# New systematics of strange hadron production from HADES

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- Why produce strangeness around threshold?
- Case of Au+Au at 1.23A GeV
- Case of $\pi^-$ + {C, W} at 1.7A GeV/c
- Upcoming data from Ag+Ag at 1.58A GeV
- Summary and outlook

# Motivation: strangeness around threshold

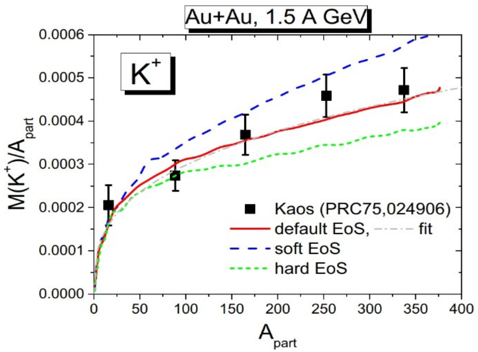
Strangeness production at energies below the NN threshold is a sensitive probe of the goodness of description of heavy ion collisions.

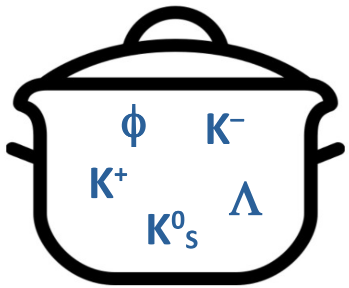
### Types of reaction channels

[ 2 ↔ 3 ] e.g. NN → NNϕ
[ → B* → ] e.g. B* → Nϕ

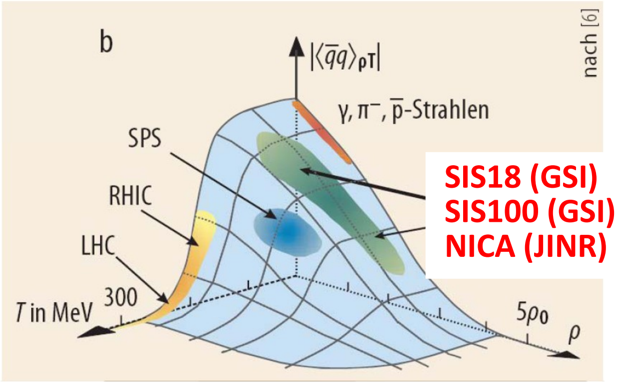
### Equation of State

(*K* modulus, *p*-dependence?)




### In-medium modifications of hadron properties ( m, Γ )




### Decays into strange products:

[ K(892) → Kπ, ϕ → K⁺K⁻
B* → Nϕ , B* → KΛ ]

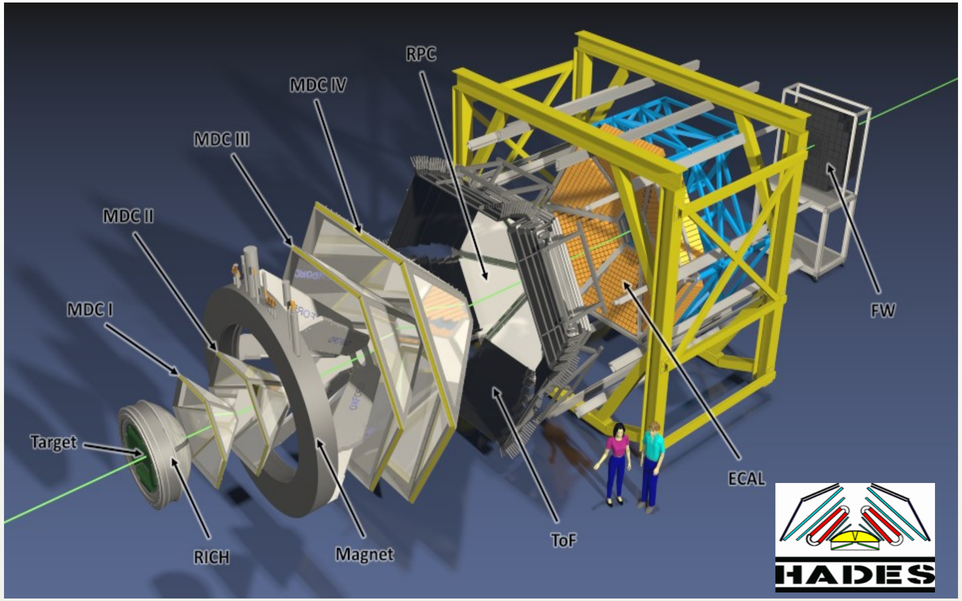
**HADES** Collaboration: **Au+Au @ 1.23A GeV** (big system , energy below strangeness thresholds)
Yields and distributions of: K⁺ , K⁻ , $K^0_S$ , Λ , ϕ
→ now many compared to transport models' predictions

***New data!*** **Ag+Ag @ 1.58A GeV** (Beam $E_{\text{kin}}$ just at K,Λ threshold)

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

- EM spectrometer enriched in hadron detection
  Wide phase space coverage: $18^\circ < \theta_{Lab} < 85^\circ$
- Measurement of charged particles:
  MDC : Momentum
  TOF & RPC : Time of Flight
- $K^0_s$ $\Lambda$ $\phi$ accessed via $K^0_s \to \pi^+\pi^-$, $\Lambda \to p\pi^-$, $\phi \to K^+K^-$

**Talks:**
17.05 Witold Przygoda ($16^{45}$)
18.05 Manuel Lorenz ($15^{15}$)
18.05 Alexandr Prozorov ($17^{15}$)
19.05 Krzysztof Nowakowski ($17^{15}$)




**Experiment Au+Au @ $T_{Beam}$ = 1.23A GeV**

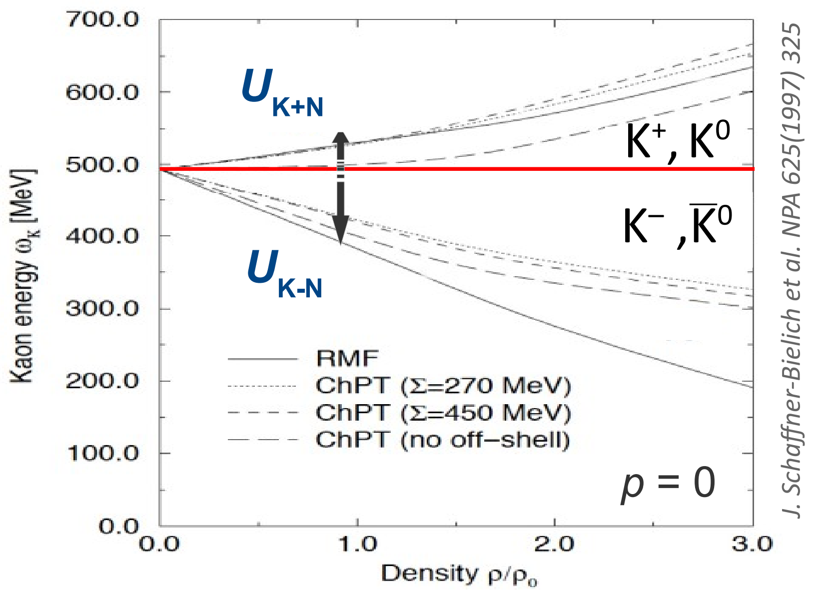
- Total No. of Events: $2.2 \times 10^9$
  Centrality: 40%
- Published data on:
  $K^+$, $K^-$, $\phi$ : *Adamczewski-Musch et al PLB 778, 403 (2018)*
  $K^0_S$, $\Lambda$ : *Adamczewski-Musch et al PLB 793, 457 (2019)*

**Experiment Ag+Ag @ $T_{Beam}$ = 1.58A GeV**

- Total No. of Events: $1.4 \times 10^{10}$
  Centrality: 70%
- Preliminary spectra, analysis ongoing

# Predicted changes of Kaon properties in medium

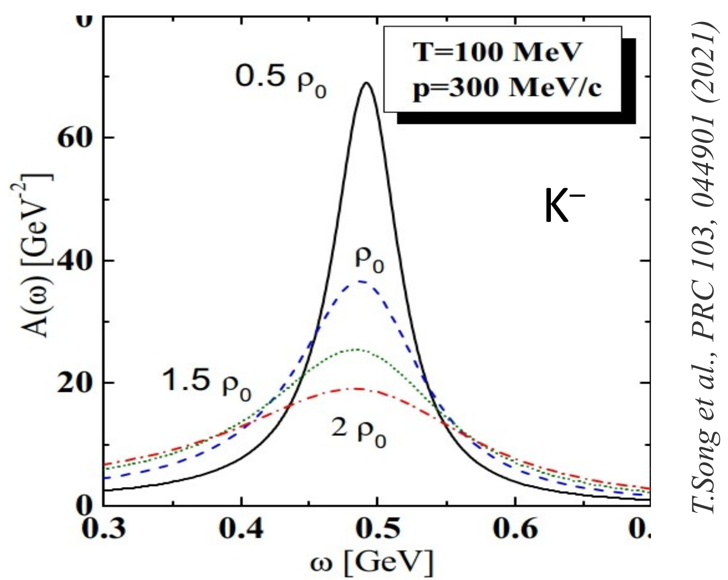
First approaches: **Potential**




$$U(\boldsymbol{p}, \rho_N) = E(\boldsymbol{p}, \rho_N) - \sqrt{m_K^2 + \boldsymbol{p}^2}$$

$K^-$ complicated due to: $\pi Y \rightarrow Y^* \rightarrow K^- N$, $Y = \{\Lambda, \Sigma\}$

*"G-matrix" approach*




Shift of mean + broadening

| *Model* | *$K^+$, $K^0$* | *$K^-$* | *Ref.* |
|---|---|---|---|
| **PHSD** | mass rises linearly with density | G-Matrix *(coupled-channels)* | Song et al. PRC 103, 044901, 2021 |
| **IQMD** | $U_{scalar} + U_{Vector} \rightarrow E$ rises with $\rho$ | $U_{scalar} + U_{Vector} \rightarrow E$ drops with $\rho$ | Hartnack et al, Phys.Rep. 510, 119,2012 |
| **BUU** | mass rises linearly with density | mass drops linearly with density | Schade et al. PRC 81, 034902, 2010 |
| **SMASH** | No modifications | No modifications | Weil et al. PRC 94, 054905, 2016 |
| **UrQMD** | No modifications | No modifications | Bass et al. PPNP, 41, 225, 1998 |

# Some features of transport models

- General description of potential/forces:

| Individual i-j | Mean Field | None |
|---|---|---|
| IQMD | BUU, PHSD, SMASH | UrQMD (default cascade mode) |

- Collisions (hadronic sector) : only 2-body or also 3-body?

| 2-body | 2- and 3- body |
|---|---|
| SMASH, UrQMD | BUU, IQMD, PHSD |

*Note: In 2-body approach particle production may undergo via an intermediate resonance.*

- Equation of State: Incompressibility modulus *K* [MeV] (used for calculations presented here)

| BUU | IQMD | PHSD | SMASH | UrQMD (cascade) |
|---|---|---|---|---|
| 215 | 200 | 300 | 240 | None |

- Changes of kaon properties inside medium

| *Model* | $K^+$, $K^0$ | $K^-$ | *Ref.* |
|---|---|---|---|
| PHSD | mass rises linearly with density | G-Matrix *(coupled-channels)* | Song et al. PRC 103, 044901, 2021 |
| IQMD | $U_{scalar} + U_{Vector} \rightarrow E$ rises with $\rho$ | $U_{scalar} + U_{Vector} \rightarrow E$ drops with $\rho$ | Hartnack et al, Phys.Rep. 510, 119,2012 |
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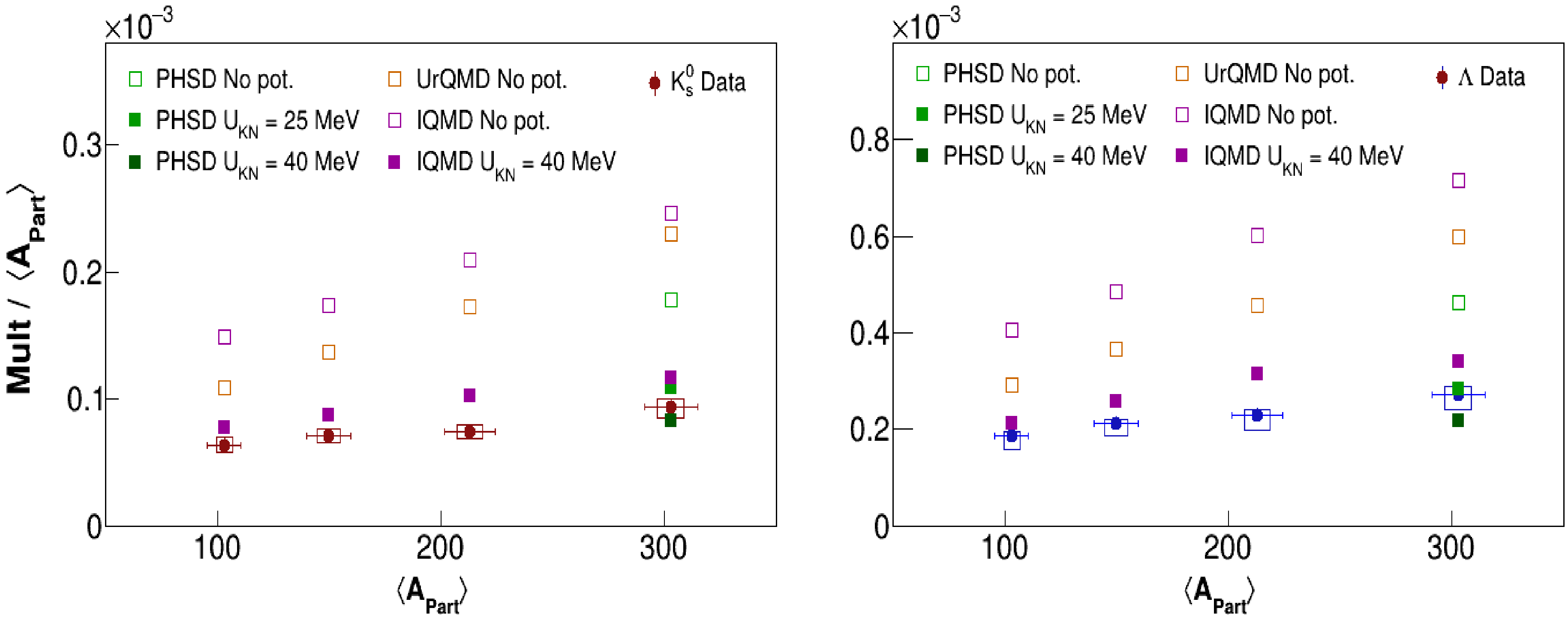
# In-medium effects of $K^0$ from Au+Au @ 1.23A GeV

Comparing $K^0$ and Λ data to transport models
( Higher $K^0$ mass → raised threshold for $K^0$ & Λ production in leading channel NN → $NK^0Y$ )

## Multiplicity of $K^0_s$ and Λ vs centrality :



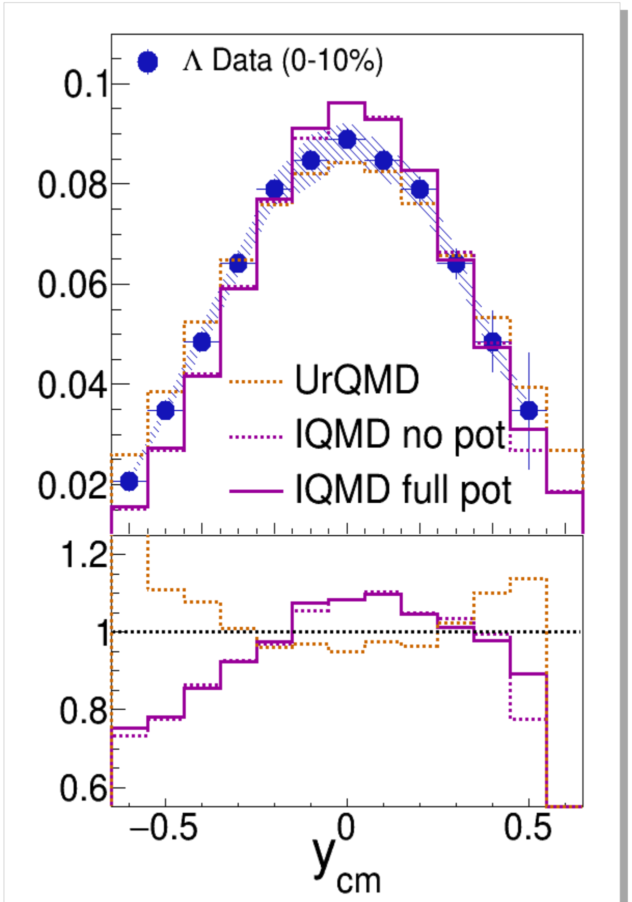

J. Adamczewski-Musch et al., PLB 793, 457 (2019)
T. Song et al., PRC 103, 044901 (2021)

Calculations **without** in-medium effects: all **overestimate** the total yield.

**PHSD**: $U_{K0\,N}$ ~ 25 .. 40 MeV describes the total yield for central colisions.
**IQMD**: $U_{K0\,N}$ = 40 MeV still overpredicts exp. data. A bit higher $U_{K0N}$ would fit better.

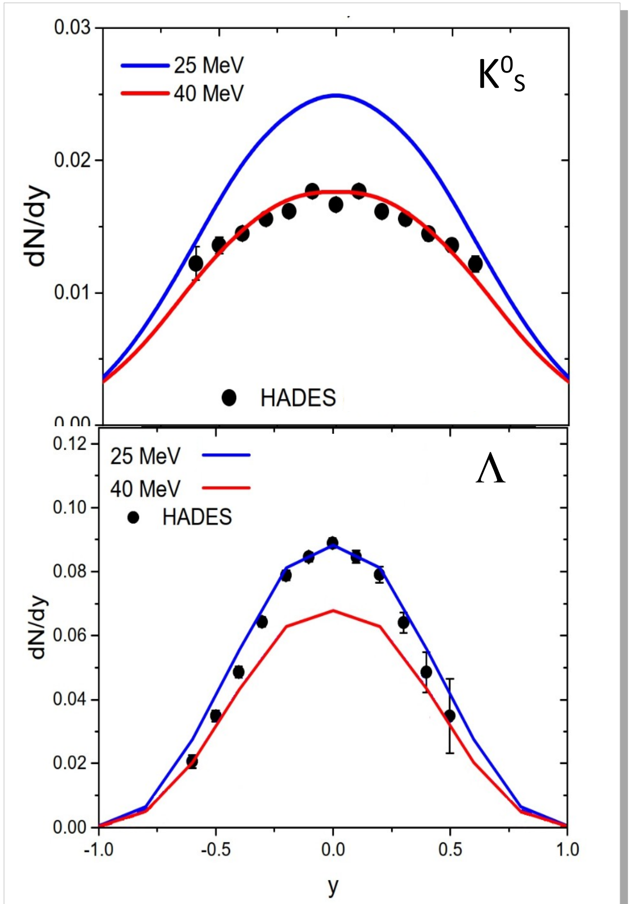
# Look in more detail: Rapidity distributions

- **IQMD** prediction for Λ (profile)



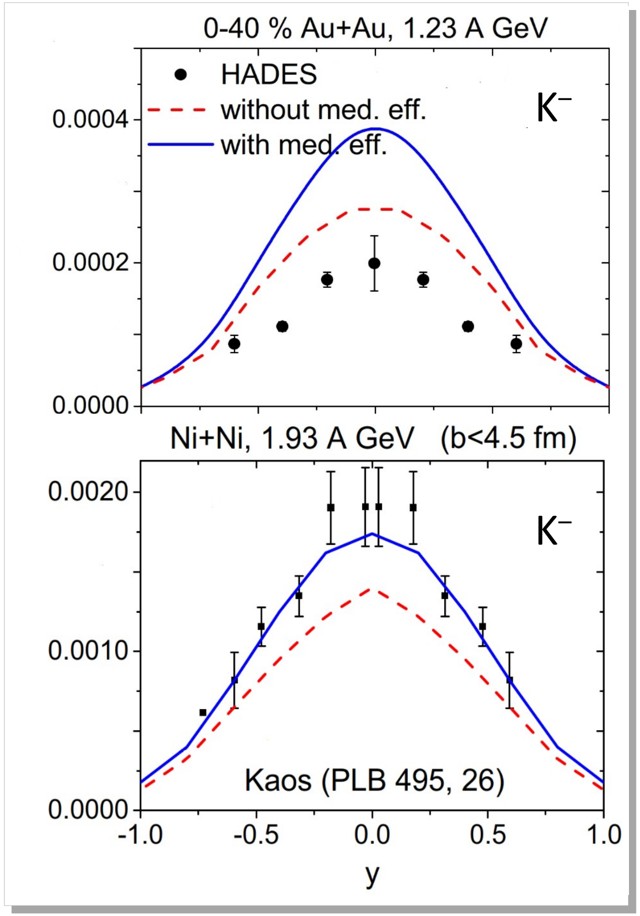

Predicted width too narrow.
In-medium effects do not help.

- **PHSD** prediction for $K^0_S$, Λ




$K^0_s$ → $U$ = 40 MeV
Λ → $U$ = 25 MeV
Order of uncertainties

- **PHSD** prediction for $K^-$

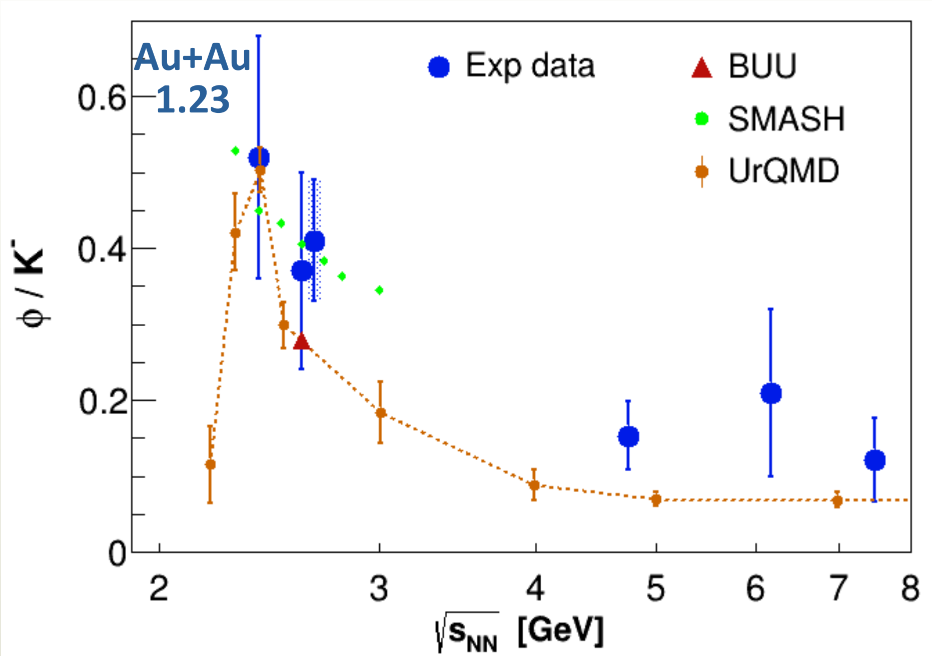



T.Song et al., PRC 103, 044901 (2021)

Overestimation in both scenarios
... but not for Ni+Ni @ 1.9A GeV

# Subthreshold ϕ mesons

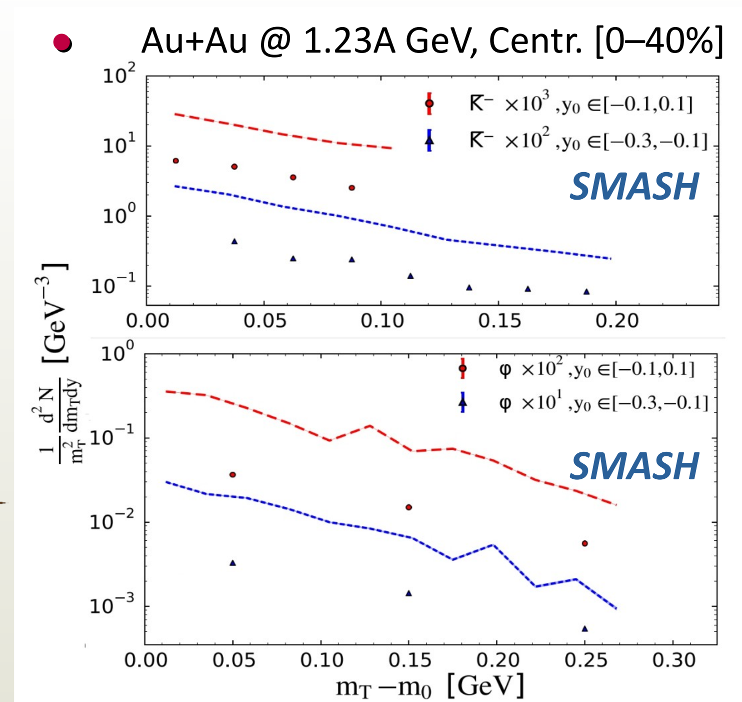
## ϕ/K⁻ enhancement observed below threshold




- **UrQMD** & **SMASH** predict ϕ/K⁻
  … but fail to describe each yield separately.
- **BUU** describes $K^{+/-}$, ϕ for Ar+KCl @ 1.76 A GeV.

## Different production mechanisms proposed

| Model | Leading mechanism: |
|---|---|
| BUU | BB → NNϕ , mB → Nϕ, mm → ϕ |
| SMASH | [Heavy N*] → Nϕ |
| UrQMD | [Heavy N*] → Nϕ |



# Direct s$\bar{s}$ production around strangeness threshold?

**Yields of strange hadrons rise with $A_{part}$ with the same exponent > 1**

Understandable for $K^+$, $K^0_s$, $\Lambda$, $K^-$ ... but not $\phi$ . Why?

**Usual explanation at energies around threshold:**

Less available energy

↓

more multi-step processes required

↓

they are available inside large medium

**Threshold $T_{Beam}$ for production in NN:**

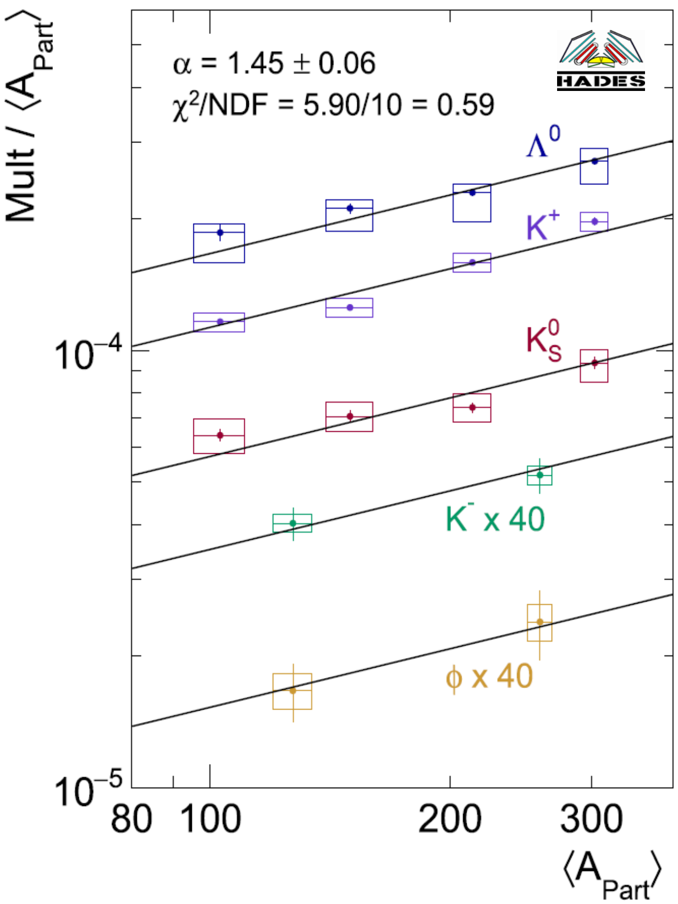
For $K^{+0}$ and $\Lambda$ NN → N $K^{+0}$ Y $T_{Beam, Thr}$ = 1.6 GeV

For $K^-$ NN → NN $K^+$ $K^-$ $T_{Beam, Thr}$ = 2.5 GeV

... leading channel $\pi$Y → $K^-$N ⇒ $K^-$ follows $K^{+/0}$ and Λ

For $\phi$ , NN → NN $\phi$ $T_{Beam, Thr}$ = 2.6 GeV

$\phi$ much more under threshold than the others.
should rise stronger with <$A_{part}$> ... but does not!




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

**Hypothesis**

Could strangeness originate from direct s$\bar{s}$ pairs?

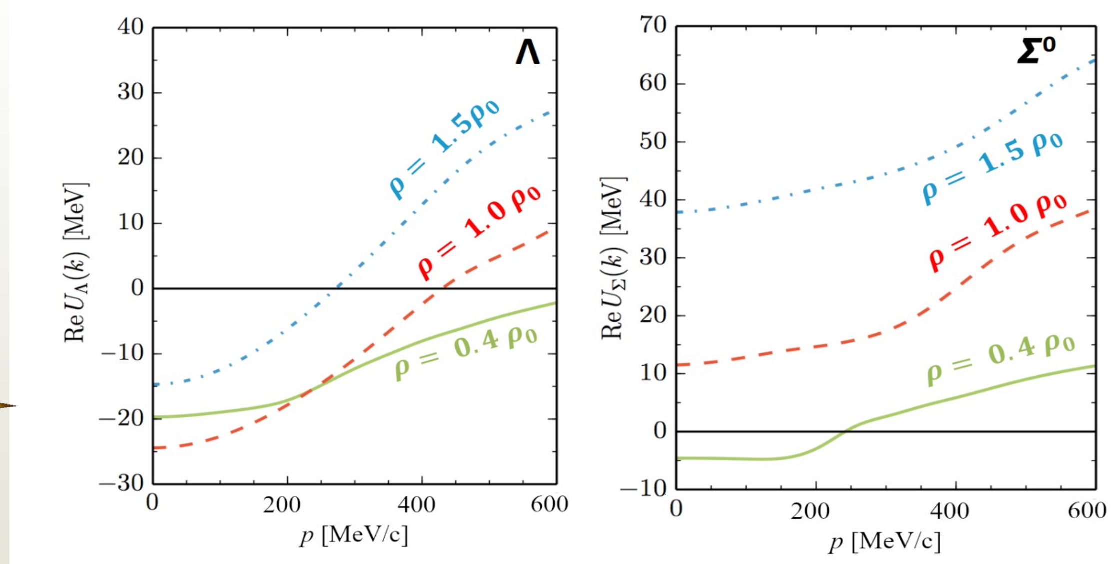
Consider **πN → KY** process.

- ***Standard scenario***:

  $U_{K0N}$ : composition of scalar and vector potentials

  $U_{\Lambda N} = U_{\Sigma N} = ⅔\, U_{NN}$

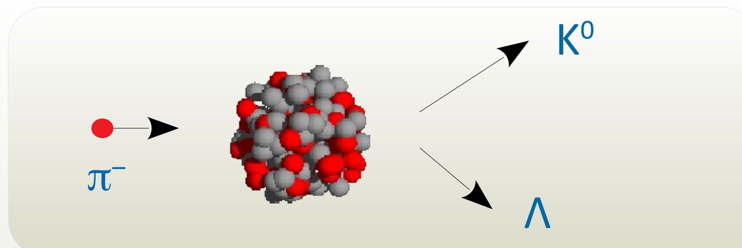
- ***χEFT NLO calculations***:
  - density-dependent
  - $U_{\Sigma N}$ mostly repulsive




S. Petschauer et al., EPJ A52, 15 (2016)

**Depth** (sign, shape) of ΛN (ΣN) potential influences **energy amount** at KΛ (KΣ) production point.

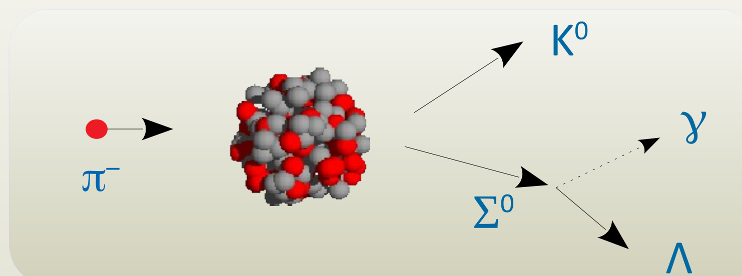
This modifies the kinematic distributions of K and Λ.




**HADES experiment**:

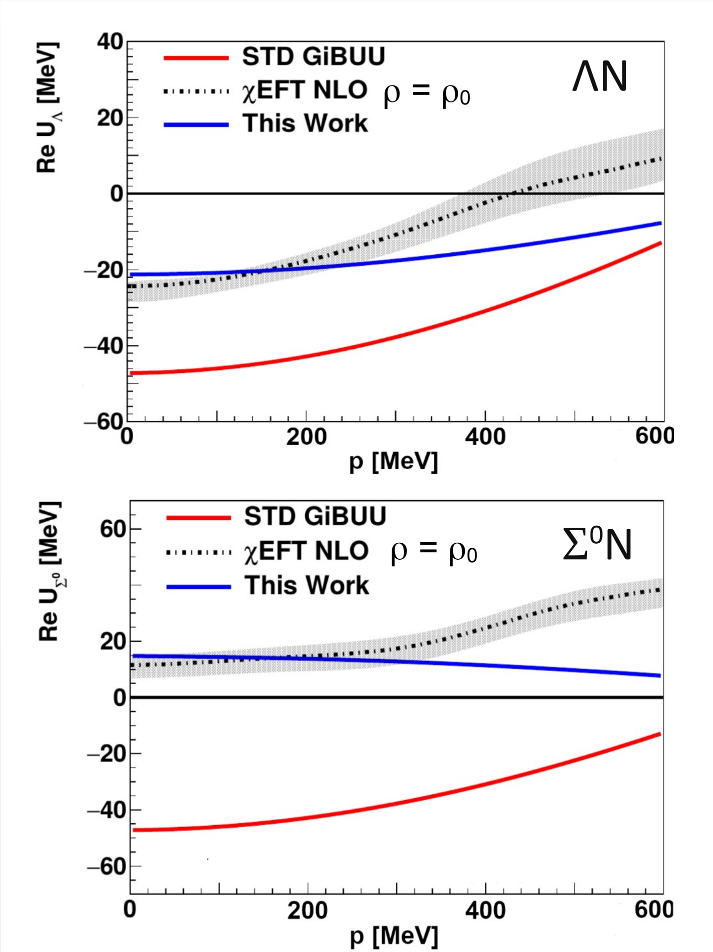
$\pi^-$ (p = 1.7 GeV/c) + $^{184}$W → **K⁰** + **Λ** + …

Tagging K⁰ with Λ : limiting possible channels

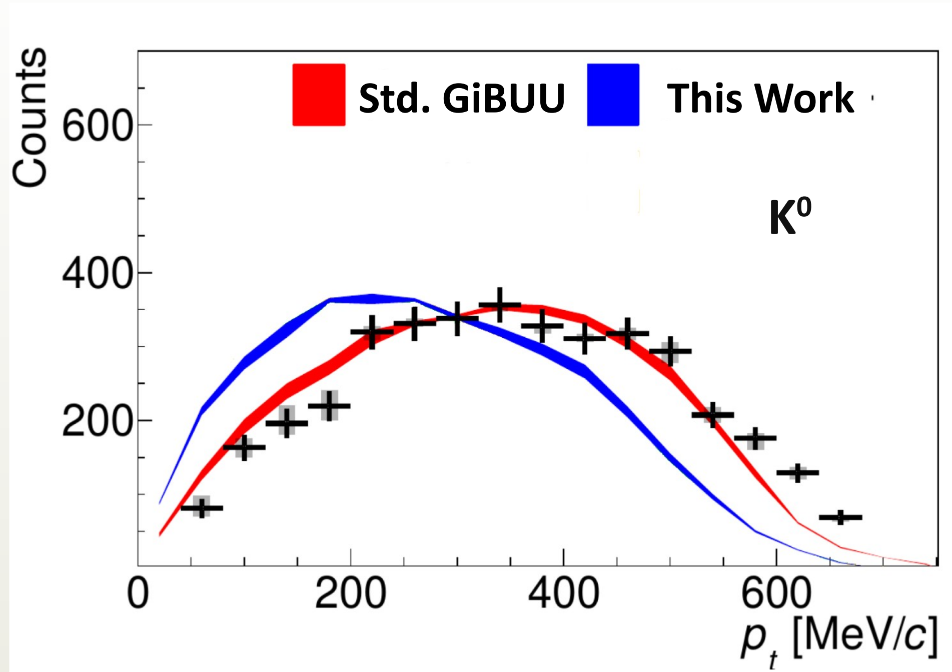


Transport model employed: **GiBUU**

**GiBUU**: for hyperons, standard NN potential can only be multiplied by factor.




- *S. Maurus, Ph. D., Technische Universitaet Munich*




"Less attractive $U_{\Lambda N}$ + repulsive $U_{\Sigma 0\ N}$" scenario inspired by *χEFT NLO*

… seems to be disfavoured by the data.

***General message:***

***different scenarios can be tested.***

# Probing absorption of $K^-$ in nuclear medium

## $K^-$ absorption in the medium?

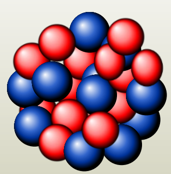
$K^+$ absorption suppressed at low *E*, due to lack of antinucleons

| $K^-$ N → π Y | $K^+$ $\bar{N}$ → π $\bar{Y}$ |
|---|---|
| $\bar{u}s$ uud → $\bar{u}u$ uds | $u\bar{s}$ $\bar{u}\bar{u}\bar{d}$ → $\bar{u}u$ $\bar{u}\bar{d}\bar{s}$ |

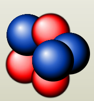
$$\frac{K^-}{K^+} \approx \frac{\text{partly absorbed}}{\text{untouched}}$$

## Measurement

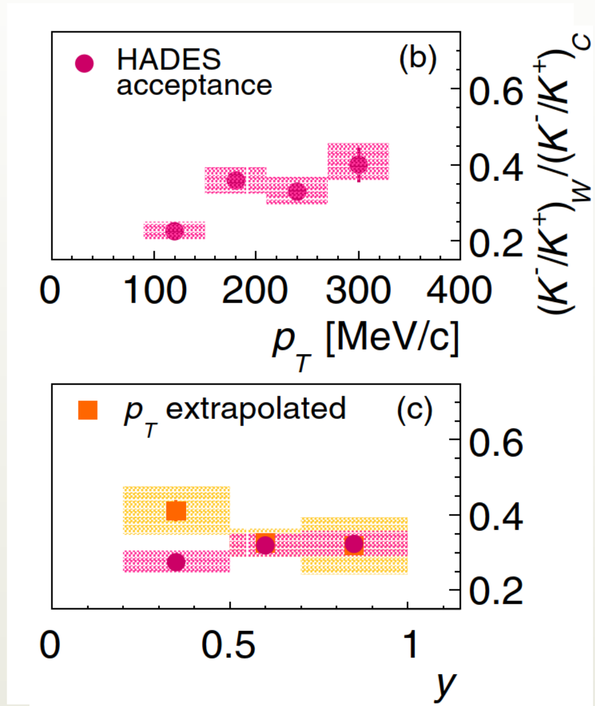
$\pi^-$ → 1.7 GeV → $^{184}W$



$\pi^-$ → $^{12}C$

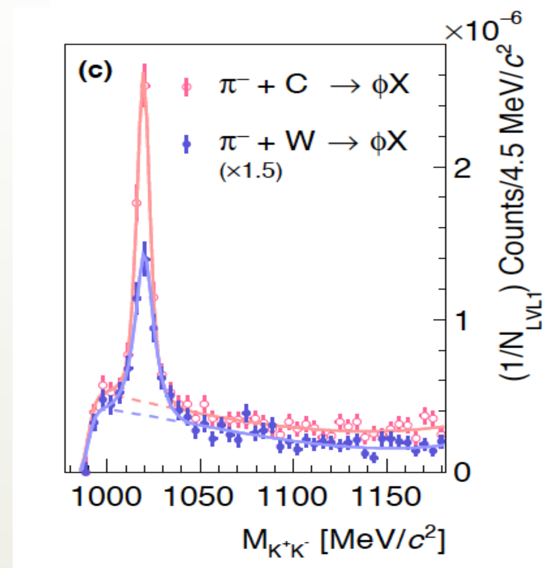


## Double ratio: Heavy / Light




Rather strong $K^-$ absorption in medium

## ϕ absorption in the medium?




$$\left.\frac{\phi}{K^-}\right|_W = 0.63 \pm 0.06 \pm 0.11$$

$$\left.\frac{\phi}{K^-}\right|_C = 0.55 \pm 0.04 \,^{+0.06}_{-0.07}$$

ϕ data suggest similar trend as $K^-$

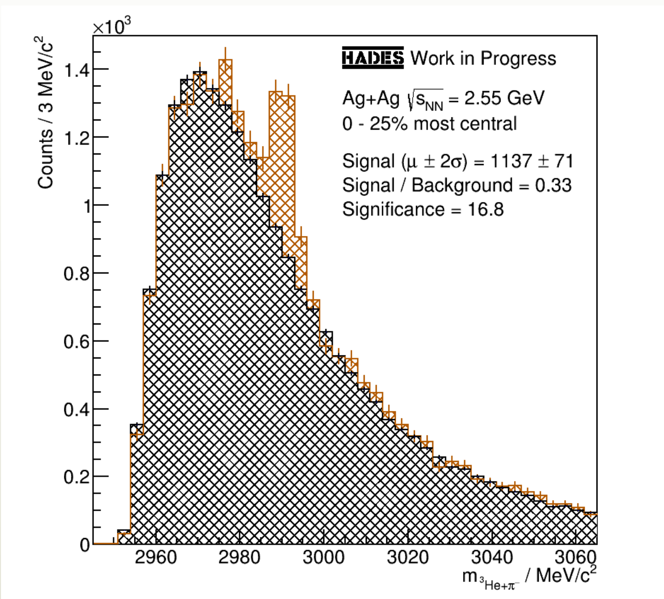
## Ag+Ag experiment:

Statistics : 14 billion events !
Centrality : 0 .. 70% wide scan !

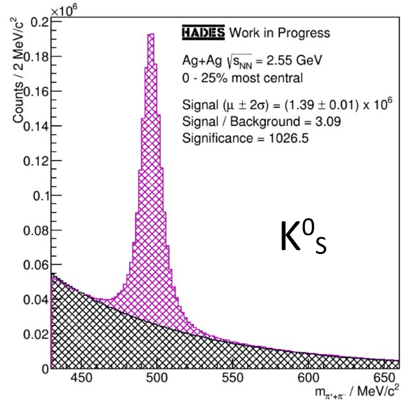
Preliminary spectra of $K^0_s$ and $\Lambda$ : wide scan !

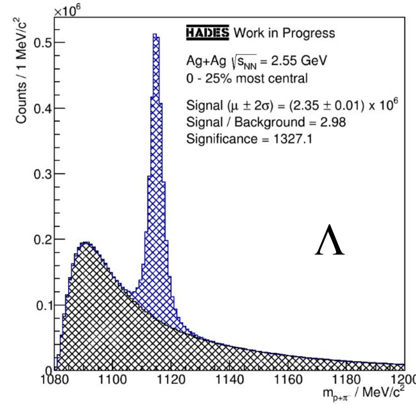
Also under way: $K^+$, $K^-$, $\phi$, ...

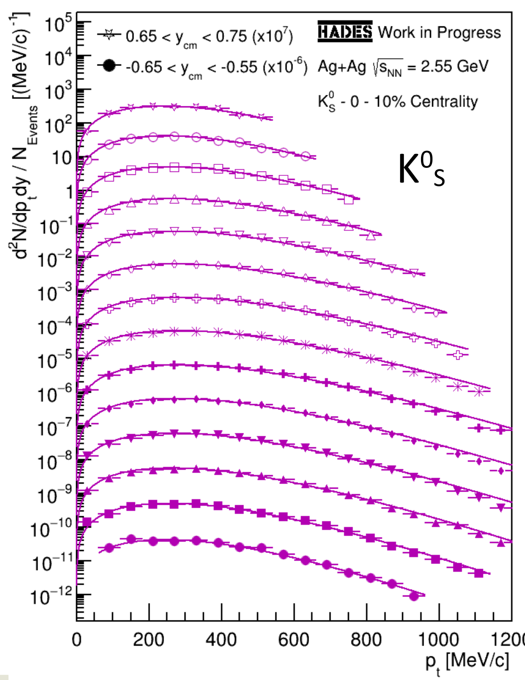
Reconstruction of ${}^3_\Lambda H$

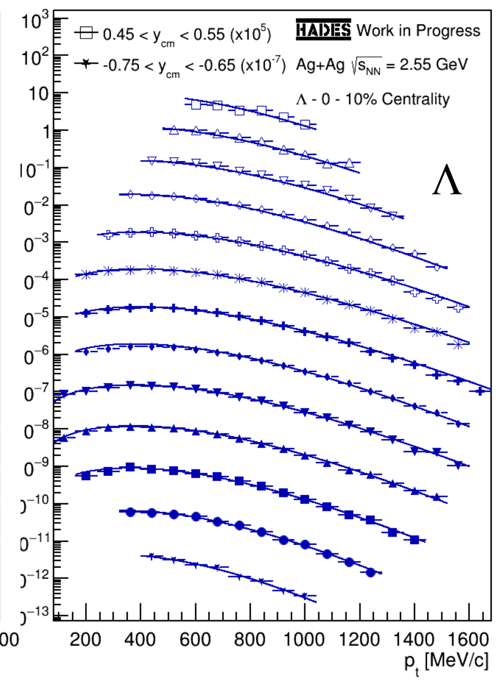



S. Spies, Uni Frankfurt, analysis ongoing



# Summary and outlook

**Yields and distributions of strangeness around free NN threshold** are sensitive to important properties of nuclear matter and implementations in transport models.

- **HADES** Collaboration published data on $K^+$, $K^-$, $K^0_s$, $\Lambda$, $\phi$ emitted from **Au+Au @ 1.23A GeV**.

- Findings for this system:
  **PHSD**, **IQMD**, **UrQMD** calculations suggest that in-medium changes of $K^0$, $\Lambda$ properties help in description of $K^0_s$ and $\Lambda$.

- **PHSD**:
  comparison to $K^0$ data: → $U_{KON}(\varrho_0, p = 0) \approx +40$ MeV
  comparison to $\Lambda$ data: → $U_{KON}(\varrho_0, p = 0) \approx +25$ MeV
  Yield of $K^-$ is too high, even without G-matrix-based in-medium effects.

- **$\phi$ / $K^-$** ratio explained by two concurrent scenarios:
  regular hadronic channels (**BUU**)
  feed-down from heavy resonances (**UrQMD** / **SMASH**)

- Simpler systems: good testing ground for scenarios of in-medium effects.
  Experiment: **$\pi^- W \to K^0 \Lambda X$ @ $p = 1.7$ GeV/c**.
  Two scenarios for $U_{\Lambda N}$ and $U_{\Sigma N}$: **(a)** ⅔ $U_{NN}$ or **(b)** $\chi$EFT NLO: overall less attractive.
  $K^0$ $p_T$ distribution compared to **GiBUU**: type **(a) scenario wins** over type (b).

- **Recent HADES experiment: Ag+Ag @ 1.6A GeV:** very high statistics, analysis is ongoing.

***Backup slides***

# Probe: single, rarely emitted kaon

**Good probe:** single, easily measurable particle, emitted from heavy-ion collision zone
Take a **Kaon**. At beam energies ~ few AGeV : usually *single* kaon is emitted

Complicated QCD lagrangian → **Klein–Gordon equation**

Vacuum mass, 0.494 GeV

$$\left[ \partial_\mu \partial^\mu \pm \frac{3i}{4 f_K^2} \rho_N \partial_t + \left( m_K^2 - \frac{\Sigma_{KN}}{f_K^2} \rho_S \right) \right] \phi_{K^\pm}(x) = 0$$

Term responsible for *splitting of masses*.
⊕ for kaon, ⊖ for antikaon

Term responsible for *drop of mass* for each type of kaons

$\rho_N$ : nuclear density ($\approx \rho_S$)
$\rho_S$ : scalar nuclear density
$f_K$ : K decay constant, 106 MeV
$\Sigma_{KN}$ : $\frac{1}{2}(m_u + m_s)$ <N|$u\bar{u}$ + $s\bar{s}$|N>
$270 \lesssim \Sigma_{KN} \lesssim 450$ MeV

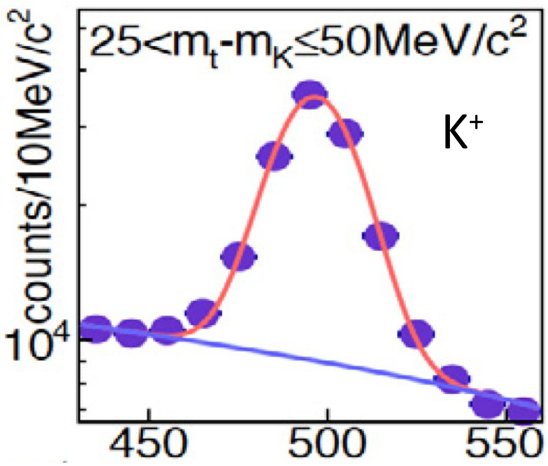
## Energy of kaon inside nuclear matter at rest:

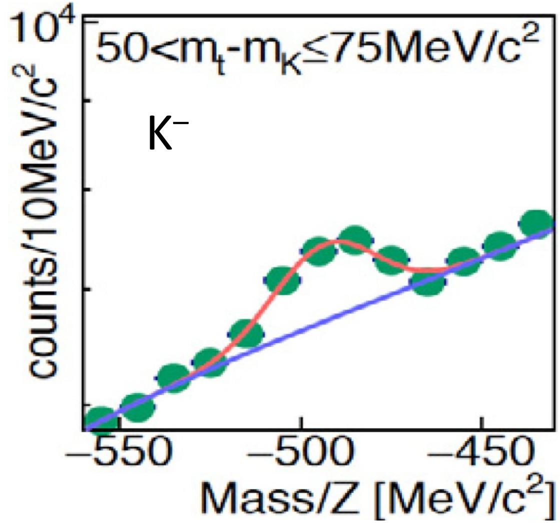
$$E(\mathbf{p}, \rho_N) = \sqrt{m_K^2 + \mathbf{p}^2 - \frac{\Sigma_{KN}}{f_K^2}\rho + \left(\frac{3}{8}\frac{\rho}{f_K^2}\right)^2} \pm \frac{3}{8}\frac{\rho}{f_K^2}$$

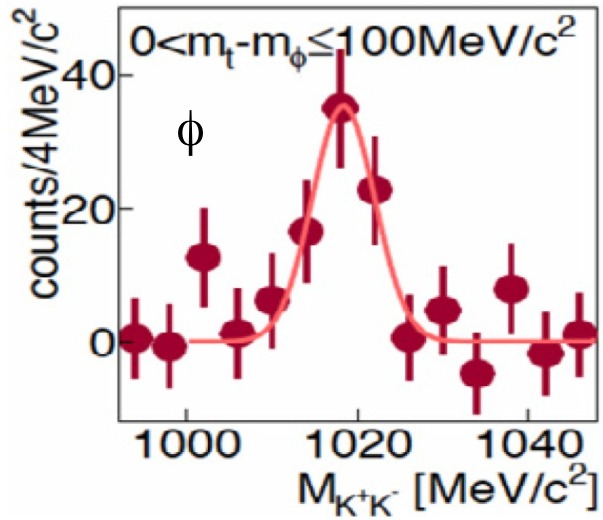
Let's compare this formula to the energy of „free" kaon (in-vacuum): $E(\mathbf{p}, 0) = \sqrt{m_K^2 + \mathbf{p}^2}$

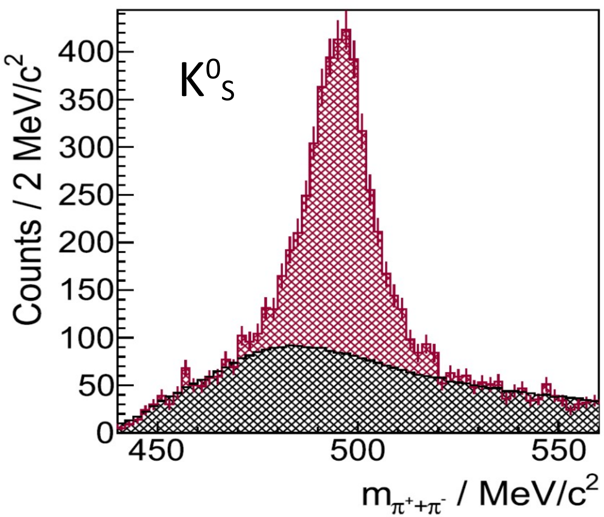
"*In-medium potential*" is defined as: $U(\mathbf{p}, \rho_N) = E(\mathbf{p}, \rho_N) - \sqrt{m_K^2 + \mathbf{p}^2}$

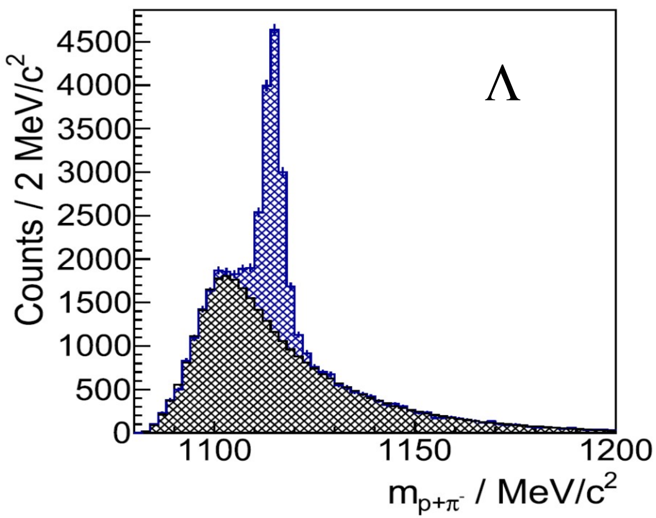
# Measurement of strange hadrons from Au+Au @ 1.23A GeV



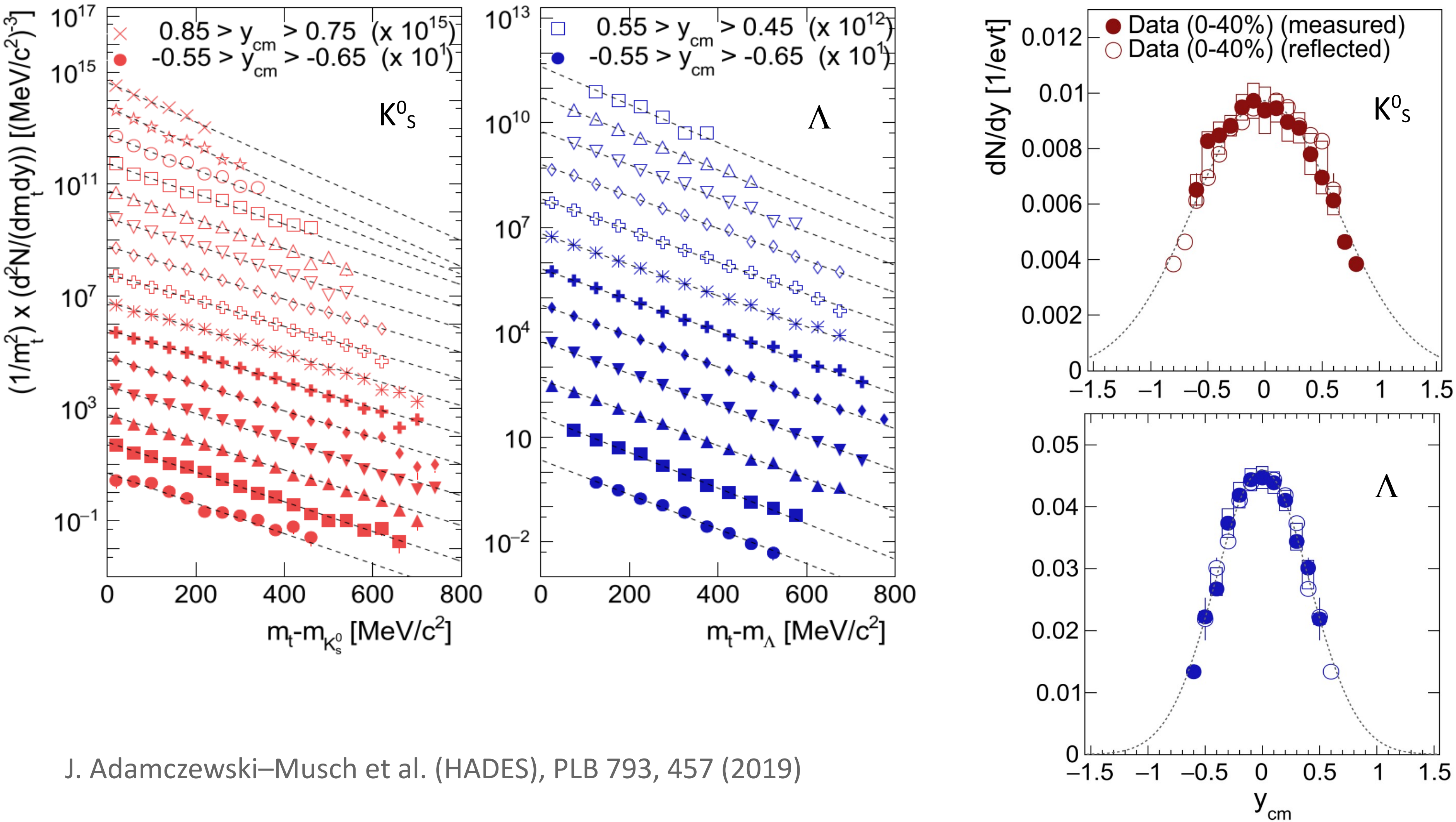



# Distributions of $K^0_s$ and $\Lambda$ from Au+Au @ 1.23A GeV



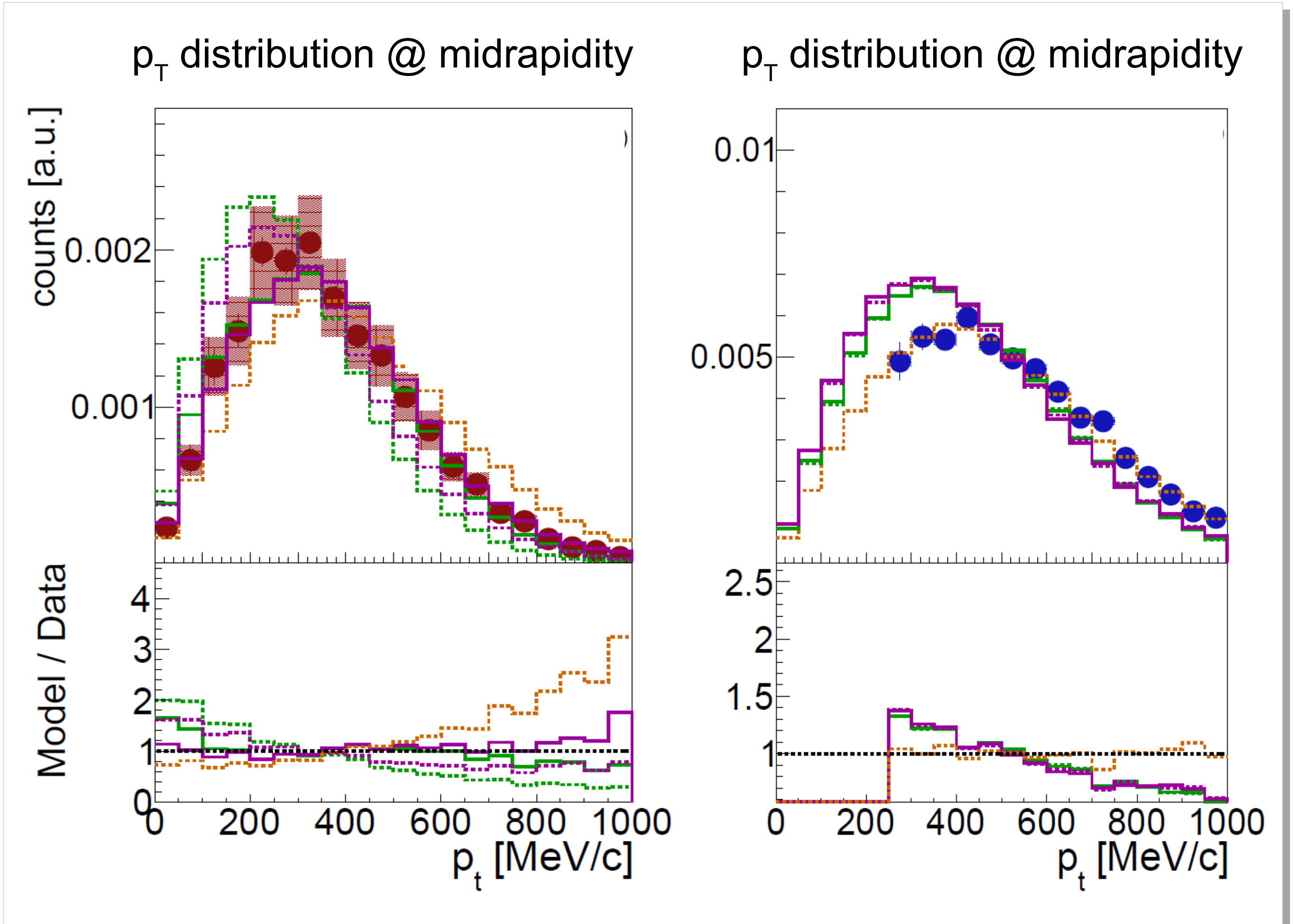

J. Adamczewski–Musch et al. (HADES), PLB 793, 457 (2019)

## 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 |

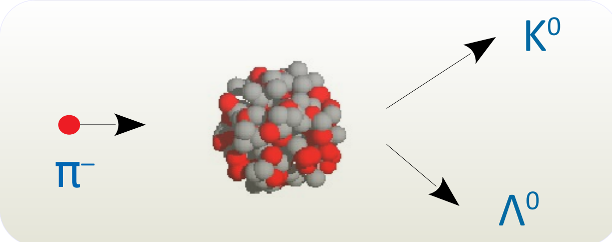



**Again, best description with the in-medium effects.**

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

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

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



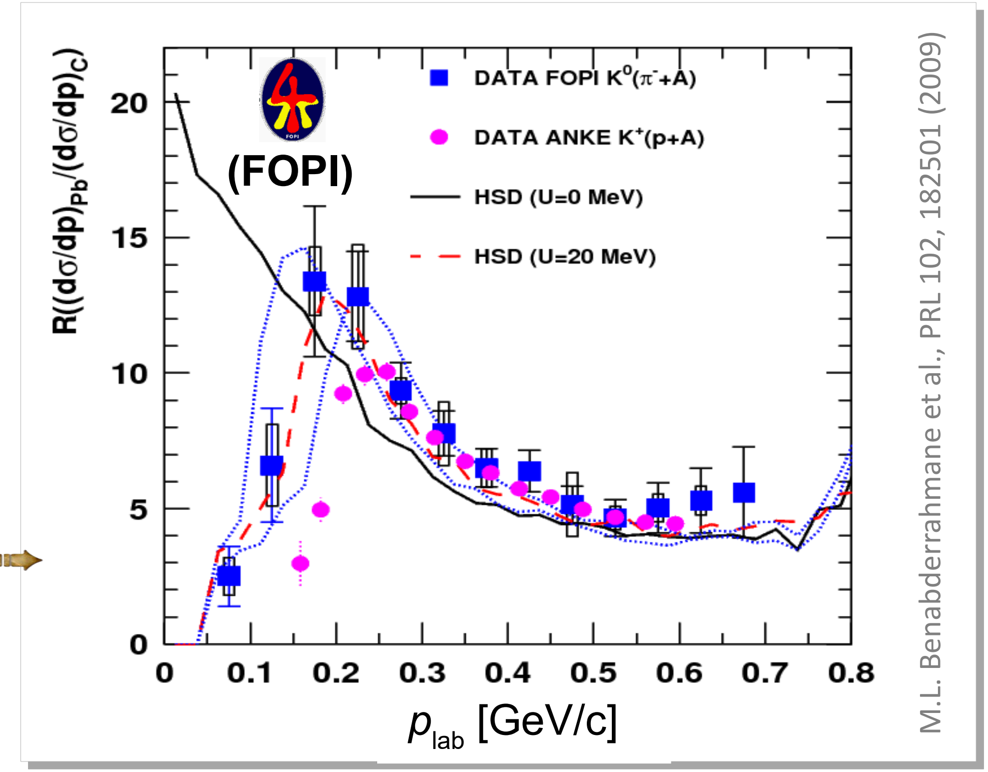

- Comparison of two reactions (FOPI, 2009) :

  $\pi^-$ (p=1.15 GeV/c) + $^{208}$Pb $\rightarrow$ $\mathbf{K^0}$ + …

  $\pi^-$ (p=1.15 GeV/c) + $^{12}$C $\rightarrow$ $\mathbf{K^0}$ + …

  Ratio of momentum distributions of kaons:

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




- Comparison to **HSD** transport model

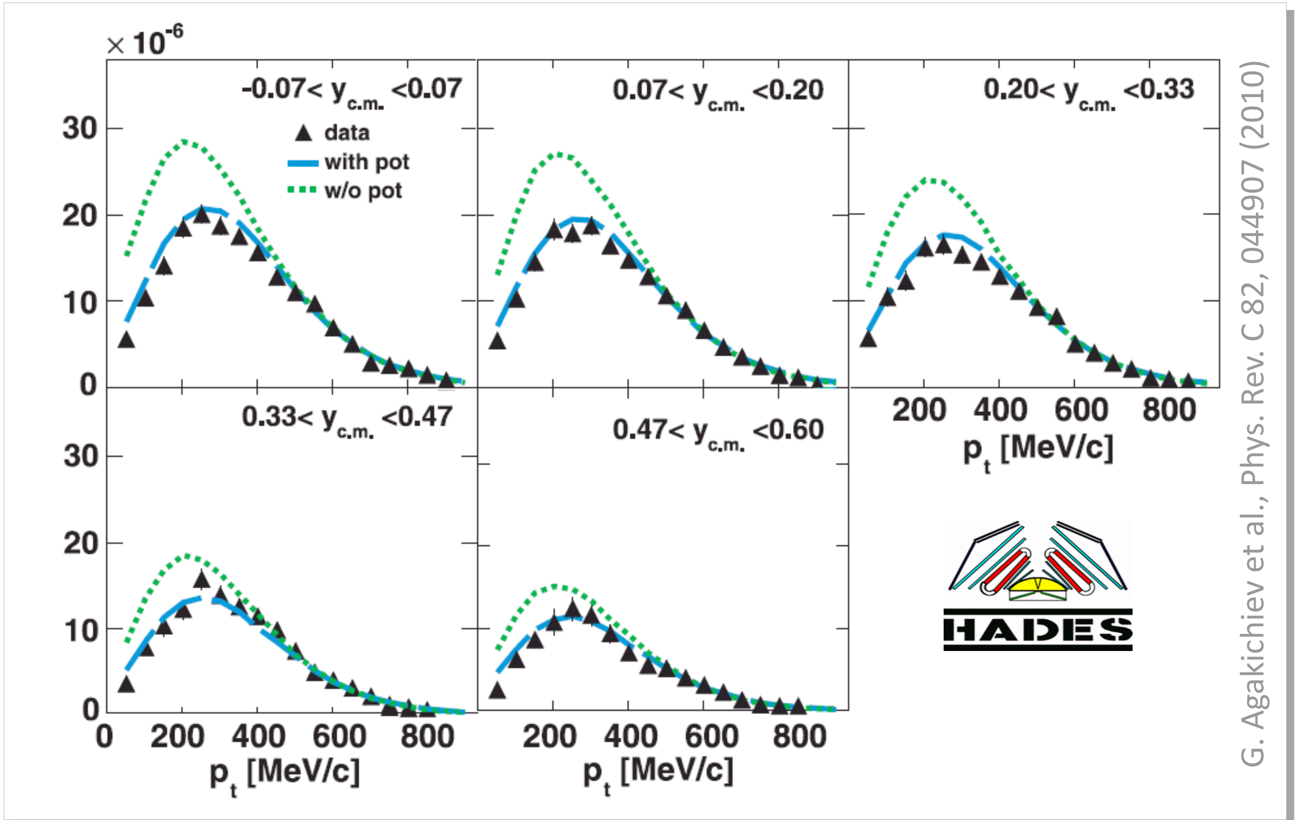
| | |
|---|---|
| ——— (solid) | No modification |
| ········ (blue dotted) | $U_{K0N}(\varrho_0)$ = 10 MeV |
| ········ (red dashed) | $U_{K0N}(\varrho_0)$ = 20 MeV |
| ········ (blue dotted) | $U_{K0N}(\varrho_0)$ = 30 MeV |

➠ Ratio explained by HSD if:

$U_{K0N}(\varrho_0)$ = +20 MeV

# $K^0$ emitted from heavy ions

**$K^0_s$ mesons** emitted from Ar+KCl @ 1.76A GeV. Distributions in phase space ($p_T$ – y) .




- Max densities: **$2\ \varrho_0$**
- Comparison to **IQMD** transport model.

  Potential type: RMF
  - non-linear ρ dependence
  - scalar and vector parts

No modification

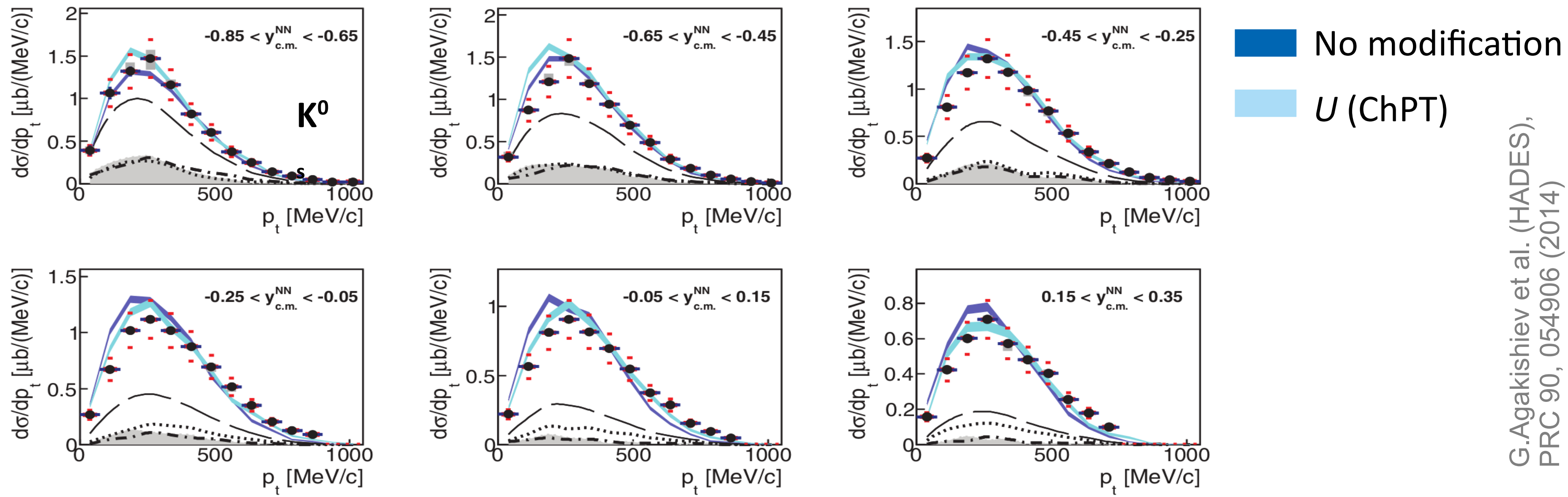
**$U_{KON}(\varrho_0) = 46$ MeV**

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

Instead of ad-hoc linear density dependence, fully covariant field theory

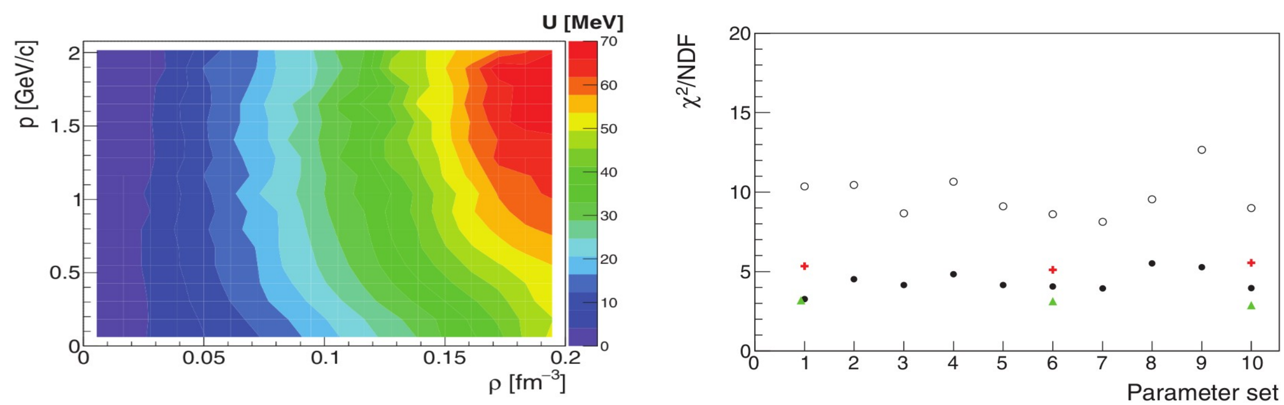
# $K^0$ emitted from nucleus (newer data)

$K^0_s$ **mesons** emitted from p ($T_B$ = 3.5 GeV) + Nb . Distribution in phase space ($p_T - y$):




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

Comparison with **GiBUU** transport model. **ChPT potential** was used (also relativistic fields, like RMF)




**Preference for ChPT scenario**

$U_{K0N}$ : **35 MeV**

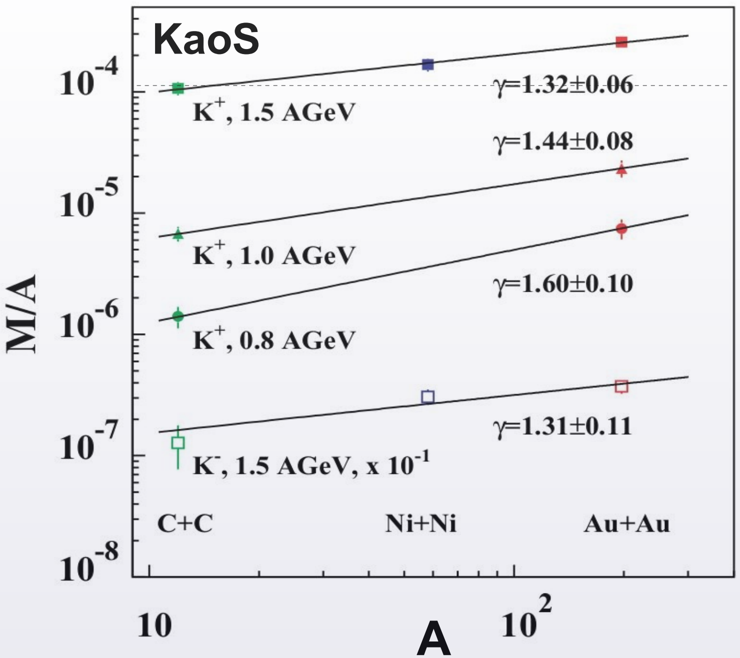
# Production of Kaons in AA: Primary or secondary?

**If primary:**

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

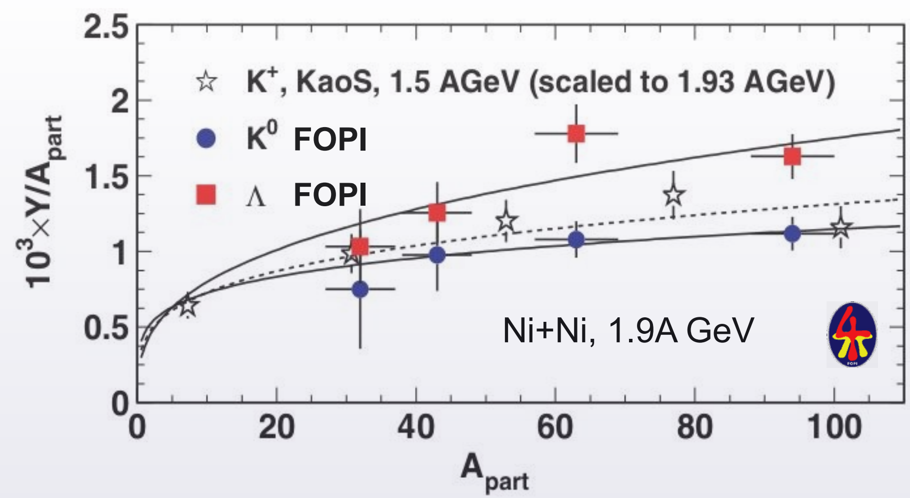
AA → KX: Glauber: AA = A ⊗ NA

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




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)

# $K^+$ emitted from collisions of heavy ions

**$K^+$ mesons** from Au ($T_B$ = 1.5 GeV) + Au

Distributions in phase space ($p - \theta_{Lab}$)

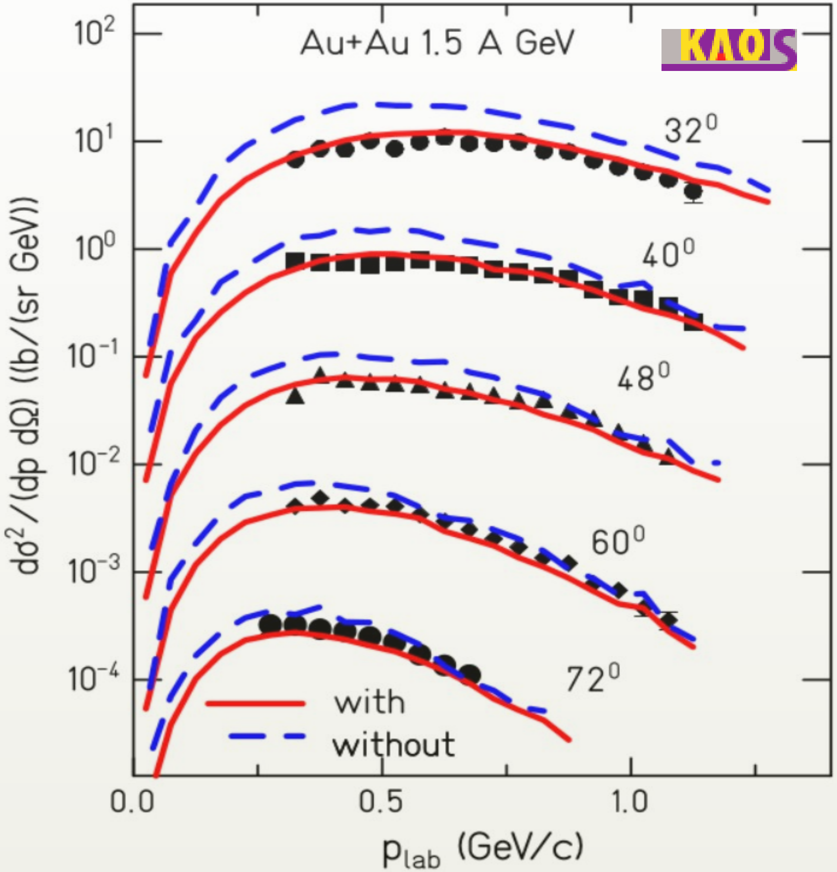
- **IQMD** simulation. Potential type: RMF
  - non-linear ρ dependence
  - scalar and vector parts

Leading production channels:

$N\Delta \rightarrow K^+ \ldots$ $NN \rightarrow K^+ \ldots$ $\pi B \rightarrow K^+ \ldots$

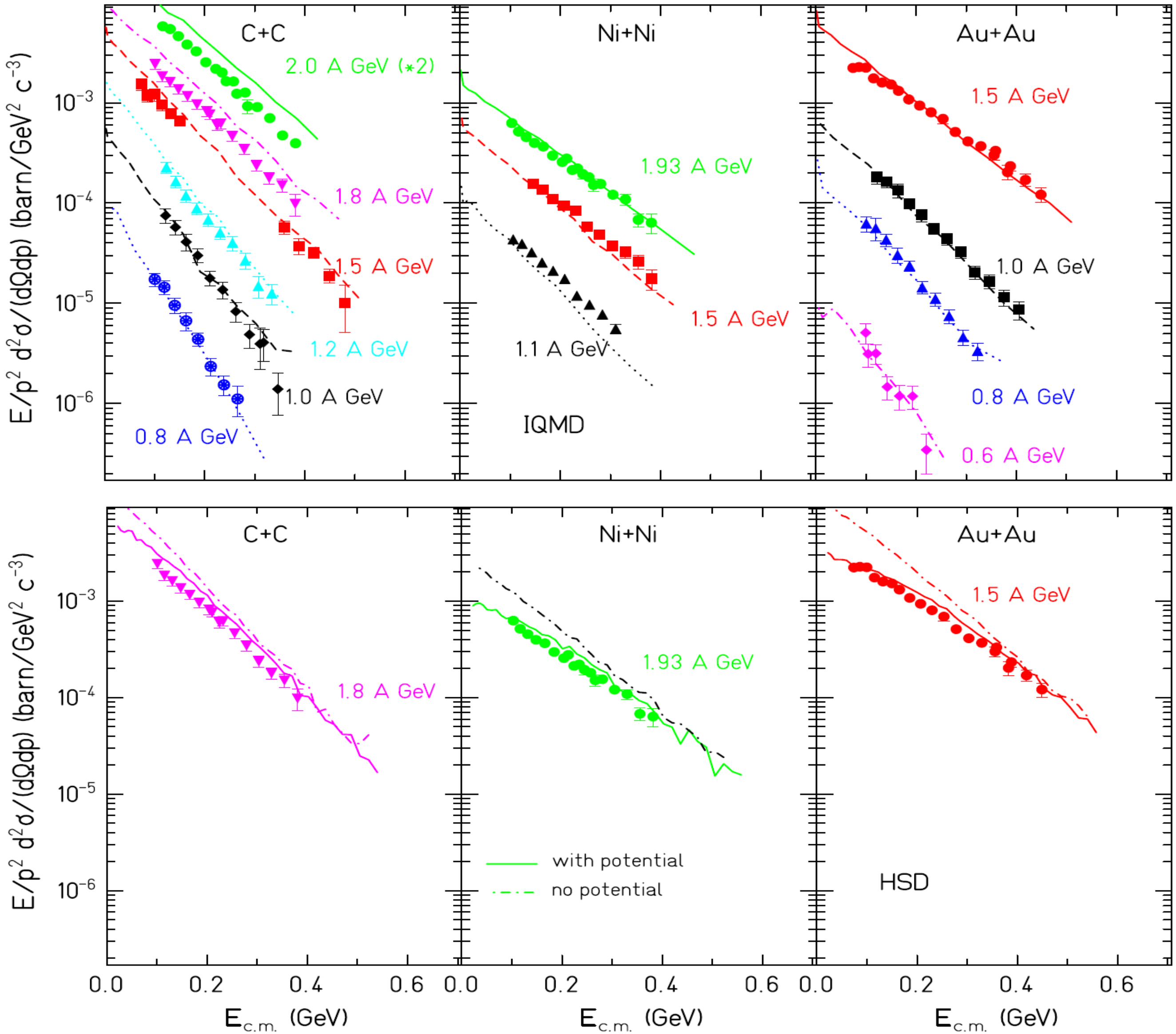
| | |
|---|---|
| ·········· | No modification |
| —— | $U_{K+N}$ $(\varrho_0)$ = 40 MeV |

Distribution in wide range of phase space described by $U_{KON}$ $(\varrho_0)$ = +40 MeV




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

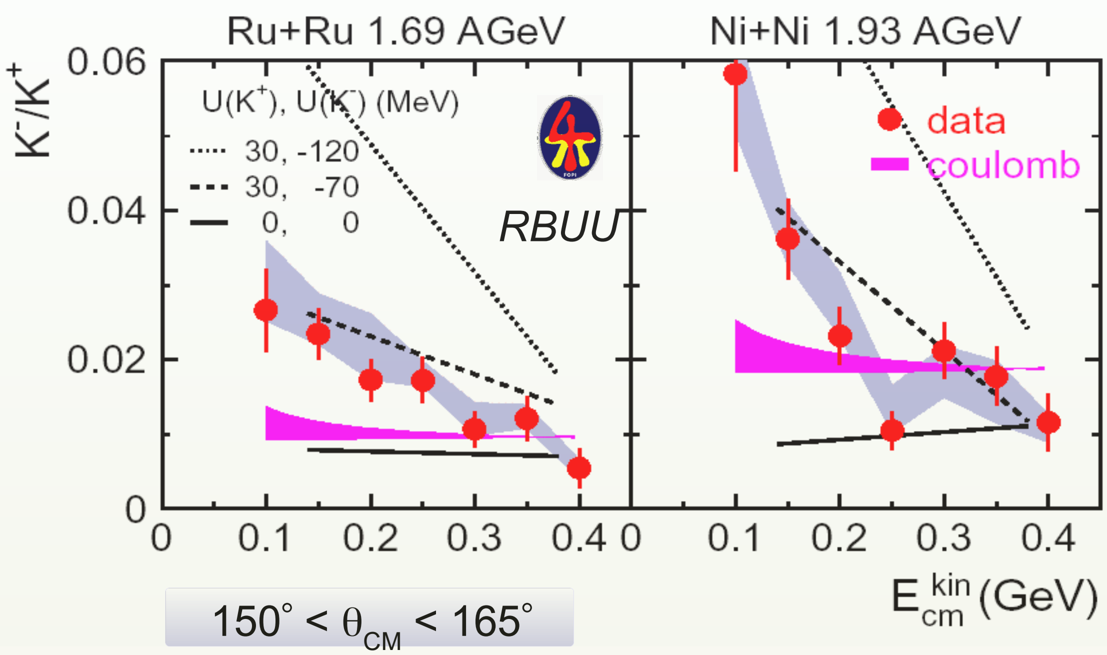
# In-medium effects of K⁺ from heavy ion collisions



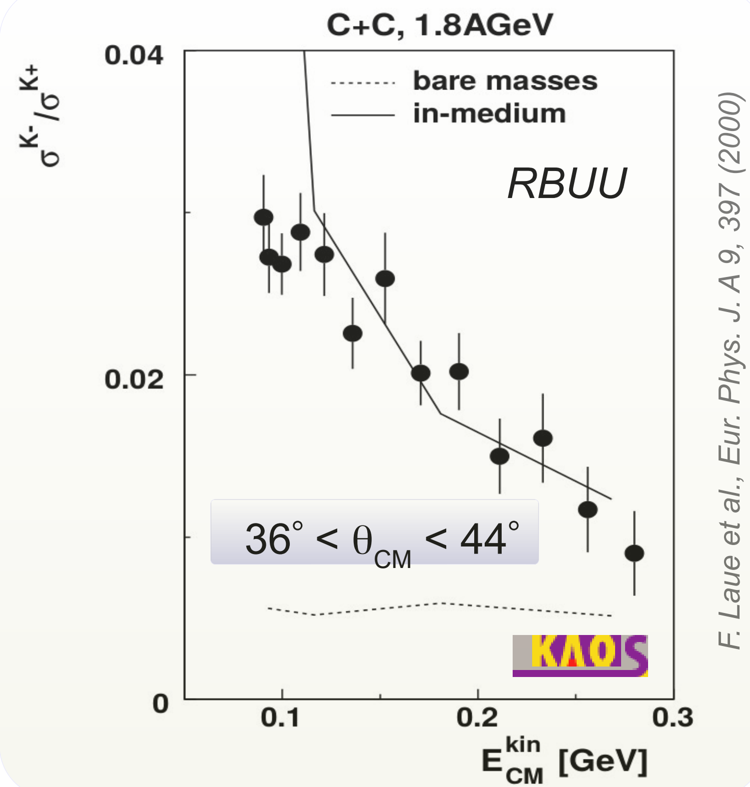

C.Hartnack et al., Phys Rep. 510, 119 (2012)

# $K^{-/+}$ emitted from heavy ion collisions

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

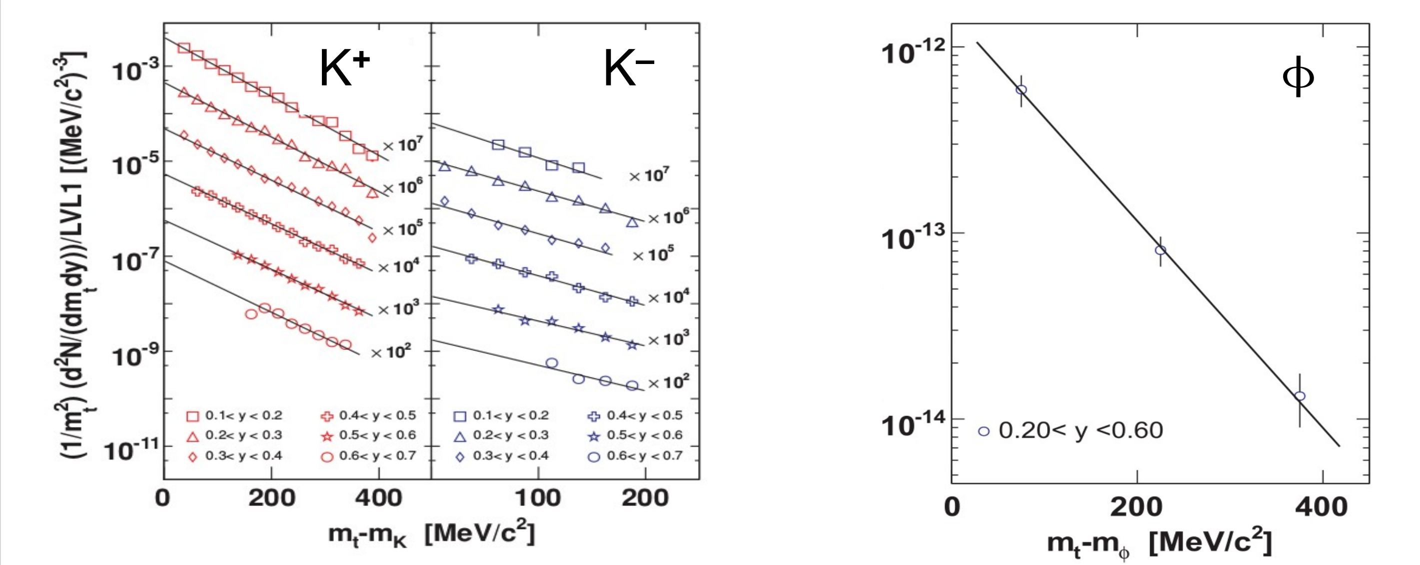



K. Wiśniewski et al., Eur. Phys. J. A 9, 515 (2000)




- Interpretation around year 2000: phenomenon *seems* to be confirmed
- … although probed in a very narrow slice of phase space.
- Statistics too limited to reach separate results ± uncertainties for $U_{K+N}$ i $U_{K-N}$ .

## $K^+$, $K^-$ and $\phi$ emitted from Ar + KCl @ 1.76*A* GeV: phase space distributions




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

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

### Fit of Boltzmann function to 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 | $T_{\mathrm{eff}}$ |
|---|---|---|
| $K^-$ | $(7.1 \pm 1.5 \pm 0.3 \pm 0.1) \cdot 10^{-4}$ | $69 \pm 2 \pm 4$ |
| $K^+$ | $(2.8 \pm 0.2 \pm 0.1 \pm 0.1) \cdot 10^{-2}$ | $89 \pm 1 \pm 2$ |
| $\phi$ | $(2.6 \pm 0.7 \pm 0.1^{+0.0}_{-0.3}) \cdot 10^{-4}$ | $84 \pm 8$ |

**Inverse slope for $K^-$ is lower than that for $K^-$ .**

( ↔ ratio of $K^-$ to $K^+$ drops with kinetic energy in CM) :

… similar conclusion as for KaoS & FOPI data @ 2000.

***Q*: Is it the result of (a) in-medium potentials or (b) $\phi \rightarrow K^-$ decays ?**

# Model of K⁻ emission from two sources

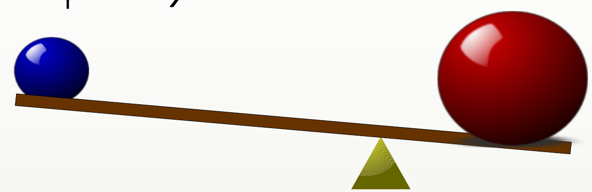
## Model assumptions:

1. Observed K⁻ originate from two sources:
   - directly from collision zone ( "*direct*" )
   - from ϕ meson decays in ϕ → K⁺ K⁻ channel (BR ≈ 50%)

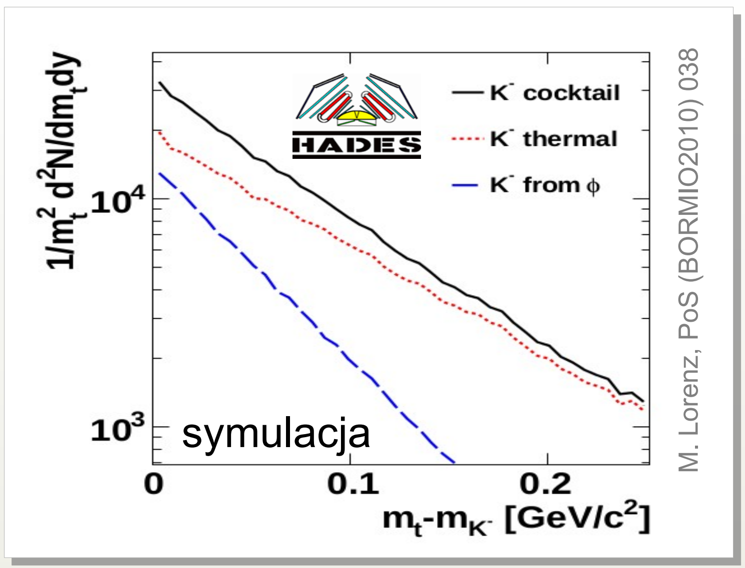
   in proportions obtained from experimental ϕ / K⁻ ration .
2. "*Direct*" K⁻ and K⁺ have the same "temperature".
3. ϕ mesons are emited with temperature obtained experimentally
   They subsequently decay into K⁺ K⁻ pair (PLUTO simulation).
4. We make cocktail of K⁻ from both sources – and check "temperature" of mixture

*K⁻ from ϕ decays*

*Direct K⁻*



*Total K⁻*




**Result: T (K⁻, cocktail) = 74 MeV**

Compared to Experimental *T* (K⁻) :

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

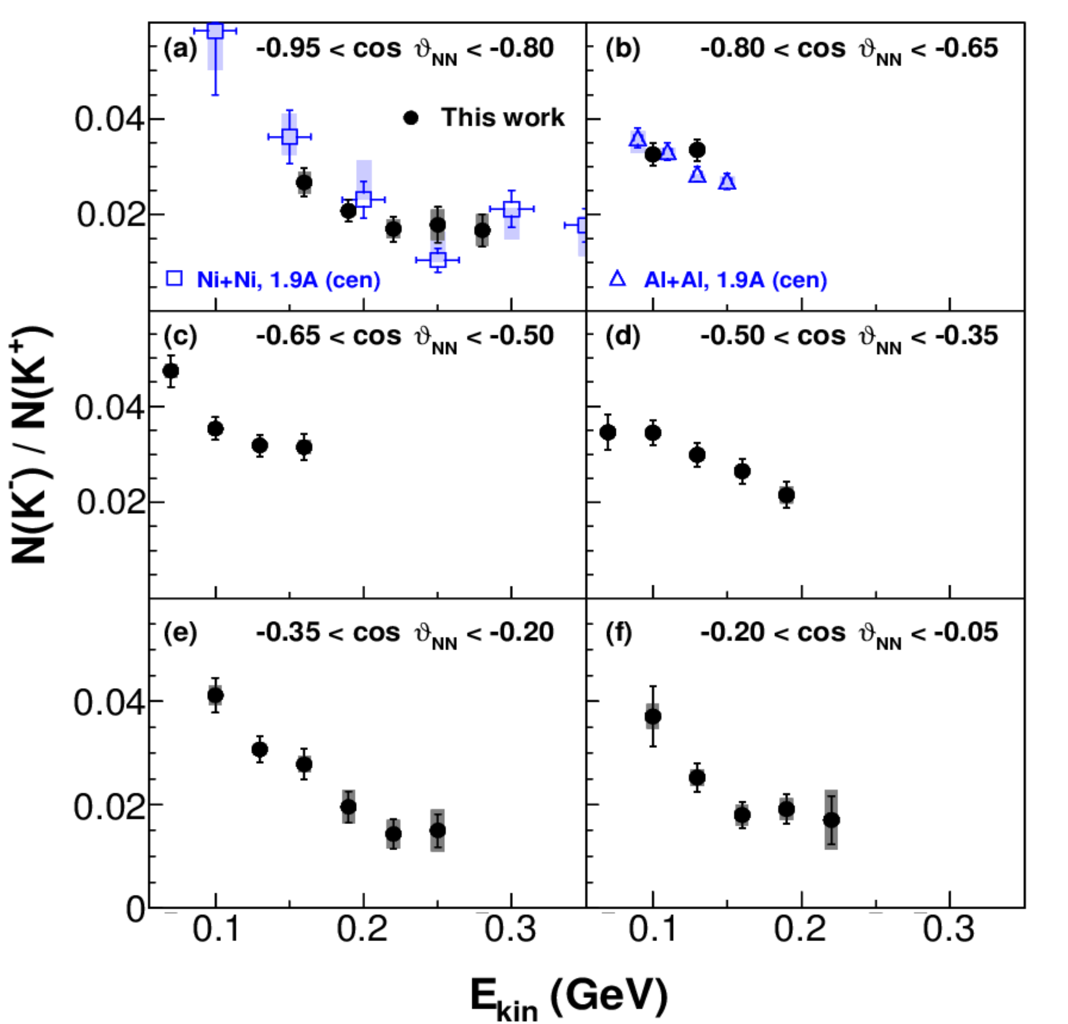
**Admixture of ϕ decays cools down the K⁻ spectrum.**

→ contributes to drop of K⁻/K⁺ ratio with energy

→ It is also possible, that ϕ feed-down (and not the medium) is the only effect responsible for K⁻/K⁺ ↘ $E_{kin}$ ...

# $K^{-/+}$ 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 $\phi$ mesons?

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

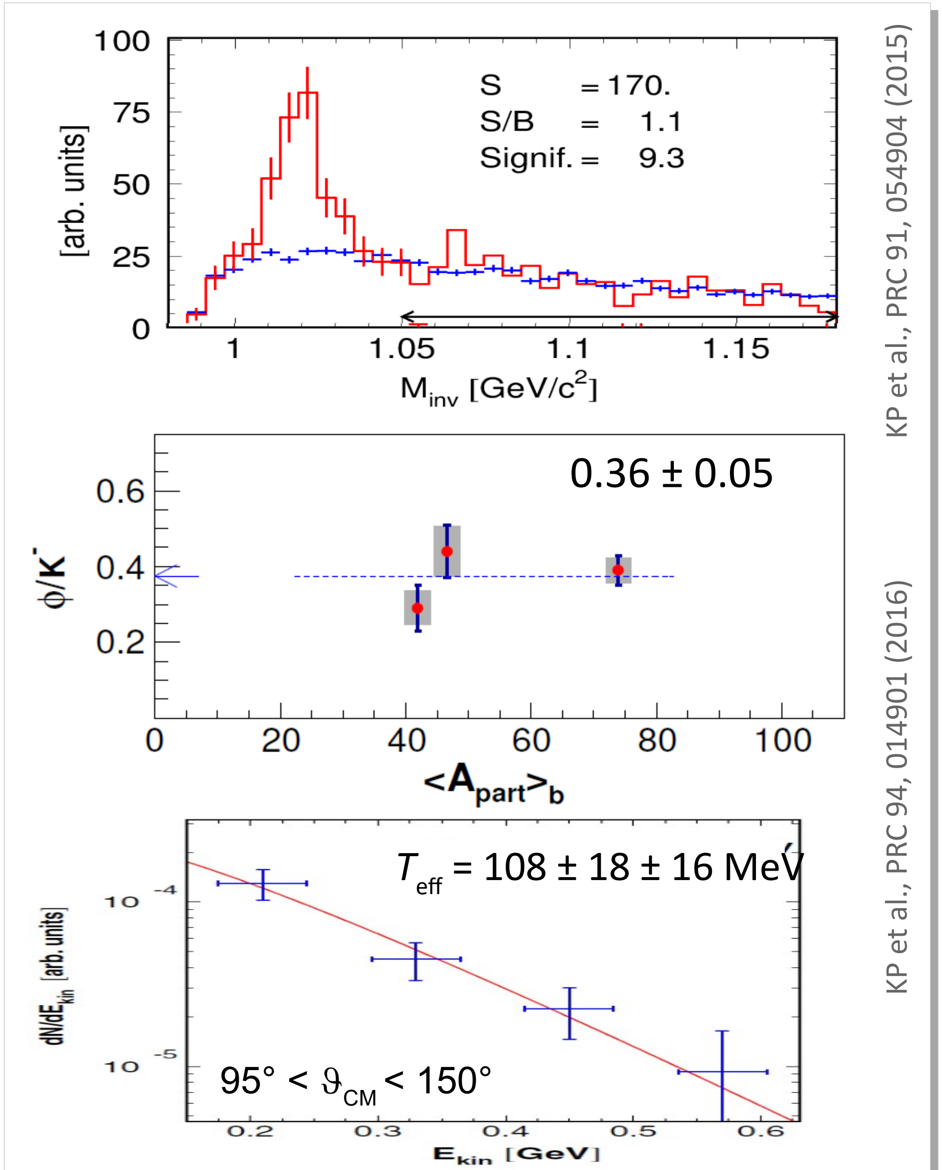
*For Al+Al @ 1.9A GeV see. :*
*P. Gasik et al (FOPI), EPJ A 52, 177 (2016)*

# Contribution of ϕ decays to K⁻ (recent data)

## ϕ mesons from AA collisions @ 1.9A GeV

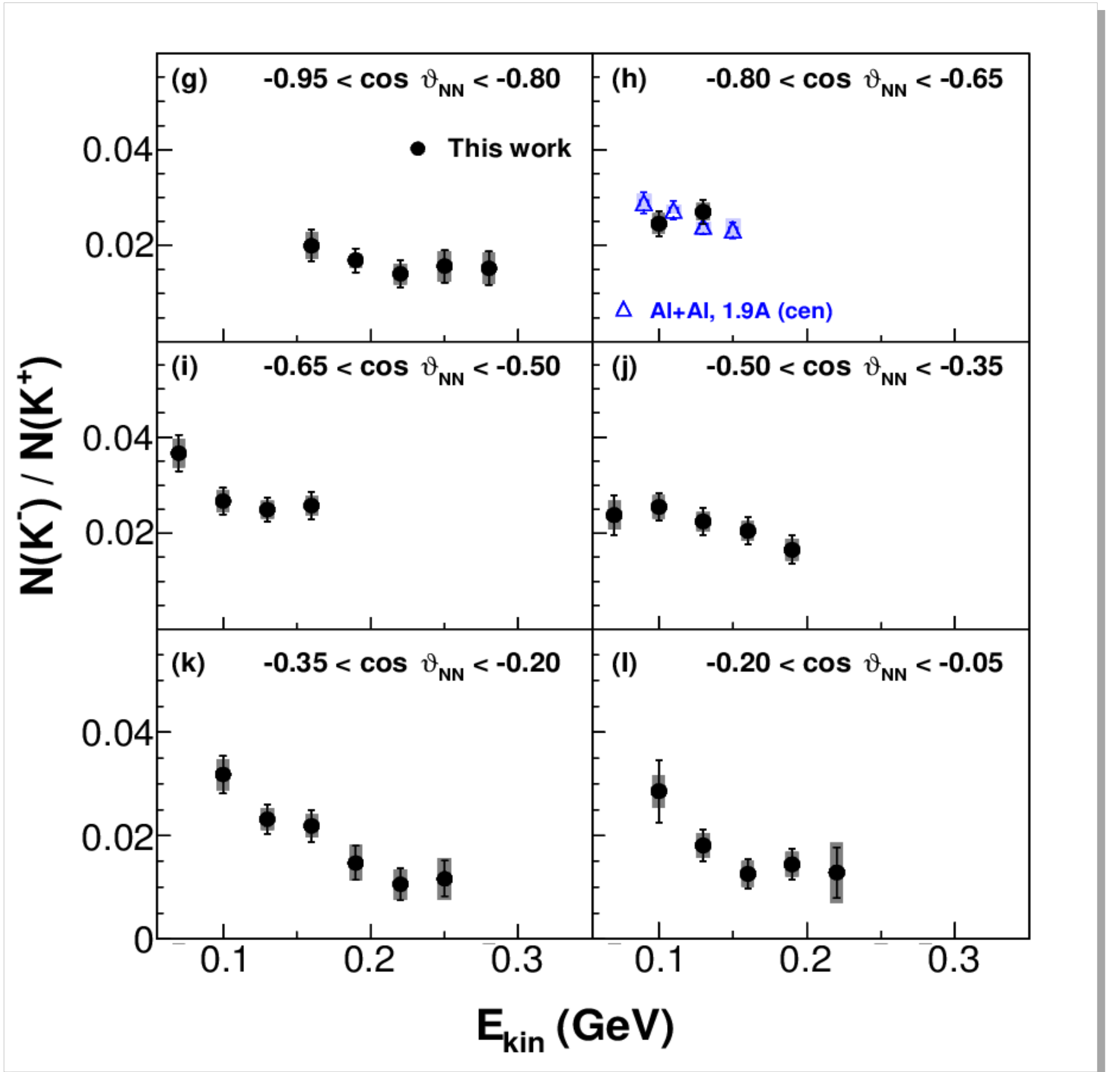
- Measured in $K^+K^-$ decay channel (BR = 50%) in 3 systems. Small samples (~150 events).
- Result: $\phi/K^- = 0.36 \pm 0.05$
- Since BR ($\phi \rightarrow K^+K^-$) ≈ 50% ,
- **About 18% of K⁻ originates from decays of ϕ mesons,** (different kinematics than for "direct")
- Energy spectra of ϕ mesons 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



# 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.

# Sub- and near-threshold Production of K⁻

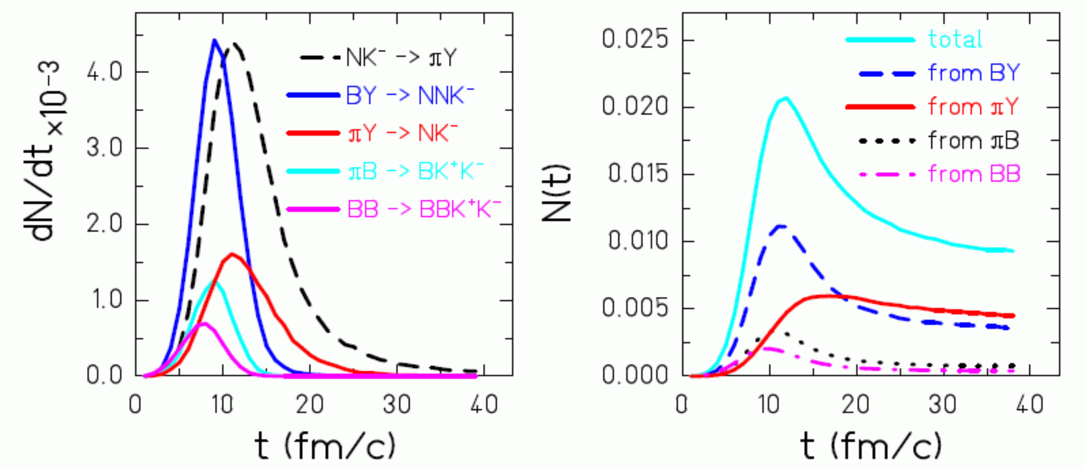
- in medium: mainly **strangeness exchange**:

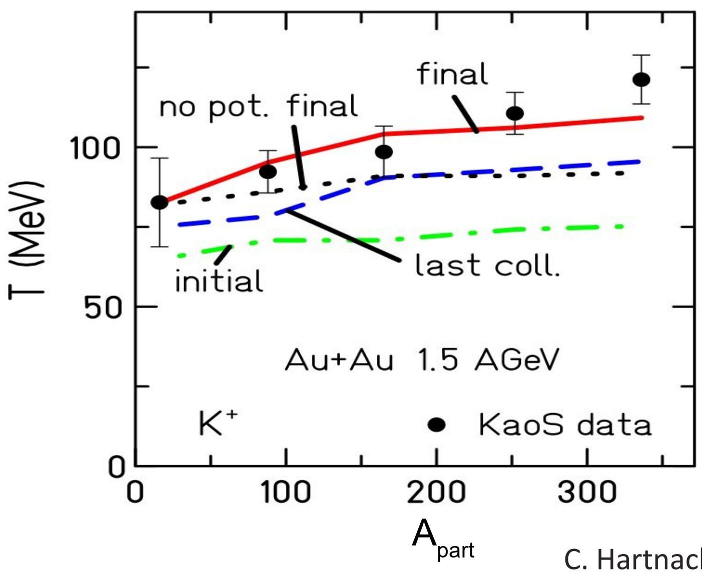
  $BY \rightarrow NNK^-, \quad \pi Y \rightarrow K^- B$

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

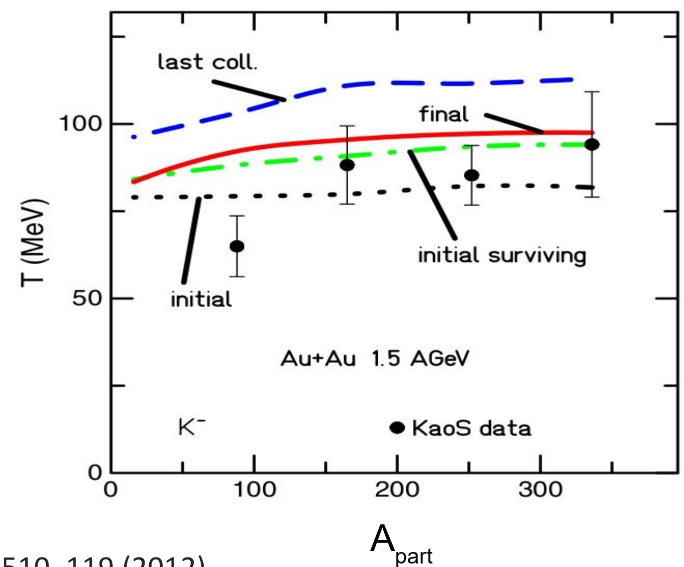
  $$\pi + Y \rightarrow \begin{matrix}\Sigma^* \\ \Lambda^*\end{matrix} \rightarrow K^- + B$$

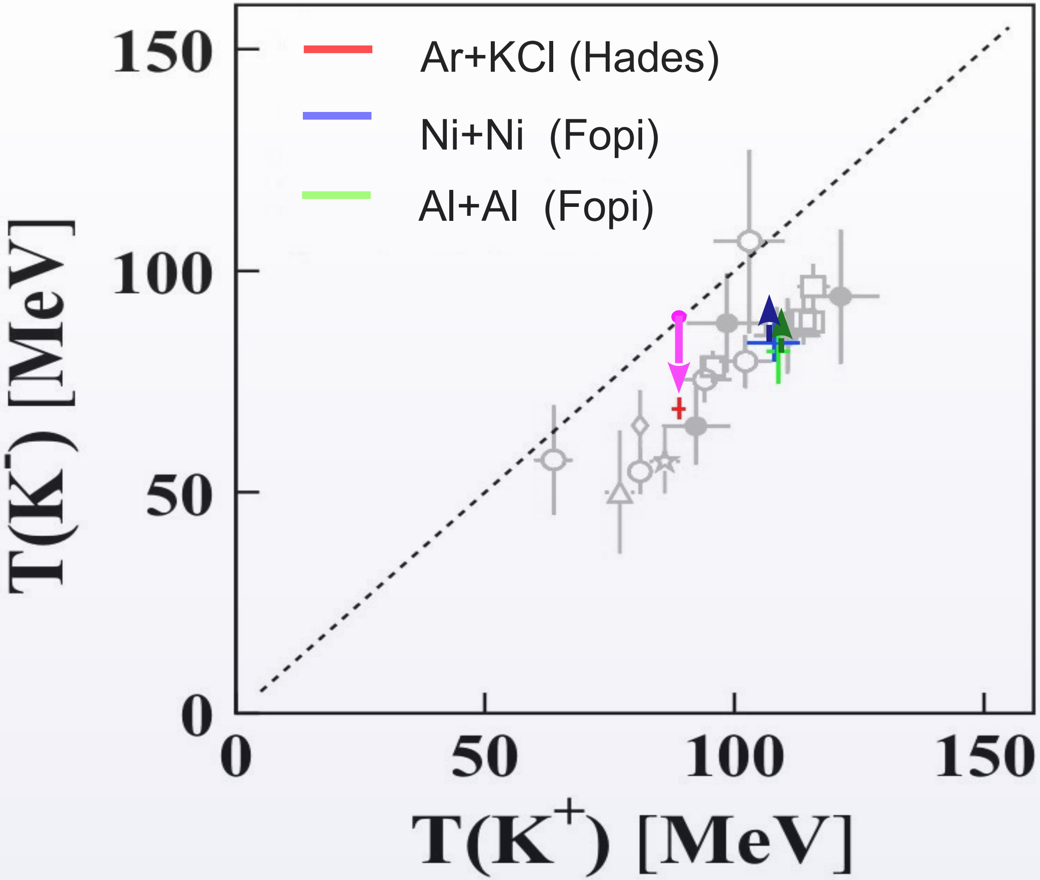
Au+Au @ 1.5A GeV (IQMD transport code)




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






*Previously*:

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

*Present studies:*

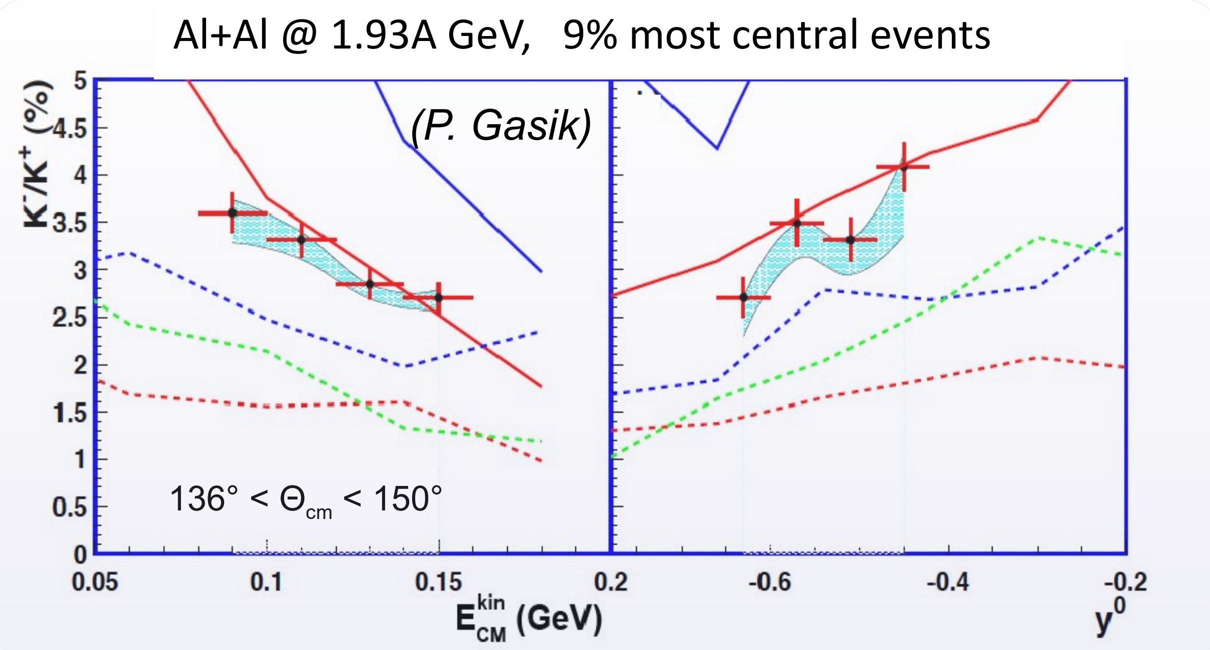
About 50% can be explained by $\phi \rightarrow K^+K^-$ decays

- $K^+$ : $U_{KN}$ 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 $\rho = \rho_0$
    $\Delta m_{K+}$ = 40 MeV, $\Delta m_{K-}$ = −100 MeV

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




IQMD, NO Pot.

HSD , NO Pot.

HSD, $U_{K+}$=40 MeV, K- Not Modified

HSD, $U_{K+}$=40 MeV, $U_{K-}$= G-Matrix

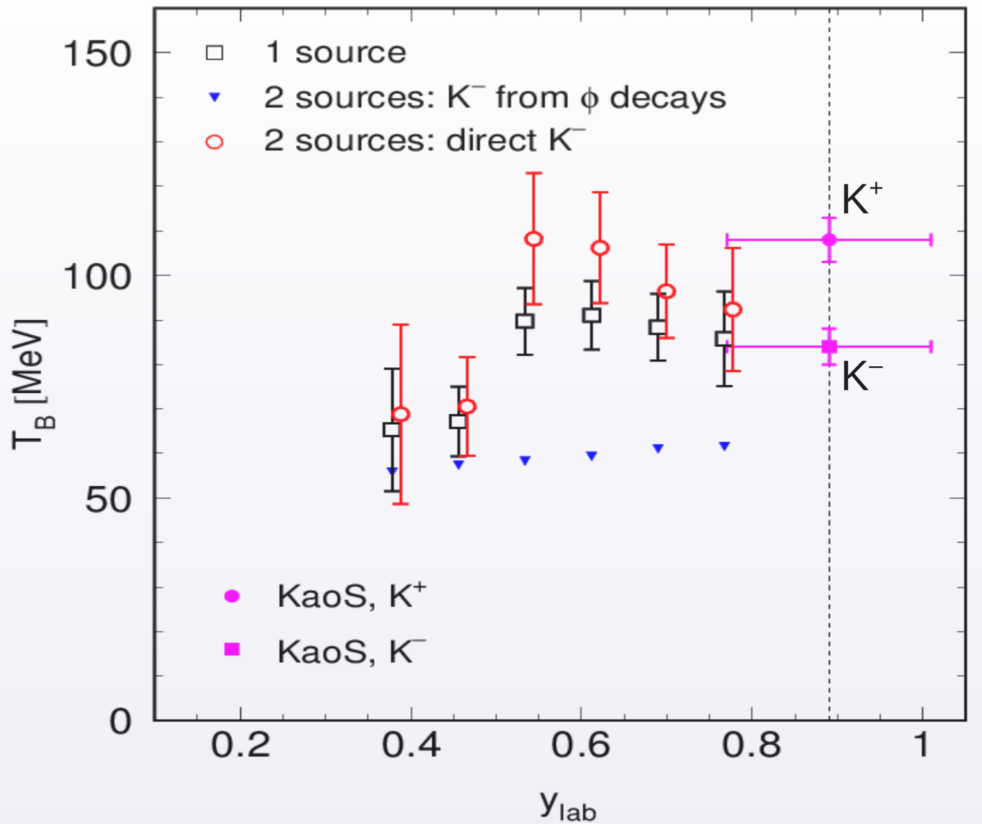
IQMD, $U_{K+}$=40 MeV, $U_{K-}$=-100 MeV

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

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

Experiment :

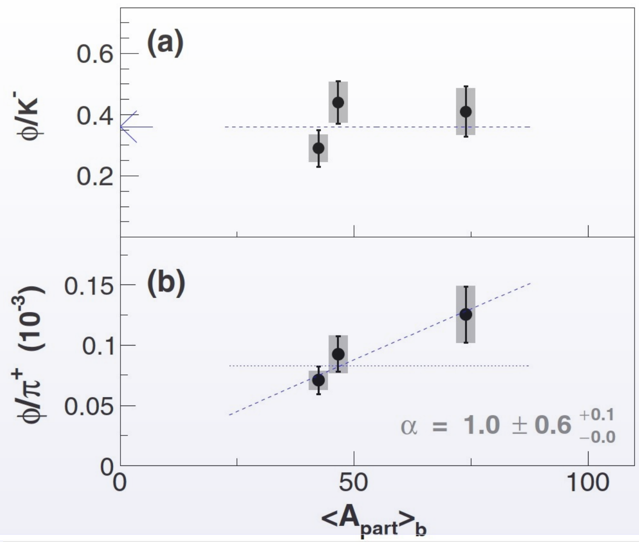
| Particle | $T_{eff}$ |
|---|---|
| | $84 \pm 4$ |
| | $108 \pm 5$ |
| | $106 \pm 18 \pm 16$ |




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

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

# φ yield compared to $K^-$

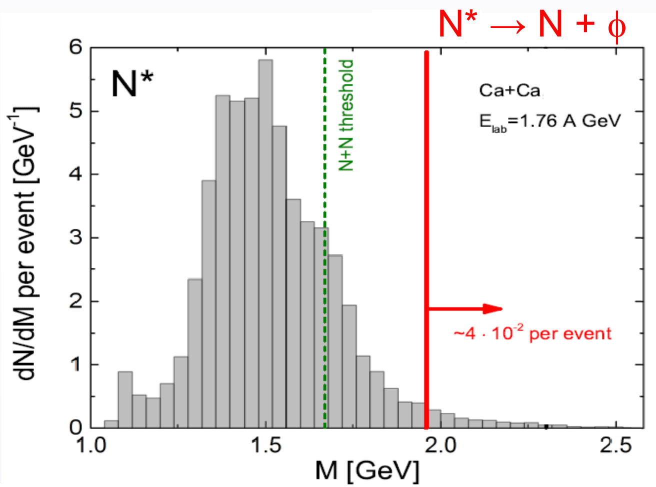


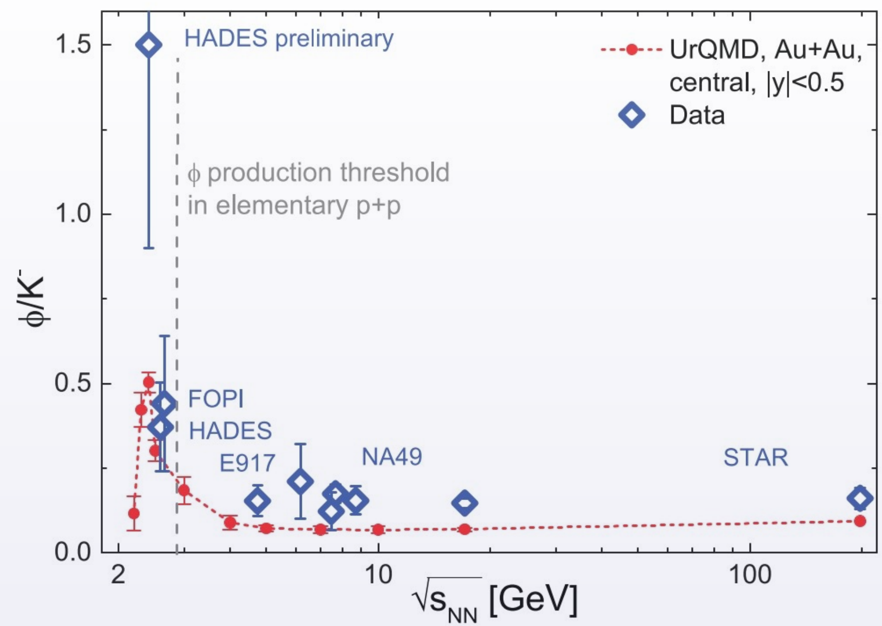

- $c\tau$ = 50 fm

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

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

- **UrQMD** model
  Resonance states <u>in medium</u>:




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