Two-particle correlation measurements in p+Nb reactions at $\sqrt{s_{NN}} = 3.18\ \mathrm{GeV}$

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DUBNA 2015

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Outline

- **Motivation: Why study particle correlations?**

- **Proton-proton correlations**

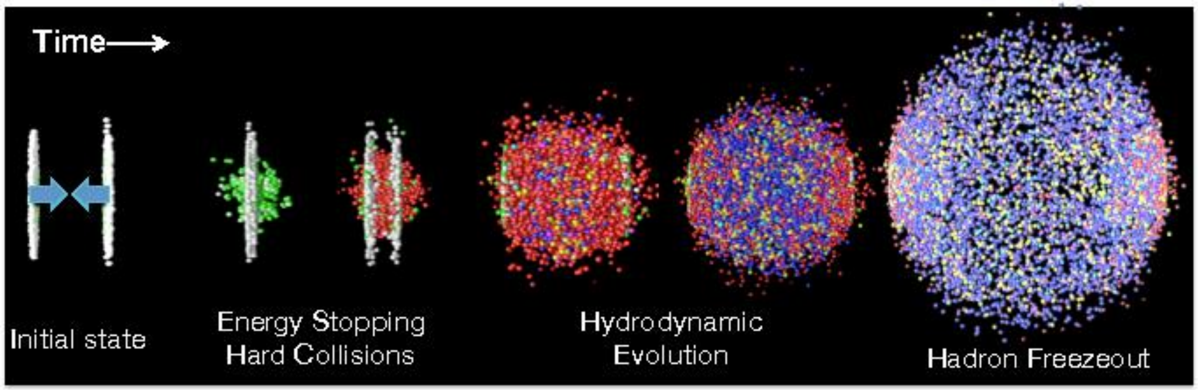
  ➡ Corrections and results from comparison with models

- **Lambda-proton correlations**

  ➡ Use of proton-proton results to investigate the interaction of Λp pairs

Motivation

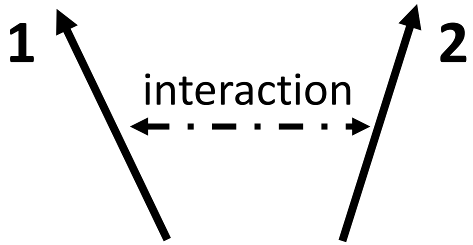
Femtoscopy and particle correlations – what for?



General picture of the time sequence of a heavy-ion collision

Gain information about the dynamics of the reaction (source)

O R

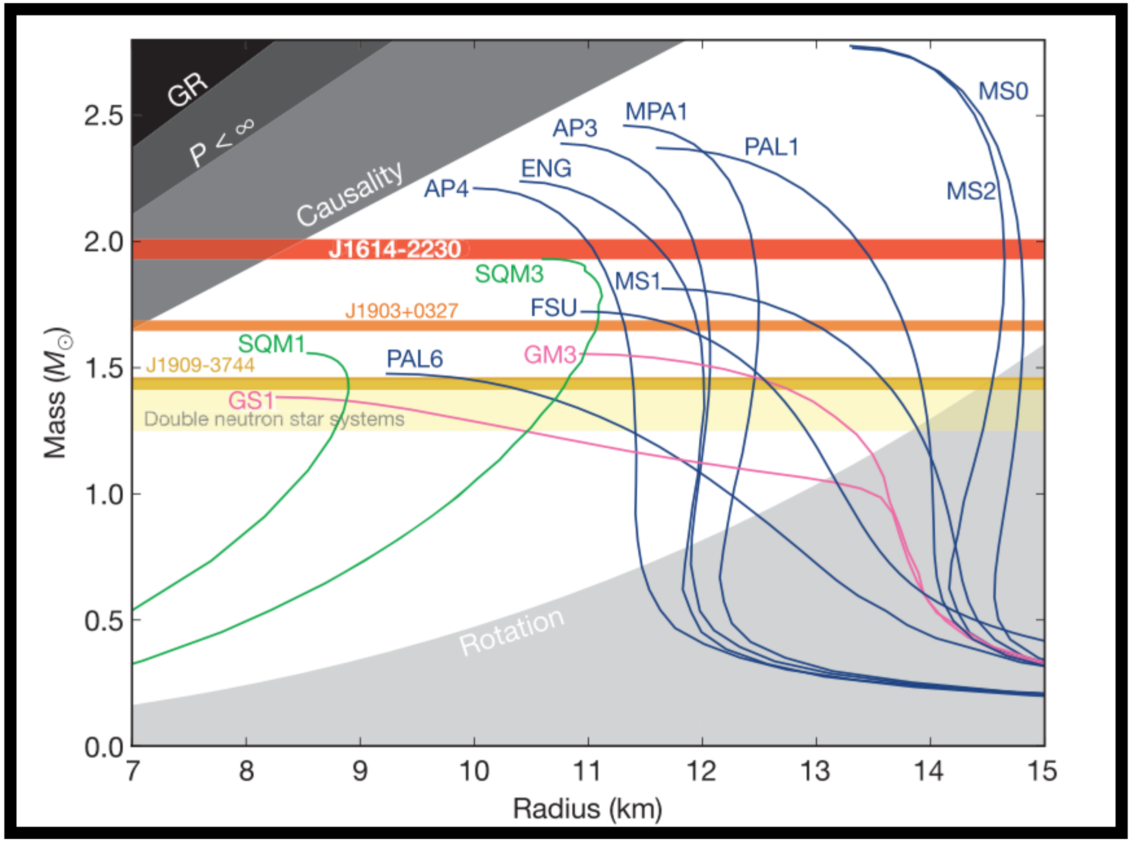


e.g. $\Lambda\mathrm{p}, \Lambda\Lambda, \ldots$

Gain information about the interaction between particles

Motivation

Why is the Λp interaction interesting?



Demorest *et al.*, *Nature* **467**, 1081 – 1083 (2010)

e.g. Λp, $\Lambda\Lambda$, ...

Interaction is a crucial input for the equation of state

Method

Theoretical correlation function:

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

Source function:
Distribution of relative distances between the particle pairs (in CMS of the pair)

Wavefunction of particle pair:
Includes the interactions and symmetries

Experimental correlation function:

$$\boxed{C(k) = \mathcal{N}\frac{N(\mathbf{p}_1,\mathbf{p}_2)_{\text{same}}}{N(\mathbf{p}_1,\mathbf{p}_2)_{\text{mixed}}}}$$

$$k = \tfrac{1}{2}|\mathbf{p}_1 - \mathbf{p}_2|$$
$$\mathbf{p}_1 + \mathbf{p}_2 = 0$$

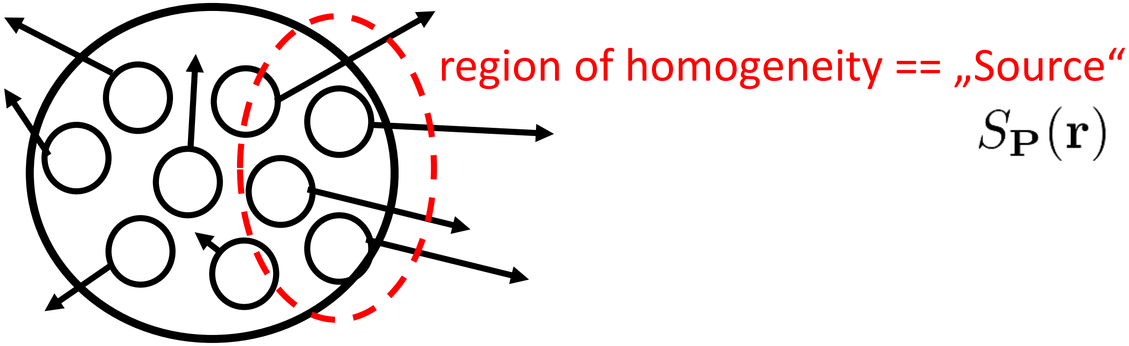
- **Same:** relative momentum dist. of particles in the same event
- **Mixed:** particles from different events (not correlated)
- **Normalization factor** $\mathcal{N}$: $C(k > 100 \text{ MeV/c}) \equiv 1$

Strategy

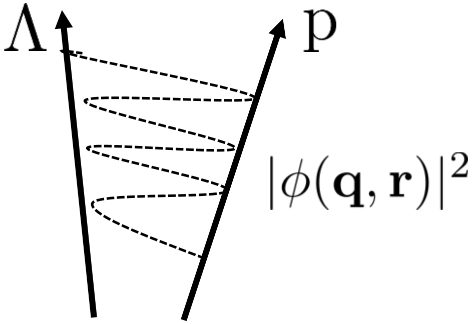
Strategy of analysis – two steps:

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

1. Understand the emission profile of the pNb system



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



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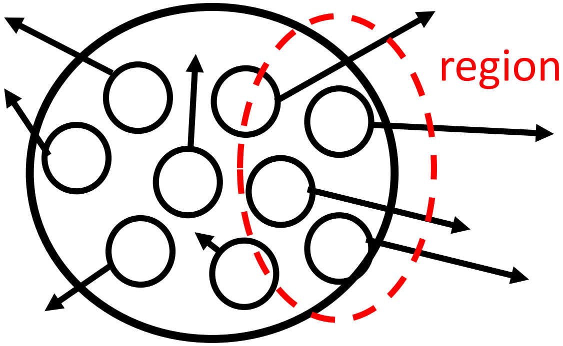

region of homogeneity == „Source“

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

Strategy

Strategy of analysis – two steps:

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

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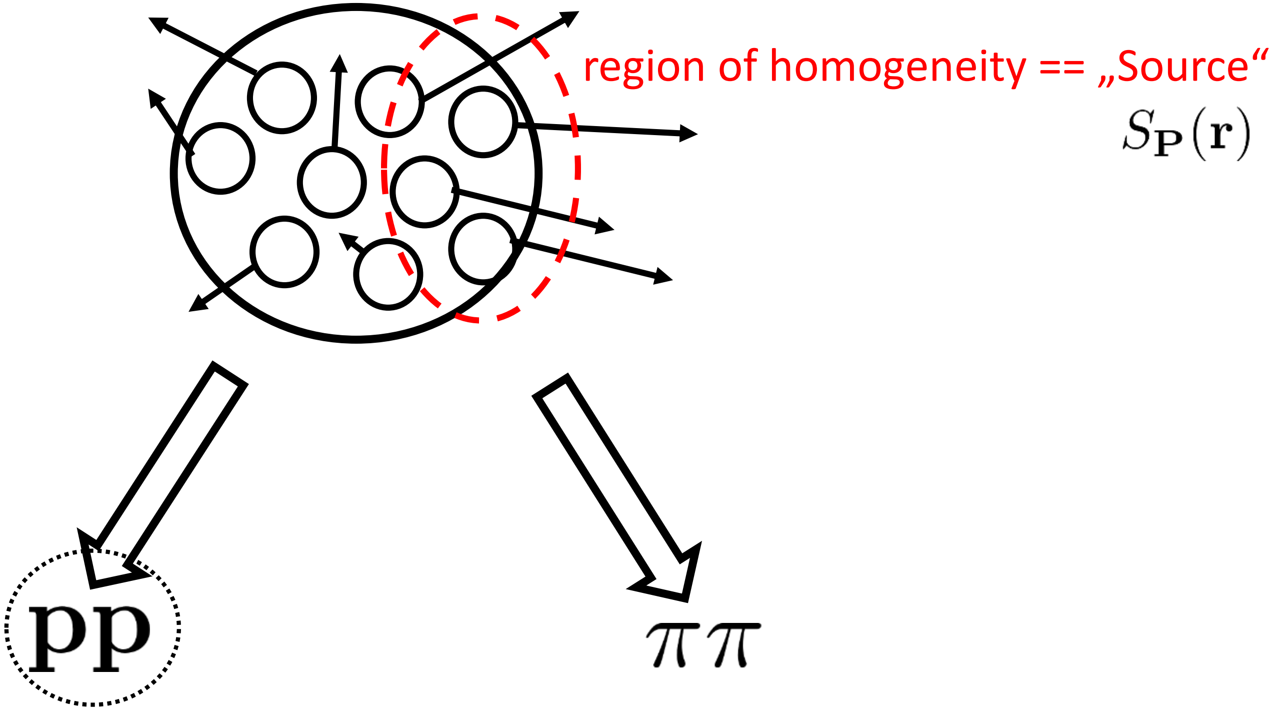


➡ **Use pairs with large statistic and well established interactions**

Reaction

System under investigation:

$$\boxed{\begin{gathered} \mathrm{p} +^{93}_{41} \mathrm{Nb} \rightarrow \mathrm{P} + \mathrm{X} \\ \mathrm{P} = \mathrm{pp}, \pi^{\pm}\pi^{\pm}, \ldots \end{gathered}}$$

Beam:

$$\xrightarrow{\mathrm{p}}$$

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

$T_p = 3.5 \text{ GeV}$

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

Target:

