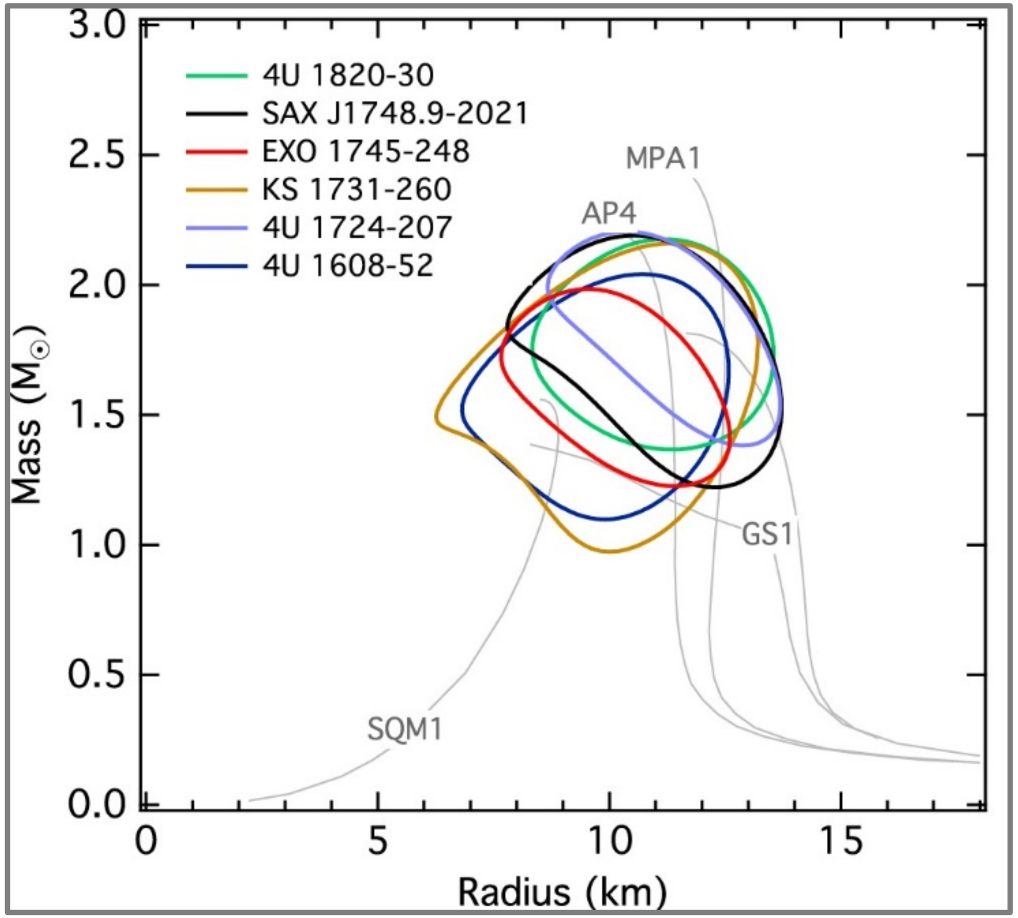
Outline

- Neutron Stars and what we learn from Femtoscopy
  - The Hyperon Puzzle
  - How can Femtoscopy help?
- Correlation functions
  - Theoretical description of the correlation function
  - Experimental correlation functions
- Results of the Analysis in the p-p collision system at 7 TeV
  - pp and Λp Correlations
  - $\Lambda\Lambda$ Correlations
  - Future prospects with CATS
- Summary and Outlook

Neutron Stars



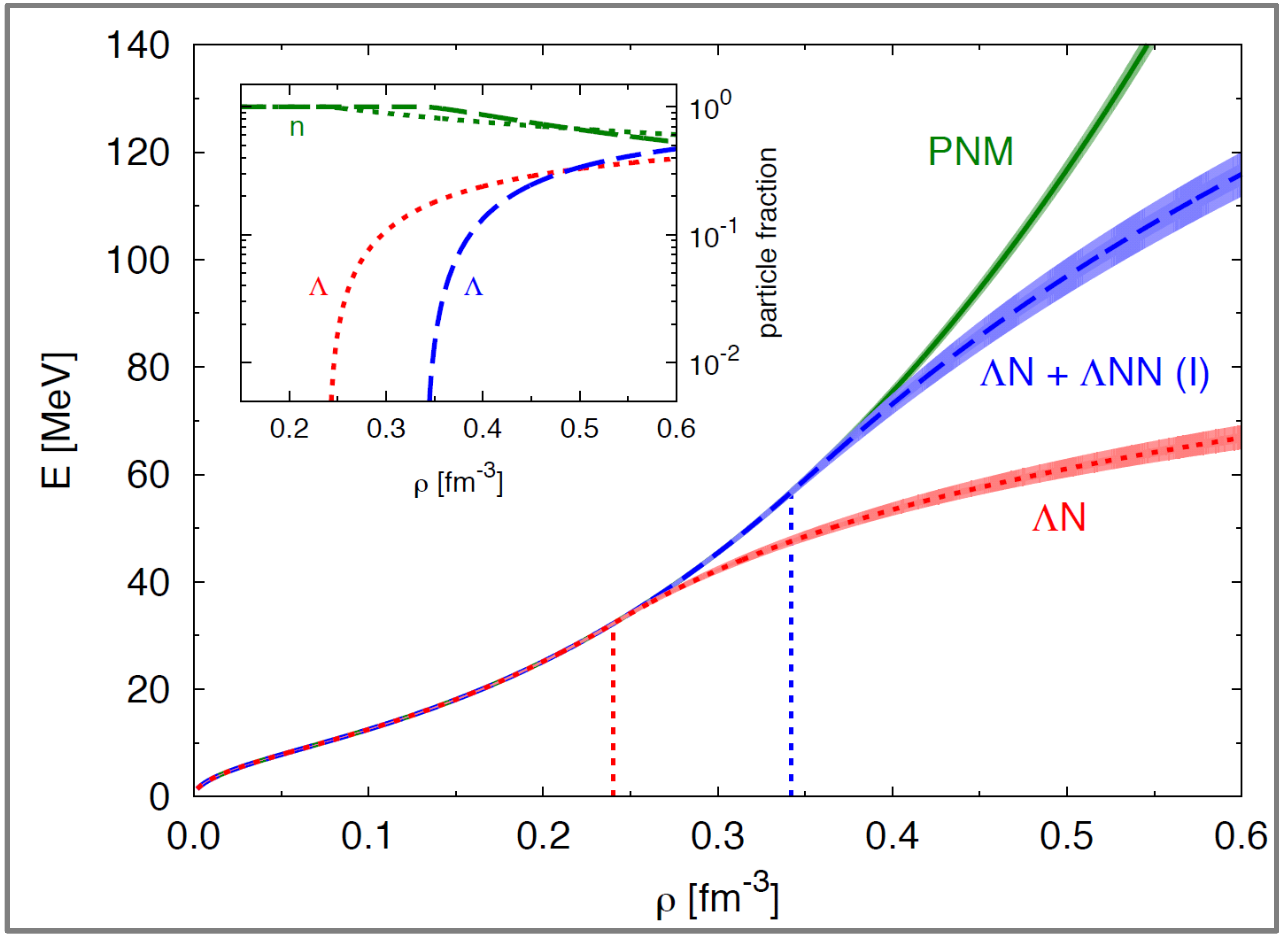
Ozel et al. 2015 (arXiv:1505.05155v2)

- Observation from X-Ray measurements of binary Systems:
  - Neutron star masses $m > m_\odot$ and radii between $5 - 15$ km
- From Shapiro Delay Measurements of binary systems: (P.Demorest et. Al, Nature 467 (2010), pp. 1081-1083)
  - Neutron star $m = (1.97 \pm 0.04) m_\odot$
- Large nucleon chemical potential ($\rho > \rho_0$)

→ Hyperon production becomes energetically possible? e.g. Λ, Ξ, Σ

The Equation of State (EoS)

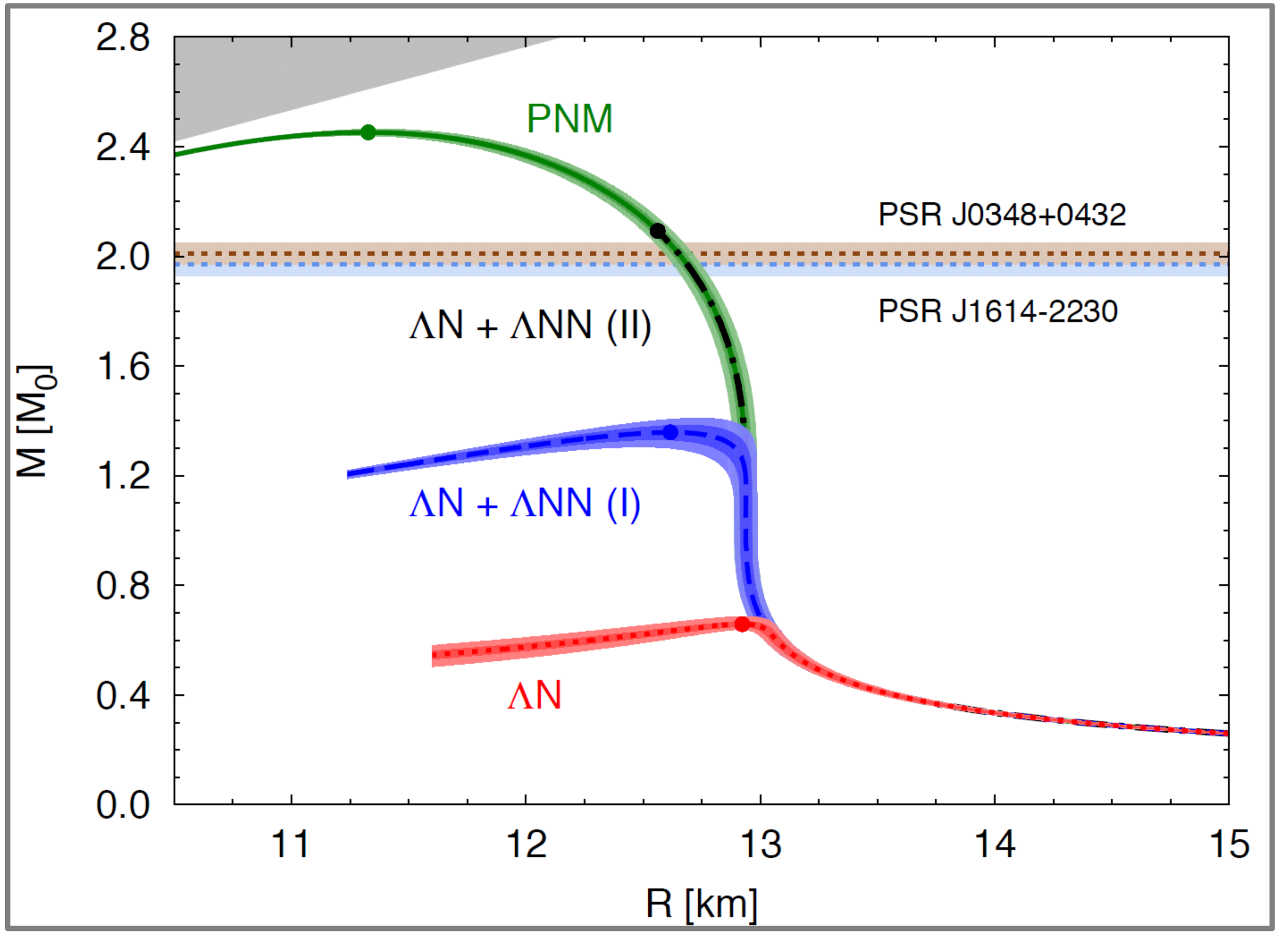
- Interaction potential between hyperons and neutron matter governs the onset of production and behavior of the EoS
- Quantum Monte Carlo study of pure nuclear matter and hyper neutron matter
  - Attractive ΛN interaction softens EoS
  - Repulsive ΛNN interaction stiffens EoS



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

Mass – Radius Relation of Neutron Stars

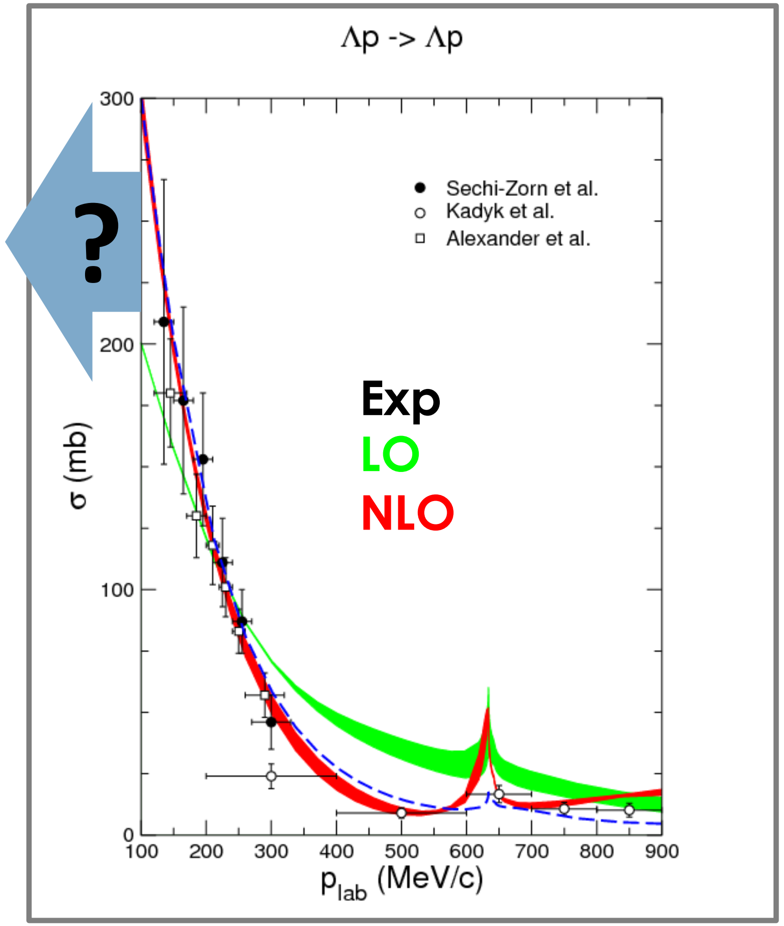
- EoS allows to solve the Tolman-Oppenheimer-Volkoff Equations
  - ➢ Mass Radius Relation
- Repulsive 3 body interaction shifts onset of hyperon production to larger densities and allows for higher masses
  - Not well constrained
- To understand the role of hyperons in neutron stars more constraints on the hyperon-neutron force are needed



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

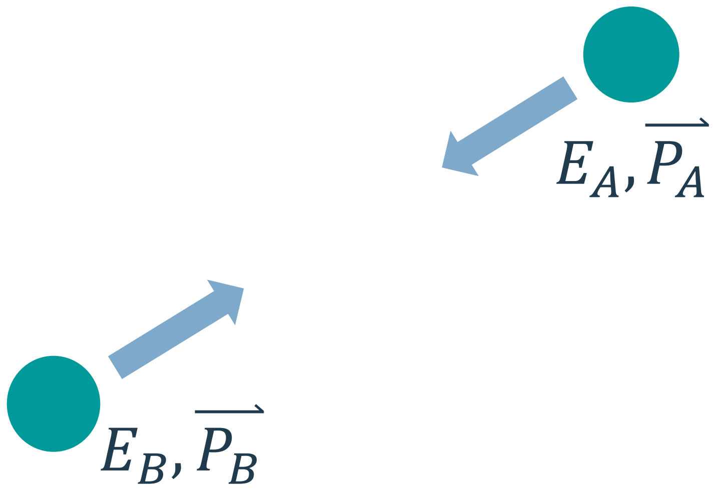
Global Proton-Λ Scattering Data

- 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
- Different type of measurement needed to obtain constraints at low momentum
- Can we use Femtoscopic measurements?

