Strangeness in Nucleus

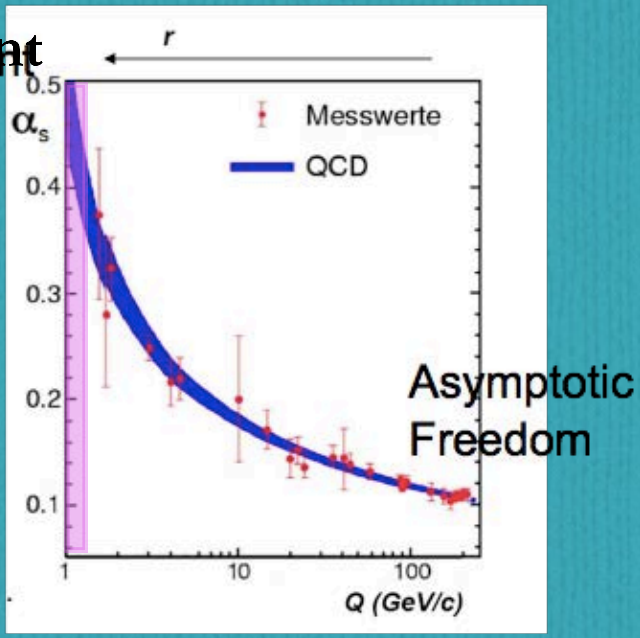
L. Fabbietti
Technische Universitaet Muenchen
Excellence Cluster "Origin and Structure of the Universe"
https://www.e12.ph.tum.de/groups/kcluster
Utrecht University WS2014-15

O. Arnold, Jia-Chii Berger-Chen, T. Gaitanos, K. Lapidus, J. Weil

- K^0_s in p+A reactions: detailed studies of the production and interaction
- Λ-p femtoscopy in p+A collisions: a new method to test the Hyperon-Nucleon interactions

Effective Strange Hadron-Hadron Interaction

Confinement



Small Q (~1 GeV)

Large Distances (1 fm)

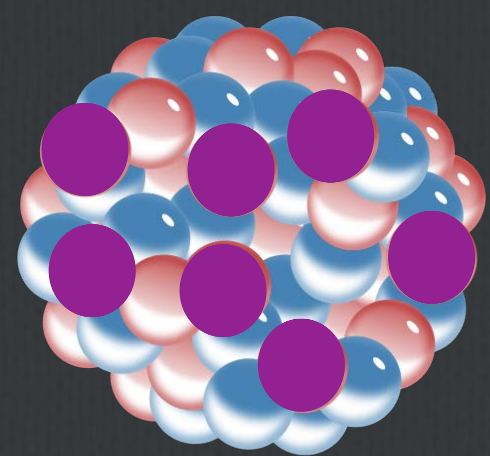
Effective Field Theory of interacting Hadrons

- Test-bed of the strong interaction in few body systems
- Strange quarks are intermediate between "light" and "heavy"

-> Interplay between spontaneous and explicit chiral symmetry breaking in low energy QCD.

- Testing ground: K-N and $\bar{K}$-N interactions

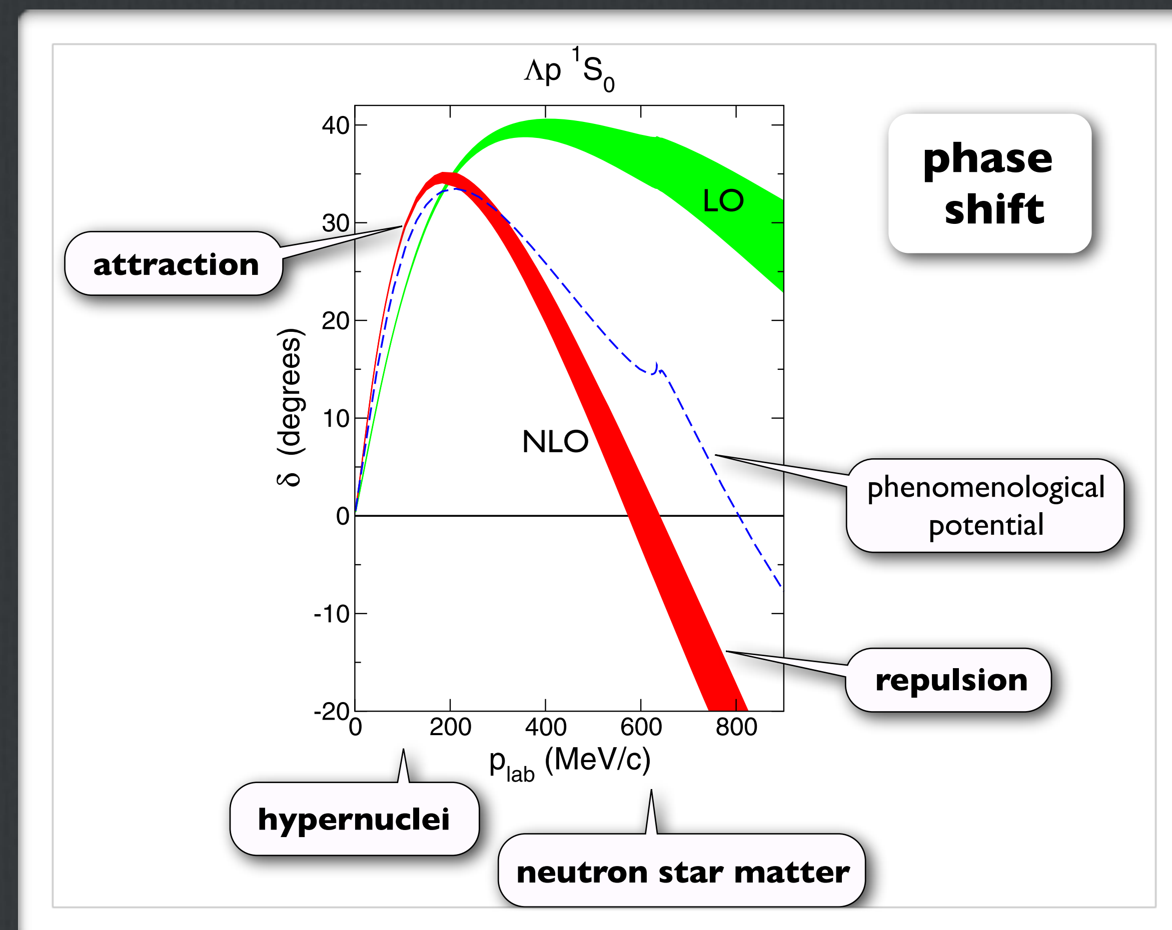
Hyperon Star



Neutron

Λ

J. Haidenbauer, S. Petschauer et al., Nucl. Phys. A 915 (2013) 24



← Λ-p distance

Possible Processes:

$$n + n \rightarrow n + \Lambda$$

$$p + e^- \rightarrow \Lambda + \nu_{e^-}$$

$$n + n \rightarrow p + \Sigma^-$$

$$n + e^- \rightarrow \Sigma^- + \nu_{e^-}$$

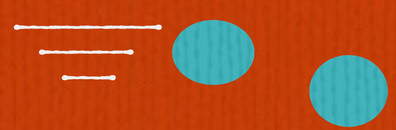
It all depends upon the Λ-N and Λ-NN interaction and whether or not it has a repulsive core

This repulsive core could stiffen again the EOS allowing for heavy neutron stars

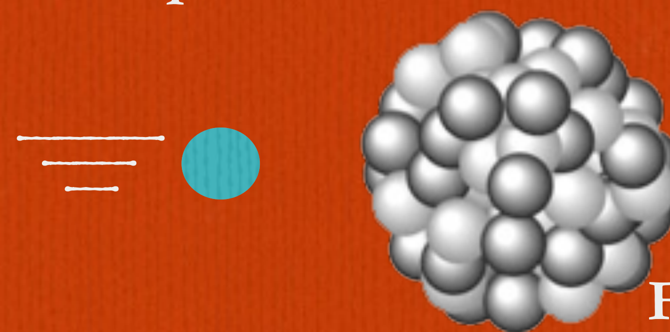
Reactions in the GeV Energy Range

Fixed Target experiments, E_{kin}~ AGeV

proton-proton

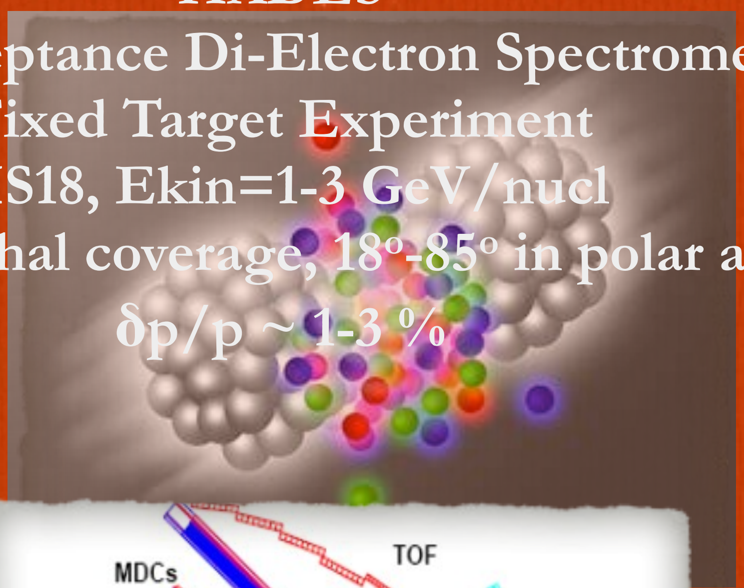


proton-nucleus



Heavy-ion Collisions ϱ_B <2-3 ϱ_0

HADES



High Acceptance Di-Electron Spectrometer

Fixed Target Experiment

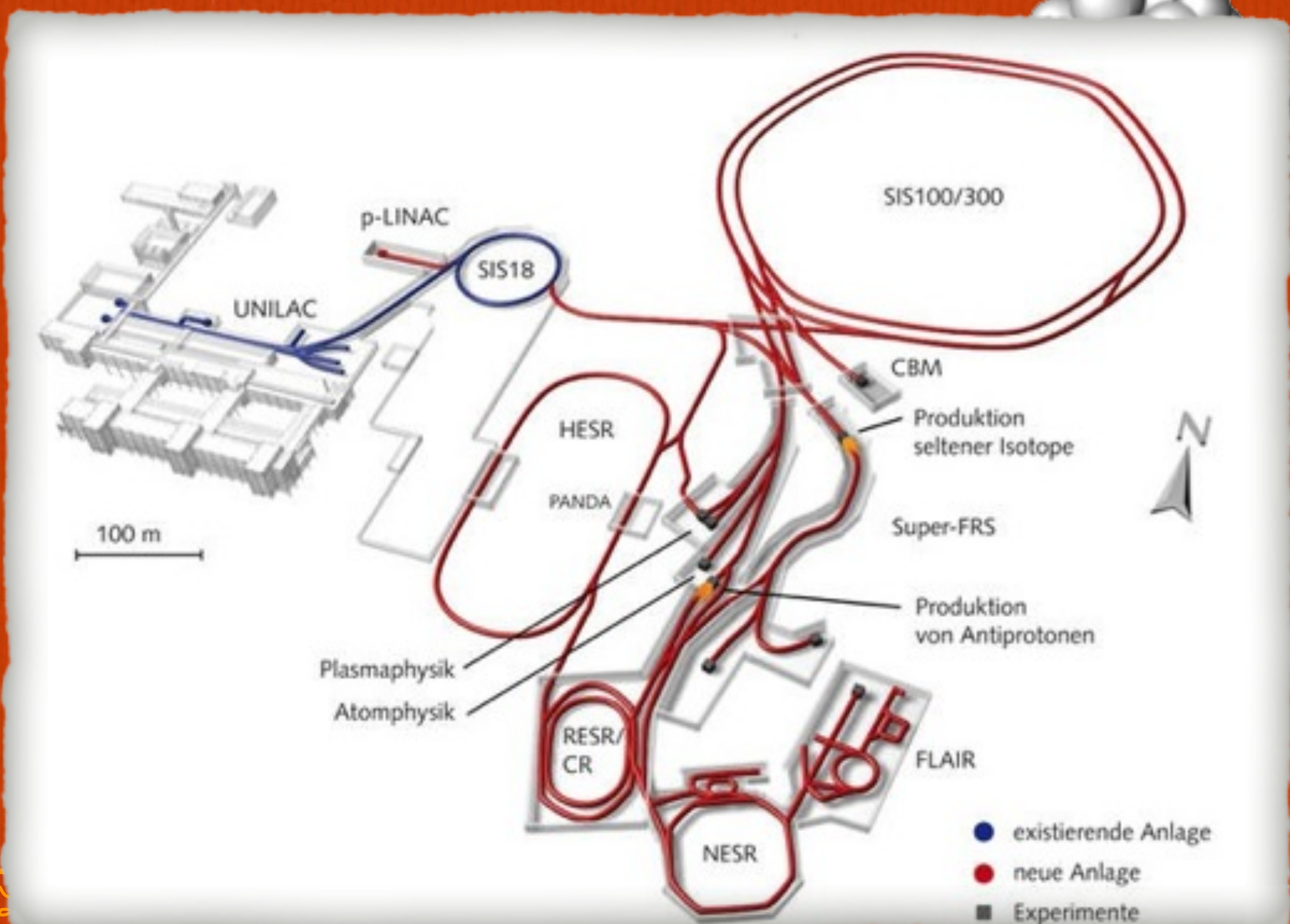
SIS18, Ekin=1-3 GeV/nucl

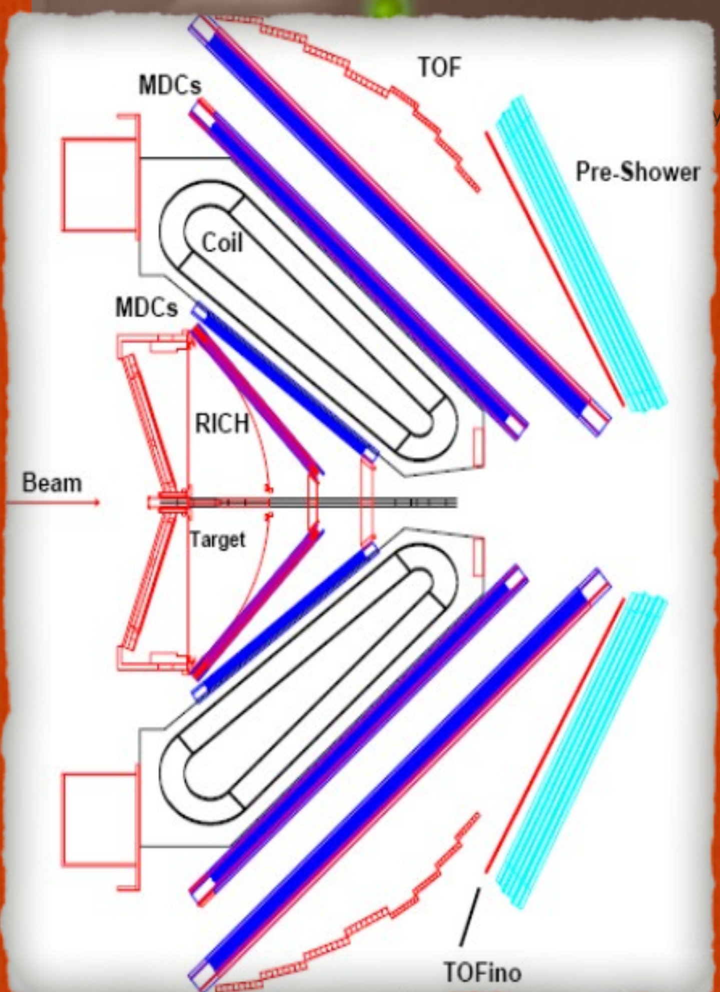
Full azimuthal coverage, 18°-85° in polar angle