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

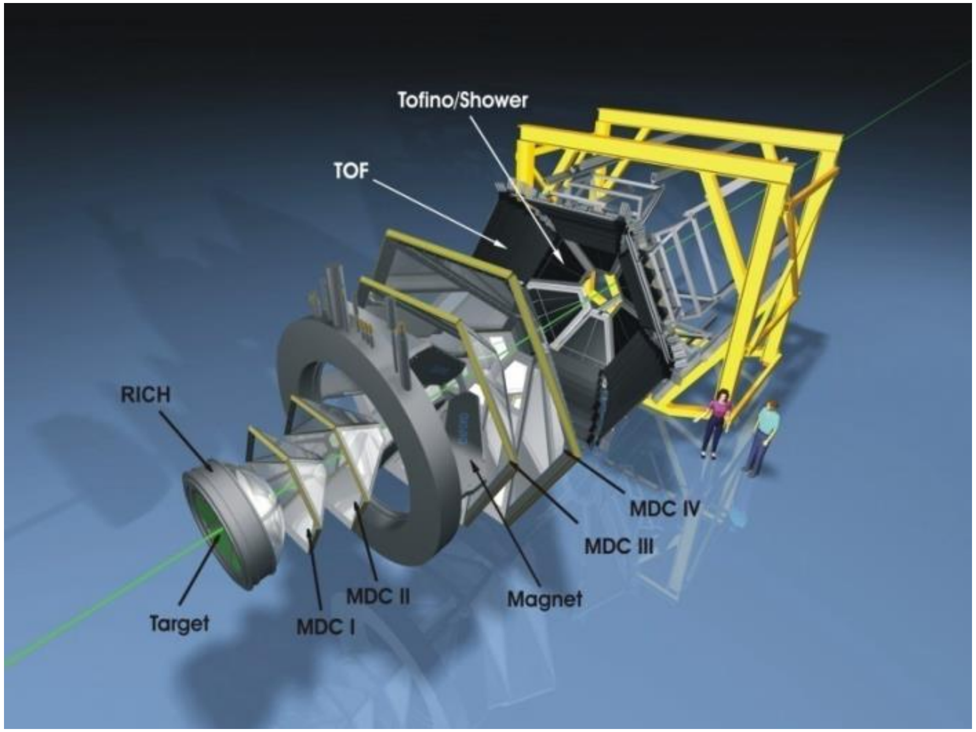
2.8% interaction probability

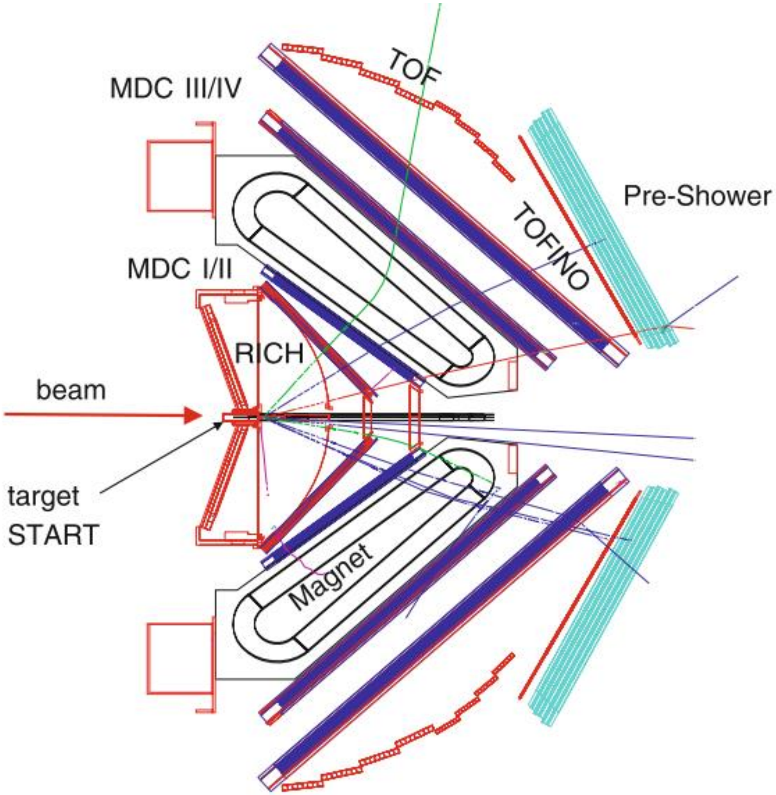
$\langle A_{part} \rangle \sim 2.7$

Femtoscopy in a small system!

Experiment

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



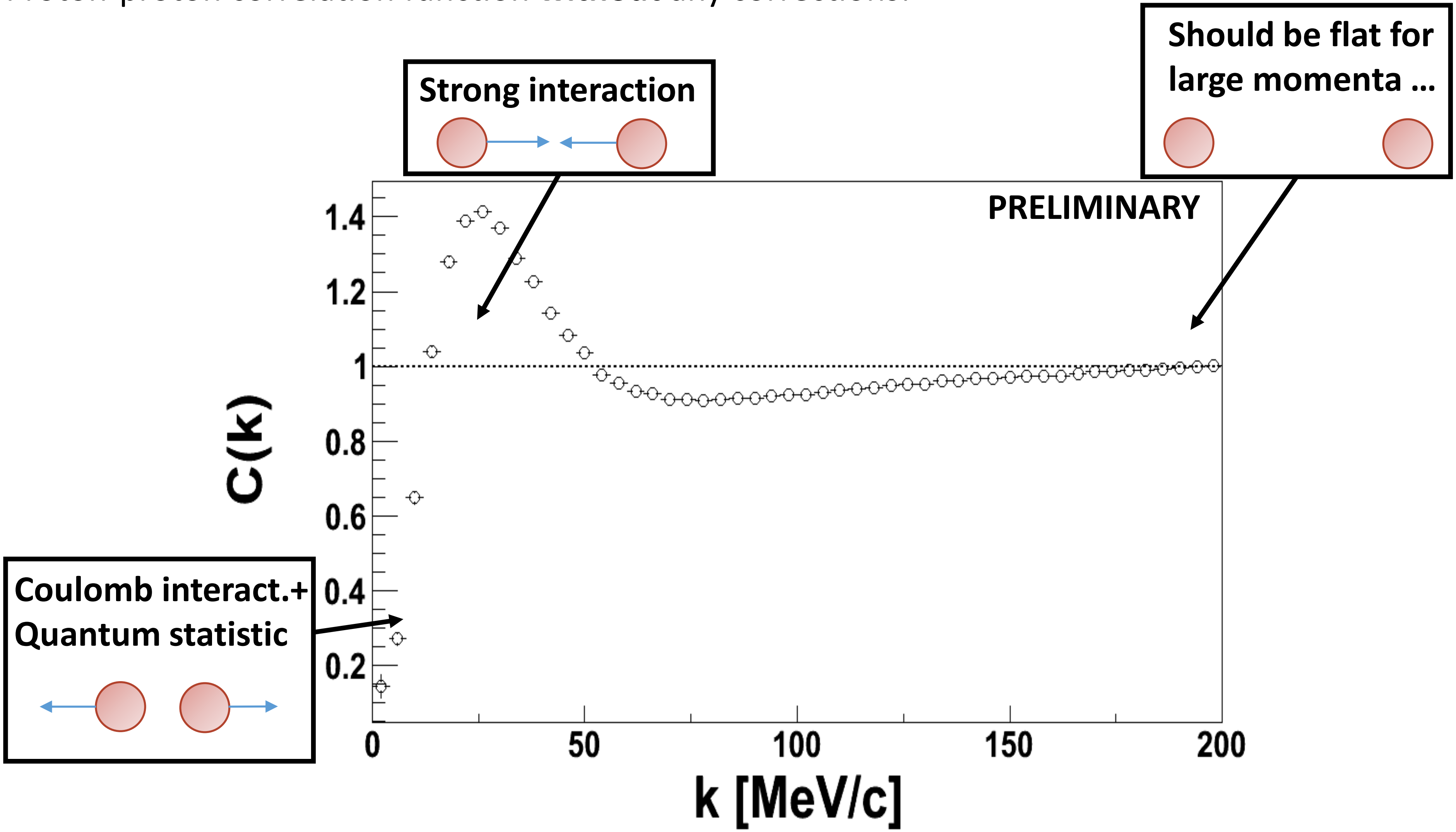


Features of HADES:

- 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:

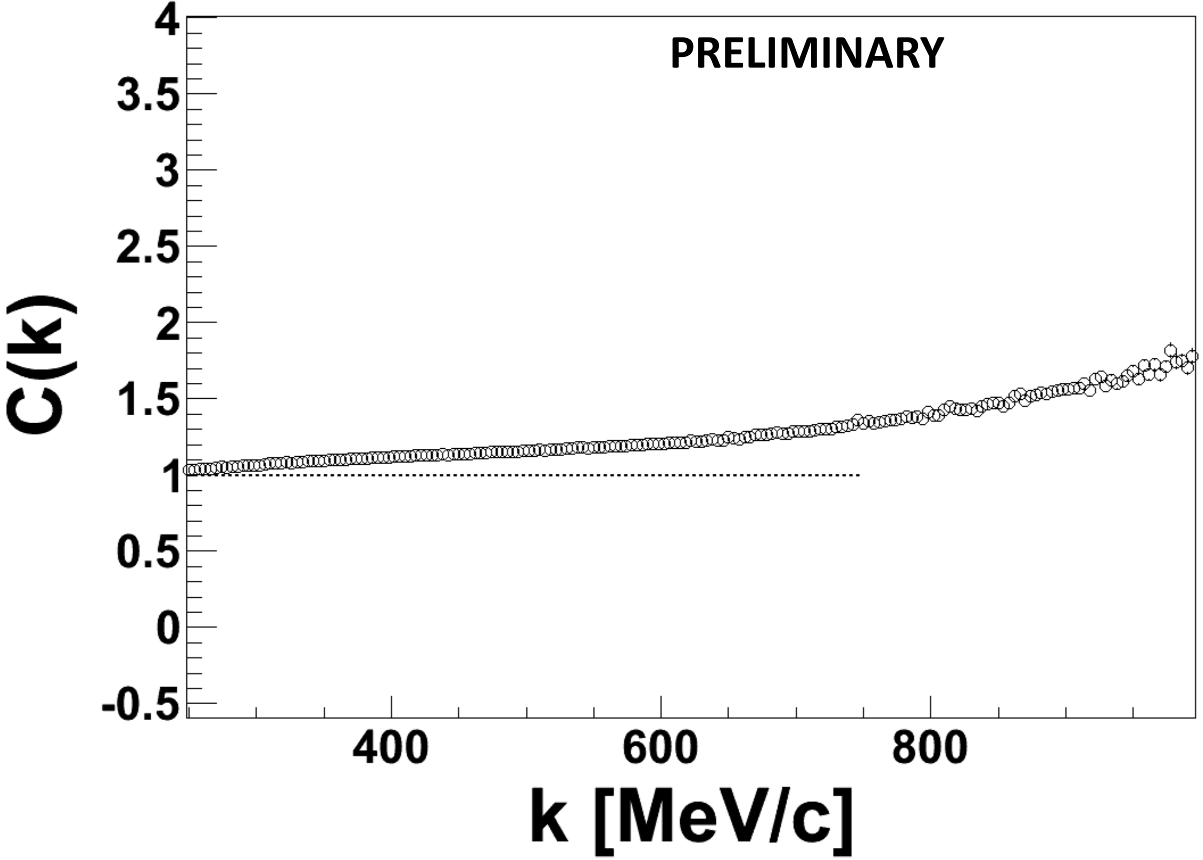


Correlation Function

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

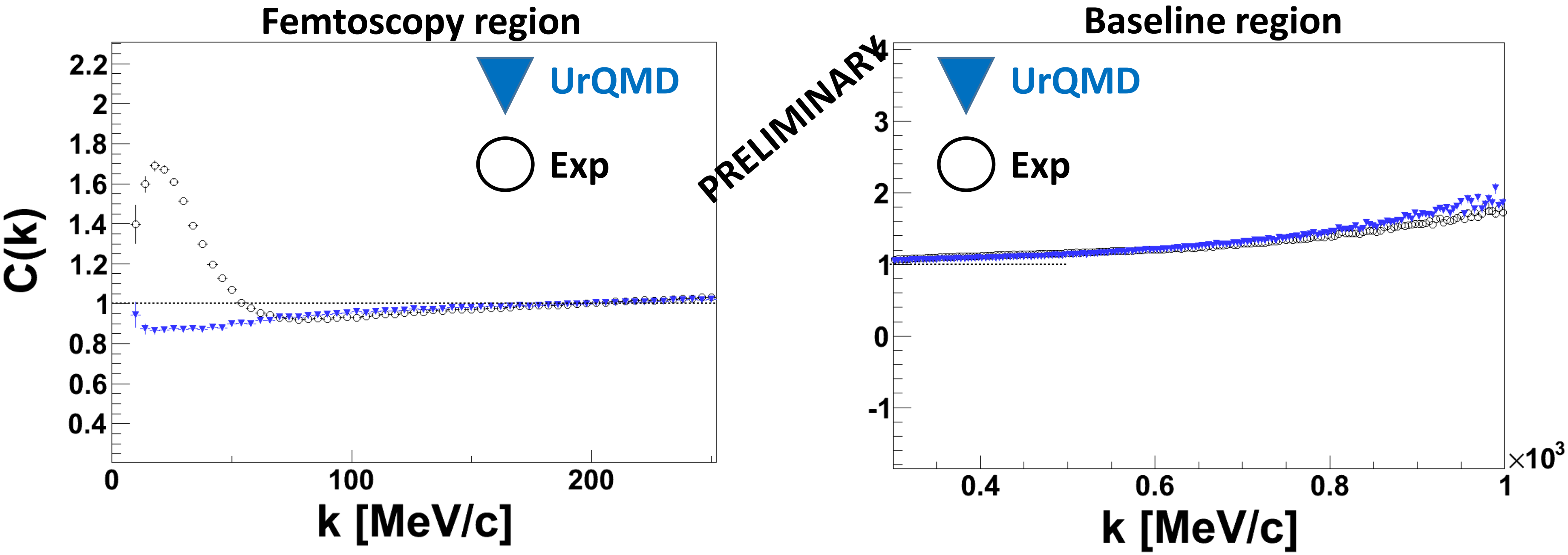


Correlation Function

Information about the source – proton proton correlation function:

Can we model them (LRC)? ✓

Proton-Proton correlations



Femtoscopy region

Baseline region

Define LRC free CF:

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

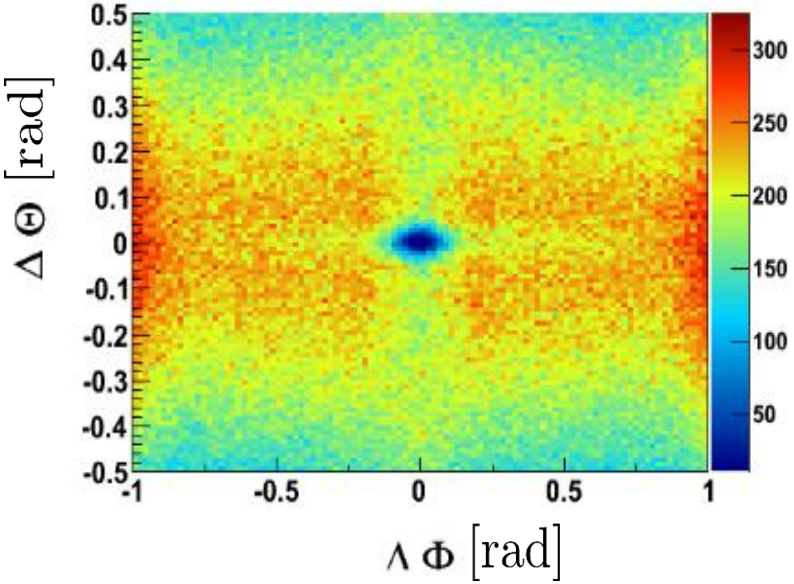
Correlation Function

Information about the source – proton proton correlation function:

Further corrections? ✓

Proton-Proton correlations

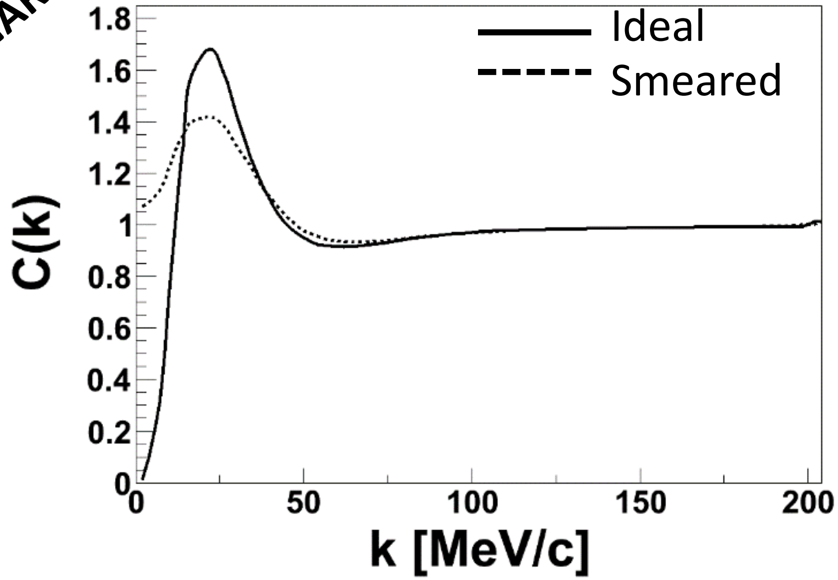
Reject pairs which are too close together



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

PRELIMINARY

Correct for finite momentum resolution



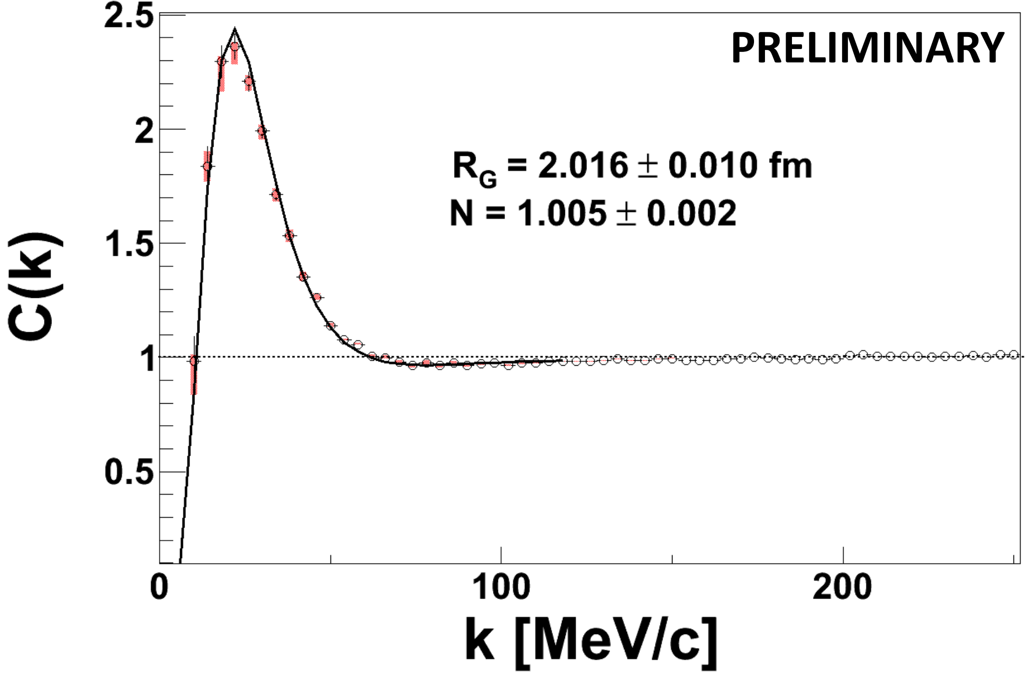
$$\frac{C_{\text{real}}(k)}{C_{\text{measured}}(k)} = \frac{C_{\text{ideal}}(k)}{C_{\text{smeared}}(k)}$$

Correlation Function

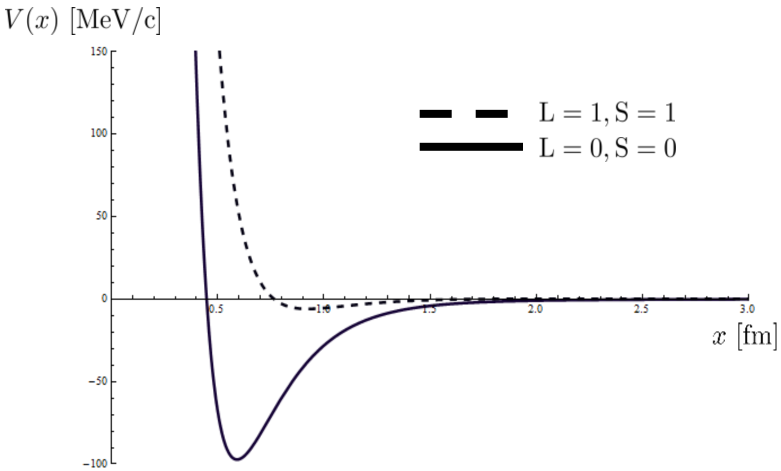
Information about the source – proton proton correlation function:

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

$$\frac{d^2w}{d\rho^2} + \left[1 - \frac{2\eta}{\rho} - \frac{l(l+1)}{\rho^2} - \frac{2\mu}{k^2} V(\rho)\right] = 0$$

$$S(r) \sim \exp(-r^2/4R_G^2)$$

$$R_G^{pp} = 2.016 \pm 0.010^{+0.039}_{-0.027} \text{ fm}$$

Interaction

Strategy of analysis:

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

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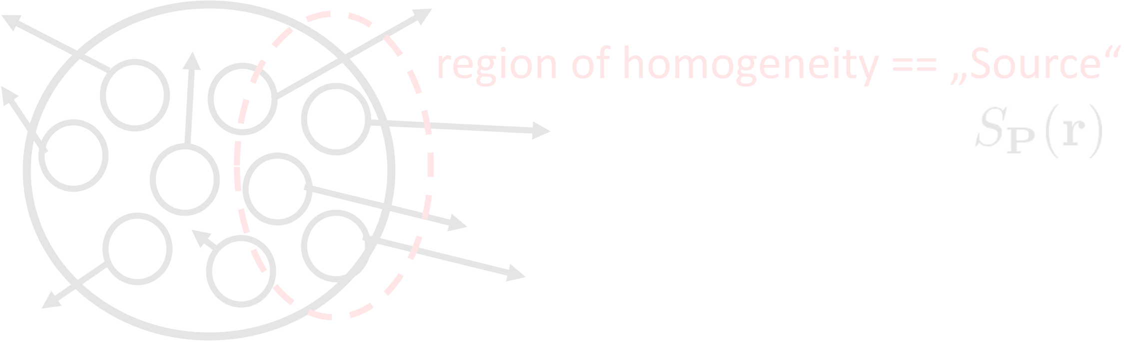

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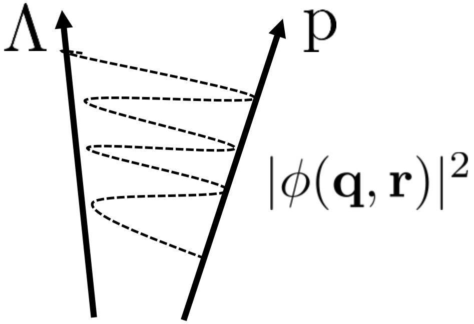
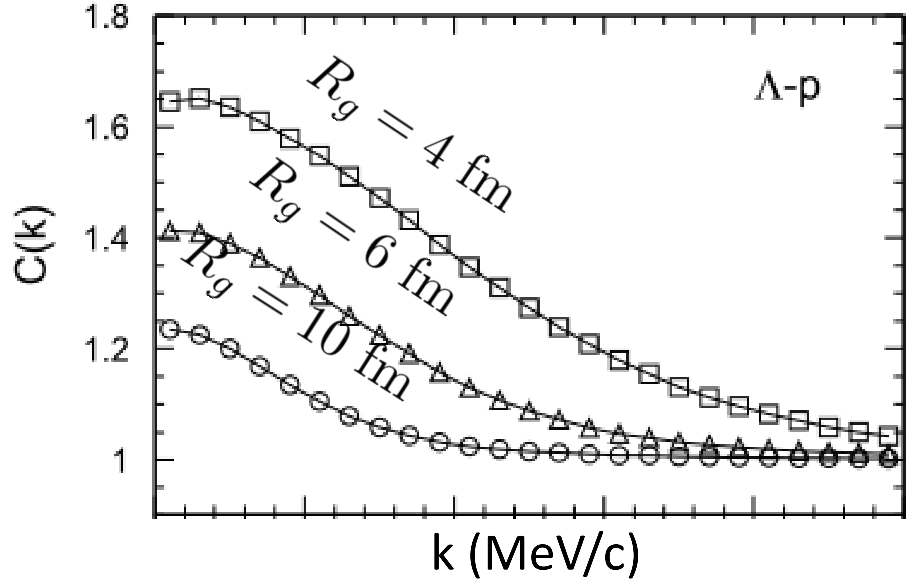


Interaction

Study interaction between Λp

Theoretical calculation



F. Wang, and S.Pratt, Phys. Rev. Lett. **83** (1999) 3138

Can we use the proton-proton measurement to constrain the Lambda-proton source function?

Interaction

Study interaction between Λp

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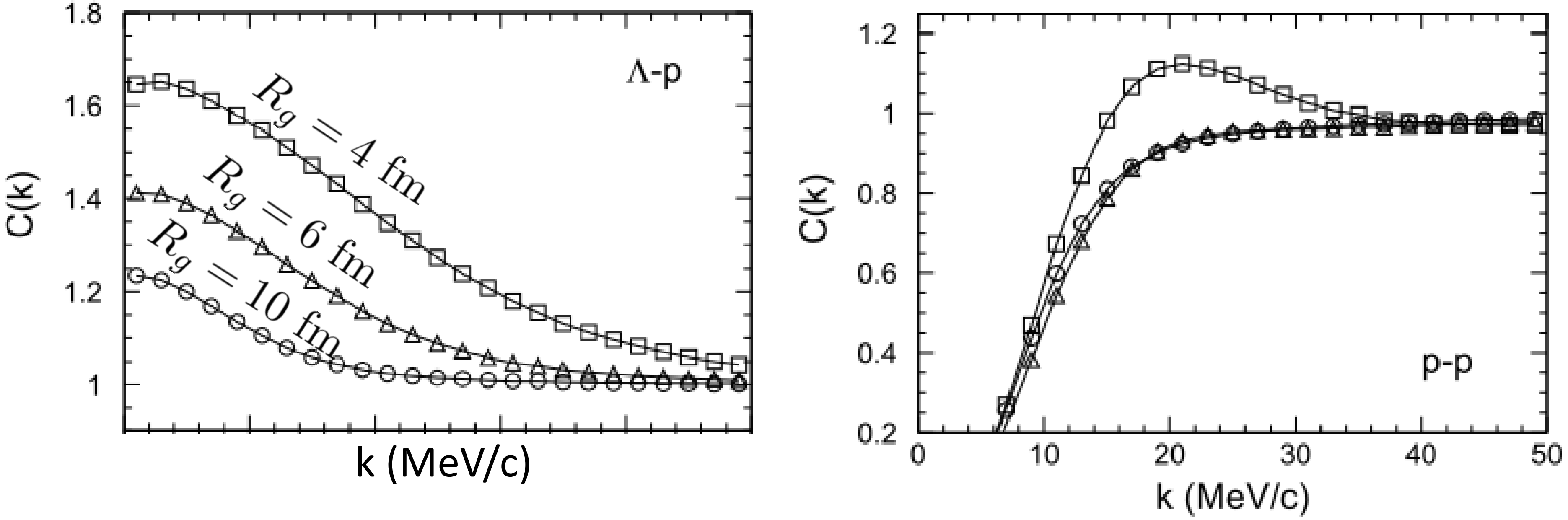

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Can we use the proton-proton measurement to constrain the Lambda-proton source function?

