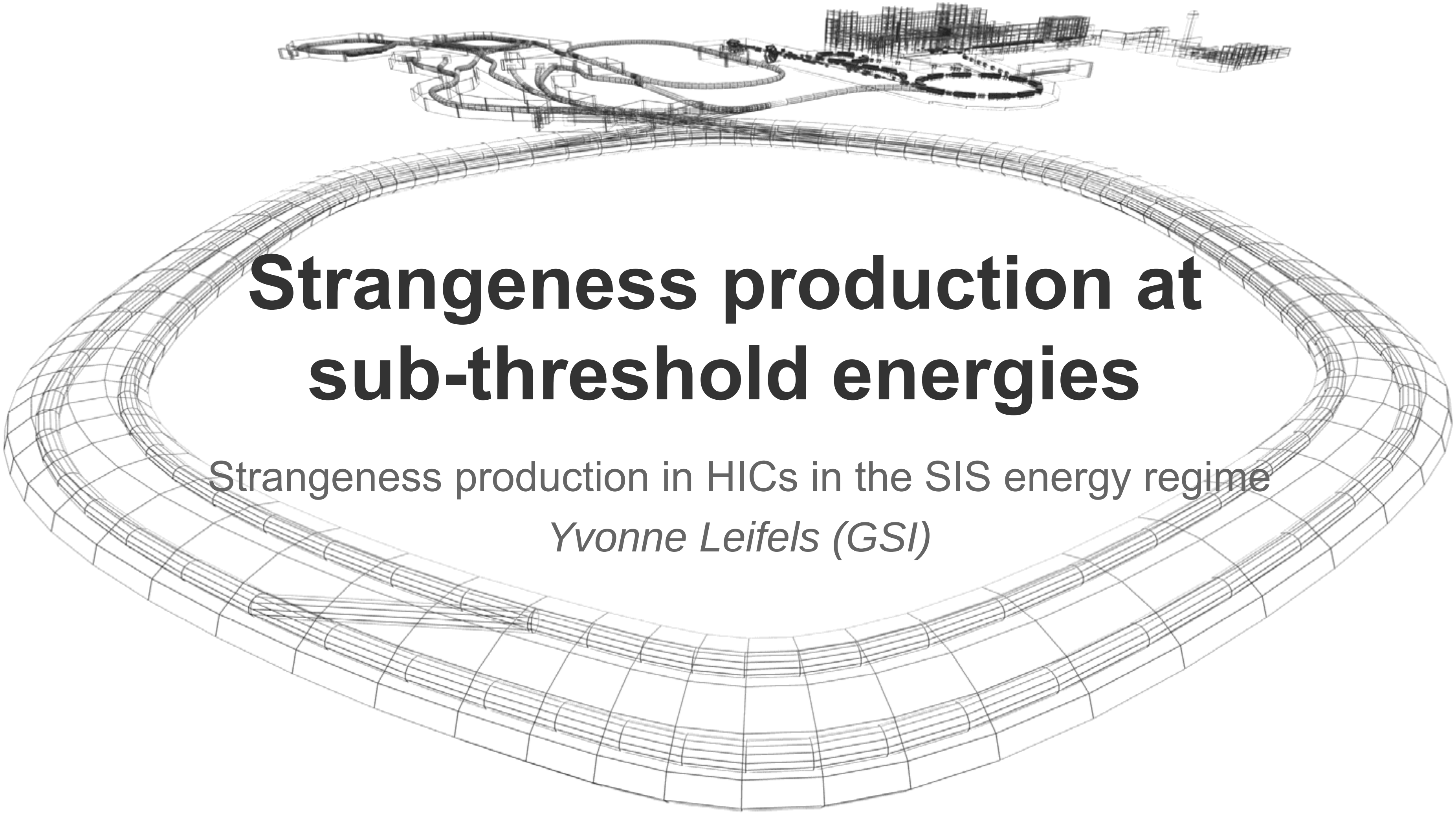
GSI Helmholtzzentrum für Schwerionenforschung GmbH



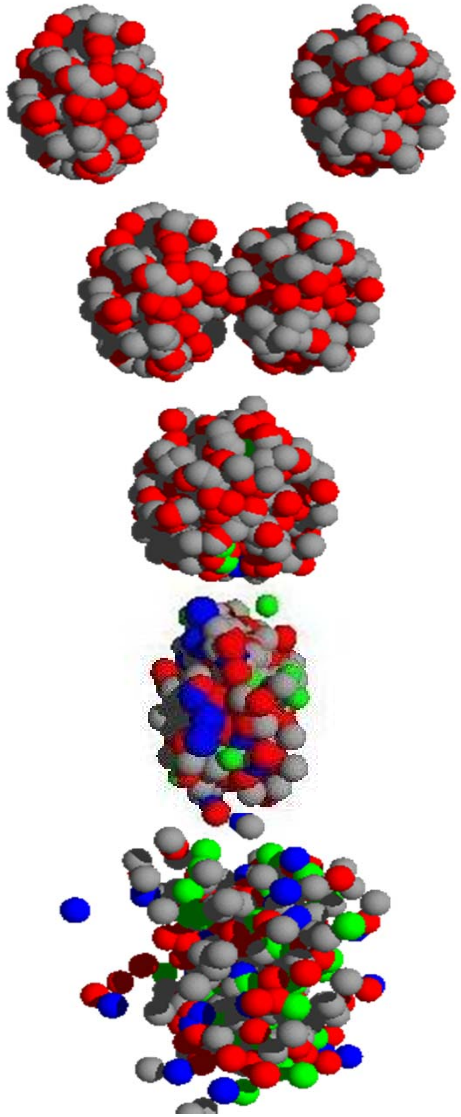
Strangeness production at sub-threshold energies

Strangeness production in HICs in the SIS energy regime

Yvonne Leifels (GSI)

Outline

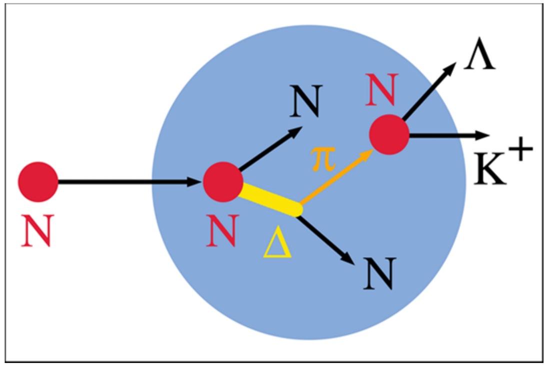
- Introduction
- K^+ and K^0, K^-
  - yields and spectra
  - Φ production
  - flow
- Hyperons
  - bound states with strangeness
- Summary and Conclusion



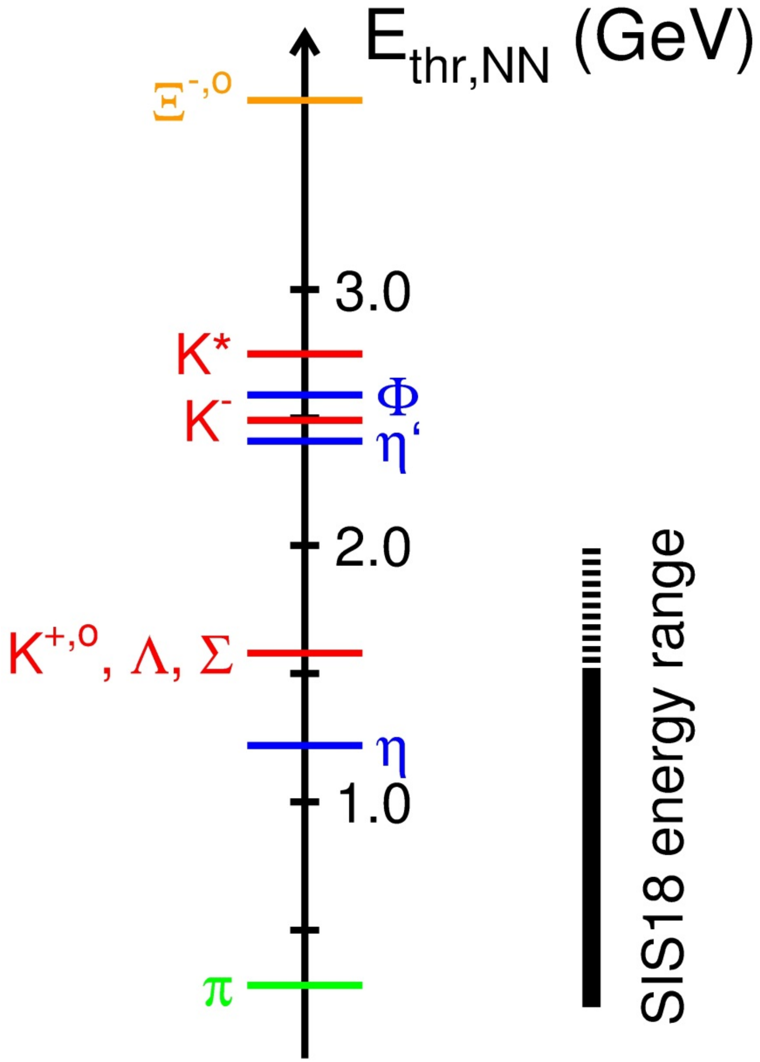
Thanks to:
FOPI collaboration in particular W. Reisdorf
J. Aichelin, E. Bratkovskaya,
C. Hartnack, A. LeFevre
and to KaoS and HADES and...

Introduction

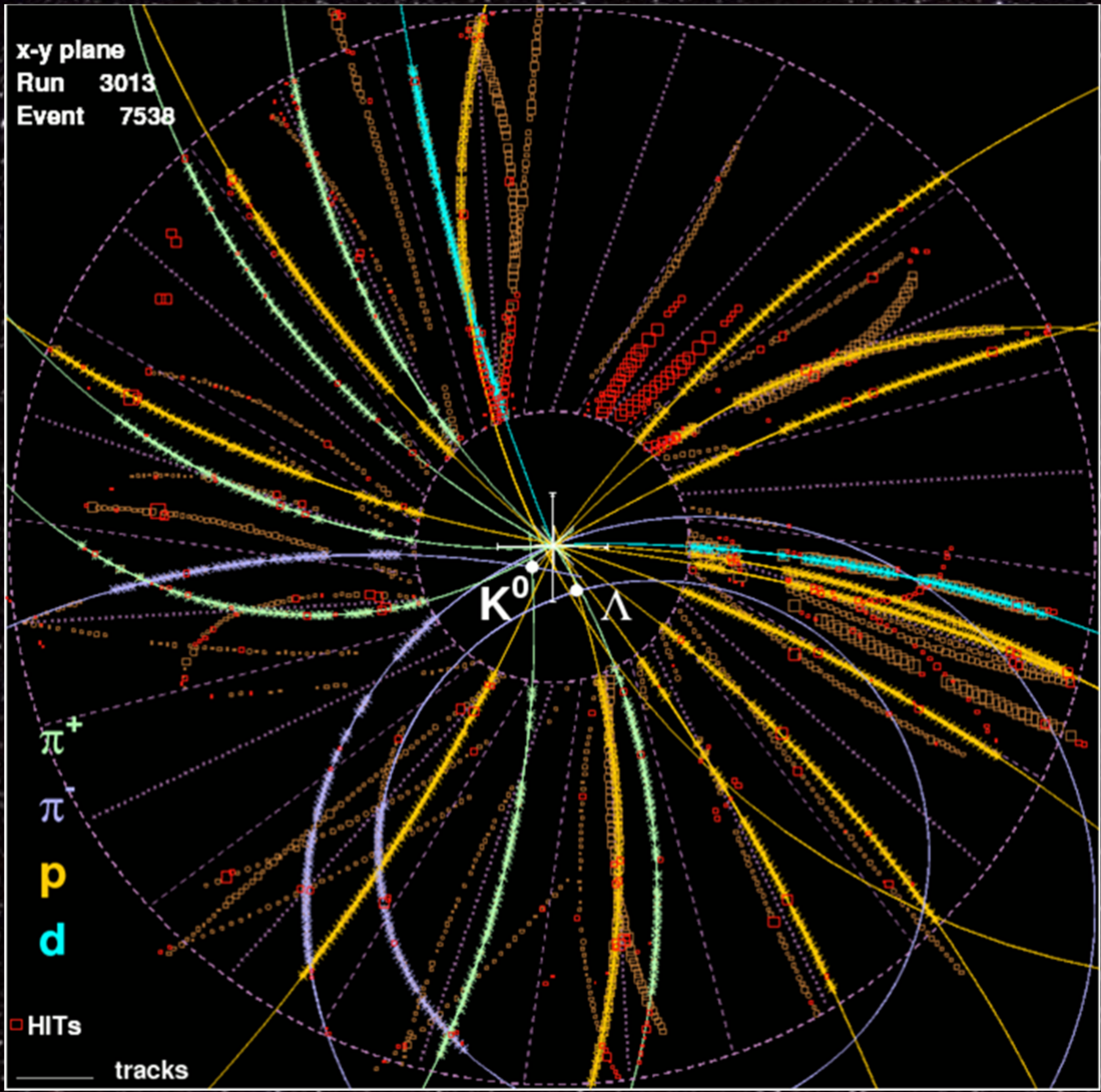
Strangeness production in heavy-ion collisions at energies below or close to the threshold in NN system



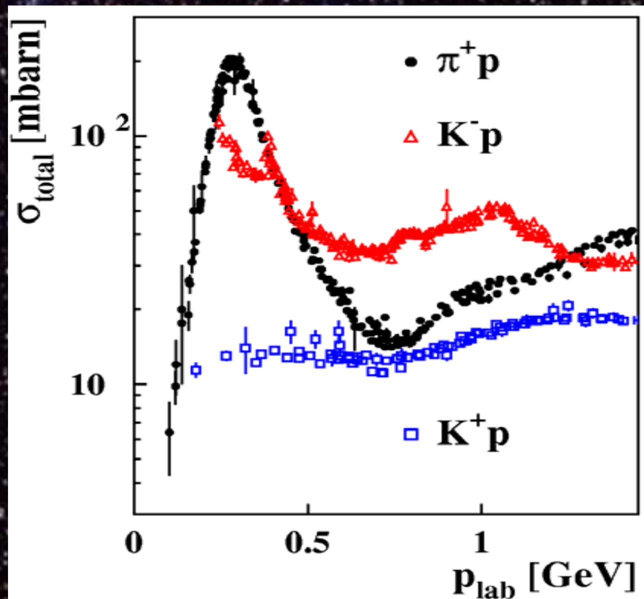
- Fermi momenta may contribute energy
- multistep processes can cumulate the energy needed
- intermediate resonances used as an energy reservoir
- production at high densities due to short life time of resonances



Ni+Ni 1.93 AGeV



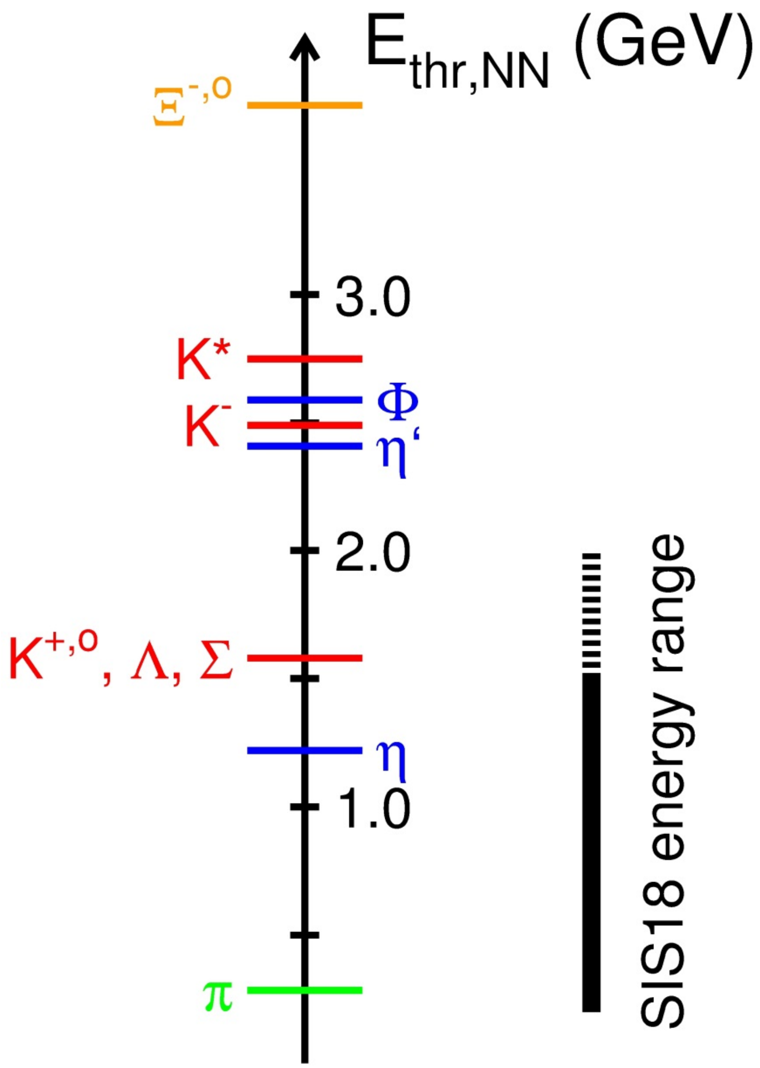
- K^+ only weakly interacting
- K^- strongly absorbed (like pions)
  - Strangeness Exchange
    $\pi + \Lambda \leftrightarrow K^- + N$



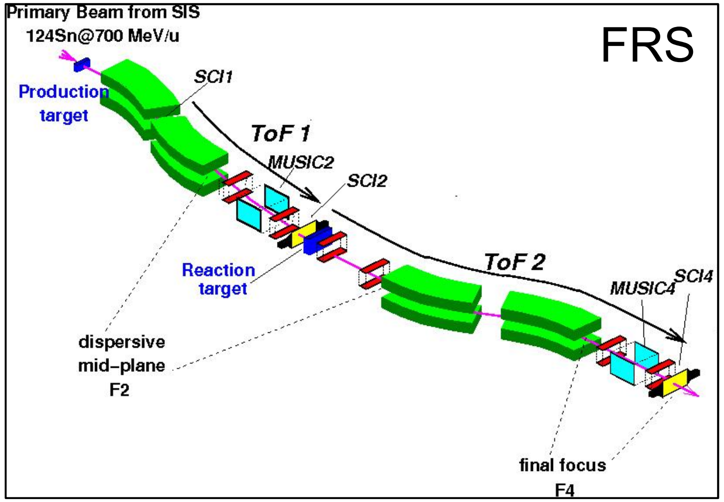
Introduction

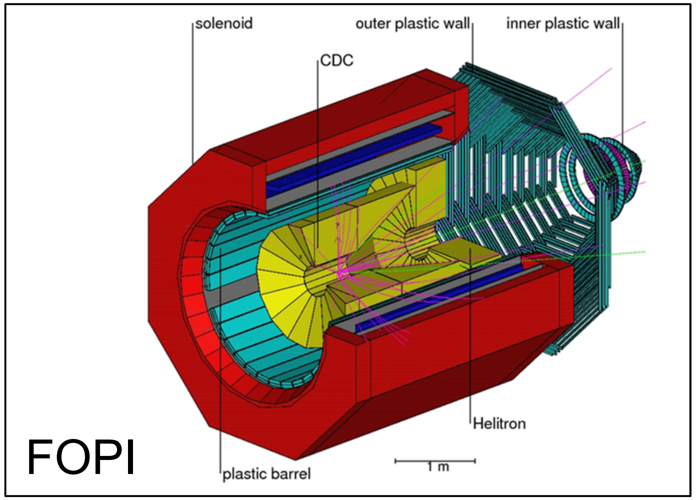
Production of strange particles in heavy-ion collisions at energies close to threshold energies:

