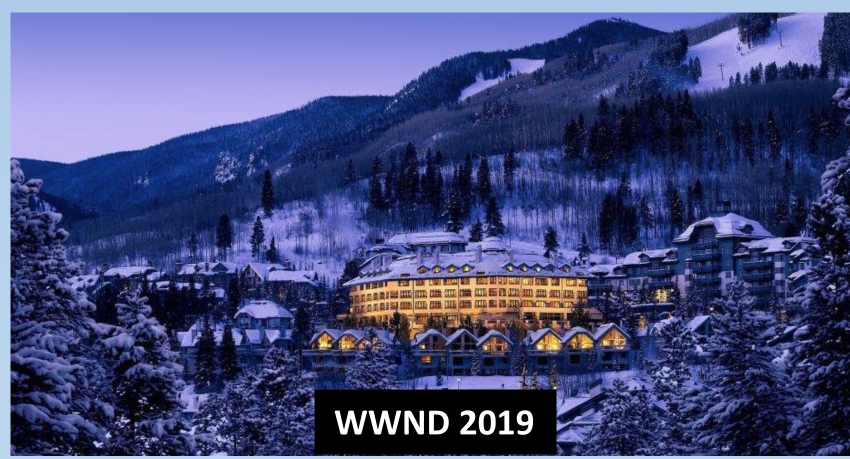
Femtoscopy as a precision tool for studying the p-Λ and Λ-Λ interaction

Dimitar Mihaylov
for the ALICE collaboration

SFB 1258 Neutrinos Dark Matter Messengers



10th January 2019

Overview

1) Femtoscopy
   Introduction and motivation
   Modeling the correlation function
   Correcting the correlation function

2) The p-Λ correlation function
   ALICE data from pp collisions at 13 TeV
   Effects of m_{T} scaling and short-lived resonances

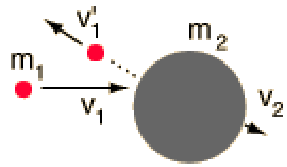
3) The Λ-Λ interaction
   Constrain the scattering parameters
   Is a bound state allowed?

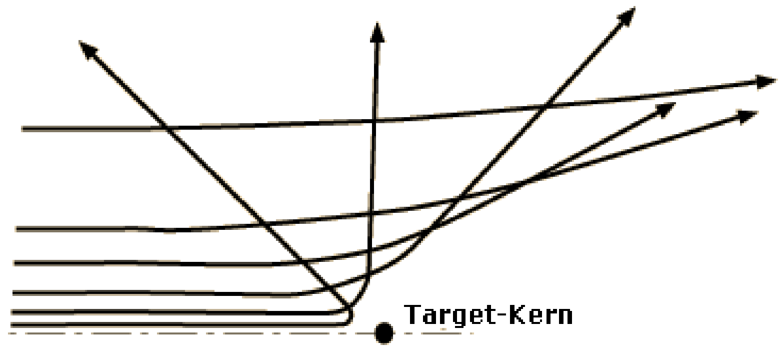
The story continues in the talk of
Valentina Mantovani Sarti

Hadron interactions

Scattering data and interaction parameters

- **Scattering experiments**
  Extraction of the differential cross section $\frac{\mathbf{d}\boldsymbol{\sigma}}{\mathbf{d}\boldsymbol{\Omega}}$





Phase shifts

Partial Wave Expansion: $$\sigma = \frac{4\pi}{k^2}\sum_l (2l+1)\sin^2(\delta_l)$$

Effective range

Effective range expansion: $$\lim_{k\to 0} k\cot\left(\delta_l(k)\right) \approx + \frac{1}{f_0} + \frac{1}{2} d_0 k^2$$

Scattering length

Works for s-waves

Different sign convention in femtoscopy

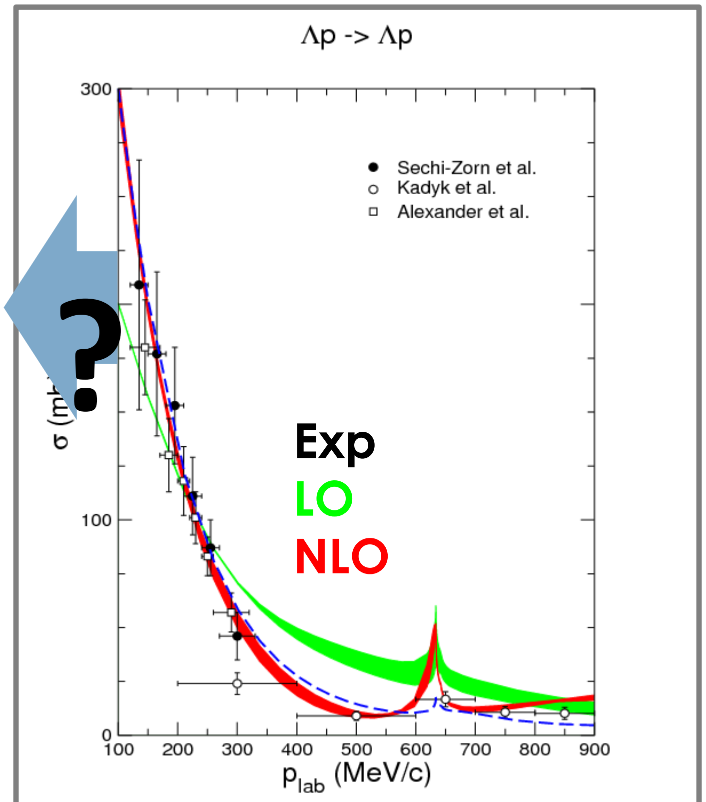
Hadron interactions

Hyperon-Nucleon scattering

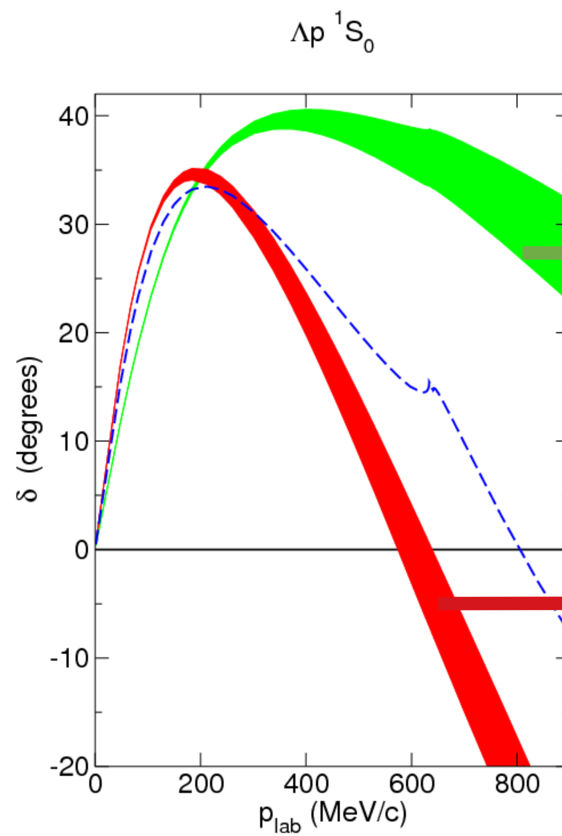
LO less attractive than **NLO**

$f_0(^1S_0) = 1.91$ fm

$f_0(^1S_0) = 2.91$ fm



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



Interaction always attractive

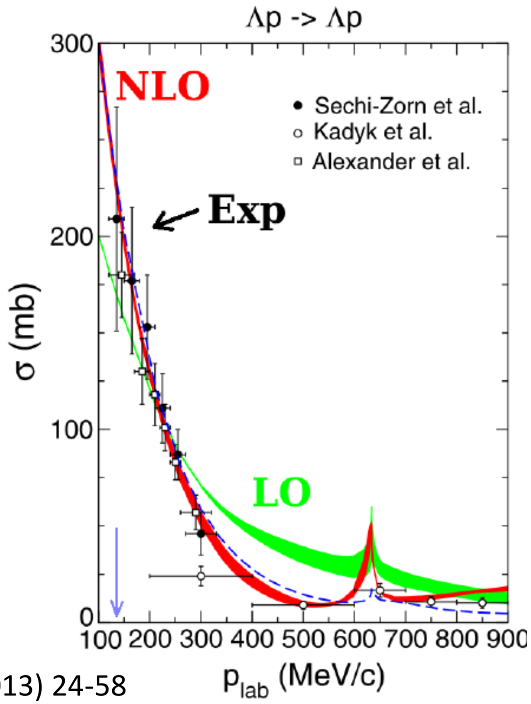
Repulsive core of the interaction

Motivation

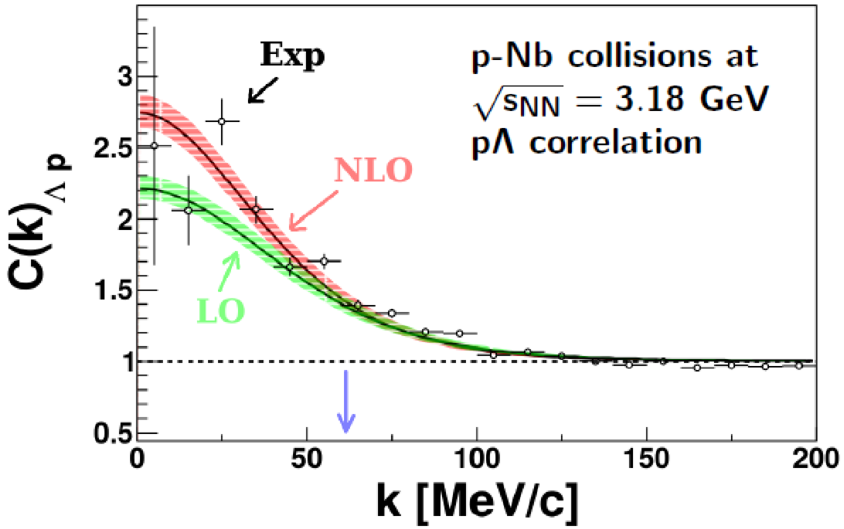
Why femtoscopy?

