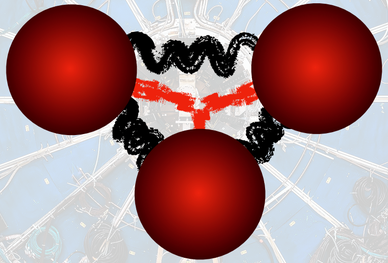
HADRON 2023

Novel technique to access the three-body interactions with ALICE at the LHC



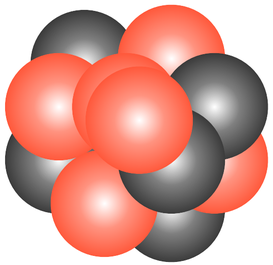
Laura Šerkšnytė
Technical University of Munich
On behalf of the ALICE Collaboration

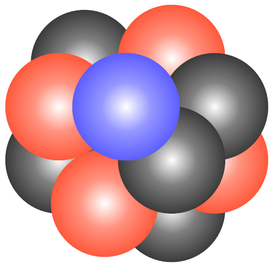
Genova 07.06.23

Many-body systems

- Properties of nuclei and hypernuclei cannot be described satisfactorily with two-body forces only

  L. Girlanda et al., PRC 102, 064003 (2020)





ρ

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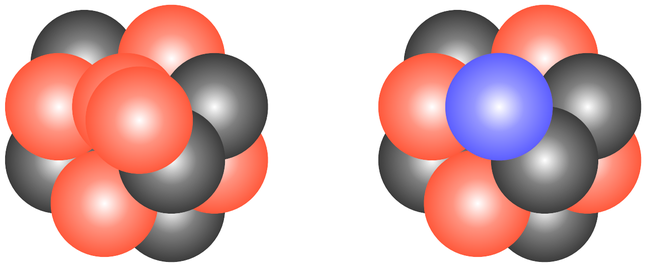
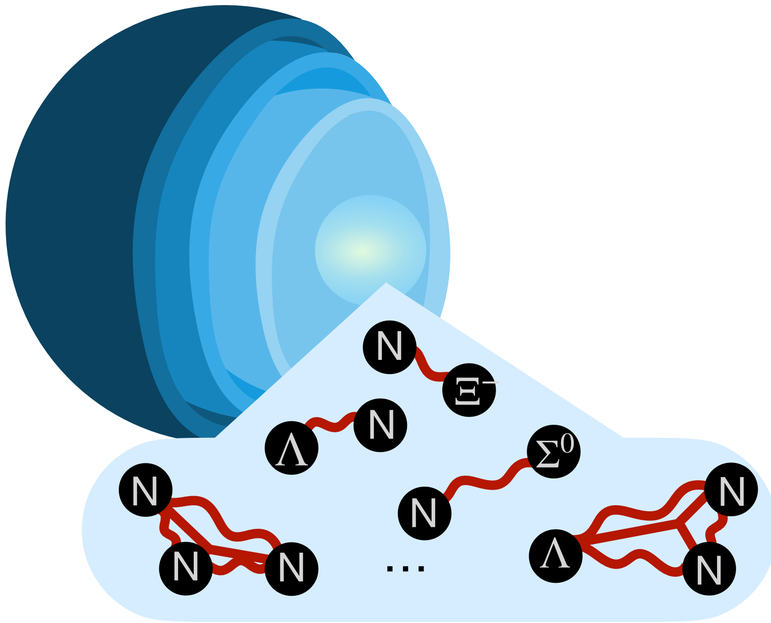


ρ

- The equation of state of dense matter is increasingly sensitive to the three-body forces with increasing density
- Description of such dense systems as neutron stars also requires three-body interactions

  D. Lonardoni et al., PRL 114, 092301 (2015)



Marcel Lesch 8 Jun 2023, 15:12

Neutron stars and three-body forces

- Three-body interaction models are fitted to reproduce measured (hyper)nuclei properties

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  → Very different consequences to the resulting mass to radii relation for neutron stars

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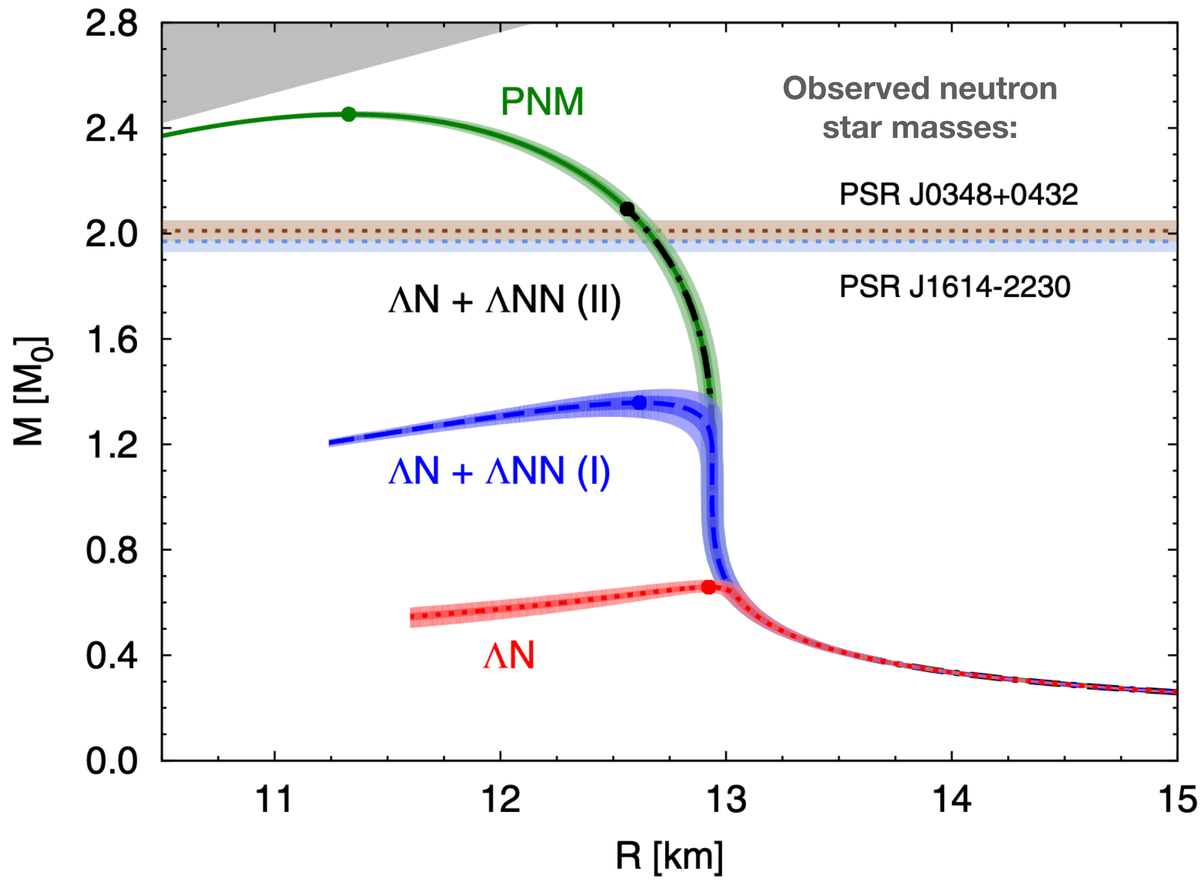

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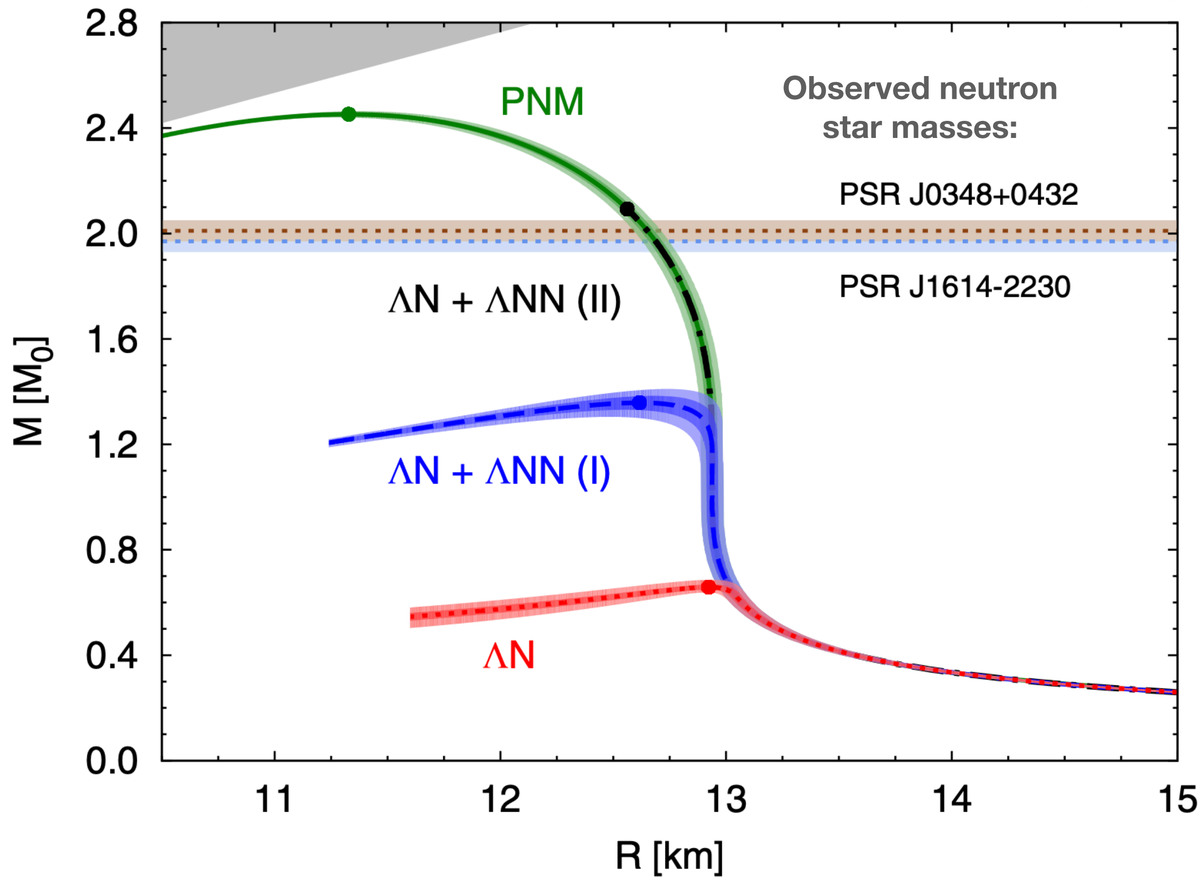
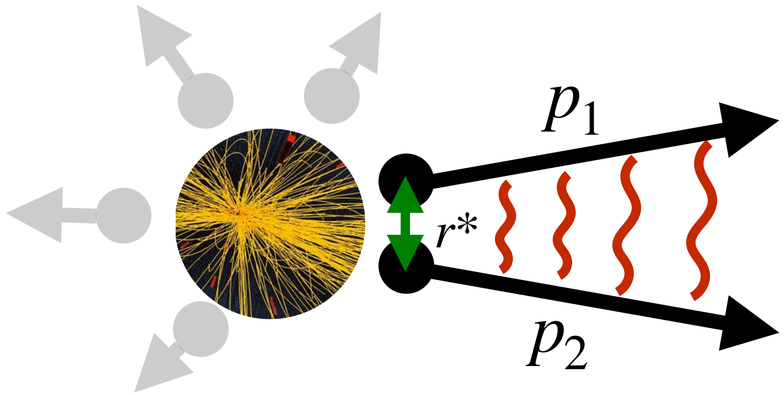


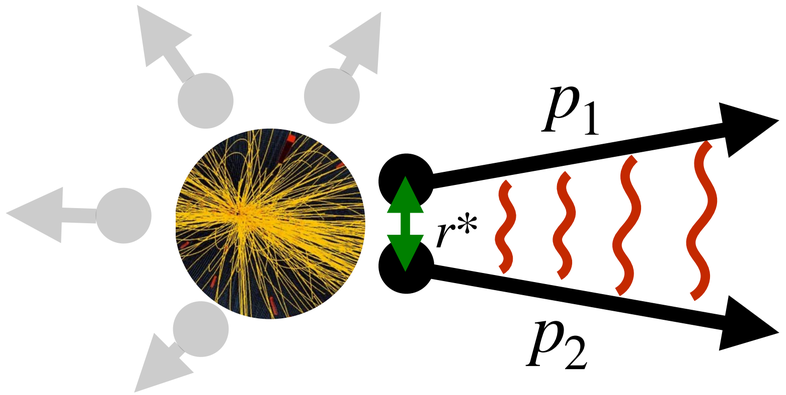
New observables are required to solve the three-body problem!