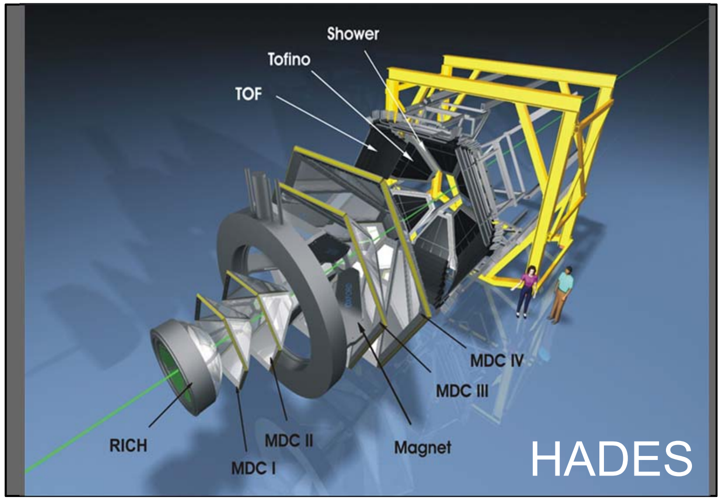
- Access to bulk properties to nuclear matter
- Production processes
- Reaction dynamics
- Interaction of particles in dense matter
- In-medium properties
- Exotic states
  - hyper-nuclei
  - K^-, η‘ bound states



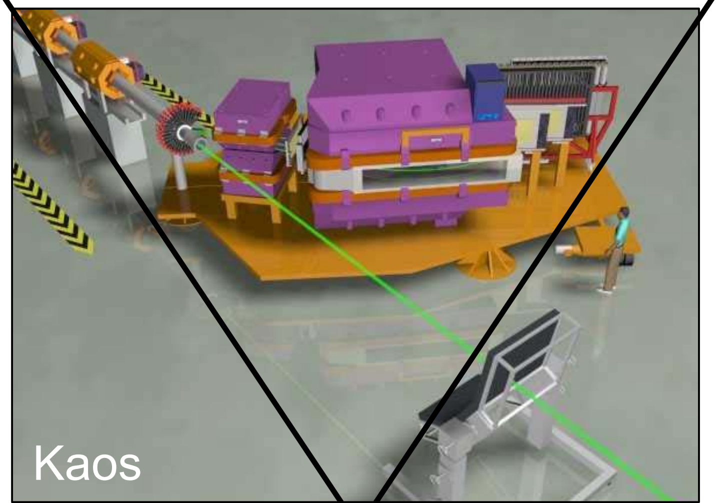
Experiments at SIS18-GSI

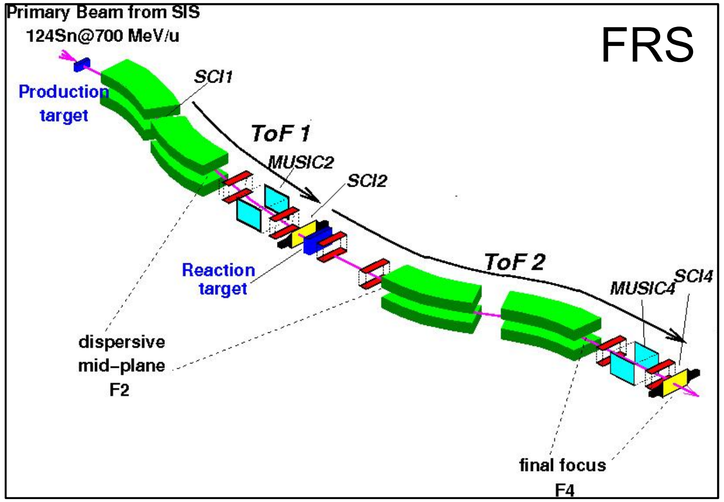


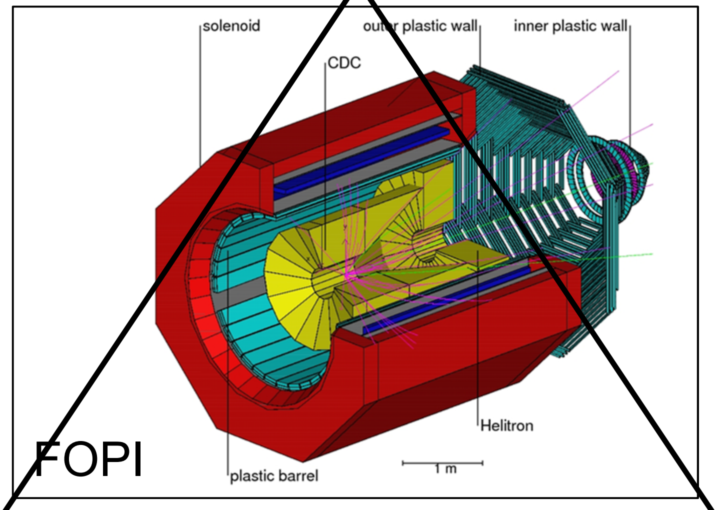


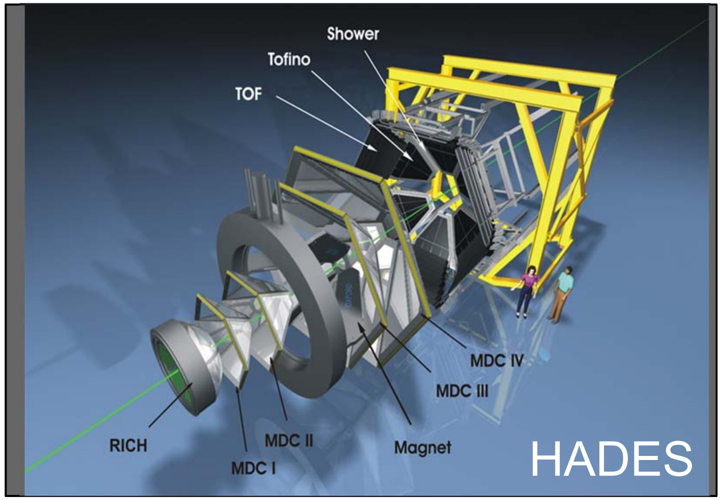


Experiments at GSI





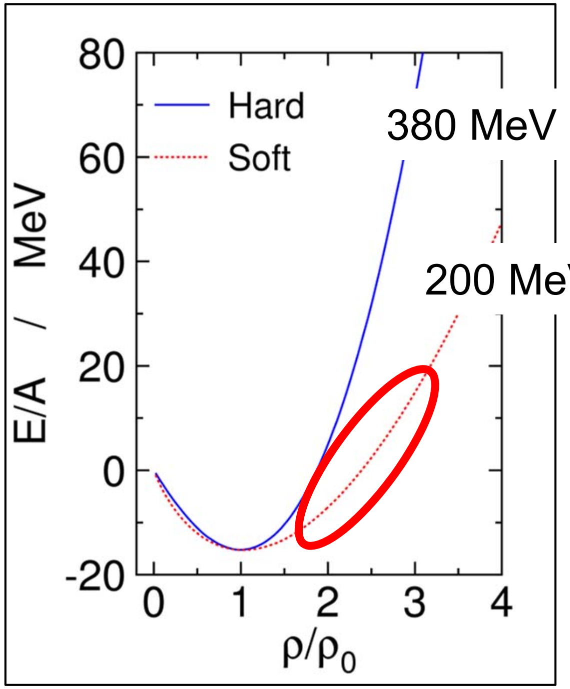


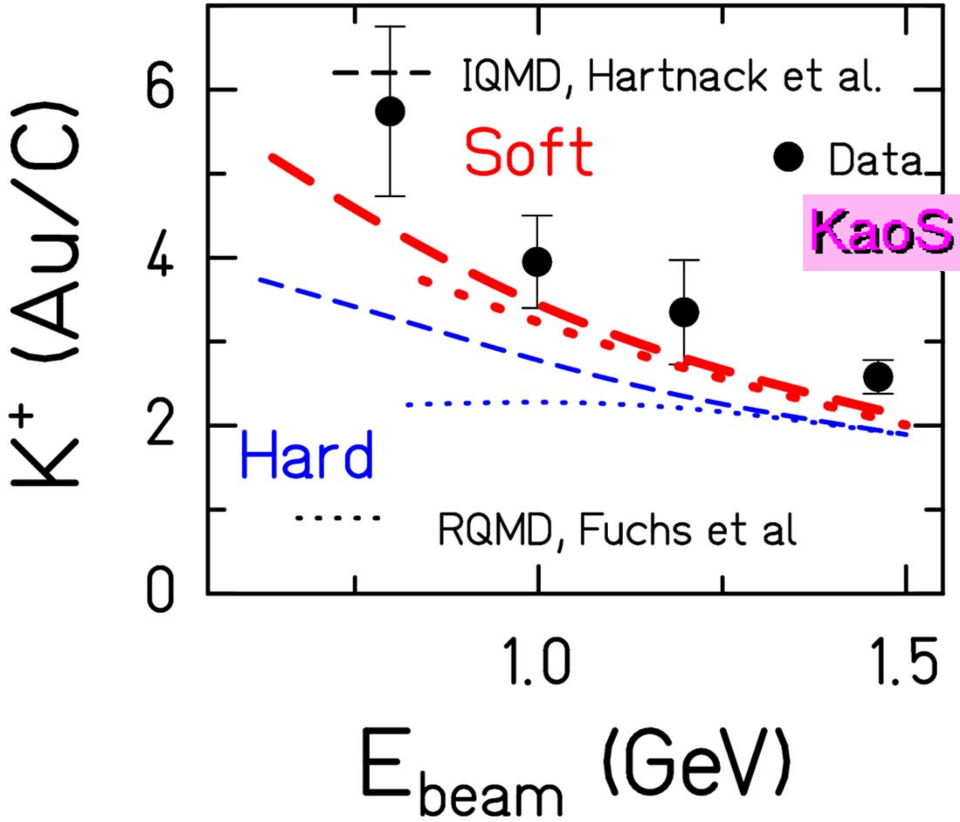


Bulk properties of nuclear matter
Equation of state

Independent on
- models
- details of the input
  - cross sections
  - in medium potentials etc

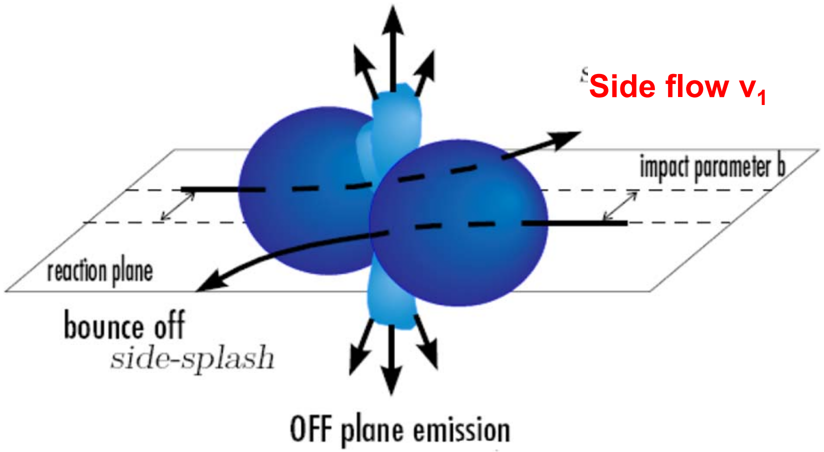
Testing densities at 2-3 ρ_0





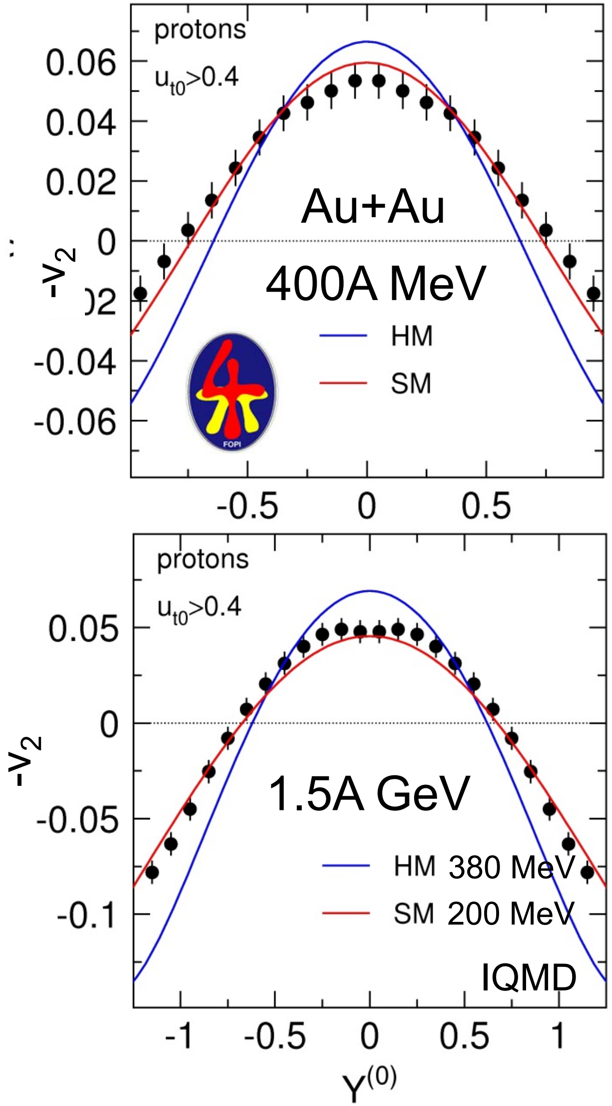
Data: C. Sturm et al., PRL 86 (2001) 39
IQMD: C. Hartnack et al., PRL96:012302,2006
RQMD: C. Fuchs et al., PRL 86 (2001) 1974

Bulk properties of nuclear matter
Flow of nucleons



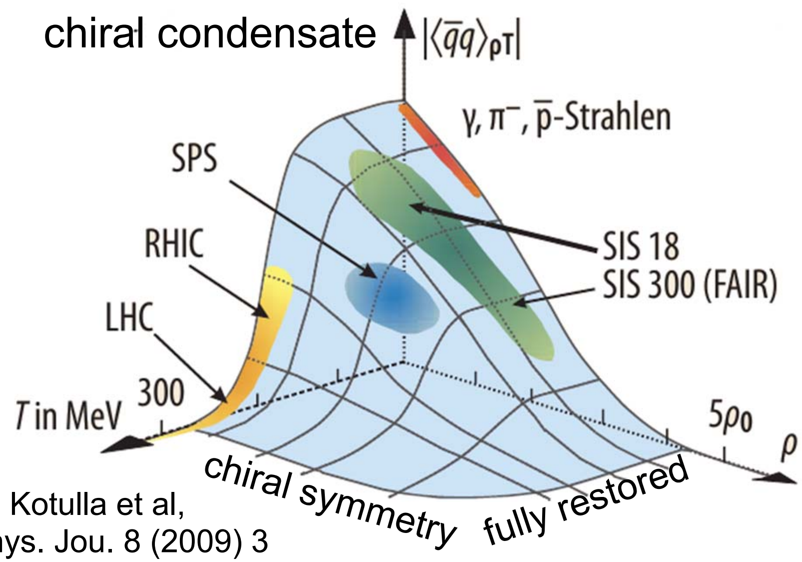
$$\frac{dN}{d\phi} \sim 1 + 2v_1\cos(\phi) + 2v_2\cos(2\phi), \ldots \phi = \phi_R - \varphi$$

- reaction dynamics described
- pion production reproduced~10%
- proton yield overestimated
  - yields depending on EOS (cluster production)
- consistent description of flow and strangeness production possible

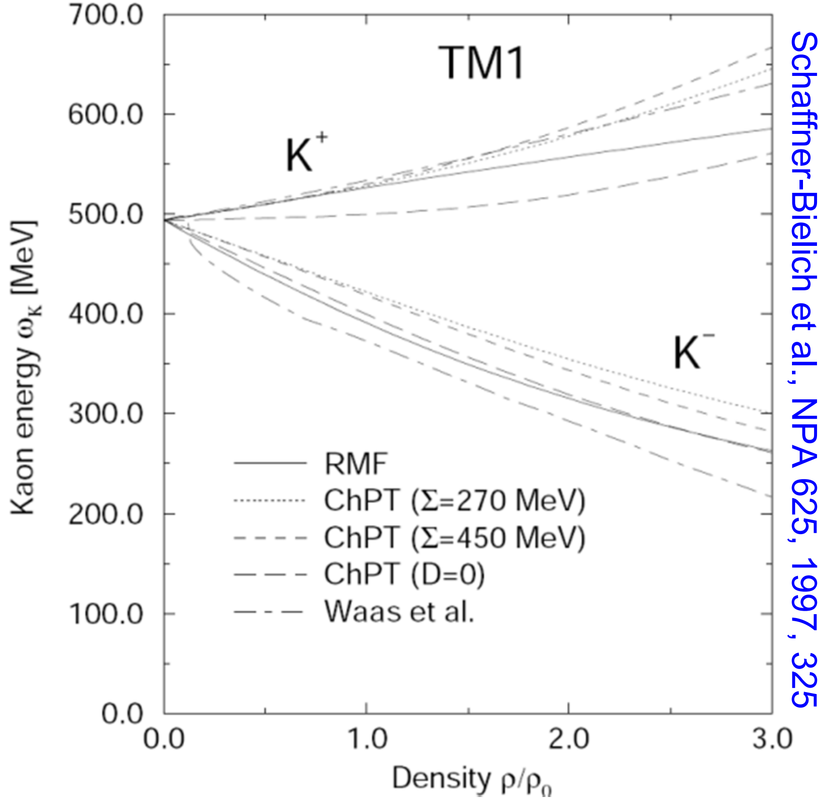


W. Reisdorf et al, Nucl. Phys. A 876 (2012) 1

In medium properties of pseudo-scalar mesons



M. Kotulla et al,
Phys. Jou. 8 (2009) 3
nach W. Weise (2007)



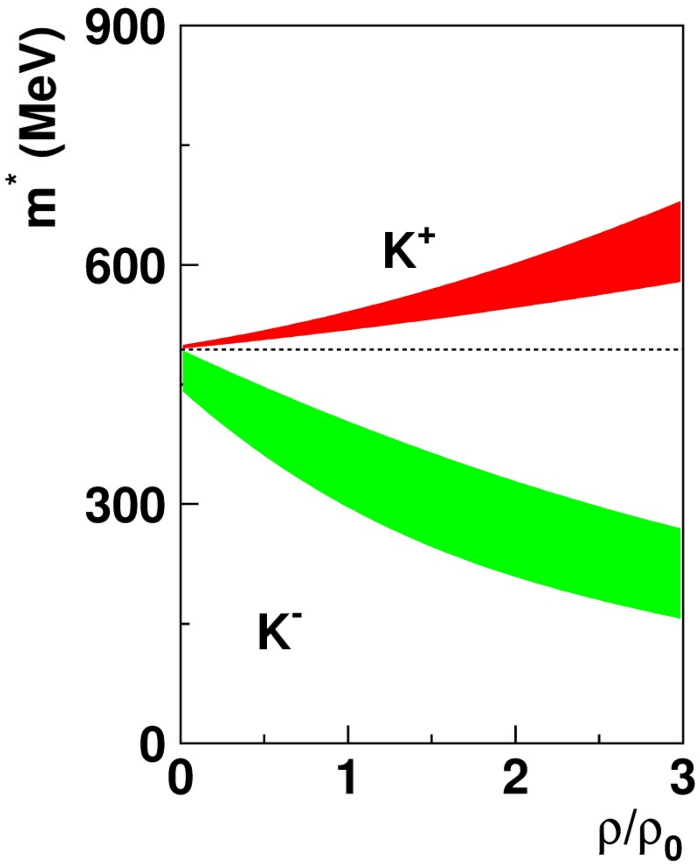
Modified properties of hadrons in dense baryonic matter?

$$\frac{\langle\bar{q}q\rangle^*}{\langle\bar{q}q\rangle} \sim \frac{M^*}{M}$$

Braun – Rho – Scaling (PRL 66,1991):
Masses of non-strange hadrons scale with quark condensate

K^-N – interaction attractive close to ground state densities (→SIDDHARTA), but strength (depth of potential) unclear at high densities -> spectral function

In medium-properties



G.E Brown et al. Nucl. Phys. A 567 (1994) 937
T. Waas, N. Kaiser, W. Weise, Phys. Lett. B 379 (1996) 34
J. Schaffner-Bieliich et al.Nucl. Phys. A 625 (1997)