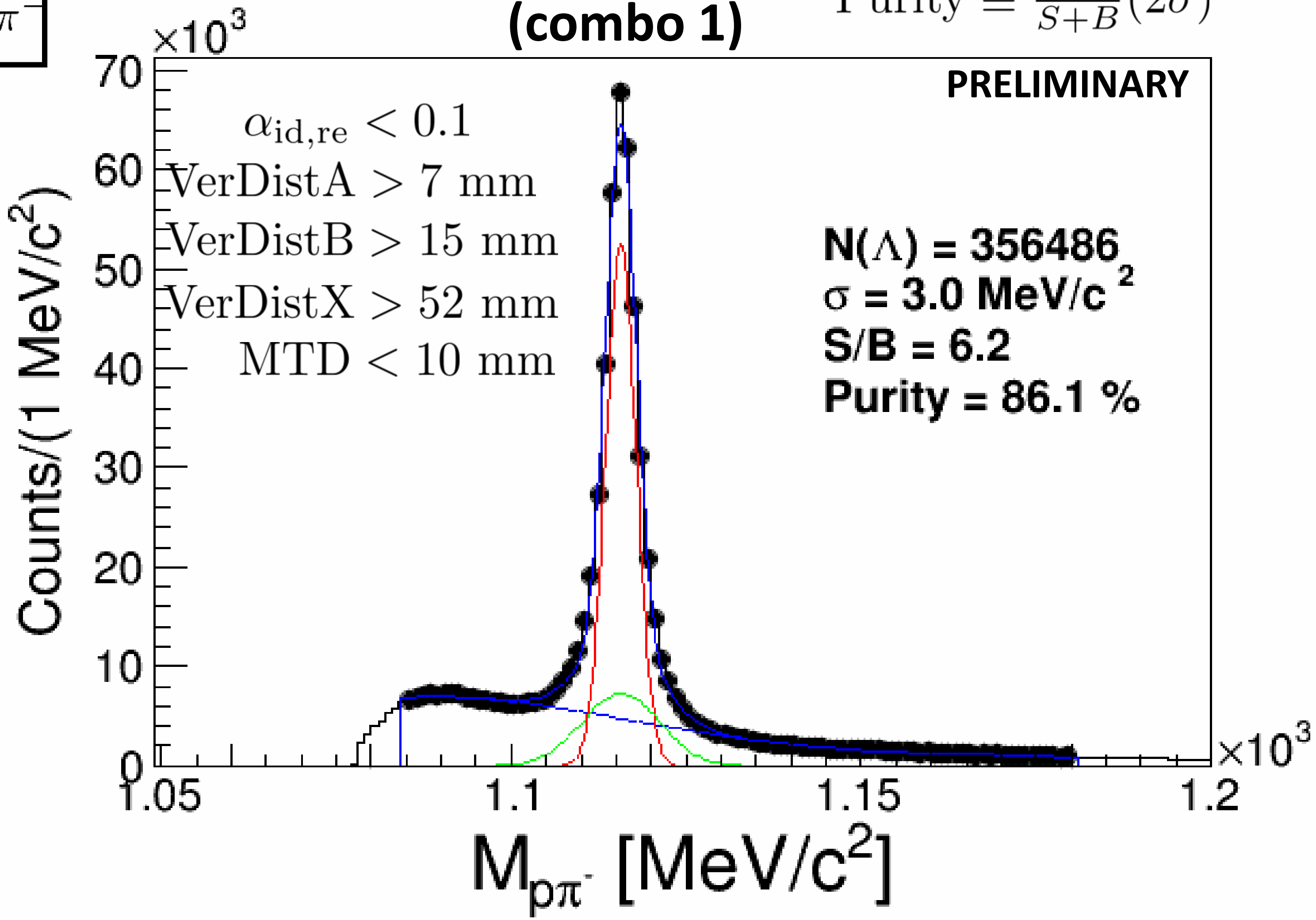
Interaction

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

$\Lambda \rightarrow p\pi^-$

(combo 1)

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



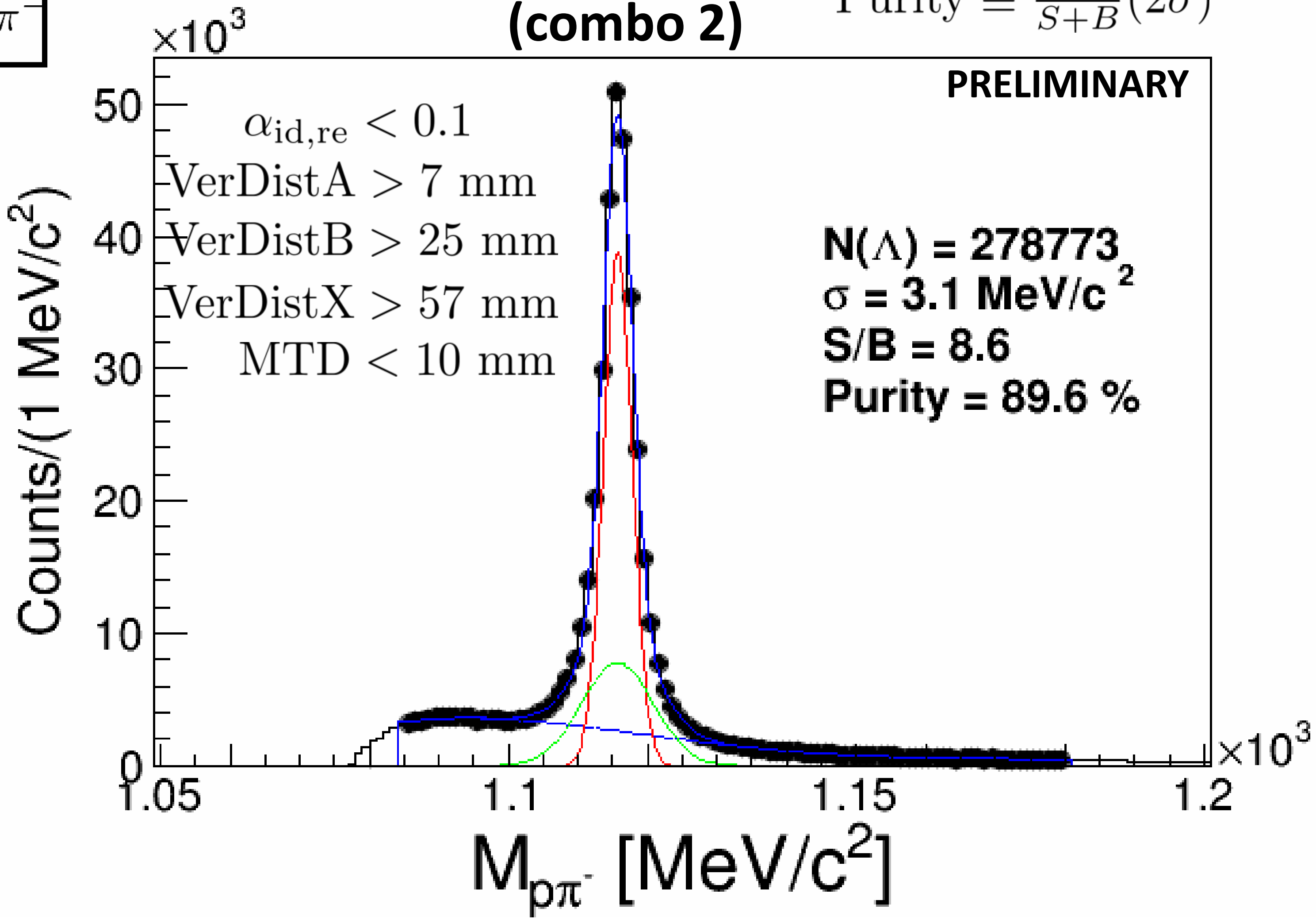
Interaction

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

$\Lambda \rightarrow p\pi^-$

(combo 2)

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



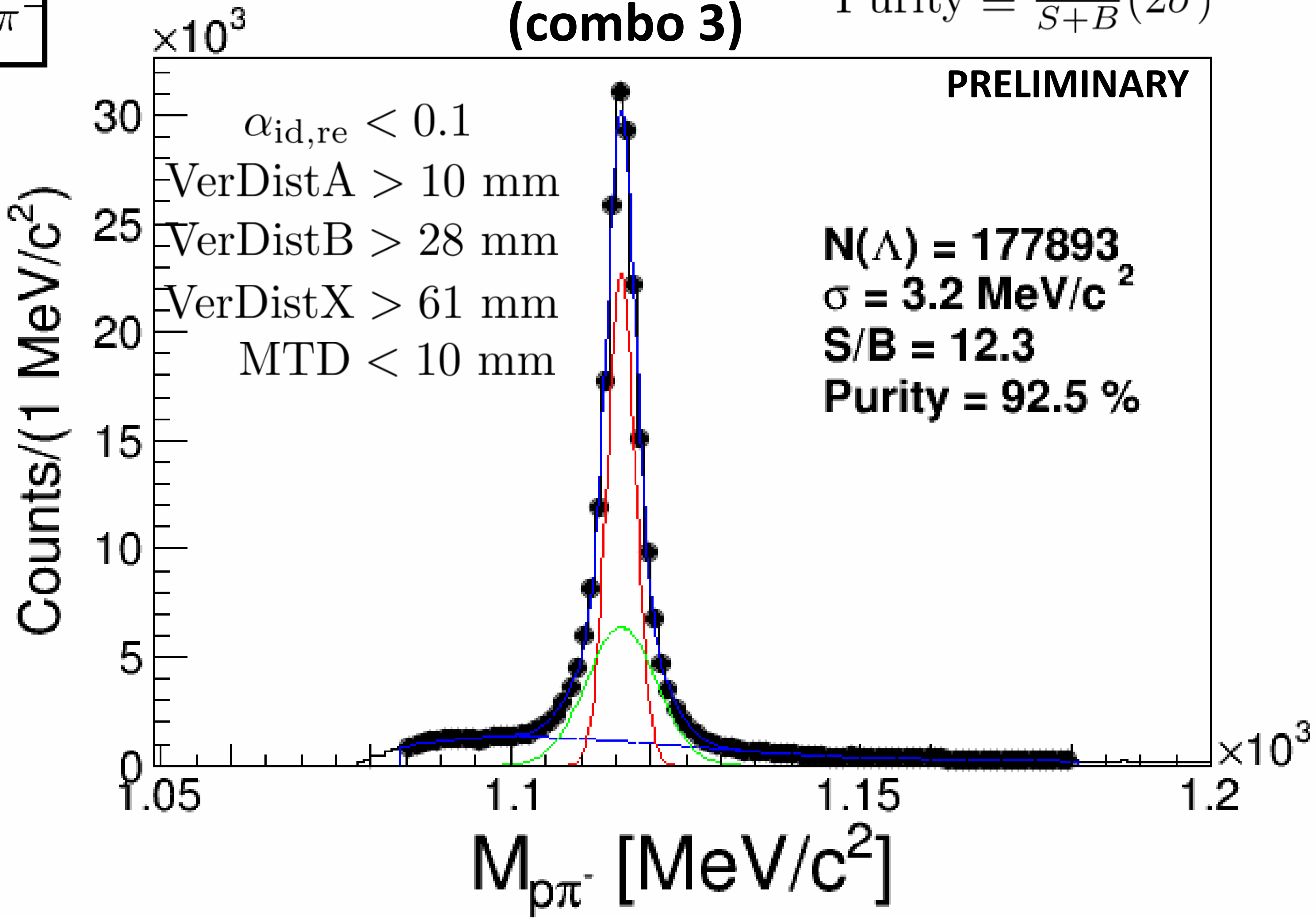
Interaction

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

$\Lambda \to p\pi^-$

(combo 3)

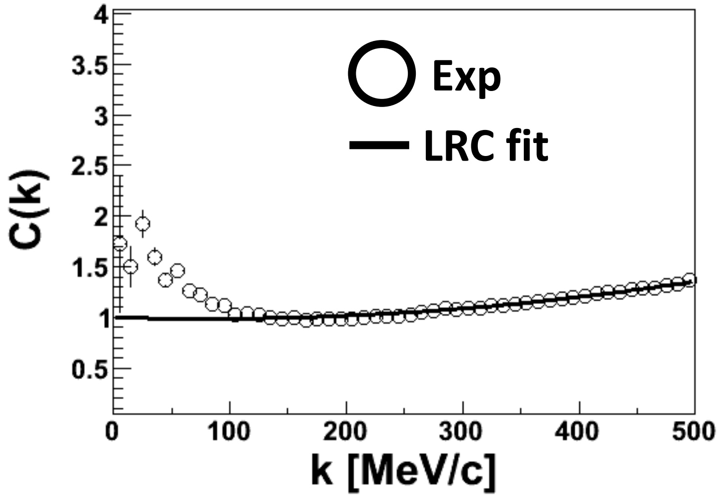
$$\text{Purity} \equiv \frac{S}{S+B}(2\sigma)$$



