relativistic Heavy Ion Collisions

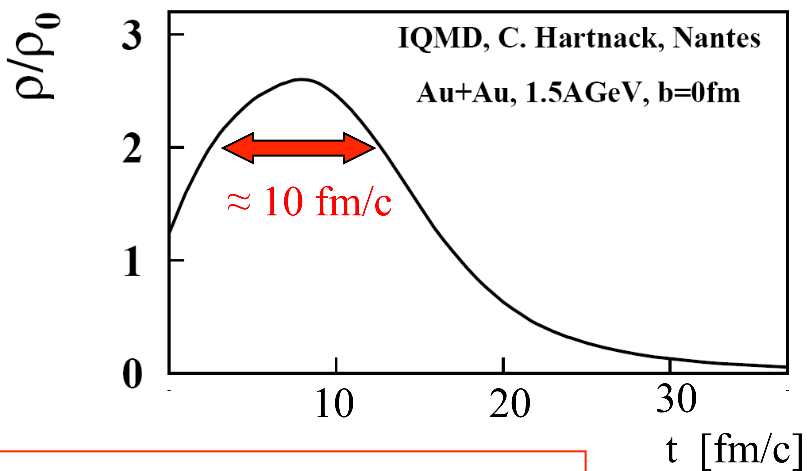




- high density and temperature on a very short time scale
- thermodynamical equilibrium not necessarily achieved

The case of moderate beam energies





Enhancement of baryon density :

$\Delta\tau\ (\rho/\rho_0 > 2) \approx 10$ fm/c

→ comparatively long life-time

at moderate densities !

Particle production
at or below threshold :

- co-operative processes
  (i.e. multi step processes)
- production confined to the
  high density phase !

multi step processes:
i.e.

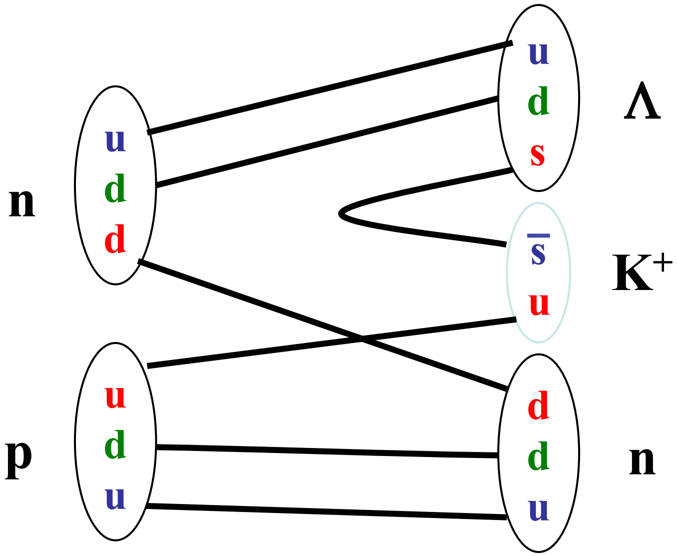
$NN \rightarrow N\Delta$

$\searrow \pi N$

$\searrow \pi N \rightarrow K^+\Lambda$

Associated production of strange mesons in elementary nucleon-nucleon reactions

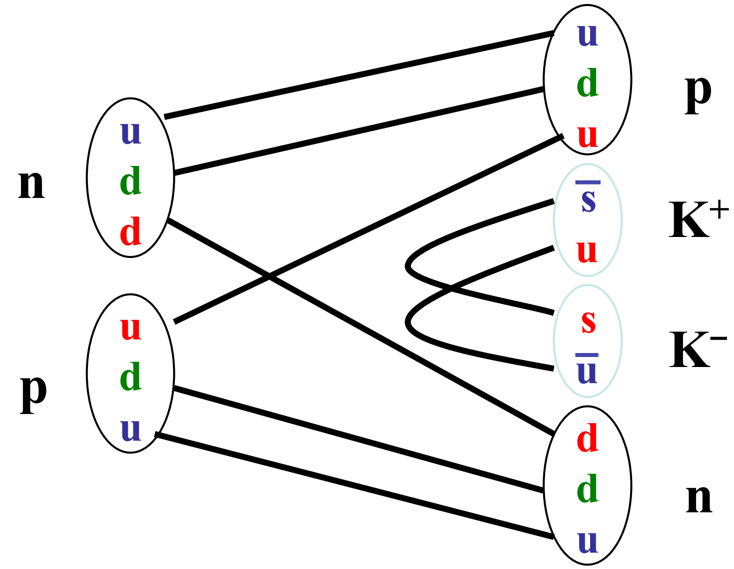
Kaons



production threshold
in NN collisions :

$E_{lab} = 1.58\ GeV$

Antikaons



production threshold
in NN collisions :

$E_{lab} = 2.5\ GeV$

Additional channels in nucleus-nucleus collisions

e.g. $NN \rightarrow N\Delta$

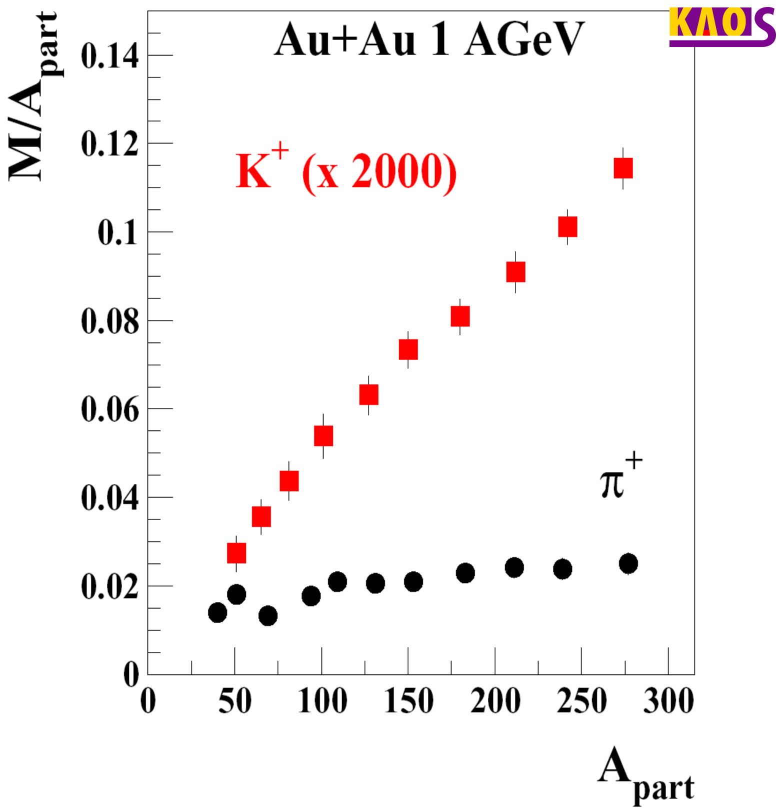
$N\Delta \rightarrow NK^{+}Y$

$\pi N \rightarrow K^{+}Y$ (Y=Λ,Σ)

multi step processes !

Au + Au 1 GeV / nucleon :
Kaons are predominantly produced during the high density phase of the collision!

"Subthreshold" K^+ production

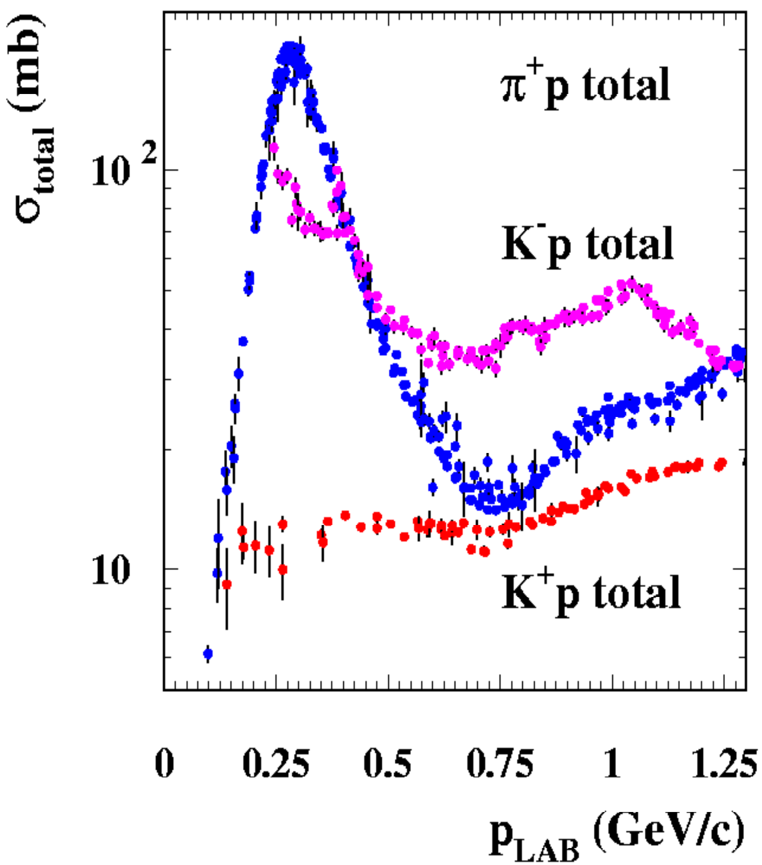


peripheral → central collisions

M: multiplicity = number / per collision

A_{part} : number of participating nucleons

Final state interaction



mean free path at ρ_0:

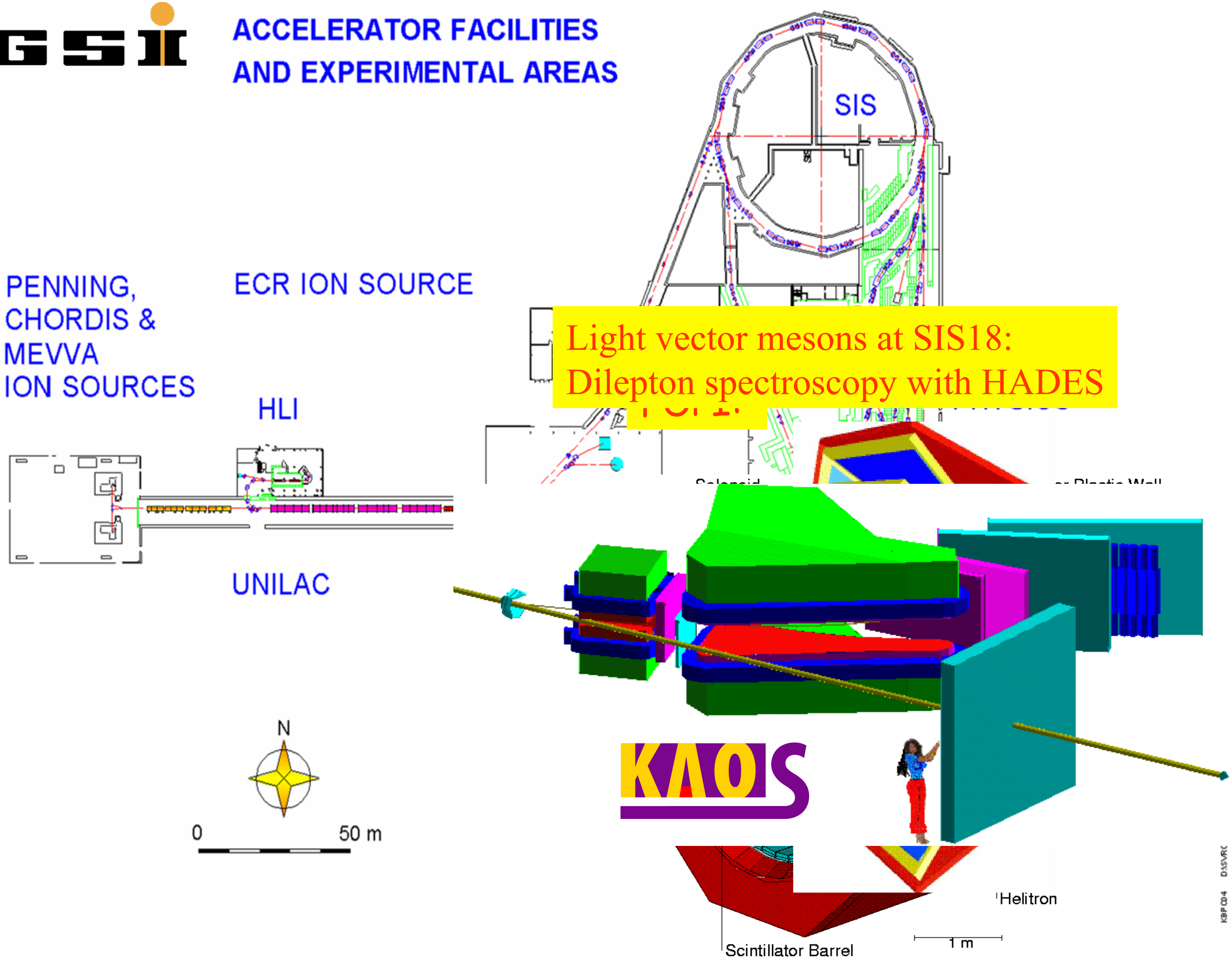
$\lambda_{\pi^+} \cong 0.3\,fm$

$\lambda_{K^+} \cong 5\,fm$

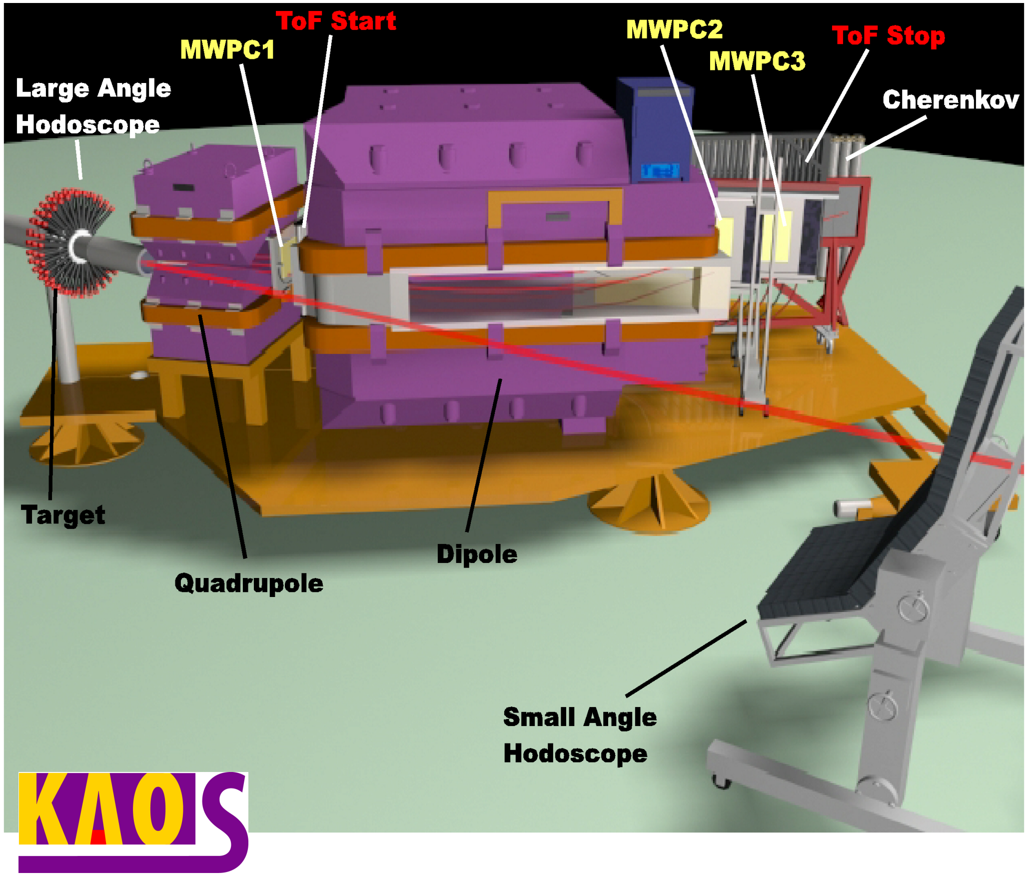
$\lambda_{K^-} \cong 0.8\,fm$

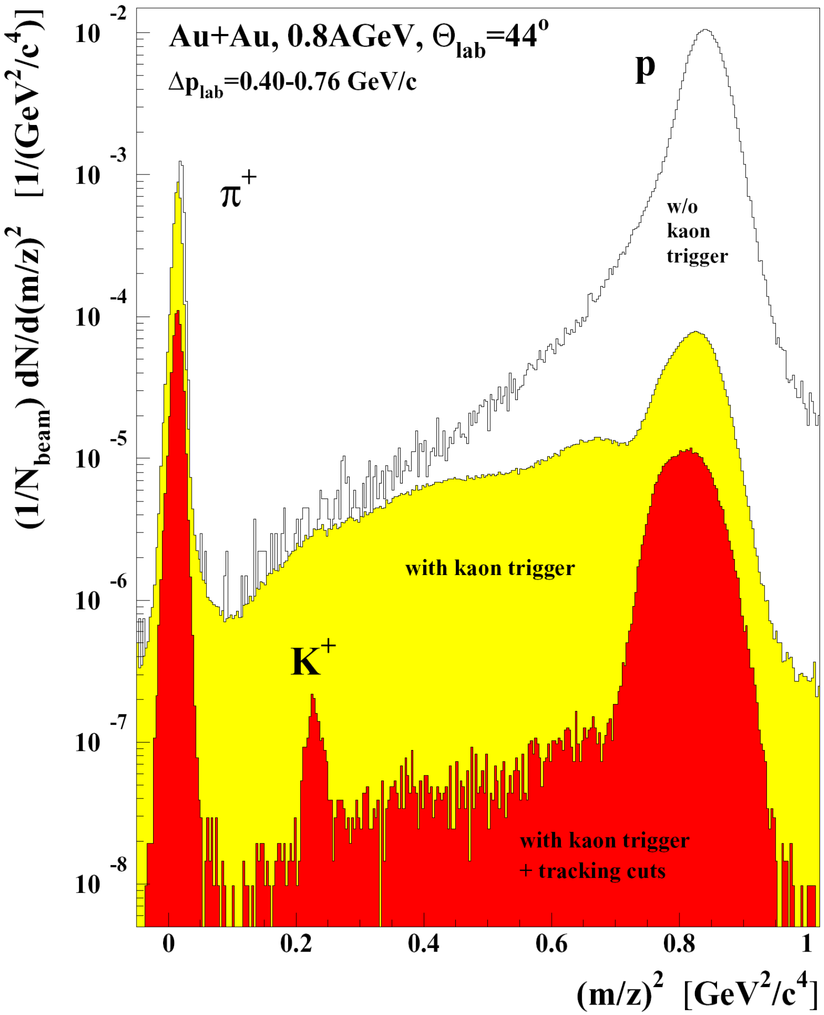
K^+
- no absorption
- only elastic scattering