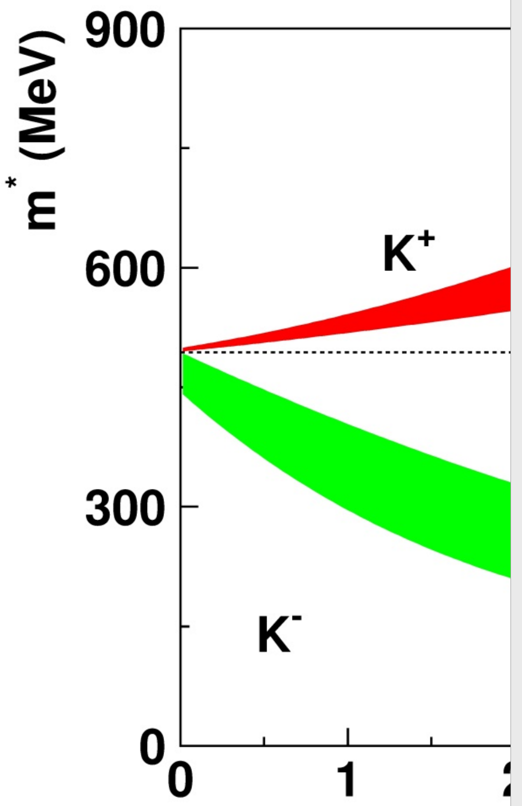
Microscopic transport models needed

Production:
$P \sim \exp(-m^*/T)$
→ **Yields**

Propagation:
$F = -\nabla U$
→ **Spectra**
→ **Flow**

Bound states:
$B = \Sigma_i m_i - \Sigma_i m_i^*$
→ **Search for bound states**

In medium-properties



HSD (V1.5, BUU – Bratkovskaya)

IQMD (KQMD.V0711 – Hartnack)

→ BUU vs QMD code

→ EOS (soft, κ = 200-230 MeV)

→ Kaon production and propagation

→ equal cross sections (production/re-scattering)

→ "equal" KN potential

→ Treatment of anti-kaons

→ IQMD quasi particles

→ HSD G-Matrix formalism

$U(\rho=\rho_0, p=0) = -50$ MeV

→ C. Hartnack et al. Phys. Rep. 510, 119 (2012)

oduction:

~ exp (-m*/T)

Yields

opagation:

=-∇U

Spectra

Flow

ound states:

$= \Sigma_i m_i - \Sigma_i m_i^*$

Search for

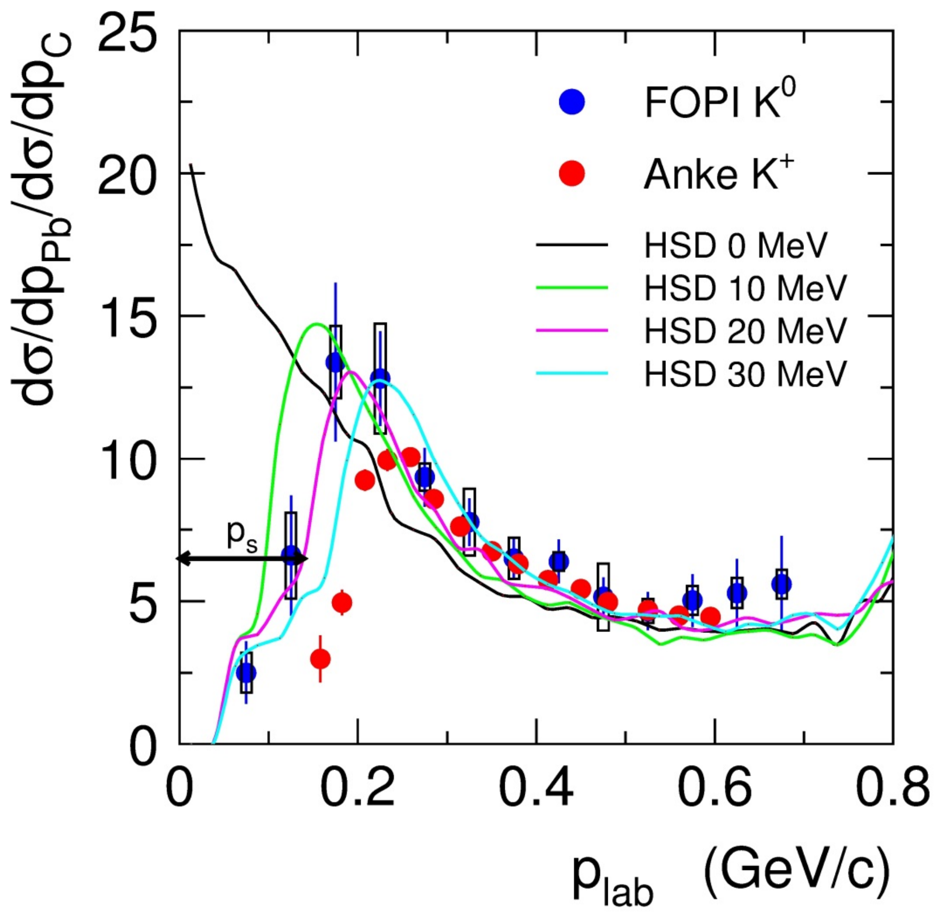
ound states

G.E Brown et al. Nucl. Phys. A 567 (1994) 937

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

J. Schaffner-Bieliich et al.Nucl. Phys. A 625 (1997)

In medium KN-Potential in pion induced reactions



FOPI data @ SIS

M.L. Benabderramahne et al., *PRL* (2009)

$\pi + A \rightarrow K^0 + X$ at 1.15 GeV/c

Anke data @ COSY

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

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

Model interpretation with HSD:

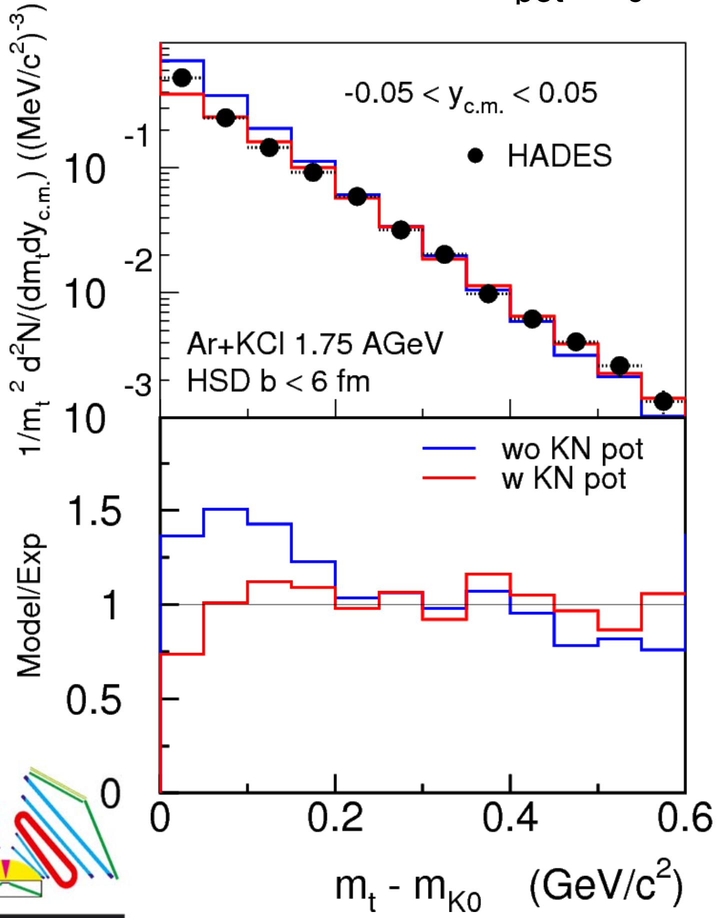
$U_{KN}(\rho_0) = + 20 +/- 10$ MeV

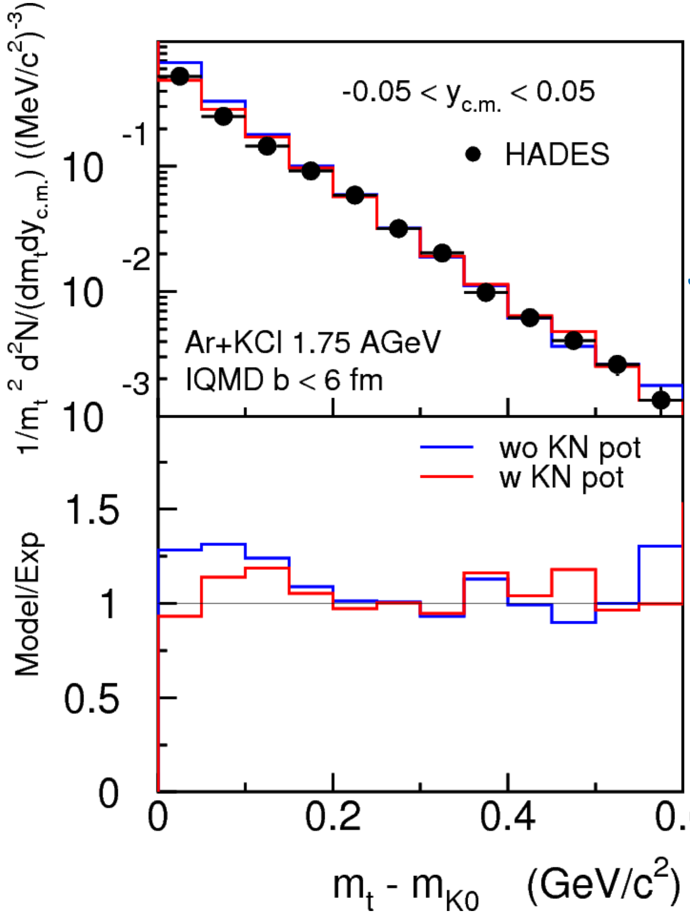
Result limited by statistics

→ more systematic studies

In-medium KN Potential in heavy ion collisions

KN $U_{pot}(\rho_0)$ = +40 MeV both IQMD and HSD



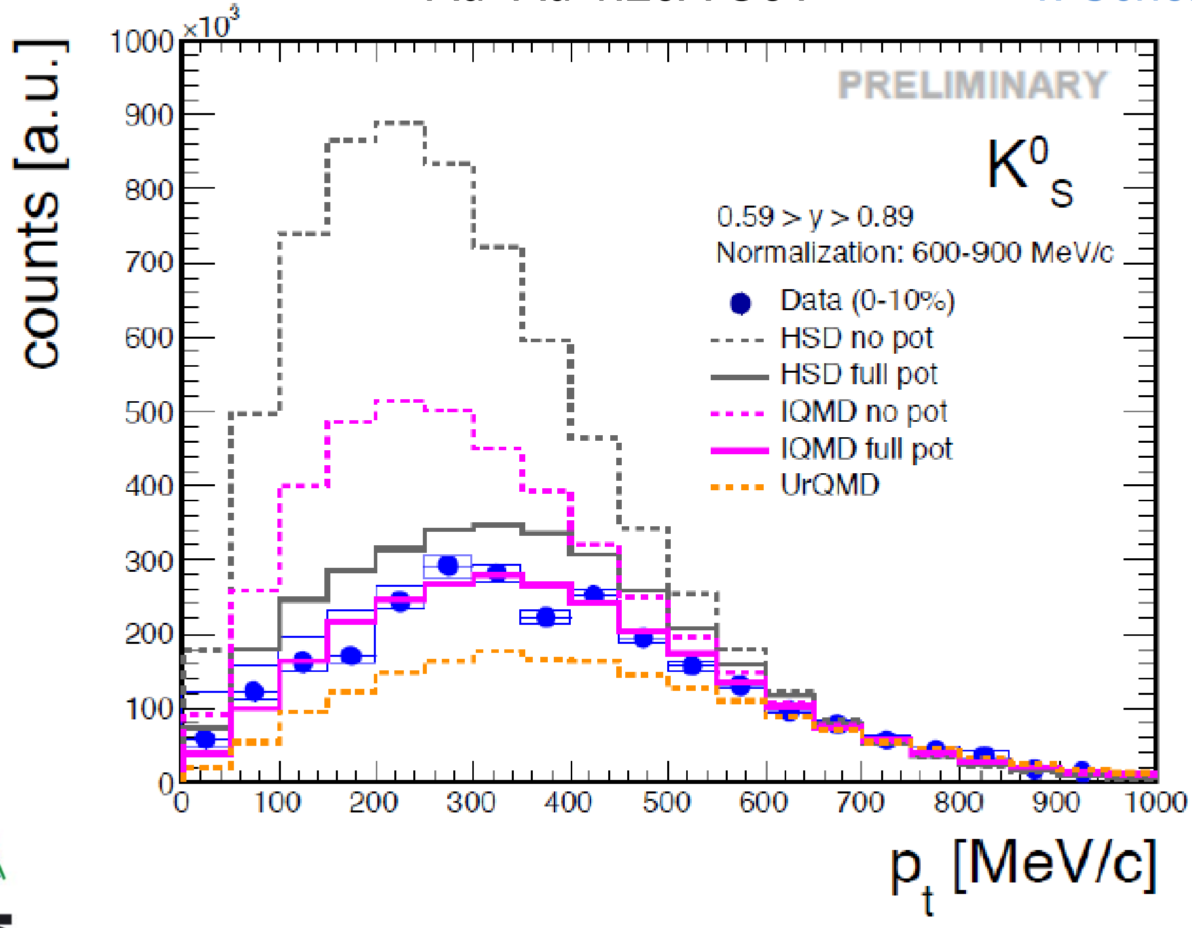


HADES, Phys. Rev. C82:0044907, 2010

In-medium KN-potential from low momenta

Au+Au 1.25A GeV

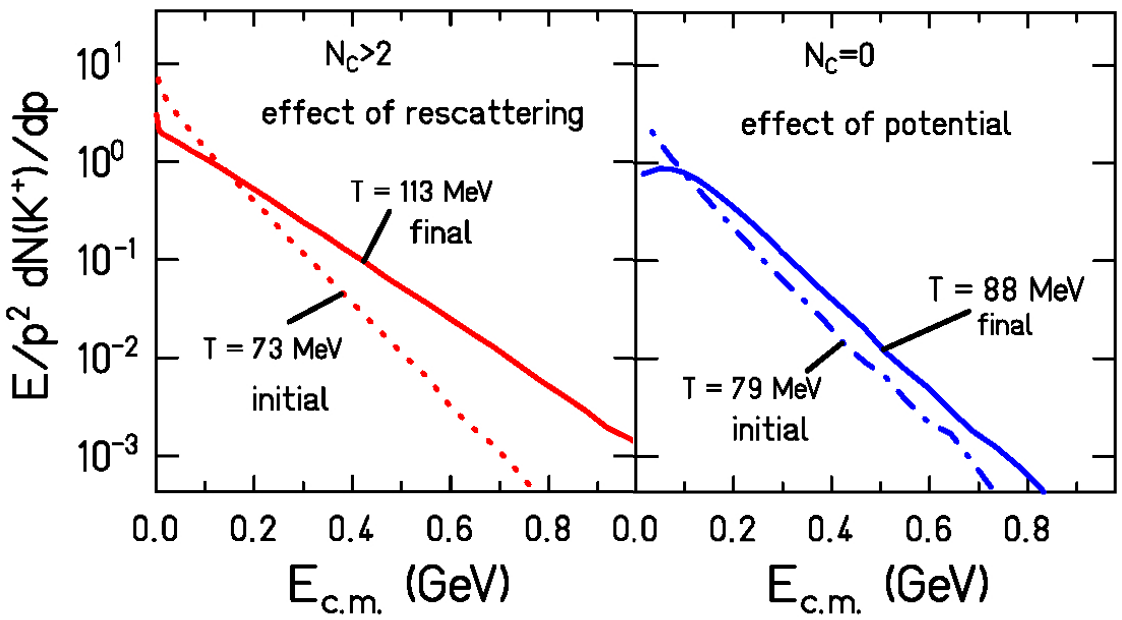
T. Scheib, SQM 2016



KN $U_{pot}(\rho_0) = +40$ MeV both IQMD and HSD

In-medium potential
What is influencing the shape of the K^+ spectra?

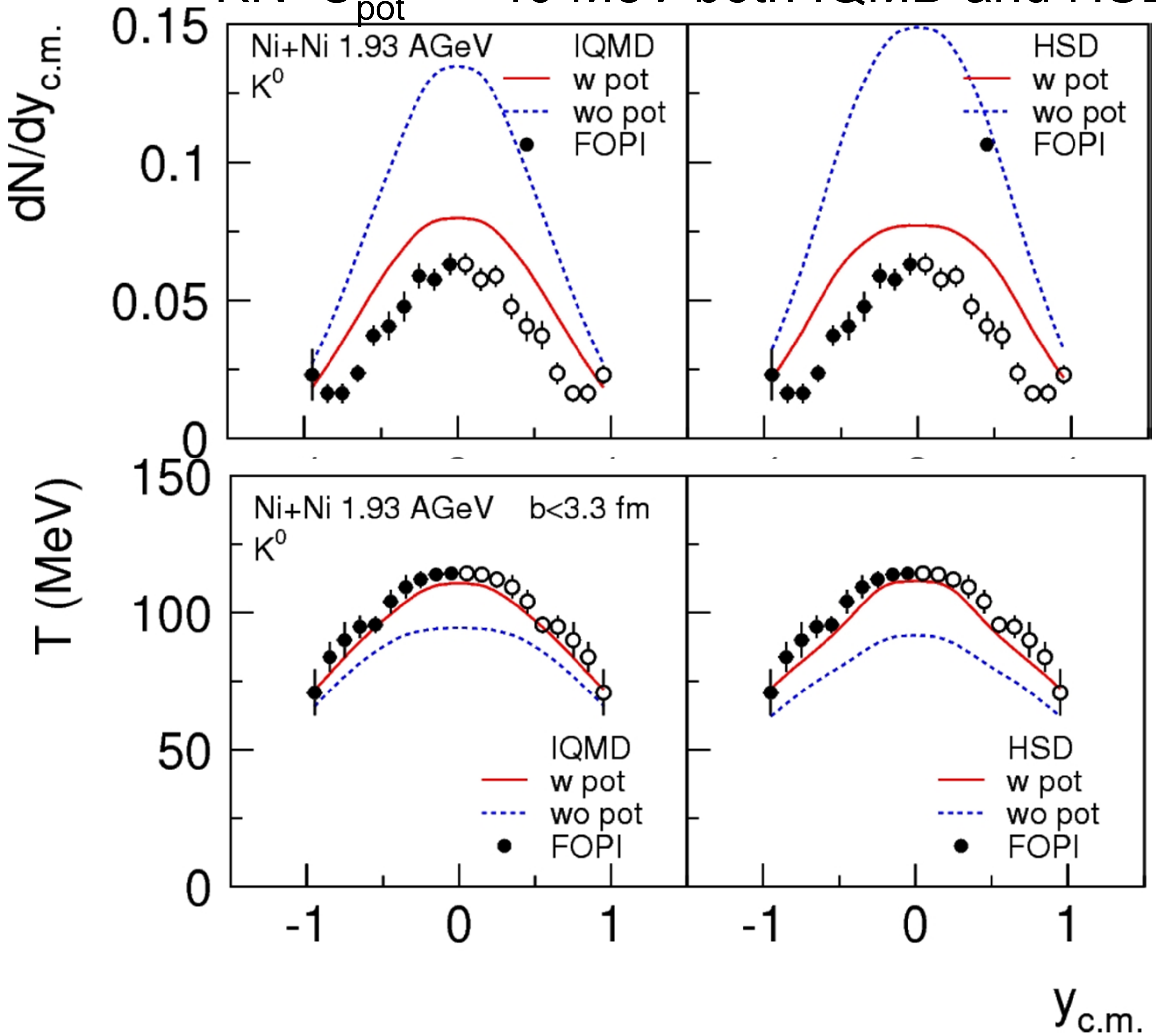
Au+Au 1.5AGeV central



- rescattering tends to align the Kaons to the nucleons → T higher
- potential causes repulsion → T lower

