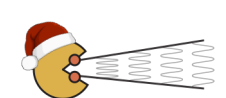


New experimental approaches to probe strange and exotic matter in neutron stars

V. Mantovani Sarti (TUM)
SFB Colloquium 18.12.2023



1. Why do we need strange and exotic matter in neutron stars?
2. How can we measure YN and YNN interactions nowadays?
3. Future perspective and challenges





Multi-messenger era: exciting times for neutron stars studies

Heavy neutron stars observations

PSR J0740+6620 $M = 2.08 \pm 0.07 M_{\odot}$

Z. Arzoumanian et al. Astrophys.J. Suppl. 235 (2018)

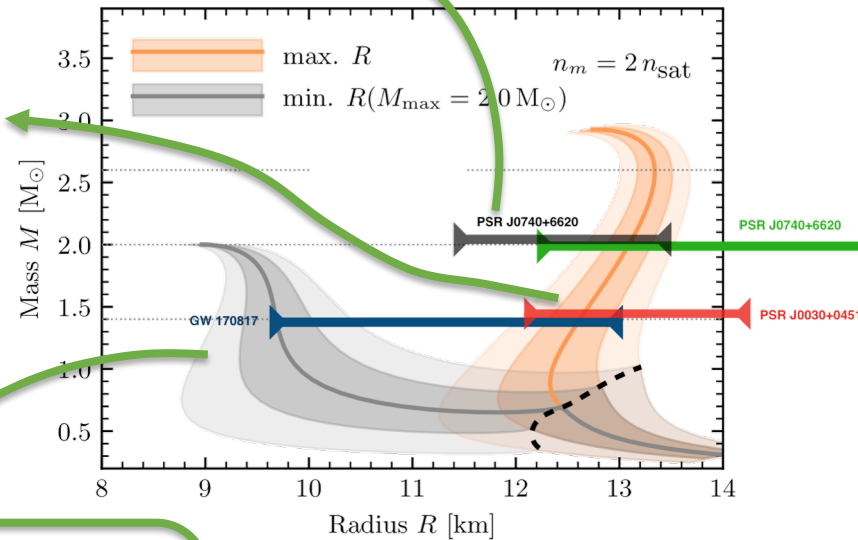
Precise radii measurements from NICER

PSR J0030+0451

$M = 1.44^{+0.15}_{-0.14} M_{\odot}$

$R = 13.02^{+1.24}_{-1.06}$ km

M. Miller et al. Astrophys.J.Lett. 887 (2019) 1, L24



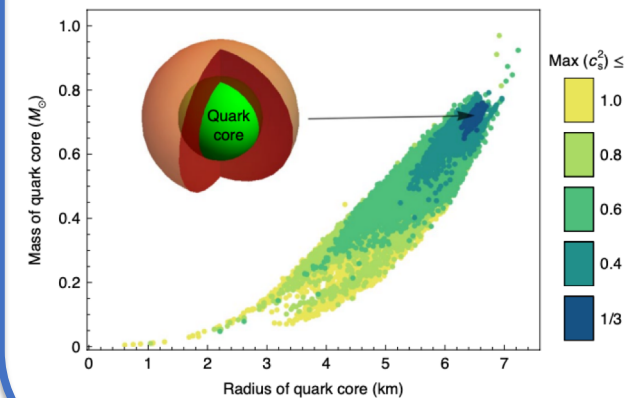
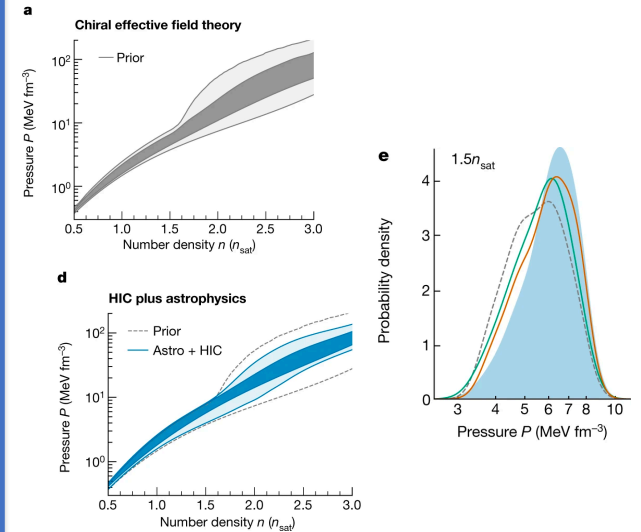
Gravitational waves from binary NS mergers

GW170817 $M_1 = 1.46^{+0.12}_{-0.10} M_{\odot}$, $\Lambda_1 = 255^{+416}_{-171}$

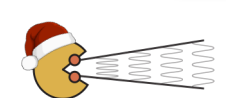
$M_2 = 1.27 \pm 0.09 M_{\odot}$, $\Lambda_2 = 661^{+858}_{-375}$

Novel approaches to constrain the EoS

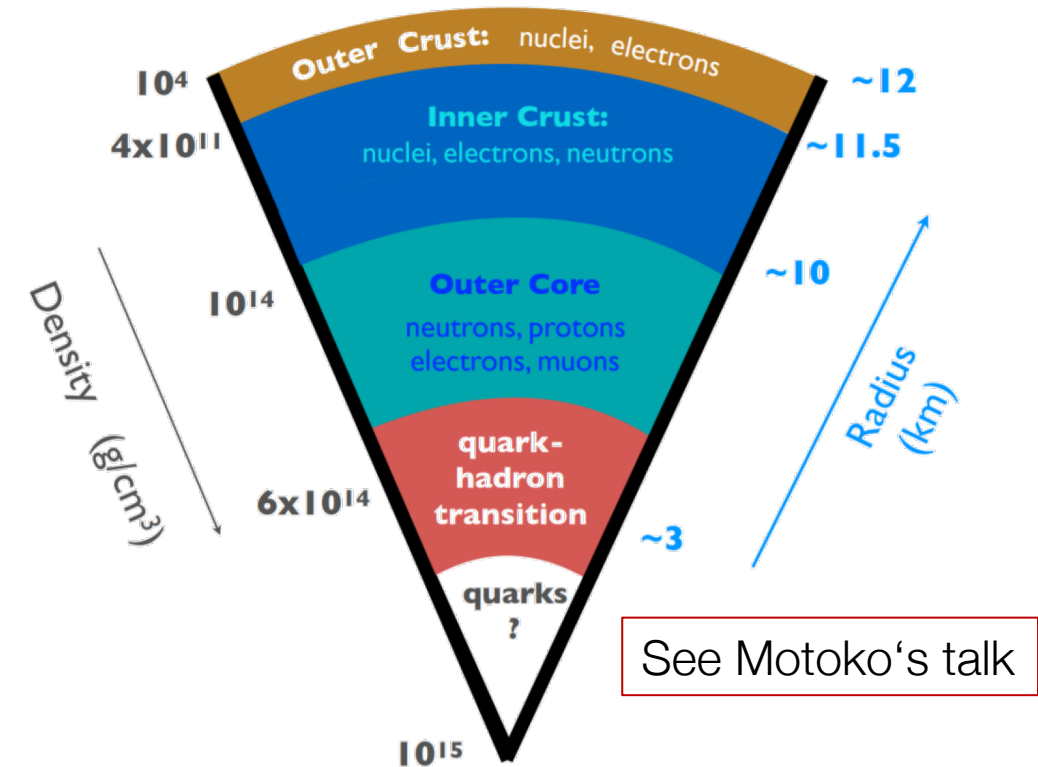
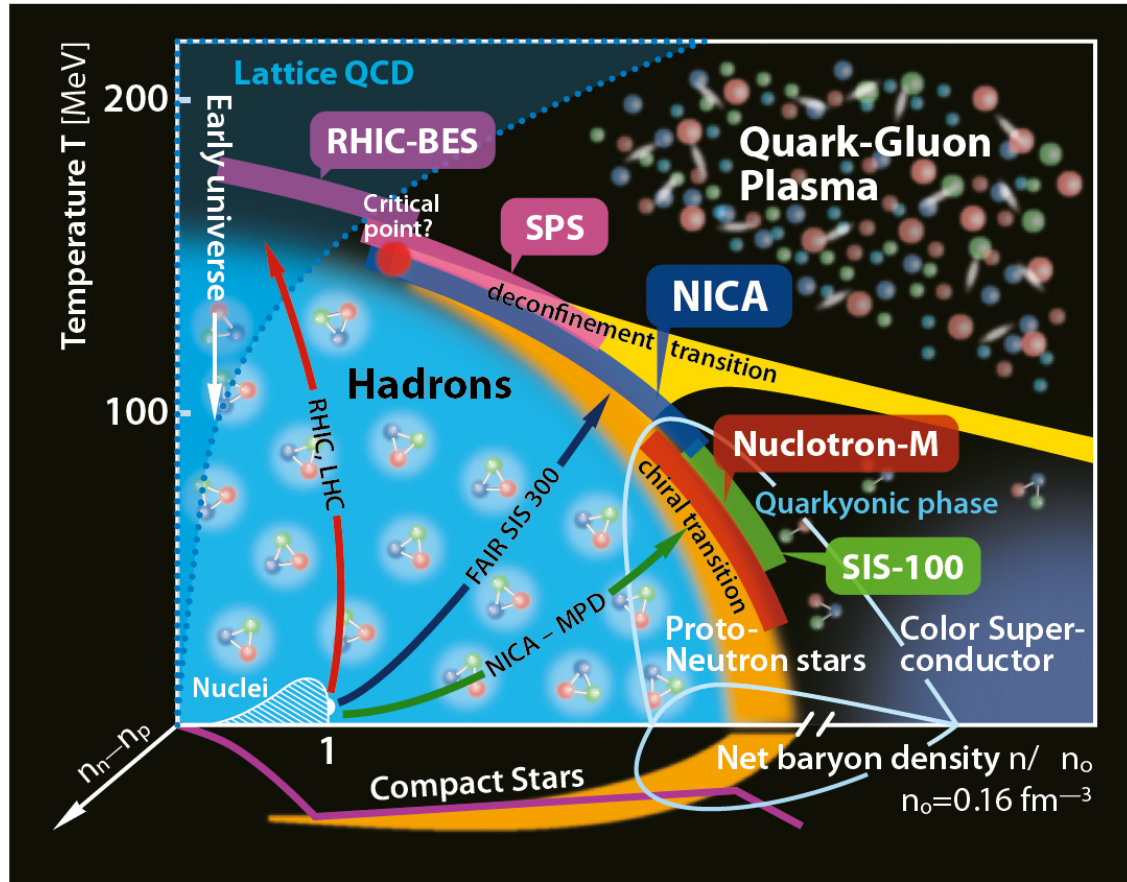
S. Huth et al. Nature 606 (2022) 276-280



E. Annala et al. Nature Physics 16 (2020)



Neutron stars: perfect laboratory for nuclear physics



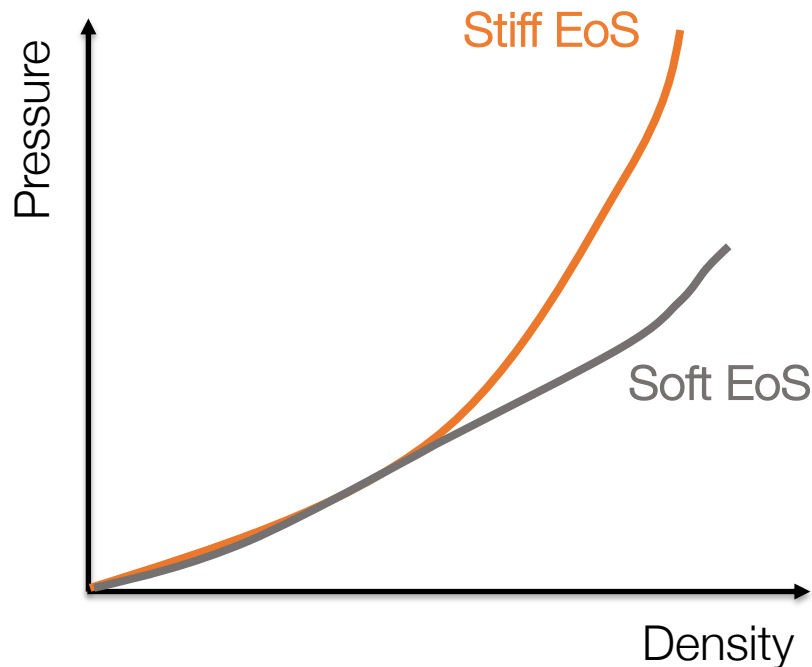
See Motoko's talk

Nuclear matter under extreme conditions ($\rho \sim 6\rho_0$ ⁽¹⁾)
 → Possibility to have ingredients beyond ordinary matter

(1) L. Brandes, W. Weise and N. Kaiser Phys.Rev.D 107 (2023) 1, 014011

The equation of state of matter in the core of NS

- Equation of State (EoS)
 - relation between the pressure and density, depends on the constituents and their interaction



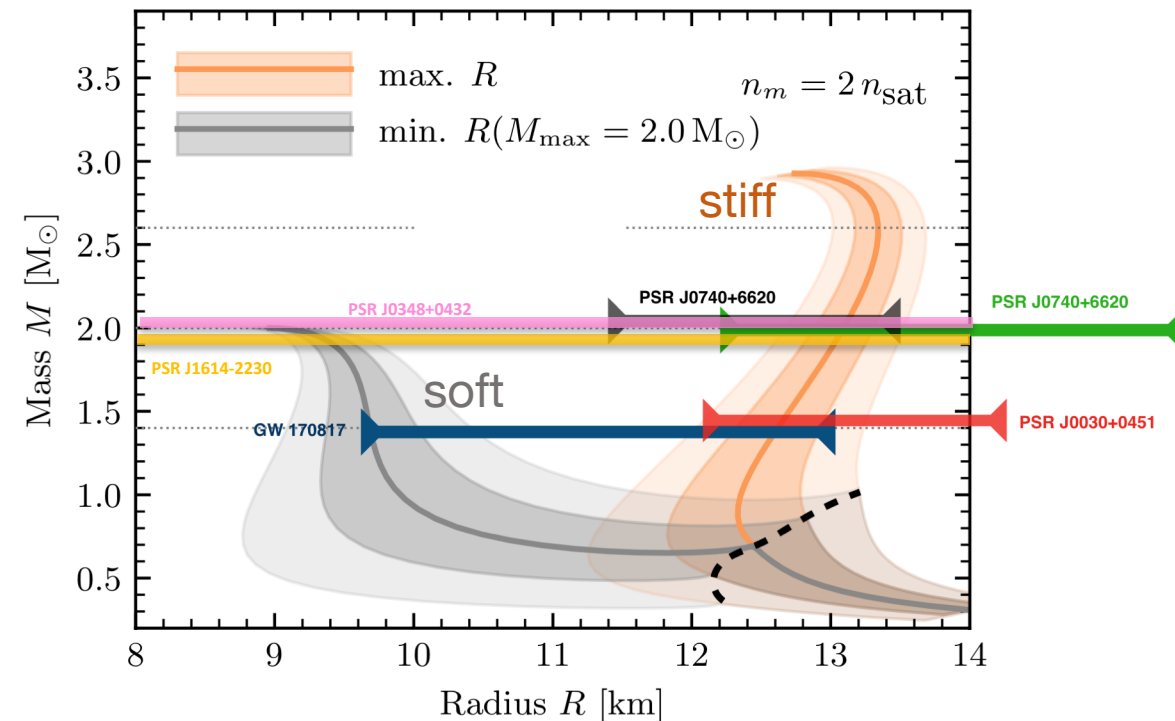
Tollmann
Oppenheimer
Volkoff
↔
eqns.

- From current astrophysical constraints
 - very "soft" and very "stiff" EoS seems to be ruled out

What are the constituents to consider?

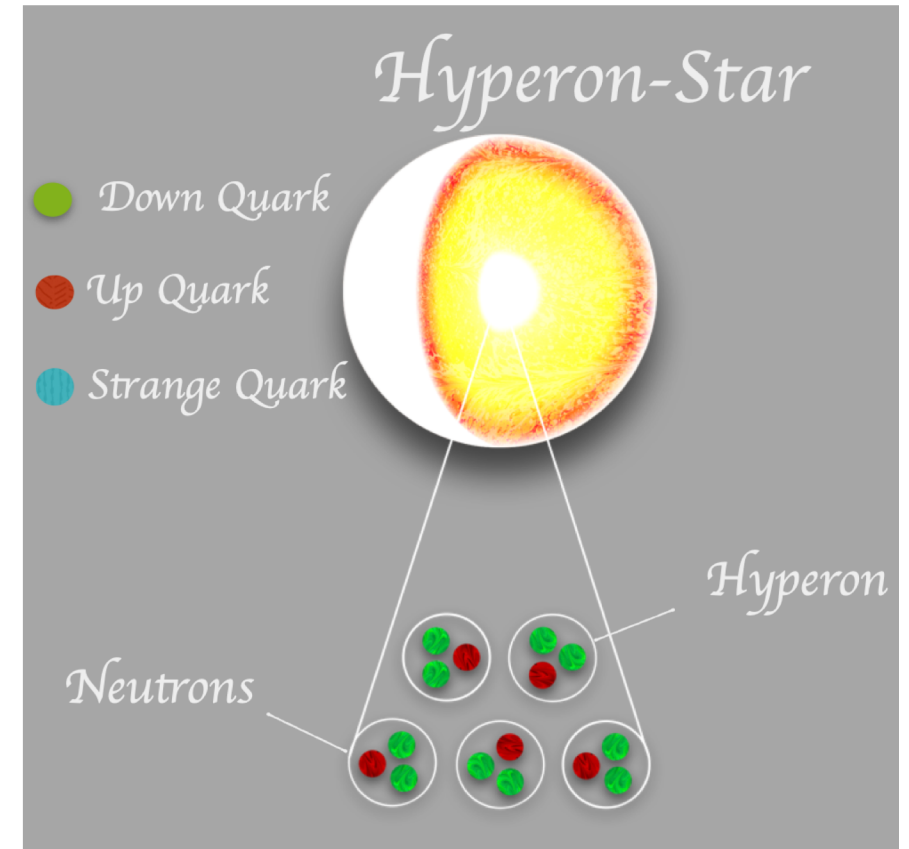
How do they interact in this dense medium?

from NICER website

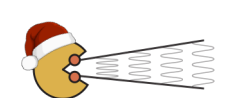


Hyperons in neutron stars: why?

- In NSs hyperon production becomes energetically favorable around $2-3 \rho_0$ ⁽¹⁾

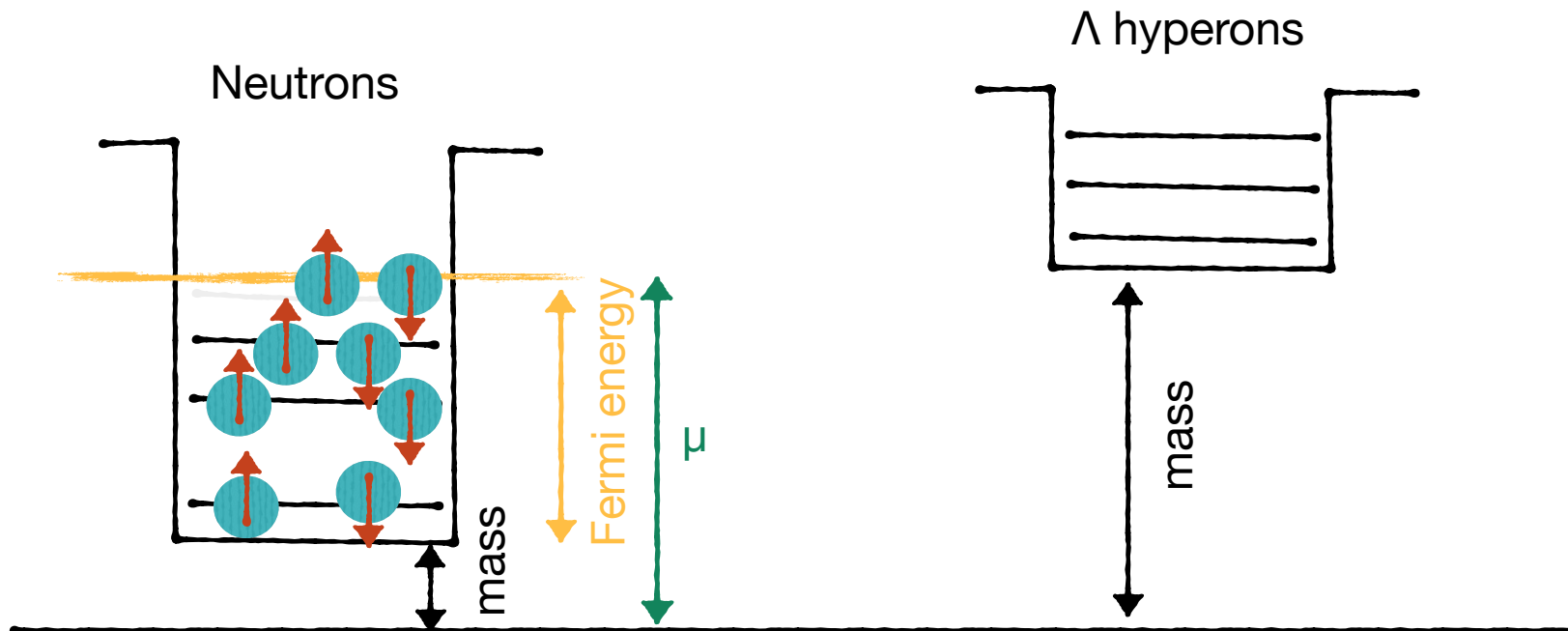


(1) V.A. Ambartsumyan, G.S. Saakyan, *Sov. Astron.* 4 (1960) 187
 S. Balberg, A. Gal, *Nuclear Phys.* A625 (1997)
 N.K. Glendenning, *Astrophys. J.* 293 (1985)
 J. Schaffner, I.N. Mishustin, *Phys. Rev. C*53 (1996)
 L. Tolos et al., *Astrophys. J.* 834 (1) (2017)
 D. Lonardoni et al., *PRC* 89 (2014)
 H. Djapo et al., *PRC* 81 (2010)
 L. Tolos, L. Fabbietti *Prog.Part.Nucl.Phys.* 112 (2020)



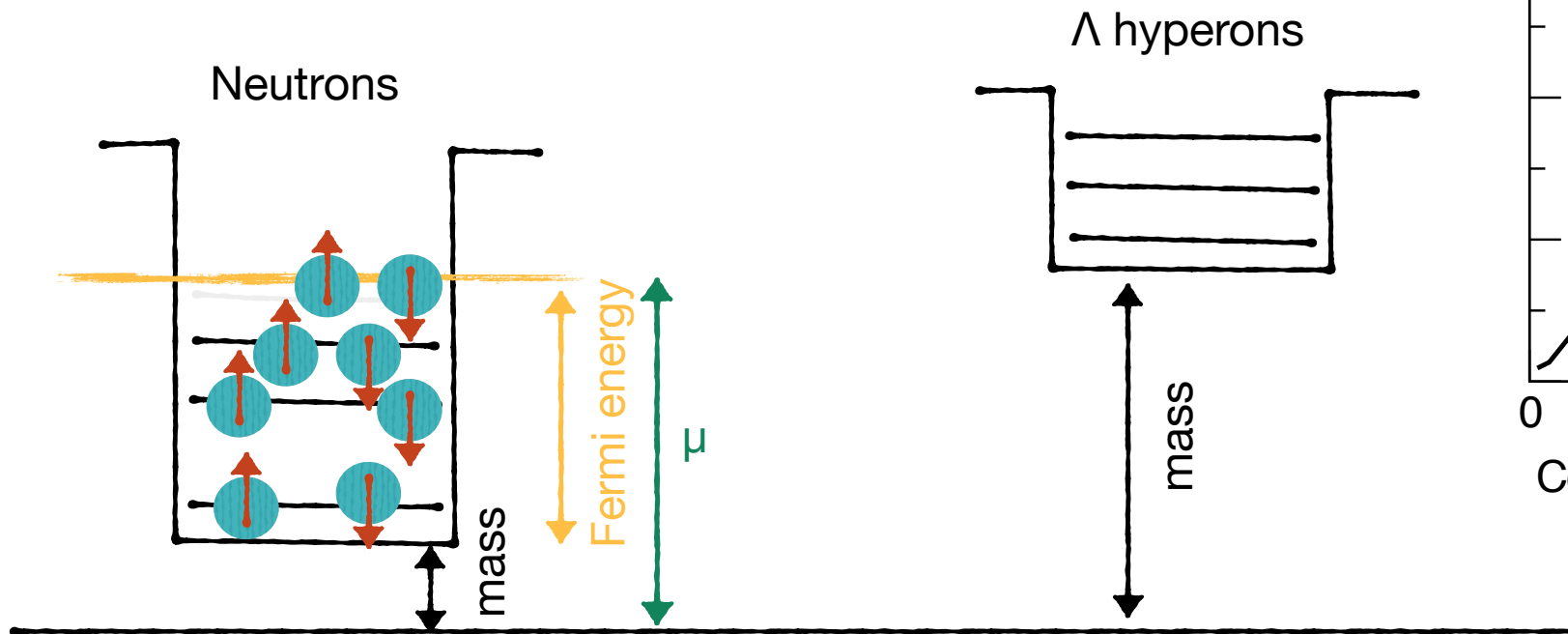
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 - chemical potential $\mu = m + \text{Fermi energy}$
 - Fermi energy increases with density

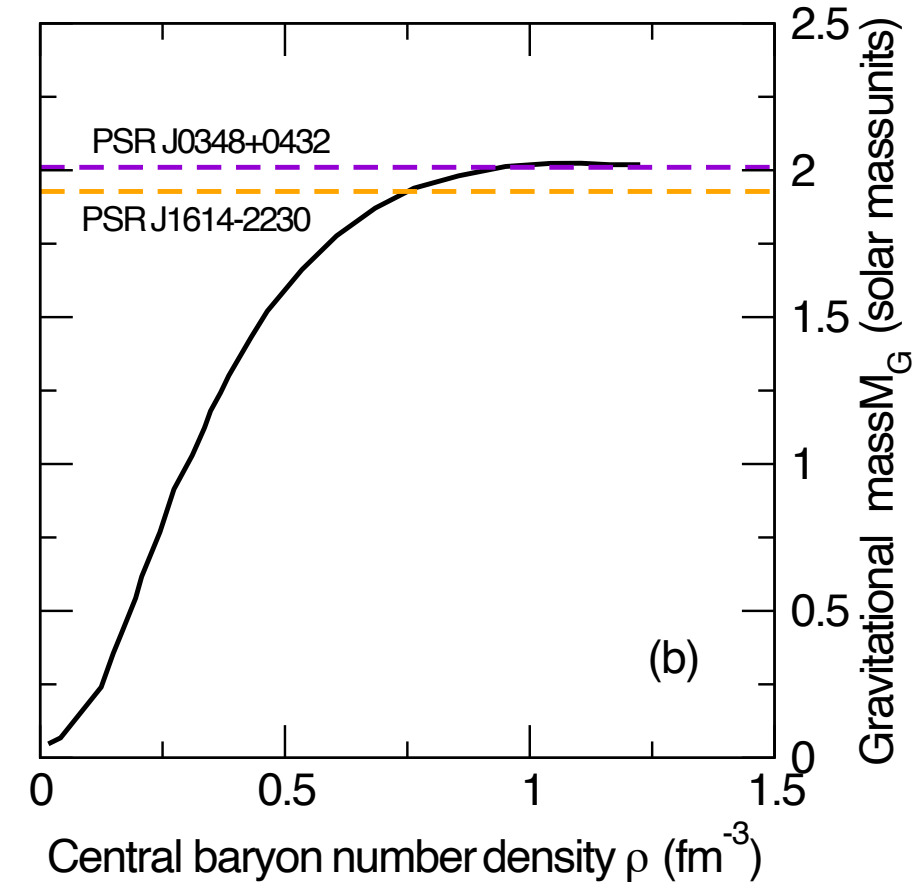


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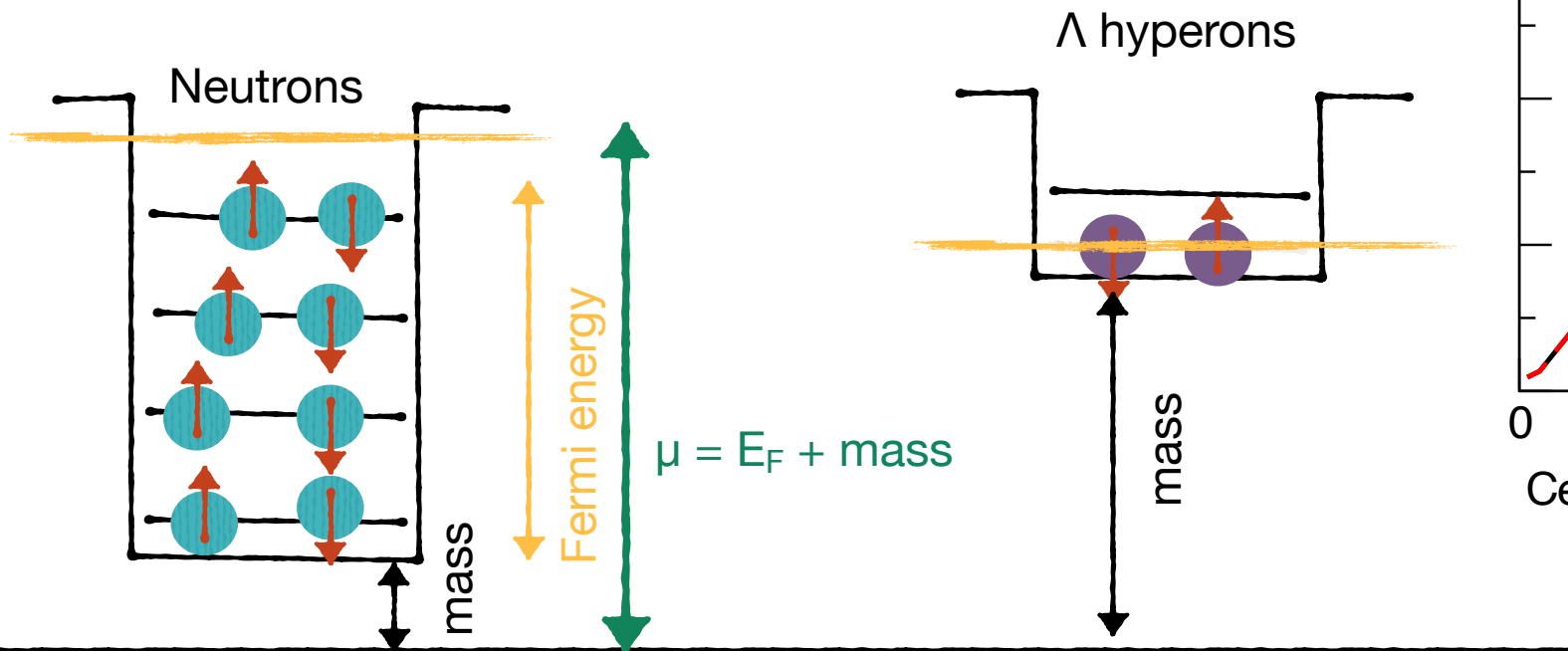


(1) I. Vidaña Proc.Roy.Soc.Lond.A 474 (2018) 0145

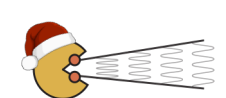
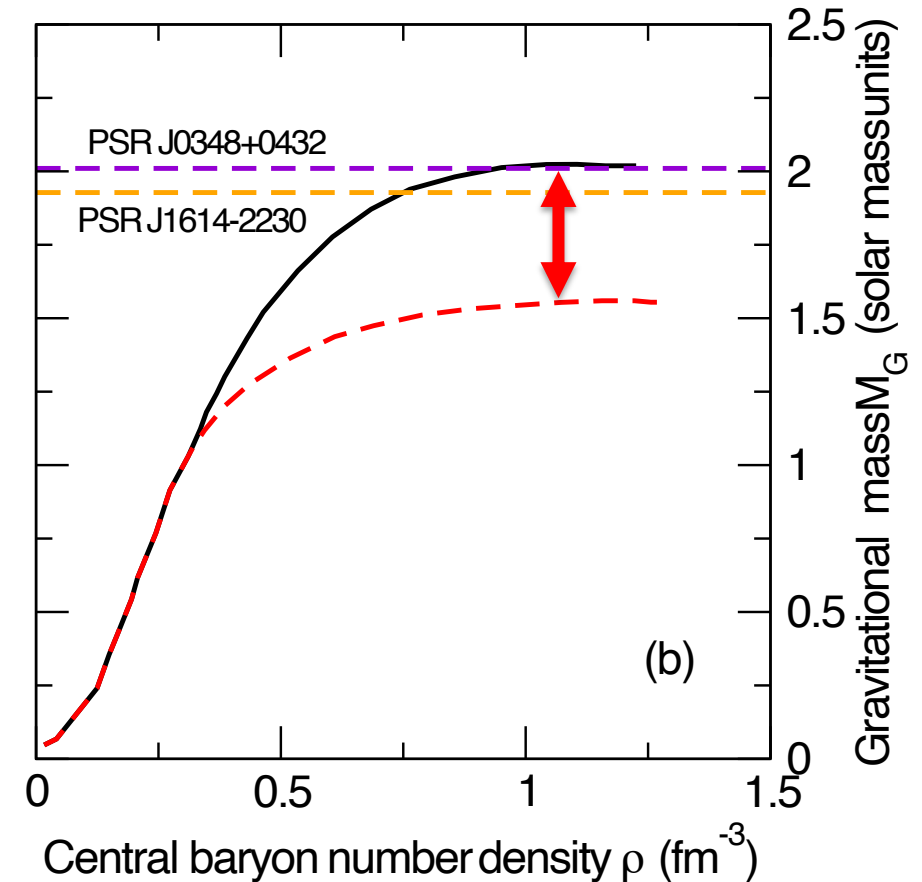


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 - chemical potential $\mu = m + \text{Fermi energy}$
 - Fermi energy increases with density
 - $\mu_n = \mu_\Lambda$: neutrons conversion into hyperons
 - softening EoS and reduction of mass

