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

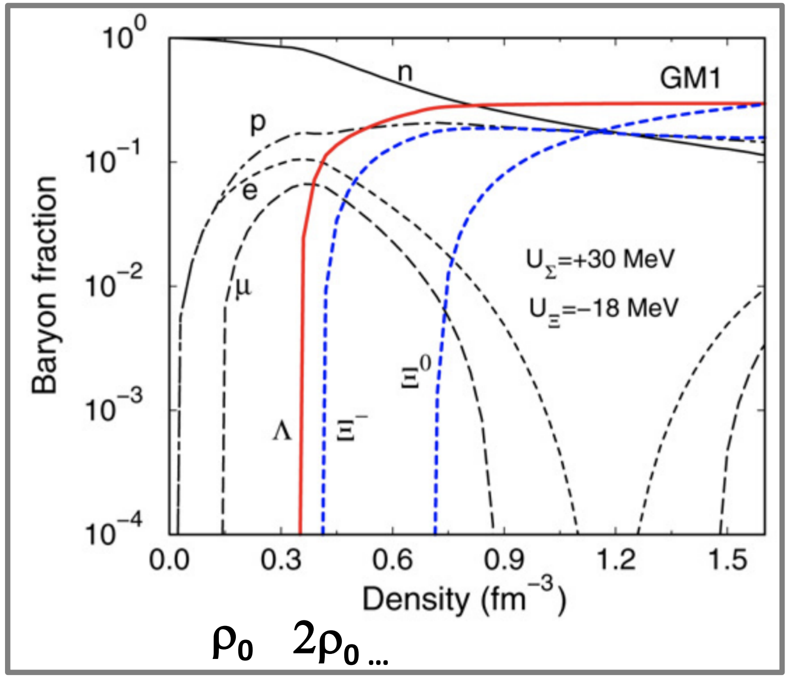
BERNHARD HOHLWEGER FOR THE ALICE COLLABORATION

E62 DENSE AND STRANGE HADRONIC MATTER

GROUP PROF. DR. LAURA FABBIETTI

PHYSIK-DEPARTMENT - TECHNISCHE UNIVERSITÄT MÜNCHEN

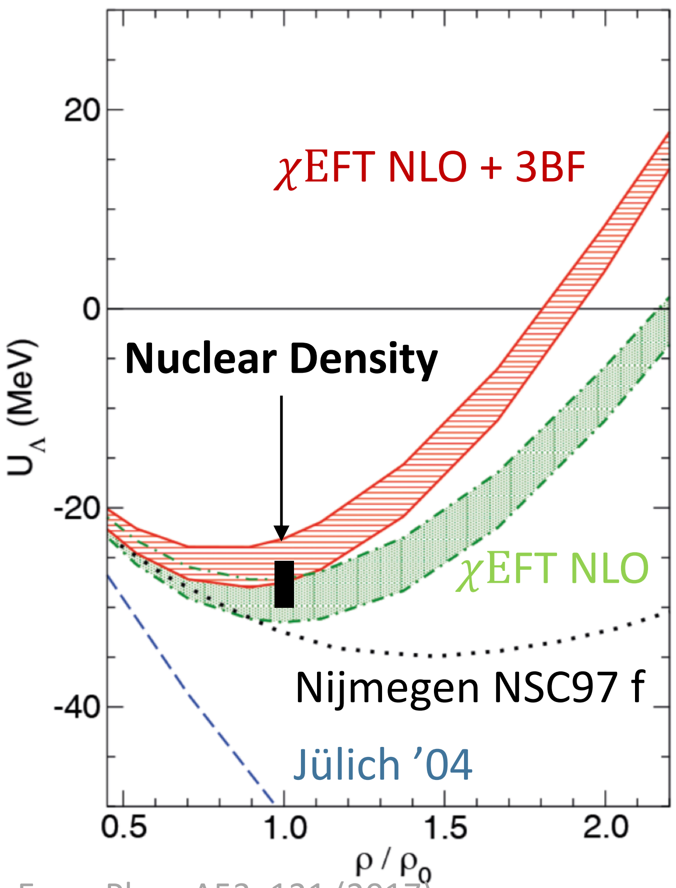
Hyperons in Neutron Stars?



J. Schaffner-Bielich, NPA 804 (2008), 309-321

- Hyperon production becomes energetically favorable at finite densities
- Hyperon interaction potential predicts
  - Onset of their production
  - Effect on the Equation of State (EoS)
- For the Λ Hyperon χEFT in NLO predicts repulsion

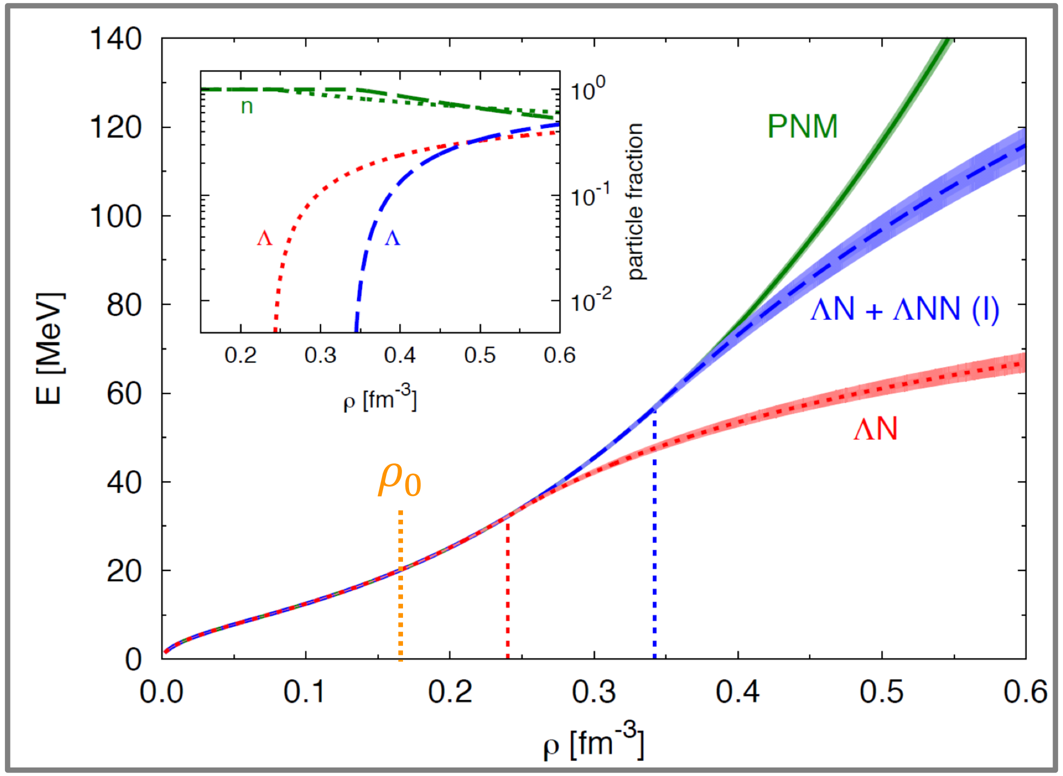
Λ potential in symmetric nuclear matter



Euro. Phys. A53, 121 (2017)

