# Proton-Proton and Proton-Lambda correlations in p+Nb reactions measured with HADES

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# Outline

- **Two particle correlations: Definition**

- **Proton-proton correlations**

  → Corrections and results from comparison with models

- **Lambda-proton correlations**

  → Use of proton-proton results to investigate the interaction of $\Lambda p$ pairs

# Introduction

**Theoretical correlation function:**

$$C^{ab}(\mathbf{P},\mathbf{q}) = \frac{\mathcal{P}(\vec{p}_a,\vec{p}_b)}{\mathcal{P}(\vec{p}_a)\mathcal{P}(\vec{p}_b)} = \int d^3r' S_{\mathbf{P}}(\mathbf{r}')|\phi(\mathbf{q},\mathbf{r}')|^2$$

**Source function:**
Distribution of relative distance between the particle pairs (in CMS)

**Wavefunction of particle pair:**
Includes the interactions

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**Experimental correlation function:**

$$C(k) = \frac{A(k)}{B(k)}$$

$k = \frac{1}{2}|\mathbf{p}_1 - \mathbf{p}_2|$

$\mathbf{p}_1 + \mathbf{p}_2 = 0$ **Pair reference frame (PRF)**

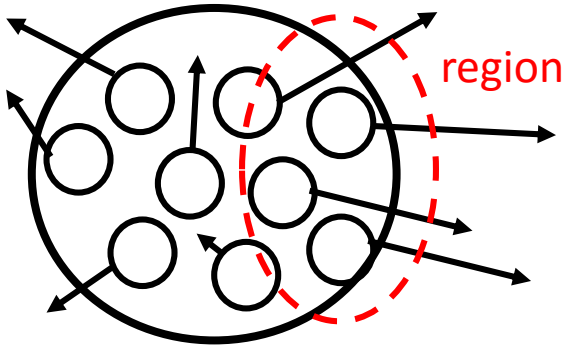
- **Same:** relative momentum dist. of particles in the same event
- **Mixed:** particles from different events (not correlated)
- **Normalized to unity**: $C(k > 100\ \mathrm{MeV/c}) \equiv 1$

# Introduction

**Strategy of analysis – two steps:**

$$C^{ab}(\mathbf{P},\mathbf{q}) = \frac{\mathcal{P}(\vec{p}_a,\vec{p}_b)}{\mathcal{P}(\vec{p}_a)\mathcal{P}(\vec{p}_b)} = \int d^3r' \underbrace{S_{\mathbf{P}}(\mathbf{r}')}_{1.} \underbrace{|\phi(\mathbf{q},\mathbf{r}')|^2}_{2.}$$

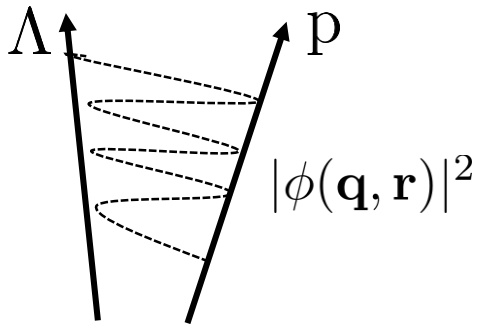
*1. Understand the emission profile of the pNb system*



region of homogeneity == „Source“

$S_{\mathbf{P}}(\mathbf{r})$

*2. Use the information of point 1 to investigate particle interactions which are not well known*



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$$C^{ab}(\mathbf{P},\mathbf{q}) = \frac{\mathcal{P}(\vec{p}_a,\vec{p}_b)}{\mathcal{P}(\vec{p}_a)\mathcal{P}(\vec{p}_b)} = \int d^3r' \underbrace{S_{\mathbf{P}}(\mathbf{r}')}_{\text{1.}} |\phi(\mathbf{q},\mathbf{r}')|^2$$

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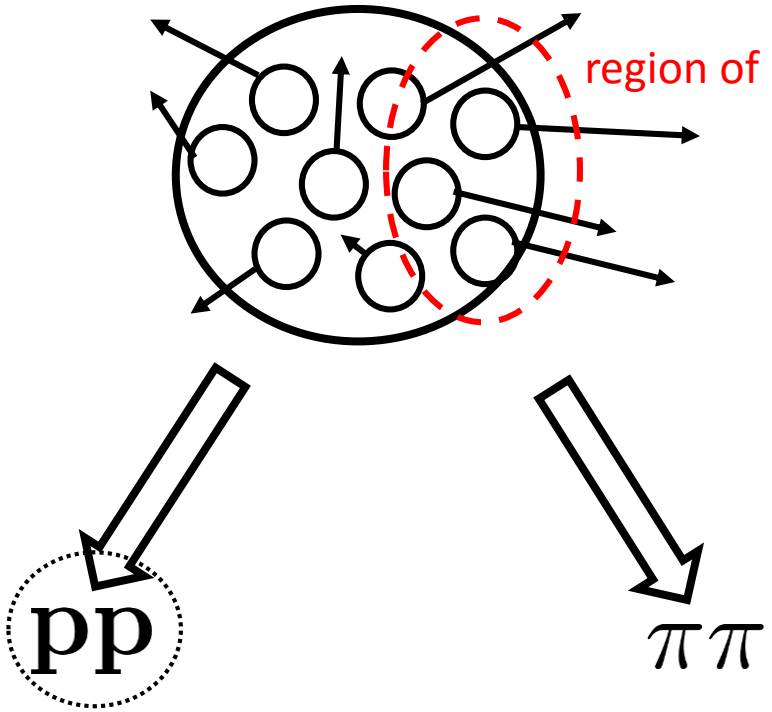



Use $\mathbf{pp}$ pairs since we have plenty of protons and we know their interaction

# Reaction

**System under investigation:**

$$\mathrm{p} + {}^{93}_{41}\mathrm{Nb} \rightarrow \mathrm{P} + \mathrm{X}$$

$$\mathrm{P} = \mathrm{pp}, \pi^{\pm}\pi^{\pm}, \ldots$$

**Beam:**

$\mathrm{p}$ ⟶

$\sim 2 \cdot 10^6/\mathrm{s}$

$T_p = 3.5$ GeV

$\sqrt{s_{NN}} = 3.18$ GeV

**Target:**

12-fold segmented target of $^{93}\mathrm{Nb}$ discs

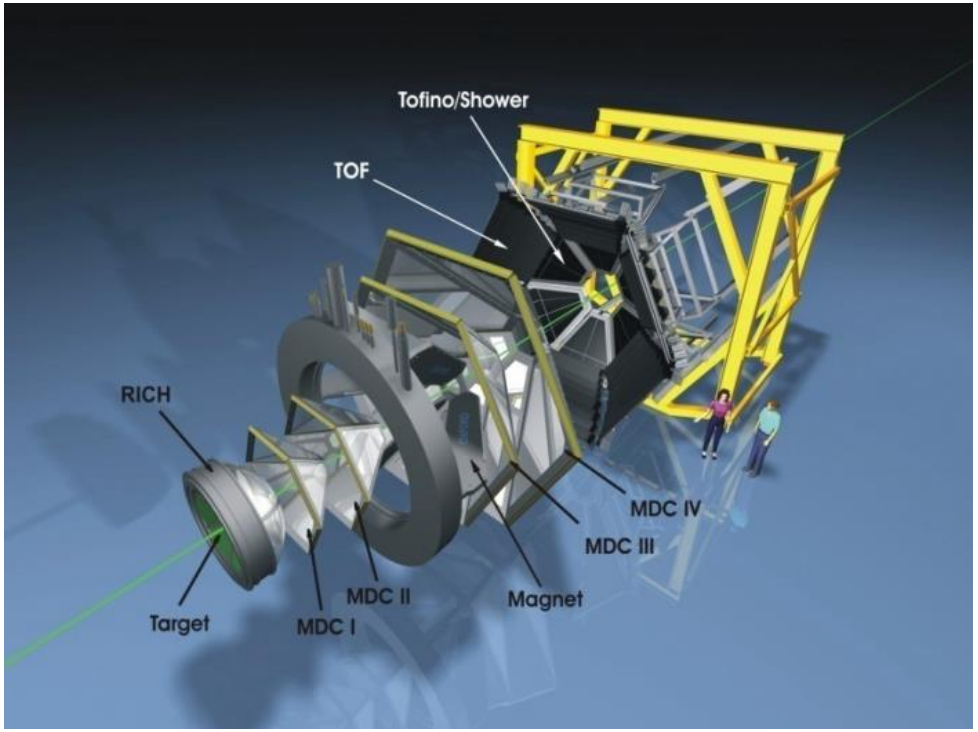
$2.8\%$ interaction probability

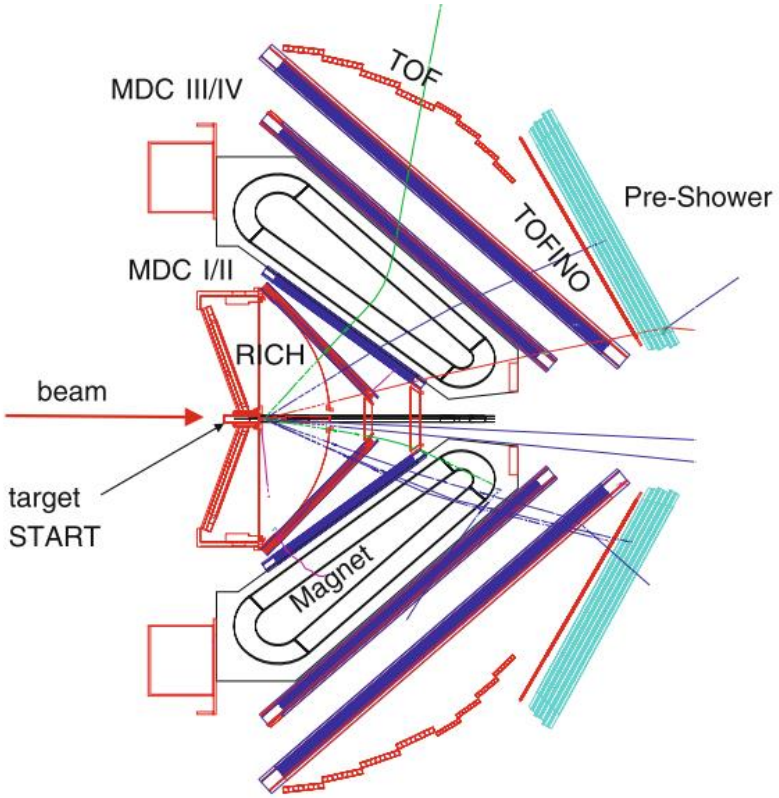
$\langle A_{part} \rangle \sim 2.7$

Femtoscopy in a small system!