Advantages of femtoscopy

- Femtoscopy can be used to study any particle pairs
- Femtoscopy investigates the low-momentum interaction region
- This is in contrast to scattering and hypernuclei experiments, where only limited data is available for more exotic particle pairs



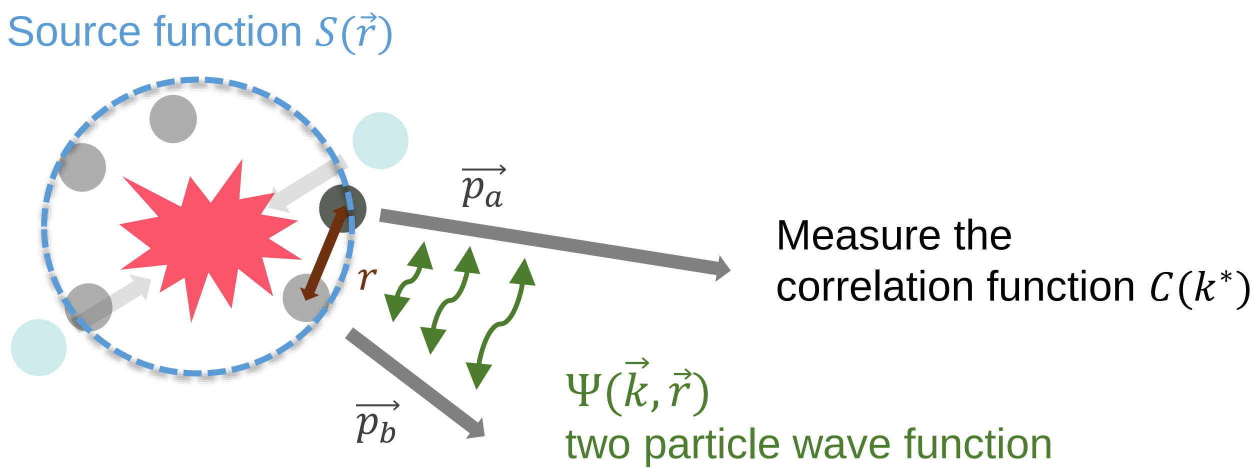
Nucl. Phys. A915 (2013) 24-58



Phys. Rev. C 94, 025201

Femtoscopy

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

Femtoscopy
Analysis strategy

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

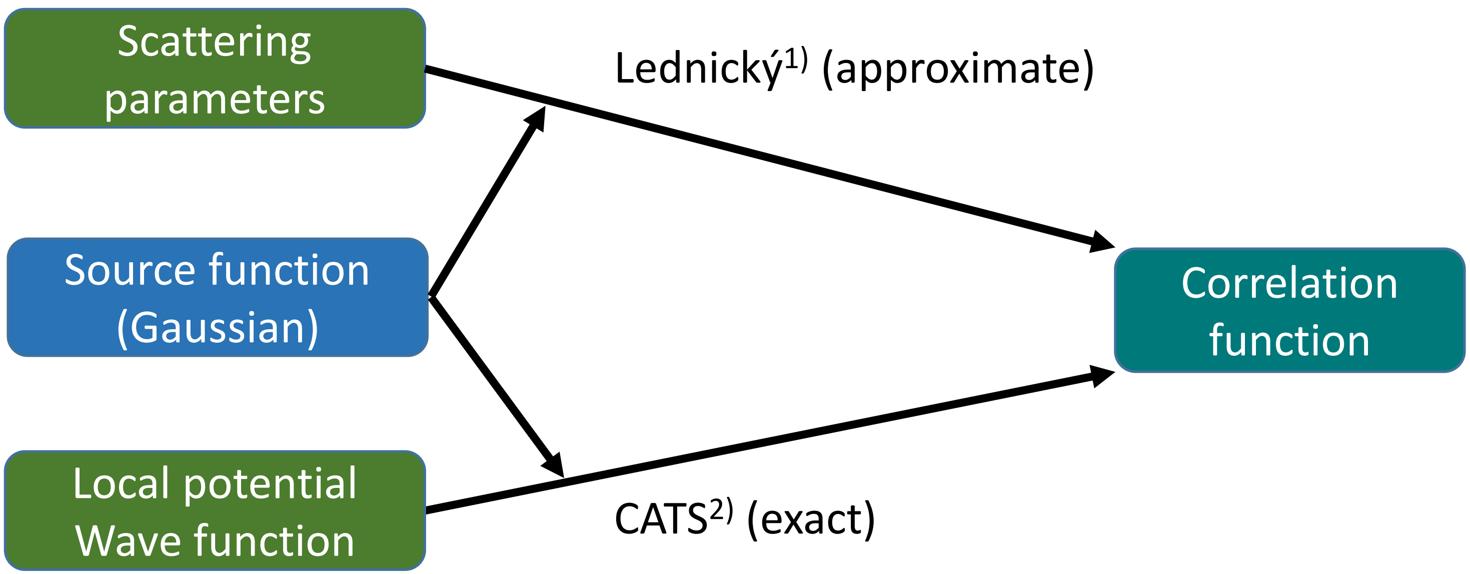
- We would like to **study the** **interaction**
- **Assumption:**
  In small (pp and p-Pb) collision systems the emission source $S(\vec{r})$ is Gaussian and approximately the same for all particle pairs
  Possible differences of the radii due to kinematic effects and the contribution from short-lived resonances were investigated and are included in the systematics
- The **p-p interaction** is known, hence can be used to **fix the source**
  The potential used is Argonne V18: Wiringa, Robert B. et al. Phys.Rev. C51 (1995) 38-51
- Effects of momentum resolution and feed-down contributions are included in the theoretical calculations, following *arXiv:1805.12455*

Femtoscopy

The tools

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

How to compute C(k)?



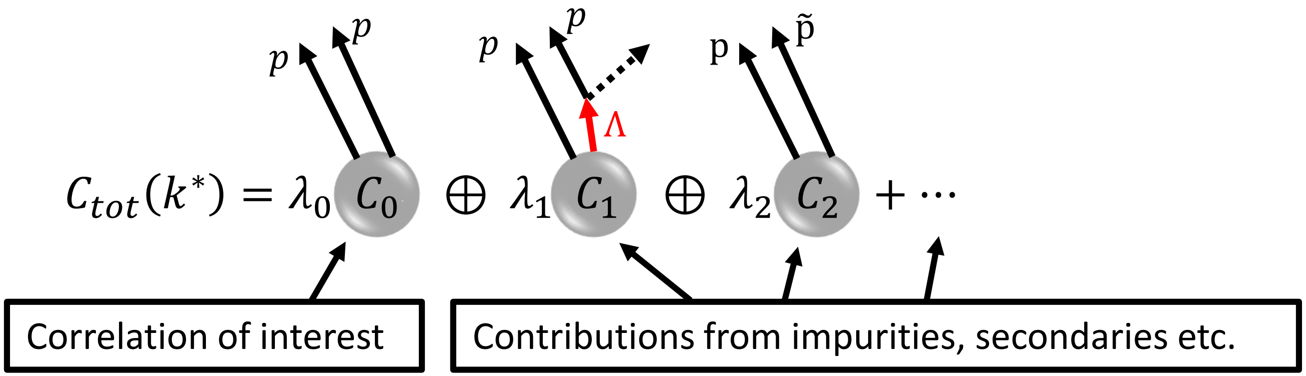
1) R. Lednicky and V. L. Lyuboshits, Sov. J. Nucl. Phys. 35, 770 (1982), [Yad. Fiz.35,1316(1981)]

2) Mihaylov, Mantovani et al., Eur. Phys. J. C (2018) **78**: 394

Femtoscopy

Correction for feed-down (1/2)

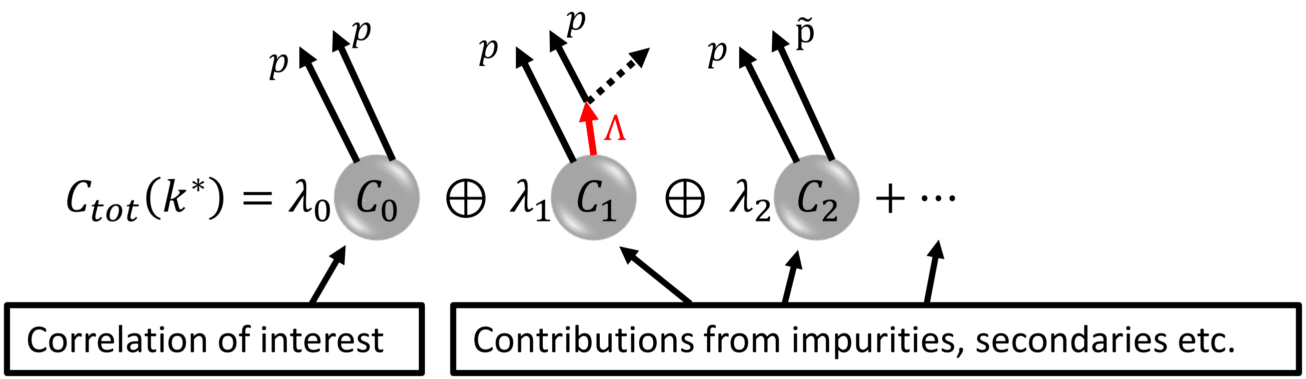
- **Determine the amount of impurities and secondaries** based on a data-driven MC study as done in arXiv:1805.12455



- 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

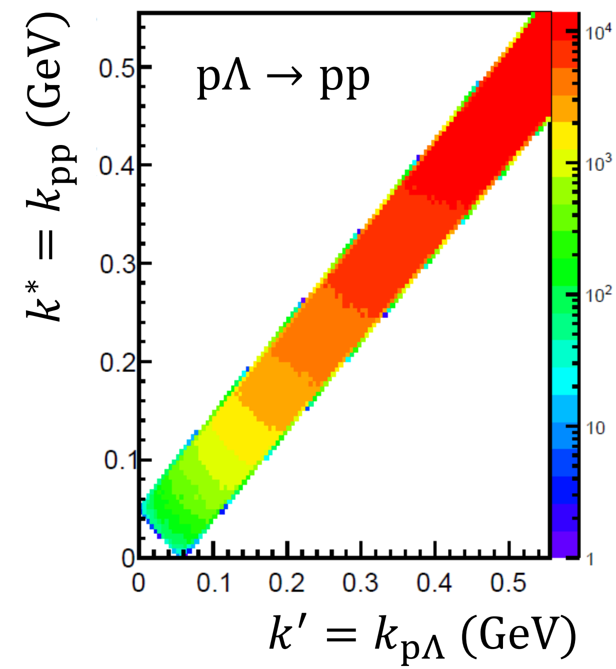
Femtoscopy

Correction for feed-down (2/2)



- The correlation function of the feed-down contributions (like C_1) are a convolution between the “mother” correlation function and a smearing matrix modelling the kinematics of the decay $C \rightarrow B_C$