The Equation of State

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



- With the onset of the production of hyperons the EoS softens

The Equation of State

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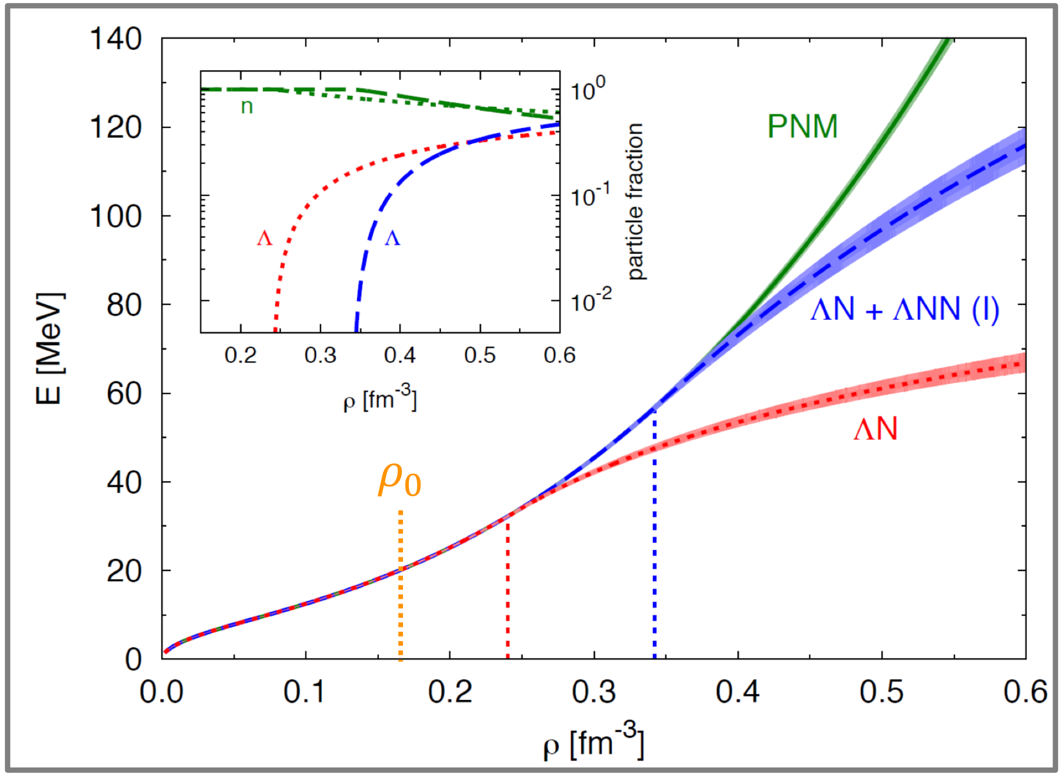
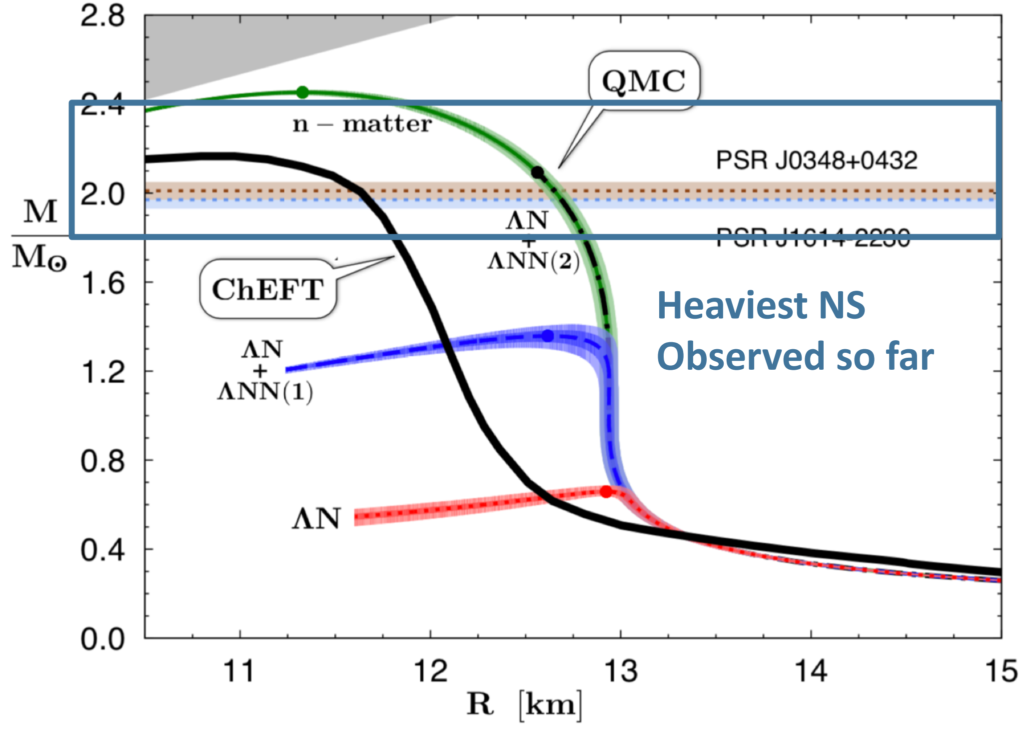


Tolman-Oppenheimer-Volkoff Equations

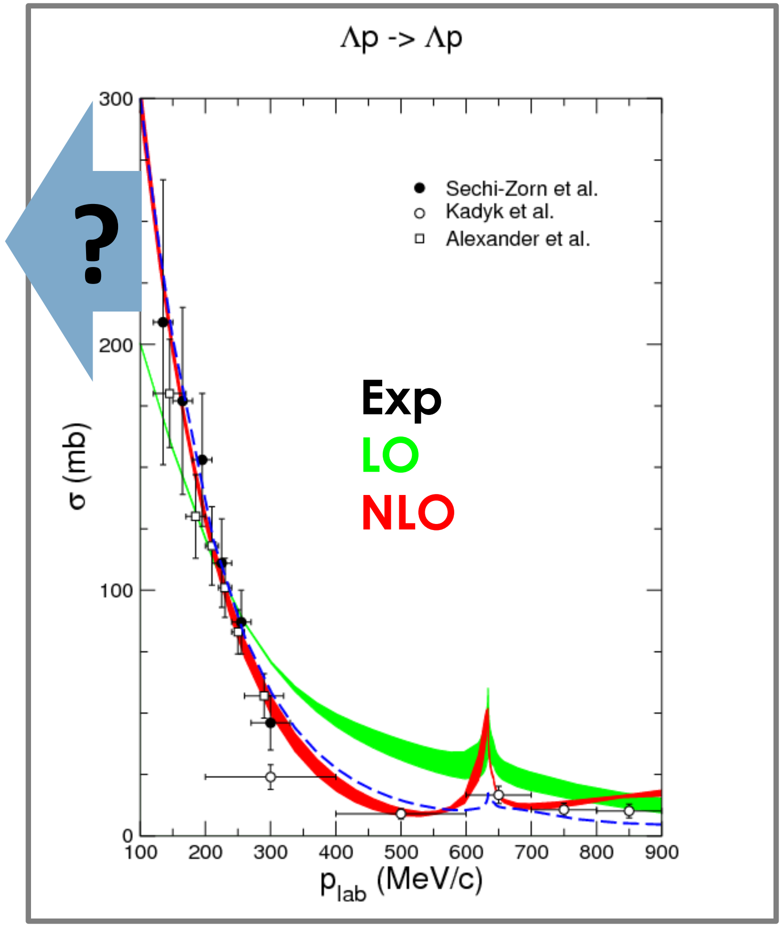
ChEFT Calculations from: T. Hell, W.W. PRC90 (2014) 045801



- With the onset of the production of hyperons the EoS softens
- EoS allowing for hyperon production fail to describe heavy neutron stars → **Hyperon Puzzle**

Global Proton-Λ Scattering Data

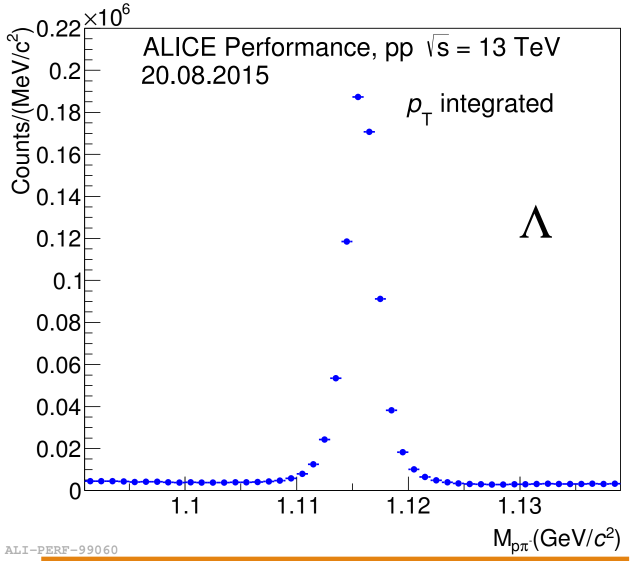
- Data from scattering experiments from 1968 and 1971 in bubble chambers
  - $K^- + p \rightarrow \Sigma^0 + \pi^0, \Sigma^0 \rightarrow \Lambda + \gamma$
  - Production threshold for Λ's : $p \gtrsim 100$ MeV
- One observed double Λ hyper-nucleus (Nagara Event) predicts a shallow Λ–Λ attraction
- Different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