# Experiment

**H**igh **A**cceptance **D**i-**E**lectron **S**pectrometer - **HADES:**



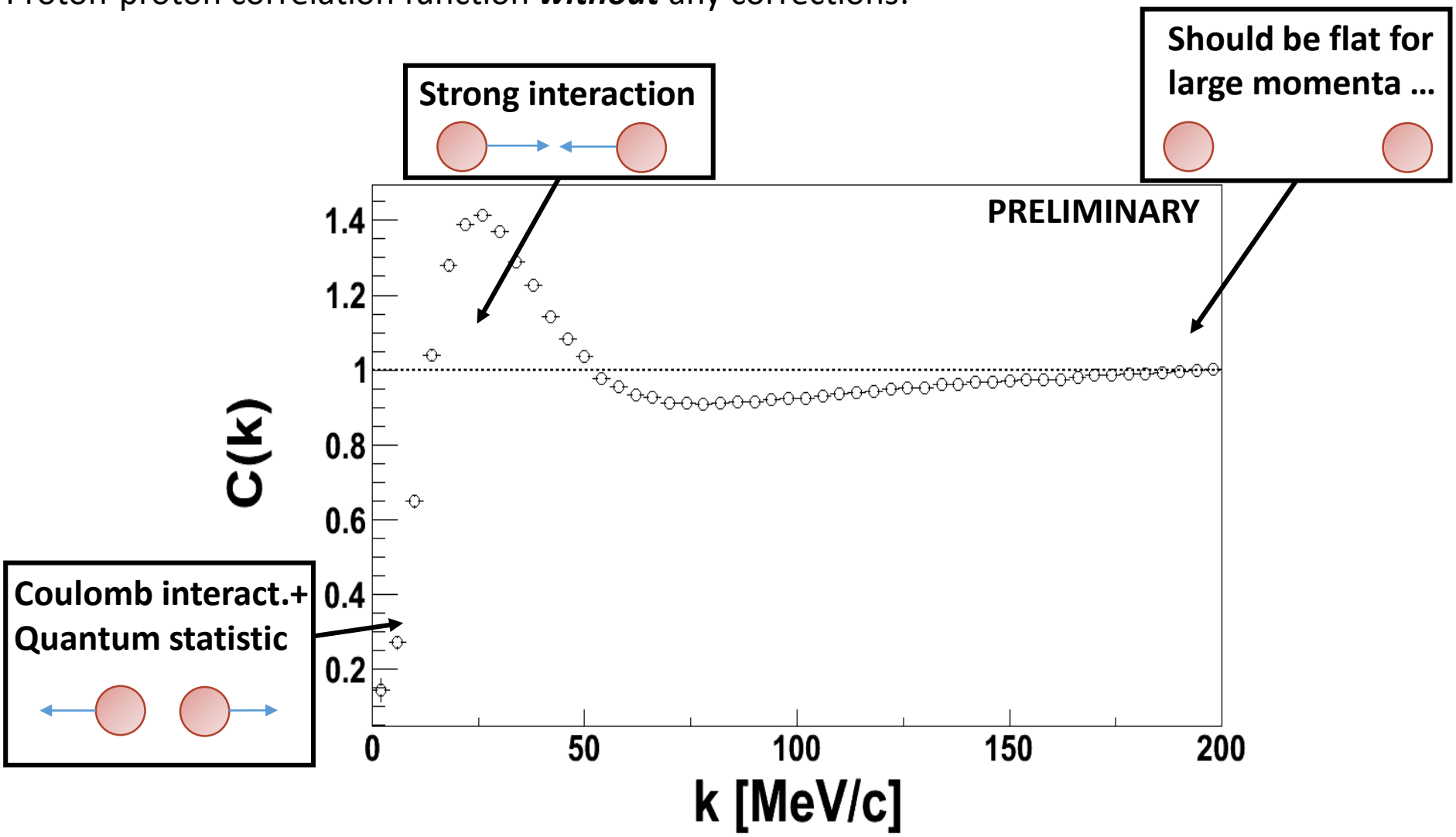




**Features of HADES:**

- Large geometric acceptance $\phi \in [0, 2\pi], \Theta \in [15°, 85°]$
- Momentum resolution $\sim 2 - 6\%$

# Correlation Function

**Information about the source – proton proton correlation function:**
Proton-proton correlation function ***without*** any corrections:

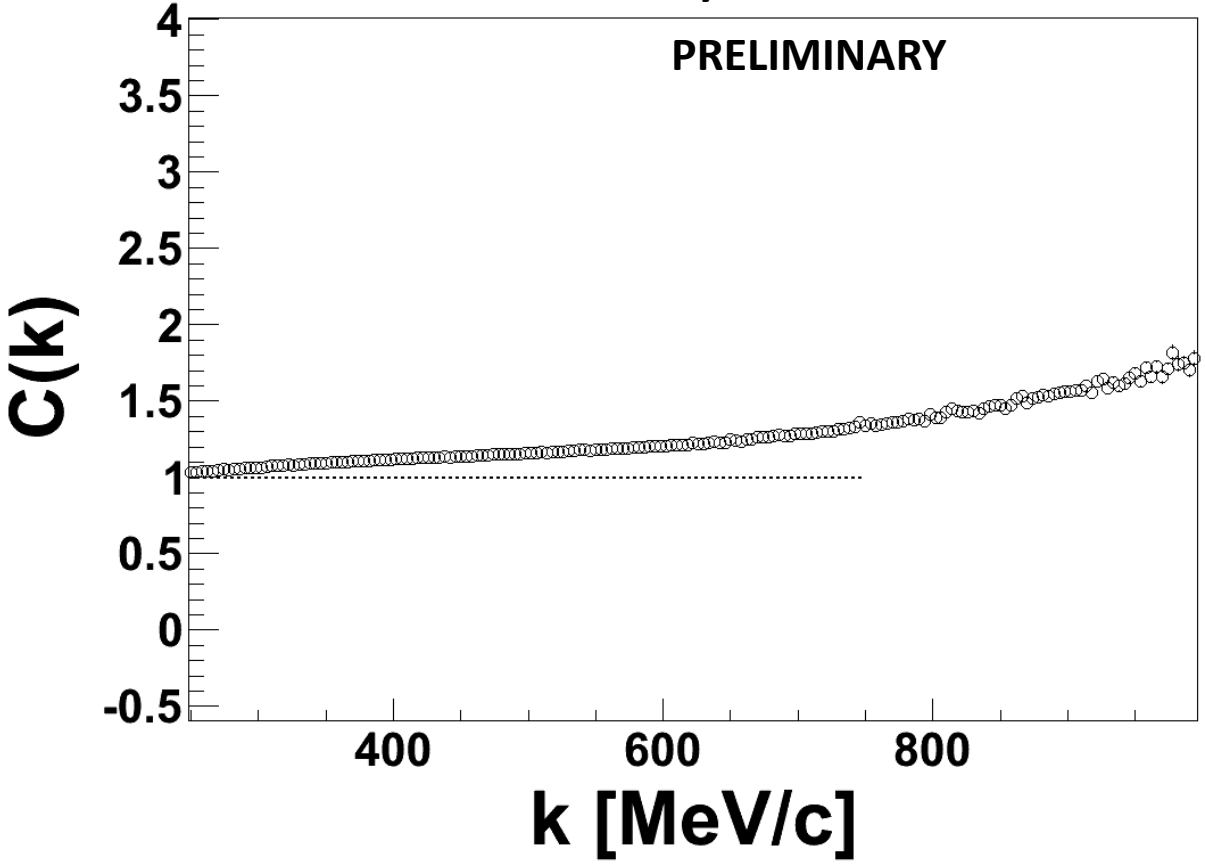


# Correlation Function

**Information about the source – proton proton correlation function:**
Proton-proton correlation function ***without*** any corrections:

**Should be flat for large momenta …**

**…. unfortunately *not* the case**

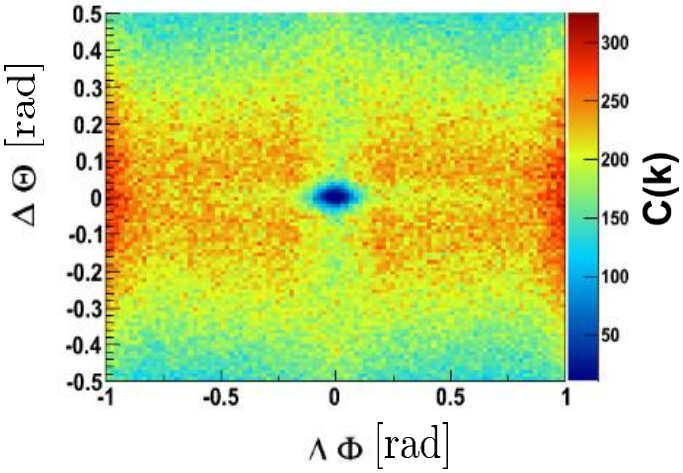


# Correlation Function

**Information about the source – proton proton correlation function:**

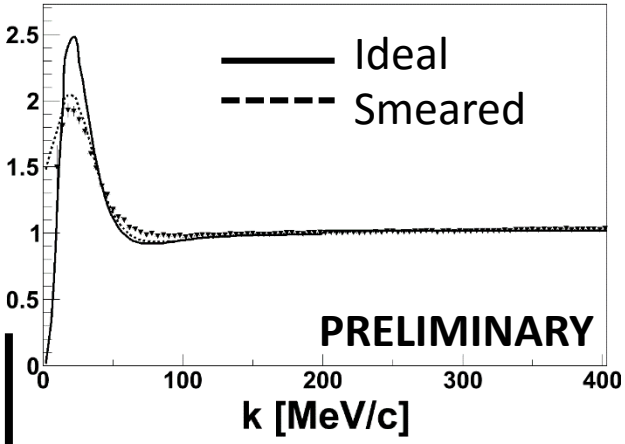
*Corrections*

**Reject pairs which are too close together**



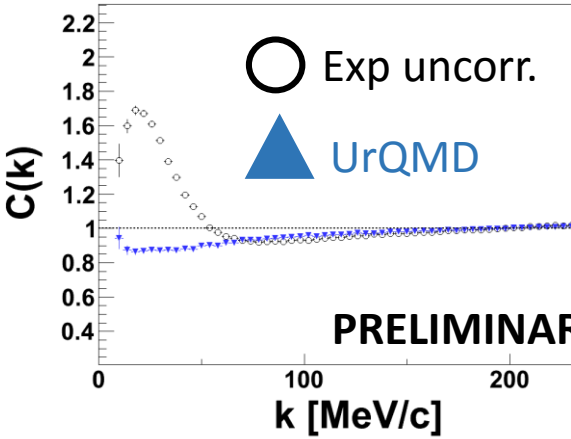

$$|\Delta\phi| > 3 \times 0.039 \text{ rad}$$
$$|\Delta\Theta| > 3 \times 0.015 \text{ rad}$$

