Strangeness with Pion Beams

Elementary Reactions

* Channels and Tools
* Expected Statistics

π+A:

* K0, K+ in cold nuclear matter: what can we still do?
* K^-: Absorption Measurements
* Λ: analysis of the kinematic variables and femtoscopy

Kaon and Antikaon Production in π+p collisions

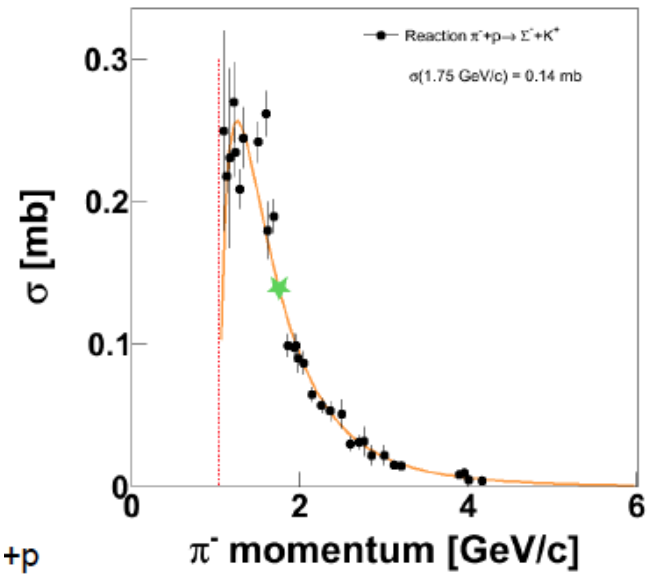
$\pi^- + p@1.7\,\mathrm{GeV/c}$

Threshold:

$\Sigma^- K^+$	≈ 1.035 GeV/c
ΛK^0	≈ 0.896 GeV/c
$\Sigma^0 K^0$	≈ 1.031 GeV/c
ϕ+n	≈ 1.559 GeV/c

$\sigma_{TOT}(\pi^- + N) = 34mb\,@1.7GeV/c$

$\Sigma^- K^+$	≈ 0.14 mb
ΛK^0	≈ 0.16 mb
$\Sigma^0 K^0$	≈ 0.14 mb
$\Lambda(1405) K^0$	≈ 0.04 mb
η+n	≈ 0.52 mb
ω+n	≈ 1.84 mb
ϕ+n	≈ 0.03 mb



+p

$$\sigma(s) = a \cdot \left(1 - \frac{s_0}{s}\right)^b \cdot \left(\frac{s_0}{s}\right)^c$$

SIBIRTSEV, A. CASSING, W. *arXiv:nucl-th/* (1998)

Feasibility Studies

Baryon Analysis

$$\pi^- + p \xrightarrow{1.616GeV} K^+ + \Sigma^-$$
$$\Sigma^- \rightarrow n + \pi^-$$

$$\pi^- + p \xrightarrow{1.62\ \ GeV} K^0 + \Lambda$$
$$K^0 \rightarrow \pi^0 + \pi^0$$
$$K^0 \rightarrow \pi^+ + \pi^-$$
$$\Lambda \rightarrow p + \pi^-$$
$$\Lambda \rightarrow n + \pi^0$$

$$\pi^- + p \xrightarrow{1.62\ \ GeV} K^0 + \Sigma^0$$
$$K^0 \rightarrow \pi^0 + \pi^0$$
$$K^0 \rightarrow \pi^+ + \pi^-$$
$$\Sigma^0 \rightarrow \Lambda + \gamma$$
$$\Lambda \rightarrow p + \pi^-$$

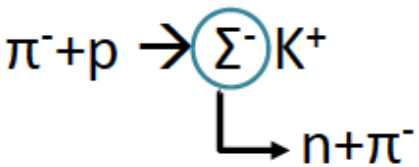
Meson Analysis

$$\pi^- + p \xrightarrow{1.616GeV} \eta + n$$
$$\eta \rightarrow 2\gamma$$
$$\eta \rightarrow \pi^+\pi^-\pi^0$$
$$\pi^0 \rightarrow 2\gamma$$

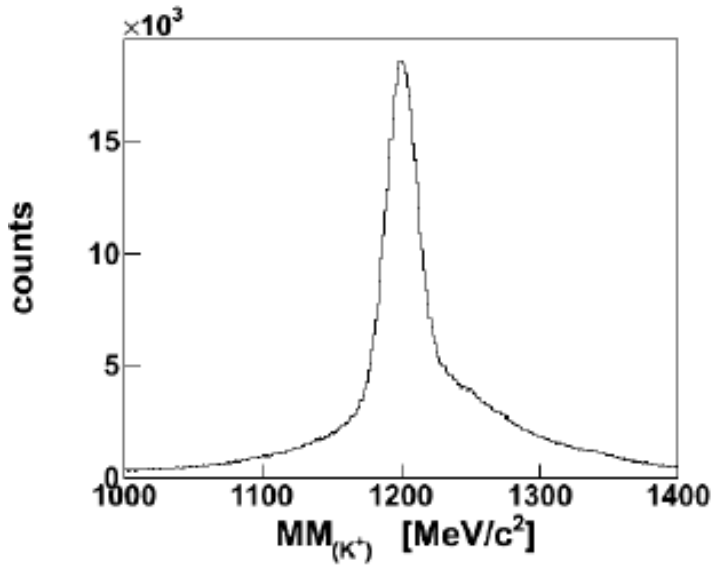
$$\pi^- + p \xrightarrow{1.616GeV} \omega + n$$
$$\omega \rightarrow \pi^+\pi^-\pi^0$$
$$\pi^0 \rightarrow 2\gamma$$

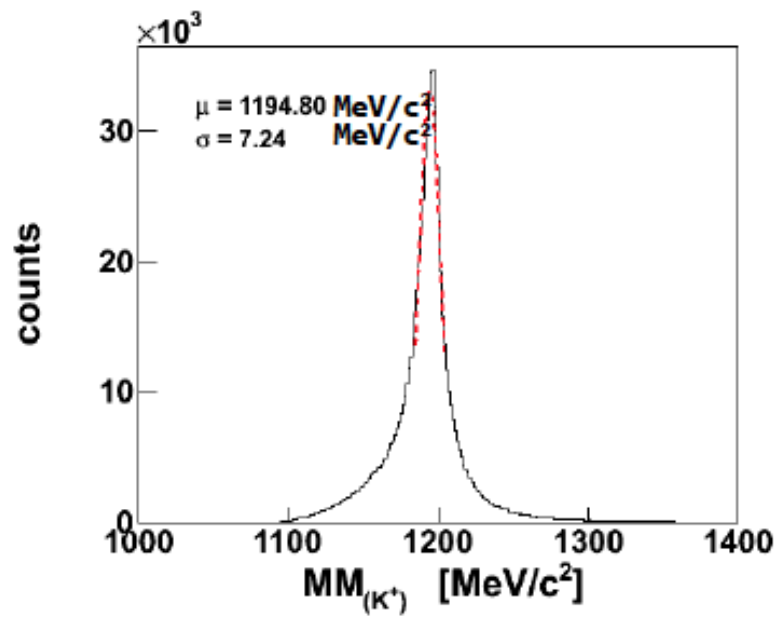
$$\pi^- + p \xrightarrow{1.616GeV} \phi + n$$
$$\phi \rightarrow K^+ + K^-$$

Analysis Tools



Pluto Events
Geant
DST
Physics Analysis





+ Cut on Neutron missing mass
+ Kinematic Refit

Rates

$\pi^- + p@1.7\,\mathrm{GeV/c}$ $\sigma_{TOT}(\pi^- + N) = 34mb\,@1.7GeV/c$

$$Reaction_{day} = \Phi_{\pi^-} \cdot I_{Prob}$$

$$I_{prob} = \sigma_{tot} \cdot L \cdot \rho \frac{N_A \cdot Z}{M_{mol}}$$

$$I_{prob} = 34mb \cdot 5 \cdot 10^{-2}m \cdot 71Kg/m^3 \frac{6,02 \cdot \frac{10^{23}}{mol} \cdot 2}{2.02g/mol}$$