In-medium KN potential
K^0 in Ni+Ni at 1.9A GeV

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

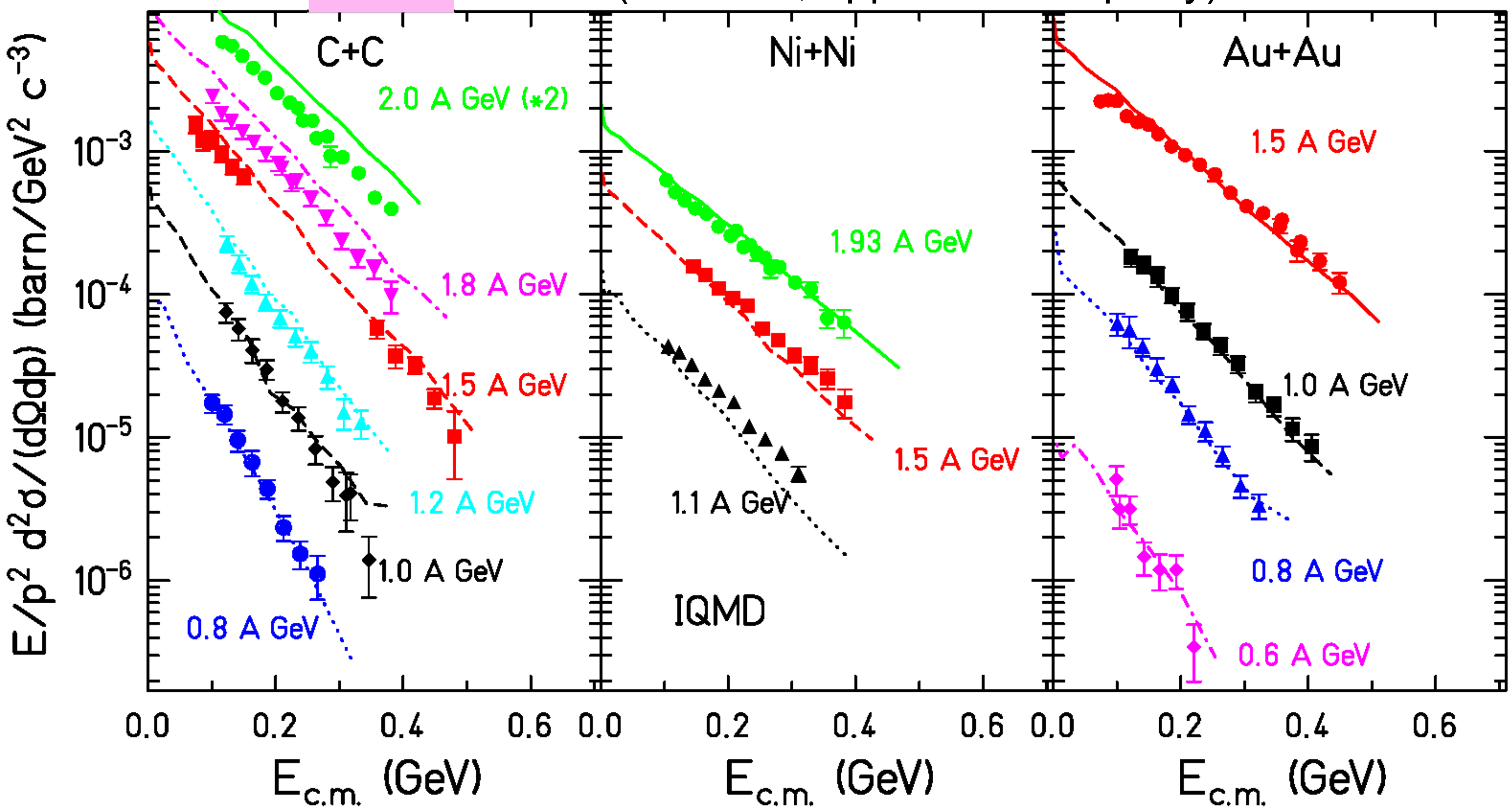


X. Lopez
M. Merschmeyer

Most of experimental data reasonably well described by HSD and IQMD

In-medium KN potential
Heavy ion collisions C+C to Au+Au

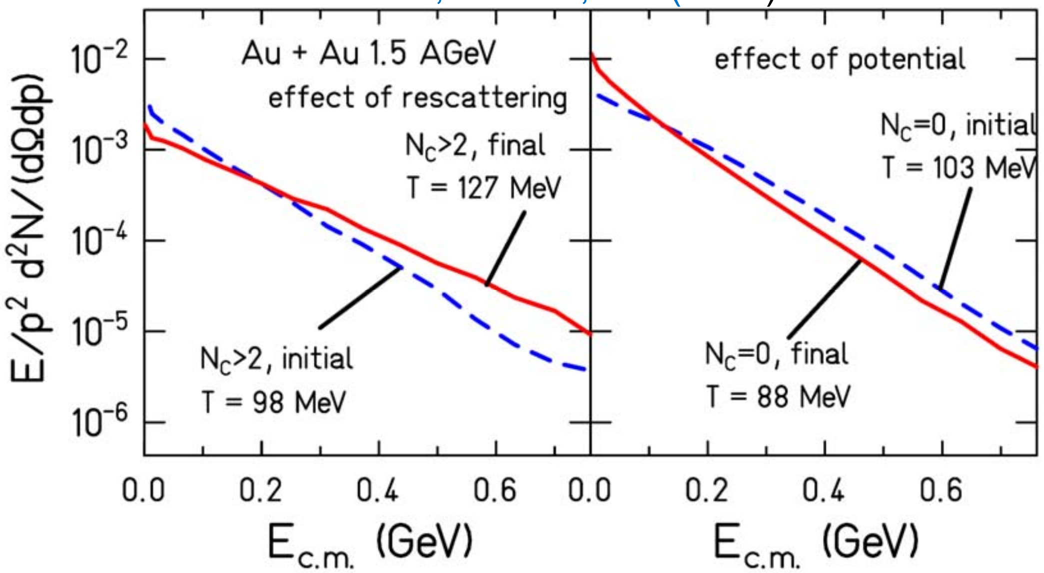
KaoS K^+ data (inclusive, approx. mid-rapidity)



→ repulsive KN potentia U_{pot} (ρ_0) = +20...40 MeV

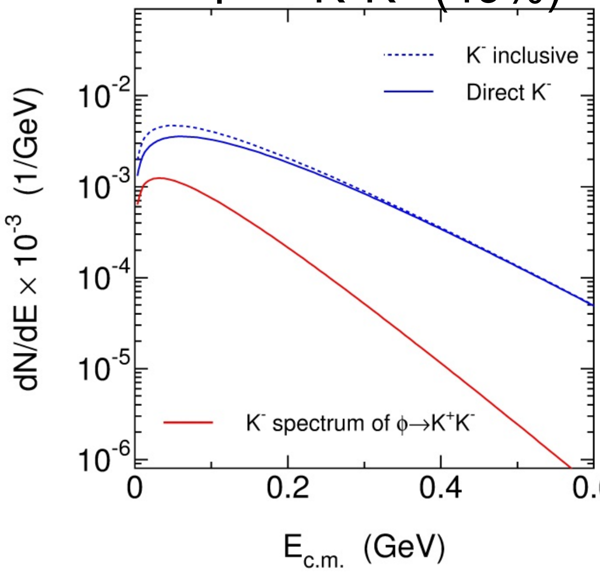
In-medium potentials
K^- spectra

C. Hartnack et al., PR 510, 119 (2012)



Al+Al 1.9A GeV

$\Phi \rightarrow K^+K^-$ (49%)



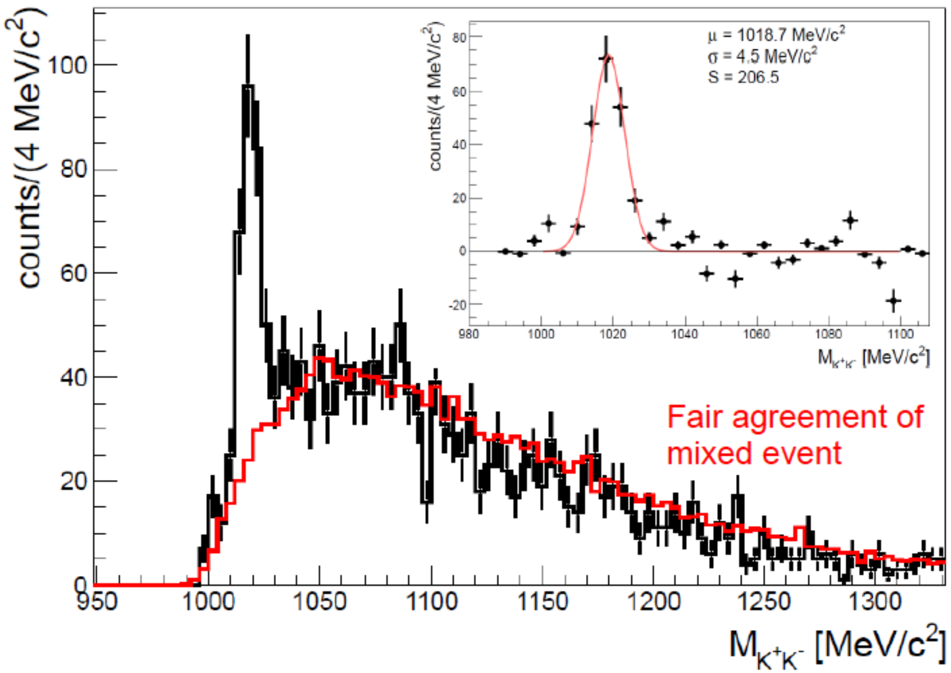
P.Gasik et al., EPJA 52, 177 (2012)

- only 20% of all K^- survive
- absorption at low momenta → T higher
- re-scattering tends to align the Anti-kaons to the nucleons → T higher
- potential causes attraction → T lower
- contribution of the Φ decay → T lower

In medium potentials
Φ production

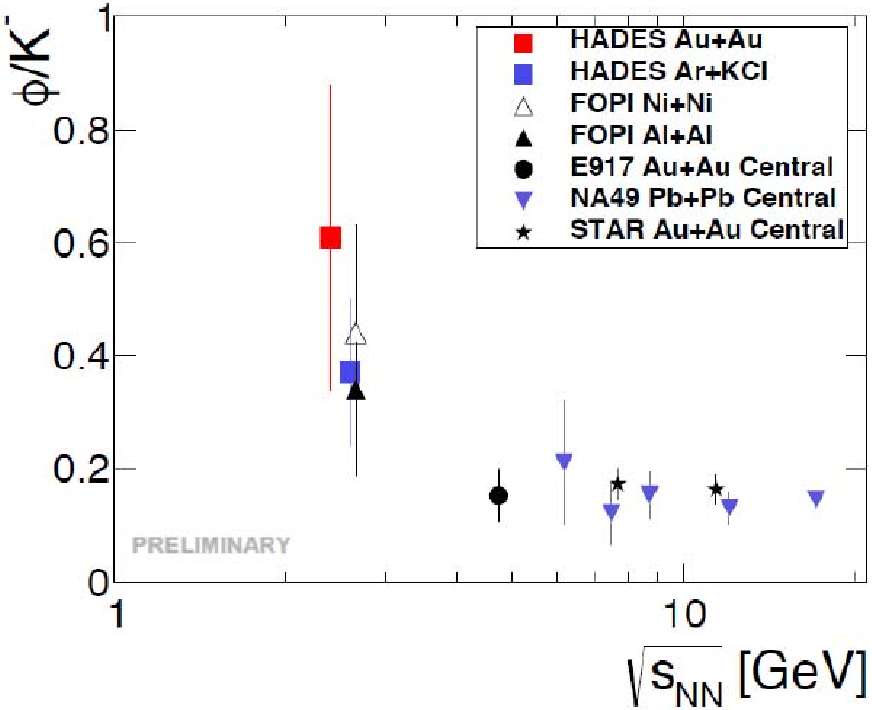
Au + Au 1.25A GeV

Φ → K^+K^- (49%)



Φ meson reconstructed via charged kaons

T. Scheib SQM 2016
Thesis: H. Schuldes

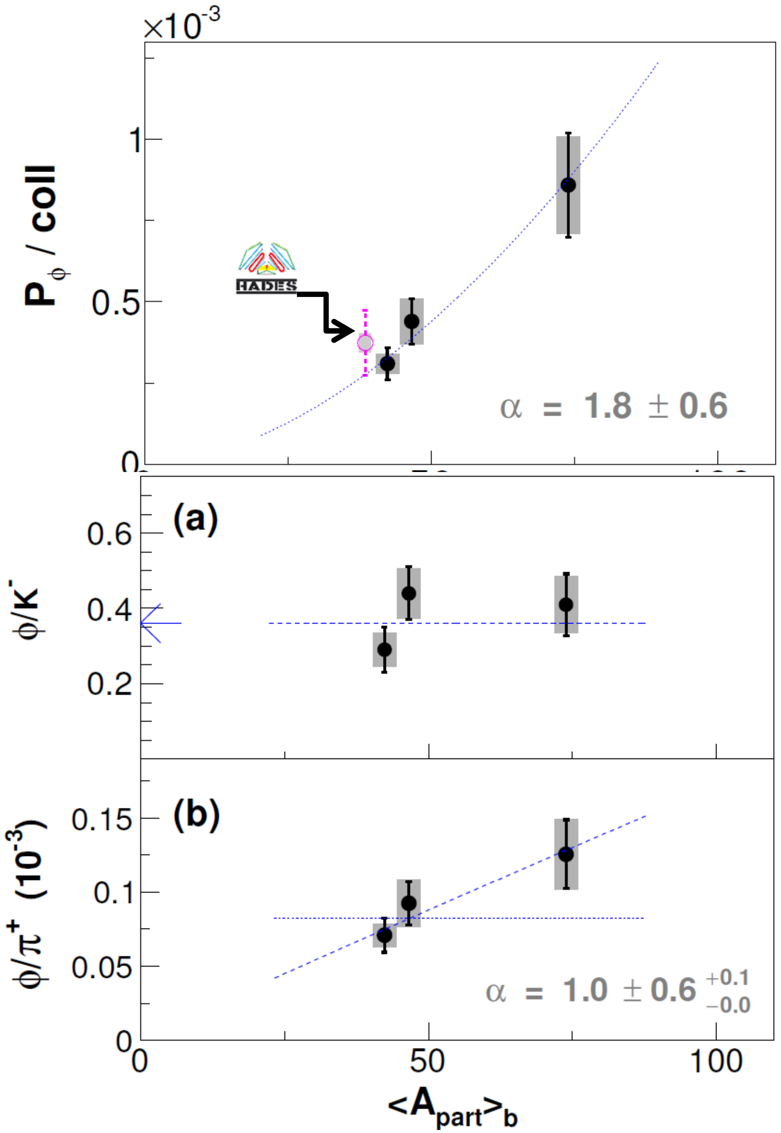


Strong rise of Φ/K^- ratio with decreasing beam energy as predicted by stat. model and described by UrQMD
→ talk of Markus Bleicher

In-medium potential
Φ production

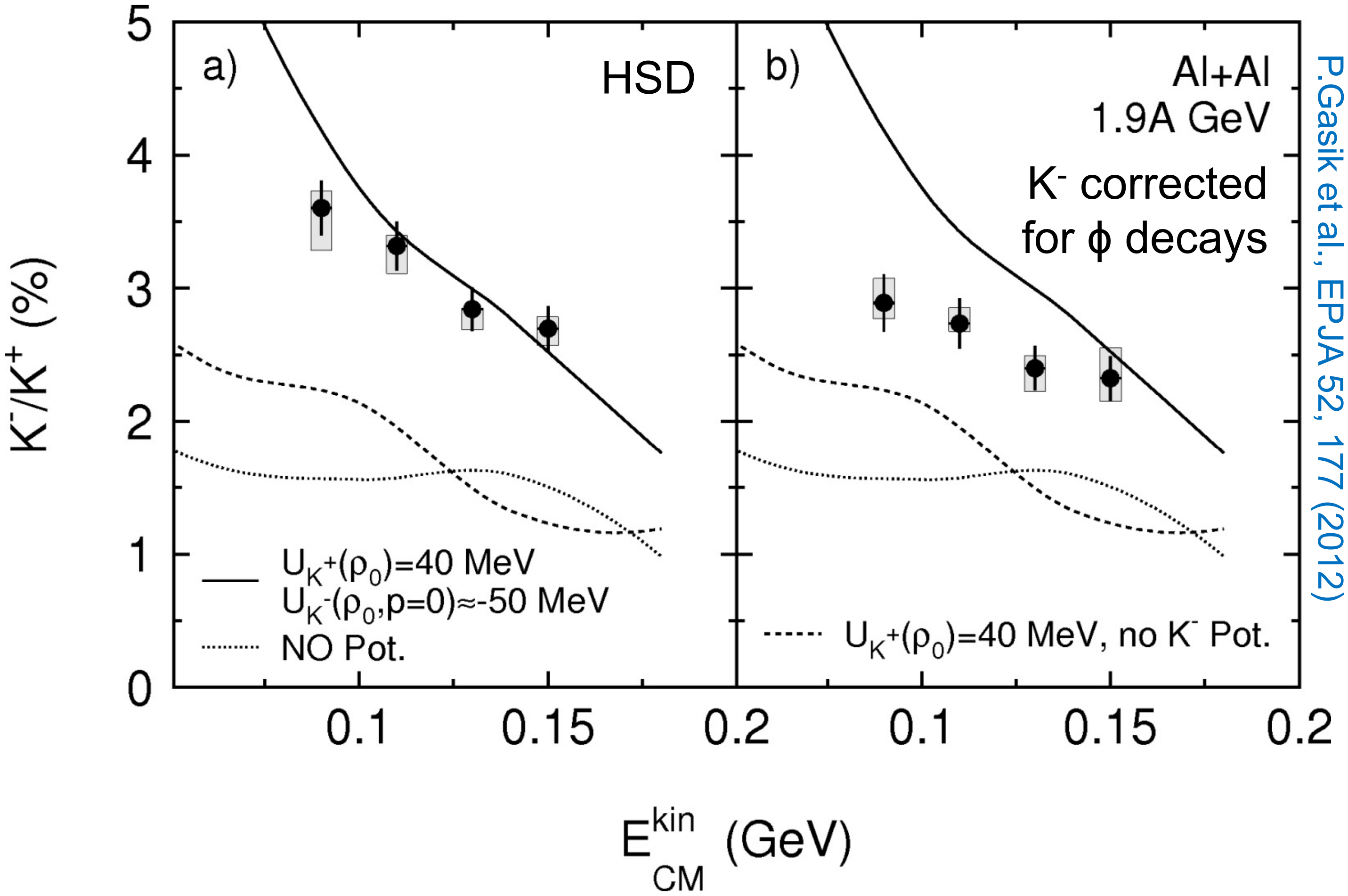
FOPI: Al+Al/Ni+Ni 1.9A GeV

- Φ production as function of number of participating nucleons rising with centrality
- Φ/K^- independent of centrality
  - linked?
- Φ/π ratio rises with centrality?
- Φ in Al+Al 1.9AGeV
  - contribution to K^- production 17±3±2 %
  - T_{eff} = 93 ± 14 (stat)$_{-17}^{+15}$(syst) MeV



K. Piasecki et al., PRC 94, 014901 (2016)

In medium potentials
K^- Spectra and the contribution of Φ decay



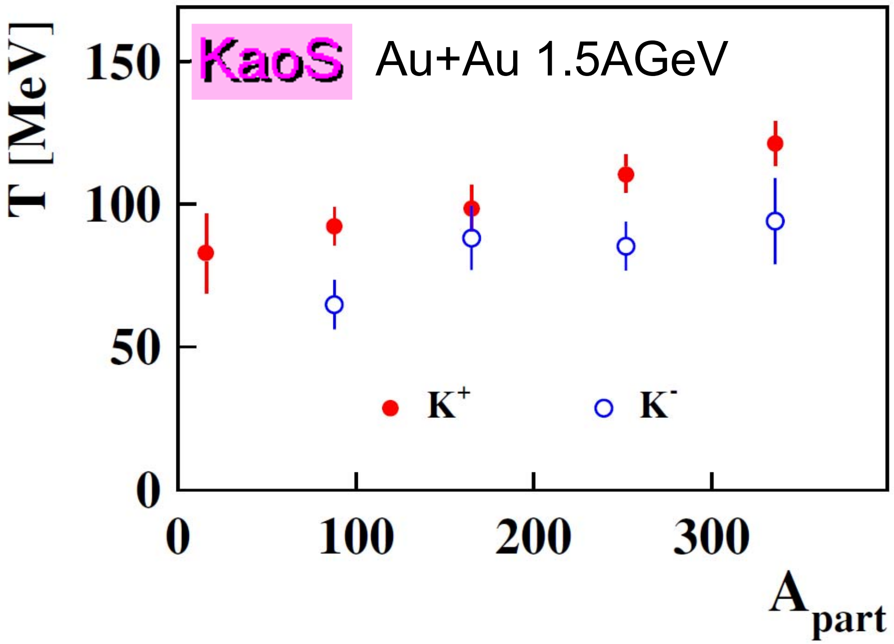
P.Gasik et al., EPJA 52, 177 (2012)