**Correct for finite momentum resolution**




$$\frac{C_{\text{real}}(k)}{C_{\text{measured}}(k)} = \frac{C_{\text{ideal}}(k)}{C_{\text{smeared}}(k)}$$

**Correct for long range correlations**

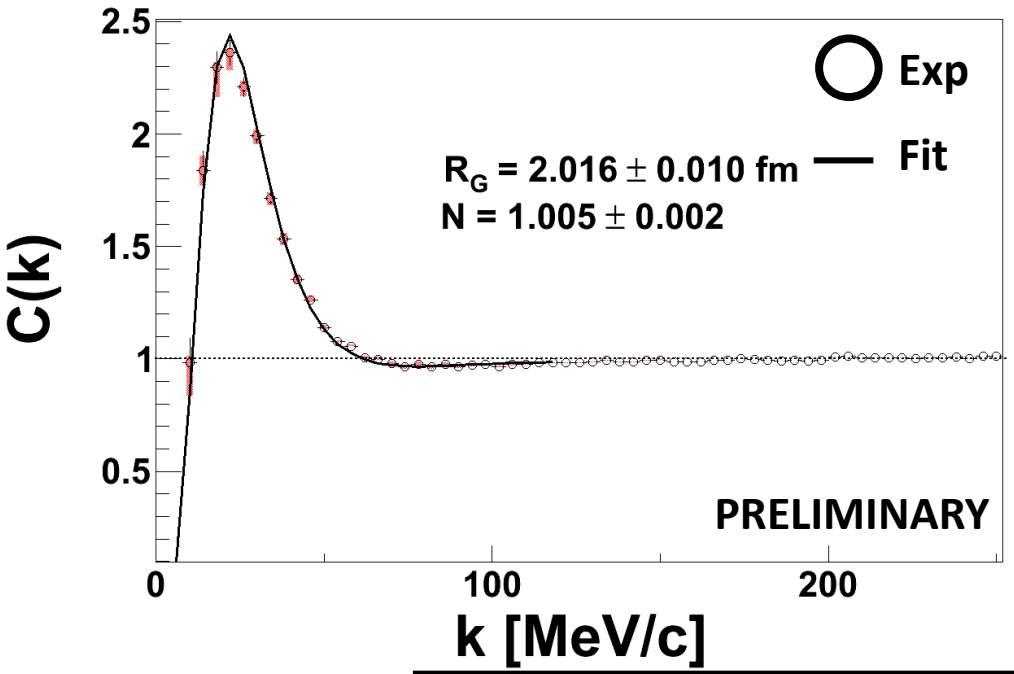



$$C(k) \equiv C_{\text{raw}}(k)/C_{\text{UrQMD}}(k)$$

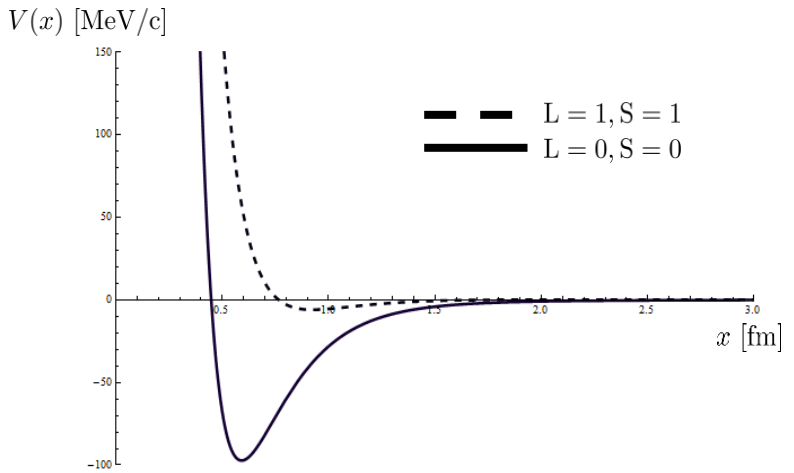
# Source Size

**Information about the source – proton proton correlation function:**

Extract source size: $C^{ab}(k) = N \int d^3r' S_{\mathbf{P}}(\mathbf{r}') |\phi(\mathbf{k}, \mathbf{r}')|^2$




Potential used for strong interaction:




B. D. Day, Phys. Rev. C 24, (1981), 1203

$$\frac{d^2w}{d\rho^2} + \left[1 - \frac{2\eta}{\rho} - \frac{l(l+1)}{\rho^2} - \frac{2\mu}{k^2} V(\rho)\right] = 0 \qquad S(r) \sim \exp(-r^2/4R_G^2)$$

$$R_G = 2.016 \pm 0.010^{+0.109}_{-0.118} \text{ fm}$$

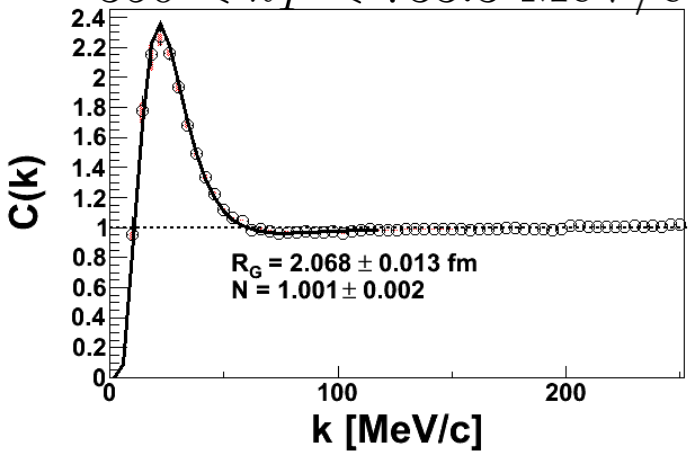
# Source Size

**Starting point: Correlations between baryons - protons**

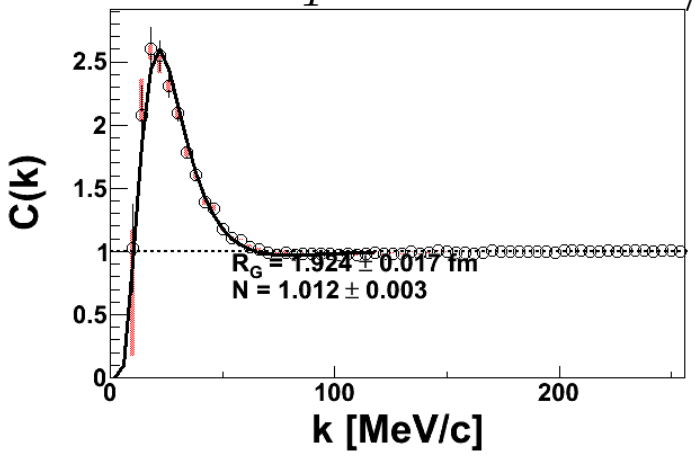
Extract one dimensional source parameters

.... as a function of $k_T = |\mathbf{p}_{1T} + \mathbf{p}_{2T}| \in [350, 1500]$ MeV/c