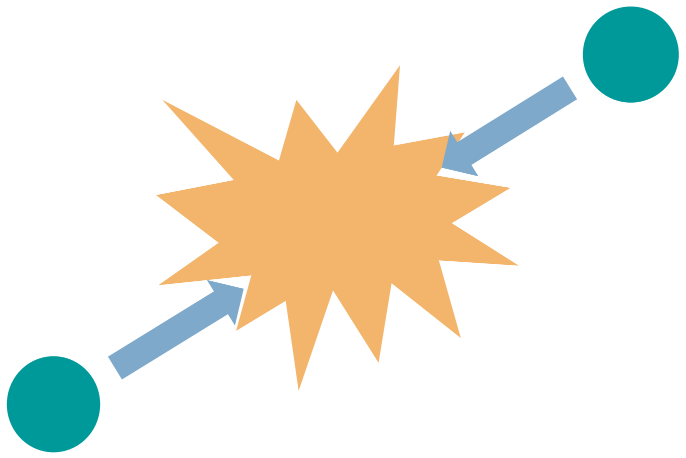


LO: H. Polinder, J.H., U. Meiβner, NPA 779 (2006) 244
NLO: J.Haidenbauer., N.Kaiser, et al., NPA 915 (2013) 24

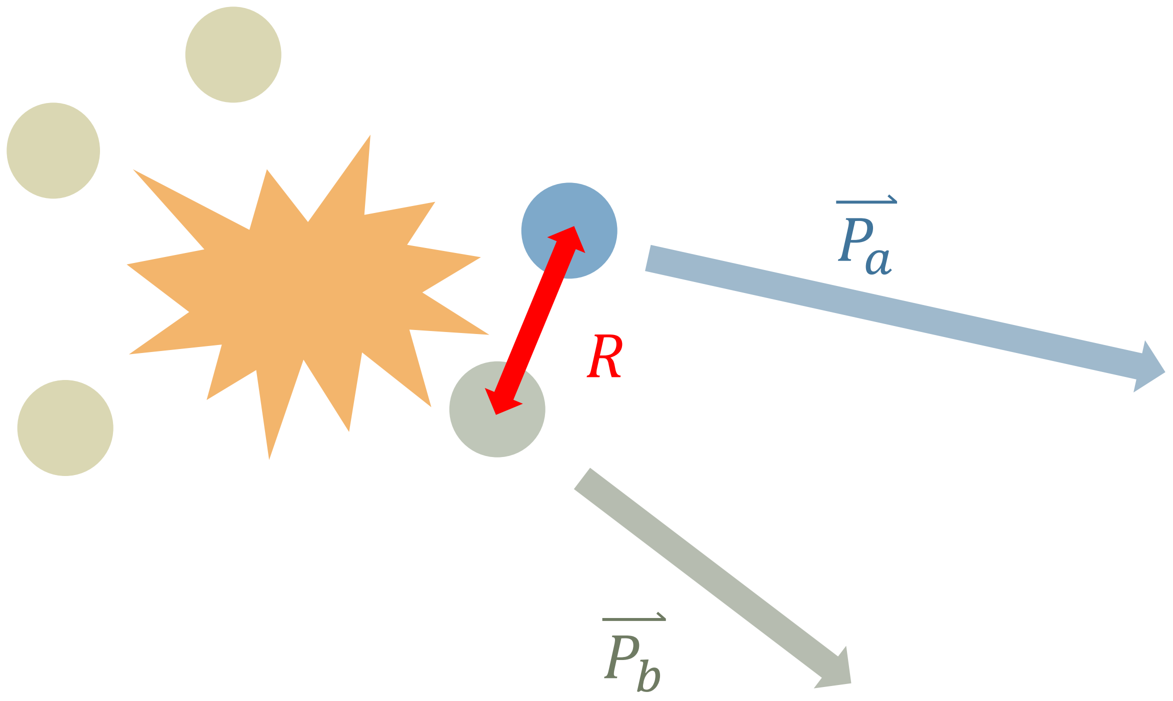
Nuclear Collisions



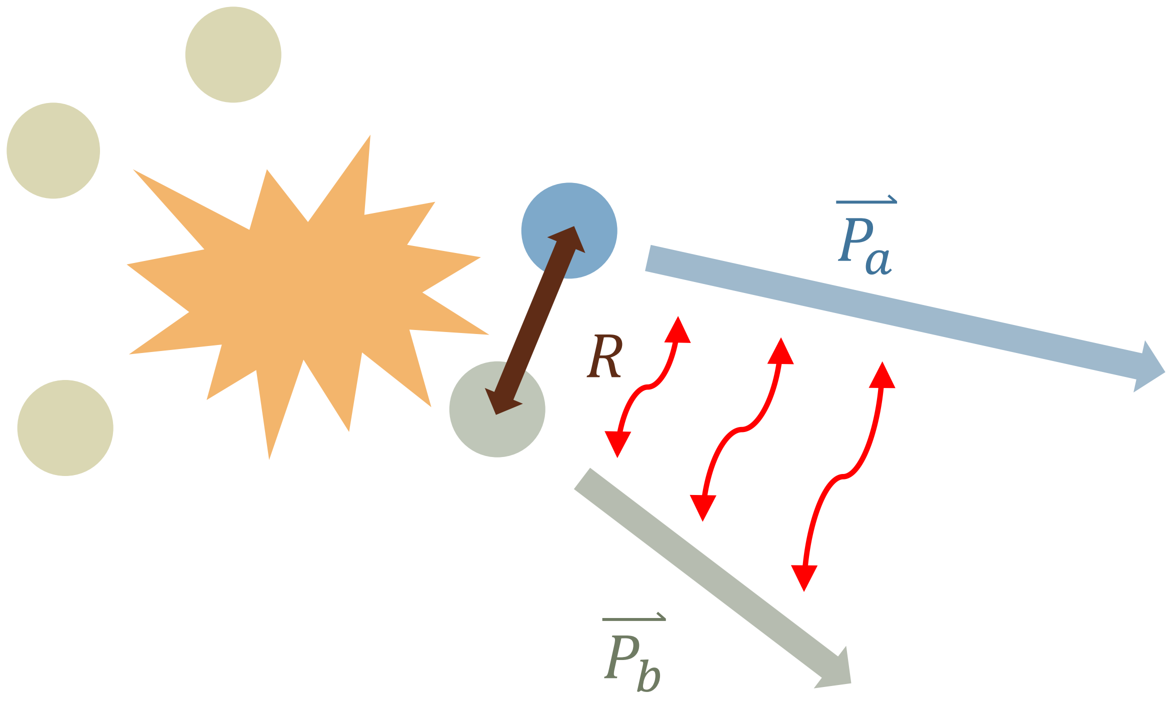
Nuclear Collisions



Particle Production



Particle Propagation



The Correlation Function

Theoretical formulation of the Correlation Function:

$$C(\overrightarrow{\boldsymbol{p}_a}, \overrightarrow{\boldsymbol{p}_b}) = \frac{P(\overrightarrow{p_a}, \overrightarrow{p_b})}{P(\overrightarrow{p_a})P(\overrightarrow{p_b})} = C(k) = \int S(\vec{\boldsymbol{r}}, k)|\psi(\vec{\boldsymbol{r}}, k)|^2 \, d\vec{\boldsymbol{r}}$$

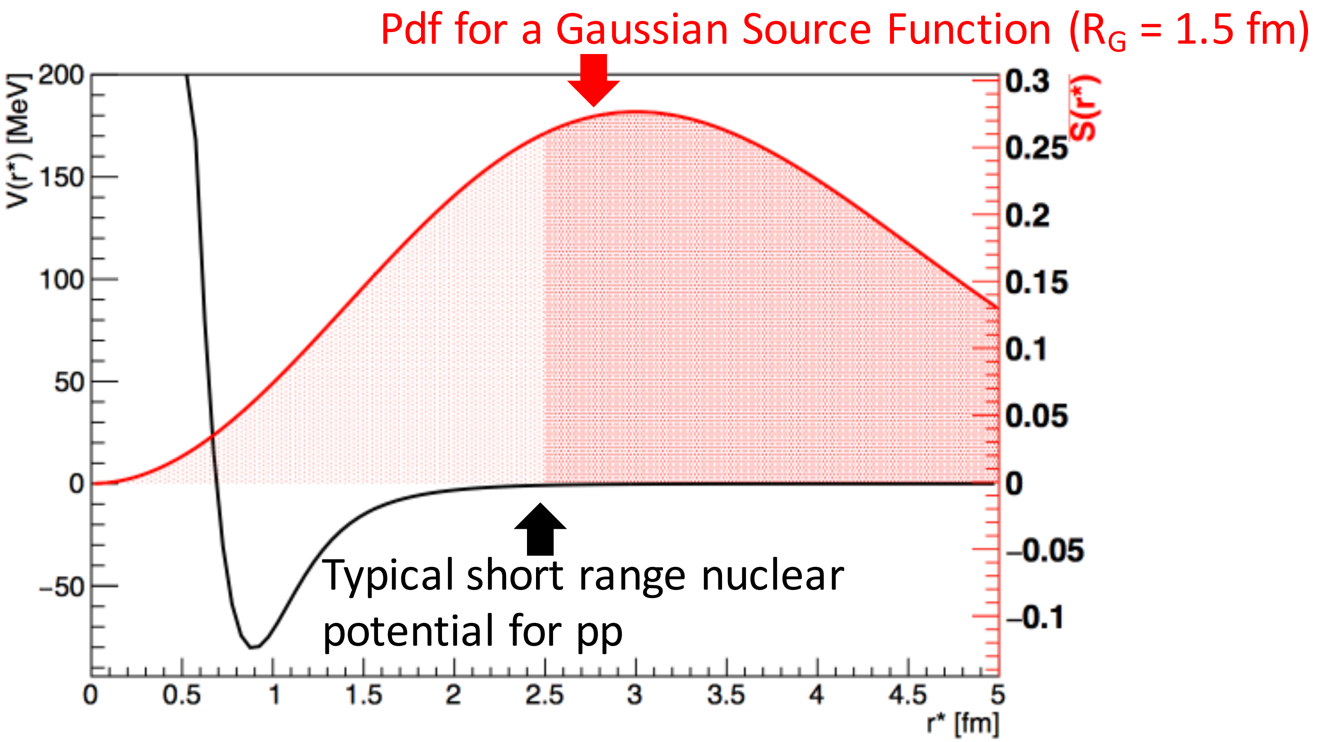
Source

Wave Function

If we know about the **source**, we can learn about the **interaction**

Fix the parametrization of the source by fitting the pp and Λp Correlation Function simultaneously to test different models of the pΛ interaction

Small Source -> Repulsive Core



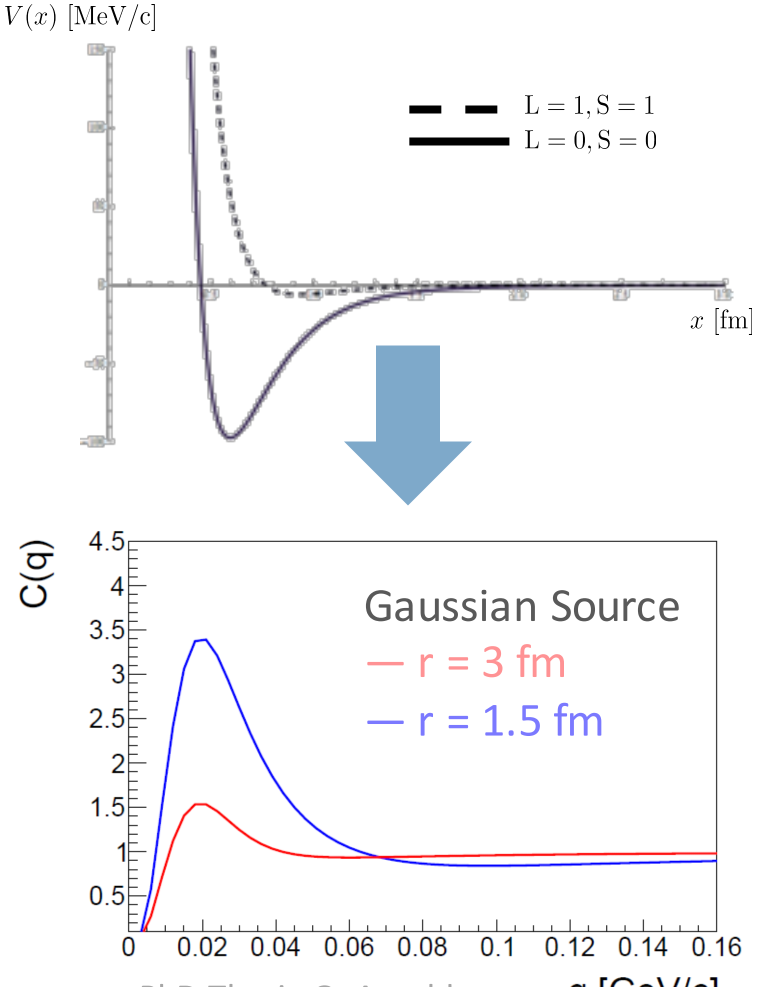
The pp Correlation Function

- Governed by:
  - Coulomb Interaction
  - Strong Interaction
  - Quantum Statistics
- Koonin Fit Function
  - Assumes a **Gaussian source** of size R_G

$$C(k) = \int dr^3 \phi_{rel}^2(r,k) \exp\left(-\frac{r^2}{4R_G^2}\right)$$

S. E. Koonin, Phys. Lett. B 70 (1977) 43
S. Pratt et al., Nucl. Phys. A 566 (1994) 103c

  - ϕ_{rel} from solving the Schrödinger Equation with the **known potentials** for the Coulomb and Strong interaction



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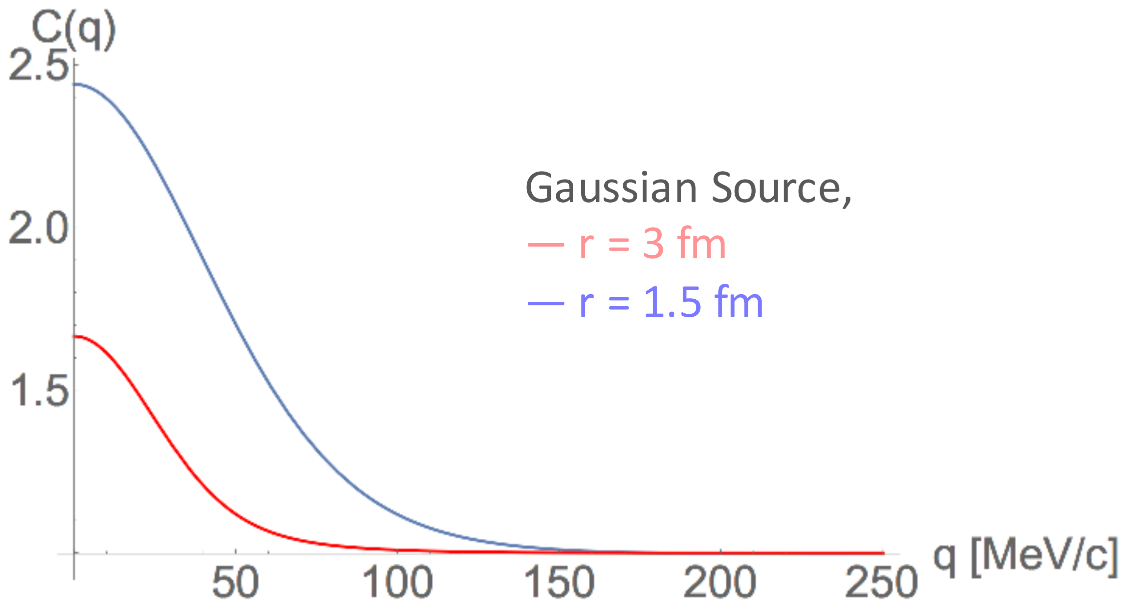
The Λp Correlation Function

- Governed by:
  - Strong Interaction
  - No Coulomb Interaction
- Lednický model
  - Assumes a **Gaussian source** of size R_G
  - Based on the effective Range expansion
  - The interaction is modeled using the **scattering length** (f_0) and the **effective range** (d_0)



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

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

The Λp Correlation Function

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  - Strong Interaction
  - No Coulomb interaction

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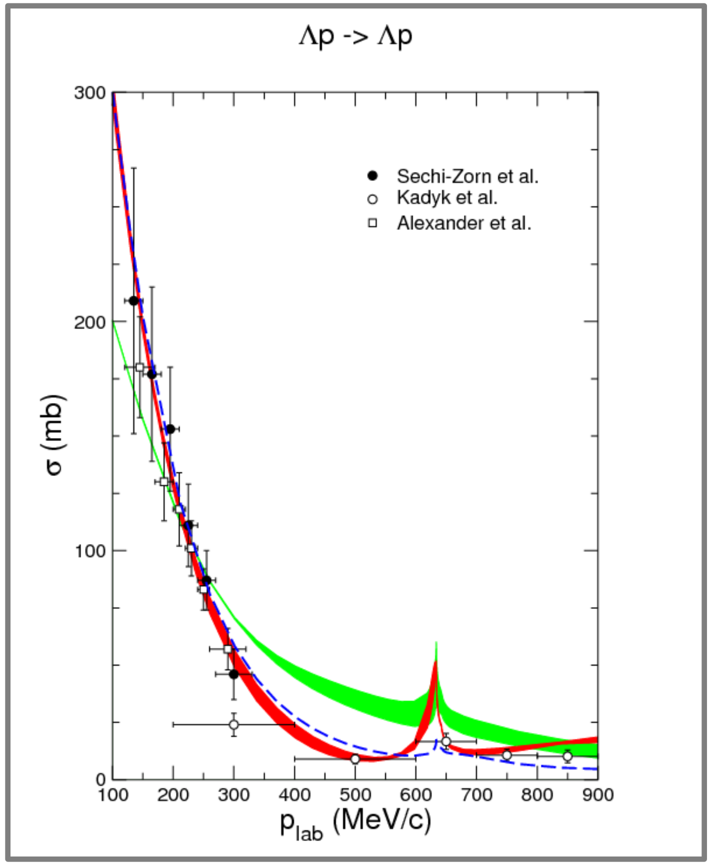


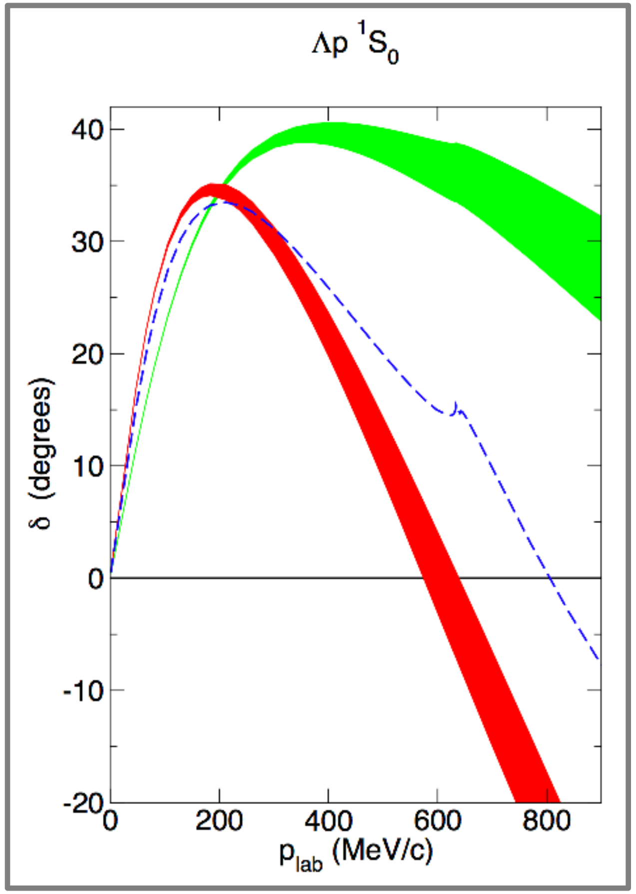
An expression containing f_0

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

Choice of Parameters: LO vs. NLO

- Calculations based on an chiral effect field theory calculations
- Discrimination of the two models not possible due to the lack of data
- NLO predicts a repulsive core of the interaction potential

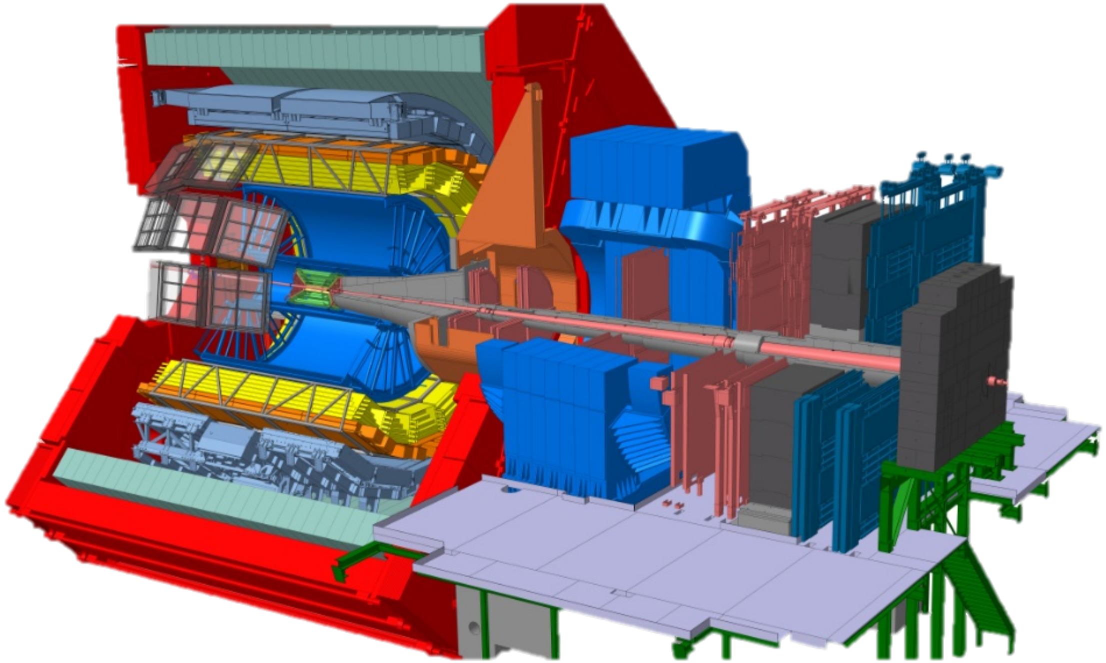
	NLO						LO
Λ [MeV]	450	500	550	600	650	700	600
$a_s^{\Lambda p}$	-2.90	-2.91	-2.91	-2.91	-2.90	-2.90	-1.91
$r_s^{\Lambda p}$	2.64	2.86	2.84	2.78	2.65	2.56	1.40
$a_t^{\Lambda p}$	-1.70	-1.61	-1.52	-1.54	-1.51	-1.48	-1.23
$r_t^{\Lambda p}$	3.44	3.05	2.83	2.72	2.64	2.62	2.13



Nucl. Phys. A915 (2013) 24-58, arXiv:1304.5339

A Large Ion Collider Experiment

pp 7 TeV



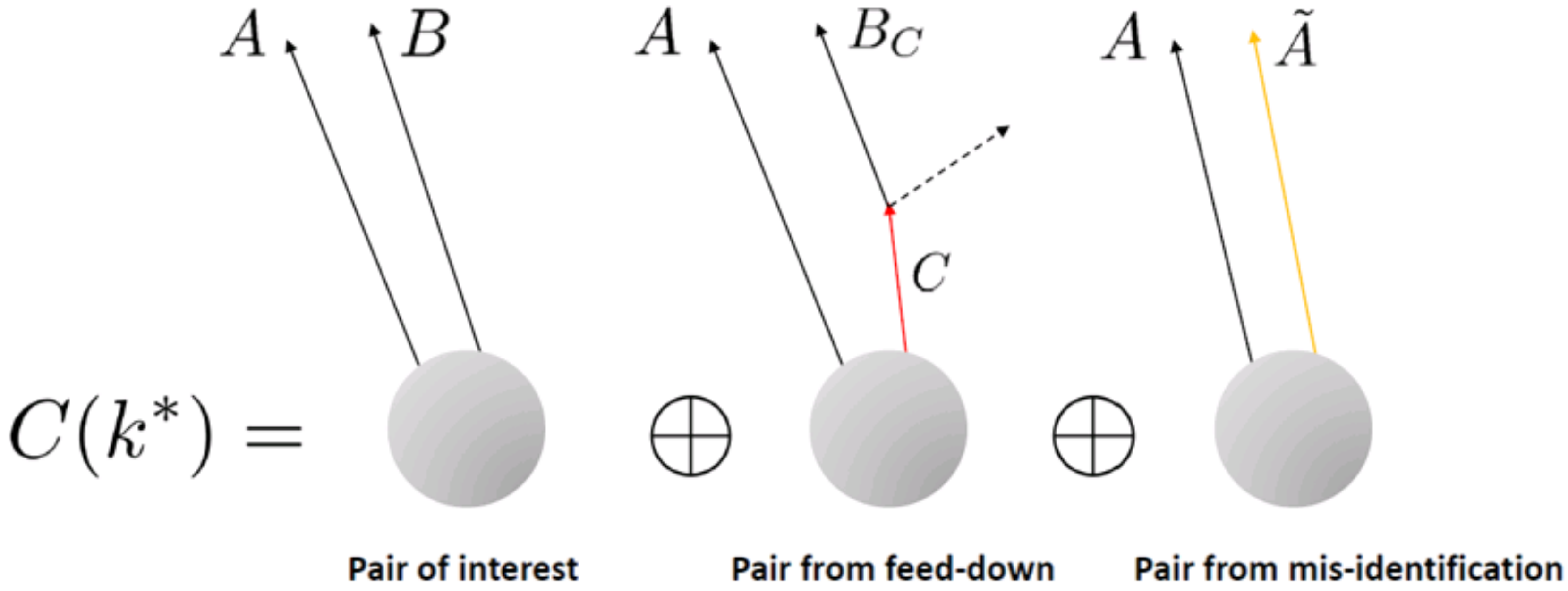
- Tracking and Particle Identification (PID) of charged particles
  - $|\eta| < 0.9$
  - 2π coverage in the azimuth
- Inner Tracking System (ITS)
- Time Projection Chamber (TPC)
- Time of Flight (TOF) System

The Experimental Correlation Function

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

The Experimental Correlation Function

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



The Experimental Correlation Function

$$C(\overrightarrow{\boldsymbol{p}_a}, \overrightarrow{\boldsymbol{p}_b}) = \frac{P(\overrightarrow{p_a}, \overrightarrow{p_b})}{P(\overrightarrow{p_a})P(\overrightarrow{p_b})} = \mathcal{N}\frac{N_{SE}(k)}{N_{ME}(k)} = \lambda_1 C_1(k) + \lambda_2 C_2(k) + \cdots$$

Correlation function of interest

Contributions from impurities, secondaries etc.

λ Parameters can be related to measured single-particle quantities, e.g. Purity $\mathcal{P}$ or feed-down fractions f

(PhD Thesis of O. Arnold - https://www.das.ktas.ph.tum.de/DasDocs/Public/PhD_Theses/arnold-oliver_thesis.pdf)

Decomposition of the Correlation Functions

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

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

Secondary contributions from measurements

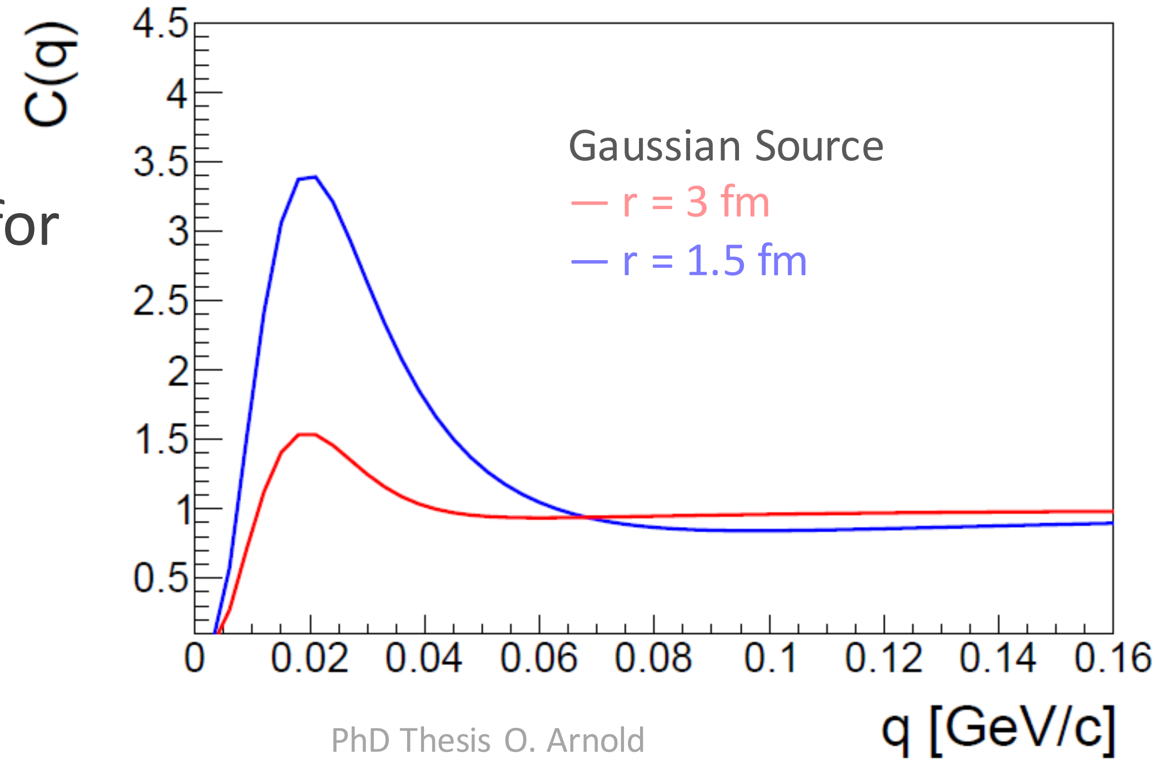
Pair	Percentage %
pp	75
$p_\Lambda p$	16
$p_\Lambda p_\Lambda$	1
$p_{\Sigma^+} p$	6
$p_{\Sigma^+} p_{\Sigma^+}$	0
$p_{\Sigma^+} p_\Lambda$	0
$\tilde{p}p$	2
$\tilde{p}\tilde{p}$	0

