What do Hadron-Hadron interaction have to do with Neutron Stars? Maybe nothing

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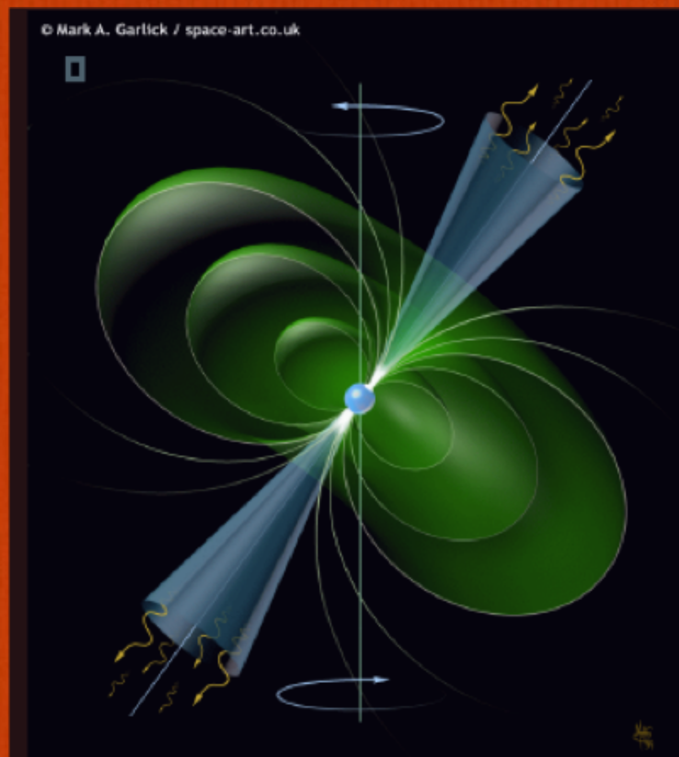
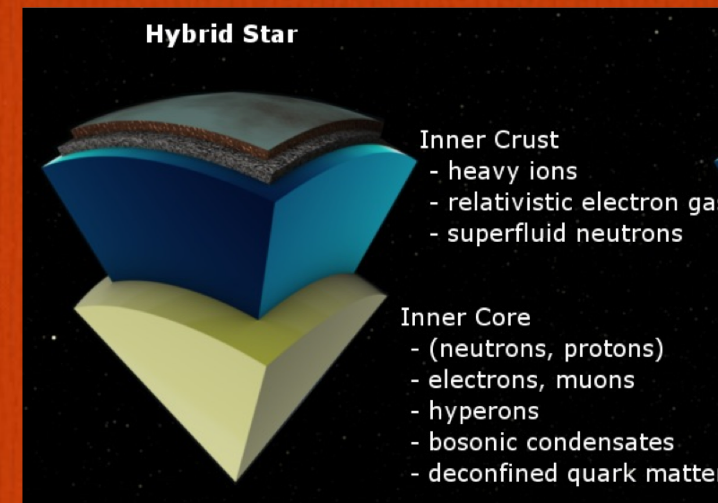
TUM and LNF

Facts about Neutron Stars

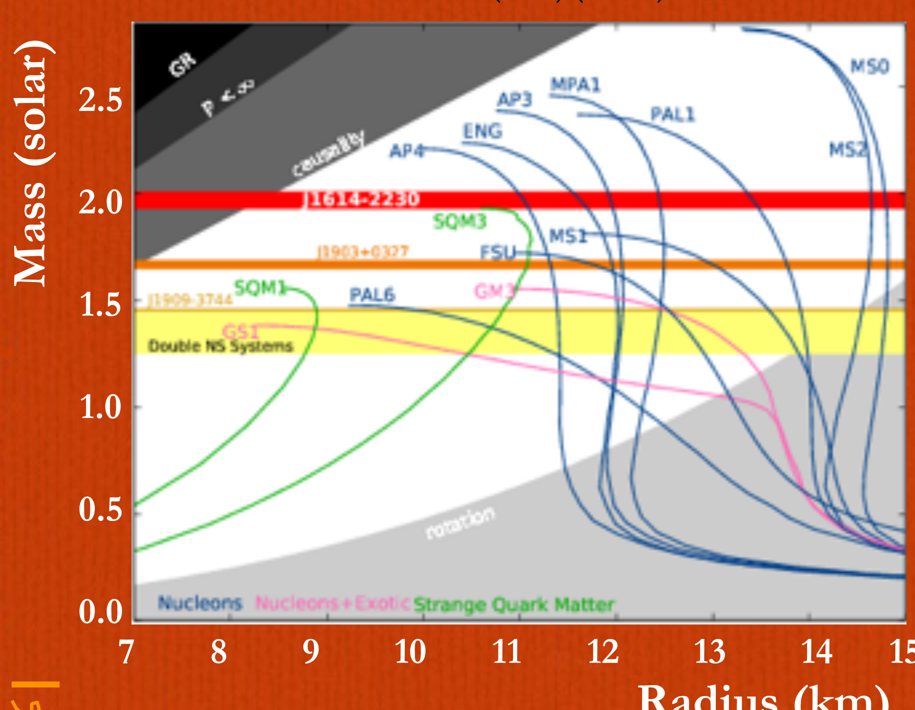


R ~ 10–15 km
M ~ 1.5 M☉

density



P. Demorest et al. Nature (467) (2010) 1081

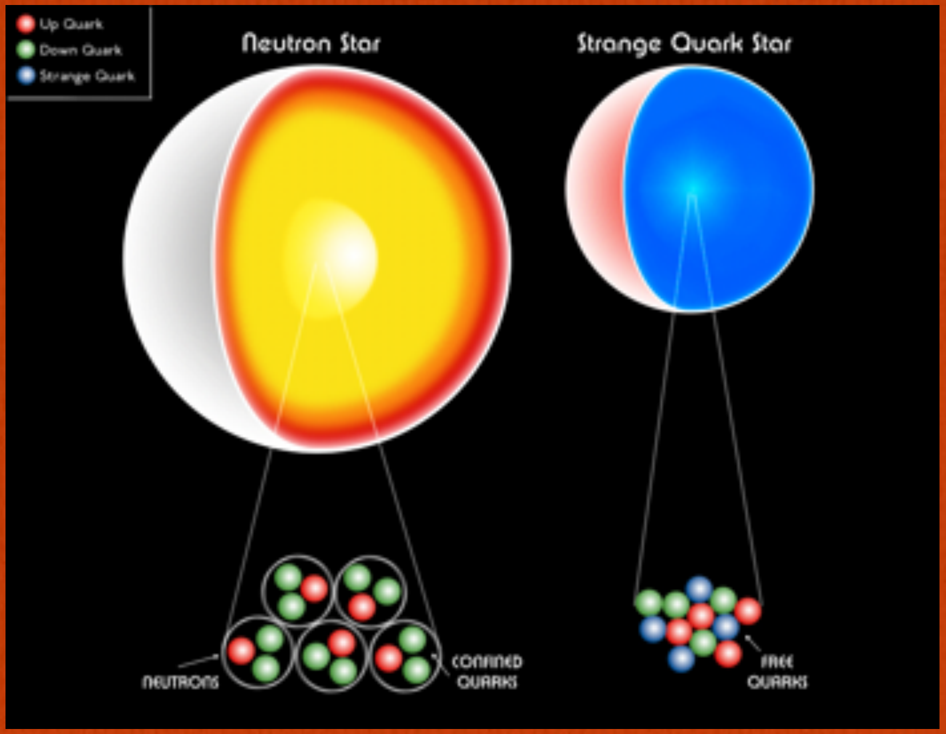


- Very high density in the interior
- Strong magnetic fields
- Rotating object emitting Synchrotron radiation in Radio-Frequency (Pulsar character)
- Mass measured in binary systems with White Dwarfs (Shapiro Delay, WD Spectroscopy)
- Radius Measurement very difficult
- Masses ranging from 1.4 $M_\odot$ to 2 $M_\odot$

What is inside Neutron Stars??

Speculations about Neutron Stars

NSF, universetoday.com



- Hadron composition
  - Only Nucleons
  - Antikaons-Nucleons condensate
  - Nucleons and Hyperons
- Nuclear Pasta
  - lasagne
  - spaghetti
- Quark star (Color super-conducting strange quark matter)

For each assumption about the content the specific Equation of State (EOS) should be determined to check whether this matches the NS Data

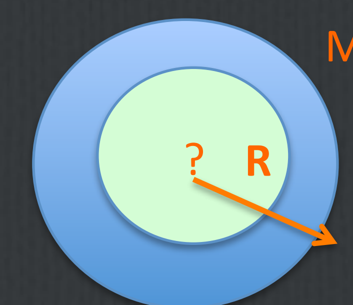
How to test different Hypotheses

1) Equation of State (EOS): How pressure depends on density
2) This equation is defined by a parameter we call <u>Compressibility</u>

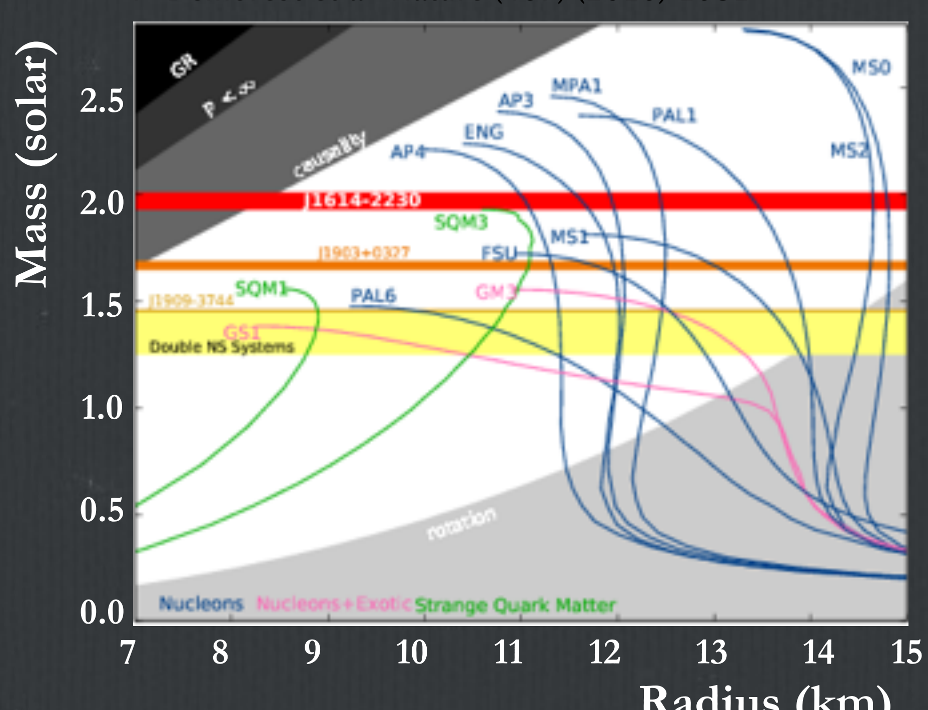
<u>Soft EOS:</u> matter can be compressed easily
Stiff <u>EOS:</u> compression becomes difficult

2) Given an object with a certain density the internal pressure must be compensated by gravity

3) From P(R)=0 -> the relation M(R) can be determined for each EOS as a function of the assumed density



P. Demorest et al. Nature (467) (2010) 1081

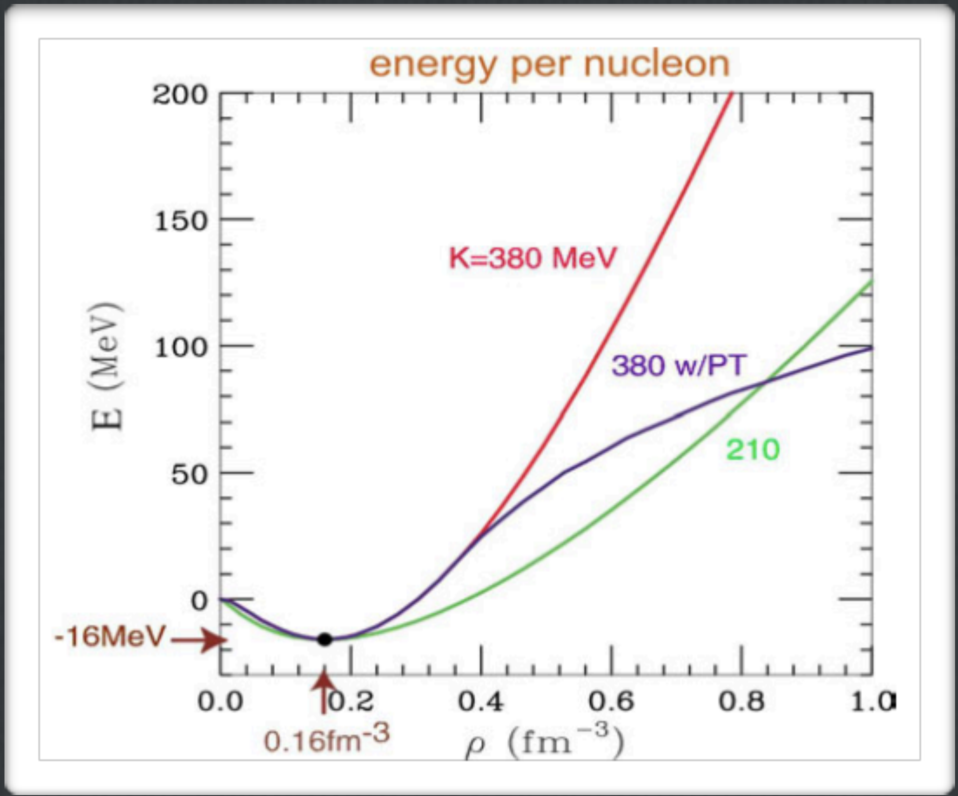


$\rho = 2\text{-}8\ \rho_0$

It is not so easy to fix the density but the EOS must cross the measured values of the masses!

Determination of the EOS of nuclear matter

P. Danielewicz nucl-th/0512009



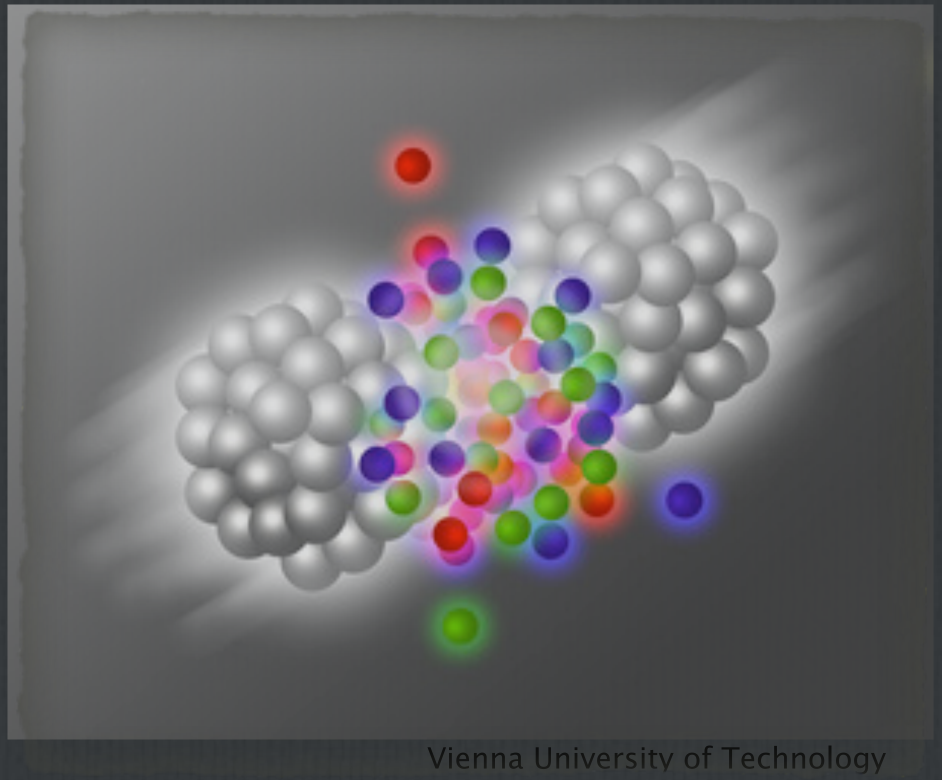
$$E = \alpha \cdot \rho + \beta \cdot \rho^{\gamma}$$

The compressibility parameter :

$$K = 9\rho_0^2 \frac{d^2}{d\rho^2}\left(\frac{E}{A}\right)$$

Soft EOS : K< 290 MeV
Stiff EOS: K> 290 MeV

Tool: Particle Production in heavy ion collisions



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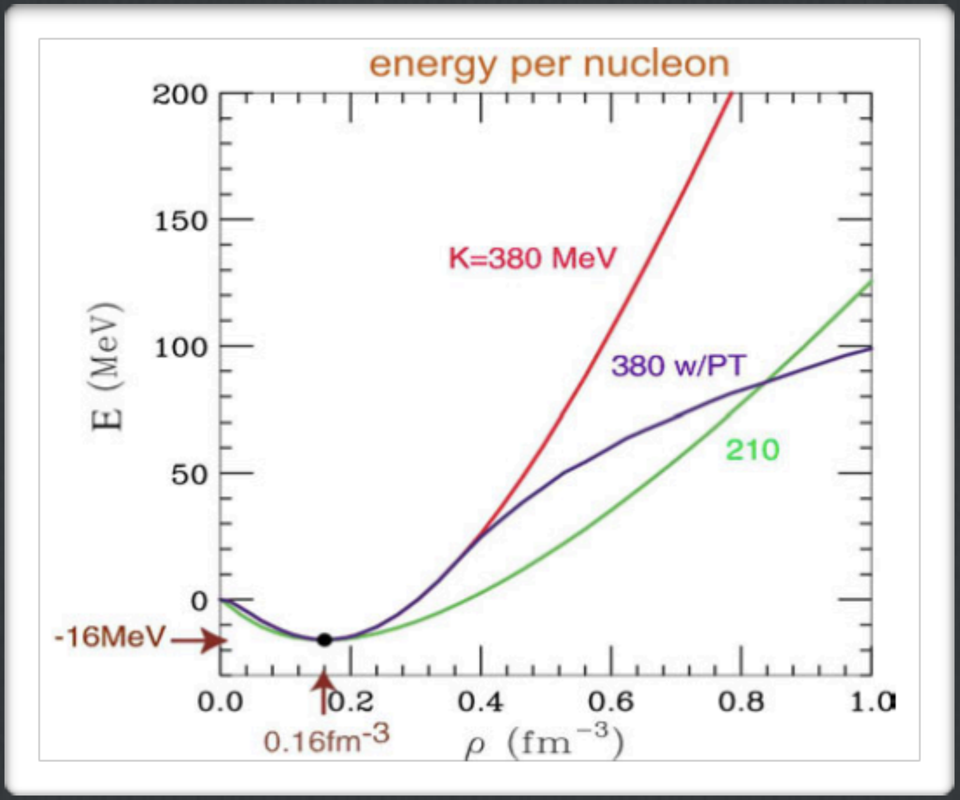