Light vector mesons at SIS18: Dilepton spectroscopy with HADES

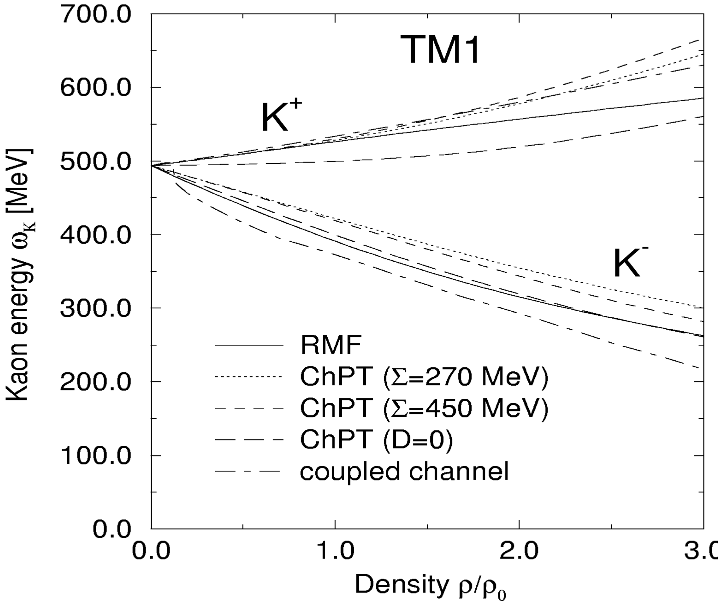


The Kaonspectrometer at GSI/SIS18





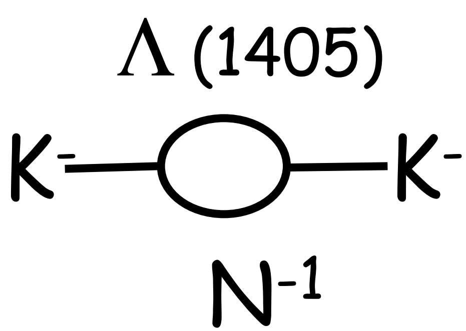
In-medium modification of Kaons and Antikaons in dense nuclear matter



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

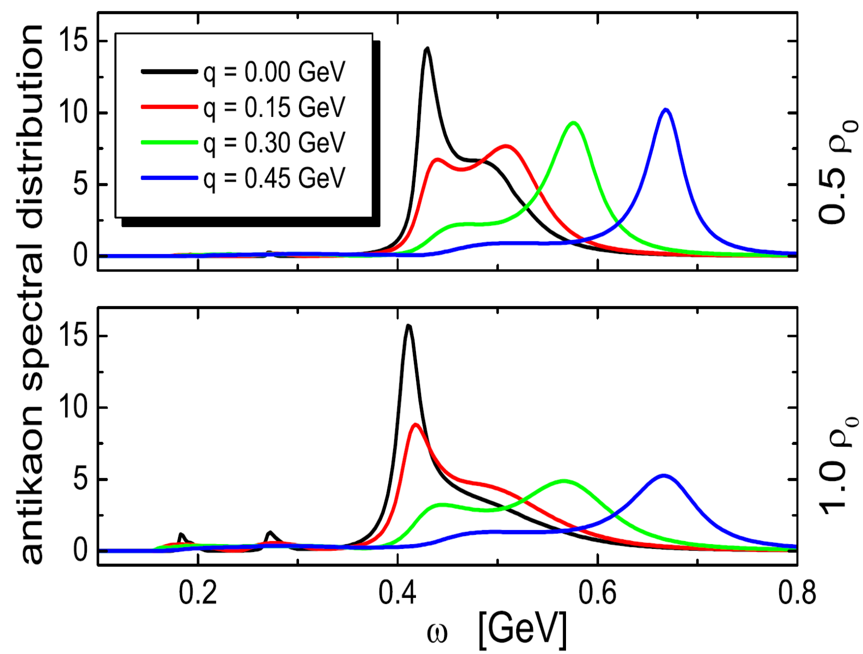
T. Waas, N. Kaiser, W. Weise, Phys. Lett. B 379 (1996) 34

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



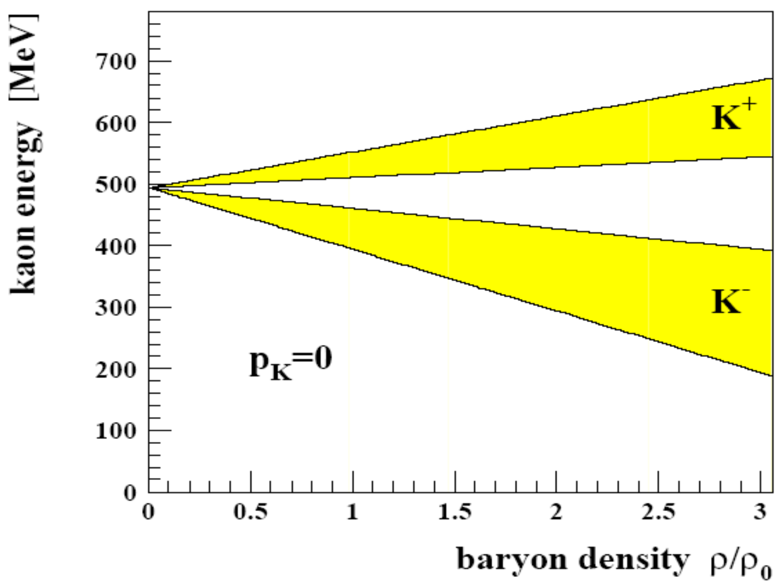
self-consistent coupled channel calculation with mean field (s,p,d waves)

M.F.M. Lutz, C.L. Korpa, M. Möller, nucl-th/07071283



In-medium modification of Kaons and Antikaons

(envelope of several microscopic calculations:
all predict the same trend !)



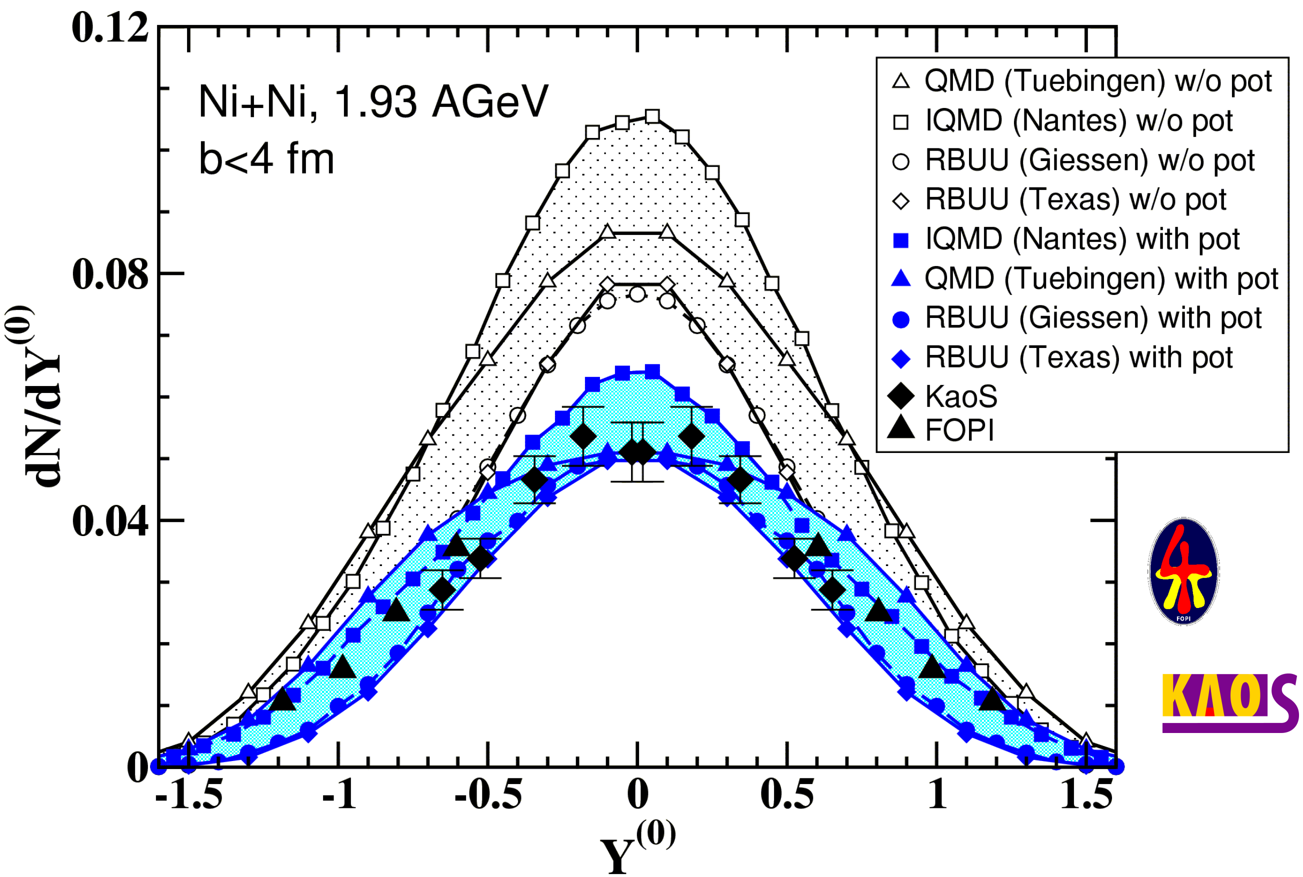
repulsive K^+ N potential

attractive K^- N potential

<u>This should effect:</u>
production → yield
propagation → angular distributions

In-medium modification of Kaons

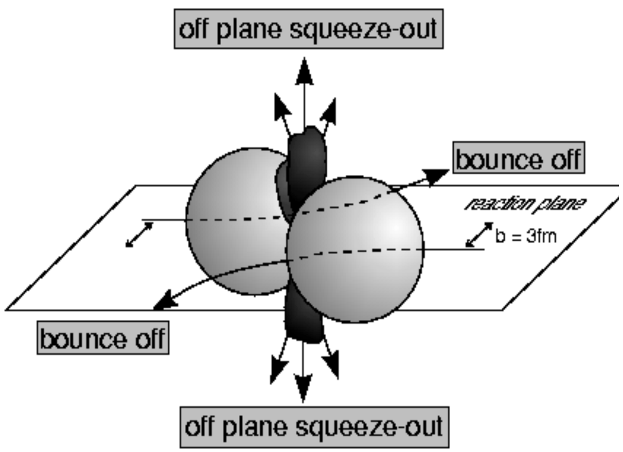
Data: M. Menzel et al., (KaoS Collab.), Phys. Lett. B 495 (2000) 26
K. Wisniewski et al., (FOPI Collab.), Eur. Phys. J A 9 (2000) 515

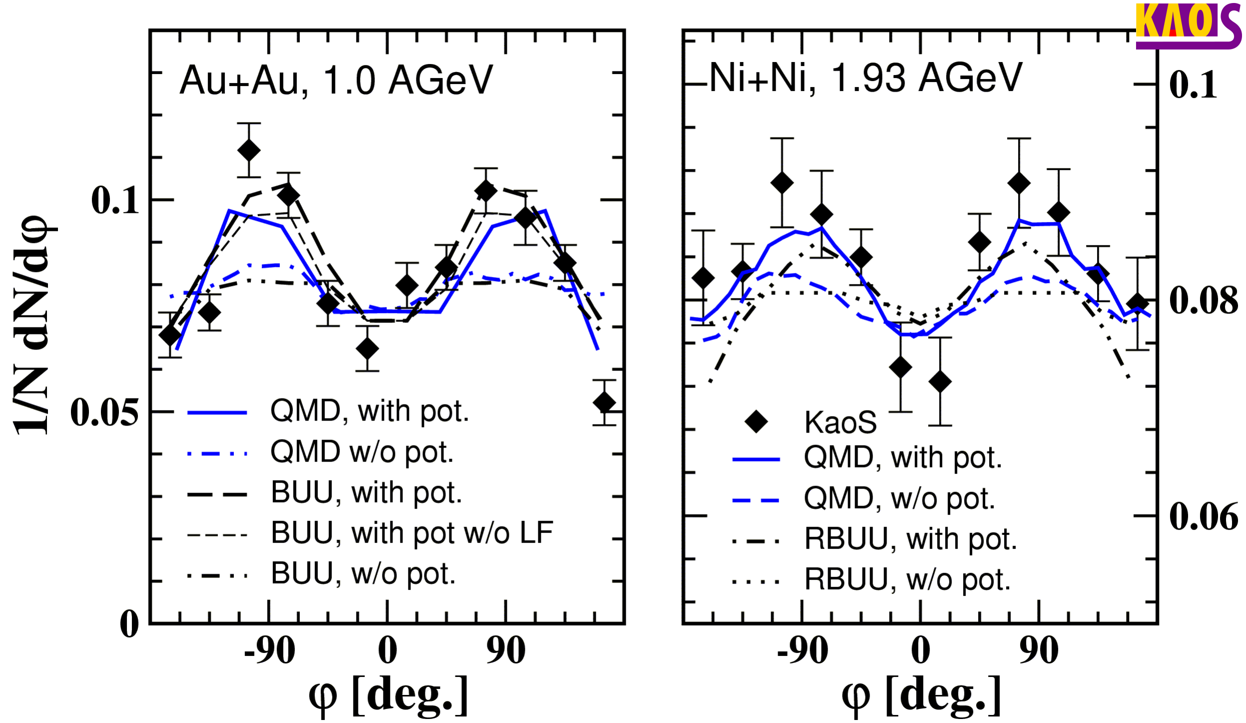


Reduced K^+ yield due to increased in-medium K^+ mass

K+ azimuthal emission pattern from A+A collisions

Data: Y. Shin et al., (KaoS Collaboration), Phys. Rev. Lett. 81 (1998) 1576
F. Uhlig et al., (KaoS Collaboration), Phys. Rev. Lett. 95 (2005) 012301
Calculations see A. Larionov, U. Mosel, nucl-th/0504023

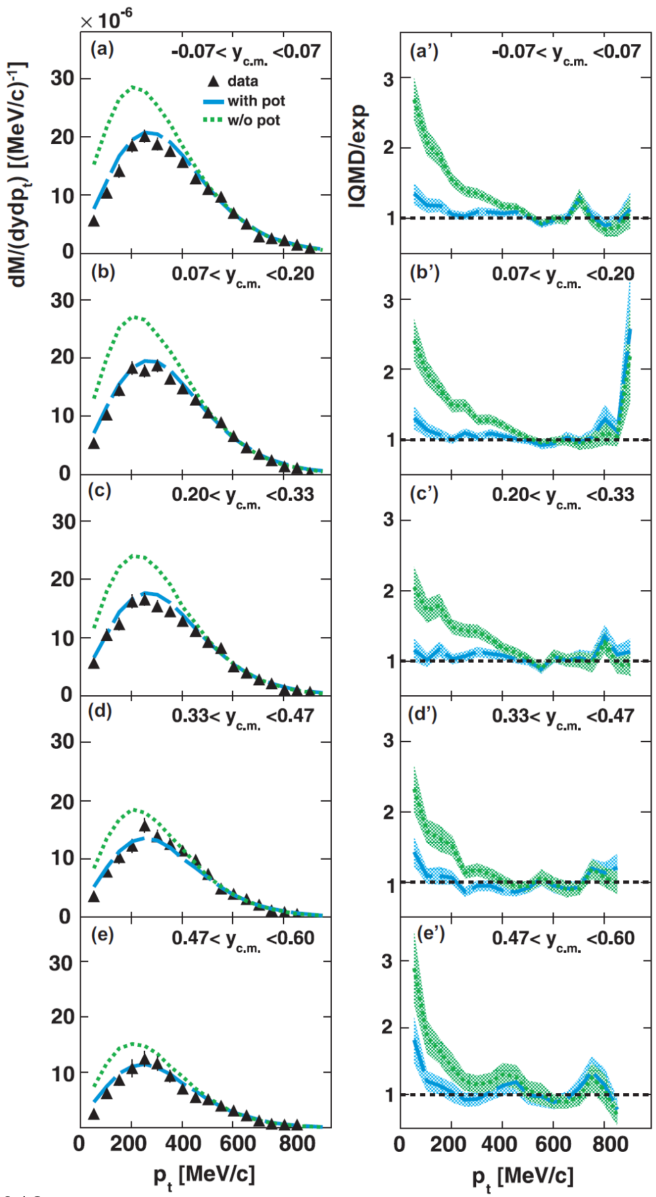




Evidence for a repulsive K^+N interaction !

K^0 production in Ar + KCl reactions

HADES



Ar + KCl 1.756 GeV / nucleon
PRC82 (2010)

IQMD:
repulsive K^0N-potential of 46MeV

Strangeness production in proton - nucleus collisions

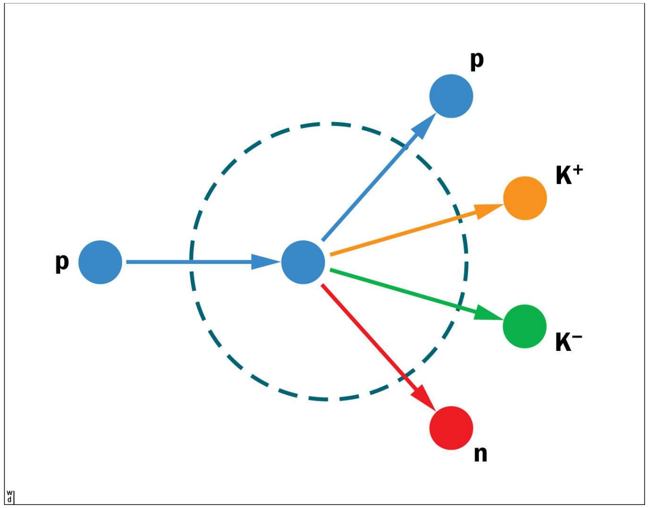
Search for in-medium effects at saturation density !

