Marrying Femtoscopy and Coalescence

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Mini Workshop on the origin of nuclear clusters in hadronic collisions
19.05.2020

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ALICE Experiment 202
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excellence

SFB 1258 Neutrinos
Dark Matter
Messengers

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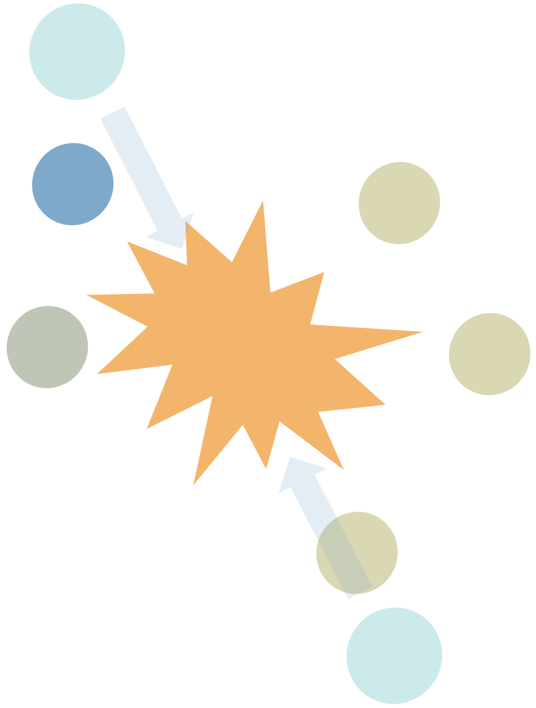
Part I: Femtoscopy

Two particle correlation function

- Study of correlations in the relative momentum k^*distribution of particle pairs



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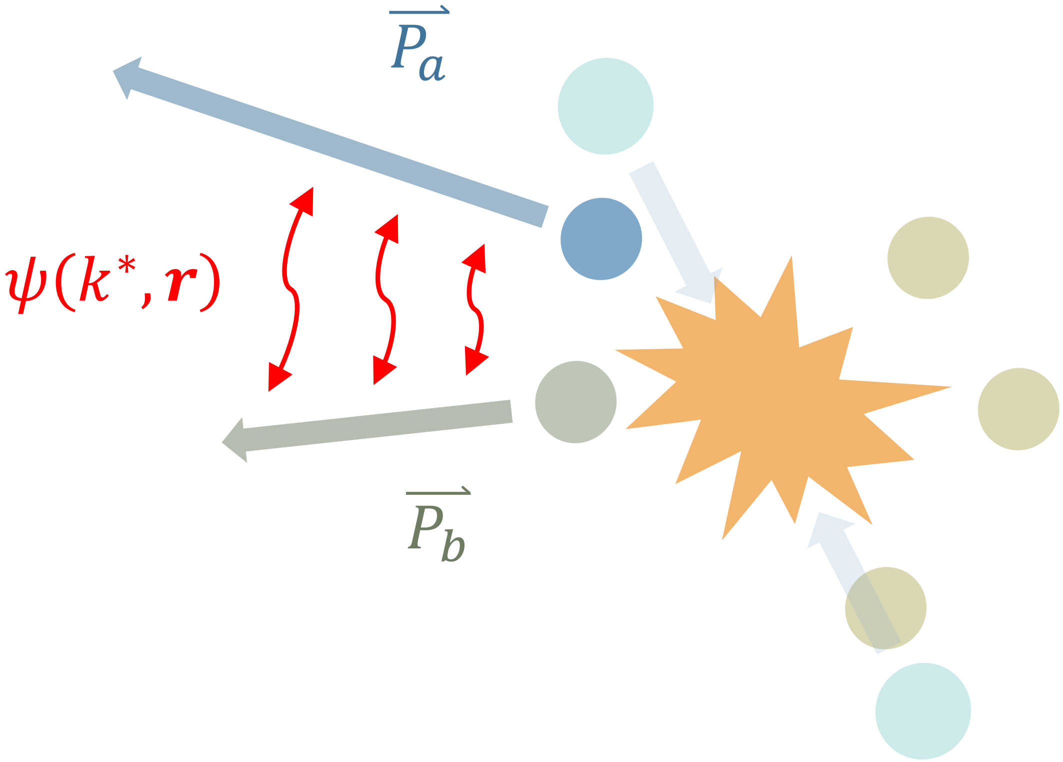
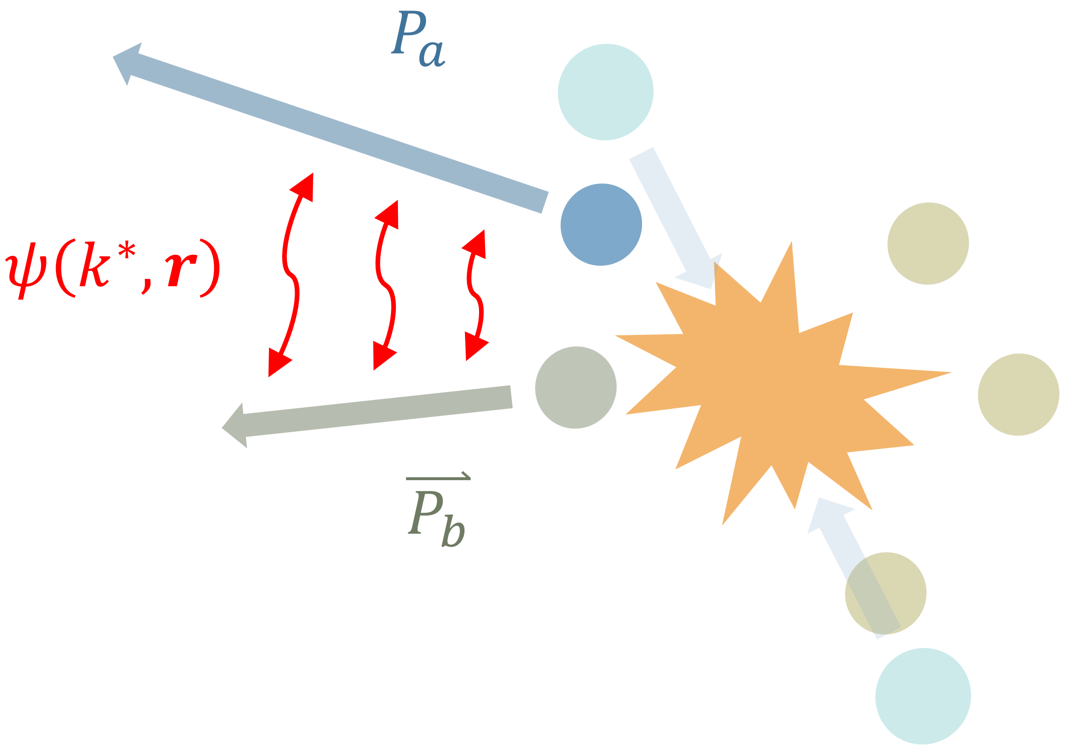


Two particle correlation function

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

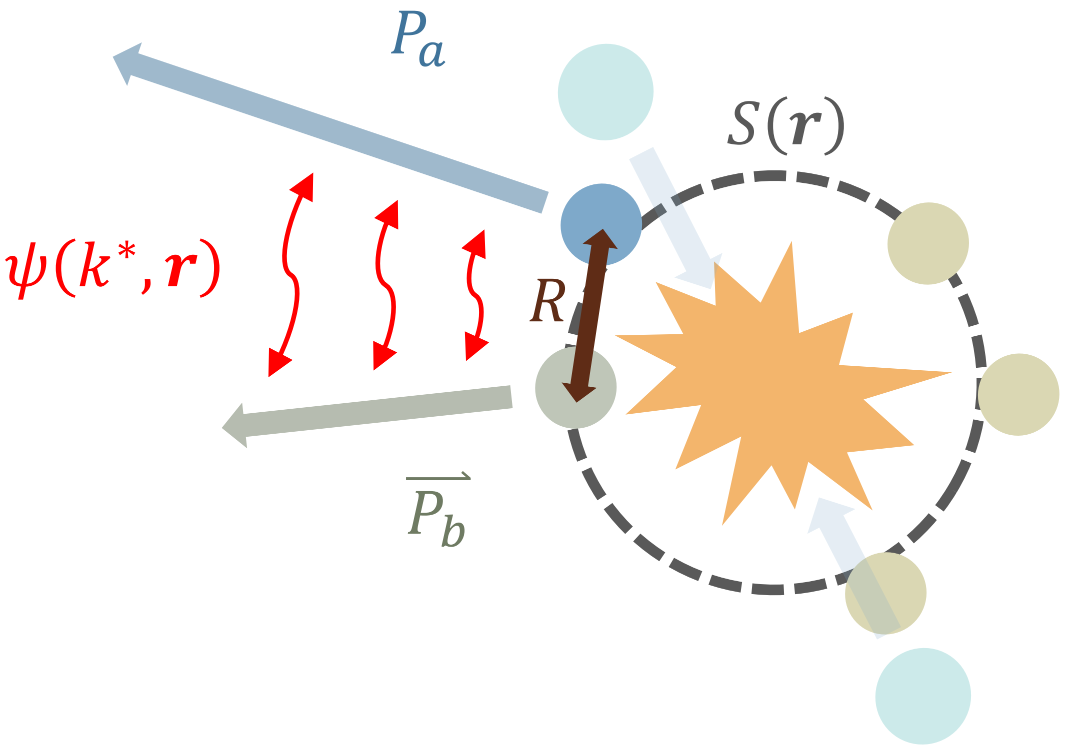
- Study of correlations in the relative momentum k^*distribution of particle pairs
  - Attractive interaction → $C(k^*) > 1$
  - Repulsive interaction → $C(k^*) < 1$



$$C(k^*) = \frac{\mathcal{P}(\vec{p}_a,\vec{p}_b)}{\mathcal{P}(\vec{p}_a)\mathcal{P}(\vec{p}_b)} = \mathcal{N}\frac{N_{same}(k^*)}{N_{mixed}(k^*)}$$