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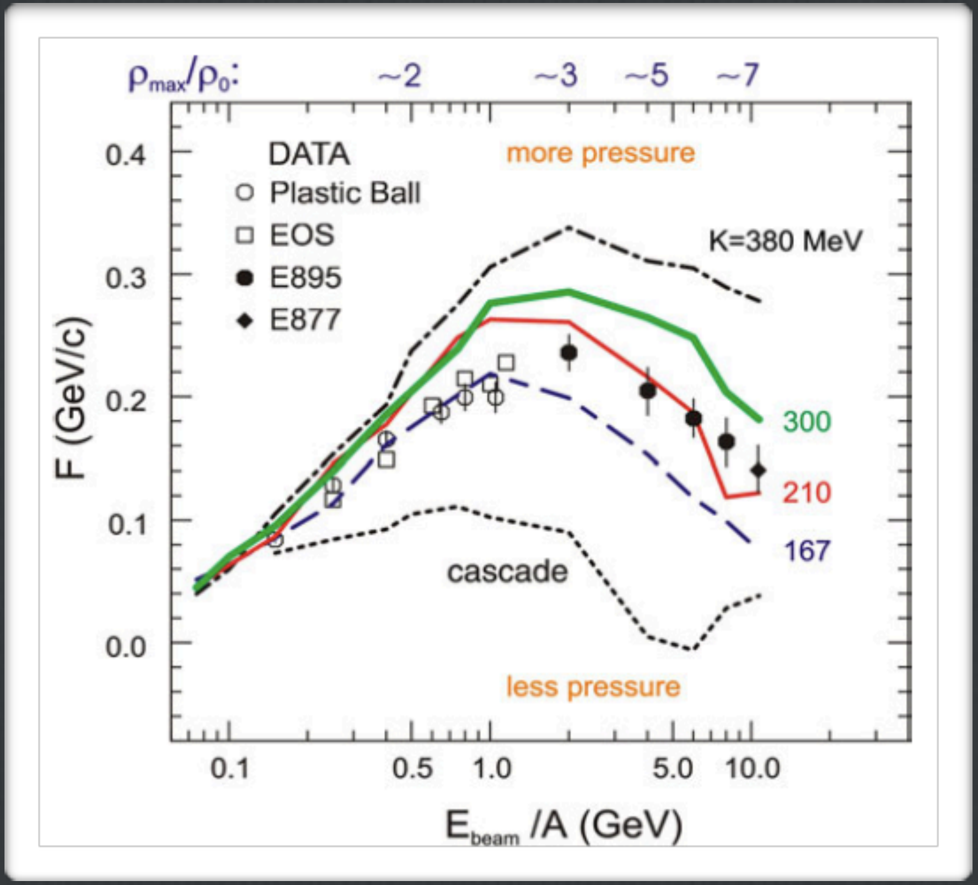
The compressibility parameter :

$$K = 9\rho_0^2 \frac{d^2}{d\rho^2}\left(\frac{E}{A}\right)$$

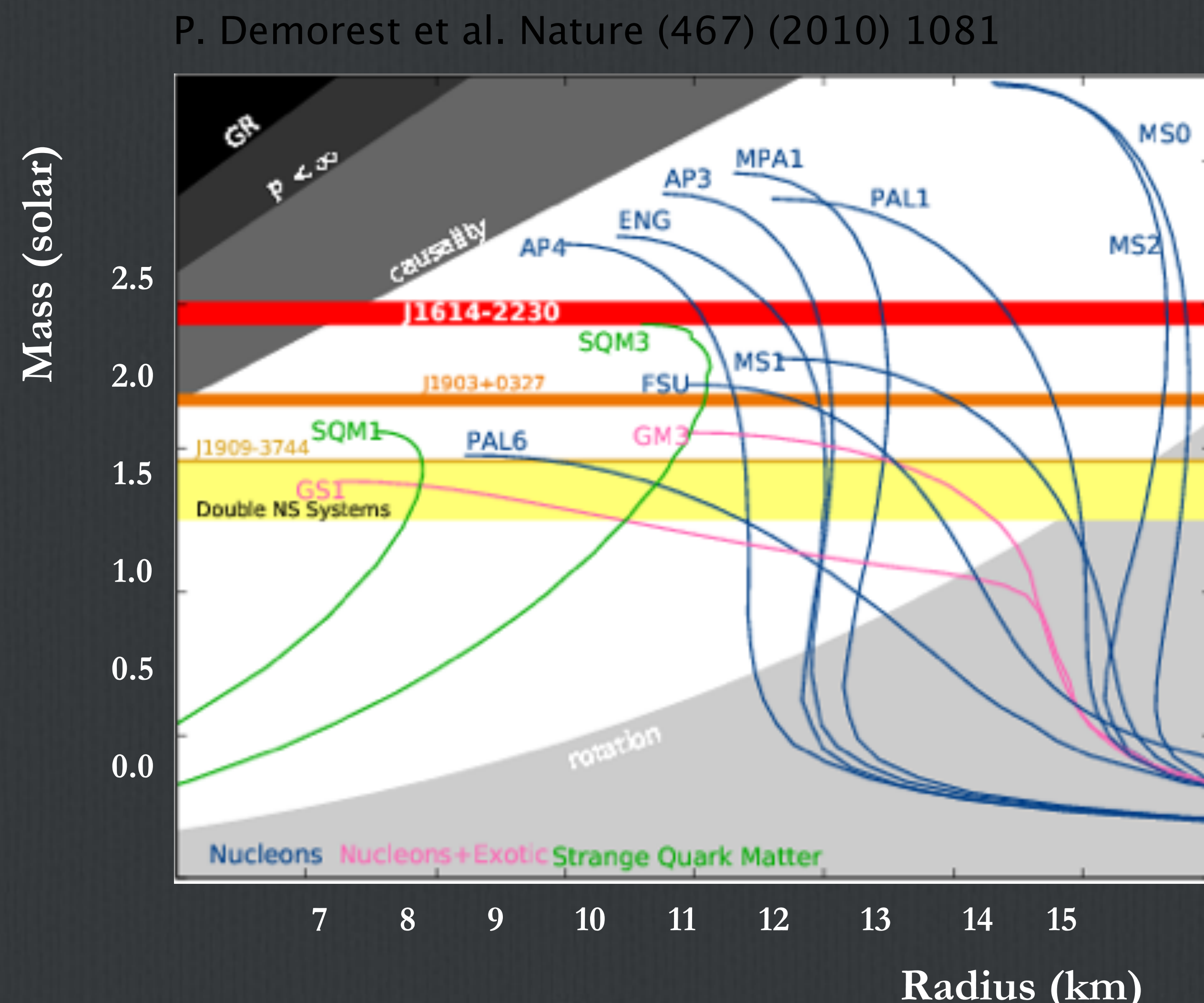
Soft EOS : K< 290 MeV
Stiff EOS: K> 290 MeV

$$F = \left.\frac{dp_X}{dY_{CM}}\right|_{Y_{CM}=0}$$



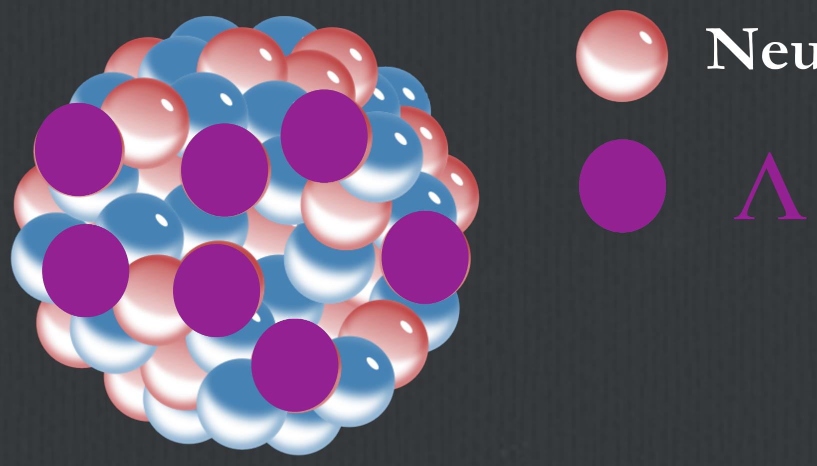
<u>Soft EOS</u> from particle production in Heavy Ion Collisions

Large Masses Issue

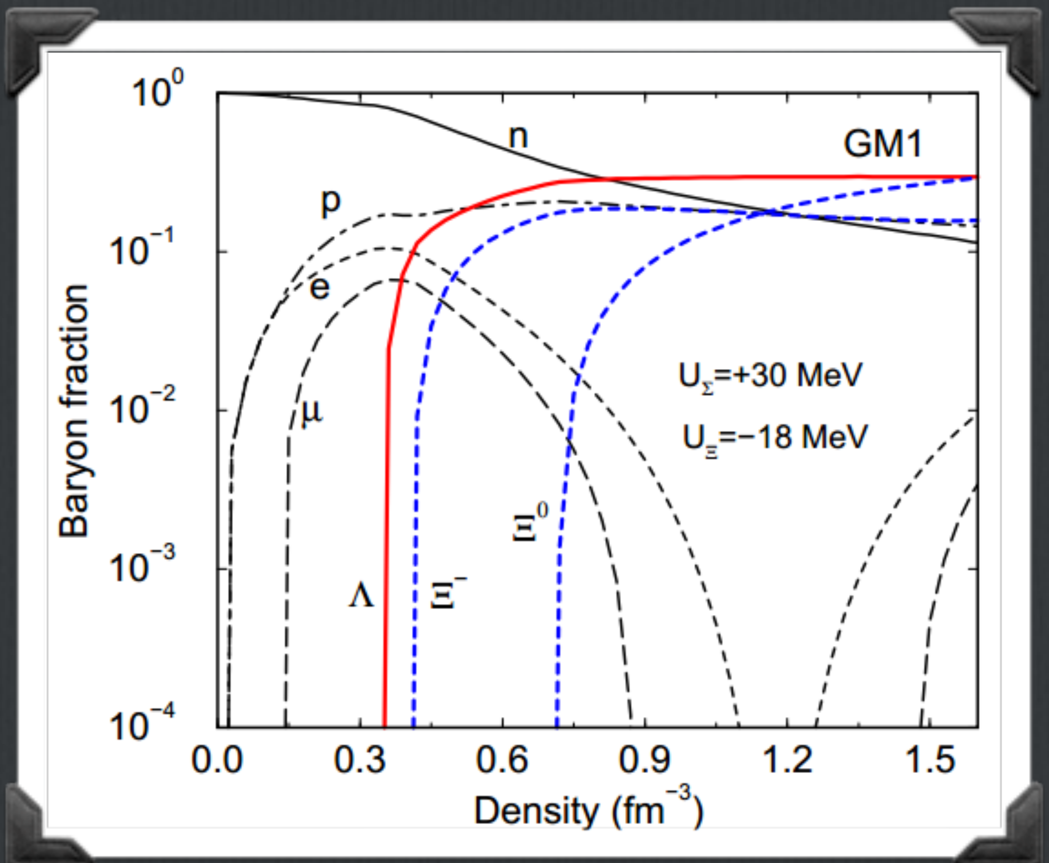


- Production of strangeness is energetically favourable
- It relieves the Fermi pressure of neutrons and protons
- But… a decrease of the pressure softens the EOS
- Decrease of the maximum mass of neutron stars
- 2 $M_\odot$ neutron star measured
- EOS cannot be too soft
- Some EOS are disfavoured, for example Antikaon condensate

Hyperon Star



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



ϱ0 2ϱ0 3ϱ0 4ϱ0 …..

Possible Processes:

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

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

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

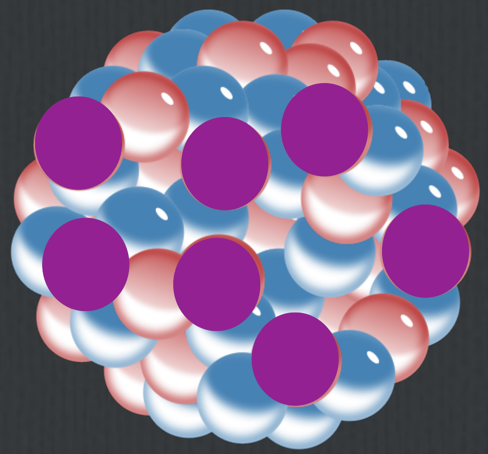
$$n + e^- \rightarrow \Sigma^- + \nu_{e^-}$$

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 ($\sim 2M_\odot$) since the hyperon appearance implies new degree of freedom and hence a softening of the EOS

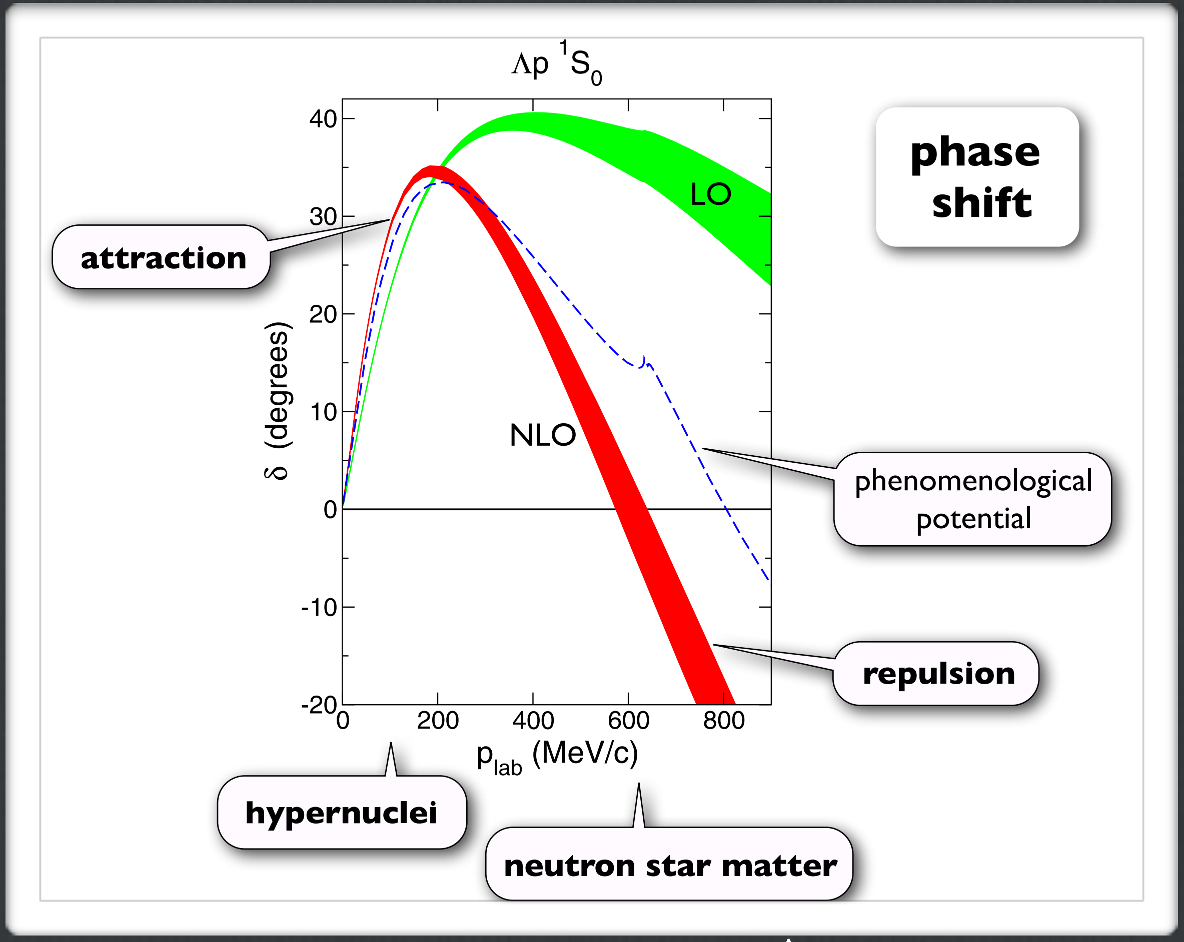
Hyperon Star



Neutron

Λ

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



Λ-p distance

Possible Processes:

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

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

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

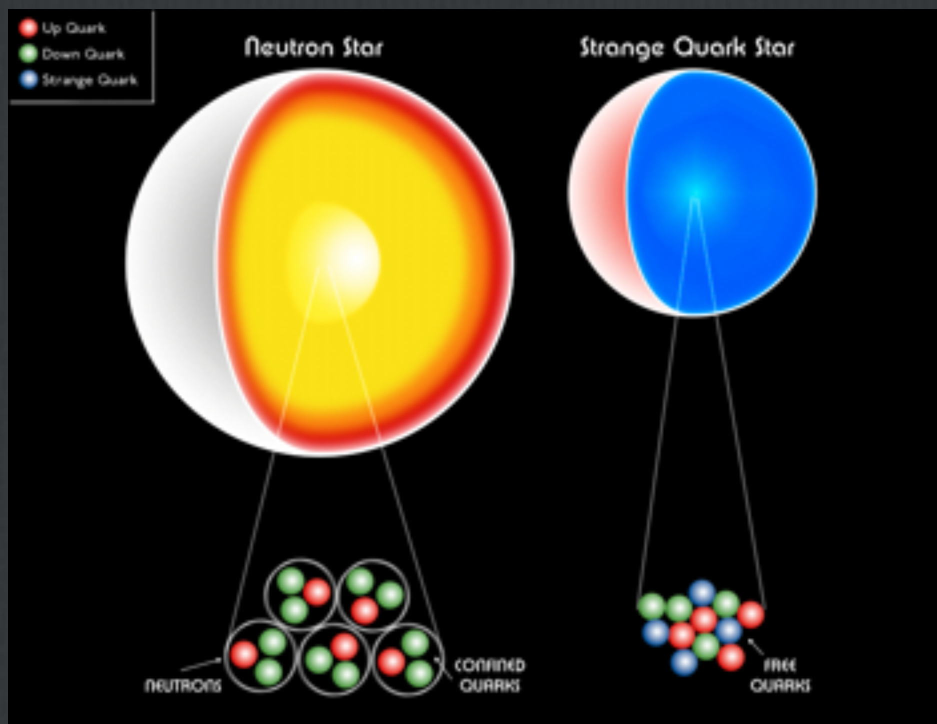
$$n + e^- \rightarrow \Sigma^- + \nu_{e^-}$$

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

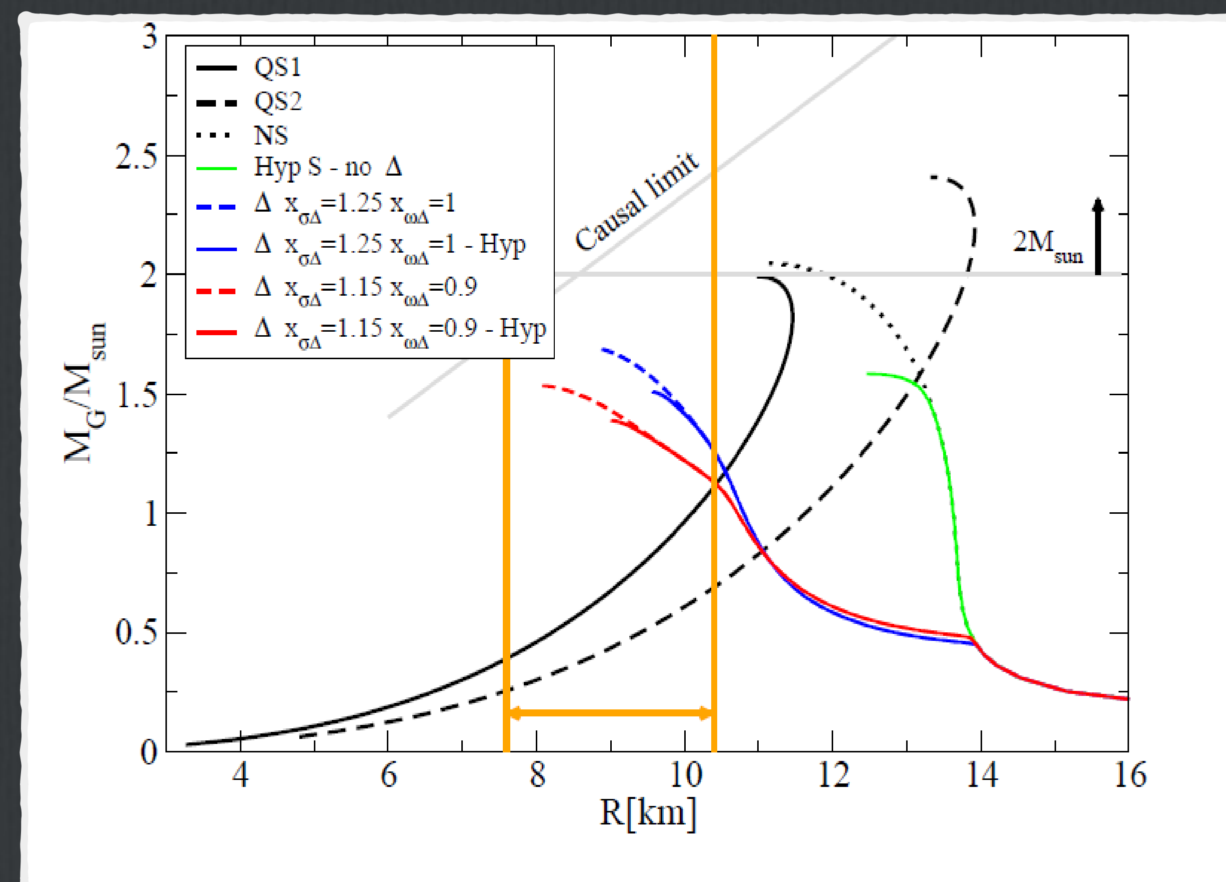
2 Families of Compact Stars

NSF, universetoday.com



1) Hadronic Stars (with Nucleons, baryonic resonances and Hyperons inside) with low Mass (up to 1.5 $M_{\odot}$) and small Radii (9-10 Km)
2) Strange Quark Stars with high Mass and large Radii

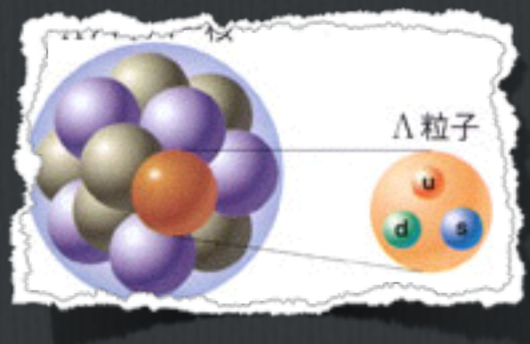
A. Drago, A. Lavagno, G. Pagliara Phys. Rev. D89 (2014) 043014



Transition from one kind of star to the other

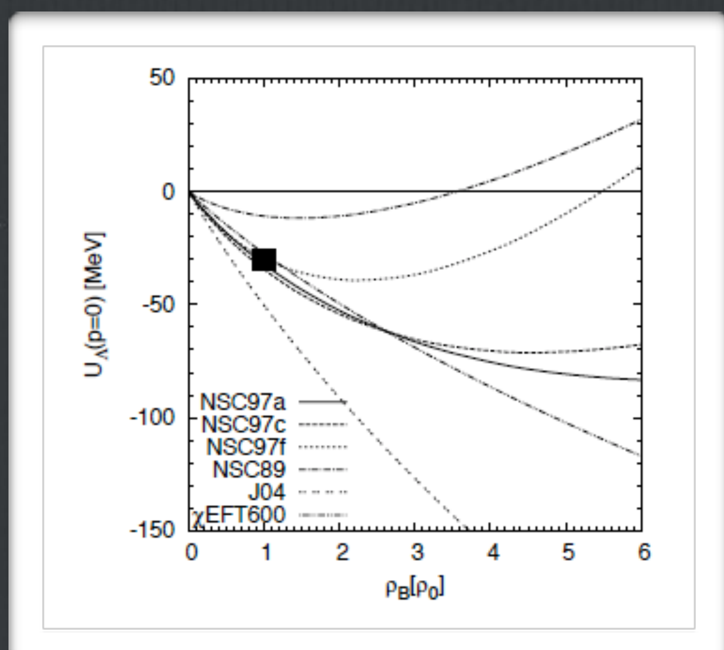
Measurements of the Radii of low-mass NS are necessary!

