Properties of strange hadrons in vacuum and cold nuclear matter

Laura Fabbietti, Technische Universitaet Muenchen

Data -> HADES At SIS18, GSI

Analysis of the data and tuning of the transport codes:

TECHNISCHE UNIVERSITÄT MÜNCHEN

HISKP

Petersburg Nuclear Physics Institute

JUSTUS-LIEBIG-UNIVERSITÄT GIESSEN

FIAS Frankfurt Institute for Advanced Studies

Andrej Sarantsev

Theodor Gaitanos

Janus Weil

Energy Regime

Proton Energy [GeV]	1-4	30	
Heavy Ion Energy [AGeV]	1-2	2-10	$\sqrt{s} = 4 - 11\, GeV$
	At SIS18	At SIS100	

Purpose: Creation of Compressed baryonic matter
ρ up to 5-6 ρ_0??

Content

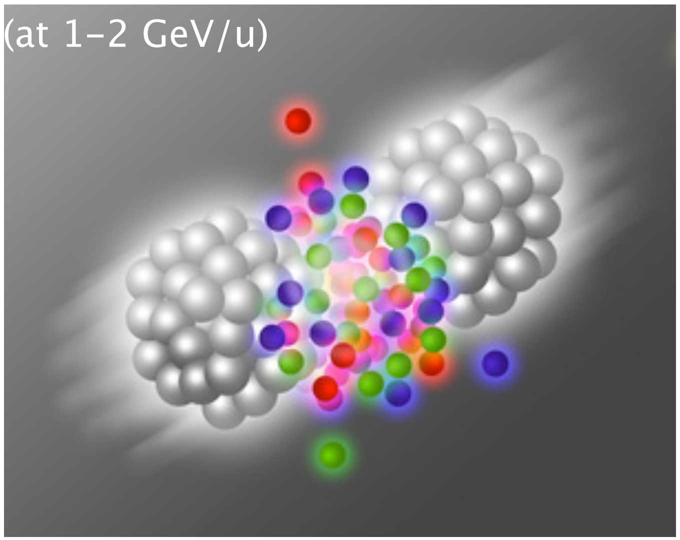
- Role of resonances in strangeness production in p+p collisions at 3.5 GeV
- K0s properties in cold nuclear matter p+Nb at 3.5 GeV

How to understand HIC in the GeV regime

Examine strangeness in nuclear matter in the lab (HADES experiment, GSI, Darmstadt)

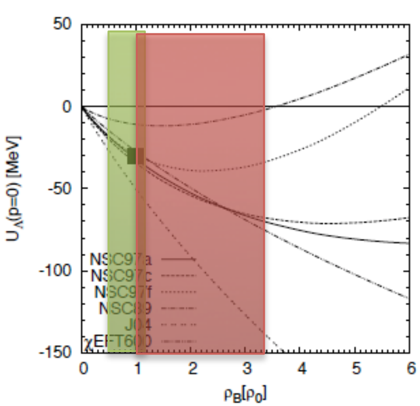
Heavy-ion collisions $\rho_B \leq 2\text{–}3\rho_0$

(at 1–2 GeV/u)



Vienna University of Technology

- N-N primary reactions
- πN, ΔN secondary reactions
- Resonance Excitation
- Propagation of particles through nuclear matter
- Scattering and Absorption
- In-Medium Spectral Function
- Mean field Approaches

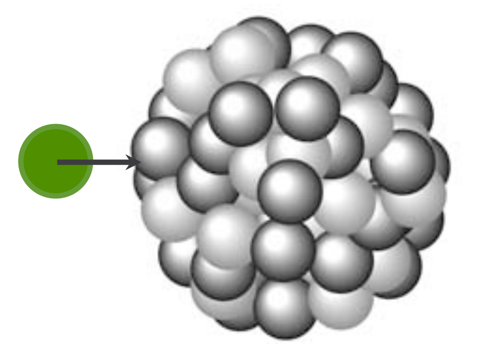


H.Dapo et al. EPJ A **36**, 101 (2008)

Λ(1116)

proton–proton

proton/pion Nucleus $\rho_B \leq \rho_0$



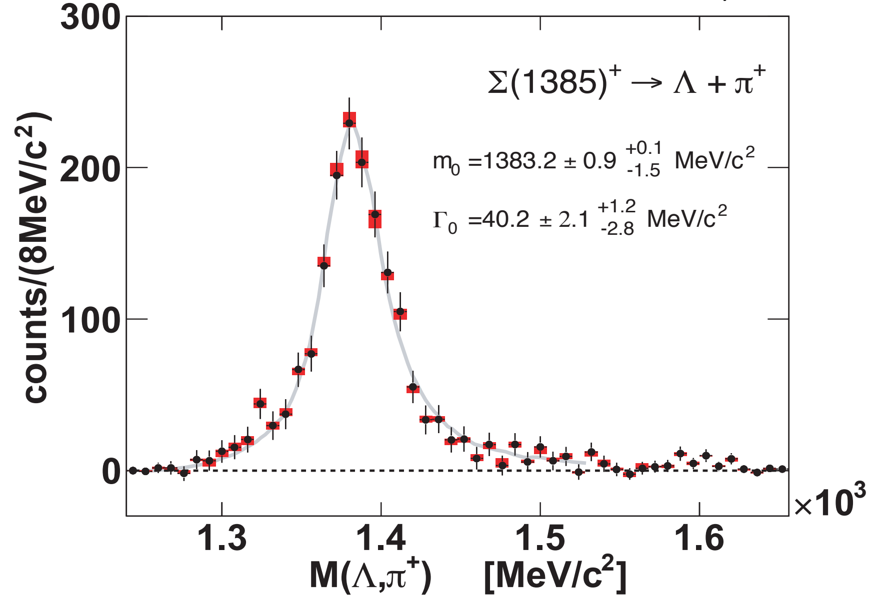
Role Played by Resonances at intermediate Energies: I

$$p + p(@3.5\,GeV) \rightarrow$$

$$\Sigma(1385)^{+} + K^{+} + n$$

$$\Lambda + \pi^{+}$$

HADES Phys.Rev. C85 (2012) 035203 PDG Entry 2012

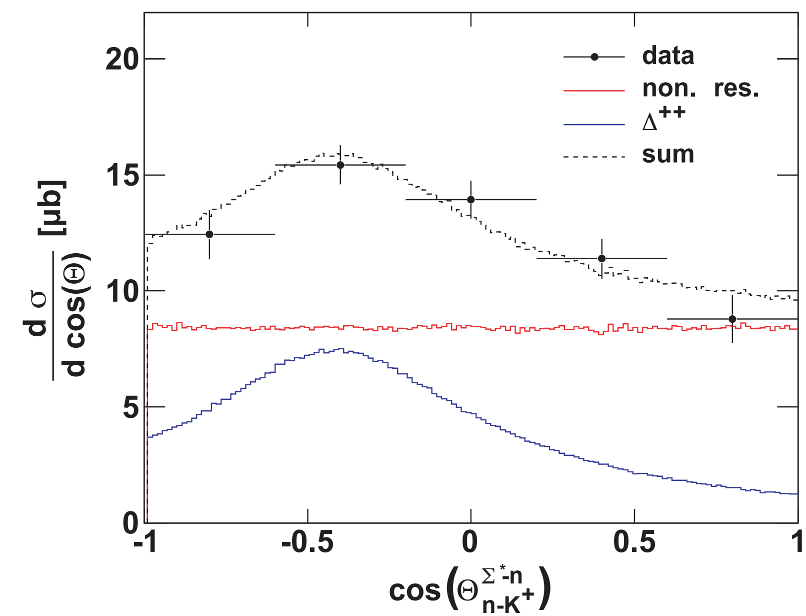


[Chinowsky, W. *et al.* Phys.Rev. 165 (1968) 1466-1478]

$$\Delta(1900-2000)^{++} \rightarrow \Sigma(1385)^{+} + K^{+}$$

$$\Gamma = 150 - 200\mathrm{MeV/c^2}$$

~ 30% Δ^{++}



Role of the Δ*(1940) in the π+*p*→*K*+Σ+(1385) and *pp*→*nK*+Σ+(1385) reactions

[Ju-Jun Xie], [En Wang], [Bing-Song Zou]

arxiv.1405.5586

Role Played by Resonances at intermediate Energies: II

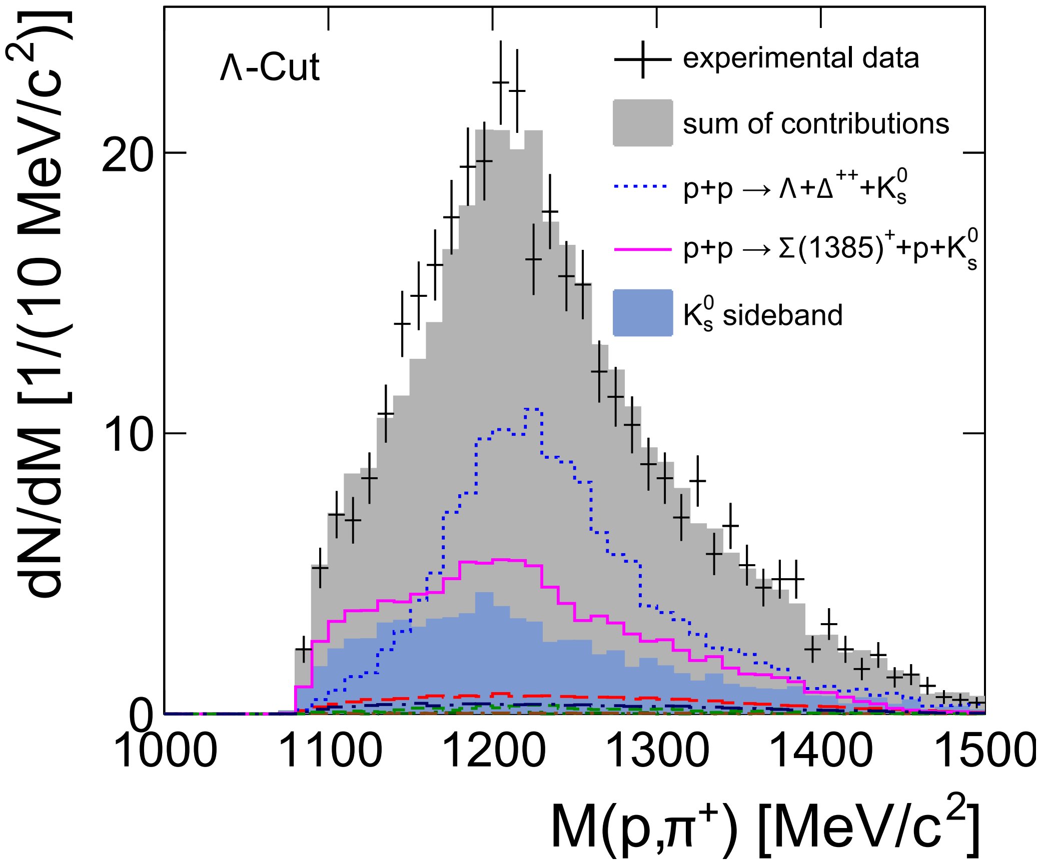
$$p + p(@3.5\,GeV) \rightarrow$$

$$\Lambda + \Delta^{++} + K_S^0$$

$$\Sigma^0 + \Delta^{++} + K_S^0$$

$$\searrow p + \pi^+$$

HADES, arXiv:1403.6662



$$\sigma(p + p \rightarrow \Lambda + \Delta^{++} + K_S^0) = 26.27 \pm 0.64^{+2.57}_{-2.13} \pm 1.84\ \mu b$$

$$\sigma(p + p \rightarrow \Lambda + p + \pi^+ + K_S^0) = 2.57 \pm 0.02^{+0.21}_{-1.98} \pm 0.18\ \mu b$$

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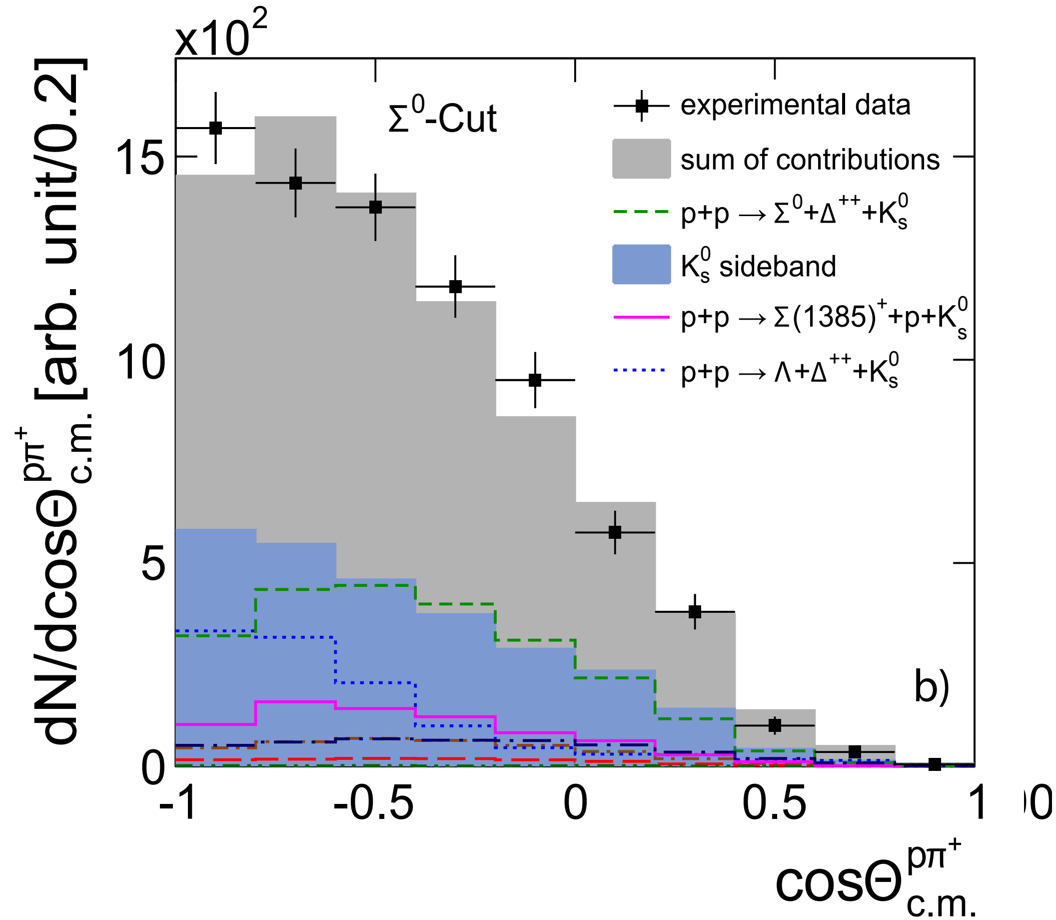

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Issue with the Resonances in hadron-hadron collisions: Interferences

$$p + p(@3.5\,GeV) \rightarrow$$

$$p + K^{+} + \Lambda$$

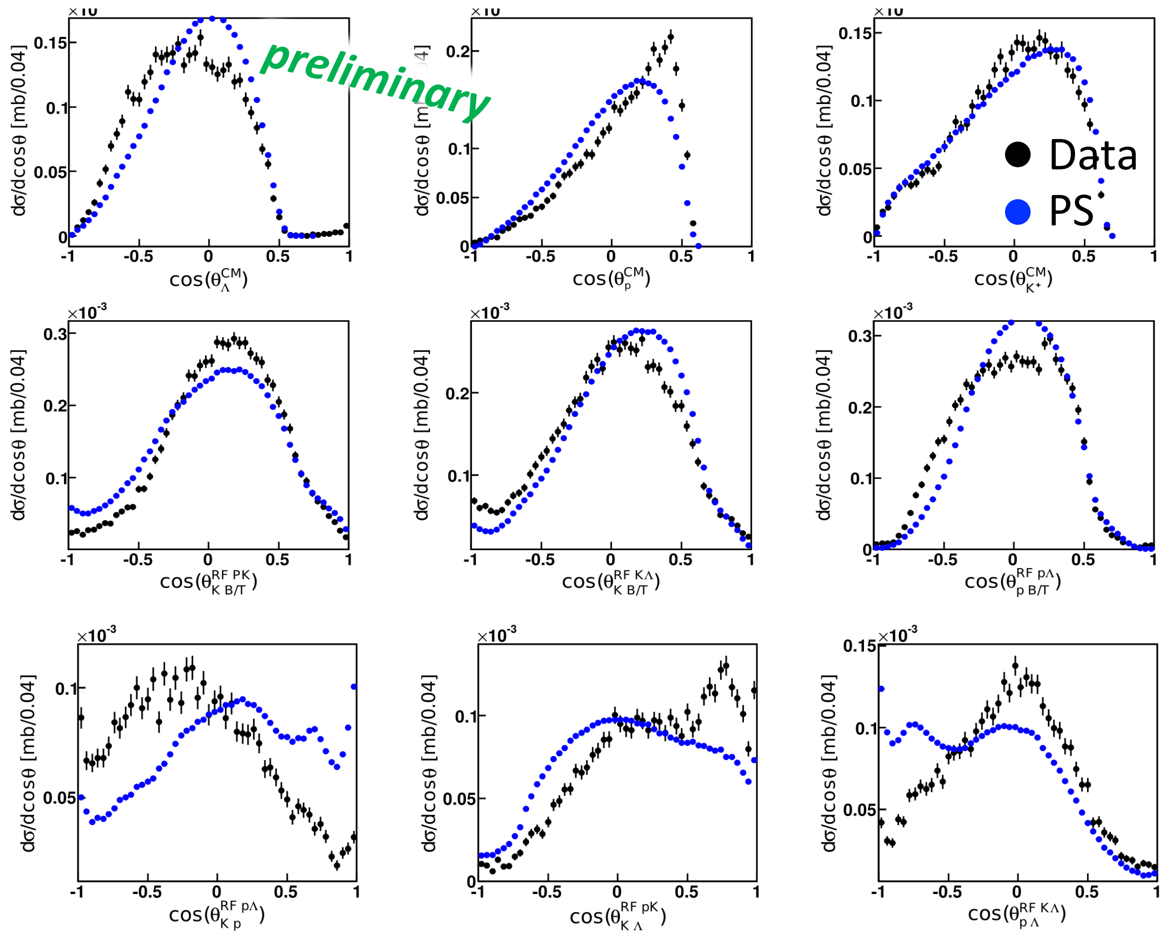
$$p + N^{*} \rightarrow p + K^{+} + \Lambda$$

CM Angle

Inside the HADES acceptance

Jackson Angle

Helicity Angle



Issue with the Resonances in hadron-hadron collisions: Interferences

$$p + p(@3.5\,GeV) \rightarrow$$

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Bonn-Gatchina Partial Wave Analysis

http://pwa.hiskp.uni-bonn.de/

A.V. Anisovich, V.V. Anisovich, E. Klempt, V.A. Nikonov and **A.V. Sarantsev**
Eur. Phys. J. A 34, 129152 (2007)

What we included to model the $PK^{+}\Lambda$ process:

N^{*} Resonances in the PDG with measured decay into $K^{+}\Lambda$

N(1650), N(1710), N(1720), N(1875), N(1880), N(1895), N(1900)
Non-resonant $PK^{+}\Lambda$ production waves
Interferences

Issue with the Resonances in hadron-hadron collisions: Interferences

$$p + p(@3.5\,GeV) \rightarrow$$

$$p + K^{+} + \Lambda$$

$$p + N^{*} \rightarrow p + K^{+} + \Lambda$$

Measured Data

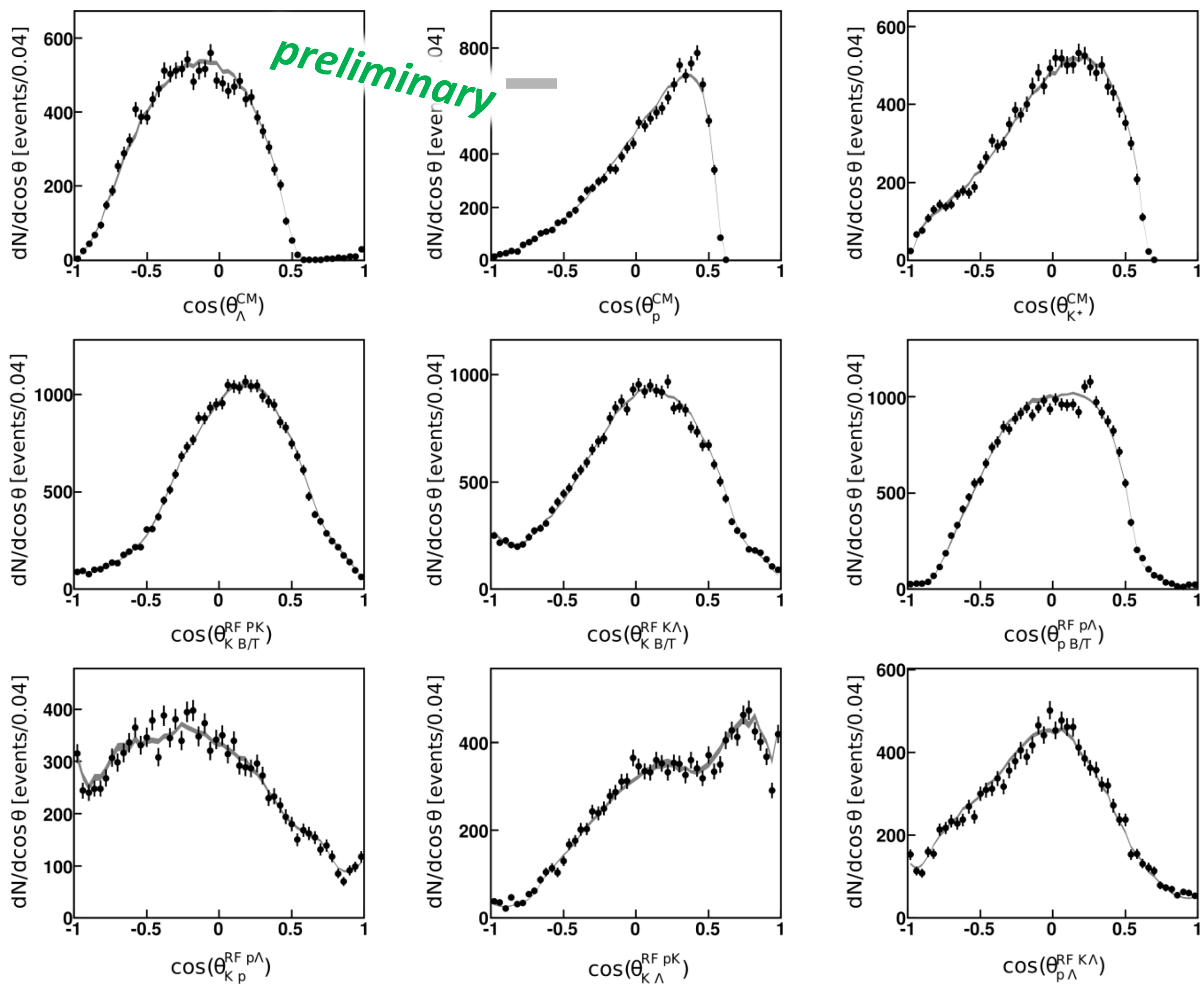
PWA solutions

CM Angle

Inside the HADES acceptance

Jackson Angle

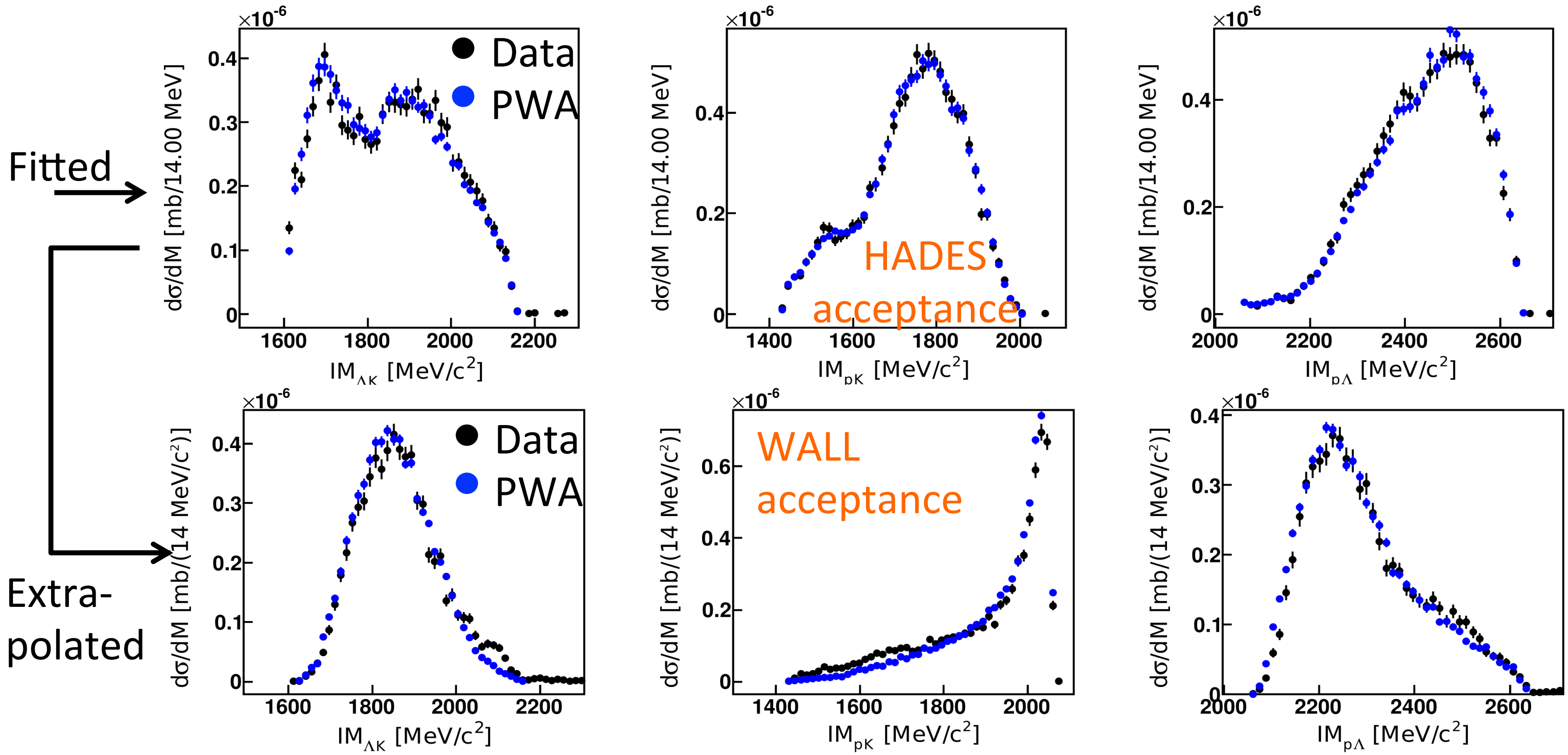
Helicity Angle



Issue with the Resonances in hadron-hadron collisions: Interferences

$$p + p(@3.5\,GeV) \rightarrow$$

$$p + K^{+} + \Lambda \qquad\qquad p + N^{*} \rightarrow p + K^{+} + \Lambda$$



included resonances: N(1650), N(1710), N(1720), N(1900), N(1895)

Non-resonant waves:
$(pL)(^1S_0) - K$ $(pL)(^3S_1) - K$ $(pL)(^1P_1) - K$
$(pL)(^3P_0) - K$ $(pL)(^3P_2) - K$ $(pL)(^3P_1) - K$
$(pL)(^3D_1) - K$ $(pL)(^1D_2) - K$ $(pL)(^3D_2) - K$

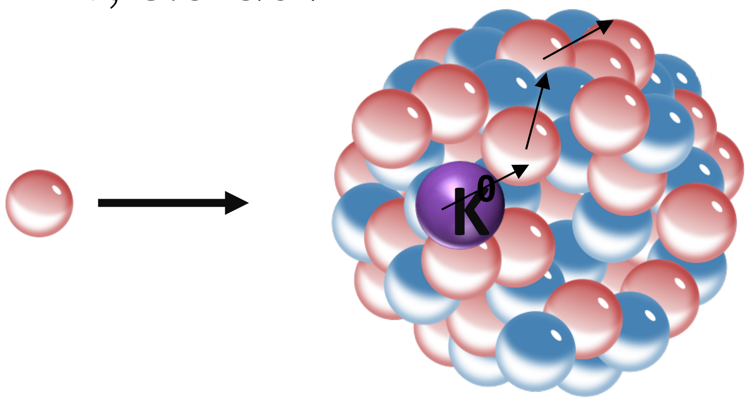
Intermediate Conclusions I

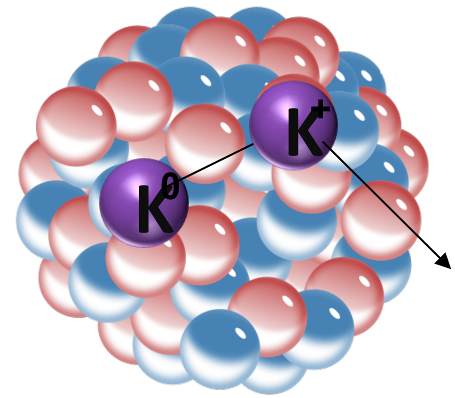
- **Decay chains for Resonances** can be determined by exclusive/semi-exclusive measurements of final state in p+p and p+n collision for energies between 2-10 GeV
- **Interferences** among resonances play an important role for some final states (for **dileptons too** btw) but those can be estimated using PWA on elementary collisions like p+N and π+N. A 4π distribution can be extracted which one could **implement into transport models.**
- Still... A systematic analysis of different data sets at different energies is needed to pin down quantitatively the contribution of N* to pKΛ e.g.

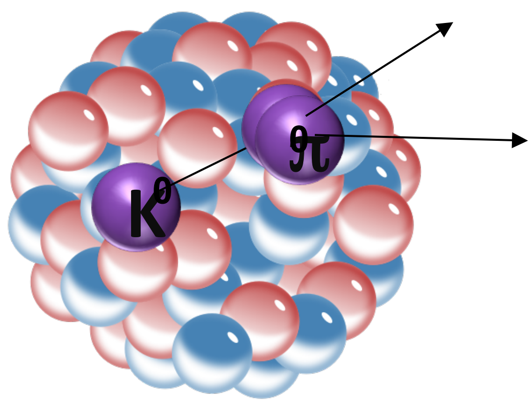
- <u>**Upcoming**</u> measurements **of π+N and π+A** for p=0.8-1.65 GeV/c and planned PWA analysis to determine N* and Δ yields and their contribution to the strange and dilepton final states.

Kaons in really cold nuclear matter

p+Nb, 3.5 GeV





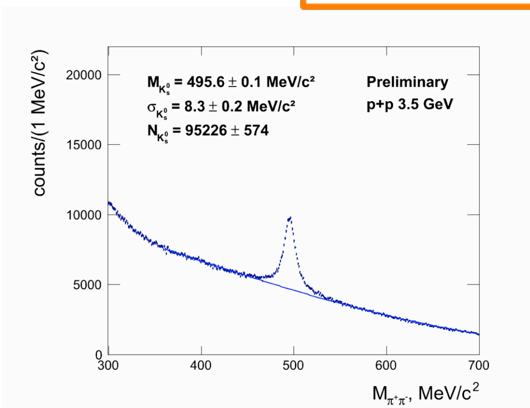


<u>Inside the Nucleus</u>:
The K^0 experiences a potential due to the surrounding nucleons.
Modification of these processes.

K^0_S in cold nuclear matter

Neutral kaons measured by HADES in p+p and p+^{93}Nb collisions at 3.5 GeV:

p+p@3.5 GeV



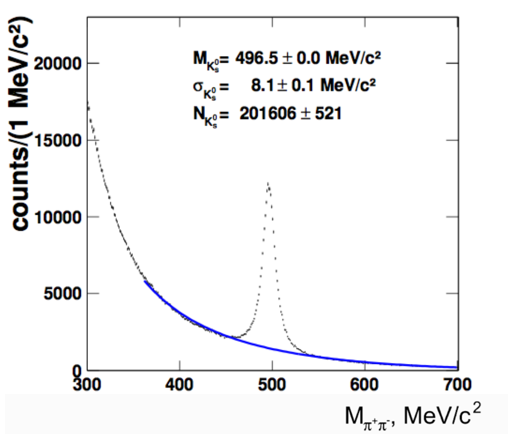
Kaon emission in pNb reactions is a complex process.

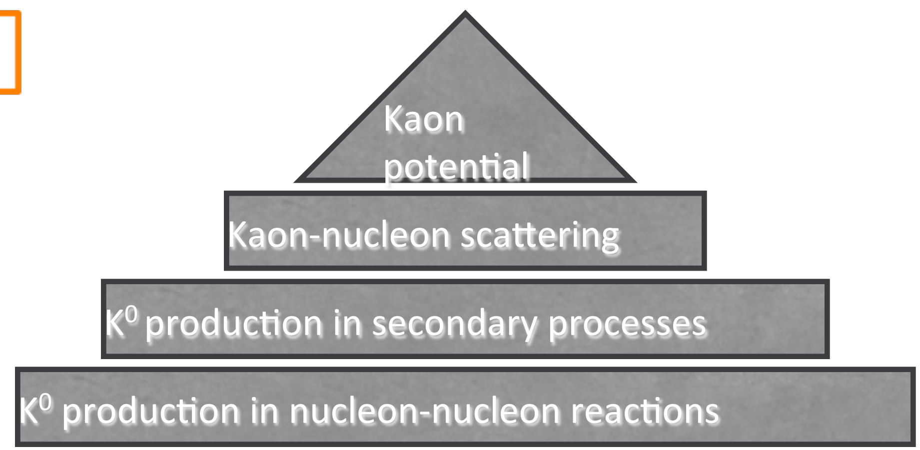
Data are interpreted with the GiBUU transport model (collaboration with **T. Gaitanos and J. Weil**)

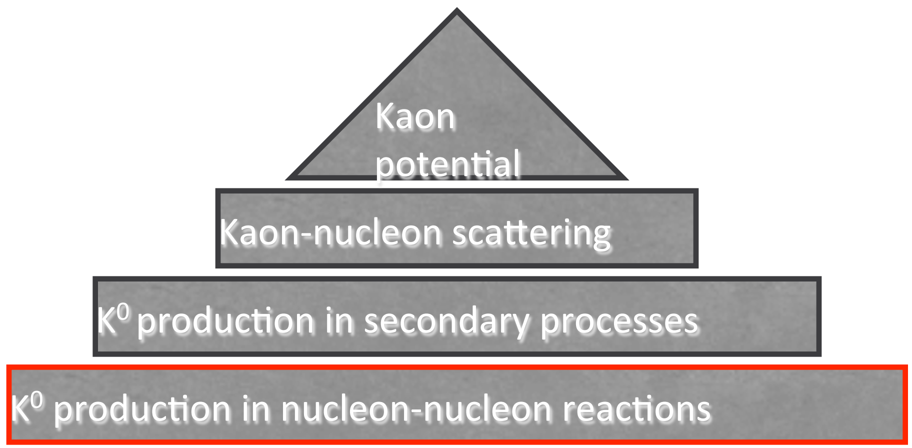
O. Buss et al., Phys. Rept. 512, 1 (2012)

http://gibuu.physik.uni-giessen.de/GiBUU/

p+Nb@3.5 GeV






Kaon
potential
Kaon-nucleon scattering
K^0 production in secondary processes
K^0 production in nucleon-nucleon reactions

Resonance model of kaon production

All production channels:

No.	Reaction
1	$pp \to p\Lambda K^+$
2	$pn \to n\Lambda K^+$
3	$pp \to p\Sigma^0 K^+$
4	$nn \to n\Sigma^- K^+$
5	$pn \to n\Sigma^0 K^+$
6	$np \to p\Sigma^- K^+$
7	$pp \to n\Sigma^+ K^+$
8	$nn \to \Delta^-\Lambda K^+$
9	$pp \to \Delta^{++}\Sigma^- K^+$
10	$\Delta^{++}n \to p\Lambda K^+$
11	$\Delta^- p \to n\Sigma^- K^+$
12	$\Delta^{++}p \to \Delta^{++}\Lambda K^+$
13	$\Delta^+ n \to \Delta^0\Lambda K^+$
14	$\Delta^+ p \to \Delta^+\Lambda K^+$
15	$\Delta^{++}n \to \Delta^{++}\Sigma^- K^+$
16	$\Delta^0 p \to \Delta^+\Sigma^- K^+$
17	$\Delta^+ n \to \Delta^+\Sigma^- K^+$
18	$\Delta^{++}p \to \Delta^{++}\Sigma^0 K^+$
19	$\Delta^+ n \to \Delta^0\Sigma^0 K^+$
20	$\Delta^+ p \to \Delta^+\Sigma^0 K^+$
21	$\Delta^+ p \to \Delta^0\Sigma^+ K^+$
22	$\Delta^+\Delta^{++} \to \Delta^{++}\Lambda K^+$
23	$\Delta^0\Delta^{++} \to \Delta^+\Lambda K^+$
24	$\Delta^0\Delta^+ \to \Delta^0\Lambda K^+$
25	$\Delta^{++}\Delta^0 \to \Delta^{++}\Sigma^- K^+$
26	$\Delta^-\Delta^0 \to \Delta^-\Sigma^- K^+$
27	$\Delta^0\Delta^{++} \to \Delta^+\Sigma^0 K^+$
28	$\Delta^-\Delta^+ \to \Delta^0\Sigma^- K^+$

Cross section parameterization:

$$\sigma(B_1 B_2 \to B_3 Y K) = a\left(\frac{s}{s_0} - 1\right)^b \left(\frac{s_0}{s}\right)^c,$$

Note: this is what's inside transport code

np-reactions isospin interrelations (one example):

$$\begin{aligned} \sigma(nn \to \Delta^-\Lambda K^+) &= \sigma(pp \to \Delta^{++}\Lambda K^0) \\ = 3\sigma(pn \to \Delta^0\Lambda K^+) &= 3\sigma(np \to \Delta^+\Lambda K^0) \\ = 3\sigma(pp \to \Delta^+\Lambda K^+) &= 3\sigma(nn \to \Delta^0\Lambda K^0), \end{aligned}$$

almost no experimental data for np!

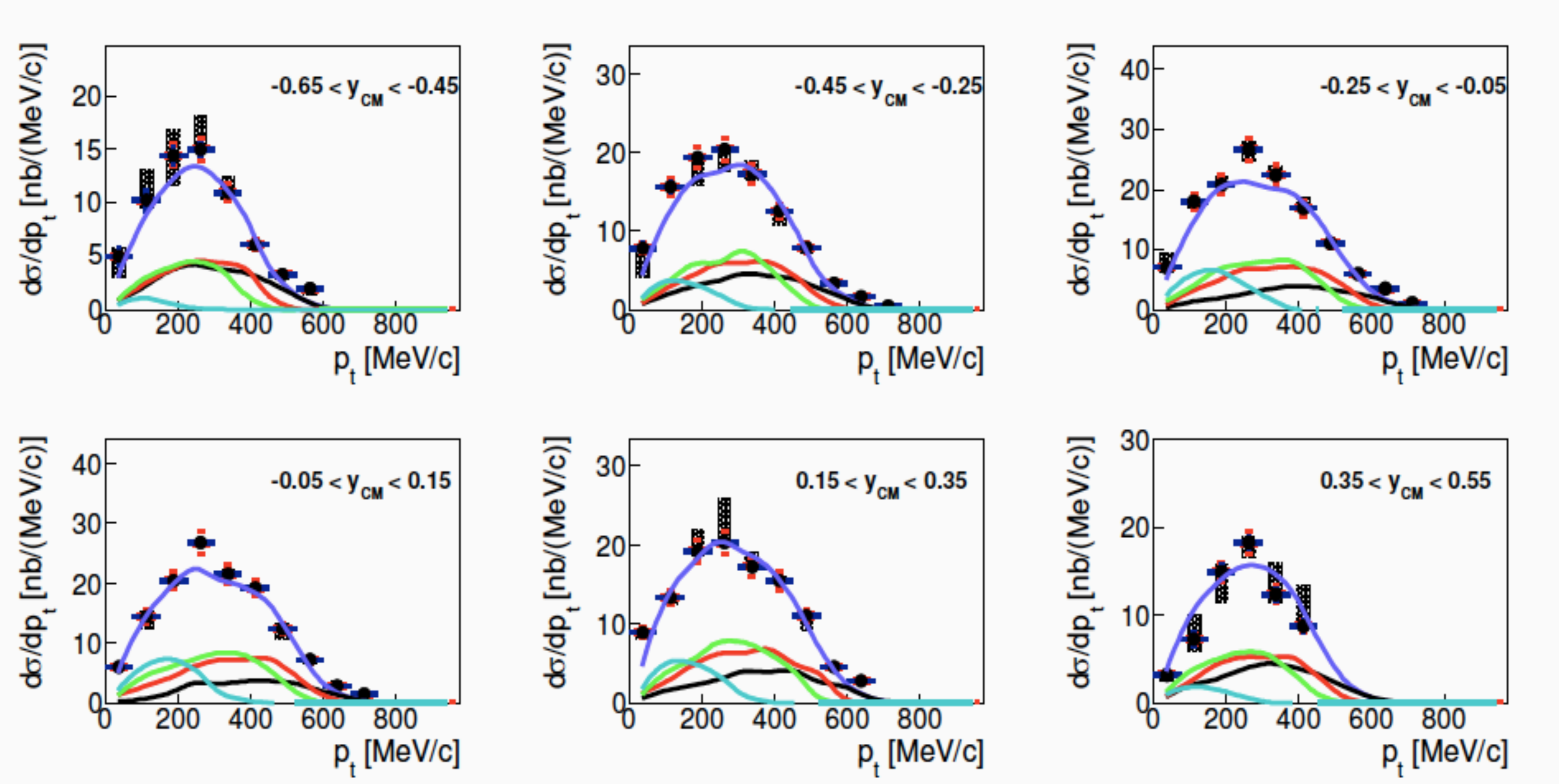
K^0 production channels:

Number of particles	Final state	What is in the model
3-body	$p\ \Sigma^+\ K^0$	$p\ \Sigma^+\ K^0$
4-body	$p\ \pi^+\ \Lambda\ K^0$	$\Delta^{++}\ \Lambda\ K^0$
	$p\ \pi^+\ \Sigma^0\ K^0$	$\Delta^{++}\ \Sigma^0\ K^0$
	$n\ \pi^+\ \Sigma^+\ K^0$	$\Delta^+\ \Sigma^+\ K^0$
	$p\ \pi^0\ \Sigma^+\ K^0$	

Note:
1. Pion production goes exclusively through Δ.
2. No angular anisotropies in production.

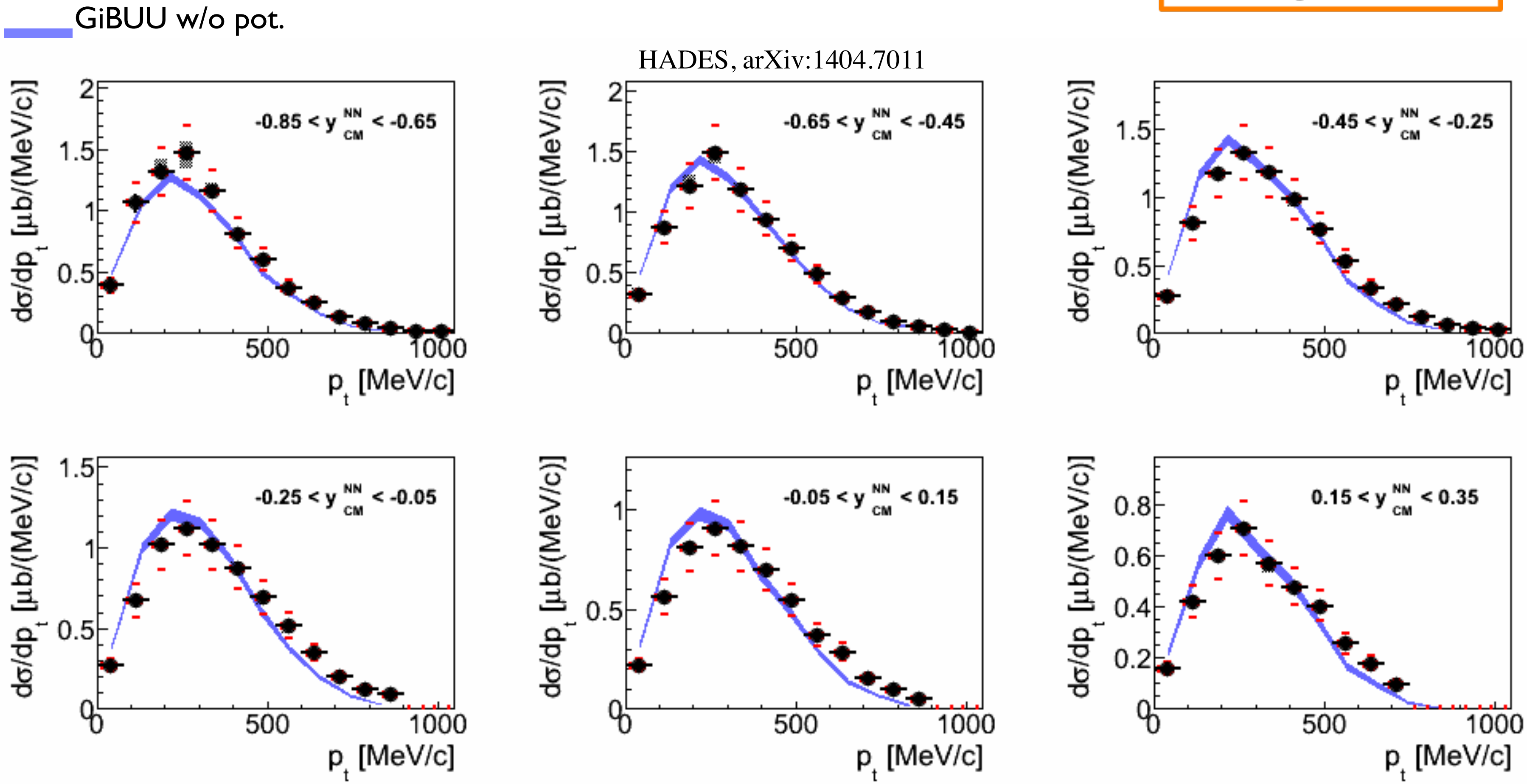
$K^0{}_S$ from p+p@ 3.5GeV

HADES arXiv:1403.6662 [nucl-ex]., accepted by PRC

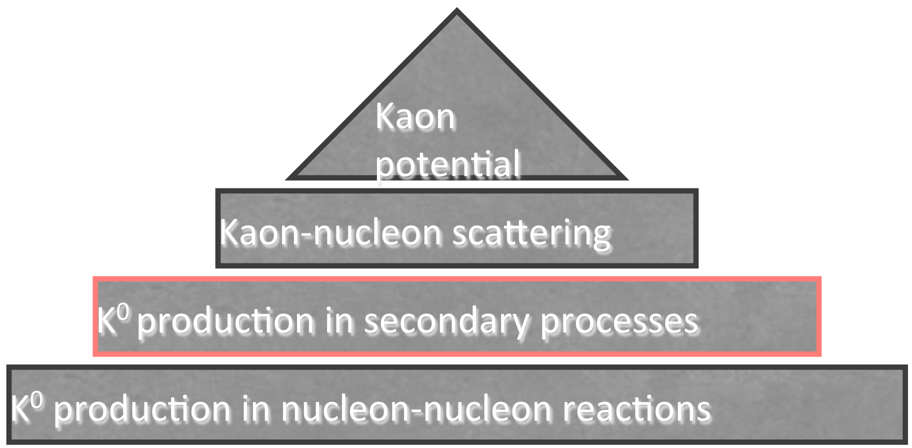


pNb data vs. tuned resonance model

p+Nb@3.5 GeV



- KN potential is OFF.
- 3-body reactions in np (np → NYK) poorly constrained, scale factor 0.5 is applied to the Tsushima parameterizations.
- GiBUU simulations based on tuned resonance model describe data.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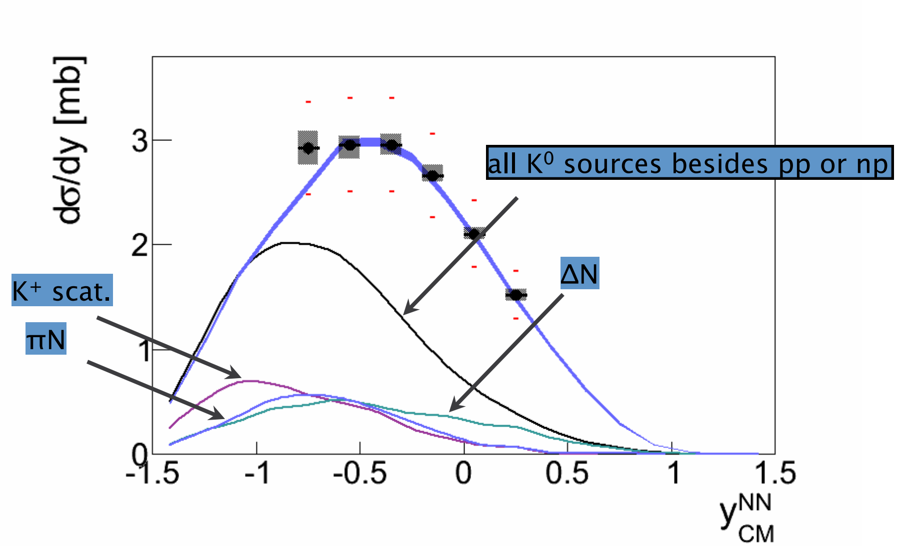
Rapidity distribution and role of secondary reactions

p+Nb@3.5 GeV

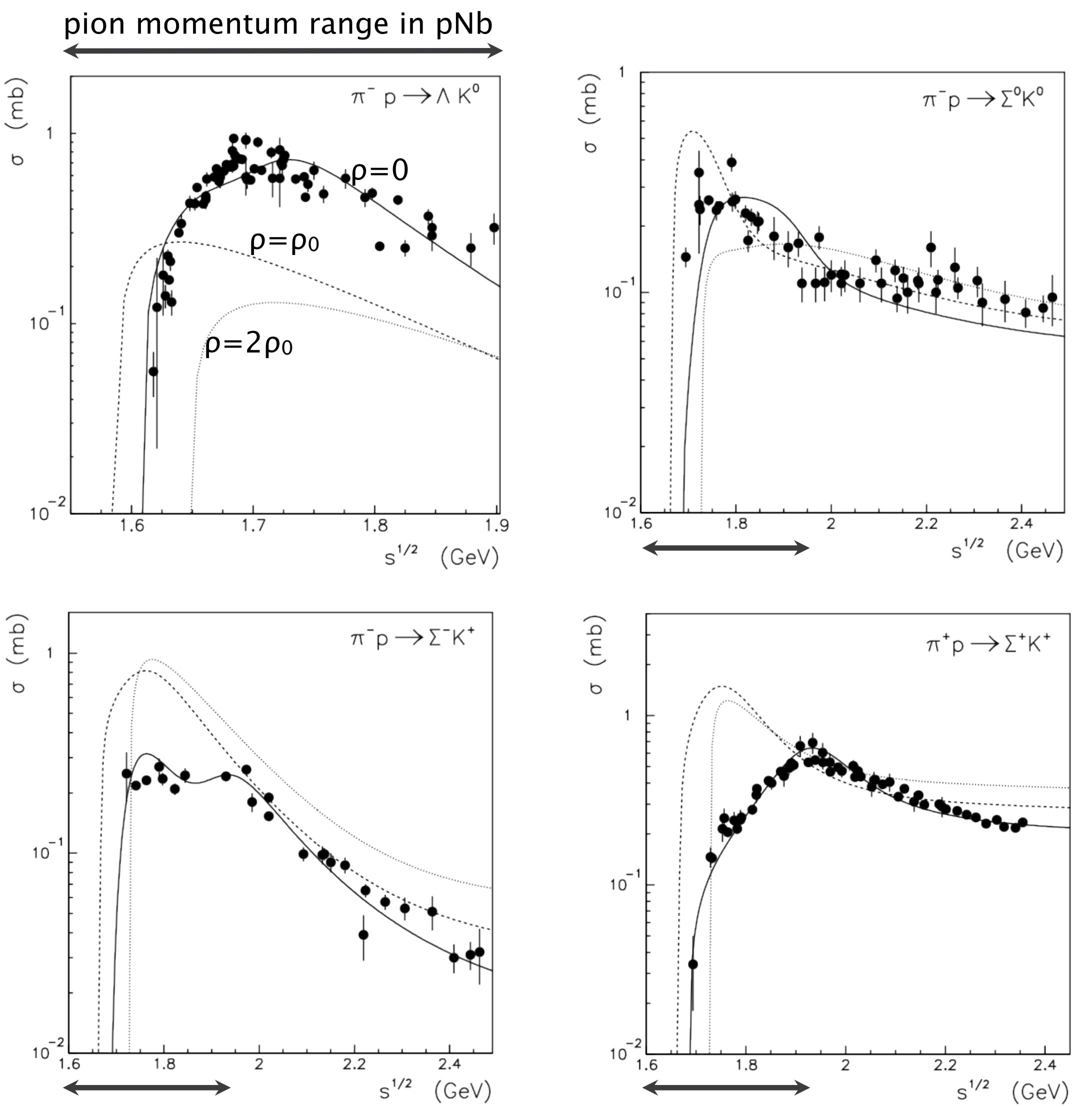
HADES, arXiv:1404.7011



- Significant contribution of secondary reactions at backward rapidities (~70%).
- Three main sources:
- ΔN-reactions. Rely on the resonance model (Tsushima et al.).
- πN-reactions.
- KN scattering.

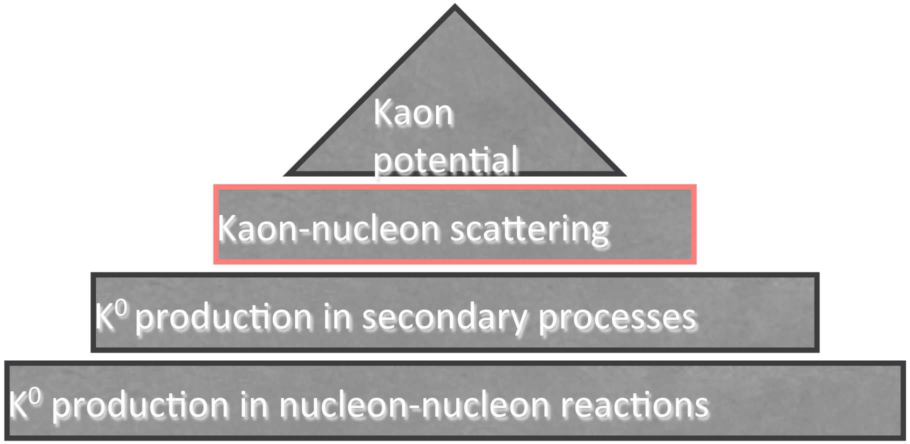
How well the two last processes are known?

Secondary processes: pion-nucleon **reactions**



- Elementary cross sections are known well and parametrized in the model.
- No angular distributions implemented in the model.

Pictures from K. Tsushima, A. Sibirtsev, A.W. Thomas, PRC62 (2000) 064904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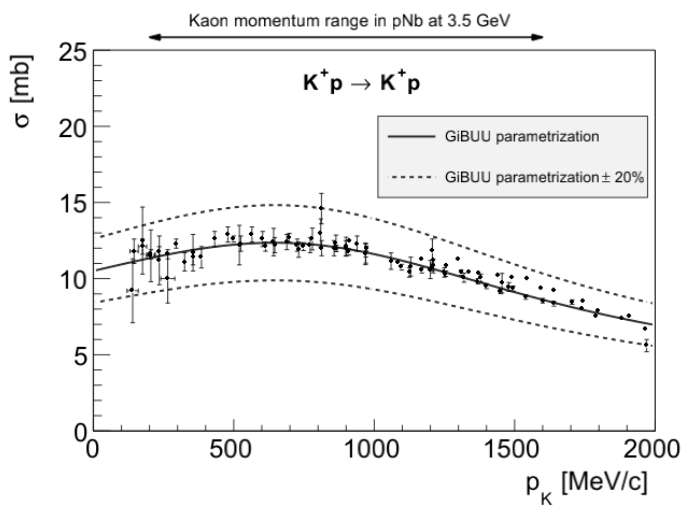
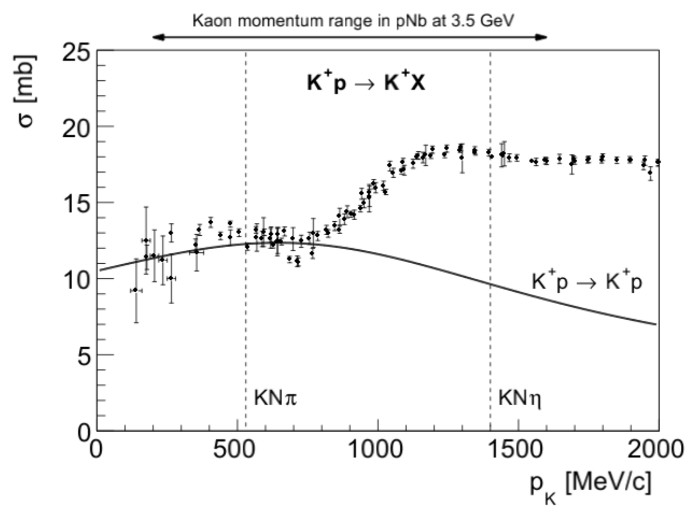
Kaon-nucleon scattering

Elastic cross section



Parametrization: M. Effenberger, PhD. Giessen, 1999.

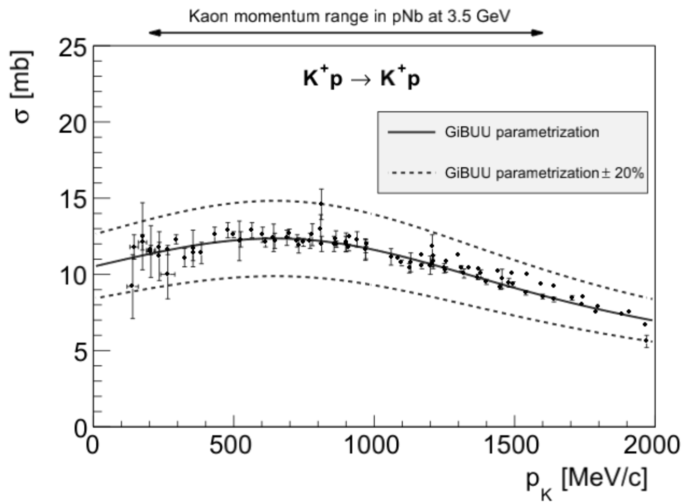
Total cross section



- Vacuum cross sections are well known.
- K^0N scattering from isospin considerations.
- No angular distributions implemented in the model (some data are available).

Kaon-nucleon scattering

Elastic cross section



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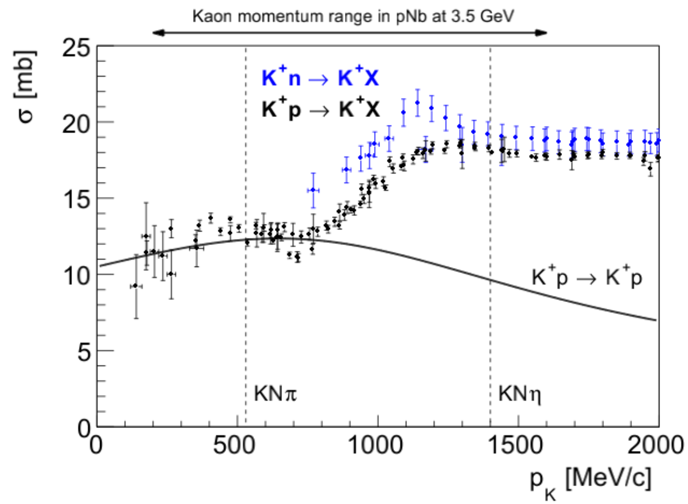

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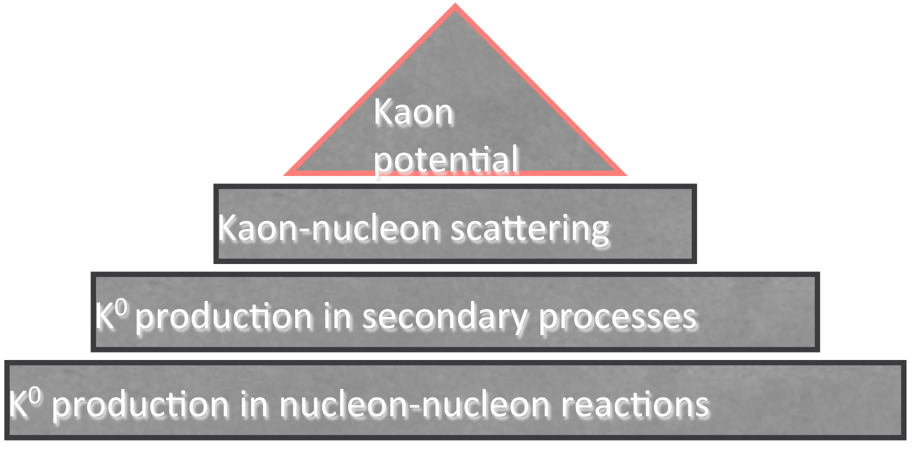
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Kaons properties in Matter

How to describe the properties of Kaon in nuclear matter?
Effective Chiral Lagrangian with Kaons and Nucleons as degree of Freedom

Mean Field Dynamics

C. Fuchs Progr. In Part and Nucl. Phys. 56 (2006) 1-103

$$\left[\left(\partial_\mu \pm iV_\mu\right)^2 + m_K^{*2}\right]\phi_{K^\pm}(x) = 0$$

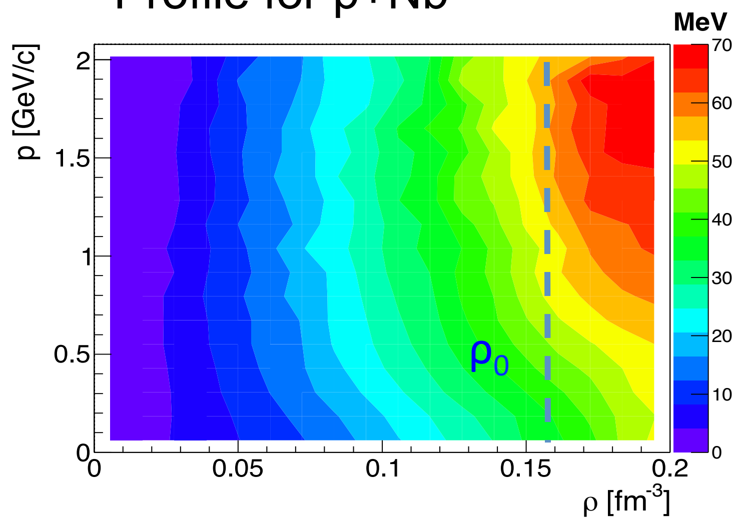
$$m_K^* = \sqrt{m_K^2 - \frac{\Sigma_{KN}}{f_\pi^{*2}}\rho_S + V_\mu V^\mu}$$

$$V_\mu = \frac{3}{8 f_\pi^{*2}} j_\mu$$ Vector potential attractive for K^- repulsive for K^+

Σ_{KN} = Scalar potential, ~300-450 MeV, same for K^+ and K^-

$$\boxed{E(\mathbf{k}) = \sqrt{\mathbf{k}^2 + m_\mathrm{K}^2 - \frac{\Sigma_\mathrm{KN}}{f_\pi^2}\rho_\mathrm{s} + V_0^2} \pm V_0}$$

Profile for p+Nb



IM<<Re -> No K^+ absorption

T. Gaitanos, K. Lapidus -> GiBUU

HADES, arXiv:1404.7011

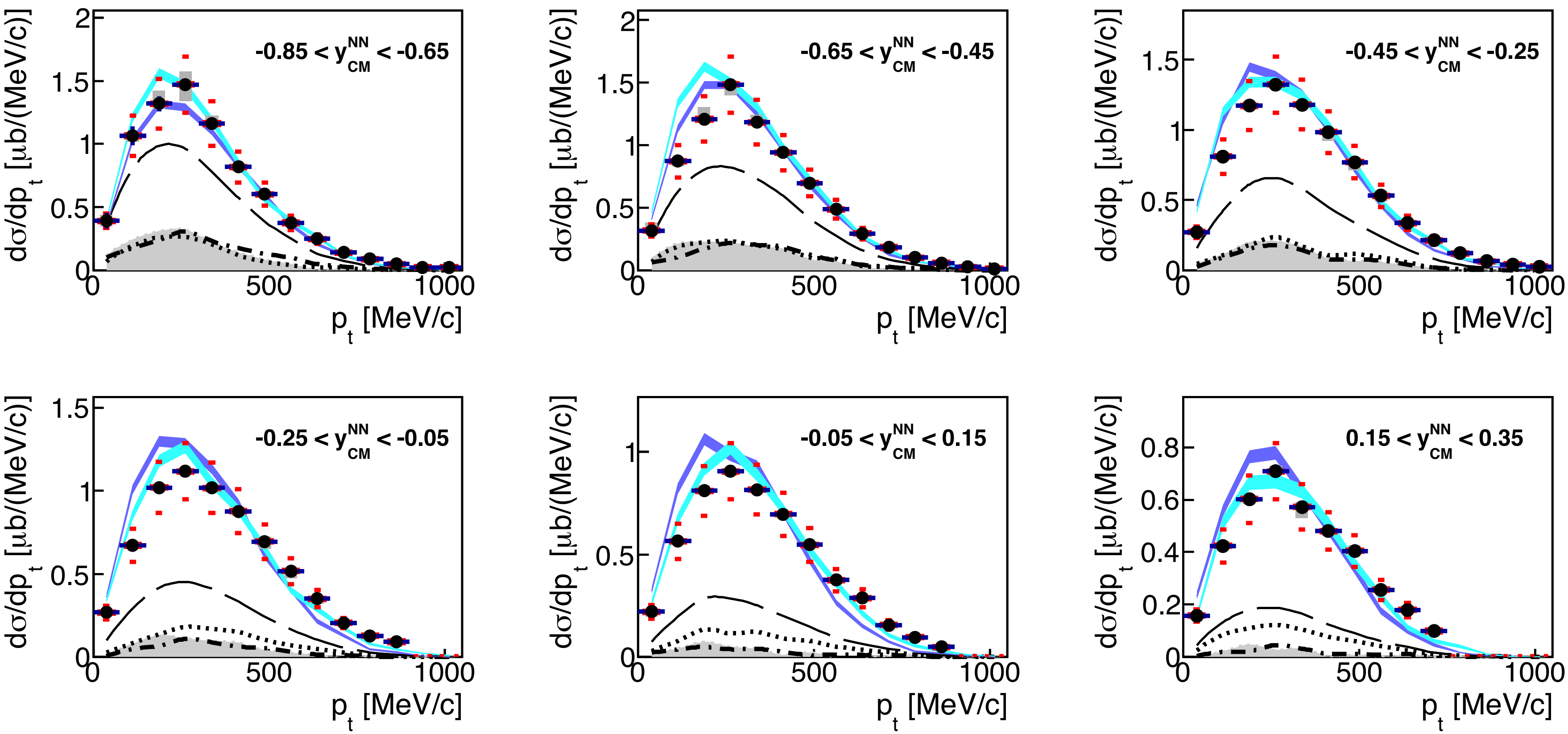
Effect of the potential in pNb: p-θ spectra

GiBUU w/o pot.

GiBUU w. pot.

HADES, arXiv:1404.7011

p+Nb



$p+p/p+n \to K^0 + X$

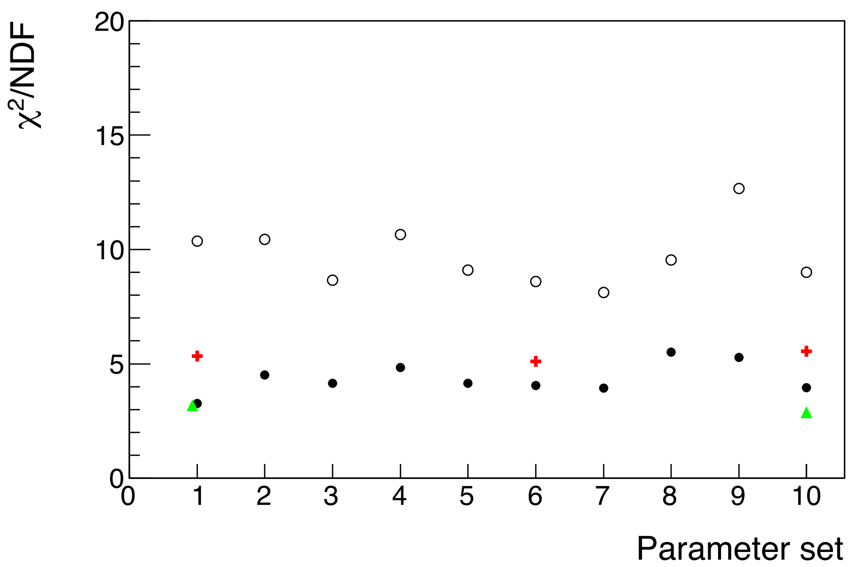
ΔN

$K^+ N \to K^0 N$

πN

Systematic check

HADES, arXiv:1404.7011



$$\sigma(\Delta N \to KX) \quad \pm 1.25$$

$$\sigma(np \to NYK) \quad \pm 1.25$$

$$\sigma(\pi N \to KX) \quad \pm 1.25$$

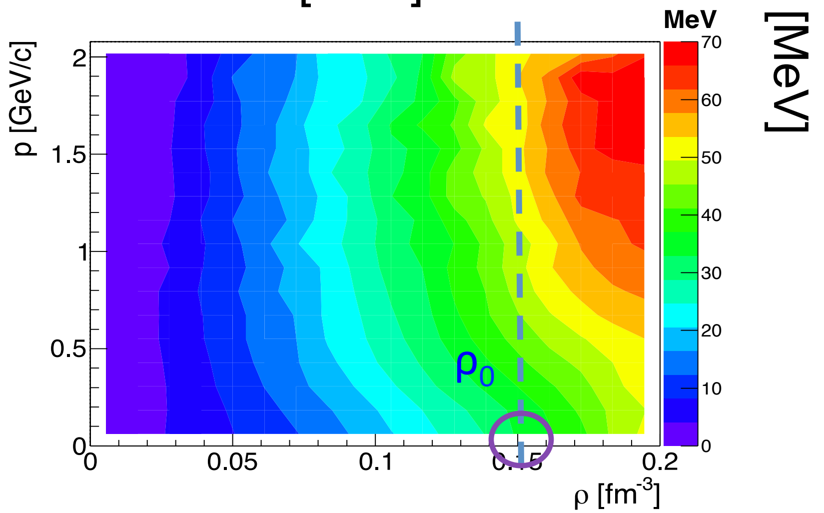
$$\sigma(KN \to KX) \quad \pm 1.25$$

$$NN \to \Delta(1232) Y^* K \quad -1.25$$

- ○ w/o potential
- • with potential ("U = +35 MeV")

$$\chi^2 = \sum_i \frac{\left((d\sigma/dp_t)_i^{\text{exp.}} - (d\sigma/dp_t)_i^{\text{sim.}}\right)^2}{\sigma^2_{\text{exp.syst.}}}$$

ChPT kaon potential
U = E*- E [MeV]



Intermediate Conclusions II

p+A at 3.5 GeV : $\rho 0$
detailed comparison of the experimental data for the inclusive K0s to ONE
Transport model (GiBUU)
Pirimide Approach:
-> Elementary cross-sections
-> Check scattering effects via Rapidity density distribution
-> Secondary processes included
-> Test of the Chiral potential

Result for K0s:
Repulsive potential around **40 MeV for k=0 and $\rho=\rho 0$**
Factor 2 larger than extracted from Flow in HIC and previous π+A measurement

-> new Measurements for π+A at high rate with HADES in 3 weeks.

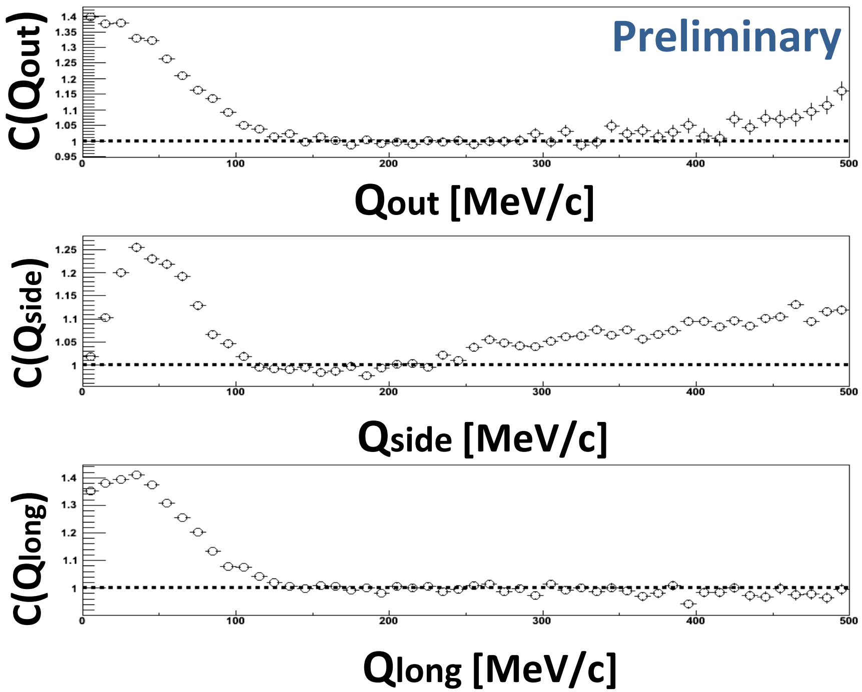
Λ

System of interest: p+Nb at 3.5 GeV

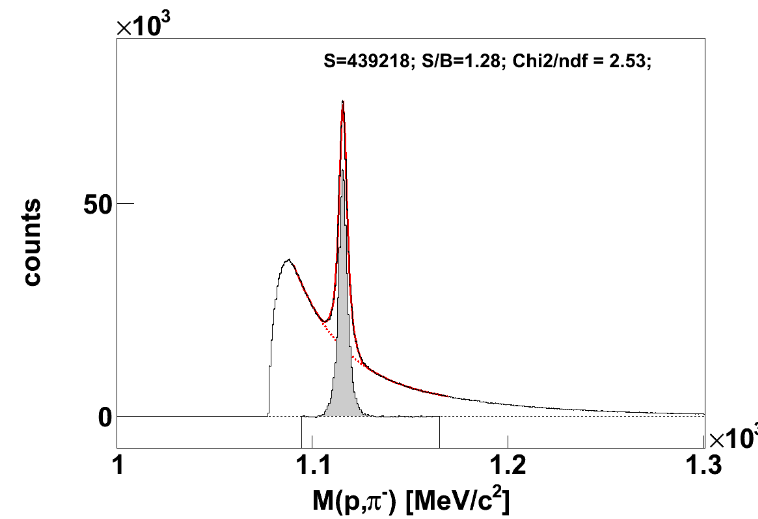
Femtoscopy is seldomly done at low energies → Possibility to test model predictions at this low energies and establish trends with results from larger energies

Results from the p+Nb system:

Proton-Proton – correlations:



Reconstruction via $\Lambda \rightarrow p + \pi^-$



Correlation function depends on scattering length:

Lednicky model

$$C(k) = 1 + \sum_s \rho_s \left[\frac{1}{2} \left| \frac{f^s(k)}{r_0} \right|^2 \left(1 - \frac{d_0^s}{2\sqrt{\pi} r_0} \right) + \frac{2\Re(f^s(k))}{\sqrt{\pi} r_0} F_1(Qr_0) - \frac{\Im(f^s(k))}{r_0} F_2(Qr_0) \right]$$

Thank you