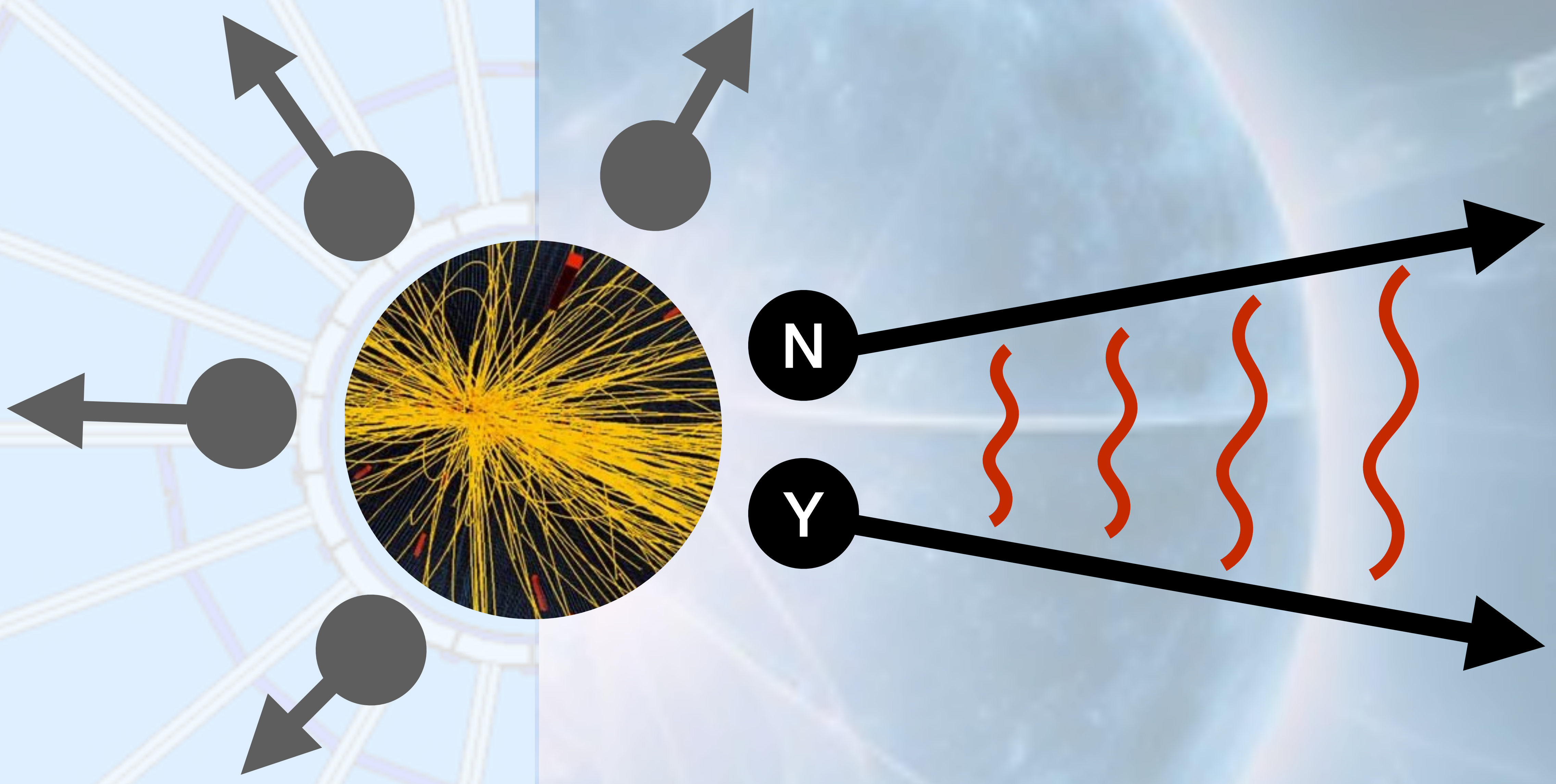
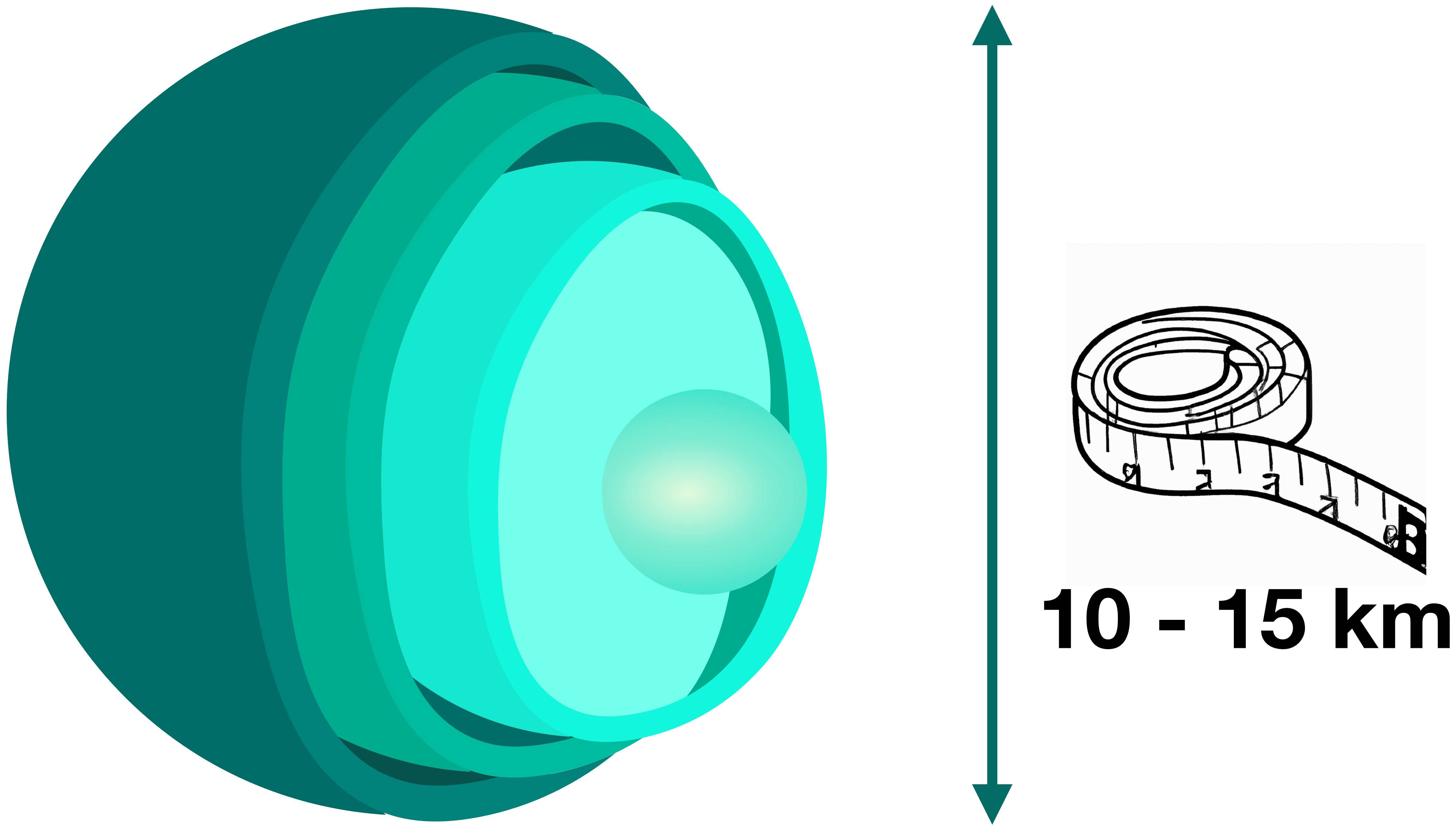
OVERVIEW OF TWO BODY INTERACTIONS WITH STRANGENESS



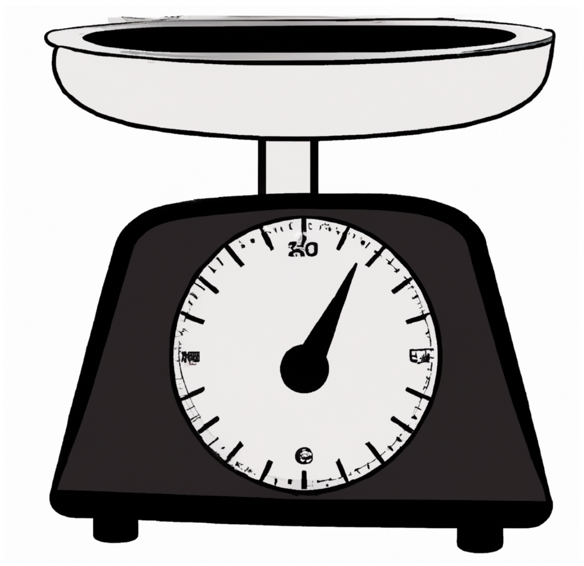
...and their importance for neutron stars

Laura Šerkšnytė
Technical University of Munich
JENAA workshop
19.08.2024 CERN

Neutron stars and strangeness



10 - 15 km



$1.5 - 2.2\ M_{sun}$

- Very dense, compact objects
- At finite densities **hyperon** production might become energetically favourable

Newest results on NS properties:
20 Aug 16:00 Anna Watts (NICER)

Neutron stars and strangeness

- Very dense, compact objects
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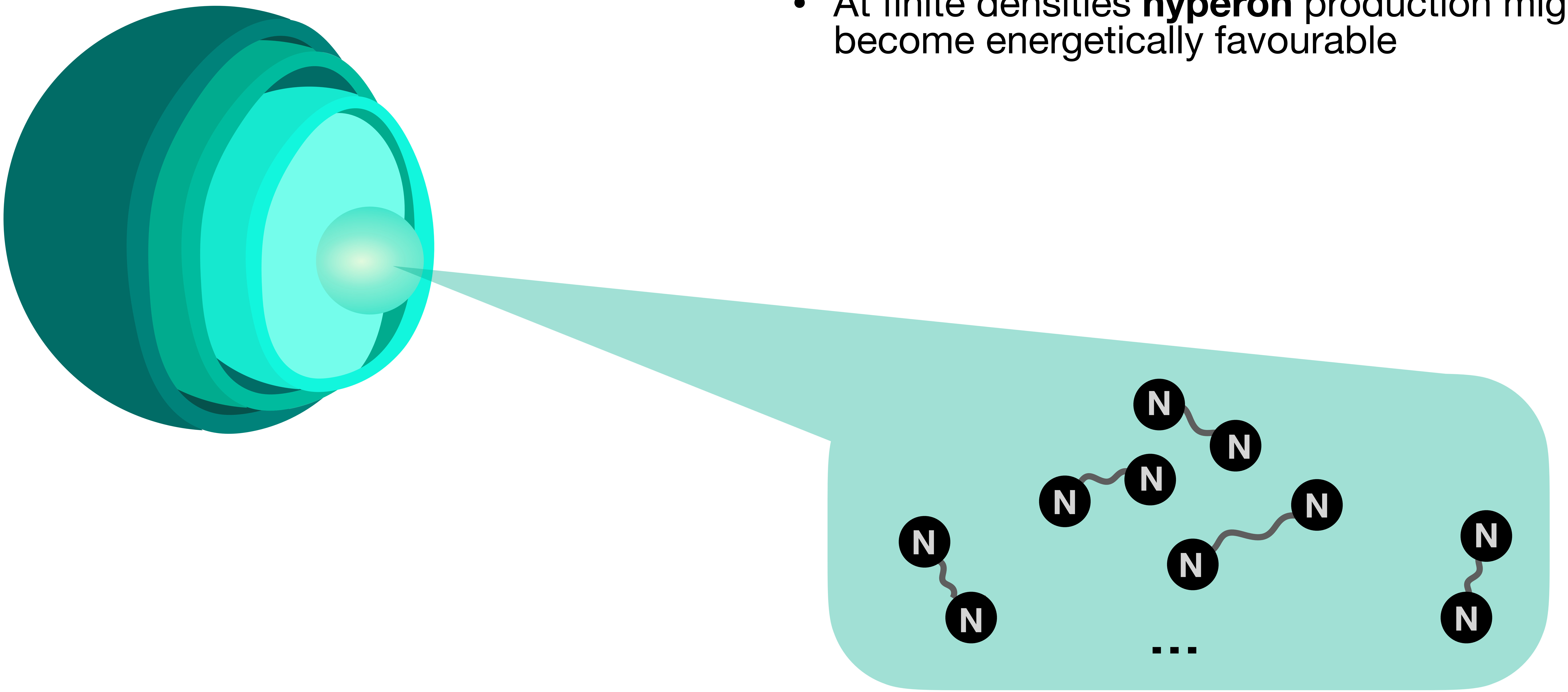

Neutron stars and strangeness

- Very dense, compact objects
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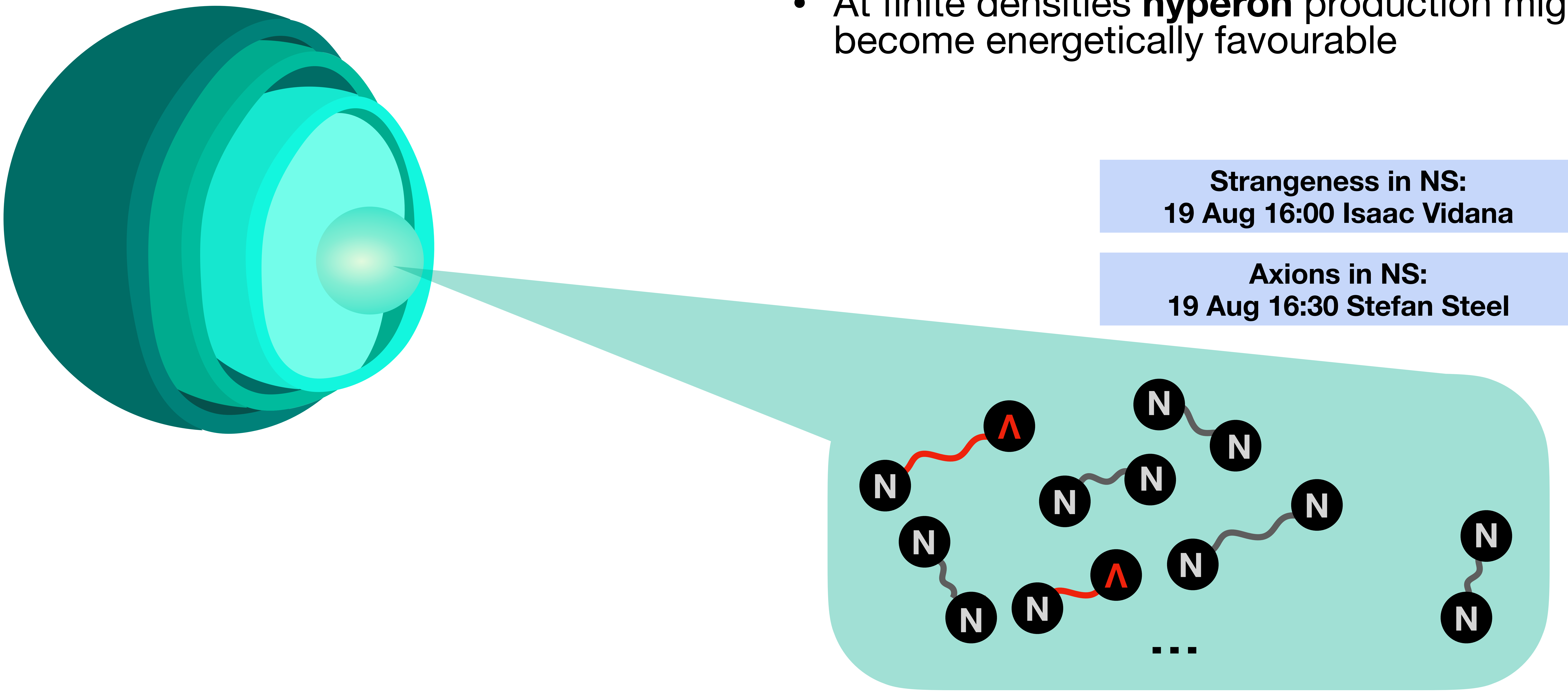
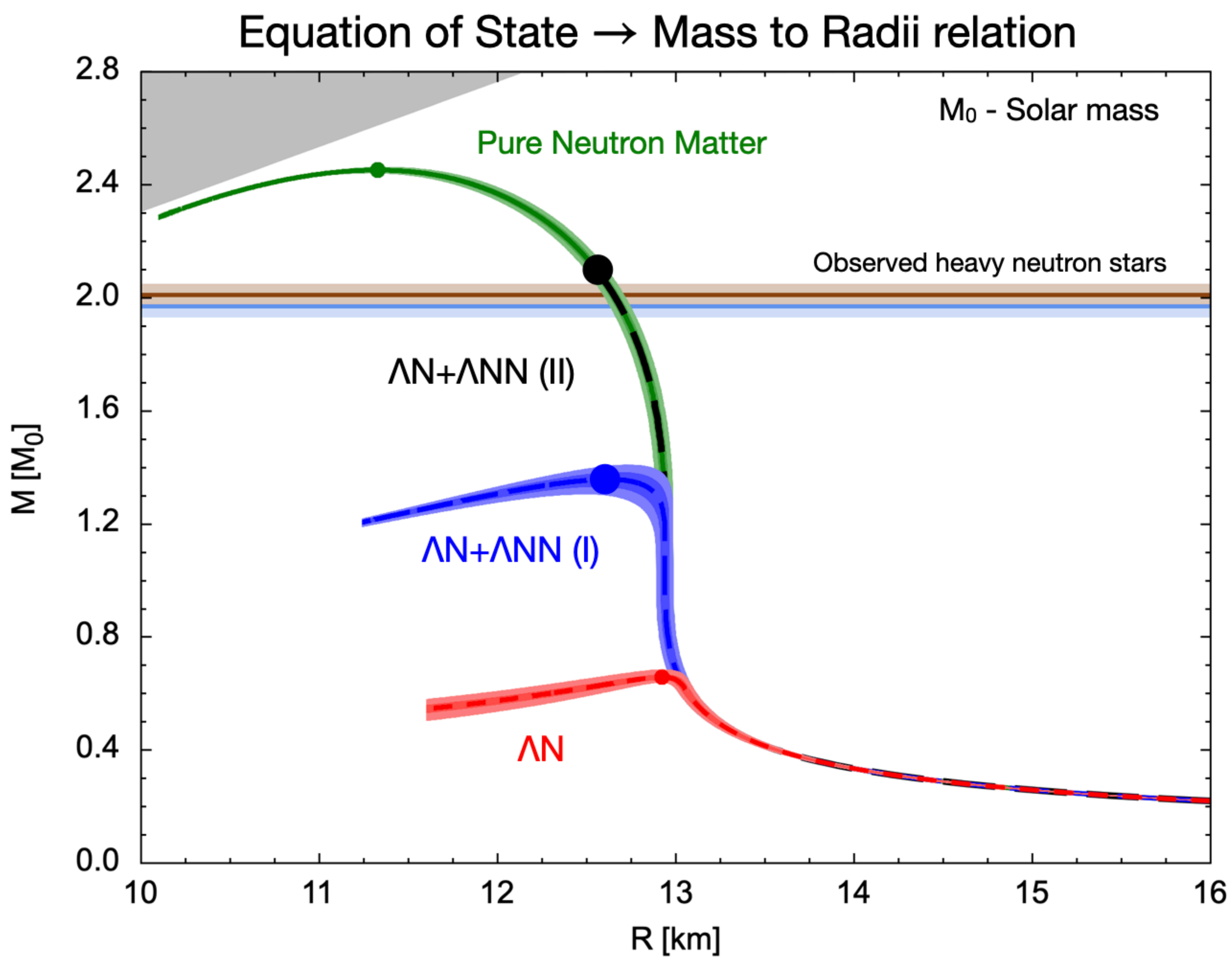
Strangeness in NS:
19 Aug 16:00 Isaac Vidana

Axions in NS:
19 Aug 16:30 Stefan Steel

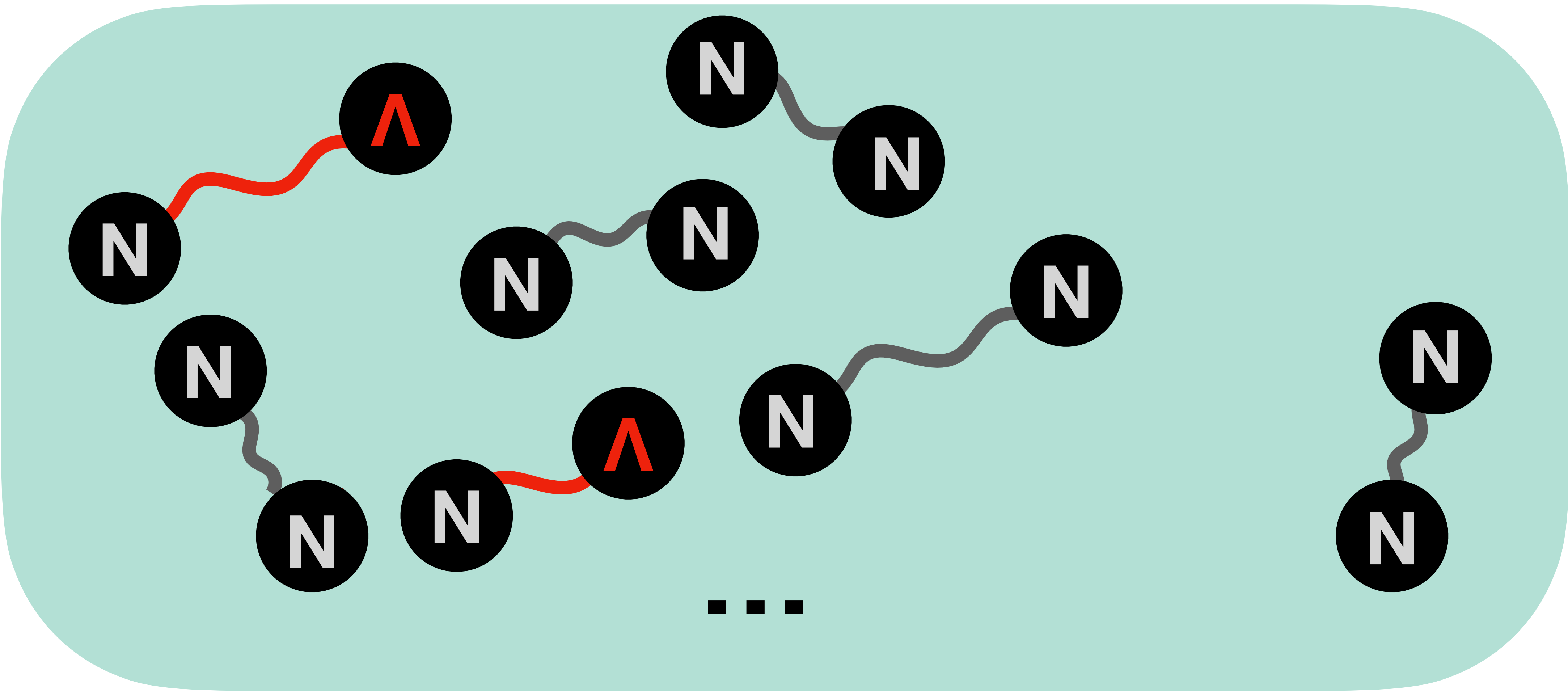


Neutron stars and strangeness

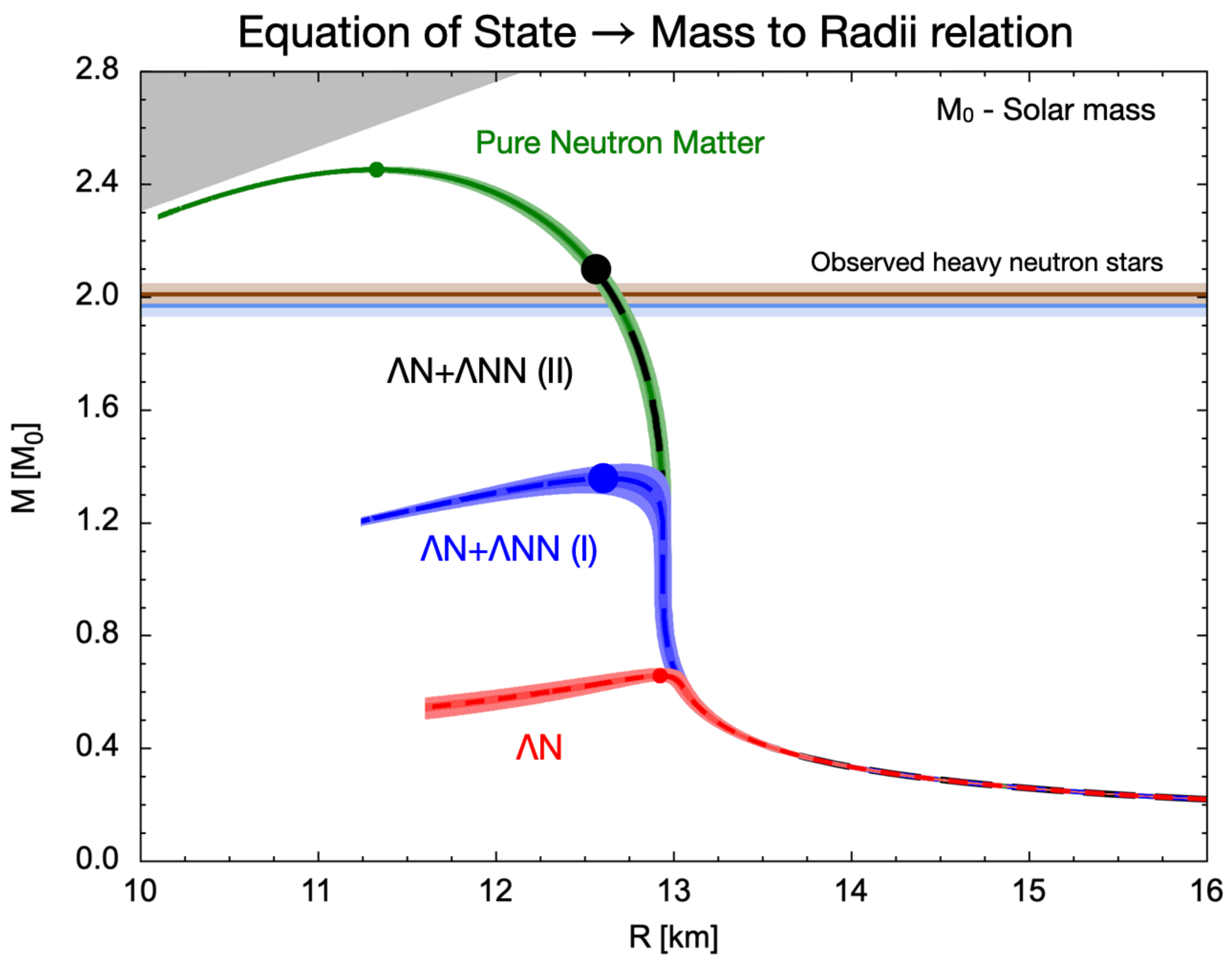


Adapted from D. Lonardoni et al., PRL 114, 092301 (2015)

- Very dense, compact objects
- At finite densities **hyperon** production might become energetically favourable
- Exact composition strongly depends on constituent interactions and couplings



Neutron stars and strangeness



Adapted from D. Lonardoni et al., PRL 114, 092301 (2015)

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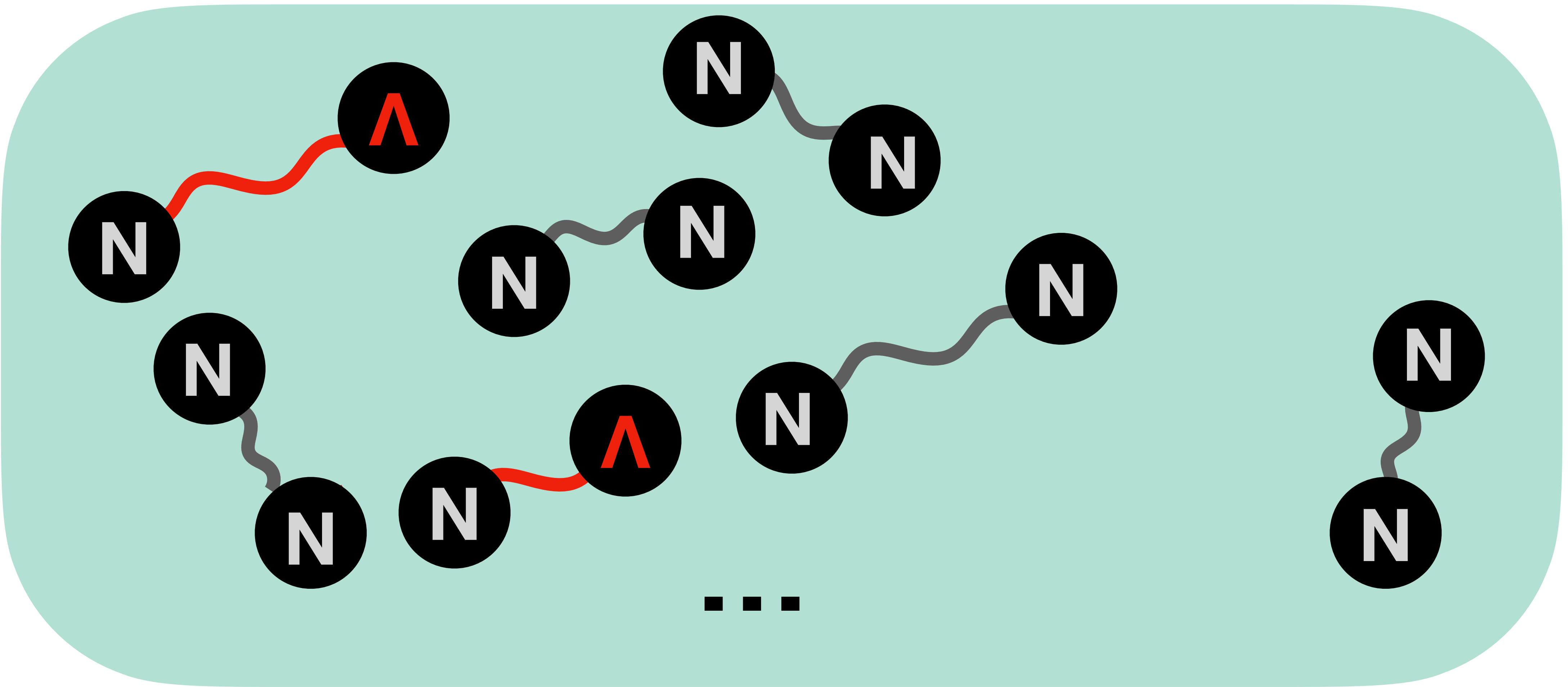
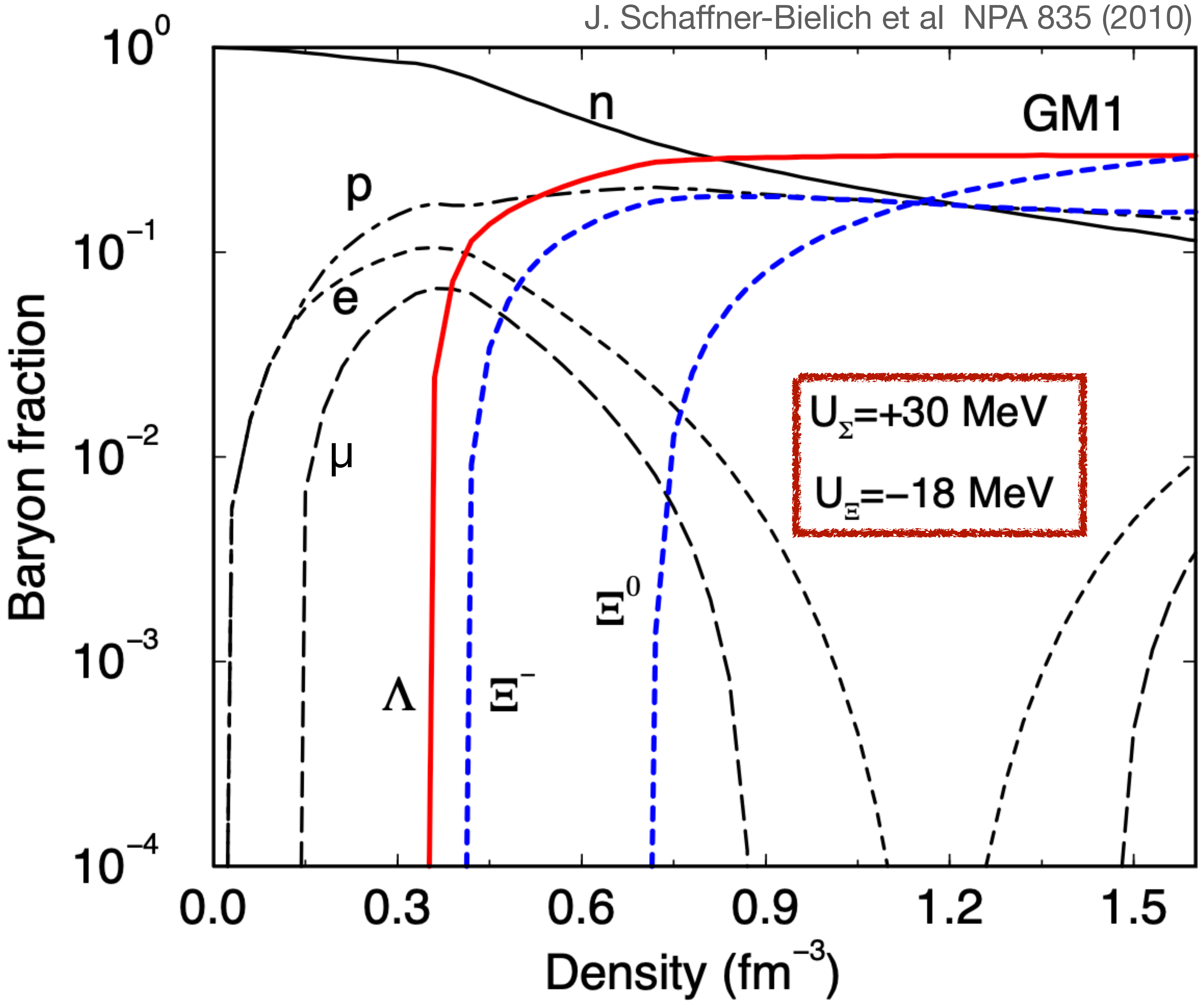
- Exact composition strongly depends on constituent interactions and couplings

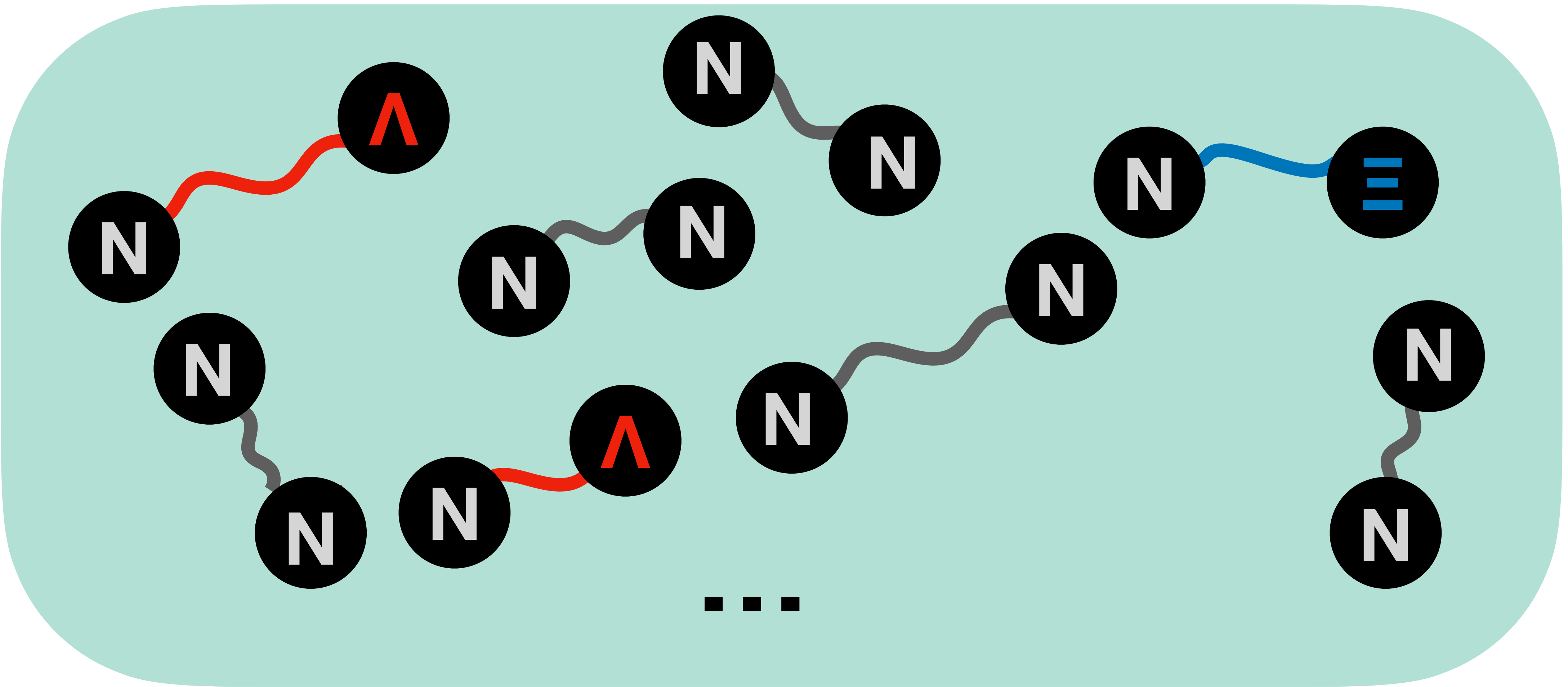
Three-body forces:
19 Aug 14:30 Raffaele Del Grande



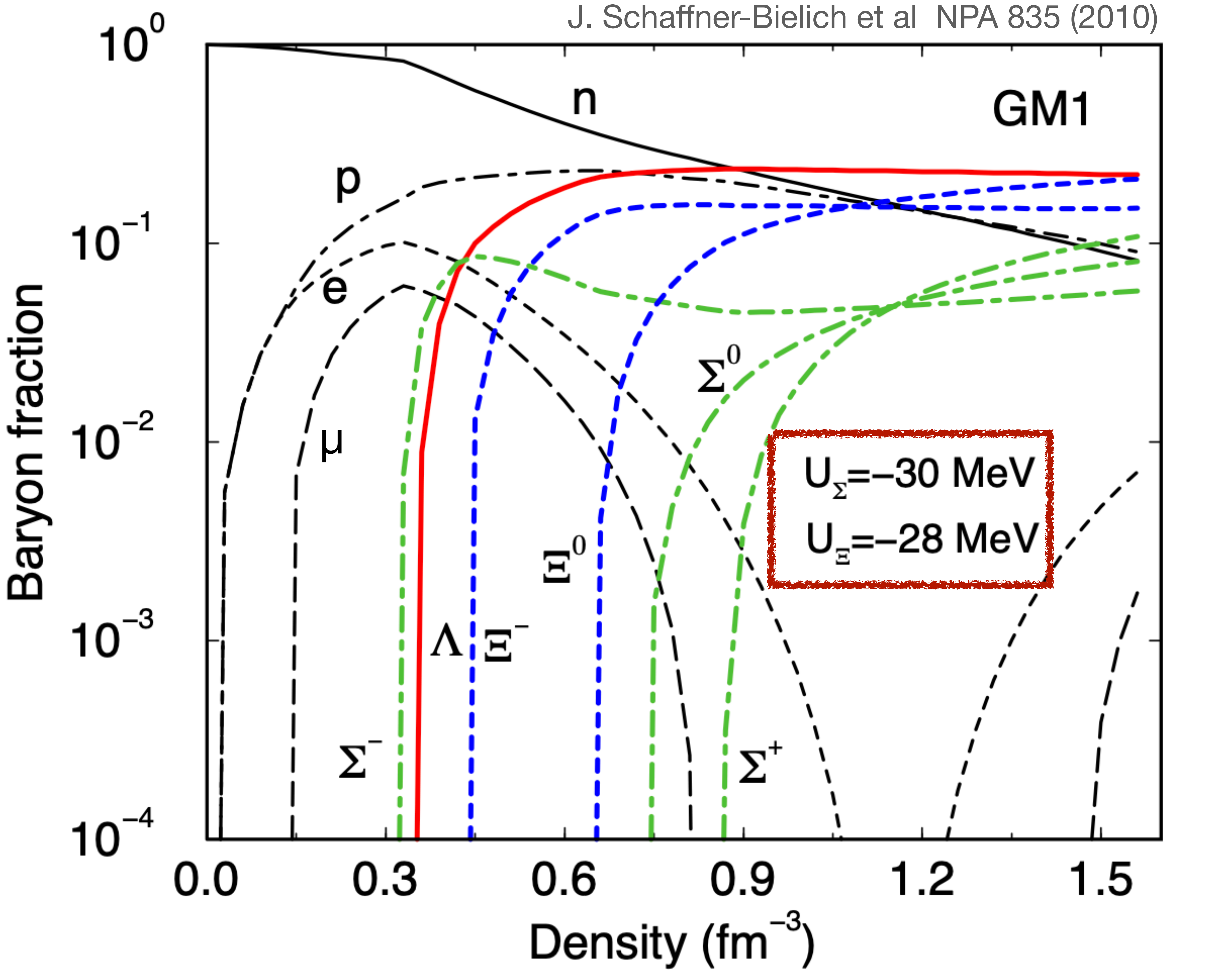
Neutron stars and strangeness



- Very dense, compact objects
- At finite densities **hyperon** production might become energetically favourable
- Exact composition strongly depends on constituent interactions and couplings
  - Density dependence