Experimental Evidence I



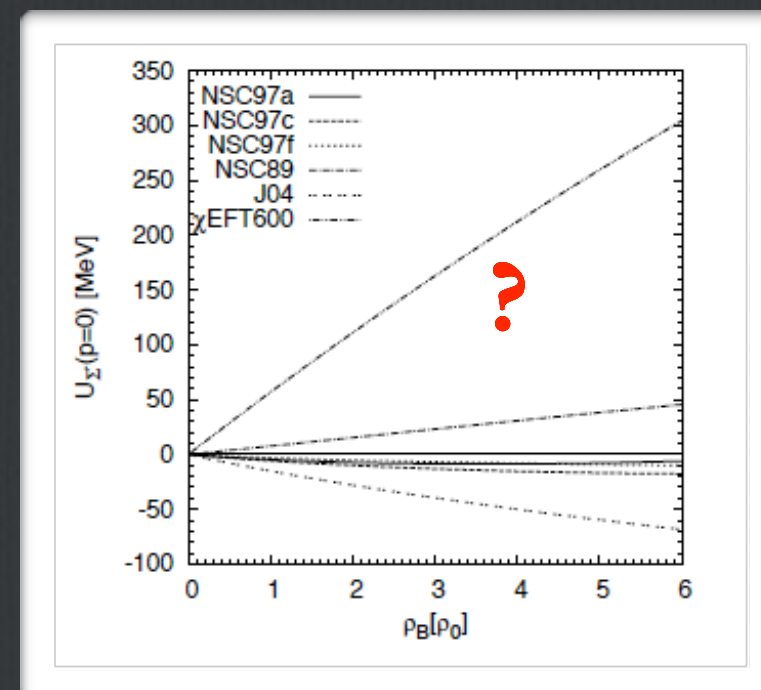
Λ- or Σ- Hypernuclei

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

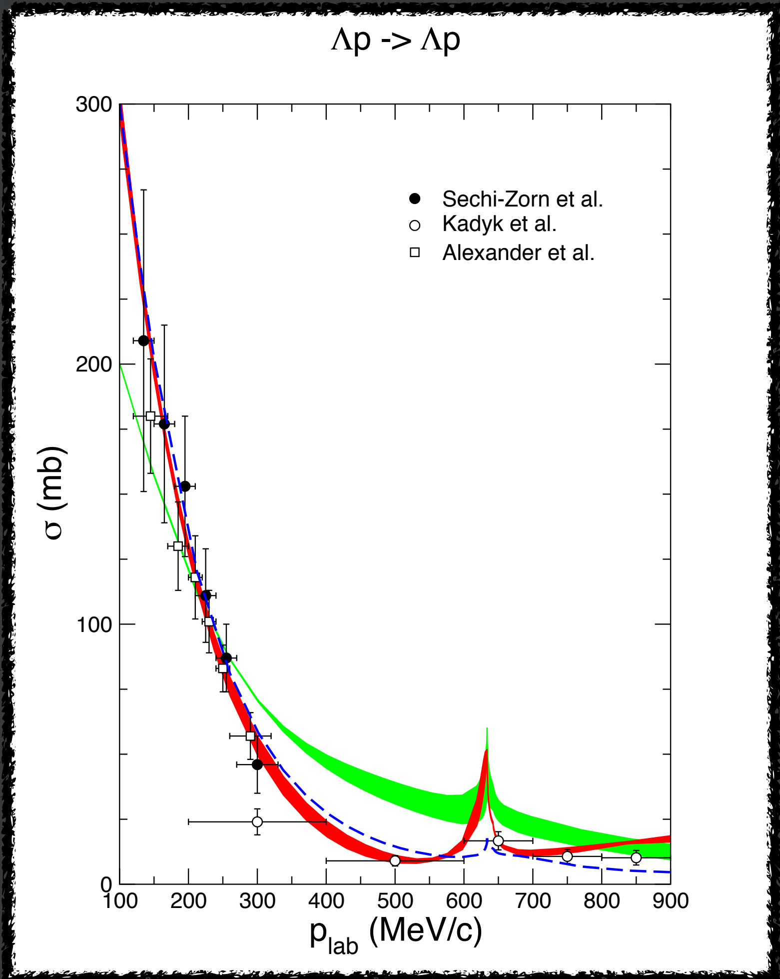
Experimental Evidence II

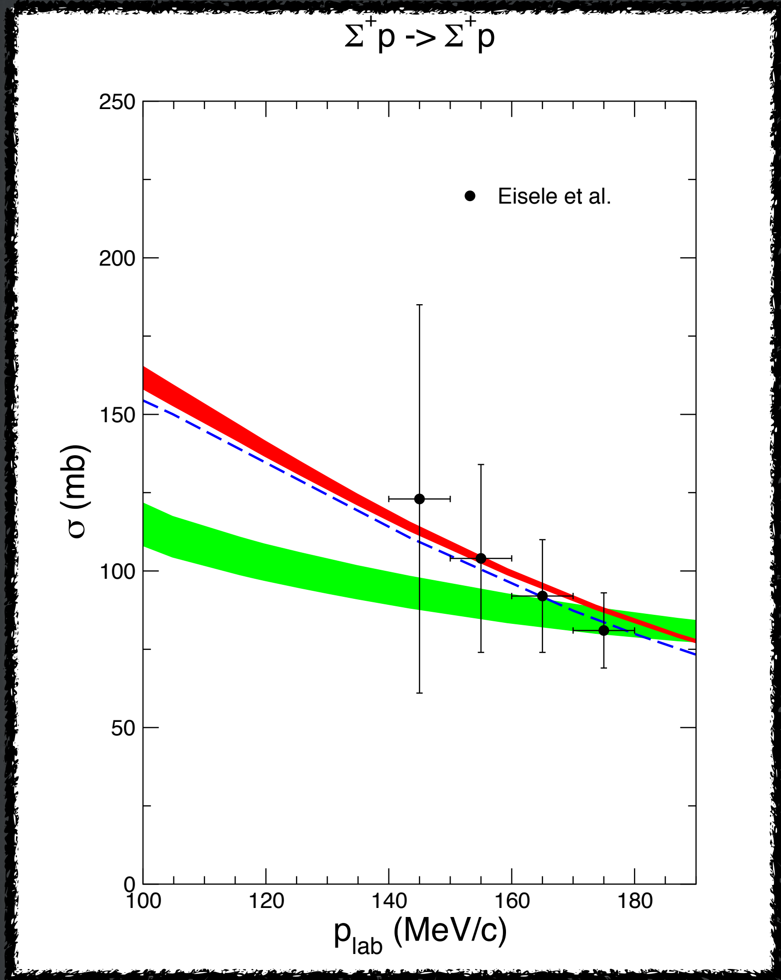
Λ-p Σ-p scattering

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

Cross-section -> scattering length -> Interacting Potential

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





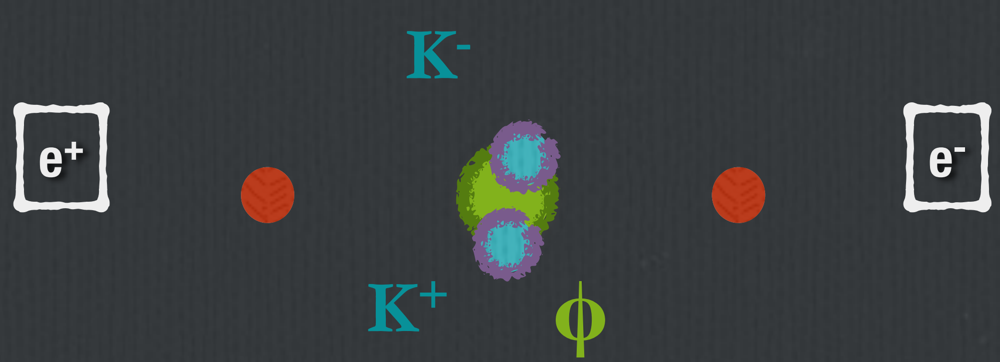
Scarce Data and all above 150 MeV/c

Low, Intermediate and High Energy Experiments

Our Plan: study the Hyperon-Nucleon interaction more in detail with accelerator experiments

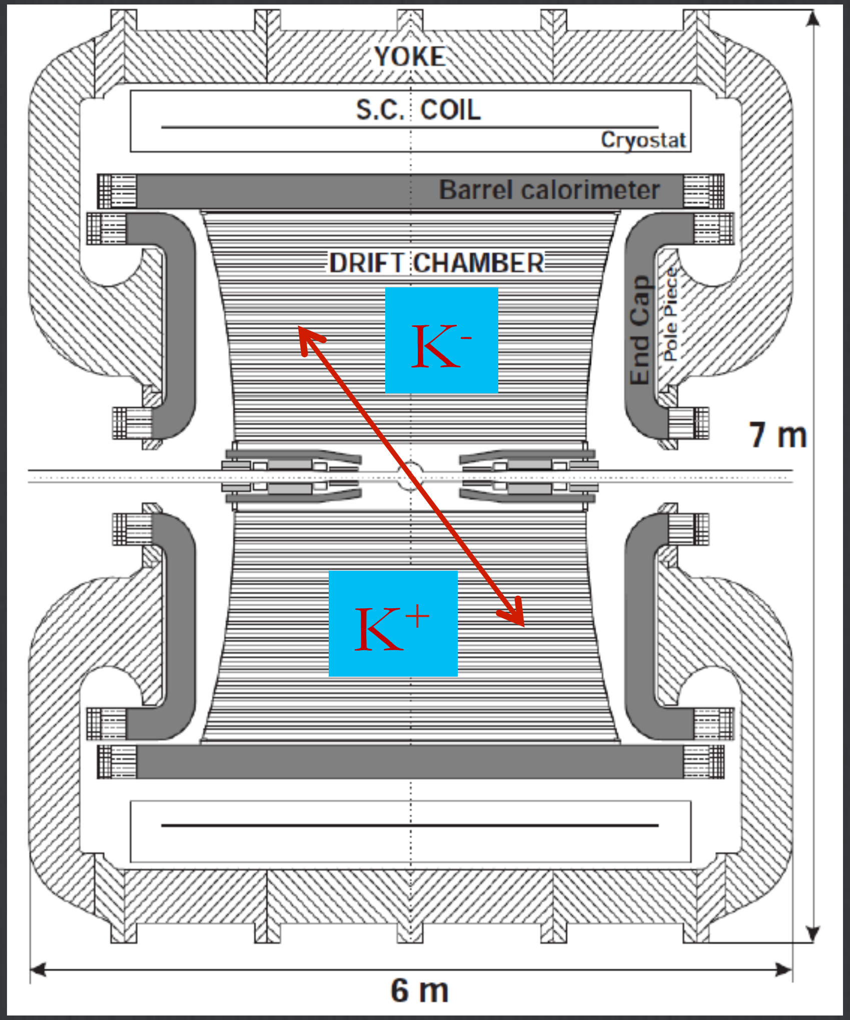
K^- "beams" with very low (~100 MeV) momentum	p+A collisions at fixed target experiment with E_{KIN}~ GeV	p+p and p+A collisions at the LHC (TeV Regime)
Λ and Σ production in exclusive reactions with small relative momenta	Λ and Σ production in a rather controlled environment. Study of the Λ/Σ-nucleon interaction via **Femtoscopy**	Λ and Σ production in a rather complex environment. Study of the Λ/Σ-nucleon interaction via **Femtoscopy**
Limited Statistics (15.000 evts)	Moderate statistics (350.000 evts)	Good statistics (3.000.000 evts)

$K^- + {}^4He$ reactions at Daφne



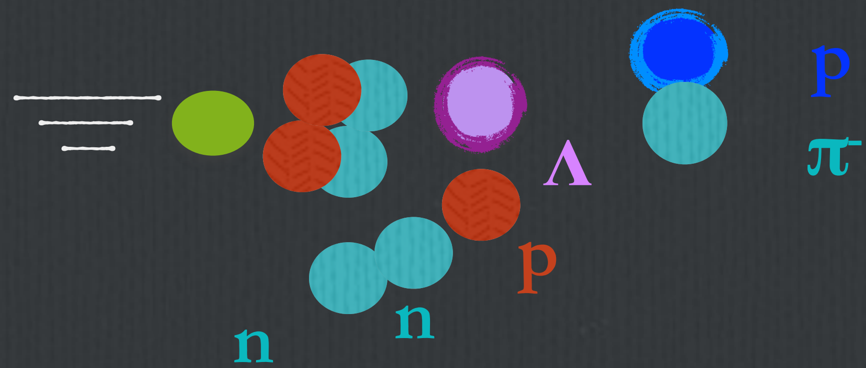
- K- Momentum = 127 MeV/c
- $\sigma p/p \sim 0.4$ MeV/c
- 96% geometrical acceptance
- Calorimeter for γs: $\sigma_m \sim 18$ MeV/c^2
- Vertex resolution: 1 mm
- Gas: 90% He, 10% C_4H_{10}

KLOE Experiment

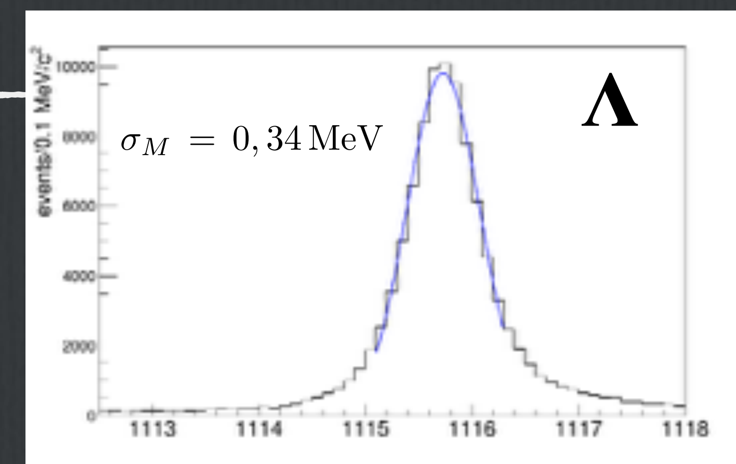


K- ^{4}He

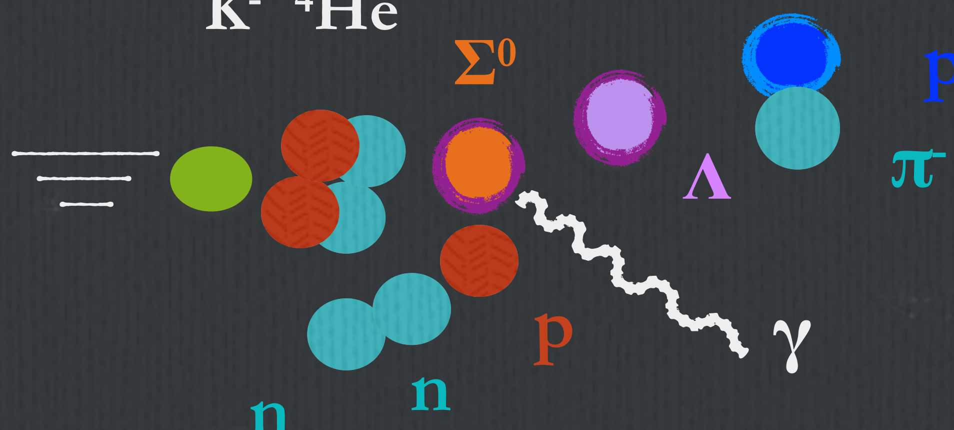
K- ^{4}He



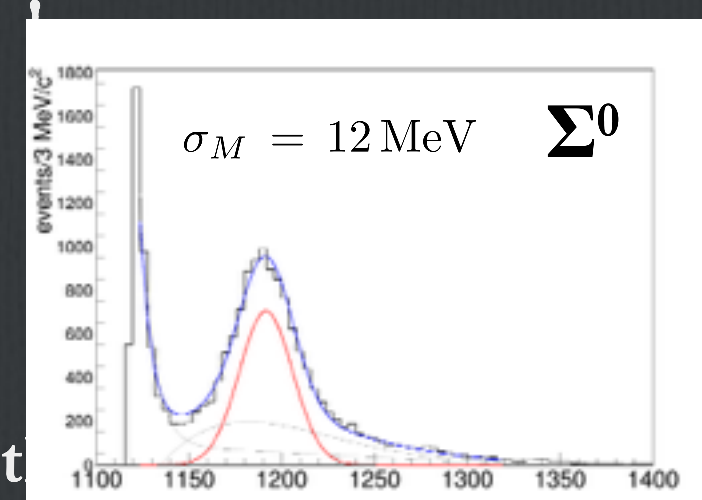
$$K^- + ^4He \rightarrow \Lambda + p + n + n$$



K- ^{4}He



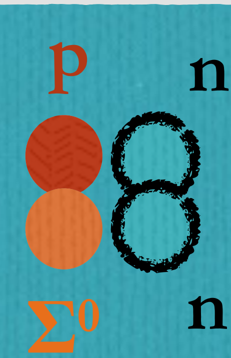
$$K^- + ^4He \rightarrow \Sigma^0 + p + n + n$$



γ can to be detected in t

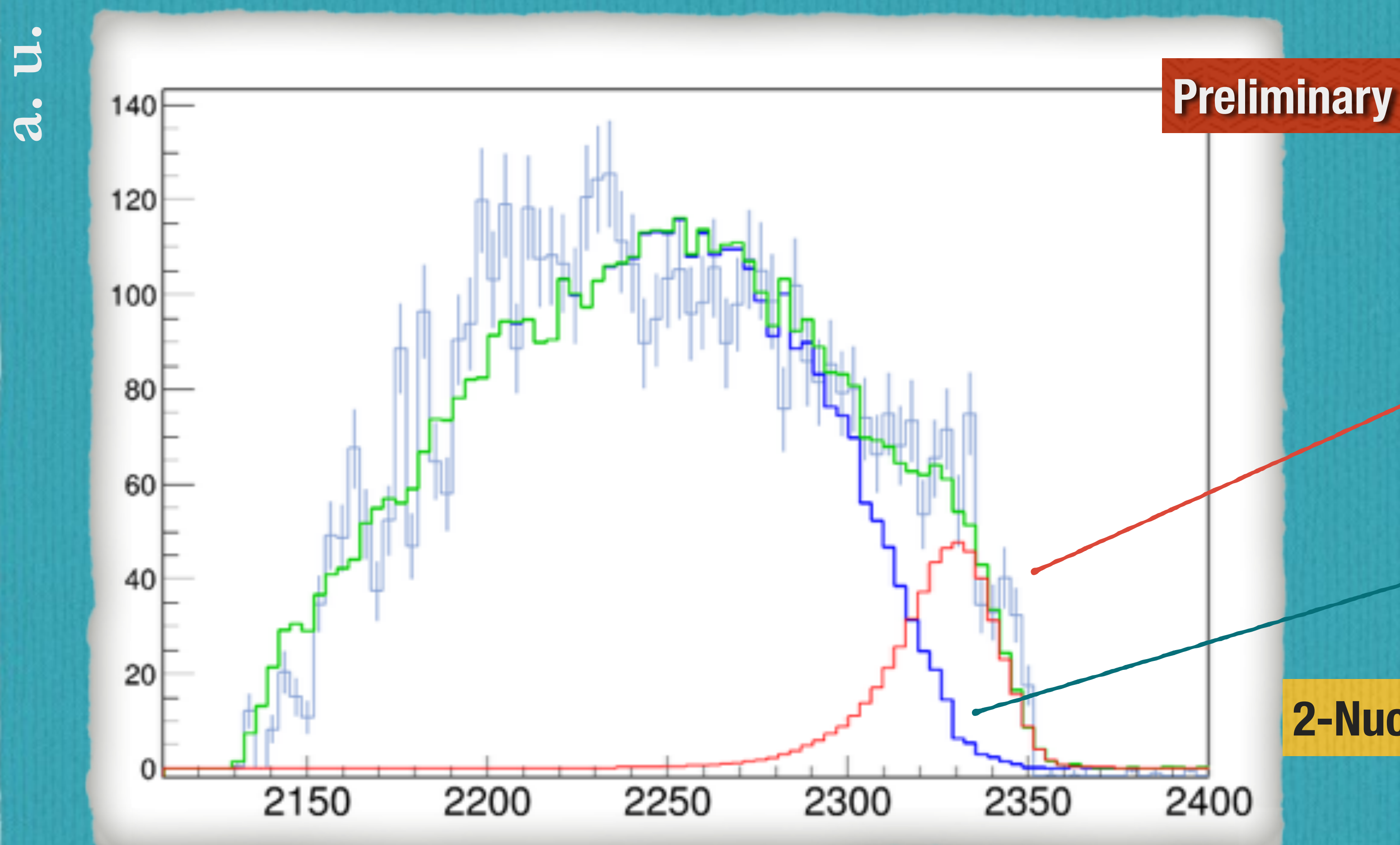
Σ^0-Nucleon Correlation

Low Energy K^-



Σ^0-p long-range correlation
Σ^0-n short-range correlation

Experimental Data compared to Calculations



Σ^0-p Invariant Mass [MeV/c^2]

2-Nucleons Absorption

$$K^- + pp\,(nn) \rightarrow \Sigma^0 + p\,(nn)$$

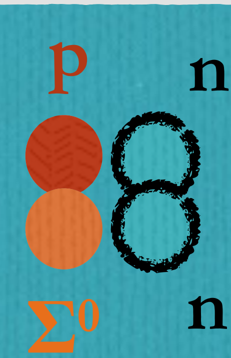
3-Nucleons Absorption ???

$$K^- + ppn\,(n) \rightarrow \Sigma^0 + p + n\,(n)$$

2-Nucleons Absorption + Final State Interaction ???