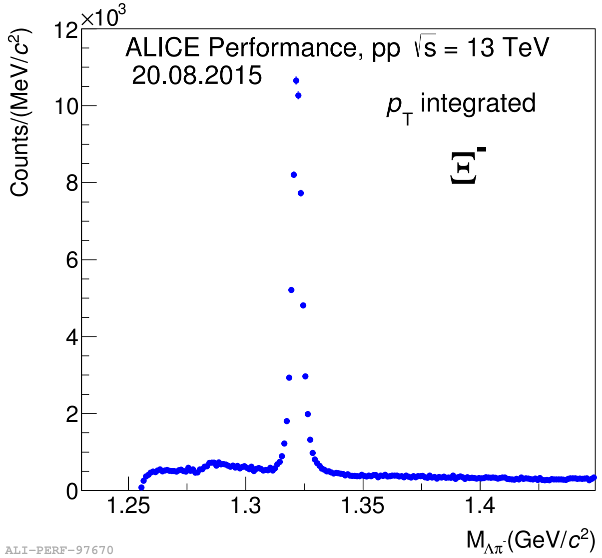


LO: H. Polinder, J.H., U. Meiβner, NPA 779 (2006) 244
NLO: J.Haidenbauer., N.Kaiser, et al., NPA 915 (2013) 24

A Large Ion Collider Experiment

- 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





pp $\sqrt{s}$ = 13 TeV	
Particle	# baryons (uncorrected)
p	113.7 x 10^6
$\bar{p}$	97.4 x 10^6
Λ	22.3 x 10^6
$\bar{\Lambda}$	21.0 x 10^6
Ξ^-	0.51 x 10^6
Ξ^+	0.53 x 10^6

p-Pb $\sqrt{s_{NN}}$ = 5.02 TeV	
Particle	# baryons (uncorrected)
p	155 x 10^6
$\bar{p}$	133 x 10^6
Λ	26 x 10^6
$\bar{\Lambda}$	24 x 10^6
Ξ^-	0.9 x 10^6
Ξ^+	0.9 x 10^6

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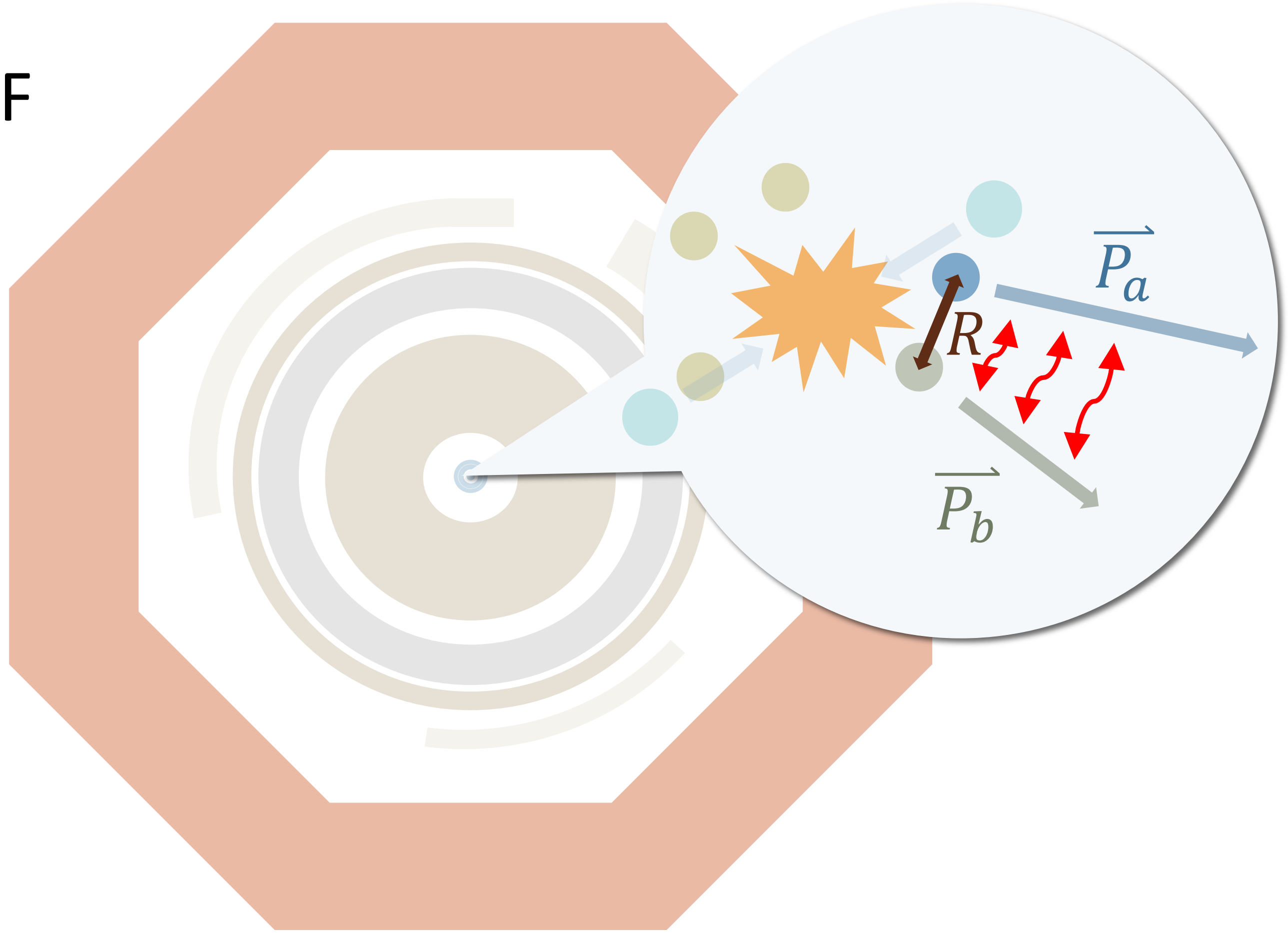

Femtoscopy

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

Wave Function

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

Femtoscopy

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Source → $S(\boldsymbol{r}, k)$

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

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

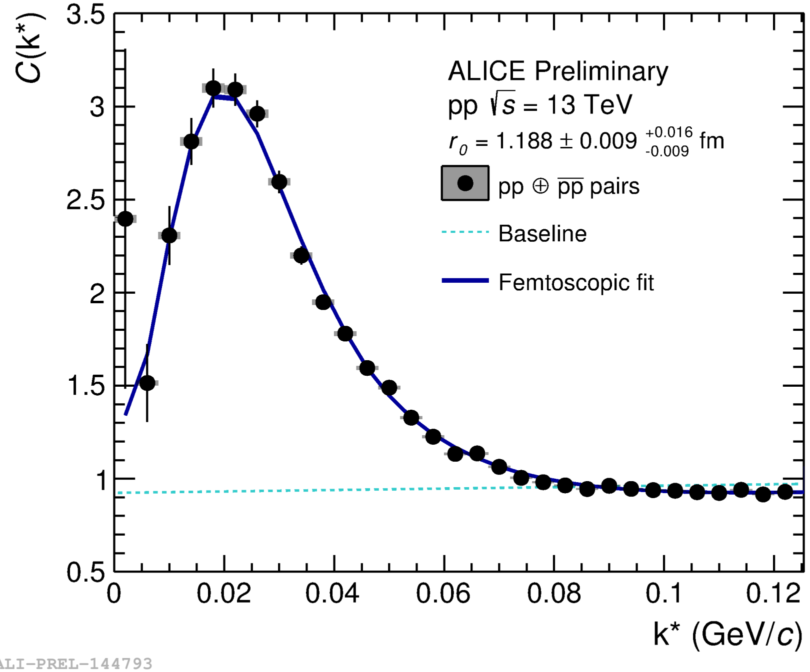
$$C(k^*) = N \cdot C_{baseline}(k^*) \cdot \left(1 + \lambda_{genuine} \cdot \left(C_{genuine}(k^*) - 1\right) + \sum \lambda_{ij} \cdot \left(C_{ij}(k^*)\right) - 1\right)$$