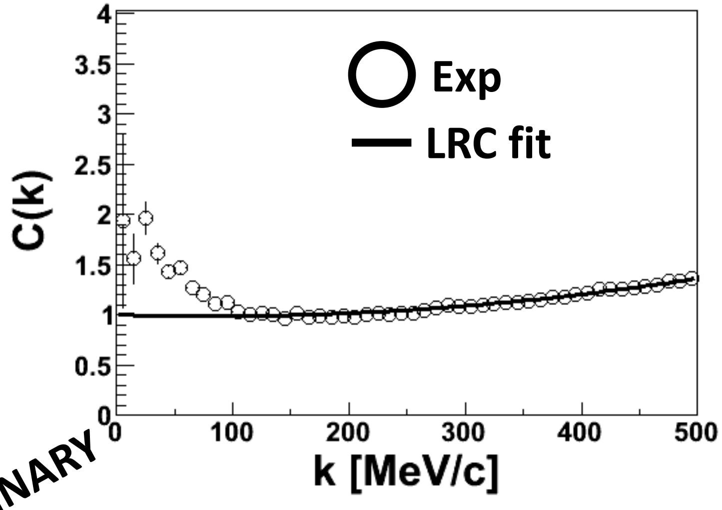
Interaction

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

combo1

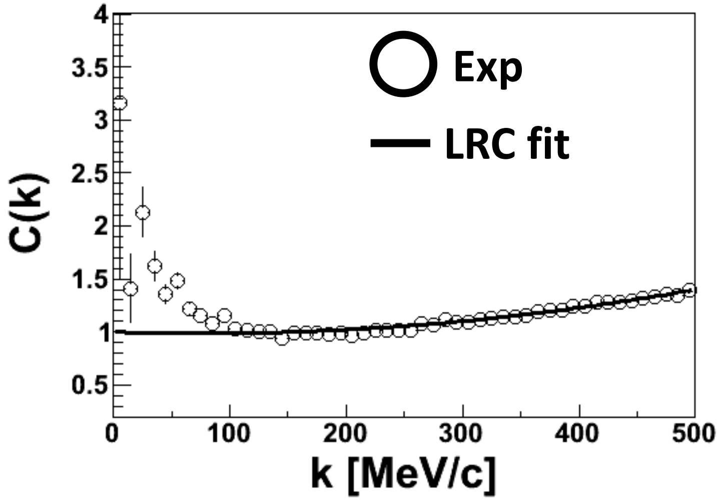


combo2



PRELIMINARY

combo3



Model the long-range part with a polynomial

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

Interaction

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

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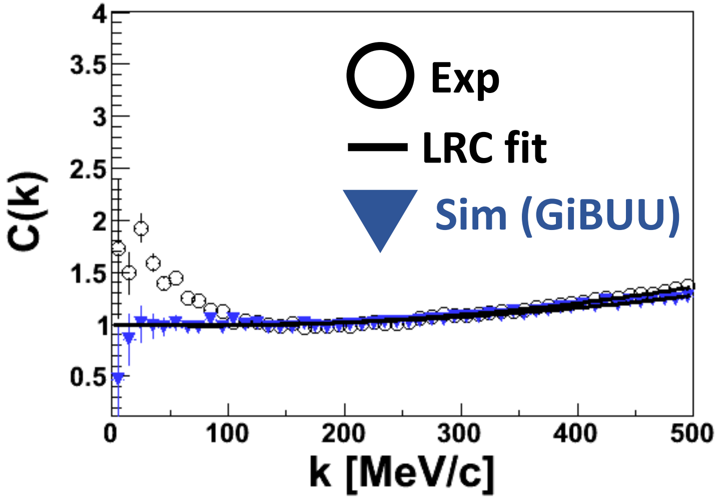
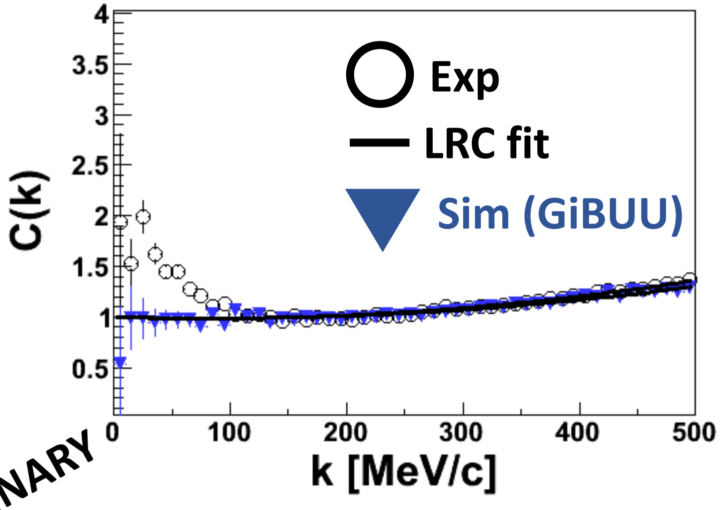
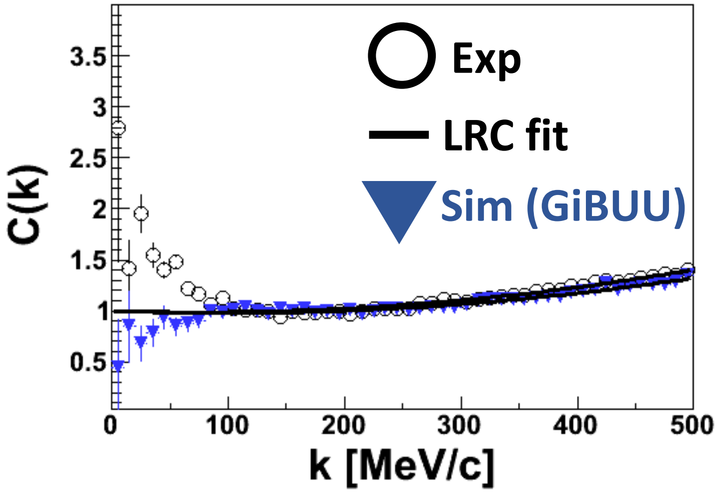


combo2



PRELIMINARY

combo3



Model the long-range part with a polynomial

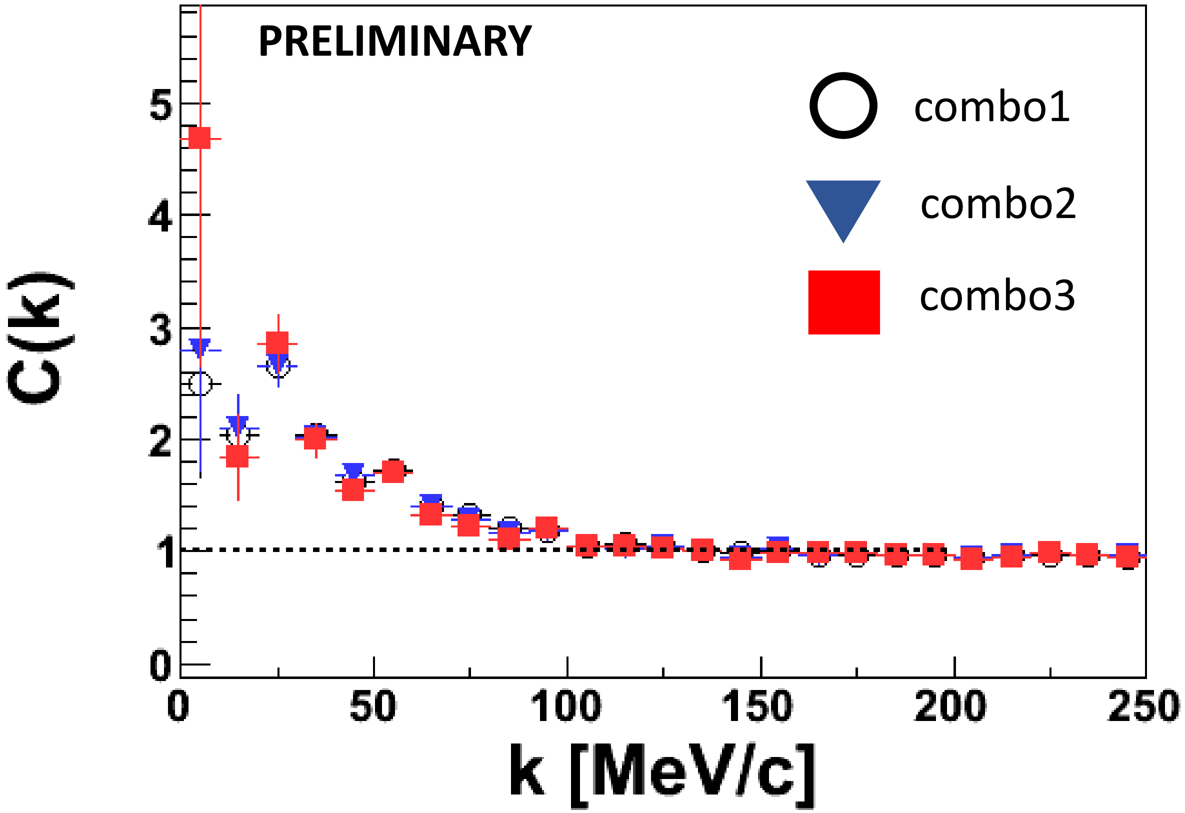
$$C_{\mathrm{LRC}} = 1 + ak + bk^2 \quad k \in [250, 600]\ \mathrm{MeV/c}$$

➡ 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



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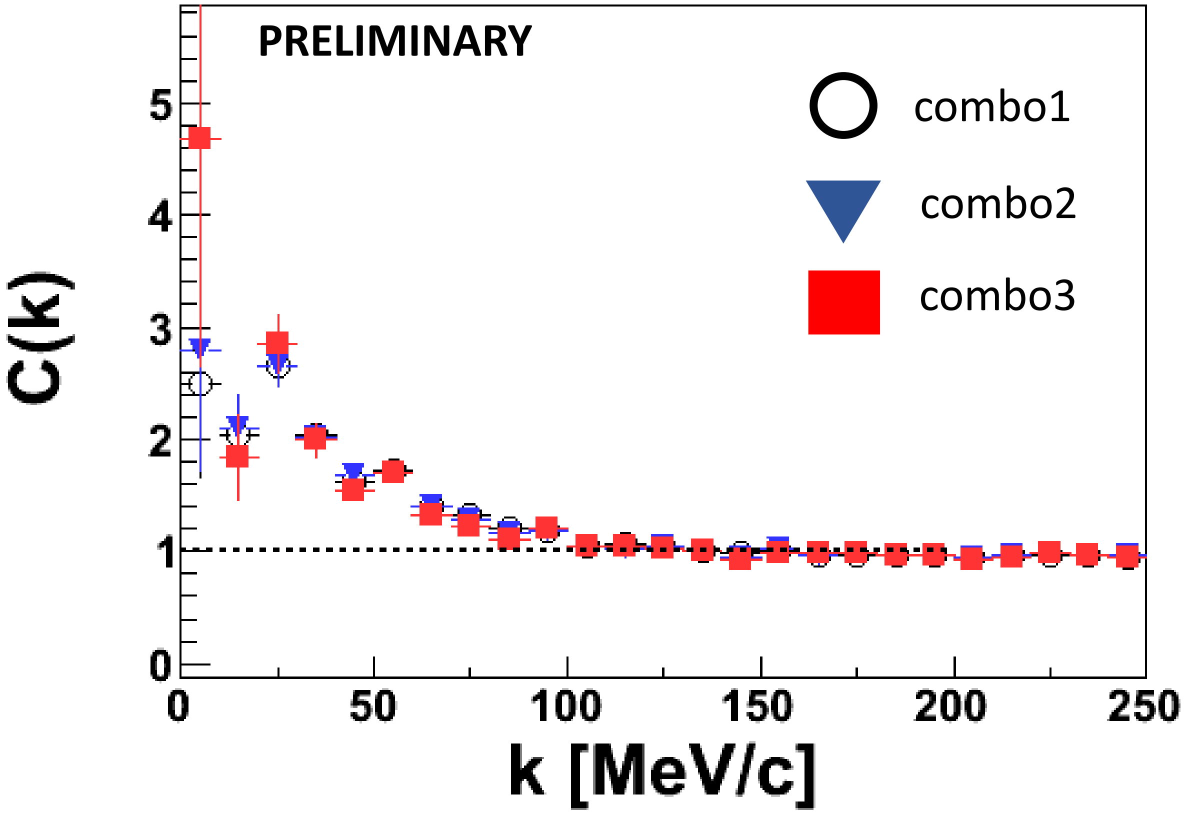

R. Lednicky, V.L. Lyuboshitz, Sov. J. Nucl. Phys., **35**, 770 (1982)

Use Lednicky's model to extract interaction parameters. It is based on:

$$f(\mathbf{k} \to \mathbf{k}') = \left(a^{-1} + \frac{1}{2} r k^2 - ik\right)^{-1} \quad R_G^{\Lambda p}$$

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Apply corrections – investigate systematics:

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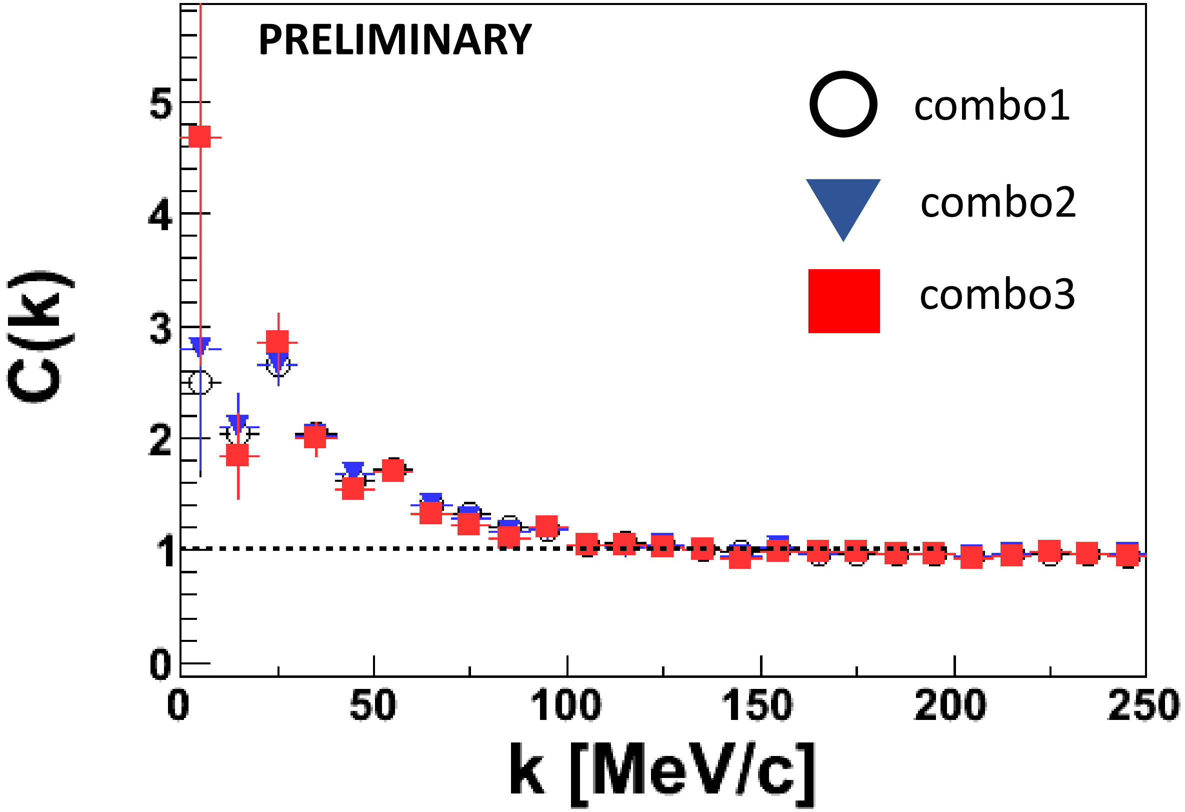