Neutron stars and strangeness



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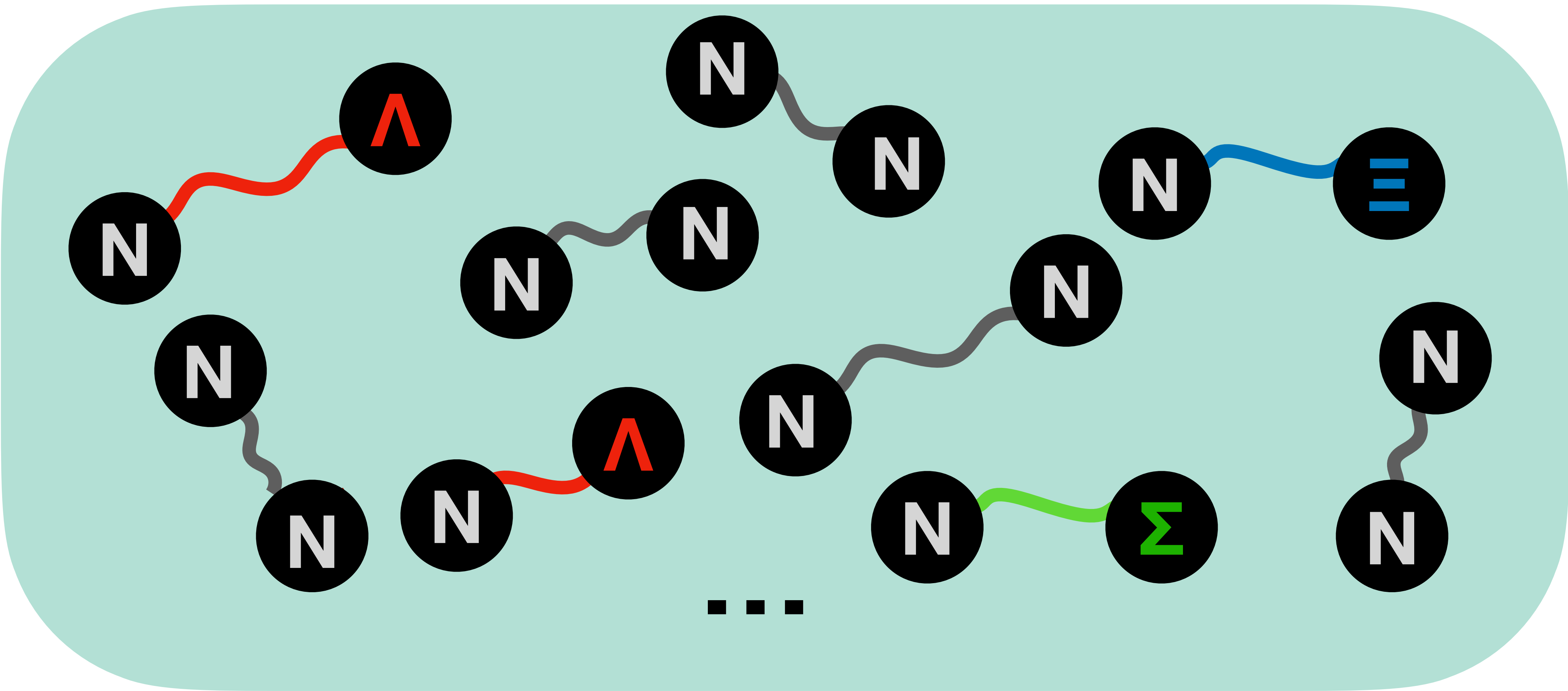
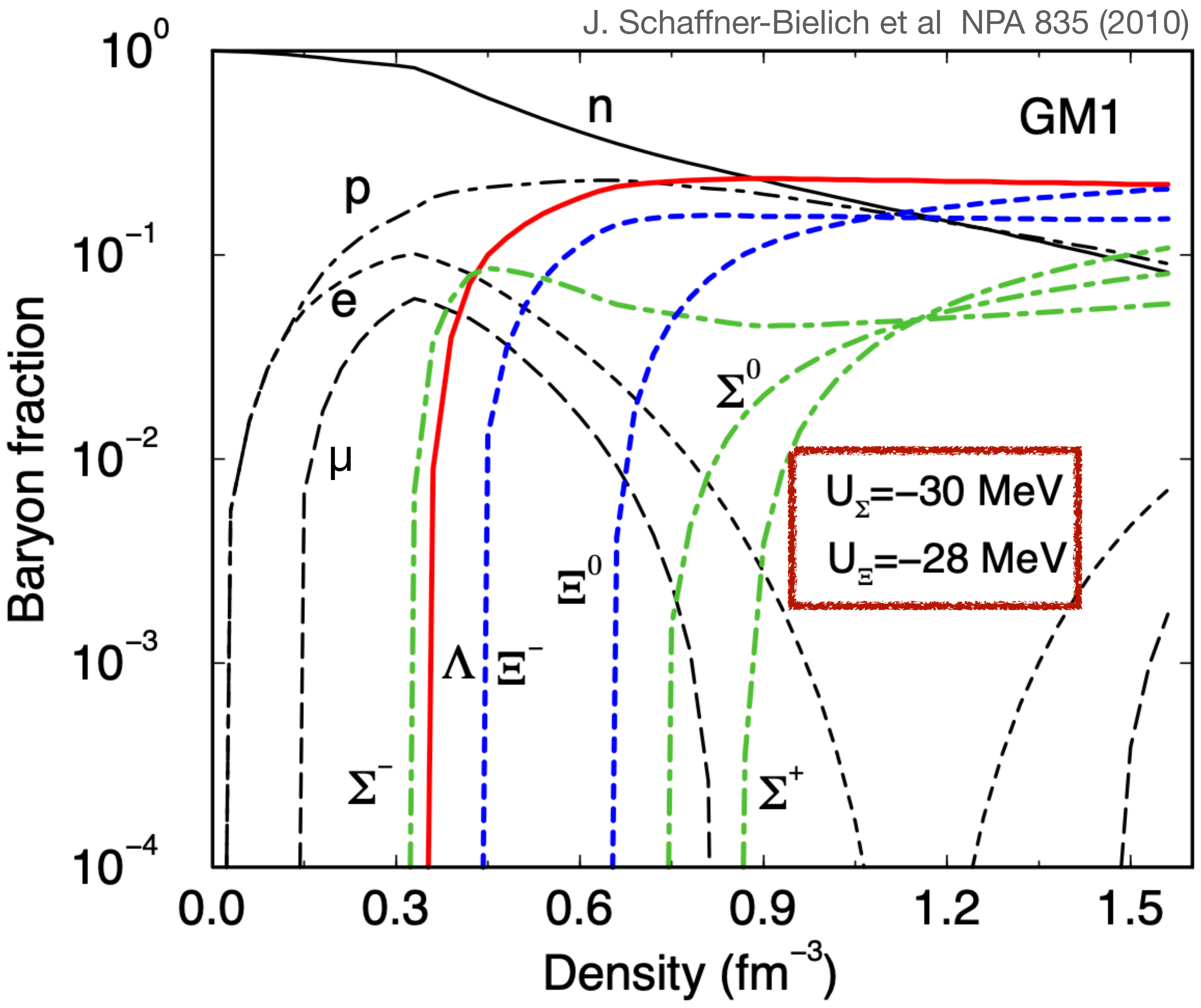


Neutron stars and strangeness



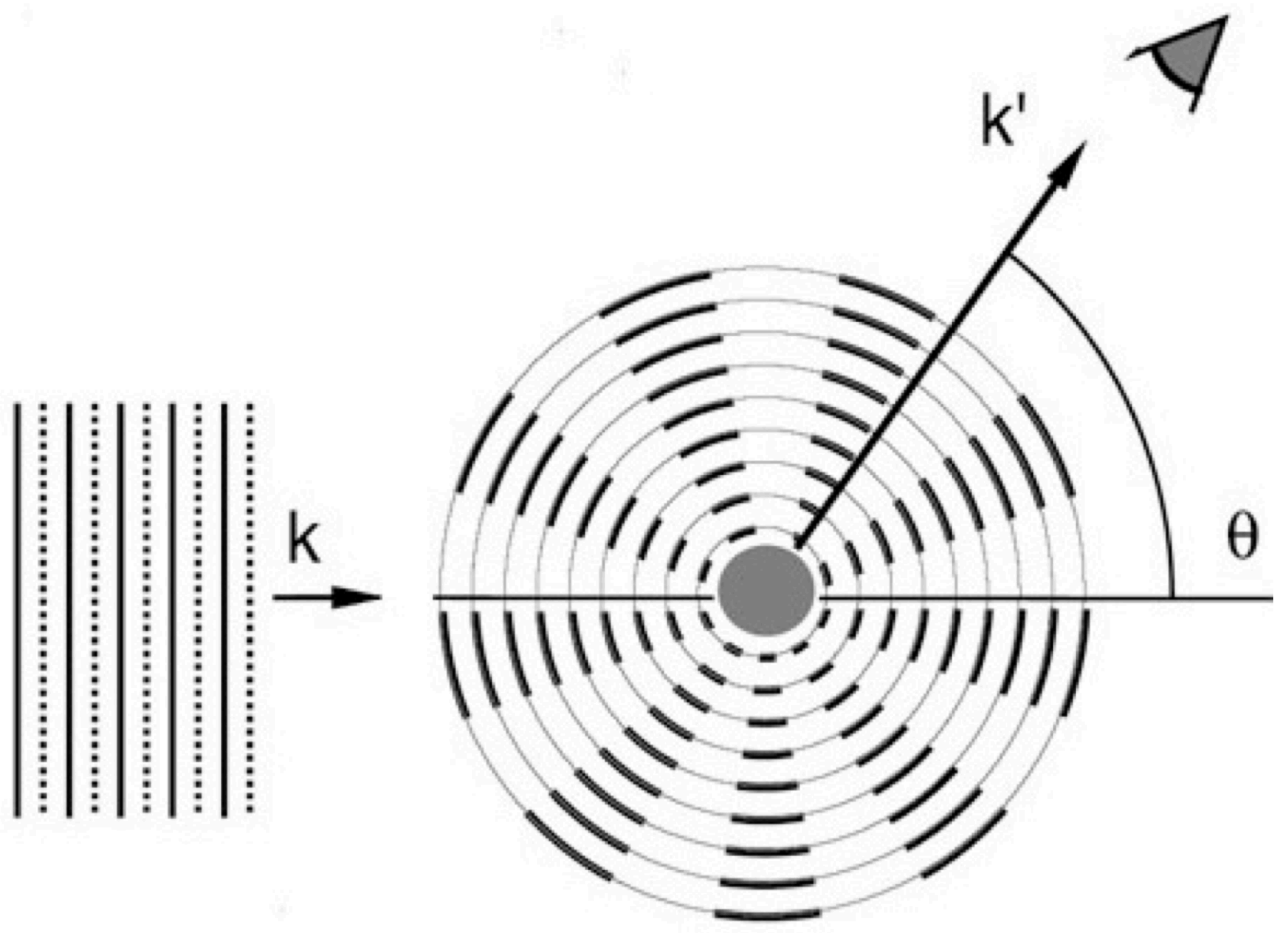
- Very dense, compact objects
- At finite densities **hyperon** production might become energetically favourable
- Exact composition strongly depends on constituent interactions and couplings
  - Density dependence

What is the current status of interaction studies?

Interactions: theory and experiment

	ISI = 0	ISI = 1	ISI = 2	ISI = 3	ISI > 3
	NN	NΛ, NΣ	ΛΛ, NΞ	ΛΞ, NΩ	ΞΞ, ΛΩ, ΣΩ, ΞΩ, ΩΩ

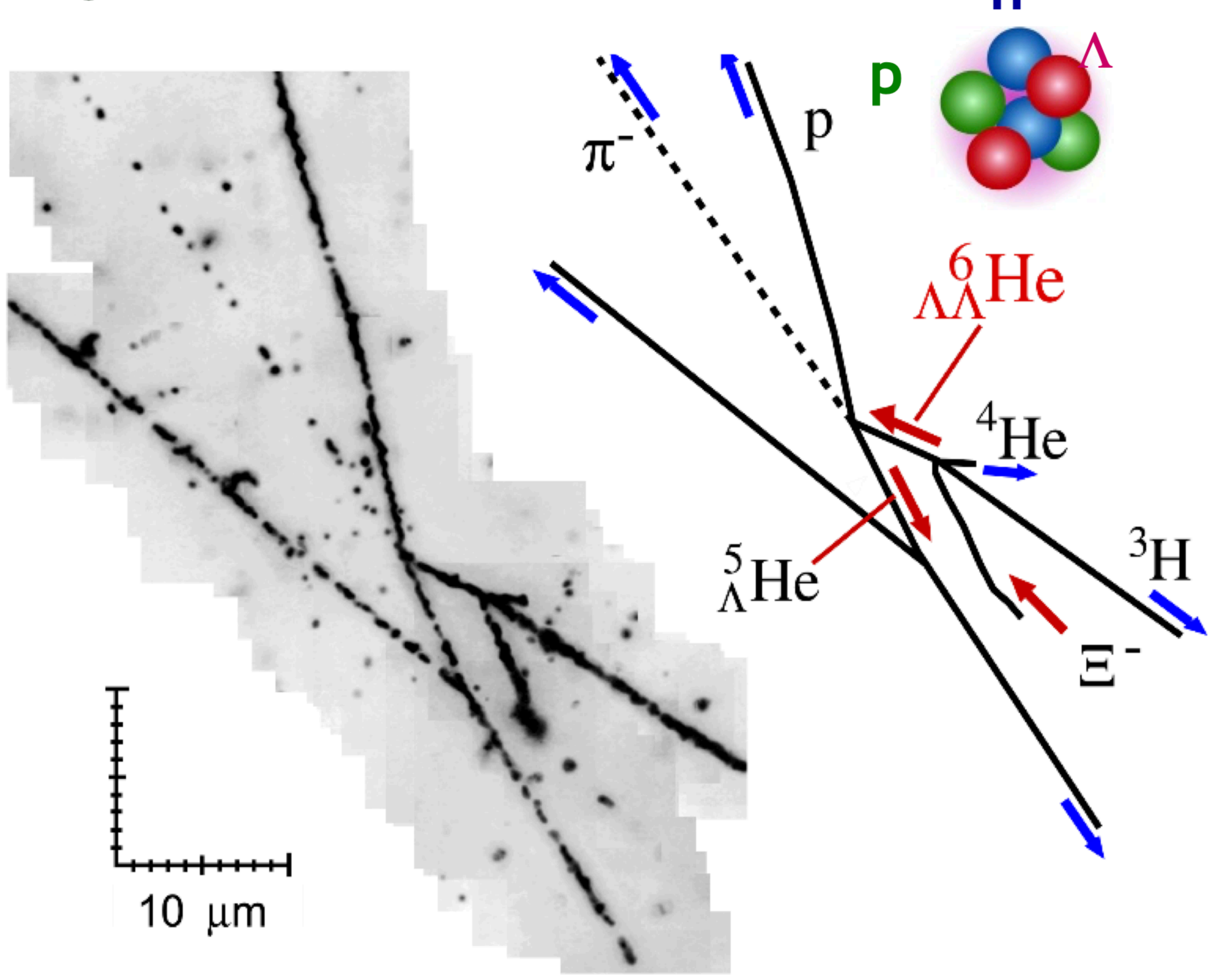
Scattering experiments



Interactions: theory and experiment

	ISI = 0 NN	ISI = 1 NΛ, NΣ	ISI = 2 ΛΛ, NΞ	ISI = 3 ΛΞ, NΩ	ISI > 3 ΞΞ, ΛΩ, ΣΩ, ΞΩ, ΩΩ
Scattering experiments	✓	✓	✓		
Hypernuclei		✓	✓		

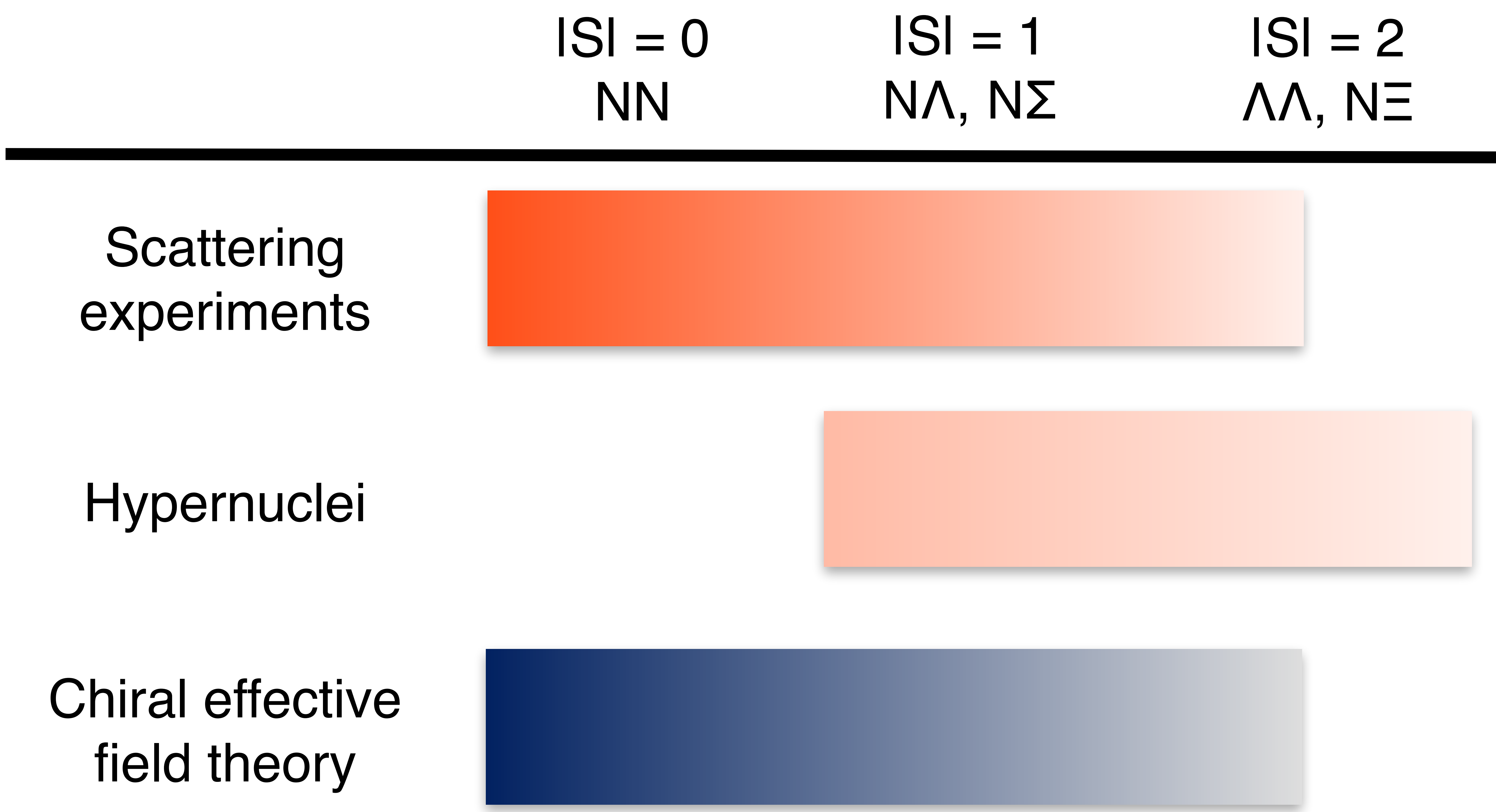
Nagara event

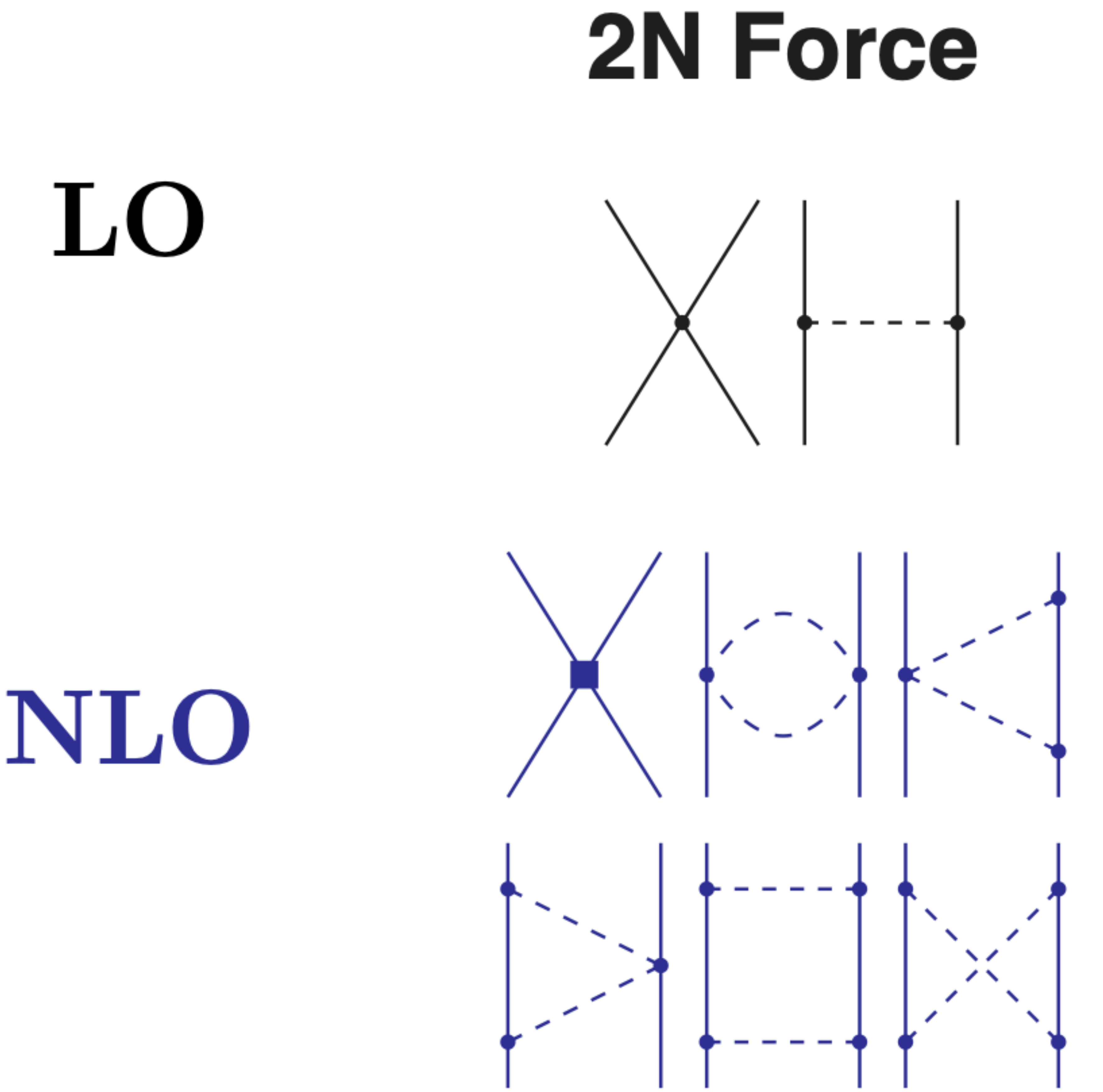


$^{6}_{\Lambda\Lambda}$He -> $^{5}_{\Lambda}$He + p + π^-

H. Takahashi et al., PRL 87 (2001) 212502
T. Nagae et al., PRL 80 (1998) 1605-1609
S.H. Hayakawa et al. PRL. 126 (2021), 06250
J.K Ahn et al., PRC 88 (2013), 014003

Interactions: theory and experiment

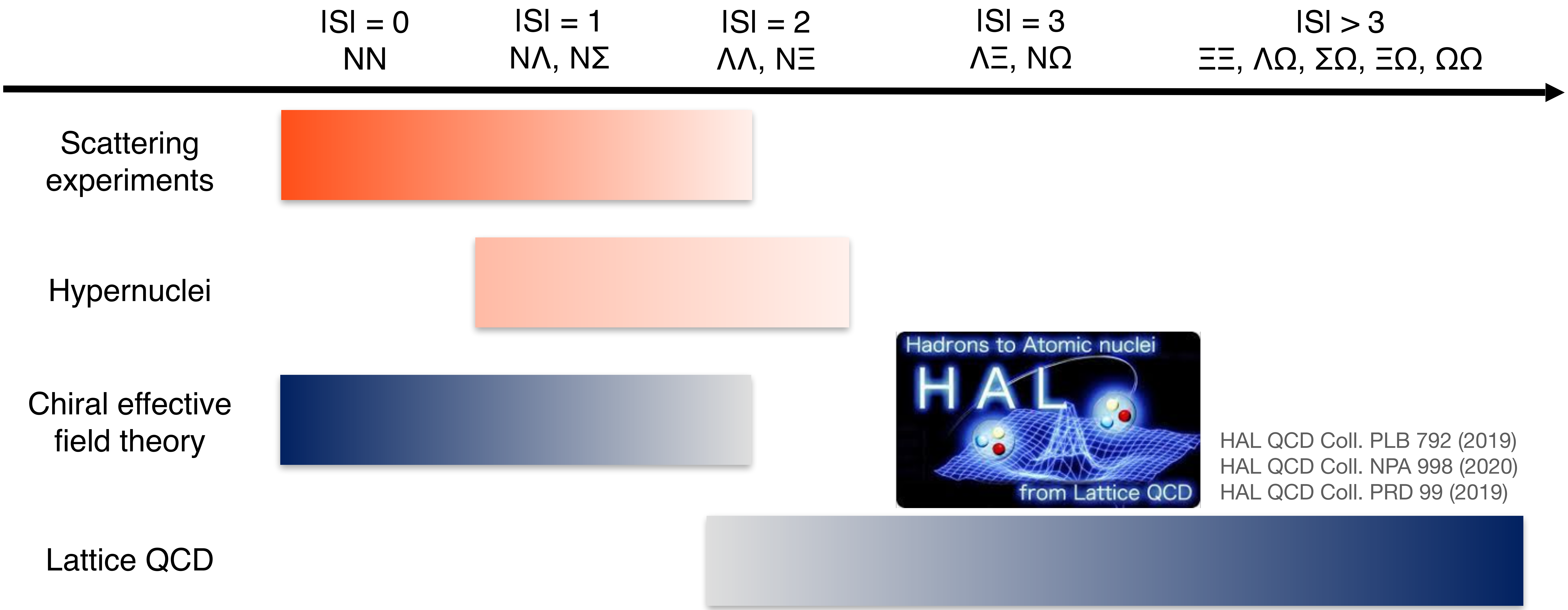




- hadrons as degrees of freedom
- low-energy constants constrained to the data

J.Haidenbauer., N.Kaiser et al., NPA 915 (2013)
J.Haidenbauer, U. Meiβner, EPJA 56 (2020)

Interactions: theory and experiment



Interactions: theory and experiment

|S| = 0
NN

|S| = 1
NΛ, NΣ

|S| = 2
ΛΛ, NΞ

|S| = 3
ΛΞ, NΩ

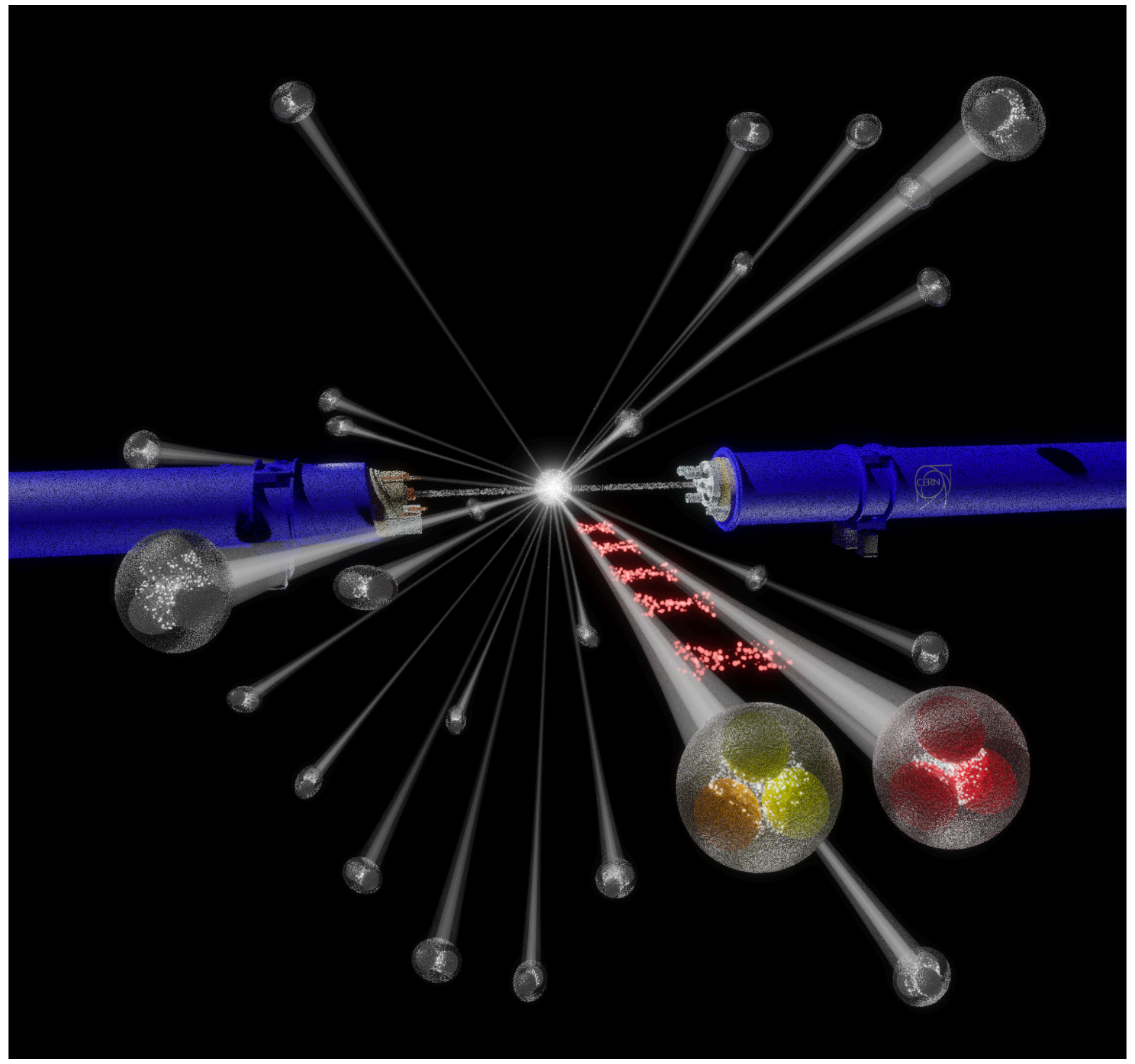
|S| > 3
ΞΞ, ΛΩ, ΣΩ, ΞΩ, ΩΩ

Scattering experiments

Hypernuclei

Chiral effective field theory

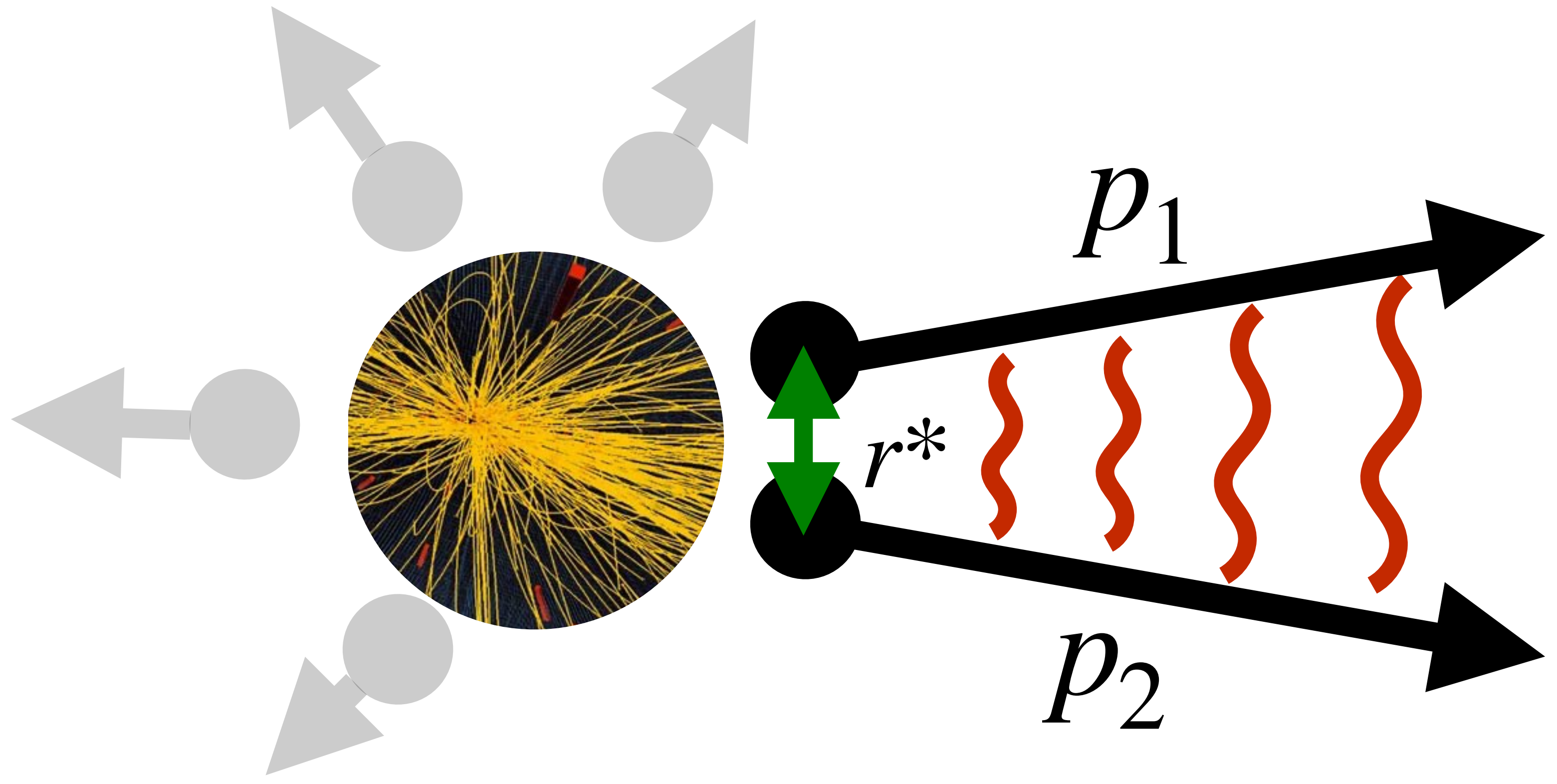
Lattice QCD



Correlations

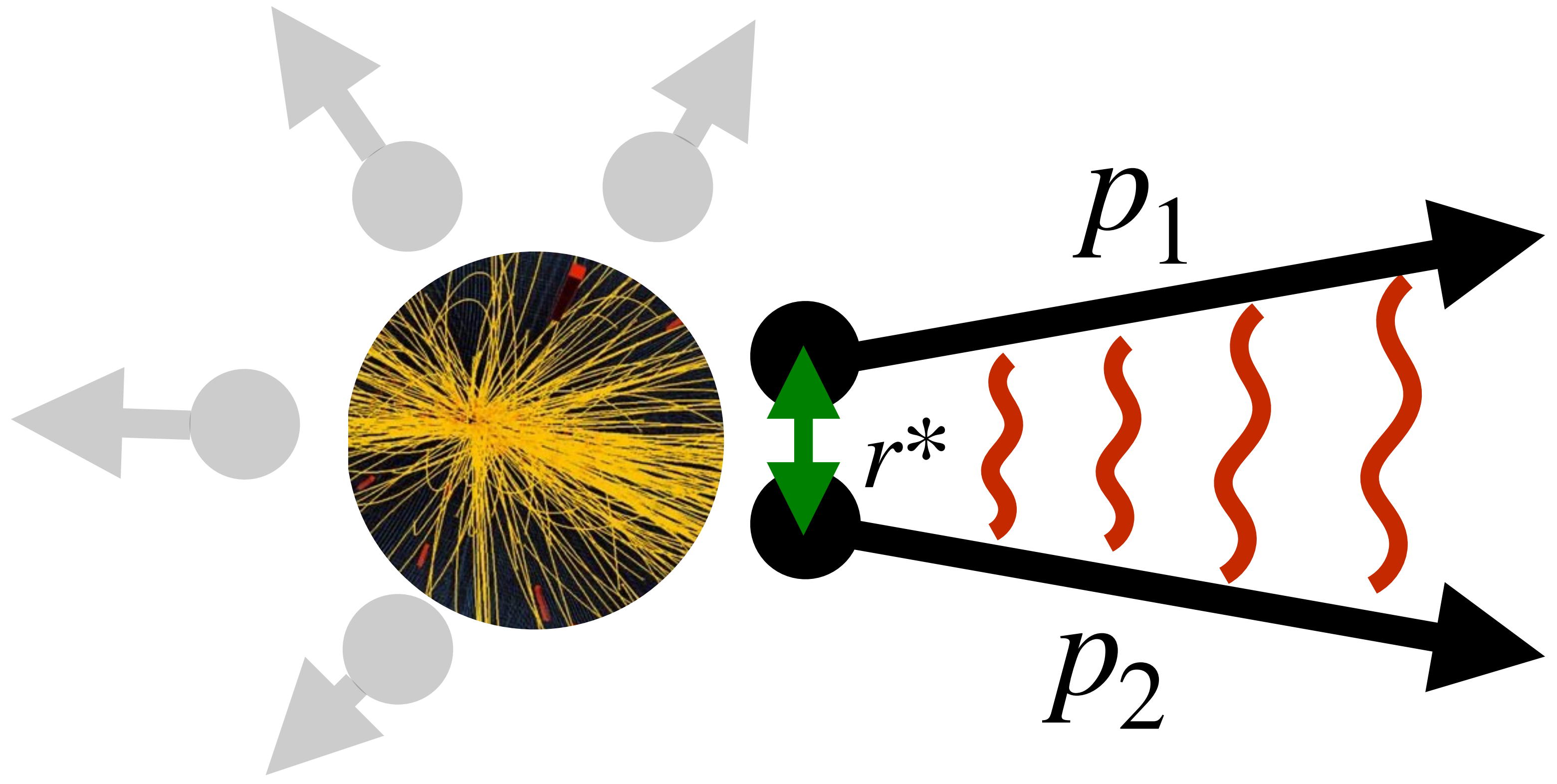
What can we do at the LHC?