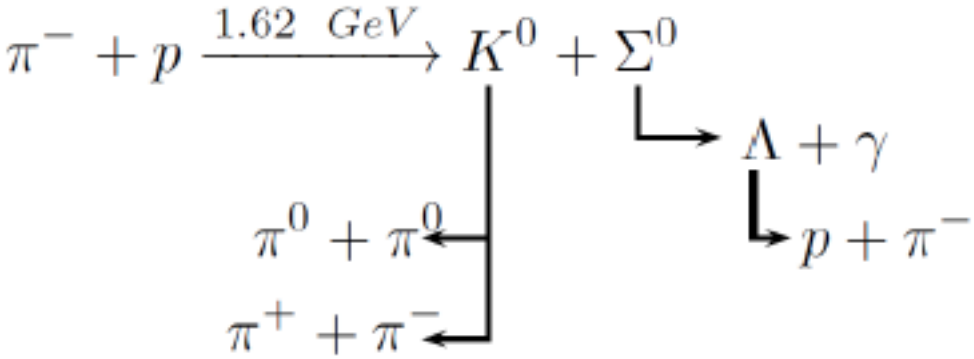
$$I_{prob} = 0.0072$$ For a 5 cm long LH_2 target

$$\Phi_{\pi^-} = \frac{\pi^-}{s} \cdot \frac{s}{day} \cdot Dead\,time \cdot \; Duty\,Factor$$

$$\Phi_{\pi^-} = 3.6 \cdot 10^5 \frac{1}{s} \cdot 8.64 \cdot 10^4 \frac{s}{day} \cdot 0.3 \cdot 0.8$$

$$Reaction_{day} = 5.37 \cdot 10^7$$

Exclusive and Semi-Exclusive Analysis: $K^0\Sigma^0$



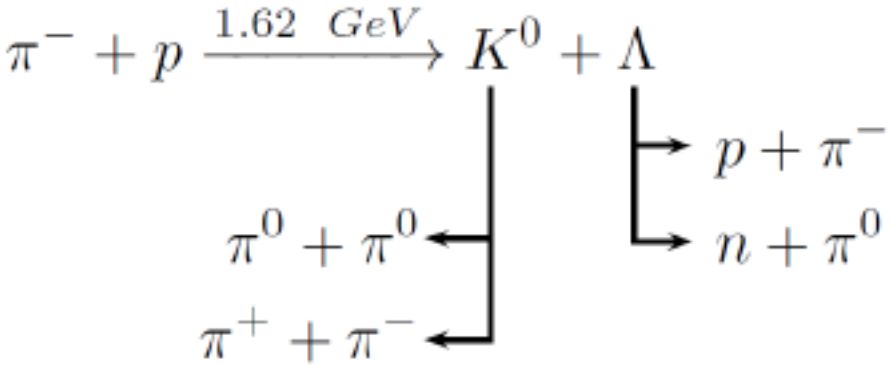
Sigma^0 + K^0
Exclusive Analysis:

Cut on Lambda
Cut on K0
Anti-cut on wrong Lambda+K0 combinations.
Kinematic-Refit on K0

Semi Exclusive Analysis:
Cut on K0
Kinematic-Refit on K0

!! ONLY K0S have been simulated, hence a further factor 0.5 should be considered!

Exclusive and Semi-Exclusive Analysis: $K^0\Lambda$



Lambda + K^0
Exklusive Analyse:

Cut on Lambda
Cut on K0
Anti-cut on wrong Lambda+K0 combinations.
Kinematic-Refit on K0

Semi Exclusive Analysis:
Cut on K0
Kinematic-Refit on K0

!! ONLY K0S have been simulated, hence a further factor 0.5 should be considered!

Expected Rate/ day

1 day = 3 shifts	$\Sigma^- K^+$	ΛK^0	$\Sigma^0 K^0$
Cross-sections [mb]	0.14	0.16/2	0.14/2
Production/day	221.117	126350	110.000
Reco Efficiency **E**	$14\% \cdot (0.9)^2 \cdot 0.95*$	0.7%	0.6%
Reco Efficiency **SE**	/	4.4%	4.4%
Reconstruction/day **E**	24.000	900	700
Reconstruction/day **SE**	/	6500	5.000

$\sigma_{TOT}(\pi^- p) = 34mb$

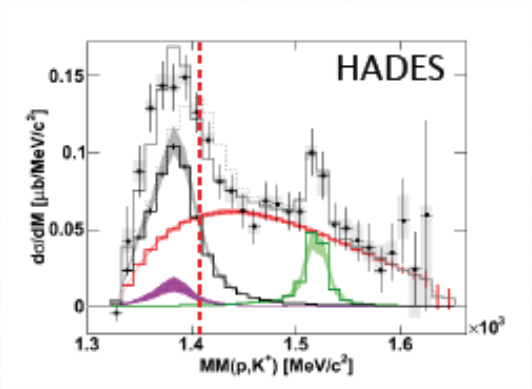
*: 0.95 =TOF Purity, 0.9= Purity dE/dx
Both numbers are included in the other two analyses already

Factor 2 because we only see K0s

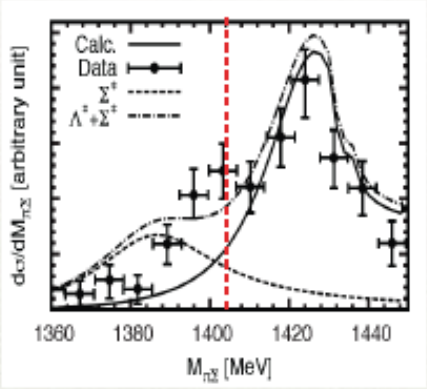
Λ(1405) in π+p reactions

Shift Puzzle

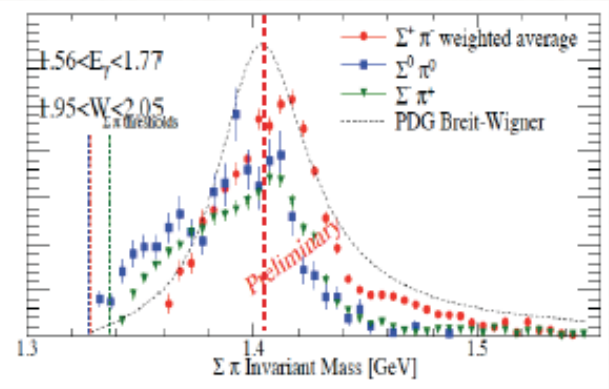
p+p at 4.3 GeV/c



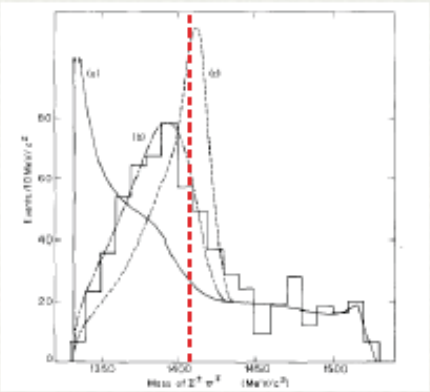
K⁻+d at 0.7–0.85 GeV/c



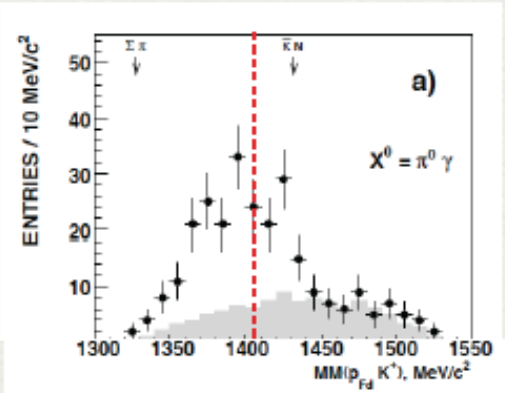
γ+p at 1.6–1.8 GeV/c



π⁻+p at 1.69 GeV/c

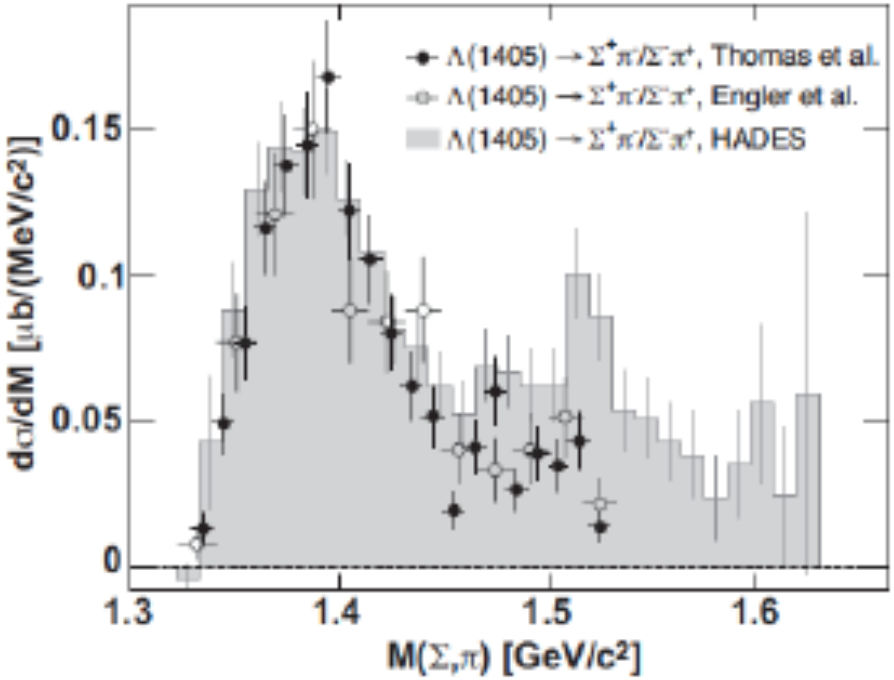


p+p at 3.65 GeV/c



O. Braun et al. Nucl. Phys. B129 (1977) 1.
K. Moriya et al. arXiv:1110.0469 [nucl-ex].
D.W. Thomas et al. Nucl. Phys. B56 (1973) 15.
I. Zychor et al. Phys. Lett. B660 (2008) 167–171.

p+p and π+p


Λ(1405) → Σ⁺π⁻/Σ⁻π⁺, Thomas et al.
Λ(1405) → Σ⁺π⁻/Σ⁻π⁺, Engler et al.
Λ(1405) → Σ⁺π⁻/Σ⁻π⁺, HADES
dσ/dM [μb/(MeV/c²)]
0.15
0.1
0.05
0
1.3
1.4
1.5
1.6
M(Σ,π) [GeV/c²]

