FOPI

Nuclear medium modifications of properties of kaons measured around threshold with FOPI

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

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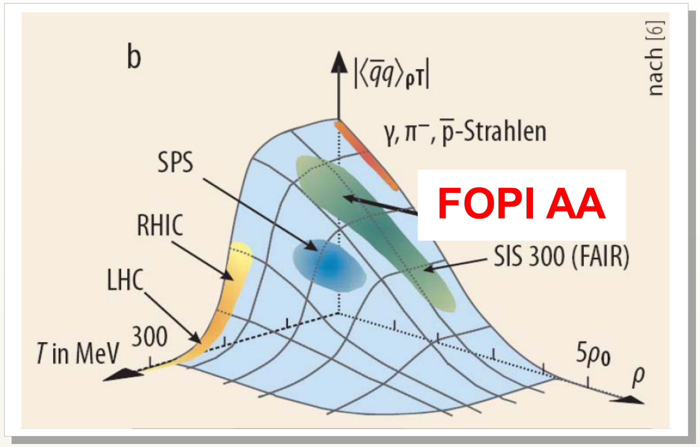
Probing partial restoration of chiral symmetry



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

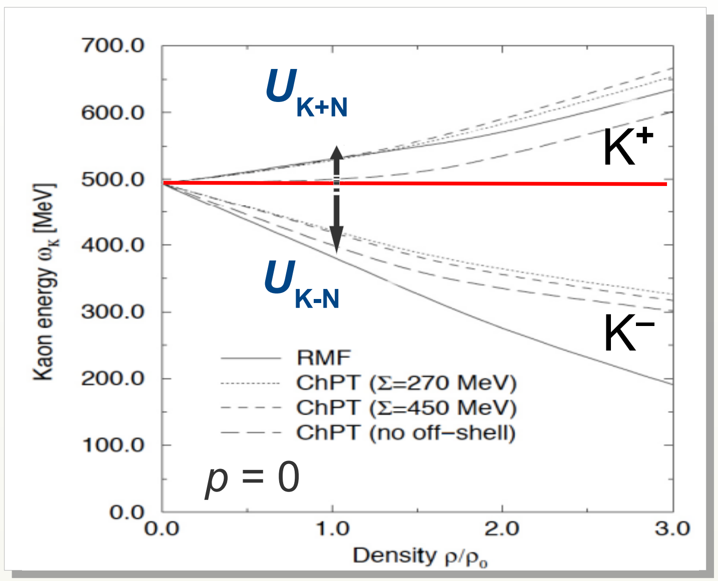
Gell-Mann Oakes Renner – relation:

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

Decay constant

Mass

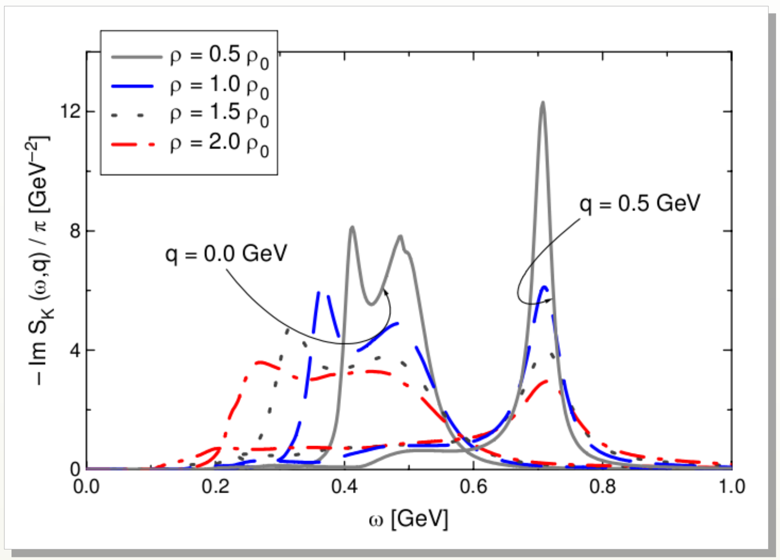
First approaches: Potential



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

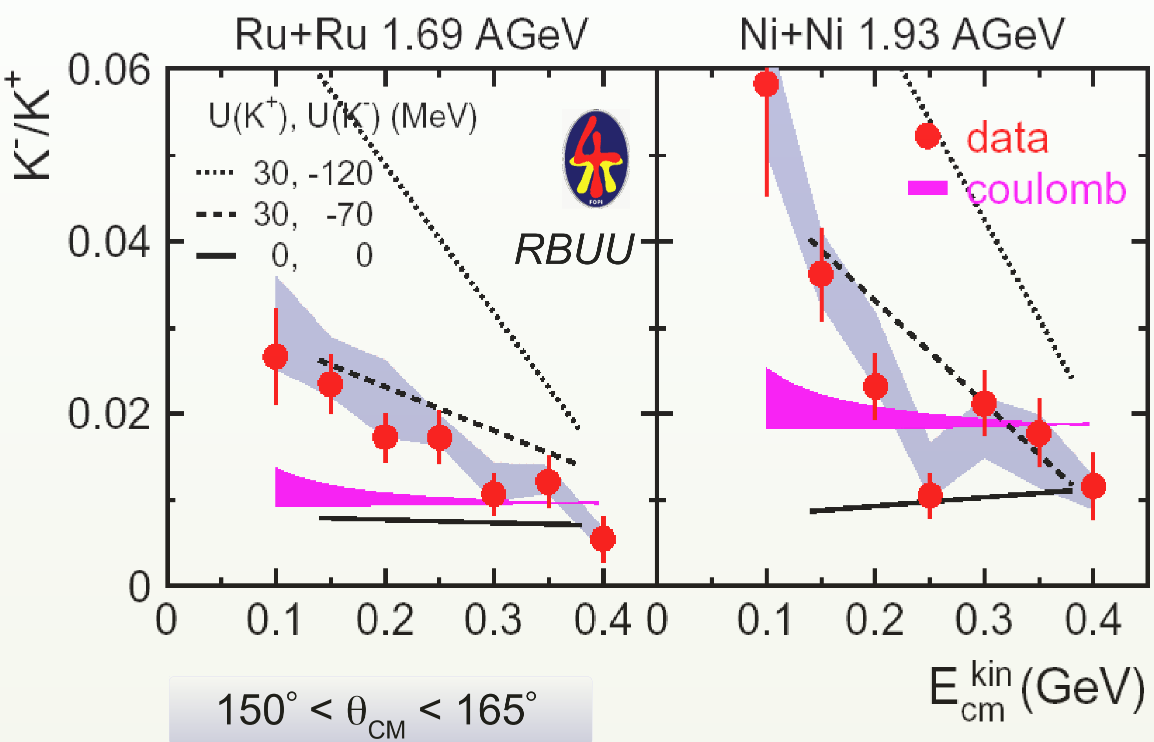


M.F. M. Lutz, PPNP 53 (2004) 125

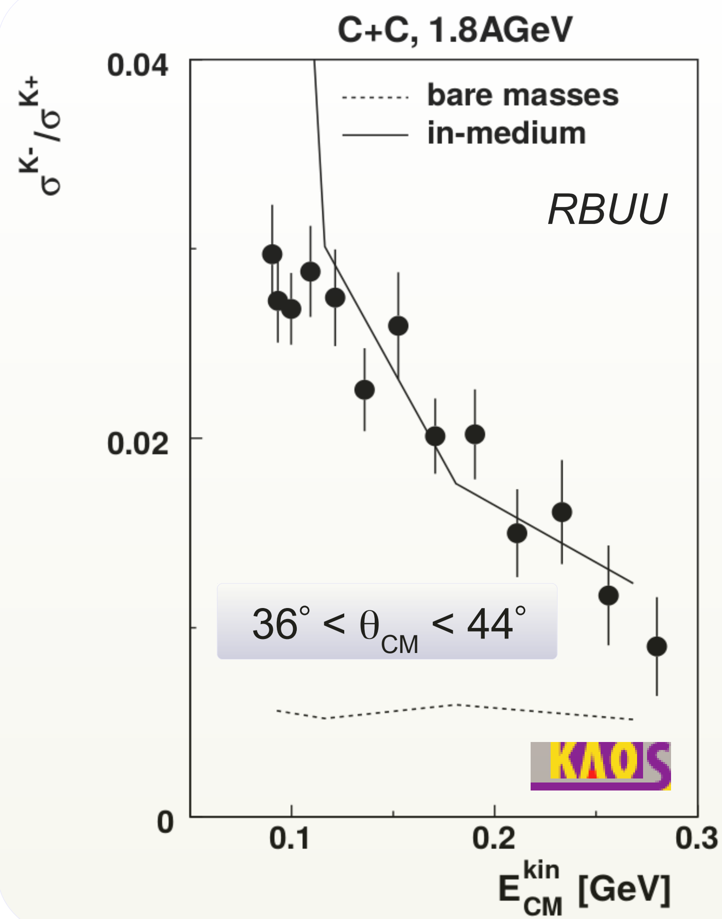
„Potential" only on average

In-medium modifications via K⁻/K⁺

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}.

In-medium modifications via Flow

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

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

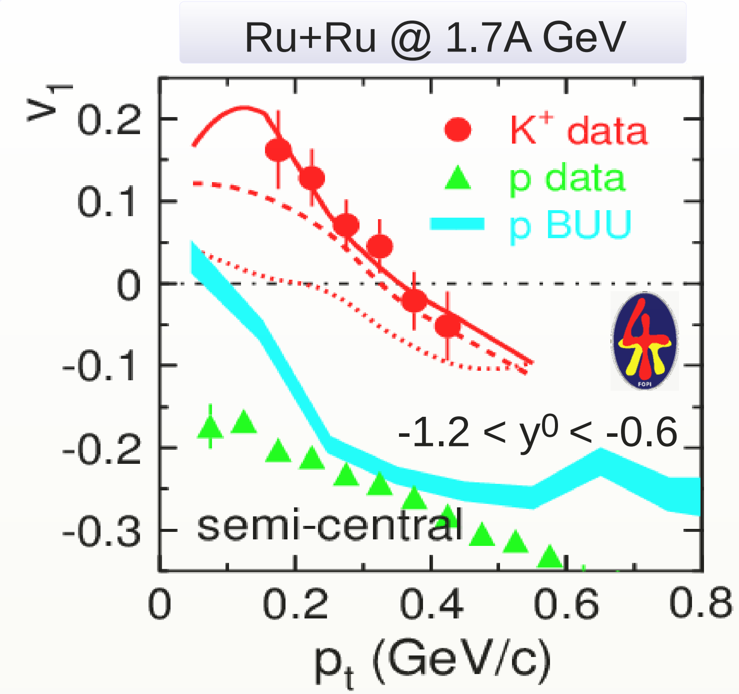
  ➔ Preference for $U_{K+N} \approx$ 20 MeV
  No information on U_{K-N}

- KaoS analysis:

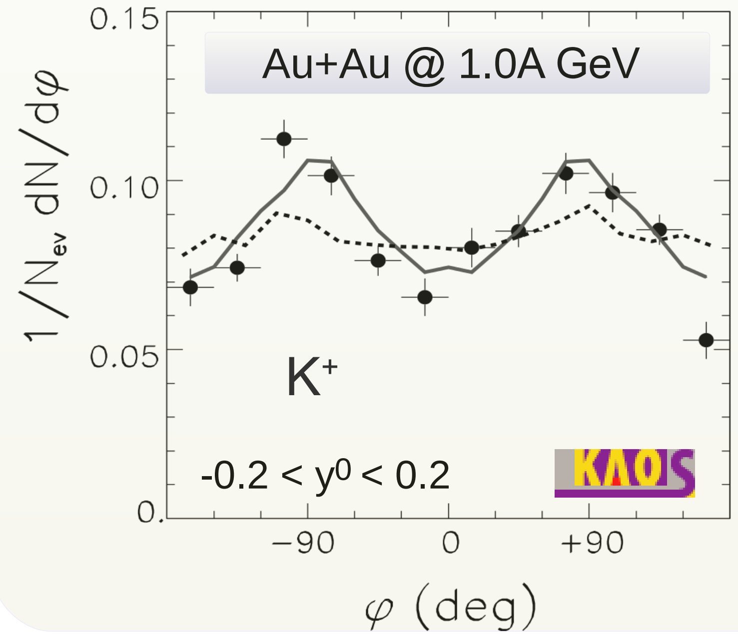
  Fit to d*N*/dϕ (K^+)
  for 2 systems at 1 – 2A GeV

  ➔ 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

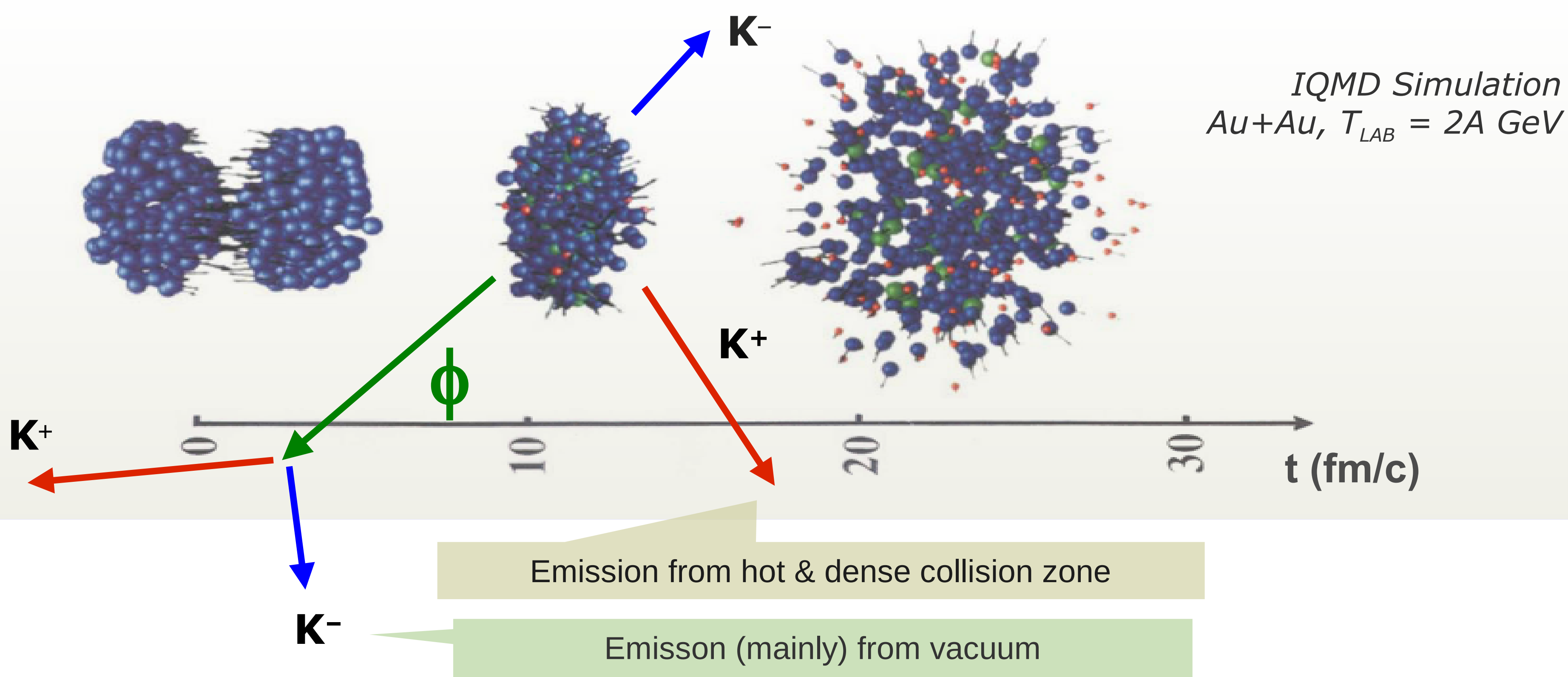


Y. Shin et al., Phys.Rev.Lett 81, 1576 (1998)

ϕ meson : a missing player

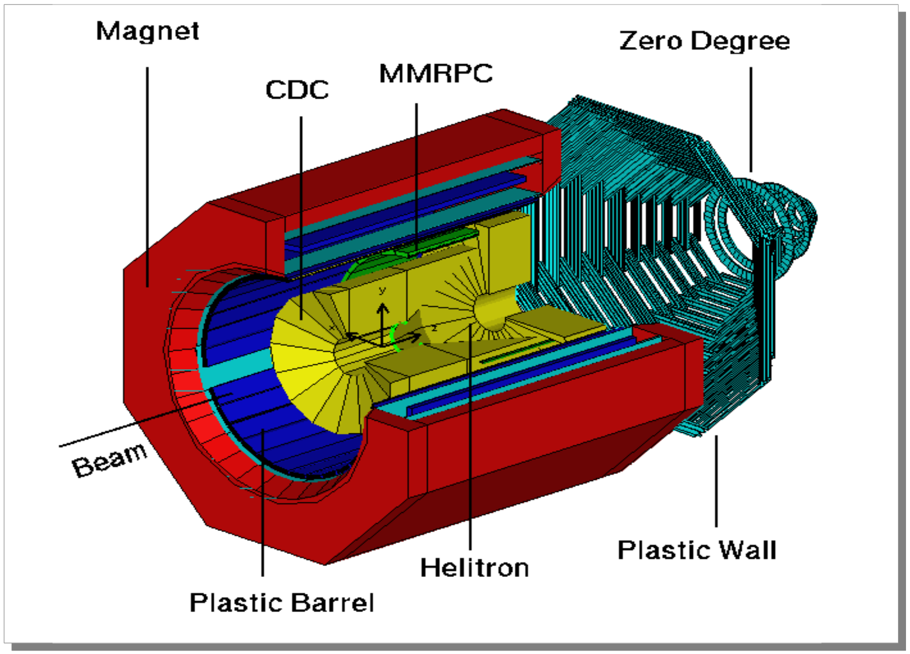
ϕ $(s\bar{s})$: m = 1.02 GeV
$E_{b,\ threshold}$ = 2.6 GeV (SIS-18: sub-threshold only)

$c\tau$ = 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

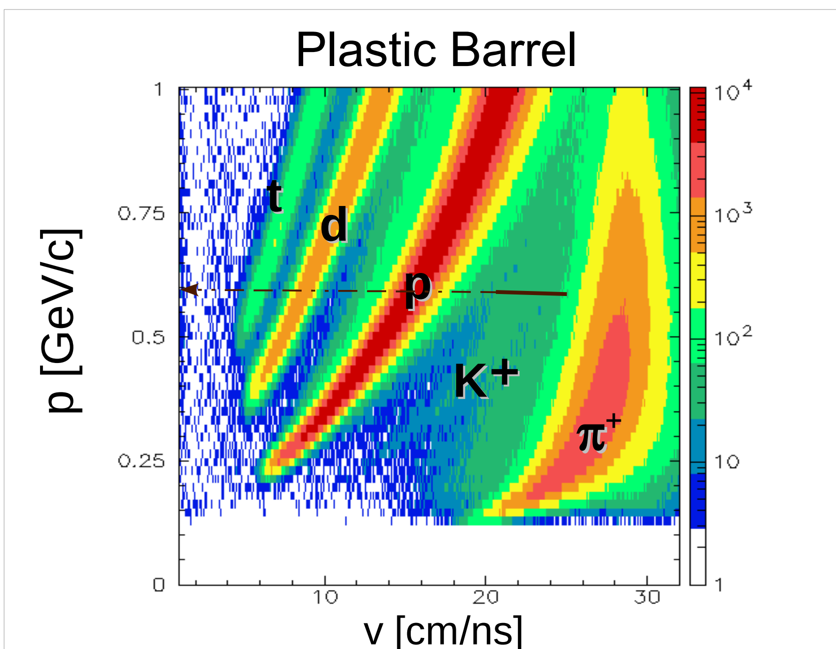
FOPI experimental setup

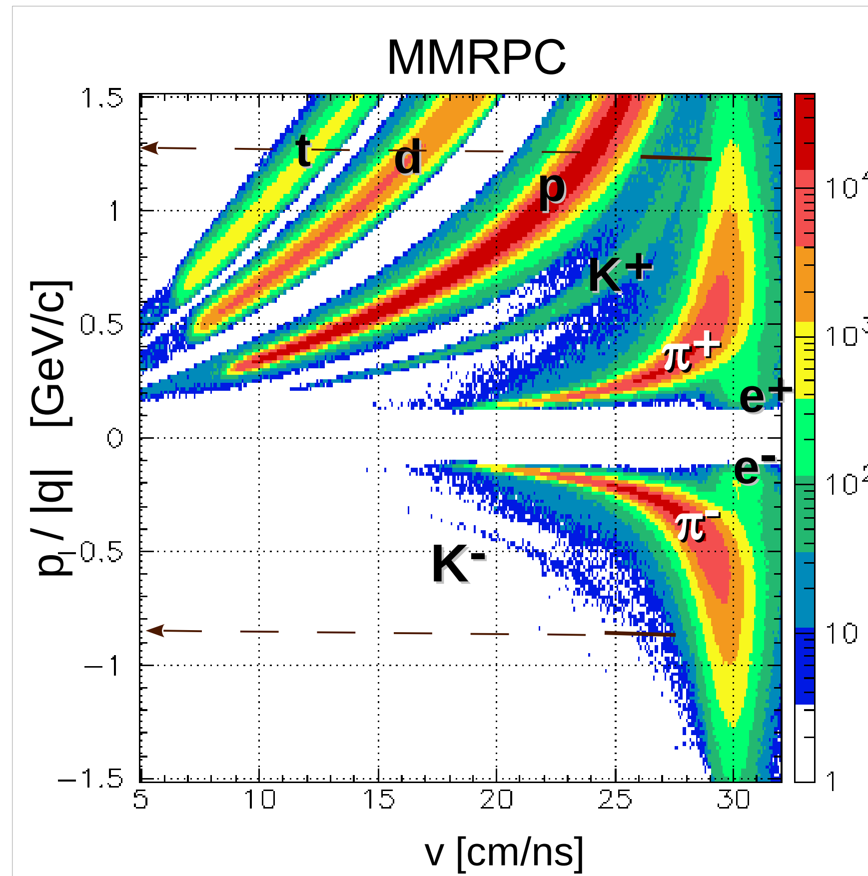


- Nearly 4π coverage
- Drift chambers: CDC, Helitron

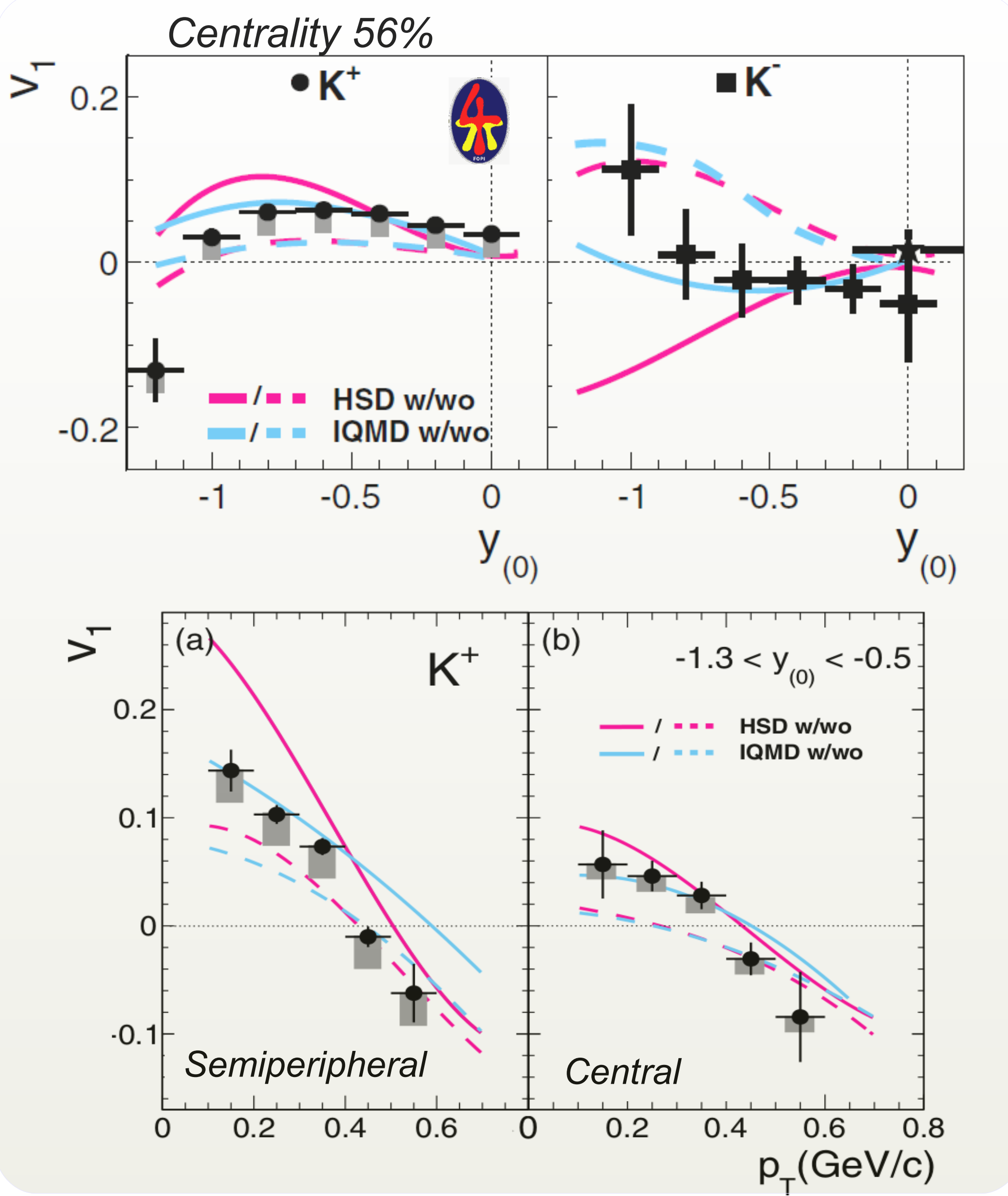
  ToF : Plastic Barrel, RPC

  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

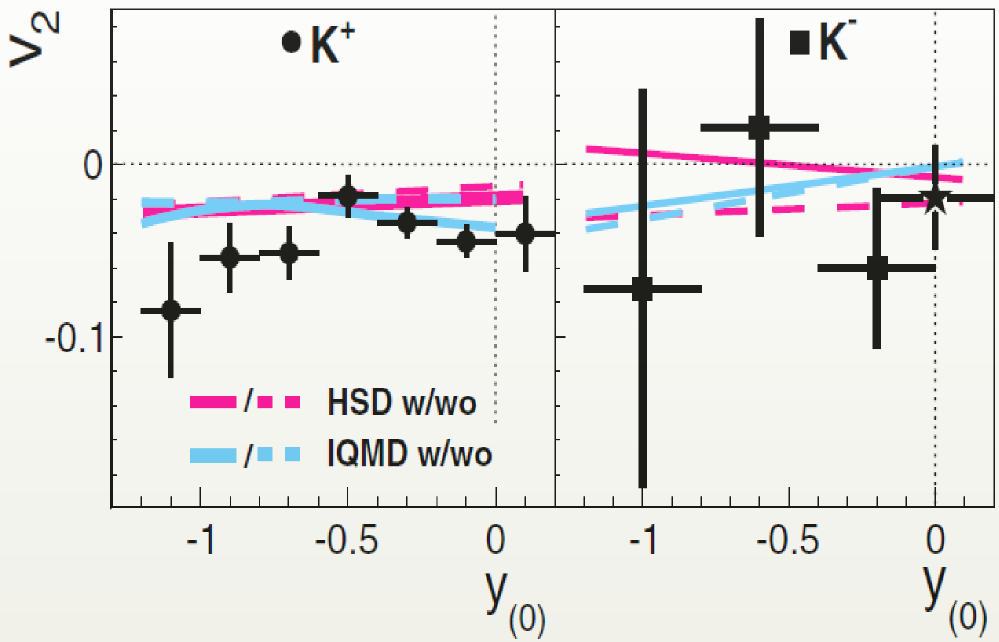


IQMD	solid line	U_{K+N} = +20 MeV, U_{K-N} = -45 MeV
	dashed line	0 MeV
HSD	solid line	U_{K+N} = +20 MeV, U_{K-N} = -50 MeV
	dashed line	0 MeV

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.

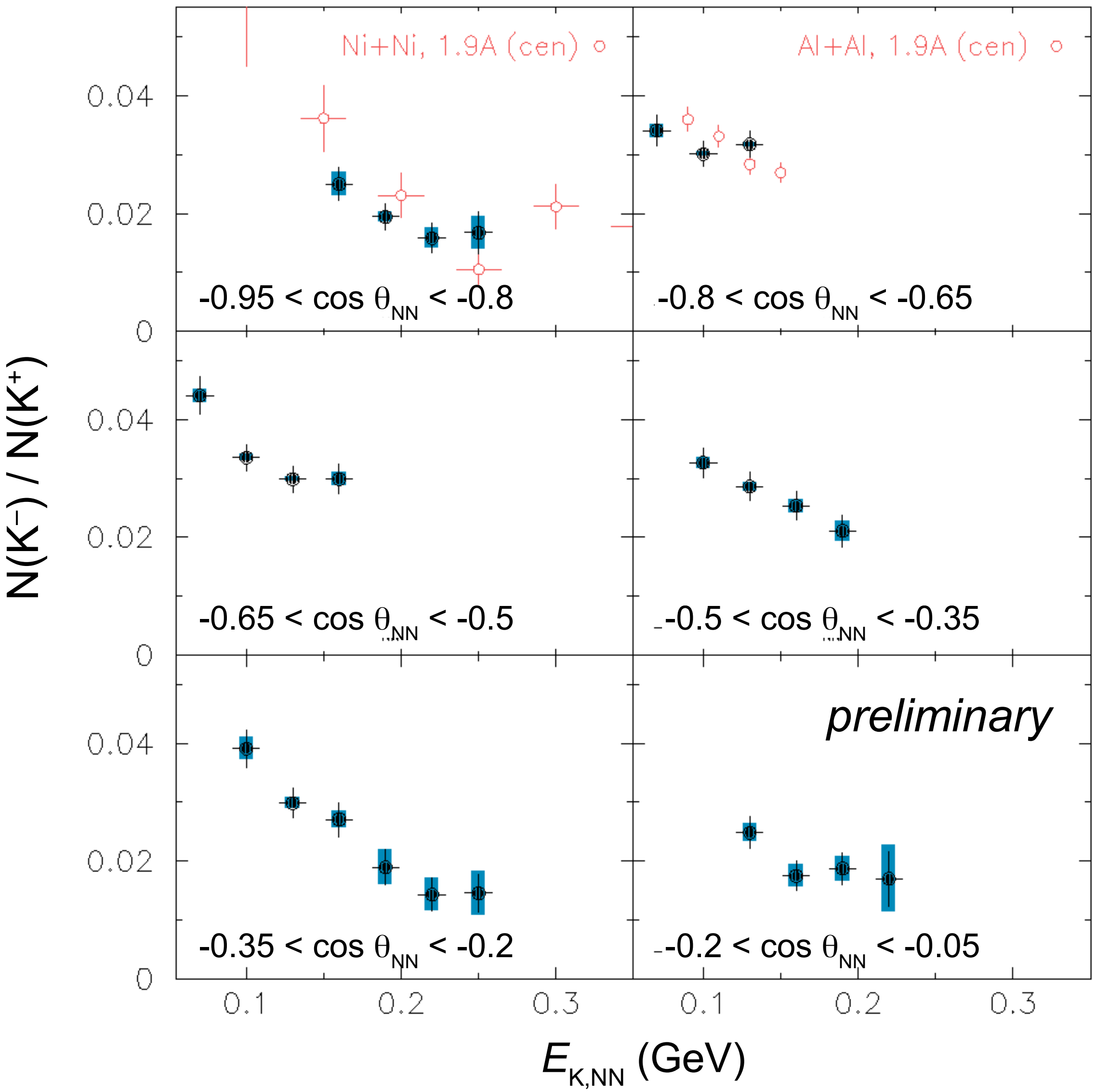


IQMD	solid	U_{K+N} = +20 MeV, $U_{K–N}$ = -45 MeV
	dashed	0 MeV
HSD	solid	U_{K+N} = +20 MeV, $U_{K–N}$ = -50 MeV
	dashed	0 MeV

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

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

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



New data (full dots) :

- wide phase space coverage
- more statistics

To be compared with Transport Models

For Al+Al @ 1.9*A* GeV, see:
P. Gasik et al (FOPI), EPJ A 52, 177 (2016)

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%,

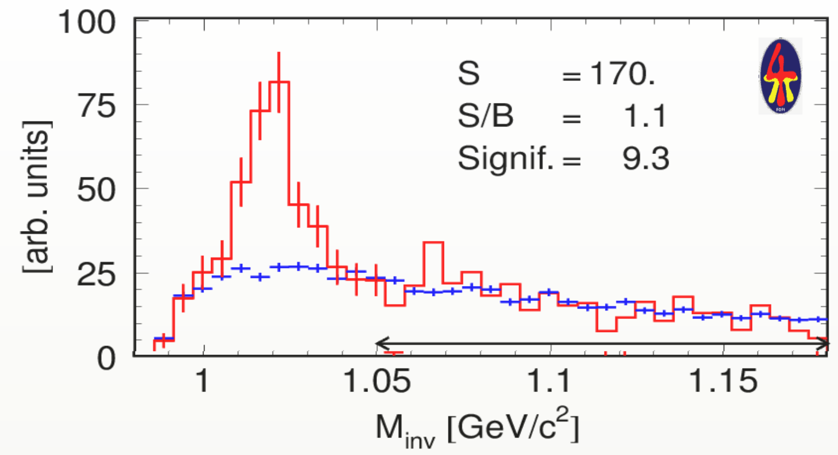
  - About 18% K^- originates from ϕ meson decays, occuring mostly outside medium.

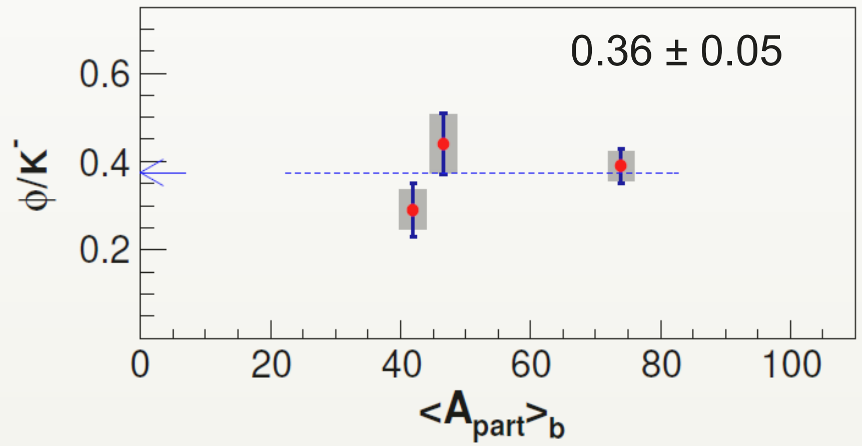
- Energy spectra of ϕ mesons reconstructed and fitted in 2 cases.

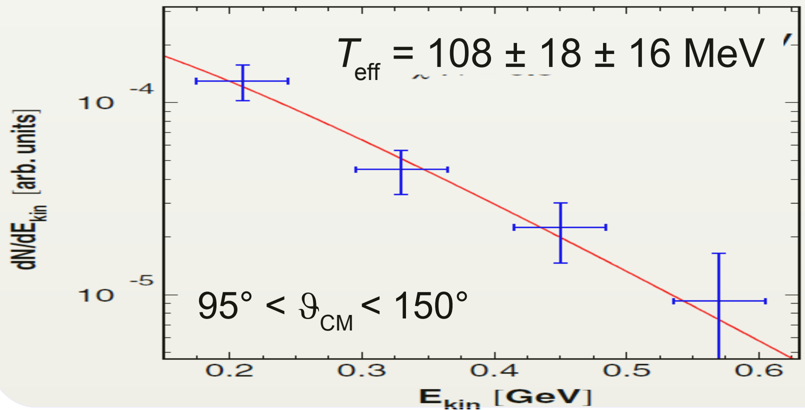
  K^- from ϕ meson decays: „colder" than these emitted directly from collision zone.

- No data on θ anisotropy (low statistics)

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





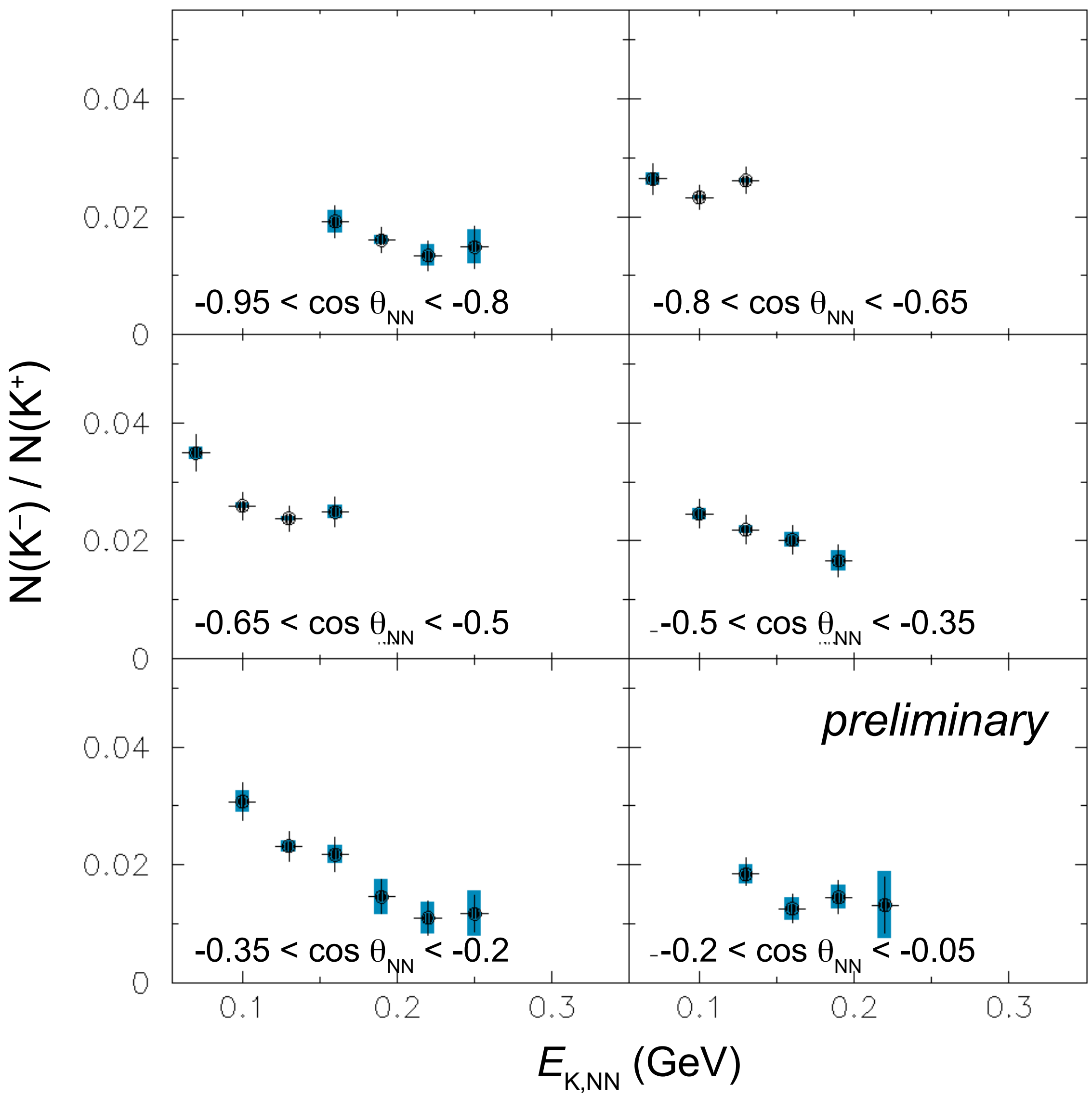


KP et al., PRC 91, 054904 (2015)

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

Phase space distribution of K^-/K^+ without ϕ component

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



$$K^-_{Total} = K^-_{Direct} + K^-_{From\ \phi}$$

$$K^-_{Direct} = K^-_{Total} - K^-_{From\ \phi}$$

To be compared with Transport Models in case if ϕ emission is not well reproduced.

Summary

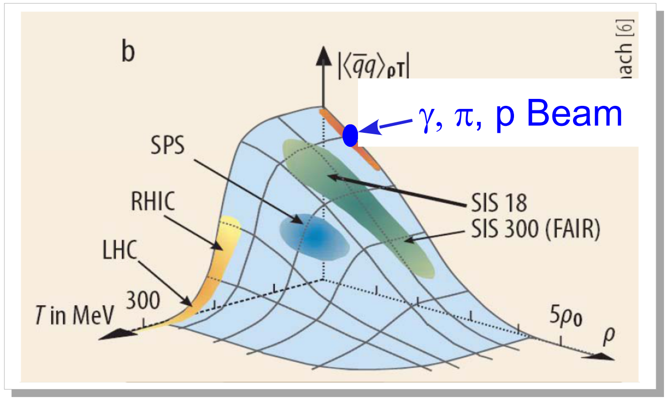
Within last decade a new generation of $K^{+,-}$ measurements was performed thanks to the installation of high resolution ToF detector.

- 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

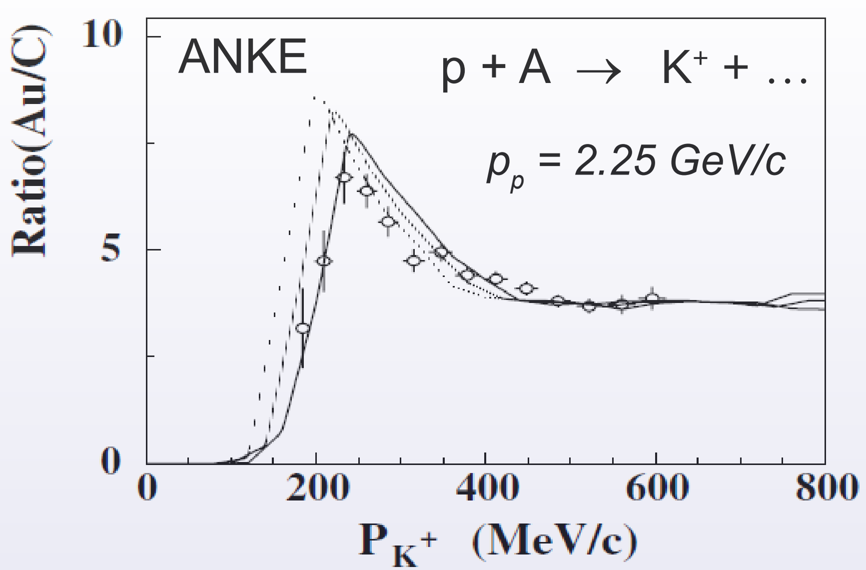
In-medium modifications of $K^{+/0}$ at $\rho < \rho_0$



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

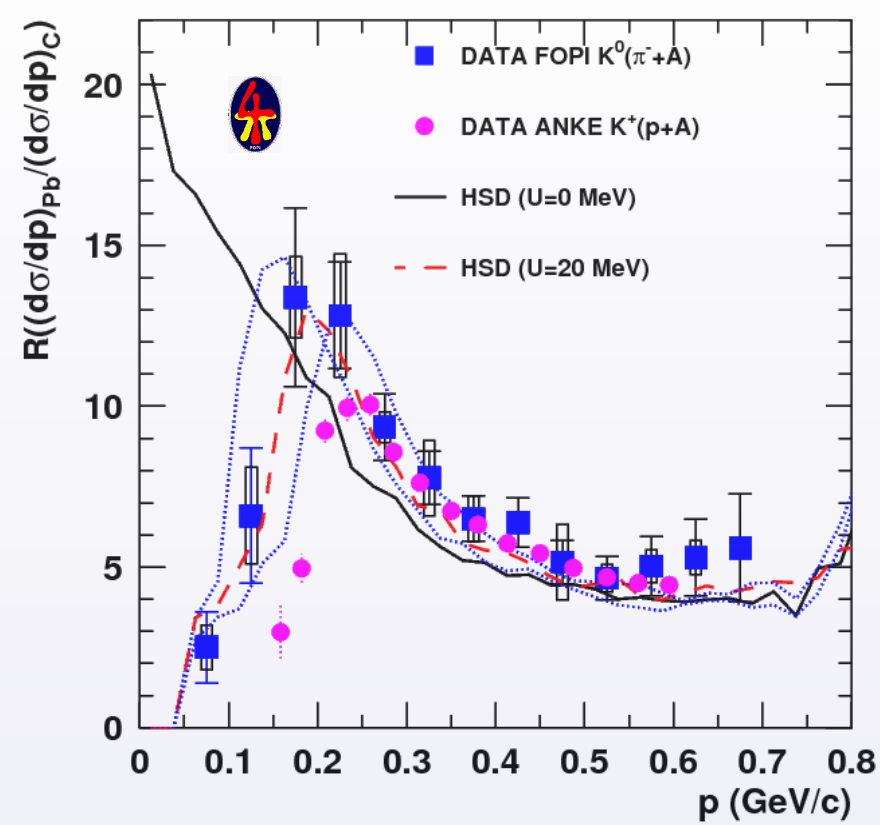
π^- (p=1.15 GeV/c) + A → K^0 + … *FOPI*

p (p=2.25 GeV/c) + A → K^+ + … *ANKE*



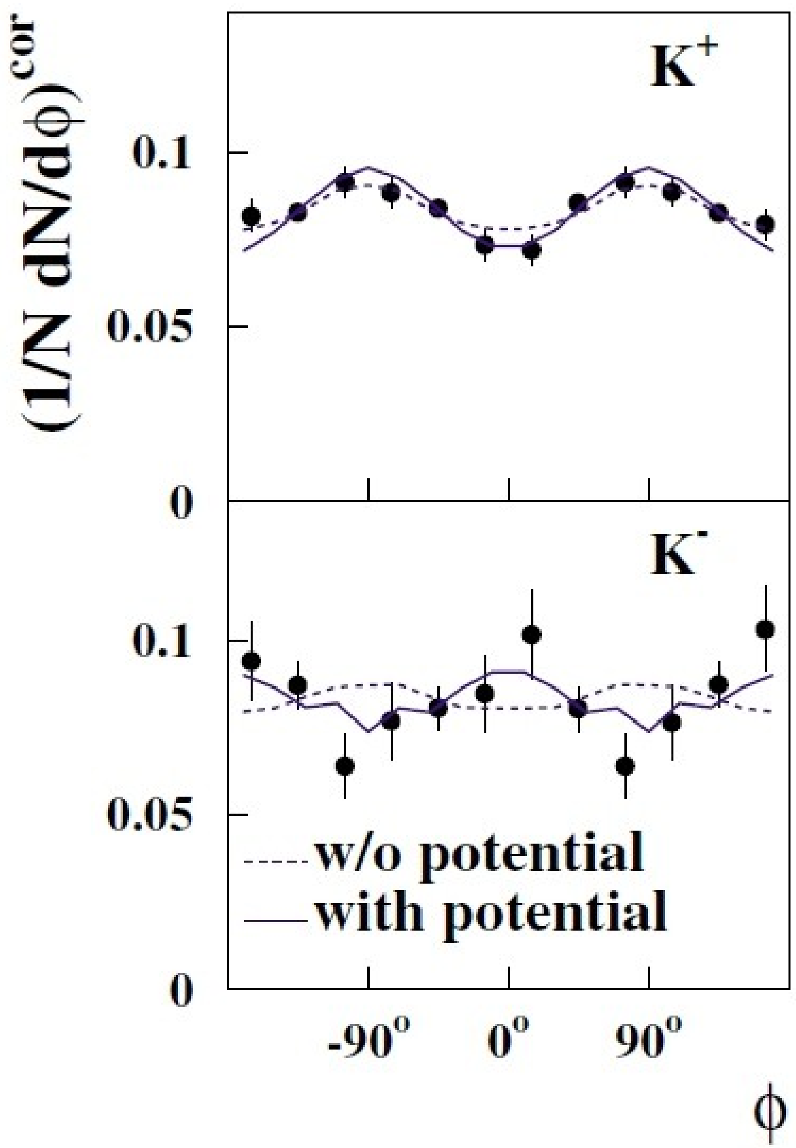
Z. Rudy et al., EPJA 23, 379 (2005)

CBUU transport code	· · · ·	V_{KN} = 0 MeV
	·········	V_{KN} = 10 MeV
	———	V_{KN} = 20 MeV



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

F. Uhlig et al. (KaoS), Phys. Rev. Lett. 95, 012301 (2005)



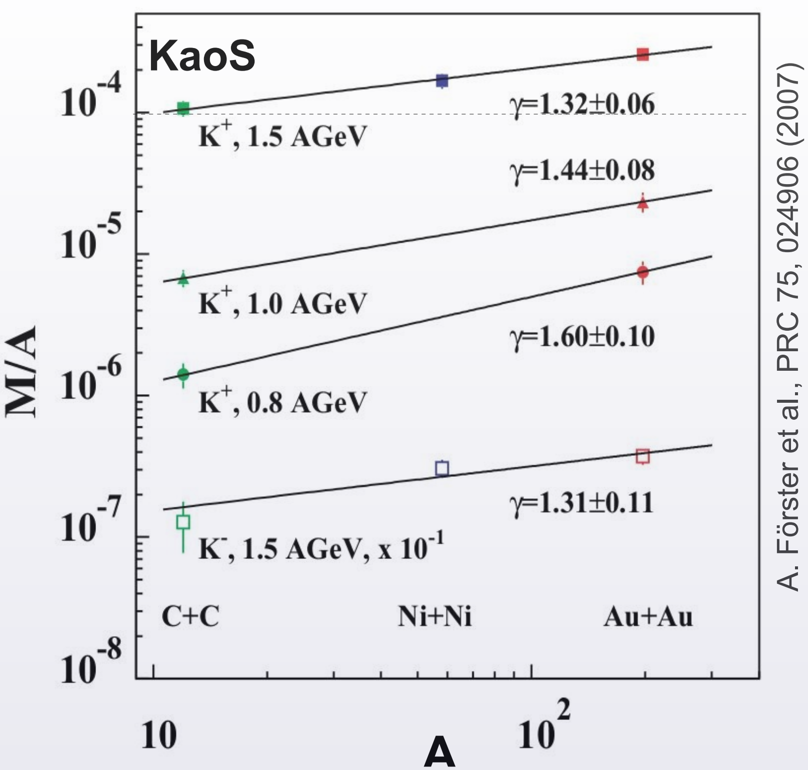
Production of Kaons in AA: Primary or secondary?

If primary:

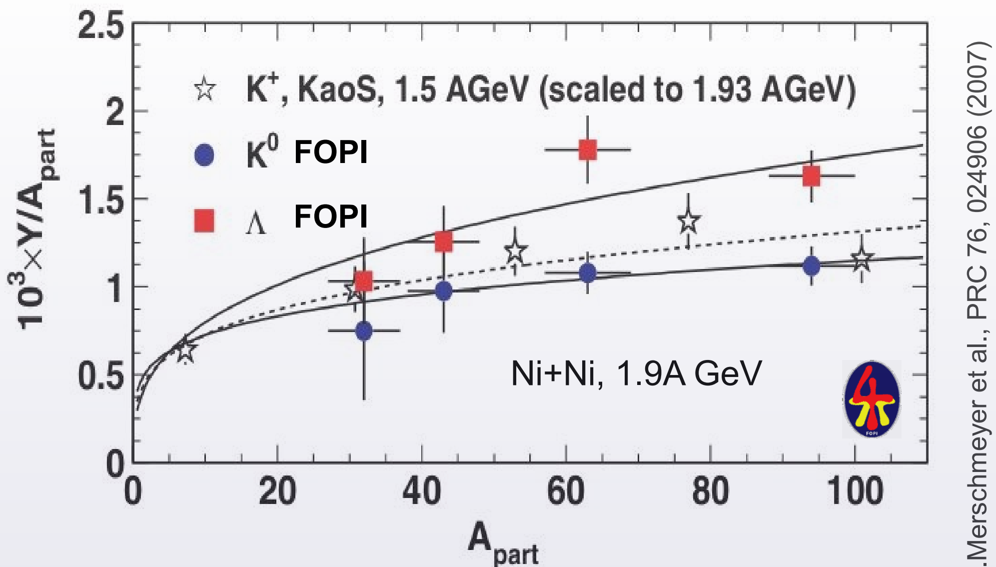
For pA → KX: $MUL_K = \frac{\sigma_K}{\sigma_{inelastic}} = const$

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:

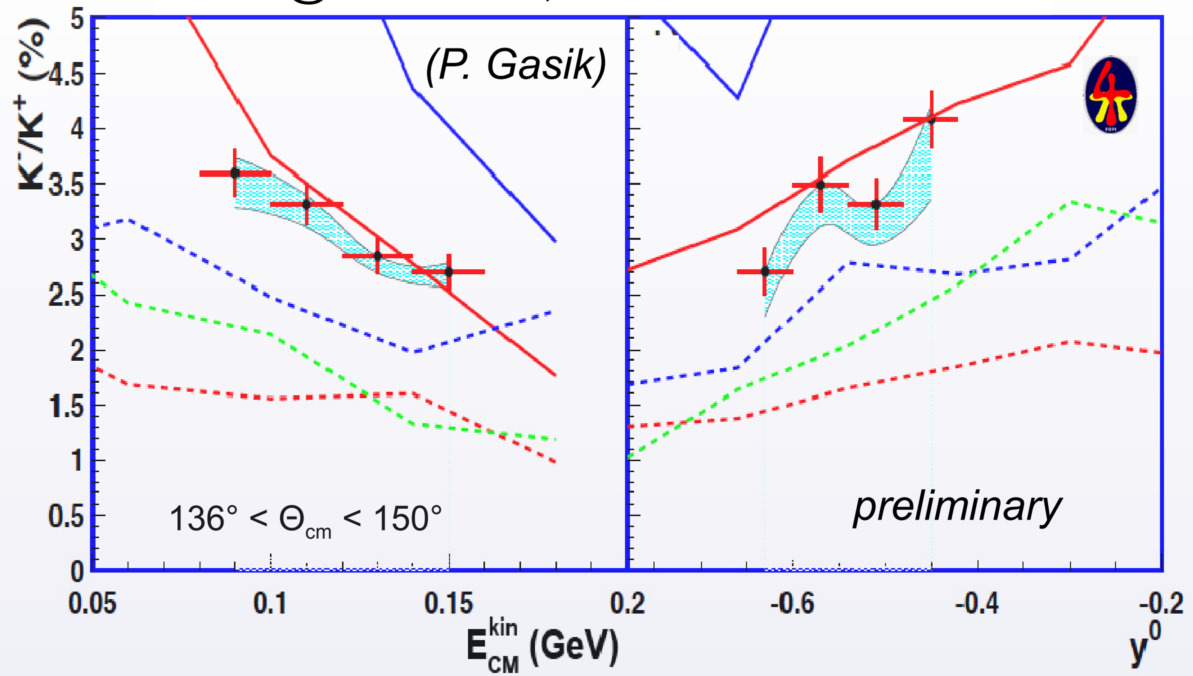
- $N_{beam} + N_{target}$, N_{target} has Fermi motion
- predominantly via ΔN , ΔΔ → $K^{+,0}$ Y B
  πN , πΔ → $K^{+,0}$ Y
  Y = [Λ,Σ]
- U_{KN} involved (increases K mass → lower yields)

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 $\rho=\rho_0$
    Δm_{K+} = 40 MeV, Δm_{K-} = −100 MeV

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



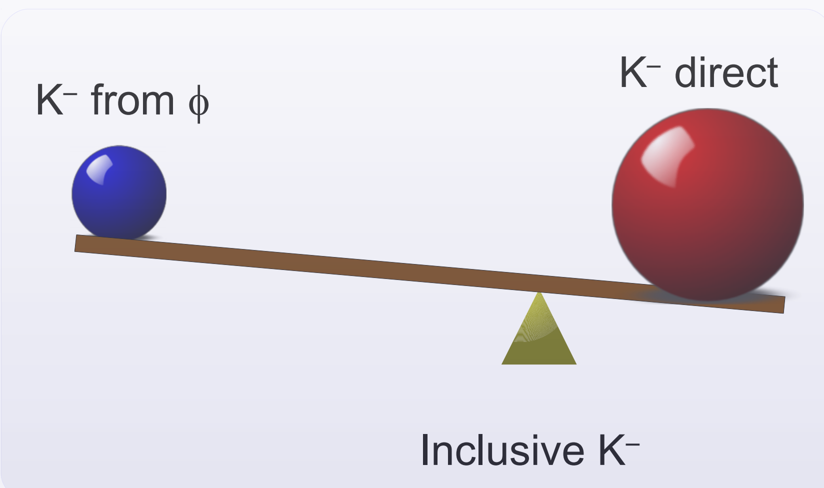
IQMD, NO Pot.
HSD , NO Pot.
HSD, U_{K+}=40 MeV, K- Not Modified
HSD, U_{K+}=40 MeV, U_{K-}= G-Matrix
IQMD, U_{K+}=40 MeV, U_{K-}=-100 MeV

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

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

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

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



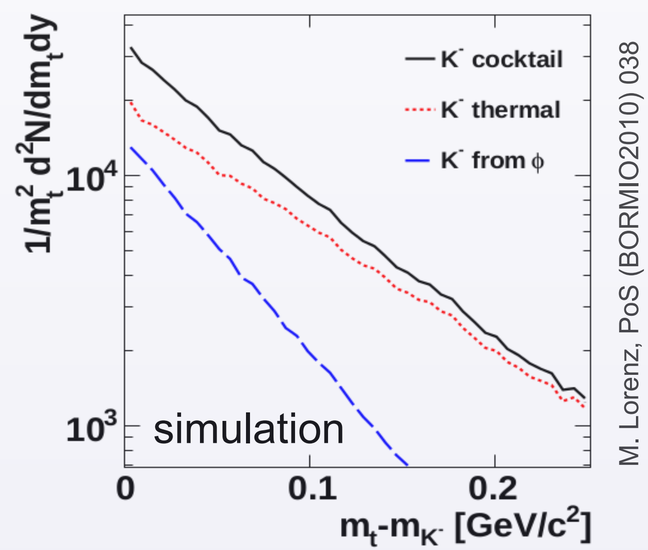
- Ar+KCl @ 1.76A GeV (HADES)

Experiment :

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

Conjecture :

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

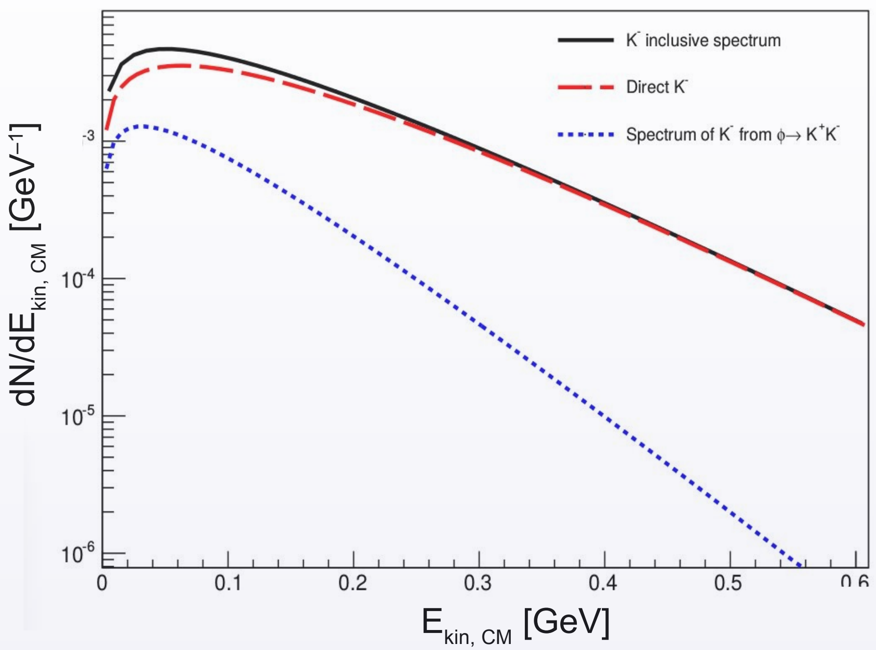


ϕ admixture reduces T(K^-) from 89 MeV to 74 MeV

- 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

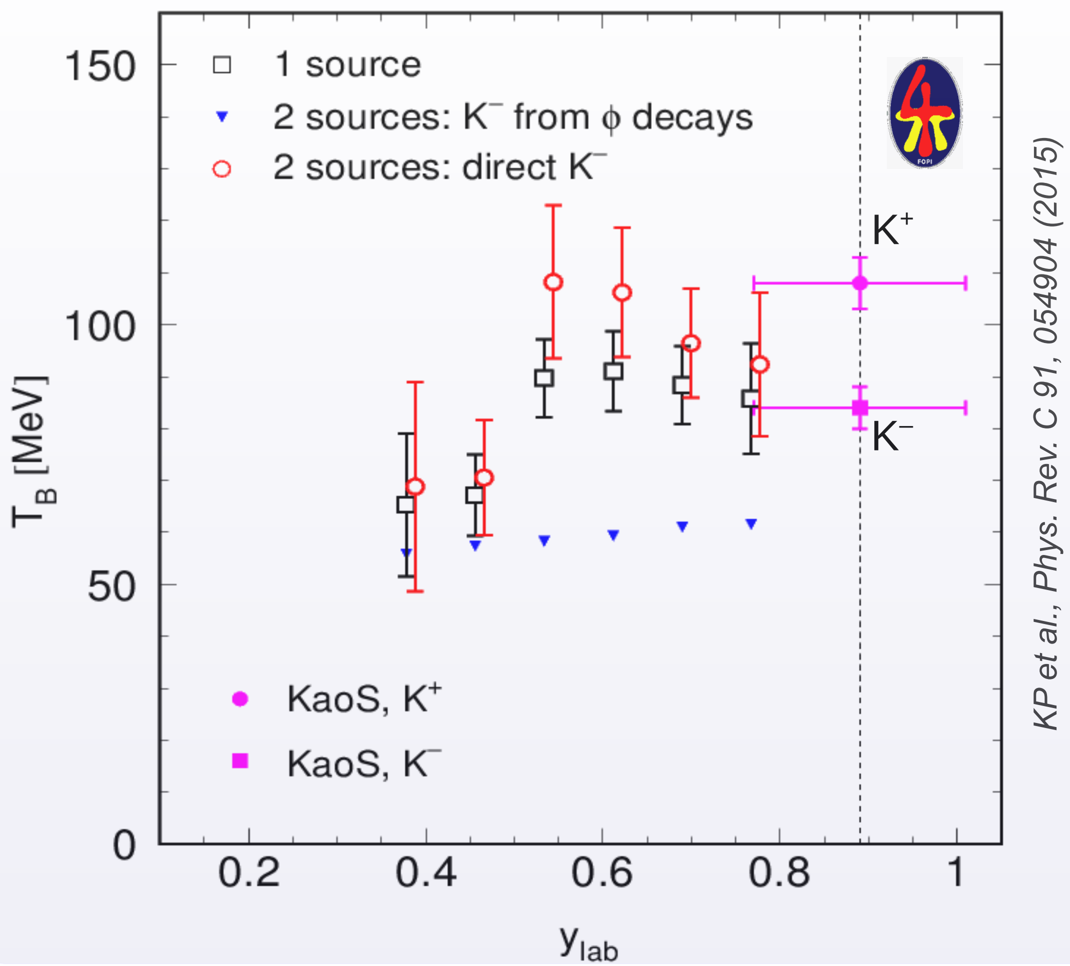
T (K⁻ direct) = 92 ± 16 MeV

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

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

Experiment :

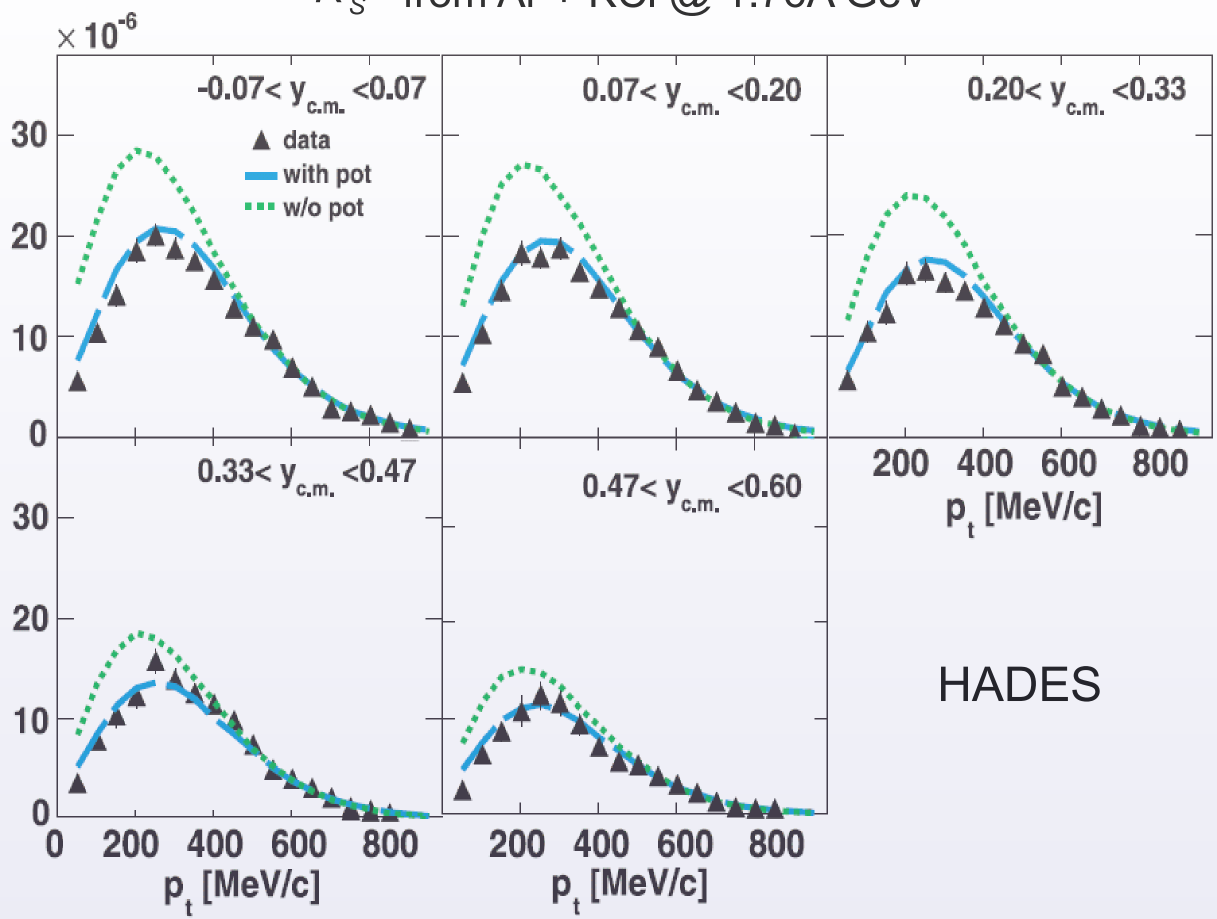
Particle	T_{eff}
K^-	84 ± 4
K^+	108 ± 5
ϕ	$106 \pm 18 \pm 16$



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

Modifications of K^0 in AA collisions

K_S^0 from Ar + KCl @ 1.76A GeV



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

K_S^0 cτ = 2.7 cm

K_L^0 cτ = 15.3 m

IQMD transport calc. :

No potential

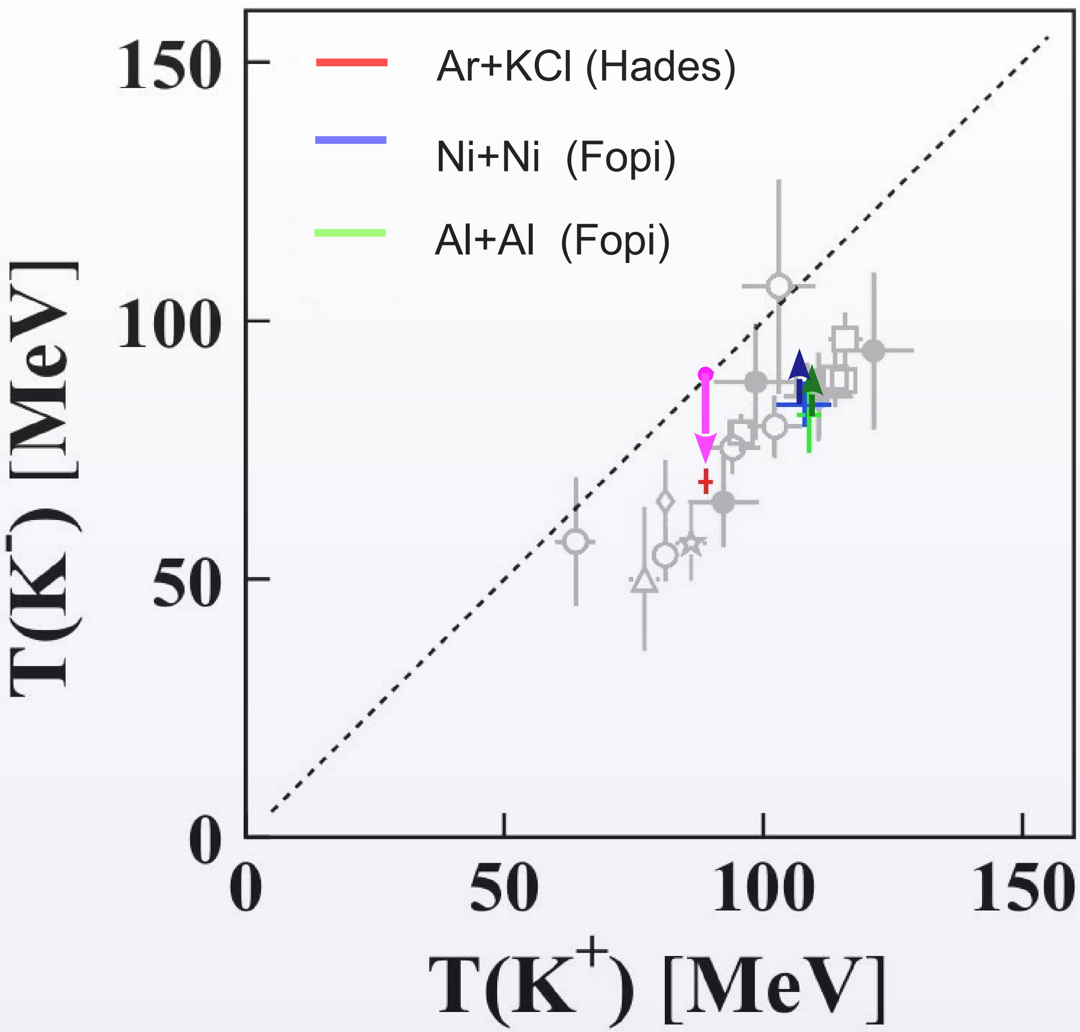
U_{K0N} = 46 MeV

→ U_{KN} at $\rho \sim 2\,\rho_0$

seems to be stronger than for

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

Effect of ϕ decays on K^- slopes

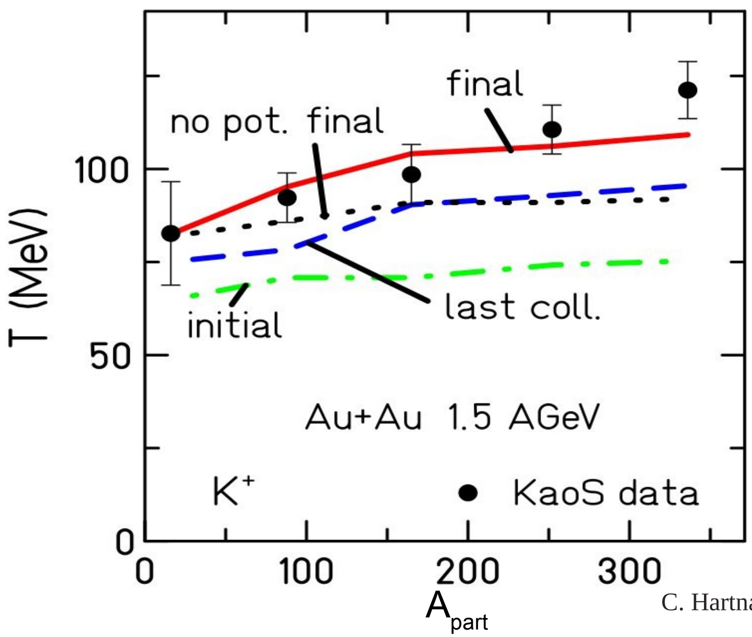


Previously:

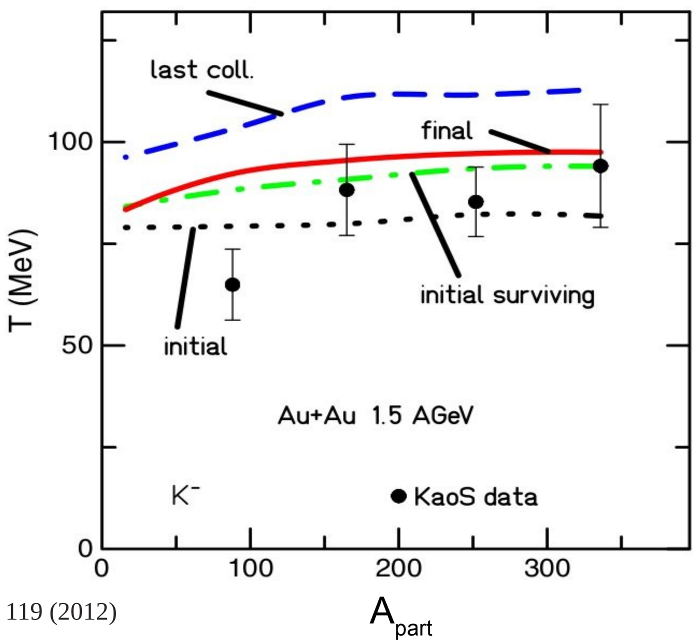
Difference of K^+,K^- slopes explained by U_{KN} potentials

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

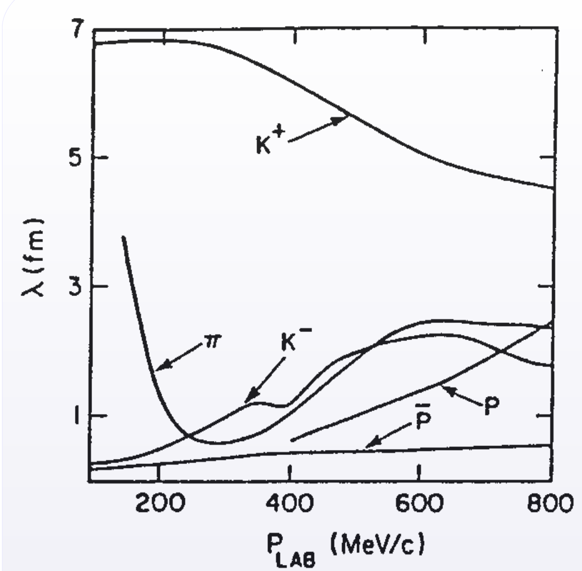
	K^+	K^-	ϕ
Production (primary)	BB → BYK$^+$ $T_{pp \to p\Lambda K+}$ = 1.58 GeV	BB → BBK$^+$K$^-$ $T_{pp \to ppK+K-}$ = 2.5 GeV	BB → BBϕ $T_{pp \to ppK+K-}$ = 2.6 GeV
Production (secondary)	πB → YK$^+$	πY → (Σ^* →) BK$^-$ BY → NK$^-\Lambda$ BY → BBK$^-$ πB → BK$^+$K$^-$ ϕ → K$^+$K$^-$	πB → Bϕ ρB → Bϕ πN* → Nϕ $\rho\pi$ → ϕ *K$^+$K$^-$ → ϕ negligible*
Absorption	K$^+$Y → πB	K$^-$B → πY	ϕN → KΛ
Elastic scat. (char. exch.)	K$^+$B ↔ K$^+$ B K$^+$n ↔ K^0 p	K$^-$B ↔ K$^-$B K$^-$p ↔ $\bar{K}^0$n	ϕN → ϕN

[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}
π + ρ	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:

$BB \rightarrow \phi$, $B = \{N, \Delta\}$

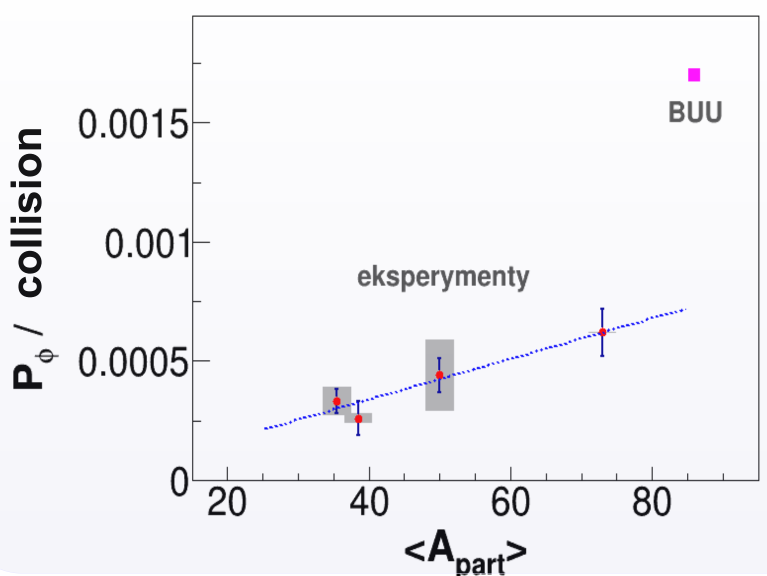
$\mu B \rightarrow \phi$, $\mu = \{\pi, \rho\}$

$\pi\rho \rightarrow \phi$

$K^+K^- \rightarrow \phi$ negligible

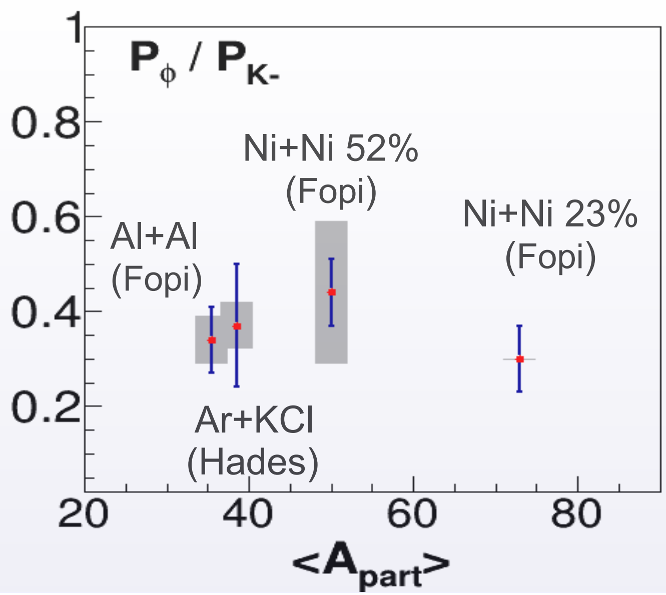
Yields from	Ni + Ni (1.93 GeV)
B + B	3.5×10^{-4}
π + B	2.9×10^{-4}
ρ + B	8.9×10^{-4}
$\pi + \rho$	1.6×10^{-4}
π + N(1520)	0.5×10^{-4}
Total yield	1.7×10^{-3}

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



BUU:

ϕ yield overestimated



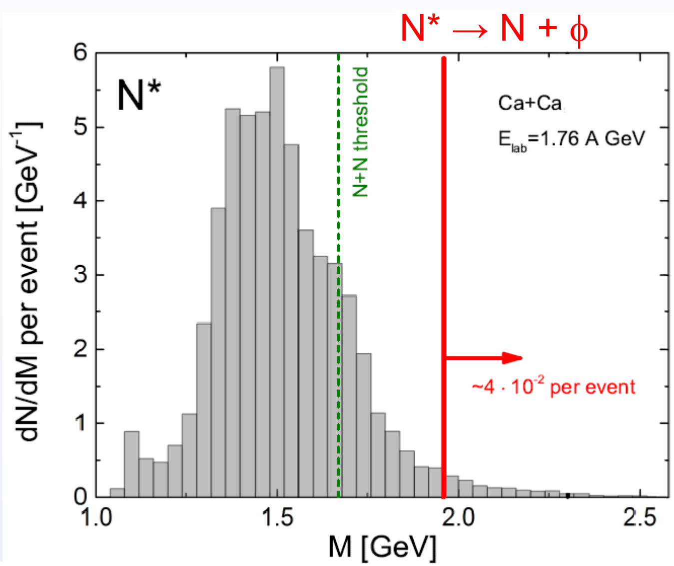
- $c\tau$ = 50 fm

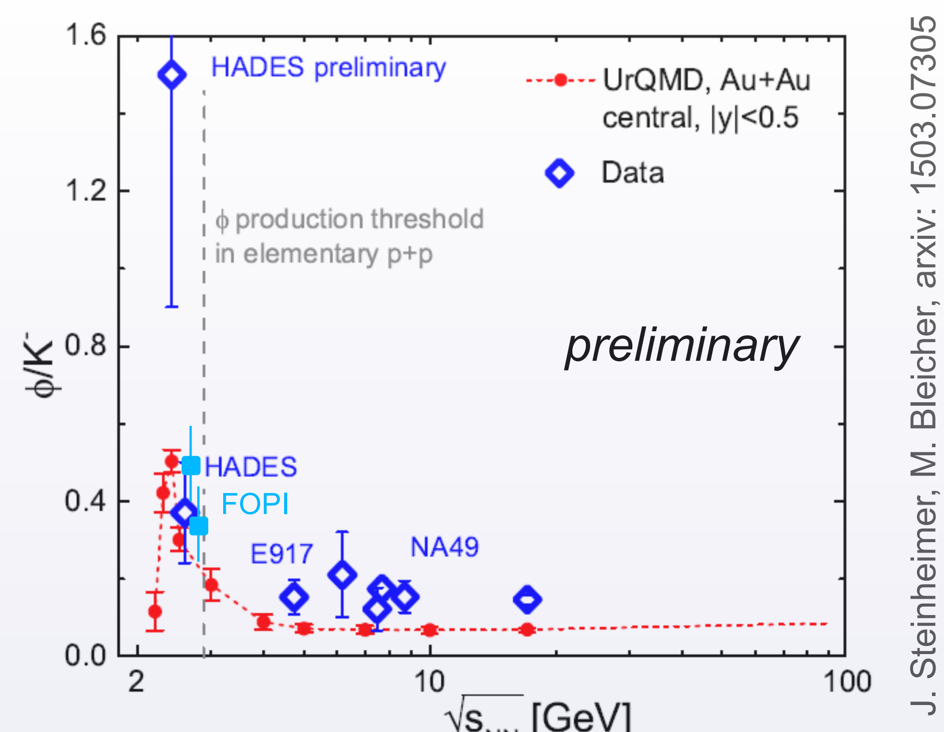
  $\phi \rightarrow K^+K^-$ (BR ~ 50%)

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

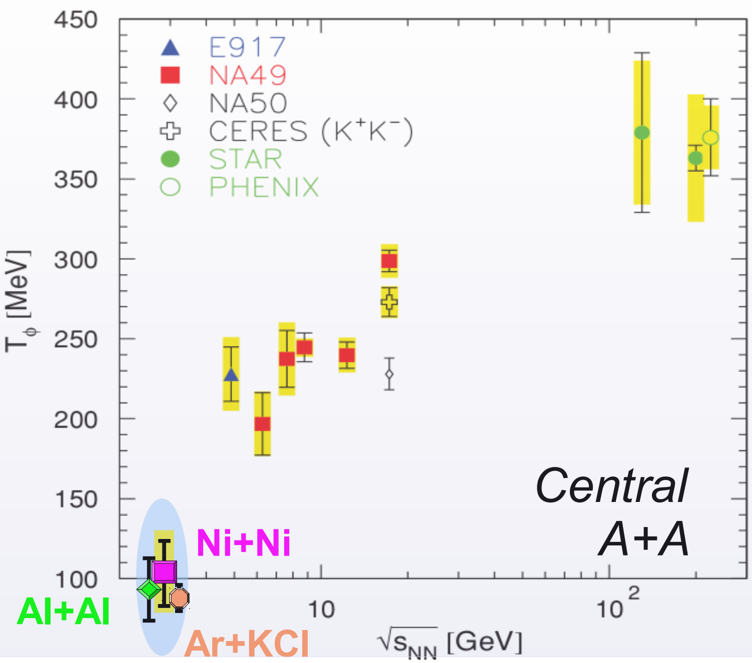
- **UrQMD** model

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





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)

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

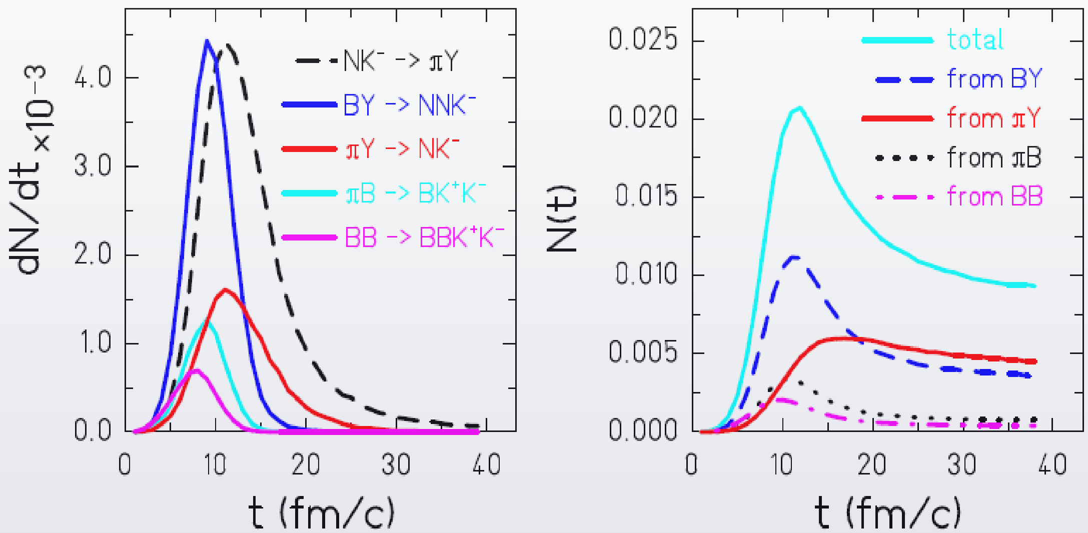
  $BY \rightarrow NNK^-$, $\pi Y \rightarrow K^- B$

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

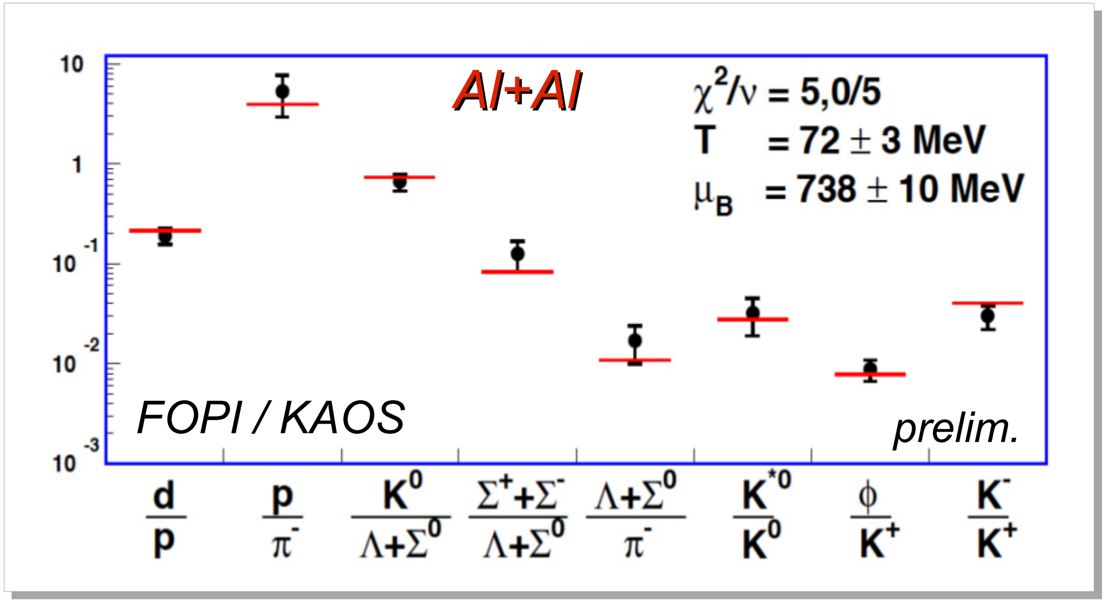
$$\pi + Y \rightarrow \begin{matrix} \Sigma^* \\ \Lambda^* \end{matrix} \rightarrow K^- + B$$

Q: Can we see them?

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



- **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

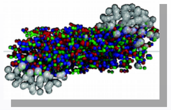
→ Grand Canonical ensemble;

→ For S≠0, Canonical ensemble

→ calc: THERMUS code

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

→ *SM* fitting quite well



UrQMD v 2.3

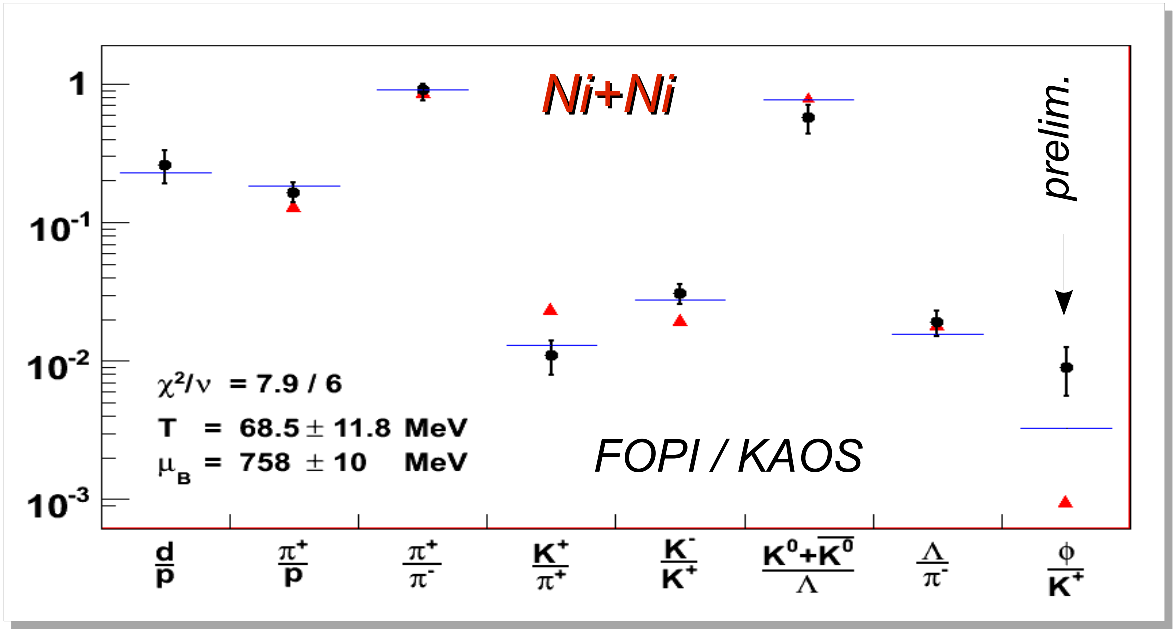
→ No equilibration assumed

→ Cascade model – no mean field

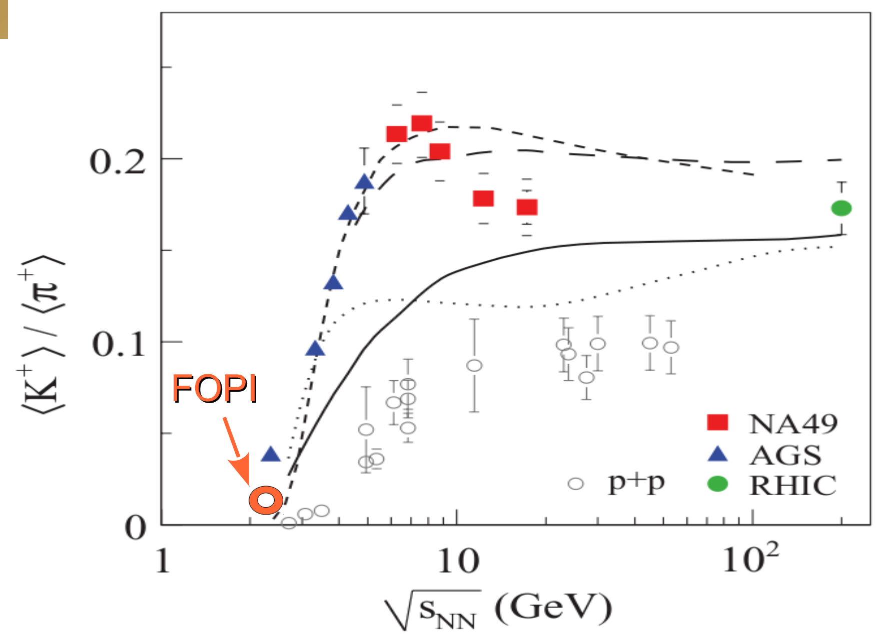
– no in-medium effects

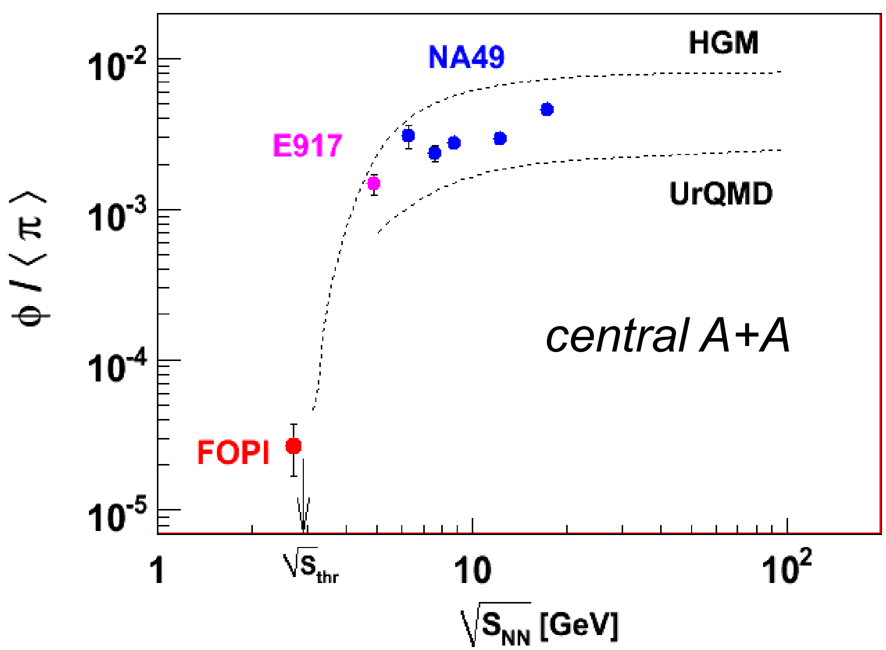
→ *J. Phys. G: Nucl. Part. Phys. 25 (1999) 1859*

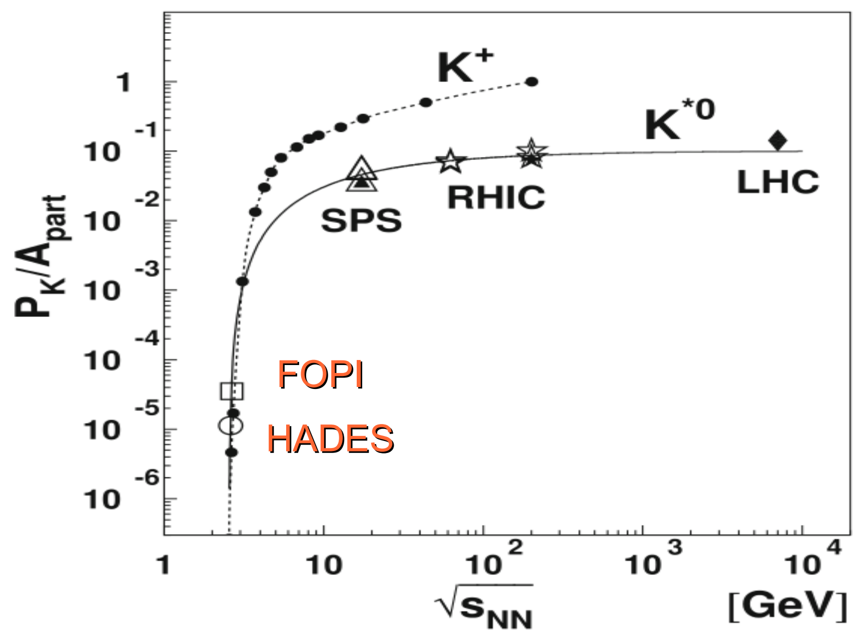
→ *UrQMD* fits quite well too



Strange meson excitation functions near threshold



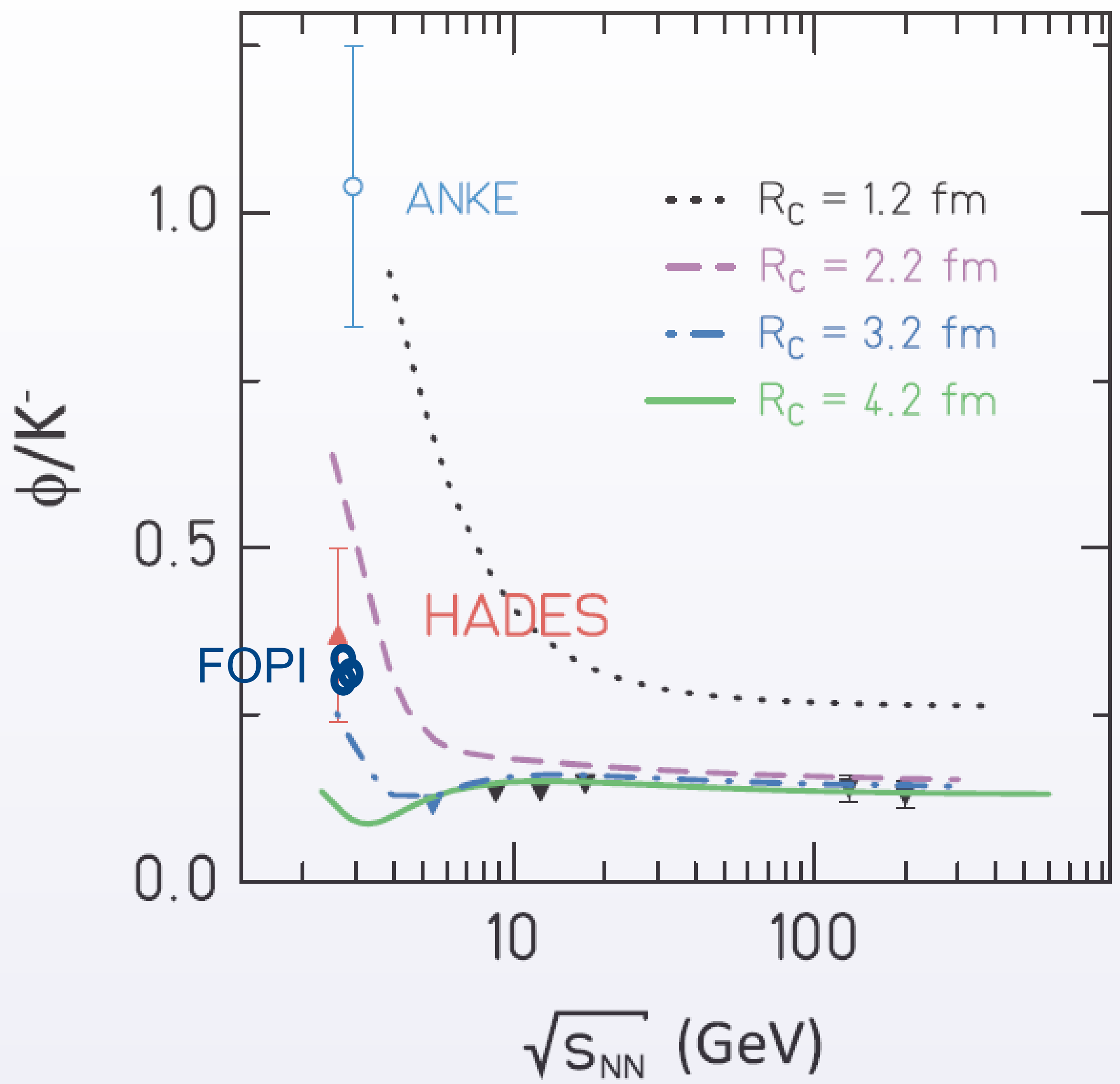




C. Alt et al. (NA49), Phys. Rev. C **78**, 044907 (2008)
B. Back et al. (E917), Phys. Rev. C **69**, 054901 (2004)

G. Agakishiev et al., Eur. Phys. J. A (2013) 49: 34

ϕ/K^- within the statistical model approach



J. Cleymans et al. PLB **603**, 146 (2004)

G. Agakishiev et al., PRC 80, 025209 (2009)