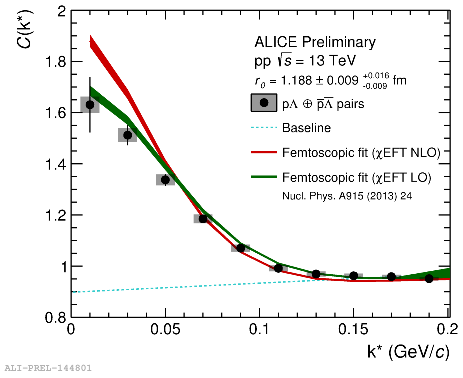
CATS Correlation Analysis Tool Using the Schrödinger Equation		**Lednický**
Numerical Solver		Analytical Model
Analytical source distribution Distributions from transport models	SOURCE	Gaussian source distribution
Solution of the two particle Schrödinger Equation ➢ Can incorporate any strong interaction 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

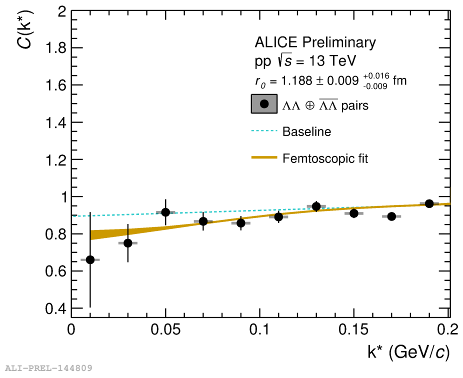
arXiv:1802.08481 (Accepted by EPJC)

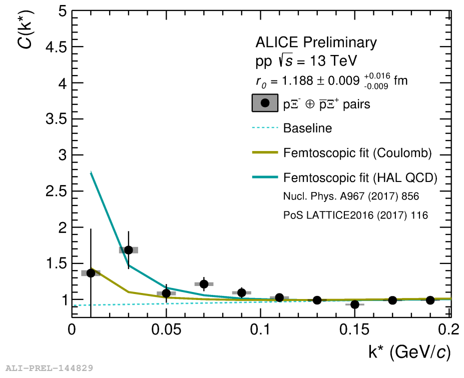
R. Lednicky and V. L. Lyuboshits, Sov. J. Nucl. Phys. **35**, 770 (1982), [Yad. Fiz.35,1316(1981)].

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





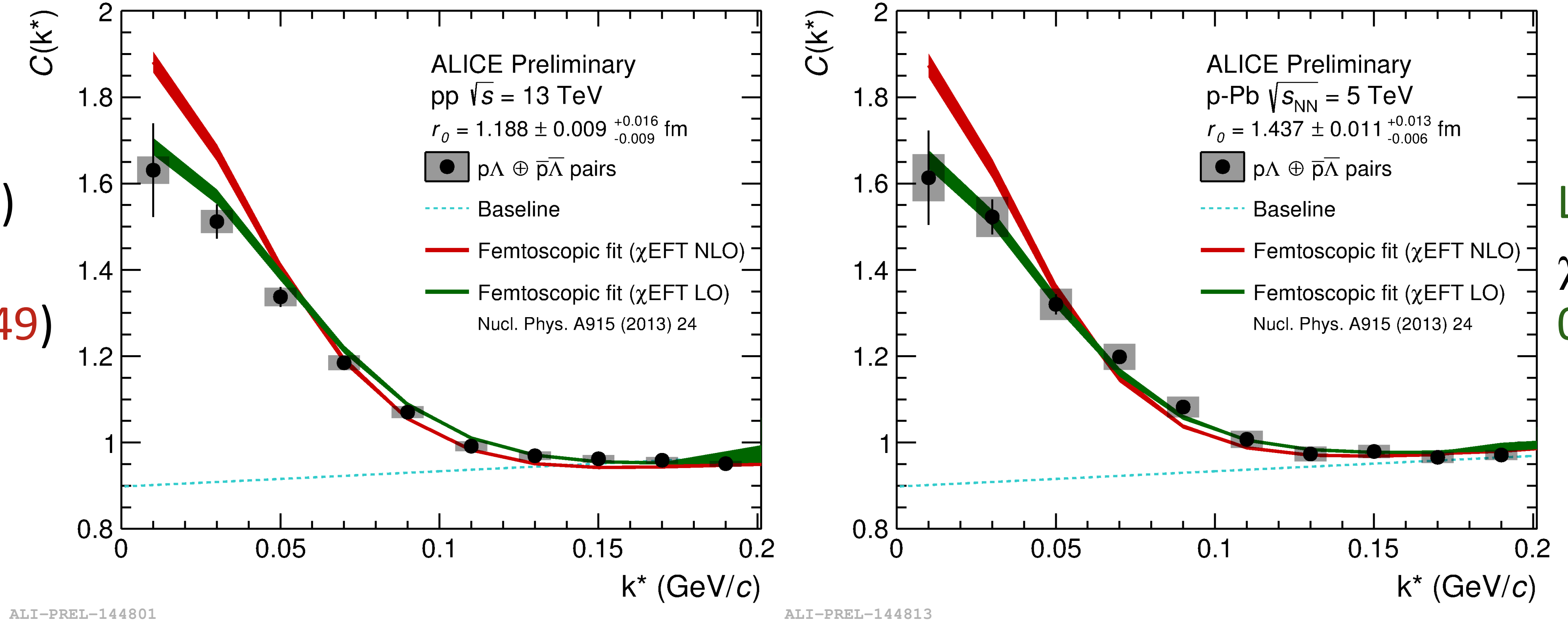




- Gaussian source and Argonne ν_{18} potential describes the p-p correlation function
  - Source size of the p-p (13 TeV) system r_0=1.12 fm
  - Source size of the p-Pb (5.02 TeV) system r_0=1.44 fm
    - For interaction studies the multiplicity integrated correlation function can be used

p-Λ Correlations: Gaussian Source

LO (NLO)
χ2/ndf
0.49 (2.49)