$p + C \rightarrow K^+ + X$ (1.6, 2.5, 3.5 GeV)

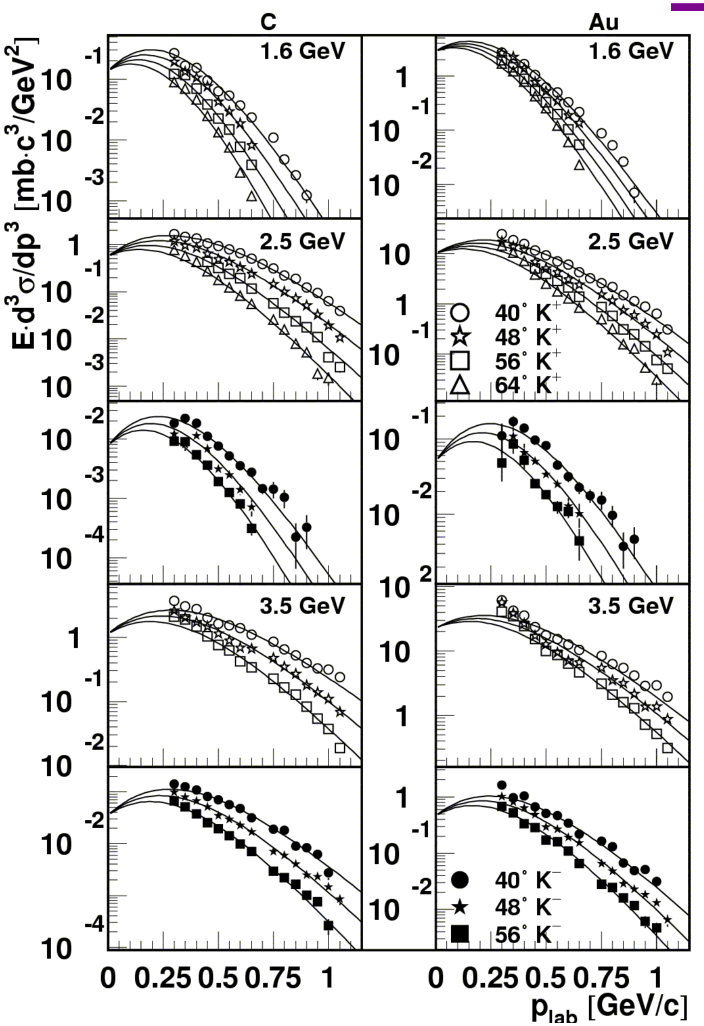
$p + C \rightarrow K^- + X$ (2.5, 3.5 GeV)

$p + Au \rightarrow K^+ + X$ (1.6, 2.5, 3.5 GeV)

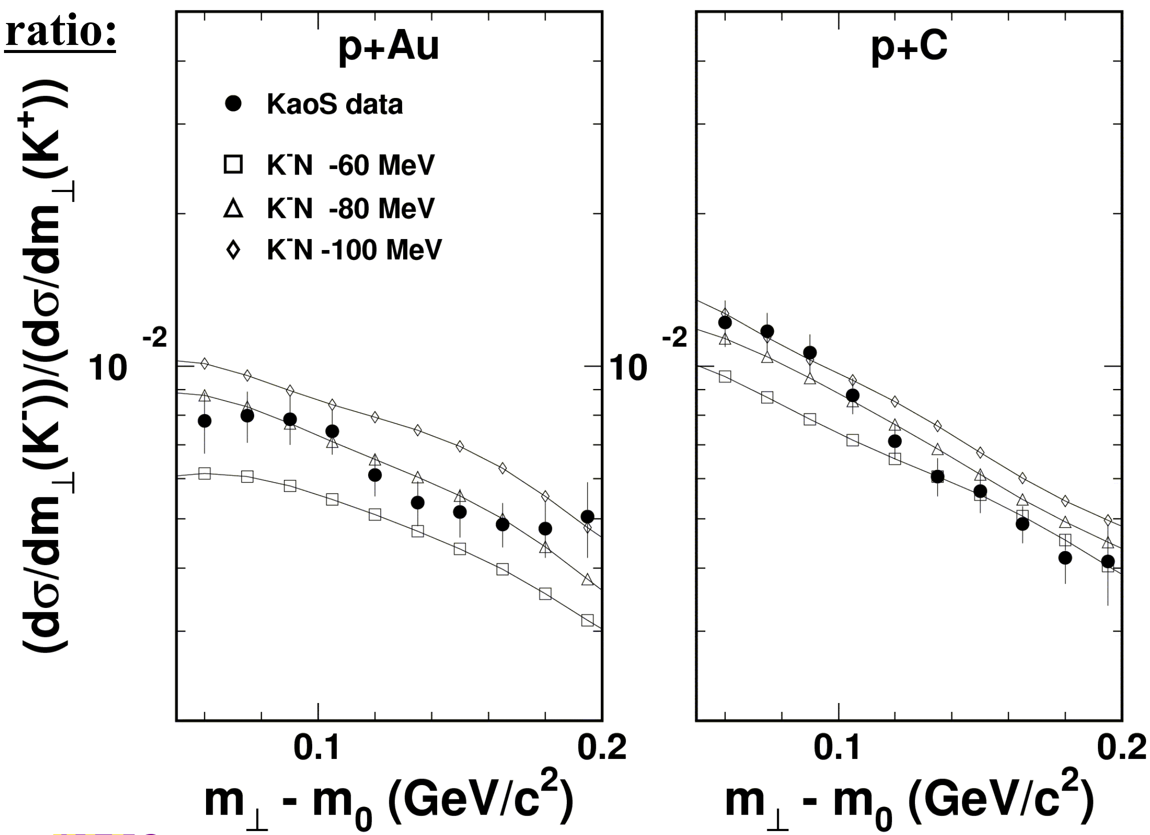
$p + Au \rightarrow K^- + X$ (2.5, 3.5 GeV)



W. Scheinast et al., (KaoS Collaboration)
Phys. Rev. Lett. 96 (2006) 072301



Kaon and Antikaon in-medium potentials at ρ_0



Transport calculation:
H. W. Barz et al.,
PRC68 (2003) 041901

contributing channels:

$p + N \rightarrow K^+ + \Lambda$

$p + N \rightarrow N + N + K^+ + K^-$

$\Lambda + N \rightarrow N + N + K^-$

In-medium KN potentials used:

$$V_{K^+N} = +(25 \pm 5)\rho/\rho_0\ MeV$$

$$V_{K^-N} = -(80 \pm 20)\rho/\rho_0\ MeV$$

Conclusion
In-medium modification of Kaons and Antikaons

Yield and elliptic flow of Kaons in A+A collisions:

↳ The in-medium Kaon-Nucleon potential is repulsive

Yield of Kaons and Antikaons in proton-nucleus collisions:

↳ in-medium K^-N potential $V_{K^-N} = -\ 80 \pm 20\ \rho/\rho_0$ MeV

↳ in-medium K^+N potential $V_{K^+N} = 25 \pm 5\ \rho/\rho_0$ MeV

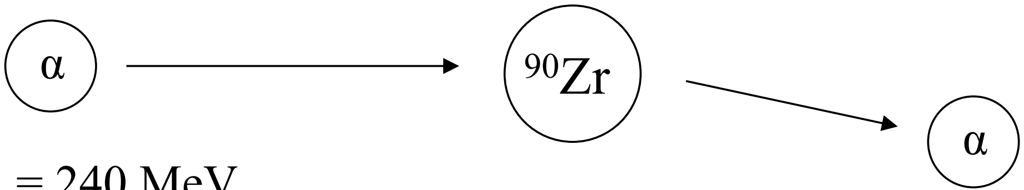
Yield and elliptic flow of Antikaons in A+A collisions:

↳ Quantitative interpretation of data requires off-shell transport calculations (dealing with spectral functions !)

The compression modulus of nuclear matter **at saturation density ρ_0** : Excitation of the giant monopole resonance

inelastic scattering of α particles on nuclei

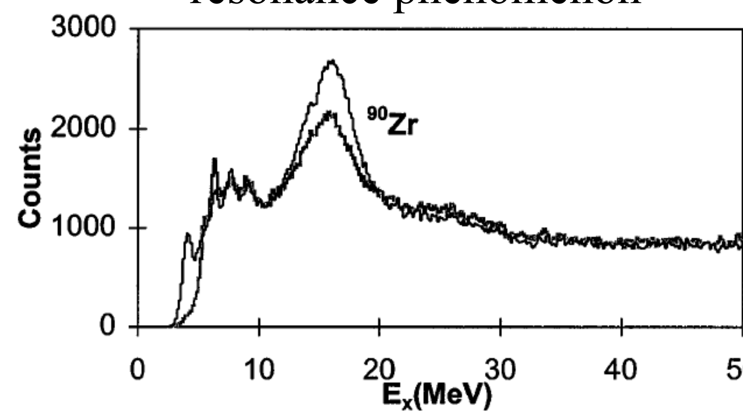
Youngblood et al. , Phys. Rev. Lett. 82 (1999)691



E_{kin} = 240 MeV

measure of the total energy of the outgoing α particle → E_x

"resonance phenomenon"

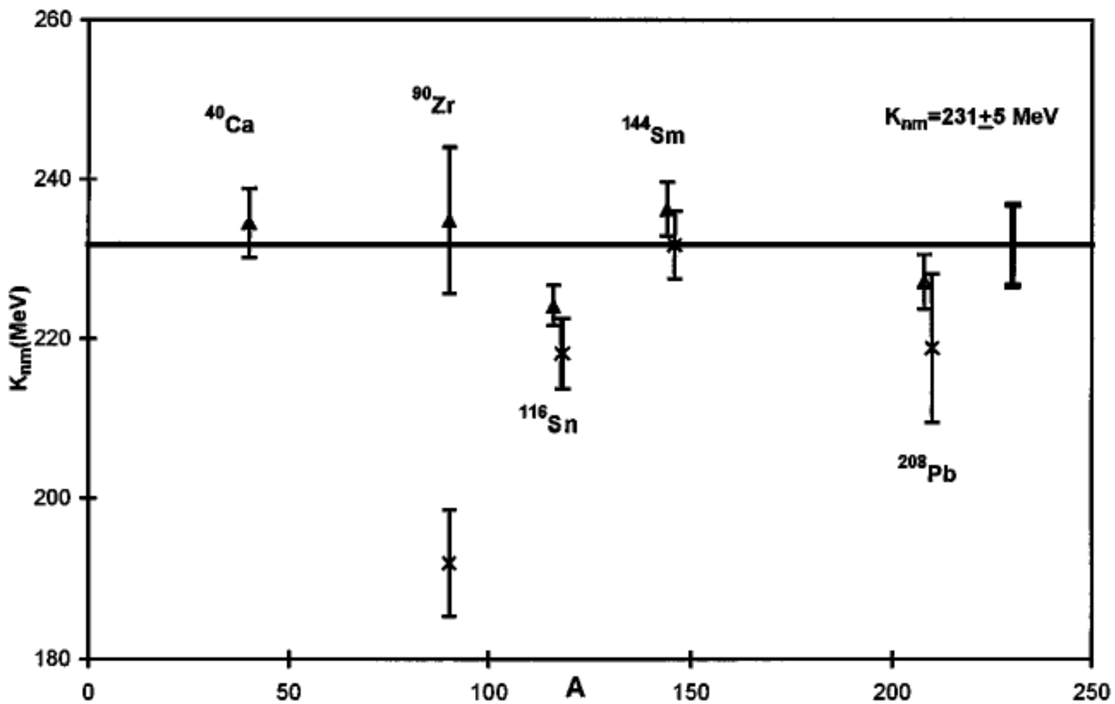


The energy loss of the α particle of about 15 – 25 MeV excites slight density oscillations with elongations of about 1/100 ρ_0 (around saturation density ρ_0). It is a collective excitation of the nucleus and calls the Giant Monopole Resonance or the "breathing mode" of nuclei.

From the measured excitation energy distribution E_x :
→ frequency
→ restoring force (potential) of the oscillation
→ "spring constant" κ = compression modulus

"Excitation of the Giant Monopole Resonance
by inelastic scattering of α particles on nuclei"

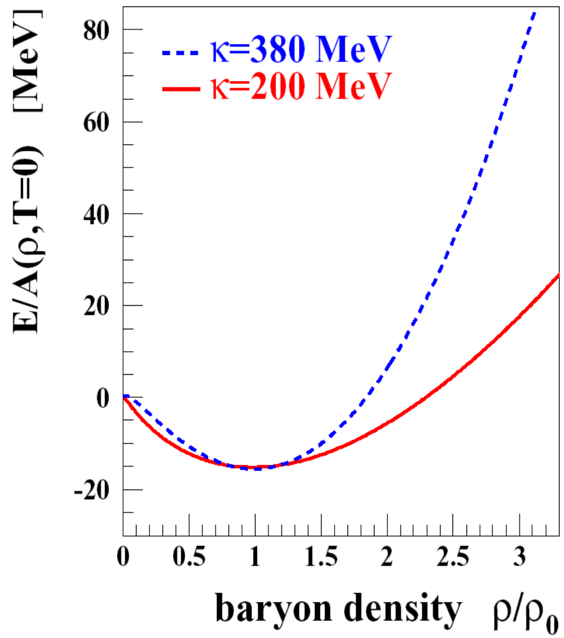
Youngblood et al. , Phys. Rev. Lett. 82 (1999)691



$\kappa = 231 \pm 5$ MeV

nuclear equation-of-state at T = 0 :
"compressional" energy

$$E/A(\rho, T=0) = \frac{1}{\rho}\int U(\rho)\, d\rho$$

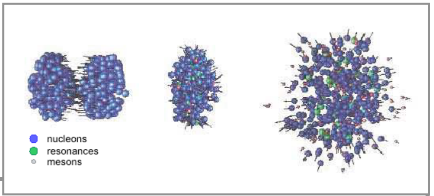


stiff EoS

soft EoS

Compression Modulus :

$$\kappa = \left(9\rho^2 \frac{\partial^2 E/A(\rho, T=0)}{\partial \rho^2}\right)_{\rho=\rho_0}$$



Nucleus-Nucleus Collisions

In transport models:
effective NN-Potential

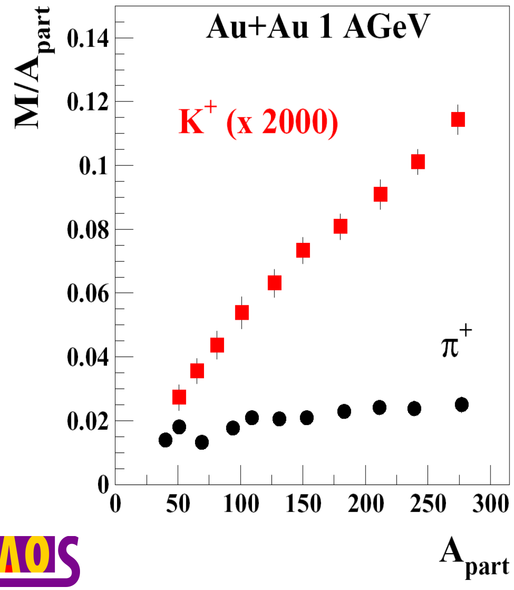
e.g. Skyrme type:

$$U(\rho) = \alpha\left(\frac{\rho}{\rho_0}\right) + \beta\left(\frac{\rho}{\rho_0}\right)^{\gamma}$$

	α [MeV]	β [MeV]	γ
κ = 380 MeV	-124	70.5	2
κ = 200 MeV	-356	303	7/6

"Subthreshold" K^+ production linked to the nuclear equation-of-state

production threshold: E_{lab}= 1.58 GeV



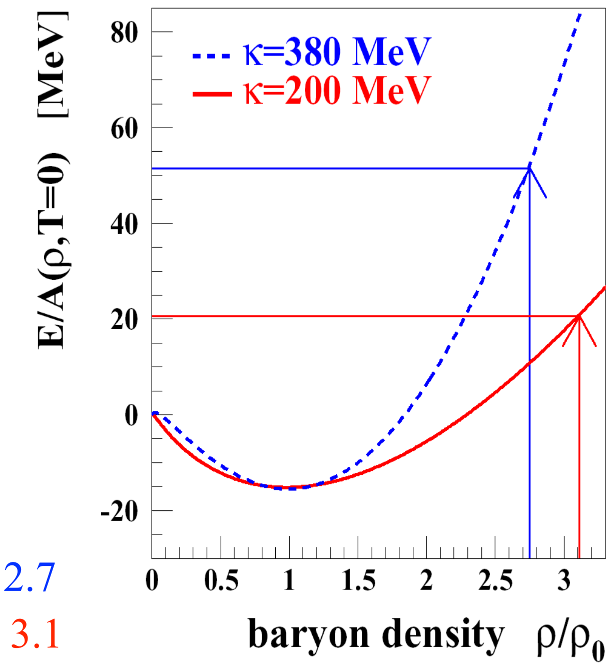
"Subthreshold"
K^+ mesons
predominantly produced by collective effects
→ **multi step processes**

↓

Probability of **multi step processes** increases nonlinearly with the **baryon density**

e.g.

$$NN \rightarrow N\Delta$$
$$N\Delta \rightarrow NK^+Y$$
$$\pi N \rightarrow K^+Y$$
$$(Y=\Lambda,\Sigma)$$



IQMD:
Au+Au
1AGeV

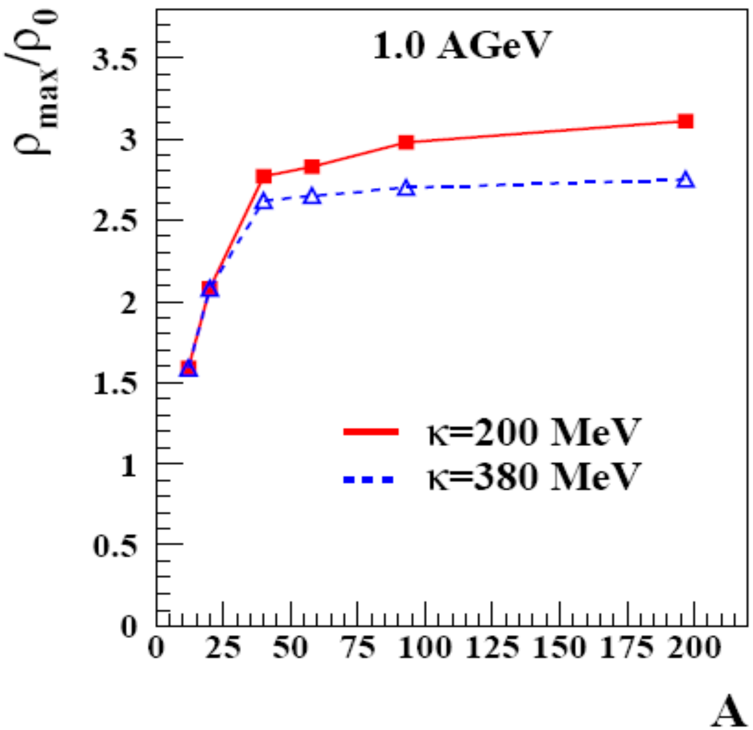
stiff EoS $\rho_{max} / \rho_0 \cong 2.7$
soft EoS $\rho_{max} / \rho_0 \cong 3.1$

What could be a sensitive observable ?

