News on strangeness production from HADES and global systematics @ $\sqrt{s} \leq 3$ GeV

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- Why to study strangeness around threshold?
- Case of Au+Au at 1.23A GeV
- Case of π^- + W at 1.7A GeV/c
- Global strangeness systematics @ $\sqrt{s} \leq 3$ GeV
- Upcoming data from Ag+Ag at 1.58A GeV
- Summary and outlook

Motivation: strangeness around threshold

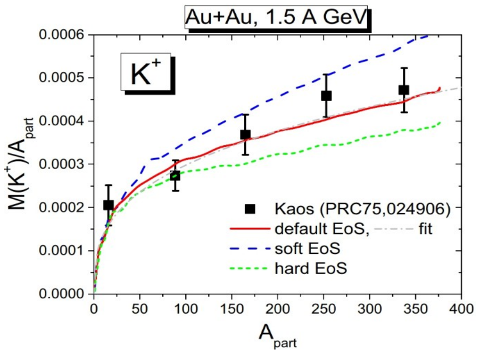
Strangeness production at energies below the NN threshold is a sensitive probe of the goodness of description of heavy ion collisions.

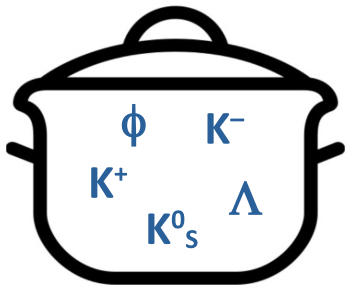
Types of reaction channels

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

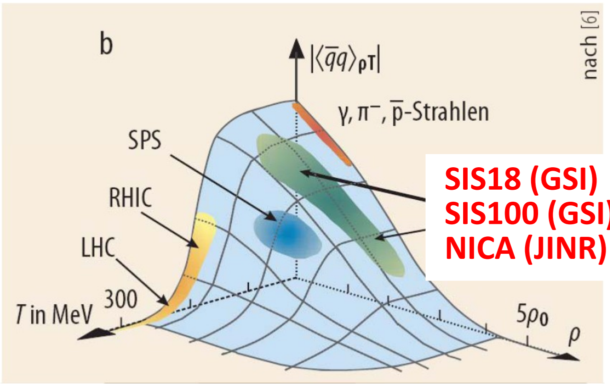
Equation of State

(K modulus, p-dependence?)





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



Decays into strange products:

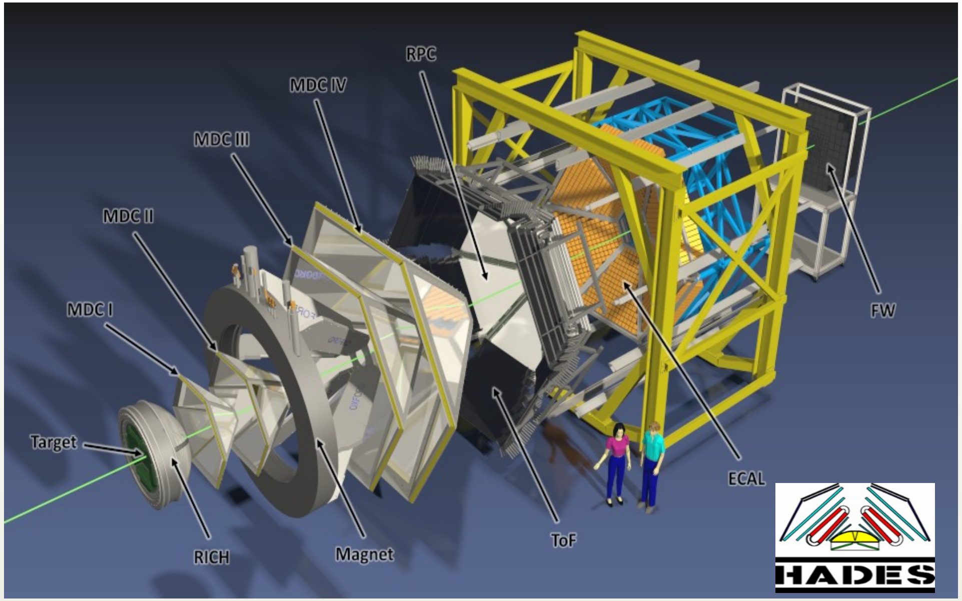
[K(892) → Kπ, ϕ → K⁺K⁻
B* → Nϕ , B* → KΛ]

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_{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 $\mathbf{K^0_s} \rightarrow \pi^+\pi^-$, $\mathbf{\Lambda} \rightarrow p\pi^-$, $\boldsymbol{\phi} \rightarrow K^+K^-$
  $^{3,4}{}_\Lambda H$ accessed via $\mathbf{^3{}_\Lambda H} \rightarrow {}^3He\,\pi^-$, $\mathbf{^4{}_\Lambda H} \rightarrow \alpha\,\pi^-$



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

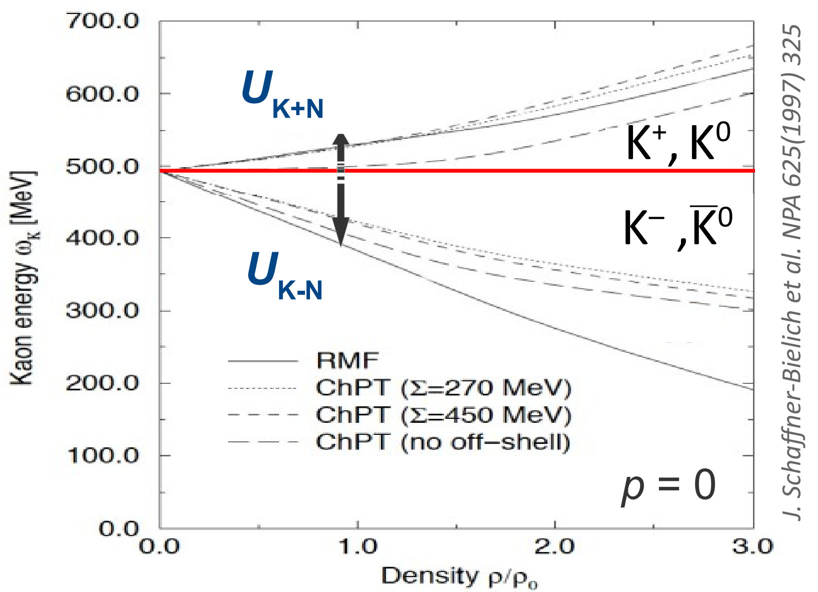
- Total No. of Events: 2.2×10^9
  Centrality: 40%
- Published data on:
  K^+, K^-, ϕ : *Adamczewski-Musch et al PLB 778, 403 (2018)*
  K^0_S, Λ : *Adamczewski-Musch et al PLB 793, 457 (2019)*