Two-body femtoscopy



Emission source $S(r^*)$

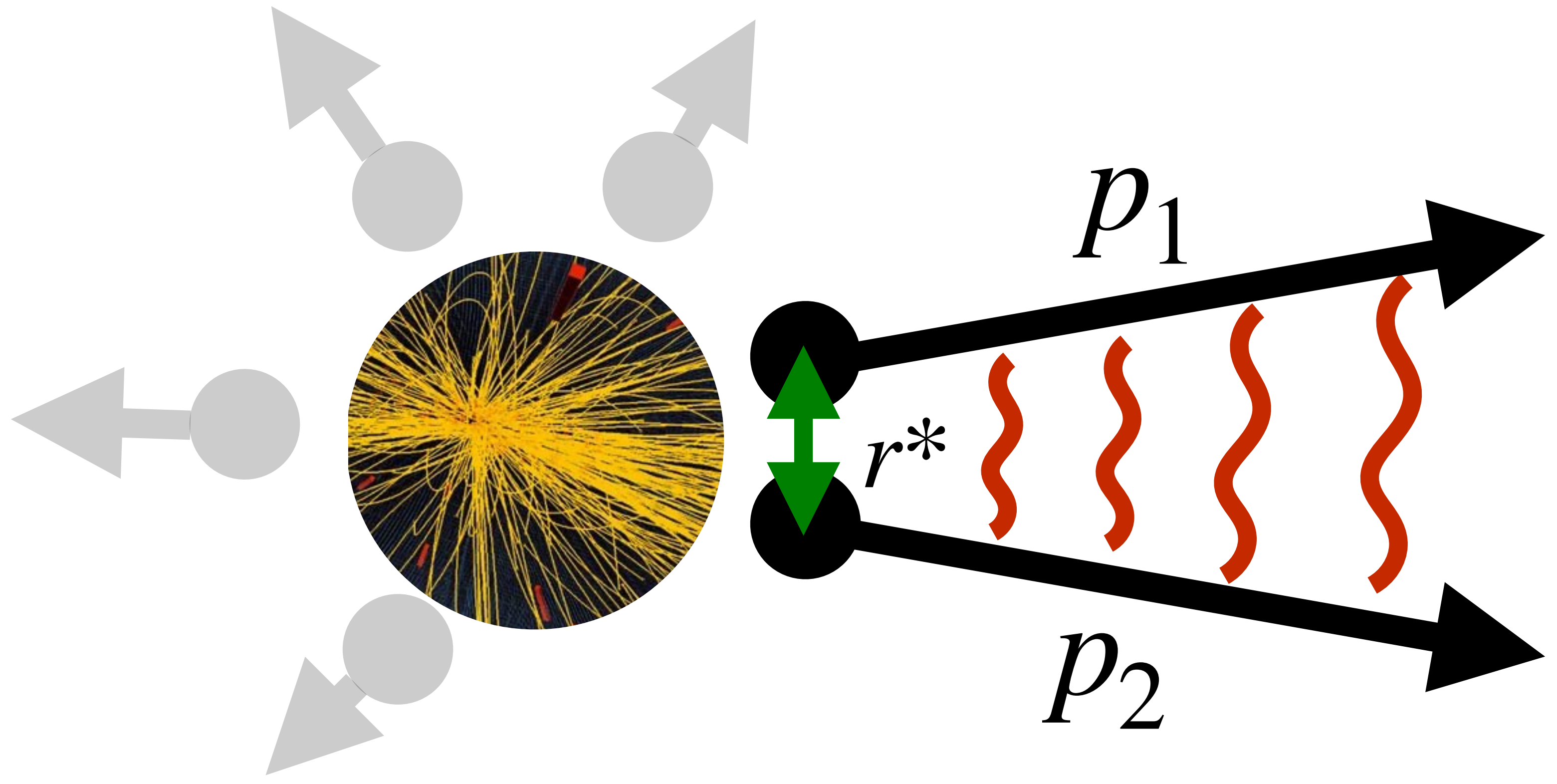
Two-body femtoscopy

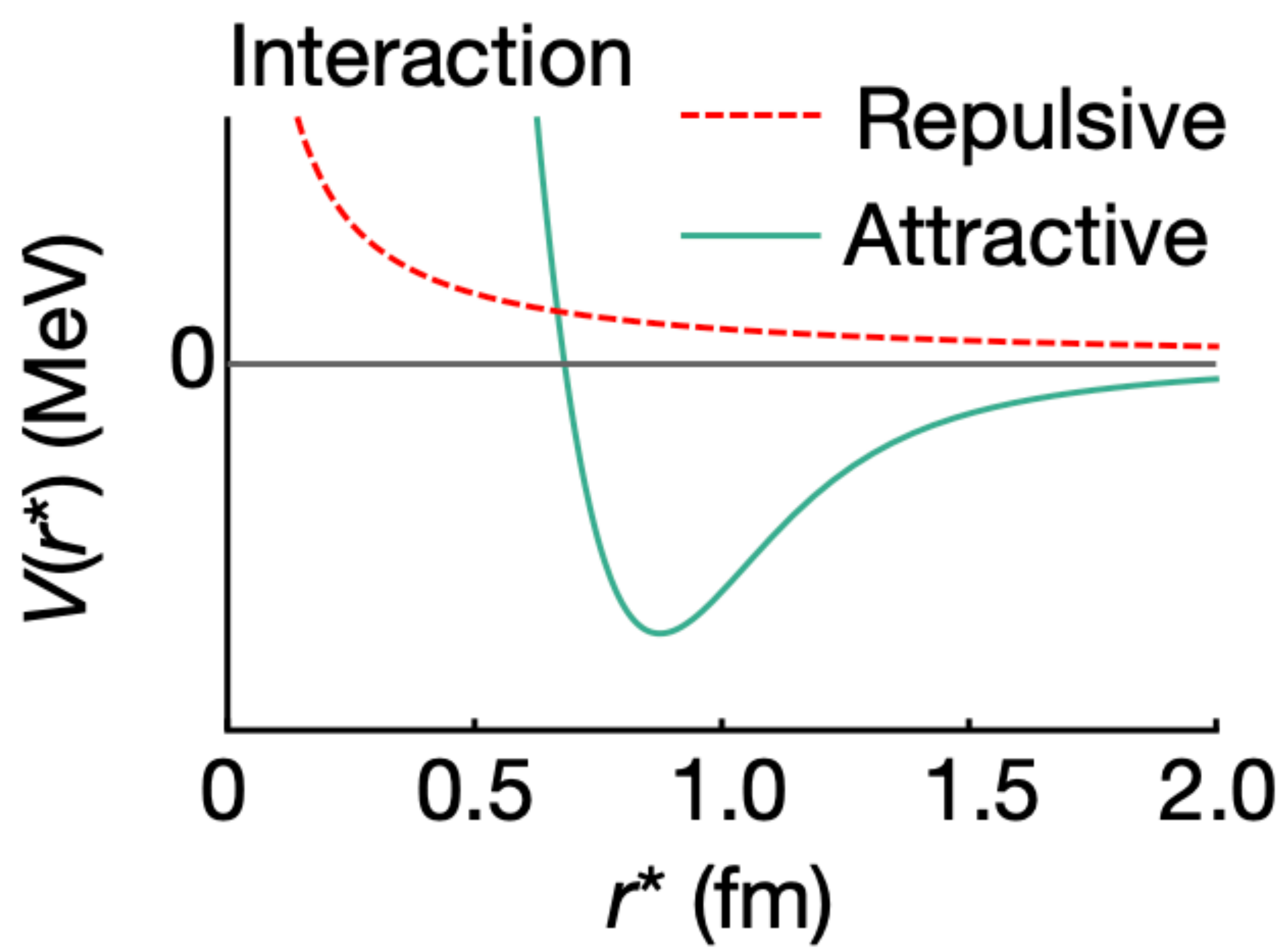


Emission source $S(r^*)$

$$C(k^*) = \mathcal{N}\frac{N_{\text{same}}(k^*)}{N_{\text{mixed}}(k^*)} = \int S(r^*)\left|\psi(\mathbf{k}^*, \mathbf{r}^*)\right|^2 \mathbf{d}^3 r^*$$

Two-body femtoscopy





Emission source *S(r*)*

Schrödinger equation

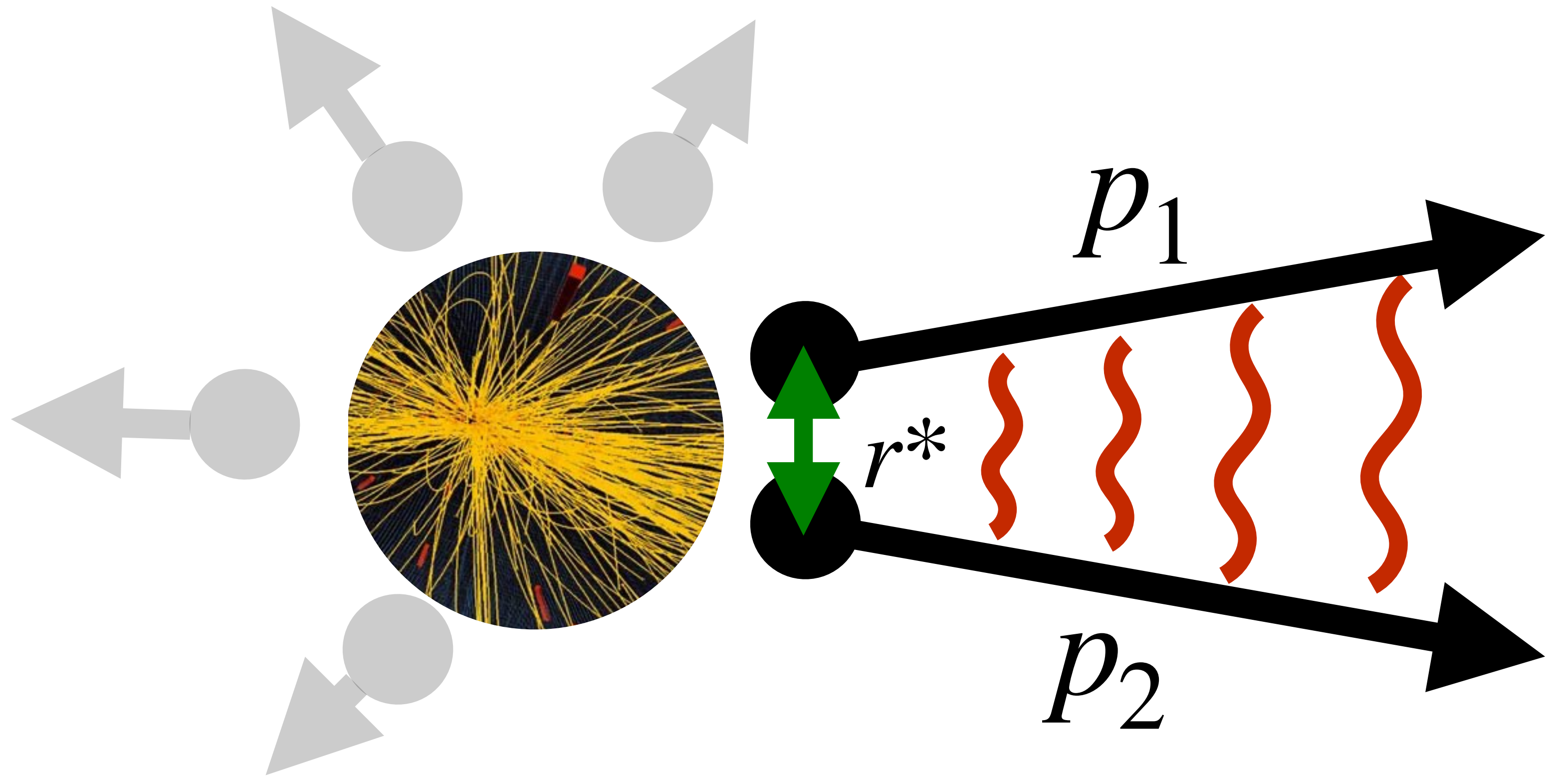
Two-particle wave function

$$\left|\psi\left(\mathbf{k}^*, \mathbf{r}^*\right)\right|$$

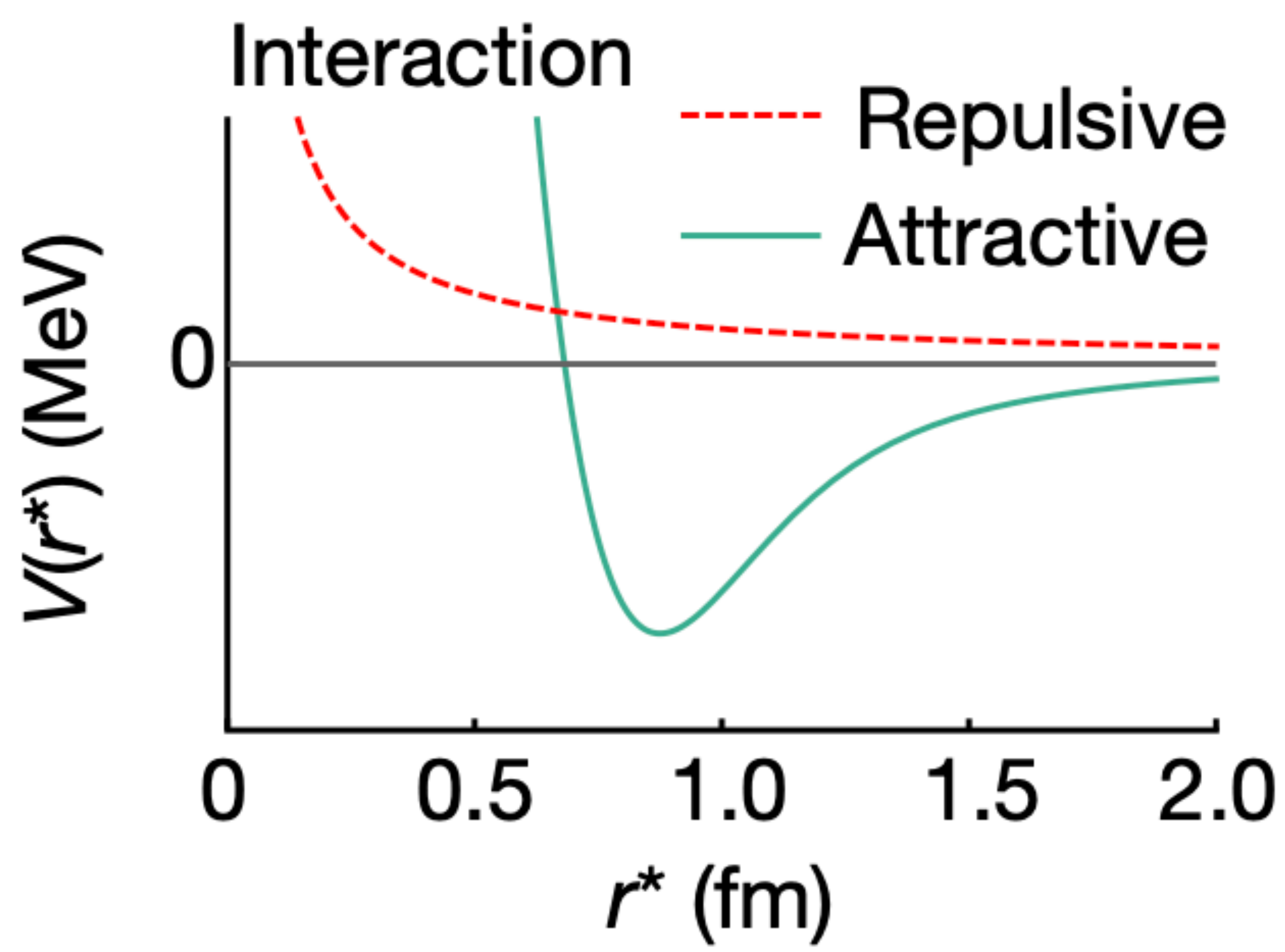
D.L. Mihaylov et al, EPJ C78 (2018)

$$C\left(k^*\right) = \mathcal{N}\frac{N_{\mathrm{same}}\left(k^*\right)}{N_{\mathrm{mixed}}\left(k^*\right)} = \int S\left(r^*\right)\left|\psi\left(\mathbf{k}^*, \mathbf{r}^*\right)\right|^2 \mathbf{d}^3 r^*$$

Two-body femtoscopy

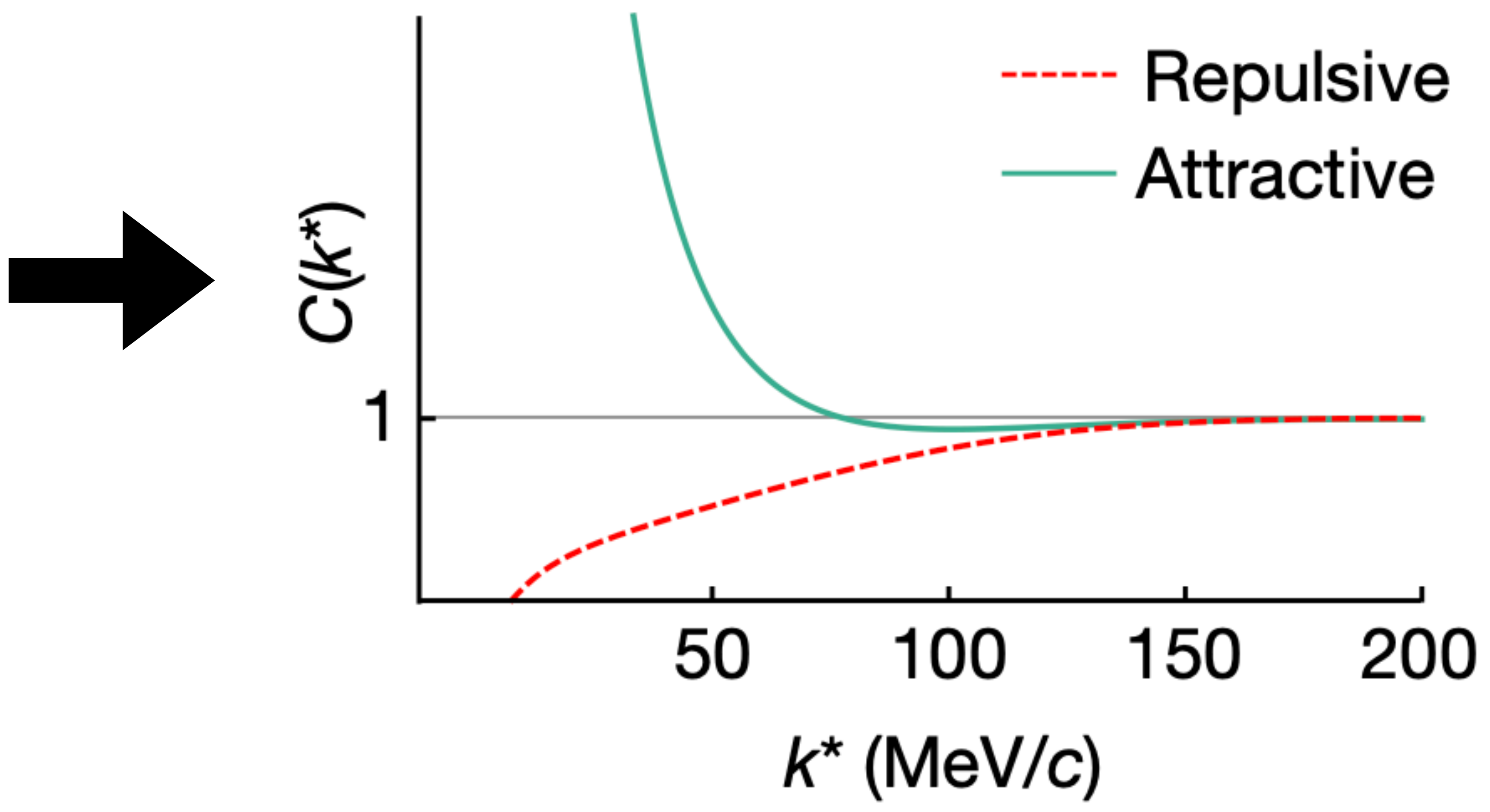


Emission source $S(r^*)$



Schrödinger equation
Two-particle wave function
$\left|\psi(\mathbf{k}^*, \mathbf{r}^*)\right|$

D.L. Mihaylov et al, EPJ C78 (2018)



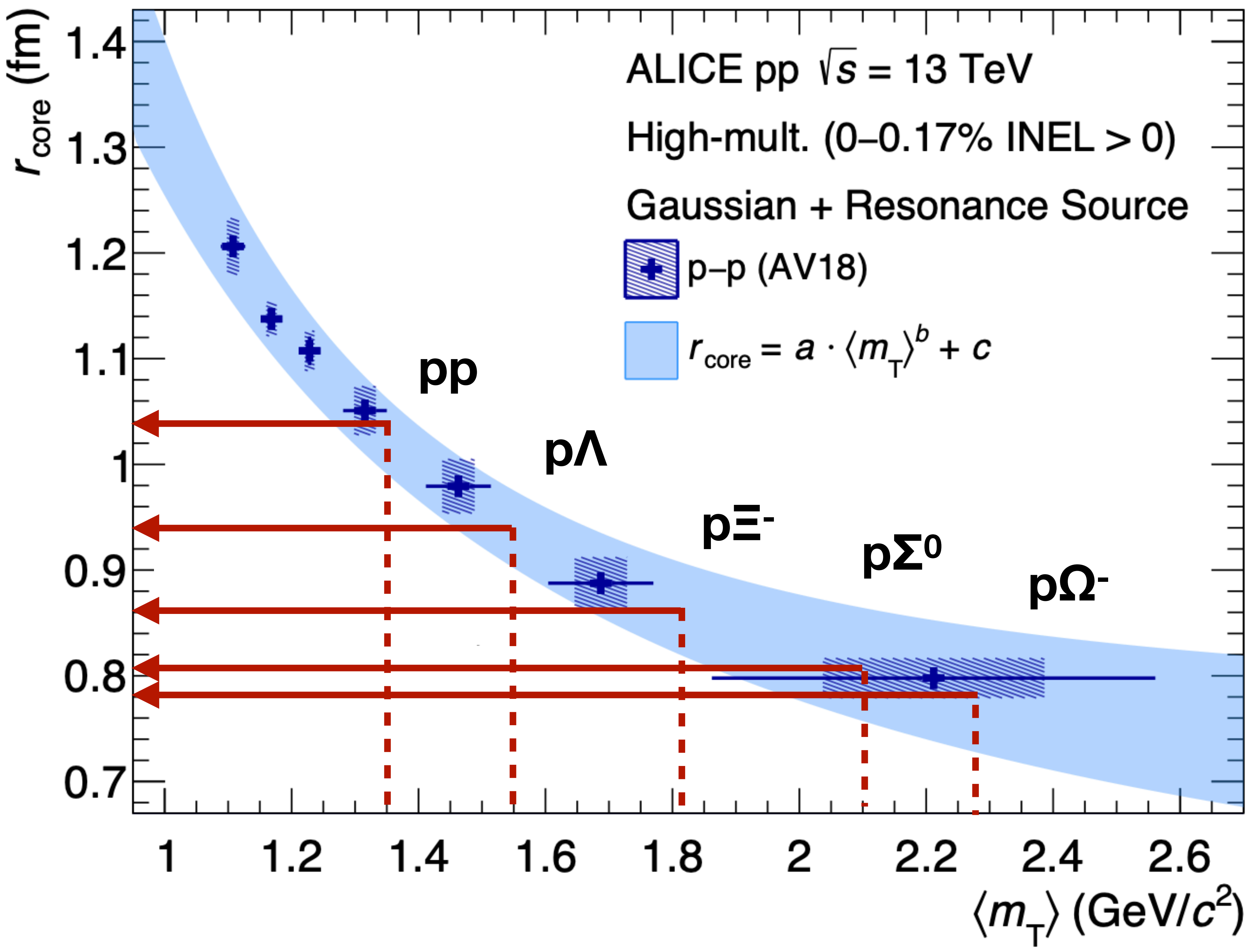
Correlation function $C(k^*)$

$$C(k^*) = \mathcal{N} \frac{N_{\mathrm{same}}(k^*)}{N_{\mathrm{mixed}}(k^*)} = \int S(r^*) \left|\psi(\mathbf{k}^*, \mathbf{r}^*)\right|^2 \mathbf{d}^3 r^*$$

ALICE, Nature 588, 232–238 (2020)

Source

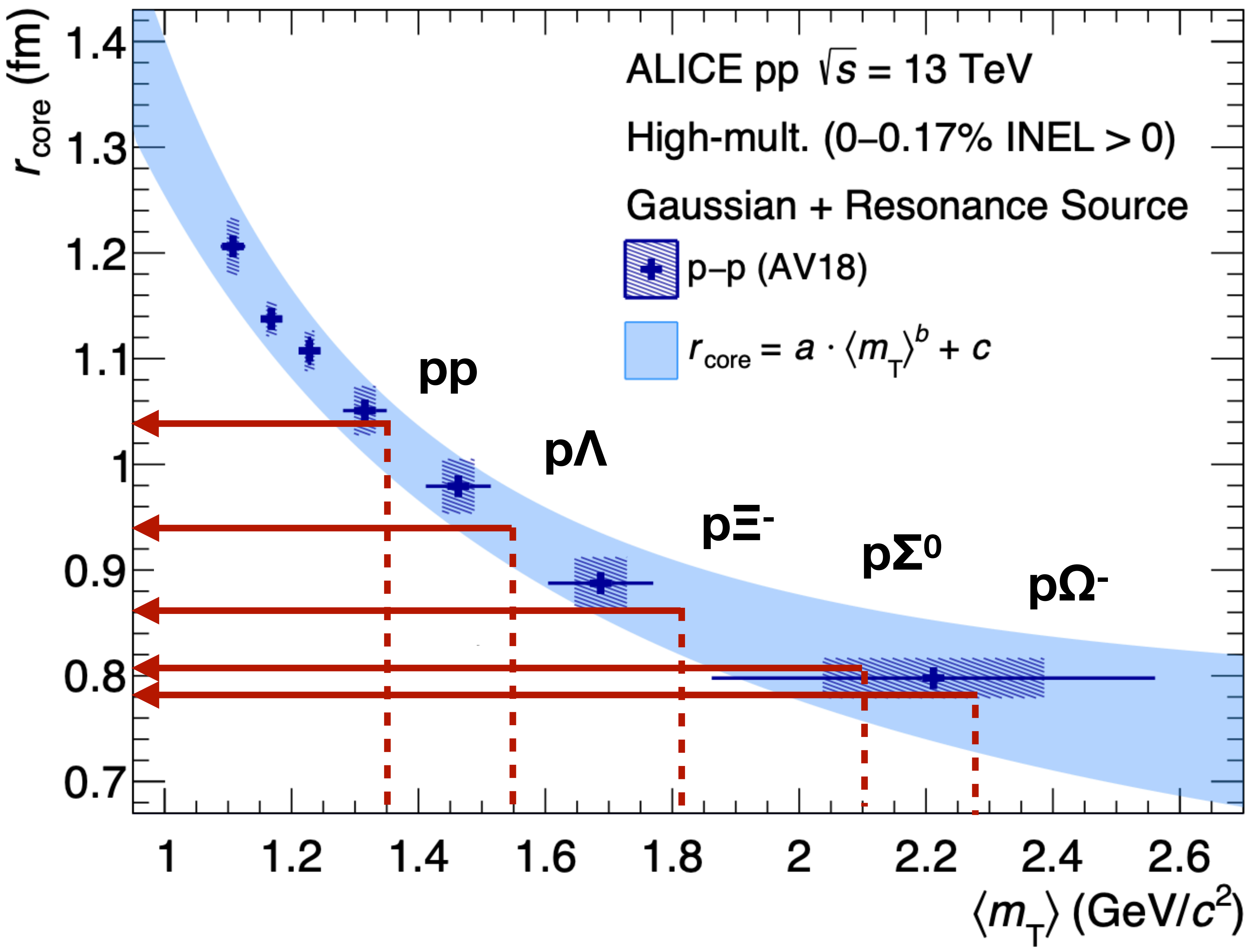
Particles emitted at ~1 fm

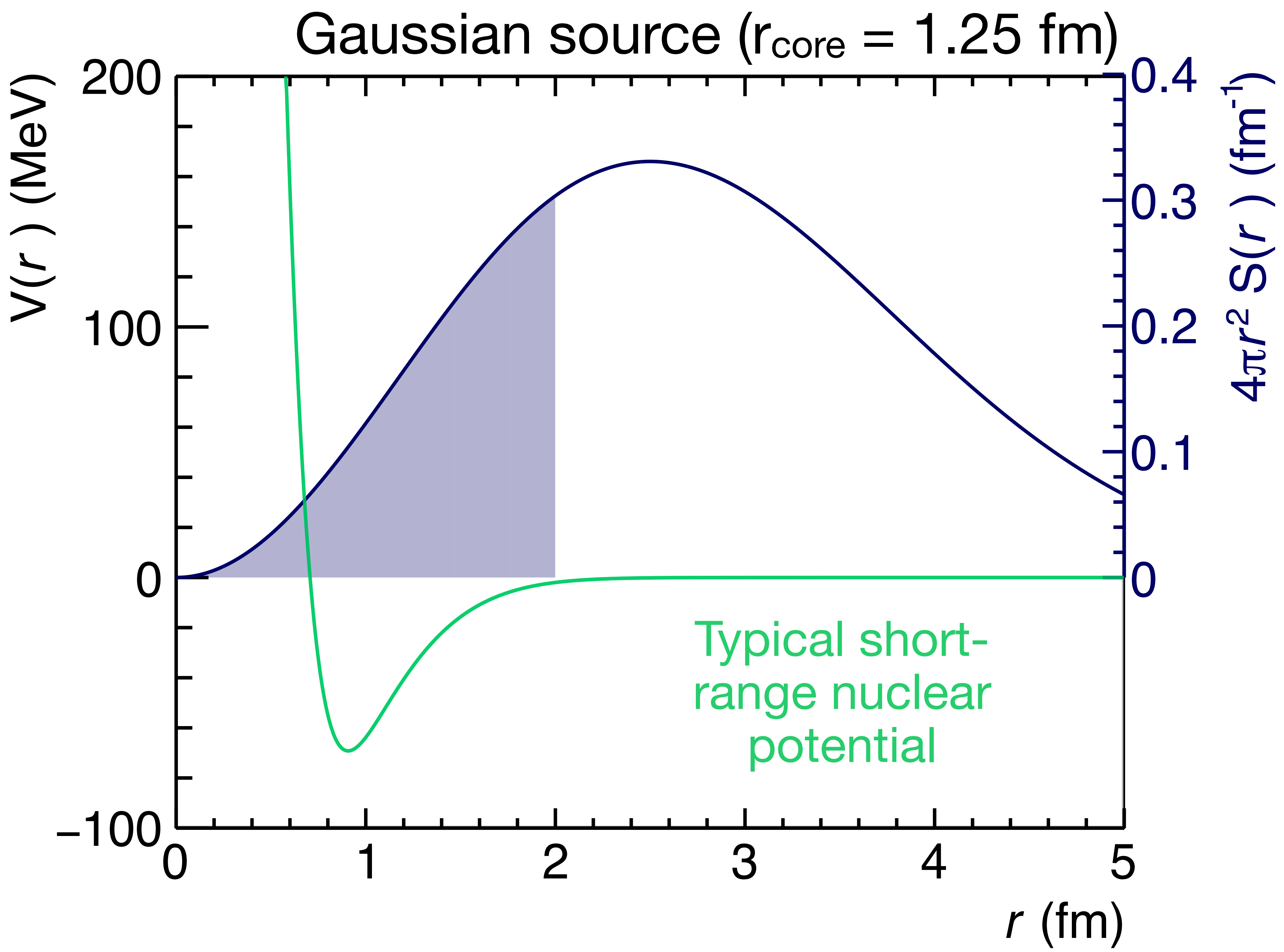


Emission source:
19 Aug 12:00 Dimitar Mihaylov

Source

Particles emitted at ~1 fm → Access to the short-range strong interaction

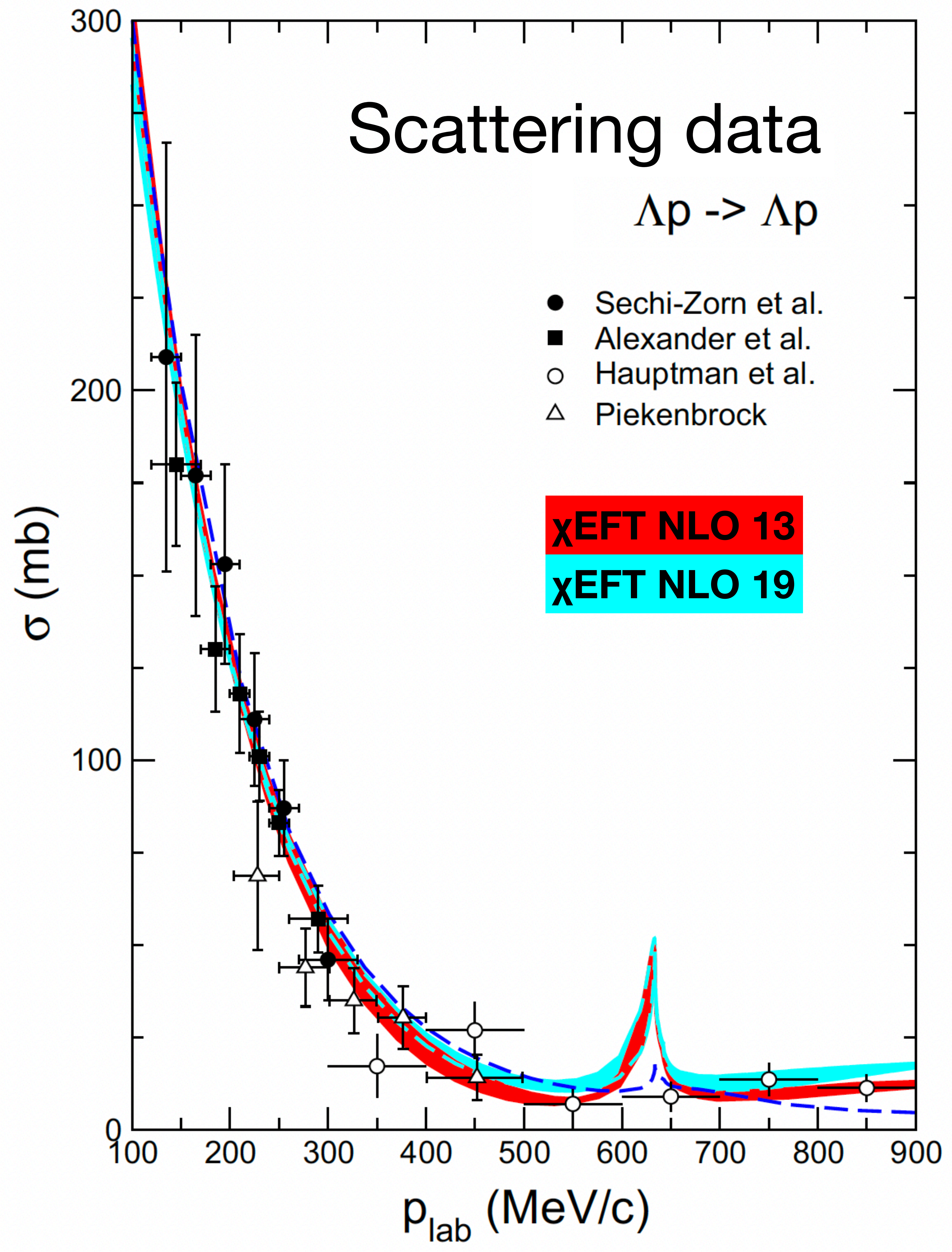




Emission source:
19 Aug 12:00 Dimitar Mihaylov

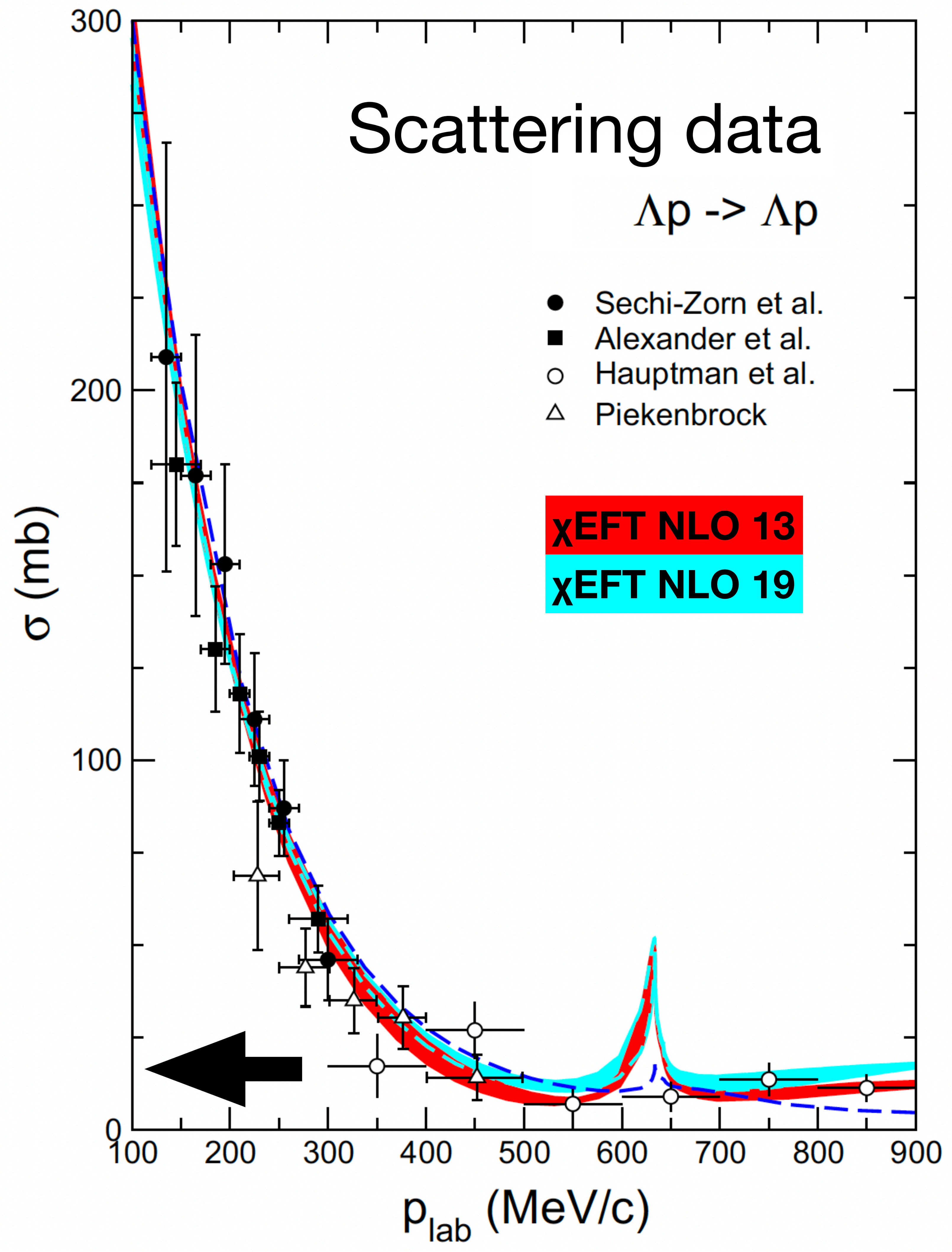
ALICE Coll., Phys. Lett. B 811, 135849 (2020)
ALICE Coll., arXiv:2311.14527 (2023)
Dimitar Mihaylov et al., Eur.Phys.J.C 83 (2023) 7, 590

|S|=1 sector: p-Λ interaction



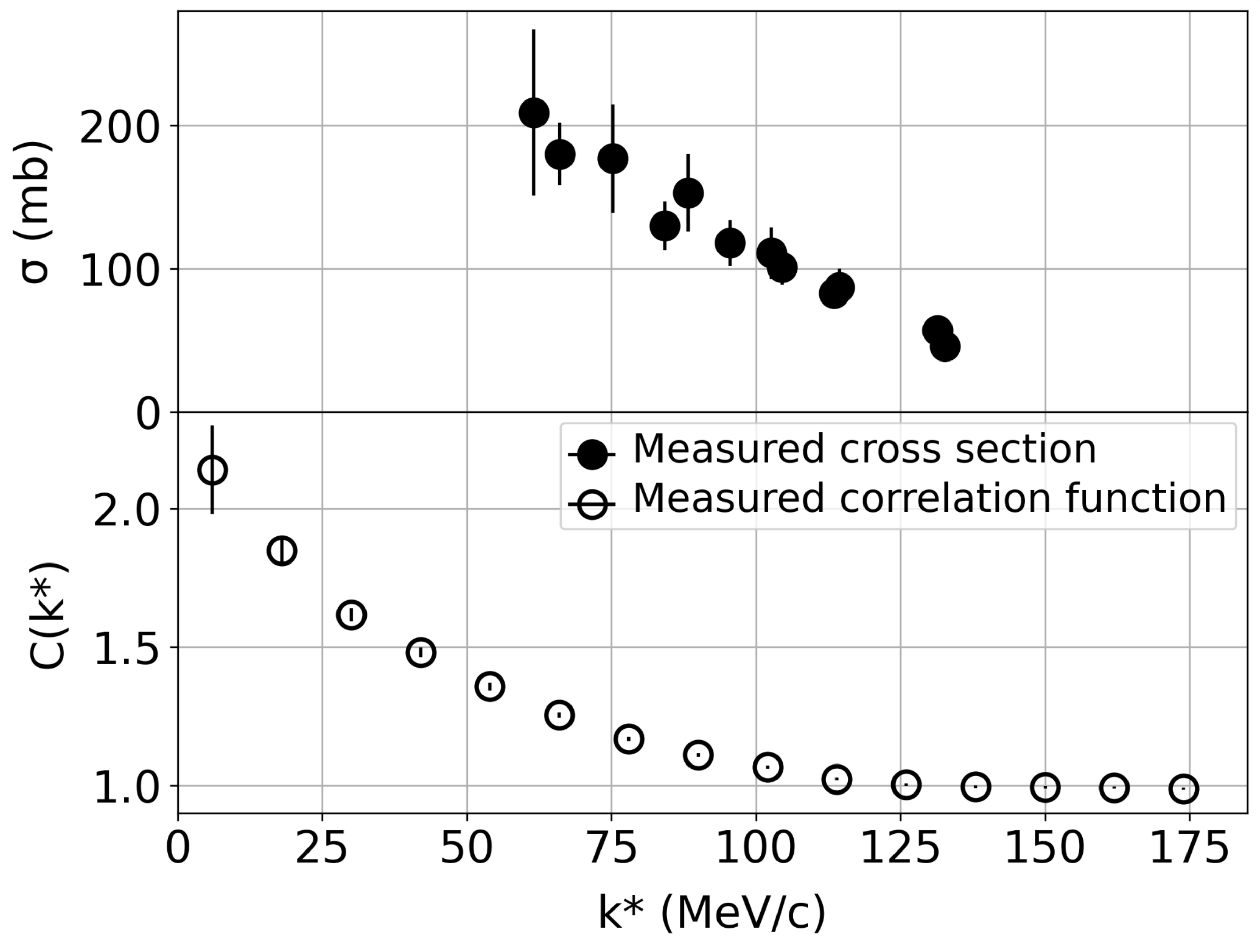
Haidenbauer et al. Eur.Phys.J.A 56 (2020) 3, 91

|S|=1 sector: p-Λ interaction



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

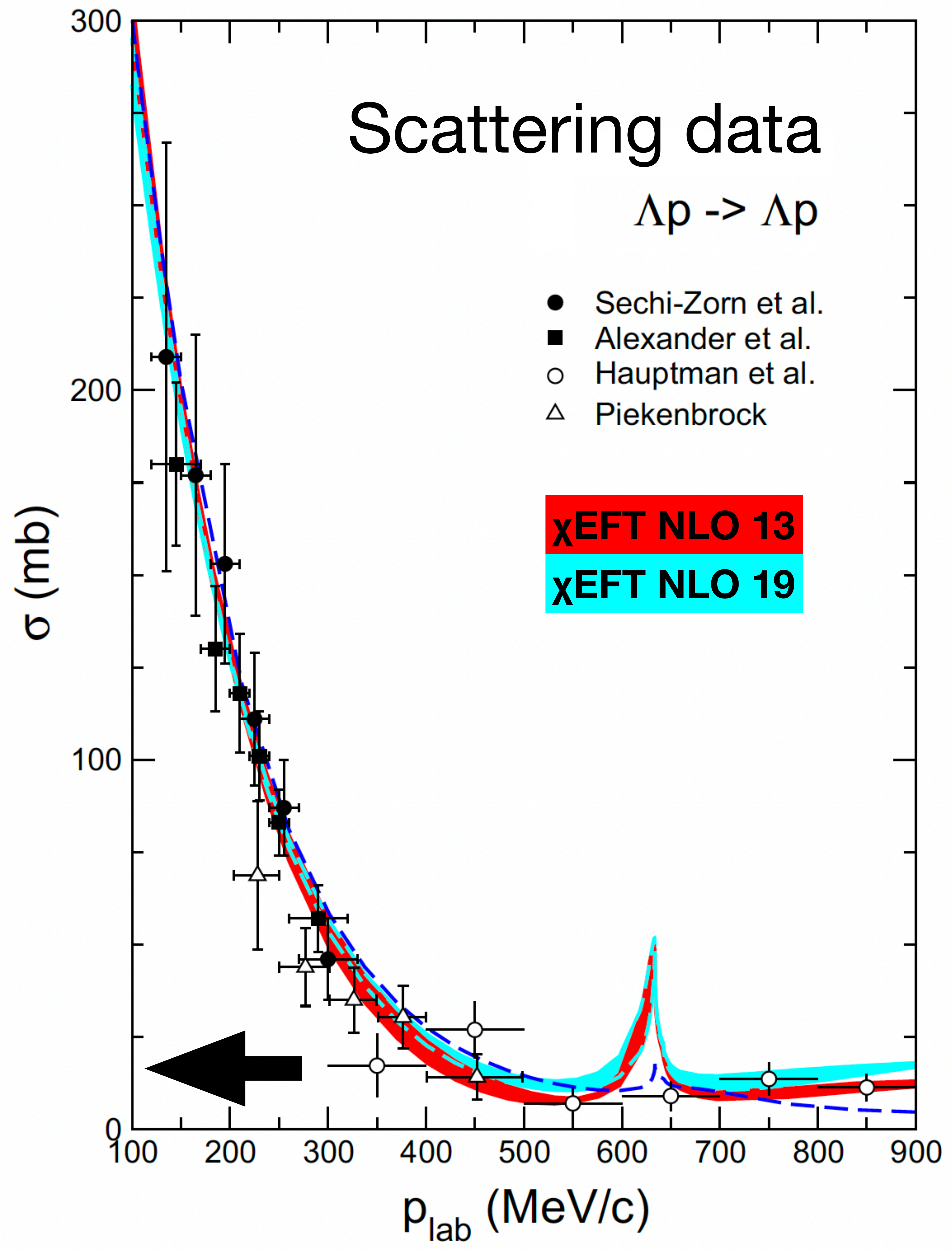
|S|=1 sector: p-Λ interaction



Courtesy of Dimitar Mihaylov based on:

Alexander et al. Phys. Rev. 173, 1452 (1968)