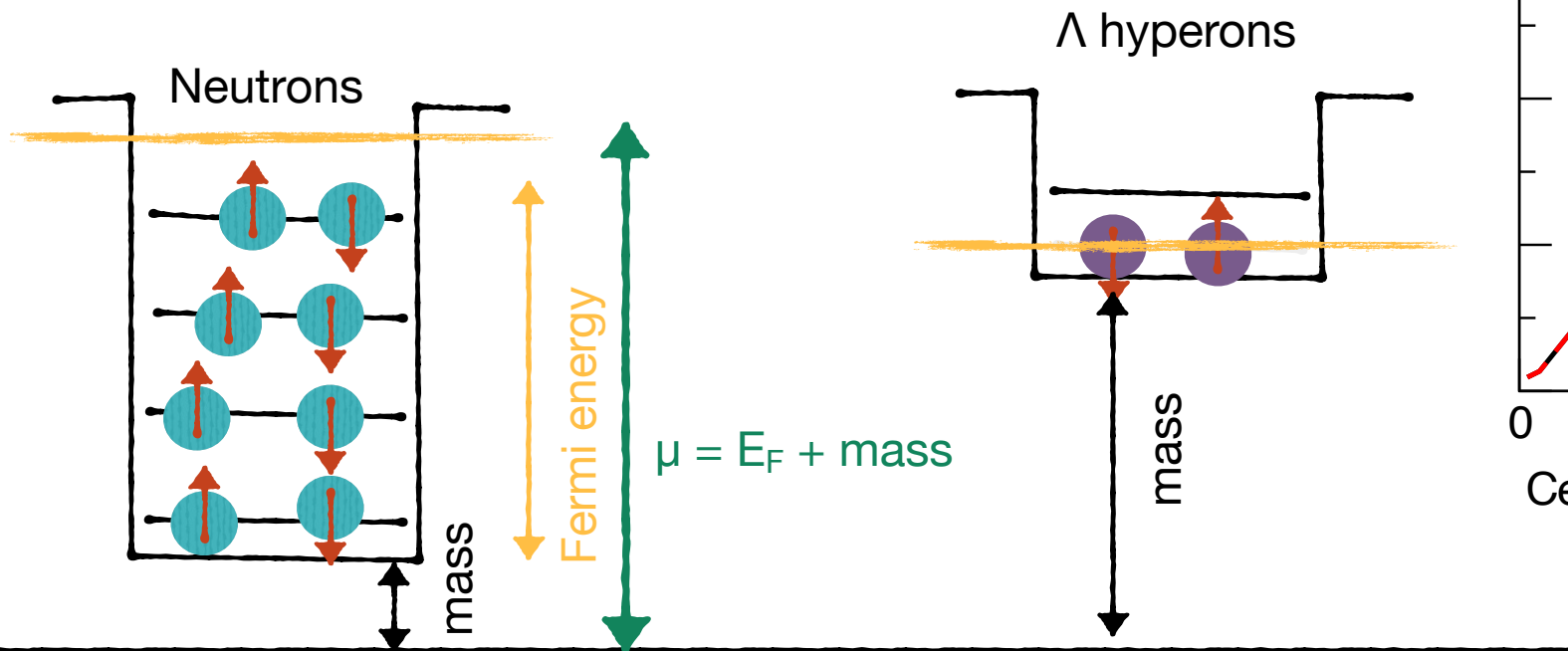


(1) I. Vidaña *Proc.Roy.Soc.Lond.A* 474 (2018) 0145

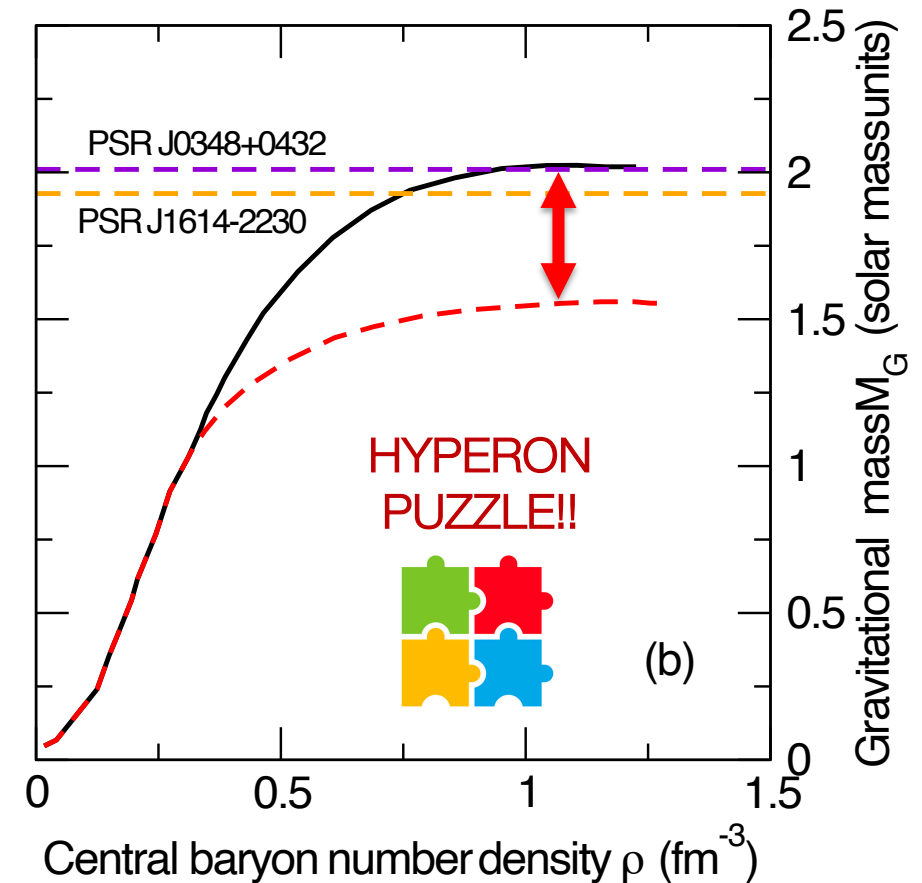


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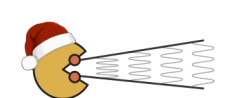
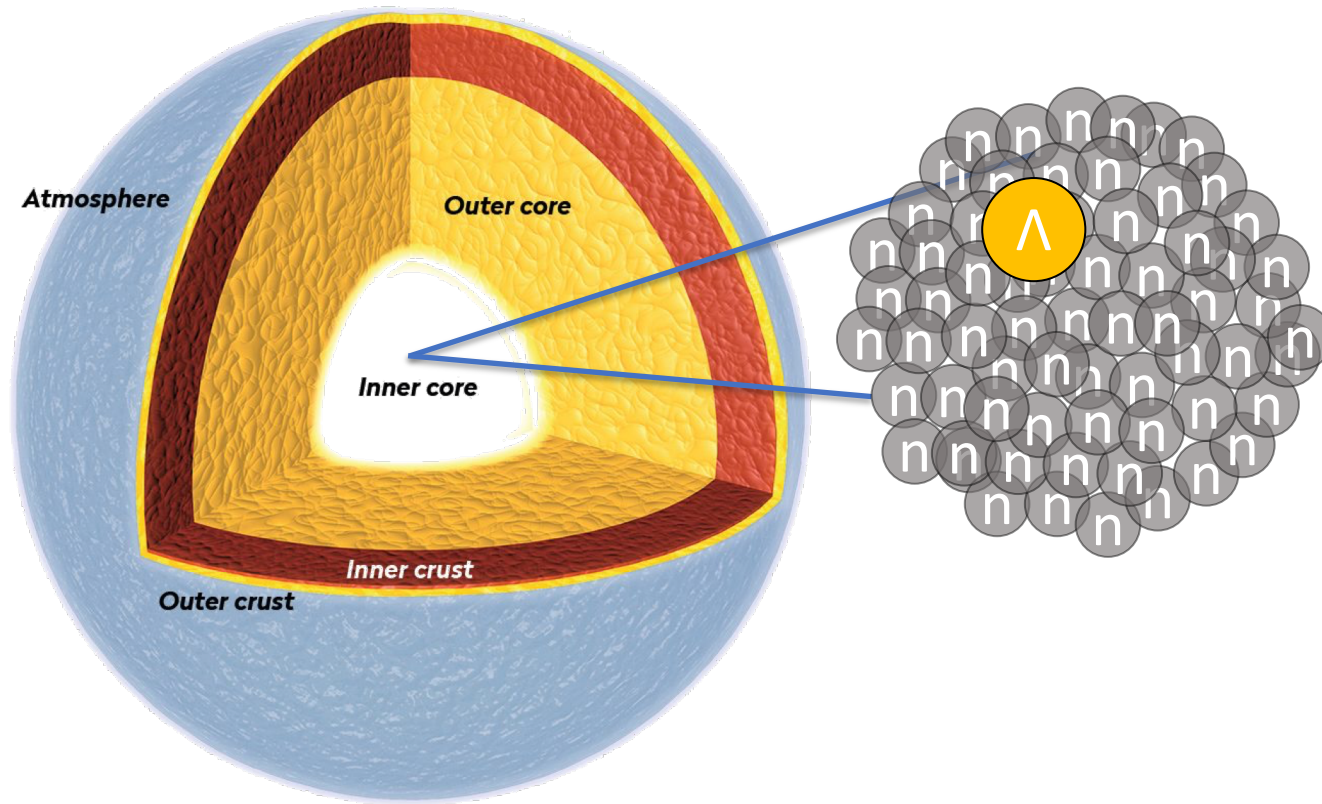
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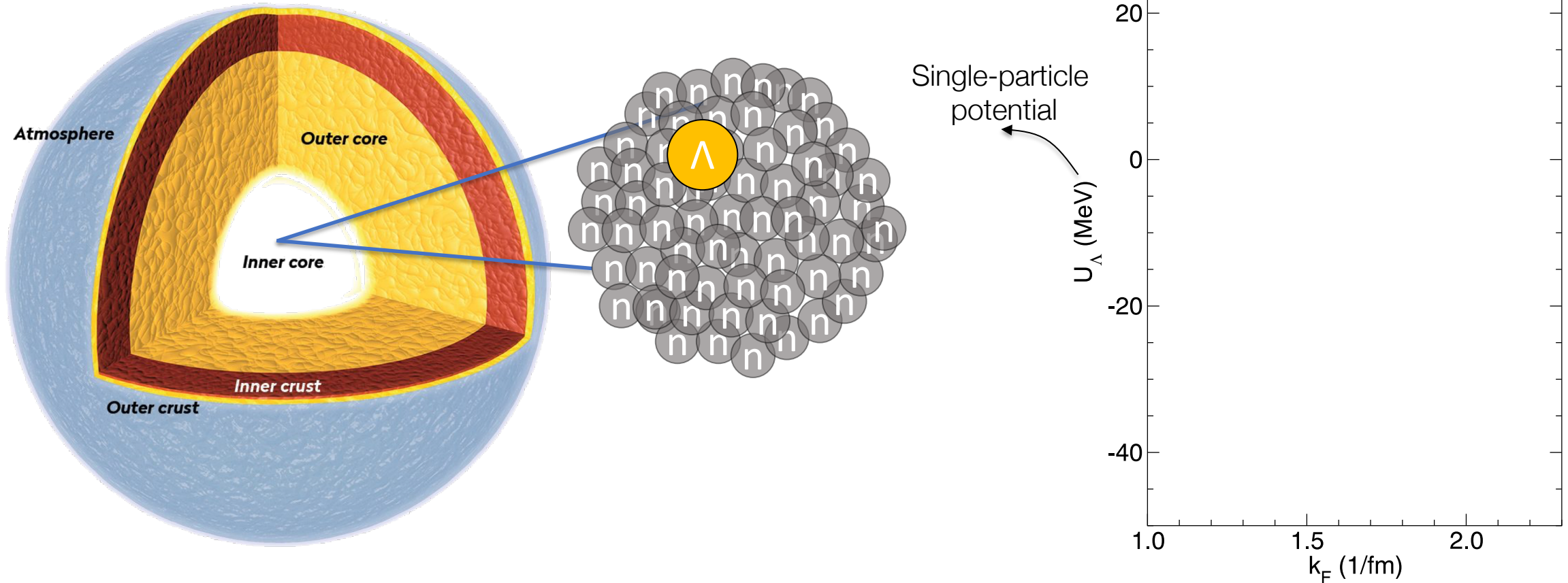
(1) I. Vidaña Proc.Roy.Soc.Lond.A 474 (2018) 0145



- Driven by the average potential the hyperon "feels" in the dense medium

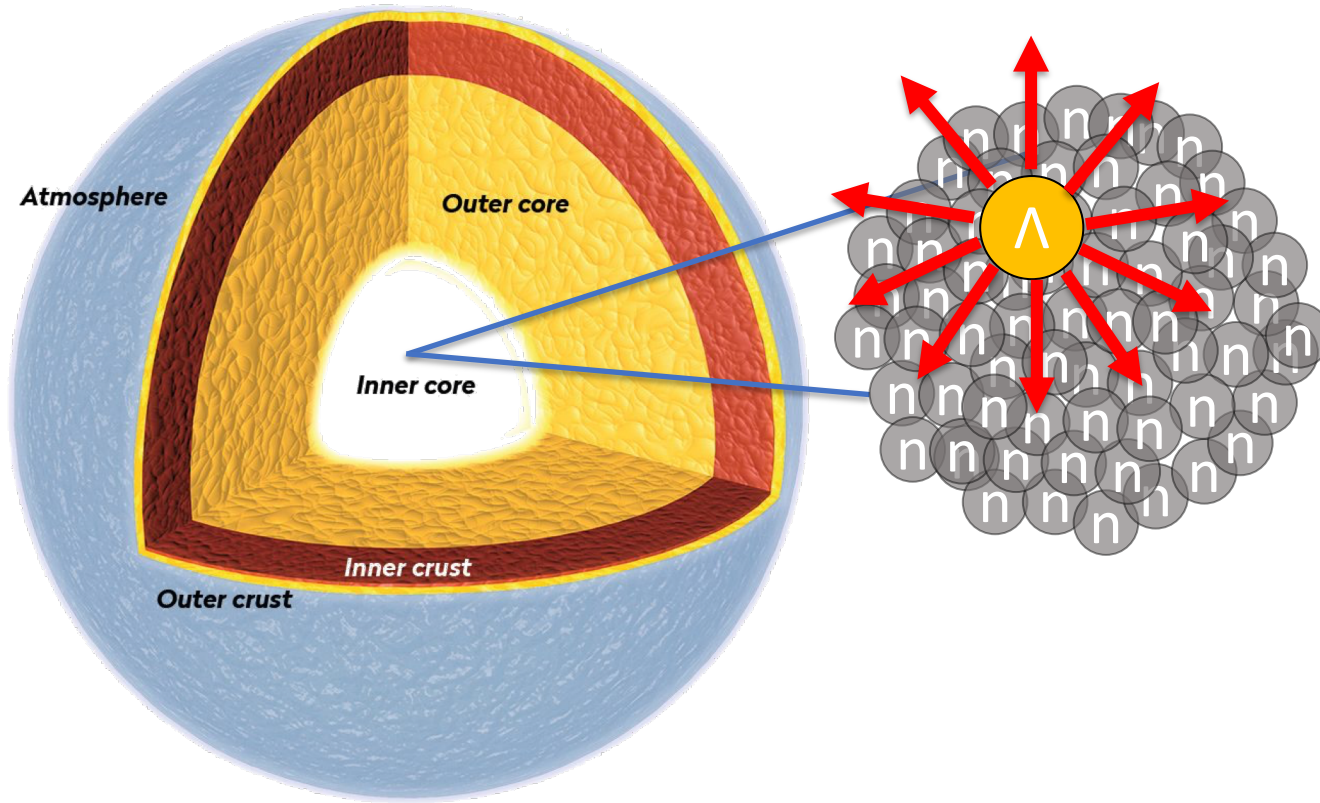


- Driven by the average potential the hyperon "feels" in the dense medium
- Single-particle potentials $U_Y(\rho) \rightarrow$ depends on YN and YNN interactions

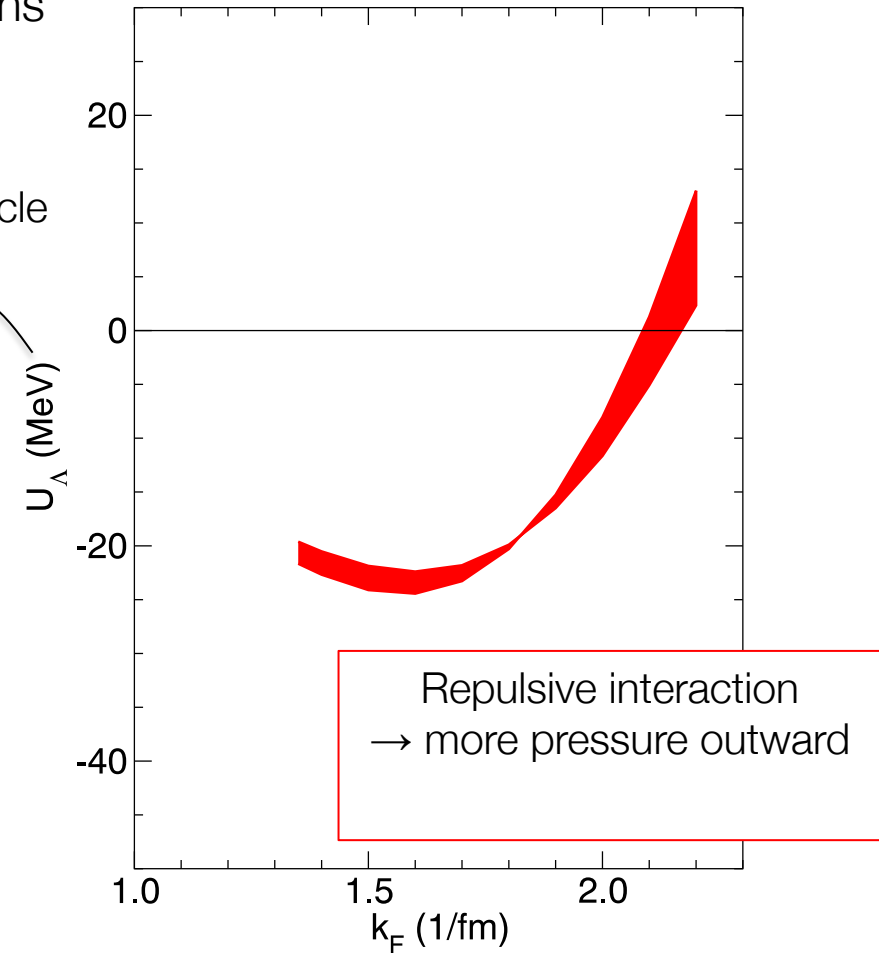


Interactions and EoS

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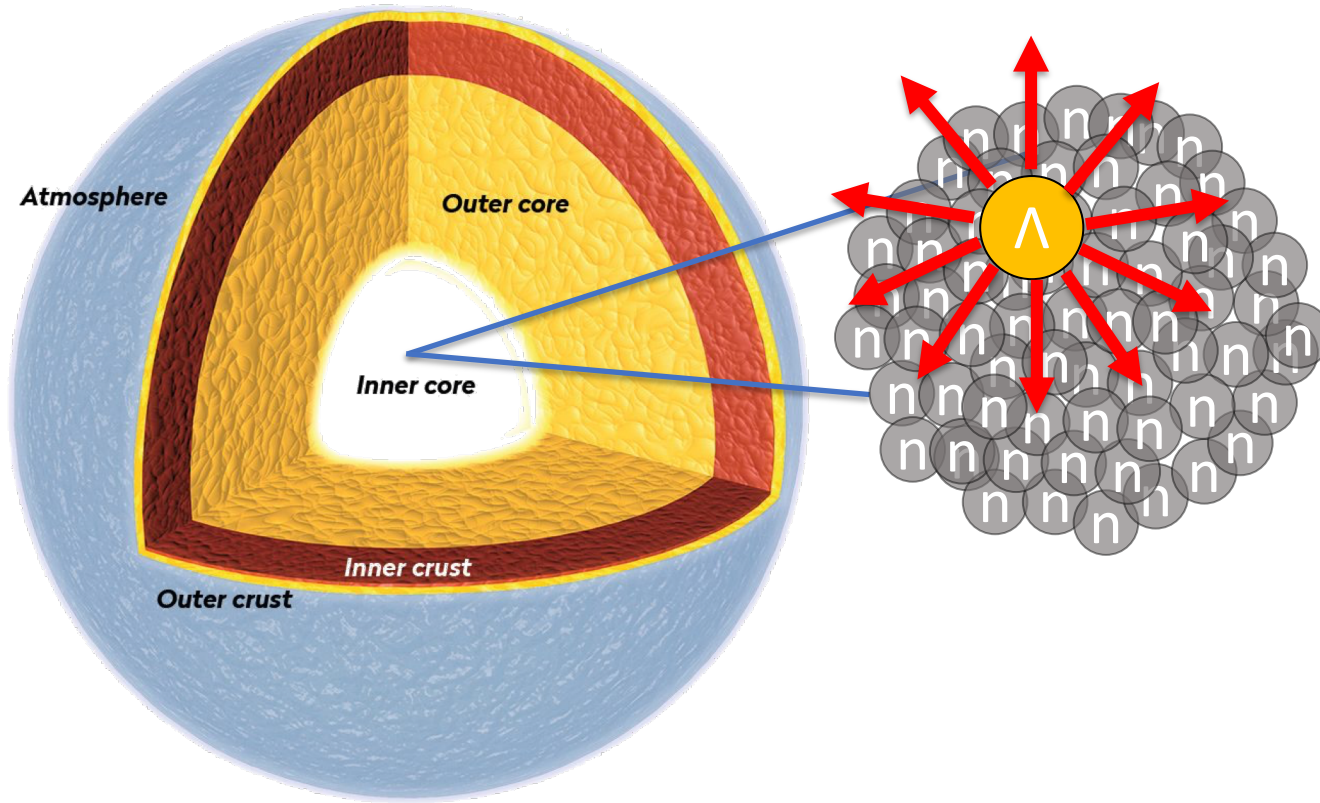


Single-particle potential

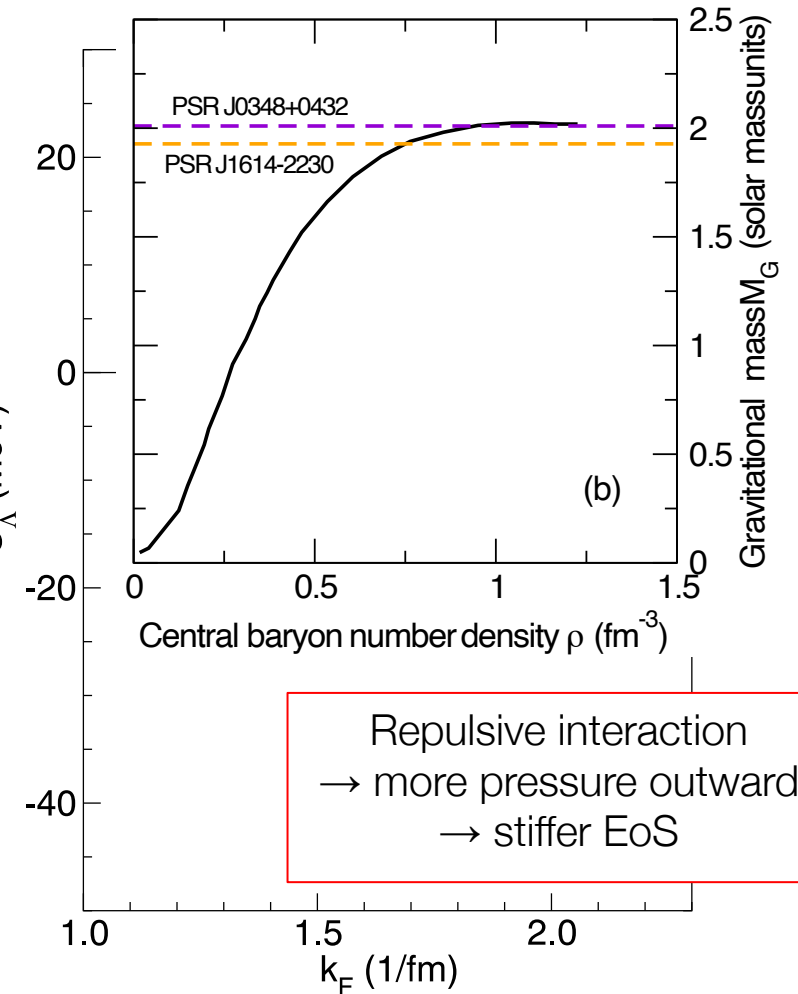


Interactions and EoS

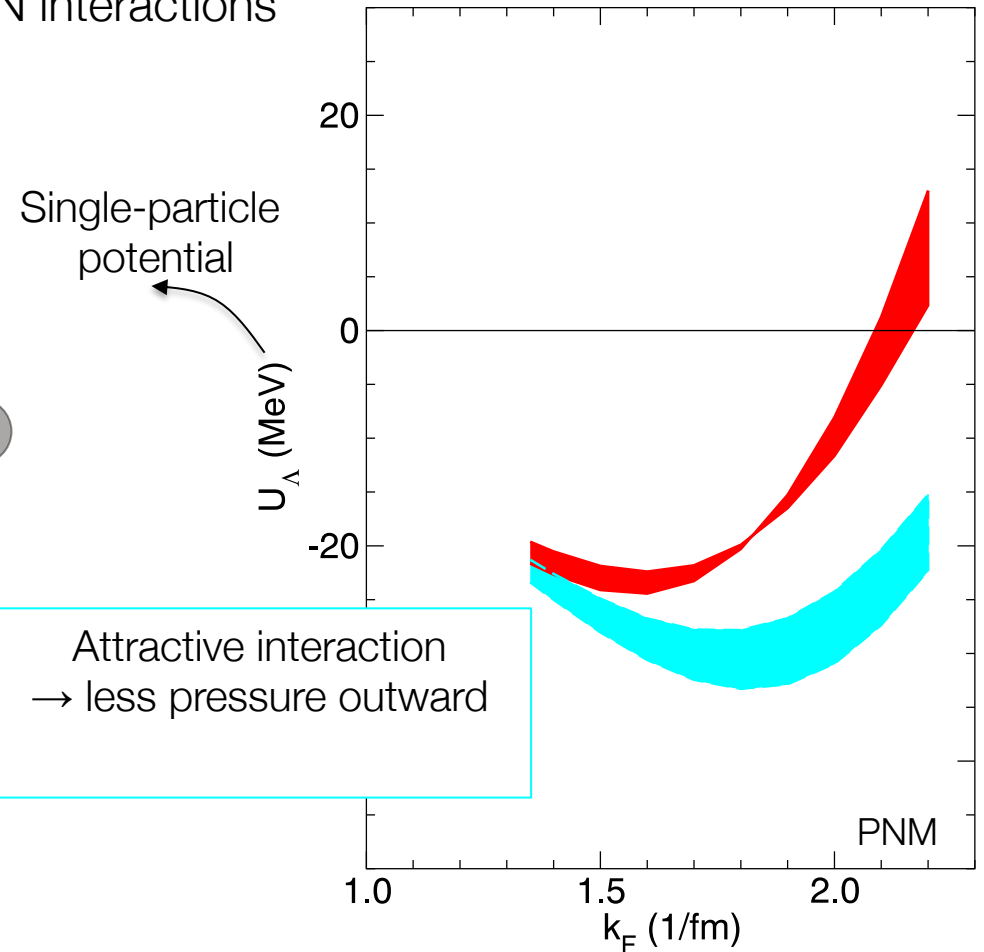
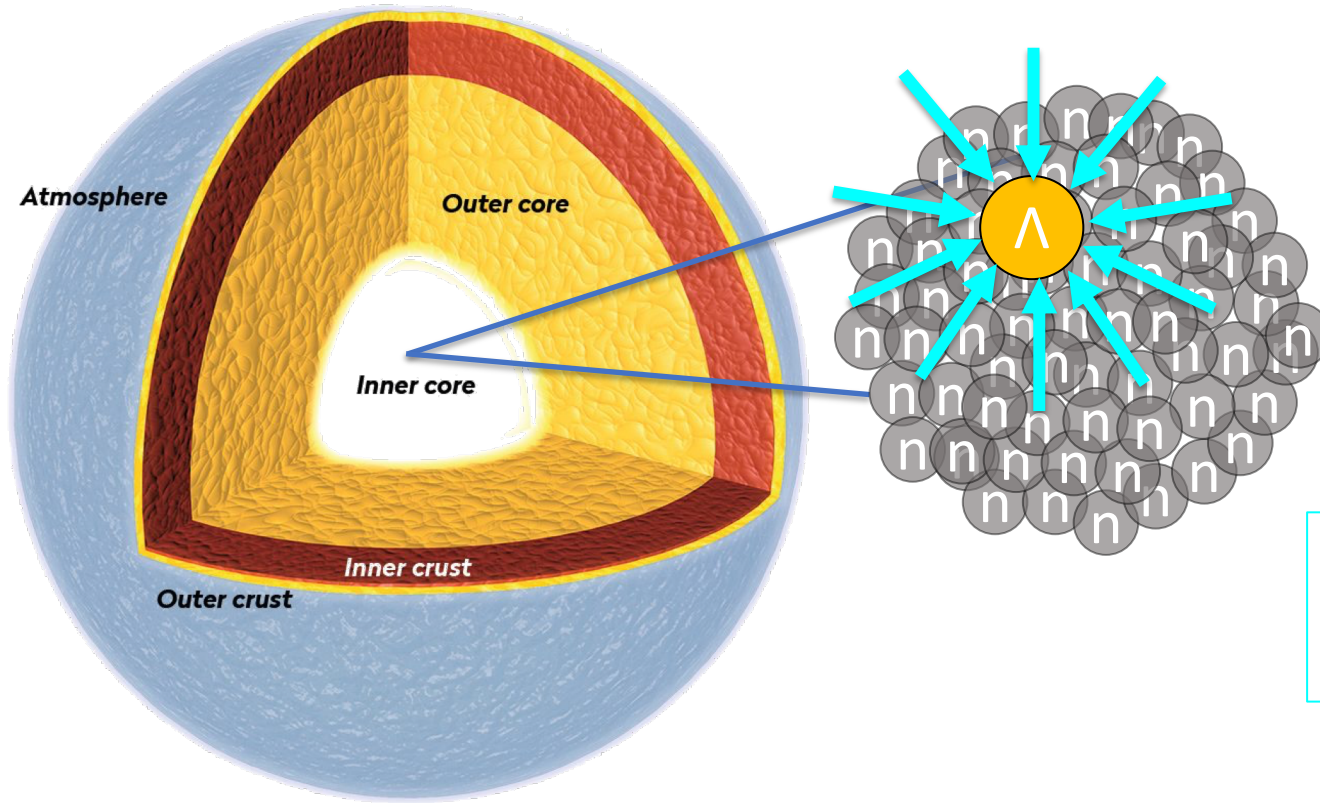
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Single-particle potential



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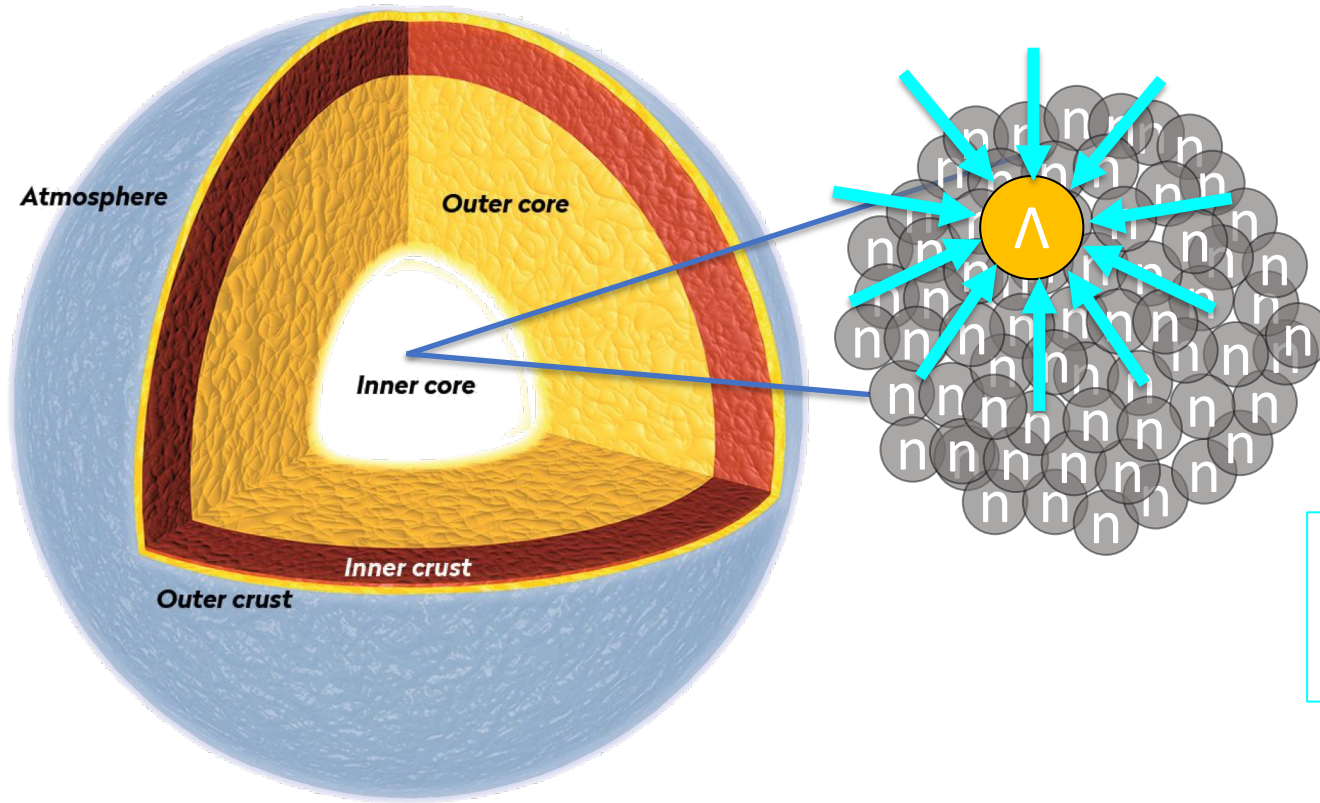


NLO13: J.Haidenbauer et al., NPA 915, 24 (2013)

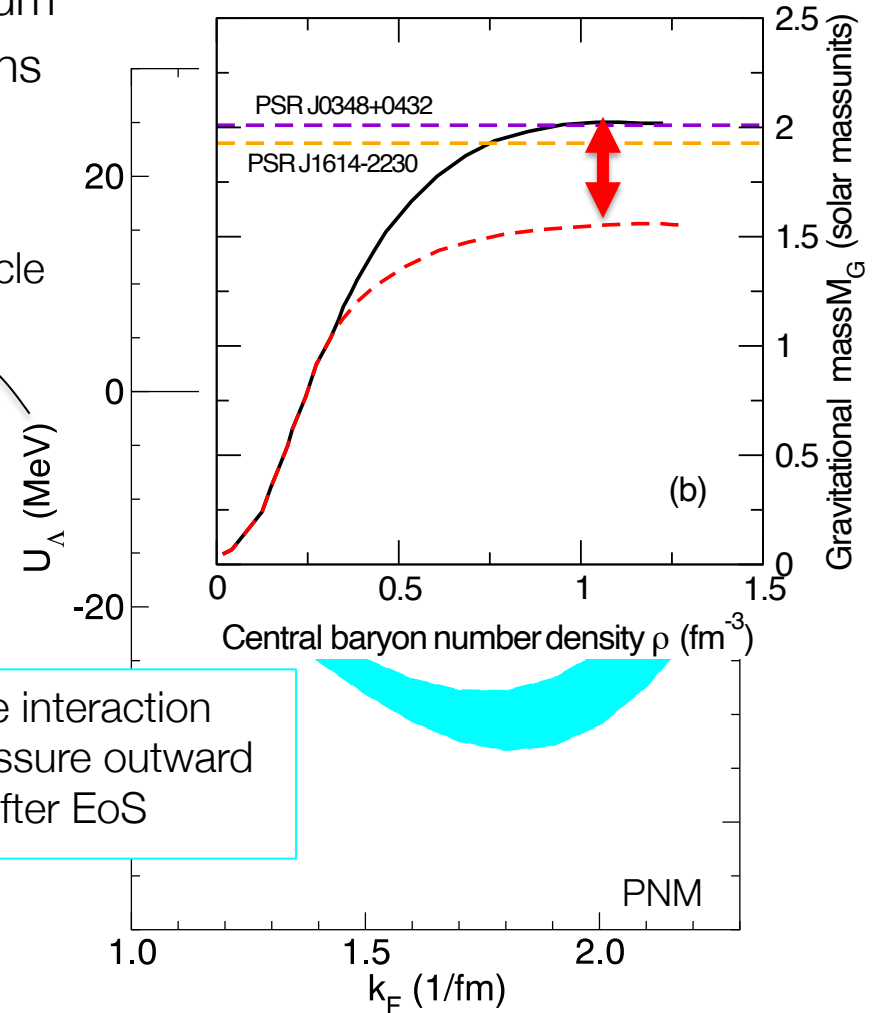
NLO19: J.Haidenbauer, U. Meißner, Eur.Phys.J.A 56 (2020)

Interactions and EoS

- Driven by the average potential the hyperon "feels" in the dense medium
- Single-particle potentials $U_Y(\rho) \rightarrow$ depends on YN and YNN interactions



Single-particle potential



Attractive interaction
 \rightarrow less pressure outward
 \rightarrow softer EoS

NLO13: J.Haidenbauer et al., NPA 915, 24 (2013)
NLO19: J.Haidenbauer, U. Meißner, Eur.Phys.J.A 56 (2020)

The hyperon puzzle in neutron stars....at the beginning of this talk

- The solution discussed today

- High precision data to improve the knowledge on
 - two body YN and YY interaction⁽¹⁾
 - three-body hyperonic forces⁽²⁾

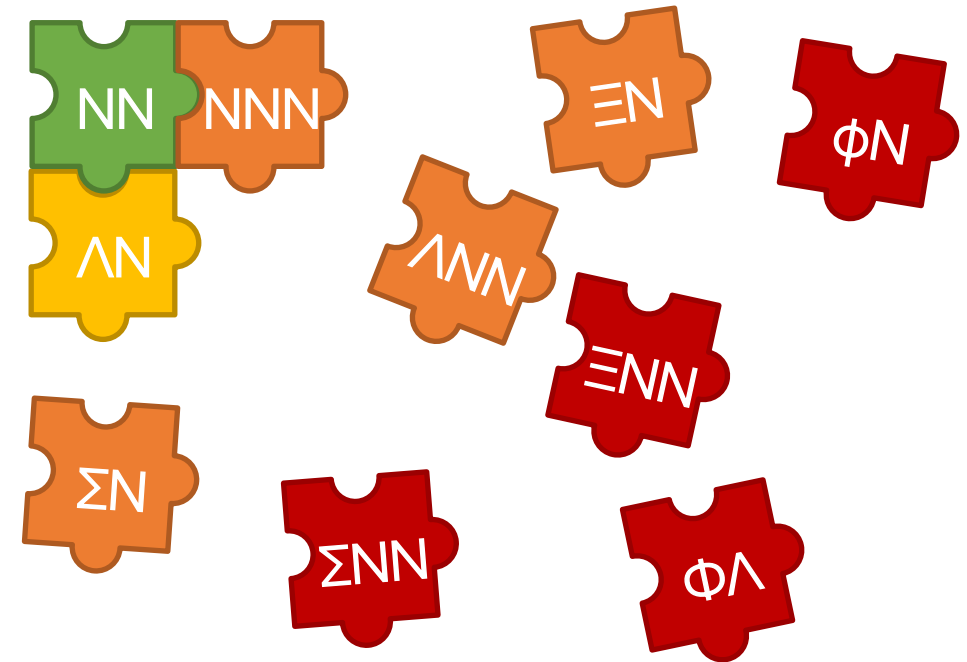
- Other solutions are discussed:

- Hybrid EoS and quark matter core

S. Weissenborn et al. AJ 740 (2011), D. Blaschke et al., PRC 105 (2022),
 I Bombaci et al. EPJA 524 (2016), A. Drago et al. EPJA 52 (2016)
 G. Baym et al., Astrophys.J. 934 (2022)

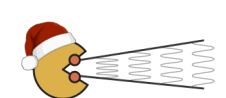
- presence of Δ isobars and kaon condensate

A. Drago et al. PRC 90 (2014), P. Robes et al. AJ 883 (2019), T. Schuerhoff et al. AJ 724 (2010)

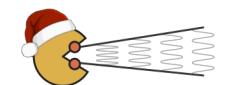


(1) S. Weissenborn et al. PRC 85 (2012)
 M. Oertel et al., JPG 42 (2015)

(2) D. Logoteta et al., Eur.Phys.J.A 55 (2019)
 D. Lonardonì et al., PRL 114 (2015)
 D. Gerstung et al., EPJA 56 (2020)

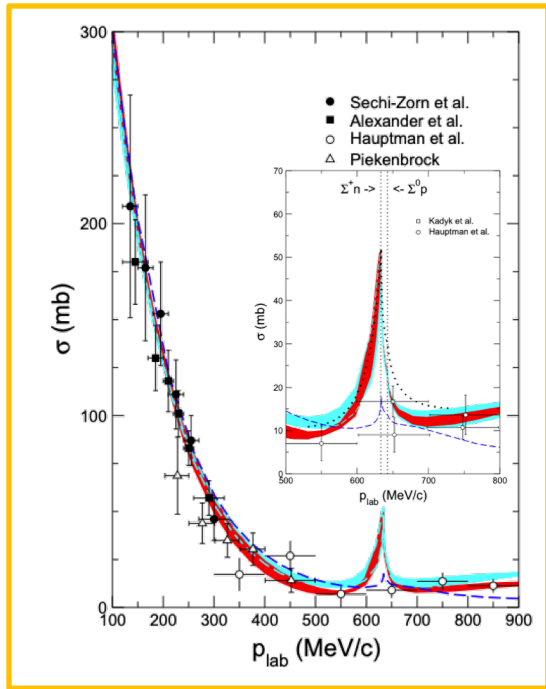


Accessing interactions with hyperons and nucleons





Experimental tools: scattering data



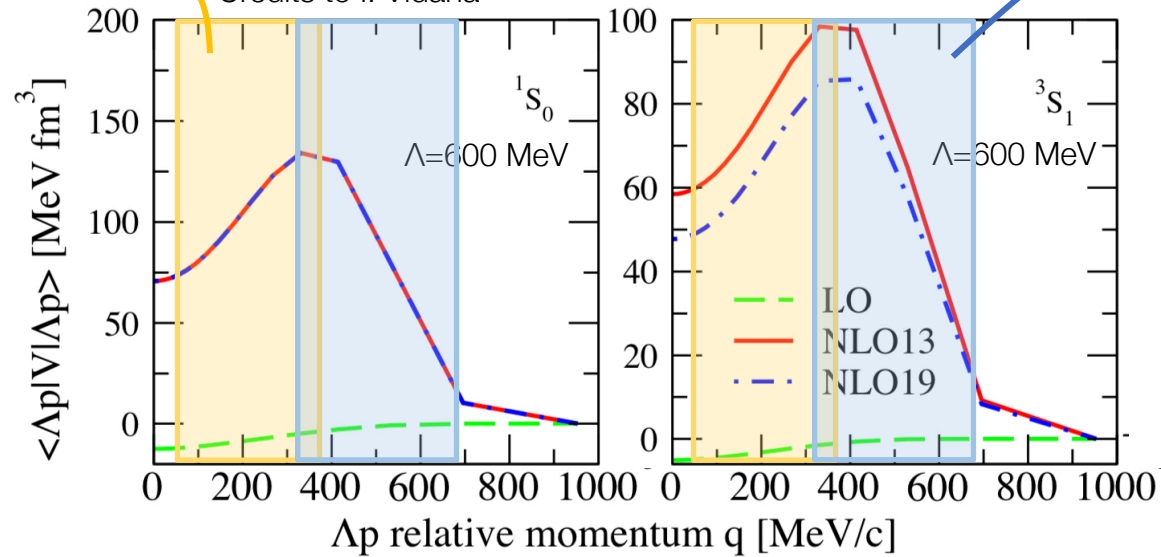
Scarce data for pΛ at low momenta

Spin-averaged cross-sections

LO: J.Haidenbauer et al., NPA 915, 24 (2013)
 NLO13: J.Haidenbauer et al., NPA 915, 24 (2013)
 NLO19: J.Haidenbauer, U. Meißner, Eur.Phys.J.A 56 (2020)