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

- Total No. of Events: 1×10^{10}
  Centrality: 70%
- Preliminary spectra:
  K^0_S, Λ : *S. Spies, EPJ WoC 259, 01007 (2022)*
  … analysis ongoing

Predicted changes of Kaon properties in medium

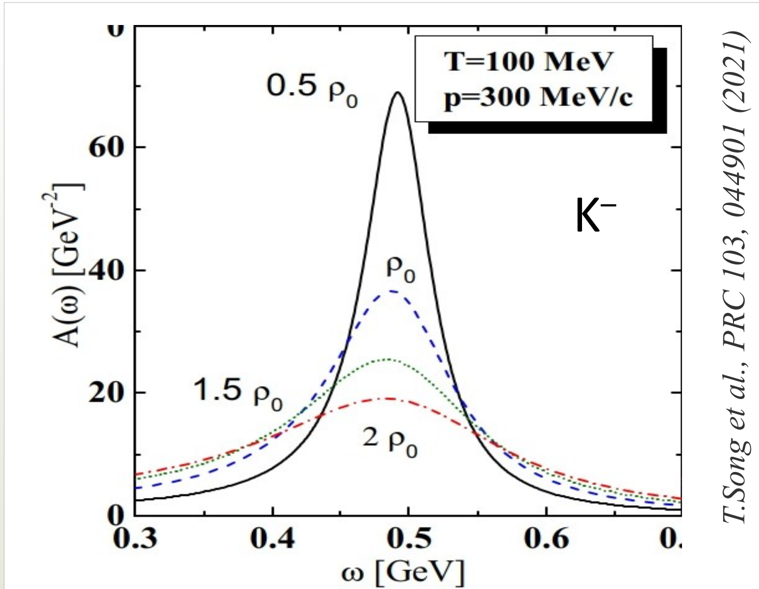
First approaches: **Potential**



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

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

"G-matrix" approach



Shift of mean + broadening

Model	K^+, K^0	K^-	Ref.
PHSD	mass rises linearly with density	T-Matrix *(coupled-channels)*	Song et al. PRC 106, 024903, 2022
IQMD	$U_{scalar} + U_{Vector} \to E$ rises with ρ	$U_{scalar} + U_{Vector} \to E$ drops with ρ	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 ρ	$U_{scalar} + U_{Vector} \rightarrow E$ drops with ρ	Hartnack et al, Phys.Rep. 510, 119,2012
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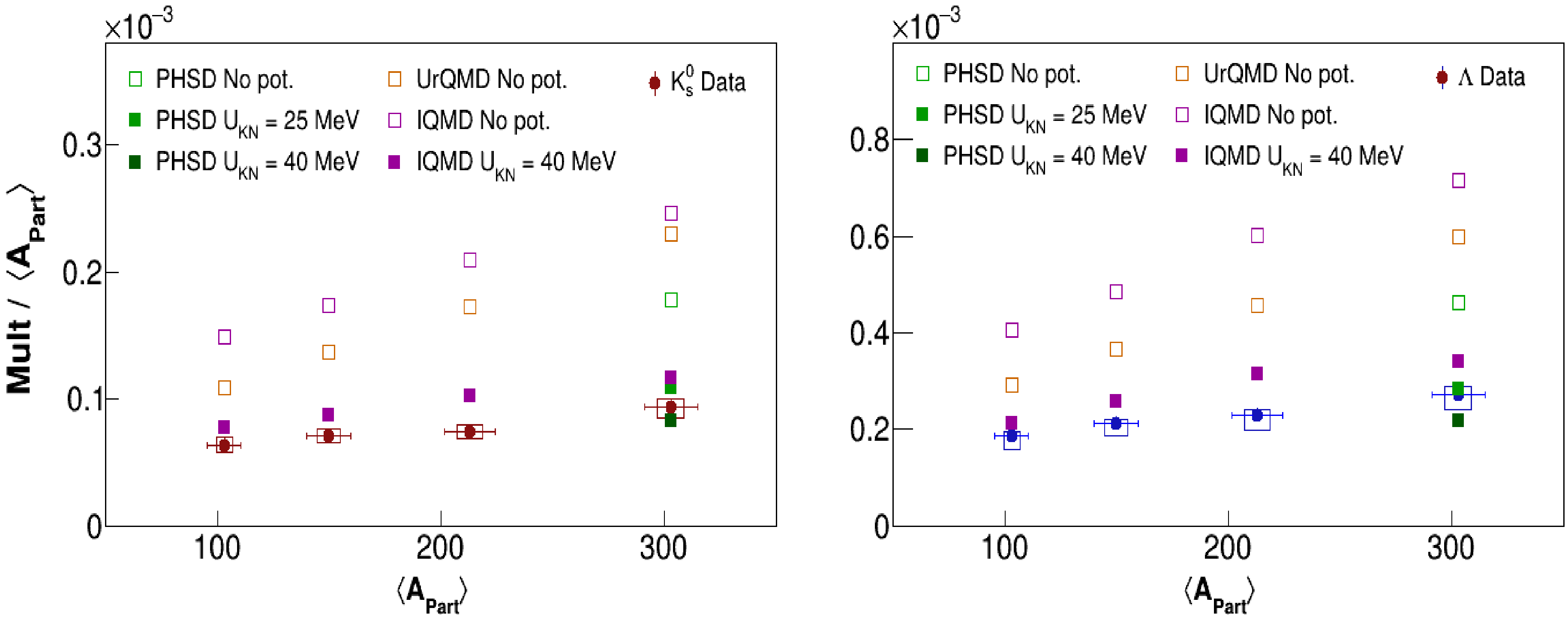
Comparing K^0 and Λ data to transport models
(Higher K^0 mass → raised threshold for K^0 & Λ production in leading channel $NN \to NK^0Y$)

Multiplicity of K^0_s and Λ vs centrality :



