p-Ξ and K-p femtoscopy in ALICE: going beyond scattering experiments

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35TH WINTER WORKSHOP ON NUCLEAR DYNAMICS (BEAVER CREEK, CL) – 10.01.2019

Outline

1. How do we learn about hadron-hadron interactions?
   - Scattering experiments: Kaon-Nucleon interaction
   - Hypernuclei: Hyperon-Nucleon interactions (focusing on Ξ hypernuclei)
2. Basics of Femtoscopy in small colliding systems in ALICE
3. Two selected results:
   - Results for **p-Ξ^- correlation function** in p-Pb 5.02 TeV ⇒first evidence of **strong attractive potential**
   - Results for **K^--p correlation function** in pp 5,7,13 TeV ⇒high precision data close to threshold and first evidence of the **opening of the isospin breaking channel K^0-n**

Why we are interested in hadron-hadron interactions?

- **Hadron-hadron interactions** are the pillars to understand

1. **Behaviour of nuclear matter under extreme conditions** (high T and/or densities)
   ⇒ Equation of State (EoS) for Neutron Stars (NSs)
2. **Existence of states beyond the standard quark model**
   ⇒ molecular states, di-baryons, pentaquarks…

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     ⇒ molecular states, di-baryons, pentaquarks…

- Two examples to show the importance of a better understanding of hadron-hadron interactions:

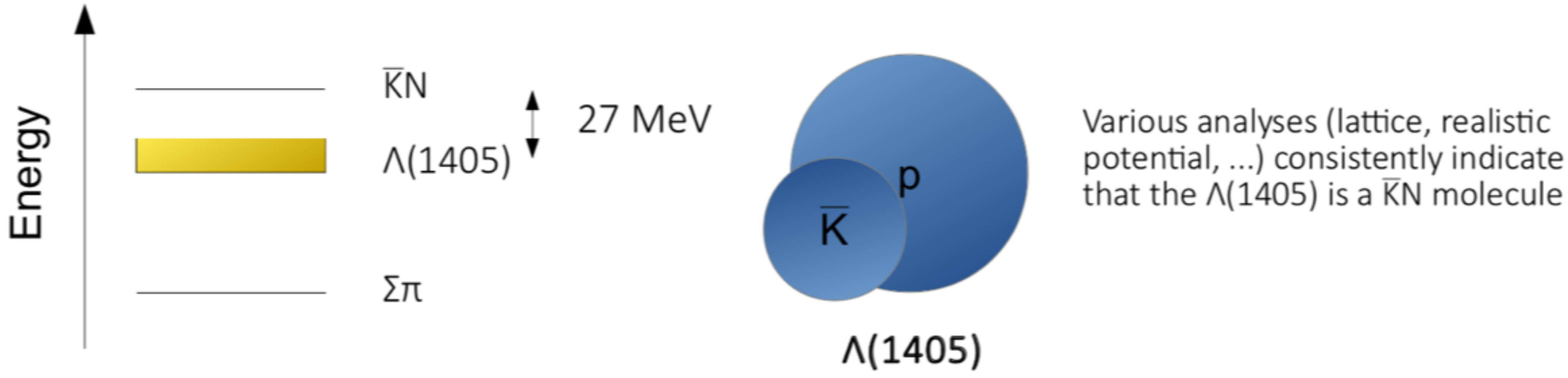
  1. **Multistrange hyperon-nucleon interactions (ΞN)** ⇒ the attractive/repulsive nature of the interaction drastically affects the EoS for NSs
     - No scattering data, only 1 hypernucleus observed so far
  2. Molecular state as **Λ(1405)** emerging from the **strongly attractive $\bar{K}$N interaction**
     - Kaonic atom data at threshold + old and imprecise scattering data above threshold

So far Hadron-Hadron interactions have been studied through Scattering Experiments and Hypernuclei…..

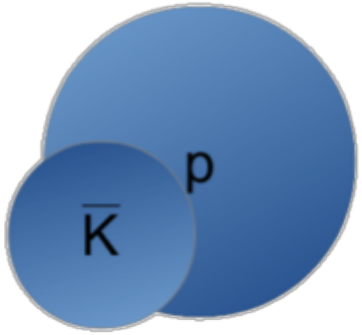
Kaon-Nucleon interaction: a gate to low energy QCD

1. Kaons are the lightest particles with strangeness content
   - interaction with protons and neutrons at very low energy is fundamental to constrain the low energy QCD sector
   - $\bar{K}N$ potential is **attractive** while KN is **repulsive**

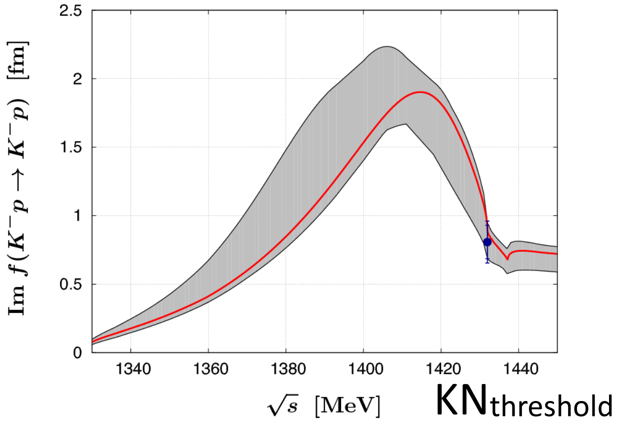
2. Λ(1405) is the ONLY state commonly considered as a meson-baryon molecule

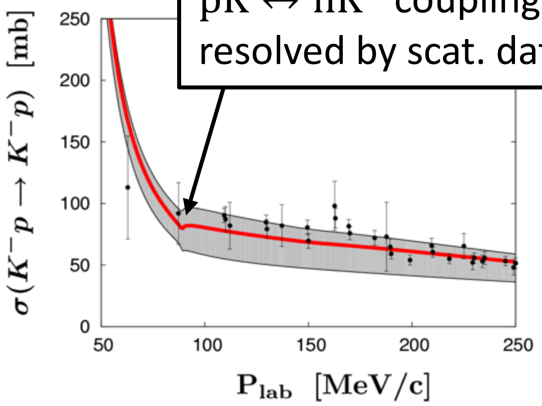


Kaon-Nucleon interaction: scattering experiments



$\Lambda(1405)$





Note that the effect of $p\bar{K} \leftrightarrow n\bar{K}^0$ coupling is not resolved by scat. data

$p_{lab} = 0$

Y. Ikeda et al Nucl.Phys. A881 (2012) 98-114

kaonic atoms

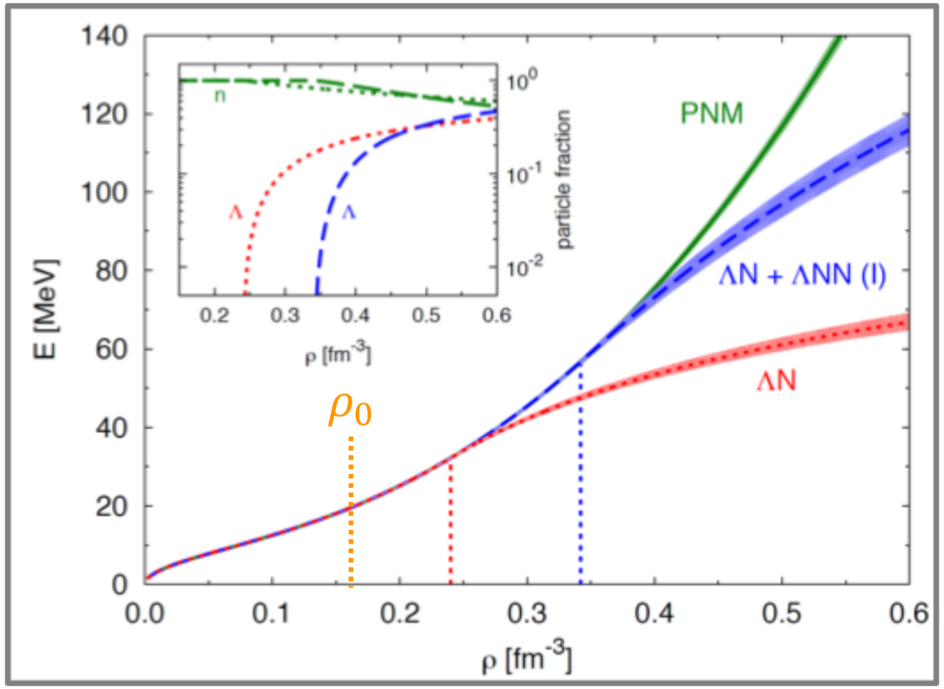
Siddharta er al. Phys.Lett. B704 (2011)

Scattering data

G.S. Abrams *et al.* Phys.Rev. 139 (1965) B454-B457

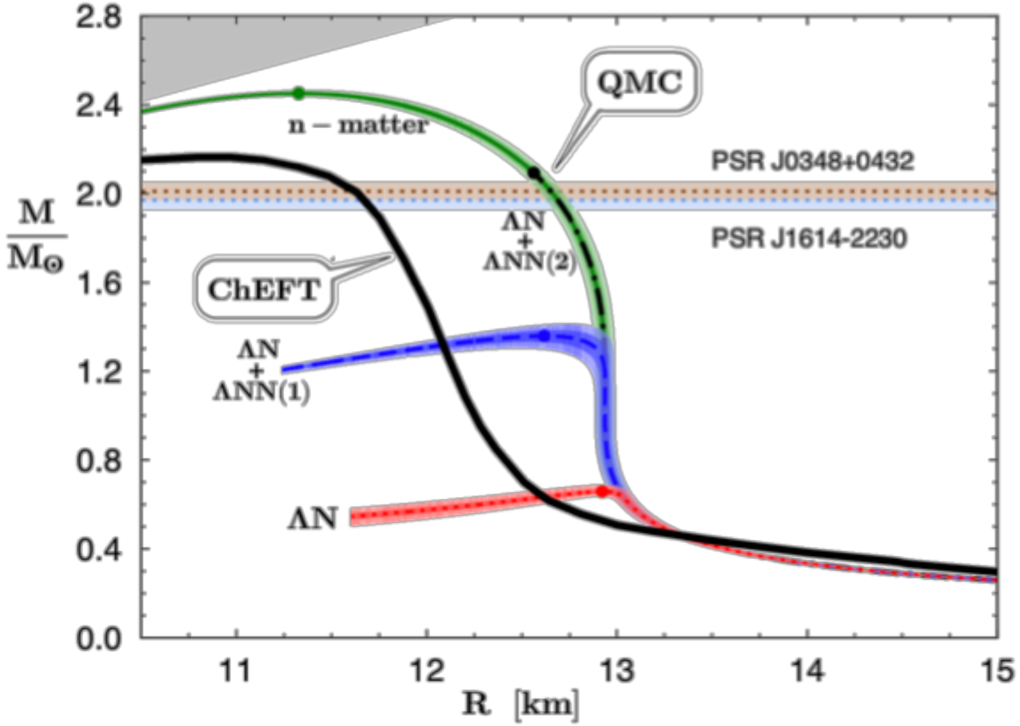
Hyperon-Nucleon interactions in Neutron Stars

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



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

- The appearance of Hyperons **softens** the EoS
- **Maximum NS masses get smaller**