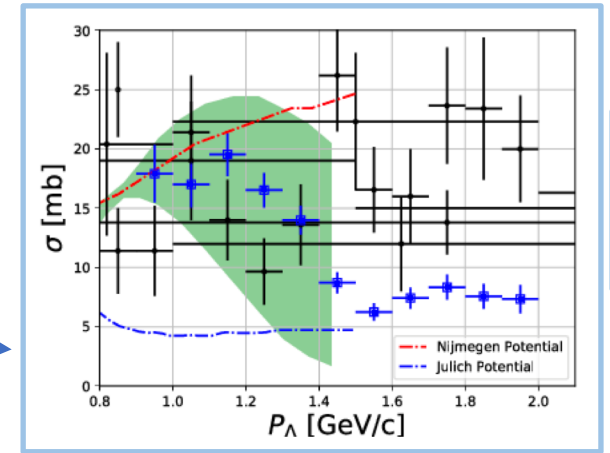
Constrain the behaviour of $V_{p\Lambda}$

Credits to I. Vidaña

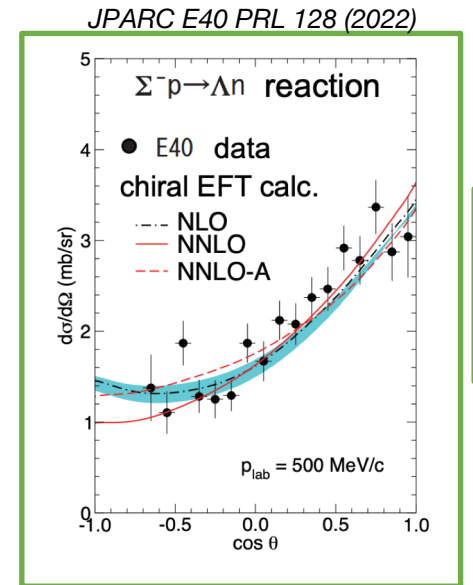


cross-sect. $\propto \delta_{l,S}$

$$a_{0,S} = - \lim_{k \rightarrow 0} \frac{1}{k} tg \delta_{0,S}(k)$$



CLAS

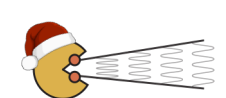


JPARC

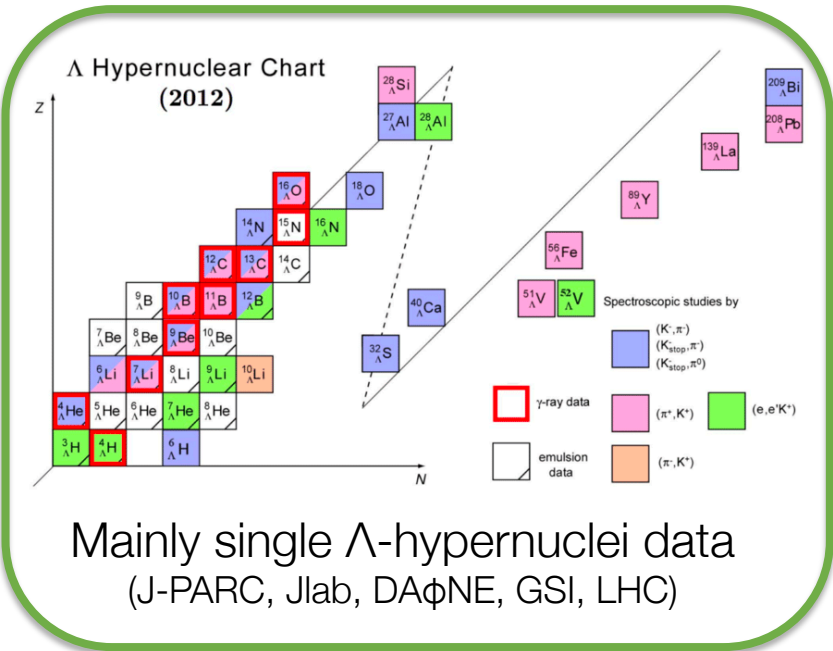
Probe $\Lambda N \leftrightarrow \Sigma N$ transition

Access to spin dependence with JPARC extension

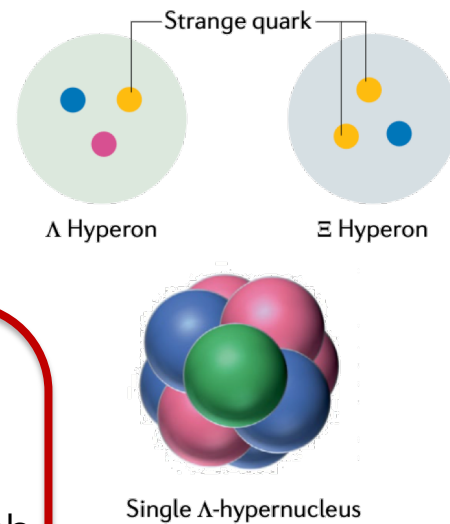
[HEF-ex @ JPARC](#)



Experimental tools: hypernuclear measurements

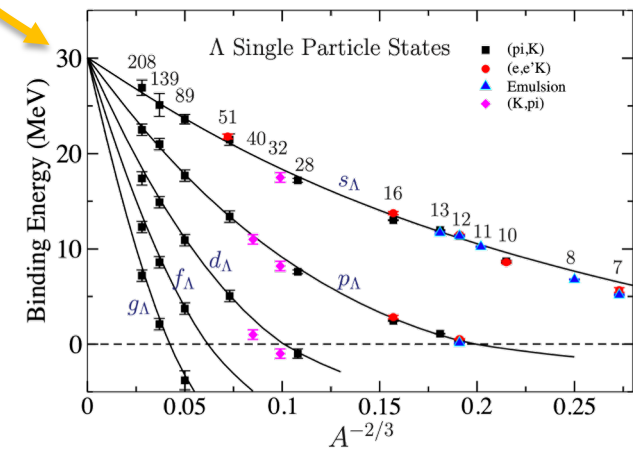
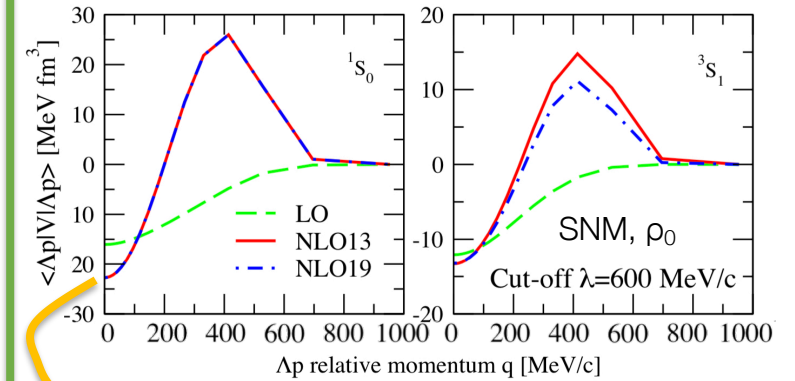


One of the nucleons is replaced by a Λ hyperon



Density dependence of YN and access (indirect) to YNN forces

$V_{p\Lambda}(\rho, q) + \text{Potential depth } U_Y \text{ at } \rho_0$

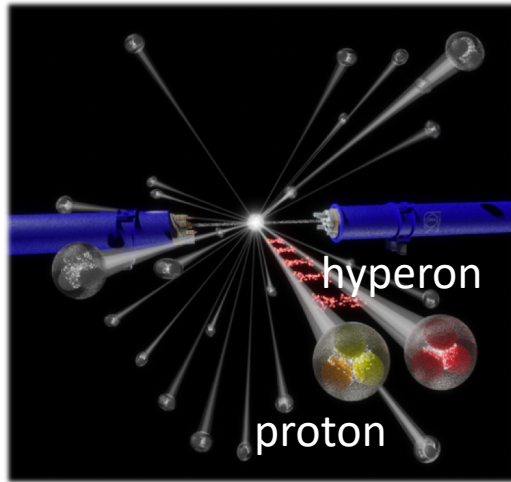


E. Friedman, A. Gal arXiv:2204.02264 [nucl-th]

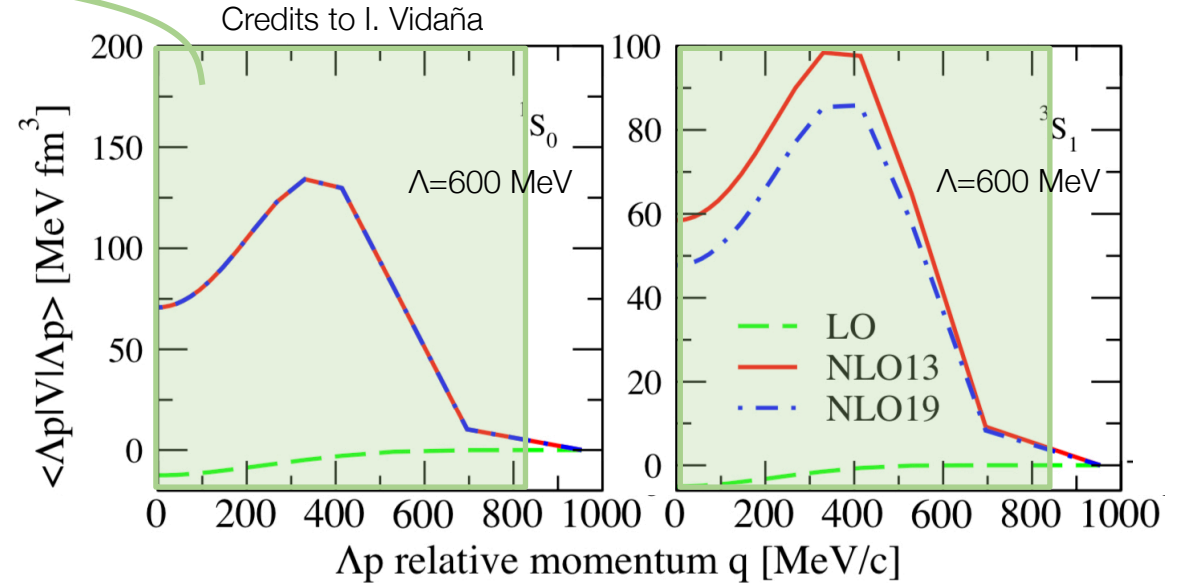
Bright future for hypernuclear data:

- J-PARC HIHR ultra-high resol. spectroscopy [HEF-ex @ JPARC](#)
 - Extension of hypernuclear landscape to n-rich Λ -hypernuclei currently very challenging
- Finuda (K): M. Agnello et al., PRL 108 (2012)*
JLAB (e): S.N. Nakamura et al., PRL 110 (2013)
FAIR & HIAF: T. R. Saito et al. EPJA 57 (2021)

Femtoscscopy as a novel approach to measure interactions



Full scan of $V_{p\Lambda}$ in q- and r-space



- Measurements of correlation functions of pairs **down to zero relative momentum**
 - Large statistics of YN, YY pairs
 - Possibility to access the short-range strong interaction in pp collisions
- Increased statistics in LHC Run 3 and Run 4 grant the access to three-body YNN interactions

L. Fabbietti, V. M.S. and O. Vazquez-Doce, *Ann.Rev.Nucl.Part.Sci.* 71 (2021)

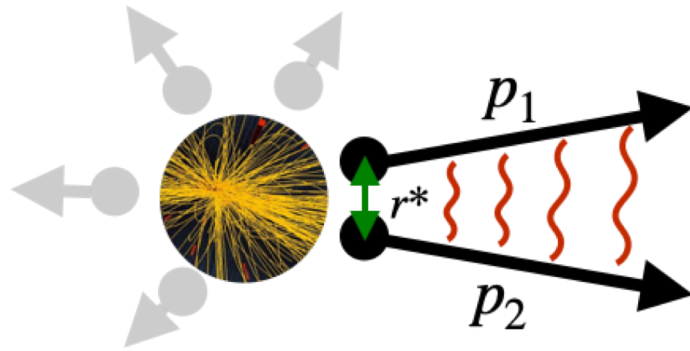
CATS Framework: D. Mihaylov et al., *Eur. Phys. J. C*78 (2018) 394

ALICE Coll.
 PRC 99 (2019) 2, 024001
 PLB 797 (2019) 134822
 PRL 123 (2019) 112002
 PRL 124 (2020) 09230
 PLB 805 (2020) 135419
 PLB 811 (2020) 135849
 Nature 588 (2020) 232-238
 PRL 127 (2021), 172301
 PLB 822 (2021), 136708
 PRC 103 (2021) 5, 055201

PLB 833 (2022), 137272
 PLB 829 (2022), 137060
 PRD 106 (2022), 5, 05201
 PLB 844 (2023), 137223
 EPJA 59 (2023) 7, 145
 PLB 845 (2023) 138145
 arXiv: 2308.16120 [nucl-ex], subm. to Nature Comm.
 ... and more to come.

STAR Collaboration
 Nature 527 (2015) 345-348
 PRL 114 (2015), 022301
 PLB 790 (2019) 490-497

Measuring two-body interactions at LHC

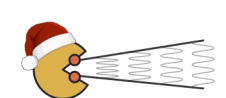


Emission source $S(r^*)$
ALICE Coll. PLB 811 (2020) 135849

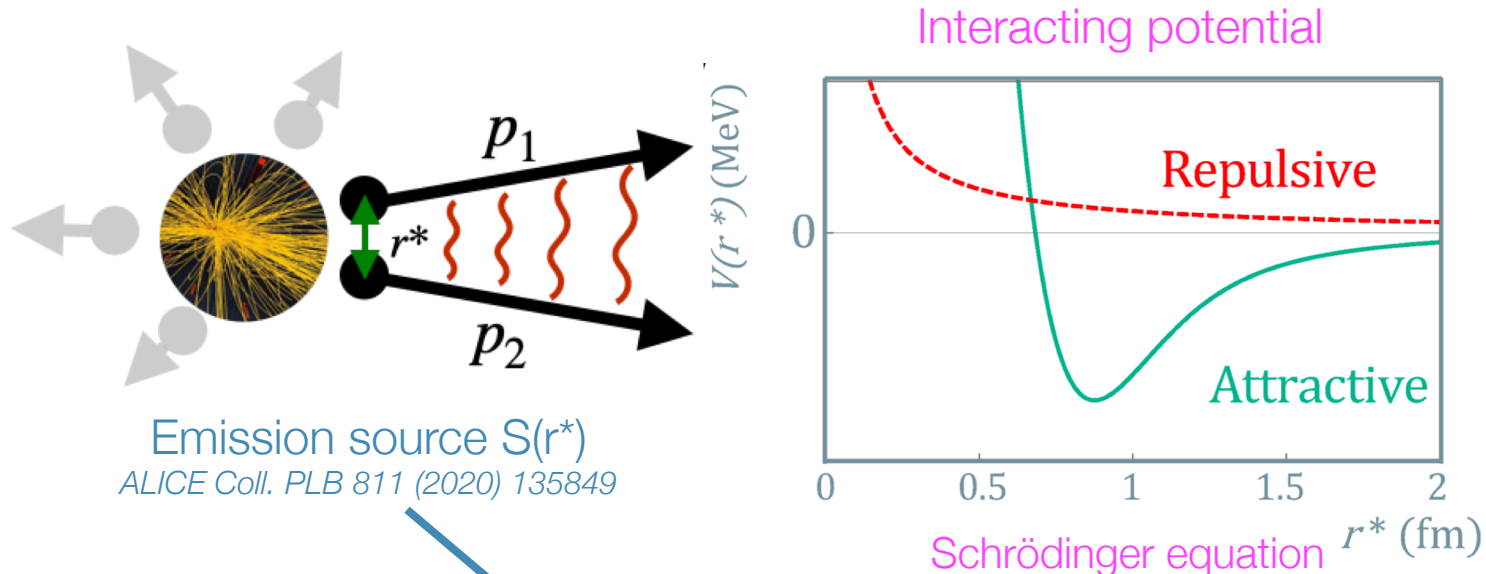
$$C(k^*) = \int \overbrace{S(\vec{r}^*)} |\psi(\vec{k}^*, \vec{r}^*)|^2 d^3\vec{r}^* = \mathcal{N}(k^*) \frac{N_{same}(k^*)}{N_{mixed}(k^*)}$$

L. Fabbietti, V. M. S., and O. Vazquez-Doce, Ann.Rev.Nucl.Part.Sci. 71 (2021)

M.Lisa, S. Pratt et al, Ann.Rev.Nucl.Part.Sci. 55 (2005), 357-402



Measuring two-body interactions at LHC



Emission source $S(r^*)$
ALICE Coll. PLB 811 (2020) 135849

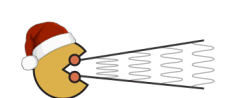
Schrödinger equation

Two-particle wave function

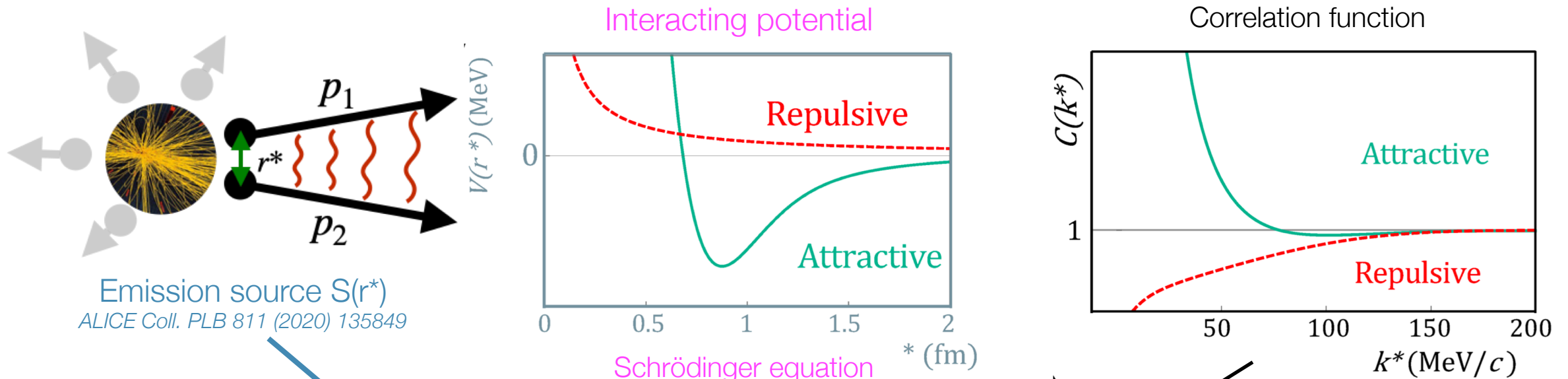
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L. Fabbietti, V. M. S., and O. Vazquez-Doce, *Ann.Rev.Nucl.Part.Sci.* 71 (2021)

M.Lisa, S. Pratt et al, *Ann.Rev.Nucl.Part.Sci.* 55 (2005), 357-402



Measuring two-body interactions at LHC



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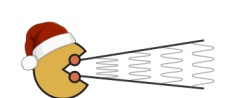
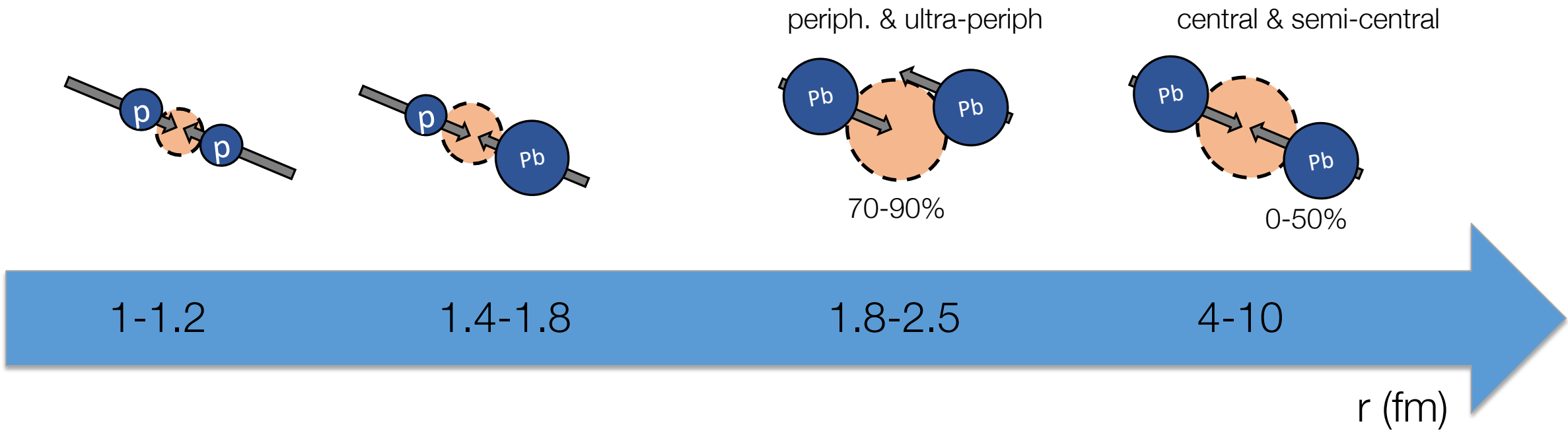
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L. Fabbietti, V. M. S., and O. Vazquez-Doce, *Ann.Rev.Nucl.Part.Sci.* 71 (2021)

M.Lisa, S. Pratt et al, *Ann.Rev.Nucl.Part.Sci.* 55 (2005), 357-402

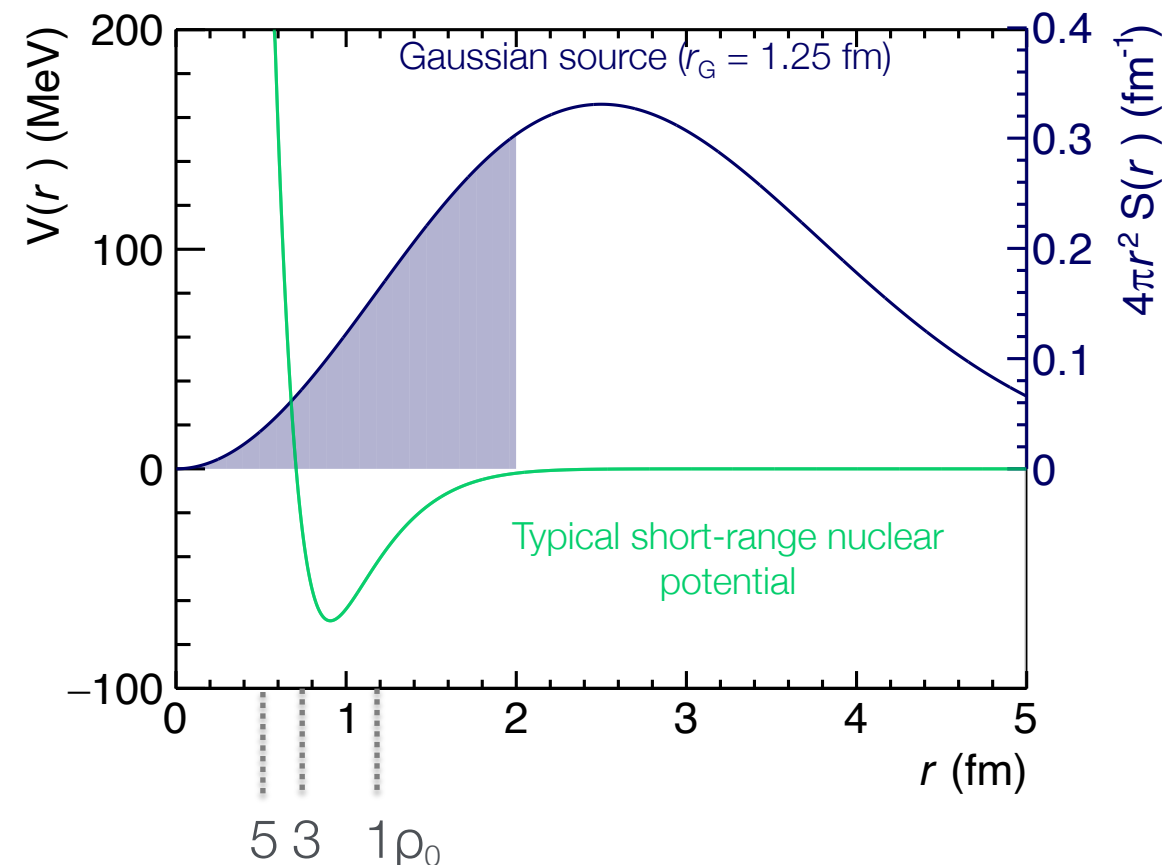
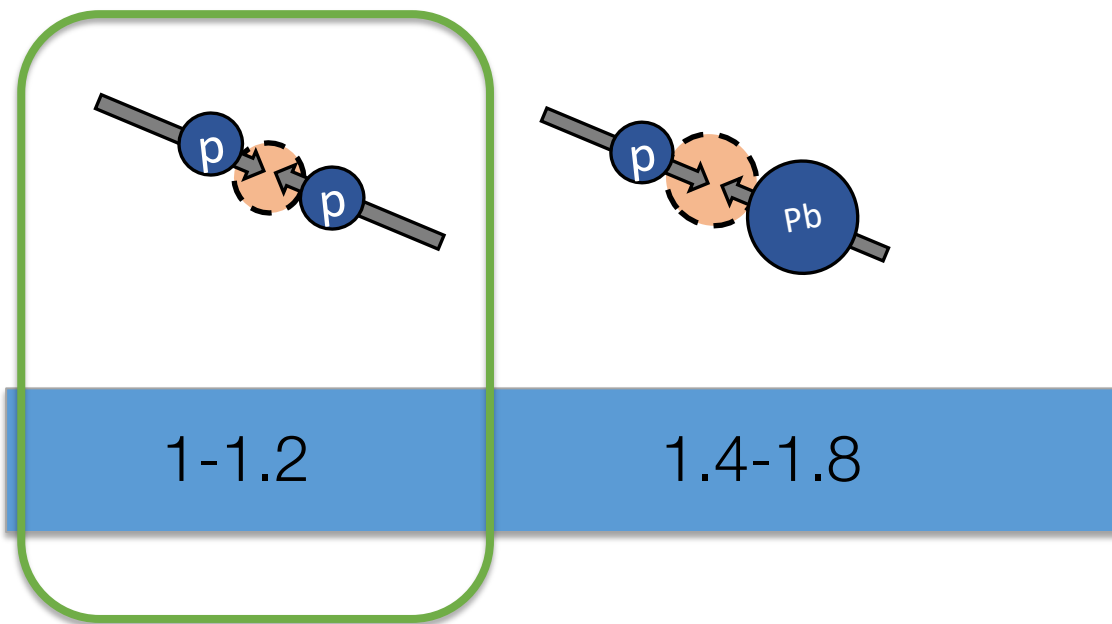
Accessing the full interaction range at LHC

- By changing the colliding system we can probe distances ranging from 1 fm up to 10 fm



Correlation studies in small colliding systems

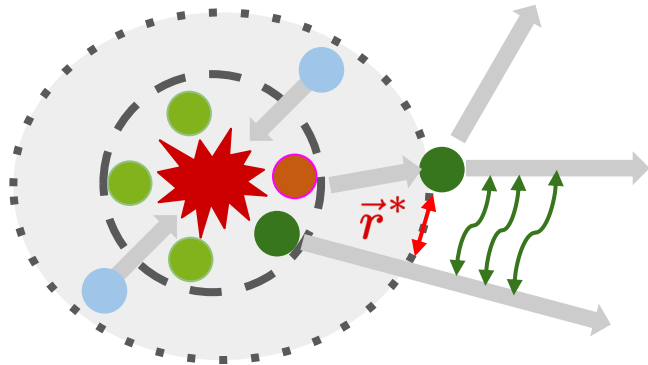
- By changing the colliding system we can probe distances ranging from 1 fm up to 10 fm
- Accessing the strong interaction \rightarrow relative distances of ~ 1 fm \rightarrow pp
- Small interparticle distance \rightarrow doorway to studying large densities



L. Fabbietti, V. M. S., and O. Vazquez-Doce, *Ann.Rev.Nucl.Part.Sci.* 71 (2021)

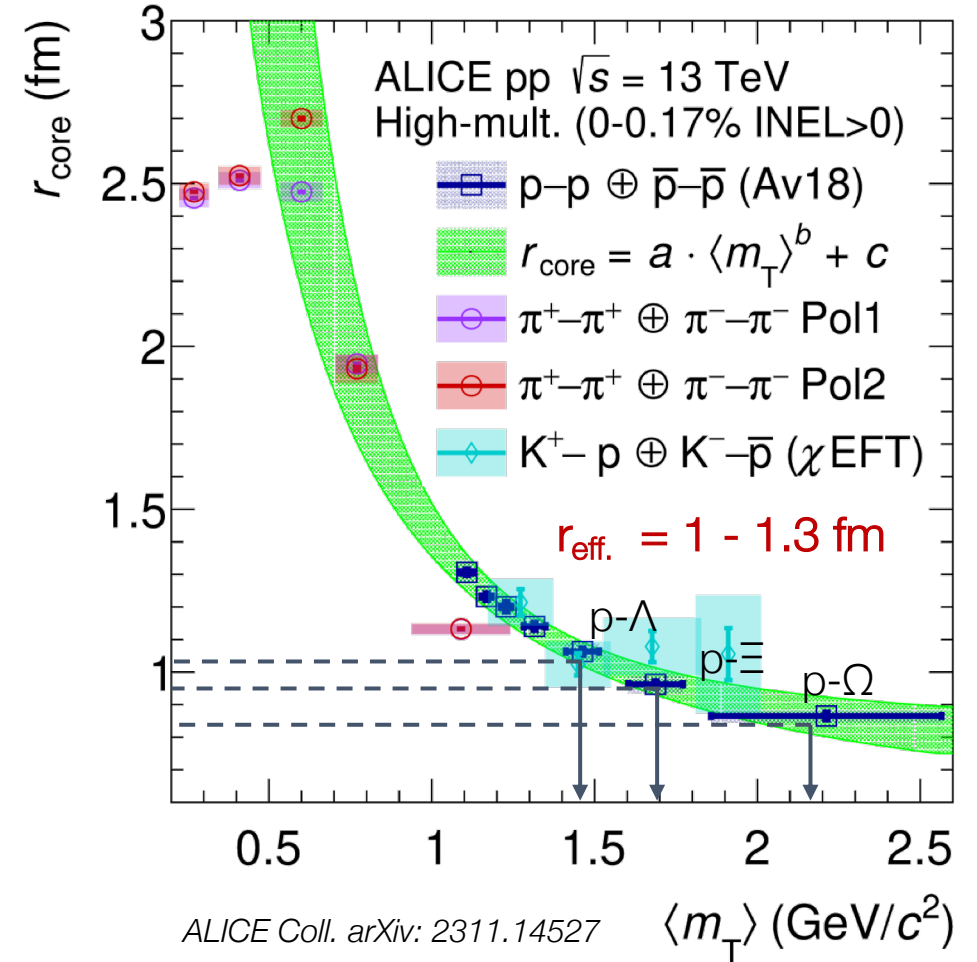
One source to rule them all in small colliding systems

- Source anchored to p-p pairs *ALICE Coll. PLB 811 (2020) 135849*
 - most known interaction!
 - validated on other standard candle“ pairs
pK⁺, π[±] π[±], pπ[±]
- Modeling of a common core + halo of strongly decaying resonances (cτ ~1 fm) for each pair(*)



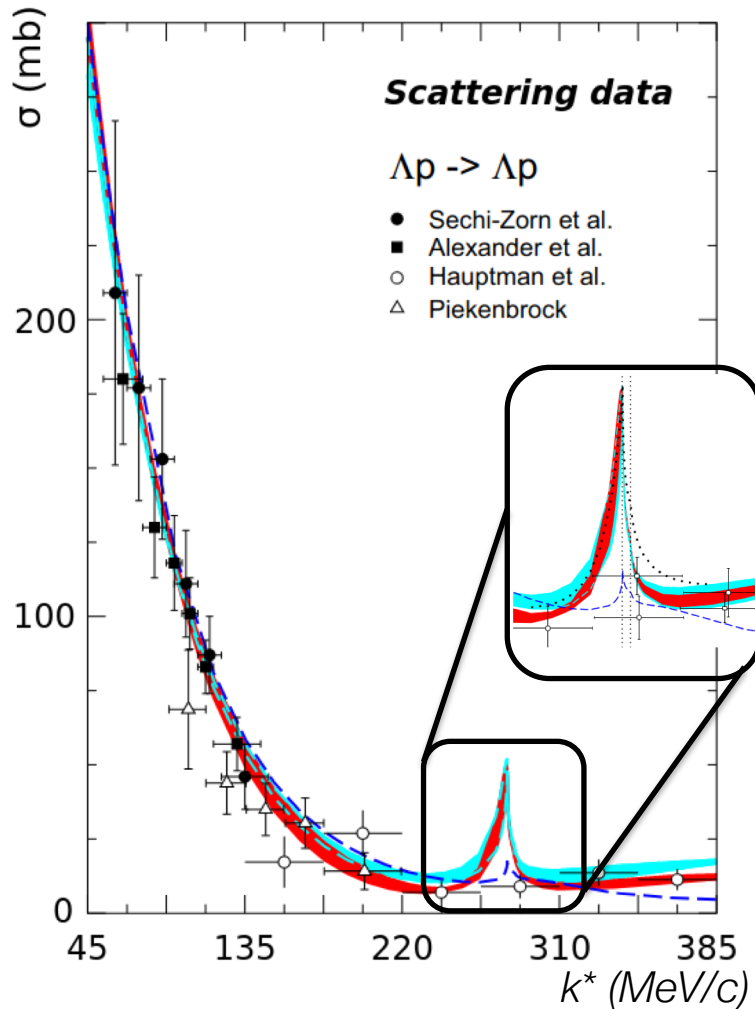
- Determination of the source for each pair at the corresponding $\langle m_T \rangle$
→ direct access to the interaction signal

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



(*) U. A. Wiedemann, U. W. Heinz, *Phys.Rept.* 319, 145-230 (1999)

The Λ N interaction and the role of Σ N coupling



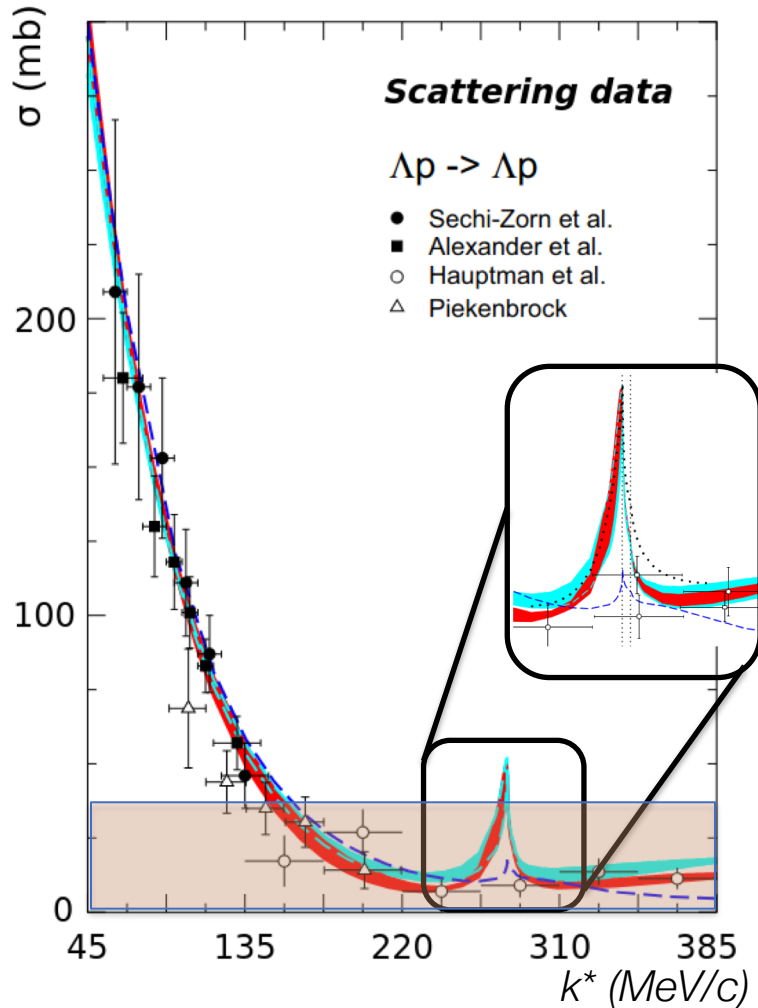
- Σ N coupling strength relevant for EoS
- deeply affects the behaviour of Λ at finite density
- implications for 3-body interactions^(*)

NLO13: J.Haidenbauer, N.Kaiser et al., NPA 915, 24 (2013)