Two particle correlation function

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



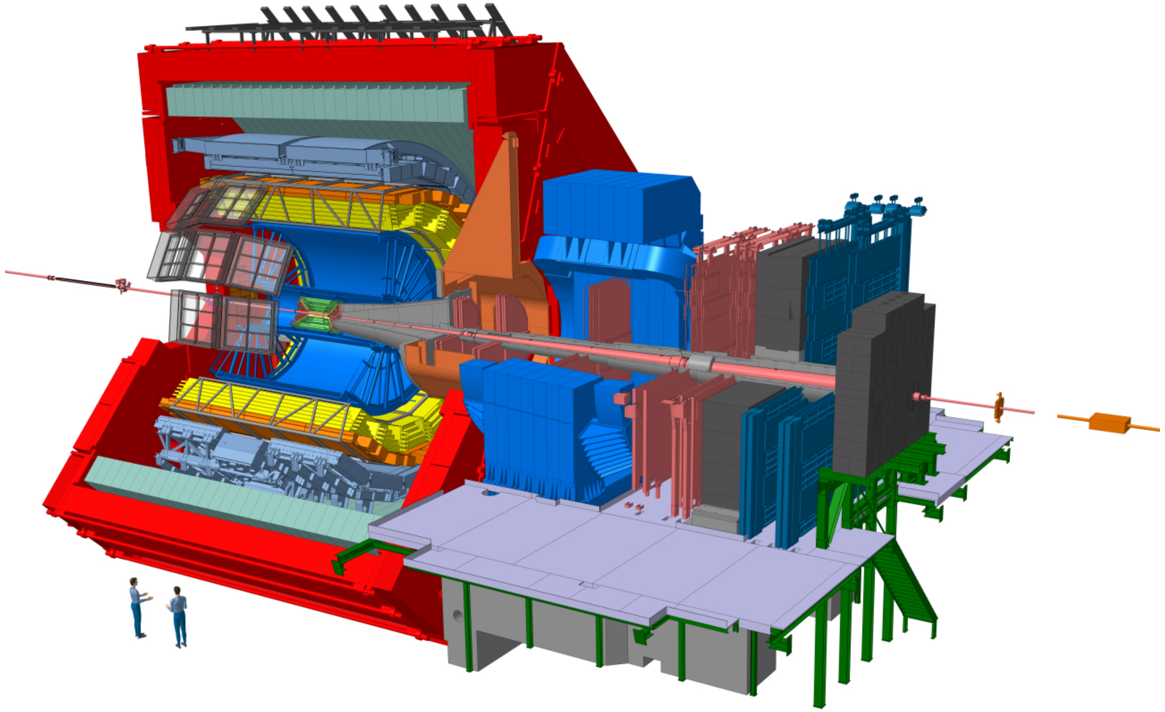
- Study of correlations in the relative momentum k^*distribution of particle pairs
- Linked to the **source** and two-particle wave function
  - Source typically assumed to be Gaussian:

$$S(r) = \frac{2\sqrt{\pi}r^2}{r_0^3}\exp\left(-\frac{r^2}{4r_0^2}\right)$$

$$C(k^*) = \frac{\mathcal{P}(\vec{p}_a, \vec{p}_b)}{\mathcal{P}(\vec{p}_a)\mathcal{P}(\vec{p}_b)} = \mathcal{N}\frac{N_{same}(k^*)}{N_{mixed}(k^*)} = \int S(\boldsymbol{r})|\psi(k^*, \boldsymbol{r})|^2 d^3r$$

The detector: ALICE

- Excellent tracking of charged particles (ITS & TPC) and particle identification
  - p, K and π via measurements of TPC dE/dx and TOF
  - Reconstruction of Hyperons
    - $\Lambda \rightarrow p\pi^{-}$
    - $\Xi^{-} \rightarrow \Lambda\pi^{-}$
    - $\Omega^{-} \rightarrow \Lambda K^{-}$
- Measurement of the p-p and p-Λ correlation function



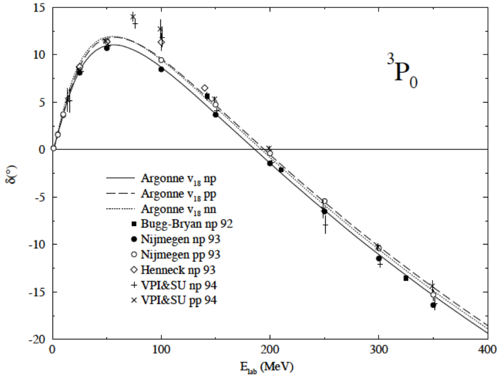
System	# Events
pp 7 TeV	3.4 x 10^{8} minimum bias
pp 13 TeV	15 x 10^{8} minimum bias
	10 x 10^{8} high multiplicity (0-0.17% INEL > 0)
p-Pb 5.02 TeV	6.0 x 10^{8} minimum bias

Computing the correlation function

$$C(k^*) = \int S(\boldsymbol{r})|\psi(k^*,\boldsymbol{r})|d^3r$$

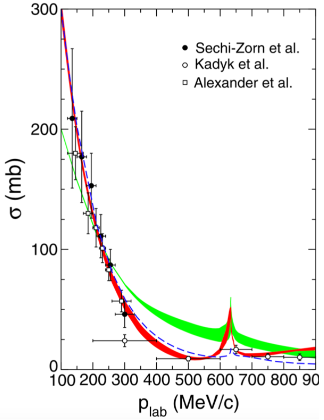
- Evaluation of $C(k^*)$ within the **CATS framework**
  10.1140/epjc/s10052-018-5859-0
- **Numerically** solving the single channel Schrödinger equation
  - Pairs of p-p: Quantum statistics, Coulomb and Strong (Argonne ν_{18}) interaction
  - Pairs of p-Λ: Strong (χ EFT LO & NLO) interaction

N–N → N–N



R. B. Wiringa, V. G. J. Stoks, R. Schiavilla, PRC 51 (1995) 38-51.

p–Λ → p–Λ



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

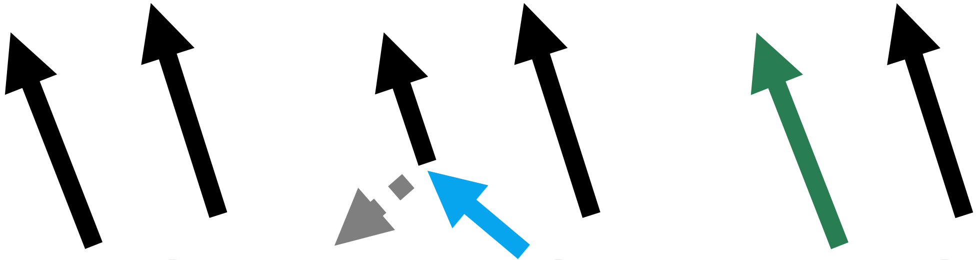
$$\Downarrow$$

$$\hat{\mathcal{H}} \cdot \psi(k^*,\boldsymbol{r}) = \mathrm{E} \cdot \psi(k^*,\boldsymbol{r})$$

$$\Downarrow$$

$$\psi(k^*,\boldsymbol{r})$$

Residual and non-femtoscopic 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

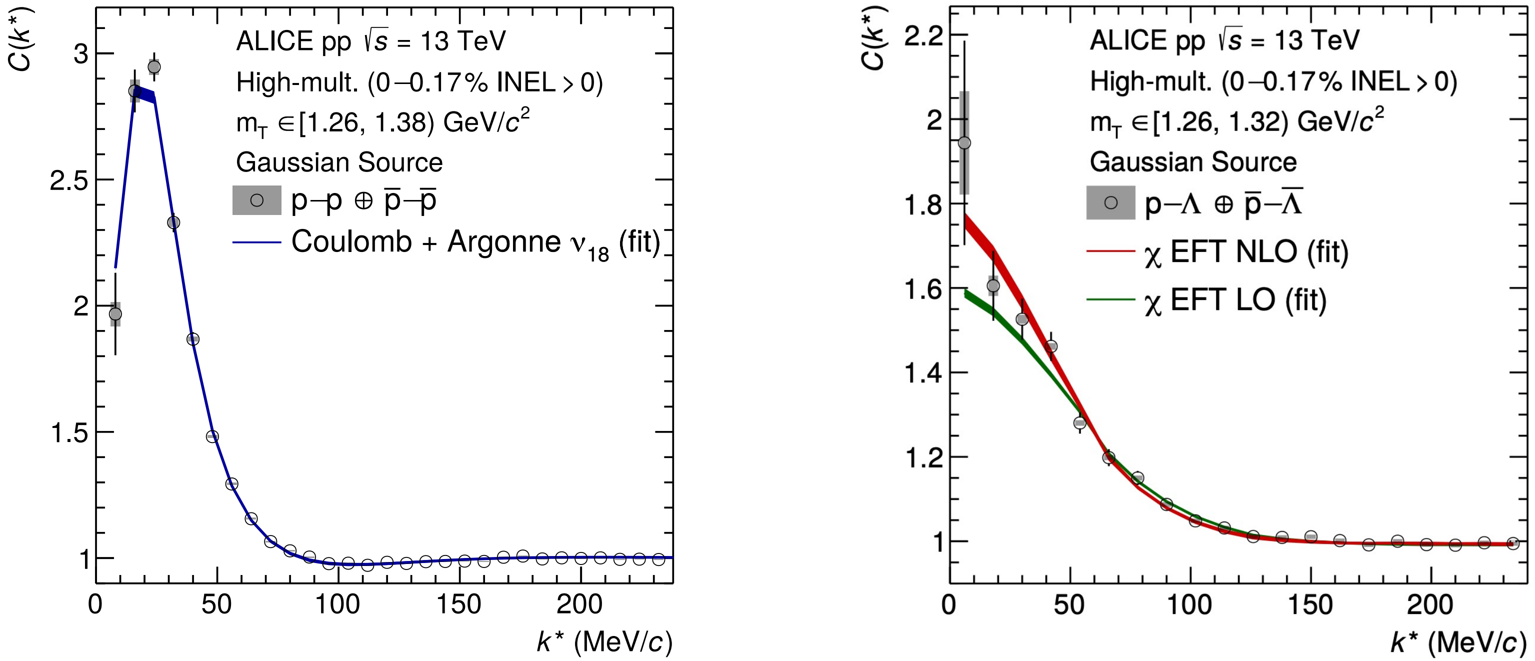
- Pair contributions quantified by purity ($\mathcal{P}_i$) and feed-down fractions (f_i)

$$\lambda_{ij} = \mathcal{P}_1 \cdot f_{i_1} \cdot \mathcal{P}_2 \cdot f_{j_2}$$

- Finite momentum resolution of the detector
- Non flat baseline

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

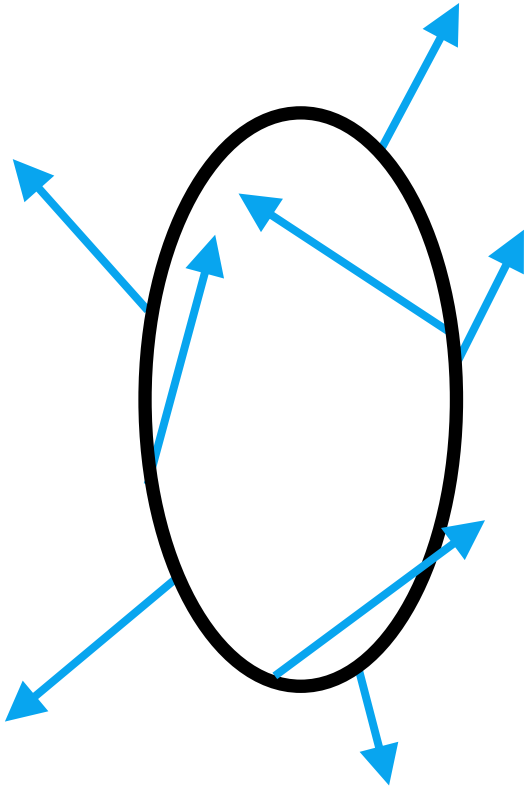
Fitting a gaussian source



- Is there a common scaling of the source size amongst particle pairs?
  - Compare results extracted from p-p and p-Λ correlations

https://arxiv.org/abs/2004.08018

Length of homogeneity



- Correlations for femtoscopic measurements appear for small relative momenta
- Example I: Random emission
  - E.g. Emission of particles from a thermal bath

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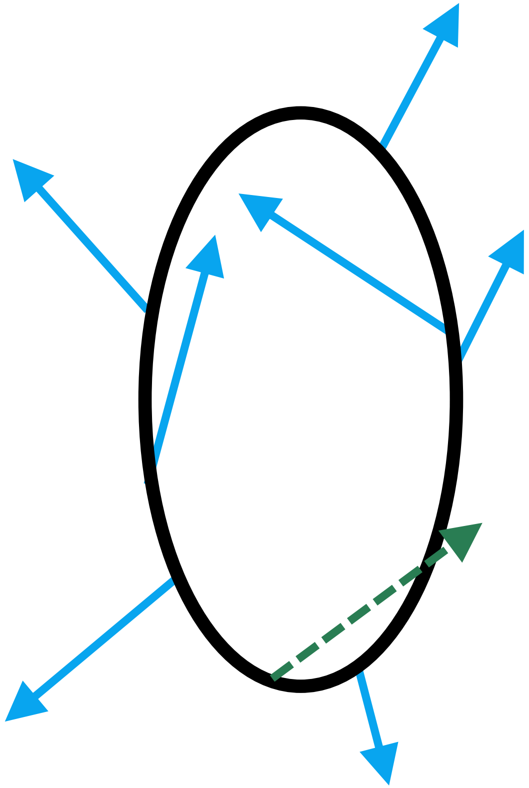

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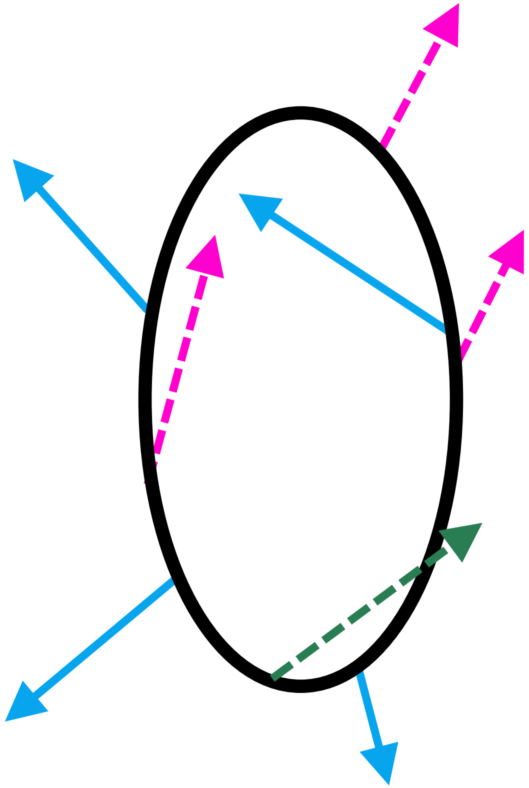

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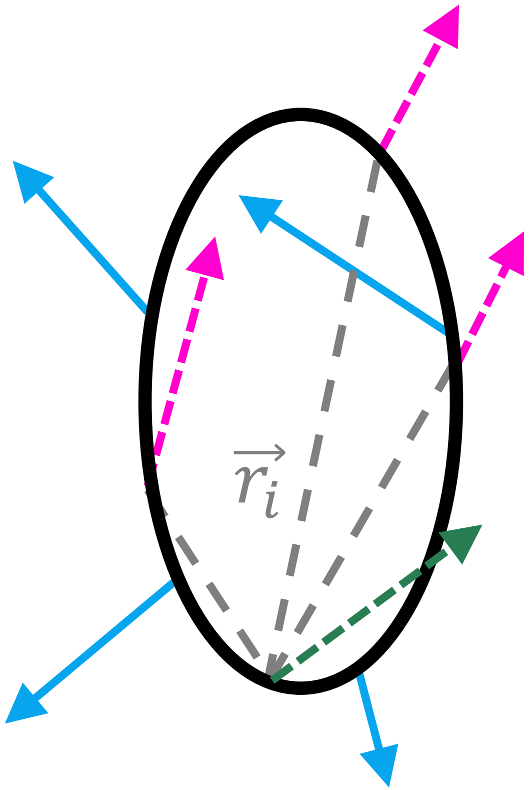

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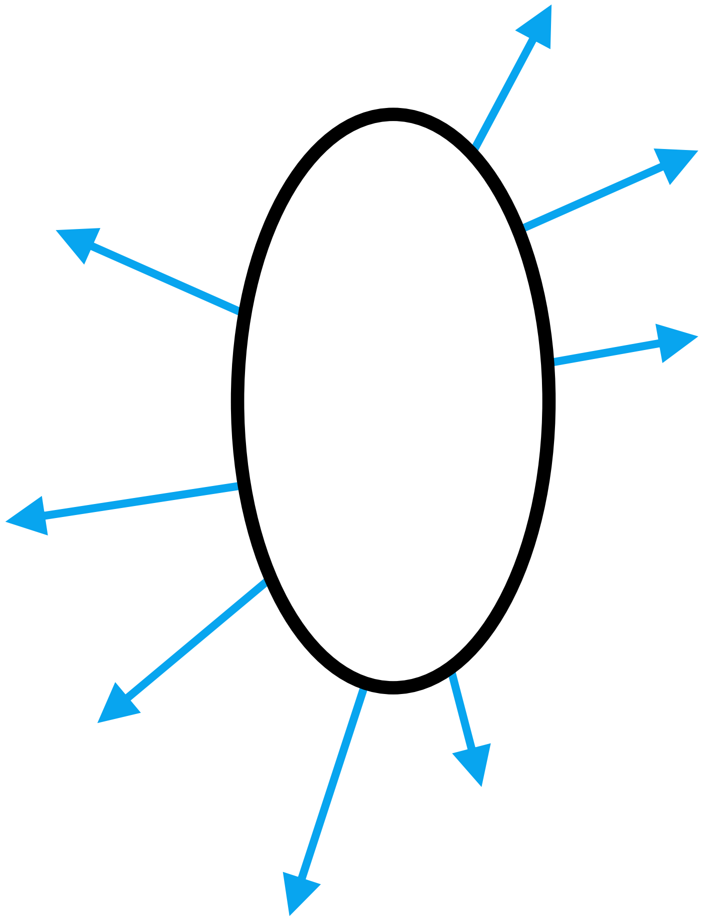

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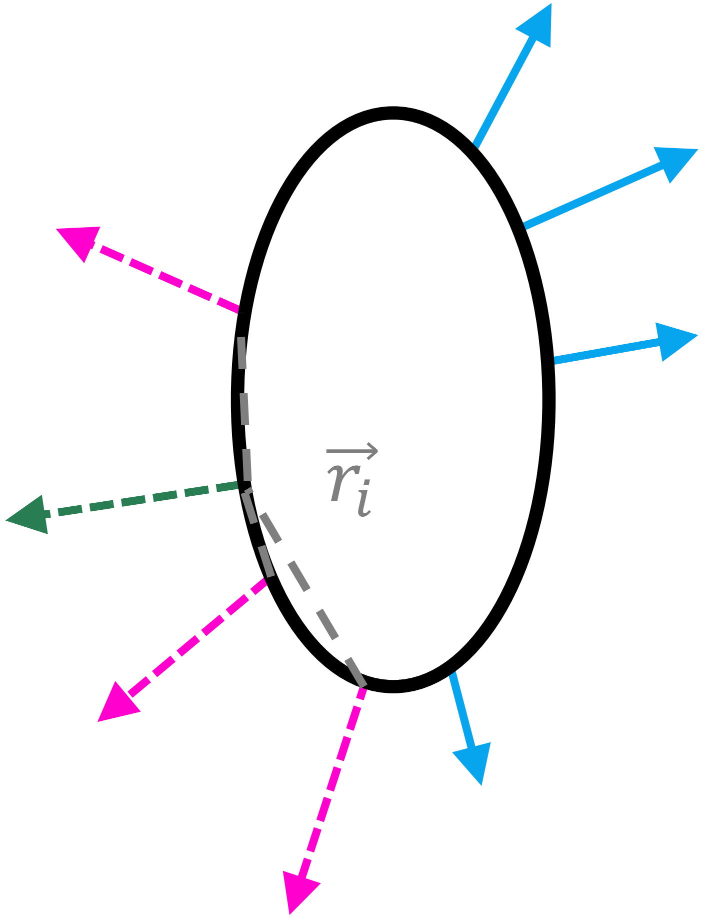
Length of homogeneity



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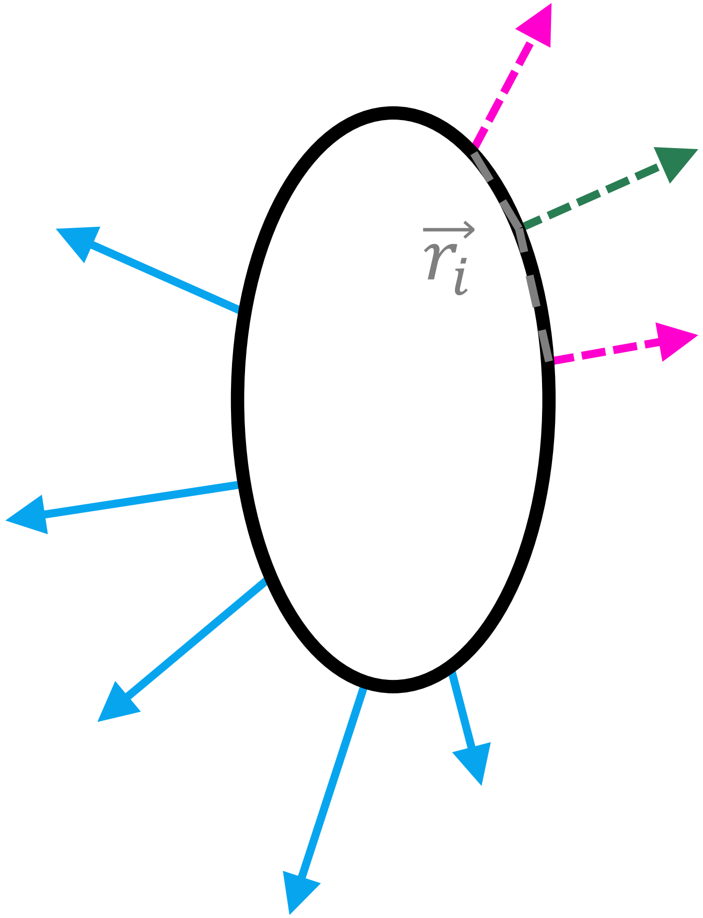

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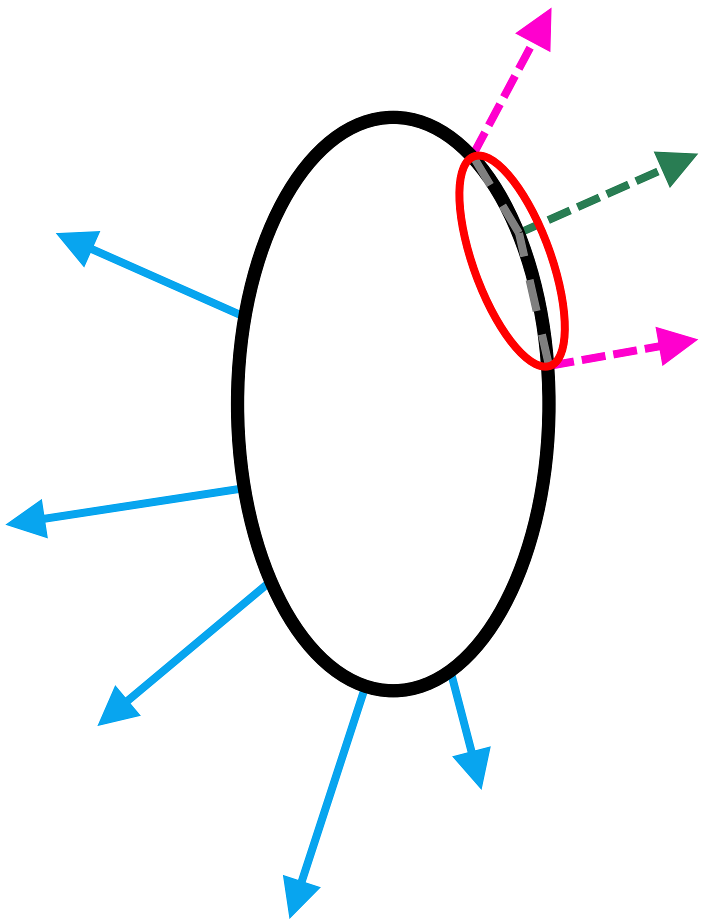
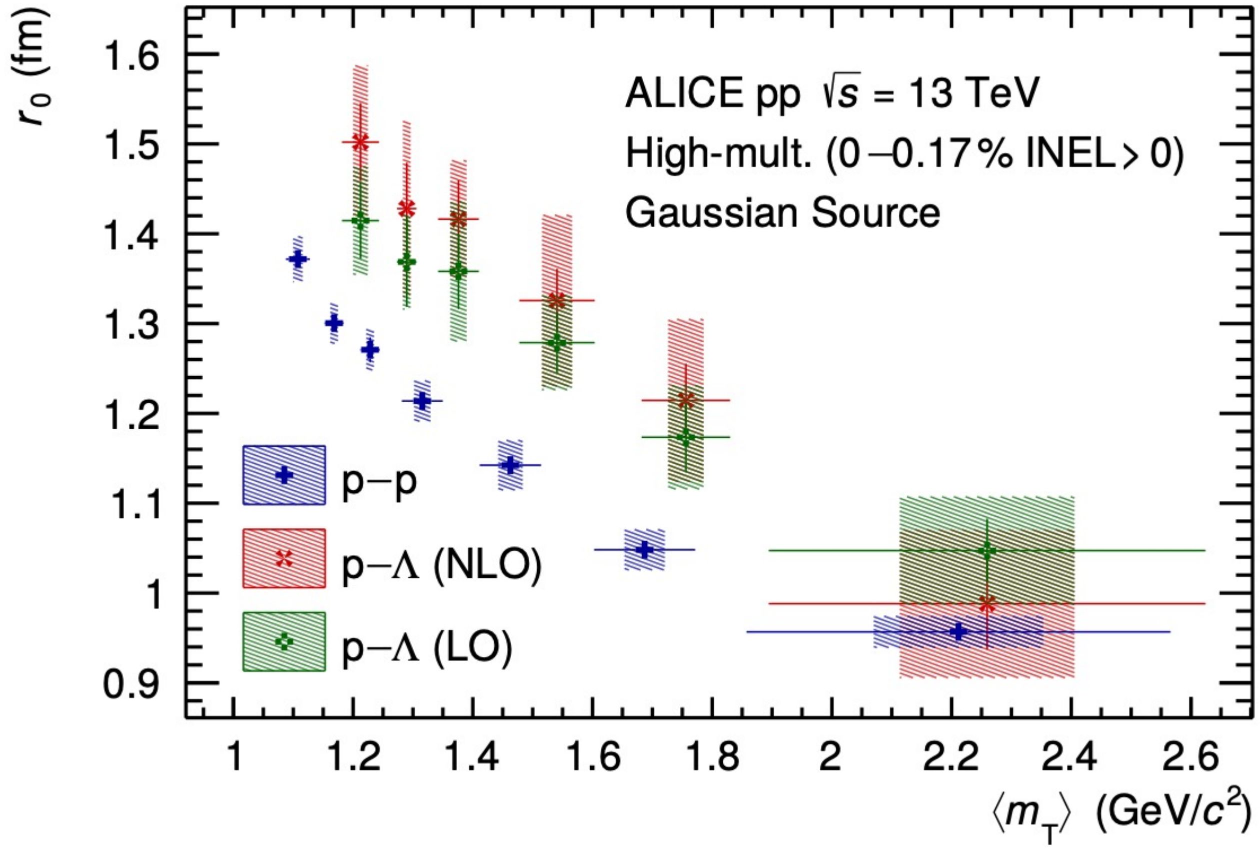


- Correlations for femtoscopic measurements appear for small relative momenta
- Example I: Random emission
- Example II: Collective emission of particles
  - E.g. (An-) isotropic flow
  - Correlations are created in a confined part of the reaction volume
  - Femtoscopy measures the **length of homogeneity**

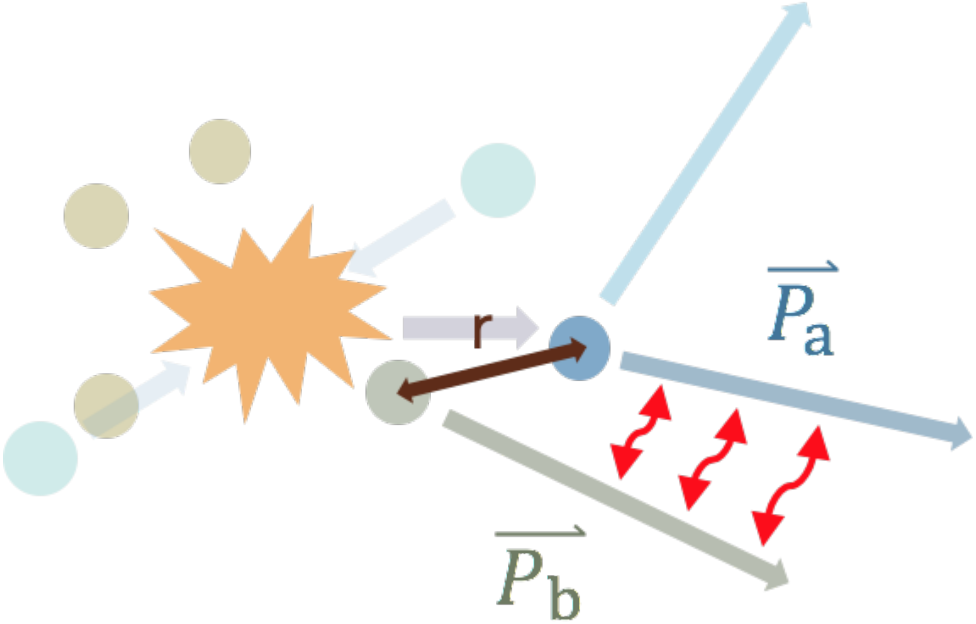
m_T dependence of the gaussian source



- *(An)isotropic pressure gradients* affect the emission
  - Initial geometric anisotropies introduce a transverse modulation
  - Expanding source with *common velocity field*
- Boost shifts particle momenta depending on their mass
  - ➢ Fit of the correlation functions in $<m_T>$ bins
  - m_T scaling of source radii (A.Kisiel PRC 84,044913, 2011)
  - Offset between source sizes of different pairs

Effect of resonances on the source

- Short lived resonances → $c\tau \sim r_0$
  - E.g N*(Γ~150 – 200 MeV), Δ(Γ~150 MeV) …
- **Exponential** modulation of the Gaussian source profile
  - Specific to each pair
- Resonance contribution from Statistical Hadronization Model in the canonical approach
  - Priv. Comm. with Prof. F. Becattini



Particle	Primordial fraction	Resonances	
		1 < cτ < 2 fm	2 < cτ < 15 fm
Proton	33 %	64 %	3 %
Lambda	34 %	8 %	58 %

Effect of resonances on the source

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

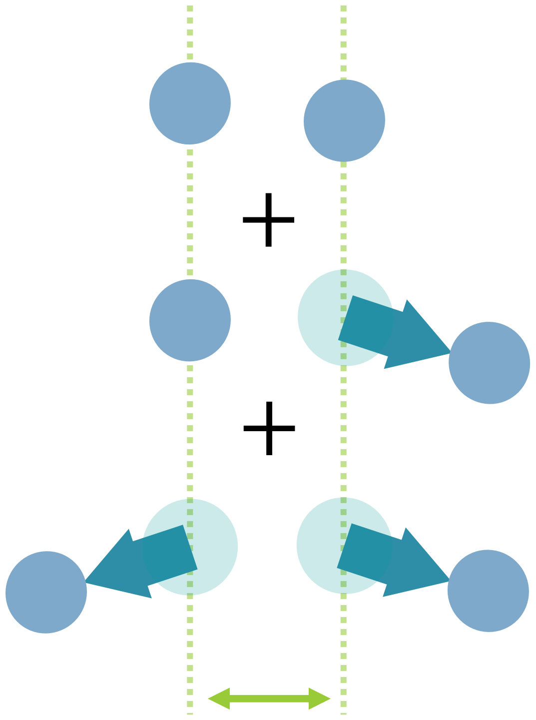
$$G(r,r_{core}) = \frac{2\sqrt{\pi}r^2}{r_{core}^3}\exp\left(-\frac{r^2}{4r_{core}^2}\right)$$

