FOPI

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ϕ meson production in AA collisons at 1.9A GeV: Centrality dependence, and contribution of ϕ decays to K^- spectra

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- Physics motivation
- ϕ meson centrality study @1.9*A* GeV
- Influence of ϕ on K^-
- Summary and conclusions

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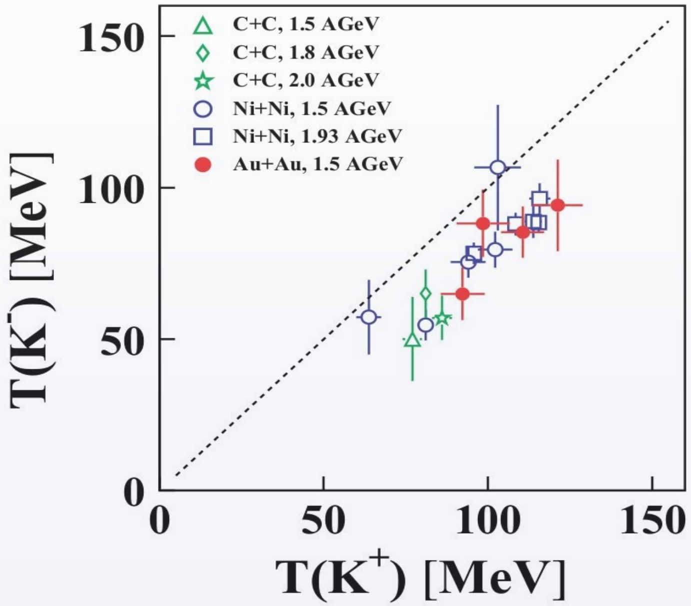
ϕ mesons, and link to Kaon dynamics

- ϕ ($s\bar{s}$) : m = 1.02 GeV
- $T_{threshold}$ (NN) = 2.6 GeV (SIS-18: sub-threshold only)
- $c\tau$ = 50 fm
- $\phi \rightarrow K^+K^-$ (BR ~ 50%)

Q1: What is the production scenario of subthreshold ϕ mesons?

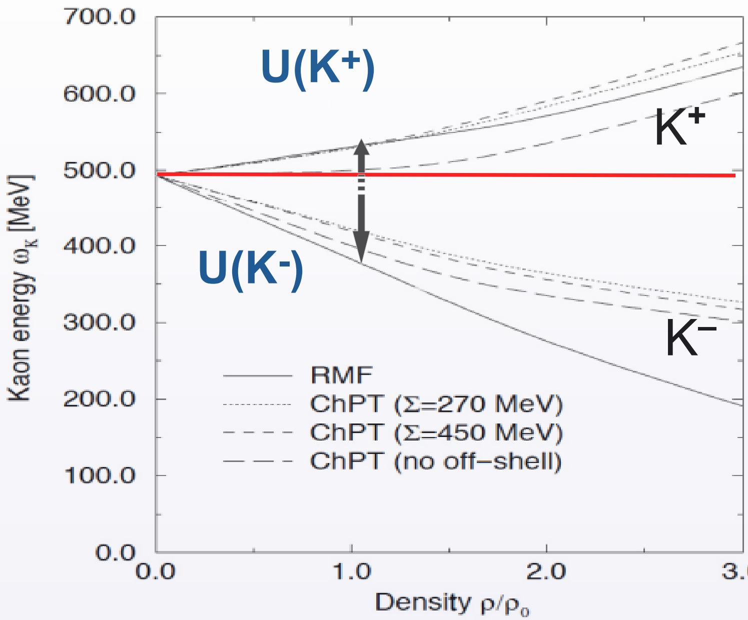
- $K^{+/-}$ production near threshold (1..2A GeV)



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

- Effects involved:
  - ▶ KN scattering
  - ▶ K^- absorption
  - ▶ In-medium effects

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



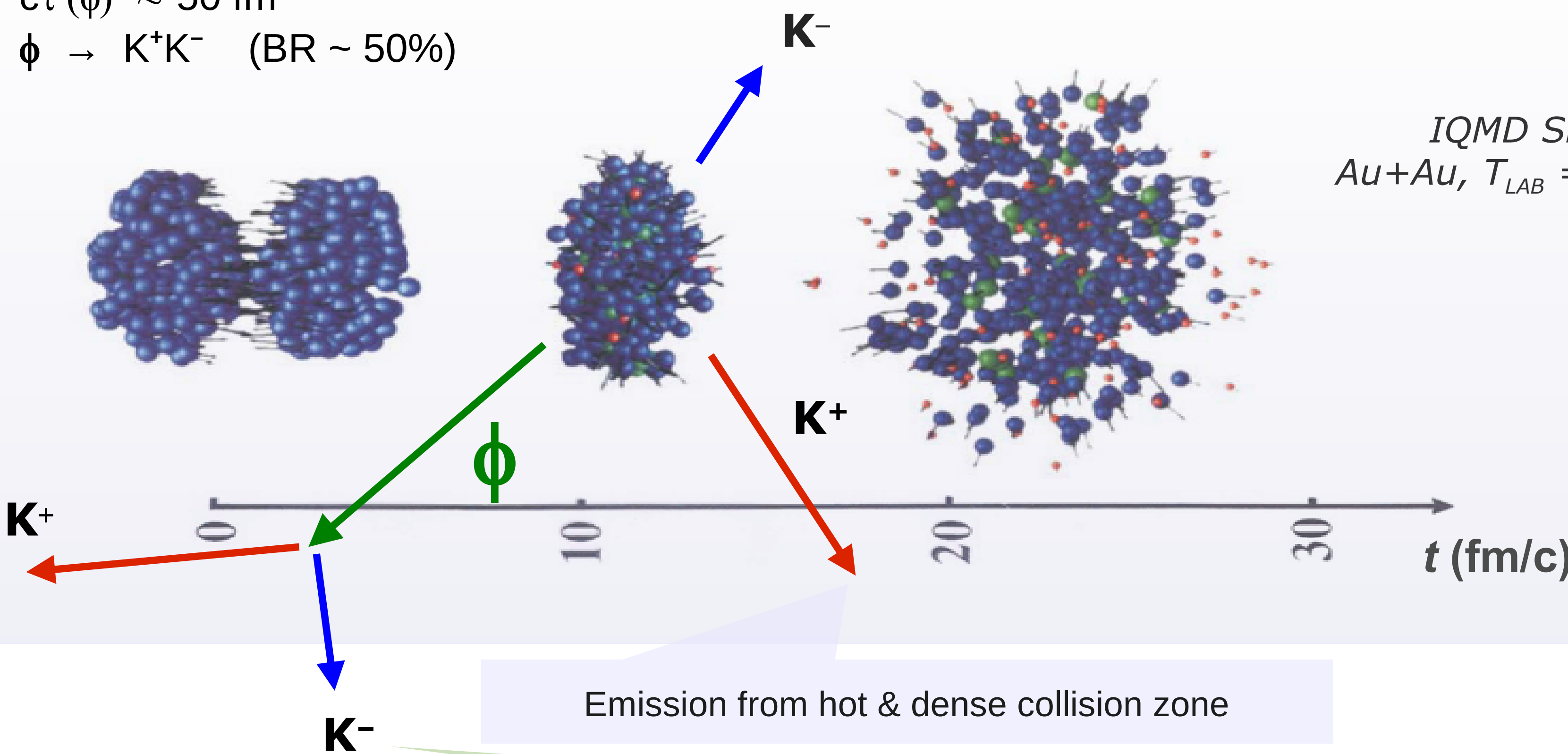
J. Schaffner-Bielich et al. NPA 625, 325 (1997)

- 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}

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



Emission from hot & dense collision zone

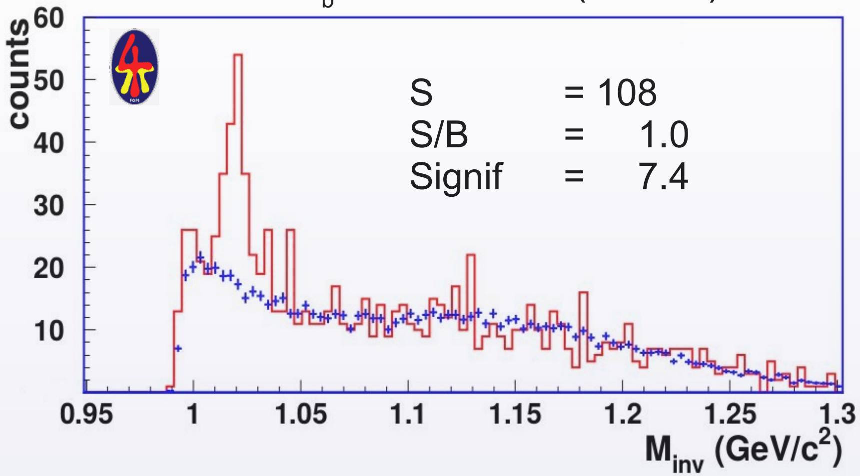
Emission (mainly) in vacuum

Q2: How strong is the ϕ contribution to K^- yields ?

Q3: Does the $\phi \rightarrow K^+K^-$ decay modify the *T* (inverse slopes) of K^- spectra?

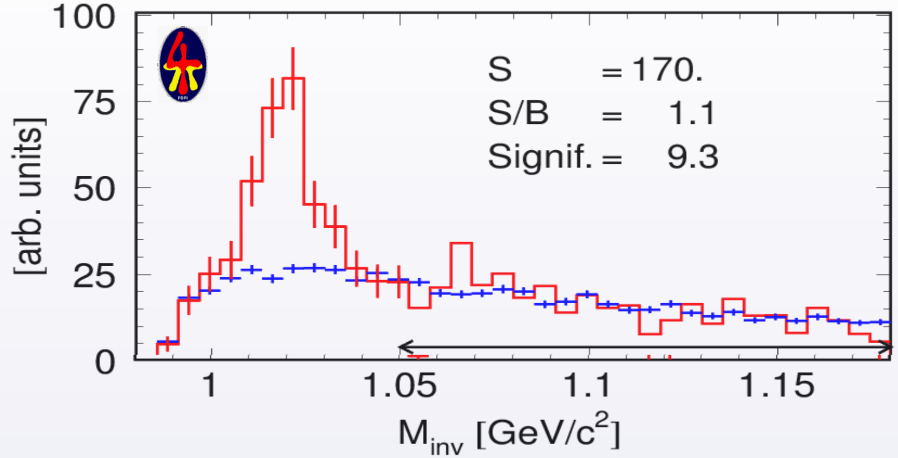
ϕ meson data @ 1.9A GeV

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



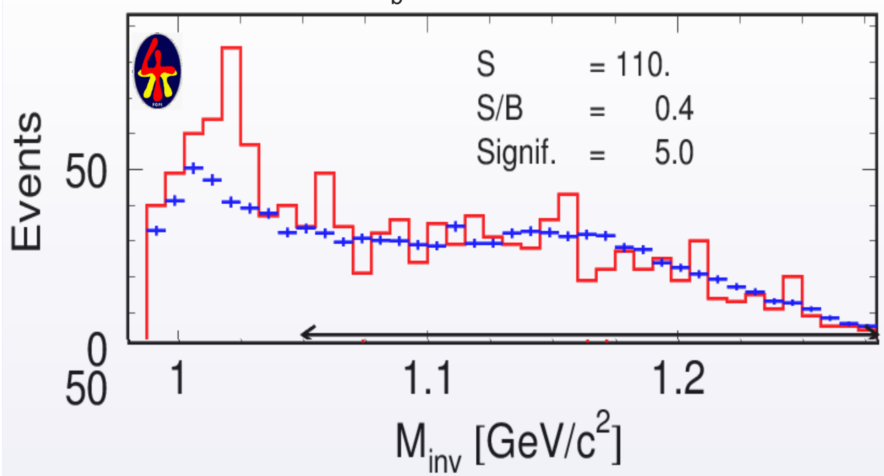
P. Gasik et al. arXiv: 1512.06988

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



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

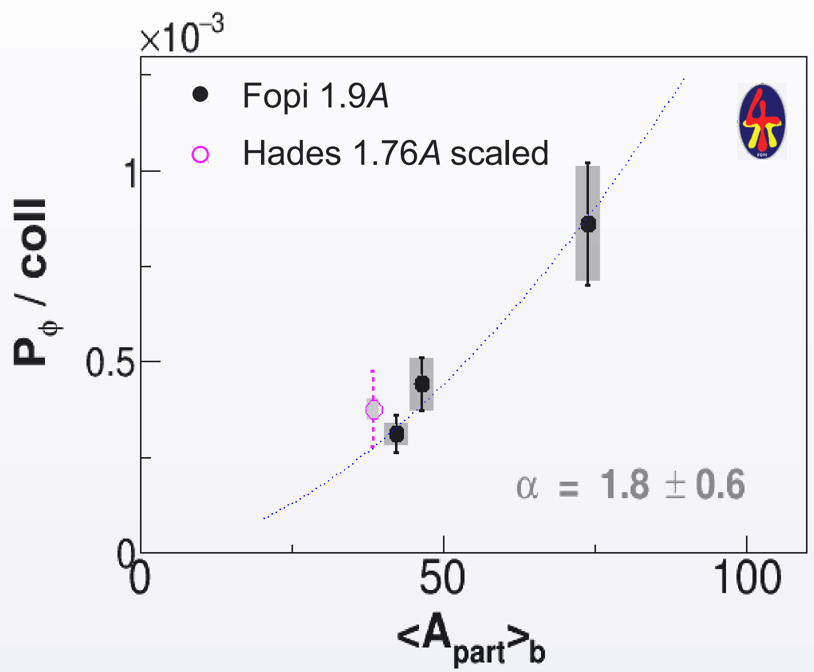
Ni+Ni, T_b = 1.9A GeV (central)