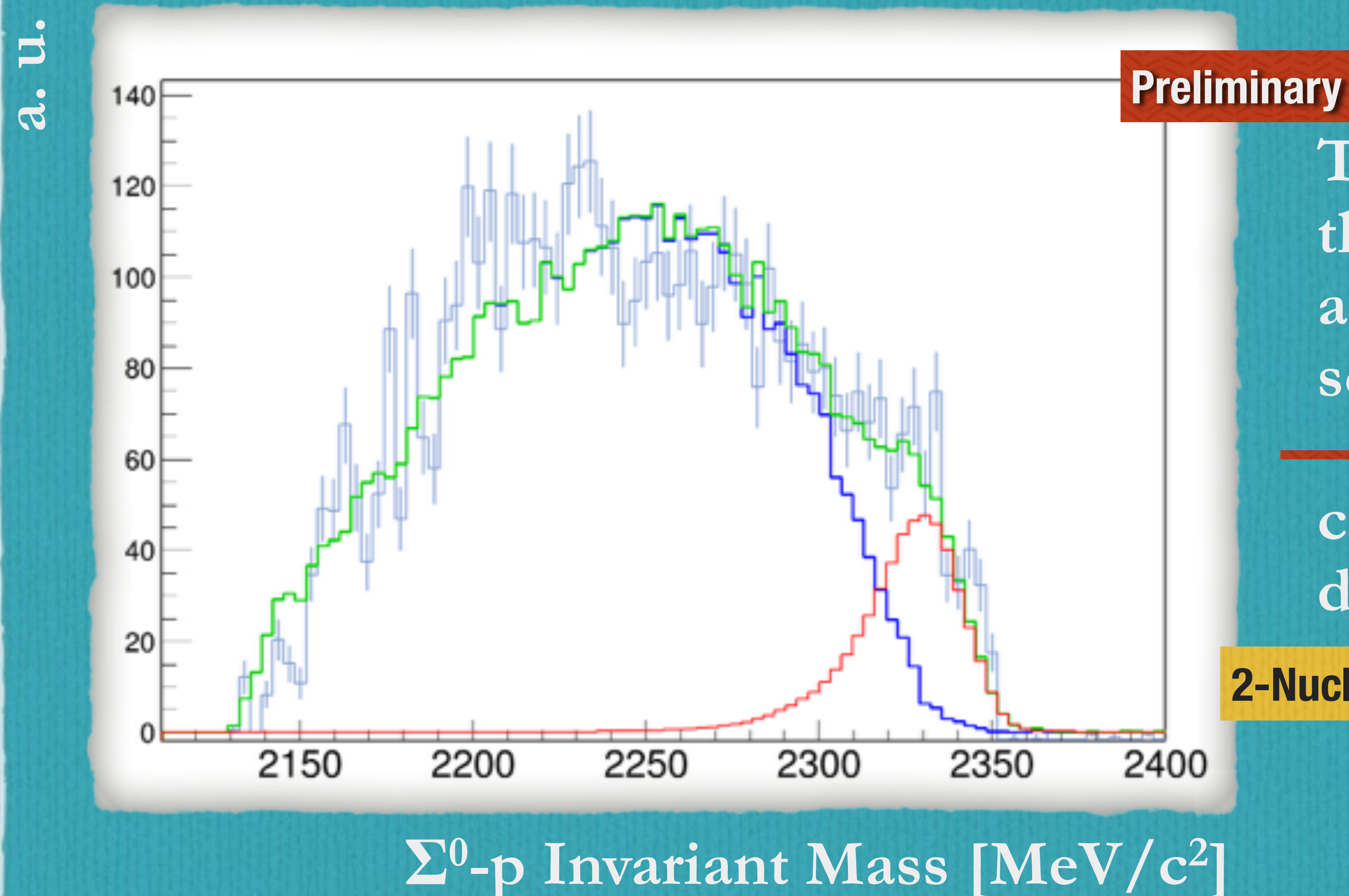
Σ^0-Nucleon Correlation

Low Energy K^-



Σ^0-p long-range correlation
Σ^0-n short-range correlation

Experimental Data compared to Calculations



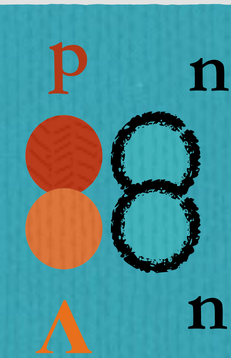
The probability distribution of the momenta of the FS hadrons are calculated on the base of the scattering amplitudes.

→ Test assumptions via the comparison with experimental data!

2-Nucleons Absorption + Final State Interaction ???

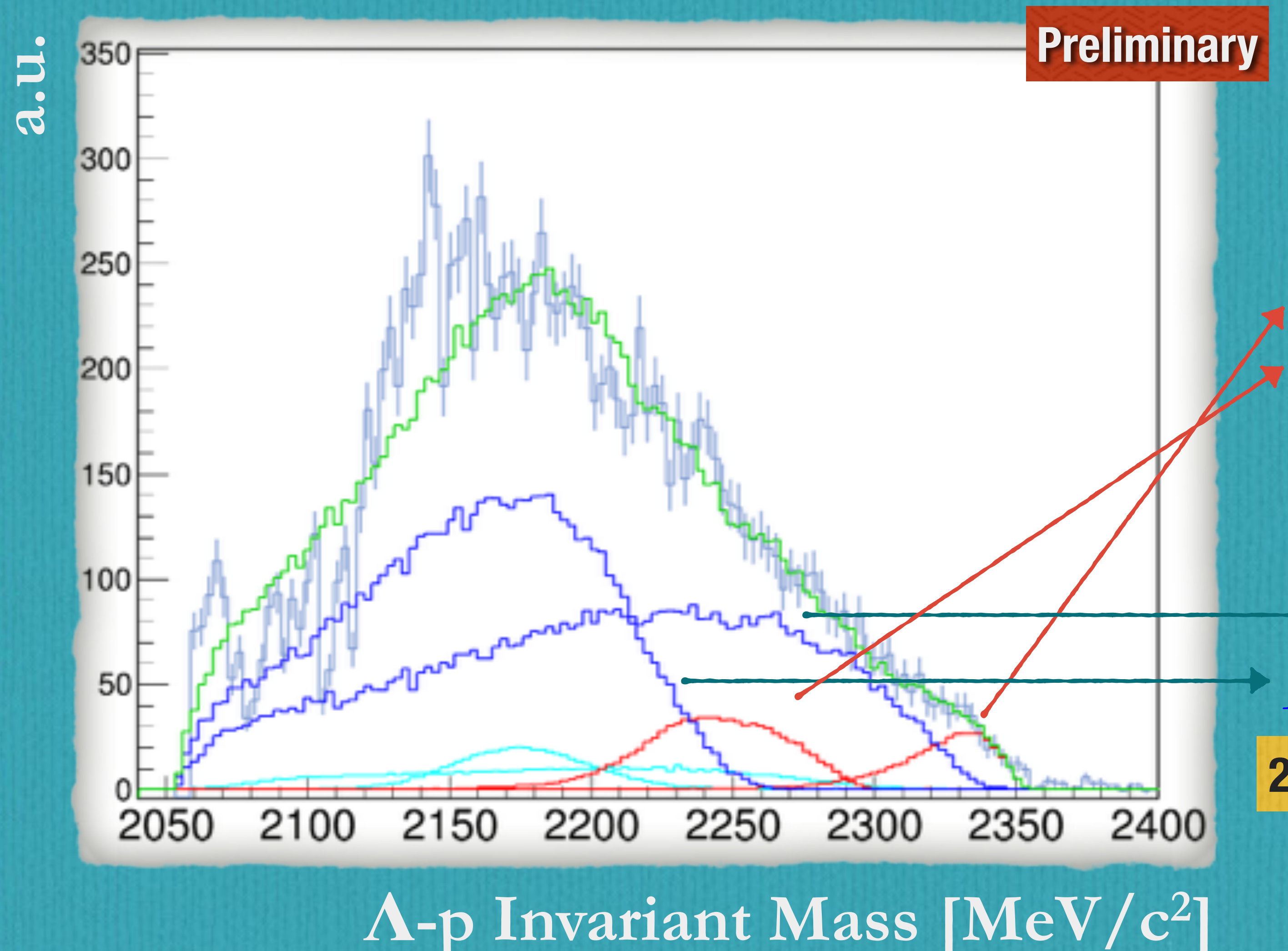
Λ-Nucleon Correlation

Low Energy K^-



Λ-p long-range correlation
Λ-n short-range correlation

Experimental Data compared to Calculations



2-Nucleons Absorption

$$K^- + pp\,(nn) \rightarrow \Lambda + p\,(nn)$$

$$K^- + pp\,(nn) \rightarrow \Sigma^0(\rightarrow \Lambda + \gamma) + p\,(nn)$$

3-Nucleons Absorption ???

$$K^- + ppn\,(n) \rightarrow \Lambda + p + n\,(n)$$

$$K^- + ppn\,(n) \rightarrow \Sigma^0(\rightarrow \Lambda + \gamma) + p + n\,(n)$$

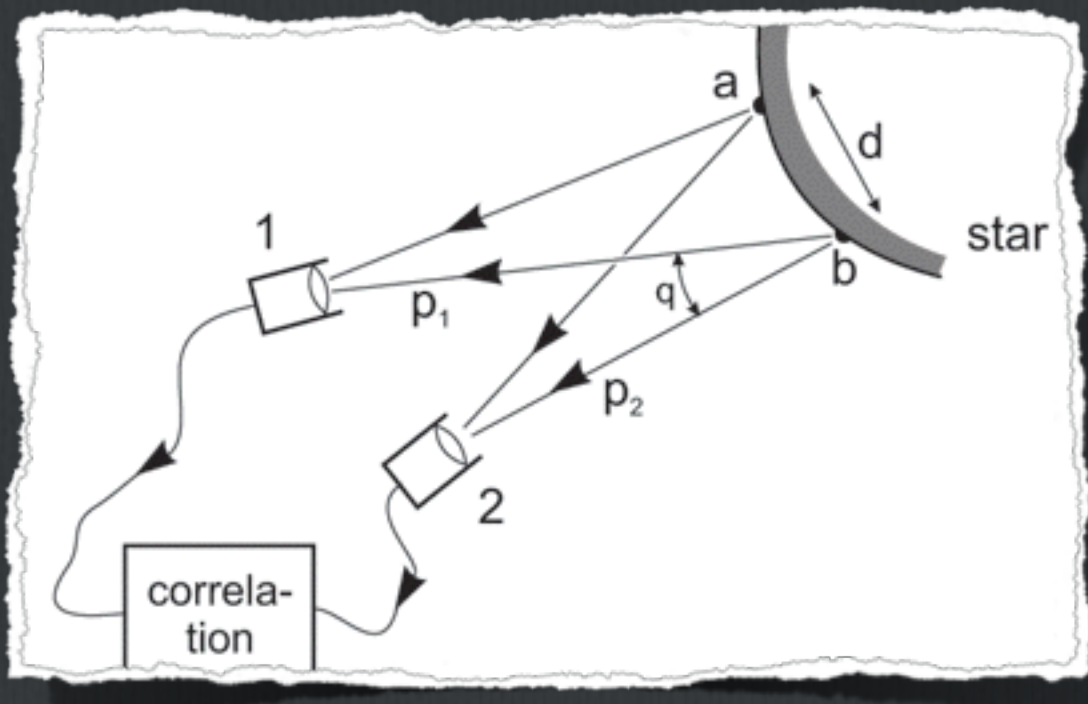
2-Nucleons Absorption + Final State Interaction ???

- Λ-Nucleon and Σ-Nucleon interactions can be tested via exclusive hadronic reactions with stopped and in-flight K^- "beams".
- Long and short- range interactions can be addressed
- let's see

Scattering data provide information for hyperon Momenta above 150/200 MeV.
Is there a tool to investigate the low momenta region?

We try with Femtoscopy

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

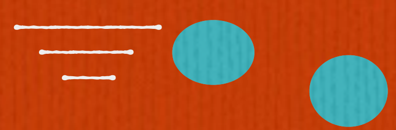
$$C(k) = \mathcal{N}\frac{N(\mathbf{p}_1, \mathbf{p}_2)_{\mathrm{same}}}{N(\mathbf{p}_1, \mathbf{p}_2)_{\mathrm{mixed}}} \qquad k = \tfrac{1}{2}|\mathbf{p}_1 - \mathbf{p}_2|$$

Experimental Observable

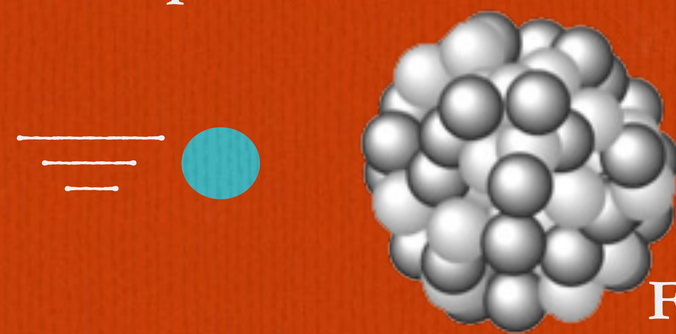
Reactions in the GeV Energy Range

Fixed Target experiments, $E_{kin} \sim$ AGeV

proton-proton



proton-nucleus



Heavy-ion Collisions $\rho_B < 2\text{-}3\ \rho_0$

HADES

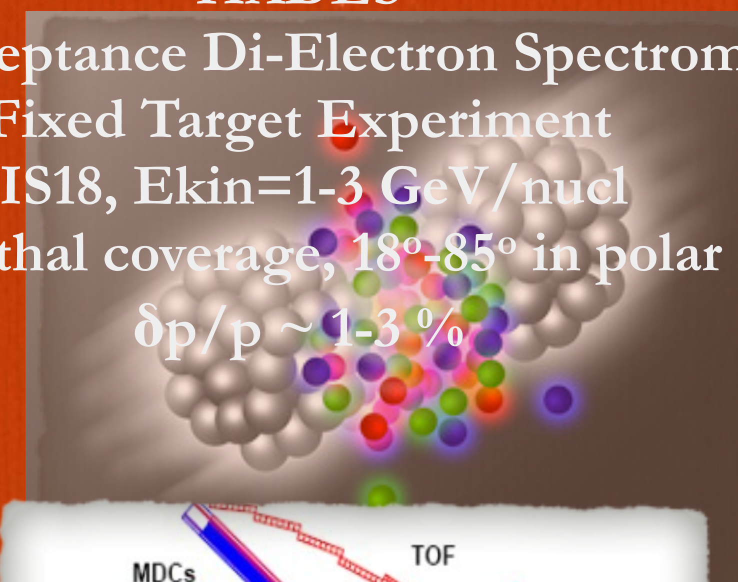
High Acceptance Di-Electron Spectrometer

Fixed Target Experiment

SIS18, Ekin=1-3 GeV/nucl

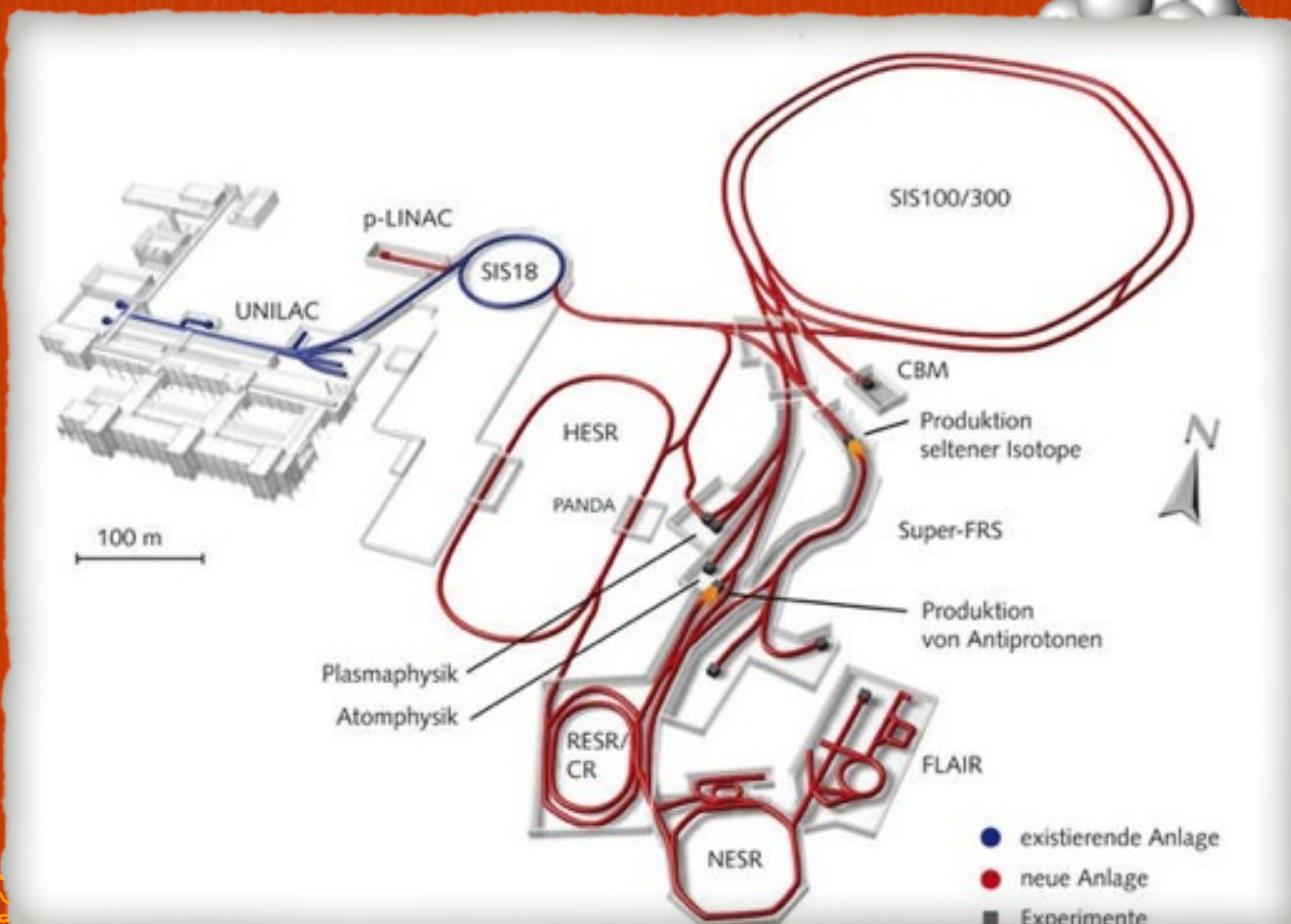
Full azimuthal coverage, 18°-85° in polar angle

