Neutron Stars in the laboratory: how we can test the hypothesis of Hyperon Stars

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Technische Universität München

E62 – Dense and Strange Matter

https://www.denseandstrange.ph.tum.de

Virtual Seminar on Multi-messanger Astronomy

Outline

- (strange) Hadron interactions
- Hyperon Puzzle in Neutron Stars
- The measurement of Hadron Hadron Correlations
- Experimental Results: RUN1 and RUN2
  - pp Collisions at 7 TeV, 5 TeV and 13 TeV, p-Pb at 5.02 TeV measured by ALICE
  - pp, pΛ , $\Lambda\Lambda$, pΞ^- Correlations
- Outlook

(Strange) Hadron Interactions

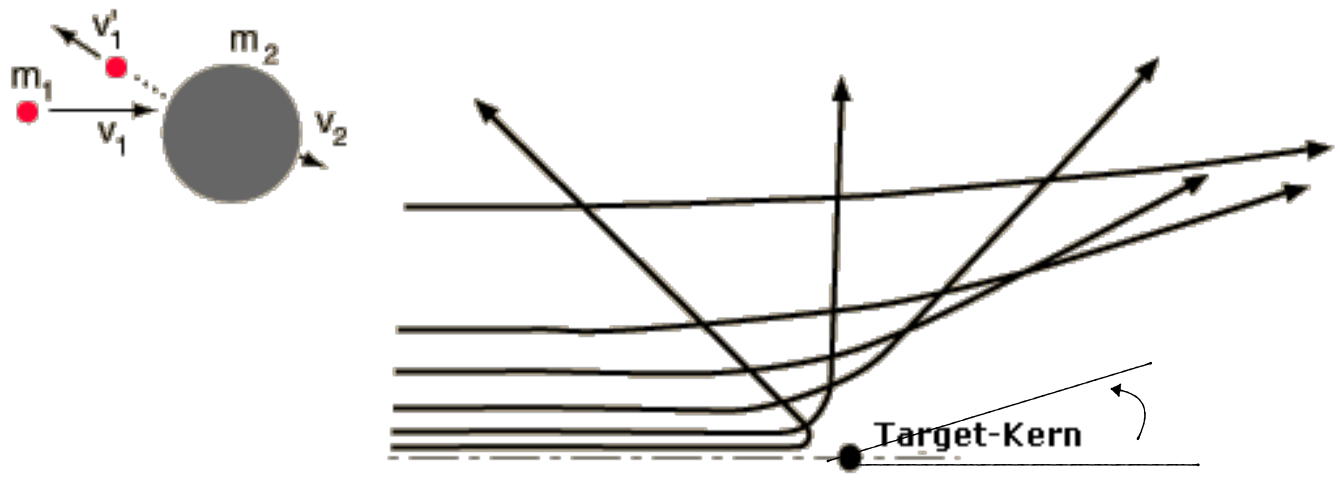
$$\Lambda = \; uds \;\; I(J^P) = 0(\frac{1}{2}^+)$$

$$\Sigma^0 = \; uds \;\; I(J^P) = 1(\frac{1}{2}^+)$$

$$\Xi^- = \; dss \;\; I(J^P) = \frac{1}{2}(\frac{1}{2}^+)$$

Scattering Data and Interaction Parameters

Scattering experiments -> Extraction of the differential cross section



$$\longrightarrow \quad \frac{d\sigma}{d\Omega}$$

Partial Wave Expansion:

$$\sigma = \frac{4\pi}{k^2}\sum_{l}(2l+1)\sin^2(\delta_l).$$

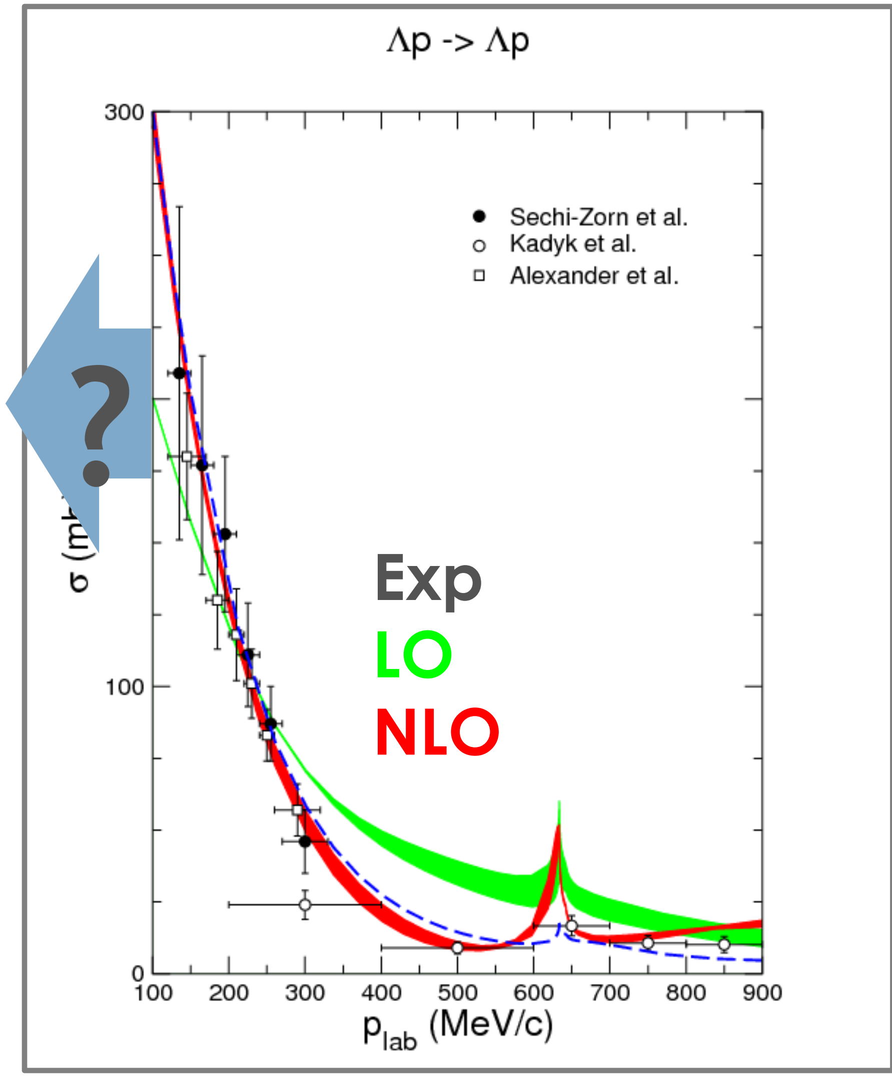
δ_l = phase shifts

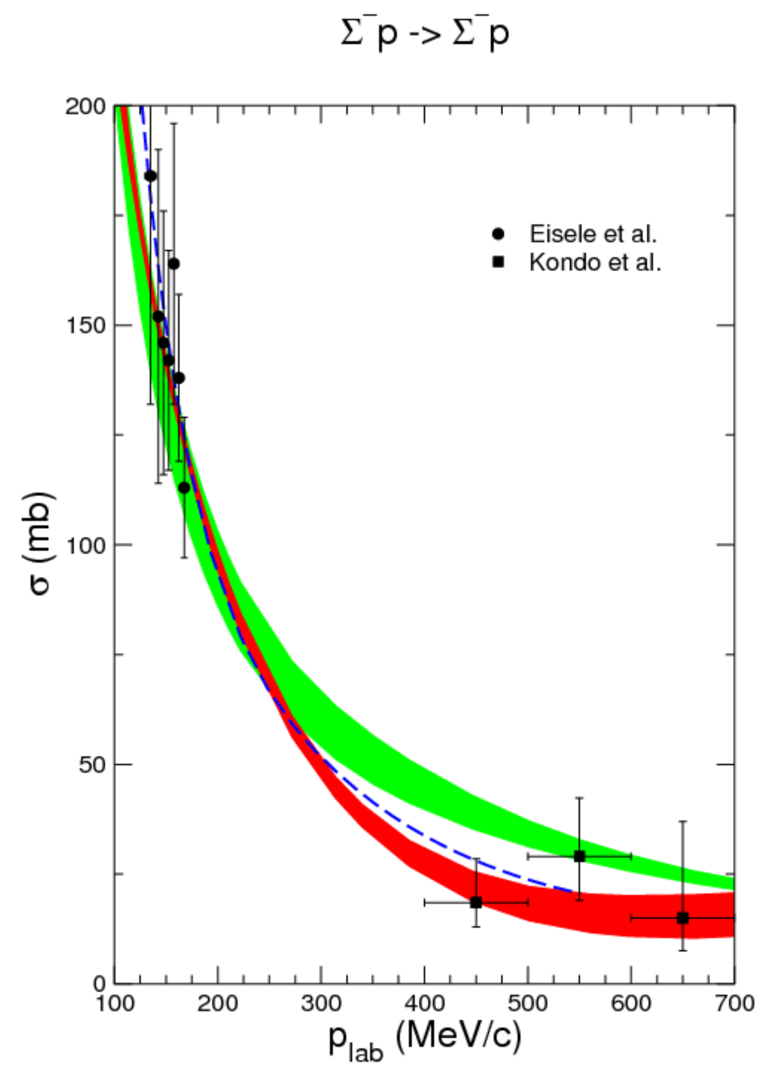
Scattering Length

$$f_0 = -\lim_{k\to 0}\frac{1}{k}\tan\delta_0(k)$$

l=0, s-wave Only!

Hyperon-Nucleon Scattering





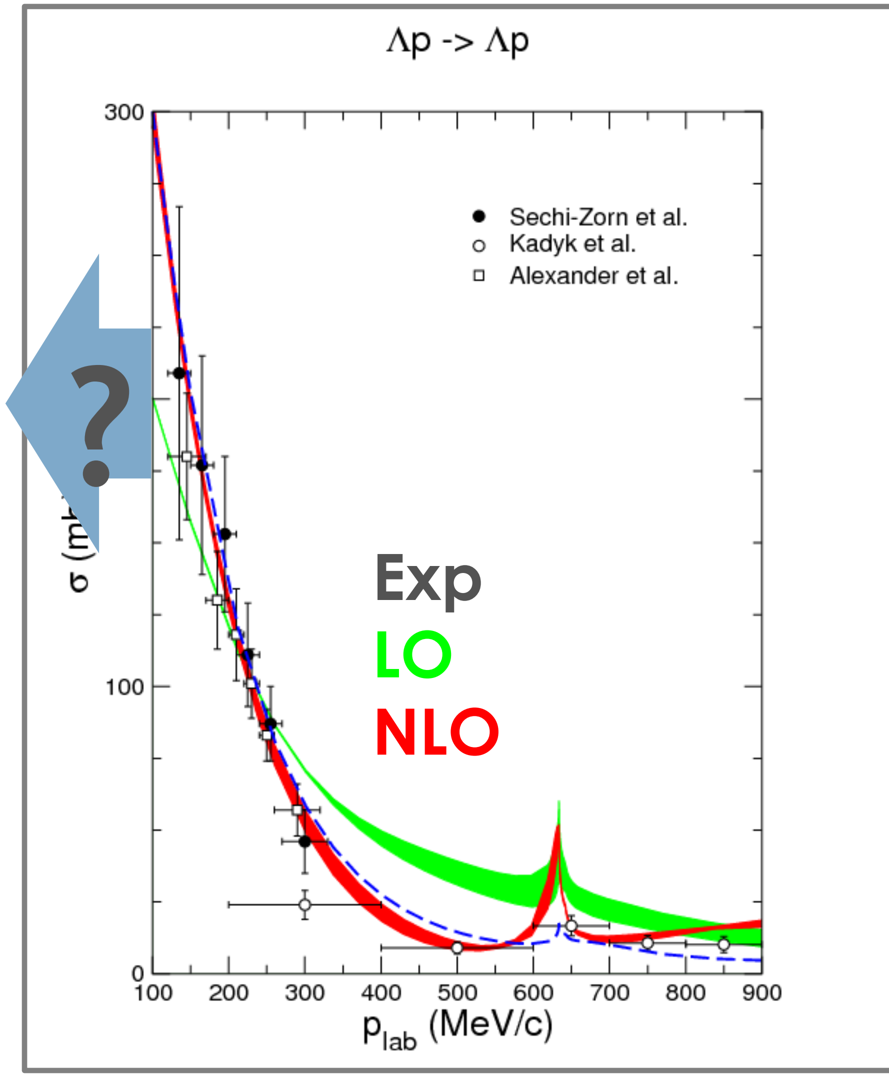
LO: H. Polinder, J.H., U. Meißner, NPA 779 (2006) 244
NLO: J.Haidenbauer., N.Kaiser, et al., NPA 915 (2013) 24

Data from scattering experiments and bubble chambers detectors from 1968 and 1971

$$K^- + p \to \Sigma^0 + \pi^0,\ \Sigma^0 \to \Lambda + \gamma$$
$$K^- + p \to \Sigma^- + \pi^+ \ldots$$

Production Threshold for $\Lambda's:\ \ p \geq 100\, MeV$

Hyperon-Nucleon Scattering

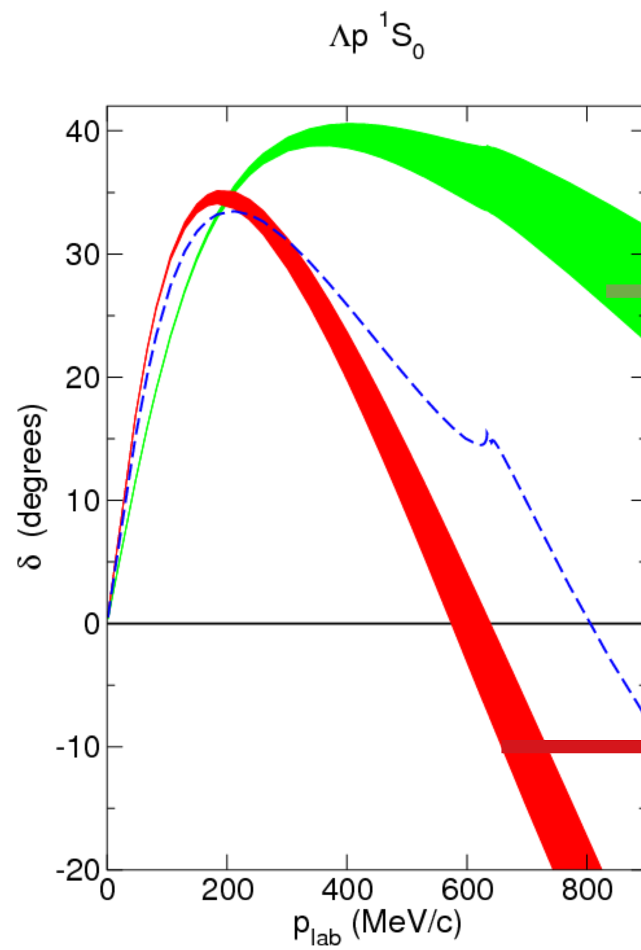


LO: H. Polinder, J.H., U. Meißner, NPA 779 (2006) 244
NLO: J.Haidenbauer., N.Kaiser, et al., NPA 915 (2013) 24

LO less attractive than NLO

$$a^1S_0 = -1.91\,fm$$

$$a^1S_0 = -2.91\,fm$$



Interaction always attractive

Interaction becomes repulsive
Repulsive core of the interaction

Data from scattering experiments and bubble chambers detectors from 1968 and 1971

$$K^- + p \rightarrow \Sigma^0 + \pi^0,\ \Sigma^0 \rightarrow \Lambda + \gamma$$
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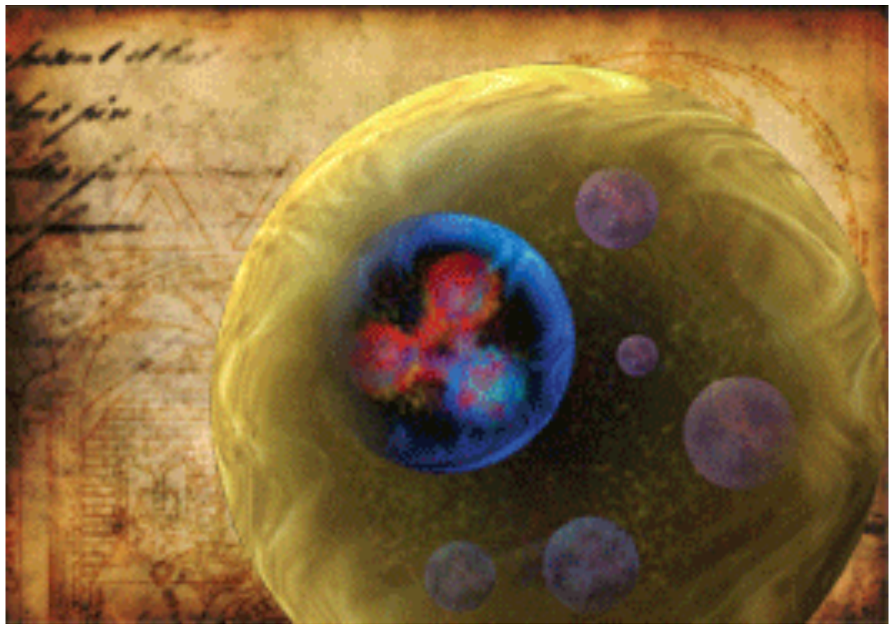
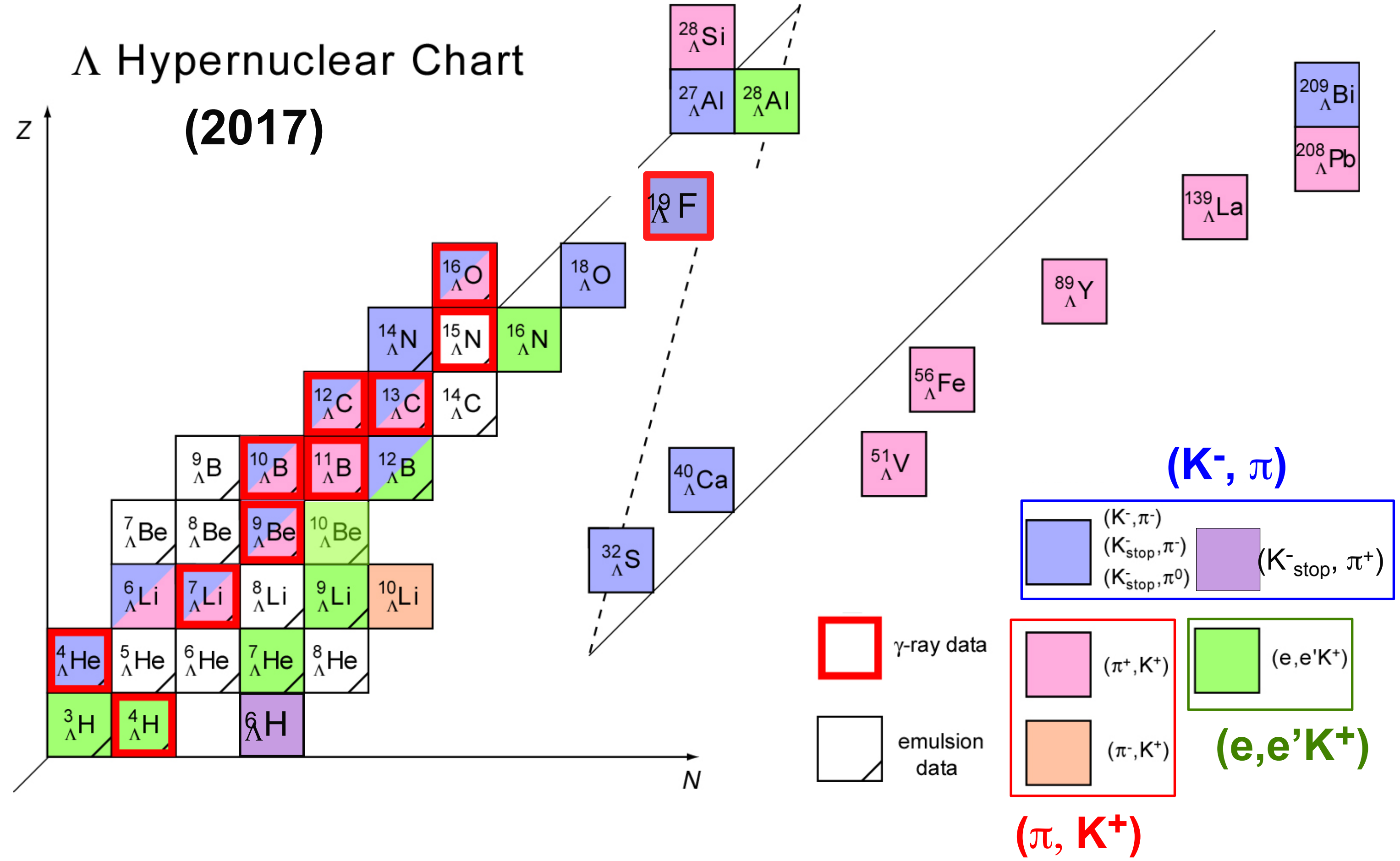
Hypernuclei

