FOPI

Strange meson production near threshold in nucleus-nucleus collisions

FOPI

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- Physics motivation
- Primary or secondary production?
- K^- production: a complex case
- In-medium modifications of $K^{+,-,0}$
- K^* (892) strange meson resonance
- Summary and conclusions

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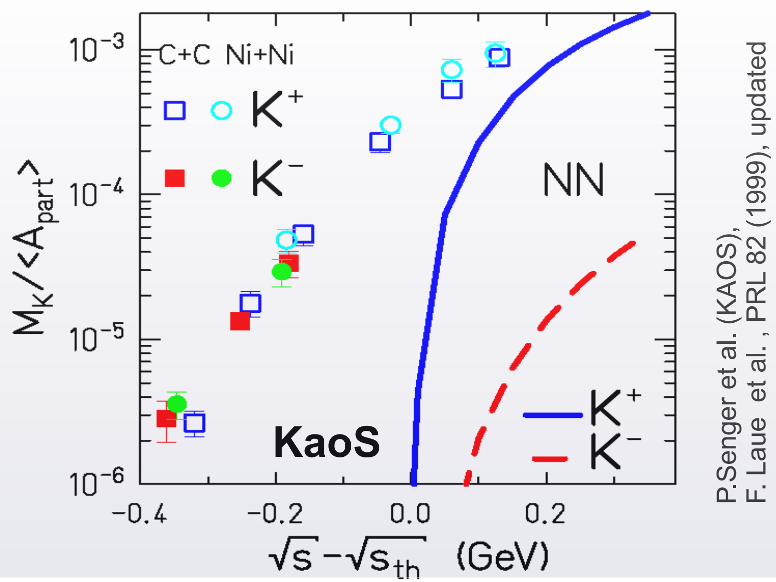
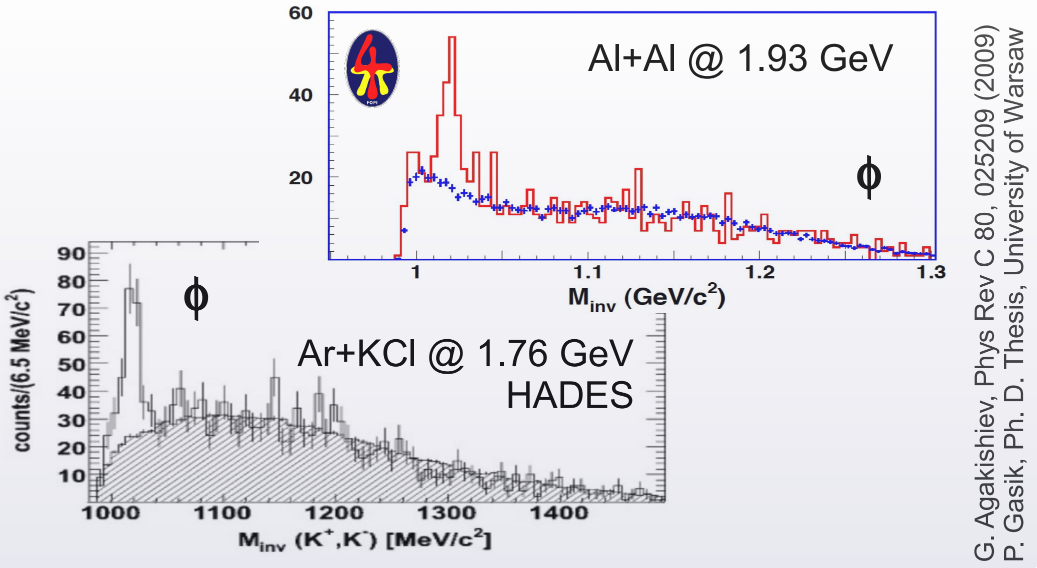
Strange mesons in AA collisions

- **Production thresholds in free NN collision :**

NN → N**K**$^{+/\circ}\Lambda$	T_{lab}= 1.6 GeV
NN → NN**K**$^{-}$K^{+}	T_{lab}= 2.5 GeV
NN → NNϕ	T_{lab}= 2.6 GeV

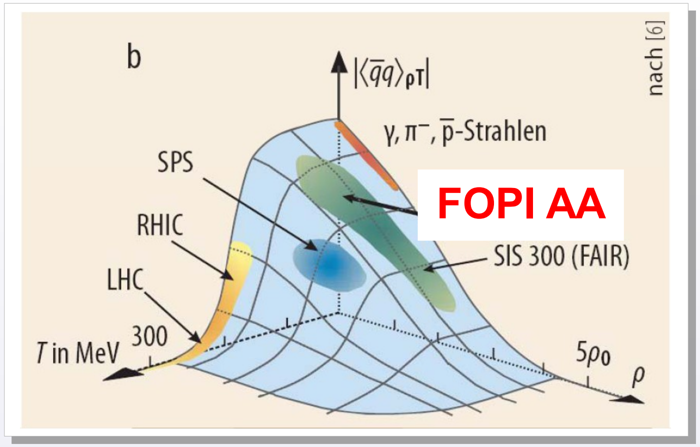




They a r e here . . .

- <u>Strange mesons in AA collisions</u>:
  - Are the production processes primary or secondary?
  - Decays? Contributions from intermediate resonances?
  - Modification of properties in medium?
  - Production of strange resonances?

Probing partial restoration of chiral symmetry



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

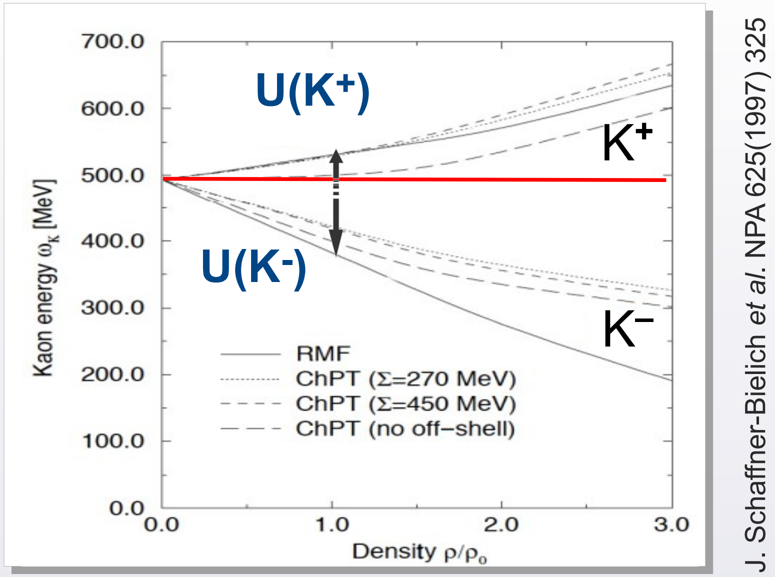
Gell-Mann Oakes Renner – relation:

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

Decay constant

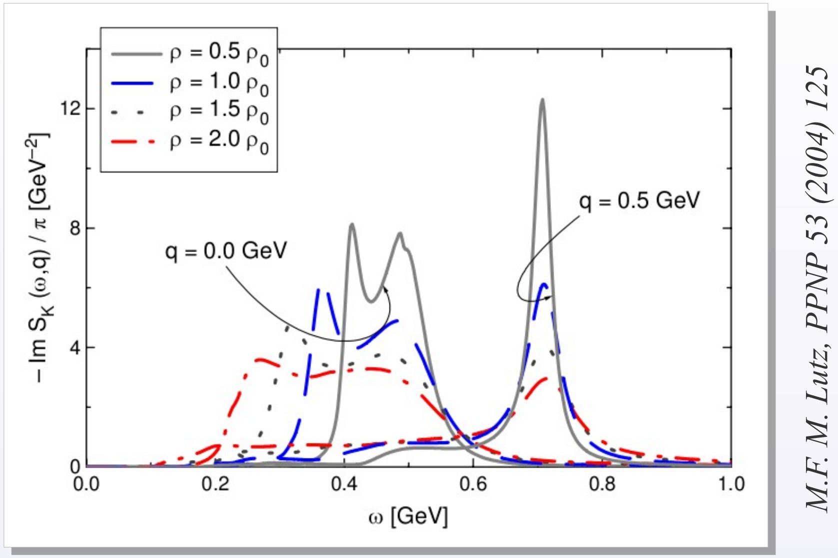
Mass

- First approaches: Potential



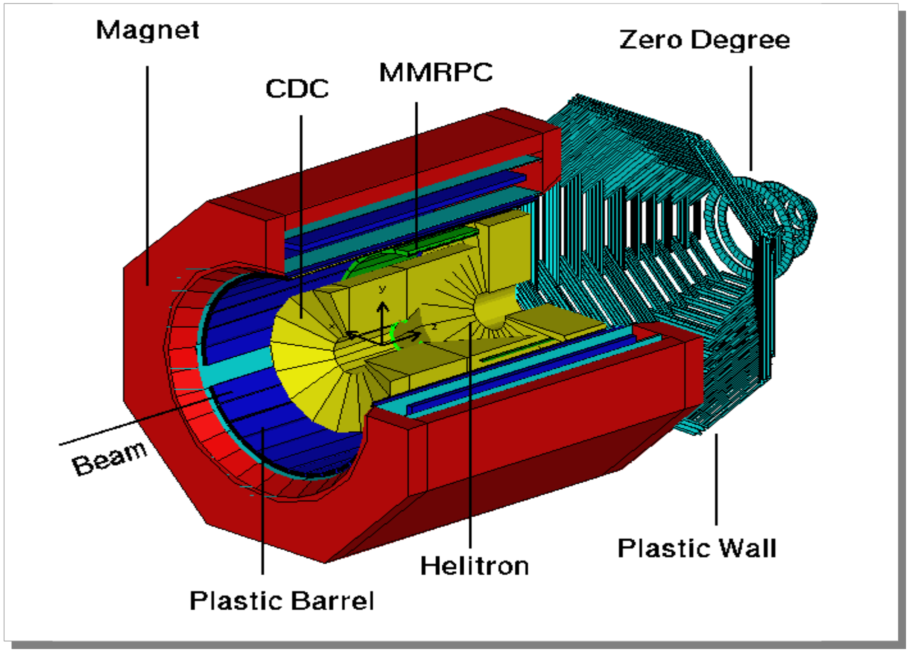
- $\vec{F} = -\vec{\nabla} U$ ⇒ K^- attracted, K^+ repelled