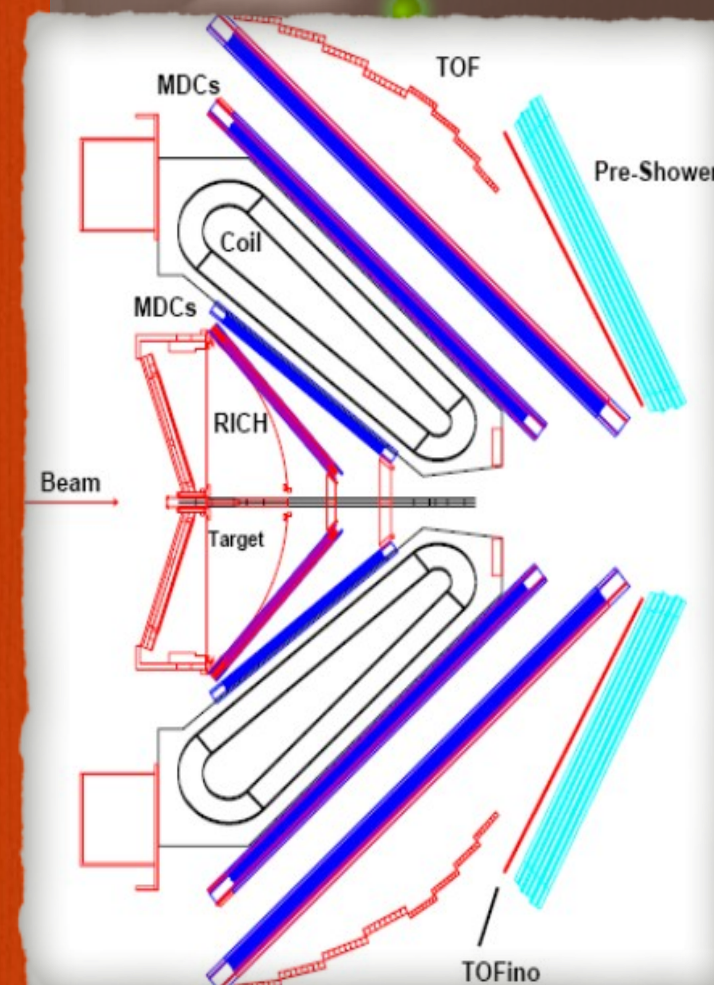
$\delta p/p \sim 1\text{-}3\ \%$



π-proton

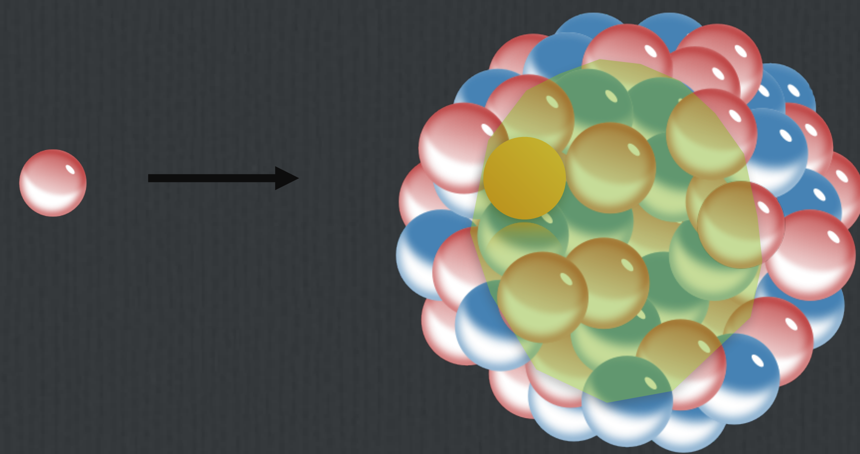
π-nucleus





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

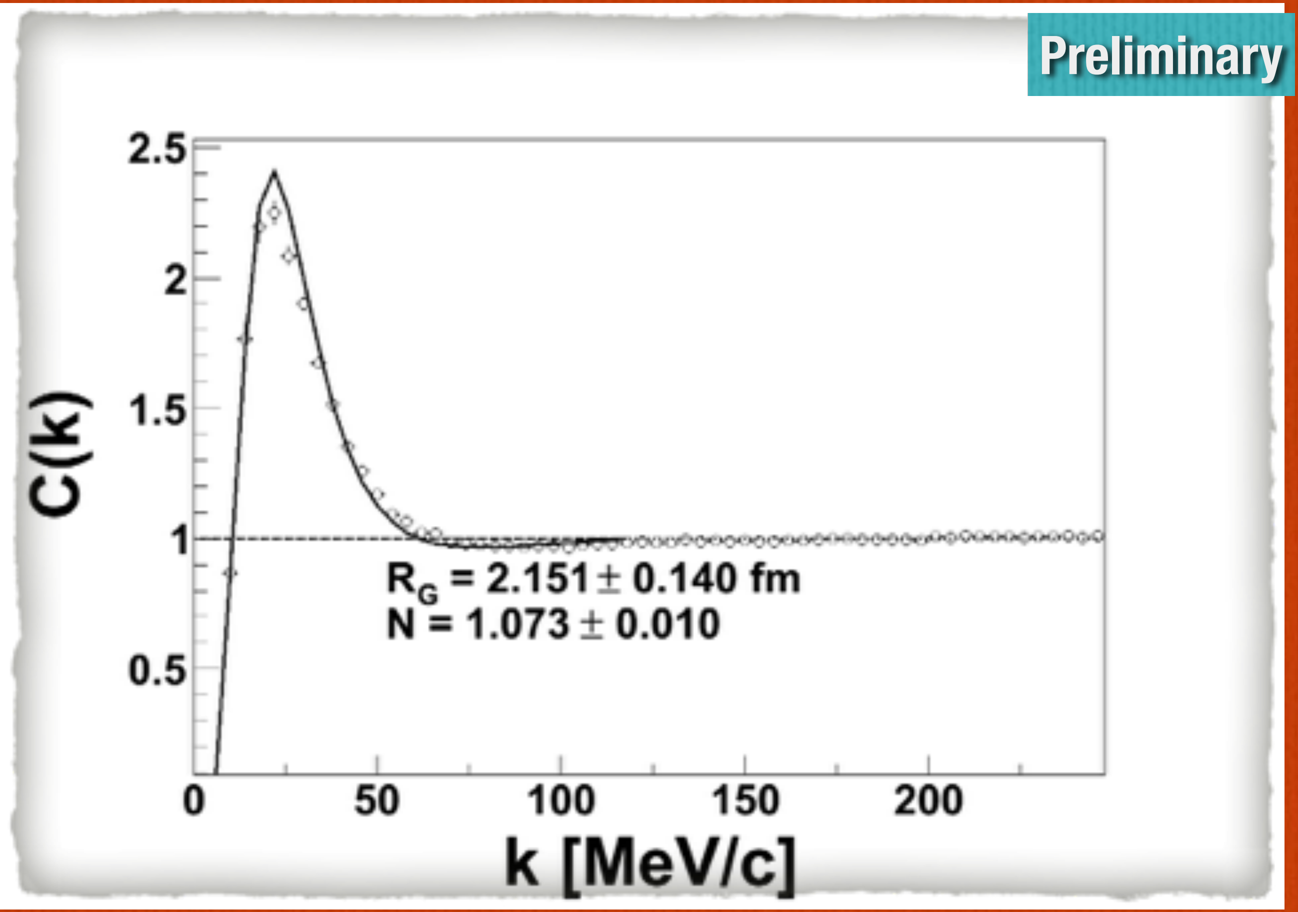
pp Pairs:
Coulomb Interaction
Strong Interaction
Quantum Statistics for Fermions

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

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



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

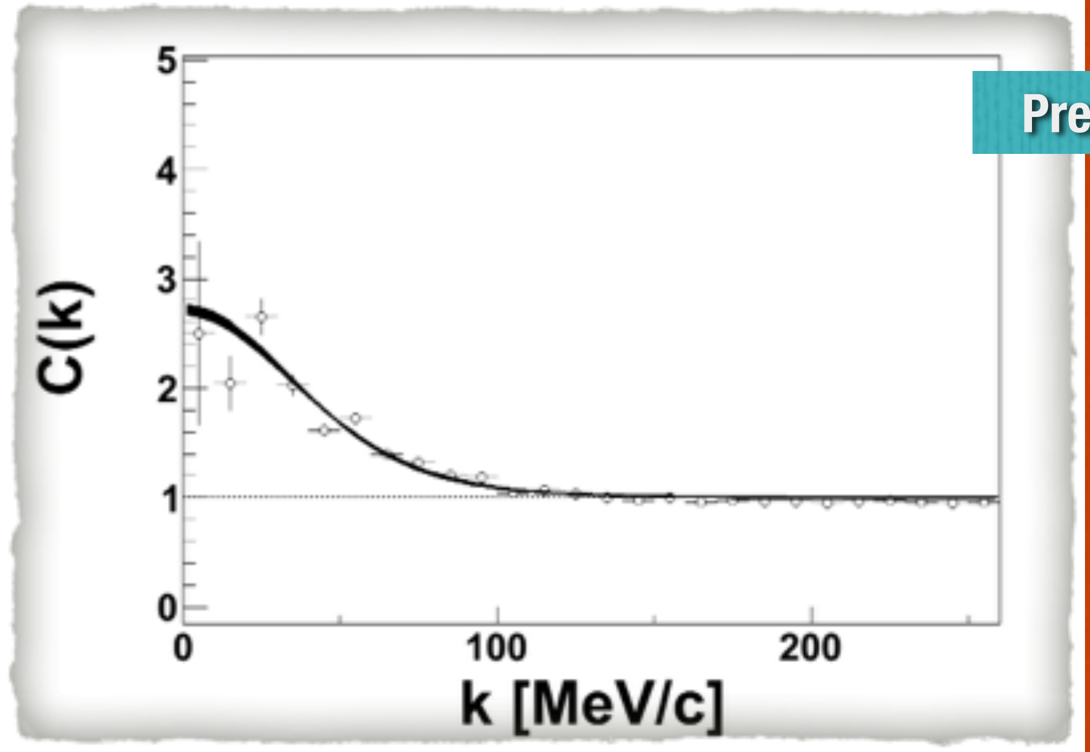
Λp Scattering Length

Experimental Distribution

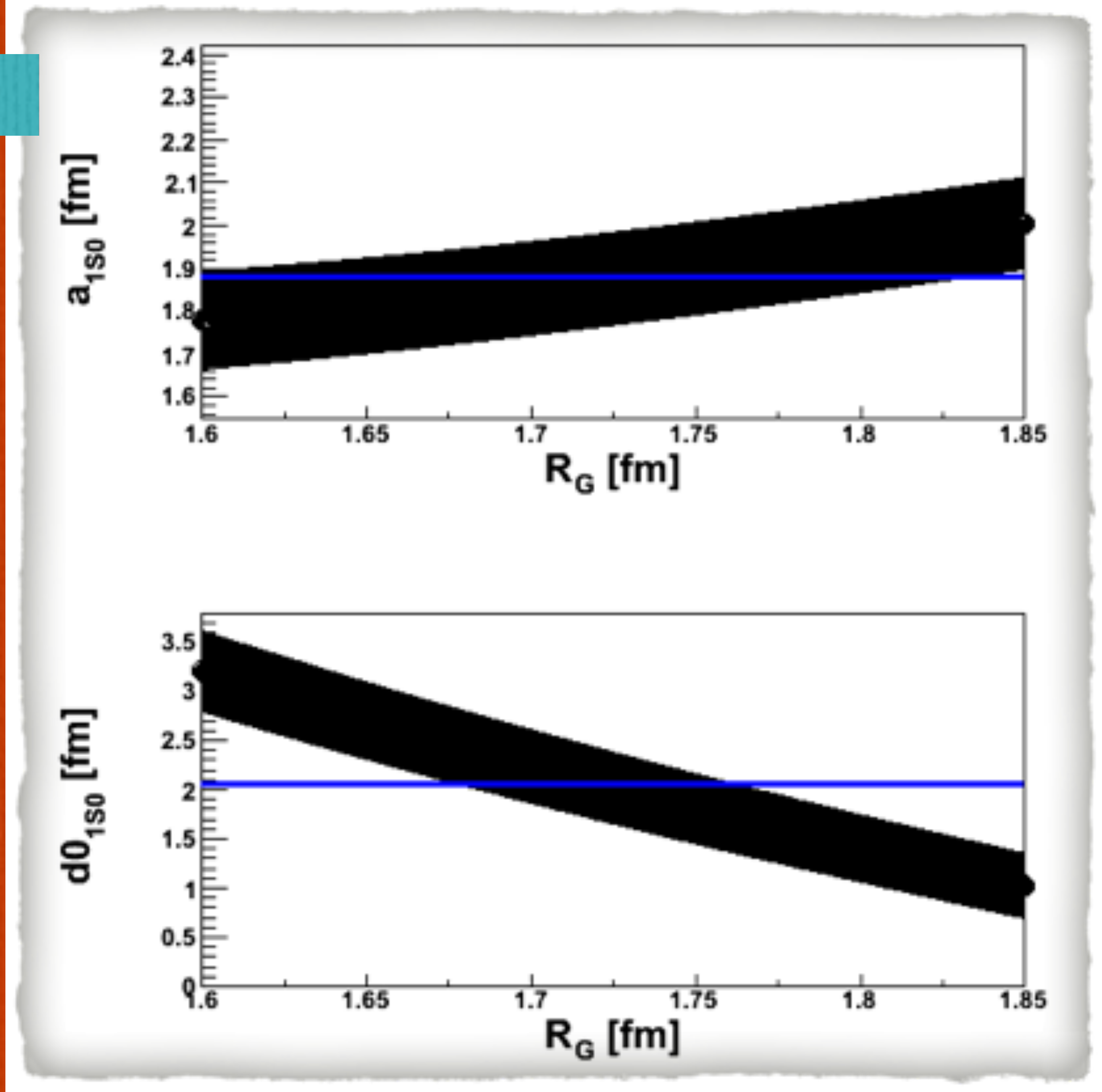
$$C(k) = \mathcal{N}\frac{N(\mathbf{p}_1,\mathbf{p}_2)_{\mathrm{same}}}{N(\mathbf{p}_1,\mathbf{p}_2)_{\mathrm{mixed}}} \qquad k = \frac{1}{2}|\mathbf{p}_1 - \mathbf{p}_2|$$

Fit Function

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



Preliminary



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.

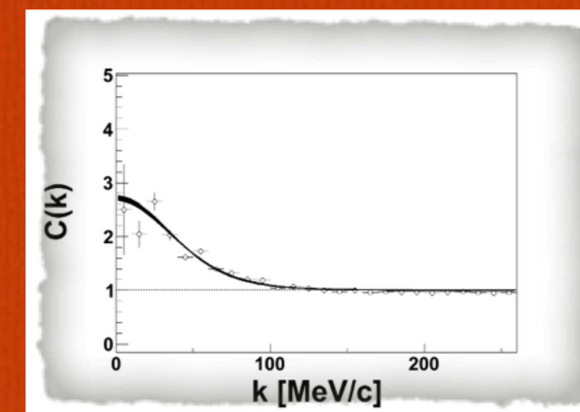
Test-Bed for Lattice Calculations

Simulation of the particle Production and Freeze-Out coordinates

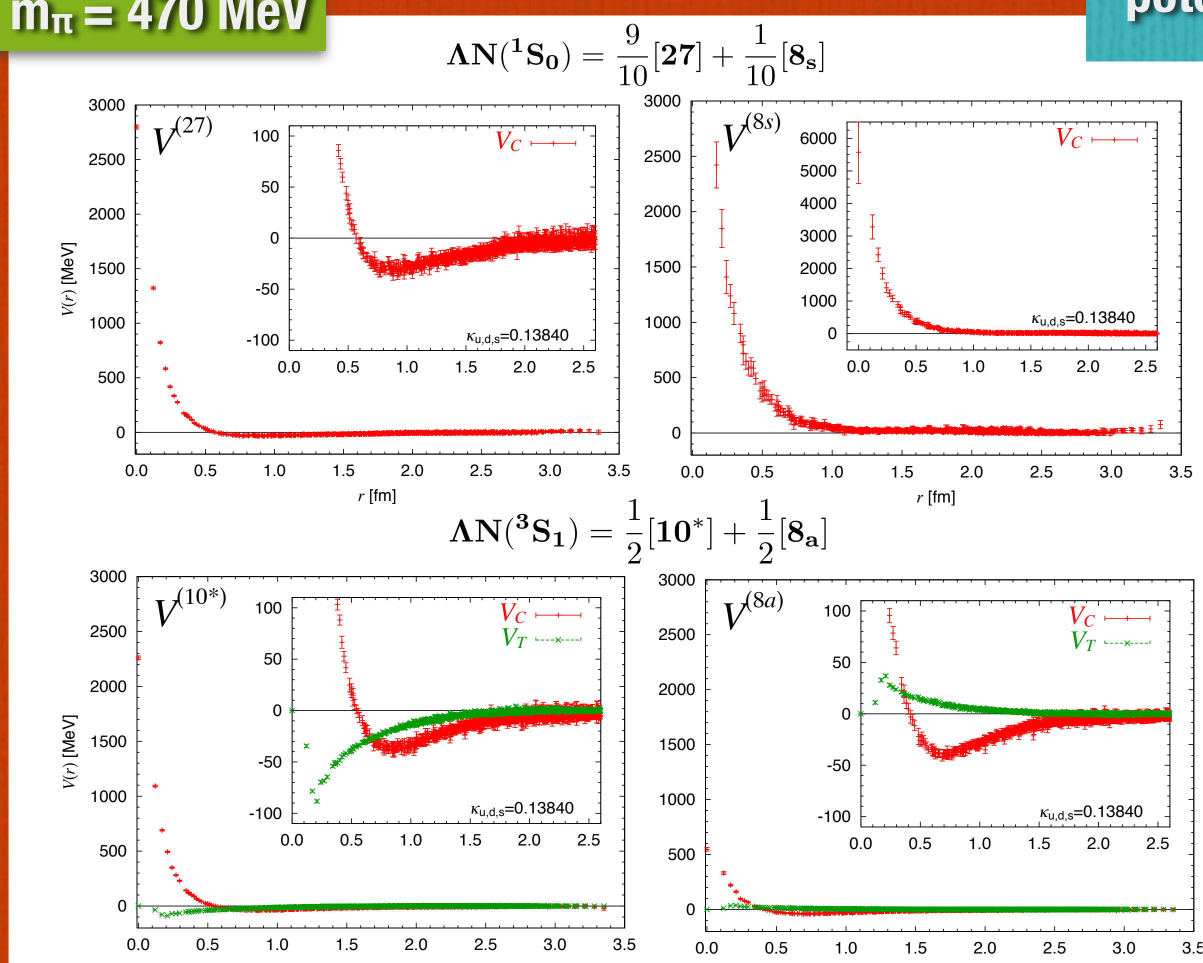
After-Burner which includes the relevant Interactions

Comparison with the measured correlations

Constrain the potential



$m_\pi = 470$ MeV



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

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

Mainly a matter of statistics

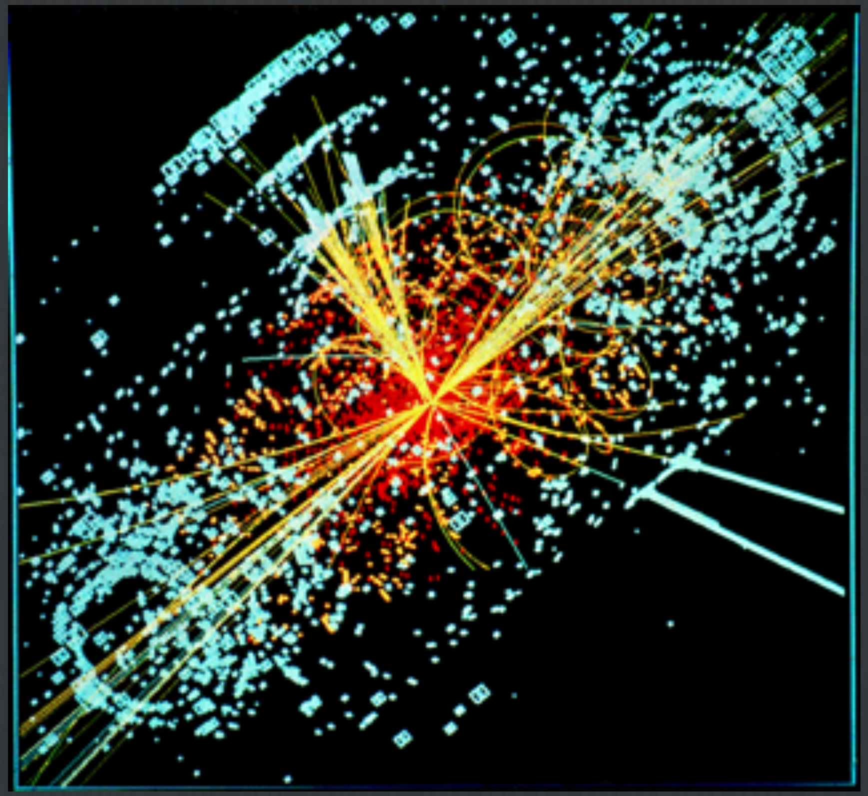
The Experimental Data

p+p/A at 3.2 GeV

6 Particles/Evt

only 350.000 Λ but "clean" environment
better knowledge of the emitting source

p+p/A at 7 TeV



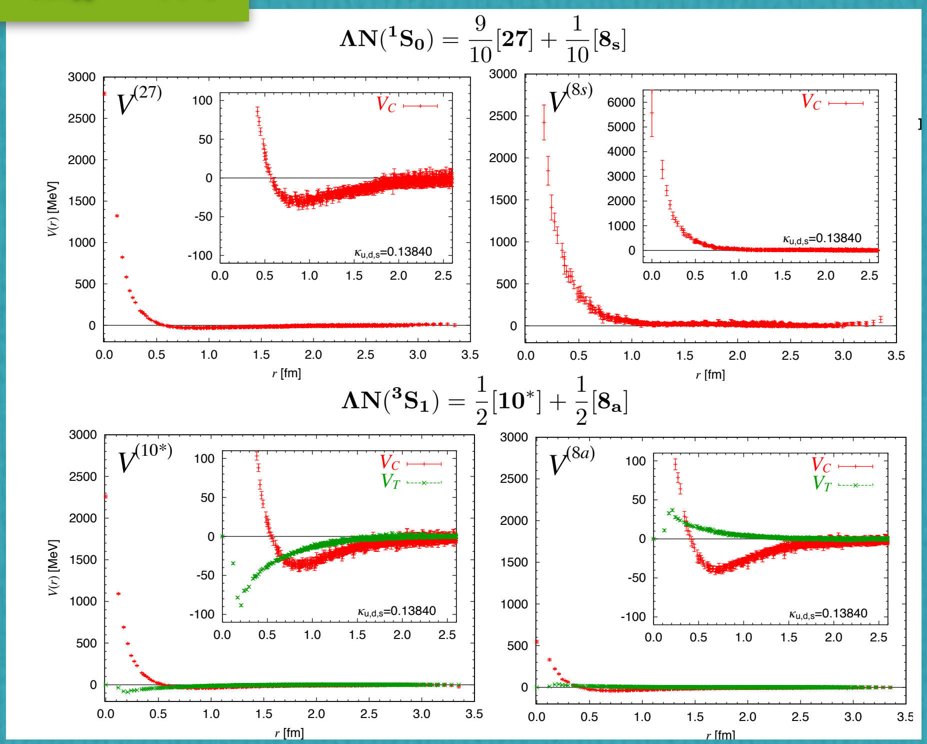
2000 Particles/Evt

large Λ and Σ statistics (~ 3 Mevt) but
more complicated source to be described

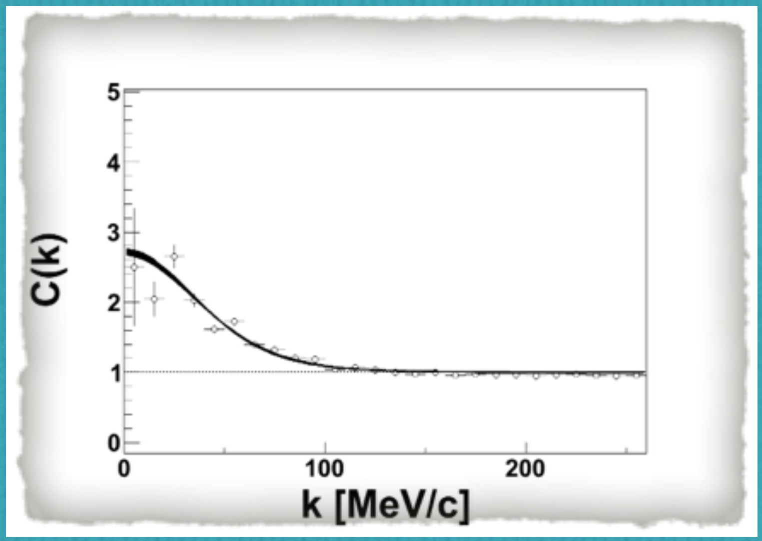
Summary

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

$m_\pi = 470$



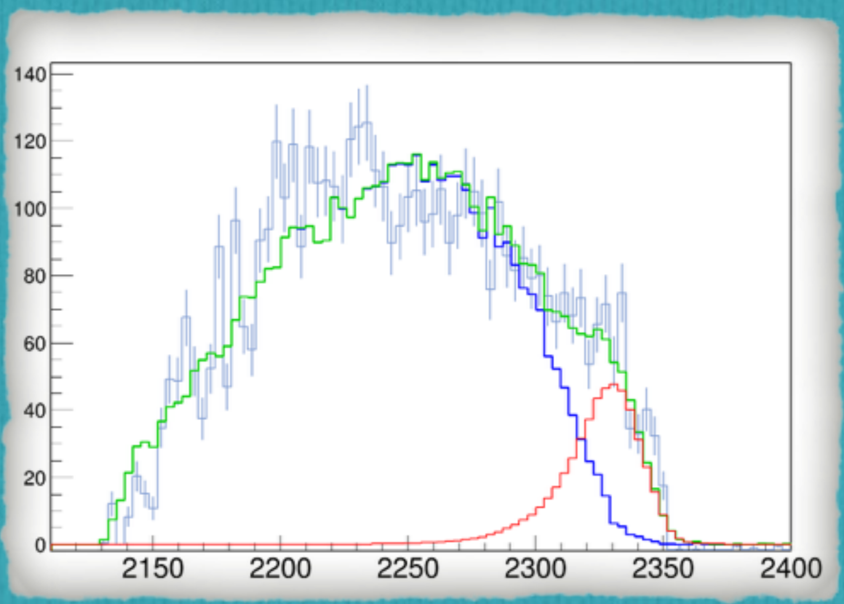
T. Inoue et al. Nucl. Phys. A881 (2012)



Verify the short and long-range Hyperon-nucleon FSI with the low energy data.

Solve the puzzle of hyperon in Neutron Stars

a. u.

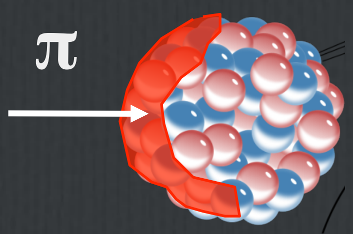


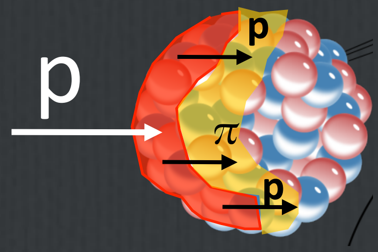
Σ^0-p Invariant

The people in Munich

Thanks

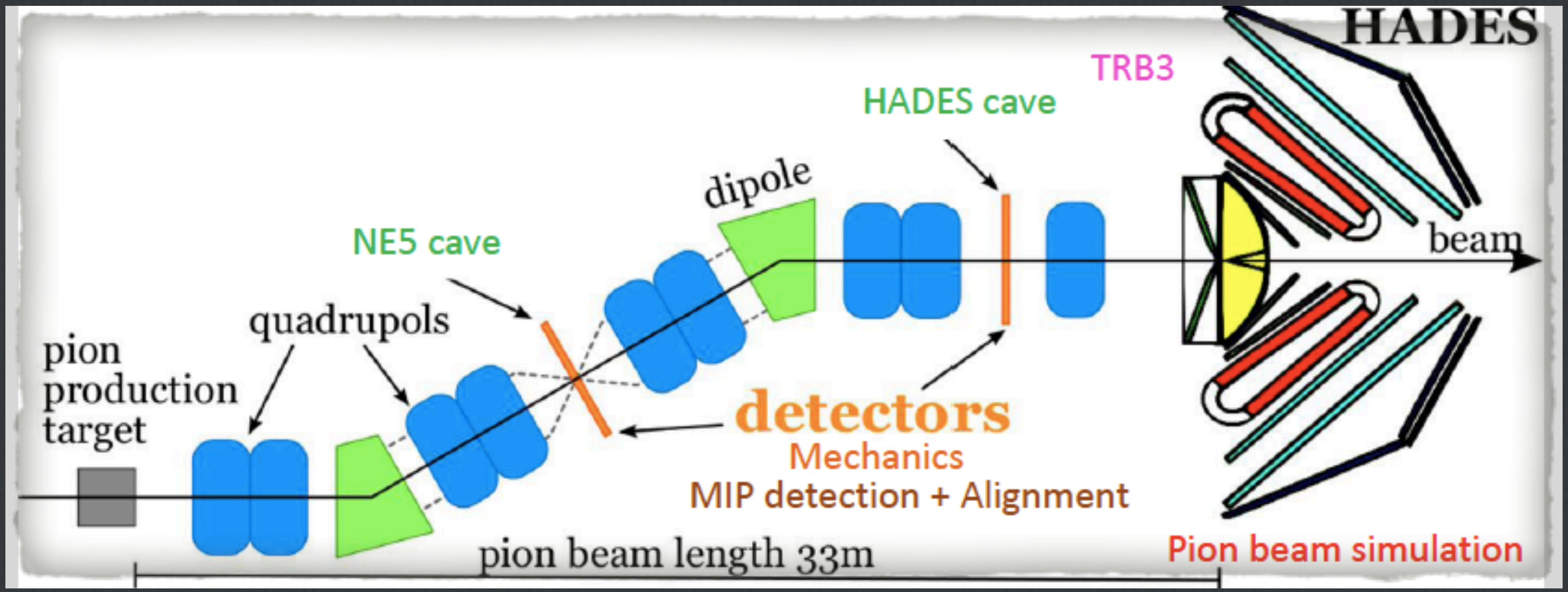
Experiments with π Beams





- 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

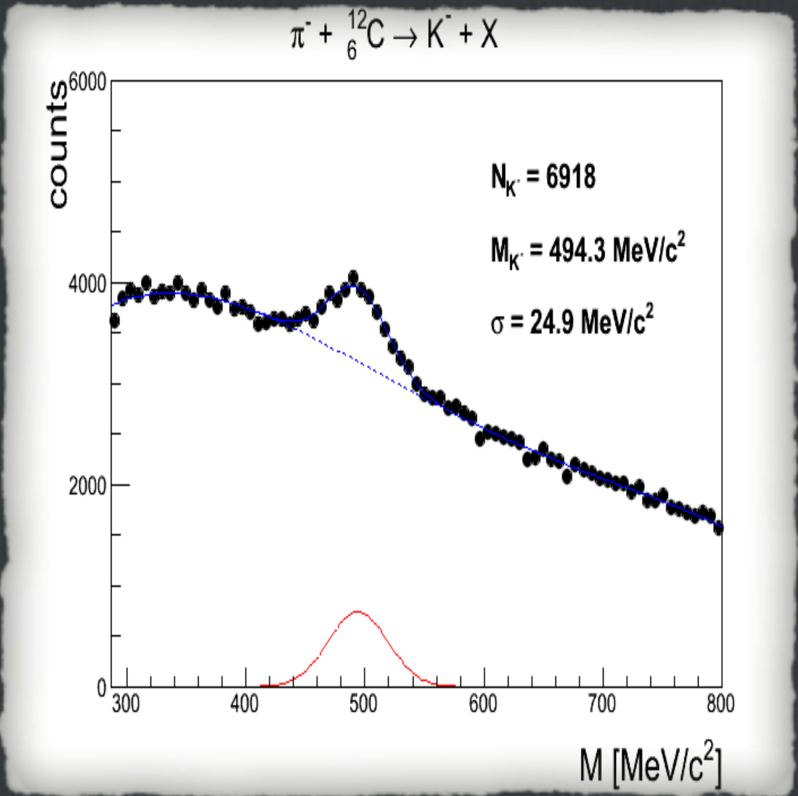


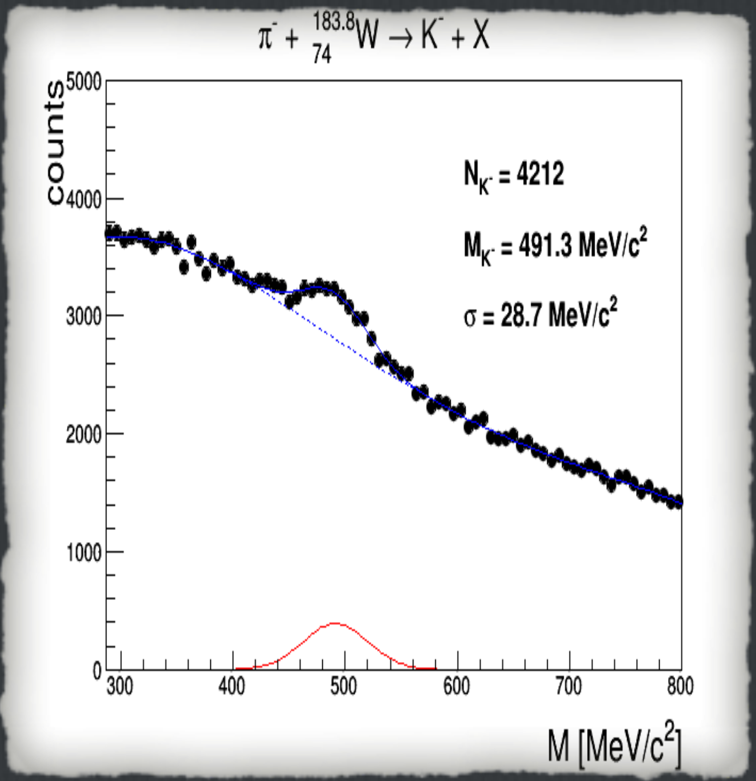
CERBEROS: 3-heads dog at the HADES entrance

Experiments with π Beams

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

Study of Hadron-nucleon interaction



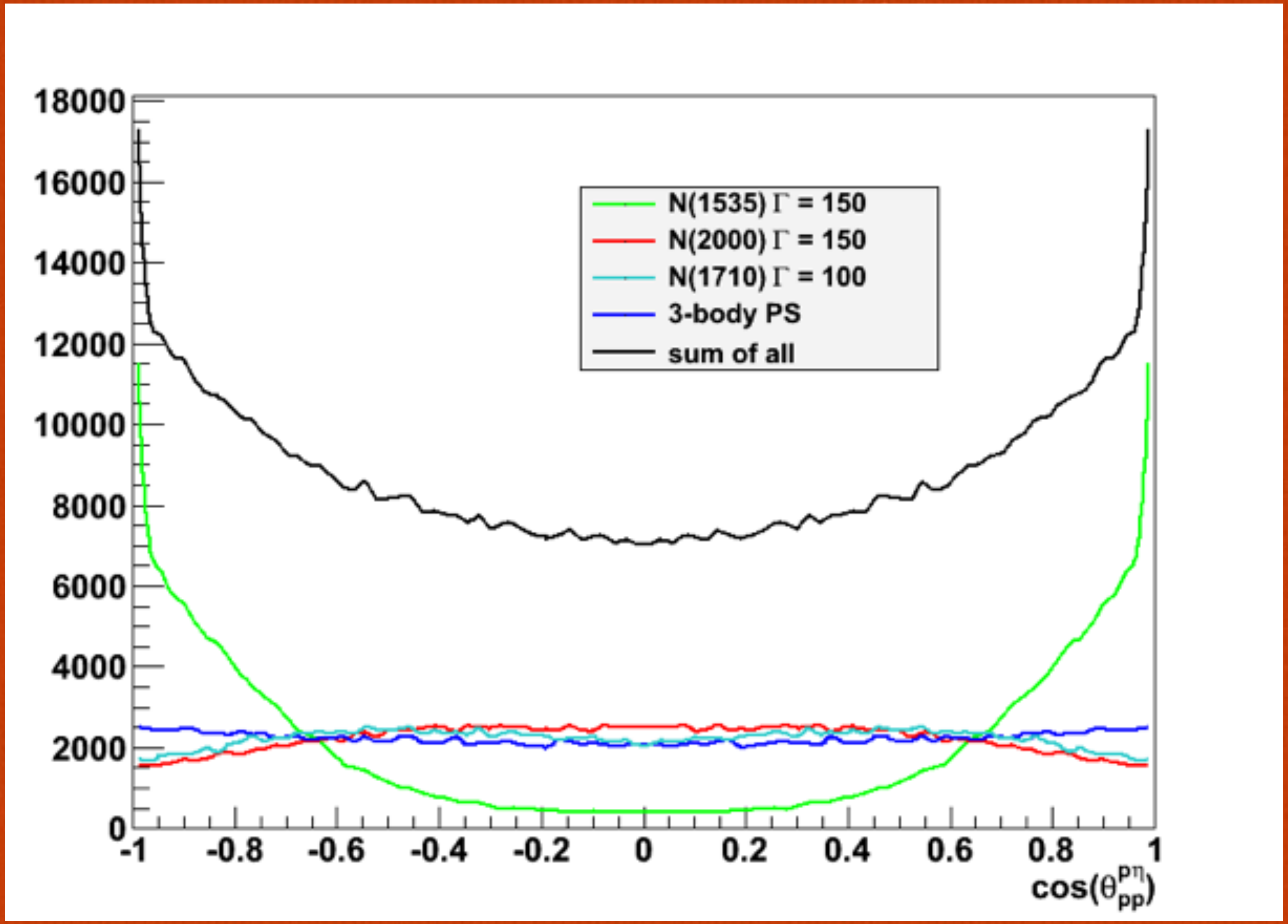


First Measurement of $\bar{K}$ absorption in normal nuclear matter

η: Pluto simulations in 4π

K. Lapidus

Angle between the η-meson and proton in the proton-proton rest system (symmetric by construction)

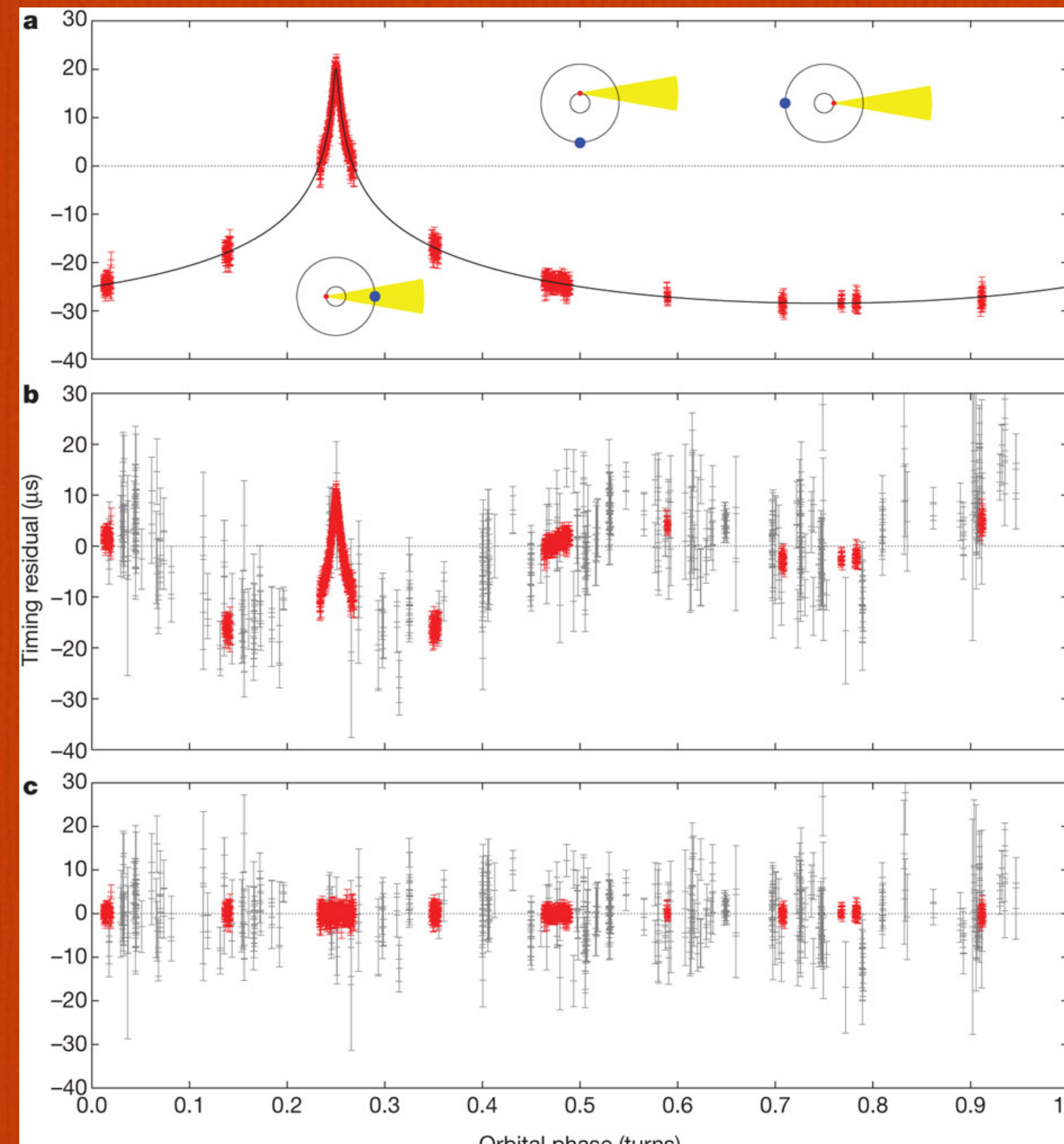


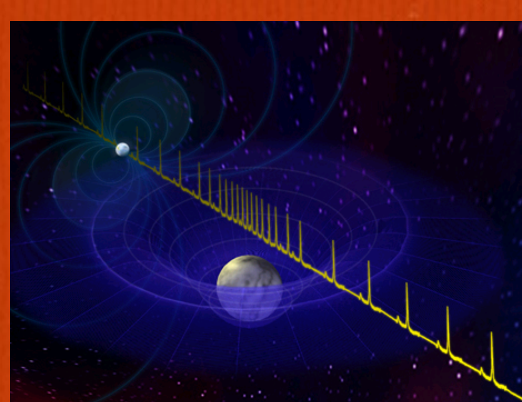
Already N(1710) can not be distinguished from the 3-body phase-space distribution

Shapiro Delay

- GR: speed of light depends on the gravitational potential strength along its path
- Shapiro Idea:
  - Measure the echo of radar pulses from Venus or Mars
  - Time delay should increase by 2×10^{-4} s if pulses pass near the sun
- Same effect for radio pulses of NS when passing the White-Dwarf Companion

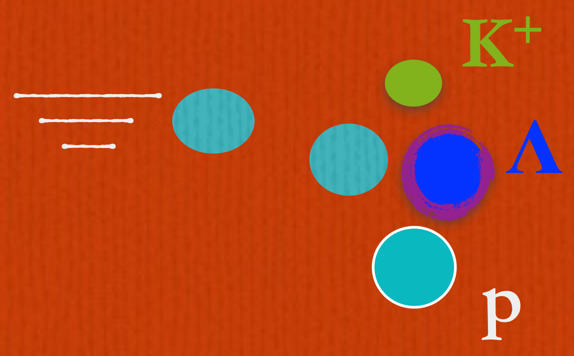
→ Mass determination for the two stars.

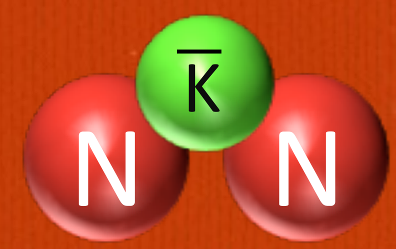




Interferences among Resonances

proton-proton



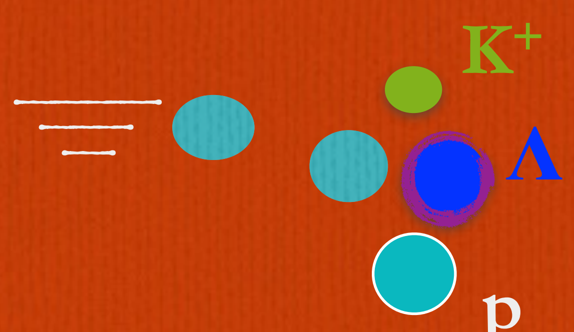


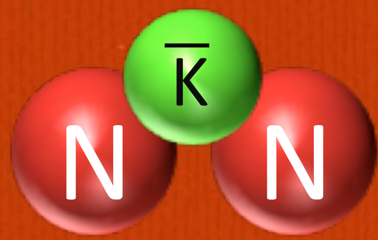
Property	Value
charge	+1
strangeness	-1
participants	ppK^-, $pn\overline{K}^0$
J^P	0^-

$$p + p \rightarrow ppK^- + K+ \rightarrow p + \Lambda + K^+$$

Interferences among Resonances

proton-proton





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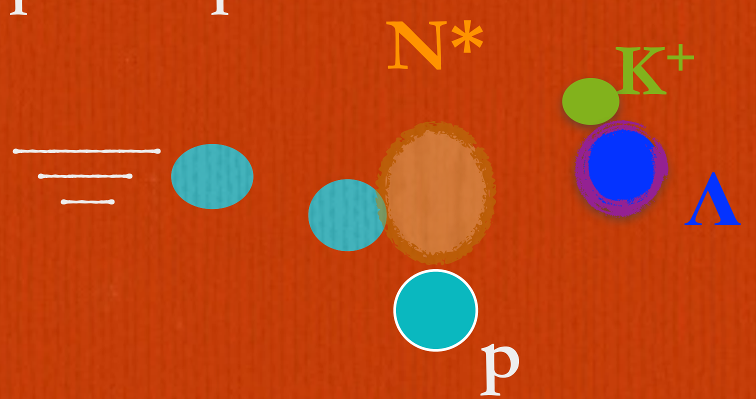
proton-proton

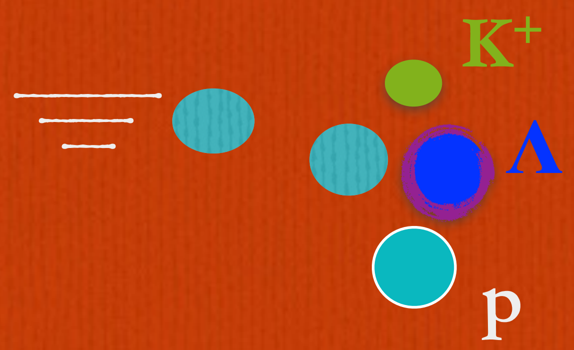


How many N* do exist?
Can these interfere with each others?
Interference: Coherent some of the different amplitudes contributing to the same final state

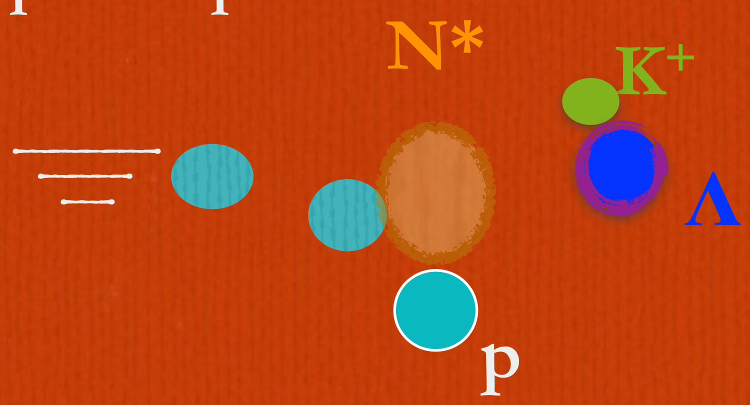
Interferences among Resonances

E. Epple, R. Muenzer

proton-proton



proton-proton



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

Notation in PDG	Old notation	Mass [GeV/c^2]	Width [GeV/c^2]	$\Gamma_{\Lambda K}/\Gamma_{All}$ %
N(1650) $\frac{1}{2}^-$	N(1650)S_{11}	1.655	0.150	3-11
N(1710) $\frac{1}{2}^+$	N(1710)P_{11}	1.710	0.200	5-25
N(1720) $\frac{3}{2}^+$	N(1720)D_{13}	1.720	0.250	1-15
N(1875) $\frac{3}{2}^-$	N(1875)D_{13}	1.875	0.220	4±2
N(1880) $\frac{1}{2}^+$	N(1880)P_{11}	1.870	0.235	2±1
N(1895) $\frac{1}{2}^-$	N(1895)S_{11}	1.895	0.090	18±5
N(1900) $\frac{3}{2}^+$	N(1900)P_{13}	1.900	0.250	0-10

Non Resonant final states

$(p\Lambda)(^{2S+1}L_J)$-K+

Given the transition amplitude for 1 possible wave

$$\boxed{A^{\alpha}_{tr}(s) = \left(a^{\alpha}_1 + a^{\alpha}_3\sqrt{s}\right) e^{ia^{\alpha}_2}}$$

One has to sum all the possible contributing waves to get the total amplitude

The Partial Wave Analysis Framework

E. Epple, R. Muenzer

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)

A total Amplitude is fitted event-by-event to the data and it includes:

N(1650), N(1710), N(1720), N(1875), N(1880), N(1895), N(1900)

Non-resonant $PK^{+}\Lambda$ production waves

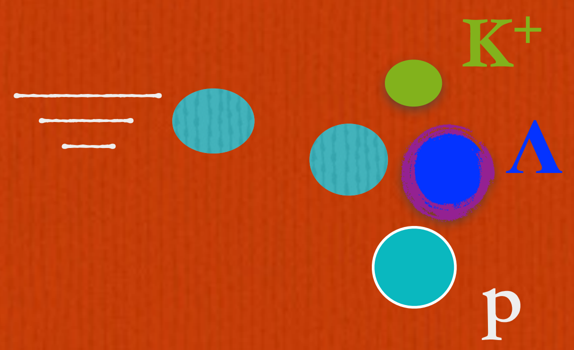
Interferences

110 different solutions have been tested to the p+p at 3.5 GeV data
4 best solutions are identified on the base of the likelihood of the fit

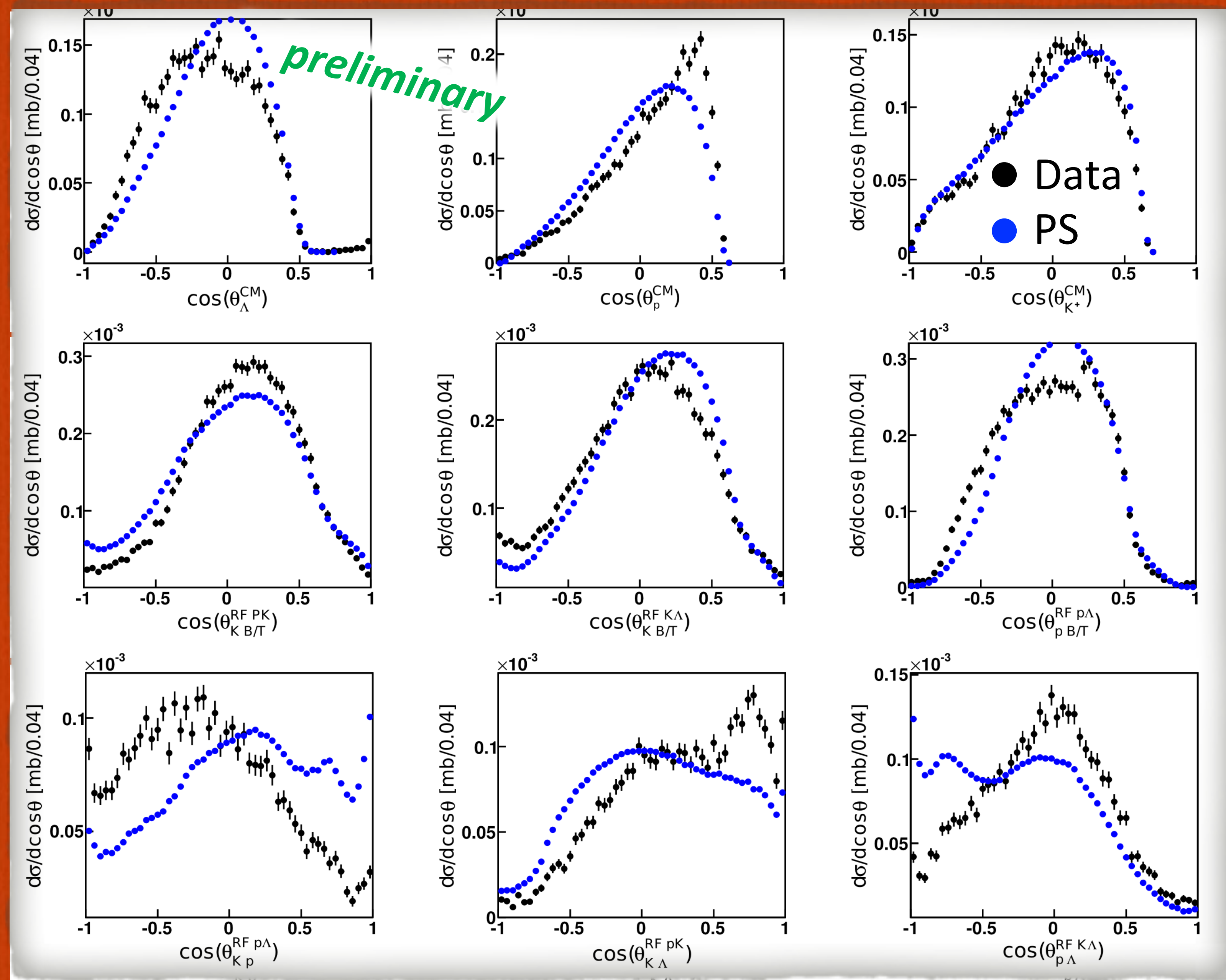
PWA Results

E. Epple, R. Muenzer

proton-proton



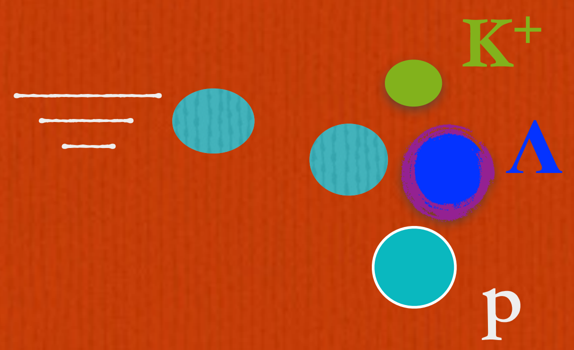
Angular Distributions of the $pK^+\Lambda$ final state



PWA Results

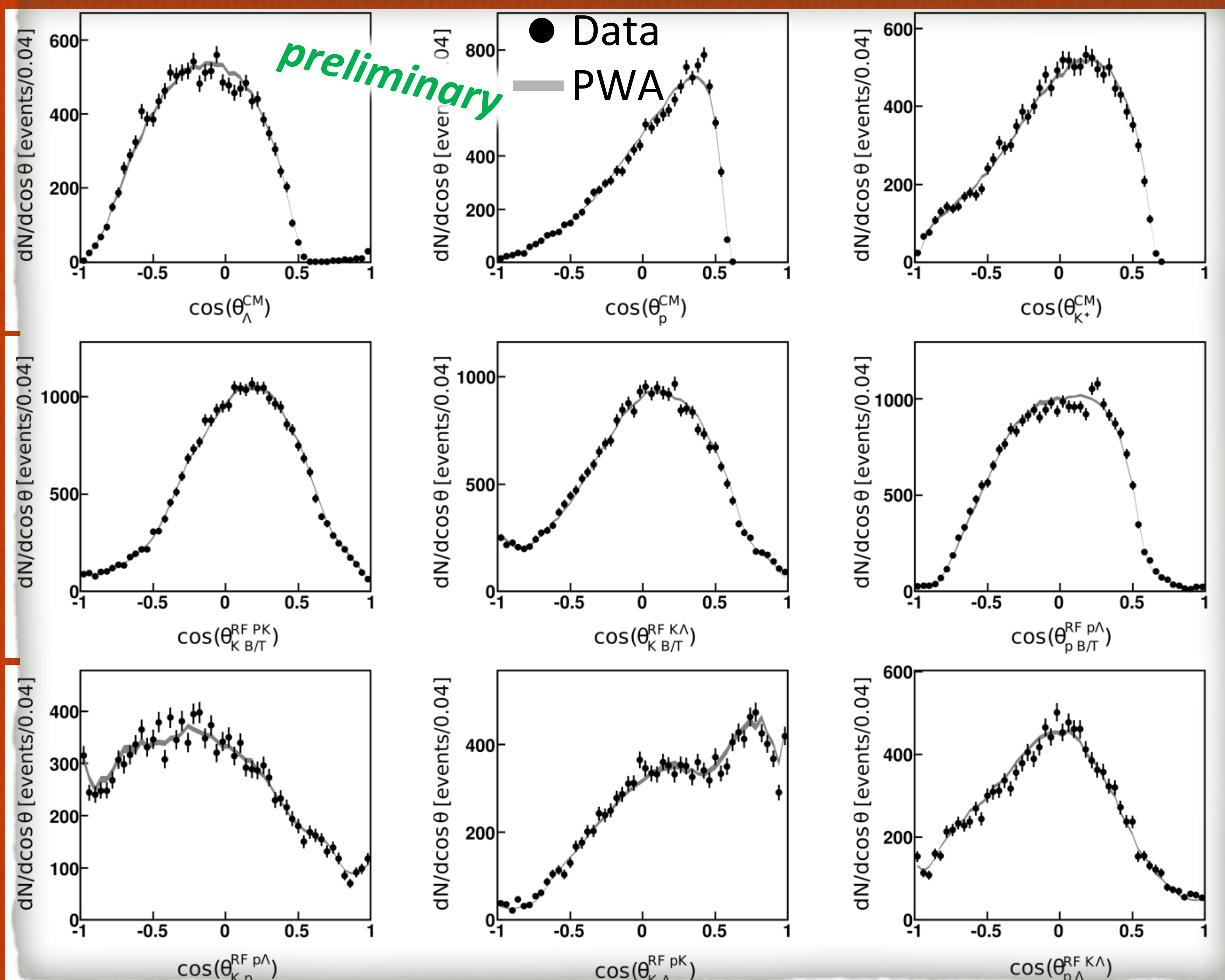
E. Epple, R. Muenzer

proton-proton



Name	N* combination
1/8	N(1650), N(1710), N(1720), N(1900)
3/8	N(1650), N(1710), N(1720), N(1880)
6/9	N(1650), N(1710), N(1720), N(1900), N(1895)
8/8	N(1650), N(1710), N(1720), N(1895), N(1880)

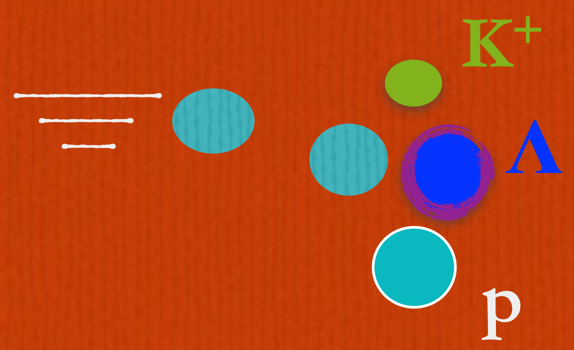
Angular Distributions of the $pK^+\Lambda$ final state



PWA Results

E. Epple, R. Muenzer

proton-proton



Name	N* combination
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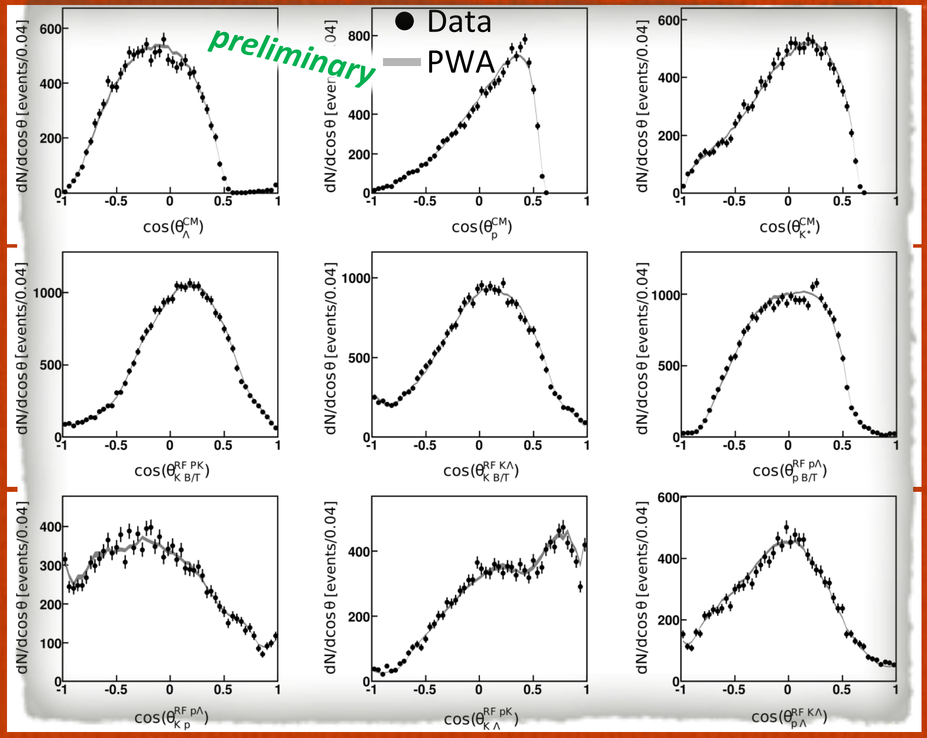
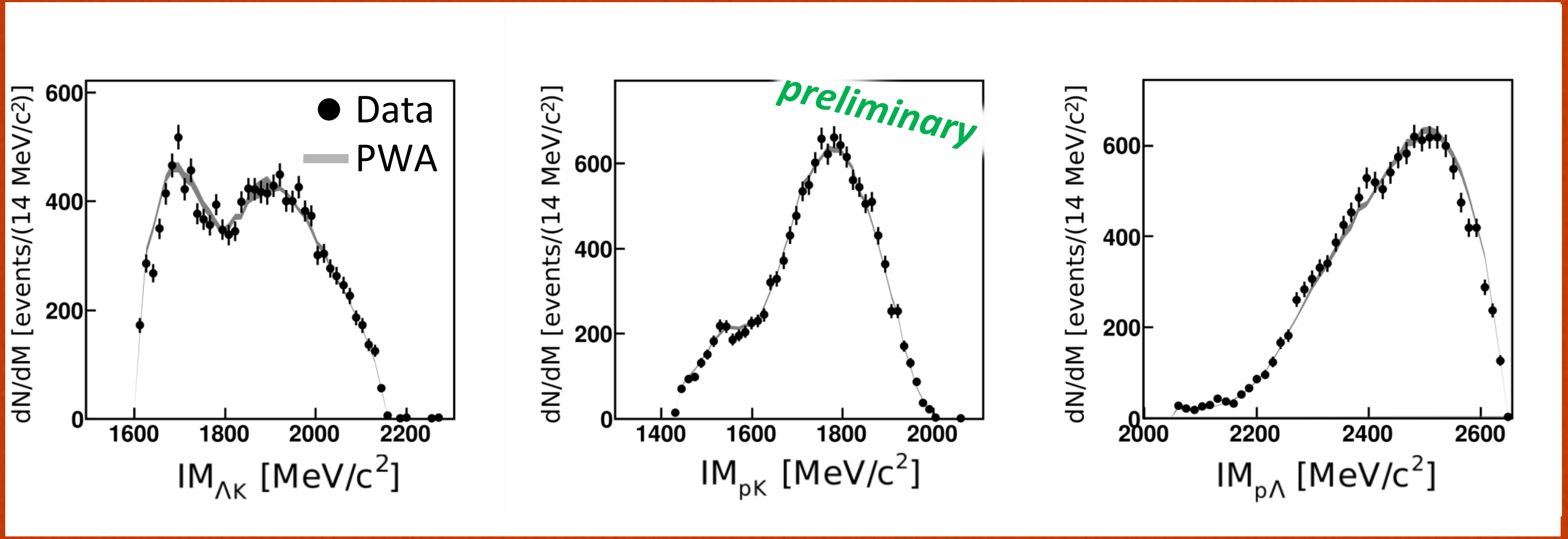
Angular Distributions of the $pK^+\Lambda$ final state