Femtoscopy



Emission source *S(r*)*

Femtoscopy



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$$C\left(k^*\right) = \mathcal{N}\frac{N_{\text{same}}\left(k^*\right)}{N_{\text{mixed}}\left(k^*\right)} = \int S\left(r^*\right)\left|\psi\left(\mathbf{k}^*, \mathbf{r}^*\right)\right|^2 \mathbf{d}^3 r^*$$

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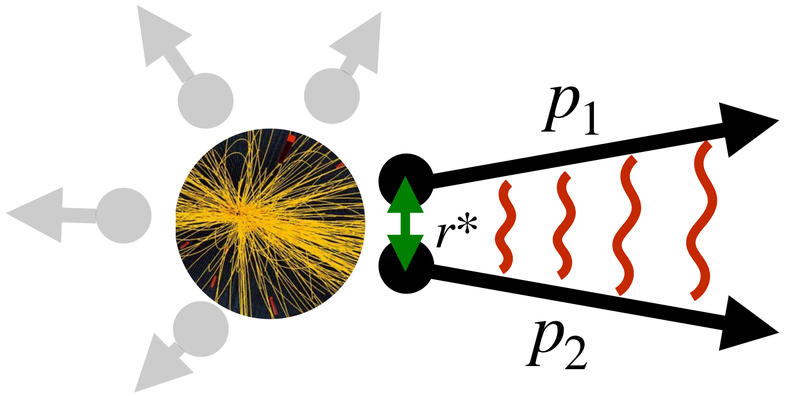
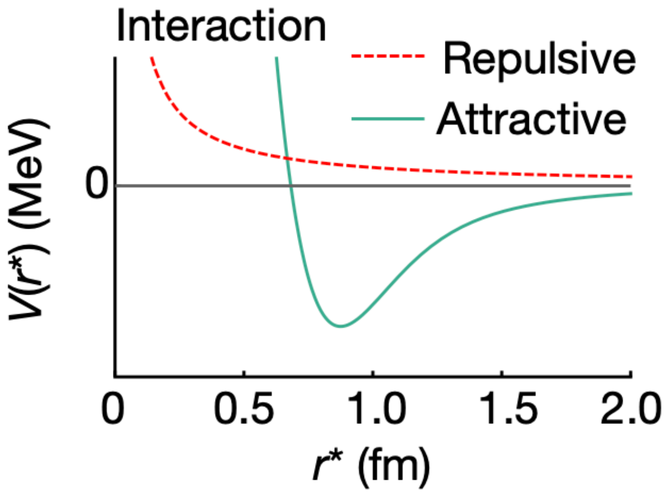


Emission source $S(r^*)$



Schrödinger equation

Two-particle wave function

$$\left|\psi\left(\mathbf{k}^*, \mathbf{r}^*\right)\right|$$

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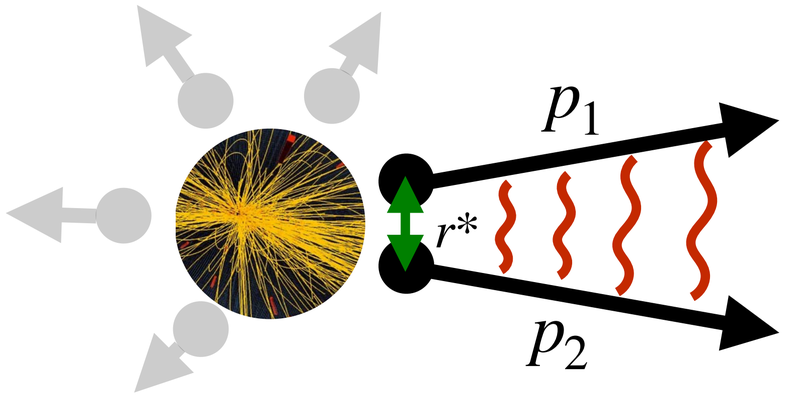

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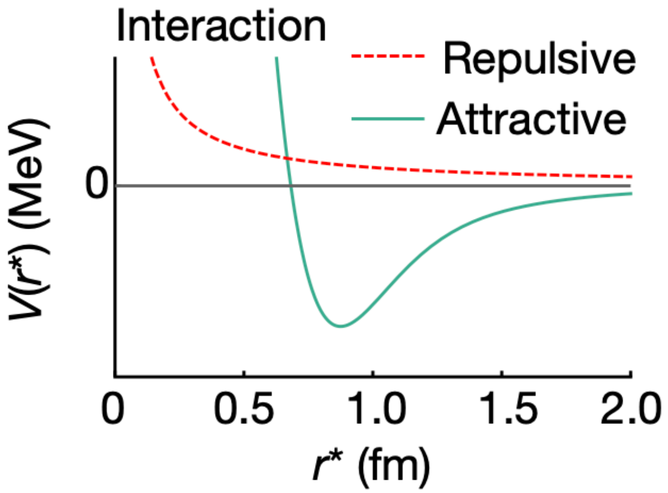

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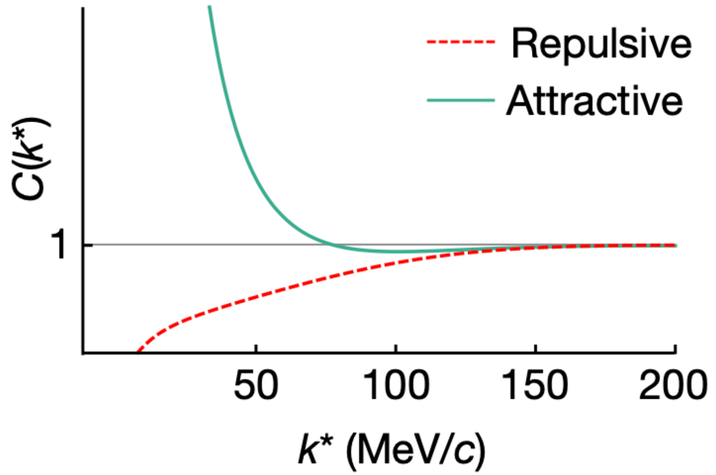

Correlation function $C(k^*)$

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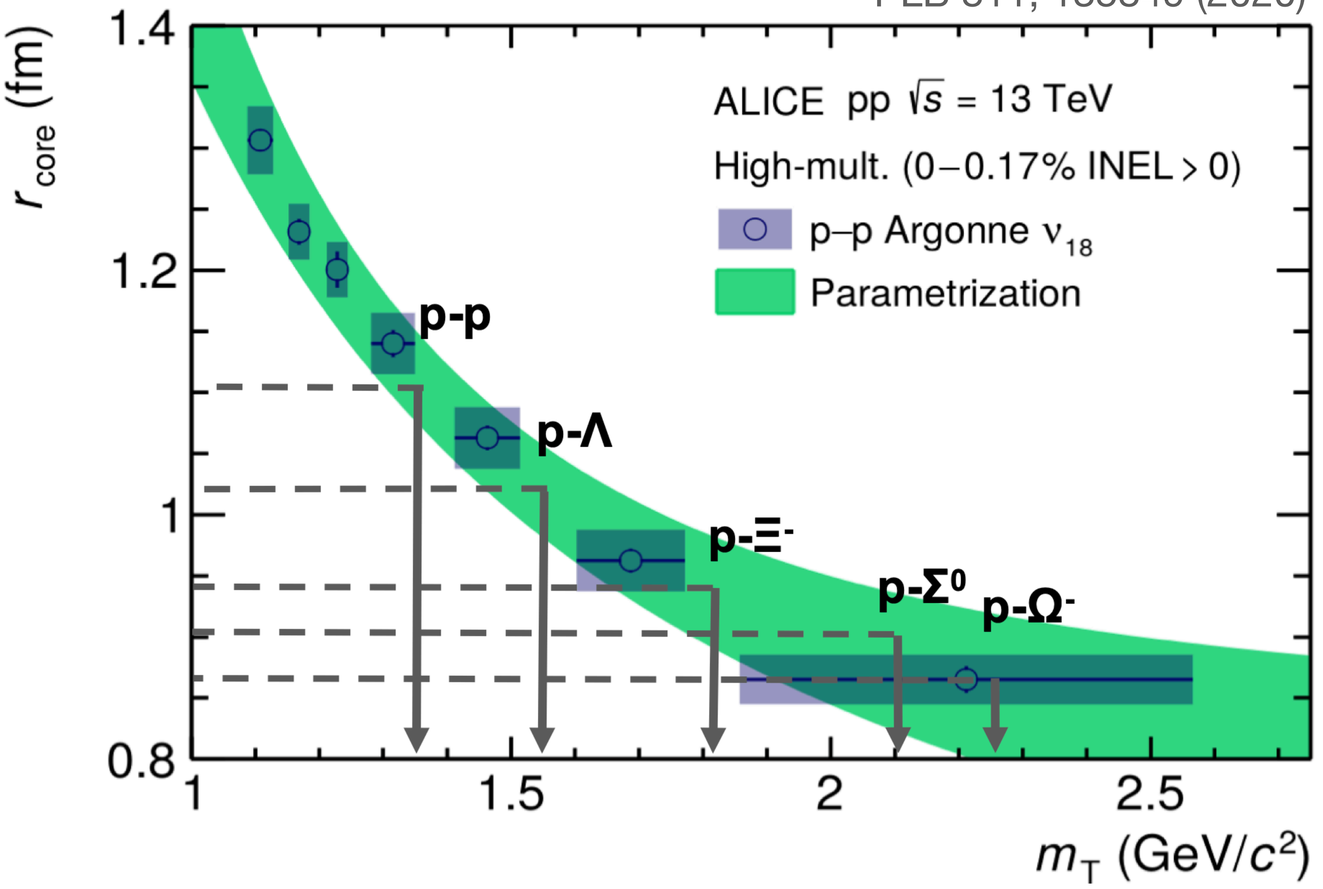
Emission source

- Two main contributions:
  - general: Collective effects result in Gaussian core
  - specific: Decaying resonances require source correction

- Access to very small distances in pp collisions at the LHC

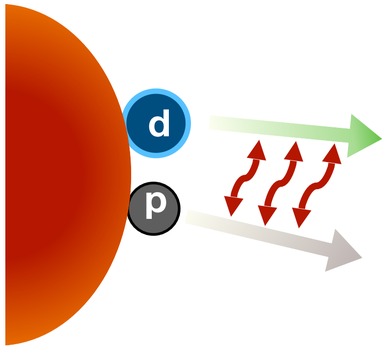
PLB 811, 135849 (2020)

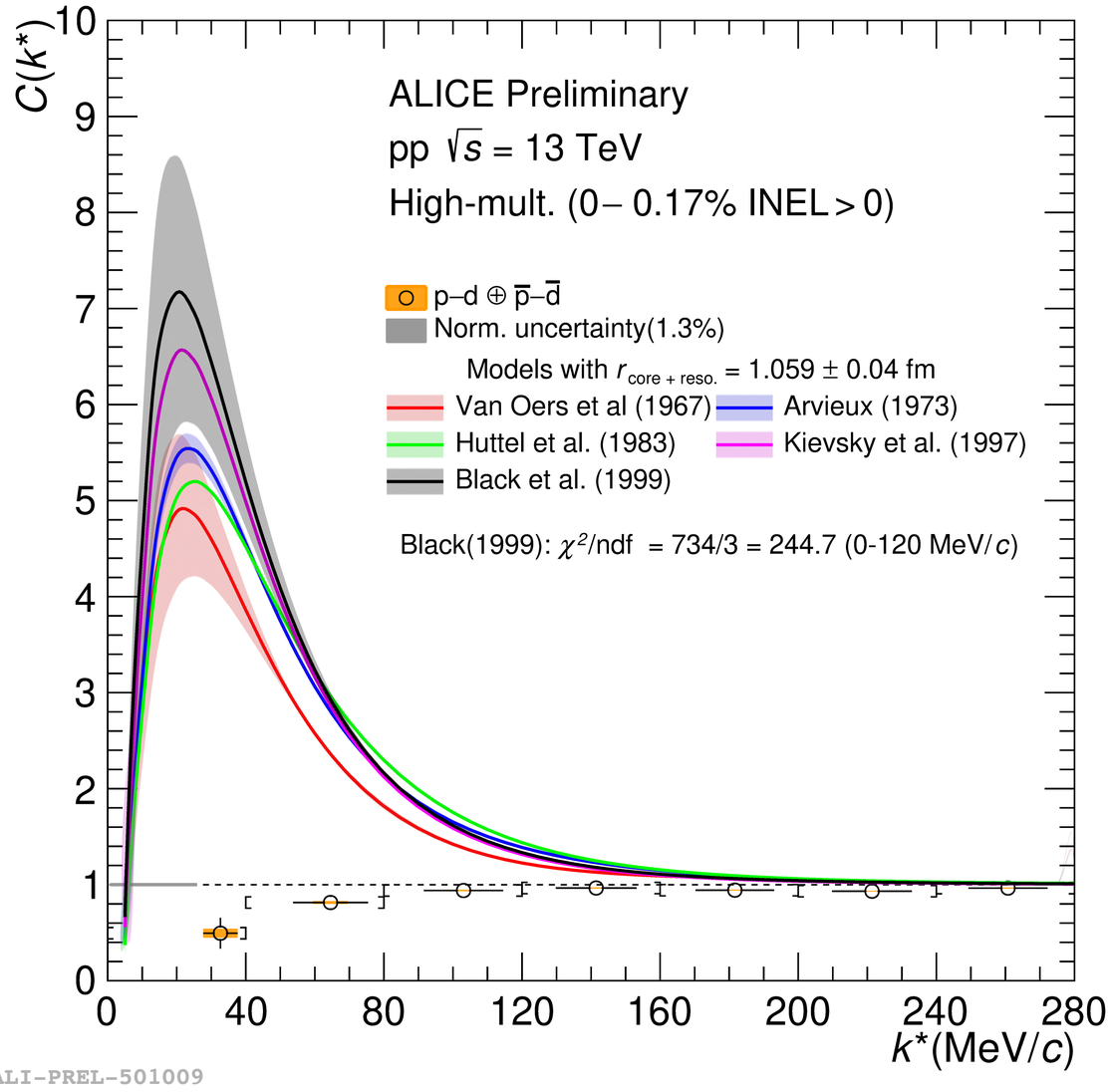


Proton-deuteron correlation

- Effective two-body system
  - Coulomb + Strong interactions via Lednický model; only s-wave
    R. Lednický, Phys. Part. Nuclei 40, 307–352 (2009)
  - Anchored to scattering experiments
  - Emission source: from m_T scaling

$$r_{\text{eff}}^{\text{pd}} = 1.059^{+0.04}_{-0.04}\ \text{fm}$$





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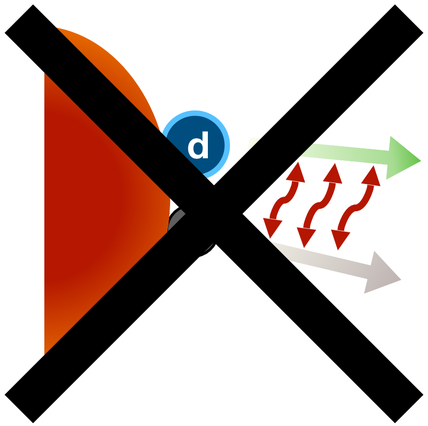