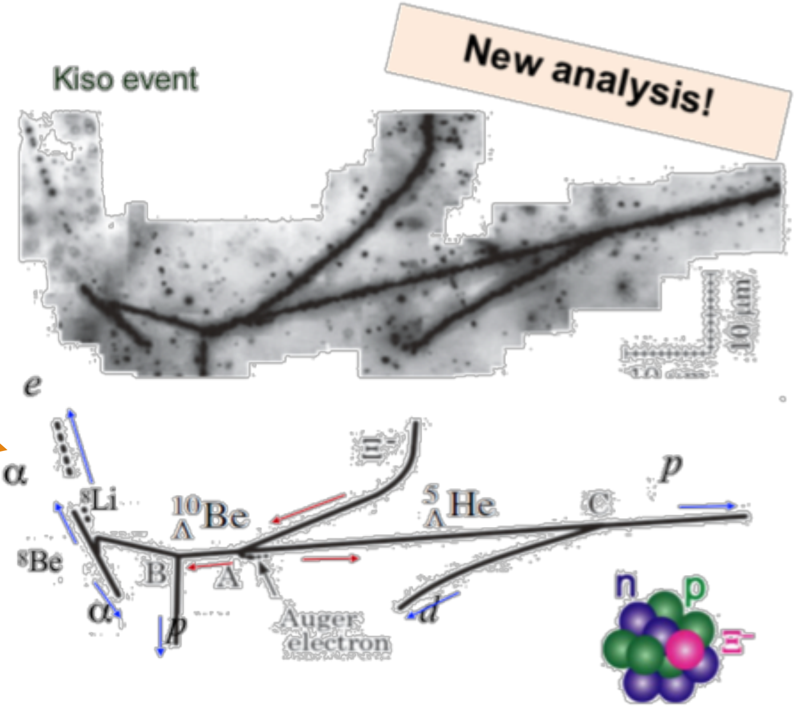
D. Lonardoni, A. Lovato, S. Gandolfi, F. Pederiva Phys. Rev. Lett. 114, 092301 (2015)

ChEFT Calculations from: T. Hell, W.W. PRC90 (2014) 045801

Ξ-Nucleon interaction : hypernuclei data

- **HYPERNUCLEI DATA:**
  - **Λ hypernuclei** data: $B_{\Lambda\,\mathrm{nucleus}} = 30$ MeV
  - **Ξ hypernuclei** data show **shallow attractive** interaction [Kiso Evt]
  - **ΛΛ hypernuclei** exist as well showing **weakly attraction** [Nagara Evt]
  - **Σ hypernuclei:** only ${}^{4}_{\Sigma}$He observed, ongoing at JPARC-E13 Coll.

Courtesy H. Tamura, Bormio Winter Meeting 2018



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

The first clear Ξ hypernucleus

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

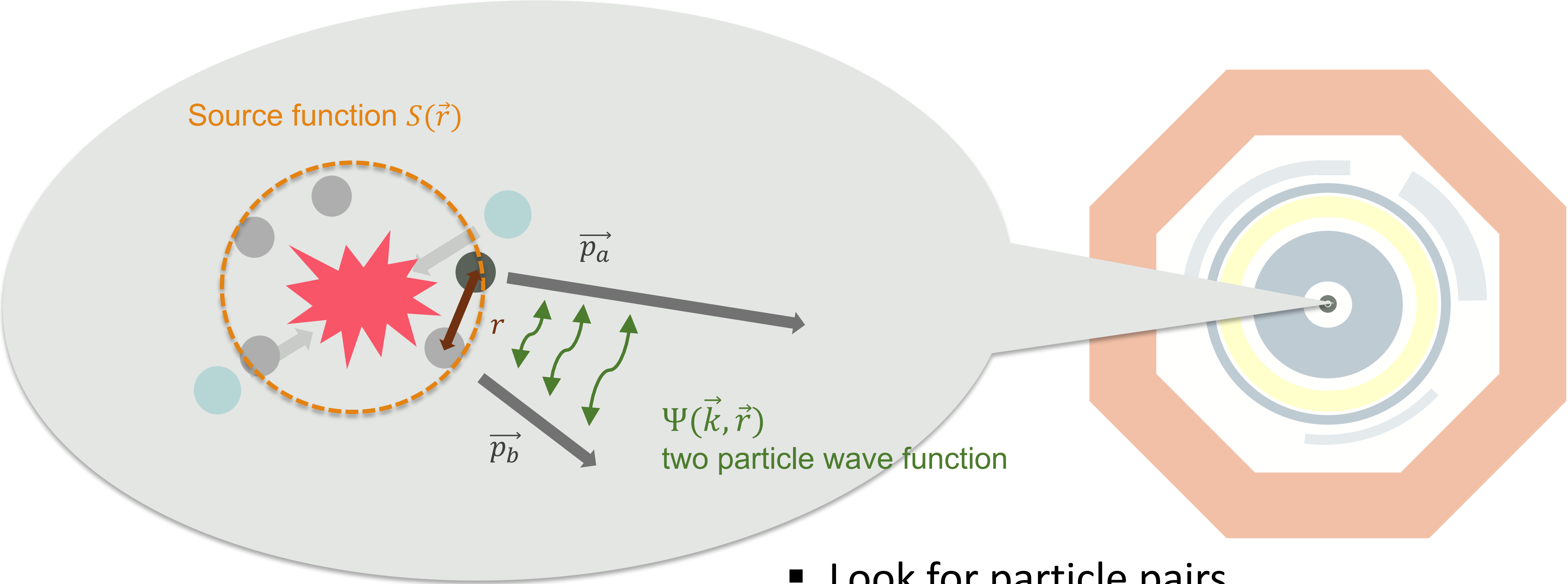
K. Nakazawa *et al.* PTEP 2015, 033D02

Take home message

- Hadron-Hadron interactions are fundamental to constrain:
  - Behavior of nuclear matter at large densities ⇒ EoS of NSs
  - Existence of states beyond the standard quark model
- Two striking examples:
  - Kaon - Nucleon ⇒ more precise data needed above threshold ⇒ $\Lambda(1405)$, low energy QCD models
  - Ξ – Nucleon ⇒ only one hypernuclei event, data in vacuum needed ⇒ hyperon puzzle in NSs
- Scattering experiments cannot be applied to multi-strange hyperons and cannot access the low-momentum range, hypernuclei experiments are often based on single events
- What is the next step?
  Femtoscopy

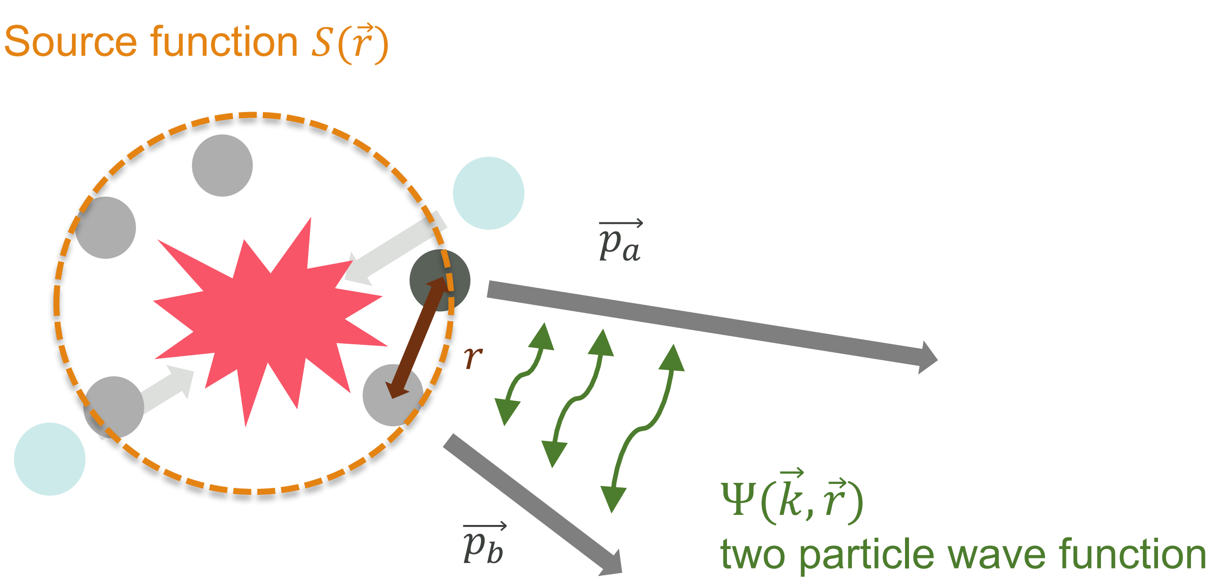
BASICS OF FEMTOSCOPY

Basics of Femtoscopy



- Look for particle pairs
- Measure the relative momentum k distribution in your experimental set up
- Search for correlations

Key observable: the correlation function



Statistical definition ***Experimental definition*** ***Theoretical definition***

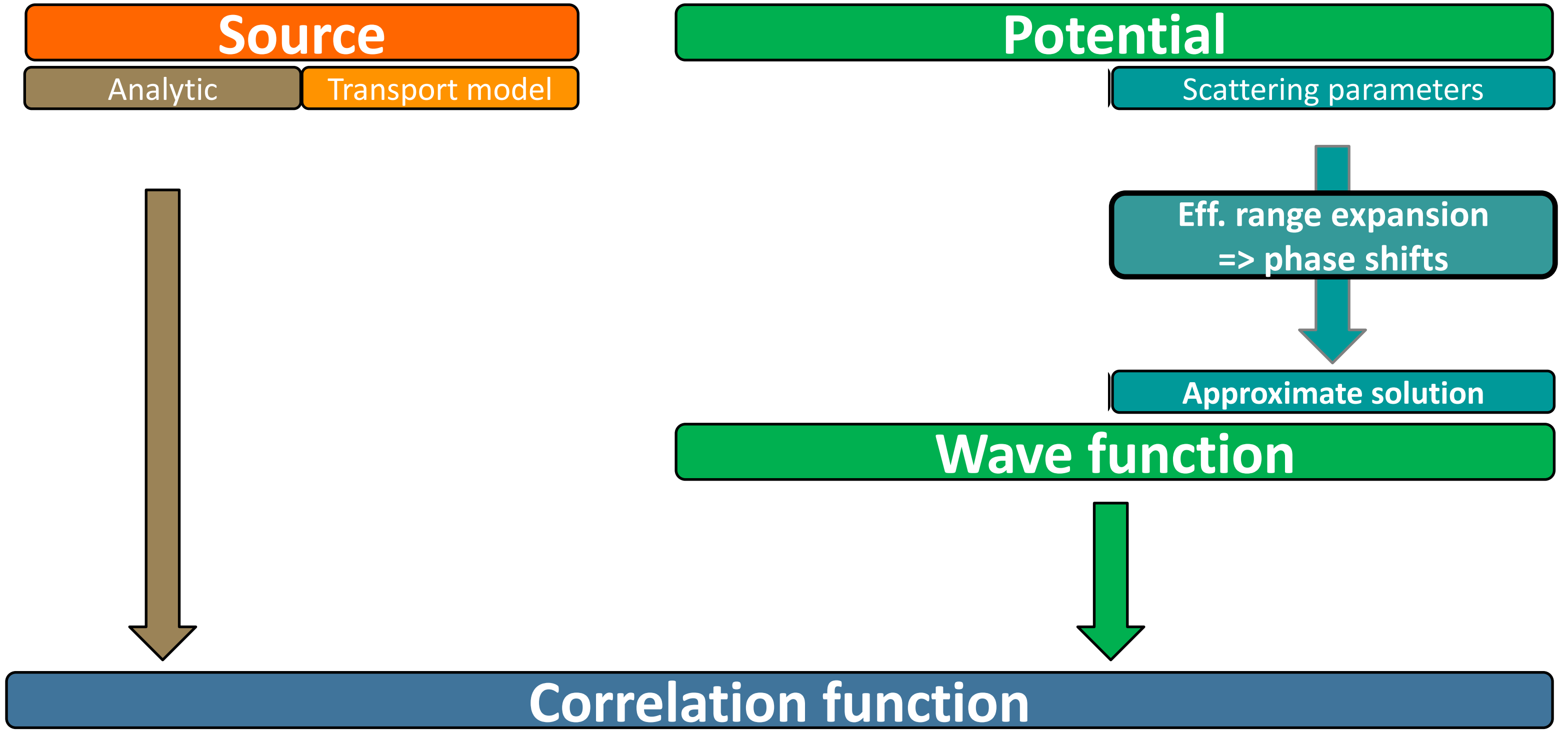
$$C(k) = \frac{\mathcal{P}(\vec{p}_a,\vec{p}_b)}{\mathcal{P}(\vec{p}_a)\mathcal{P}(\vec{p}_b)} = \mathcal{N}\frac{N_{\mathrm{Same}}(k)}{N_{\mathrm{Mixed}}(k)} = \int S(\vec{r})\left|\Psi(\vec{k},\vec{r})\right|^2 \mathrm{d}^3\vec{r} \xrightarrow{k\to\infty} 1$$