ALICE Coll, PLB 833 (2022), 137272



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

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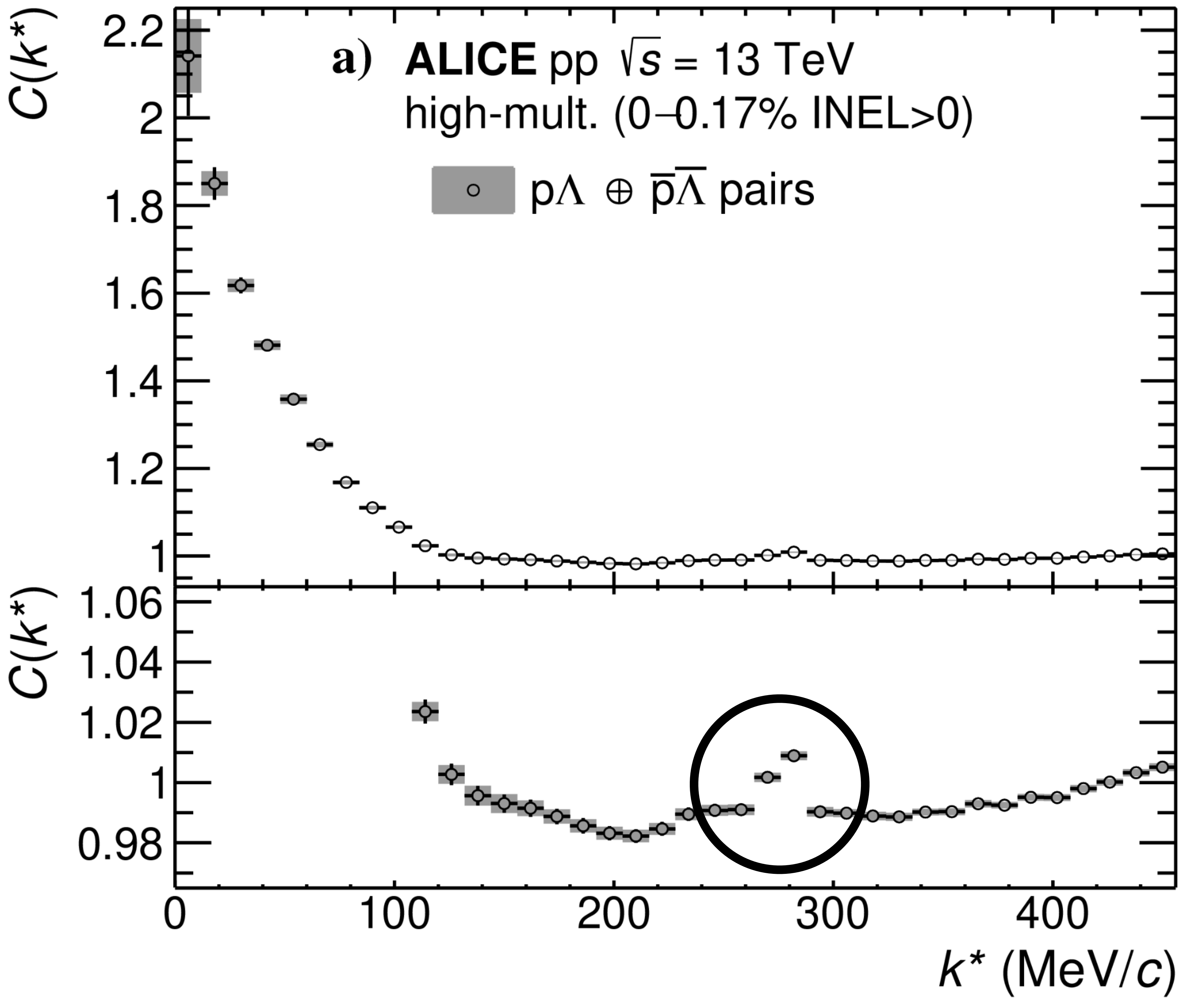

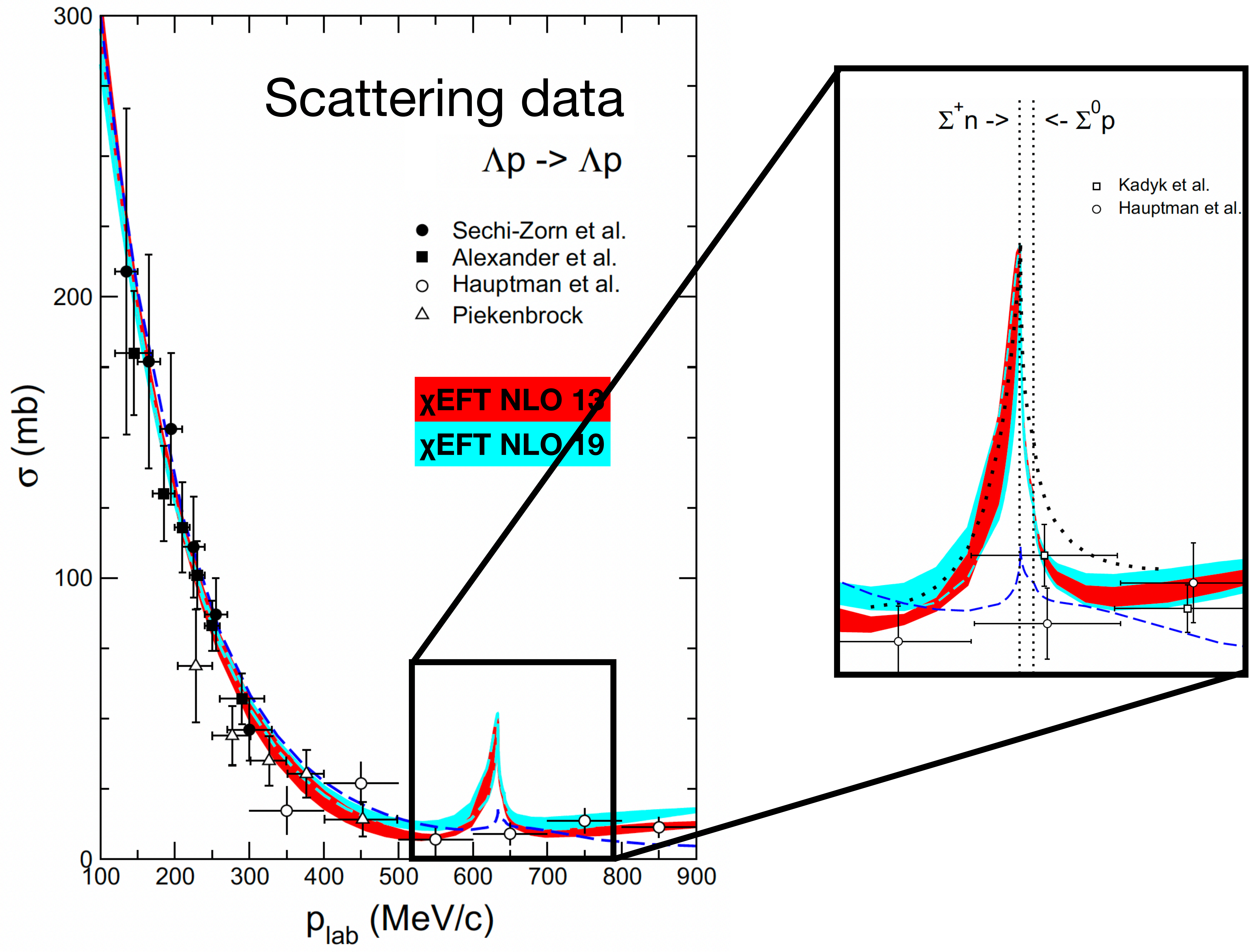

Based on ALICE Coll. PLB 833 (2022), 137272

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

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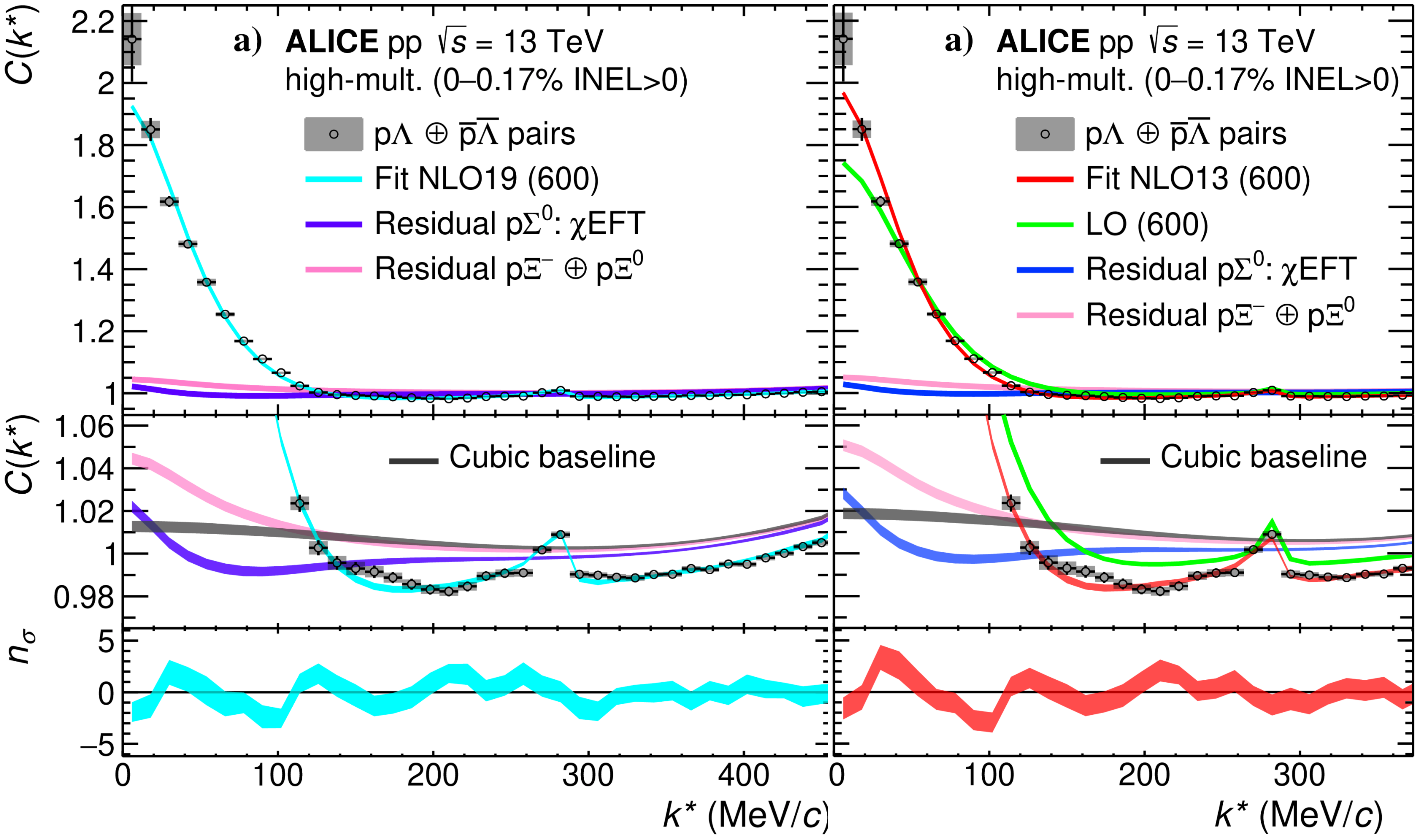
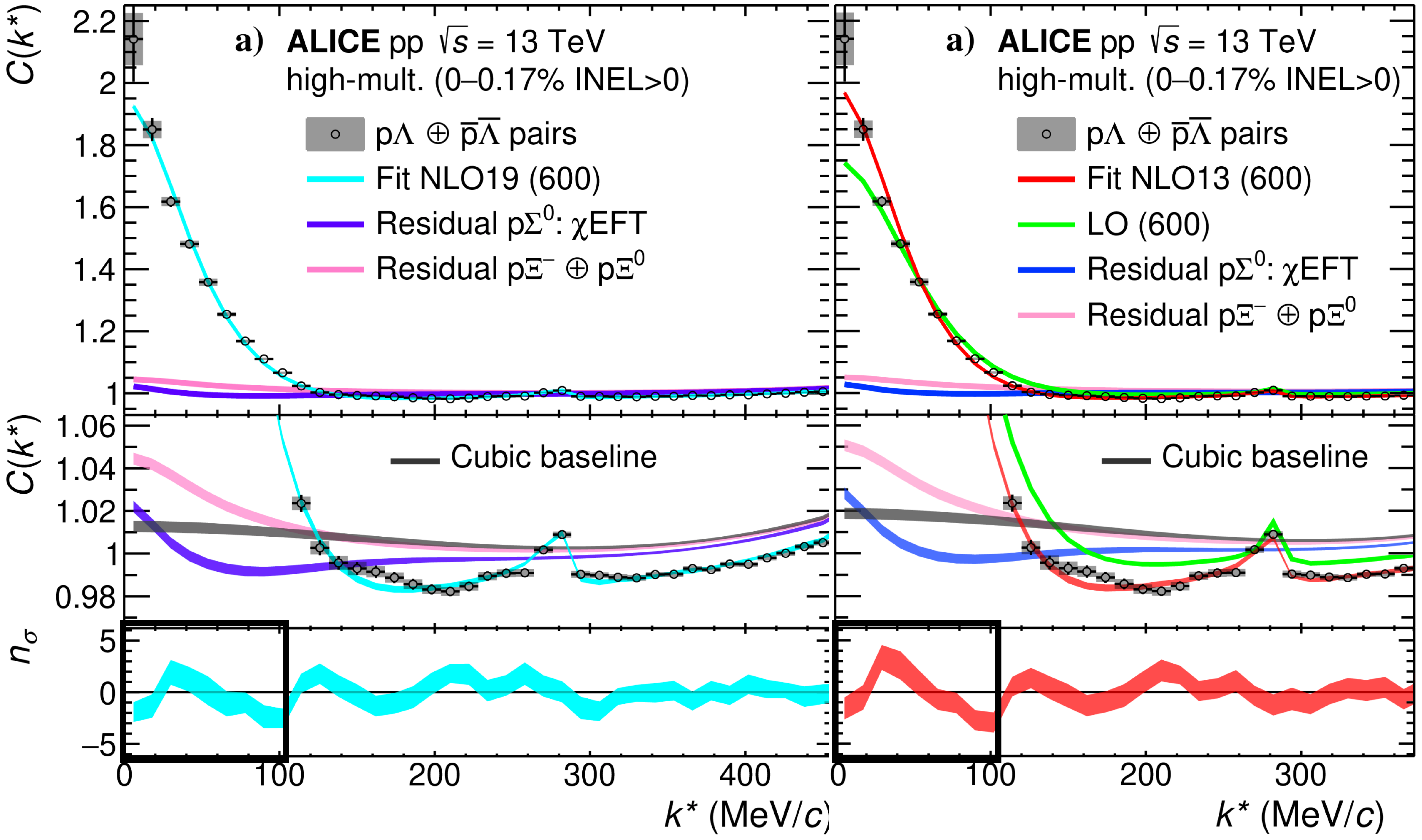


- Observation of the NΛ↔NΣ cusp
- Superior precision at low momenta over existing data
- Preference towards the NLO19
- NLO19 deviates by ~3σ at low k*

Based on ALICE Coll. PLB 833 (2022), 137272

|S|=1 sector: p-Λ interaction



~3σ ~4σ

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Based on ALICE Coll. PLB 833 (2022), 137272

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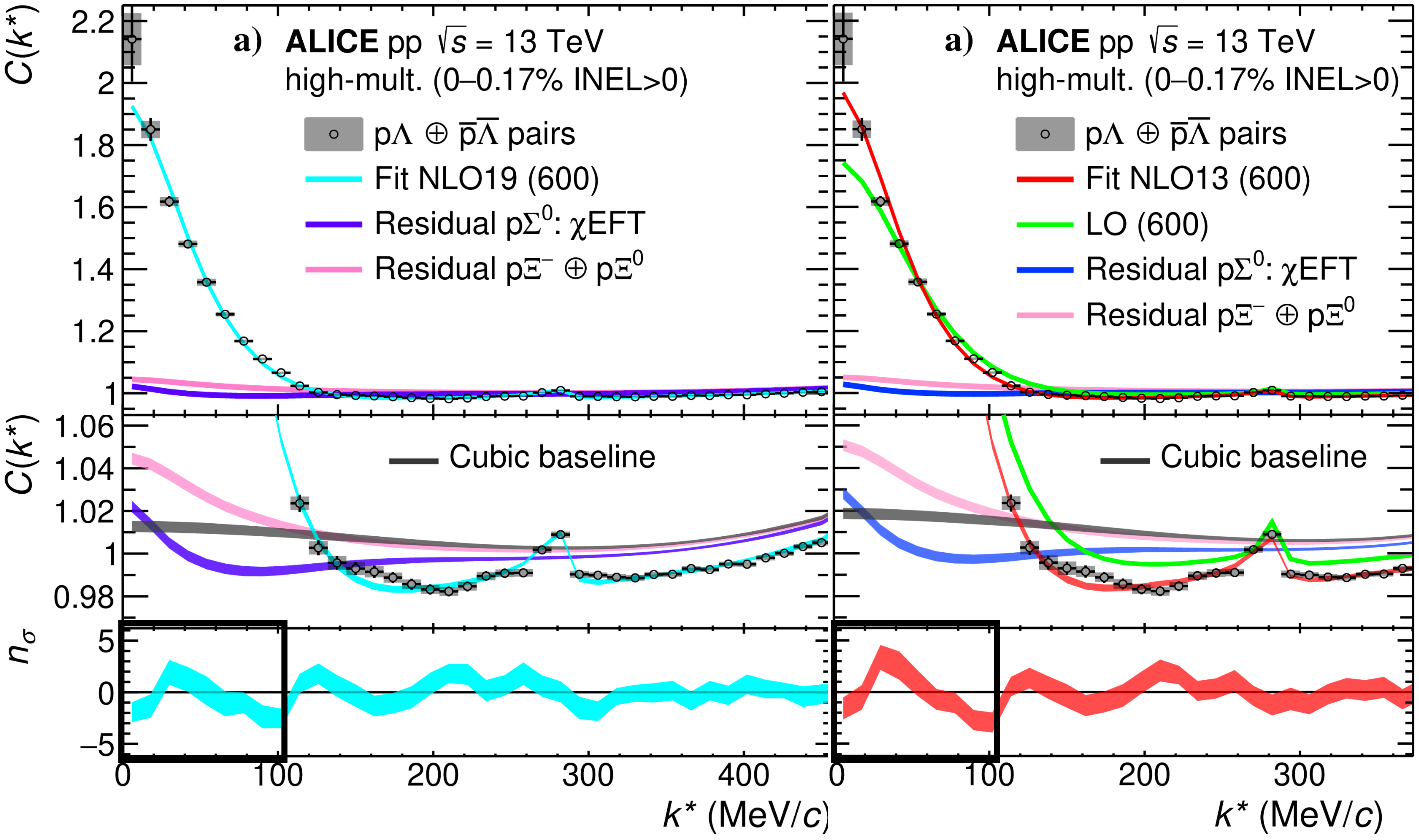


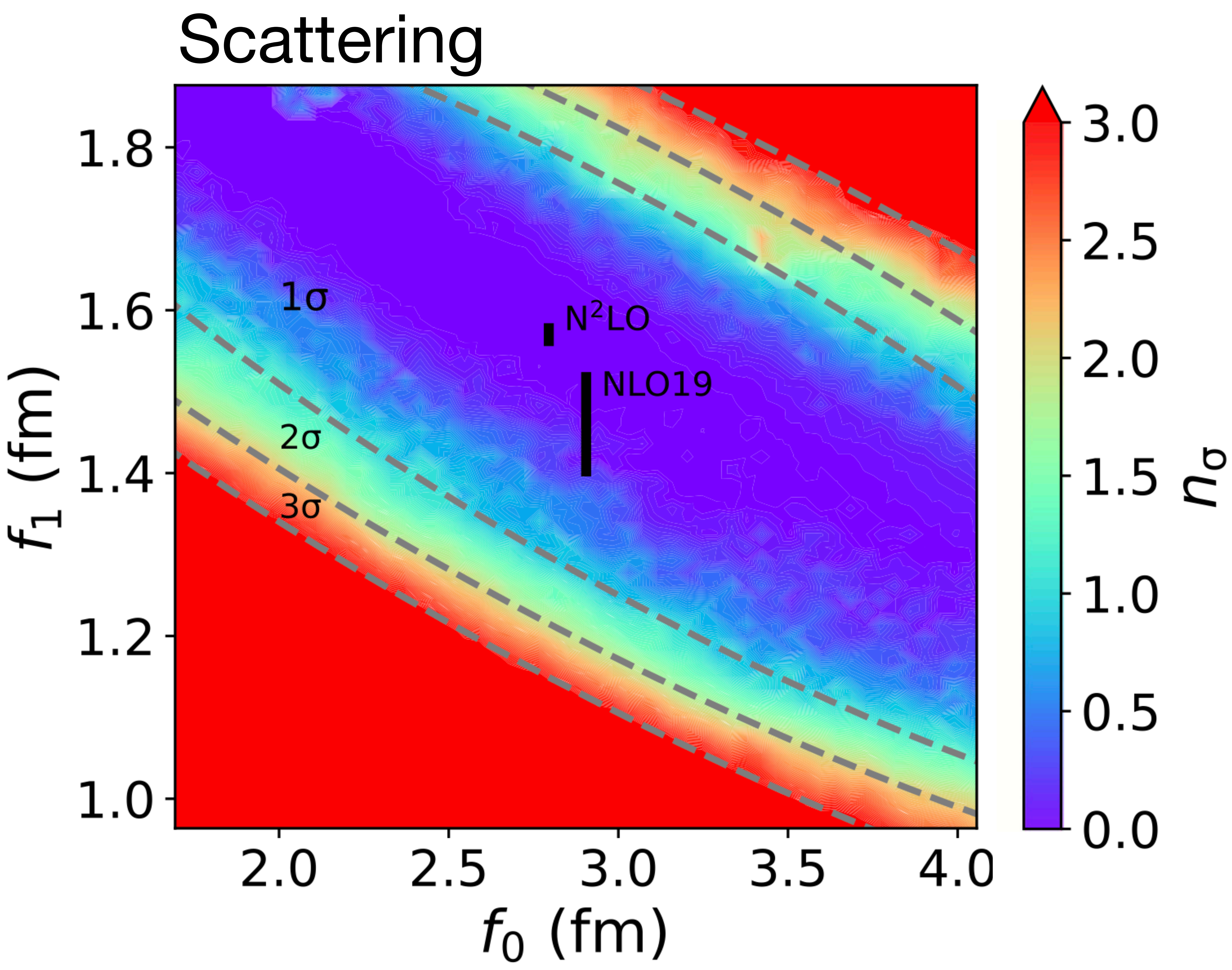
~3σ ~4σ

- Observation of the NΛ↔NΣ cusp
- Superior precision at low momenta over existing data
- Preference towards the NLO19
- NLO19 deviates by ~3σ at low k*

Further improvement of the model is possible!

Based on ALICE Coll. PLB 833 (2022), 137272

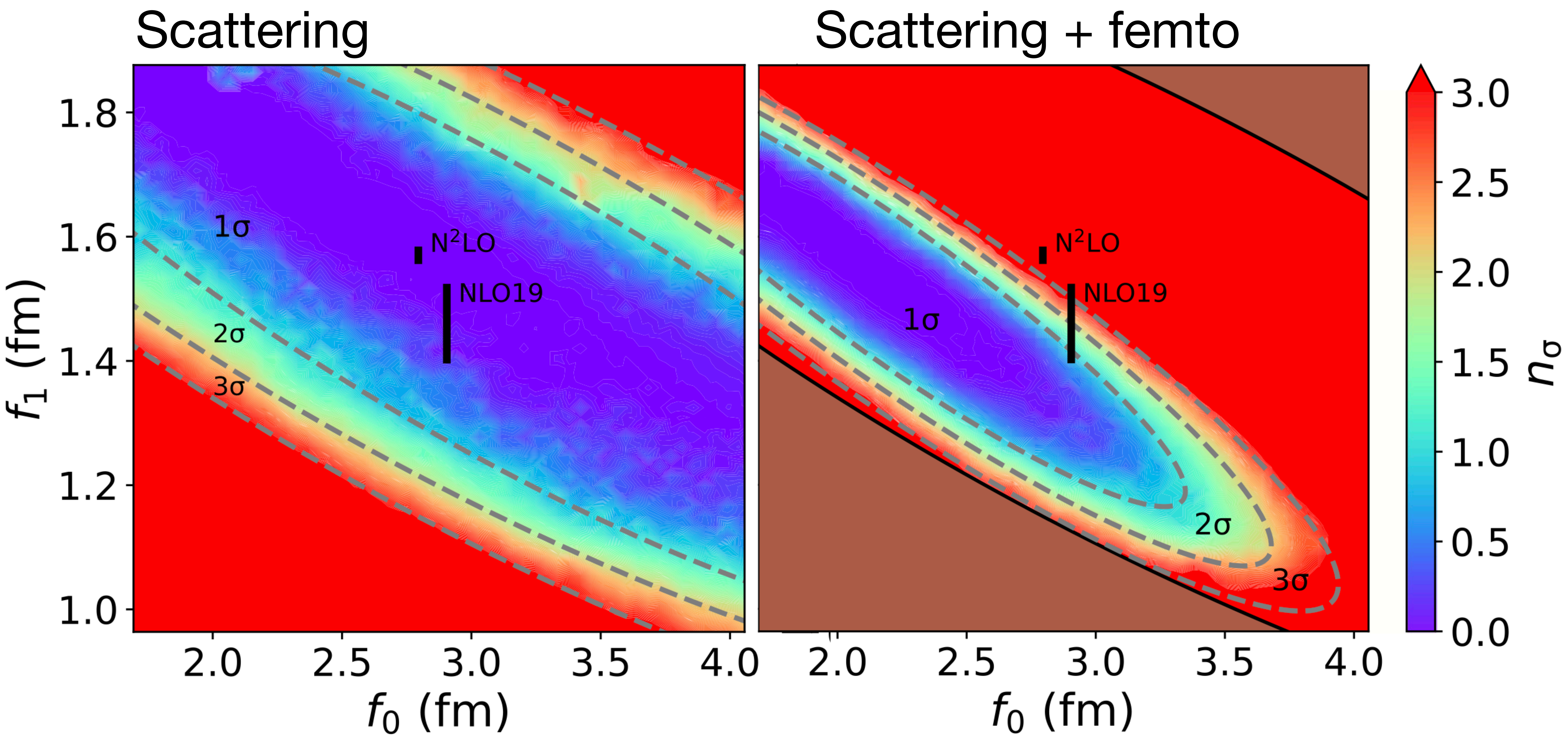
Refitting the theory



D. Mihaylov et al, PLB 850 (2024), 138550

Refitting the theory

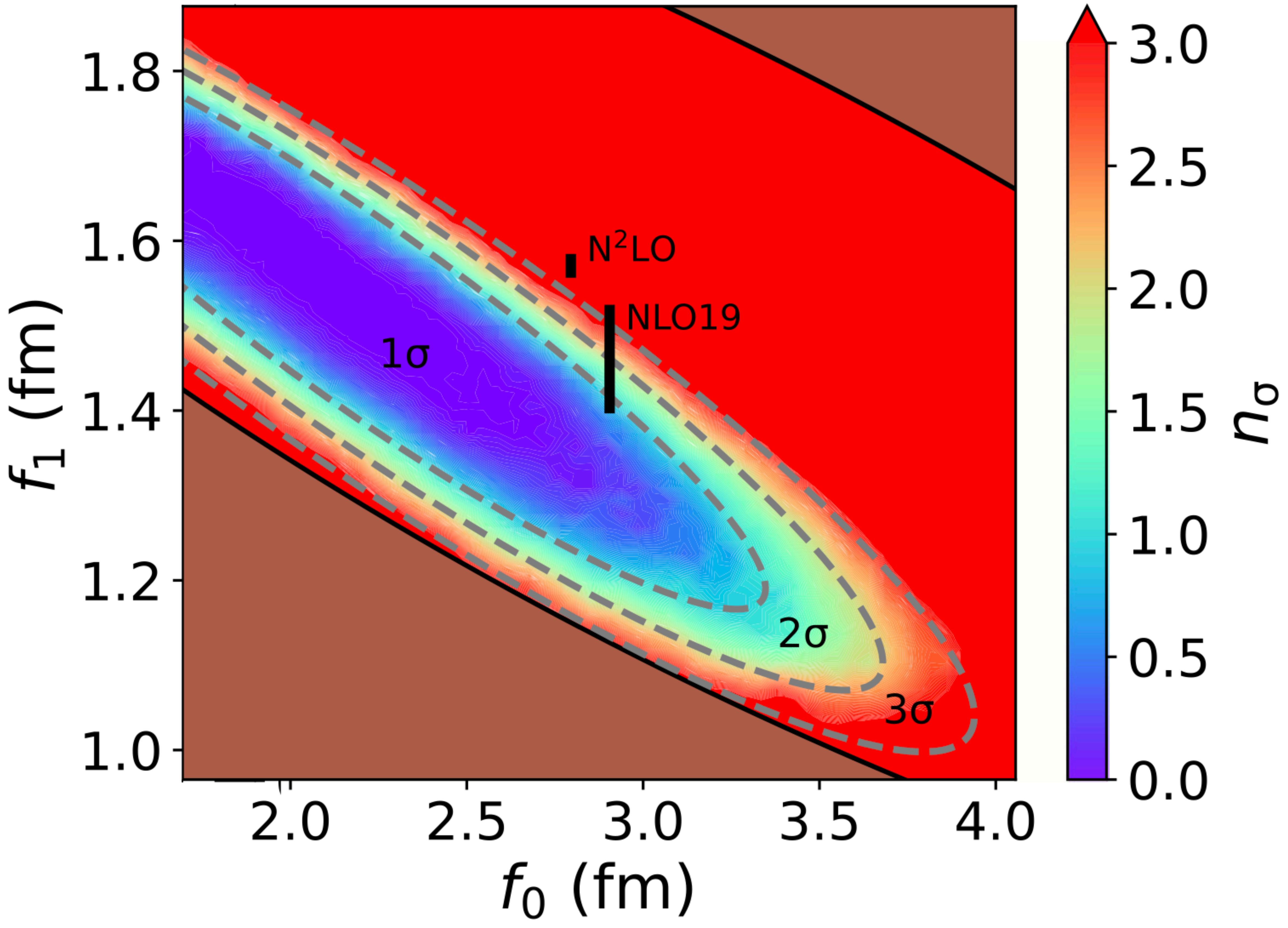
- New limits for the scattering lengths: $f_1 \approx 2.2\mathrm{fm} - 0.3f_0(\pm 0.1\mathrm{fm})$



D. Mihaylov et al, PLB 850 (2024), 138550

Refitting the theory

- Constrain low-energy constants of χEFT to the new results
- Evaluate the in-medium potential U_Λ



D. Mihaylov et al, PLB 850 (2024), 138550

Refitting the theory

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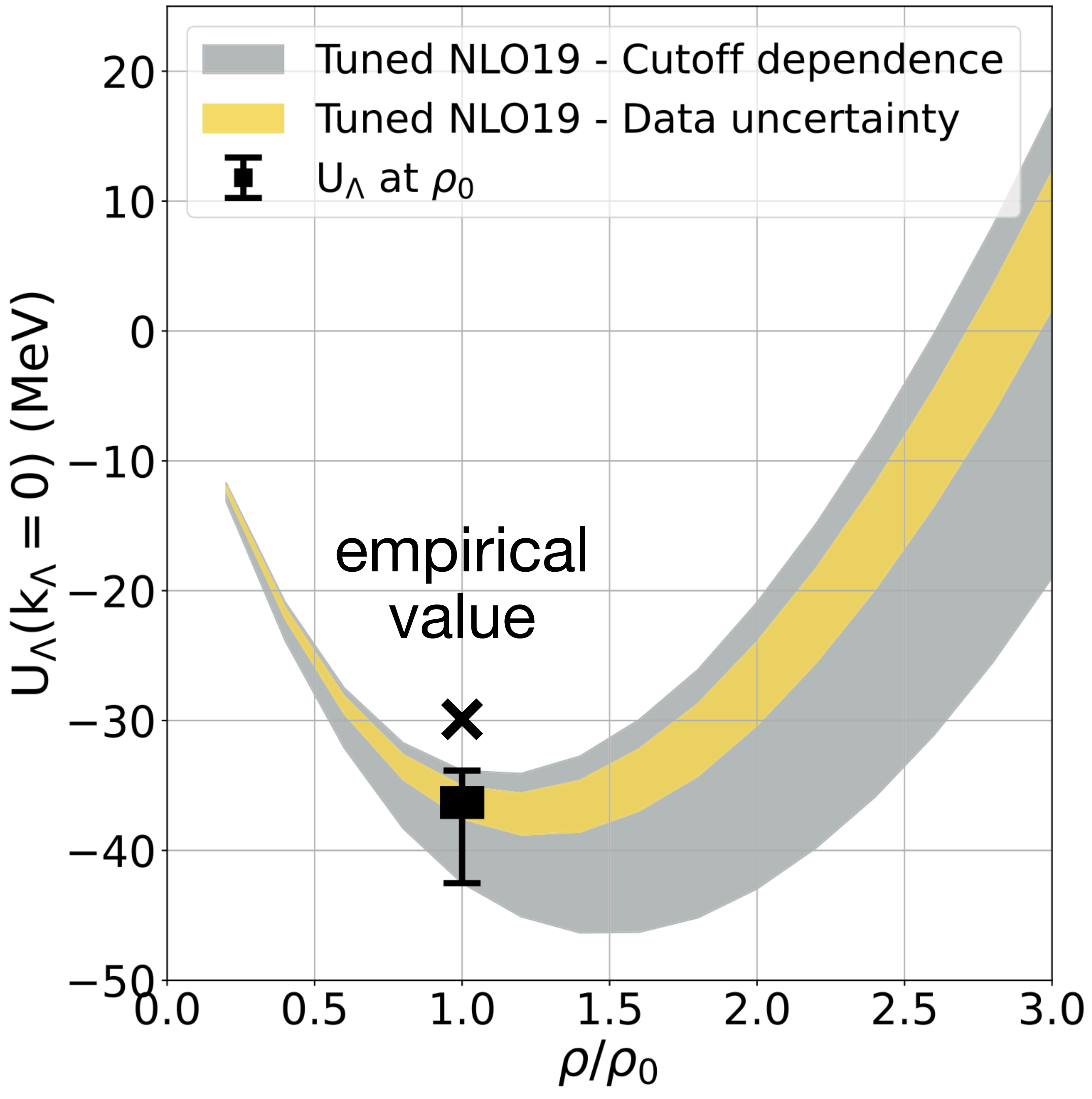
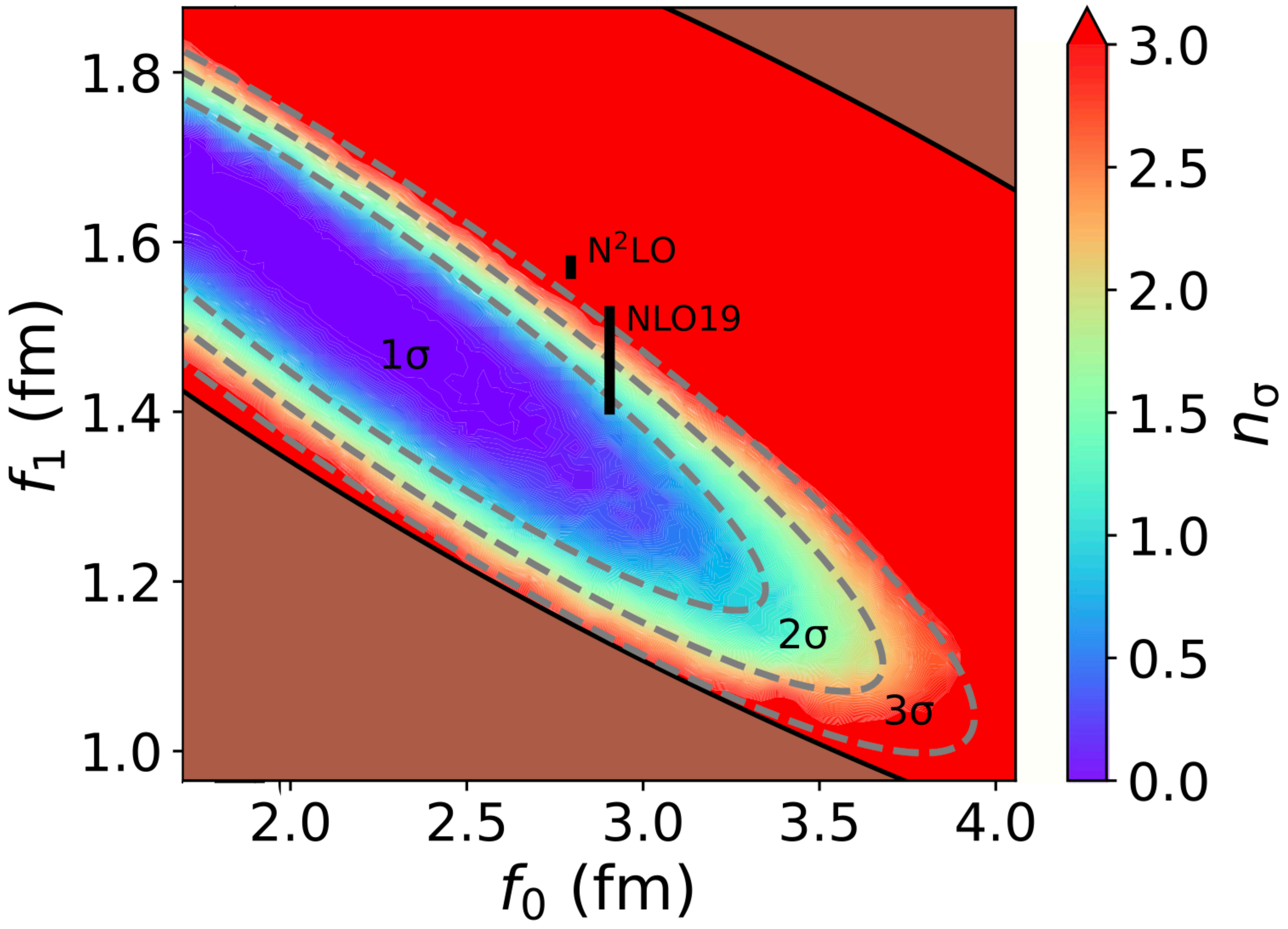


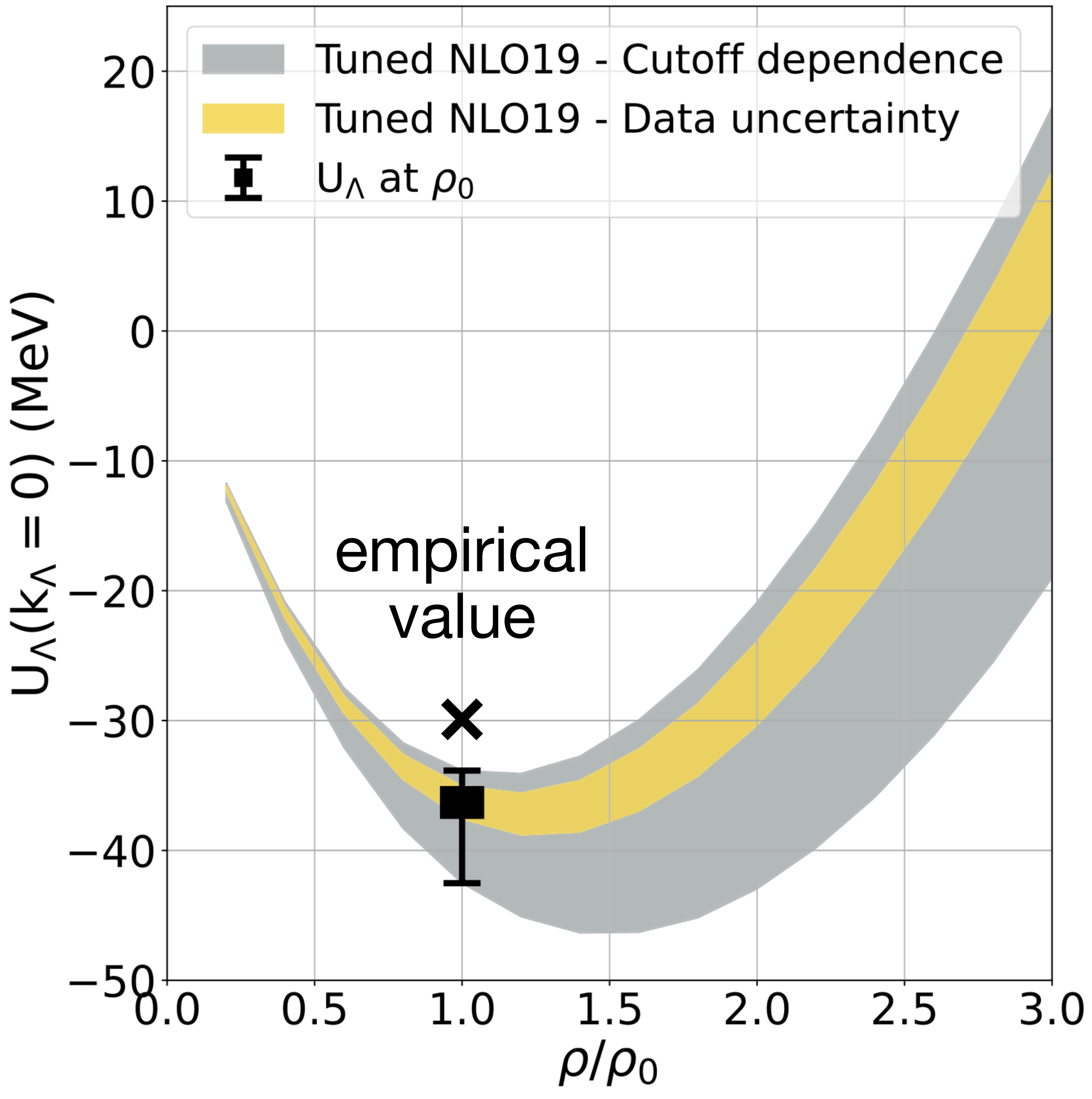


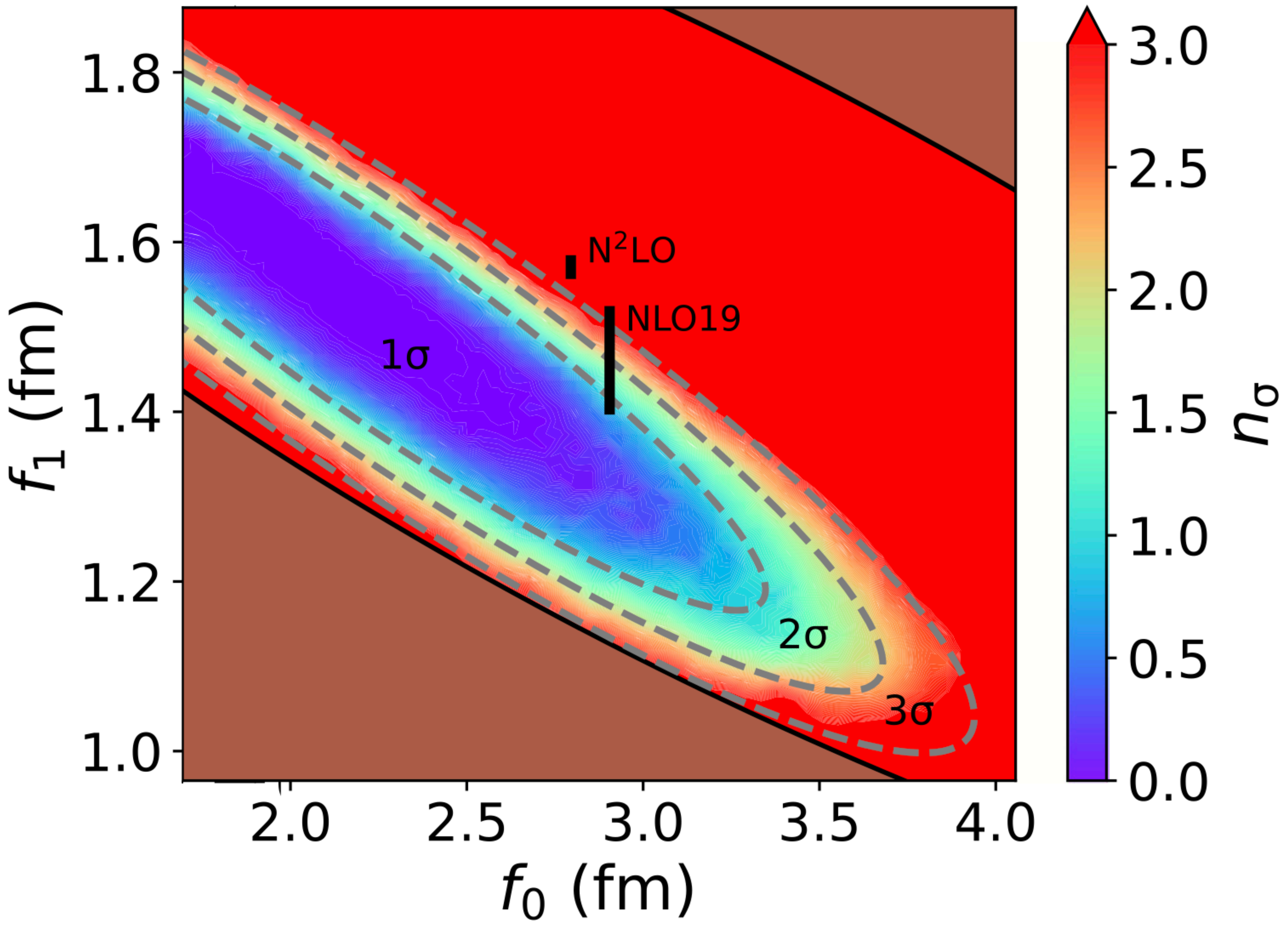
D. Mihaylov et al, PLB 850 (2024), 138550

Refitting the theory

- Constrain low-energy constants of χEFT to the new results
- Evaluate the in-medium potential U_Λ

Compatible with repulsive three-bodv forces!