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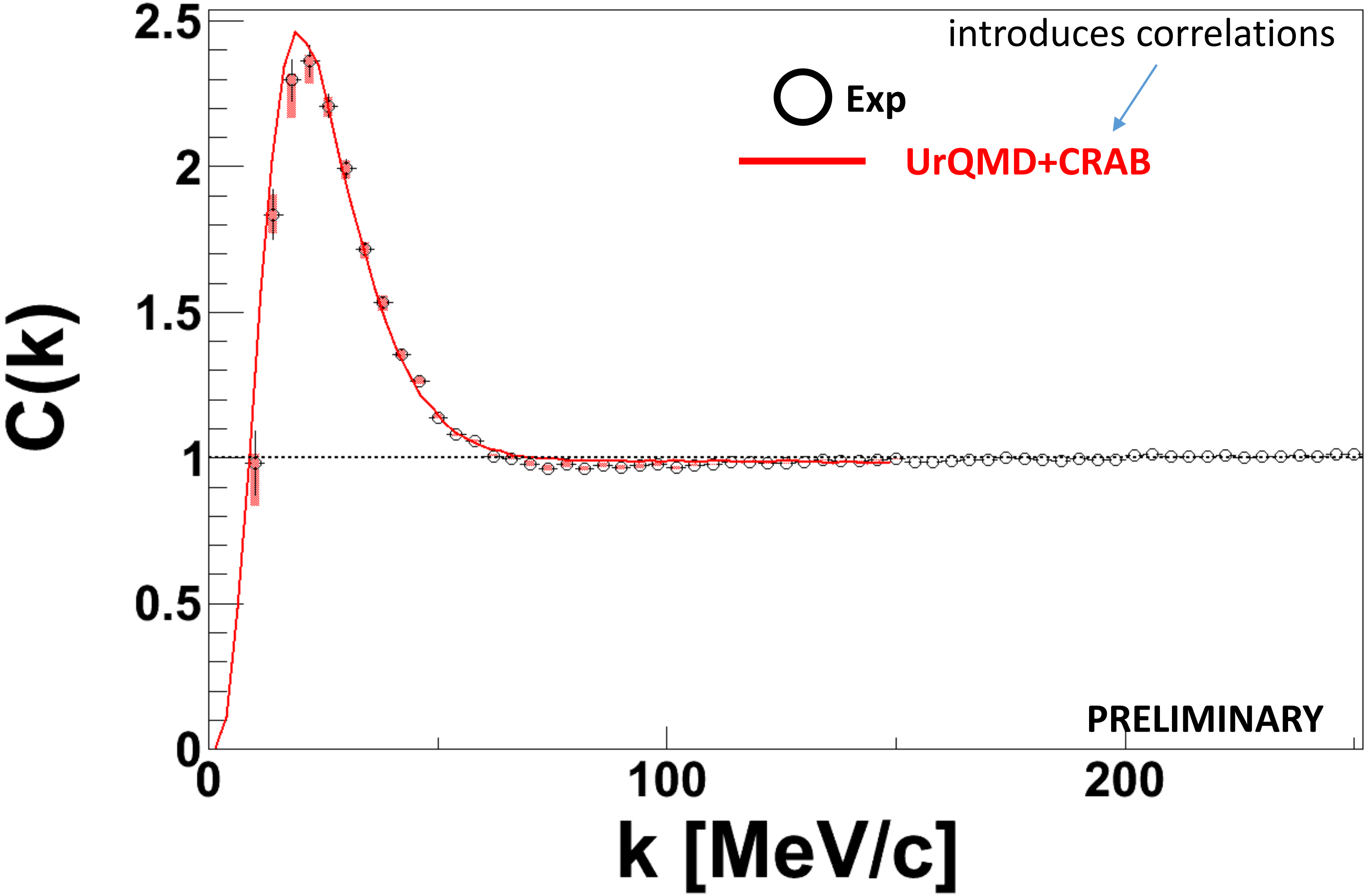
Interaction

Proton-proton correlation function comparison to transport theory:



Analysis – The Source

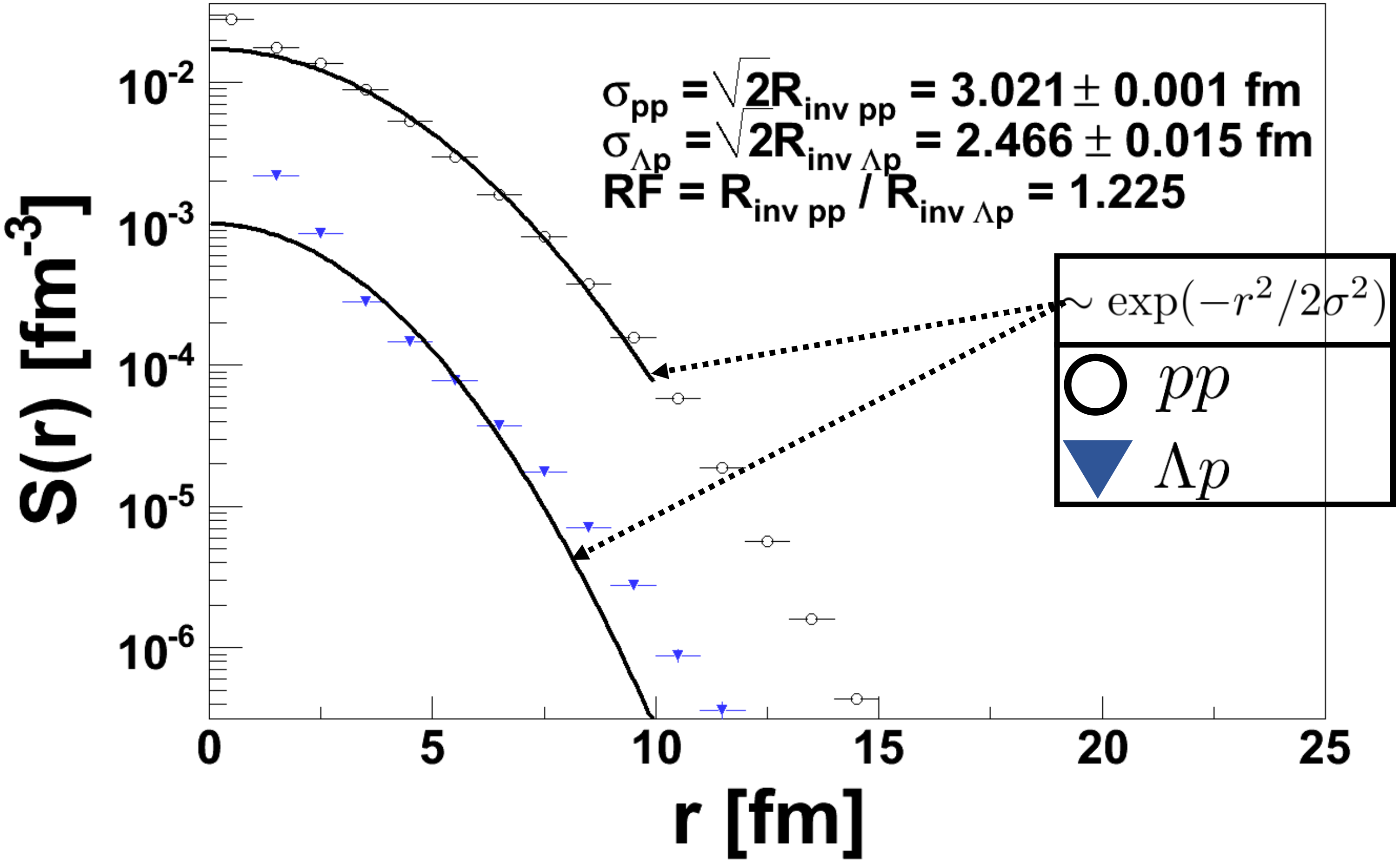
Source comparison from transport theory

Source function derived from UrQMD model:

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

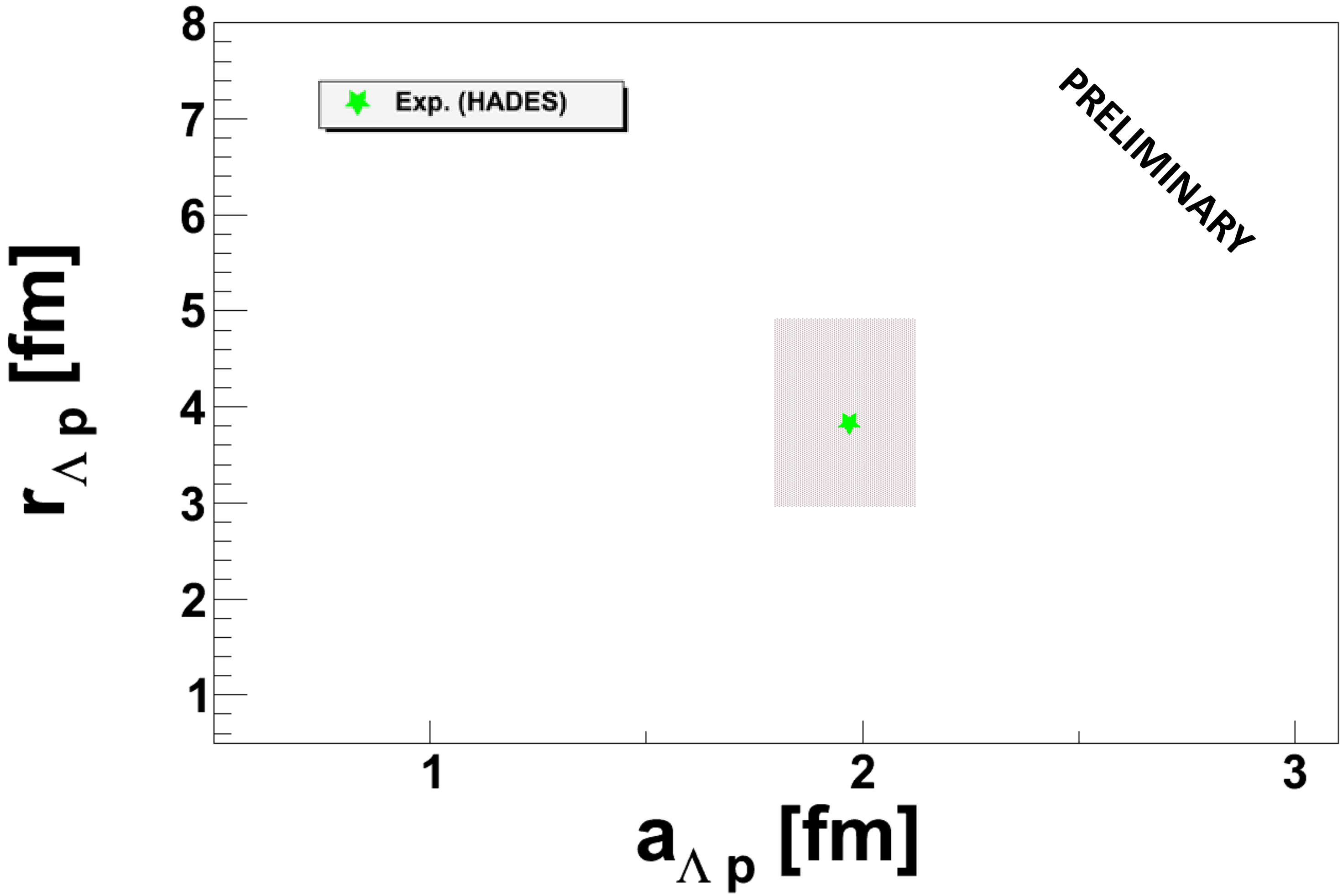
$$4\pi \int drr^2 S(r) = 1$$

$k < 100$ MeV/c



Interaction

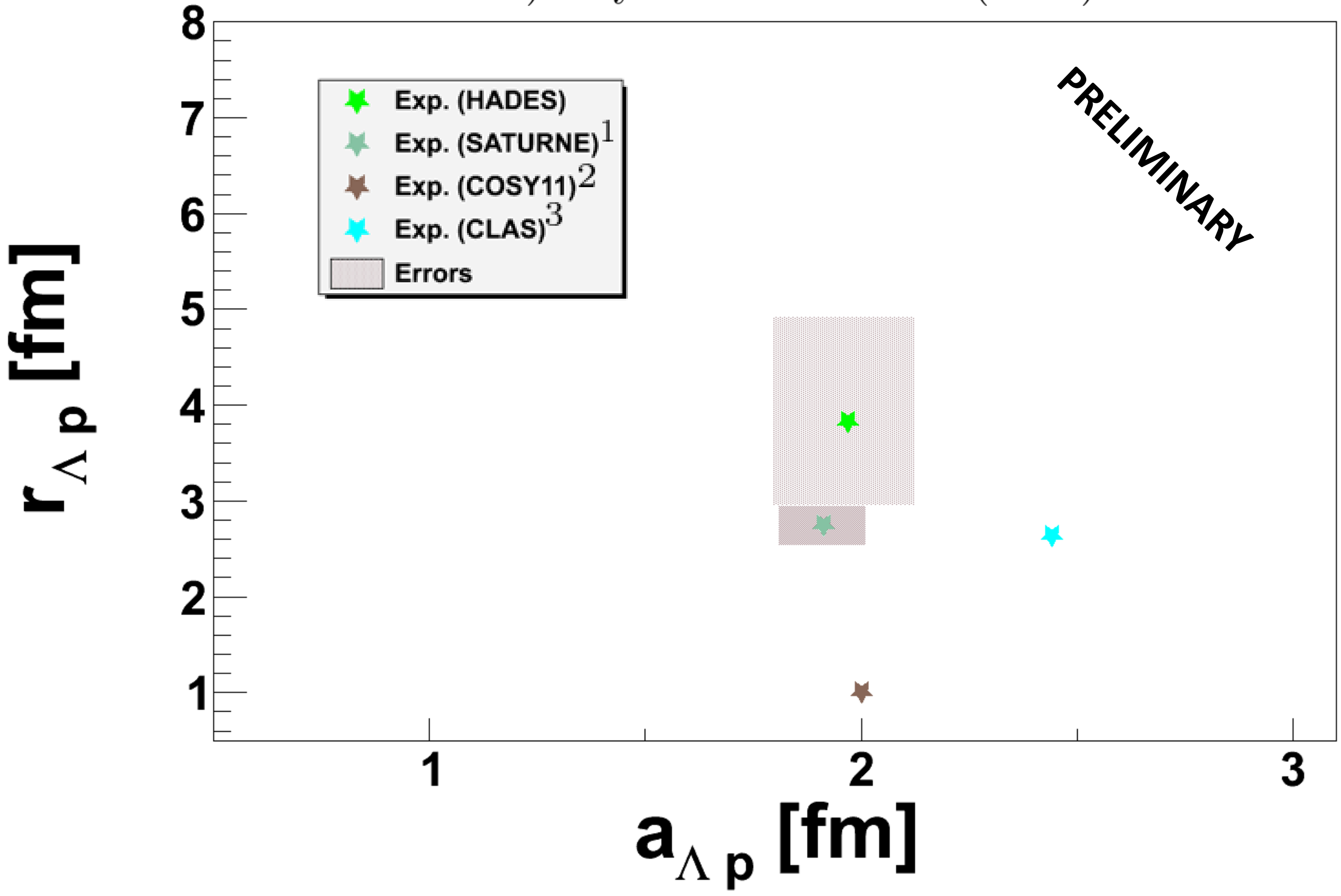
Comparison to other measurements and to models:



Interaction

Comparison to other measurements and to models:

1) Eur.Phys.J. A21 (2004) 313 – 321
2) Eur.Phys.J. A2 (1998) 99 – 104
3) Phys.Atom.Nucl. 72 (2009) 668 – 674



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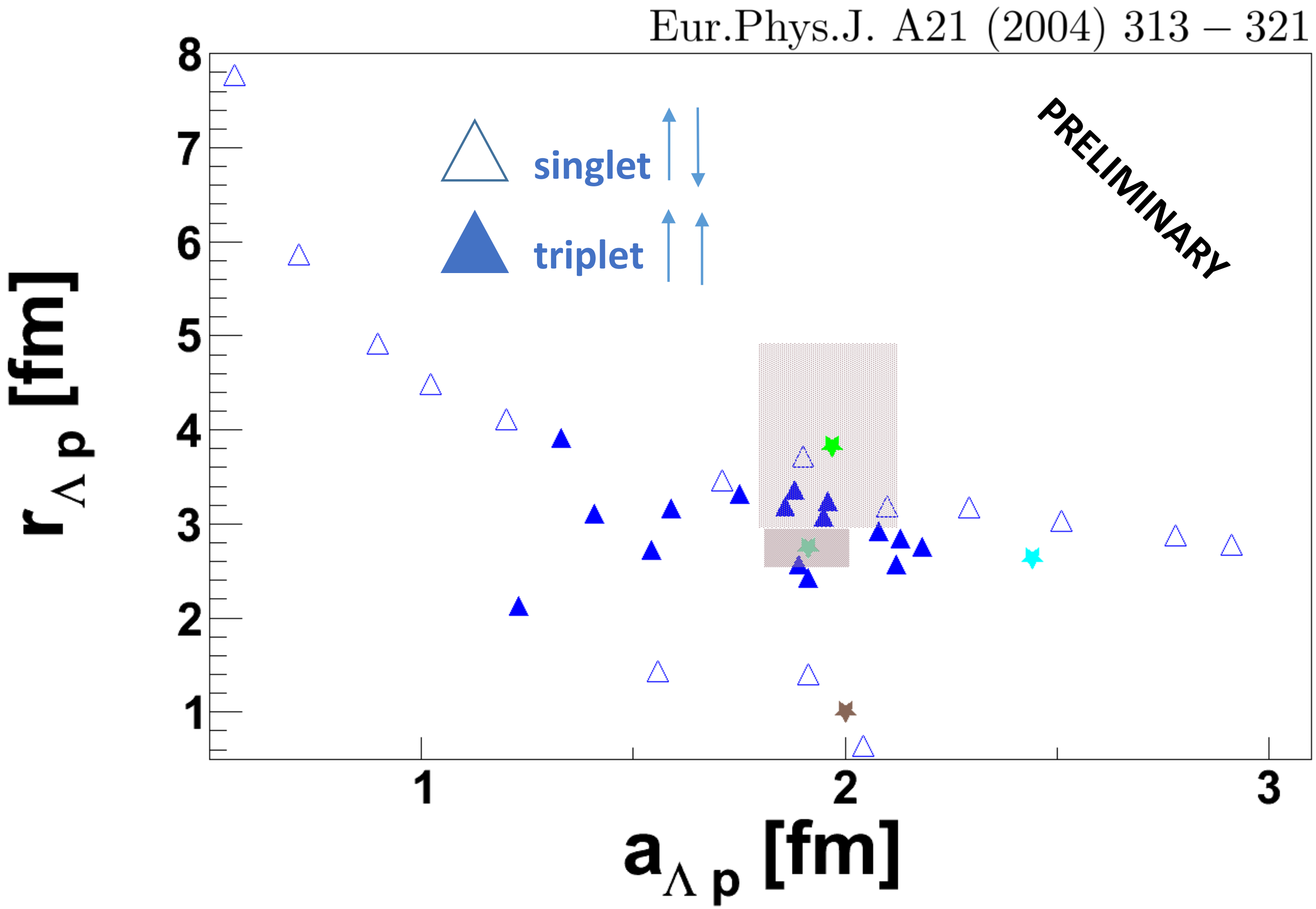

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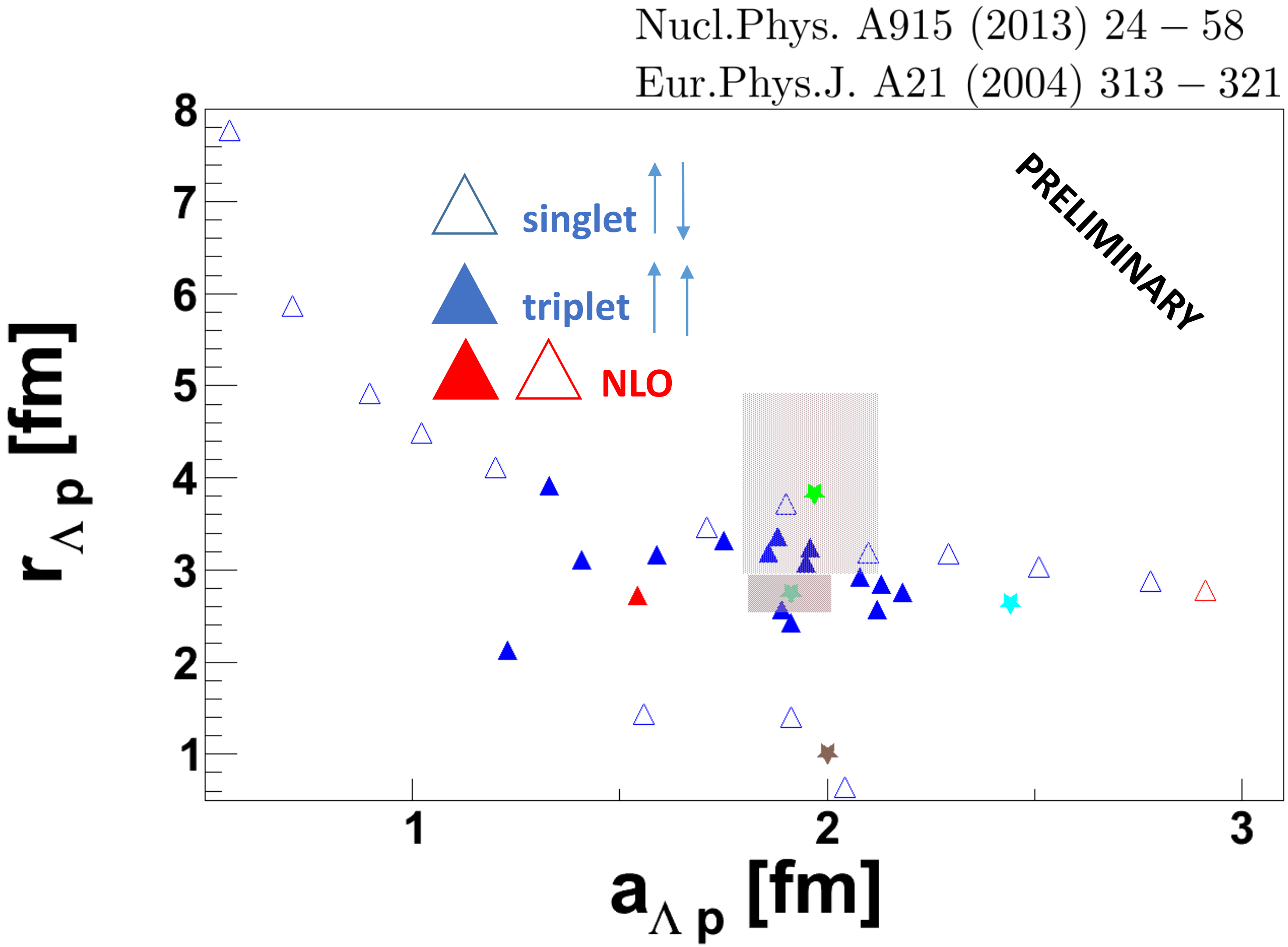
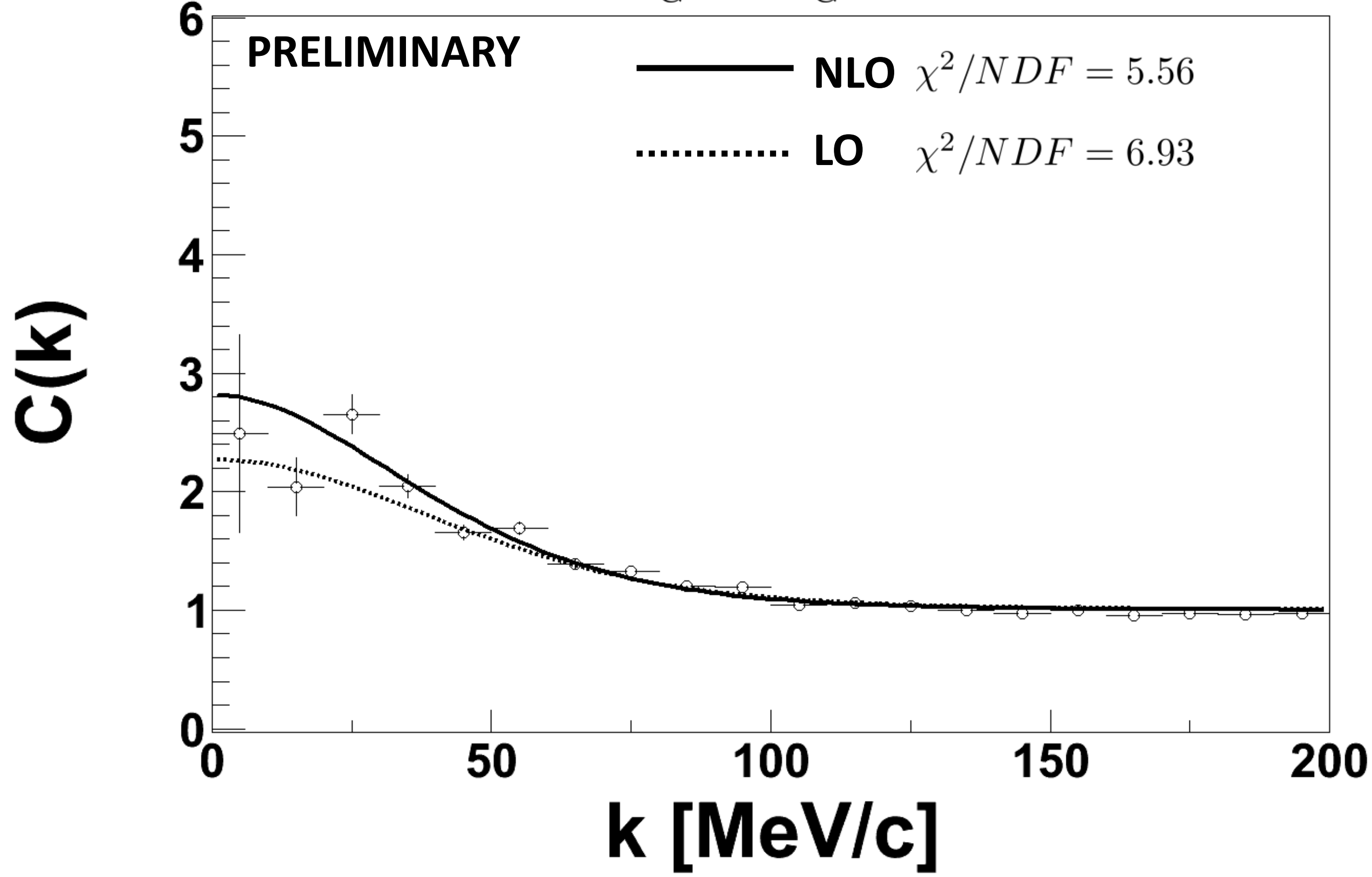


Interaction

Comparison to other measurements and to models:

Nucl.Phys. A915 (2013) 24 – 58

$R_G^{\Lambda p} = R_G^{pp}/RF = 2.016/1.225$ fm



Summary

Summary

- Correlation function for protons calculated and source size for proton pairs extracted
- The source size of protons used as input to extract an effective scattering length for Lambda-proton pairs

Extracted values:

$$R_G^{pp} = 2.016^{+0.04}_{-0.029} \text{ fm}$$

$$a^{\Lambda p} = 1.967^{+0.157}_{-0.169} \text{ fm}$$

$$r^{\Lambda p} = 3.824^{+1.096}_{-0.872} \text{ fm}$$

Thank you

Thank you for your attention

The HADES collaboration

Backup

BACKUP

Correlation Function

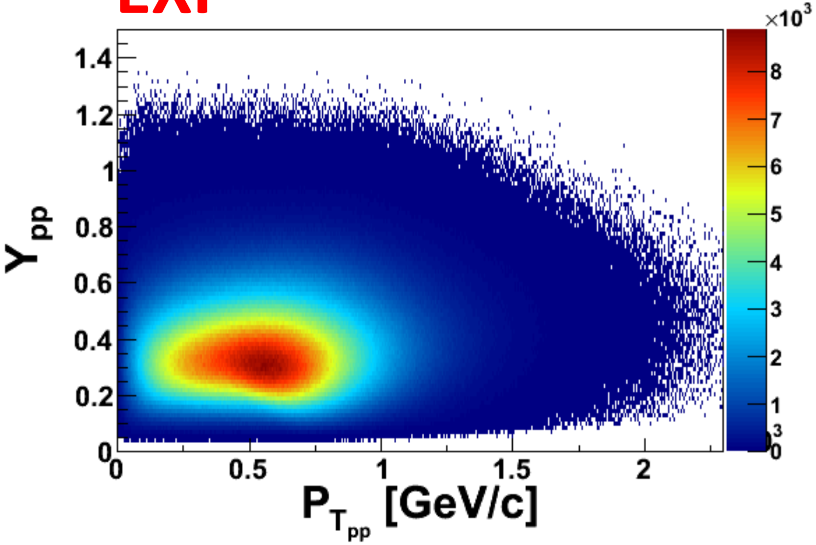
Results from pNb femtoscopy – Correlation function (angle integrated):

Can we model them (LRC)?