http://eaae-astronomy.org/blog/?cat=254





Hypernuclei can be produced

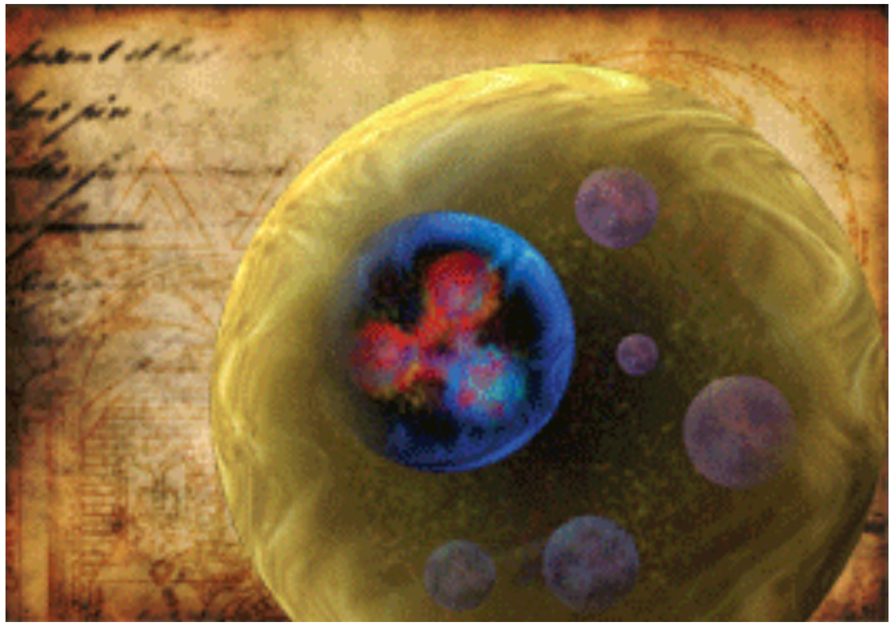
Binding Energy of Λ to nucleus = 30 MeV

O. Hashimoto and H. Tamura, Prog. Part. Nucl. Phys. 57 (2006) 564.

Wirth and Roth Phys.Rev.Lett. 117 (2016) 182501

Hypernuclei

http://eaae-astronomy.org/blog/?cat=254



Hypernuclei can be produced
Binding Energy of Λ to nucleus = 30 MeV

Nothing is known about Σ - hypernuclei

Hypernuclei

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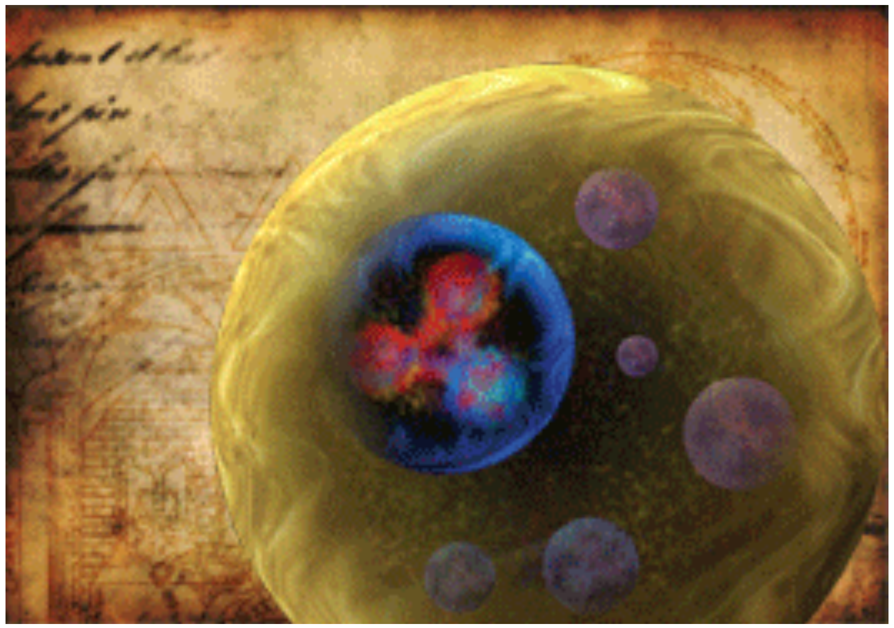
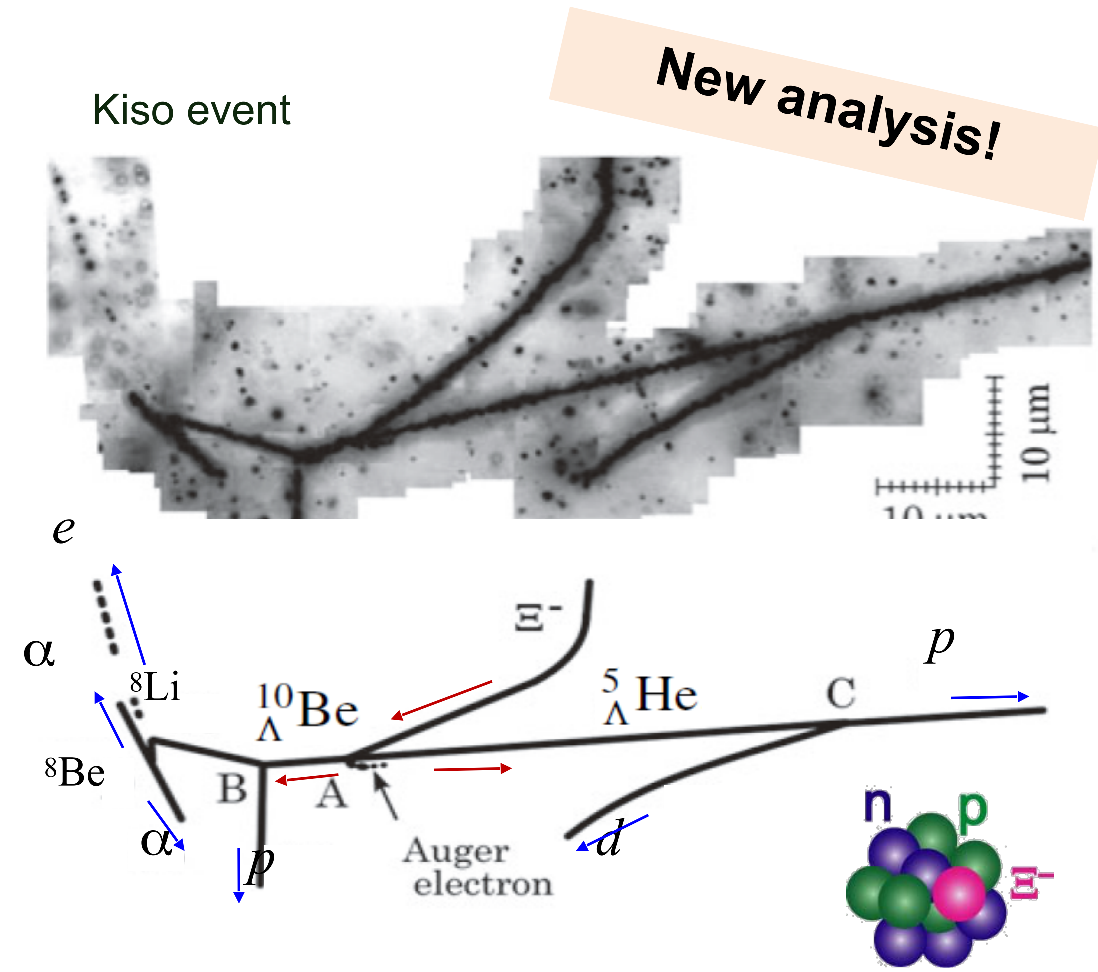


Courtesy H. Tamura, Bormio Winter Meeting 2018



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Ξ - Hypernucleus shows a shallow attractive interaction

$$\Xi^- + {}^{14}\mathrm{N} \rightarrow {}^{10}_{\Lambda}\mathrm{Be} + {}^{5}_{\Lambda}\mathrm{He}$$

The first clear Ξ hypernucleus

$$B_{\Xi^-} = 4.38 \pm 0.25\ \mathrm{MeV},$$
$$- \quad 1.11 \pm 0.25\ \mathrm{MeV}$$

K. Nakazawa et al. PTEP 2015, 033D02

Hypernuclei

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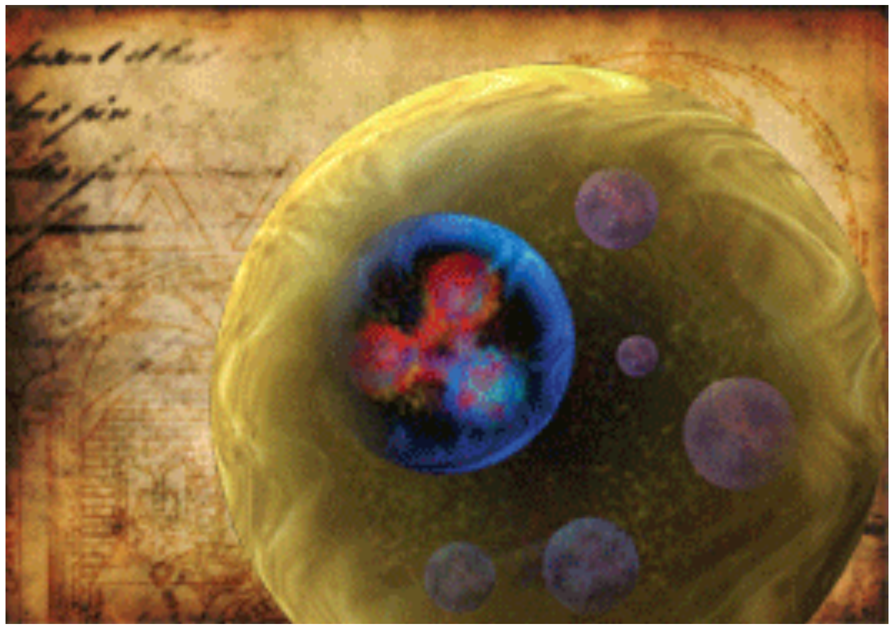
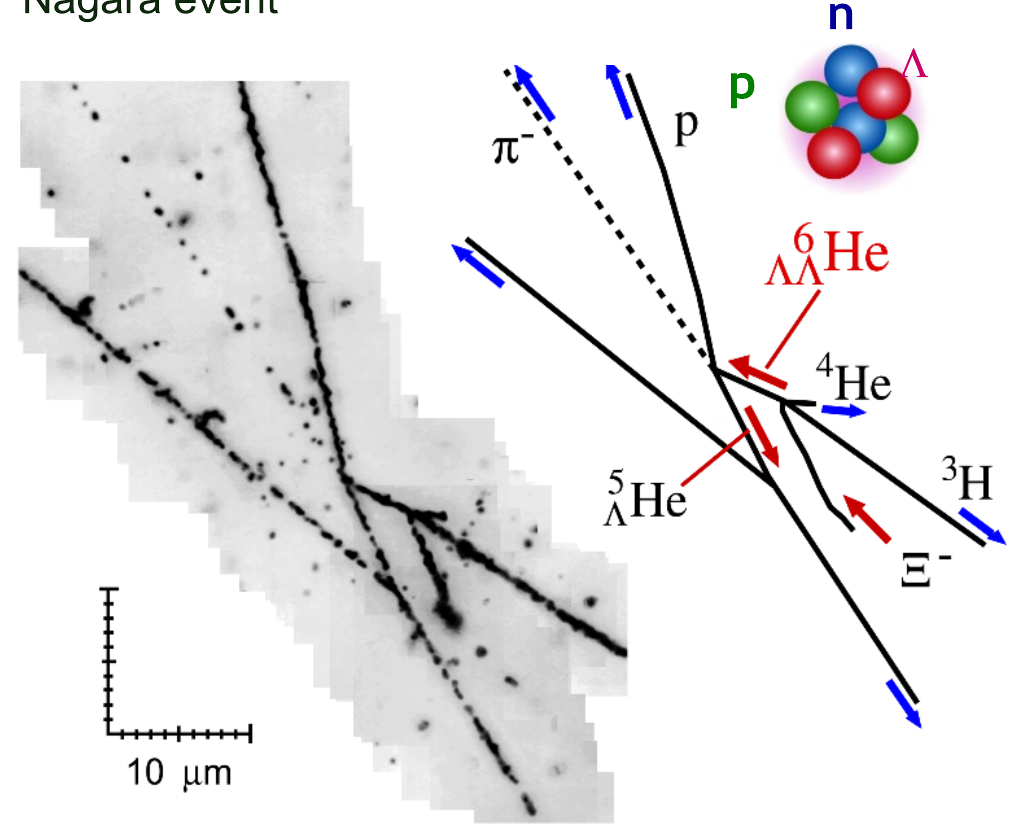


Nagara event



Hypernuclei can be produced
Binding Energy of Λ to nucleus = 30 MeV

Nothing is known about Σ - hypernuclei

Ξ - Hypernucleus shows a shallow attractive interaction

Even $\Lambda\Lambda$-hypernuclei exist

$^{6}{}_{\Lambda\Lambda}He \to {}^{5}{}_{\Lambda}He + p + \pi^-$

$\Delta B_{\Lambda\Lambda} = 0.67 \pm 0.17$ MeV

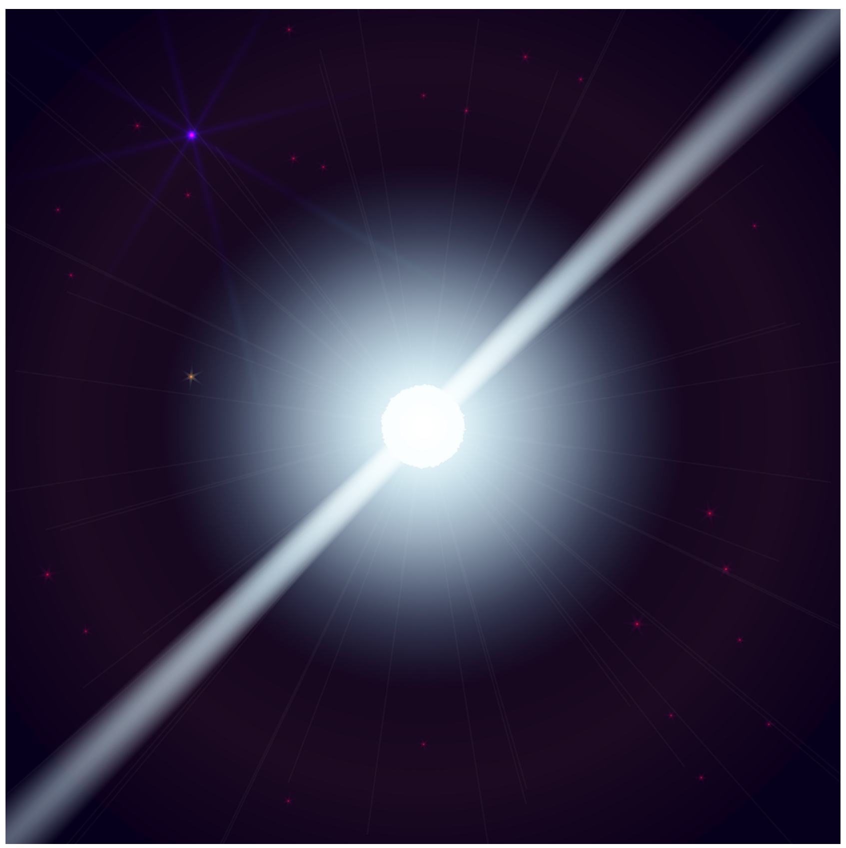
H. Takahashi et al., PRL 87 (2001) 212502