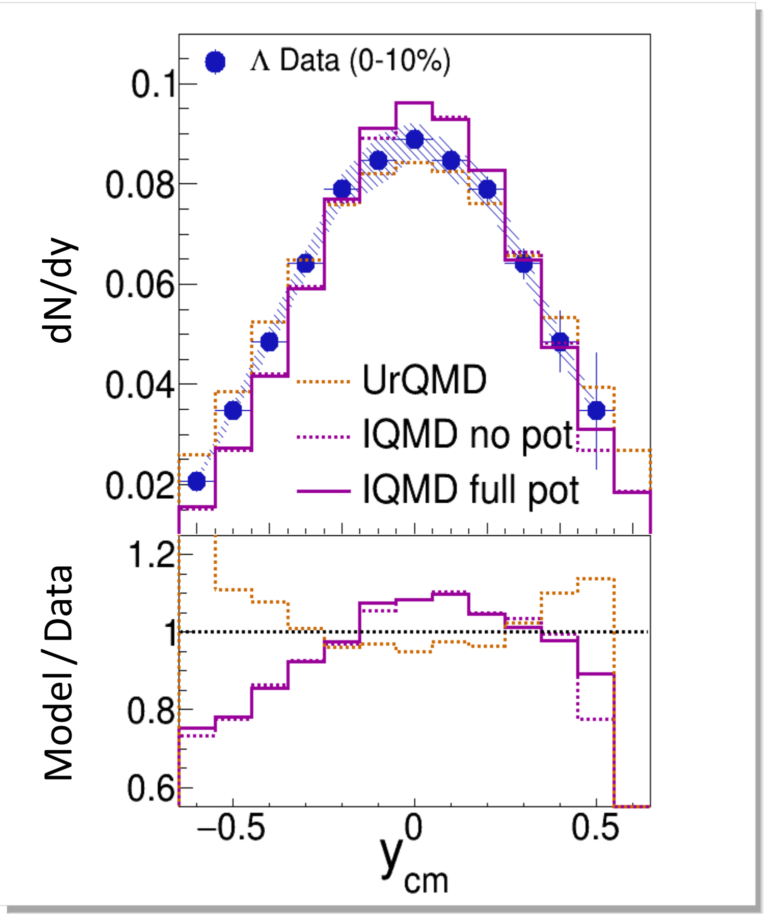
J. Adamczewski-Musch et al., PLB 793, 457 (2019)
T. Song et al., PRC 103, 044901 (2021)

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

PHSD: $U_{K0\,N} \sim +25 .. 40$ 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.

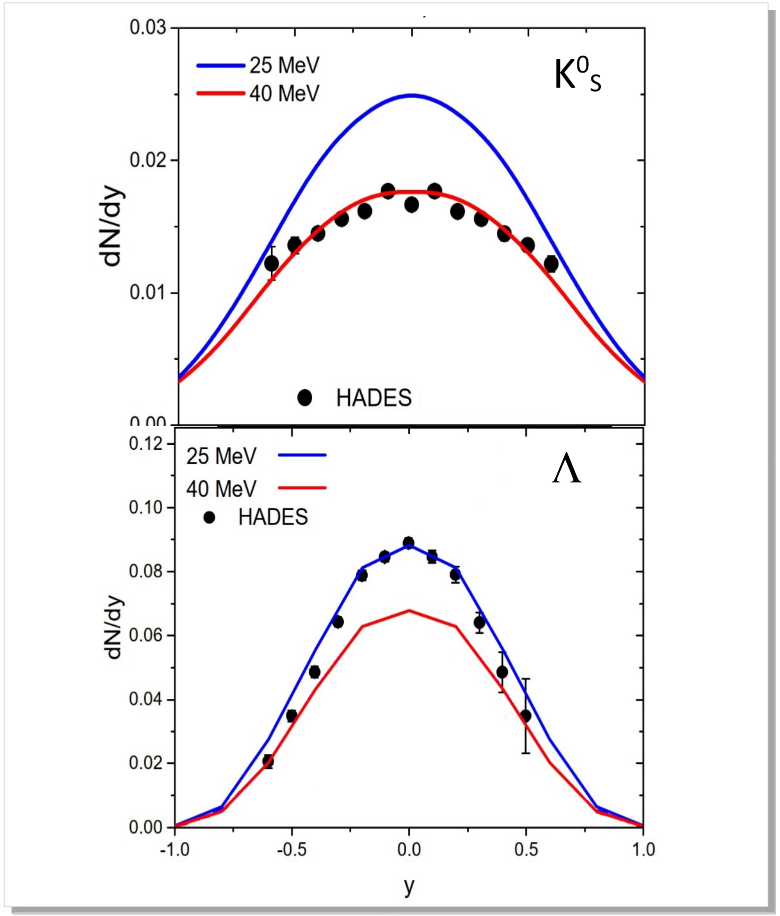
Rapidity distributions from Au+Au @ 1.23A GeV

- **IQMD** prediction for Λ (profile)



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

- **PHSD** prediction for K^0_S, Λ



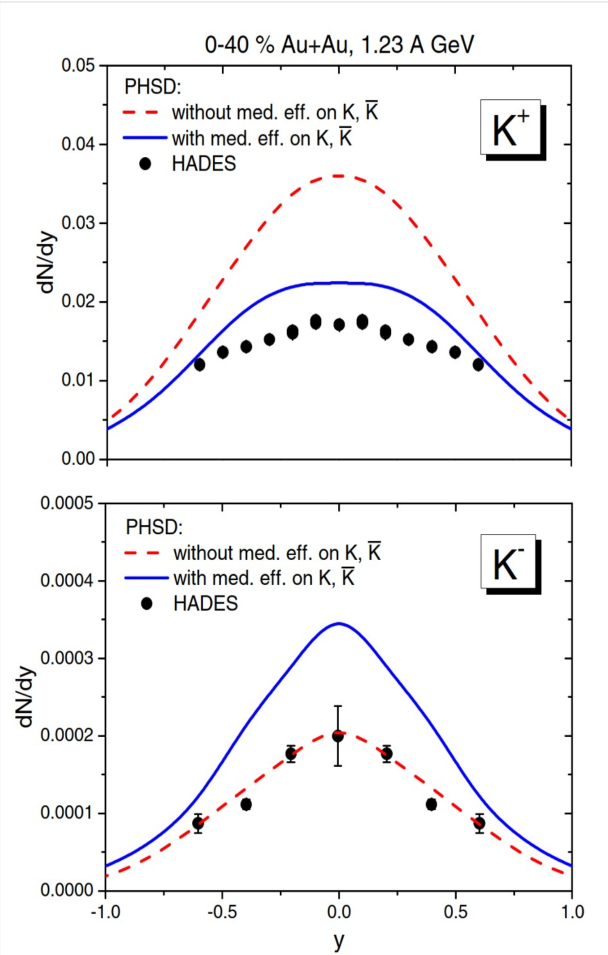
T.Song et al., PRC 103, 044901 (2021)

➡ $K^0_s \rightarrow U = +40$ MeV
$\Lambda \rightarrow U = +25$ MeV
Order of uncertainties

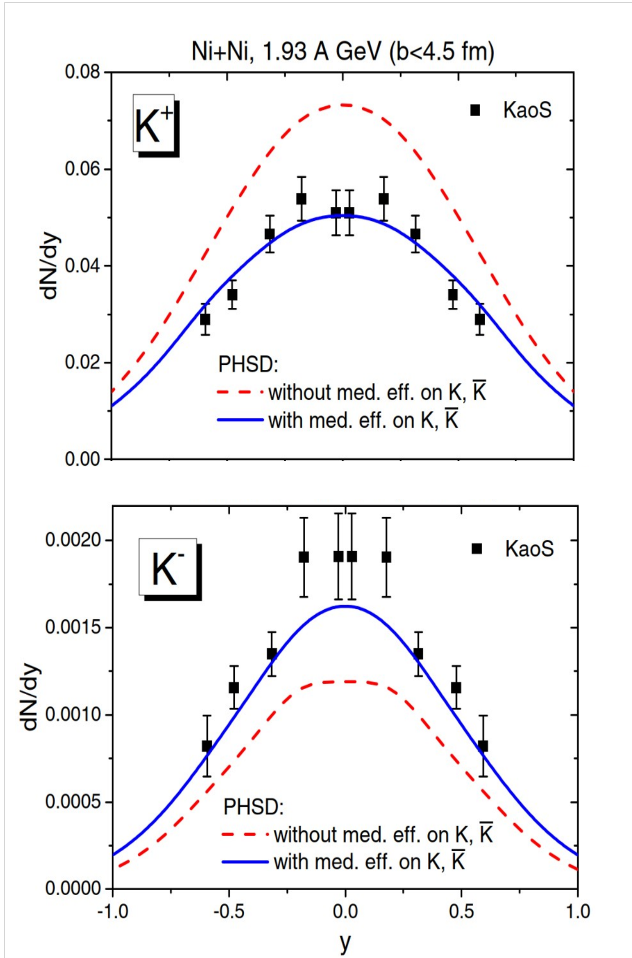
In-medium effects of $K^{+/-}$ within PHSD

T.Song et al., PRC 106, 024903 (2022)

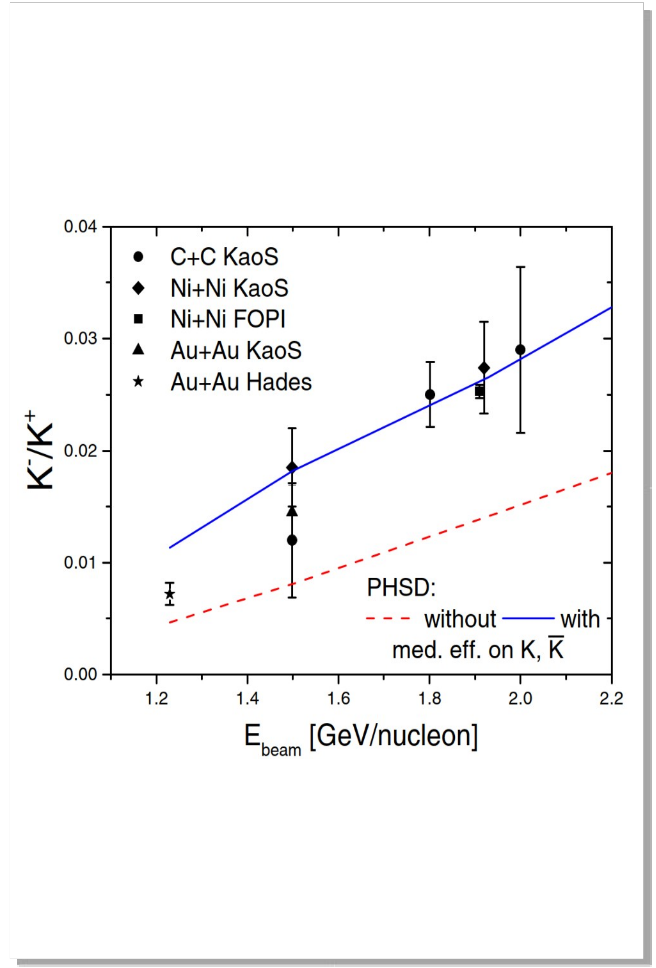
- Au+Au @ 1.23A GeV, centr 0..40%



- Ni+Ni @ 1.93A GeV, b < 4.5 fm



- K^-/K^+ as function of beam energy



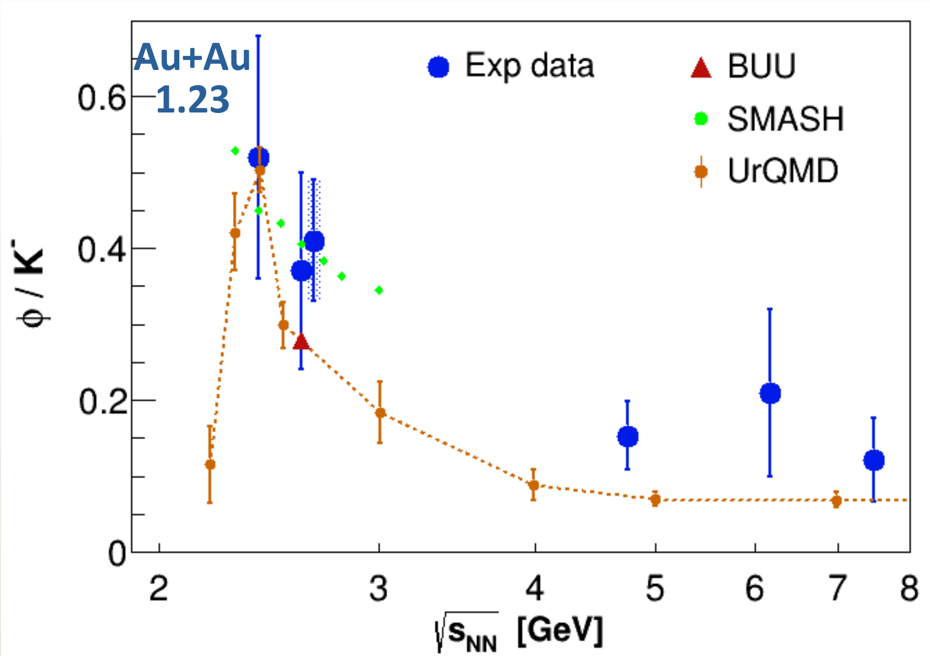
$K^+ \rightarrow U > +25$ MeV
$K^- \rightarrow U = 0$ MeV

$K^+ \rightarrow U = +25$ MeV
$K^- \rightarrow$ in-medium T-Matrix ✓

In-medium effects needed to reproduce K^-/K^+

Subthreshold ϕ mesons

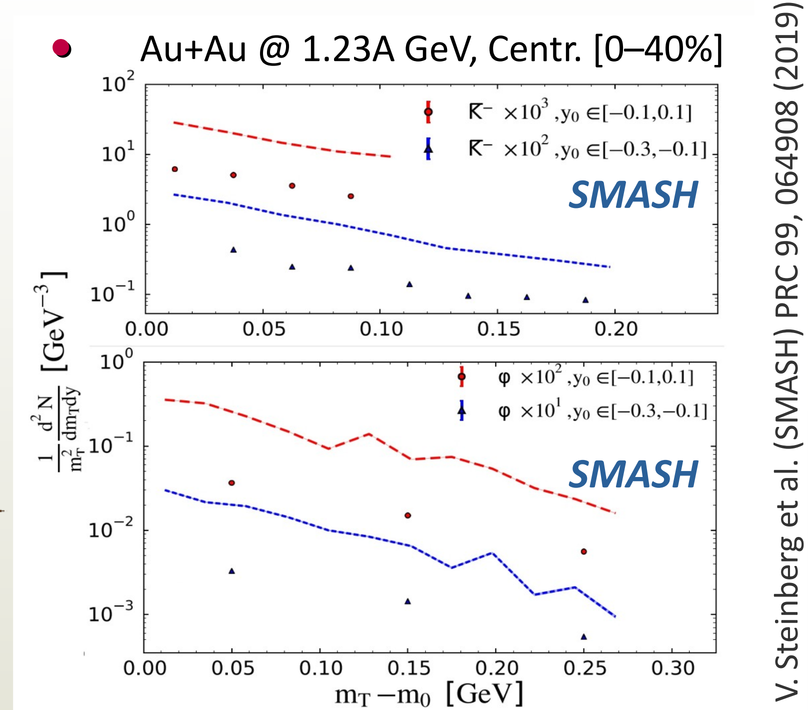
ϕ/K⁻ enhancement observed below threshold



- **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



V. Steinberg et al. (SMASH) PRC 99, 064908 (2019)

Testing ground for potentials

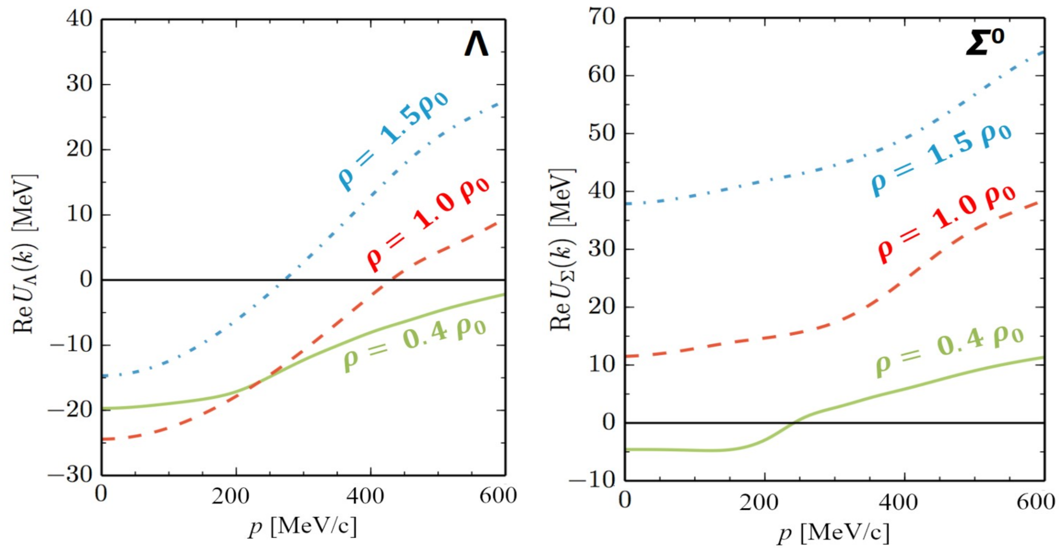
Consider **πN → KY** process.

- ***Standard scenario***:

  U_{K0N} : composition of scalar and vector potentials

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

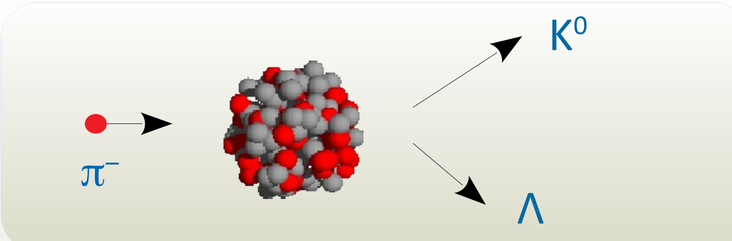
- ***χEFT NLO calculations***:
  - density-dependent
  - $U_{\Sigma N}$ mostly repulsive



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

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

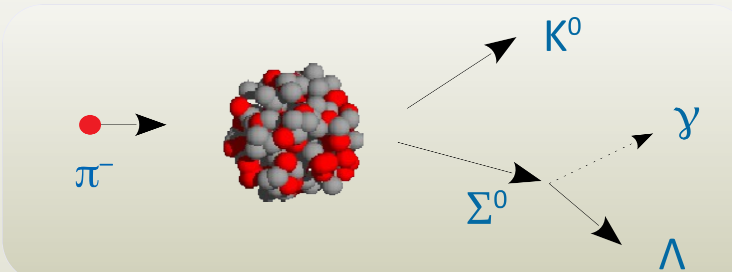
This modifies the kinematic distributions of K and Λ.



HADES experiment:

π^- (p = 1.7 GeV/c) + ^{184}W → $K^0 + \Lambda$ + ...

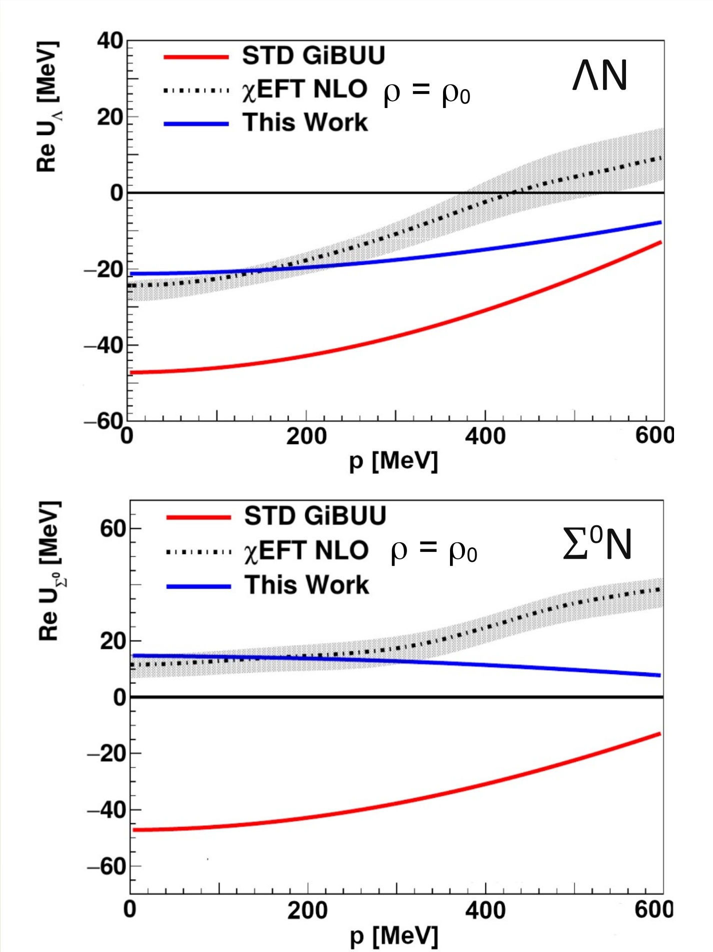
Tagging K^0 with Λ : limiting possible channels



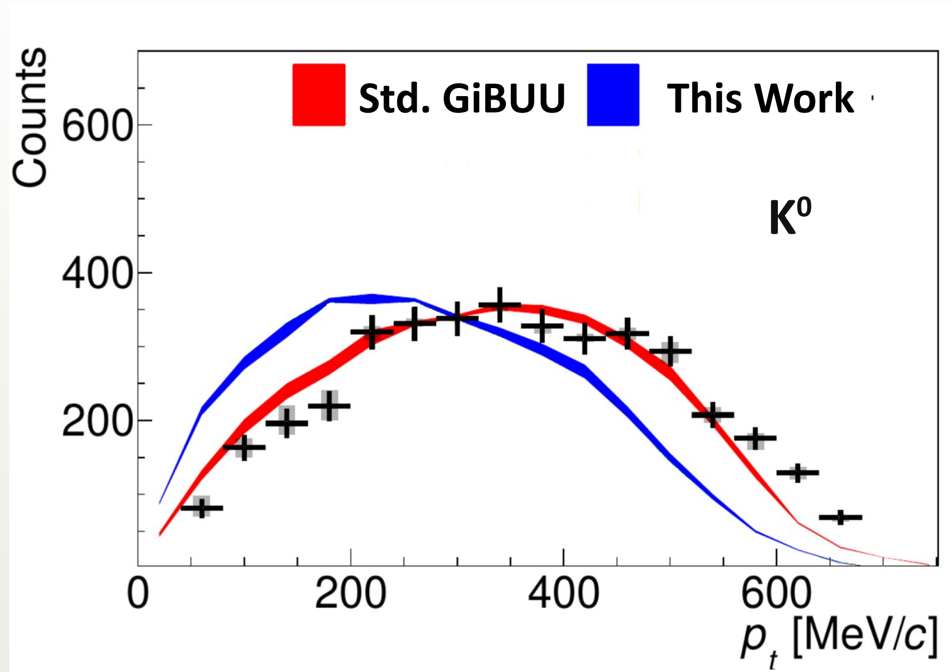
Testing ground for potentials

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.

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, Λ, K^- ... but not ϕ . 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 Λ NN $\rightarrow$ N K^{+0} Y $T_{Beam, Thr}$ = 1.6 GeV

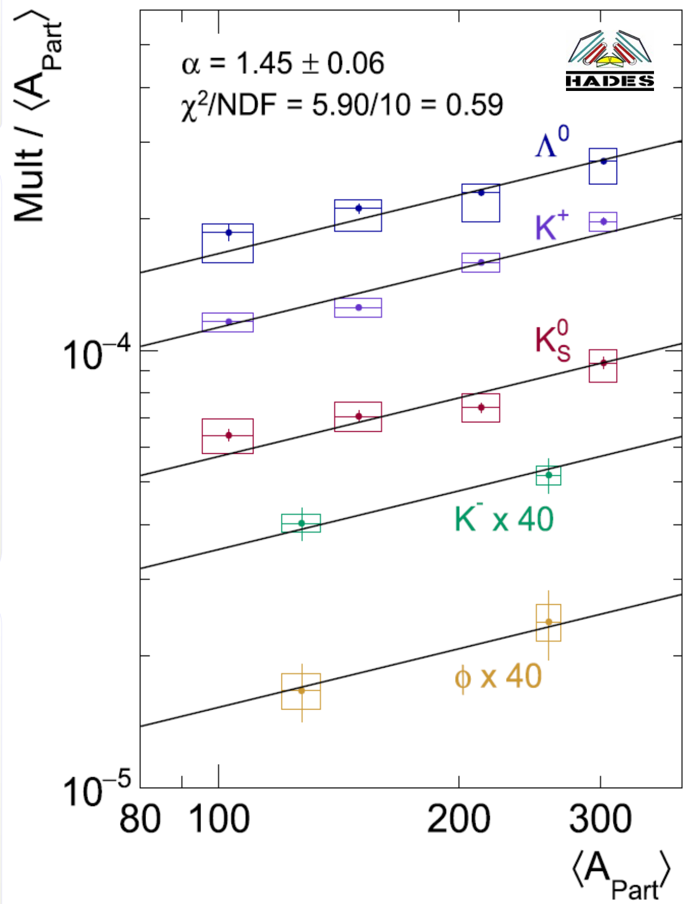
For K^- NN $\rightarrow$ NN K^+ K^- $T_{Beam, Thr}$ = 2.5 GeV

... leading channel πY $\rightarrow$ K^-N $\Rightarrow$ K^- follows $K^{+/0}$ and Λ

For ϕ , NN $\rightarrow$ NN ϕ $T_{Beam, Thr}$ = 2.6 GeV

ϕ much more under threshold than the others.

should rise stronger with $\langle A_{part} \rangle$ ... but does not!



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

Hypothesis

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

Global systematics of strangeness production @ $\sqrt{s} \leq 3$ GeV

About 90 published yields of $K^{+,-,0}$, ϕ, Λ at $\sqrt{s} \leq 3$ GeV. Time to try systematics: $P = f(\sqrt{s}, \langle A_{part} \rangle)$.

Problem with published $\langle A_{part} \rangle_b$ E.g. for K^+ :

- Ⓐ 30 values from geometrical model (all Fopi and AGS, some KaoS data)
- Ⓑ 10 values from optical Glauber model (D. Miśkowiec) (some KaoS data)
- Ⓒ 4 values from Glauber Monte Carlo (Hades Au+Au 1.23A GeV)

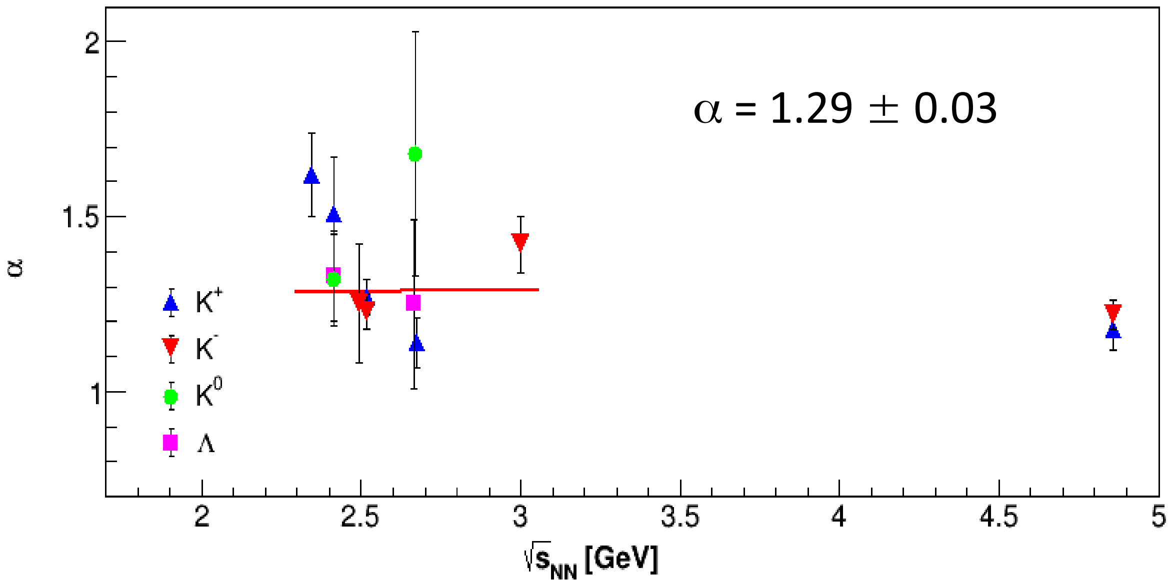
Approach: use published centralities and perform Glauber MC to extract $\langle A_{part} \rangle_b$.

Let's examine α in $P \sim \langle A_{part} \rangle^{\alpha}$.

Stacking together $K^{+/-/0}$ and Λ ,

$\Rightarrow$ α as $f(\sqrt{s})$ seems to **be stable**

and agrees with AGS data @ $\sqrt{s_{NN}}$ = 4.9 GeV.

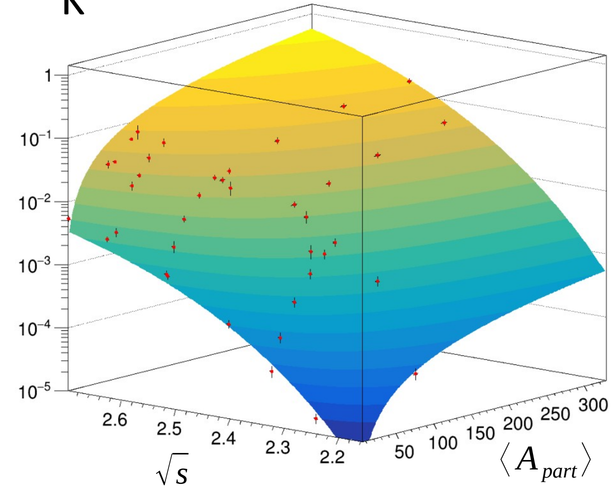


Global systematics of strangeness production @ $\sqrt{s} \leq 3$ GeV

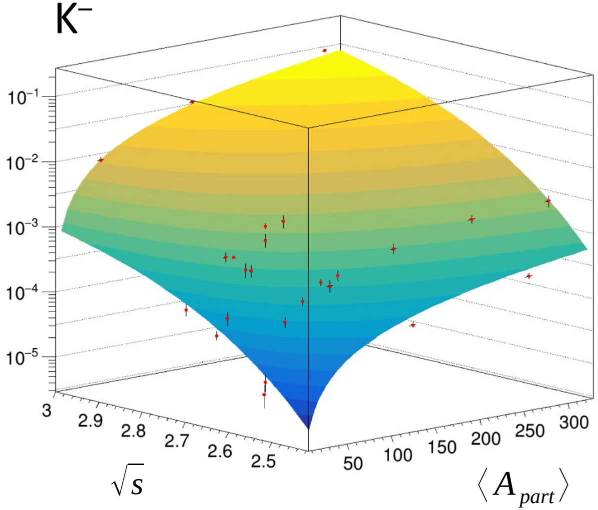
Best-fit function: $P = 10^{N} \cdot \langle A_{part} \rangle^{\alpha} \cdot \exp\left(-\frac{Const}{\sqrt{s}^{\beta}}\right)$, *Const* adjusted for each hadron

Hadron	K^+	K^-	K^0	Λ	ϕ
No. points	39	25	10	12	9
χ^2/ν	3.4	2.1	3.0	1.6	0.1
N	-2.52±0.05	-3.63±0.07	85.3±0.4	-2.98±0.08	-4.6±0.2
α	1.31±0.02	1.29±0.03	1.22±0.05	1.15±0.04	1.27±0.12
β	6.21±0.02	6.67±0.02	0.119±0.004	17.21±0.04	10.50±0.05
Const	1100	2450	230	9 000 000	55 000