$\delta p/p$ ~ 1-3 %

π-proton

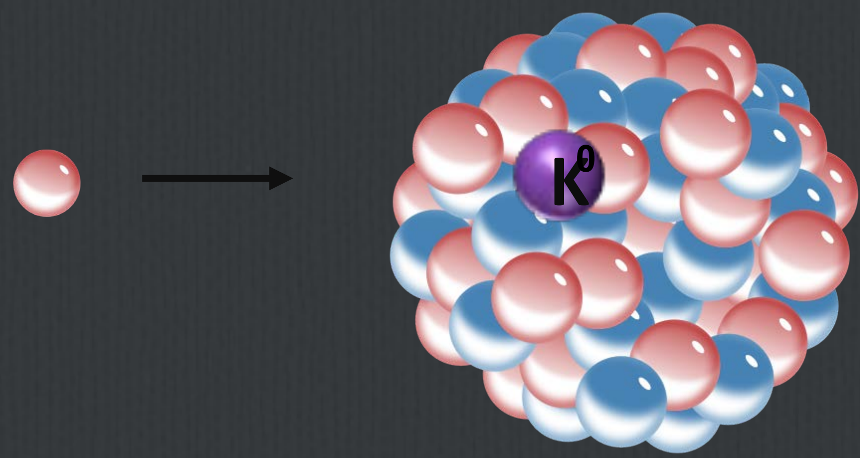
π-nucleus

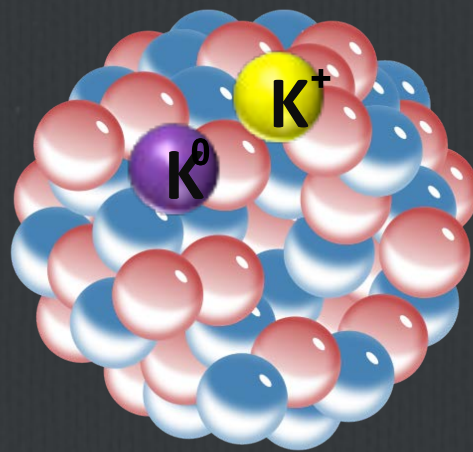


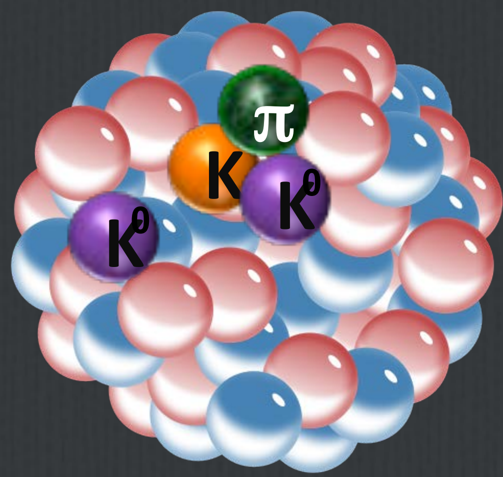


Kaons in the Nucleus

p+Nb, 3.5 GeV







Kaon interactions in nuclear medium:

- Elastic scattering
- Charge Exchange
- Inelastic reactions
- π-induced secondary reactions…

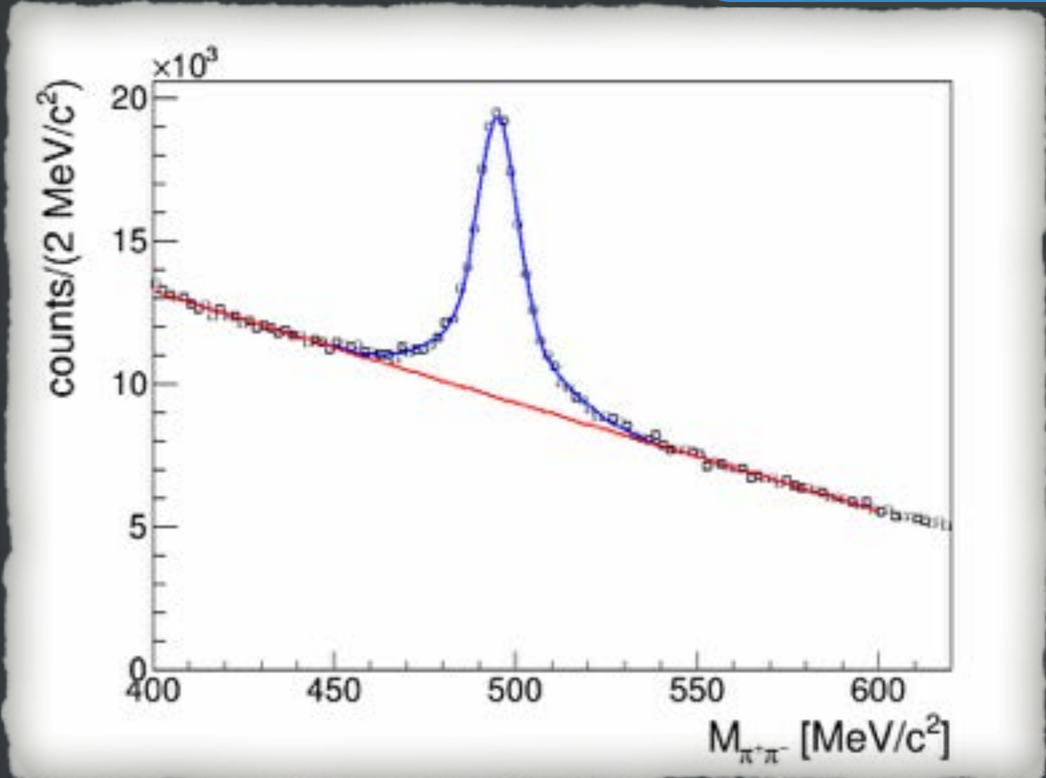
K^0_S Detection in p-induced reactions

“Associate K0 production in p+p collisions at 3.5 GeV: the role of the Δ(1232)++, G. Agakishiev et al. (HADES Coll.) Phys. Rev C90 (2014) 015202
“*Medium effects in proton-induced K^0 production*” G. Agakishiev et al. (HADES Coll.) Phys. Rev. C90 (2014) 054906

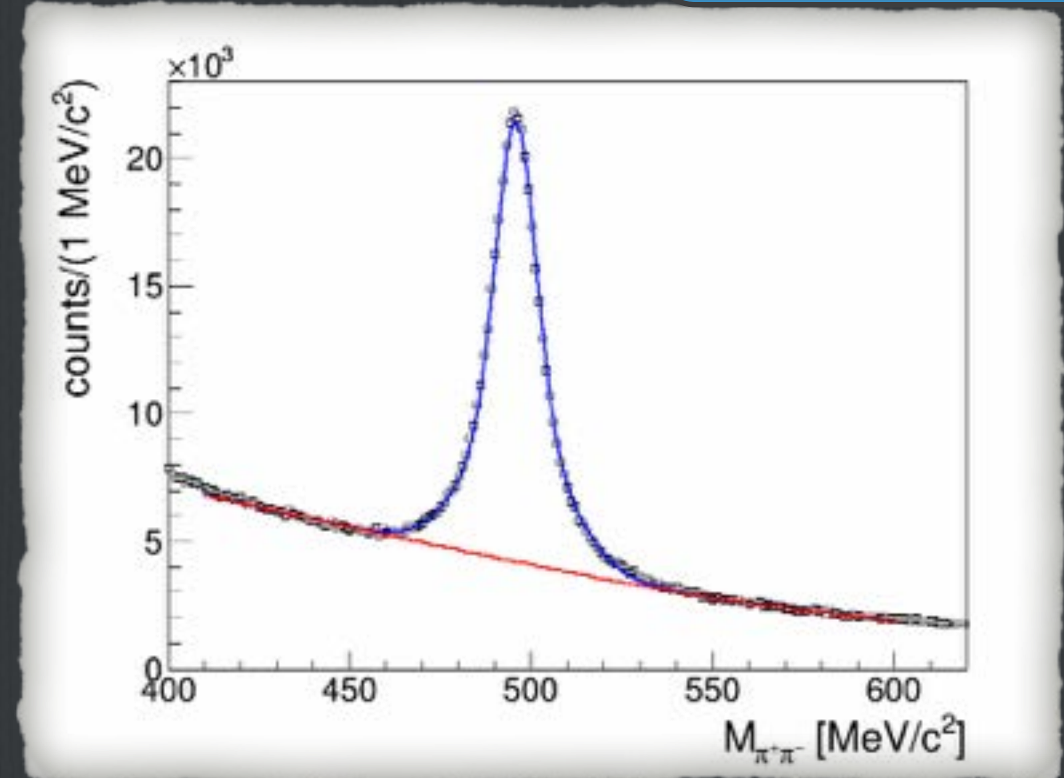
J.-C. Chen, K. Lapidus

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

vacuum $\varrho_B = 0$ p+p at 3.5 GeV



in-medium $\varrho_B \leq \varrho_0$ p+Nb at 3.5 GeV



Data are interpreted with the GiBUU transport model

O. Buss et al., Phys. Rept. 512, 1 (2012)
http://gibuu.physik.uni-giessen.de/GiBUU/

K^0 in p+p: reference measurement

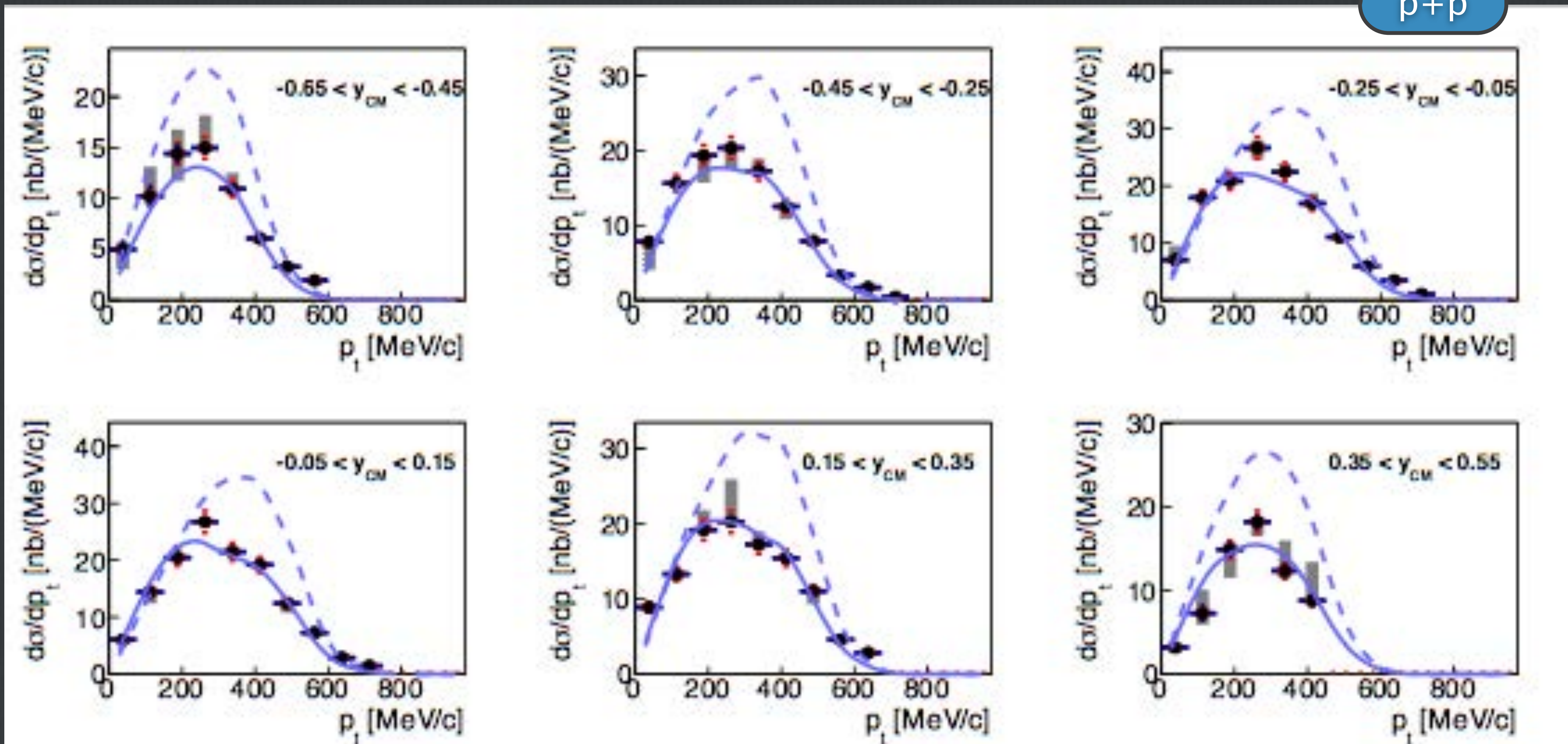
J.-C. Chen, K. Lapidus

- - - - Tsushima

—— Tsushima improved

G. Agakishiev et al. (HADES Coll.) Phys. Rev C90 (2014) 015202

p+p



- 4-body states produced via Δ-resonances
- Final states with two pions (5-body) added to the model via NN $\rightarrow \Delta^{++}$ Y* K, Y* is $\Sigma(1385)$ or $\Lambda(1405)$.
- Good description of the elementary reference.