Λ-Λ is weakly attractive

Hyperon Puzzle in Neutron Stars

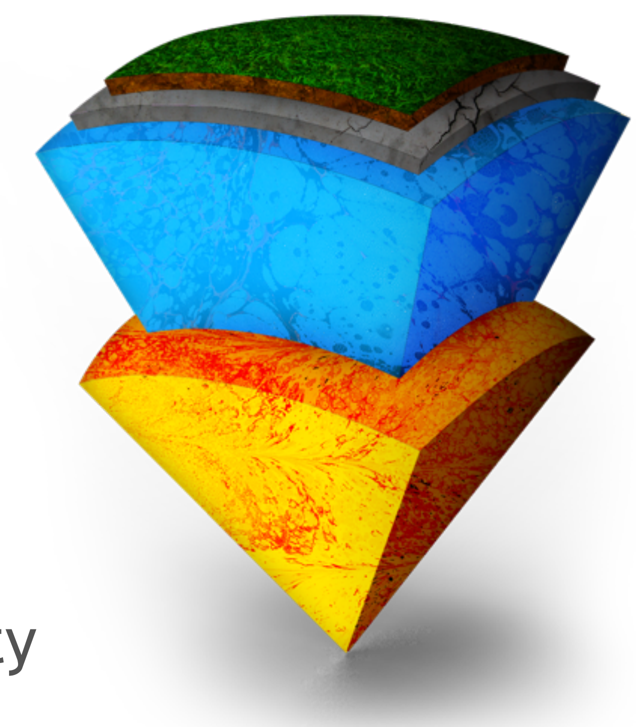
Neutron Stars

$$R \approx 10 - 15\ Km$$
$$M \approx 1.5 - 2\ M_{\odot}$$



Courtesy of Shutterstock

density



<u>Outer Crust:</u>
Ions, electrons Gas,
Neutrons

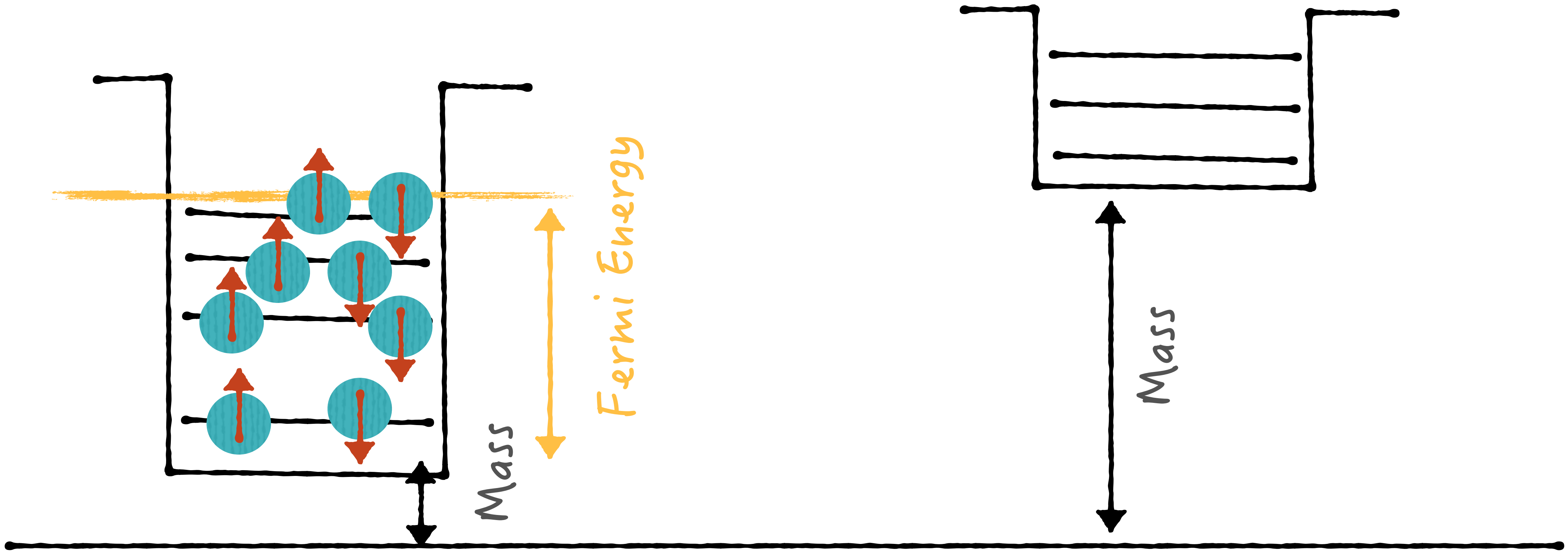
<u>Inner Core: ??</u>
Neutrons ?? Protons ??
Hyperons ??
Quark Matter ??

- Very high density in the interior
- 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

What is inside Neutron Stars??

Neutrons (uud, m= 938 MeV)

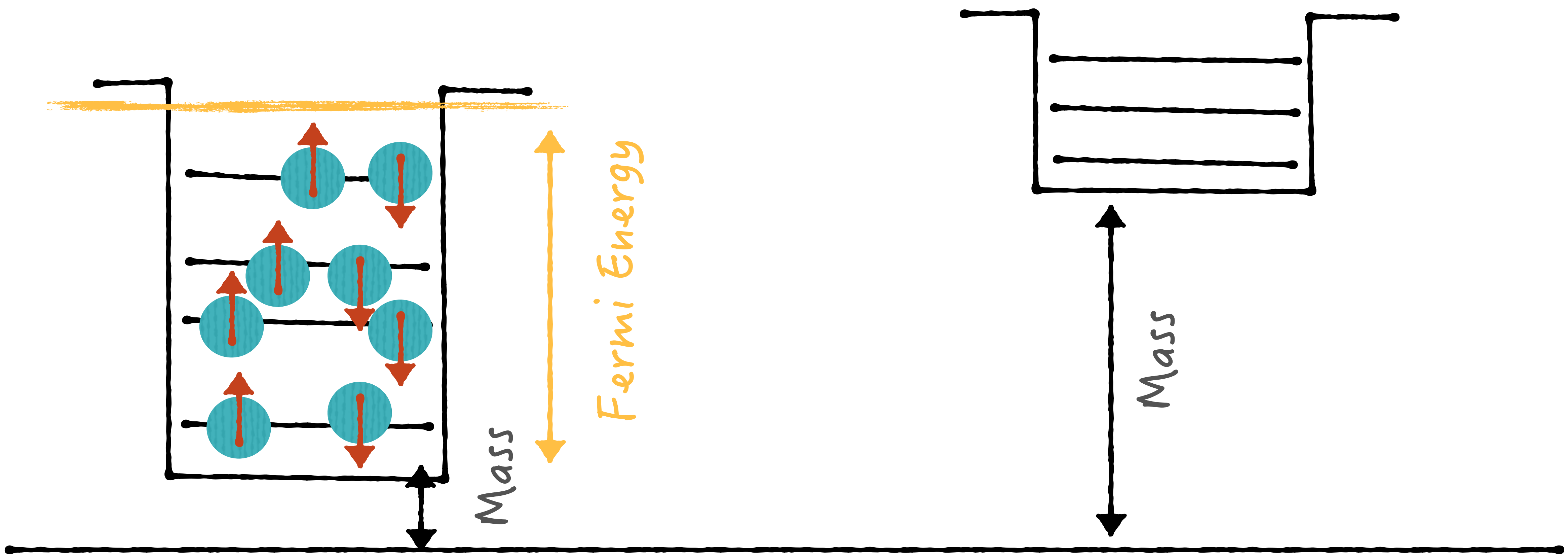
Λ Hyperons (uds, m= 1115 MeV)



Chemical Potential $\mu = E_F + mass$

If the density increases also the Fermi Energy increases and hence the chemical potential

Neutrons (uud, m= 938 MeV)　　Λ Hyperons (uds, m= 1115 MeV)



Chemical Potential $\mu = E_F + mass$

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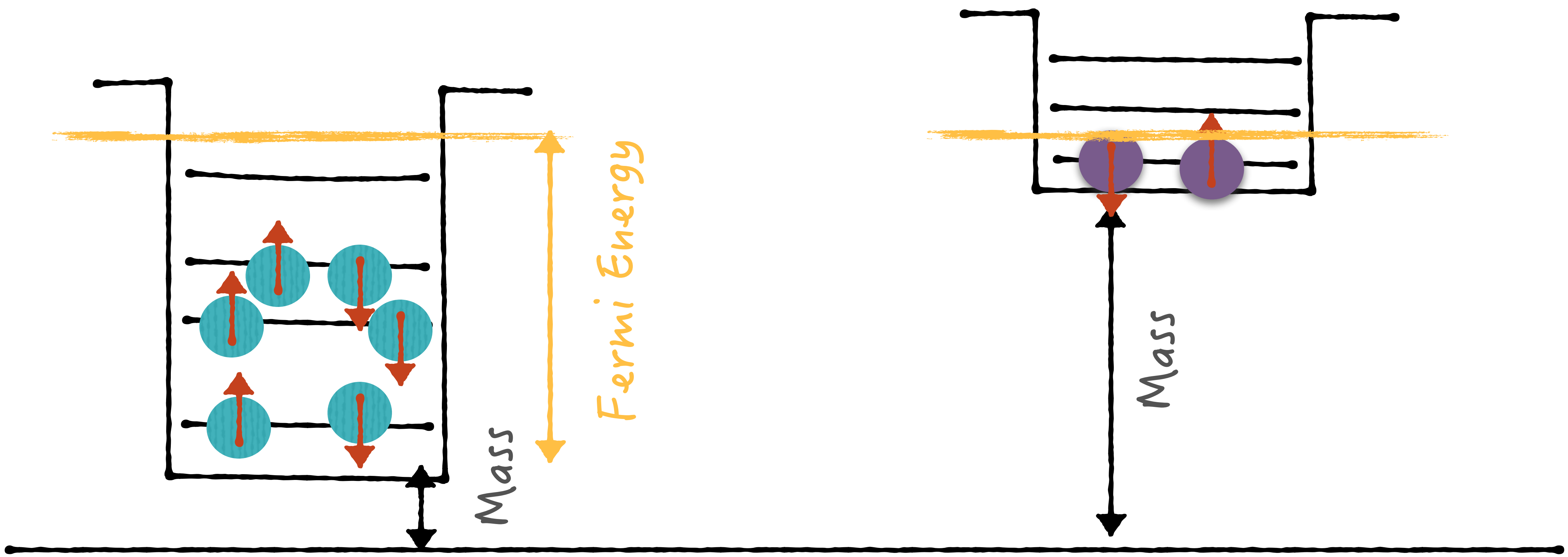
Strange Hadron Production in Dense Neutron-Rich Matter

Neutrons (uud, m= 938 MeV) **Λ Hyperons (uds, m= 1115 MeV)**



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

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

$$\Lambda + \Lambda \rightarrow \Xi + N$$

$$p + e^- \rightarrow \Lambda + \nu_e -$$

$$n + \Lambda \rightarrow \Xi + N$$

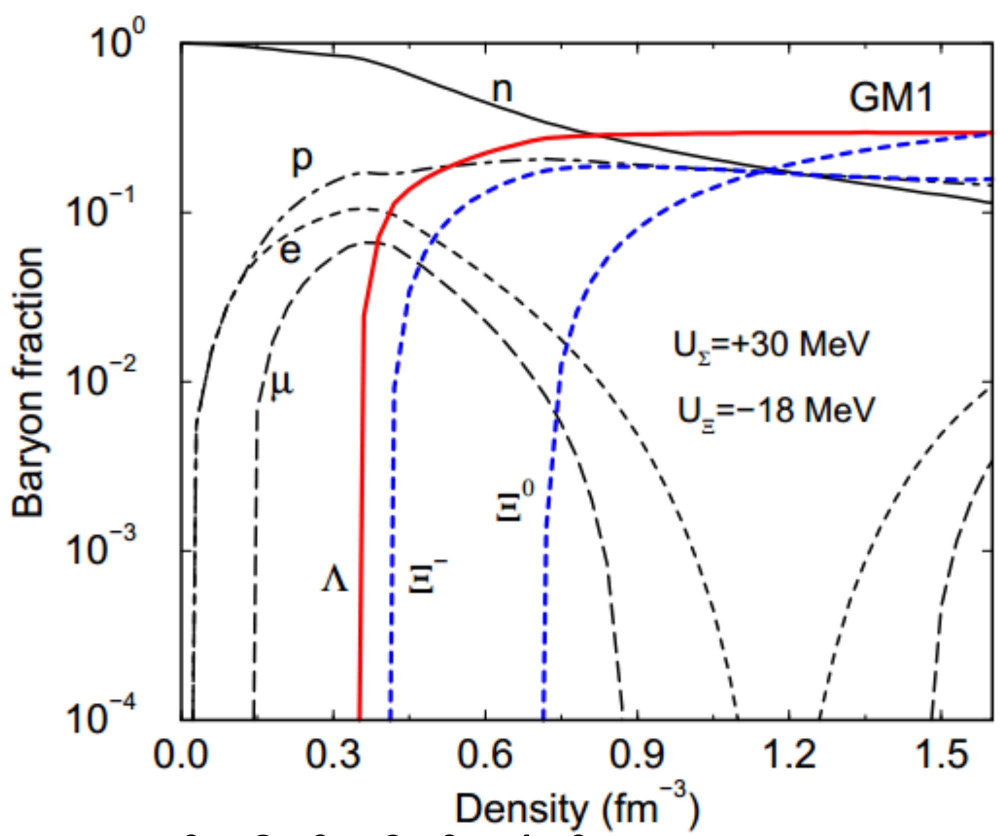
In order to have chemical equilibrium $\mu_{neutron} = \mu_\Lambda$

If the Y-nucleon interaction is attractive the processes is even more likely

The Hyperon Puzzle in Neutron Stars

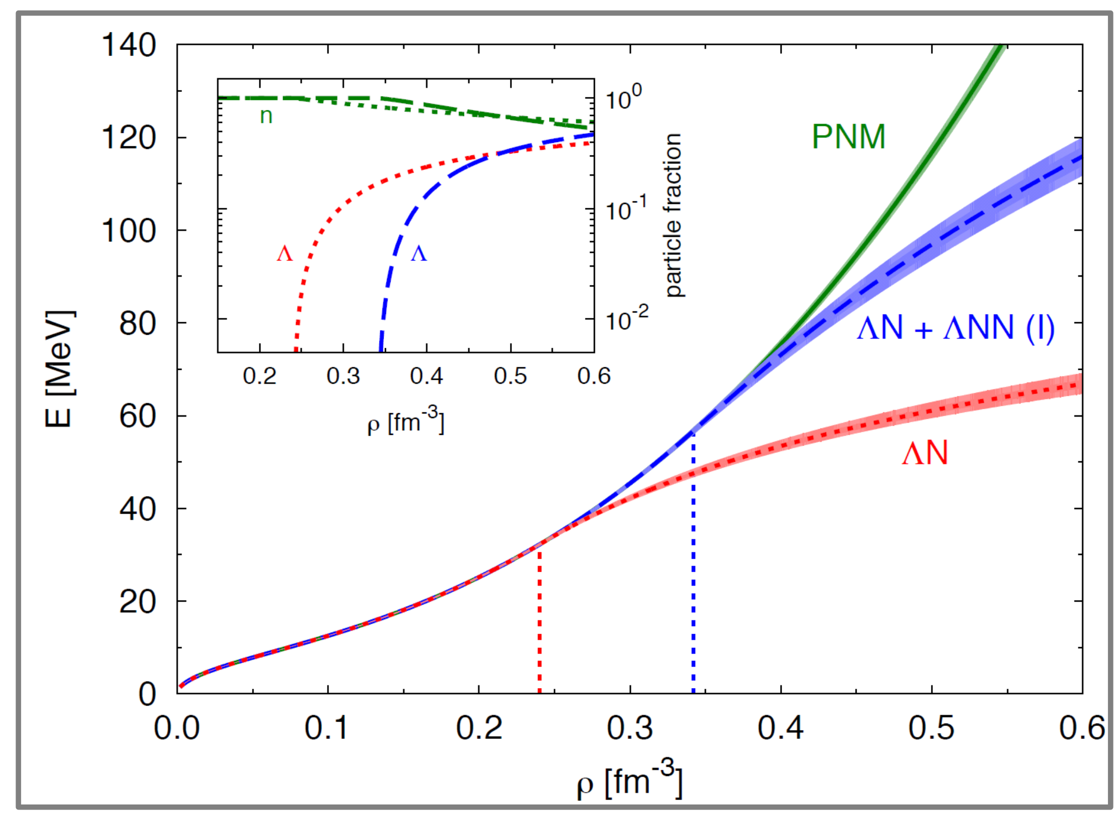
Hyperons should appear in dense neutron-rich matter starting from moderate large densities
Threshold depends on the Y-N interaction

The appearance of Hyperons softens the EoS



ϱ0 2ϱ0 3ϱ0 4ϱ0 .....

J. Schaffner-Bielich, NPA 804 (2008)



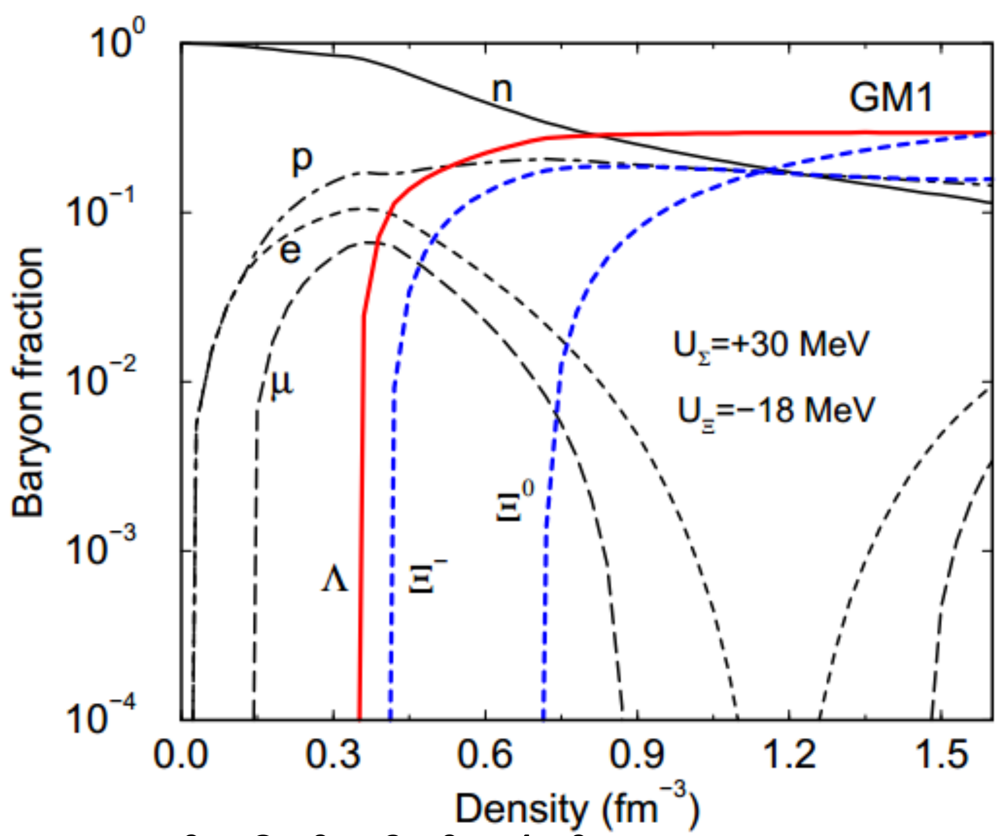
D. Lonardoni, A. Lovato, S. Gandolfi, F. Pederiva Phys. Rev. Lett. 114, 092301 (2015)

The Hyperon Puzzle in Neutron Stars

Hyperons should appear in dense neutron-rich matter starting from moderate large densities
Threshold depends on the Y-N interaction

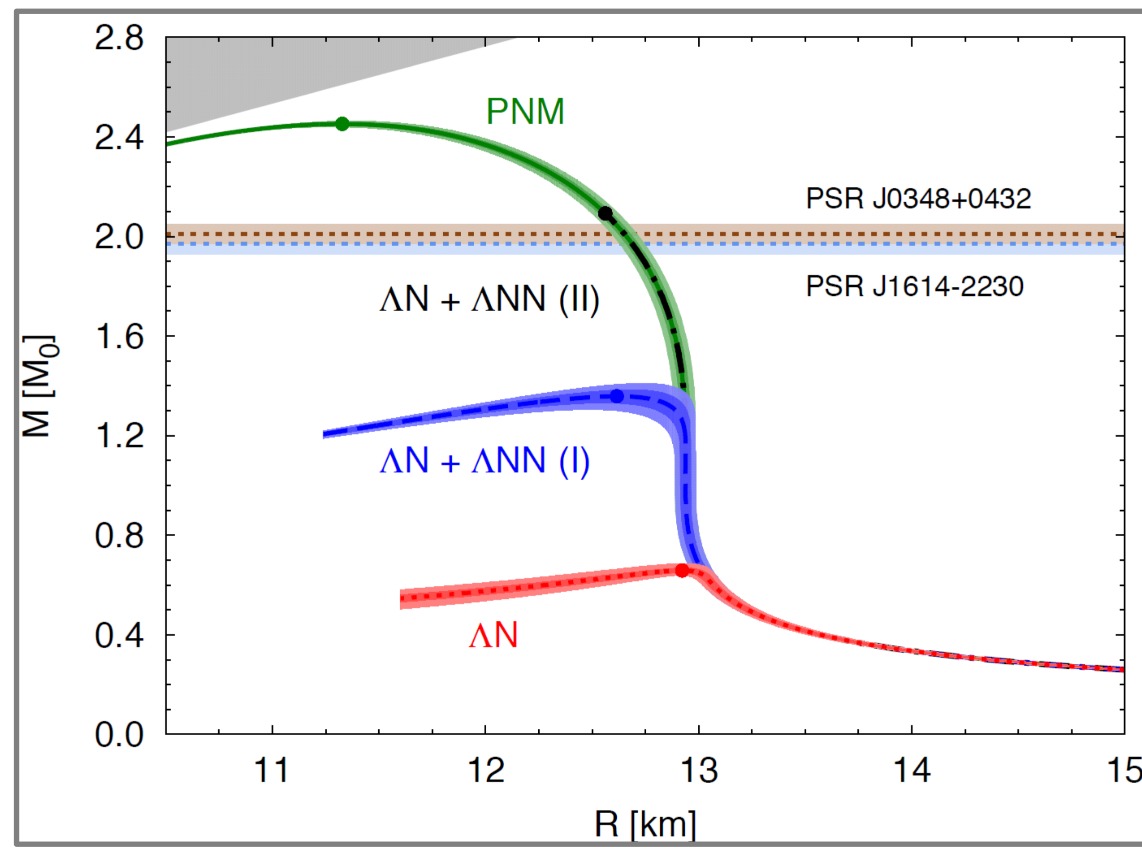
The appearance of Hyperons softens the EoS

Maximum NS masses get smaller



$\varrho 0 \quad 2\varrho 0 \quad 3\varrho 0 \quad 4\varrho 0$ …..