Pair	Percentage %
$p\Lambda$	49
$p\Lambda_{\Xi^-}$	10
$p\Lambda_{\Xi^0}$	10
$p\Lambda_{\Sigma^0}$	16
$p_\Lambda\Lambda$	5
$p_\Lambda\Lambda_{\Xi^-}$	1
$p_\Lambda\Lambda_{\Xi^0}$	1
$p_\Lambda\Lambda_{\Sigma^0}$	2
$p_{\Sigma^+}\Lambda$	0
$p_{\Sigma^+}\Lambda_{\Xi^-}$	0
$p_{\Sigma^+}\Lambda_{\Xi^0}$	1
$p_{\Sigma^+}\Lambda_{\Sigma^0}$	2
$\tilde{p}\Lambda$	1
$p\tilde{\Lambda}$	2
$\tilde{p}\tilde{\Lambda}$	0

The p-p collision system

- Mini Jet Background not present for baryon baryon pairs
  (see J.Adam et al., Europ. Phys. Jour. C, Aug. 17, 77:569)
- Evolution of the system is better understood compared to Pb-Pb
  - Same freeze out times and source size for all particles
- Small source sizes
  - Stronger signal
  - Sensitivity to the shape of the potential

pp Correlation Function



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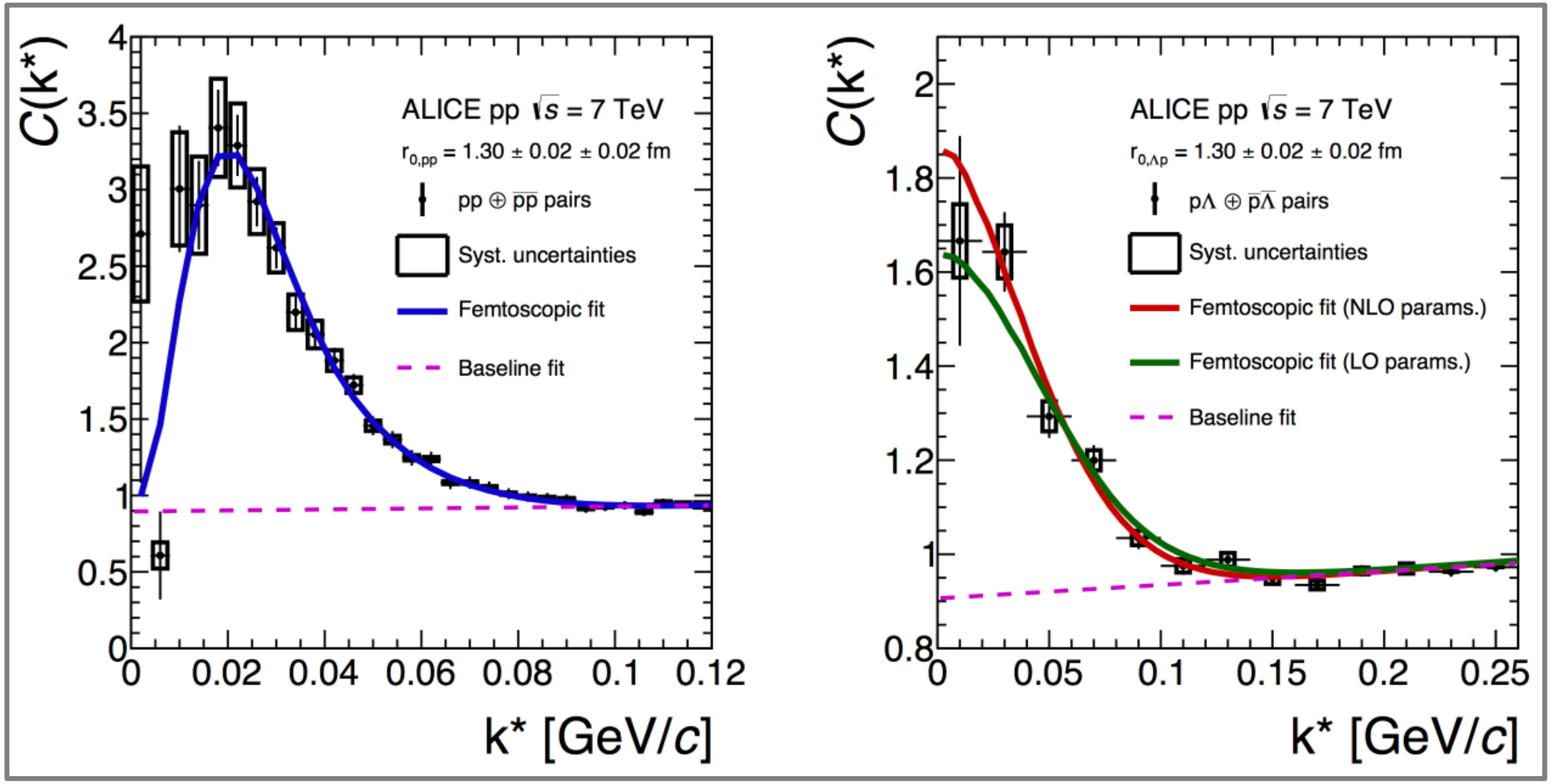
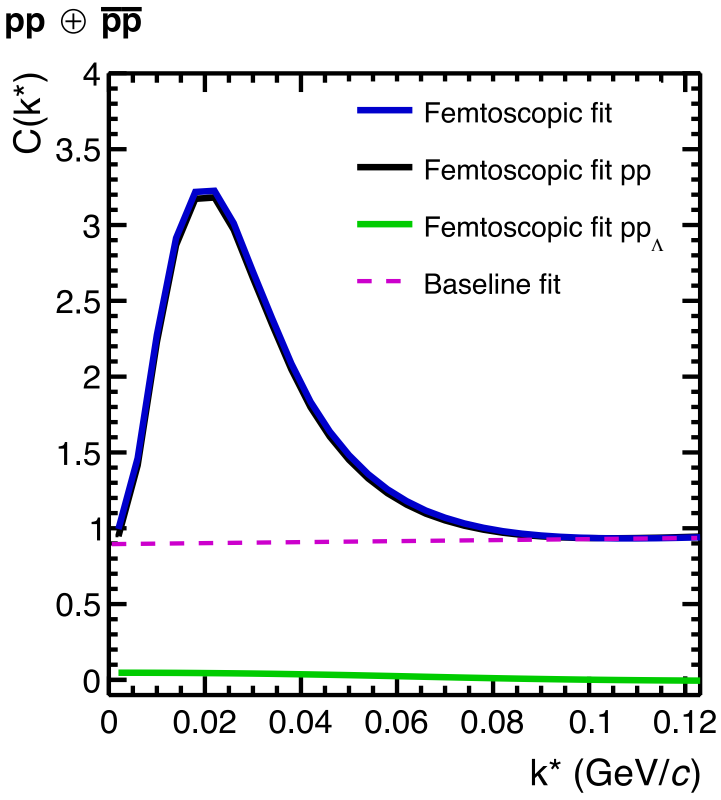
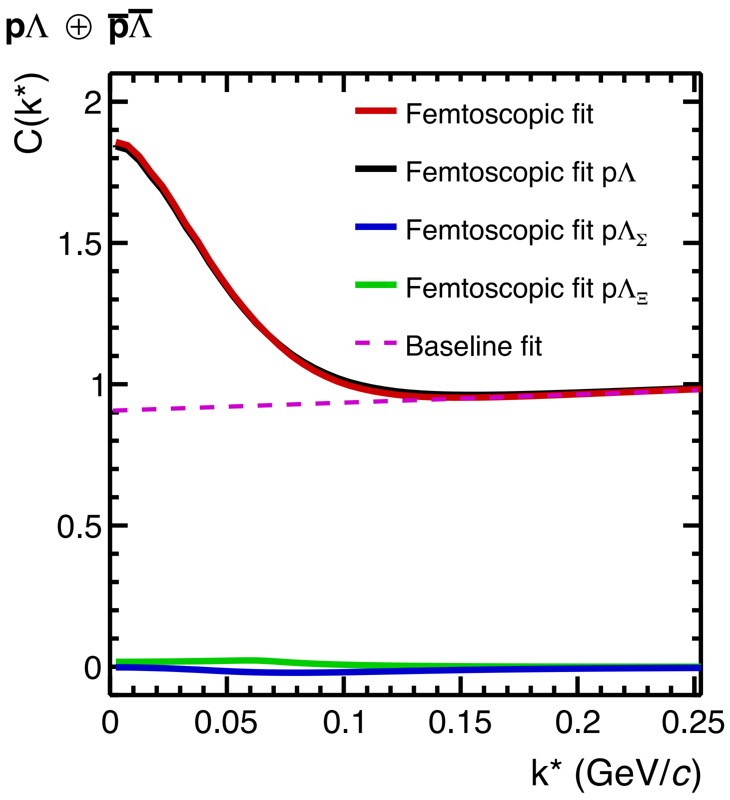
The pp and Λp Correlation Function

- **NLO** and **LO** Parameters show different features at low k^*
- More statistics are required to distinguish between the two calculations
  - LHC Run 2
  - Other collision systems e.g. p-Pb



Fit Decomposition

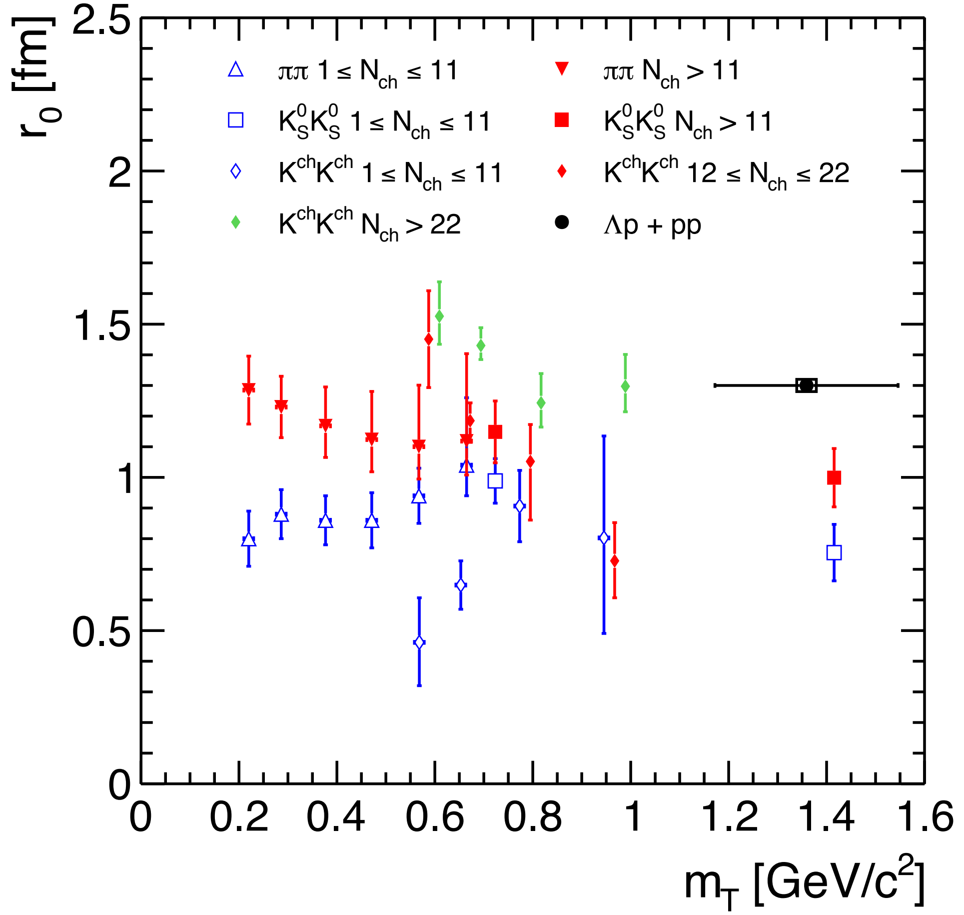




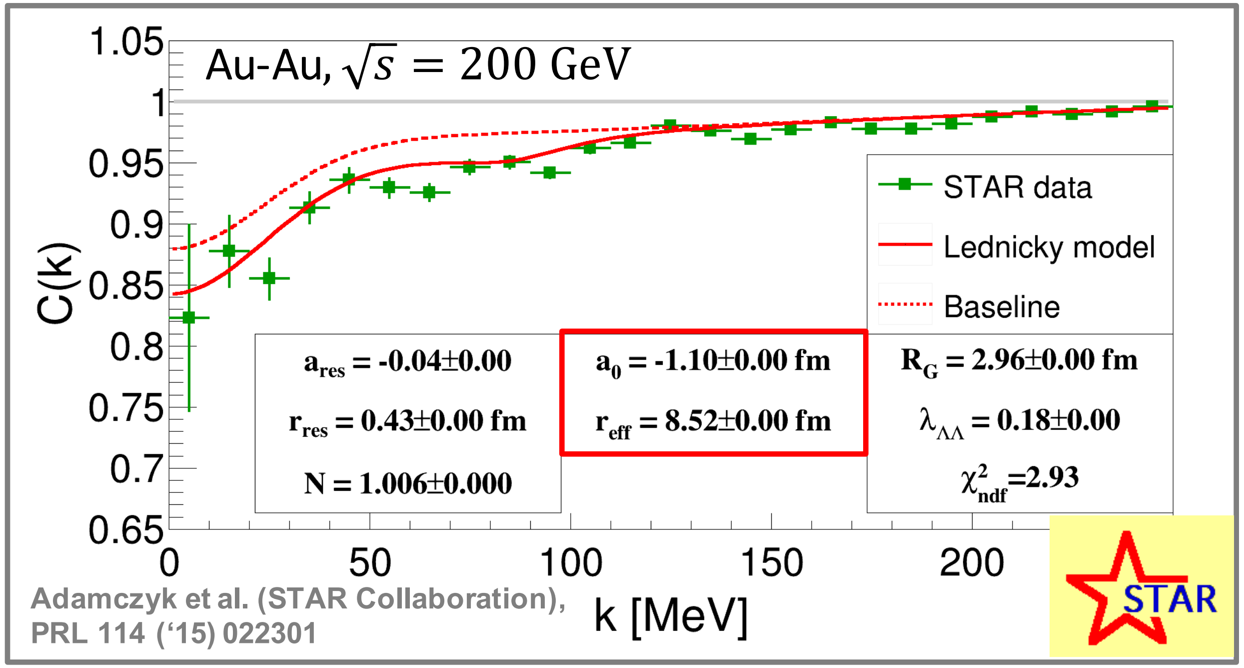
? Any Sensitivity to the repulsive core of the potential?
Included in pp not in Λp currently.