D. Mihaylov et al, PLB 850 (2024), 138550

Interaction with strangeness

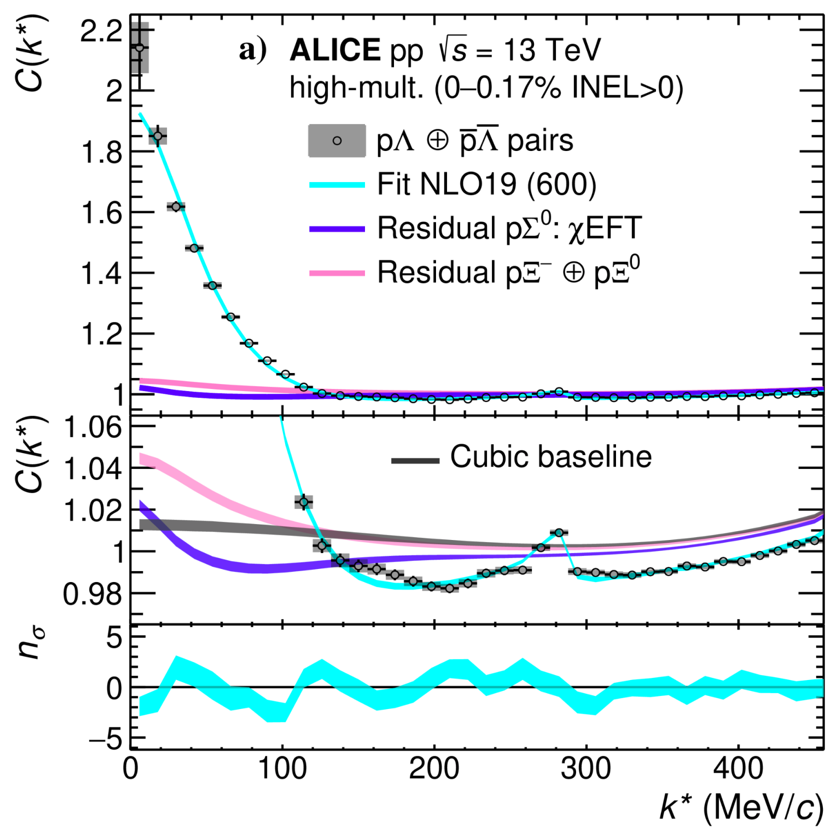
|S| = 0
NN

|S| = 1
NΛ, NΣ

|S| = 2
ΛΛ, NΞ

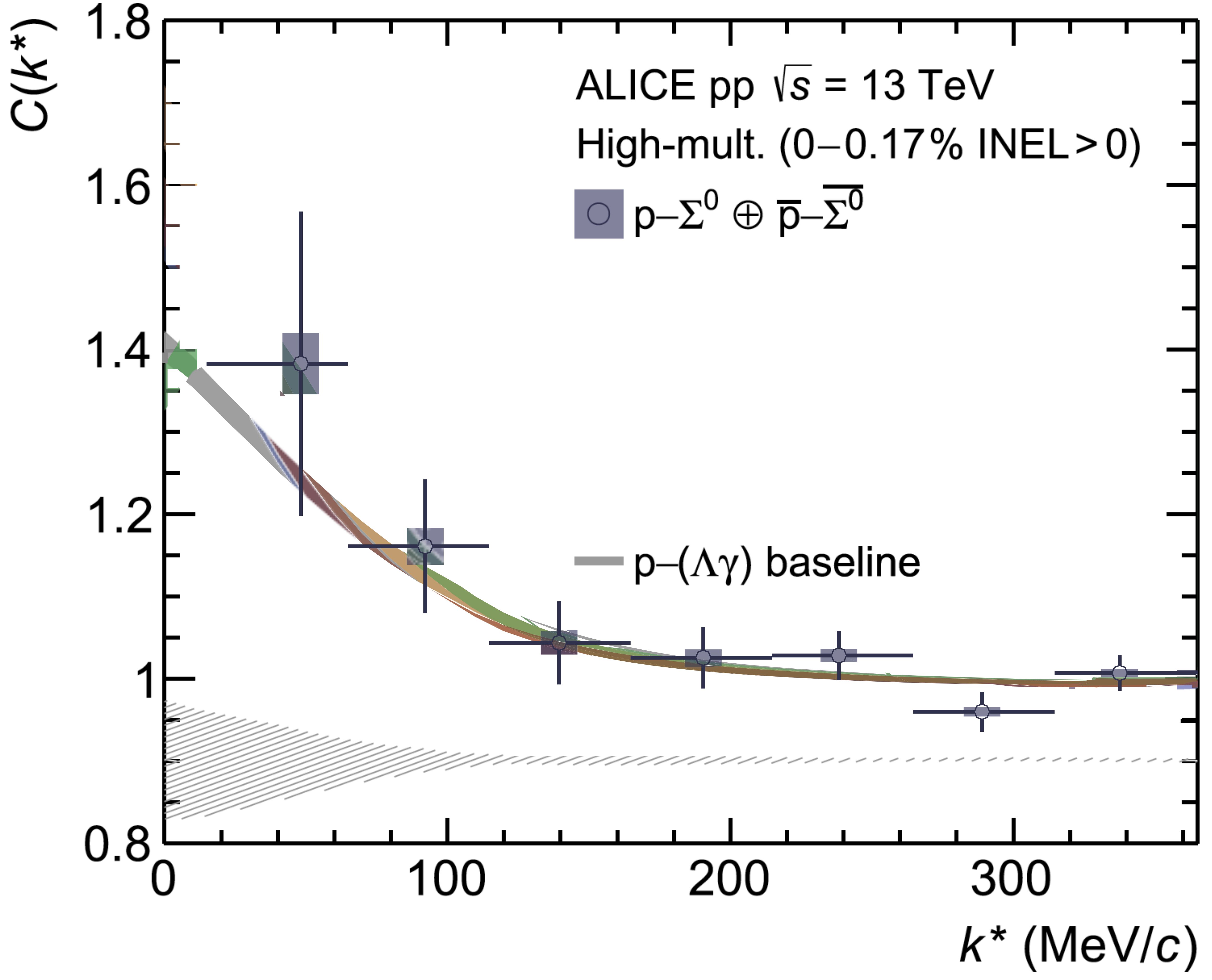
|S| = 3
ΛΞ, NΩ

|S| > 3
ΞΞ, ΛΩ, ΣΩ, ΞΩ, ΩΩ



|S|=1 sector: p-Σ⁰ interaction

ALICE Coll., PLB 805, 135419 (2020)



- Complicated reconstruction of the Σ^0 particle:

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

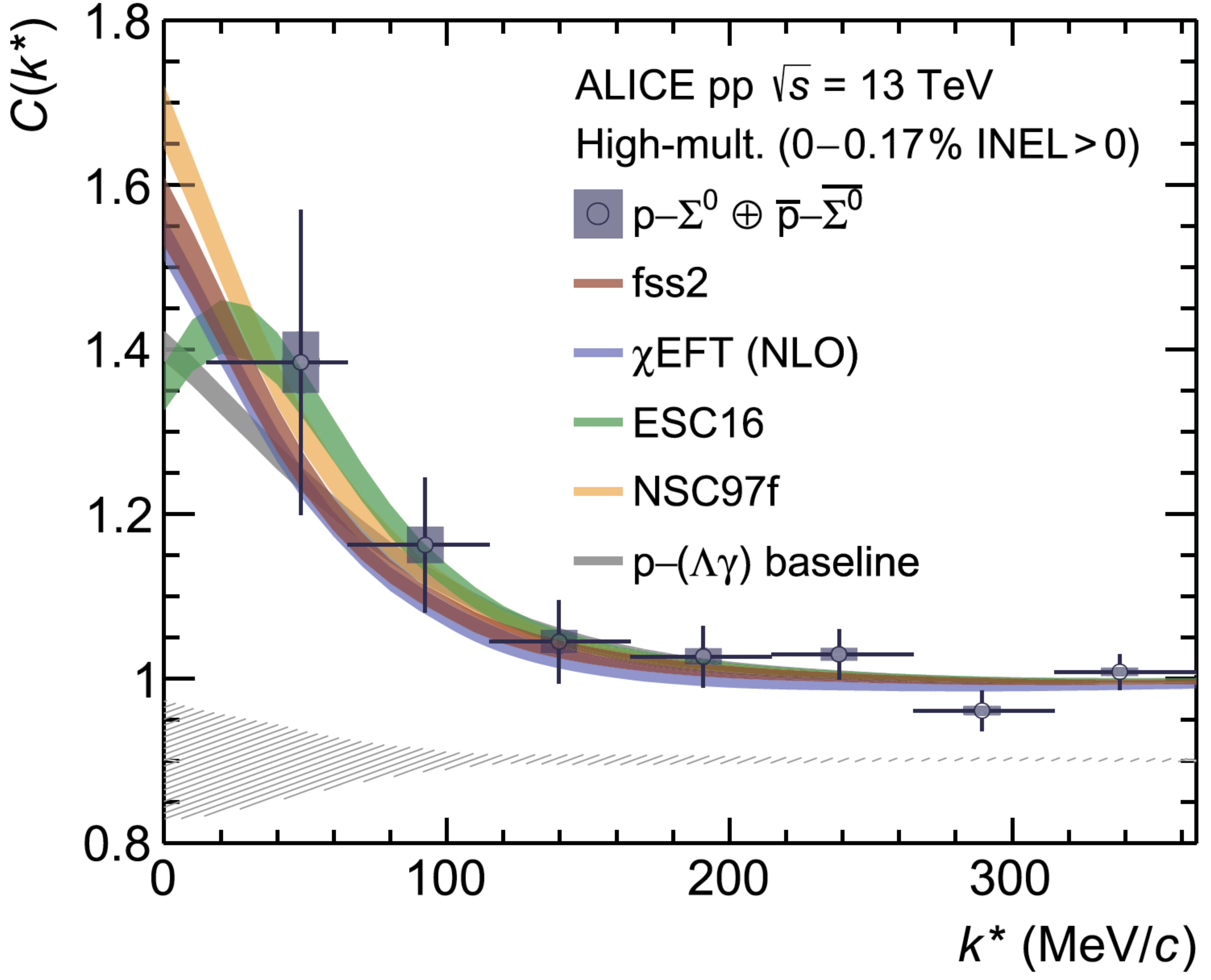
$$\Lambda \rightarrow p + \pi^-$$

- Results in a complicated baseline defined by the residual p-Λ interaction

- Shallow $\mathrm{p} - \Sigma^0$ interaction
  - data compatible to baseline within (0.2-0.8)σ

|S|=1 sector: p-Σ^0 interaction

ALICE Coll., PLB 805, 135419 (2020)



- Complicated reconstruction of the Σ^0 particle:

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

$$\Lambda \rightarrow p + \pi^-$$

- Results in a complicated baseline defined by the residual p-Λ interaction
- Shallow $\mathrm{p} - \Sigma^0$ interaction
  - data compatible to baseline within (0.2-0.8)σ
- Cannot differentiate between models due to limited statistics

Interaction with strangeness

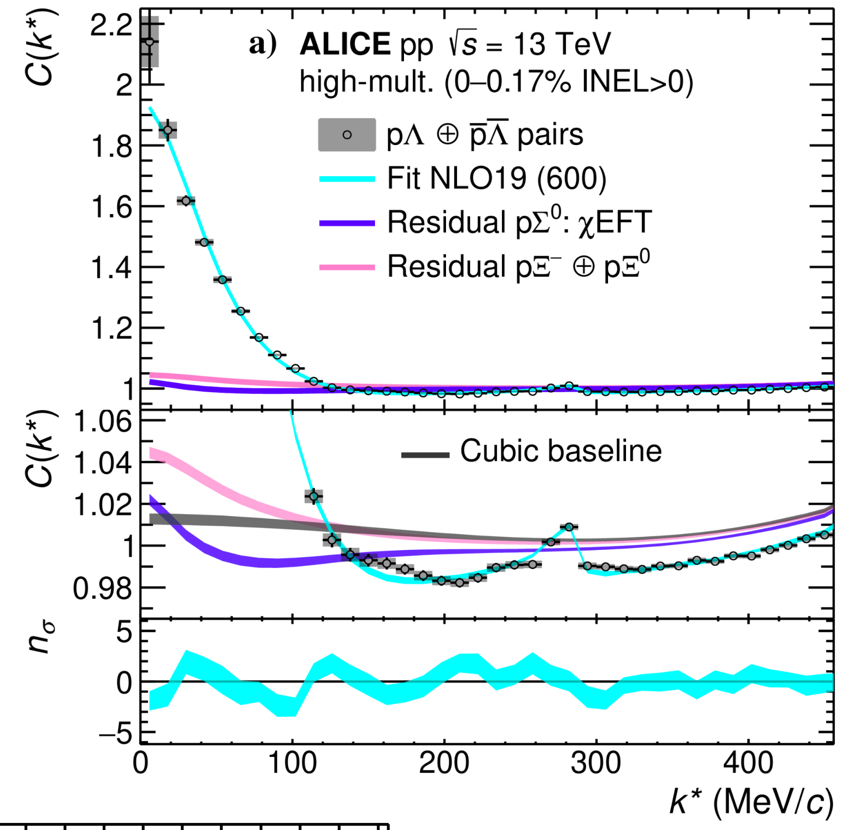
|S| = 0
NN

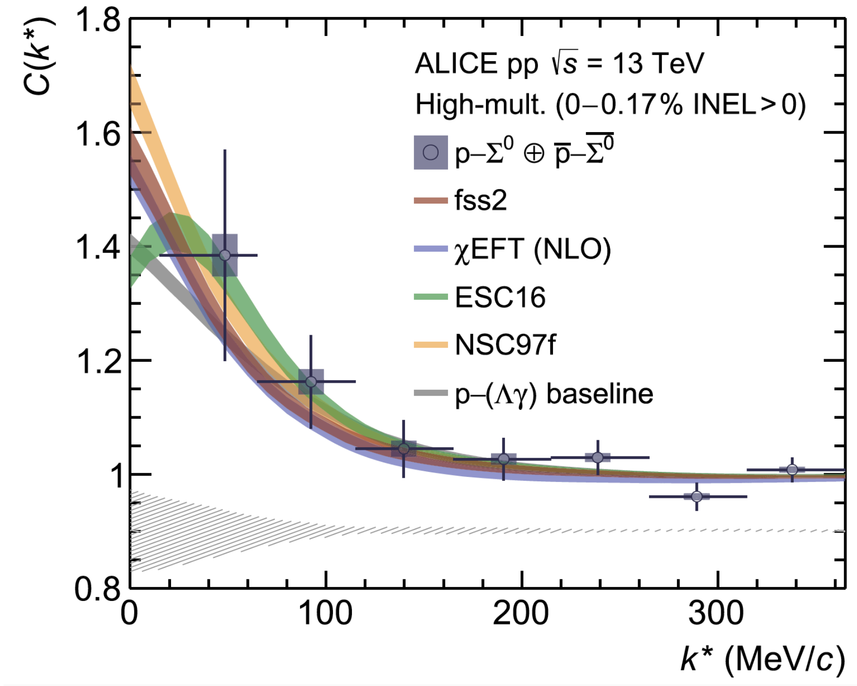
|S| = 1
NΛ, NΣ

|S| = 2
ΛΛ, NΞ

|S| = 3
ΛΞ, NΩ

|S| > 3
ΞΞ, ΛΩ, ΣΩ, ΞΩ, ΩΩ

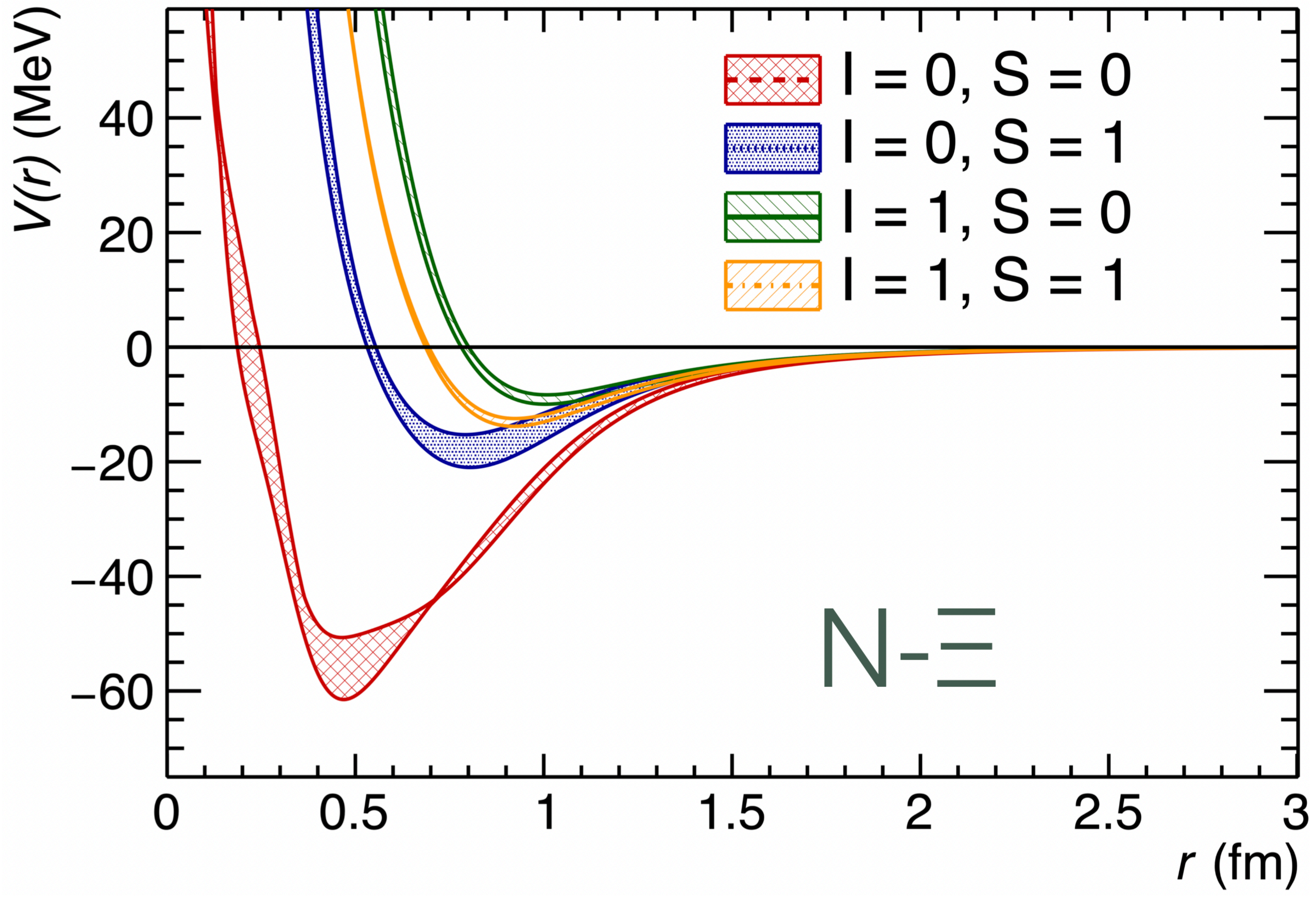




|S|=2 sector: p-Ξ^- interaction

- Theory:
  - Lattice QCD potentials by HAL QCD Collaboration
  - Solve Schrödinger Equation to obtain wave function and evaluate correlation

Based on:
HAL QCD Coll. NPA 998 (2020)
T. Hatsuda, Front. Phys. 13(6), 132105 (2018)



|S|=2 sector: p-Ξ⁻ interaction

- Theory:
  - Lattice QCD potentials by HAL QCD Collaboration
  - Solve Schrödinger Equation to obtain wave function and evaluate correlation

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

Based on:
HAL QCD Coll. NPA 998 (2020)
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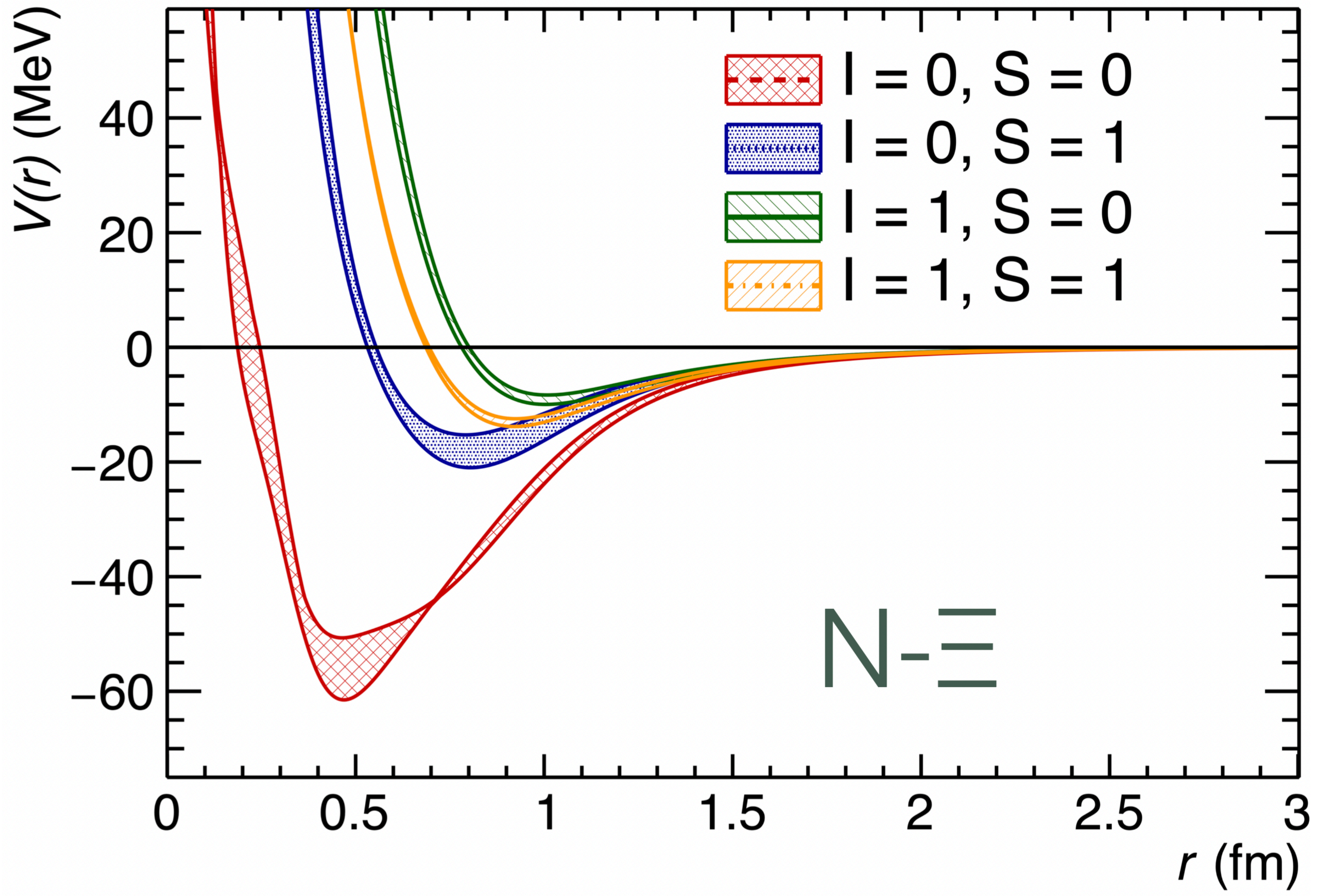

|S|=2 sector: p-Ξ^- interaction

- Theory:
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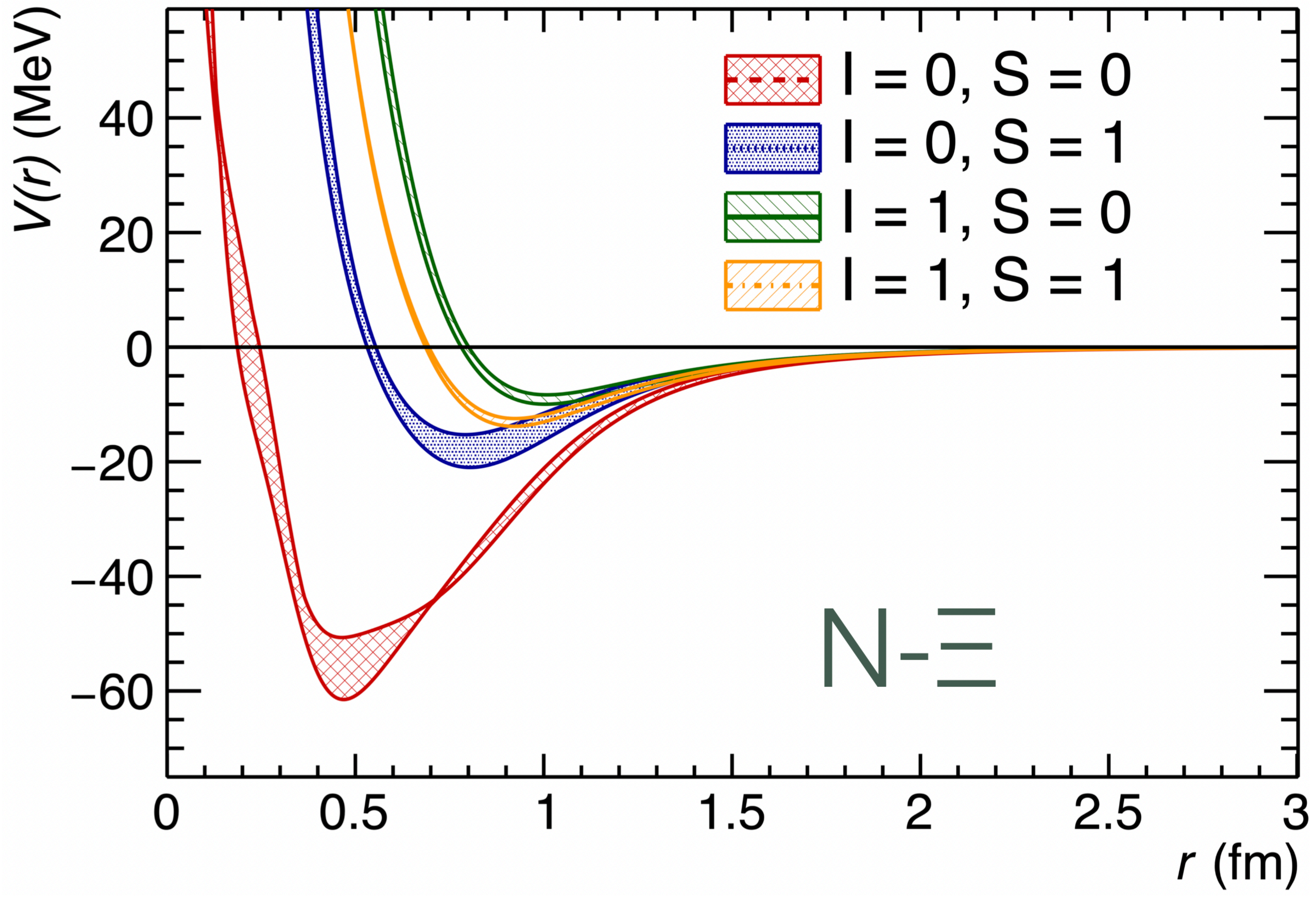
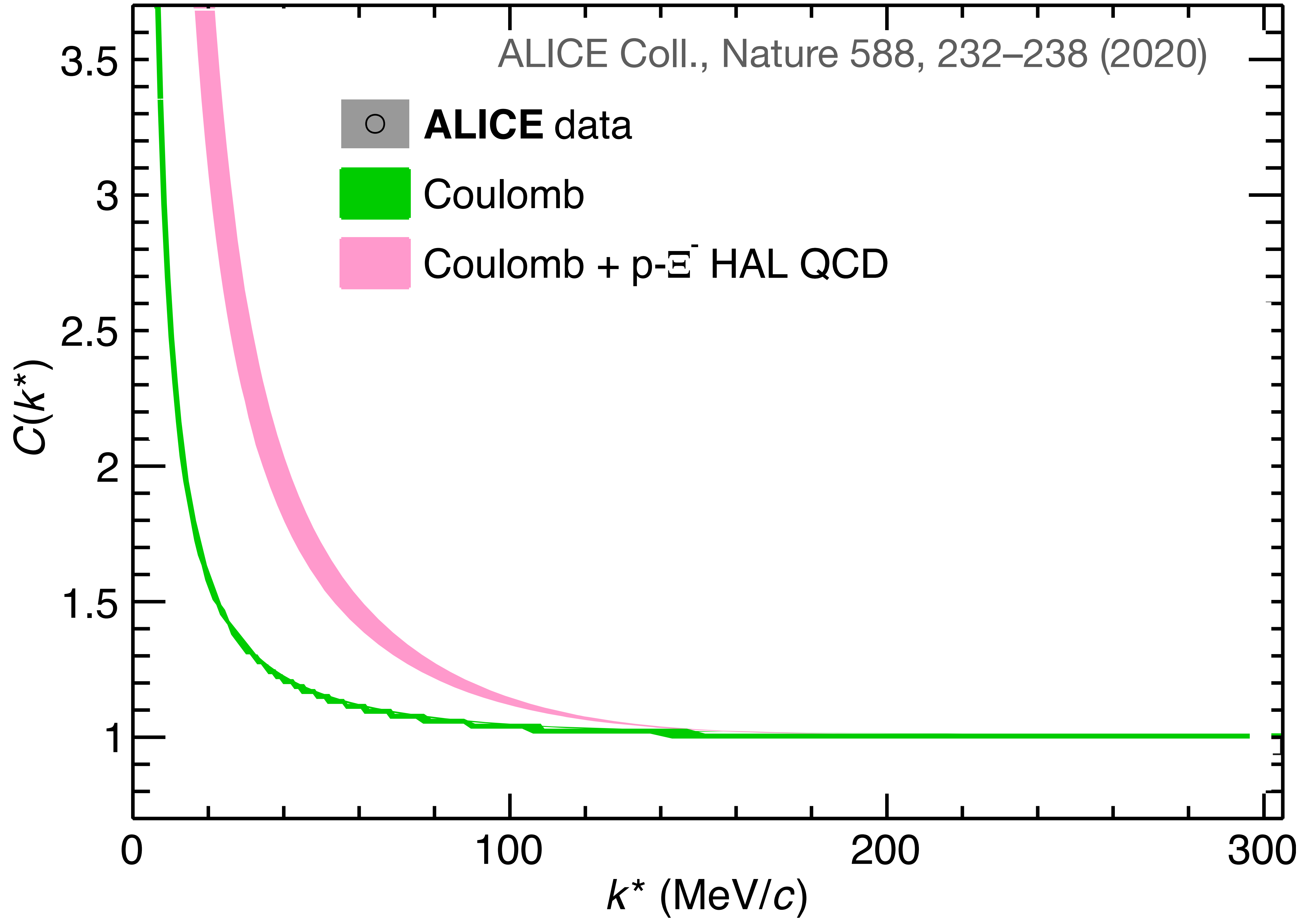


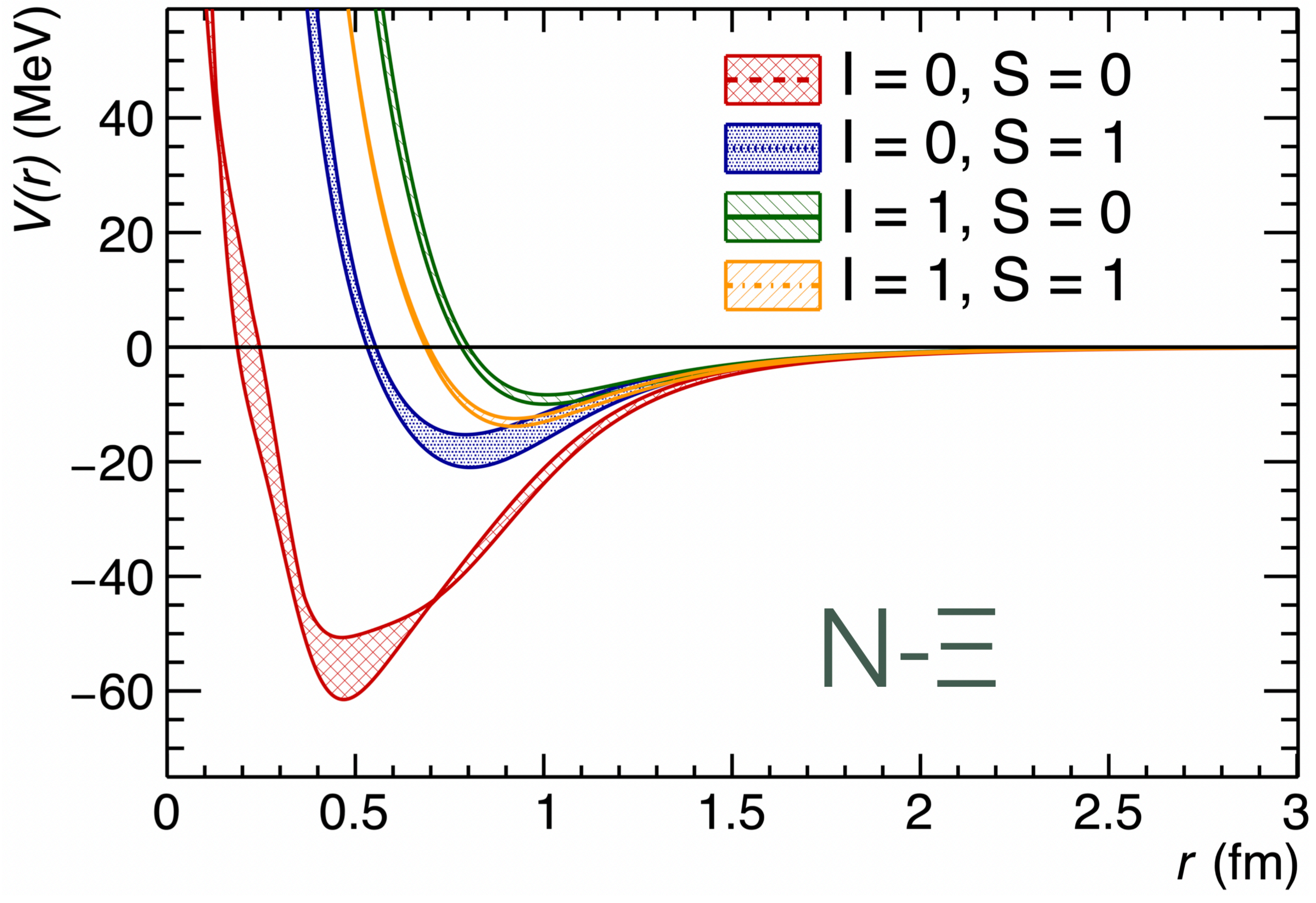


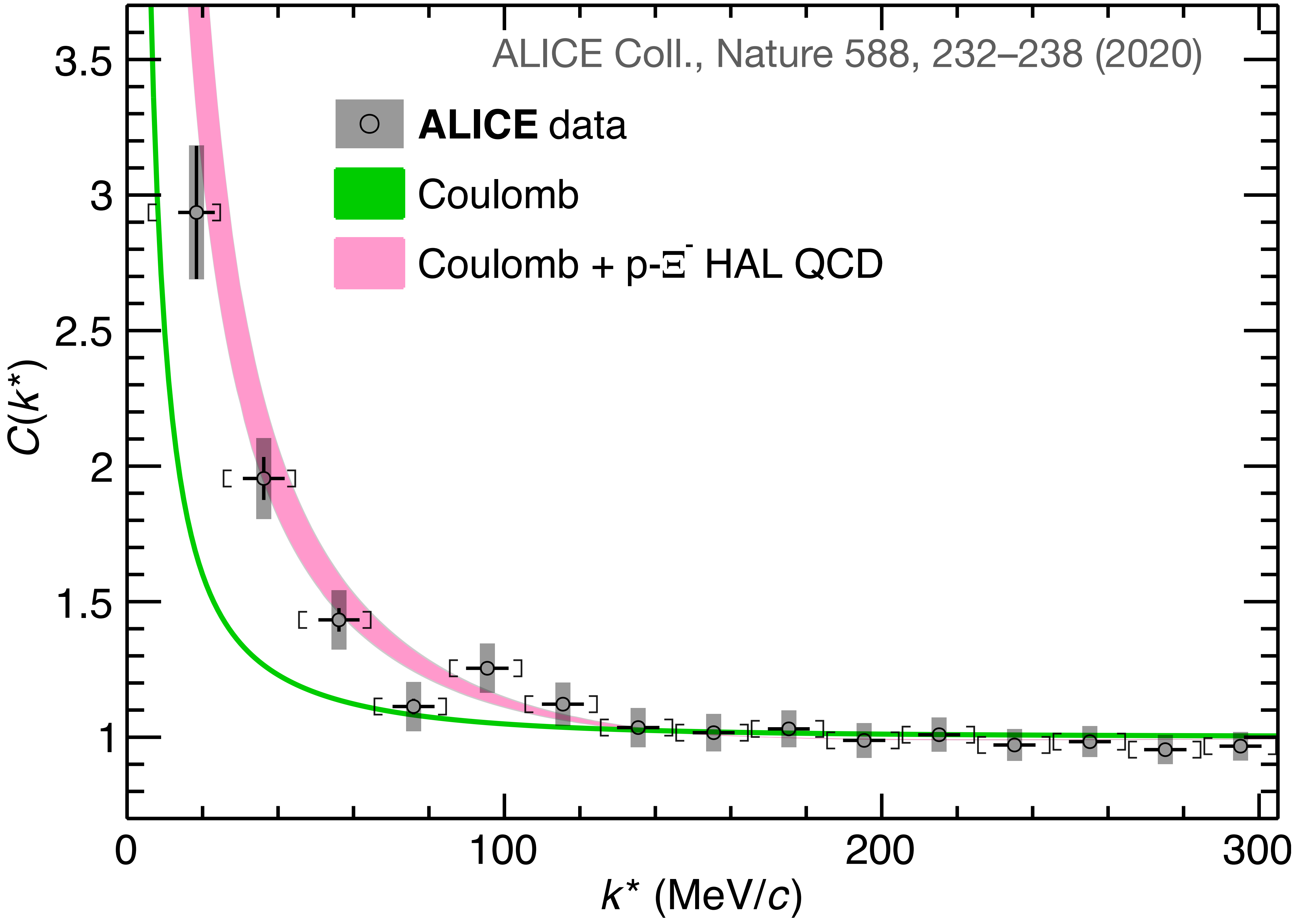
|S|=2 sector: p-Ξ⁻ interaction

- Theory:
  - Lattice QCD potentials by HAL QCD Collaboration
  - Solve Schrödinger Equation to obtain wave function and evaluate correlation

- Femtoscopy data:
  - Lattice QCD potentials by HAL QCD Collaboration
  - HAL QCD potential in agreements with data

Based on:
HAL QCD Coll. NPA 998 (2020)
T. Hatsuda, Front. Phys. 13(6), 132105 (2018)