In-medium kaon potential

T. Gaitanos, K. Lapidus

ChPT potential, ~35 MeV (ϱ=ϱ₀, k=0)

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

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

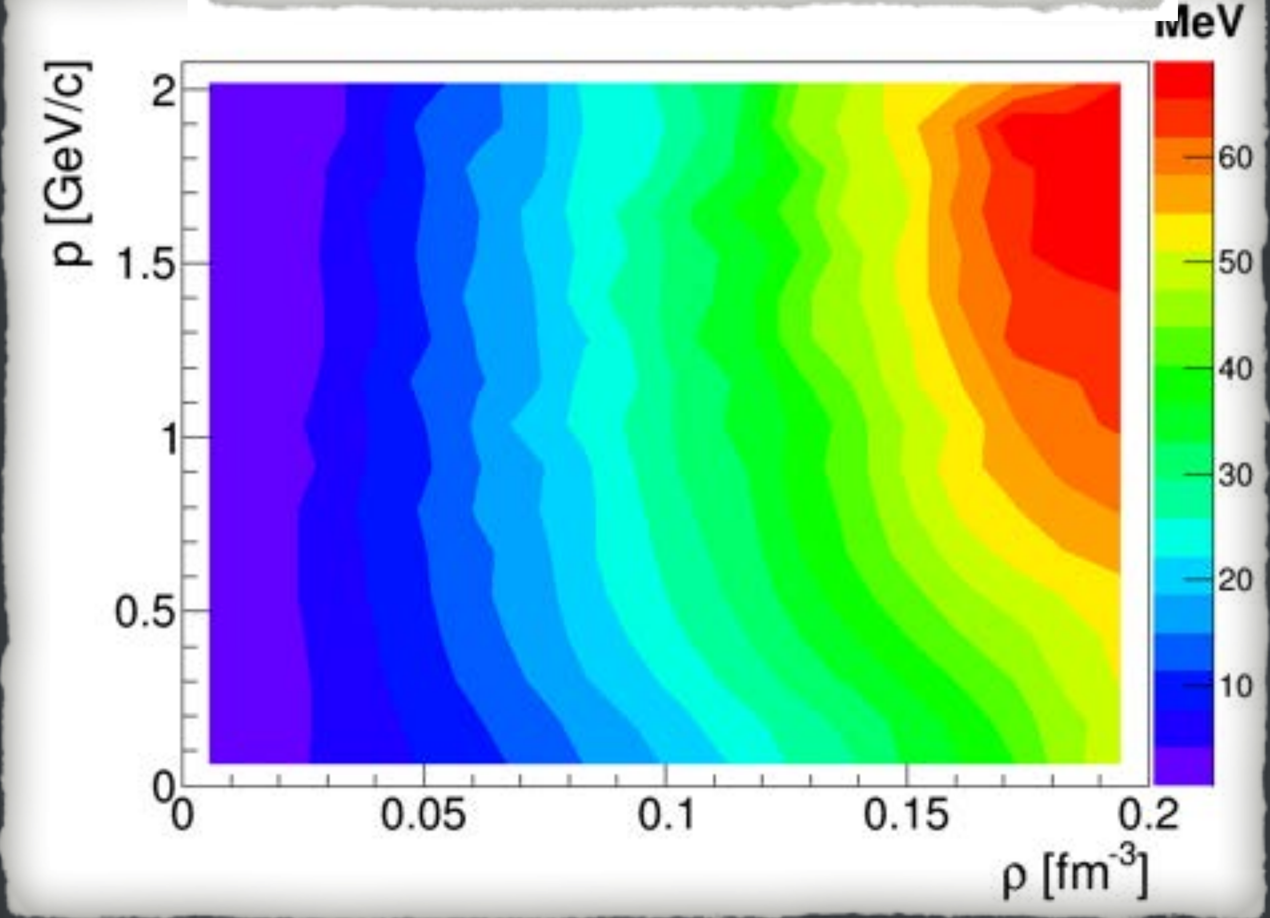
$$E^* = \sqrt{\mathbf{k}^{*2} + m_K^{*2}} + V_0$$

$$\mathbf{k}^* = \mathbf{k} - \mathbf{V}$$

$$\Sigma_{KN} = 250 - 450\,\mathrm{MeV}$$

$$f_\pi = 93\,\mathrm{MeV},\ f_\pi^{*2} = 0.6 f_\pi^2$$

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



For nuclear matter at rest <V$_{1,2,3}$> = 0 ⇒ k* = k

$$U = \sqrt{\mathbf{k}^{*2} + m^{*2}} + V_0 - \sqrt{\mathbf{k}^2 + m_{vac.}^2},\ m* < m$$

Effect of the potential in p+Nb: p_t-y

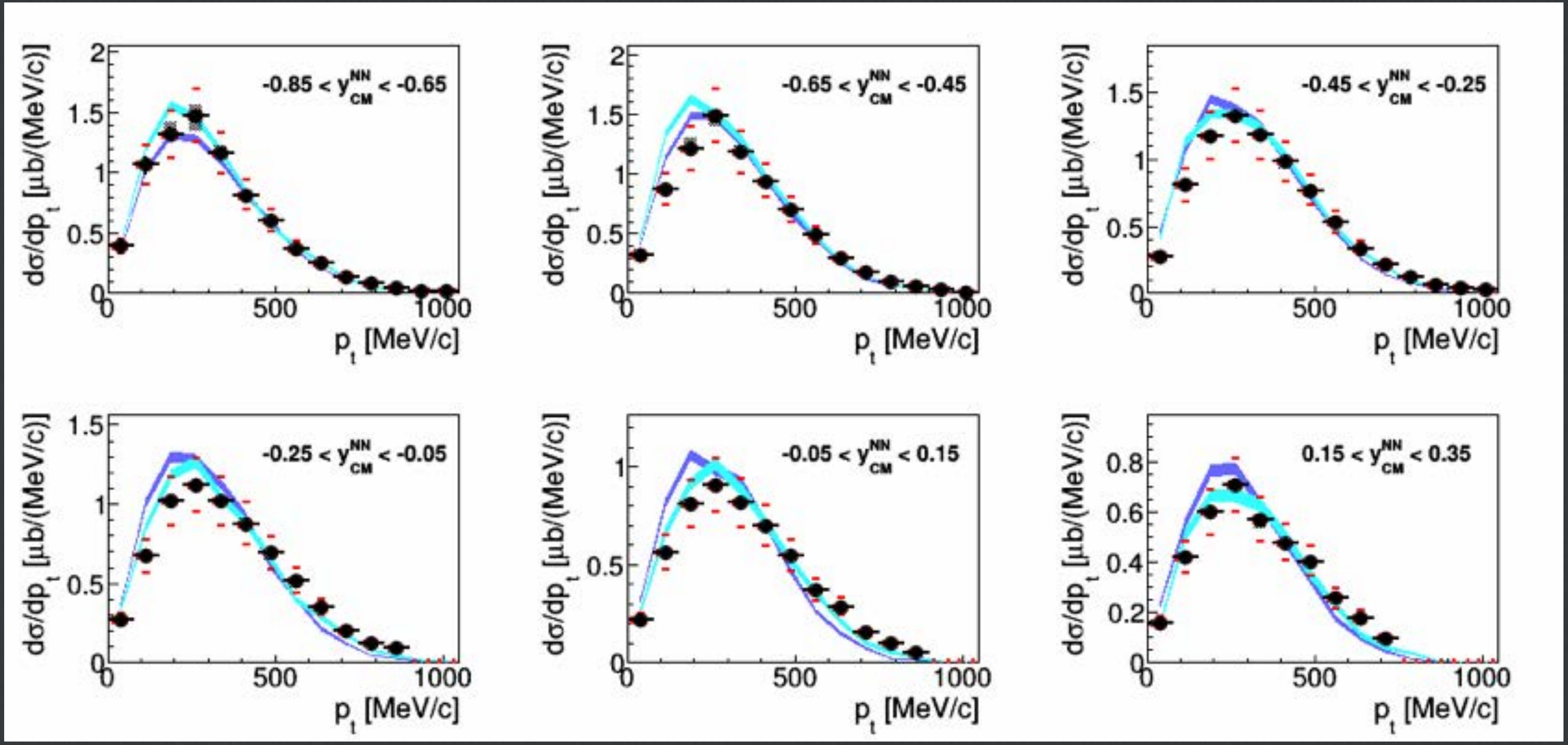
K. Lapidus

p+Nb

GiBUU w/o pot.

GiBUU w. pot.

G. Agakishiev et al. (HADES Coll.) Phys. Rev. C90 (2014) 054906

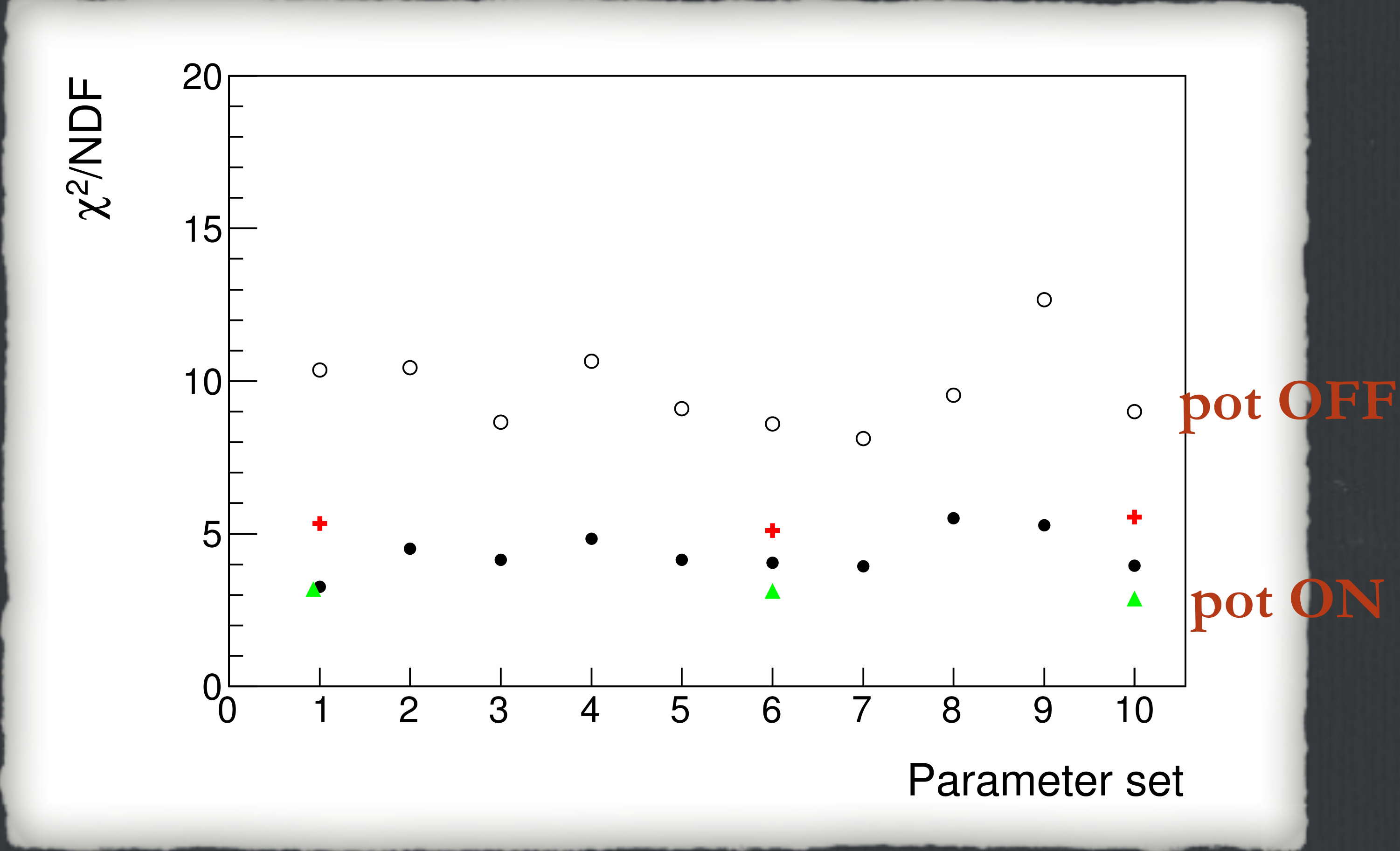


- Systematical modification of p_t-spectra owe to the repulsive potential.
- Uncertainties in the model parameters (np cross sections, …).