Radius

ALICE Phys. Lett. B717 (2012), pp. 151–161. Neutral Kaons femtoscopy
ALICE Phys. Rev. D87.5 (20 Charged Kaons femtoscopy



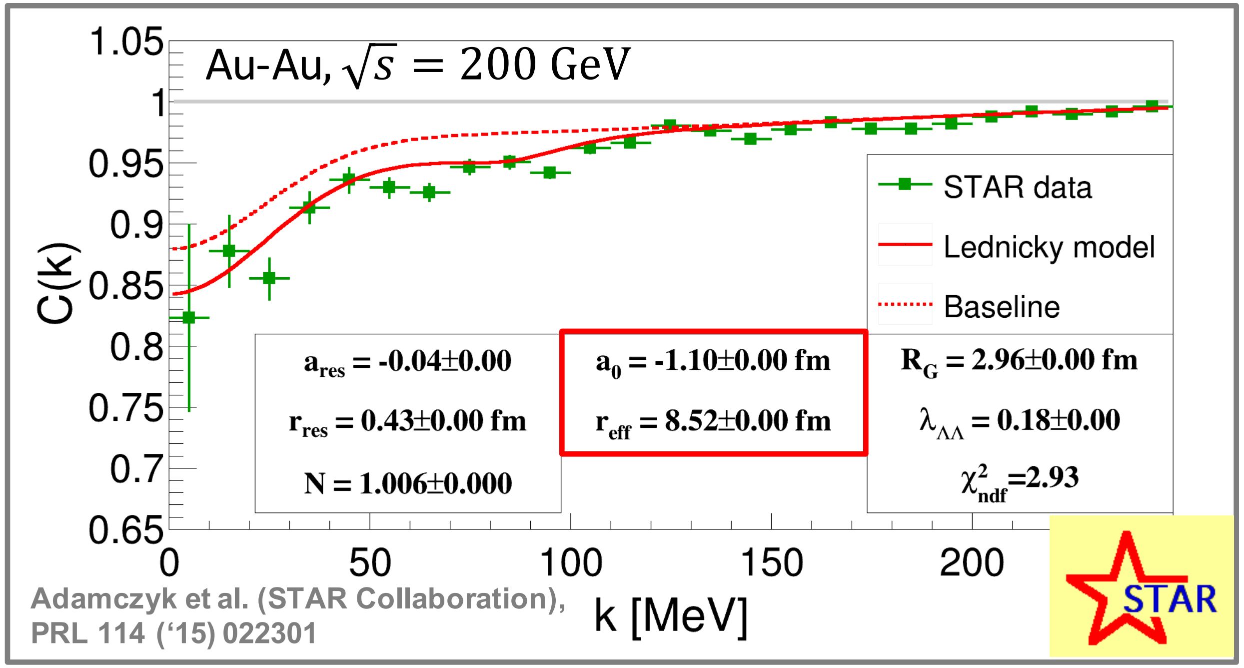
The ΛΛ Correlation Function

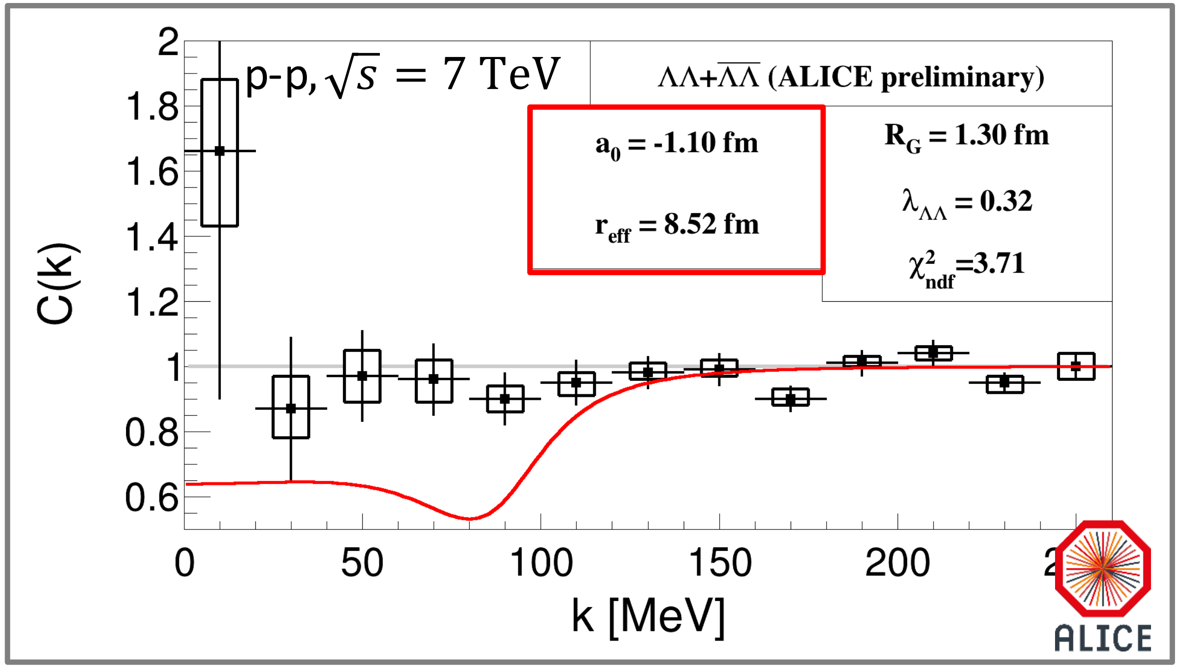


Adamczyk et al. (STAR Collaboration), PRL 114 ('15) 022301

- Analysis of the ΛΛ correlation function in Au-Au Collisions (STAR):
  - Fit of the Lednický Model with an additional residual term as a free parameter
  - Results in a slightly repulsive interaction ($a_0 < 0$ fm)
- Modeled correlation function does not describe ALICE Data with an adjusted source

The ΛΛ Correlation Function





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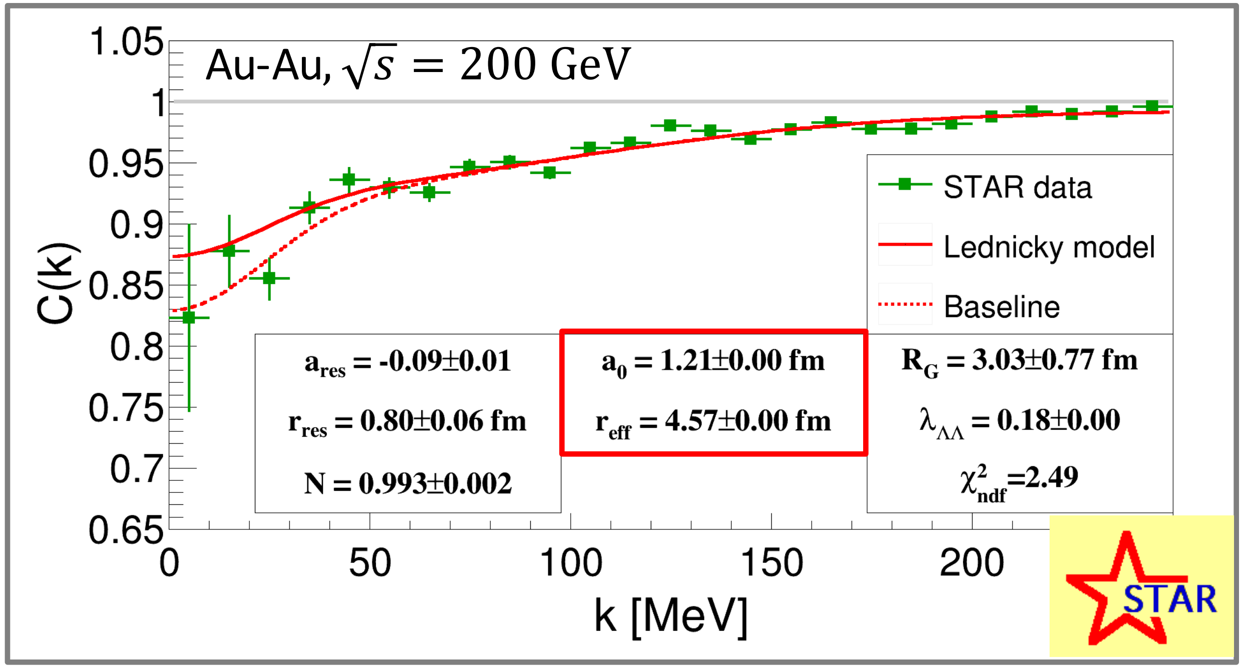
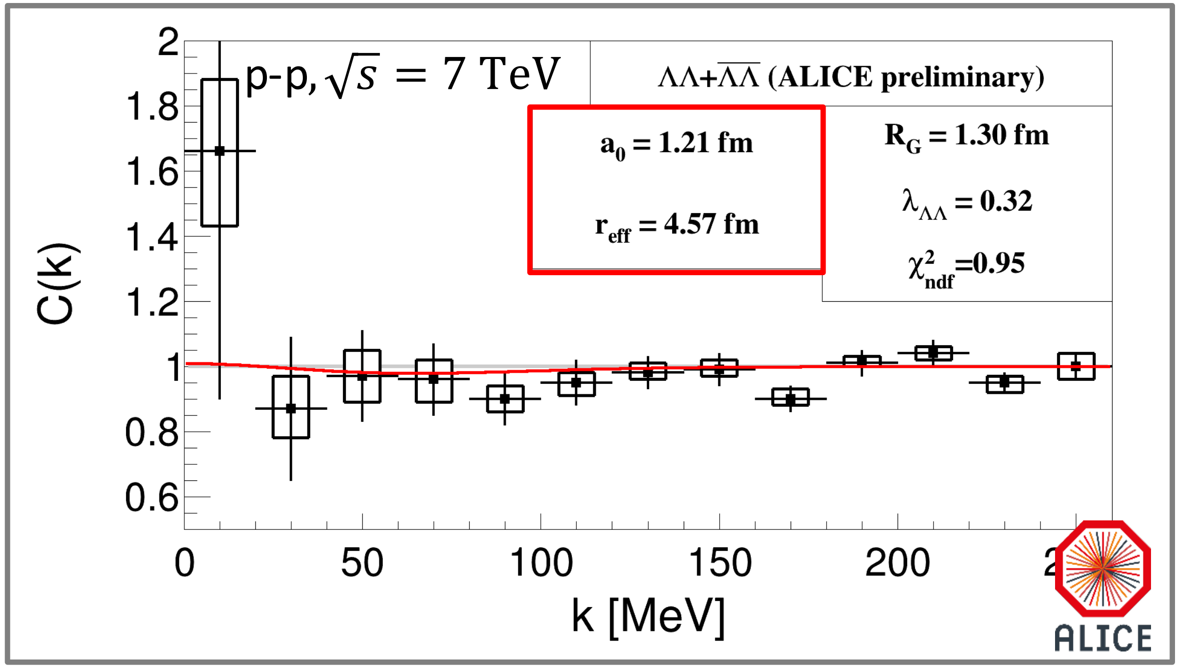
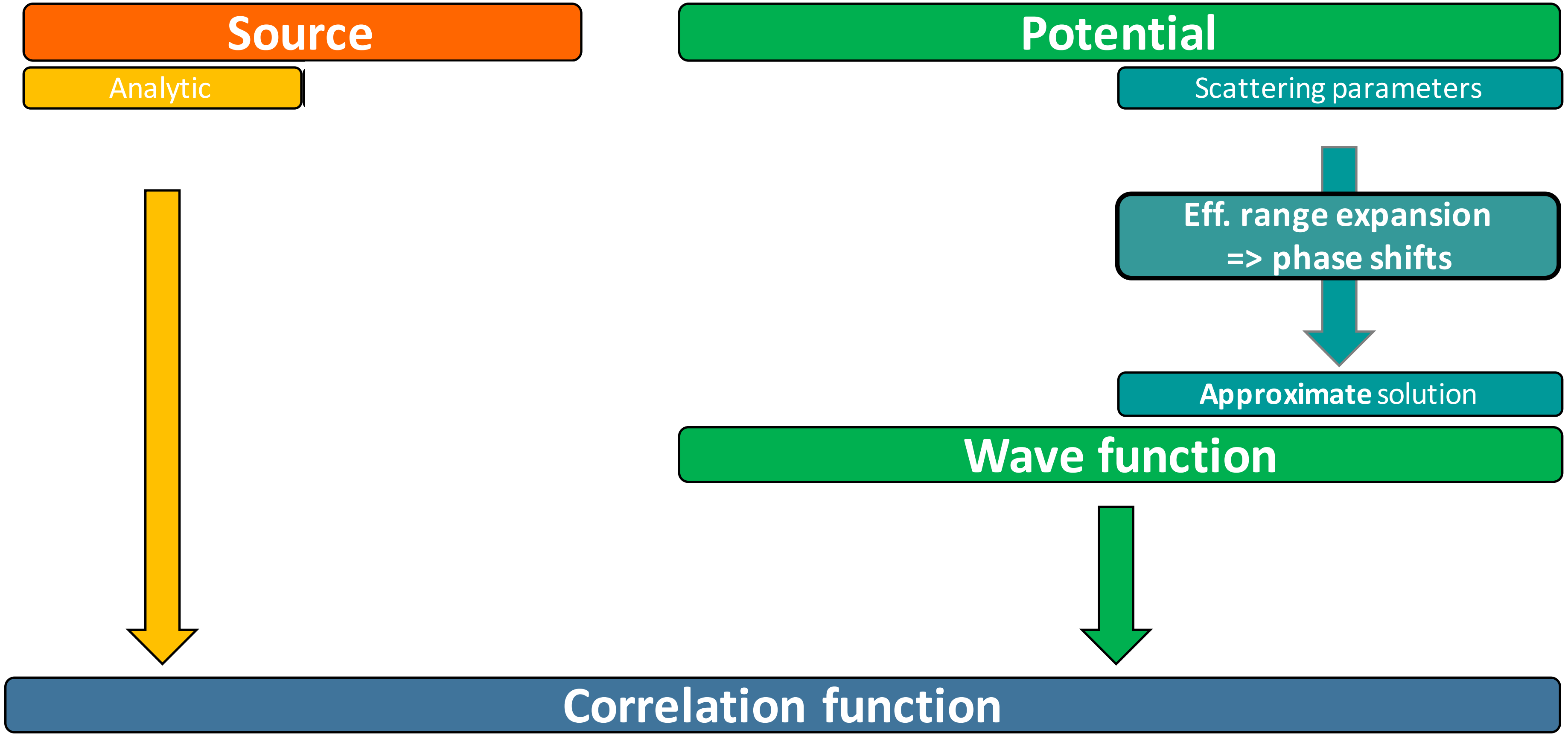
The ΛΛ Correlation Function





- Reanalysis of the data (K. Morita et al., T.Furumoto, AO PRC91('15) 024916) finds an attractive interaction ($a_0 > 1.25$ fm)
- An attractive interaction allows to describe both STAR and ALICE data
- Larger statistics of Run 2 could yield a conclusive answer