In-medium potential
K^- spectra

Au+Au 1.5A GeV

Apparent slopes of K^- systematically steeper than K^+
Because of:

- Attractive $\bar{K}N$ potential
- Contribution of Φ decay?
  - shown in M. Bleichers talk

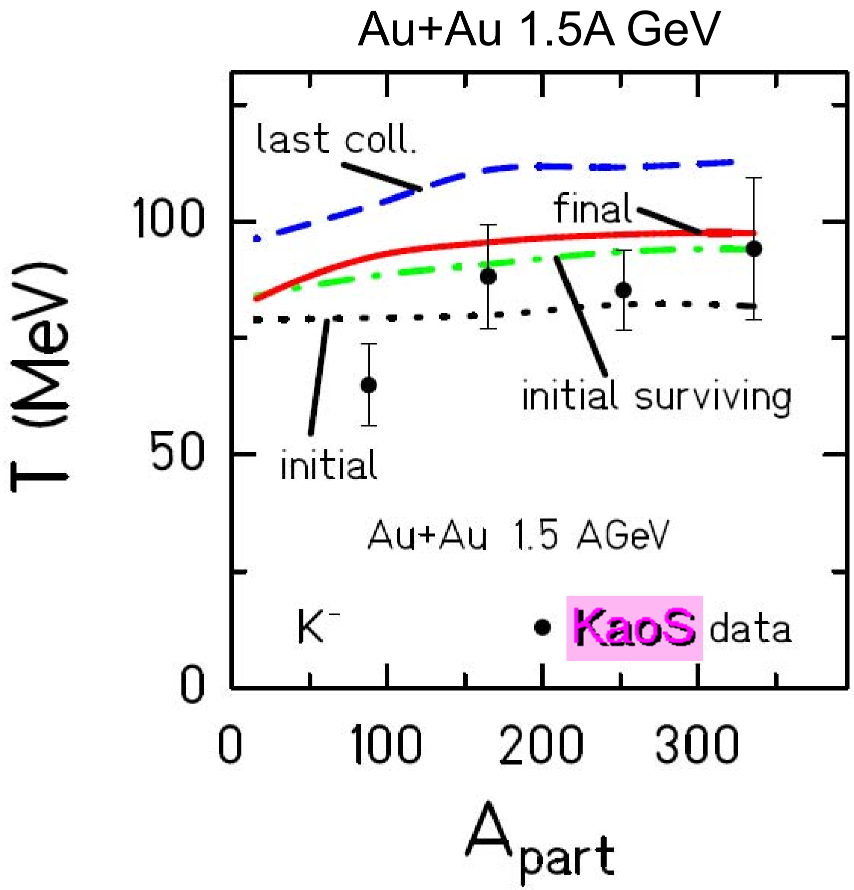


A. Förster et al., JPG 91, 6 (2005)

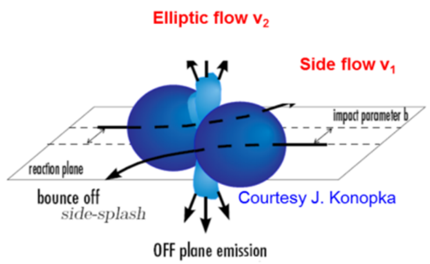
In-medium potential
K^- spectra

Apparent slopes of K^- systematically steeper than K^+
Because of:

- Attractive $\bar{K}N$ potential
- Contribution of Φ decay?

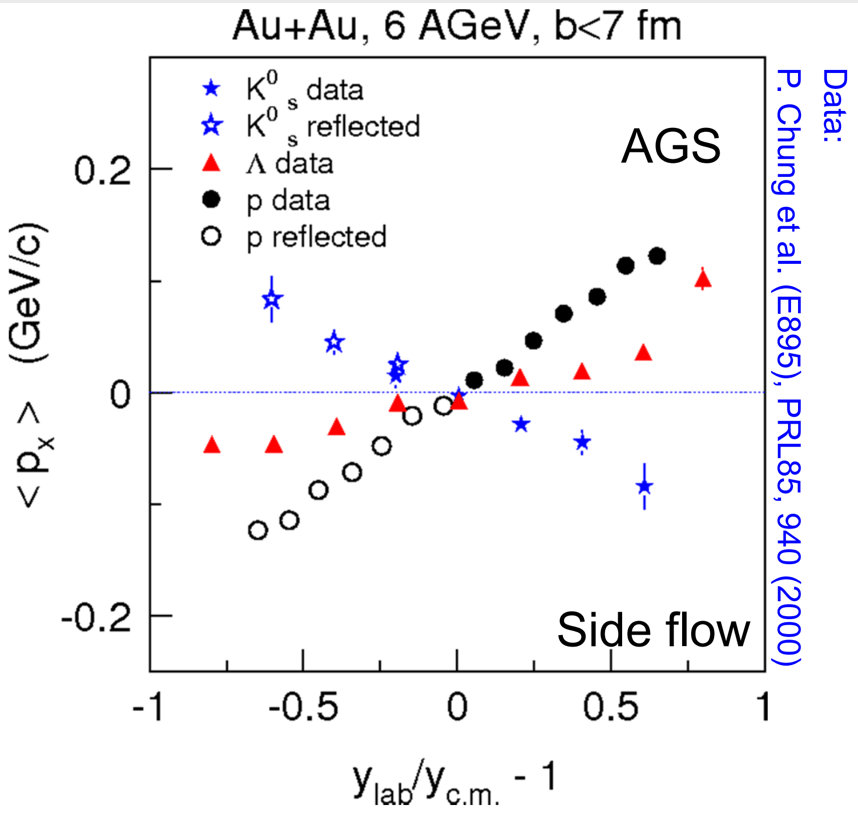


In-medium potential
Side flow v_1



$$\frac{dN}{d\Phi} \sim 1 + 2v_1\cos\Phi + 2v_2\cos^2\Phi$$

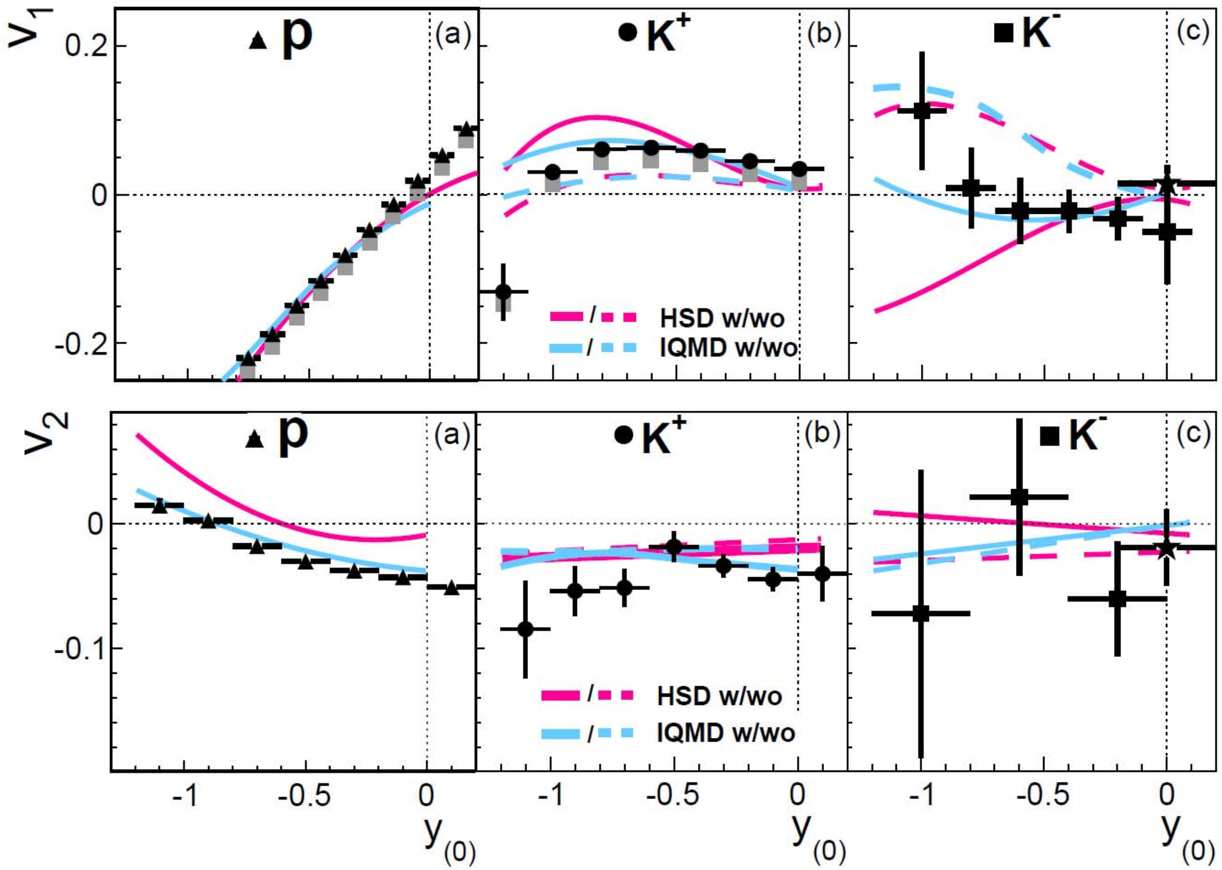
$$\Phi = \varphi - \Phi_{Reac}$$



- Very strong kaon antiflow signal,
- as big as proton flow (opposite sign!)
- Comparisons to microscopic transport models
  → repulsive KN potential
- Λs subject to an attractive potential

In medium KN potential
Flow in Ni+Ni collisions

Ni+Ni b< 6 fm

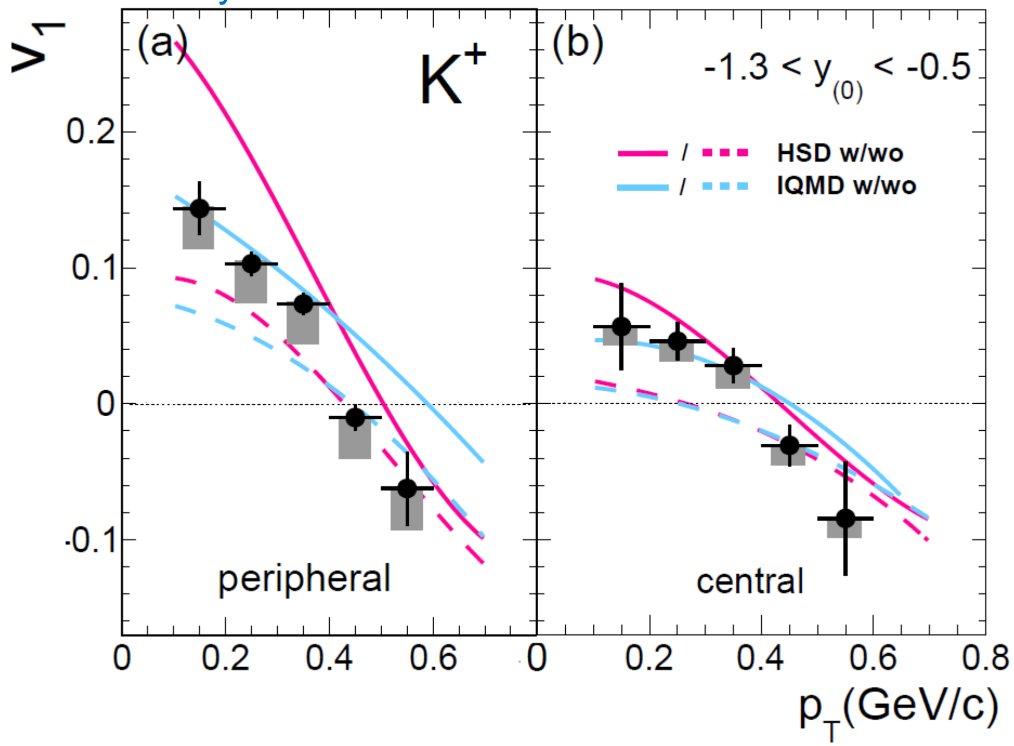


V. Zinyuk et al. PRC (2014)

- K^+ v_1 better described with potential $U_{KN}(\rho_0)$= +20 MeV)
- K^+ v_2 no large sensitivity
- Data for K^- better described with potential

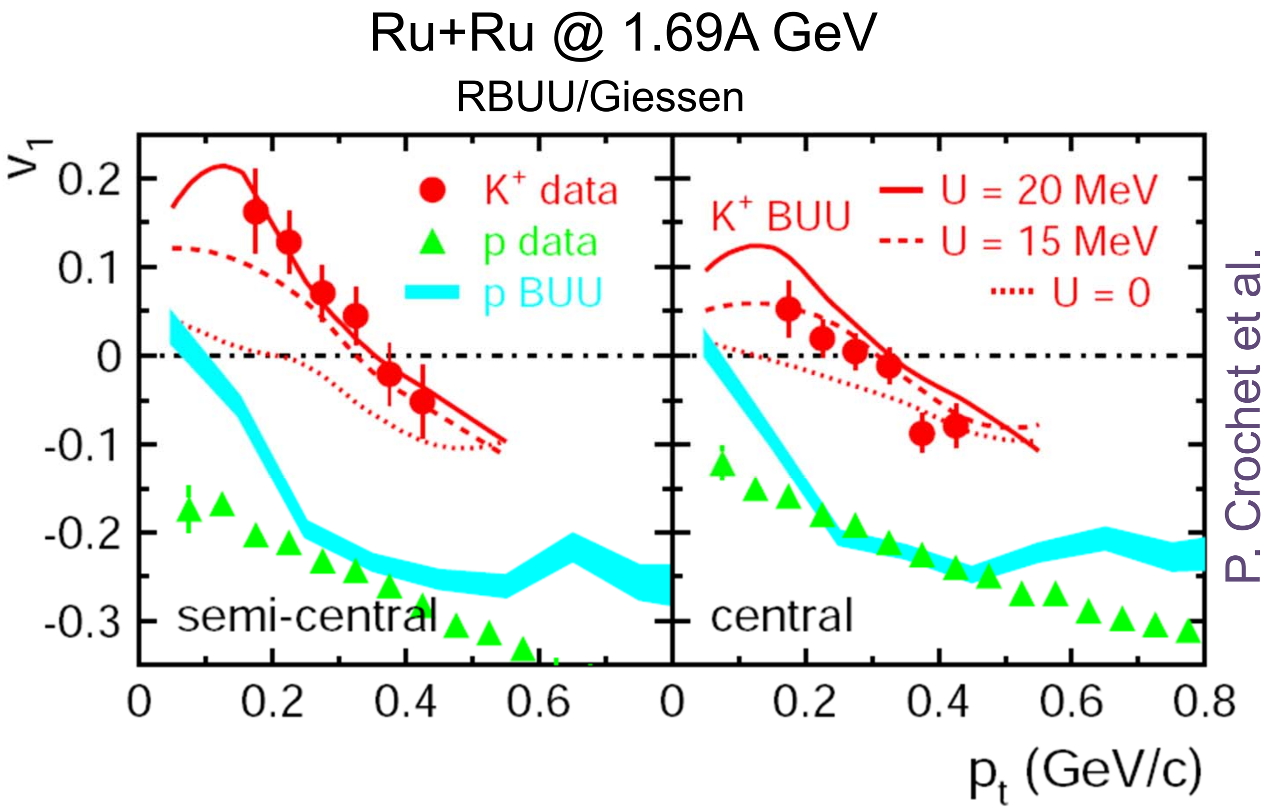
Systematic studies on flow – Ni+Ni

V. Zinyuk et al.



- Side flow best described with repulsive KN potential U_{pot} <~20 MeV
- consistent with older FOPI data on kaon flow
- more flow data on heavier systems needed
- FOPI measured Ru+Ru and Ni+Pb
- HADES measured Au+Au 1.25A GeV
- Kaos measured Au+Au/Ni+Ni at mid-rapidity

Systematic studies on flow – Ru+Ru

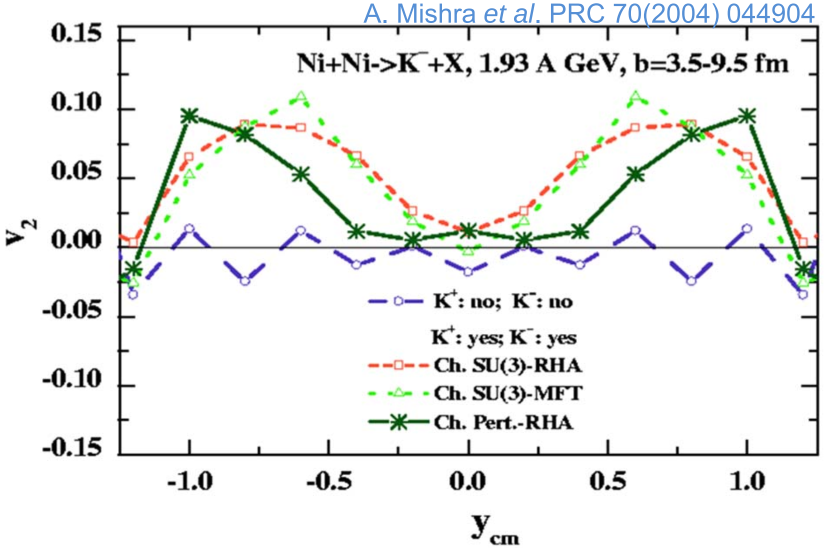


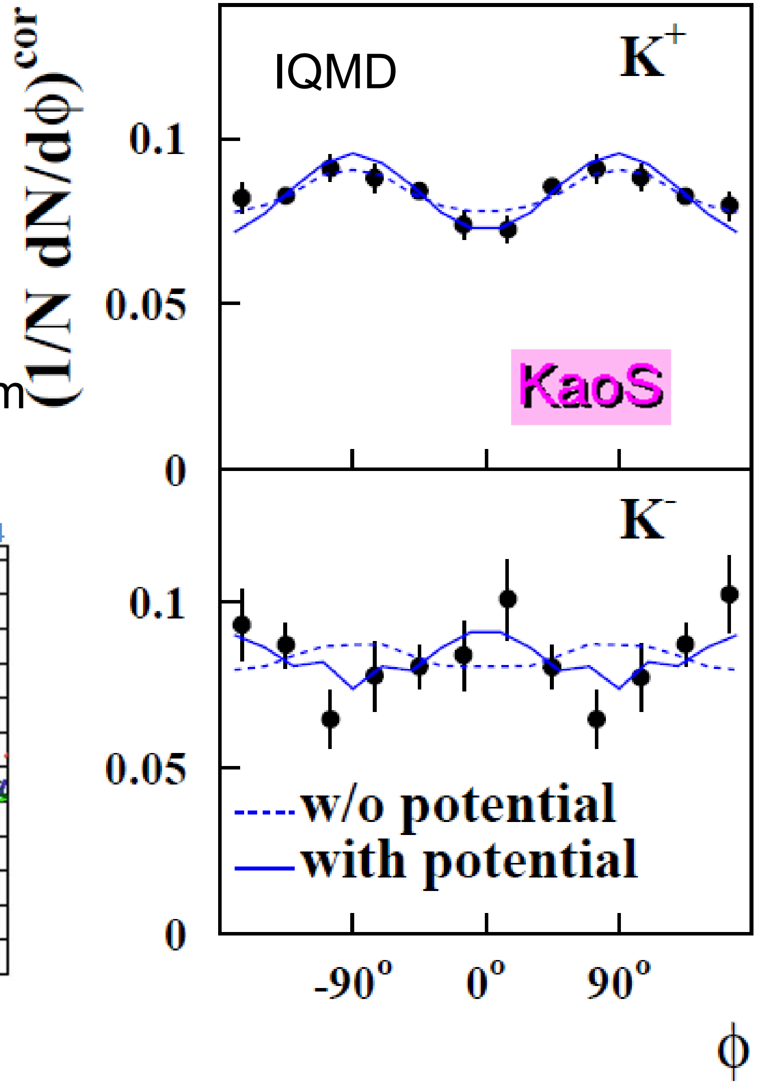
In-medium K^-N potentials
Elliptic flow in Ni+Ni 1.9AGeV

Data Kaos:
F. Uhlig et al.

