HADES

FOPI

News on in-medium modifications of properties of kaons measured around threshold

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- Introduction to phenomenon
- Case of K^0_s from Au+Au @ 1.2A GeV
- Case of K^+ and K^- from Ni+Ni @ 1.9A GeV
- Summary & outlook

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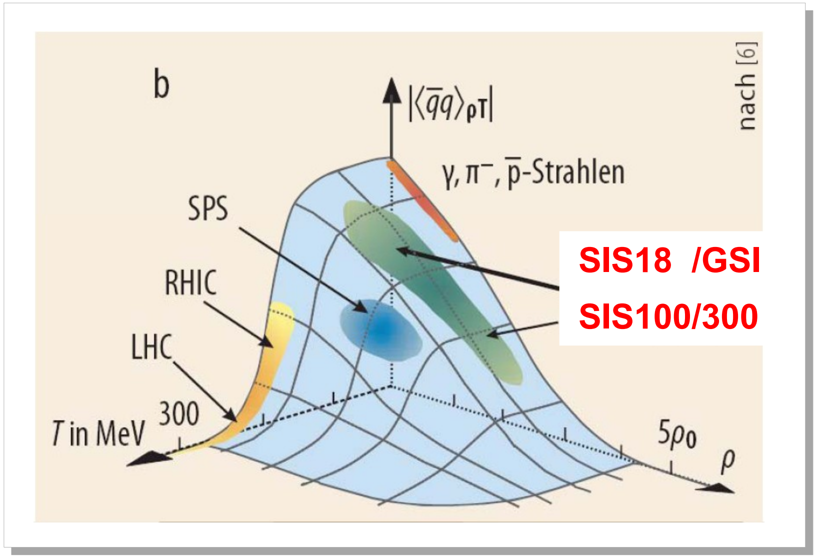
Partial restoration of chiral symmetry



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

- **QCD**: vacuum is not empty → $\bar{q}q$ condensate
- **Gell-Mann Oakes Renner relation:**

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

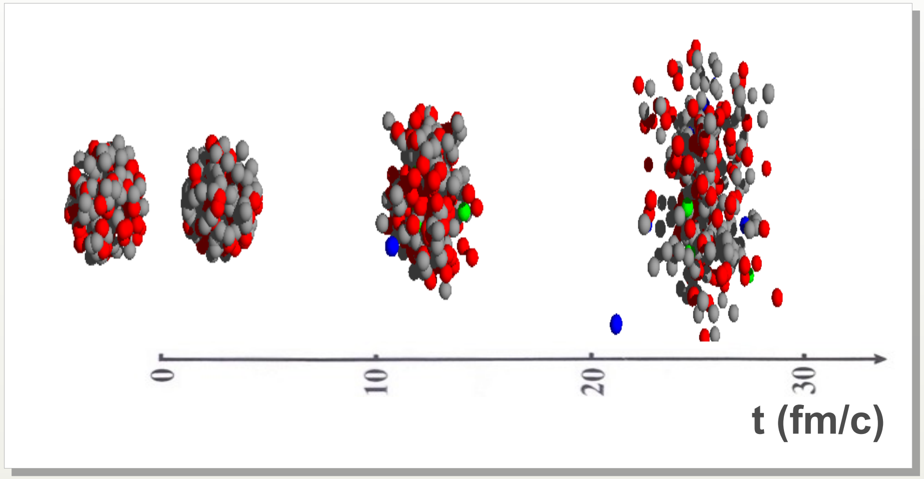
Decay constant

Mass

Heavy-ion collisions: medium + probe

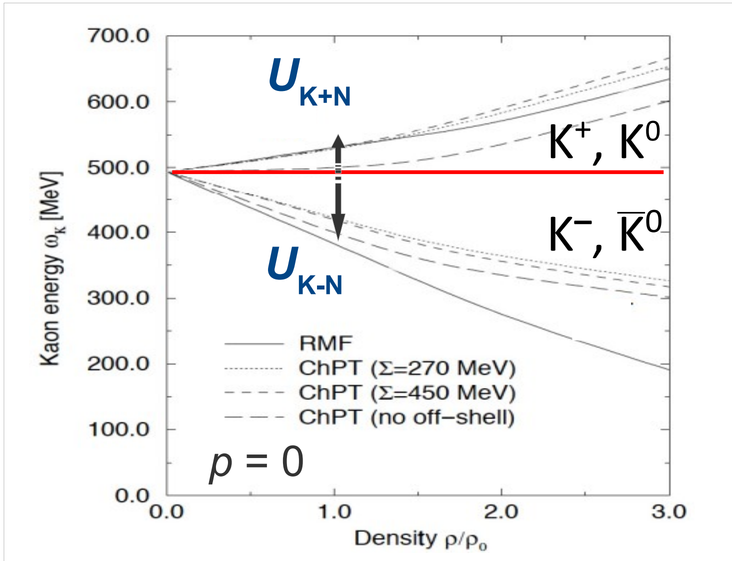
- **A good probe:**
  - a single, easily measurable particle emitted from heavy-ion collision zone.
- Take **Kaons** :
  - Threshold E_{kin} for NN → NK⁺Λ : 1.6 GeV

    At a few AGeV usually *single* kaon emitted



Changes of Kaon properties in medium

Approximate description: **Potential**



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

Effects induced by in-medium potential :

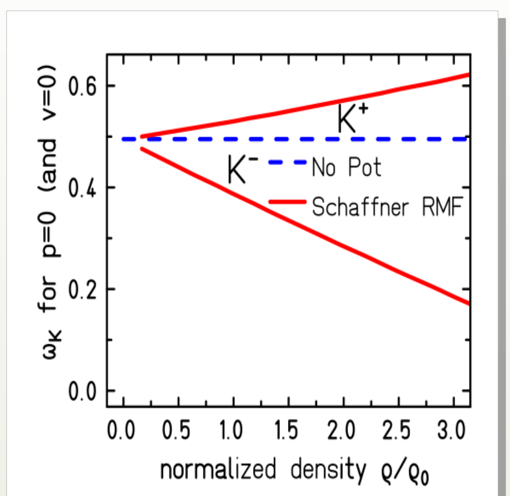
- As $m_K \neq m_{Vacuum}$, production threshold changes
- As **K⁺, K⁰** escapes the collision zone:
  $m_K \searrow m_{Vacuum}$ ➠ Kaon gives energy to E_{kin} (speeds up)
- As **K⁻, K̄⁰** escapes the collision zone:
  $m_K \nearrow m_{Vacuum}$ ➠ Antikaon takes energy from E_{kin} (slows down)

Transport models – simple approaches

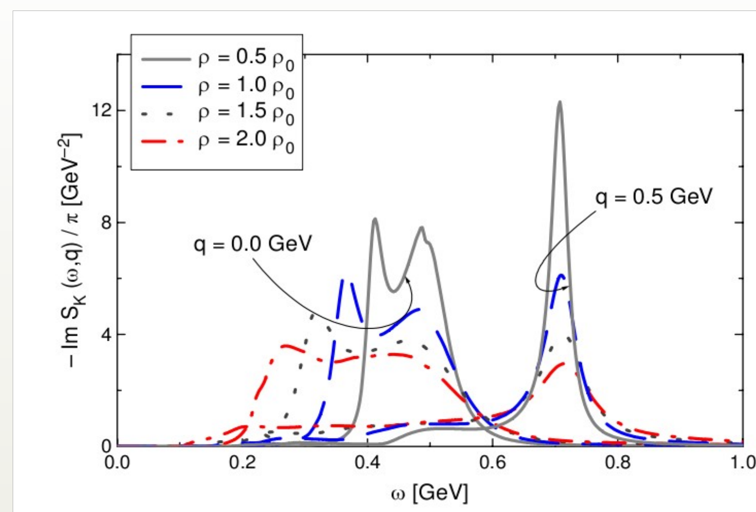
Hypothesis:

Mass effectively changes proportionally to the medium density

$$m_K(\rho) = m_{K,vac} \cdot \left(1 \pm \alpha \frac{\rho}{\rho_0}\right)$$



… or more advanced (eg. Chiral EFT w.CC → HSD)



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

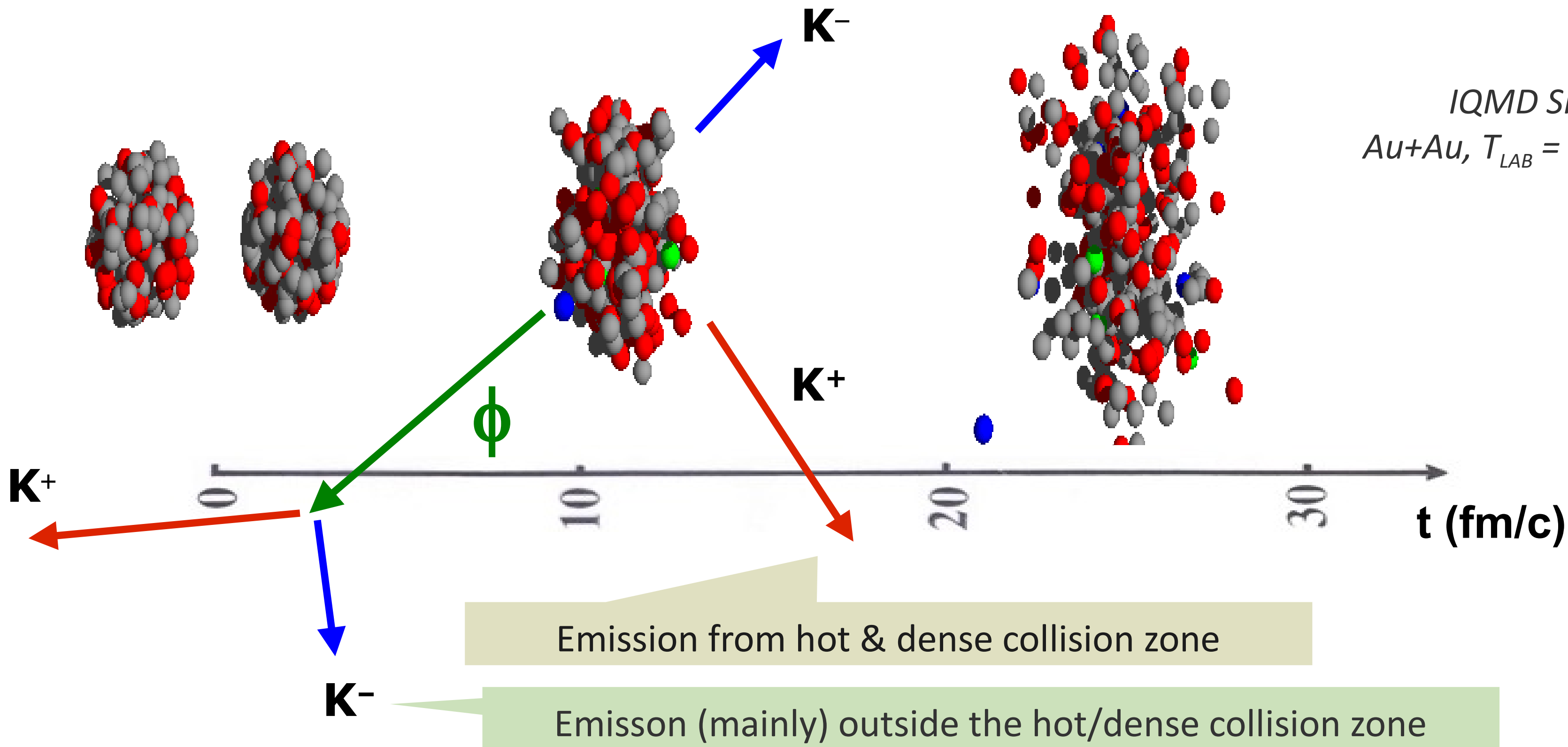
ϕ meson: a hidden player

$\phi\ (s\bar{s})$: m = 1.02 GeV

$T_{beam,threshold}$ = 2.6 GeV

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

IQMD Simulation
Au+Au, T_{LAB} = 1.5A GeV



- K^- from ϕ decay (decay kinematics) mixes with K^- from collision zone.
- First attempt to gain some knowledge on $\phi \rightarrow K^+K^-$: year 2003, 23 ϕ events

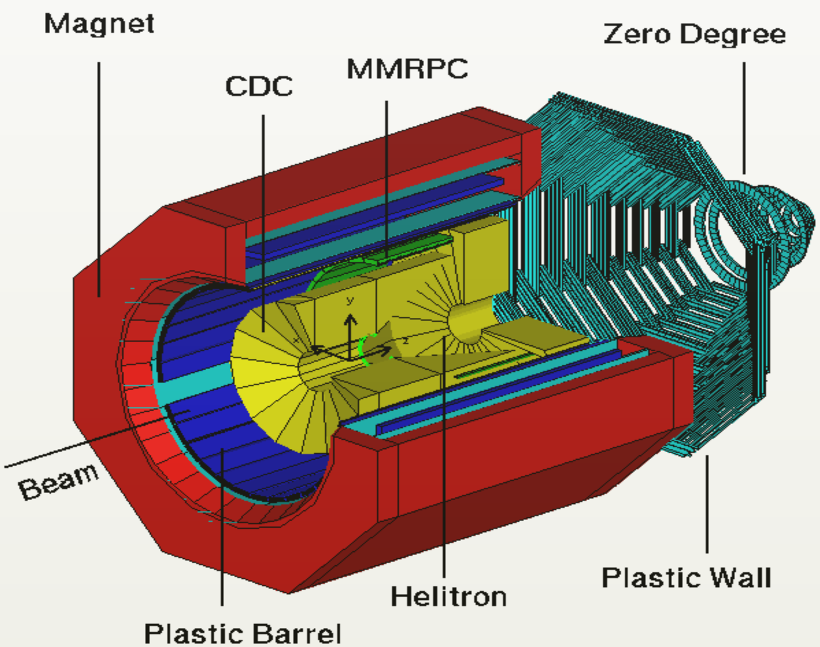
A. Mangiarotti et al. (FOPI), NPA 714, 81 (2003)

FOPI and HADES experimental setups @ GSI, Darmstadt

FOPI (*FOur PI*)

Spectrometer for charged particles
Operating in 1990–2012.

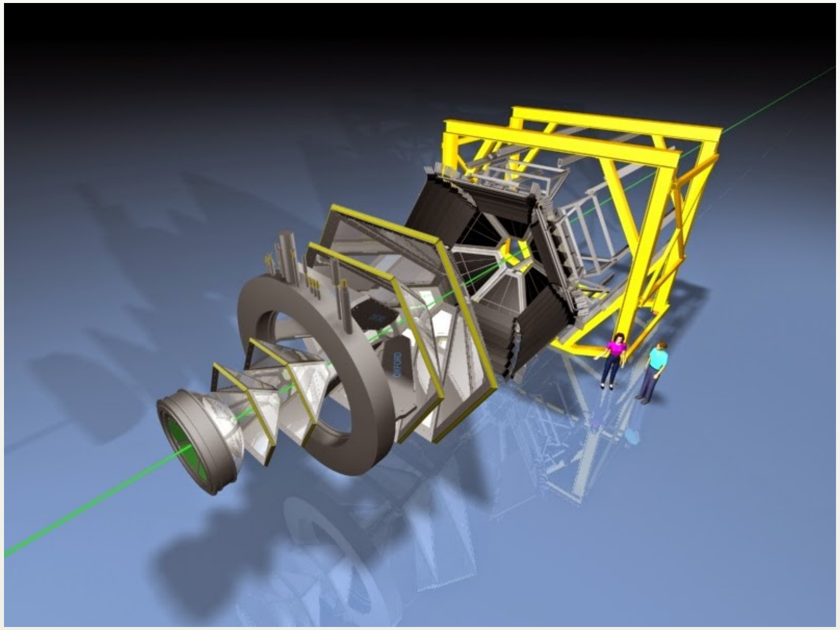
CDC: momentum
Plastic Barrel & MMRPC : Time-of-flight



HADES (*High-Acceptance Di-Electron Spectrometer*)

Adjusted to measure hadrons
Operating: currently

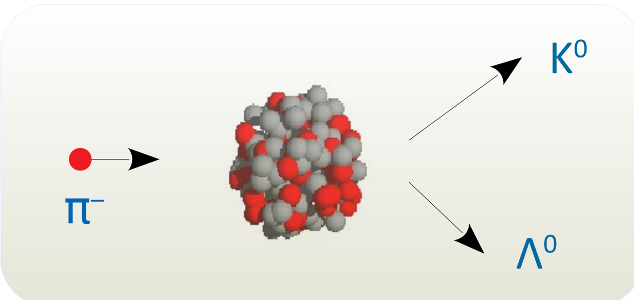
MDC: momentum
TOF & RPC : Time-of-flight



FOPI and HADES: Similar acceptance for Kaon measurements
Access to K^0_s via $K^0_s \to \pi^+ \pi^-$ (BR = 63%)

π meson hits the nucleus : production of kaons at $\rho \approx \rho_0$.

possible single-step channels: $\pi^- p \to K^0\Sigma^0$, $\pi^- p \to K^0\Lambda^0$, $\pi^- n \to K^0\Sigma^-$

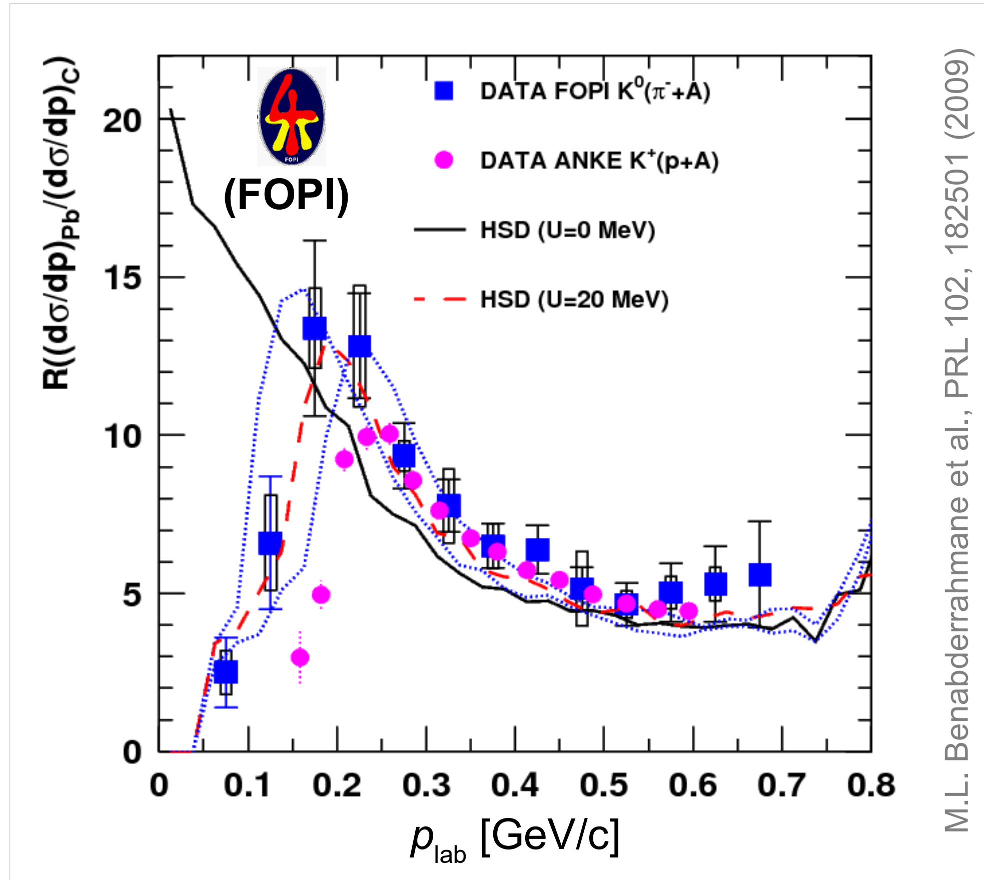


- Comparison of two reactions (FOPI, 2009) :

π^- (p=1.15 GeV/c) + ^{208}Pb $\to$ **K^0** + ...

π^- (p=1.15 GeV/c) + ^{12}C $\to$ **K^0** + ...

Ratio of momentum distributions of kaons:



Distribution for K^0 emitted from Pb shifted to higher momenta.

