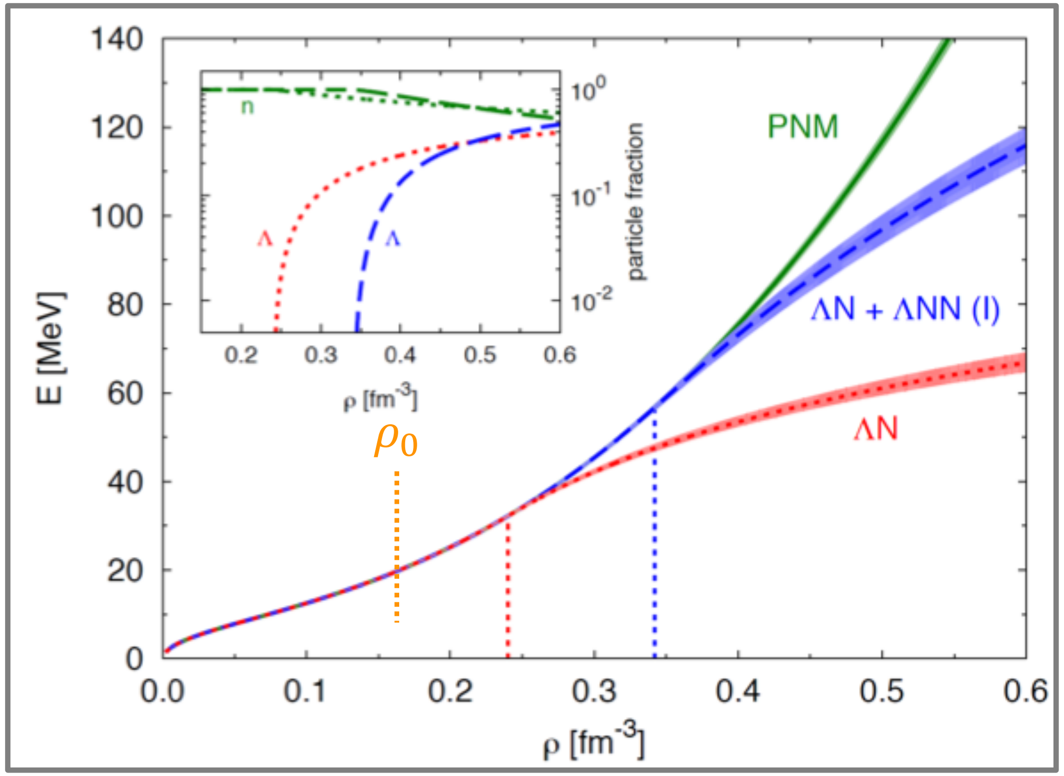
Baryon-baryon femtoscopy in pp and p-A collisions with ALICE