Interaction with strangeness

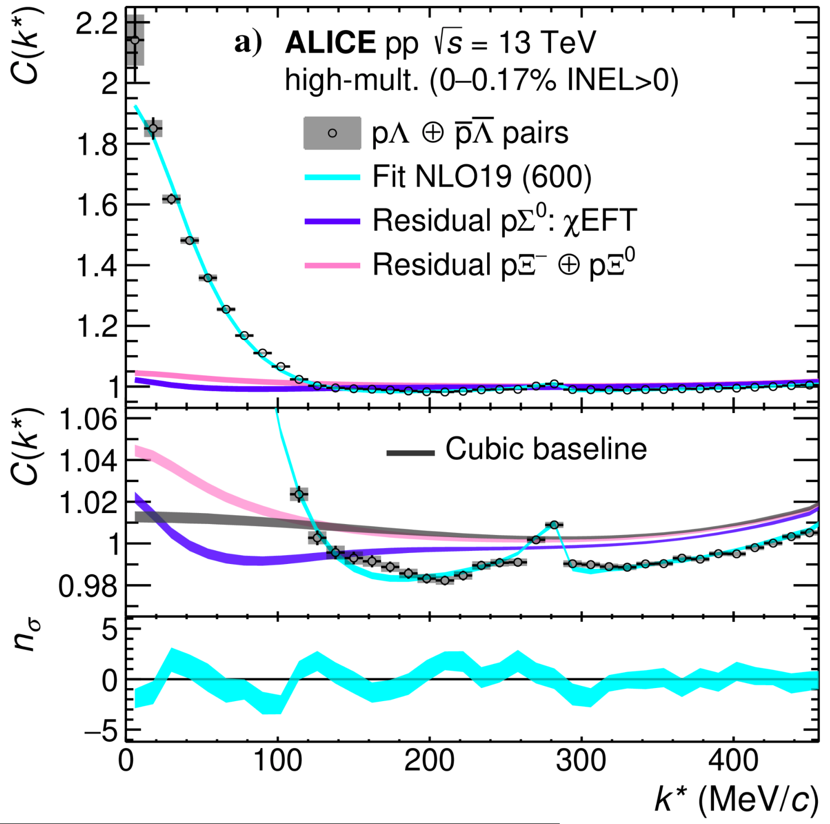
|S| = 0
NN

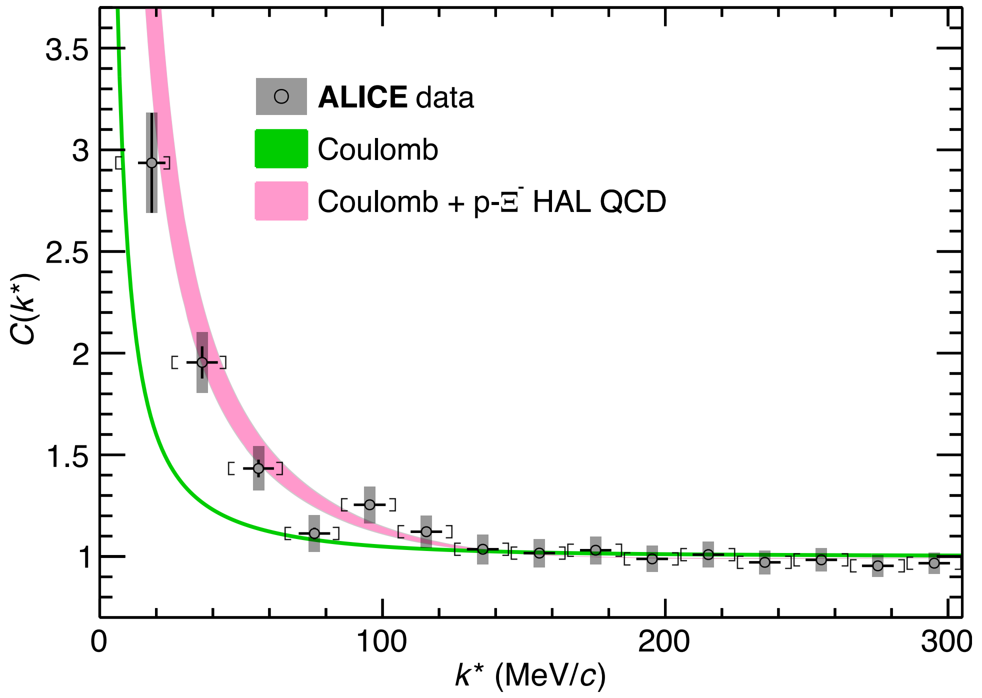
|S| = 1
NΛ, NΣ

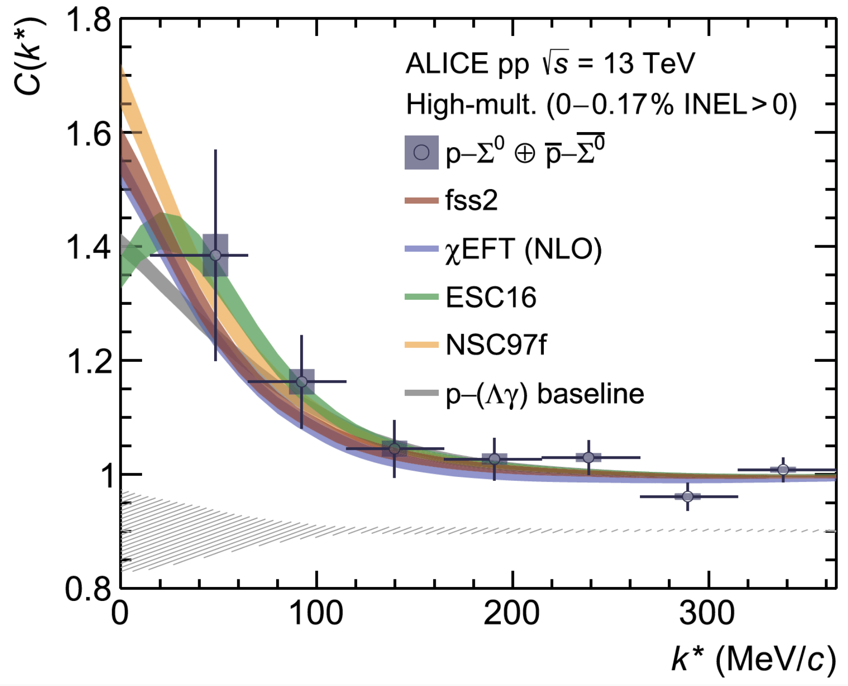
|S| = 2
ΛΛ, NΞ

|S| = 3
ΛΞ, NΩ

|S| > 3
ΞΞ, ΛΩ, ΣΩ, ΞΩ, ΩΩ







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|S| = 2
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|S| = 3
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|S| > 3
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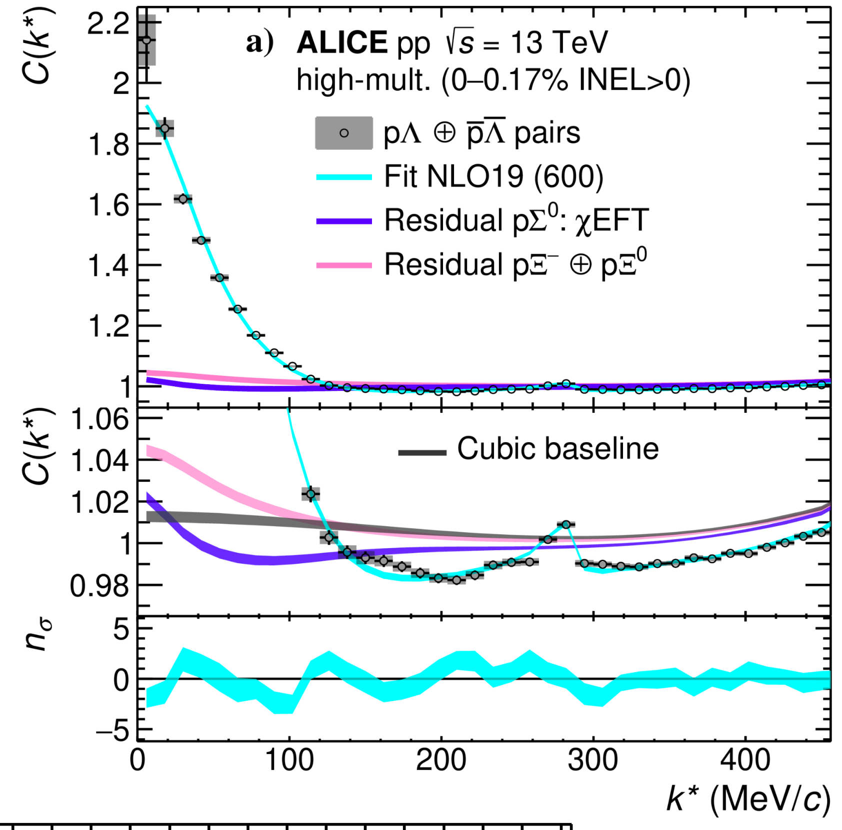
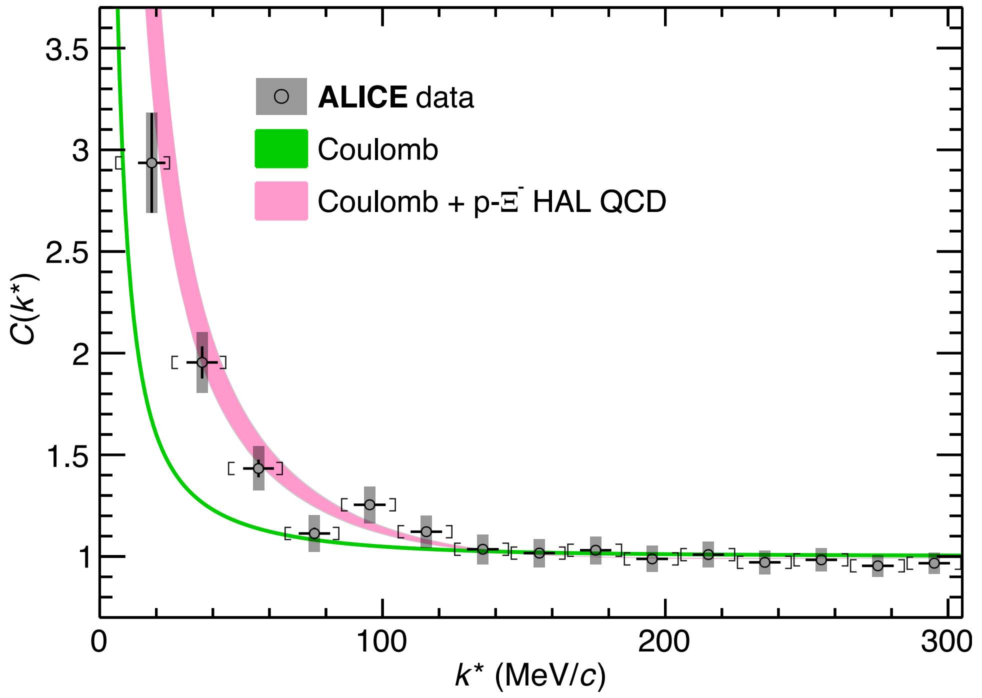
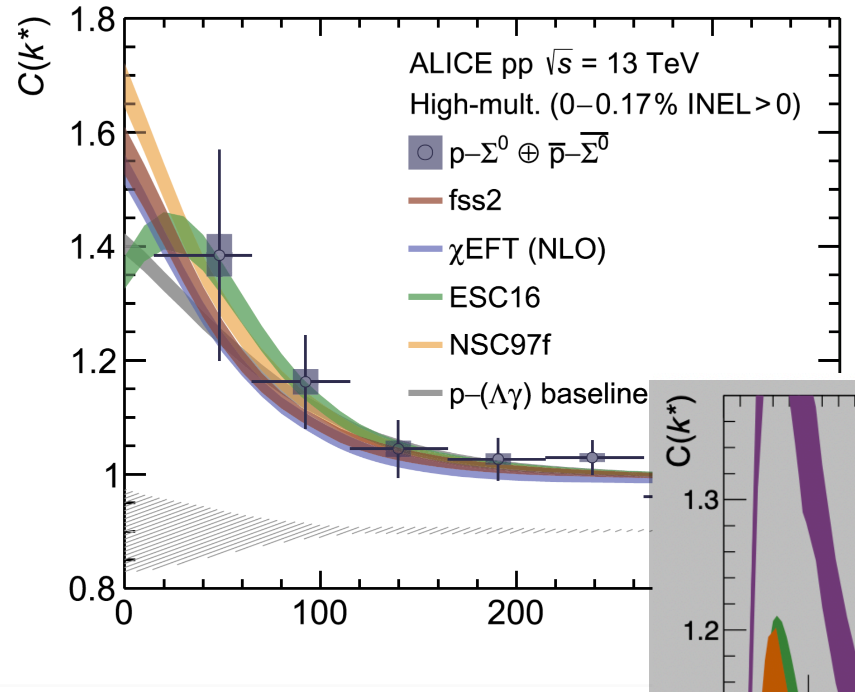
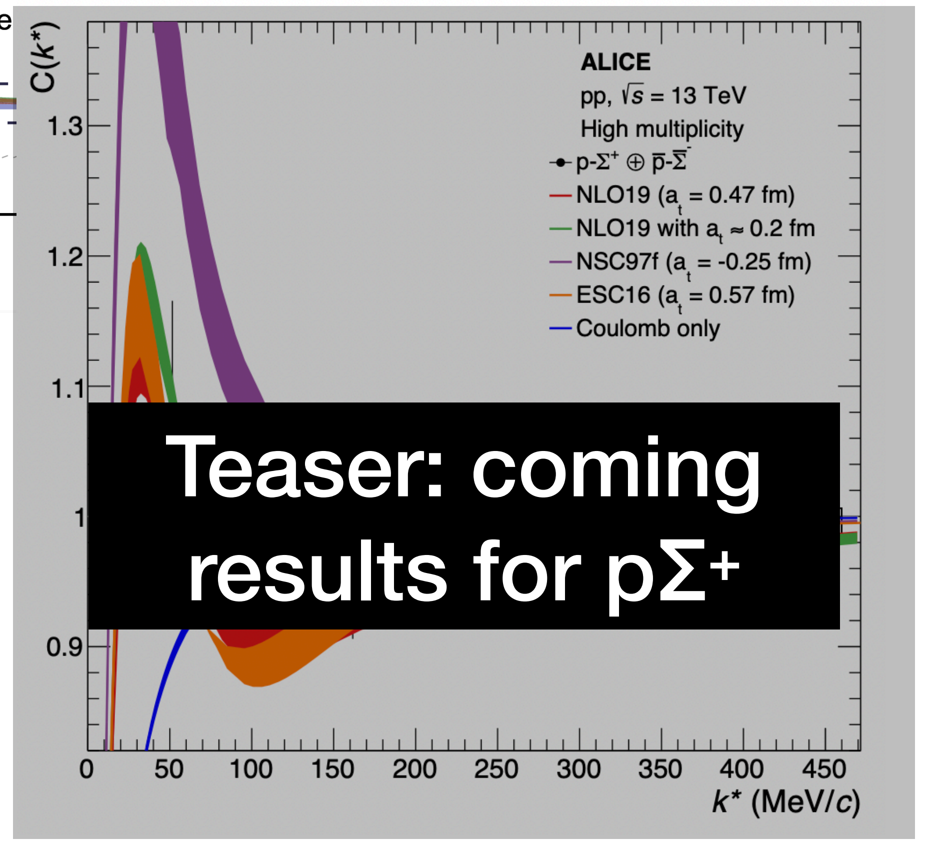








Teaser: coming results for pΣ+

Interaction with strangeness

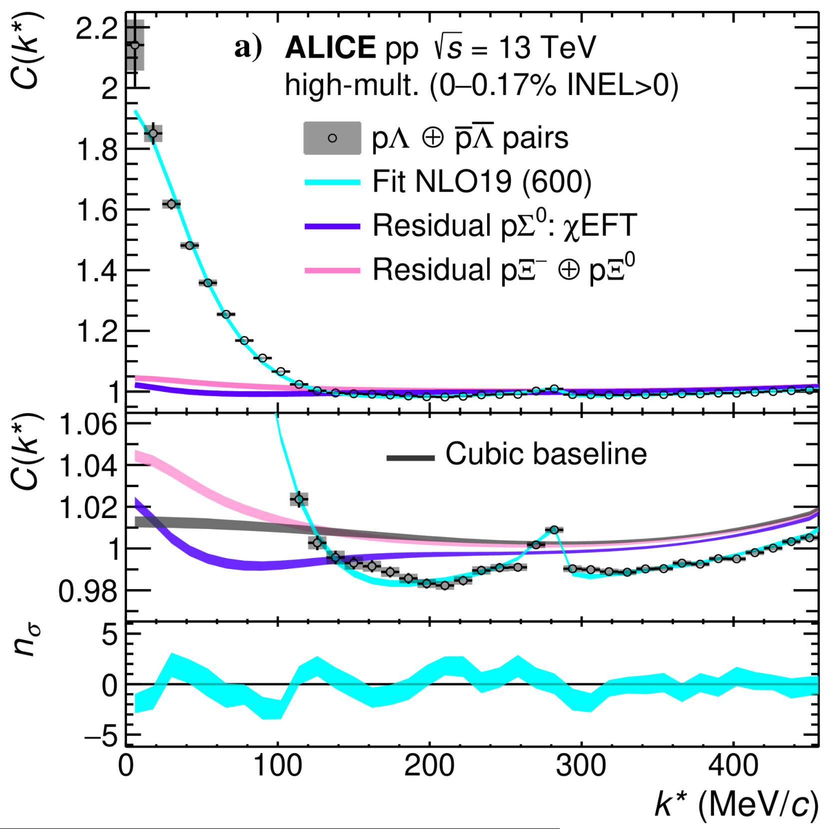
|S| = 0
NN

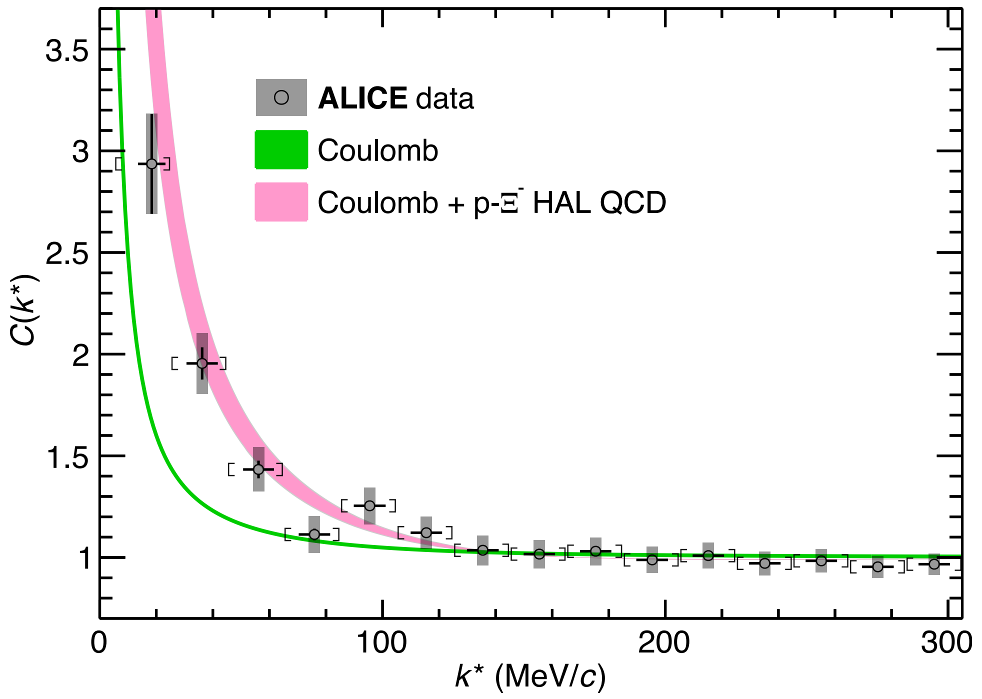
|S| = 1
NΛ, NΣ

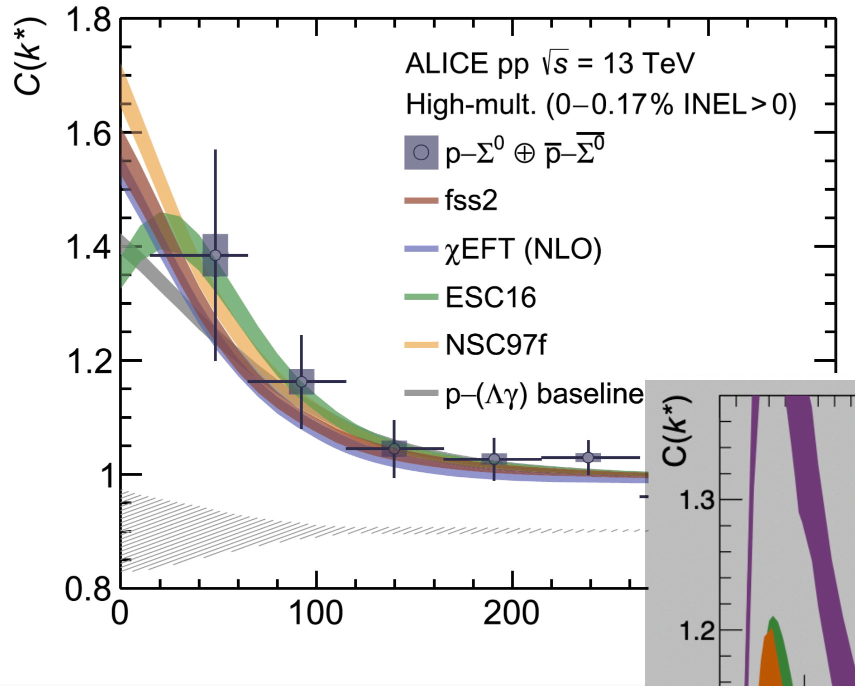
|S| = 2
ΛΛ, NΞ

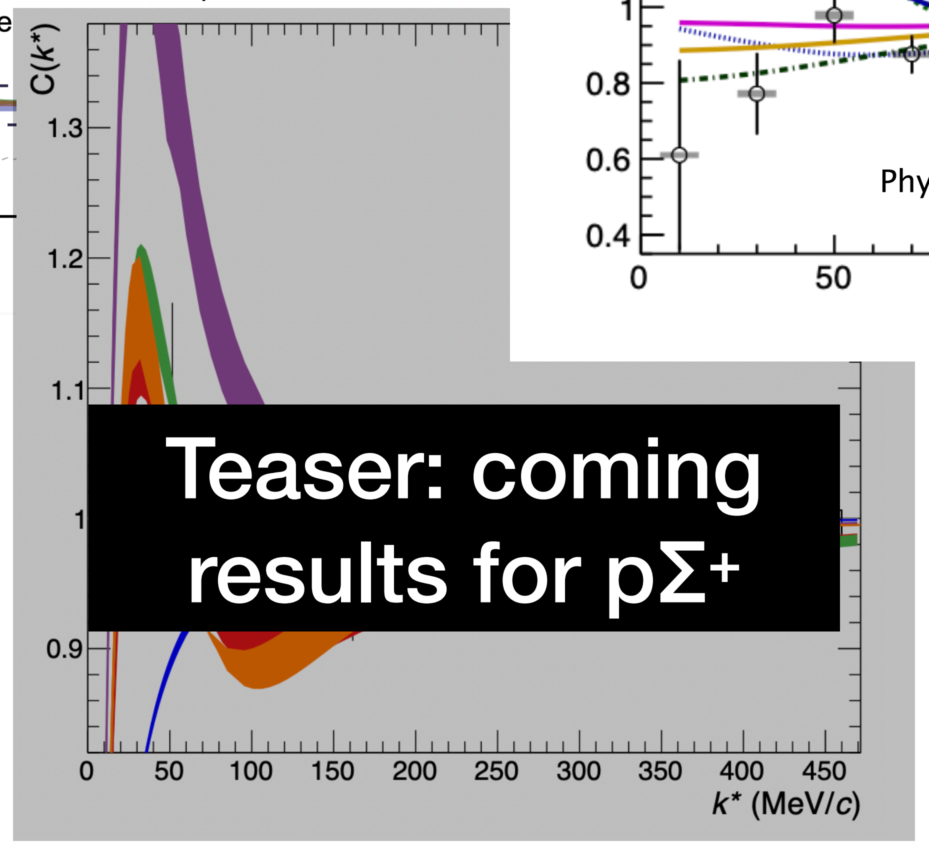
|S| = 3
ΛΞ, NΩ

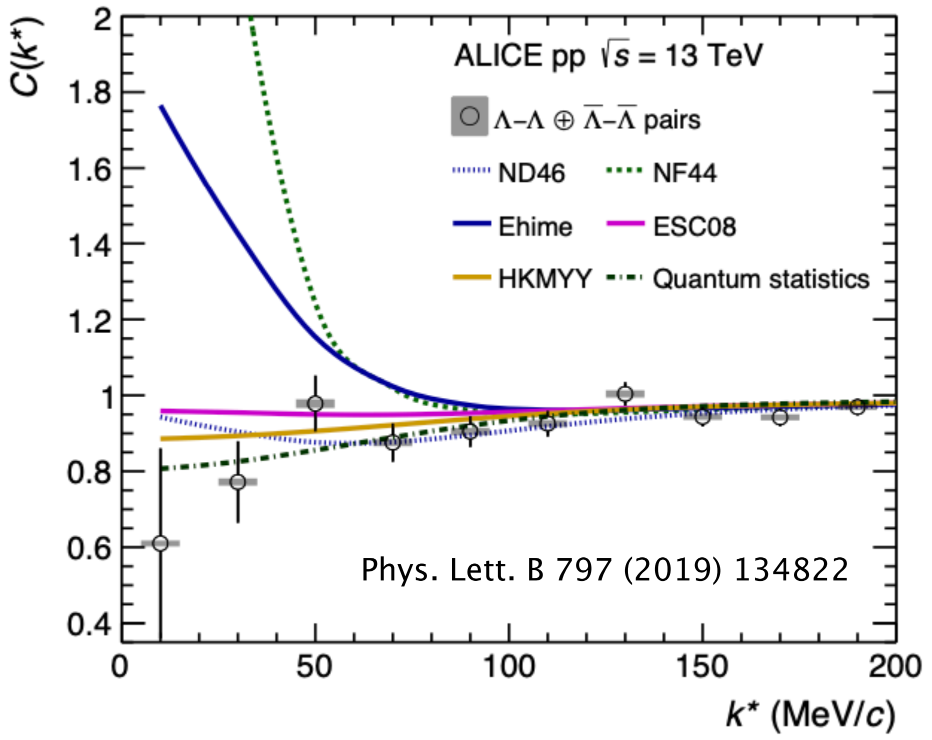
|S| > 3
ΞΞ, ΛΩ, ΣΩ, ΞΩ, ΩΩ





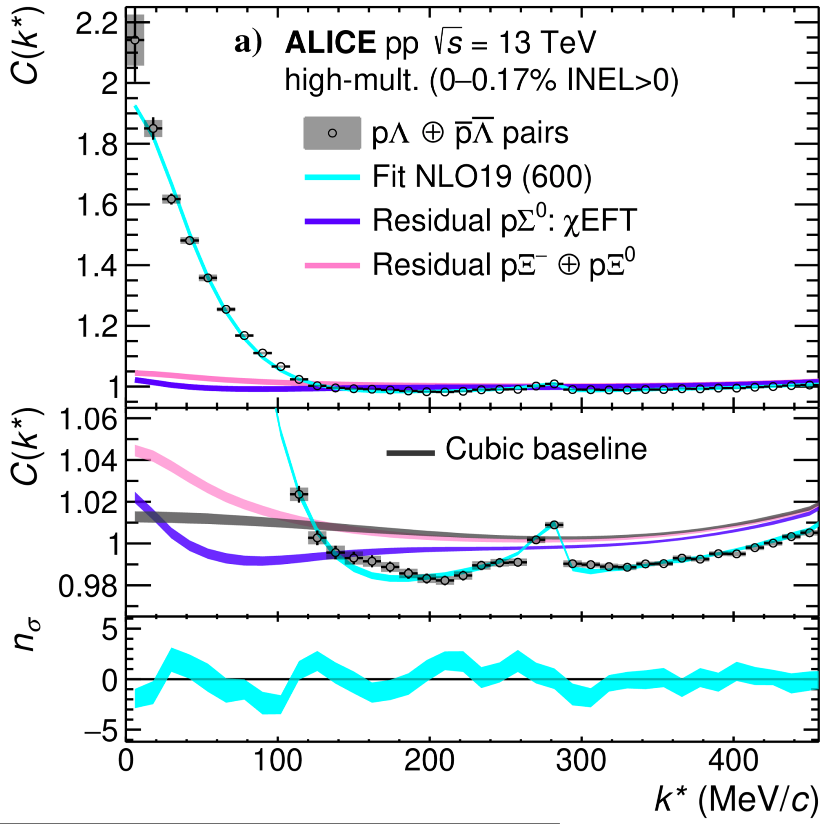


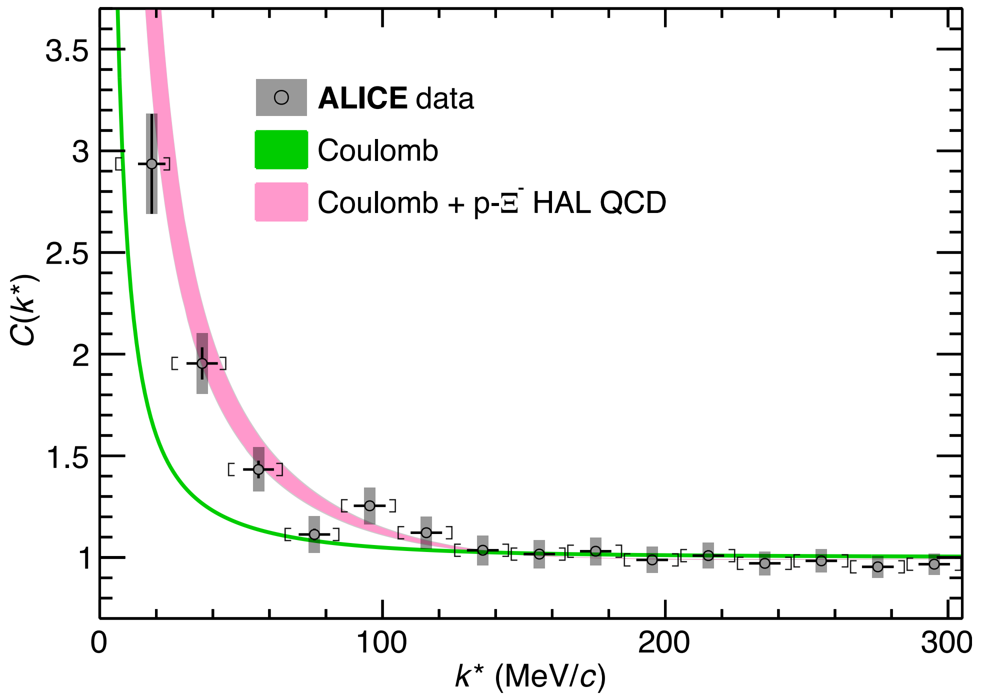


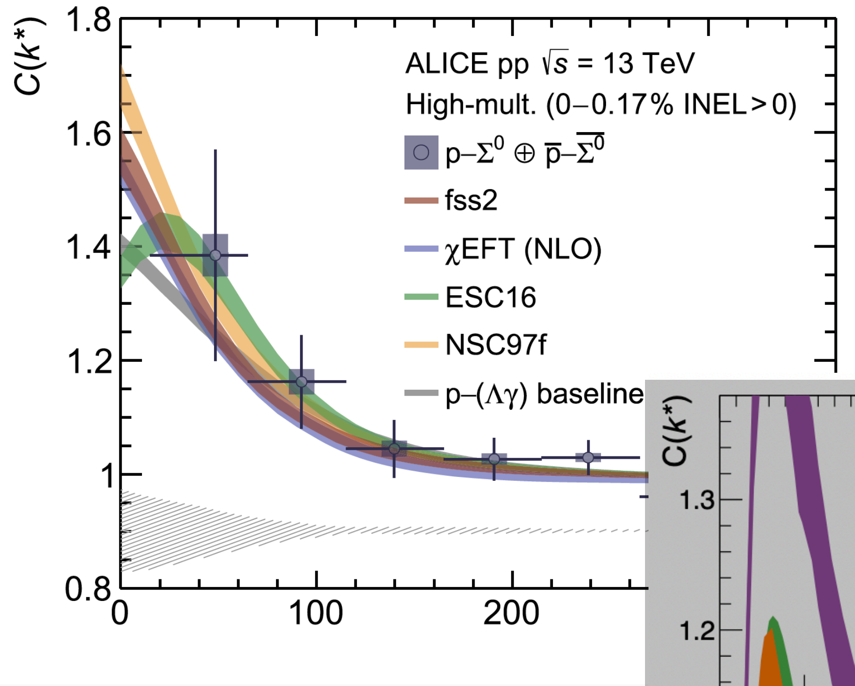


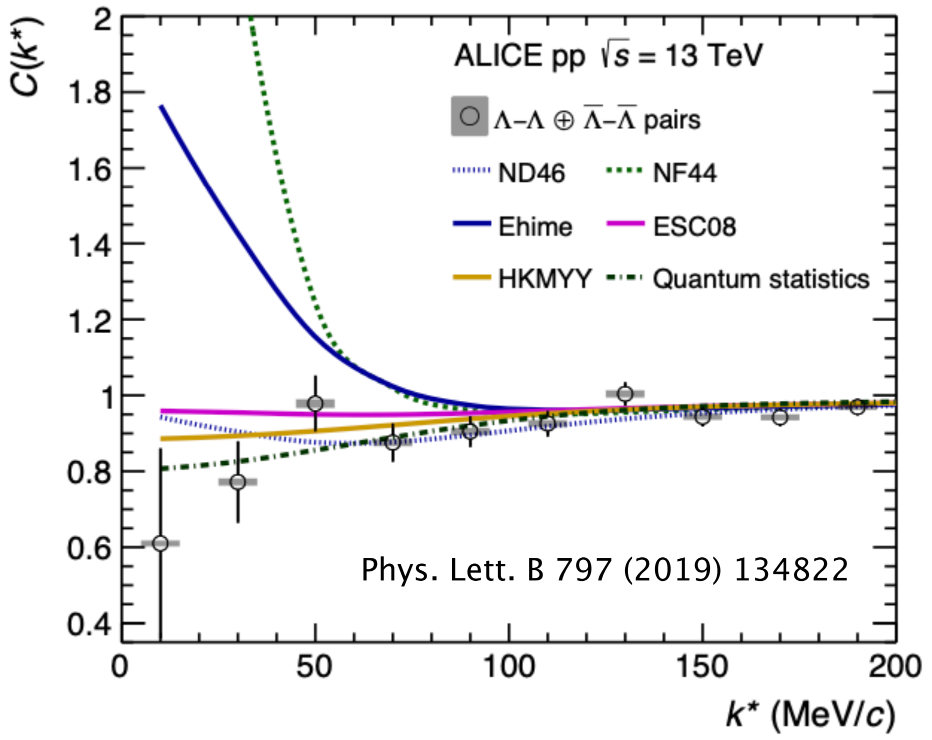
Interaction with strangeness

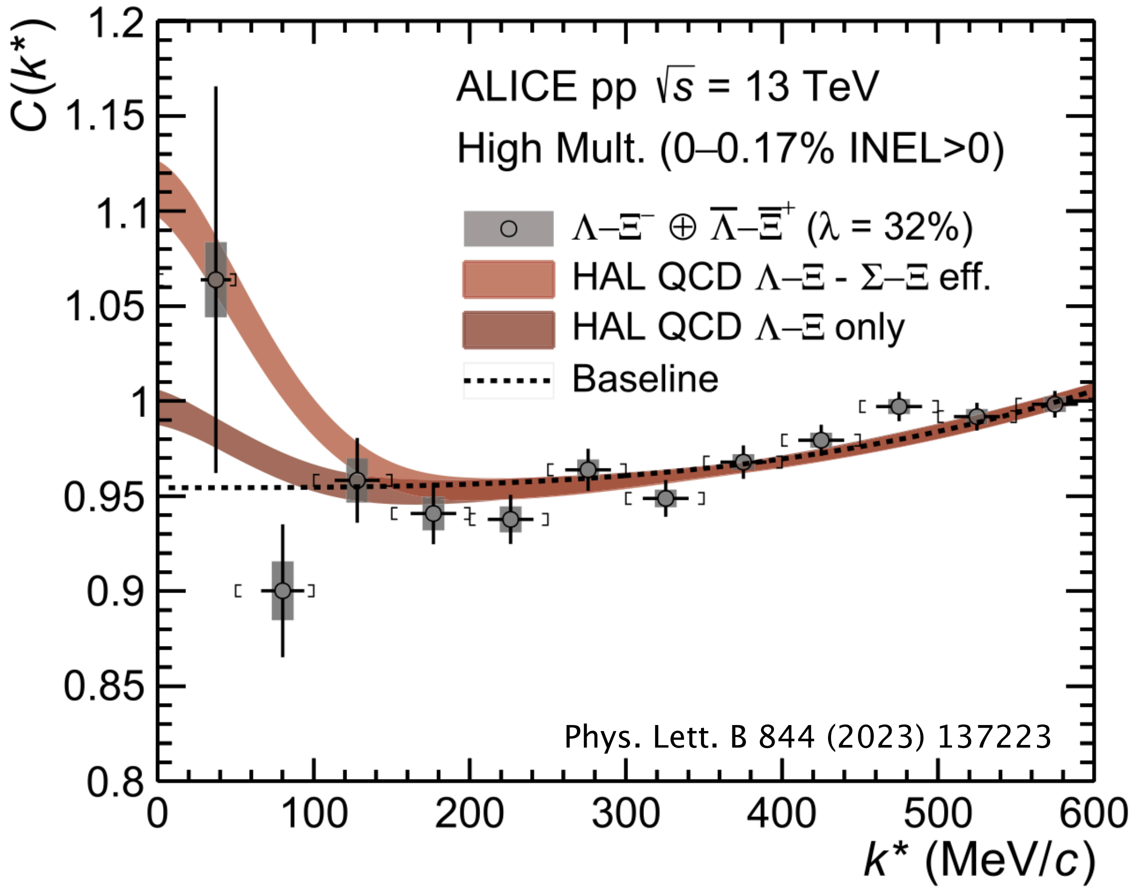
|S| = 0	|S| = 1	|S| = 2	|S| = 3	|S| > 3
NN	NΛ, NΣ	ΛΛ, NΞ	ΛΞ, NΩ	ΞΞ, ΛΩ, ΣΩ, ΞΩ, ΩΩ

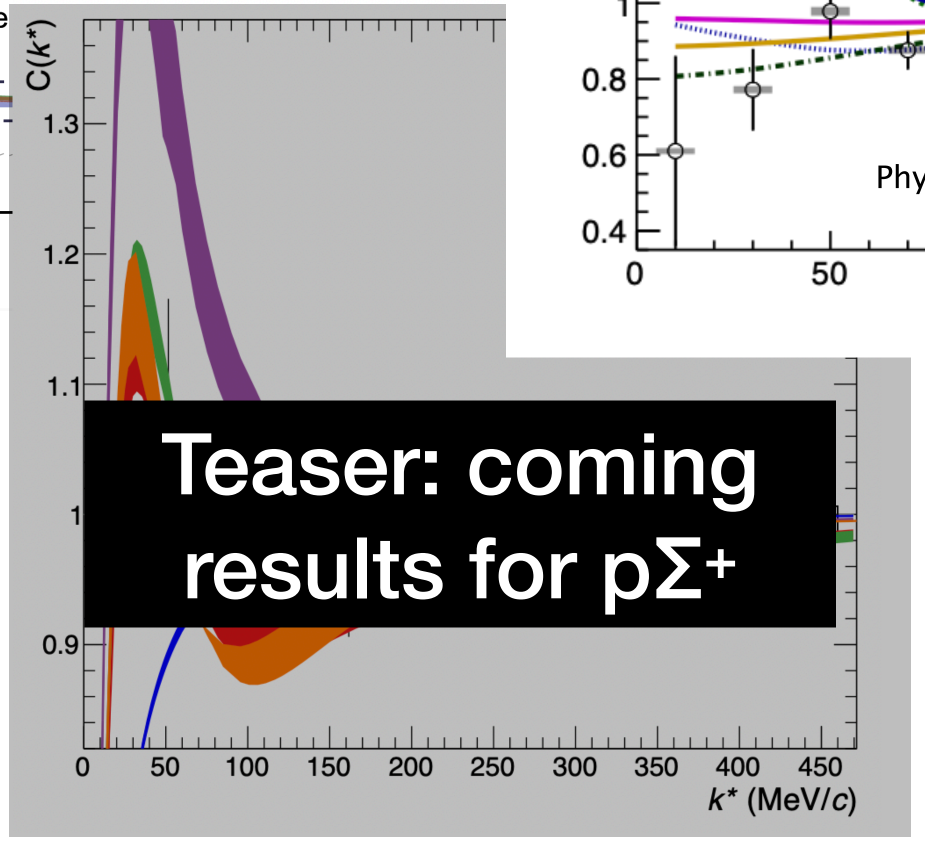












Teaser: coming results for pΣ+

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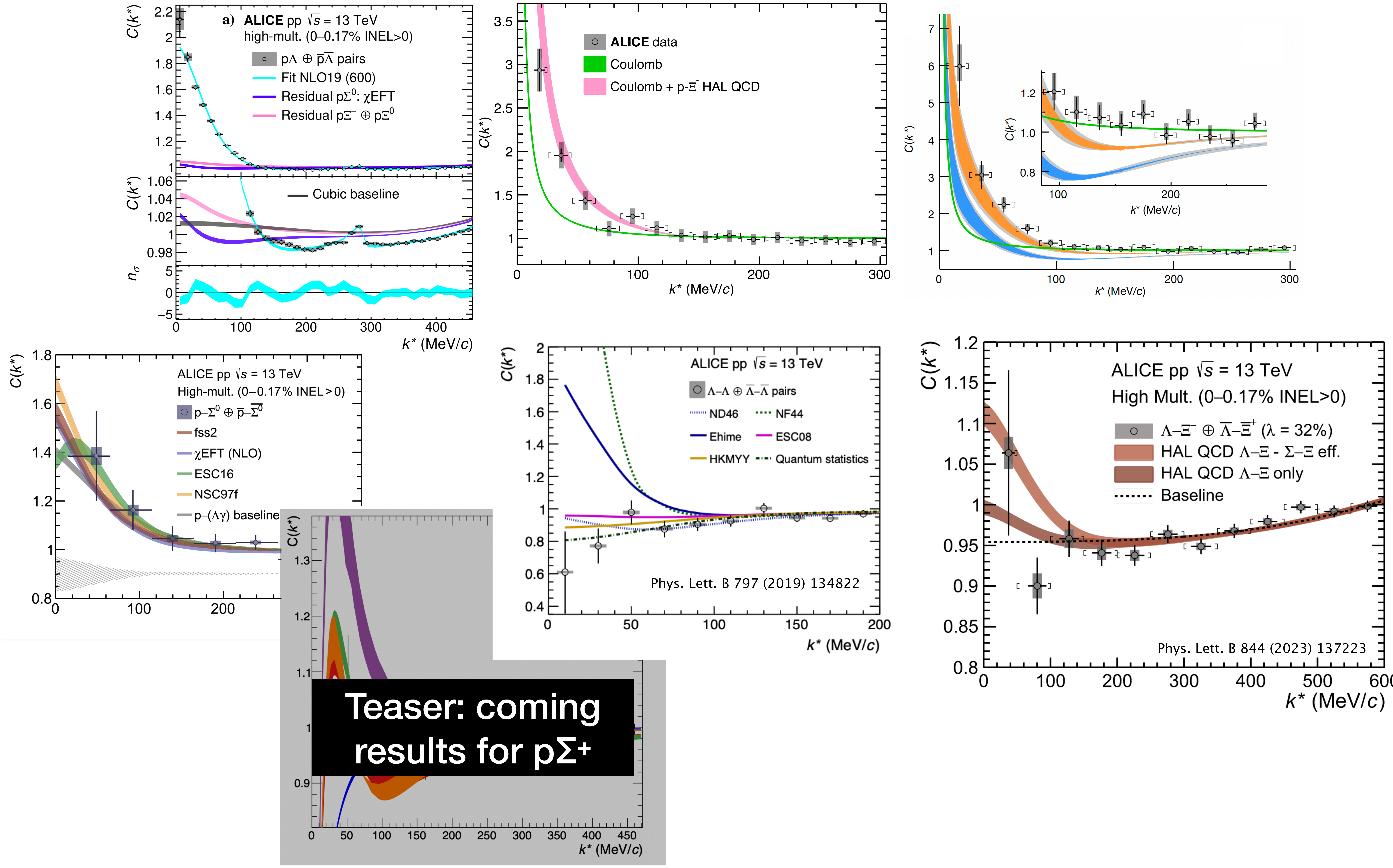