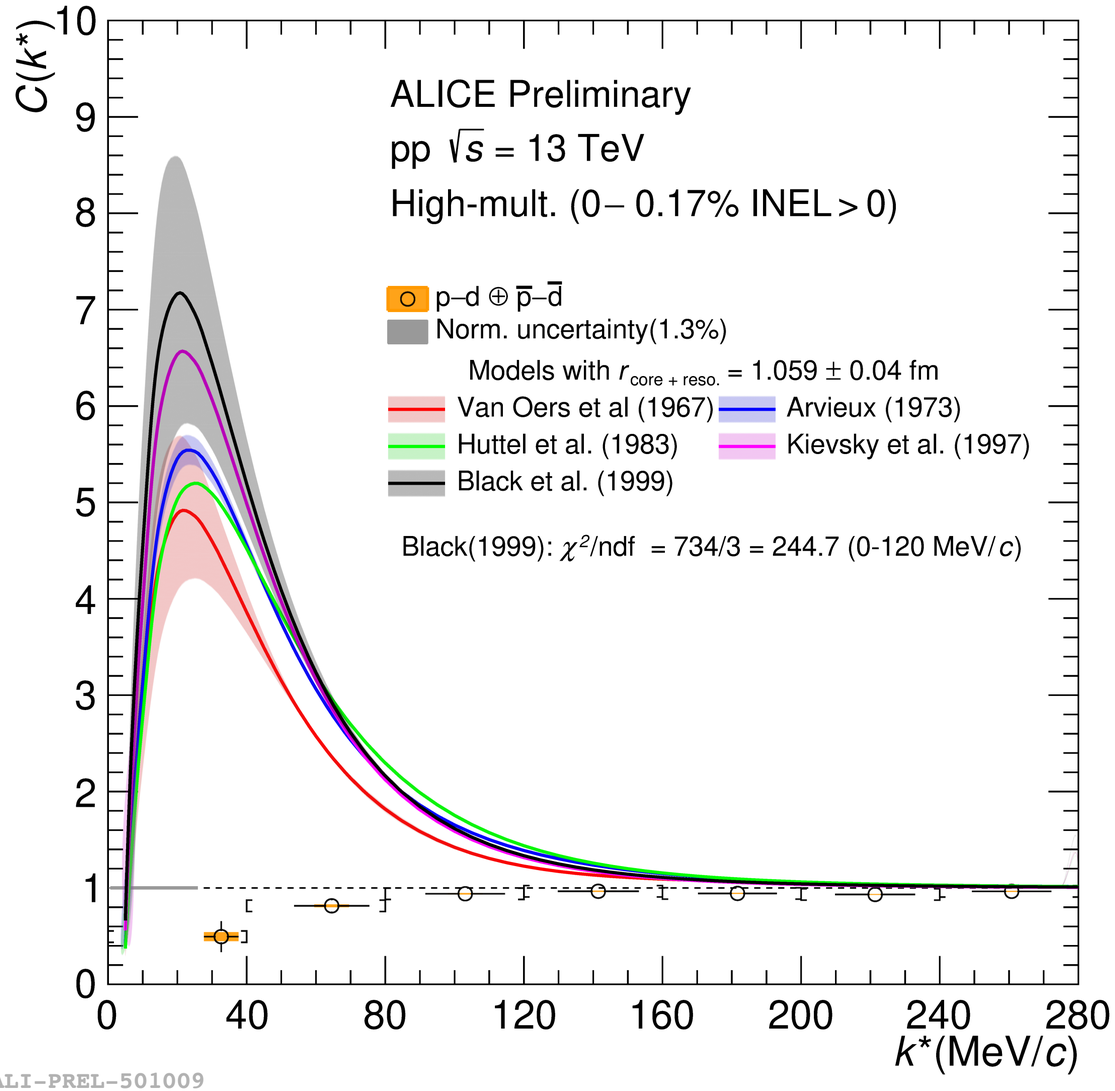

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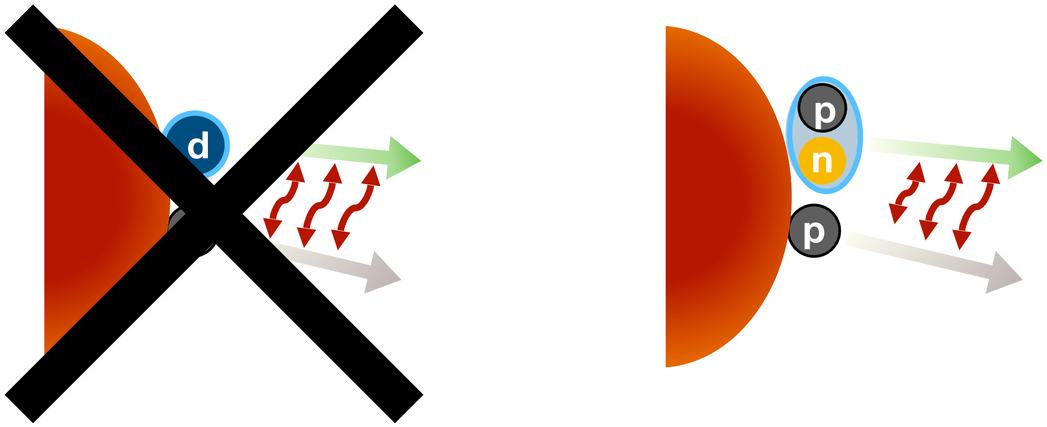
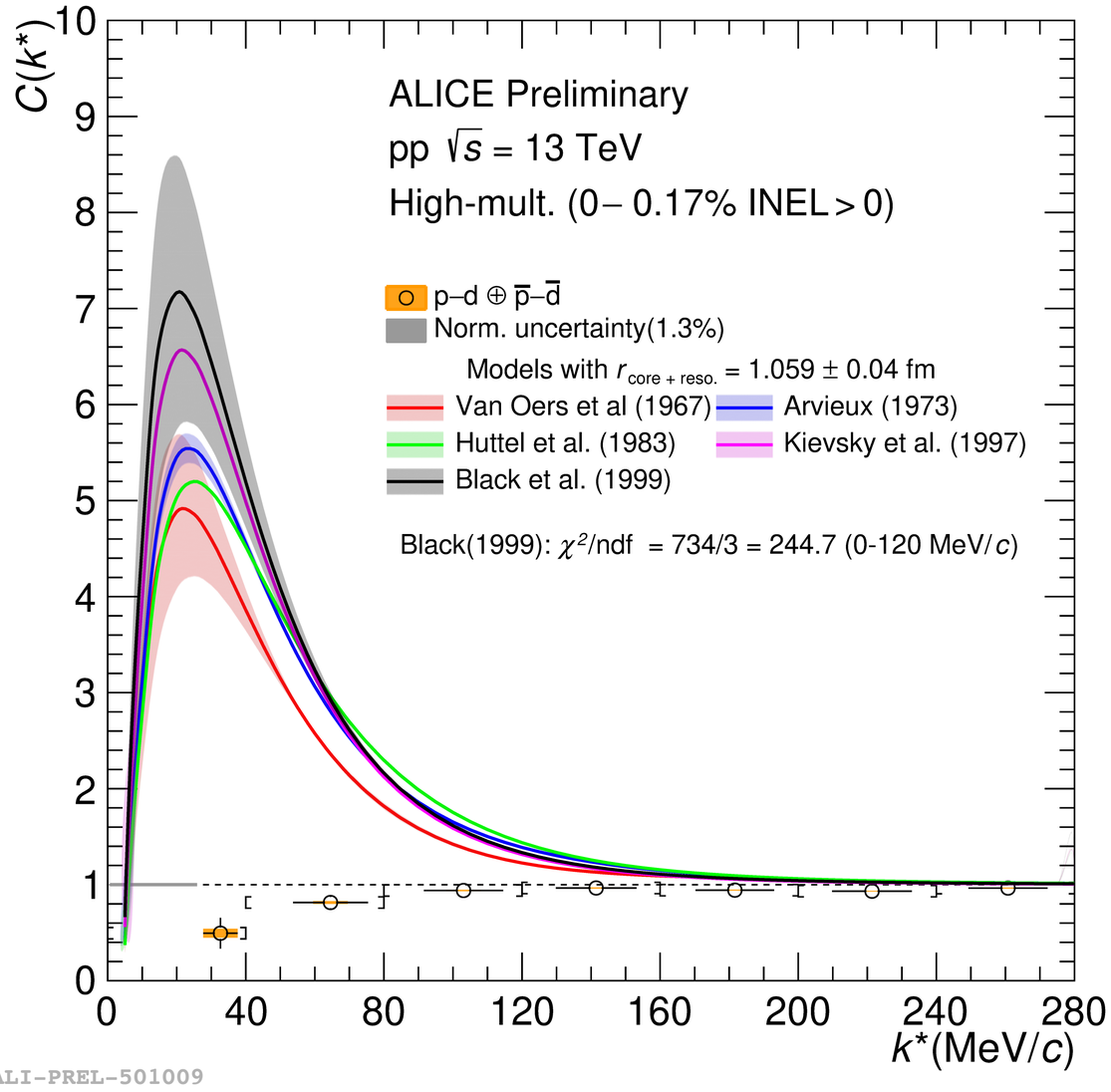


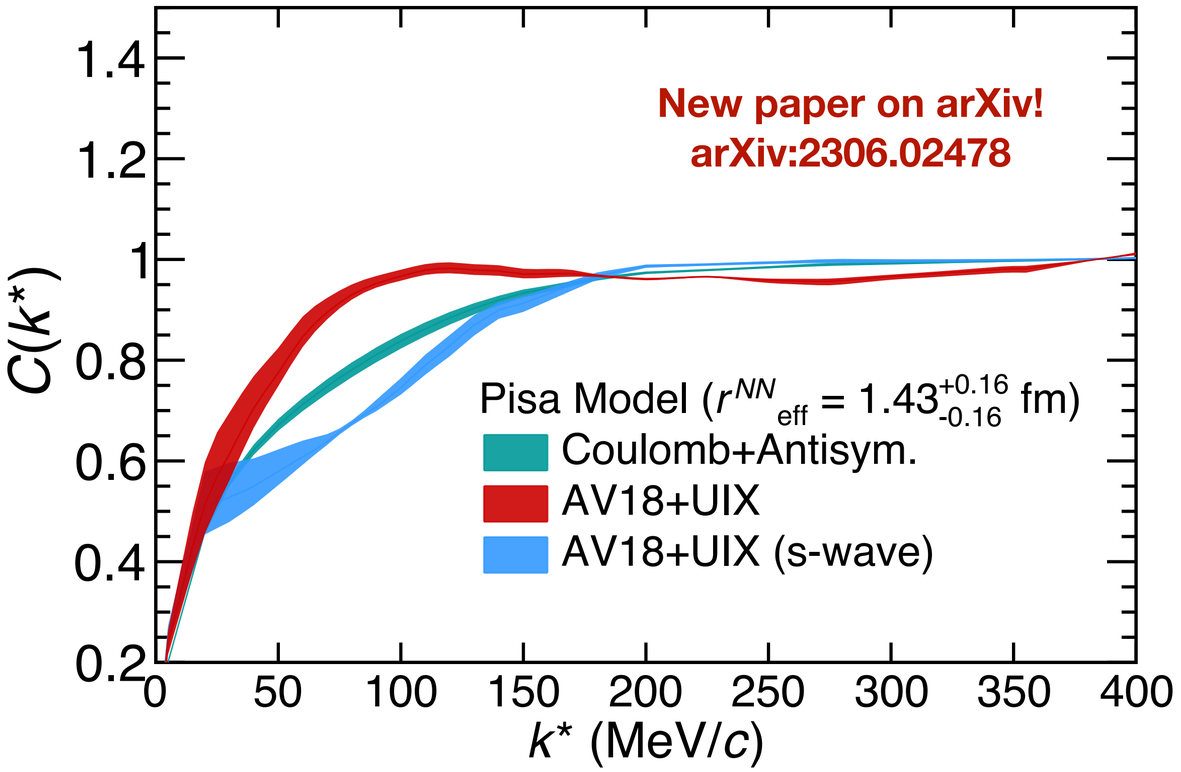


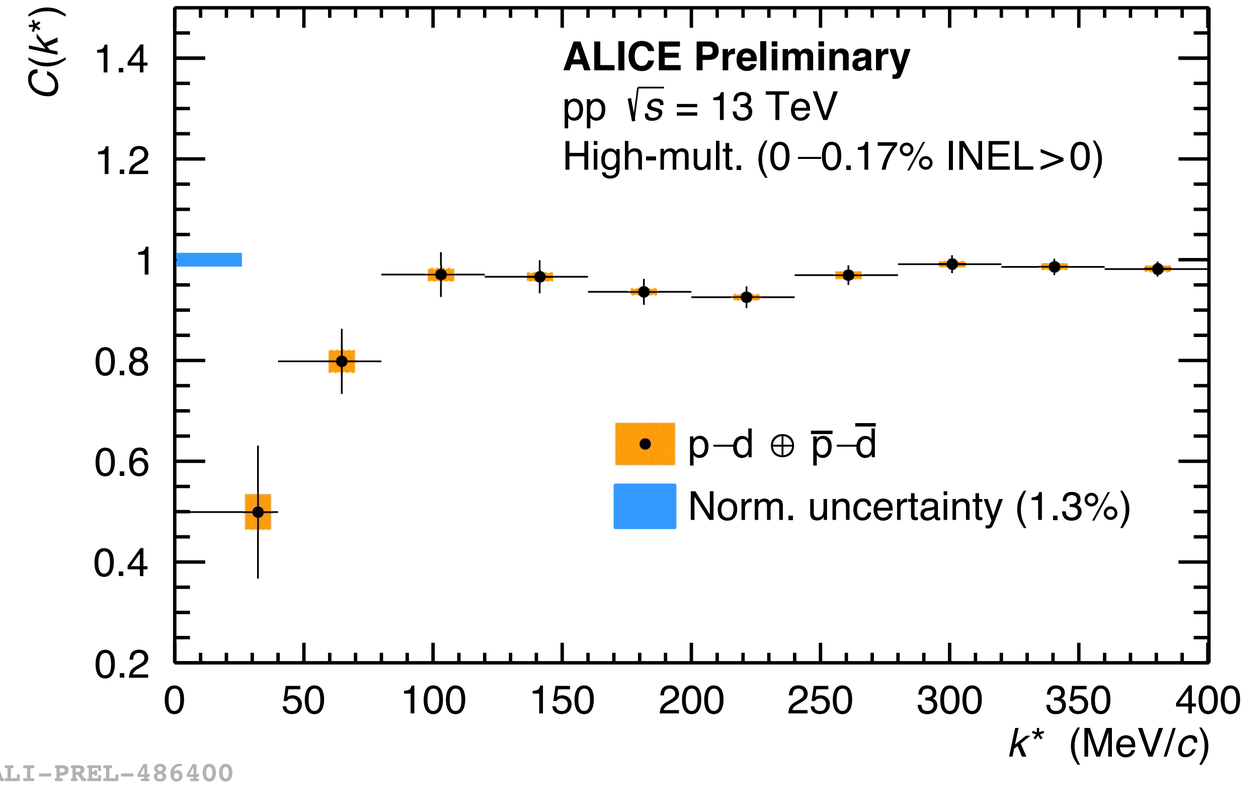
ALI-PREL-501009

Three-body dynamics in p-d system

- Modelling of the p-d correlation function as a three-body system can describe the data well