Invariant Mass Distributions



PWA Results

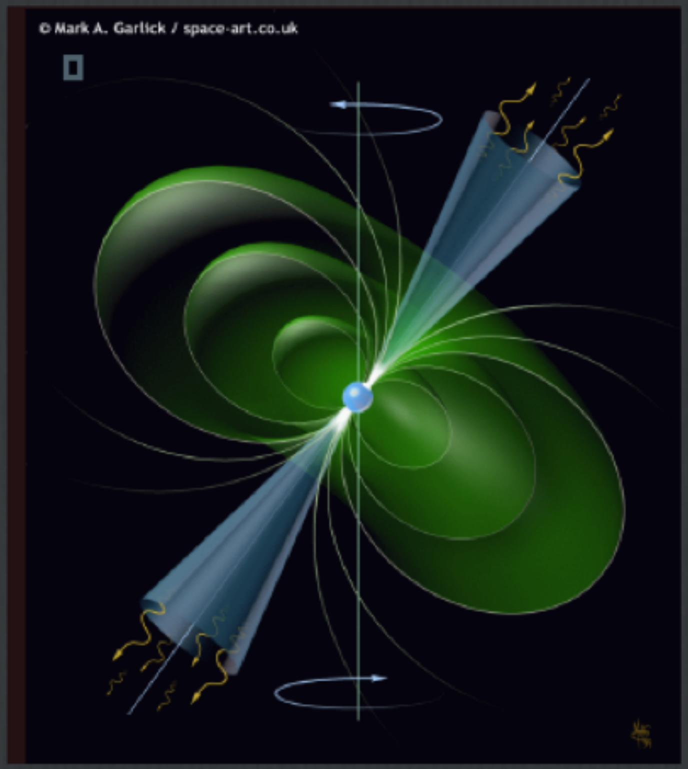
$p + p \rightarrow p + \Lambda + K^+$ $\sqrt{s} = 3.2\,\mathrm{GeV}$

Exclusive measurement of the final state including all angular distributions and invariant mass distributions
Not shown here: the data can not be reproduced by an incoherent sum of different resonant and non-resonant channels

Interferences play an important role in nucleon-nucleon collisions at $\sqrt{s} = 3.2\,\mathrm{GeV}$, when do these interferences fade away?

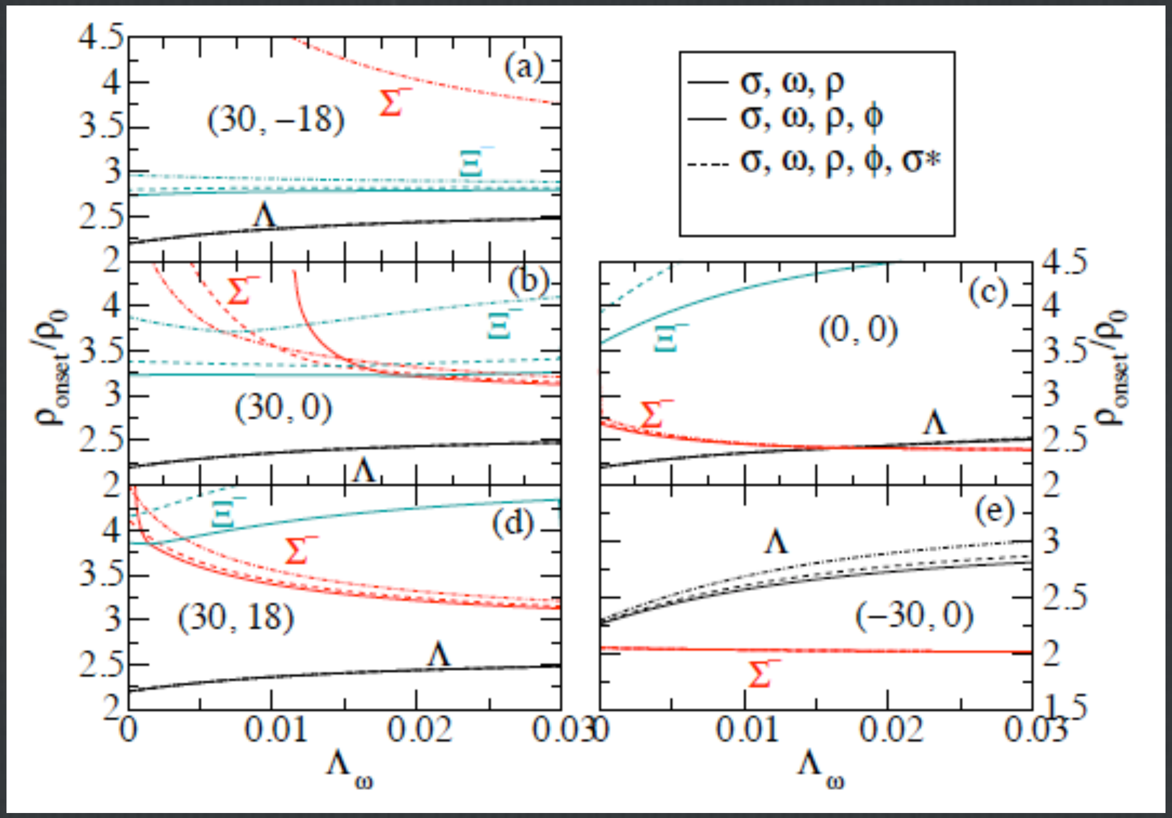
The same is currently investigated for the resonancese mainly contributing to the dilepton final states (Δ(1232), N(1440)..)

Strange Hadrons in Neutron Stars



R ~ 10–15 km
M ~ 1.5 M⊙

Onset of strange hyperons production



C. Providencia et al, Phys. Rev. C87, 055801-055809 (2013)

$U_\Lambda = -28\,\mathrm{MeV}$

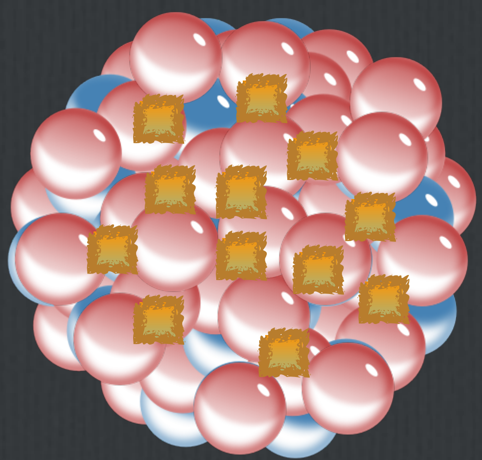
(U_Σ, U_Ξ)

Hyperons are produced already at moderate densities
EOS with strangeness can reach high masses only if

ΛN, Σ
ΛΛ, ΣΣ
ΛNN, ΣNN

Interactions are repulsive on the short-range

Scenario Nr. 1: Kaon Condensate



Neutron

Kaon

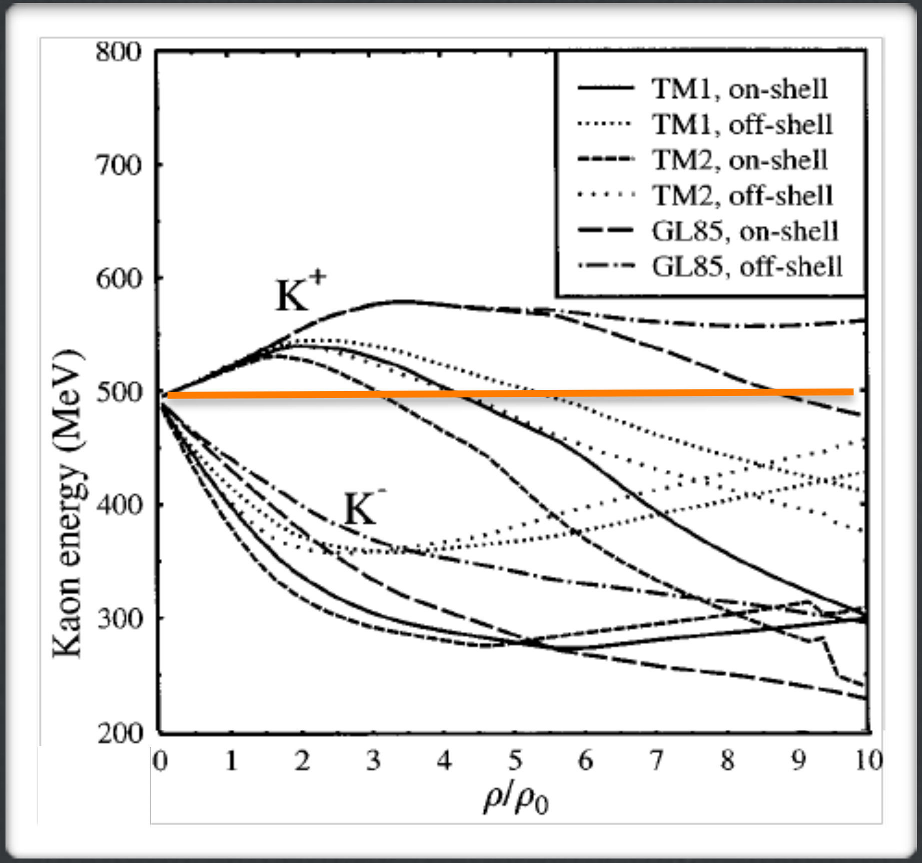
No Pauli Blocking!

if $m_{K^{-*}} < \mu_{e^-}$

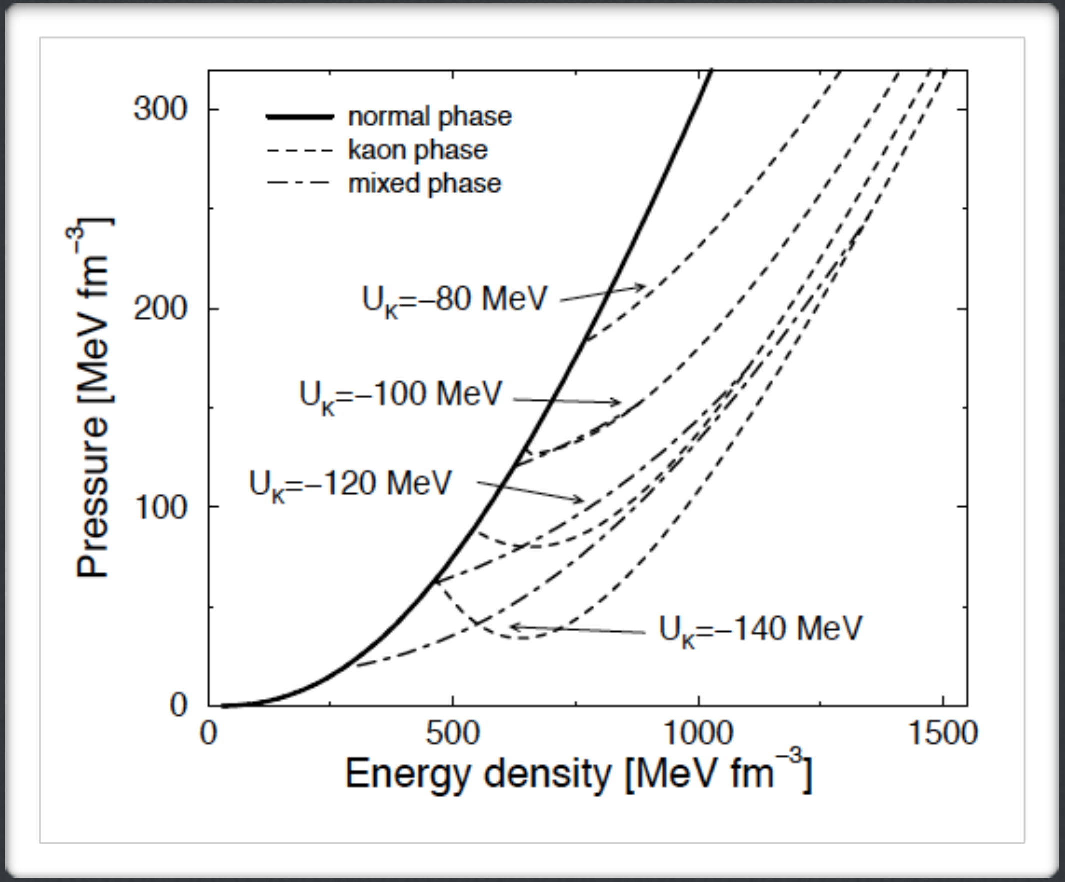
$$e^- \rightarrow K^- + \nu_e$$

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

J. Schaffner and I. N. Mishustin
Phys. Rev. **C 53**, 3 (1996)

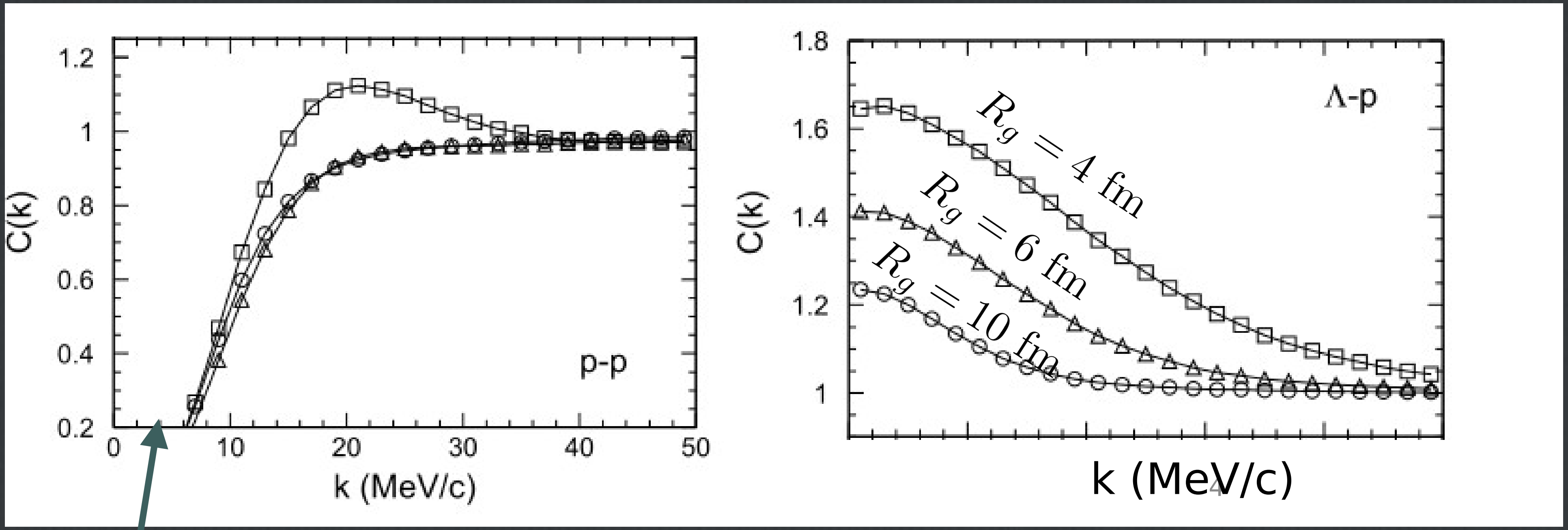


A. Ramos, J. Schaffner-Bielich and J. Wambach
nucl-th/0011003



The Experimental Data

Examples from Calculations

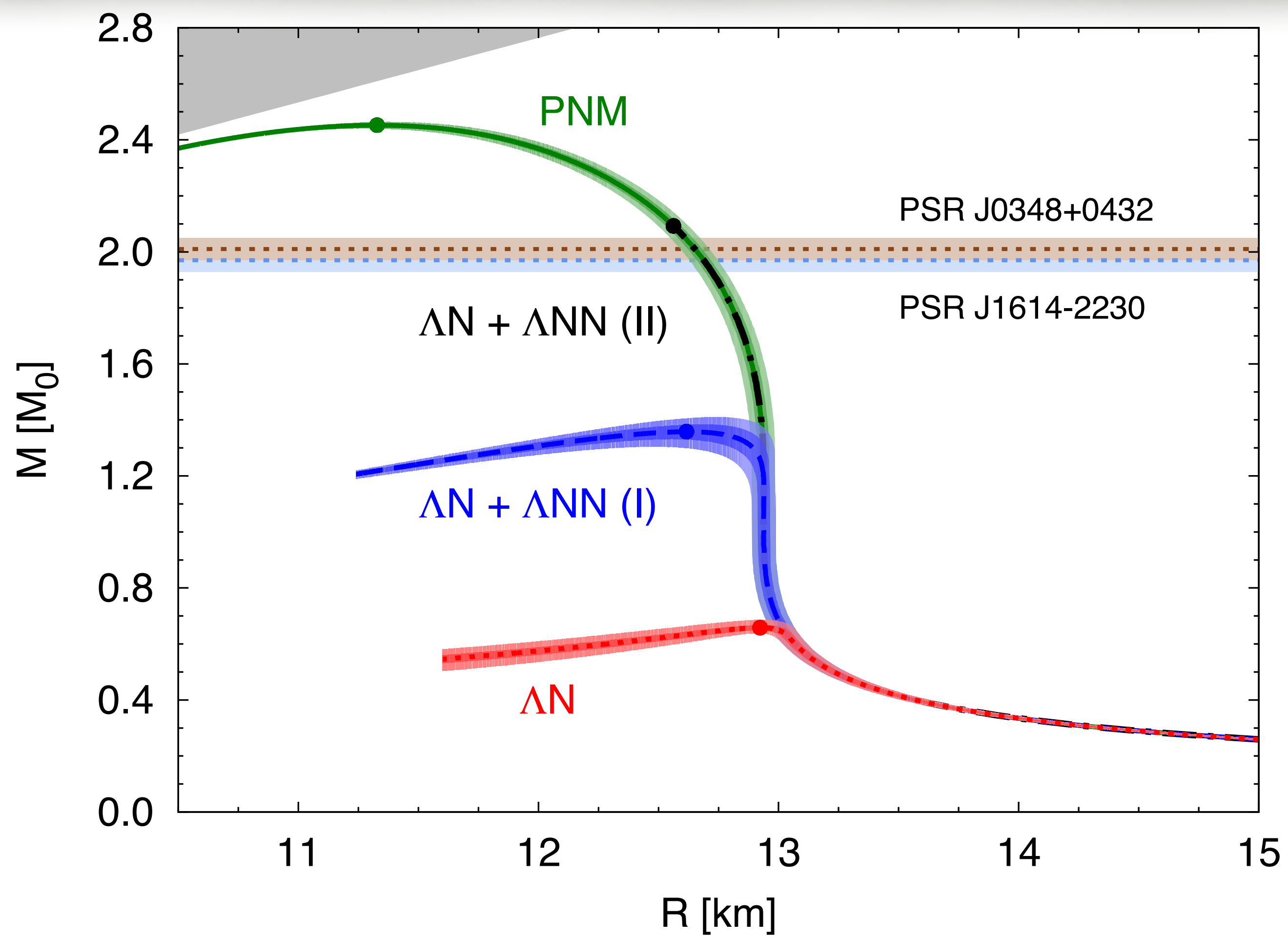


repulsive Coulomb + Strong Force core for pp interaction

How is it for Λ?

Not clear yet because large statistics is needed

Massive Hyperon-Stars?



new **QMC calculations**

using phenomenological hyperon-nucleon

hyperon-NN **three-body** interactions

D. Lonardoni, A. Lovato, S. Gandolfi, F. Pederiva; arXiv:1407.4448