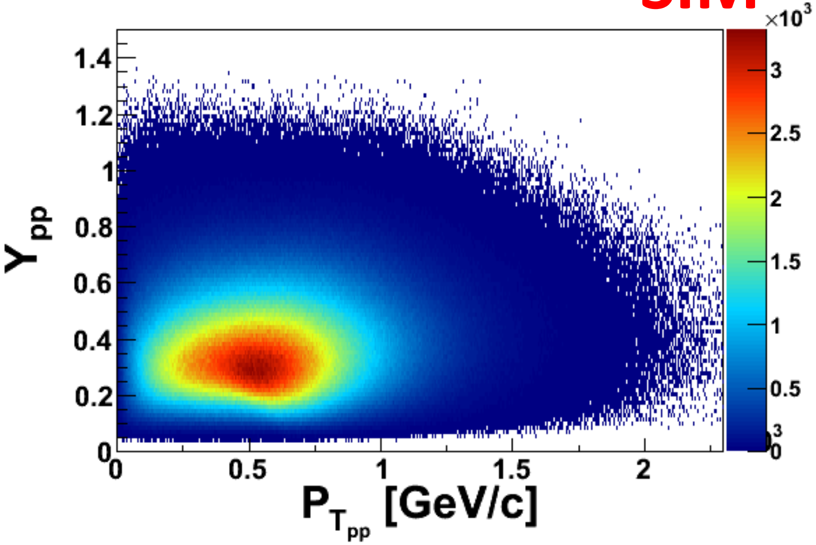
*Use **UrQMD** transport simulations (no HBT effects):*

2D kinematic distributions **in the HADES acceptance**

EXP



SIM



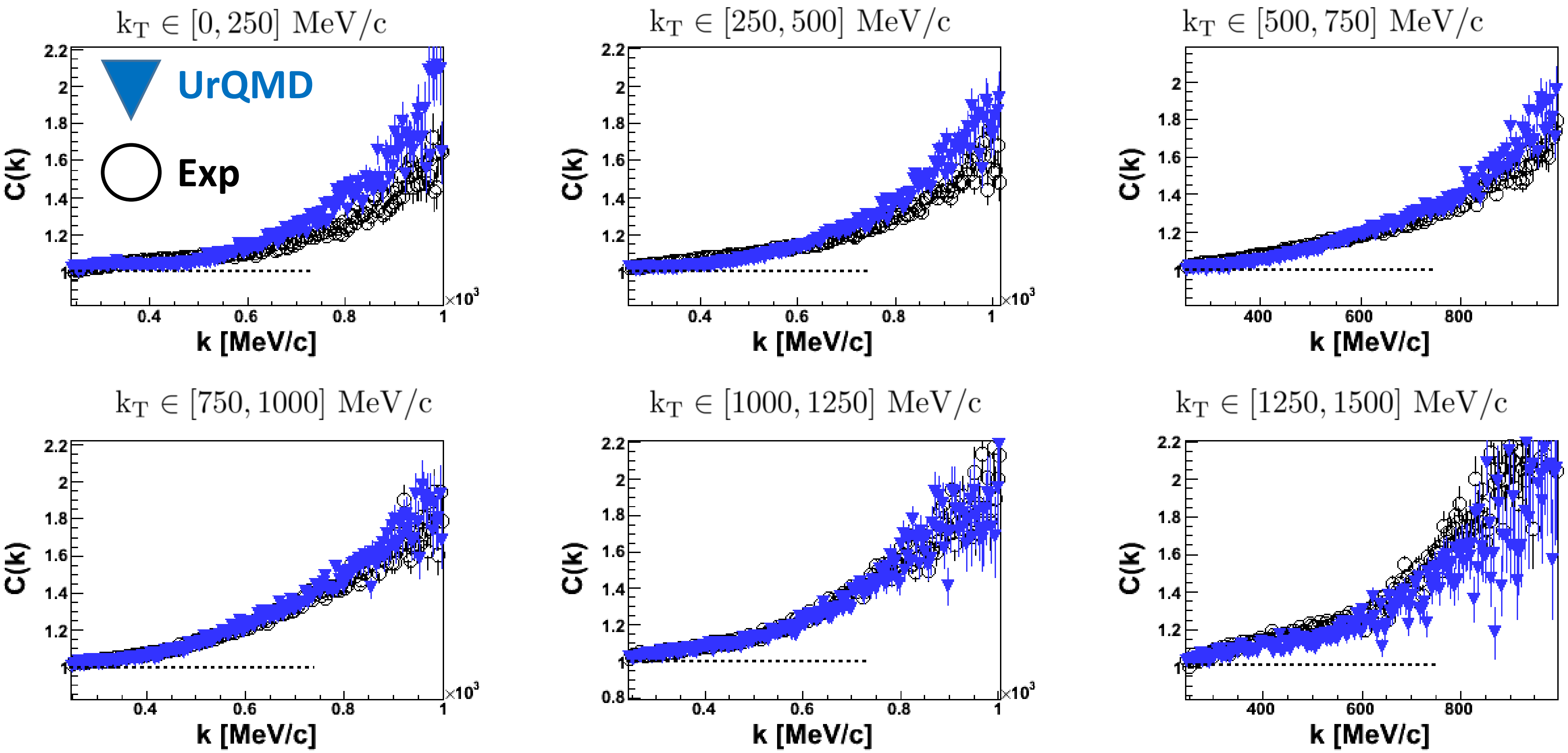
The shape of the simulated Phase-space (right) looks very similar

Backup

Results from pNb femtoscopy – Correlation function (angle integrated):

Can we model them (LRC)?

Baseline: as a function of pair transverse momentum $\mathrm{k_T} = |\mathbf{p}_{1\mathrm{T}} + \mathbf{p}_{2\mathrm{T}}|$

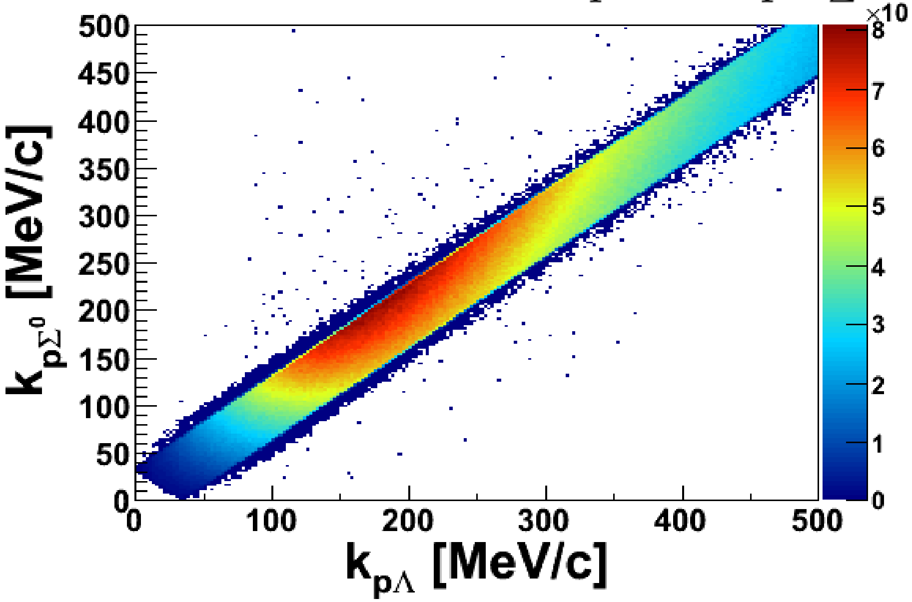


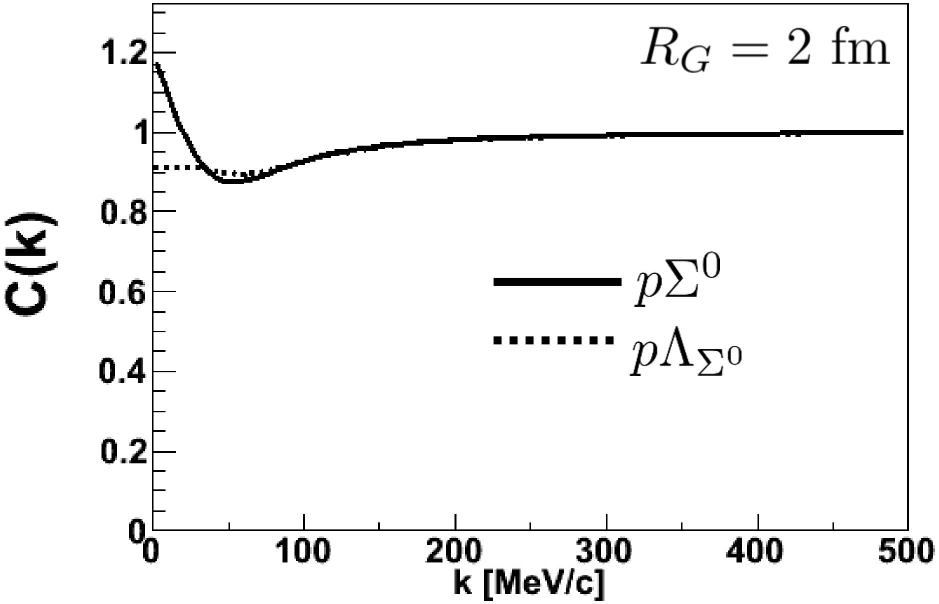
Backup

Influence of the purity on the correlation function:

Residual correlations from $p\Sigma^0$ (based on Stavinsky *et al. – arXiv:0704.3290v1 [nucl-th]*)

Transformation matrix $p\Sigma^0 \rightarrow p\Lambda_{\Sigma^0}$



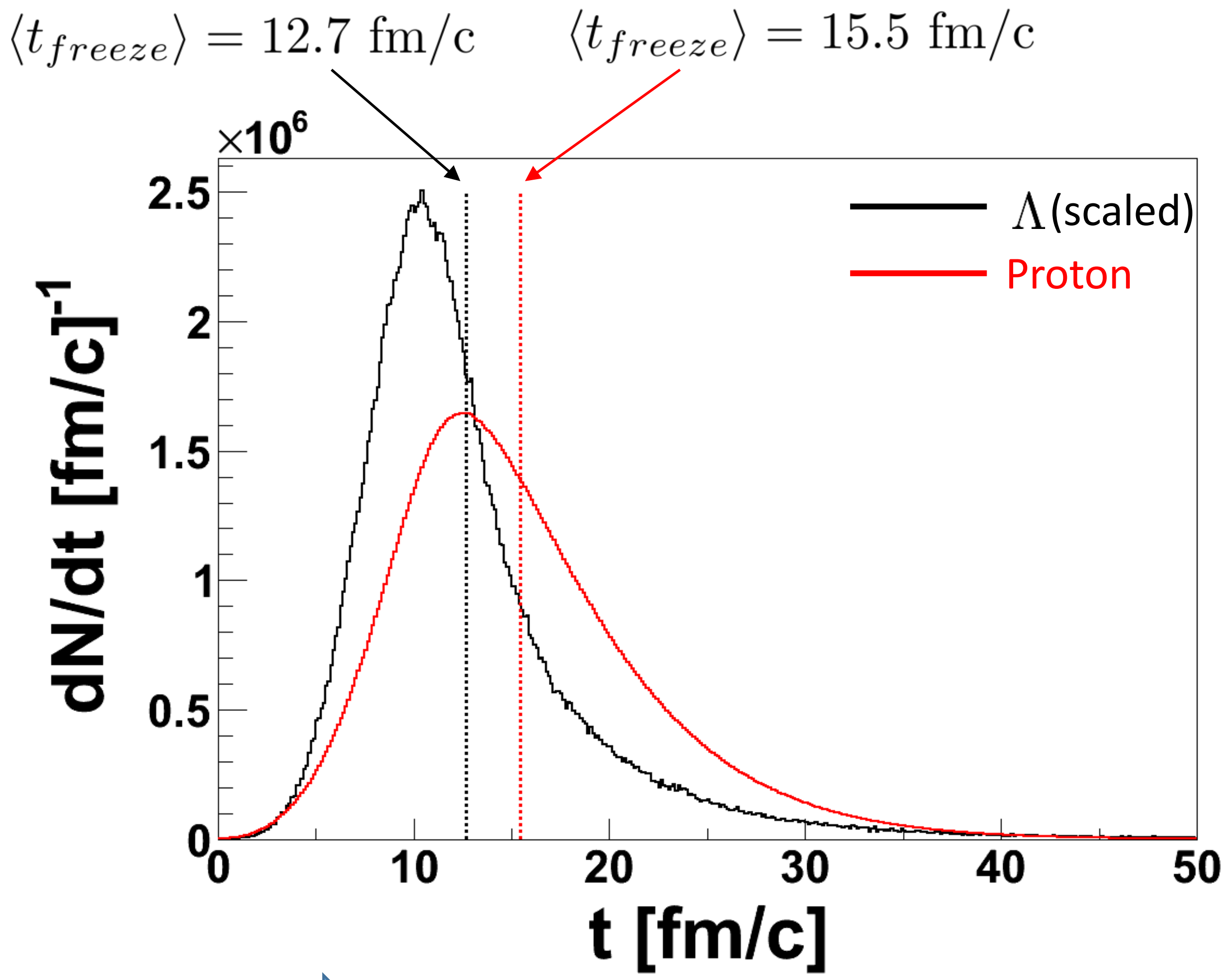


$$C^{p\Sigma^0 \rightarrow p\Lambda_{\Sigma^0}}(k) = \frac{\int dk_{p\Sigma^0} C^{p\Sigma^0}(k_{p\Sigma^0}) W(k_{p\Sigma^0}, k)}{\int dk_{p\Sigma^0} W(k_{p\Sigma^0}, k)}$$

→ Residual correlations from $p\Sigma^0$ are very small

Interaction

Source extraction from transport theory (UrQMD):



$\langle t_{freeze} \rangle = 12.7 \text{ fm/c}$

$\langle t_{freeze} \rangle = 15.5 \text{ fm/c}$

→ $\Lambda ' s$ leave the system earlier

Correlation Function

Information about the source – proton proton correlation function:

Proton-proton correlation function **corrected** for all efficiencies: