FOPI

FOPI

Production of $K^{\pm}$ and ϕ mesons at 1.9A GeV with FOPI

Krzysztof Piasecki

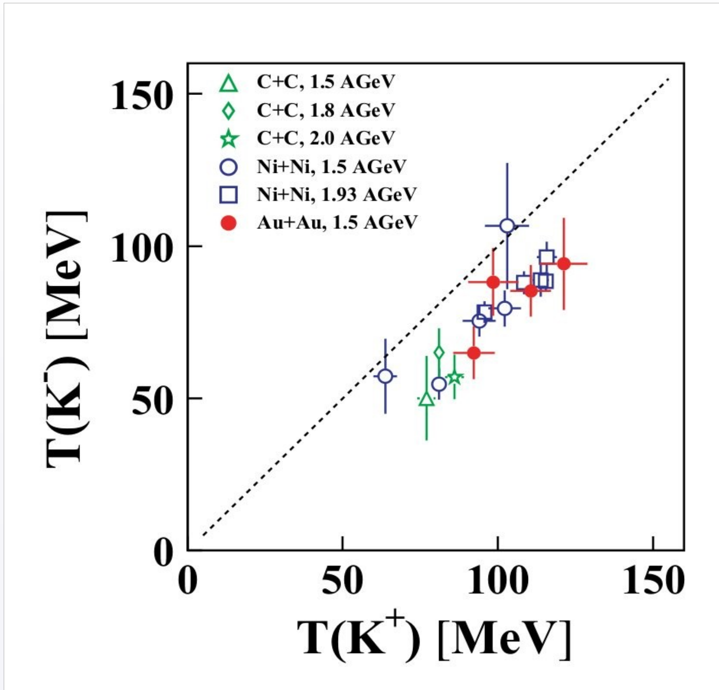
Institute of Experimental Physics, University of Warsaw, Poland

- Physics motivation
- $K^{+/-}$ phase space investigation
- In-medium modifications of $K^{+/-}$
- ϕ meson centrality study
- Influence of ϕ on K^-
- Summary and conclusions

FACULTY OF PHYSICS WARSAW UNIVERSITY

Kaon dynamics near threshold

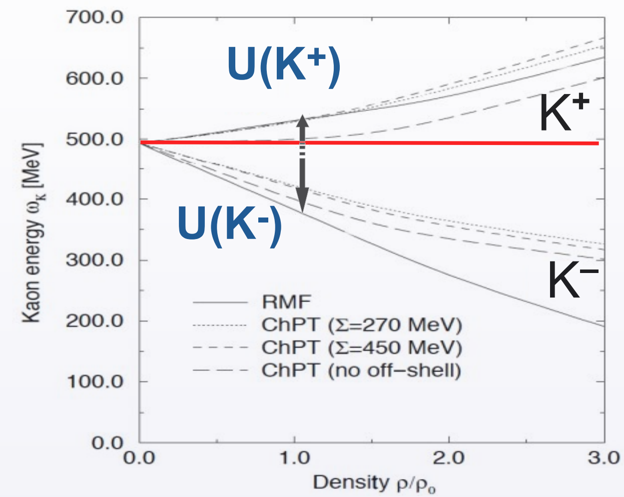
- $K^{+/-}$ production near threshold (1..2A GeV)



A. Foerster et al. (KaoS) PRC 75, 024906 (2007)

- Interplay between:
  - KN scattering
  - K^- absorption
  - In-medium effects

- In-medium modifications of $K^{+/-}$ mass

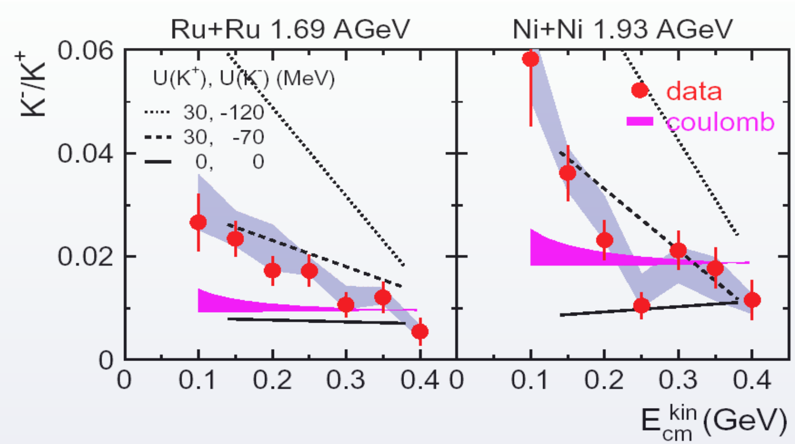


J. Schaffner-Bielich et al. NPA 625, 325 (1997)

- As K escapes the collision zone,

$m_{K-} \nearrow m_0 \rightarrow$ K^- reduces E_{kin}

$m_{K+} \searrow m_0 \rightarrow$ K^+ increases E_{kin}

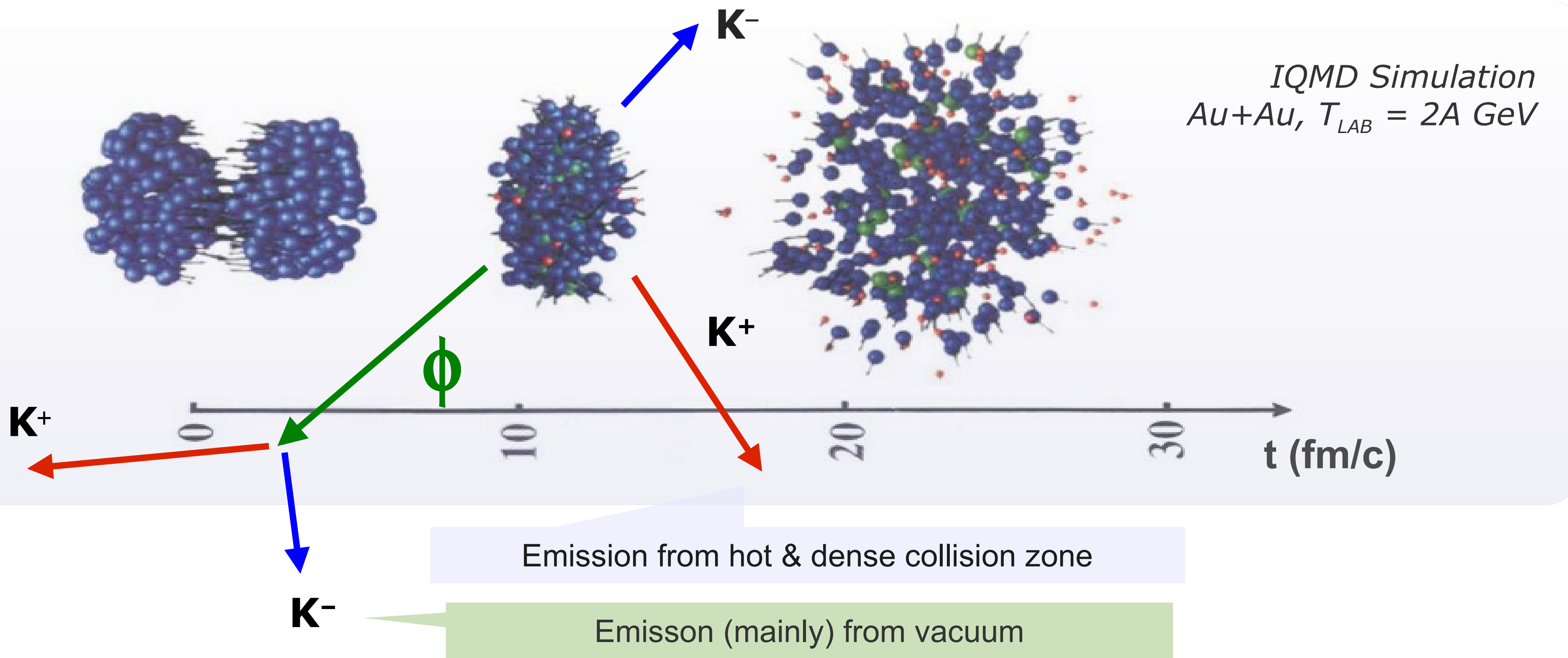


K. Wiśniewski et al., Eur. Phys. J. A 9, 515 (2000)

ϕ meson: a missing player

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

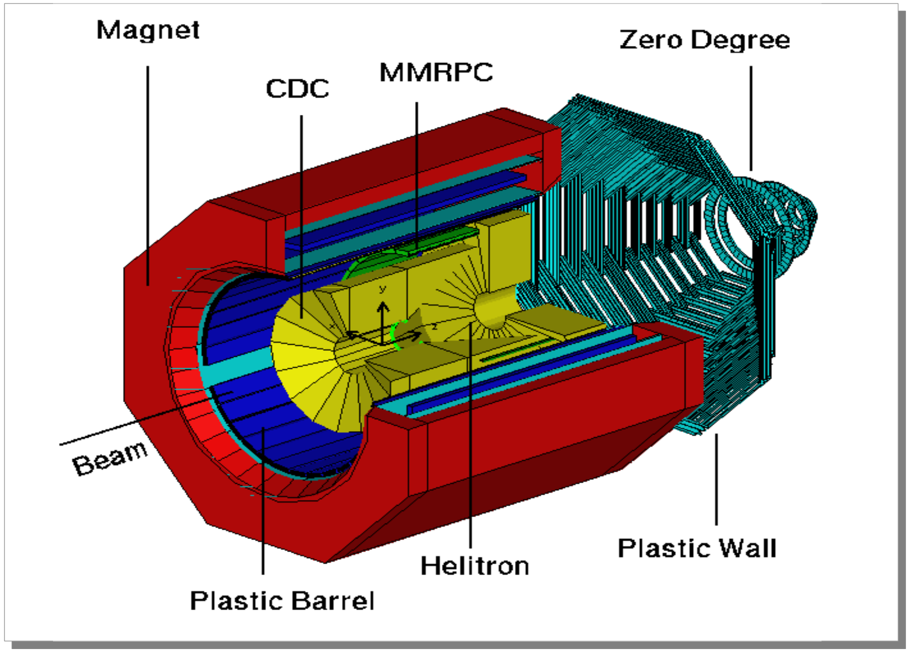
- $c\tau$ = 50 fm
- $\phi \rightarrow K^+K^-$ (BR ~ 50%)



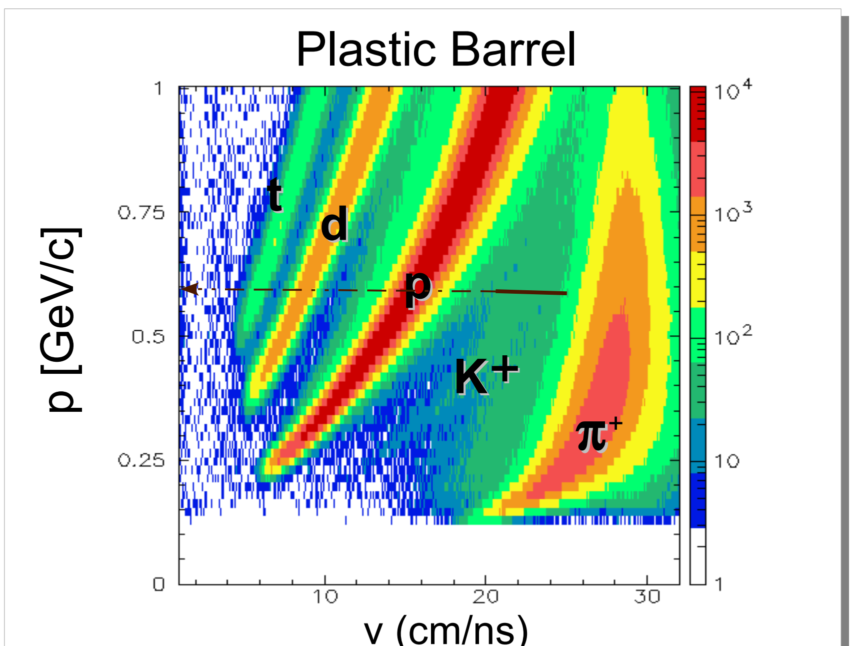
Q1: How strong is the $\phi \rightarrow K^+K^-$ contribution to K^-, K^+ yields ?

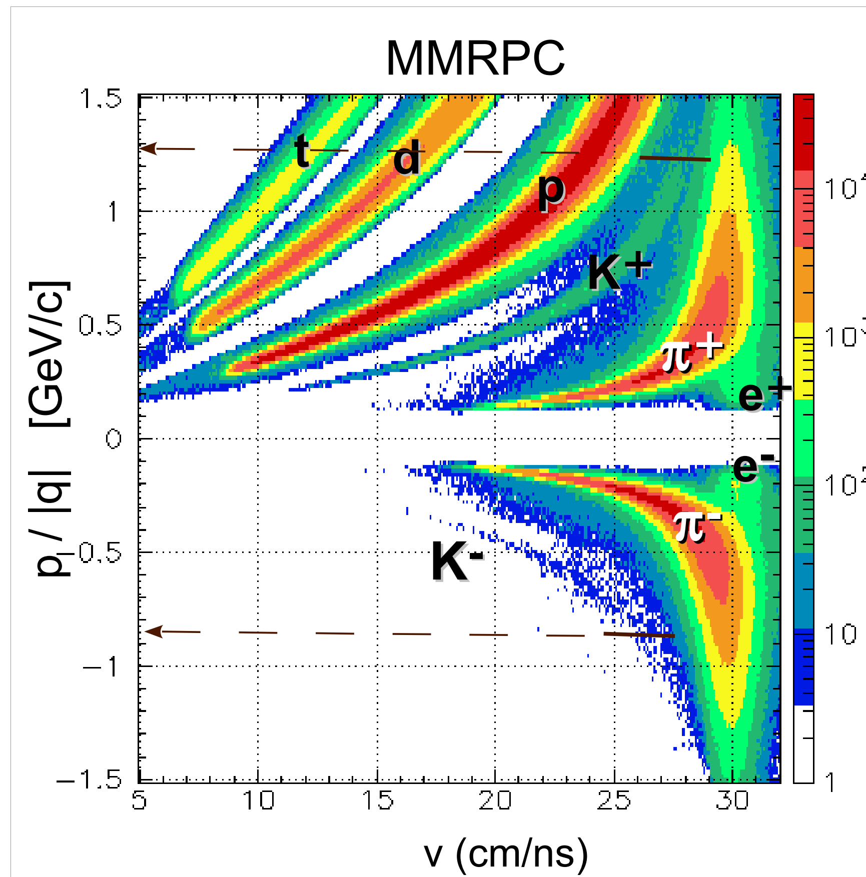
Q2: Can it modify the T (inverse slopes) of K^- / K^+ ?

FOPI experimental setup

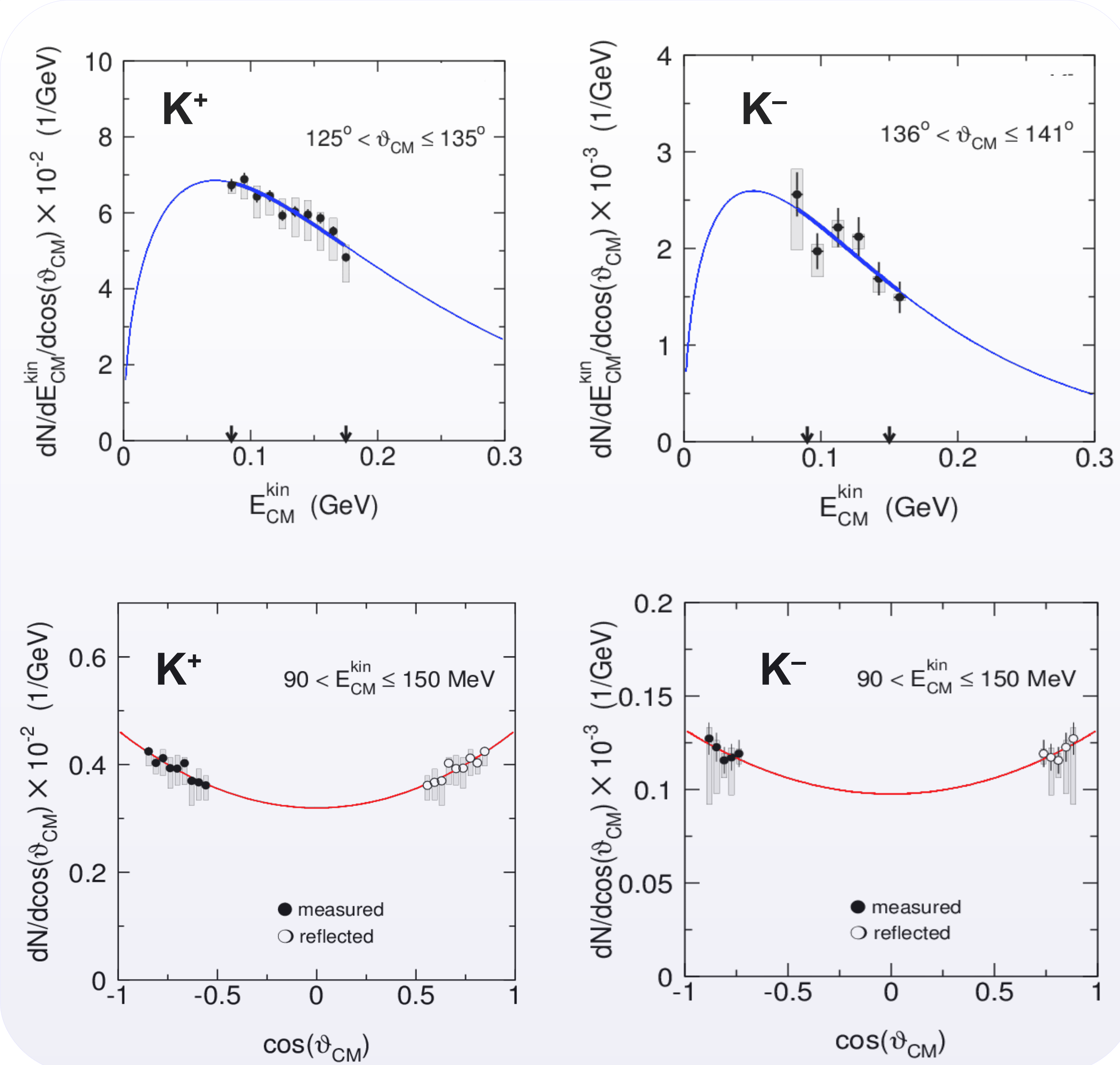


- Nearly 4π coverage
- Drift chambers: CDC, Helitron
  ToF : Plastic Barrel, RPC
  Forward: Plastic Wall, Zero Degree
- Direct PID of $\pi^{\pm}$, $K^{\pm}$, p, d, t, $^{3,4}He$





Phase space analysis of $K^{\pm}$ from central Al+Al @ 1.9A GeV



- Assumed distribution

$$\frac{d^2N}{dE^k\,d\theta} = N\cdot pEe^{-E/T}\cdot\left(1+a_2\cos^2\theta\right)$$

- Inverse slopes:

$$T(K^+) = 109 \pm 2\,^{+6}_{-13}\ \mathrm{MeV}$$
$$T(K^-) = 82 \pm 6\,^{+21}_{-6}\ \mathrm{MeV}$$

- Anisotropy of ϑ distribution

$$a_2(K^+) = 0.45 \pm 0.08\,^{+0.18}_{-0.11}$$
$$a_2(K^-) = 0.35 \pm 0.40\,^{+0.11}_{-0.83}$$

- Production yields:

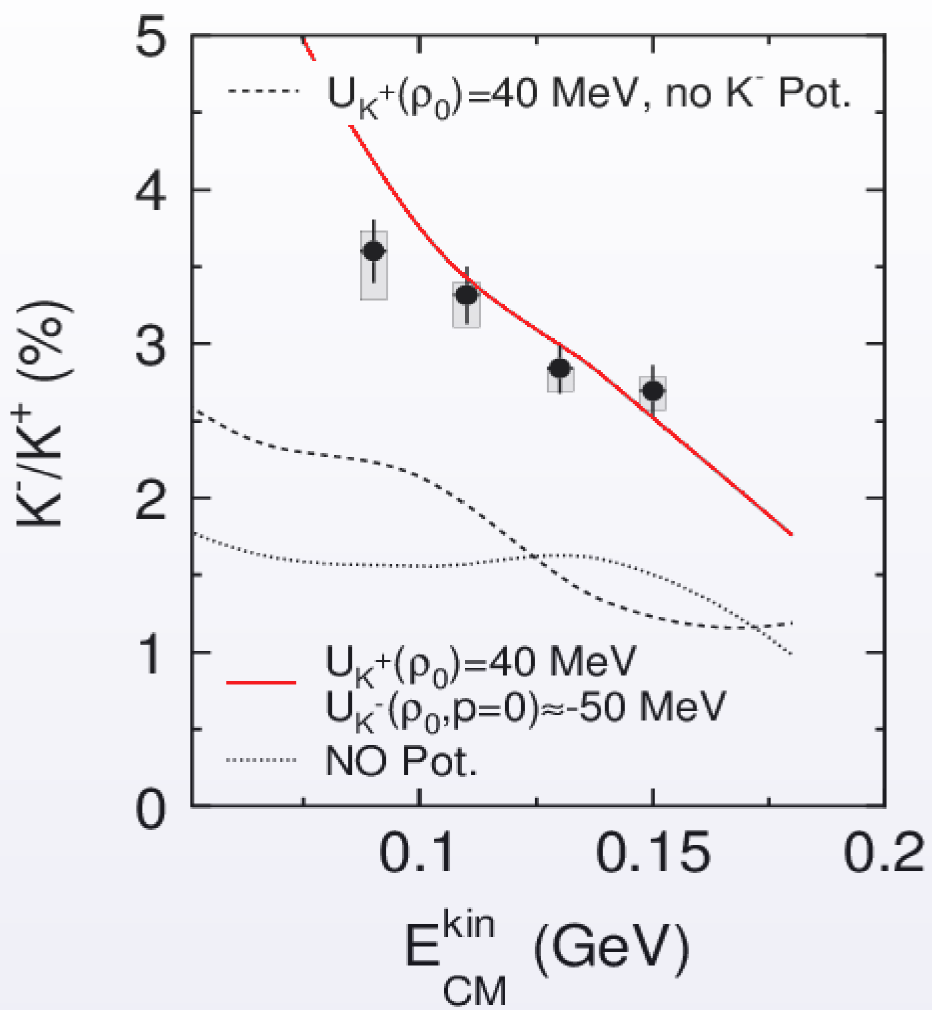
$$P(K^+) = \left[3.75 \pm 0.07\,^{+0.33}_{-0.64}\right] \times 10^{-2}$$
$$P(K^-) = \left[9.5 \pm 1.0\,^{+2.6}_{-0.1}\right] \times 10^{-4}$$

P. Gasik et al., arXiv: 1512.06988

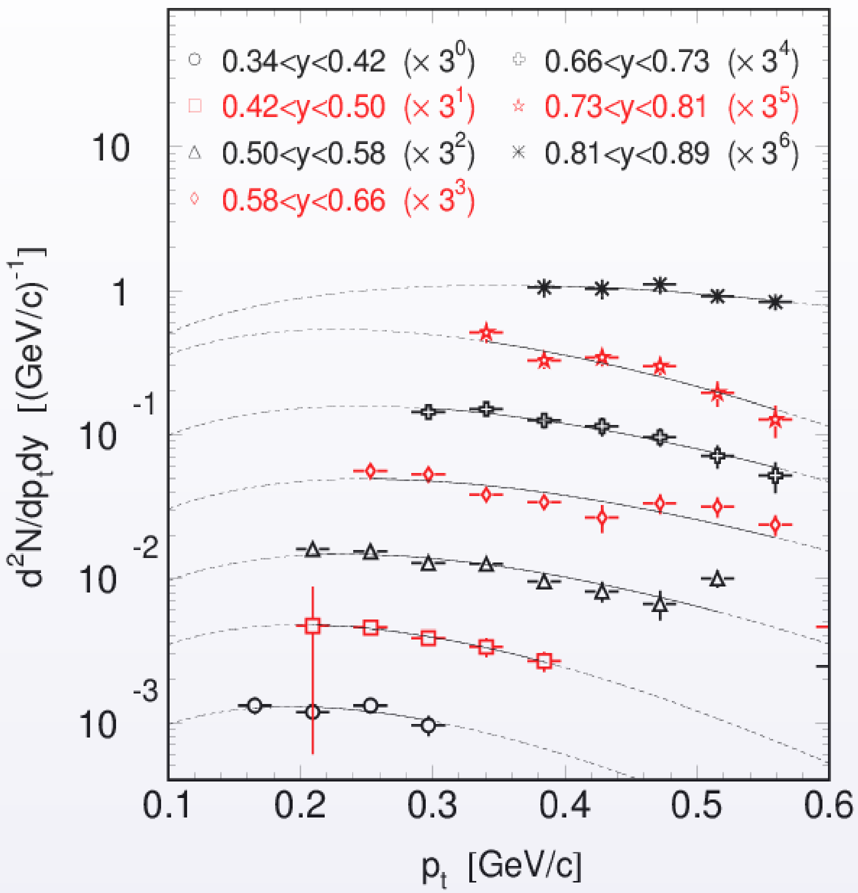
Experiment and HSD on the E_{kin} dependence of K^-/K^+

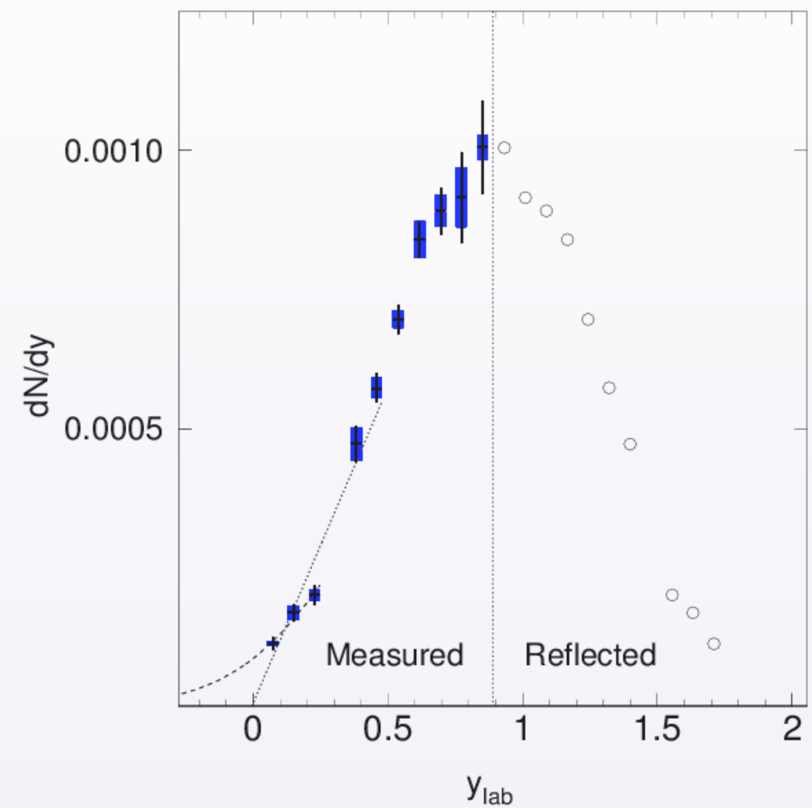
- Central Al+Al @ 1.9A GeV

P. Gasik et al., arXiv: 1512.06988



Phase space analysis of K⁻ from semi-central Ni+Ni @ 1.9A GeV



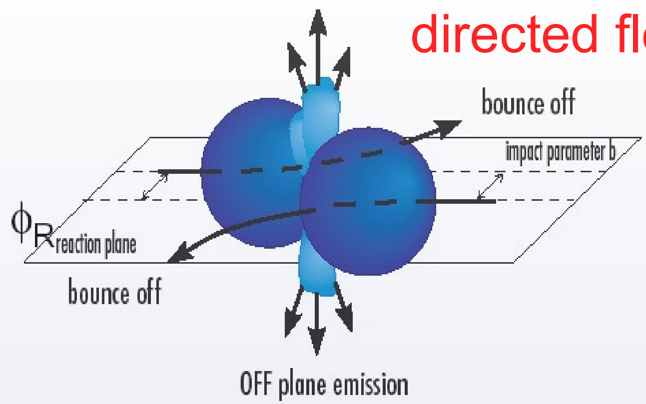


$$P(K^-) = [9.8 \pm 0.2 \pm 0.6] \times 10^{-4}$$

K. Piasecki et al., PRC 91, 054904 (2015)

Flow of K± from (semi-)central Ni+Ni @ 1.9A GeV

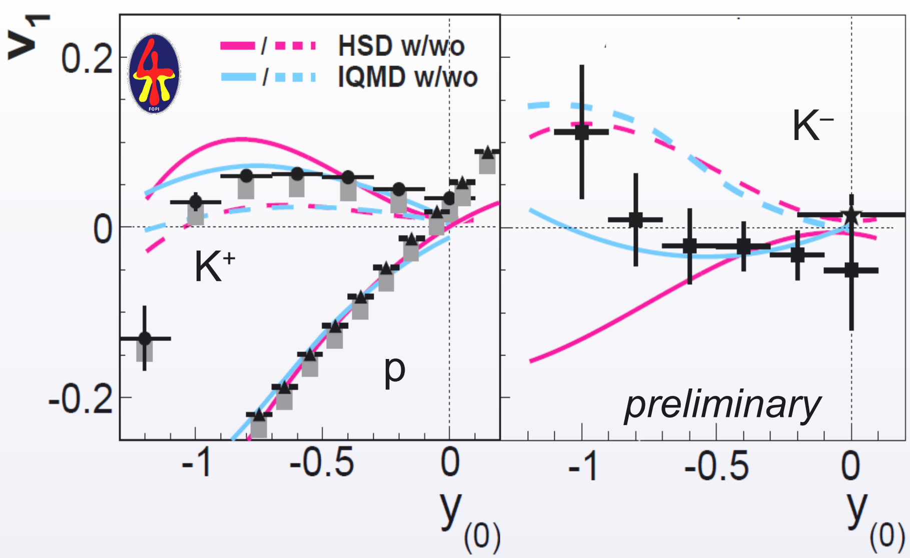
directed flow v_1

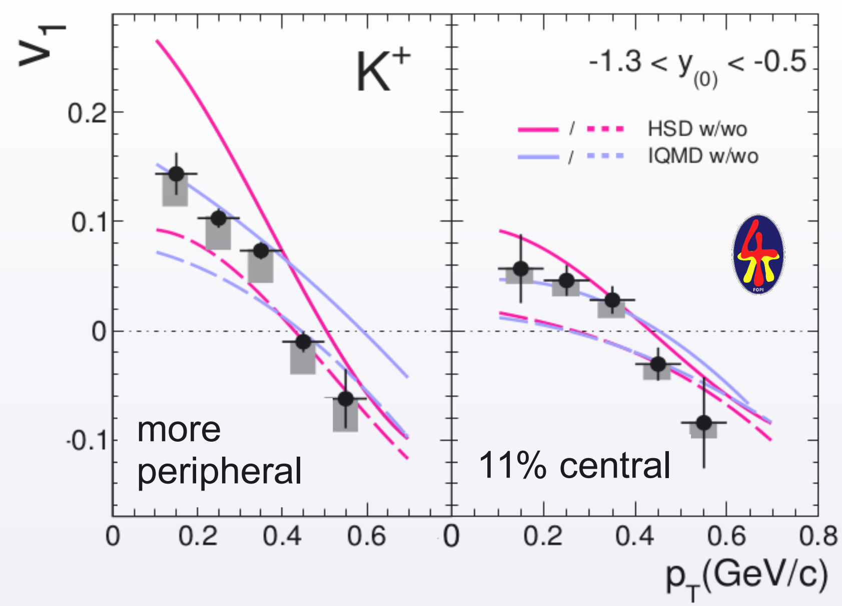


$$\frac{dN}{d\phi} \sim 1 + 2v_1 \cos\phi + 2v_2 \cos(2\phi) + \ldots$$

v_1 , v_2 = *Fourier coefficients*

40% central





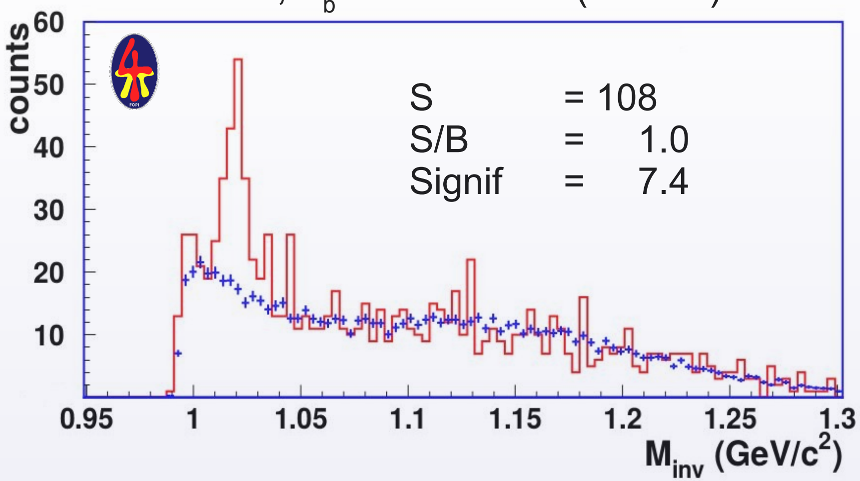
HSD : U_{K+N} = 20 MeV U_{K-N} ≈ -50 MeV
IQMD : U_{K+N} = 20 MeV U_{K-N} = -40 MeV

~ In favour of the potential

V. Zinyuk et al., PRC 90, 025210 (2014)

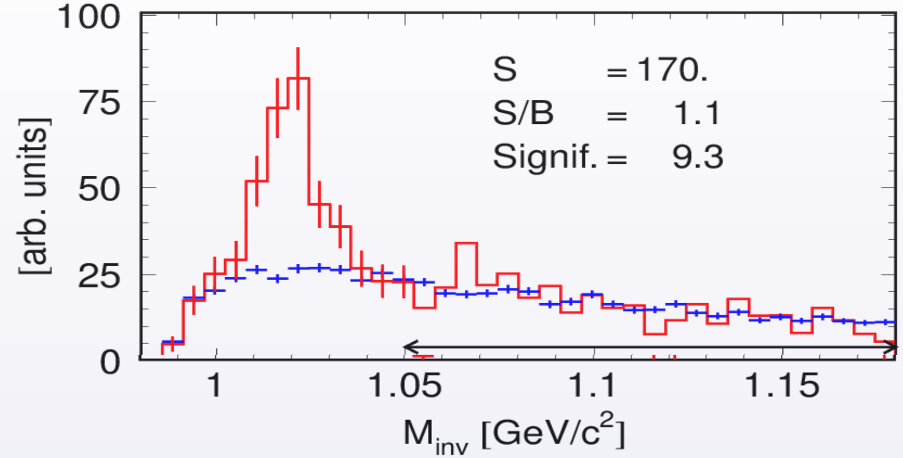
ϕ (1020) mesons

Al+Al, T_b = 1.9A GeV (central)



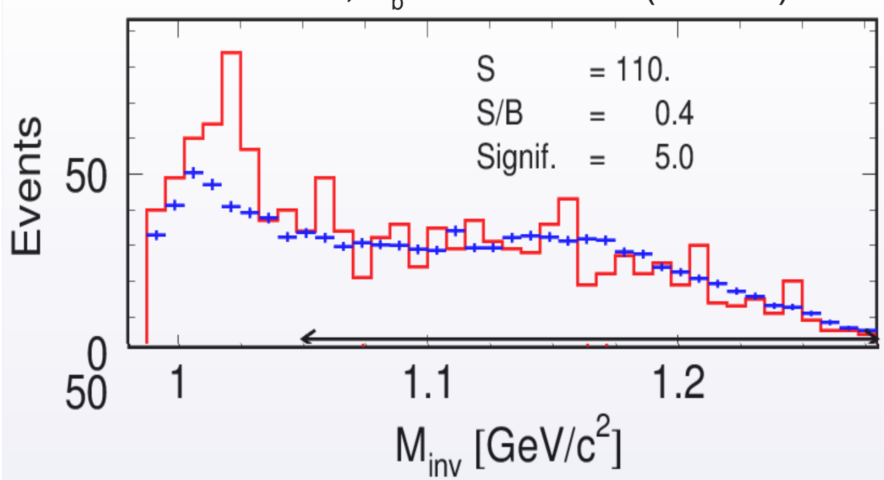
P. Gasik et al. arXiv: 1512.06988

Ni+Ni, T_b = 1.9A GeV (semi-)central



K. Piasecki et al., PRC 91, 054904 (2015)

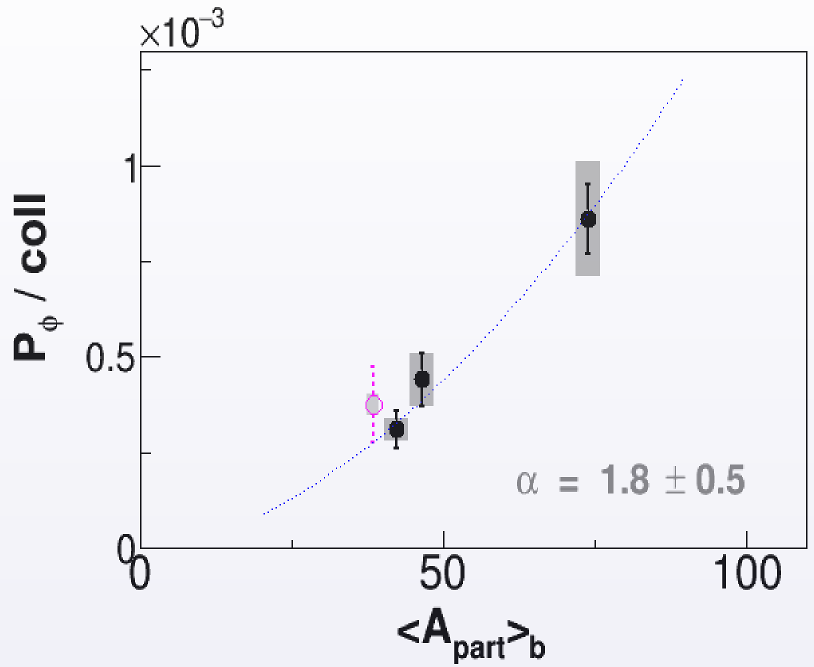
Ni+Ni, T_b = 1.9A GeV (central)

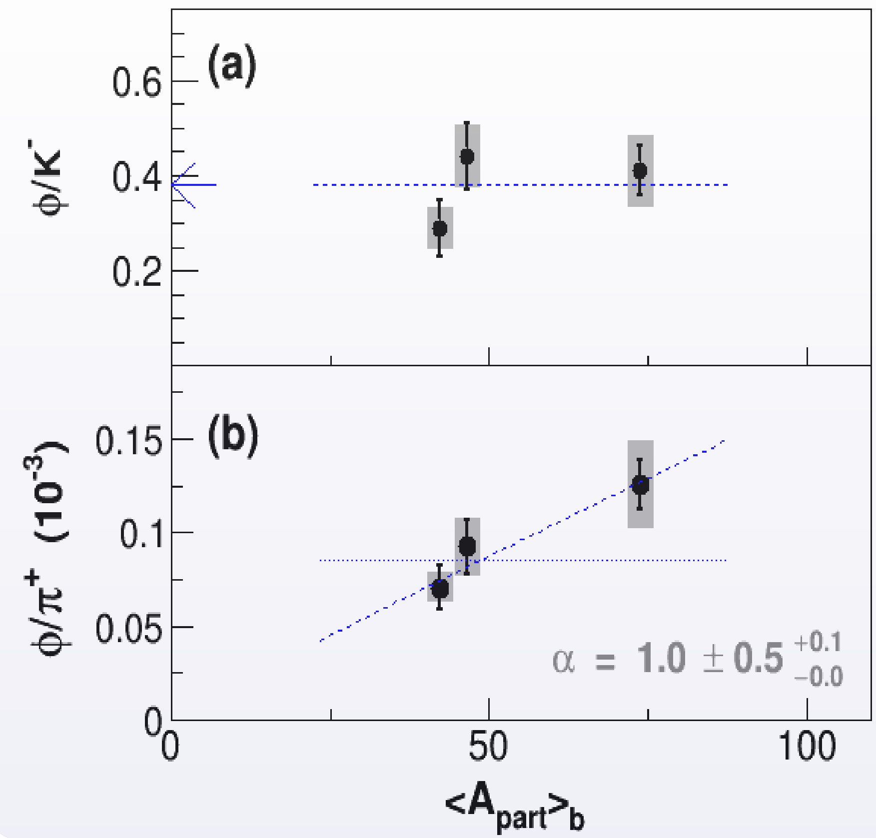


K. Piasecki et al. arXiv: 1602.04378

	$\langle A_{part} \rangle_b$	$P(\phi)$ [$\times 10^{-4}$]
Al+Al	42	$3.3 \pm 0.5 ^{+0.4}_{-0.8}$
Ni+Ni	46.5	$4.4 \pm 0.7 ^{+1.6}_{-1.1}$
Ni+Ni	74	$8.6 \pm 0.9 \pm 1.5$

ϕ mesons: centrality dependence @ 1.9*A* GeV



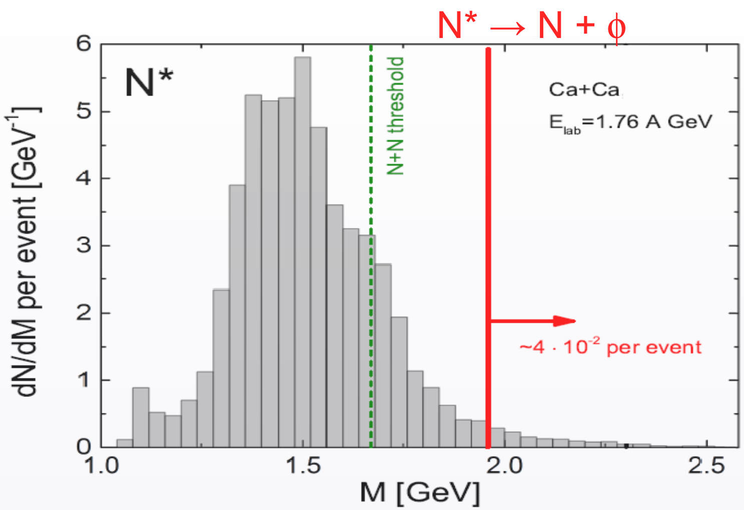


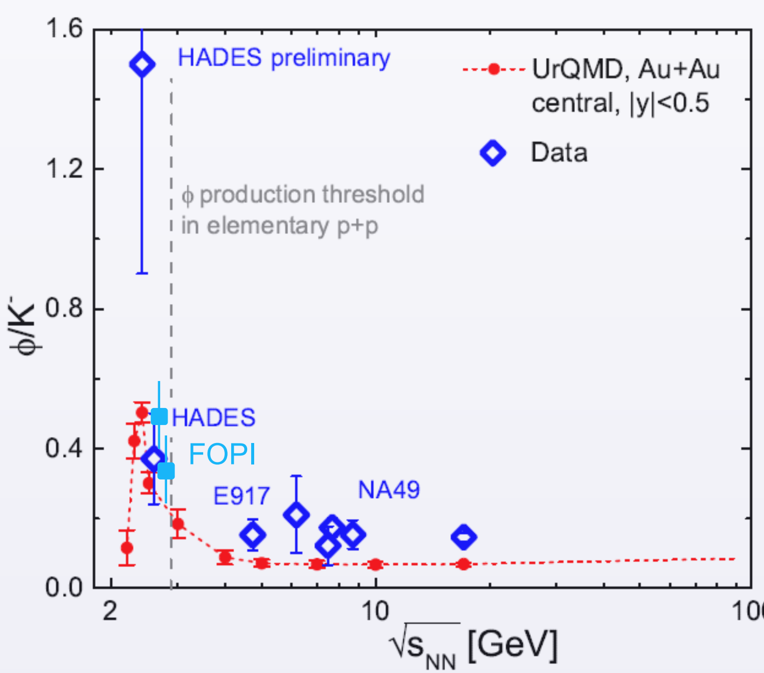
- $P_\phi \sim A_{part}^{\alpha}$ → $\alpha = 1.8 \pm 0.5$
- $\phi/K^- = const = 0.37 \pm 0.05$ → 18% of K^- come from ϕ decays

- $\phi/\pi^+ \sim A_{part}^{\alpha}$ → $\alpha = 1.0 \pm 0.5$

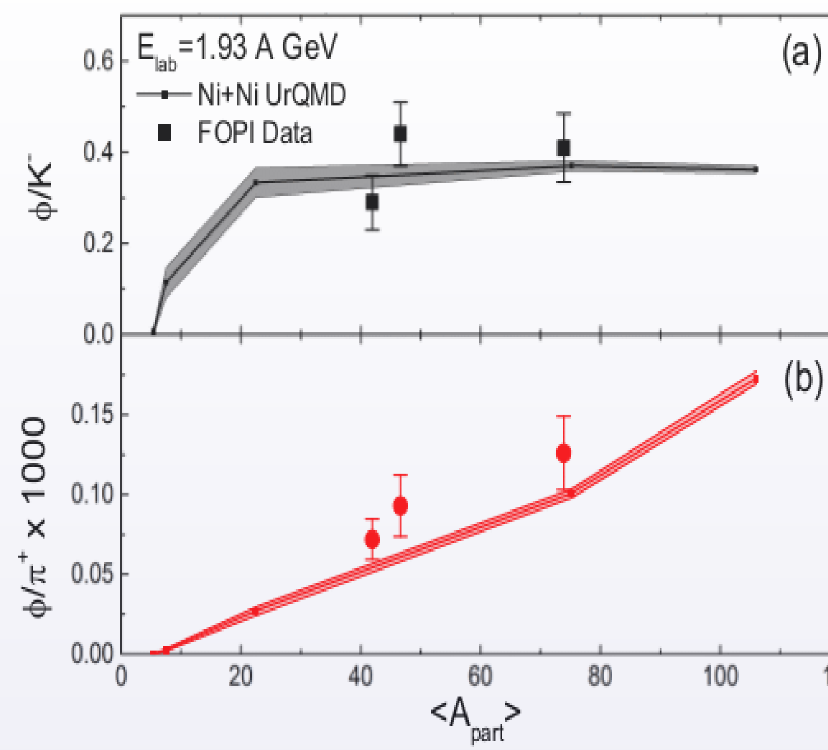
  But $\phi/\pi^+ = const$ still probable

ϕ mesons in UrQMD transport model





- Production via decays of massive resonances: N*(1990) … N*(2250)
- ϕ/K^- : – peak at subthreshold energies
  – In agreement with FOPI, HADES data



J. Steinheimer, M. Bleicher, J.Phys.G 43, 015104 (2016)

ϕ meson production modelled

BUU transport model

- Ni+Ni @ 1.9*A* GeV, $<A_{part}>_b$ = 86 (very central)

Yield from	Ni (1.93*A* GeV) + Ni
$B + B$	11.2×10^{-4}
$\pi + B$	2.4×10^{-4}
$\rho + B$	8.6×10^{-4}
$\pi + \rho$	1.5×10^{-4}
$\pi + N(1440)$	0.6×10^{-4}
$\pi + N(1520)$	0.5×10^{-4}
Total	2.5×10^{-3}
Data from experiment [28]	
For $T = 130$ MeV	$(1.2 \pm 0.4 \pm 0.6) \times 10^{-3}$
For $T = 70$ MeV	$(4.5 \pm 1.4 \pm 2.2) \times 10^{-3}$

H. Schade et al., PRC 81, 034902 (2010)

- Compared to FOPI data:

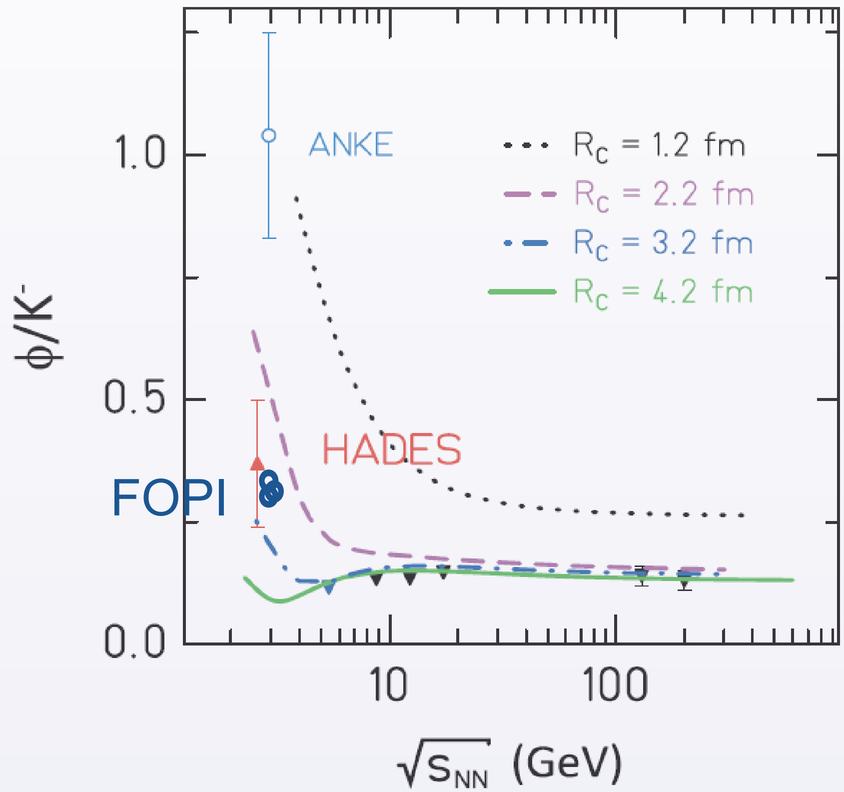
Ni+Ni @ 1.9*A* GeV, $<A_{part}>_b$ = 74

$P(\phi) = [8.6 \pm 0.9 \pm 1.5] \times 10^{-4}$

→ Seems BUU predictions too high.

Statistical Model

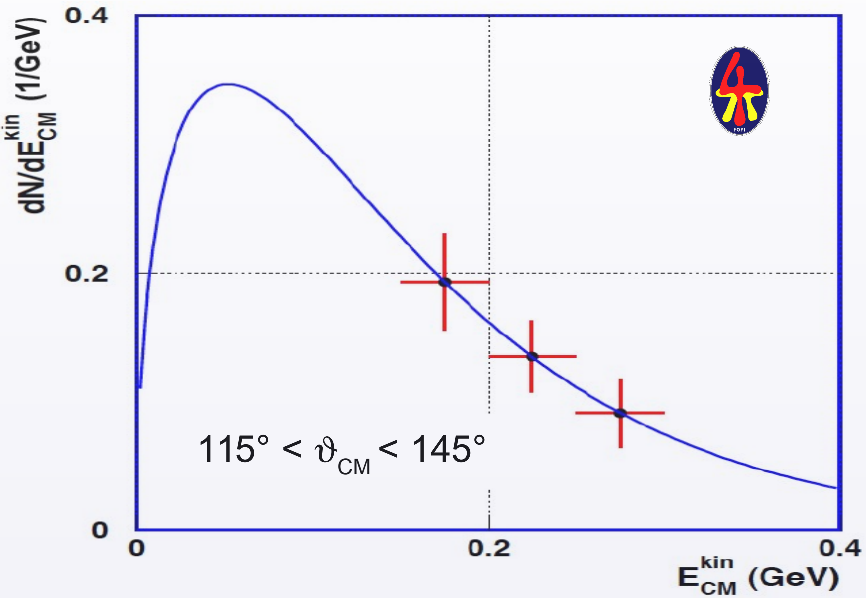
- Smaller volume for $s\bar{s}$ production
- ϕ/K^- ratio grows around threshold



J. Cleymans et al. PLB 603, 146 (2004)
G. Agakishiev et al., PRC 80, 025209 (2009)

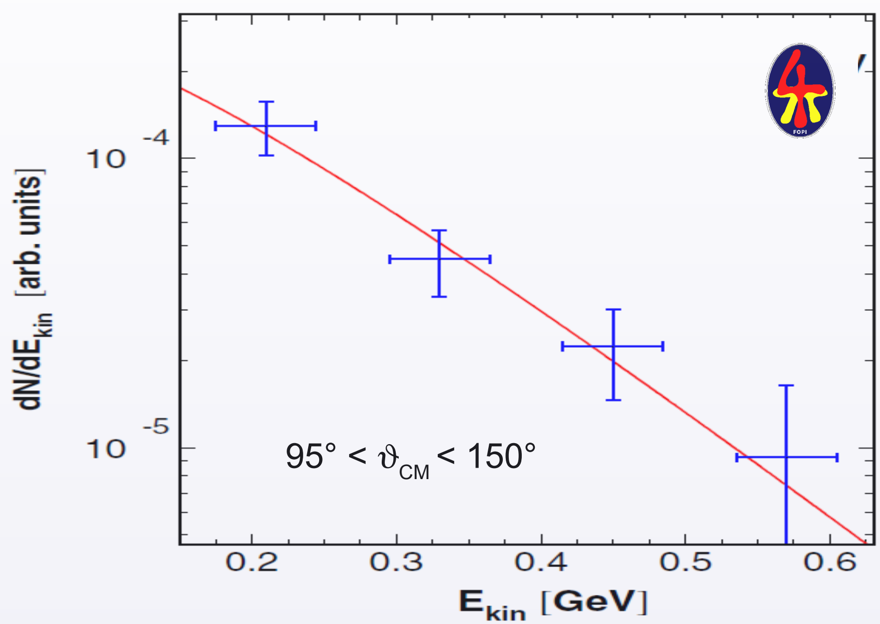
ϕ meson phase space: first insights

- Al+Al @ 1.9A GeV (central)



T_{eff} = 94 ± 14 ± 16 MeV

- Ni+Ni @ 1.9A GeV (semi-central)



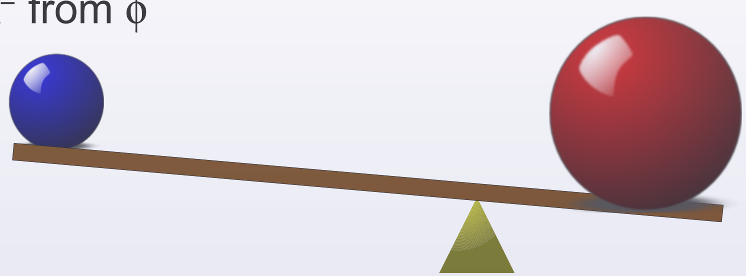
T_{eff} = 108 ± 18 ± 16 MeV

2-source model of K^- 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



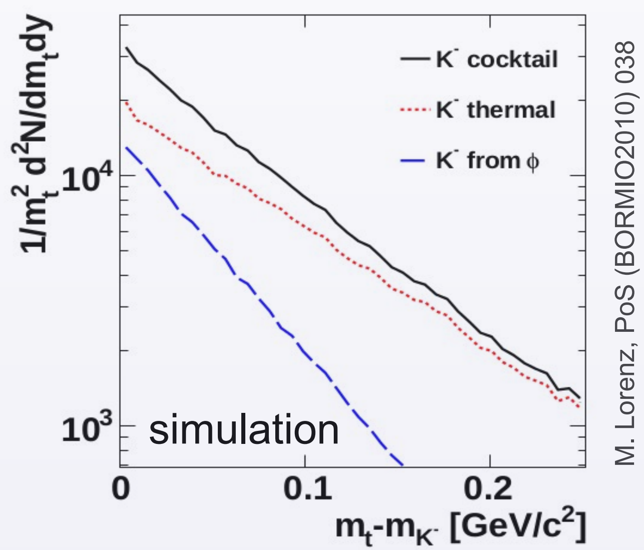
- Ar+KCl @ 1.76A GeV (HADES)

Experiment :

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

Conjecture :

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



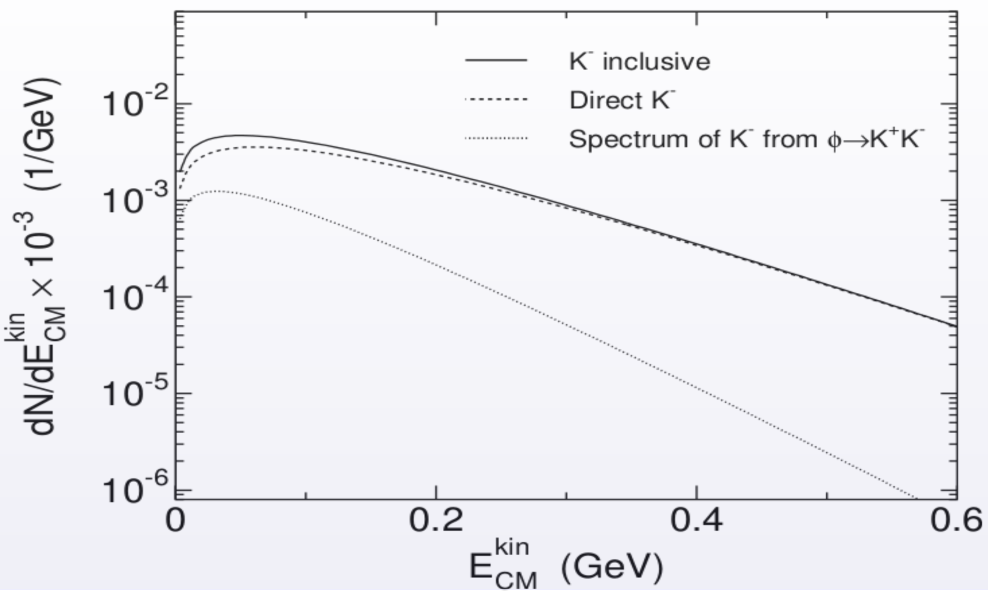
ϕ admixture reduces T(K^-) from 89 MeV to 74 MeV

2-source model of K^- emission

- Al+Al @ 1.9A GeV (FOPI)

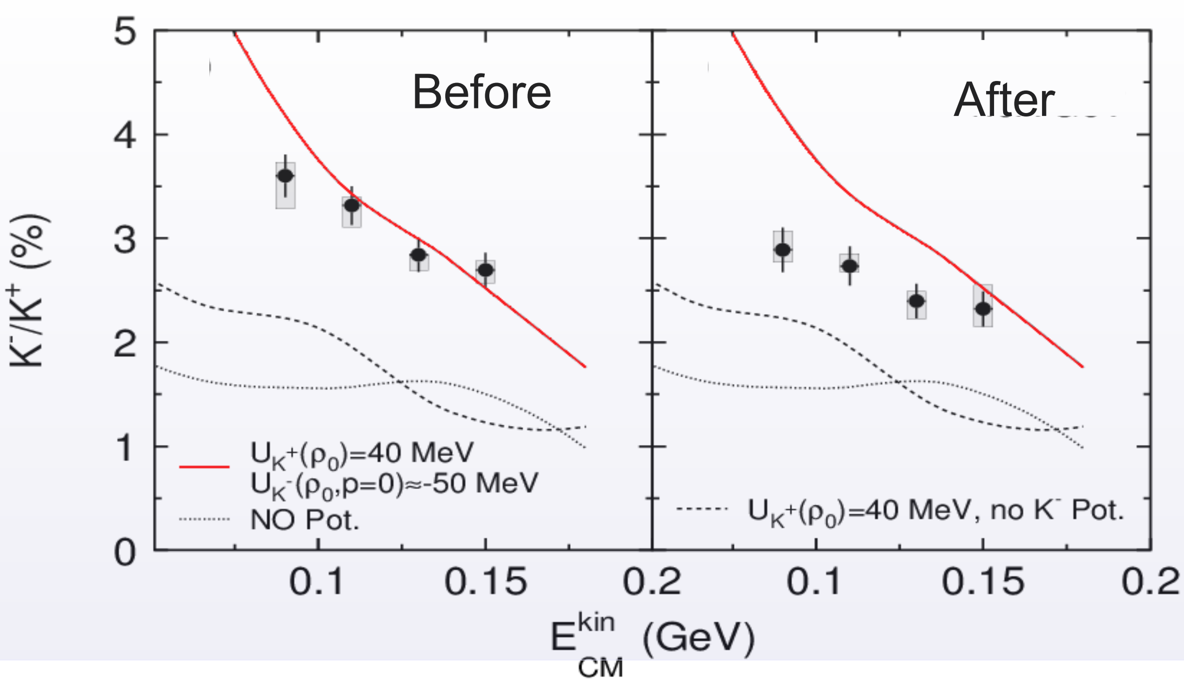
Particle	T_{eff}
K^-	$82 \pm 7 \pm 11$
K^+	$109 \pm 2 \pm 9$
ϕ	$93 \pm 14 \pm 16$

T (K^- direct) = 92 ± 16 MeV



- Back to HSD calculations:
  - ϕ contribution to K^- was minimal
  - *Idea*: for the experimental data, strip the ϕ contribution from K^-

→ $|U_{K-N}|$ less than 50 MeV



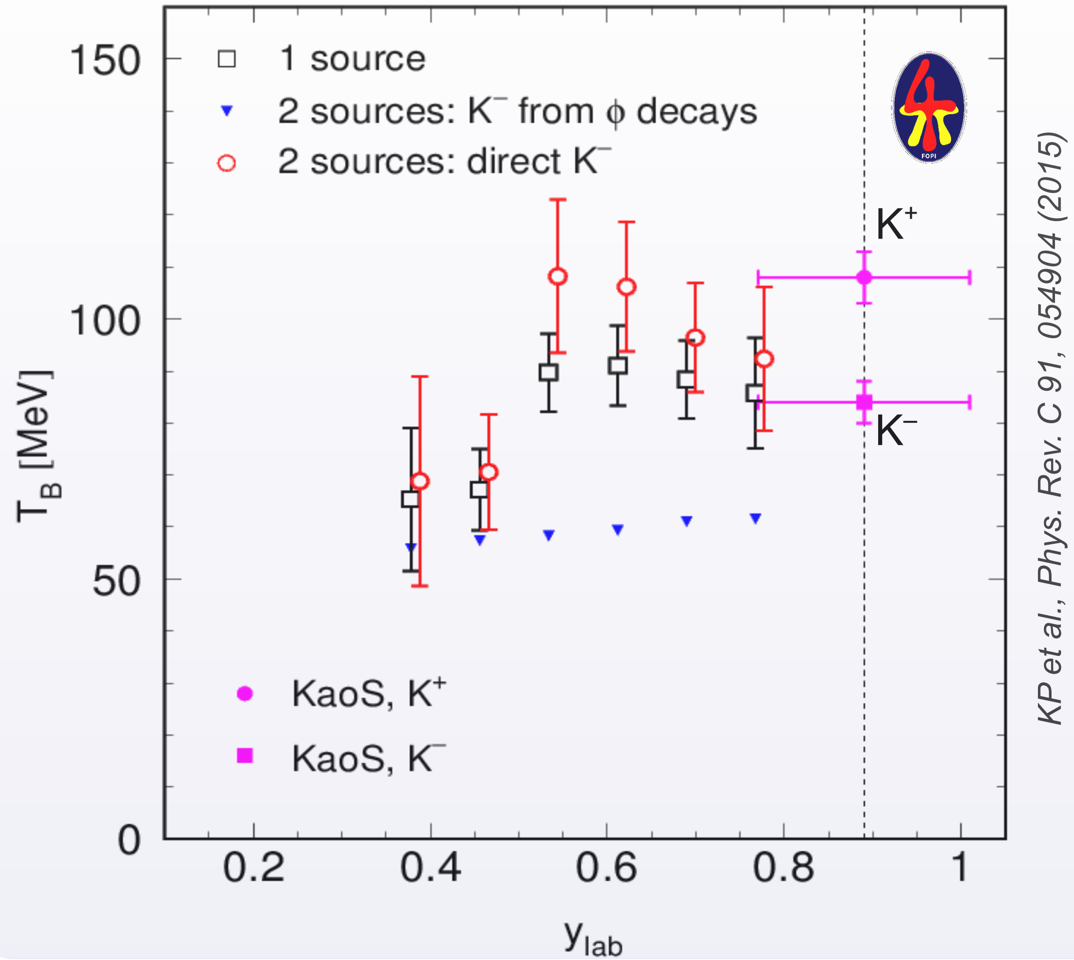
P. Gasik et al. arXiv: 1512.06988

2-source model of K^- emission

- 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 $T_{inclusive}$

Summary and conclusions

- Phase space distributions of K^+ and K^- analysed for Al+Al and Ni+Ni @ 1.9*A* GeV
  - *T* and a_2 parameters found for Al+Al, $T = f(y)$ and d*N*/d*y* found for Ni+Ni
  - Directed (v_1) flow of K+ and K^- measured
- Transport Models' comparison to phase space distributions:
  - From $K^-/K^+ = f(E_{kin})$, $U_{K+N}(\rho_0) = +40$ MeV , $U_{K-N}(\rho_0) = -50$ MeV
  - From v_1 of K^+, K^- , $U_{K+N}(\rho_0) \approx +10$ MeV , $U_{K-N}(\rho_0) \approx -25$ MeV
- Investigation of ϕ mesons @ 1.9*A* GeV
  - $P(\phi)$ in the order of 10^{-4}, $\sim A_{part}^{\,1.8 \pm 0.5}$
  - $\phi/K^- = 0.37 \pm 0.05$ (~18% contribution to K^-)
  - $\phi/\pi^+ \sim A_{part}^{\,1.0 \pm 0.5}$ (but *const* also ok)
- Influence of ϕ on K^- mesons
  - *T* (direct) higher than *T* (inclusive)
  - U_{K-N} extracted from HSD lower than previously found –50 MeV.

Thank You!

Sub- and near-threshold Production of K^-

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

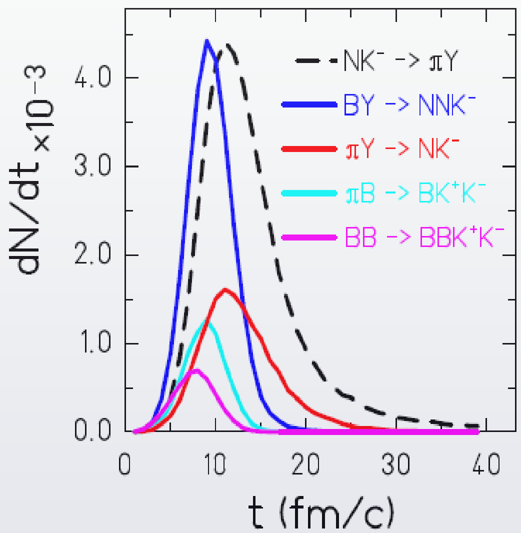
$$BY \rightarrow NNK^-, \quad \pi Y \rightarrow K^- B$$

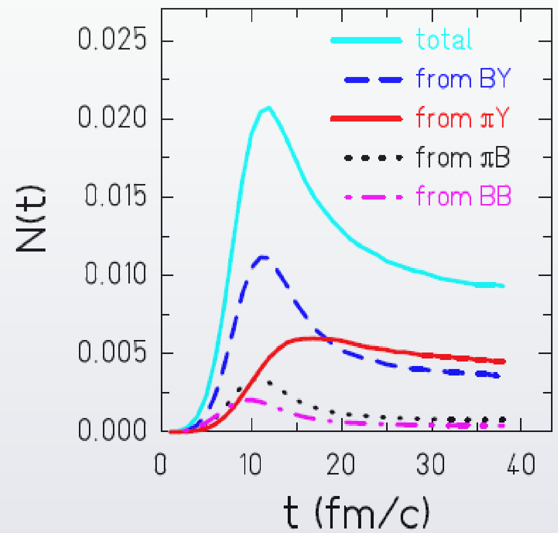
  - strong reabsorption: $K^- B \rightarrow \pi Y$
  - coupled to resonances $\Sigma(1385)$, $\Lambda(1405)$

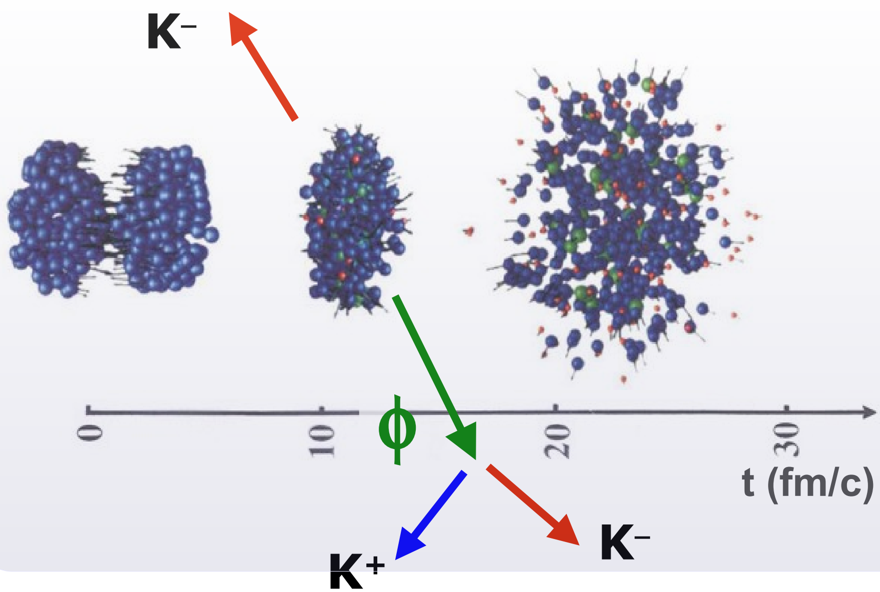
$$\pi + Y \rightarrow \begin{matrix}\Sigma^* \\ \Lambda^*\end{matrix} \rightarrow K^- + B$$

Q: Can we see them?

Au+Au, T_b = 1.5A GeV (IQMD transport code)







- $\phi(1020) \rightarrow K^- K^+$ decay (mostly outside collision zone)

  Q: How strong is this contribution?

- In-medium effects: "U_{KN} potential" or "spectral density"

  Q: How strong is this influence?

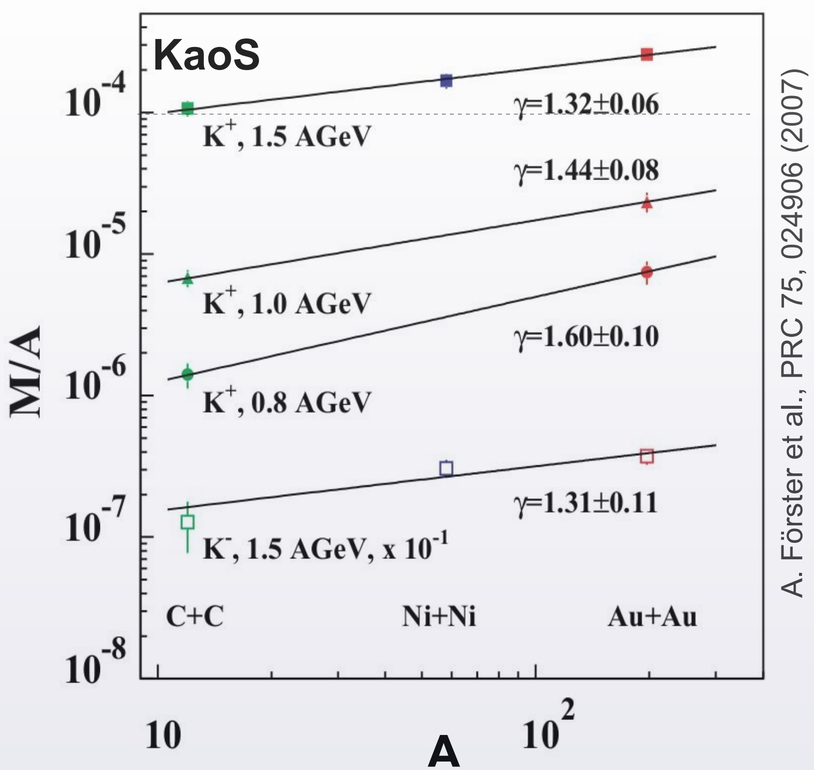
Production of Kaons in AA: Primary or secondary?

If primary:

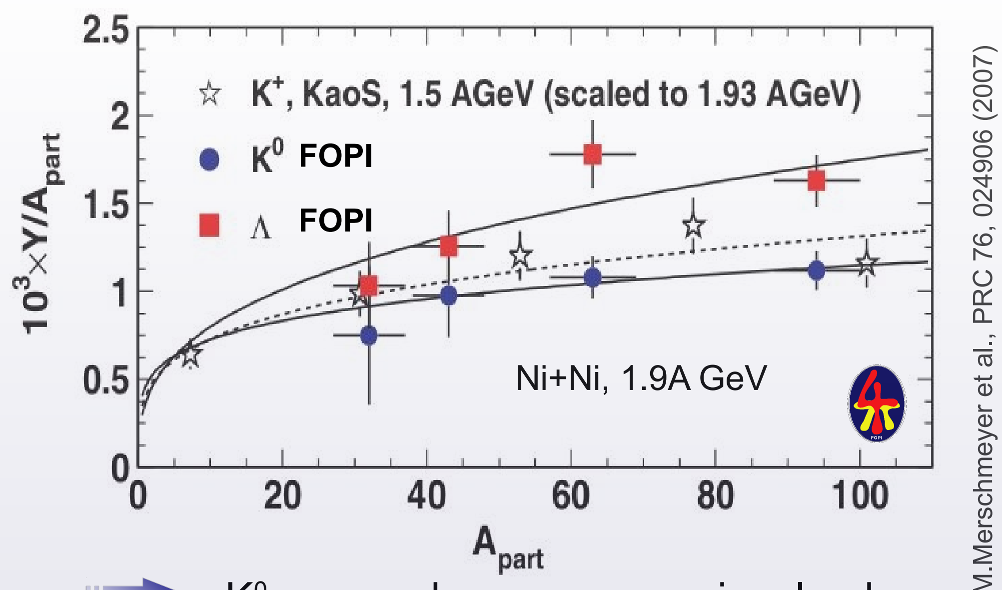
For pA → KX: $MUL_K = \frac{\sigma_K}{\sigma_{inelastic}} = const$

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:

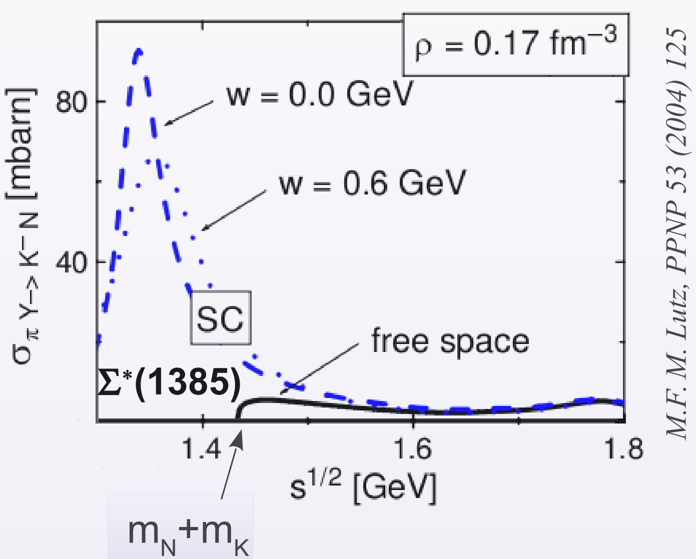
- $N_{beam} + N_{target}$, N_{target} has Fermi motion
- predominantly via ΔN , ΔΔ → $K^{+,0}$ Y B
  πN , πΔ → $K^{+,0}$ Y
  Y = [Λ,Σ]
- U_{KN} involved (increases K mass → lower yields)

$\Sigma^*(1385)$ resonance

Chiral effective field theory w/ coupled-channels

- K^- production in medium ($\pi Y \rightarrow K^- N$) coupled to strange resonances e.g. $\Sigma^*(1385)$, $\Lambda^*(1405)$:

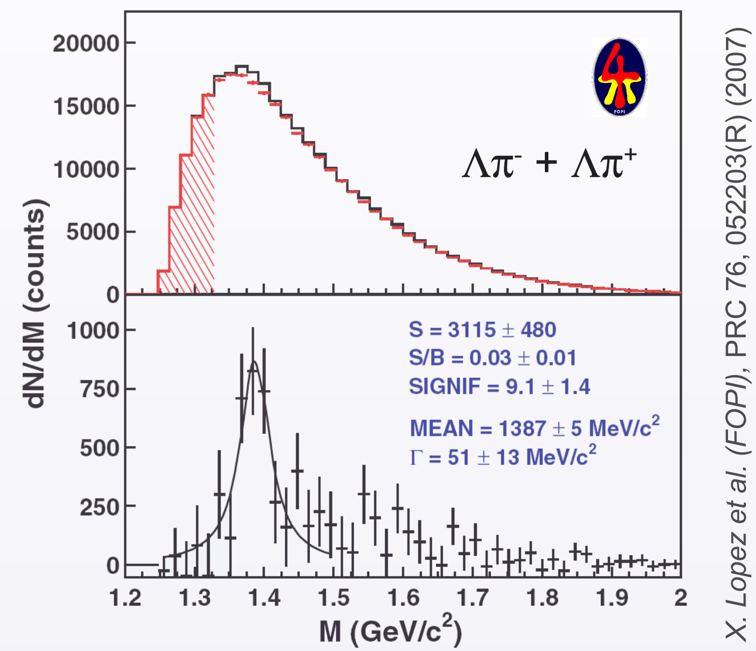
$$(\pi\Lambda \rightarrow \Sigma^* \rightarrow K^- N)$$



- Σ^* resonance **found** in HI collisions
  Input to fix $\pi + \Lambda \rightarrow K^- + N$ in medium

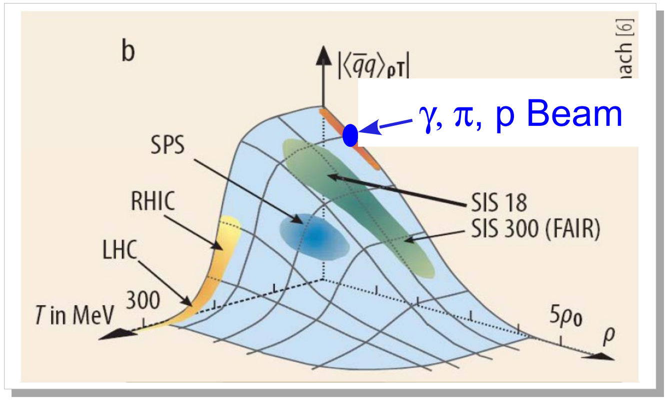
- Al+Al @ 1.9A GeV

$$\Sigma^{\pm *}(1385) \rightarrow \Lambda + \pi^{\pm} \quad (88 \pm 2\%)$$
$$\hookrightarrow p + \pi^-$$



$\dfrac{Y(\Sigma^{*-}+\Sigma^{*+})}{Y(\Lambda+\Sigma^0)}$	
FOPI	0.125 ± 0.042
Statist. Model	0.097
UrQMD	0.177

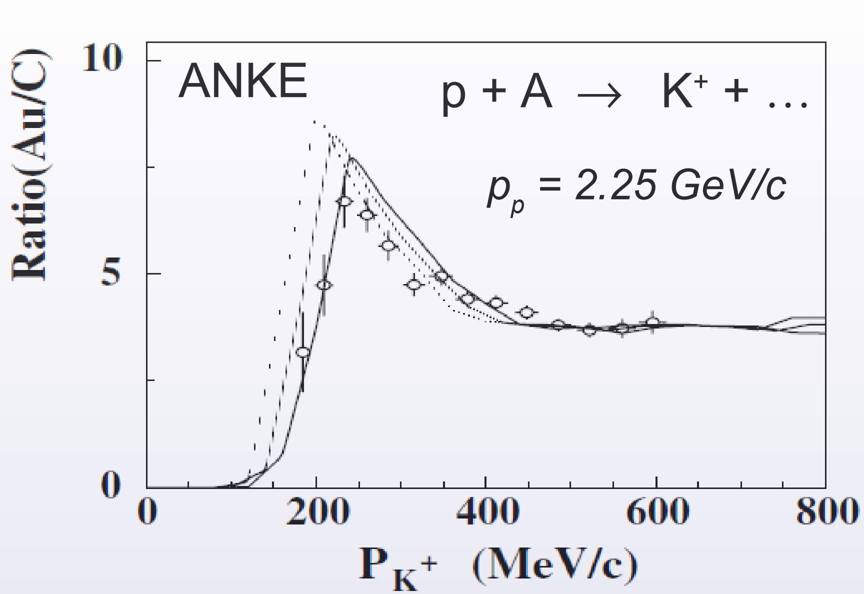
In-medium modifications of $K^{+/0}$ at $\rho < \rho_0$



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

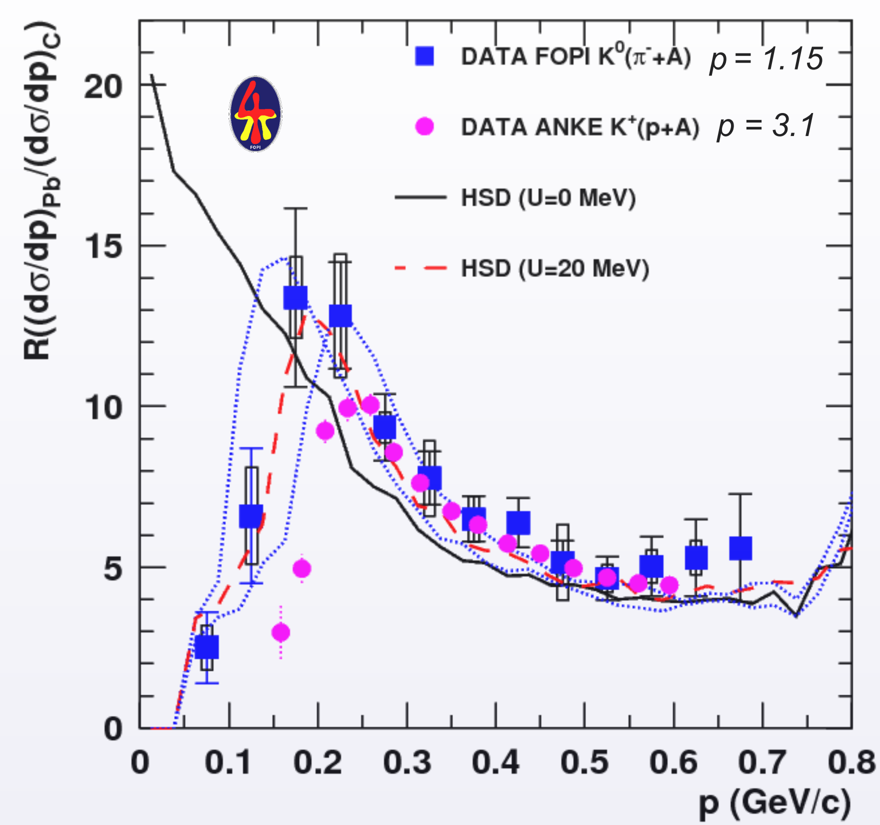
π^- (p=1.15 GeV/c) + A → K^0 + … *FOPI*

p (p=2.25 GeV/c) + A → K^+ + … *ANKE*



M. Nekipelov et al, PLB 540, 207 (2002)
Z. Rudy et al., EPJA 23, 379 (2005)

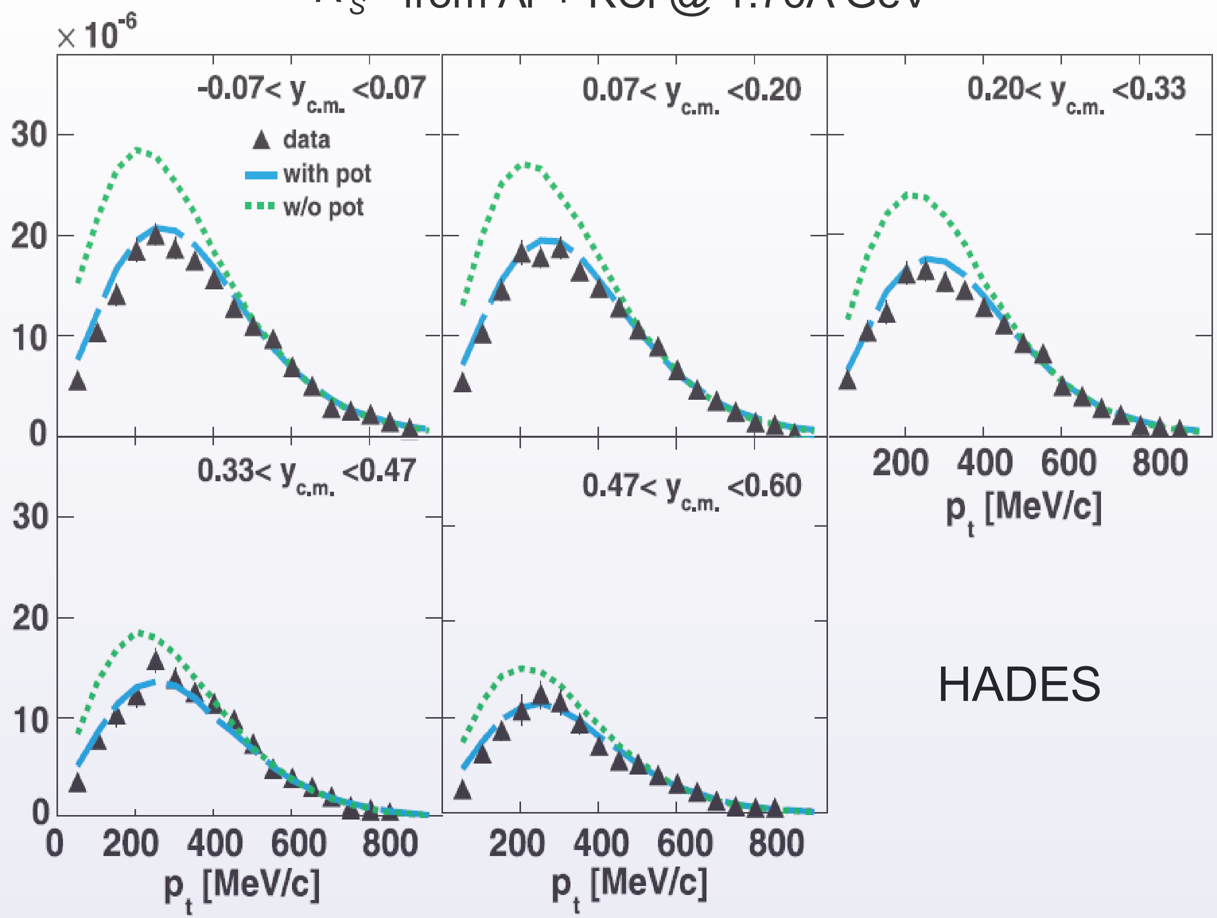
CBUU transport code		
	· · · ·	U_{KN} = 0 MeV
	········	U_{KN} = 10 MeV
	——	U_{KN} = 20 MeV



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 $\rho \leq \rho_0$

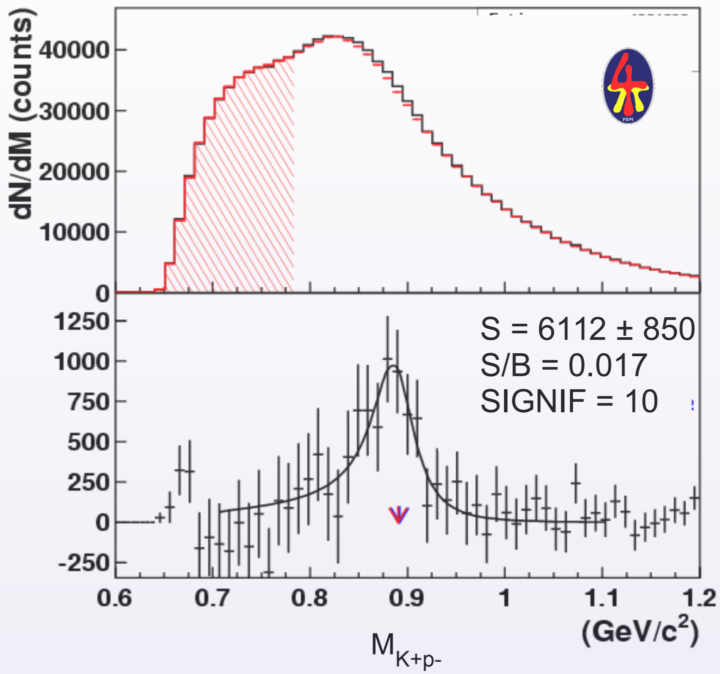
Kaonic resonance: K*(892)

$K^{0*}(892) \rightarrow K^+ \pi^-$ (~ 67%)

E_{th} = 2.75 GeV *(SIS-18 energies: deeply subthreshold)*

$c\tau$ = 4 fm *(short lived)*

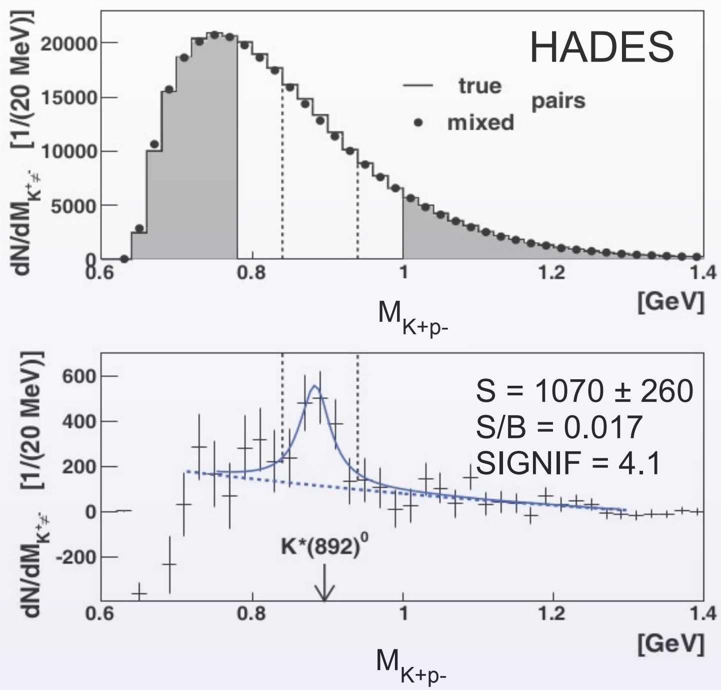
Al+Al @ 1.9A GeV



$$\frac{P(K^{0*})}{P(K^0)} = 0.032 \pm 0.003 \pm 0.012$$

X. Lopez et al., J. Phys. G 35 (2008) 044020

Ar+KCl @ 1.76A GeV

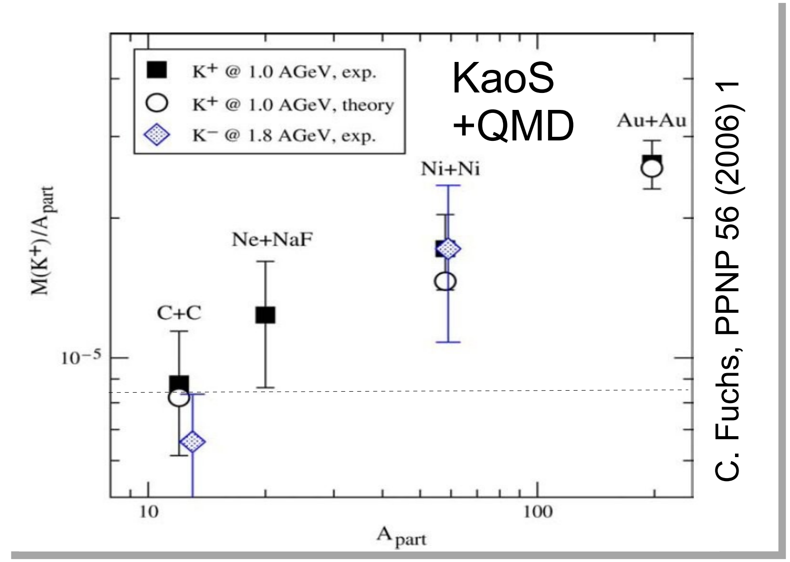


$$\frac{P(K^{0*})}{P(K^0)} = 0.019 \pm 0.005 \pm 0.003$$

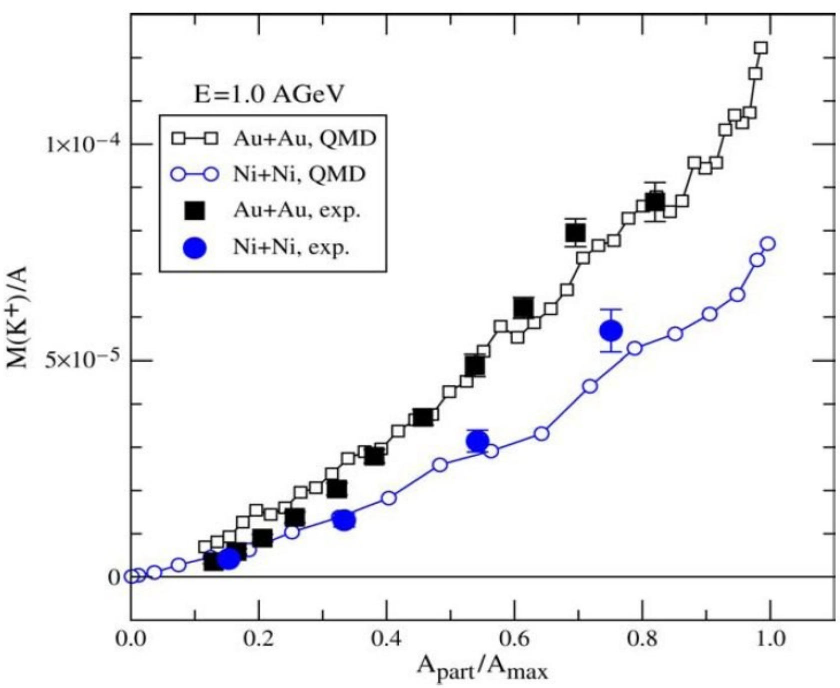
G. Agakishiev et al., Eur. Phys. J. A (2013) 49: 34

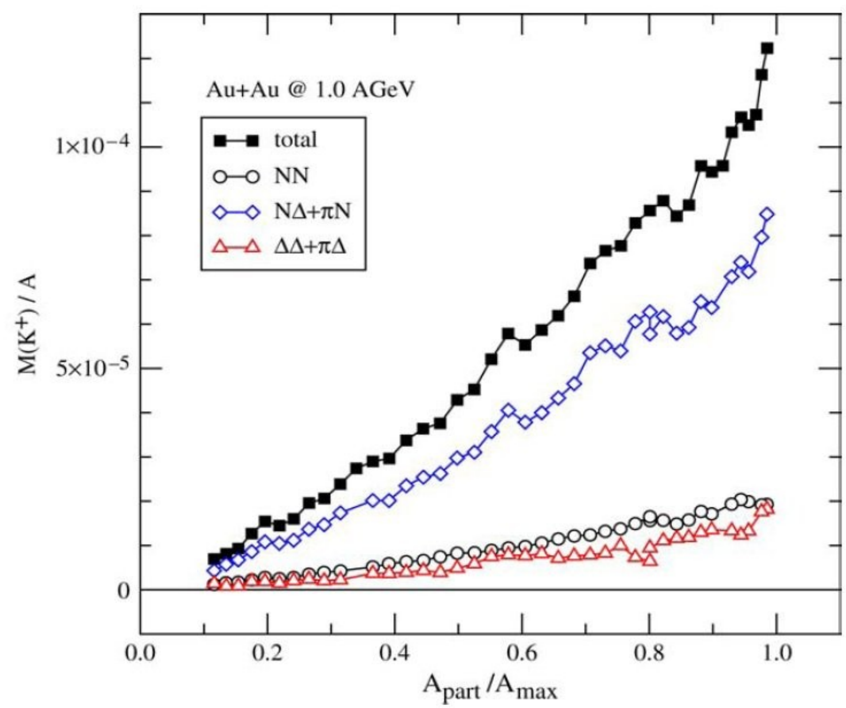
- K⁺ Primary: (Fermi momentum)
  NN → N**K⁺**Y (Y = Λ, Σ)

  K⁺ Secondary:
  BB → B**K⁺**Λ (BB = NΔ, ΔΔ)
  πB → **K⁺**Y (B = N,Δ)



➡ Secondary processes involved

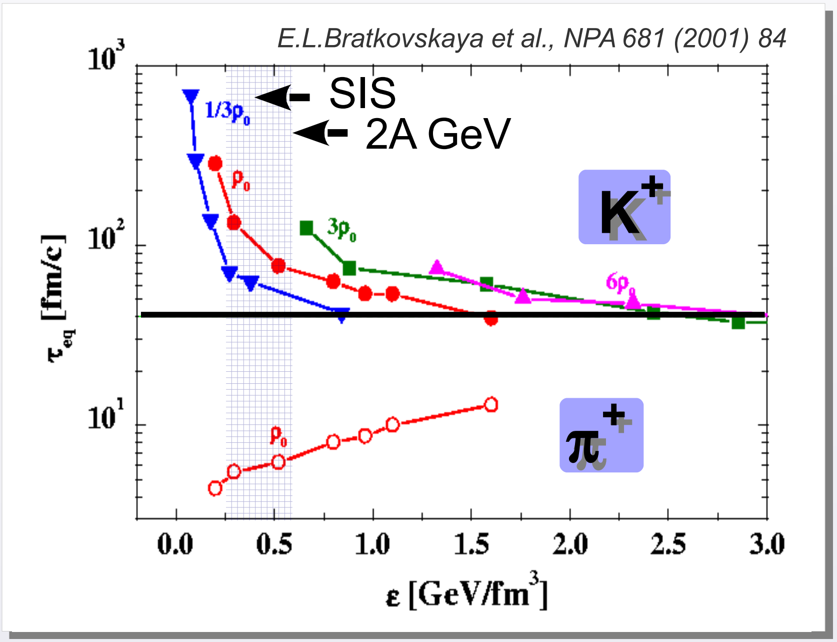




HSD transport model

- *'Infinite' hadronic matter*, initial $\varepsilon=\varepsilon_0$, $\rho_B=\rho_0$, $\rho_S=0$
- τ_{eq}: characteristic time of yield buildup

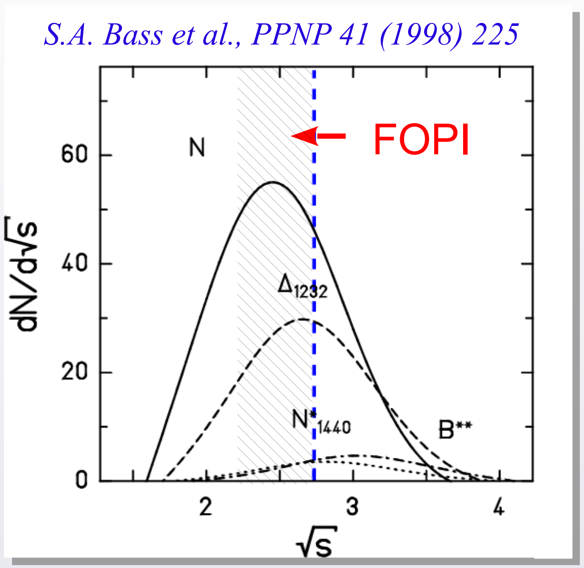
  τ_{eq} @ 2/3 of $N_{equilibrium}$



$\tau_{eq} \gg \tau_{collision}$

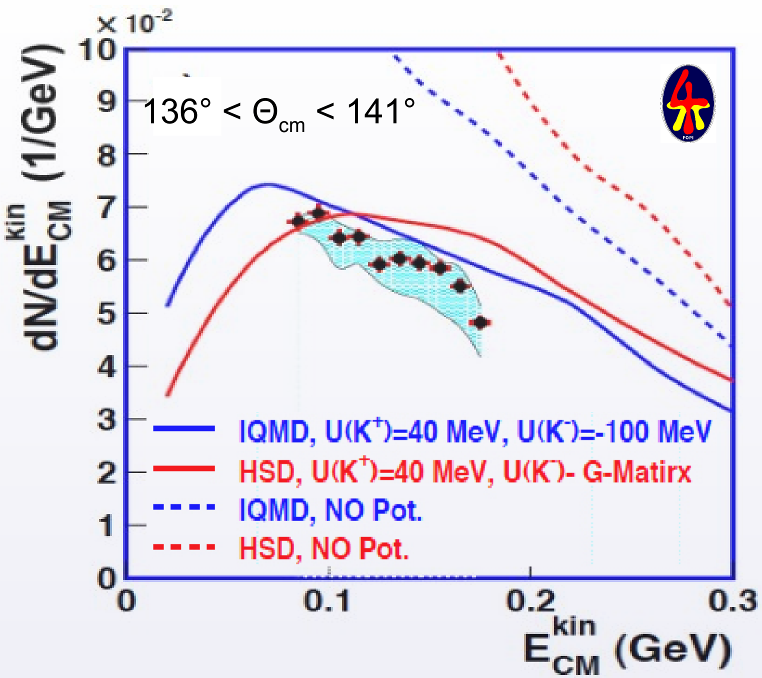
no thermalization of strangeness

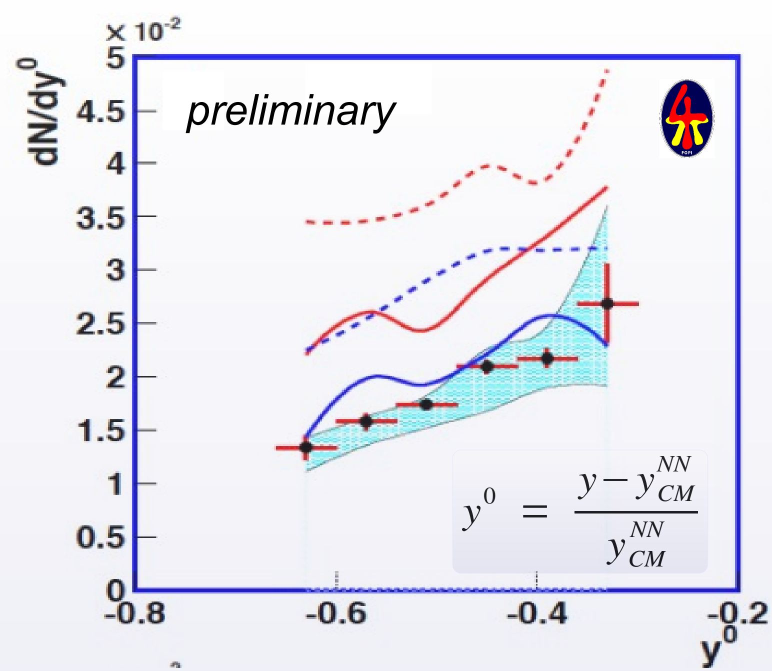
- At SIS energies, resonance production (Δ, N*) reaches maximum



K^+ phase space: experiment vs transport

Al+Al @ 1.93A GeV , ~ 9% most central events *(P. Gasik)*





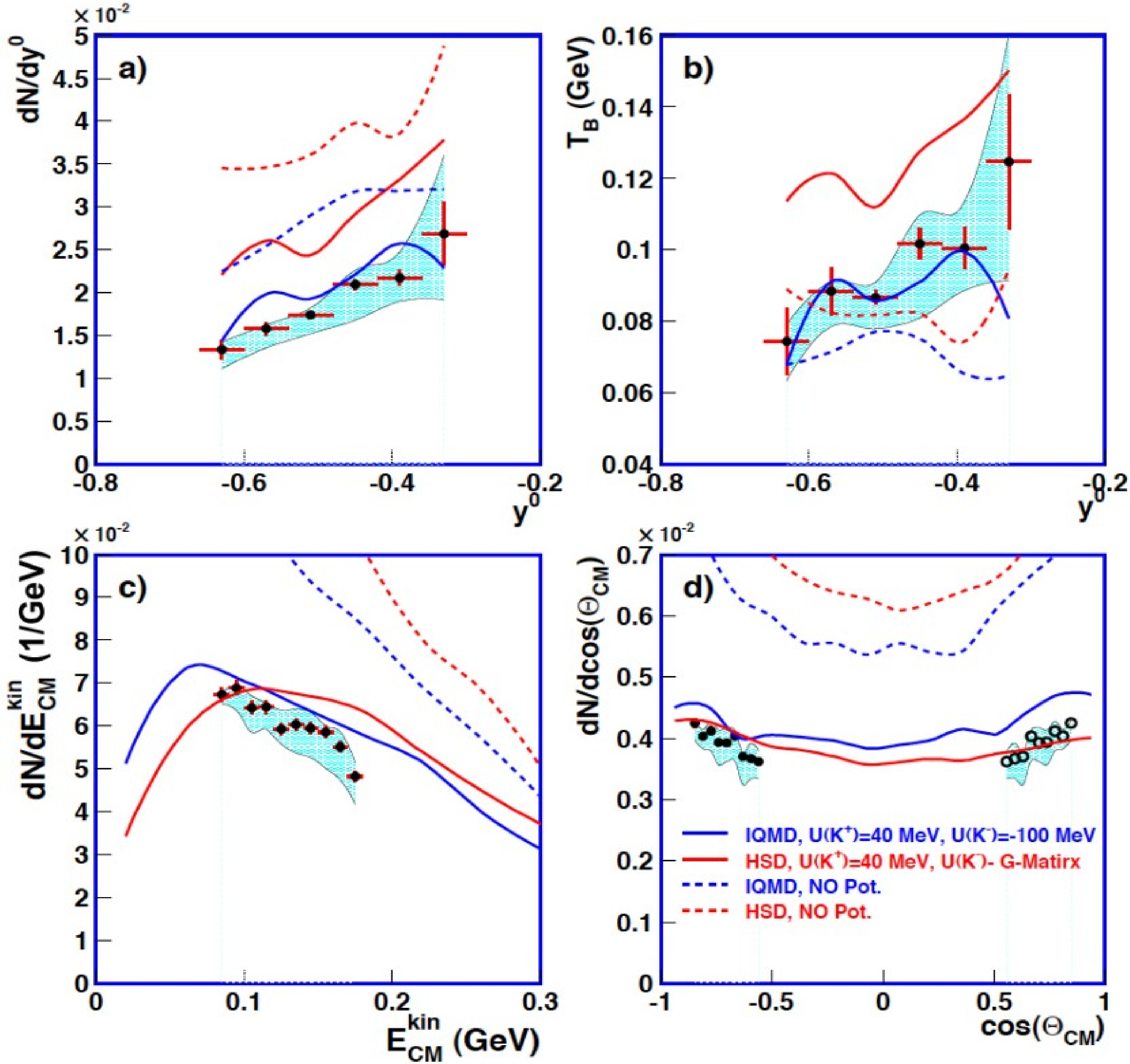
Calc.: Y. Leifels (GSI/Darmstadt).
Ref.: C.Hartnack, H.Oeschler, Y.Leifels, E.Bratkovskaya, J.Aichelin, nucl-th/1106.2083v2

- **IQMD**
  - Soft EoS ($K \approx 200$ MeV)
  - $m_{K\pm}(\rho) = m_{K\pm}(\rho_0) \cdot \left(1+\alpha_\pm \cdot \frac{\rho}{\rho_0}\right)$
  - $\alpha_{K+/K-}$ = 0.08 (-0.21)
    At $\rho=\rho_0$ Δm_{K+} = 40 MeV, Δm_{K-} = –100 MeV

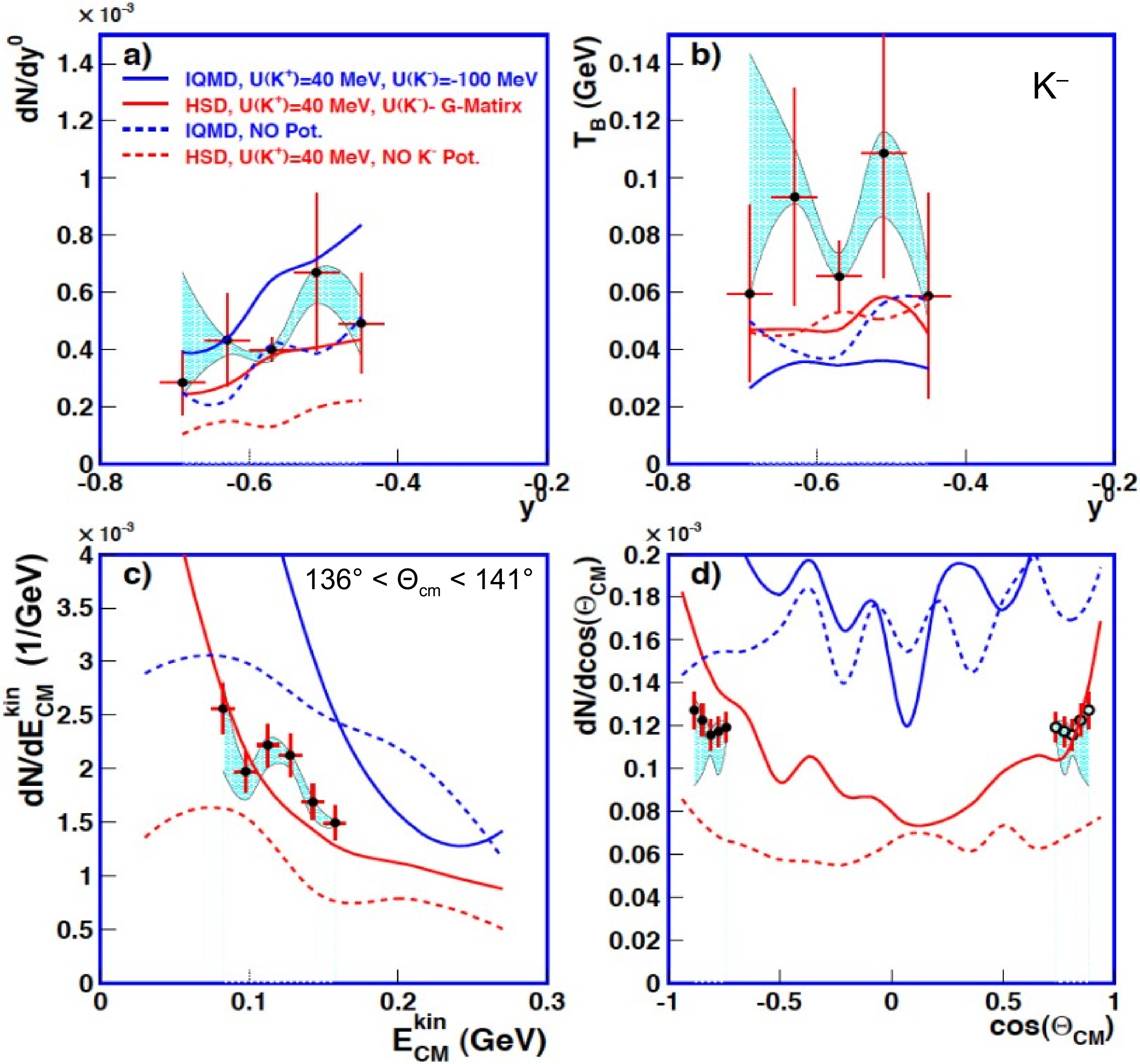
- **HSD**
  - Semi-soft EoS ($K \approx 250$ MeV)
  - K^+ mass modifications as in IQMD
  - K^- production: off-shell G-matrix

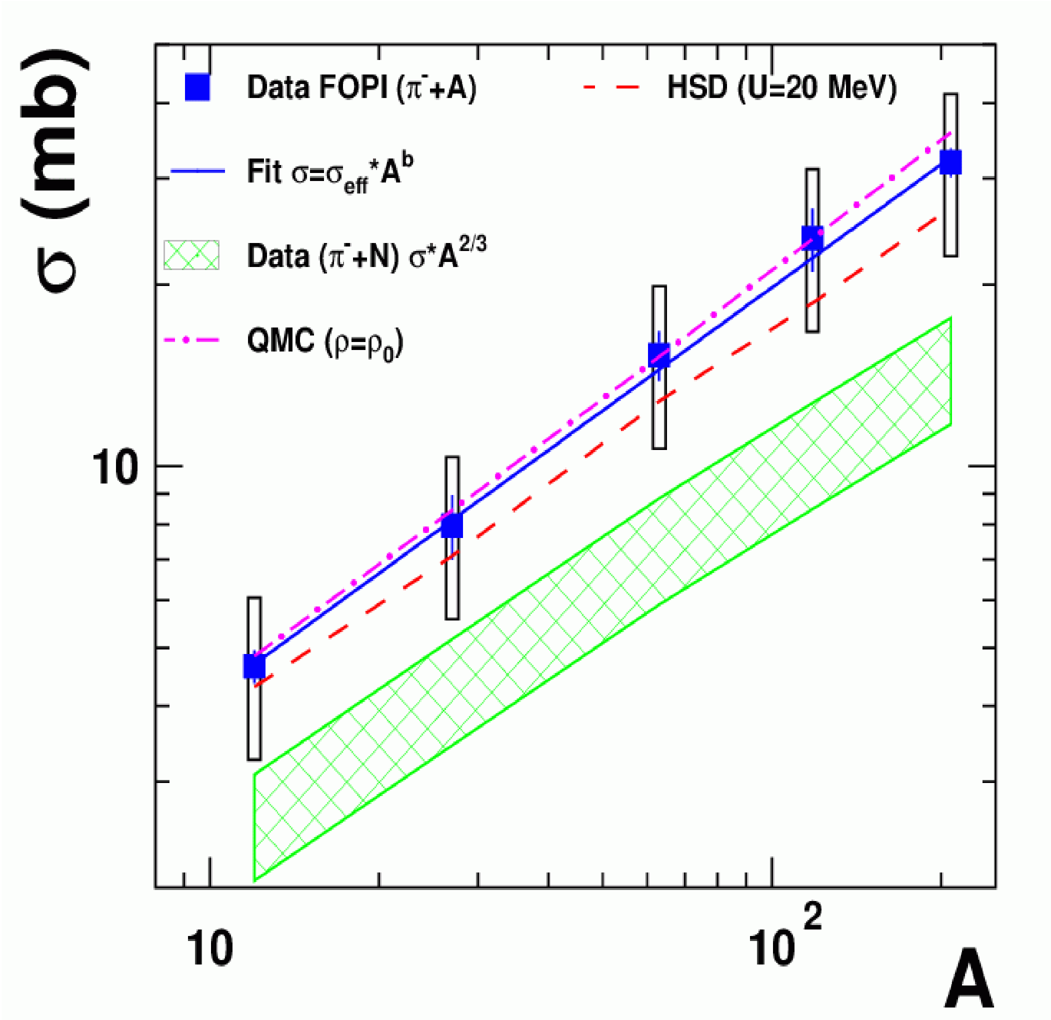
- Clear preference for $U_{KN} \neq 0$ option
- Still description not ideal

Al+Al, E=1,9A GeV + IQMD/HSD



Al+Al, E=1,9A GeV + IQMD/HSD





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

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

In-Medium Σ*(1385)

Chiral unitary theory

$\Sigma^*(1385) \rightarrow \Lambda(\Sigma) + \pi$ at $\rho=\rho_0$

$c\tau$ = 5 fm

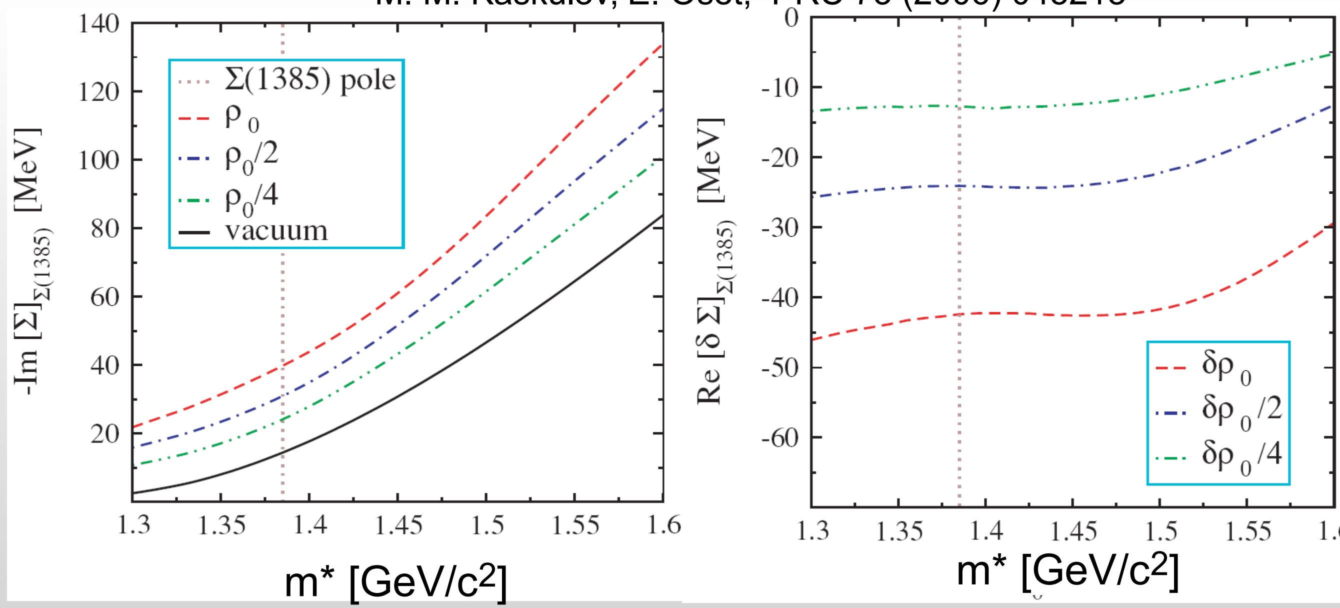
at $\rho = \rho_0$:

$\Gamma = -2\mathrm{Im}[\Sigma]_{\Sigma(1385)} = 76$ MeV

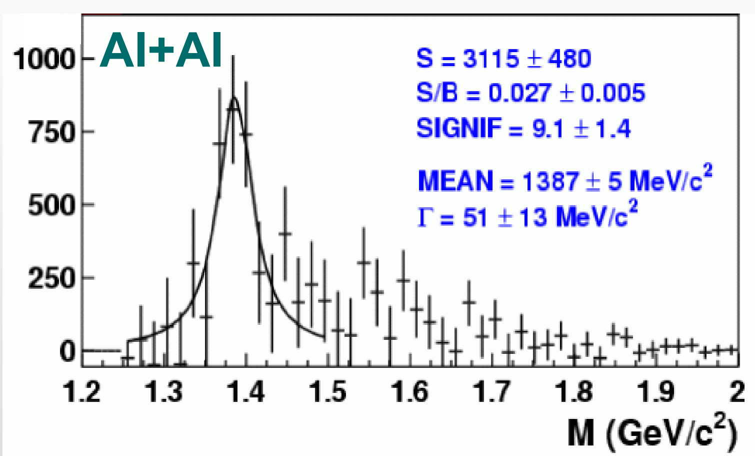
Mass:

$V_{\Sigma^* N} \approx -45$ MeV (attractive)

M. M. Kaskulov, E. Oset, PRC 73 (2006) 045213



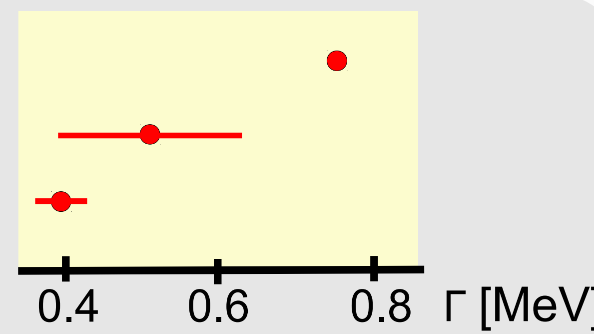
X. Lopez et al., PRC 76, 052203(R) (2007)



Chiral unitary theory

FOPI expt. data

PDG mass (ρ = 0)



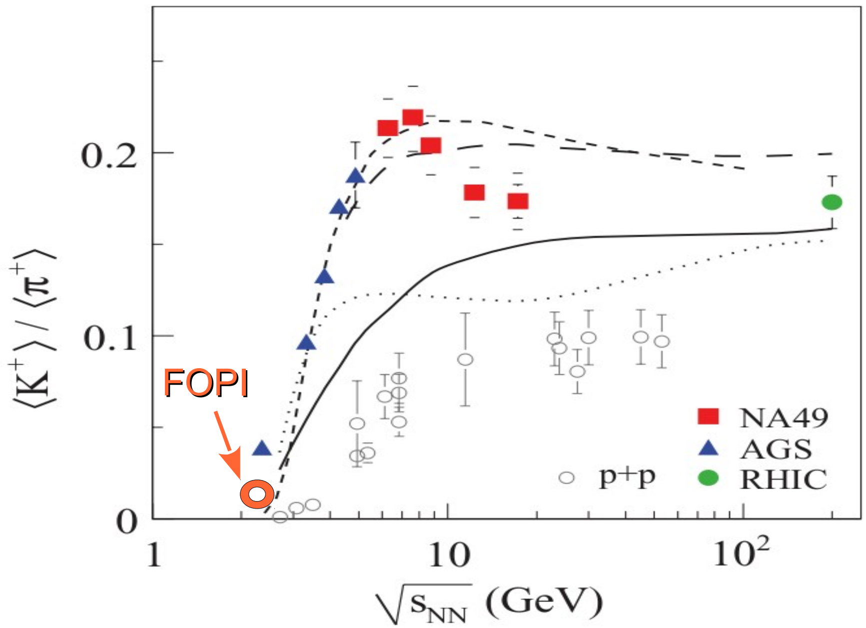
short lifetime → Σ* should probe finite density!

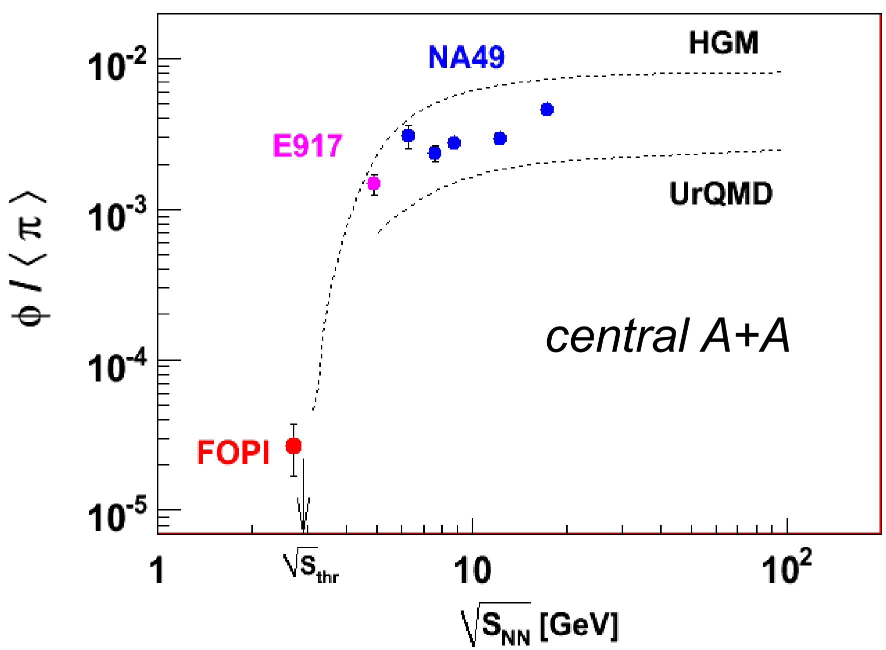
Γ broadening not yet observed (more statistics...)

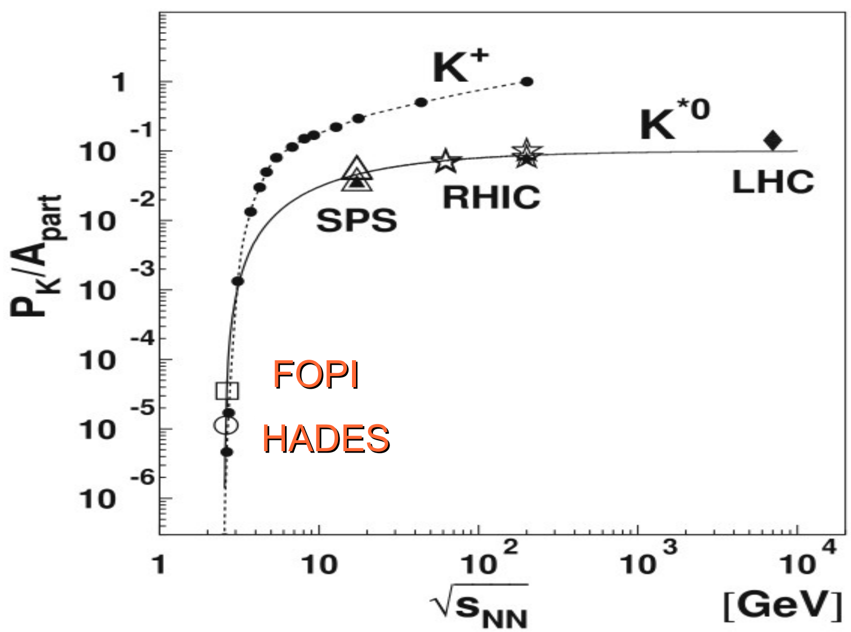
Need to measure with heavier system

Need to include spectral function in transport codes

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

Strangeness production and absorption

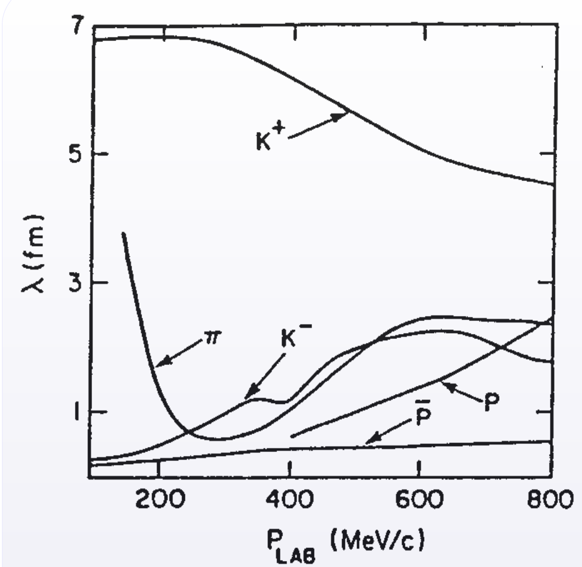
	K^+	K^-	ϕ
Production (primary)	$BB \to BYK^+$ $T_{pp \to p\Lambda K+}$ = 1.58 GeV	$BB \to BBK^+K^-$ $T_{pp \to ppK+K-}$ = 2.5 GeV	$BB \to BB\phi$ $T_{pp \to ppK+K-}$ = 2.6 GeV
Production (secondary)	$\pi B \to YK^+$	$\pi Y \to (\Sigma^* \to)\ BK^-$ $BY \to NK^-\Lambda$ $BY \to BBK^-$ $\pi B \to BK^+K^-$ $\phi \to K^+K^-$	$\pi B \to B\phi$ $\rho B \to B\phi$ $\pi N^* \to N\phi$ $\rho\pi \to \phi$ $K^+K^- \to \phi$ *negligible*
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

Neutral strangeness: K^0 and Λ^0

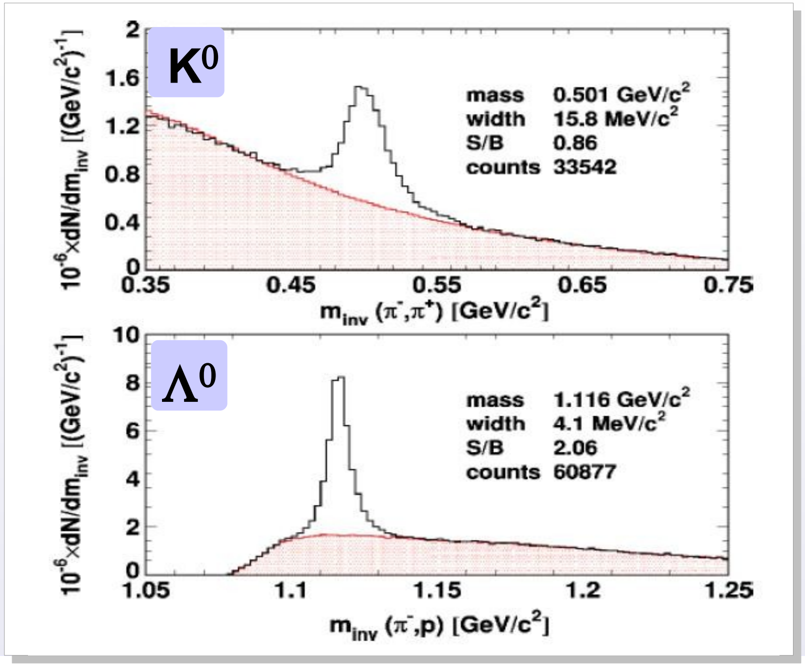
Ni+Ni @ 1.9A GeV

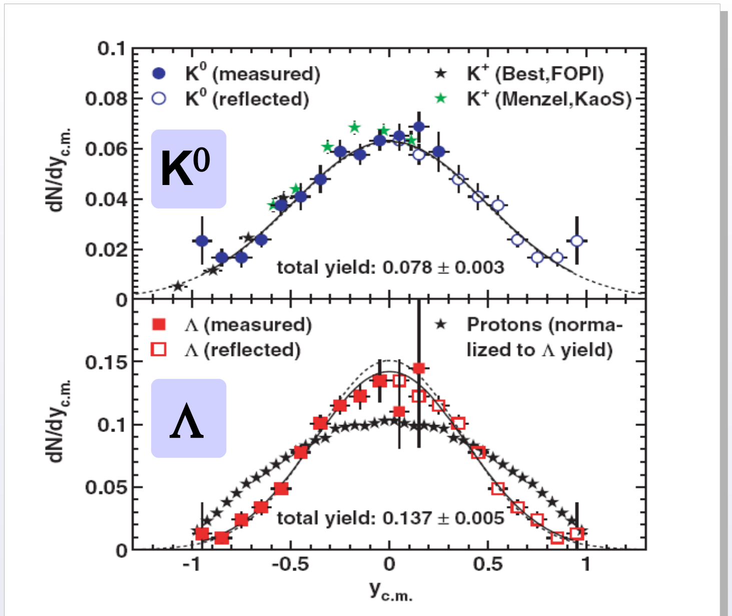
- K^0 and Λ^0 (from secondary vertices)

  $K^0 \rightarrow \pi^+ + \pi^-$ (BR = 69%)
  $\Lambda^0 \rightarrow \pi^- + p$ (BR = 64%)

	$K^0\ (d\,\bar{s})$	$\Lambda^0\ (uds)$
Ni+Ni	30 k	60 k
Al+Al	60 k	100 k

M. Merschmeyer, X. Lopez et al. (FOPI), PRC 76, 024906 (2007)





→ Λ^0 and K^0 obeying Boltzmann distributions

→ Λ^0 and proton: emission patterns different (p → transparency)

Statistical model

Assumption: equilibrium @ chemical freeze-out

Density of species i **:**
(in grandcanonical ensemble)

$$n_i(\mu, T) = \frac{N_i}{V} = \frac{g_i}{2\pi^2}\int_0^\infty \frac{p^2\,dp}{\exp\left(\frac{E_i - \mu_B B_i - \mu_S S_i - \mu_{I_3} I_{3i}}{T}\right) \pm 1}$$

Free parameters: chemical potential μ_B
temperature T

For particle *ratios* : V cancels out
Fixed by conservation laws: μ_S, μ_{I3}

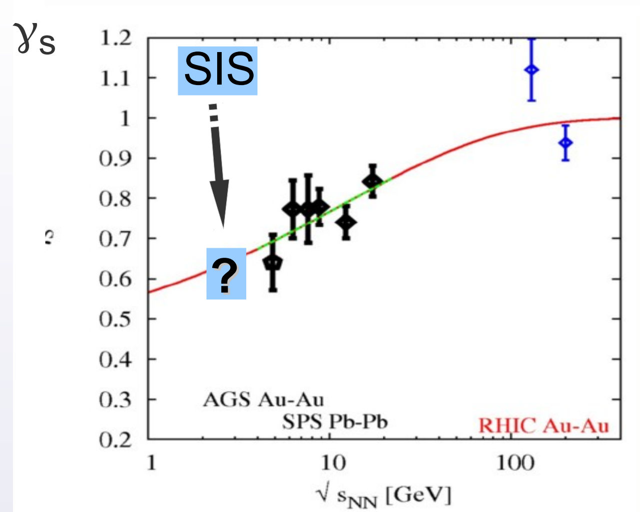
...but

No equilibration of strangeness (?)

Extension:

$$\exp(...) \rightarrow \exp(...)\cdot\frac{1}{(\gamma_S)^{n_S}}$$

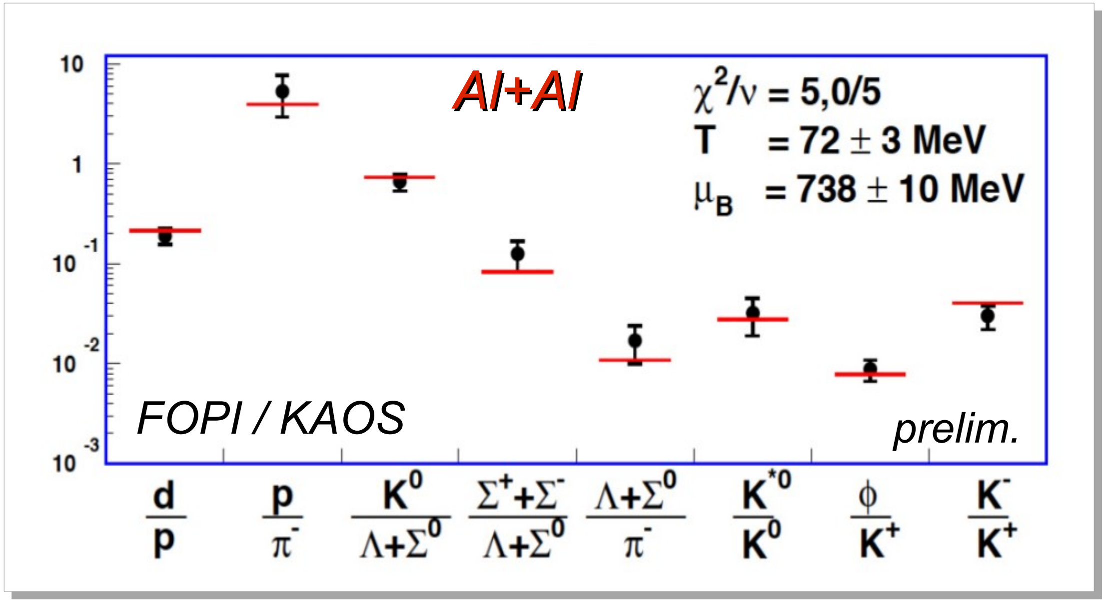
γ_S "strangeness undersaturation factor"
n_S number of strange quarks



F. Becattini et al., PRC 73, 044905 (2006)

Particle yields vs Statistical Model and UrQMD

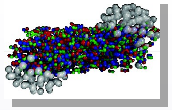
- **Al+Al** : 8 independent ratios involving
  p, d, π^-, K^+, K^-, K^0_s, ϕ, K^{*0}, $\Sigma^{*\pm}$, Λ
- **Ni+Ni** : 8 independent ratios involving
  p, d, π^+, π^-, K^+, K^-, K^0_s, ϕ, Λ



Statistical Model

→ Grand Canonical ensemble;
→ For S≠0, Canonical ensemble
→ calc: THERMUS code
S.Wheaton, J.Cleymans , hep-ph/0407175

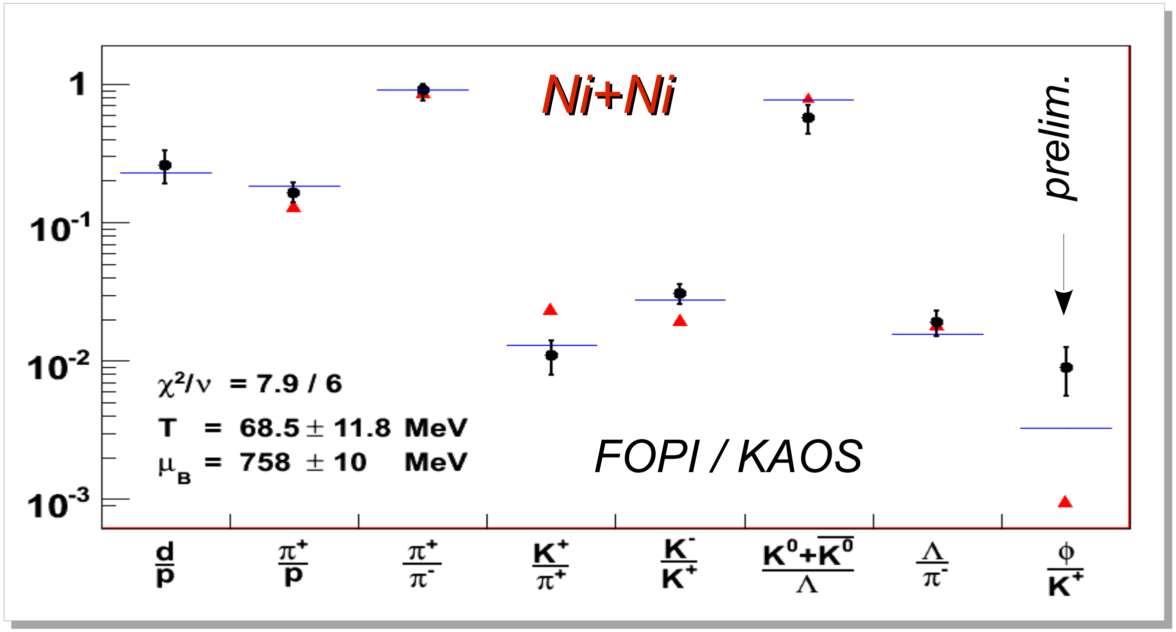
→ *SM* fitting quite well



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



Freeze-out in phase diagram