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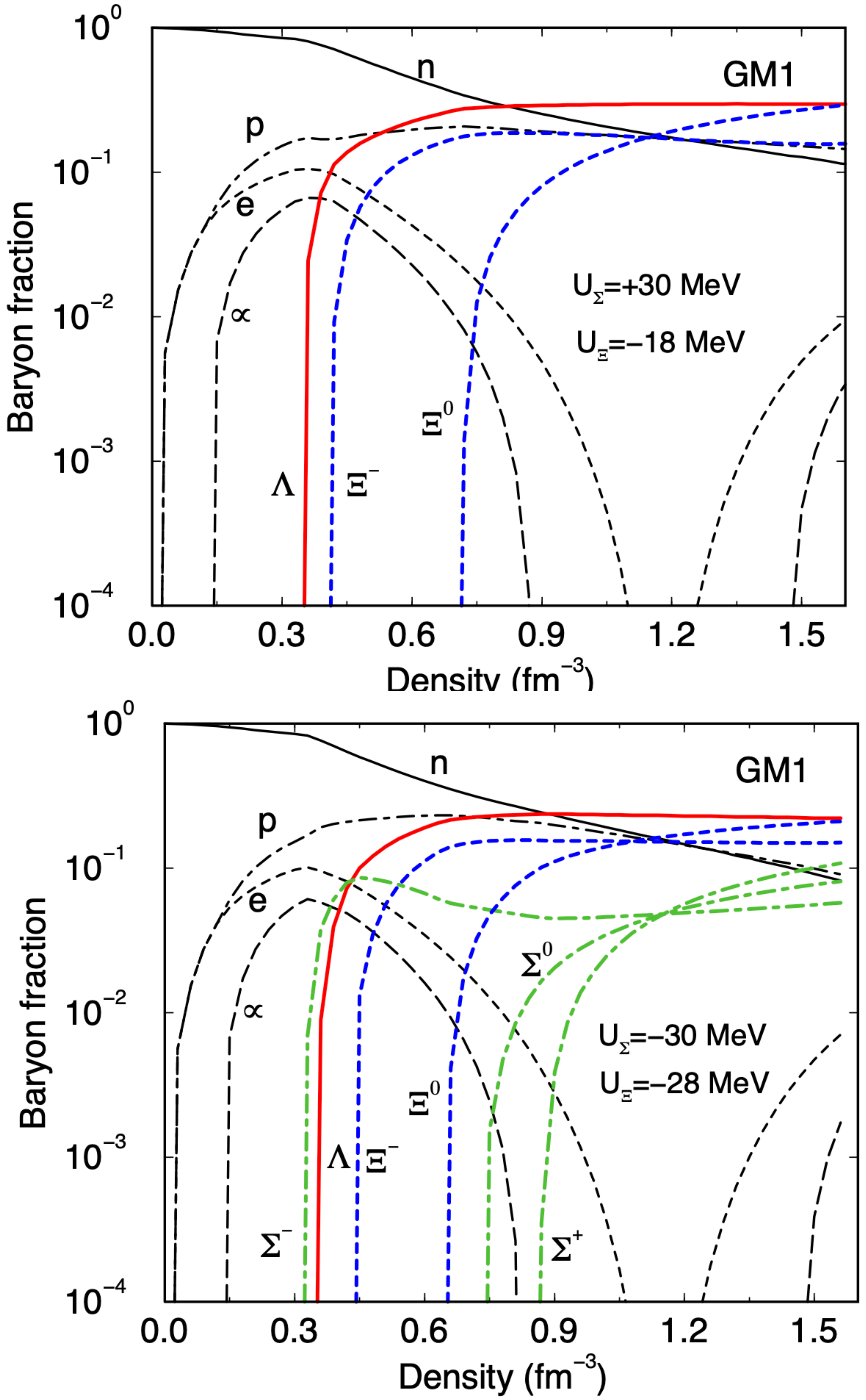

J. Schaffner-Bielich et al NPA 835 (2010)

Back to the beginning

Status: 2010

J. Schaffner-Bielich et al NPA 835 (2010)

Status: 2020

Back to the beginning

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J. Schaffner-Bielich et al NPA 835 (2010)

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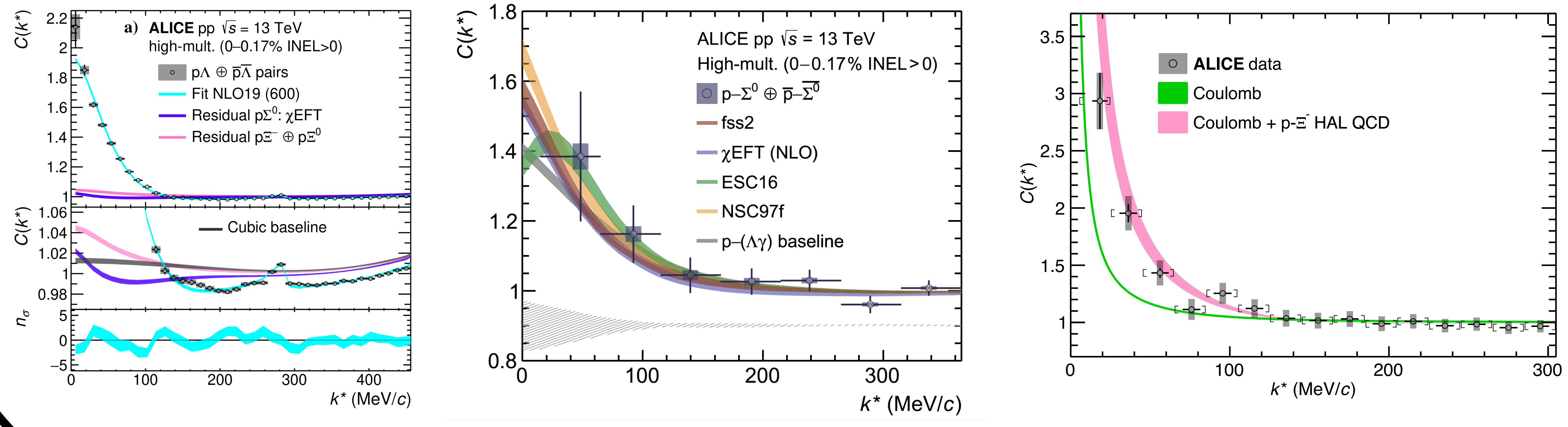

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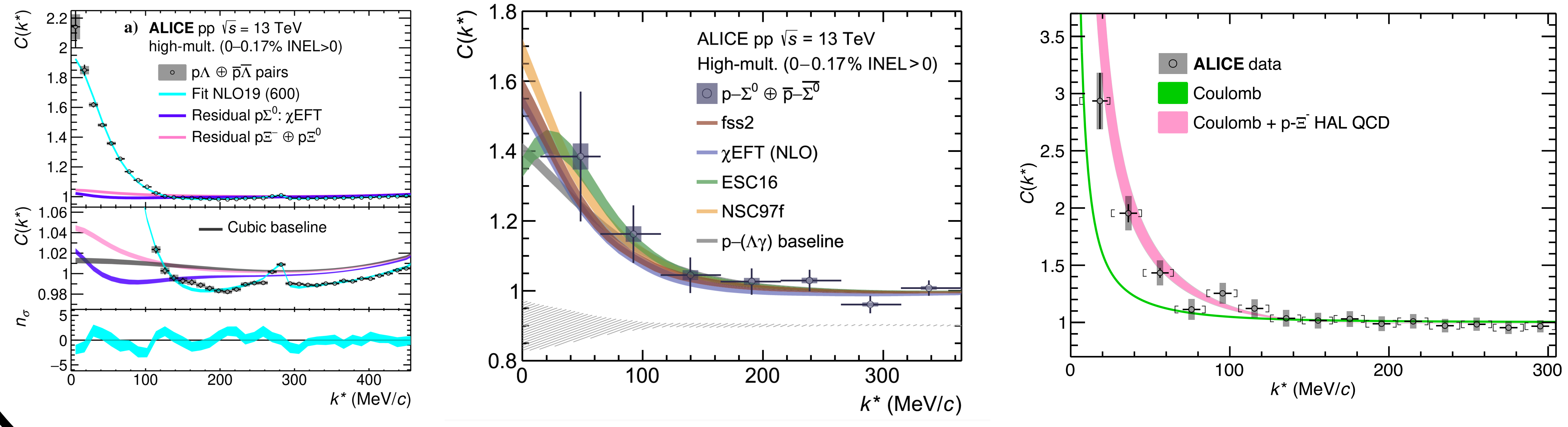
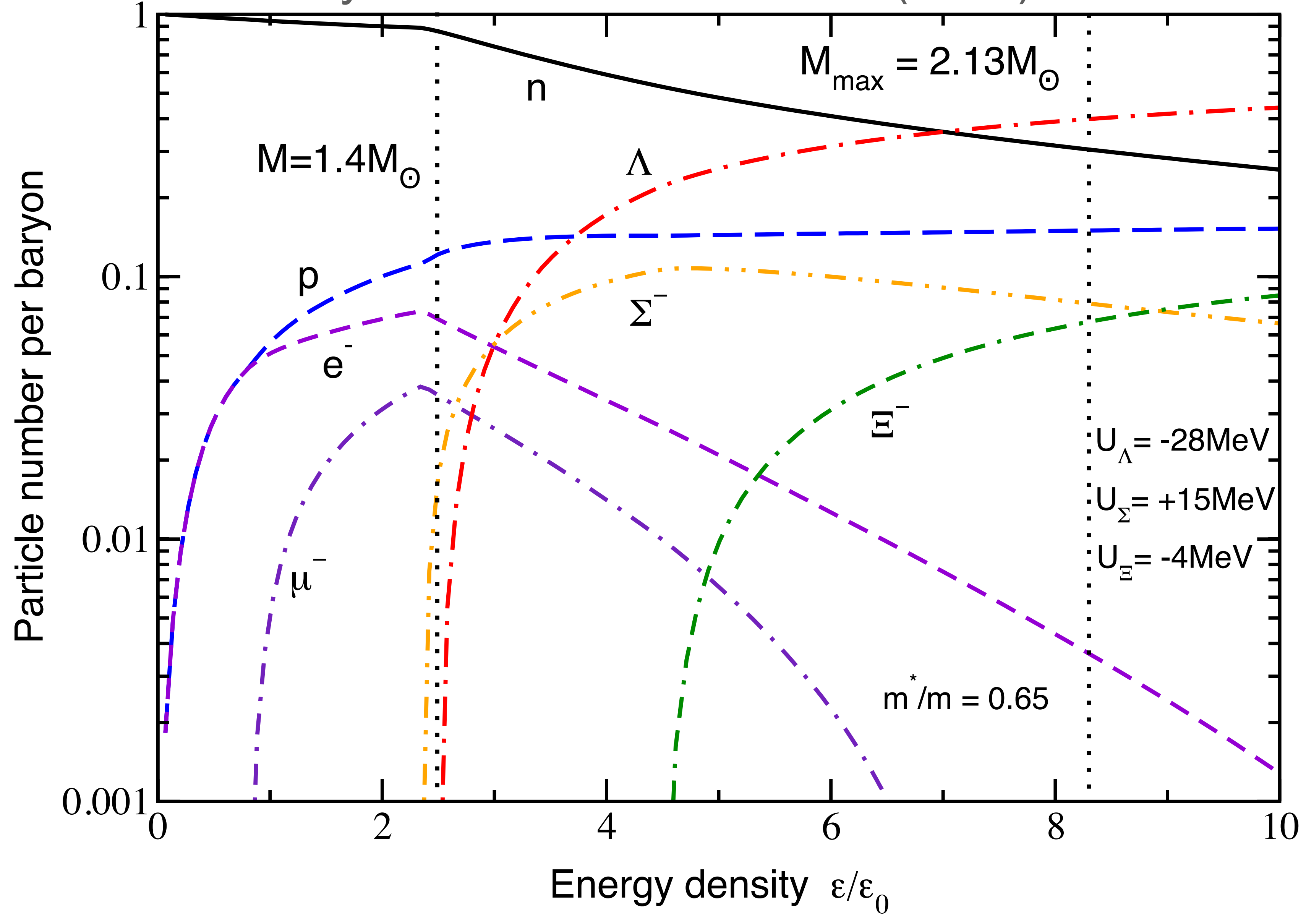


Courtesy of J. Schaffner-Bielich (2020)



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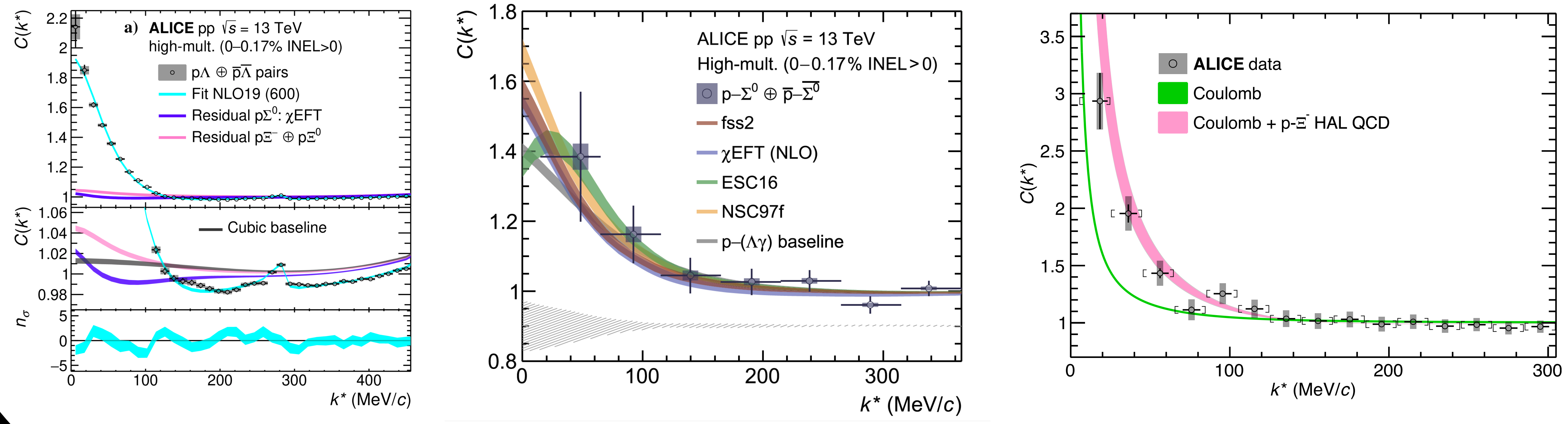
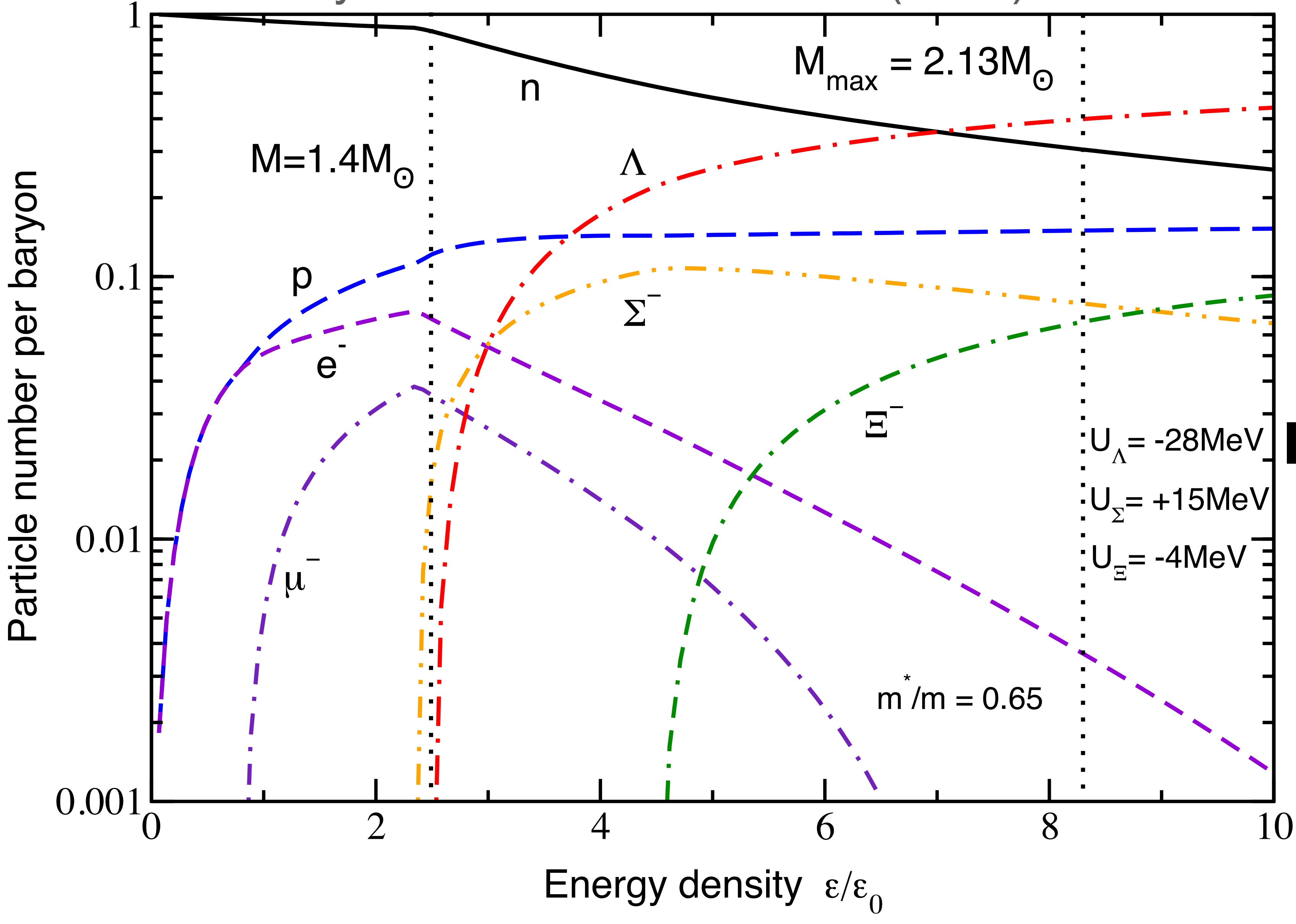
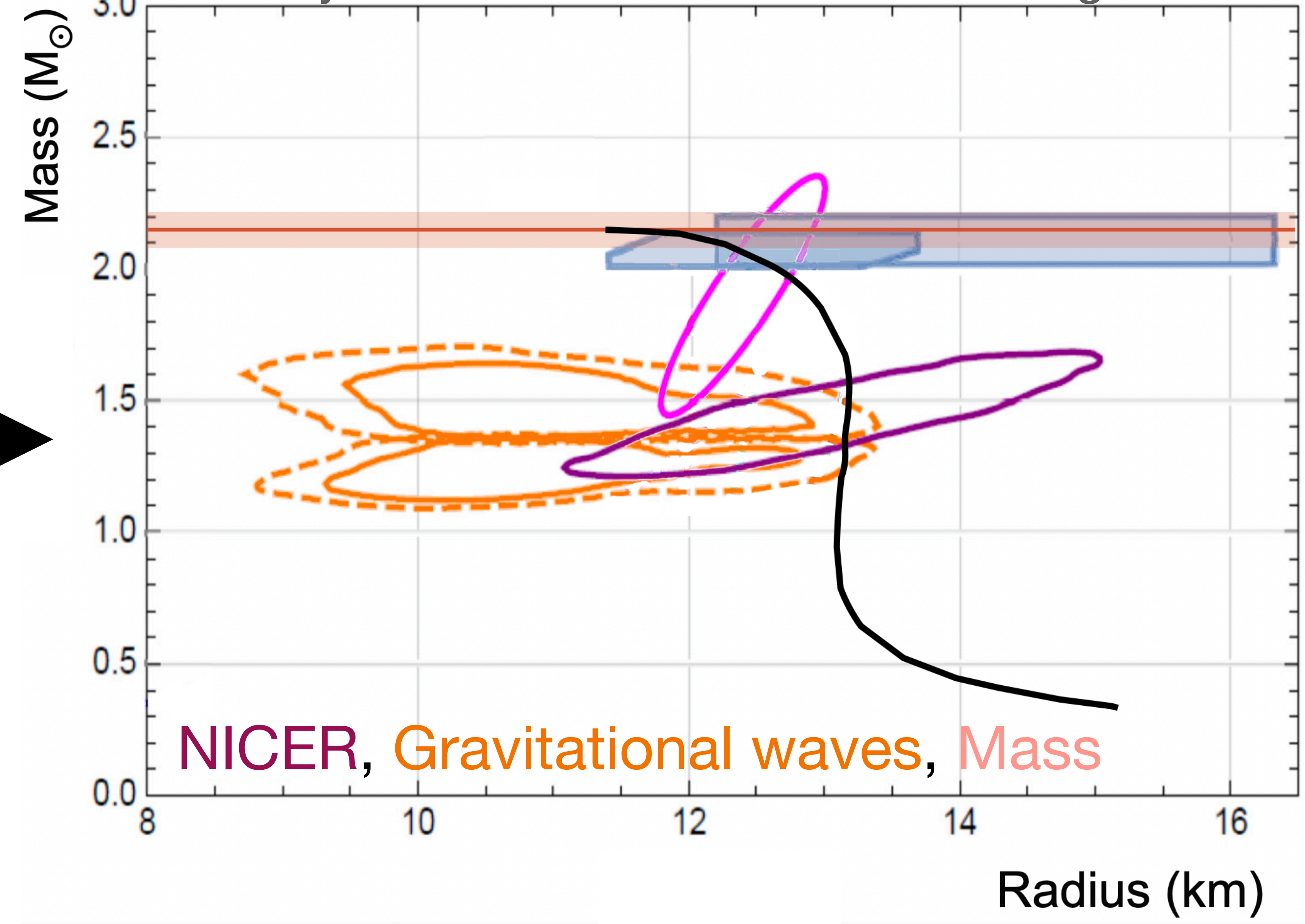


Courtesy of J. Schaffner-Bielich (2020)



Courtesy J. Schaffner-Bielich and B. Dönigus 2020



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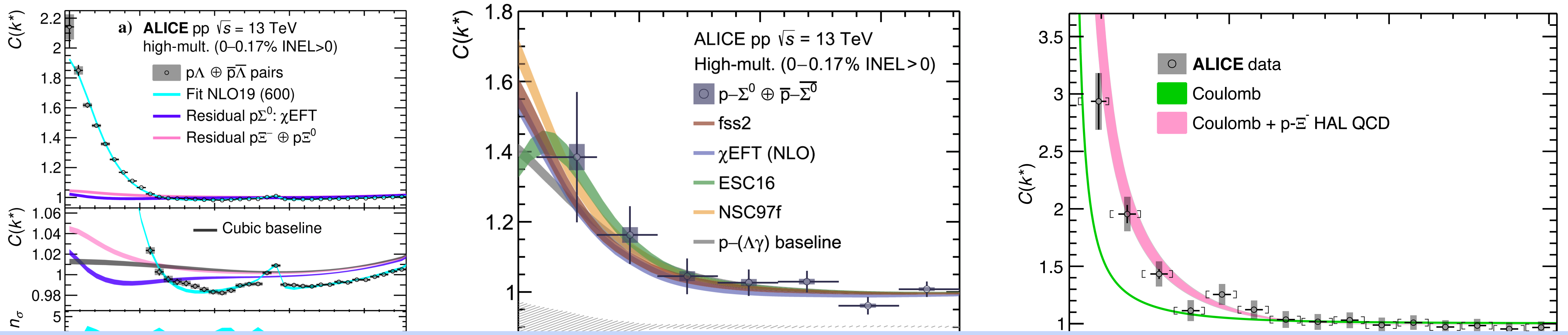
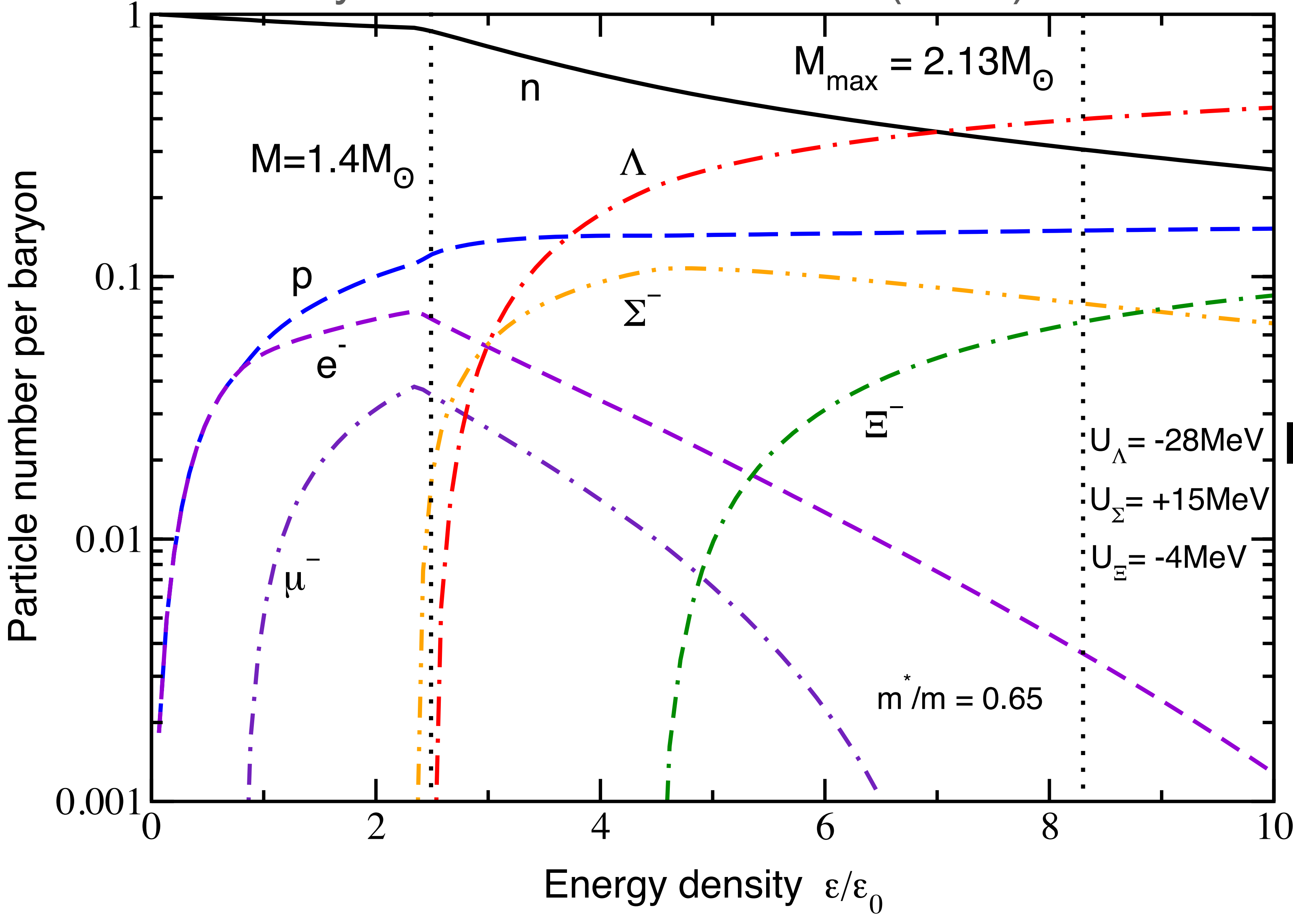


Next question: What if the new Λ potential is used in EoS?
19 Aug 16:00 Isaac Vidana

Courtesy of J. Schaffner-Bielich (2020)



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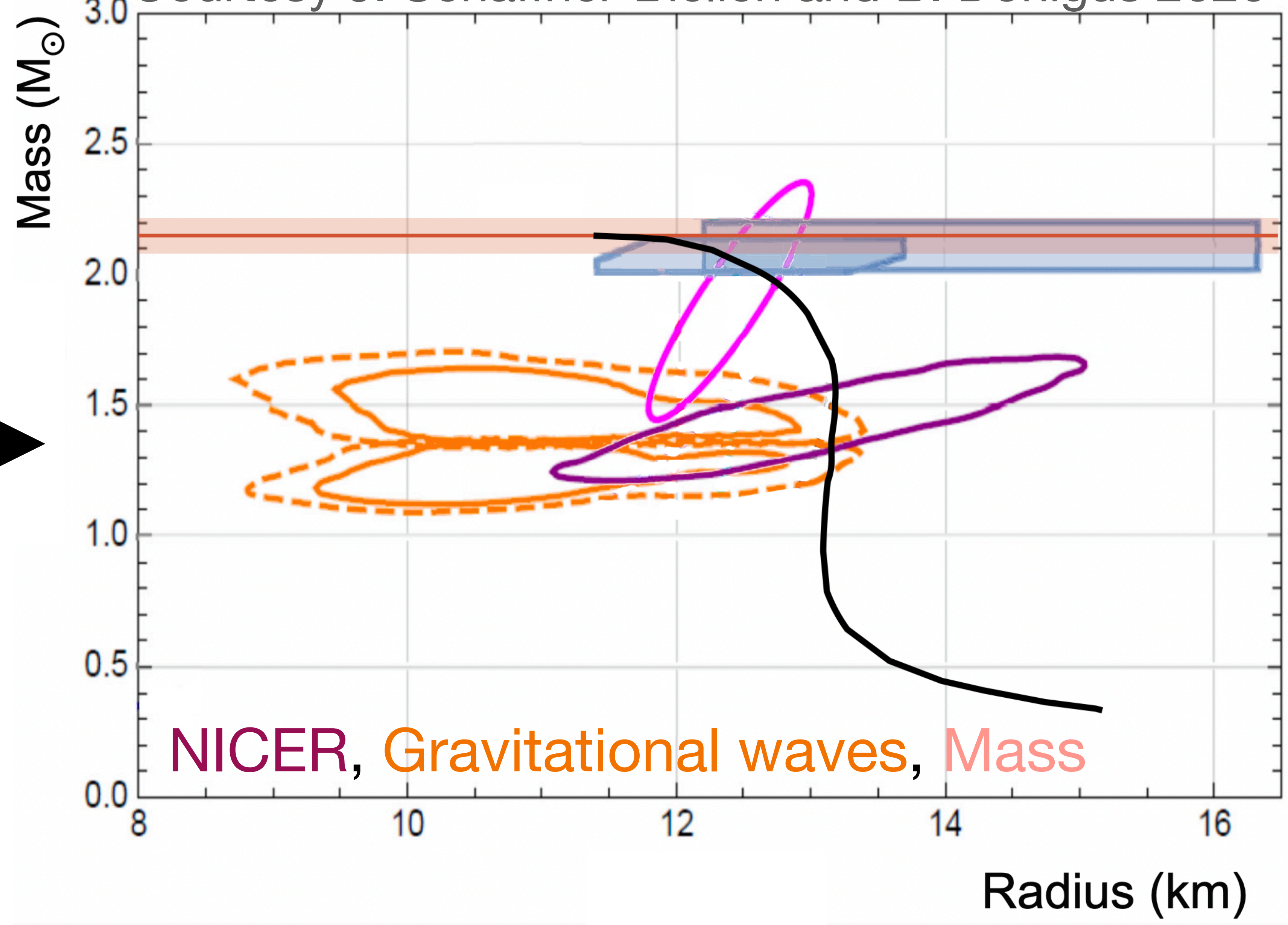
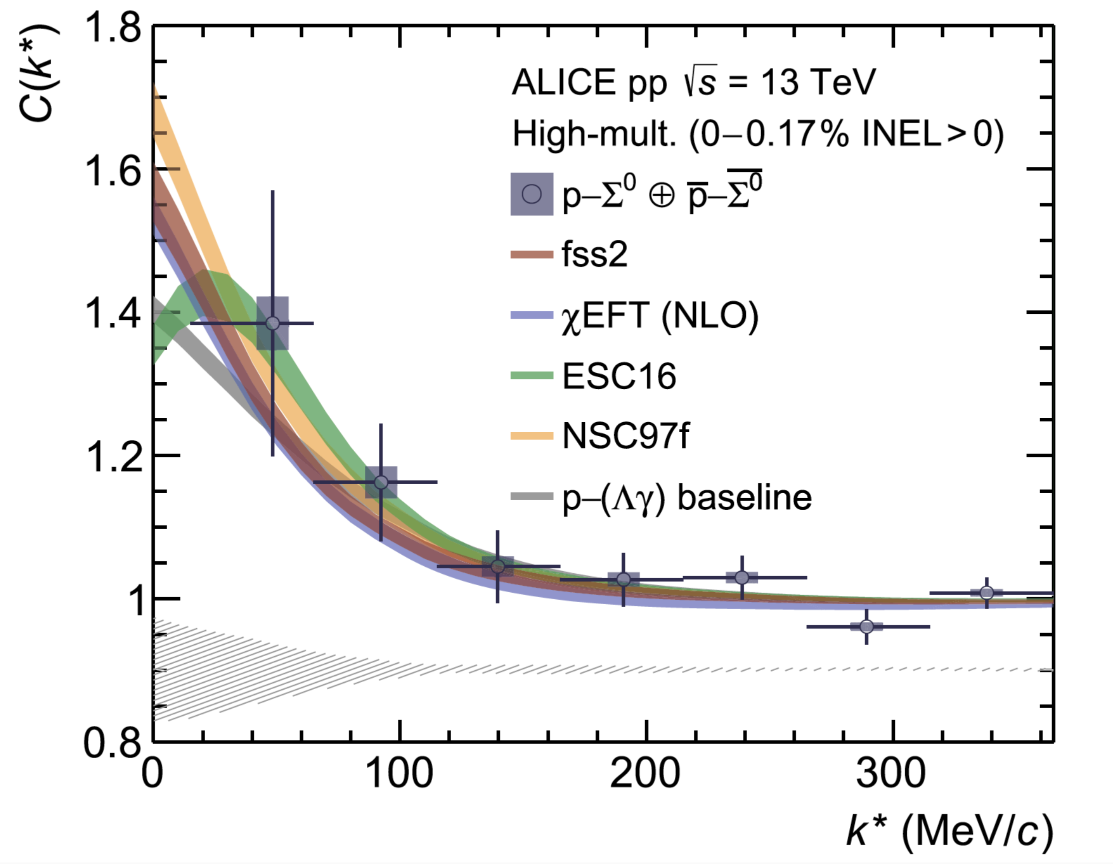
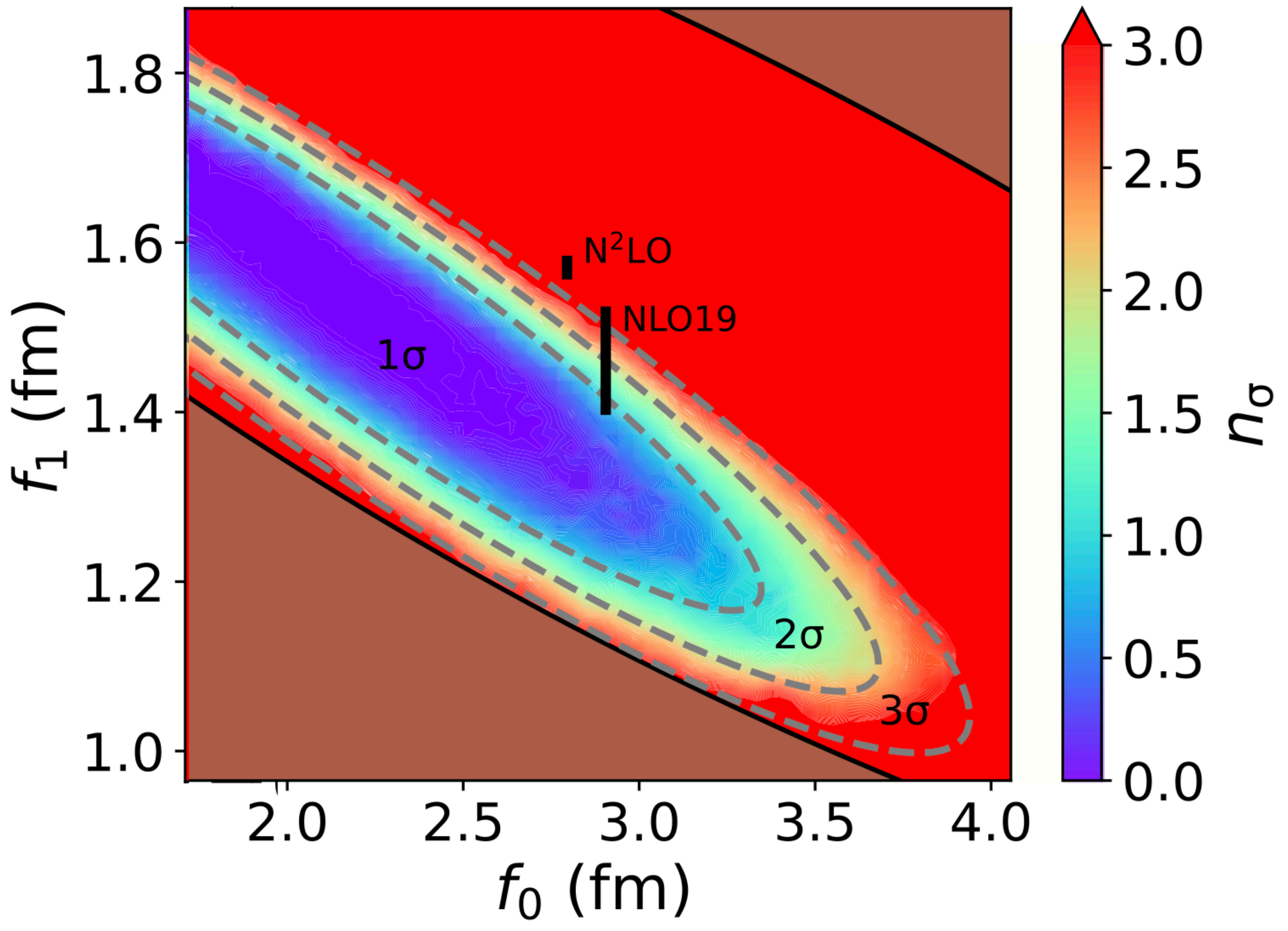
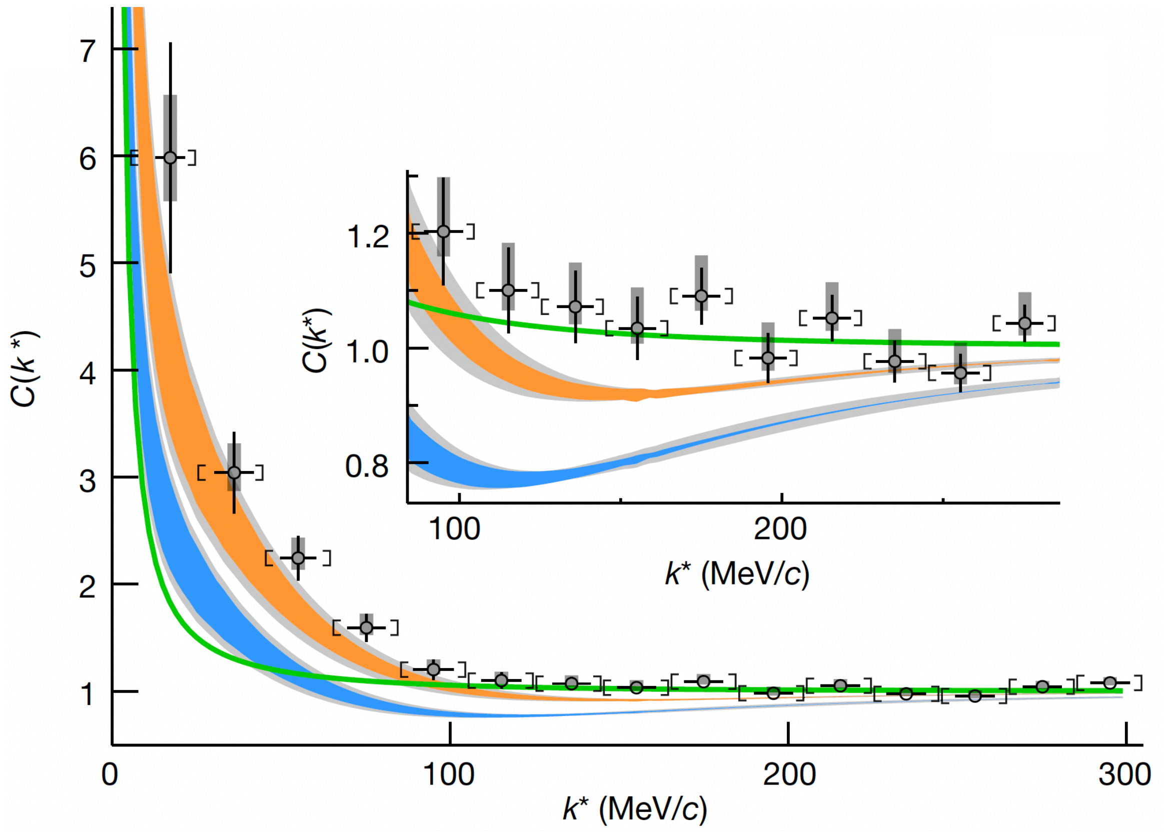


Summary

- Significant improvement in the understanding of pΛ interaction and refitted low-energy constants in χEFT
- Access to |S|>1 systems where was significant lack in experimental constraints
- First test of lattice calculations in strangeness |S|=2 and |S|=3 sectors
- Correlation studies have become a well-established technique to study the strong interaction