- Comparison to **HSD** transport model:

solid	No potential
blue dotted	U_{KON} (ϱ_0) = 10 MeV
red dashed	U_{KON} (ϱ_0) = 20 MeV
blue dotted	U_{KON} (ϱ_0) = 30 MeV

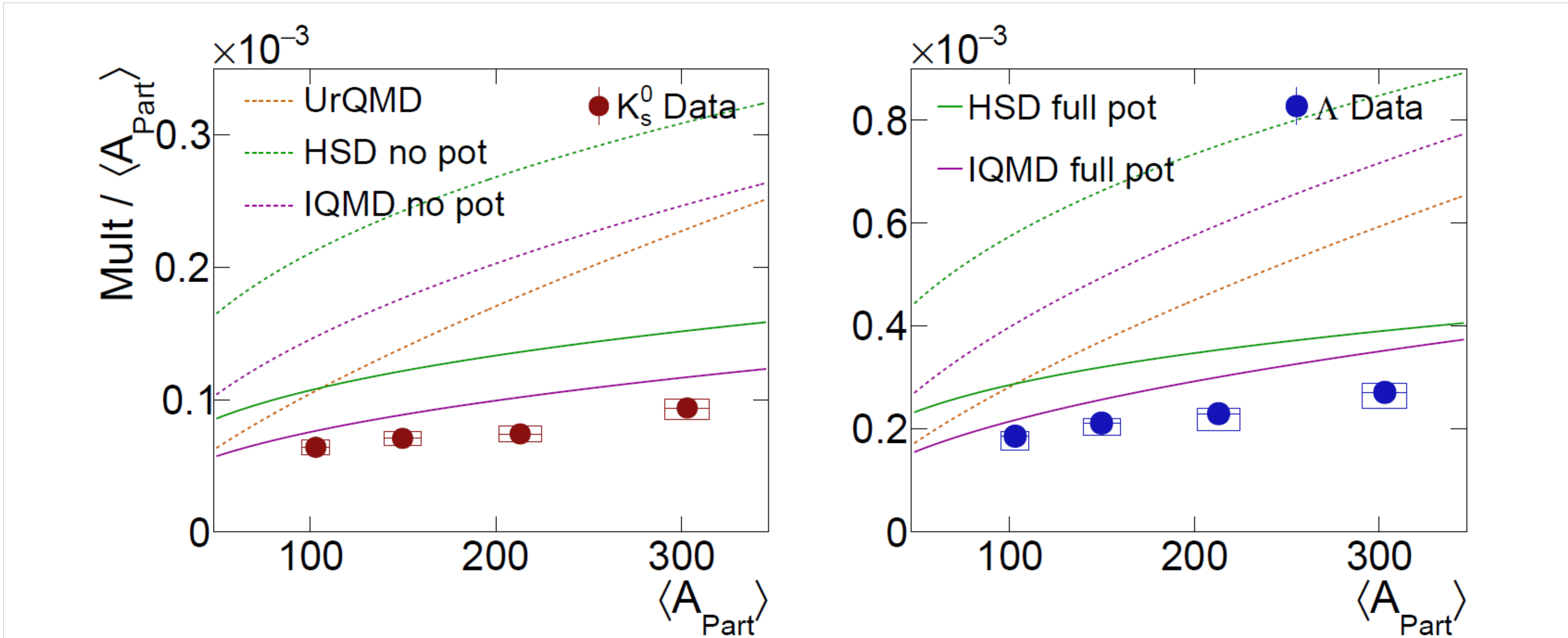
Data in agreement if U_{KON} (ϱ_0) = +20 MeV

HADES

Comparing K^0 and Λ data to transport models with/without in-medium effects
(Basic production channel: NN → $NK^0\Lambda$)

1. Multiplicity of K^0_s and Λ vs centrality :

J. Adamczewski–Musch et al. (HADES), PLB 793, 457 (2019)



➤ Transport calculations :

HSD	—	$U_{KON}(\varrho_0) = 40$ MeV
IQMD	—	$U_{KON}(\varrho_0) = 40$ MeV

Absolute yield overstated by calculations.
Large spread in yield between different models.

No scenario without in-medium potential reproduces the $<A_{part}>$ scaling.

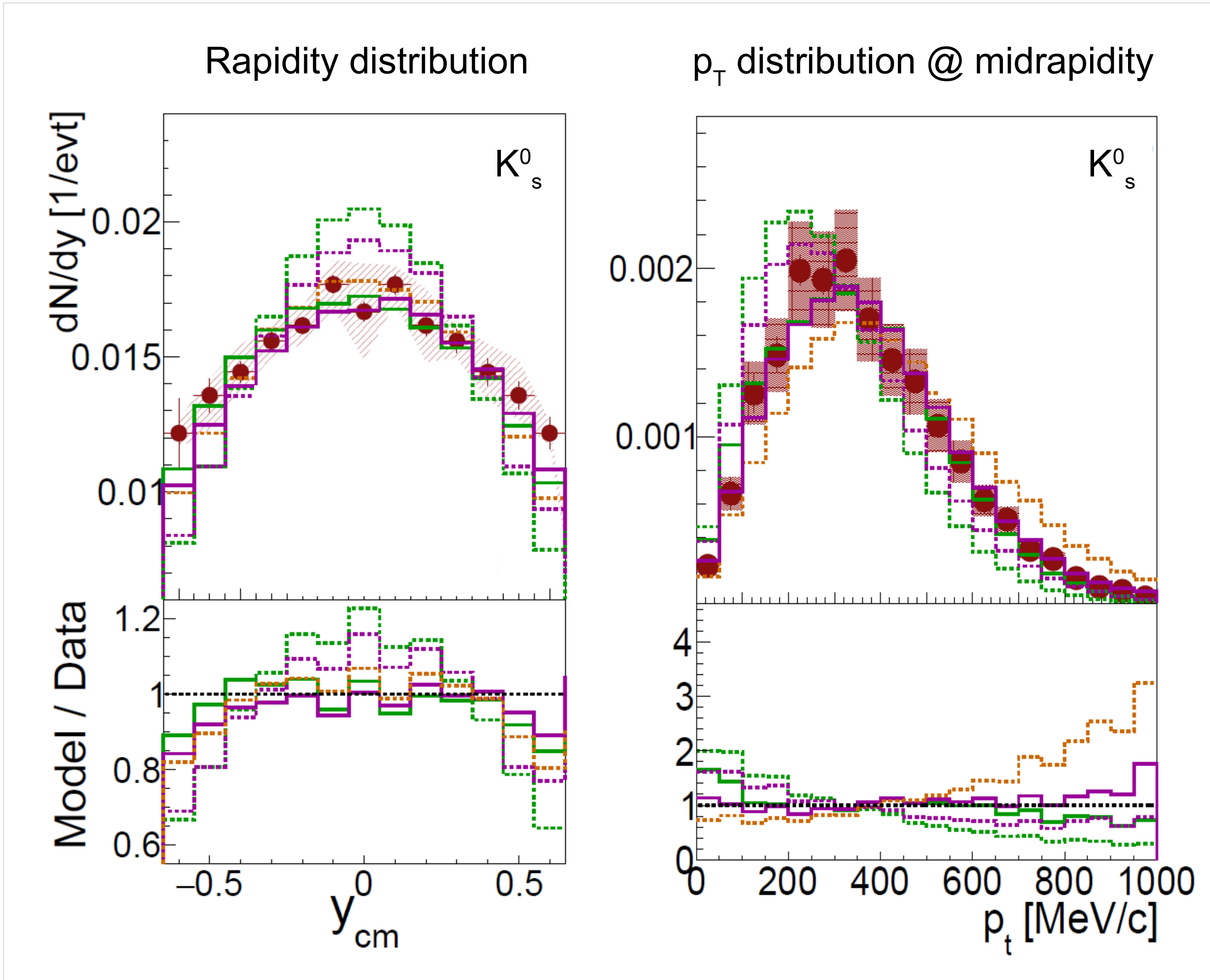
Switching the potential on ...
... improves the description significantly!

2. Phase space distributions of K^0_s , 10% most central evts

Model curves were normalized to exp. data (comparison of profiles)

Legend

UrQMD	dotted	No potential
IQMD	dotted	No potential
HSD	solid	No potential
IQMD	solid	$U_{K0N}(\varrho_0)$ = 40 MeV
HSD	dotted	$U_{K0N}(\varrho_0)$ = 40 MeV



Again, best description with the in-medium effects.

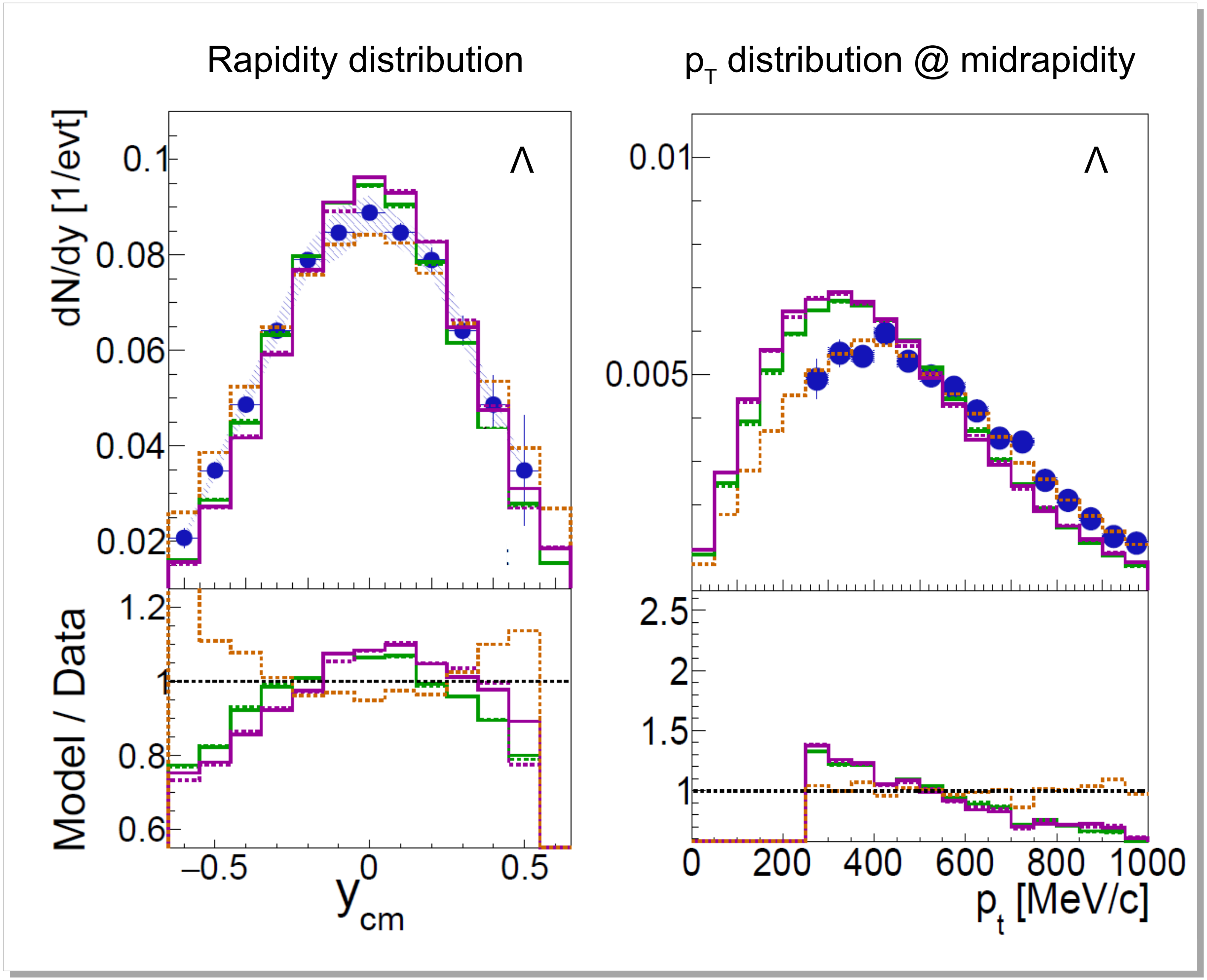
J. Adamczewski–Musch et al. (HADES), PLB 793, 457 (2019)

2. Phase space distributions of Λ , 10% most central evts

Model curves were normalized to exp. data (comparison of profiles)

Legend

UrQMD	dotted	No potential
IQMD	dotted	No potential
HSD	solid	No potential
IQMD	solid	$U_{KON}(\rho_0)$ = 40 MeV
HSD	dotted	$U_{KON}(\rho_0)$ = 40 MeV

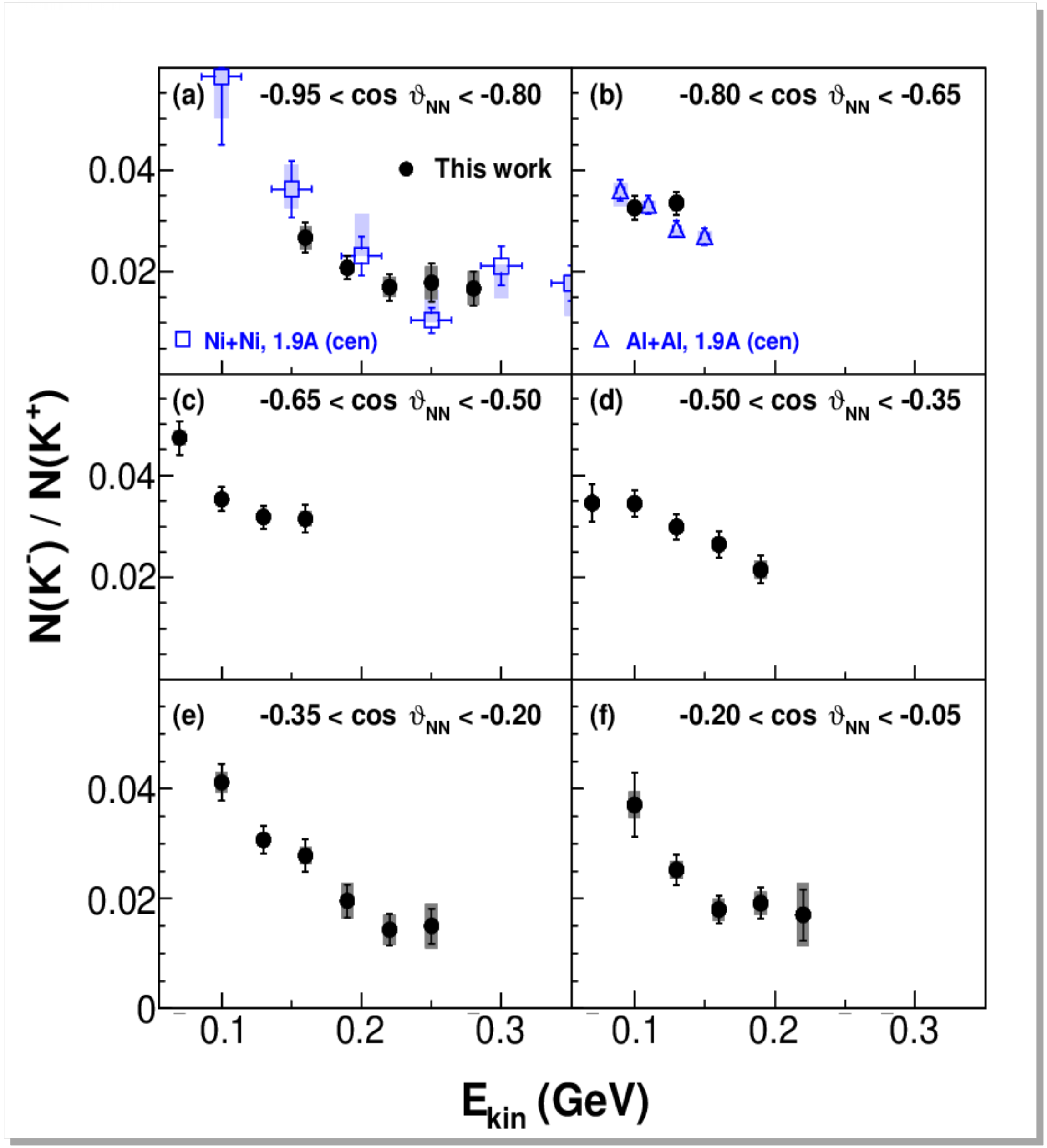


- Inclusion of in-medium effects for K^0_s does not affect Λ
- UrQMD describes the profile best.

J. Adamczewski–Musch et al. (HADES), PLB 793, 457 (2019)

$K^{-/+}$ emitted from Ni+Ni collisions (recent data)

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



New data (full dots)

- wide phase space coverage
- more statistics

KP *et al.* (FOPI), PRC 99, 014904 (2019)

... To be compared with Transport models

But ... what about ϕ mesons?

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

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

Contribution of ϕ decays to K^- (recent data)

ϕ mesons from AA collisions @ 1.9A GeV

- Measured in K^+K^- decay channel (BR = 50%) in 3 systems. Small samples (~150 events).
- Result: $\phi/K^- = 0.36 \pm 0.05$

  (In agreement with HADES data for Ar+KCl @ 1.76A GeV,
  G. Agakishiev et al., PRC 80 (2009) 025209

  Even higher ϕ/K^- ratio found by HADES for Au+Au @ 1.2A GeV,
  J. Adamczewski-Musch et al., PLB 778, 403 (2018))

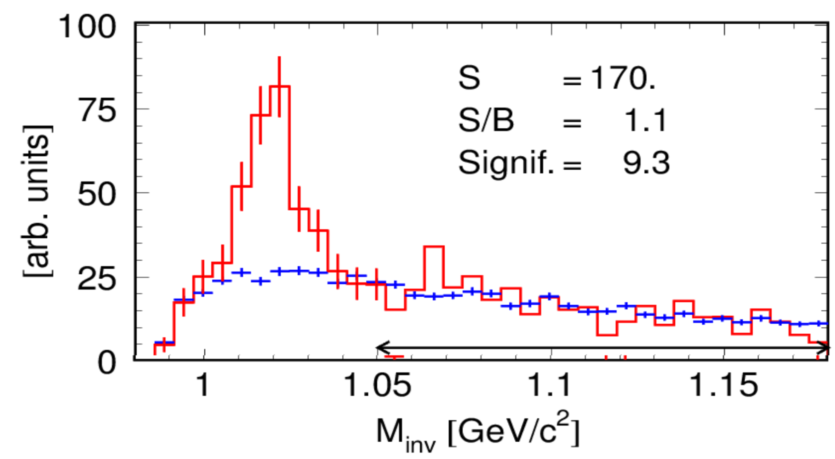
- Since BR ($\phi \rightarrow K^+K^-$) ≈ 50% ,

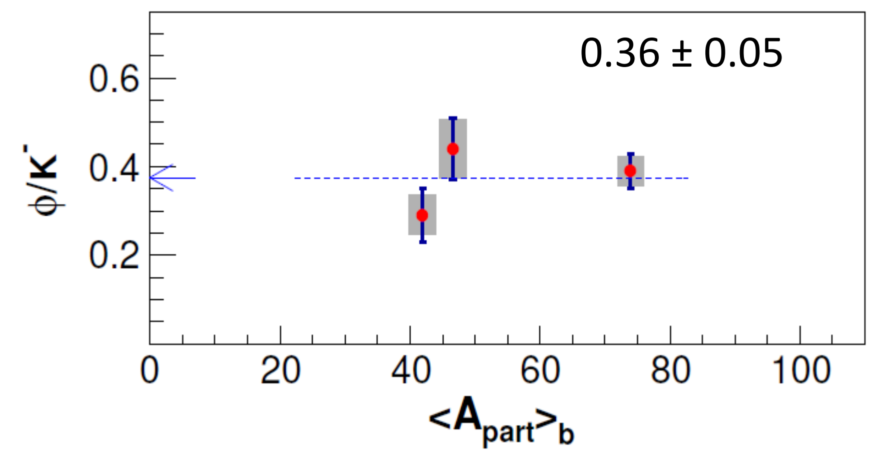
  → **About 18% of K^- originates from decays of ϕ mesons,**
  (different kinematics than for "direct")

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

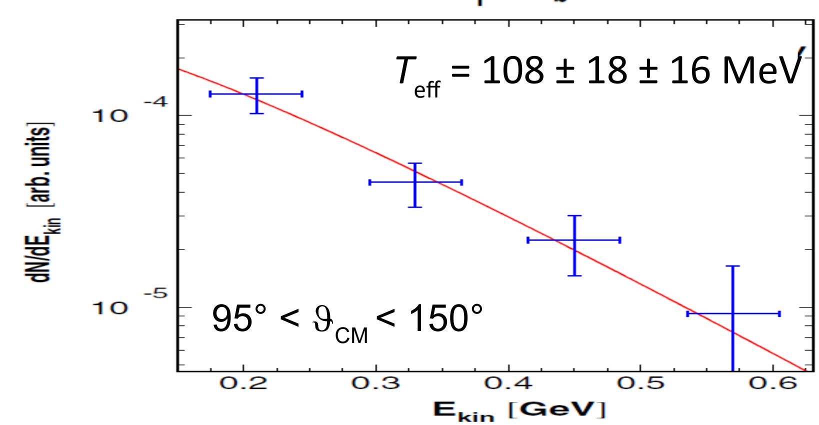
  → K^- from ϕ decays: "colder" than these emitted directly from collision zone.

→ We can subtract contribution from K^- spectra, and obtain the K^-/K^+ ratio built by particles without the ϕ decay contribution





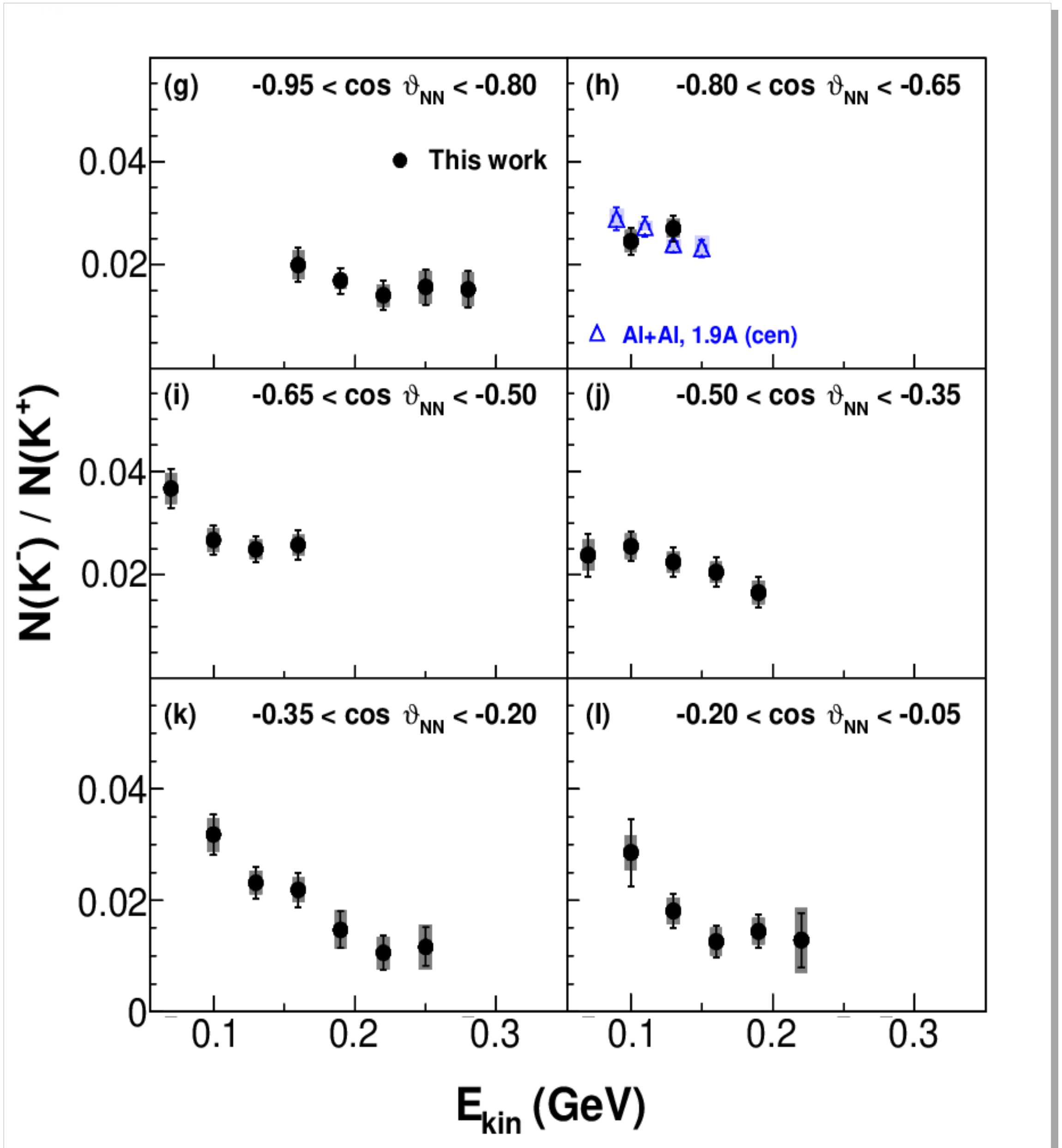
KP et al., PRC 91, 054904 (2015)



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

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

Ratio of K^-/K^+ (K^- without ϕ contribution) from Ni+Ni @ 1.9*A* GeV, centrality 56%



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

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

Energy dependence still drops.

→ perhaps the K^- modifications still non-negligible

... to be compared with Transport Models,

in case if ϕ emission not well reproduced.

However, $\Lambda(1520) \rightarrow pK^-$ could be another player, (never measured @ T_b < 10A GeV)

See **Dominika Wójcik's Poster**

Summary & Outlook

Modifications of kaon properties in medium are the result of **partial restoration of chiral symmetry**.
Frequent parametrization: extra kaon-nucleus potential as function of density.

- **First tests:** K^0_s emitted from $\pi^- A$: $U_{KON}(\varrho_0) \approx +20$ MeV.
- **Recent analyses:**
  - **Case of K^0_s (and Λ) from Au+Au @ 1.23A GeV (HADES)**
    - Data: Yields against centrality, Pt-y spectra in wide acceptance.
    - Models: UrQMD (no in-medium), HSD & IQMD (no in-medium or $U_{KON}(\varrho_0) \approx 40$ MeV)
    - Results: Yields of K^0_s and Λ : clear preference for in-medium scenario
      K^0_s (p_t and rapidity profiles) : clear preference for in-medium scenario
      Λ (p_t and rapidity profiles) : clear preference for UrQMD,
      for HSD, IQMD bad prediction in either scenario
  - **Case of K^- and K^+ from Ni+Ni @ 1.9A GeV (FOPI)**
    - Data: Ratio of K^-/K^+ yields scanned across phase space ($E_{kin,NN}$ vs $\cos\theta_{NN}$)
      ϕ : yields and ϕ/K^- ratio against centrality, E_{kin} spectrum
      Ratio of K^-/K^+ with ϕ contribution removed
    - Ready to be compared to transport models
    - Possible new side feeding to K^- : $\Lambda(1520)$. See Dominika Wójcik's Poster!

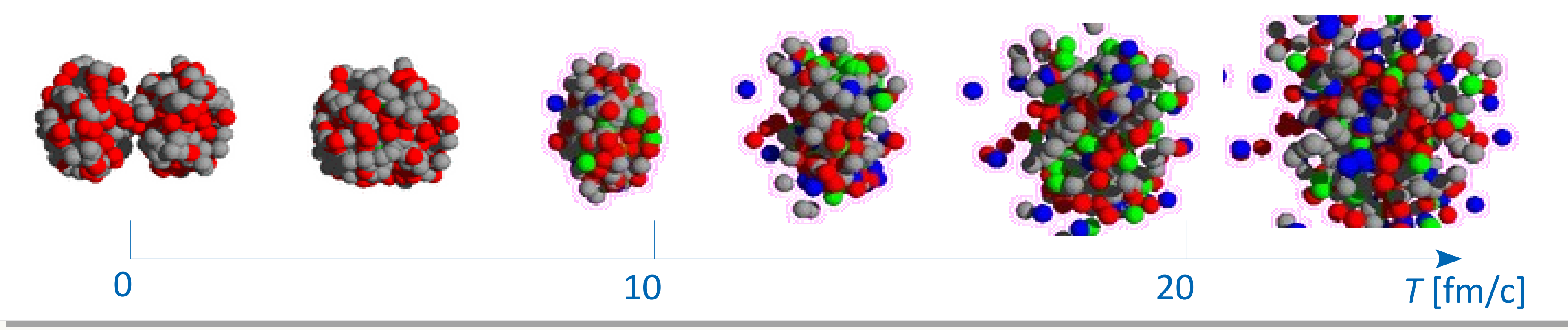
OUTLOOK

- New data on Ag+Ag @ 1.58A GeV taken by HADES in march this year – stay tuned!

Thank You!

Backup slides

IQMD simulation of Au+Au collision at T_B = 1.5A GeV



C. Hartnack "The nuclear equation of state is soft" SQM 2006

(1 fm/c = $3.3 \cdot 10^{-23}$ s)

4 fm/c: onset of Δ (1232) production

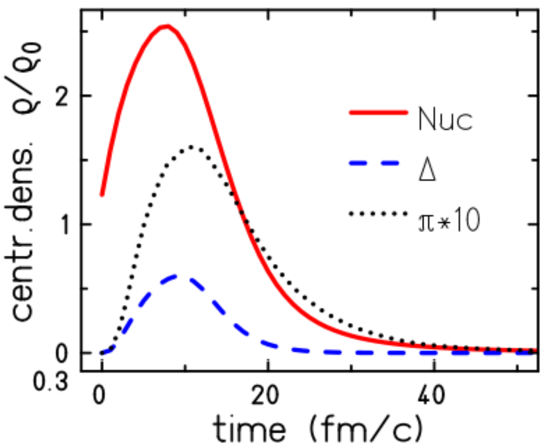
8 fm/c: max. nucleon density (2–3 × ρ_0)

10 fm/c: max. density of Δ

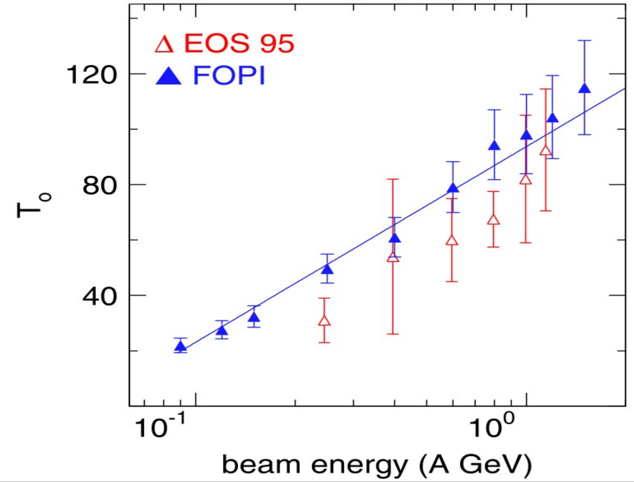
12 fm/c: max. density of π

20–30 fm/c: π multiplicity → saturates

Δ multiplicity → drops to 0



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



W. Reisdorf et al., NPA 848, 366 (2010)

ChPT Lagrangian

on this framework has been used by many other authors [8,12,29–38]. The corresponding chiral $\mathrm{SU}(3)_L \times \mathrm{SU}(3)_R$ Lagrangian used by Kaplan and Nelson reads

$$\begin{aligned}\mathcal{L} = &\frac{1}{4} f^2 \mathrm{Tr}\, \partial^\mu \Sigma \partial_\mu \Sigma^+ + \frac{1}{2} f^2 \Lambda [\mathrm{Tr}\, M_q(\Sigma - 1) + \mathrm{h.c.}] + \mathrm{Tr}\, \bar{B}(i\gamma^\mu \partial_\mu - m_B)B \\ &+ i\mathrm{Tr}\, \bar{B}\gamma^\mu [V_\mu, B] + D\mathrm{Tr}\, \bar{B}\gamma^\mu\gamma^5\{A_\mu, B\} + F\mathrm{Tr}\, \bar{B}\gamma^\mu\gamma^5[A_\mu, B] \\ &+ a_1 \mathrm{Tr}\, \bar{B}(\xi M_q \xi + \mathrm{h.c.})B + a_2 \mathrm{Tr}\, \bar{B}B(\xi M_q \xi + \mathrm{h.c.}) \\ &+ a_3 [\mathrm{Tr}\, M_q \Sigma + \mathrm{h.c.}]\mathrm{Tr}\, \bar{B}B. \end{aligned} \tag{1}$$

The degrees of freedom in the Lagrangian (1) are the baryon octet B

$$B = \begin{pmatrix} \frac{\Lambda}{\sqrt{6}} + \frac{\Sigma^0}{\sqrt{2}} & \Sigma^+ & p \\ \Sigma^- & \frac{\Lambda}{\sqrt{6}} - \frac{\Sigma^0}{\sqrt{2}} & n \\ \Xi^- & \Xi^0 & -\frac{2}{\sqrt{6}}\Lambda \end{pmatrix} \tag{2}$$

with a degenerate mass m_B, and the pseudoscalar meson octet ϕ

$$\phi = \sqrt{2} \begin{pmatrix} \frac{\eta_8}{\sqrt{6}} + \frac{\pi^0}{\sqrt{2}} & \pi^+ & K^+ \\ \pi^- & \frac{\eta_8}{\sqrt{6}} - \frac{\pi^0}{\sqrt{2}} & K^0 \\ K^- & \overline{K^0} & -\frac{2}{\sqrt{6}}\eta_8 \end{pmatrix} \tag{3}$$

entering into the chiral pseudoscalar meson fields

$$\Sigma = \exp(2i\phi/f_\pi) \quad \text{and} \quad \xi = \sqrt{\Sigma} = \exp(i\phi/f_\pi). \tag{4}$$

The pseudoscalar meson decay constants are equal in the $\mathrm{SU}(3)_V$ limit and given by the weak pion decay constant $f_\pi \simeq 93$ MeV. The current quark mass matrix which is responsible for explicit chiral symmetry breaking is given by

$$M_q = \begin{pmatrix} m_q & 0 & 0 \\ 0 & m_q & 0 \\ 0 & 0 & m_s \end{pmatrix} \tag{5}$$

RMF Lagrangian

2. The RMF model

It has been demonstrated by many studies that the RMF model gives a good description of nuclear matter in bulk as well as of properties of nuclei [27,28]. We start from the Lagrangian

$$\begin{aligned}\mathcal{L} = &\overline{\Psi}_N(i\gamma^\mu\partial_\mu - m_N)\Psi_N + \tfrac{1}{2}\partial^\mu\sigma\partial_\mu\sigma - U(\sigma) \\ &- \tfrac{1}{4}G^{\mu\nu}G_{\mu\nu} + \tfrac{1}{2}m_\omega^2 V^\mu V_\mu - \tfrac{1}{4}\boldsymbol{B}^{\mu\nu}\boldsymbol{B}_{\mu\nu} + \tfrac{1}{2}m_\rho^2 \boldsymbol{R}^\mu \boldsymbol{R}_\mu \\ &- g_{\sigma N}\overline{\Psi}_N\Psi_N\sigma - g_{\omega N}\overline{\Psi}_N\gamma^\mu\Psi_N V_\mu - g_{\rho N}\overline{\Psi}_N\gamma^\mu\boldsymbol{\tau}\Psi_N\boldsymbol{R}_\mu, \end{aligned} \tag{1}$$

where the nucleons interact via an attractive scalar (σ) and repulsive vector $(V^\mu, \boldsymbol{R}^\mu)$ meson fields. The term $U(\sigma)$ stands for the scalar self-interaction

$$U(\sigma) = \tfrac{1}{2}m_\sigma^2\sigma^2 - \frac{b}{3}\sigma^3 + \frac{c}{4}\sigma^4 \tag{2}$$

The implementation of Λ hyperons proceeds through the additional Lagrangian

$$\mathcal{L}_\Lambda = \overline{\Psi}_\Lambda(i\gamma^\mu\partial_\mu - m_\Lambda)\Psi_\Lambda - g_{\sigma\Lambda}\overline{\Psi}_\Lambda\Psi_\Lambda\sigma - g_{\omega\Lambda}\overline{\Psi}_\Lambda\gamma^\mu\Psi_\Lambda V_\mu. \tag{4}$$

3.1. One-boson-exchange approach

In the kaon sector, we start from the following Lagrangian [13]:

$$\mathcal{L}_{KN} = D_\mu^* \bar{K} D^\mu K - m_K^2 \bar{K}K - g_{\sigma K} m_K \bar{K}K\sigma - g_{\delta K} m_K \bar{K}\boldsymbol{\tau}K\boldsymbol{\delta} \tag{15}$$

with the covariant derivative

$$D_\mu = \partial_\mu + ig_{\omega K}V_\mu + ig_{\rho K}\boldsymbol{\tau}\boldsymbol{R}_\mu. \tag{16}$$

K^0_s and Λ production from Au+Au @ 1.23A GeV

χ^2/ndf between data and model prediction

Model	KN potential	K^0_s			Λ			α
		p_t	y	Mult	p_t	y	Mult	
UrQMD	no	105	4.1	1619	2.3	3.6	3020	16
HSD	yes	7.0	2.7	670	39	6.3	626	6.3
IQMD	yes	6.0	2.0	99	38	12	214	0.3

Strangeness production and absorption

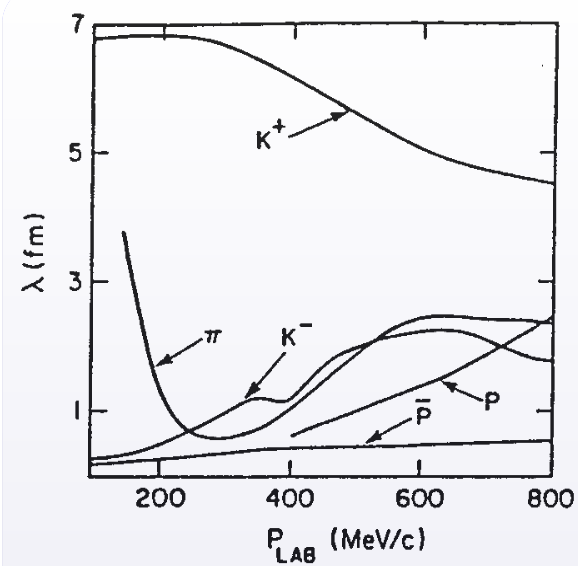
	K^+	K^-	ϕ
Production (primary)	$BB \to BYK^+$ $T_{pp\to p\Lambda K+}$ = 1.58 GeV	$BB \to BBK^+K^-$ $T_{pp\to ppK+K-}$ = 2.5 GeV	$BB \to BB\phi$ $T_{pp\to ppK+K-}$ = 2.6 GeV
Production (secondary)	$\pi B \to YK^+$	$\pi Y \to (\Sigma^* \to)\ BK^-$ $BY \to NK^-\Lambda$ $BY \to BBK^-$ $\pi B \to BK^+K^-$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

[B] = *p, n, N, N*, Δ*

[Y] = *Λ, Σ*

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

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



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

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

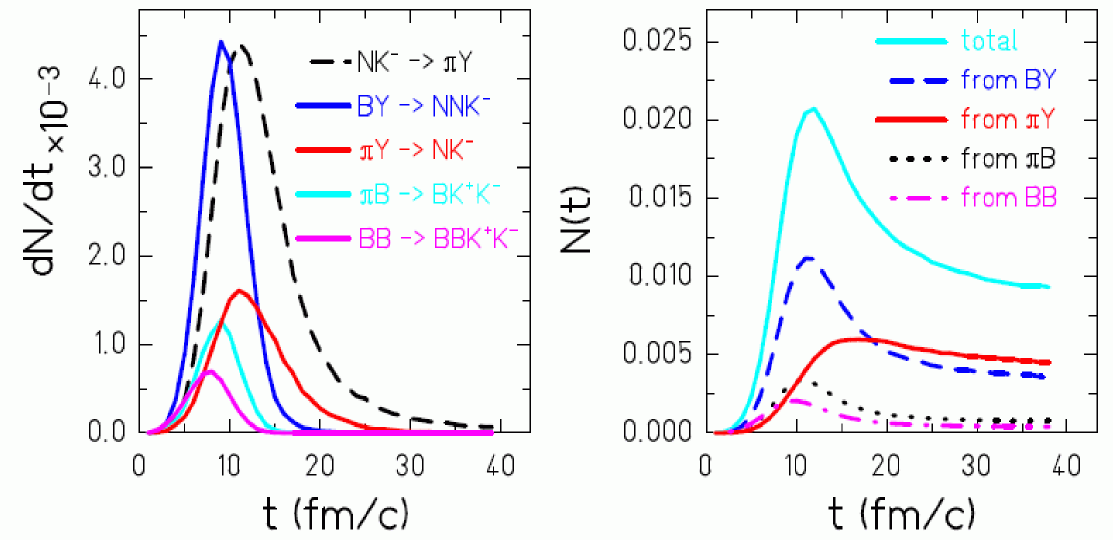
$$BY \rightarrow NNK^-, \quad \pi Y \rightarrow K^- B$$