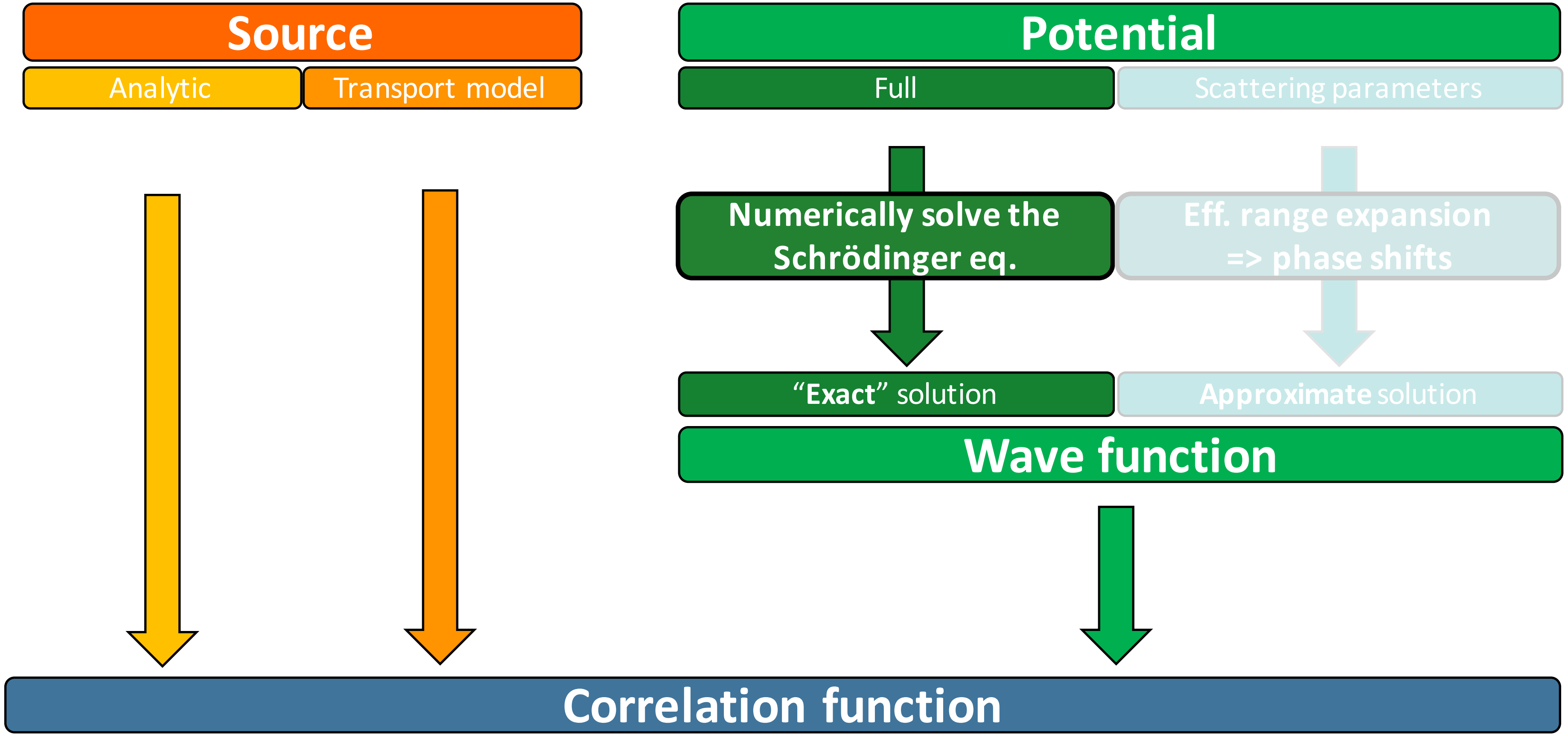
Lednicky Model



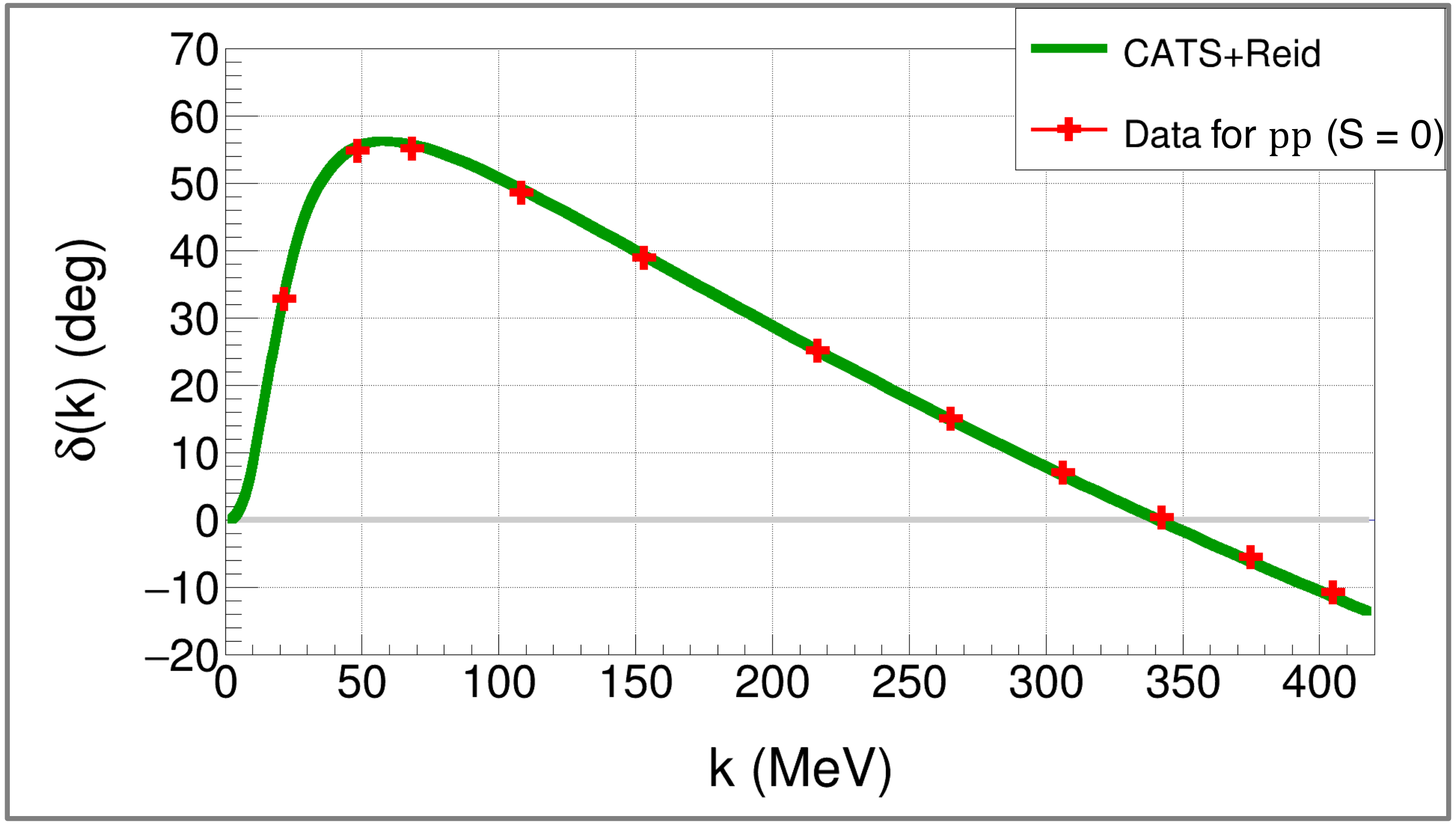
CATS – Correlation Analysis Tool Using the Schrödinger Equation

http://www.denseandstrange.ph.tum.de/index.php?id=78

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

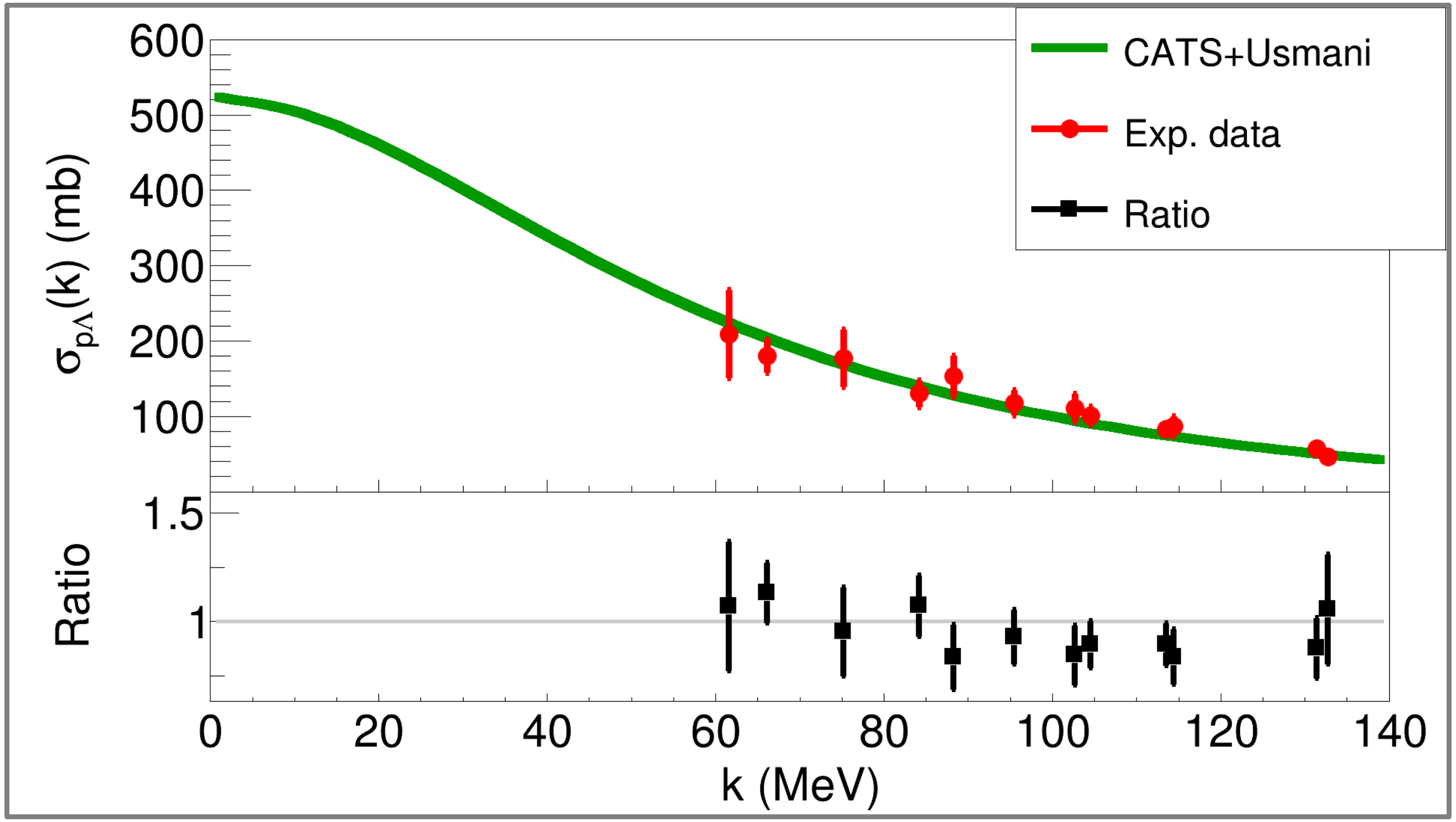


Phase Shift calculations for pp (S = 0)



- Using CATS phase shifts δ_l can be extracted for any given potential
  - Comparison to global data

Cross section calculations for Λp

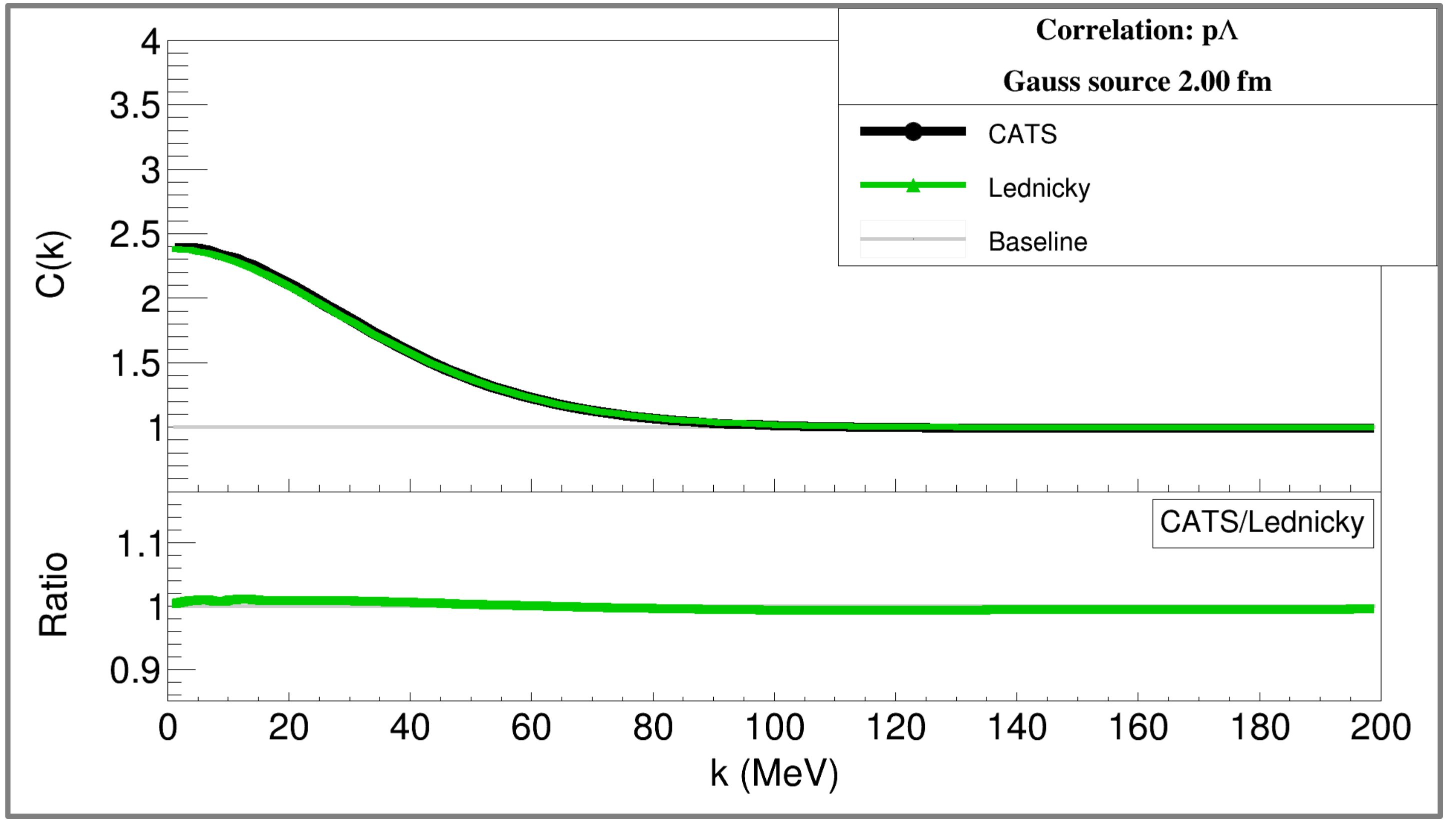


- Λp cross sections for any given potential can be extracted
  - Comparison to global data

Comparison CATS to Lednicky

- **CATS:**
  - Usmani Potential for the interaction
  - Gaussian Source
- **Lednicky:**
  - Scattering parameters and effective range obtained from the Usmani Potential