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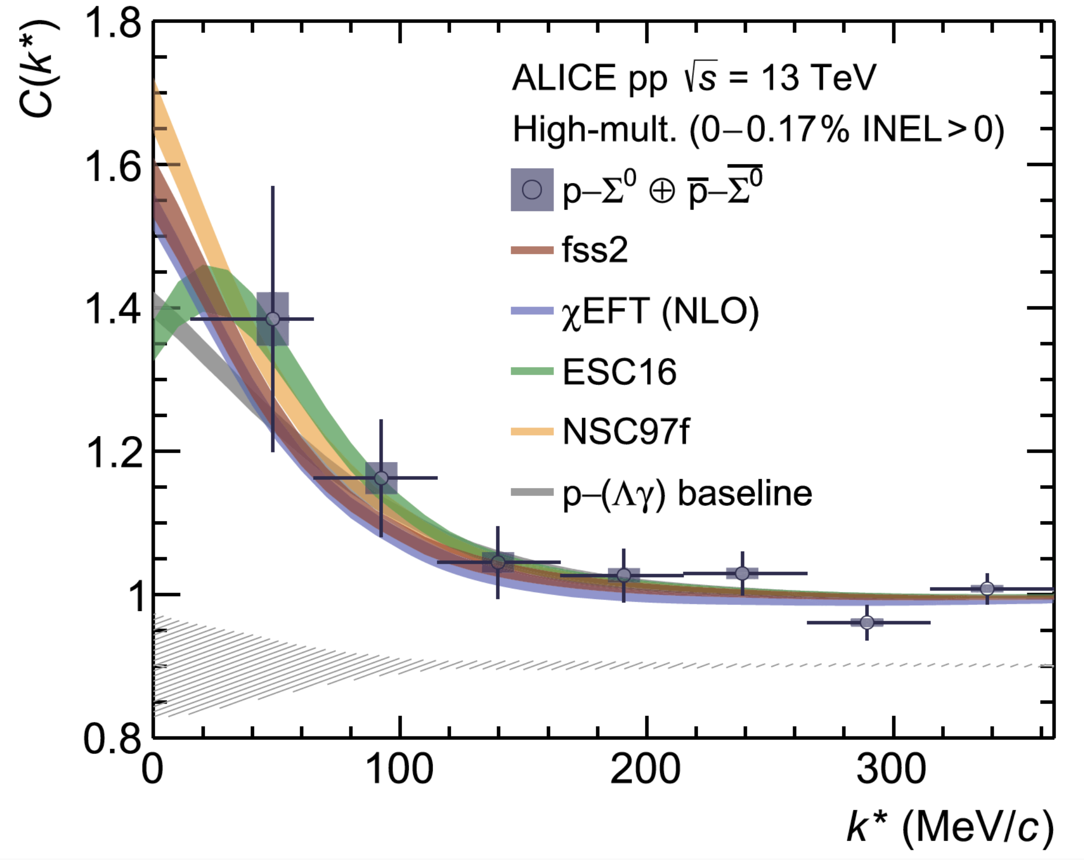
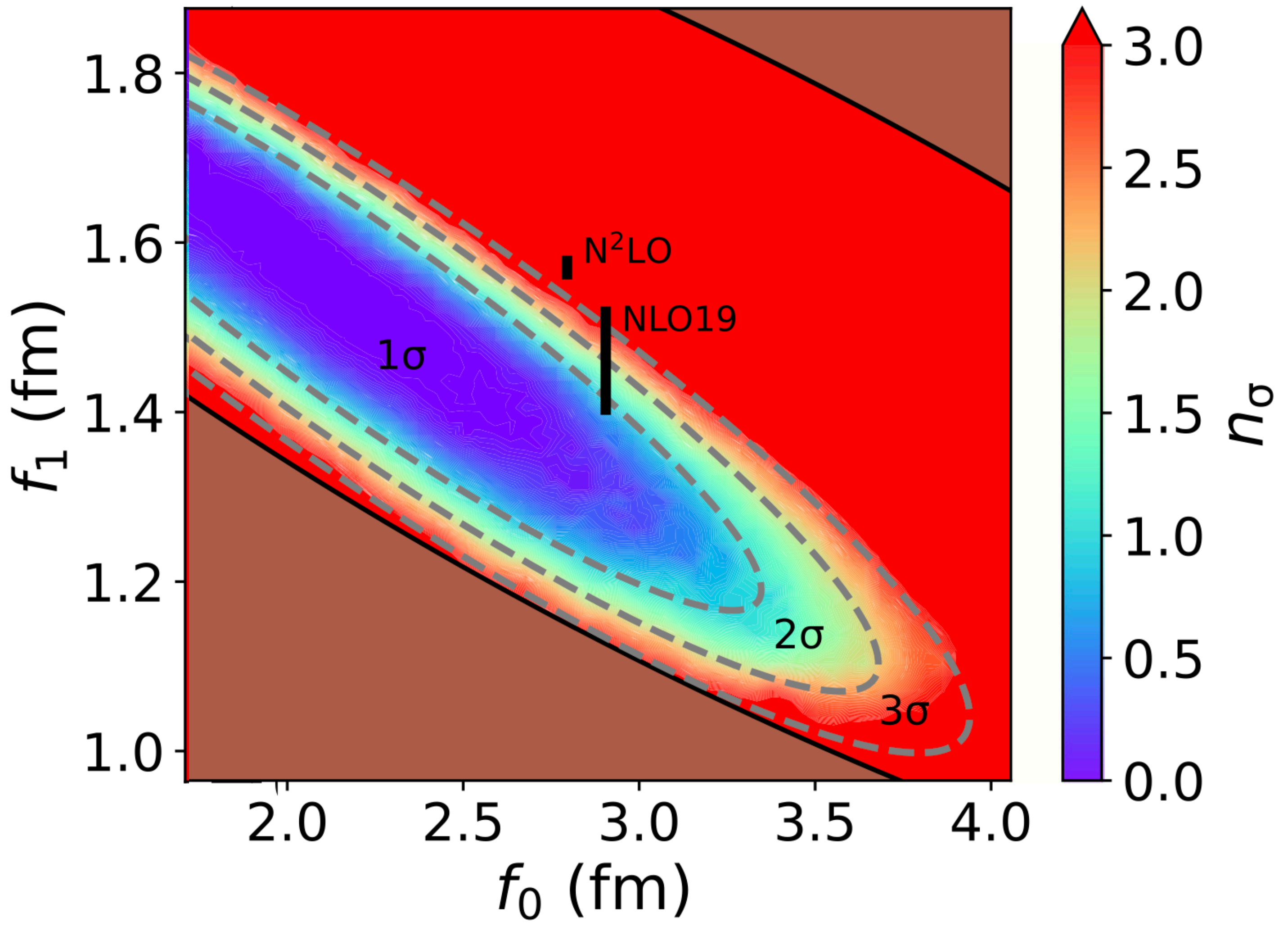
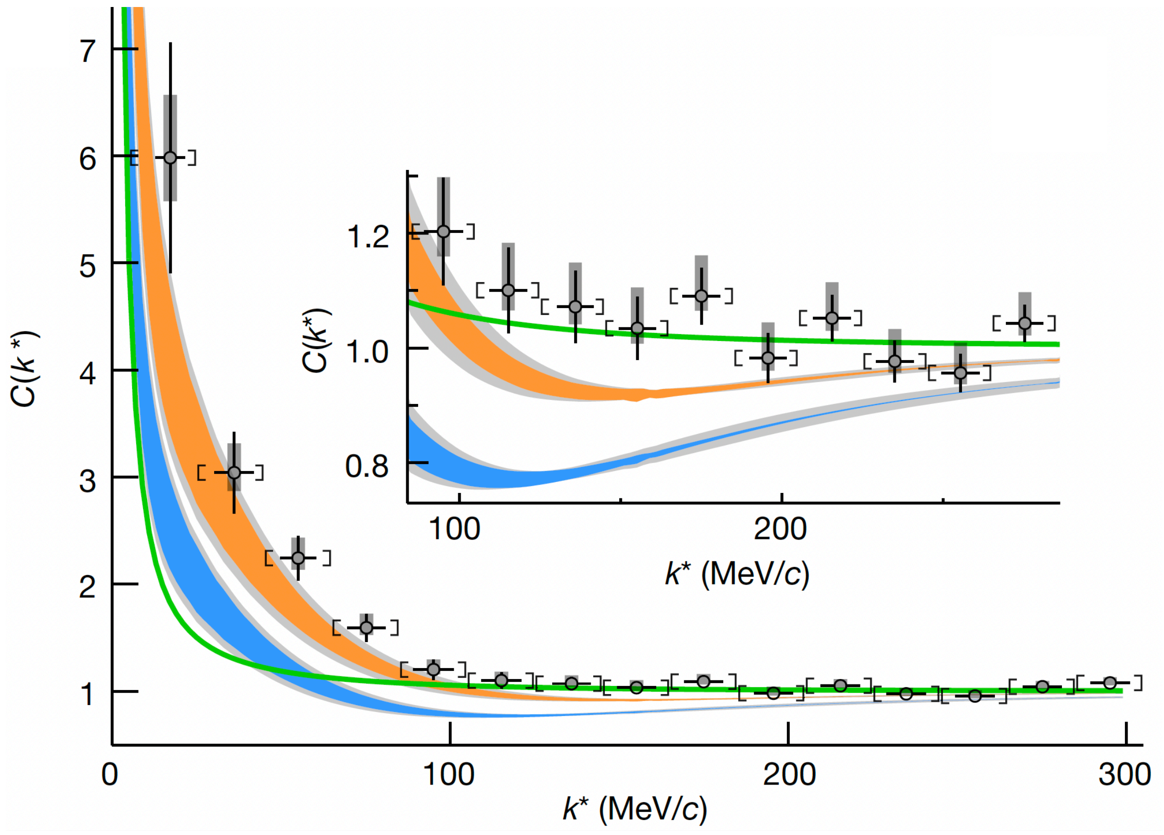
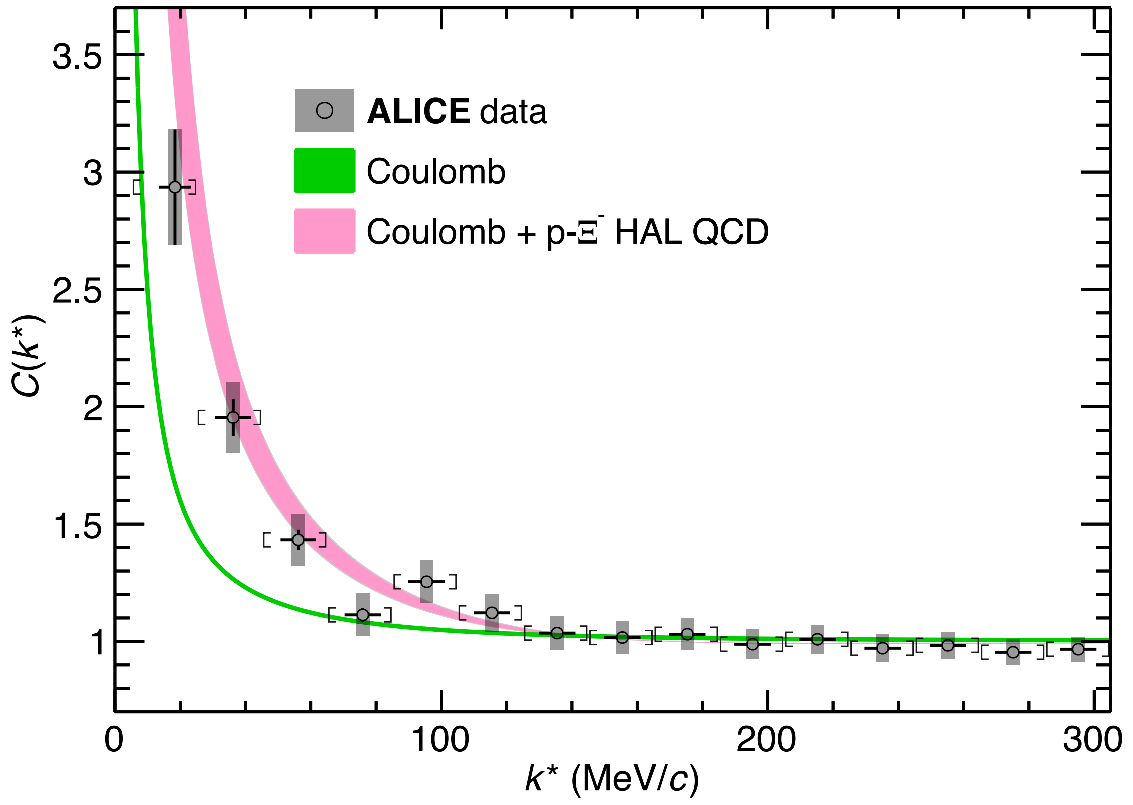






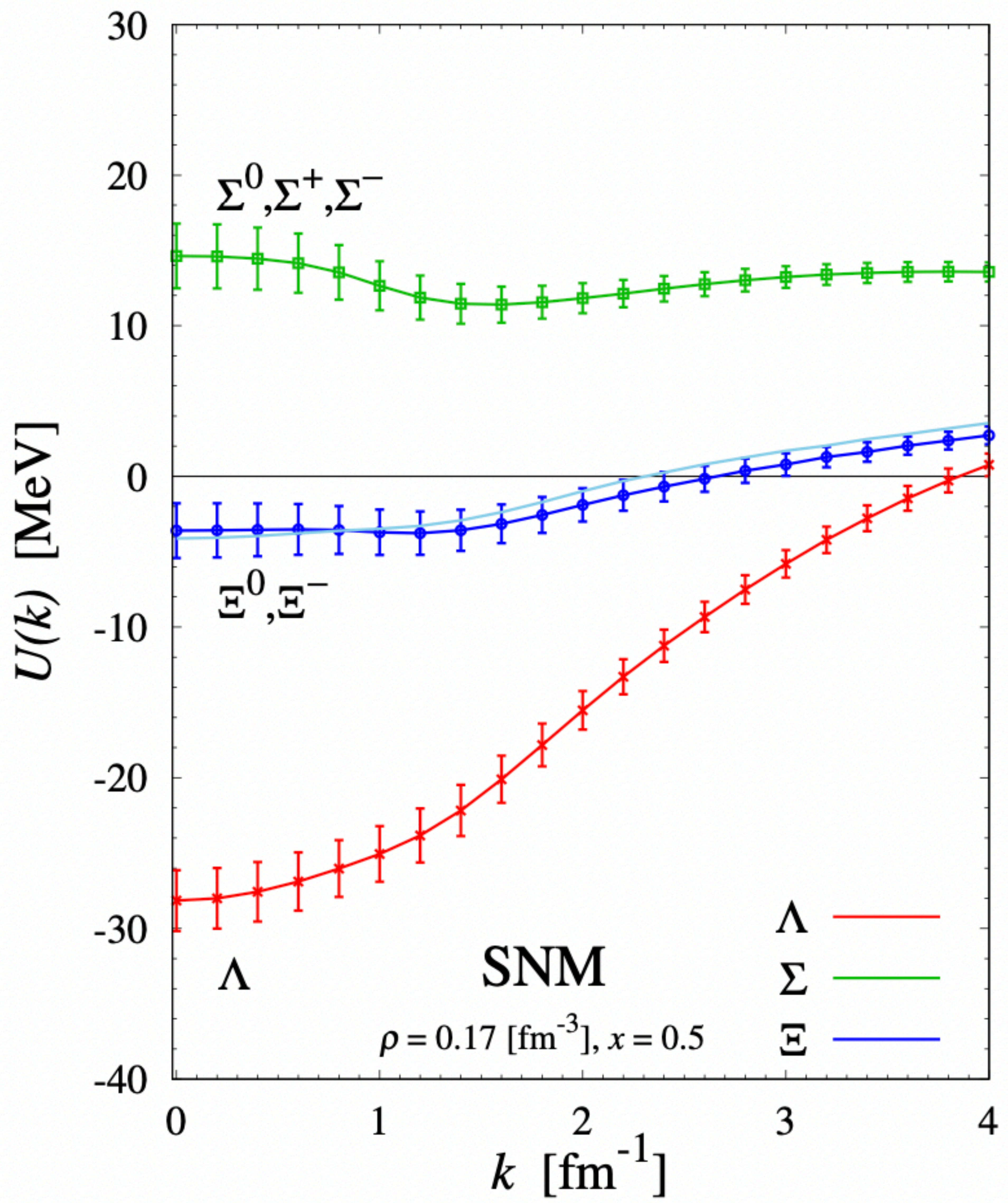


Back up

Potentials based on lattice

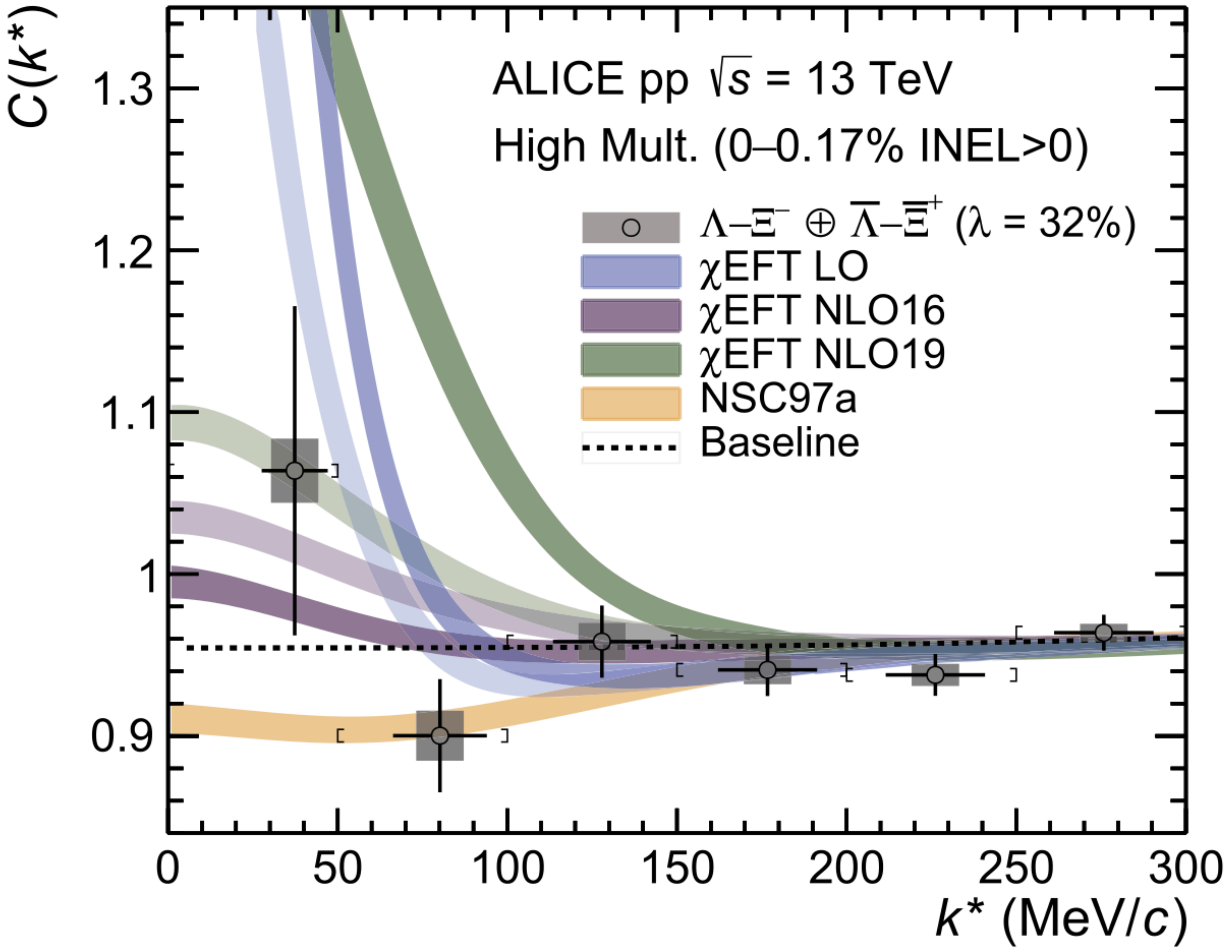
- In T. Inoue, T. AIP Conf. Proc. 2130 (2019), the single particle potentials have been calculated using lattice results
- Employing lattice results are compatible with femto data

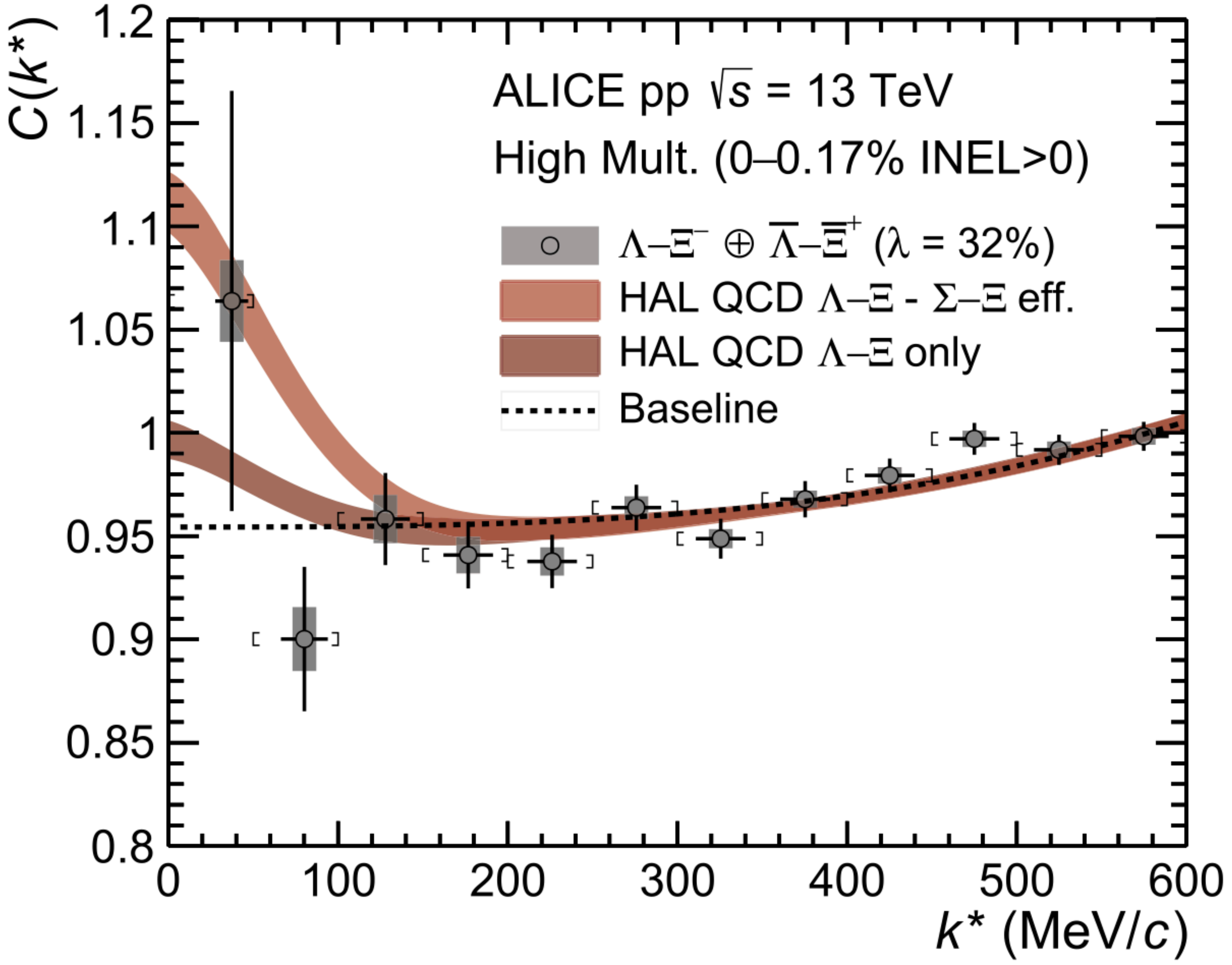
- Results in slightly repulsive sigma single particle potential and slightly attractive xi single particle potential



Λ-Ξ correlation

- The limitations of the data sample prevent from drawing further conclusions on the influence of coupled channels in the correlation function, and no significant cusp-like structures are observed at the opening of the Ξ-Σ or n-Ω channels.



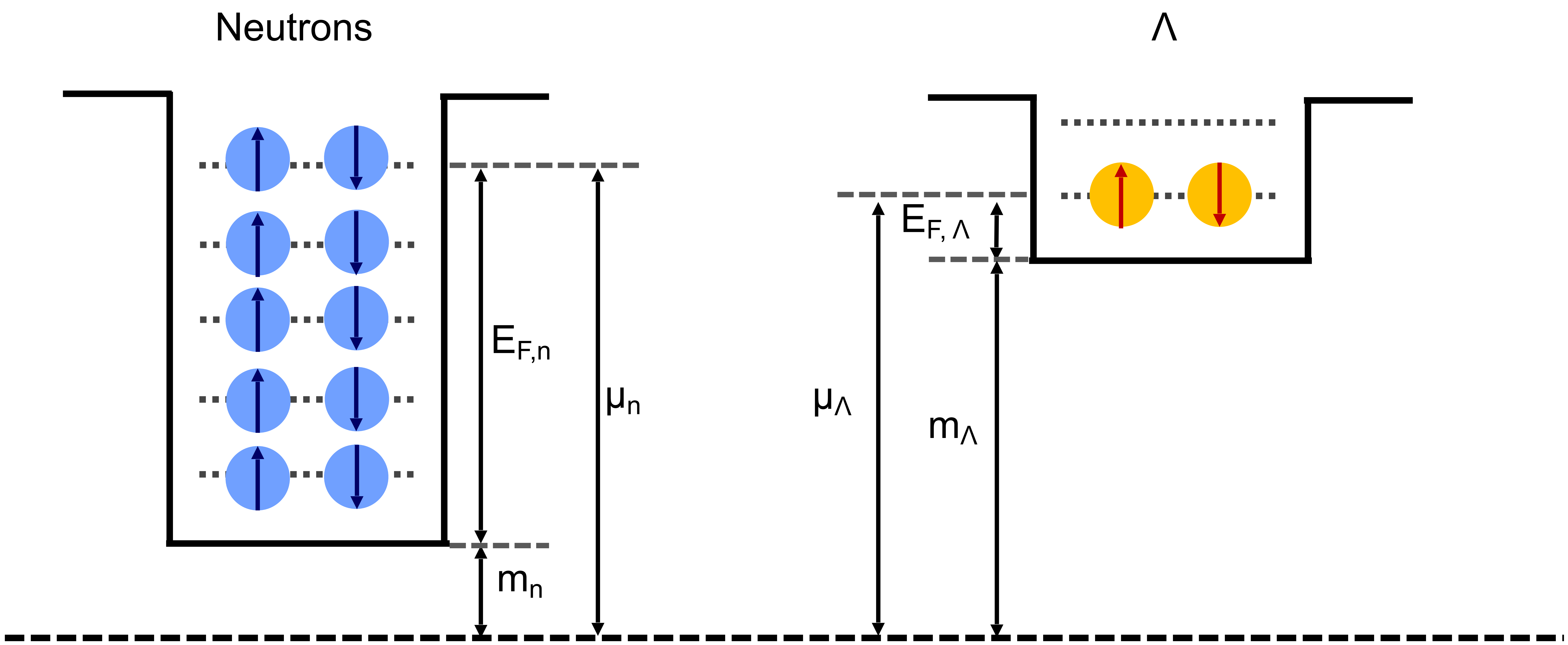


Neutron Stars and the Hyperon Puzzle

- Chemical potential μ = m + Fermi energy
- Fermi energy increases with density

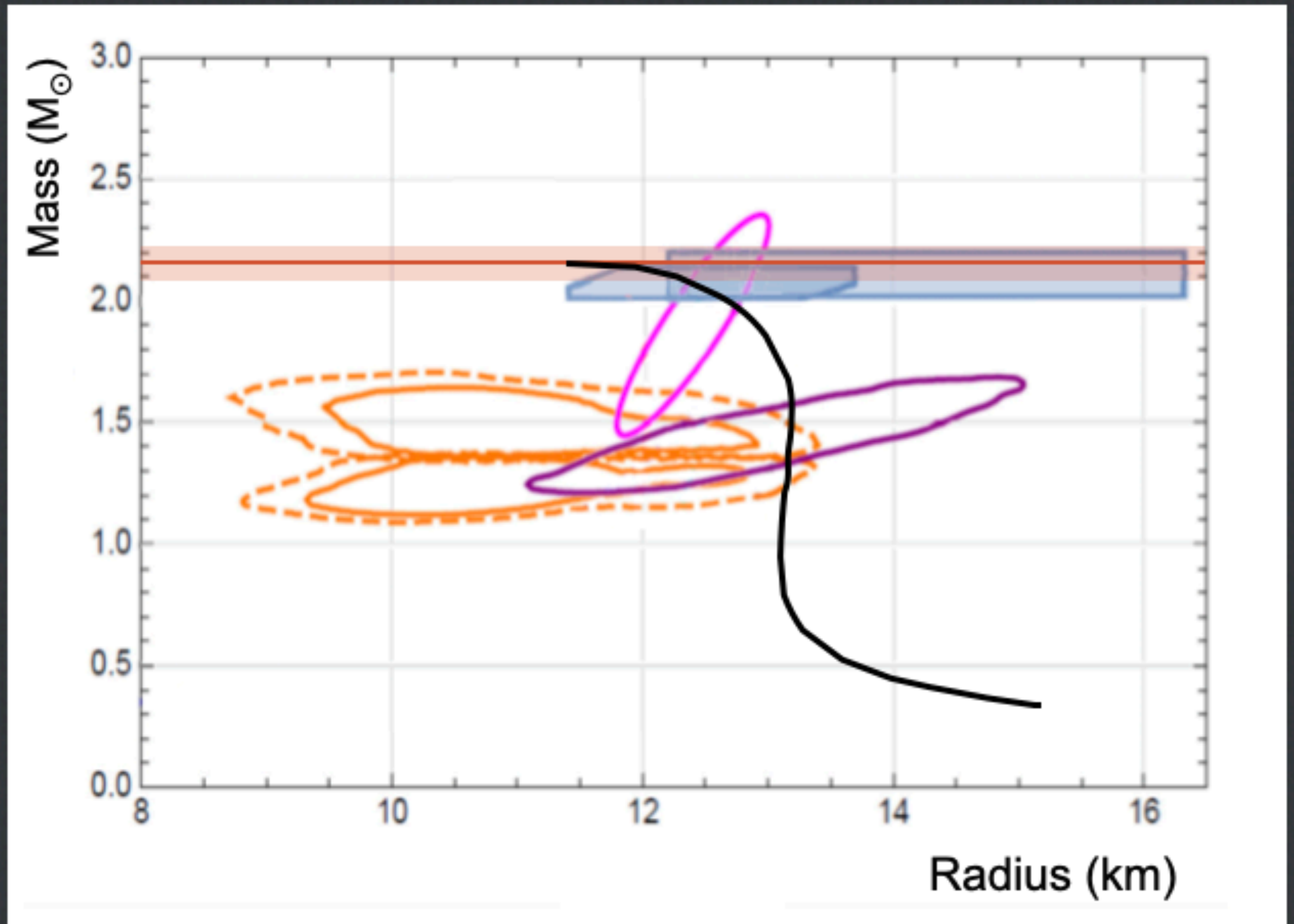
→ $\mu_n = \mu_\Lambda$: conversion into baryons with strangeness (hyperons)

Courtesy of Marcel Lesh



NS measurement references

Mass and Radius measurements from astrophysics

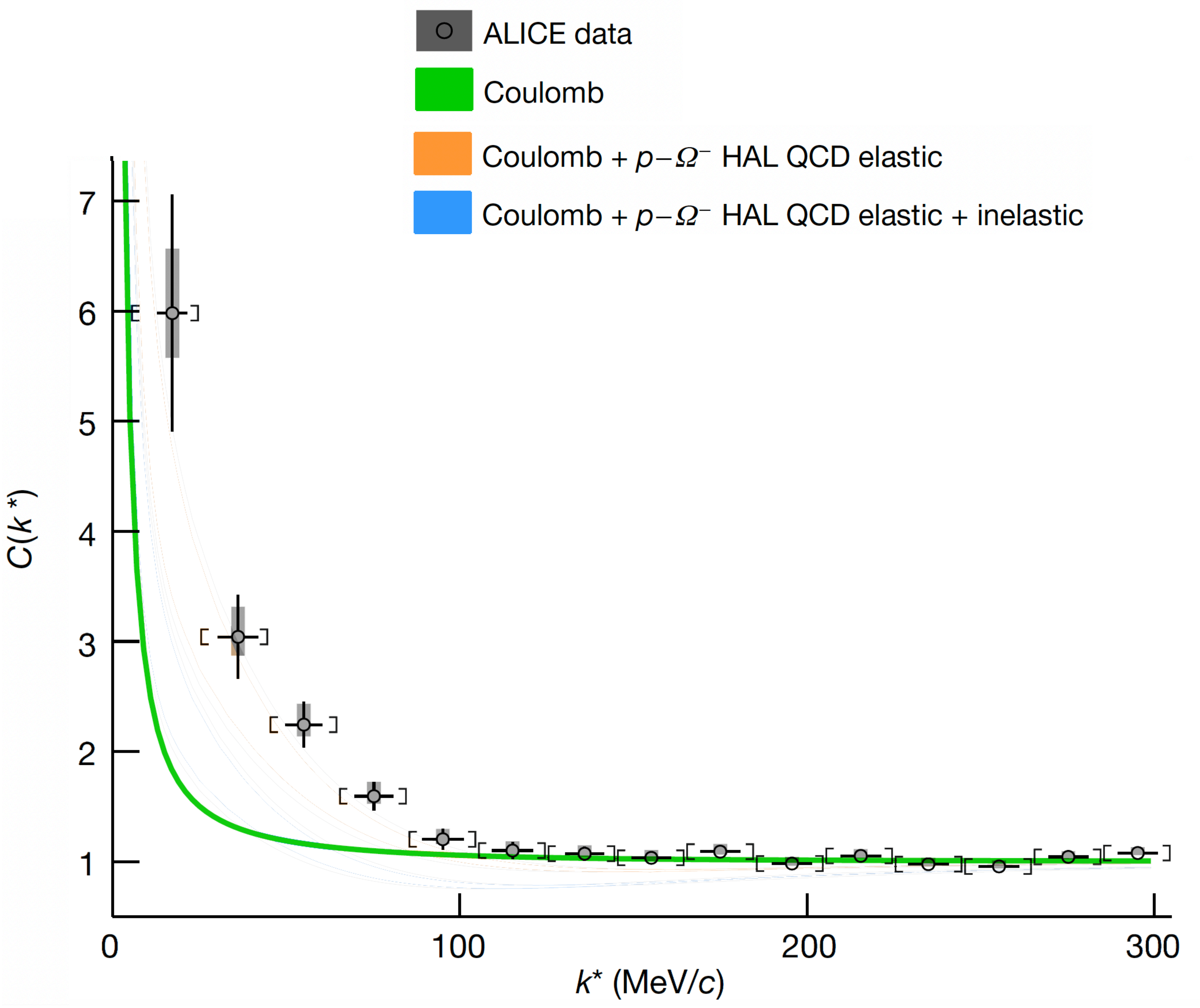


NICER experiment: M.C Miller et al. Astroph. J Lett. 918 (2021) 2, L28;

Mass measurement: H. T. Cromartie et al. *Nature Astron.* 4 (2019) 1, 72-76

Gravitational waves data: B. P. Abbott et al. Phys. Rev. Lett 119 161101 (2017)

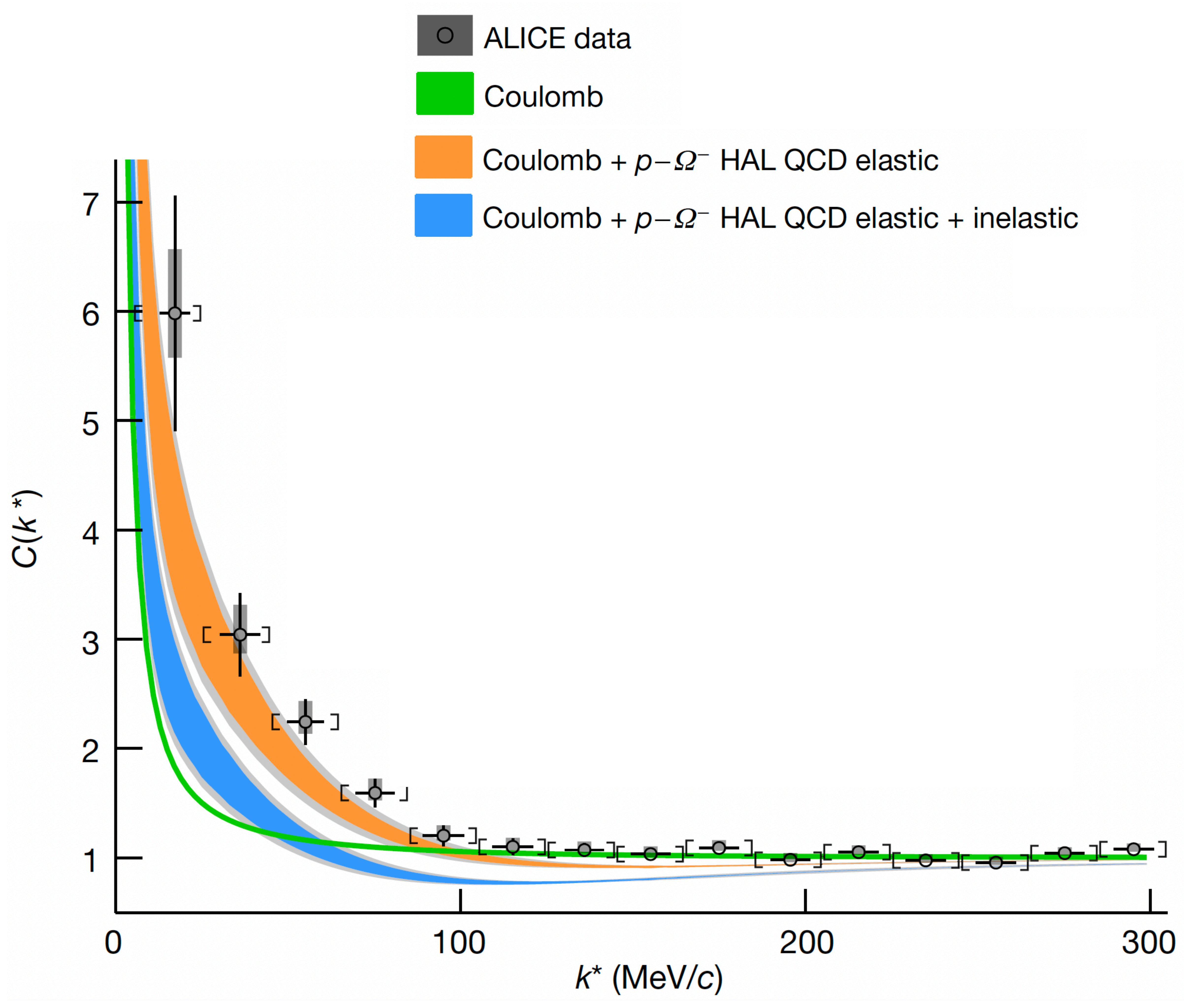
|S|=3 sector: p-Ω⁻ interaction



ALICE Coll., Nature 588, 232–238 (2020)

- Enhancement above Coulomb only
  → strong interaction present

|S|=3 sector: p-Ω^- interaction



ALICE Coll., Nature 588, 232–238 (2020)

- Enhancement above Coulomb only → strong interaction present
- Interaction of p–Ω^- pairs in $^3S_1$ + $^5S_2$ states
  - Attraction in $^5S_2$ results in a bound state (B.E. = 1.54 MeV)
  - Inelastic channels (e.g. pΩ →ΛΞ) in $^3S_1$ not yet calculated on the lattice:
    - Inelastic channels dominated by absorption
    - Neglecting inelastic channel

    Negligible contribution of NΩ-ΛΞ coupling found in Λ-Ξ correlation function ALICE Coll., Phys. Lett. B (2022) 137223

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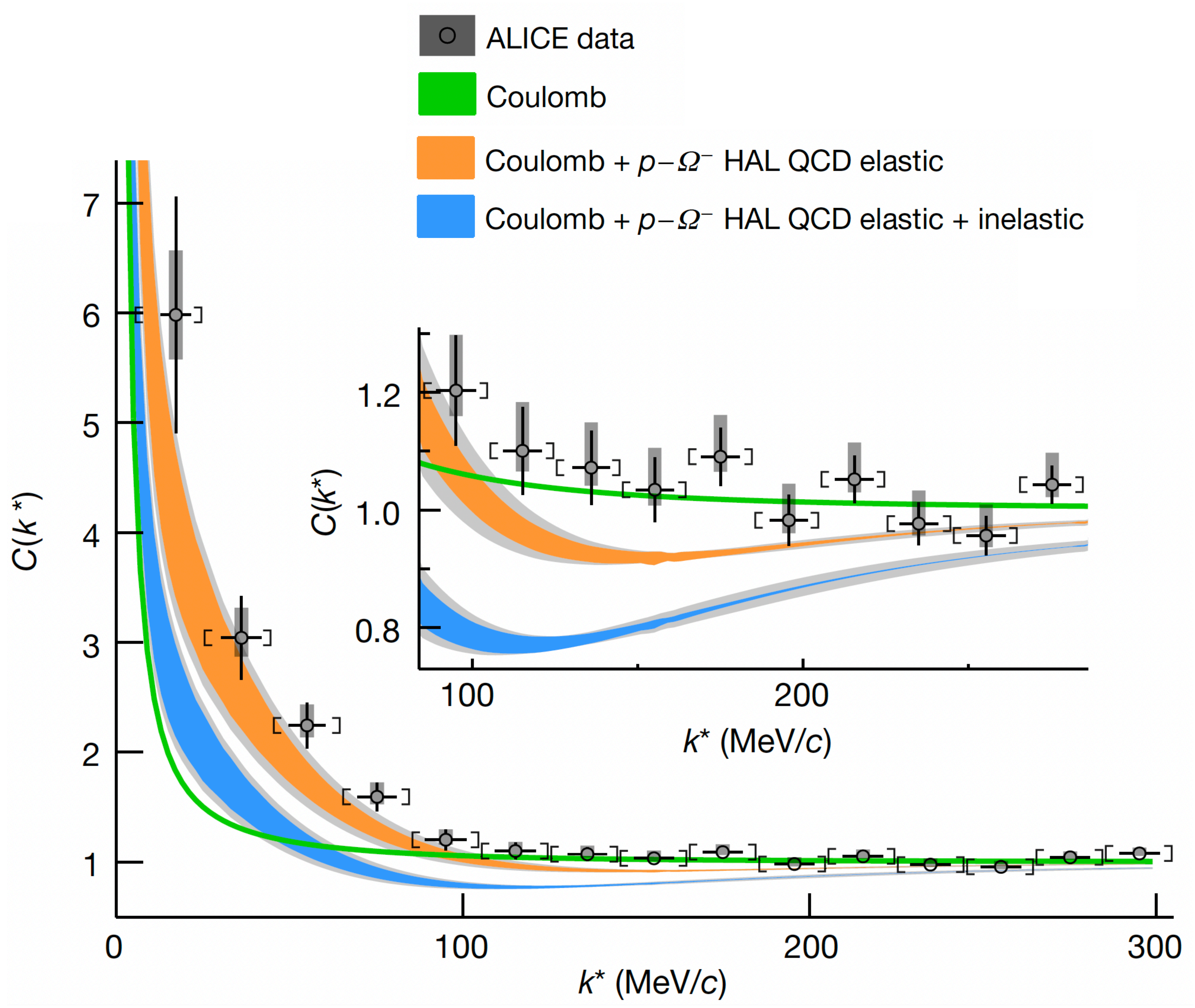

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- No indication of a bound state in data