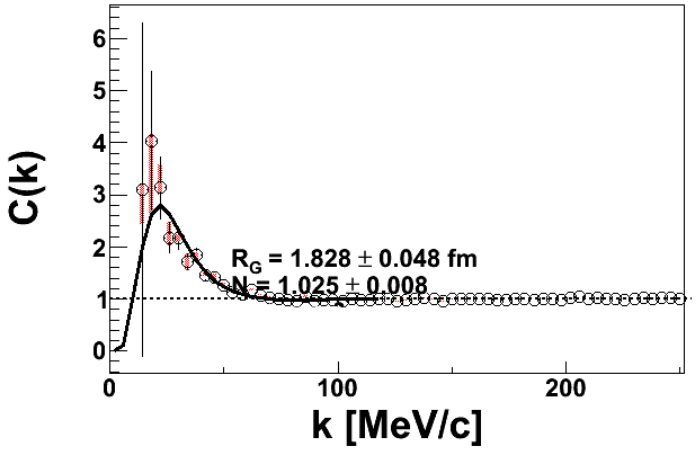
$350 < k_T < 733.3$ MeV/c

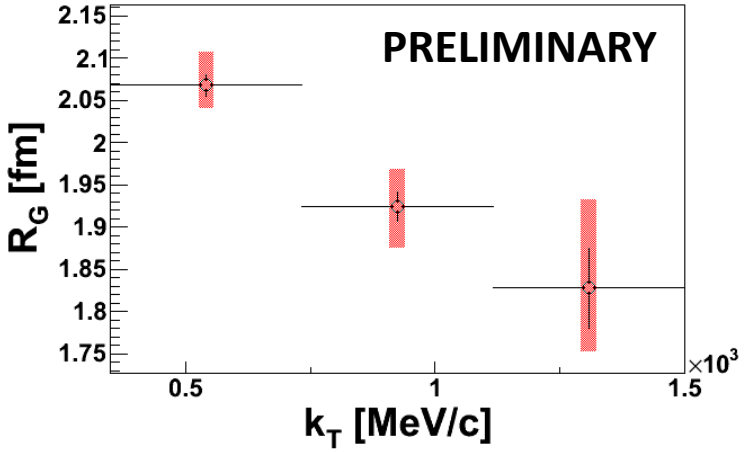



$733.3 < k_T < 1116.7$ MeV/c




$1116.7 < k_T < 1500$ MeV/c



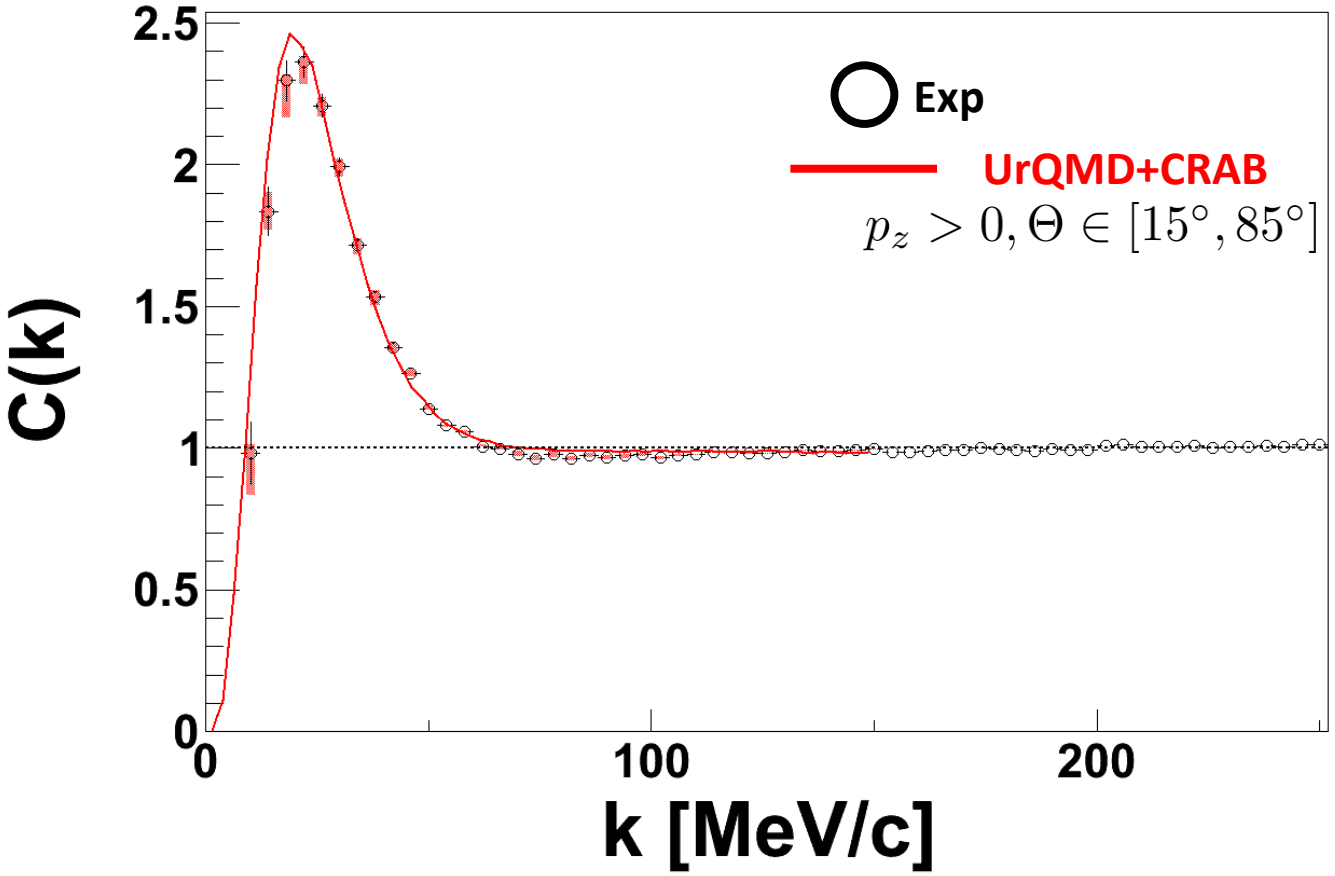



# Model comparison

**Source comparison to transport theory (same potential used than for the fit):**

In one dimension:

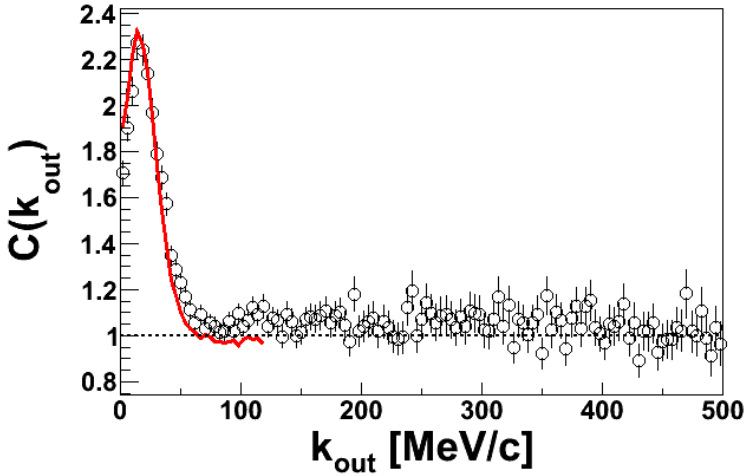
**Calculation of UrQMD correlation function with help of CRAB**

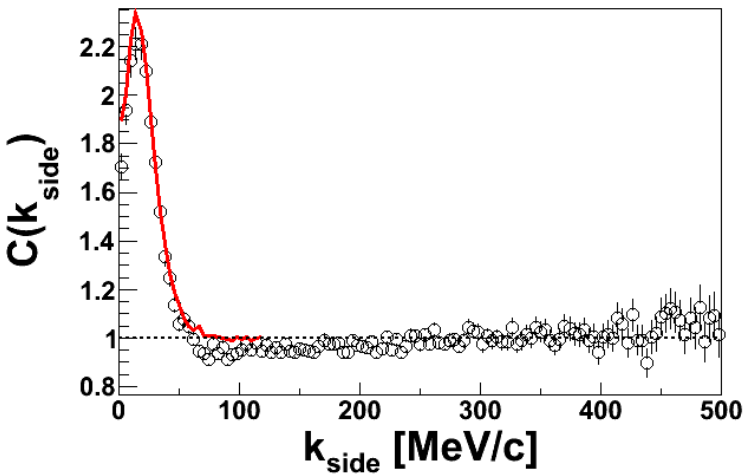


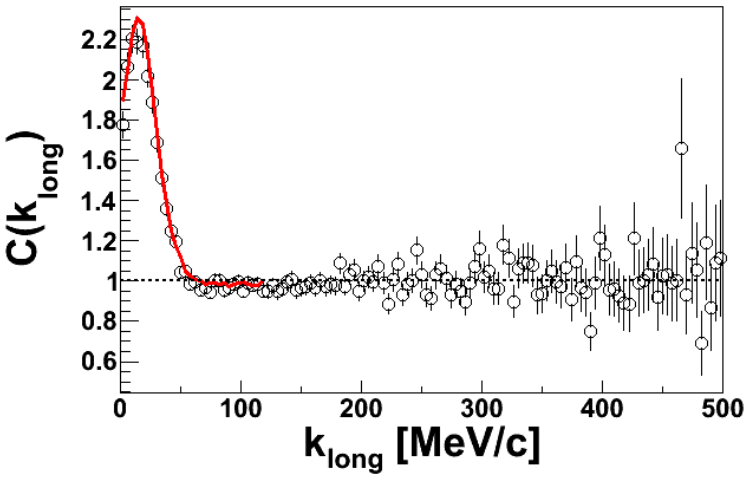
# Model comparison

**Source comparison to transport theory (same potential used than for the fit):**

In three dimensions:




Exp

UrQMD+CRAB

$p_z > 0, \Theta \in [15°, 85°]$

UrQMD gives a good source description for protons

# Interaction

**Strategy of analysis:**

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**2.**

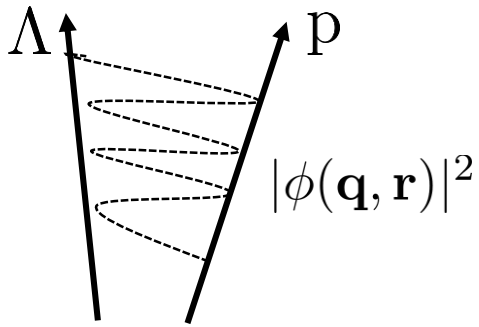
*1. Understand the emission profile of the pNb system*



region of homogeneity == „Source“

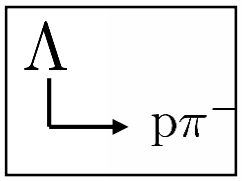
$S_{\mathbf{P}}(\mathbf{r})$

*2. Use the information of point 1 to investigate particle interactions of not well known type*



