Measurements of the Λ–Λ, p-Λ and p-Ξ^- interaction via the femtoscopy method

Bernhard Hohlweger

Stranex Trento

22.10.2019

BMBF Forschungsschwerpunkt ALICE Experiment 202 ALICE

150 Jahre culture of excellence

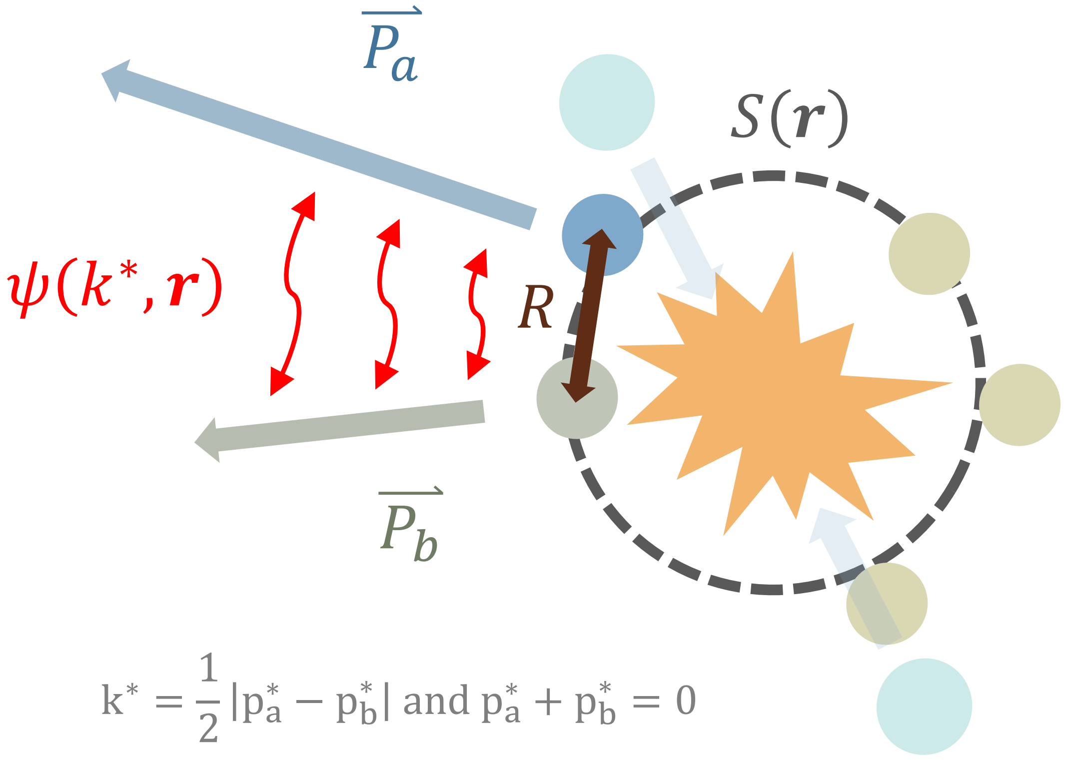
SFB 1258 Neutrinos Dark Matter Messengers

ALICE

Femtoscopic measurement

$$C(k^*) = \frac{\mathcal{P}(\vec{p}_a, \vec{p}_b)}{\mathcal{P}(\vec{p}_a)\mathcal{P}(\vec{p}_b)} = \int S(\boldsymbol{r})|\psi(k^*, \boldsymbol{r})|d^3r = \mathcal{N}\frac{N_{same}}{N_{mixed}}$$

- Traditionally used to study the emission source $S(\boldsymbol{r})$ with particles of known interaction
- Reversing the paradigm: Study interactions
  - All detectable particle species can be studied



$k^* = \frac{1}{2}|p_a^* - p_b^*|$ and $p_a^* + p_b^* = 0$

Femtoscopic measurement

$$C(k^*) = \frac{\mathcal{P}(\vec{p}_a, \vec{p}_b)}{\mathcal{P}(\vec{p}_a)\mathcal{P}(\vec{p}_b)} = \int S(\boldsymbol{r})|\psi(k^*, \boldsymbol{r})|d^3r = \mathcal{N}\frac{N_{same}}{N_{mixed}}$$

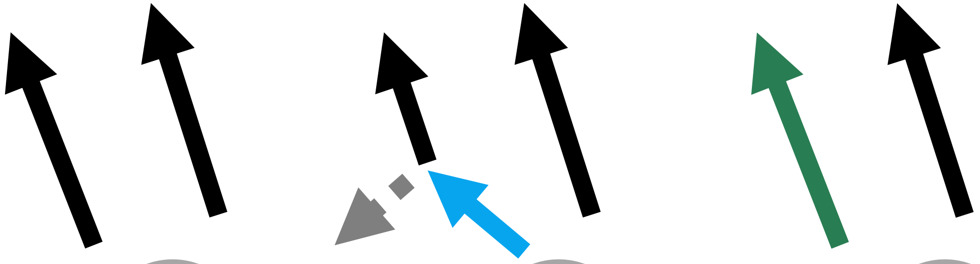
Evaluation of C(k*) within the **CATS framework**

https://doi.org/10.1140/epjc/s10052-018-5859-0

- Analytically using the **Lednicky model**

  R. Lednicky and V.L. Lyuboshits, Sov. J. Nucl. Phys. 53, 770 (1982)
  - Modelling of the interaction via scattering length (f_0) and effective range (d_0)
- **Numerically** solving the Schrödinger equation
  - Accounting for any (local) strong interaction potentials, quantum statistics and Coulomb interaction

Residual correlations



$$C_{tot}(k^*) = \lambda_0 C_0 \oplus \lambda_1 C_1 \oplus \lambda_2 C_2 \oplus \dots$$

Contributions from: genuine feed-down misidentifications

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

- Pair contributions quantified by purity ($\mathcal{P}_i$) and feed down fractions (f_i):

$$\lambda_{ij} = \mathcal{P}_{i_1} \cdot f_{i_1} \cdot \mathcal{P}_{j_2} \cdot f_{j_2}$$

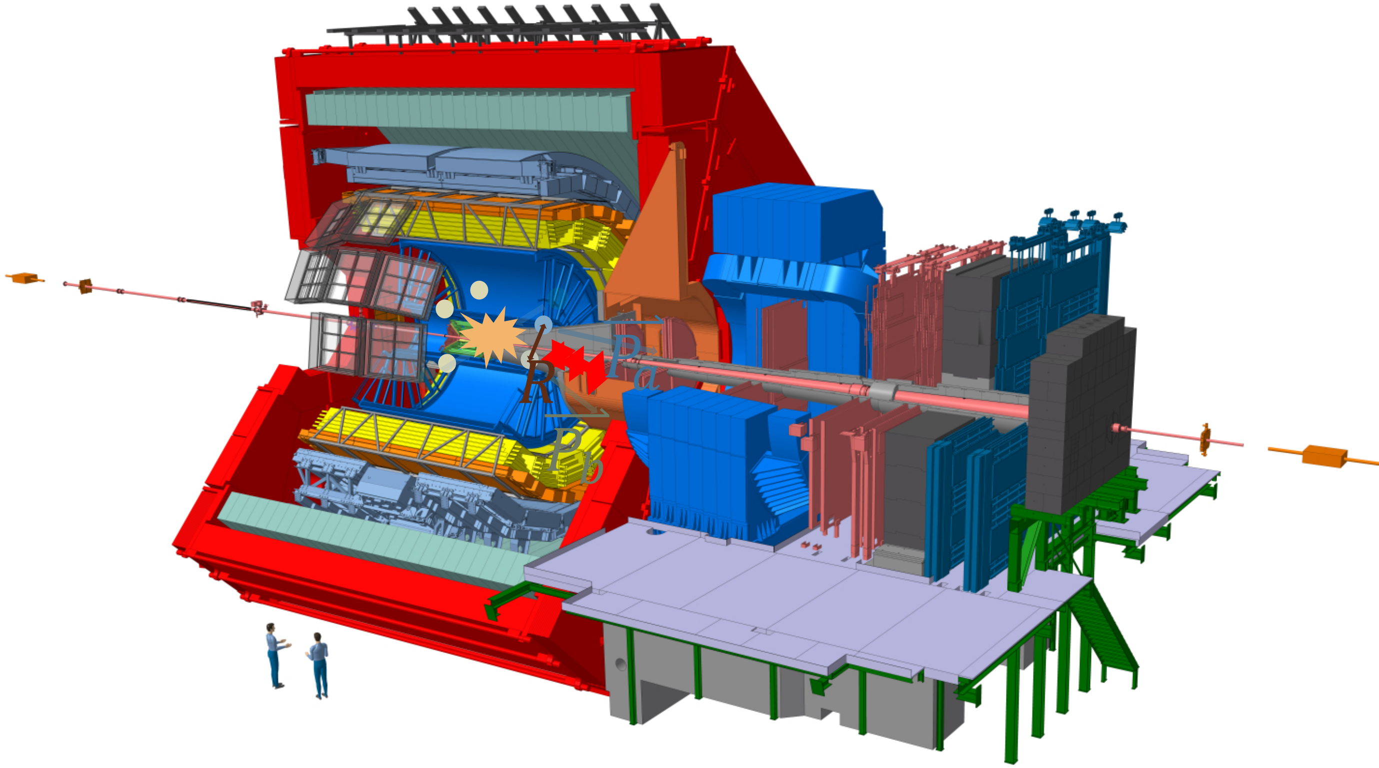
- Smearing for finite momentum resolution of the detector
- Non flat baseline

(Details see Phys. Rev. C 99 (2019), 024001)

The Detector: ALICE

- Particle identification with TPC (dE/dx) and TOF
  - Direct detection of charged particles (p,K,π)
  - Reconstruction of Hyperons:
    $\Lambda \rightarrow p\pi^{-}$ and $\Xi^{-} \rightarrow \Lambda\pi^{-}$
- Datasets:

System	# Events
pp 7 TeV	3.4×10^{8} minimum bias
p-Pb 5.02 TeV	6.0×10^{8} minimum bias
pp 13 TeV	15×10^{8} minimum bias
	10×10^{8} high multiplicity (0-0.072% INEL)

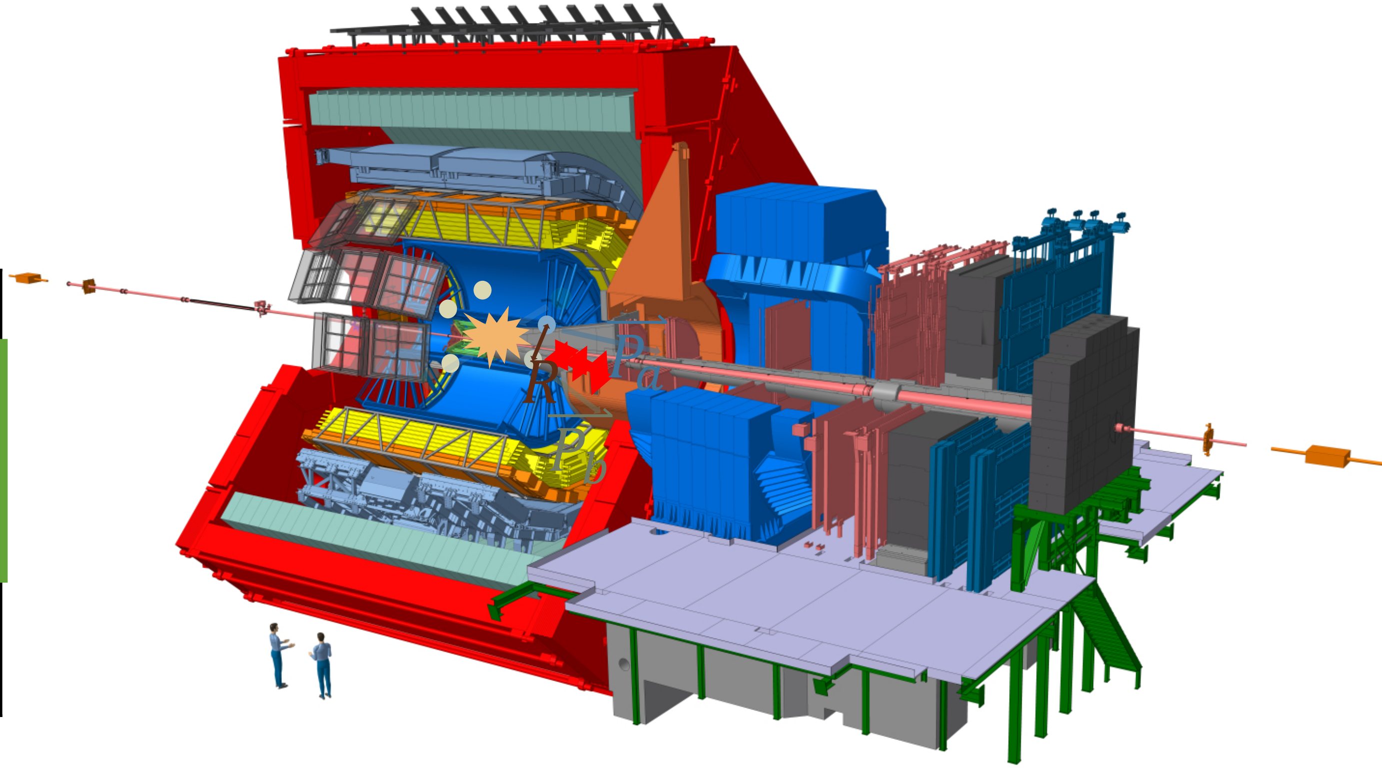


The Detector: ALICE

- Particle identification with TPC (dE/dx) and TOF
  - Direct detection of charged particles (p,K,π)
  - Reconstruction of Hyperons:
    $\Lambda \rightarrow p\pi^-$ and $\Xi^- \rightarrow \Lambda\pi^-$
- Datasets:

Λ–Λ

System	# Events
pp 7 TeV	3.4 x 10^8 minimum bias
p-Pb 5.02 TeV	6.0 x 10^8 minimum bias
	15 x 10^8 minimum bias
pp 13 TeV	10 x 10^8 high multiplicity (0-0.072% INEL)