- Ni+Ni mid-central collisions
  - $0.3 < y/y_{beam} < 0.7$
  - $0.2 < p_t < 0.8$ GeV/c
- only weak sensitivity for K^- in-medium potential seen within IQMD

A. Mishra *et al*, PRC 70(2004) 044904





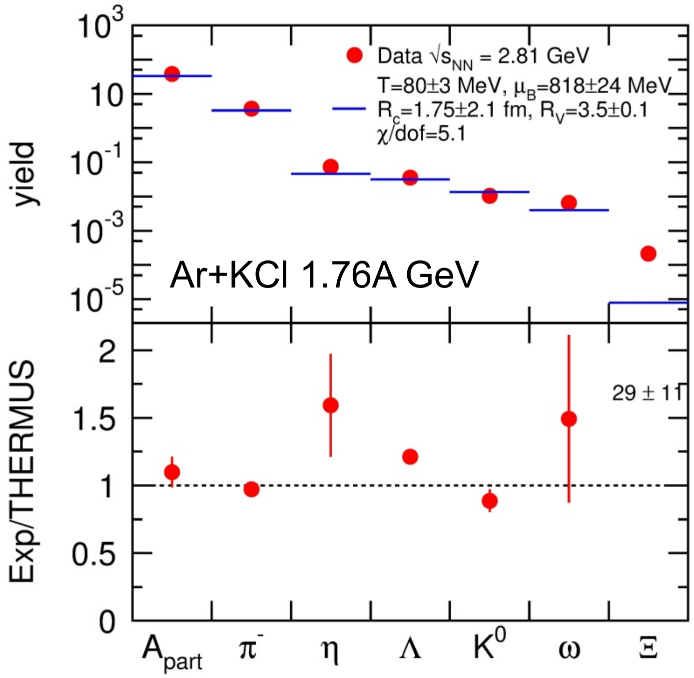
Summary

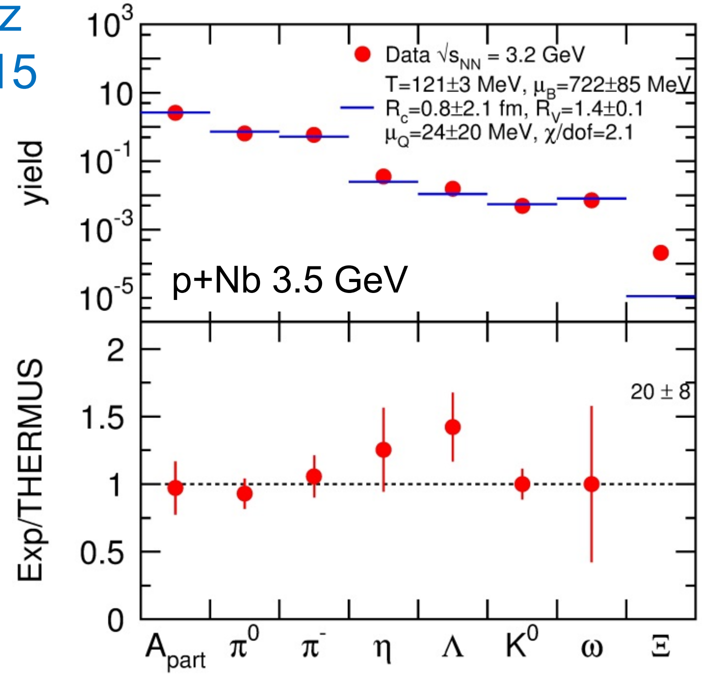
- Strangeness production close to threshold
  - high intensity beams and high quality data and rare probes
  - sensitive probe
    - bulk properties and reaction dynamics
    - in – medium potentials
      - production, re-scattering, absorption must be under control
      - **repulsive K^+N potential ($U(\rho_0)$= 20 – 40 MeV)**
      - **data are consistent with a "shallow" attractive K^-N potential ($U(\rho_0)$ ~ -50 MeV)**
        - **K+ : low momentum part of spectra, slopes**
        - **K+ : v_1 and v_2 at low energies**
        - **K- : slopes or K-/K+ ratios at higher beam energies**
        - **K- : v_1 (and v_2)**
  - microscopic transport models crucial
- more data is needed – HADES, CBM@FAIR, BM@N
  - flow data in heavier systems, double strangeness, exotics (hyper nuclei)
  - elementary productions cross sections

After discussing in-medium potentials, rescattering and other effects.....

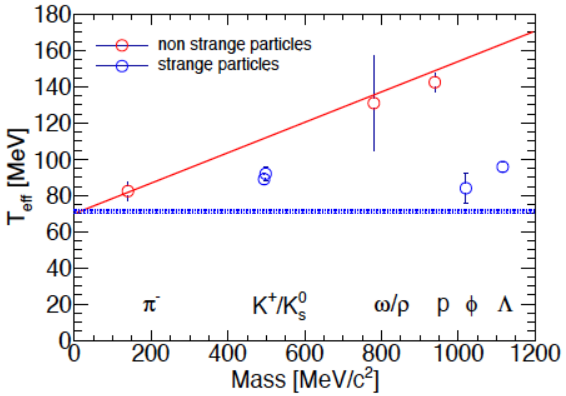
After discussing in-medium potentials, rescattering and other effects.....

M. Lorenz
SQM 2015

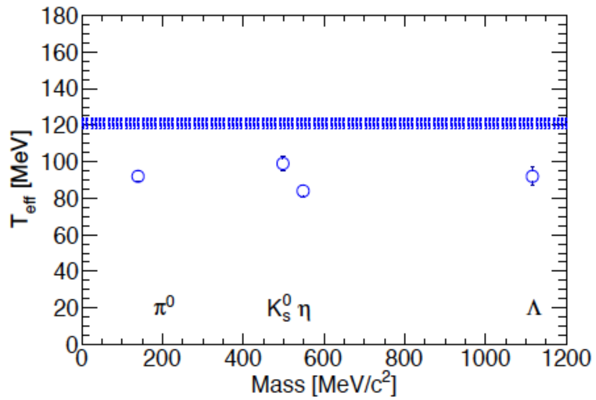




$T_{chem} > T_{kin}$

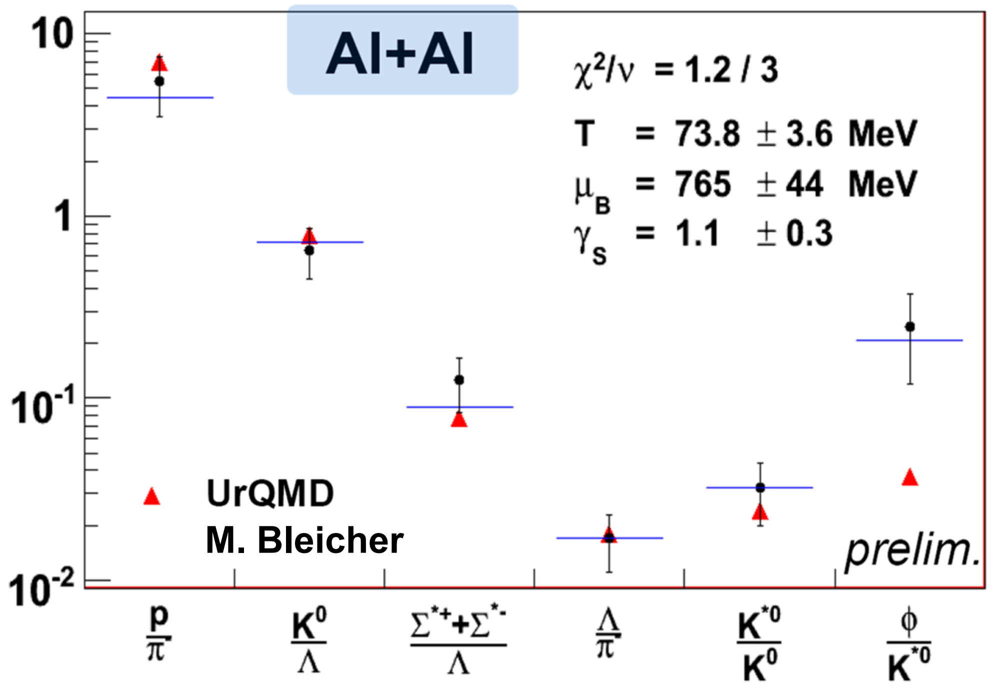


$T_{chem} \leq T_{kin}$



And in Al+Al....

FOPI data for Al+Al at 1.91 AGeV
Statistical model analysis with
THERMUS code (K. Piasecki)

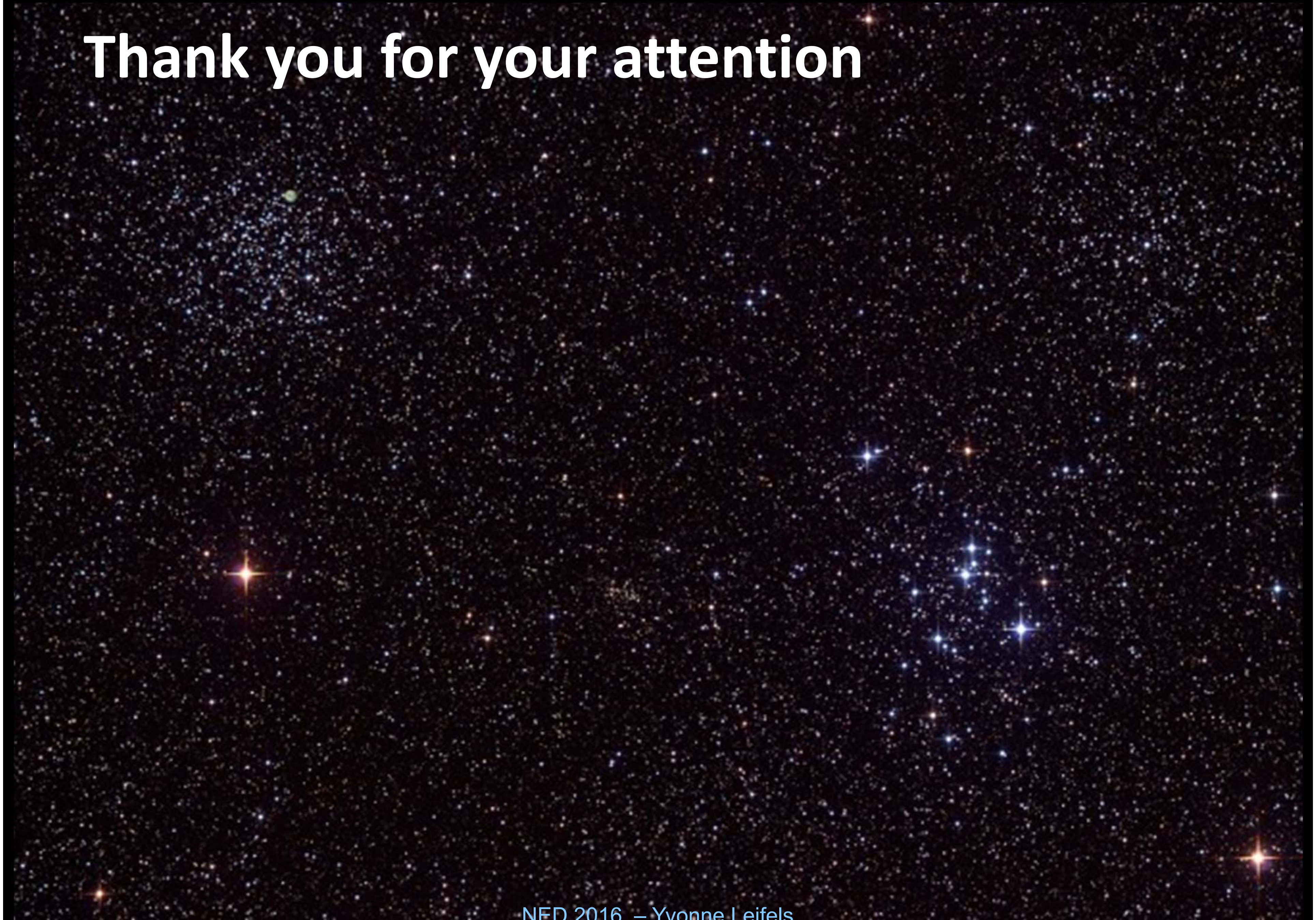


- Particle yields are described by Thermal models with reasonable parameters consistent over the complete energy range upto LHC. But at SIS energies:
  - Al+Al collisions are most probably not equilibrated
  - Phase space distributions are generally elongated beyond 400AMeV even in Au+Au
  - Systems are not completely mixed
  - No equilibration within microscopic models
  - Microscopic models are able to account for particles ratios for which production cross sections are *known*

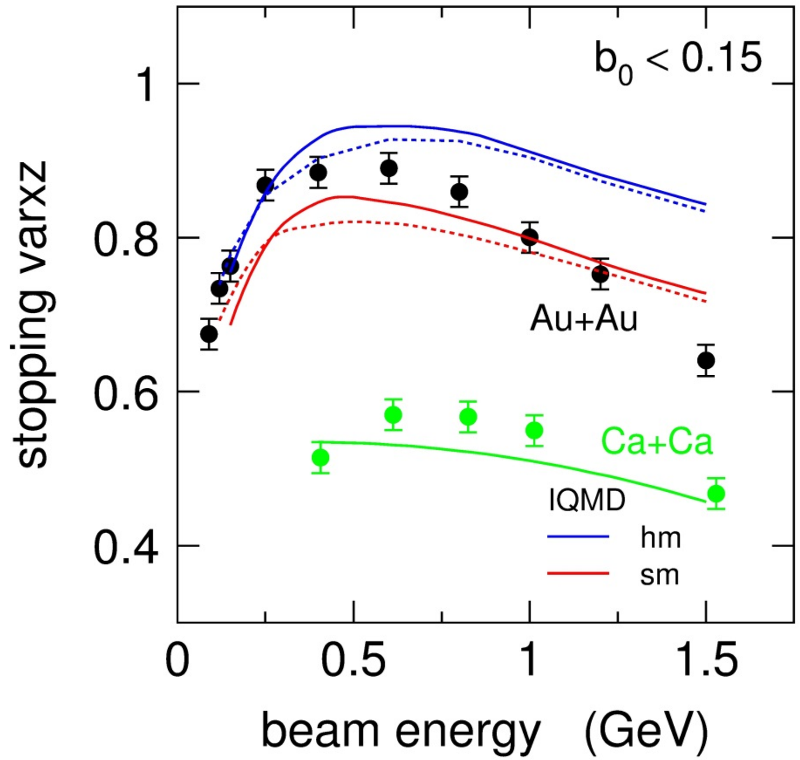
The FOPI collaboration

THU Beijing – NIPNE Bucharest – KFKI RMKI Budapest – LPC Clermont-Ferrand – GSI Darmstadt – Helmholtzzentrum Rossendorf – Universität Heidelberg – IMP Lanzhou – ITEP Moscow – KI Moscow – TU München – Korea University Seoul – University of Split - IPHC Strasbourg – SMI Vienna – University of Warsaw – RBI Zagreb

Thank you for your attention

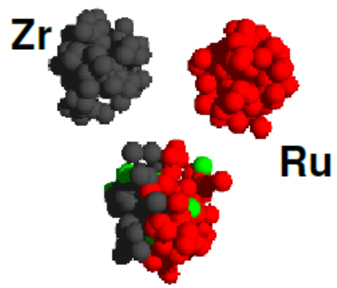


Heavy ion collisions between 0.4 – 1.5A GeV



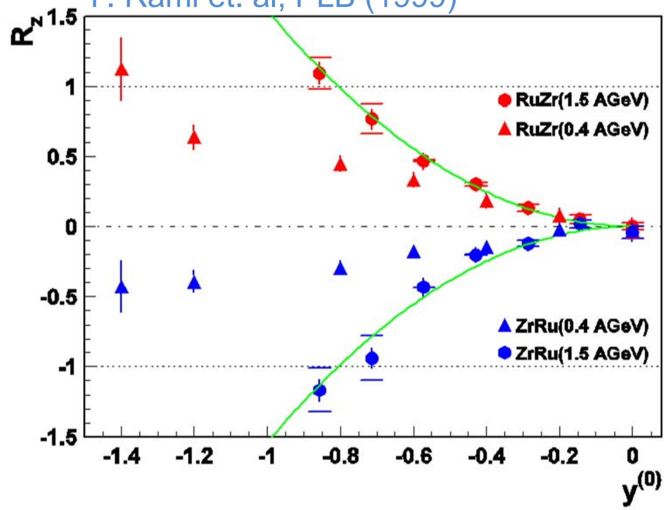
Define stopping:

$$\text{var xz} = \frac{\sigma^2_{y_t}}{\sigma^2_{y_l}}$$

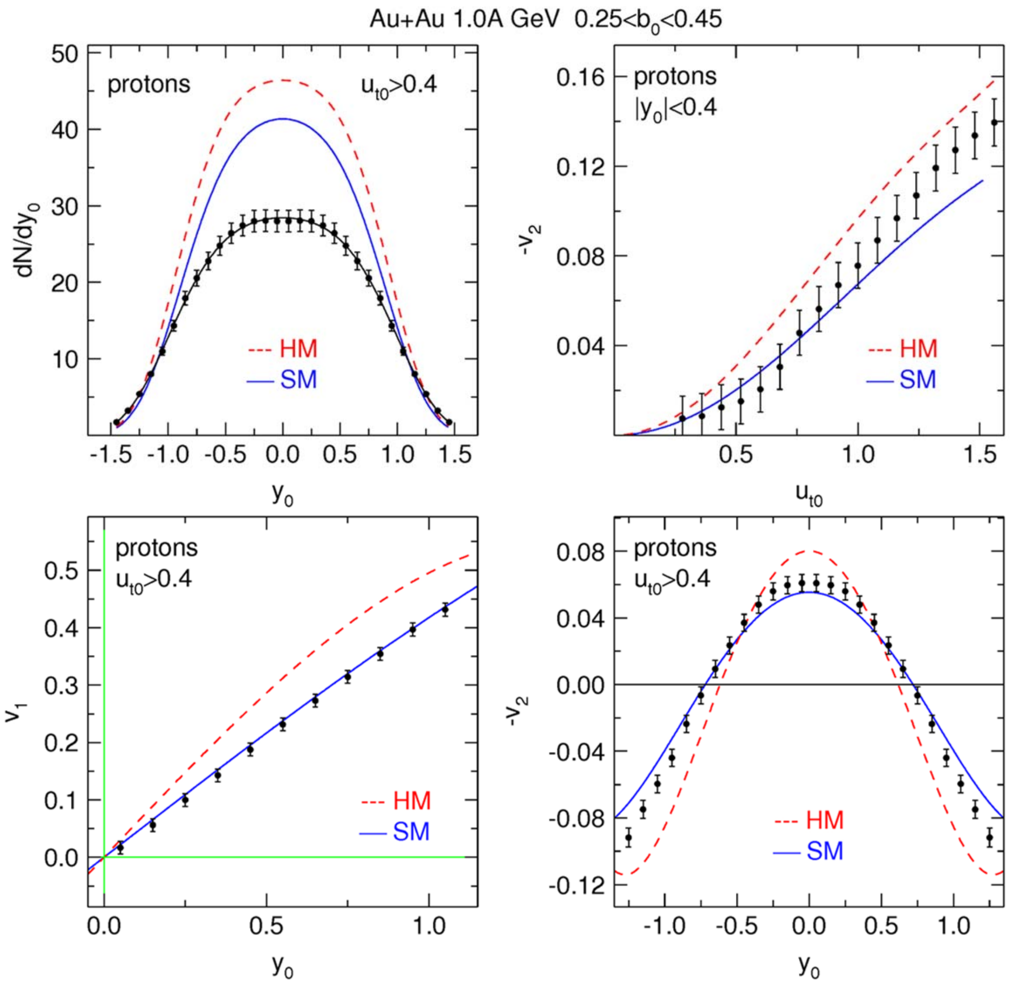


$$R_p = \frac{M_p^{RuZr}}{M_p^{ZrRu}} \qquad R_Z = \frac{2M_p^X - (M_p^{ZrZr} + M_p^{RuRu})}{M_p^{ZrZr} - M_p^{RuRu}}$$

