First experimental hint on the three-body strong interaction with ALICE

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On behalf of the ALICE collaboration

STRANU: Hot Topics in STRANgeness NUclear and Atomic Physics

26th May 2021

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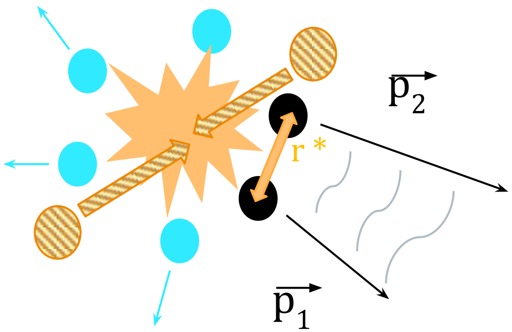
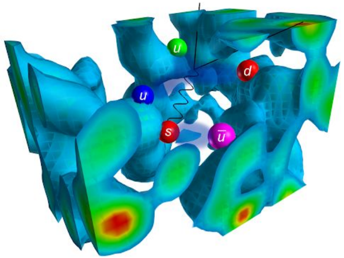
Investigating handron-hadron interaction at LHC

ALICE at the LHC

Hadron-hadron
strong interactions

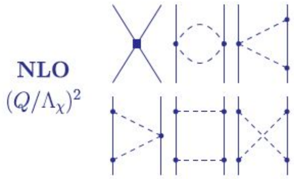


Test of first
principle
calculations

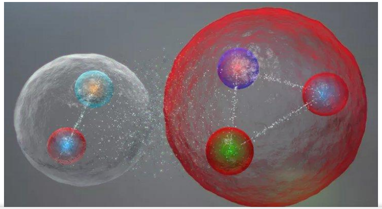


D. B. Leinweber/University of Adelaide

New constraints
for chiral
effective field
theory

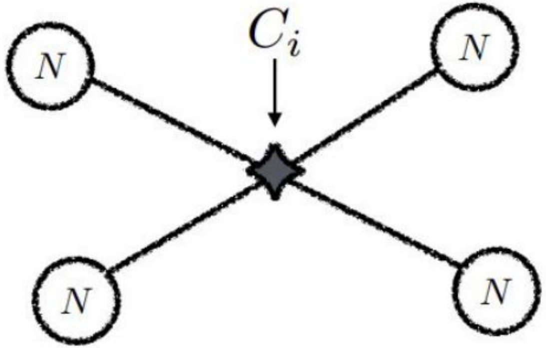


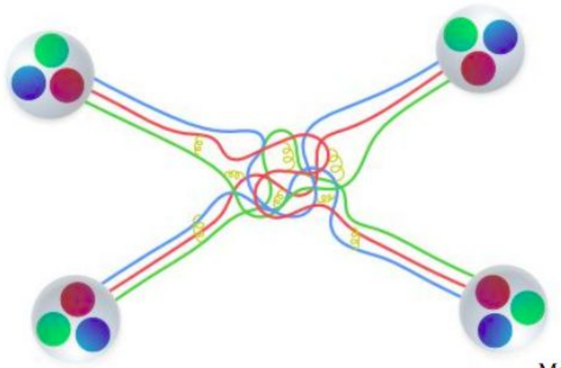
Search for
new bound
states



Strong interaction between (strange) hadrons

Residual strong interaction among hadrons





Marc Illa
THEIA-STRONG2020

$$\mathcal{L}_{EFT}[\pi, N, \ldots; m_\pi, m_N, \ldots, C_i]$$

$$\mathcal{L}_{QCD}[q, \bar{q}, A; m_q, \alpha_s]$$

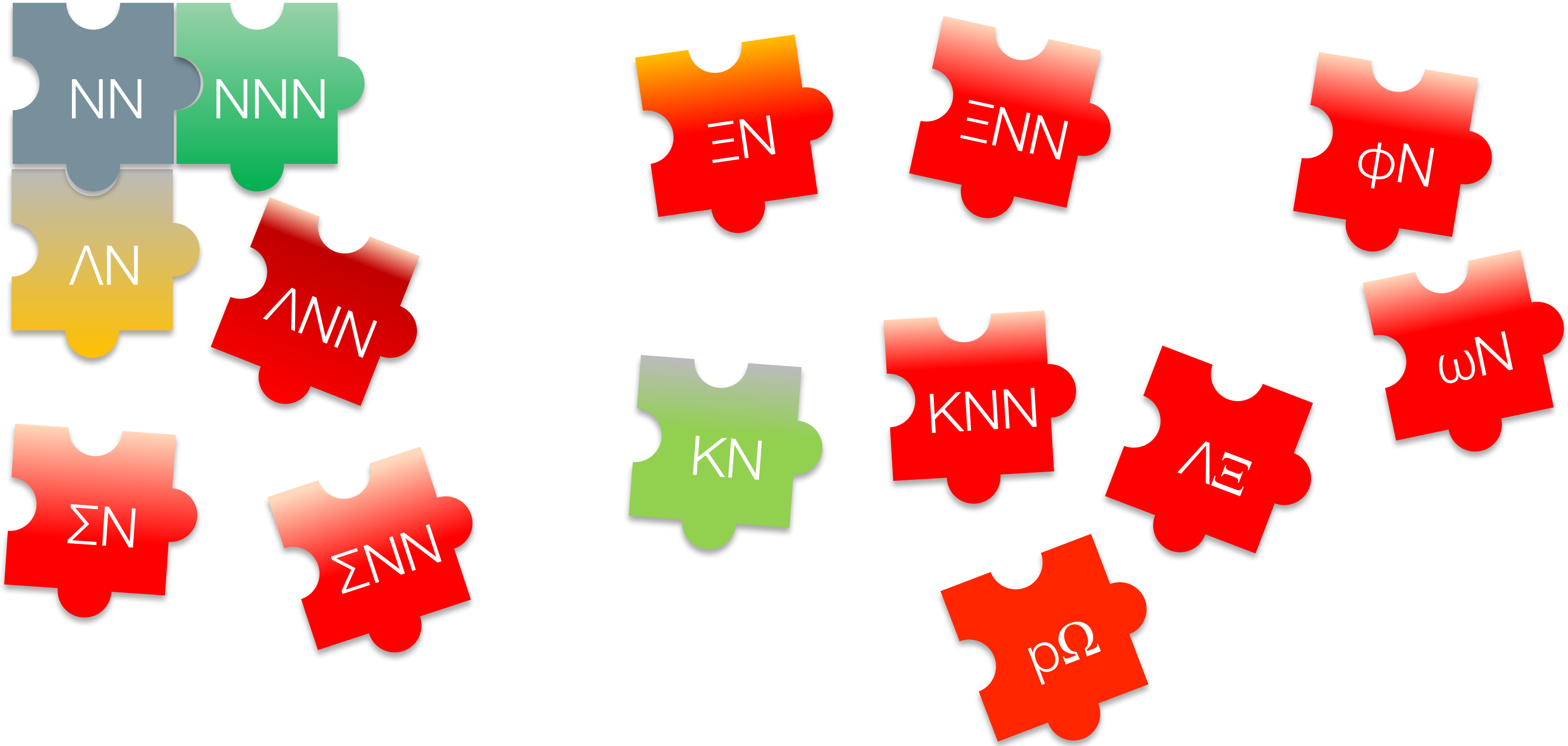
Non-perturbative region of QCD

- **Hadrons** as degrees of freedom
- **Effective theories** (EFT) with low-energy coefficients **constraint by data**

Lattice QCD

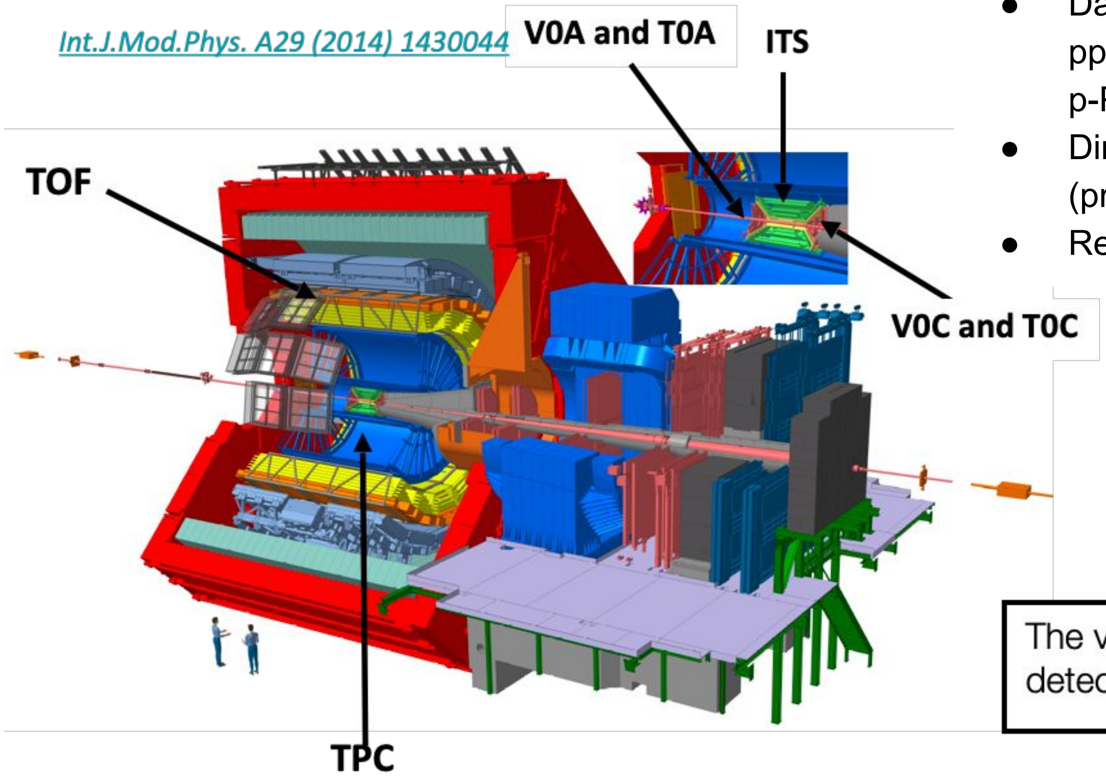
- Understanding of the interaction starting from **quark and gluons**

The SU(3) interactions puzzle



ALICE data

[Int.J.Mod.Phys. A29 (2014) 1430044]

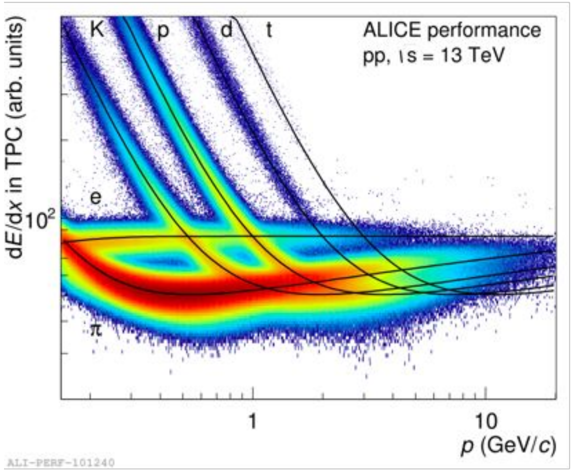


- Data set:
  pp 13 TeV (1000 M high multiplicity events),
  p-Pb 5.02 TeV (600 M minimum bias)
- Direct detection of charged particles (protons, kaons, pions)
- Reconstruction of hyperons:

$$\Lambda \rightarrow p\pi^-$$
$$\Xi^- \rightarrow \Lambda\pi^-$$
$$\Omega^- \rightarrow \Lambda K^-$$
$$\Sigma^0 \rightarrow \Lambda\gamma$$

The very good PID capabilities of the detector result in very pure samples!

Hyperons @ ALICE in pp collisions



$$\Lambda \to p\pi^-$$
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$$\Omega^- \to \Lambda K^-$$
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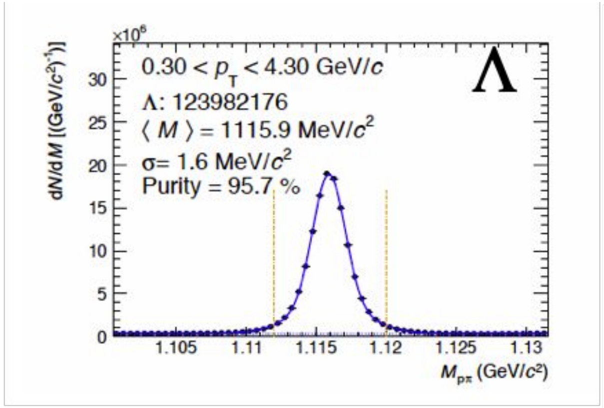
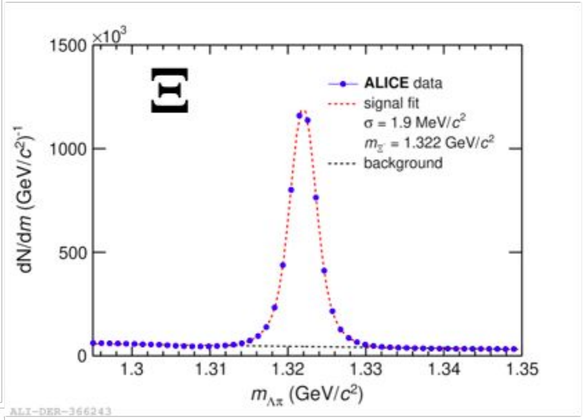
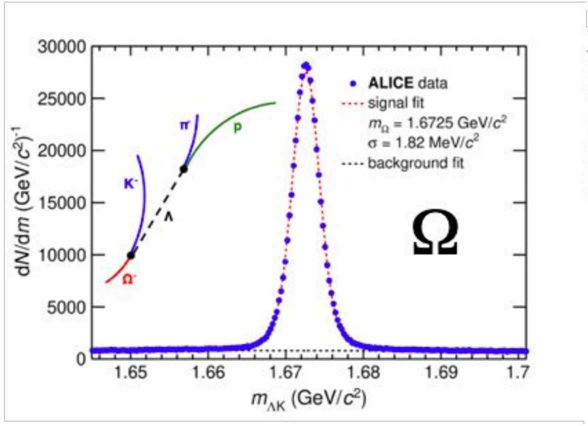
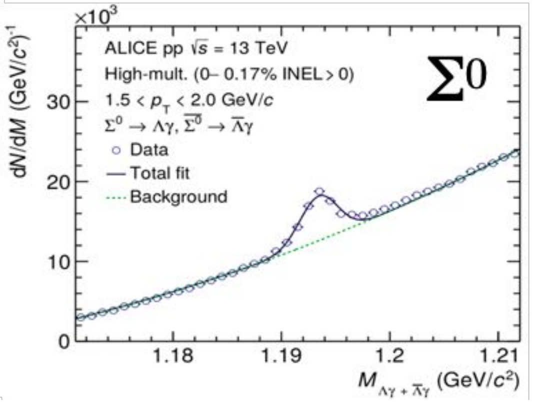


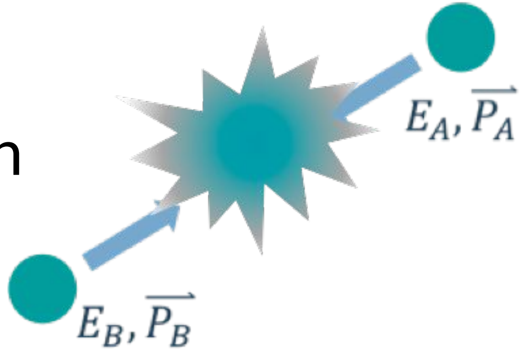




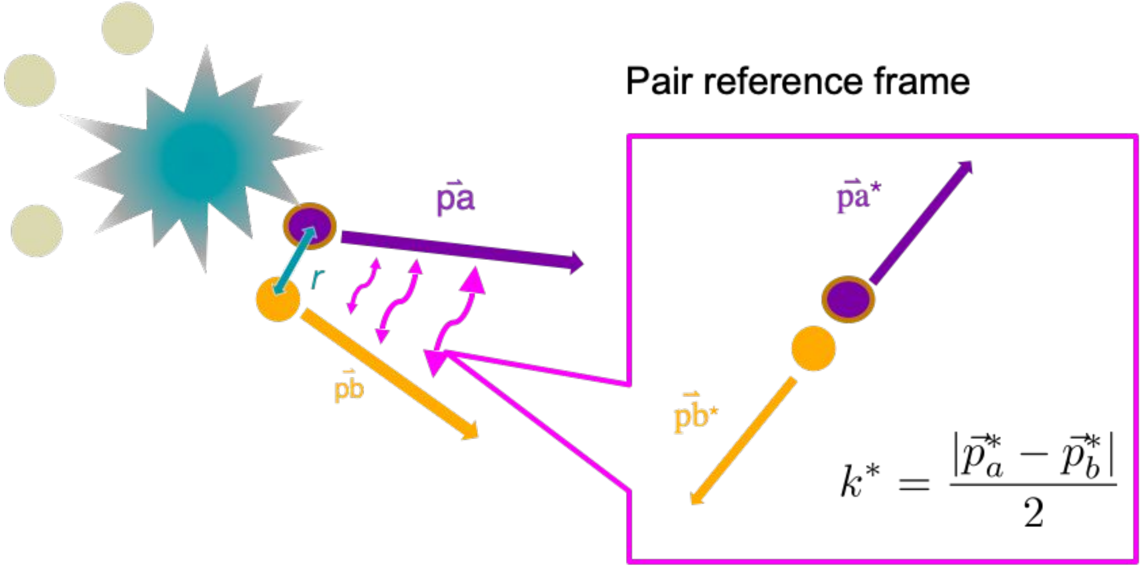


The femtoscopy technique

Nuclear Collision



The femtoscopy technique



Schrödinger Equation:

V(r) -> $\left|\psi\left(\vec{k}^*, \vec{r}\right)\right|^2$ relative wave function for the pair

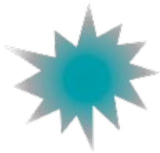
$$C(k^*) = \int S(r) \left|\psi\left(\vec{k}^*, \vec{r}\right)\right|^2 d^3r = \zeta(k^*) \bullet \frac{N_{same}(k^*)}{N_{mixed}(k^*)}$$

Emission source   Two-particle wave function

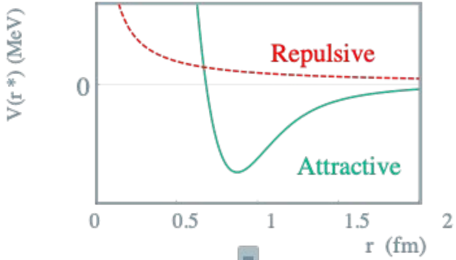
- >1 if the interaction is attractive
- = 1 if there is no interaction
- <1 if the interaction is repulsive

Example

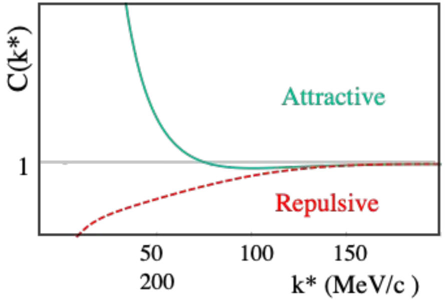
Source parametrisation



Interacting potential



Correlation function



Gaussian source

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

Schrödinger equation**

Two-particle wave function

$$\left|\Psi(k^*, r)\right|$$

****CATS** (Correlation Analysis Tool using the Schödinger equation)
D. Mihaylov et al., Eur. Phys. J. C78 (2018) 394

$$C(k^*) = \int S(r) \left|\psi\left(\vec{k}^*, \vec{r}\right)\right|^2 d^3r = \zeta(k^*) \bullet \frac{N_{same}(k^*)}{N_{mixed}(k^*)}$$

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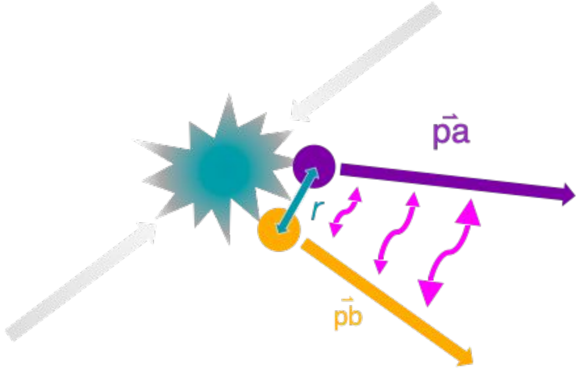
Femtoscopy in small colliding systems



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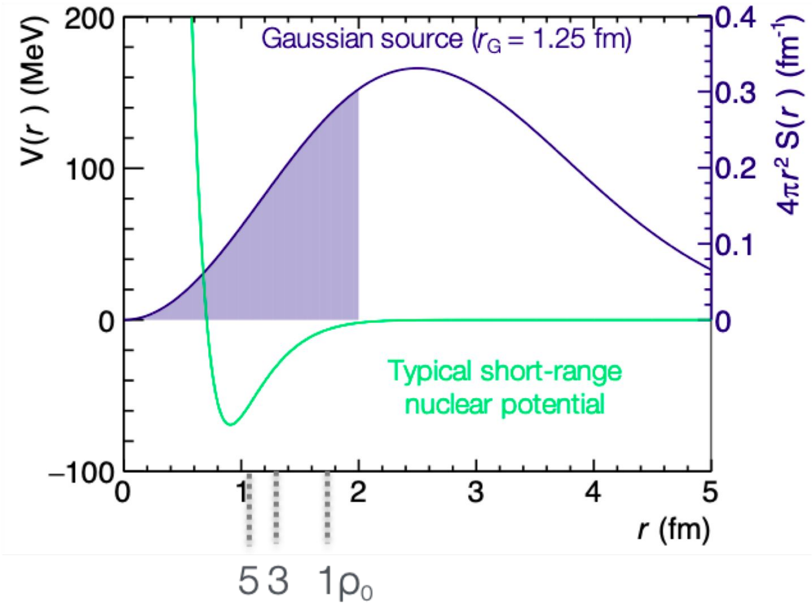
Emission source — Two-particle wave function



Small particle-emitting source created in pp and p–Pb collisions at the LHC

- Essential ingredient for detailed studies of the strong interaction

Source determination

The first step is "traditional" femtoscopy: known interaction → determine source size

- p–p interaction: Argonne v18 potential
- crosscheck with p–Λ (χEFT)

[ALICE Coll., Phys. Lett. B 811 (2020) 135849]

Source determination

<u>The first step is "traditional" femtoscopy:</u> known interaction → determine source size

- p–p interaction: Argonne v18 potential
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Determine **gaussian "core" radius**
- As a function of pair $<m_T>$
- **Common to all hadron-hadron pairs**

✖

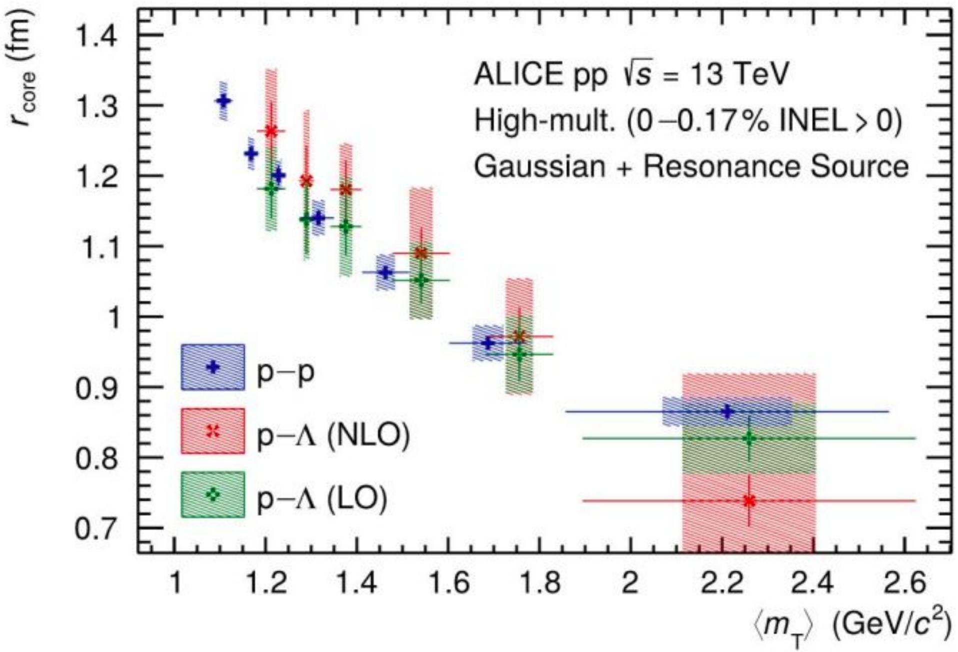
Effect of strong short-lived resonances
<u>Adds **exponential tail** to the source profile</u>
→ Angular distributions from EPOS

→ Production fraction from SHM

	Primordial	Resonances lifetime
p	35.8 %	1.65 fm
Λ	35.6 %	4.69 fm

[ALICE Coll., Phys. Lett. B 811 (2020) 135849]

Source determination



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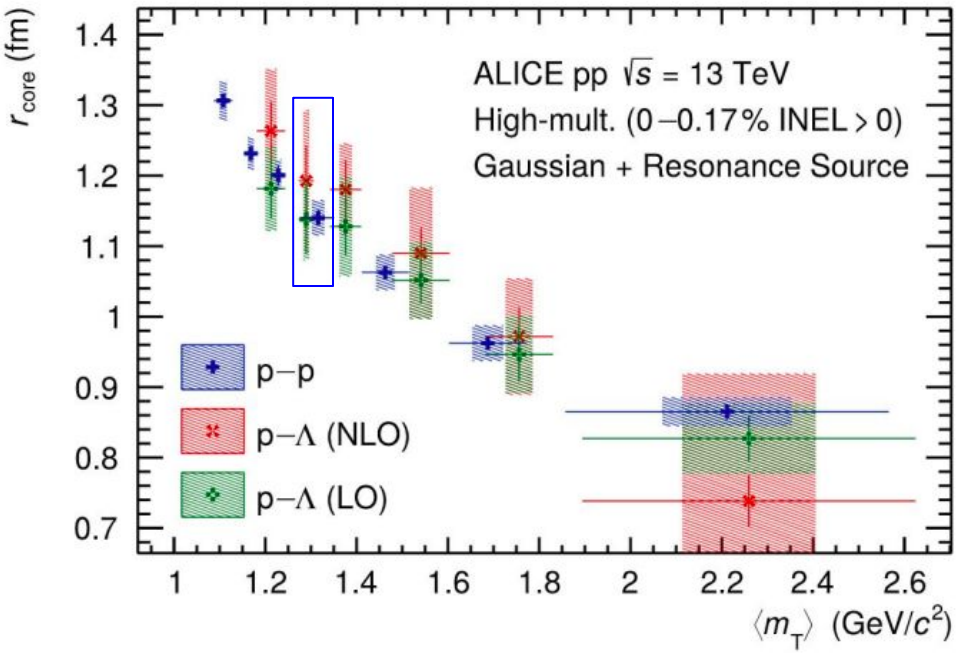
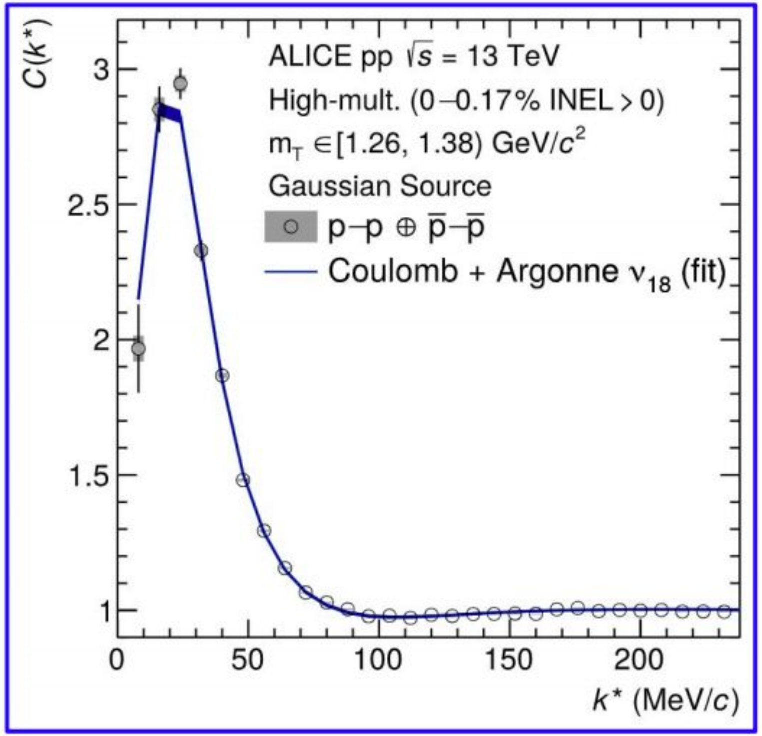
Source determination





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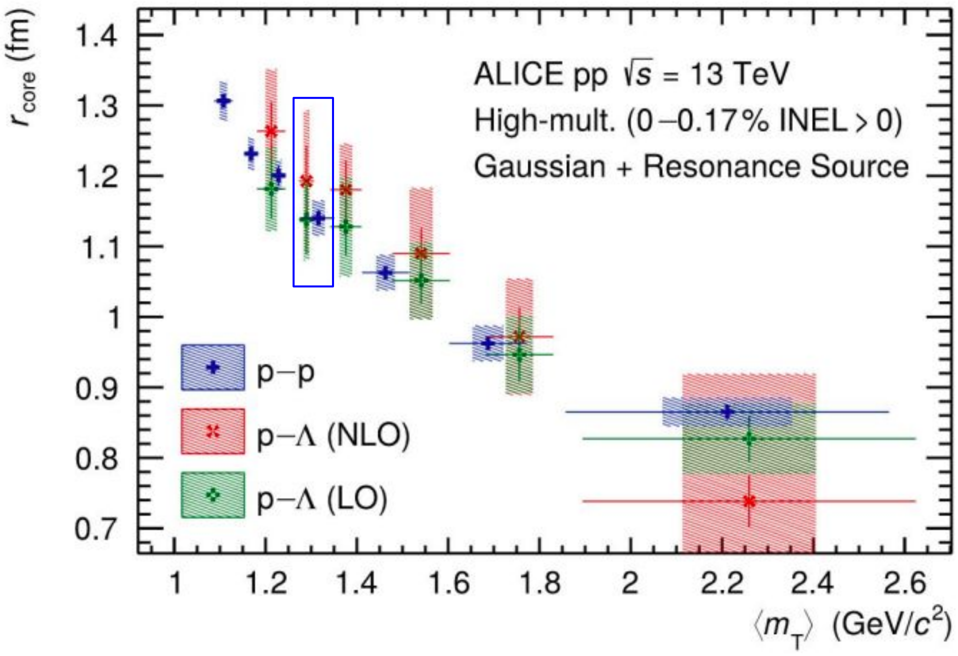
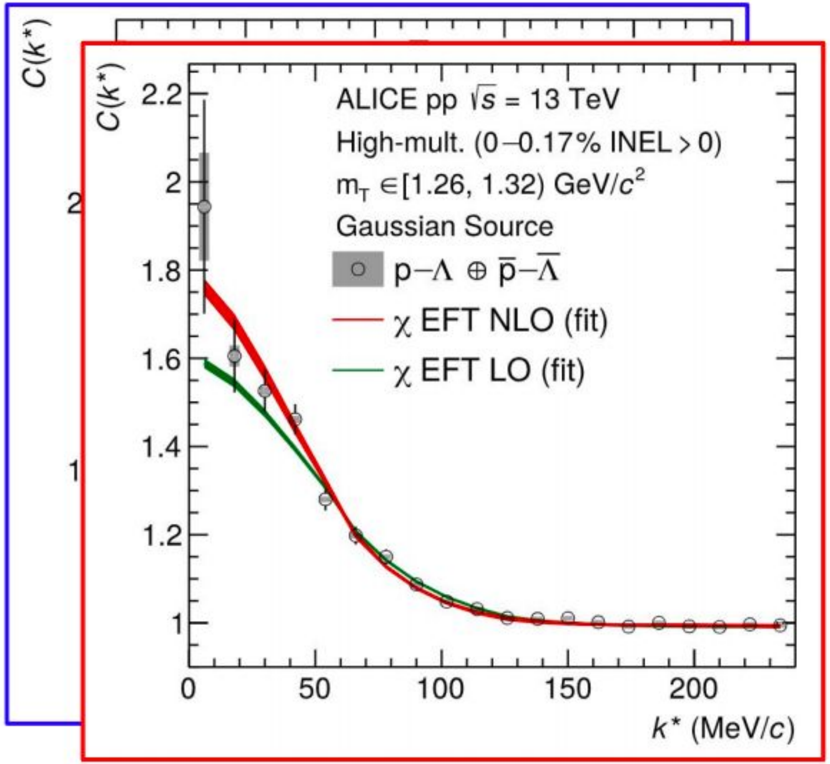
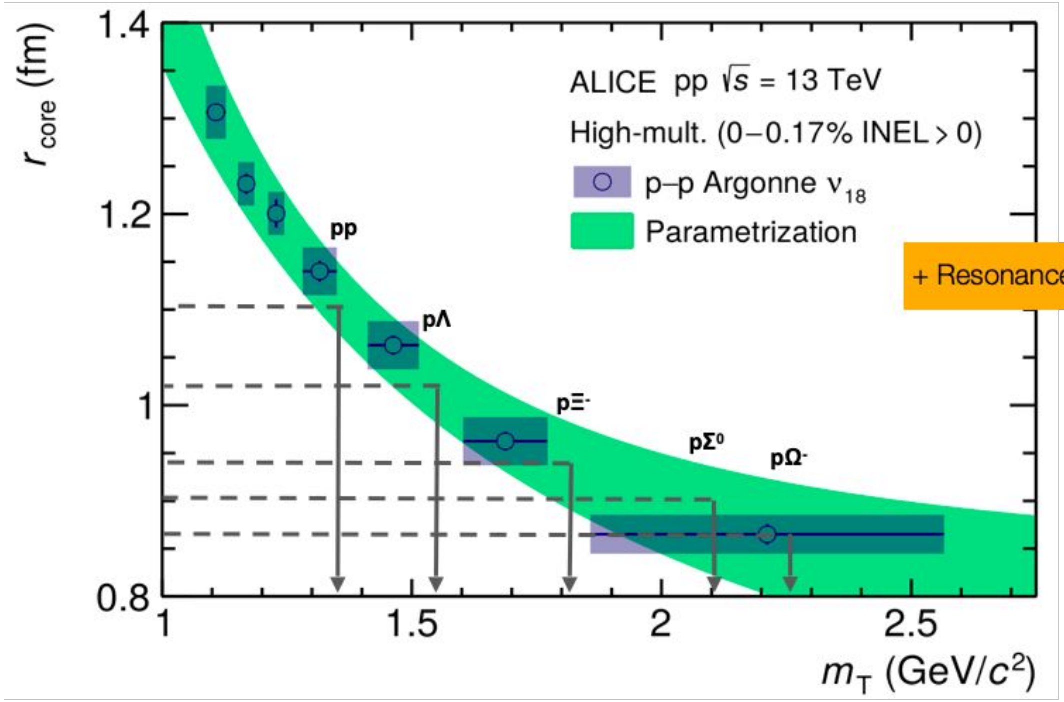


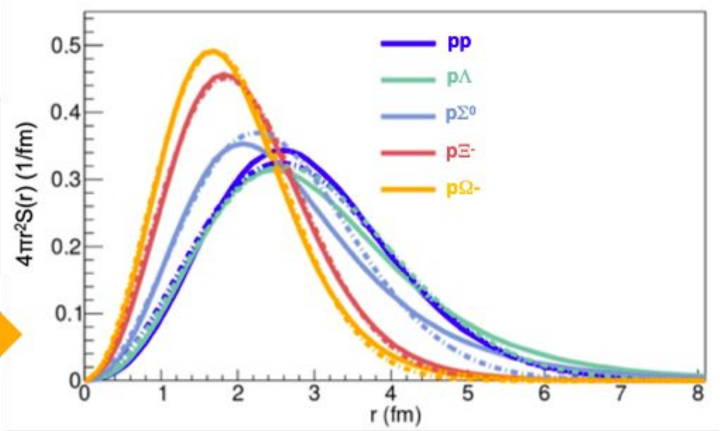


[ALICE Coll., Phys. Lett. B 811 (2020) 135849]

Gaussian source with resonances

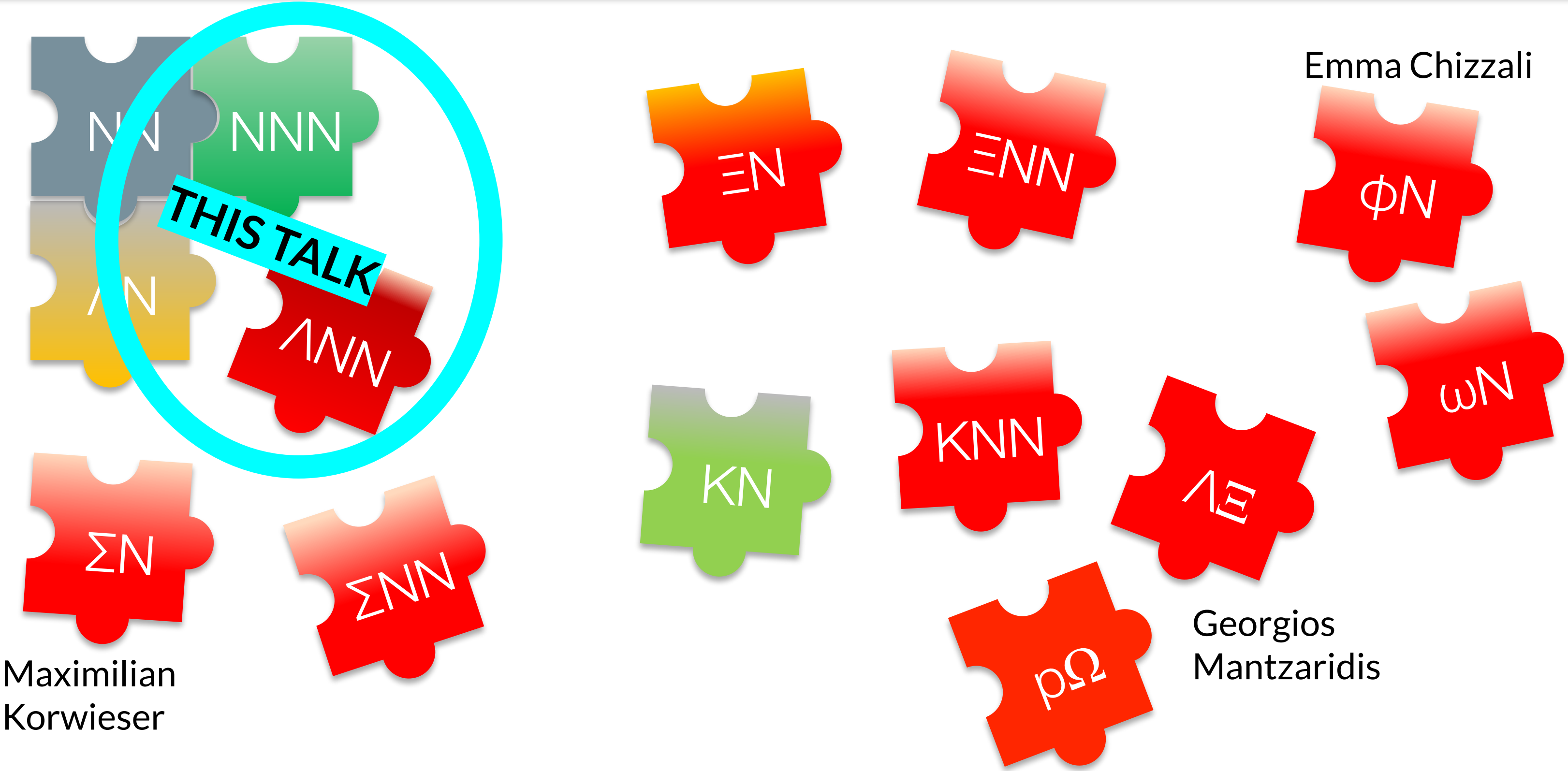
Physics Lett. B, 811, 135849





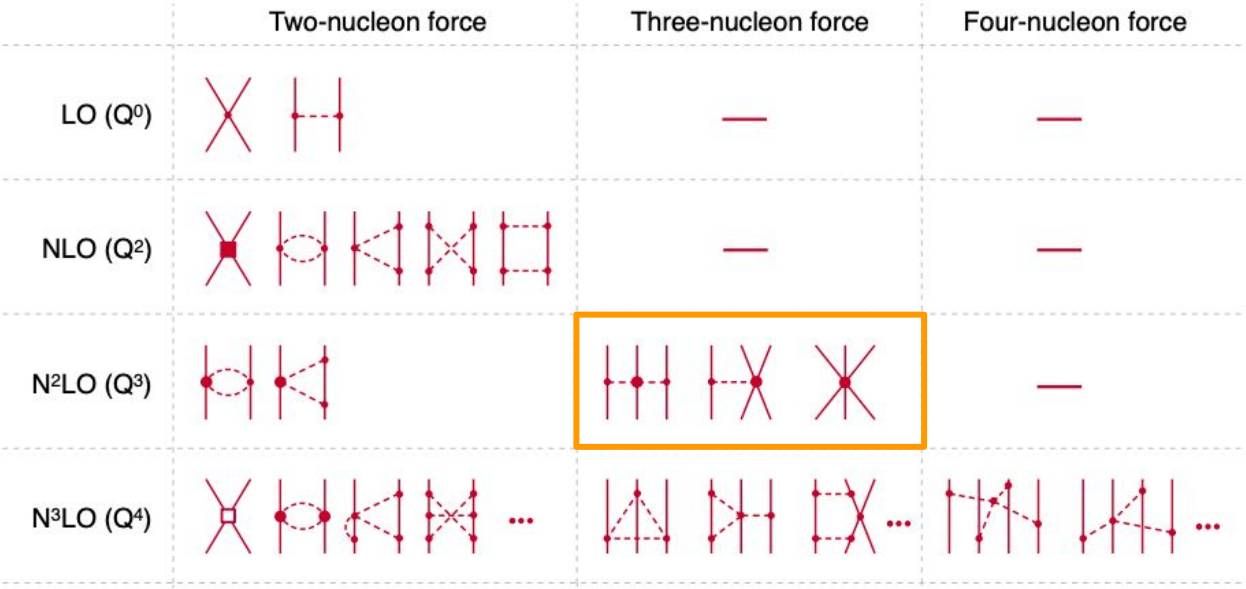
Pair	r_{Core} [fm]	r_{Eff} [fm]
p-p	1.1	1.2
p-Λ	1.0	1.3
p-Σ^0	0.87	1.02
p-Ξ^-	0.93	1.02
p-Ω^-	0.86	0.95

The SU(3) interactions puzzle



Three-body interaction

- Many-body systems **cannot be described satisfactorily** with two-body forces only → Three body forces included in the χEFT calculations at NNLO



[from J. Haidenbauer's talk at MESON 2021]

Three-body interaction

The parameters of the models are tuned using the binding energies of nuclei and hyper-nuclei but…

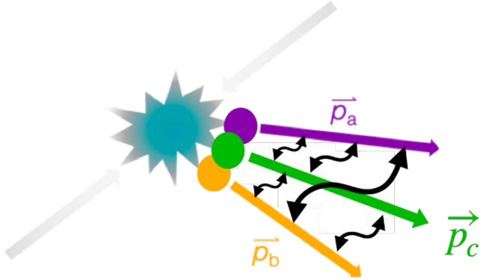
1. such measurements yield the **superposition of two and many-body effects**;

2. the interaction is tested at **“large” distances.**

—> In ^{12}C the average distance among nucleons is $\langle d \rangle \sim 2.2$ fm

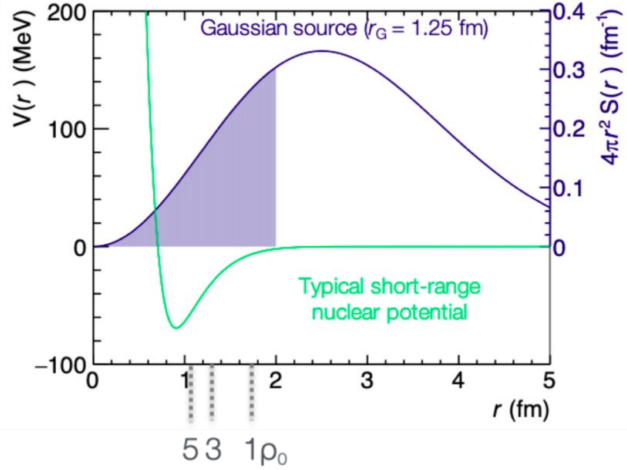
Three-body interaction

Three particles are emitted from a same common source and may undergo **final state interactions** before the detection.



Advantages:

- No higher order many-body effects which are instead present in bound objects;
- The typical source radii in two-body femtoscopy is ~1.25 fm —> test of the interaction at short distances



Three-body correlation function

Two-body correlation function

$$C(\mathbf{p}_1,\mathbf{p}_2) \equiv \frac{P(\mathbf{p}_1,\mathbf{p}_2)}{P(\mathbf{p}_1)\cdot P(\mathbf{p}_2)} = \frac{N_{same}(k^*)}{N_{mixed}(k^*)}$$

→

Three-body correlation function

$$C(\mathbf{p}_1,\mathbf{p}_2,\mathbf{p}_3) \equiv \frac{P(\mathbf{p}_1,\mathbf{p}_2,\mathbf{p}_3)}{P(\mathbf{p}_1)\cdot P(\mathbf{p}_2)\cdot P(\mathbf{p}_3)} = \frac{N_{same}(Q_3)}{N_{mixed}(Q_3)}$$

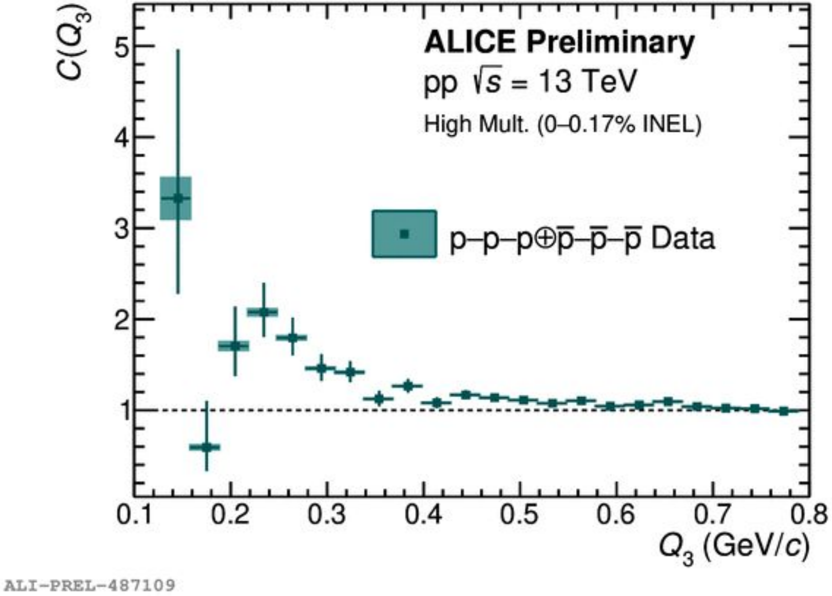
The small statistics requires to project the correlation function on **one** observable.
The hyper-momentum Q_3 (Lorentz invariant) is defined as:

$$Q_3 = \sqrt{-q_{12}^2 - q_{23}^2 - q_{31}^2}$$

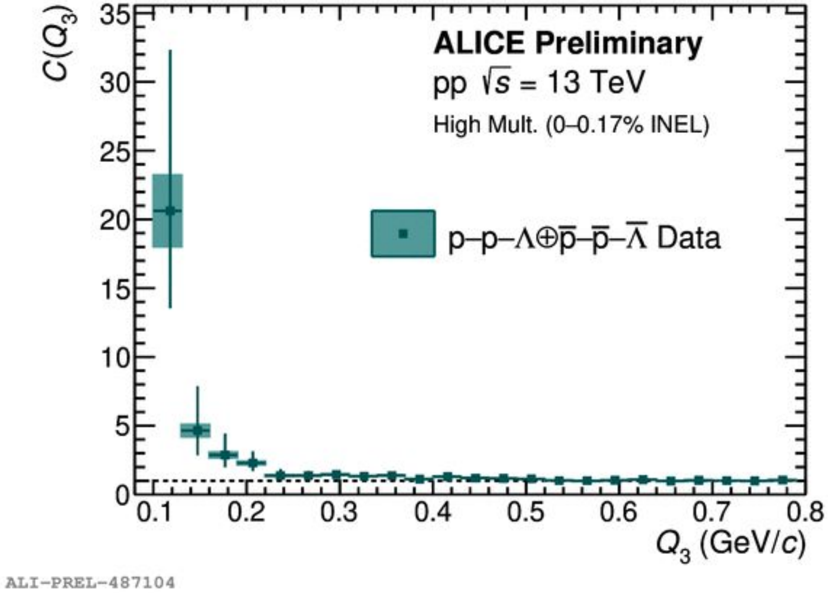
$$q^\mu = \left(p_i - p_j\right)^\mu - \frac{\left(p_i - p_j\right)\cdot P}{P^2}P^\mu \qquad P \equiv p_i + p_j$$

p-p-p and p-p-Λ Correlation Functions

Measured triplets
at Q_3 < 0.4 GeV/c ----> 1011



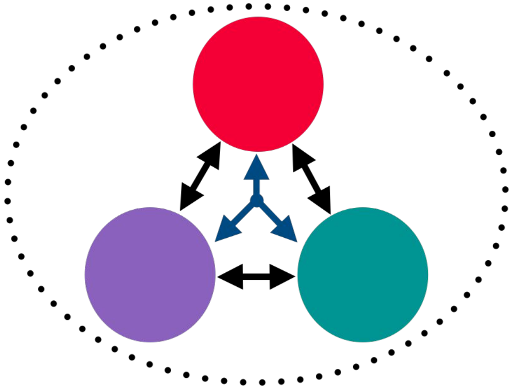
Measured triplets
at Q_3 < 0.4 GeV/c ----> 496



<u>**These are not genuine three-body correlation functions**</u>

Accessing the genuine three-body correlation

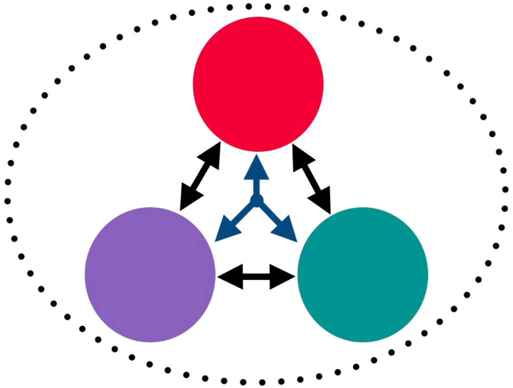
- Measured three particle correlation function includes both two-body and genuine three-body interactions.



Accessing the genuine three-body correlation

- Measured three particle correlation function includes both two-body and genuine three-body interactions.

- We use Kubo's cumulant expansion method for the same pair distribution and define a femtoscopic cumulant to access genuine three body correlation.



JOURNAL OF THE PHYSICAL SOCIETY OF JAPAN, Vol. 17, No. 7, JULY 1962

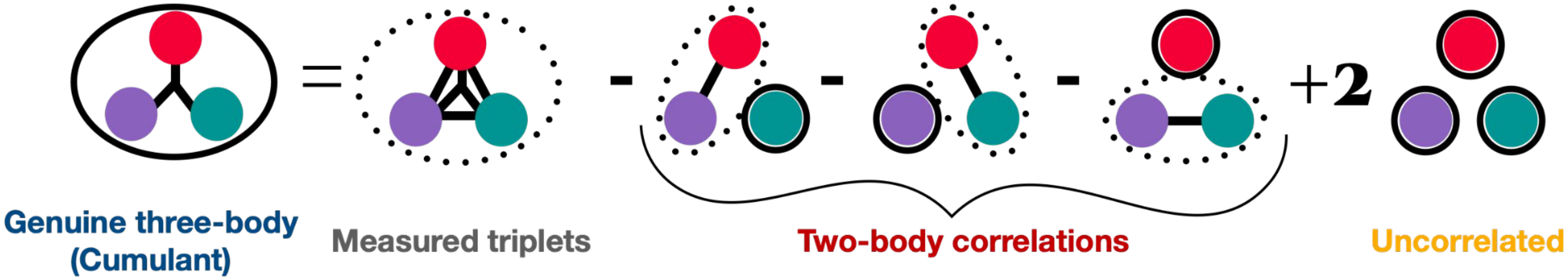
Generalized Cumulant Expansion Method*

Ryogo KUBO

Department of Physics, University of Tokyo

(Received April 11, 1962)

Kubo’s cumulant expansion method



In terms of correlation functions:

$$\mathbf{c}_3\left(\mathbf{p}_1,\mathbf{p}_2,\mathbf{p}_3\right) = C([\mathbf{p}_1,\mathbf{p}_2,\mathbf{p}_3]) - \underbrace{C([\mathbf{p}_1,\mathbf{p}_2],\mathbf{p}_3) - C(\mathbf{p}_1,[\mathbf{p}_2,\mathbf{p}_3]) - C([\mathbf{p}_1,\mathbf{p}_3],\mathbf{p}_2)} + 2$$

Genuine three-body (Cumulant) | Measured triplets | Two-body correlations | Uncorrelated

The pairs in the square brackets are correlated, the particle outside is not correlated.

Lower order contributions evaluation

Data-driven approach

Using the **same** and **mixed events** distributions:

$$C([\mathbf{p}_1, \mathbf{p}_2], \mathbf{p}_3) = \frac{N_2(\mathbf{p}_1, \mathbf{p}_2)\ N_1(\mathbf{p}_3)}{N_1(\mathbf{p}_1)\ N_1(\mathbf{p}_2)\ N_1(\mathbf{p}_3)}$$

The hyper-momentum Q_3 is calculated from the measured single particle momenta

$$(\mathbf{p}_1, \mathbf{p}_2, \mathbf{p}_3) \rightarrow Q_3$$

Projector method

Using the **two-body correlation function** of the pair (1,2).

A kinematic transformation from

$$k^*_{12} \text{ (pair)} \rightarrow Q_3 \text{ (triplet)}$$

$$C(k^*_{12}) \rightarrow C(Q_3)$$

is performed.

For the pair i-j we have

$$C_3^{ij}(Q_3) = \int \underbrace{C_2(k^*_{ij})}_{\text{two-body correlation function}} \underbrace{W_{ij}(k^*_{ij}, Q_3)}_{\text{projector}} \, dk^*_{ij}$$

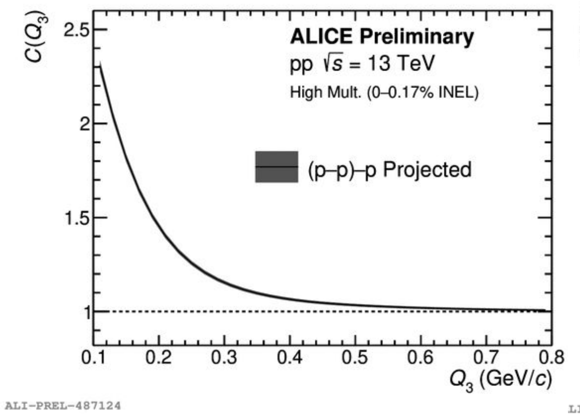
Two-body correlations

$$C_{ij}(Q_3) = \int C_{ij}(k^*) \cdot W_{ij}(k^*, Q_3)\ dk^*$$

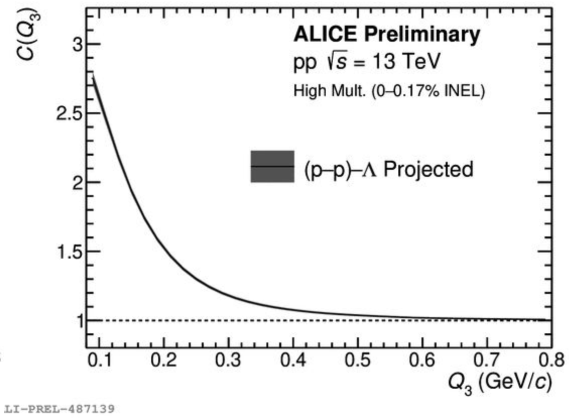
Outputs:

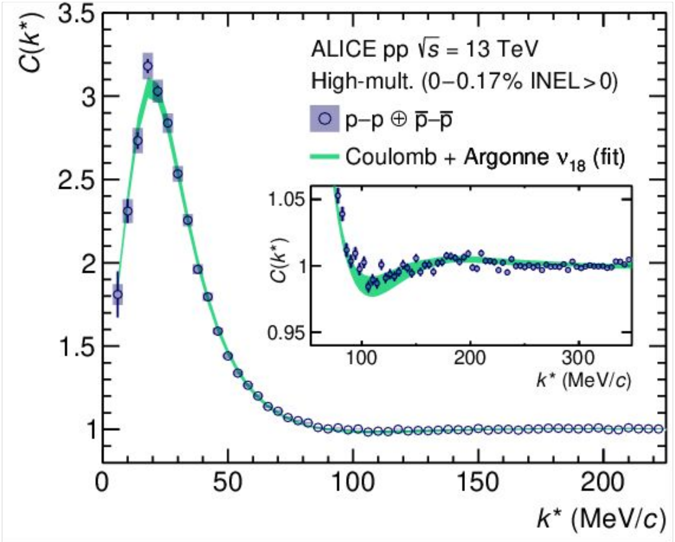
Input:
proton-proton

(proton-proton)-proton



(proton-proton)-Λ





[ALICE Collaboration / Physics Letters B 805 (2020) 135419]

Two-body correlations

$$C_{ij}(Q_3) = \int C_{ij}(k^*) \cdot W_{ij}(k^*, Q_3)\ dk^*$$

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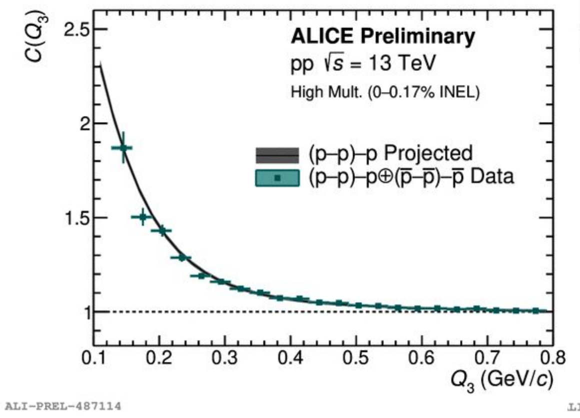
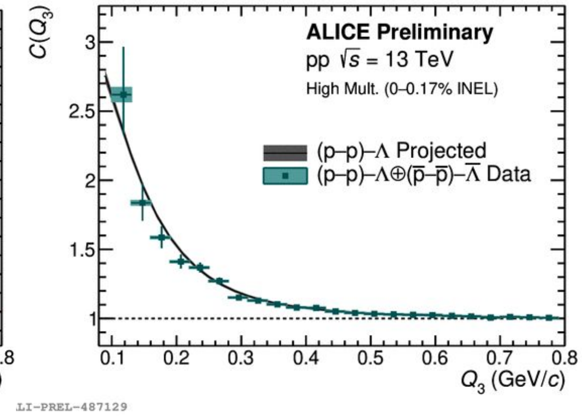
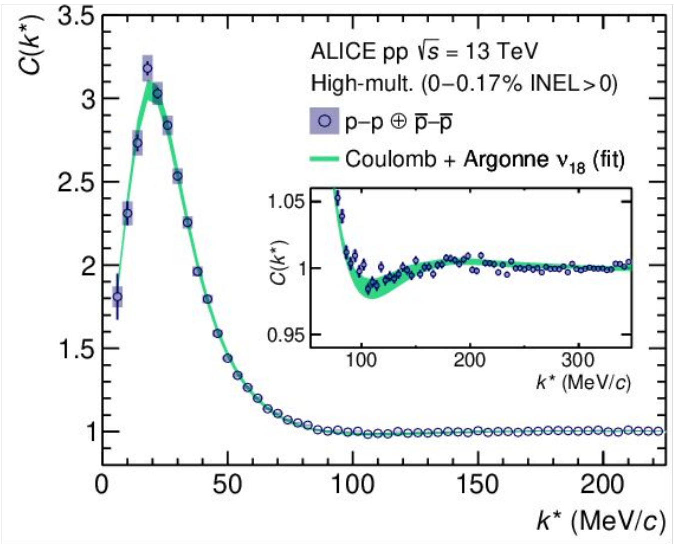


(proton-proton)-Λ





Data-driven approach VS Projector method

[ALICE Collaboration / Physics Letters B 805 (2020) 135419]

Two-body correlations

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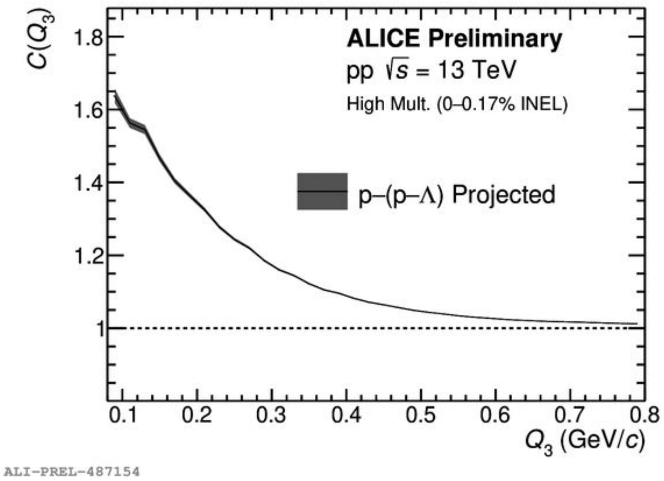
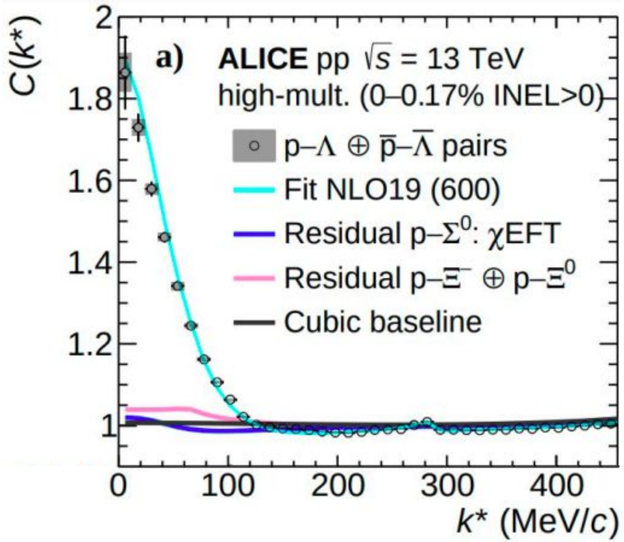
(proton-Λ)-proton



Input:
proton-Λ



[ALICE Collaboration / arXiv:2104.04427 (submitted to PRL)]

Two-body correlations

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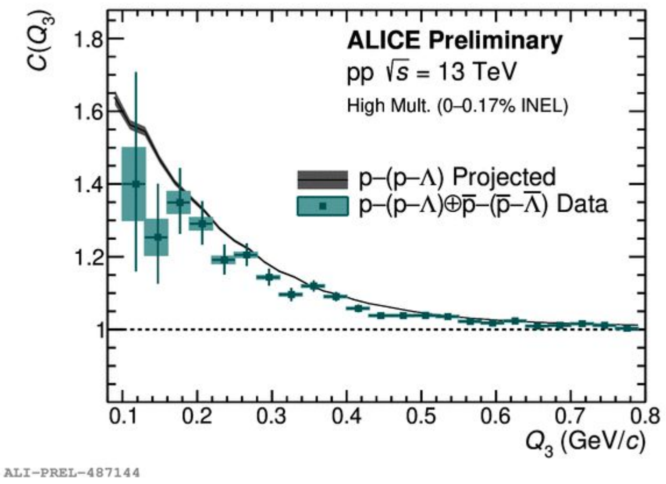
Output:
(proton-Λ)-proton



Data-driven approach VS Projector method

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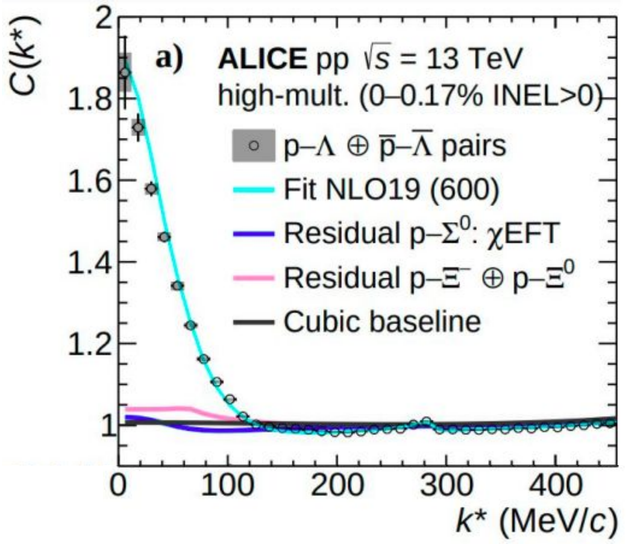

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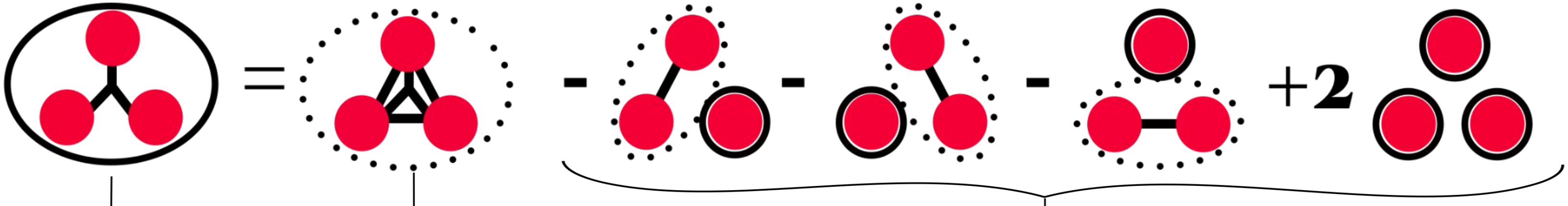
Kubo's Cumulant expansion method

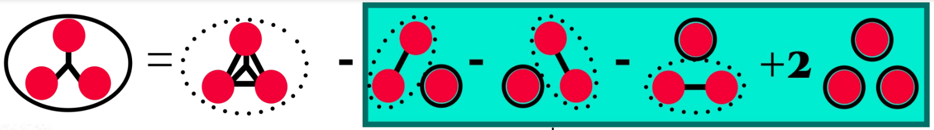


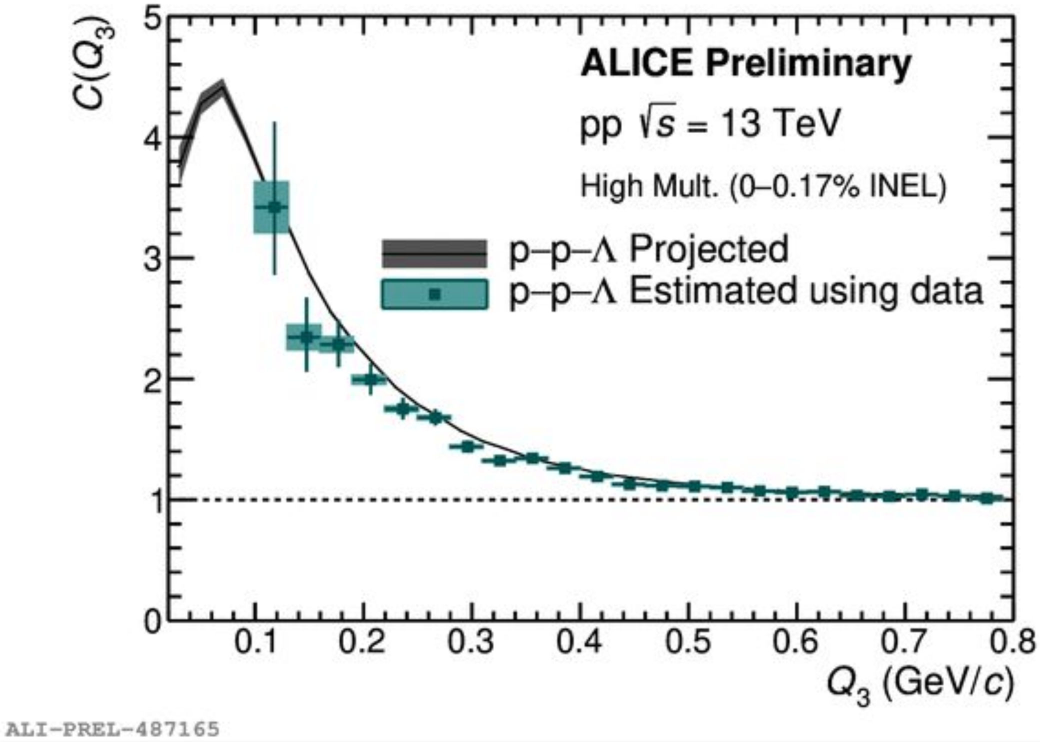
Measured correlation function

Lower order correlations

Three-body cumulant
(to be extracted)

p-p-Λ: two-body CF projected onto Q_3





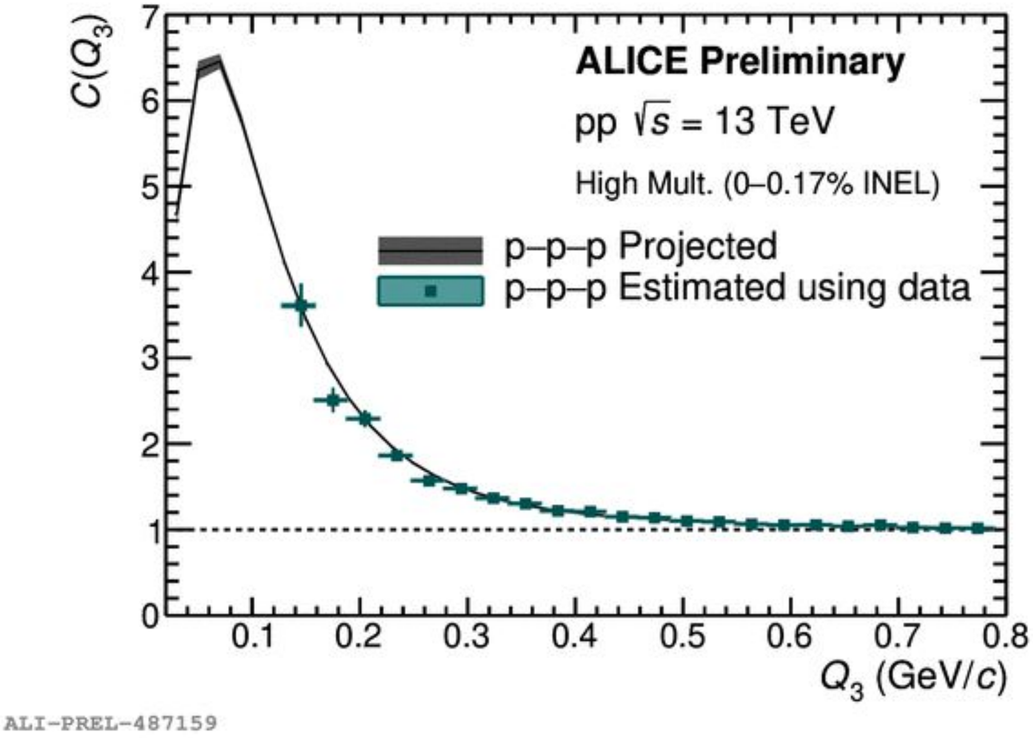
Lower order contributions to the three-body cumulant

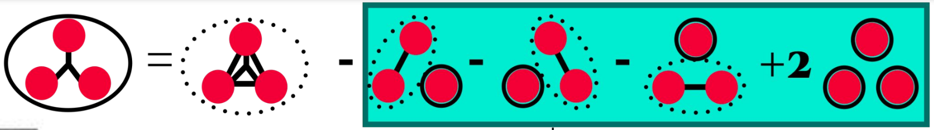
$$C_{pp\Lambda}^{\mathrm{two-body}}(Q_3) = C_3^{pp}(Q_3) + 2\ C_3^{p\Lambda}(Q_3) - 2$$

Comparison:

- **Data-driven approach**
- **Projector method**

p-p-p: two-body CF projected onto Q_3





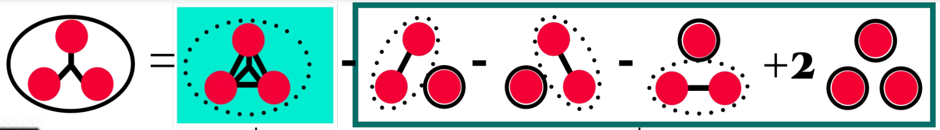
Lower order contributions to the three-body cumulant

$$C_{ppp}^{\text{two-body}}(Q_3) = 3\ C_3^{pp}(Q_3) - 2$$

Comparison:

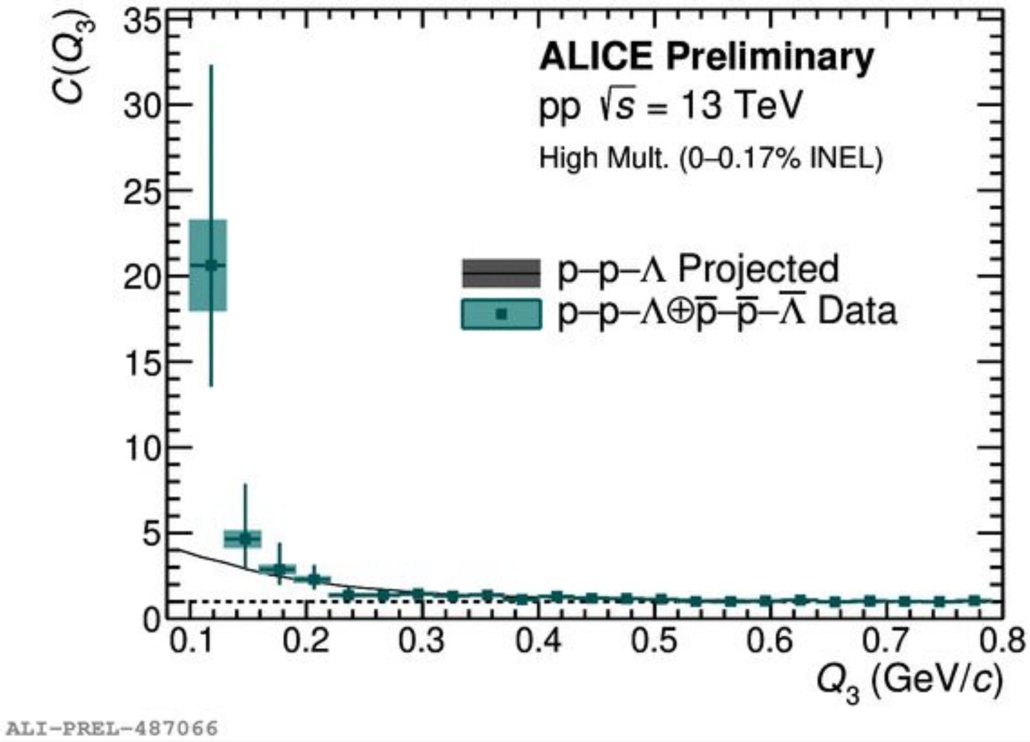
- Data-driven approach
- Projector method

p-p-Λ Correlation Function



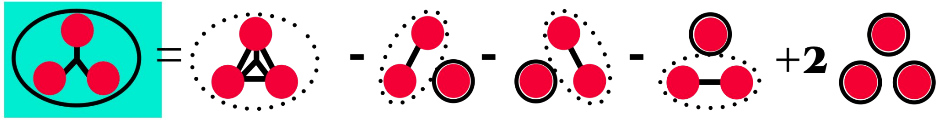
The measured p-p-Λ correlation function

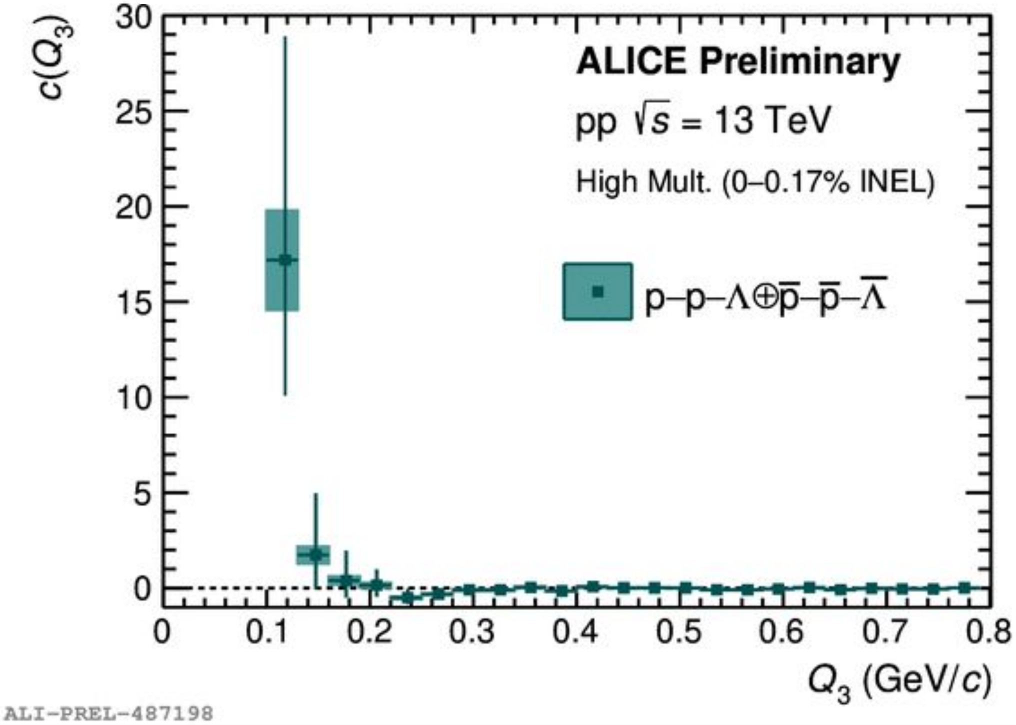
Lower order contributions calculated with the projector method



The shape deviates from the two-body correlations projected onto Q_3 (gray curve).

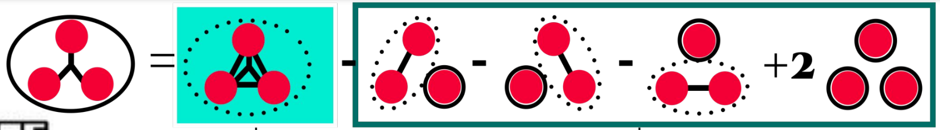
p-p-Λ Cumulant





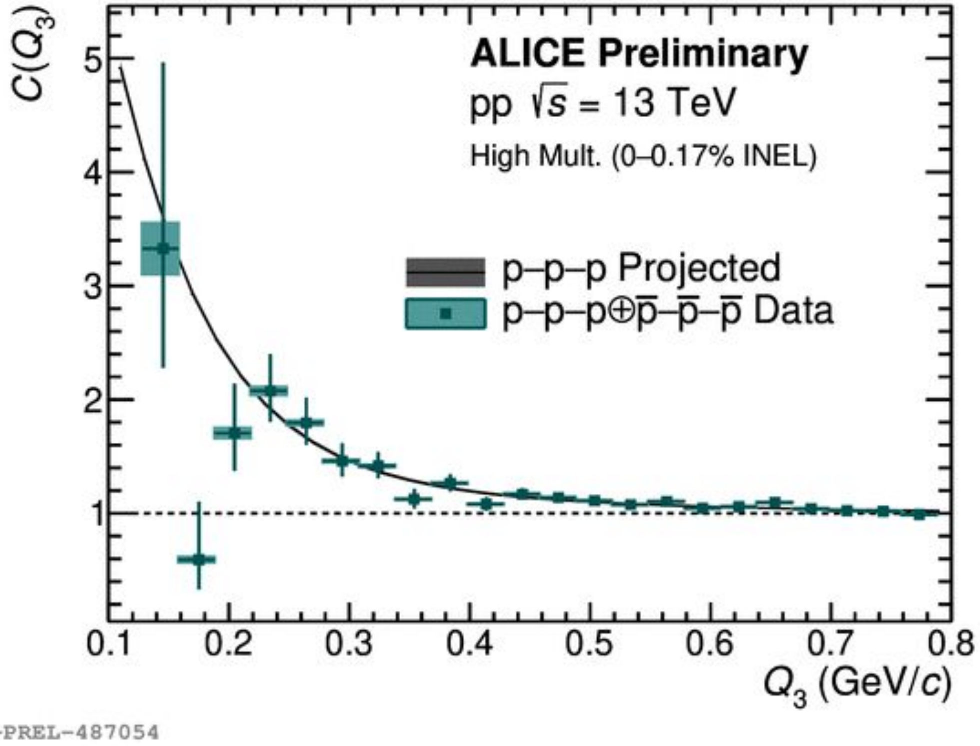
Positive cumulant indicates an attractive p-p-Λ interaction

p-p-p Correlation Function



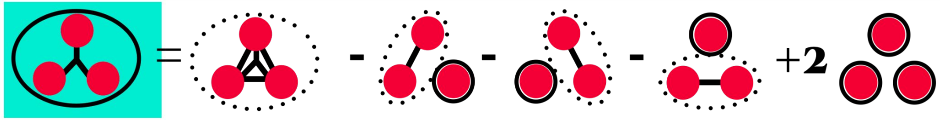
The measured p-p-p correlation function

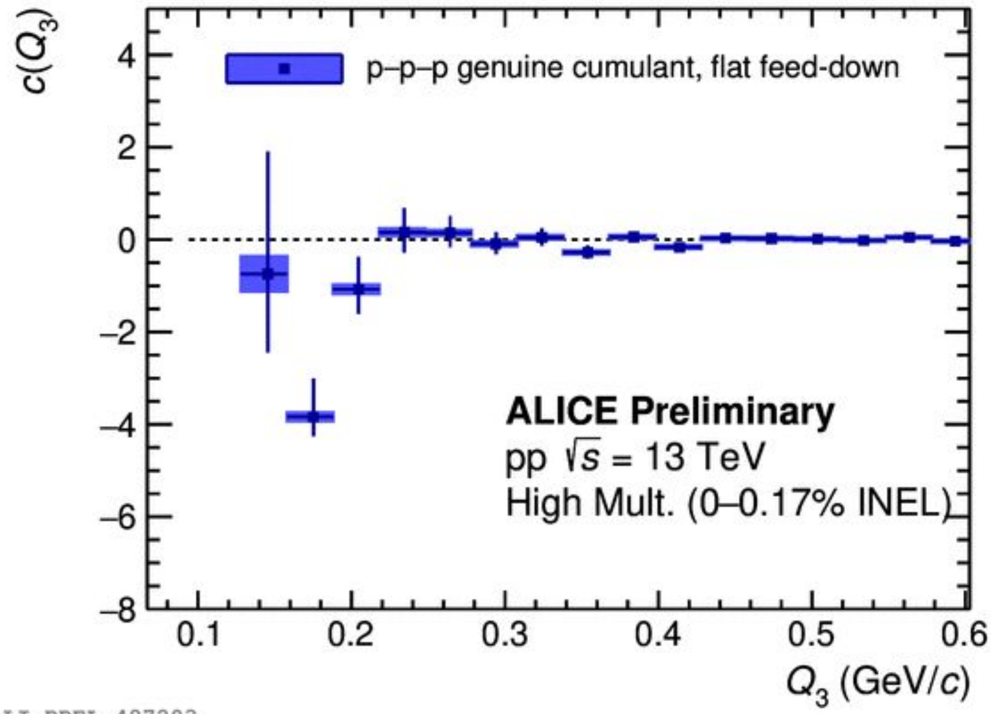
Lower order contributions calculated with the projector method



Significant deviation of the measured correlation function from the two-body correlations projected onto Q_3 (gray curve).

p-p-p Cumulant





ALI-PREL-487203

Cumulant extracted. The feed-down from the resonances is also considered.

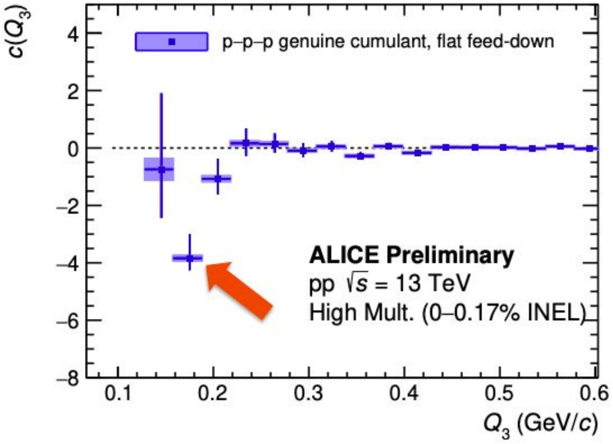
The statistical significance for the measured deviation is:

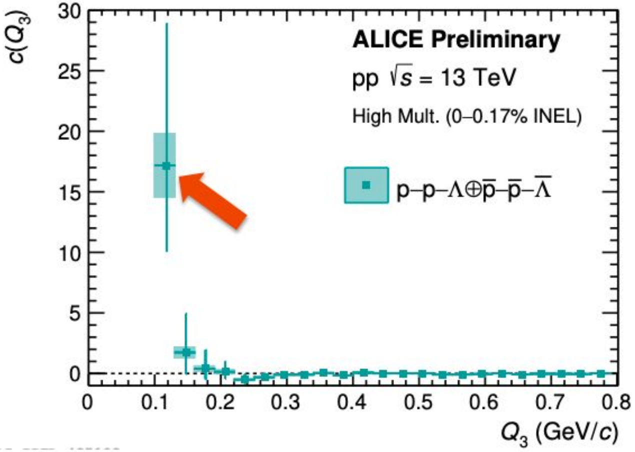
n_σ = 2.9 in the first 9 bins

MODELS TO INTERPRET THE DATA ARE NEEDED (theoretical calculation of the three-body scattering)

Summary

- First measurement of three-baryon correlation functions
- Cumulants for p-p-p and p-p-Λ extracted with the Kubo's method

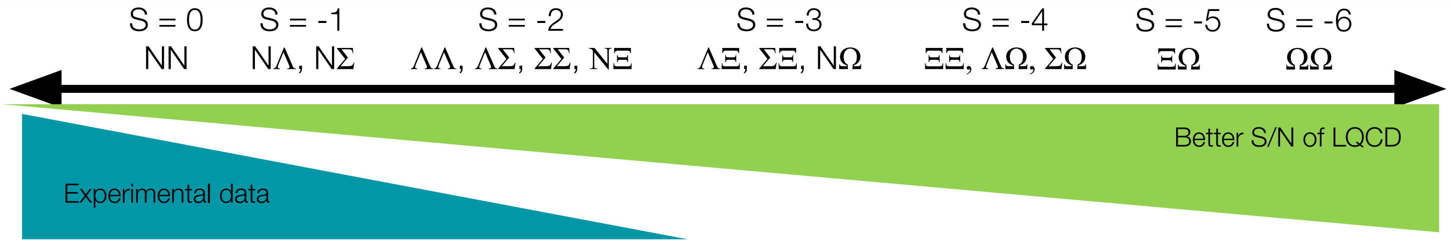




- **p-p-p:** signal below 0 indicating a genuine three-body repulsive interaction (**n_σ = 2.9**)
- **p-p-Λ:** signal above 0 indicating an attractive interaction
- ALICE Run-3 data should provide statistically significant results
- **Calculations for the three-body scattering are needed**

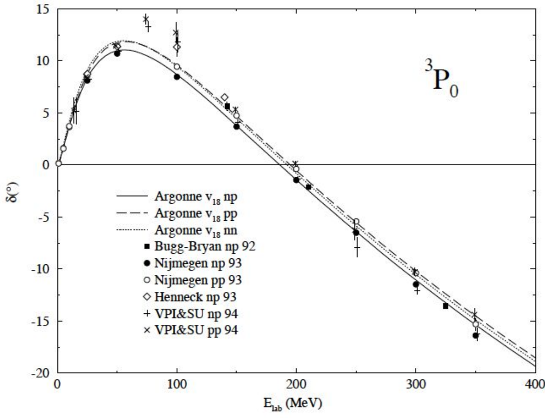
Thank You

Strong interaction between (strange) hadrons



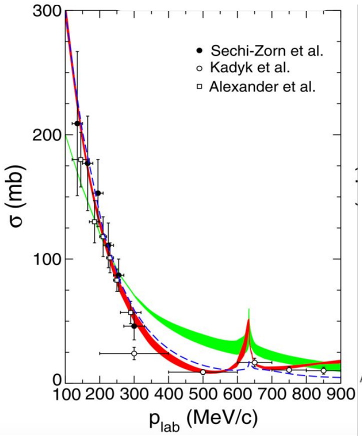
Strong interaction between (strange) hadrons

N–N → N–N



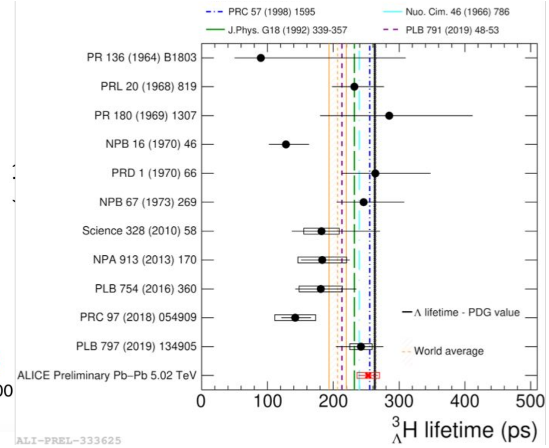
R. B. Wiringa, V. G. J. Stoks, R. Schiavilla, PRC 51 (1995) 38-51.

p–Λ → p–Λ

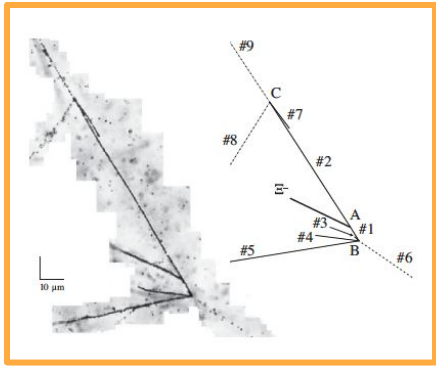


LO from H. Polinder, J.Haidenbauer, U. Meißner, NPA 779 (2006) 244 and NLO from J.Haidenbauer., N.Kaiser et al., NPA 915 (2013) 24.

Hypertriton lifetime



Ξ hypernucleus



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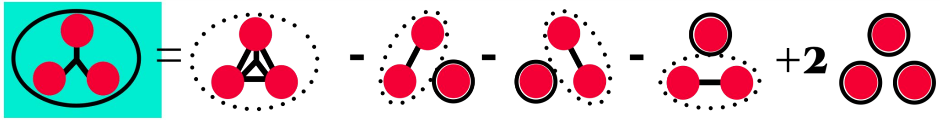
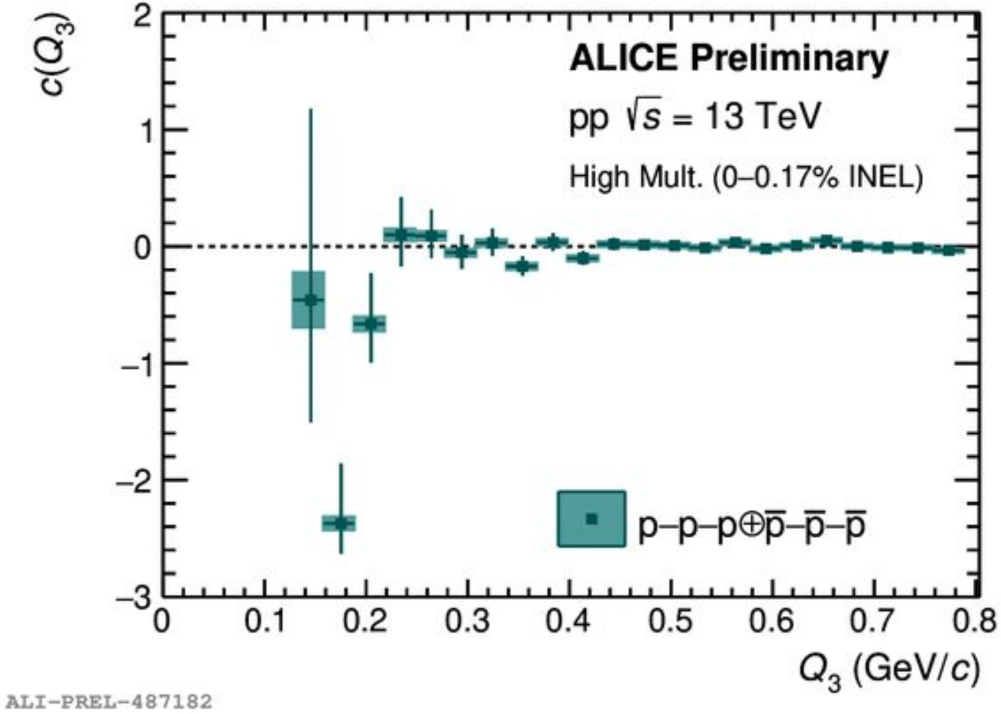
ppp Cumulant





Contributions to the measured cumulant:

p-p-p	61.8%
p-p-p_{Λ} x3	19.6%
p-p-$p_{\Sigma+}$ x3	8.5%
p-p_{Λ}-p_{Λ} x3	0.69%
p-p_{Λ}-$p_{\Sigma+}$ x3	0.3 %
p-$p_{\Sigma+}$-$p_{\Sigma+}$ x3	0.13%

Kubo's cumulant expansion method

- X_i denotes the general i-th stochastic variable
- The most general decomposition of 2-particle correlation is:

$$\langle X_1 X_2 \rangle = \langle X_1 \rangle \langle X_2 \rangle + \langle X_1 X_2 \rangle_c$$

- By definition, the 2nd term on the right is the 2-particle cumulant
- Cumulants cannot be measured directly, however:

$$\langle X_1 X_2 \rangle_c = \langle X_1 X_2 \rangle - \langle X_1 \rangle \langle X_2 \rangle$$

Kubo's cumulant expansion method

- The most general decomposition of 3-particle correlation is:

$$\begin{aligned} \langle X_1 X_2 X_3 \rangle &= \langle X_1 \rangle \langle X_2 \rangle \langle X_3 \rangle \\ &+ \langle X_1 X_2 \rangle_c \langle X_3 \rangle + \langle X_1 X_3 \rangle_c \langle X_2 \rangle + \langle X_2 X_3 \rangle_c \langle X_1 \rangle \\ &+ \langle X_1 X_2 X_3 \rangle_c \end{aligned}$$

- Using the 2-particle cumulant: $\langle X_1 X_2 \rangle_c = \langle X_1 X_2 \rangle - \langle X_1 \rangle \langle X_2 \rangle$

- Working recursively from higher to lower orders, we have 3-particle cumulant expressed in terms of the measured 3-, 2-, and 1-particle averages:

$$\begin{aligned} \langle X_1 X_2 X_3 \rangle_c &= \langle X_1 X_2 X_3 \rangle \\ &- \langle X_1 X_2 \rangle \langle X_3 \rangle - \langle X_1 X_3 \rangle \langle X_2 \rangle - \langle X_2 X_3 \rangle \langle X_1 \rangle \\ &+ 2 \langle X_1 \rangle \langle X_2 \rangle \langle X_3 \rangle \end{aligned}$$

The femtoscopy technique

Based on the correlation function $C(k^*) = \dfrac{P(\overrightarrow{p_a}, \overrightarrow{p_b})}{P(\overrightarrow{p_a})P(\overrightarrow{p_b})}$ k* = reduced relative momentum with $\overrightarrow{p_a^*} + \overrightarrow{p_b^*} = 0$

Theoretically formulated:

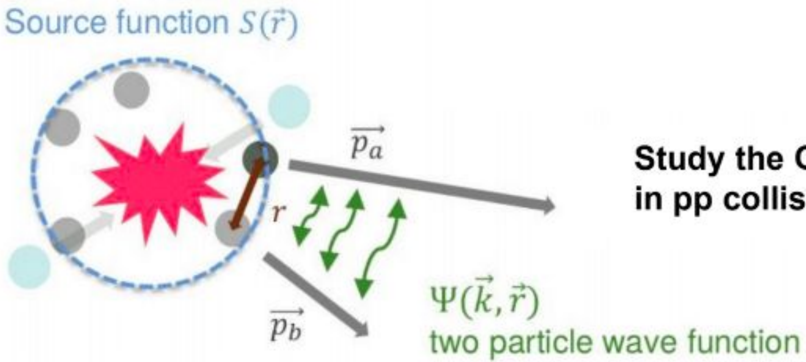
$$C(k^*) = \int S(\vec{r}, k)\,|\psi(\vec{r}, k)|^2\, d\vec{r}$$

(Koonin-Pratt equation)

Source

Relative wave function:
Sensitivity to the interaction potential

Theory



Study the C(k*) of hadron-hadron pairs in pp collisions ⇒ small particle source (~1 fm)

The femtoscopy technique

Based on the correlation function $C(k^*) = \frac{P(\overrightarrow{p_a}, \overrightarrow{p_b})}{P(\overrightarrow{p_a})P(\overrightarrow{p_b})}$ k* = reduced relative momentum with $\overrightarrow{p_a^*} + \overrightarrow{p_b^*} = 0$

Theoretically formulated:

$$C(k^*) = \int S(\vec{r}, k)|\psi(\vec{r}, k)|^2 \, d\vec{r}$$

(Koonin-Pratt equation)

Source

Relative wave function:
Sensitivity to the interaction potential

Theory

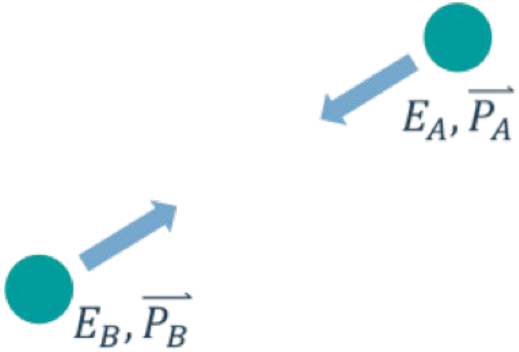
Experimentally:

$$C(k^*) = \xi(k^*) \otimes \frac{N_{\text{same}}(k^*)}{N_{\text{mixed}}(k^*)}$$

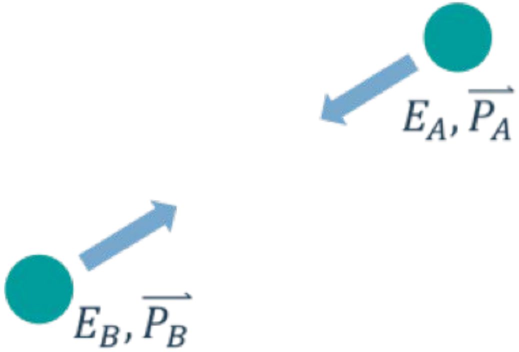
→ Pairs of particles from same collision

→ Particles produced in different collisions

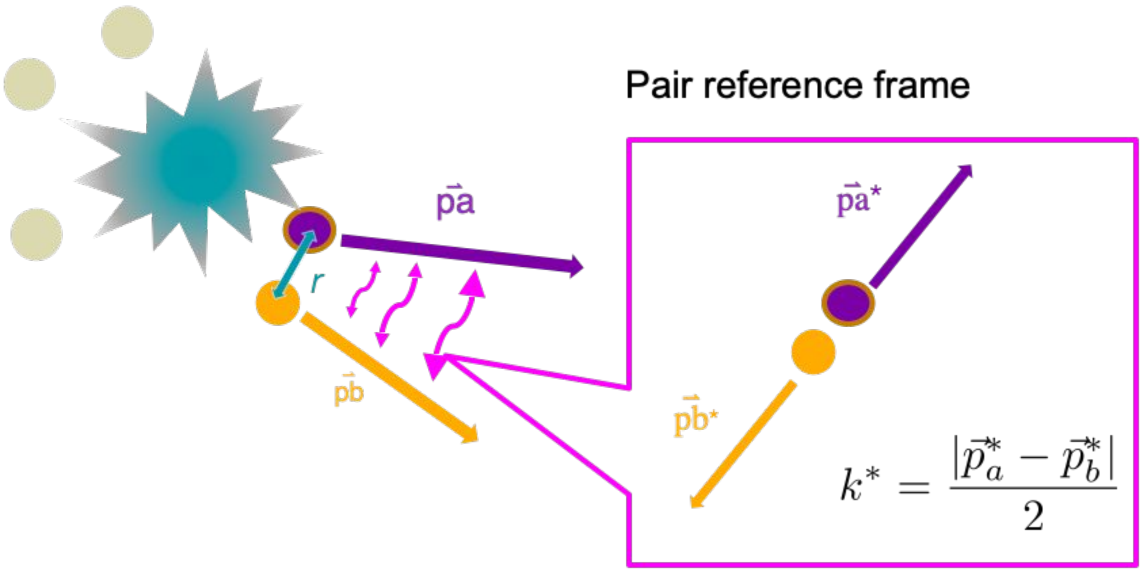
The femtoscopy technique



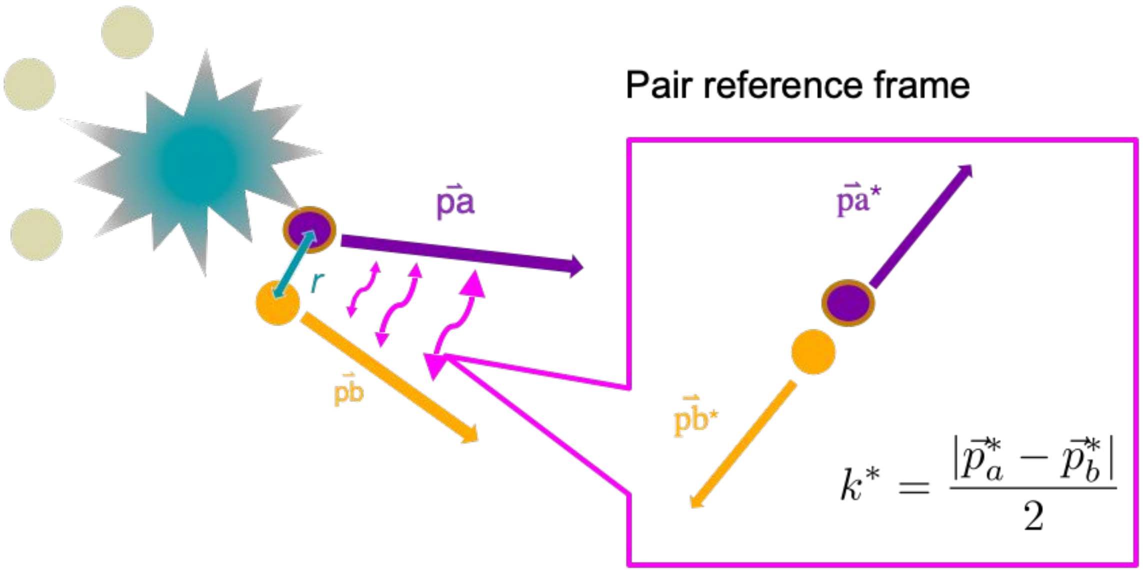
The femtoscopy technique



The femtoscopy technique



The femtoscopy technique



$$k^* = \frac{|\vec{p}_a^* - \vec{p}_b^*|}{2}$$

Schrödinger Equation:

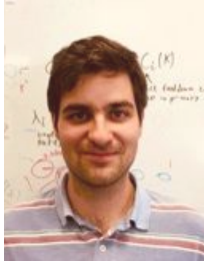
V(r) -> $\left|\psi\left(\vec{k}^*, \vec{r}\right)\right|^2$ relative wave function for the pair

The Femto-Guys

The Group Leader

Laura Fabbietti

Valentina Mantovani Sarti



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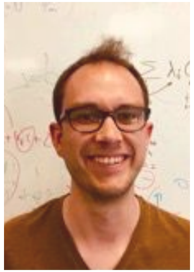

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Raffaele Del Grande

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