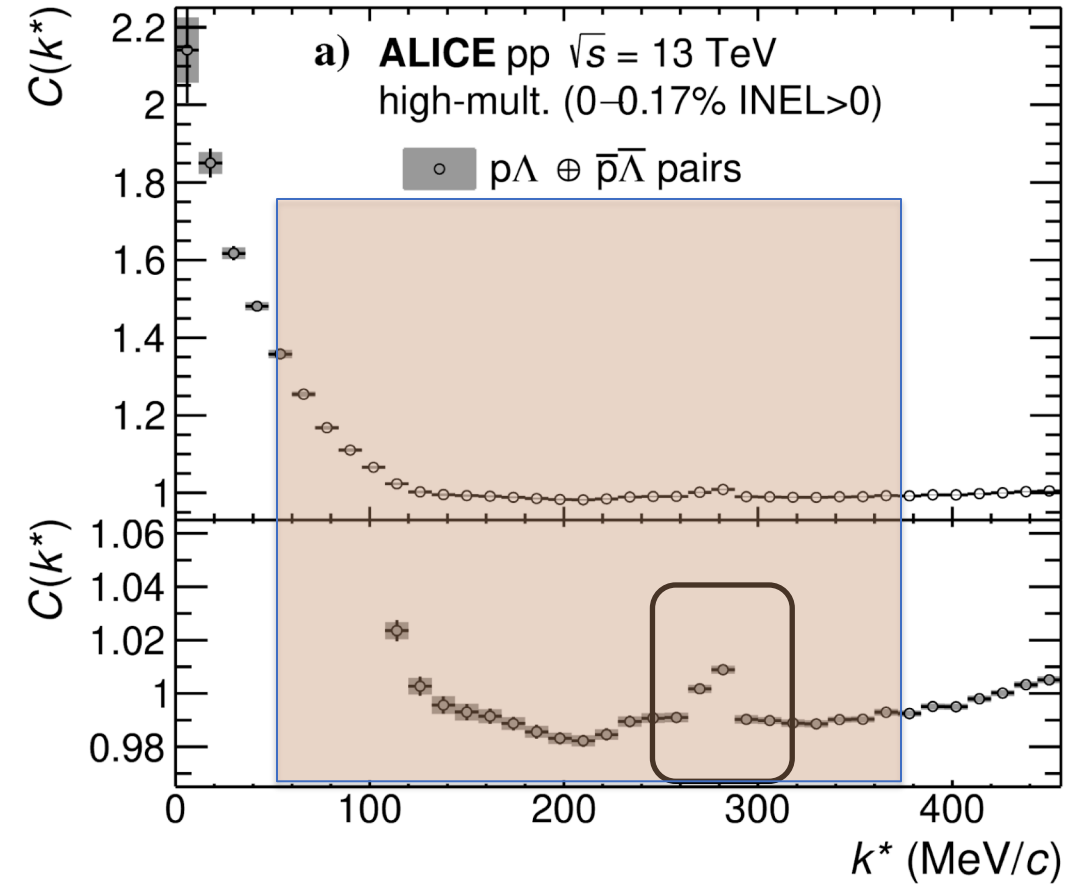
NLO19: J.Haidenbauer, U. Meißner, Eur.Phys.J.A 56 (2020)

(*)D. Gerstung et al. Eur.Phys.J.A 56 (2020) 6, 175

High-precision data on ΛN - ΣN interaction at LHC



- Extension of kinematic range
- Measurement down to zero momentum
- Factor 20 improved precision in data ($<1\%$)
- First experimental evidence of ΣN cusp in 2-body channel



NLO13: J.Haidenbauer, N.Kaiser et al., NPA 915, 24 (2013)

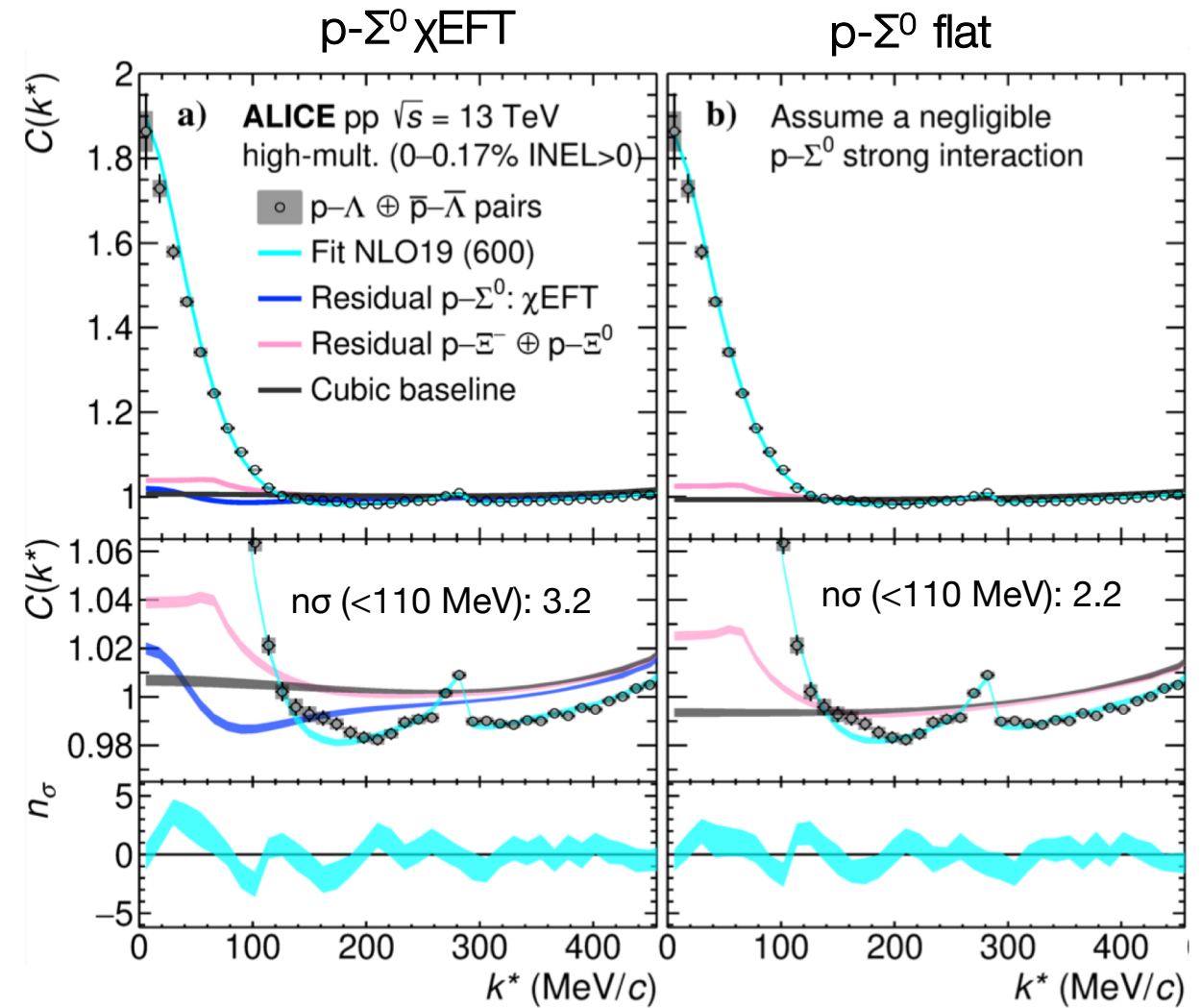
NLO19: J.Haidenbauer, U. Meißner, Eur.Phys.J.A 56 (2020)

(*)D. Gerstung et al. Eur.Phys.J.A 56 (2020) 6, 175

High-precision data on ΛN - ΣN interaction at LHC

- New scenario arising for ΛN - ΣN interaction
 - NLO19 potentials favoured
 - Sensitivity to residual p - Σ^0 interaction
 - Crucial input from several measurements:
 - $p\Sigma^{+,-}$ correlations in LHC Run 3
 - $p\Sigma^{+,-}$ scattering data J-PARC E40
- Deviations with correlation data observed

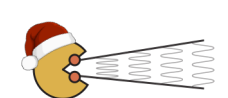
First-ever combined analysis using available $p\Lambda$ scattering and correlation data



ALICE Coll. PLB 833 (2022), 137272

(1) D. Gerstung et al. Eur.Phys.J.A 56 (2020) 6, 175

(2) ALICE Coll. PLB 805 (2020) 135419



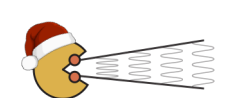
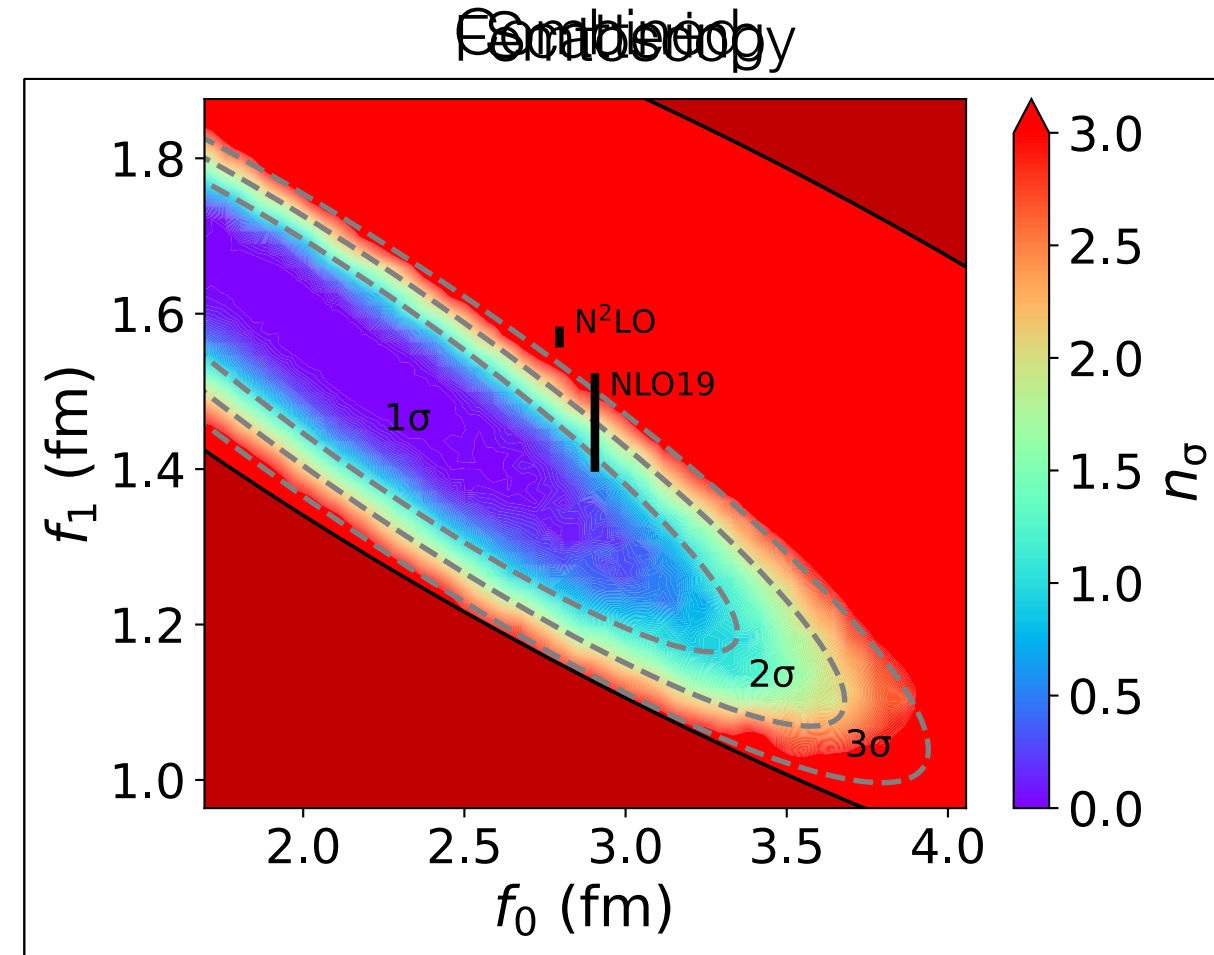
Combining scattering and correlation data on $p\Lambda$

Work in preparation with Dr. Mihaylov and Dr. Haidenbauer

- First combined analysis of low-energy $p\Lambda$ scattering and correlation data
 - 12 elastic $p\Lambda$ cross-sections
 - $p\Lambda$ correlation in 6 m_T ranges

ALICE Coll. PLB 811 (2020) 135849
CECA: D. Mihaylov et al. EPJC 83 (2023)
- Phenomenological potential tuned to reproduce scattering parameters of χ EFT potentials at NLO⁽¹⁾
- Tightest constraints available on two-body $p\Lambda$ scattering parameters

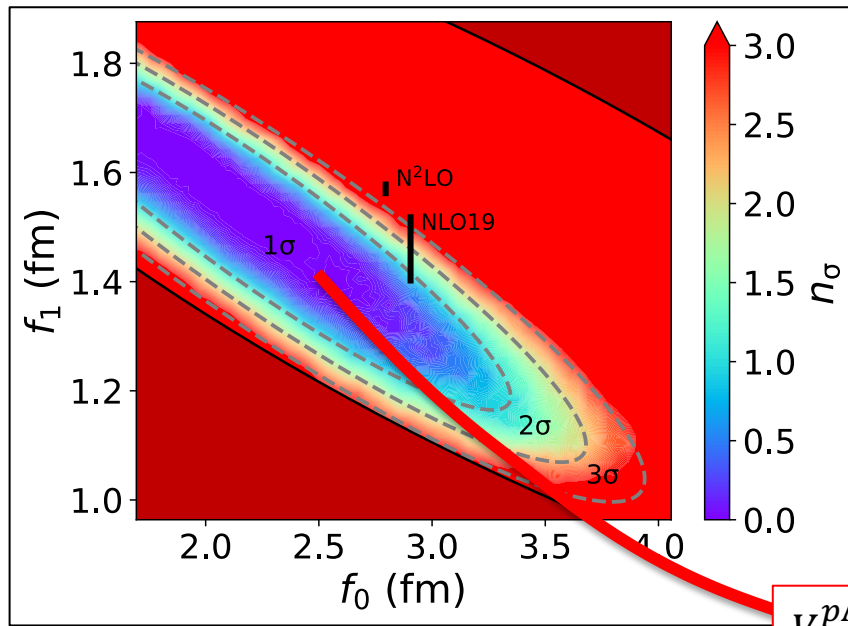
How does the current experimental uncertainty propagate to U_Λ at ρ_0 ?



Quantifying the two-body contribution of U_Λ

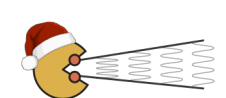
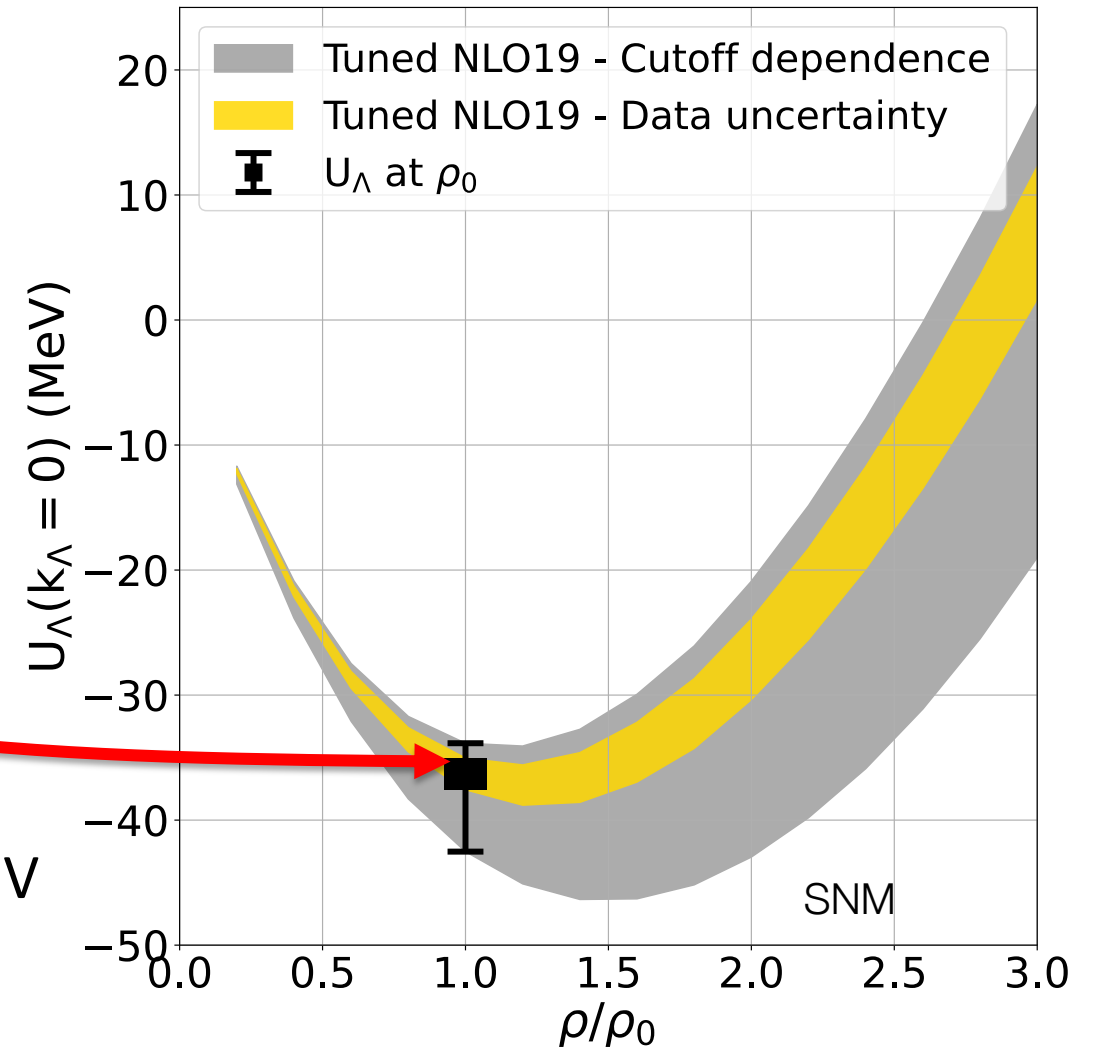
Work in preparation with Dr. Mihaylov and Dr. Haidenbauer

Combined



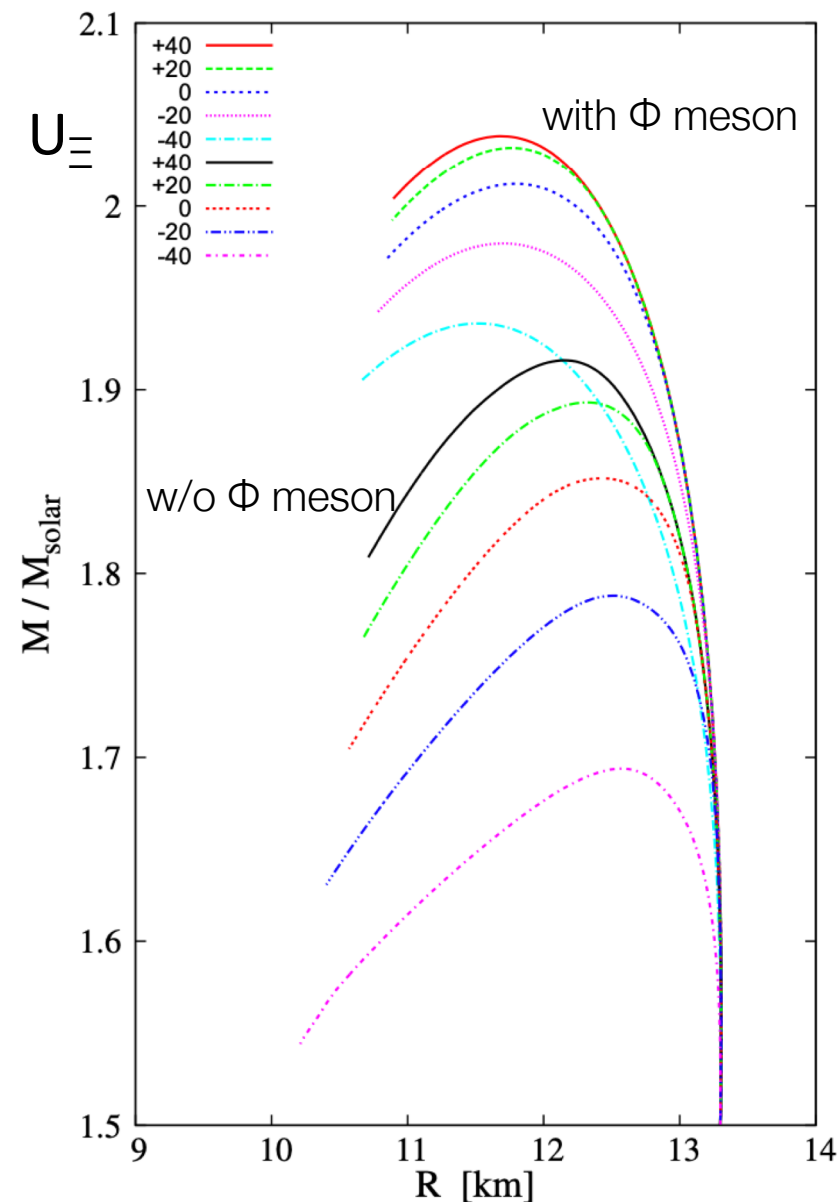
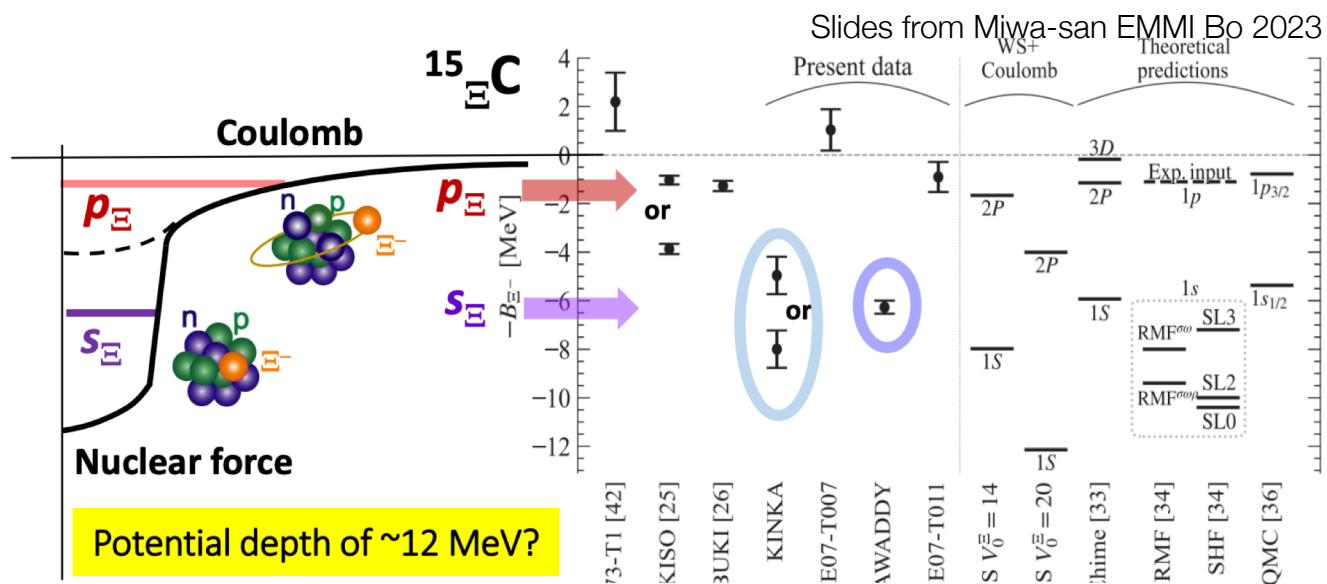
$V_{NLO19}^{p\Lambda}$ in mom. space
via G-matrix approach

$$U_\Lambda^{2BF}(\rho_0) = -36.3 \pm 1.3(stat)_{-6.2}^{+2.5}(syst) \text{ MeV}$$



Effect of Ξ hyperon in neutron stars

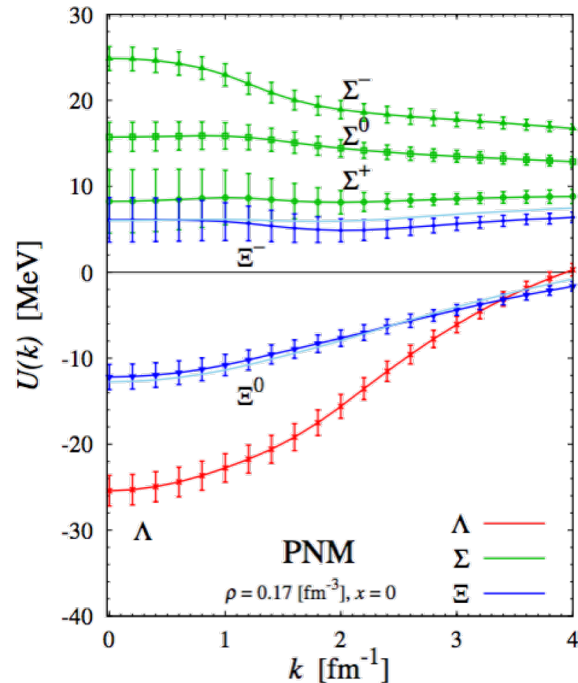
- U_{Ξ} plays a crucial role in the EoS of NSs
 → repulsive single-particle pot. stiffens the EoS
- Continuous effort in hypernuclei challenging measurements
K. Nakazawa et al. PTEP 2015, 033D02 (2015)
S. H. Hayakawa, PRL 126, 062501 (2021)



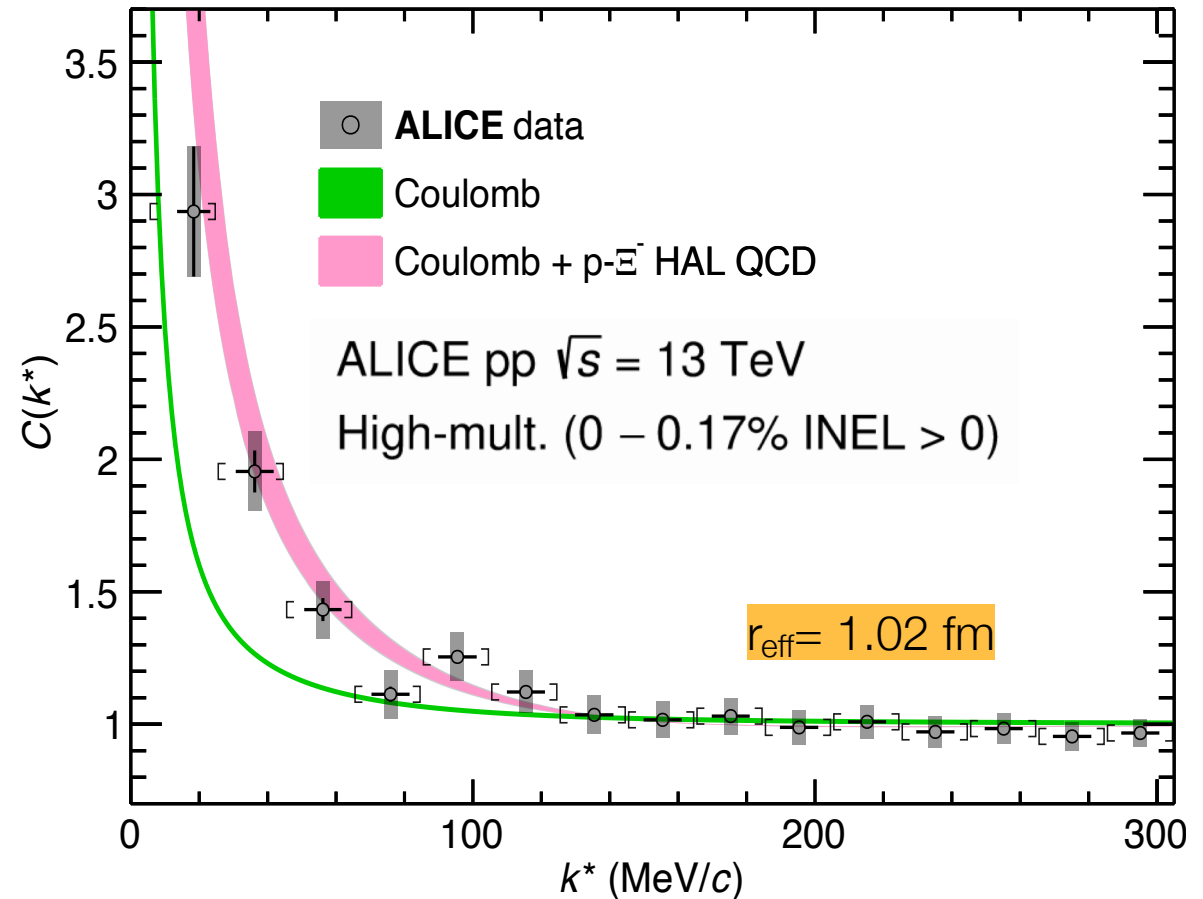
What about constraining the $N\Xi$ interaction in vacuum?

First measurements of the $p-\Xi^-$ interaction at LHC

- First observation of the strong attractive interaction
- Agreement with HAL QCD lattice potentials⁽¹⁾ confirmed in pp and p-Pb colliding systems
- HAL QCD predictions in PNM $U_{\Xi} \sim +6$ MeV⁽²⁾ → stiffening of the EoS??



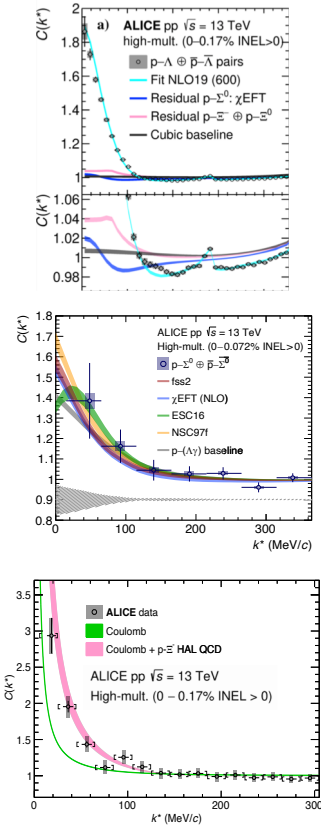
ALICE Coll. Nature 588, 232–238 (2020)



(1) T. Hatsuda *Front. Phys.* 13(6), 132105 (2018)
 (2) HAL QCD Coll., *PoS INPC2016* (2016) 277

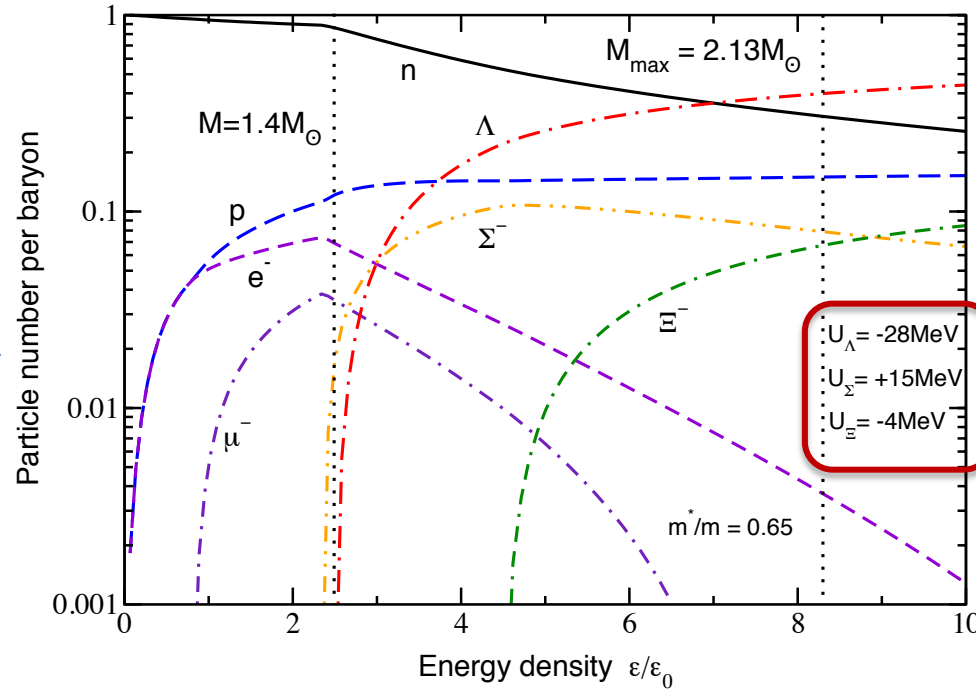
Towards a realistic EoS with hyperons

Correlation
2-body interaction



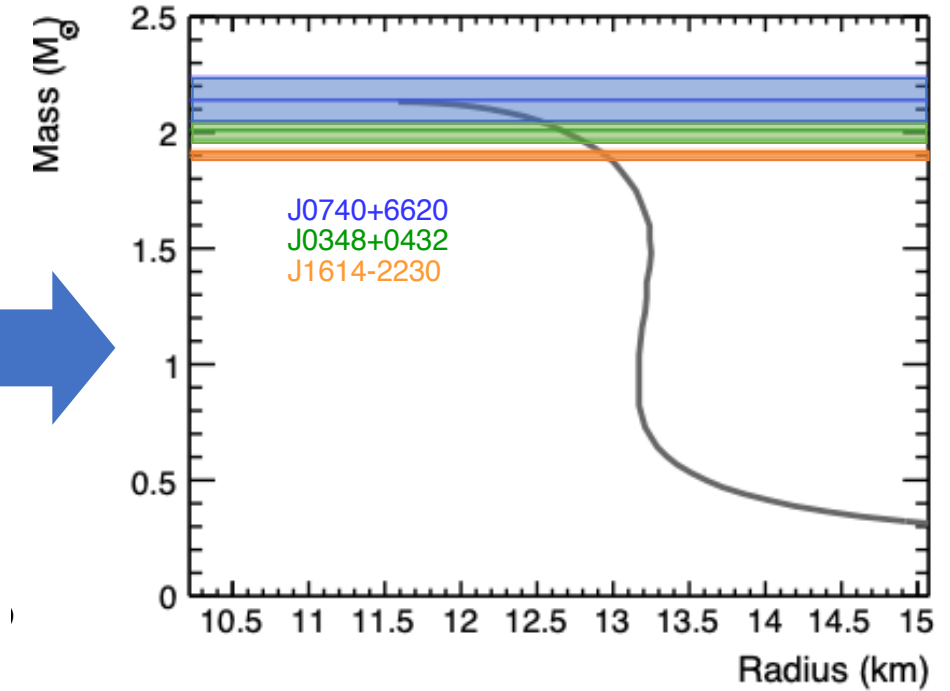
Single-particle potentials
EoS

Courtesy J. Schaffner-Bielich 2020



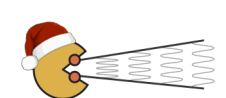
Mass vs Radius relation
for hyperon stars

Courtesy J. Schaffner-Bielich and B. Dönig 2020



This is only an example.
Experimental uncertainties need to be propagated and
some interactions are missing ...

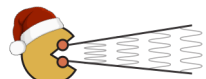
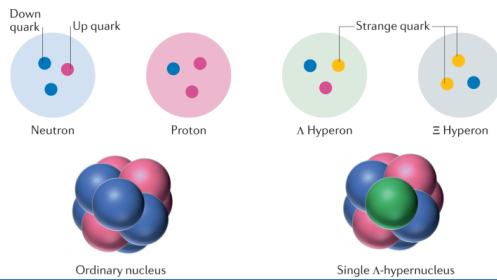
*L. Fabbietti, V. M. S. and O. Vazquez-Doce
Ann.Rev.Nucl.Part.Sci. 71 (2021)
S. Weissenborn et al., J. NPA 881 (2012)
J. Schaffner-Bielich, I. Mishustin, PRC 53 (1996)
N. Hornick et al., PRC 98 (2018)*



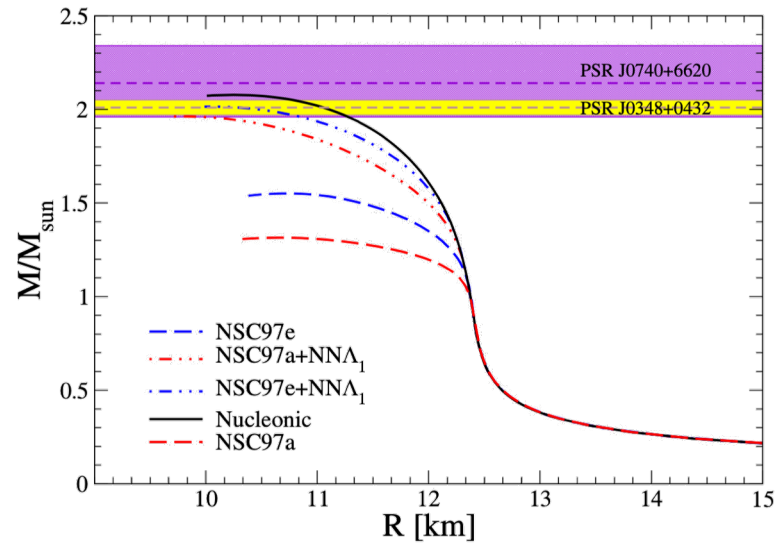
Hyperonic three-body interactions... a key ingredient!

- Hypernuclei properties demand something beyond 2-body only

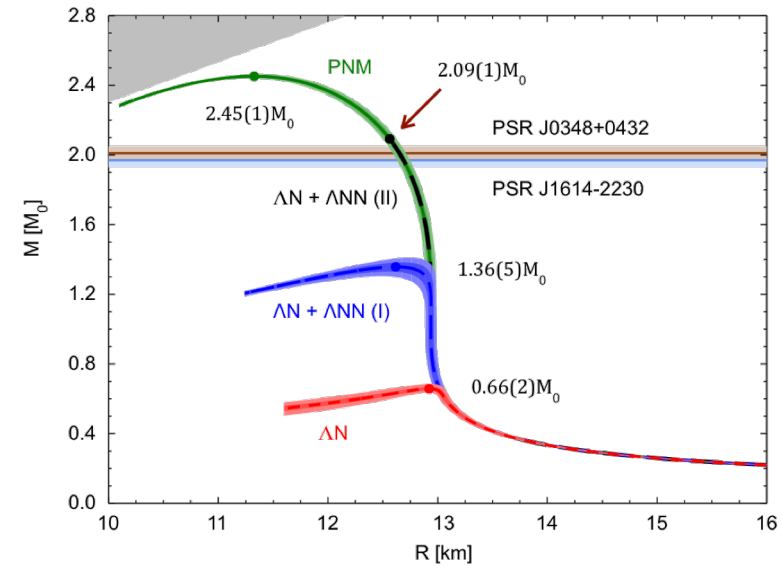
L.E. Marcucci et al., Front. Phys. 8:69 (2020)



Hyperonic three-body interactions... a key ingredient!