  → Includes two-body (AV18) and three-body (UIX) interactions





ALI-PREL-486400

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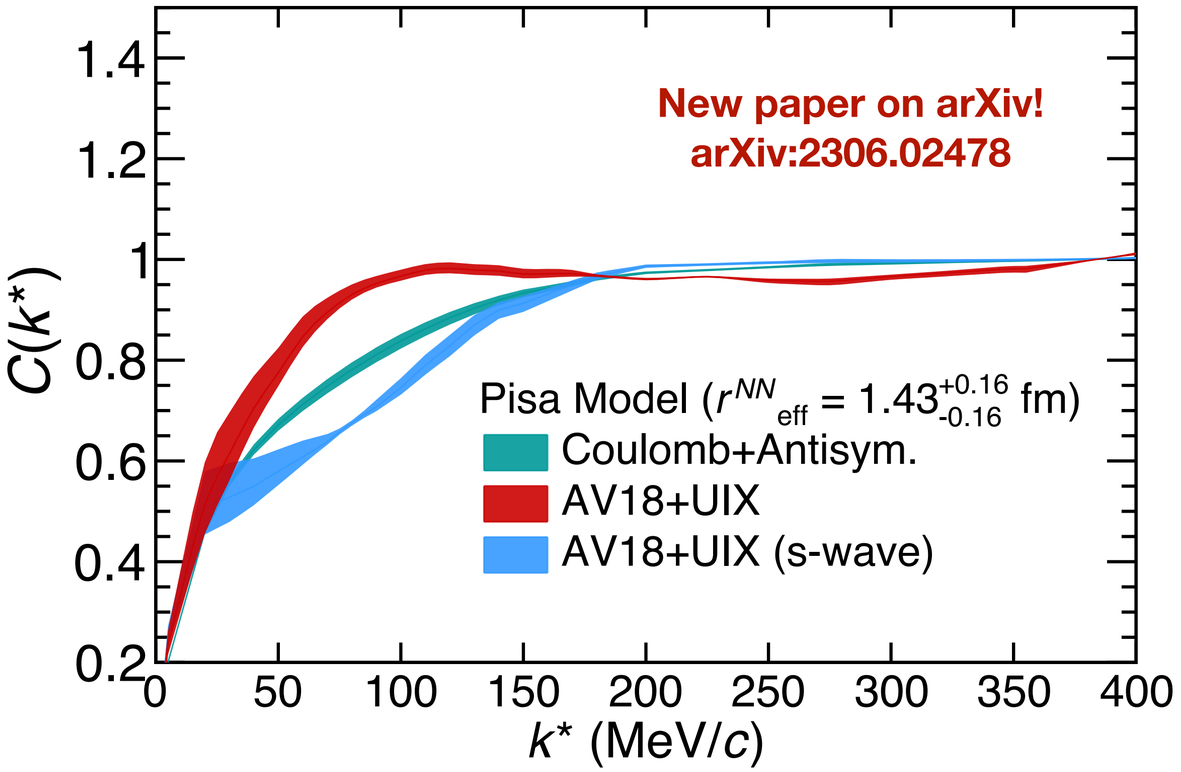
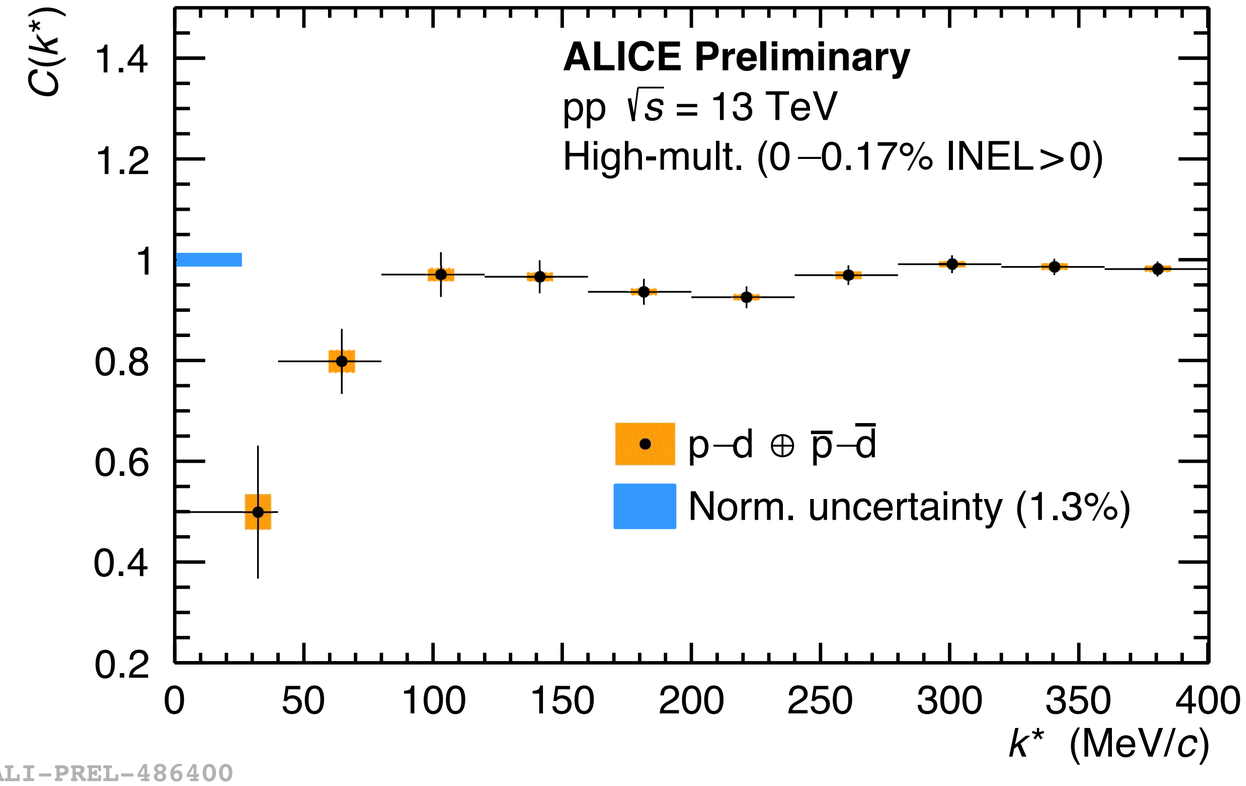




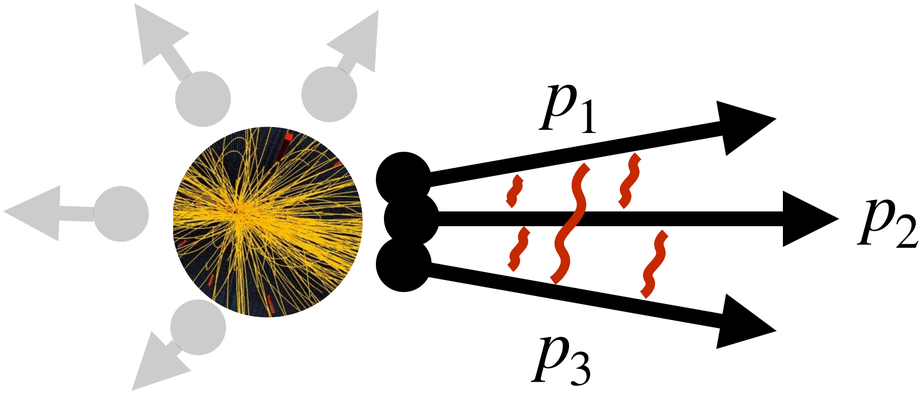
System sensitive to the three-body dynamics and also the three-body interaction!

Three-particle femtoscopy

- Experimental three-particle correlation function

$$C\left(Q_3\right) = \mathcal{N}\frac{N_{\text{same}}\left(Q_3\right)}{N_{\text{mixed}}\left(Q_3\right)}$$

$$Q_3 = \sqrt{-q_{ij}^2 - q_{jk}^2 - q_{ki}^2}$$



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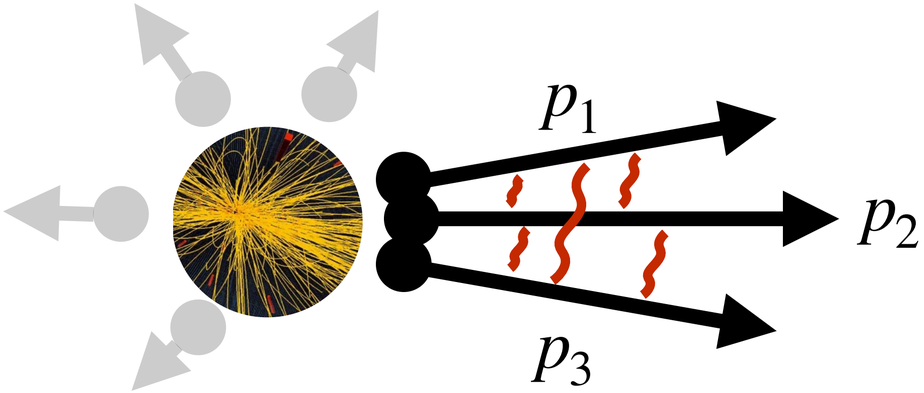
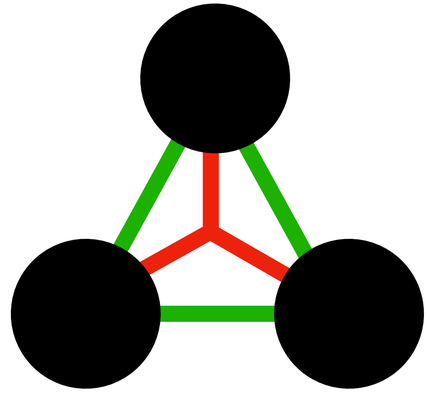


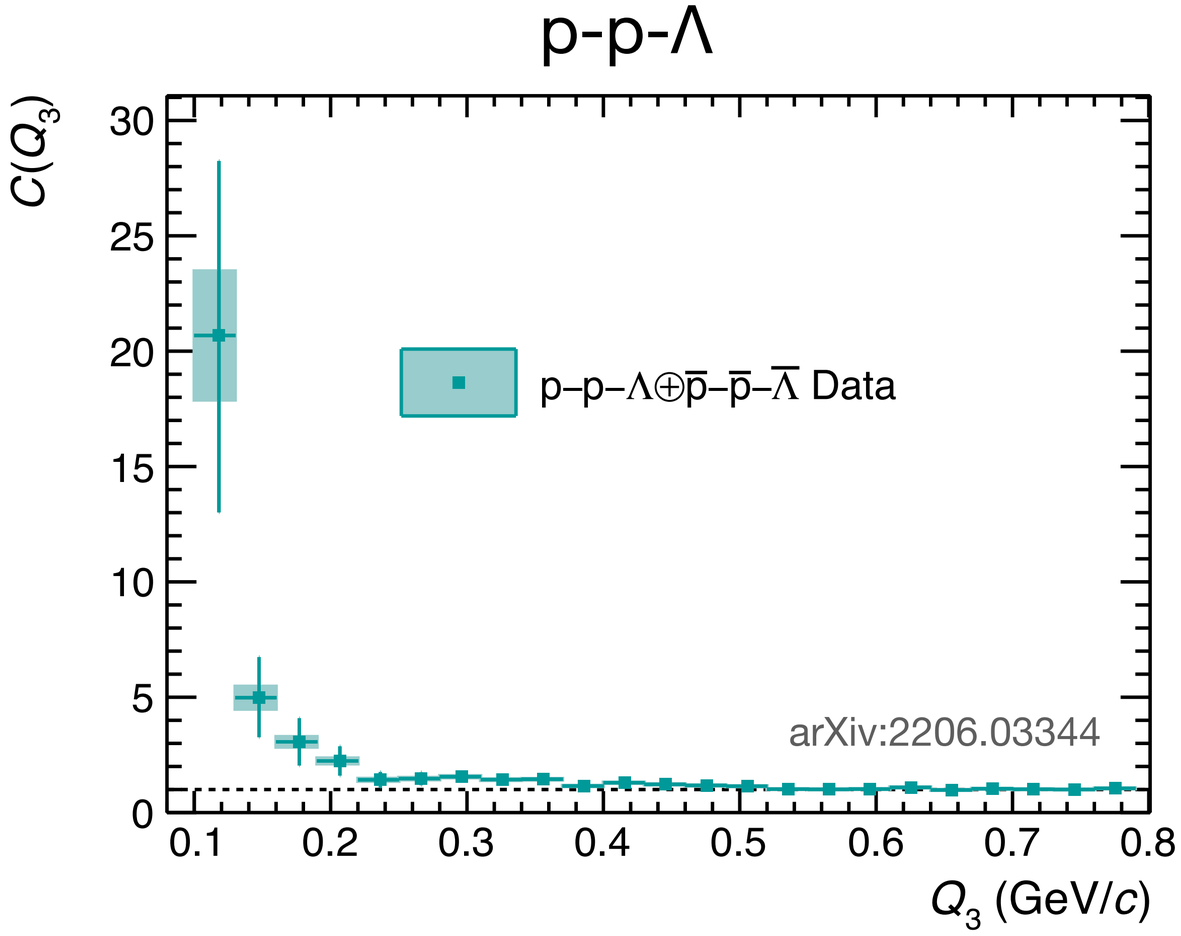
- Theoretical three-particle correlation function
  - two-body interactions
  - three-body interaction

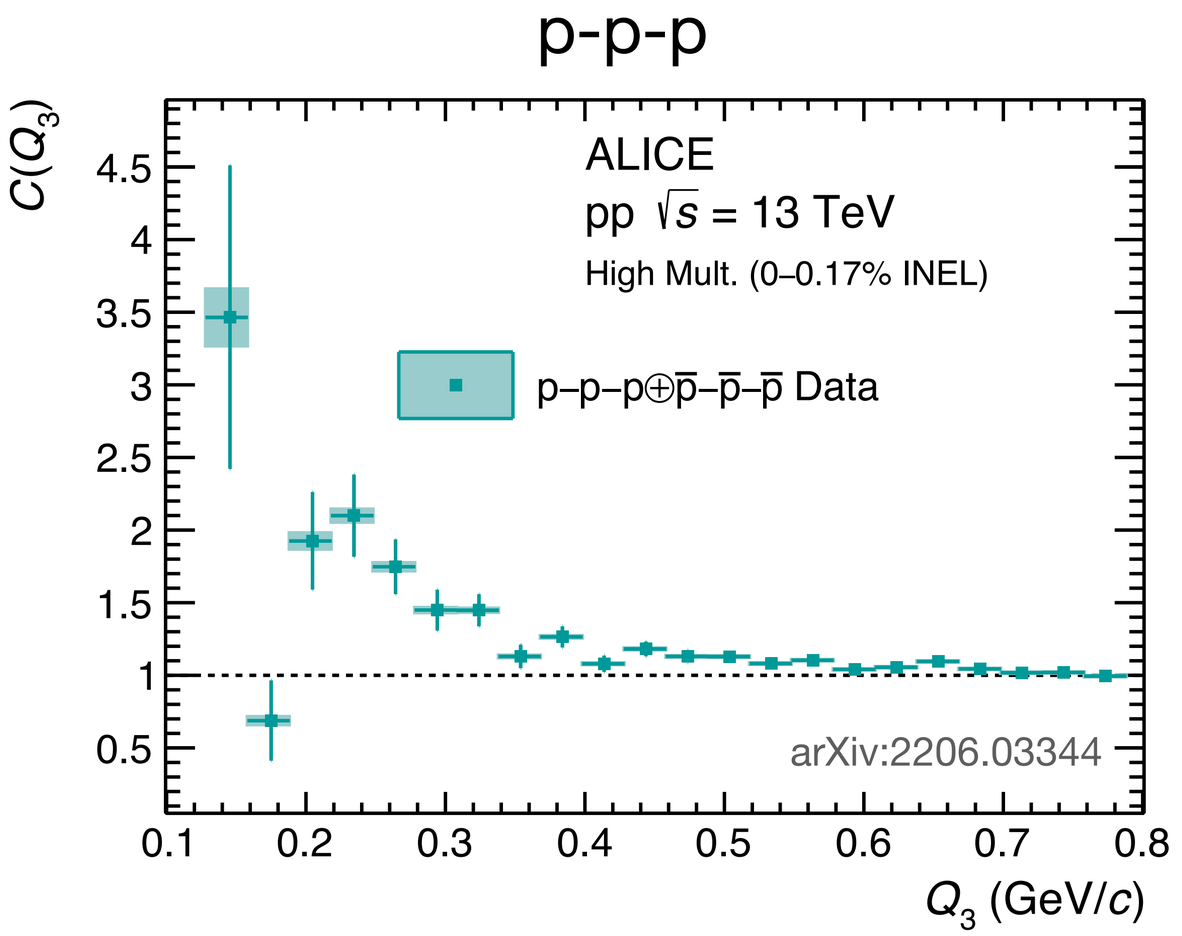
$$C_3\left(\mathbf{p}_1,\mathbf{p}_2,\mathbf{p}_3\right) = \iiint S_3\left(\mathbf{r}_1,\mathbf{r}_2,\mathbf{r}_3\right)\left|\Psi\left(\mathbf{r}_1,\mathbf{r}_2,\mathbf{r}_3,\mathbf{p}_1,\mathbf{p}_2,\mathbf{p}_3\right)\right|^2 d^3\mathbf{r}_1 d^3\mathbf{r}_2 d^3\mathbf{r}_3$$



Measured correlation functions

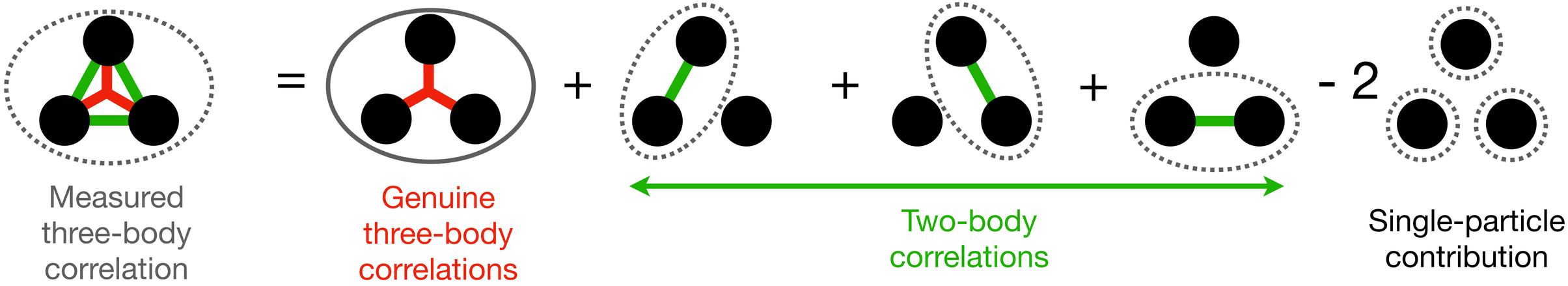
- Measured correlation functions are not equal to unity
  - Are two- or/and three-body interactions responsible?





Cumulants in femtoscopy

The total three-particle correlations can be expressed as a sum of genuine three-body correlation and the lower-order contributions employing Kubo's cumulants [1]:



In terms of correlation functions:

$$c_3\left(Q_3\right) = C\left(Q_3\right) - C_{12}\left(Q_3\right) - C_{23}\left(Q_3\right) - C_{31}\left(Q_3\right) + 2$$

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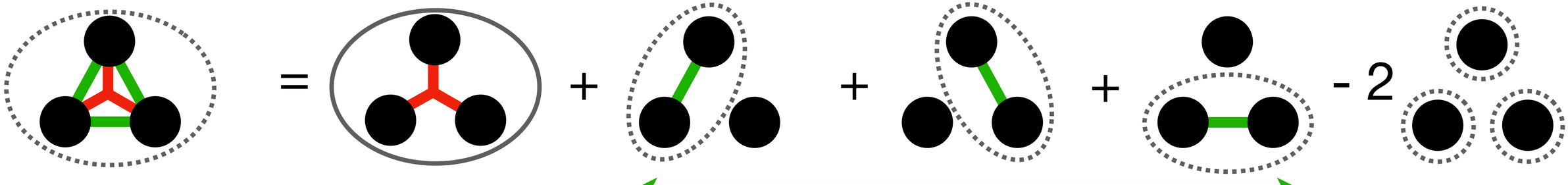

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Lower-order contributions

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Lower-order contributions

- Two methods:
  - Data-driven method: event mixing
  - Projector method: project two-body correlation function on the three-particle phase space

Del Grande, Šerkšnytė et al. EPJC 82 (2022) 244

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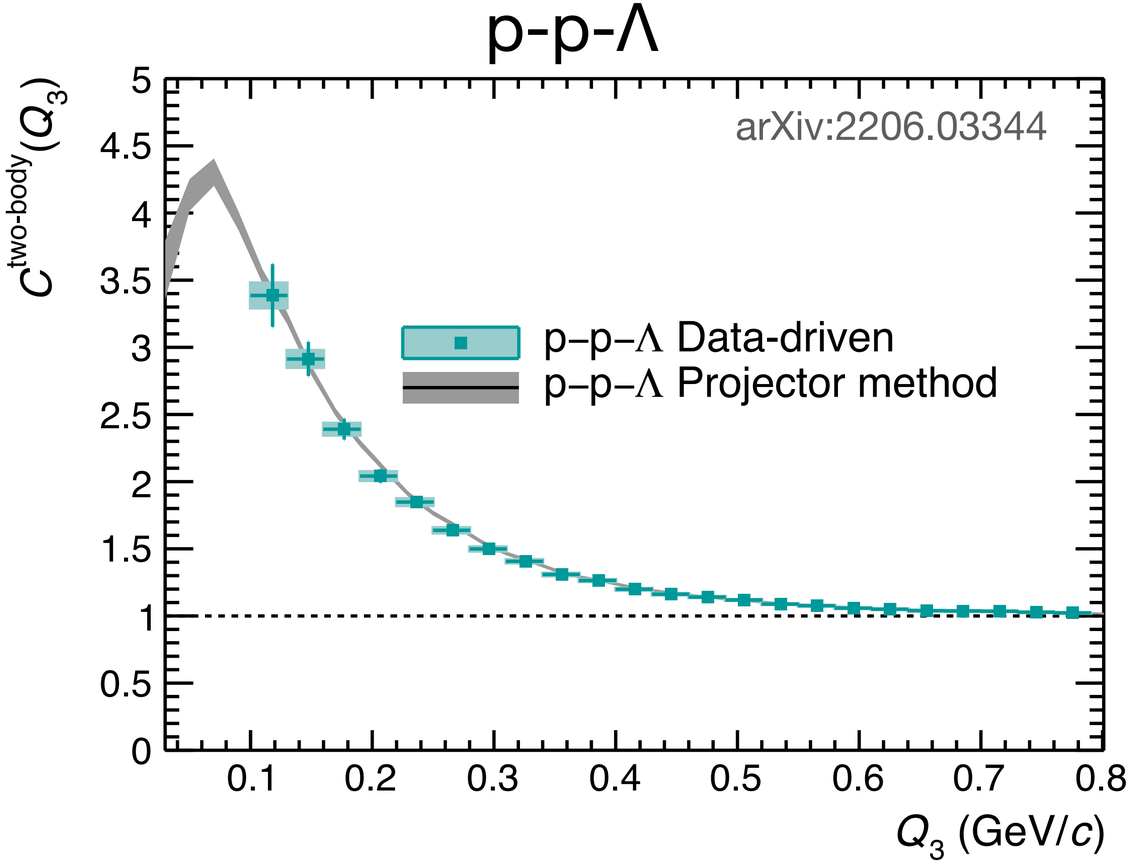
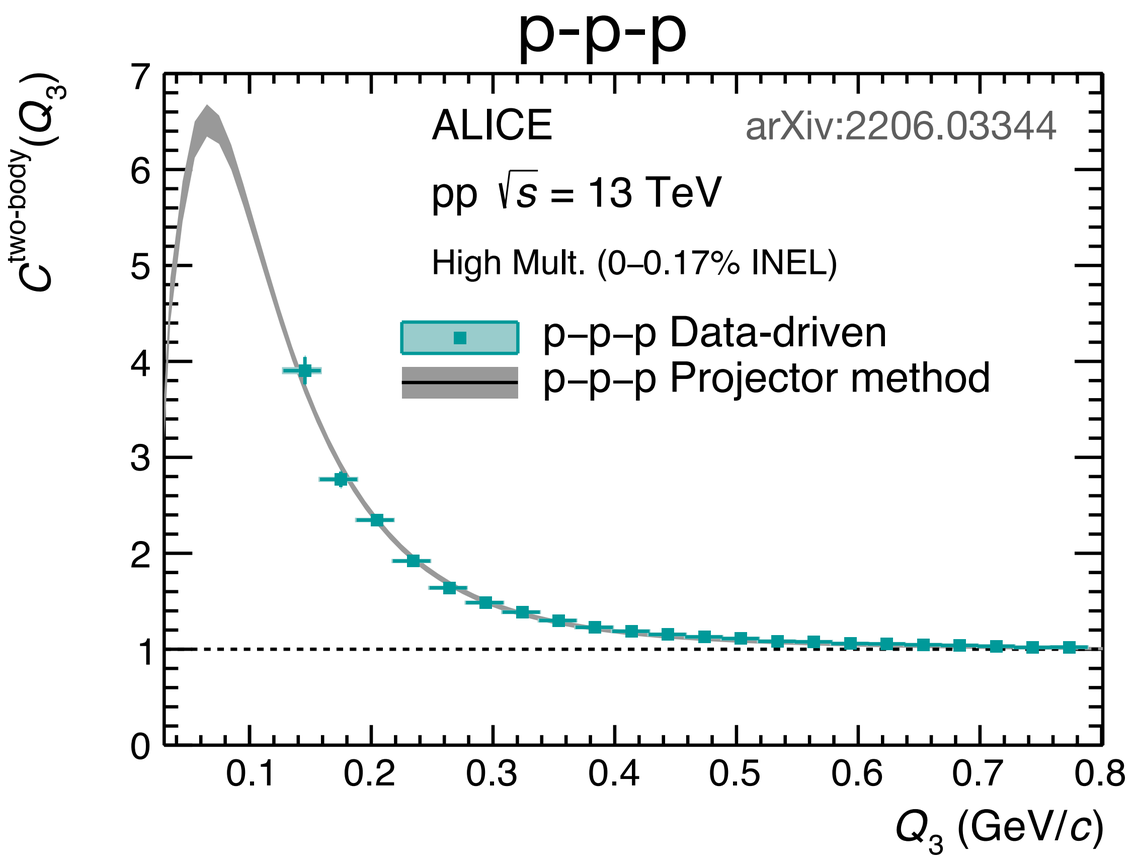
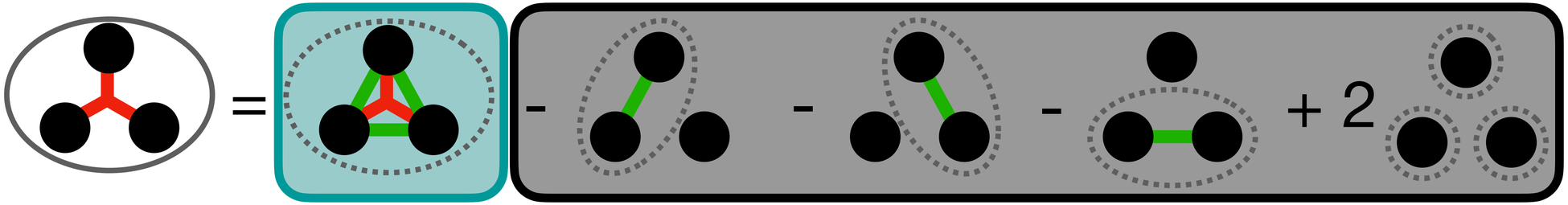
Lower-order contributions under control!