F. Rami et. al, PLB (1999)



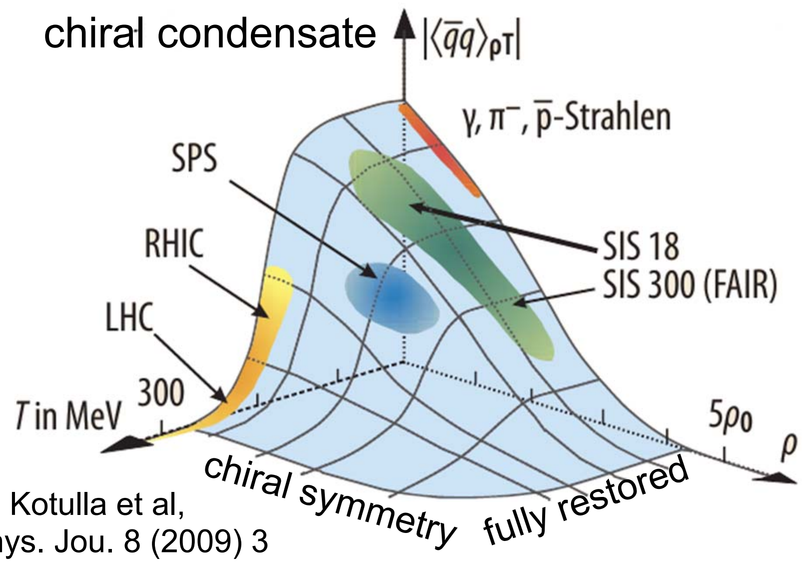
Description of “bulk” properties by the models



- ➢ reaction dynamics described
- ➢ pion production reproduced~10%

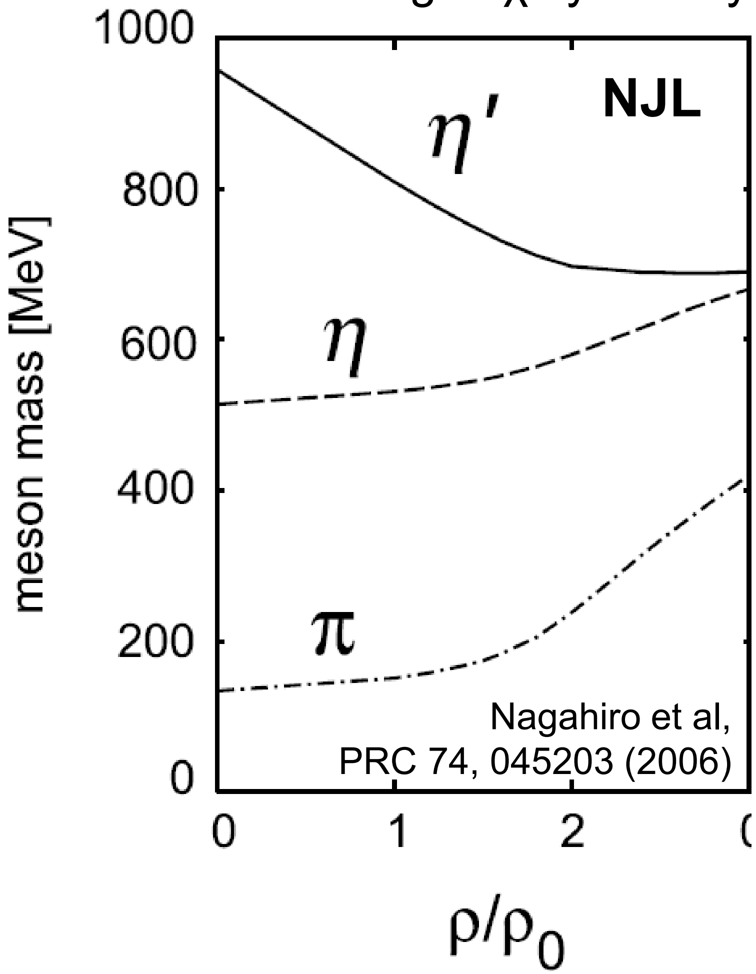
- ➢ Proton yield overestimated
  - o yields depending on EOS (cluster production)
- ➢ flows described by SM
- ➢ HSD and IQMD describe experimental equally well (if clusters are omitted)

In medium properties of pseudo-scalar mesons



M. Kotulla et al,
Phys. Jou. 8 (2009) 3
nach W. Weise (2007)

Partial restoration of dynamical breaking of χ symmetry



Nagahiro et al,
PRC 74, 045203 (2006)

Modified properties of hadrons in dense baryonic matter?

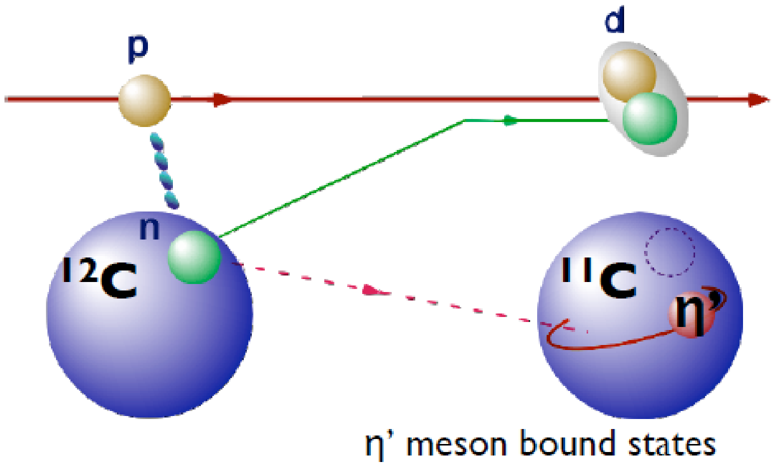
$$\frac{\langle\bar{q}q\rangle^*}{\langle\bar{q}q\rangle} \sim \frac{M^*}{M}$$

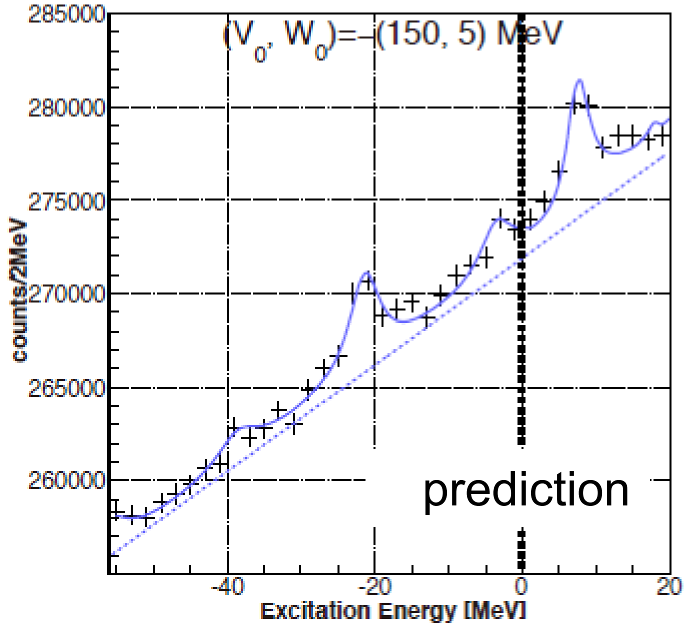
Braun – Rho – Scaling (PRL 66,1991):
Masses of non-strange hadrons scale with quark condensate

Search for η' bound states

K. Itahashi, H. Fujooka et al.
@ FRS/GSI

$$V_{\eta'}(r) = (V_0 + iW_0)\,\frac{\rho(r)}{\rho_0}$$



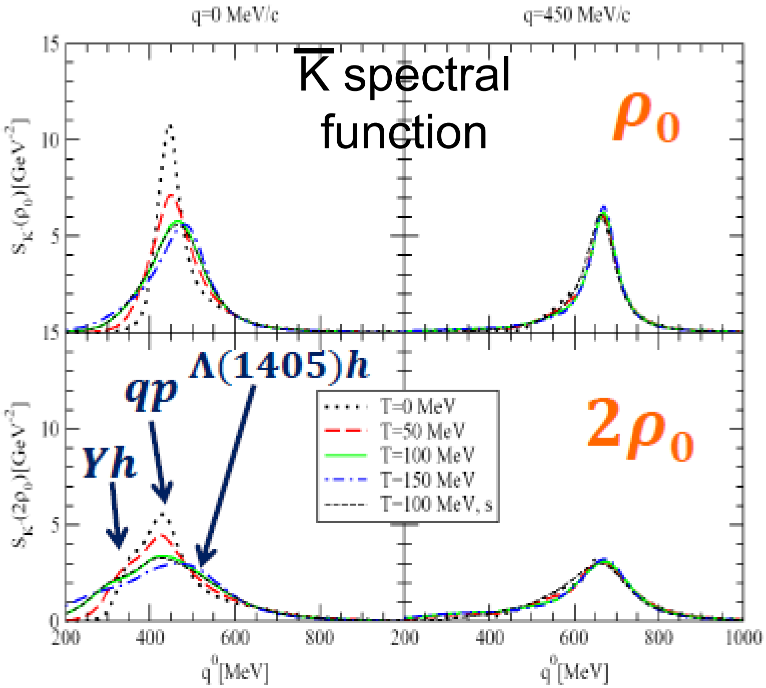


no distinct structures observed
(accepted in PRL)

Advancing HSD

K/$\overline{K}$N in hot/dense matter: self-consistent and unitary coupled-channel approach

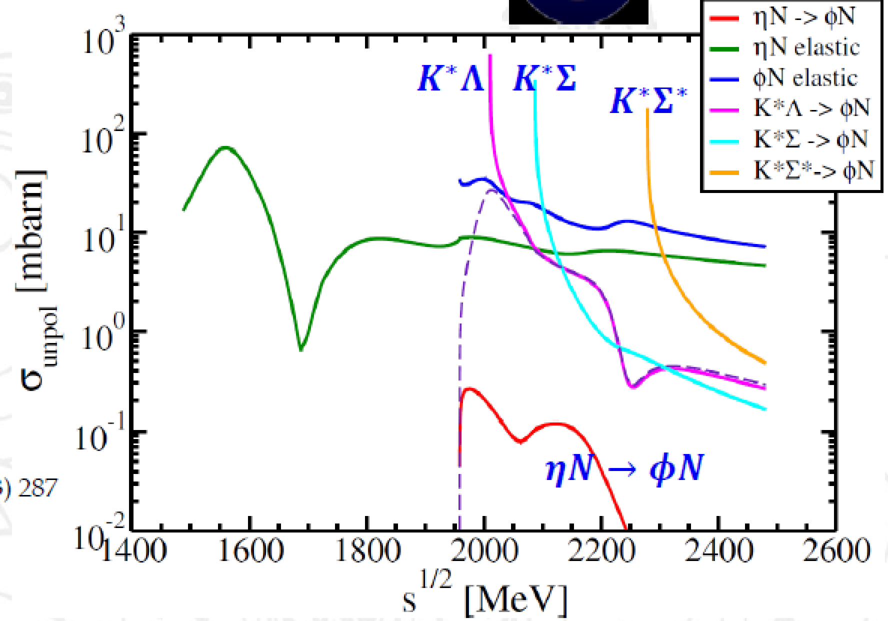
Binary reactions:
cross sections/transition rates
Propagation:
K, $\overline{K}$ and Y optical potentials
Production:
K, $\overline{K}$ (off-shell) spectral functions



ϕ and Ξ production in the hadronic phase

- ηN channel small
- strangeness exchange

Daniel Cabrera



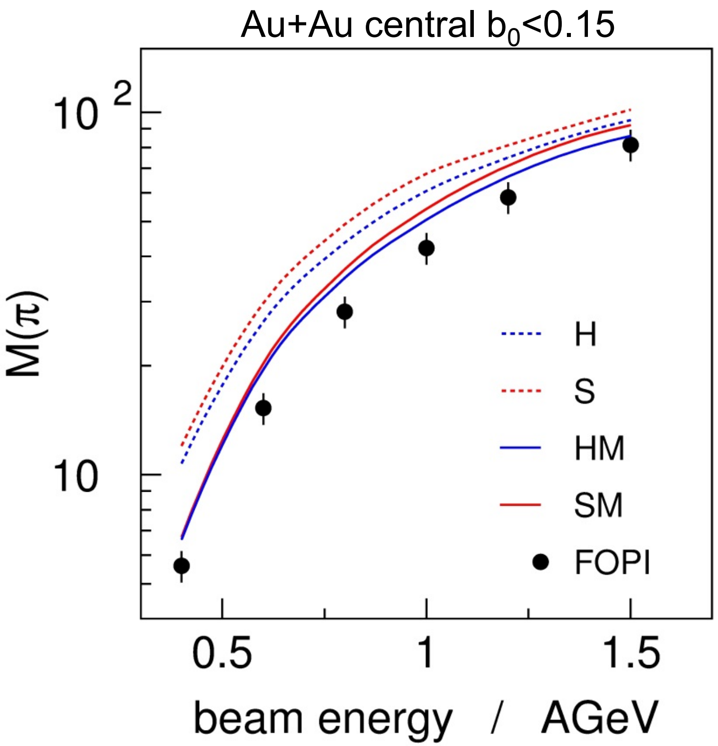
Inside IQMD

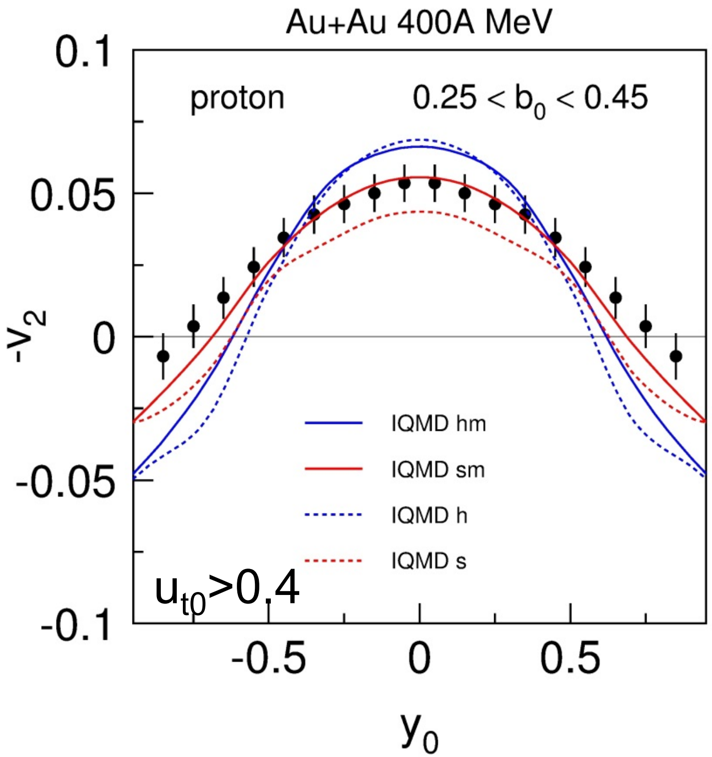
After the convolution of the Skyrme type potentials supplemented by momentum dependent interactions (mdi) for infinite saturated nuclear matter at equilibrium

$$U = \alpha \cdot \left(\frac{\rho_{int}}{\rho_0}\right) + \beta \cdot \left(\frac{\rho_{int}}{\rho_0}\right)^{\gamma} + \delta \cdot \ln^2\left(\varepsilon \cdot (\Delta\vec{p})^2 + 1\right) \cdot \left(\frac{\rho_{int}}{\rho_0}\right)$$

	α (MeV)	β (MeV)	γ	δ (MeV)	ε $\left(\frac{c^2}{\mathrm{GeV}^2}\right)$	κ (MeV)
S	-356	303	1.17	—	—	200
SM	-390	320	1.14	1.57	500	200
H	-124	71	2.00	—	—	376
HM	-130	59	2.09	1.57	500	376
INT	-157	103	1.58	—	—	284
VH	-110	56	2.40	—	—	456

Are there other solutions?





Choice in IQMD for

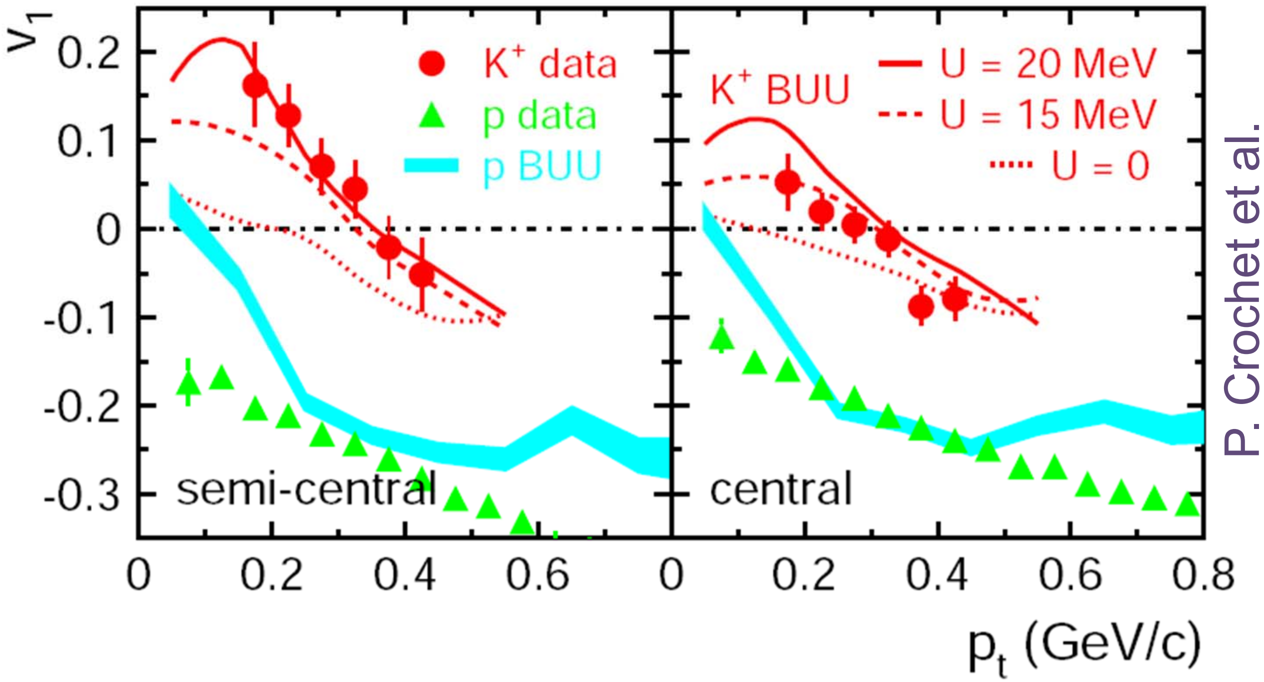
- σ_{NN}, momentum dependence of optical potentials, prescription of Pauli blocking and detailed balance etc.