VALENTINA MANTOVANI SARTI FOR THE ALICE COLLABORATION

PHYSIK-DEPARTMENT - TECHNISCHE UNIVERSITÄT MÜNCHEN

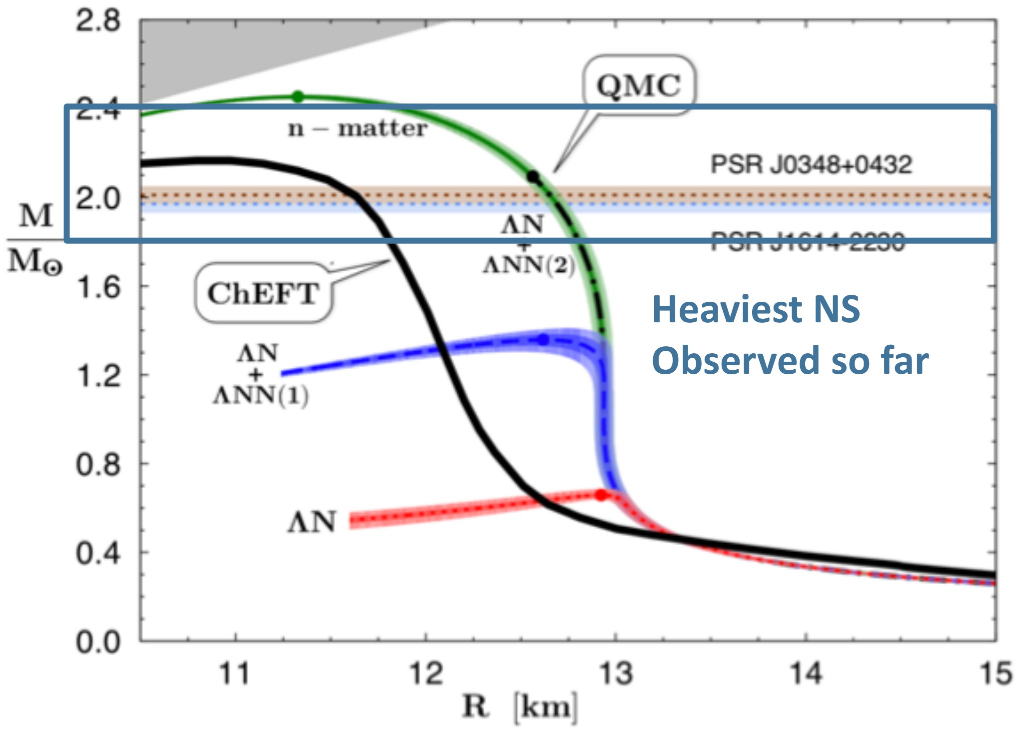
The Equation of State in Neutron Stars

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



Tolman-Oppenheimer-Volkoff Equations

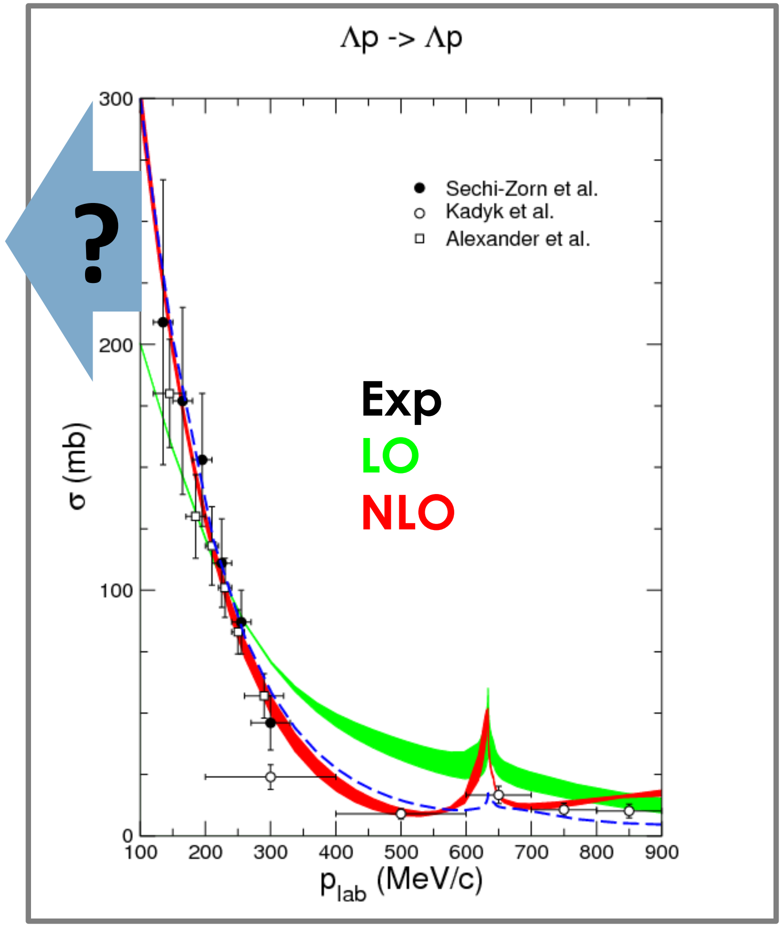
ChEFT Calculations from: T. Hell, W.W. PRC90 (2014) 045801



- With the onset of the production of hyperons the EoS softens
- EoS allowing for hyperon production fail to describe heavy neutron stars → **Hyperon Puzzle**
- **2-body and 3-body interactions are fundamental ingredients for the EoS**

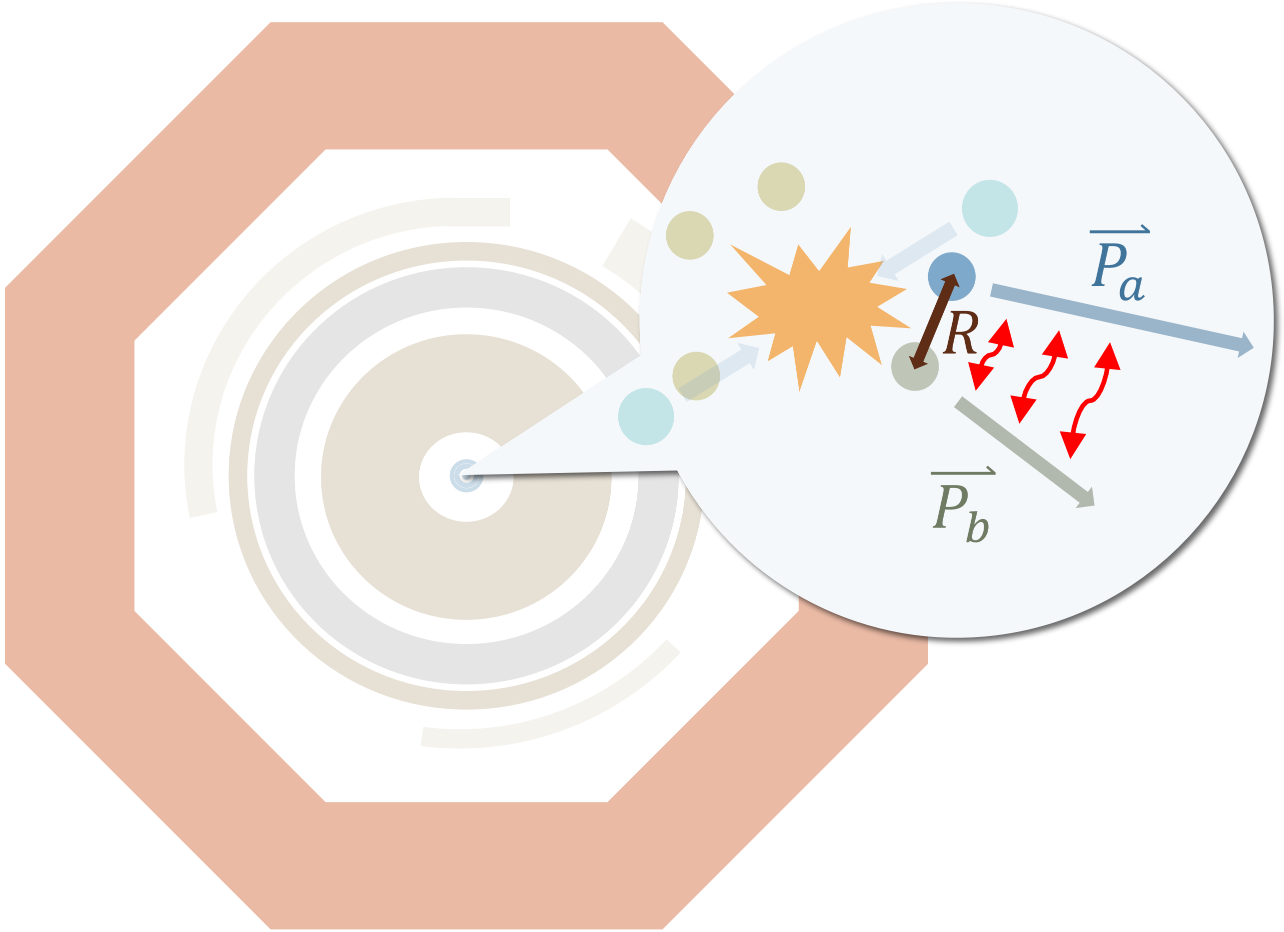
Y-N Scattering Data and Hypernuclei data

- Data from scattering experiments from 1968 and 1971 in bubble chambers
  - $K^- + p \rightarrow \Sigma^0 + \pi^0, \Sigma^0 \rightarrow \Lambda + \gamma$
  - Production threshold for Λ's : $\mathrm{p} \gtrsim 100$ MeV
- One observed double Λ hyper-nucleus (Nagara Event) predicts a shallow Λ–Λ attraction
- Different types of measurements needed to obtain constraints at low momentum
- Can we use Femtoscopic measurements?