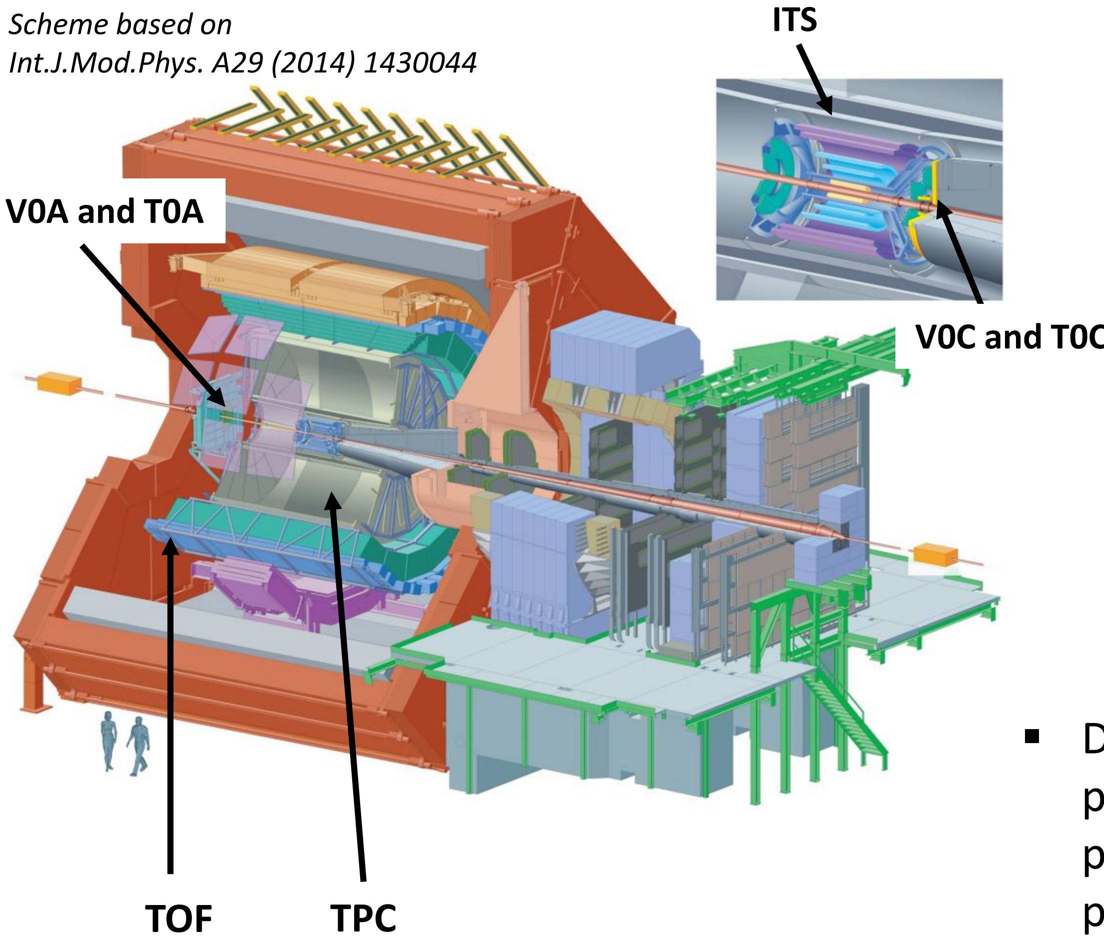
$$C_i(k^*) = \frac{\int dk' T_{\mathrm{res},i}^{k' \rightarrow k^*} C_i(k')}{\int dk' T_{\mathrm{res},i}^{k' \rightarrow k^*}}$$



Femtoscopy in ALICE

Quick overview

Scheme based on
Int.J.Mod.Phys. A29 (2014) 1430044



- In this and the next talk: Measurement of p-p, p-Λ, Λ-Λ, p-Ξ and p-K correlations
- Triggering: V0 detectors
- Vertex reconstruction: ITS
- Tracking: ITS and TPC
- Particle identification of protons, kaons and pions: TPC and TOF
- Reconstruction of hyperons:

  $\Lambda \to p\pi^-$ (BR c.a. 64%)

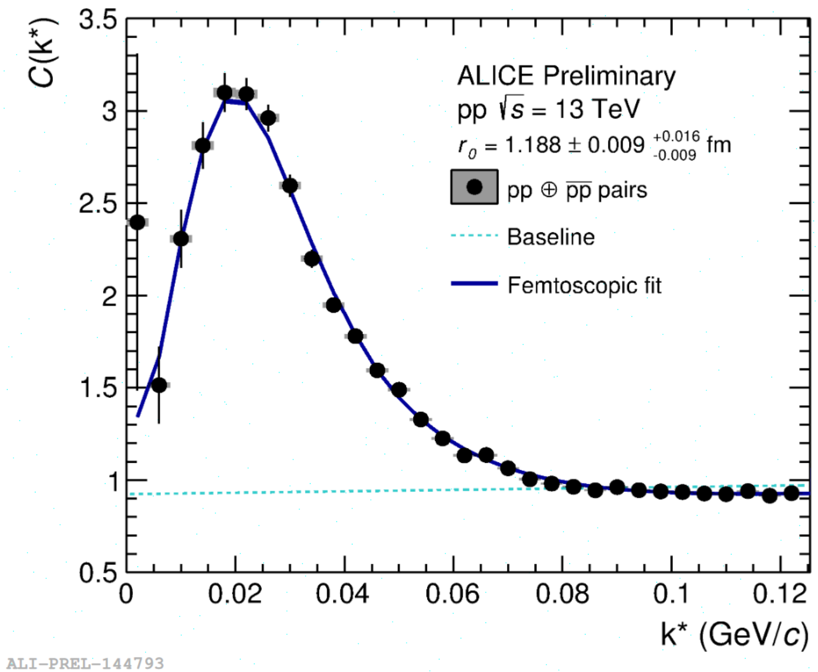
  $\Xi^- \to \Lambda\pi^-$ (BR c.a. 100%)

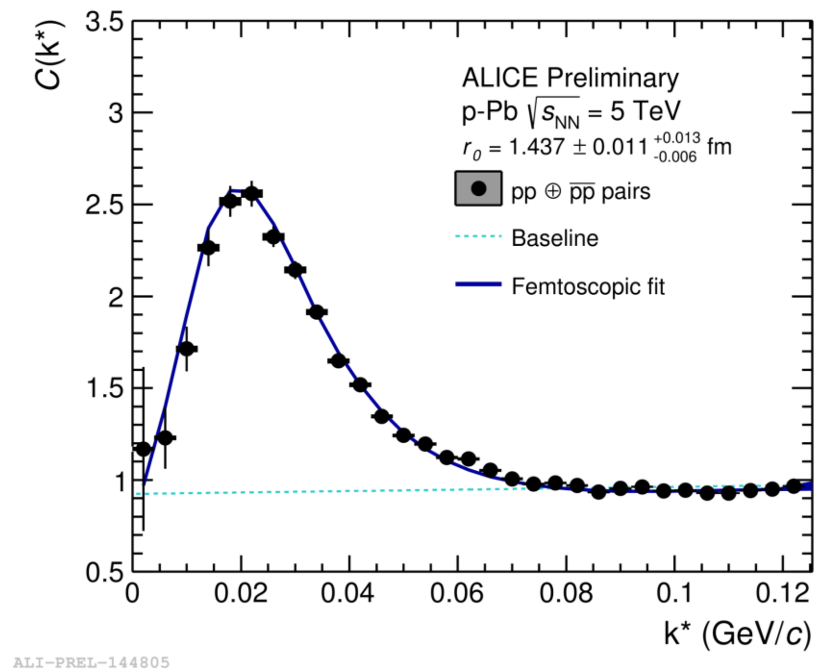
- Data sets:
  pp 7 TeV (340 M min. bias events)
  pp 13 TeV (1000 M min. bias evets)
  p-Pb 5.02 TeV (600 M min. bias events)

Femtoscopy in ALICE

pp correlation function

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



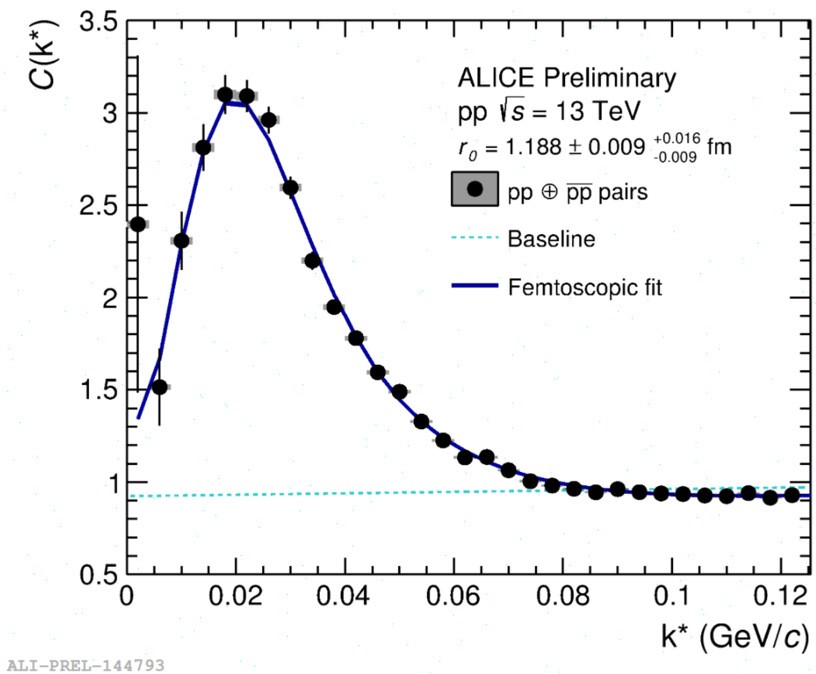


- Assuming a Gaussian profile the source size (r_0) is extracted by fitting the correlation function
- This allows to study the interaction potential in other systems

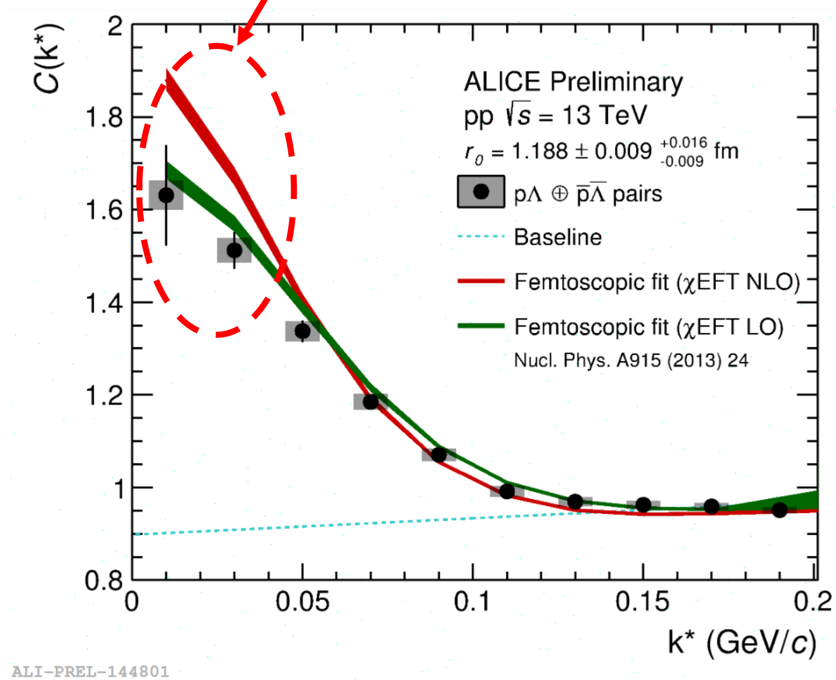
1) Femtoscopy
2) **The p-Λ correlation function**
3) The Λ-Λ interaction

p-Λ correlation
Run2 results

- Analysis of **pp collisions @ 13 TeV**
- The source fixed from the p-p correlation



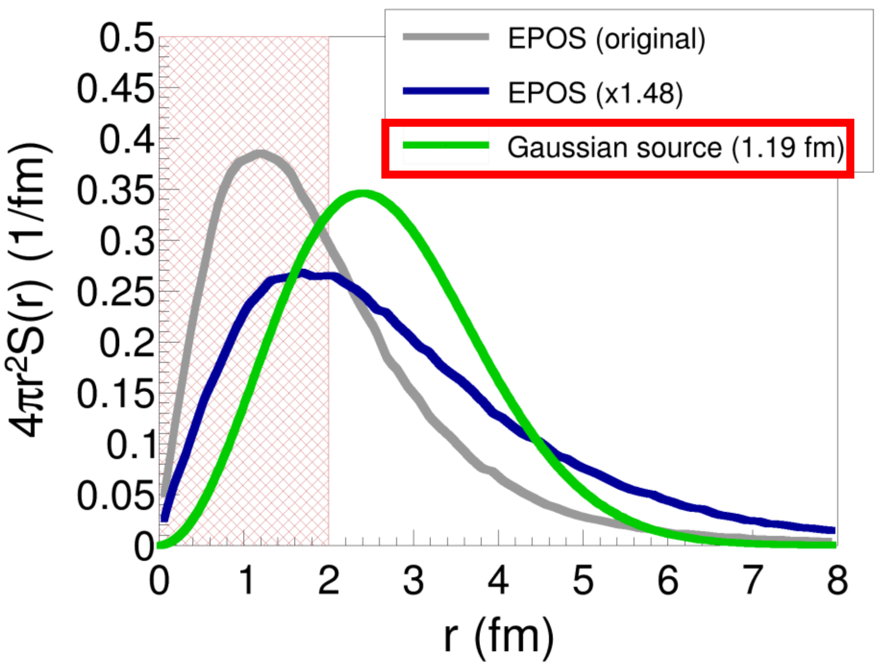
Already interesting

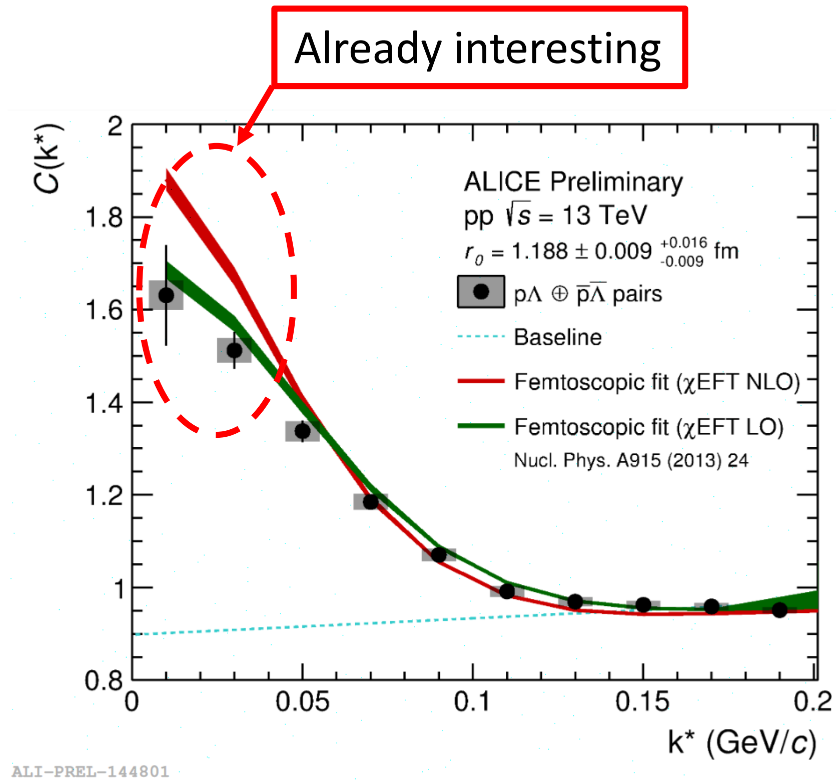


LO fits better than NLO?
Is the source correct?

p-Λ correlation
Run2 results

- Analysis of **pp collisions @ 13 TeV**
- The source fixed from the p-p correlation

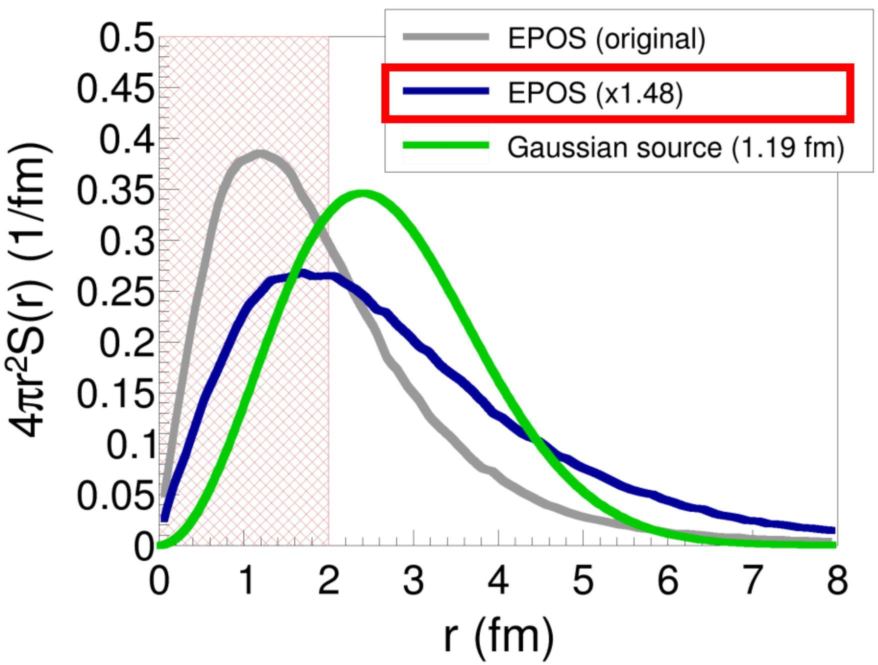




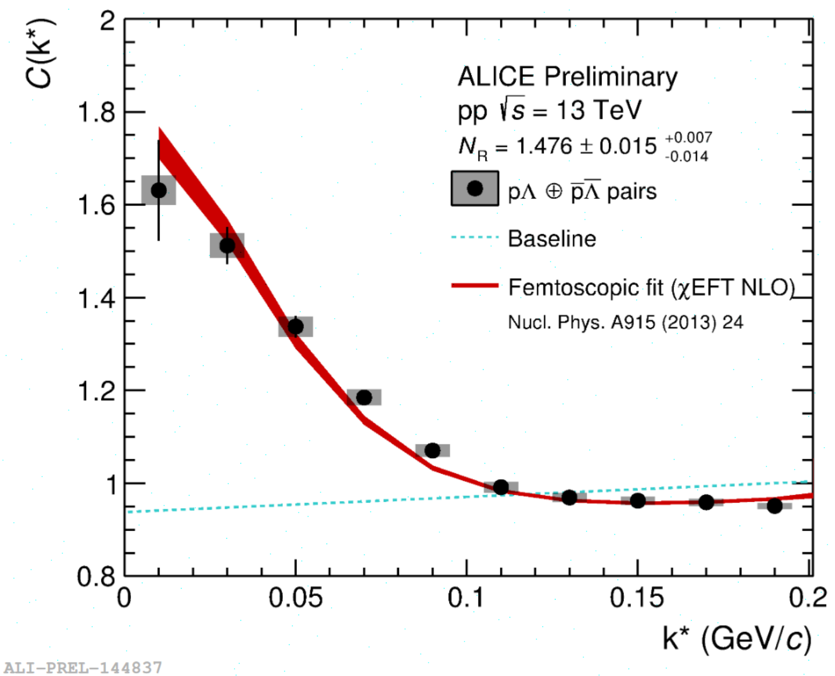
LO fits better than NLO?
Is the source correct?

p-Λ correlation
Changing the emission source

- Take-home message: **the p-Λ correlation is sensitive to the profile of the source function**!



Rescaled EPOS* source



* *T. Pierog et al, Phys.Rev. C92 (2015) no.3, 034906*

The emission source
Non-Gaussian effects

- Assume a Gaussian "core" source
  Outlook: non-Gaussianity can be tested with transport models

- Kinematic effects, e.g. m_{T} dependent source
  Experimentally accessible only for p-p and p-Λ, the m_{T} scaling assumed to be the same for all baryon-baryon pairs

- Decays of short-lived ($c\tau \sim 1$ fm) resonances, which introduce an exponential tail to the source

- These effects are included in the systematic uncertainties

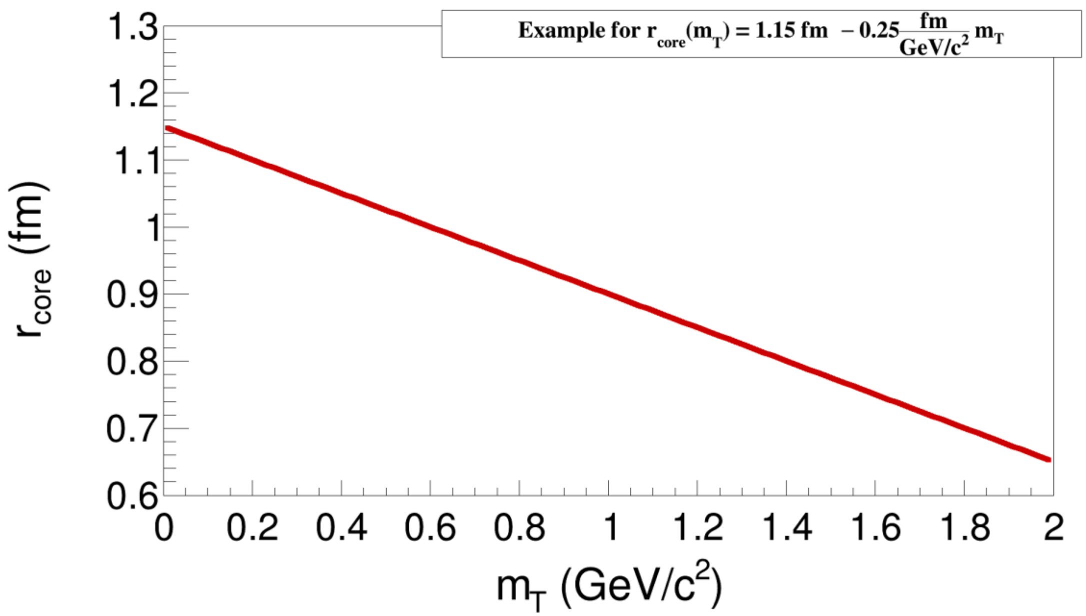
The emission source

Core radius in m_{T}

Gaussian “core” radius:

$$G(r, r_{\mathrm{core}}) = \frac{2\sqrt{\pi} r^2}{r_{\mathrm{core}}^3} \exp\left(-\frac{r^2}{4r_{\mathrm{core}}^2}\right)$$