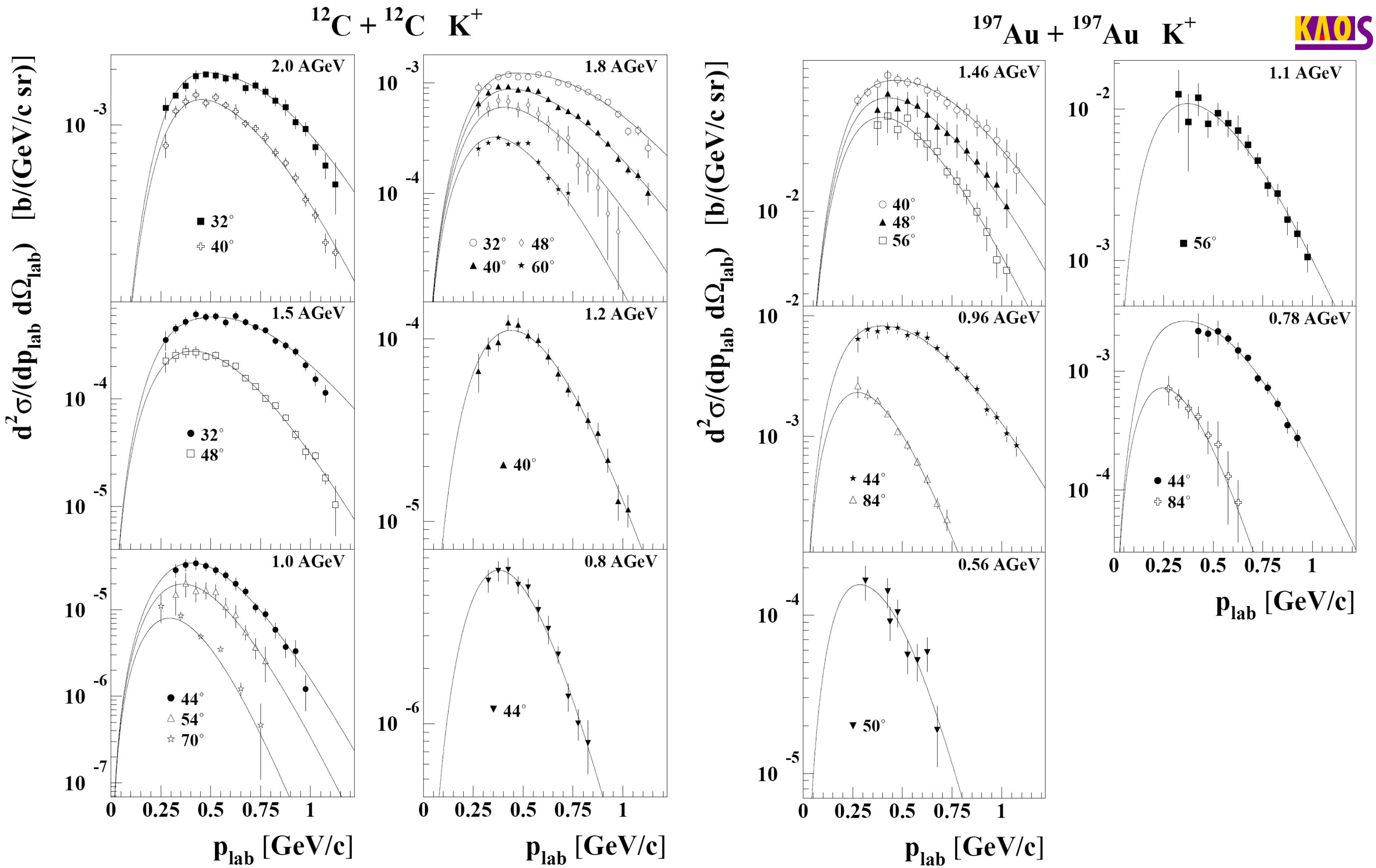
Idea: measure K^+ production in **Au+Au** and **C+C** collisions !

The light collision system serves as a "reference" system because there is almost no compression expected !

IQMD C. Hartnack

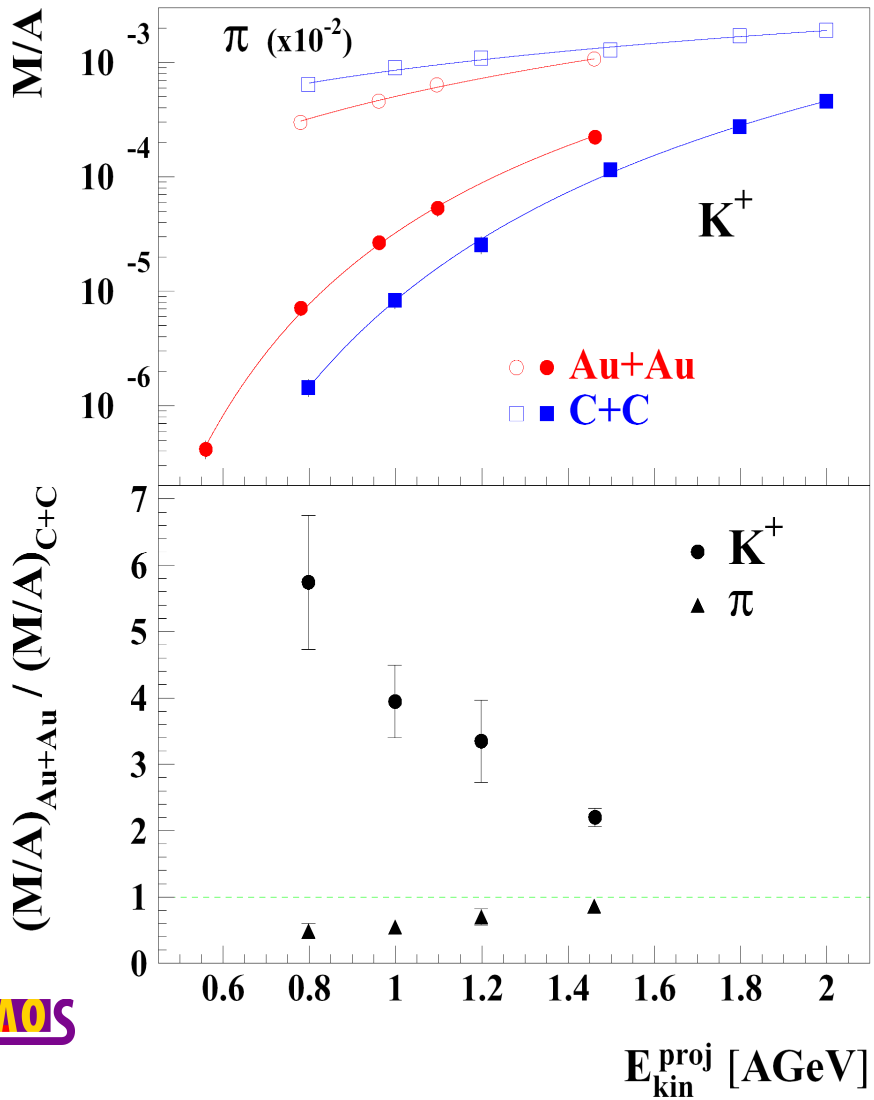


K^+ production in Au+Au and C+C collisions



Production excitation functions in Au+Au and C+C collisions

Phys. Rev. Lett. 86 (2001) 39

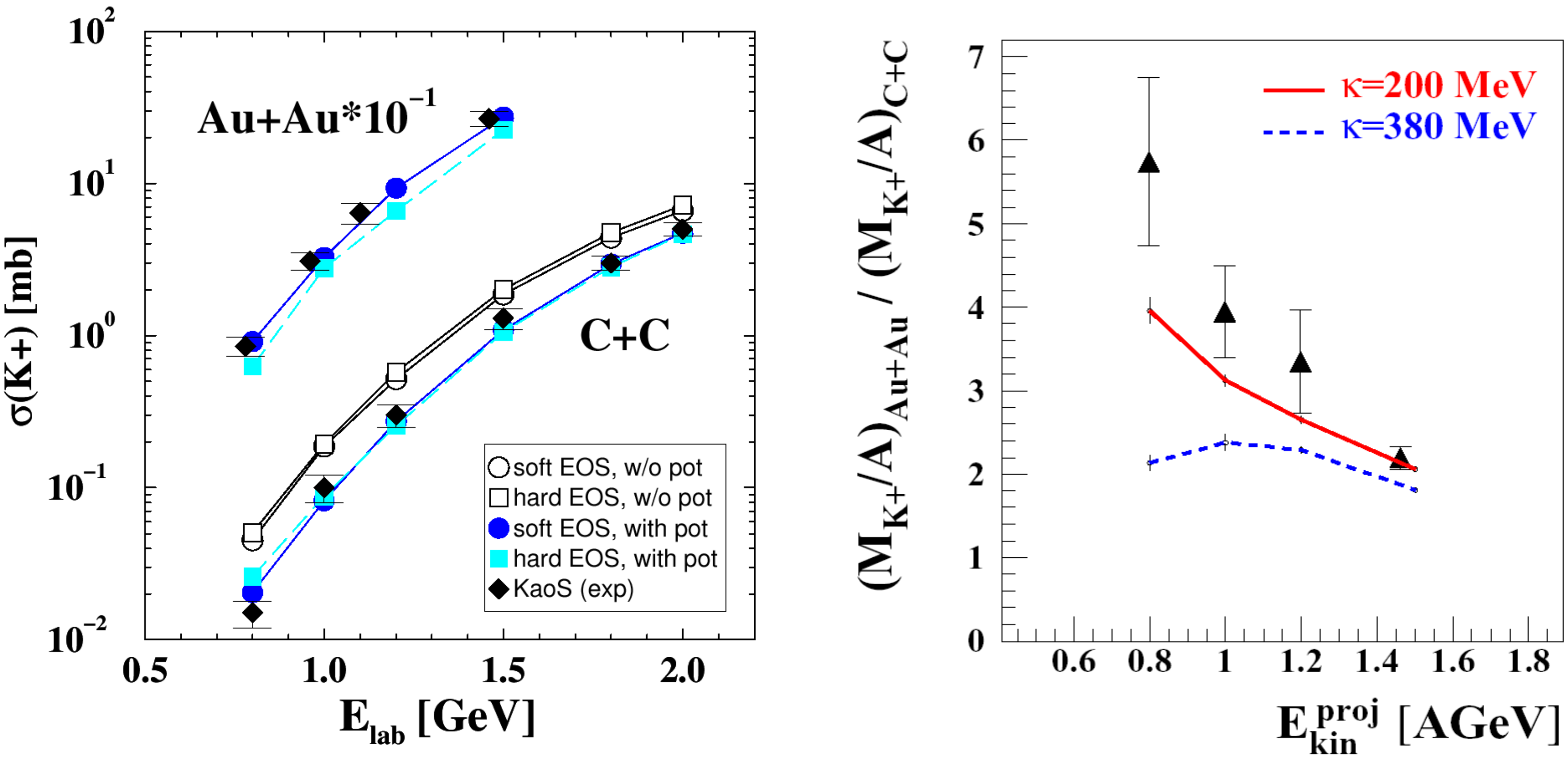


enhanced K^+ production
in Au+Au reactions

The compression modulus of nuclear matter at $\rho = 2 - 3\ \rho_0$

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

Theory: RQMD C. Fuchs et al., Phys. Rev. Lett. 86 (2001) 1974

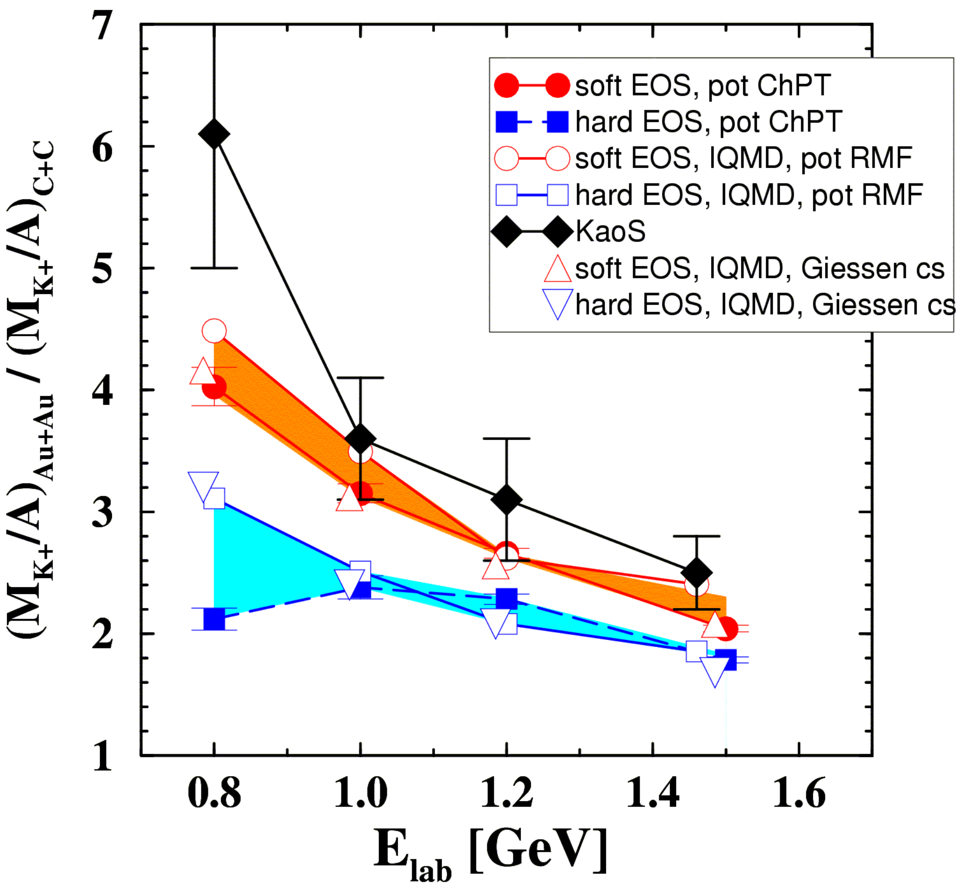


soft nuclear equation-of-state: $\kappa \approx 200$ MeV

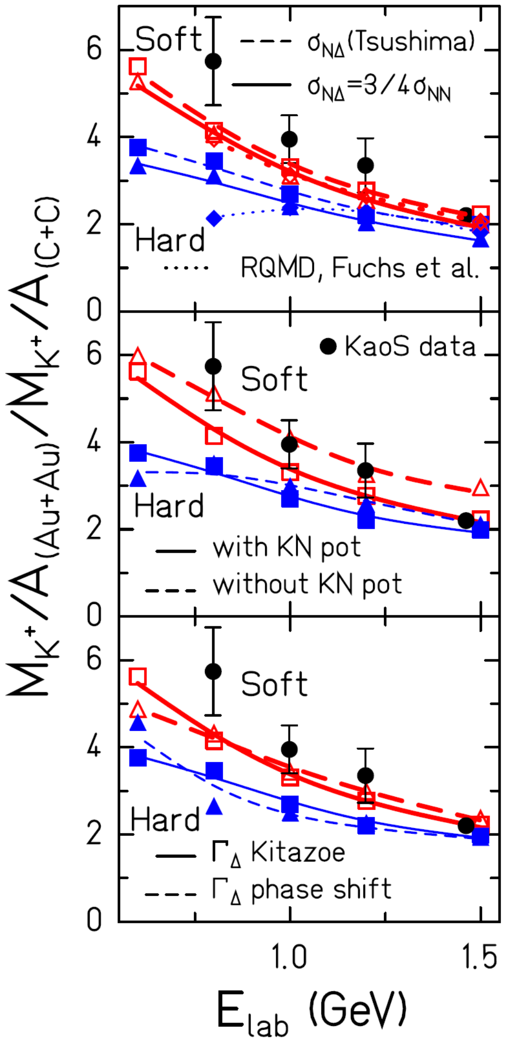
The compression modulus of nuclear matter at $\rho = 2 - 3\ \rho_0$

Experiment: C.S. et al., Phys. Rev. Lett. 86 (2001) 39

Theory: RQMD C. Fuchs et al., Phys. Rev. Lett. 86 (2001) 1974
IQMD C. Hartnack, J. Aichelin



IQMD



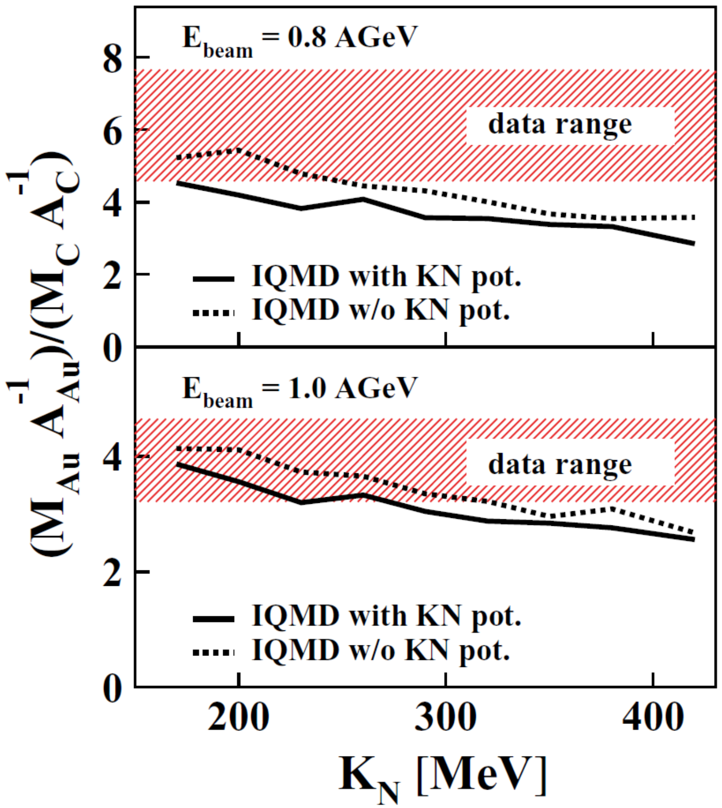
Variation of:

cross sections

in-medium
KN potentials

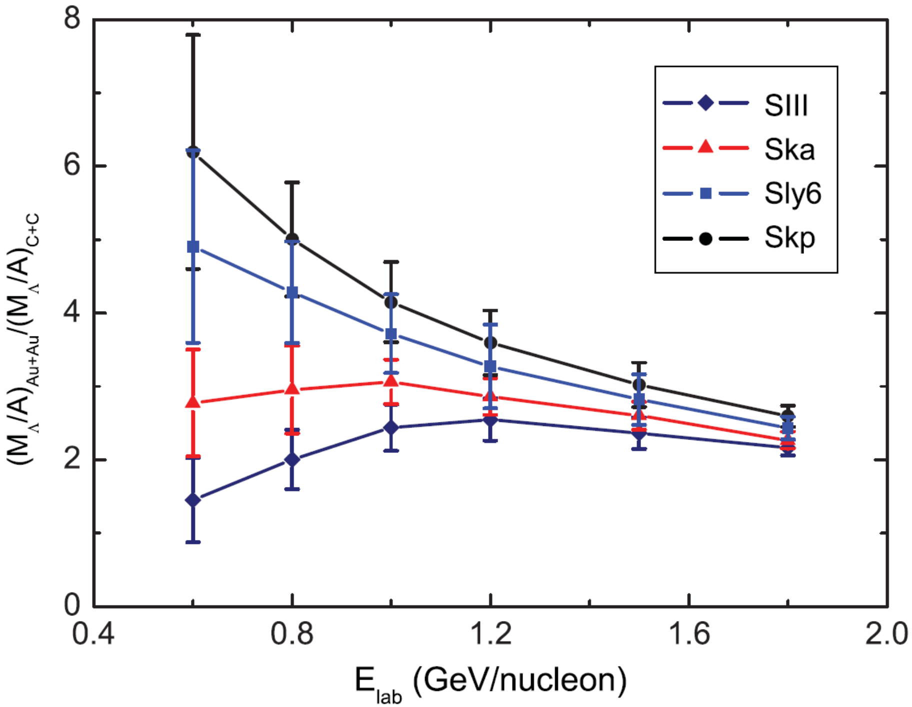
Δ lifetime

C. Hartnack, H. Oeschler, and J. Aichelin, Phys. Rev. Lett. **96** (2006) 012302



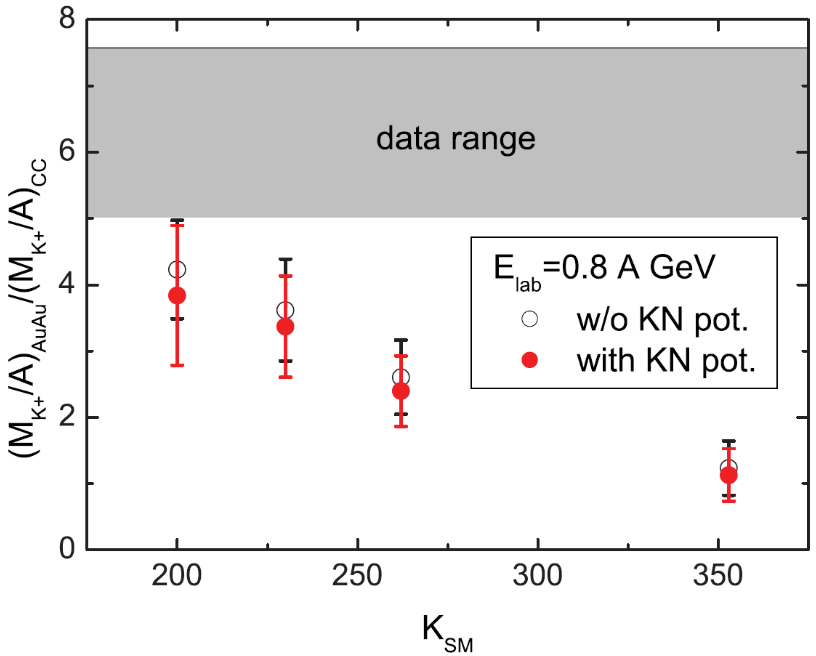
<u>conclusion:</u>
calculations using a potential according to a “soft” nuclear equation-of-state describe the data at best !

