FOPI

In-medium modifications of properties of near-threshold kaons in wide range of phase space with FOPI

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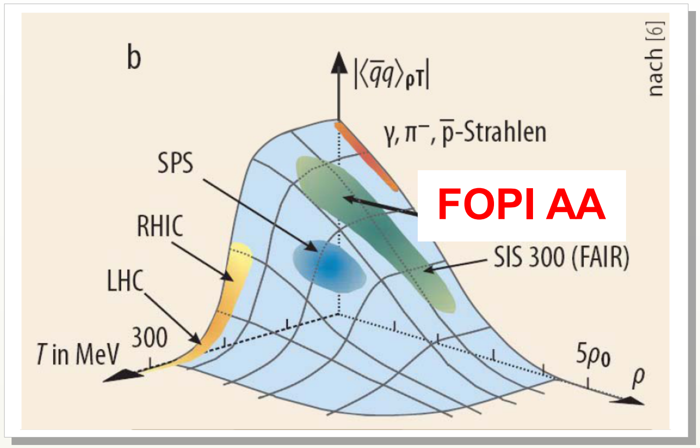
- Physics motivation
- Experimental status a decade ago
- New experimental findings
- Summary

Faculty of Physics
Warsaw University

Probing partial restoration of chiral symmetry



M. Kotulla et al., Physik Journal 8 (2009) 3

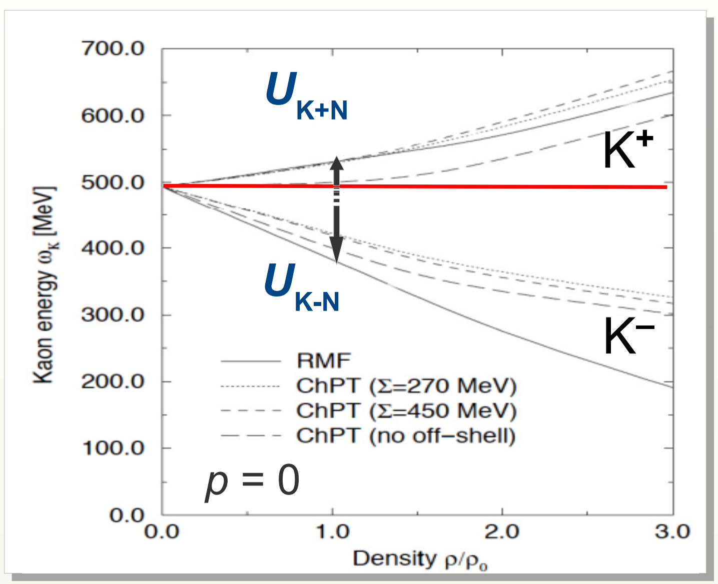
Gell-Mann Oakes Renner – relation:

$$m_K^{*2}\, f_K^{*2} = -\frac{m_u + m_s}{2}\langle \bar{u}u + \bar{s}s \rangle + \Theta\left(m_s^2\right)$$

Decay constant

Mass

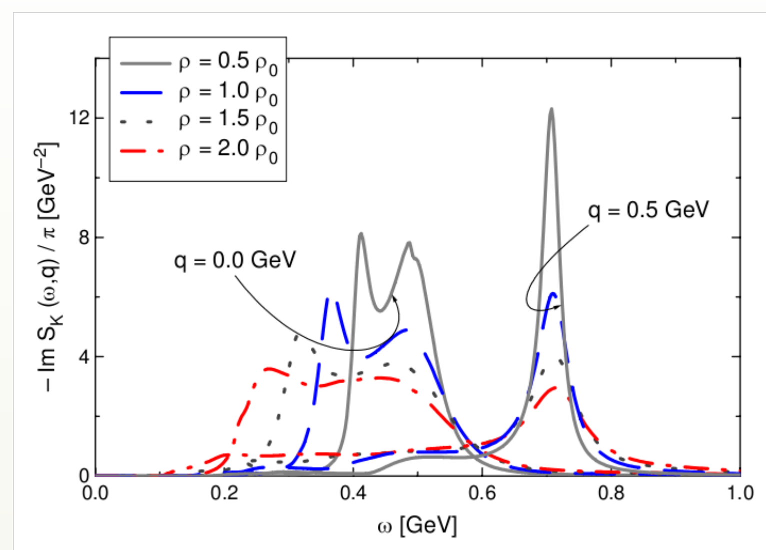
First approaches: Potential



J. Schaffner-Bielich *et al.* NPA 625(1997) 325

$\vec{F} = -\vec{\nabla}\, U$ ⇒ K⁻ attracted, K⁺ repelled

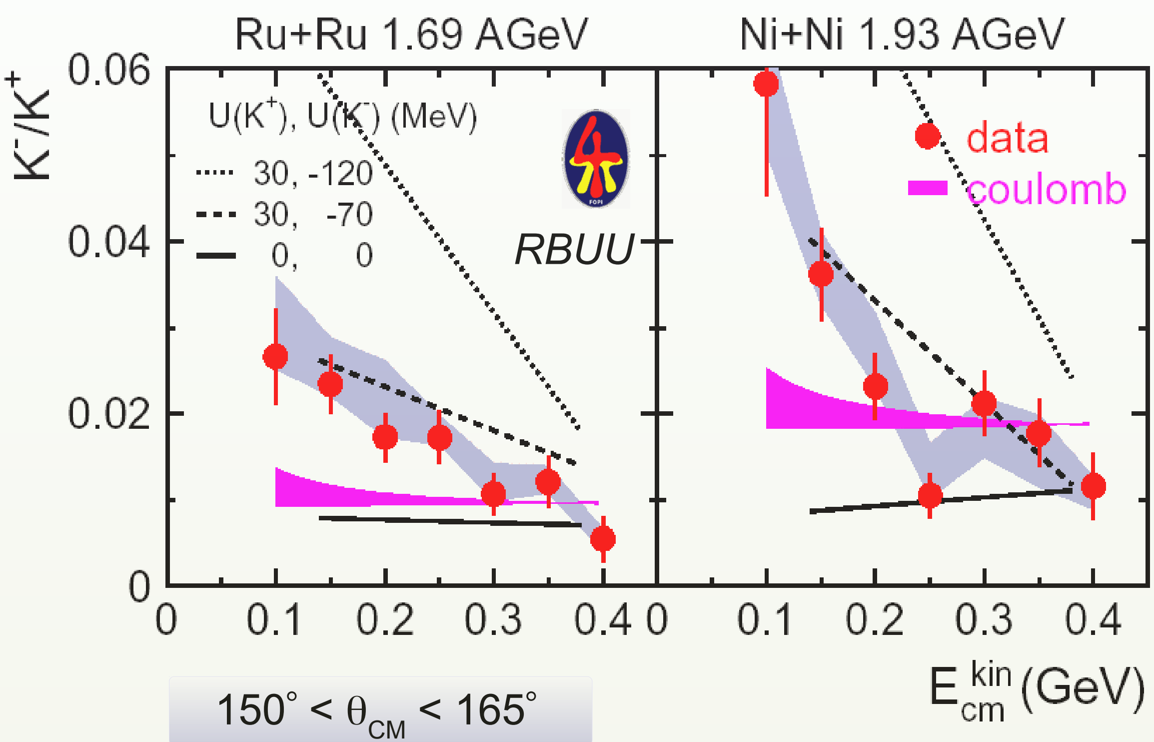
Chiral effective field theory w/ couple-channels



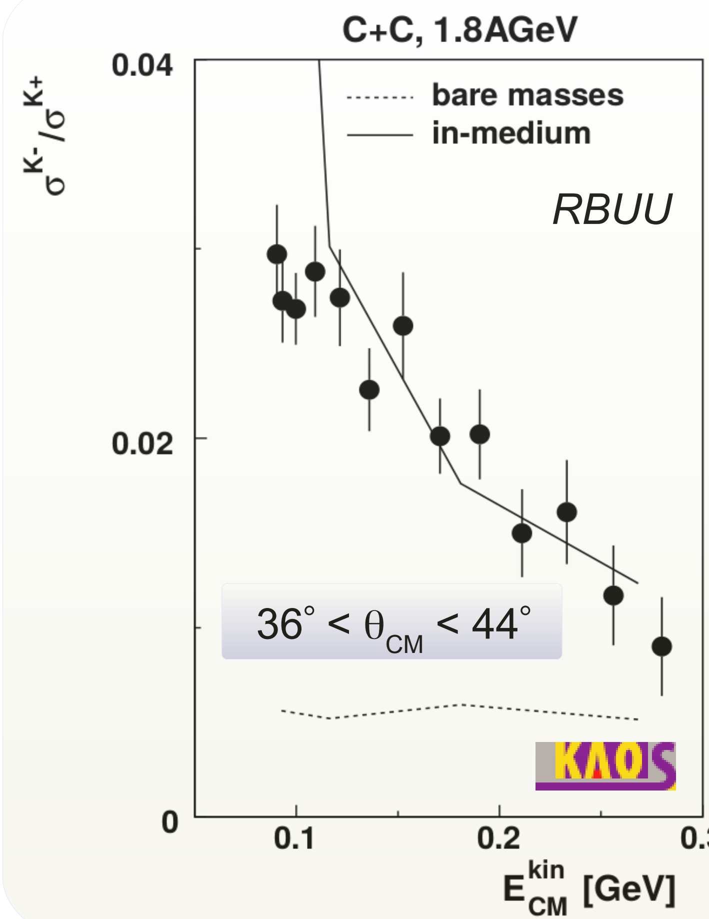
M.F. M. Lutz, PPNP 53 (2004) 125

„Potential" only on average

Experimental status a decade ago



K. Wiśniewski et al., Eur. Phys. J. A 9, 515 (2000)



F. Laue et al., Eur. Phys. J. A 9, 397 (2000)

- Effect itself appears to be confirmed…
- … but probed within very narrow slice of phase space
- Statistics too limited for providing uncertainties of extracted U_{KN}.

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

v_1 , v_2 = *Coefficients of Fourier expansion*

Experimental status a decade ago

- FOPI analysis:

  v_1 (K$^+$) as function of p_T
  for 2 systems at 1.5 – 2*A* GeV

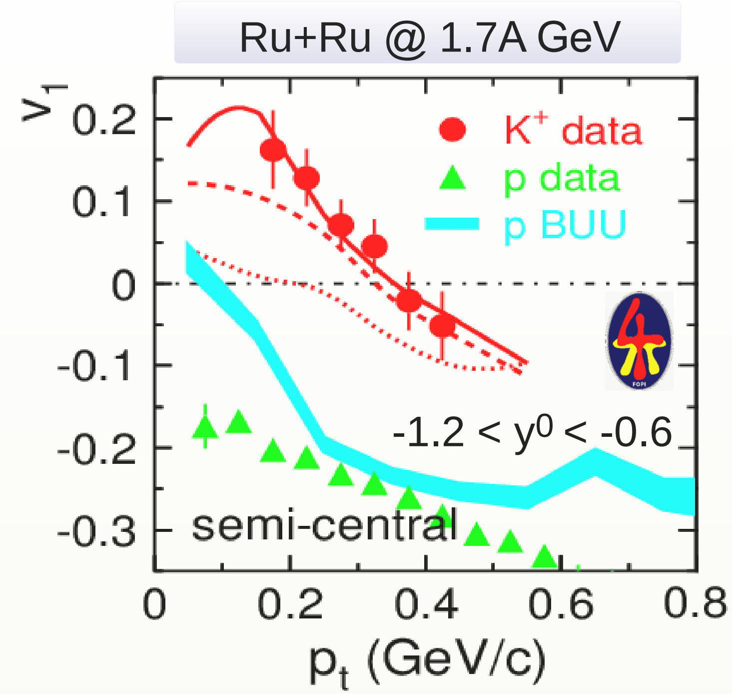
  → Preference for $U_{K+N} \approx 20$ MeV
  No information on U_{K-N}

- KaoS analysis:

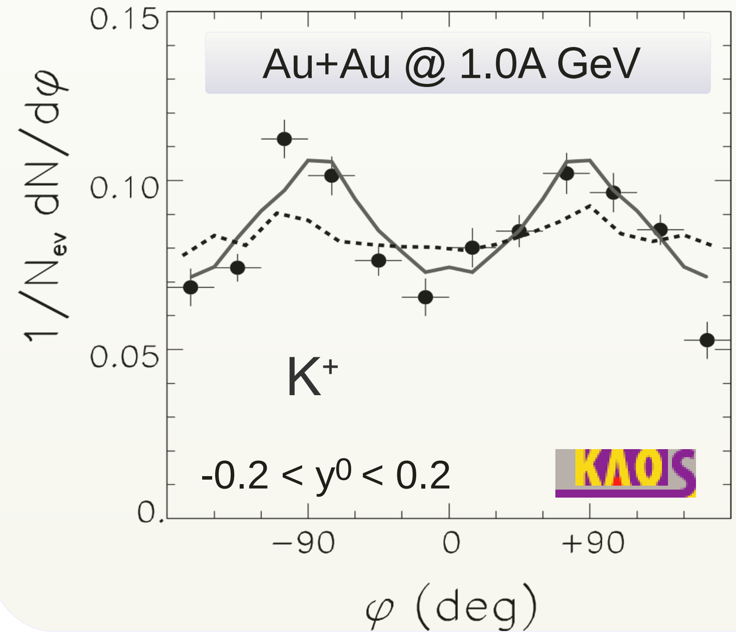
  Fit to d*N*/dϕ (K$^+$)
  for 2 systems at 1 – 2A GeV