Single-particle momenta

Relative distance / reduced momentum in the rest frame of the pair

Lisa, Pratt, Wiedemann,Solz, Ann.Rev.Nucl.Part.Sci. 55 (2005) 357-402

Lednicky Model

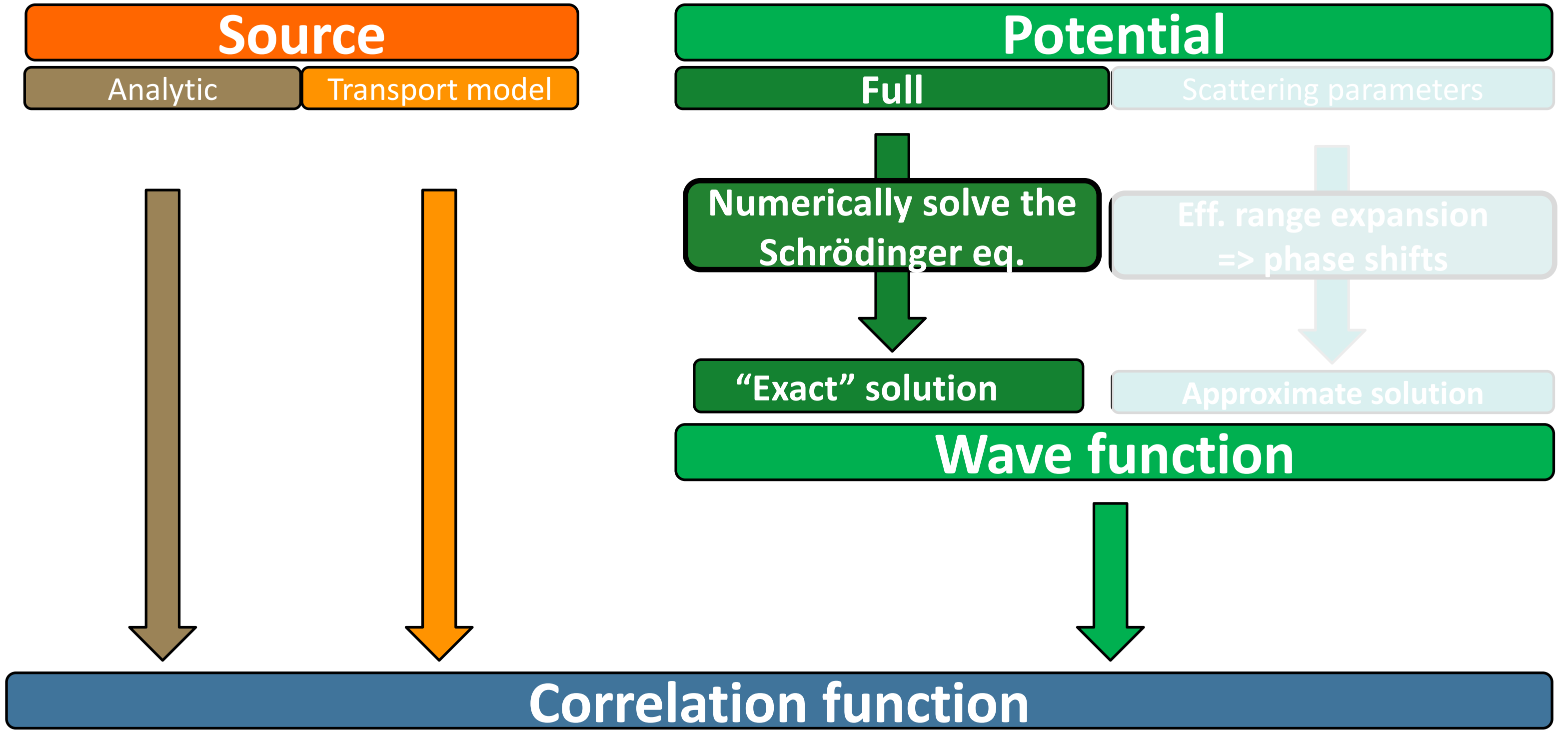


$$C(k) = 1+\sum_S \rho_S \left[\frac{1}{2} \left| \frac{f^S(k)}{R_G^{\Lambda p}} \right|^2 \left(1 - \frac{d_0^S}{2\sqrt{\pi} R_G^{\Lambda p}} \right) + 2 \frac{\mathcal{R} f^S(k)}{\sqrt{\pi} R_G^{\Lambda p}} F_1(Q R_G^{\Lambda p}) - \frac{\mathcal{I} f^S(k)}{R_G^{\Lambda p}} F_2(Q R_G^{\Lambda p}) \right]$$

Depends on scattering parameters, might locally break down for small sources

R. Lednicky and V. L. Lyuboshits, Sov. J. Nucl. Phys. **35**, 770 (1982), [Yad. Fiz.35,1316(1981)].

CATS – Correlation Analysis Tool Using the Schrödinger Equation

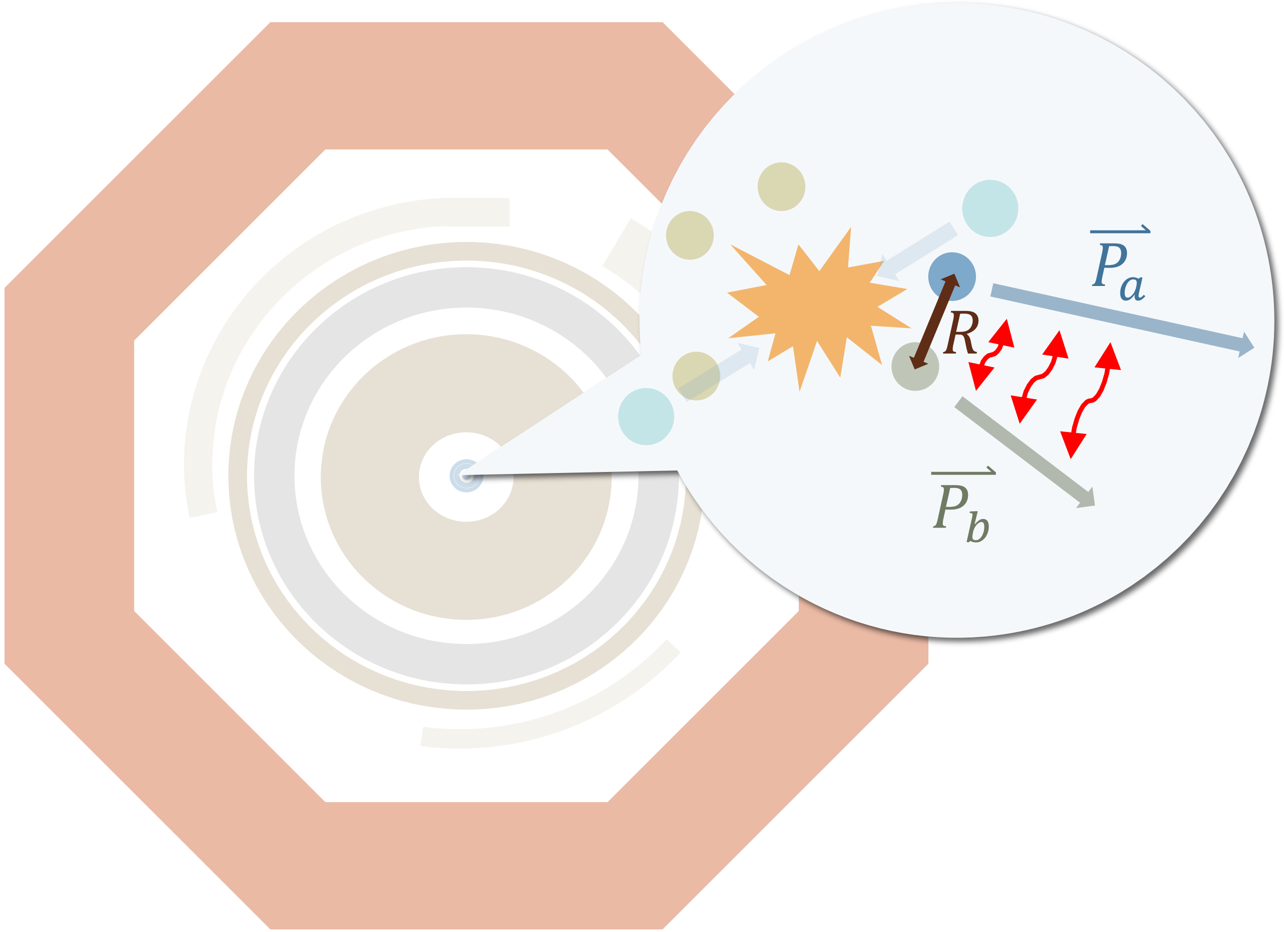


$$C(k) = \int S(\vec{r},k)\,|\psi(\vec{r},k)|^2\, d\vec{r} \xrightarrow{k\to\infty} 1$$