Robust observable ?



	K_∞ [MeV]	ρ_0 [fm^{-3}]
Skp	200	0.162
Sly6	230	0.160
Ska	262	0.155
SIII	353	0.145

Lanzhou QMD Transport Model
Zhao-Qing Feng, PRC **83** (2011) 067604



Conclusion
Nuclear equation-of-state

$\rho \approx 1\ \rho_0$

Excitation of the giant monopole resonance in inelastic α-nucleus collisions

↳ The compression modulus of nuclear matter $K = 231 \pm 5$ MeV

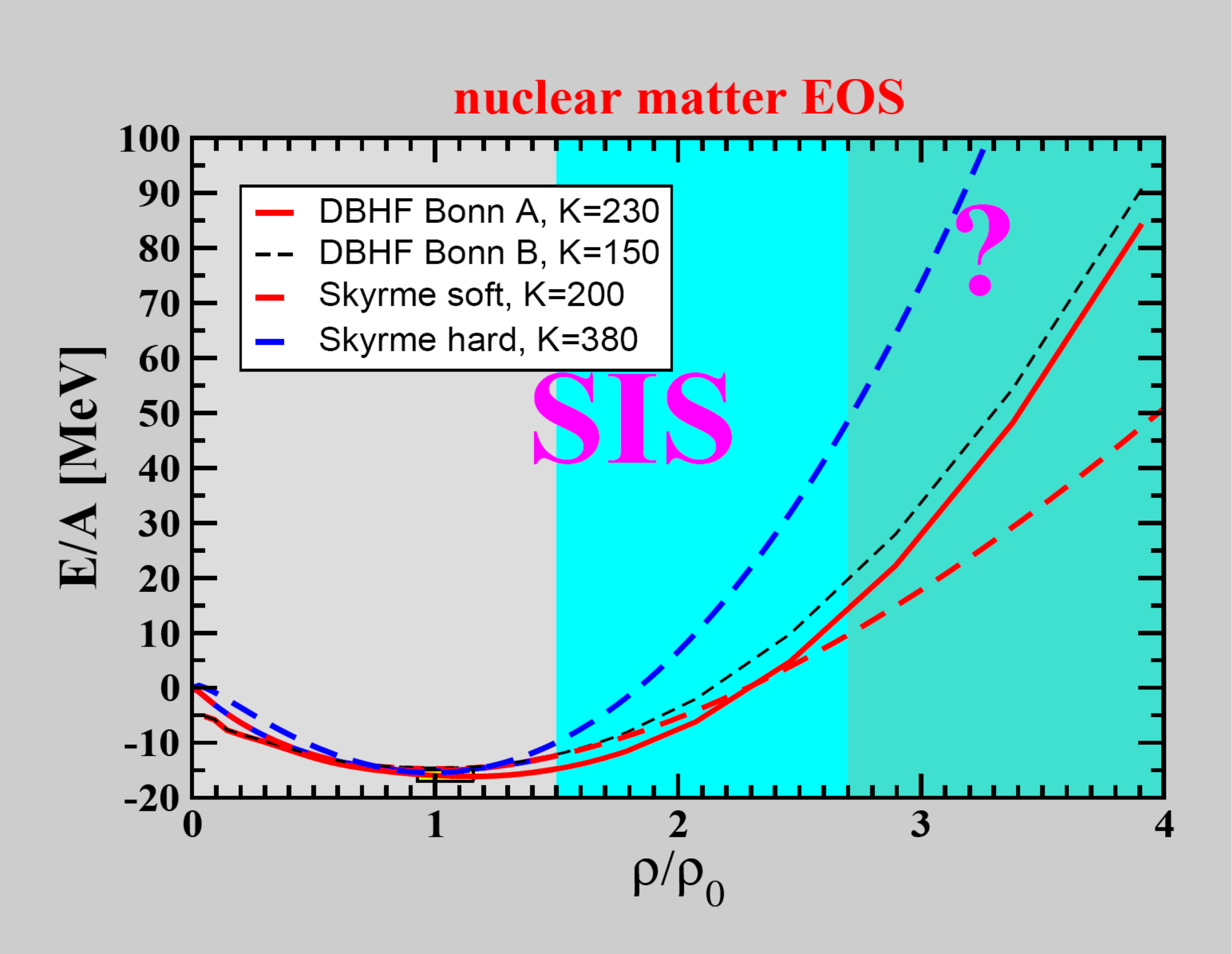
$\rho \approx 2\text{–}3\ \rho_0$

Double ratio of the K^+ production excitation functions in Au+Au and C+C

↳ Robust observable

↳ The nuclear matter equation-of-state is soft ($K \approx 200$ MeV)

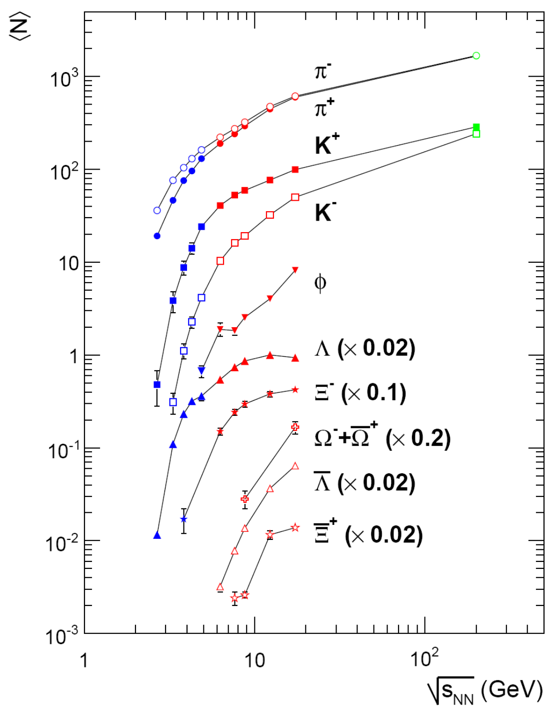
The Nuclear EoS at the highest baryon densities ?



Outlook: multi-strange Hyperons at FAIR energies

Direct production:

$pp \rightarrow \Xi^- K^+K^+p$ (E_{thr} = 3.7 GeV)
$pp \rightarrow \Omega^- K^+K^+K^0p$ (E_{thr} = 7.0 GeV)
$pp \rightarrow \Lambda^0\Lambda^0 pp$ (E_{thr} = 7.1 GeV)
$pp \rightarrow \Xi^+ \Xi^- pp$ (E_{thr} = 9.0 GeV)
$pp \rightarrow \Omega^+ \Omega^- pp$ (E_{thr} = 12.7 GeV)



Production via multiple strangeness exchange reactions:

Hyperons (s quarks):
1. $pp \rightarrow K^+\Lambda^0p$, $pp \rightarrow K^+K^-pp$,
2. $p\Lambda^0 \rightarrow K^+\Xi^- p$, $\pi\Lambda^0 \rightarrow K^+\Xi^-\pi$,
3. $\Lambda^0\Lambda^0 \rightarrow \Xi^- p$, $\Lambda^0K^- \rightarrow \Xi^-\pi^0$
4. $\Lambda^0\Xi^- \rightarrow \Omega^- n$, $\Xi^-K^- \rightarrow \Omega^-\pi^-$

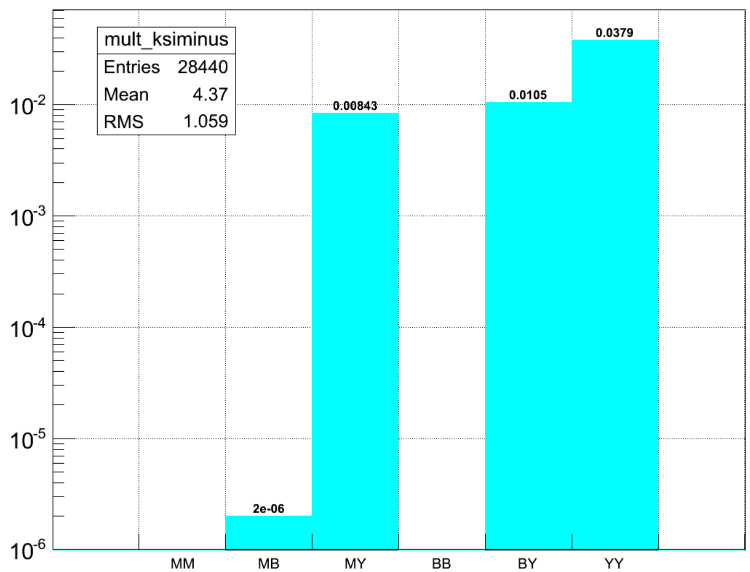
Antihyperons (anti-s quarks):
1. $\Lambda^0 K^+ \rightarrow \Xi^+\pi^0$,
2. $\Xi^+ K^+ \rightarrow \Omega^+ \pi^+$.

Outlook: multi-strange Hyperons at FAIR energies

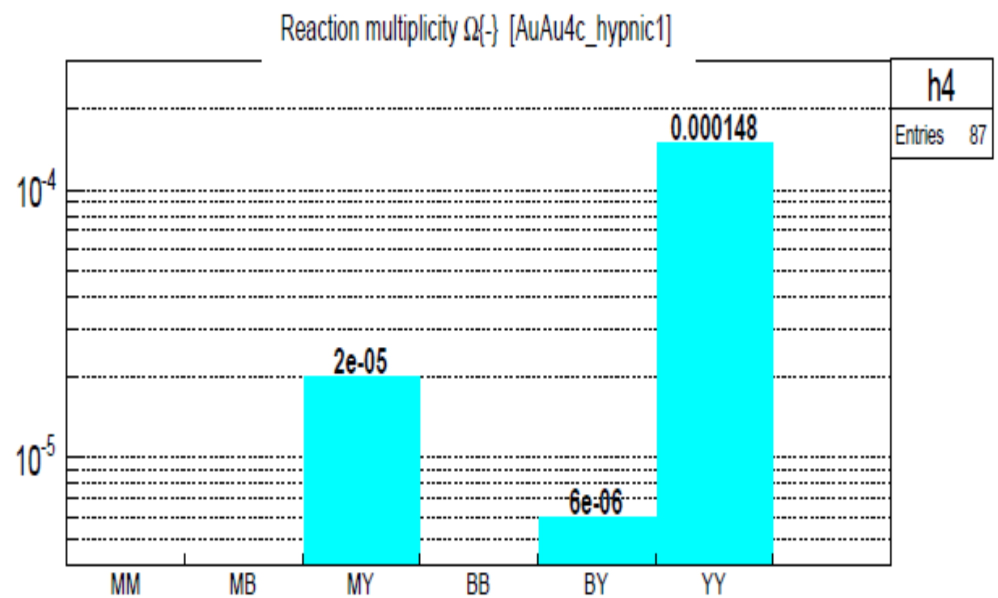
HYPQGSM calculations

Yu.A. Murin[†1], *K.K. Gudima*[1,2], *E.I. Litvinenko*[1], *V.A. Vasendina*[1], *and A.I. Zinchenko*[1]
[1]Joint Institute for Nuclear Research (JINR), Dubna, Russia; [2]Institute of Applied Physics of Academy of Sciences of Moldova, Chisinau, Moldova

$\Xi^- \rightarrow \Lambda\pi^-$



$\Omega^- \rightarrow \Lambda K^-$



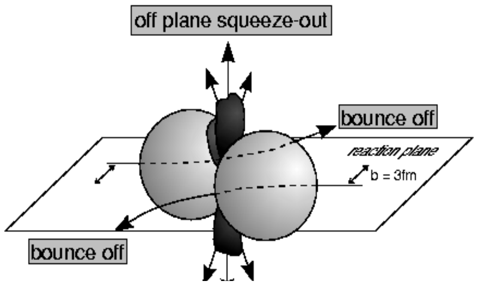
MB MY BB BY YY

Y: hyperon B: Baryon M: meson

Multi-strange hyperon production dominantly via ΛΛ collisions

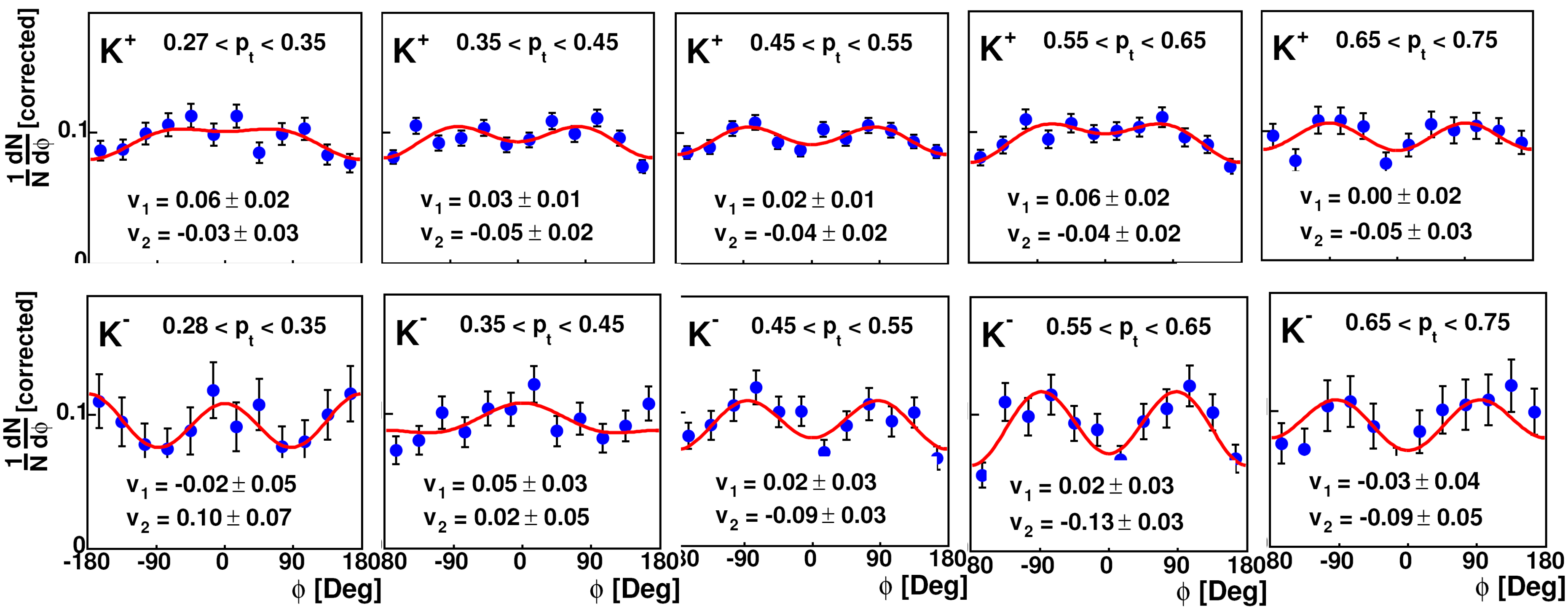
additional slides ...