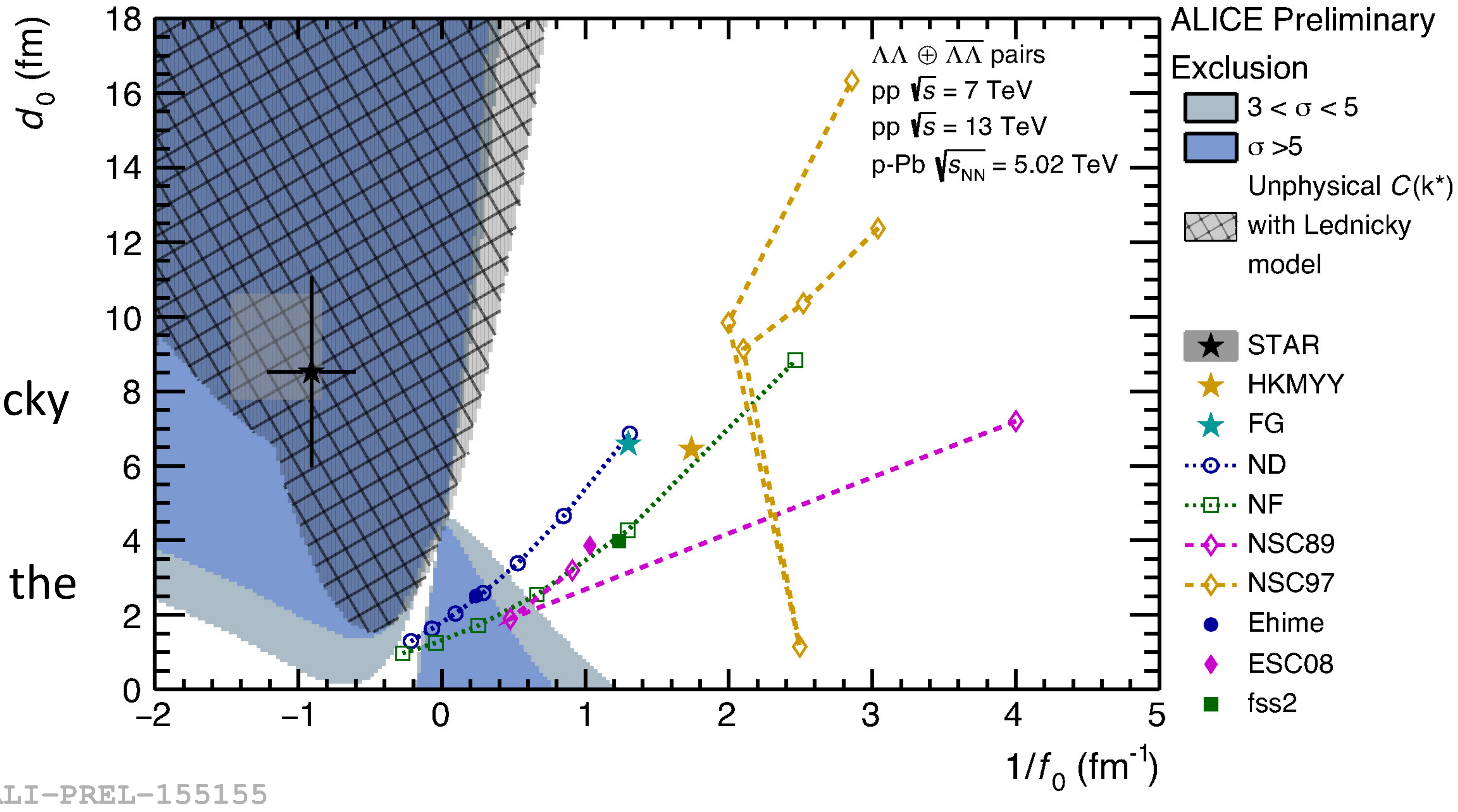


LO (NLO)
χ2/ndf
0.28 (1.69)

- With a Gaussian source the data of both collision systems favor χEFT LO calculations over NLO calculations

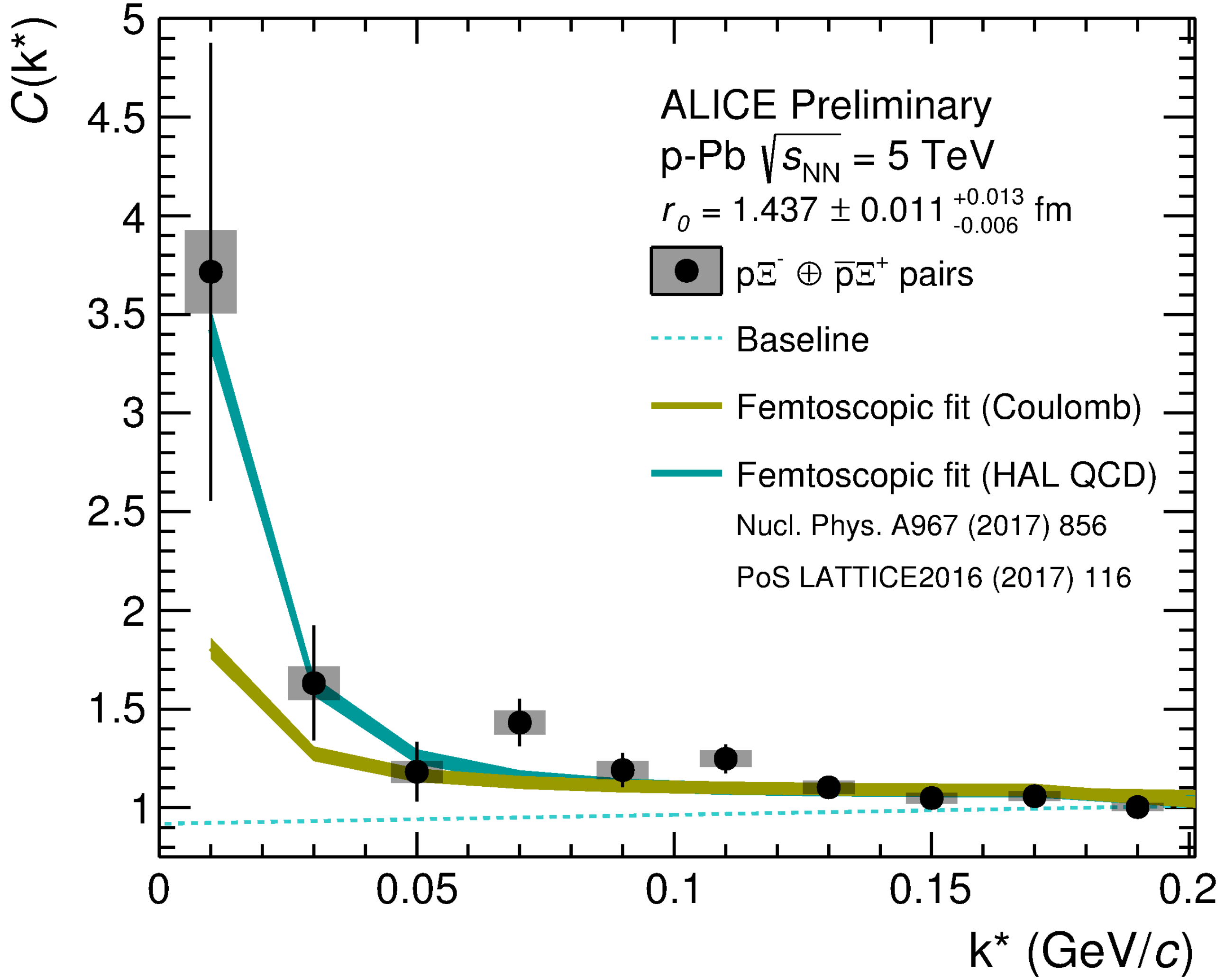
Λ–Λ Correlations: Exclusion Plot

- Combination of all available datasets
- Test of the agreement between data and the prediction by the Lednicky model by nσ
- Small source size limits the prediction power of Lednicky



p-Ξ⁻ Correlations

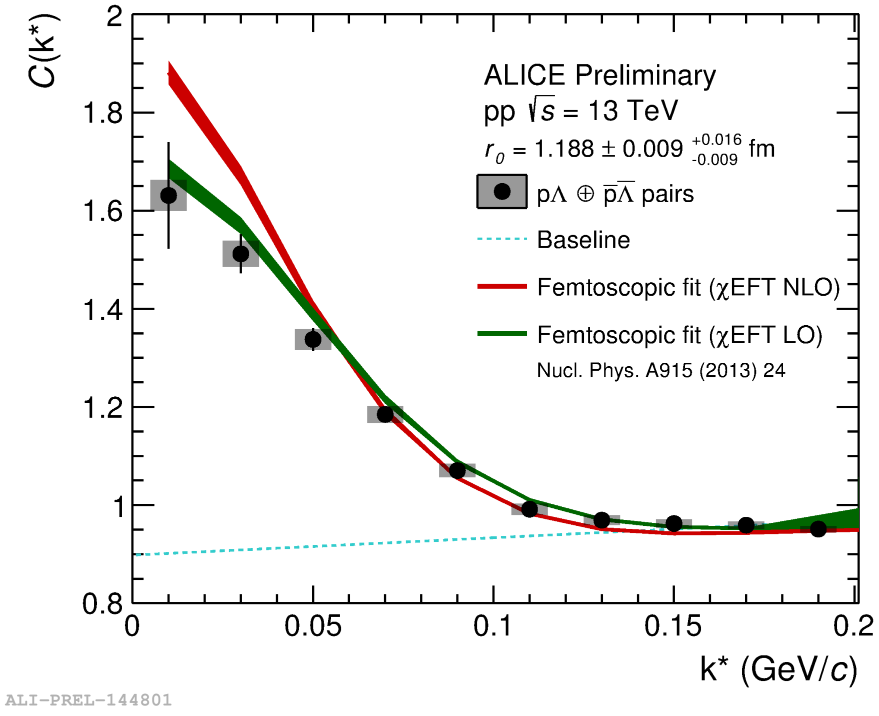
- In p-Pb data the strong interaction of p-Ξ⁻ can be directly seen in the correlation function
  - p-Value with and without strong potential (Coulomb only): 0.055 vs. 0.004
- Allows to test model calculations e.g. the preliminary QCD Strong potential by the HAL QCD collaboration