Wang and Pratt, Phys. Rev. Lett. 83, 3138, 1999



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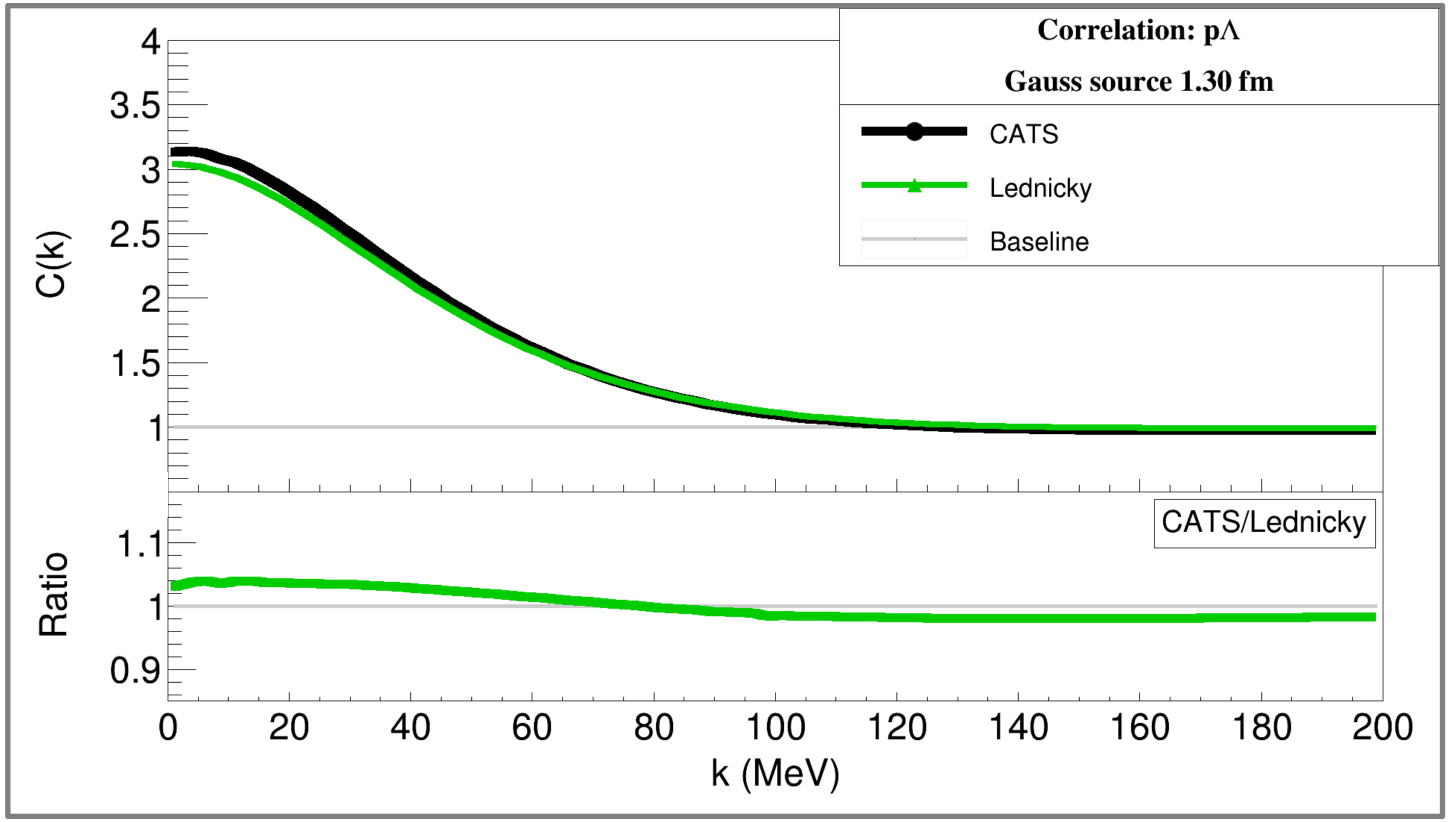
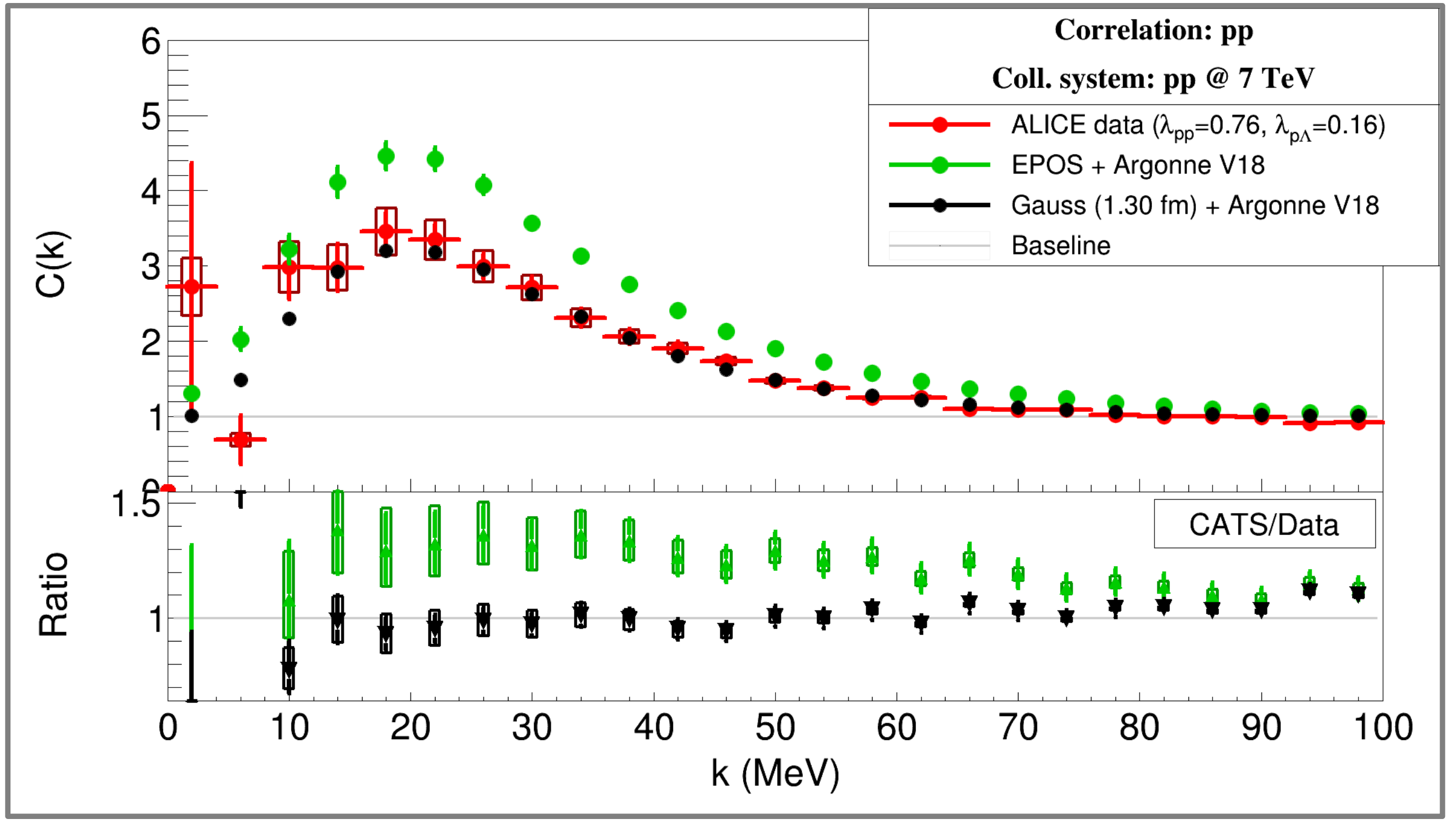


- Agreement within 4% for a source size R_G = 1.30 fm
  - Corrections for small source sizes in the Lednicky Model play a role

Comparison to Data

- CATS allows to describe experimental data of our ALICE analysis
- Input 1:
  - Argonne V18 Potential
  - Gaussian Source function with R_G = 1.30 fm
- Input 2:
  - Argonne V18 Potential
  - Source Distribution from EPOS
- EPOS not suitable to describe the source



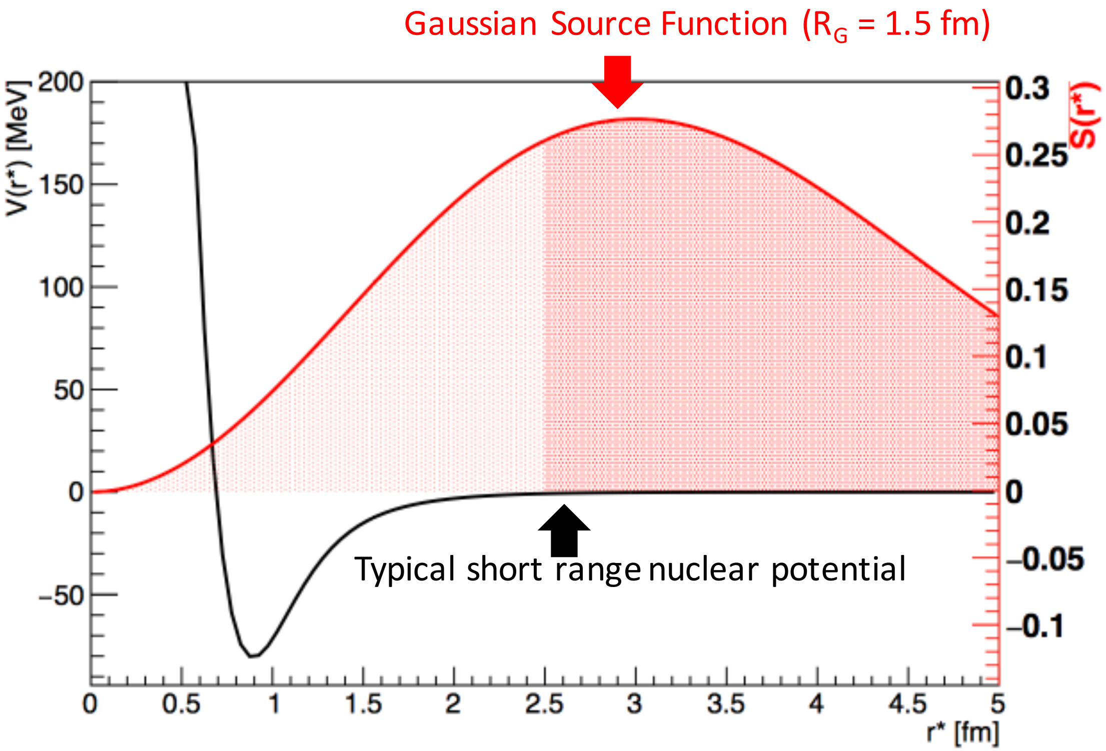
Argonne V18 potential and data: Phys. Rev. C 51, 38

Future prospects of Femtoscopy

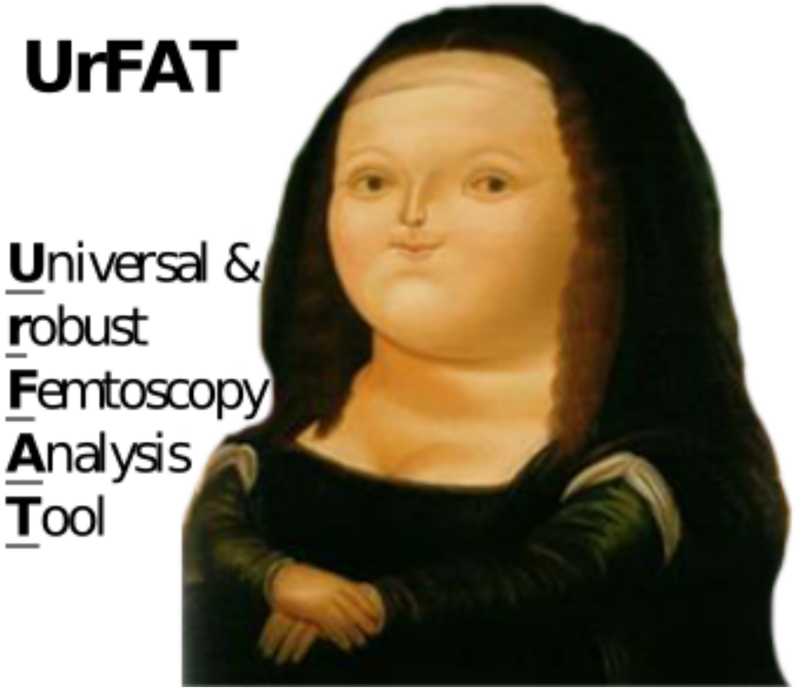
- Reduce degrees of freedom by fitting different collision systems (pp 7 and 13 TeV and pPb at 5 TeV) at different energies at the same time

➢ **Scattering experiments:** intermediate region outside the core of the potential

- **Femtoscopy:** pairs are also produced in the region inside the core
  - ➢ Access to the shape of the potential?



Summary and Outlook



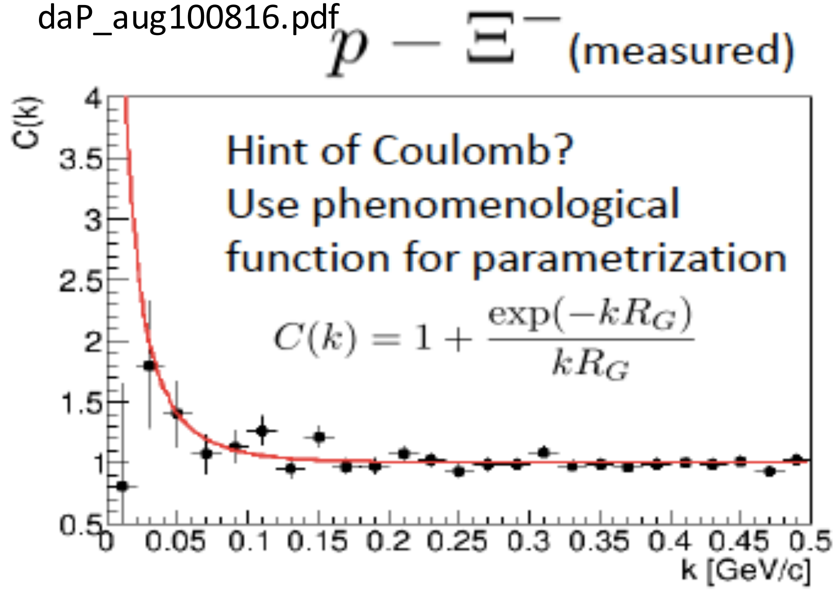
- Femtoscopy in small systems is feasible
- New method to calculate different contributions to the total correlation function based on single particle properties
- Modelling of the correlation function with CATS
- Analysis of Run 2 Data in p-p at 13 TeV and p-Pb Collisions at 5 TeV ongoing
  - Additionally obtain the Σ and Ξ Correlation Function
- Universal and Robust Femto Analysis Tool
  - Fit the correlation function of various systems simultaneously in combination with CATS

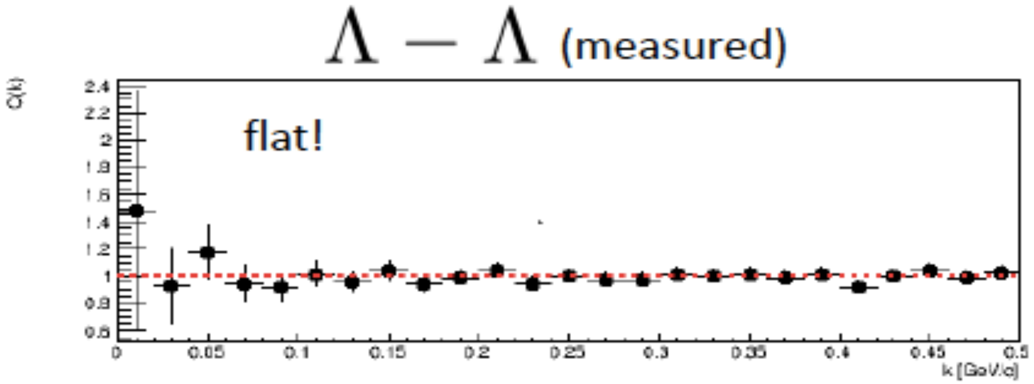
Thank you for your attention!