Fit r_{core} from the experimental data differentially in m_{T}

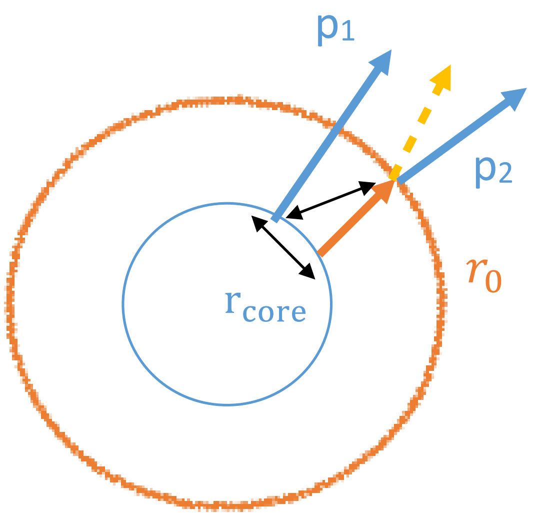


The emission source
Short lived resonances

If a "core" particle is a short lived resonance, it will decay following an exponential law:

$$E(r, M_{\text{res}}, \tau_{\text{res}}, p_{\text{res}}) = \frac{1}{s}\exp\left(-\frac{r}{s}\right)$$

$$s = \beta\gamma\tau_{\text{res}} = \frac{p_{\text{res}}}{M_{\text{res}}}\tau_{\text{res}}$$



- The amount of resonances and the parameters $M_{\text{res}}, \tau_{\text{res}}$ are determined from a statistical hadronization model (canonical)
  F. Becattini et al, J.Phys. G38 (2011) 025002
- p_{res} determined by assuming a 2-body decay

The emission source
Short lived resonances

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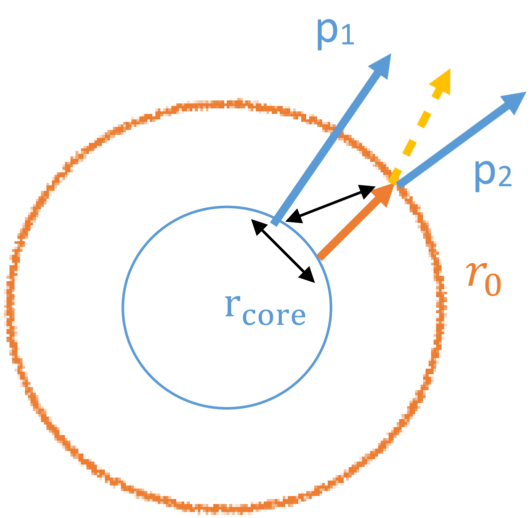


Particle	M_{res} [MeV]	τ_{res} [fm]
p	1361.52	1.65
Λ	1462.93	4.69

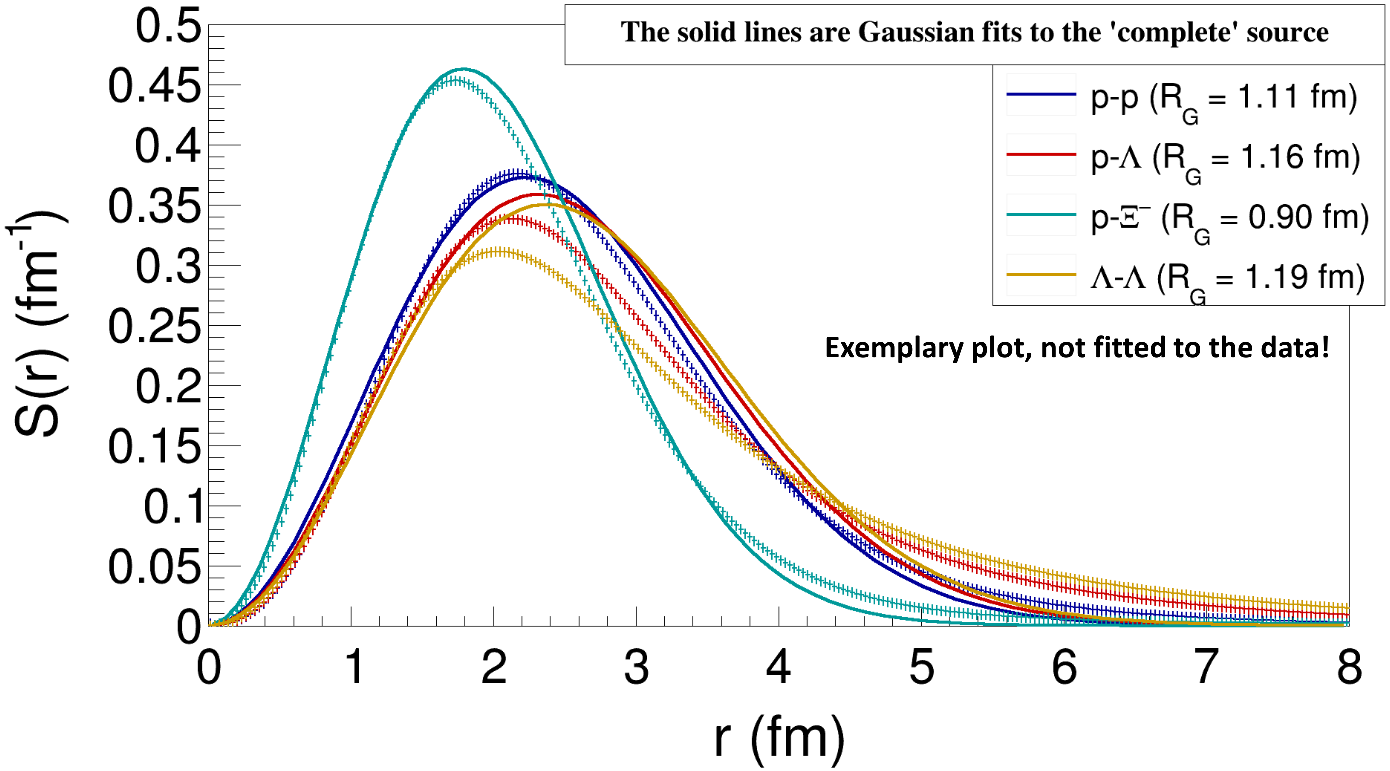
c.a. 36% of primary particles for both p and Λ

The emission source

Total source

The final "effective" source is given by the convolution of the core and the exponential tail:

$$S_{\text{eff}}^{(E)}(r, r_{\text{core}}(m_{\text{T}}), M_{\text{res}}, \tau_{\text{res}}, p_{\text{res}}) = G\big(r, r_{\text{core}}(m_{\text{T}})\big) \oplus E(r, M_{\text{res}}, \tau_{\text{res}}, p_{\text{res}})$$



1) Femtoscopy
2) The p-Λ correlation function
3) **The Λ-Λ interaction**

Λ-Λ interaction

Overview

- No scattering data
- A single event from hypernuclei
- Femtoscopic analysis in heavy-ion collisions (STAR) extremely inconclusive, due to the unconstrained residual signal

Original analysis by STAR
Phys.Rev.Lett. 114 (2015) no.2, 022301

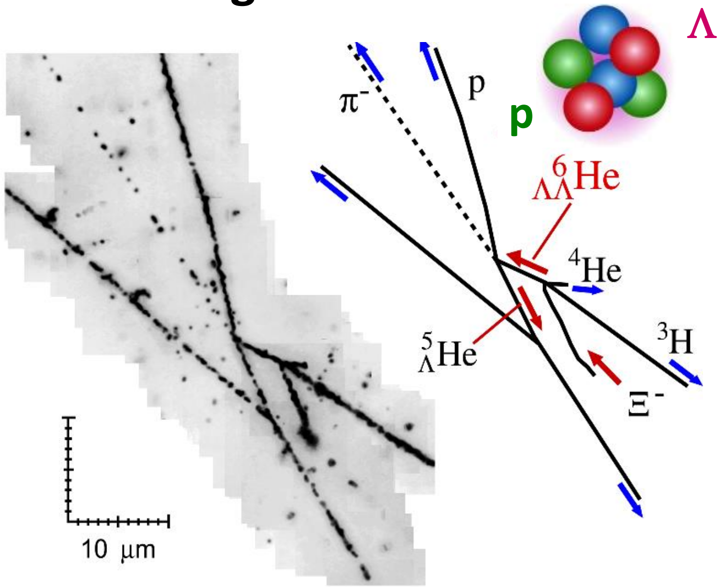
Repulsive potential?

Reanalyisis by Morita et al.
Phys.Rev. C91 (2015) no.2, 024916

Attractive potential?

Small scattering length ($|f_0| \leq 1$ fm)
Large effective range ($d_0 \geq 4$ fm)

"Nagara" event



$$^{\;\;6}_{\Lambda\Lambda}\mathrm{He} \rightarrow {}^{5}_{\Lambda}\mathrm{He} + \mathrm{p} + \pi^{-}$$

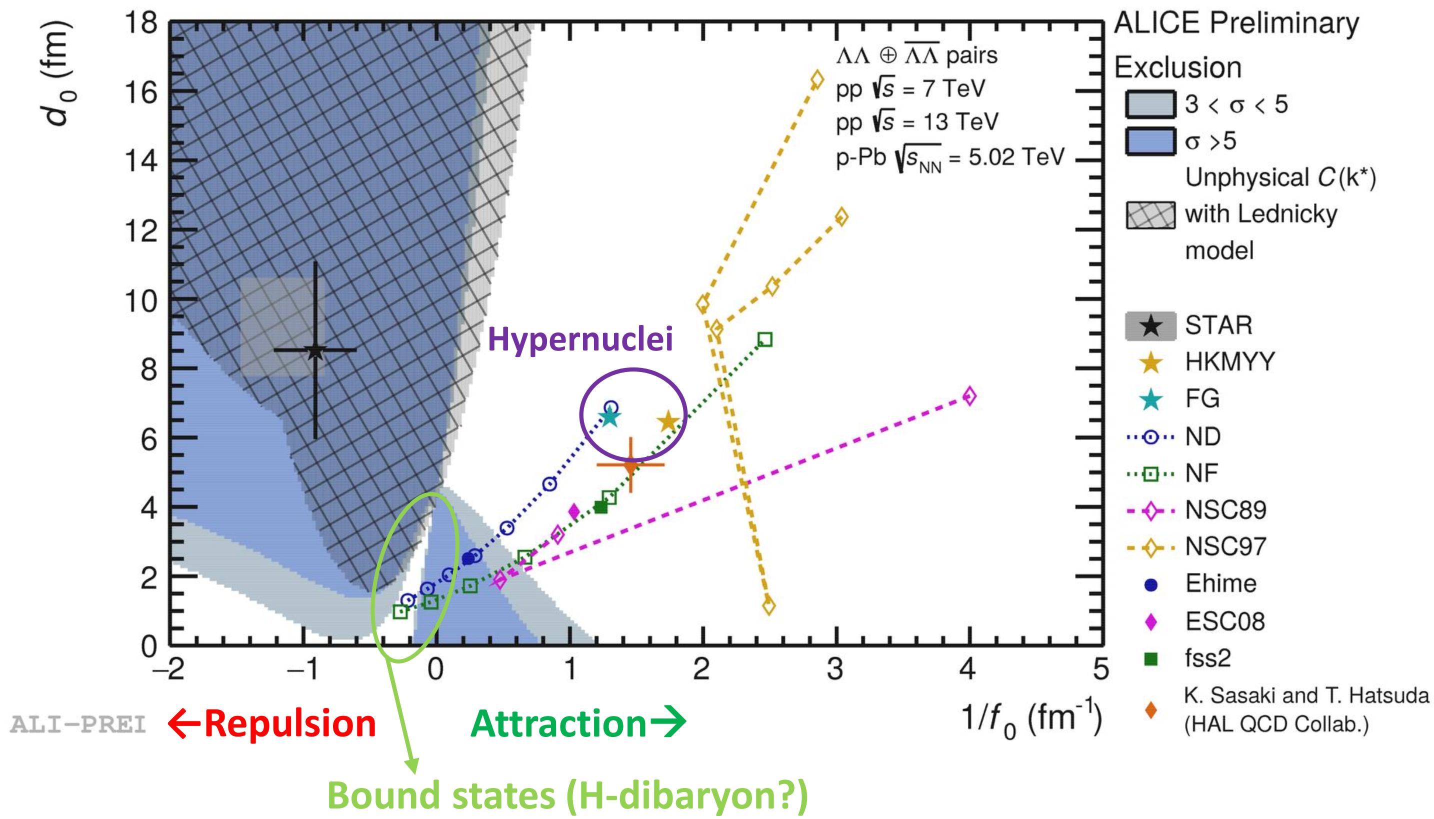
$$\Delta B_{\Lambda\Lambda} = 0.67 \pm 0.17\ \mathrm{MeV}$$