  → Preference for U_{K+N}
  No information on U_{K-N}

→ **Fragmentary insight, coarse results**



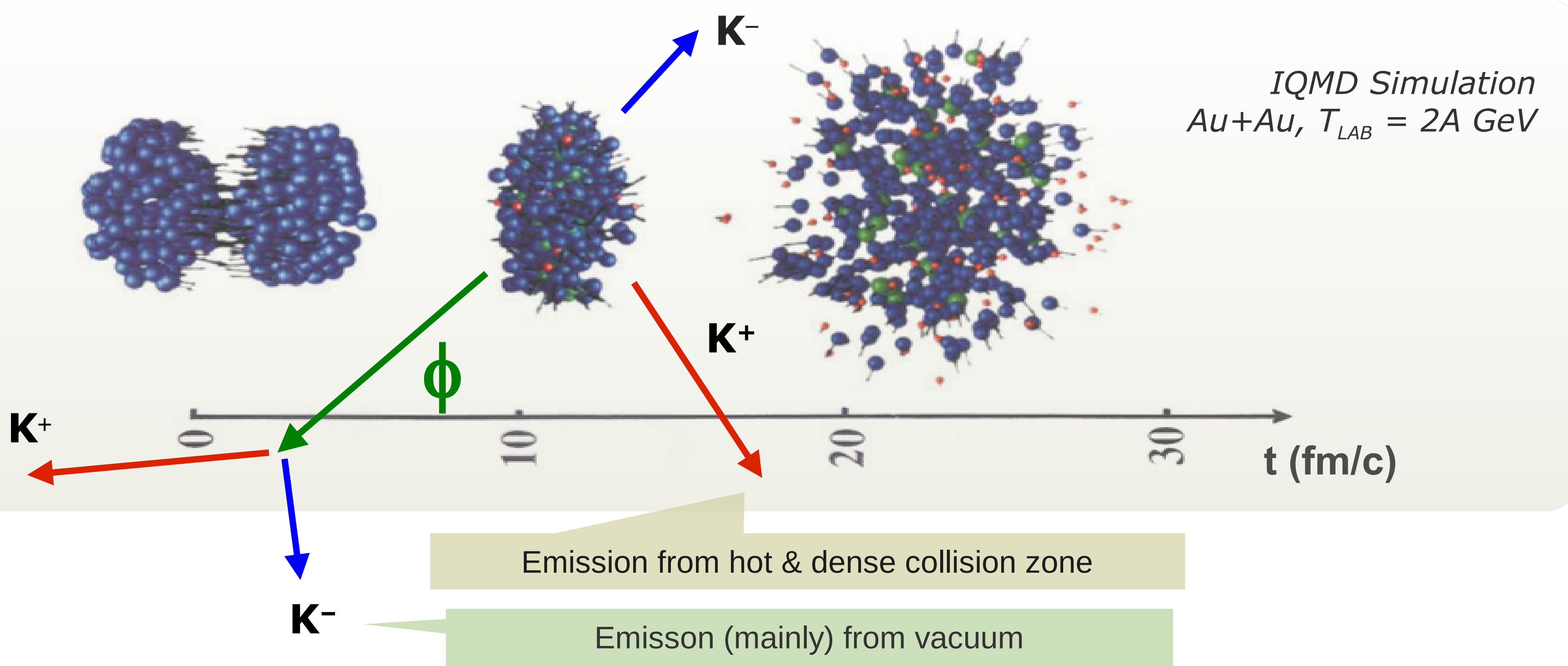
P. Crochet et al., Phys. Lett. B 486 (2000) 6



Y. Shin et al., Phys.Rev.Lett 81, 1576 (1998)

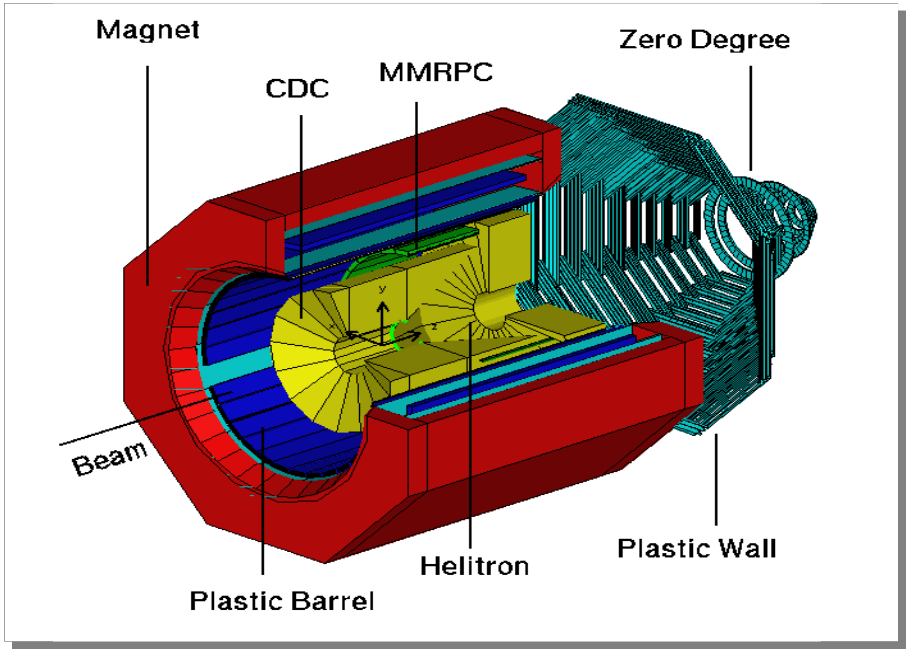
ϕ ($s\bar{s}$) : m = 1.02 GeV
$E_{b,\ threshold}$ = 2.6 GeV (SIS-18: sub-threshold only)

$c\tau$ = 50 fm
$\phi \rightarrow K^+K^-$ (BR ~ 50%)

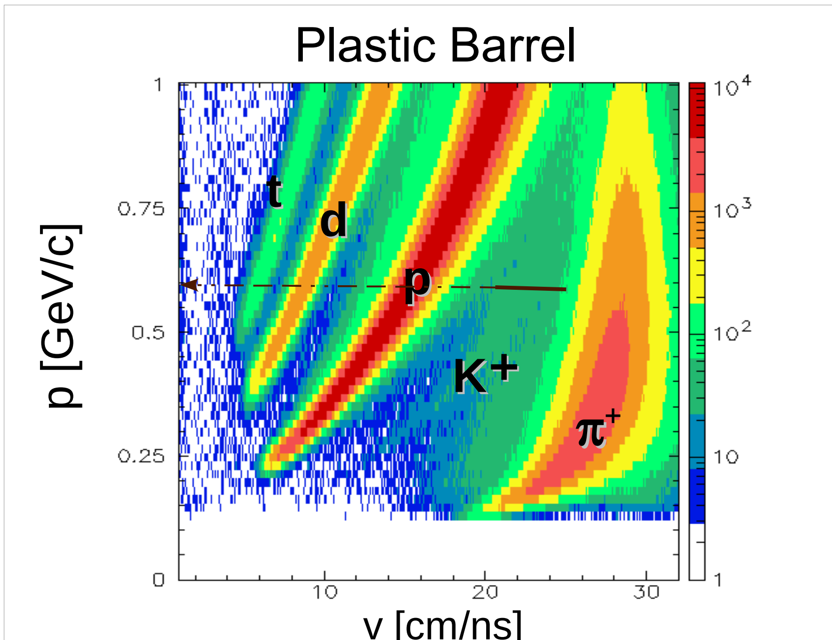


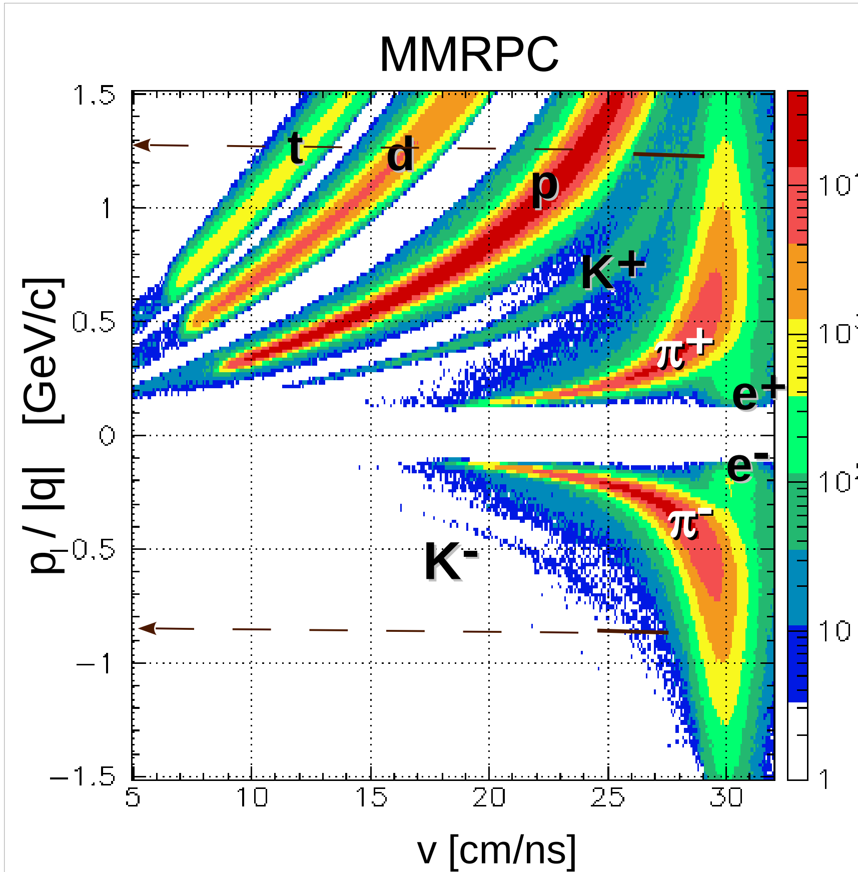
- K^- from ϕ decay (mostly in vacuum) mixes with K^- from collision zone.
- A decade ago the ϕ/K^- ratio @ SIS energies was not known