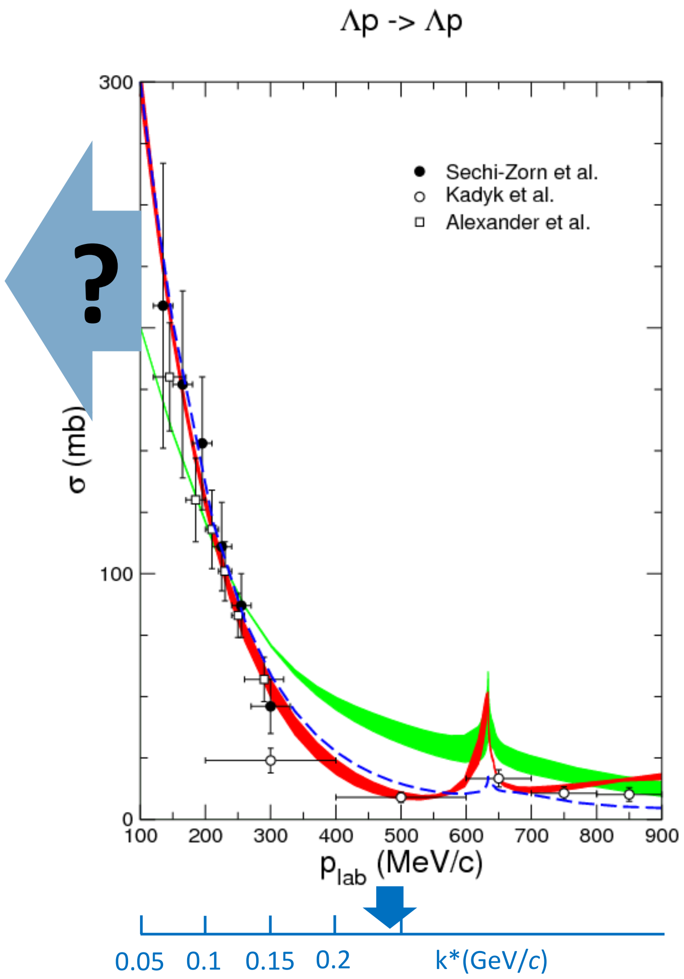


ALI-PREL-144825

Summary

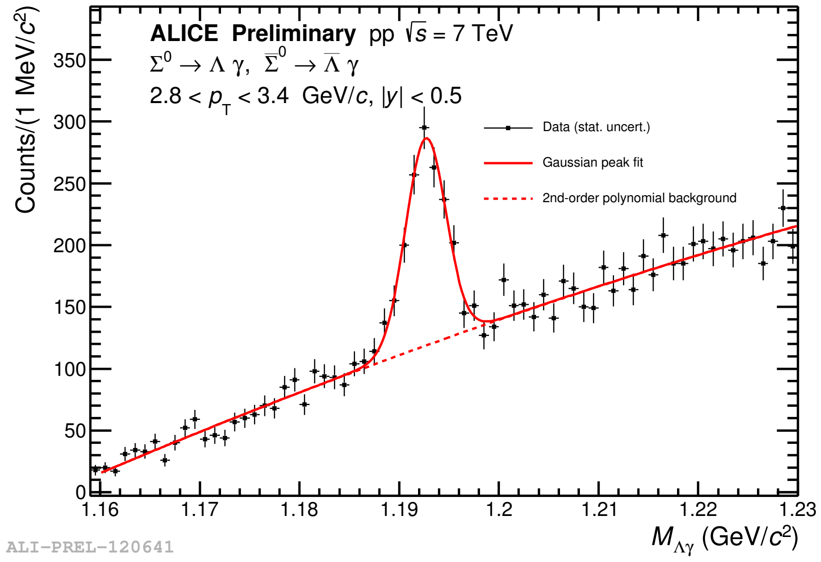
- Femtoscopy is an excellent tool to study interactions of particle pairs
  - Significant sensitivity to the interaction potentials
  - For hyperons accesses novel regions not constrained by scattering experiments
- The attractive p-Ξ^- interaction was observed for the first time

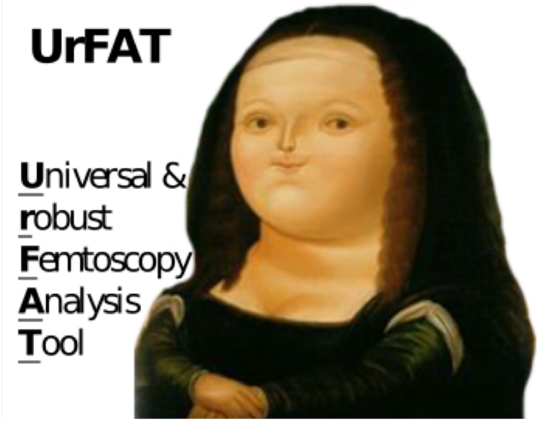




Outlook

- Run2 statistics might allow to study the p-Σ^0 correlation function
  - $\Sigma^0 \rightarrow \Lambda + \gamma$
    - $\hookrightarrow e^+ + e^-$
- Ongoing analysis of p-K pairs
- 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