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

Femtoscopy at **A L**arge **I**on **C**ollider **E**xperiment



- We measure **p-p, p-Λ, Λ-Λ, p-Ξ**
- Proton identification with TPC and TOF
- Reconstruction of hyperons
  - $\Lambda \rightarrow p\pi^-$ (BR ~ 64%)
  - $\Xi^- \rightarrow \Lambda\pi^-$ (BR ~ 100%)
- Datasets:
  - pp 7 TeV: $3.4 \cdot 10^8$ Events
  - pp 13 TeV: $10 \cdot 10^8$ Events
  - p-Pb 5.02 TeV: $6.0 \cdot 10^8$ Events

Femtoscopy

The correlation function:

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

Experimentally obtained as:

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

Given by:

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

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

Source → $S(\boldsymbol{r}, k^*)$

Relative Wave Function → $\psi(\boldsymbol{r}, k^*)$

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

Femtoscopy

The correlation function:

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

Experimentally obtained as:

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

Given by:

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

Source → $S(\boldsymbol{r}, k)$

Relative Wave Function → $\psi(\boldsymbol{r}, k)$

Assumption of a **common source**: Combined fit of the **p-p, p-Λ, p-Ξ** and Λ–Λ Correlation Function

Femtoscopy

The correlation function:

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

Experimentally obtained as:

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

Sensitivity to the interaction potential

Given by:

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

Source

Relative Wave Function

Strong constraint

Assumption of a **common source**: Combined fit of the **p-p**, **p-Λ**, **p-Ξ** and Λ–Λ Correlation Function

Modelling the Correlation function

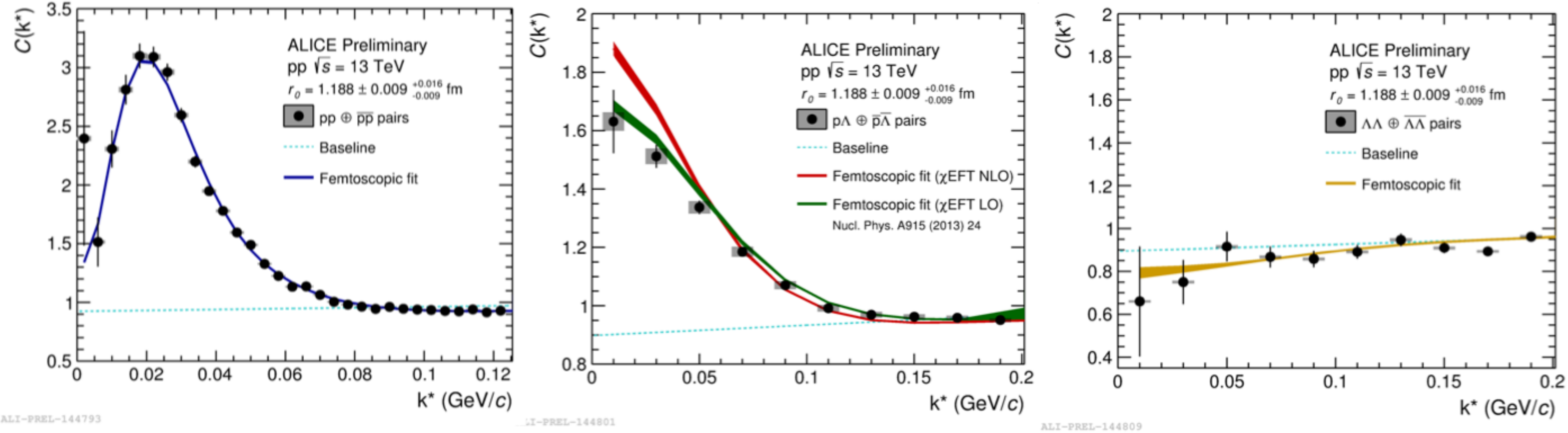
$$C(k^*) = N \cdot C_{\text{baseline}}(k^*) \cdot \left[1 + \lambda_{\text{genuine}} \cdot \left(C_{\text{genuine}}(k^*) - 1\right) + \sum \lambda_{ij} \cdot \left(C_{ij}(k^*) - 1\right)\right]$$

CATS Correlation Analysis Tool Using the Schrödinger Equation		**Lednický**
Numerical Solver		Analytical Model
Analytical source distribution Distributions from transport models	SOURCE	Gaussian source distribution
Solution of the two particle Schrödinger Equation ➢ Can incorporate any strong interaction potential, Coulomb interaction and effects of quantum statistics	WAVE FUNCTION	Based on the effective Range expansion ➢ The interaction is modeled using the scattering length (f_0) and the effective range (d_0)
p-p, p-Ξ and p-Λ (NLO) Correlation function	Used to fit the	p-Λ (LO) and Λ–Λ 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)