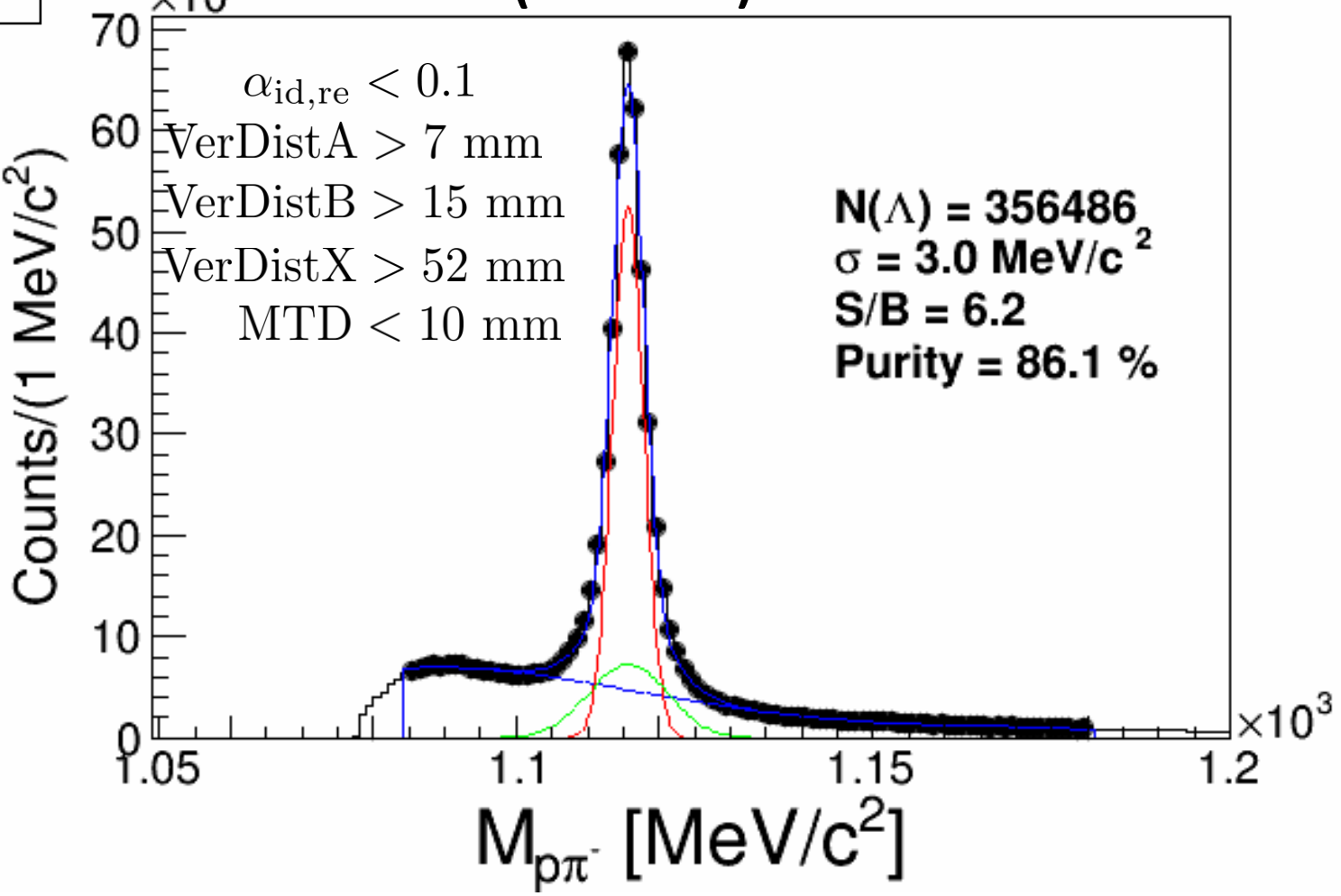
# Interaction

**Select $\Lambda's$ with large purity – different cut combinations to investigate systematics:**




**(combo 1)**

$\text{Purity} \equiv \frac{S}{S+B}(2\sigma)$



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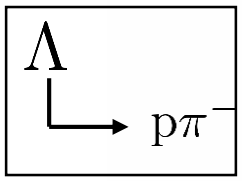
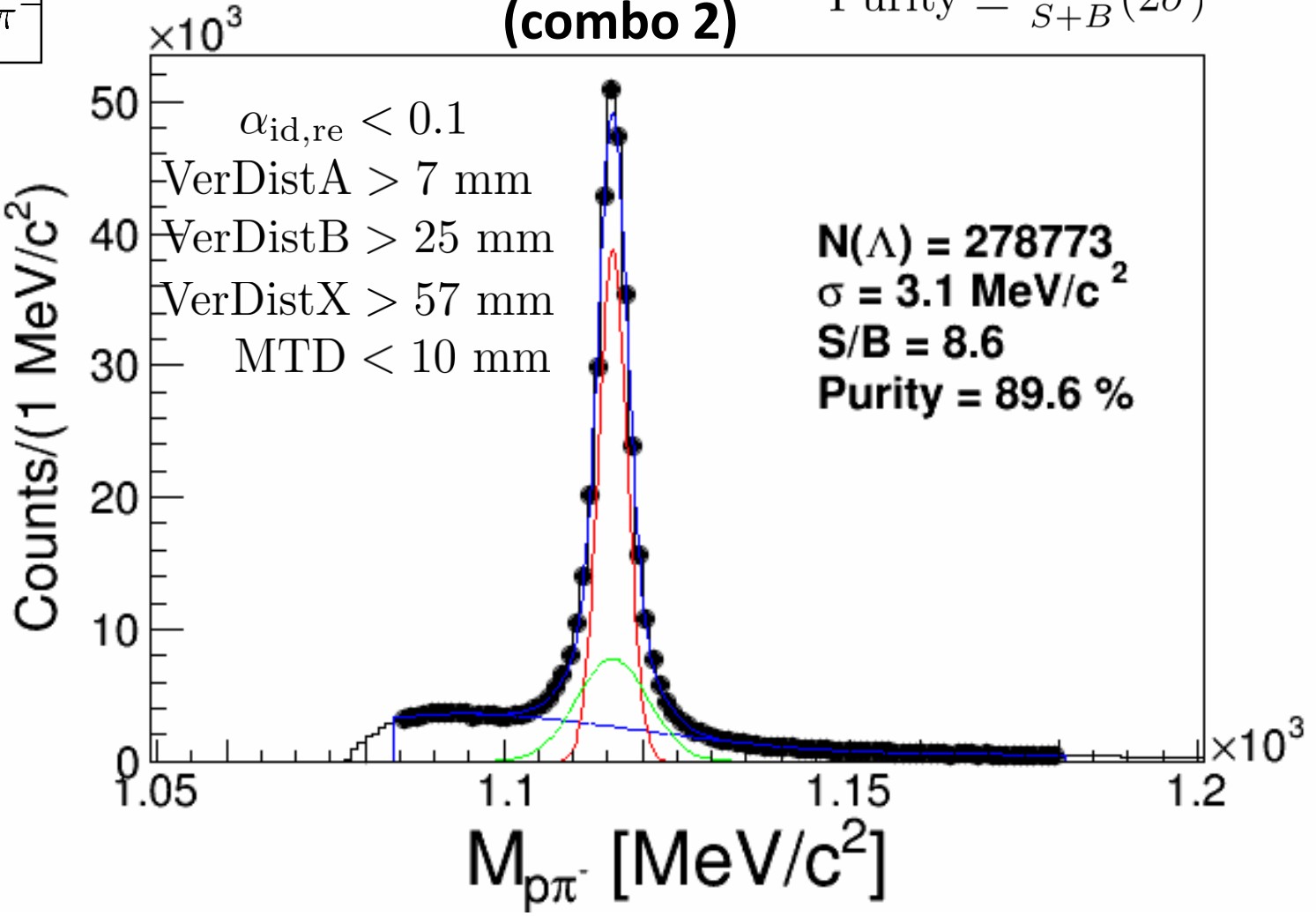



**(combo 2)**

$\text{Purity} \equiv \frac{S}{S+B}(2\sigma)$



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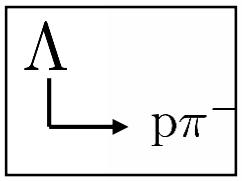



**(combo 3)**

$\text{Purity} \equiv \frac{S}{S+B}(2\sigma)$

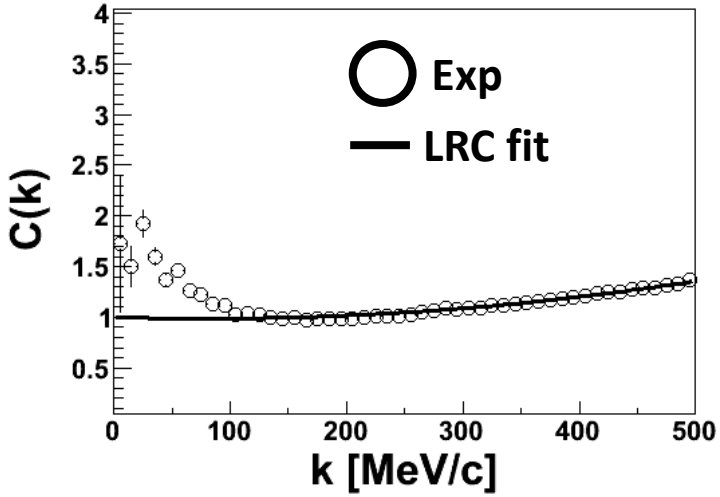
$\alpha_{\text{id,re}} < 0.1$
$\text{VerDistA} > 10$ mm
$\text{VerDistB} > 28$ mm
$\text{VerDistX} > 61$ mm
$\text{MTD} < 10$ mm

**N(Λ) = 177893**
**σ = 3.2 MeV/c²**
**S/B = 12.3**
**Purity = 92.5 %**

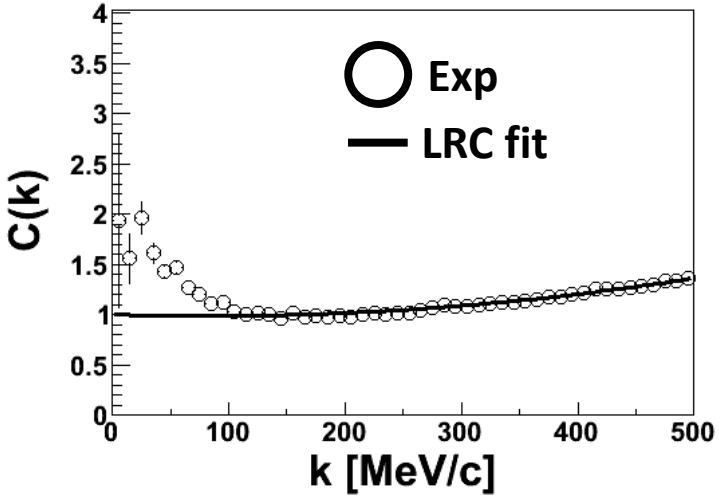
# Interaction

**Again corrections: Influence of long range correlations for all three cut combinations:**

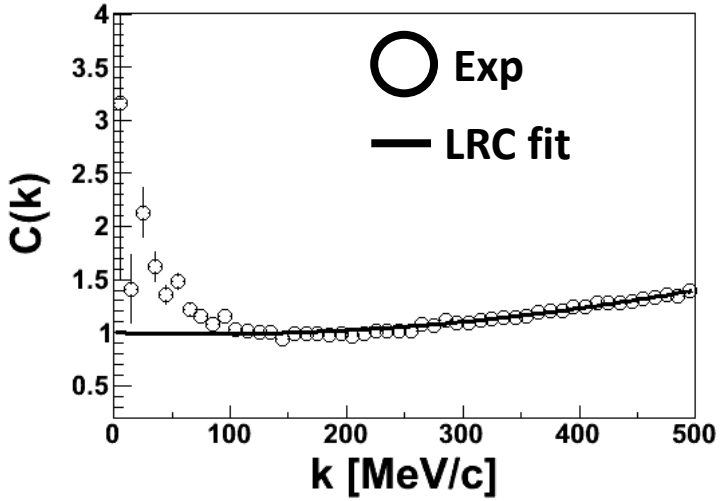
**combo1**




**combo2**




**combo3**




Model the long-range part with a polynomial

$$C_{\mathrm{LRC}} = 1 + ak + bk^2 \quad k \in [250, 600]\ \mathrm{MeV/c}$$

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**Again corrections: Influence of long range correlations for all three cut combinations:**