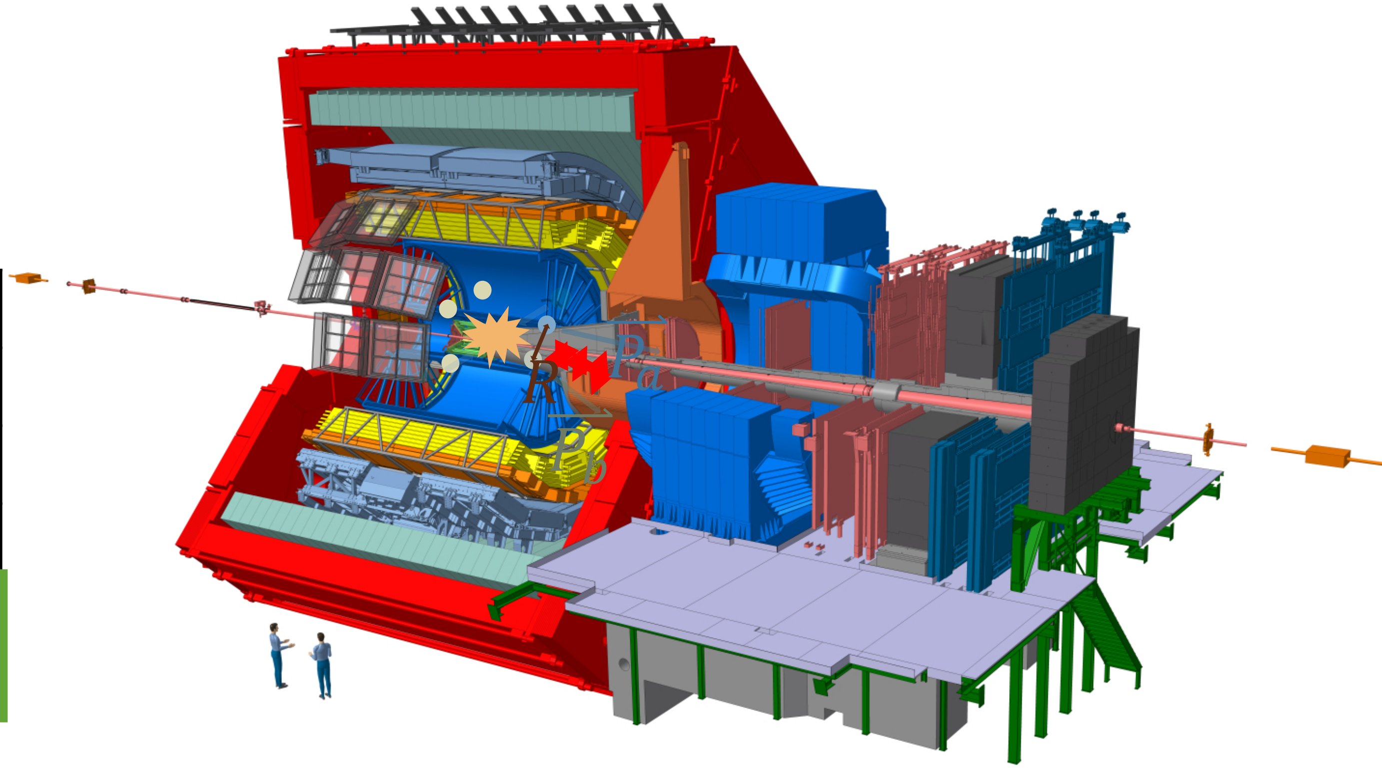


The Detector: ALICE

- Particle identification with TPC (d*E*/dx) and TOF
  - Direct detection of charged particles (p,K,π)
  - Reconstruction of Hyperons:
    $\Lambda \rightarrow p\pi^{-}$ and $\Xi^{-} \rightarrow \Lambda\pi^{-}$
- Datasets:

System	# Events
pp 7 TeV	3.4 x 10^{8} minimum bias
p-Pb 5.02 TeV	6.0 x 10^{8} minimum bias
	15 x 10^{8} minimum bias
pp 13 TeV	10 x 10^{8} high multiplicity (0-0.072% INEL)

p–Λ
p–Ξ

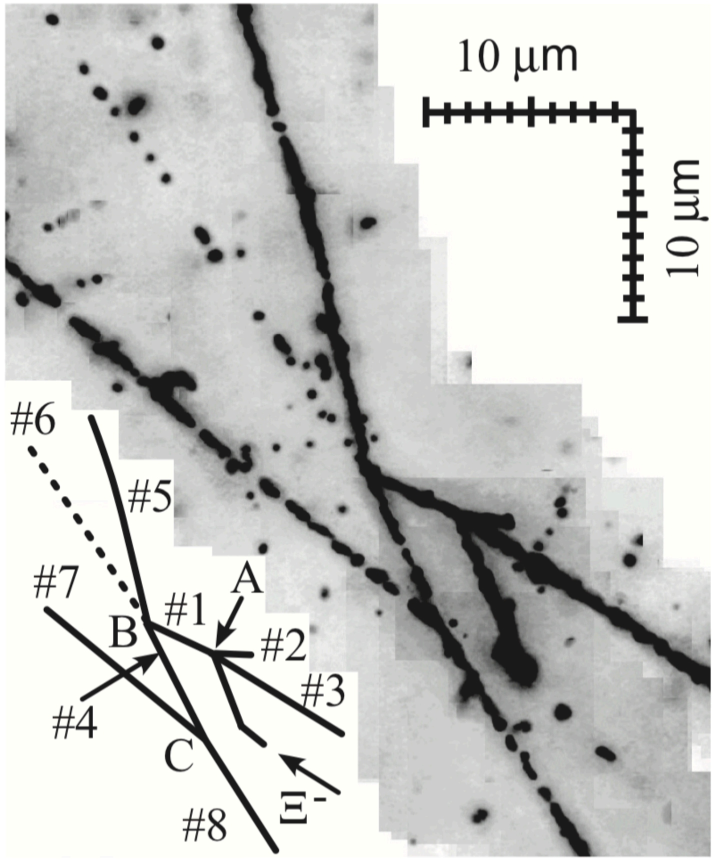


Λ–Λ Femtoscopy

Published: ALICE Collaboration, PLB 797, 134822
https://doi.org/10.1016/j.physletb.2019.134822
Datasets: Minimum Bias pp 7 & 13 TeV, p-Pb 5.02 TeV

Λ–Λ interaction

- No scattering data
- The observed double Λ hyper-nuclei events predict a shallow attraction
  H. Takahashi et al., PRL 87 (2001) 212502.
  - $B_{\Lambda-\Lambda} = 6.91 \pm 0.16$ MeV
- Femtoscopic analysis in heavy-ion collisions (STAR) extremely inconclusive, due to the unconstrained residual signal



J. K. Ahn *et al.*, PRC 88, 014003 (2013)

Original analysis by STAR
PRL 114 (2015), 022301.

Reanalyisis by Morita *et al.*
PRC 91 (2015), 024916.

Repulsive potential?

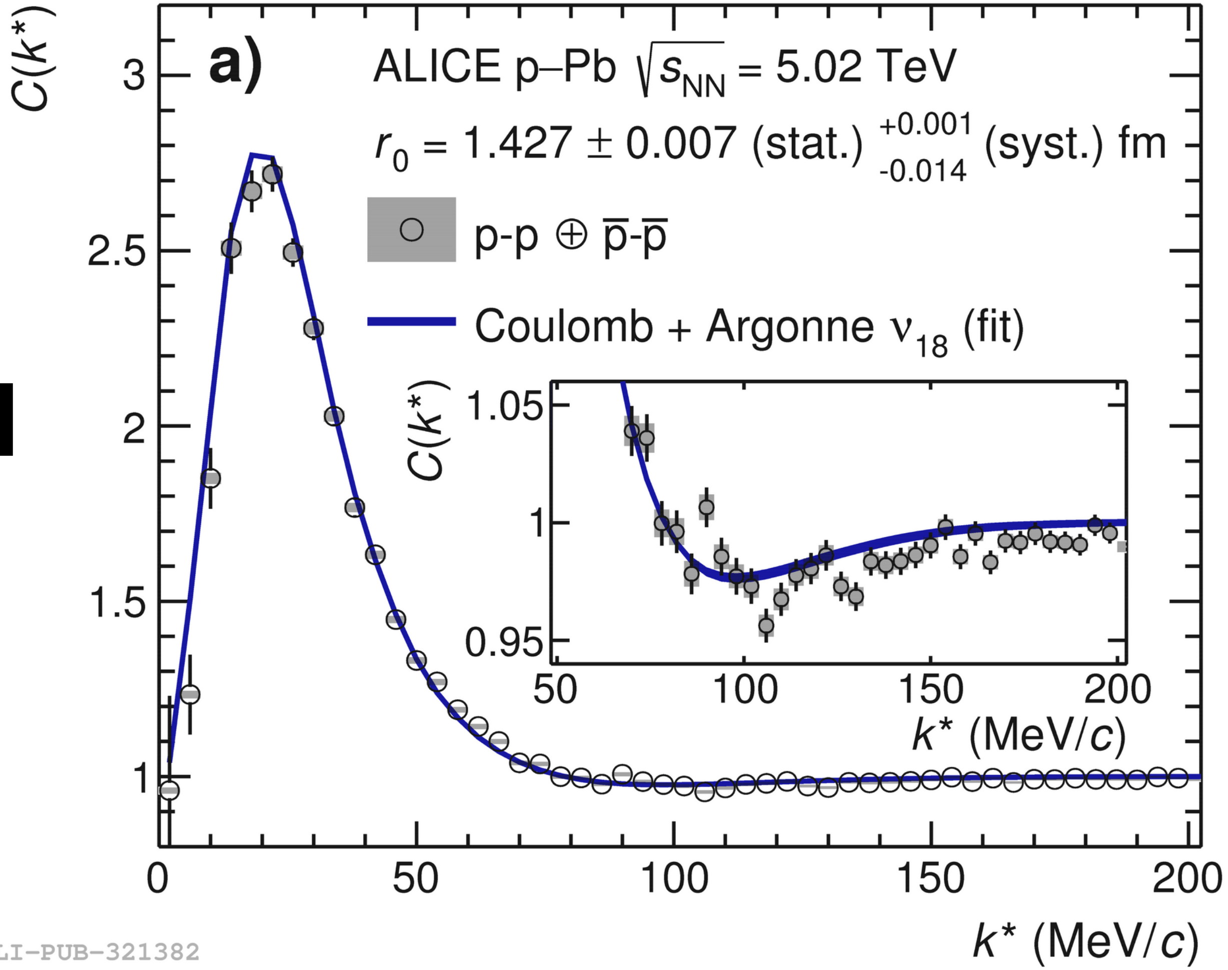
Attractive potential?

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

Constraining the source

- Assumption: $S(\mathbf{r})$ Gaussian and same for all particle pairs
  - p-p interaction: well known
- Source sizes for the three systems:

System	Radius
pp 7 TeV	$1.125 \pm 0.018(\text{stat.})^{+0.058}_{-0.035}(\text{syst.})$fm
pp 13 TeV	$1.182 \pm 0.008(\text{stat.})^{+0.005}_{-0.002}(\text{syst.})$fm
p-Pb 5 TeV	$1.427 \pm 0.007(\text{stat.})^{+0.001}_{-0.014}(\text{syst.})$fm



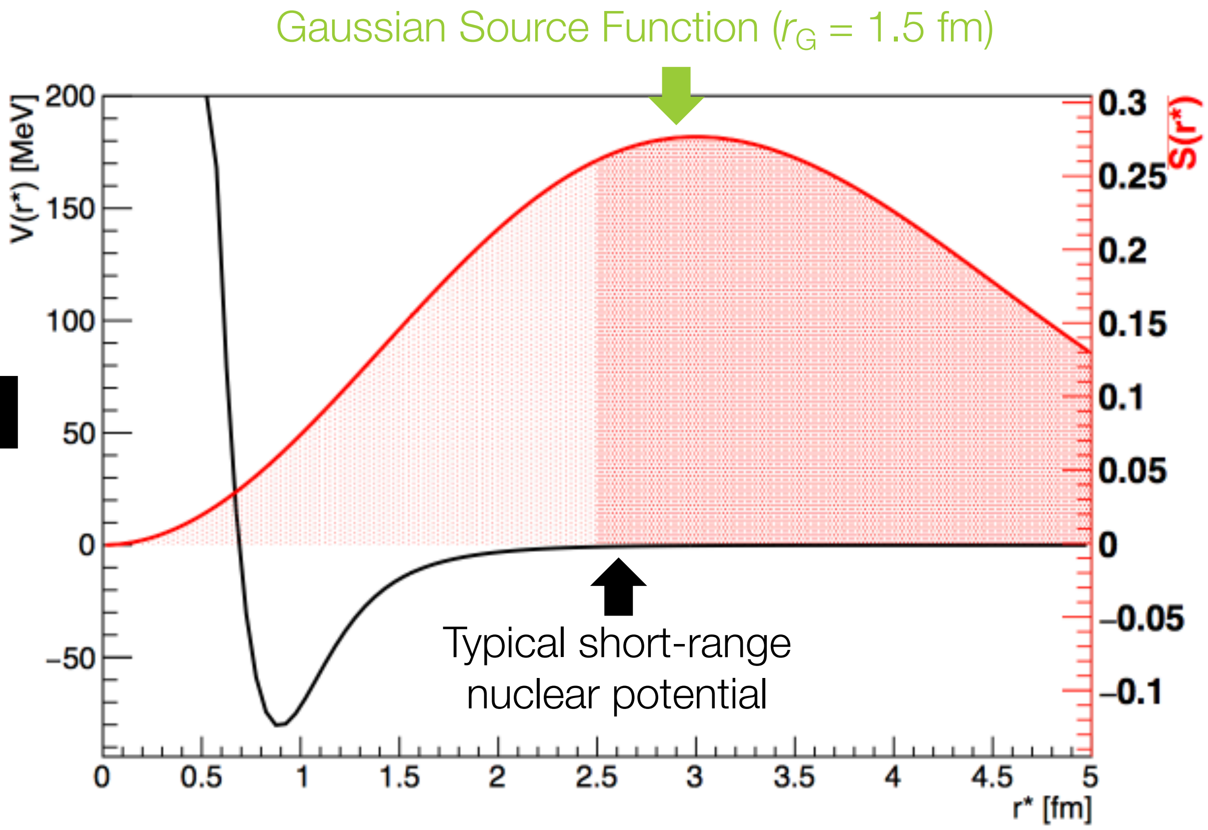
ALI-PUB-321382

Constraining the source

- Assumption: $S(r)$ Gaussian and same for all particle pairs
  - p-p interaction: well known
- Source sizes for the three systems:

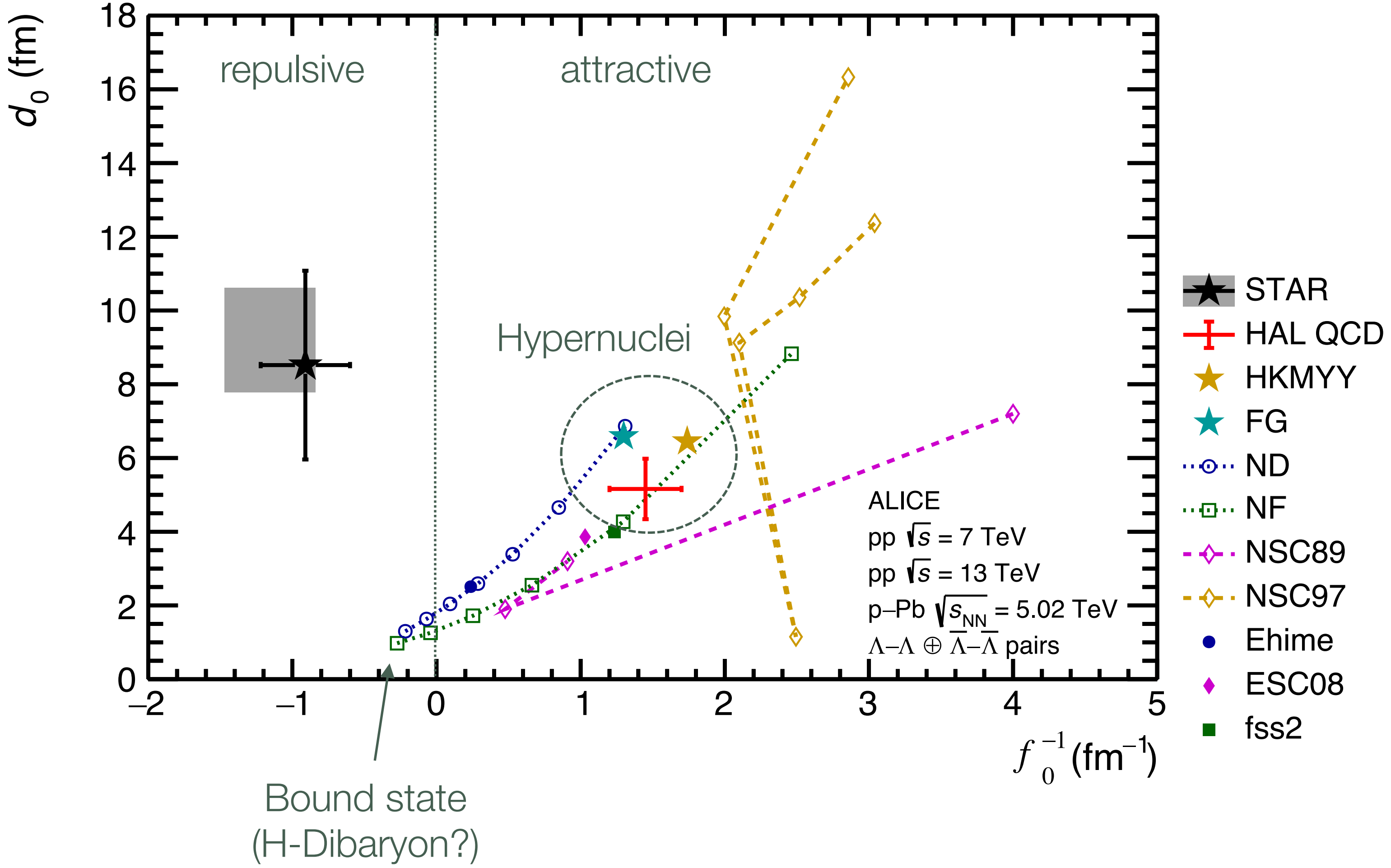
System	Radius
pp 7 TeV	$1.125 \pm 0.018(\mathrm{stat.})^{+0.058}_{-0.035}(\mathrm{syst.})\mathrm{fm}$
pp 13 TeV	$1.182 \pm 0.008(\mathrm{stat.})^{+0.005}_{-0.002}(\mathrm{syst.})\mathrm{fm}$
p-Pb 5 TeV	$1.427 \pm 0.007(\mathrm{stat.})^{+0.001}_{-0.014}(\mathrm{syst.})\mathrm{fm}$

- Source size of the same magnitude as strong interaction potentials

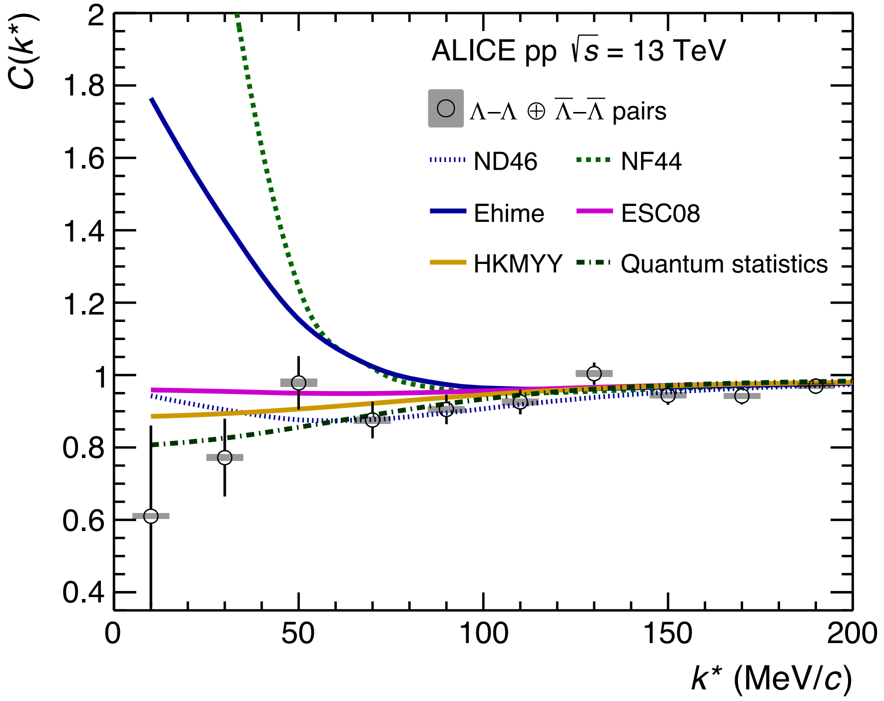


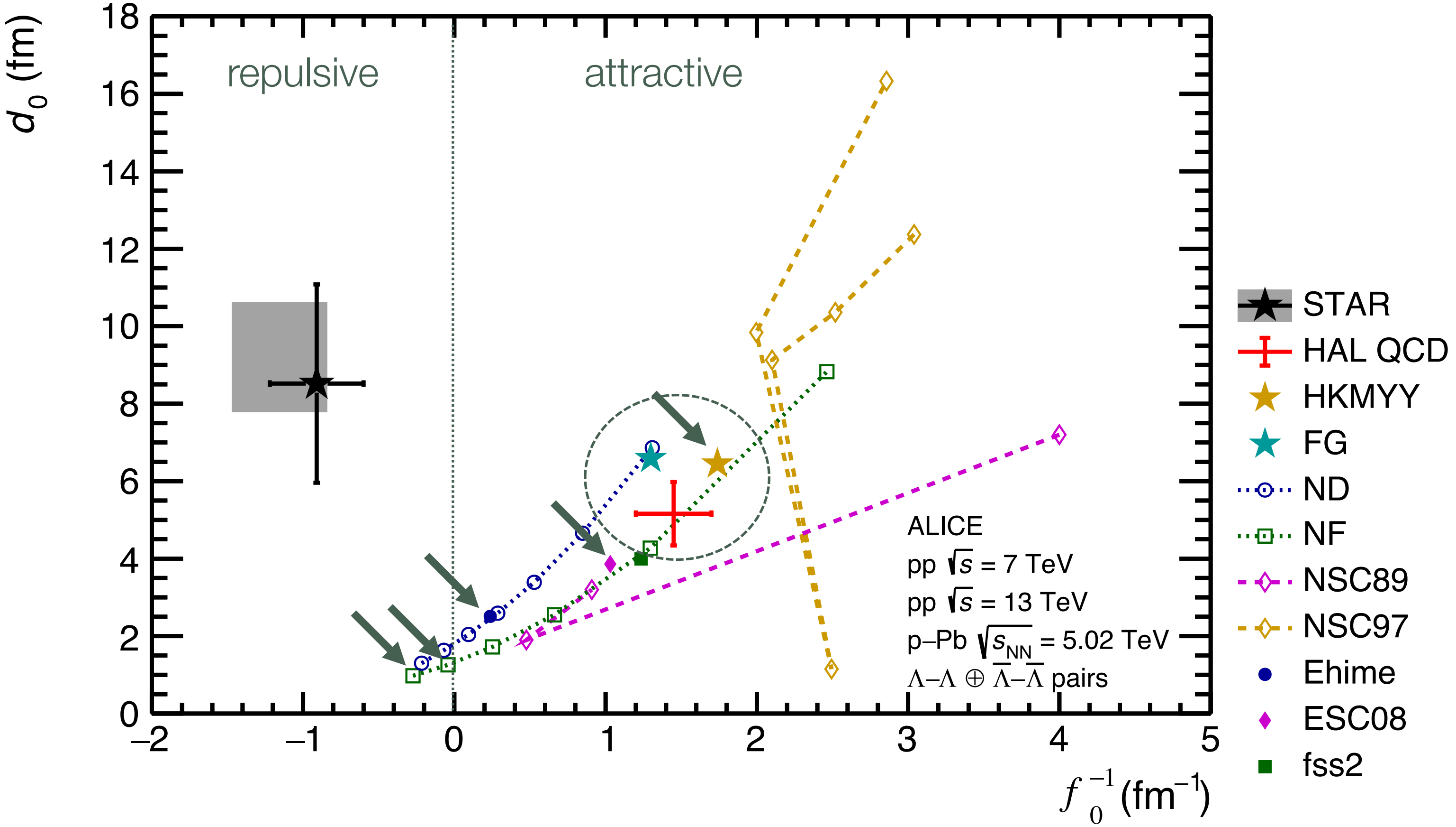
Λ–Λ interaction

- Theoretical models and experimental measurements cover a wide range in the scattering parameter phase space
  - Measurement: STAR Collab., PRL 114 (2015) 022301.
  - Models from K. Morita *et al.*, PRC 91 (2015) 024916.
  - HAL QCD: K. Sasaki and T. Hatsuda (HAL QCD Collab.), private communication.



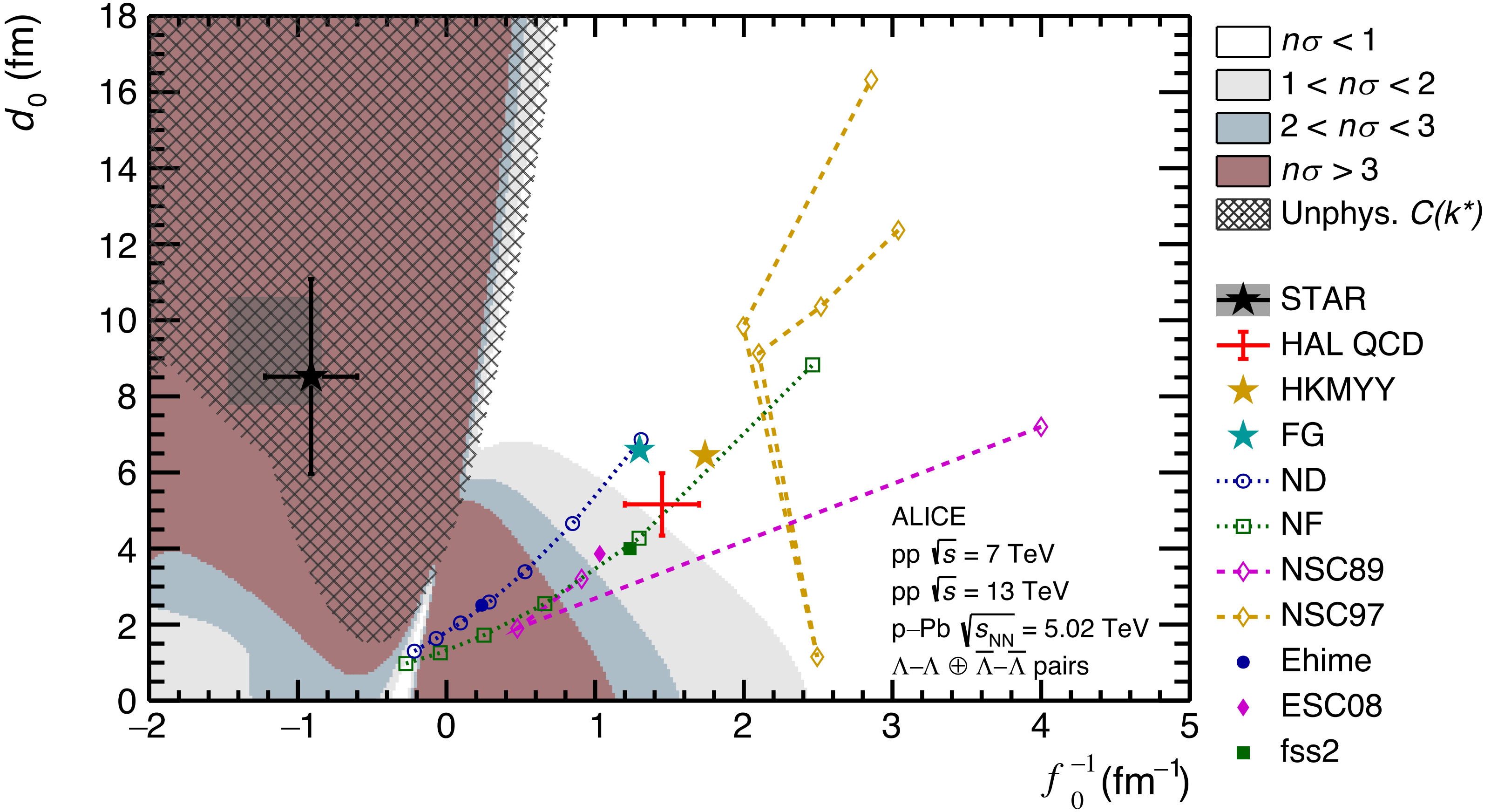
Λ–Λ interaction





Λ–Λ femtoscopy

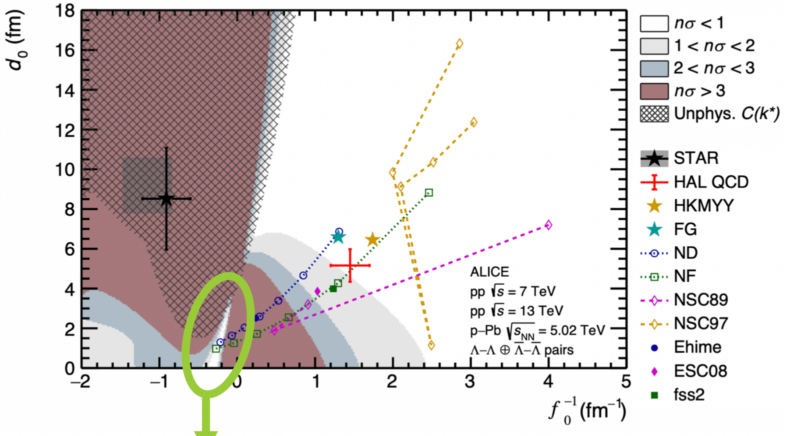
- Combination of all analyzed datasets
  - pp 7 & 13 TeV
  - p–Pb 5.02 TeV
- Test of the agreement between data and the prediction by the Lednický model in nσ
  - Under the hypothesis of a common, Gaussian source
  - Small source size limits the prediction power of the Lednický model

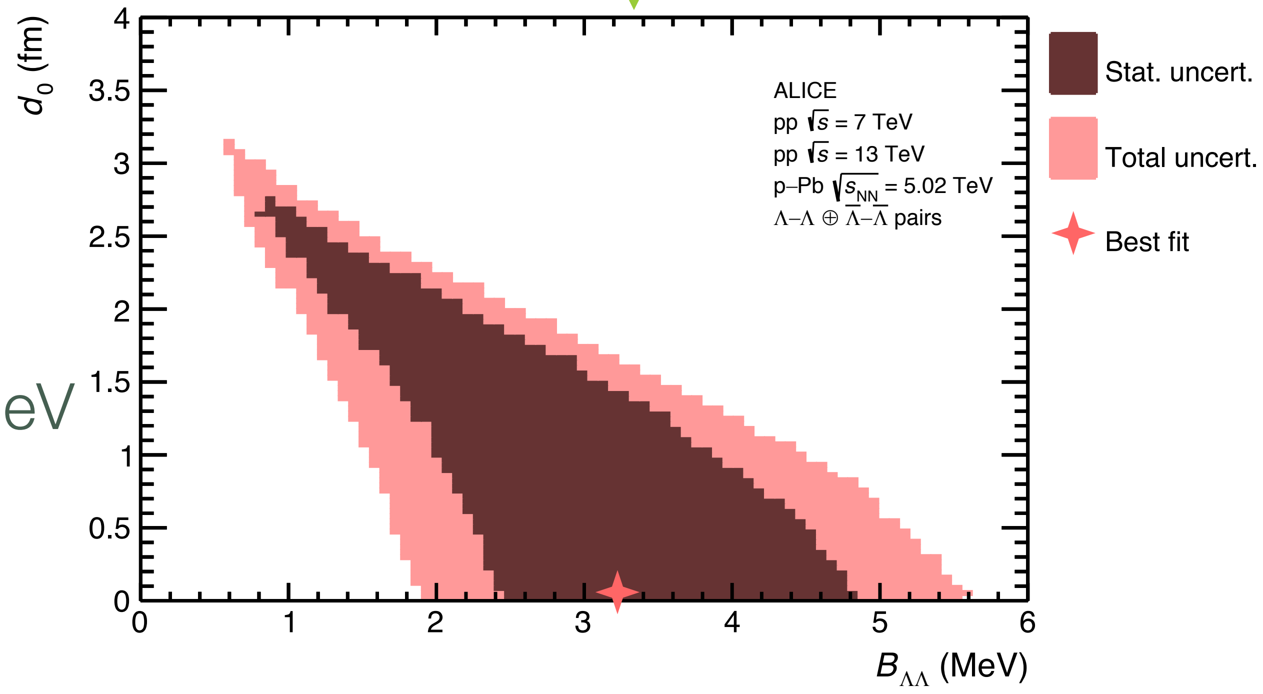


Λ–Λ femtoscopy – H-Dibaryon

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

S. Gongyo et al., PRL 120 (2018) 212001.
P. Naidon and S. Endo, Rept. Prog. Phys. 80 (2017) 056001.





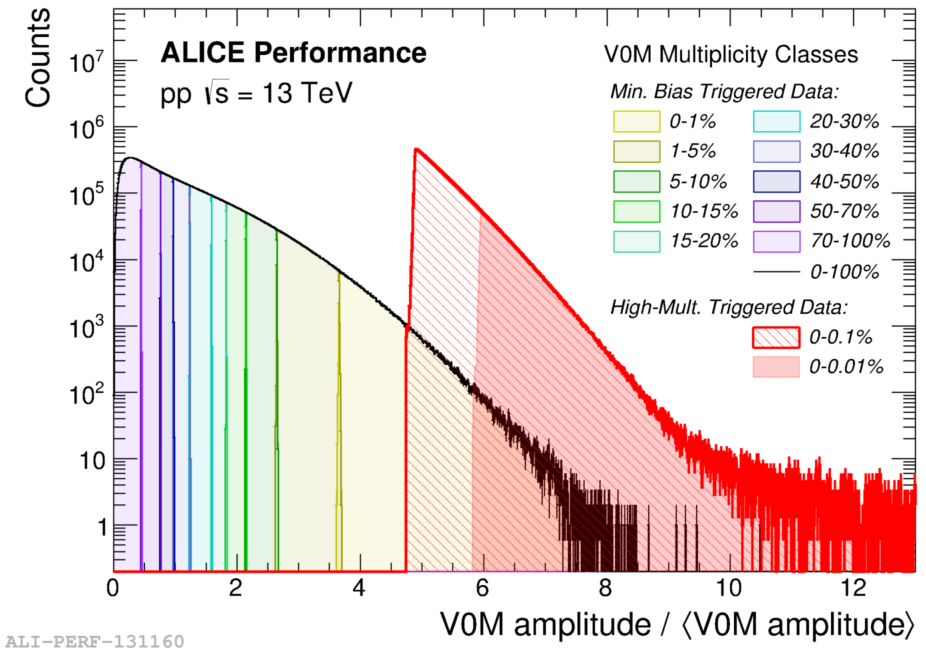
- H-Dibaryon: Tight constraints on the allowed binding energy
  - $B_{\Lambda-\Lambda} = 3.2^{+1.6}_{-2.4}\,(\text{stat.})^{+1.8}_{-1.0}\,(\text{syst.})$ MeV
  - More stringent than previous measurements

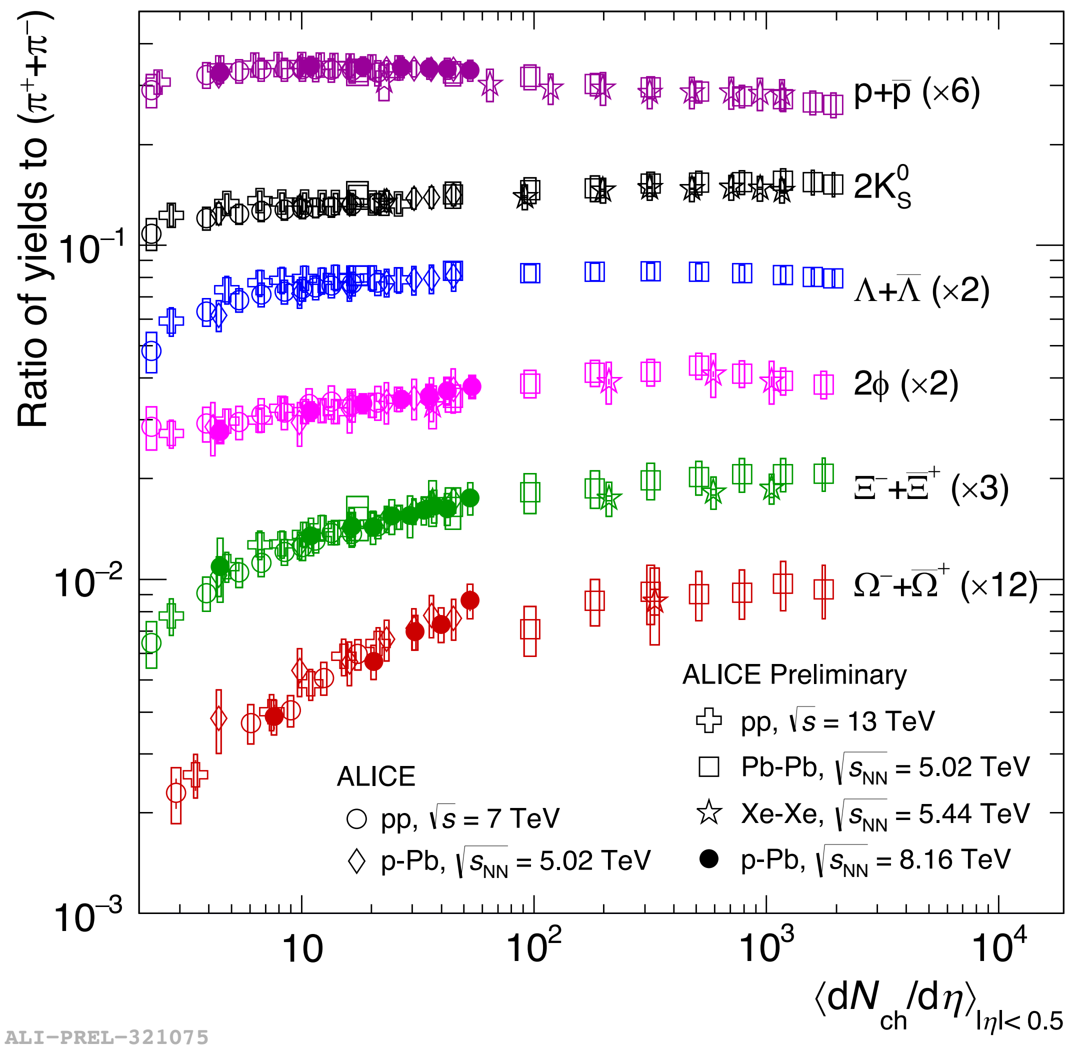
High multiplicity dataset

p-p collisions at 13 TeV

High Multiplicity Dataset

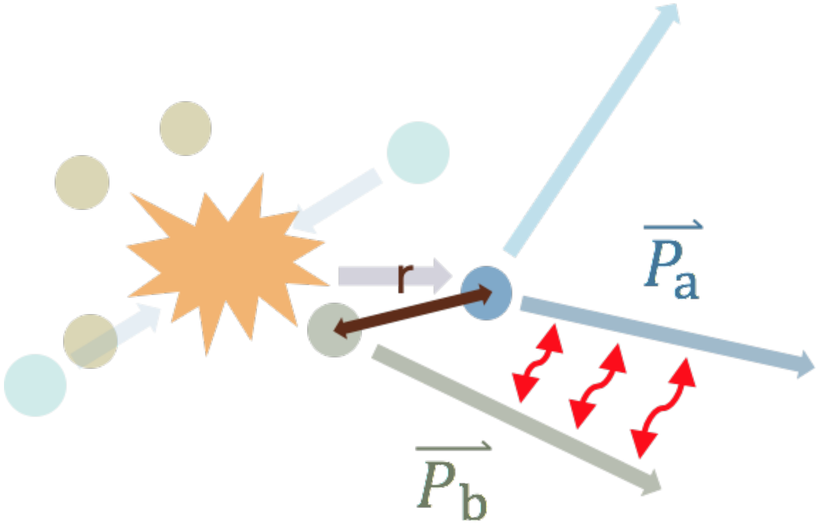
- Increased average multiplicity & production of hyperons
  - Significant increase in amount of pairs by a factor of 5-10





Collective effects and strongly decaying resonances

(An)isotropic flow + **Strongly decaying resonances**



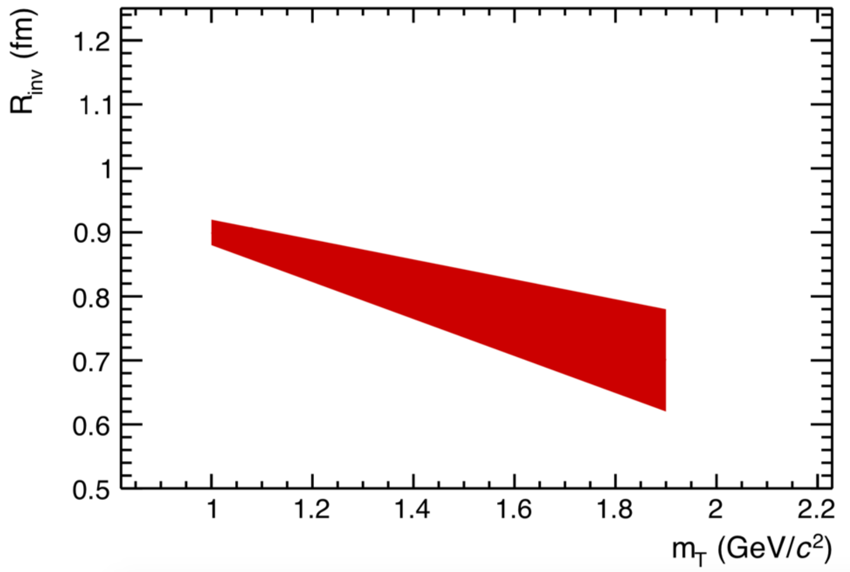
- (An) isotropic pressure gradients affect the emission
  - Initial geometric anisotropies introduce a transverse modulation
  - Expanding source with common velocity field
- Affects particles depending on their masses

- Resonances with ct ~ r0 ~ 1 fm (Δ^*, N*, Σ^*) introduce an exponential tail to the source
- Different for each particle species

Collective effects and strongly decaying resonances

(An)isotropic flow + **Strongly decaying resonances**

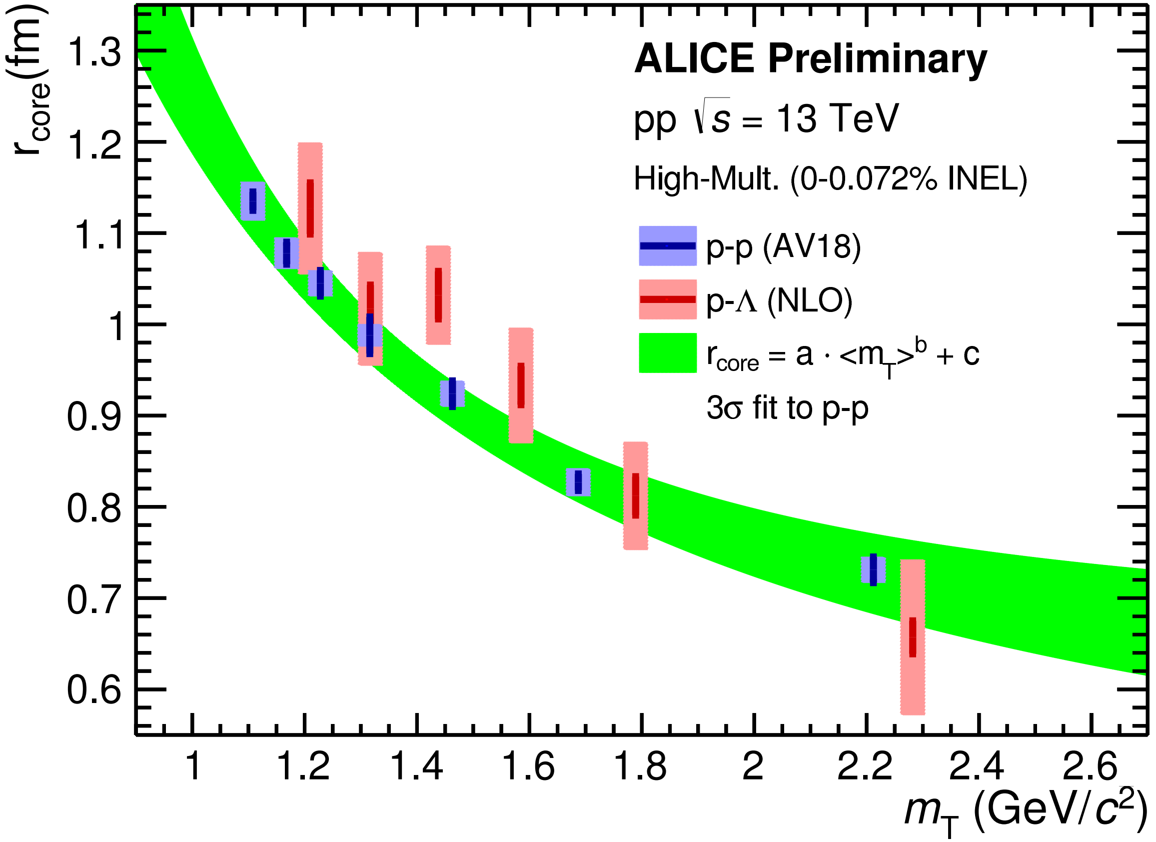
Gaussian core ⊗ Exponential tail



Particle	Primordial fraction	Resonances	
		$1 < c\tau < 2$ fm	$c\tau > 2$ fm
Proton	33 %	56 %	2 %
Lambda	35 %	8 %	58 %

- Amount of resonances determined within the Statistical Hadronization Model in the canonical approach
- Priv. Comm. with Prof. F. Becattini
  J.Phys. G38 (2011) 025002.

m_T dependence of the Gaussian *core* radius

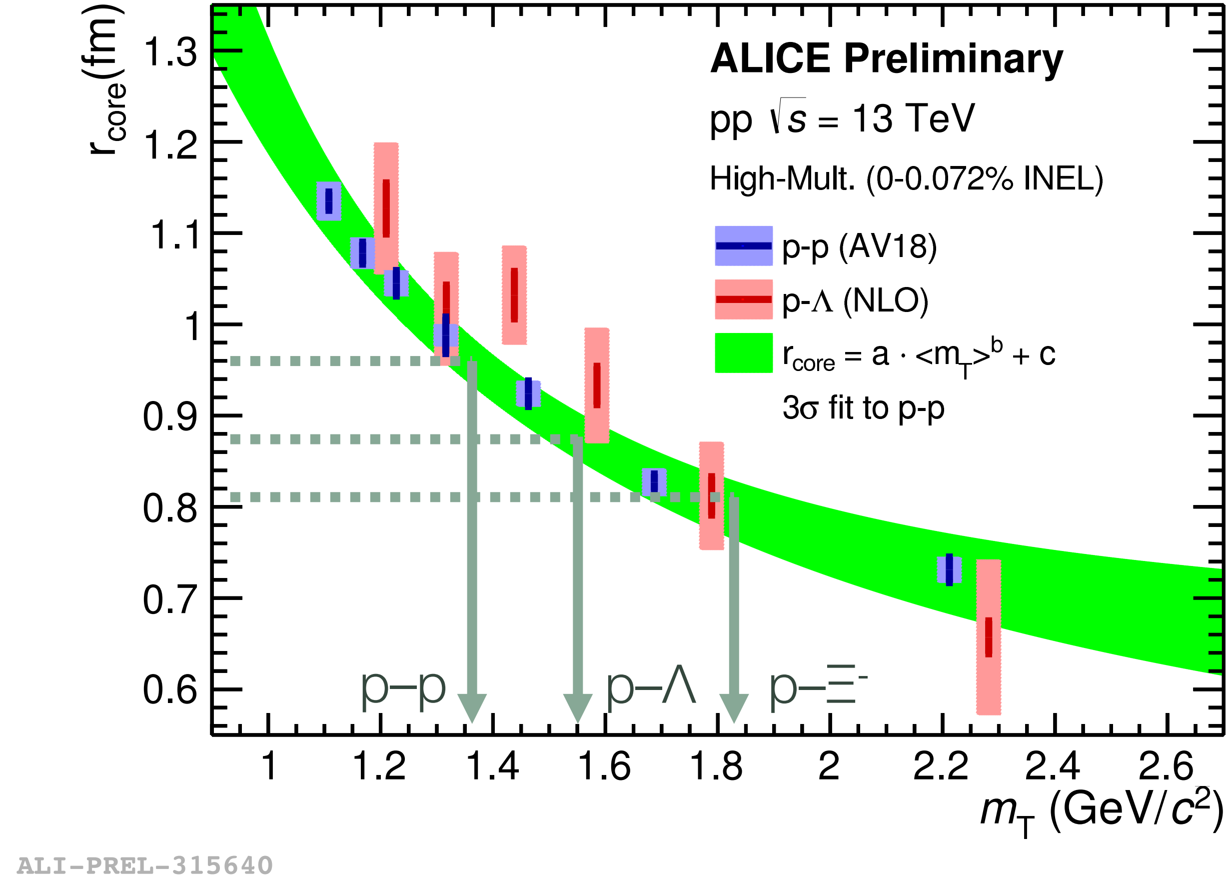


ALI-PREL-315640

- Core radius for p–p and p–Λ in agreement

D. Mihaylov (ALICE)
WPCF2019

m_T dependence of the Gaussian *core* radius



D. Mihaylov (ALICE)
WPCF2019

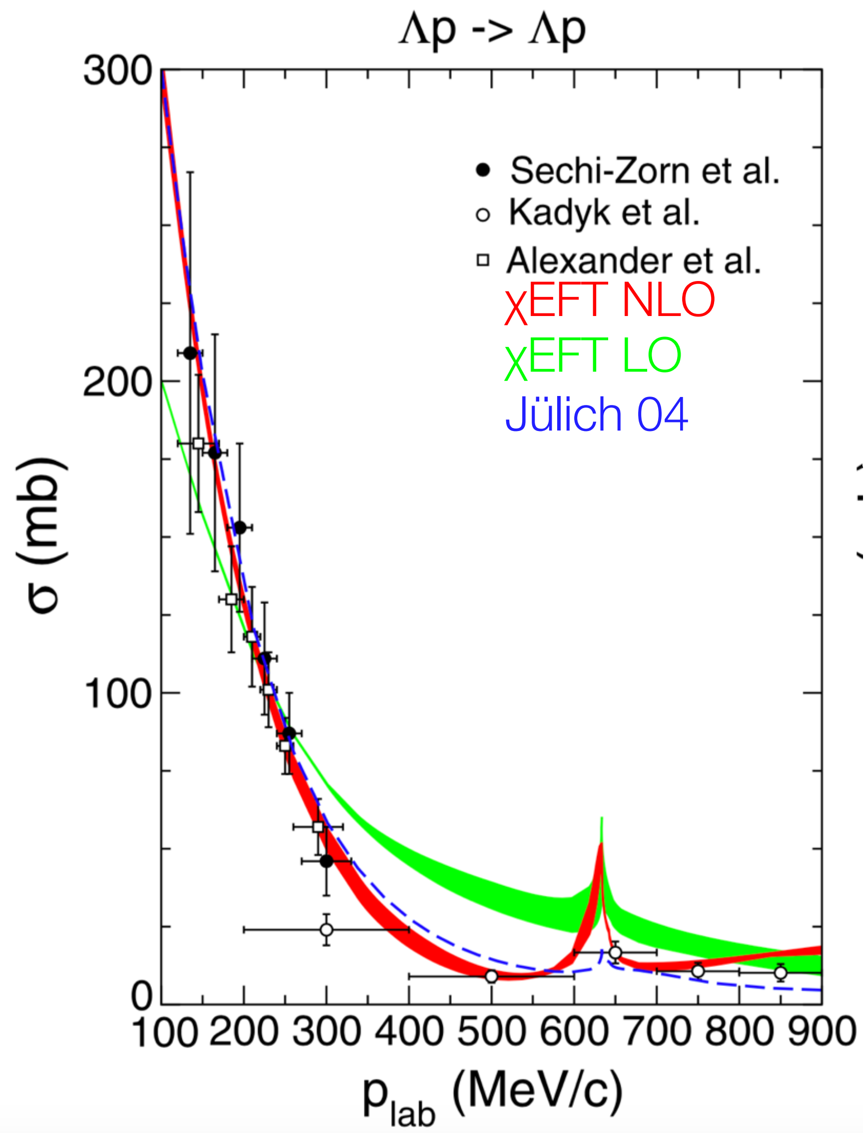
- Fix the value of r_{Core} of each particle species based on their $<m_T>$
  - ➢Add specific resonance contribution to obtain the corresponding pair source

p-Λ Femtoscopy

Dataset: High multiplicity pp 13 TeV

Proton Λ interaction

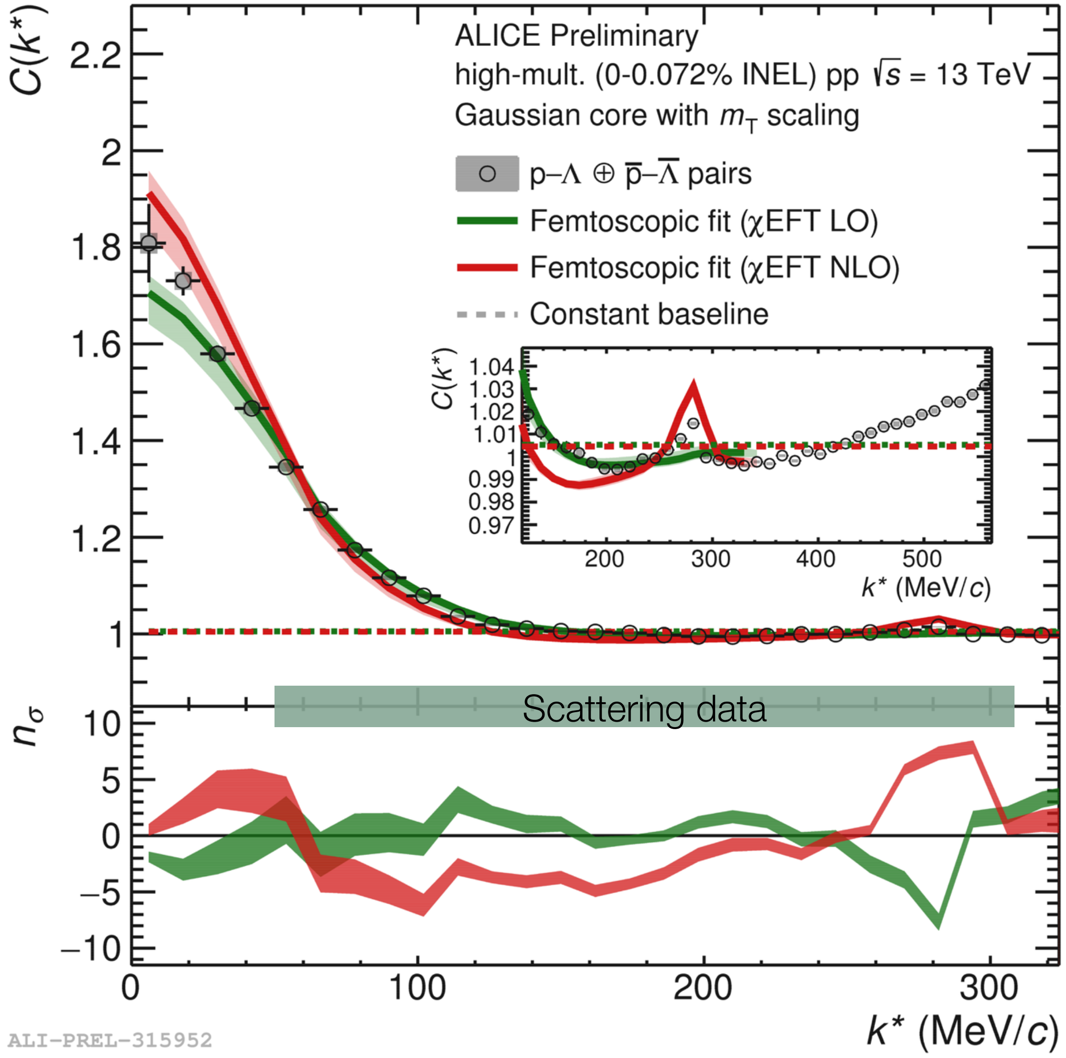
- Indirect measurement via hypernucleii
- Scarce scattering data
  - No constraints at lab momenta below 100 MeV/*c*
- Theoretical predictions for cusp in Λ–N due to the Σ–N - Λ–N coupling
  - Coupling introduces a repulsive short range component in the p–Λ interaction
  - Not experimentally confirmed so far



J. Haidenbauer et al., Nucl. Phys. A 915 (2013) 24.

Measurement of the p–Λ correlation function

- Significant extension of the kinematic range
- Clear experimental evidence for the cusp
- Different variations of the baseline
  - Constant, linear & quadratic
  - Best fit for LO: $n_\sigma > 8$
  - Best fit for NLO: $n_\sigma > 10$
- LO and NLO calculations of the interaction within χEFT **fail to reproduce the data**
  - Entering a precision era!



p-Ξ^- Femtoscopy

Continuation of the analysis in minimum bias p-Pb 5.02 TeV

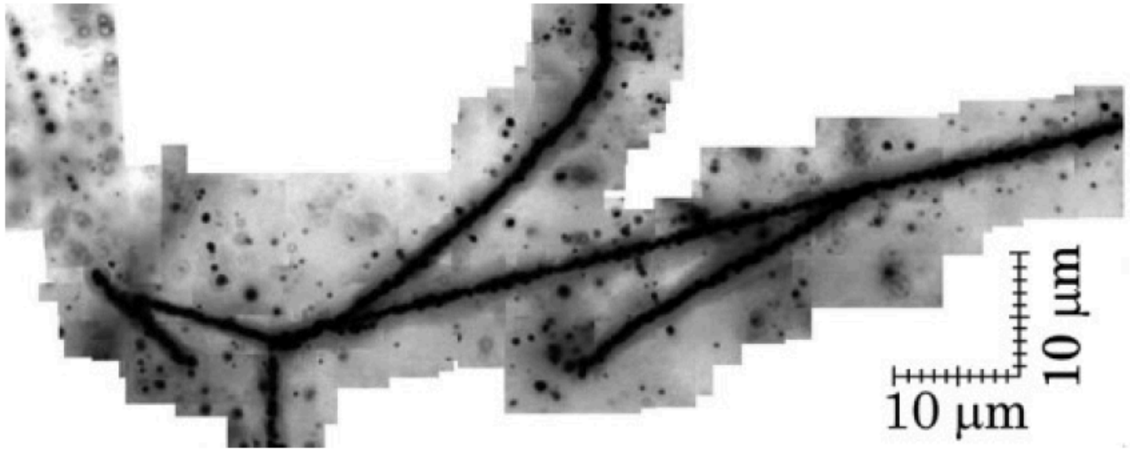
ALICE Collaboration, PRL 123, 112002

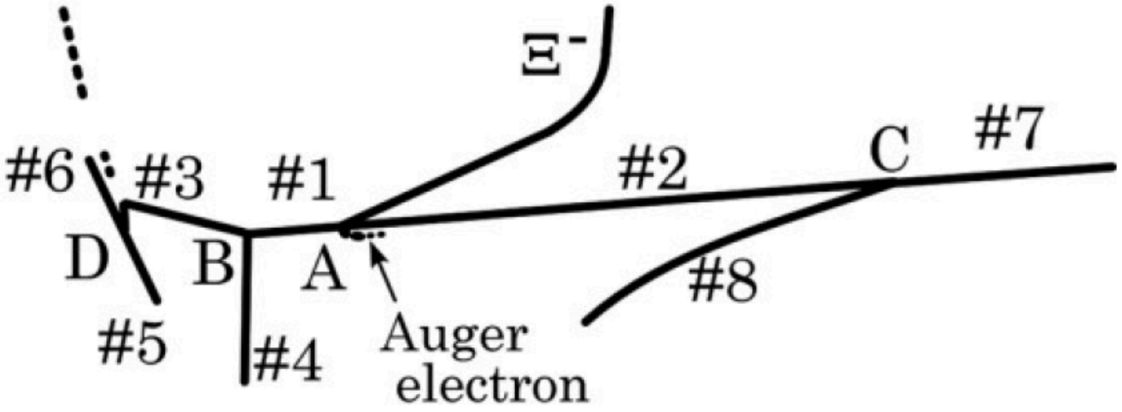
https://doi.org/10.1103/PhysRevLett.123.112002

Dataset: High multiplicity pp 13 TeV

Data on Ξ interaction

- Kiso and Ibuki Event: Ξ^- hyper nucleus
- Points towards an attractive interaction
  - Hyper nucleus binding energy $B_{\Xi^-} \sim 1$ MeV



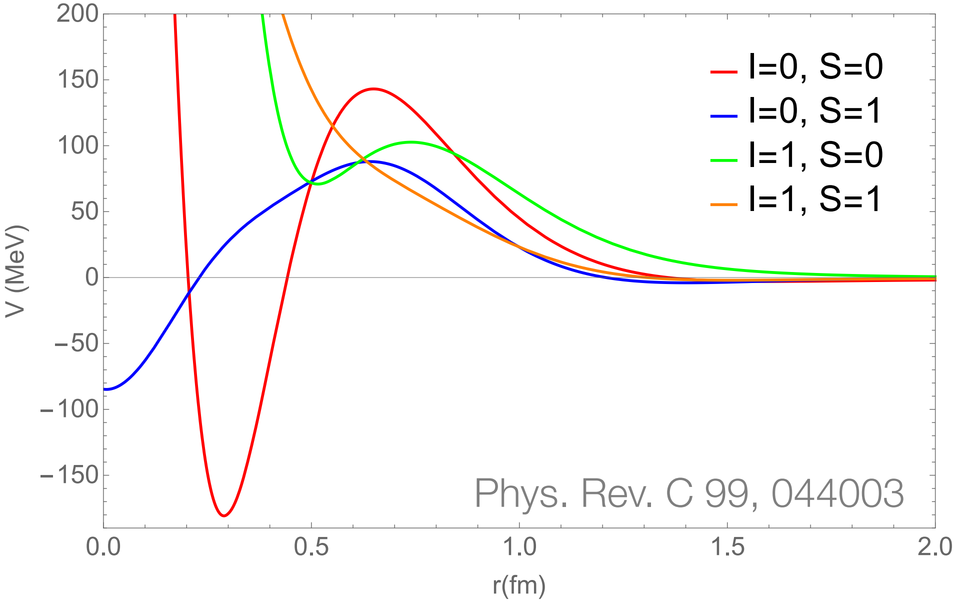


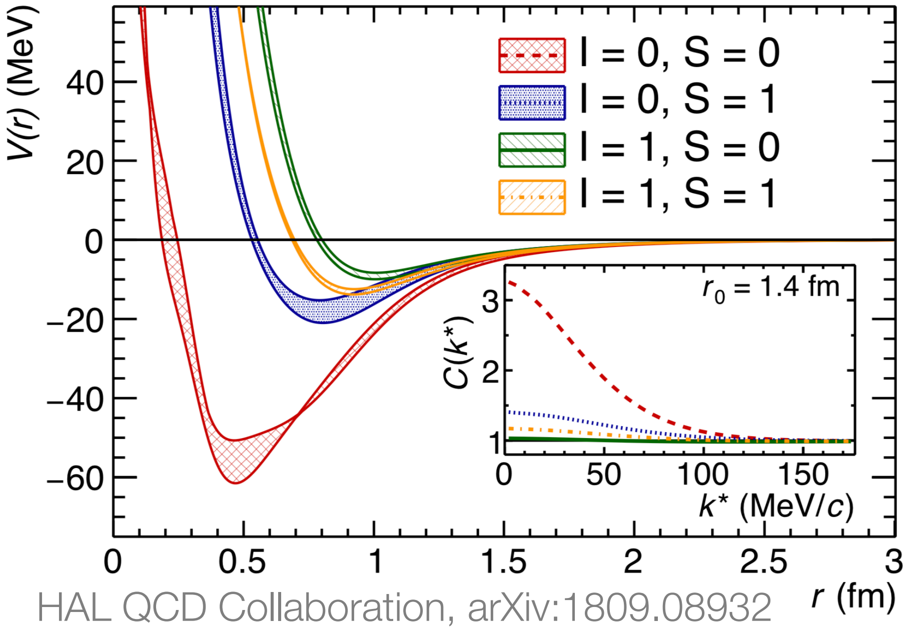
K. Nakazawa et al. PTEP 2015, 033D02

The N-Ξ interaction

	I = 0	I = 1	Detectable
n-Ξ^-	✗	✓	No
p-Ξ^0	✗	✓	Difficult
p-$\bar{\Xi}^+$	✓	✗	Difficult
p-Ξ^-	✓	✓	Yes

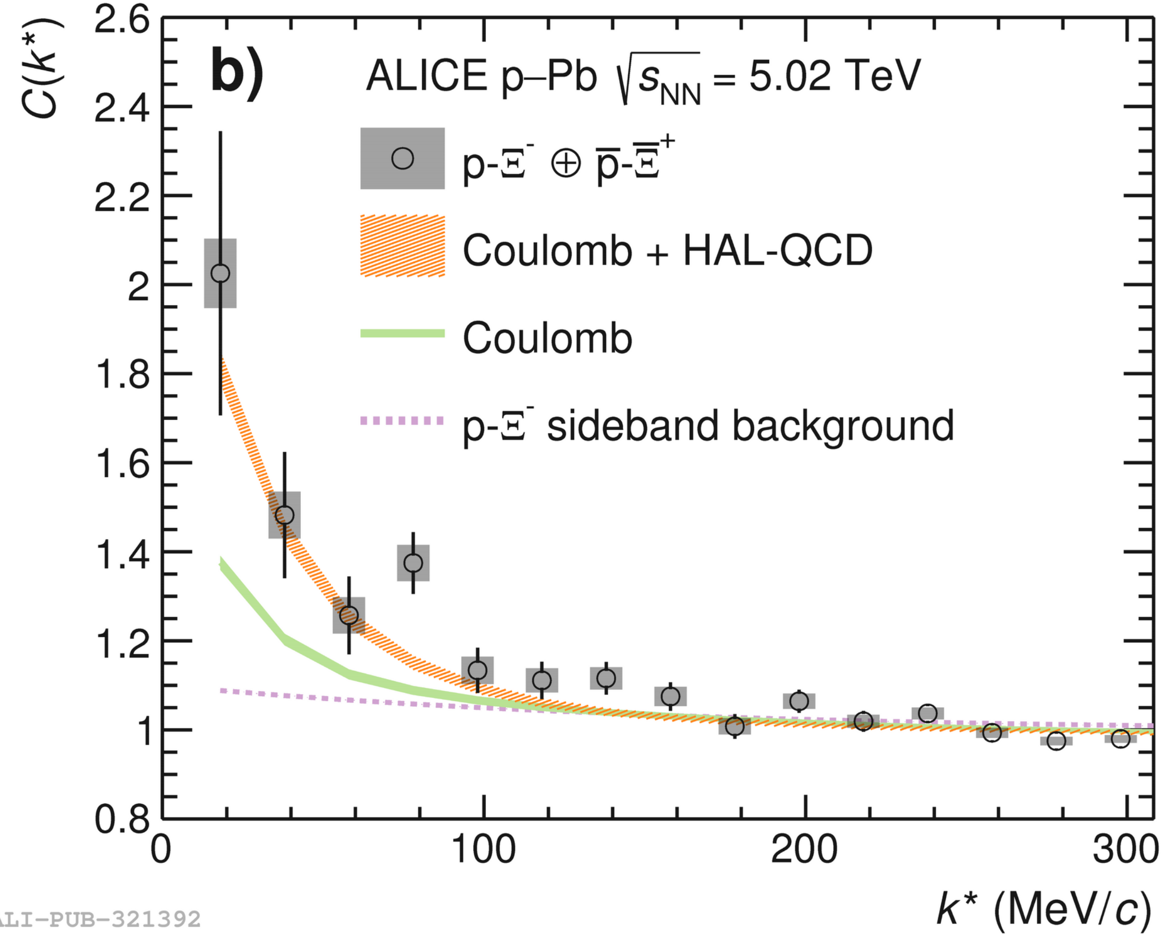
- Null Hypothesis: Coulomb only
- HAL QCD Potential
- NEW: Potential by Nijmegen group

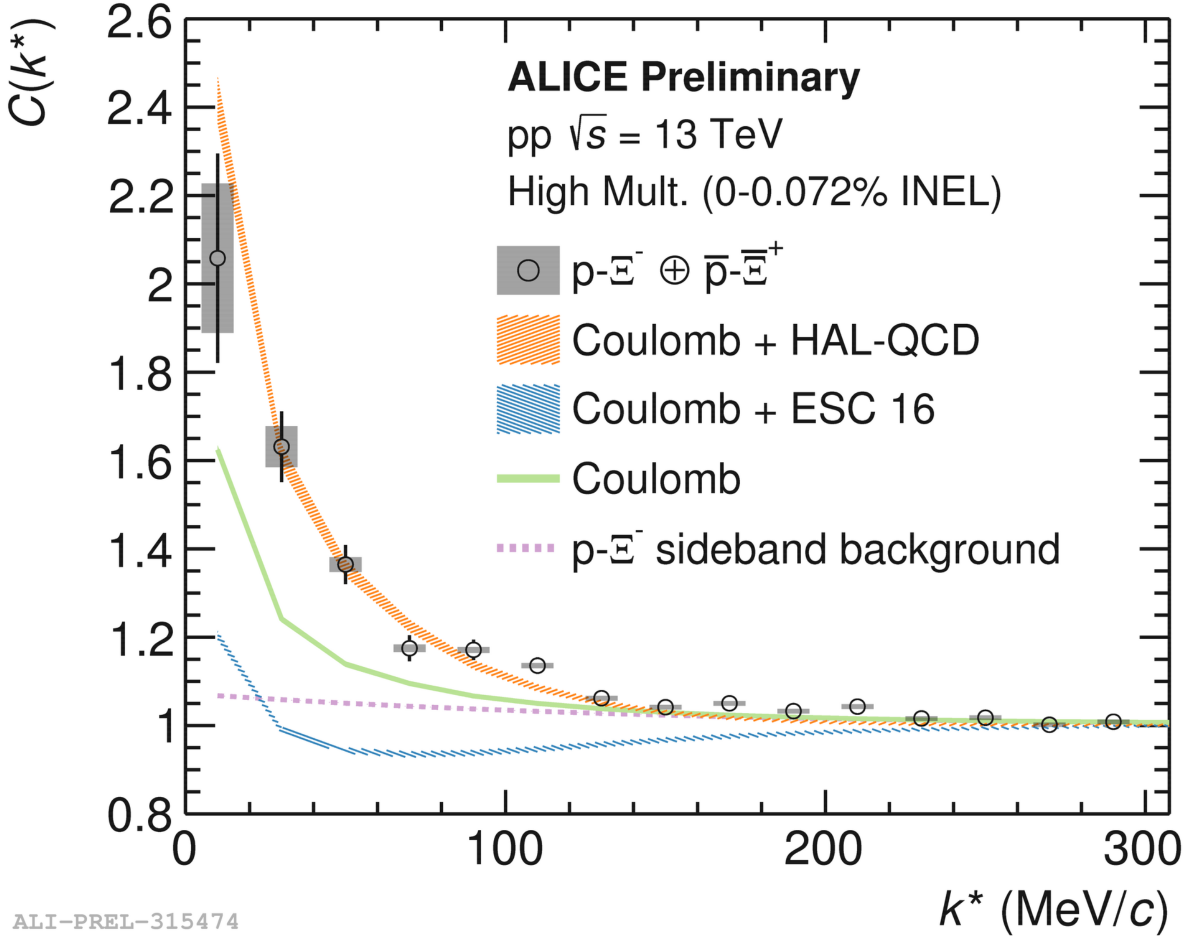




HAL QCD Collaboration, arXiv:1809.08932

Measurement of the p-Ξ⁻ interaction





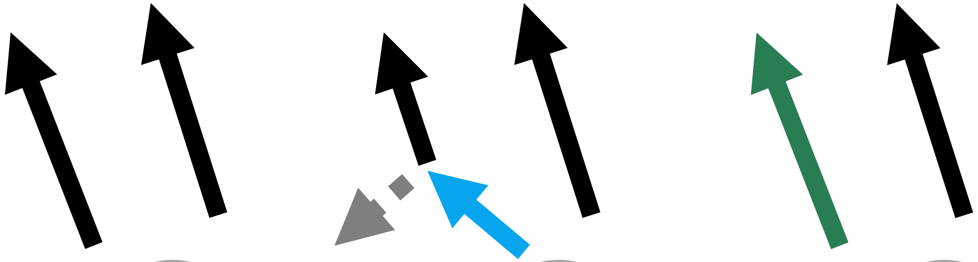
https://doi.org/10.1103/PhysRevLett.123.112002

Summary and Outlook

- Λ–Λ correlation function interaction studies
  - Combined analysis of different datasets
    - Analysis of high multiplicity data
  - Constraint on the parameter space
    - Upper limit on the binding energy of a hypothetical Λ–Λ bound state
- p–Λ correlation function interaction studies
  - Experimental confirmation of cusp effects in p–Λ
  - Providing constraints with unprecedented precision for theory
- p-Ξ^- correlation function interaction studies
  - Continuation of the p-Pb analysis
  - Confirms previous results: Observation of attractive strong interaction
  - Test of additional models

Backup

Decomposition of C(k*)

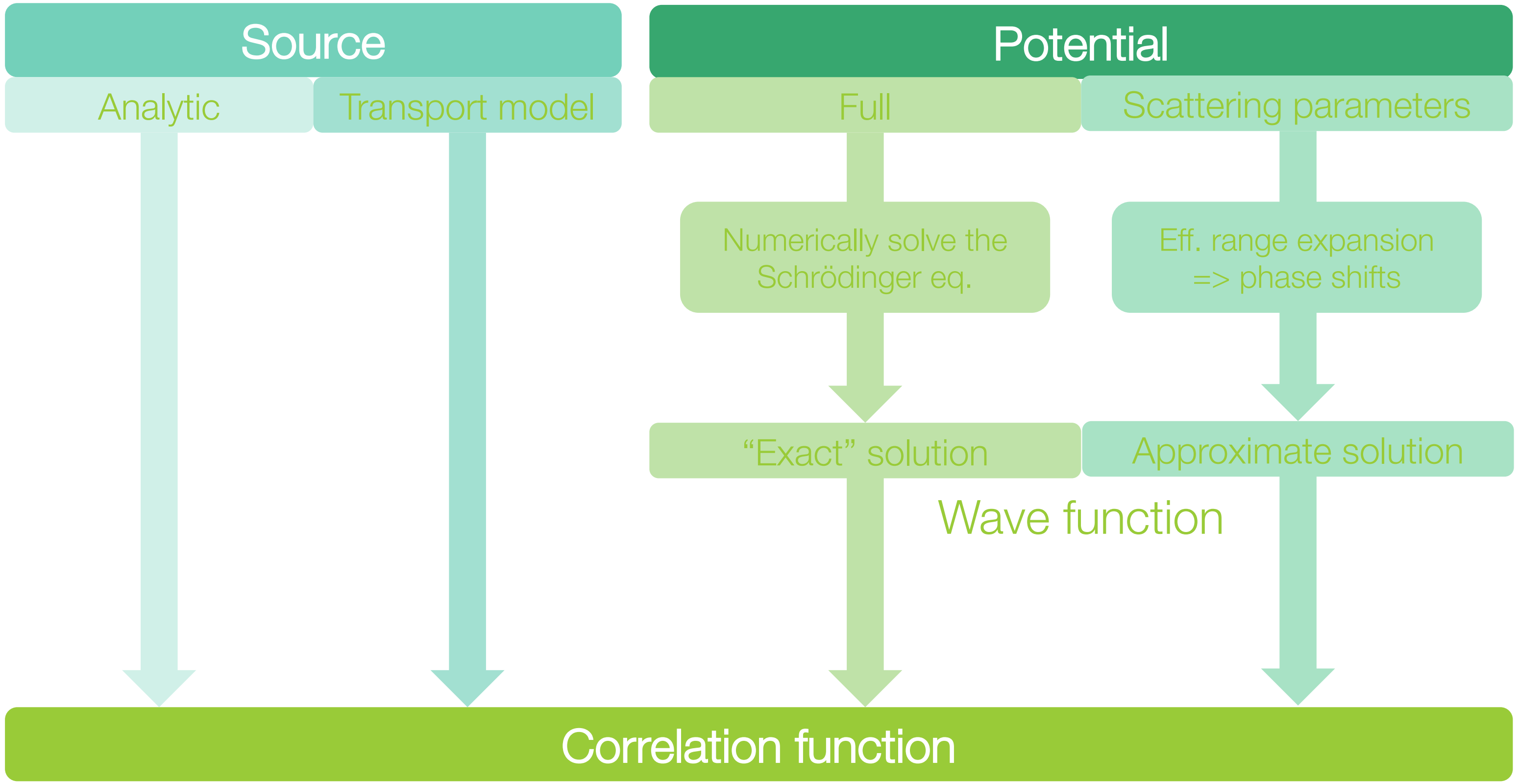


$$C_{tot}(k^*) = \lambda_0 C_0 \oplus \lambda_1 C_1 \oplus \lambda_2 C_2 \oplus \ldots$$

Contributions from: genuine feed-down impurities

- Purity ($\mathcal{P}_i$) and Feed down fractions (f_i) yield weight of pair contributions as $\lambda_{ij} = \mathcal{P}_{i_1} \cdot f_{i_1} \cdot \mathcal{P}_{j_2} \cdot f_{j_2}$ (Details see Phys. Rev. C 99 (2019), 024001)
  - Purity: Fits of the Invariant mass and MC truth information
  - Feed down fractions: MC template fits to data
  - For all pairs: Genuine pair contribution dominates

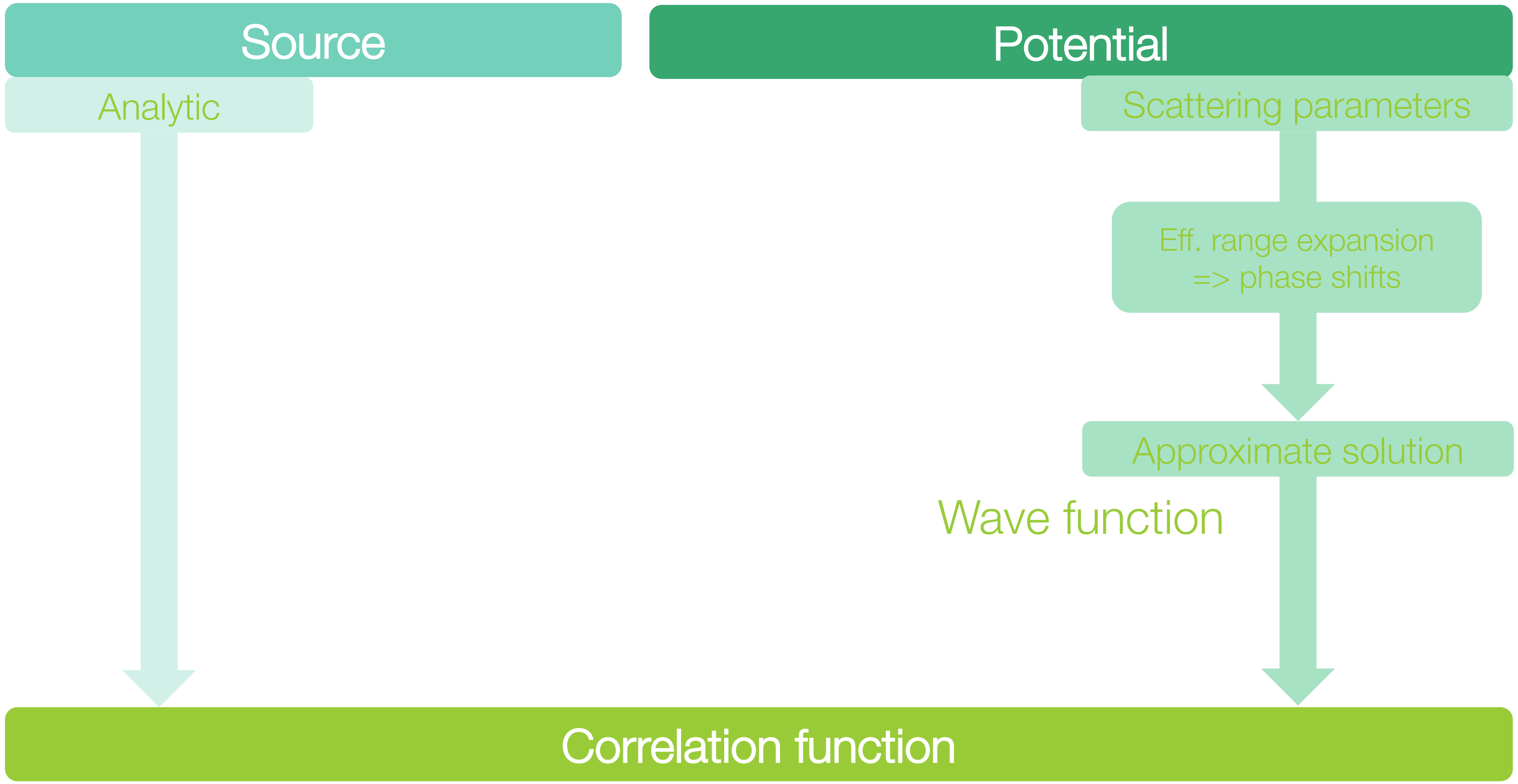
Modelling the correlation function



$$C(k^*) = \frac{P(\mathbf{p}_a, \mathbf{p}_b)}{P(\mathbf{p}_a)P(\mathbf{p}_b)} = \mathcal{N} \cdot \frac{N_{same}}{N_{mixed}} = \int S(r) \; |\Psi(k^*, \vec{r})|^2 \, d\vec{r}$$

Emission source Two-particle wave function

Lednicky model

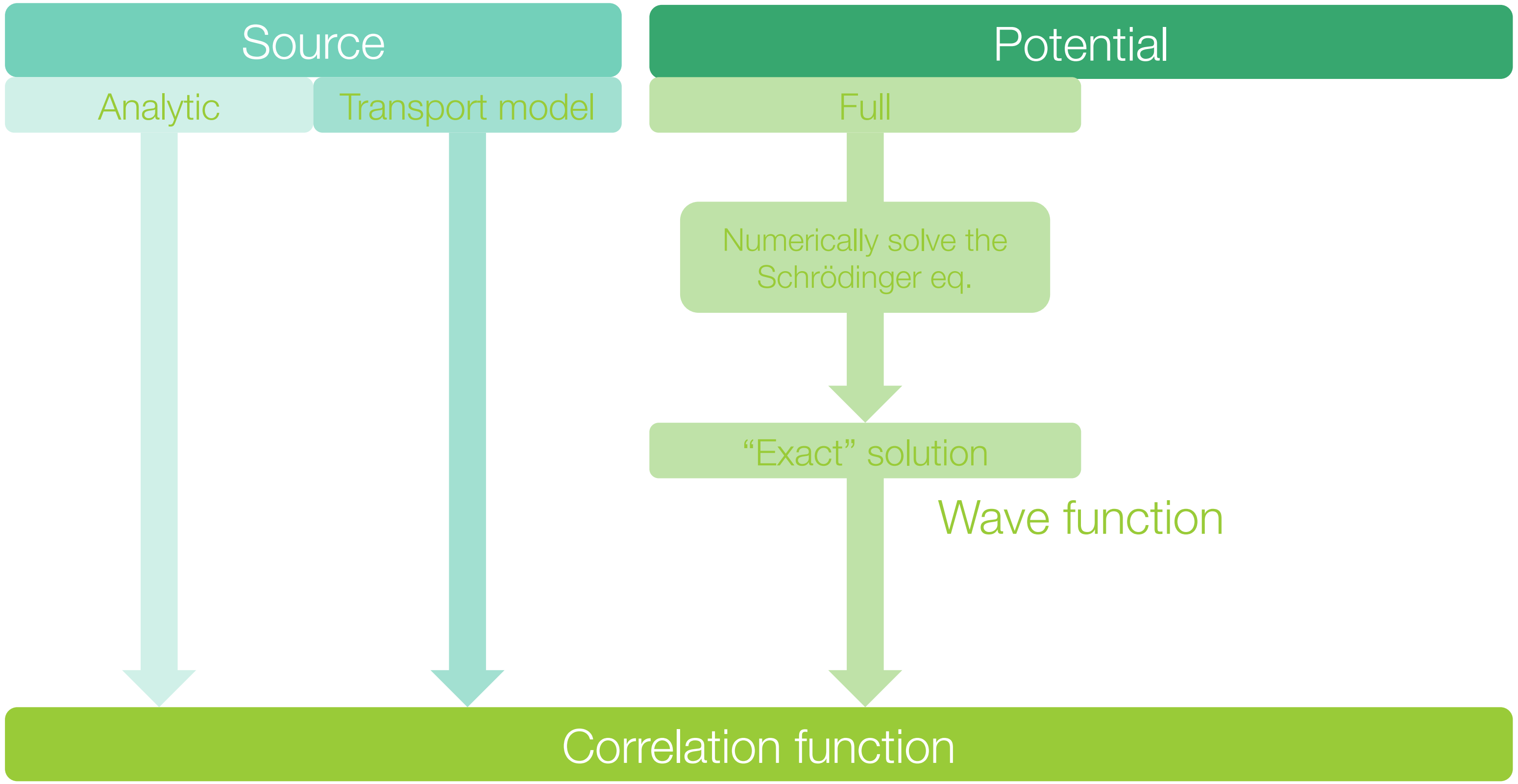


$$C(k) = 1 + \sum_S \rho_S \left[\frac{1}{2} \left| \frac{f^S(k)}{R_G^{\Lambda p}} \right|^2 \left(1 - \frac{d_0^S}{2\sqrt{\pi} R_G^{\Lambda p}} \right) + 2 \frac{\mathcal{R} f^S(k)}{\sqrt{\pi} R_G^{\Lambda p}} F_1(Q R_G^{\Lambda p}) - \frac{\mathcal{I} f^S(k)}{R_G^{\Lambda p}} F_2(Q R_G^{\Lambda p})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

R. Lednicky and V.L. Lyuboshits, Sov. J. Nucl. Phys. 53, 770 (1982)

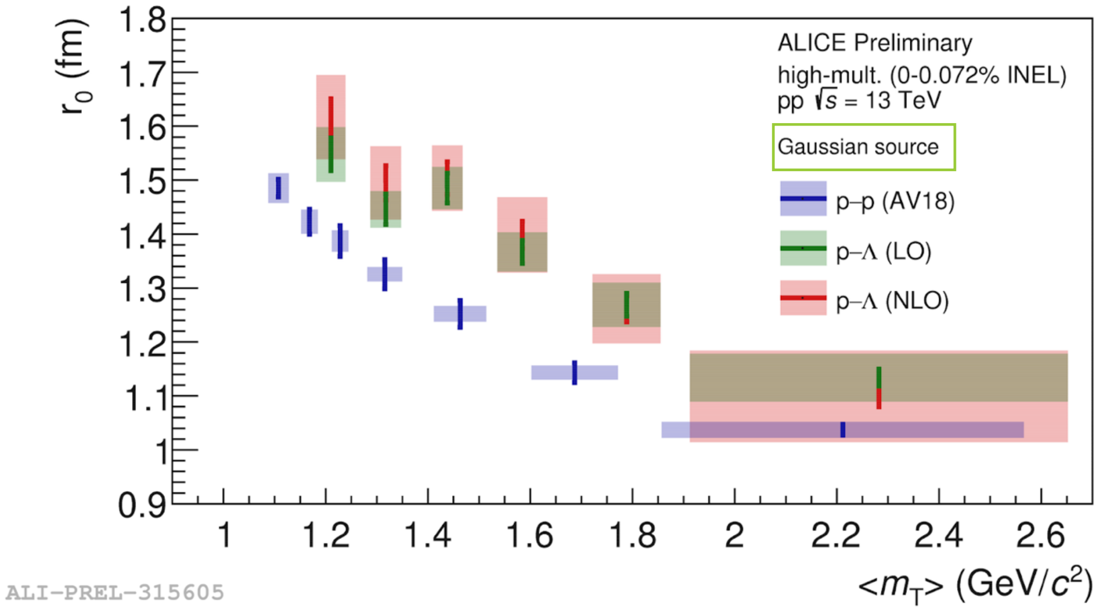
- Might locally break down for small sources

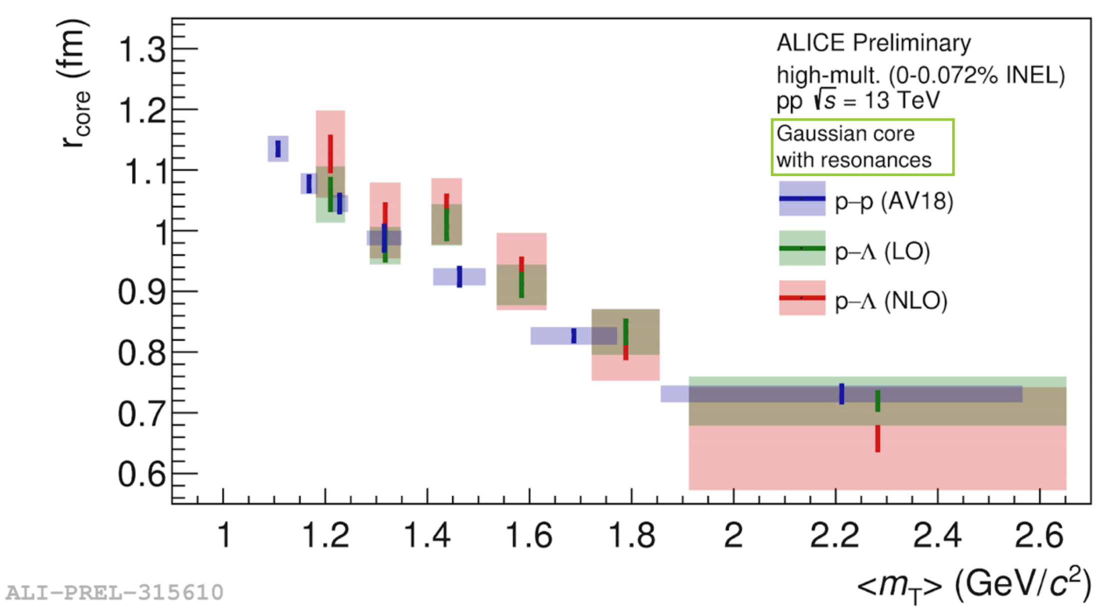
CATS



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

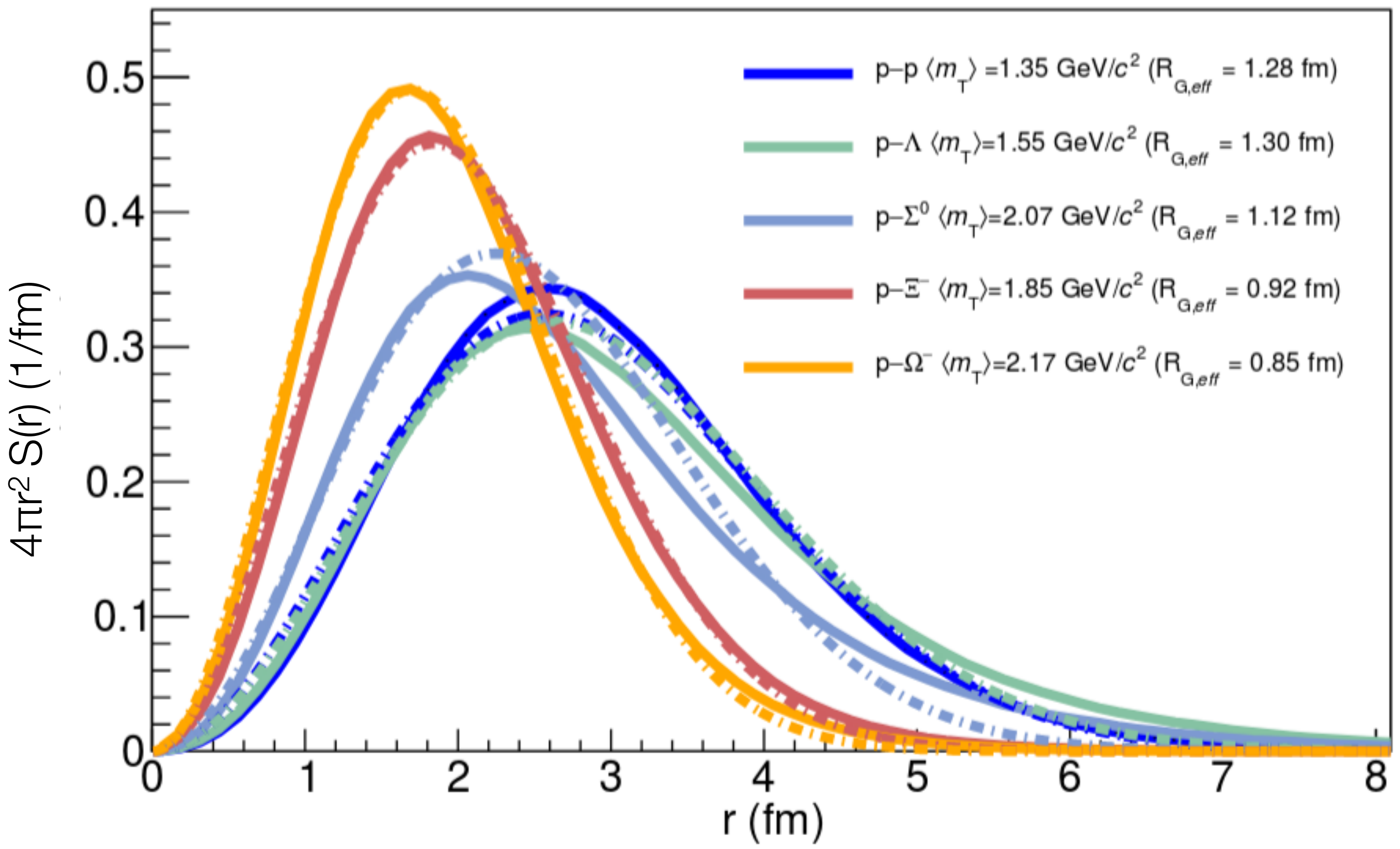
The source function



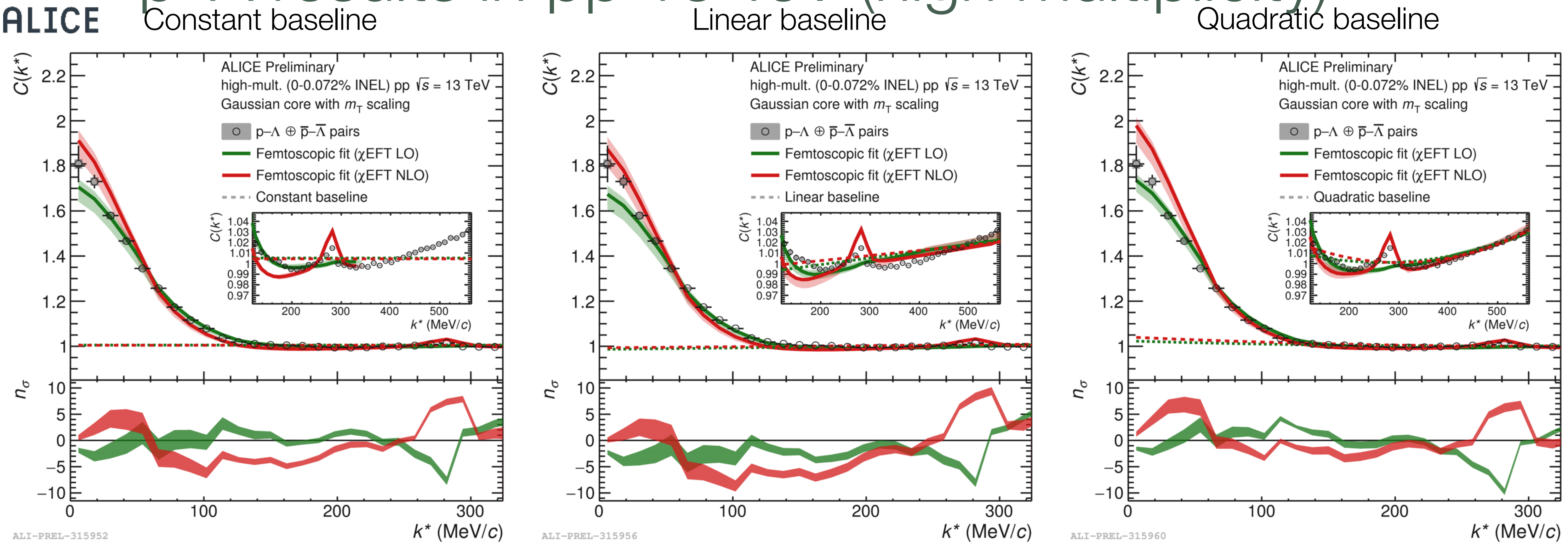


- Each $<m_T>$ bin fitted independently with the two source models
- The results are compared for p-p and p-Λ correlation
- Our Ansatz: The scaling should be the same.
  - The basic MC model works

Source r_{Core} + resonances



p–Λ results in pp 13 TeV (high multiplicity)



- Different variations of the baseline: Constant, linear & quadratic
  - Best fit for LO: $n_\sigma > 8$
  - Best fit for NLO: $n_\sigma > 10$

Measurement of the p-Ξ^- interaction

- Identification via $\Xi^- \rightarrow \Lambda\pi^-$
- Treatment of residual correlations
  - Misidentification of Ξ^-
    - Ξ^- Purity ~ 92 %
      $\rightarrow \lambda_{p-\tilde{\Xi}}$ pair contribution ~ 8.5 %
    - $C_{p-\tilde{\Xi}}(k^*)$ from the sidebands of the Ξ^- selection
  - p-Ξ^-(1530)
    $\rightarrow \lambda_{p-\Xi^-(1530)}$ pair contribution ~ 8.2 %