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

RESULTS

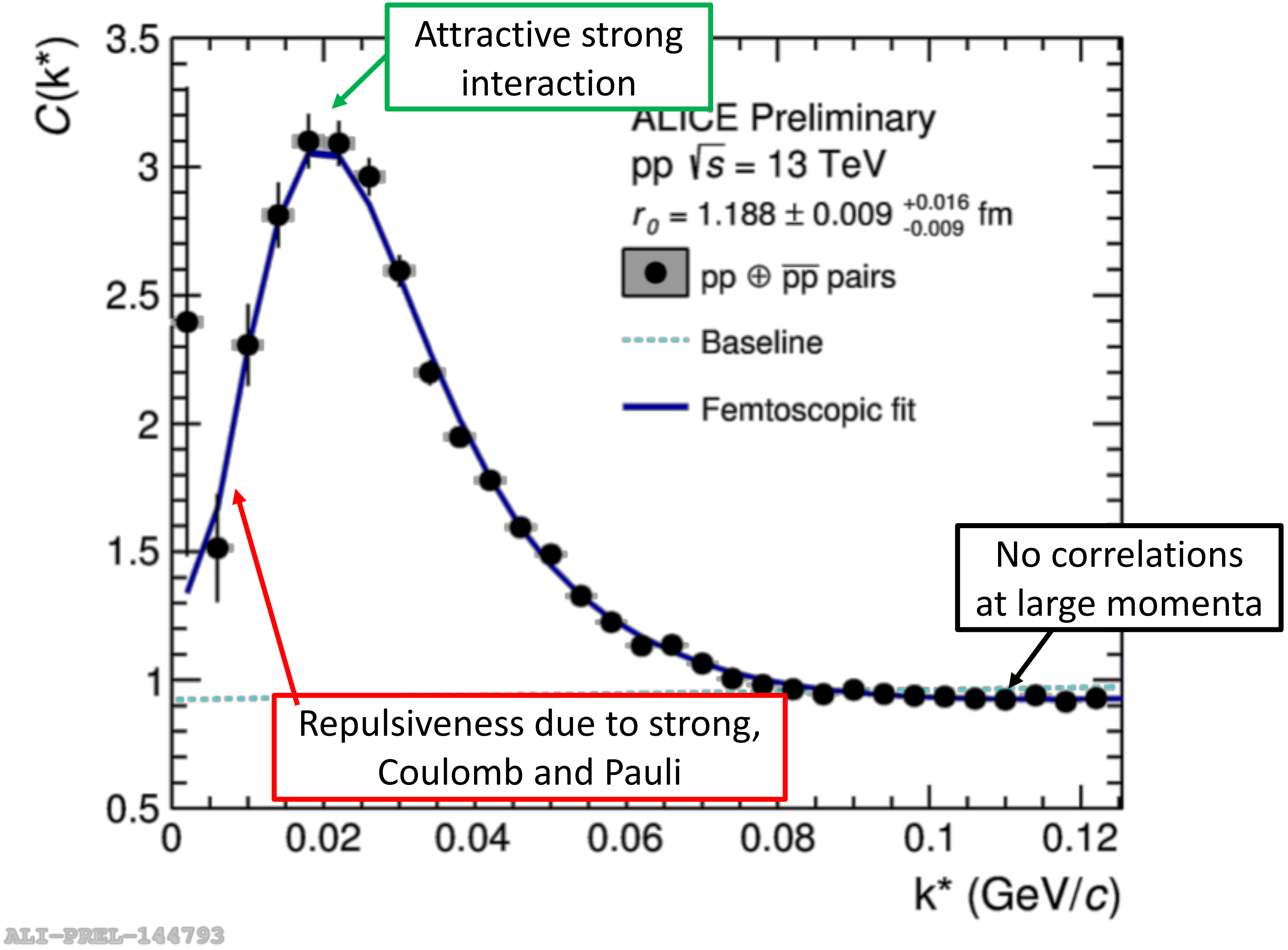
The ALICE data sets



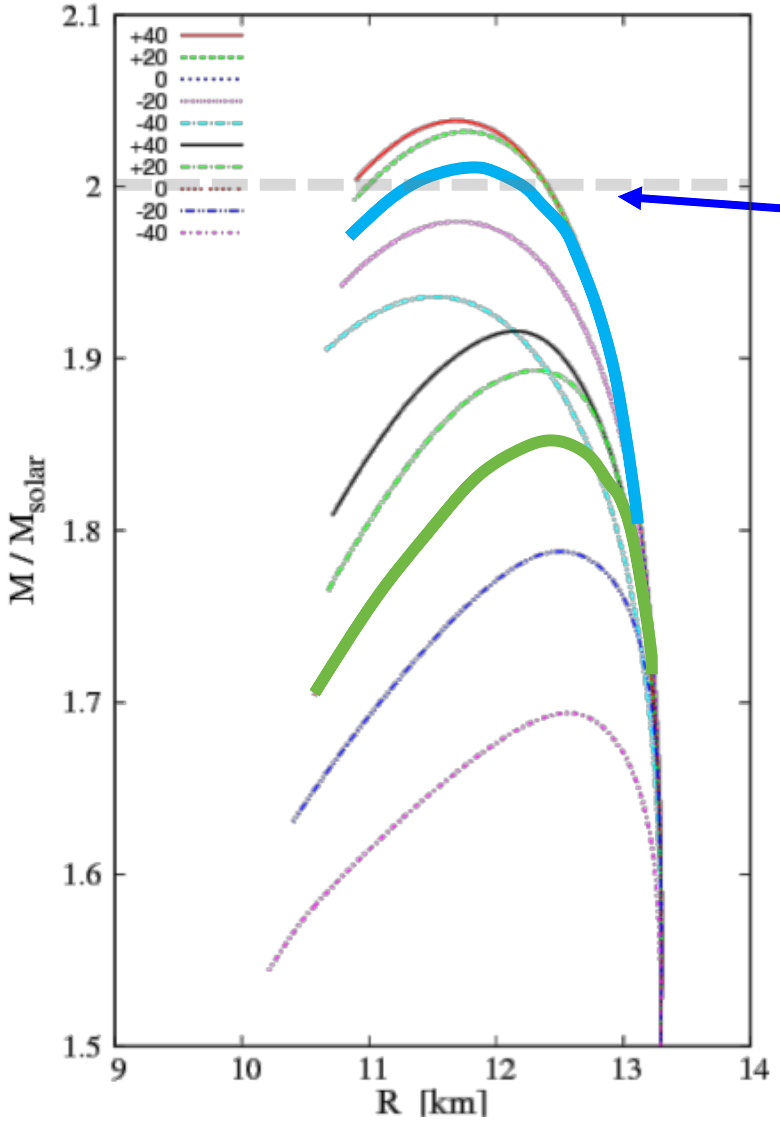
- We measure **p-p**, **p-Λ**, **Λ-Λ**, **p-Ξ, K-p correlations**
- Proton identification with TPC and TOF
- Reconstruction of hyperons
  - $\Lambda \rightarrow p\pi^-$ (BR ~ 64%)
  - $\Xi^- \rightarrow \Lambda\pi^-$ (BR ~ 100%)
- Datasets:
  - **pp 13 TeV:** **$10 \cdot 10^8$ Events**
  - **p-Pb 5.02 TeV:** **$6.0 \cdot 10^8$ Events**
- Assumption of a **common Gaussian source**
  - **Constrained from p-p**
  - **Infer on p-Λ, p-Ξ**, Λ–Λ and **K-p interactions**

Correlation function and Interactions

$$C(k^*) \longrightarrow \begin{cases} > 1 \text{ attraction} \\ = 1 \text{ no interaction} \\ < 1 \text{ repulsion} \end{cases}$$



p-Ξ⁻ interaction and Neutron Stars

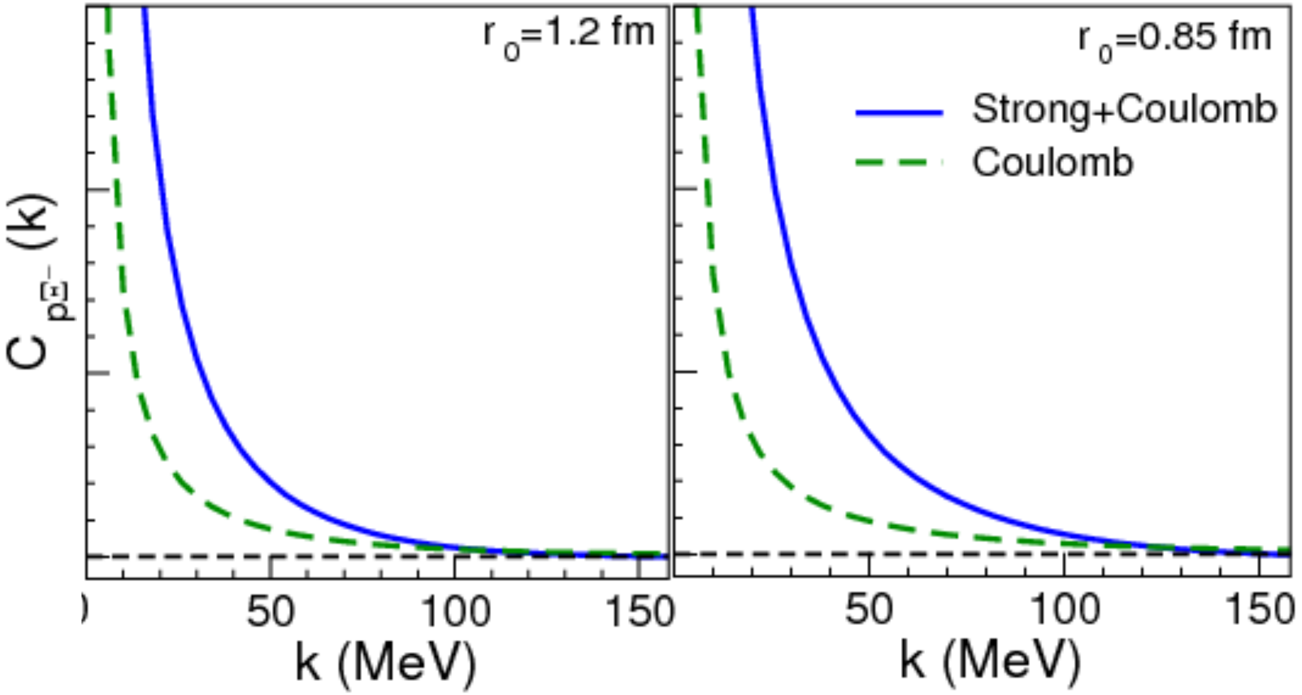


Weissborn et al., NPA881 (2012) 62-77

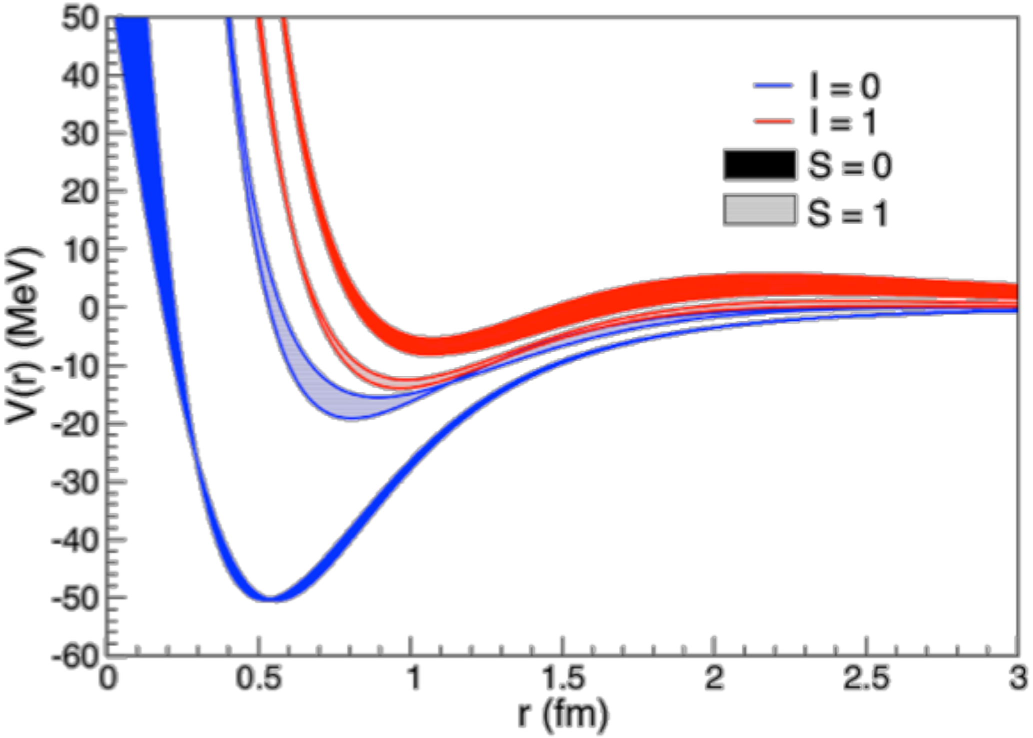
- Single-hyperon potential fundamental ingredient in EoS for NSs
- **Repulsive interaction⇒Production of Ξ⁻ pushed to higher densities ⇒ stiffer EoS, higher masses**
- A complication: in the case of neutron stars only the n-Ξ interaction is important, but for us neutrons are not detectable
- Experimentally challenging to isolate the I=1 channel

	I=0	I=1	Detectable
n-Ξ⁻	X	✓	No
p-Ξ⁰	X	✓	Difficult
p-Ξ⁻	✓	✓	Yes

Theoretical p-Ξ^- Correlation function



D.L.Mihaylov, V.M.S, O.W.Arnold, L.Fabbietti, B.Hohlweger, A.M.Mathis, Eur.Phys.J. C78 (2018) no.5,394



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

- Comparison **Coulomb-only/Coulomb+Strong**
- Strong potential from preliminary calculations from HAL-QCD collaboration

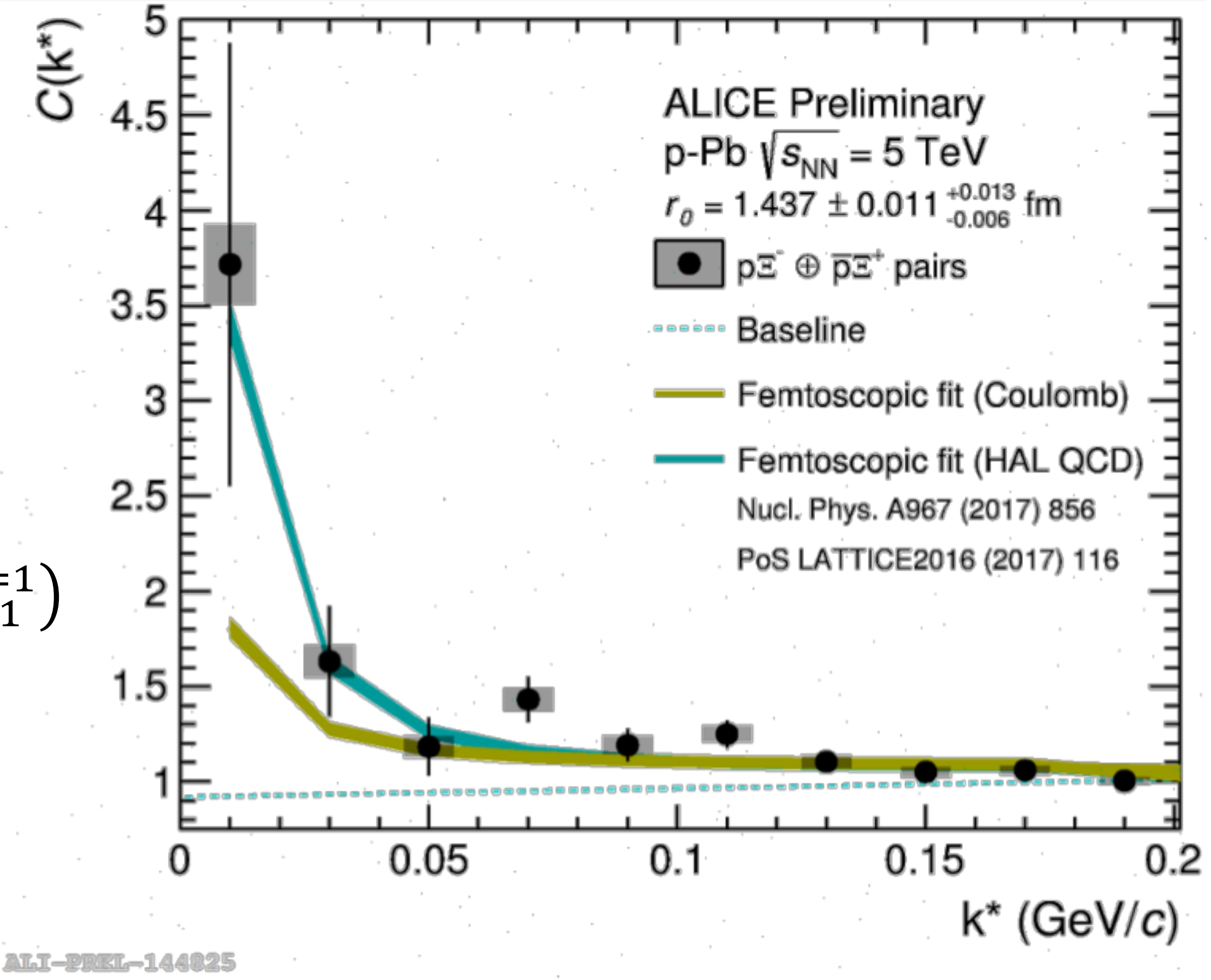
$$C(k^*) = \frac{1}{8}\left(C_{I=0}^{S=0} + C_{I=1}^{S=0}\right) + \frac{3}{8}\left(C_{I=0}^{S=1} + C_{I=1}^{S=1}\right)$$

p-Ξ⁻ Correlation Function in p-Pb 5.02 TeV

- **First observation of strong attractive interaction in p-Ξ⁻**
- modeled with preliminary QCD strong potential by the HAL QCD collaboration
  Potential from Hatsuda et al., NPA967 (2017) 856, PoS Lattice2016 (2017) 116

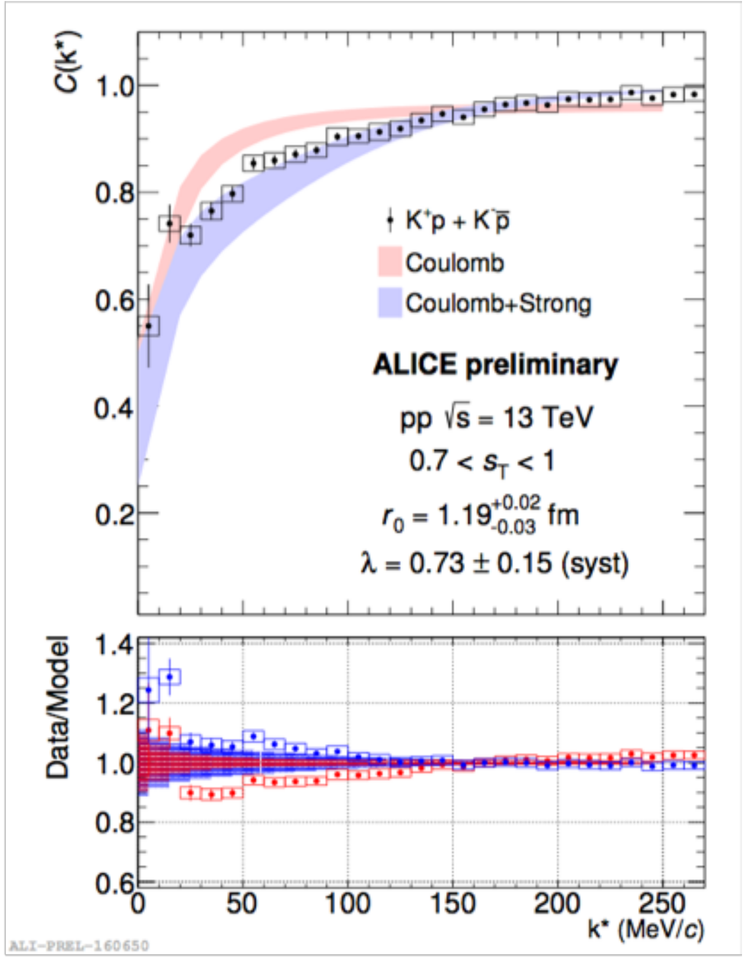
$$C(k^*) = \frac{1}{8}\left(C_{I=0}^{S=0} + C_{I=1}^{S=0}\right) + \frac{3}{8}\left(C_{I=0}^{S=1} + C_{I=1}^{S=1}\right)$$

COULOMB-ONLY HYPOTHESIS EXCLUDED AROUND 3σ



K-p and $\overline{K}$-p correlations

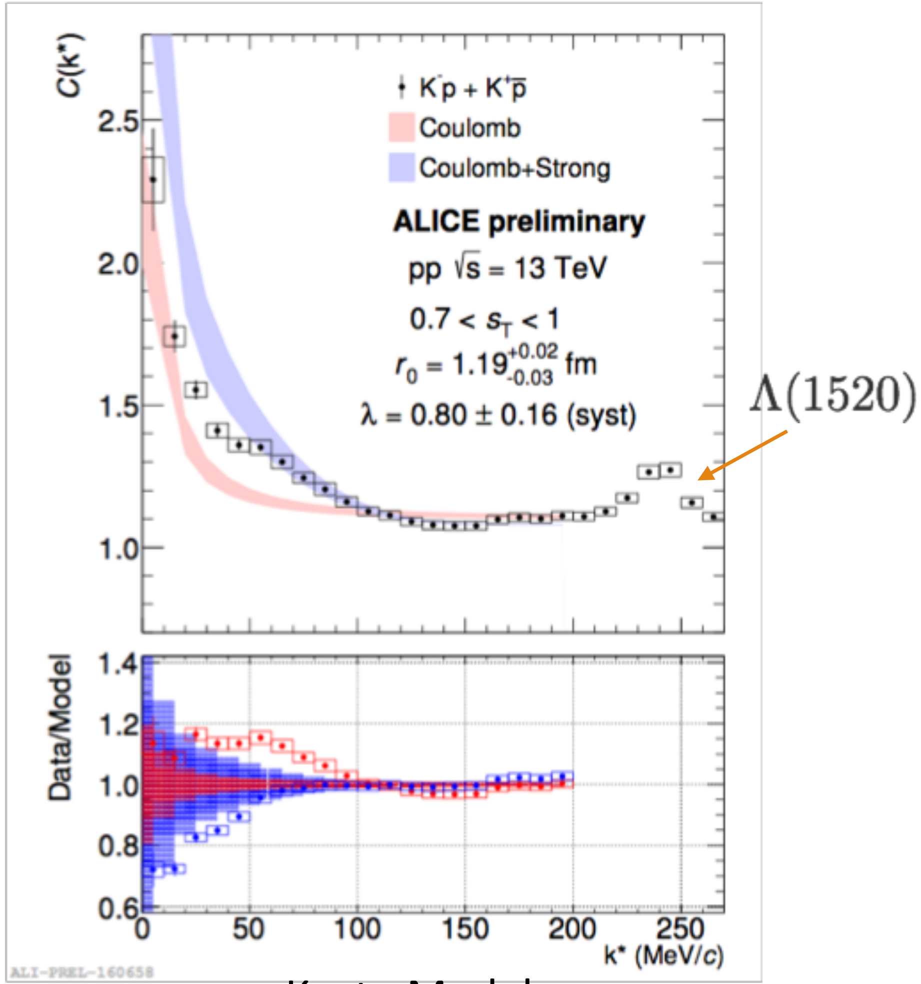
K^+- p: Repulsive Strong Interaction



Jülich Model

(Haidenbauer et al., Phys.Rev. C66 (2002) 055214)

K^- - p: Attractive Strong Interaction

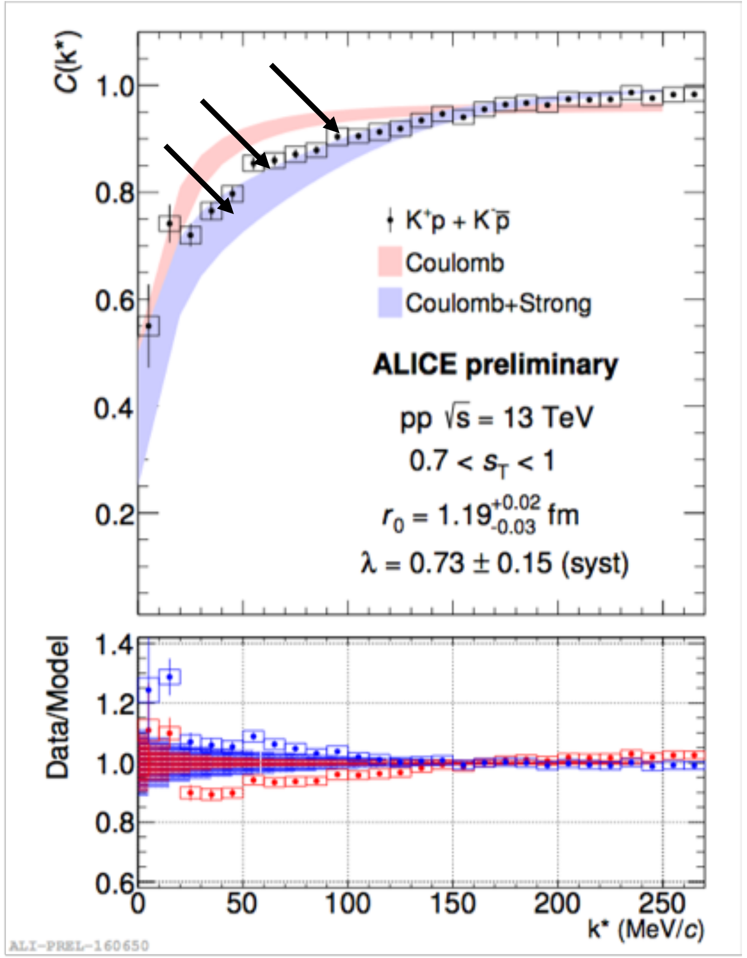


Kyoto Model

(Hyodo et al., Phys.Rev. C95 (2017) no.6,065202)