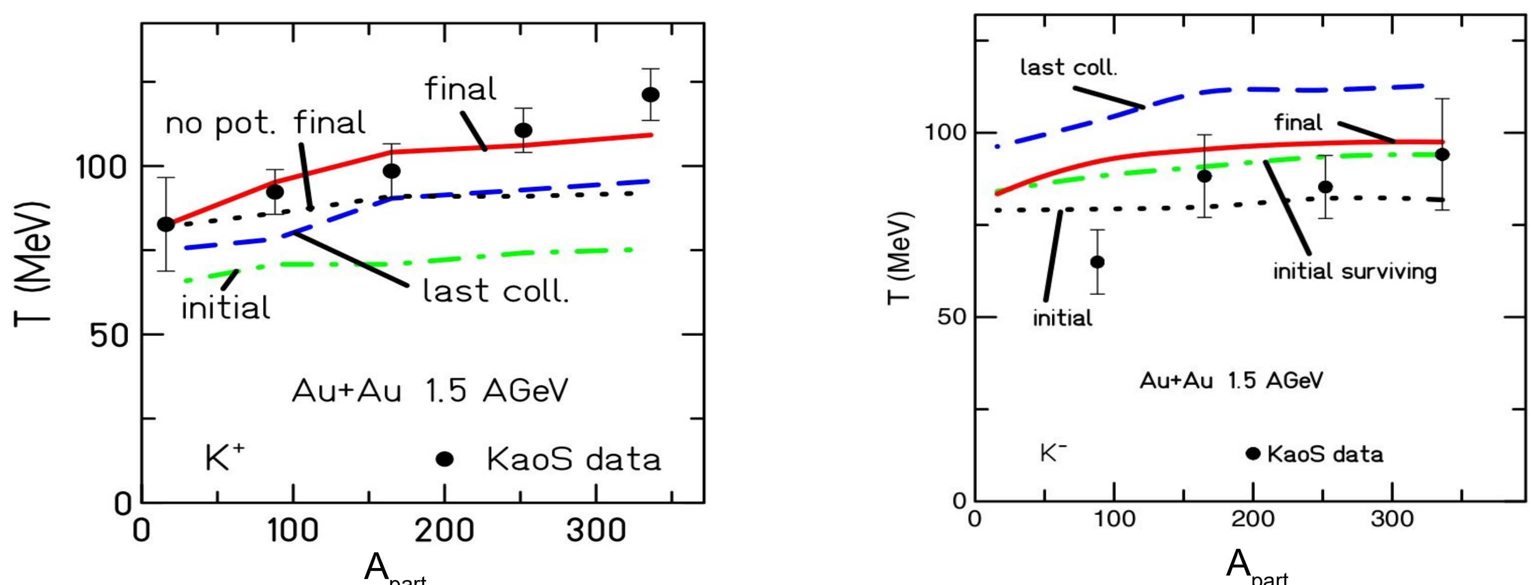
  - strong reabsorption: $K^- B \rightarrow \pi Y$
  - coupled to resonances Σ(1385), Λ(1405)

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

Q: Can we see them?

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

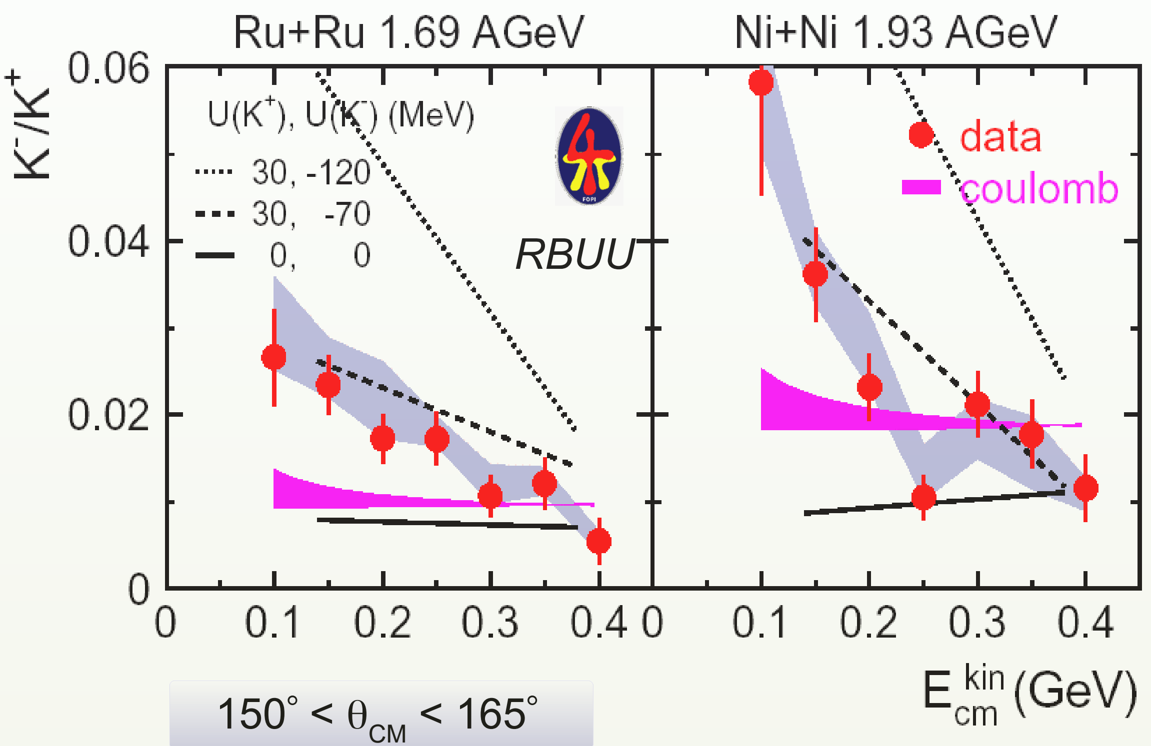




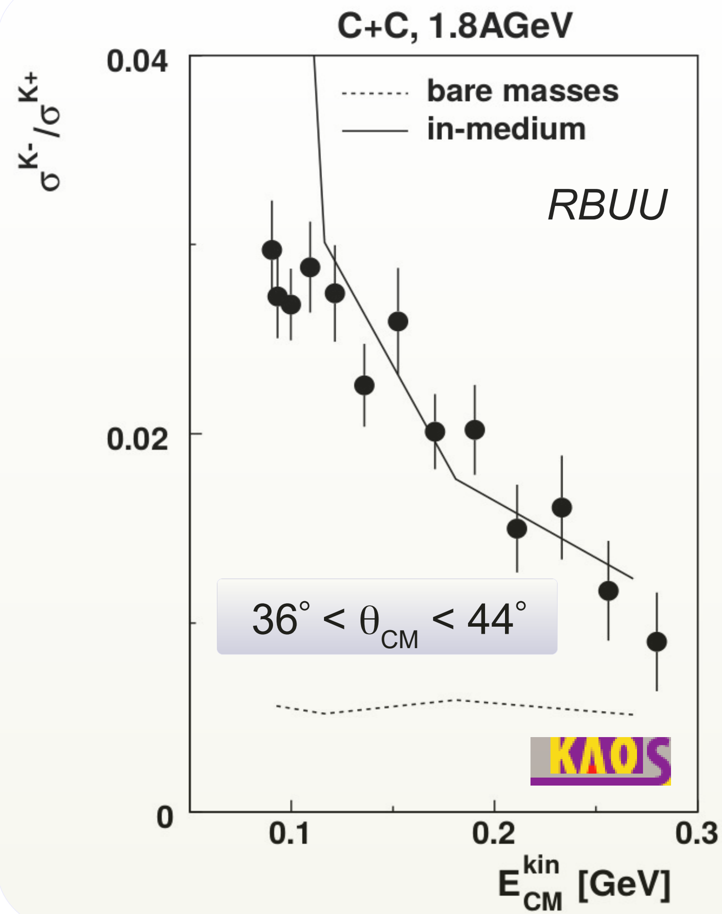
C. Hartnack *et al.* Phys. Rep. 510, 119 (2012)

Observable: Ratio of K⁻/ K⁺ kinetic energy spectra

First findings: FOPI, KaoS @ SIS18 accelerator, GSI Darmstadt



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



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

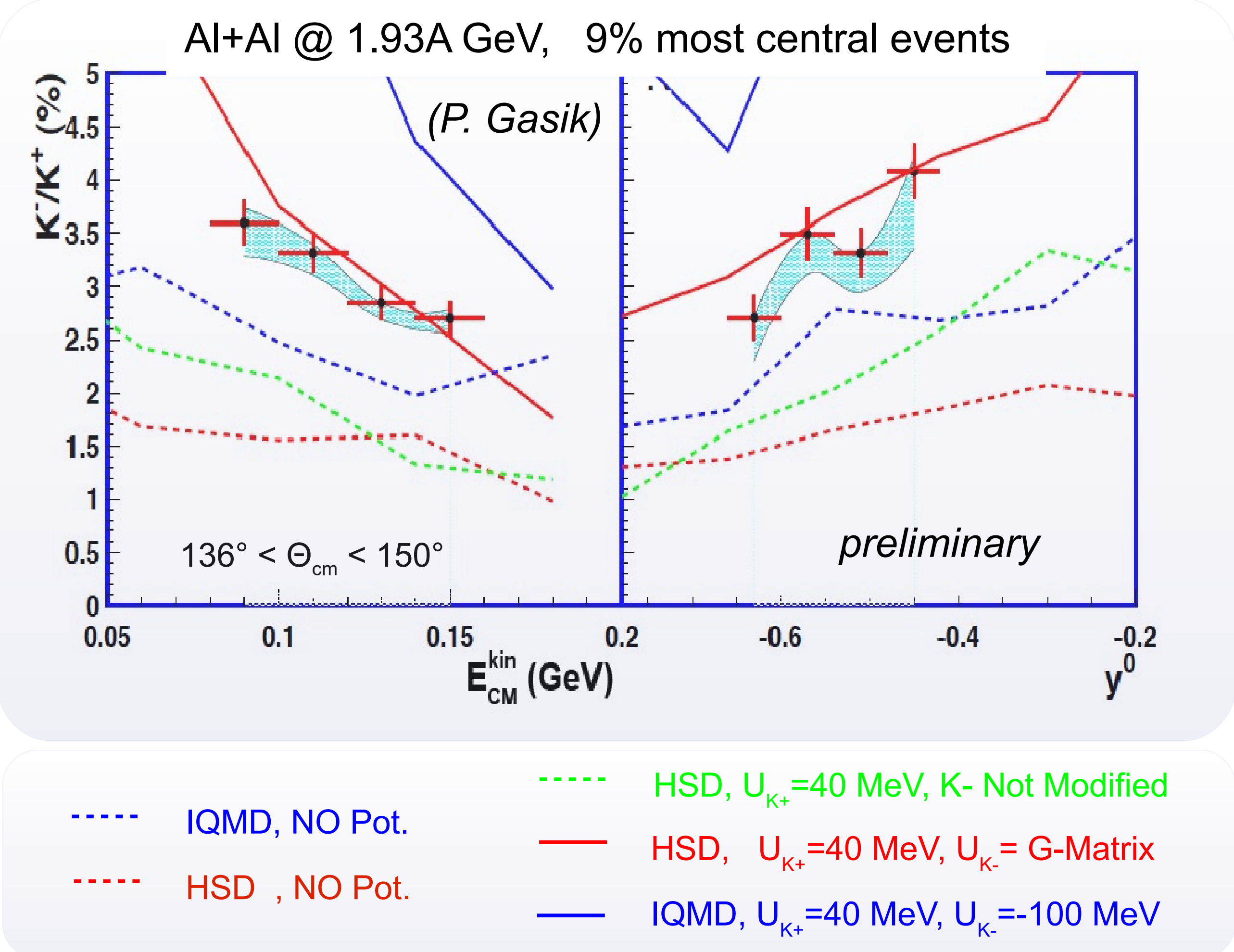
- Effect itself appears to be confirmed…
- … but probed within very narrow slice of phase space
- Statistics too limited for providing uncertainties of extracted U_{KN}.

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

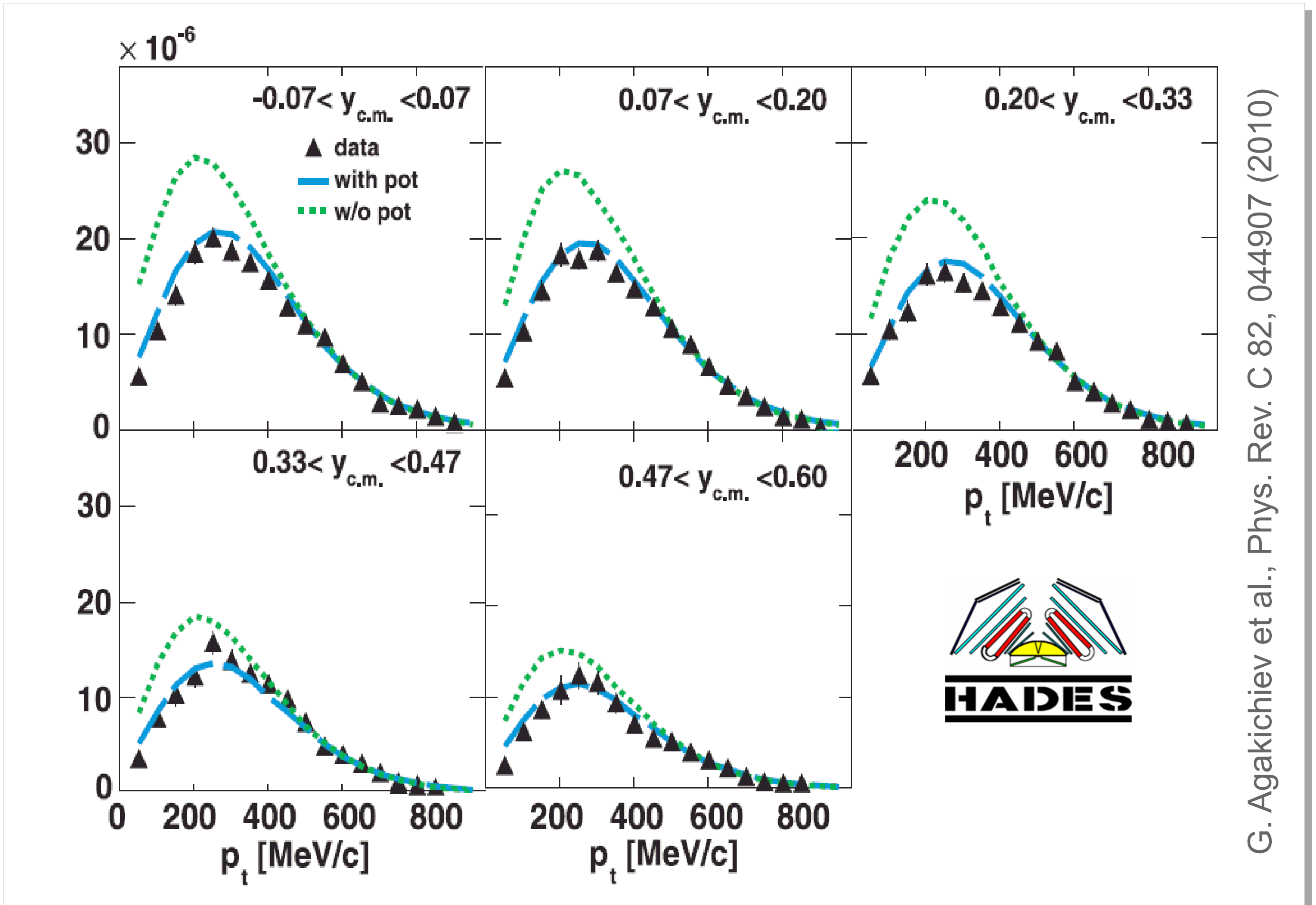
- HSD transport code
  - K^+ as in IQMD
  - K^- : off-shell G-matrix approach



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

In-medium effects of K^0 from Ar+KCl @ 1.76A GeV

Transverse momentum distributions of K^0_s

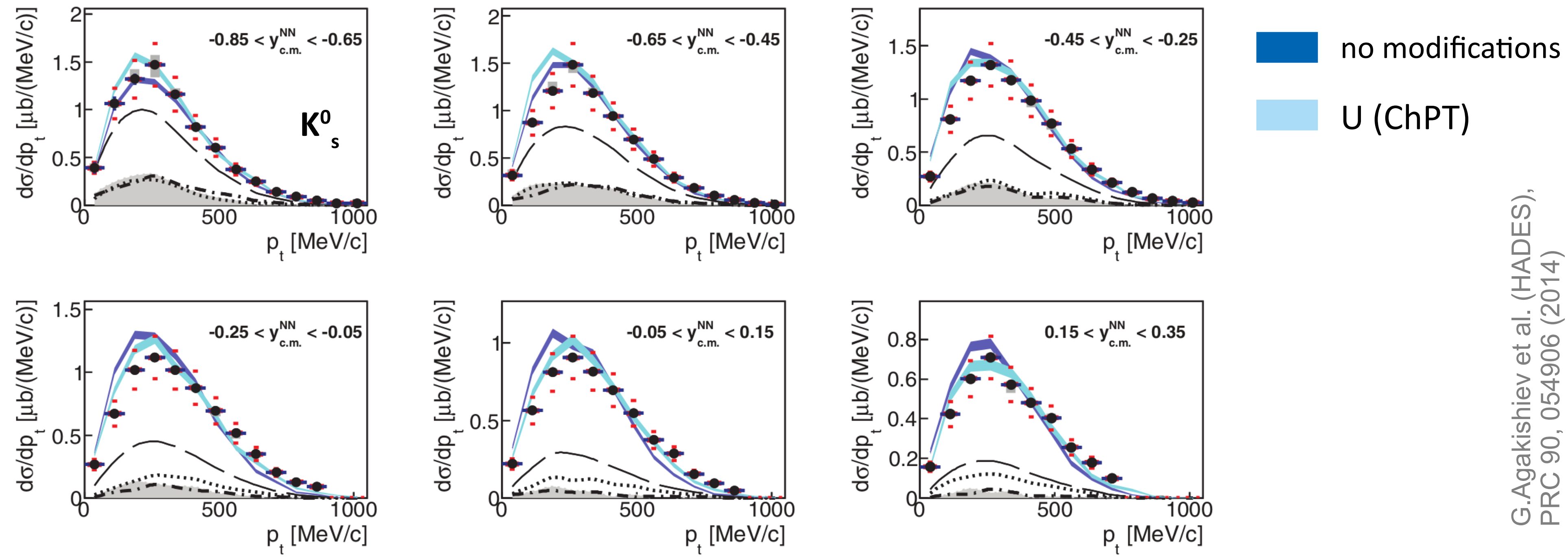


- Densities reached: 2 ρ_0
- K^0_S $c\tau$ = 2.7 cm
  K^0_L $c\tau$ = 15.3 m
- ***IQMD*** transport calc. :
  No potential
  $U_{KON}(\rho_0)$ = 46 MeV

Obtained $U_{KON}(\rho_0)$ for Ar+KCl seems to be stronger than in case of $U_{KON}(\rho_0)$ for $\pi^- A \to K^0 + \ldots$

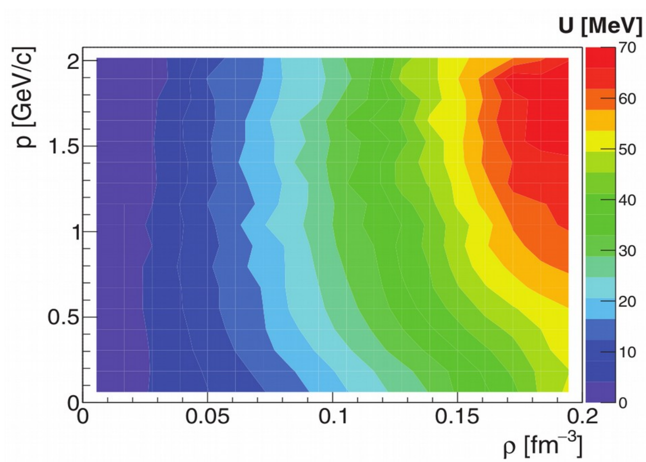
(1) Non-linear dependency of $U_{KON}(\rho)$? (2) Momentum-dependent potential?