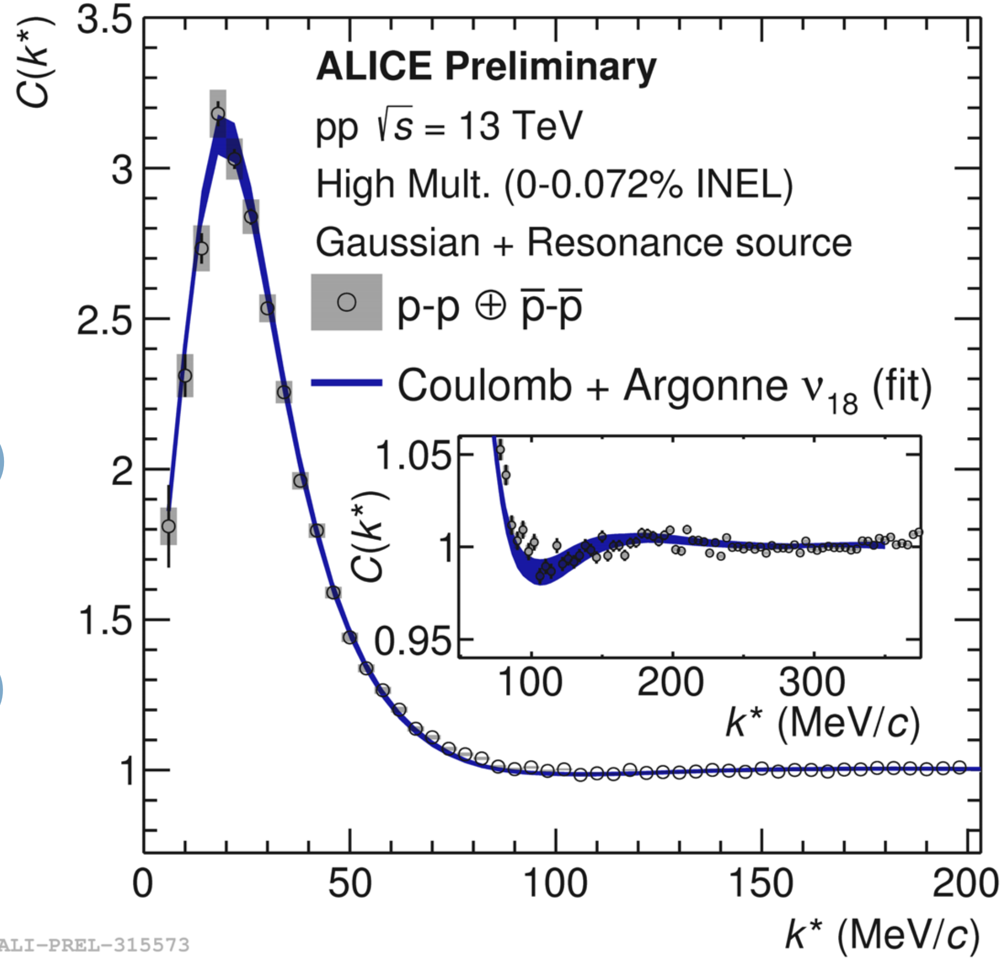
$$\otimes$$

Folded

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

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





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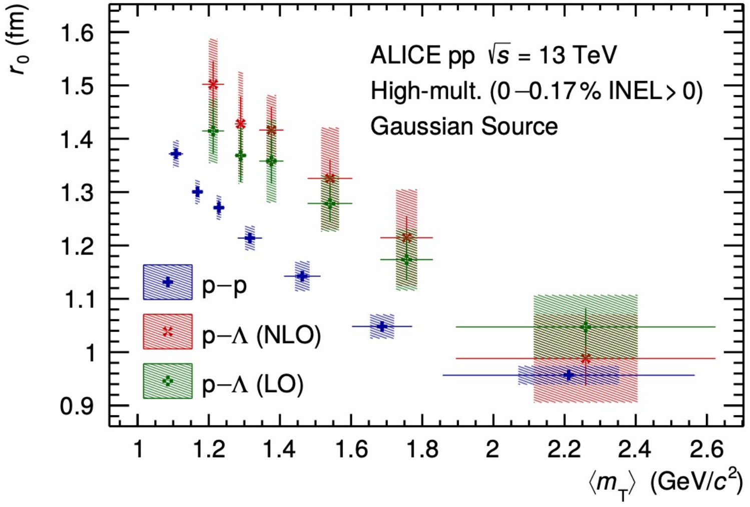
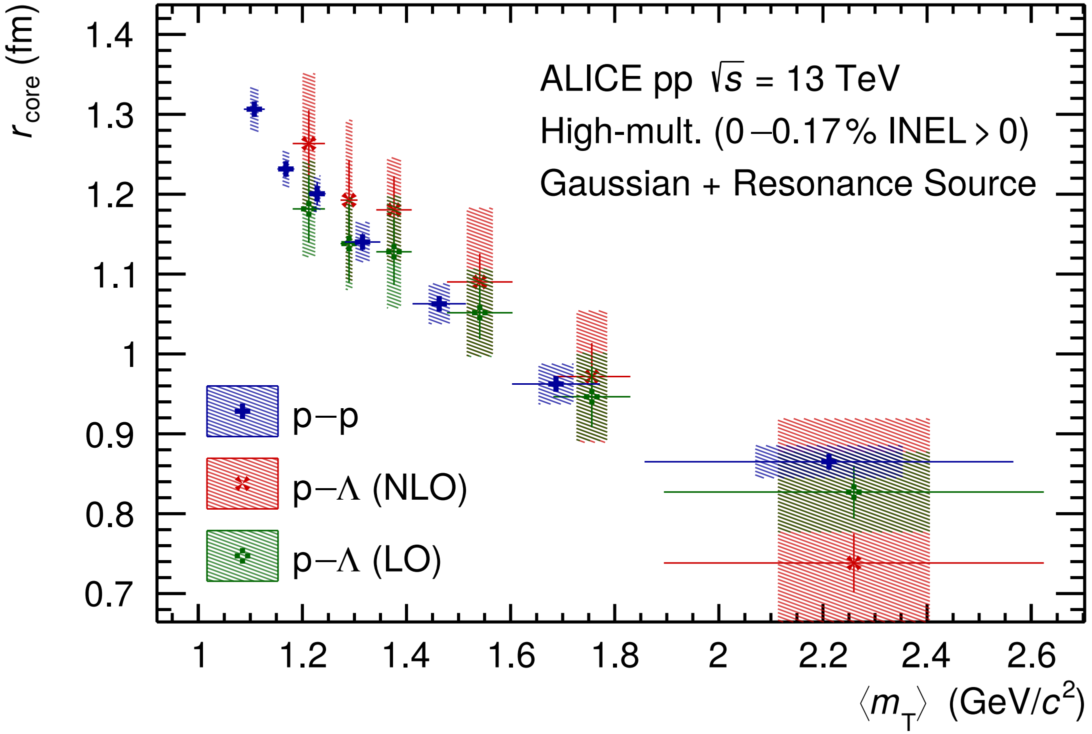
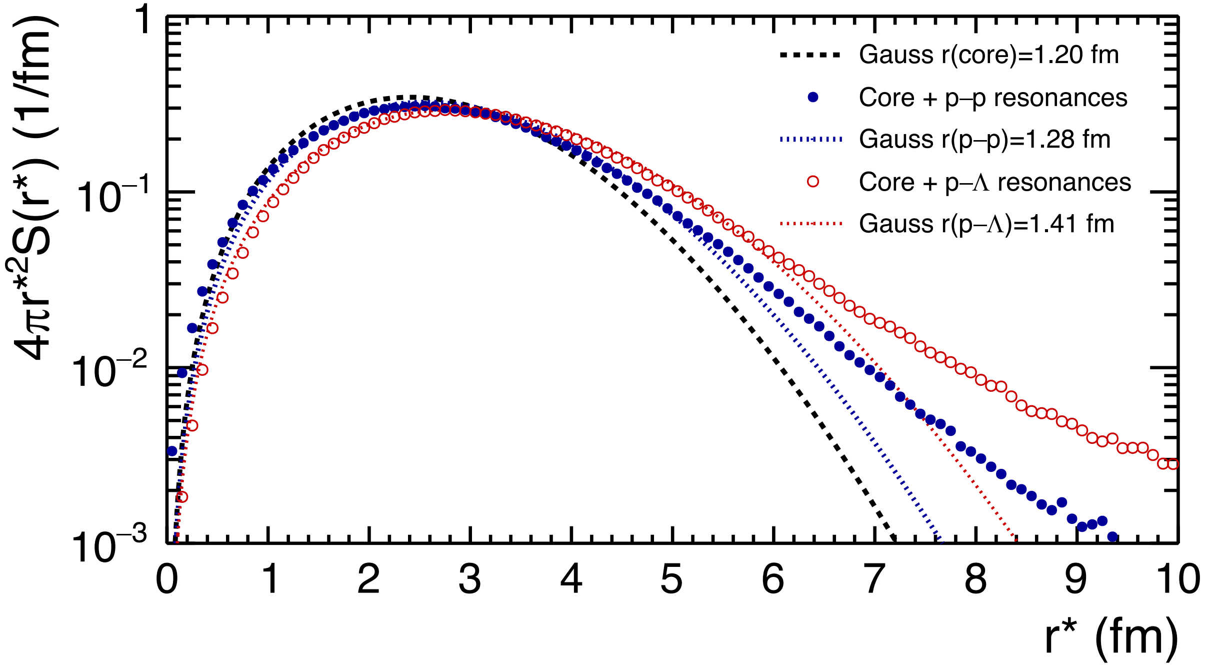
A Gaussian source with resonances





- Common m_T scaling for the source sizes extracted from both p-p and p-Λ correlations
  - Motivation for a search of a universal particle search via application of the formalism to e.g. π-π correlations

How good is the Gaussian description?



- Description of the source distributions by a Gaussian up to ~ 6 fm
- Largest modification of the core source for p-Λ pairs due to longer lifetime of resonances decaying to a Λ

Part II: Coalescence Studies

Measurement of the coalescence parameter B_2

Definition of the coalescence parameter for a nucleus *i* with A nucleons is defined as:

$$E_i \frac{\mathrm{d}^3 N_i}{\mathrm{d}p_i^3} = B_\mathrm{A} \left(E_\mathrm{p} \frac{\mathrm{d}^3 N_\mathrm{p}}{\mathrm{d}p_\mathrm{p}^3} \right)^A \xrightarrow{\text{deuterons}} B_2 = \frac{E_i \dfrac{\mathrm{d}^3 N_\mathrm{d}}{\mathrm{d}p_\mathrm{d}^3}}{\left(E_\mathrm{p} \dfrac{\mathrm{d}^3 N_\mathrm{p}}{\mathrm{d}p_\mathrm{p}^3} \right)^2}$$

Experimental parameter tightly connected to the coalescence probability

Larger B_A ⟺ Larger coalescence probability

The closer nucleons are in phase space the higher the probability

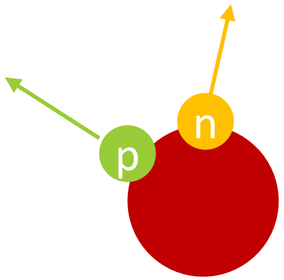
Femtoscopy to Coalescence

$$B_2(p) \approx \frac{3}{2m}\int \mathrm{d}^3q\,\underbrace{\boxed{\mathscr{D}(\vec{q})}}_{\text{Wigner density}}\overbrace{\boxed{\mathscr{C}_2^{\mathrm{PRF}}(\vec{p},\vec{q})}}^{\text{Correlation radius}}$$

From K. Blum and M. Takimoto (Phys. Rev. C 99, 044913)

Zoom into the production of nuclei through coalescence

- Probability of a proton and a neutron to find each other described by their emission profile
- Weighted by the probability to form a Deuteron