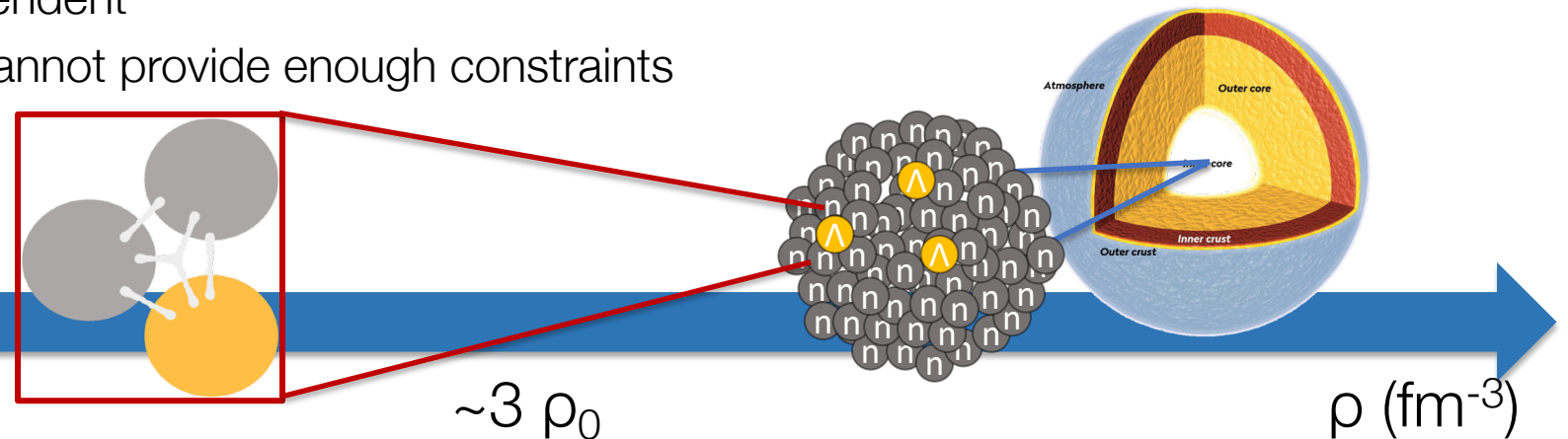


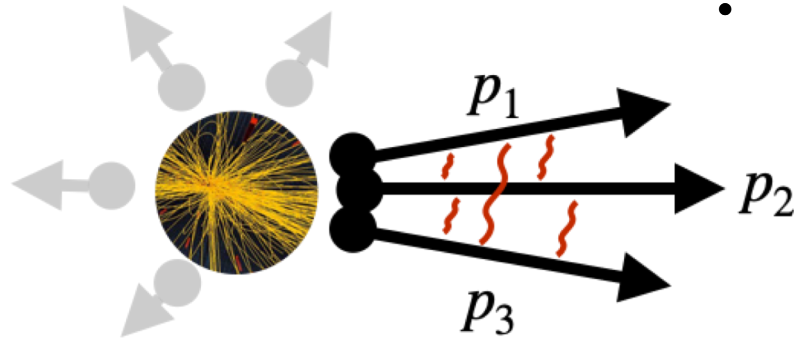
D. Logoteta et al., Eur.Phys.J.A 55 (2019)



D. Lonardoni et al., PRL 114 (2019)

- Repulsive 3-body Λ NN interaction widely advocated to stiffen the EoS:
 - Effect on EoS largely model dependent
 - current experimental database cannot provide enough constraints





- Three-particle correlation function

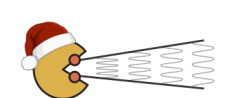
$$C(\mathbf{p}_1, \mathbf{p}_2, \mathbf{p}_3) \equiv \frac{P(\mathbf{p}_1, \mathbf{p}_2, \mathbf{p}_3)}{P(\mathbf{p}_1)P(\mathbf{p}_2)P(\mathbf{p}_3)} = \mathcal{N} \frac{N_{\text{same}}(Q_3)}{N_{\text{mixed}}(Q_3)}$$

$$Q_3 = \sqrt{-q_{ij}^2 - q_{jk}^2 - q_{ki}^2}$$

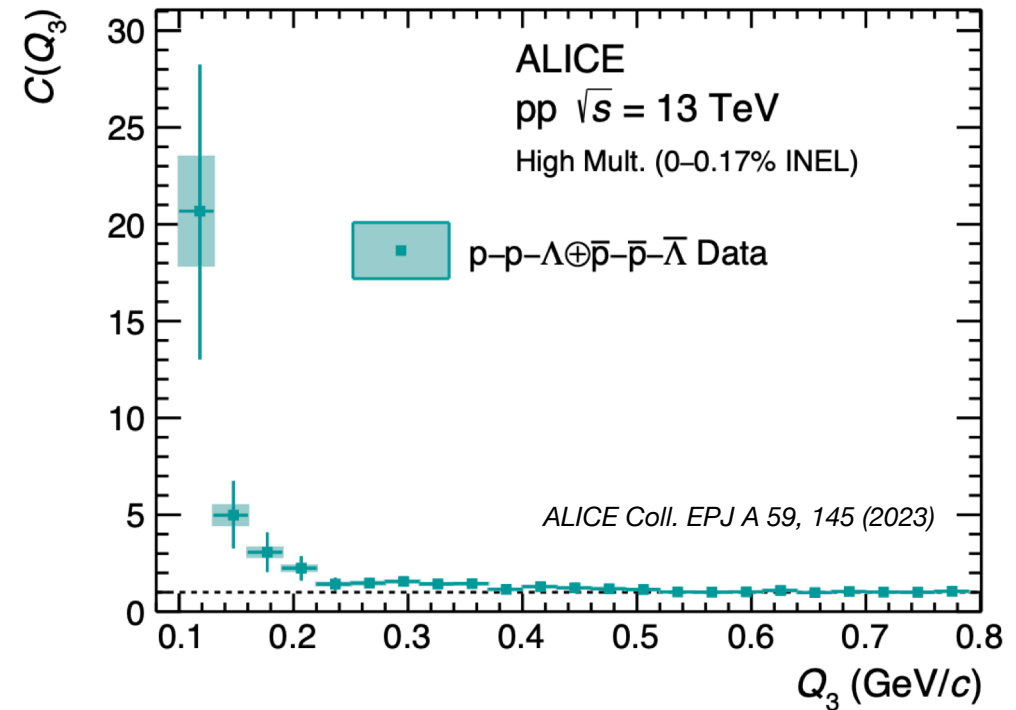
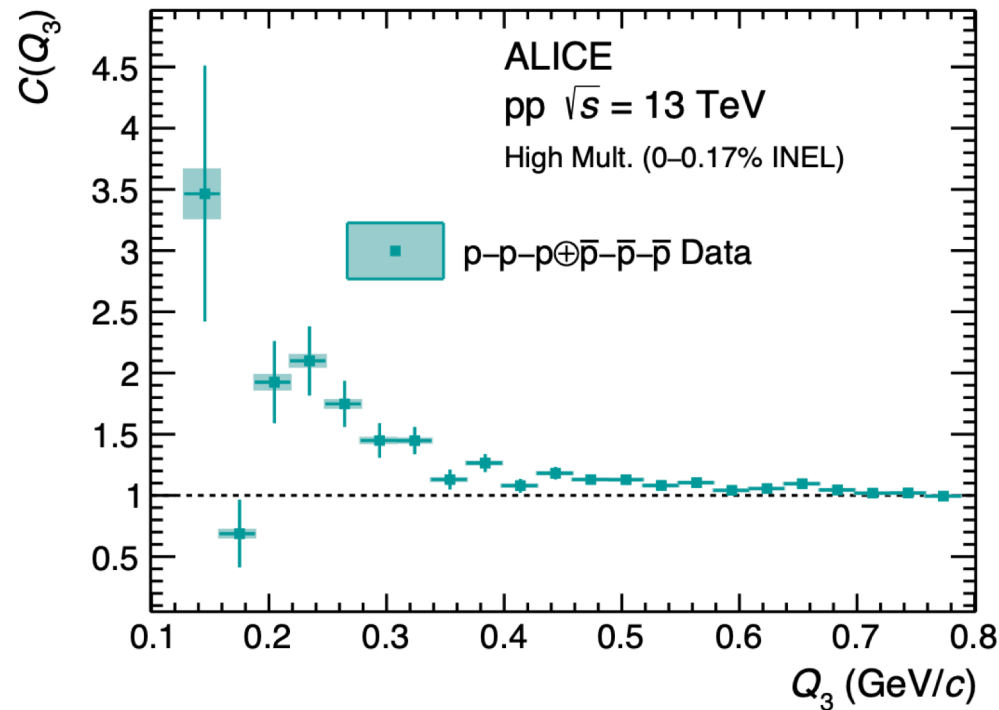
- Applied multi-pion correlations to study coherent emission
ALICE Coll. Phys.Rev.C 89 (2014), Phys.Rev.C 93 (2016)

First measurements of p-p-p and p-p- Λ correlations in pp collisions by ALICE

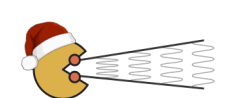
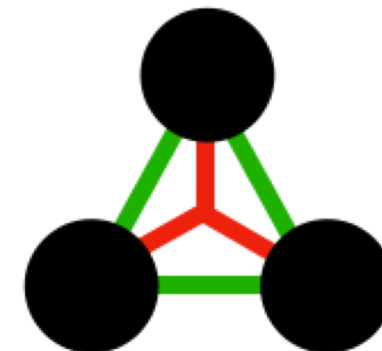
ALICE Coll. EPJ A 59, 145 (2023)



Accessing the ppp and pp Λ interactions at LHC

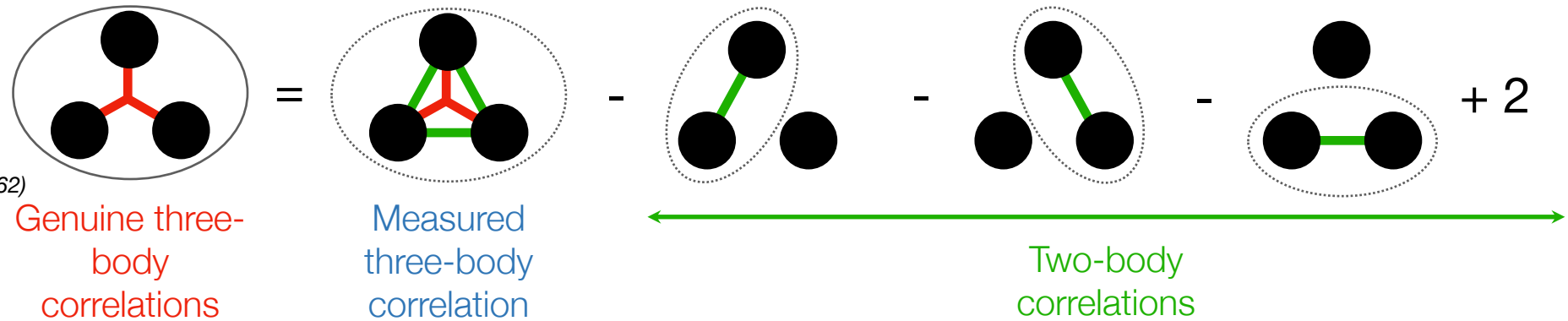


- Signal different from unity at low Q_3
- How can we interpret these three-body correlations?
 - Two-body interactions
 - Three-body interactions



Cumulants in femtoscopy

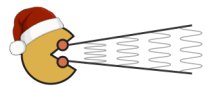
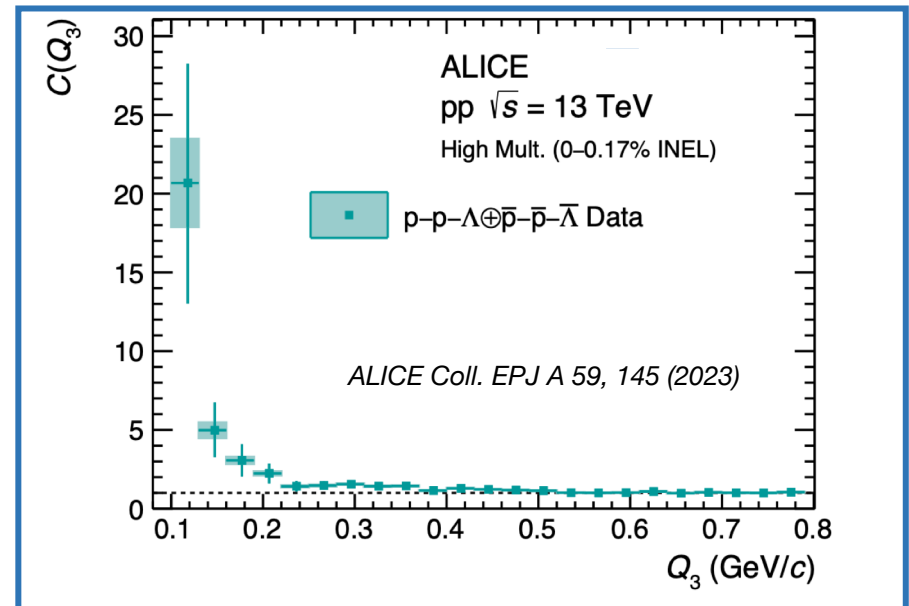
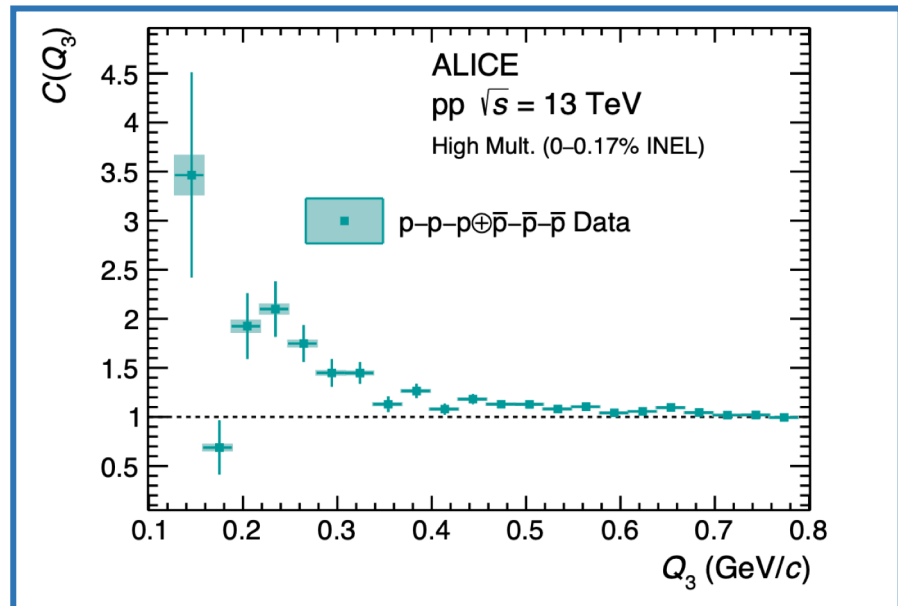
Kubo's rule⁽¹⁾:



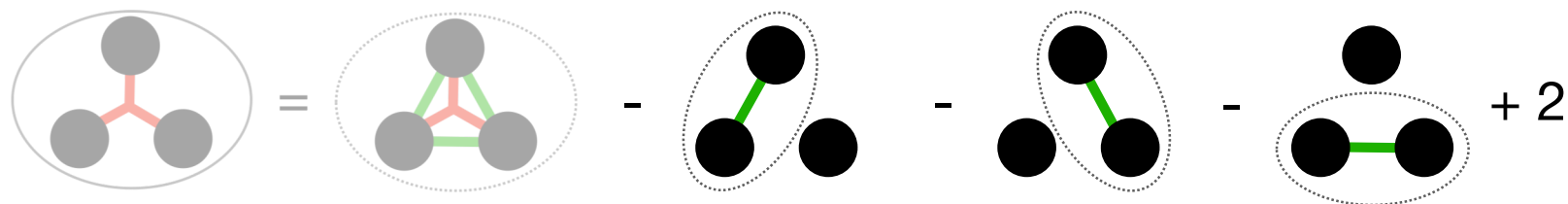
(1) R. Kubo, J. Phys. Soc. Jpn. 177 (1962)

Correlations:

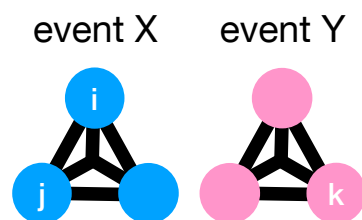
$$c_3(Q_3) = C(Q_3) - C_{12}(Q_3) - C_{23}(Q_3) - C_{31}(Q_3) + 2$$



Lower order contributions: two different approaches



- Using directly the data
- Two particles from the same event and one particle from another:



$$C_{ij}([\mathbf{p}_i, \mathbf{p}_j], \mathbf{p}_k) = \frac{N_2(\mathbf{p}_i, \mathbf{p}_j)N_1(\mathbf{p}_k)}{N_1(\mathbf{p}_i)N_1(\mathbf{p}_j)N_1(\mathbf{p}_k)}$$

ALICE Coll. arXiv: 2206.03344 nucl-ex

- Projector method
- Evaluate two-body contribution in three-body correlation function
 - Two-particle measured or theoretical correlation function $C([\mathbf{p}_i, \mathbf{p}_j])$
- Kinematic transformation in phase space

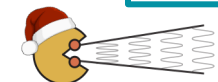
$$C_{ij}(Q_3) = \int \underbrace{C(k_{ij}^*)}_{\text{two-body CF}} \underbrace{W_{ij}(k_{ij}^*, Q_3)}_{\text{projector}} dk_{ij}^*$$

Measured/modeled 2-body correlation functions

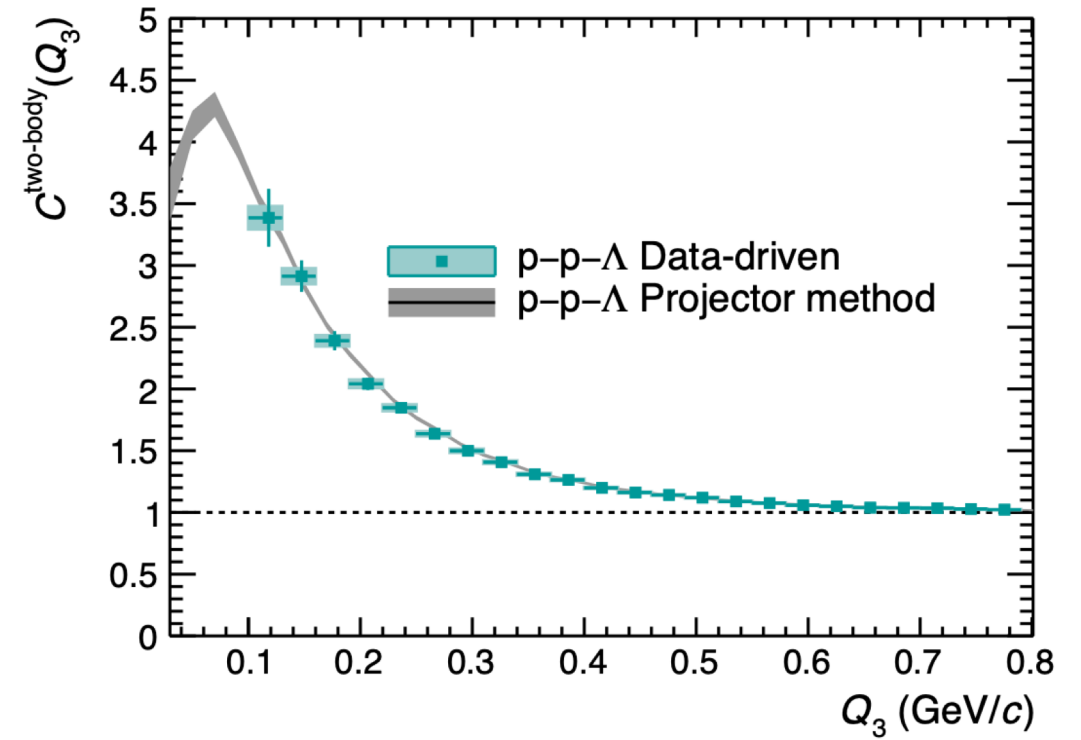
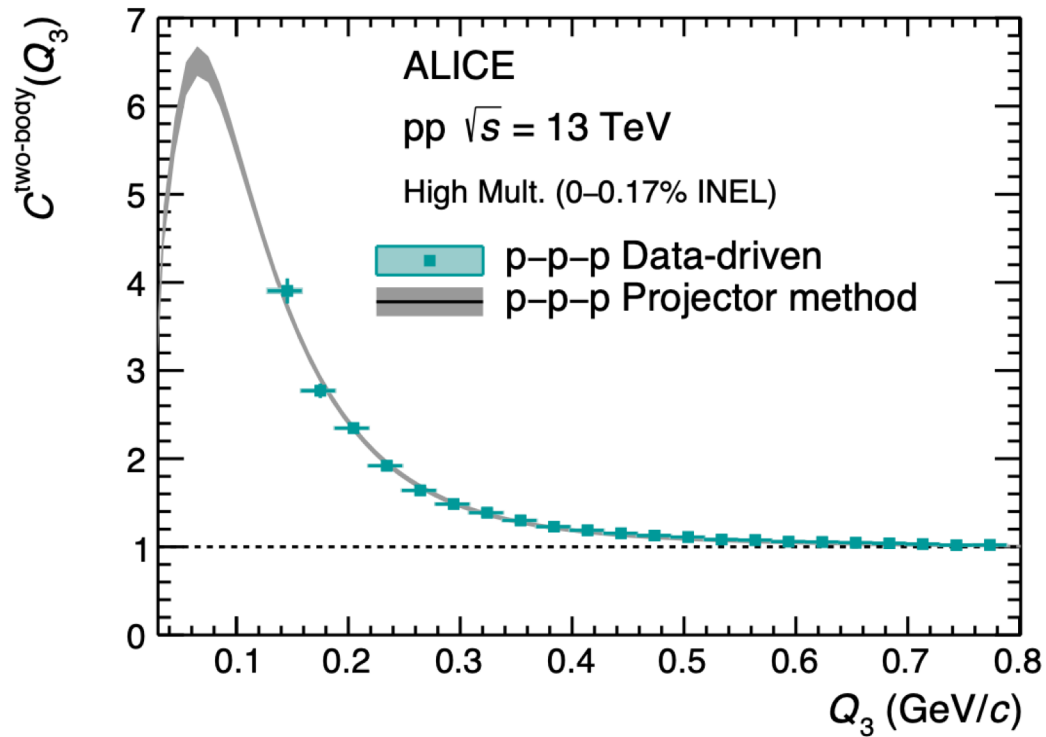
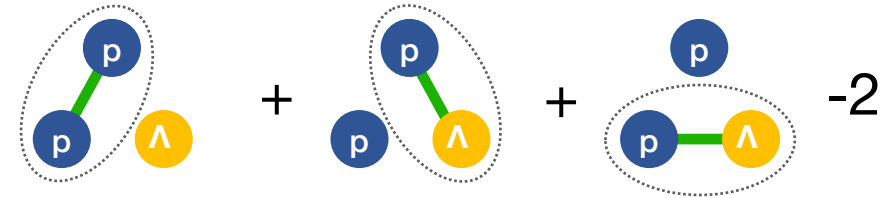
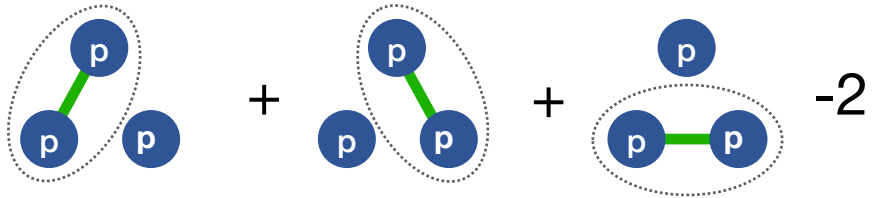
Jacobian from 2-body to 3-body coordinates

p-p: ALICE Coll. PLB 805 (2020) 135419
pA: ALICE Coll. PLB 833 (2022), 137272

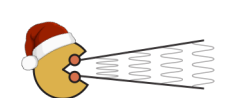
R. Del Grande, L. Serksnyte et al. EPJC 82 (2022)



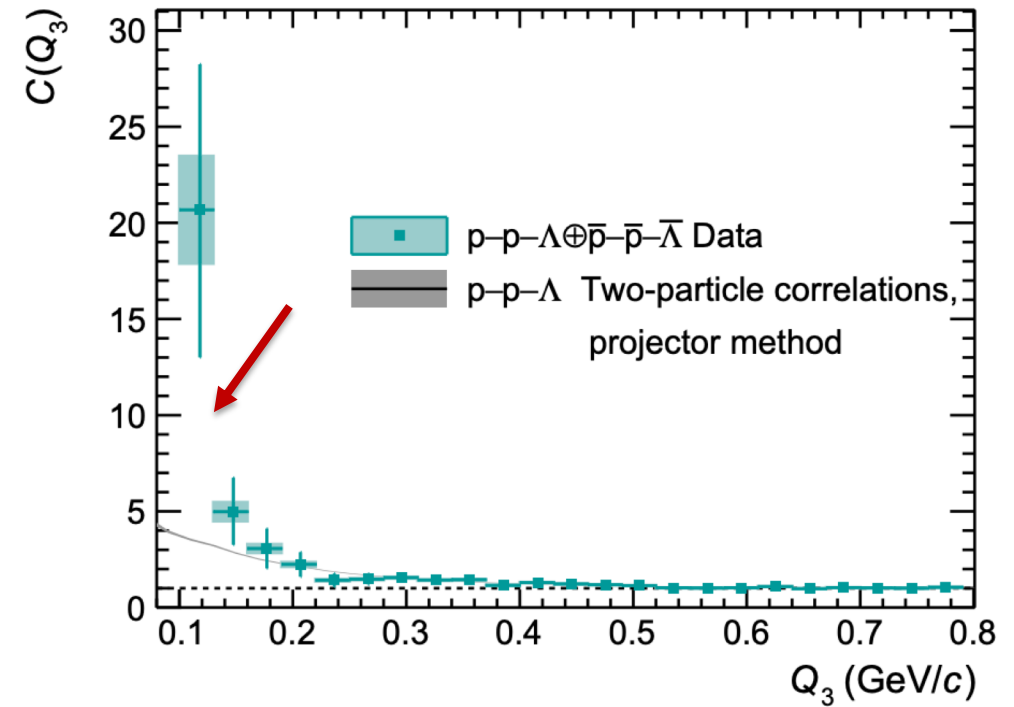
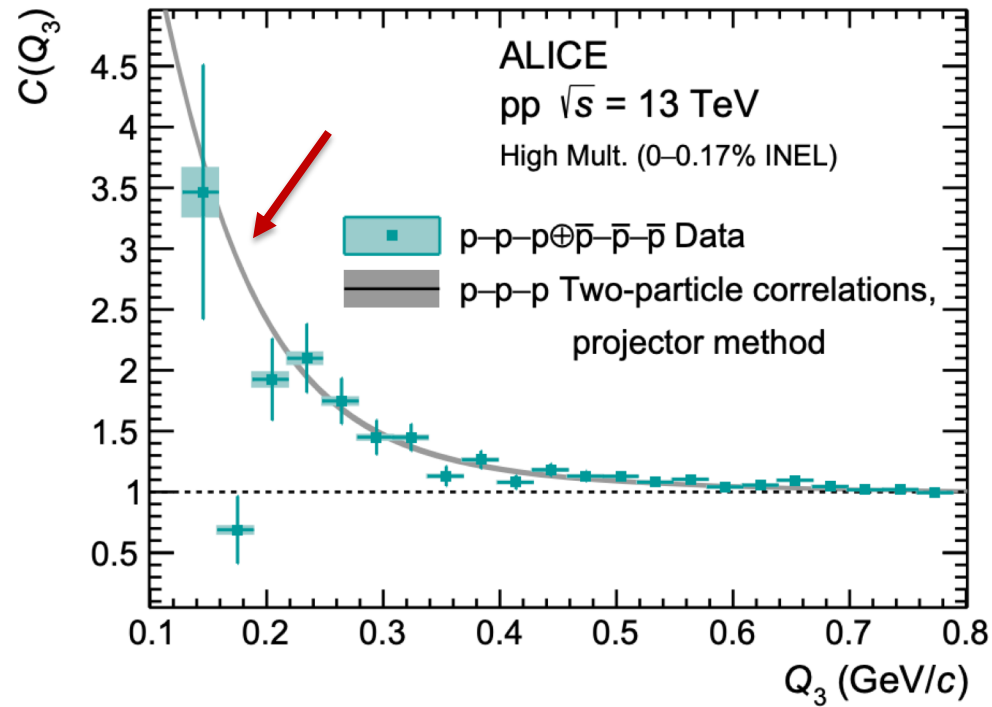
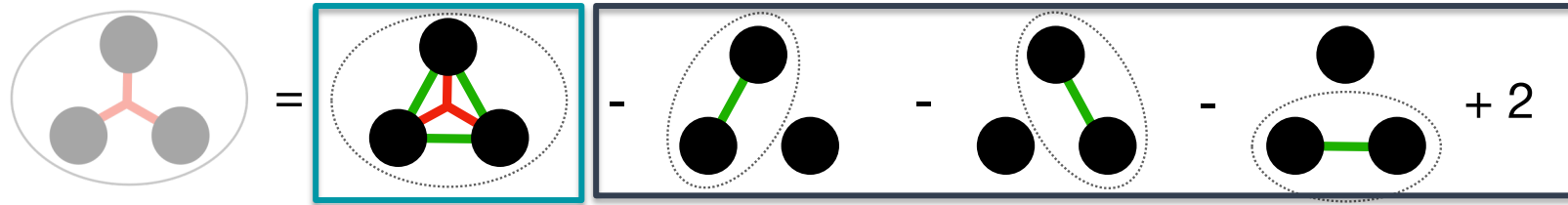
Lower order contributions in p-p-p and p-p- Λ



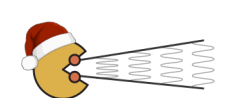
ALICE Coll. EPJ A 59, 145 (2023)



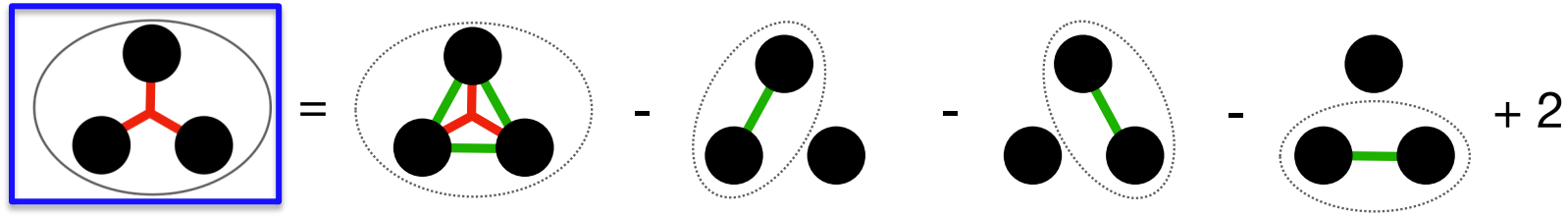
Understanding the three-particle correlation functions



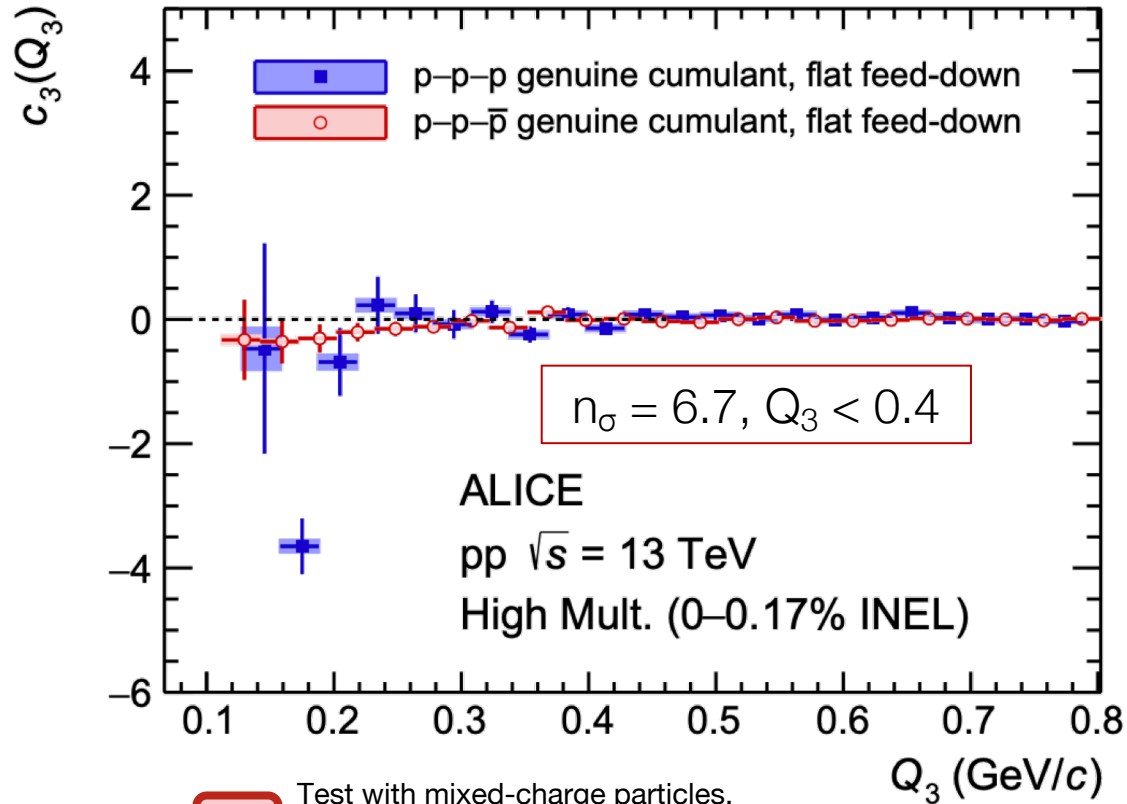
ALICE Coll. EPJ A 59, 145 (2023)



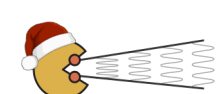
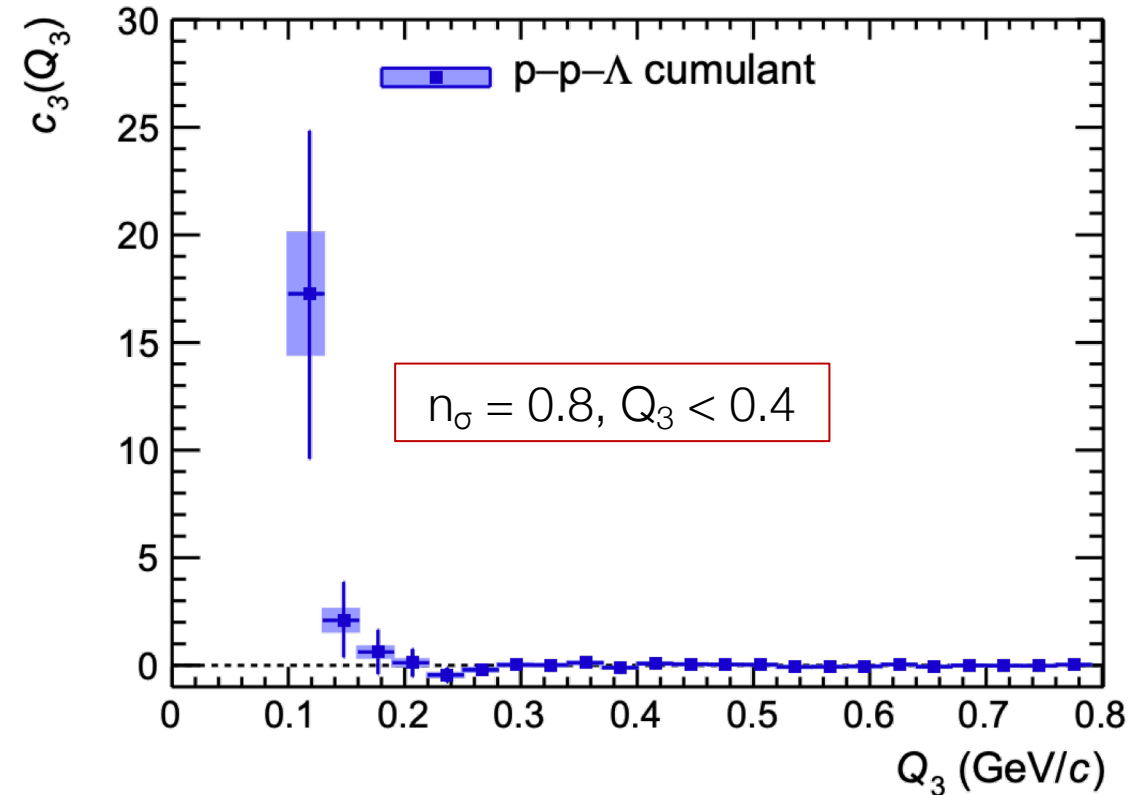
p-p-p and p-p- Λ cumulants



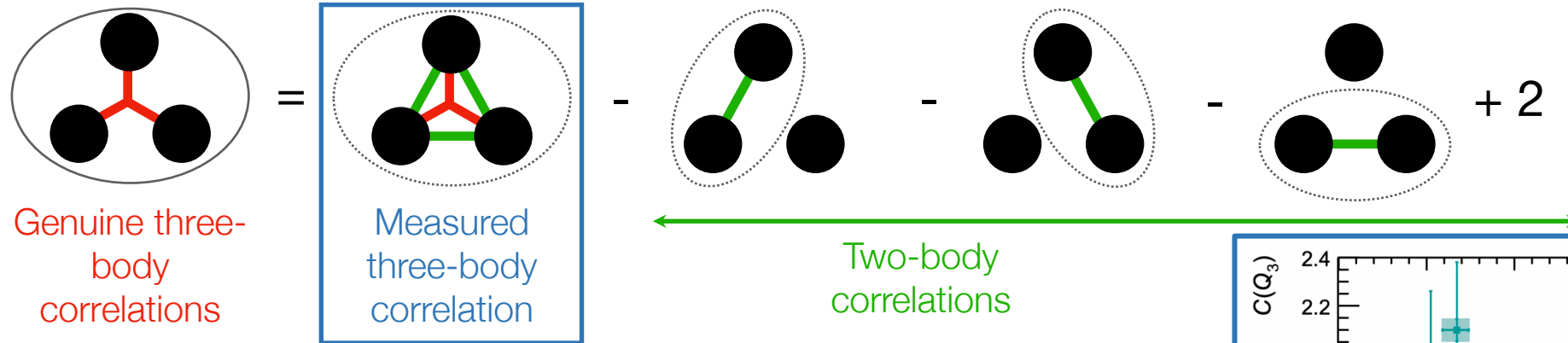
ALICE Coll. EPJ A 59, 145 (2023)



Test with mixed-charge particles, cumulant negligible.