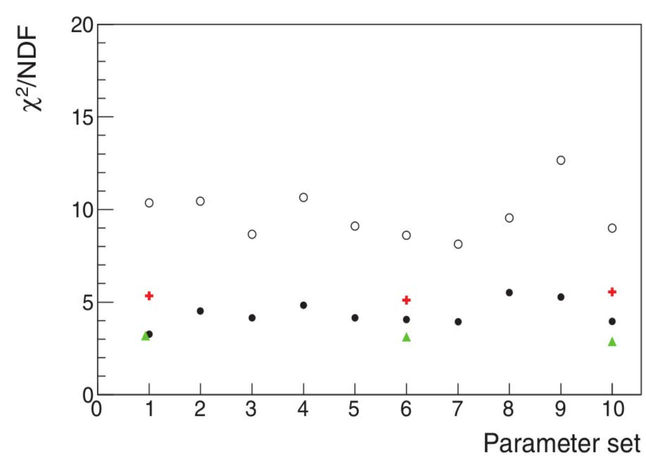
K^0_s mesons from p (T_B = 3.5 GeV) + Nb . Phase space distributions ($p_T - y$):



G.Agakishiev et al. (HADES), PRC 90, 054906 (2014)

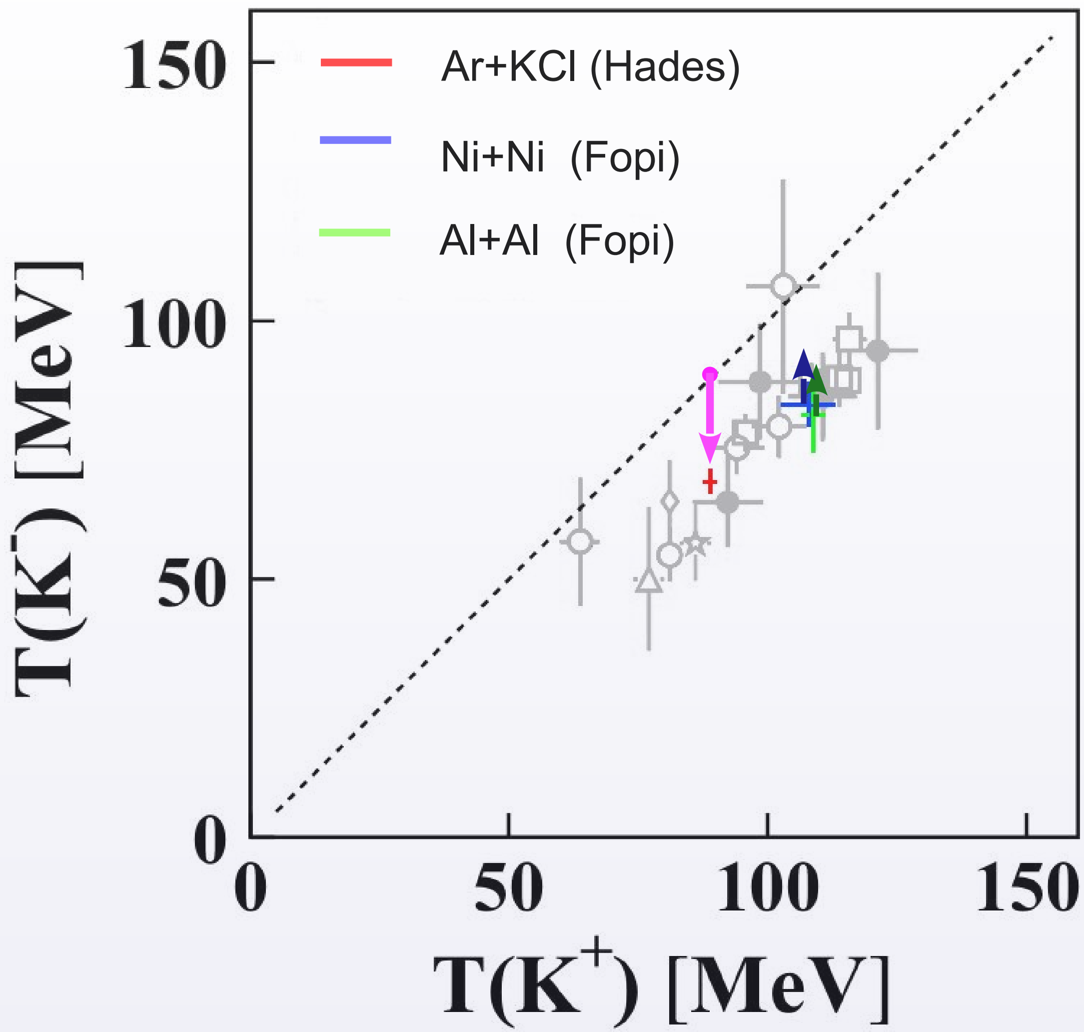
Comparison to **GiBUU** transport model. The **ChPT potential** was used; for first time **U = f(p)**





Preference for ChPT scenario

Effect of ϕ decays on K^- slopes



Previously:

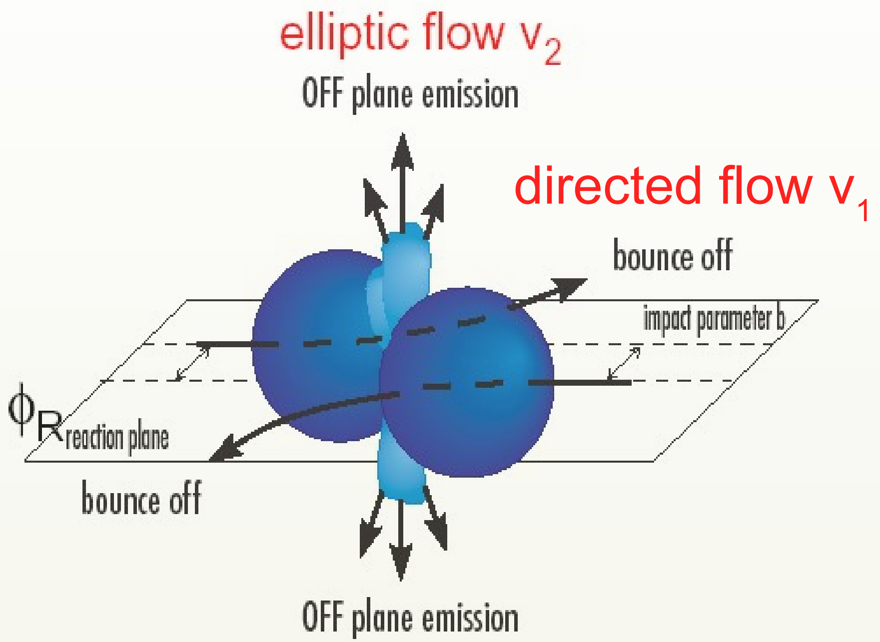
Difference of K^+,K^- slopes explained by U_{KN} potentials

Present studies:

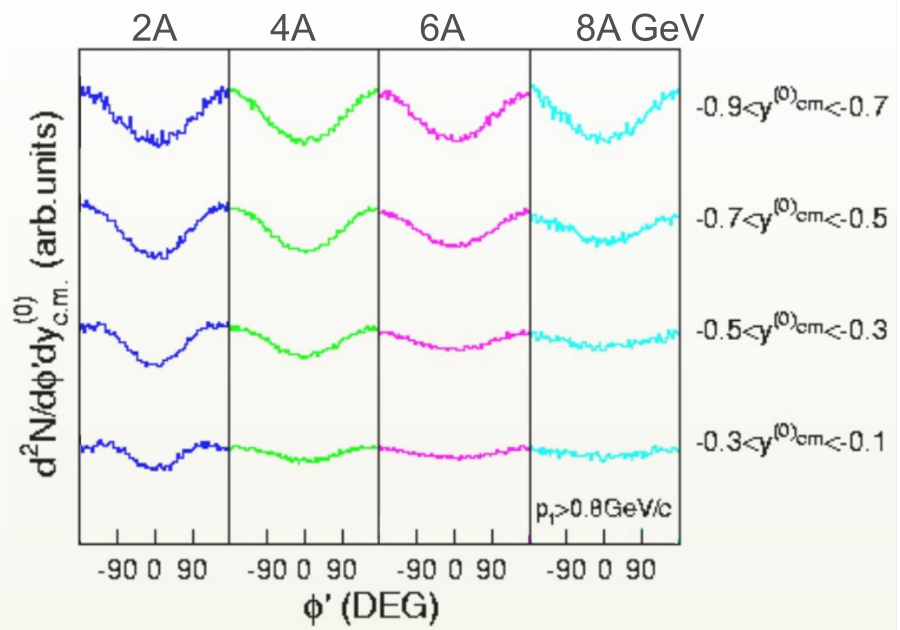
About 50% can be explained by $\phi \rightarrow K^+K^-$ decays

Observable: azimutal angle distribution ("Flow")

Azimuthal angle distribution wrt Reaction Plane
After (p_T – y), ϕ is a 3rd phase space dimension.



dN/dϕ have oscillatory character, e.g. for p^+ :



C.Pinkenburg *et al.*, PRL 83,1295 (1999)

Azimuthal distribution is decomposed into Fourier series:

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

v_1 , v_2 , … = Coefficients of Fourier expansion ("flow coefficients")

Mass change effect: wrt. flow of matter (usually protons), K^- should flow more like protons do
K^+ should flow more against.

Observable: azimutal angle distribution (Flow)

First findings: FOPI & KaoS

- KaoS analysis:

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

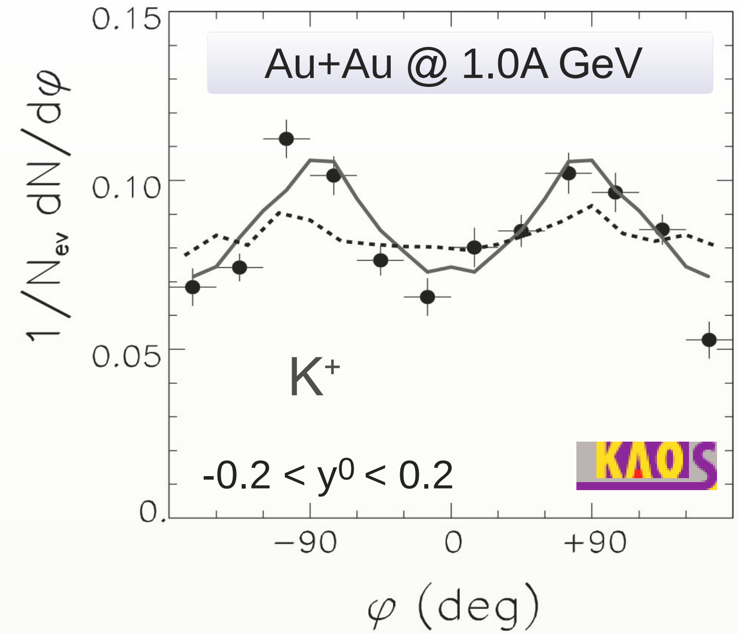
  ➔ Preference for U_{K+N}
  No information on $U_{K–N}$

- FOPI analysis:

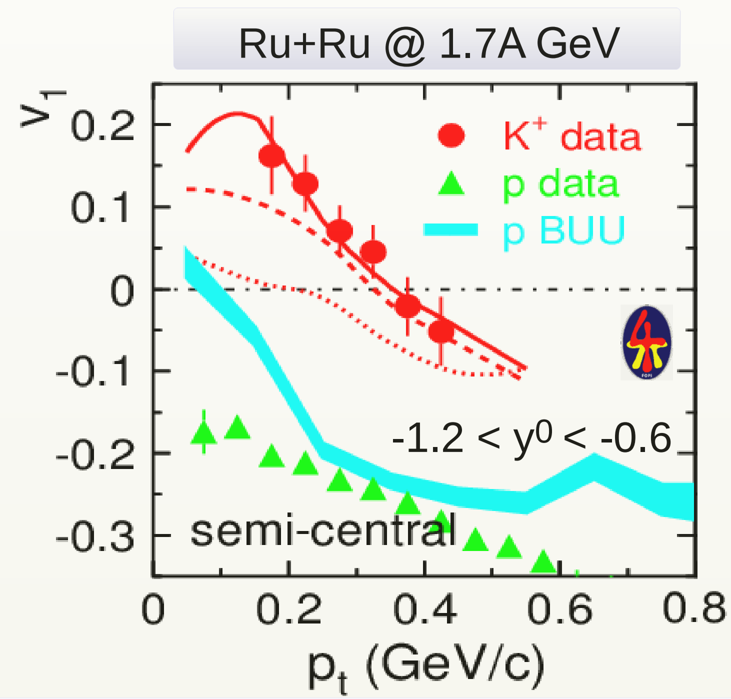
  v_1 (K^+) as function of p_T
  for 2 systems at 1.5 – 2A GeV

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

➔ Fragmentary insight, coarse results

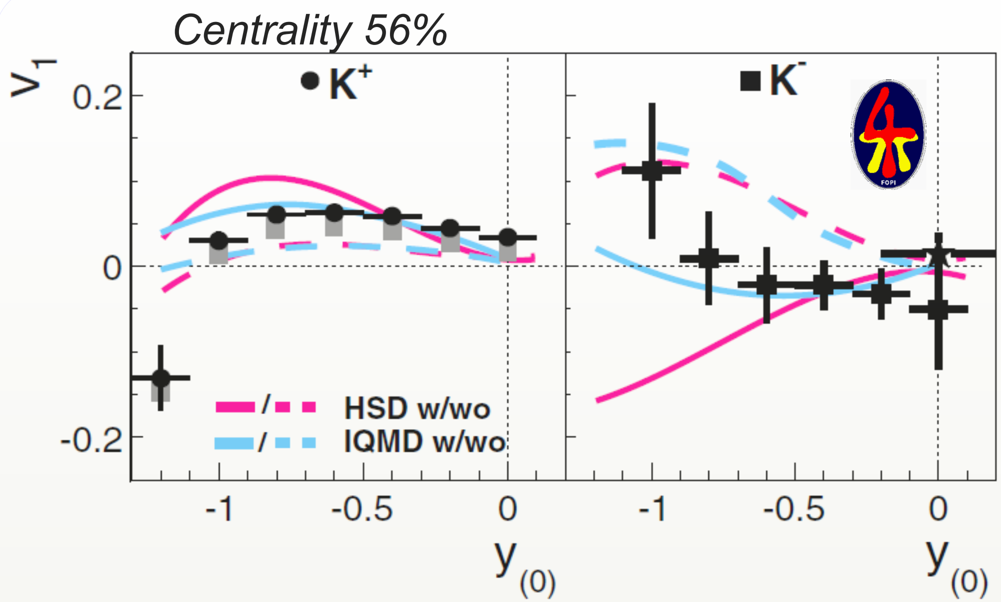


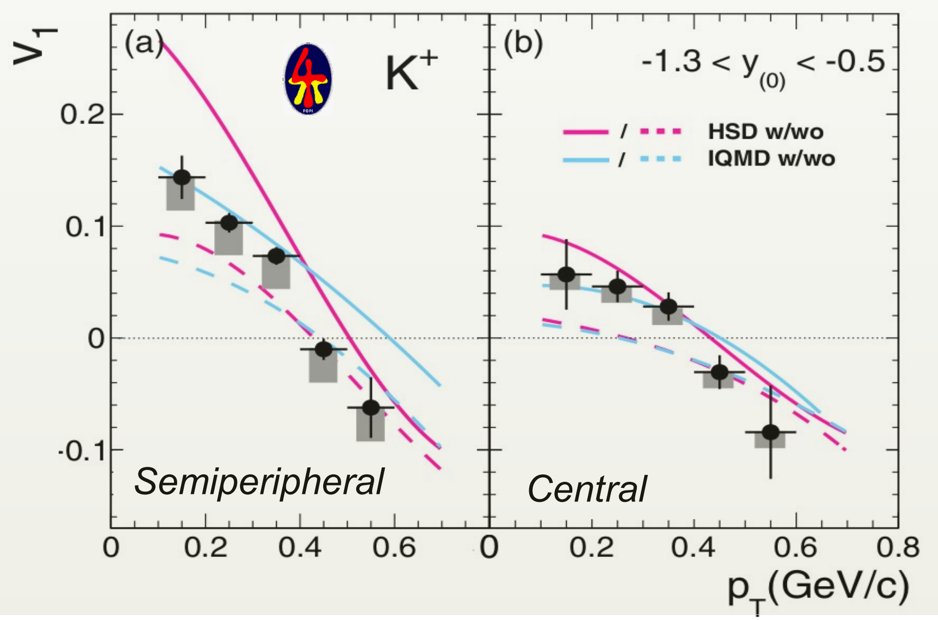
Y. Shin et al., Phys.Rev.Lett 81, 1576 (1998)



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

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





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

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

v_1 : Rather weak U_{K+N} potential.
Preference for $U_{K-N} \approx$ –25..50 MeV

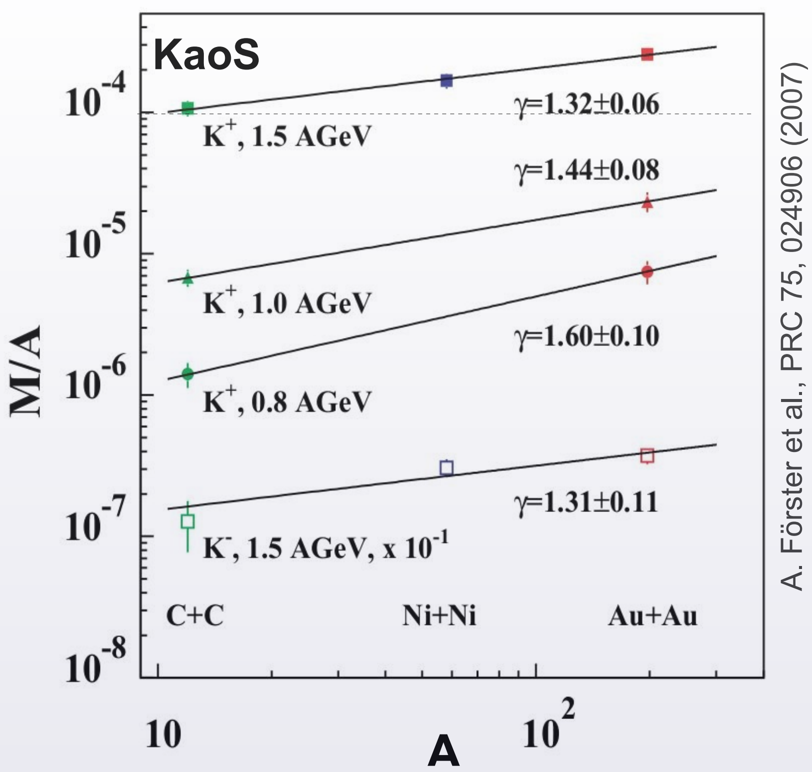
Production of Kaons in AA: Primary or secondary?