FOPI experimental setup

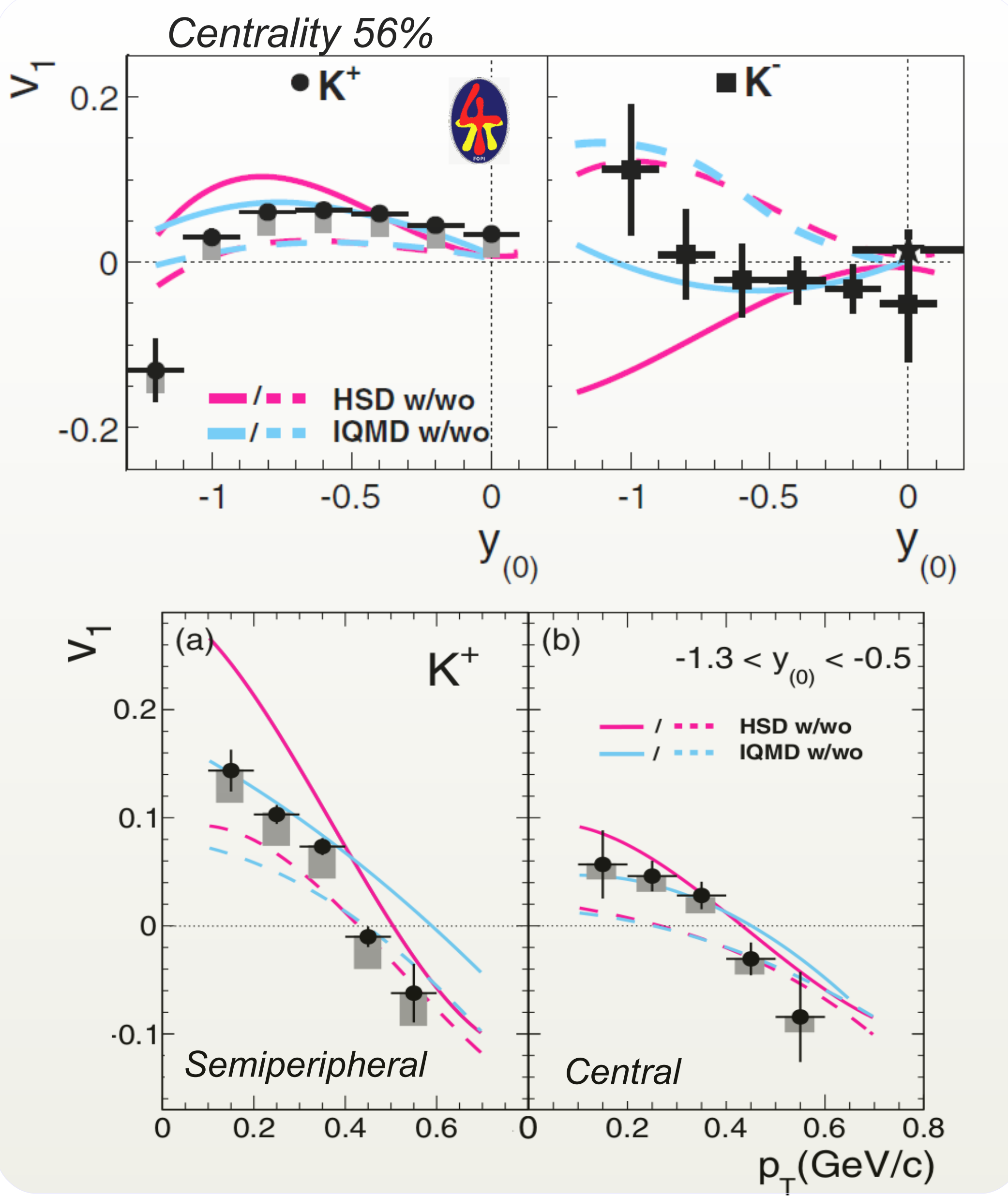


- Nearly 4π coverage
- Drift chambers: CDC, Helitron
  ToF : Plastic Barrel, RPC
  Forward: Plastic Wall, Zero Degree
- Direct PID of $\pi^{\pm}$, $K^{\pm}$, p, d, t, ^{3,4}He





Flow of K^+ and K^- from Ni+Ni @ 1.9*A* GeV

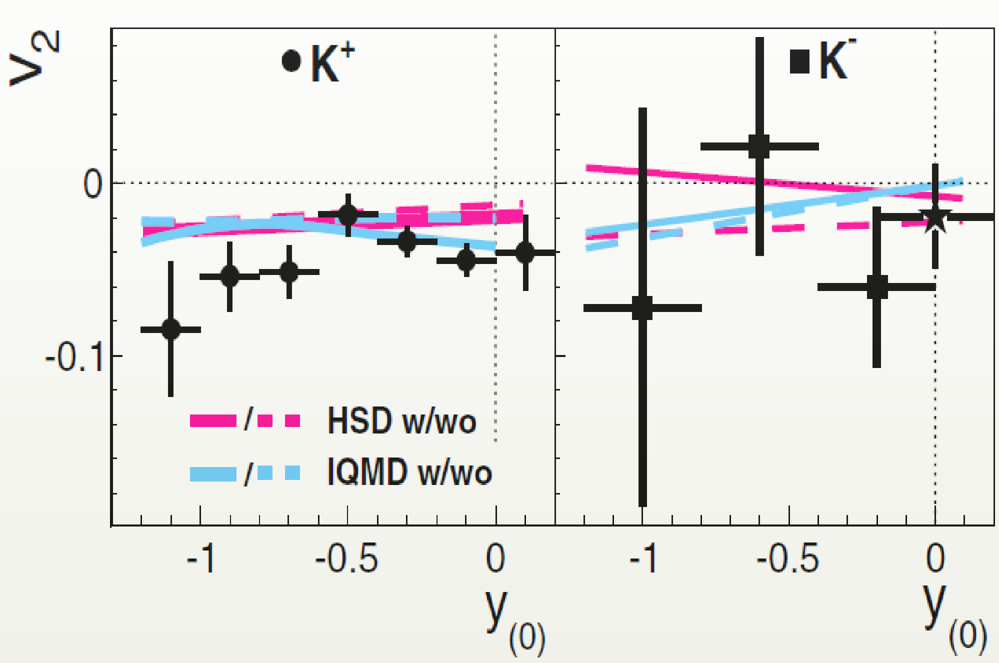


IQMD	solid	U_{K+N} = +20 MeV U_{K-N} = -45 MeV
	dashed	0 MeV
HSD	solid	U_{K+N} = +20 MeV U_{K-N} = -50 MeV
	dashed	0 MeV

V. Zinyuk et al., Phys. Rev. C90, 025210 (2014)

v_1 : Rather weak U_{K+N} potential.
Preference for U_{K-N} ≈30-50 MeV.

Flow of K^+ and K^- from Ni+Ni @ 1.9*A* GeV, cont.



IQMD

U_{K+N} = +20 MeV
$U_{K–N}$ = -45 MeV

0 MeV

HSD

U_{K+N} = +20 MeV
$U_{K–N}$ = -50 MeV

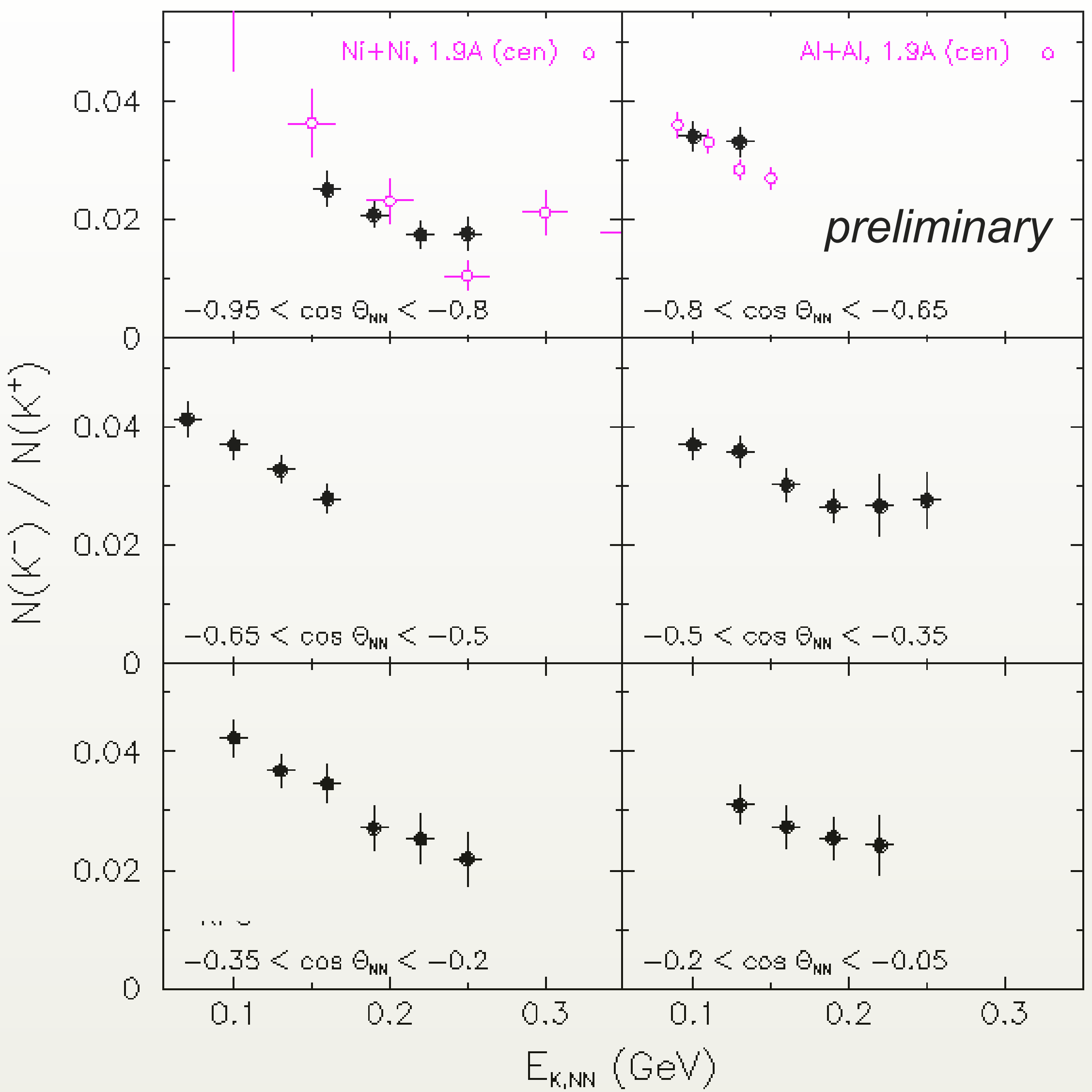
0 MeV

V. Zinyuk et al., Phys. Rev. C90, 025210 (2014)

v_2: first results od rapidity scan,
but predicted sensitivity to U_{KN} too weak, compared to experimental results

In-medium modifications via K^-/K^+ : what's new?

Ratio of K^- over K^+ from Ni+Ni @ 1.9*A* GeV, centrality 56%



New data:

- wide phase space coverage
- more statistics

To be compared with Transport Models

Contribution of ϕ decays to K^-

ϕ mesons from AA collisions @ 1.9*A* GeV

- Measured in K^+K^- decay channel (BR=50%)
  Found in 3 systems (small samples).

- $\phi/K^- = 0.36 \pm 0.05$
  Since BR ($\phi \rightarrow K^+K^-$) = 50%,

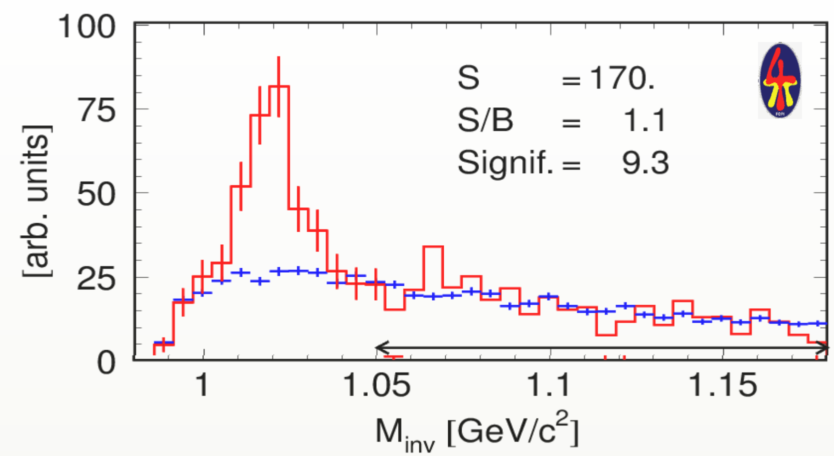
  - About 18% K^- originates from
    ϕ meson decays,
    occuring mostly outside medium.

- Energy spectra of ϕ mesons
  reconstructed and fitted in 2 cases.

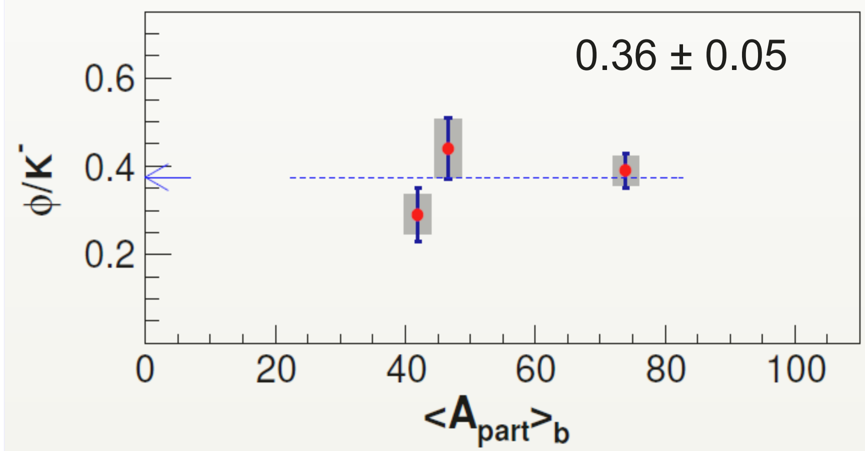
  K^- from ϕ meson decays: „colder” than
  these emitted directly from collision zone.