K^+ and K^- azimuthal angular distributions in Au + Au collisions 1.5 GeV / nucleon



fit: $$\frac{dN}{d\phi} \propto 1 + 2v_1\cos(\phi) + 2v_2\cos(2\phi)$$

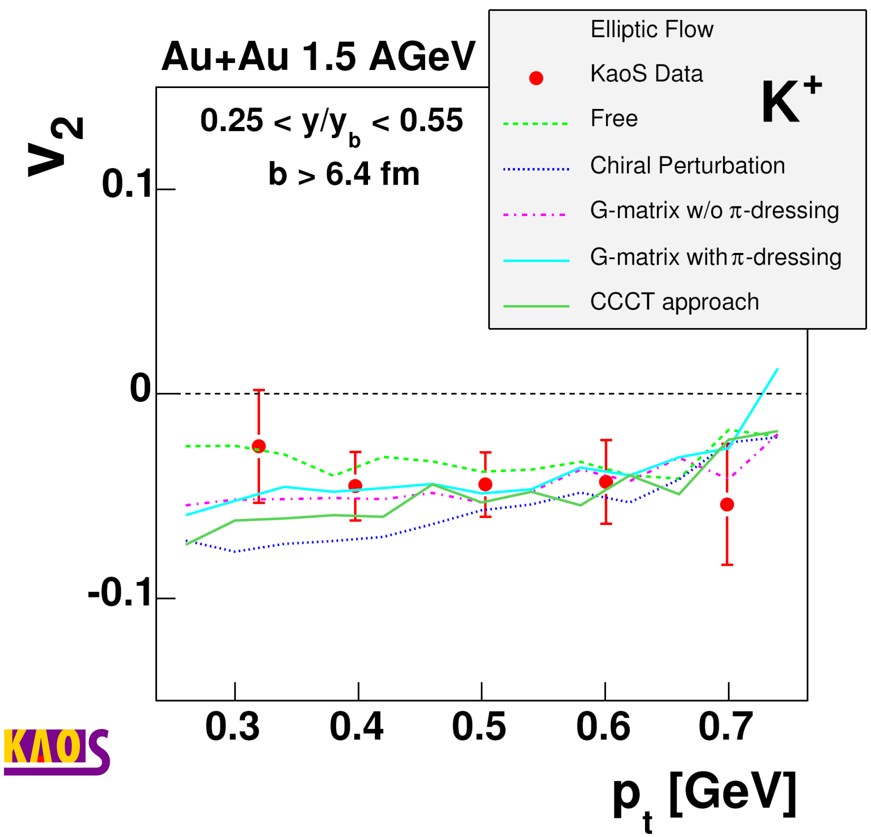
semi-central collisions (b > 6.4 fm)

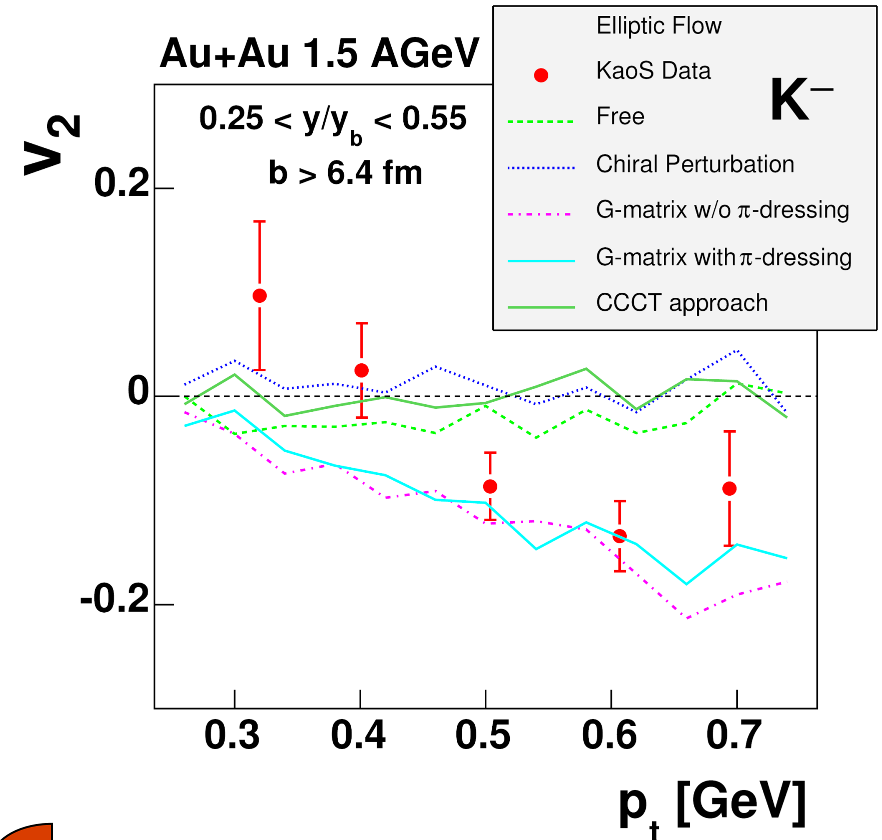


M. Płoskon, PhD Thesis 2005

Elliptic flow of K⁺ and K⁻ mesons:
Comparison to off-shell transport calculations and in-medium spectral functions

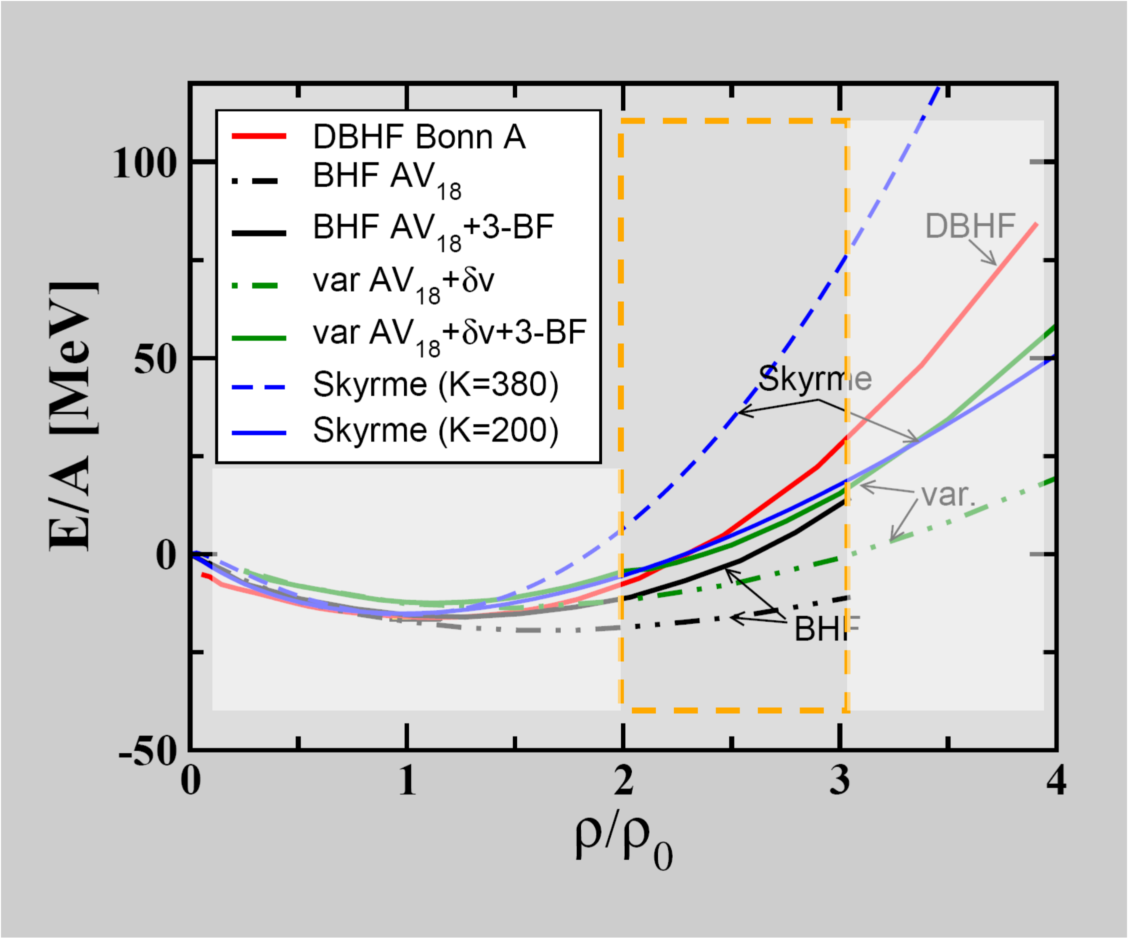
Data: M. Płoskon, PhD Thesis, Univ. Frankfurt 2005
Off-shell transport calculations: W. Cassing et al., NPA 727 (2003) 59, E. Bratkovskaya, priv. com.
Coupled channel G-Matrix approach (K^- spectral functions): L. Tolos et al., NPA 690 (2001) 547





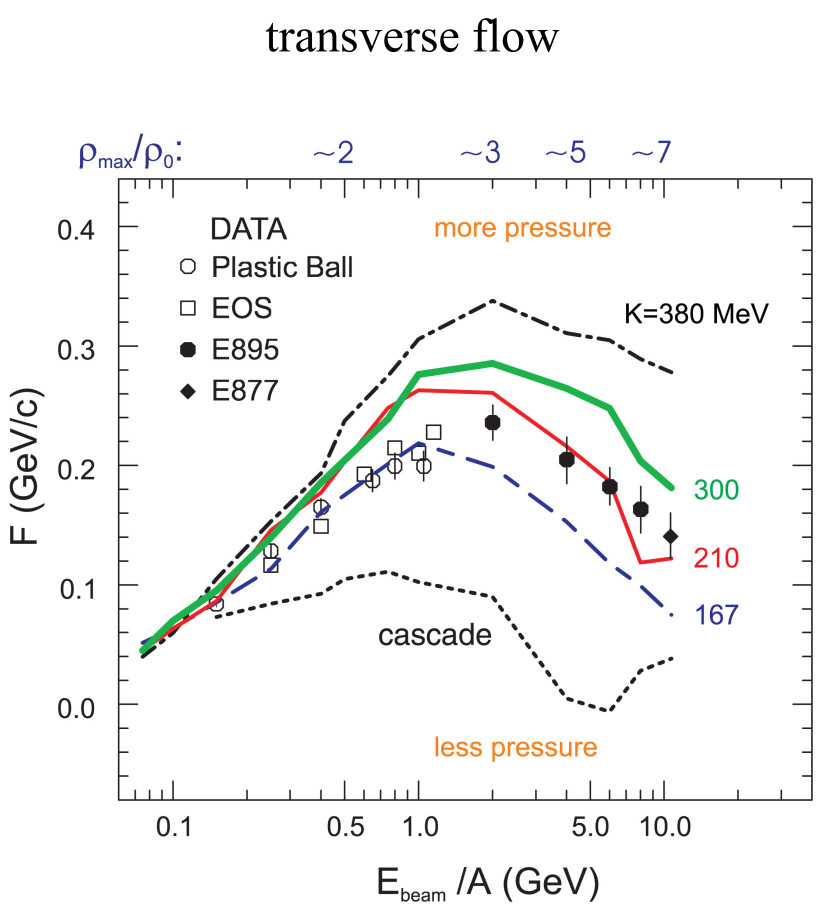
not yet conclusive !

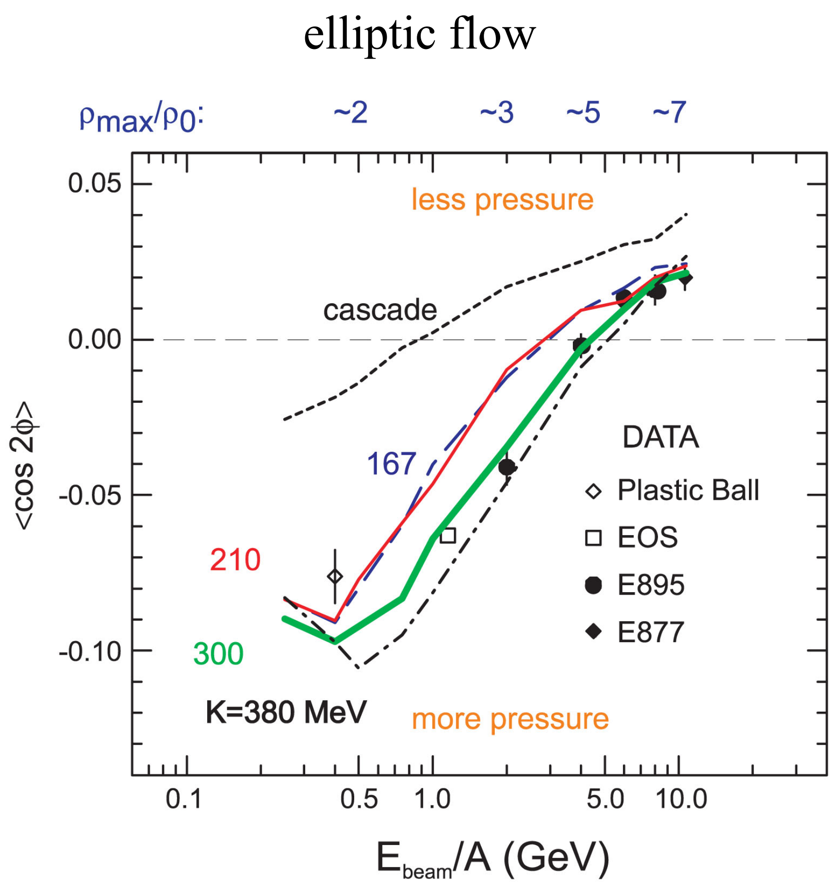
The equation-of-state of (symmetric) nuclear matter



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

Flow and the Nuclear EoS

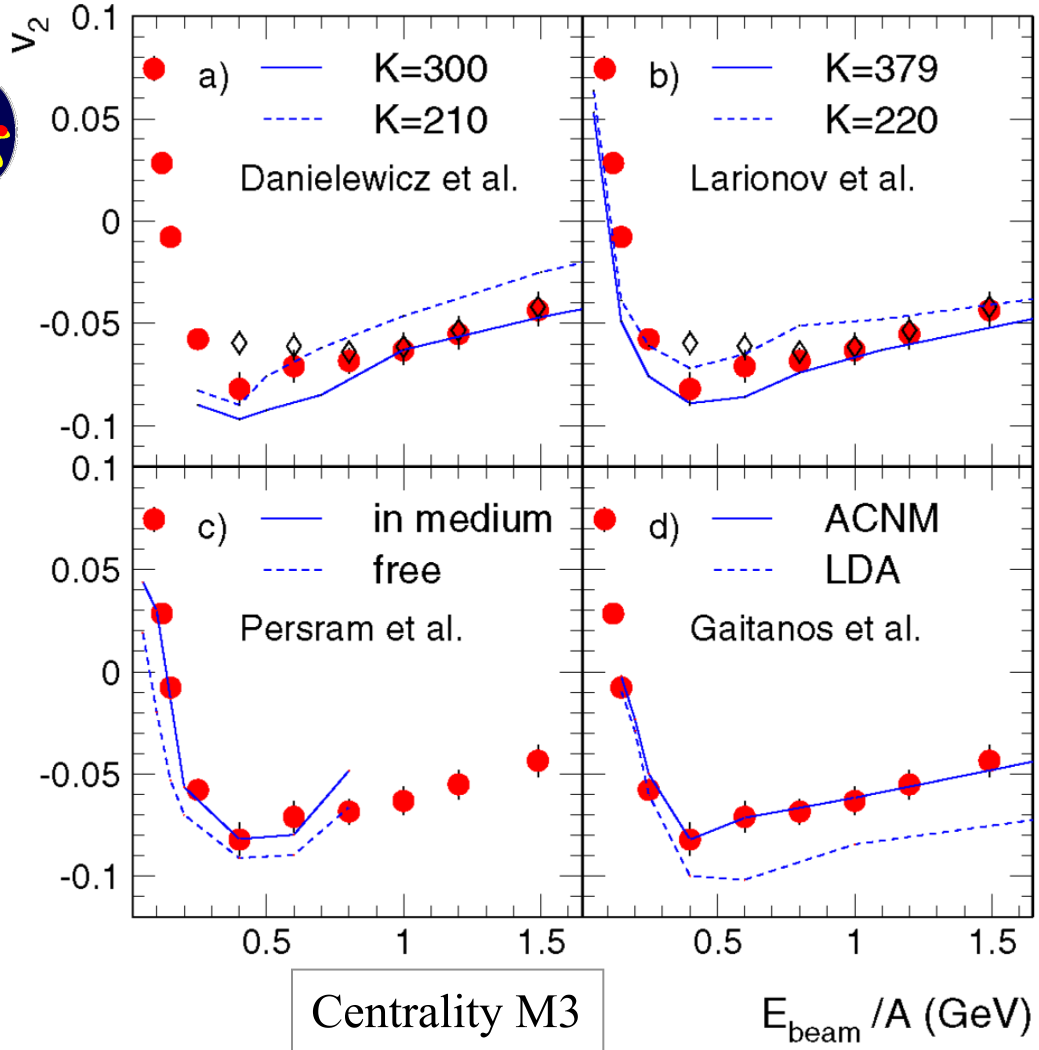




P. Danielewicz, R. Lacey, W. G. Lynch , Science 298 (2002) 1592-1596

Elliptic flow and the Nuclear EoS

Andronic et. al. PLB 612 (2005) 173–180
FOPI Collaboration



Centrality M3
• Z = 1
◊ Protons

BUU transport models:

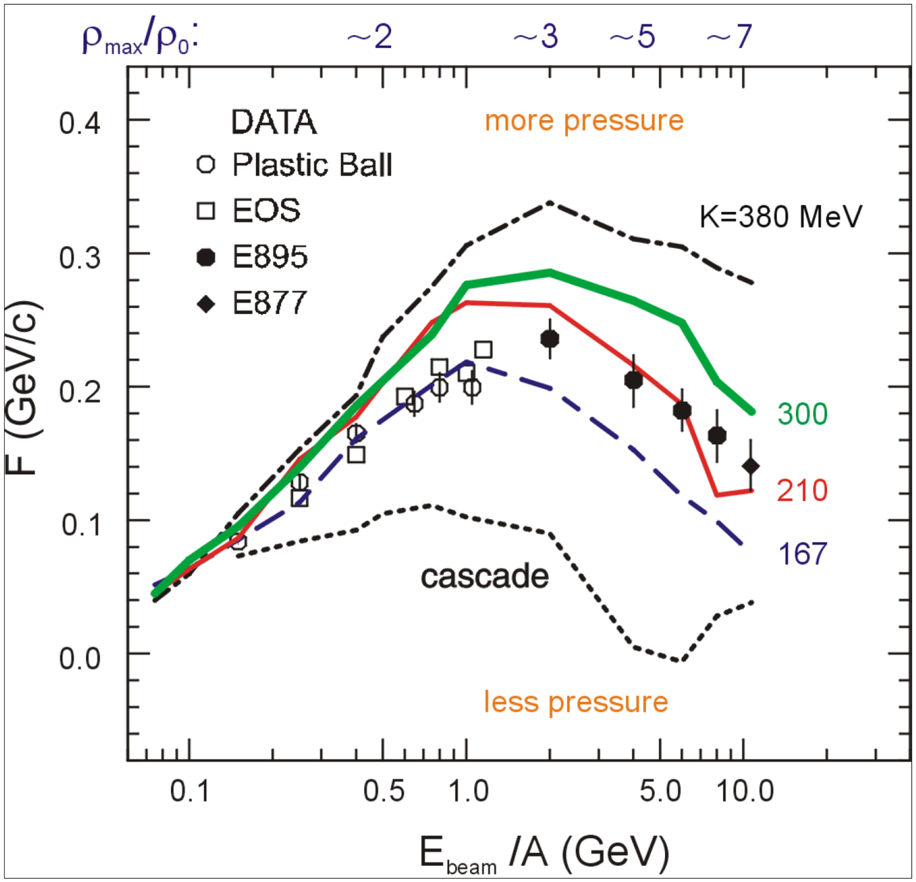
“soft” / “stiff” EoS

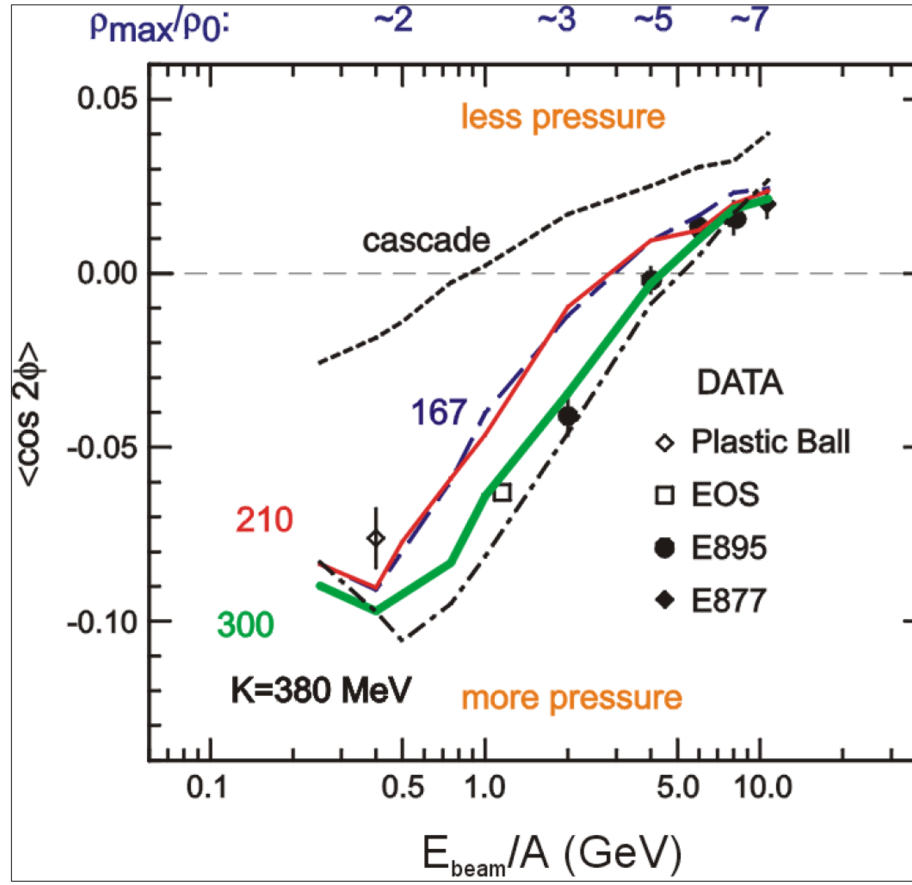
c) in-medium NN cross section

d) **A**symmetric **C**olliding **N**uclear **M**atter approximation

Probing the nuclear equation-of-state: proton collective flow

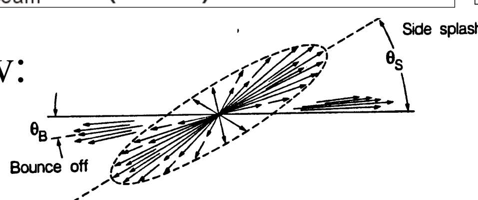
P. Danielewicz, R. Lacey, W.G. Lynch, Science 298 (2002) 1592