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

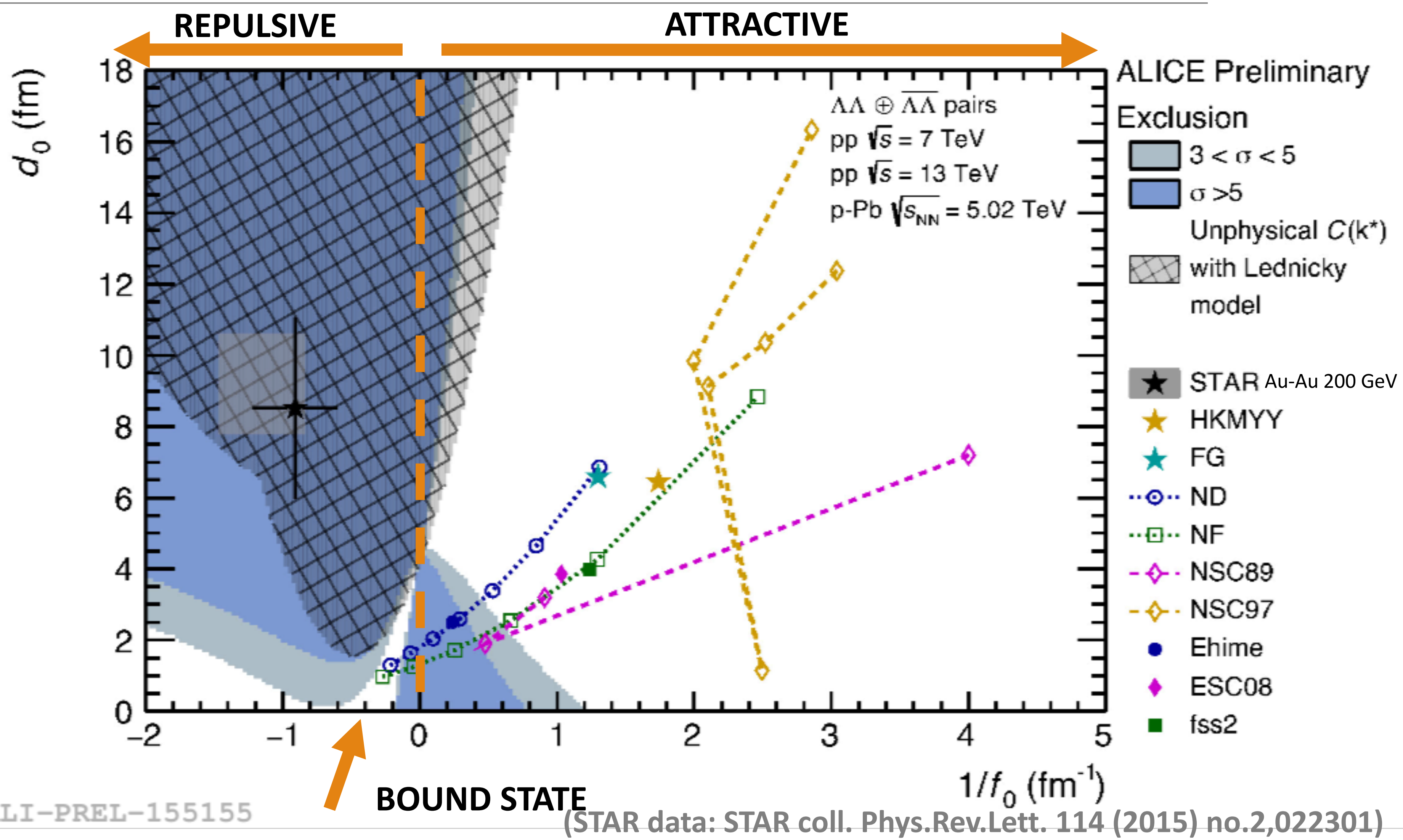
Gaussian Source – pp collisions $\sqrt{s} = 13$ TeV



- Gaussian source and Argonne ν_{18} potential describes the p-p correlation function
  - Source size of the **pp (7 TeV)** system **r_0=1.14 fm** **(ALICE Coll. arXiv:1805.12455)**
  - Source size of the **pp (13 TeV)** system **r_0=1.19 fm**
  - Source size of the **p-Pb (5.02 TeV)** system **r_0=1.44 fm**
- p-Λ correlation ⇒ strong sensitivity to the source ⇒ more investigations of the source are needed

Λ–Λ Correlations: Combined Exclusion Plot

- Combination of all available datasets: **pp 7 TeV, pp 13 TeV, p-Pb 5.02 TeV**
- Test of the **agreement between data and the prediction by the Lednicky model by nσ**
- Small source size, large d_0 and negative f_0 limit the prediction power of Lednicky



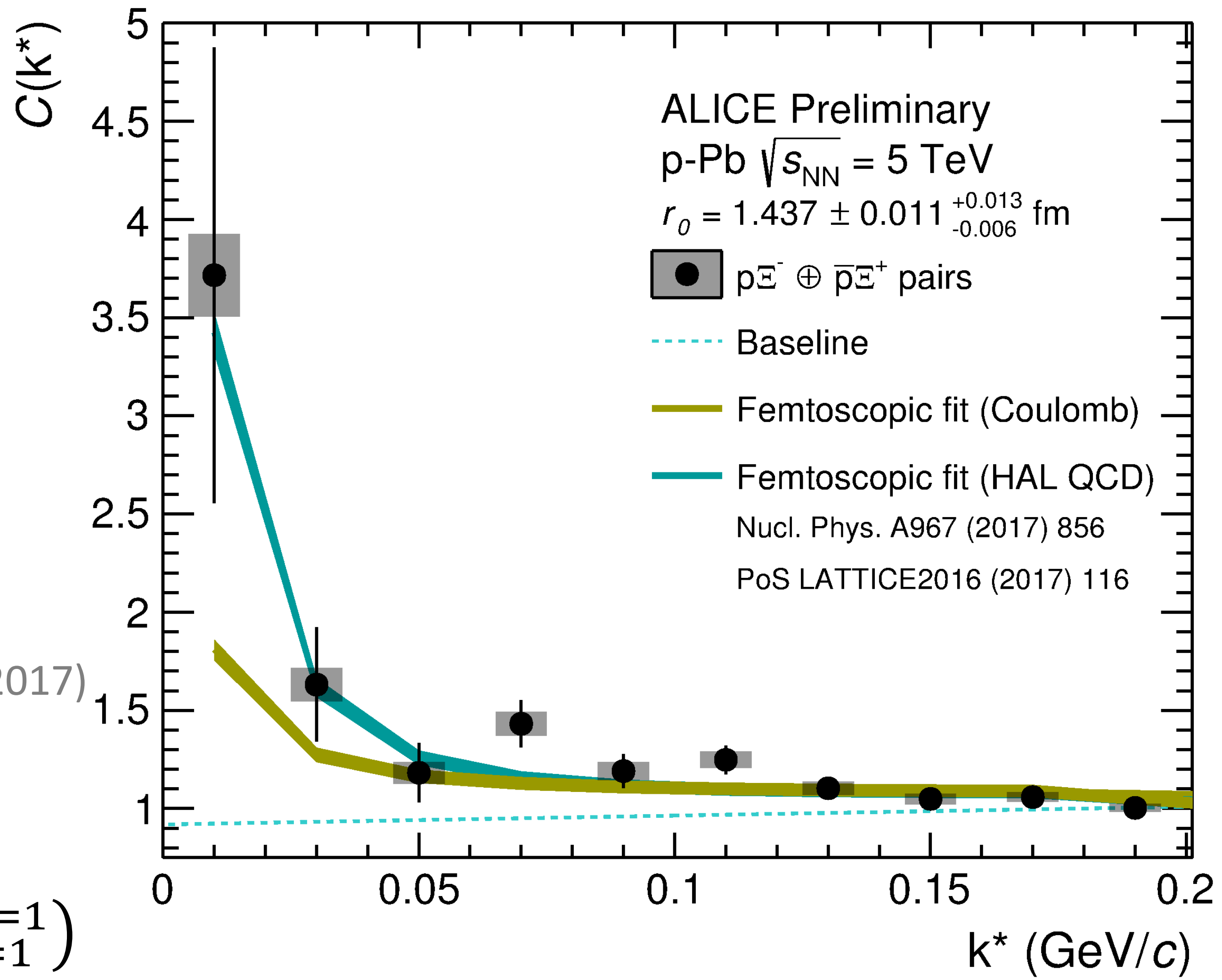
(STAR data: STAR coll. Phys.Rev.Lett. 114 (2015) no.2,022301)