Λ-Λ is weakly attractive

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

Λ-Λ interaction
ALICE results

- Use Lednický to test the compatibility of different scattering parameters (f_0, d_0) to the data
- Plot the deviation from the data in $\mathrm{n}\sigma$
- Combine the results from **pp @ 7 TeV, pp @ 13 TeV and p-Pb @ 5.02 TeV**



Λ-Λ interaction

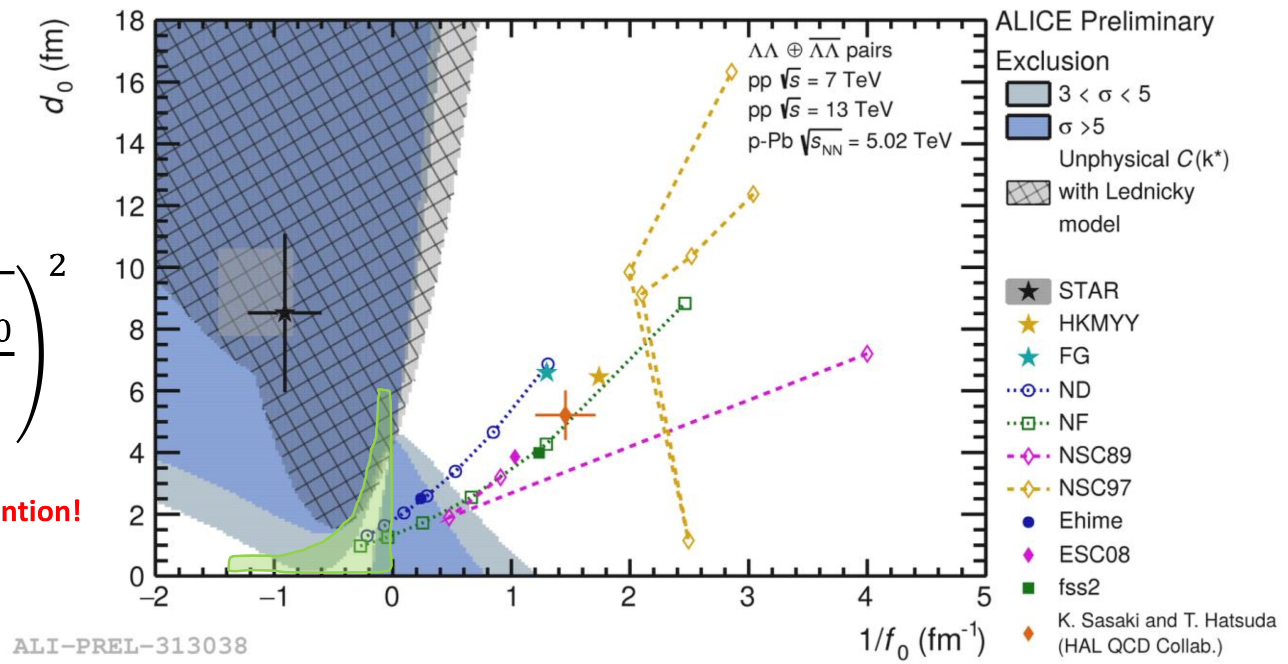
Bound state (H-dibaryon)?

- Zoom in the “bound” allowed area of the parameter space
- Compute the **binding energy** using the relation below

$$B_{\Lambda\Lambda} = \frac{1}{m_{\Lambda} d_0^2}\left(1 - \sqrt{1 + \frac{2d_0}{f_0}}\right)^2$$

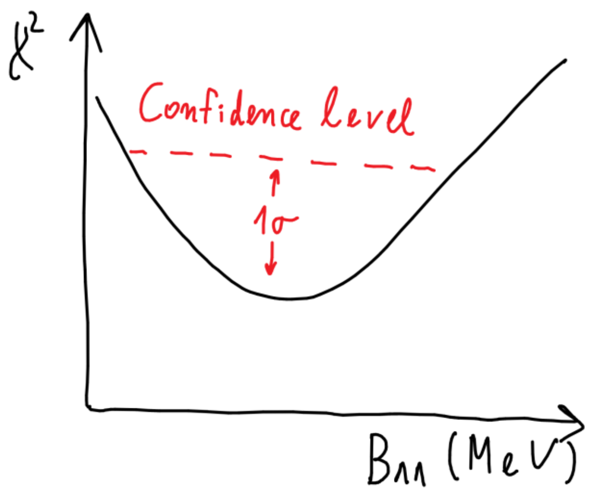
Femto sign convention!

Rept.Prog.Phys. 80 (2017) no.5, 056001
Phys.Rev.Lett. 120 (2018) 212001



Λ-Λ interaction
Bound state (H-dibaryon)?

We aim at extracting a confidence level for $B_{\Lambda\Lambda}$



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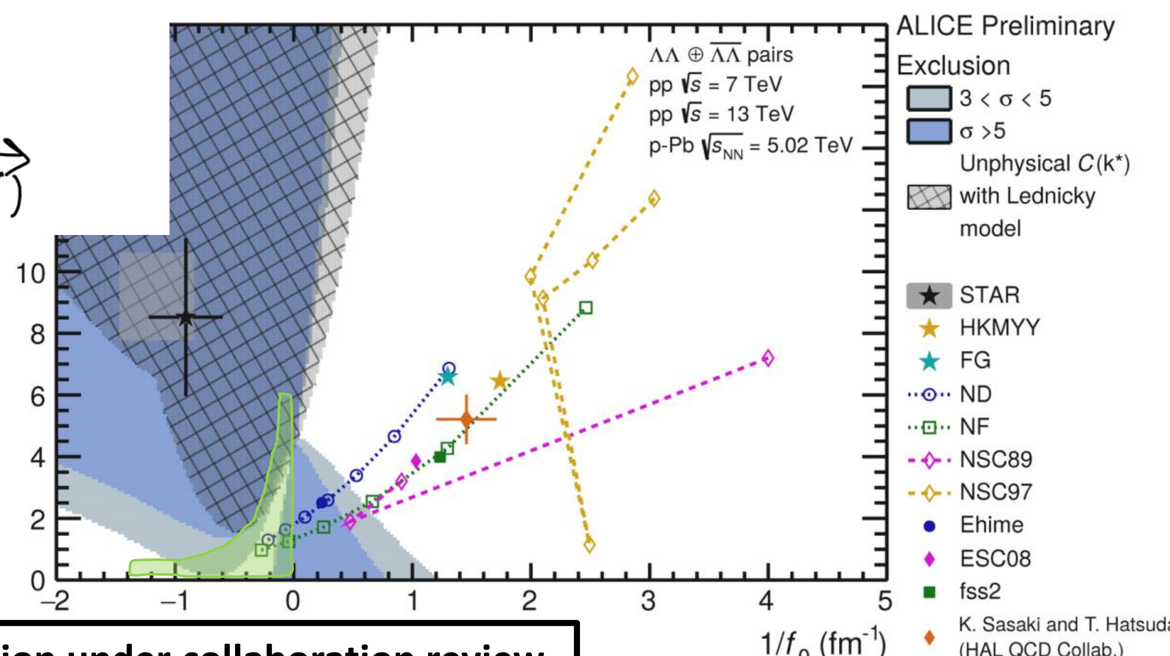


Publication under collaboration review.

Summary

- Femtoscopy in small collision systems as a complementary tool to scattering and hypernuclei experiments
  "The low energy scattering experiment"

- Analysis techniques
  Residual correlations
  Constraining the emission source using pp correlations

- p-Λ interactions entering the precision era
  Allowing to test the profile of the emission source in more details:
  m_{T} *scaling and effect of short-lived resonances*

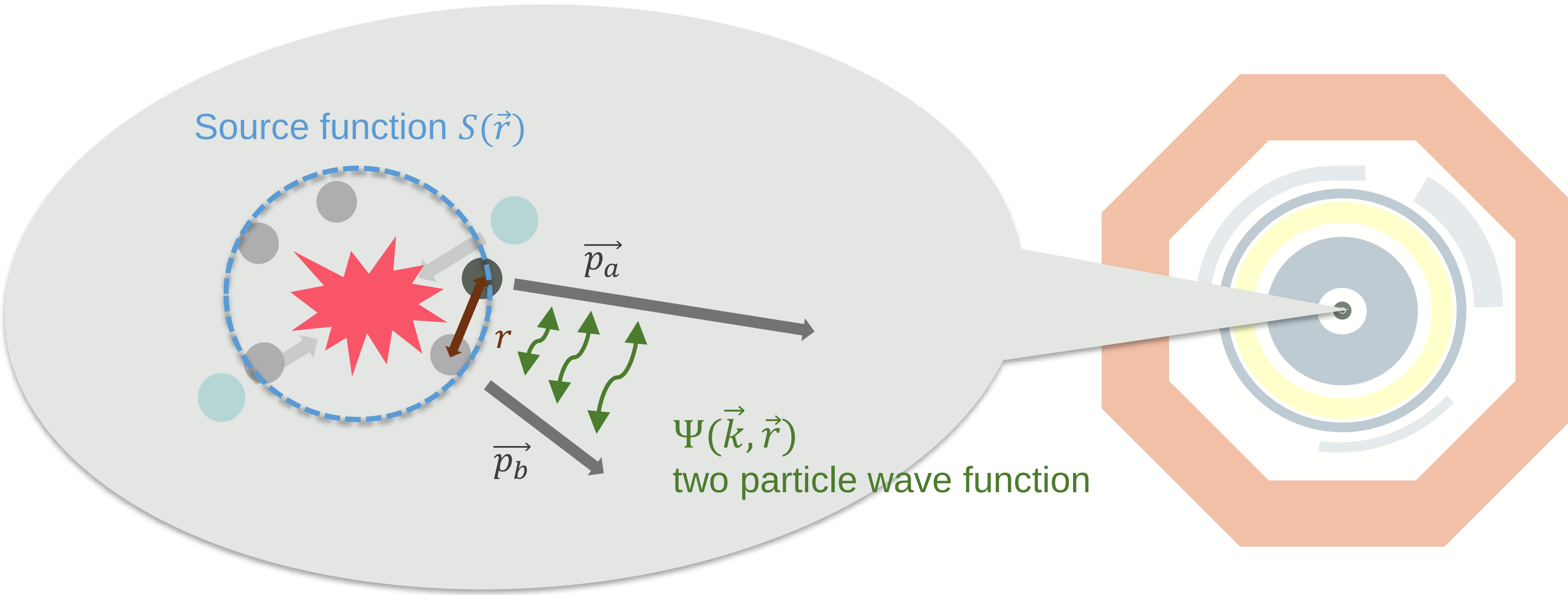
- Constraining the Λ-Λ scattering parameters
  Compatible with an slightly attractive potential
  Constraining the allowed binding energy of a H-dibaryon