J. Schaffner-Bielich, NPA 804 (2008)



D. Lonardoni, A. Lovato, S. Gandolfi, F. Pederiva Phys. Rev. Lett. 114, 092301 (2015)

These predictions are only qualitative to this end

What do we need to do?

* Measure 2 body and 3 bodies interactions that allow to constrain a theory as χEFT

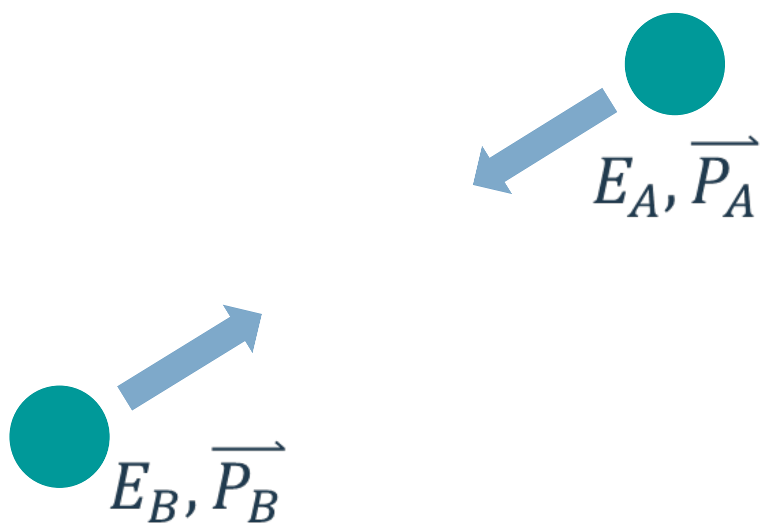
* Extend this search to all hyperons

* Compute more reliable single particle potentials

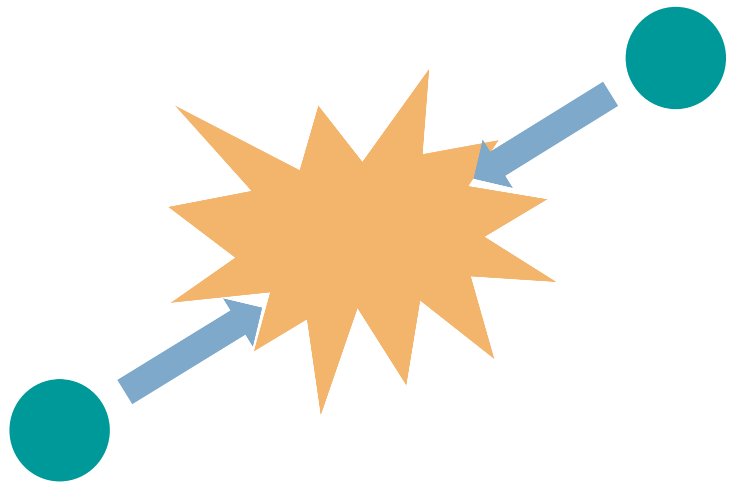
* Compute more solid EoS for dense nuclear matter with hyperons and kaons content

The measurement of Hadron Hadron Correlations

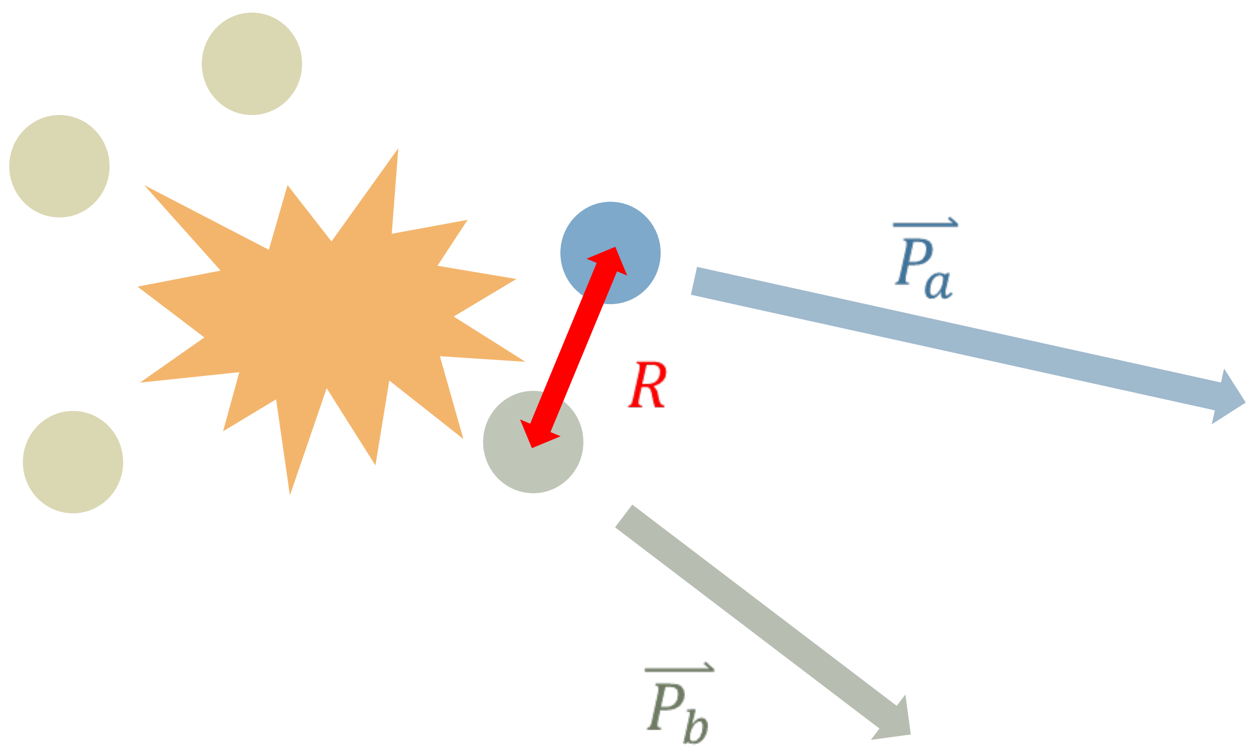
Nuclear Collisions



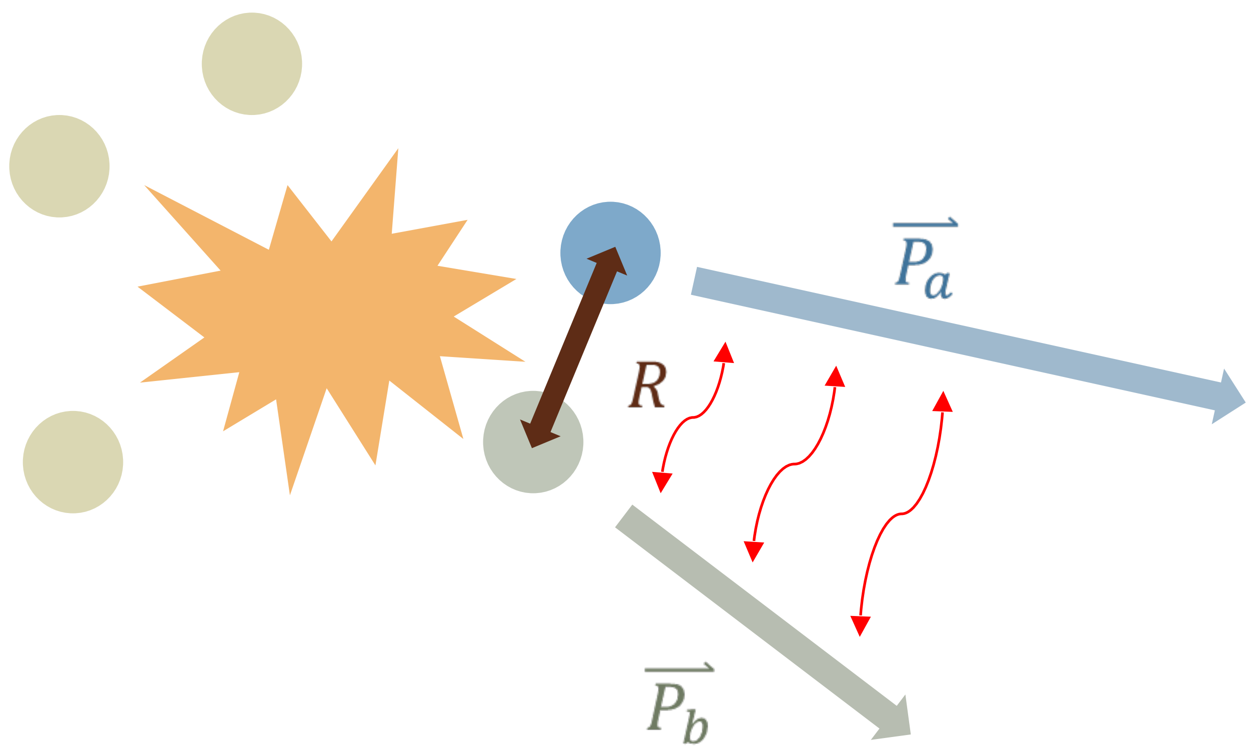
Nuclear Collisions



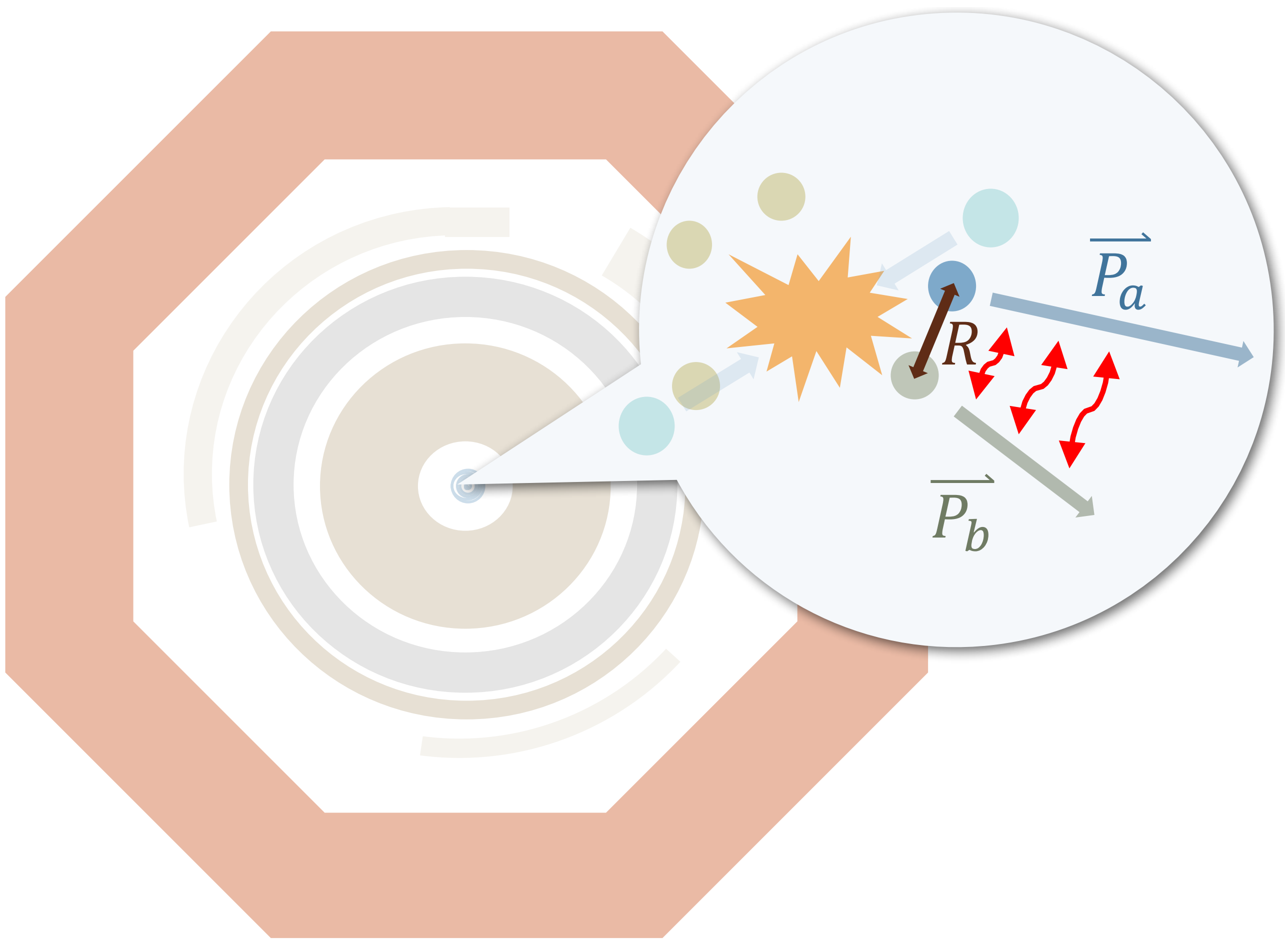
Particle Production



Particle Propagation



The ALICE Data Set



We measure **pp**, **pΛ**, **ΛΛ**, **pΞ**, **pK**, **p**$_{\Sigma^0}$, **pΩ-**

Proton and Pion identification with TPC and TOF

Reconstruction of hyperons

$\Lambda \rightarrow p\pi^-$ (BR ~ 64%)

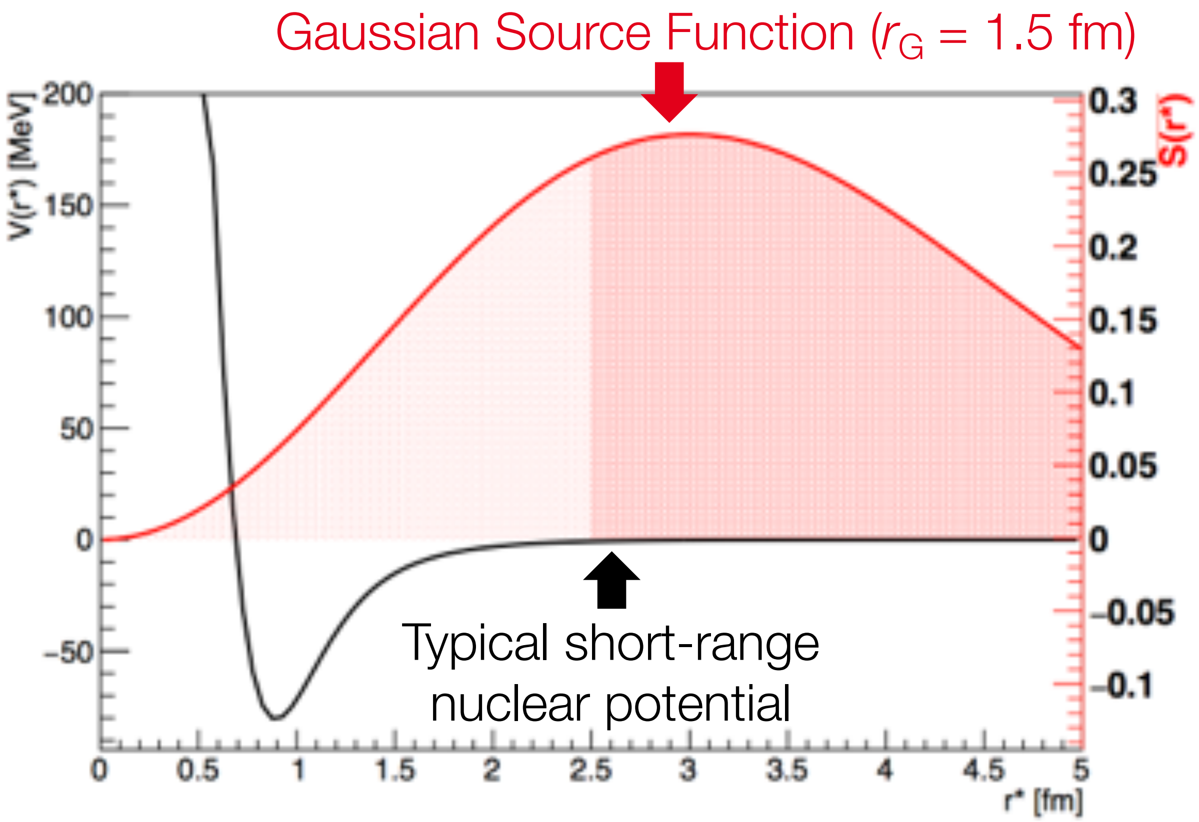
$\Xi^- \rightarrow \Lambda\ \pi^-$ (BR ~ 100%)

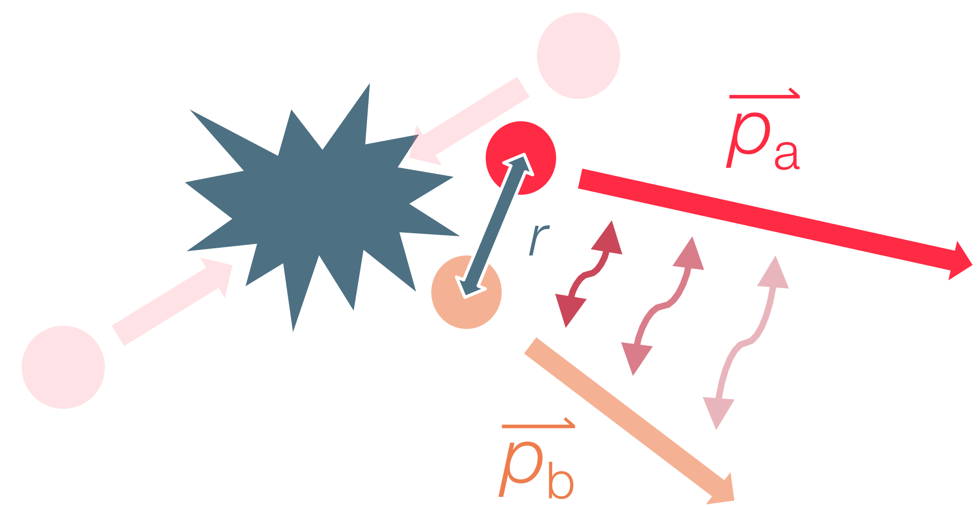
$$\Sigma^0 \rightarrow \Lambda + \gamma$$

Datasets:

- pp 7 TeV: $3.4 \cdot 10^8$ MB Events
- pp 5 TeV: $10 \cdot 10^8$ MB Events
- pp 13 TeV: $15 \cdot 10^8$ MB Events
- pp 13 TeV: $1 \cdot 10^8$ HM Events
- p-Pb 5.02 TeV: $6.0 \cdot 10^8$ MB Events

The unique benefit of small sources





Small particle-emitting source created in pp and p–Pb collisions at the LHC

- –Essential ingredient for detailed studies of the strong interaction
- –Assuming the same particle source for all pairs

»

p–p correlation is used to constrain the source, since Coulomb and Strong interactions are well known

The Correlation Function

The correlation function:

$$C(k^*) = \frac{P(\boldsymbol{p}_a, \boldsymbol{p}_b)}{P(\boldsymbol{p}_a)P(\boldsymbol{p}_b)},$$

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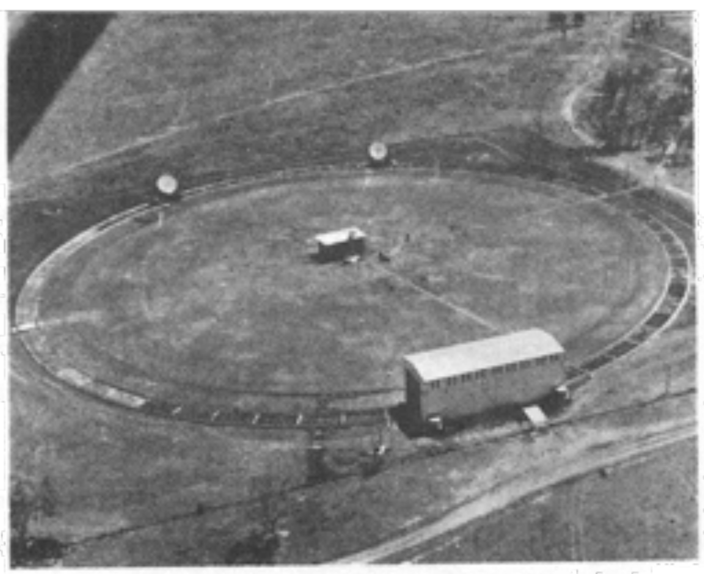
Experimentally obtained as:

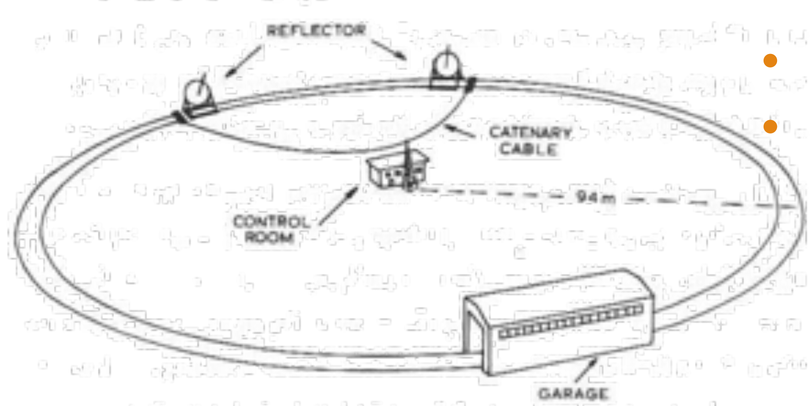
$$C(k^*) = \boldsymbol{\mathcal{N}} \frac{N_{Same}(k^*)}{N_{Mixed}(k^*)}$$

Idea stolen from Astronomy!

- **1950 H**anbury **B**rown-**T**wiss (HBT) interferometry (Nature volume 178 (1956)1046–1048)



- **Two mirror connected to PMT**
- **“correlator” ⇒** “.. ... collected light as rain in a bucket ..” (more or less what we do when collecting pairs of particles)
- **<u>REMARK:</u>** it was already known that such intensity interferometry was working for radio-wave (classical object). The application to photons has indeed been received initially with skepticism ⇒ wave-particle duality and B/F Quantum Statistics
- **<u>HB and T applied the technique to measure the angular size of the star Sirius (8.6 ly) by studying optical intensity correlations between two telescopes</u>**



- Data taken for 18 hours over 5 month period
- Data yielded an angular diameter of (0.005936”)

$$0.0068'' \pm 0.0005'' = 3.1 \times 10^{-8} \text{ radians}$$

G.Baym **Acta Phys.Polon. B29 (1998) 1839-1884**

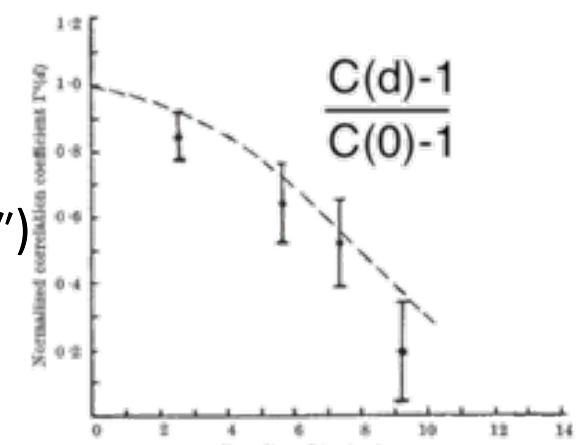
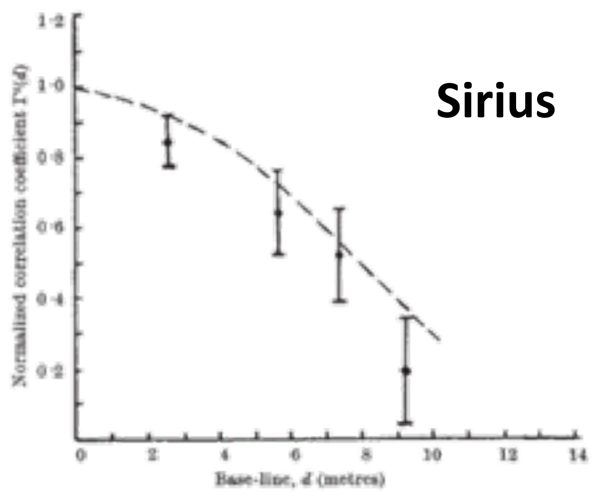


Fig. 2. Comparison between the values of the normalized correlation coefficient Γ²(d) observed from Sirius and the theoretical values for a star of angular diameter 0·0063". The errors shown are the probable errors of the observations

13

Idea stolen from Astronomy!



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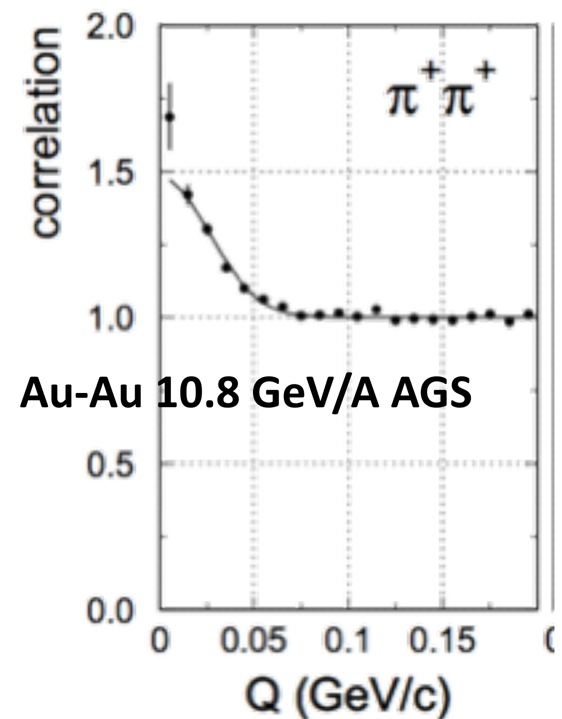
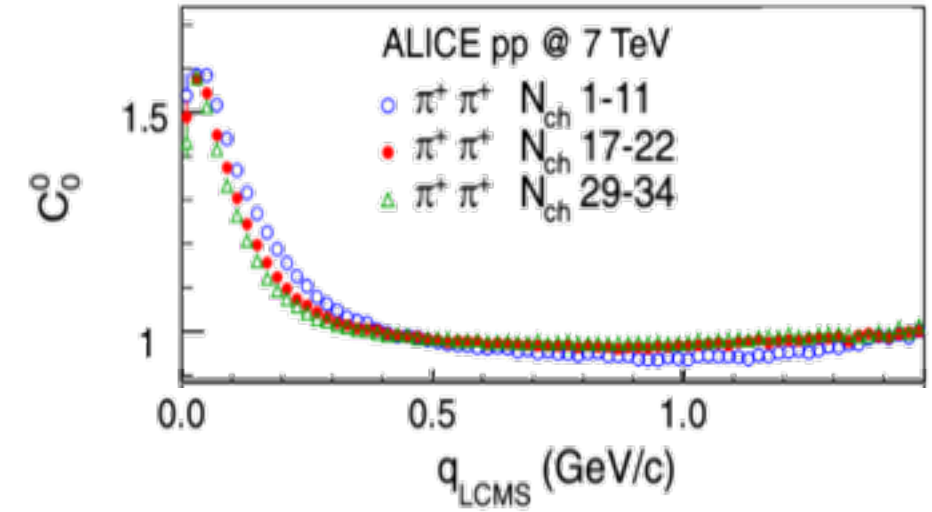
Sirius



$$(\hbar/\Delta q)_{AA} \approx 4 \text{ fm}$$



p-p 7 TeV ALICE
(ALICE Coll. PRD84, 112004 (2011))

$$(\hbar/\Delta q)_{pp} \approx 1 - 1.5 \text{ fm}$$

- **1959 Goldhaber, Goldhaber, Lee and Pais, 1977 Koonin**
- From **end of 80s** ⇒ used to study the **space-time geometry evolution in heavy-ion collisions and elementary collisions**

14

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Given by:

$$C(k^*) = \int S(\boldsymbol{r}, k^*)|\psi(\boldsymbol{r}, k^*)|^2\, d\vec{\boldsymbol{r}}$$

$$\xrightarrow{k^* \to \infty} 1$$

Source

Relative Wave Function

$$k^* = \frac{|\boldsymbol{p}_a^* - \boldsymbol{p}_b^*|}{2} \text{ and } \boldsymbol{p}_a^* + \boldsymbol{p}_b^* = 0$$

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Assumption of a **common source** with **Gaussian shape** for the **pp, pΛ, p**Ξ, $\Lambda\Lambda$ and pK Correlation Function

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Strong constraint

The Correlation Function

(D.L.Mihaylov et al. Eur.Phys.J. C78 (2018) no.5,394)

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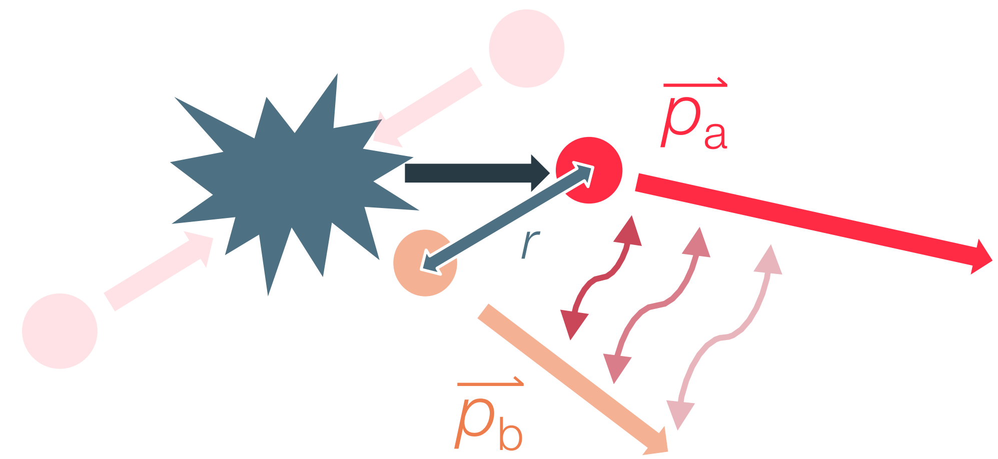
Assumption of a **common source** with **Gaussian shape** for the **pp, pΛ, pΞ**, $\Lambda\Lambda$ and pK Correlation Function

Strong constraint

correlations functions allow to study the interactions

Collective effects and strongly decaying resonances

(An)isotropic flow + Strongly decaying resonances



- *(An)isotropic pressure gradients* affect the emission
  - Initial geometric anisotropies introduce a transverse modulation
  - Expanding source with *common velocity field*
- Affects particles depending on their mass

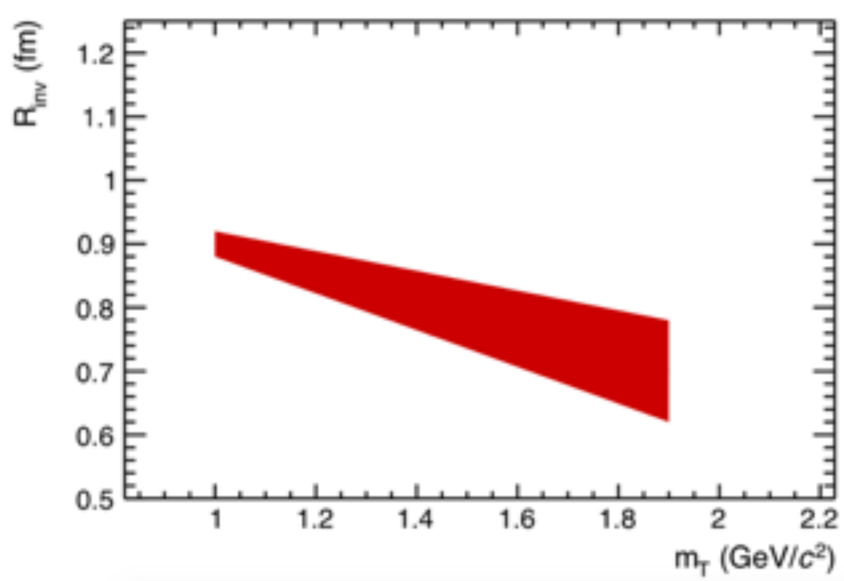
- Resonances with cτ ~ r_0 ~ 1 fm (Δ, N*) introduce an *exponential tail* to the source
- Different for each particle species!

Collective effects and strongly decaying resonances

(An)isotropic flow + **Strongly decaying resonances**

$\underbrace{\hspace{6cm}}$

Gaussian core ⊗ Exponential tail



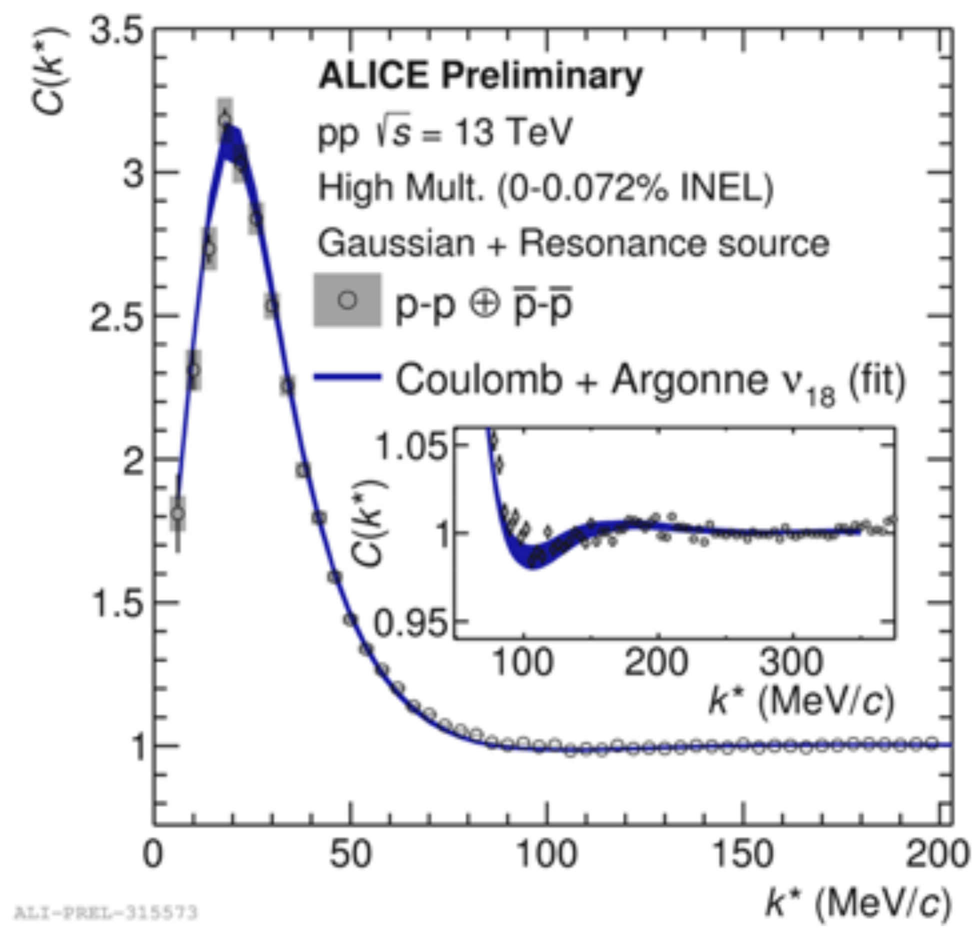
Particle	Primordial fraction	Resonances $1 < c\tau < 2$ fm	Resonances $c\tau > 2$ fm
Proton	33 %	56 %	2 %
Lambda	35 %	8 %	58 %

- Yield of resonances determined from Canonical Statistical Hadronization Model
- Priv. Comm. with Prof. F. Becattini
  J.Phys. G38 (2011) 025002.

Application of the model to p–p correlations

(An)isotropic flow — **Strongly decaying resonances**

$$\underbrace{\text{Gaussian core}}_{\text{(An)isotropic flow}} \otimes \text{Exponential tail}$$



$r_{Core} = 0.995 \pm 0.005 \ ^{+0.024}_{-0.022}$ fm

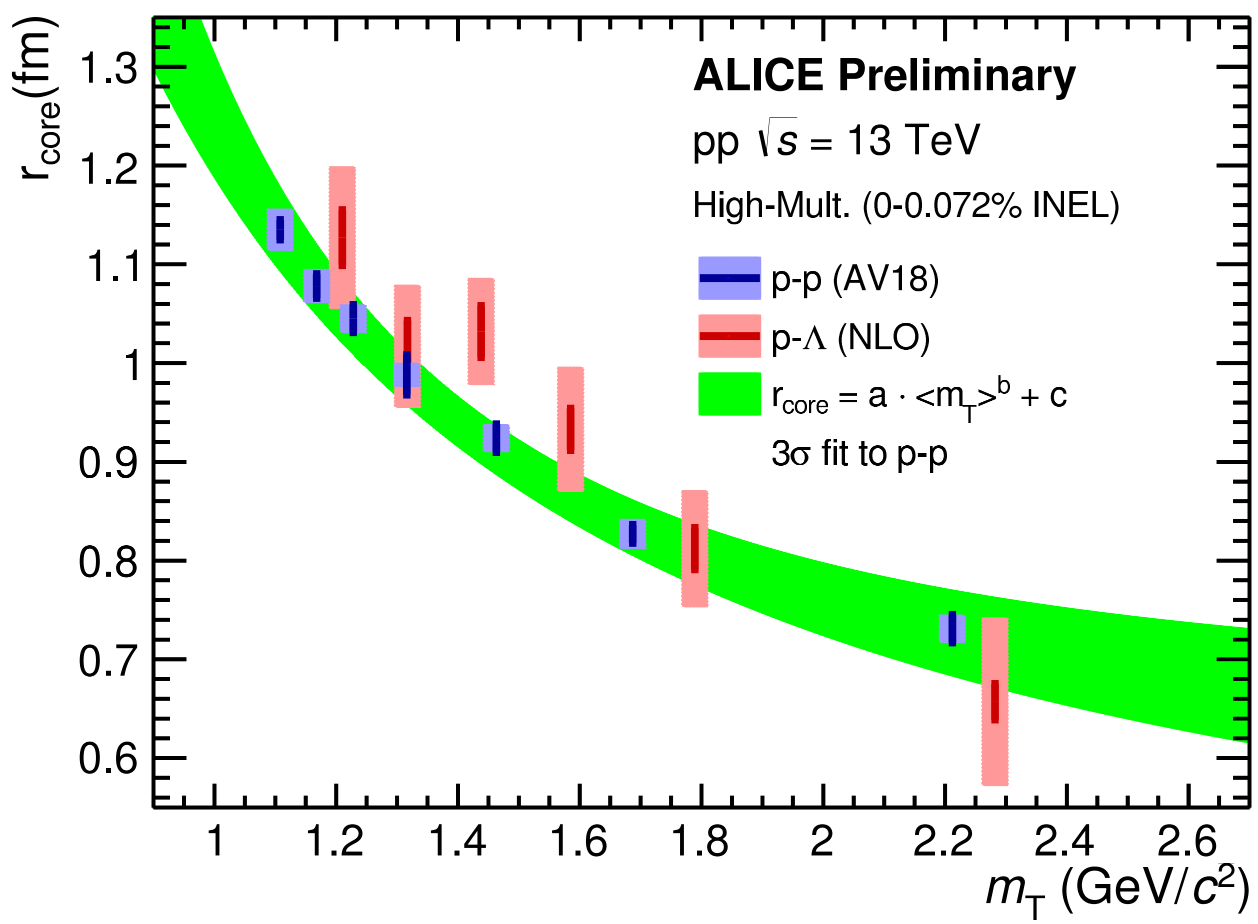
$r_{Eff} = 1.249 \pm 0.008 \ ^{+0.024}_{-0.021}$ fm

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

Coulomb + AV18 Potential
+ Modelled Source

m_T dependence of the Gaussian *core* radius

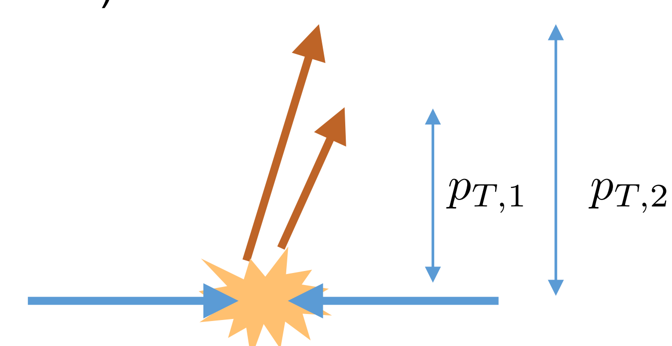
arXiv:2004.08018



ALI-PREL-315640

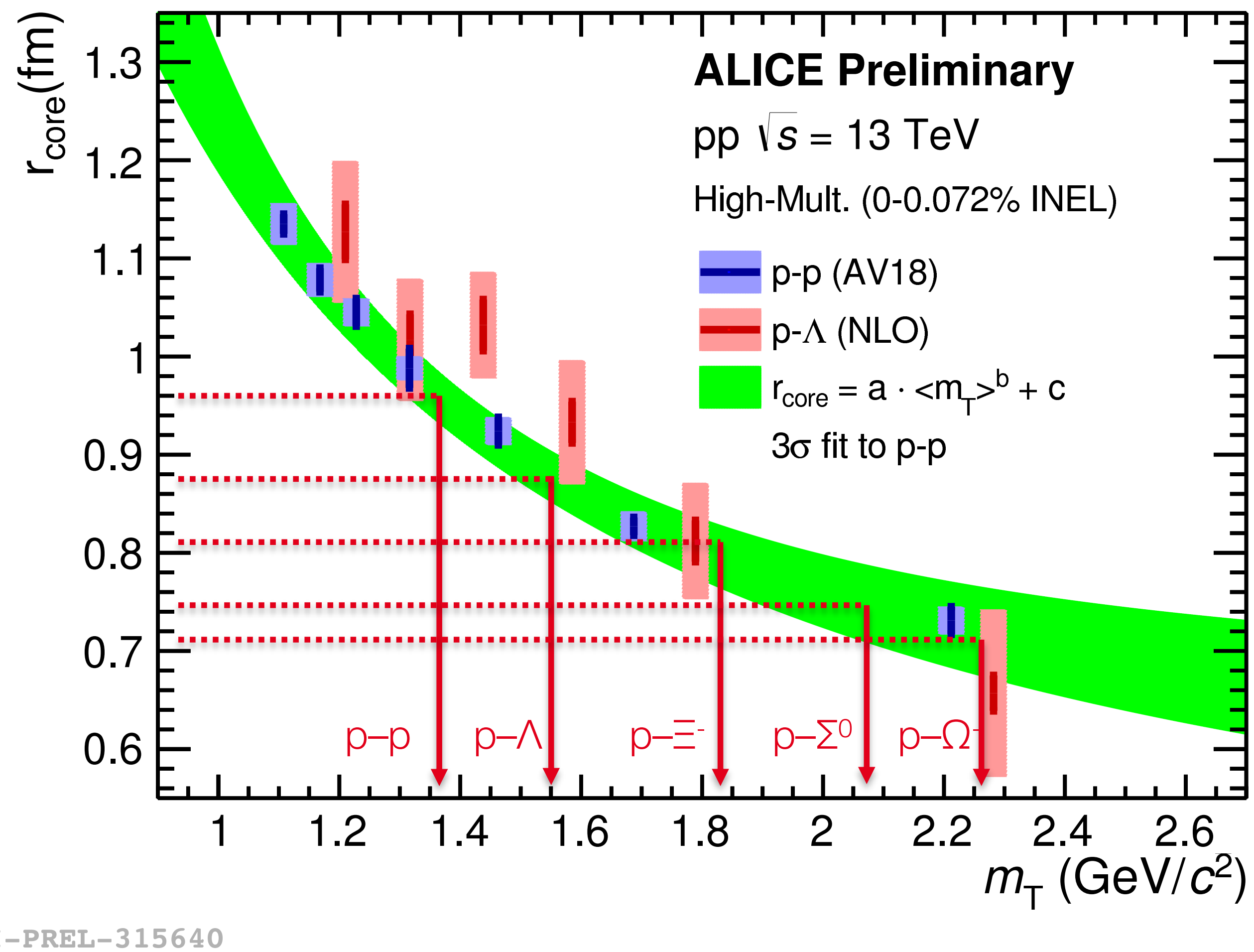
- Core radius for p–p and p–Λ in good agreement

$$m_T = \sqrt{m_{pair}^2 + k_T^2} \qquad k_T = |\vec{p}_{T,1} + \vec{p}_{T,2}|/2$$



m_T dependence of the Gaussian *core* radius

arXiv:2004.08018



Pair	r_{Core} (fm)	r_{Eff} (fm)
p–p	1.00	1.25
p–Λ	0.88	1.30
p–Σ^0	0.75	1.14
p–Ξ^-	0.80	0.92
p–Ω^-	0.73	0.85

- Fix the value of r_{Core} of each particle species based on their $\langle m_T \rangle$
  - Add specific resonance contribution to obtain the corresponding pair source

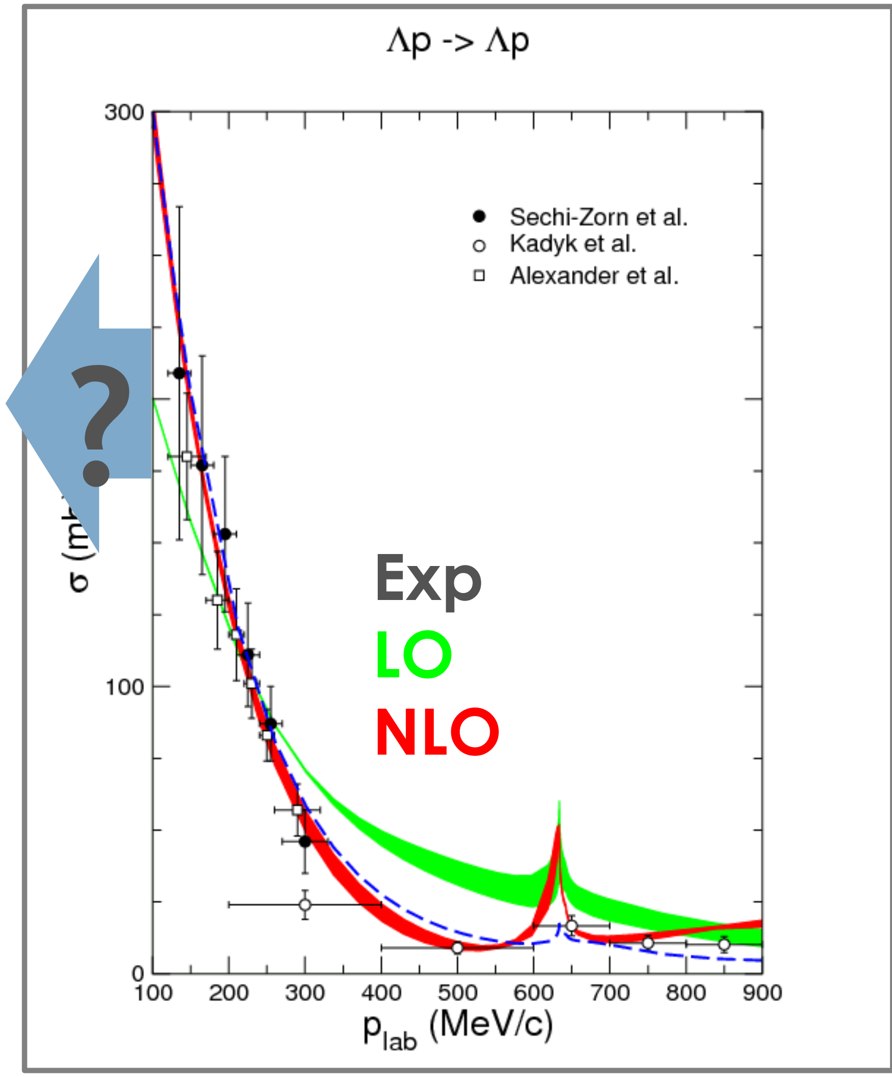
Femtoscopy with Λ and Σ baryons

Precision and pioneering feasibility studies in the $|S| = 1$ sector

ALICE Collaboration, *Phys.Lett.B* 805 (2020) 135419

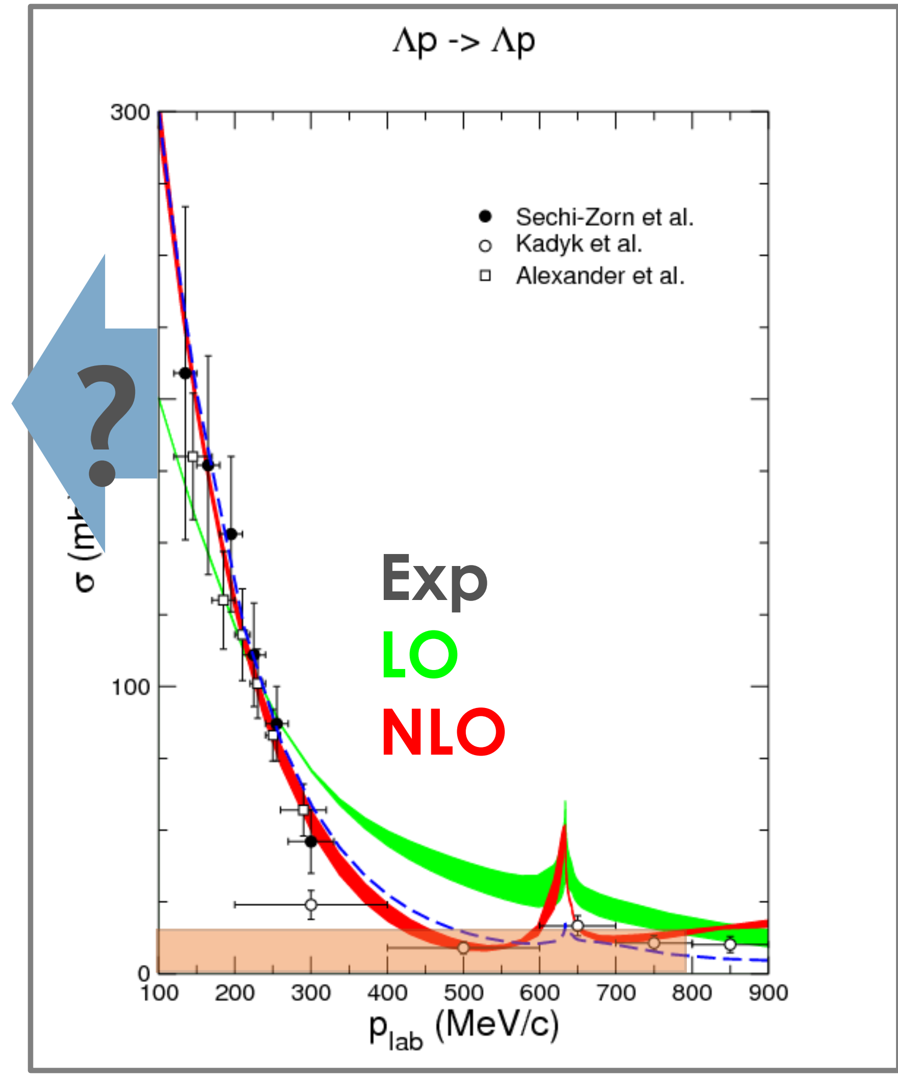
pp $\sqrt{s}$ = 13 TeV (high mult.)

Proton-Λ : Scattering vs Femtoscopy Data



LO: H. Polinder, J.H., U. Meißner, NPA 779 (2006) 244
NLO: J.Haidenbauer., N.Kaiser, et al., NPA 915 (2013) 24

Proton-Λ : Scattering vs Femtoscopy Data



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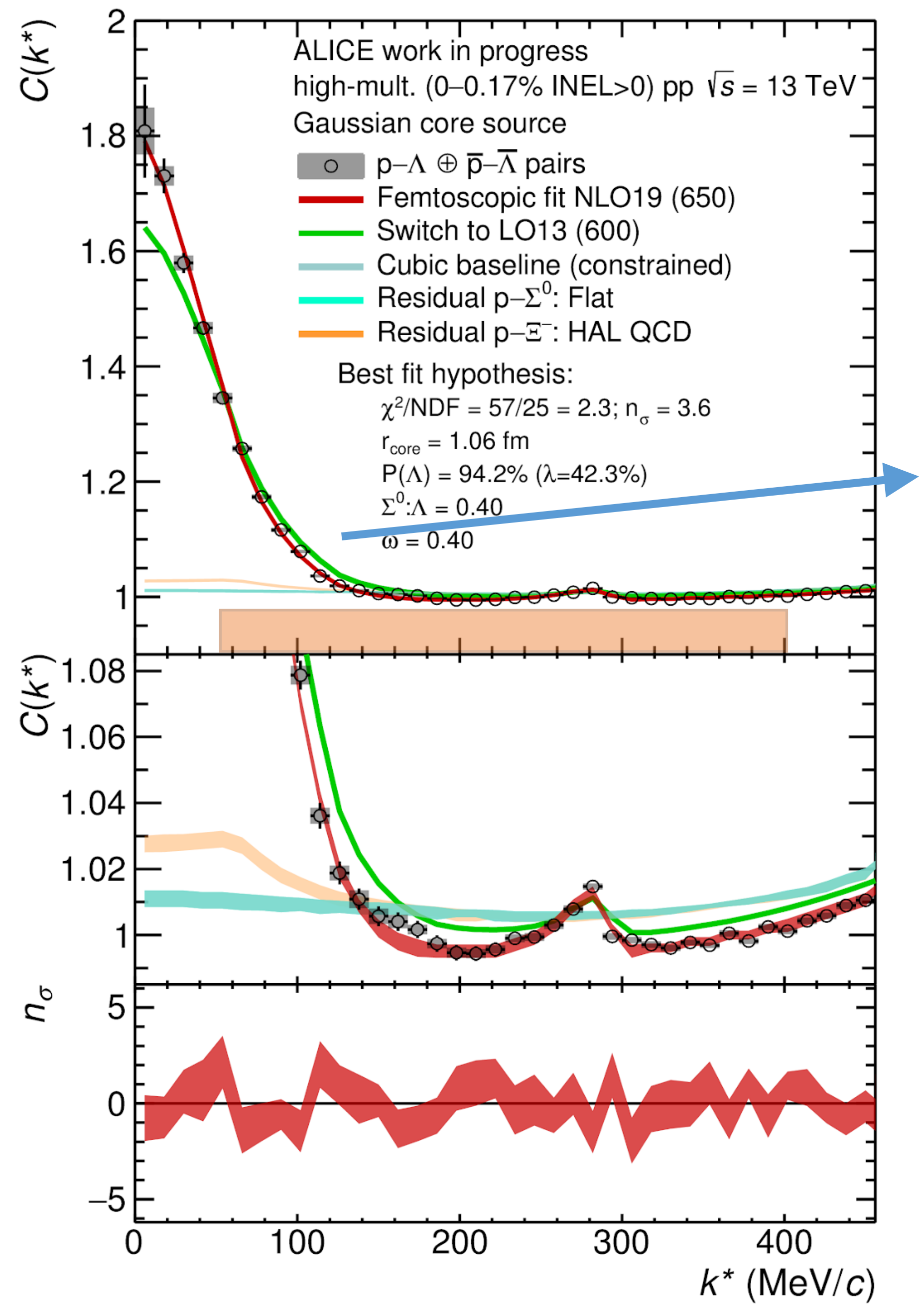


C(k*)> 1:
Attractive interaction

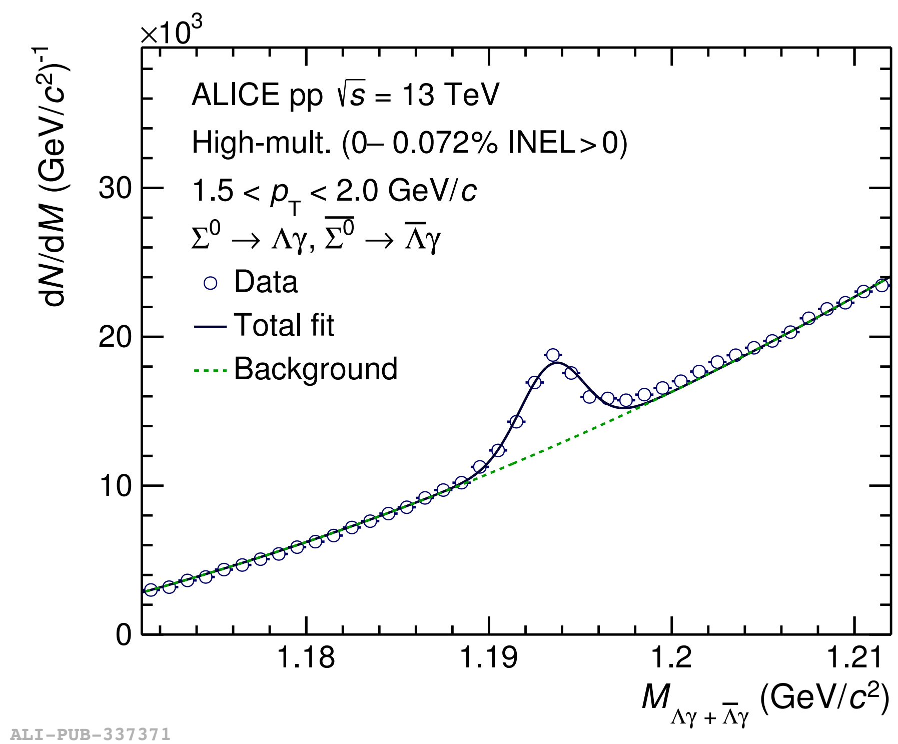
- Combination of spin singlet and triplet
- * Extension to the low momentum regime
- * <1% errors !!

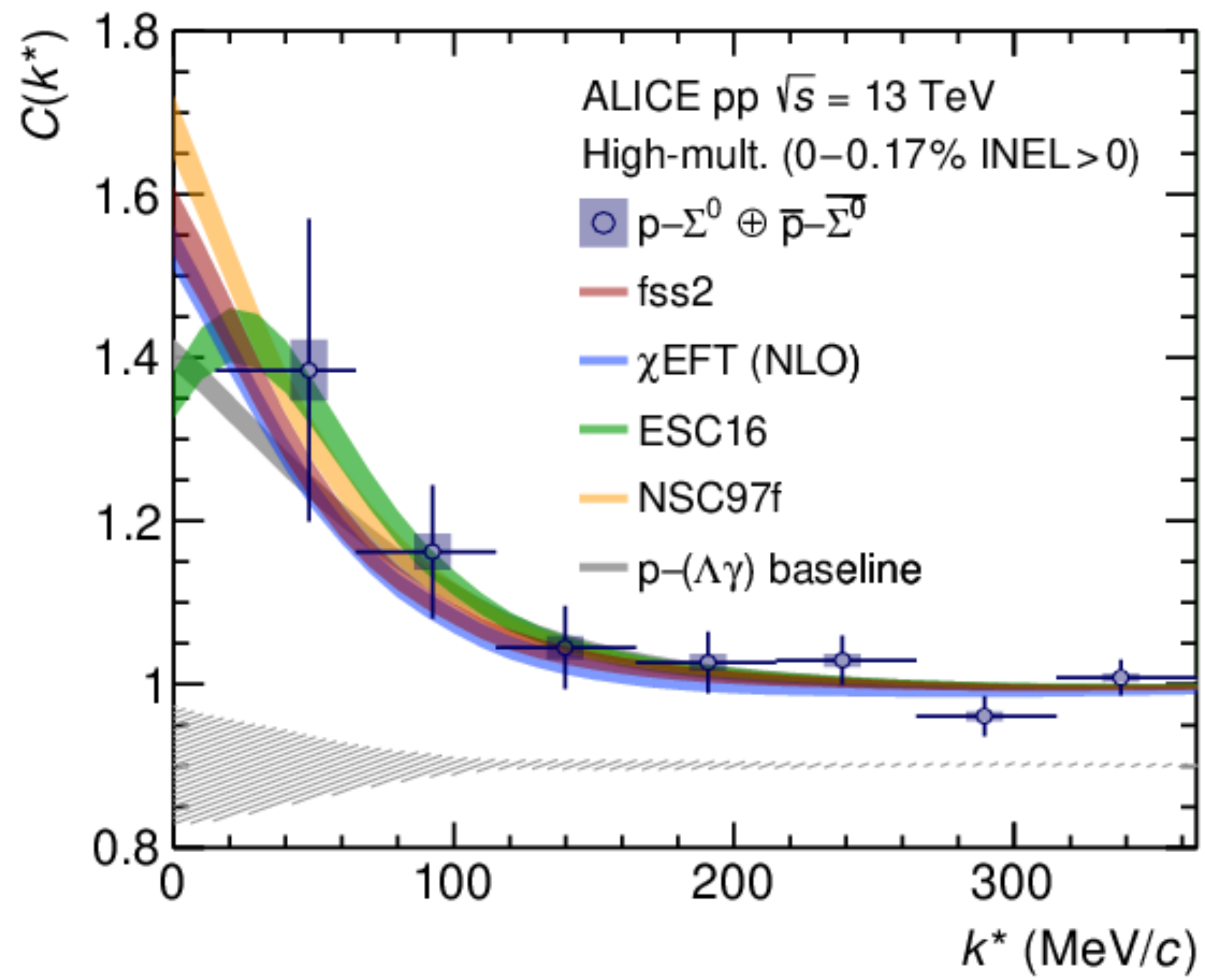
p–Σ⁰ – first measurement of the correlation function

ALICE Collaboration, *Phys.Lett.B* 805 (2020) 135419

- $\Sigma^0 \rightarrow \Lambda\,\gamma$ (BR: almost 100 %)
  - Identification of the photon via conversions
  - Significant contribution from correlated p–(Λγ) background due to low purity

- Significant differences among the models will allow decisive measurements in future





χEFT: J. Haidenbauer et. al, Nucl. Phys. A915 (2013) 24–58.
NSC97f: T. A. Rijken et. al, Phys. Rev. C59 (1999) 21–40
ESC16: M. M. Nagels et. al, Phys. Rev. C99 (2019) 044003
fss2: Y. Fujiwara et al., Prog. Part. Nucl. Phys. 58, 439–520 (2007)

p–Ξ^- femtoscopy

Benchmarking lattice QCD

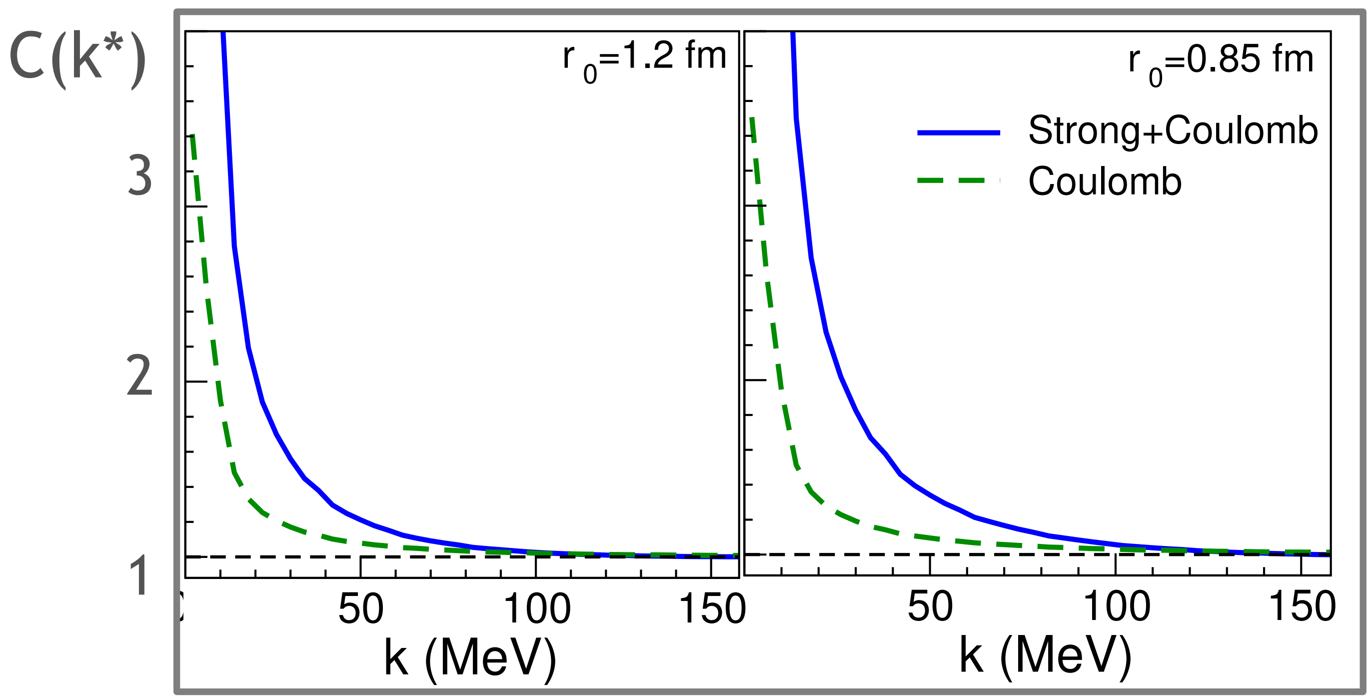
ALICE Collaboration, Phys. Rev. Lett. 123 (2019) 112002

pp $\sqrt{s}$ = 13 TeV (high mult.)
p–Pb $\sqrt{s_{NN}}$ = 5.02 TeV

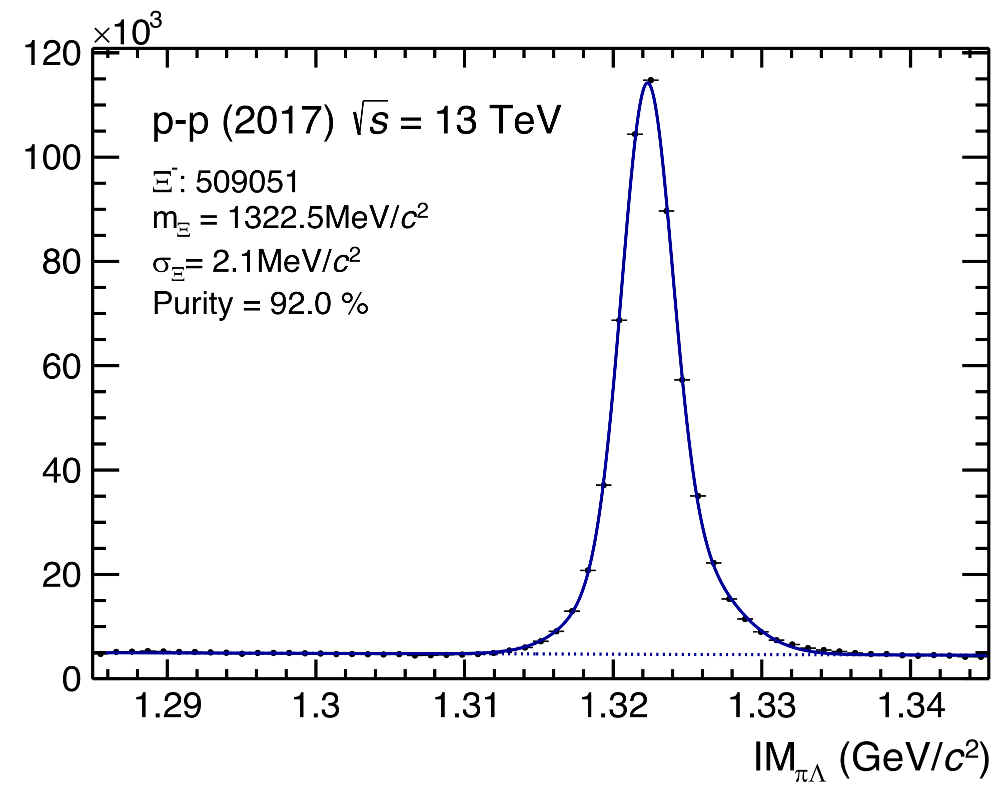
Ξ^-

- **Preliminary** calculations by the HAL QCD Collaboration
- Taking the strong interaction into account creates a significantly different Correlation function than Coulomb only

- Decay mode $\Xi^{\pm} \rightarrow \Lambda + \pi$
$$p + \pi$$



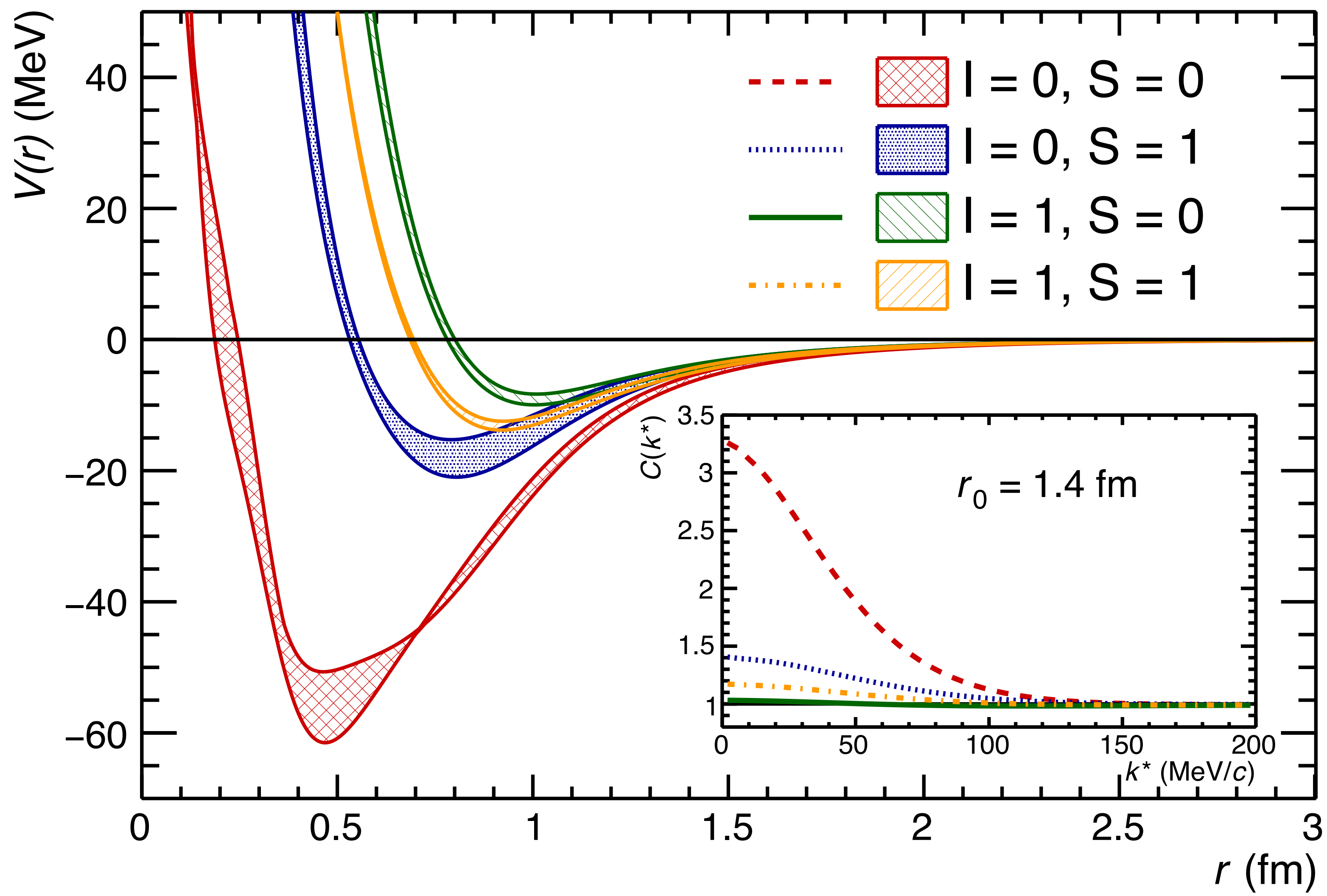
arXiv:1702.06241 , Nuclear Physics A 967 (2017) 856–859



CATS (D.L.Mihaylov et al. Eur.Phys.J. C78 (2018) no.5,394)

Lattice Interaction

(Potential from Hatsuda et al., NPA967 (2017) 856, PoS Lattice2016 (2017) 116)