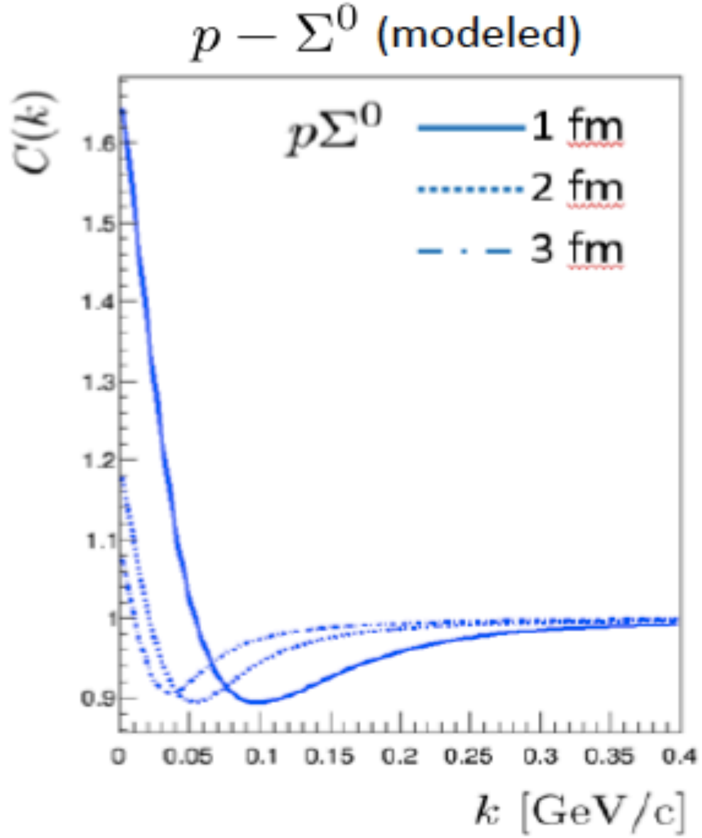
Considered Shapes

Study of the theoretical prediction for the $p\Sigma^0$ correlation in

https://indico.cern.ch/event/562339/contributions/2271695/attachments/1322381/1983690/oarnold_Update_LambdaP_aug100816.pdf







arXiv:0704.3290

http://inspirehep.net/record/1283372

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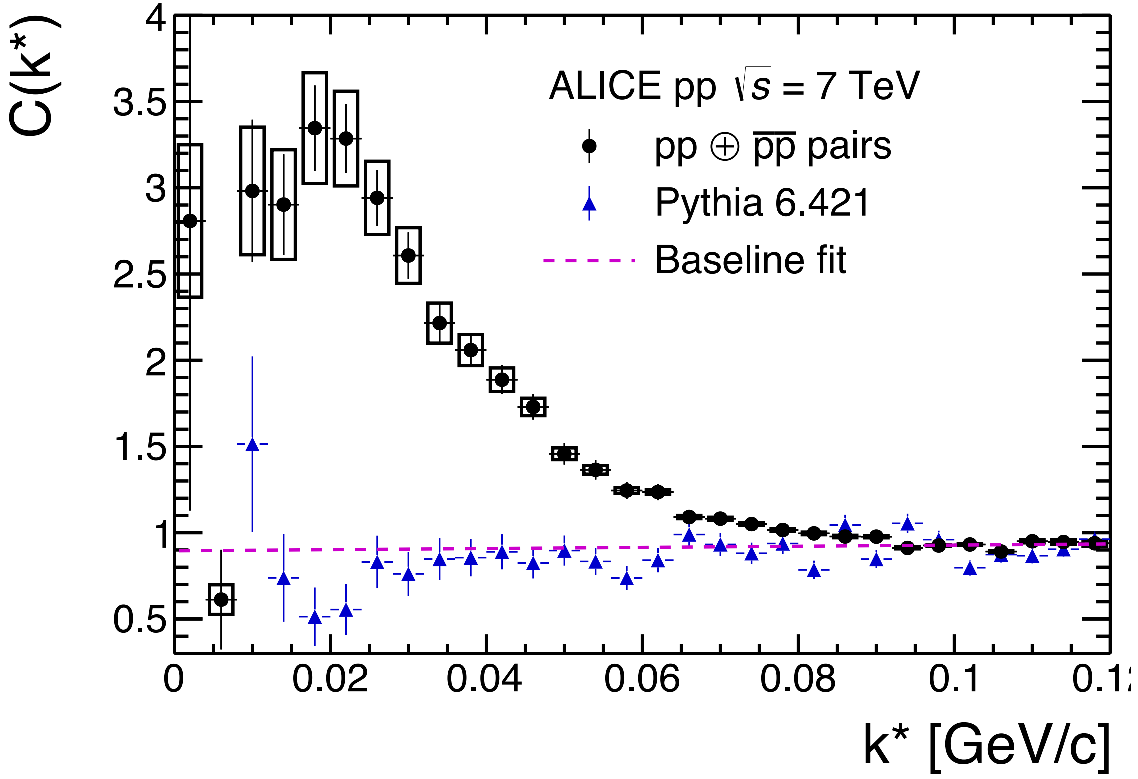
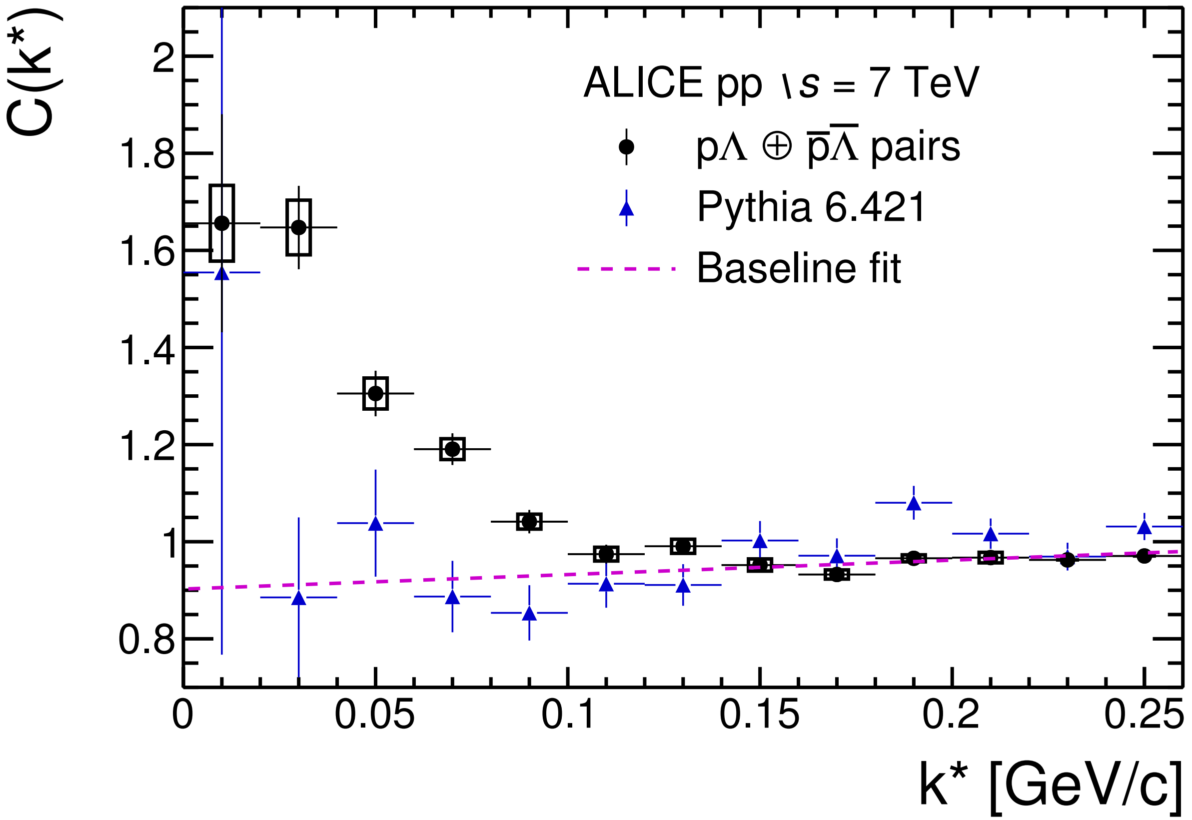
A. Kiesel et al Phys.Rev. C89 (2014) no.5, 054916

Pythia low k*

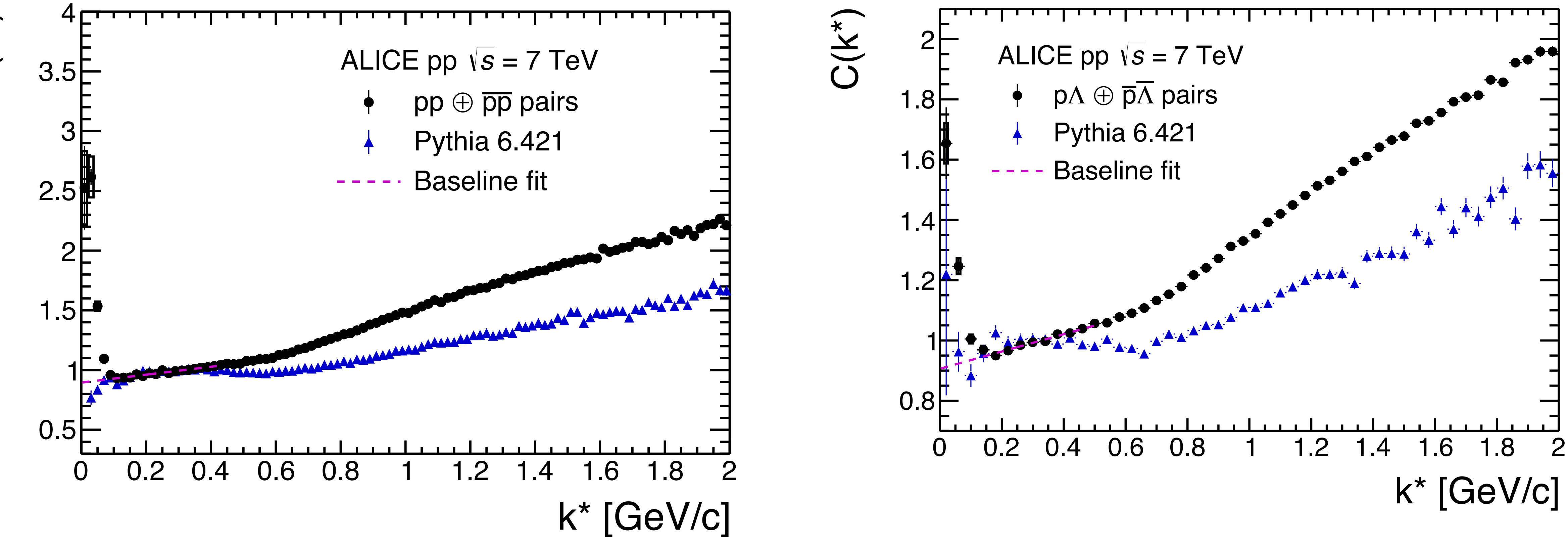


ALICE pp $\sqrt{s}$ = 7 TeV
pp ⊕ $\overline{pp}$ pairs
Pythia 6.421
Baseline fit
C(k*)
k* [GeV/c]



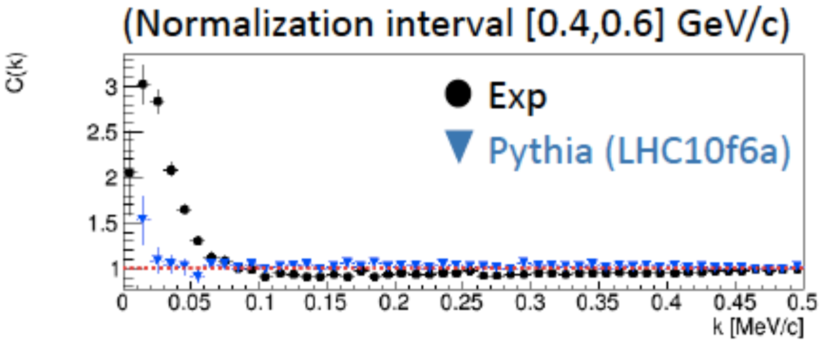
ALICE pp $\sqrt{s}$ = 7 TeV
pΛ ⊕ $\overline{p\Lambda}$ pairs
Pythia 6.421
Baseline fit
C(k*)
k* [GeV/c]

Pythia high k*

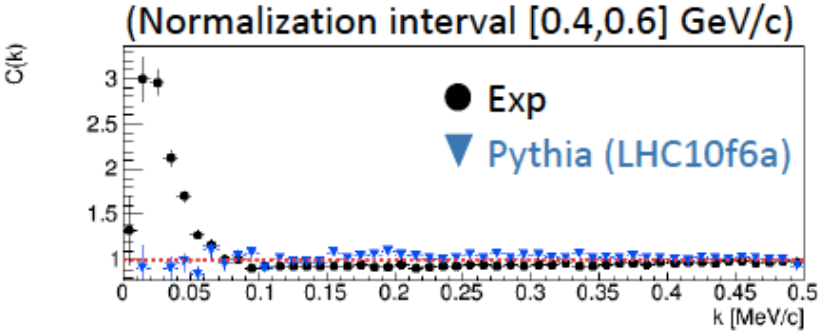


Minijets Background

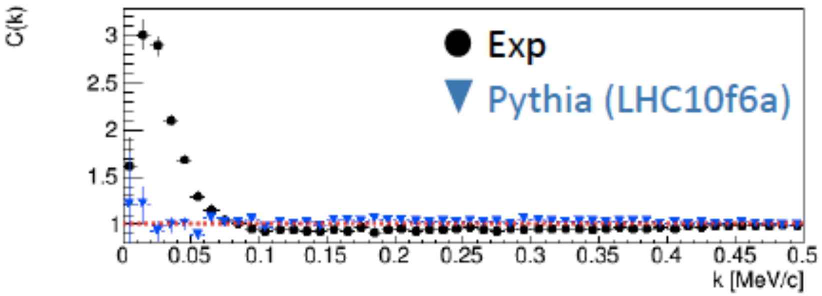
orrelations:



pp

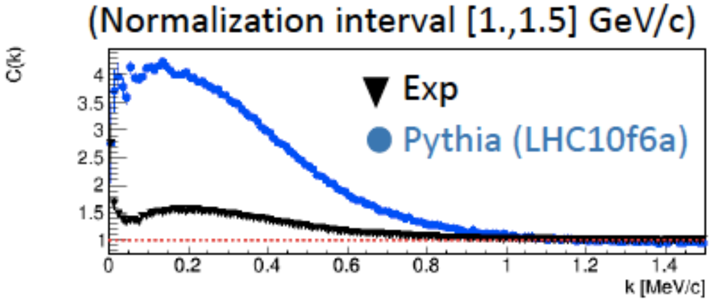


$\bar{p}\bar{p}$

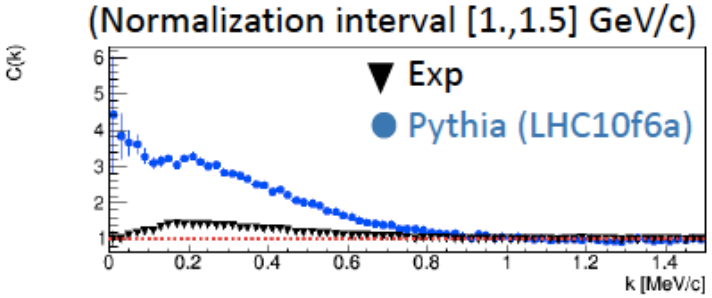


$pp + \bar{p}\bar{p}$

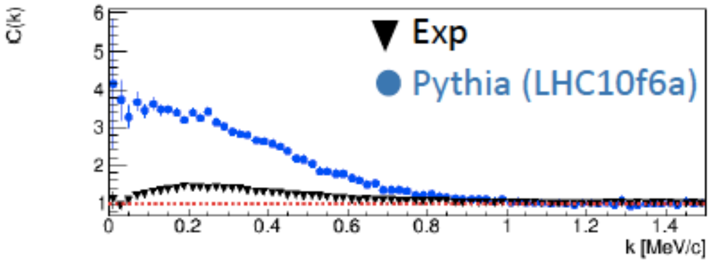
n Correlations:



$p\bar{p}$



$p\bar{\Lambda}$



$\bar{p}\Lambda$

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