χ^2 Analysis

K. Lapidus

G. Agakishiev et al. (HADES Coll.) Phys. Rev. C90 (2014) 054906

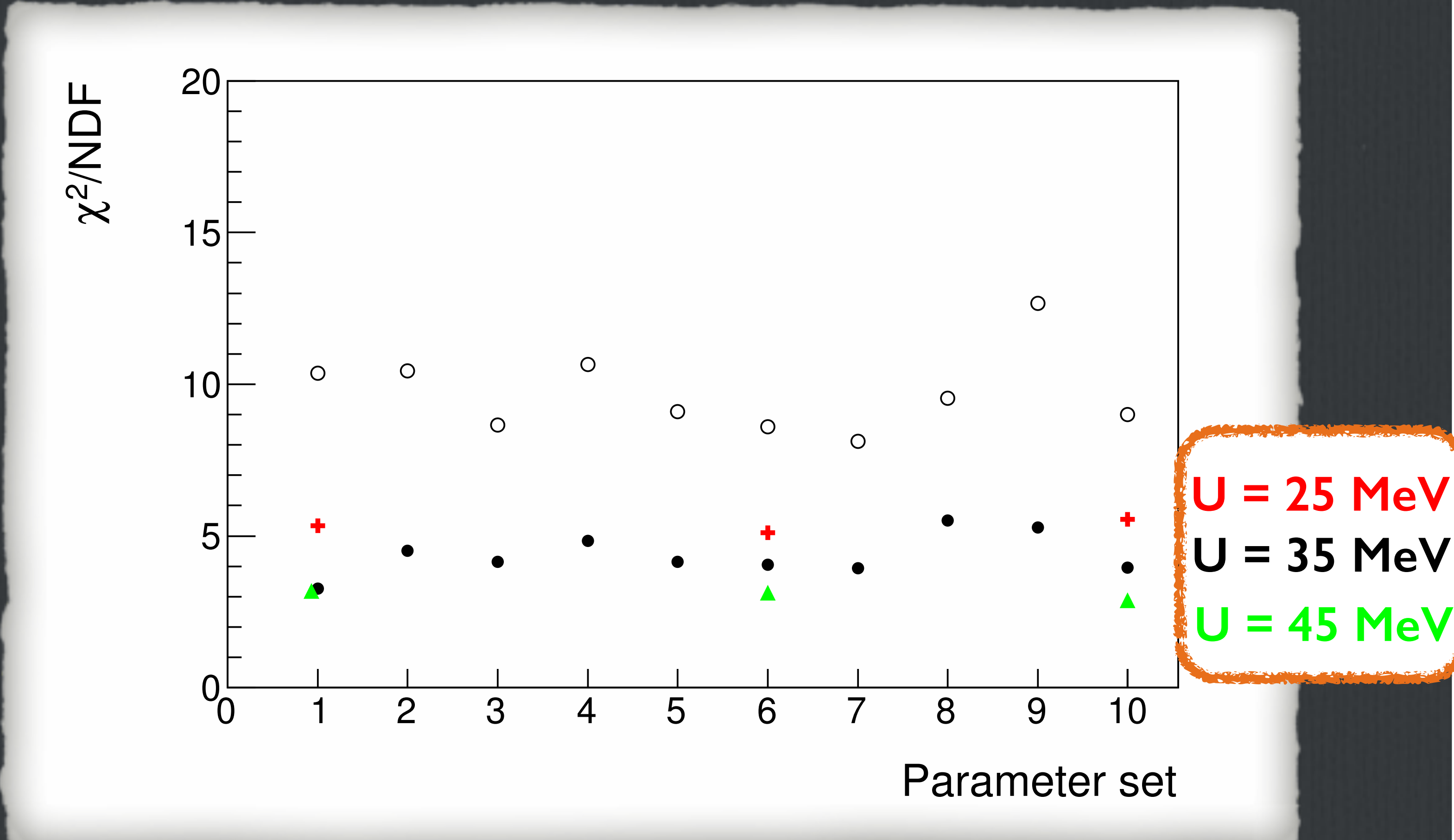


Set	Meaning
1	"standard"
2	ΔN +25%
3	ΔN −25%
4	πN +25%
5	πN −25%
6	np3 +25%
7	np3 −25%
8	KN +25%
9	KN −25%
10	np3 +30% & 5b −30%

χ^2 Analysis

K. Lapidus

G. Agakishiev et al. (HADES Coll.) Phys. Rev. C90 (2014) 054906



Set	Meaning
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5	πN −25%
6	np3 +25%
7	np3 −25%
8	KN +25%
9	KN −25%
10	np3 +30% & 5b −30%

Potential strength is adjusted by changing:

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

$$U = \sqrt{\mathbf{k}^{*2} + m^{*2}} + V_0 - \sqrt{\mathbf{k}^2 + m_{vac.}^2}, \quad m* < m$$

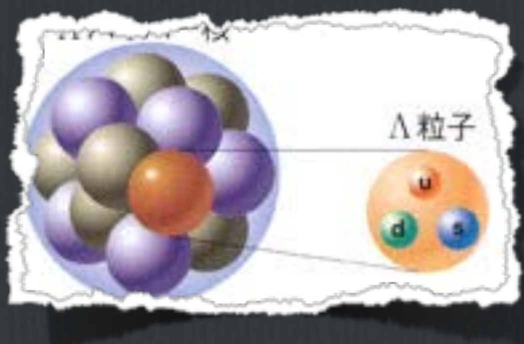
All the results

System (energy)	Experiment	Kaon potential at ρ p=0 [MeV]
π+A (1.02 GeV)	FOPI	20 ± 5
p+A (2.3 GeV)	ANKE	20 ± 5
Ar+KCl (1.76 GeV)	HADES 1)	39
p+Nb (3.5 GeV)	HADES 2)	40 ± 5

FOPI: M. Benabderrahmane et al.,
Phys. Rev. Lett. 102 (2009) 182501.

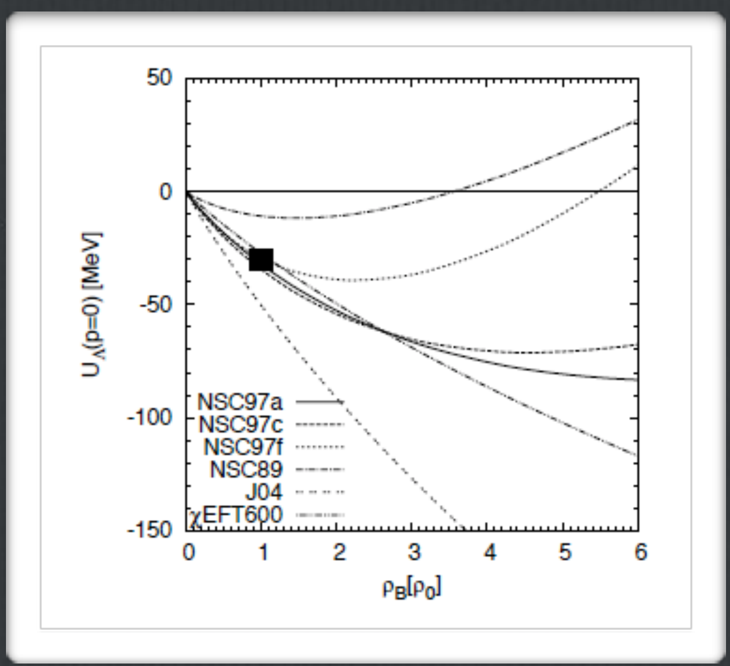
HADES: 1) G. Agakishiev et al., Phys. Rev. C 82 (2010) 044907;
2) Phys. Rev. C90 (2014) 054906.

Hyp-N: Experimental Evidence I



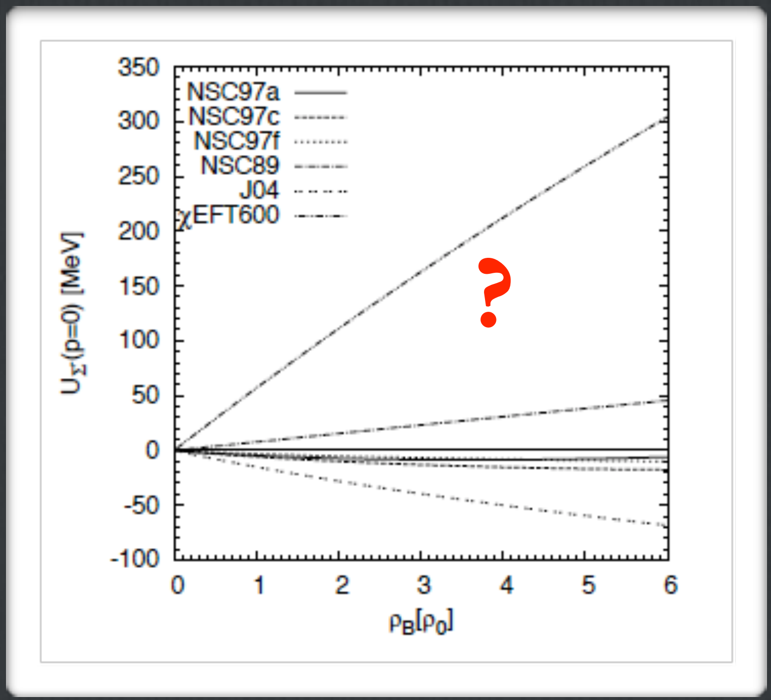
Λ- or Σ- Hypernuclei

Λ-Nucleon Potential



U~ -30 MeV (attractive) from Hypernuclei
No idea yet about the momentum and density dependence

Σ-Nucleon Potential



No Idea at all

Hyp-N: Experimental Evidence II

Λ-p Σ-p scattering

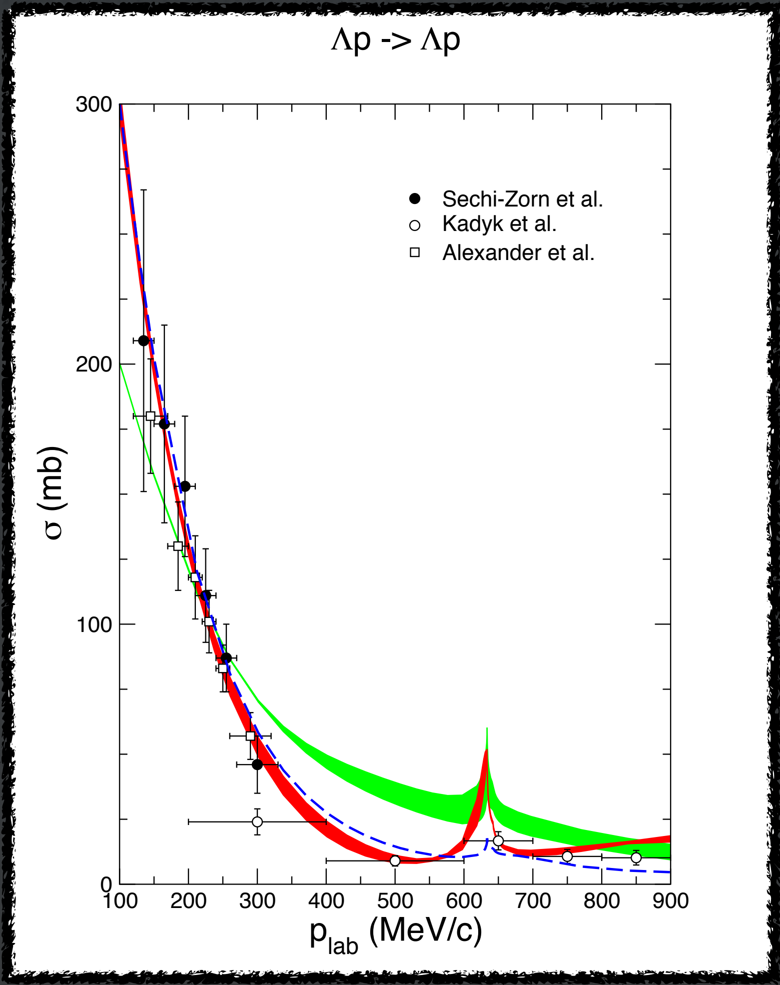
Λ and Σ beams from K-+p collisions "seen" by Bubble chambers

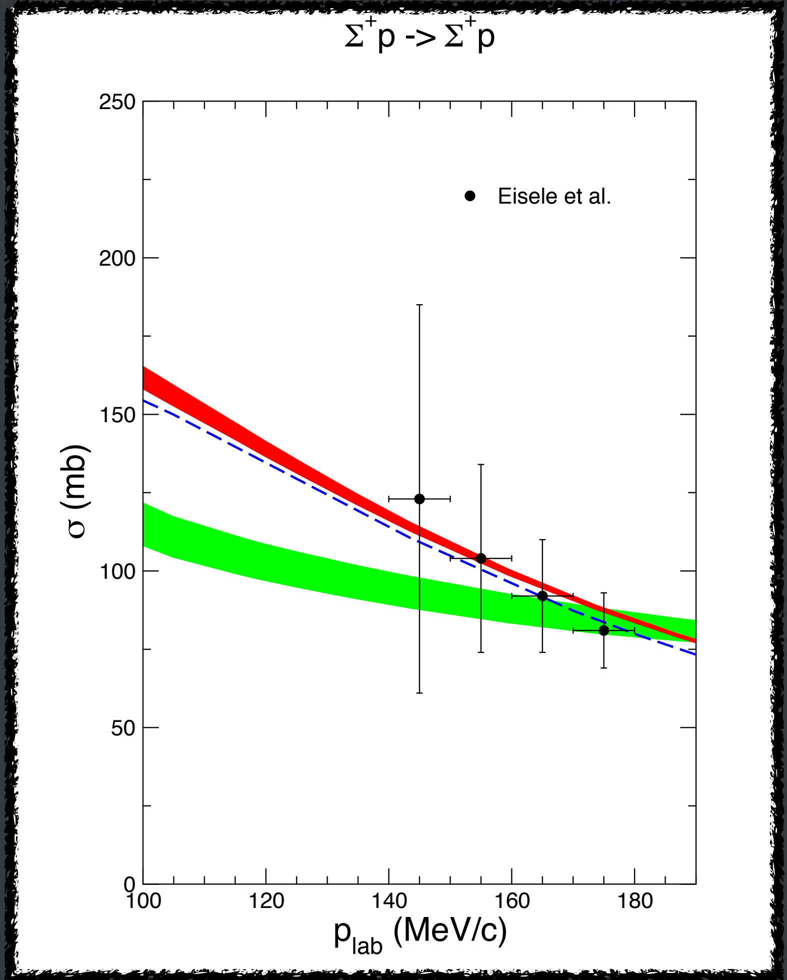
Λ

p

Cross-section -> scattering length -> Interacting Potential

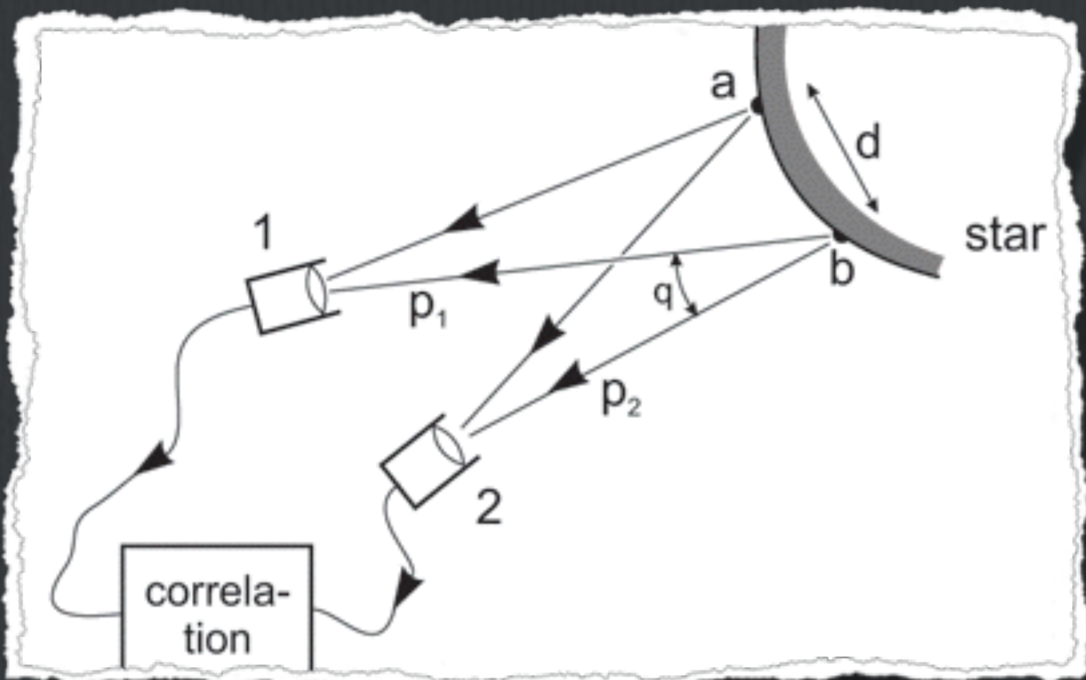
J. Haidenbauer, S. Petschauer et al., Nucl. Phys. A 915 (2013) 24