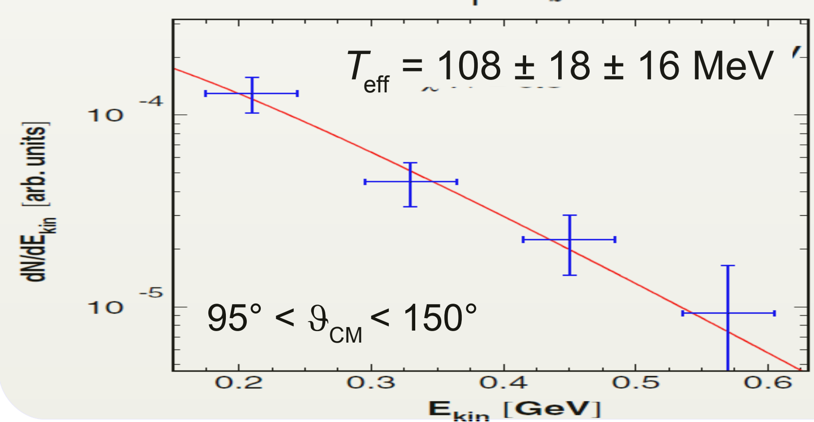
- No data on θ anisotropy (low statistics)

One can subtract contribution from K^- spectra,
and obtain K^-/K^+ of particles
solely from the medium



KP et al., PRC 91, 054904 (2015)





KP et al., PRC 94, 014901 (2016)

Summary

Within last decade a new generation of $K^{+,-}$ measurements was performed thanks to the installation of high resolution ToF detector.

- Directed and elliptic flow of K^+, and K^- across (y, p_T) compared to HSD, IQMD models.
  - In-medium potentials: K^+ weak, K^- moderate.
- K^-/K^+ ratio: wide scan of phase space
  ⊕ ϕ meson yield → about 18% of K^- originate from decays of ϕ.
  - Ready for extraction of in-medium potentials via comparison to transport model predictions.
- New data on Ru+Ru @ 1.65*A* GeV : analysis has started…..

Thank You!

Backup slides

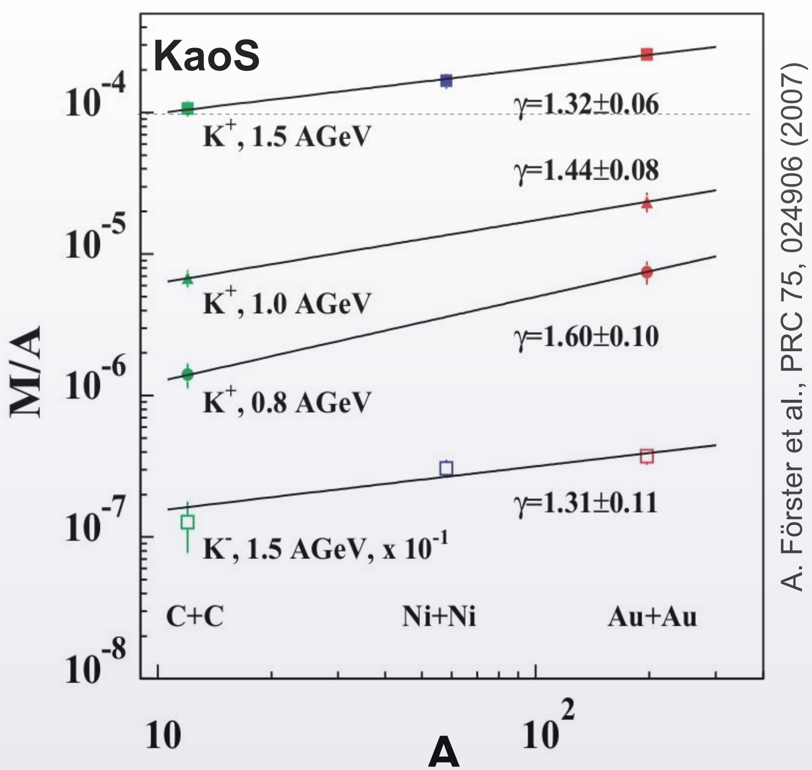
Production of Kaons in AA: Primary or secondary?

If primary:

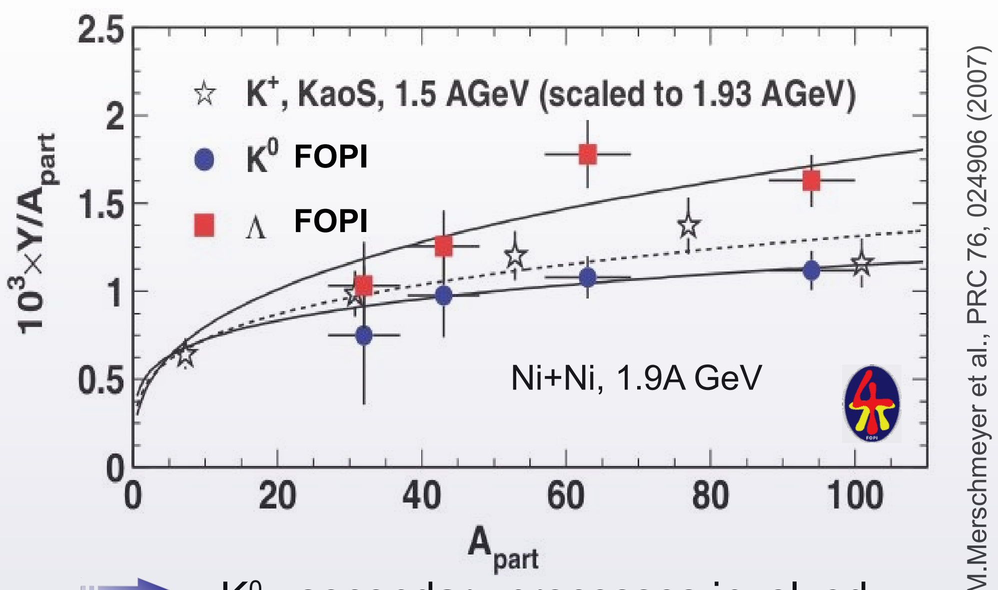
For pA → KX: $MUL_K = \frac{\sigma_K}{\sigma_{inelastic}} = const$

AA→ KX: Glauber: AA = A ⊗ NA

$\Rightarrow \; MUL_K^{AA} = A \times MUL_K^{pA} \propto A$



secondary processes are involved



K^0 : secondary processes involved

K^{+0} near-threshold production processes:

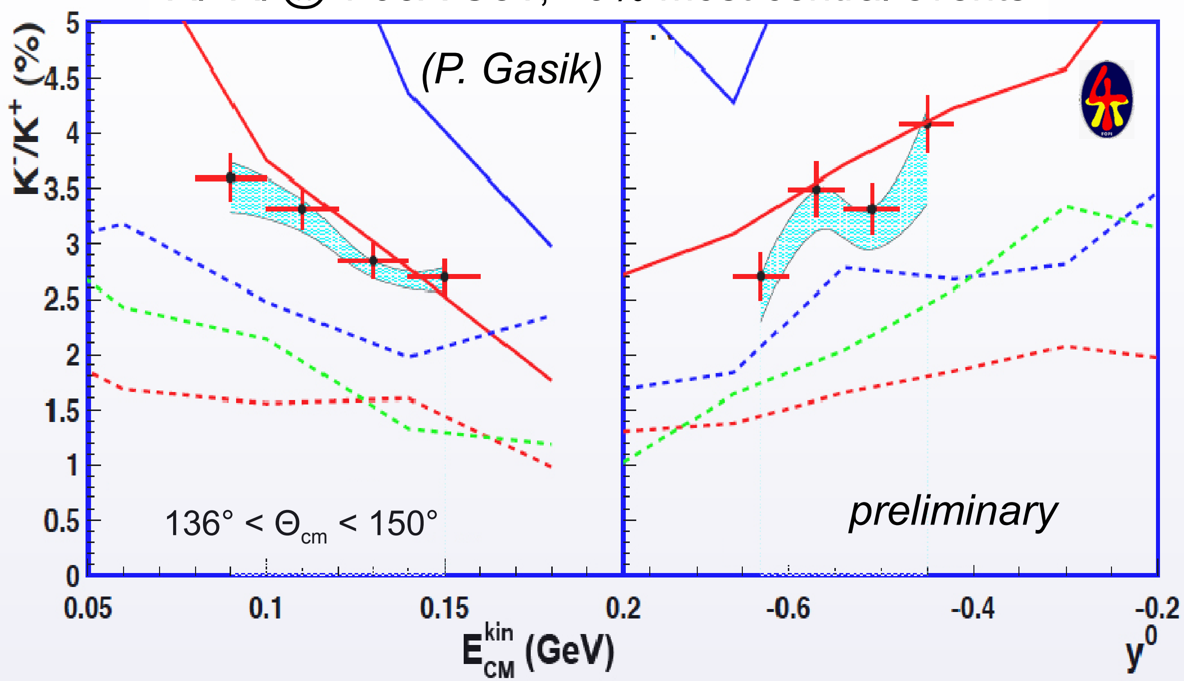
- $N_{beam} + N_{target}$, N_{target} has Fermi motion
- predominantly via ΔN , ΔΔ → $K^{+,0}$ Y B
  πN , πΔ → $K^{+,0}$ Y
  Y = [Λ,Σ]
- U_{KN} involved (increases K mass → lower yields)

K^-/K^+ : experiment vs transport

- K^+ : U_{KN} repulsive
  K^- : U_{KN} ~attractive
  K^-/K^+ : promising observable

- IQMD transport code
  - $m_{K\pm}(\rho) = m_{K\pm}(\rho_0) \cdot \left(1 + \alpha_{\pm} \cdot \frac{\rho}{\rho_0}\right)$
  - at $\rho = \rho_0$
    $\Delta m_{K+} = 40$ MeV, $\Delta m_{K-} = -100$ MeV

- HSD transport code
  - K^+ as in IQMD
  - K^- : off-shell G-matrix approach



IQMD, NO Pot.
HSD , NO Pot.
HSD, U_{K+}=40 MeV, K- Not Modified
HSD, U_{K+}=40 MeV, U_{K-}= G-Matrix
IQMD, U_{K+}=40 MeV, U_{K-}=-100 MeV

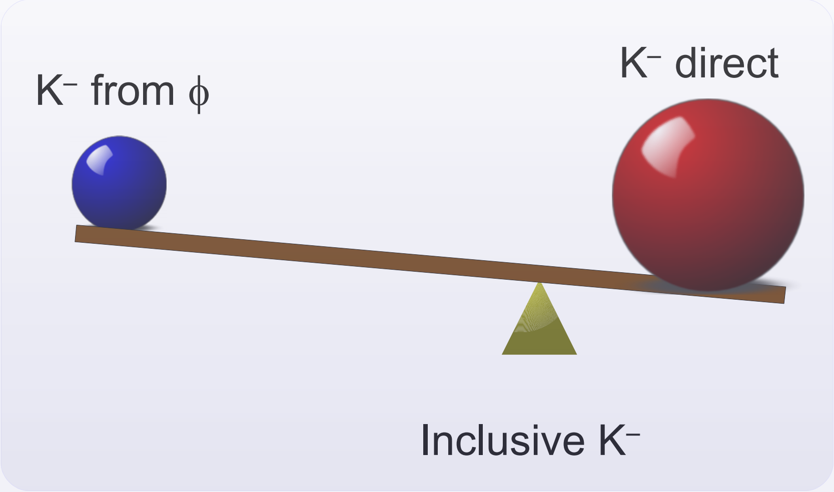
- Clear preference for $U_{KN} \neq 0$ option
- "U_{K+} only" scenario : insufficient
- IQMD: potentials used probably too strong

2-source model of ϕ emission

- $\phi \rightarrow K^+K^-$ simulation in PLUTO

ϕ source temperature : T_{IN} (ϕ) ≈ 100 MeV

Slope of daughter K^- : T_{OUT} (K^-) ≈ 60 MeV



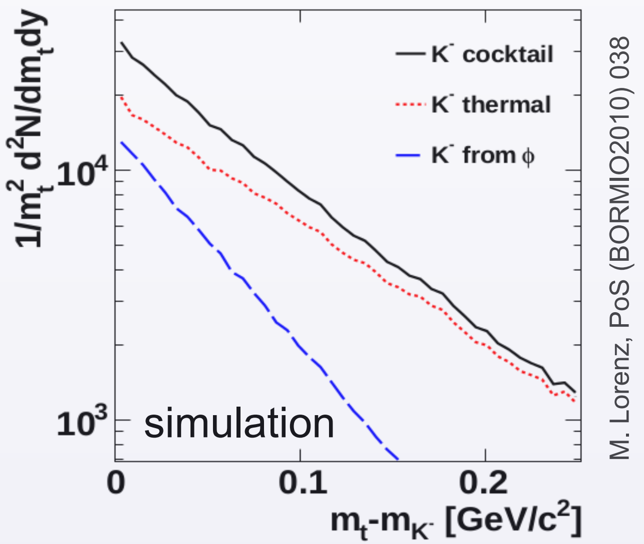
- Ar+KCl @ 1.76A GeV (HADES)

Experiment :

Particle	T_{eff}
K^-	$69 \pm 2 \pm 4$
K^+	$89 \pm 1 \pm 2$
ϕ	84 ± 8

<u>Conjecture</u> :

T (direct K^-) = T (K^+)