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

- **<u>First observation of strong attractive interaction in p-Ξ^-</u>**
  - p-Value with and without strong potential (Coulomb only): 0.055 vs. 0.004
- modeled with preliminary QCD strong potential by the HAL QCD collaboration

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

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

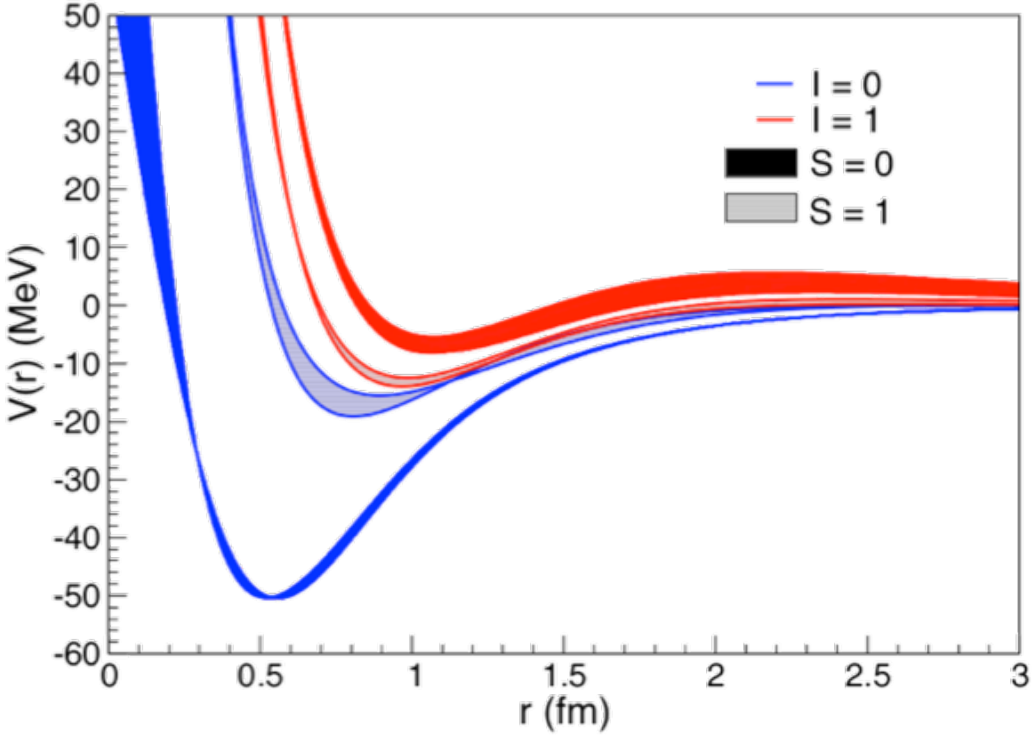


ALI-PREL-144825

Let's go back to Neutron Stars

- YN potential strongly affects the EoS of nuclear matter ⇒ not constrained for heavier hyperons such Ξ
- Extract an average value of $V_{N\Xi^-}$ at ρ_0

$$< V_{IS} >= 4\pi\rho_0 \int_0^\infty V_{IS}\, r^2\, dr$$



$<V_{IS}>$ (MeV)	I=0	I=1
S=0	-103±5	180±97
S=1	-32±4	12±14

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

Let's go back to Neutron Stars

- NS matter is a neutron-rich environment
- **Coupling of isospin quantum numbers to build different interacting pairs**

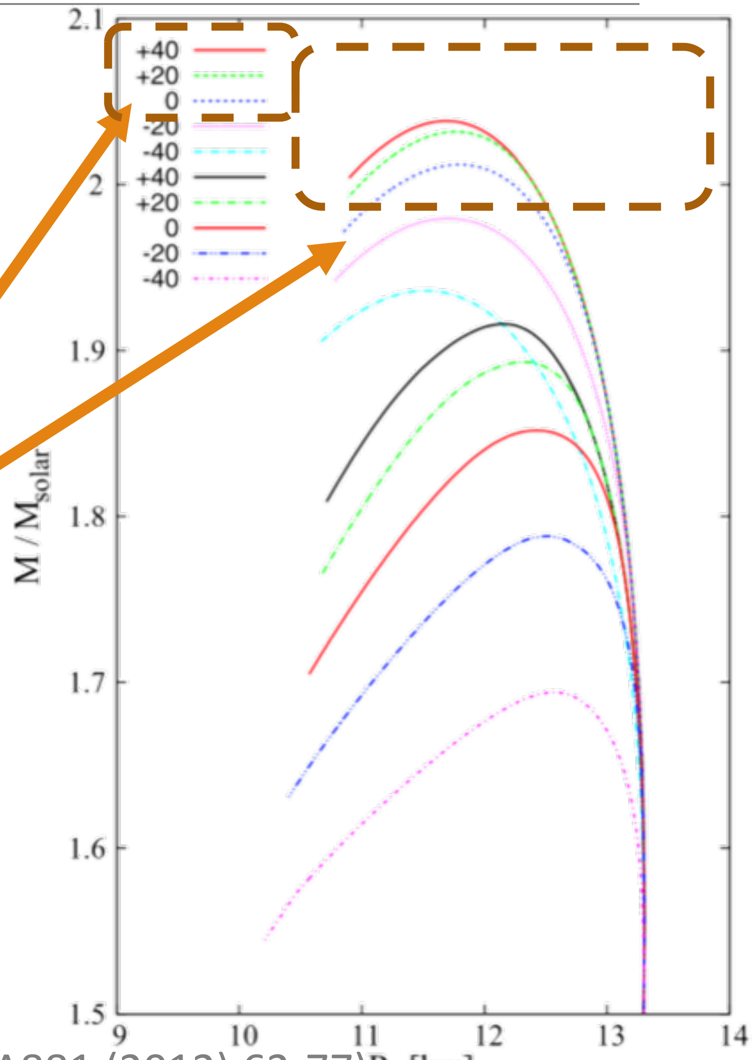
(Potential from Hatsuda et al., NPA967 (2017) 856, PoS Lattice2016 (2017) 116)