- Much more to follow in the talk of V. Mantovani Sarti

Thank you for your attention

Pirin mountain, Bulgaria

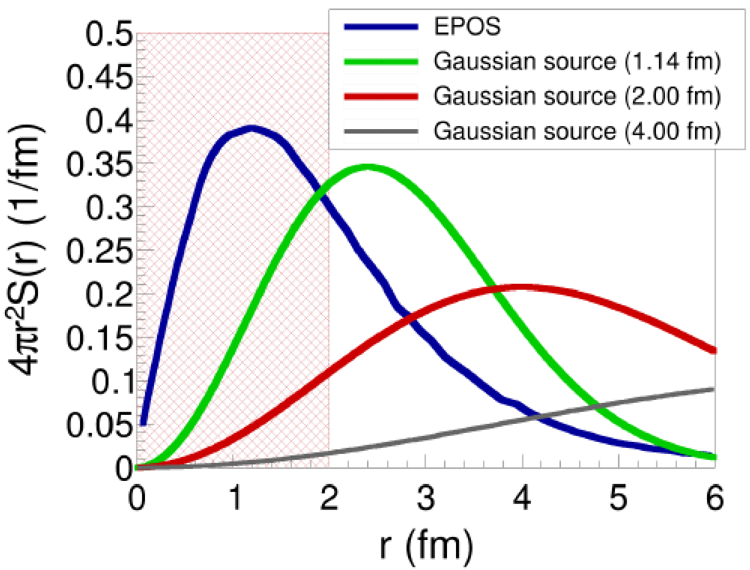
The basics

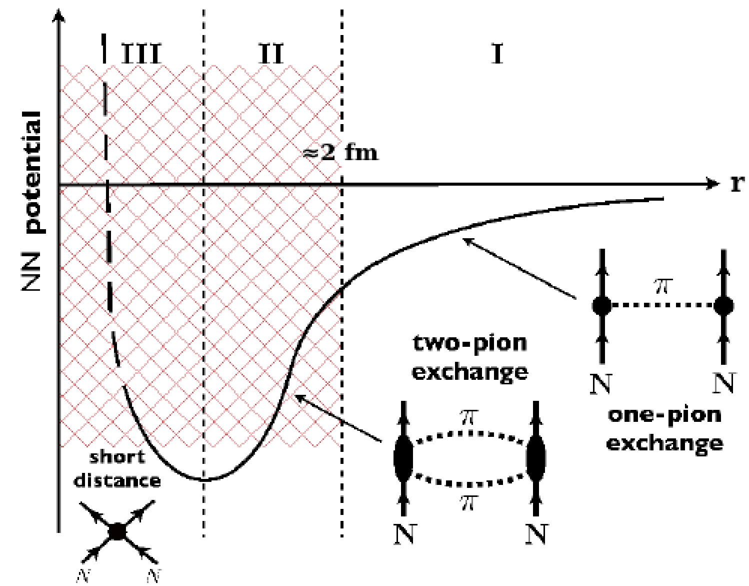


- Measure the relative momentum k distribution in your experimental set up
- Search for correlations

Femtoscopy
The scales involved

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



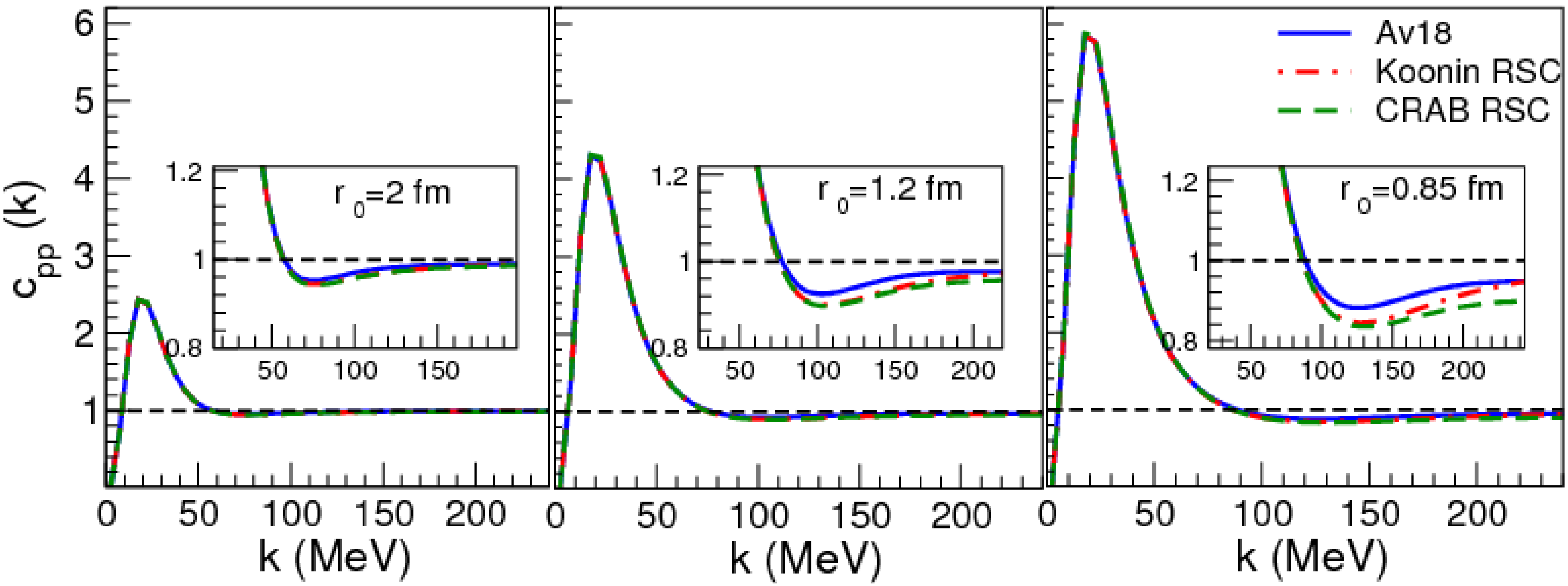


- A-A collisions: $R_{\mathrm{Gauß}} \sim 4$ fm
- p-A collisions: $R_{Gauß} \sim 2$ fm
- p-p collisions: $R_{Gauß} < 1.5$ fm

Based on Holt, Kaiser and Weise, Prog.Part.Nucl.Phys. 73 (2013) 35-83

An example

p-p correlation – effect of the source size



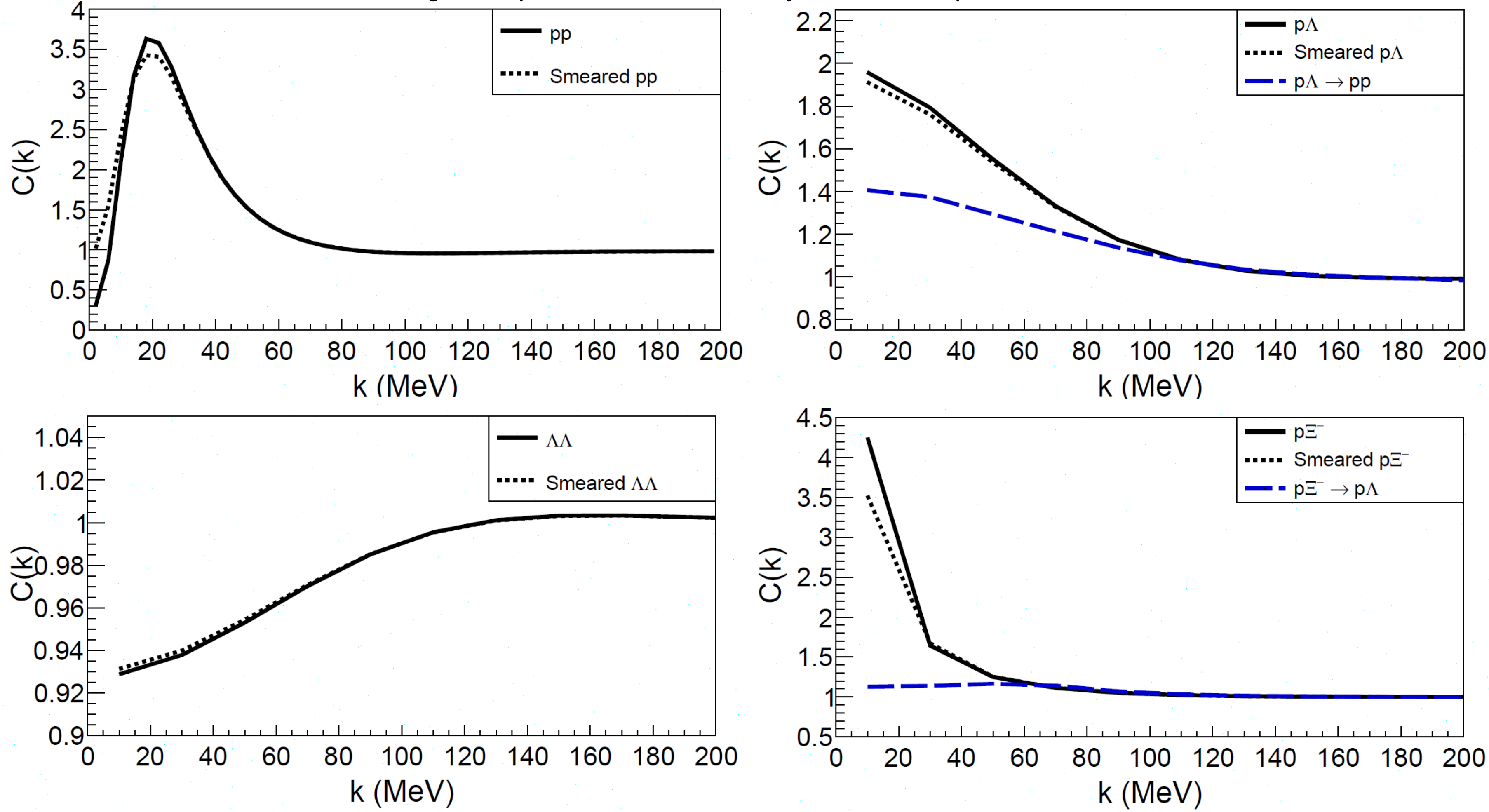
Signal strength increases with decreasing source size

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

Femtoscopy

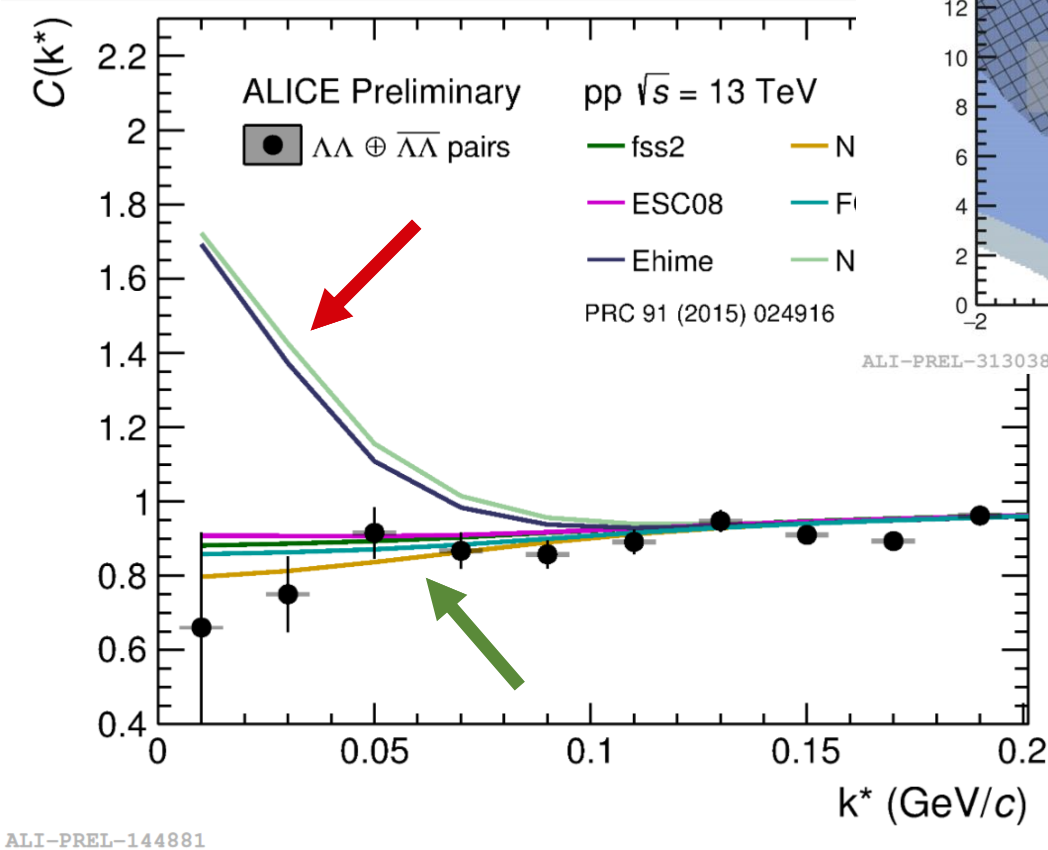
Corrections to C(k)

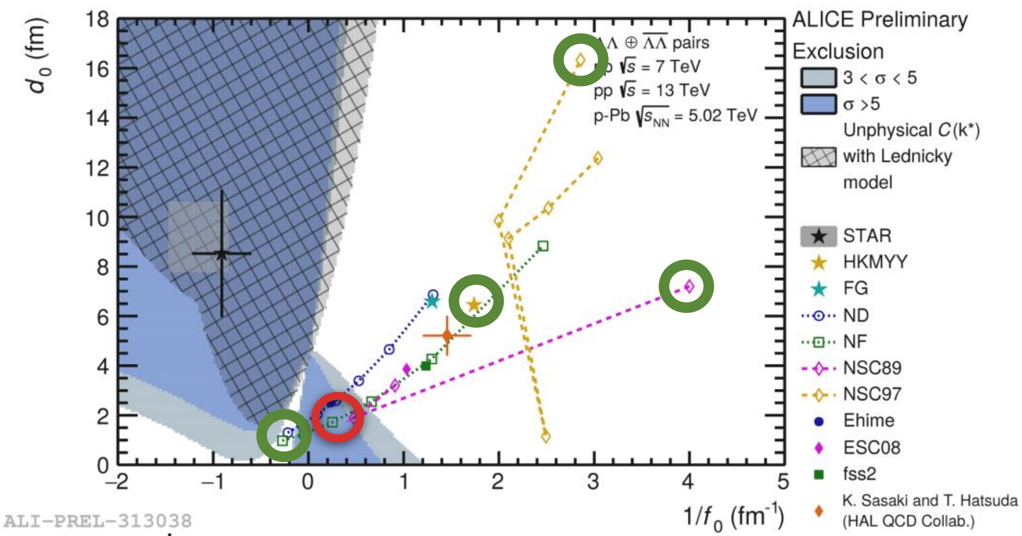
Exemplary momentum/residual smearing of the theoretical C(k), using the λ parameters obtained for the ALICE preliminaries



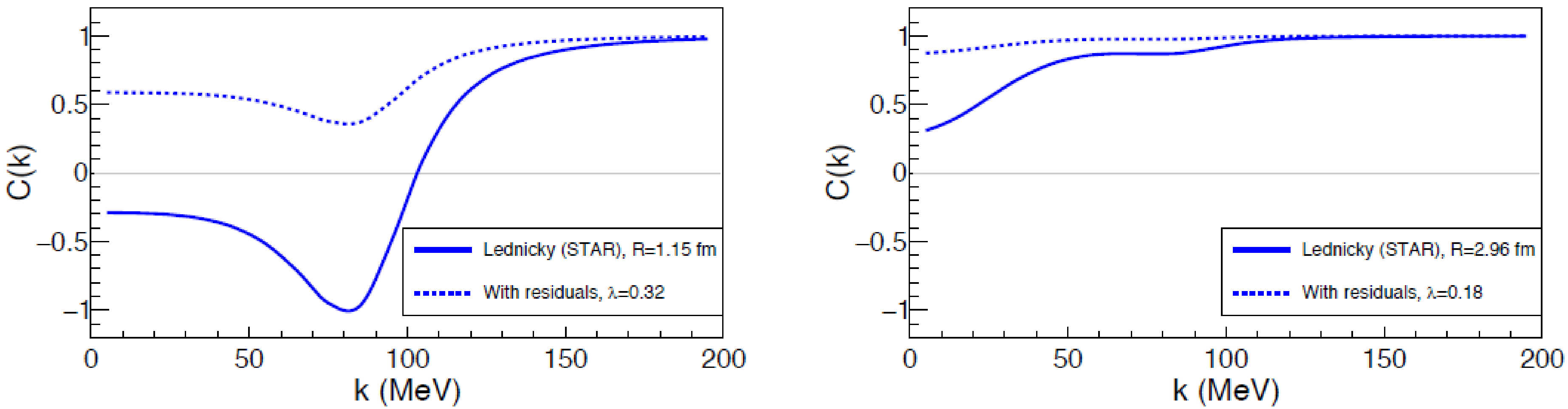
Λ-Λ interaction

The correlation functions





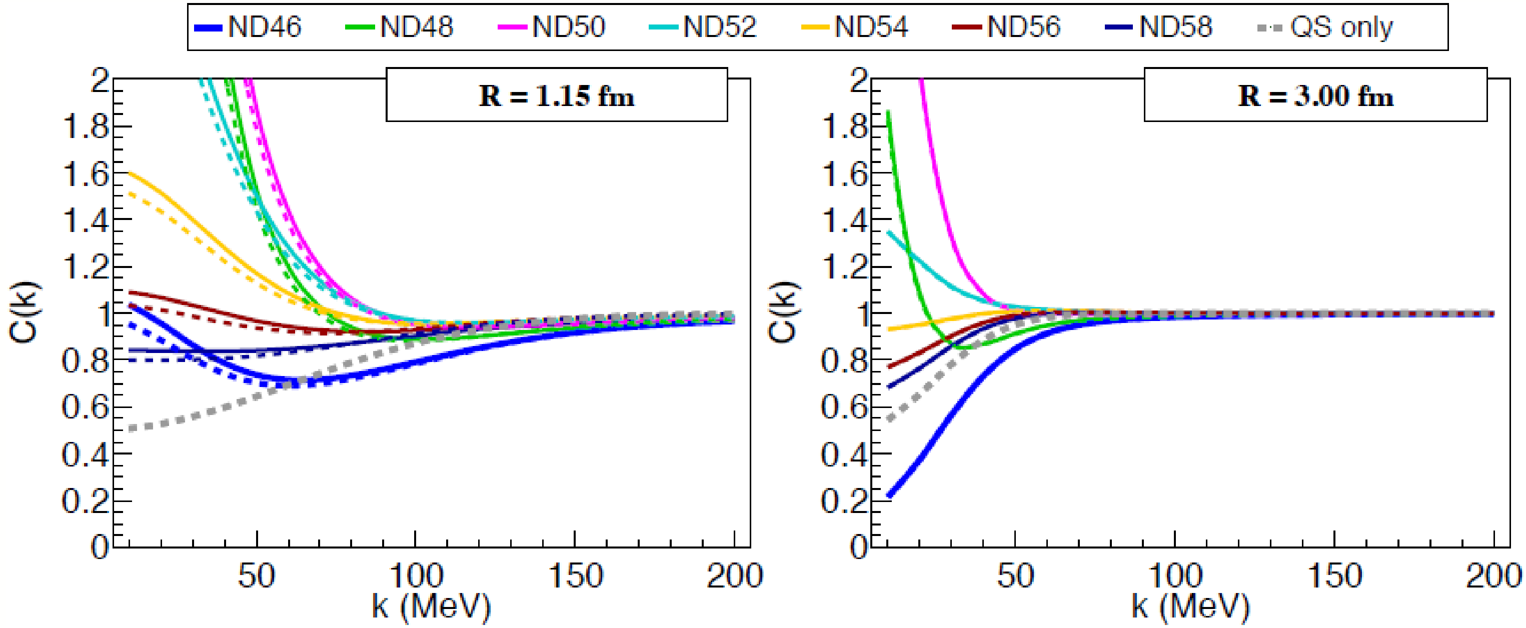
Lednický limitations



- STAR scattering parameters: f_0 = -1.1 fm, d_0 = 8.52 fm (femto sign convention)
- For certain combinations of scattering parameters and r_0 Lednicky model breaks down
  - Sign flip of the correlation function -> unphysical
  - Especially relevant for large d_0 and small source radii r_0
  - For the largest fraction of phase space the exact solution of the correlation function (CATS) is in agreement with the Lednicky model

*For pp 13 TeV only

Lednický vs CATS



- STAR scattering parameters: f_0 = -1.1 fm, d_0 = 8.52 fm (femto sign convention)
- For certain combinations of scattering parameters and r_0 Lednicky model breaks down
  - Sign flip of the correlation function -> unphysical
  - Especially relevant for large d_0 and small source radii r_0
  - For the largest fraction of phase space the exact solution of the correlation function (CATS) is in agreement with the Lednicky model