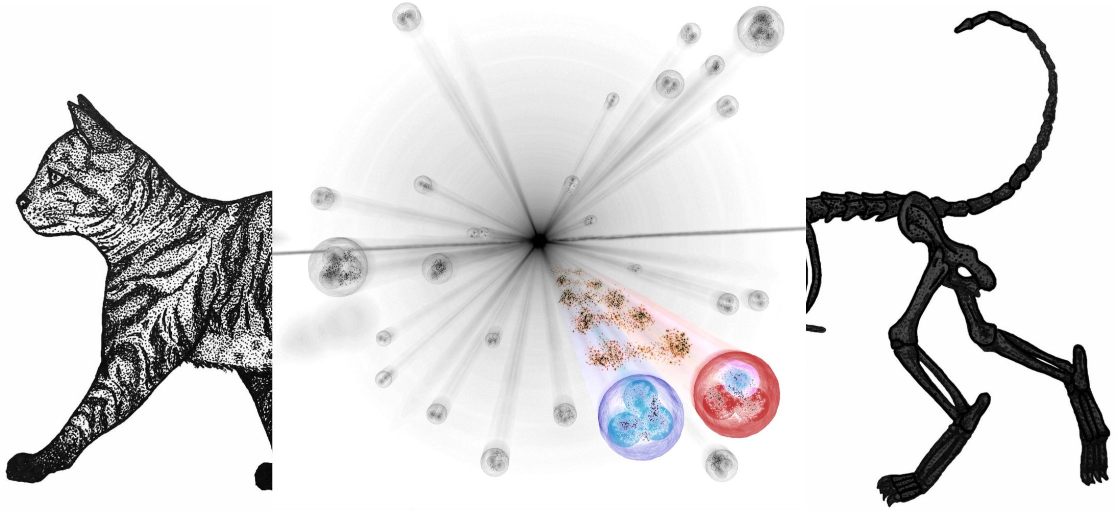
Hyperon-nucleon and hyperon-nucleon-nucleon interaction studies via femtoscopy



Dimitar Mihaylov

29nd June 2022, Prague, Czech Republic

Outline

Outline

Strange

p Λ

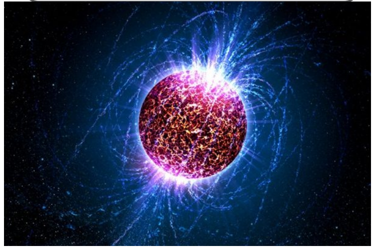
Outline

Strange

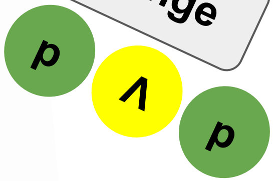
p Λ p

Outline

Neutron stars



Strange



Outline

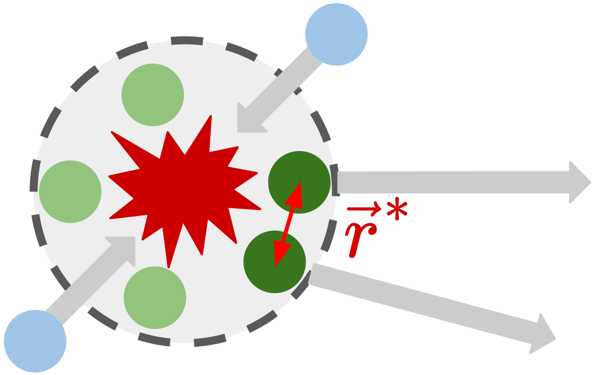
Charming

D π

D p

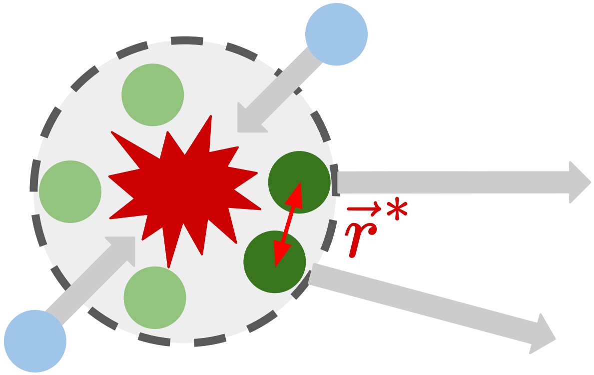
Femtoscopy

Overview

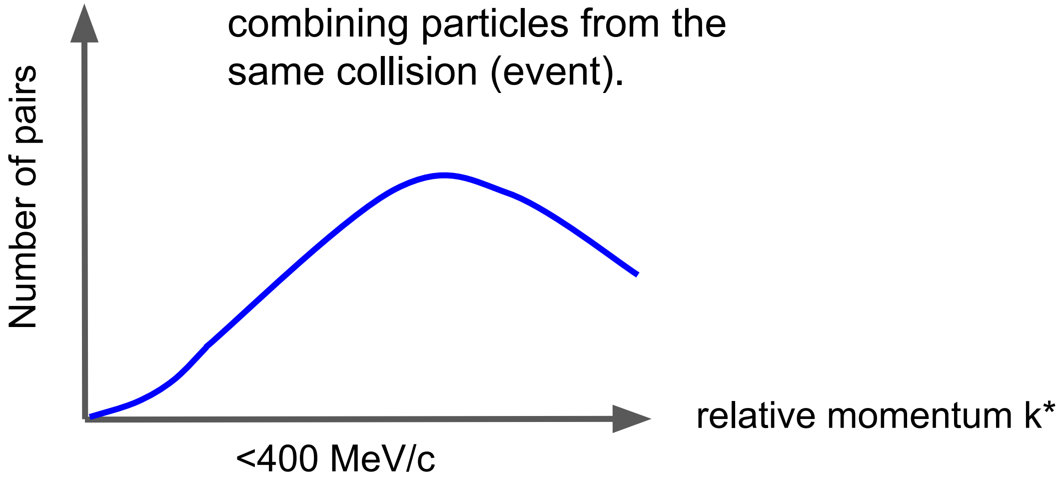


Femtoscopy

Overview

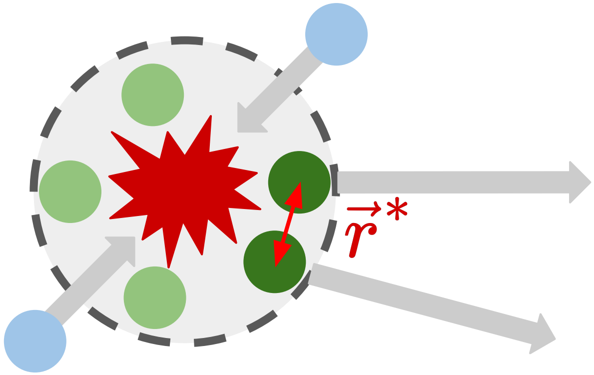


- ***Same event sample (SE)*:** Correlated pairs, obtained by combining particles from the same collision (event).



Femtoscopy

Overview



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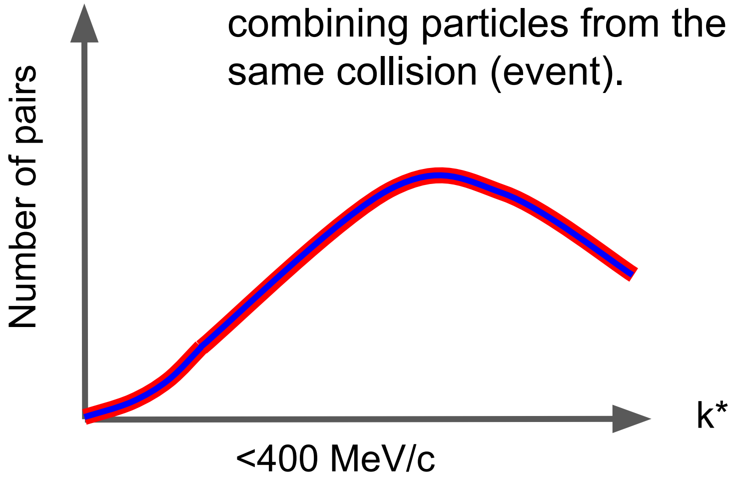
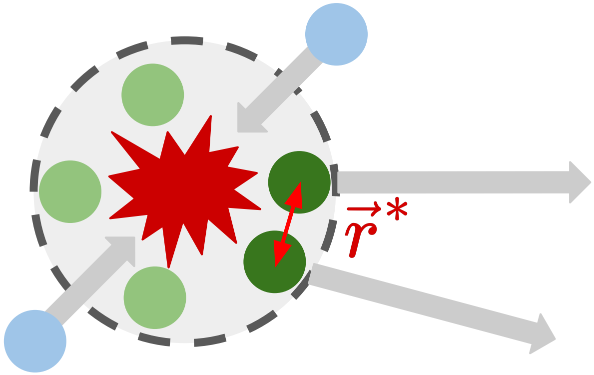
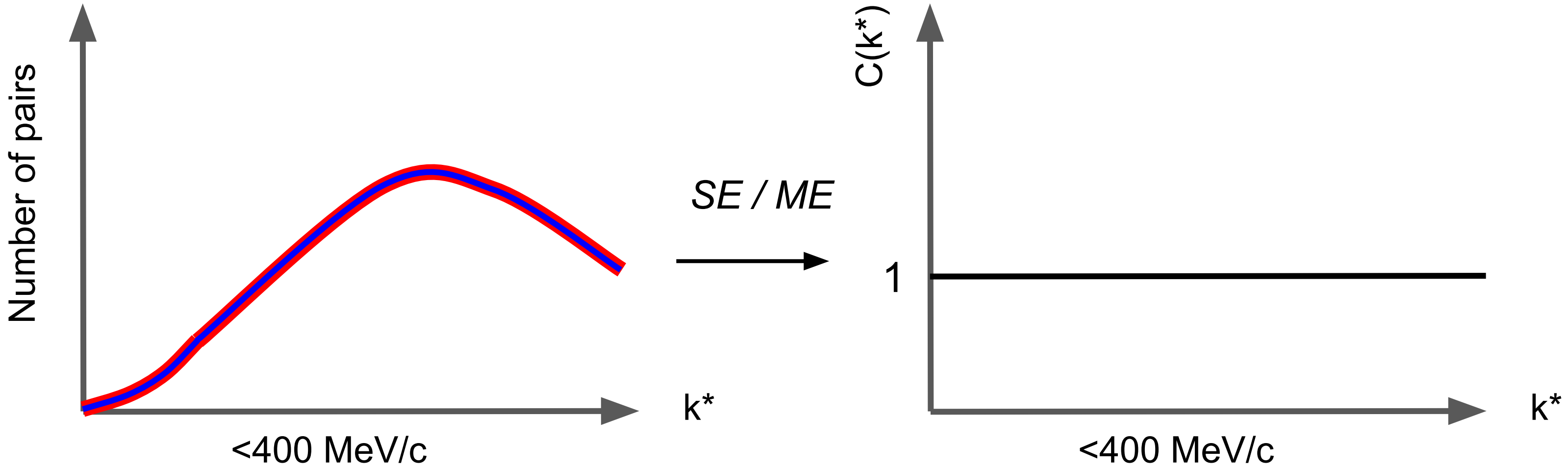


- ***Mixed event sample (ME):*** Uncorrelated pairs, obtained by combining particles from two different collisions (events).

Femtoscopy
Overview

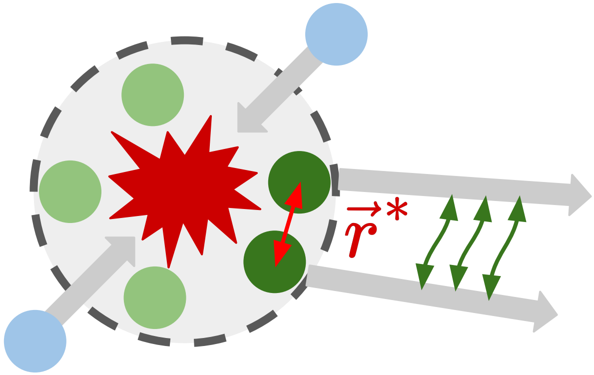


- The ***correlation function C(k*)*** = *SE / ME*, ideally equal to unity in the absence of any correlations.