ρ (fm^{-3})	p-Ξ^-, n-Ξ^0 (I=0,1)	n-Ξ^-, p-Ξ^0 (I=1)
ρ_0, Z=N	2±13 MeV	54±13 MeV

Repulsive interaction

⇒ Production of Ξ pushed to higher densities

⇒stiffer EoS, higher masses



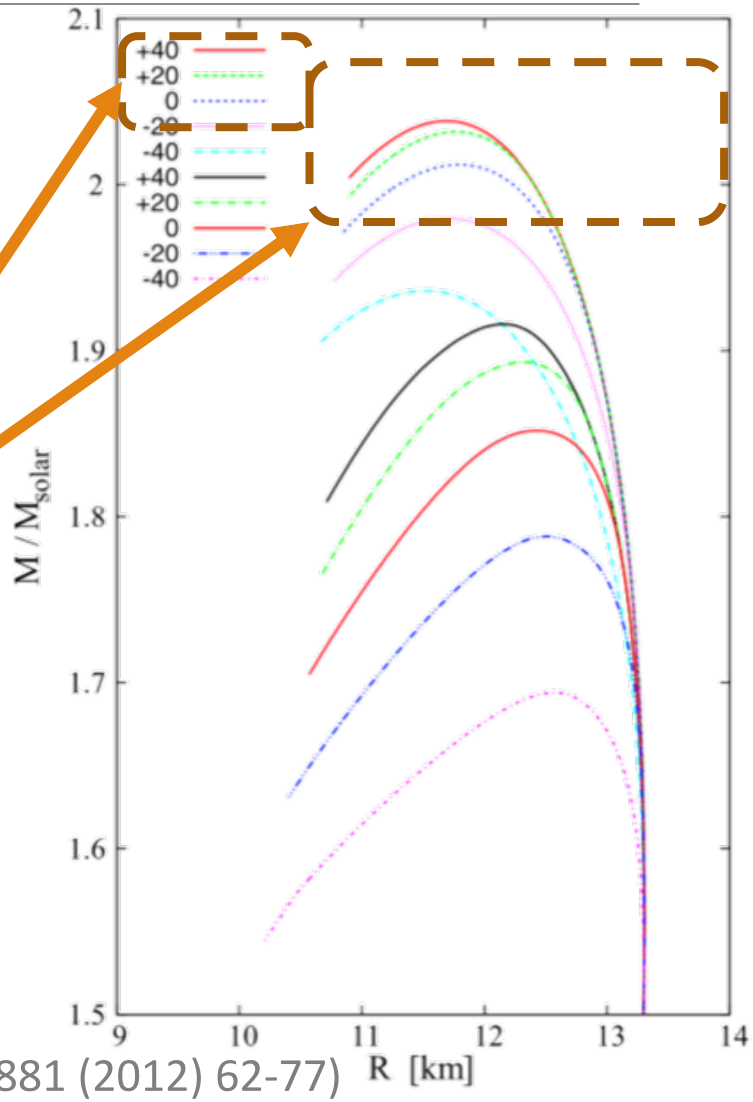
(Weissborn et al., NPA881 (2012) 62-77)

Let’s go back to Neutron Stars

- NS matter is a neutron-rich environment
- **Coupling of isospin quantum numbers to build different interacting pairs**

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

ρ (fm^{-3})	p-Ξ^-, n-Ξ^0 (I=0,1)	n-Ξ^-, p-Ξ^0 (I=1)
ρ_0, Z=N	2±13 MeV	54±13 MeV

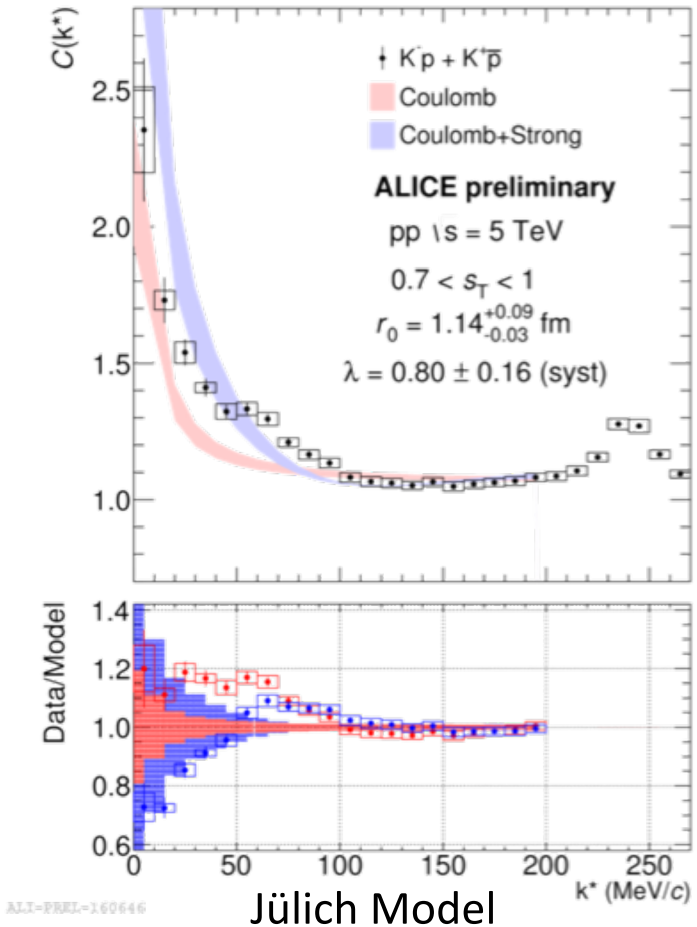


(Weissborn et al., NPA881 (2012) 62-77)