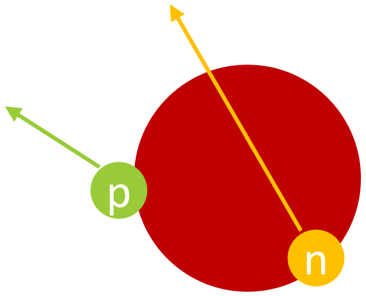
Small systems

=

Small distance in space

Only momentum correlations matter

Expect large B_A



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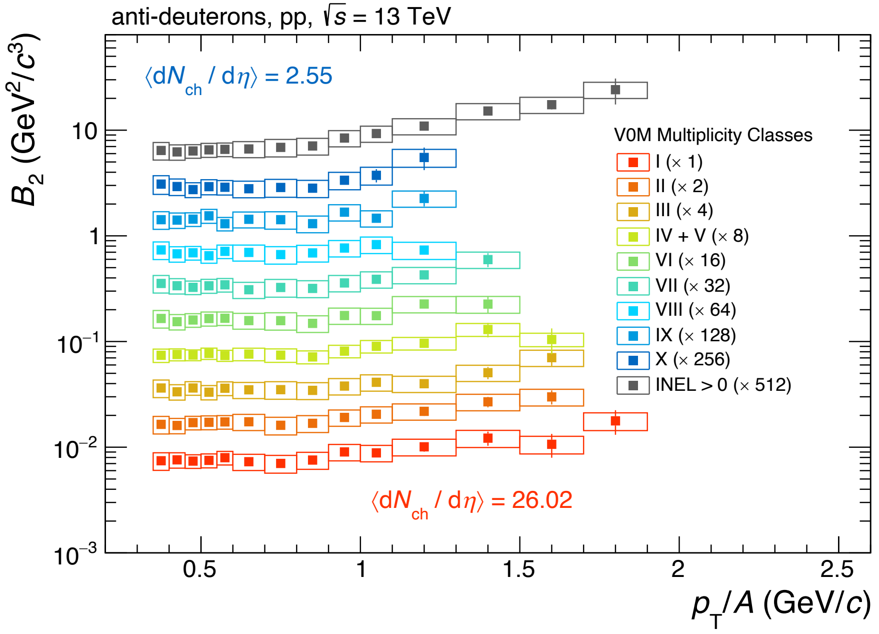
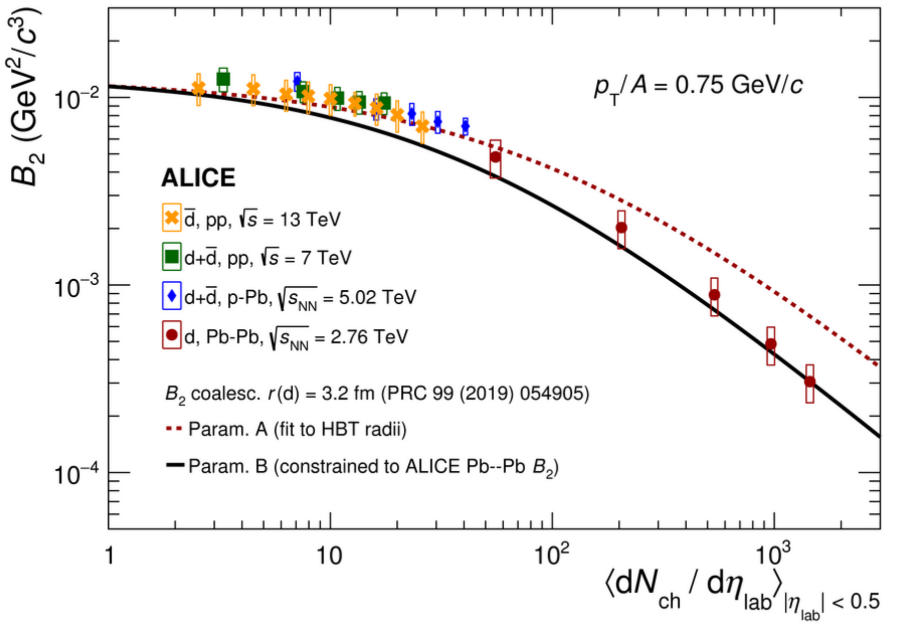
Measurement of Coalescence parameter B_2

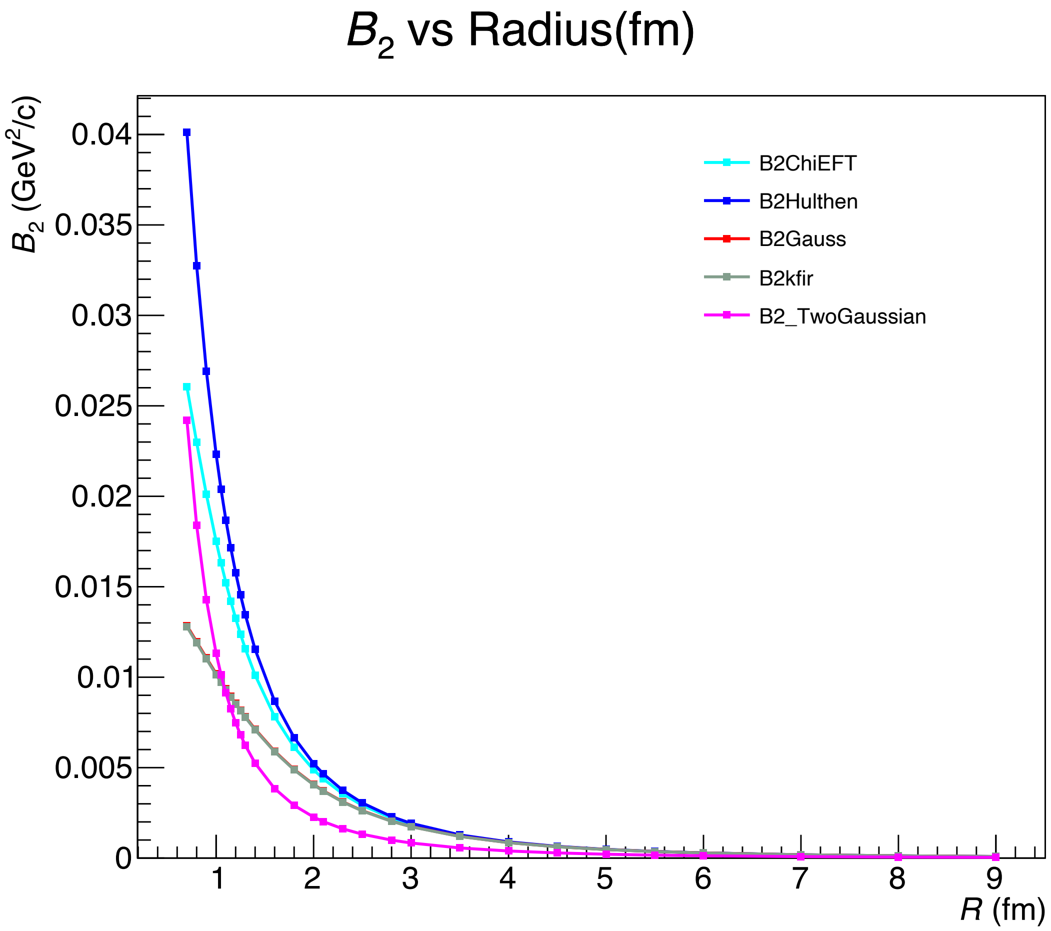




https://arxiv.org/pdf/2003.03184.pdf

- **Aim**: Describe B_2 values across different multiplicities and systems
  - Source sizes constraint from charged Kaon femtoscopy (Param. A) or a fit to the B_2 results of central Pb-Pb (Param. B)
  - Description of the d wavefunction by a Gaussian (r(d) = 3.2 fm)

Alternative wave functions for the deuteron



1. (Single) Gaussian

$$\varphi_d(r) = (\pi d^2)^{3/4} e^{\left(-\frac{r^2}{2d^2}\right)}$$

2. Hulthen

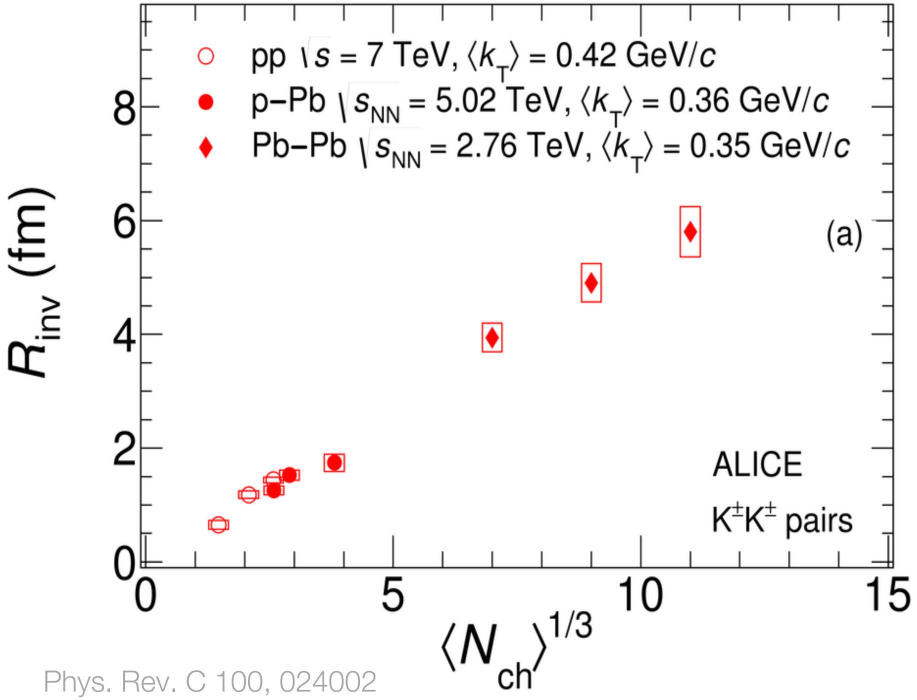
$$\varphi_d(r) = \sqrt{\frac{\alpha\beta(\alpha+\beta)}{2\pi(\alpha-\beta)^2}} \frac{e^{-\alpha r} - e^{-\beta r}}{r}$$

3. Chiral Effective Field Theory

$$\varphi_d(r) = \frac{1}{\sqrt{4\pi r}} \left[u(r) + \frac{1}{\sqrt{8}} w(r) S_{12}(\hat{r}) \right] \chi_{1m}$$