Scarce Data and all above 150 MeV/c

The Femtoscopy Method



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

Distinguishable and Undistinguishable pairs of particles emitted from a common source

Correlation function is a measure of the source size and also of the particle interaction

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

Theoretical Function

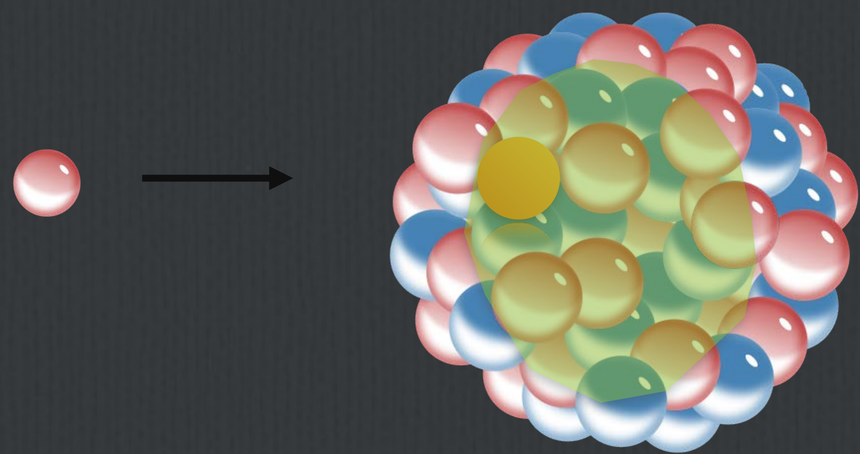
$$C(k) = \mathcal{N}\frac{N(\mathbf{p}_1,\mathbf{p}_2)_{\rm same}}{N(\mathbf{p}_1,\mathbf{p}_2)_{\rm mixed}} \qquad k = \frac{1}{2}|\mathbf{p}_1 - \mathbf{p}_2|$$

Experimental Observable

p-p-, π-π Correlations in Ar+KCl at 1.75 AGeV Hades, EPJA 47, 63 (2011)
Λ-p Correlations in Ar+KCl at 1.75 AGeV Hades, [PRC 82, 021901 (2010)].

Femtoscopy in p+A reactions (GeV)

p+Nb, 3.5 GeV



Interaction

kinematic freeze-our surface

Can be determined for p-p and Λp pairs via Transport Calculation (UrQMD)

-> The Source is hence known and the measured correlation provides the interaction strength.

Calibration on the p-p Correlation

O. Arnold

pp Pairs:
Coulomb Interaction
Strong Interaction
Quantum Statistics for Fermions

$$C(k) = \mathcal{N}\frac{N(\mathbf{p}_1,\mathbf{p}_2)_{\mathrm{same}}}{N(\mathbf{p}_1,\mathbf{p}_2)_{\mathrm{mixed}}} \qquad k = \frac{1}{2}|\mathbf{p}_1 - \mathbf{p}_2|$$

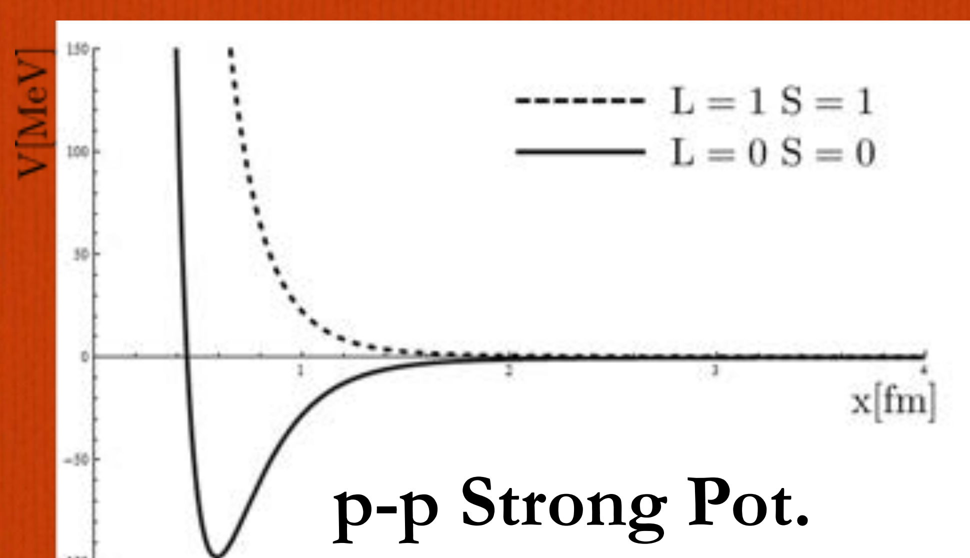
Koonin Fit Function -> Extraction of the Source Radius R_G

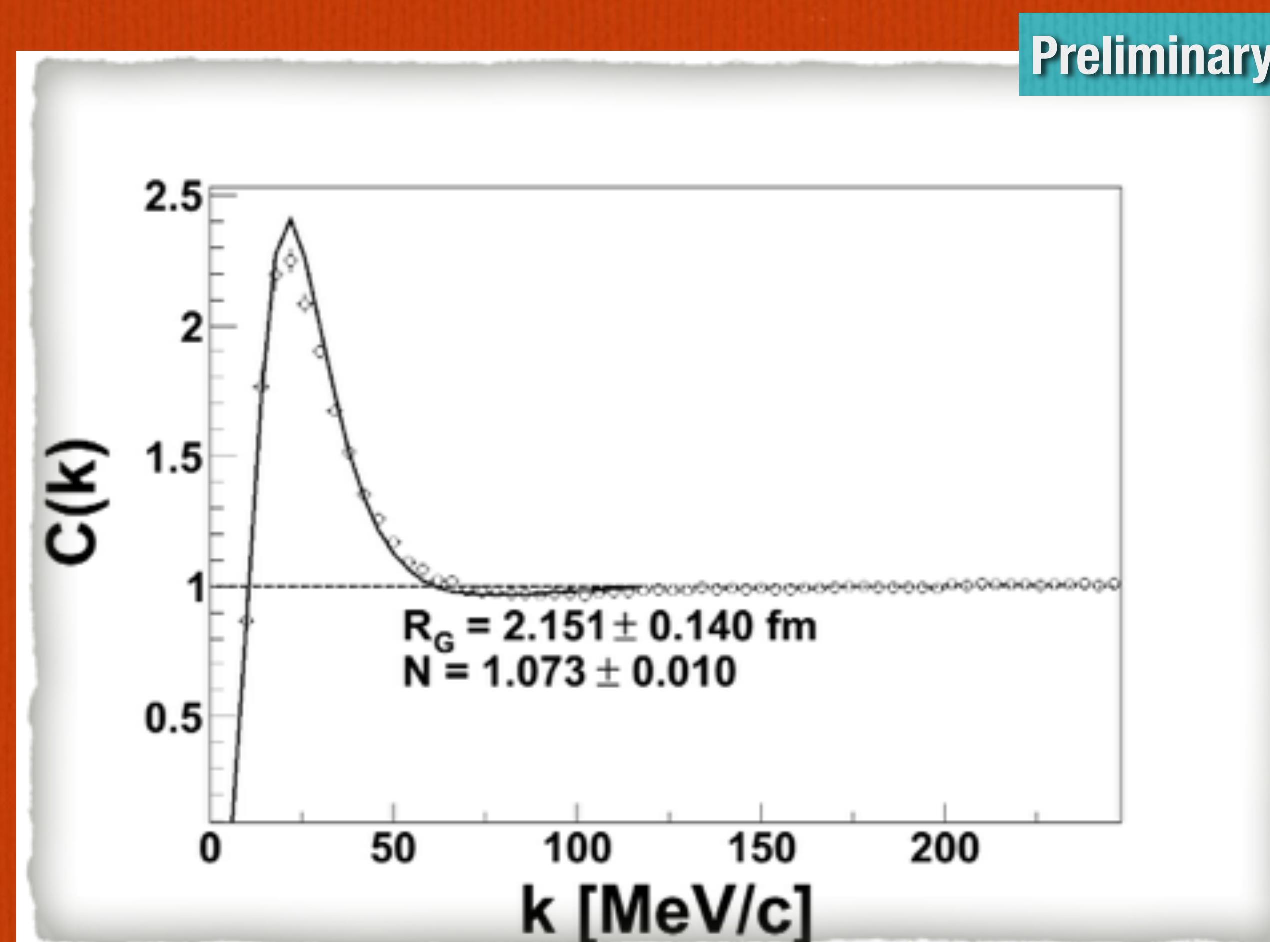
S. E. Koonin, Phys. Lett. B 70 (1977) 43

S. Pratt et al., Nucl. Phys. A 566 (1994) 103c

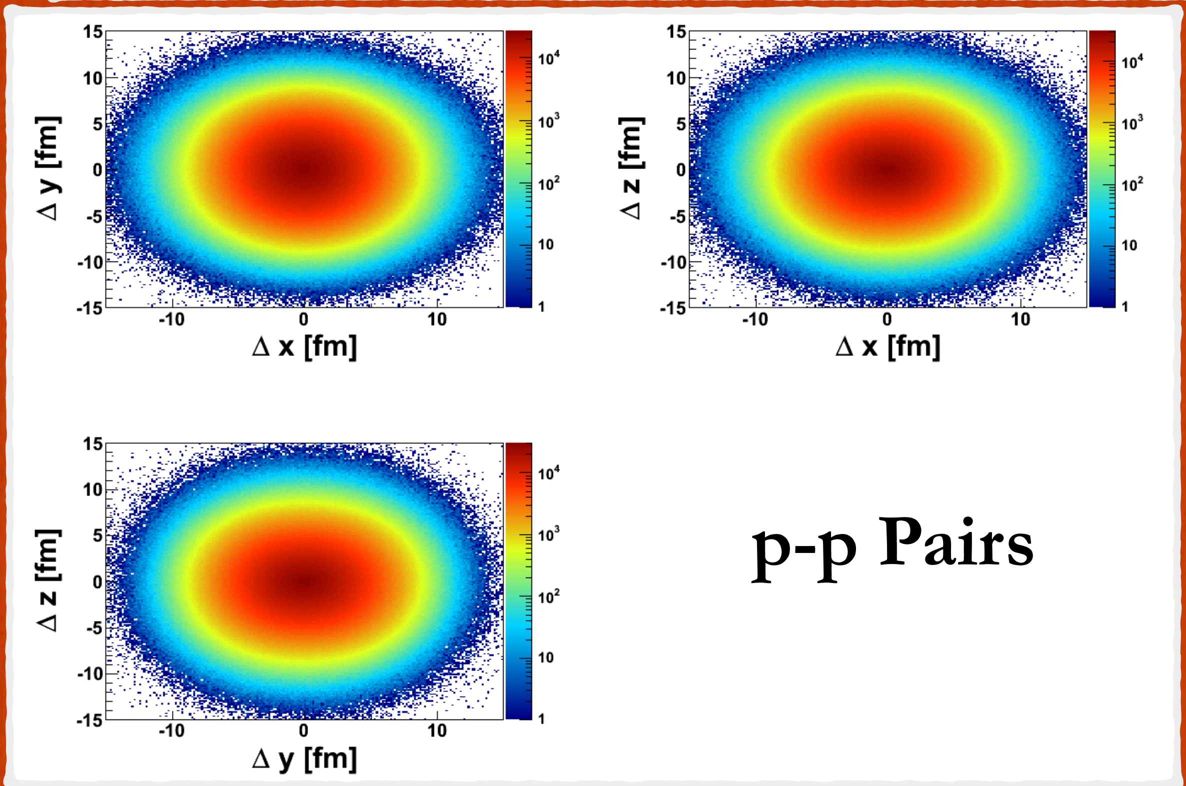
$$C(k) = \int dr^3 \phi_{\mathrm{rel}}^2(r,k) \exp\left(-\frac{r^2}{4R_G^2}\right)$$

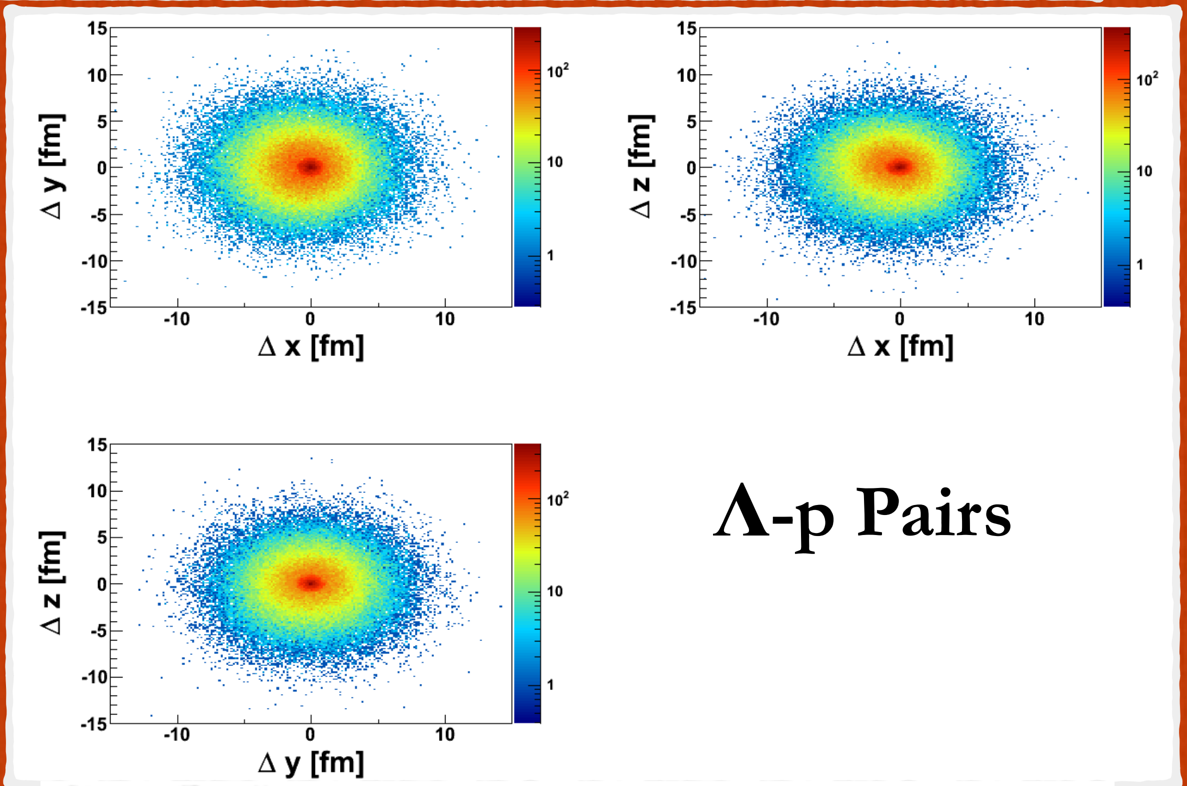
ϕ_{rel} from S.G. with Coulomb and Strong interaction





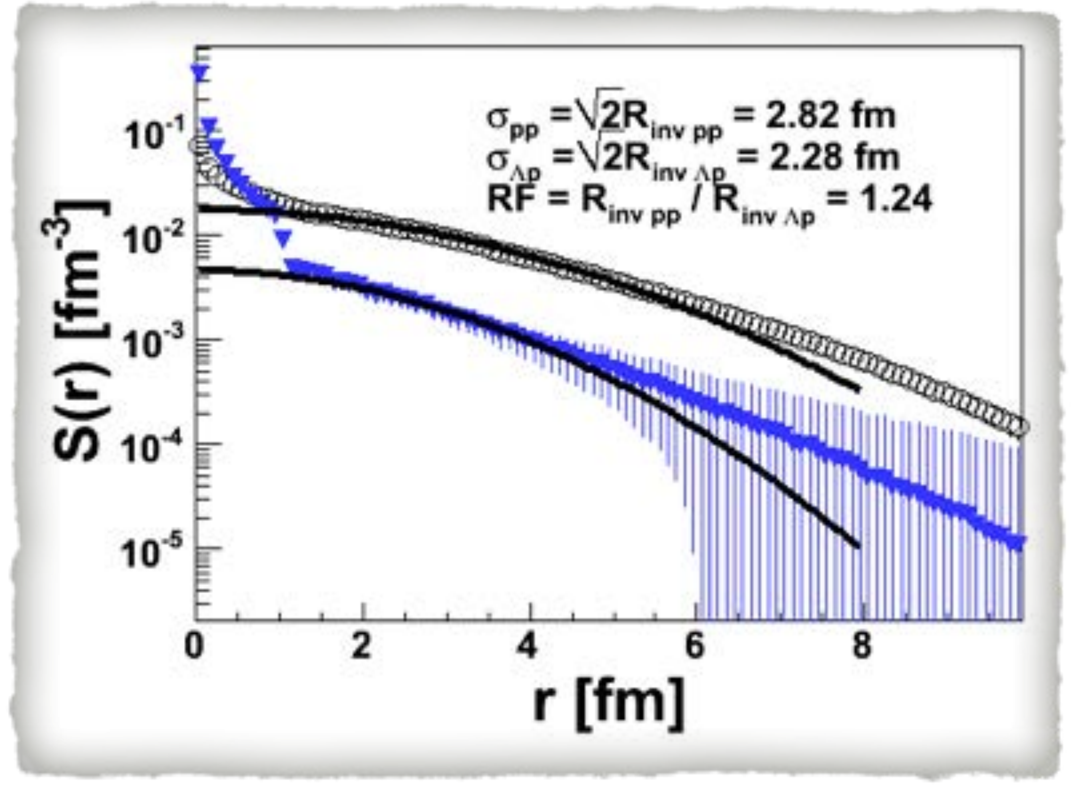
Source Determination via UrQMD





Pair Separation in the Pair-CM system

Λ-p source:
1.24 times smaller than p-p source
(from UrQMD)



Λp Scattering Length

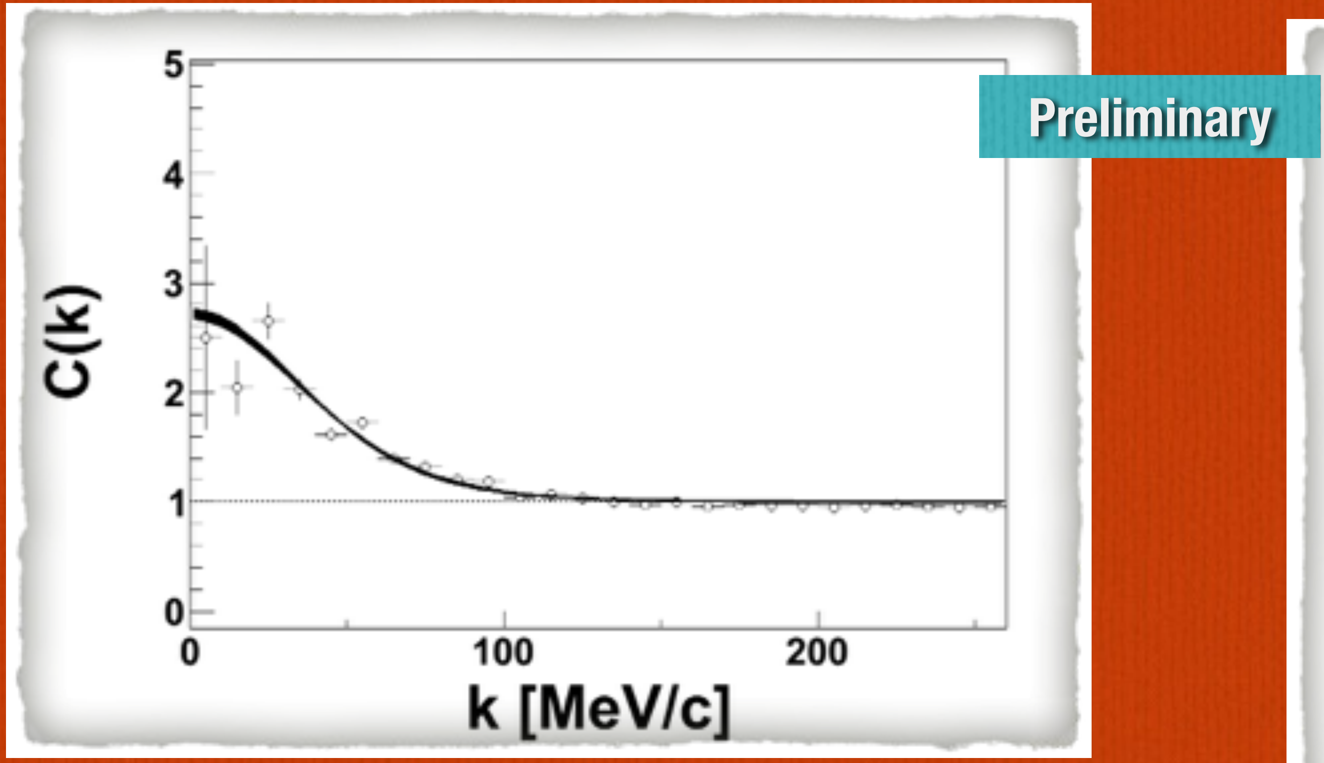
O. Arnold

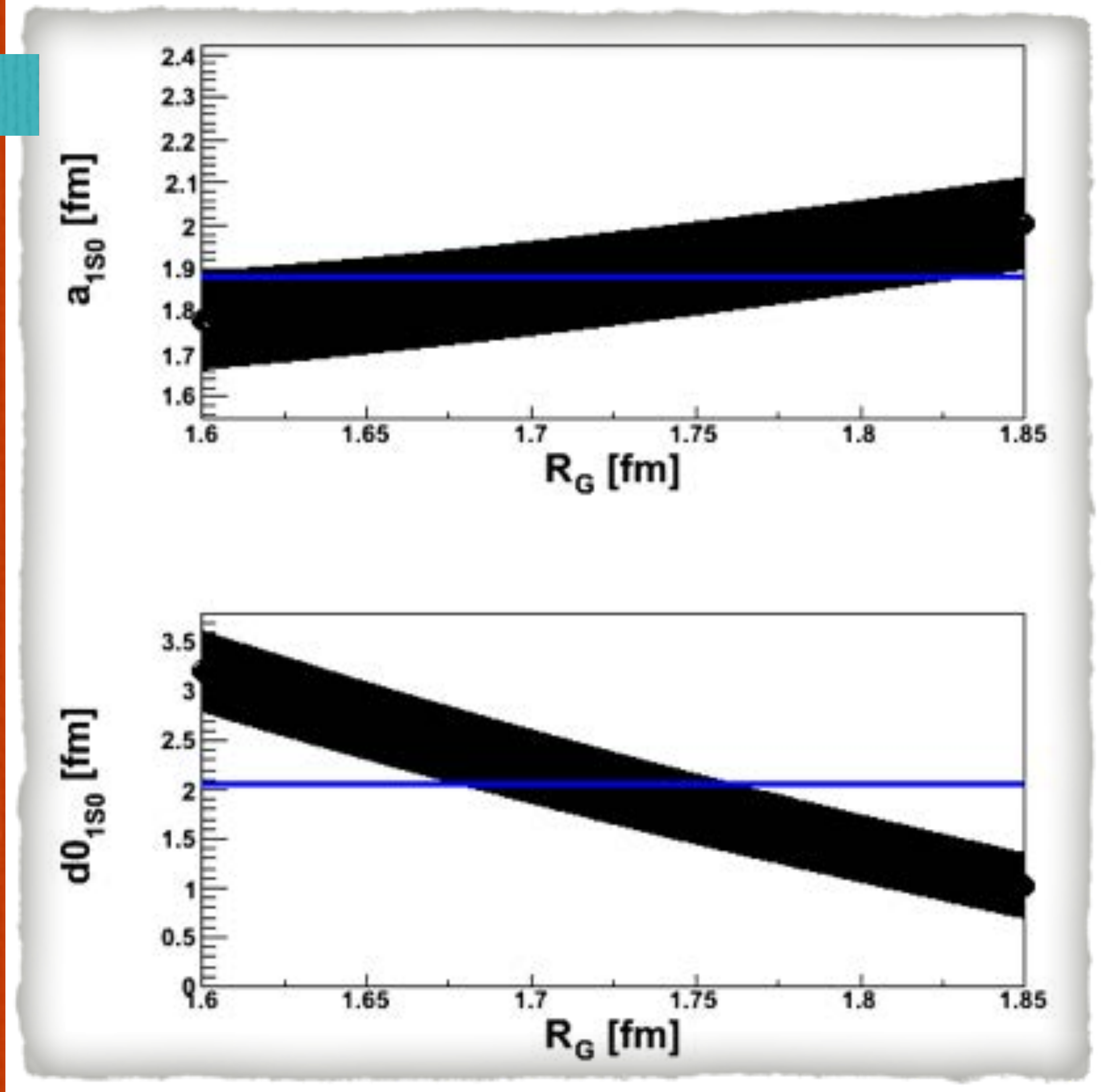
Experimental Distribution

$$C(k) = \mathcal{N}\frac{N(\mathbf{p}_1,\mathbf{p}_2)_{\text{same}}}{N(\mathbf{p}_1,\mathbf{p}_2)_{\text{mixed}}} \qquad k = \frac{1}{2}|\mathbf{p}_1 - \mathbf{p}_2|$$

Fit Function

$$C(k) = 1 + \sum_S \rho_S \left[\frac{1}{2}\left|\frac{f^S(k)}{r_0}\right|^2 \frac{2\mathcal{R}f^S(k)}{\sqrt{\pi}r_0}F_1(Qr_0) - \frac{\mathcal{I}f^S(k)}{r_0}F_2(Qr_0)\right]$$





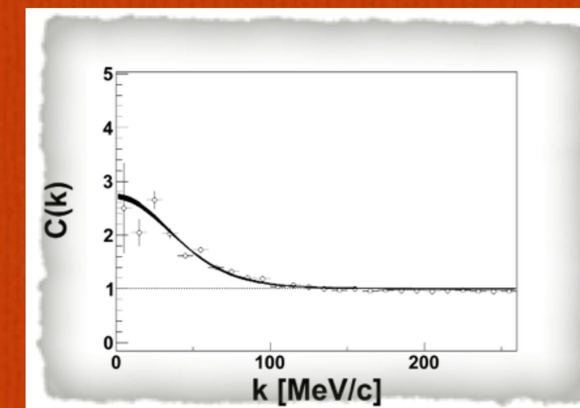
First Fit of the correlation delivers parameters in perfect agreement with scattering data !!!!