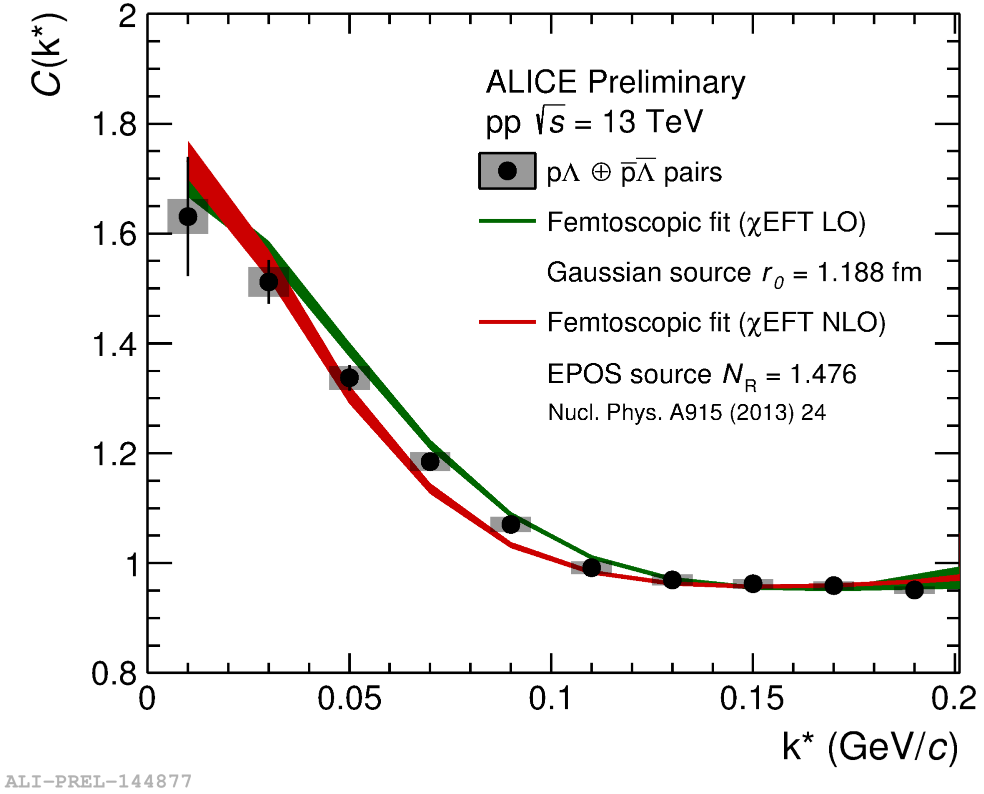




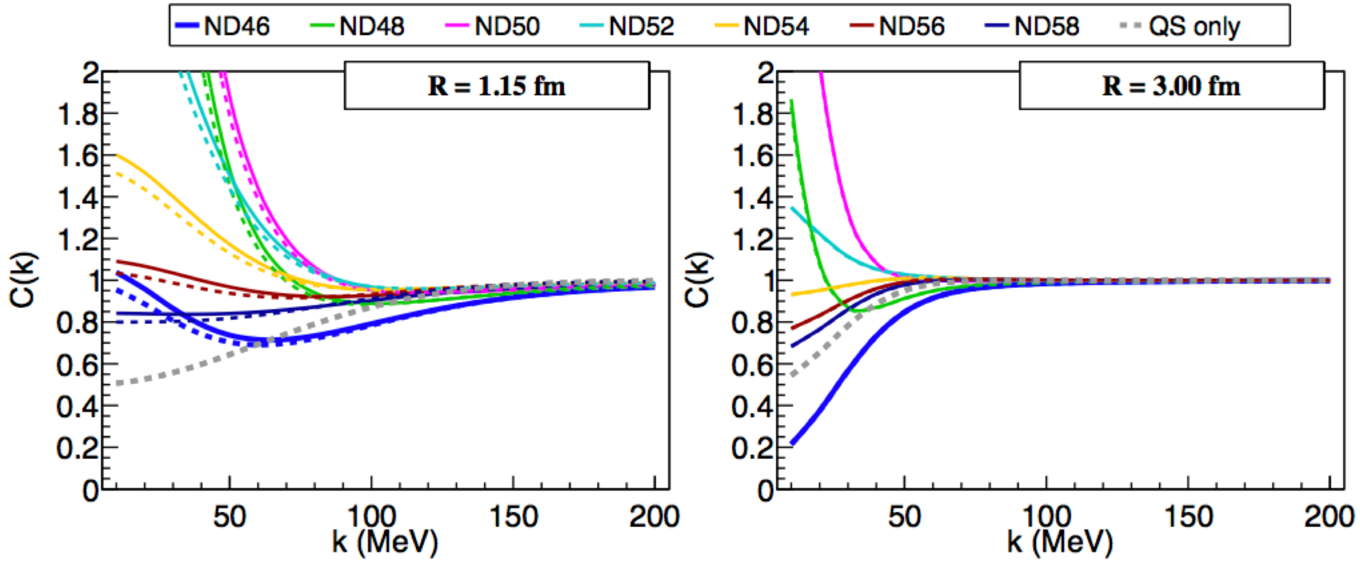
Thank you for your attention!

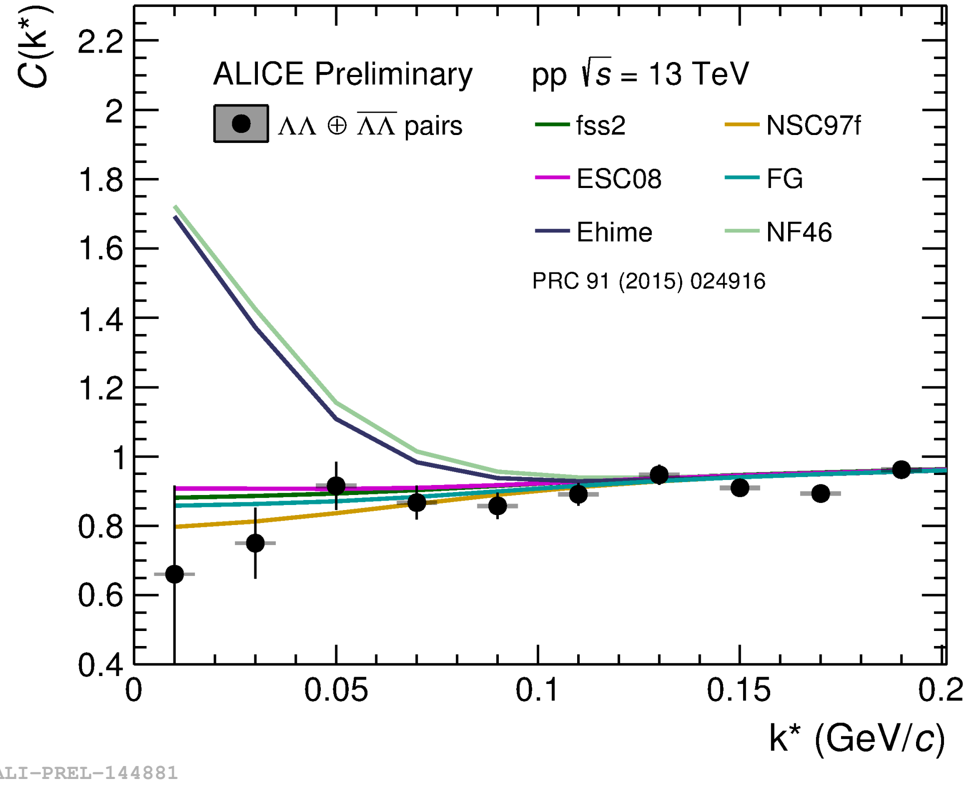
p-Λ Correlations: Scaled EPOS source

- 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

Λ–Λ Correlations: Exclusion Plot

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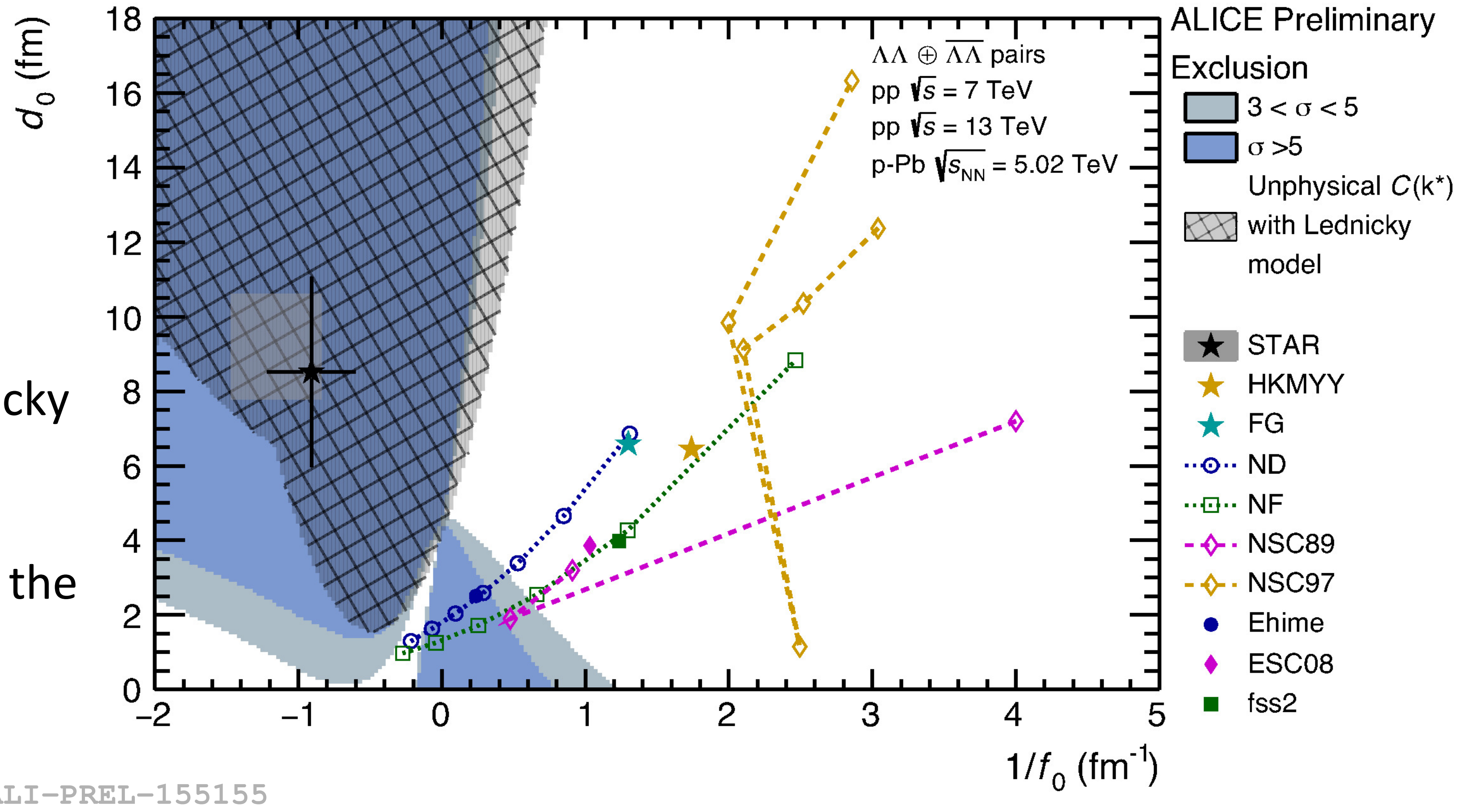