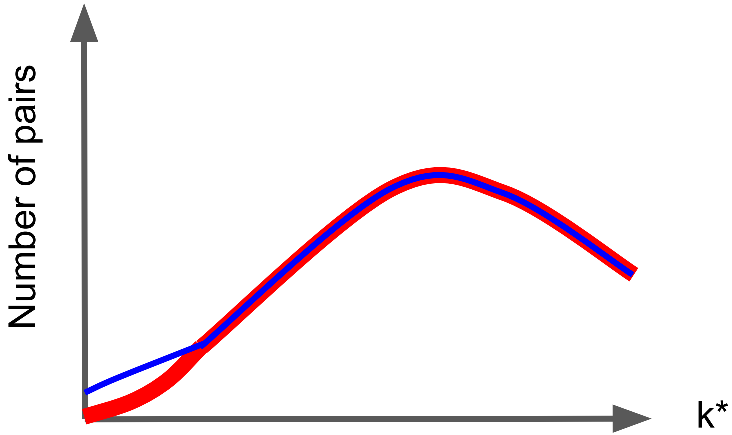


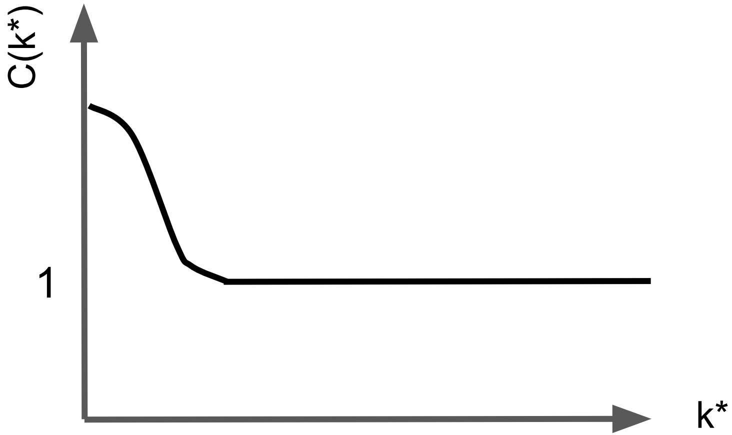
Femtoscopy

Overview



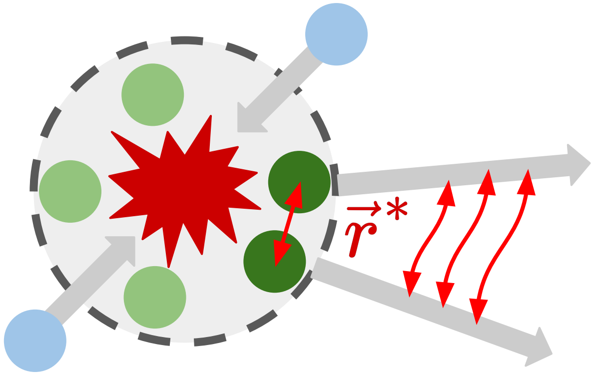
- **Attractive** final state interaction (FSI).



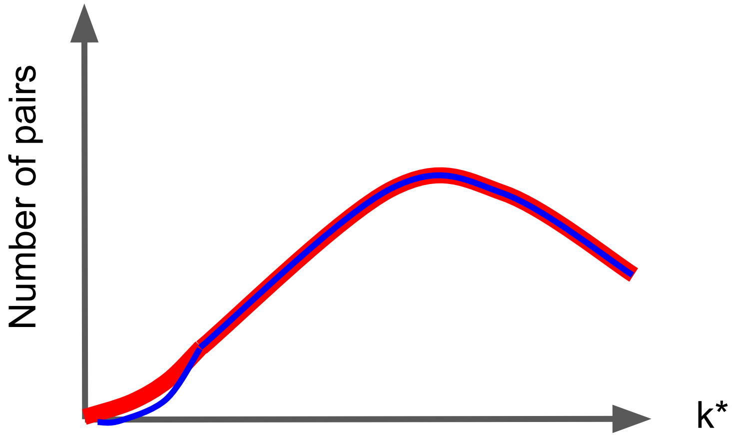


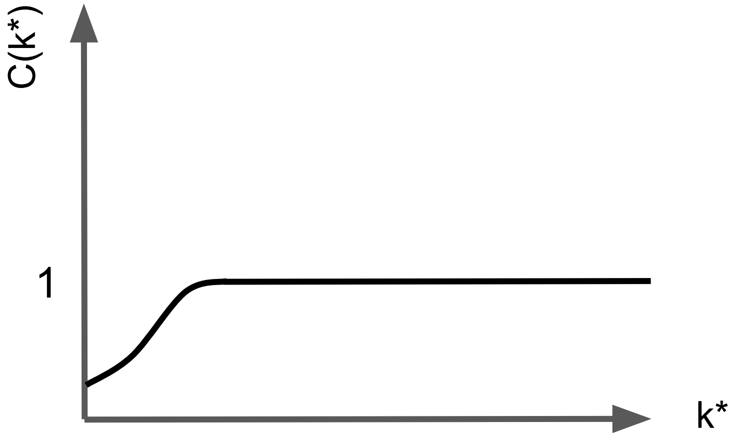
Femtoscopy

Overview



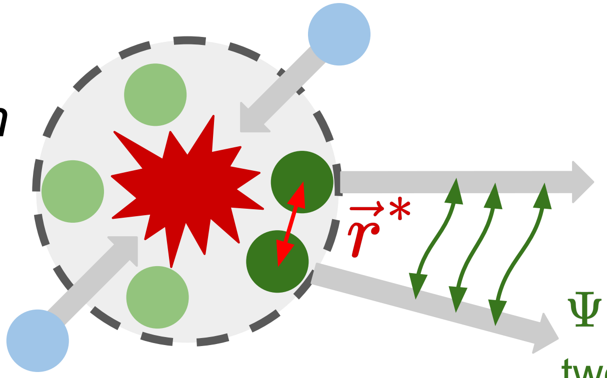
- **Repulsive** final state interaction (FSI).





Femtoscopy

Koonin-Pratt equation



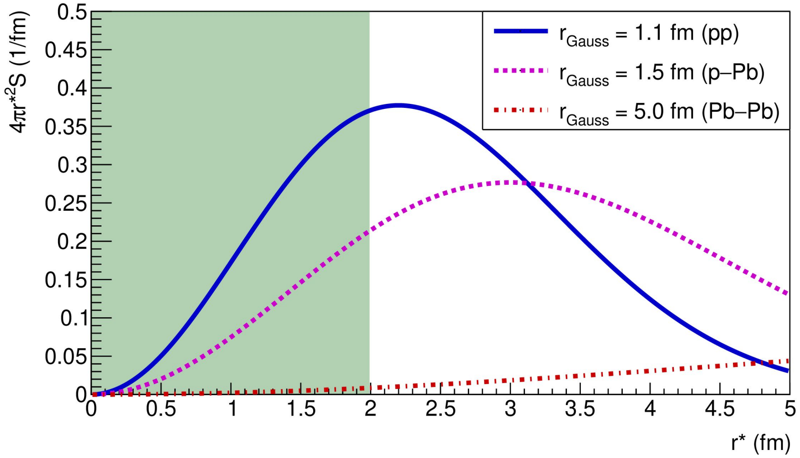
$$C(k^*) = \frac{N_{SE}(k^*)}{N_{ME}(k^*)} = \int S(r^*) \left| \Psi(\vec{k}^*, \vec{r}^*) \right|^2 d^3 r^* \xrightarrow{k^* \to \infty} 1$$

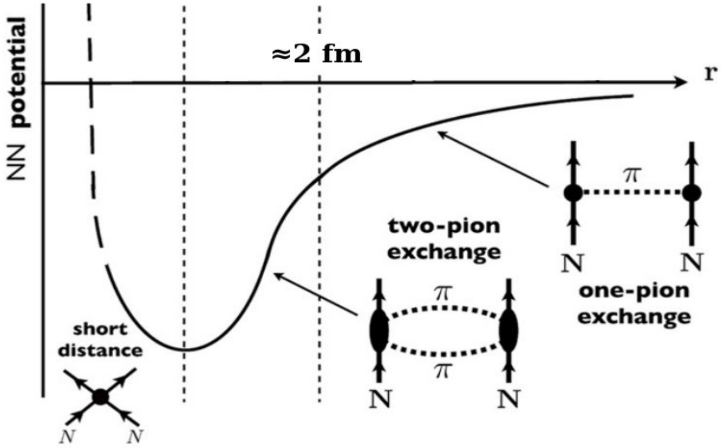
Ann.Rev.Nucl.Part.Sci.55:357-402, 2005

Relative distance and ½ relative momentum evaluated in the pair rest frame

- Measure C(k*), fix S(r*), study the interaction.
- Extension to coupled channels: *Wed-I: Yuki Kamiya*

The emission source





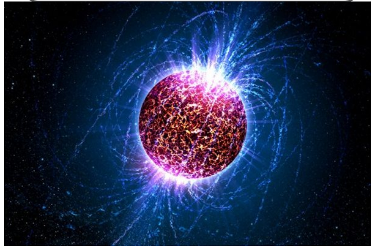
$$C(k^*) = \int S(r^*) \left| \Psi(\vec{k}^*, \vec{r}^*) \right|^2 d^3 r^*$$

Measure   Fix S(r*)   Study

- Enhanced sensitivity in **small collision systems (pp)**.
- Scan over the range of the interaction by using different collisions systems.
  Wed-I: Yuki Kamiya, Thu-I: Ramona Lea
- **Common emission** of primordial particles in pp collisions, allowing to fix S(r*) for any baryon-baryon pair using the pp correlation function.
  Phys. Lett. B 811 (2020) 135849

Outline

Neutron stars



Strange

p

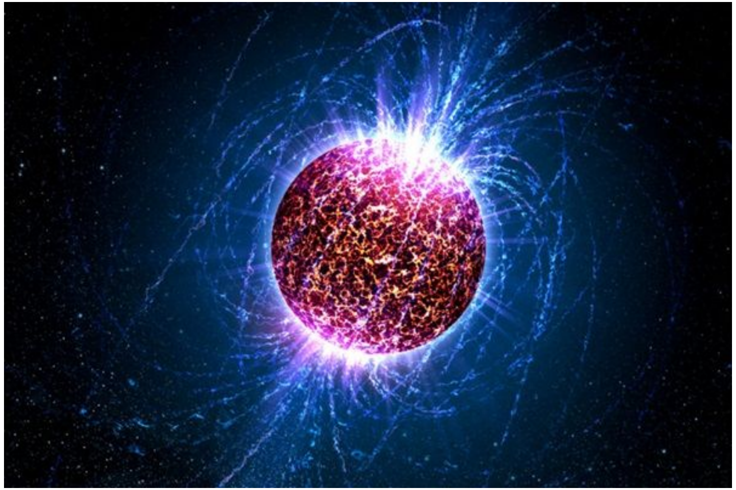
Λ

Neutron stars (NS)

Very compact, very dense
The sun packed in Manhattan

Radius: R ~ 10 km
Mass: M ~ 2 solar masses ($M_\odot$)
Density: few times ρ_0*)

*) ρ_0=0.16 fm^{-3} is the density of the nucleus of an atom, called “nuclear saturation density”.



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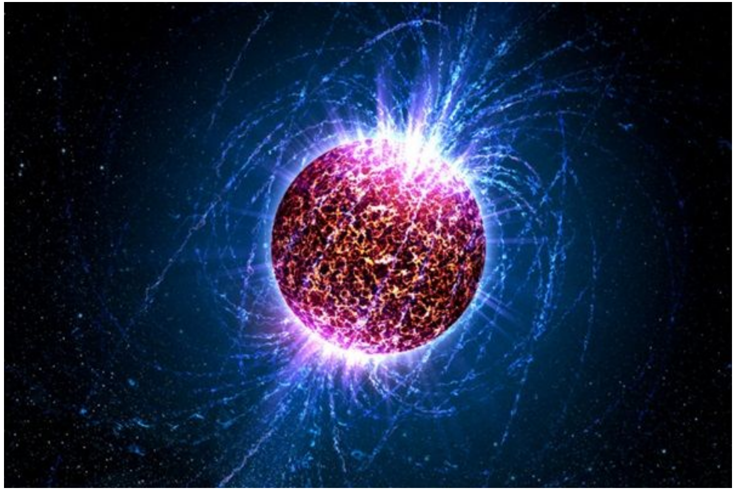

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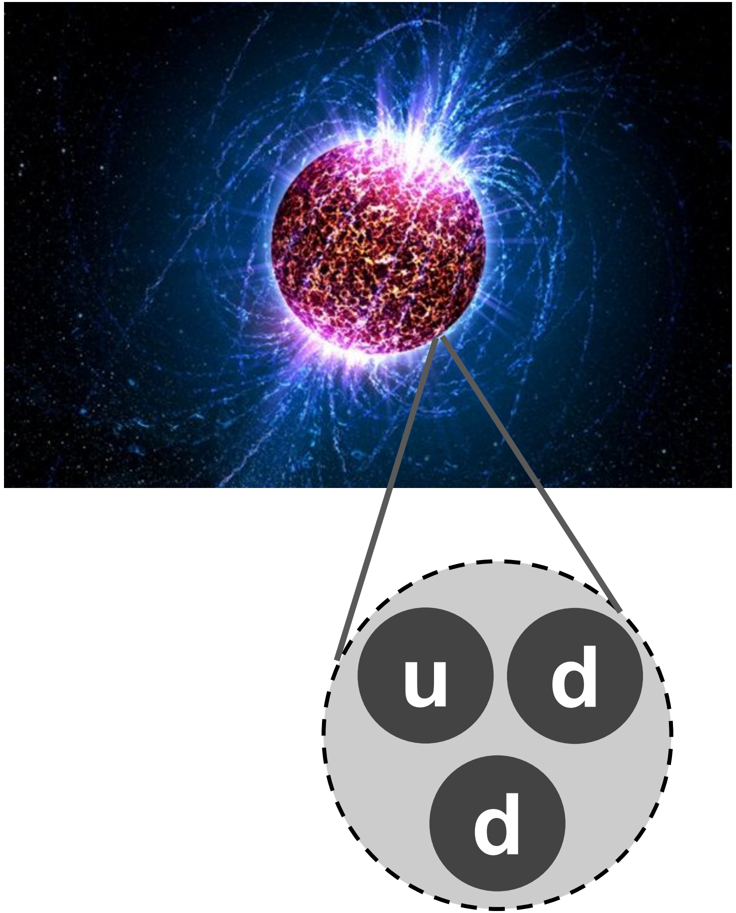
What is inside?
Tue-I @ HYP
(I. Vidana, L. Tolos, A. Ohnishi)

Neutron stars (NS)