describes most of the data

Systematic studies on flow – Ru+Ru

Ru+Ru @ 1.69A GeV

RBUU/Giessen



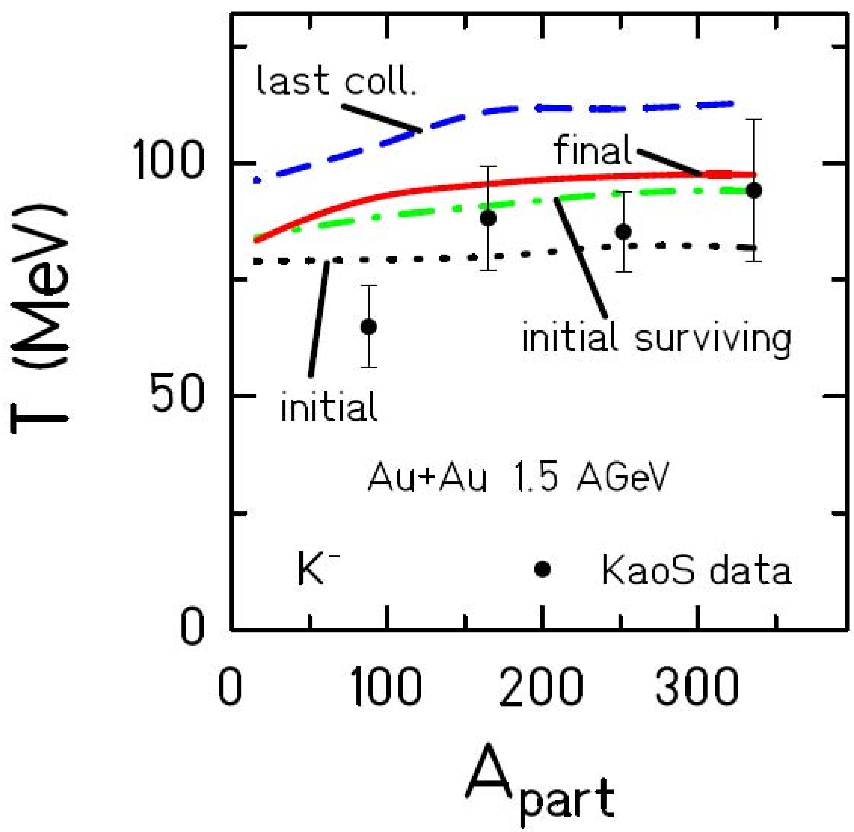
Need more data
on heavier systems

In-medium potential
K⁻ spectra

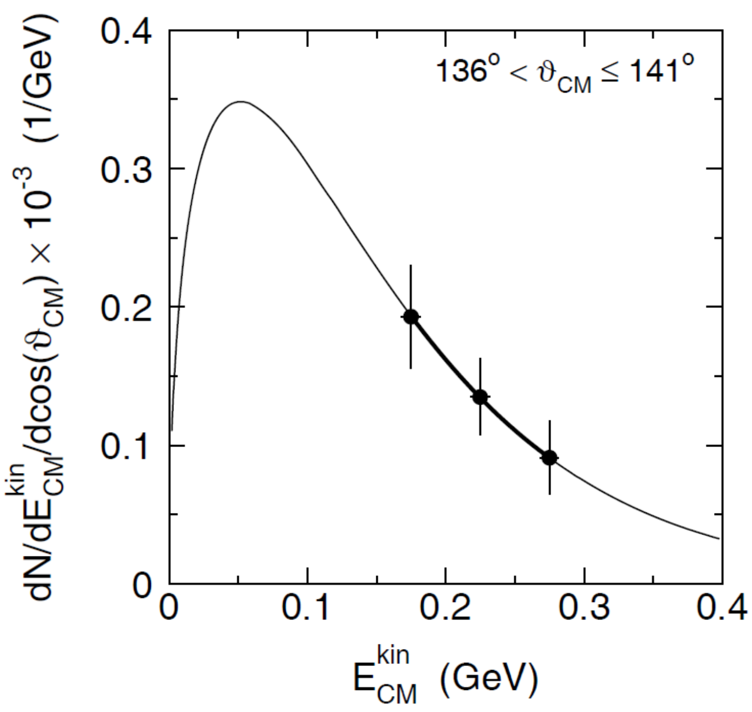
Apparent slopes of K^- systematically steeper than K^+
Because of:

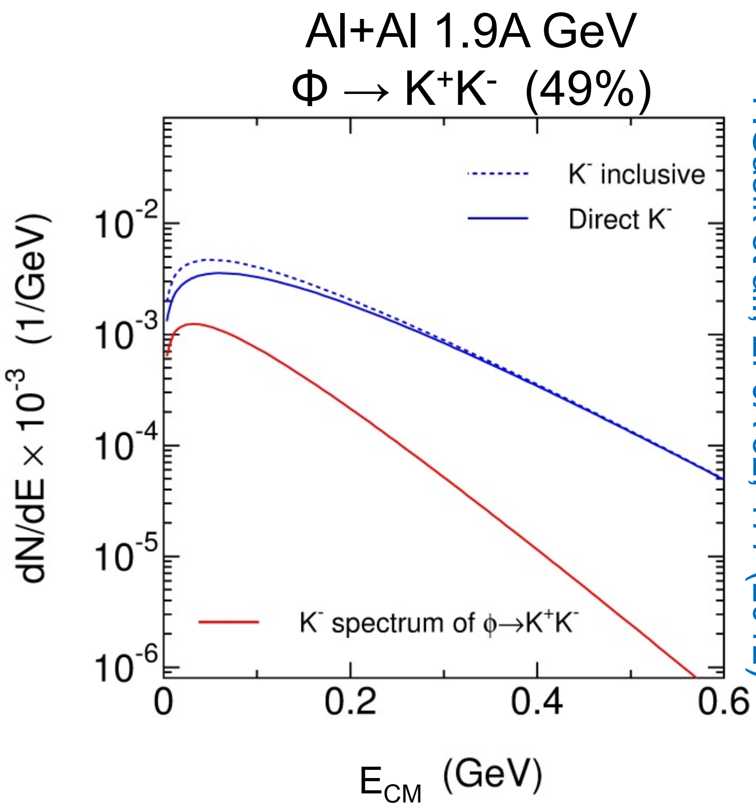
- Absorption
- Attractive $\bar{K}N$ potential
- Later production
  - $BY \rightarrow NNK^-$
  - $\pi B \rightarrow NK^-$
- Contribution of Φ decay?
  - smaller at higher energies

Au+Au 1.5A GeV



Al+Al 1.9AGeV
Substracting contribution of Φ

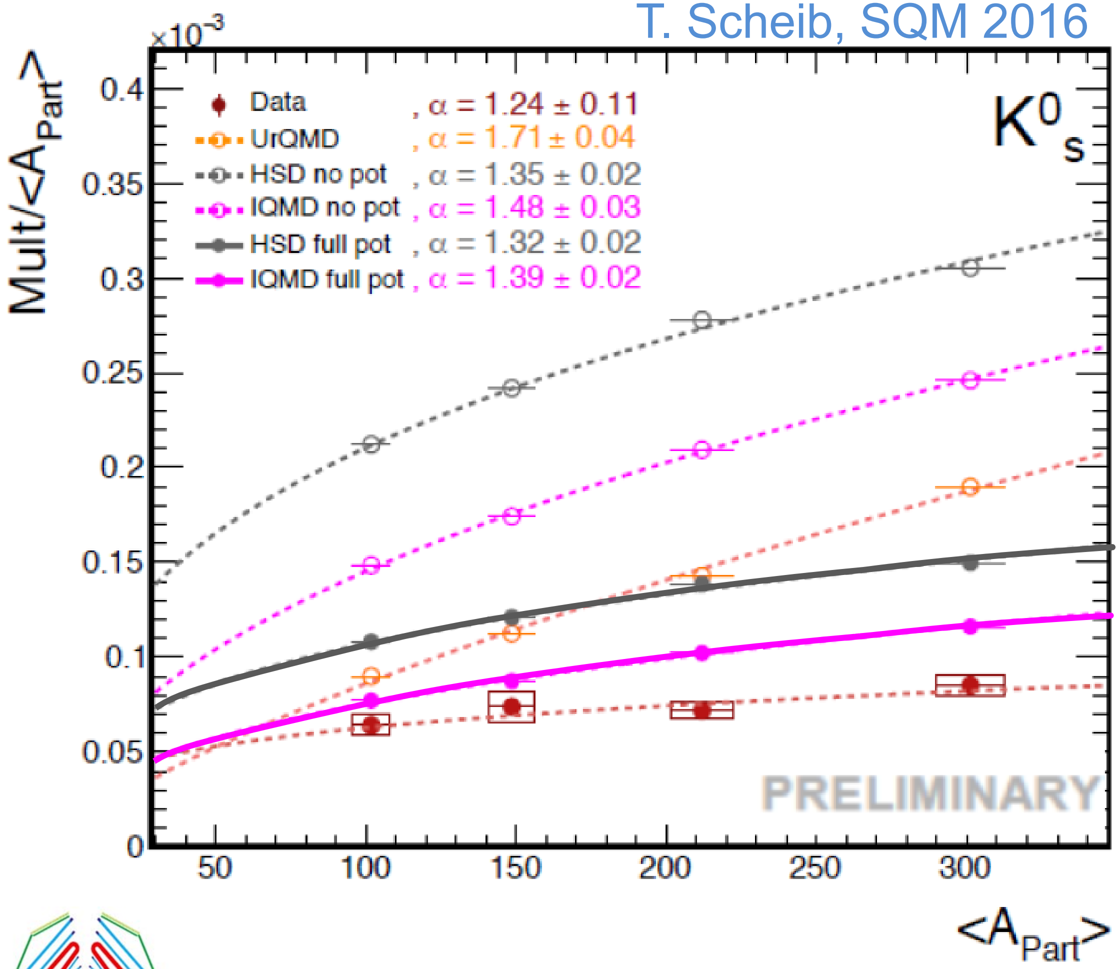




P.Gasik et al., EPJA 52, 177 (2012)

In-medium KN potential
Au+Au 1.25A GeV

T. Scheib, SQM 2016

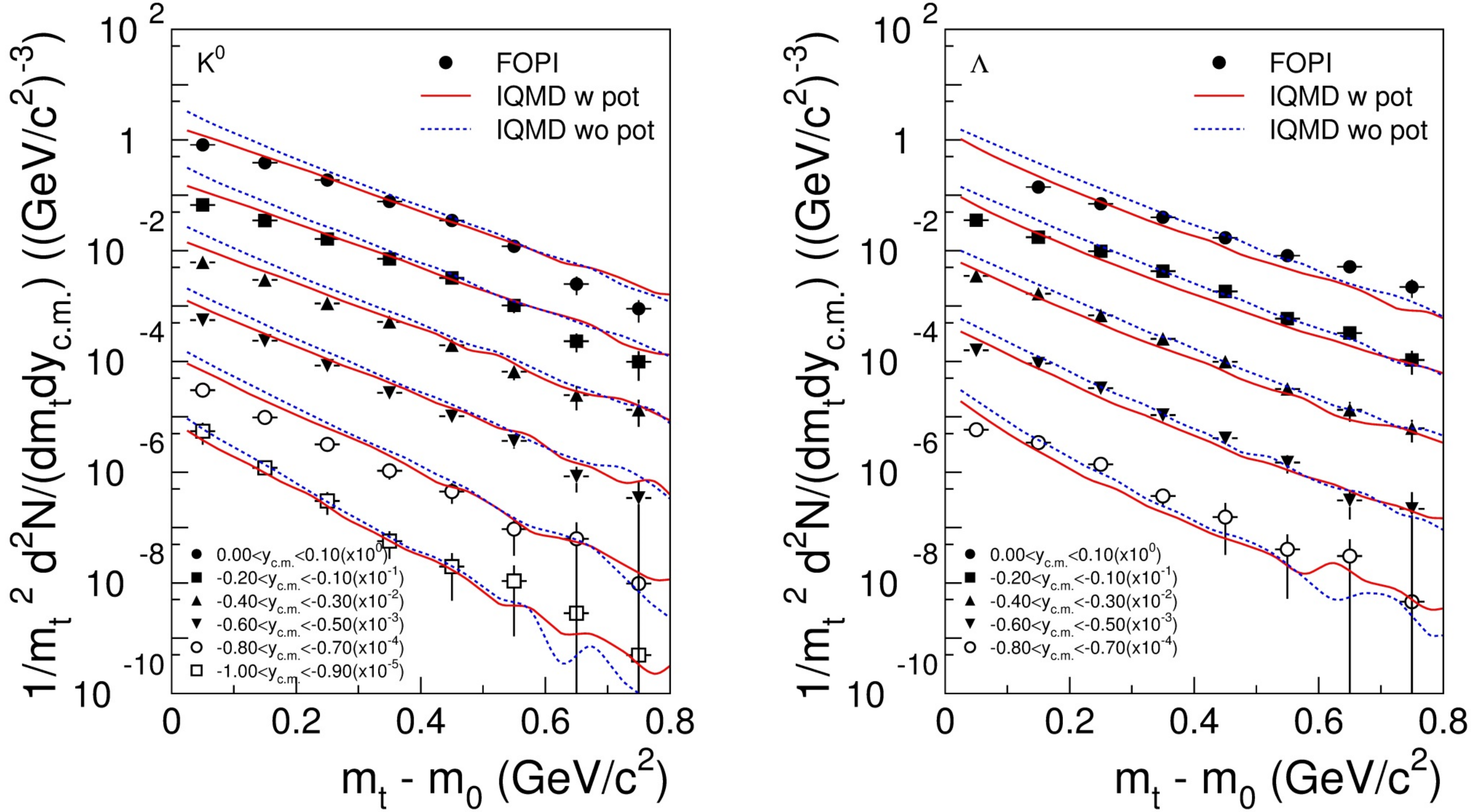


IQMD/HSD with
$U_{KN}(\rho_0)$ = +40 MeV

- yield overestimated
- Mult/<Apart> dependence similar

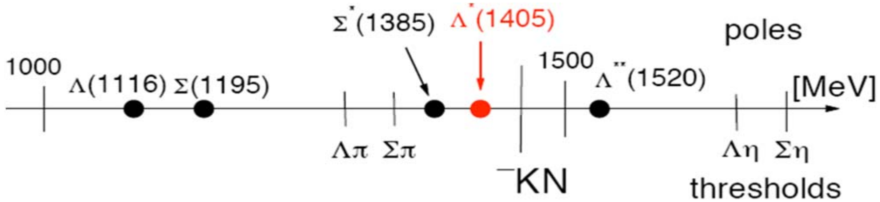
In-medium potential in heavy ion collisions

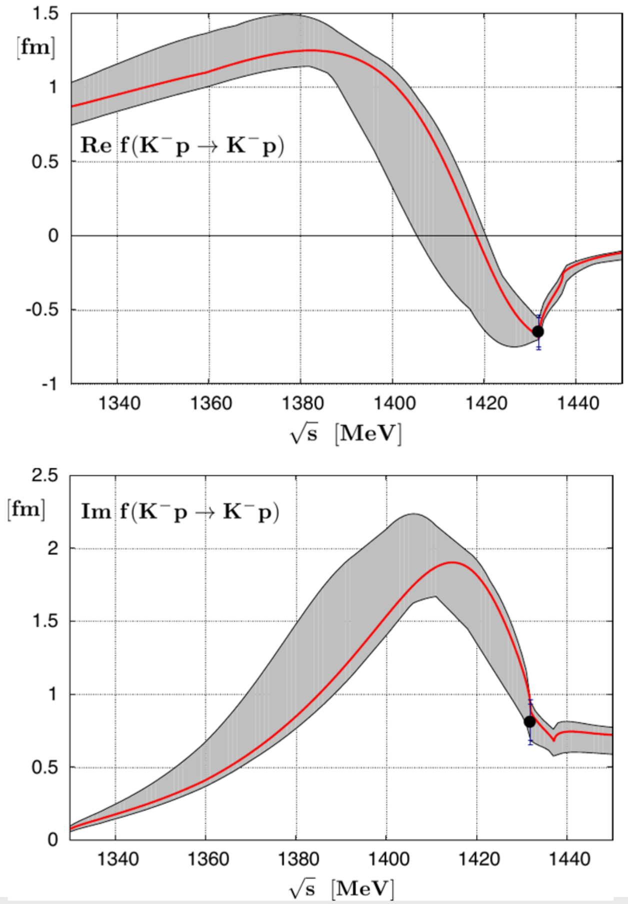
Ni+Ni 1.93A GeV (central)



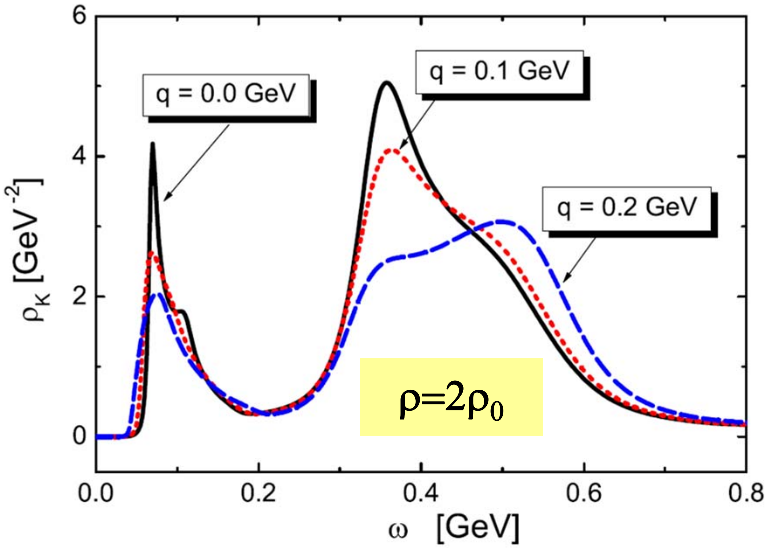
M. Merschmeyer et al., Phys. Rev. C 76 (2007) 024906

In-medium properties of pseudo-scalar mesons



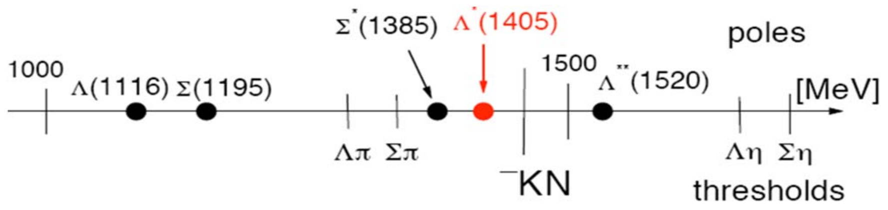


M. Bazzi et al. (Siddharta) arXiv:1105.3090 [nucl-ex]
Calc: Y. Ikeda et al. arXiv: 1109:3005

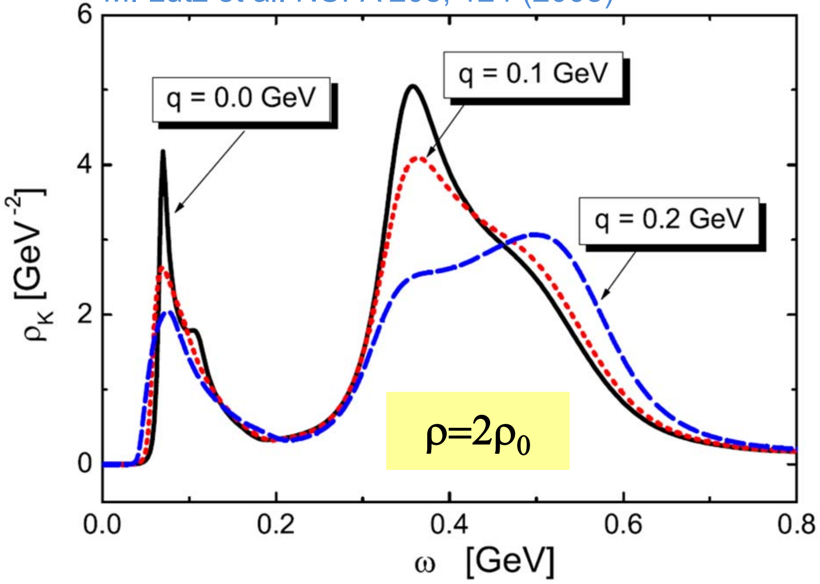


- presence of resonances
  - chiral SU(3) effective field theory with coupled channels
  - coupled channel G-Matrix approach
- K^-N – interaction attractive at finite (ground state) densities, but strength (depth of potential) unclear at high densities

In-medium properties of Anti-Kaons



M. Lutz et al. NUPA 208, 124 (2008)



- presence of resonances
  - chiral SU(3) effective field theory with coupled channels
  - coupled channel G-Matrix approach
- $K^{-}N$ – interaction attractive at finite (ground state) densities, but strength (depth of potential) unclear at high densities