Del Grande, Šerkšnytė et al. EPJC 82 (2022) 244

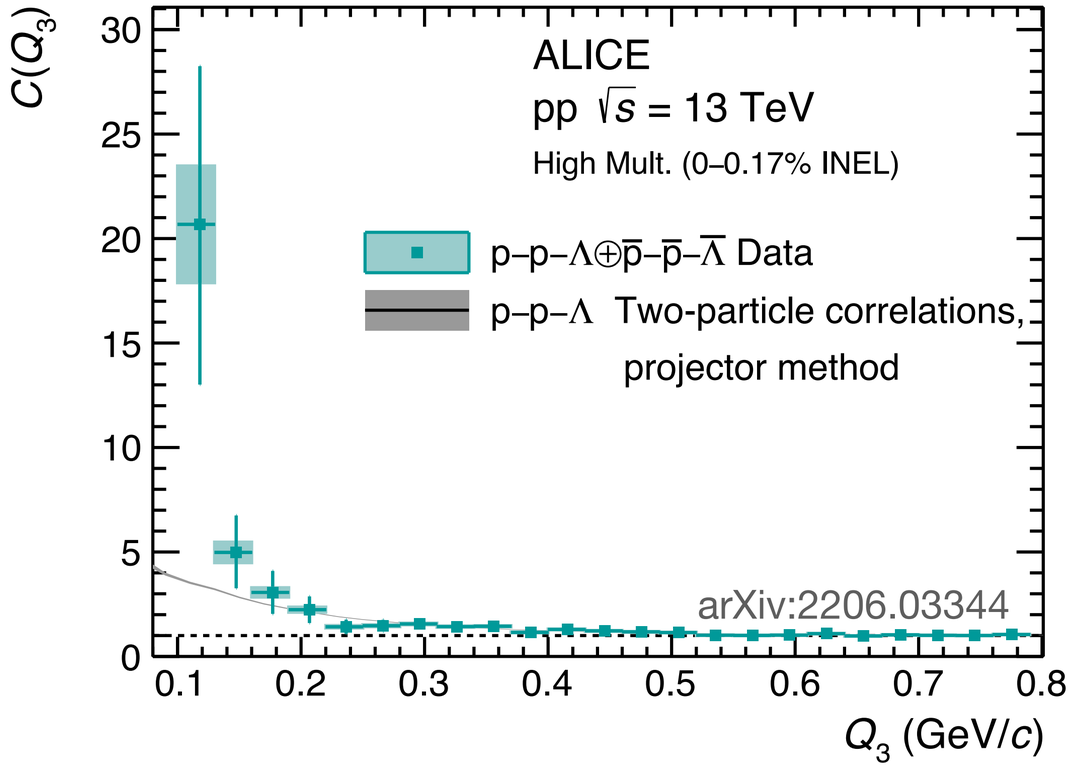




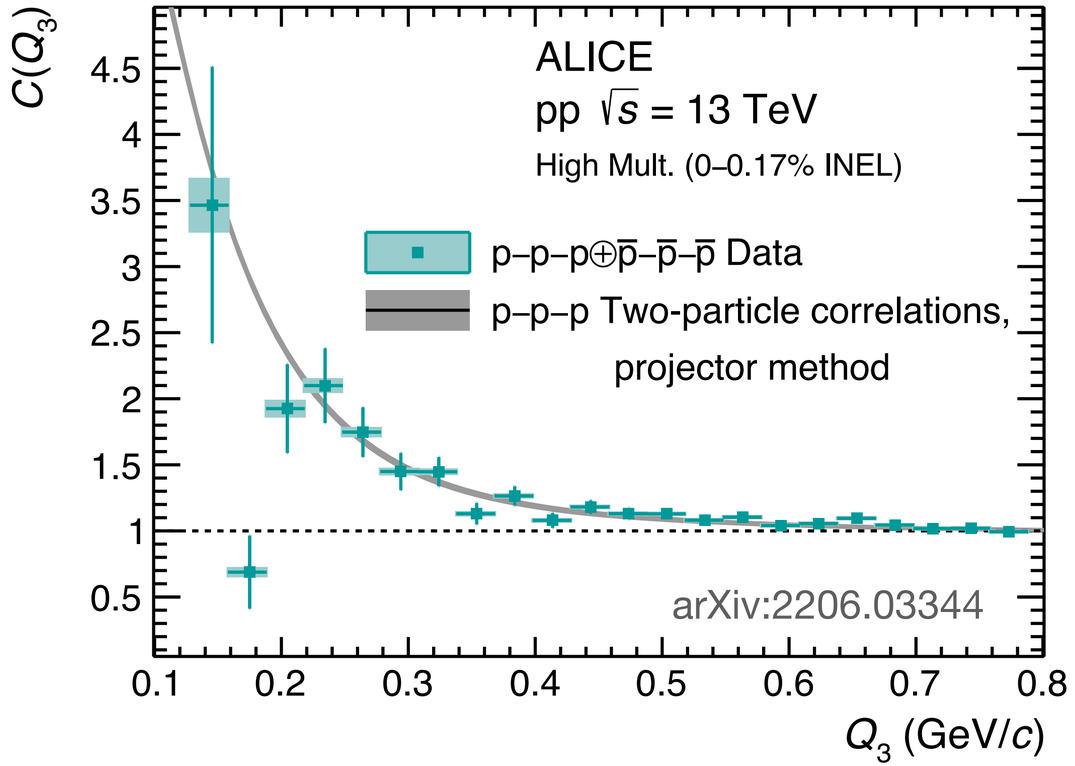
p-p-Λ and p-p-p correlation functions



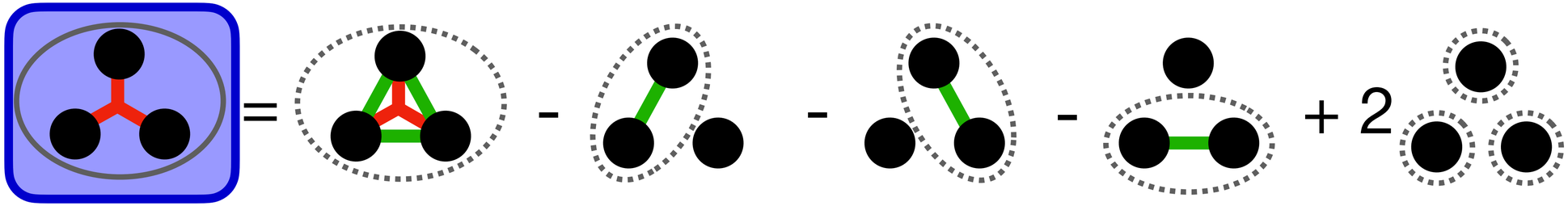
p-p-Λ



p-p-p



p-p-Λ cumulant



Hint of a positive cumulant for p-p-Λ

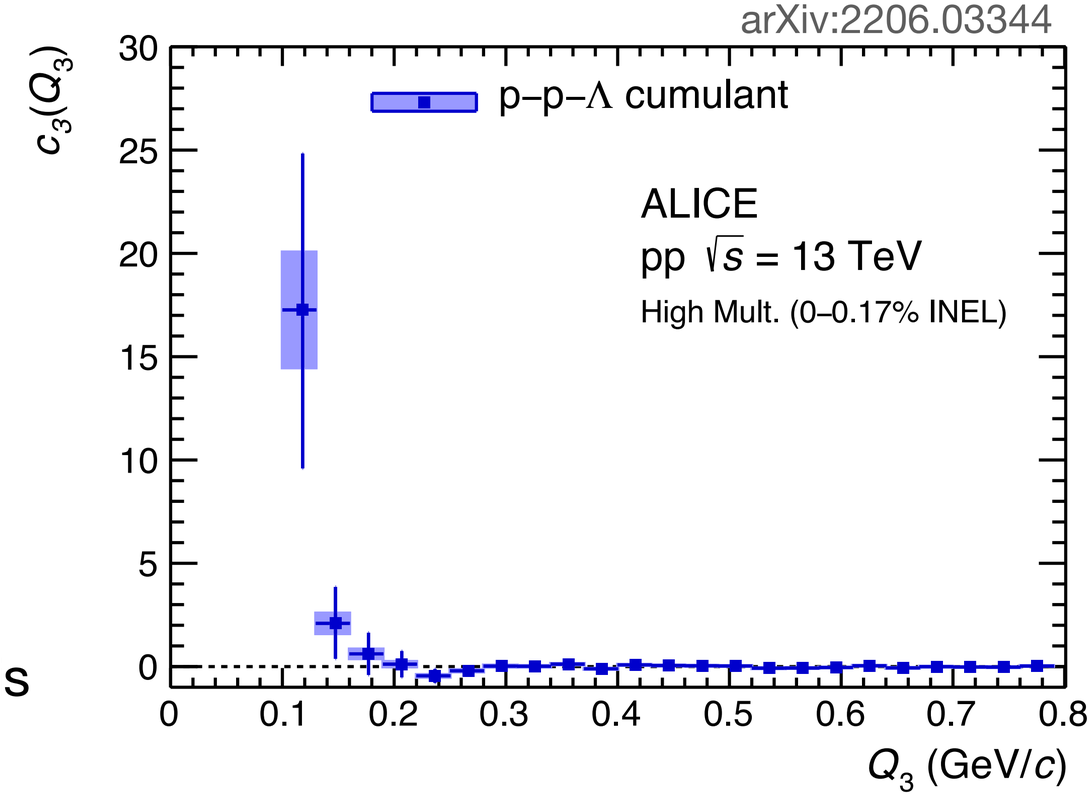
- Only two identical and charged particles
  - ✓ Main expected contribution from three-body strong interaction
- Relevant measurement for equation of state of neutron stars

Statistical significance:

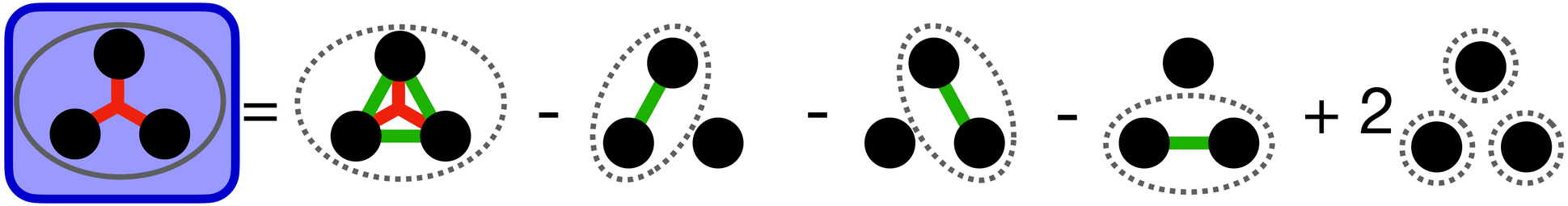
n_σ= 0.8 for Q_3 < 0.4 GeV/c

Conclusion: no significant deviation from null hypothesis

In upcoming Run 3, two orders of magnitude gain in statistics expected!



p-p-p cumulant



arXiv:2206.03344

Negative cumulant for p-p-p

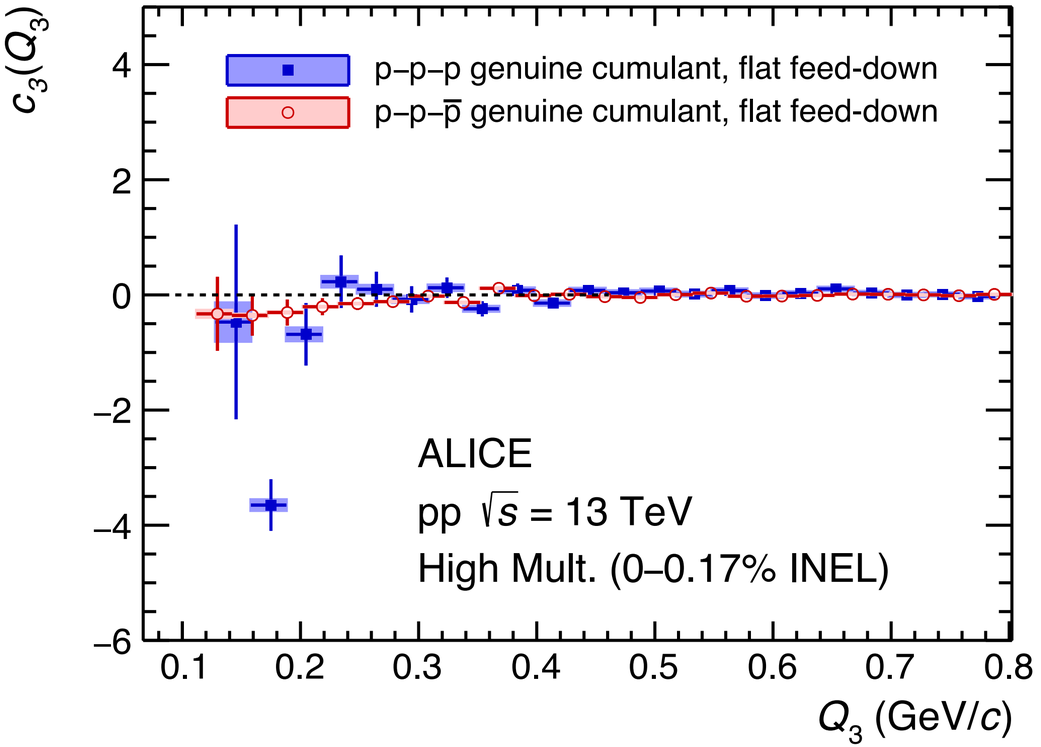
Possible forces at play:

- *Pauli blocking at the three-particle level*
- three-body strong interaction
- long-range Coulomb

Statistical significance:

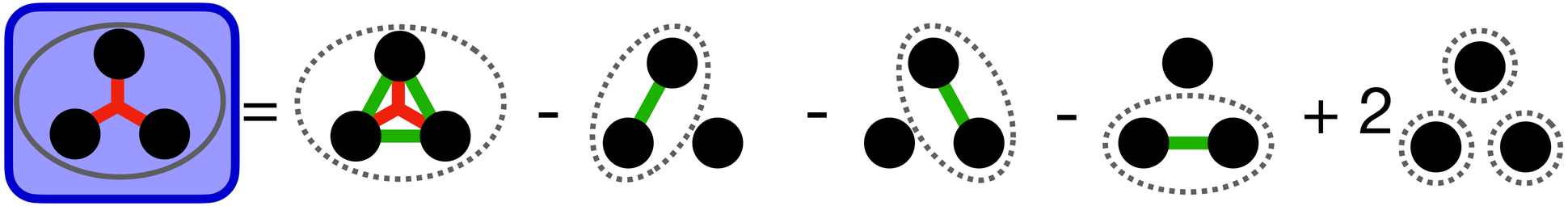
n_σ= 6.7 for Q_3 < 0.4 GeV/c

Conclusion: significant deviation from null hypothesis; ongoing collaboration with A. Kievsky, L. Marcucci and M. Viviani (Pisa University - INFN) for the theoretical interpretation



Test with mixed-charge particles, cumulant negligible.

p-p-p cumulant



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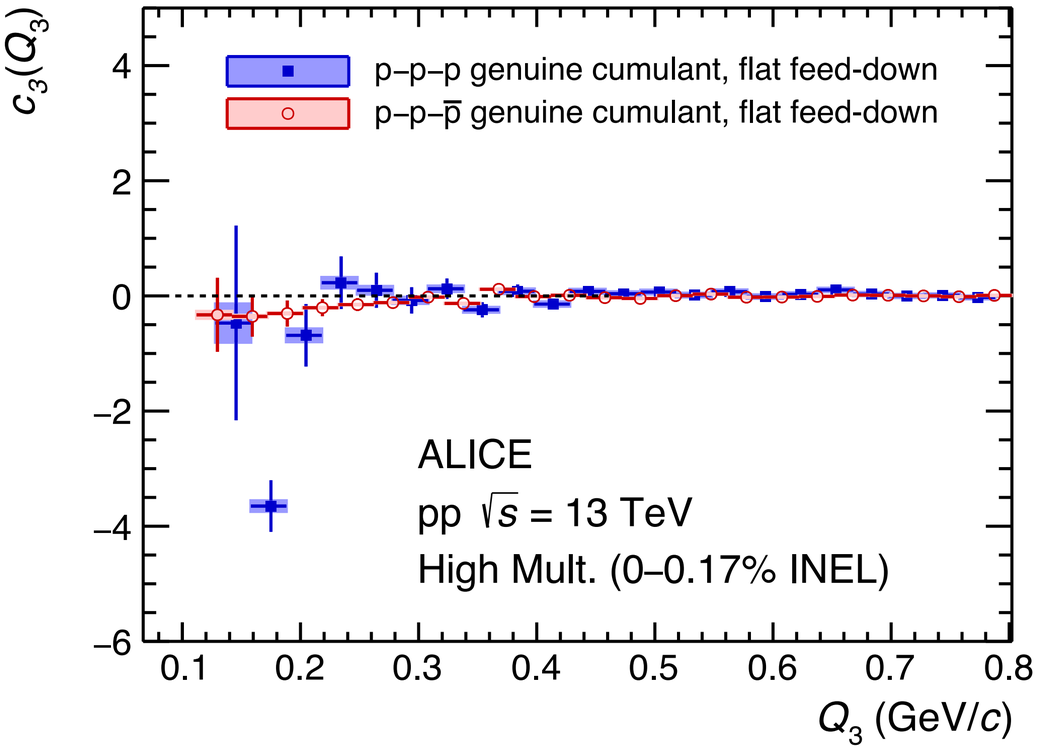
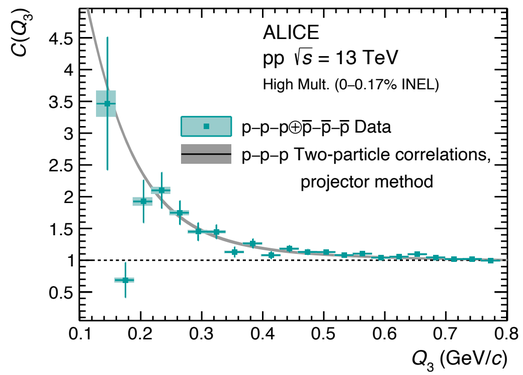
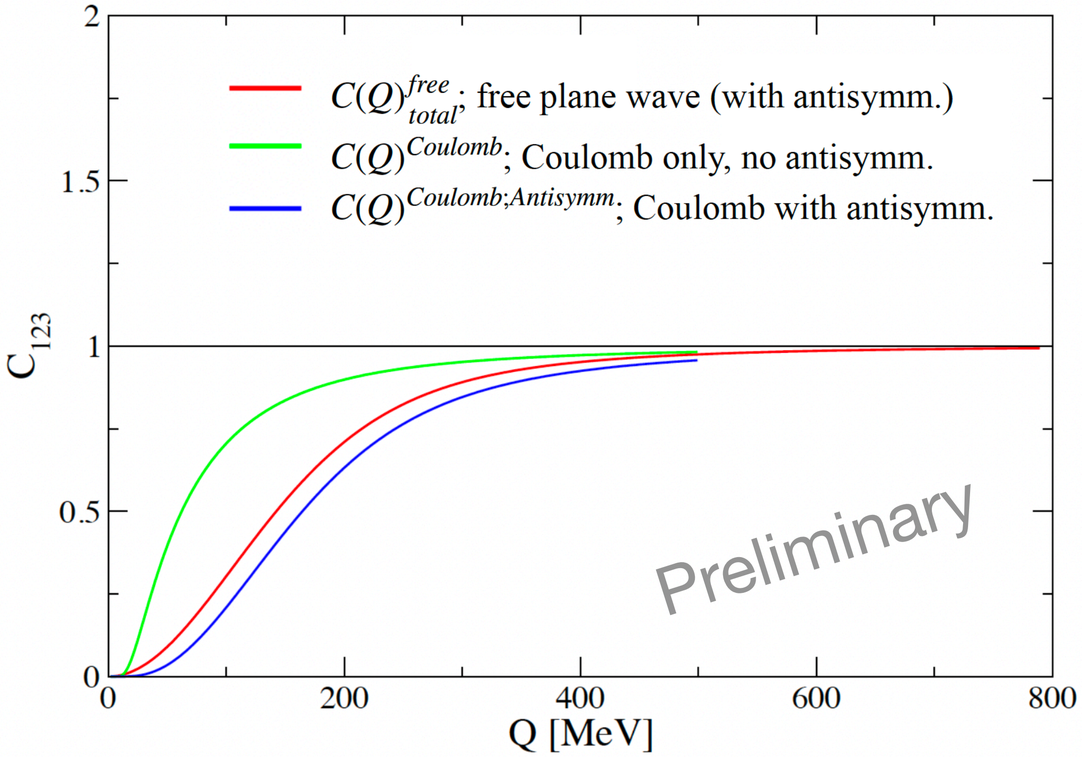


Test with mixed-charge particles, cumulant negligible.

p-p-p calculations (work in progress)

- Calculations performed by Alejandro Kievsky (PISA group)
  - described as a three-body system
  - only two-body strong interaction included
  - approximate Coulomb interaction, as a function of hyper-radius only





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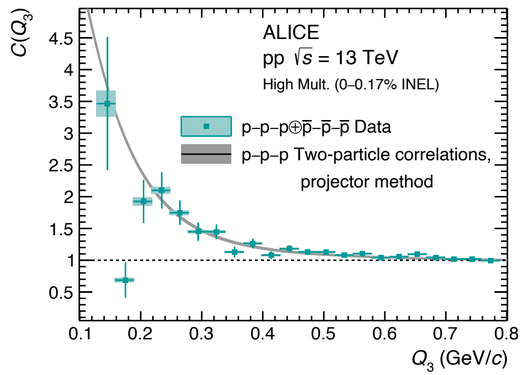
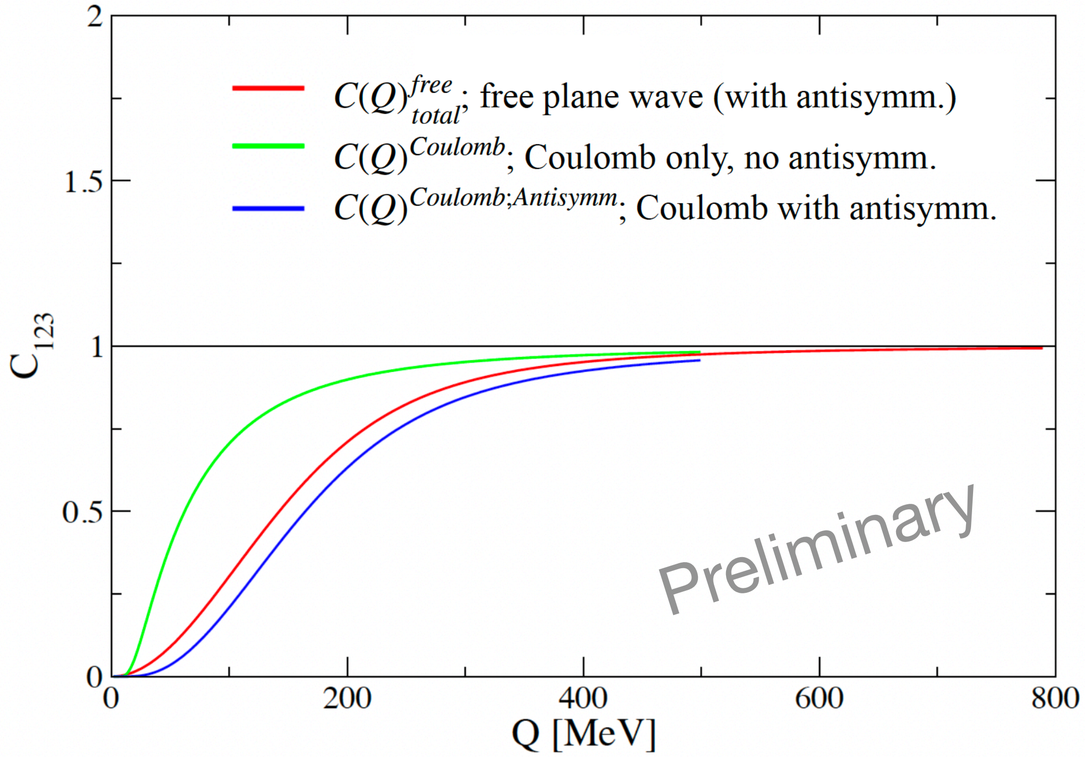
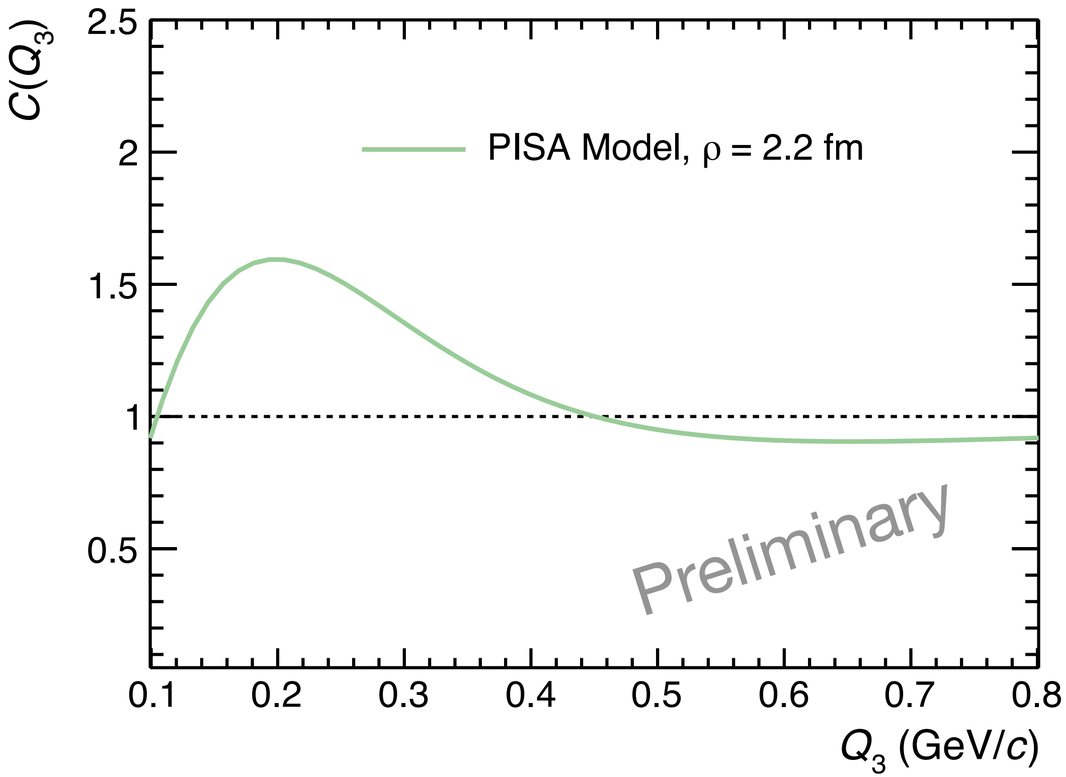


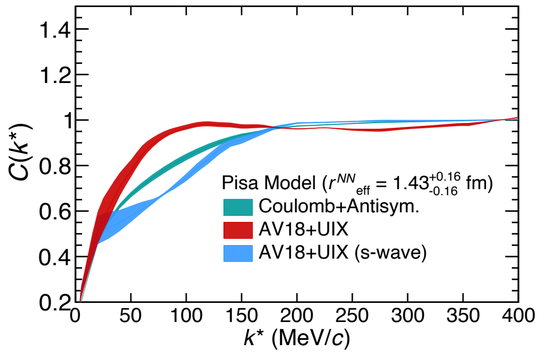


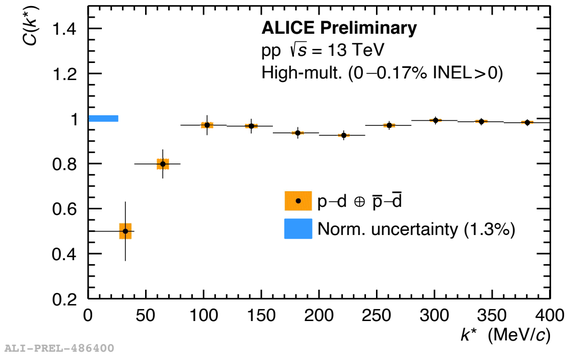


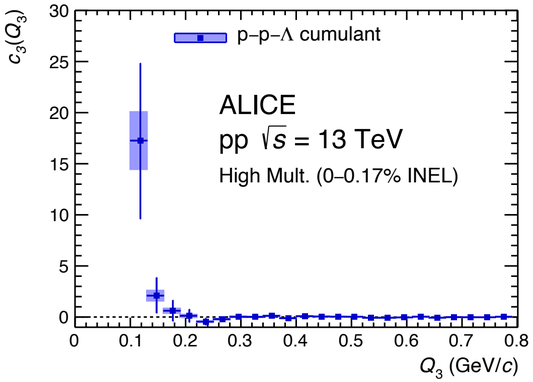
Conclusions

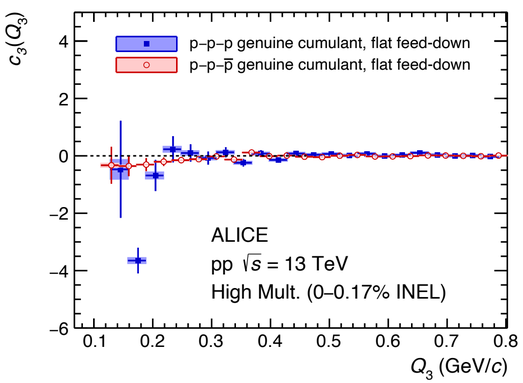
First measurements tackling the problem of genuine three-body interactions using femtoscopy!

- p-d: can be described with full three-body calculations
- p-p-Λ: no significant deviation from 0 in Run 2 data
- p-p-p: negative cumulant with a significance of 6.7σ









Final constraints on three-body interactions will arrive with Run 3 data!

Conclusions

First measurements tackling the problem of genuine three-body interactions using femtoscopy!

- p-d: can be described with full three-body calculations
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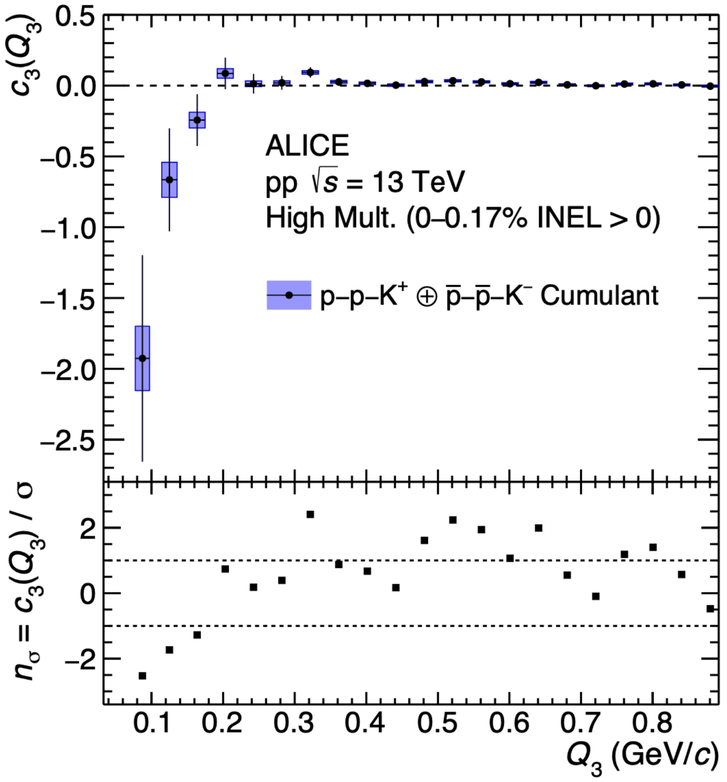
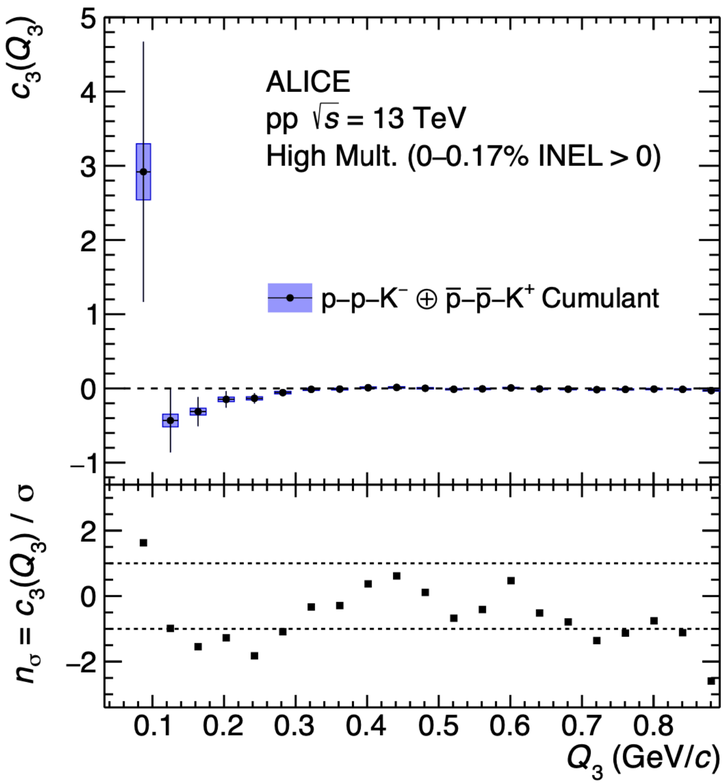
- p-p-K^+ and p-p-K^-: cumulants compatible with 0, no evidence of a genuine three-body force

New paper: arXiv:2303.13448





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Conclusions

First measurements tackling the problem of genuine three-body interactions using femtoscopy!