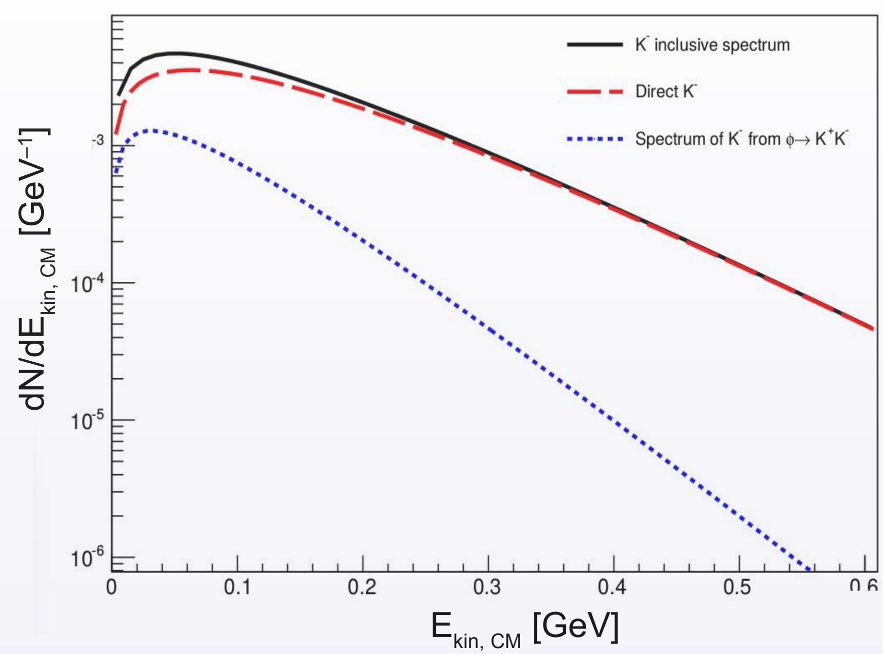


ϕ admixture reduces T(K^-) from 89 MeV to 74 MeV

- Al+Al @ 1.9A GeV (FOPI)

Experiment :

Particle	T_{eff}
K^-	$82 \pm 7 \pm 11$
K^+	$109 \pm 2 \pm 9$
ϕ	$93 \pm 14 \pm 16$



P. Gasik, Ph. D. (IFD UW), draft in preparation

→ T (K⁻ from ϕ) = 58 MeV

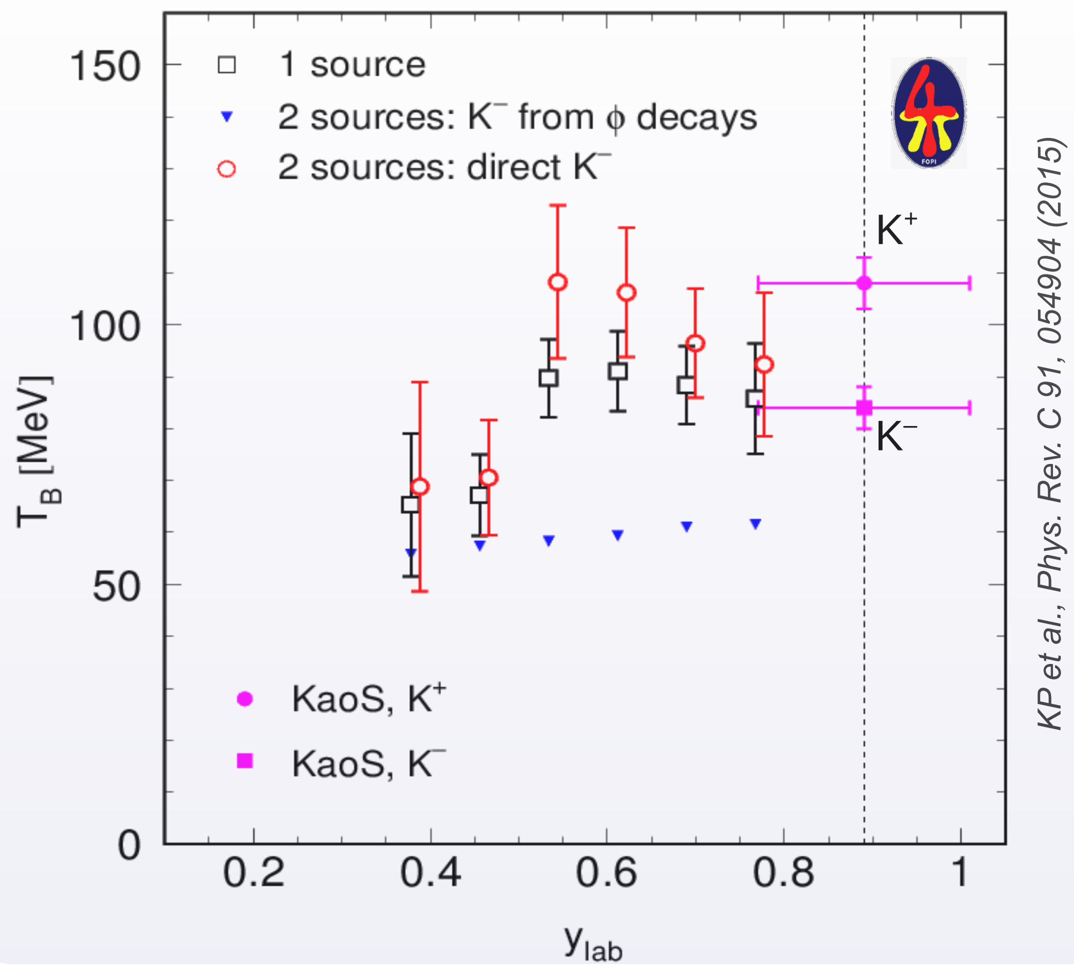
T (K⁻ direct) = 92 ± 16 MeV

→ ϕ contribution to K⁻ : indication that T_{direct} @ ~10 MeV above $T_{inclusive}$

- Ni+Ni @ 1.9A GeV (FOPI, KaoS)

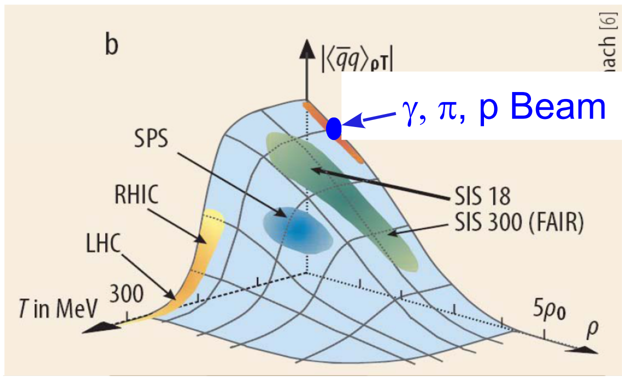
Experiment :

Particle	T_{eff}
K^-	84 ± 4
K^+	108 ± 5
ϕ	$106 \pm 18 \pm 16$



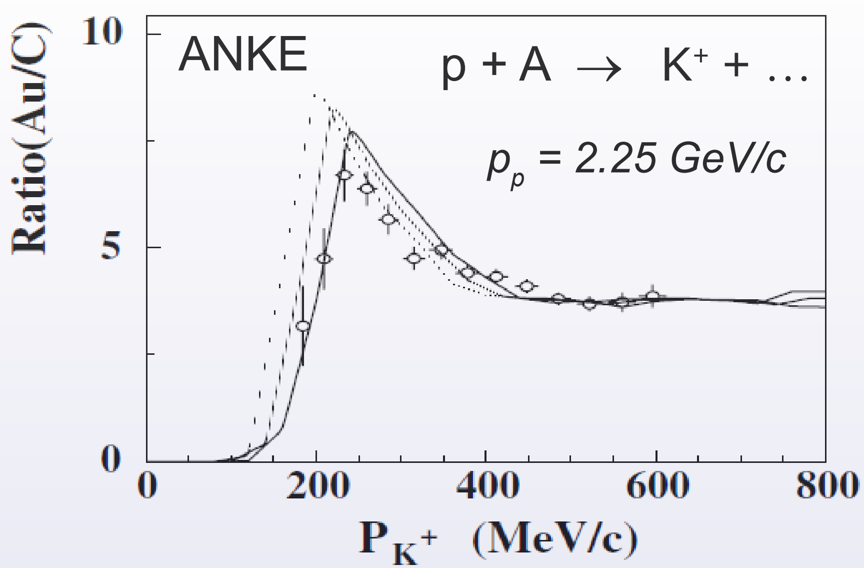
ϕ contribution to K⁻ : indication that T_{direct} @ ~10 MeV above $T_{inclusive}$

In-medium modifications of $K^{+/0}$ at $\rho < \rho_0$



M. Kotulla et al., Physik Journal 8 (2009) 3

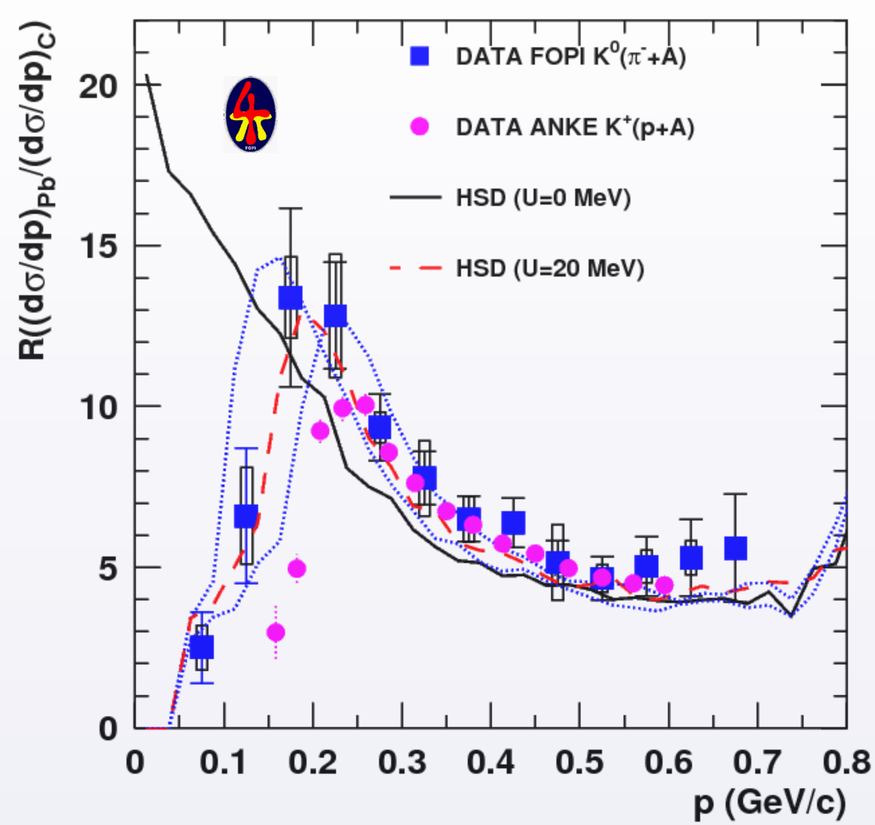
π^- (p=1.15 GeV/c) + A	→	K^0 + …	*FOPI*
p (p=2.25 GeV/c) + A	→	K^+ + …	*ANKE*