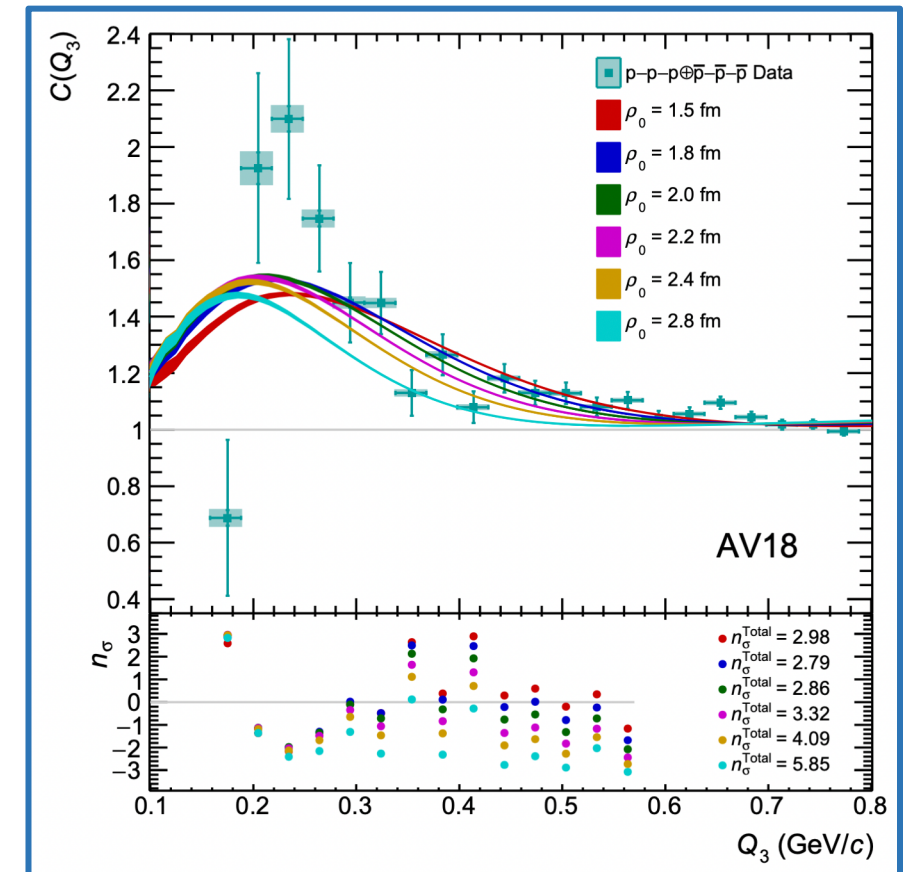
Modeling a three-body correlation function



- First-ever three-nucleon scattering wavefunctions available
 - possibility to study $3 \rightarrow 3$ process
 - 2-body interactions, Coulomb and quantum statistics included
- Depletion at low Q_3 caused by **Pauli repulsion**, dominant contribution for 3-nucleons close in space (p-d)

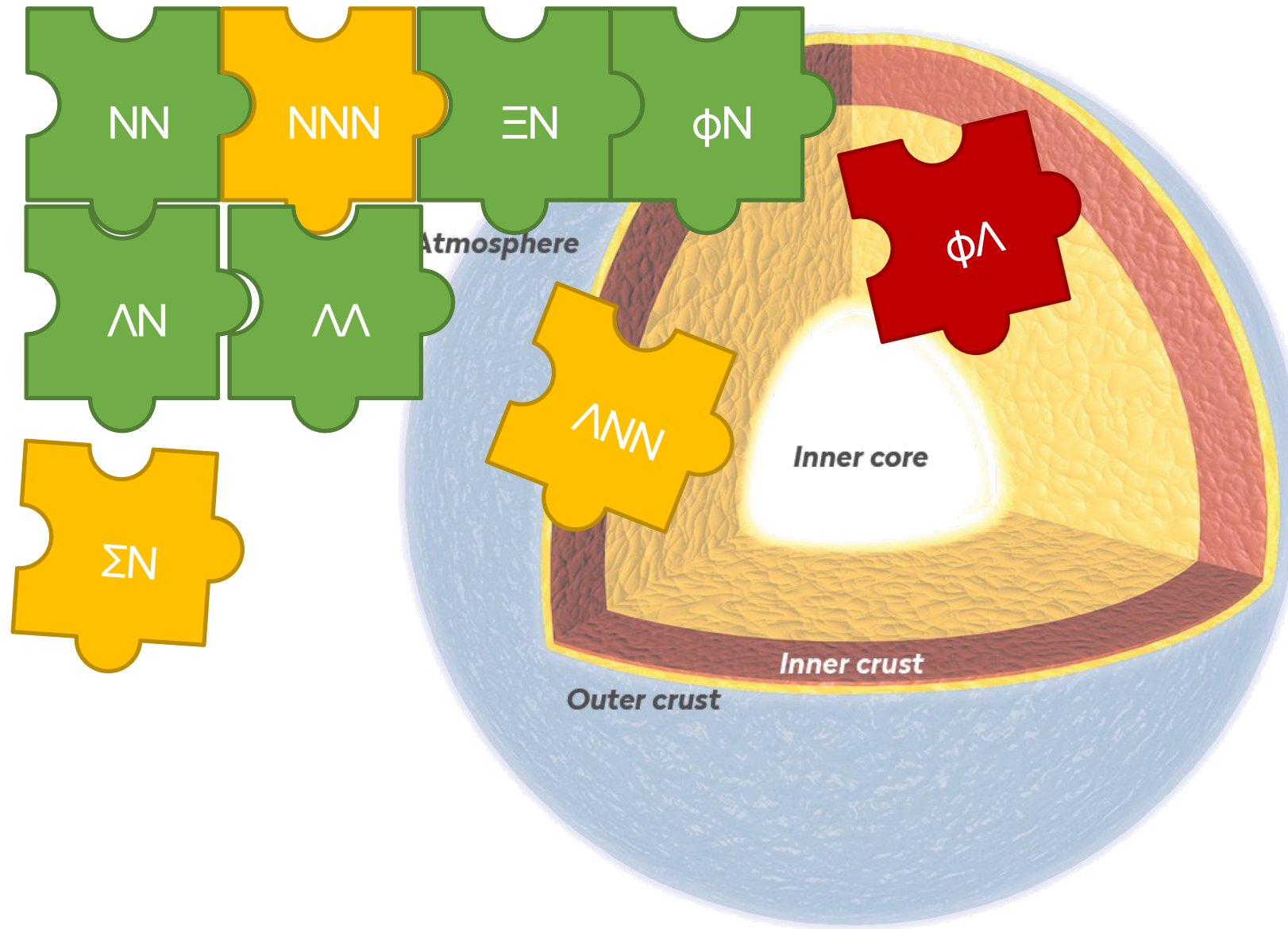
ALICE Coll. arXiv: 2308.16120, M. Viviani et al. PRC 108 (2023)

First important step towards the investigation of pp Λ correlations

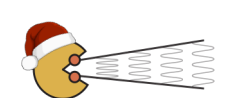


A. Kievsky et al. arXiv: 2310.10428

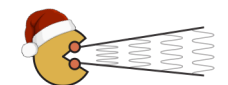
The hyperon puzzle in neutron stars...at the end of this talk



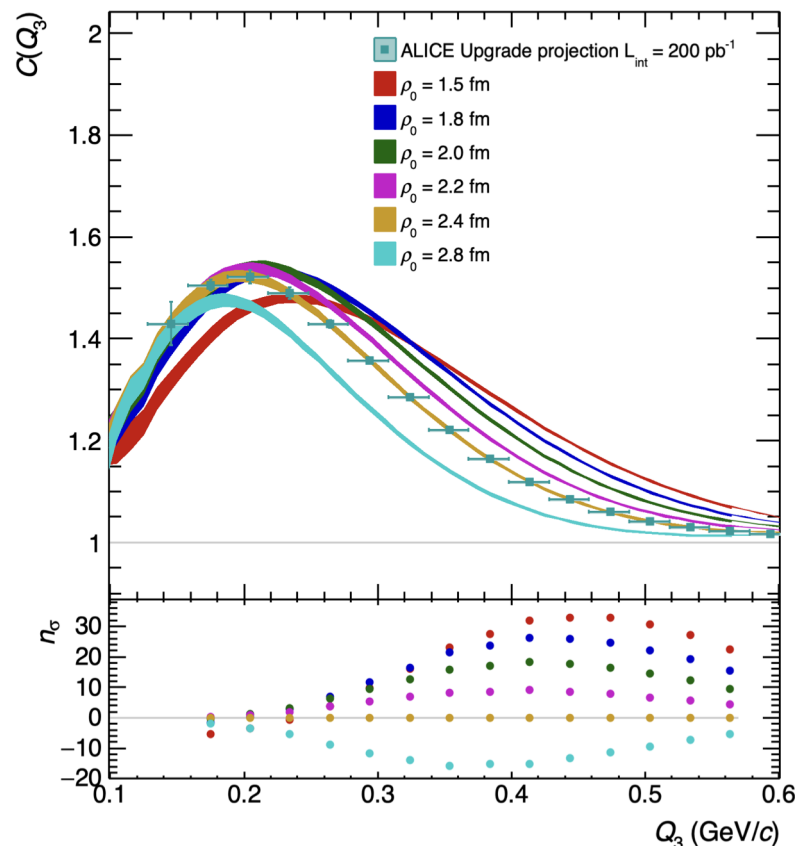
Common and complementary experimental efforts in several directions are hugely improving the situation!!



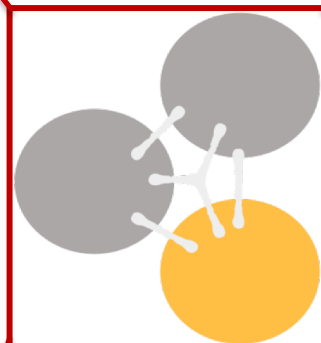
Future perspectives and challenges



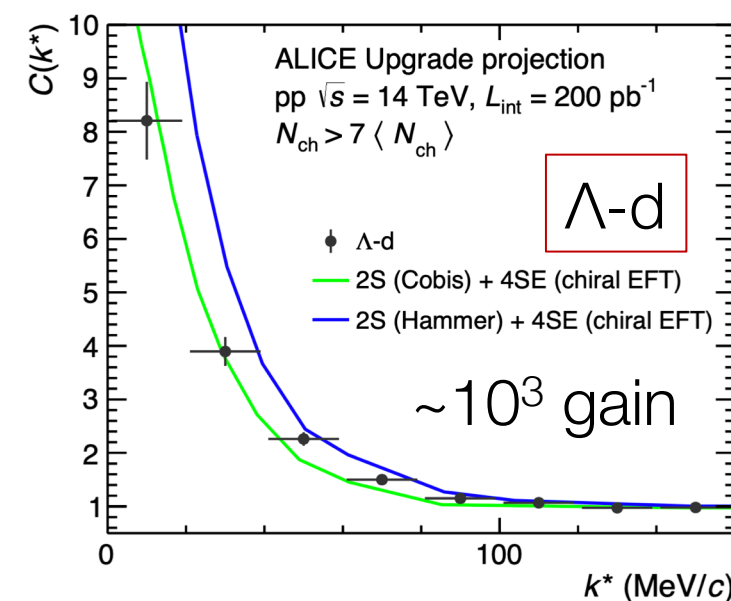
Direct (ppp,ppΛ)



Expected factor 200 gain in statistics for ppp and ppΛ at $Q_3 < 0.6 \text{ GeV/c}$



Indirect (h-d)



Scattering parameters of the doublet state related to hypertriton $^3\text{H}_\Lambda$ BE → Complementary to direct measurements J. Haidenbauer, arXiv:2005.05012

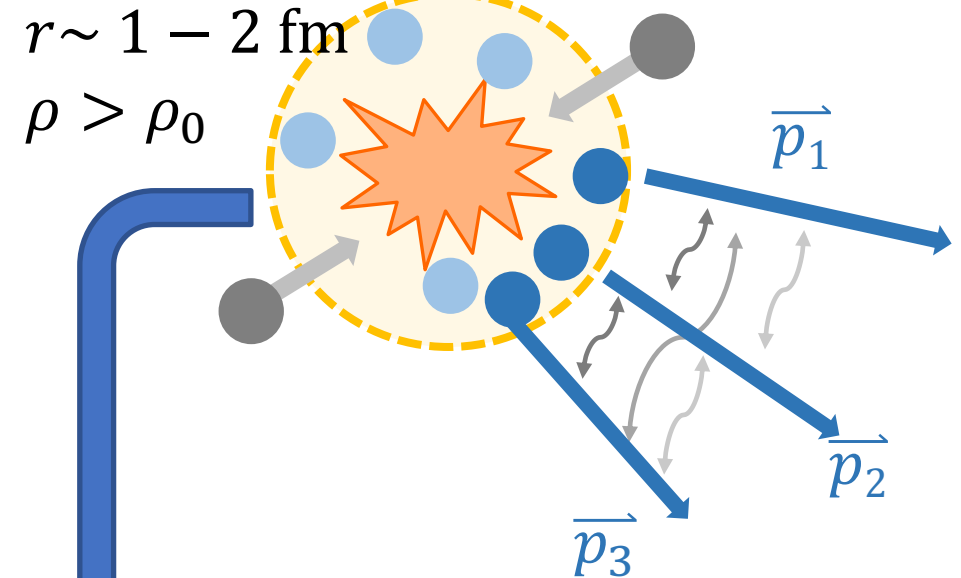
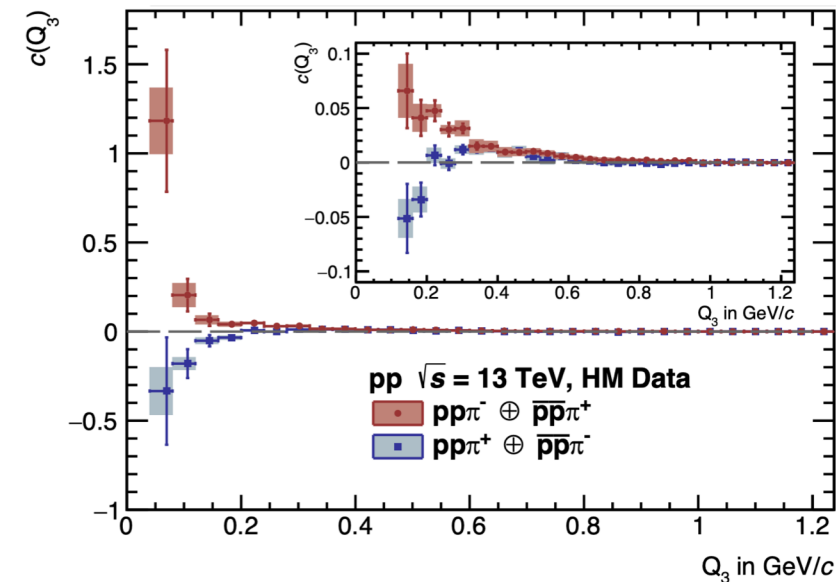
Quartet state depends on spin triplet ΛN interaction → access spin dependence

- Impact of QCD axion on the EoS
→ can lead to stiffer EoS
- Axion properties linked to in medium properties of pion

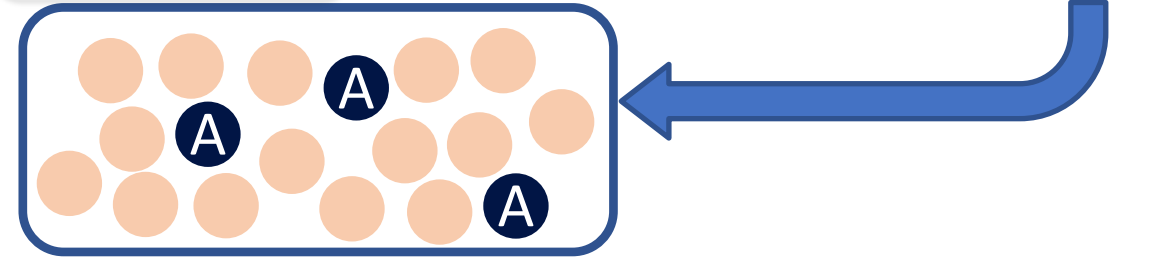
R. Balkin et al. arXiv: 2311.03995

R. Balkin et al, J. High Energy. Phys. 2020, 221 (2020)

Goal: Study of $pp\pi^\pm$ interactions using femtoscopy in small colliding systems
→ Access in-medium couplings of pions to nucleons



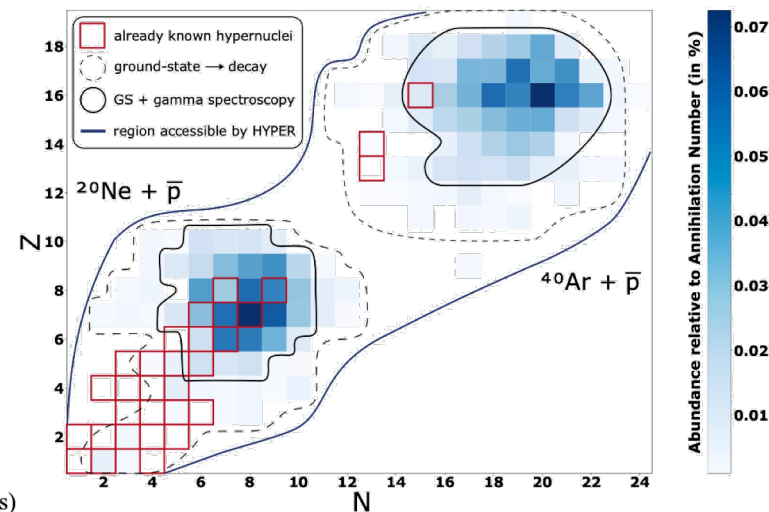
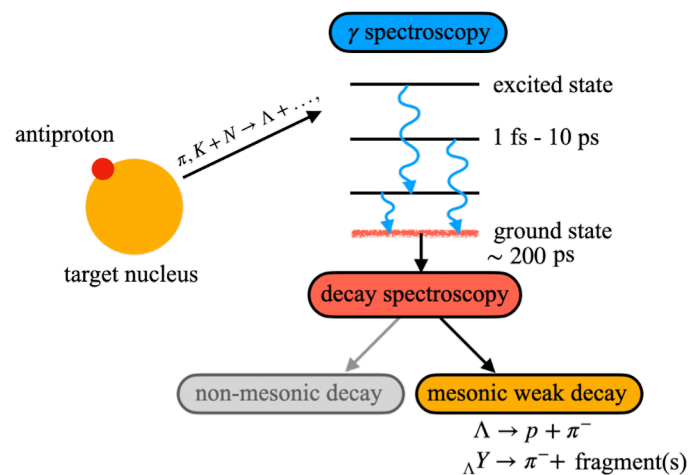
For more details:
MLL Koll. 23.11.2023
by K. Springmann



- **High-intensity \bar{p}** at low momenta (~ 100 KeV) from ELENA

- Novel method to produce hypernuclei:

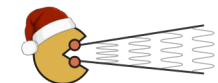
- $p + \bar{p} \rightarrow K + \bar{K}$ at nuclear surface (3%)
- 10-30% of strang. exchange $K^- + n \rightarrow \Lambda + \pi^-$ lead to hypernucleus



- Expected **10^3 hypernuclei / 2-minute cycle**

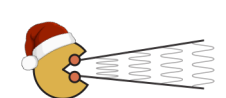
- increased prod. of hypernuclei away from β -stable valley
- Access to **intermediate mass n-rich hypernuclei** as isotopic chain of **O** ($^{13-21}_{\Lambda}O$) and **Si** ($^{29-41}_{\Lambda}O$)

Production	Main lab(s)	Refs.	Hypernuclei	Excited states	Ground state	
					binding	lifetime
In-flight (K^-, π^-)	CERN (90s), BNL		$Z_Y = Z_i - 1$	✓	✓	✗
Stopped (K^-, π^-)	CERN (70s), LNF-INFN, KEK, BNL	[28]	$Z_Y = Z_i - 1$	✓	✓	✗
(π^+, K^+)	KEK, BNL	[29, 30, 31]	$(A, Z)_Y = (A, Z)_i$	✓	✓	✗
($e, e'K^+$)	JLAB, Mainz	[32, 33]	$Z_Y = Z_i - 1$			
Heavy-ion (GeV)	GSI/FAIR, HIAF	[34, 35]	Potentially many	✗	✓ 3 MeV	✓ Sys.
Relativistic HI (100 GeV - 13 TeV)	RHIC, ALICE (CERN)		$A_Y \leq 4$	✗	✓	✓ Sys. ~ 10 ps
Λ, Ξ from in-flight \bar{p}	PANDA (FAIR)	[36, 37]	$(A, Z)_Y = (A, Z)_i$	✓	✗	✗
Stopped \bar{p}	HYPER (CERN)	This proposal	Potentially many	✓	✓	✓ ≤ 40 ps

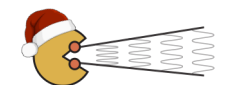


Conclusions and final remarks

- Combined experimental/theoretical effort to shed light into the inner NS core composition
- Tackling the hyperon puzzle from the two-body YN and three-body YNN interactions
 - bright future for scattering and hypernuclear measurements
- Correlation data at two- and three-body level delivering high-precision data
 - building a full experimental database for YN interactions
 - crucial input for single-particle potential and finite density calculations
 - first ppp and pp Λ data to be used to test first three-body wavefunctions in continuum
- Final answer on nature of pp Λ interaction with ALICE correlation data expected on Run 3 statistics
 - possibility to explore also more exotic NS ingredients as axions with pion-multinucleon correlations
- Possibility to explore n-rich nuclei with new proposed experiment HyperPuma
 - important constraints for behavior of hyperon in pure neutron matter



Additional slides



Multi-messenger era: exciting times for neutron stars studies

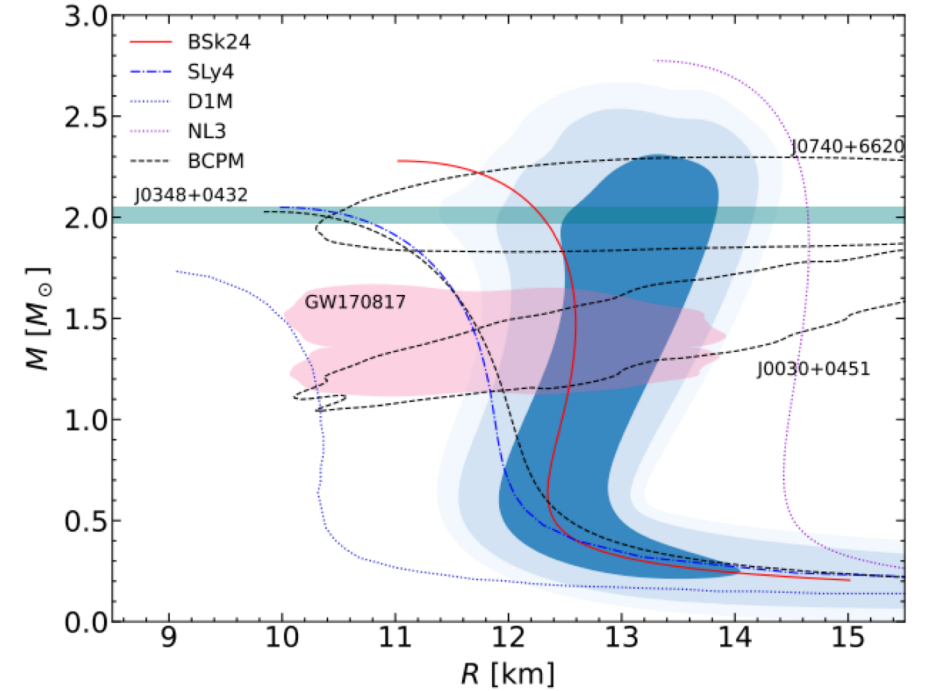
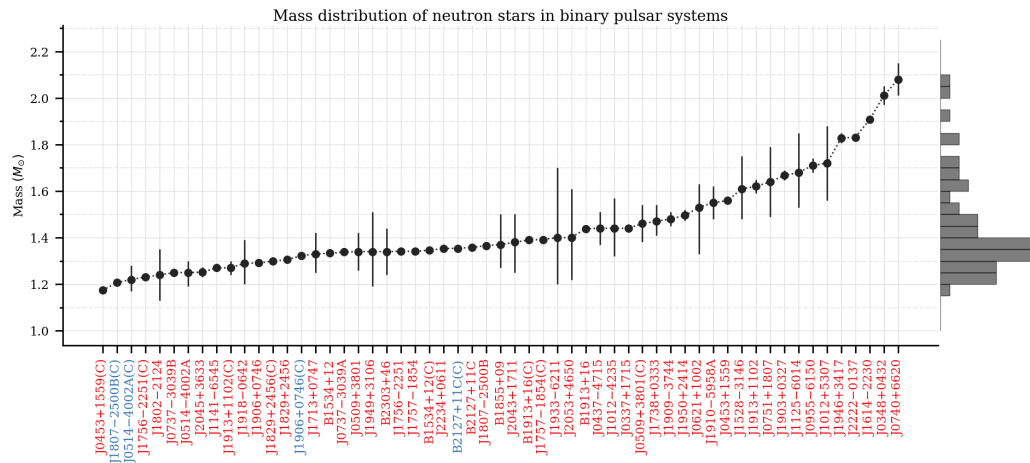
- Observation of heavy neutron stars

PSR J1614–2230⁽¹⁾ $M = 1.908 \pm 0.016M_{\odot}$

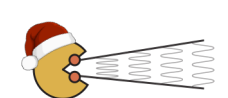
PSR J0348+0432⁽²⁾ $M = 2.01 \pm 0.04M_{\odot}$

PSR J0740+6620⁽³⁾ $M = 2.08 \pm 0.07M_{\odot}$

- NICER precise radii measurements with pulse profile modeling of X-ray emission from hot spots

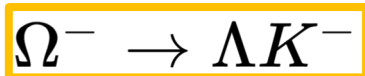
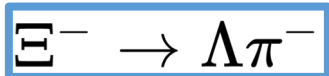


- (1) P. Demorest et al. *Nature* 467 (2010) 1081-1083, E. Fonseca et al. *Astrophys. J.* 832 (2016), Z. Arzoumanian et al. *Astrophys. J. Suppl.* 235 (2018)
- (2) J. Antoniadis et al. *Science* 340 (2013)
- (3) E. Fonseca et al. *Astrophys. J. Lett.* 915 (2021)

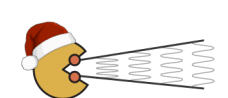
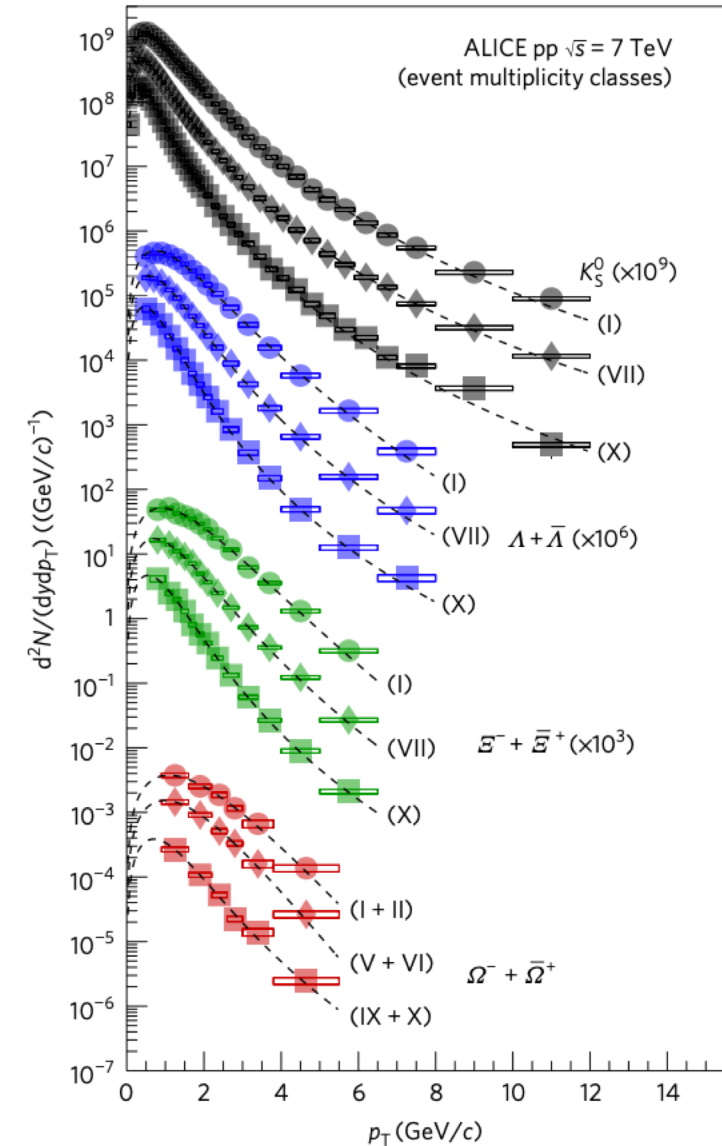


High multiplicity pp collisions

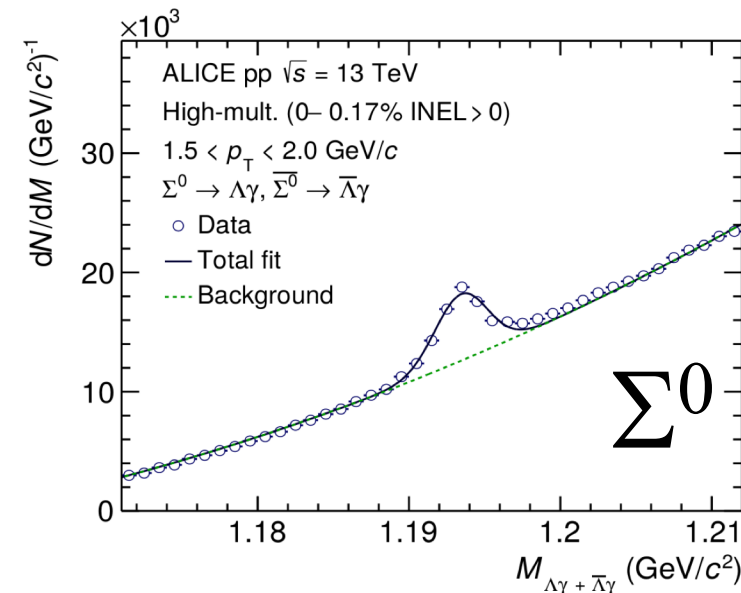
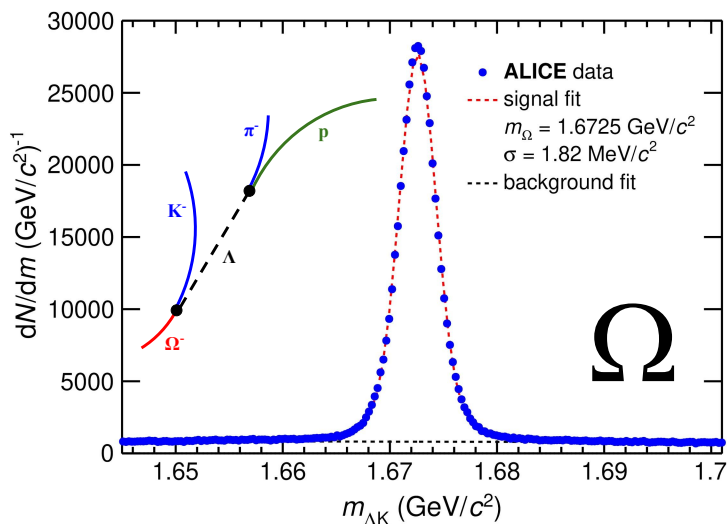
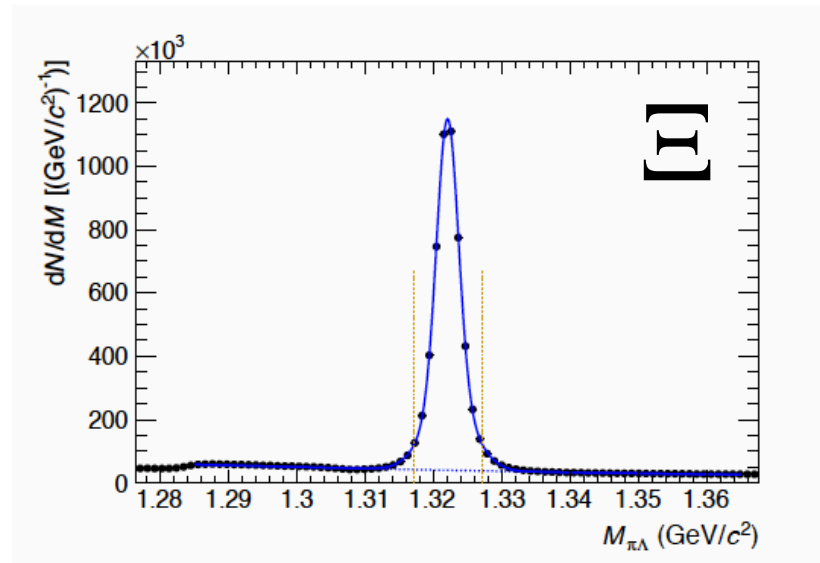
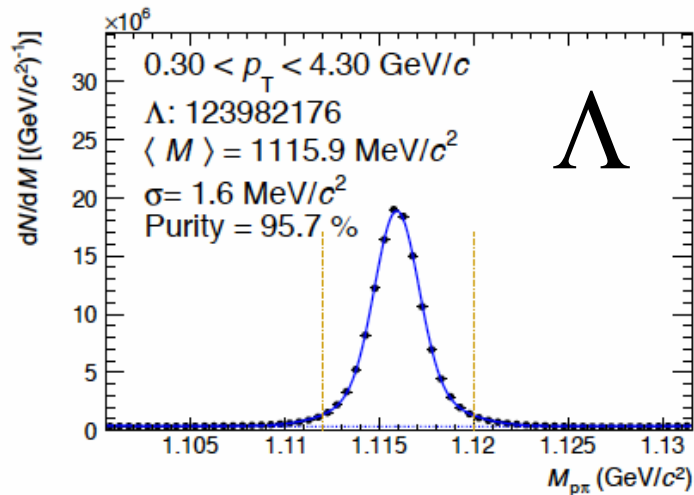
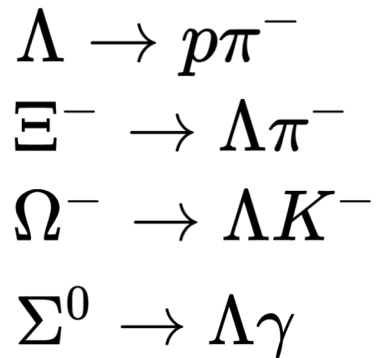
- pp collisions at ALICE are a perfect factory to produce a large amount of multi-strange hyperons
ALICE Coll. Nature Phys. 13 (2017) 535-539
- In the paper:
 - High multiplicity events pp 13 TeV → enhanced yields of multi-strange hadrons
- High capability for particle identification at transverse momenta below 1 GeV/c
 - hyperons detected through weak decays



- low contamination and high purity samples

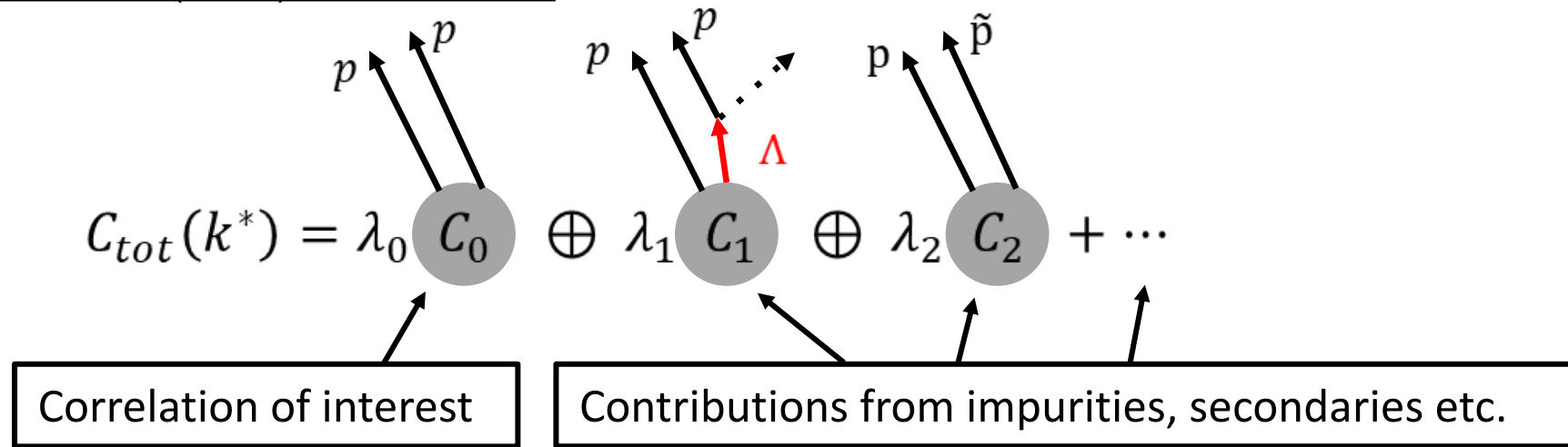


Hyperons @ ALICE in pp Collisions



Femtoscscopy - Decomposition of $C(k^*)$

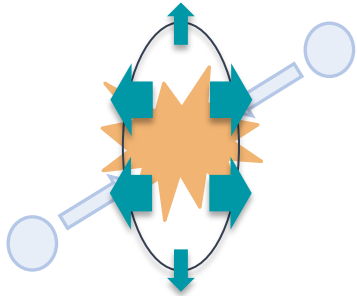
- Determine the amount of impurities and secondaries based on a data-driven MC study as done in [Phys.Rev. C99 \(2019\) no.2, 024001](#)



- Purity (\mathcal{P}) from fits to the invariant mass distribution or MC data
- Feed-down fractions (f) from MC template fits
- $\lambda_i = \mathcal{P}_{i_1} f_{i_1} \mathcal{P}_{i_2} f_{i_2}$, where $i_{1,2}$ denote the two particles of the i -th contribution

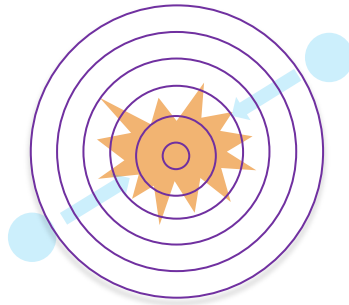
Small Sources: Collective Effects and Strong Resonances

Elliptic flow



Anisotropic pressure gradients within the source

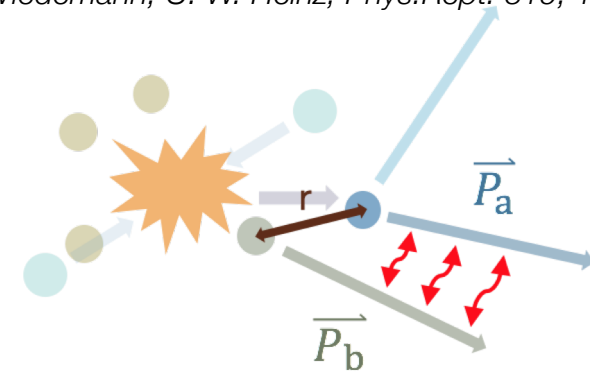
Radial flow



- Expanding source with constant velocity
- Different effect on different masses

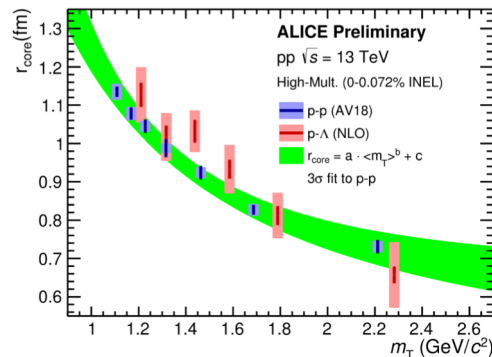
Strong decays of broad resonances

U. A. Wiedemann, U. W. Heinz, Phys.Rept. 319, 145-230 (1999)

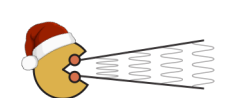


- Resonances with $c\tau \sim r_0 \sim 1$ fm (Δ^* , N^* , Σ^*) introduce an exponential tail to the source
- Different for each particle species

Core Radius

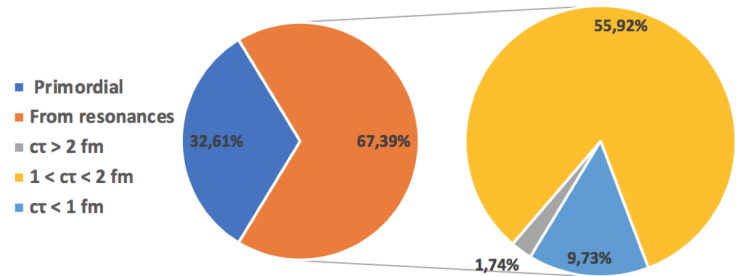


Strong decays of specific resonances

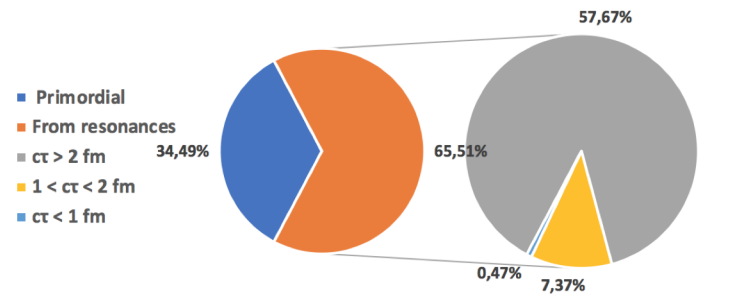


The source function - Effect of short-lived resonances

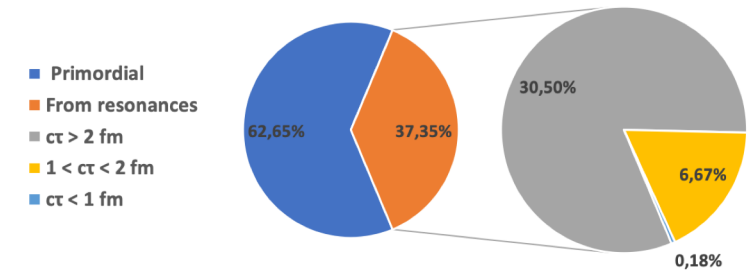
Protons



Λ s

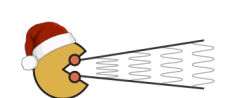


Σ^0 s

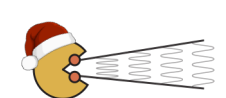
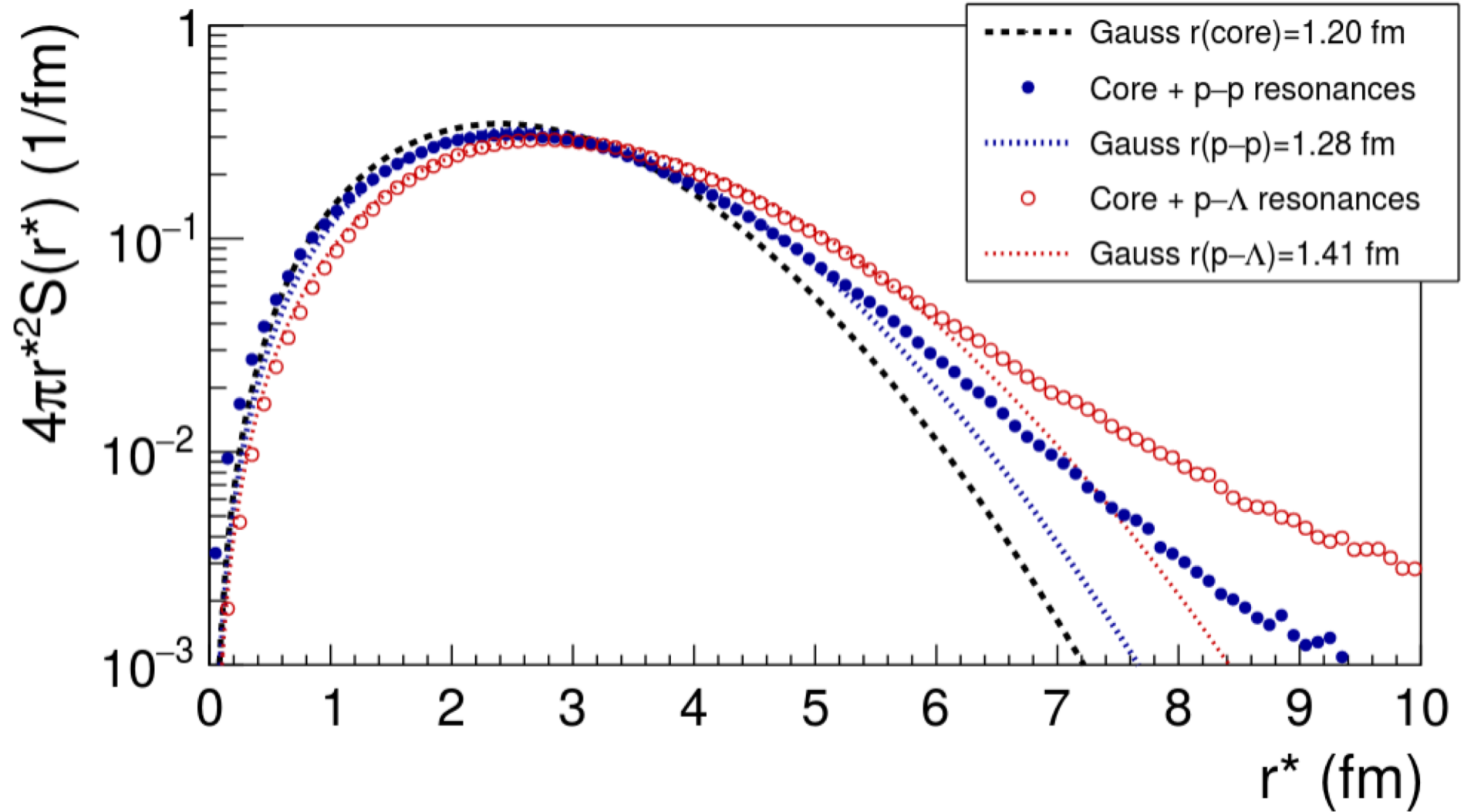


- For Ξ^- and Ω^- no contributions!
- Average mass and average $c\tau$ determined by the weighted average values of all resonances

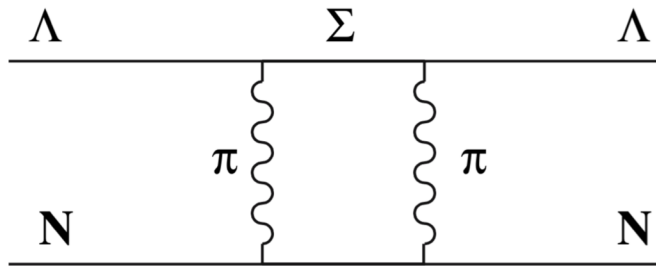
Particle	M_{res} [MeV]	τ_{res} [fm]
p	1361.52	1.65
Λ	1462.93	4.69
Σ^0	1581.73	4.28



The common source - The source pdf

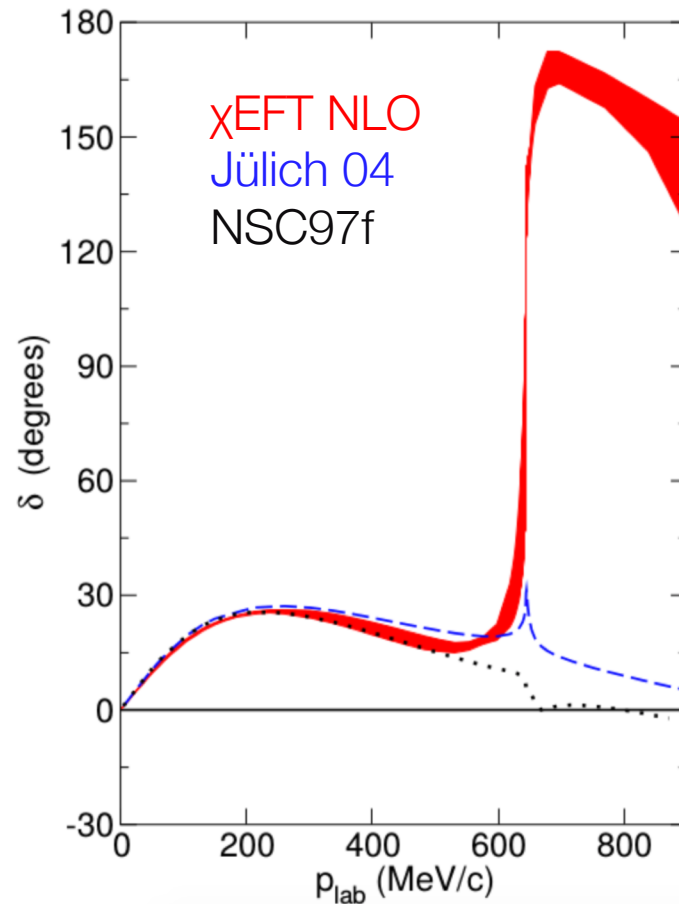


Influence of the $\Lambda N - \Sigma N$ coupled channel

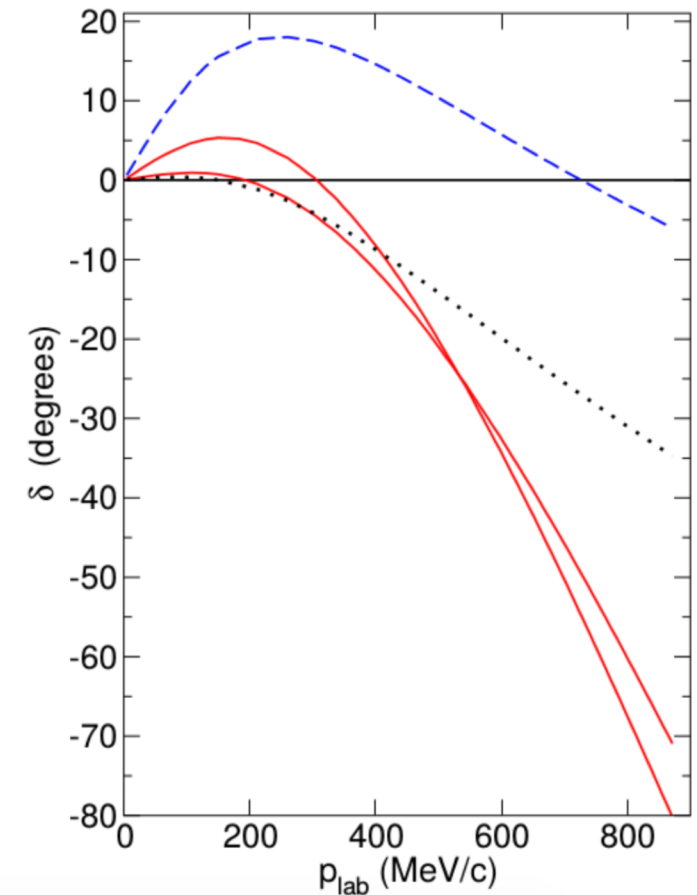


- $\Sigma N - \Lambda N$ acts as an effective attraction
- Repulsion for $\Lambda - p$ when the $\Sigma - N - \Lambda - N$ coupled channel is neglected
 - strong coupling \Rightarrow dispersion repulsive effects \Rightarrow Shift of hyperon appearance towards higher densities
 - weak coupling \Rightarrow more attractive $U_\Lambda(\rho_0, 0)$

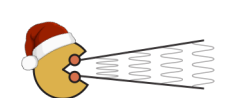
$\Lambda - p \ ^3S_1$
with the $\Sigma - N - \Lambda - N$ coupling



$\Lambda - p \ ^3S_1$
w/o the $\Sigma - N - \Lambda - N$ coupling



J. Haidenbauer *et al.*, Eur. Phys. A (2017) 53, 121.



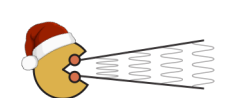
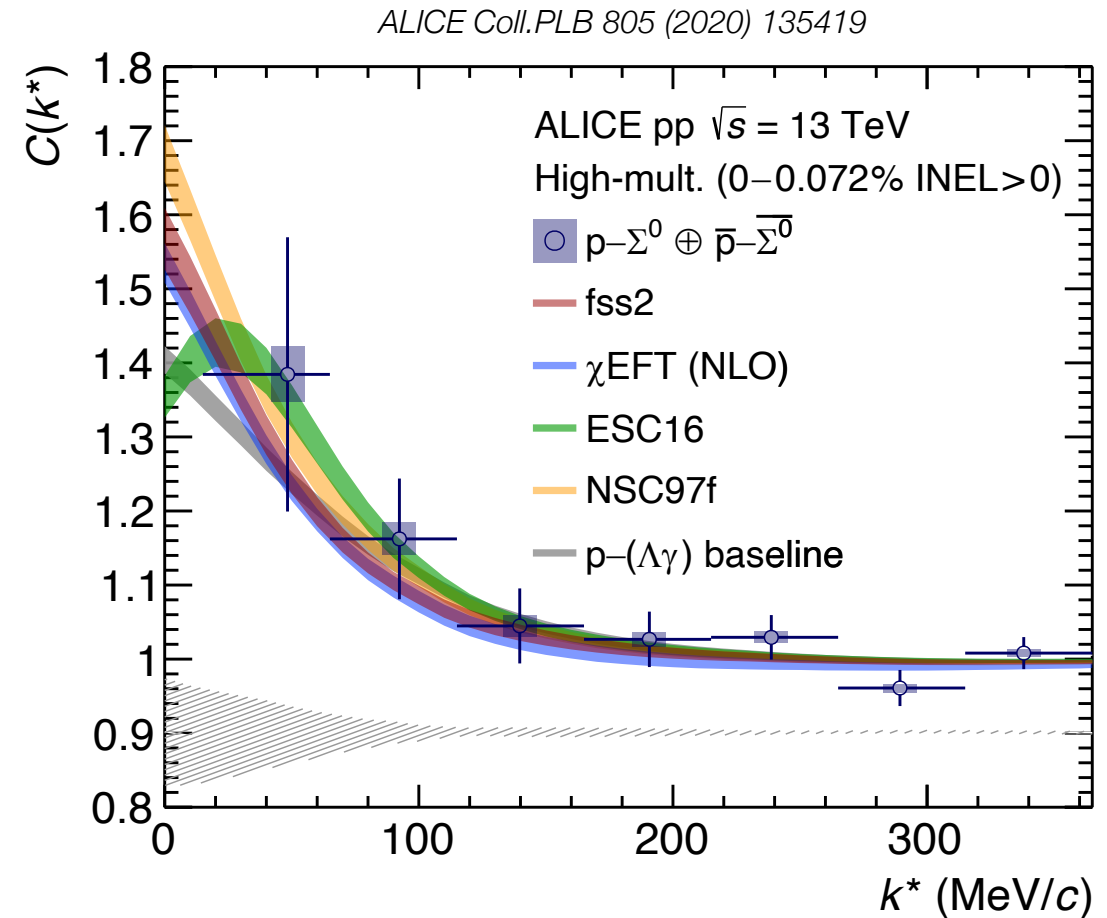
$|S|=1$: First measurement of the $p\Sigma^0$ interaction

- Experimental data on hypernuclei too scarce for a final conclusion: attractive or repulsive interaction?
- Very challenging measurement via the difficult electromagnetic decay $\Sigma^0 \rightarrow \Lambda \gamma$

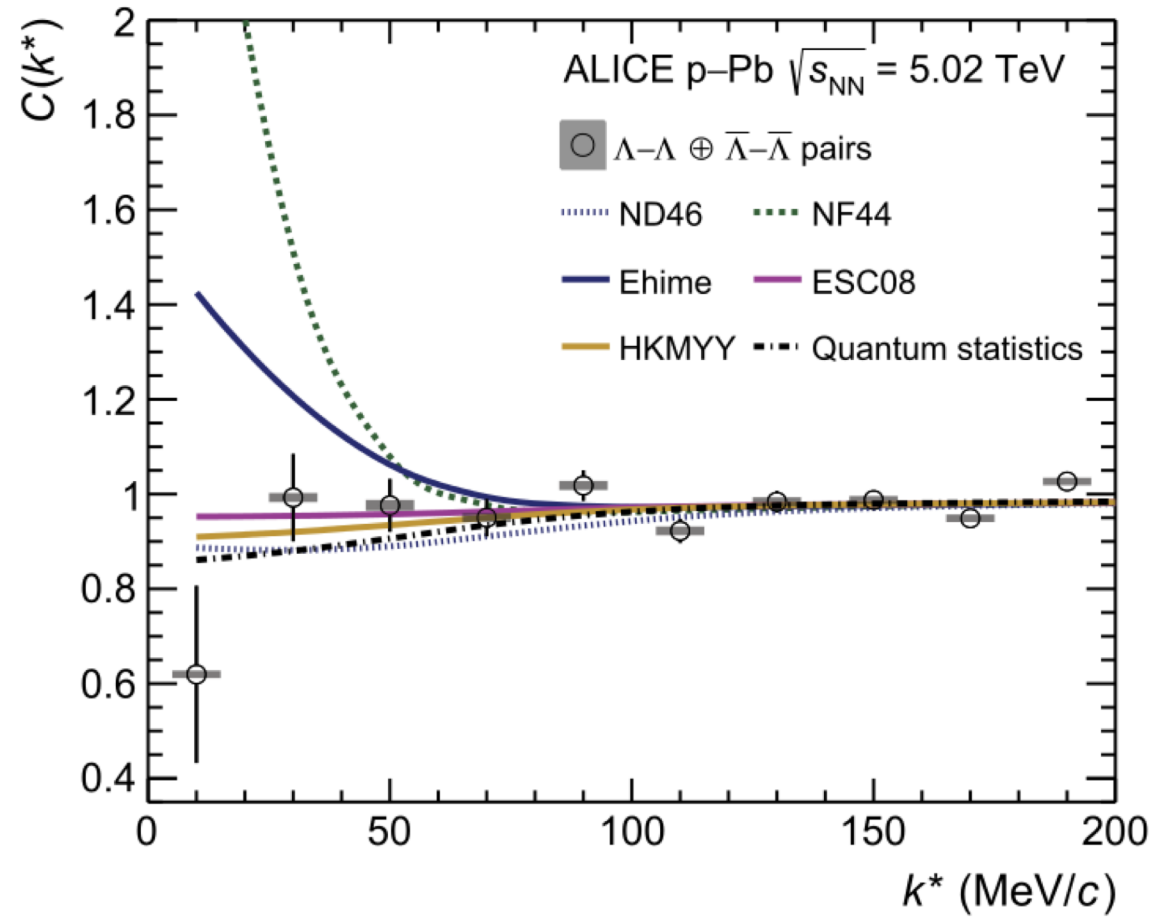
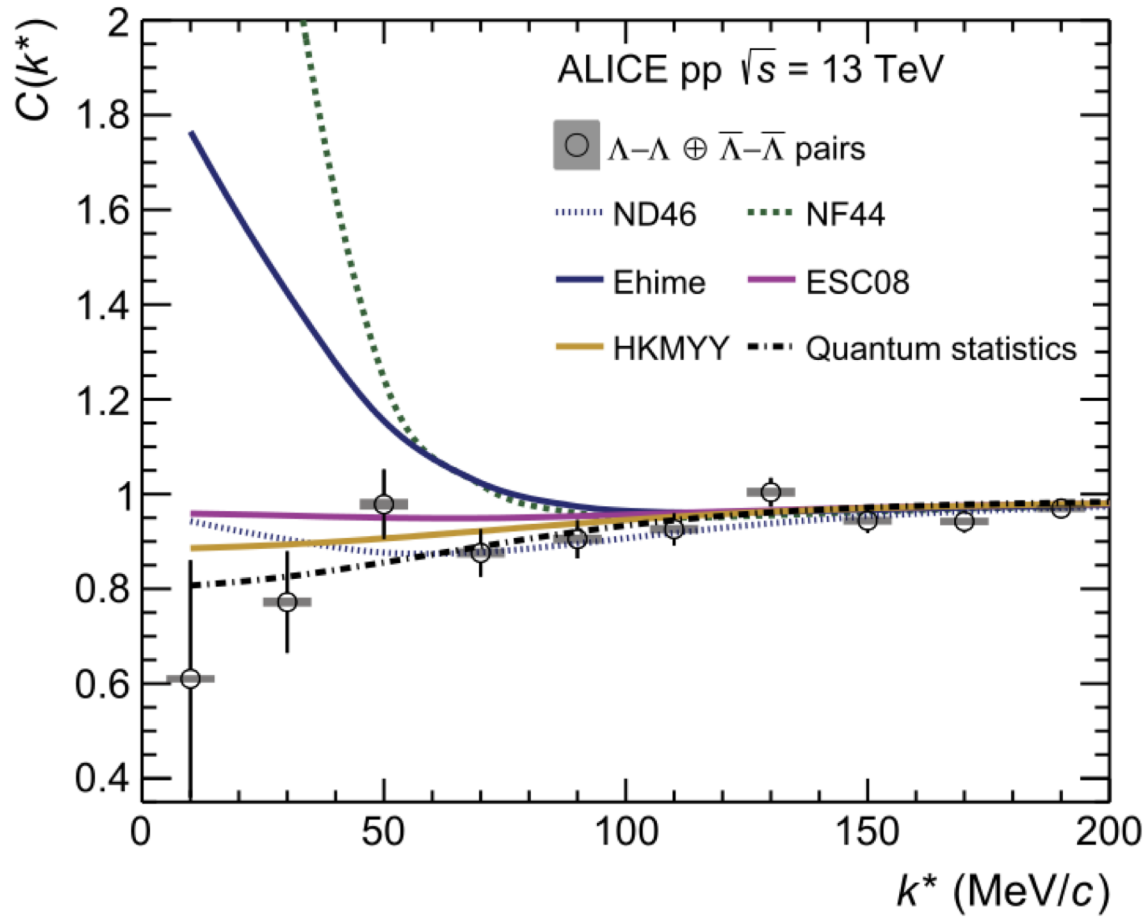
- **Correlation function is above the background \Rightarrow pointing to a very shallow attractive interaction**

Model	p-($\Lambda\gamma$) baseline	fss2	χ EFT	NSC97f	ESC16
n_σ ($k^* < 150$ MeV/c)	0.2–0.8	0.2–0.9	0.3–1.0	0.2–0.6	0.1–0.5

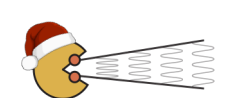
- Relevant for dense neutron matter is the interaction with neutrons and the interaction of $\Sigma^{+,-}$!
 - Disentangle the different isospin contributions
- **Larger statistics in Run3 and Run4 will definitely increase the precision and constraints on the Σ -N interaction**



Λ - Λ correlations

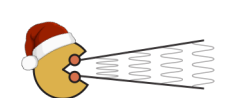
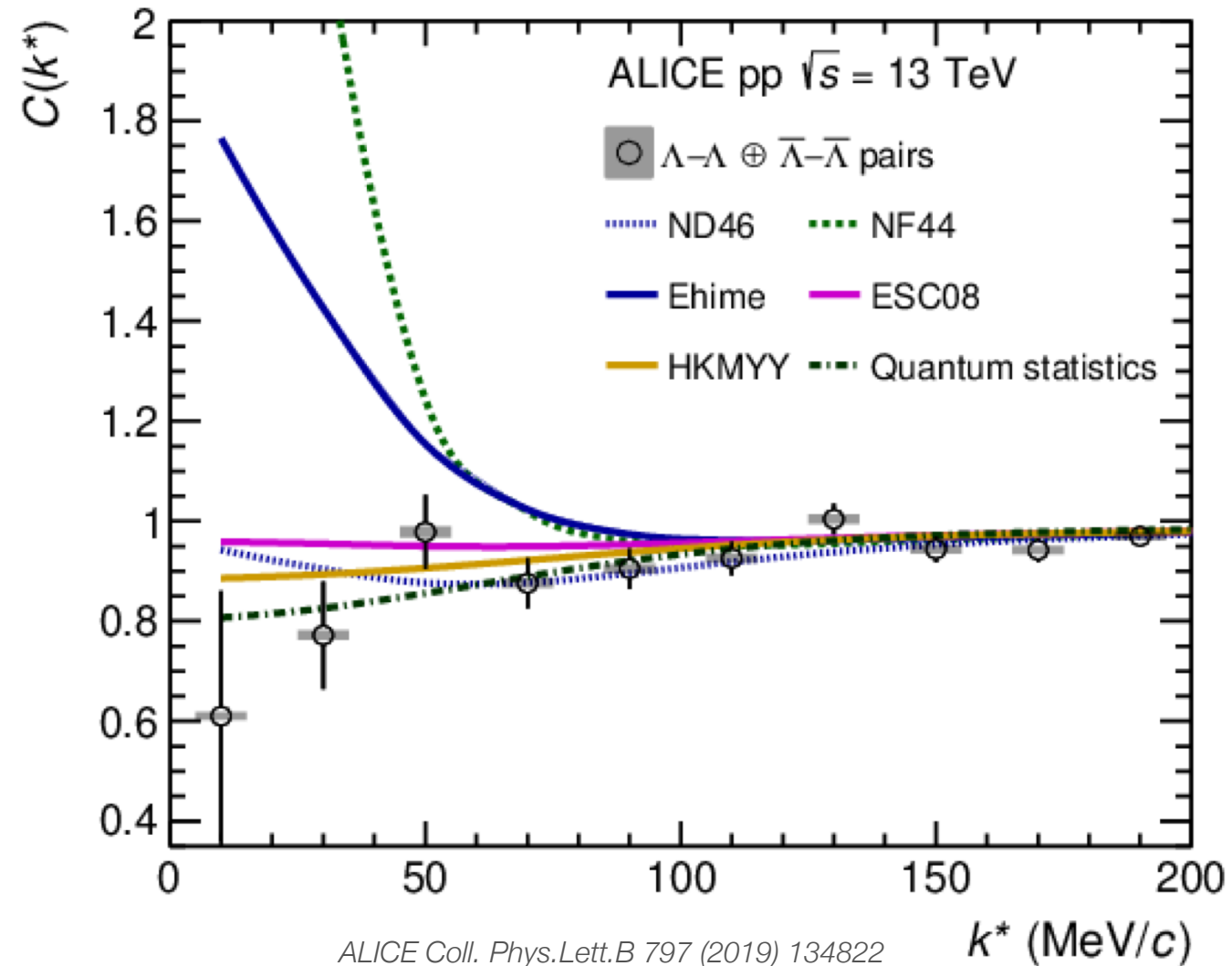


Phys.Lett.B 805 (2020) 135419



$|S|=2$: $\Lambda\Lambda$ interaction models

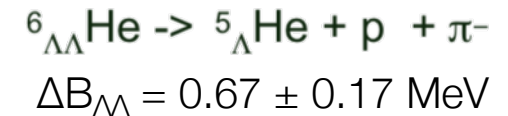
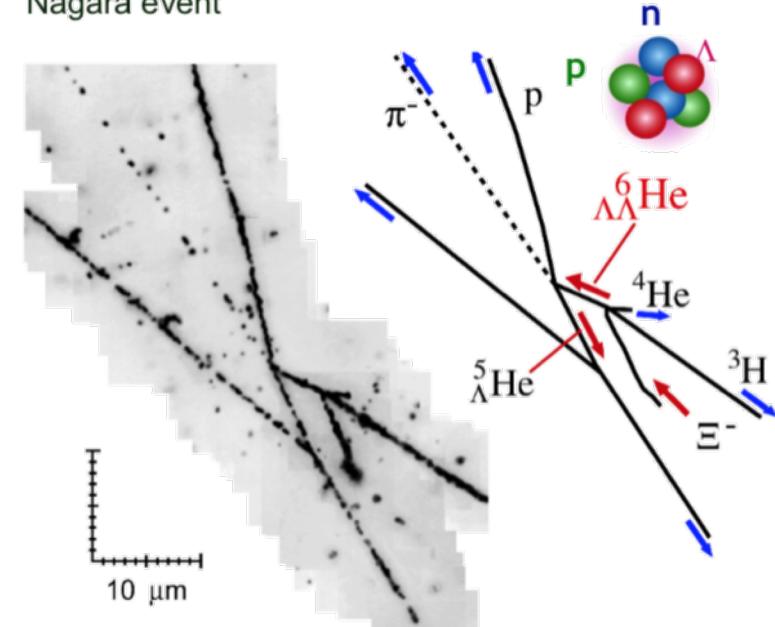
- $\Lambda\Lambda$ correlation measured in pp MB 13 TeV and p-Pb 5.02 TeV
- Comparison with available theoretical models
 - large attraction and very weakly bound state discarded
 - data compatible with a bound state (ND46) or shallow attraction (ESC08)
- Scan in scattering parameter space and express agreement data/model in number of σ deviations





- H-dibaryon: hypothetical bound state of $uuddss$
 - No final experimental evidences so far
 - Recent lattice QCD calculations at physical point with $\Lambda\Lambda$ - $N\Xi$ coupled-channel(*) \rightarrow no bound state around $\Lambda\Lambda$ or $N\Xi$ threshold (**)
- Double- Λ hypernuclei measurements
 - weak attractive interaction
 - H-dibaryon binding energy $B_{\Lambda\Lambda} = 6.91 \pm 0.16$ MeV

Nagara event

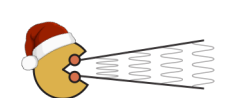


H. Takahashi et al., PRL 87 (2001) 212502

(*) *HAL QCD Coll. Nucl.Phys.A 998 (2020) 121737*
A. Ohnishi et al., Few Body Syst. 62 (2021) 3, 42
Y. Kamiya et al., PRC 105 (2022)

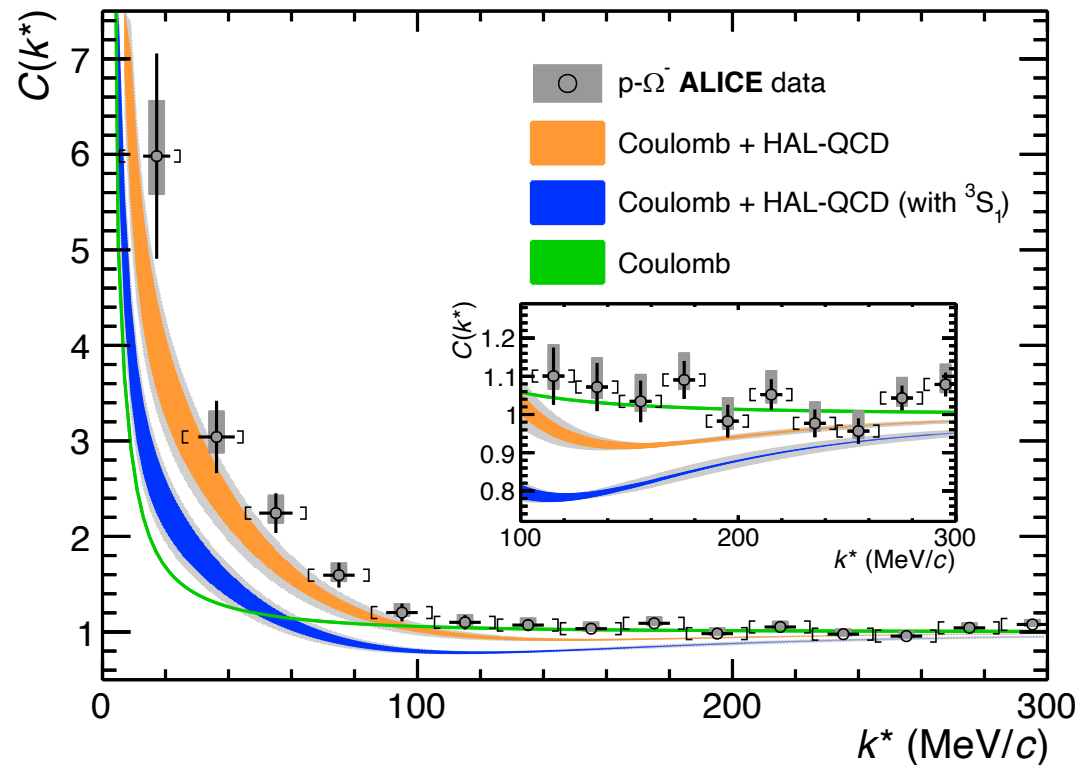
(**) *ALICE Coll. Phys. Rev. Lett 123, (2019) 112002*
ALICE Coll. Nature 588, 232–238 (2020)

Can we improve the knowledge on the $\Lambda\Lambda$ interaction and the fate of the H dibaryon?