K-p and $\overline{K}$-p correlations

K^+- p: Repulsive Strong Interaction



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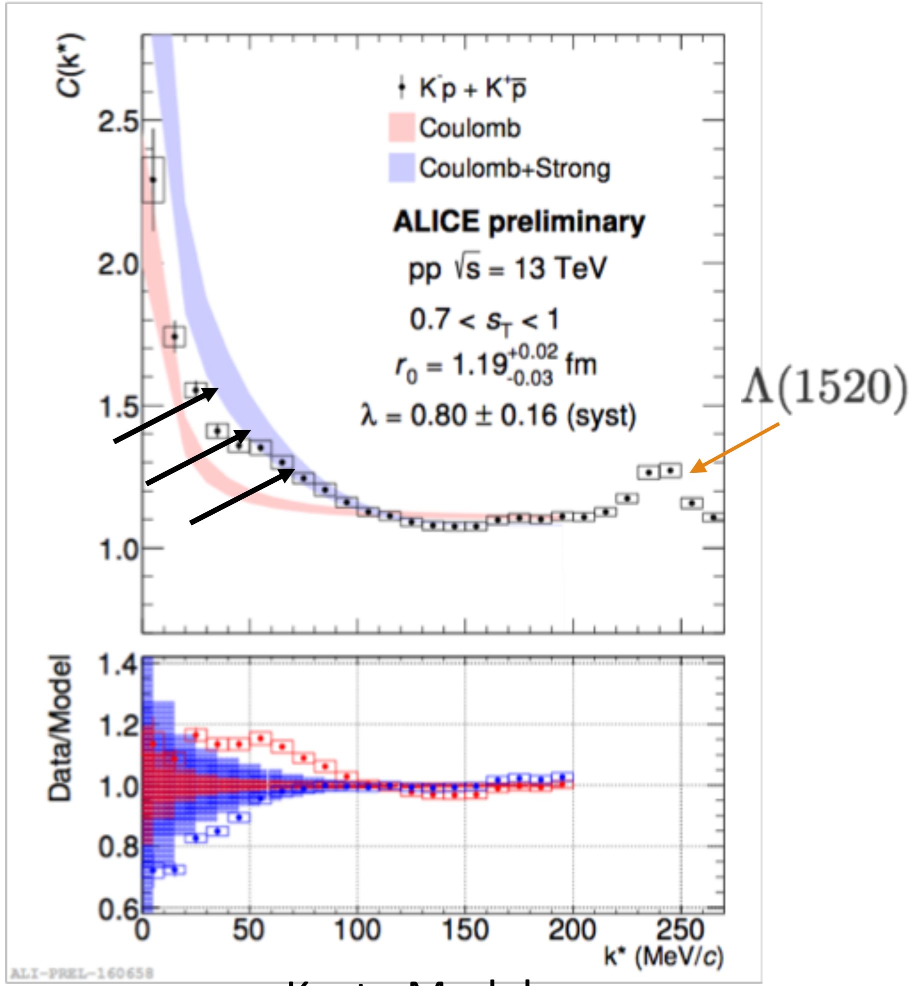
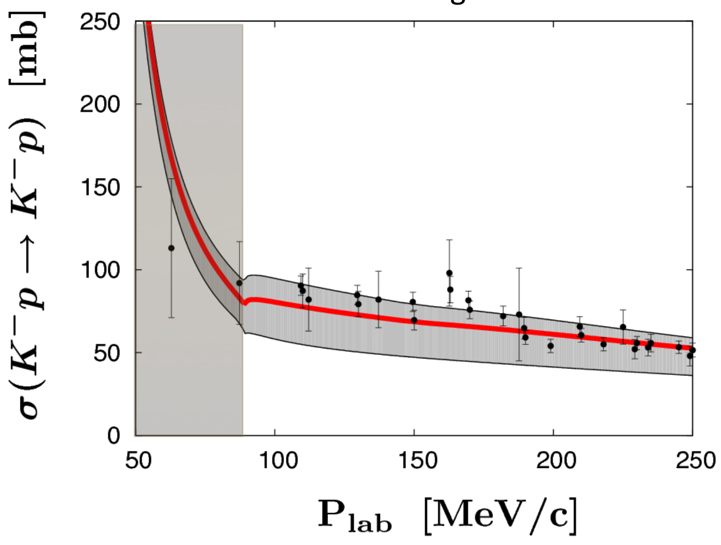


Kyoto Model

(Hyodo et al., Phys.Rev. C95 (2017) no.6,065202)

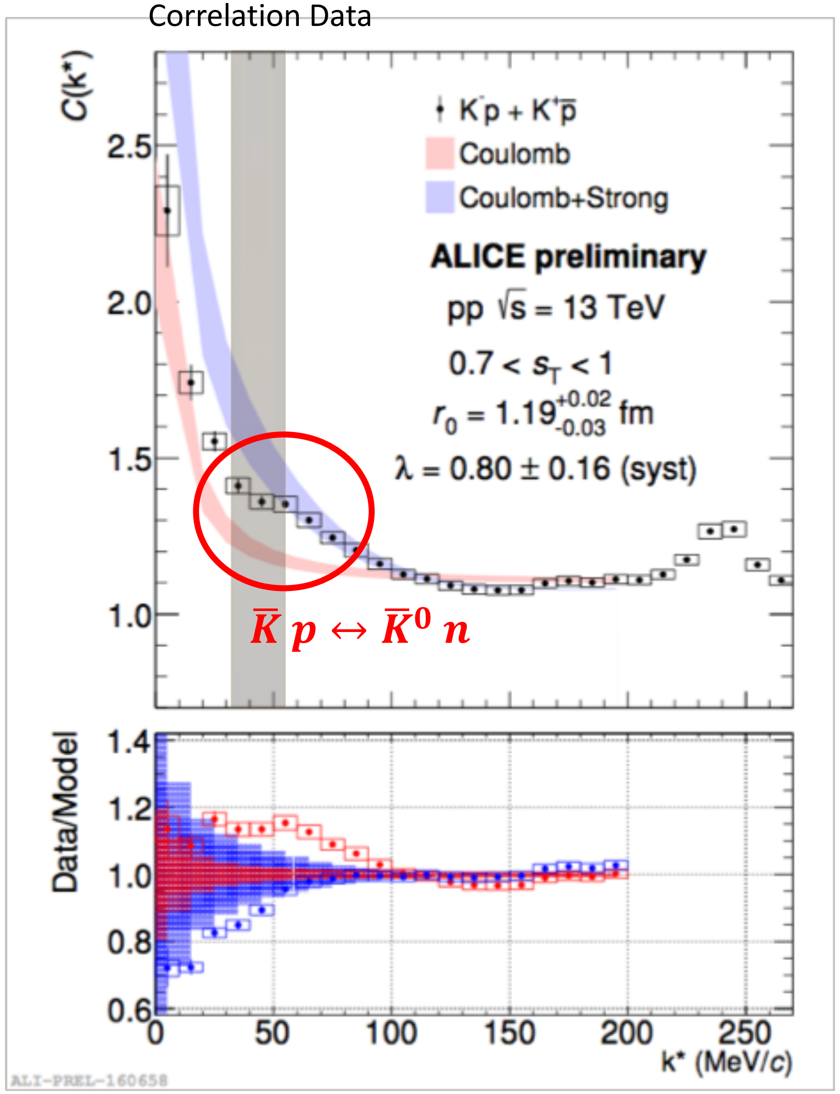
$\bar{K}$-p correlations

Scattering Data



G.S. Abrams *et al.* Phys.Rev. 139 (1965) B454-B457

Correlation Data



- Clear effect of the opening of the isospin breaking channel $\bar{K}^0 N$

$$\bar{K}^0 N \to K^- p$$

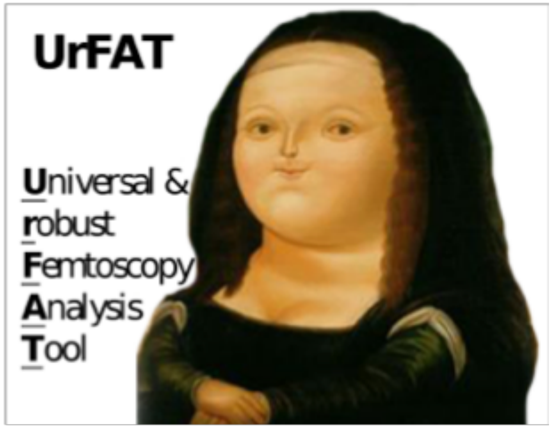
- **Unprecedented constraints for low energy QCD**

Summary and Outlook:

- **Femtoscopy** is an excellent tool to study **interactions of particle pairs**
  - Significant sensitivity to the interaction potentials
  - Access to the multistrange hyperons sector
  - Access to low momenta region with unprecedented high precision
- Observation of **attractive p-Ξ^- interaction for the first time** ⇒ set constraints on the average potential of Ξ hyperons at finite density for NS EoS
- In the meson-baryon sector ⇒ **First experimental observation of the $\bar{K}^0 N$ isospin** breaking opening channel ⇒ constraints close to threshold for low energy QCD models
- Extending the study to **more hyperon-nucleon pairs** (p-Ω, p-Σ^0) and in the future to **three-body interactions**
- **Looking forward to RUN3**!

In the future

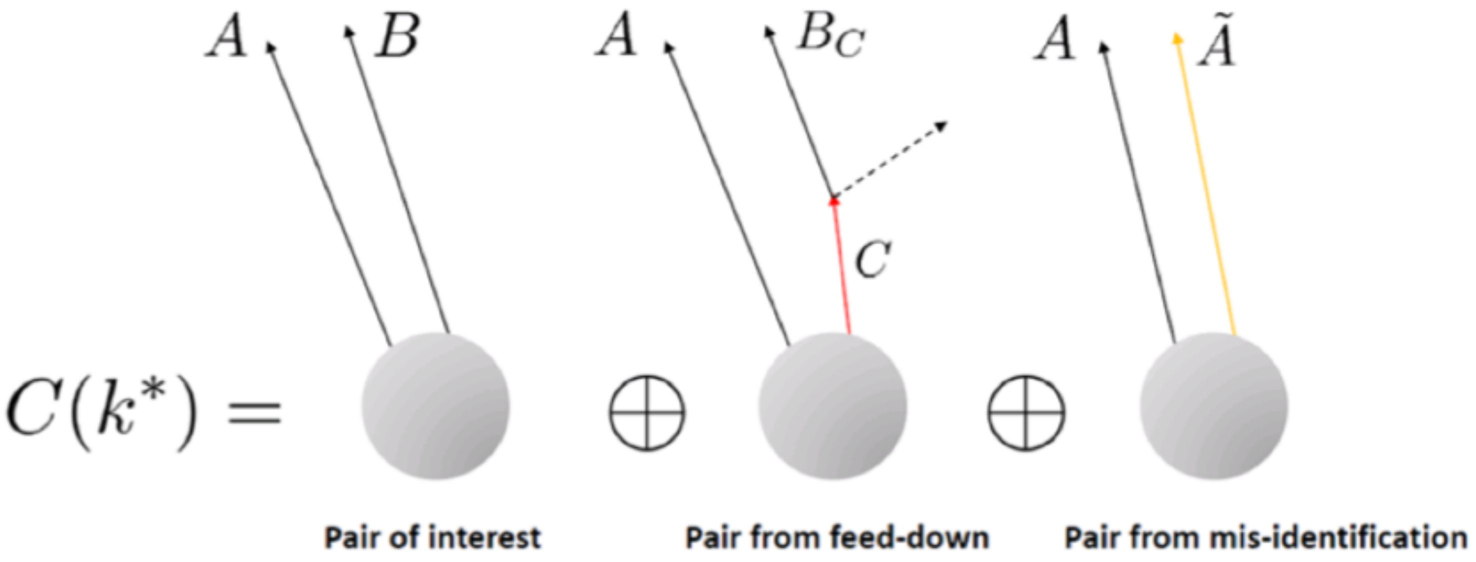
- You name the pair, we measure it:
  - Work in progress at the moment: baryon-antibaryon, p-Ω, p-Σ^0 K-d,….
- Universal and Robust Femto Analysis Tool
  - Fit the correlation function of various systems simultaneously in combination with CATS
- Development of a formalism to study three particle correlations ⇒ three-body forces including hyperons



Backup Slides

The experimental correlation function

$$C(\overrightarrow{p_a},\overrightarrow{p_b}) = \frac{P(\overrightarrow{p_a},\overrightarrow{p_b})}{P(\overrightarrow{p_a})P(\overrightarrow{p_b})} = \mathcal{N}\frac{N_{SE}(k)}{N_{ME}(k)}$$



Decomposition of the p-p correlation function

$$\{pp\} = pp + p_\Lambda p + p_\Lambda + p_\Lambda + p_{\Sigma^+} p + p_{\Sigma^+} p_{\Sigma^+} + p_\Lambda p_{\Sigma^+} + \tilde{p}p + \tilde{p}p_\Lambda + \tilde{p}p_{\Sigma^+} + \tilde{p}\tilde{p},$$

- Purity from MC (Pythia 8)
- Feed-down fractions from MC template fits to the DCA_{xy} distribution

Pair	p–p λ [%]
pp	75.19
$p_\Lambda p$	15.06
$p_\Lambda p_\Lambda$	0.75
$p_{\Sigma^+} p$	6.46
$p_{\Sigma^+} p_{\Sigma^+}$	0.14
$p_\Lambda p_{\Sigma^+}$	0.65
$\tilde{p}p$	1.52
$\tilde{p}p_\Lambda$	0.15
$\tilde{p}p_{\Sigma^+}$	0.07
$\tilde{p}\tilde{p}$	0.01

Decomposition of the p-Λ correlation function

$$\{p\Lambda\} = p\Lambda + p\Lambda_{\Xi^-} + p\Lambda_{\Xi^0} + p\Lambda_{\Sigma^0} + p_\Lambda\Lambda + p_\Lambda\Lambda_{\Xi^-} + p_\Lambda\Lambda_{\Xi^0} + p_\Lambda\Lambda_{\Sigma^0} + p_{\Sigma^+}\Lambda + p_{\Sigma^+}\Lambda_{\Xi^-} + p_{\Sigma^+}\Lambda_{\Xi^0} + p_{\Sigma^+}\Lambda_{\Sigma^0} + \tilde{p}\Lambda + \tilde{p}\Lambda_{\Xi^-} + \tilde{p}\Lambda_{\Xi^0} + \tilde{p}\Lambda_{\Sigma^0} + p\tilde{\Lambda} + p_\Lambda\tilde{\Lambda} + p_{\Sigma^+}\tilde{\Lambda} + \tilde{p}\tilde{\Lambda}.$$

- Purity from fits to the invariant mass distribution
- Feed-down fractions from MC template fits to the cosα distribution

p–Λ Pair	λ [%]	p–Λ Pair	λ [%]
$p\Lambda$	52.42	$\tilde{p}\Lambda$	0.53
$p\Lambda_{\Xi^-}$	6.94	$\tilde{p}\Lambda_{\Xi^-}$	0.07
$p\Lambda_{\Xi^0}$	6.94	$\tilde{p}\Lambda_{\Xi^0}$	0.07
$p\Lambda_{\Sigma^0}$	17.47	$\tilde{p}\Lambda_{\Sigma^0}$	0.18
$p_\Lambda\Lambda$	5.25	$p\tilde{\Lambda}$	2.95
$p_\Lambda\Lambda_{\Xi^-}$	0.69	$p_\Lambda\tilde{\Lambda}$	0.30
$p_\Lambda\Lambda_{\Xi^0}$	0.69	$p_{\Sigma^+}\tilde{\Lambda}$	0.13
$p_\Lambda\Lambda_{\Sigma^0}$	1.75	$\tilde{p}\tilde{\Lambda}$	0.03
$p_{\Sigma^+}\Lambda$	2.25		
$p_{\Sigma^+}\Lambda_{\Xi^-}$	0.30		
$p_{\Sigma^+}\Lambda_{\Xi^0}$	0.30		
$p_{\Sigma^+}\Lambda_{\Sigma^0}$	0.75		

Decomposition of the Λ-Λ correlation function

$$\{\Lambda\Lambda\} = \Lambda\Lambda + \Lambda\Lambda_{\Sigma^0} + \Lambda_{\Sigma^0}\Lambda_{\Sigma^0} + \Lambda\Lambda_{\Xi^0} + \Lambda_{\Xi^0}\Lambda_{\Xi^0} + \Lambda\Lambda_{\Xi^-}$$
$$+ \Lambda_{\Xi^-}\Lambda_{\Xi^-} + \Lambda_{\Sigma^0}\Lambda_{\Xi^0} + \Lambda_{\Sigma^0}\Lambda_{\Xi^-} + \Lambda_{\Xi^0}\Lambda_{\Xi^-}$$
$$+ \tilde{\Lambda}\Lambda + \tilde{\Lambda}\Lambda_{\Sigma^0} + \tilde{\Lambda}\Lambda_{\Xi^-} + \tilde{\Lambda}\Lambda_{\Xi^0} + \tilde{\Lambda}\tilde{\Lambda}.$$

Lambda properties obtained from the Λ purity and the cosα template fits

Λ–Λ	
Pair	λ [%]
$\Lambda\Lambda$	36.54
$\Lambda\Lambda_{\Sigma^0}$	24.36
$\Lambda_{\Sigma^0}\Lambda_{\Sigma^0}$	4.06
$\Lambda\Lambda_{\Xi^0}$	9.67
$\Lambda_{\Xi^0}\Lambda_{\Xi^0}$	0.64
$\Lambda\Lambda_{\Xi^-}$	9.67
$\Lambda_{\Xi^-}\Lambda_{\Xi^-}$	0.64
$\Lambda_{\Sigma^0}\Lambda_{\Xi^0}$	3.22
$\Lambda_{\Sigma^0}\Lambda_{\Xi^-}$	3.22
$\Lambda_{\Xi^0}\Lambda_{\Xi^-}$	1.28

Λ–Λ	
Pair	λ [%]
$\tilde{\Lambda}\Lambda$	4.11
$\tilde{\Lambda}\Lambda_{\Sigma^0}$	1.37
$\tilde{\Lambda}\Lambda_{\Xi^0}$	0.54
$\tilde{\Lambda}\Lambda_{\Xi^-}$	0.54
$\tilde{\Lambda}\tilde{\Lambda}$	0.12

Decomposition of the p-Ξ correlation function

$$\{p\Xi^-\} = p\Xi^- + p\Xi^-_{\Xi^-(1530)} + p\Xi^-_{\Xi^0(1530)} + p\Xi^-_{\Omega} + p_\Lambda\Xi^- + p_\Lambda\Xi^-_{\Xi^-(1530)} + p_\Lambda\Xi^-_{\Xi^0(1530)} + p_\Lambda\Xi^-_{\Omega} + p_{\Sigma^+}\Xi^- + p_{\Sigma^+}\Xi^-_{\Xi^-(1530)} + p_{\Sigma^+}\Xi^-_{\Xi^0(1530)} + p_{\Sigma^+}\Xi^-_{\Omega} + \tilde{p}\Xi^- + \tilde{p}\Xi^-_{\Xi^-(1530)} + \tilde{p}\Xi^-_{\Xi^0(1530)} + \tilde{p}\Xi^-_{\Omega} + p\tilde{\Xi}^- + p_\Lambda\tilde{\Xi}^- + p_{\Sigma^+}\tilde{\Xi}^- + \tilde{p}\tilde{\Xi}^-.$$

Feeding from

- Ω (BR very small)
- $\Xi^0(1530)$ and $\Xi^-(1530)$
  - Isospin partners: assume to be produced in the same amount
  - $\Xi(1530)/\Xi^- = 0.32$ (https://doi.org/10.1140/epjc/s10052-014-3191-x)
  - BR($\Xi^0(1530) \rightarrow \Xi^-$) = 2/3
  - BR($\Xi^-(1530) \rightarrow \Xi^-$) = 1/3

p–Ξ	
Pair	λ [%]
$p\Xi^-$	52.40
$p\Xi^-_{\Xi^-(1530)}$	8.32
$p\Xi^-_{\Xi^0(1530)}$	16.65
$p\Xi^-_{\Omega}$	0.67
$p_\Lambda\Xi^-$	5.25
$p_\Lambda\Xi^-_{\Xi^-(1530)}$	0.83
$p_\Lambda\Xi^-_{\Xi^0(1530)}$	1.67
$p_\Lambda\Xi^-_{\Omega}$	0.07
$p_{\Sigma^+}\Xi^-$	2.25
$p_{\Sigma^+}\Xi^-_{\Xi^-(1530)}$	0.36
$p_{\Sigma^+}\Xi^-_{\Xi^0(1530)}$	0.71
$p_{\Sigma^+}\Xi^-_{\Omega}$	0.03

p–Ξ	
Pair	λ [%]
$\tilde{p}\Xi^-$	0.53
$\tilde{p}\Xi^-_{\Xi^-(1530)}$	0.08
$\tilde{p}\Xi^-_{\Xi^0(1530)}$	0.17
$\tilde{p}\Xi^-_{\Omega}$	0.01
$p\tilde{\Xi}^-$	8.67
$p_\Lambda\tilde{\Xi}^-$	0.87
$p_{\Sigma^+}\tilde{\Xi}^-$	2.25
$\tilde{p}\tilde{\Xi}^-$	0.09

Some raw numbers

pp@13 TeV

Particle	# baryons
p	113.7×10^6
$\bar{p}$	97.4×10^6
Λ	22.3×10^6
$\bar{\Lambda}$	21.0×10^6
Ξ^-	509×10^3
Ξ^+	527×10^3

Pair	# of pairs k* < 200 MeV/c
$p-p$	190×10^3
$\bar{p}-\bar{p}$	140×10^3
$p-\Lambda$	62×10^3
$\bar{p}-\bar{\Lambda}$	49×10^3
$\Lambda-\Lambda$	5659
$\bar{\Lambda}-\bar{\Lambda}$	5243
$p-\Xi^-$	407
$\bar{p}-\Xi^+$	364

P-Pb @ 5.02 TeV

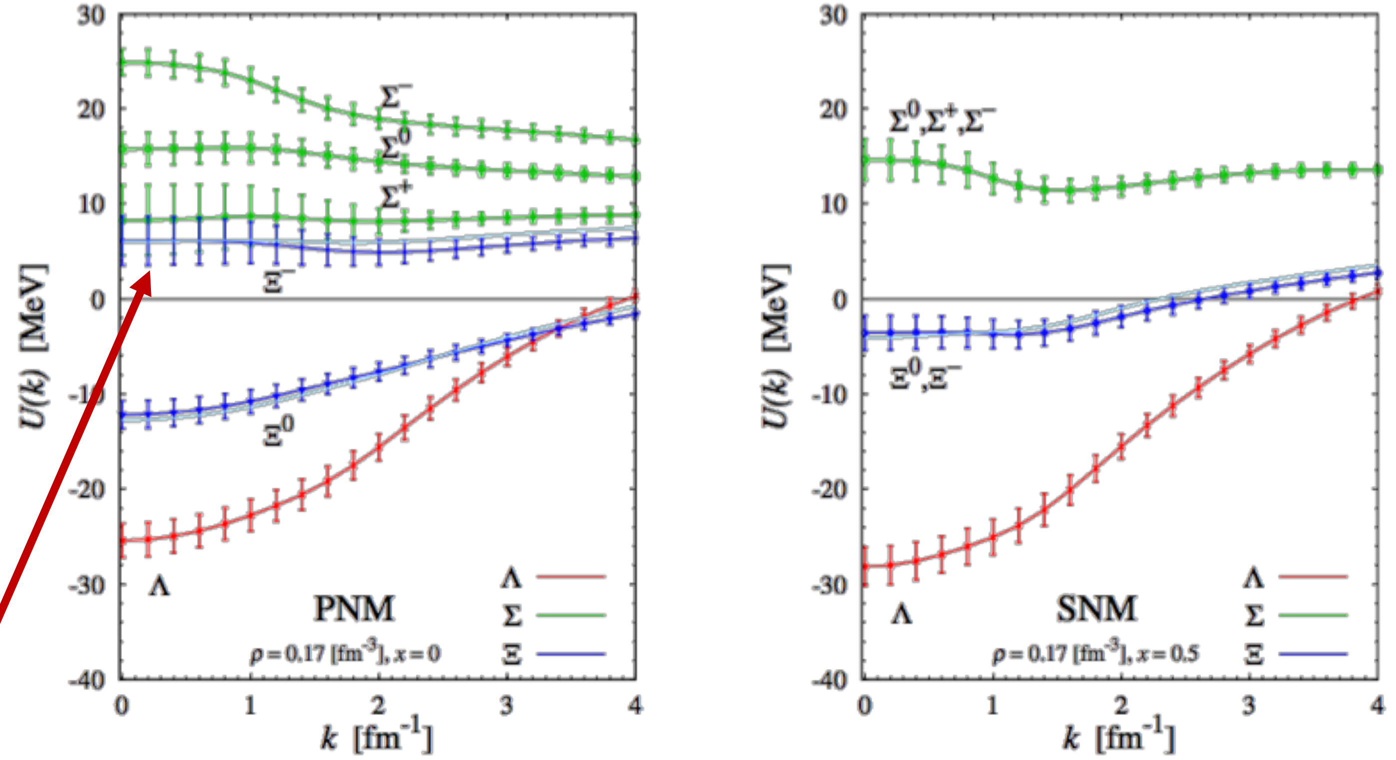
Particle	Candidates
p	155×10^6
$\bar{p}$	133×10^6
Λ	26×10^6
$\bar{\Lambda}$	24×10^6
Ξ	0.9×10^6
$\bar{\Xi}$	0.9×10^6

Combinations	Pairs (k*< 200 MeV/c)
$p-p$	517×10^3
$\bar{p}-\bar{p}$	370×10^3
$p-\Lambda$	127×10^3
$\bar{p}-\bar{\Lambda}$	62×10^3
$\Lambda-\Lambda$	13×10^3
$\bar{\Lambda}-\bar{\Lambda}$	12×10^3
$p-\Xi$	1.8×10^3
$\bar{p}-\bar{\Xi}$	1.3×10^3

Single particle potentials from Lattice

- NS environment ⇒ **P**ure **N**eutron **M**atter
- Tested HAL-QCD potential in vacuum with ALICE ⇒ Brueckner-Hartree-Fock many-body calculations ⇒ U_Y single-particle potential of hyperons in nucleonic matter
- At saturation density in PNM:

U_{Ξ^-} slightly repulsive



HAL-QCD Collaboration, arXiv:1809.08932 (2018)

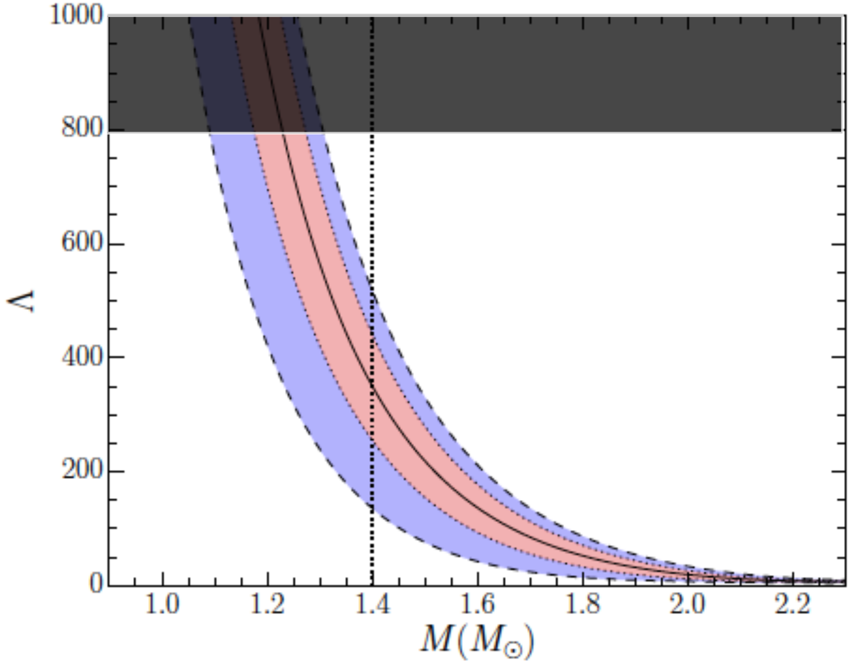
Recent Constraints from Gravitational Waves

not constraining really very much so far…

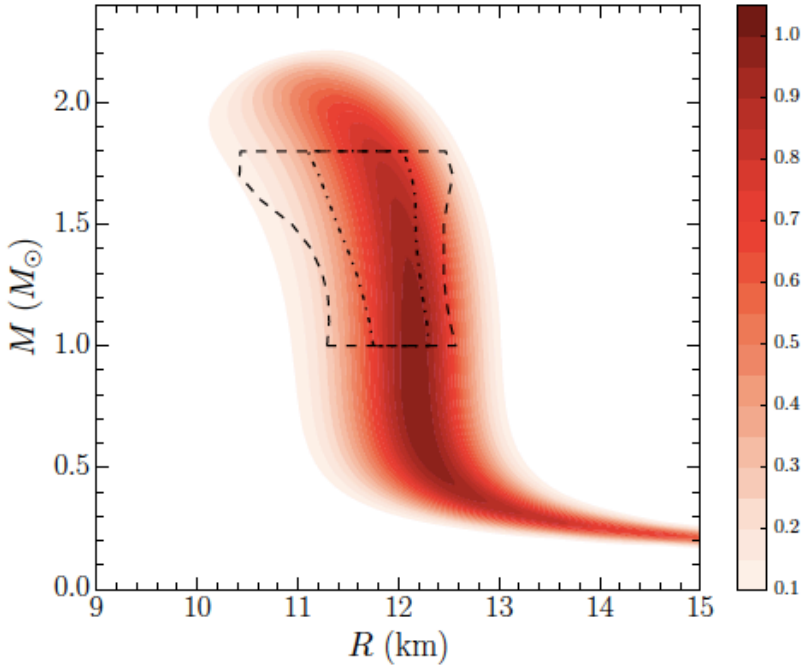
Tidal Deformability Λ: measurement of the NS deformability, upper limit extracted from GW170817

B. P. Abbott et al. (LIGO Scienti c Collaboration and Virgo Collaboration), Phys. Rev. Lett. 119, 161101 (2017).

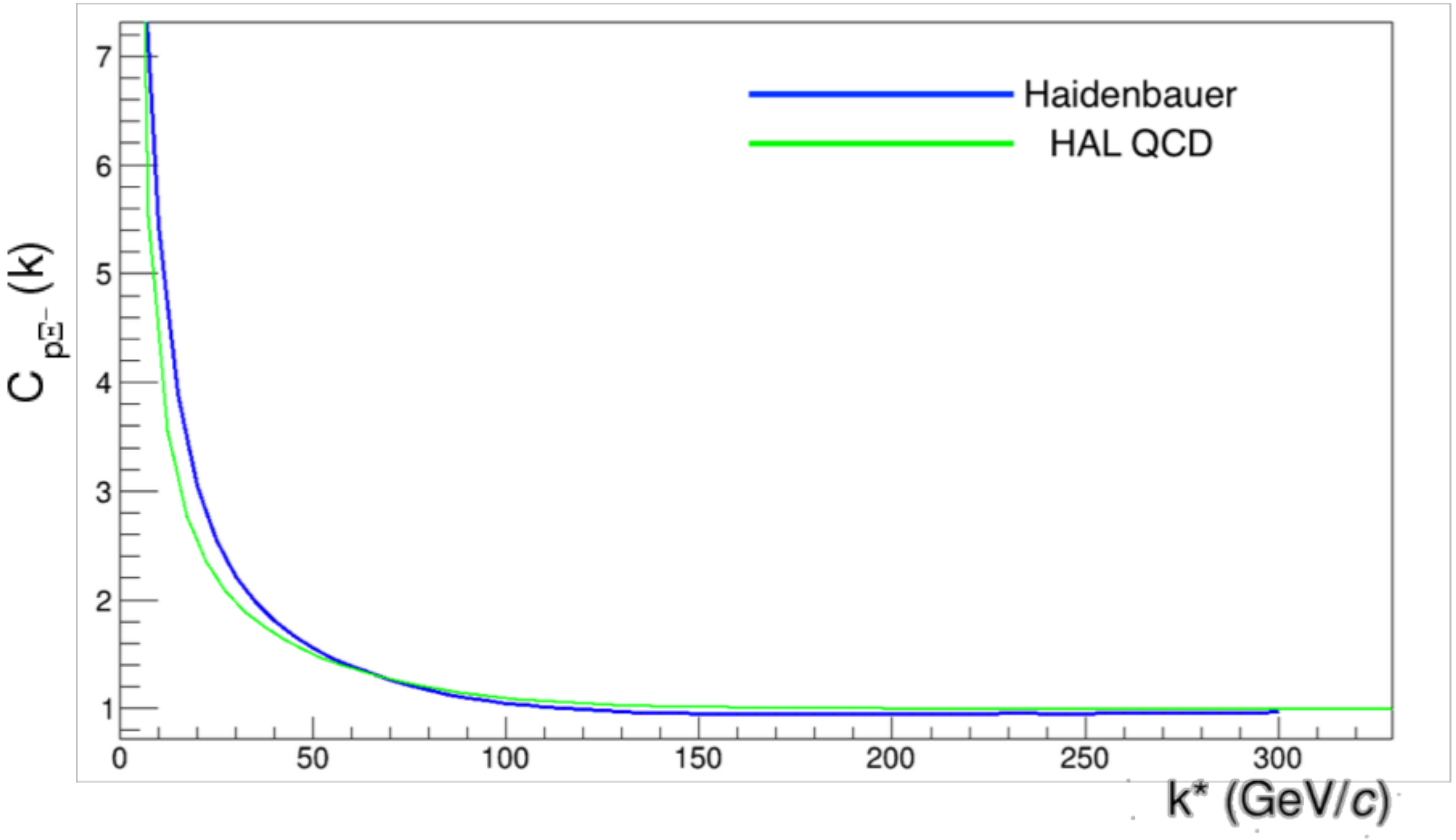
Nuclear EoS including 2N and 3N interactions are consistent with these constraints



Y. Lim, J.W. Holt Phys.Rev.Lett. 121 (2018) no.6, 062701



Theoretical p-Ξ^- Correlation function



- Comparison **HAL-QCD/χEFT from recent work by Haidenbauer and Meissner (arxiv:1810.04883)**