Dedicated measurement of source sizes

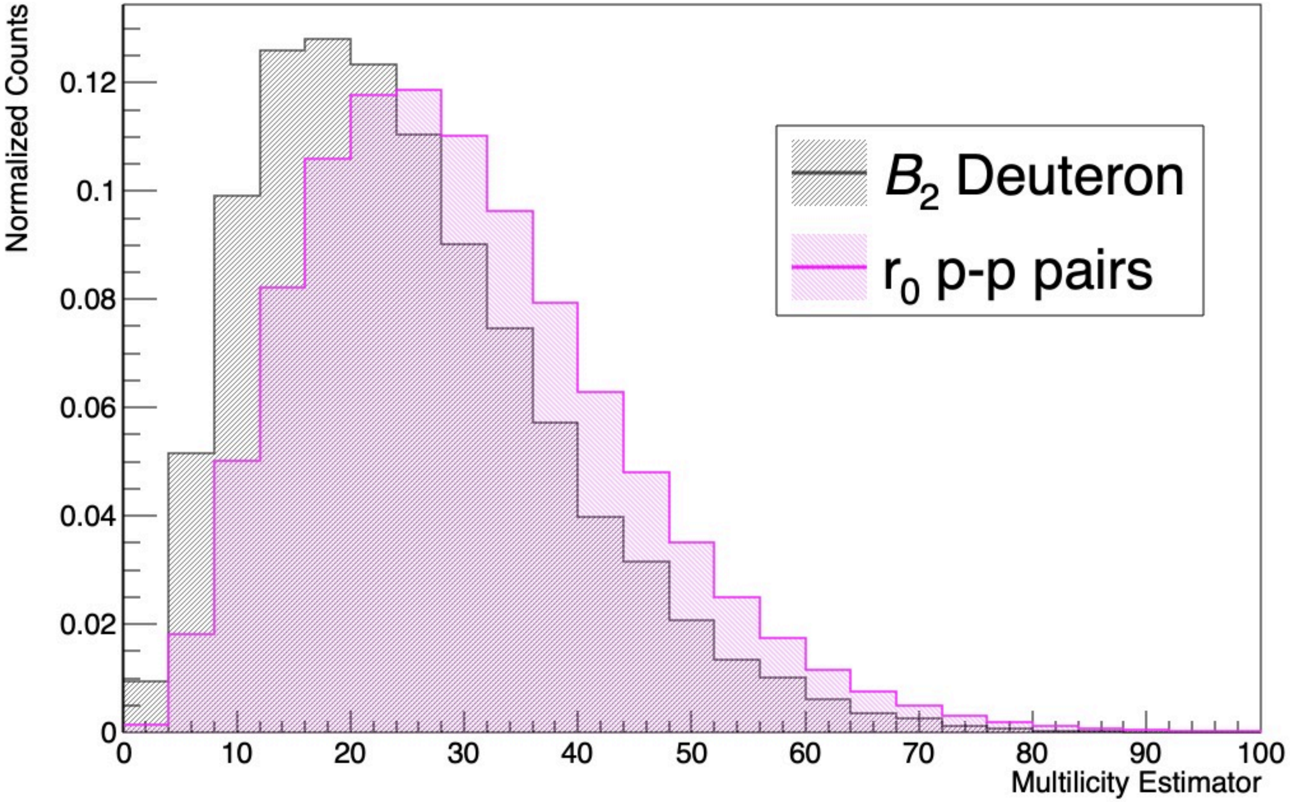
- Coalescence of emitted protons and neutrons
  - ✓ Gaussian source sizes from p-p correlations
- Comparison to $B_2(p_T)$
  - ✓ m_T dependent analysis of p-p source sizes
- Consider the multiplicity dependence of the measurement of radii and B_2
- Limited by the amount of pairs with small relative moments



Phys. Rev. C 100, 024002

Comparison of event multiplicity

Average multiplicity of evented used to …	in pp Minimum Bias collisions at 13 TeV	in p-Pb Minimum Bias collisions at 5.02 TeV
Measure the deuteron yield	23	45
Measure the p-p correlation function	30	53



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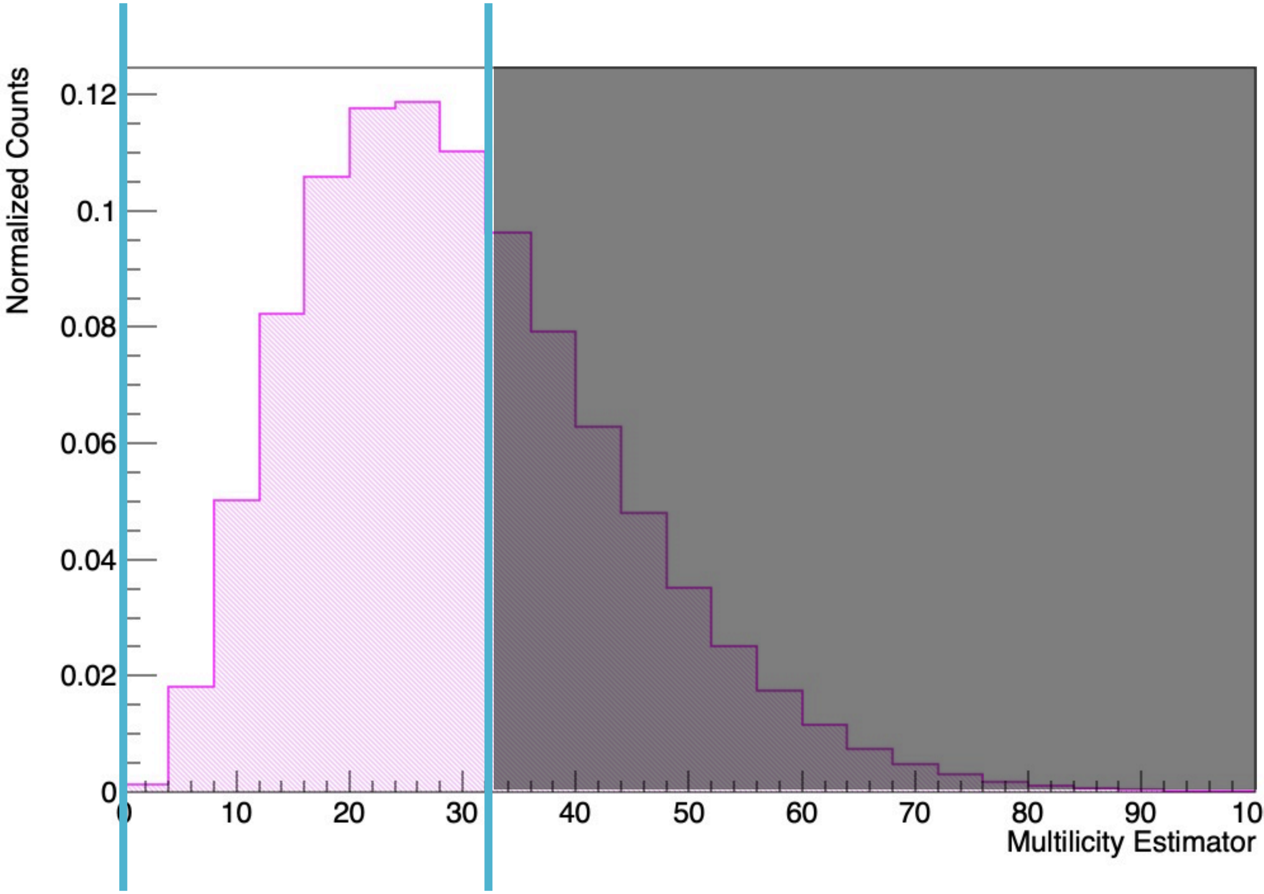
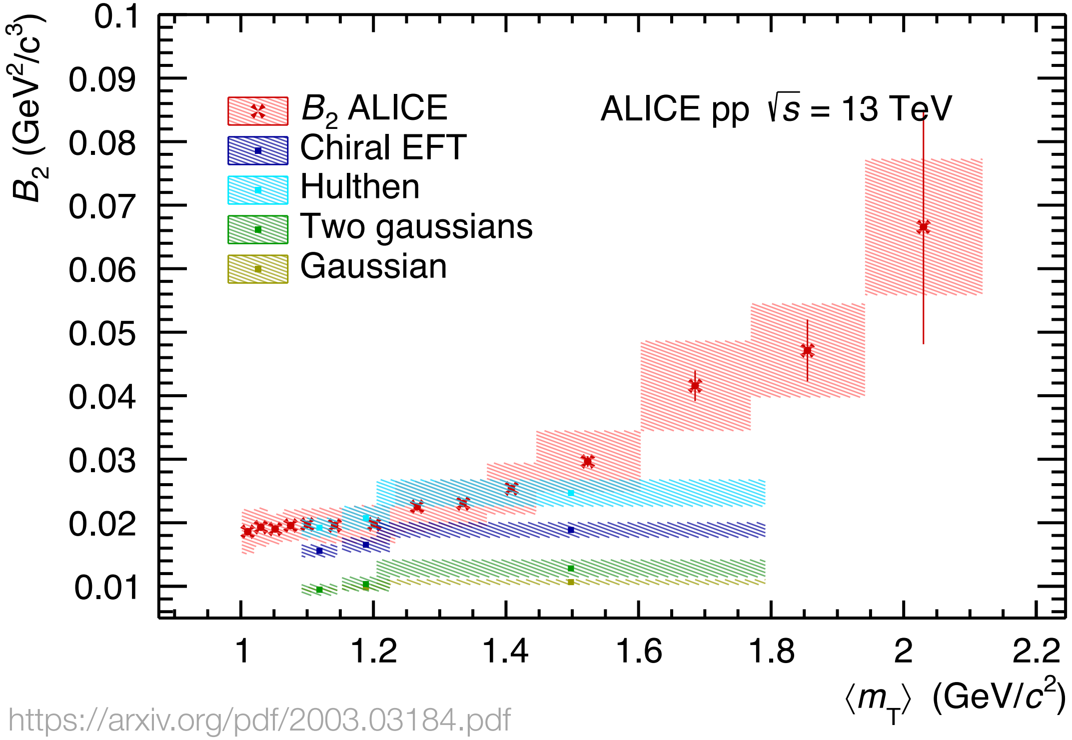
Measure the p-p correlation function	30	53
Blindfolded p-p pairs	23	46



Comparison to measurement



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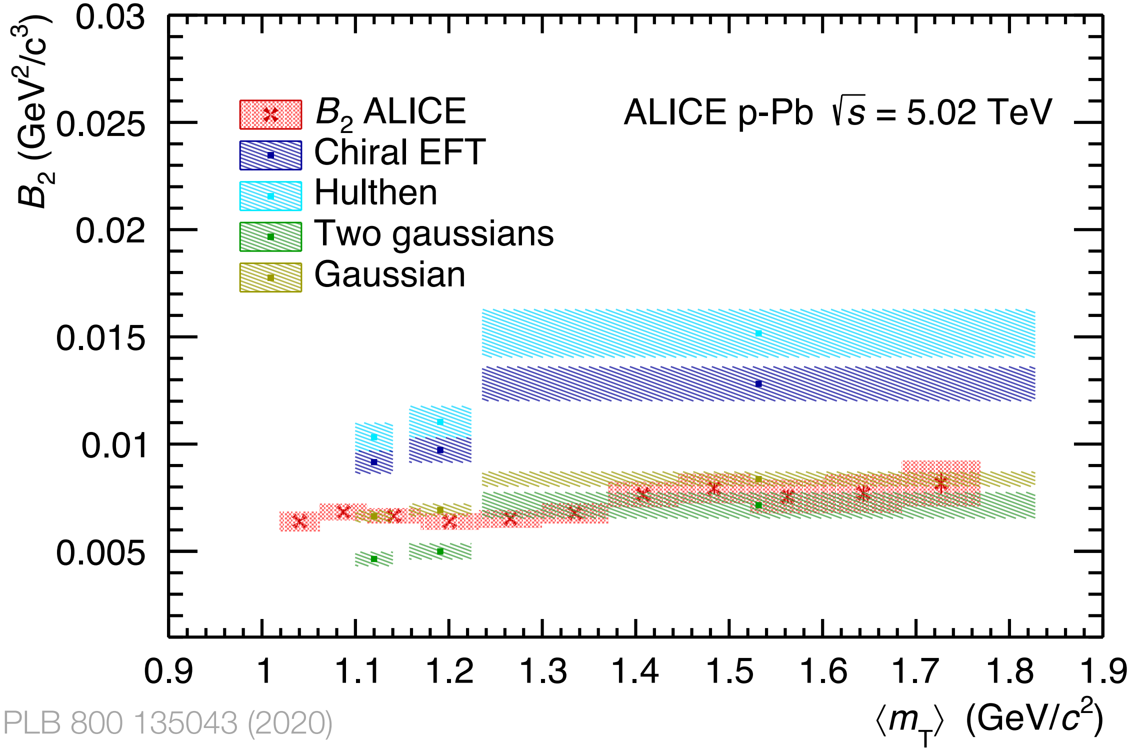