Decomposition of the p-p correlation function

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

- 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

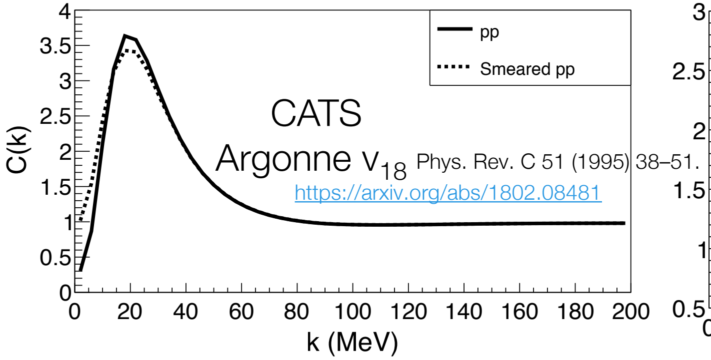
p–Ξ

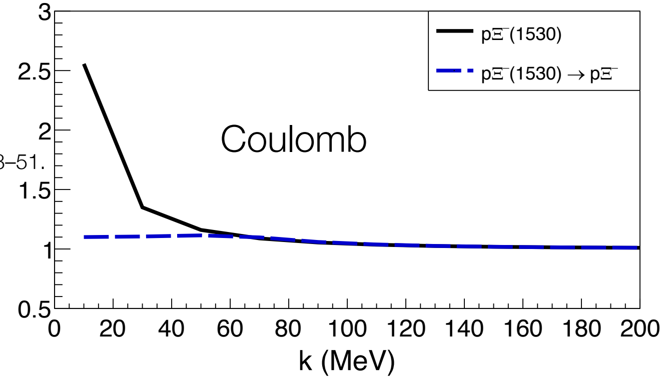
Pair	λ [%]
$p\Xi^-$	52.40
$p\Xi^-_{\Xi^-(1530)}$	8.32
$p\Xi^-_{\Xi^0(1530)}$	16.65
$p\Xi^-_{\Omega}$	0.67
$p_\Lambda\Xi^-$	5.25
$p_\Lambda\Xi^-_{\Xi^-(1530)}$	0.83
$p_\Lambda\Xi^-_{\Xi^0(1530)}$	1.67
$p_\Lambda\Xi^-_{\Omega}$	0.07
$p_{\Sigma^+}\Xi^-$	2.25
$p_{\Sigma^+}\Xi^-_{\Xi^-(1530)}$	0.36
$p_{\Sigma^+}\Xi^-_{\Xi^0(1530)}$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

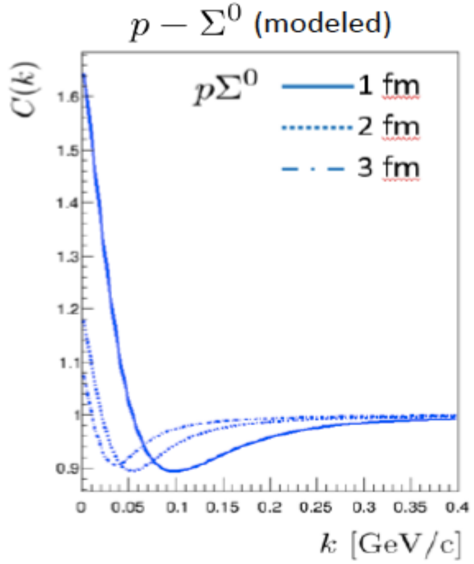
p–Ξ

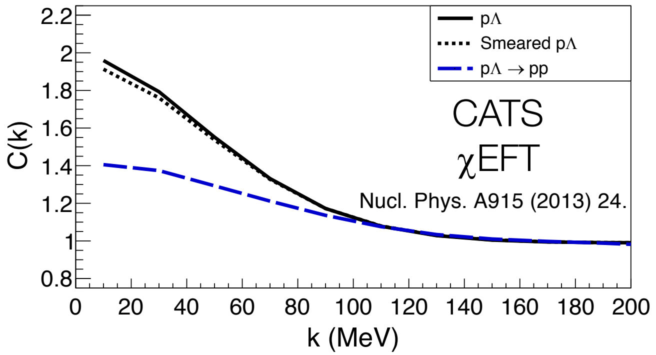
Pair	λ [%]
$\tilde{p}\Xi^-$	0.53
$\tilde{p}\Xi^-_{\Xi^-(1530)}$	0.08
$\tilde{p}\Xi^-_{\Xi^0(1530)}$	0.17
$\tilde{p}\Xi^-_{\Omega}$	0.01
$p\tilde{\Xi}^-$	8.67
$p_\Lambda\tilde{\Xi}^-$	0.87
$p_{\Sigma^+}\tilde{\Xi}^-$	2.25
$\tilde{p}\tilde{\Xi}^-$	0.09

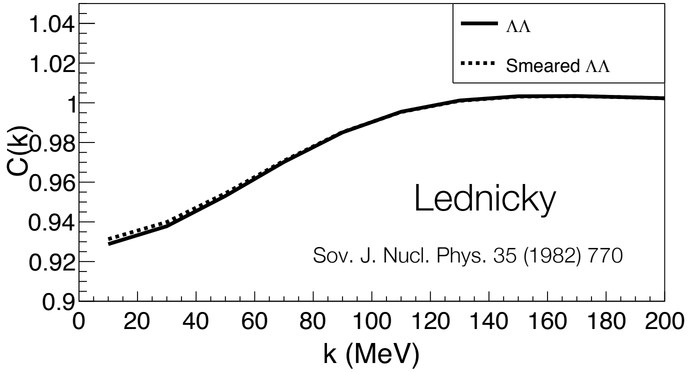
Considered Shapes

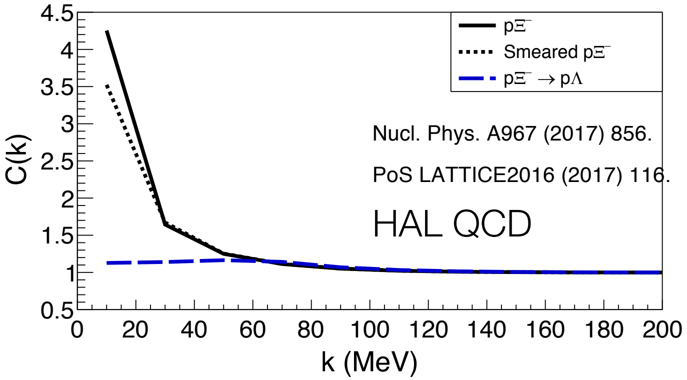












Some Numbers: pp - $\sqrt{s}$ = 13 TeV

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p	113.7 x 10^6
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Λ	22.3 x 10^6
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Pair	# of pairs k* < 200 MeV/*c*
$p - p$	190 x 10^3
$\bar{p} - \bar{p}$	140 x 10^3
$p - \Lambda$	62 x 10^3
$\bar{p} - \bar{\Lambda}$	49 x 10^3
$\Lambda - \Lambda$	5659
$\bar{\Lambda} - \bar{\Lambda}$	5243
$p - \Xi^-$	407
$\bar{p} - \Xi^+$	364

Some Numbers: p-Pb - $\sqrt{s_{NN}}$ = 5.02 TeV

p-Pb $\sqrt{s_{NN}} = 5.02$ TeV	
Particle	# baryons (uncorrected)
p	155 x 10^6
$\bar{\mathrm{p}}$	133 x 10^6
Λ	26 x 10^6
$\bar{\Lambda}$	24 x 10^6
Ξ^-	0.9 x 10^6
Ξ^+	0.9 x 10^6

Pair	# of pairs k* < 200 MeV/*c*
$\mathrm{p}-\mathrm{p}$	517 x 10^3
$\bar{\mathrm{p}}-\bar{\mathrm{p}}$	370 x 10^3
$\mathrm{p}-\Lambda$	127 x 10^3
$\bar{\mathrm{p}}-\bar{\Lambda}$	62 x 10^3
$\Lambda-\Lambda$	13 x 10^3
$\bar{\Lambda}-\bar{\Lambda}$	12 x 10^3
$\mathrm{p}-\Xi^-$	1.8 x 10^3
$\bar{\mathrm{p}}-\Xi^+$	1.3 x 10^3

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