Z. Rudy et al., EPJA 23, 379 (2005)

CBUU transport code

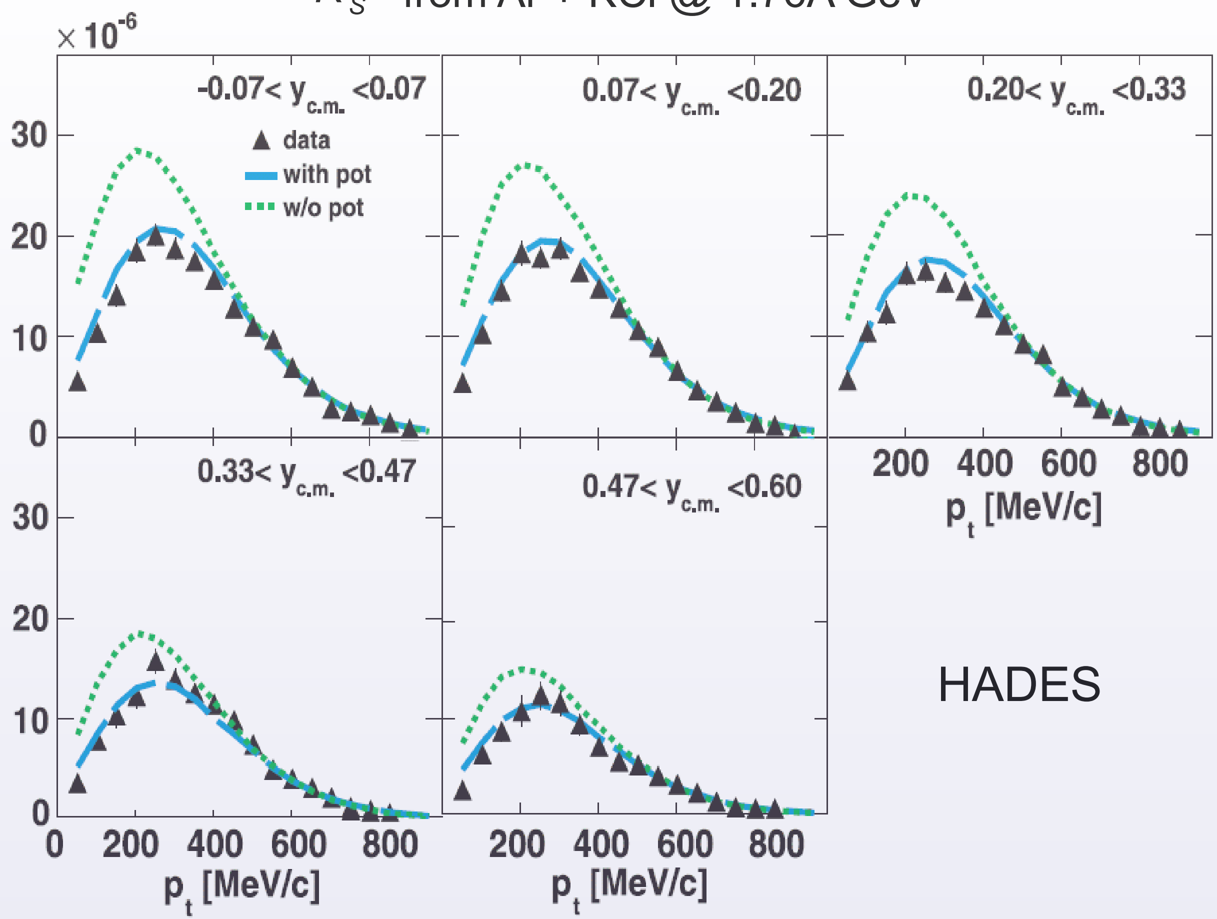
· · · ·	V_{KN} = 0 MeV
....	V_{KN} = 10 MeV
——	V_{KN} = 20 MeV



M.L. Benabderrahmane et al., PRL 102, 182501 (2009)

Modifications of K^0 in AA collisions

K^0_S from Ar + KCl @ 1.76A GeV



G. Agakichiev et al., Phys. Rev. C 82, 044907 (2010)

K^0_S cτ = 2.7 cm

K^0_L cτ = 15.3 m

IQMD transport calc. :

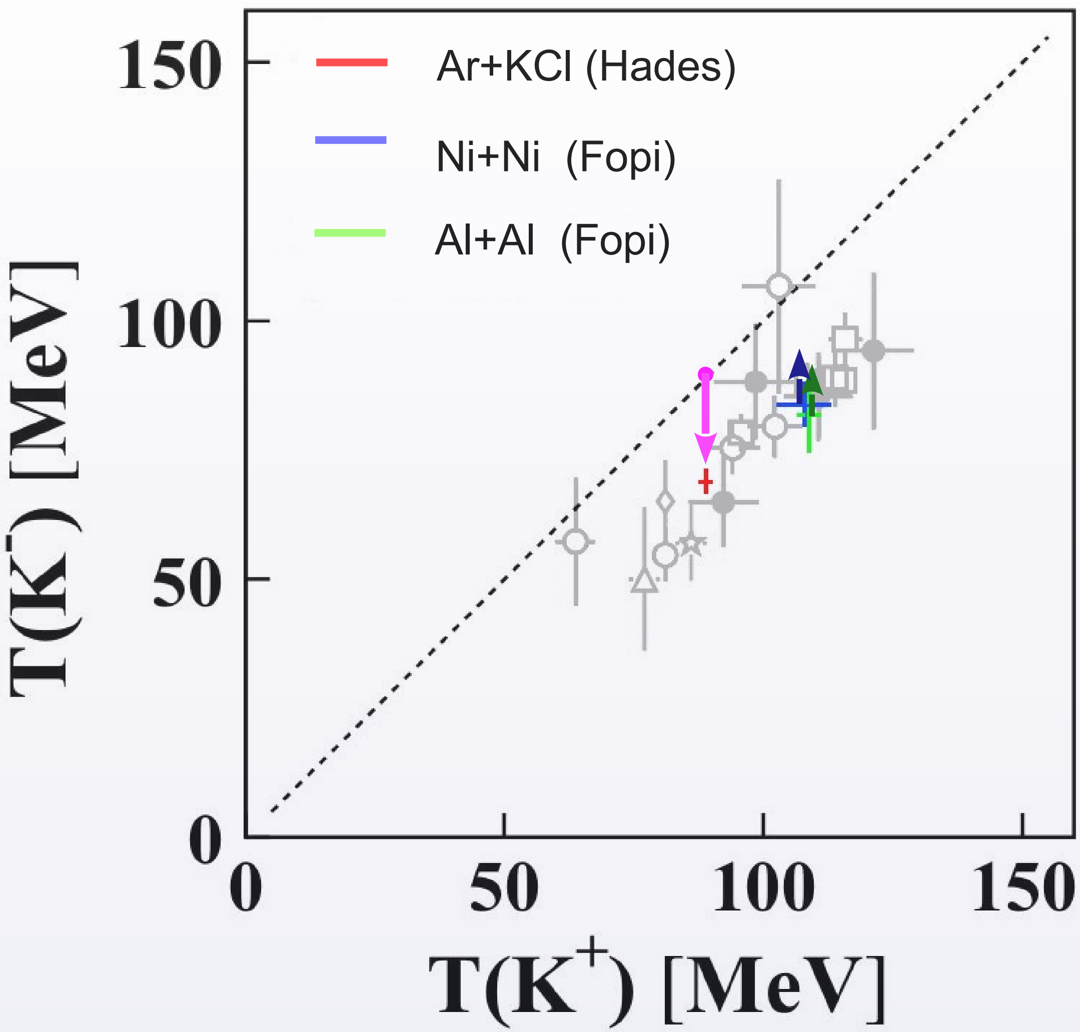
No potential

U_{K0N} = 46 MeV

➡ U_{KN} at $\rho \sim 2\,\rho_0$

seems to be stronger than for

$\pi^- A \rightarrow K^0 + \ldots$ at $\rho \leq \rho_0$

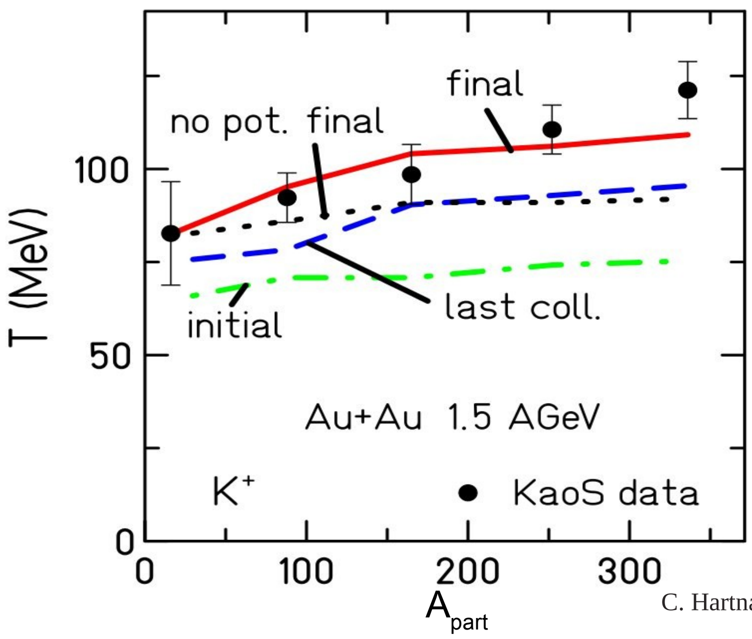


Previously:

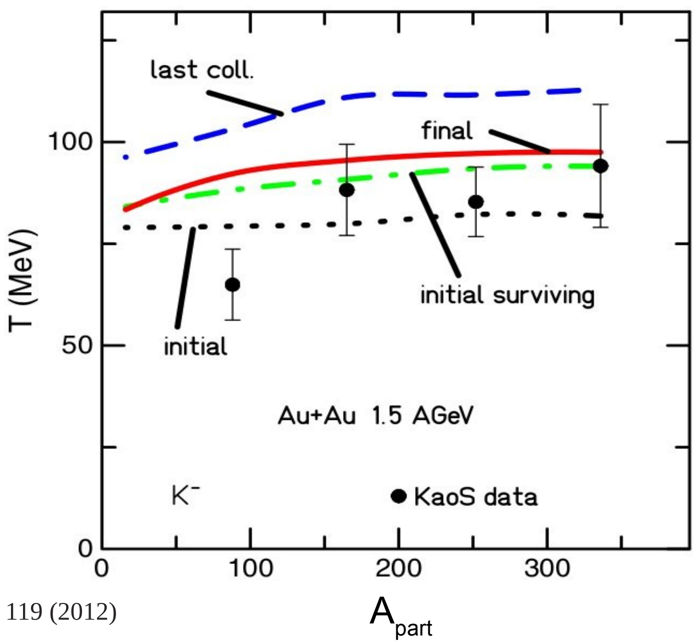
Difference of K^+,K^- slopes explained by U_{KN} potentials

Present studies:

About 50% can be explained by $\phi \rightarrow K^+K^-$ decays



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



Strangeness production and absorption

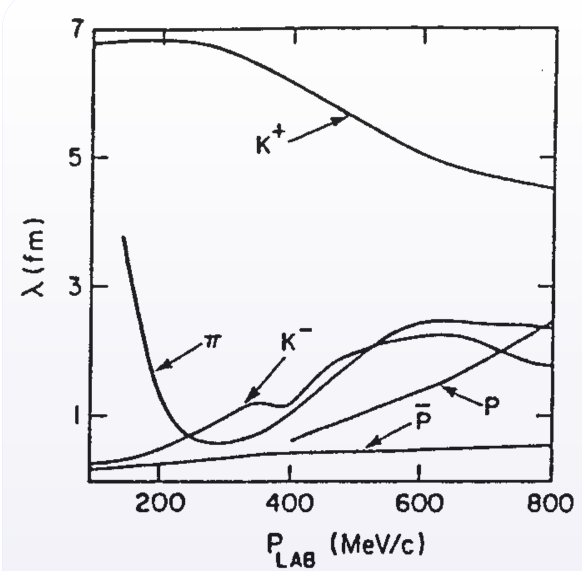
	K^+	K^-	ϕ
Production (primary)	$BB \to BYK^+$ $T_{pp\to p\Lambda K+}$ = 1.58 GeV	$BB \to BBK^+K^-$ $T_{pp\to ppK+K-}$ = 2.5 GeV	$BB \to BB\phi$ $T_{pp\to ppK+K-}$ = 2.6 GeV
Production (secondary)	$\pi B \to YK^+$	$\pi Y \to (\Sigma^* \to)\ BK^-$ $BY \to NK^-\Lambda$ $BY \to BBK^-$ $\pi B \to BK^+K^-$ $\phi \to K^+K^-$	$\pi B \to B\phi$ $\rho B \to B\phi$ $\pi N^* \to N\phi$ $\rho\pi \to \phi$ $K^+K^- \to \phi$ <u>*negligible*</u>
Absorption	$K^+Y \to \pi B$	$K^-B \to \pi Y$	$\phi N \to K\Lambda$
Elastic scat. (char. exch.)	$K^+B \leftrightarrow K^+ B$ $K^+n \leftrightarrow K^0 p$	$K^-B \leftrightarrow K^-B$ $K^-p \leftrightarrow \overline{K}^0 n$	$\phi N \to \phi N$

[B] = *p, n, N, N*, Δ*

[Y] = *Λ, Σ*

Yields from	Ni + Ni (1.93 GeV)
B + B	3.5×10^{-4}
π + B	2.9×10^{-4}
ρ + B	8.9×10^{-4}
$\pi + \rho$	1.6×10^{-4}
π + N(1520)	0.5×10^{-4}
Total yield	1.7×10^{-3}

H.W. Barz et al. (BUU) ,
Nucl. Phys. A 705 (2002) 223



C.B. Dover, G.E. Walker
Phys. Rep. **89** (1982) 1

ϕ yield – BUU predictions

- ***BUU*** calculations for Ni+Ni @ 1.93A GeV, 9% most central collisions

- ϕ production channels:

  BB → ϕ , B = {N, Δ}

  μB → ϕ , μ = {π, ρ}

  πρ → ϕ

  K^+K^- → ϕ negligible

Yields from	Ni + Ni (1.93 GeV)
B + B	3.5×10^{-4}
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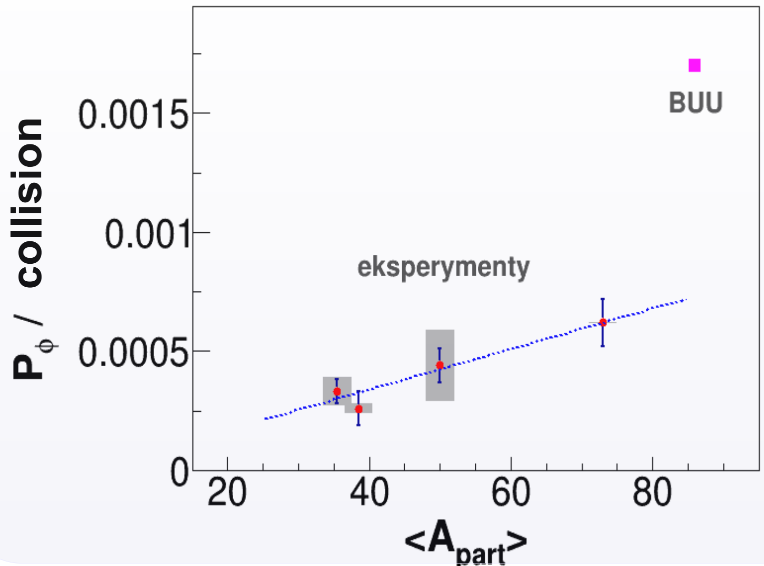
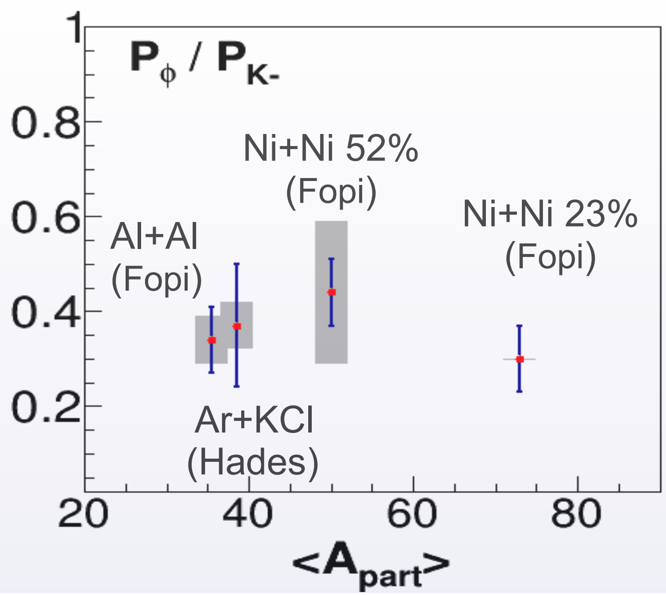


BUU:

ϕ yield overestimated



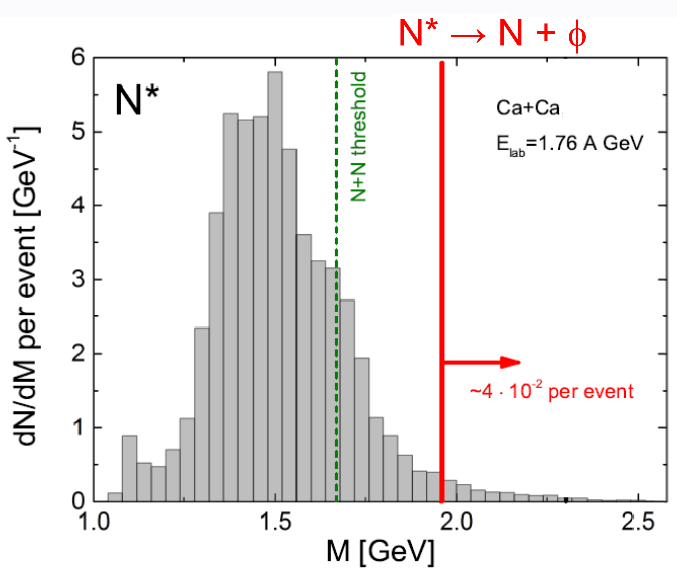
- $c\tau$ = 50 fm

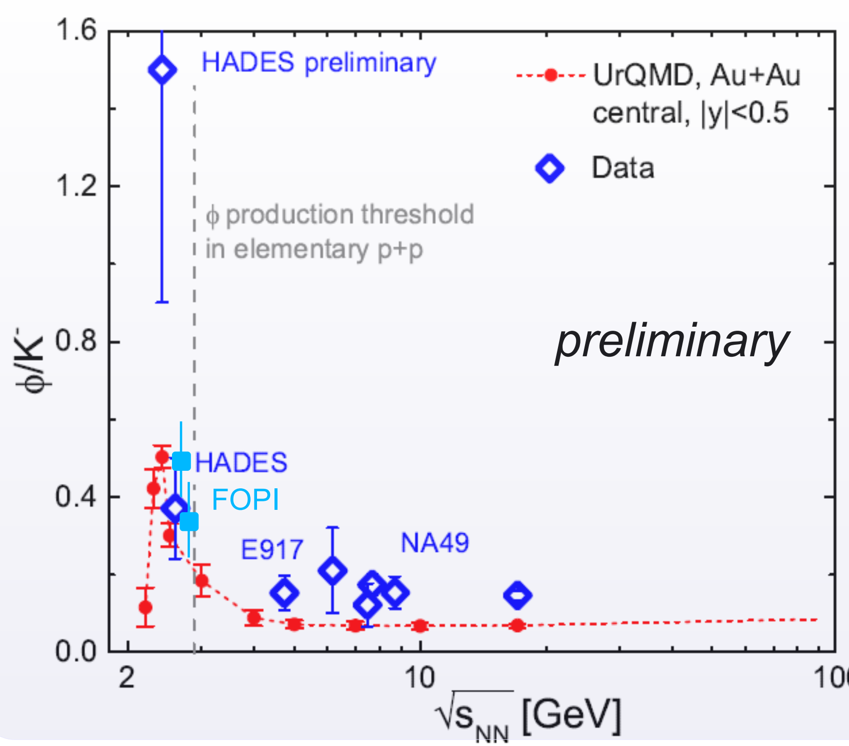
  $\phi \rightarrow K^+K^-$ (BR ~ 50%)

- $$\frac{\varphi}{K^-} \approx \frac{1}{3}$$ ➡ ~ 15 .. 20% K^- originates from ϕ decays

- **UrQMD** model

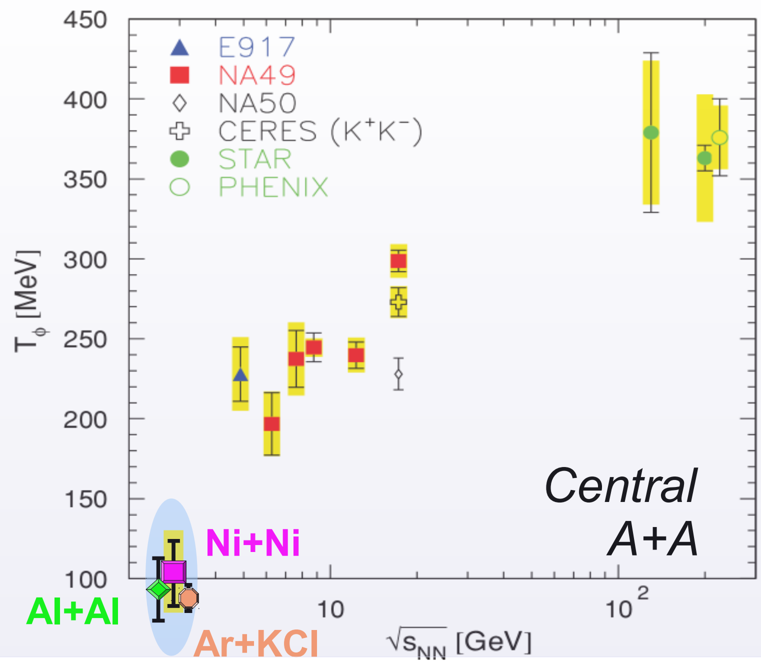
  Resonance states <u>in medium</u>:





J. Steinheimer, M. Bleicher, arxiv: 1503.07305

Excitation function of ϕ inverse slopes



C. Alt et al. (NA49), Phys. Rev. C **78**, 044907 (2008)
B. Back et al. (E917), Phys. Rev. C **69**, 054901 (2004)

Sub- and near-threshold Production of K^-

- in medium: mainly **strangeness exchange**:

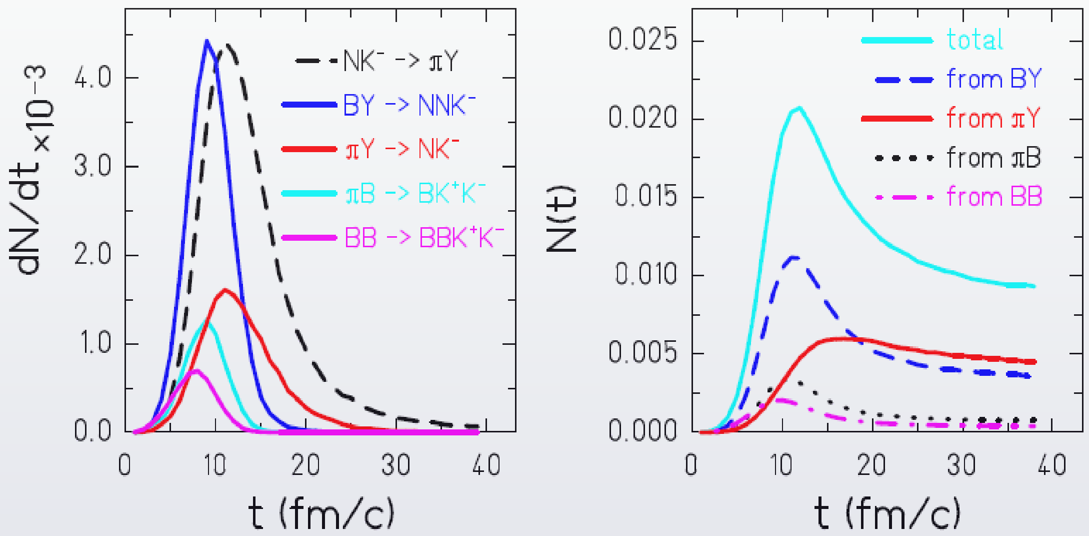
  $BY \rightarrow NNK^-$, $\pi Y \rightarrow K^- B$

  - strong reabsorption: $K^- B \rightarrow \pi Y$
  - coupled to resonances $\Sigma(1385)$, $\Lambda(1405)$

  $$\pi + Y \rightarrow \begin{matrix}\Sigma^* \\ \Lambda^*\end{matrix} \rightarrow K^- + B$$

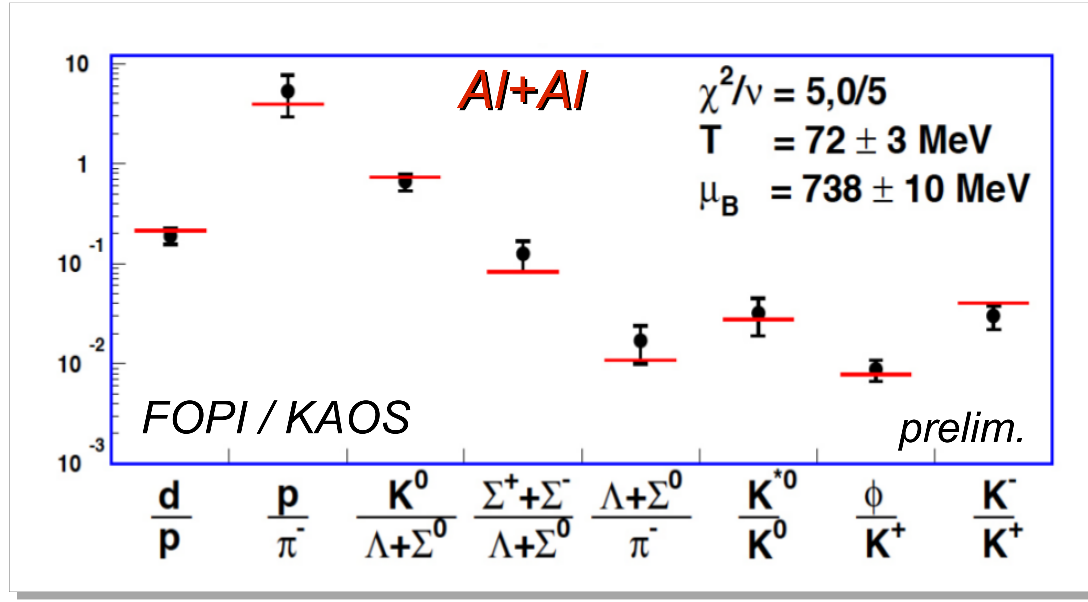
  Q: Can we see them?