NS Masses above 2M$_\odot$ are allowed

K^-- p Correlation-pp 5 TeV, 7 TeV, 13 TeV

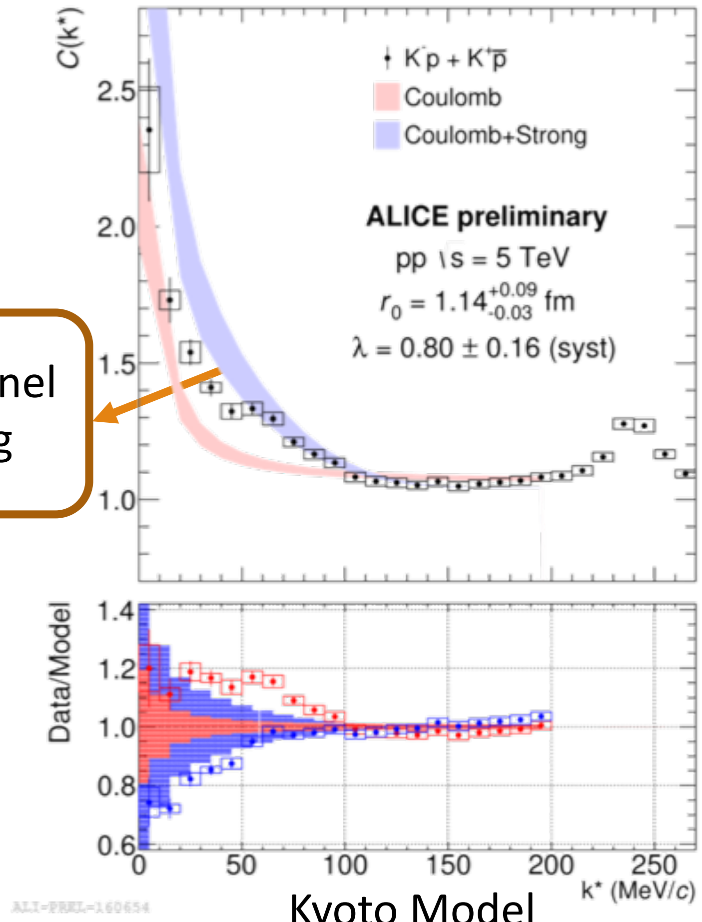
- Analysis on datasets:
  - **pp 5 TeV, 7 TeV, 13 TeV**
- **Short range $\bar{K}N$ interaction**:
  - Λ(1405), kaonic atoms and kaonic clusters
- Kaonic atoms and scattering data



Jülich Model

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

$\overline{K^0}$n channel opening



Kyoto Model

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

Analysis performed by R.Lea (INFN-TS)

Summary and Outlook:

- **Femtoscopy** is an excellent tool to study **interactions of particle pairs**
  - Significant sensitivity to the interaction potentials
  - For hyperons, accesses novel regions not constrained by scattering experiments
- **Λ-Λ analysis** strongly constrains the parameter space for the Λ-Λ interaction ⇒ the existence of H-dibaryons seems to be disfavored **(ALICE coll., Phys. Lett. B 752)**
- 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
- **$\overline{\mathrm{K}}$N analysis** ⇒ access to low momentum region ⇒ study of $\overline{\mathrm{K}^0}\mathrm{n}$ coupled channel contribution

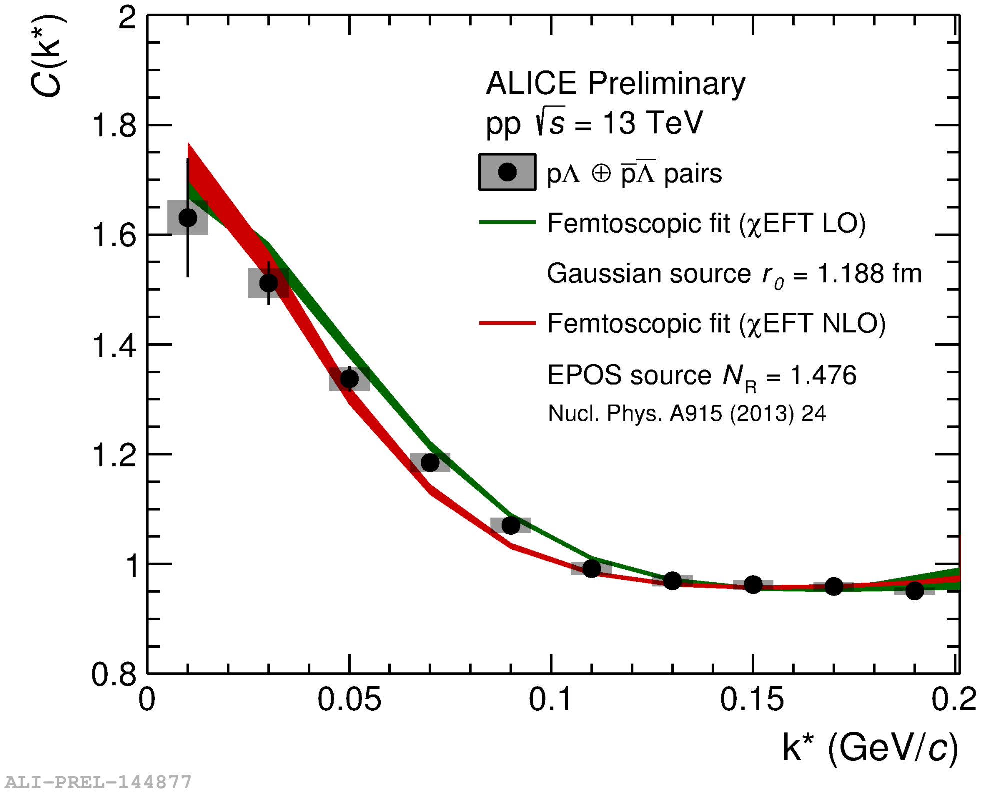
In the future

- You name the pair, we measure it: p-Ω, Ω-Ω, 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