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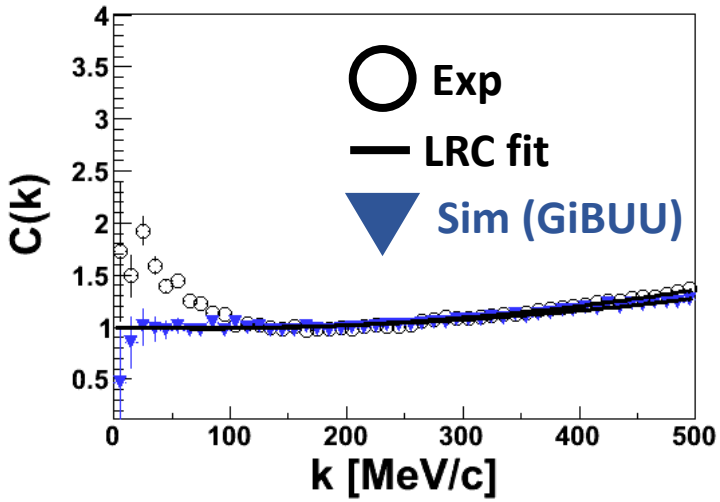
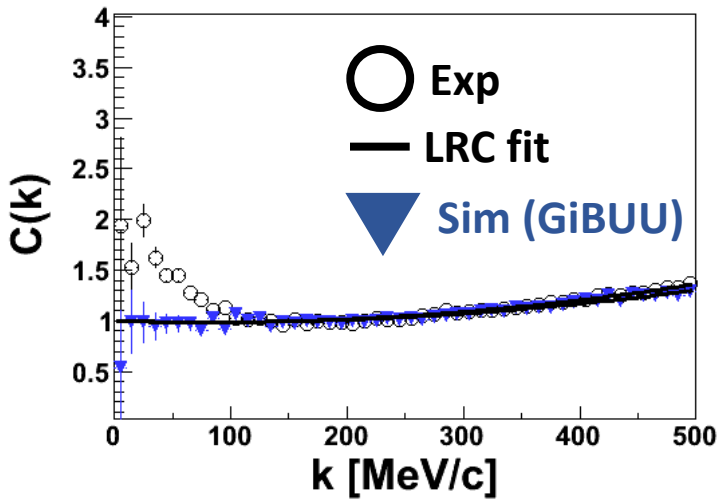
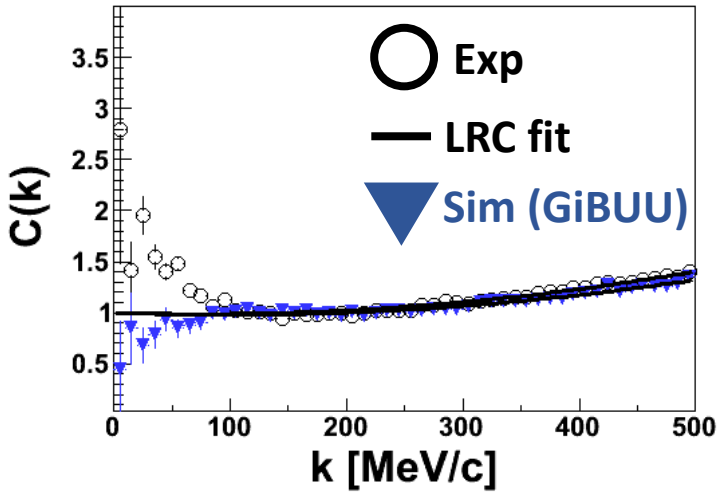



**combo2**




**combo3**




Model the long-range part with a polynomial

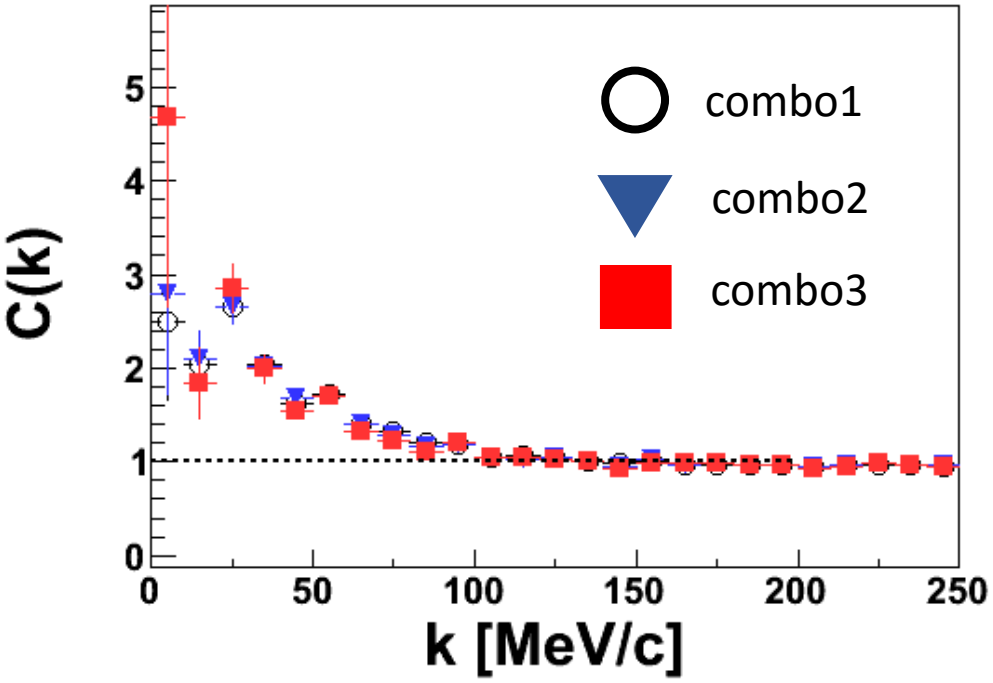
$$C_{\mathrm{LRC}} = 1 + ak + bk^2 \quad k \in [250, 600]\ \mathrm{MeV/c}$$

Simulation confirms trend of the fit from the long-range part also at small relative momenta

# Interaction

**Apply corrections – investigate systematics:**

**Correlation function after application of all corrections**



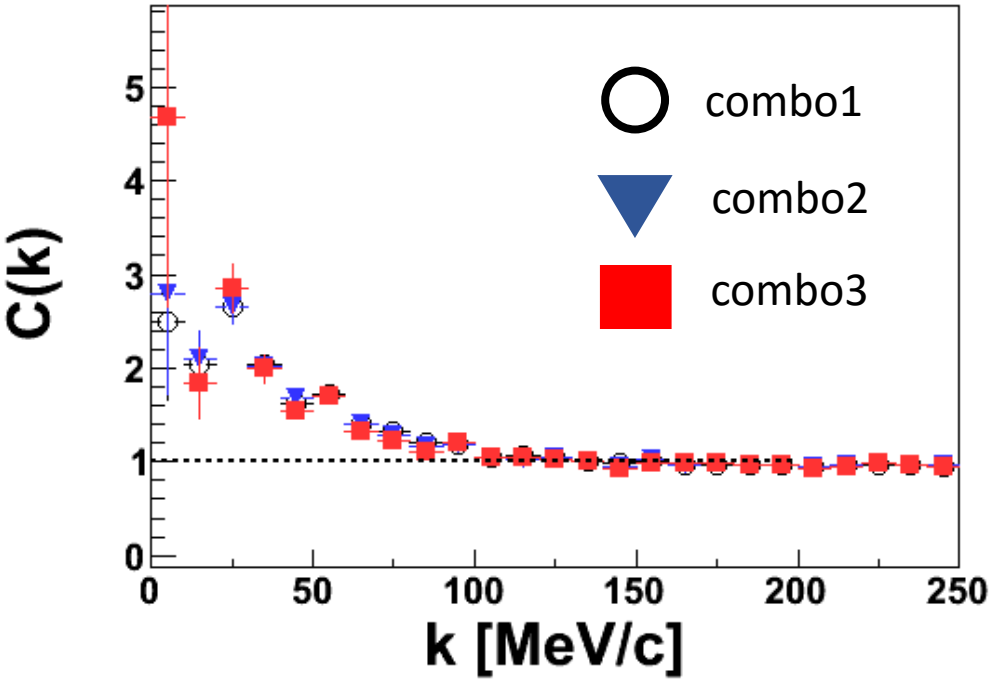

**Lednicky's model:**

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

# Interaction

**Apply corrections – investigate systematics:**

**Correlation function after application of all corrections**

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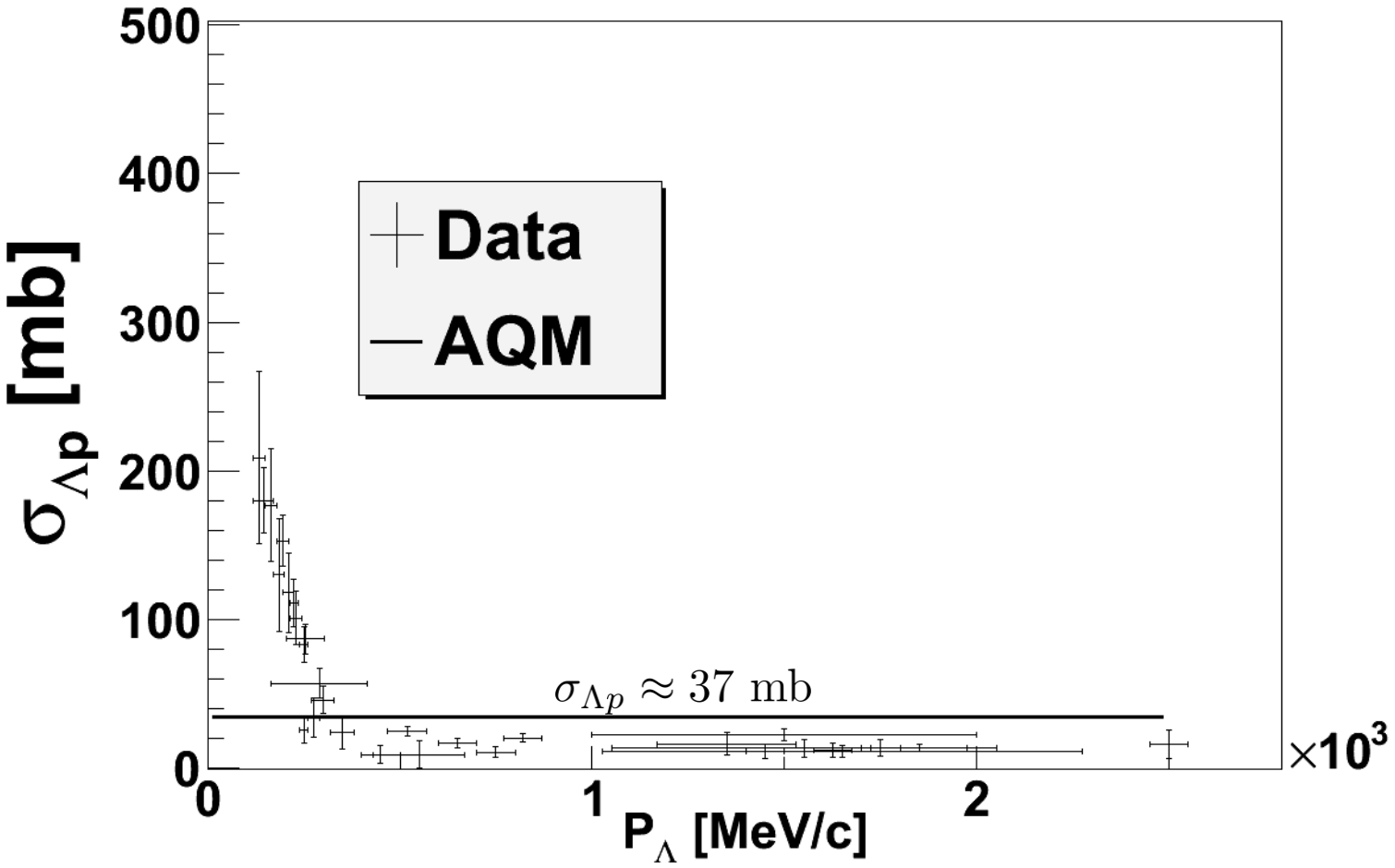
Can we use the pp measurement to fix it?

# Interaction

**Source function extraction from transport theory (UrQMD):**

Improve UrQMD for the scattering of Lambdas




**Improvement for low energies necessary**

# Interaction

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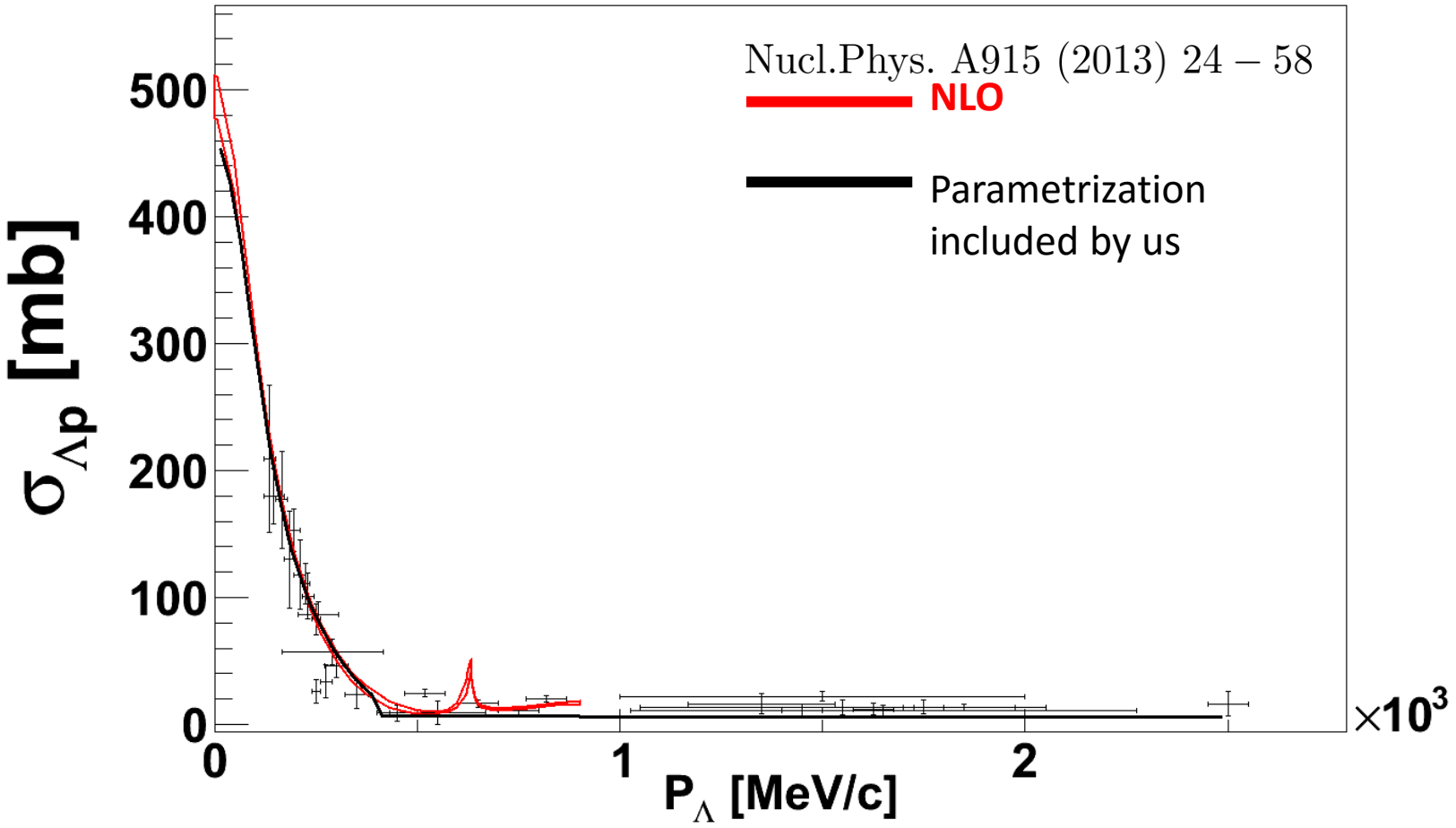
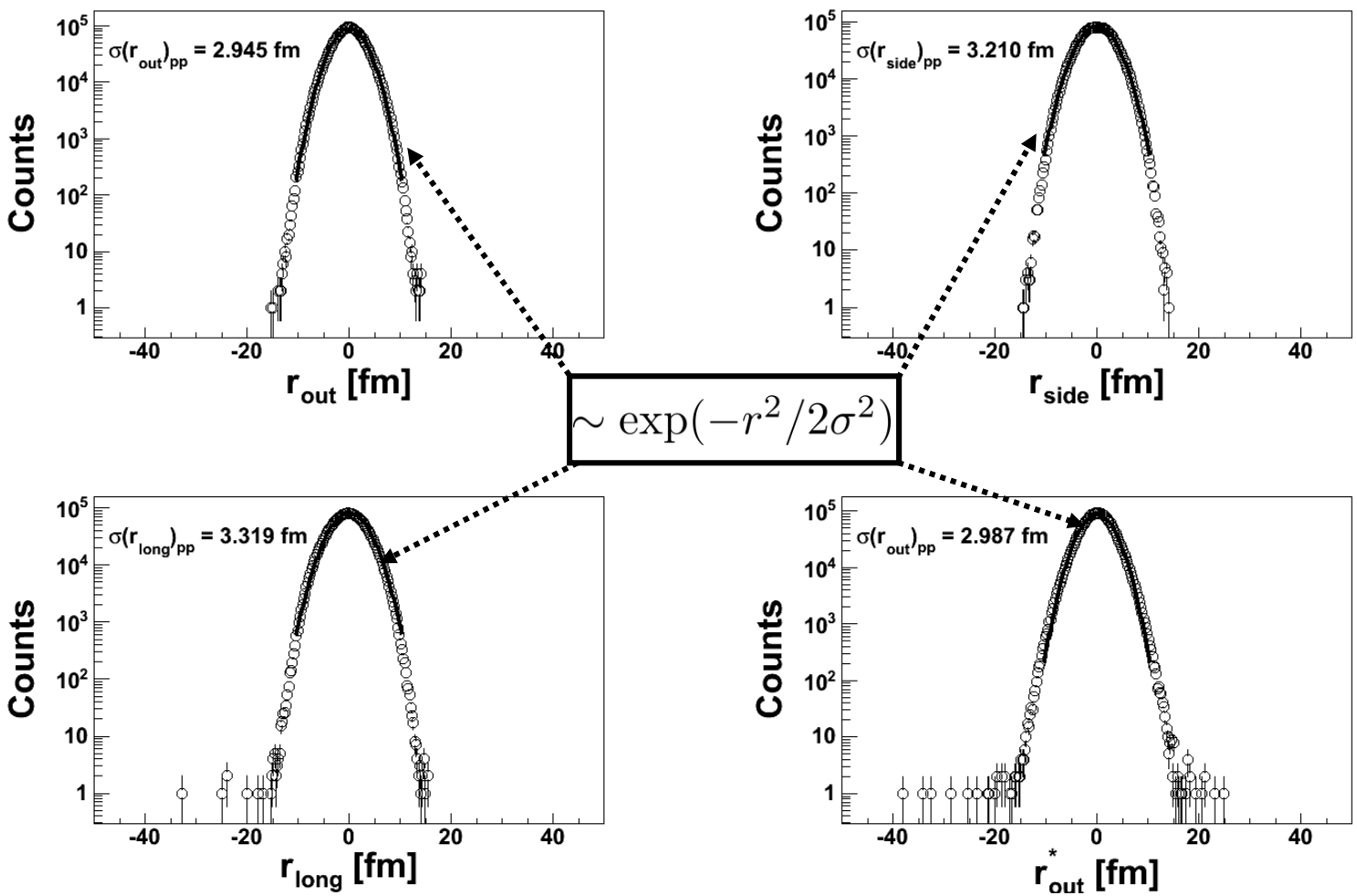


# Interaction

**Source extraction from transport theory (UrQMD) - LCMS:**

$$C^{ab}(k) = \int d^3r' S_{\mathbf{P}}(\mathbf{r}')|\phi(\mathbf{k},\mathbf{r}')|^2 \qquad k < 30 \text{ MeV/c}$$

**Proton-Proton**



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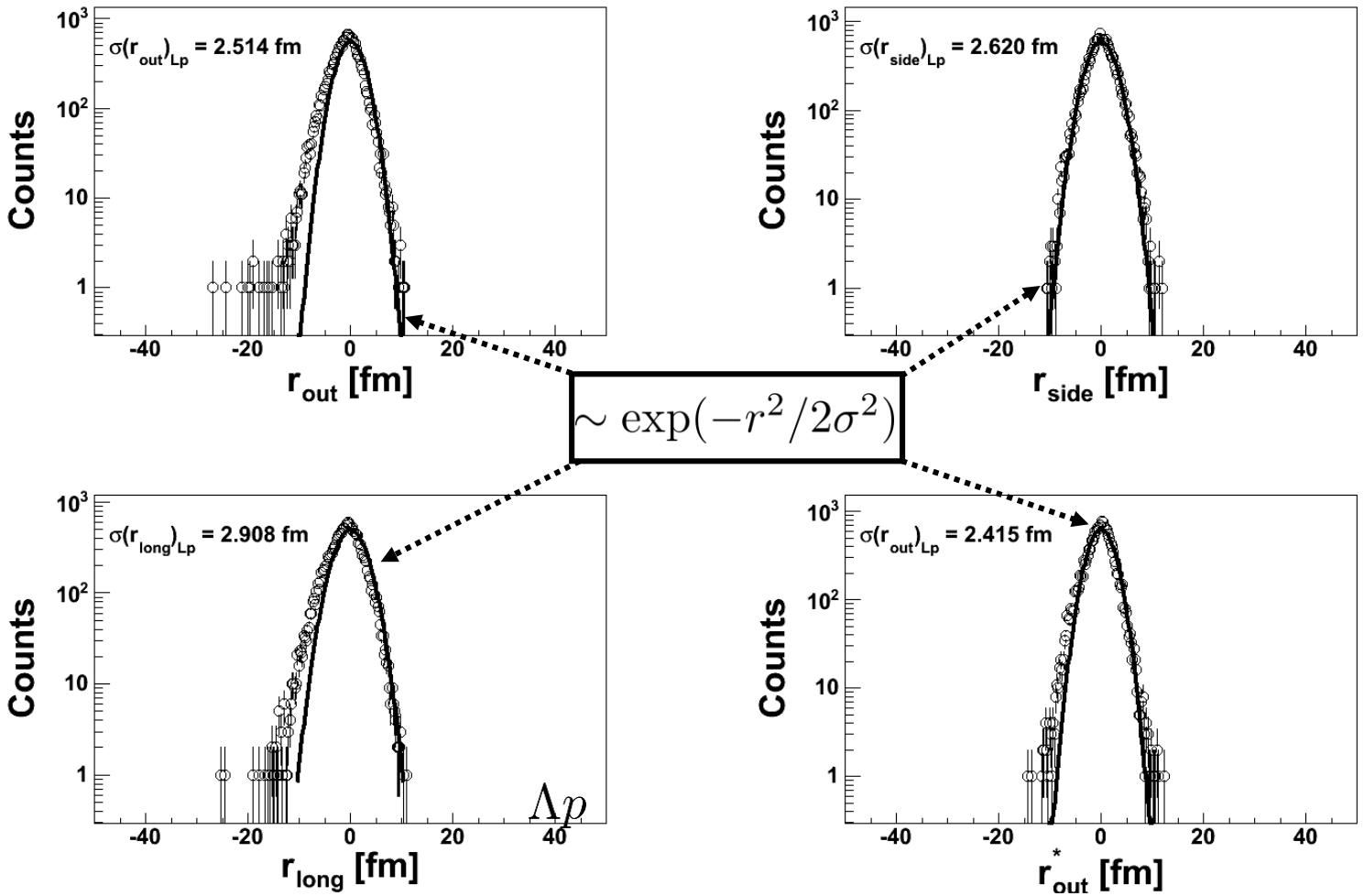
$\Lambda p$



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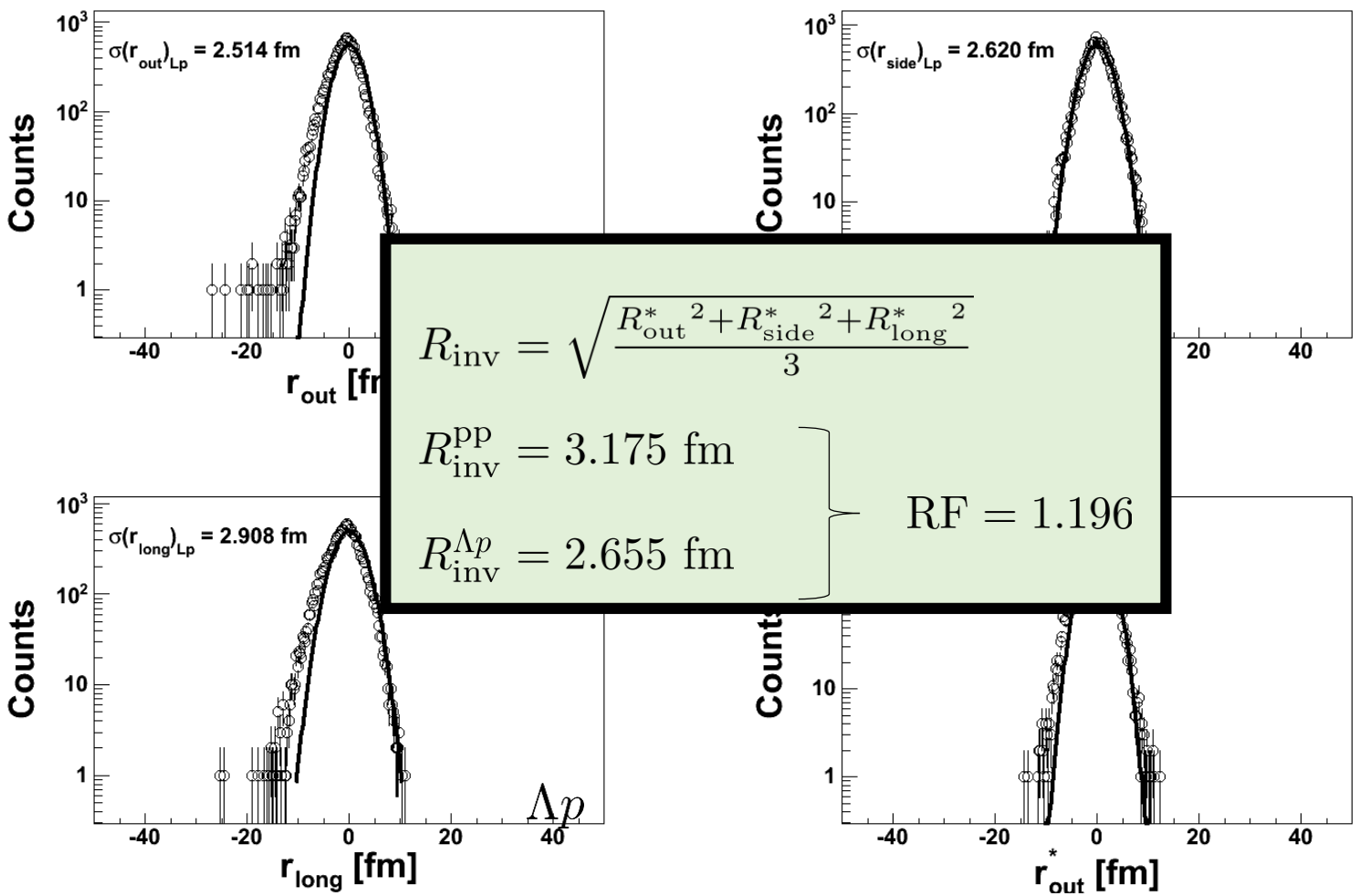



$$R_{\text{inv}} = \sqrt{\frac{{R^*_{\text{out}}}^2 + {R^*_{\text{side}}}^2 + {R^*_{\text{long}}}^2}{3}}$$

$$R^{\text{pp}}_{\text{inv}} = 3.175 \text{ fm}$$

$$R^{\Lambda p}_{\text{inv}} = 2.655 \text{ fm}$$

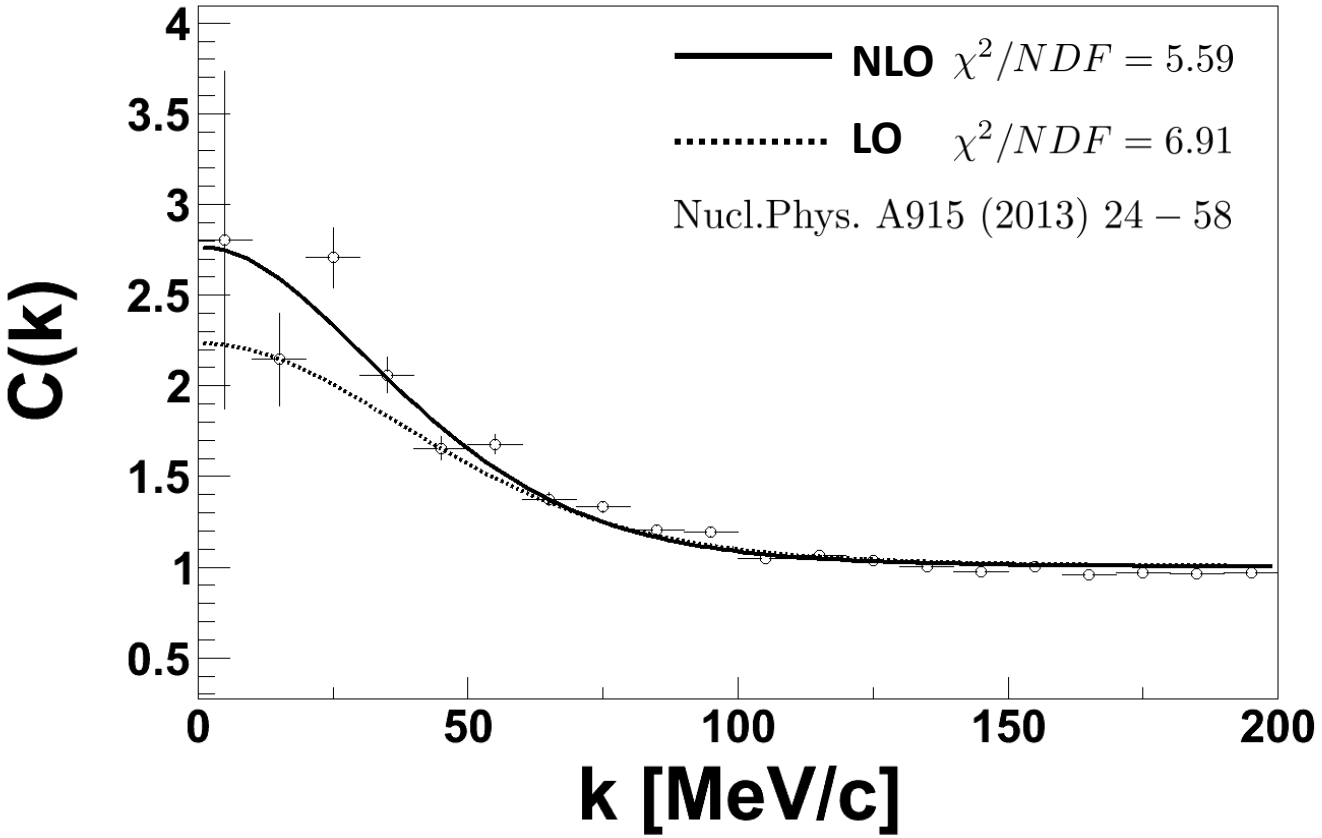
$$\text{RF} = 1.196$$

# Interaction

**Comparison to models:**

$$R_G = 2.016 \pm 0.010^{+0.109}_{-0.118} \text{ fm}$$

$$R_G^{\Lambda p} = R_G^{pp}/RF$$
$$RF = 1.196$$



# Summary & Outlook

## Summary

- Source size of emission region in pNb system determined with pp-pairs
- Knowing the source size allows to study final state interactions of not well known type

## Outlook

- Investigate systematics of the reduction factor

# Backup

**Comparison to models:**

$$R_G = 2.016 \pm 0.010^{+0.109}_{-0.118} \text{ fm}$$

$$R_G^{\Lambda p} = R_G^{pp} / RF$$
$$RF = 1.196$$