Further Improvements:

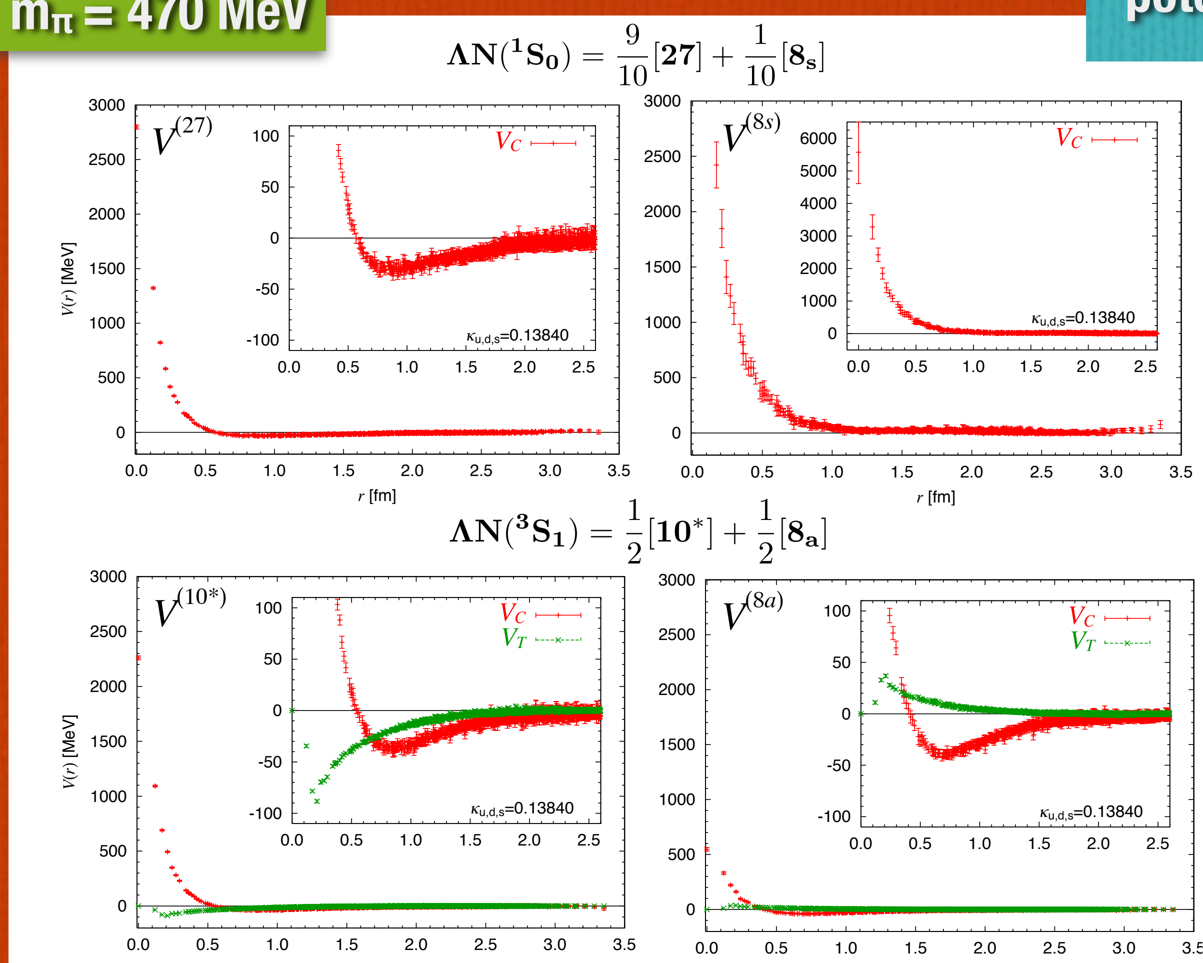
- Source-Radius Determination,
- Improved S/B Ratio,
- Fit for S=0 and S=1 components.

Test-Bed for Lattice Calculations

Simulation of the particle Production and Freeze-Out coordinates → After-Burner which includes the relevant Interactions → Comparison with the measured correlations → Constrain the potential → After-Burner which includes the relevant Interactions



m_π = 470 MeV



T. Inoue et al. Nucl. Phys. A881 (2012) 28

Hyperon-Nucleon Correlation
Hyperon-Nucleon-Nucleon Correlation??

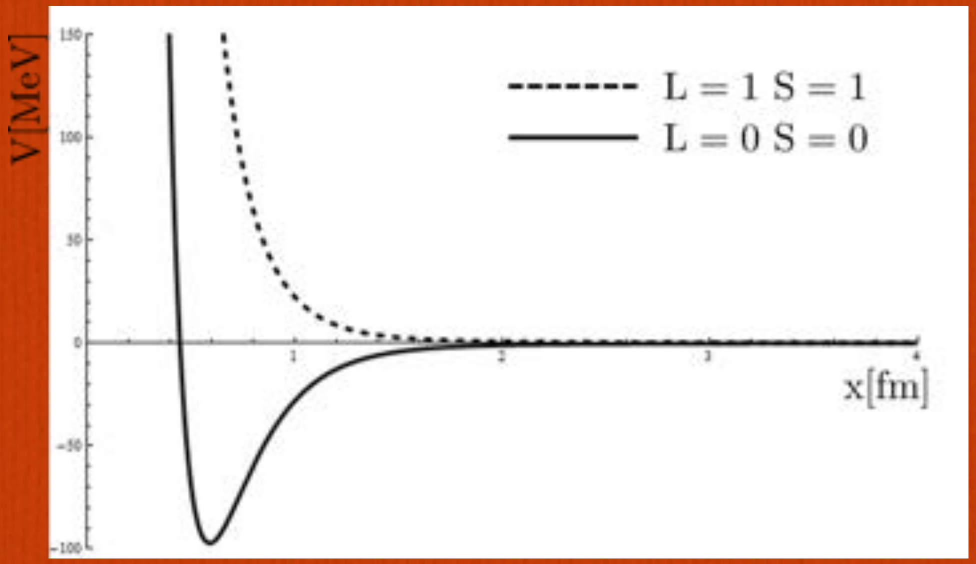
Mainly a matter of statistics

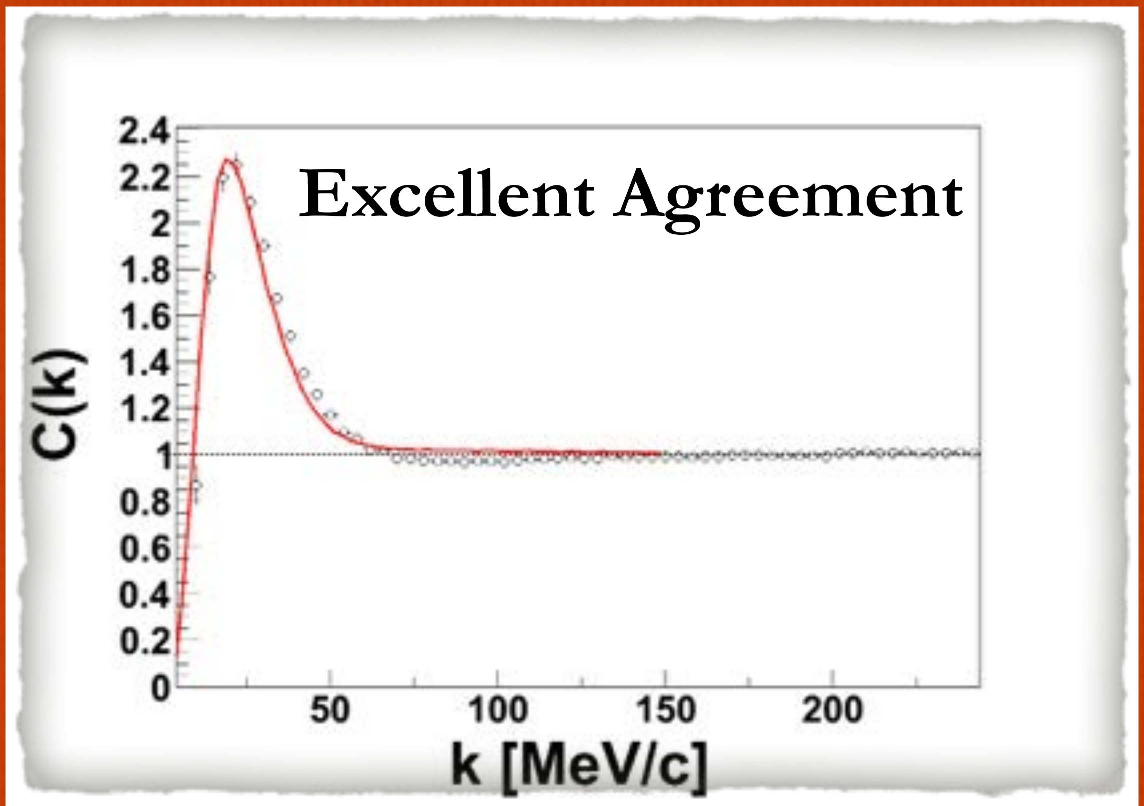
Example for p-p correlations

Simulation of the particle Production and Freeze-Out coordinates → After-Burner which includes the relevant Interactions → Comparison with the measured correlations

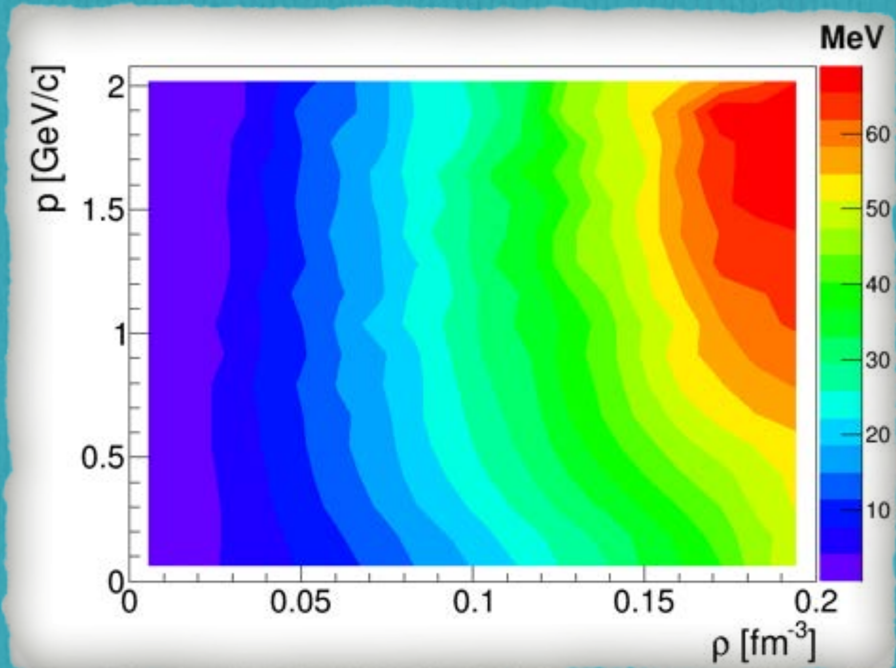
p+Nb reaction simulated in UrQMD + CRAB afterburner

Coulomb +

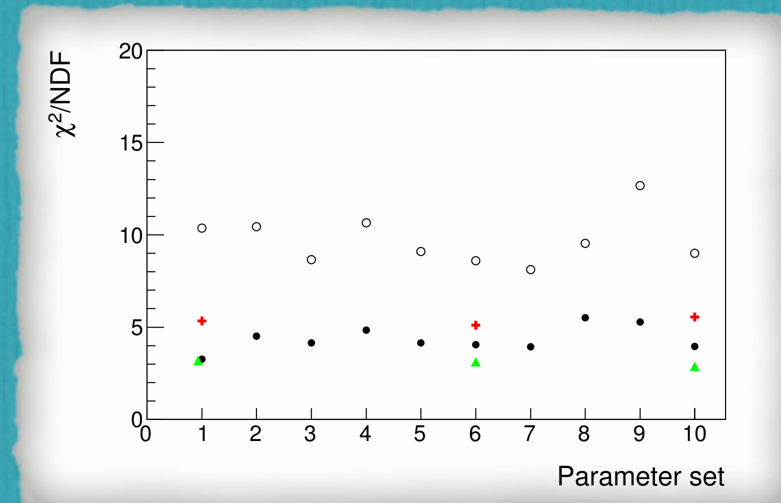




Summary and Outlook



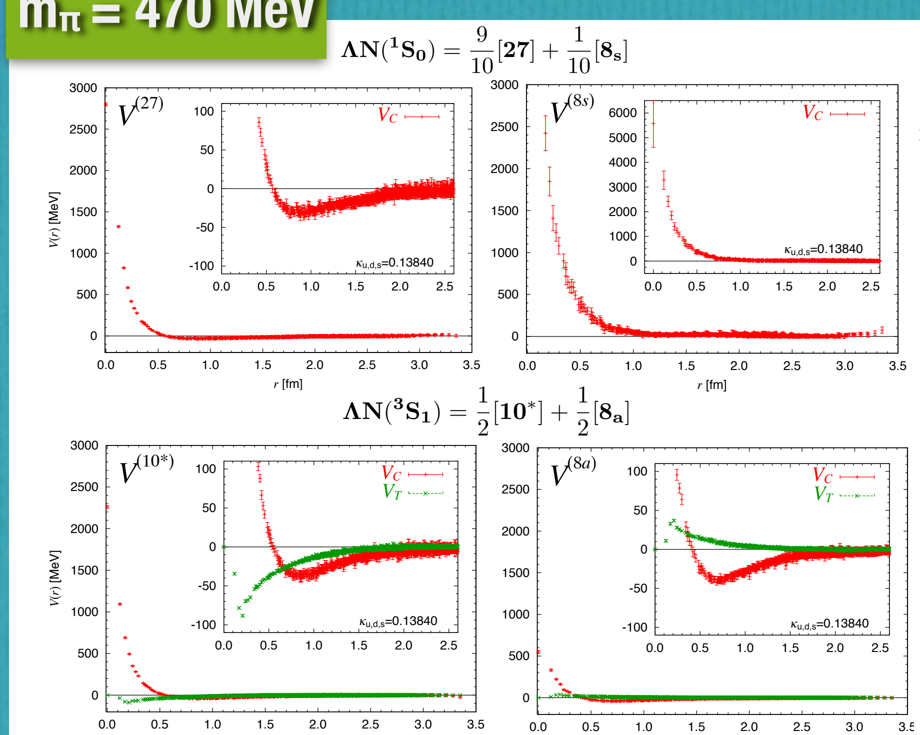
K^0_S-nucleons attractive potential verified with p+Nb reactions at 3.5 GeV