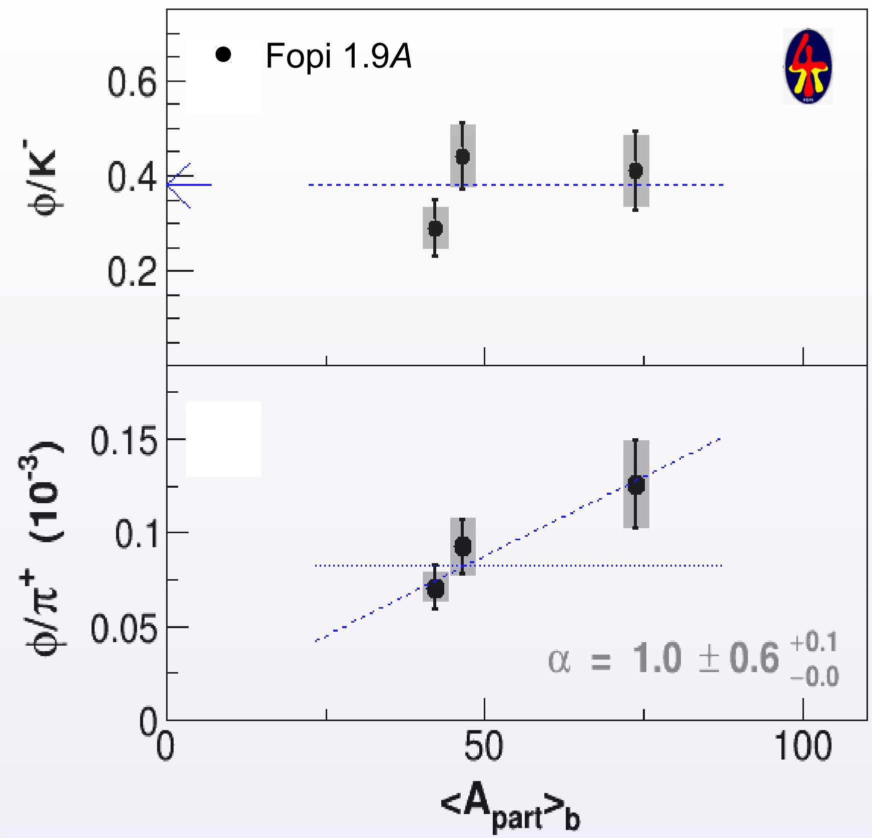


K. Piasecki et al. arXiv: 1602.04378

	$\langle A_{part} \rangle_b$	$P(\phi)$ [$\times 10^{-4}$]
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	74.5	$8.6 \pm 1.6 \pm 1.5$

ϕ mesons: centrality dependence @ 1.9*A* GeV





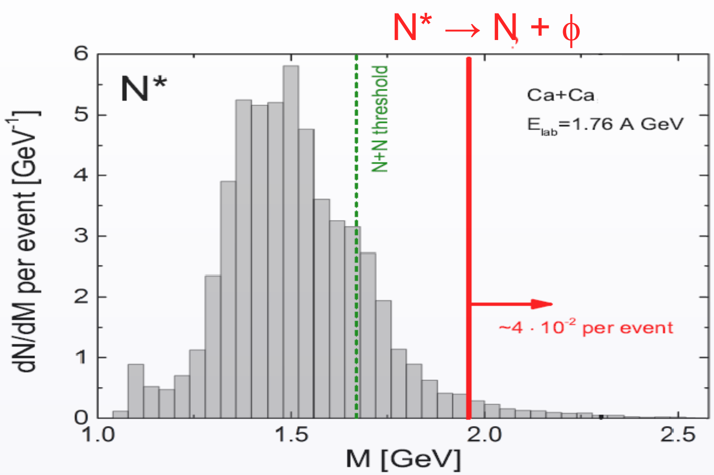
- $P_\phi \sim A_{part}{}^{\alpha}$ → $\alpha = 1.8 \pm 0.6$
- $\phi/K^- = const$ $= 0.36 \pm 0.05$ → 18% of K^- come from ϕ decays

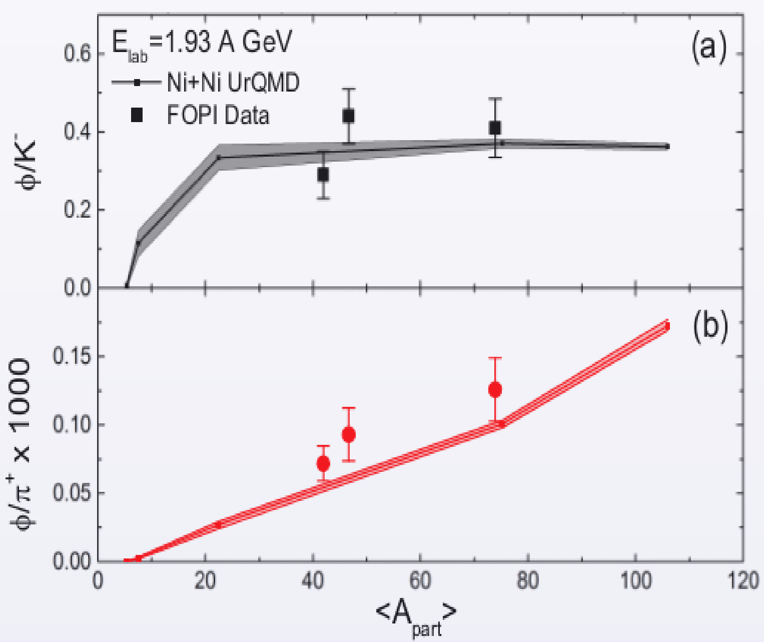
- $\phi/\pi^+ \sim A_{part}{}^{\alpha}$ → $\alpha = 1.0 \pm 0.6$

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

UrQMD

- Production via decays of massive resonances





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

BUU

- 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:

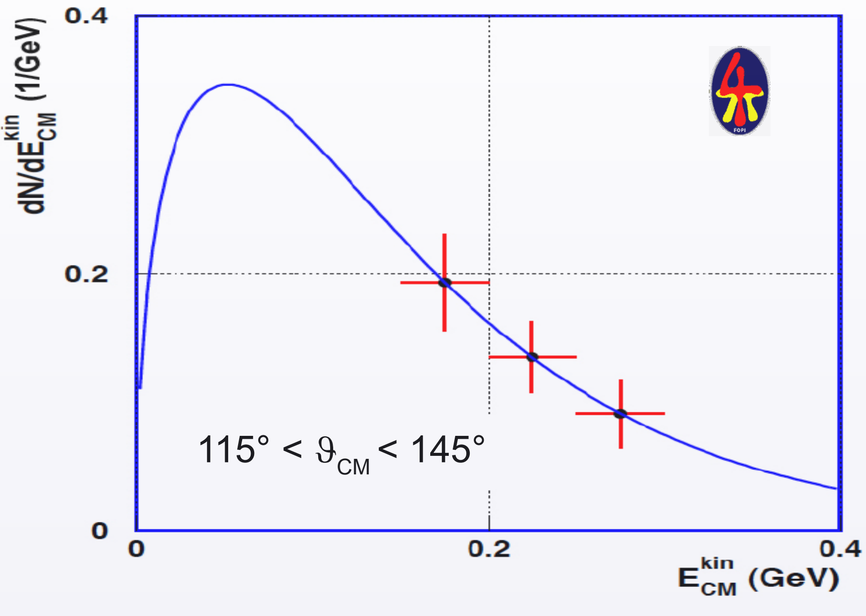
Ni+Ni @ 1.9*A* GeV, $<A_{part}>_b$ = 74

$P(\phi) = [8.6 \pm 1.6 \pm 1.5] \times 10^{-4}$

Seems BUU predictions too high.

ϕ meson phase space: first insights

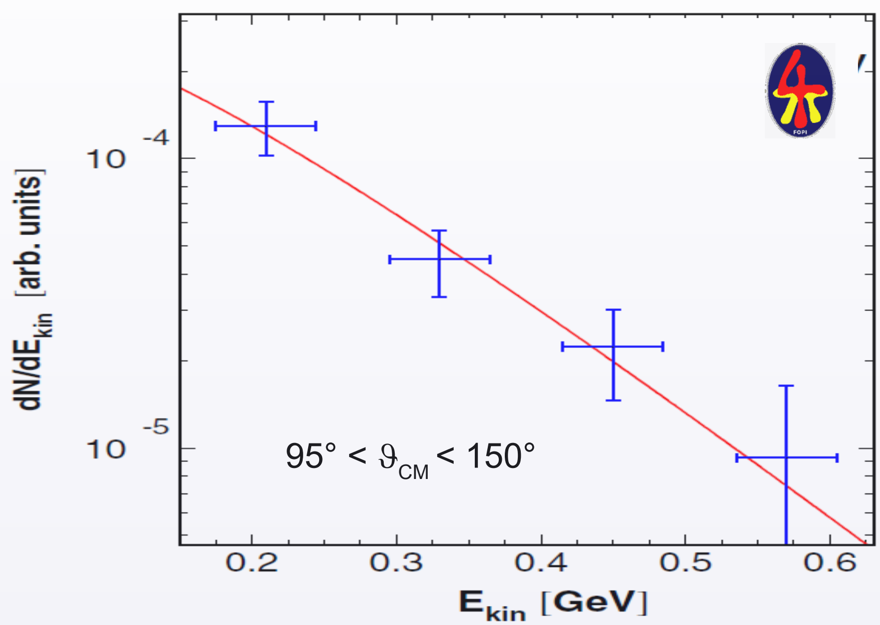
- Al+Al @ 1.9A GeV (central)



T_{eff} = 94 ± 14 ± 16 MeV

P. Gasik et al., arXiv: 1512.06988 (Accepted for EPJ A)

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



T_{eff} = 108 ± 18 ± 16 MeV

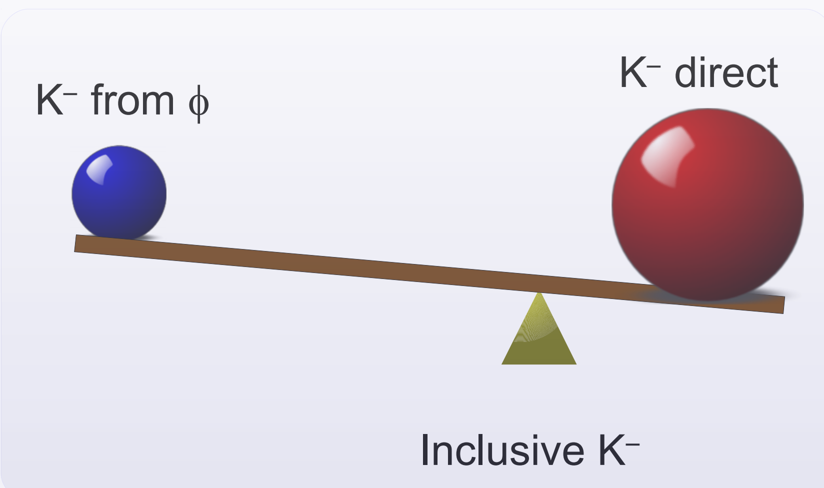
K. Piasecki et al., PRC 91, 054904 (2015)

2-sources model of K^- emission

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

ϕ source temperature : T_{IN} $(\phi) \approx 100$ MeV

Slope of daughter K^- : T_{OUT} $(K^-) \approx$ 60 MeV



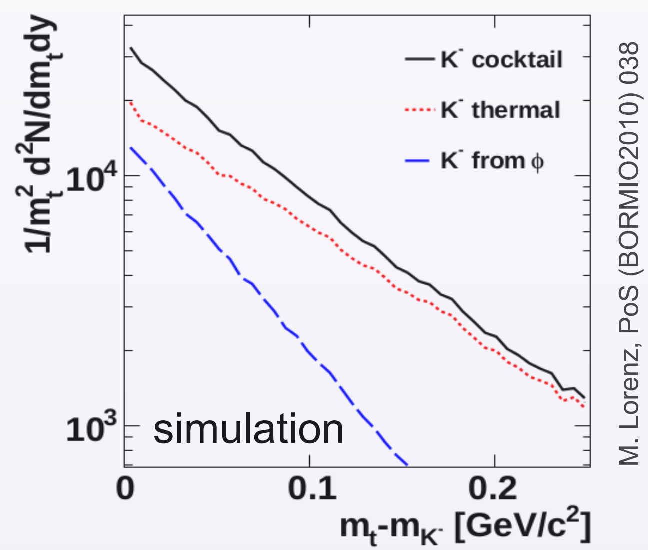
- Ar+KCl @ 1.76A GeV (HADES)

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

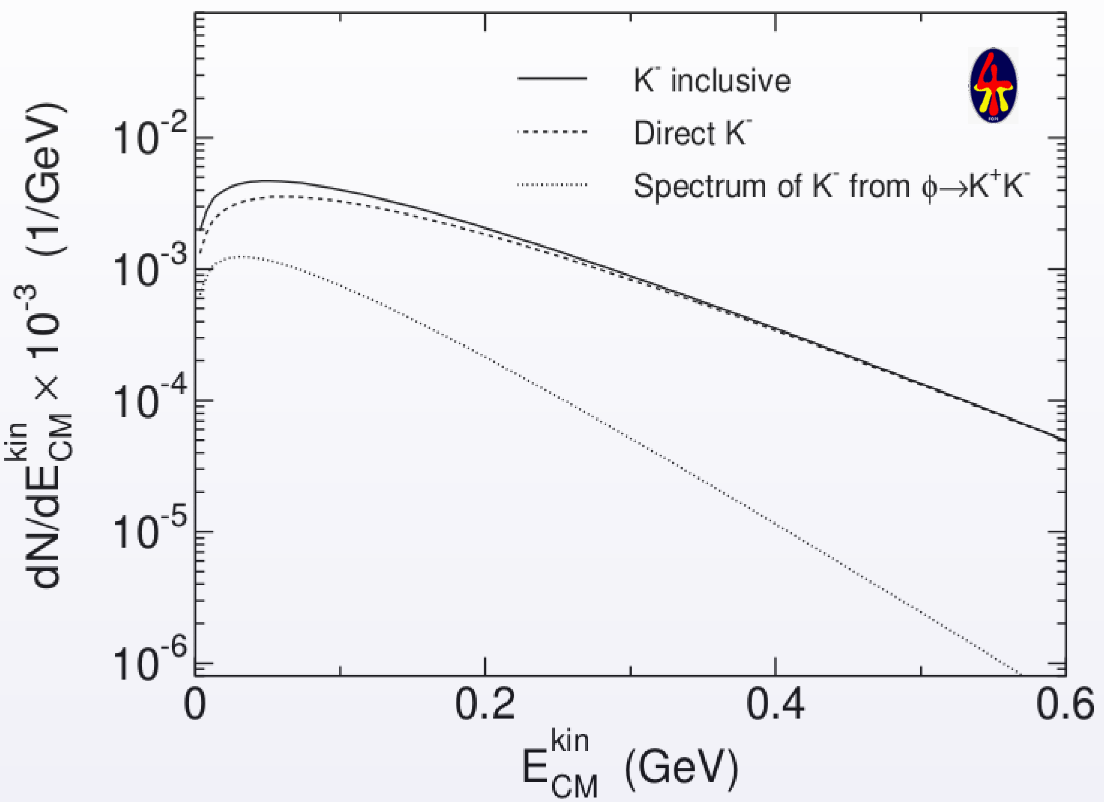
2-sources model of K⁻ emission

- 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 et al., arXiv: 1512.06988 (Accepted for EPJ A)