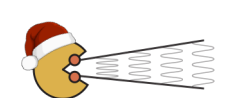


p - Ω^- correlation function in pp at 13 TeV

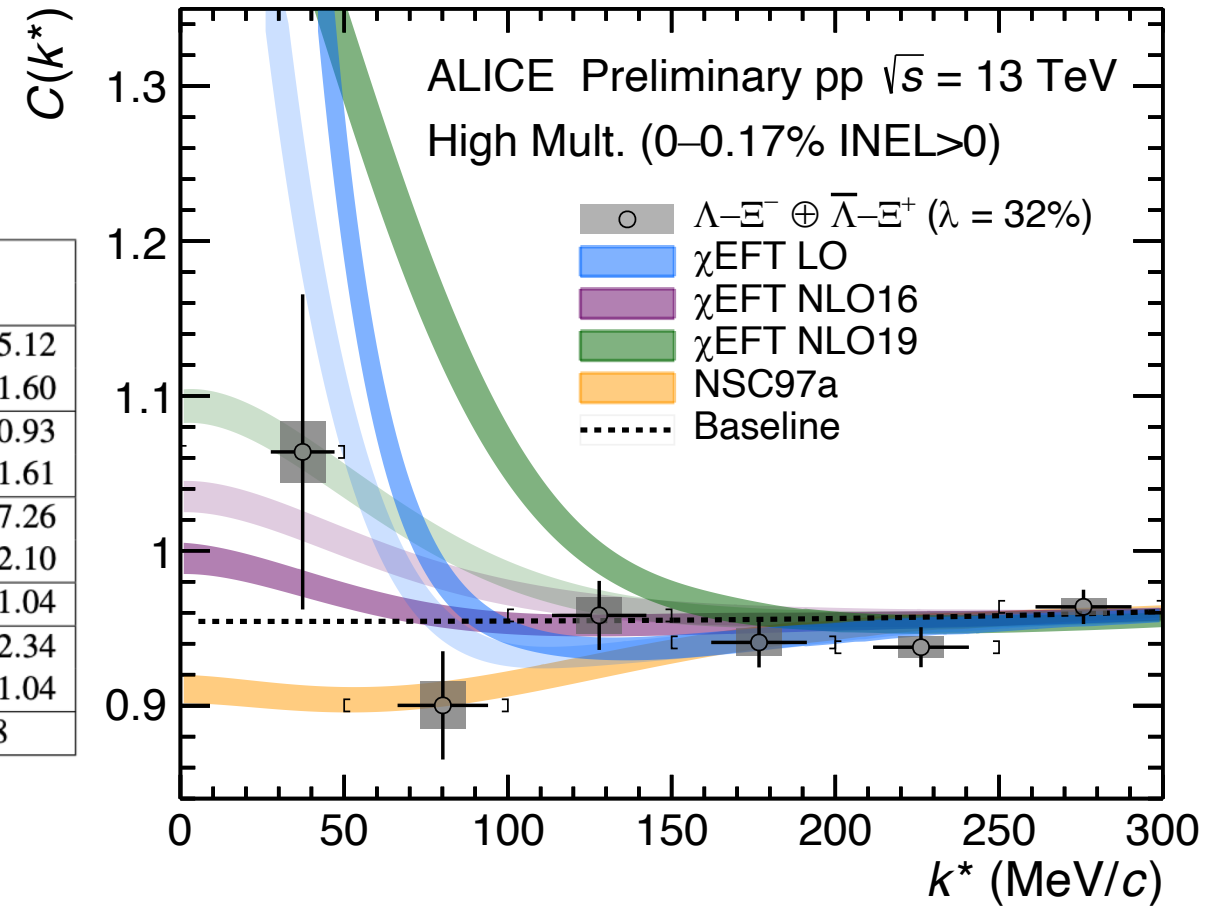
ALICE Coll. Nature 588 (2020) 232-238



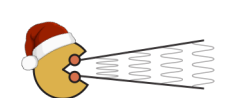
- Model corrected for residual correlations and corrections
 - Radius extracted from m_T differential p-p correlations ($r \sim 0.9$ fm)
- Enhancement above Coulomb
 - Observation of the strong interaction
- Agreement of lattice prediction depends on the treatment of inelastic channels
 - No clear depletion corresponding in the data



potential	cut-off (MeV) / version	singlet		triplet		n_σ
		f_0^0	d_0^0	f_0^1	d_0^1	
χ EFT LO [11]	550	33.5	1.00	-0.33	-0.36	3.06 – 5.12
	700	-9.07	0.87	-0.31	-0.27	0.78 – 1.60
χ EFT NLO16 [14]	500	0.99	5.77	-0.026	142.9	0.56 – 0.93
	650	0.91	4.63	0.12	32.02	0.91 – 1.61
χ EFT NLO19 [15]	500	0.99	5.77	1.66	1.49	5.47 – 7.26
	650	0.91	4.63	0.42	6.33	1.30 – 2.10
NSC97a [12]		0.80	4.71	-0.54	-0.47	0.68 – 1.04
HAL QCD [2]	$\Lambda\Xi$ - $\Sigma\Xi$ eff.	0.60	6.01	0.50	5.36	1.43 – 2.34
	$\Lambda\Xi$ - $\Lambda\Xi$ only	-	-	-	-	0.64 – 1.04
Baseline		-	-	-	-	0.78

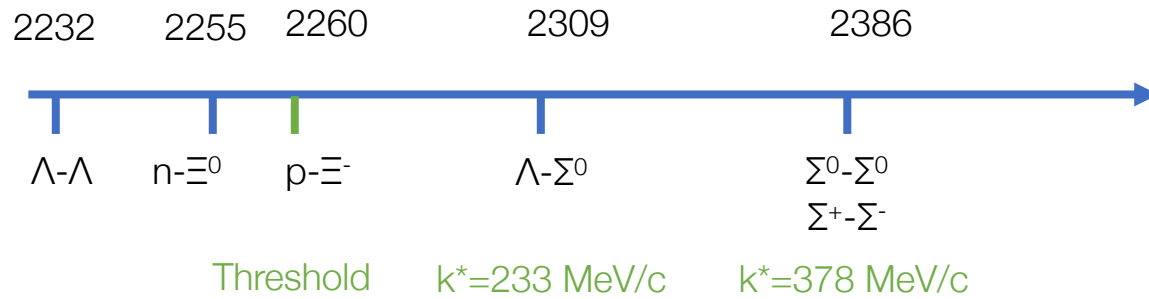


ALI-PREL-516888



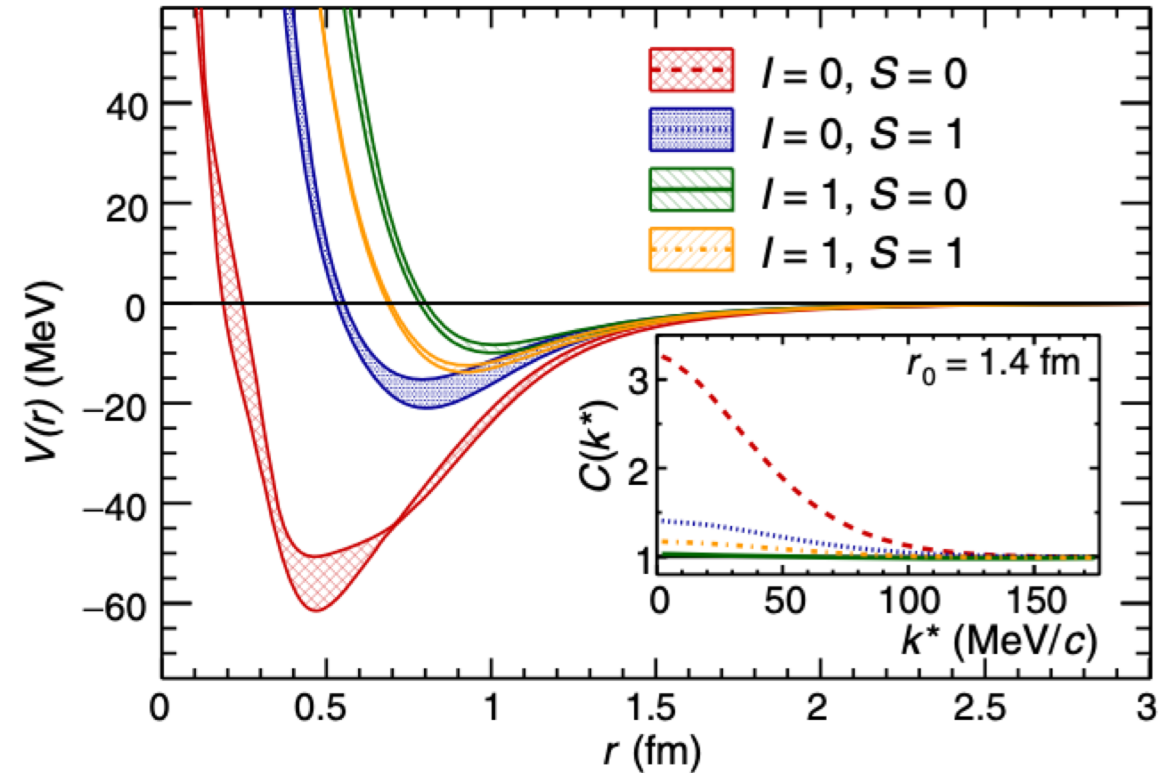
Lattice QCD potentials of the $|S| = 2$ sector: $p-\Xi^-$ interaction

- Direct comparison to HAL QCD potentials near physical quark masses^(*)
- Presence of coupled-channels



- Weak coupling to Λ - Λ channels expected from HAL QCD potentials
 - confirmed from femtoscopic^(**) and hypernuclei measurements^(***)

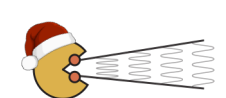
$p-\Xi^-$ interaction



(*) T. Hatsuda *Front. Phys.* 13(6), 132105 (2018)

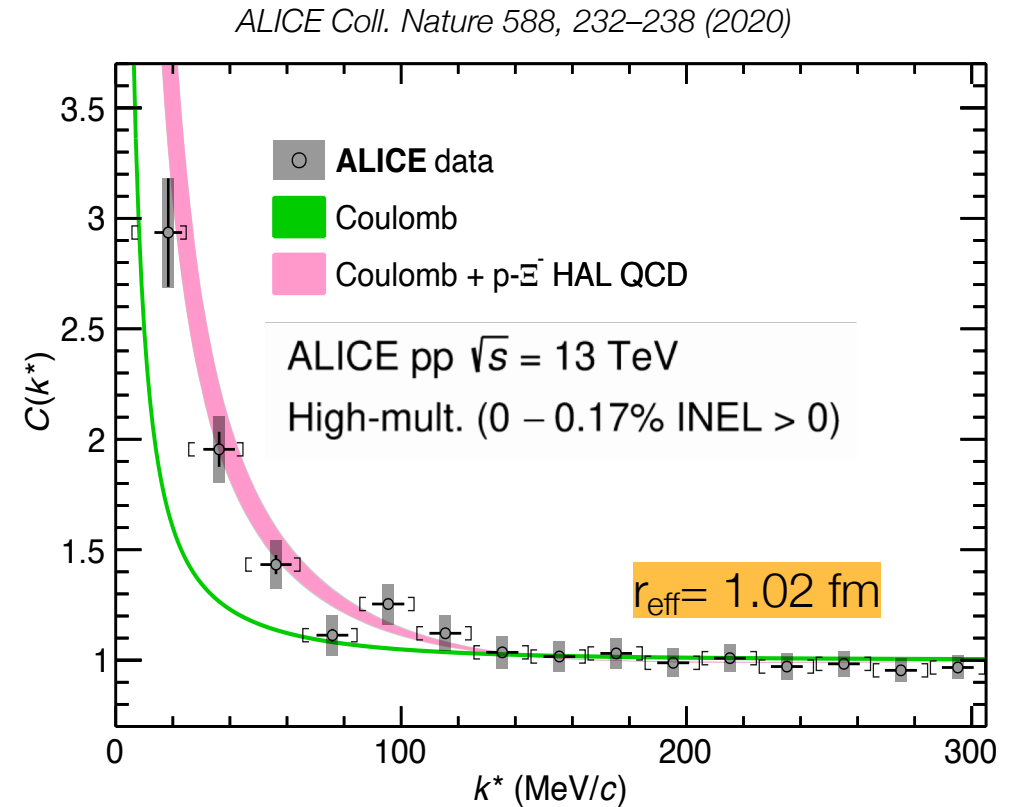
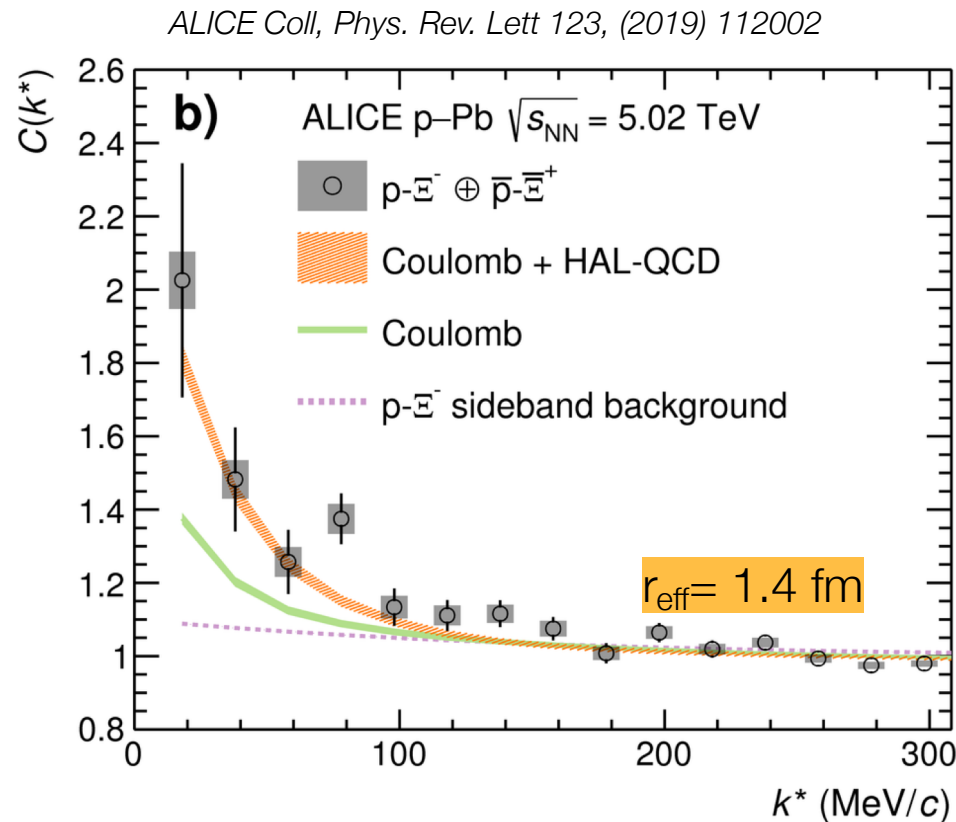
(**) ALICE Coll. *Phys. Lett. B* 797 (2019) 134822

(***) Hayakawa et al. *Phys. Rev. Lett.* 126, 062501 (2021)

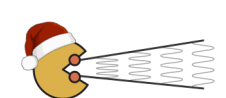


First measurements of the $p\text{-}\Xi^-$ interaction at LHC

- Observation of the strong interaction beyond Coulomb
- Agreement with lattice calculations confirmed in pp and p-Pb colliding systems
- **At finite density HAL QCD potentials predict in PNM a slightly repulsive $U_{\Xi} \sim +6 \text{ MeV}^{(*)} \rightarrow$ stiffening of the EoS**



(*) HAL QCD Coll., PoS INPC2016 (2016) 277



The projector method

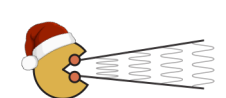
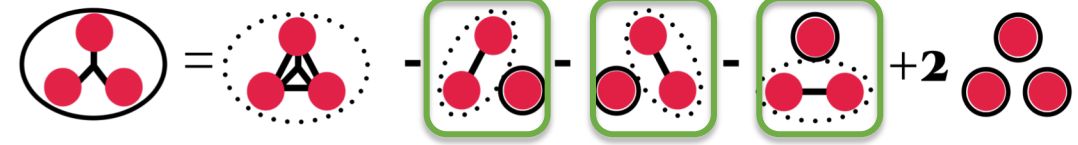
- Evaluate two-body contribution in three-body correlation function
 - With no genuine three-body correlation

$$C_3(Q_3) = C_3^{12}(Q_3) + C_3^{23}(Q_3) + C_3^{31}(Q_3) - 2$$

two-body CF projector

$$C_3^{ij}(Q_3) = \int C_2(k_1^{ij}) W^{ij}(k_1^{ij}, Q_3) dk_1^{ij}$$

$$Q_3 = \sqrt{q_{12}^2 + q_{22}^2 + q_{31}^2}$$



The projector method

- Evaluate two-body contribution in three-body correlation function
 - With no genuine three-body correlation

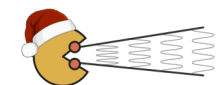
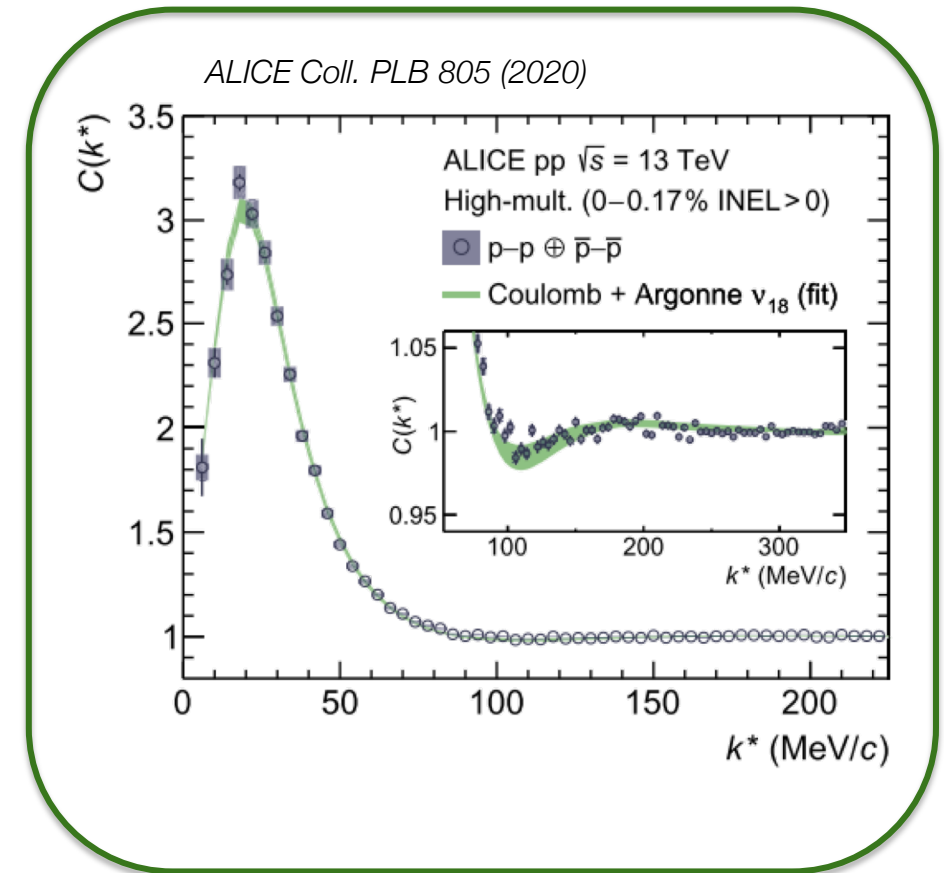
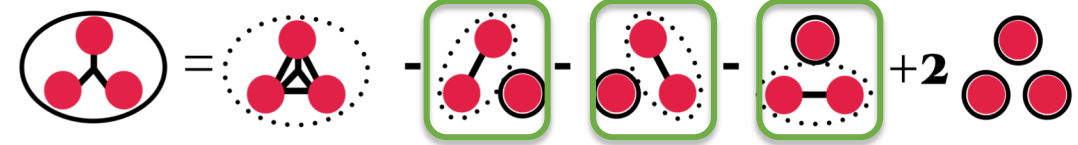
$$C_3(Q_3) = C_3^{12}(Q_3) + C_3^{23}(Q_3) + C_3^{31}(Q_3) - 2$$

two-body CF projector

$$C_3^{ij}(Q_3) = \int C_2(k_1^{ij}) W^{ij}(k_1^{ij}, Q_3) dk_1^{ij}$$

- Measured 2-body correlation functions
- same emitting source for 2-body and 3-body correlations

$$Q_3 = \sqrt{q_{12}^2 + q_{22}^2 + q_{31}^2}$$



The projector method

- Evaluate two-body contribution in three-body correlation function
 - With no genuine three-body correlation

$$C_3(Q_3) = C_3^{12}(Q_3) + C_3^{23}(Q_3) + C_3^{31}(Q_3) - 2$$

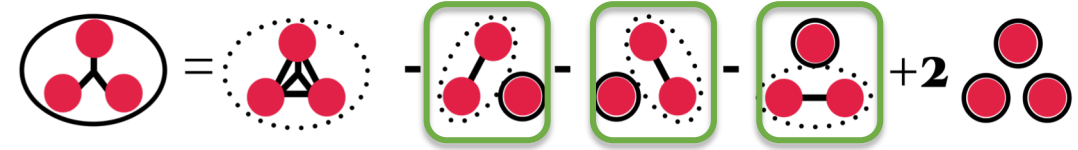
two-body CF
projector

$$C_3^{ij}(Q_3) = \int C_2(k_1^{ij}) W^{ij}(k_1^{ij}, Q_3) dk_1^{ij}$$

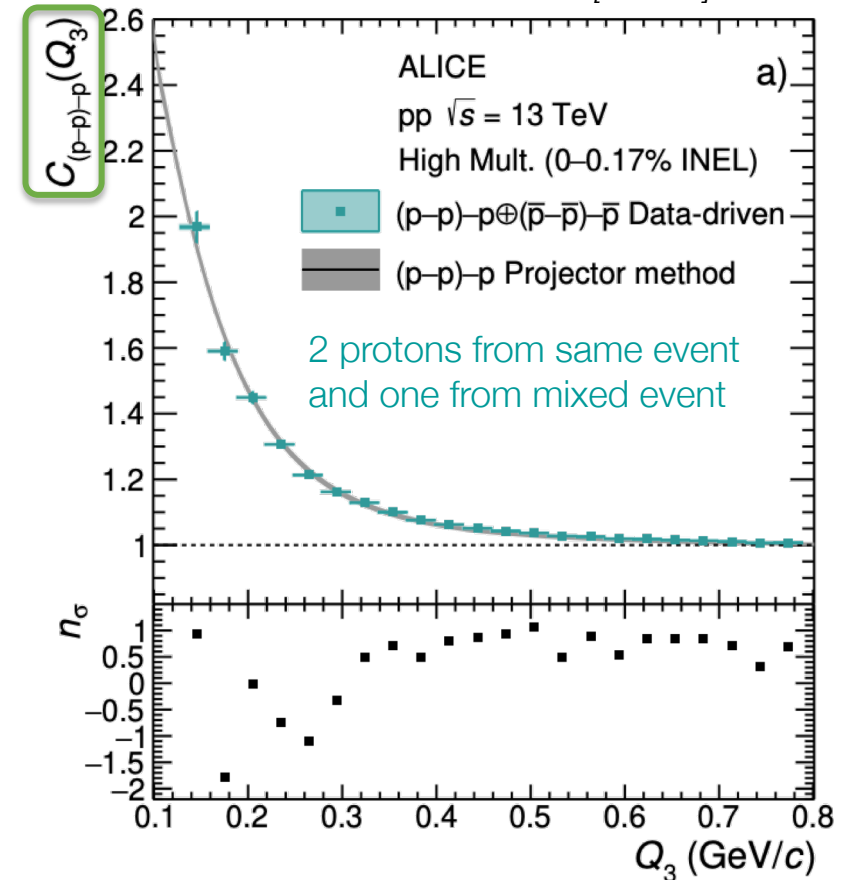
- Measured 2-body correlation functions
- same emitting source for 2-body and 3-body correlations
- Jacobian from 2-body to 3-body coordinates, integration on phase-space

- Subtract 2-body contributions with negligible uncertainties

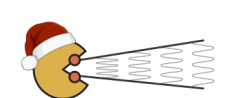
$$Q_3 = \sqrt{q_{12}^2 + q_{22}^2 + q_{31}^2}$$

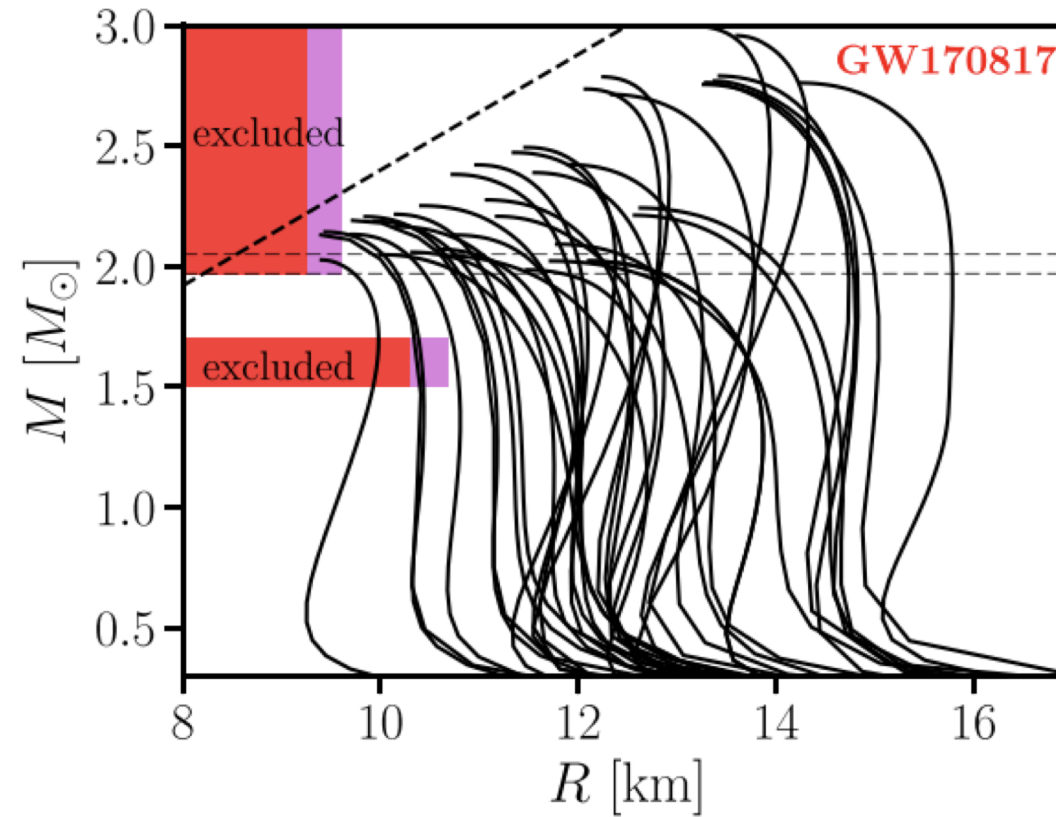


ALICE Coll. arXiv:2206.03344 [nucl-ex]

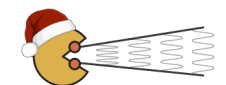


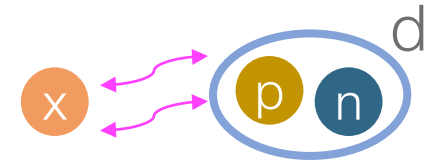
R. Del Grande, V.M.S. et al., EPJC 82 (2022)



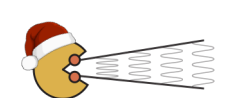
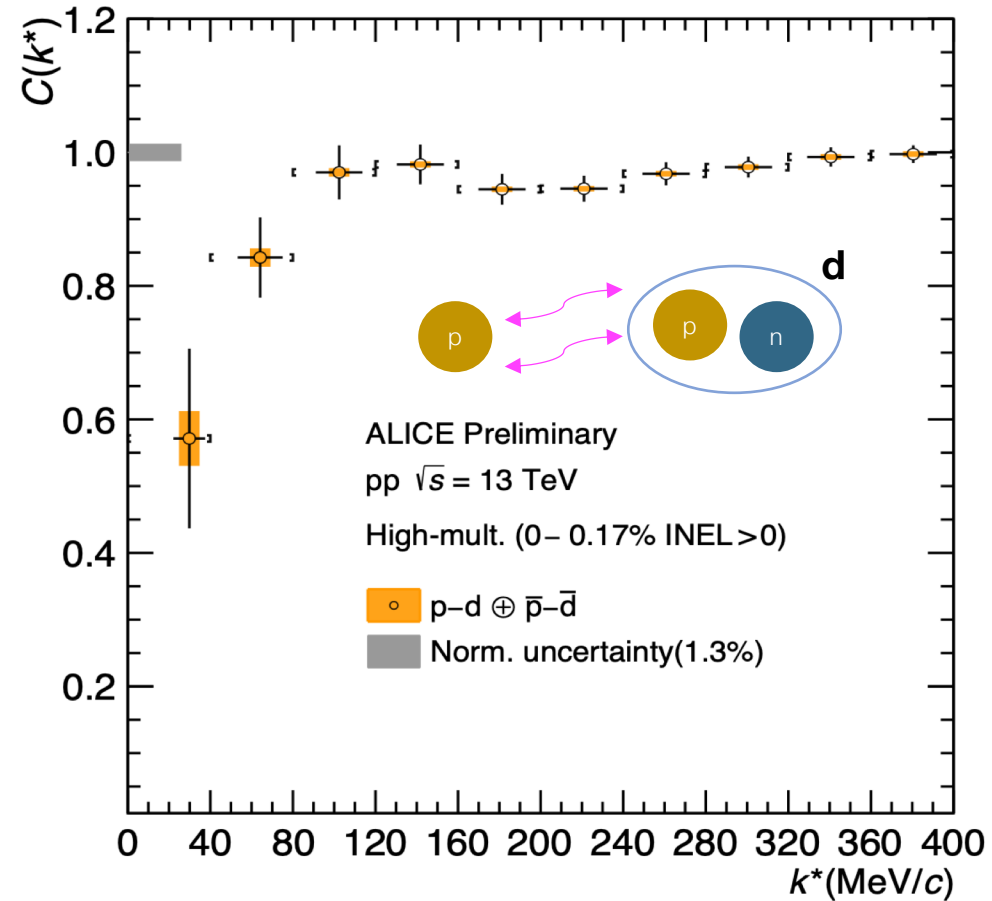
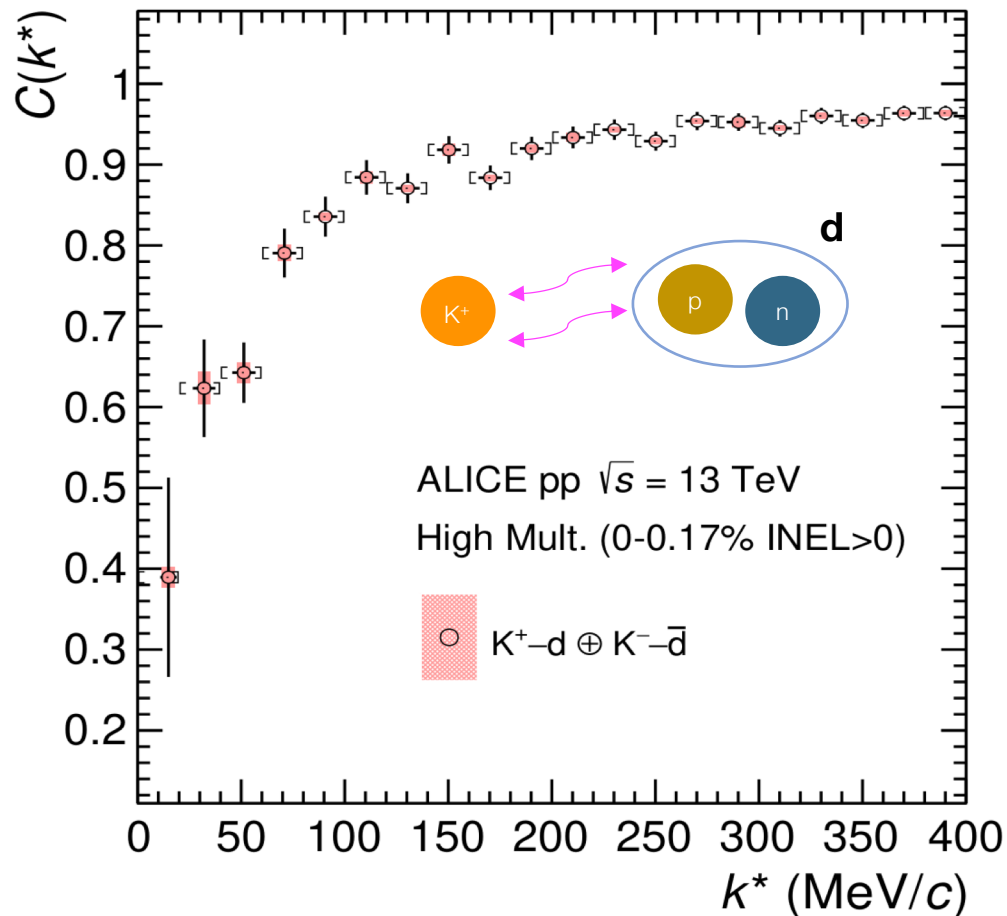


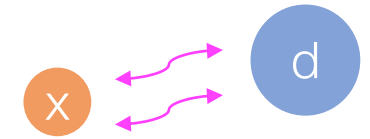
A. Bauswein, Annals of Physics 411 (2019) 167958





- Correlations between a hadron ($x = p, K^+$) and a composite object as deuteron





- Coulomb + strong interaction using the Lednický model

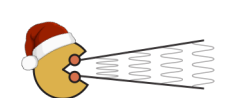
$$\psi(\vec{k}^*, \vec{r}^*) = e^{i\delta_c} \sqrt{A_c(\eta)} \left[e^{-i\vec{k}^* \cdot \vec{r}^*} F(-i\eta, 1, i\xi) + f_C(k^*) \frac{\tilde{G}(\rho, \eta)}{r^*} \right]$$

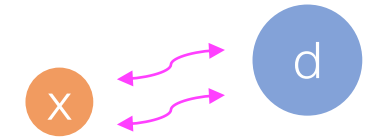
$$f_C(k^*) = \left(\frac{1}{f_0} + \frac{d_0 \cdot k^{*2}}{2} - \frac{2h(k^*)}{a_c} - ik^* A_C(k^*) \right)^{-1}$$

- Point-like particle models anchored to scattering experiments

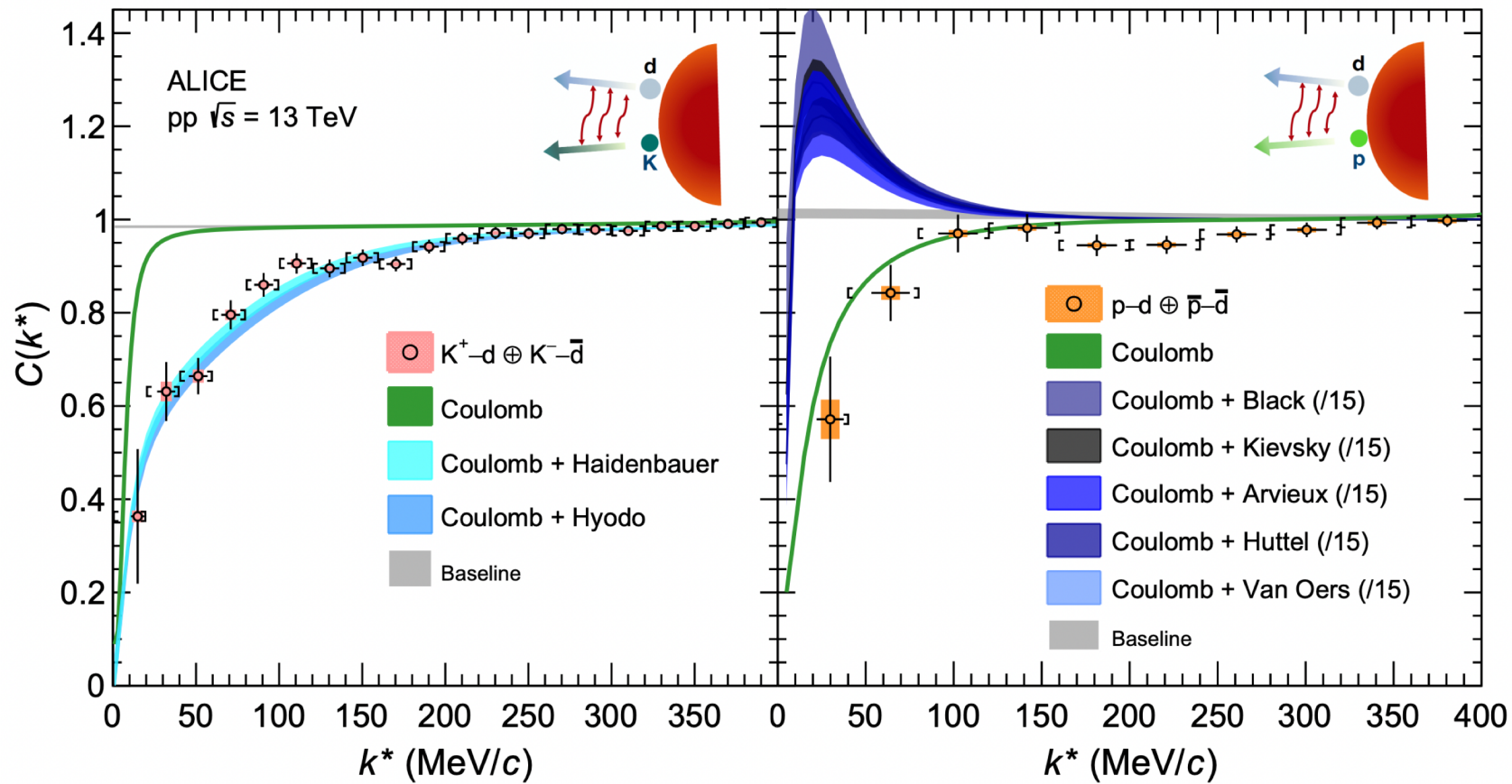
System	Spin averaged		S = 1/2		S = 3/2	
	f ₀ (fm)	d ₀ (fm)	f ₀ (fm)	d ₀ (fm)	f ₀ (fm)	d ₀ (fm)
p-d			-1.30 ^{+0.20} _{-0.20}	—	-11.40 ^{+1.20} _{-1.80}	2.05 ^{+0.25} _{-0.25}
			-2.73 ^{+0.10} _{-0.10}	2.27 ^{+0.12} _{-0.12}	-11.88 ^{+0.10} _{-0.40}	2.63 ^{+0.01} _{-0.02}
			-4.0	—	-11.1	—
			-0.024	—	-13.7	—
			0.13 ^{+0.04} _{-0.04}	—	-14.70 ^{+2.30} _{-2.30}	—
K ⁺ -d	-0.470	1.75				
	-0.540	0.0				

- Only s-wave interaction
- Source radius evaluated using the hadron-hadron universal m_T scaling

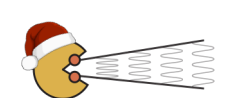




- Coulomb + strong interaction using the Lednický model



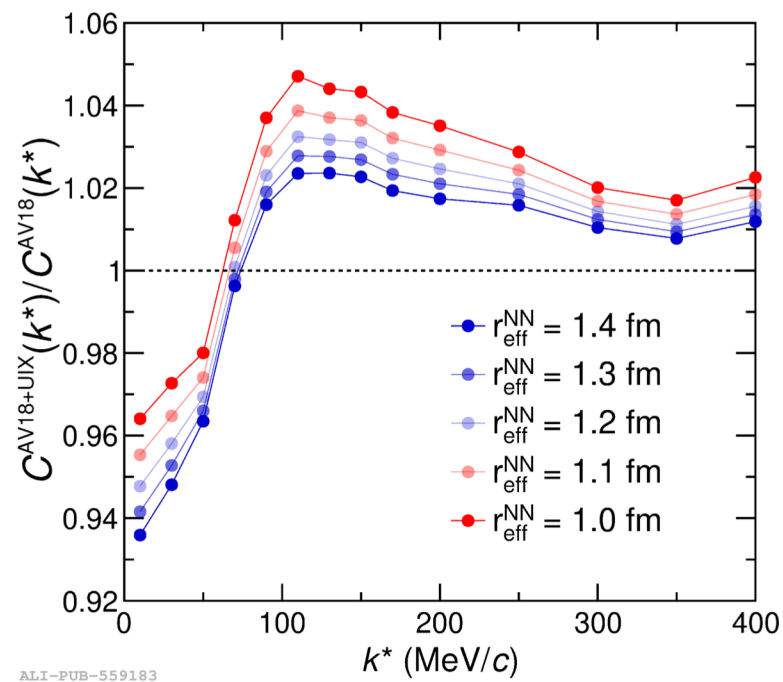
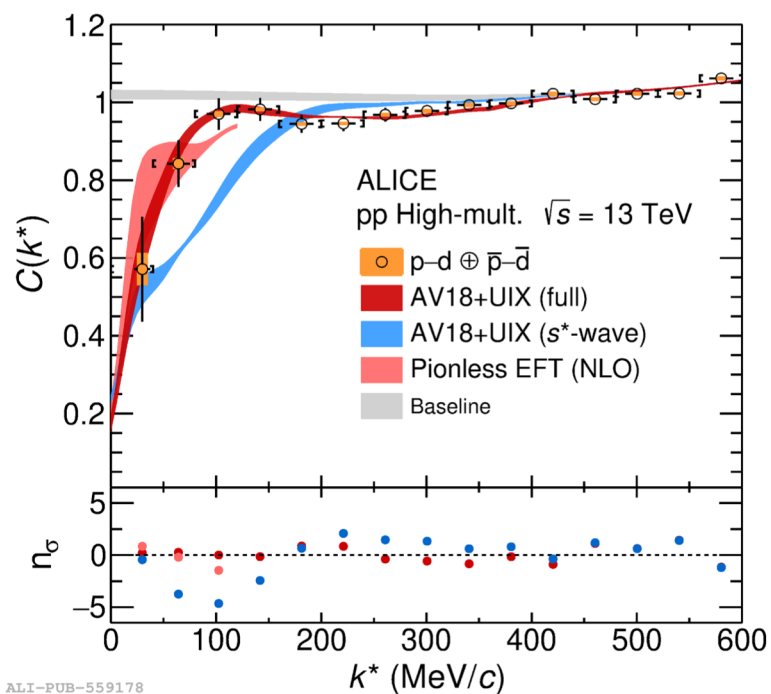
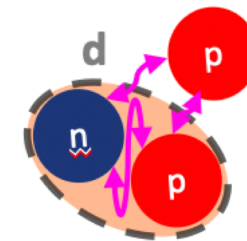
Point-like particle description doesn't work for p-d



Proton-deuteron correlation

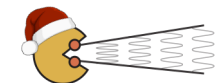
The measured p-d correlation function reflects the full three-nucleon dynamics:

- Coulomb + strong interaction (NN and NNN) + Quantum Statistics



Sensitivity to the short inter-particle distances

Hadron-nuclei correlations at the LHC can be used to study many-body dynamics



The source saga continues with Run 3 data