Transverse in-plane flow:

$F = d(p_x/A)/d(y/y_{cm})$

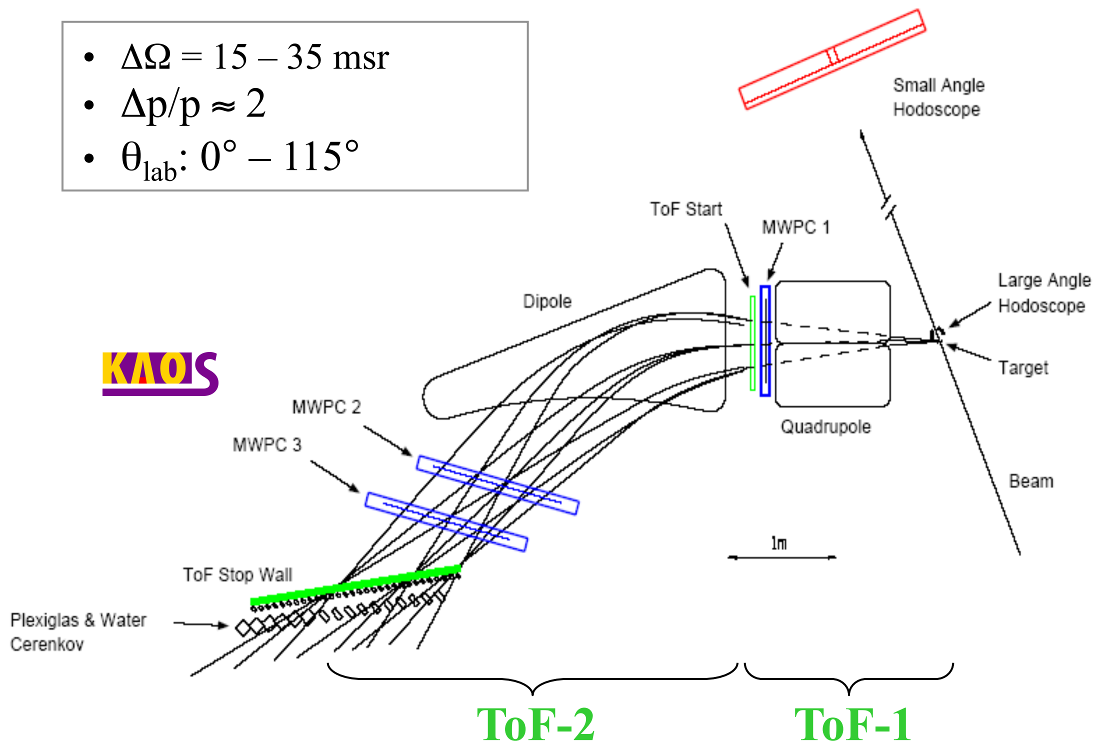


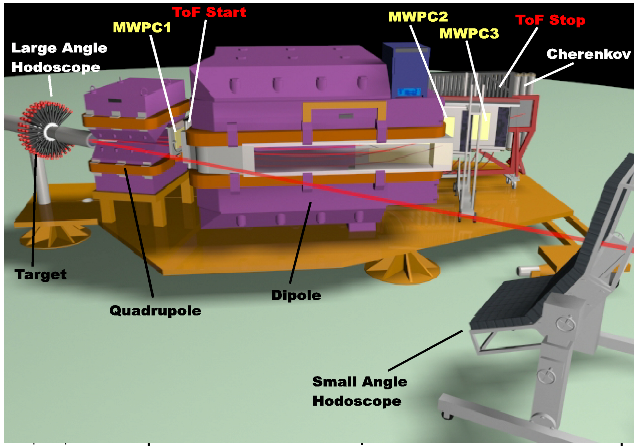
Elliptic flow:

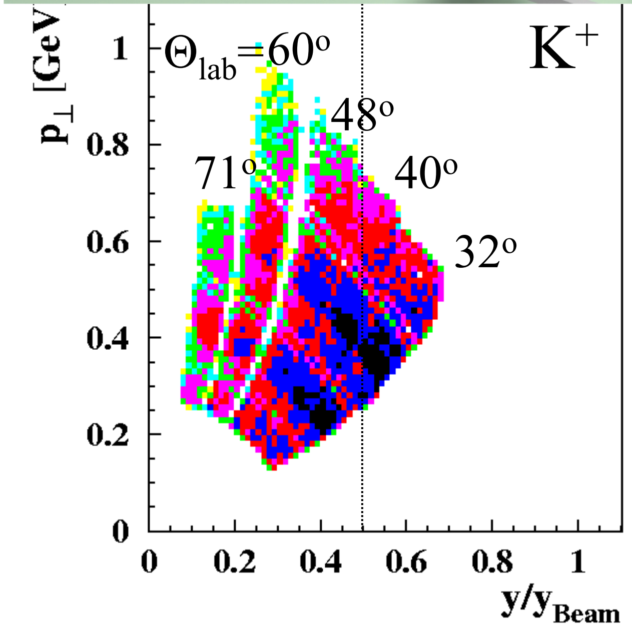
$dN/d\Phi \propto (1 + 2v_1 \cos\Phi + 2v_2 \cos 2\Phi)$

The Kaon Spectrometer

- $\Delta\Omega$ = 15 – 35 msr
- $\Delta p/p \approx 2$
- θ_{lab}: 0° – 115°



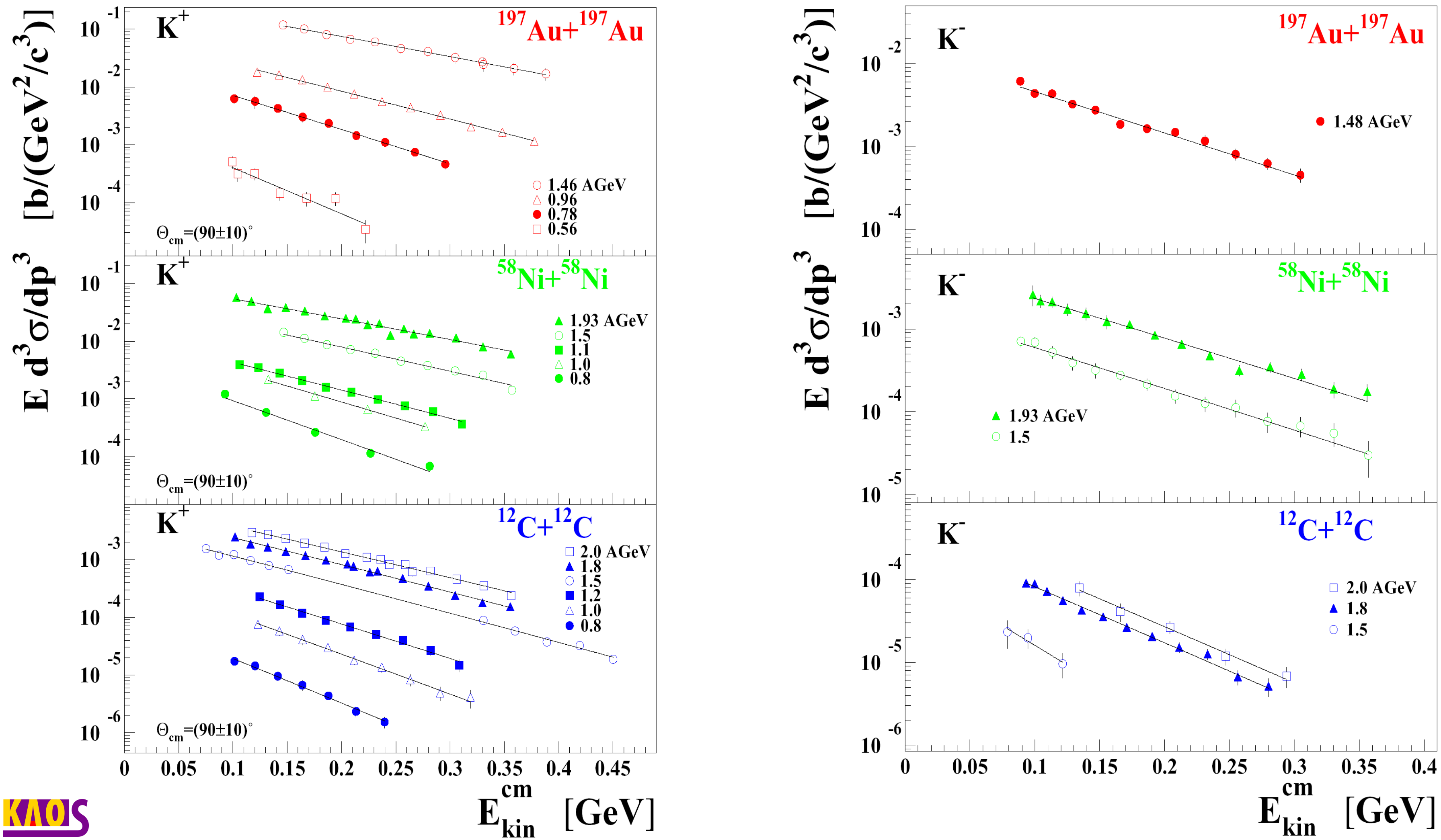




- compact size: path length 5 – 7.5 m
- Kaon Trigger (ToF + Cherenkov)
- efficient background reduction by 2xToF measurement

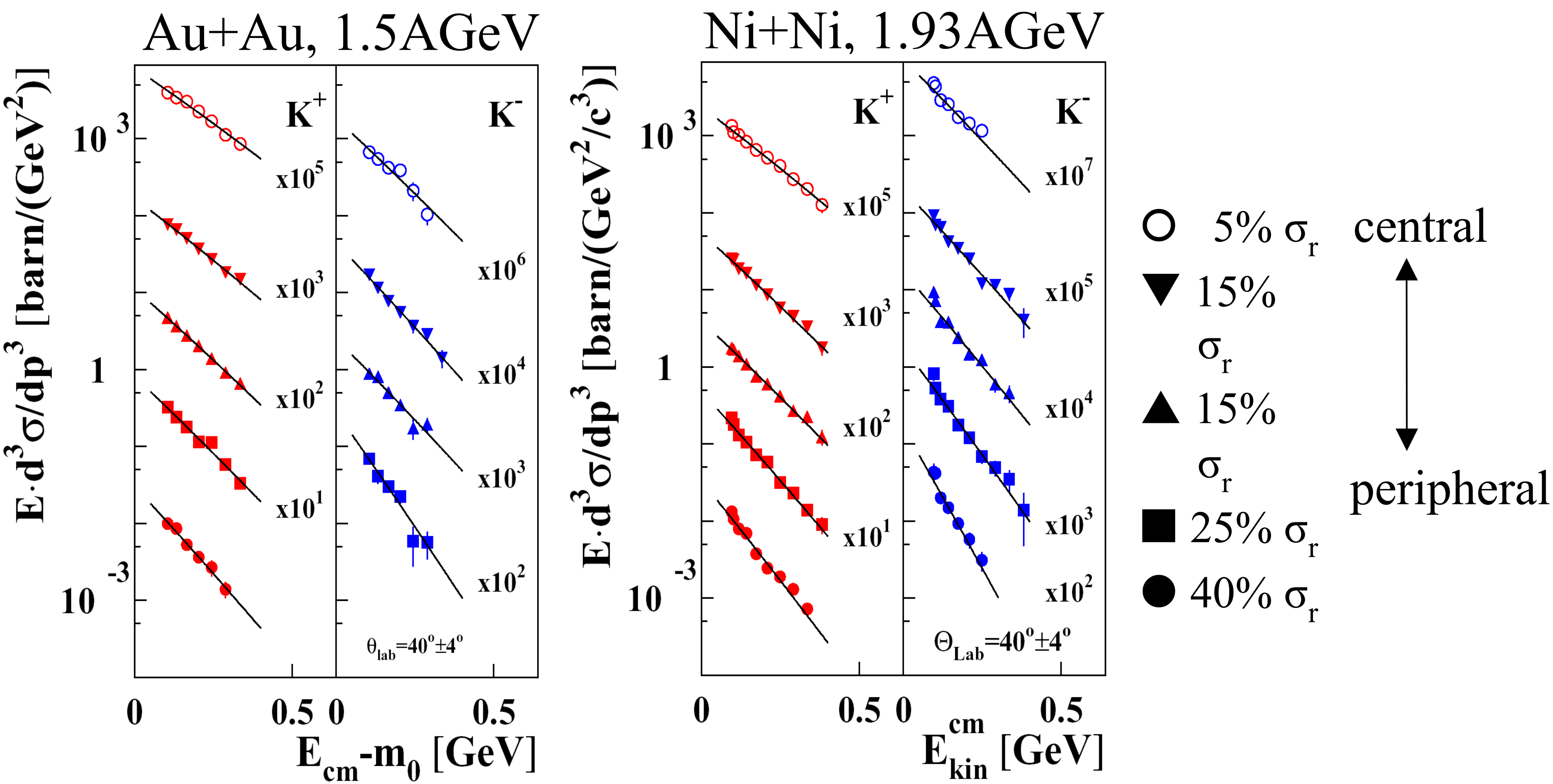
Spectral distributions from A+A ($\Theta_{cm}\approx 90^\circ$)

(w/o selection of impact parameter)



fit: $E\frac{d^3\sigma}{dp^3} = E \cdot C \cdot e^{-E_{cm}/T}$

Spectral distributions as a function of the centrality

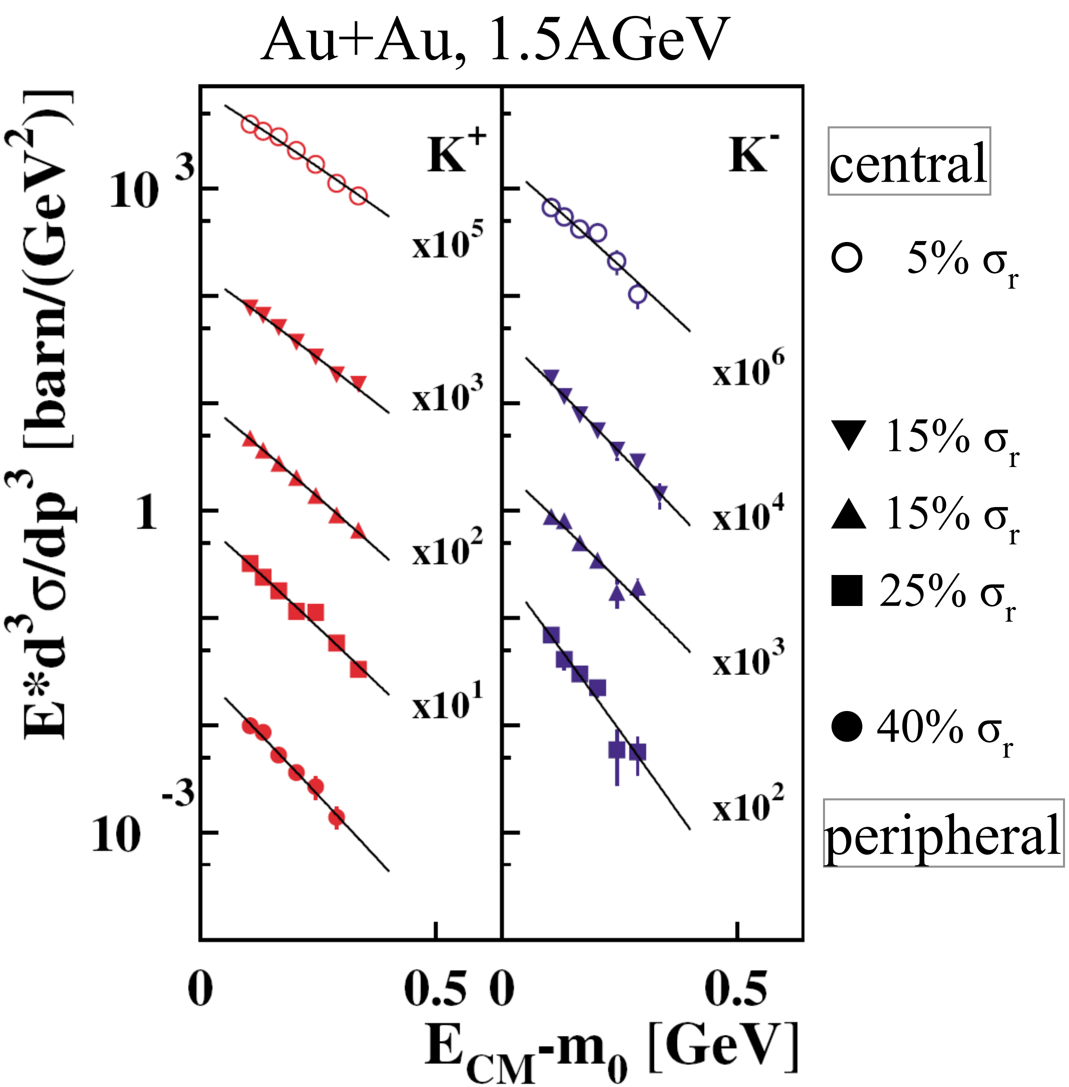


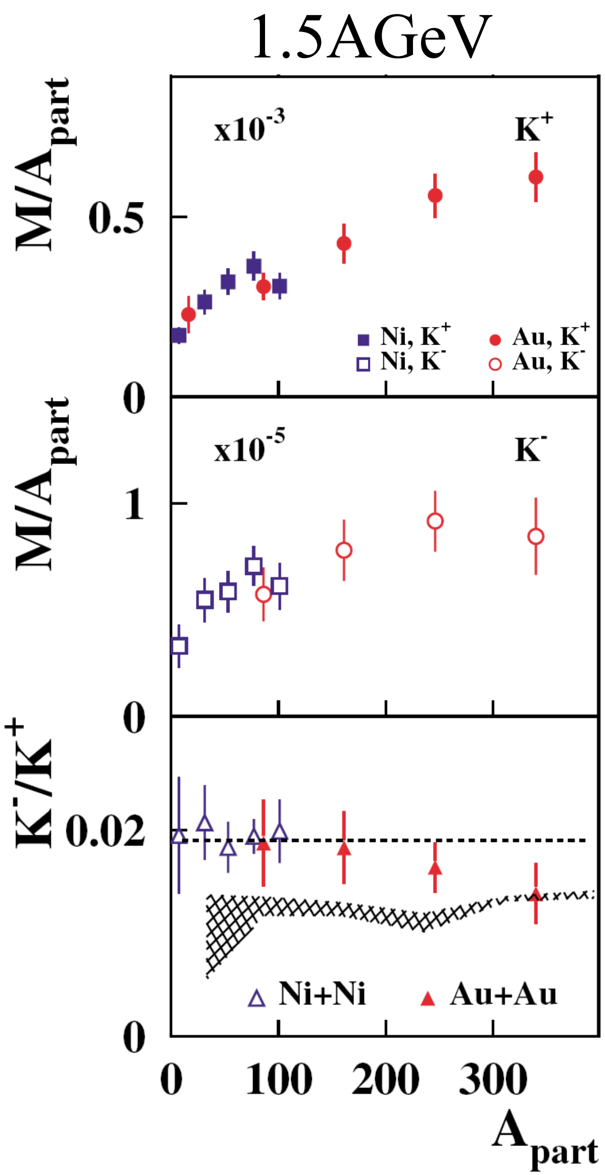
A. Förster et al.
PRL 91(2003)152301

F.Uhlig
PhD Thesis,TU Darmstadt

KAOS

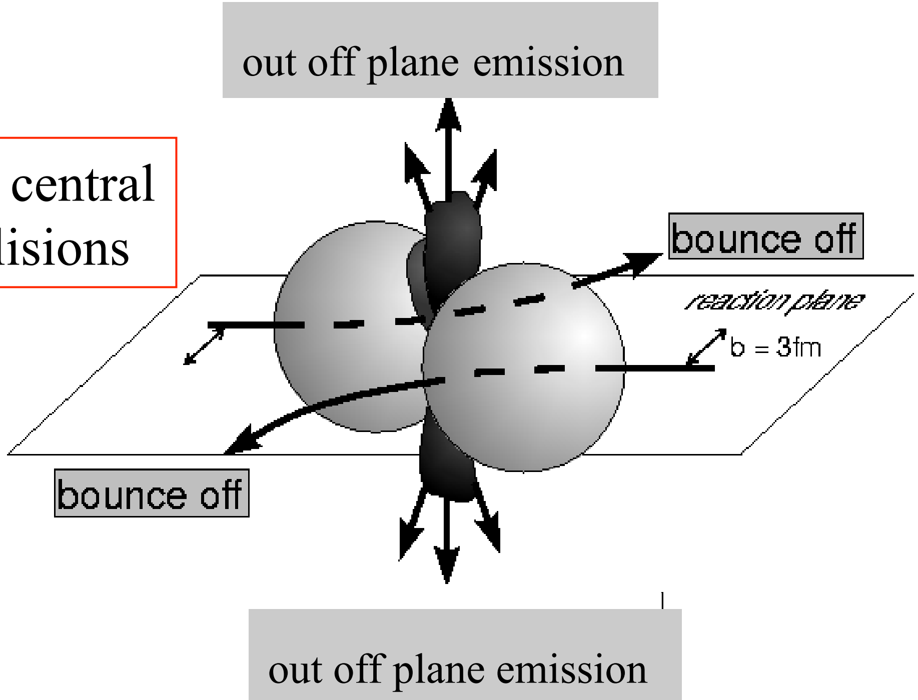
Spectral distributions as a function of the centrality

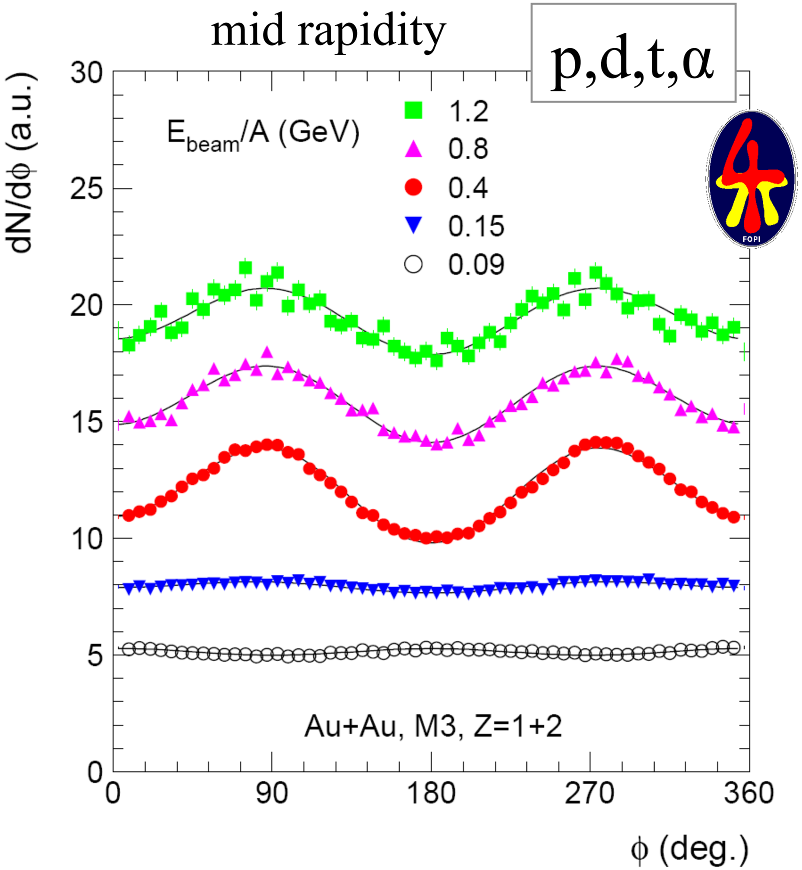




Azimuthal particle emission

semi central collisions





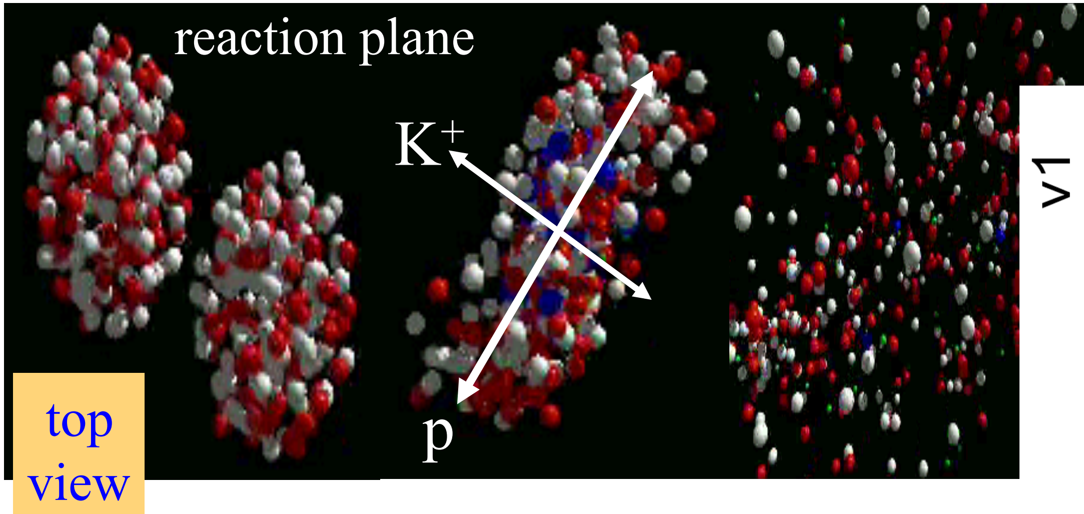
Fourier expansion of the dN/dϕ distribution:

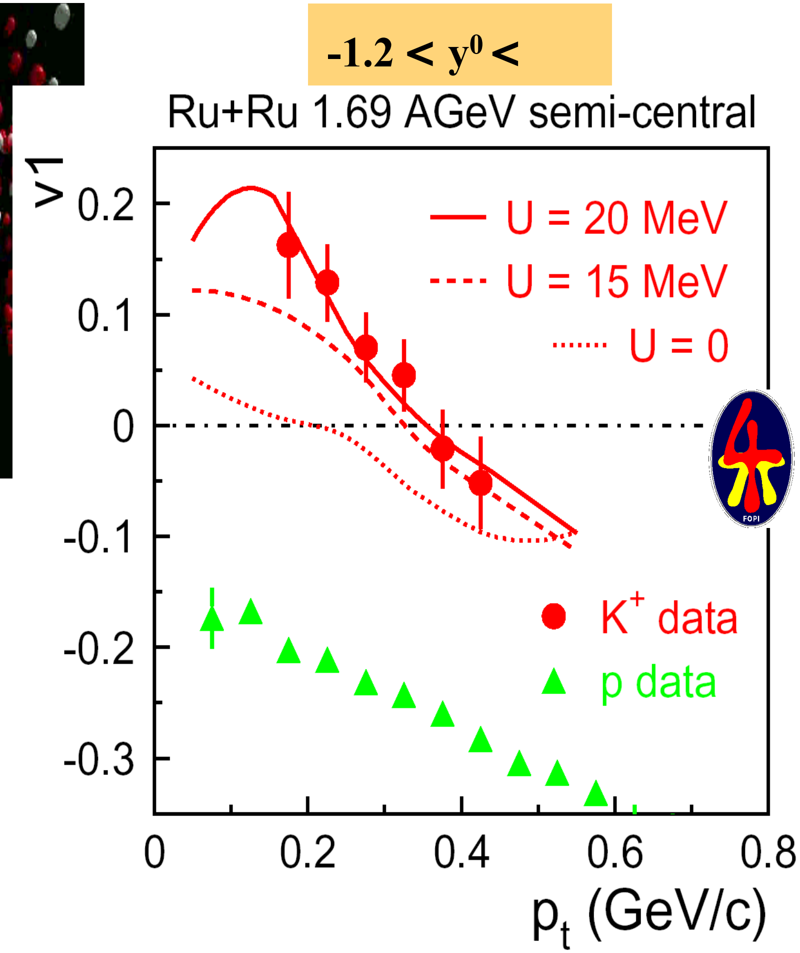
$$\frac{dN}{d\phi} \sim [1 + 2v_1 \cdot \cos(\phi) + 2v_2 \cdot \cos(2\phi)]$$

the coefficients quantify :

- v_1 the in-plane and
- v_2 the elliptic emission pattern

K⁺ sideward flow



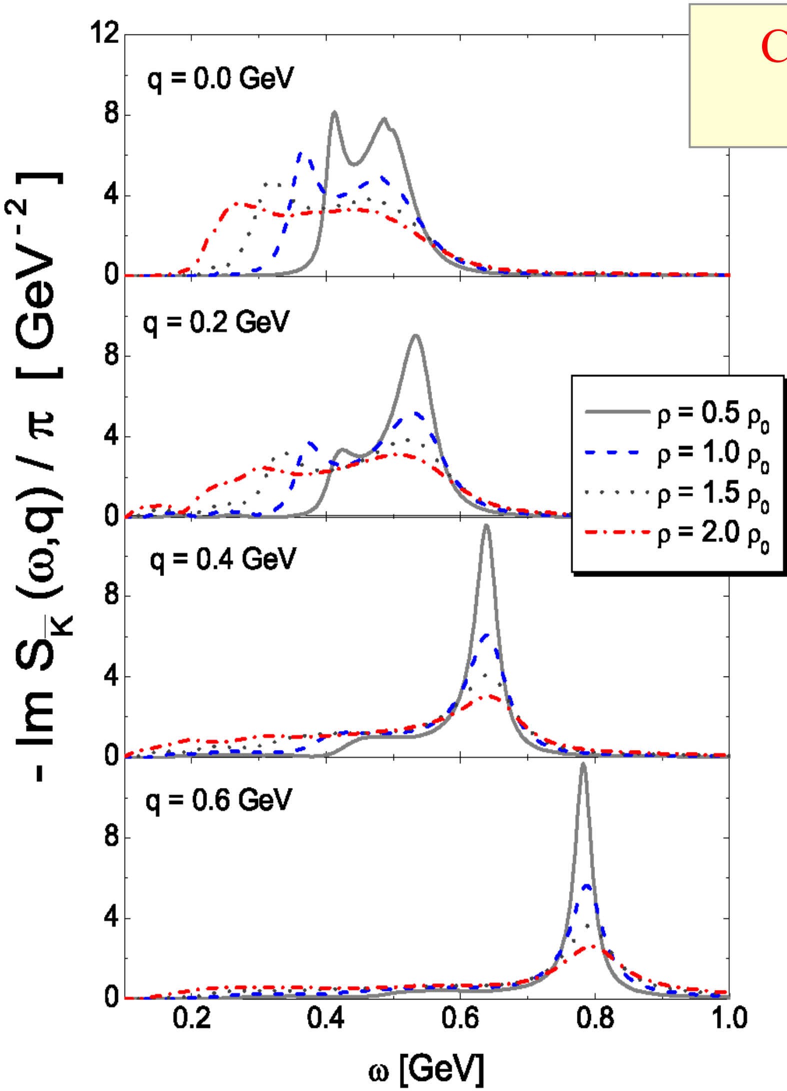


K⁺-Mesons show an “antiflow" – caused by a repulsive K⁺N potential

P. Crochet et al., Phys. Lett. B 486 (2000) 6

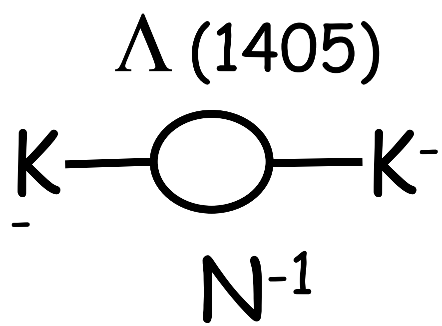
RBUU: E. Bratkovskaya , W. Cassing

The in-medium spectral function of Antikaons



Coupled channels calculation

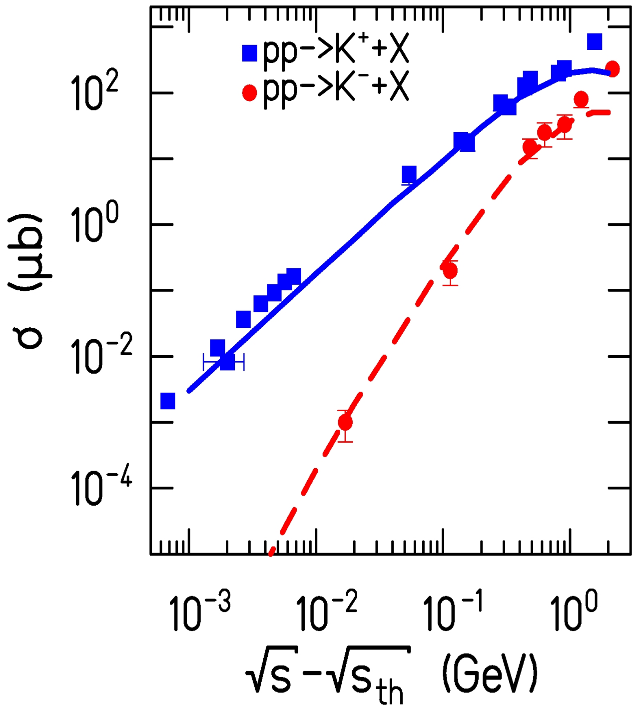
M. Lutz GSI



resonant state close to the K^-N threshold: Λ(1405)

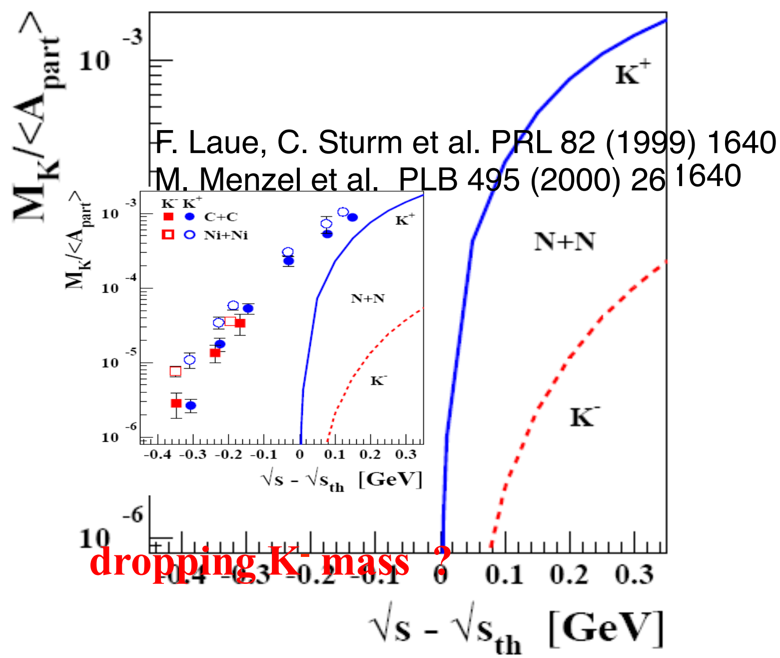
K^+ and K^- production in p+p and A+A collisions

Parameterizations: A. Sibirtsev, W. Cassing, C.M. Ko, ZPA 258 (1997) 101



$K^- / K^+ \ll 1$

$$\sqrt{s_{th}}(K^+) = m_{K^+} + m_\Lambda - m_N$$
$$\cong 0.67 GeV$$
$$\sqrt{s_{th}}(K^-) = m_{K^+} + m_{K^-}$$
$$\cong 0.99 GeV$$



VOLUME 55, NUMBER 24 PHYSICAL REVIEW LETTERS 9 DECEMBER 1985

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

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(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.