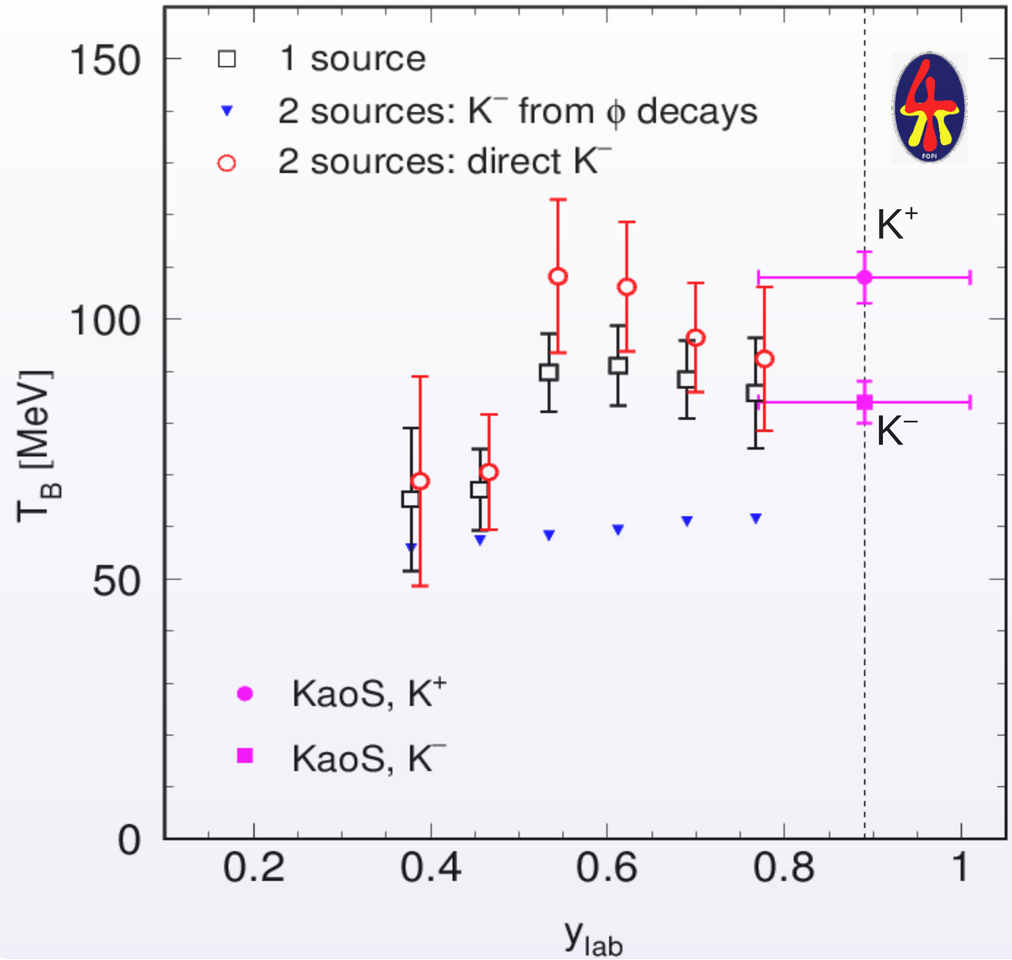


T (K⁻ direct) = 92 ± 16 MeV

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

Experiment :

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

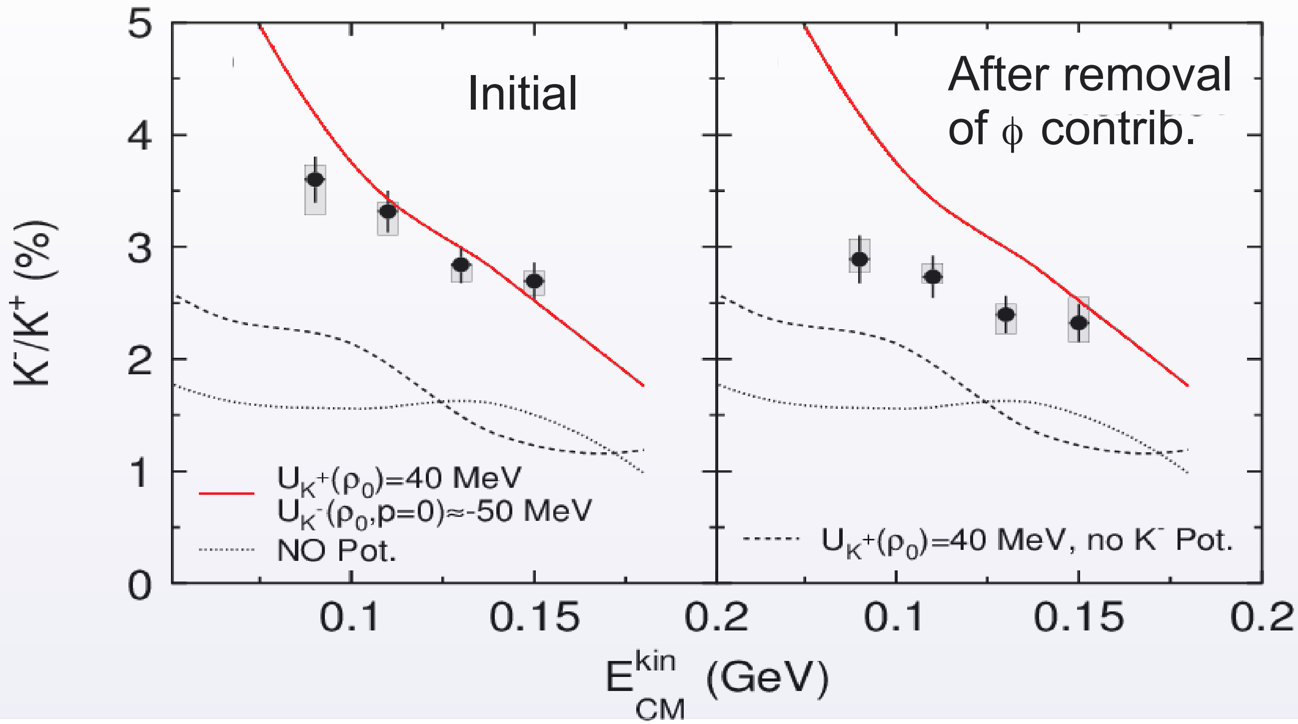


KP et al., Phys. Rev. C 91, 054904 (2015)

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

- Central Al+Al @ 1.9A GeV

P. Gasik et al., arXiv: 1512.06988 (Accepted for EPJ A)



- HSD calculations:

U_{K+N} = 0 MeV, U_{K-N} = 0 MeV

U_{K+N} = 40 MeV, U_{K-N} = 0 MeV

U_{K+N} = 40 MeV, U_{K-N} = 50 MeV

… but: ϕ contribution to K⁻ was minimal

→ *Idea*: for the experimental data, Subtract the ϕ contribution from K⁻

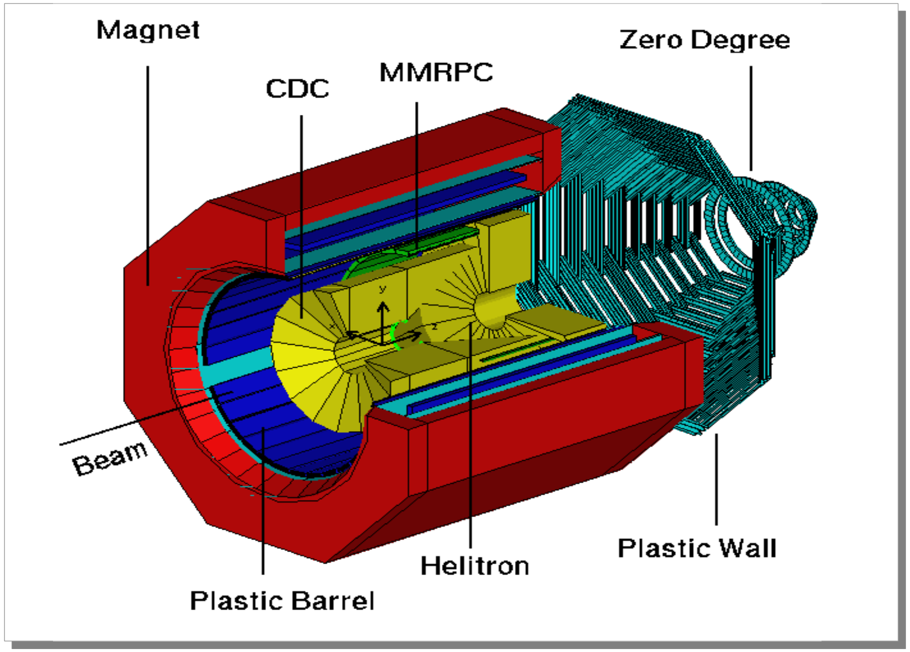
➡ | U_{K-N} | less than 50 MeV

Summary and conclusions

- Investigation of ϕ mesons from AA collisions @ 1.9*A* GeV
  - $P(\phi)$ in the order of 10^{-4}, $\sim A_{part}^{\;1.8 \pm 0.6}$
  - $\phi/K^- = 0.36 \pm 0.05$ (~18% contribution to K^-)
  - $\phi/\pi^+ \sim A_{part}^{\;1.0 \pm 0.6}$ (but *const* also ok)
- Phase space : first insights into E_{kin} spectrum
  - $T \approx 100$ MeV
- Influence of ϕ on K^- mesons
  - *T* (direct) higher than *T* (inclusive)
  - $U_{K\text{–}N}$ extracted from HSD lower than previously found –50 MeV.

Thank You!

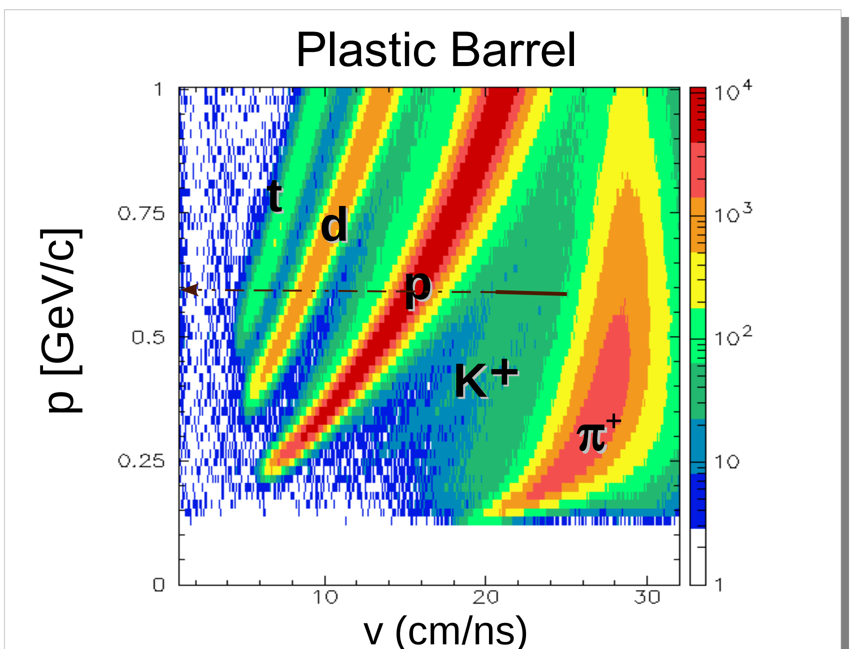
FOPI experimental setup

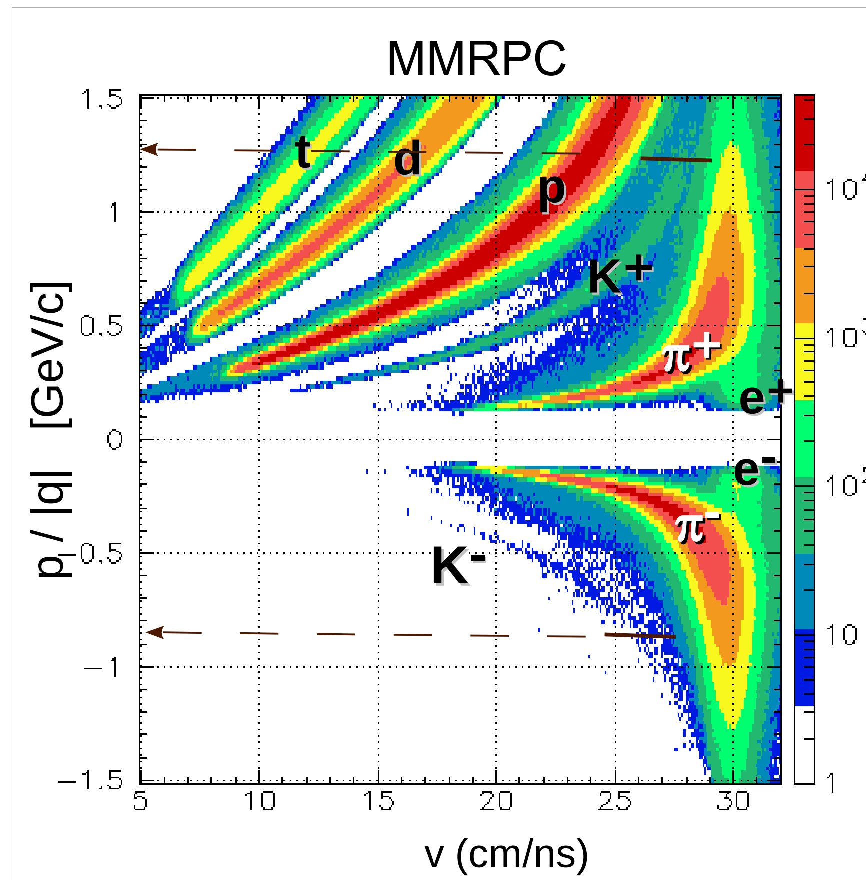


- Nearly 4π coverage
- Drift chambers: CDC, Helitron

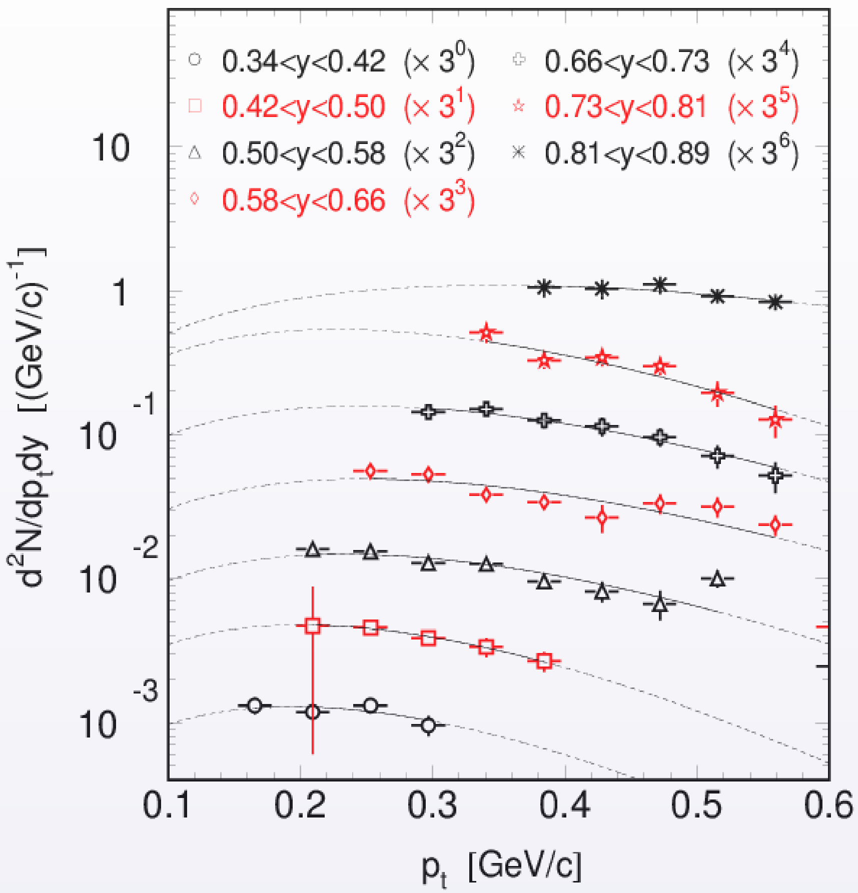
  ToF : Plastic Barrel, RPC

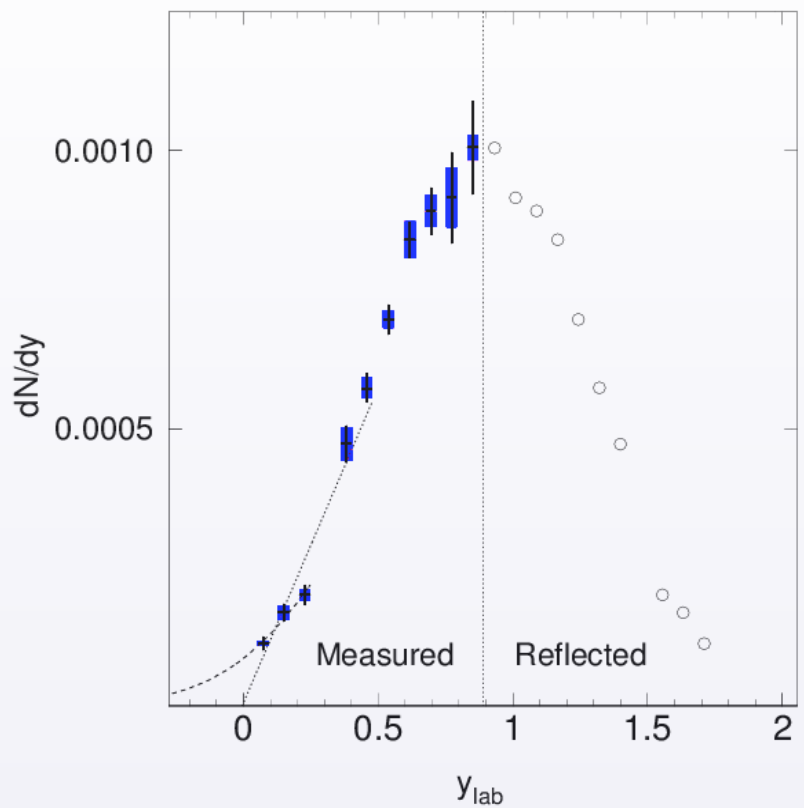
  Forward: Plastic Wall, Zero Degree
- Direct PID of $\pi^{\pm}$, $K^{\pm}$, p, d, t, $^{3,4}He$





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





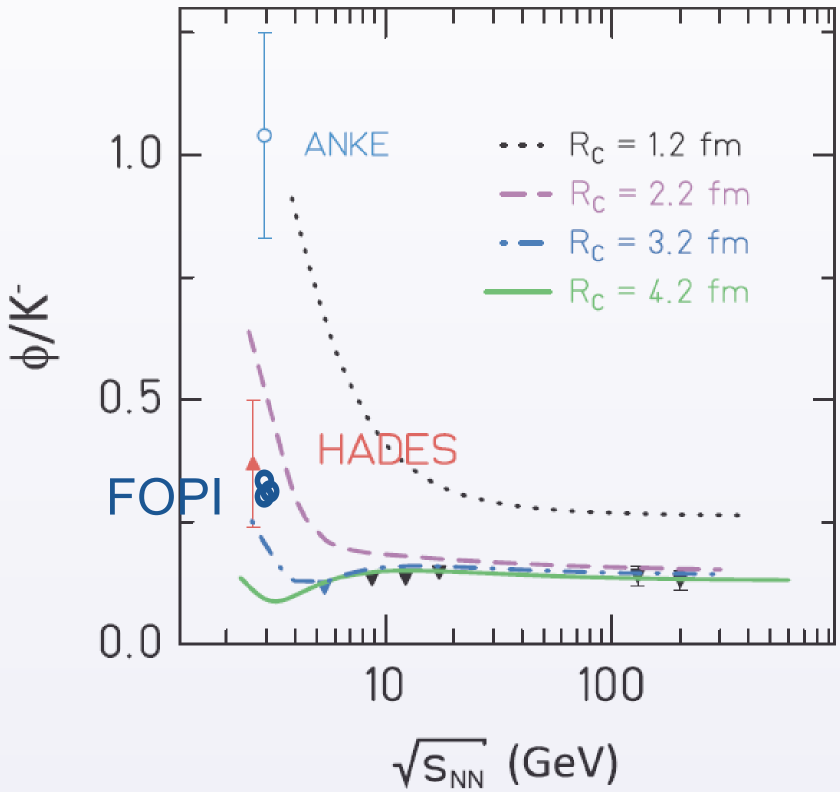
$$P(K^-) = [9.8 \pm 0.2 \pm 0.6] \times 10^{-4}$$

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

φ meson production modelled

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)

Sub- and near-threshold Production of K^-

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

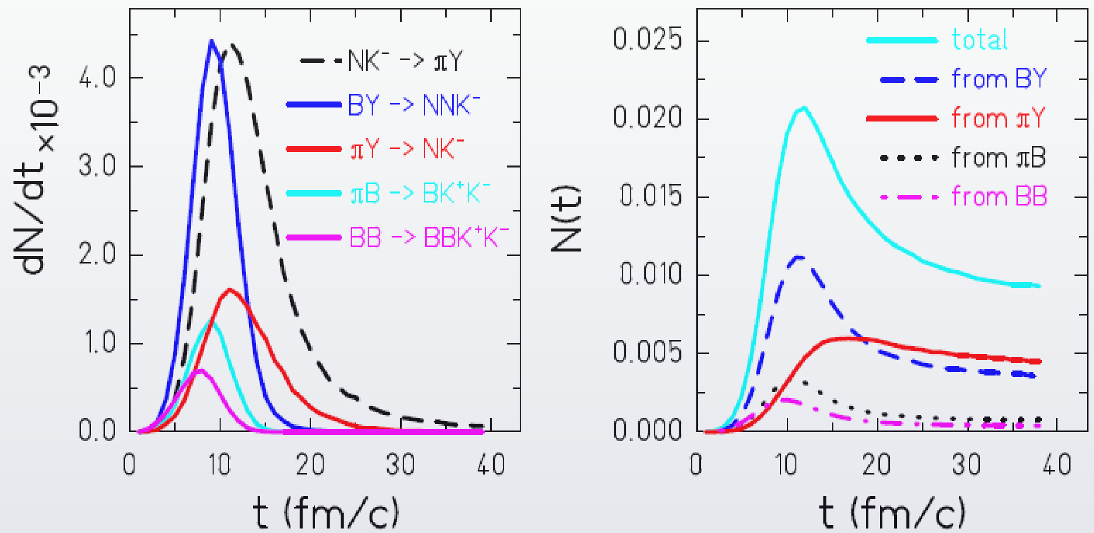
  $BY \to NNK^-, \quad \pi Y \to K^- B$

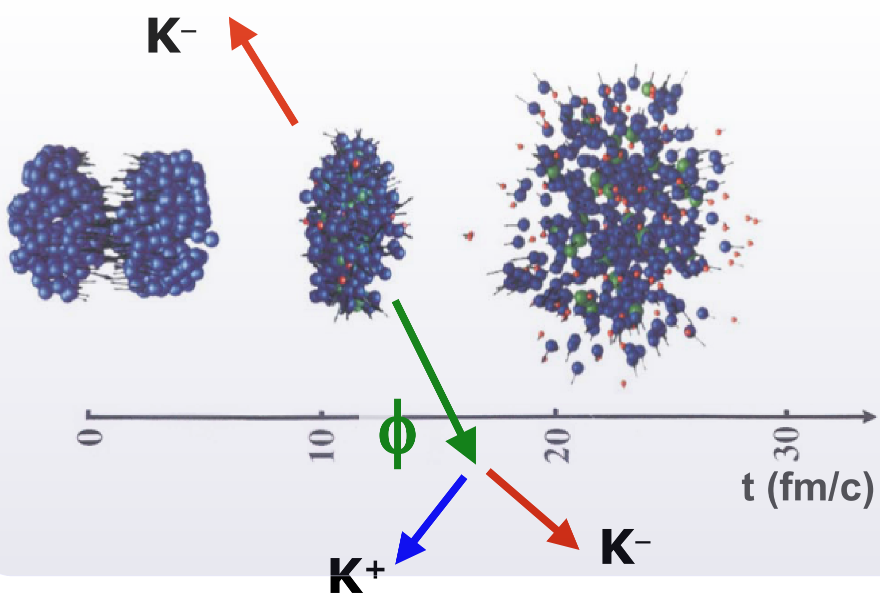
  - strong reabsorption: $K^- B \to \pi Y$
  - coupled to resonances $\Sigma(1385)$, $\Lambda(1405)$

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

  Q: Can we see them?

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





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

  Q: How strong is this contribution?

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

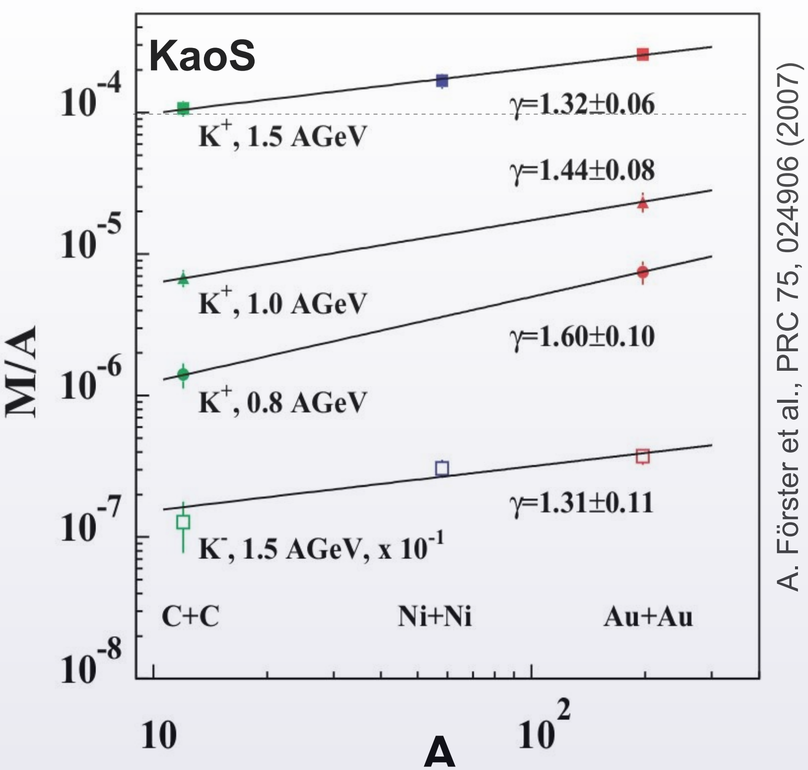
  Q: How strong is this influence?

If primary:

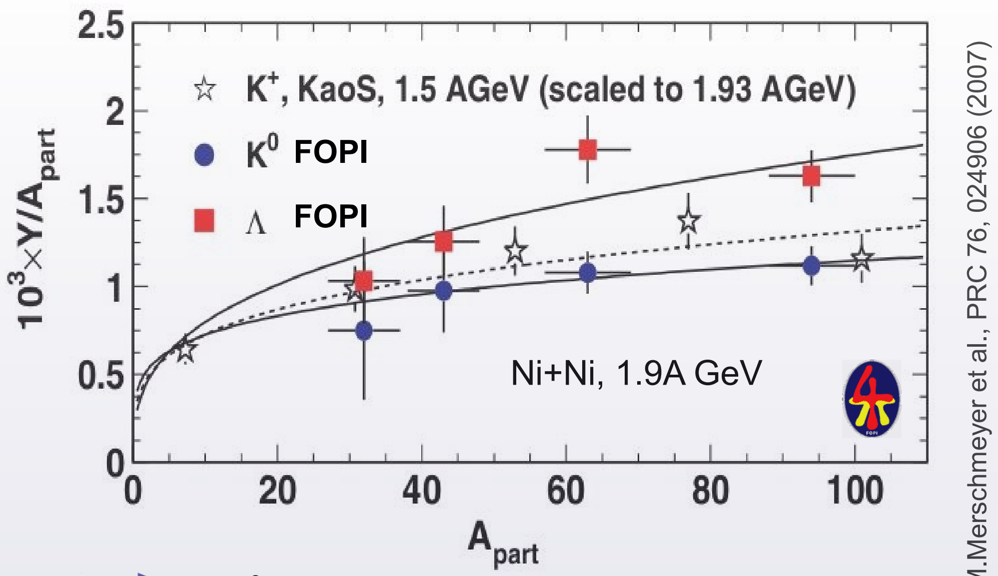
For pA → KX: $MUL_K = \frac{\sigma_K}{\sigma_{inelastic}} = const$

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:

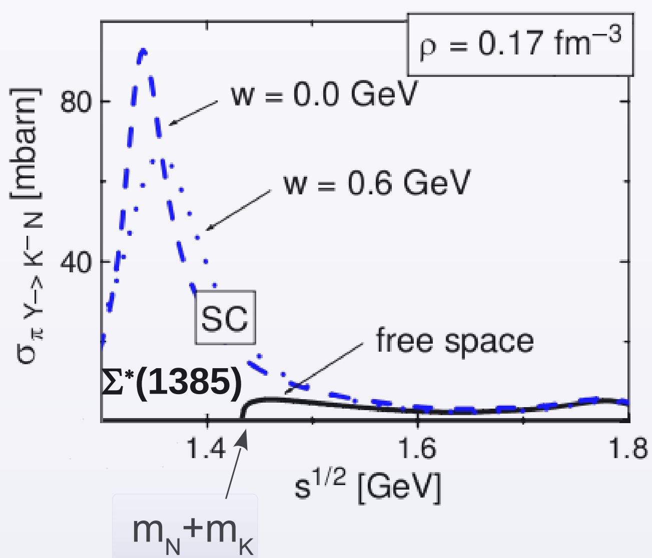
- $N_{beam} + N_{target}$, N_{target} has Fermi motion
- predominantly via ΔN , ΔΔ → $K^{+,0}$ Y B
  πN , πΔ → $K^{+,0}$ Y   Y = [Λ,Σ]
- U_{KN} involved (increases K mass → lower yields)

$\Sigma^*(1385)$ resonance

Chiral effective field theory w/ coupled-channels

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

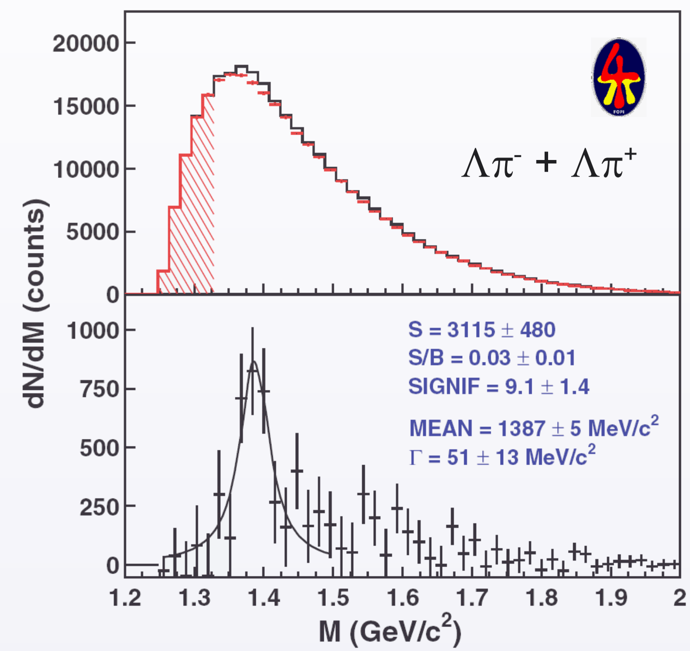
($\pi\Lambda \rightarrow \Sigma^* \rightarrow$ **K^-N**)



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

- Al+Al @ 1.9A GeV

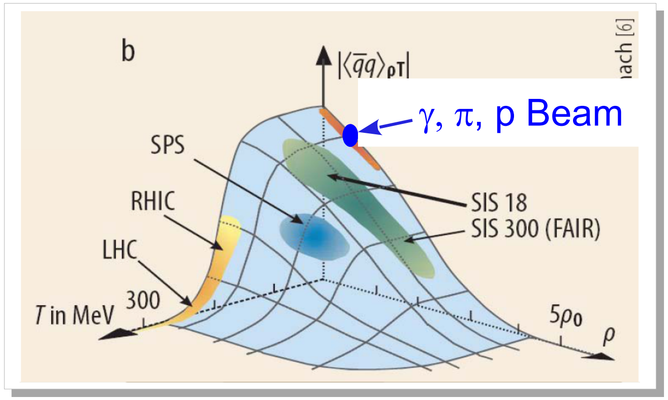
$\Sigma^{\pm *}(1385) \rightarrow \Lambda + \pi^{\pm}$ (88 ± 2%)
$\hookrightarrow p + \pi^-$



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

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

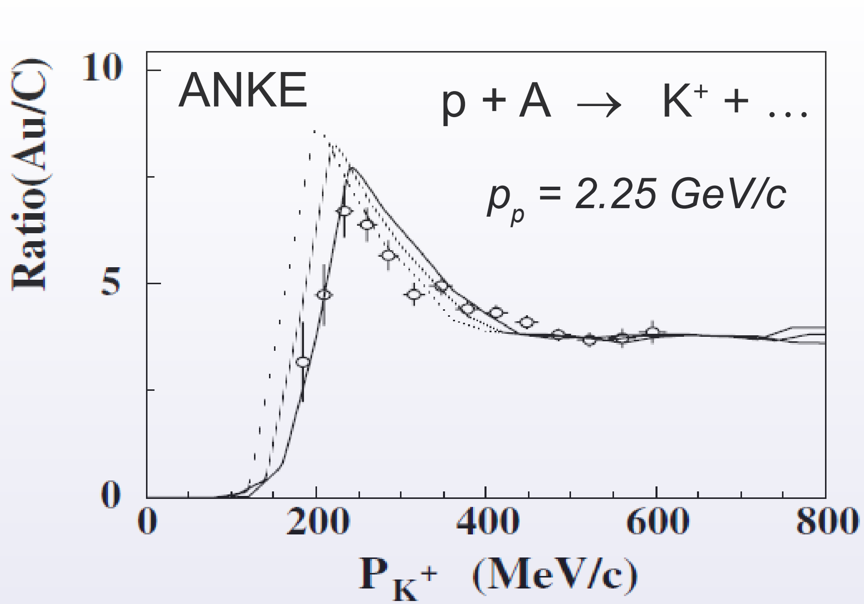
- Σ^* resonance **found** in HI collisions
  Input to fix $\pi + \Lambda \rightarrow$ **K^-**$+ N$ in medium



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

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

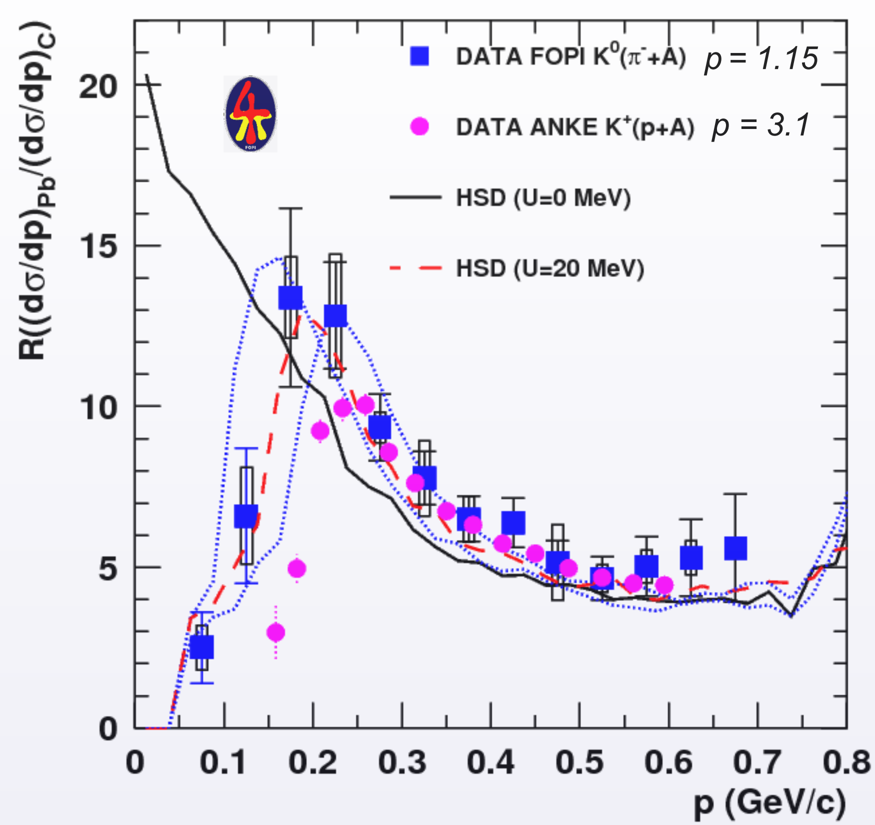
p (p=2.25 GeV/c) + A → K^+ + … *ANKE*



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

CBUU transport code

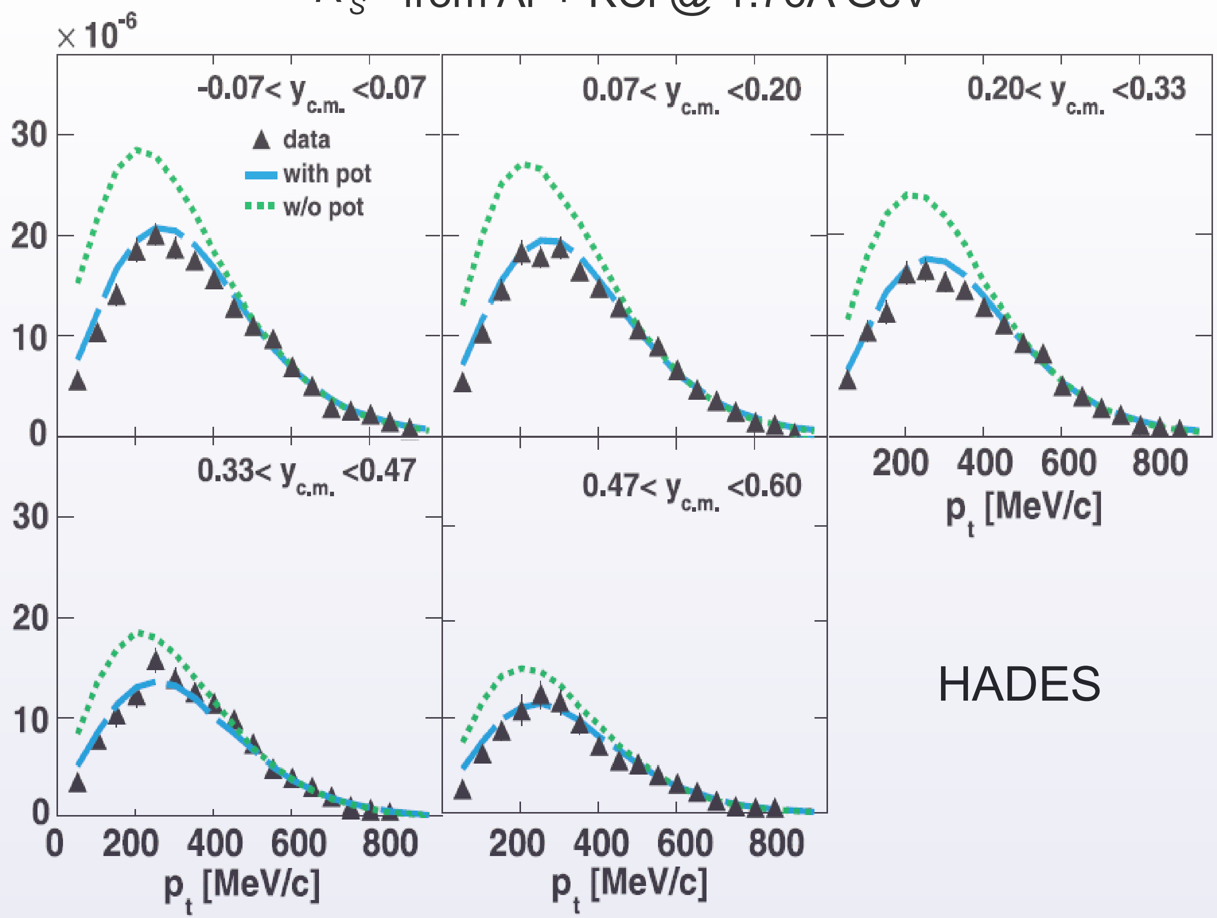
· · · ·	U_{KN} = 0 MeV
········	U_{KN} = 10 MeV
——	U_{KN} = 20 MeV



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 $c\tau$ = 2.7 cm

K^0_L $c\tau$ = 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

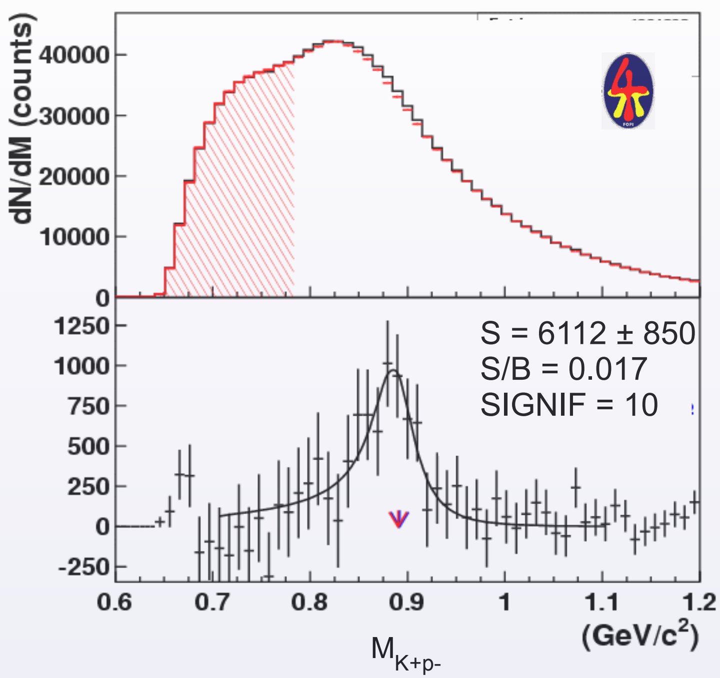
$\pi^- A \rightarrow K^0 + \ldots$ at $\rho \leq \rho_0$

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)*

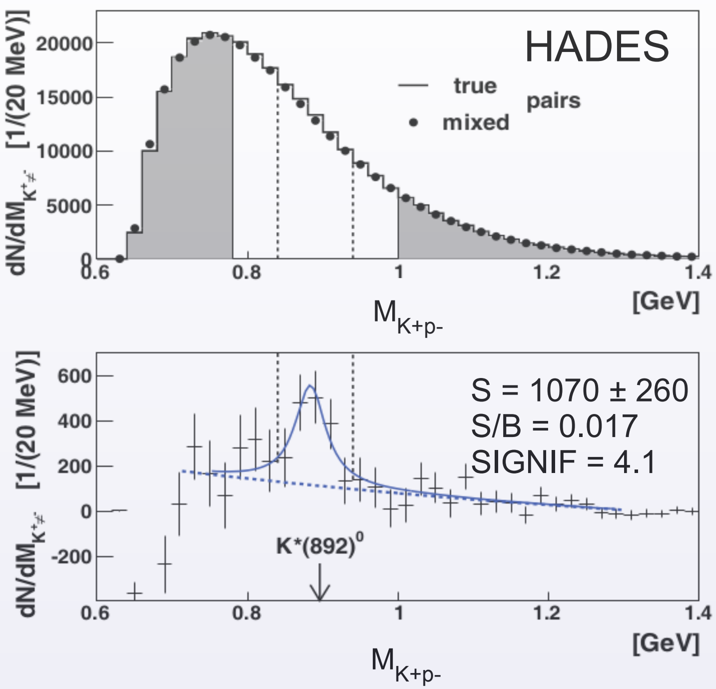
Al+Al @ 1.9A GeV



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

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

Ar+KCl @ 1.76A GeV

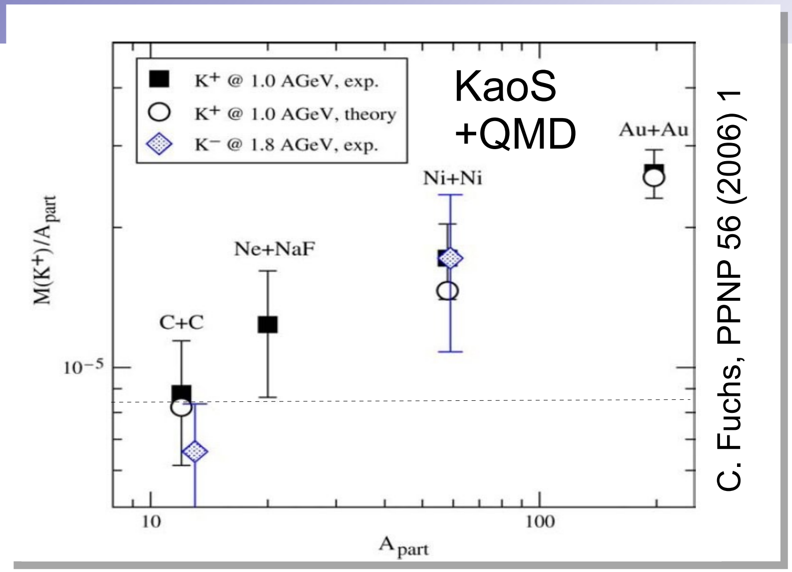


$$\frac{P(K^{0*})}{P(K^0)} = 0.019 \pm 0.005 \pm 0.003$$

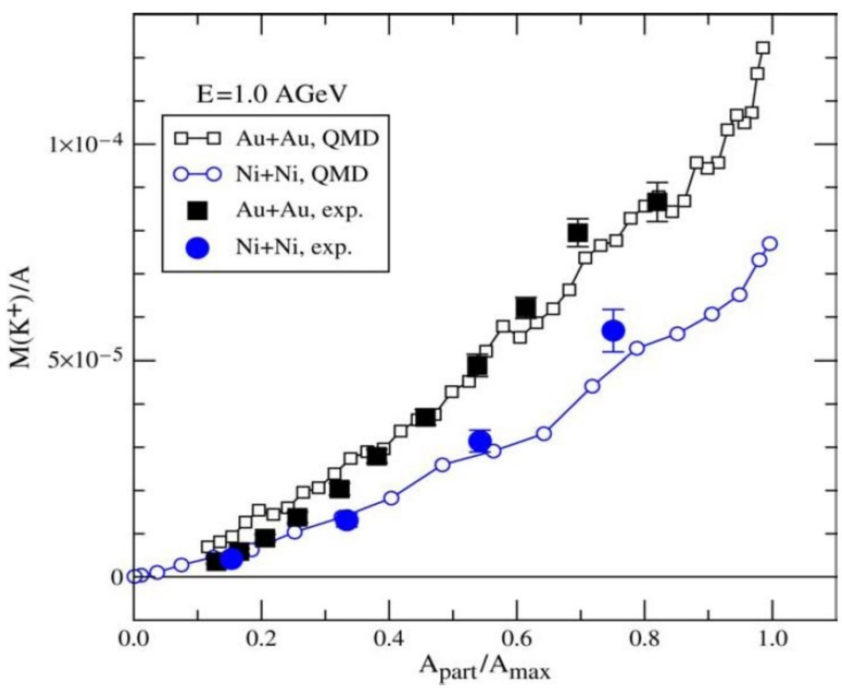
G. Agakishiev et al., Eur. Phys. J. A (2013) 49: 34

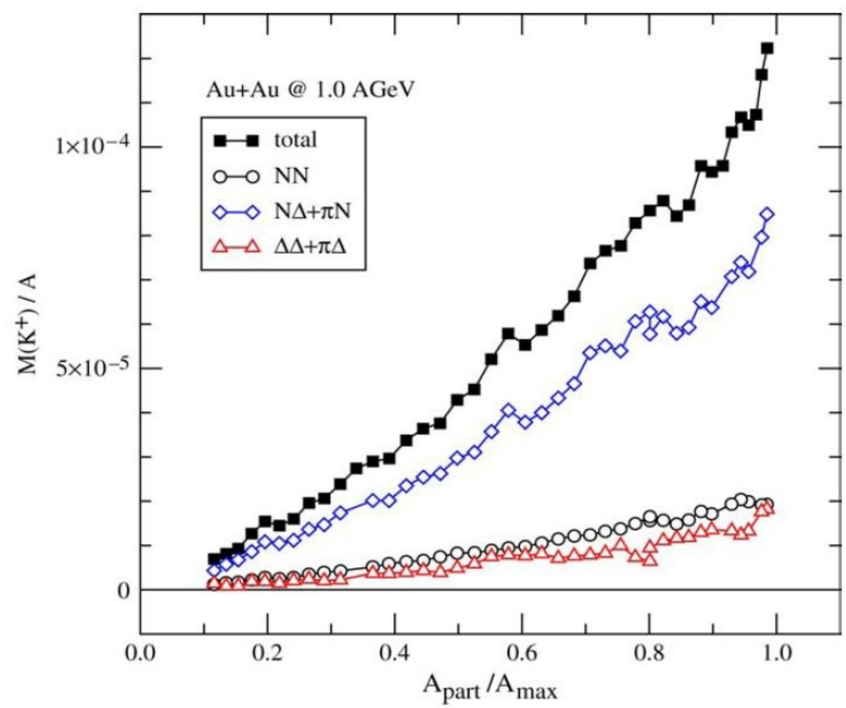
- K^+ Primary: (Fermi momentum)
  $NN \rightarrow NK^+Y$ ($Y = \Lambda, \Sigma$)

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



➡ Secondary processes involved

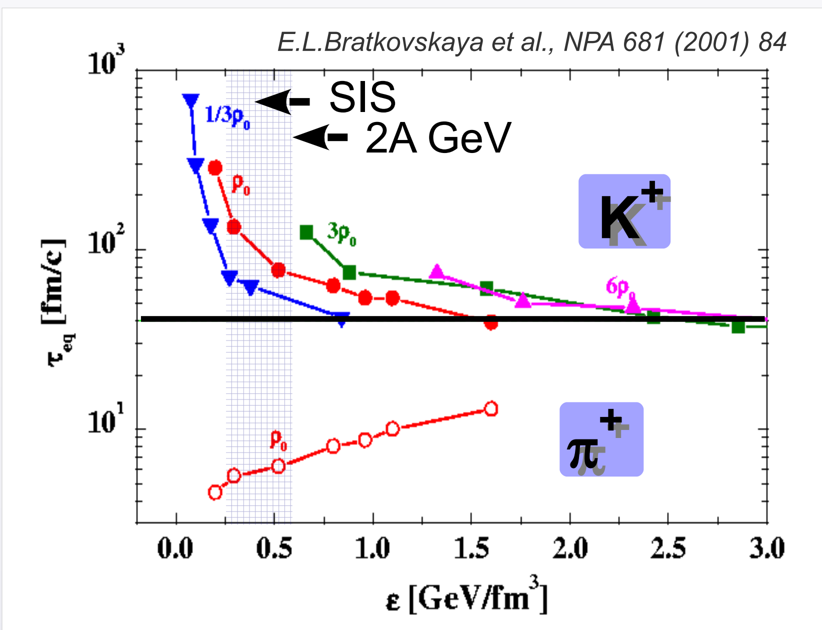




HSD transport model

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

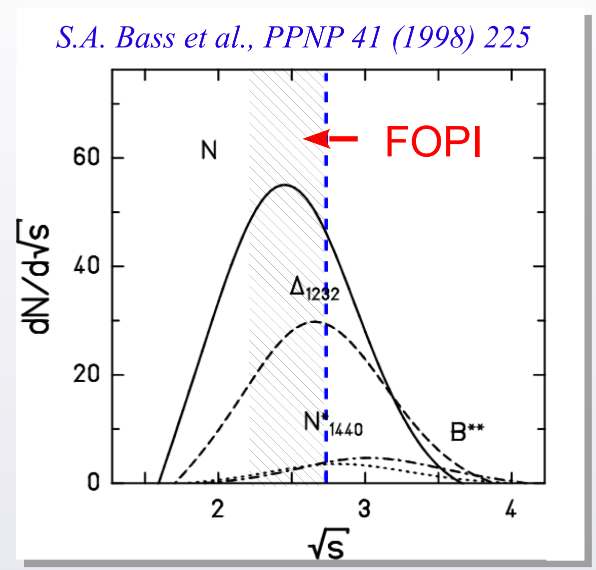
  τ_{eq} @ 2/3 of $N_{equilibrium}$



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

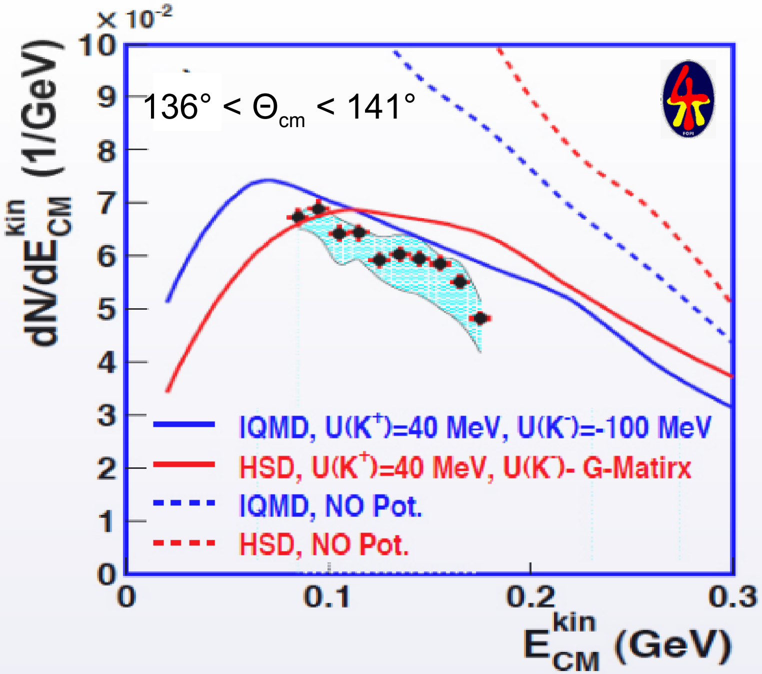
no thermalization of strangeness

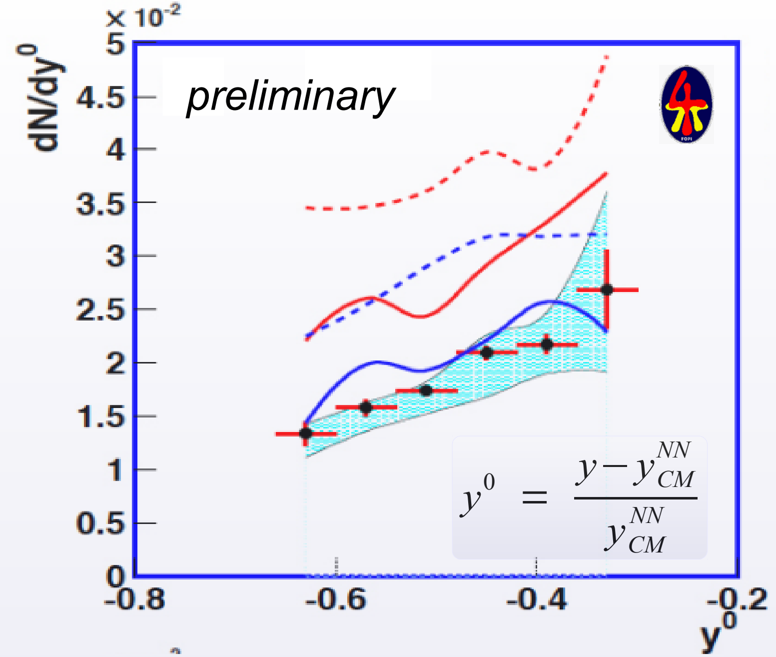
- At SIS energies, resonance production (Δ, N*) reaches maximum



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

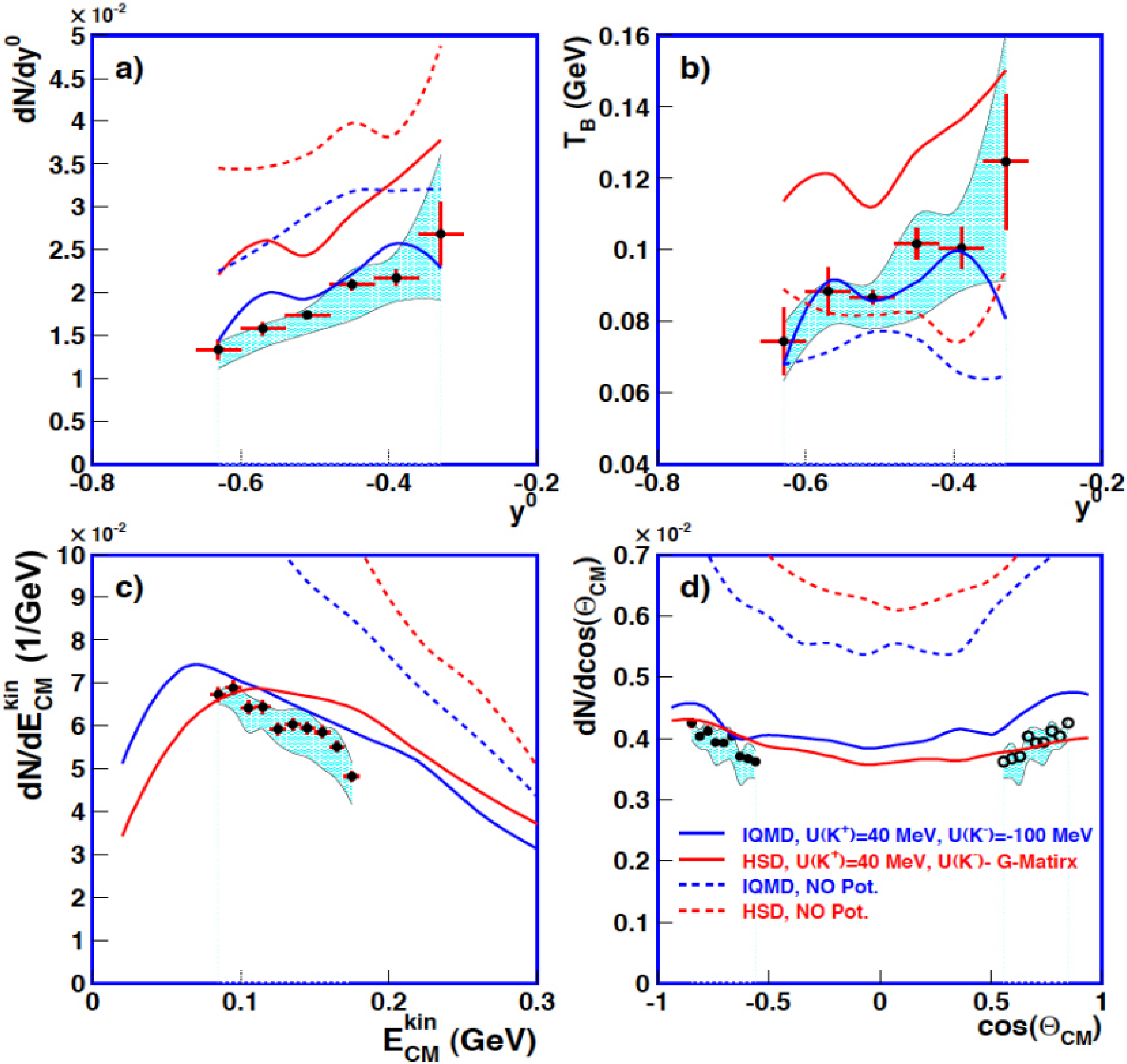
- **IQMD**
  - Soft EoS ($K \approx 200$ MeV)
  - $m_{K\pm}(\rho) = m_{K\pm}(\rho_0) \cdot \left(1 + \alpha_{\pm} \cdot \frac{\rho}{\rho_0}\right)$
  - $\alpha_{K+/K-}$ = 0.08 (-0.21)

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

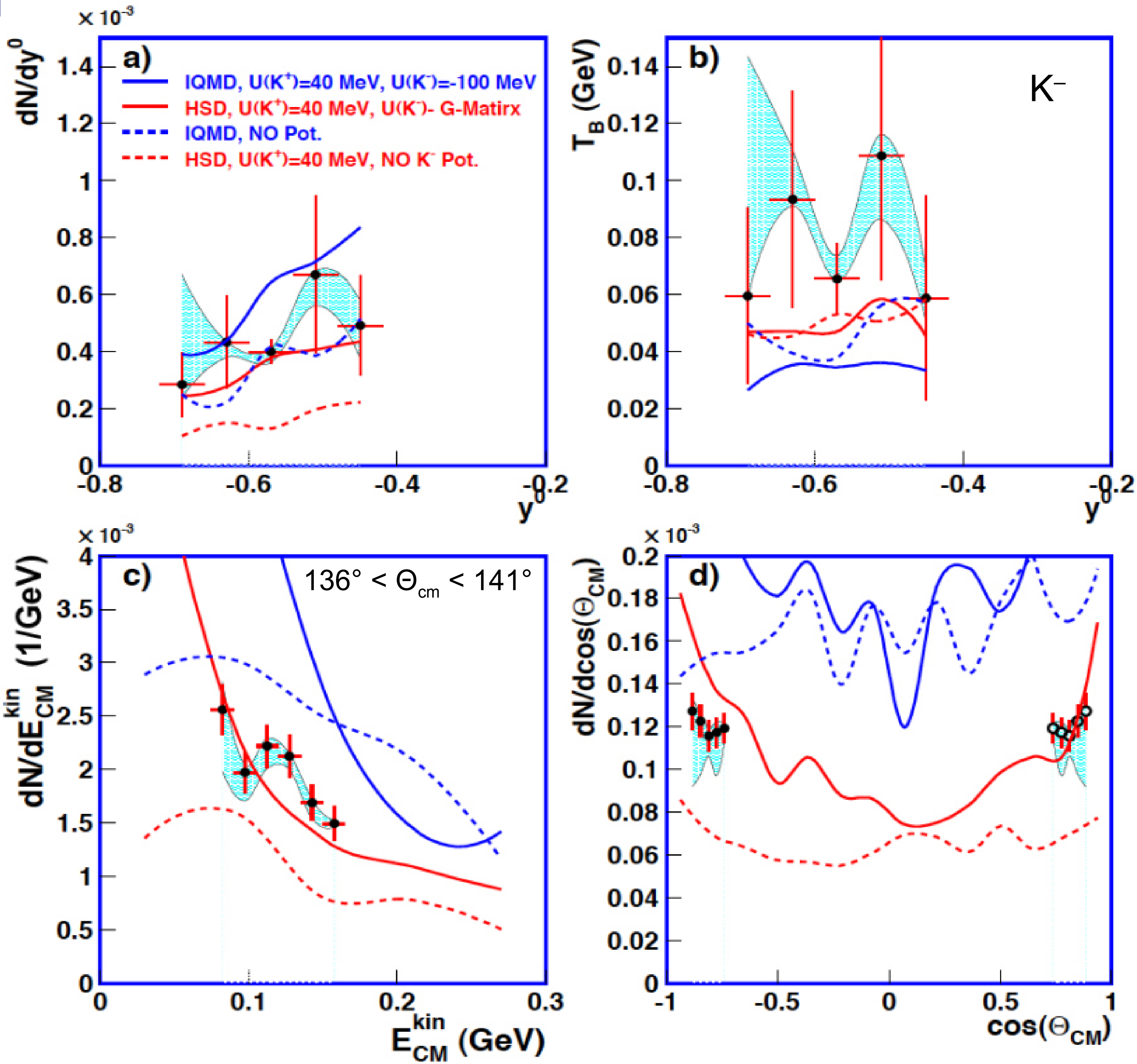
- **HSD**
  - Semi-soft EoS ($K \approx 250$ MeV)
  - K⁺ mass modifications as in IQMD
  - K⁻ production: off-shell G-matrix

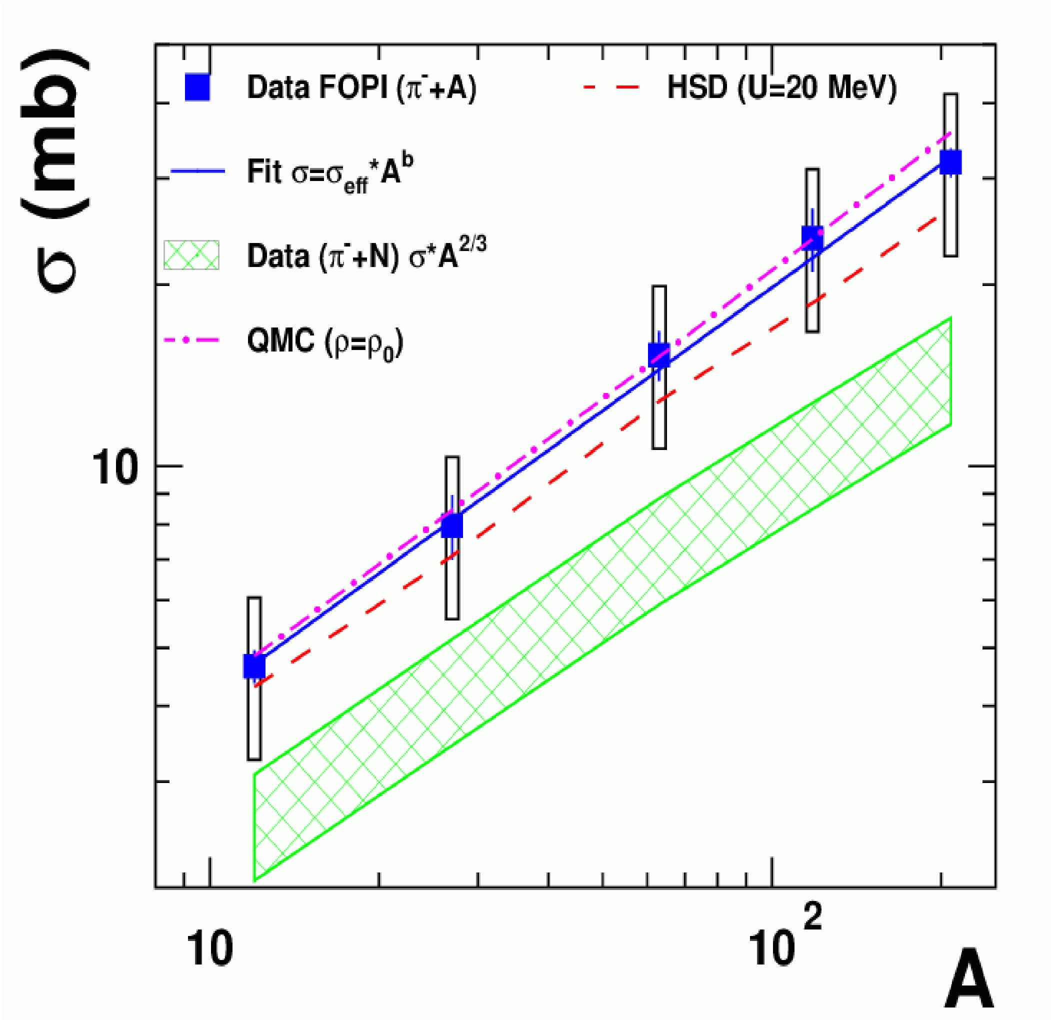
- Clear preference for $U_{KN} \neq 0$ option
- Still description not ideal

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



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

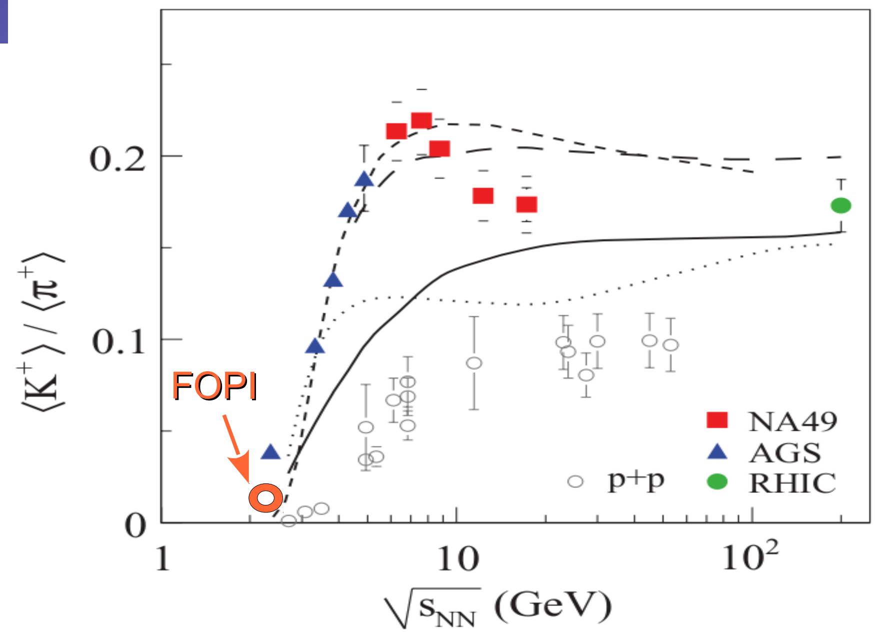


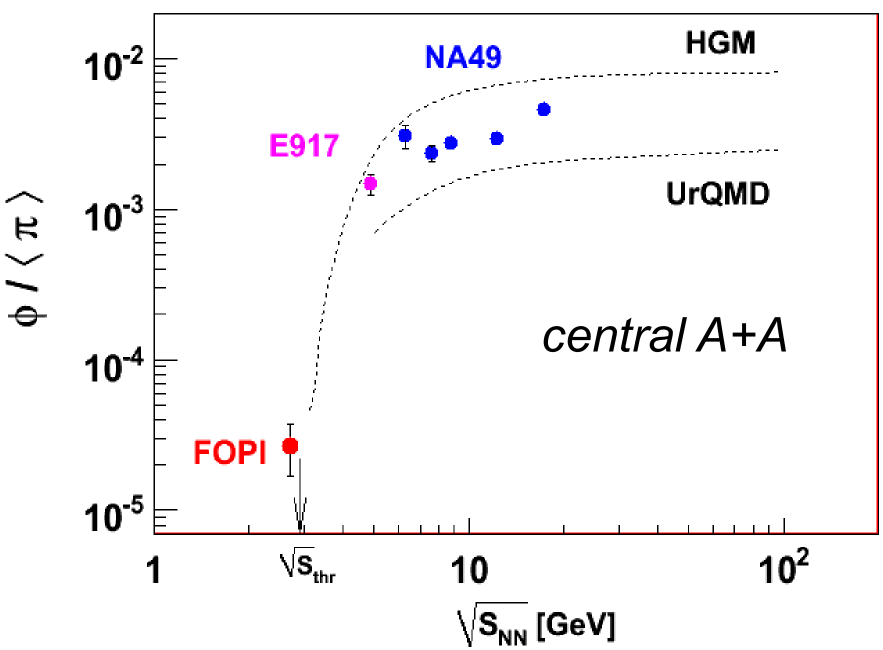


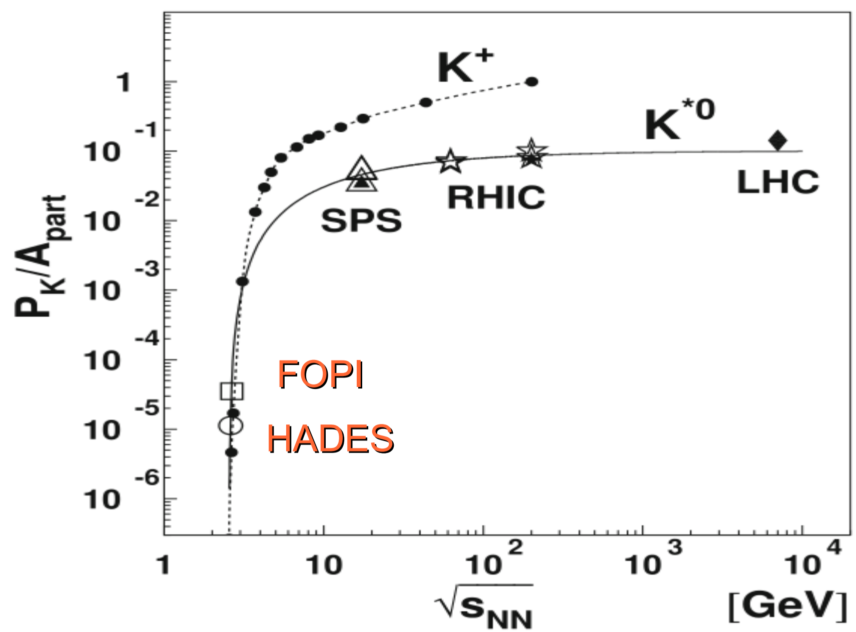
M.L. Benabderrahmane et al., PRL 102, 182501 (2009)

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

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
Strangeness production and absorption

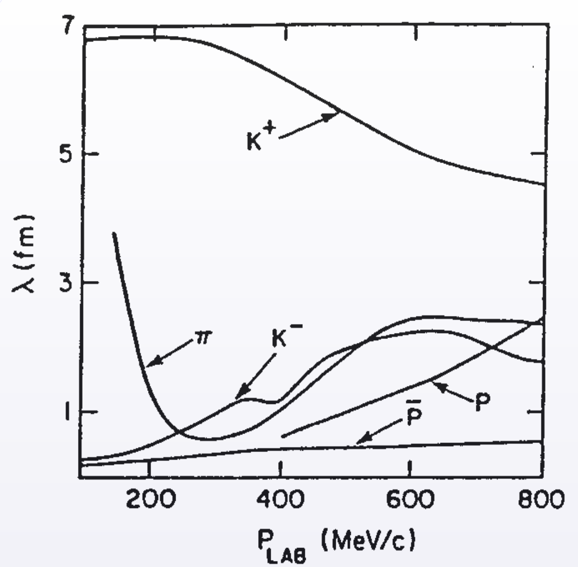
	K^+	K^-	ϕ
Production (primary)	$BB \to BYK^+$ $T_{pp\to p\Lambda K+}$ = 1.58 GeV	$BB \to BBK^+K^-$ $T_{pp\to ppK+K-}$ = 2.5 GeV	$BB \to BB\phi$ $T_{pp\to ppK+K-}$ = 2.6 GeV
Production (secondary)	$\pi B \to YK^+$	$\pi Y \to (\Sigma^* \to)\ BK^-$ $BY \to NK^-\Lambda$ $BY \to BBK^-$ $\pi B \to BK^+K^-$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

[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

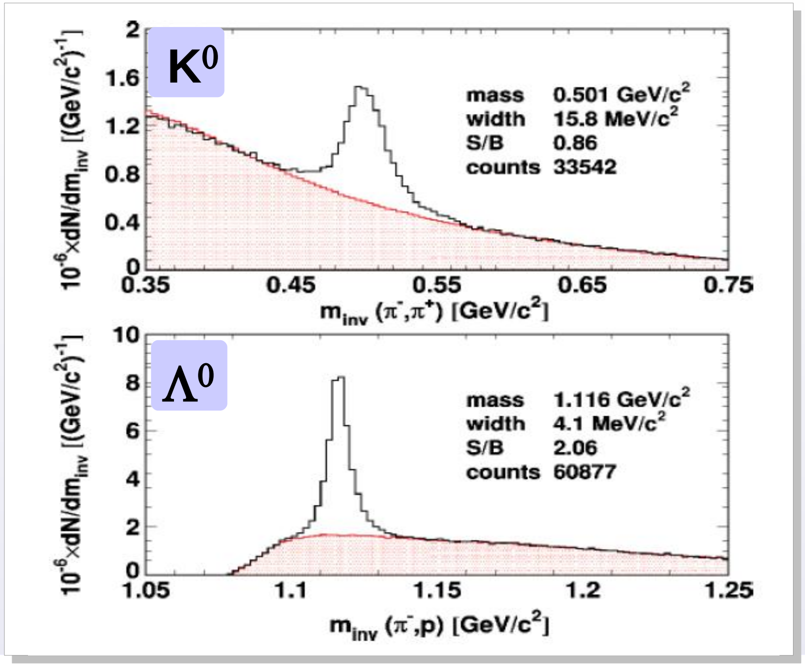
Ni+Ni @ 1.9A GeV

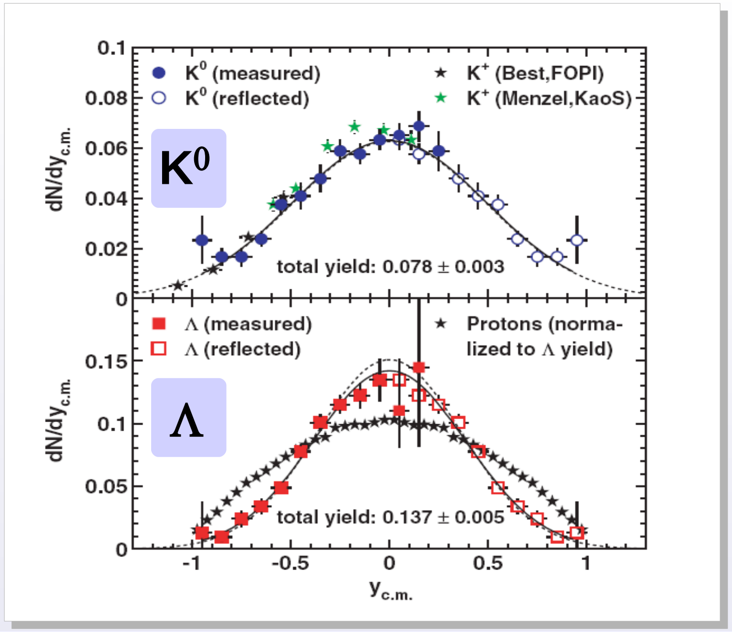
- K^0 and Λ^0 (from secondary vertices)

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

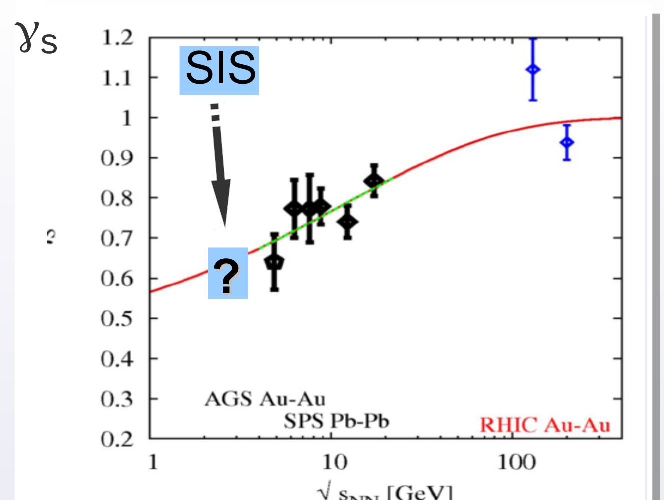
...but

No equilibration of strangeness (?)

Extension:

$$\exp(\ldots) \rightarrow \exp(\ldots)\cdot\frac{1}{(\gamma_S)^{n_s}}$$

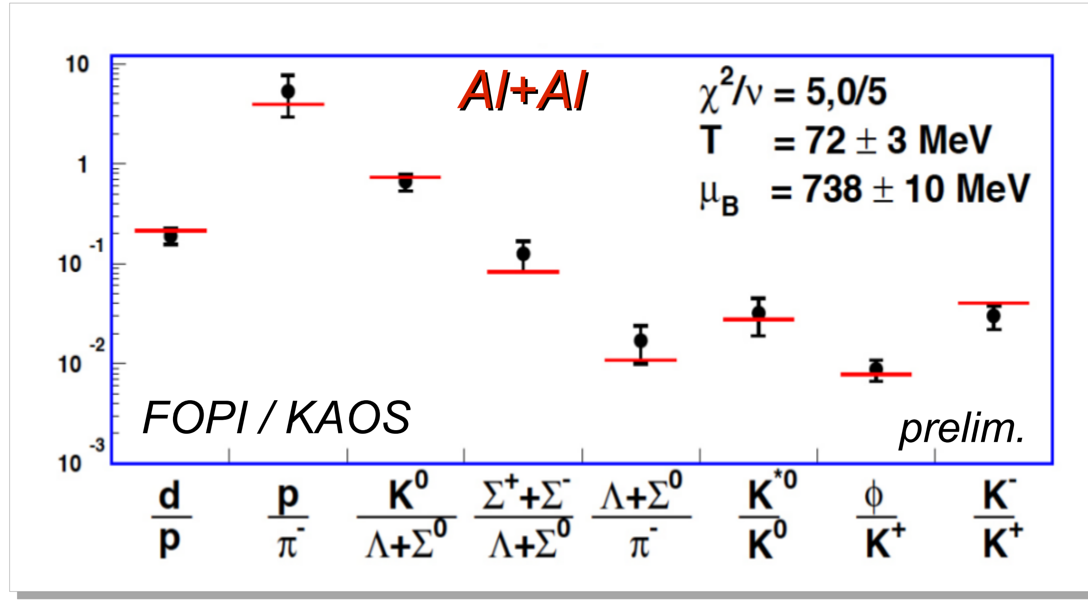
γ_S “strangeness undersaturation factor”
n_S number of strange quarks



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

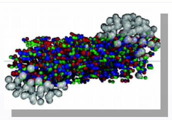
→ Grand Canonical ensemble;

→ 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