Composition

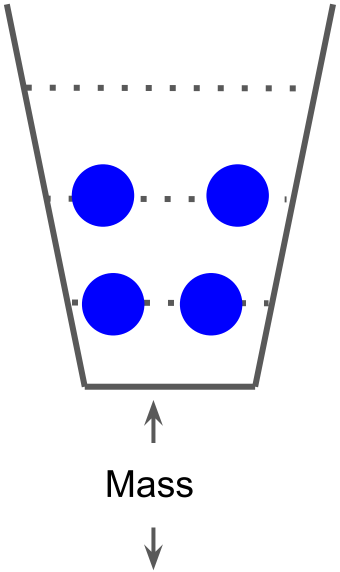
neutrons

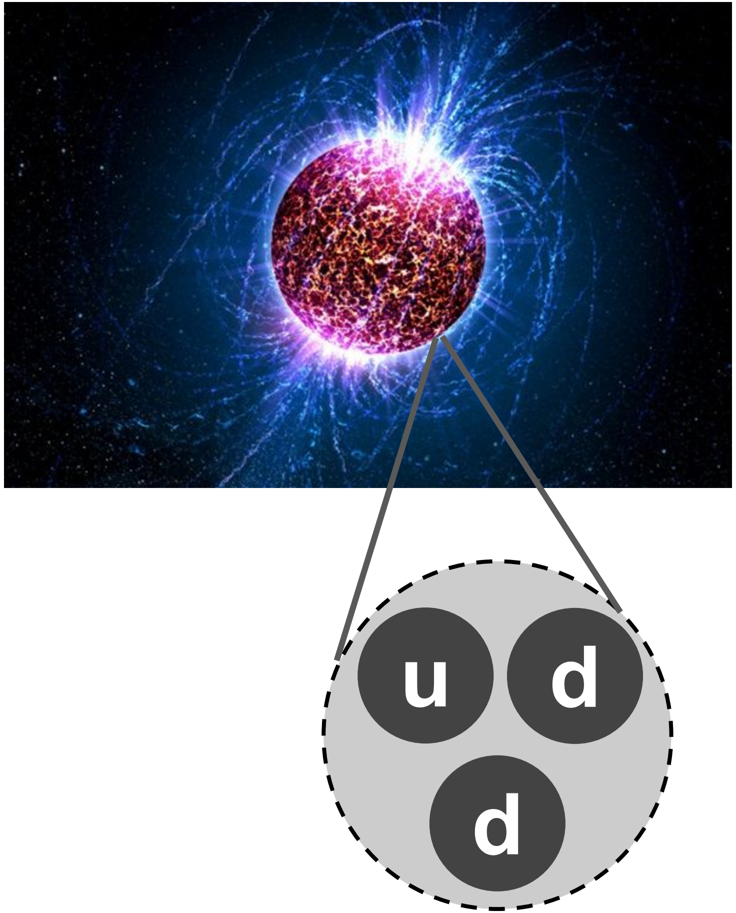


Neutron stars (NS)

Composition

neutrons



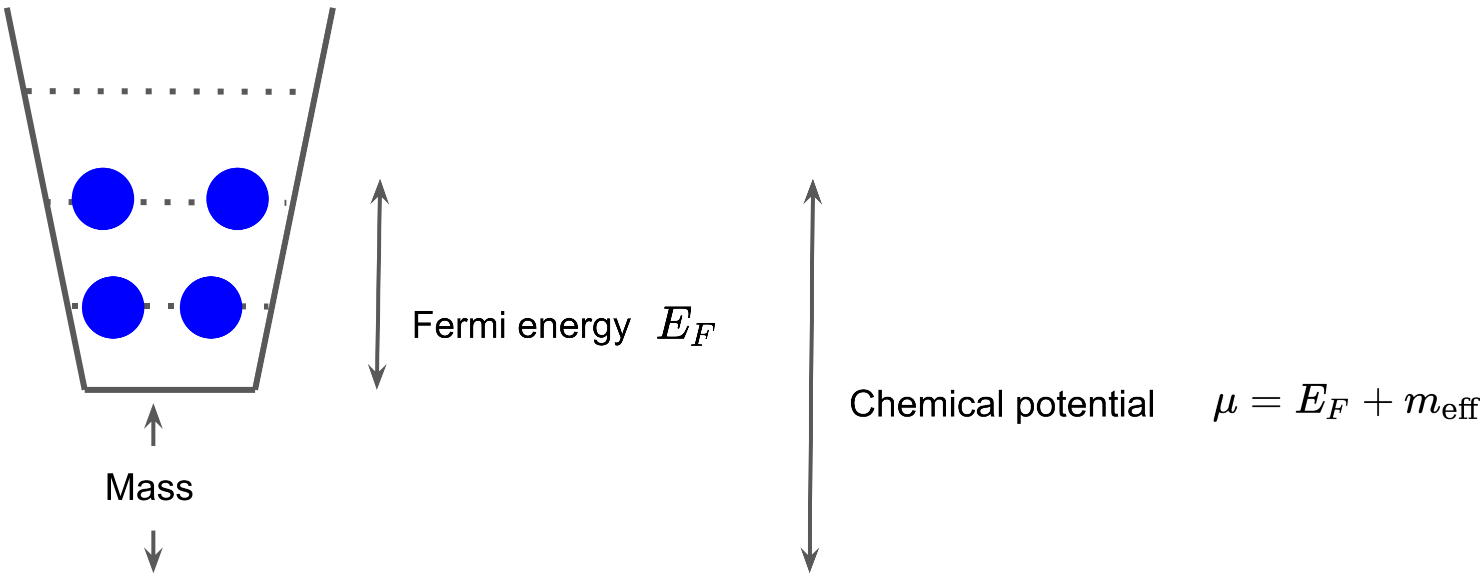


Neutron stars (NS)

Composition

- As density increases, so does the Fermi energy and chemical potential.

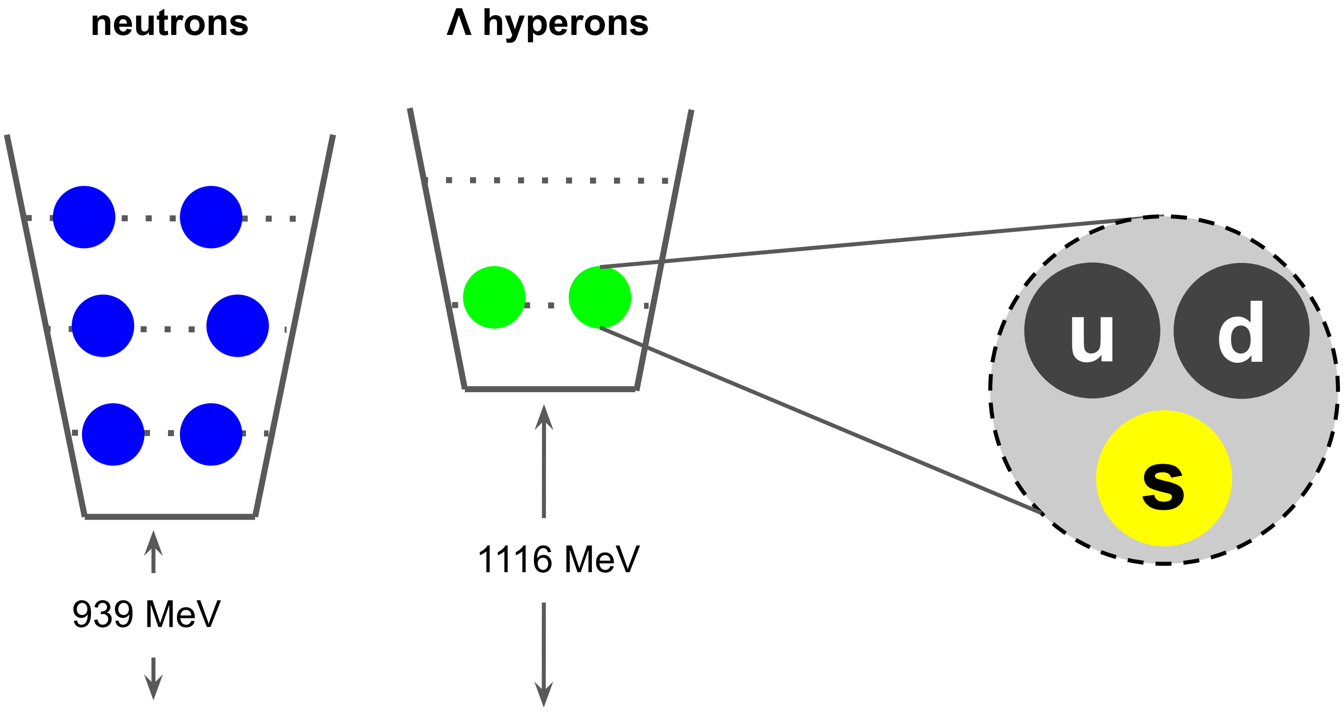
neutrons



Neutron stars (NS)

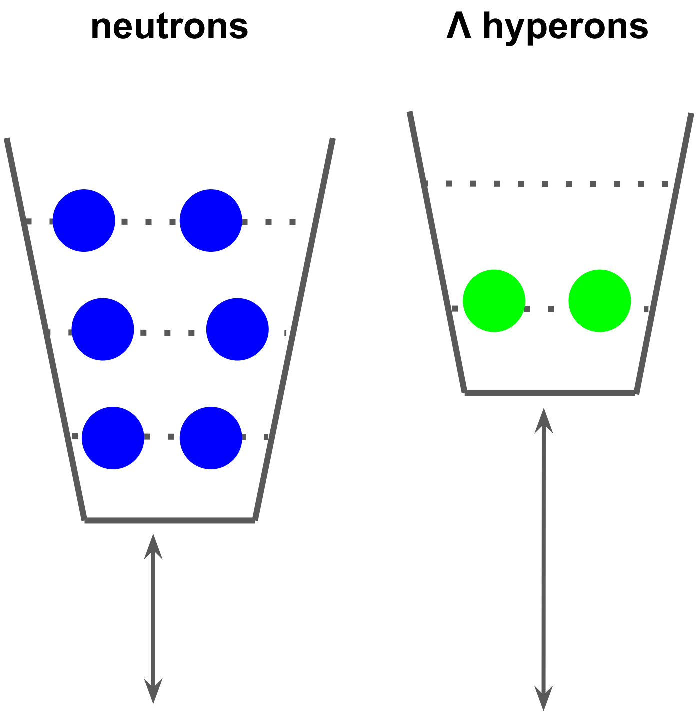
Composition

- As density increases, so does the Fermi energy and chemical potential.
- It might become **possible to form hyperons.**



Neutron stars (NS)

Composition



- As density increases, so does the Fermi energy and chemical potential.
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- Their effective **in-medium mass depends on the interaction** with the surrounding particles.

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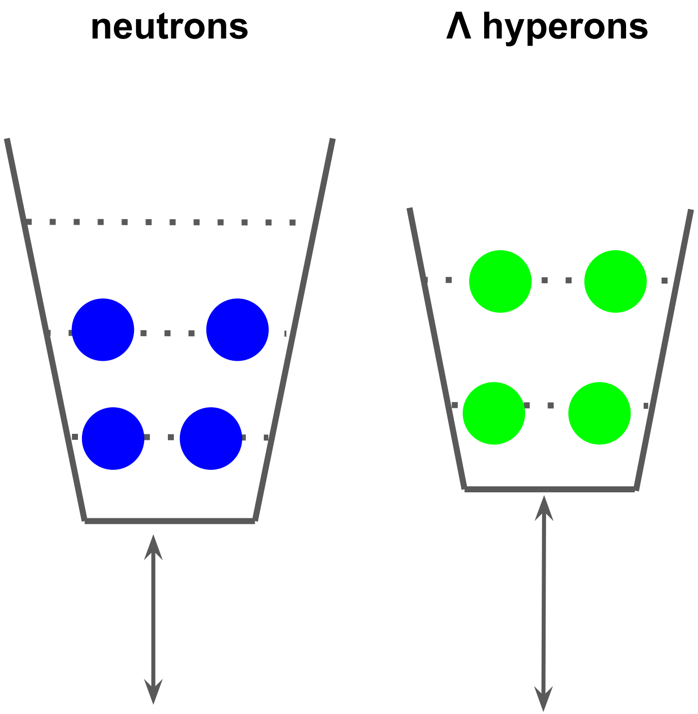
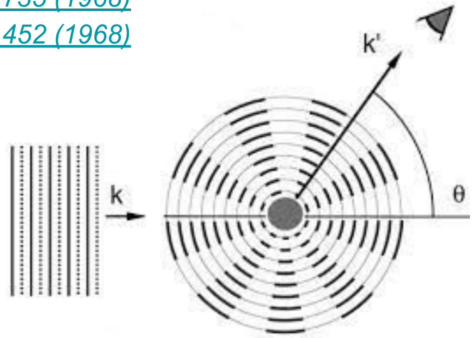


- As density increases, so does the Fermi energy and chemical potential.
- It might become **possible to form hyperons.**
- Their effective **in-medium mass depends on the interaction** with the surrounding particles.
- For the **attractive NΛ interaction**, more Λ formation.
  Known from e.g. scattering experiments

  Phys. Rev. 175, 1735 (1968)
  Phys. Rev. 173, 1452 (1968)



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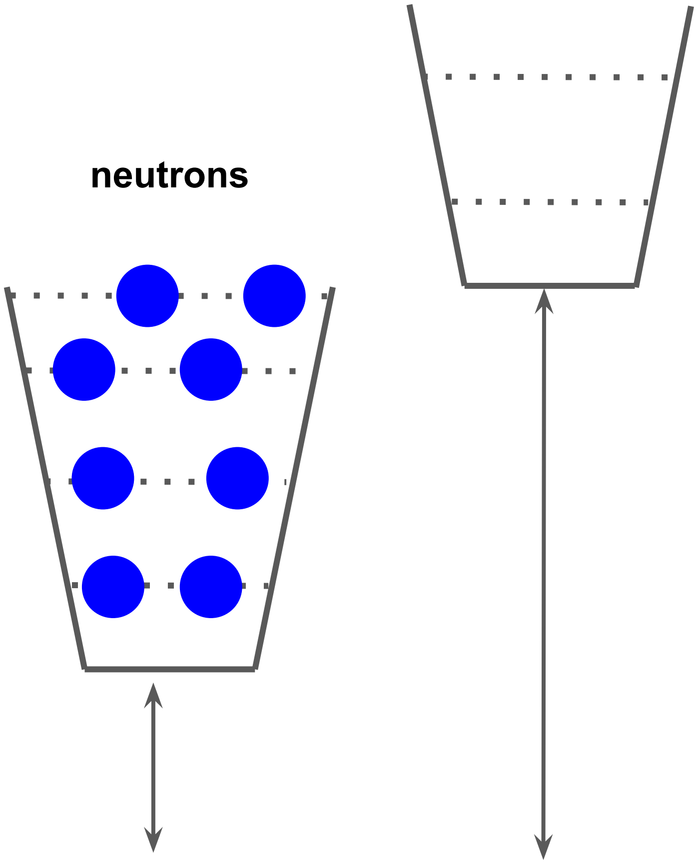
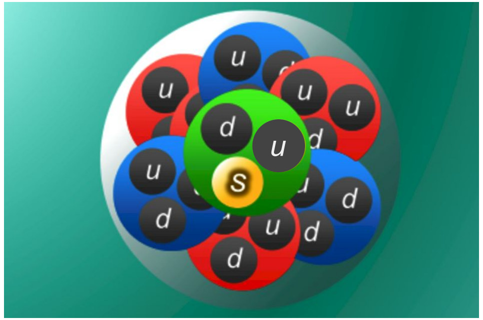


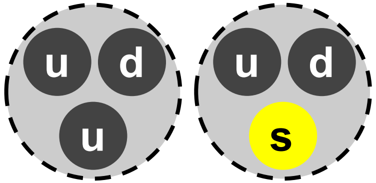
- As density increases, so does the Fermi energy and chemical potential.
- It might become **possible to form hyperons.**
- Their effective **in-medium mass depends on the interaction** with the surrounding particles.
- Any repulsion, e.g. due to many- (three-) body forces, may prohibit their formation.
  In agreement with hypernuclei experiments



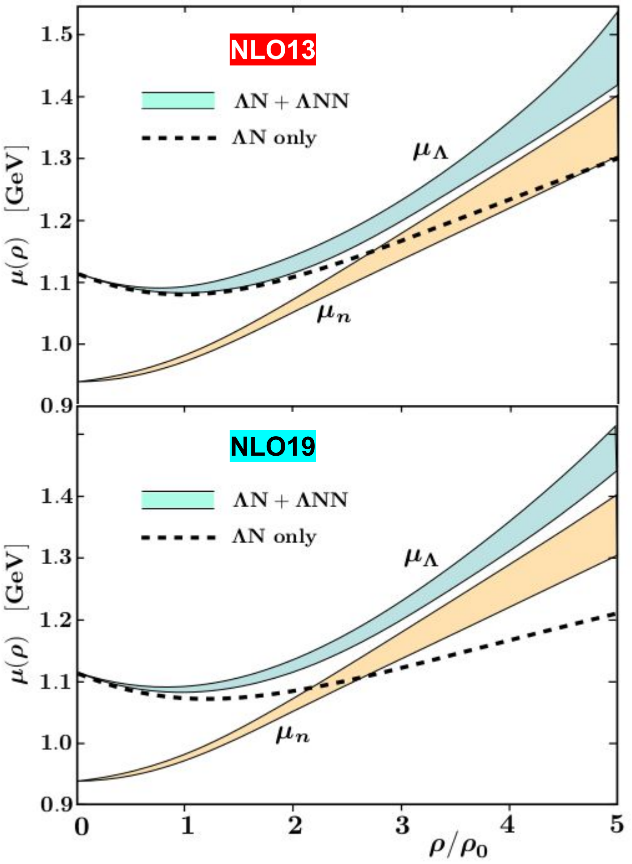
Prog. Part. Nucl. Phys., 57:564–653, 2006

pΛ interaction

Chiral effective field theory (χEFT)



Wed-II: Wolfram Weise



- The Next-to-Leading Order (NLO) calculation can be fine tuned to reproduce existing data using different parameters.
  Wed-I: Johann Haidenbauer

Eur.Phys.J.A 56 (2020) 6, 175

pΛ interaction

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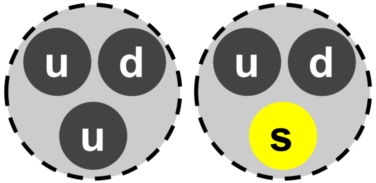

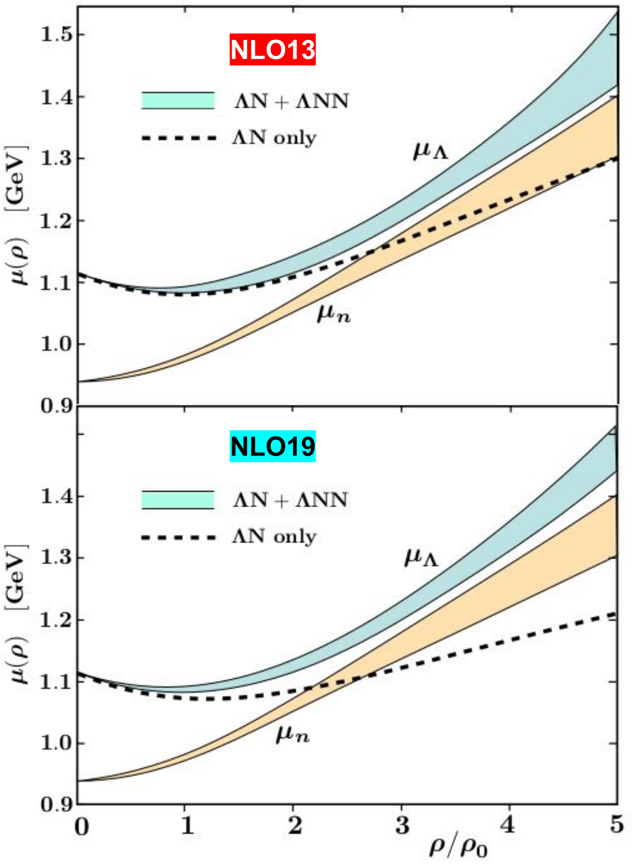

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- NLO13 has slightly stronger 2-body attraction in vacuum.
  NLO19 leads to stronger 3-body repulsion in-medium.

- Within this model, Λs cannot form inside neutron stars!
  This will explain the existence of measured massive neutron stars (M > 2 M☉).

Eur.Phys.J.A 56 (2020) 6, 175

pΛ interaction

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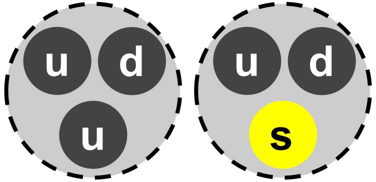

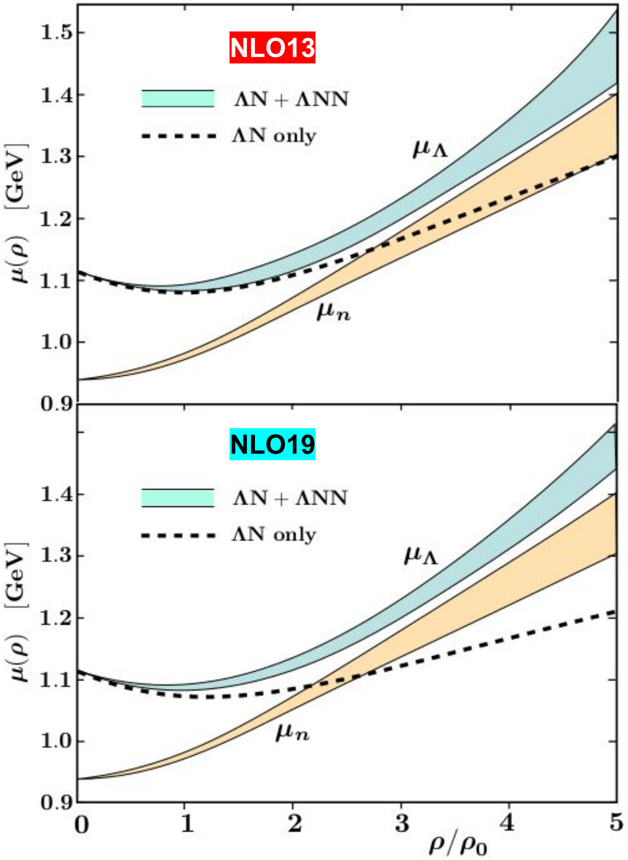

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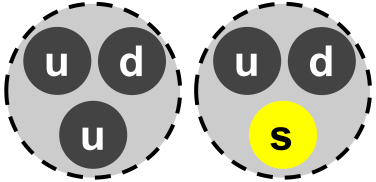
- Within this model, Λs cannot form inside neutron stars!
  This will explain the existence of measured massive neutron stars (M > 2 M⊙).

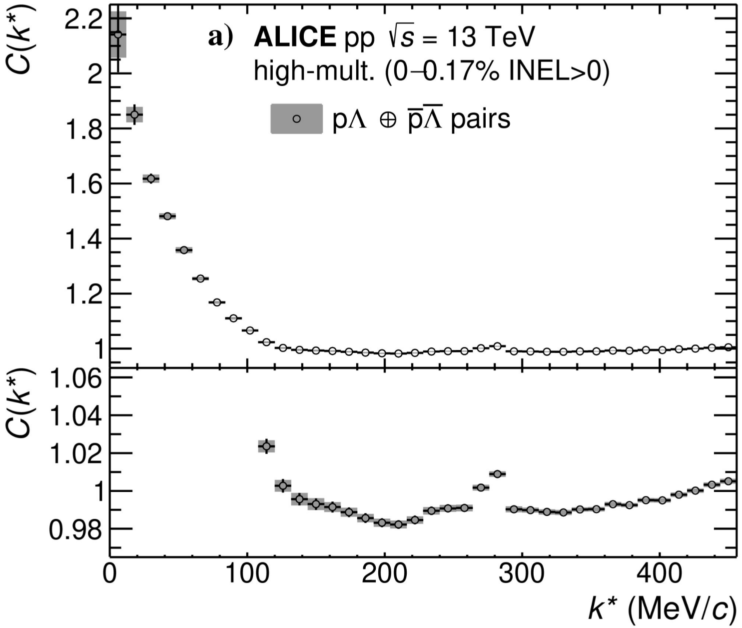
- **Experimental data is needed for both the 2-body and 3-body interaction** to obtain any quantitative conclusions.
  Tue-II: Koji Miwa
  Tue-II: Nick Zachariou

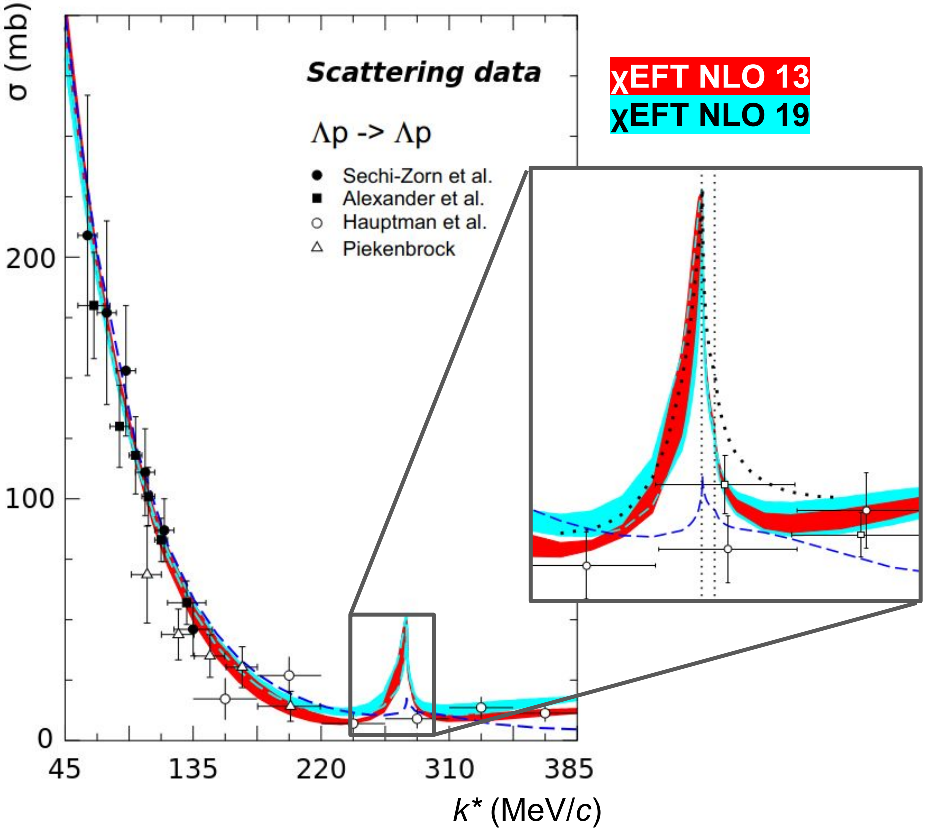
Eur.Phys.J.A 56 (2020) 6, 175

pΛ interaction

The femto era begins!



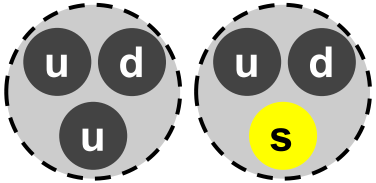


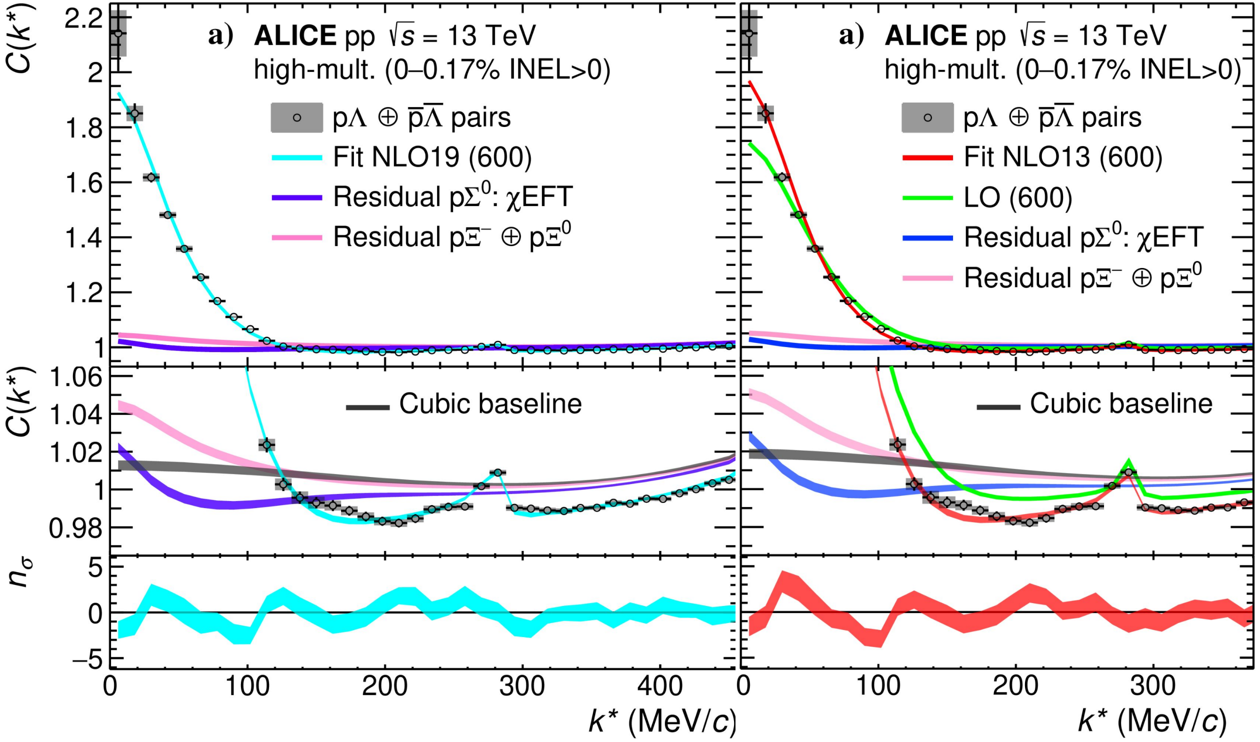


Based on arXiv:2104.04427, accepted by PLB

Eur.Phys.J.A 56 (2020) 3, 91

pΛ interaction
Results





- Observation of the **NΛ↔NΣ cusp.**
- Superior **precision at low momenta** over existing data.

Based on arXiv:2104.04427, accepted by PLB

pΛ interaction

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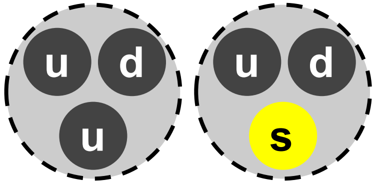
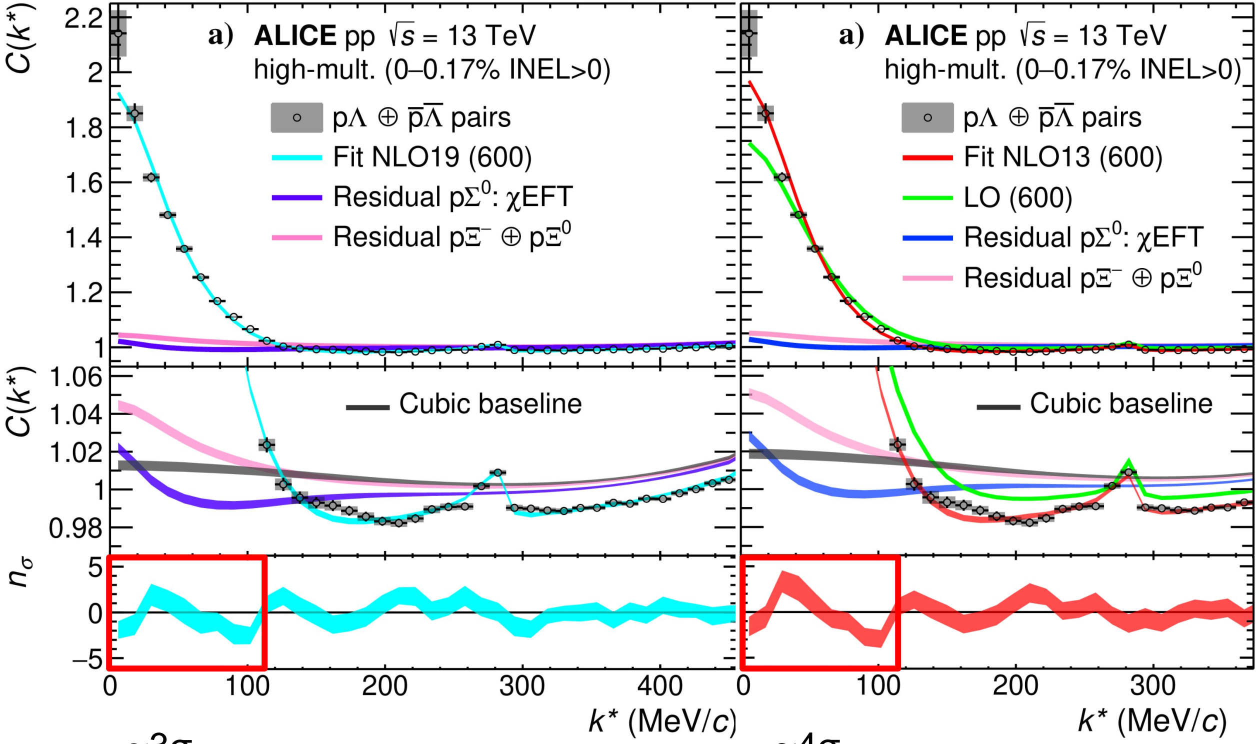




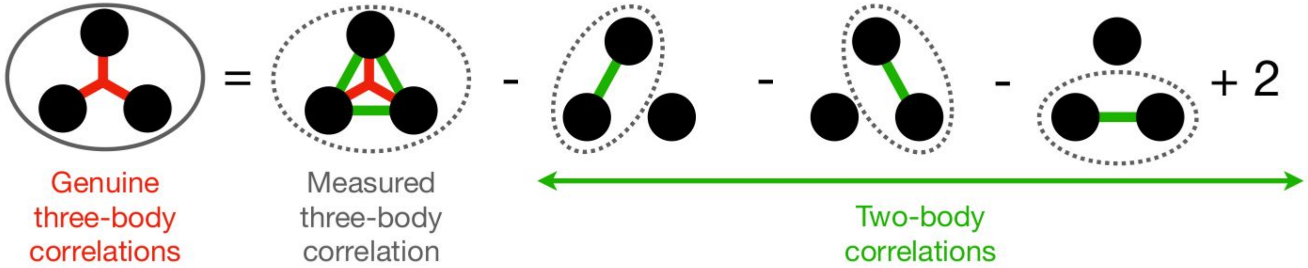
~3σ ~4σ

- Observation of the **NΛ↔NΣ cusp.**
- Superior **precision at low momenta** over existing data.
- Preference towards the NLO19.
  Differences in the coupling to NΣ, and in the interplay between two- and three-body forces. Important for the equation of state.
- NLO19 deviates by ~3σ at low k*.
  Further improvement of the model is possible!

Based on arXiv:2104.04427, accepted by PLB

ppΛ three-body interaction

Going into the future



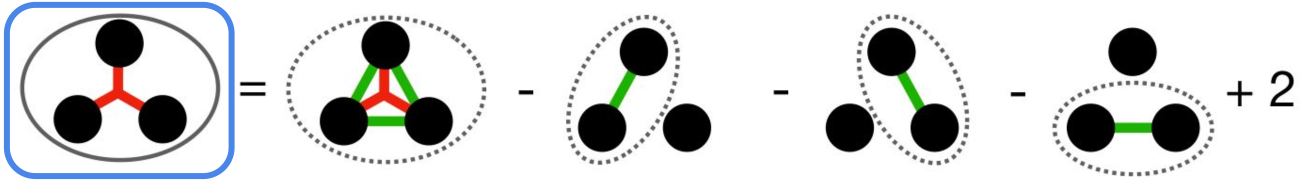
Kubo's **cumulant** expansion method to extract the **genuine 3-body** interaction

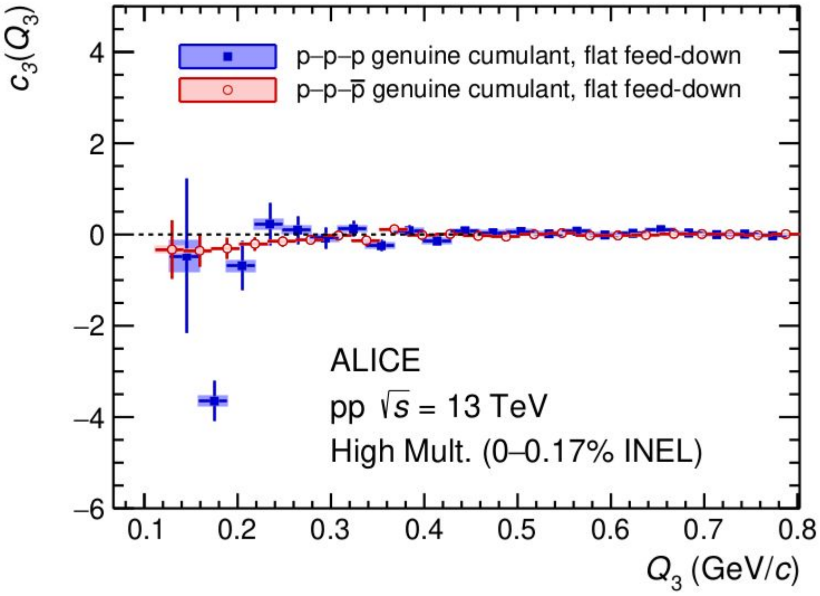
J. Phys. Soc. Jpn. 17, pp. 1100-1120 (1962)

Wed-II: Laura Šerkšnytė

ppΛ three-body interaction

Going into the future





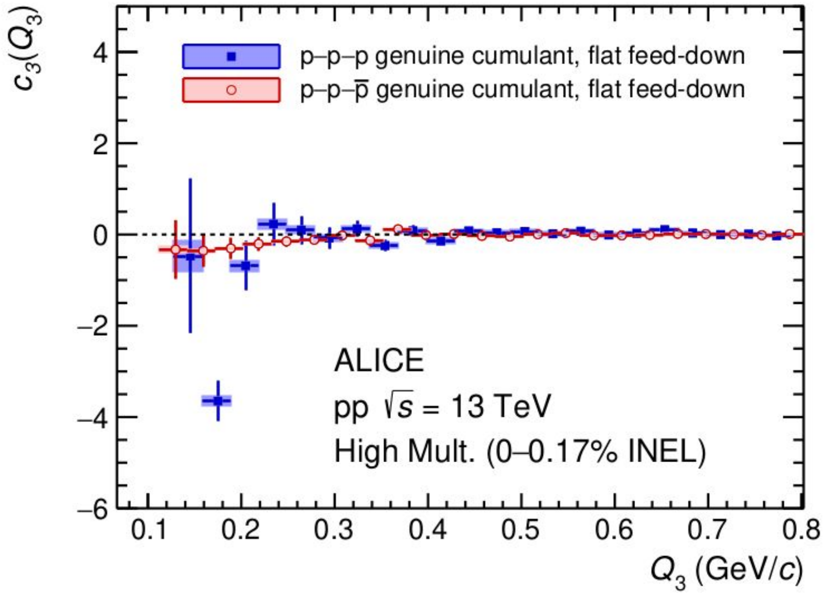
Wed-II: Laura Šerkšnytė

arXiv:2206.03344

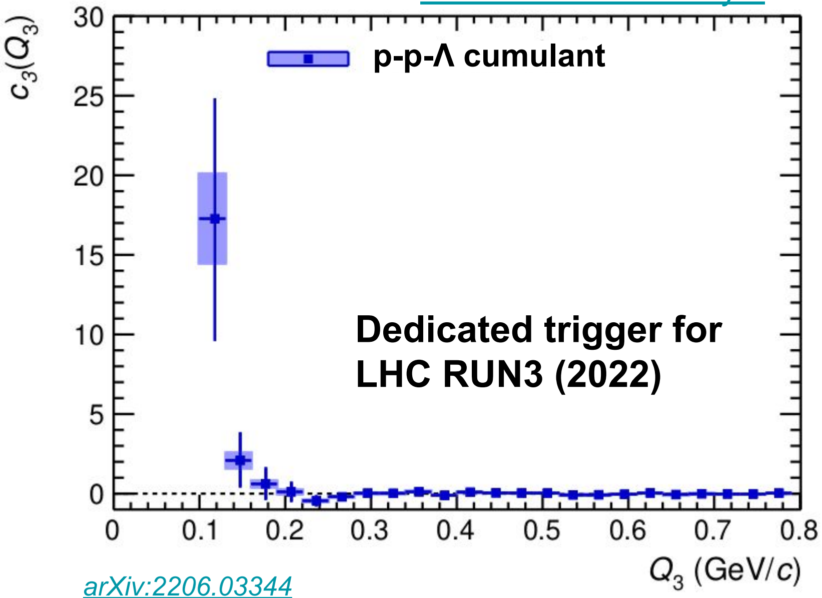
ppΛ three-body interaction

Going into the future

- Clear three body effect in ppp, in contrast to pp$\bar{p}$.
- No significant deviation from zero.



Wed-II: Laura Šerkšnytė



arXiv:2206.03344

Outline

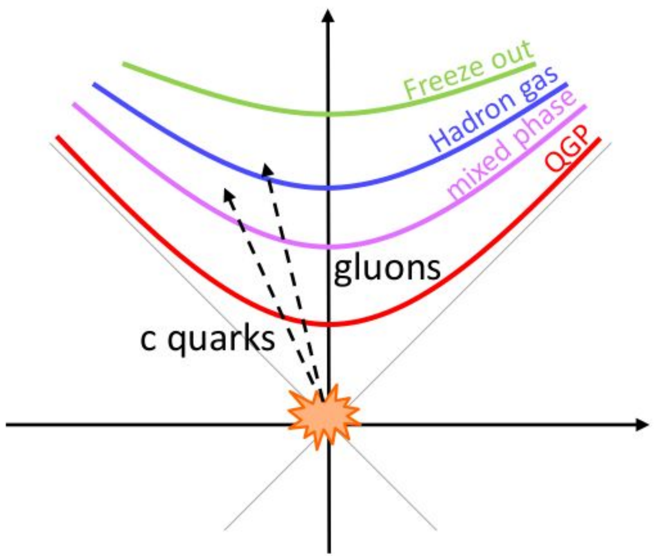
[Poster: Daniel Battistini]

Charming

D π

D p

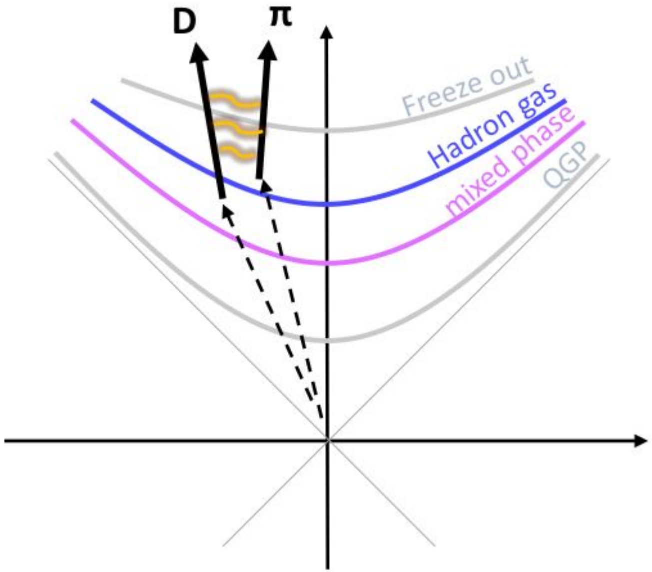
Charm - light hadron interaction
Motivation



- Charm quarks: in heavy ion collisions, produced before the formation of the quark-gluon plasma (QGP).
  ➪ **Ideal probes of the QGP**

Charm - light hadron interaction

Motivation

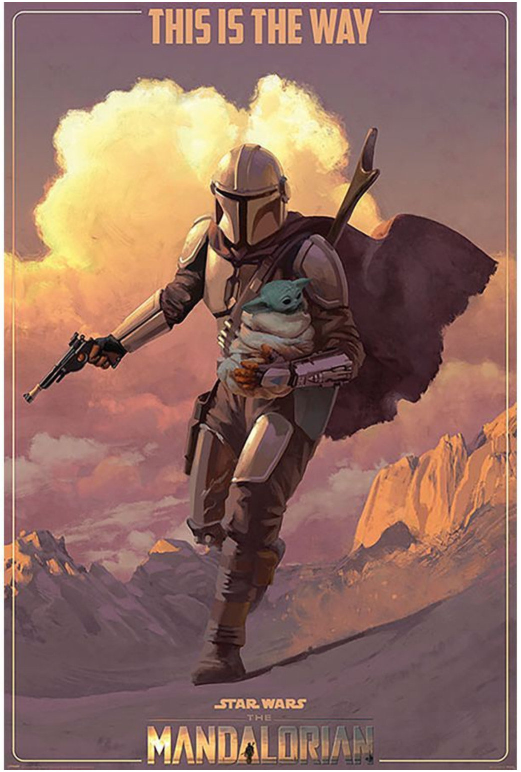


- Charm quarks: in heavy ion collisions, produced before the formation of the quark-gluon plasma (QGP).
  ➪ **Ideal probes of the QGP**

- After hadronization, charm hadrons still interact with the light hadrons, which has to be accounted for.
  ➪ **No experimental constraints**

Charm - light hadron interaction

Femtoscopy is the way



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  ➪ **Ideal probes of the QGP**

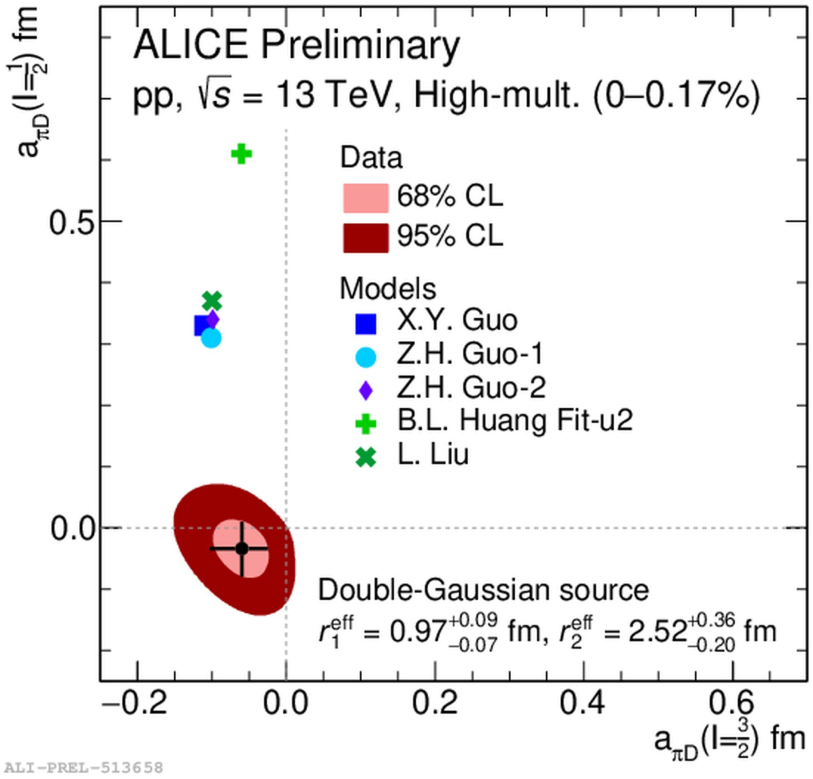
- After hadronization, charm hadrons still interact with the light hadrons, which has to be accounted for.
  ➪ **No experimental constraints**

- **Lednický model:**
  Relate the correlation function to the scattering parameters.
  Sov. J. Nucl. Phys., 35:770, 1982

Charm - light hadron interaction

D - π

Poster: Daniel Battistini



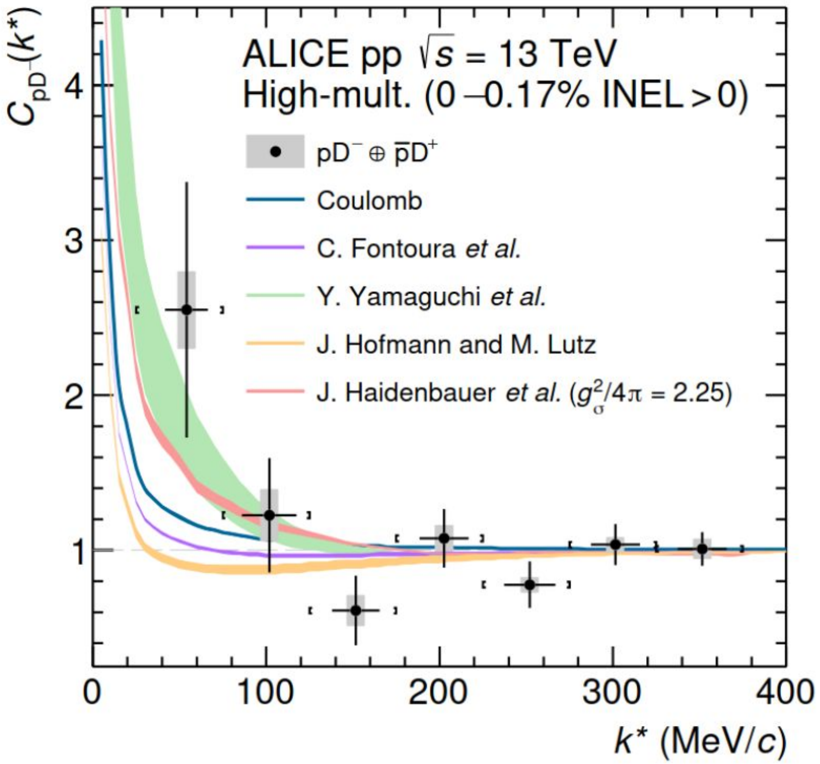
- Simultaneous analysis of π^+D^+ (I=1/2) and π^+D^- (67% I=1/2 and 33% I=3/2).
- Scattering length for I=3/2 in agreement with lattice calculations.
- Scattering length for I=1/2 significantly smaller than lattice calculations.

L. Liu et al, Phys. Rev. D87 (2013) 014508
X.-Y. Guo et al, Phys. Rev. D 98 (2018) 014510
B.-L. Huang et al, Phys. Rev. D 105 (2022) 036016
Z.-H. Guo et al Eur. Phys. J. C (2019) 79:13

Charm - light hadron interaction

D - p

[Poster: Daniel Battistini](), [arXiv: 2201.05352]()



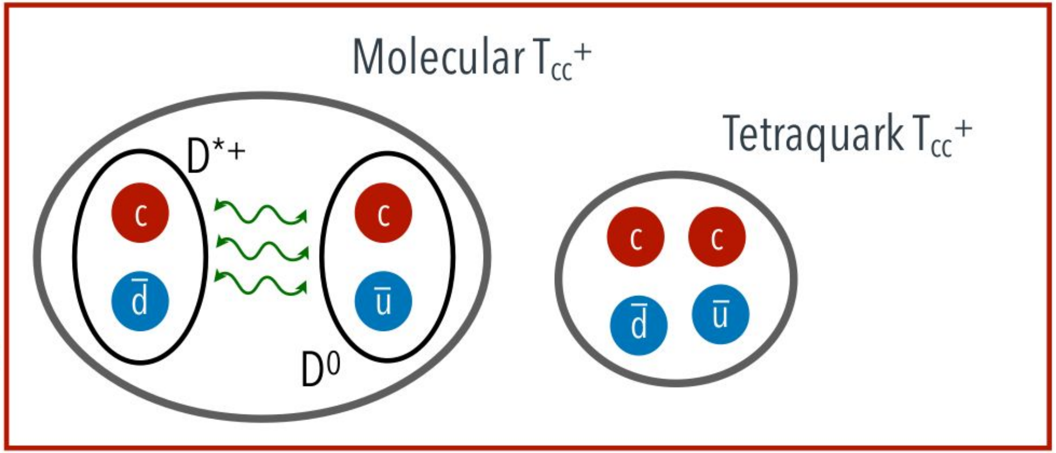
- Compatible with Coulomb only.
- Preference towards models with attractive, perhaps binding, strong interaction.
- To be clarified with LHC RUN3 data!

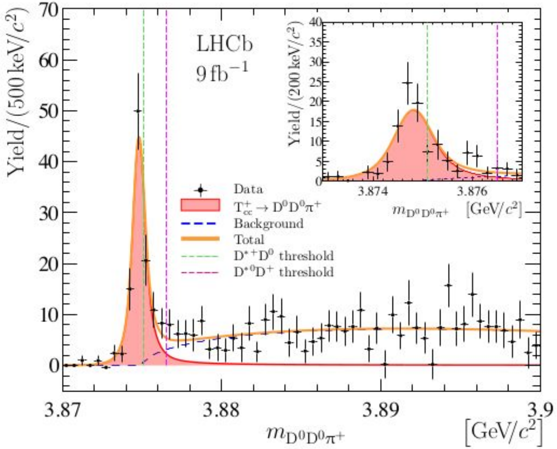
The future is charming

- Charm molecules?

System	I ($J^{P(C)}$)	Candidate
np	0 (1^+)	deuteron
ND	0 ($1/2^-$)	$\Lambda_c(2765)$
ND*	0 ($3/2^-$)	$\Lambda_c(2940)$
ND	0 ($1/2^-$)	$\Sigma_c(2800)$
$D^*\bar{D}$	0 (1^{++})	X(3872)
D*D	0 (1^+)	T_{cc}
$D_1\bar{D}$	0 (1^{--})	Y(4260)
$D_1\bar{D}^*$	0 (1^{--})	Y(4360)
$\Sigma\bar{D}$	1/2 ($1/2^-$)	$P_c(4312)$
$\Sigma\bar{D}^*$	1/2 ($1/2^-$)	$P_c(4457)$
$\Sigma\bar{D}^*$	1/2 ($3/2^-$)	$P_c(4440)$

Peng et al, Phys. Rev. D 105, 034028 (2022)





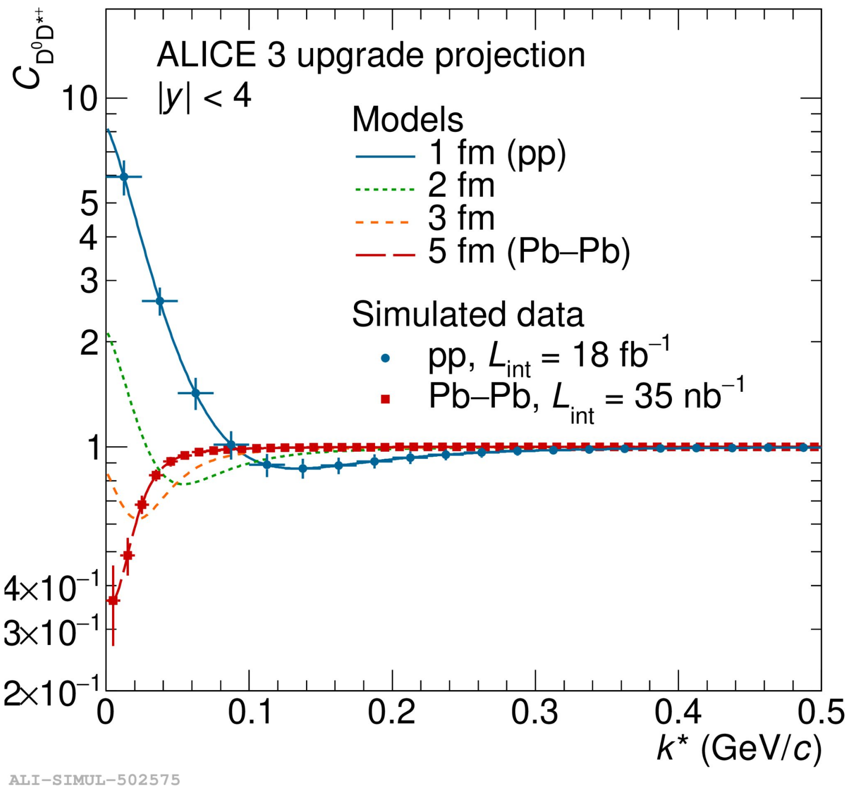
- Just below the D*D threshold **Ideal candidate to be a molecular state**

LHCb: arXiv:2109.01038

The future is charming

- Charm molecules?

ALICE3 LOI: CERN-LHCC-2022-009



- ALICE 3: large acceptance, high luminosity, excellent spatial resolution.
- Run 5: ideal laboratory for the measurement of charm-hadron momentum correlations in different colliding systems.
- Source size dependent modification of the correlation function in presence of a bound state.
  Wed-I: Yuki Kamiya
  Yuki Kamyia et al, arXiv:2203.13814

Summary

- Particle correlations as a tool to study two- and three-body interactions among any hadrons measured at accelerators.
  Wed-I: Yuki Kamiya, *Wed-II: Laura Šerkšnytė*
- **pΛ and ppΛ measurements** allowing to constrain existing χEFT models, helping to describe the composition of neutron stars.
- Further applications:
  - KN interaction and kaonic bound states
    Wed-II: Laura Šerkšnytė, *Thu-I: Ramona Lea*, *Fri-I: Oton V. Doce*
  - pd correlations
    Wed-III: Bhawani Singh, *Poster: Wioleta Rzesa*
  - Studying multi-strangeness systems
    Wed-IVa: Georgios Mantzaridis
  - **Testing the nature of charm**
    Poster: Daniel Battistini
  - **Great prospects at LHC RUN3 and beyond**

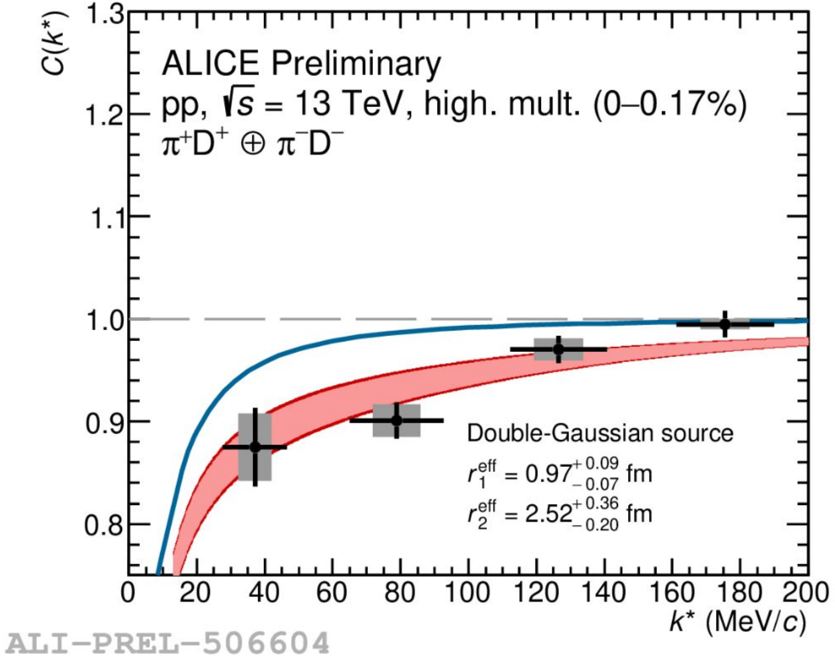
This project has received funding from the Helmholtz Institute Mainz and the European Union's Horizon 2020 research and innovation programme under grant agreement No 824093

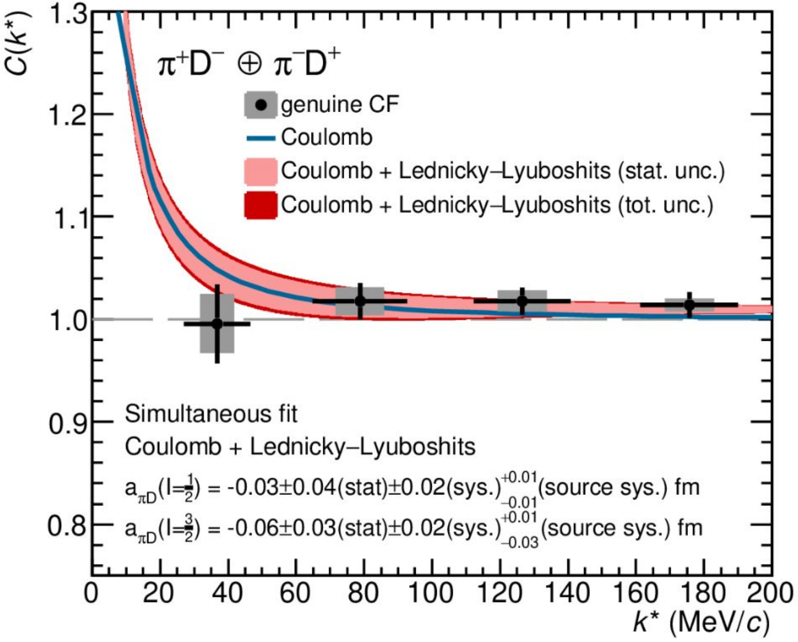
BACKUP

Charm - light hadron interaction

D - π

Poster: Daniel Battistini



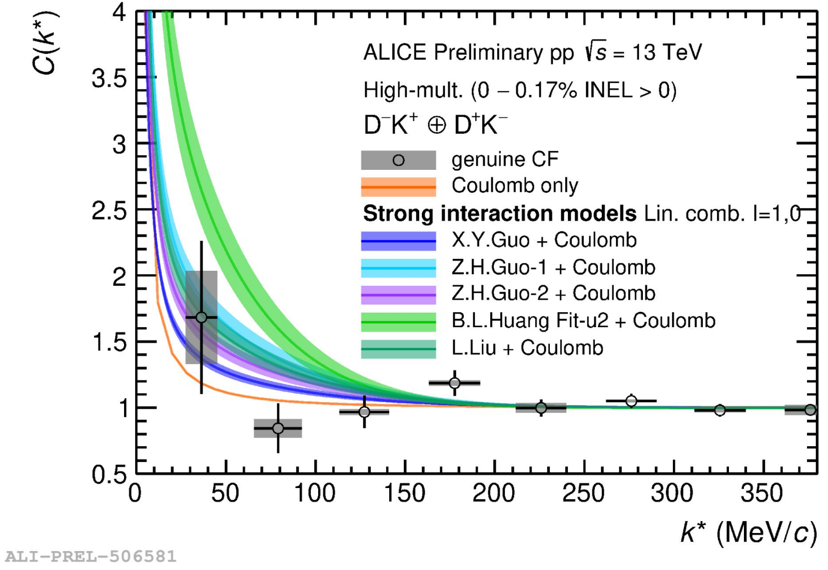


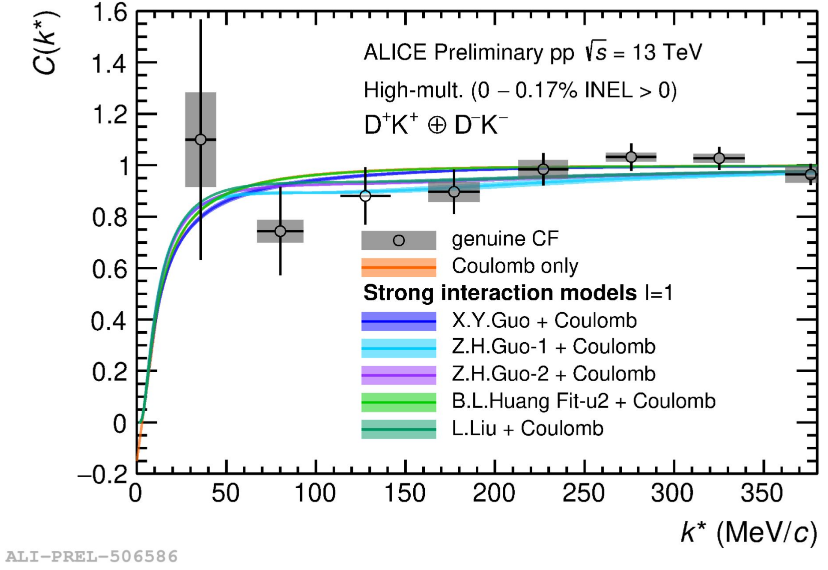
Charm - light hadron interaction

D - K

Poster: Daniel Battistini

L. Liu et al, Phys. Rev. D87 (2013) 014508
X.-Y. Guo et al, Phys. Rev. D 98 (2018) 014510
B.-L. Huang et al, Phys. Rev. D 105 (2022) 036016
Z.-H. Guo et al Eur. Phys. J. C (2019) 79:13



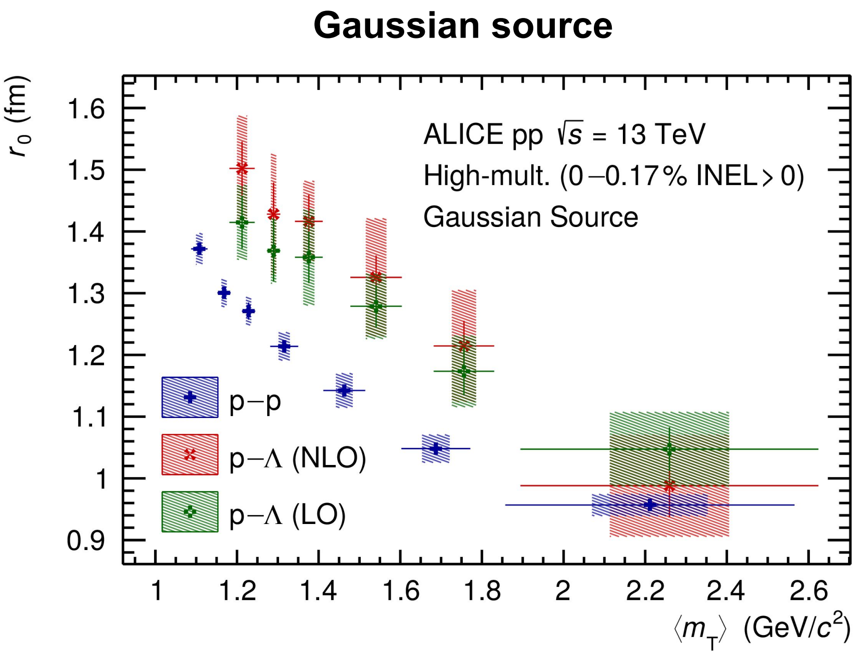


- Statistics is yet insufficient to impose constraints
  To be improved during LHC RUN3

A common source

Gaussian profile

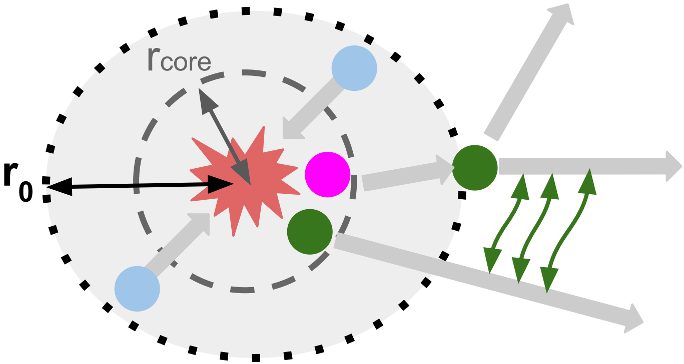
Phys. Lett. B 811 (2020) 135849



- **Different source size** for p-p and p-Λ pairs

- The Statistical Hadronization Model tells us: c.a. ⅔ of protons and Λs stem from resonances. The average lifetimes (cτ) are:
  - 1.6 fm for X→proton
  - 4.7 fm for X→Λ

- **Production through short-lived resonances**

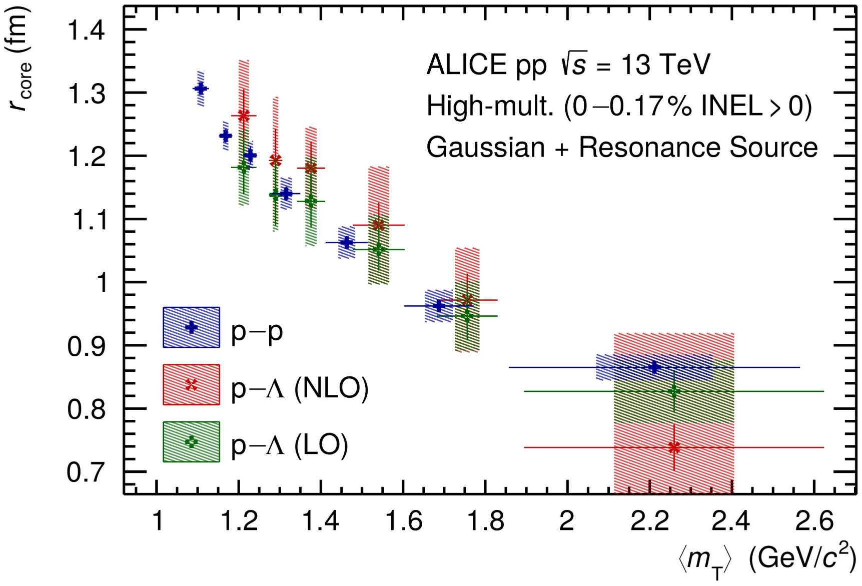


A common source

The numerical "resonance source model"

[*Phys. Lett. B 811 (2020) 135849*]

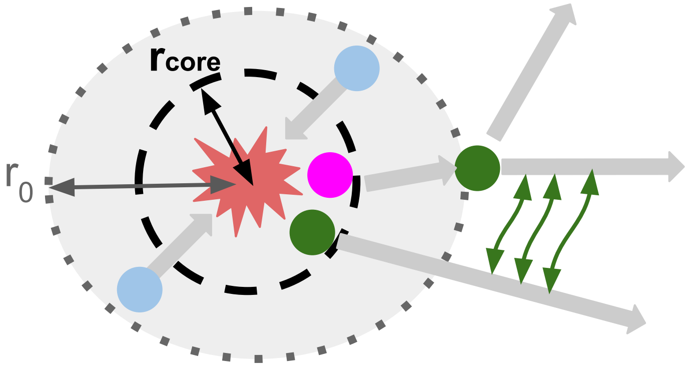
Gaussian core + resonances



- **Common source** for p-p and p-Λ pairs. Ones measured (from p-p), it is fixed for ANY baryon-baryon pair!

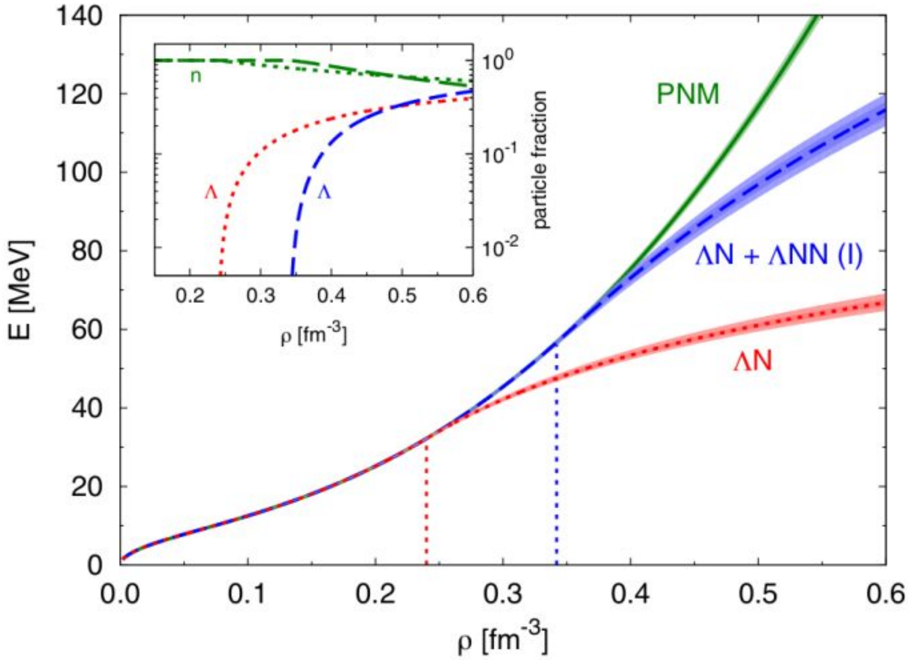
- The Statistical Hadronization Model tells us: c.a. ⅔ of protons and Λs stem from resonances. The average lifetimes (cτ) are:
  - 1.6 fm for X→proton
  - 4.7 fm for X→Λ

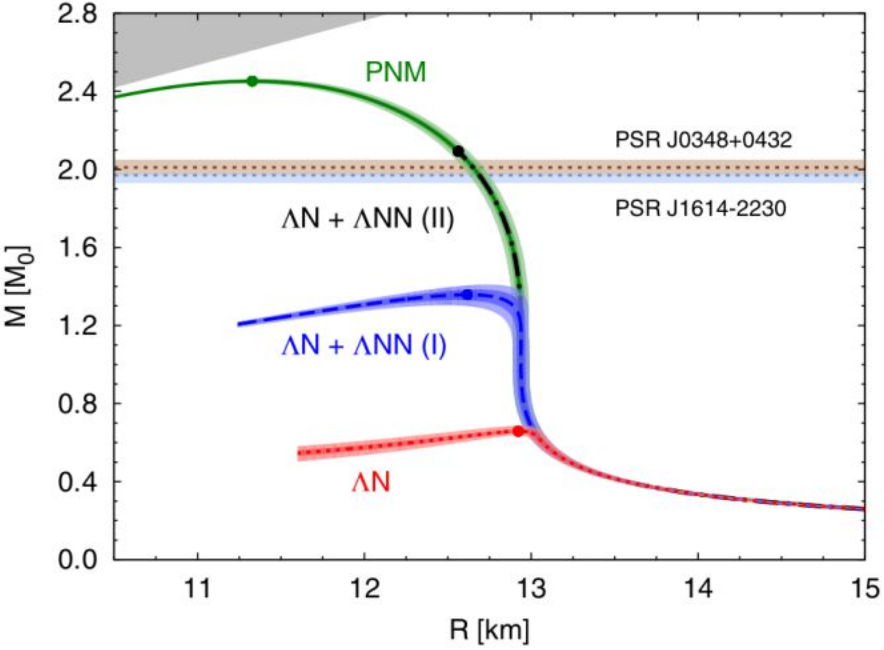
- **Production through short-lived resonances**



Neutron stars (NS)

Nuclear Equation of State (EoS) and Mass-Radius relation



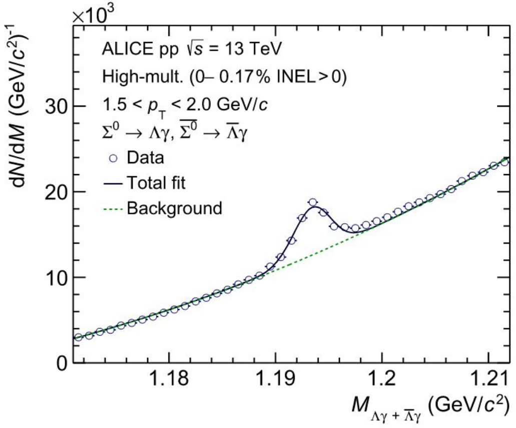


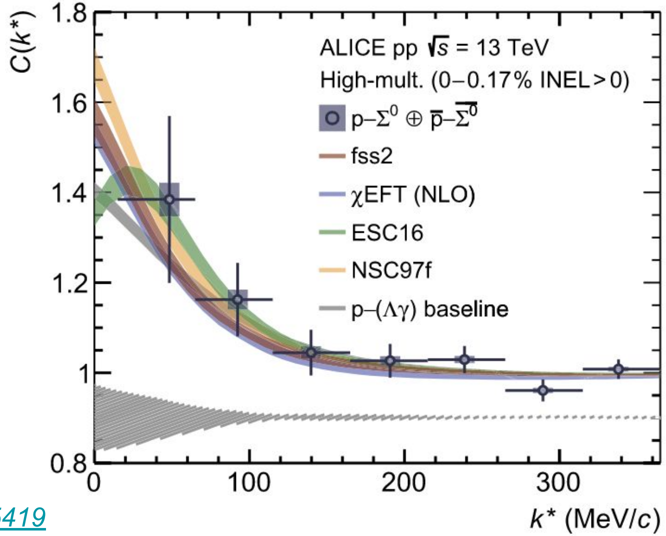
PRL 114 (2015) 9, 092301

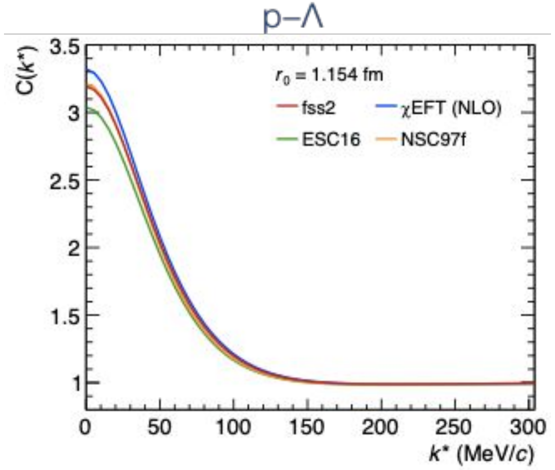
A soft EoS, allowing hyperons within NS, leads to an underprediction of measured NS masses. This is known as the **hyperon puzzle.**

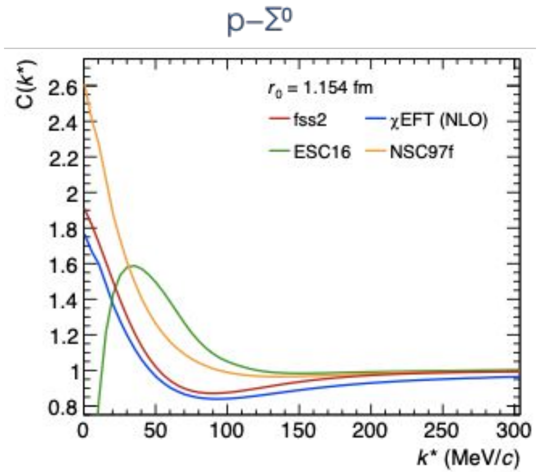
Further applications

$p\Sigma^0$









Phys.Lett.B 805 (2020) 135419

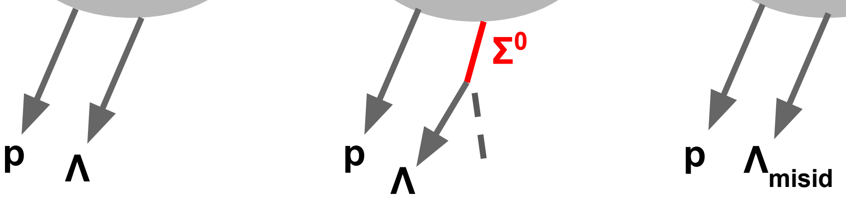
pΛ correlation function

Overview

$$C_{\text{exp}}(k^*) = b(k^*)C_{\text{th}}(k^*) = b(k^*)\sum_i \lambda_i C_{\text{th},i}(k^*)$$

Non-femto baseline

$$\lambda_0 C_{\text{th},0}(k^*) + \lambda_1 C_{\text{th},1}(k^*) + \lambda_2 C_{\text{th},2}(k^*) \cdots$$



Modeled using χEFT

corrected for using a "sideband" analysis

[Phys.Rev. C99 (2019) no.2, 024001](https://doi.org/10.1103/PhysRevC.99.024001)