If primary:

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

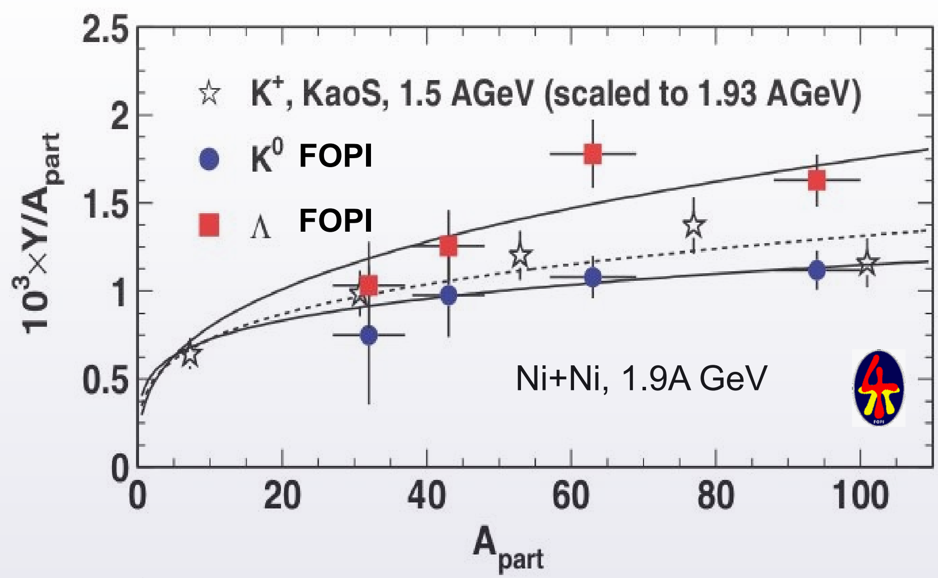
AA→ KX: Glauber: AA = A ⊗ NA

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



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

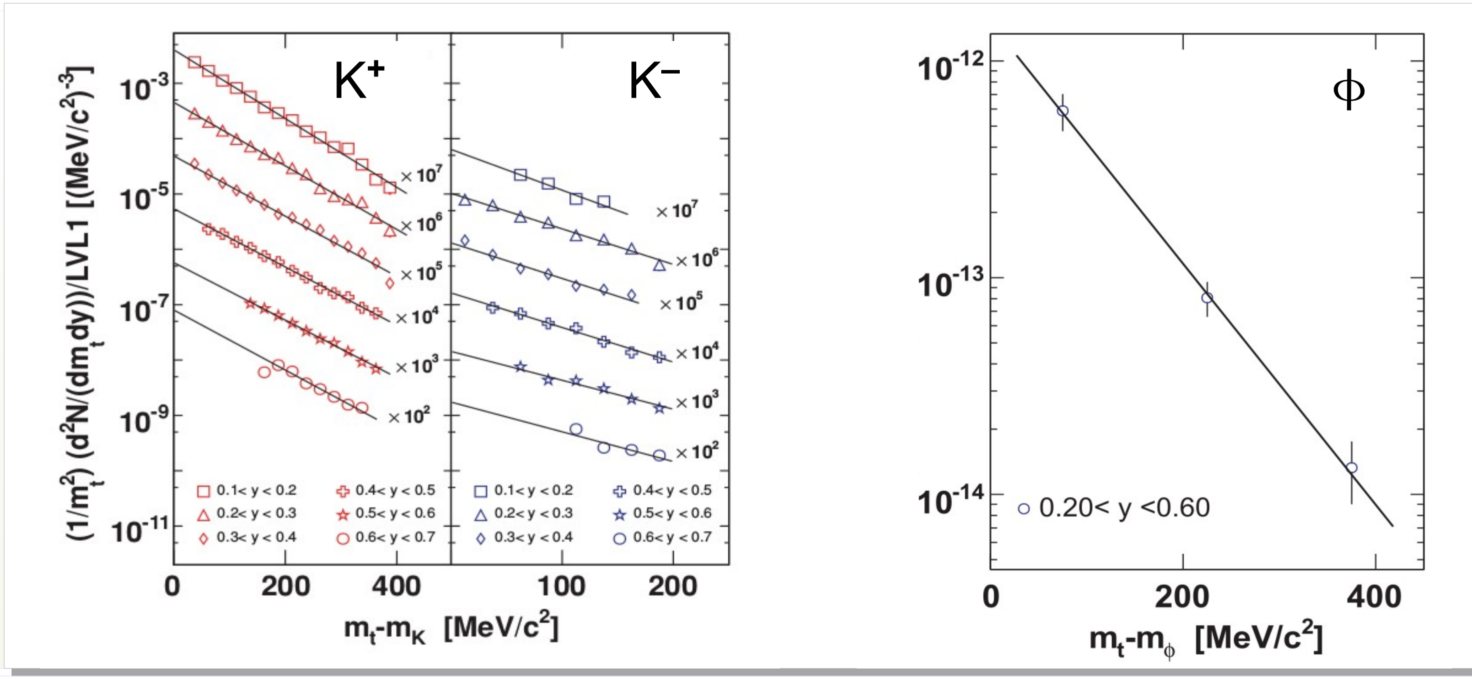
K^{+0} near-threshold production processes:

- $N_{beam} + N_{target}$, 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)

K^+, K^- and ϕ emitted from Ar + KCl @ 1.76*A* GeV: phase space distributions

HADES

$$m_T = \sqrt{p_T^2 + m^2}$$



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

Boltzmann Fit to phase space distributions

- inverse slope ("temperature")

$$\frac{1}{m_T^2}\frac{d^2N}{dm_T\,dy} = C(y)\;\exp\left[-\frac{(m_T - m_0)\;ch\,y}{T}\right]$$

Particle	Multiplicity/LVL1	$T_{\rm eff}$
K^-	$(7.1 \pm 1.5 \pm 0.3 \pm 0.1)\cdot 10^{-4}$	$69 \pm 2 \pm 4$
K^+	$(2.8 \pm 0.2 \pm 0.1 \pm 0.1)\cdot 10^{-2}$	$89 \pm 1 \pm 2$
ϕ	$(2.6 \pm 0.7 \pm 0.1^{+0.0}_{-0.3})\cdot 10^{-4}$	84 ± 8

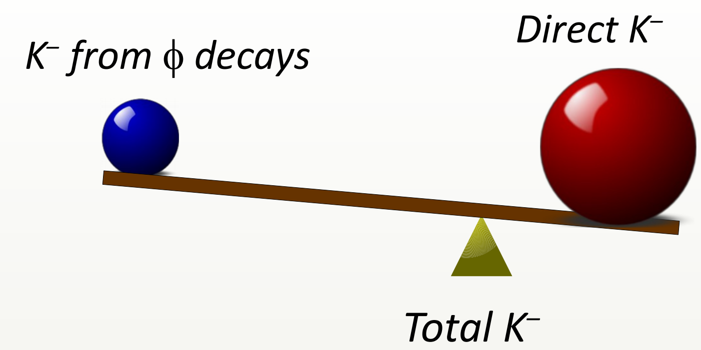
Inverse slope for K^+ is higher than that for K^- .

(↔ ratio of kinetic energy distributions of K^- to K^+ drops with energy) :
… conclusion similar to KaoS & FOPI @ 2000.

***Q*: Is it due to in-medium effects or $\phi \rightarrow K^-$ feeddown?**

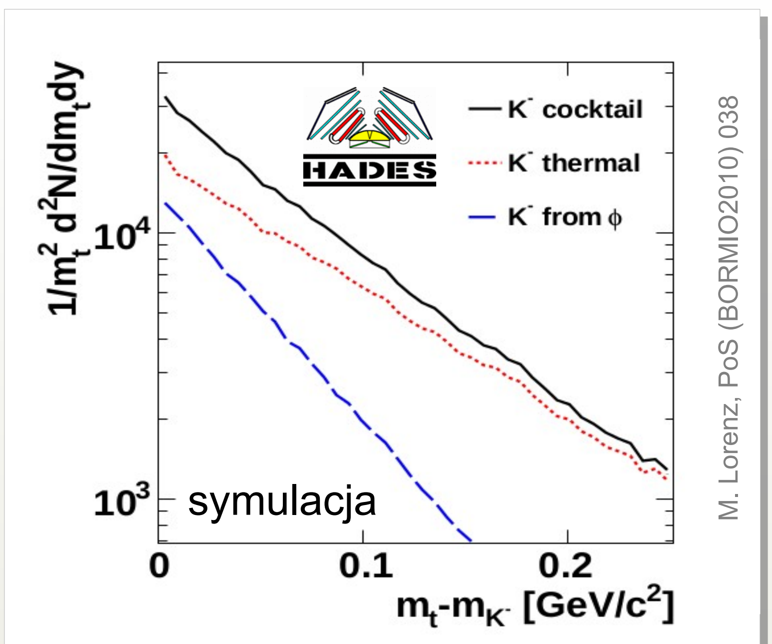
Two-source model of K^- emission

Assumptions:



1. Observed K^- originate from two sources:
   - derectly from collision zone (”*direct*”)
   - feeddown from ϕ meson decays, $\phi \to K^+ K^-$ (BR ≈ 50%)

   in a proportion as measured experimentally.
2. ”*Direct*” K^- have the same ”temperature” as K^+ .
3. ϕ mesons are emitted with ”temperature” as measured.
   Next, ϕ decay into K^+ and K^- (PLUTO simulation) .
4. We combine K^- distributions from both sources – and check the ”temperature” of total.



Result: T (K^-, total) = 74 MeV

Let’s compare to experimental $T(K^-)$:

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

ϕ admixture strongly ”cools down” the K^- spectrum.

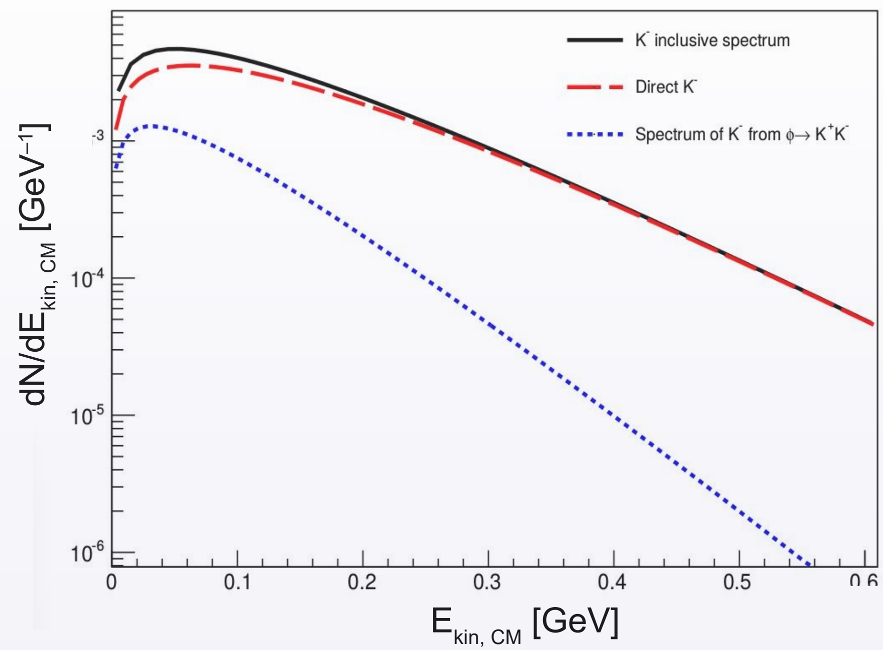
It contributes to generating a drop of ratio of K^-/K^+ kinetic energy distribution with energy.

We cannot reject that ϕ (and not in-medium) Could be the only responsible for $K^-/K^+ \searrow E_{kin}$ ...

- Al+Al @ 1.9A GeV (FOPI)

Experiment :

Particle	T_{eff}
	$82 \pm 7 \pm 11$
	$109 \pm 2 \pm 9$
	$93 \pm 14 \pm 16$



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

T (K⁻ from ϕ) = 58 MeV

T (K⁻ direct) = 92 ± 16 MeV

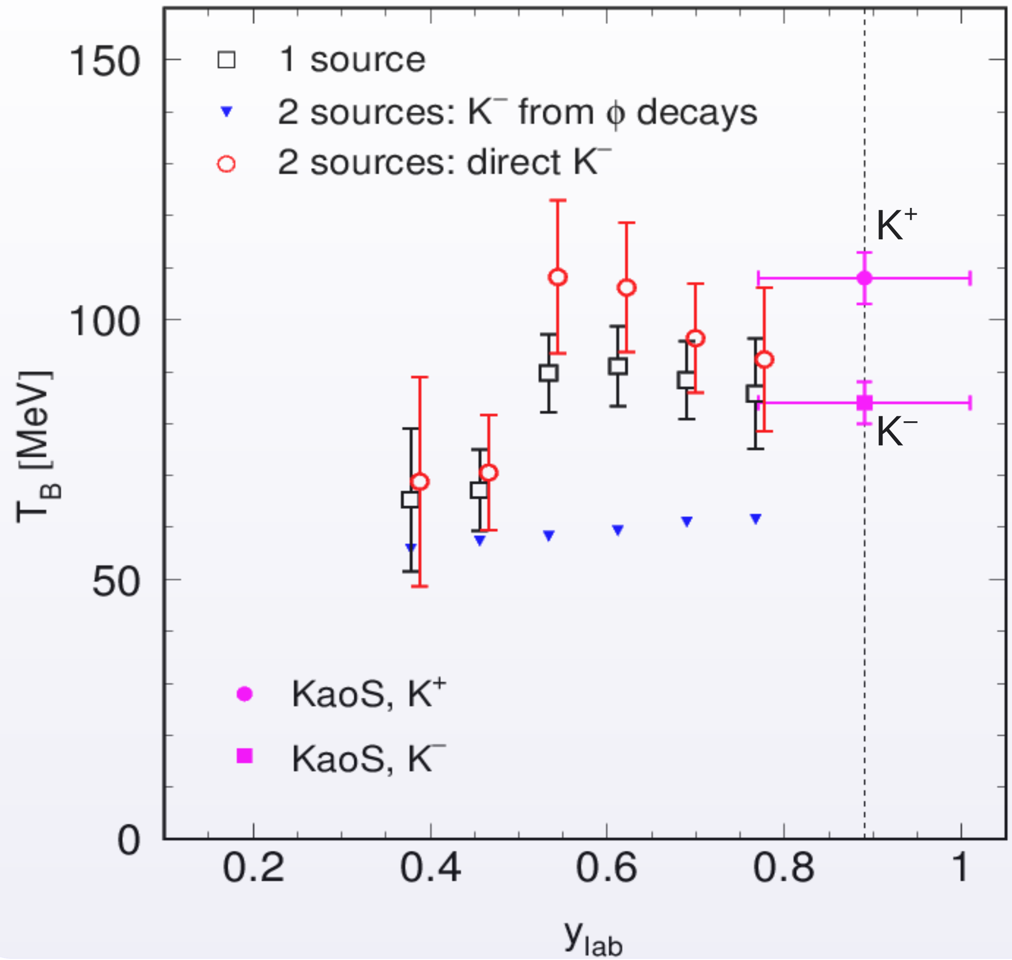
ϕ contribution to K⁻ : indication that T_{direct} @ ~10 MeV above $T_{inclusive}$

2-source model of ϕ emission

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

Experiment :

Particle	T_{eff}
	84 ± 4
	108 ± 5
	$106 \pm 18 \pm 16$



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

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

ϕ yield – BUU predictions

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

- ϕ production channels:

  BB $\rightarrow \phi$, B = {N, Δ}

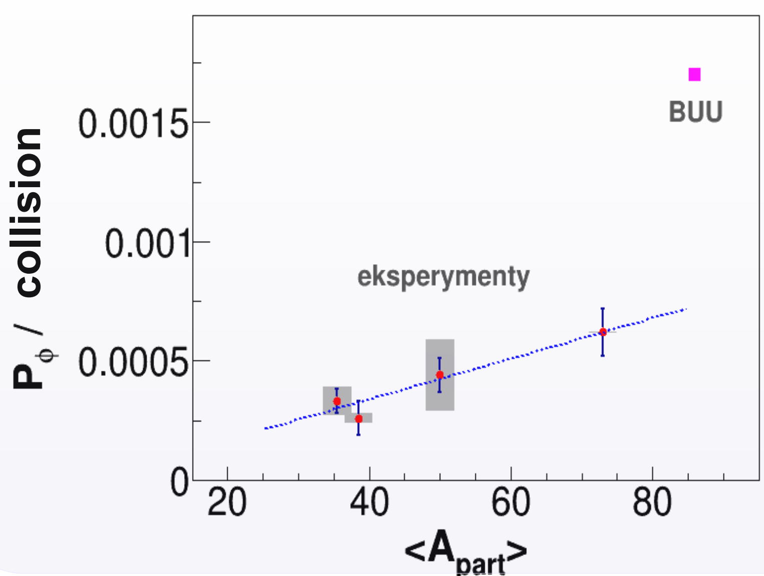
  μB $\rightarrow \phi$, μ = {π, ρ}

  $\pi\rho \rightarrow \phi$

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

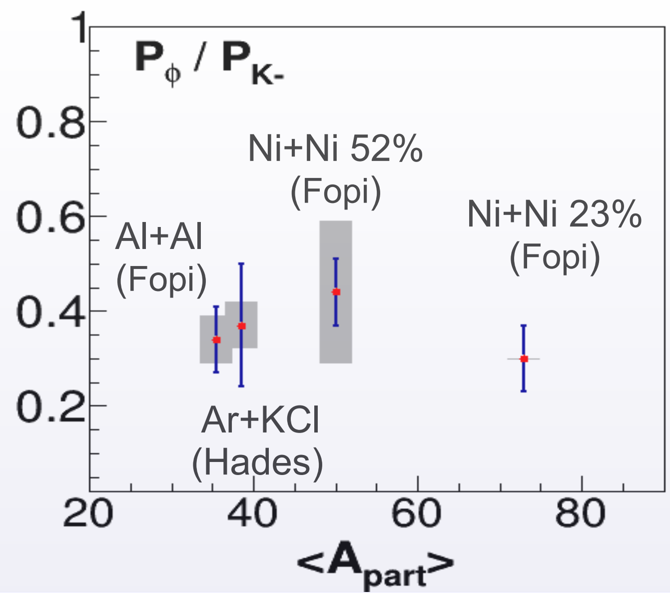
Yields from	Ni + Ni (1.93 GeV)
B + B	3.5×10^{-4}
π + B	2.9×10^{-4}
ρ + B	8.9×10^{-4}
$\pi + \rho$	1.6×10^{-4}
π + N(1520)	0.5×10^{-4}
Total yield	1.7×10^{-3}

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



BUU:

ϕ yield overestimated



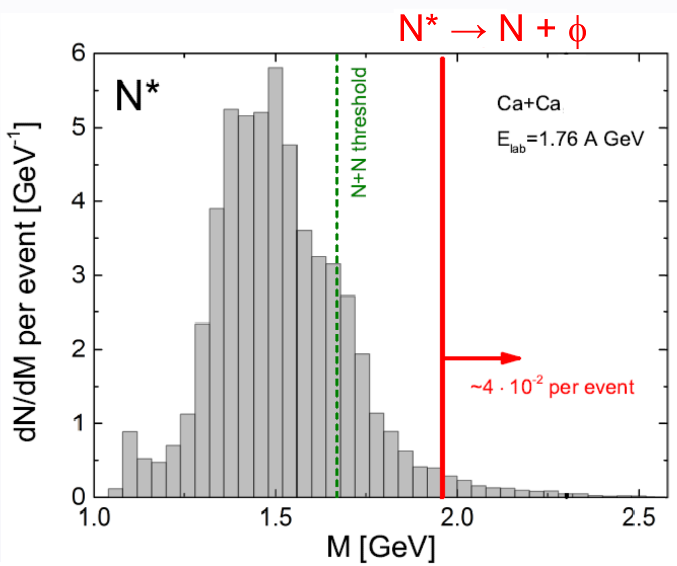
- $c\tau = 50$ fm

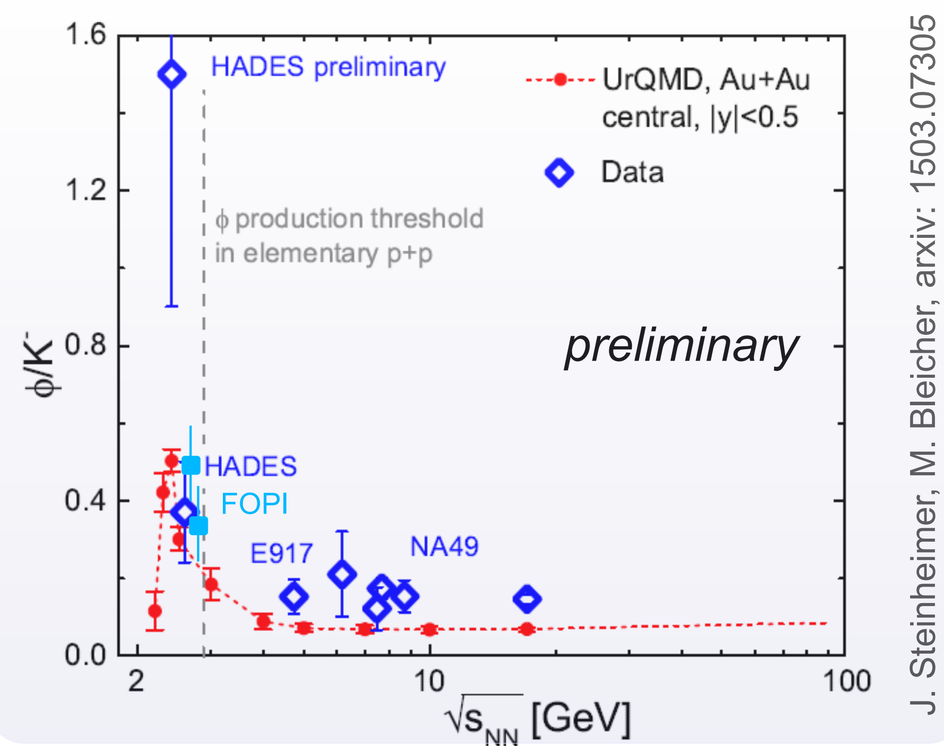
  $\phi \rightarrow K^+K^-$ (BR ~ 50%)

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

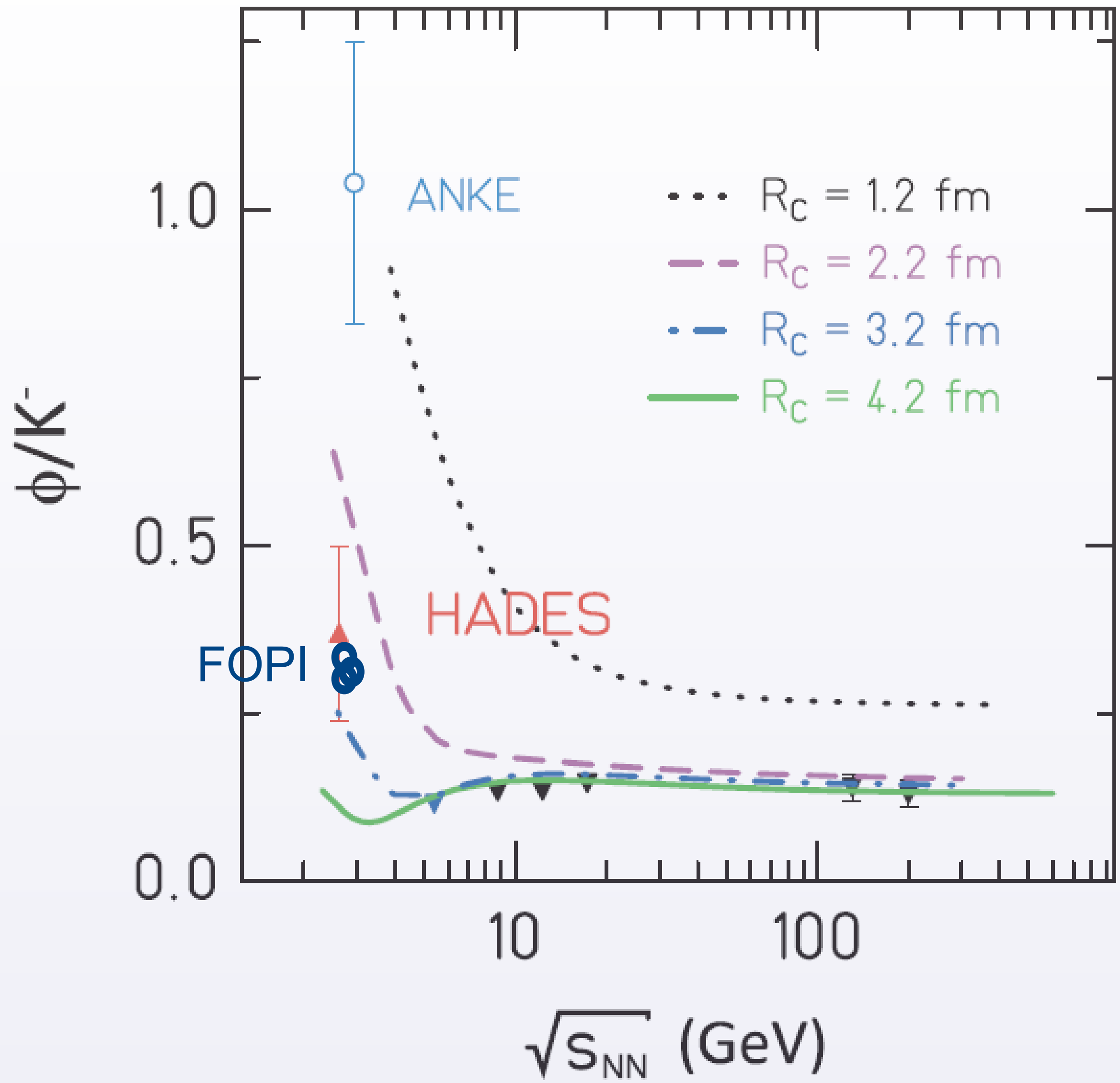
- **UrQMD** model

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





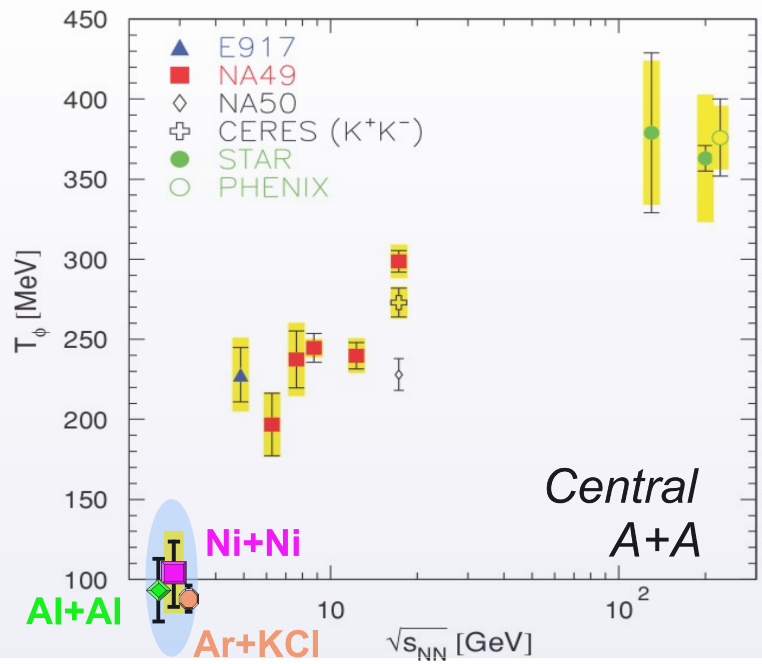
ϕ/K^- within the statistical model approach



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

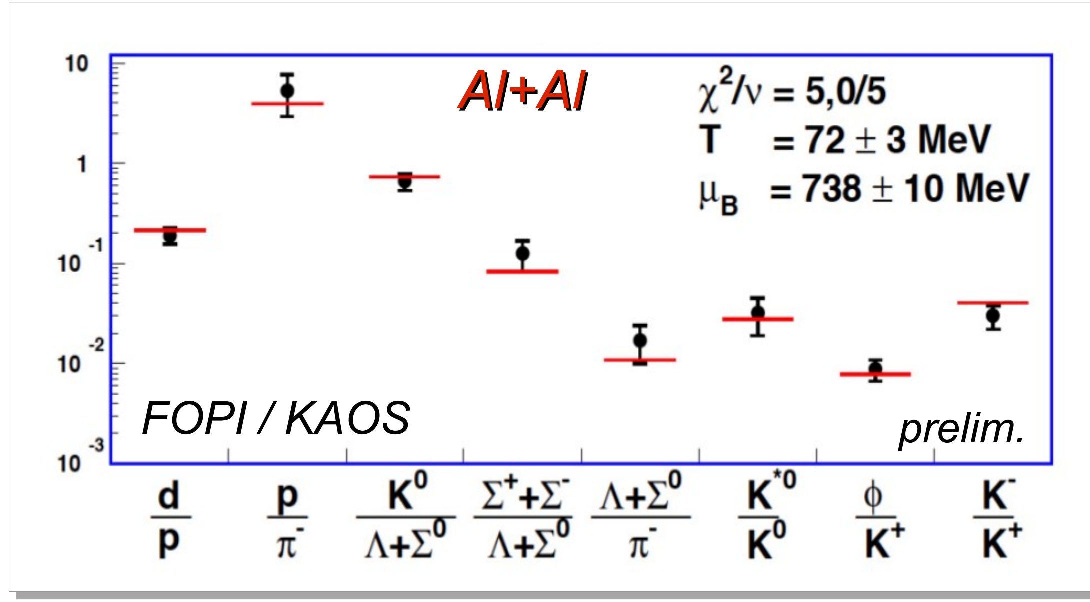
G. Agakishiev et al., PRC 80, 025209 (2009)

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)

- **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

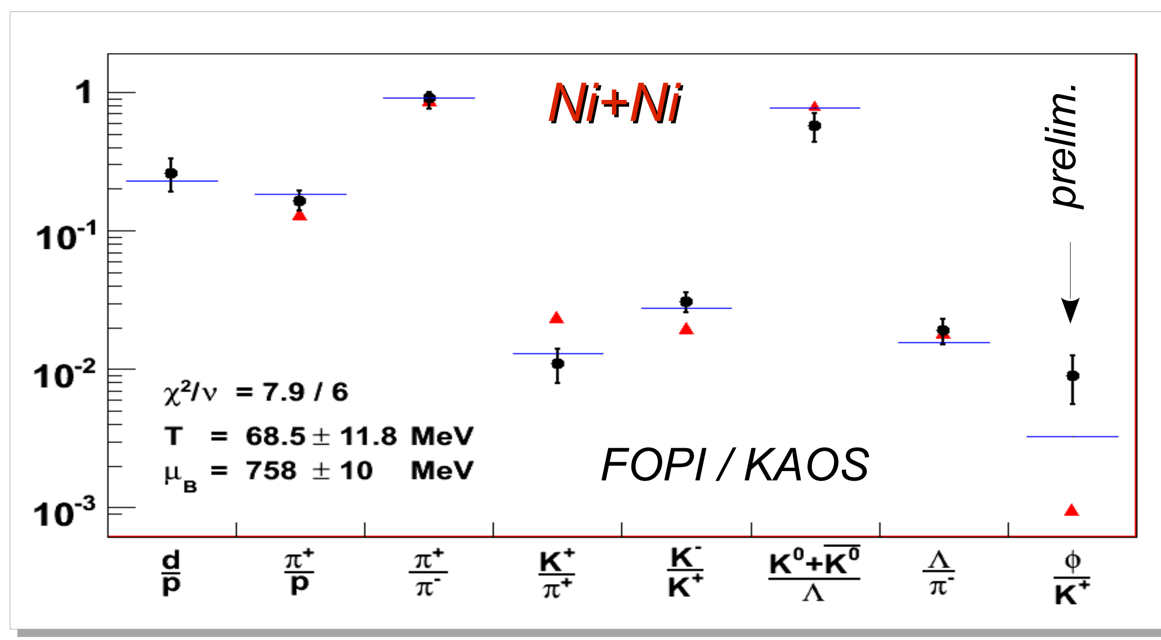
→ Grand Canonical ensemble;

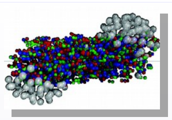
→ For S≠0, Canonical ensemble

→ 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

Λ(1520) baryon: another player ?

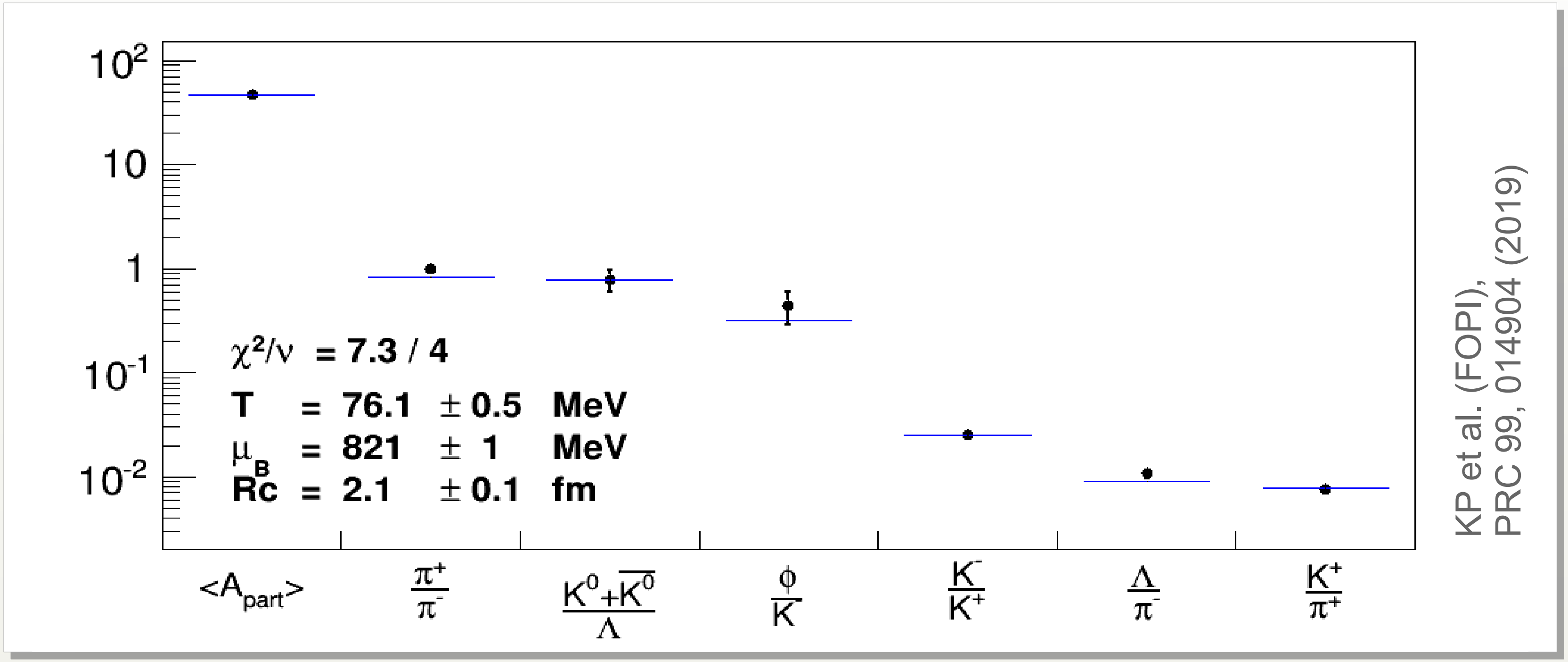
Λ(1520) : BR ($\Lambda \rightarrow pK^-$) = 22.5%.

Emission of this particle at T_B < 10A GeV never observed!

Thermal model: estimation of yield

For Ni+Ni @ 1.9A GeV (THERMUS code, canonical ensemble for strangeness production),

Step 1 : Fit of thermal parameters (T, μ_B) to the experimental data.

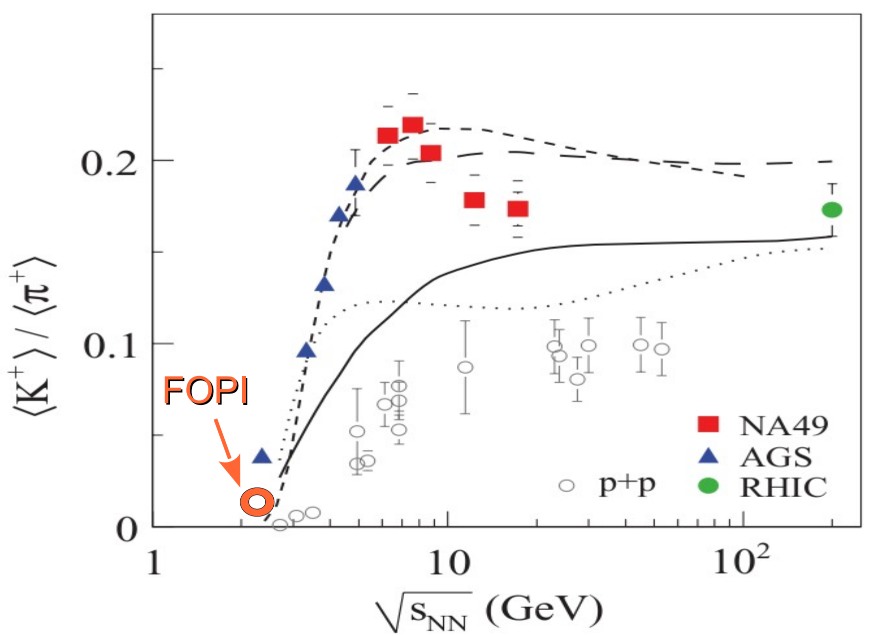


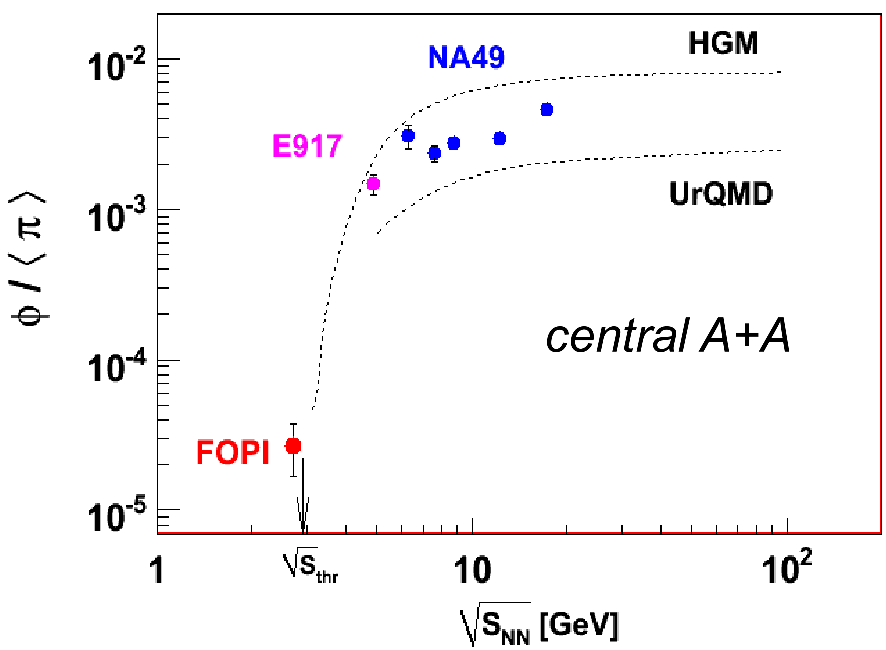
Step 2 : estimation of Λ(1520) yield compared to K^- :

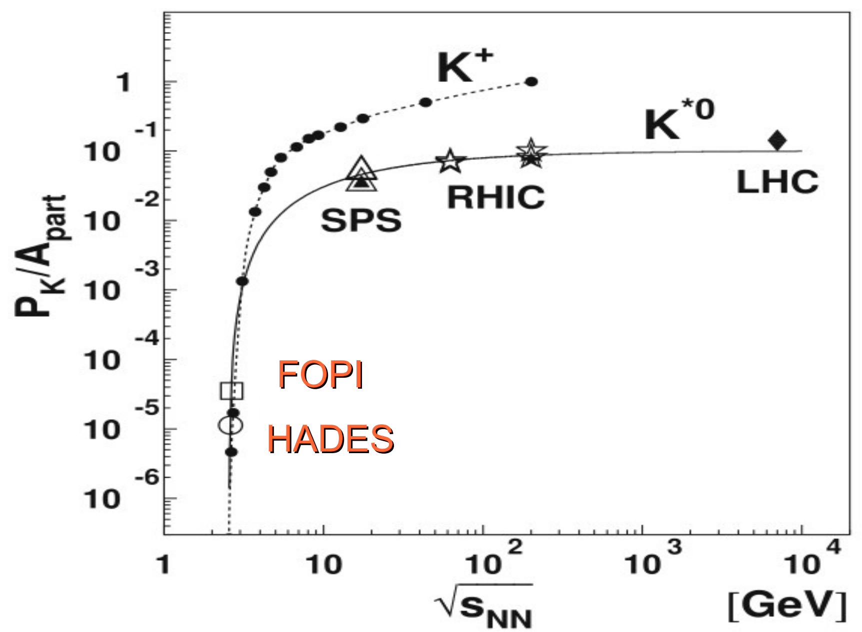
$$\frac{P(\Lambda^*)}{P(K^-)} = 0.46 \quad \Rightarrow \quad \frac{P(\Lambda^* \rightarrow K^-)}{P(K^-)} = 10\,\%$$

Contribution of Λ* to K^- seems to be non-negligible...

Strange meson excitation functions near threshold



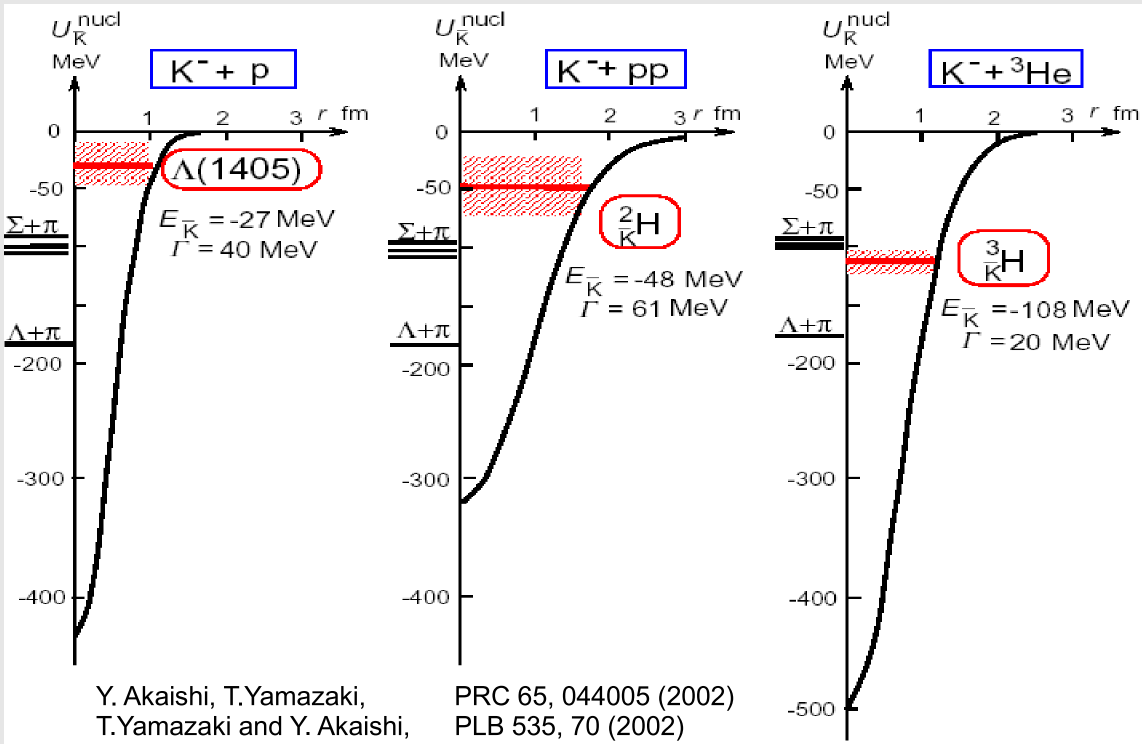




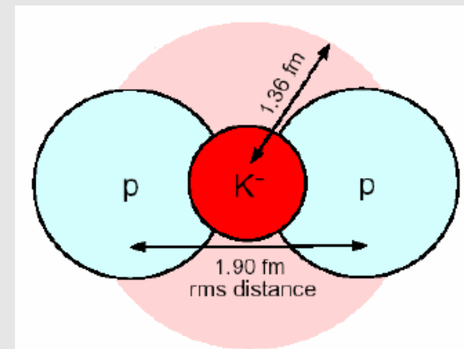
C. Alt et al. (NA49), Phys. Rev. C **78**, 044907 (2008)
B. Back et al. (E917), Phys. Rev. C **69**, 054901 (2004)

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

- $\bar{K}N$ interaction is strongly attractive !
  Λ(1405) is (K^-p) bound state.



Y. Akaishi, T.Yamazaki, PRC 65, 044005 (2002)
T.Yamazaki and Y. Akaishi, PLB 535, 70 (2002)



Consequence of strong attraction:
Shrinking!

A.Dote et al., PRC70,044313(2004)

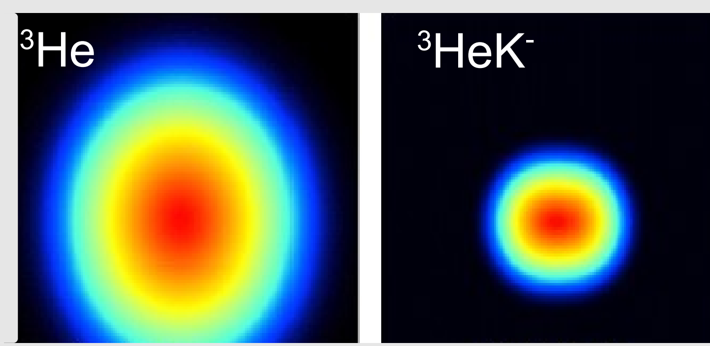
$K^-p \rightarrow \Lambda(1405)$
but:
$\Lambda(1405) \rightarrow \Sigma+\pi$
$\Sigma \rightarrow p+\pi^0,\ n+\pi^\pm$
Not seen in FOPI.

$K^- pp \rightarrow \Lambda + p$

!

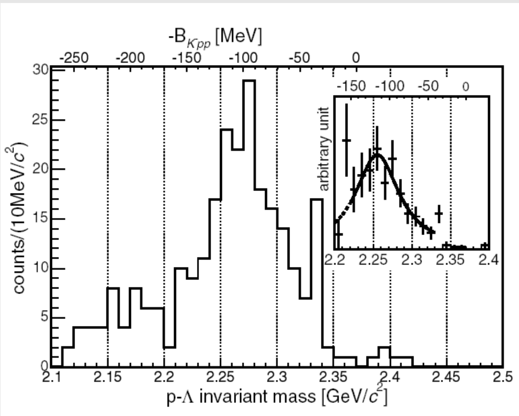
$ppnK^- \rightarrow \Lambda + d$

!



In-medium KN potential: Kaonic Clusters

FINUDA @ DaΦne:

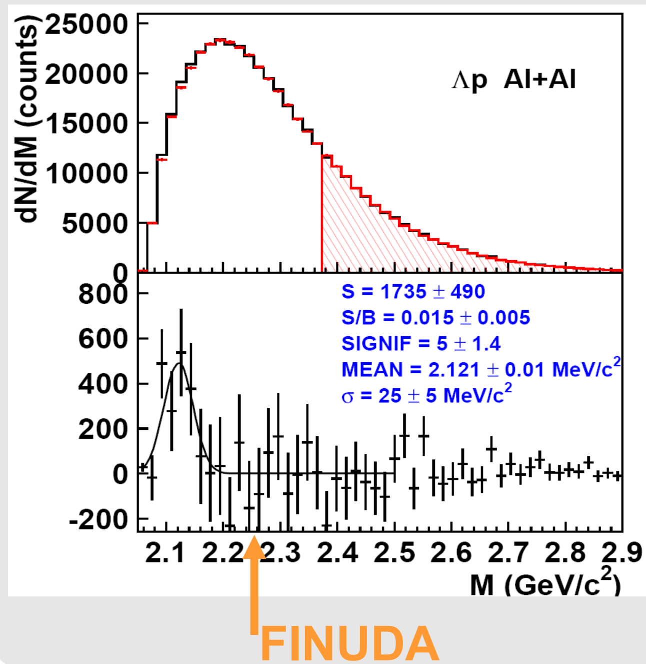


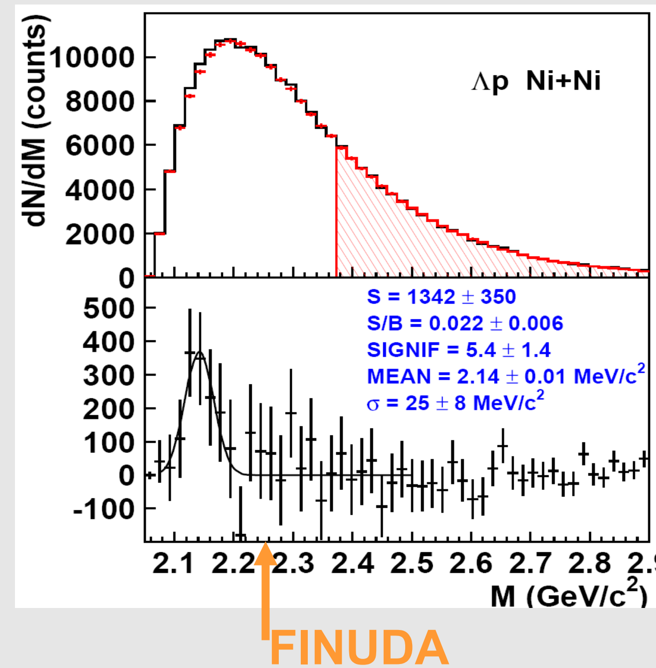
$e^+e^- \to \Phi \to K^+K^-$

$K^- + A \to$ ***(ppK^-)*** $+ X \to \Lambda + p + X$

M. Agnello et al., PRL 94, 212303 (2005)

Λp : invariant mass (M. Reithner, HK 12.3)





Excess observed in Ni+Ni and Al+Al with statistical significance of ~ 5.

Yield located in spectator/fireball interface region (like non-strange clusters).

Peak position in variance with FINUDA result.

Interpretation unclear: ΣN – FSI,

bound state ($H1^+$),

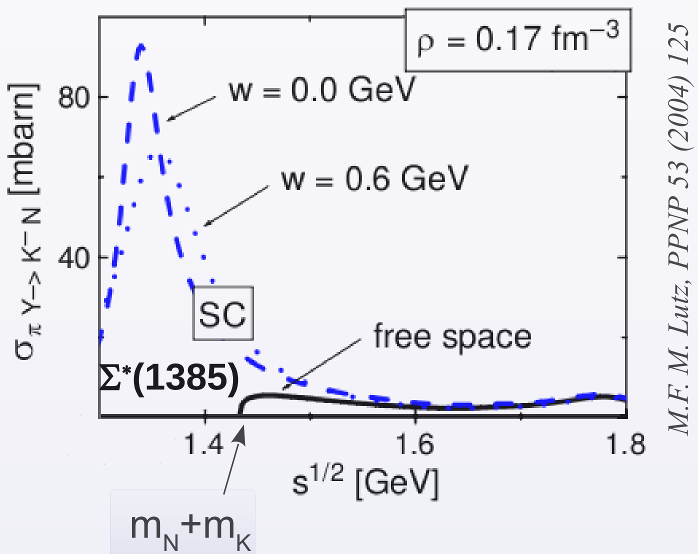
partial inv. mass of heavier state (e.g. $^4_\Lambda$He).

$\Sigma^*(1385)$ resonance

Chiral effective field theory w/ coupled-channels

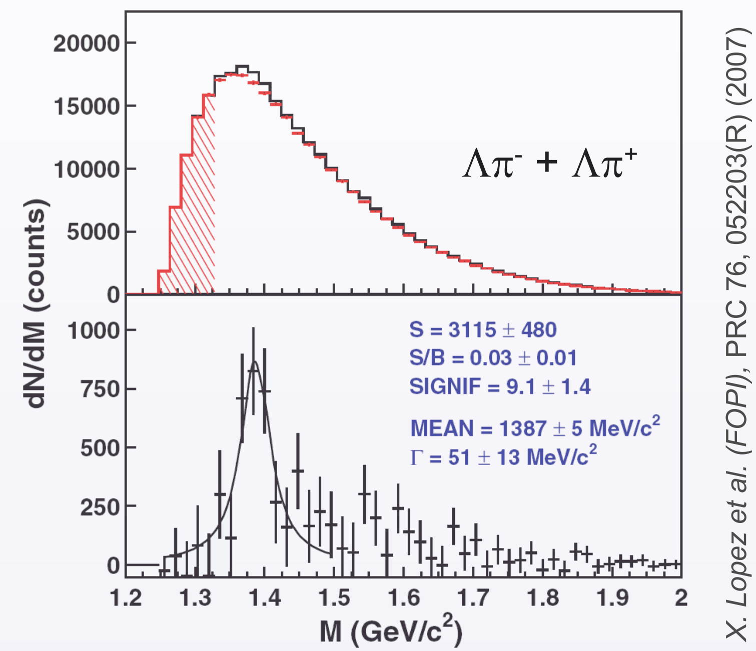
- K^- production in medium ($\pi Y \rightarrow K^- N$) coupled to strange resonances e.g. $\Sigma^*(1385)$, $\Lambda^*(1405)$:

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



- Al+Al @ 1.9A GeV

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



	$\dfrac{Y\ (\Sigma^{*-}+\Sigma^{*+})}{Y\ (\Lambda+\Sigma^0)}$
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

In-Medium $\Sigma^*(1385)$

Chiral unitary theory

$\Sigma^*(1385) \rightarrow \Lambda(\Sigma) + \pi$ at $\rho=\rho_0$
$c\tau$ = 5 fm

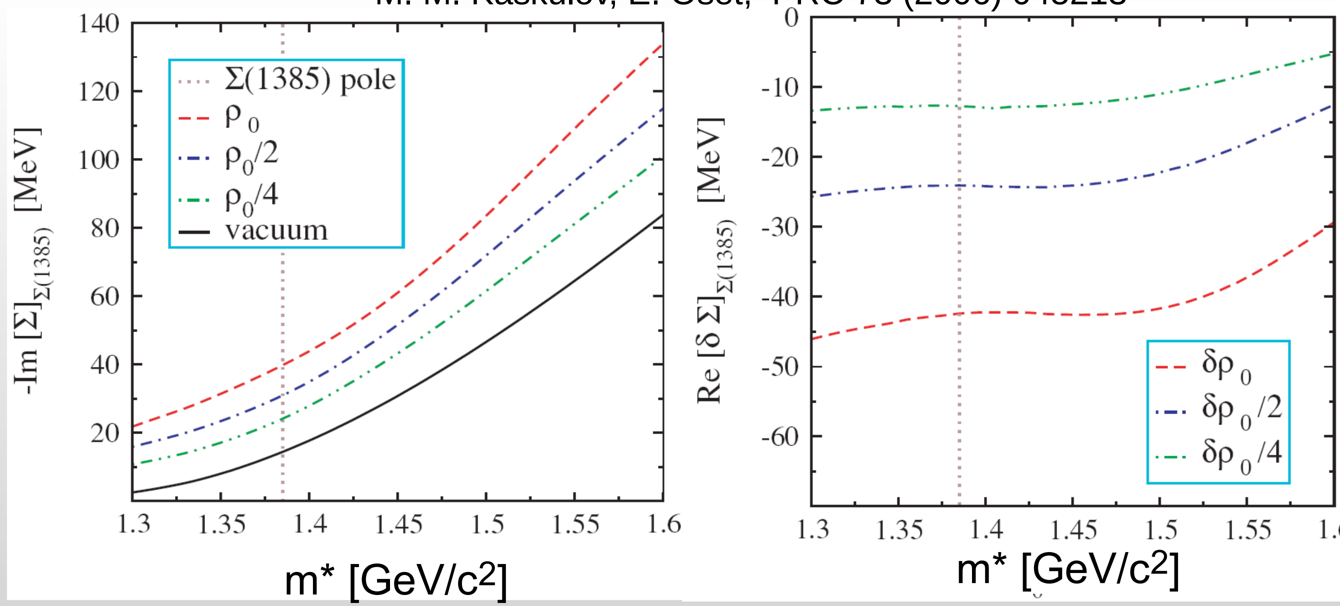
at $\rho = \rho_0$:

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

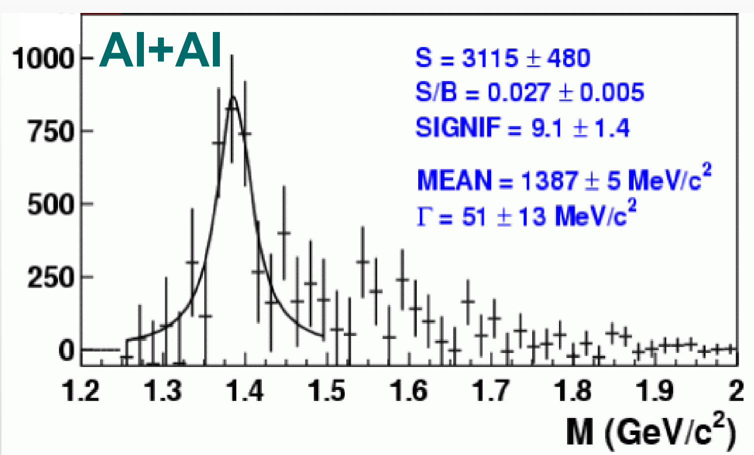
Mass:

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

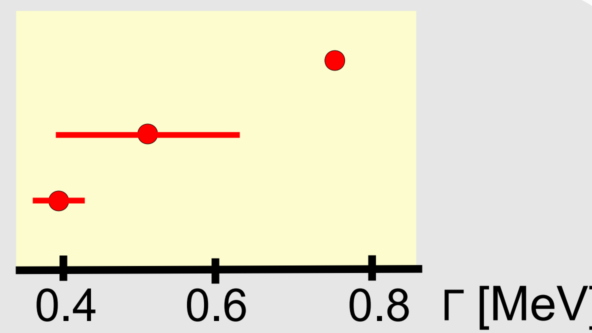
M. M. Kaskulov, E. Oset, PRC 73 (2006) 045213



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

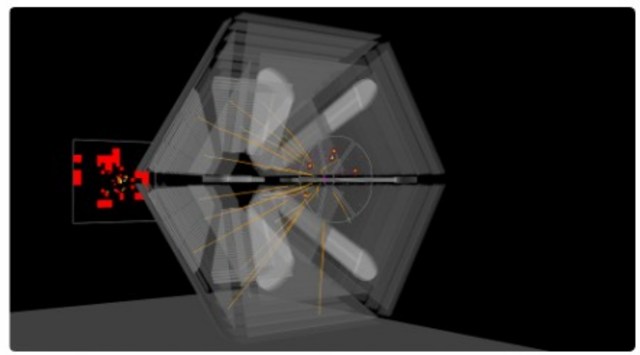
HADES: FAIR Phase 0 Experiment

HADES monitoring

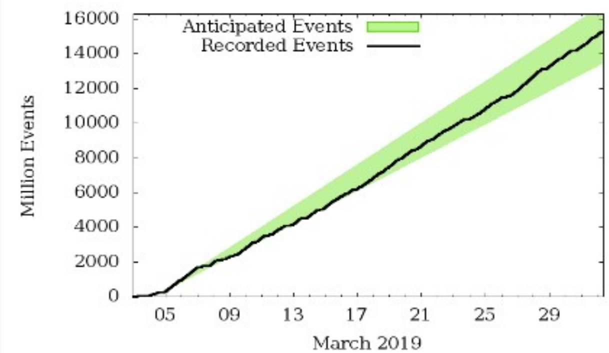
Ag+Ag 1.58A GeV

Date:	01 April 2019
Event rate:	16-18 kHz
Collected events:	15268.68×10^6
Collected data:	359.23 TB
Last update:	6:00

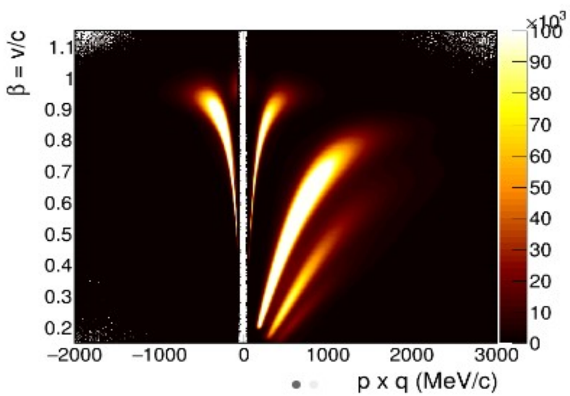
Event Display



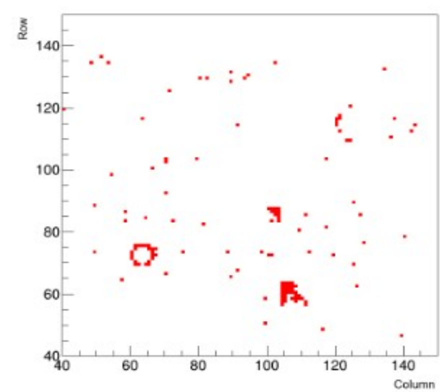
Run statistics



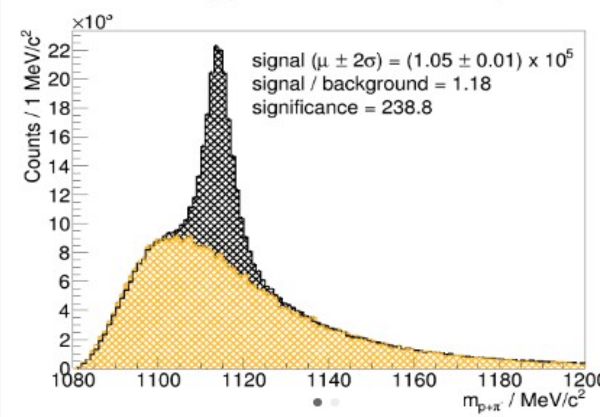
PID: Velocity vs Momentum - TOF



e^+/e^- Cherenkov Rings



Online Hyperons: $\Lambda \rightarrow p + \pi^-$



https://web-docs.gsi.de/~webhades/onlineMon/mar19/hades-online.html