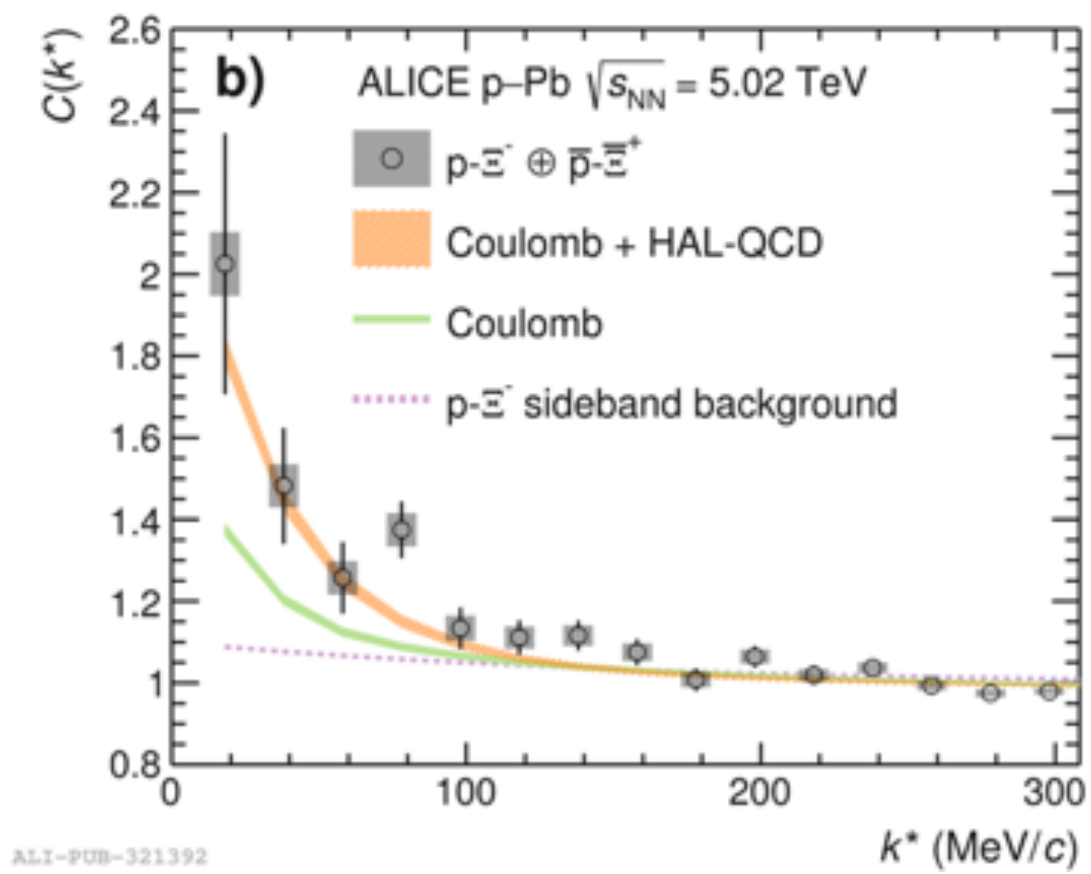
Errors due to different integration times

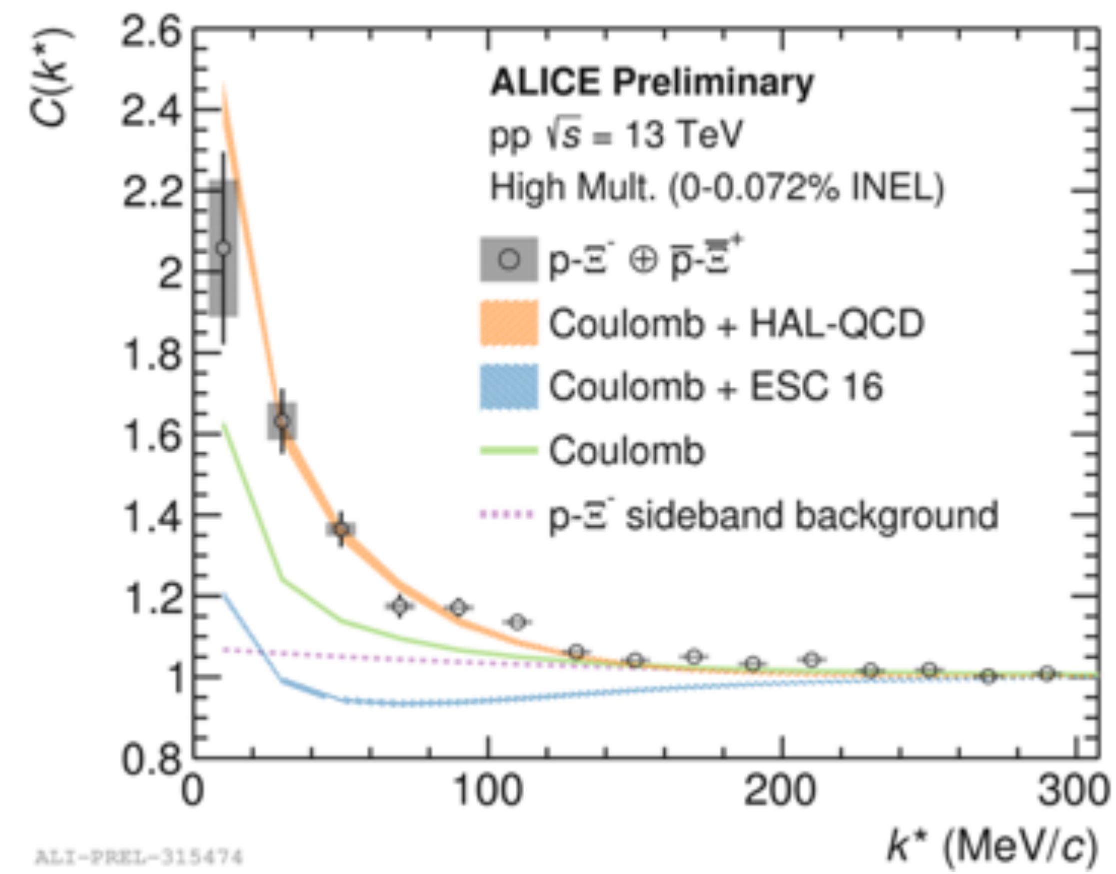
Each Potential can be converted in a correlation function via CATS

$$C(k^*) = \frac{1}{8}\left(C_{I=0}^{S=0} + C_{I=1}^{S=0}\right) + \frac{3}{8}\left(C_{I=0}^{S=1} + C_{I=1}^{S=1}\right)$$

proton-Ξ^- Correlation Function

ALICE Collaboration, PRL 123 (2019) 112002





First observation of the strong interaction in p–Ξ^-

- Coulomb-only excluded (> 4 σ)
- Compatible with Lattice (HAL-QCD) calculations

p–Ξ^- in pp 13 TeV (high mult.)

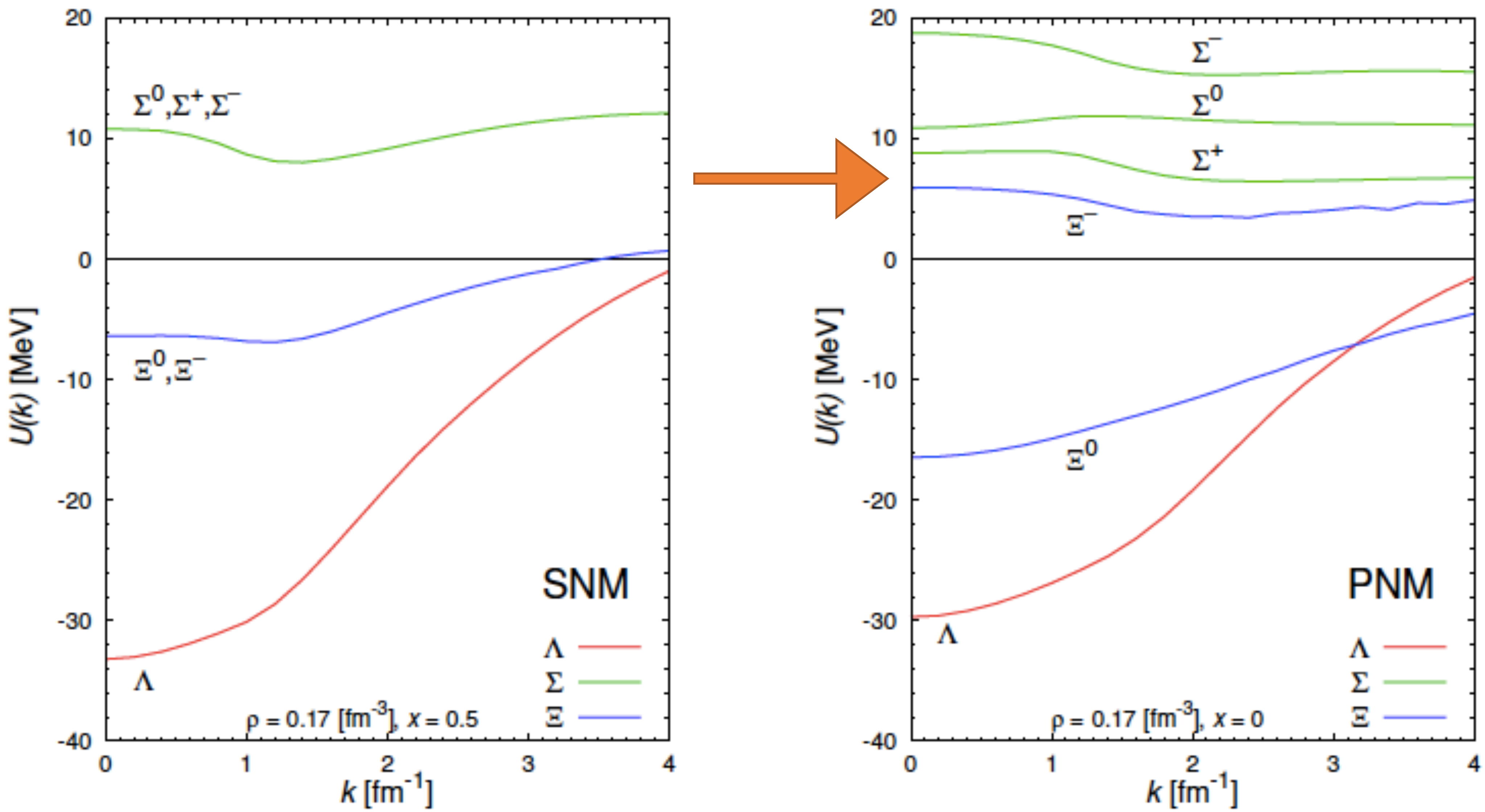
- Coulomb-only: > 5.7 σ
- HAL-QCD: (1.3-2.5) σ
- ESC16: > 18 σ

Single Particle Potentials from Lattice

Symmetric Nuclear Matter

PoS Lattice2016 (2017) 116)

Pure **Neutron** Matter



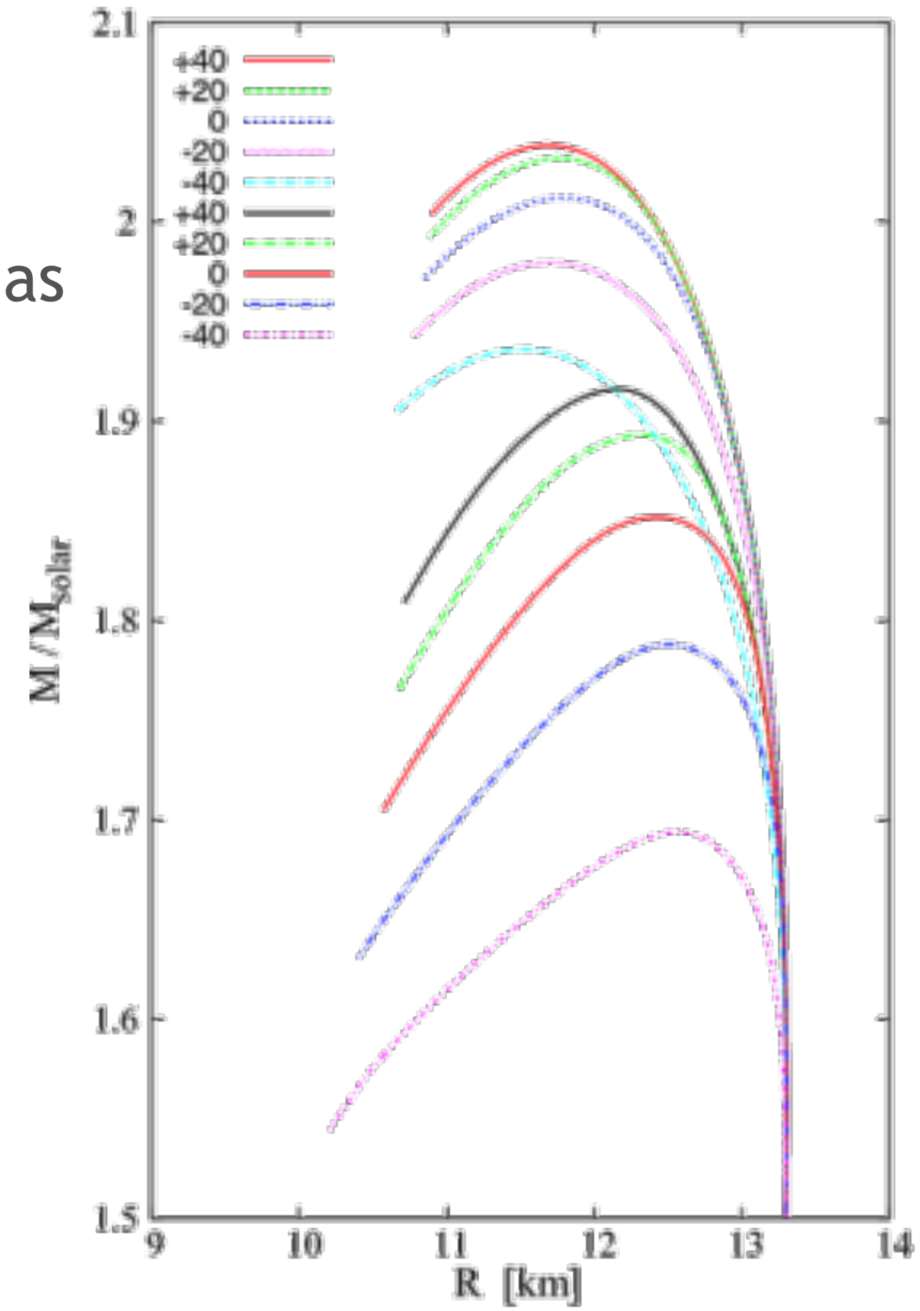
Consequences for Neutron Stars

(Weissborn et al., NPA881 (2012) 62-77)

RMF models: EOS of neutron-rich matter with hyperon content

-> uses single particle potential at saturation densities as input

$U_{NN}(\rho_0), \boxed{U_{\Lambda N}(\rho_0) = -30 \text{ MeV}}, \boxed{U_{\Sigma N}(\rho_0) = +30 \text{ MeV}}, U_{\Xi N}(\rho_0),$ variable ->



Consequences for Neutron Stars

(Weissborn et al., NPA881 (2012) 62-77)

RMF models: EOS of neutron-rich matter with hyperon content

-> uses single particle potential at saturation densities as input

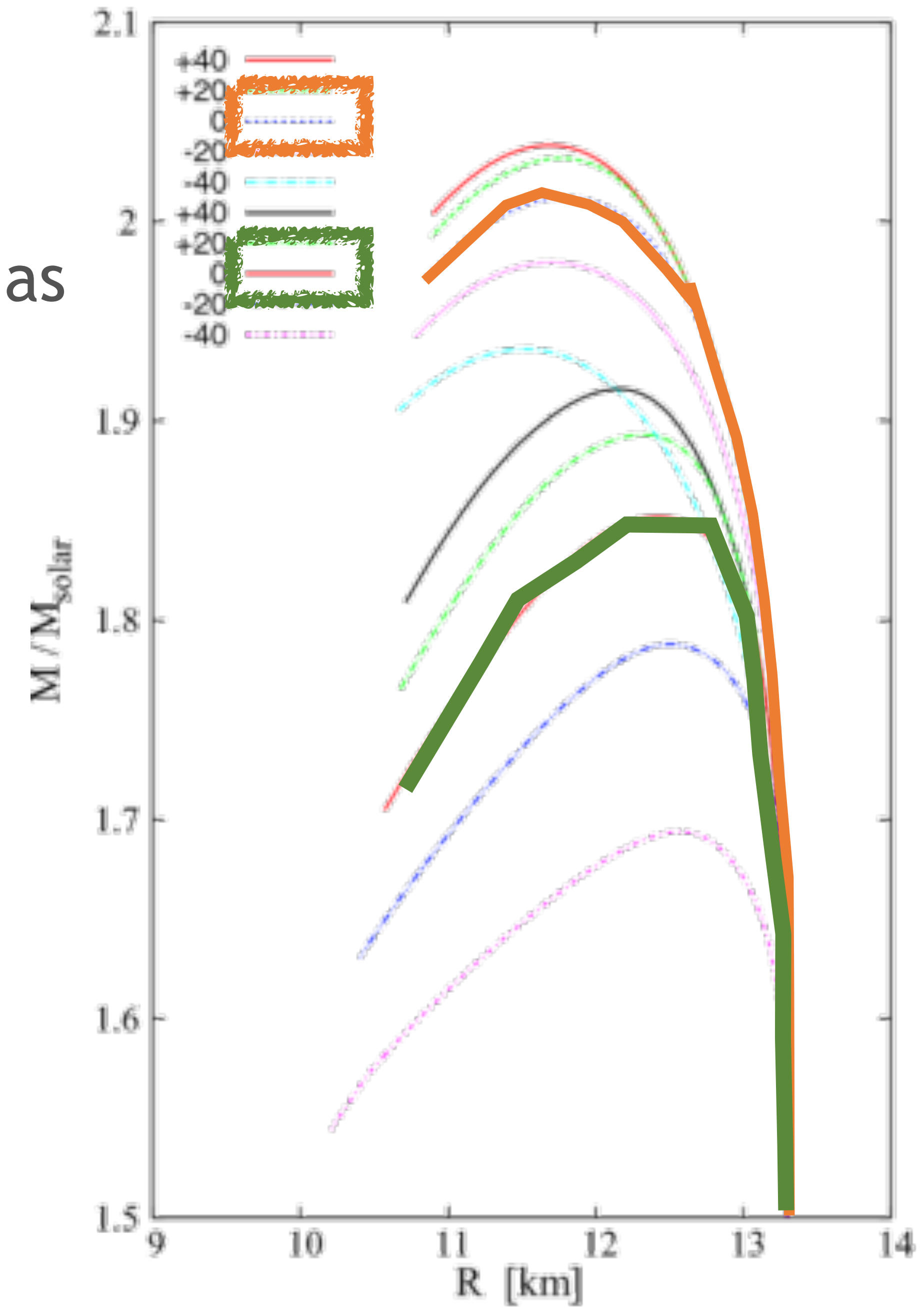
$$U_{NN}(\rho_0),\ U_{\Lambda N}(\rho_0),\ U_{\Sigma N}(\rho_0),\ U_{\Xi N}(\rho_0),$$

= -30 MeV = +30 MeV

Repulsive interaction

⇒ Production of Ξ pushed to higher densities

⇒stiffer EoS, higher masses



Summary

We managed to become the new reference for the study of two hadrons interaction with strangeness content

-> Most precise data on Λp
-> First Measurement of the $p\Sigma^0$
-> First evidence of the $p\Xi^-$ strong attraction

In RUN3 (from 2021 on) we expect factor 100 in statistics

What do we want more?
-> Three body interactions