E_{kin} = 1.62 GeV (E_{th} = 1.32 GeV)

$$\pi^- + p \rightarrow \Lambda(1405) + K^0$$

$$\Lambda(1405) \rightarrow \Sigma^+ + \pi^-$$

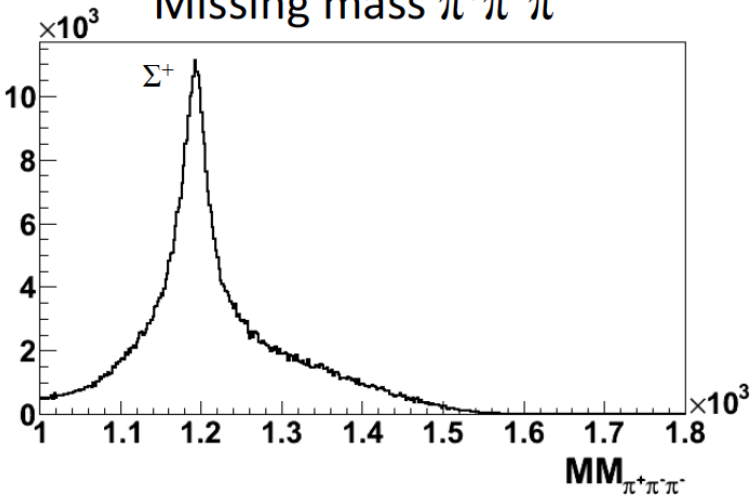
$$\Sigma^+ \rightarrow p + \pi^0$$

$$\Sigma^+ \rightarrow n + \pi^+$$

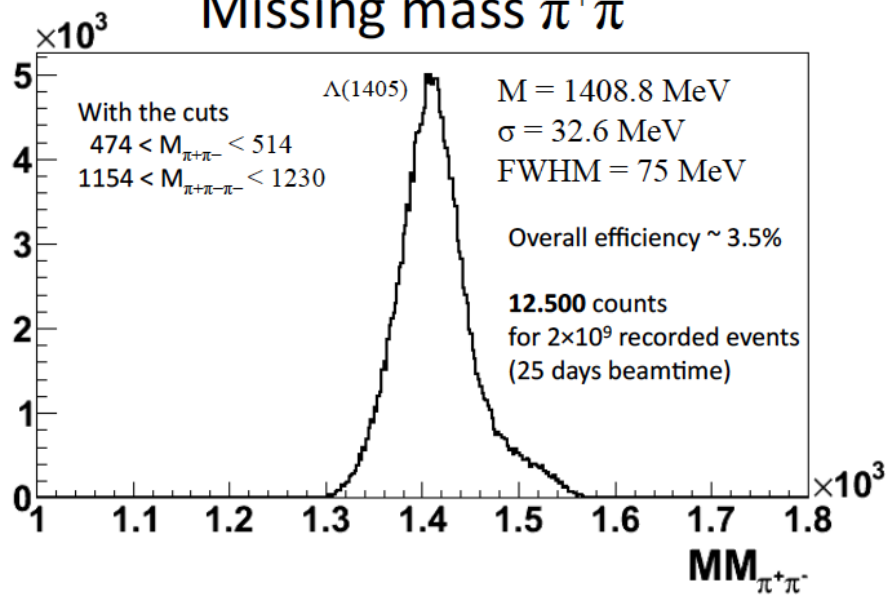
$$K^0 \rightarrow \pi^+ + \pi^-$$

Cut on K0s inv Mass
Cut on 3π Miss Mass (Σ^+)
K0 Missing Mass -> $\Lambda(1405)$

Missing mass $\pi^+\pi^-\pi^-$



Missing mass $\pi^+\pi^-$



Conclusions I

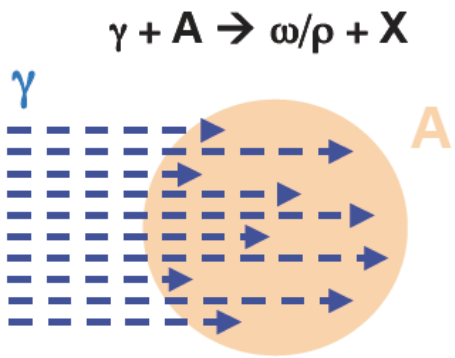
Threshold:

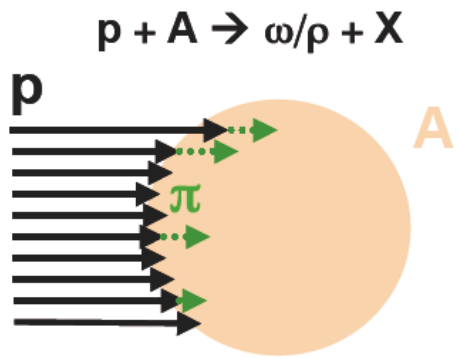
$\Sigma^- K^+$	$\approx$ 1.035 GeV/c
ΛK^0	$\approx$ 0.896 GeV/c
$\Sigma^0 K^0$	$\approx$ 1.031 GeV/c

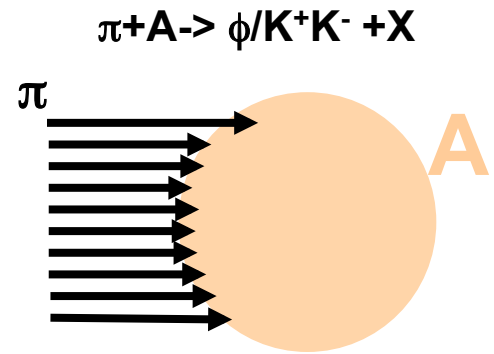
Enough stastics for PWA in 2 weeks of beam, even varying the energies.
-> Combined PWA

Λ(1405);
Threshold: Ekin= 1.3 GeV
4 HADES publications with **800 counts**
12.500 counts estimated for 25 days of beam

Production Cross-Section







Low Interaction Probability
-> Production in the whole volume

$\sigma(\text{prod}) \sim A$

Strong Interaction
-> Production close the surface
-> Production of secondary π

$\sigma(\text{prod}) \sim A^{0.8}$

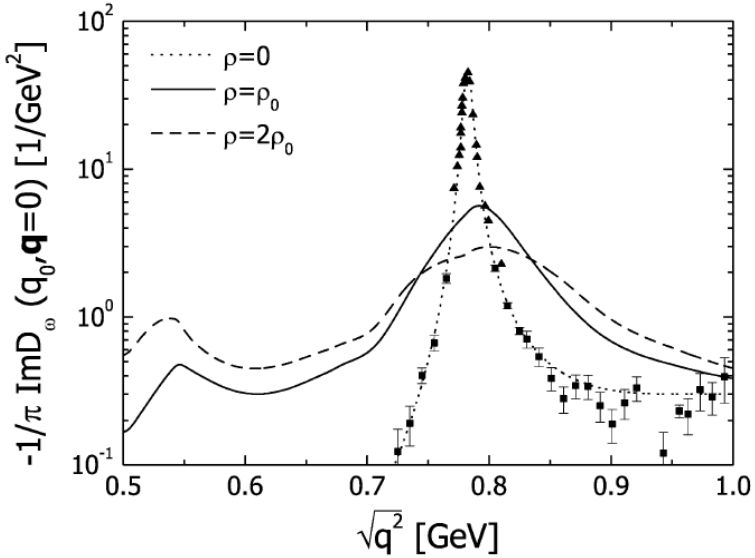
-> Production on the surface

$\sigma(\text{prod}) \sim A^{2/3} + ..$

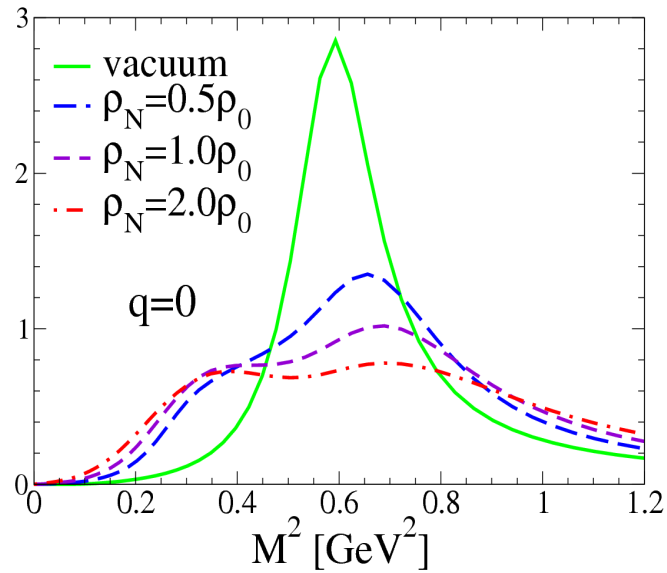
This is rather Model Dependent!!

Hadron In-Medium Modification

P.Mühlich et al.,NPA 780 (2006) 187



Urban et al.,1998



There are several scenarios.. 2 examples:

Old One: Brown-Rho scaling (1992)

$$m = m_0\left(1 - \alpha\frac{\rho}{\rho_0}\right)$$

One of the new: QCD Sum-Rules

$$-Q^2\int ds\frac{\mathrm{Im}\Pi_{Had}(s)}{(s+Q^2)s^2} = A(Q^2) + \frac{1}{Q^4}\left(B\cdot\langle\bar{q}q\rangle_{med} + C\cdot\langle G^2\rangle + \ldots\right) + \frac{1}{Q^6}\left(D\cdot\langle q^4\rangle + \ldots\right) + \ldots$$

Kaon in Matter

Mean Field Dynamics

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

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

Klein-Gordon equation with Mesons and Baryons as DOF

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

Effective or Modifies Kaon Mass

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

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

<u>How does the mass change as a function of the density of the environment?</u>

Strange condensate shows this dependency:

$$\frac{\left\langle \rho \middle| \bar{u}u + \bar{s}s \middle| \rho \right\rangle}{\left\langle \bar{u}u + \bar{s}s \right\rangle} \cong 1 - \frac{\Sigma_{KN}}{f_\pi^2 m_\pi^2}\rho + \ldots \quad \Rightarrow \quad m_K^{*2} = m_K^2 - \frac{\Sigma_{KN}}{f_\pi^2}\rho + \vartheta(k_F^4)$$

Our Understanding of the Potential

Fuchs et al., ...

VALID ONLY FOR KAONS

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

effective mass, it is the same for K^+ and K^-

$$V_\mu = \frac{3}{8f_\pi^2} j_\mu$$

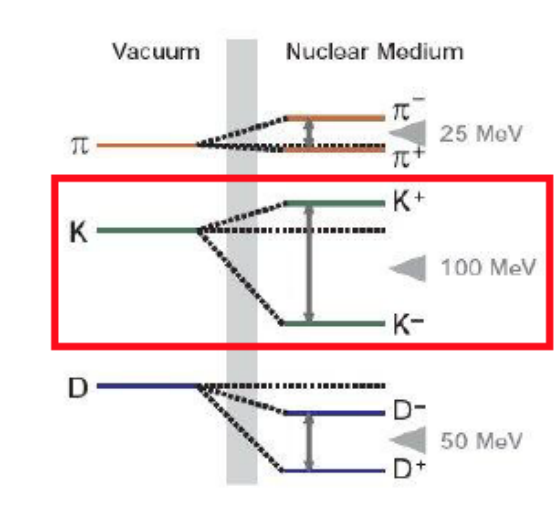
vector potential

$$k_\mu^* = k_\mu - V_\mu$$

effective momentum for K^0/K^+

$$E^* = \sqrt{k^{*2} + m_K^{*2}} + V_0$$

effective energy for K^0/K^+



Here no isospin splitting for K^+ and K^0, but can be implemented

Choice of the constants → strength of the potential

VALID ONLY FOR KAONS

As implemented by Theo

$\Sigma_{KN} = 450$ MeV

$f_\pi = 93$ MeV

$f_\pi^{*2} = 0.6 f_\pi^2$

$V_\mu = \frac{3}{8 f_\pi^{*2}} j_\mu$

in-medium pion decay constant appears only in the vector part of the potential

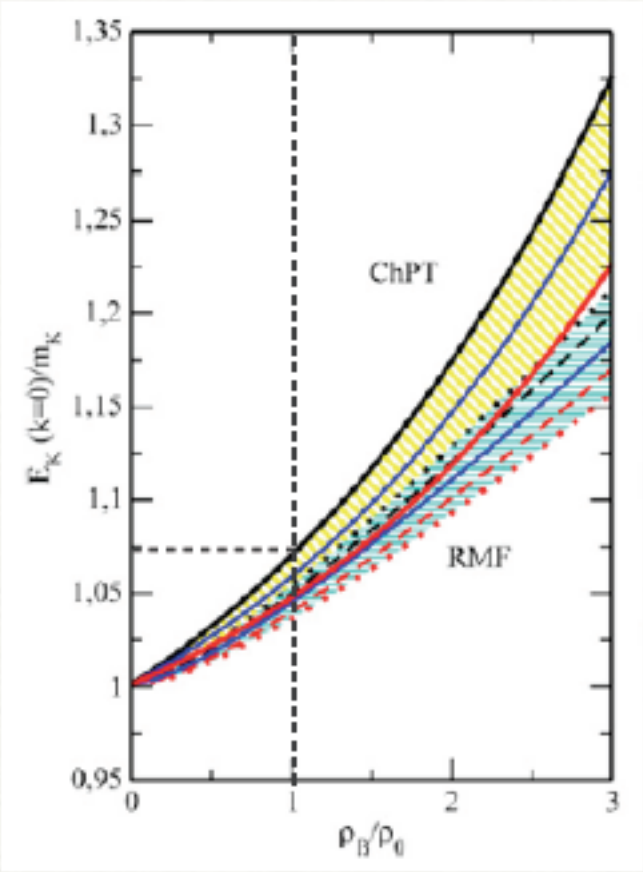
Another option (no chiral symmetry restoration effects)

$\Sigma_{KN} = 350$ MeV + vacuum pion decay constant

Is there another motivated choice of the constants?

ChPT kaon potential

VALID ONLY FOR KAONS



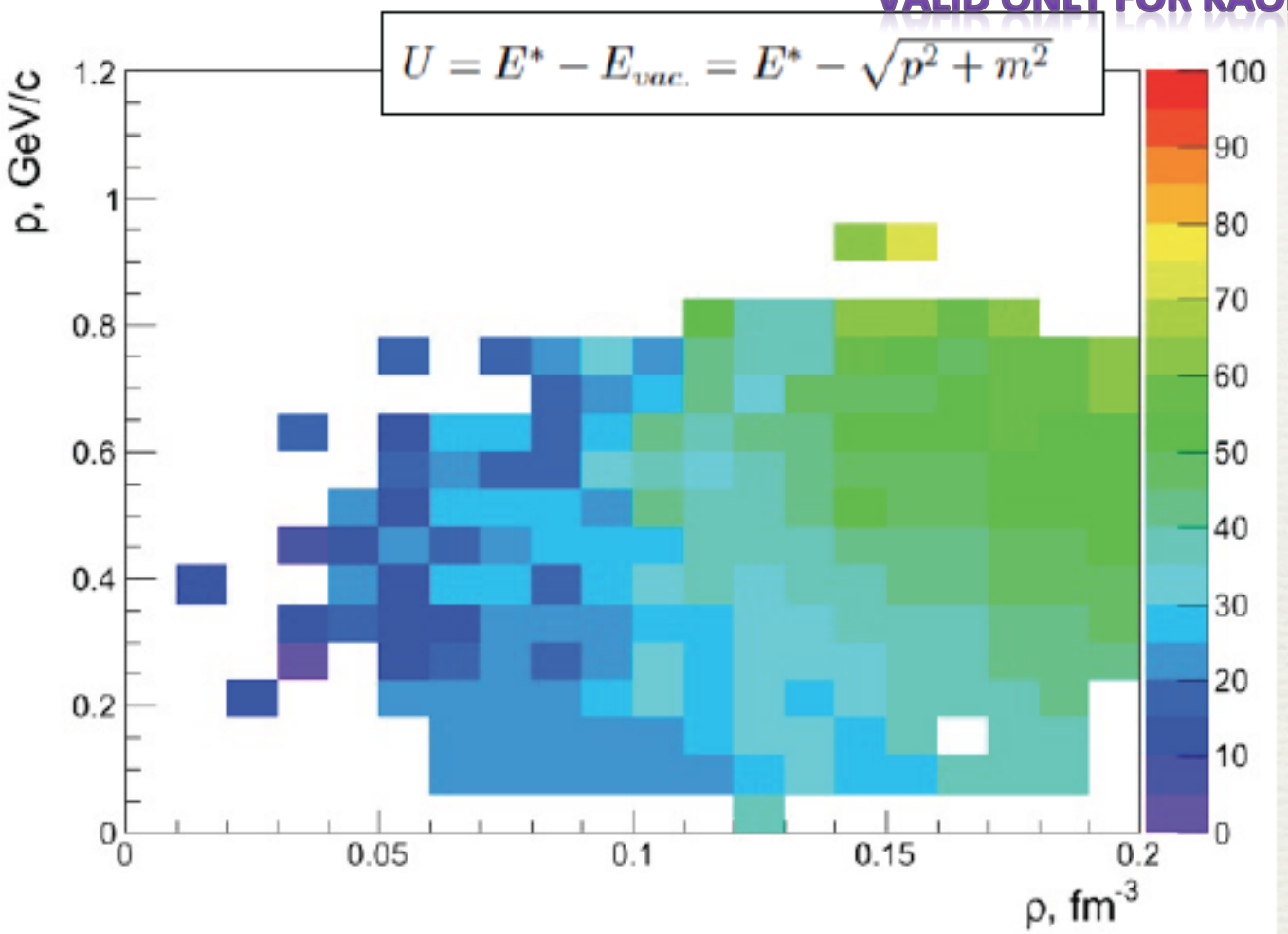
V. Prassa et al. Nucl.Phys. A789 (2007) 311

In-medium kaon potential as seen by kaons in pNb

Result of GiBUU simulations, pNb

most central collisions
beam energy E = 1.6 GeV

VALID ONLY FOR KAONS



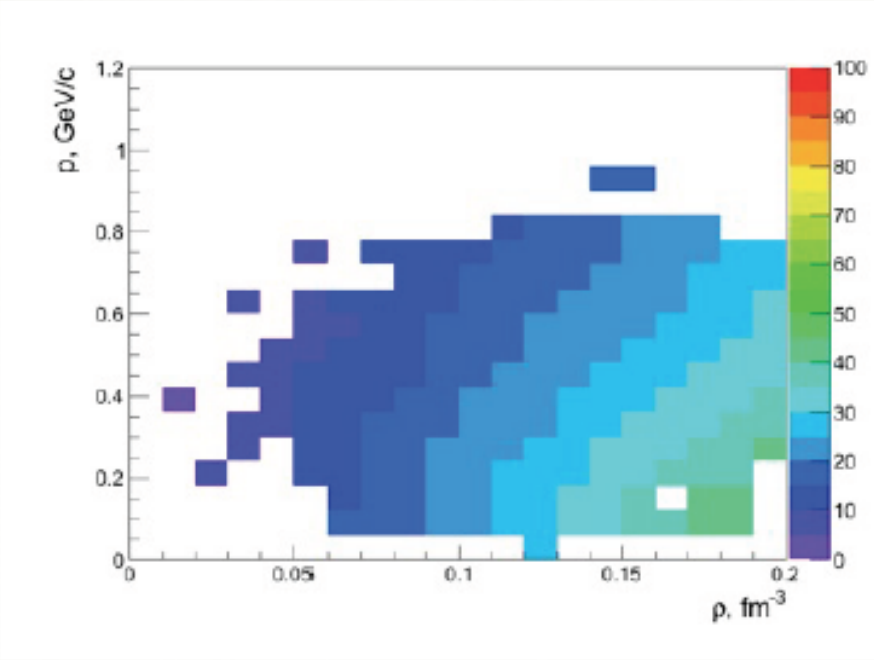
Toy potential vs. ChPT potential

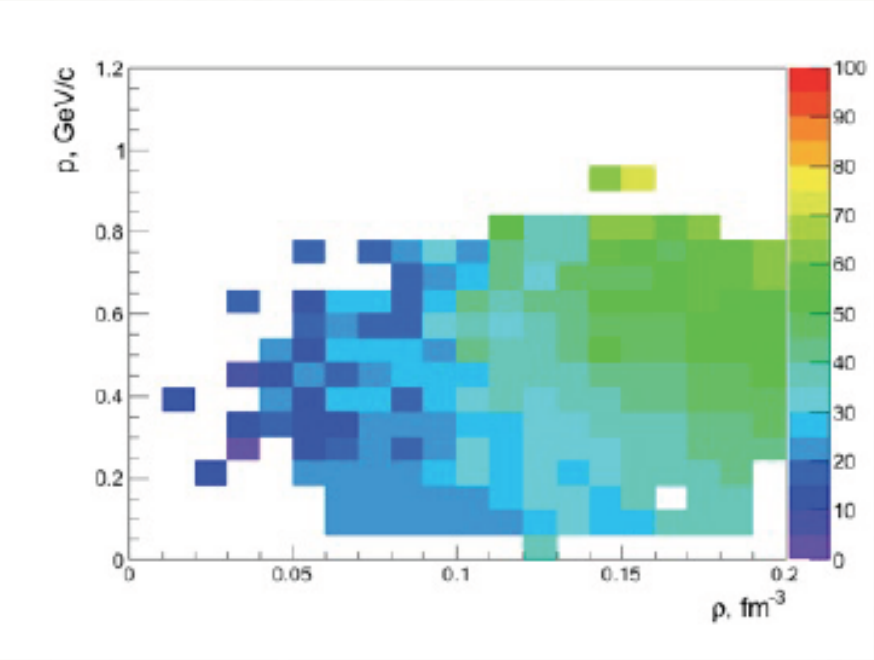
VALID ONLY FOR KAONS

$$m^* = m_{vac.} + U_0 \cdot \rho_B/\rho_0$$

$$E^* = \sqrt{m^{*2} + p^2}$$

$$U = E^* - E_{vac.} = E^* - \sqrt{p^2 + m^2}$$





approximately the same
strength set at p = 0, ρ = ρ0

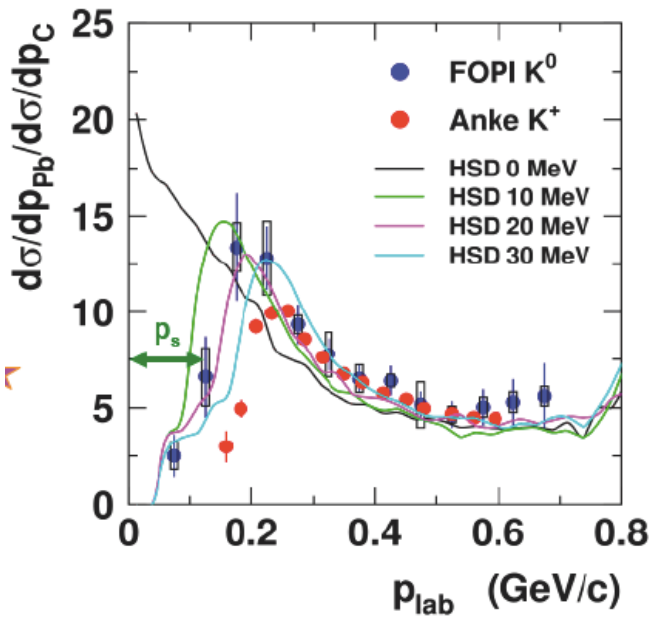
Status of K^0s in cold nuclear matter

Solid evidence of the shift of the Kaon mass (to be released on Friday)

Ar+KCL @ 1.756 AGeV HADES (Comparison with HSD and IQMD)

p+Nb @ 3.5 GeV HADES (Comparison to GIBUU)

π+A FOPI and ANKE but only compared to HSD and IQMD and small statistics (~2000 K)



M. L. Benabderramahne et al., Phys. Rev. Lett 102 183591 (2009)

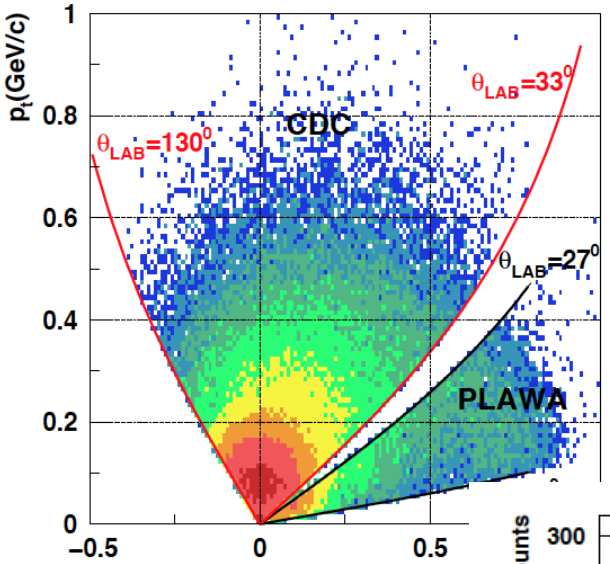
$\pi + A \rightarrow K^0 + X$ at 1.15 GeV/c (FOPI)

M. Büscher et al., EPJ A22, 301 (2004)

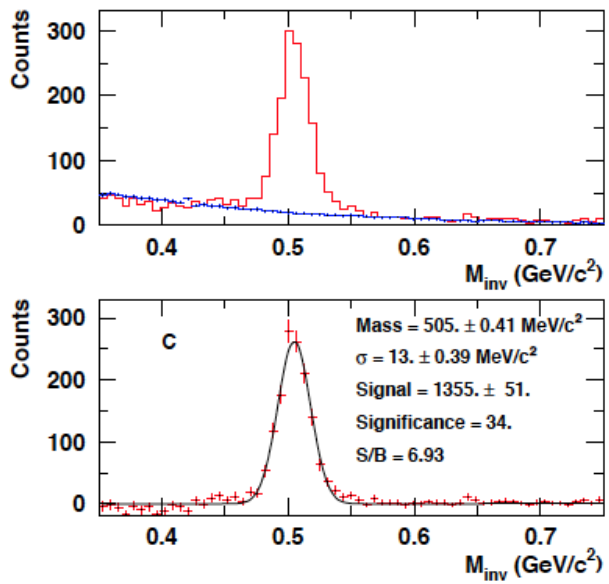
$p + A \rightarrow K^+ + X$ at 2.5 GeV/c (ANKE))

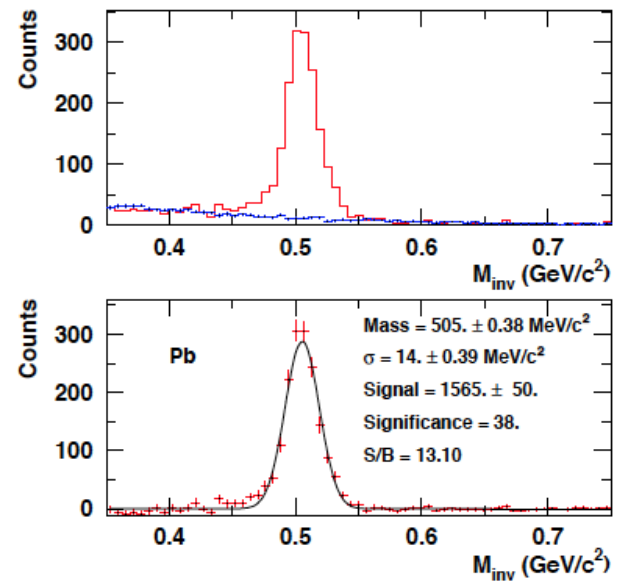
Available Statistics so far: KAONS

Covered Phase Space

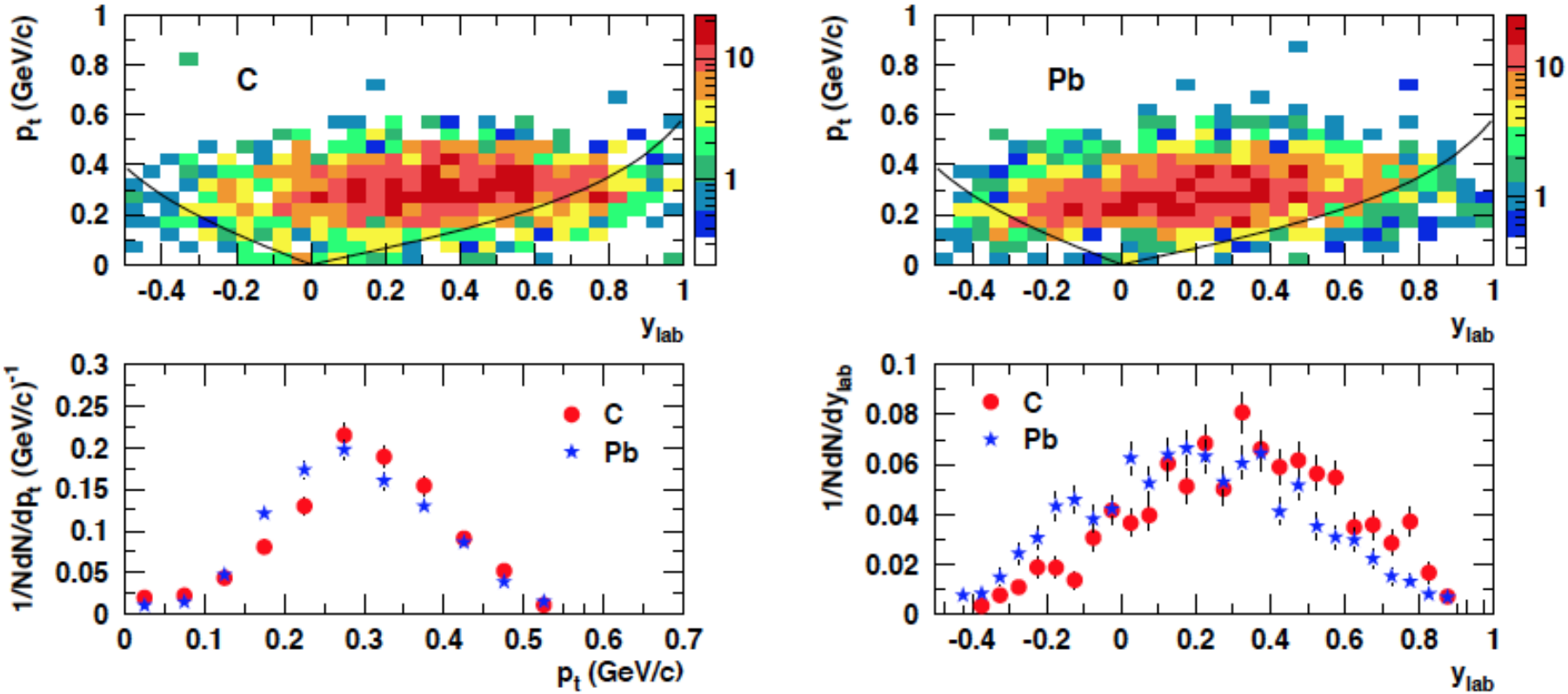


Target	Mass (MeV/c^2)	σ (MeV/c^2)
C (data)	505 ± 0.40	12.80 ± 0.40
C (simulation)	503 ± 0.40	12.58 ± 0.40
Pb (data)	505 ± 0.04	13.50 ± 0.40
Pb (simulation)	504 ± 0.33	13.75 ± 0.31



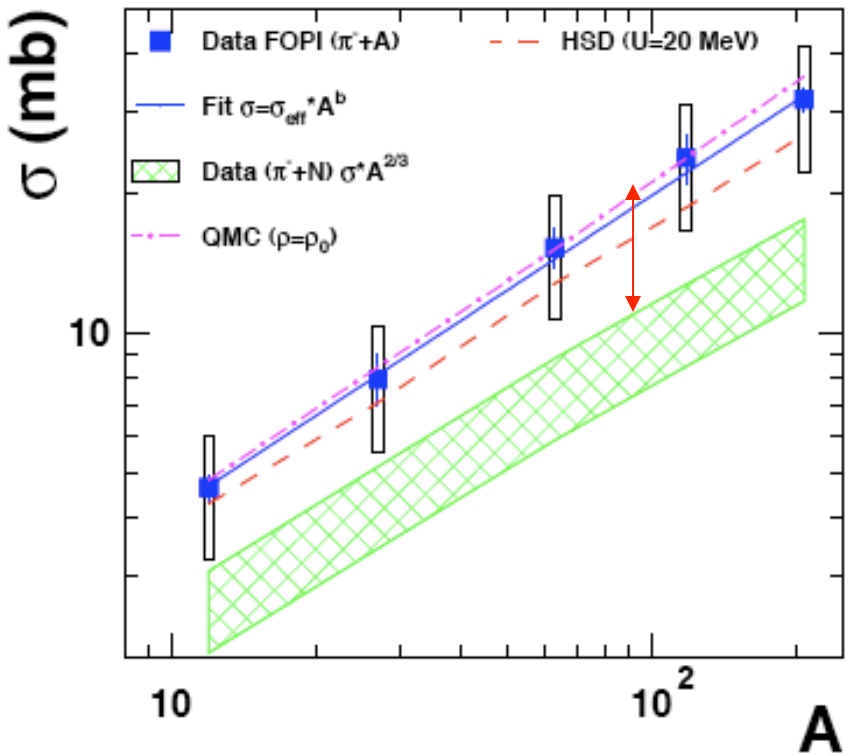


Phase Space Distribution fo K0s



Target	Number of recons. K_S^0	Number of K_S^0 in KINE	Efficiency in %
C	1150	61 820	0.93
Pb	1020	50 999	1.00

K^0_S Cross-Section π+A



$$\sigma\left(\pi^- + A \rightarrow K^0 + X\right) = \sigma_{eff} \cdot A^b$$

$$\sigma_{eff} = 0.87 \pm 0.13\ mb$$

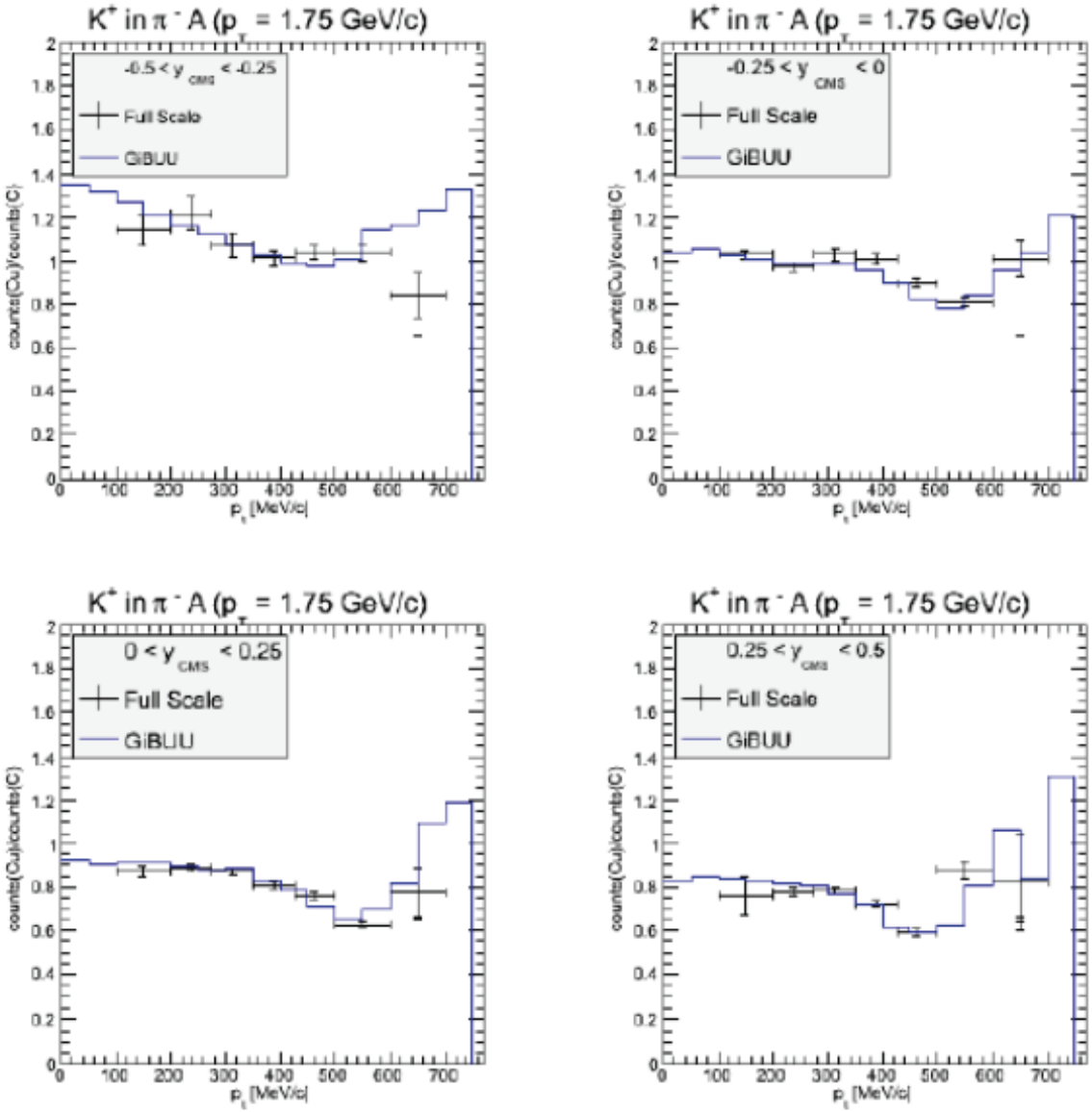
$$b = 0.67 \pm 0.03$$

Sum of elementary cross-section

Factor 2: Multiple-step processes?
Same Trend as a fc. of A

The A dependence of the Kaon production is more under control
Since K^+ and K^0_S are not absorbed in nuclear matter they can serve as reference for K^-

Reconstructed K⁺: Ratio



GiBUU ratio

Reconstructed Ratio

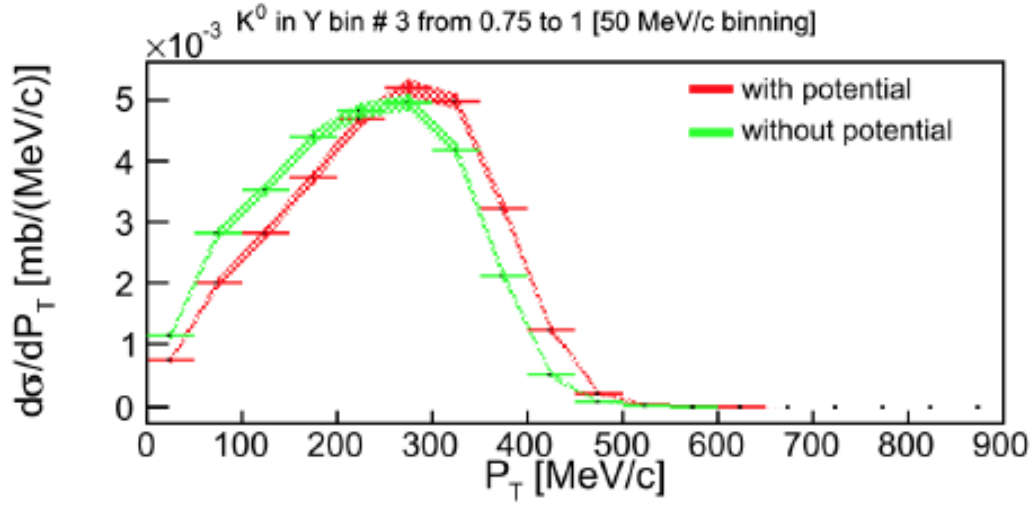
K+ Analysis:

dE/dy Cut

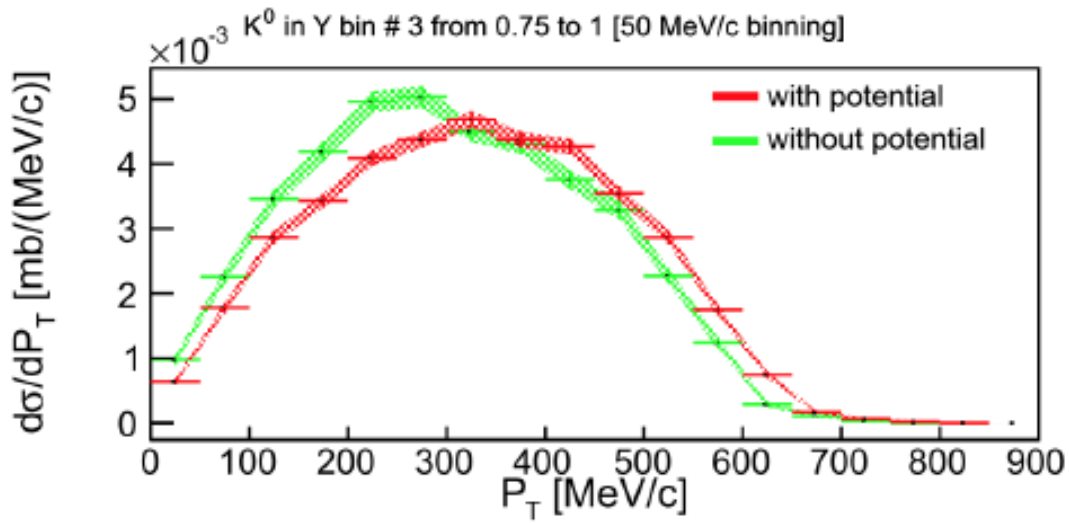
Comparison Low and High Beam Energy: K^0S

Model: GiBUU after Lapidus tuning

$$\pi^- + Cu@1.62\,\mathrm{GeV}$$



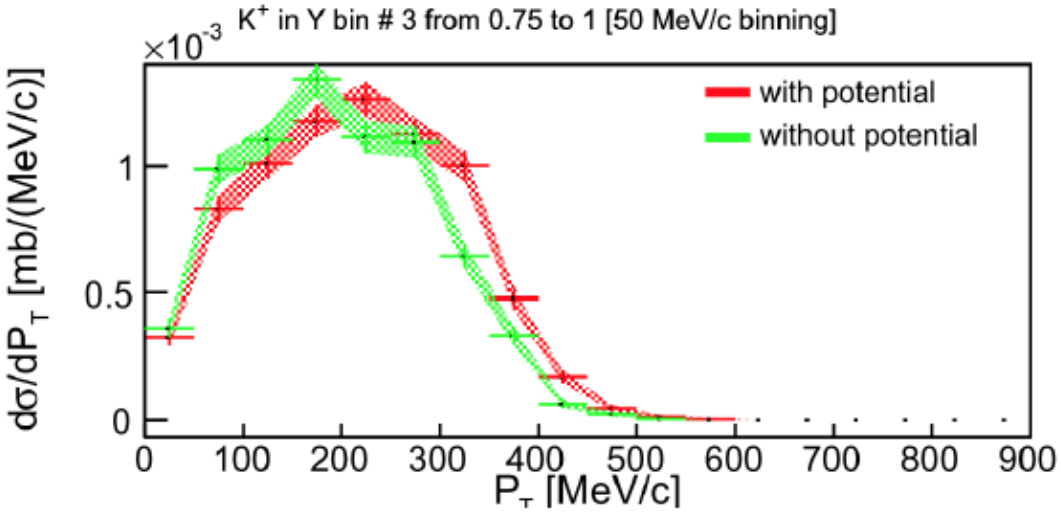
$$\pi^- + Cu@1.2\,\mathrm{GeV}$$



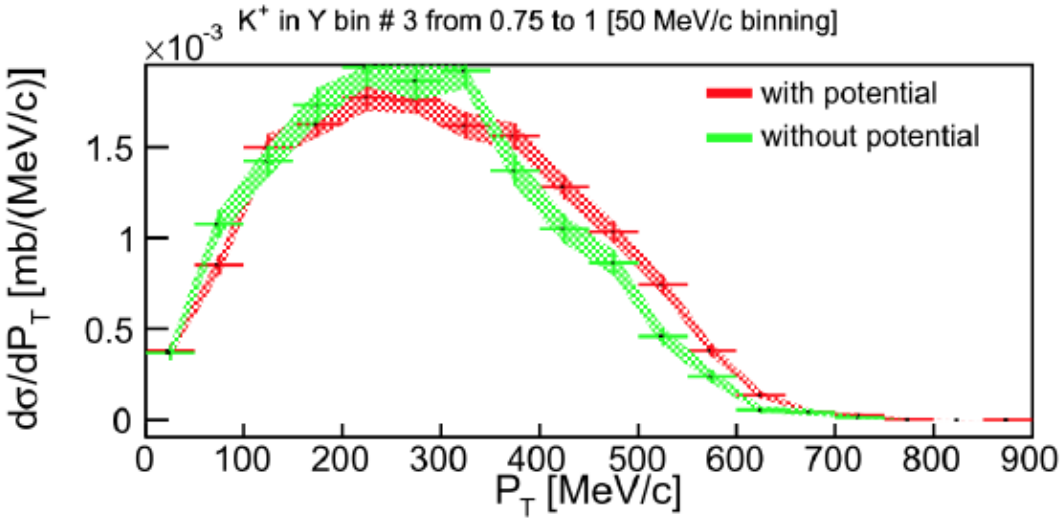
Comparison Low and High Beam Energy: K^+

Model: GiBUU after Lapidus tuning

$$\pi^- + Cu@1.62\,\mathrm{GeV}$$



$$\pi^- + Cu@1.2\,\mathrm{GeV}$$



Kaonic Atoms and Kaon Absorption

If one looks at ***kaonic atoms*** the optical potential used to parametrize the interaction looks like:

J. Yamagata et al. arXiv:nucl-th/0503039v3

$$2\mu V_{opt}(r) = -4\pi\eta a_{eff}(\rho)\rho(r) = -4\pi\eta(a_{K^-n}\rho + a_{K^-P}\rho) + 2\mu U_{Abs}$$

$$\eta = 1 + \frac{m_K}{M_N}$$

$$a_{K^-n}, a_{K^-p} = scattering \quad lengths$$ Real part only!

The Absorption part as comes from the imaginary part of a_{eff}
This value gives the absorption at **p=0**
How does this depends on the momentum?

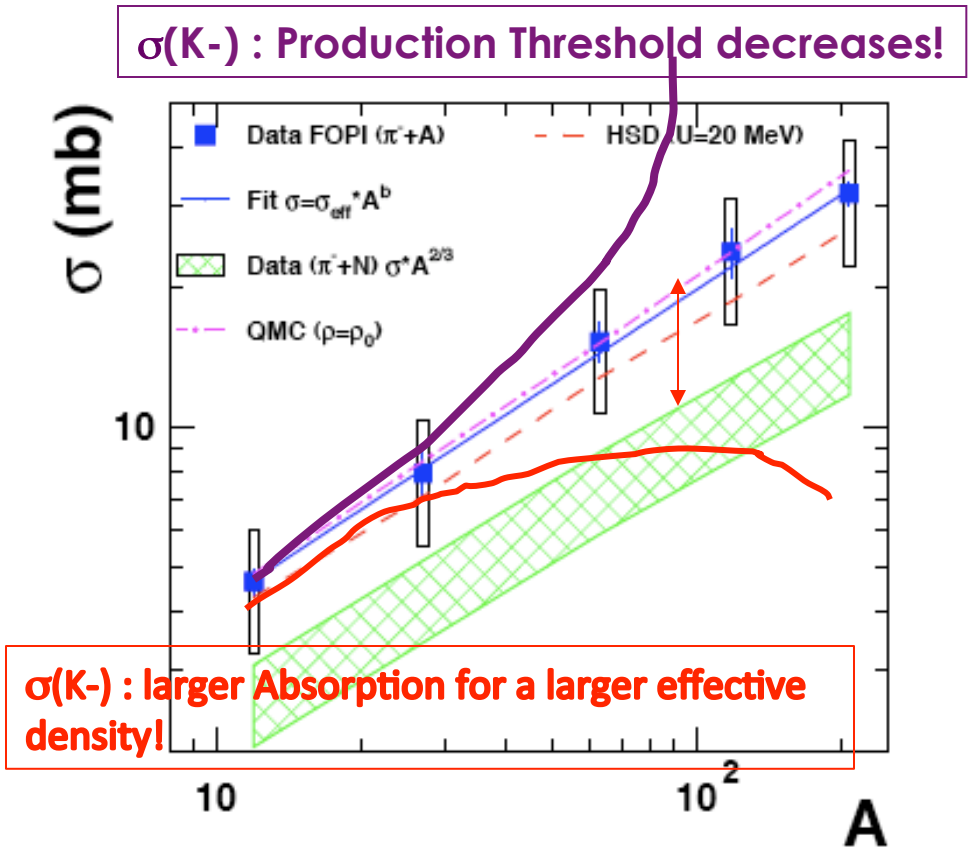
Method:

Inclusive K-
Tag of the K^- not coming from ϕ Decay via K^+K^- invariant Mass selection
To study absorption of K- without in-medium properties of ϕ

$$R = \frac{T_A}{T_C} = \frac{12\,\sigma^A_{K^-}}{A\,\sigma^C_{K^-}}$$

As a function of the Kaon Momentum!!

K^0_S Cross-Section



$$\sigma\left(\pi^- + A \rightarrow K^0 + X\right) = \sigma_{eff} \cdot A^b$$

$$\sigma_{eff} = 0.87 \pm 0.13\ mb$$

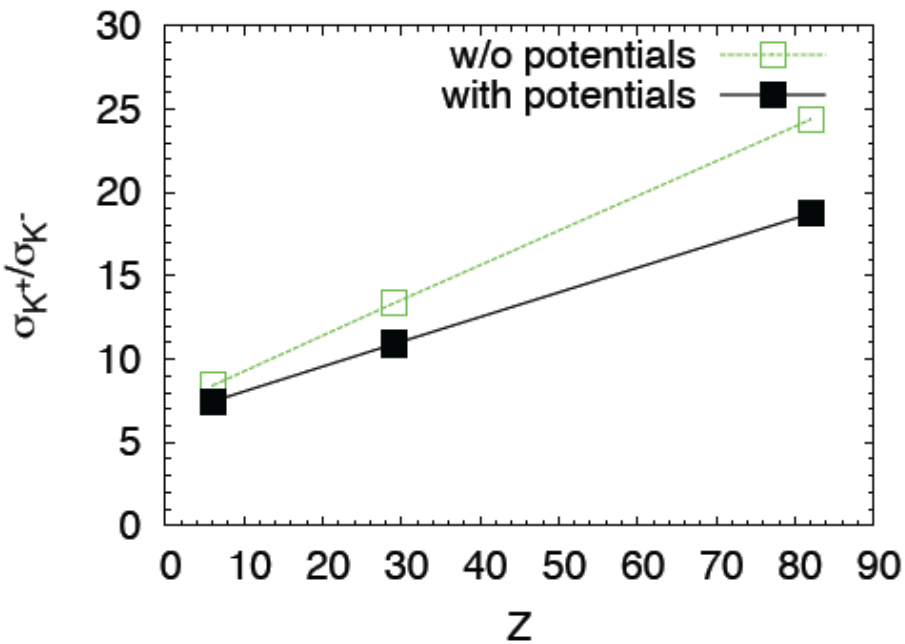
$$b = 0.67 \pm 0.03$$

Sum of elementary cross-section

Factor 2: Multiple-step processes?
Same Trend as a fc. of A

The A dependence of the Kaon production is more under control
Since K^+ and K^0_S are not absorbed in nuclear matter they can serve as reference for K^-

Calculations



BUU A. Larionov
Private communication

The A dependence of the Kaon production is more under control
Since K^+ and K^0_s are not absorbed in nuclear matter they can serve as reference for K^-

Expected Rates

With a 2.5% Interaction Target $\pi^- + p@1.7\,\mathrm{GeV/c}$

Target	Particle	Rate/day
Carbon	K^0_S	5×10^5
	K^+	5×10^5
	K^-	3×10^4
	ϕ	252
Copper	K^0_S	4.1×10^5
	K^+	5.8×10^5
	K^-	4×10^5
	ϕ	756
Wolfram	K^0_S	2.2×10^5
	K^+	3.4×10^5
	K^-	1.4×10^4
	ϕ	680

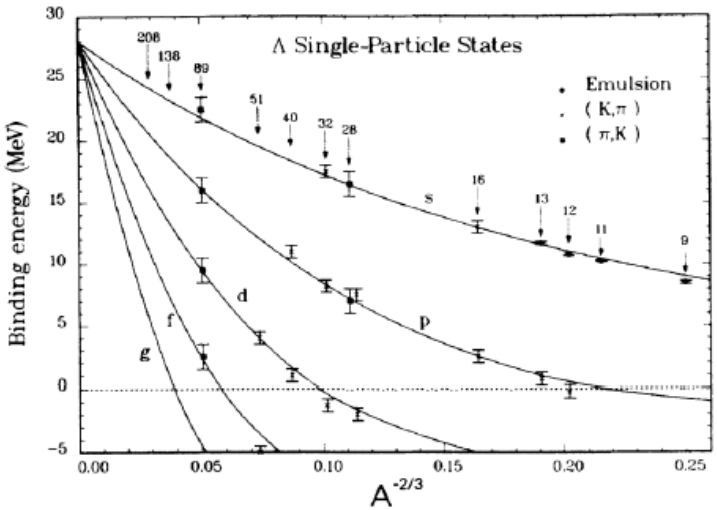
Λ

Motivation

Motivation of our work in Munich: Understand the properties and interactions of strange matter

In particular: Interaction of Λ hyperons

<u>What is often done (not by us):</u> Understand interaction with the use of hypernuclei data



D.J. Millener *et al.*, Phys. Rev. C **38** (1988) 2700

<u>Different approach:</u> Study experimental data in p+p and p+A reactions (low collective effects) with help of transport models

Femtoscopy gives us the possibility to investigate ΛN interaction in p+A reactions

Theoretical basics

Theoretical basics:

F. Wang, and S.Pratt, Phys. Rev. Lett. **83** (1999) 3138

$$C(\vec{p}_a, \vec{p}_b) = \frac{\mathcal{P}(\vec{p}_a, \vec{p}_b)}{\mathcal{P}(\vec{p}_a)\mathcal{P}(\vec{p}_b)} \approx \frac{\int d^4x_a\, d^4x_b S(p_a, x_a) S(p_b, x_b) |\phi_{rel}(\vec{p}_b - \vec{p}_a)|^2}{\int d^4x_a\, d^4x_b S_a(\vec{p}_a, x_a) S_b(\vec{p}_b, x_b)}$$

$S(p_i, x_i)$: Source function - Probability that a particle is emitted at x_i with momentum p_i

$\phi_{rel}(\vec{p}_b - \vec{p}_a)$: relative wavefunction between both particles

→ includes all final state interactions (correlations) between the emitted particles

Correlated particles: pp

repulsive:
- Quantum statistic
- Coulomb interaction

attractive:
- Strong interaction

Correlated particles: Λp

- Quantum statistic
- Coulomb interaction
- Strong interaction } attractive

In p+A and π+A collective effects should be negligible so that the correlation depends Only on the strong scattering length.
Studies are currently carried out.

Conclusion II

- First π+A large statistics sample for Kaons, Antikaons and Lambda
- ☺