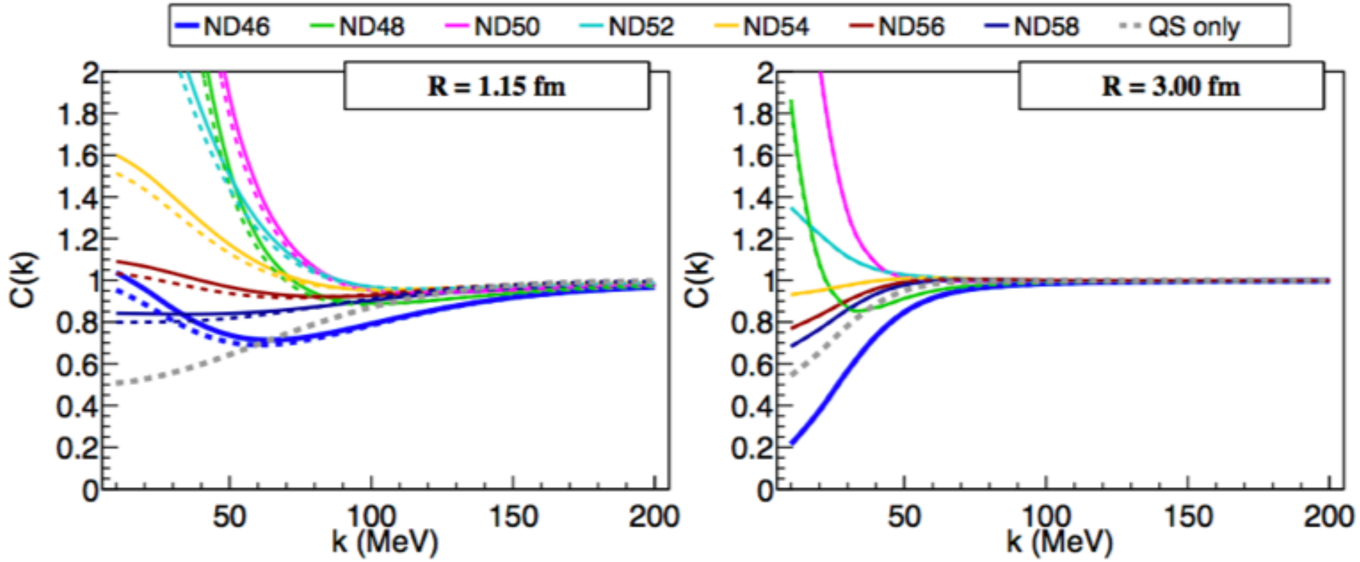
Backup Slides

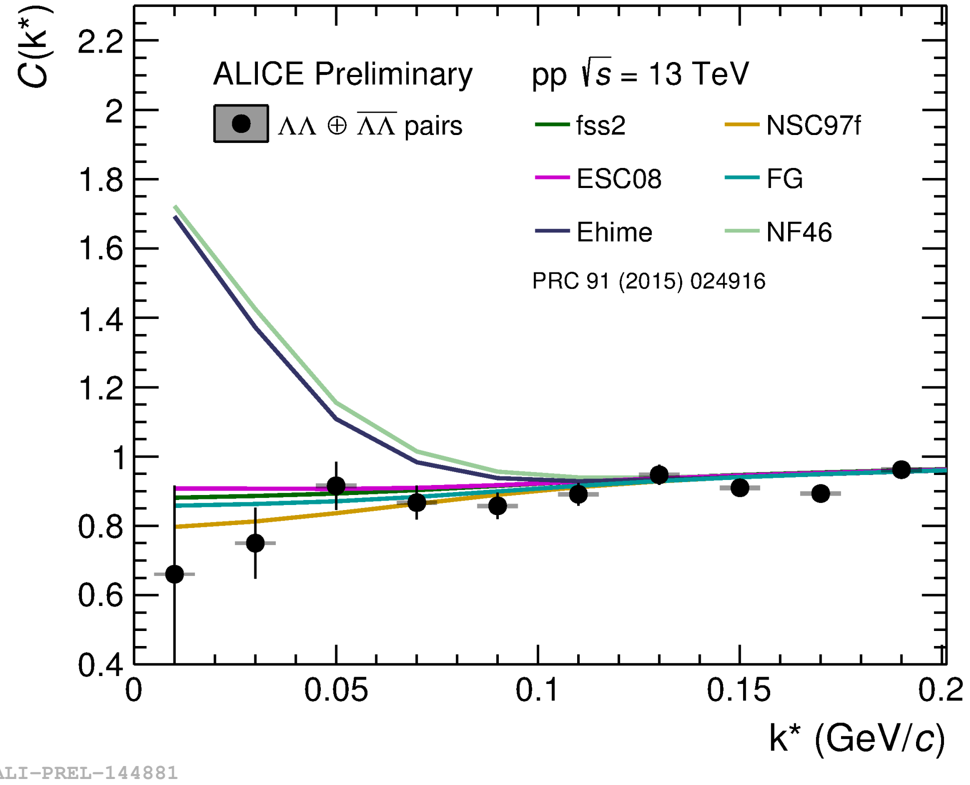
p-Λ Correlations: Scaled EPOS source

- Double Gaussian and a Cauchy source distributions fail to describe the data
- Only the rescaled EPOS source fits the data
  - Favors χEFT NLO potential
  - EPOS + NLO χ2/ndf : 1.45
  - Gauss + LO χ2/ndf : 0.49
- Take home message: Improve on understanding the source



Λ-Λ Correlations: Predictions with Lednicky





- Curves represent different points in the Λ-Λ exclusion plot
- For scattering parameters in the region $a_0 > 0$ the correlation function is not sensitive

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

	p–p
Pair	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		p–Λ
Pair	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

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

Feeding from

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

The unique opportunity of small sources