- Chiral effective field theory w/ couple-channels



→ „Potential” only on average

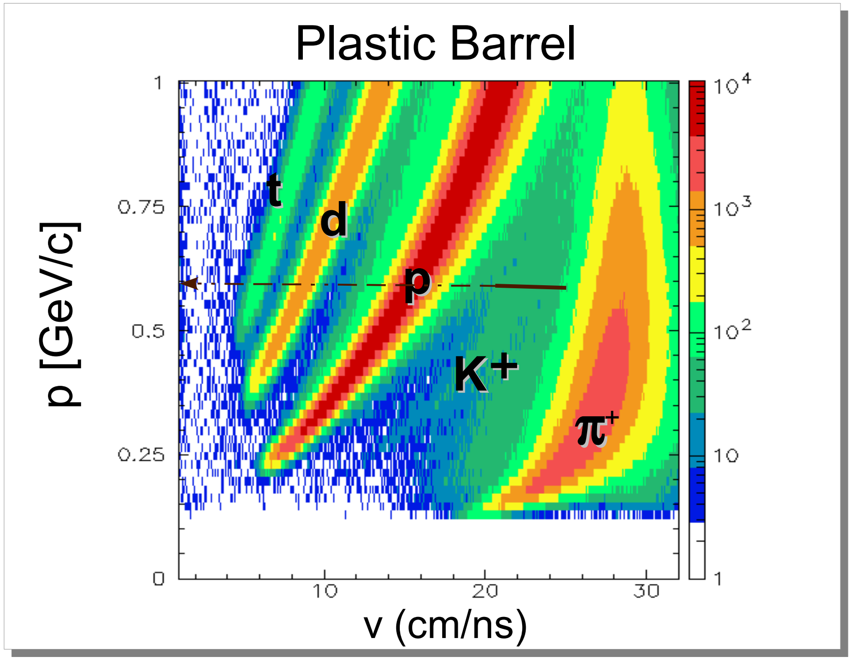
FOPI experimental setup

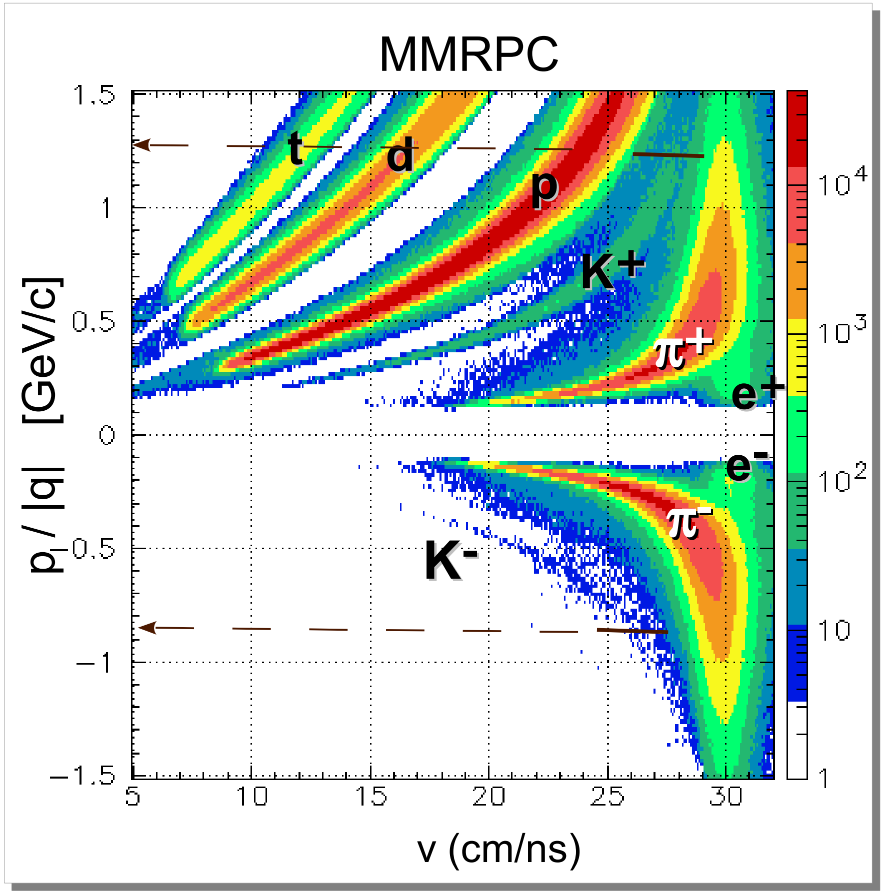


- Nearly 4π coverage
- Drift chambers: CDC, Helitron

  ToF : Plastic Barrel, RPC

  Forward: Plastic Wall, Zero Degree
- Direct PID of $\pi^{\pm}$, $K^{\pm}$, p, d, t, ^{3,4}He





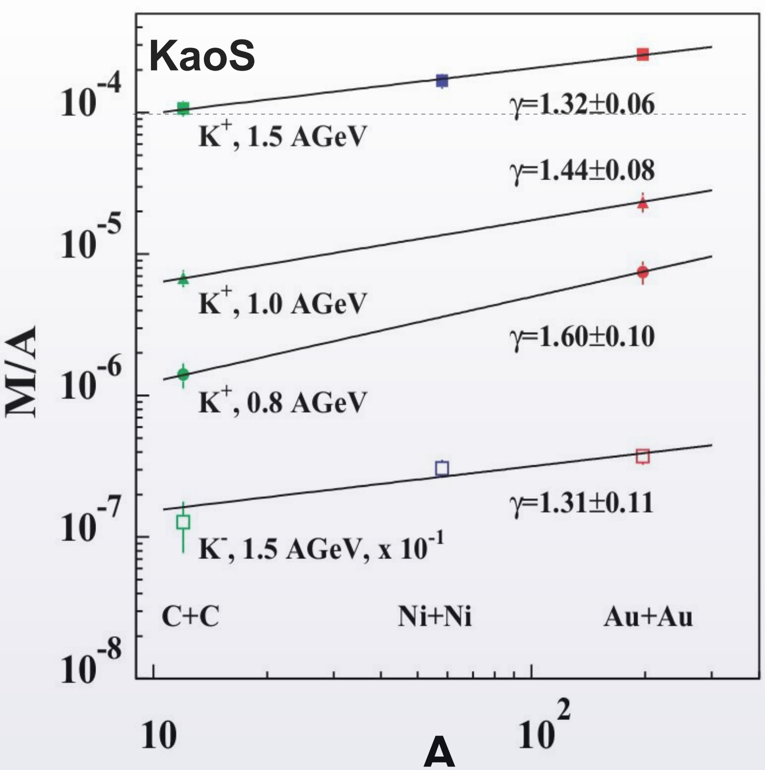
Production of Kaons in AA: Primary or secondary?

If primary:

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

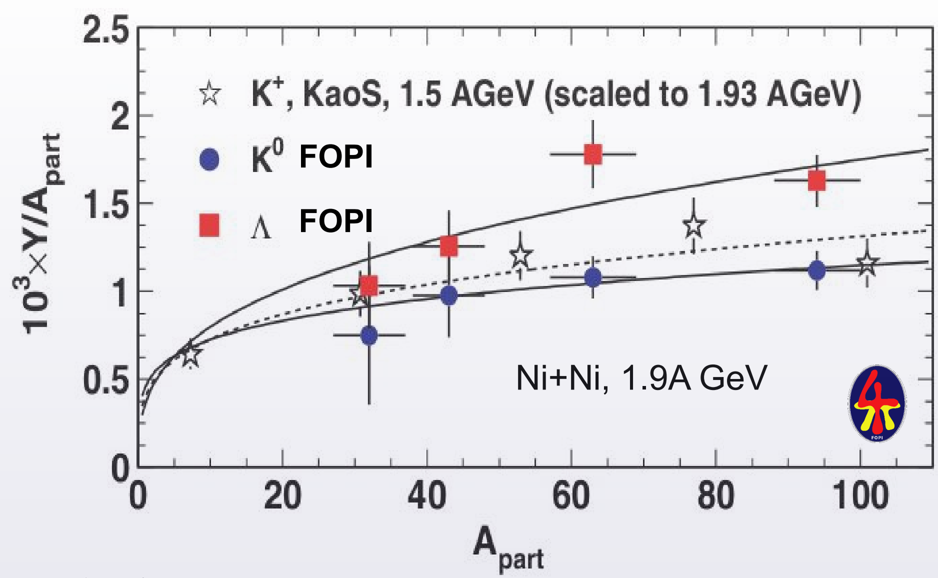
AA→ KX: Glauber: AA = A ⊗ NA

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



A. Förster et al., PRC 75, 024906 (2007)

→ secondary processes are involved



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

→ 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)

Sub- and near-threshold Production of K^-

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

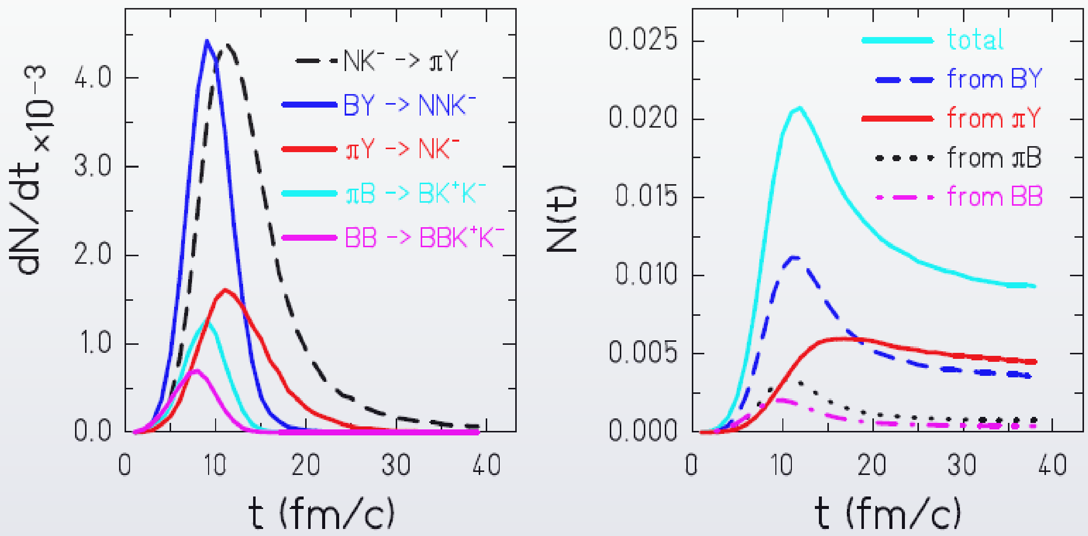
  $BY \rightarrow NNK^-, \quad \pi Y \rightarrow K^- B$

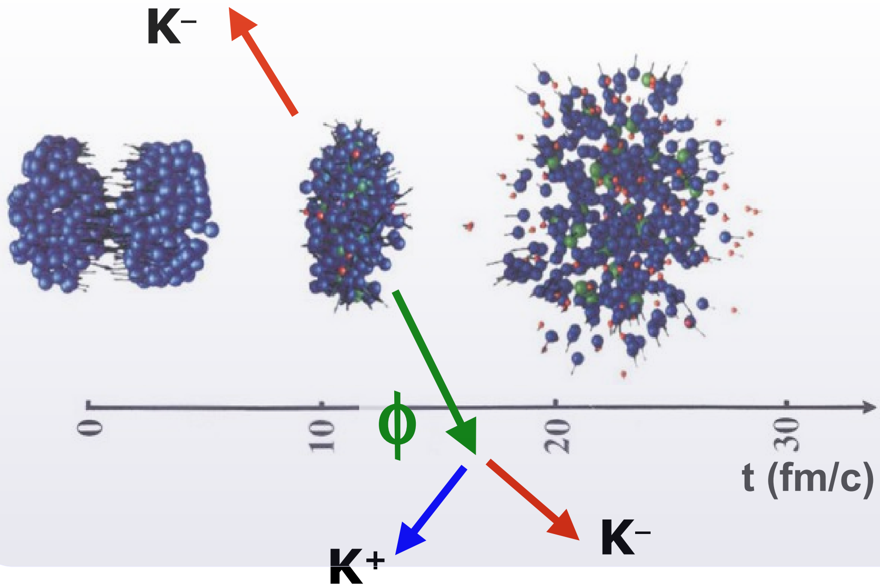
  - strong reabsorption: $K^- B \rightarrow \pi Y$
  - coupled to resonances $\Sigma(1385)$, $\Lambda(1405)$

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

  Q: Can we see them?

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





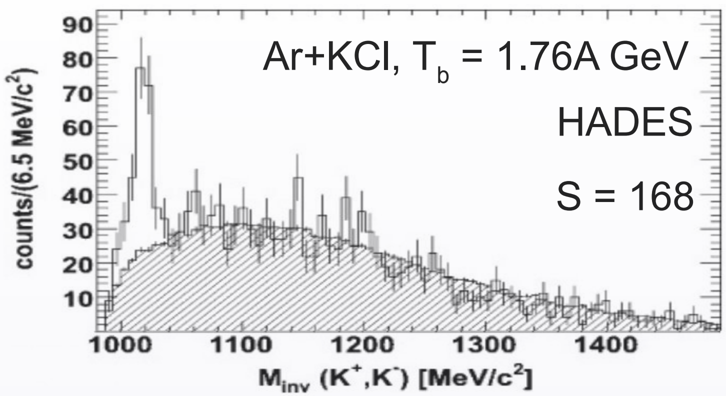
- $\phi(1020) \rightarrow$ **K^-K^+** decay (mostly outside collision zone)

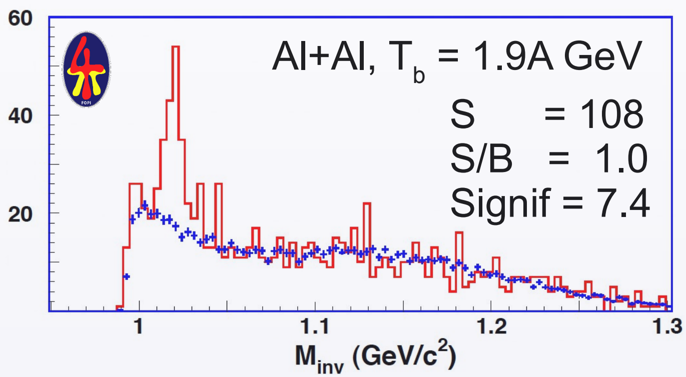
  Q: How strong is this contribution?

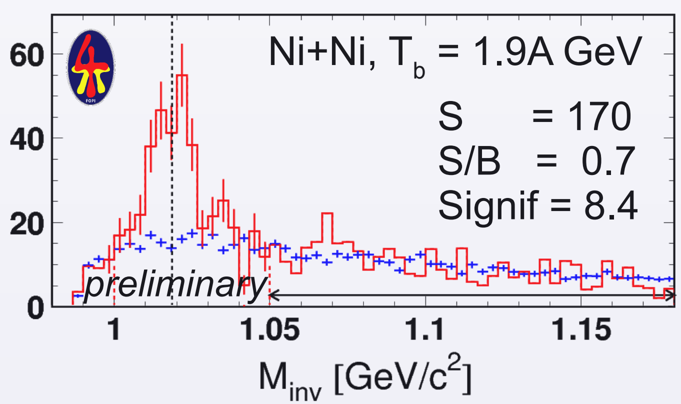
- In-medium effects: "U_{KN} potential" or "spectral density"

  Q: How strong is this influence?

ϕ (1020) mesons







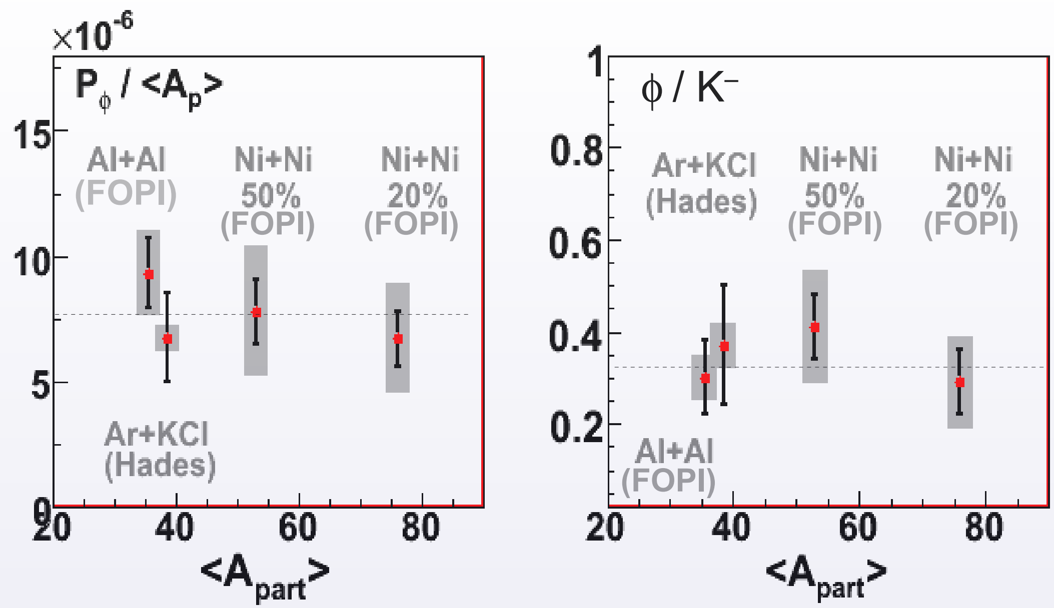
G. Agakishiev, Phys Rev C 80, 025209 (2009)
P. Gasik, Ph. D. Thesis, University of Warsaw

- ϕ ($s\bar{s}$) → K^+K^- *(BR = 49%)*

  m = 1019 MeV

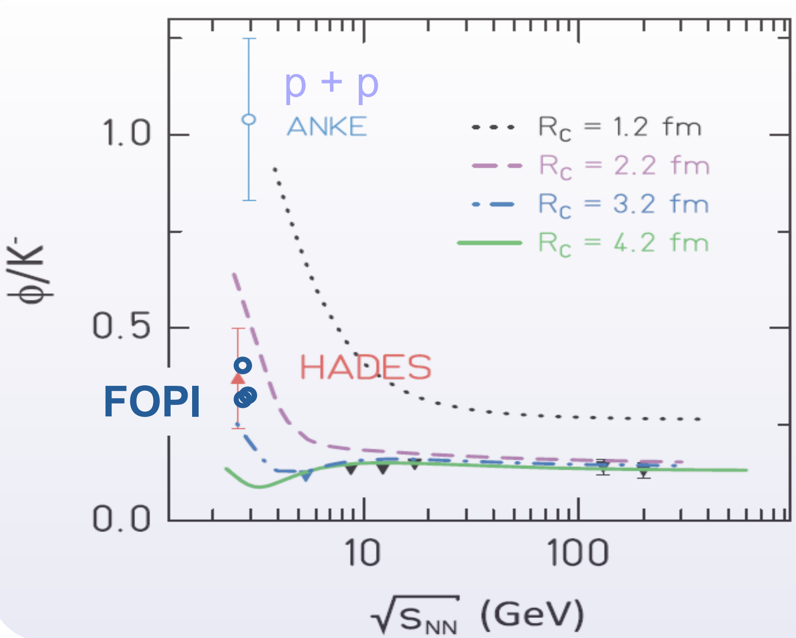
  cτ = 50 fm (*decays mostly outside collision zone*)

  E_{th} = 2.6 GeV (for SIS-18, *deeply subthreshold)*



- P_ϕ possibly ~ <A_{part}>
- $\frac{\phi}{K^-} \approx \frac{1}{3}$ → ~ 15 .. 20% of K^- produced from ϕ decays

ϕ/K^- excitation function



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

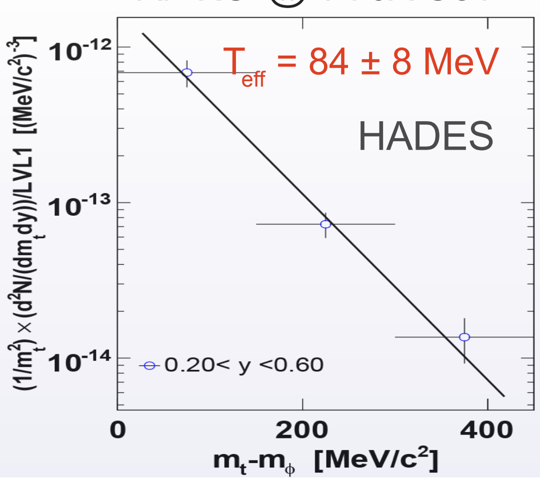
within **S**tatistical **M**odel

- For S≠0, Canonical ensemble
- ϕ : non-strange , K^- : strange
- At low $\sqrt{s}$, ϕ/K^- sensitive to $R_{Canonical}$

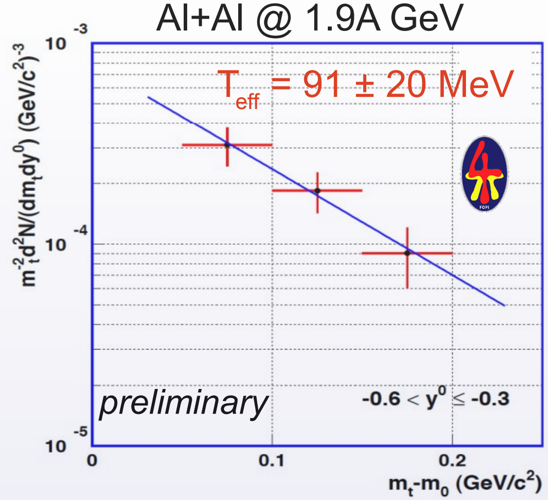
→ $R_{Canonical}$ ~ 2-3 fm

Exploring ϕ phase space

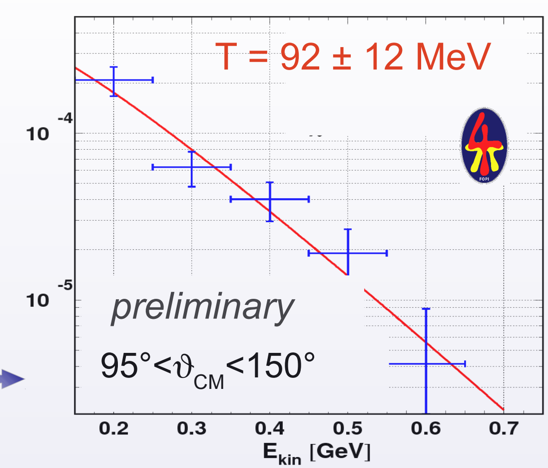
Ar+KCl @ 1.76A GeV



Al+Al @ 1.9A GeV



Ni+Ni @ 1.9A GeV

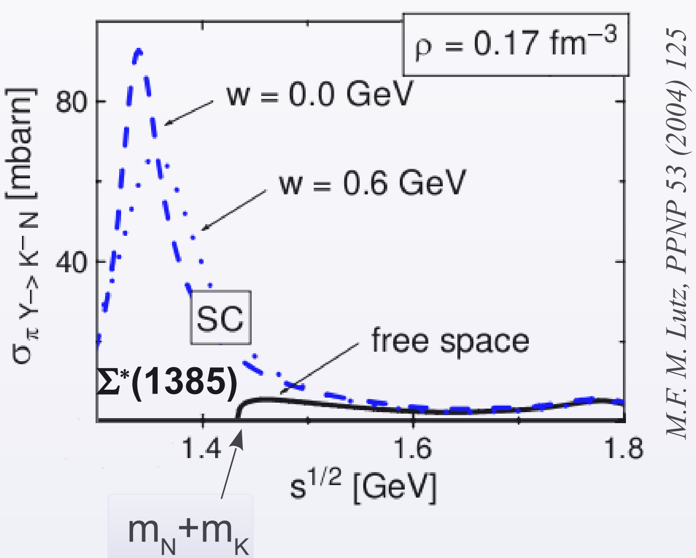


Σ^*(1385) resonance

Chiral effective field theory w/ coupled-channels

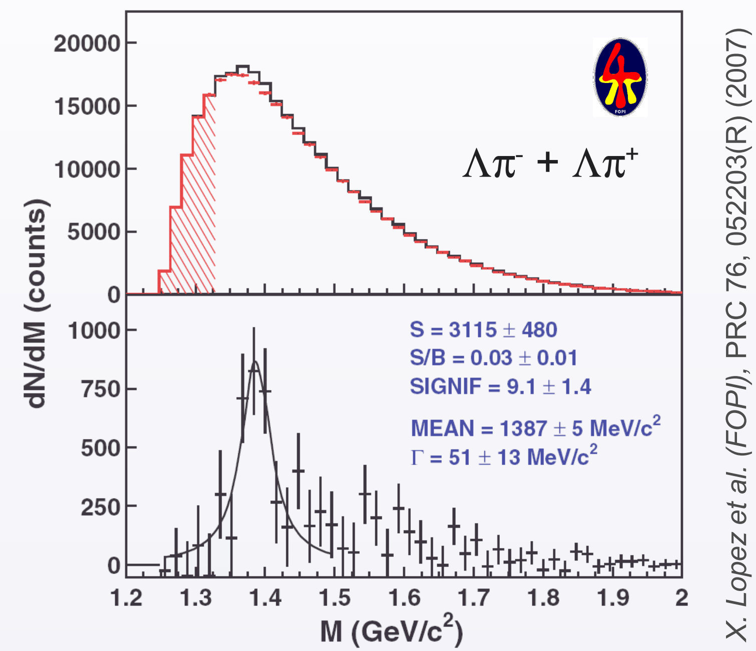
- K^- production in medium (**πY → K^-N**) coupled to strange resonances e.g. Σ^*(1385), Λ^*(1405) :

(**$\pi\Lambda$ → Σ^* → K^-N**)



- Al+Al, T_{beam} = 1.9A GeV

$\Sigma^{\pm *}$ (1385) → $\Lambda + \pi^{\pm}$ (88 ± 2%)
↳ $p + \pi^-$



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

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

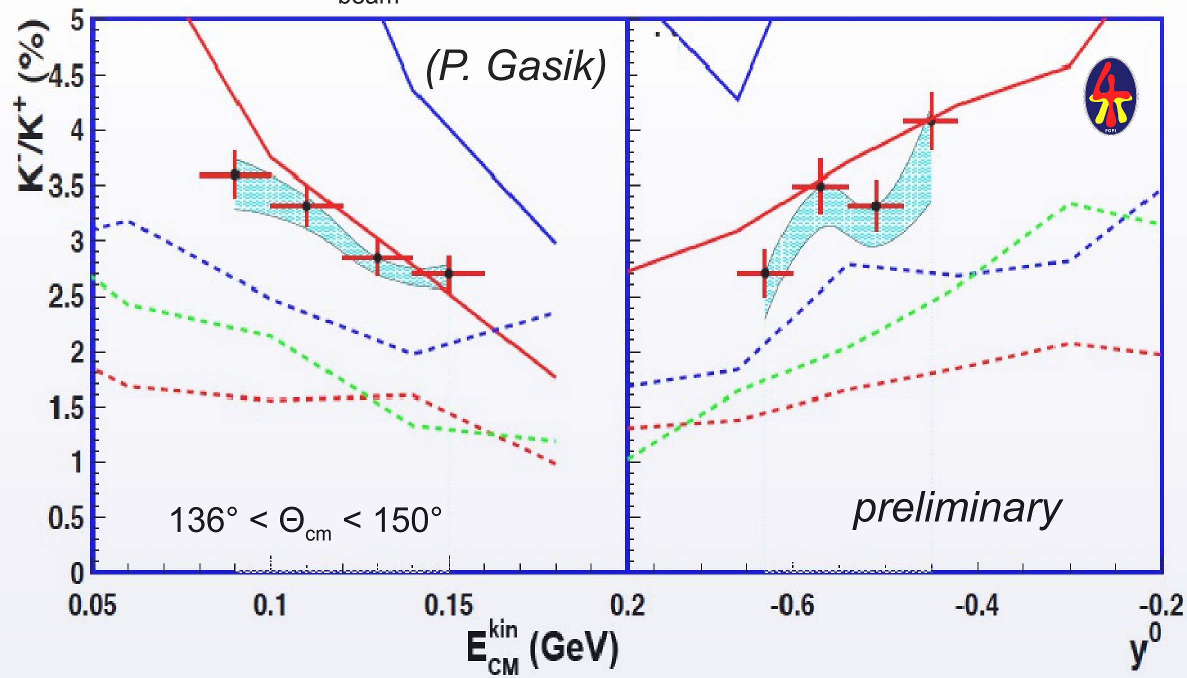
K^-/K^+ : experiment vs transport

- 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

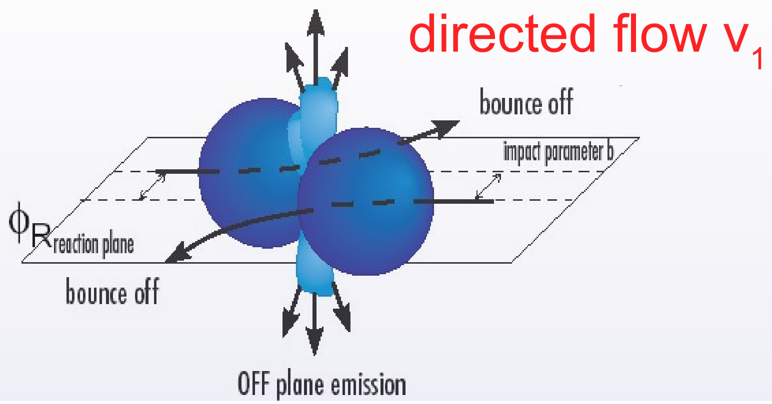
Al+Al, T_{beam} = 1.9A GeV, 9% most central events



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

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

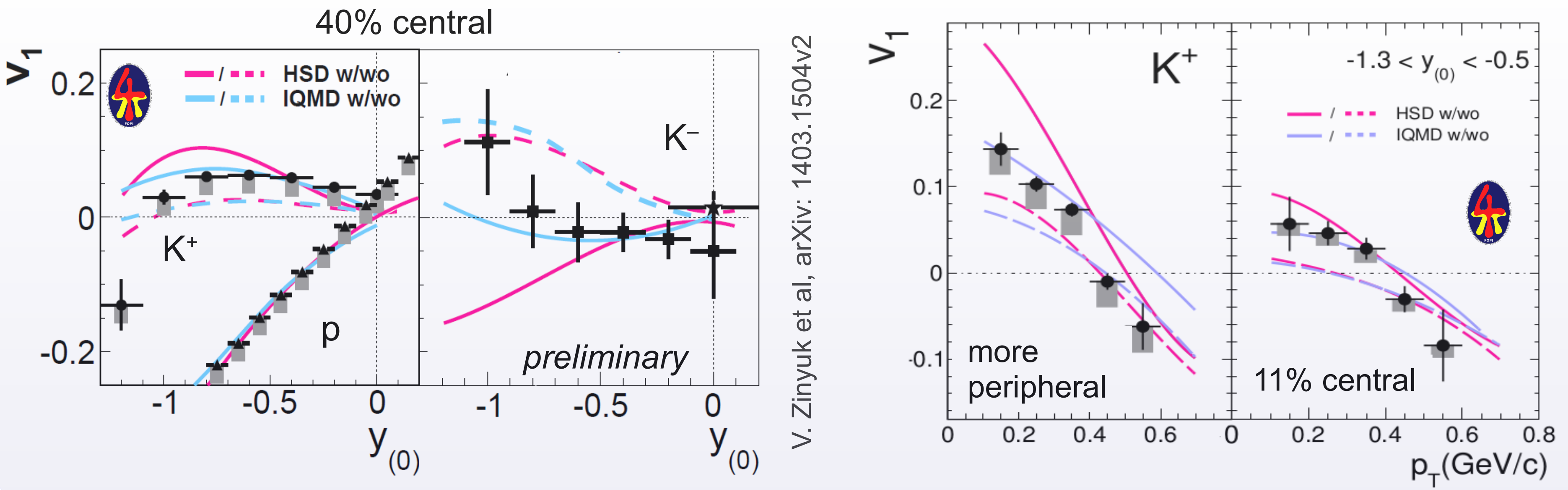
Flow of charged kaons



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

v_1, v_2 = Fourier coefficients

Ni+Ni , T_{beam} = 1.9A GeV

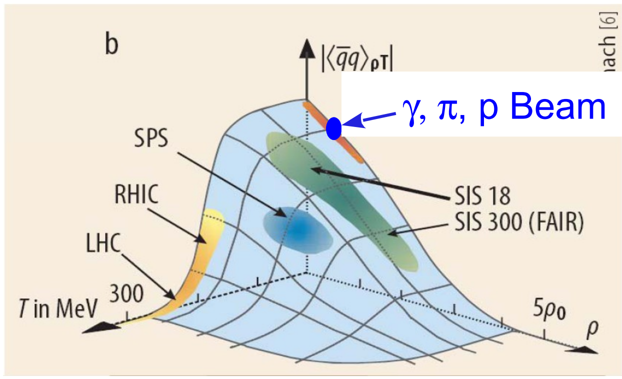


HSD : U_{K+N} = 20 MeV $U_{K-N} \approx$ -50 MeV

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

→ ~ In favour of the potential

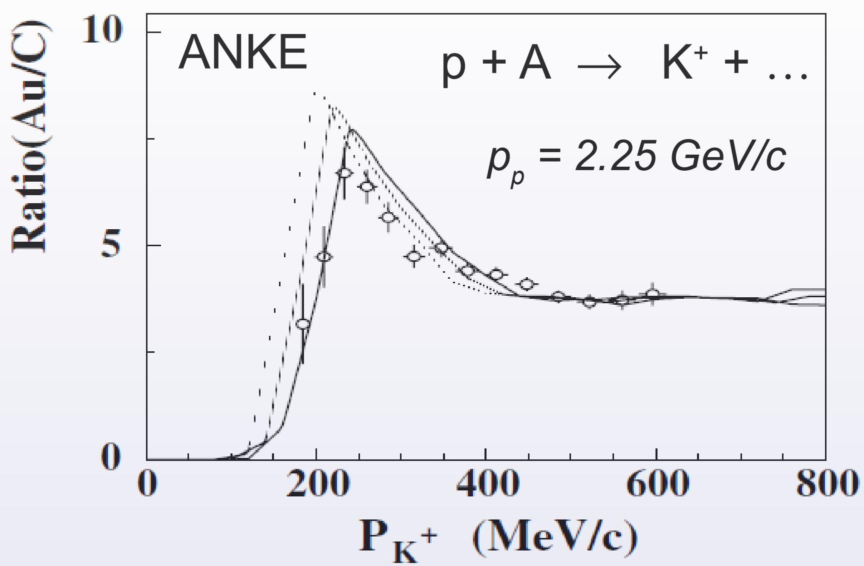
In-medium modifications of $K^{+/0}$ at $\rho < \rho_0$



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

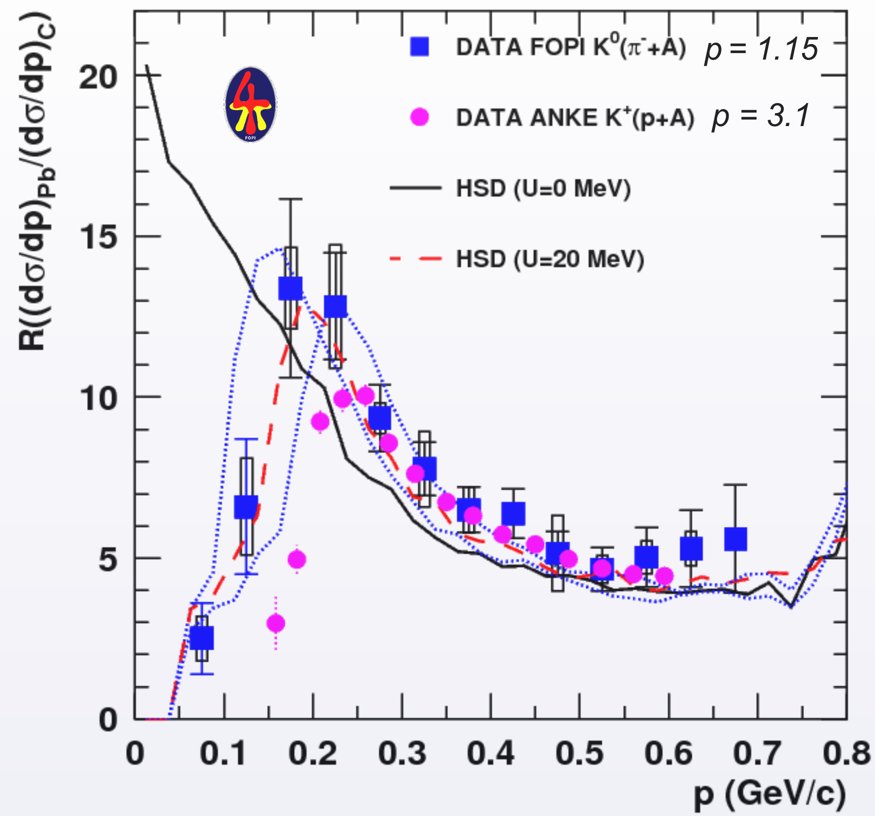
π^- (p=1.15 GeV/c) + A → K^0 + … *FOPI*

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)

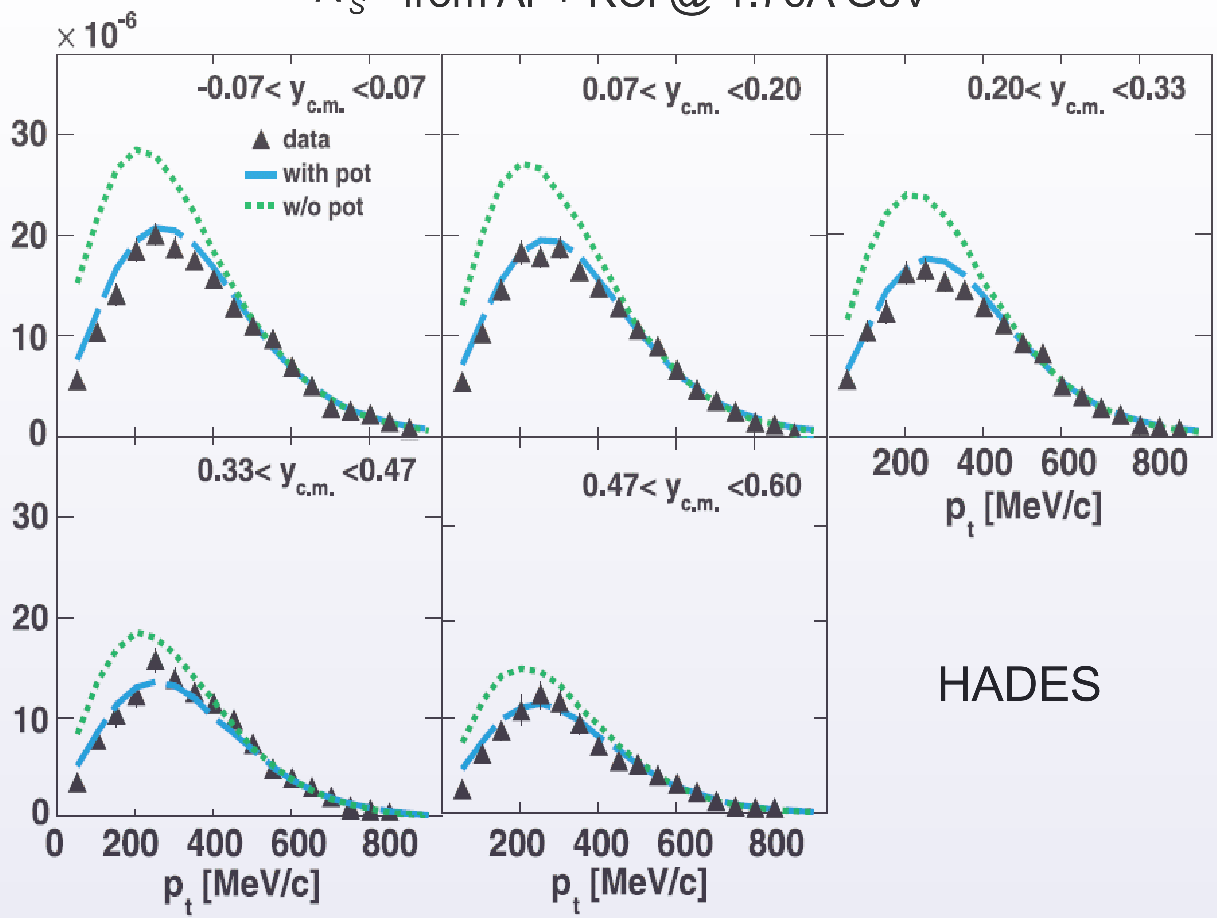
CBUU transport code		
	· · · ·	U_{KN} = 0 MeV
	········	U_{KN} = 10 MeV
	——	U_{KN} = 20 MeV



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

Modifications of K^0 in AA collisions

K_S^0 from Ar + KCl @ 1.76A GeV



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

K_S^0 $c\tau$ = 2.7 cm

K_L^0 $c\tau$ = 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

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

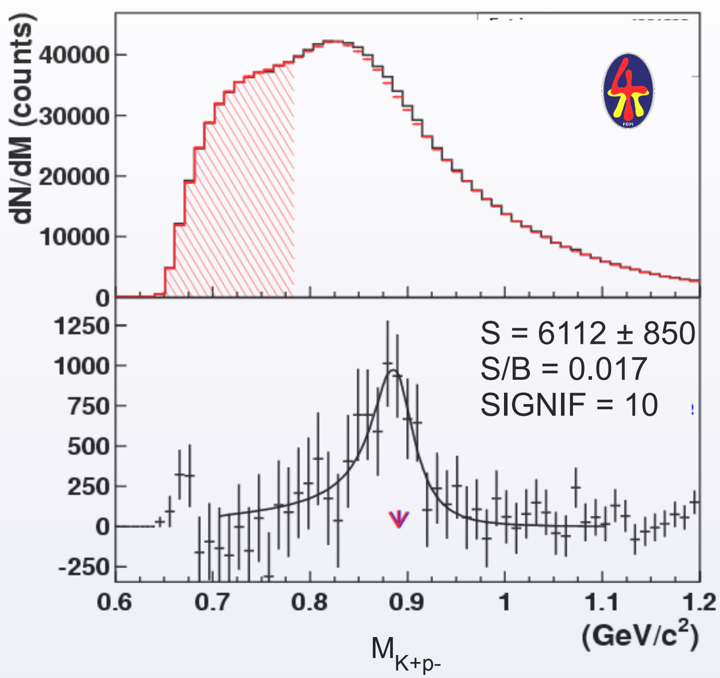
Kaonic resonance: K*(892)

K^{0*} (892) → $K^+ \pi^-$ (~ 67%)

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

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

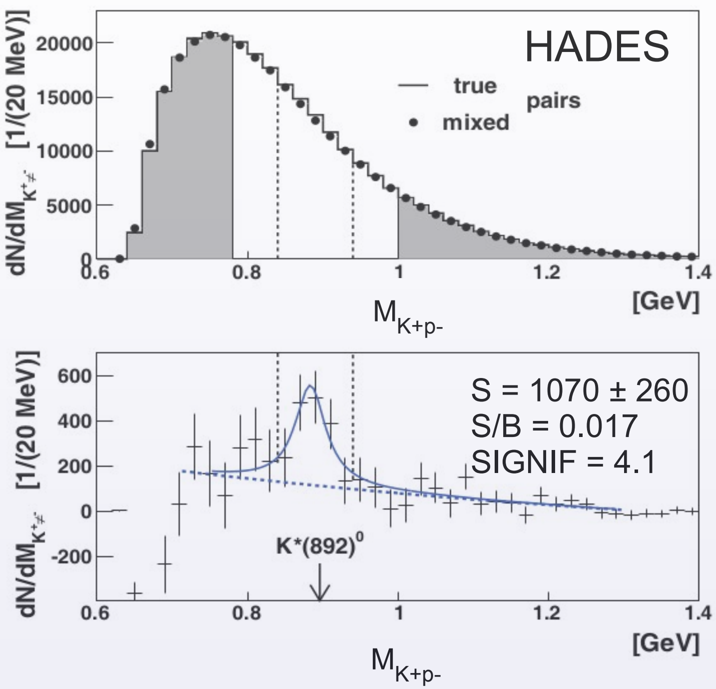
Al+Al @ 1.9A GeV



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

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

Summary and conclusions

- In sub- and near-threshold AA collisions, strange meson production needs secondary processes

- Production of K^- more complex than K^+ and influenced by:
  - ϕ(1020) $\rightarrow K^-$ via decay (15..20%)
  - $\Sigma^{\pm *}$(1385) : strangeness exchange channel via Σ^* ($\pi\Lambda \rightarrow \Sigma^* \rightarrow K^- N$)
  - in-medium modification of properties of K^-

- In-medium modifications of properties of $K^{+/-/0}$
  - Study of K^-/K^+ ratio
  - Study of v_1 ($K^{-/+}$)
  - Study of K^0_S p and p_T-Y distributions

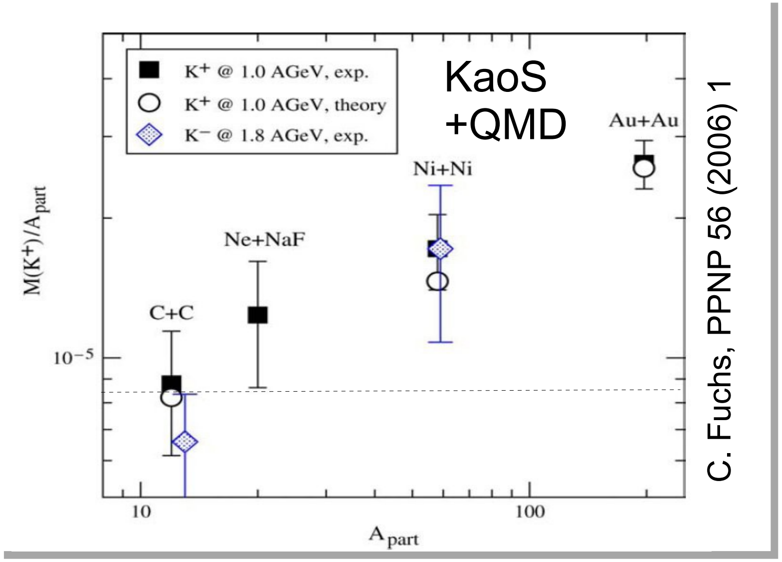
  } U_{K+N} ~ 10 .. 40 MeV
  U_{K-N} ~ -30 .. -50 MeV
  U_{K0N} ~ 20 MeV at $\rho \leq \rho_0$
  ~ 45 MeV at $\rho \sim 2\rho_0$

- K*(892) strange meson resonance observed in Al+Al @ 1.9, Ar+KCl @ 1.76

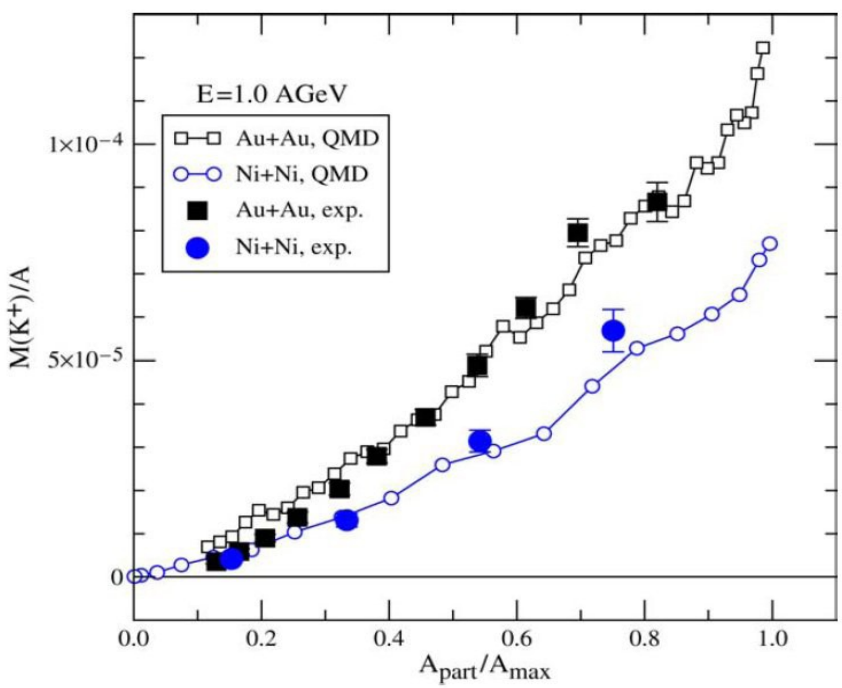
Thank You!

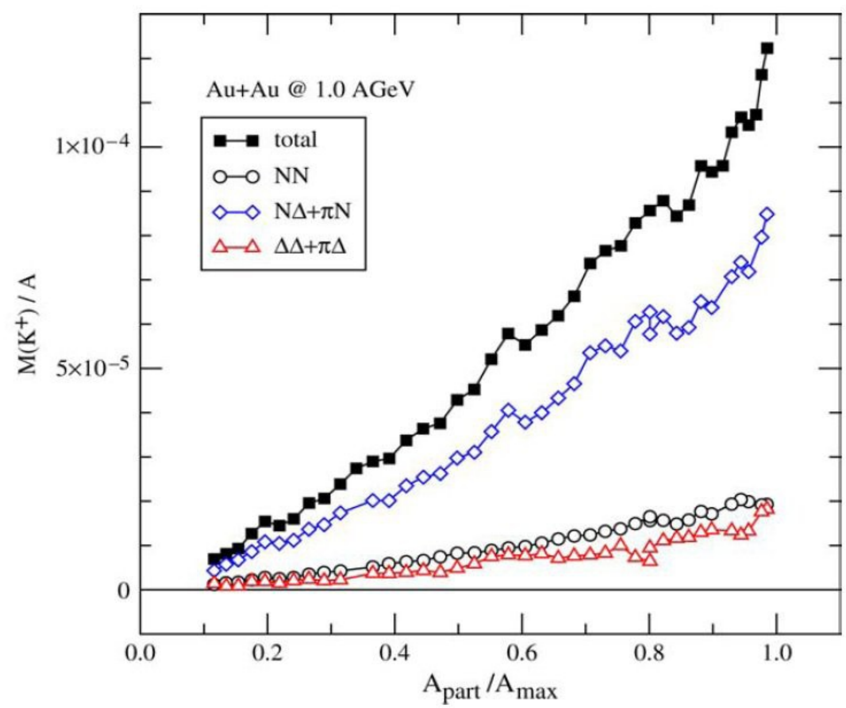
- K^+ Primary: (Fermi momentum)
  $NN \rightarrow NK^+Y$ ($Y = \Lambda, \Sigma$)

  K^+ Secondary:
  $BB \rightarrow BK^+\Lambda$ ($BB = N\Delta, \Delta\Delta$)
  $\pi B \rightarrow K^+Y$ ($B = N,\Delta$)



Secondary processes involved

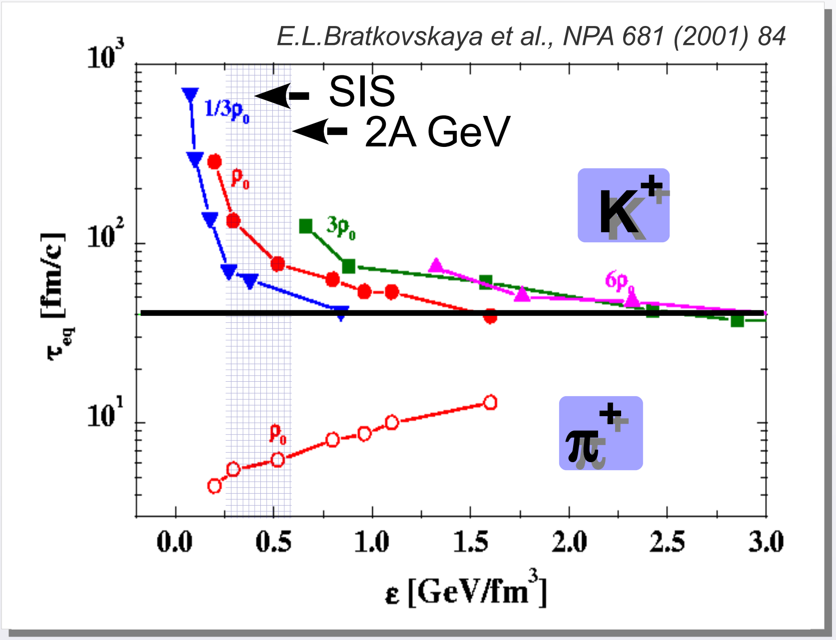




HSD transport model

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

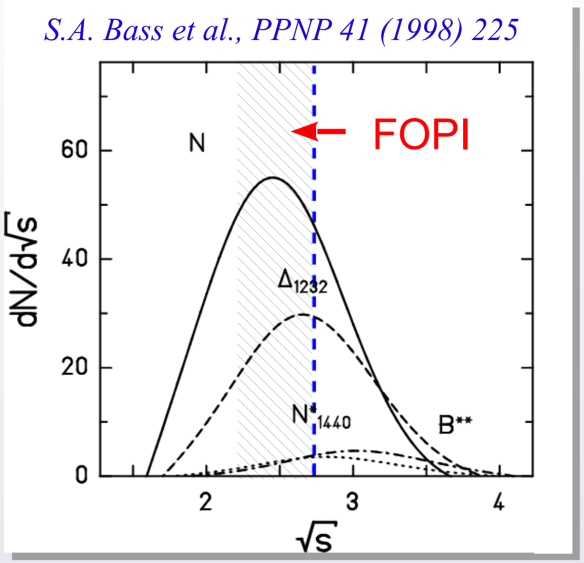
  τ_{eq} @ 2/3 of $N_{equilibrium}$



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

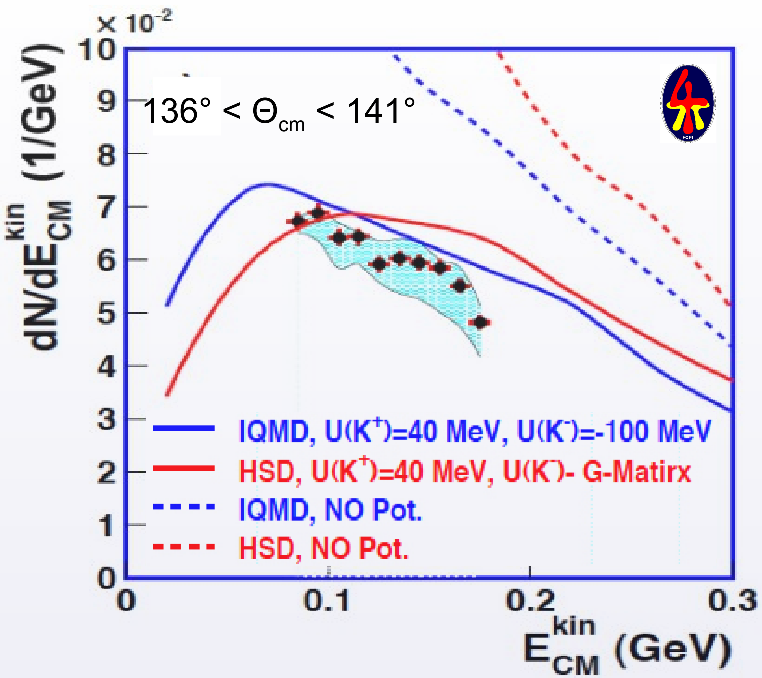
no thermalization of strangeness

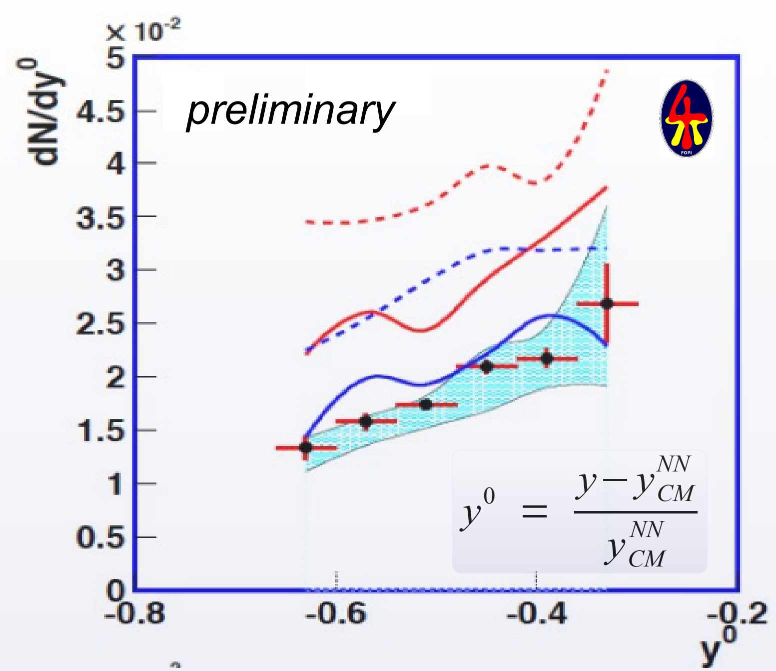
- At SIS energies, resonance production (Δ, N*) reaches maximum



K⁺ phase space: experiment vs transport

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





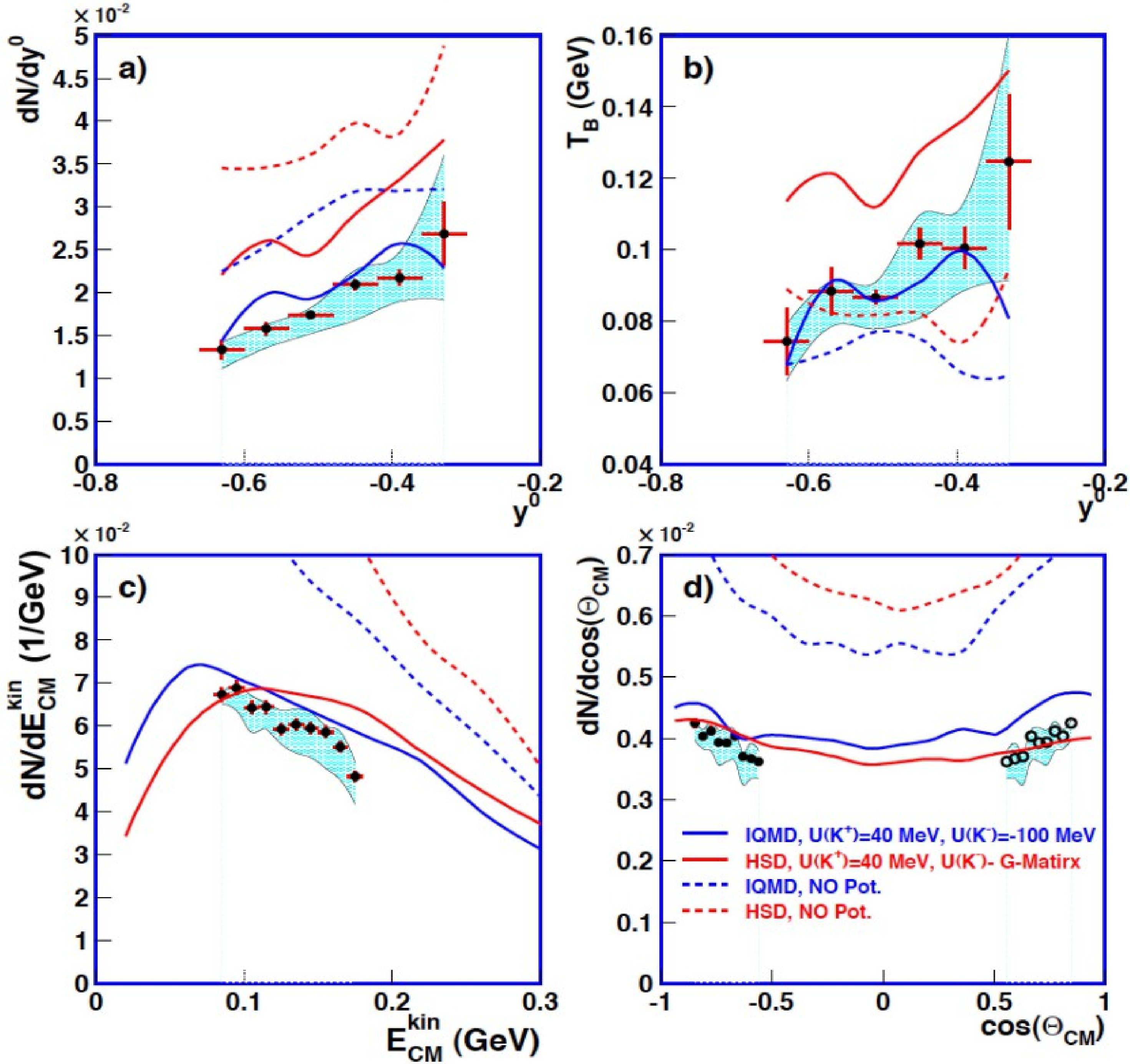
Calc.: Y. Leifels (GSI/Darmstadt).
Ref.: C.Hartnack, H.Oeschler, Y.Leifels, E.Bratkovskaya, J.Aichelin, nucl-th/1106.2083v2

- **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 $\rho=\rho_0$ $\Delta m_{K+} = 40$ MeV, $\Delta m_{K-} = -100$ MeV

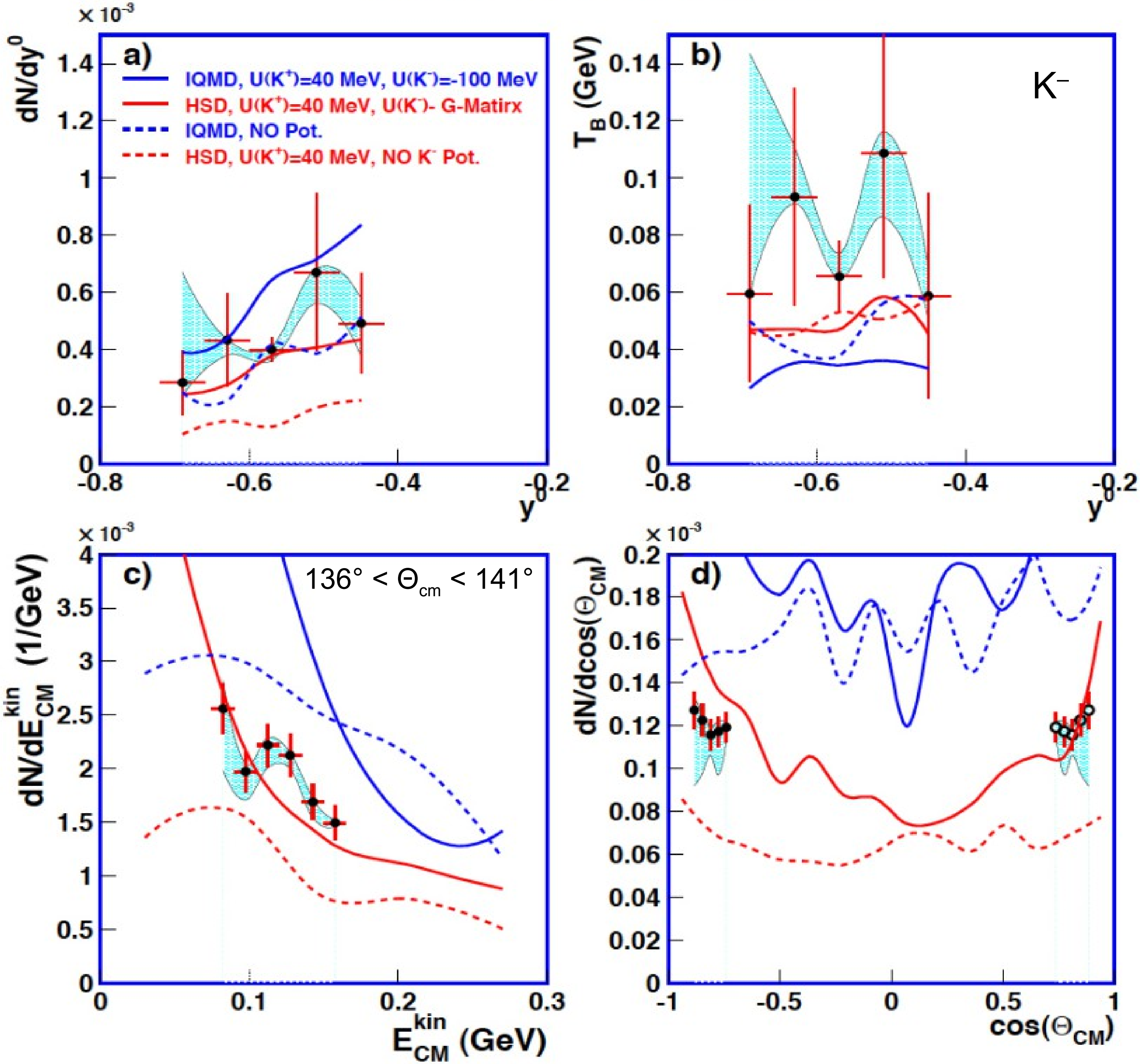
- **HSD**
  - Semi-soft EoS ($K \approx 250$ MeV)
  - K⁺ mass modifications as in IQMD
  - K⁻ production: off-shell G-matrix

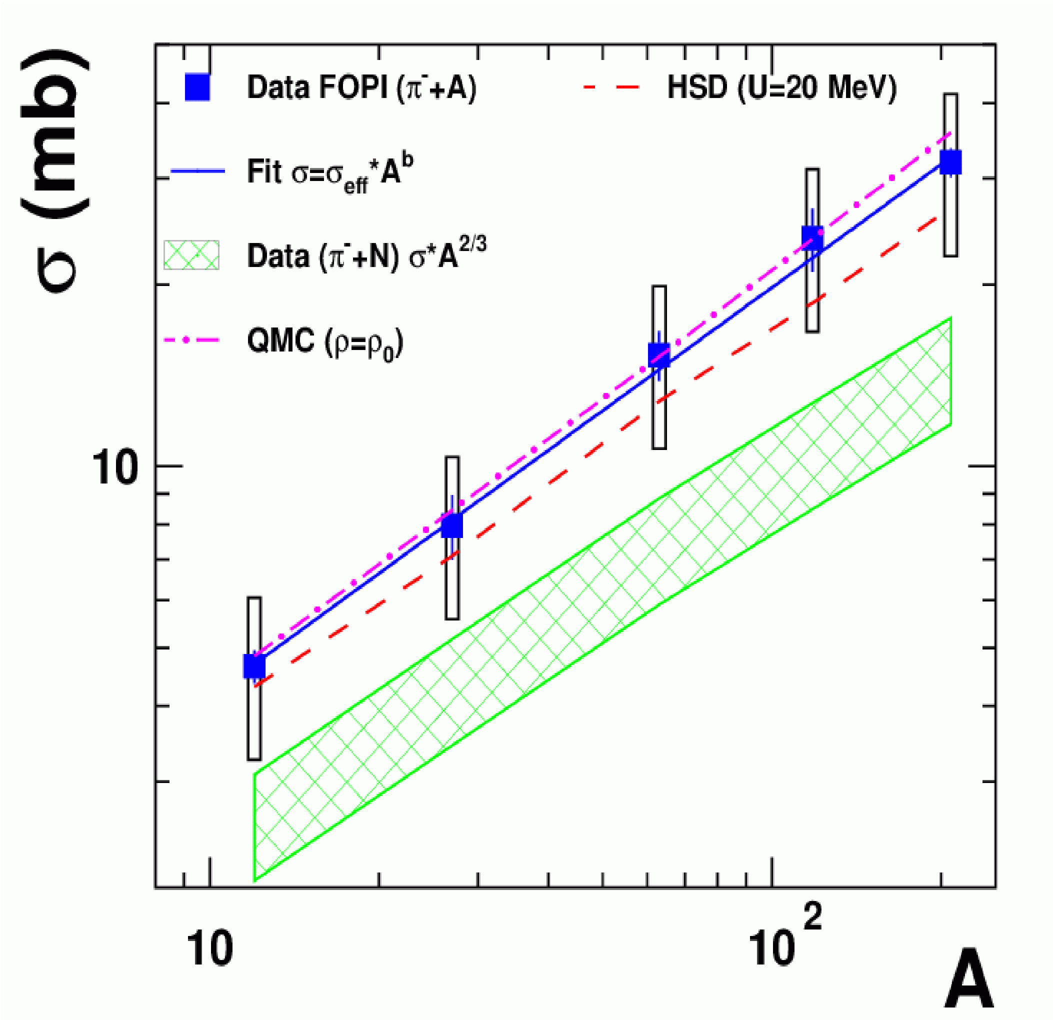
- Clear preference for $U_{KN} \neq 0$ option
- Still description not ideal

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

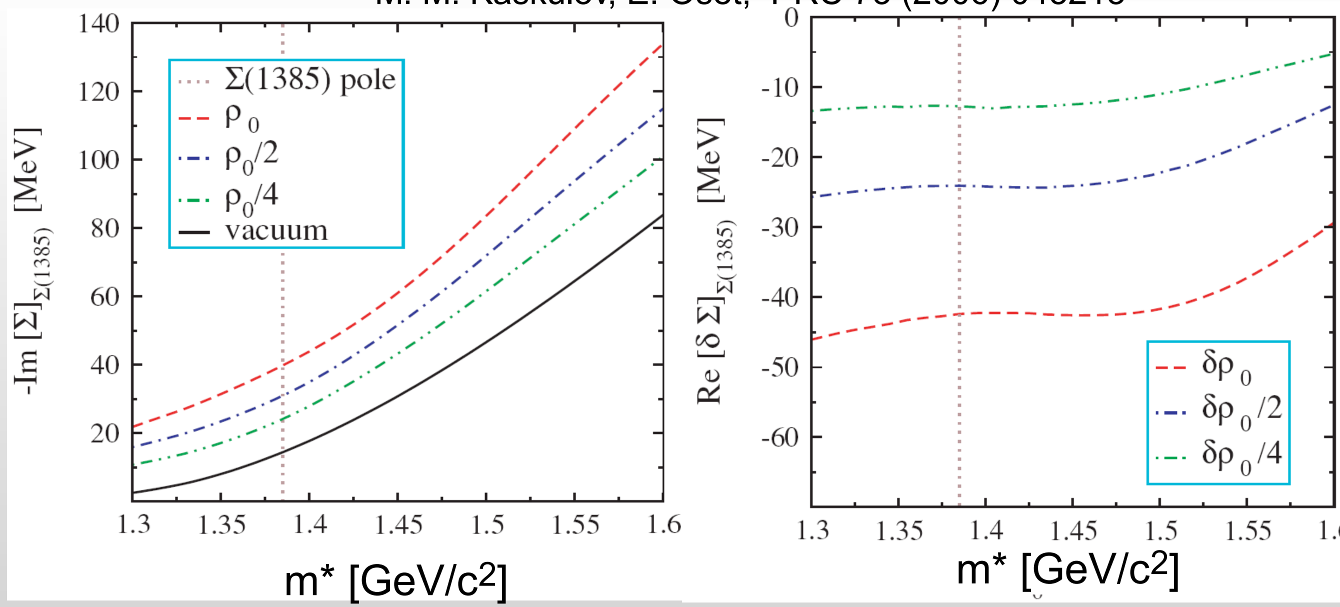
at $\rho = \rho_0$:

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

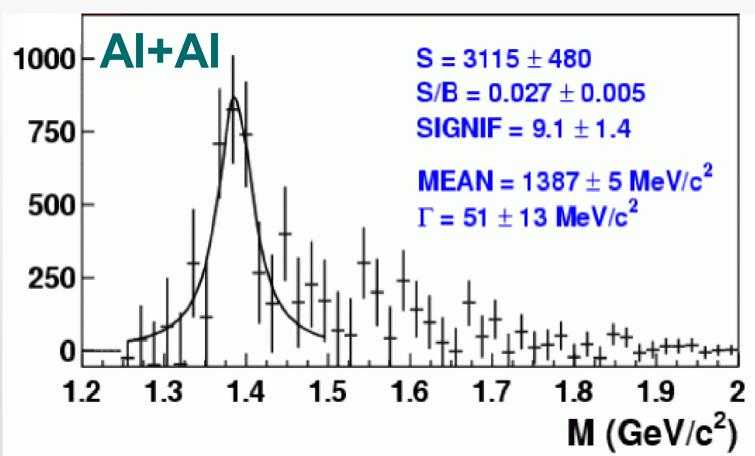
Mass:

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

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



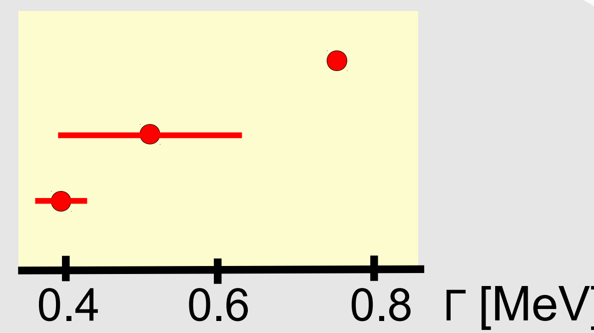
X. Lopez et al., PRC 76, 052203(R) (2007)



Chiral unitary theory

FOPI expt. data

PDG mass ($\rho = 0$)



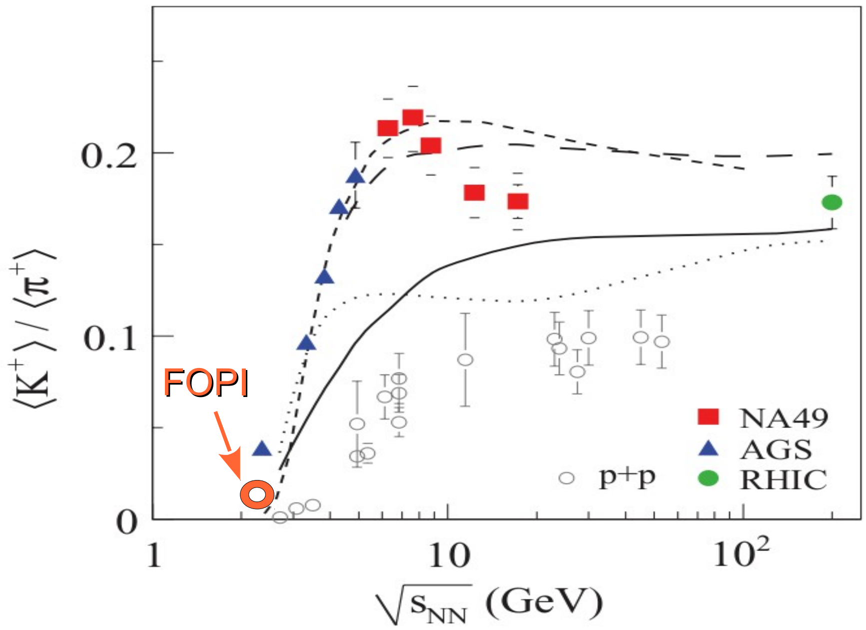
short lifetime → Σ* should probe finite density!

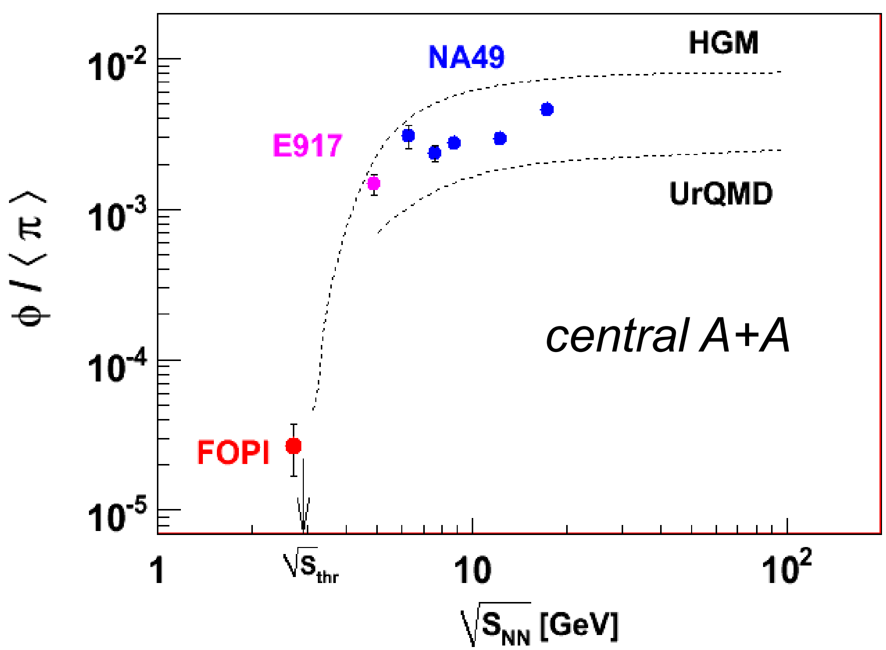
Γ broadening not yet observed (more statistics...)

Need to measure with heavier system

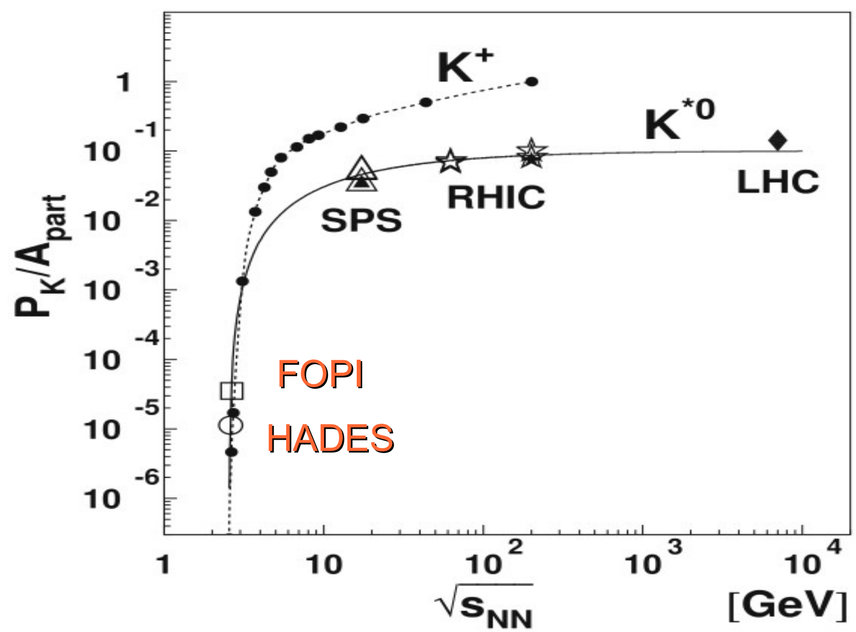
Need to include spectral function in transport codes

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

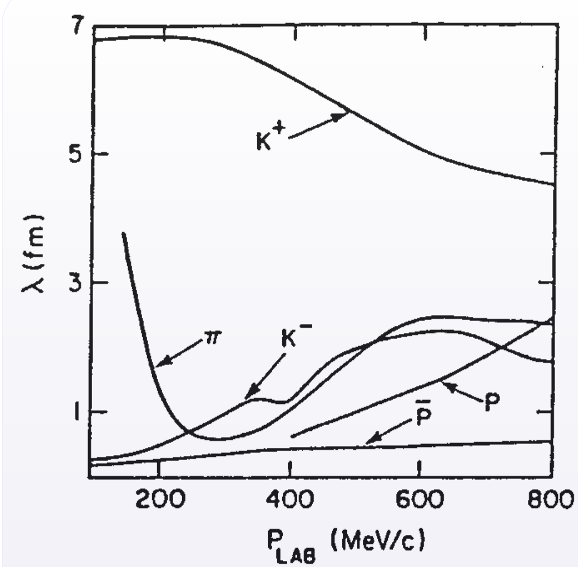
	K^+	K^-	ϕ
Production (primary)	$BB \rightarrow BYK^+$ $T_{pp\rightarrow p\Lambda K+}$ = 1.58 GeV	$BB \rightarrow BBK^+K^-$ $T_{pp\rightarrow ppK+K-}$ = 2.5 GeV	$BB \rightarrow BB\phi$ $T_{pp\rightarrow ppK+K-}$ = 2.6 GeV
Production (secondary)	$\pi B \rightarrow YK^+$	$\pi Y \rightarrow (\Sigma^* \rightarrow)\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

[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

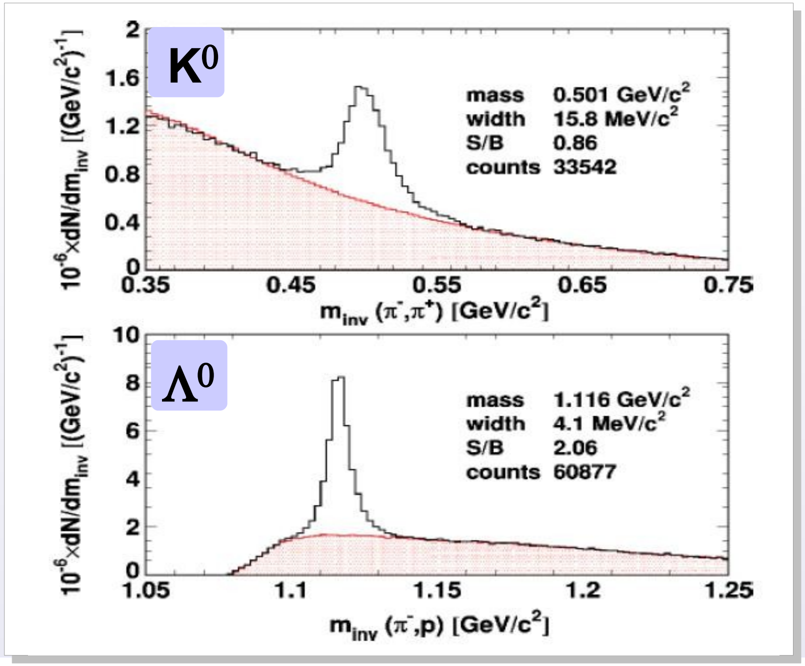
Ni+Ni @ 1.9A GeV

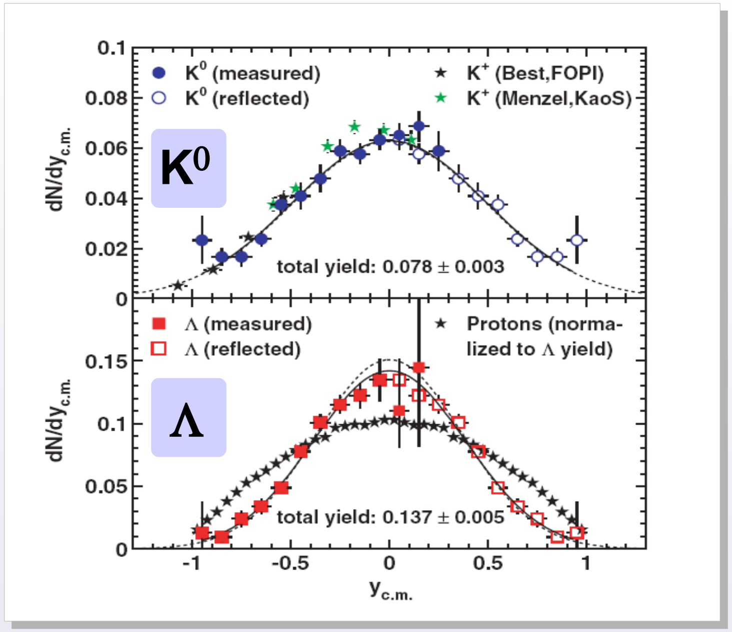
- K^0 and Λ^0 (from secondary vertices)

$K^0 \rightarrow \pi^+ + \pi^-$ (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}

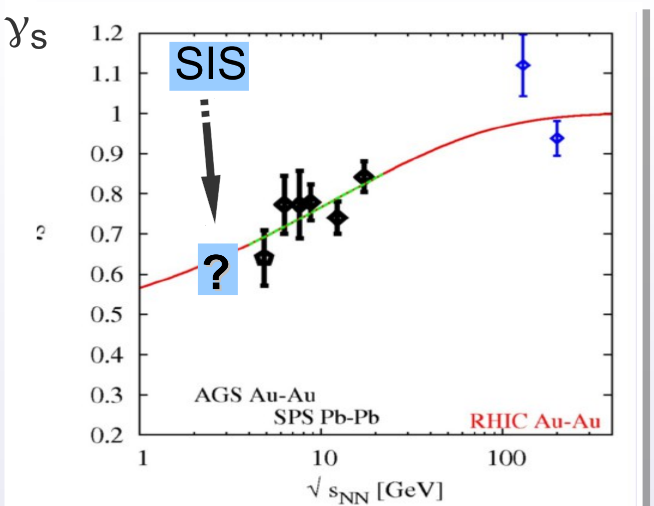
...but

No equilibration of strangeness (?)

Extension:

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

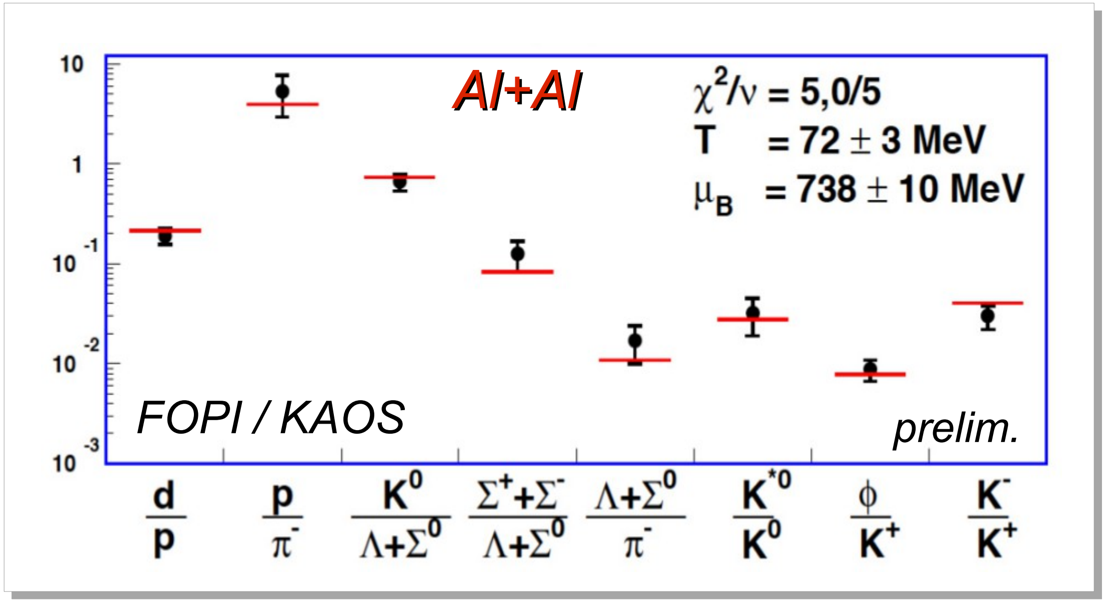
γ_S "strangeness undersaturation factor"
n_S number of strange quarks



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

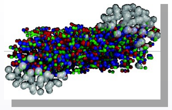
→ Grand Canonical ensemble;

→ For S≠0, Canonical ensemble

→ calc: THERMUS code

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

→ *SM* fitting quite well



UrQMD v 2.3

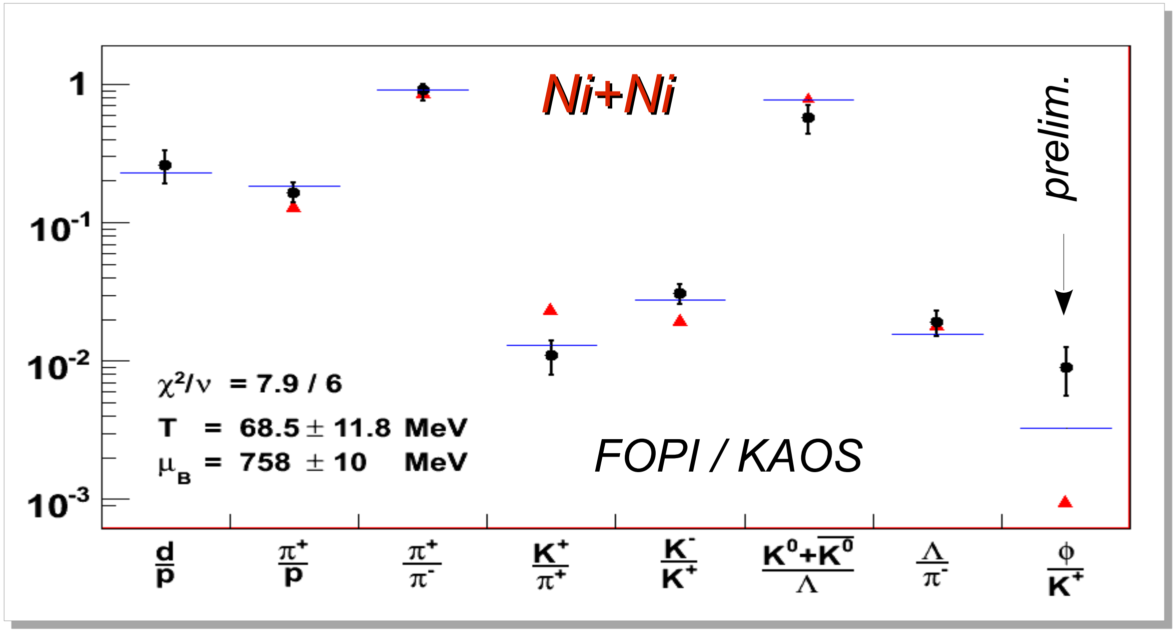
→ No equilibration assumed

→ 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