PLB 800 135043 (2020)

- Unable to simultaneously describe the B_2 measurement in both systems

Summary and Outlook

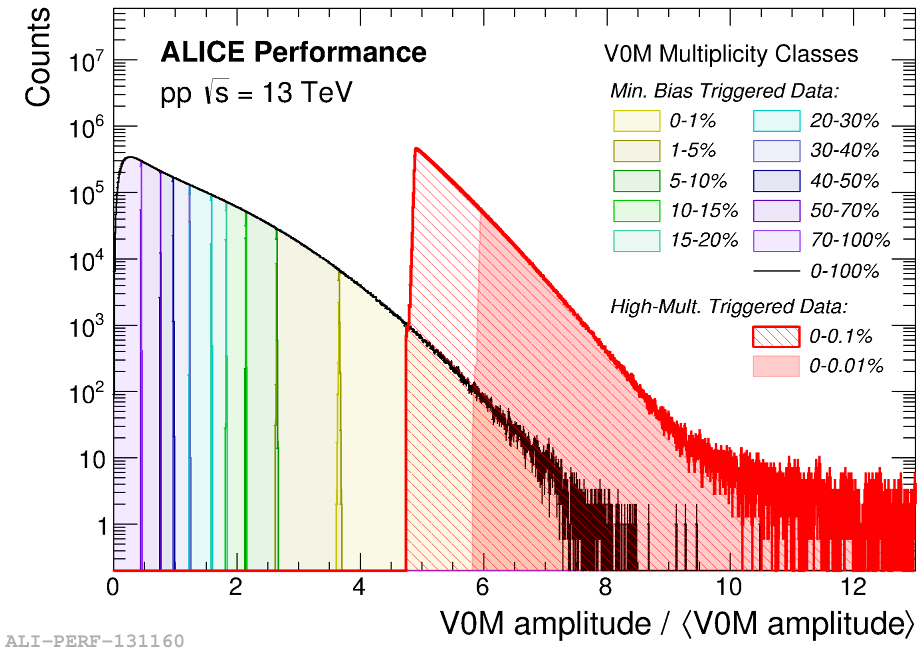
- Towards a common source of baryons in small systems
  - Explicit treatment of resonance contributions
  - Observation a common m_T scaling of source sizes from p-p and p-Λ correlations
  - Recipe also applied to π-π correlations
- Femtoscopy goes Coalescence
  - Dedicated measurement of m_T and multiplicity dependent source sizes from p-p correlations
  - Test of different deuteron wave functions
  - Unable to simultaneously describe the B_2 measurement in pp and p-Pb

Thanks for your attention

Backup

High Multiplicity Dataset

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



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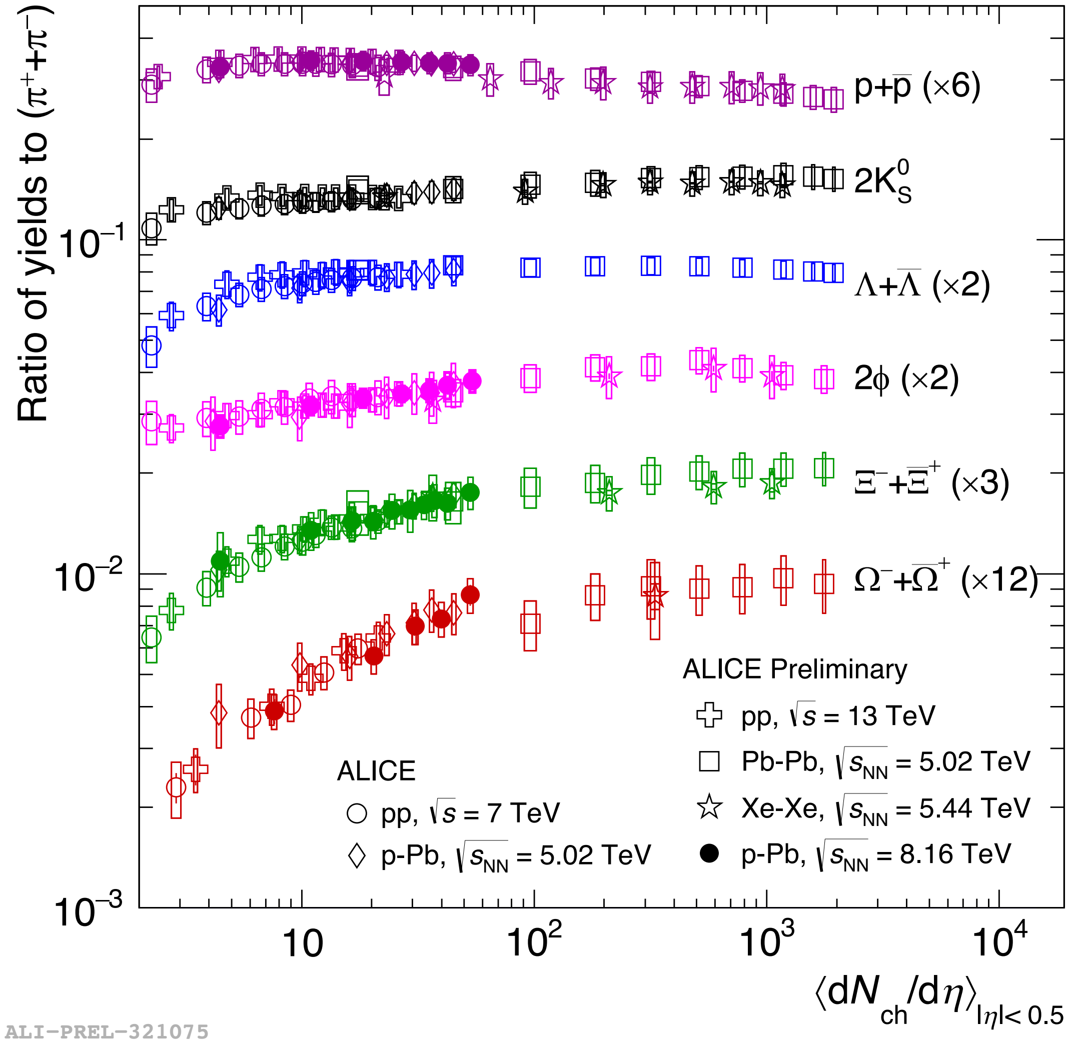

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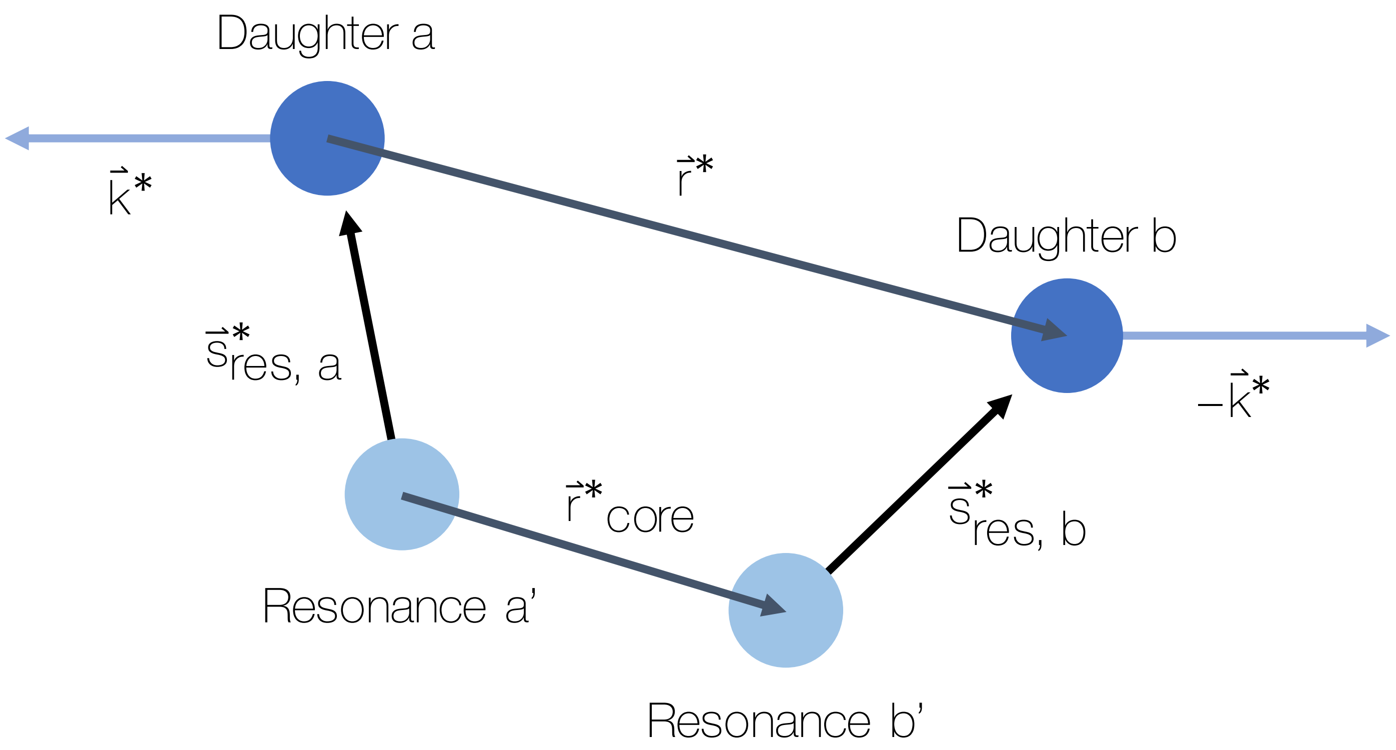
Daughter a
$\vec{k}^*$
$\vec{r}^*$
Daughter b
$\vec{s}^*_{\mathrm{res,\,a}}$
$-\vec{k}^*$
$\vec{r}^*_{\mathrm{core}}$
$\vec{s}^*_{\mathrm{res,\,b}}$
Resonance a’
Resonance b’