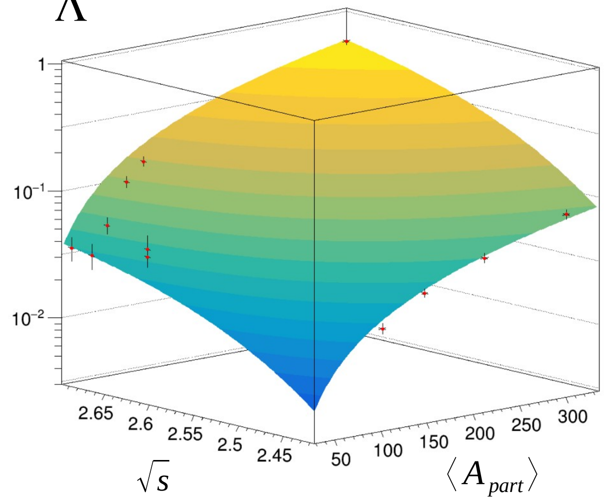
K^+



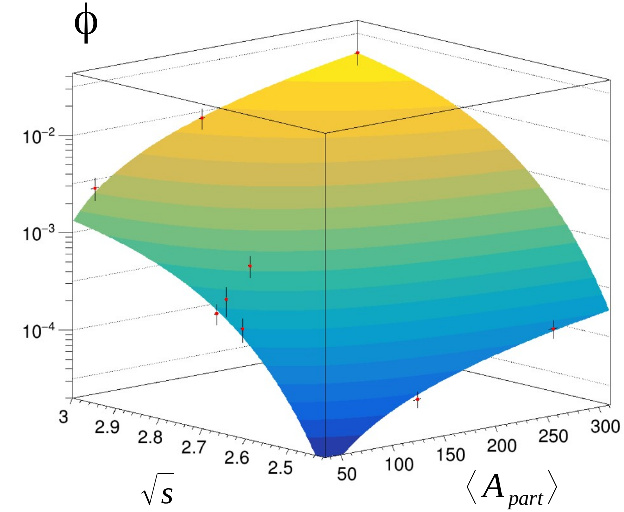
K^-



Λ

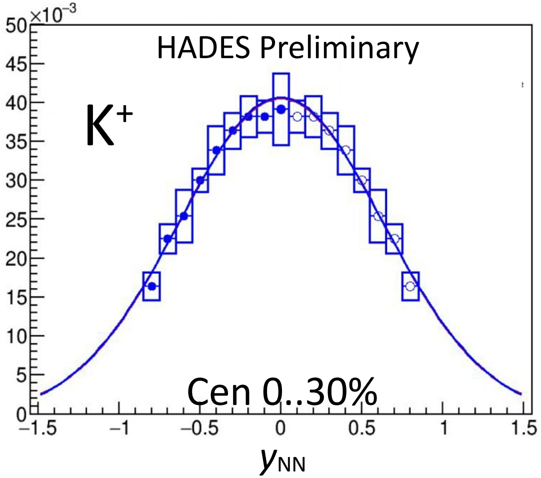


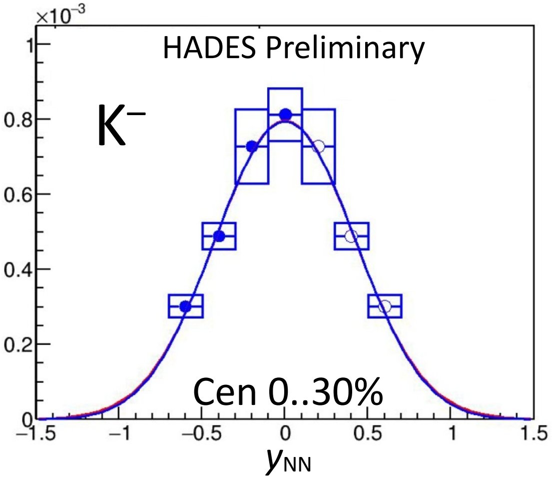
ϕ

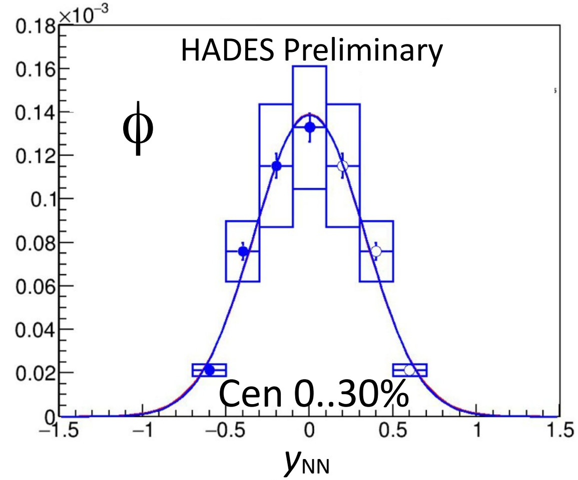


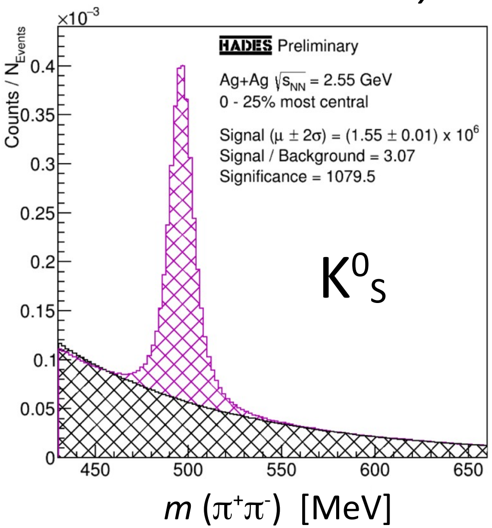
Strangeness reconstruction from Ag+Ag @ 1.58A GeV

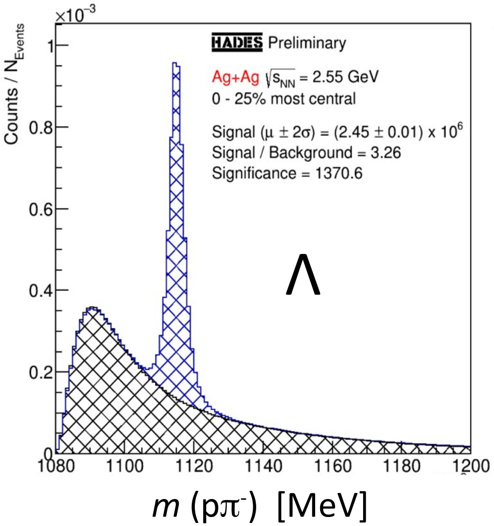
Ag+Ag @ 1.58A GeV. Statistics: ~10 G events. Centrality: 0 .. 70%

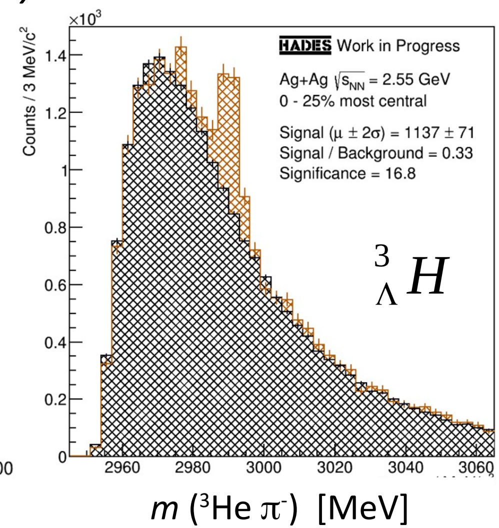


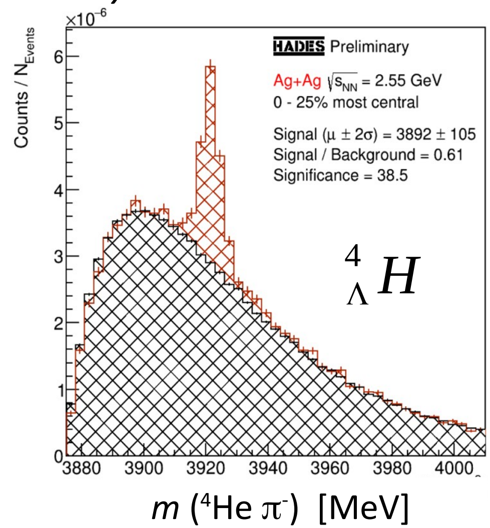












m_T spectra of K^0_S, Λ : *S. Spies, EPJ WoC 259, 01007 (2022)*
dN/dy of ϕ compared to PHSD : *T. Song et al. PRC 106, 024903 (2022)*

… work in progress ✈

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, Λ, ϕ emitted from **Au+Au @ 1.23A GeV**.

- Findings: **PHSD**, **IQMD**, **UrQMD** calculations suggest that in-medium changes of K^0, Λ properties help in description of K^0_s and Λ.

- **PHSD**:
  - comparison to K^0 data: → $U_{KON}(\varrho_0, p = 0) \approx +40$ MeV
  - comparison to Λ data: → $U_{KON}(\varrho_0, p = 0) \approx +25$ MeV
  - comparison to K^+ data: $U_{K+N}(\varrho_0, p = 0) \gtrsim +25$ MeV
  - comparison to K^- data: Sometimes no in-medium, sometimes reproduction.

- **ϕ / 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: $\pi^- W \rightarrow K^0 \Lambda X$ @ $p = 1.7$ GeV/c.
  - **GiBUU**: "Old" $U_{\Lambda N, \Sigma N} = \frac{2}{3} U_{NN}$ **scenario wins** over χEFT NLO: overall less attractive.

- **Global systematics of K^{+-0} Λ ϕ yields** @ $\sqrt{s} \leq 3$ GeV available. Global $\alpha = 1.29 \pm 0.03$ [stable as f($\sqrt{s}$)]

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