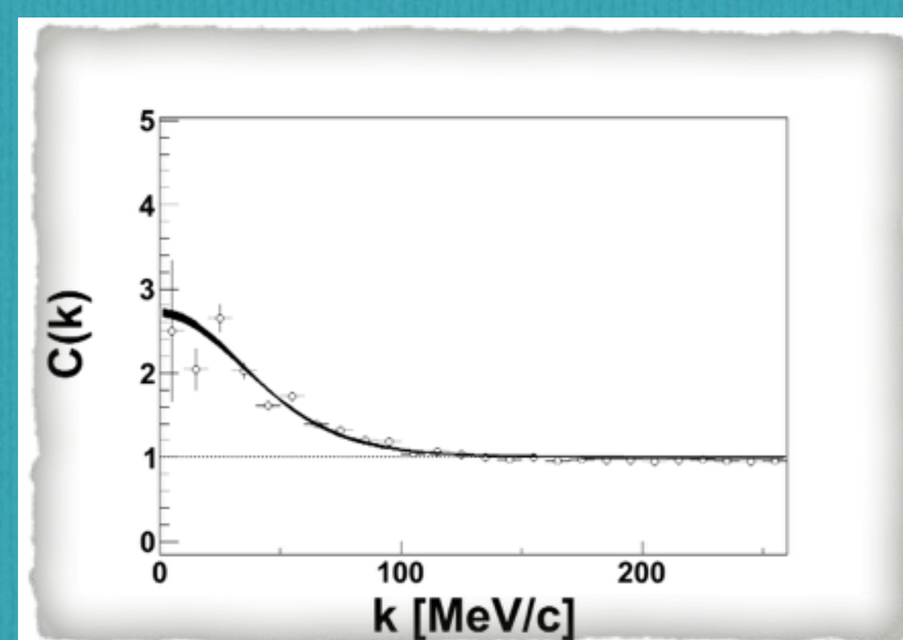
U = 25 MeV
U = 35 MeV
U = 45 MeV

Test the Hyperon-Nucleon Interaction with Femtoscopy at intermediate and high energies
(compare to Lattice potential or other calculations)

m_π = 470 MeV



T. Inoue et al. Nucl. Phys. A881 (2012)



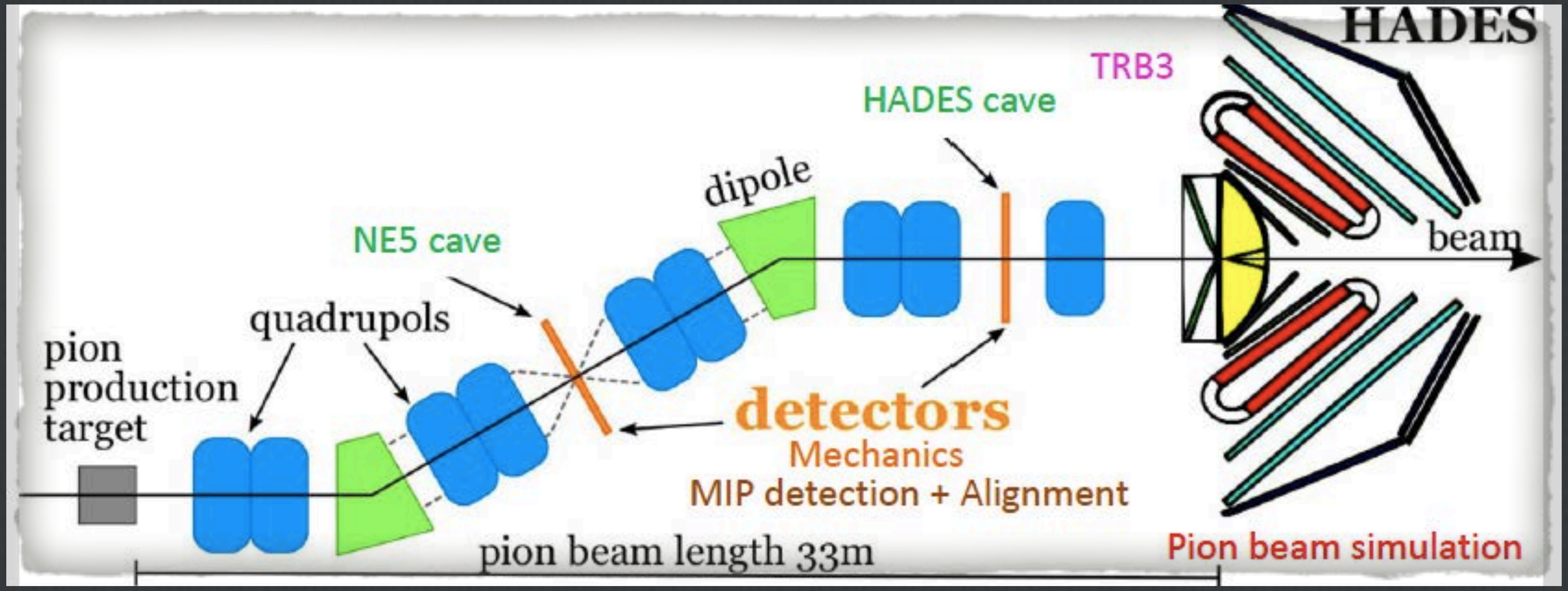
The people in Munich

Thanks

Experiments with π Beams

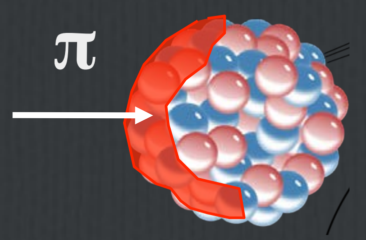
- π-absorption mostly on the nucleus surface
- less model dependent

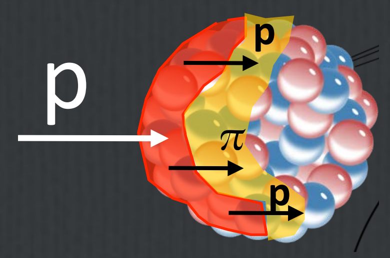
Study of Hadron-nucleon interaction
Not so easy to measure, since π -beams are secondary beams with large emittance



CERBEROS: 3-heads dog at the HADES entrance

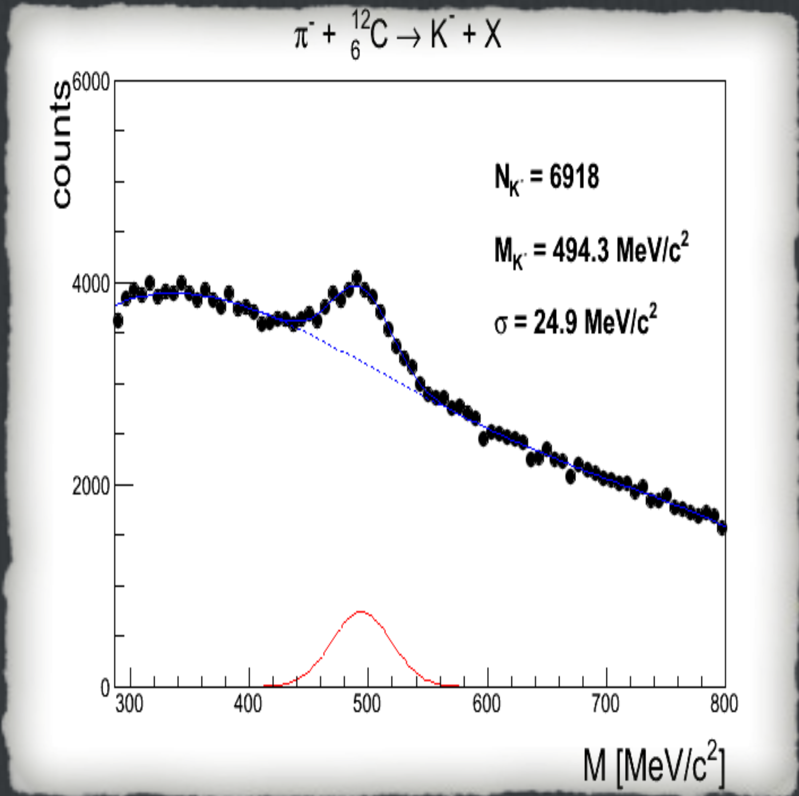
Experiments with π Beams

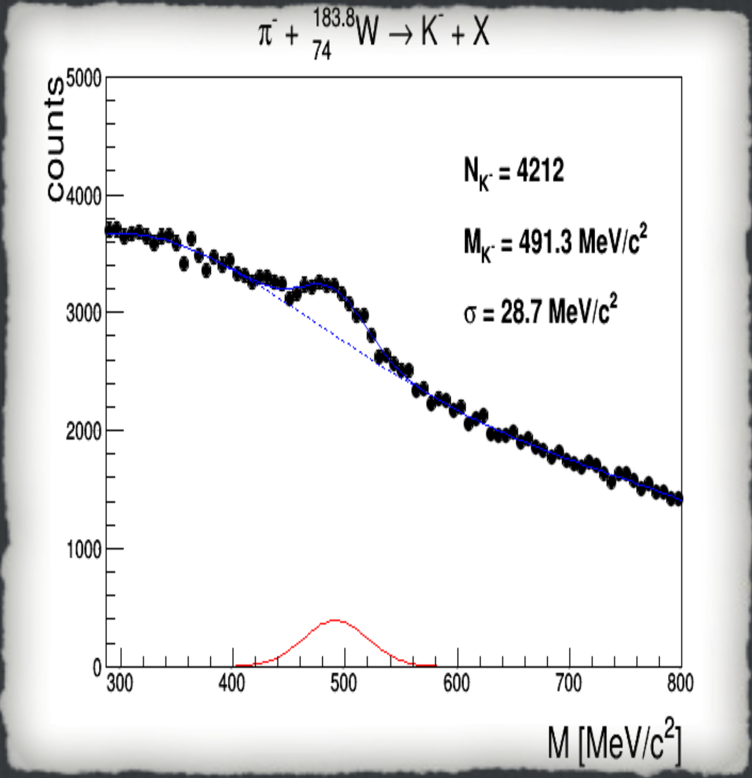




- π-absorption mostly on the nucleus surface
- less model dependent

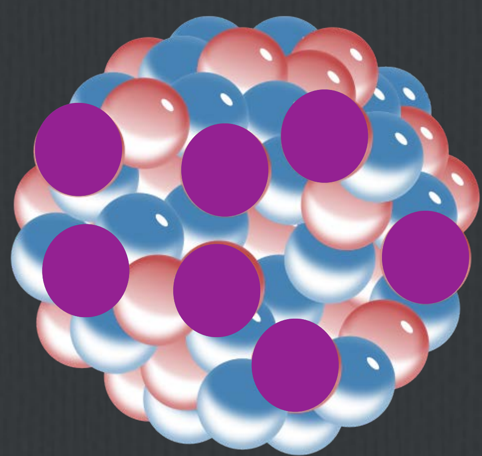
Study of Hadron-nucleon interaction





First Measurement of $\bar{K}$ absorption in normal nuclear matter

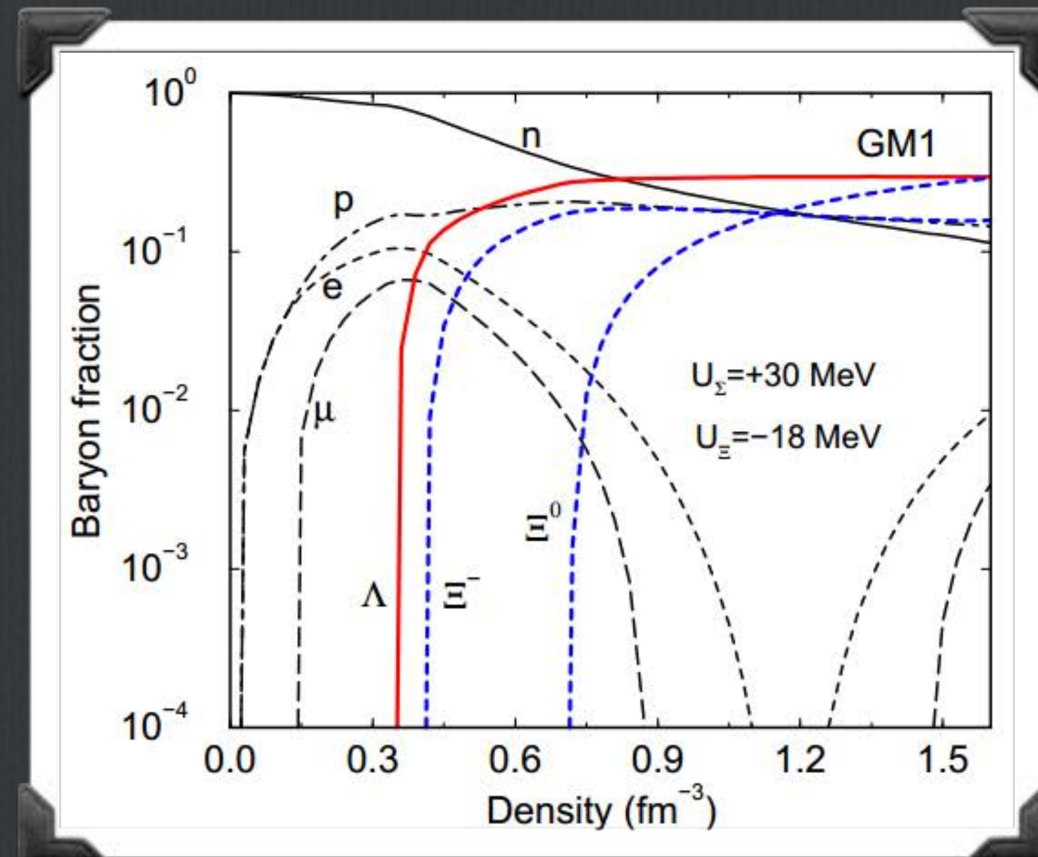
Hyperon Star



Neutron

Λ

J. Schaffner-Bielich, **NPA 804** (2008)



ϱ0 2ϱ0 3ϱ0 4ϱ0 …..

Possible Processes:

$$n + n \rightarrow n + \Lambda$$

$$p + e^- \rightarrow \Lambda + \nu_{e^-}$$

$$n + n \rightarrow p + \Sigma^-$$

$$n + e^- \rightarrow \Sigma^- + \nu_{e^-}$$

Strangeness violation possible due to large time scale of NS

Appearance of Hyperon already starting at $2\varrho_0$

This scenario might also be problematic for large masses (~ $2M_\odot$) since the hyperon appearance implies new degree of freedom and hence a softening of the EOS