Au+Au @ 1.5A GeV (IQMD transport code)



Particle yields vs Statistical Model and UrQMD

- **Al+Al** : 8 independent ratios involving
  p, d, π^-, K^+, K^-, K^0_s, ϕ, K^{*0}, $\Sigma^{*\pm}$, Λ
- **Ni+Ni** : 8 independent ratios involving
  p, d, π^+, π^-, K^+, K^-, K^0_s, ϕ, Λ



Statistical Model

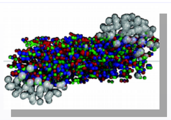
→ Grand Canonical ensemble;

→ For S≠0, Canonical ensemble

→ calc: THERMUS code

S.Wheaton, J.Cleymans , hep-ph/0407175

➞ *SM* fitting quite well



UrQMD v 2.3

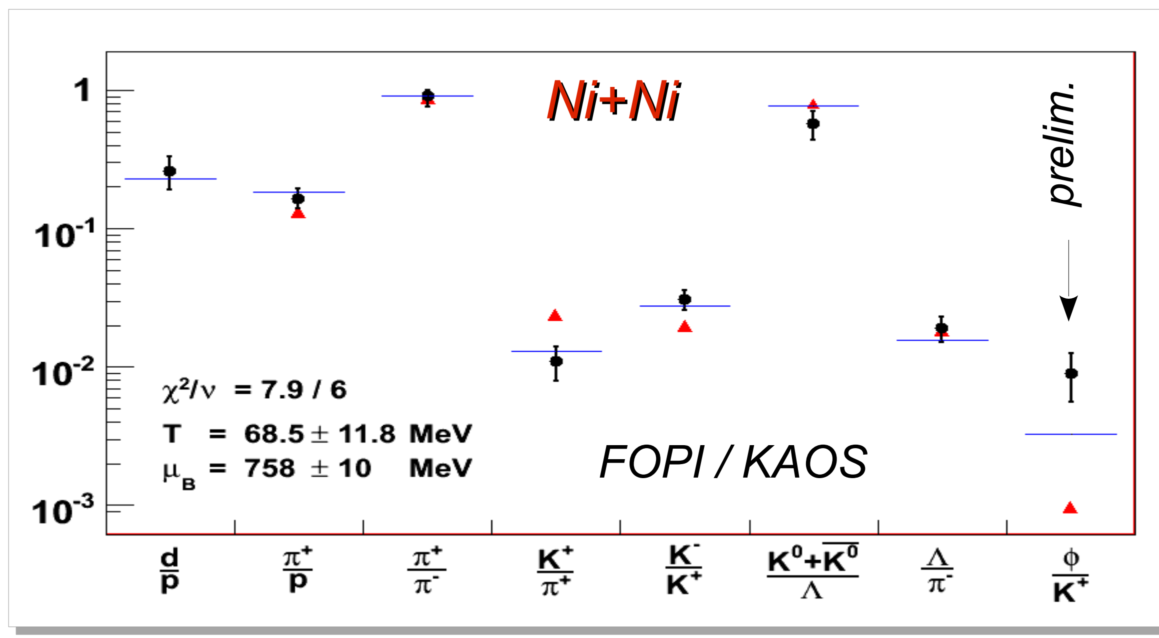
→ No equilibration assumed

→ Cascade model – no mean field

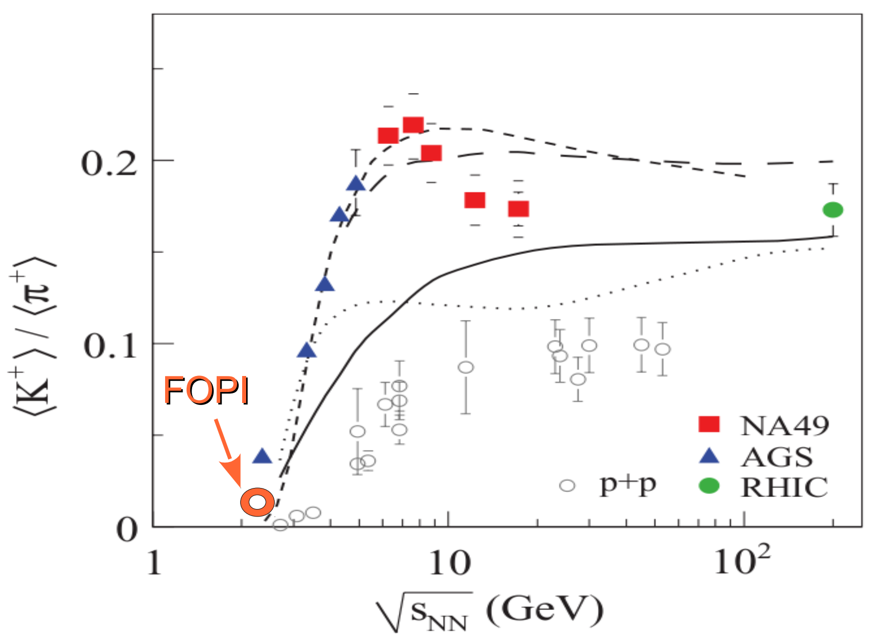
– no in-medium effects

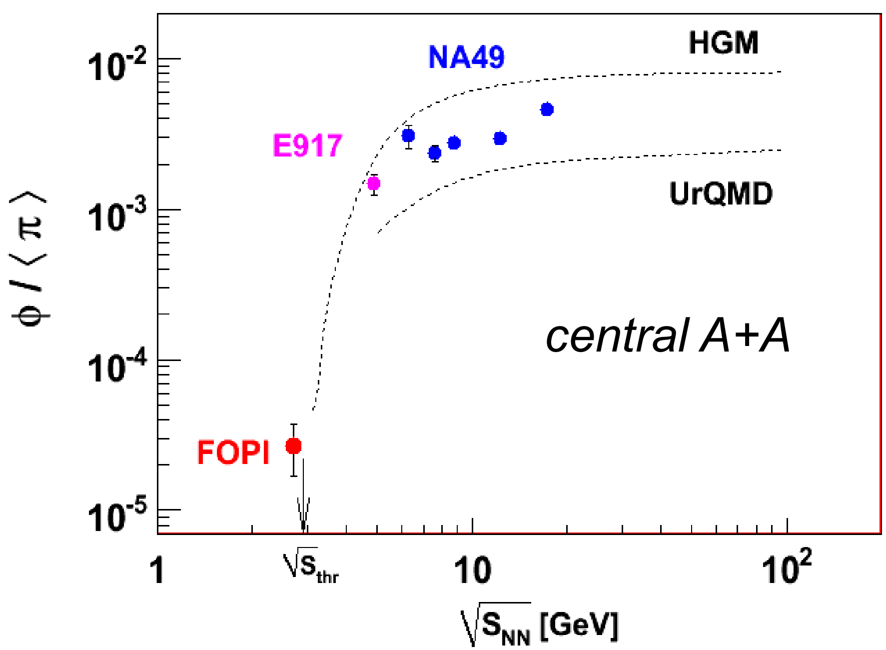
→ *J. Phys. G: Nucl. Part. Phys. 25 (1999) 1859*

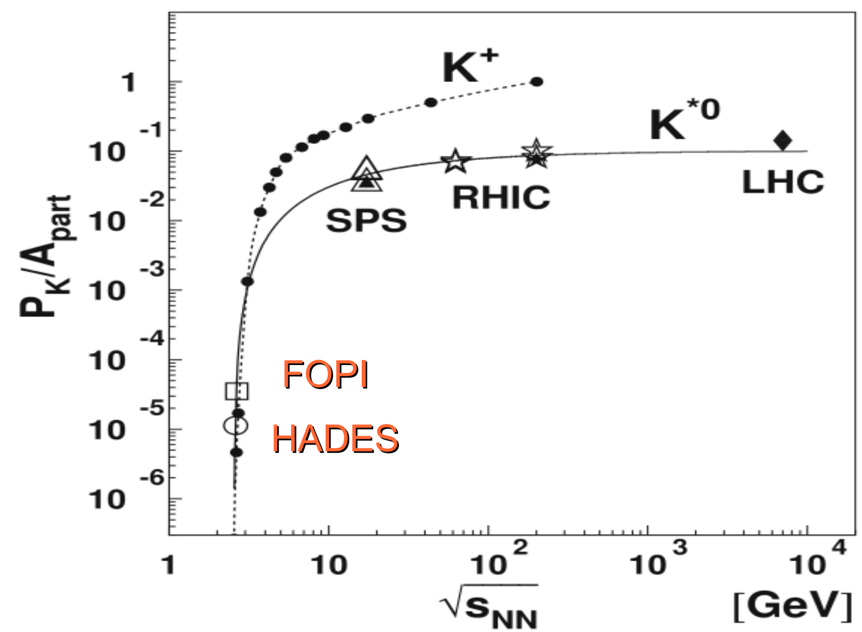
➞ *UrQMD* fits quite well too



Strange meson excitation functions near threshold







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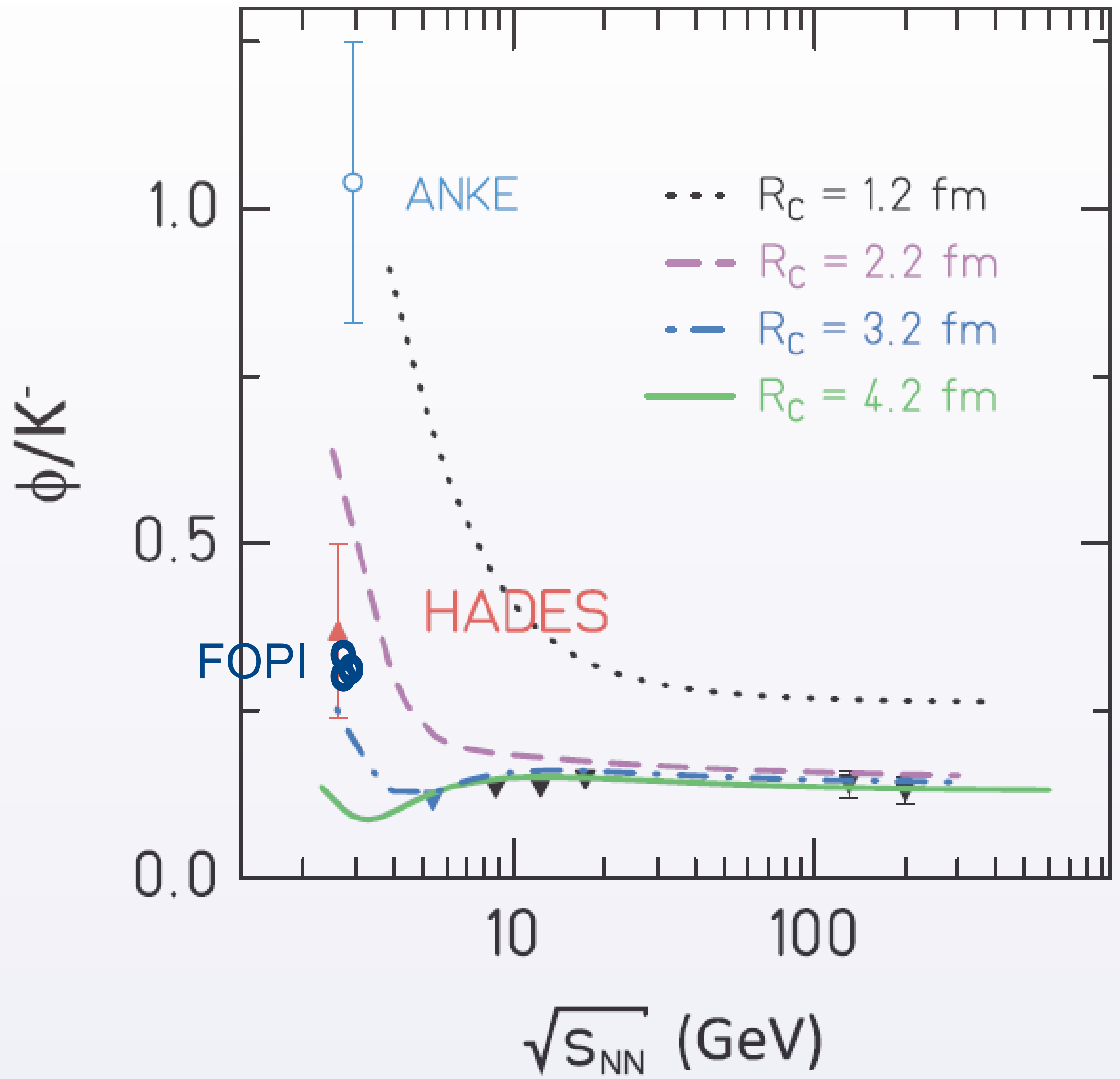
ϕ/K^- within the statistical model approach



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