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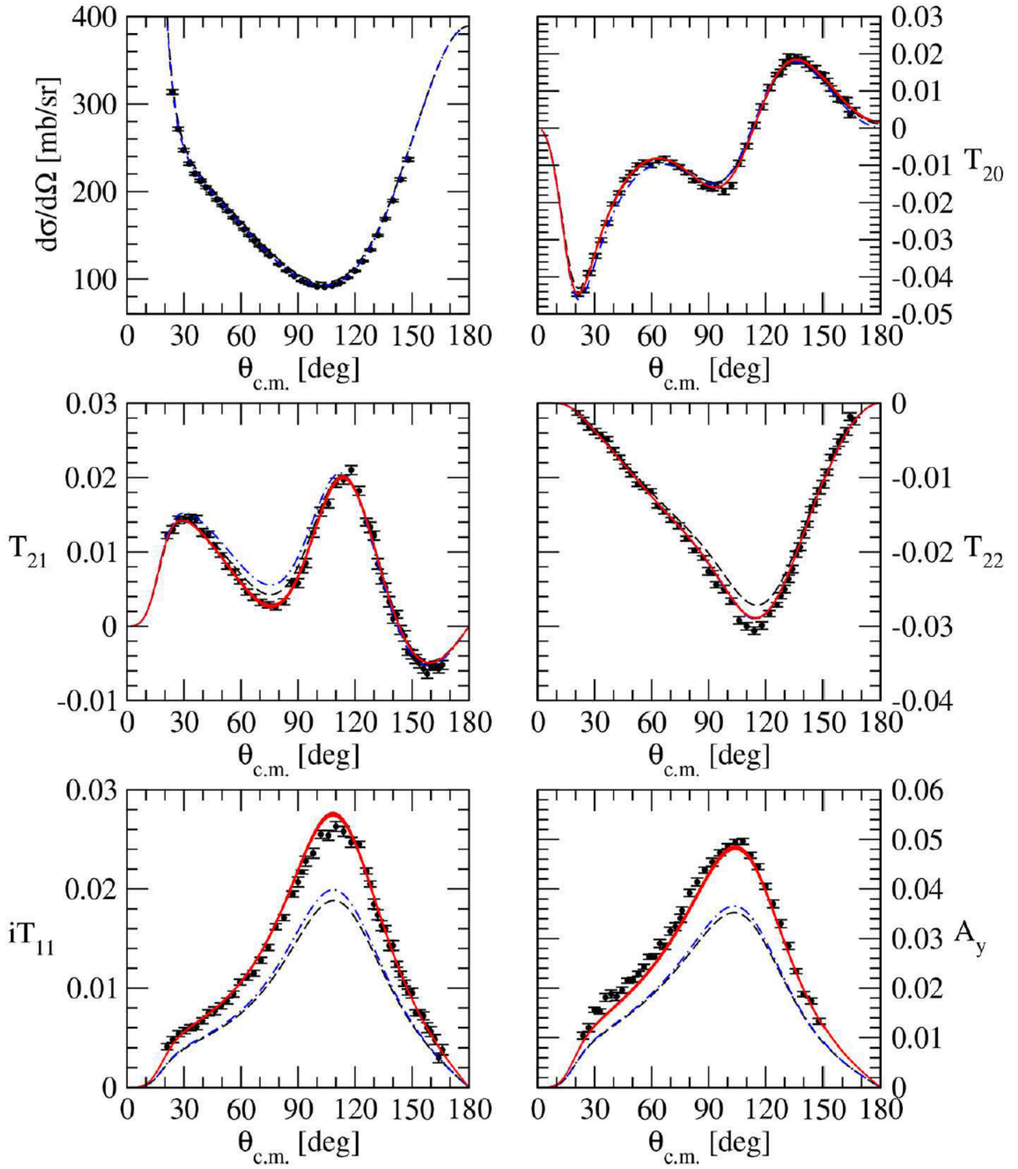
Final constraints on three-body interactions will arrive with Run 3 data!

Valentina Mantovani Sarti 5 Jun 2023, 14:30
Dimitar Mihaylov 5 Jun 2023, 17:40
Wioleta Rzęsa 7 Jun 2023, 14:24
Marcel Lesch 8 Jun 2023, 15:12
Ramona Lea 8 Jun 2023, 15:42

Back-up

p-d scattering

- Three body interactions are required to reproduce scattering data



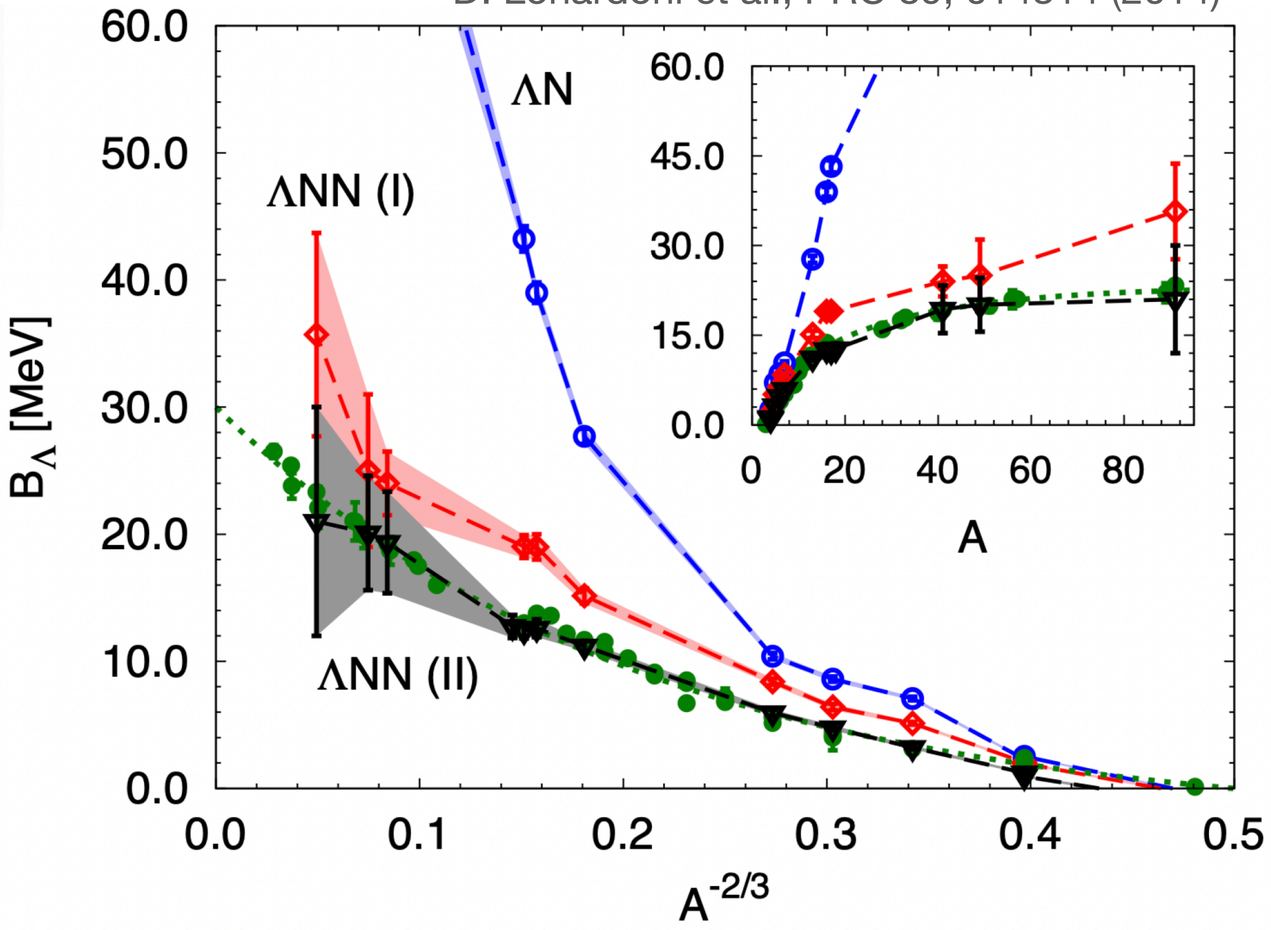
L.E. Marcucci et al., Front. Phys. 8, 69 (2020)

How to constrain three-body forces?

- Models are fitted to reproduce measured (hyper)nuclei properties
  - Access only to nuclear densities
  - Strongly dependent on the assumed two-body and many-body interactions
  - Different parametrisations of three-body forces describe better different nuclei

Parameters	System	B_Λ^{CSB}
Set (I)	${}^{4}_{\Lambda}$H	1.89(9)
	${}^{4}_{\Lambda}$He	2.13(8)
Set (II)	${}^{4}_{\Lambda}$H	0.95(9)
	${}^{4}_{\Lambda}$He	1.22(9)
Expt. [12]	${}^{4}_{\Lambda}$H	2.04(4)
	${}^{4}_{\Lambda}$He	2.39(3)

D. Lonardoni et al., PRC 89, 014314 (2014)



ALICE detector

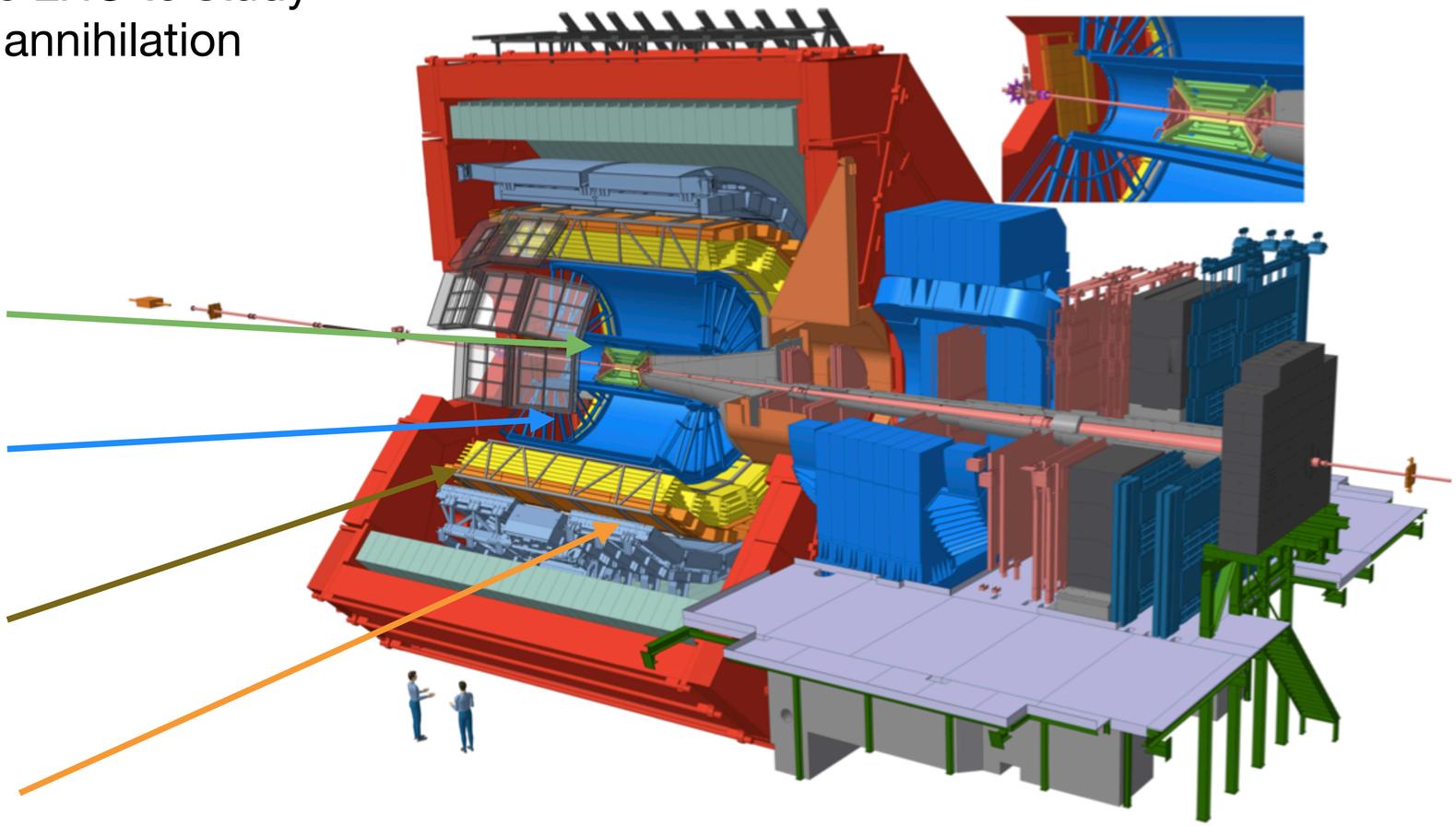
- Excellent tracking and particle identification (PID) capabilities
- Most suitable detector at the LHC to study (anti-)nuclei production and annihilation

Inner **T**racking **S**ystem
Tracking, vertex, PID (d*E*/d*x*)

Time **P**rojection **C**hamber
Tracking, PID (d*E*/d*x*)

Transition **R**adiation **D**etector

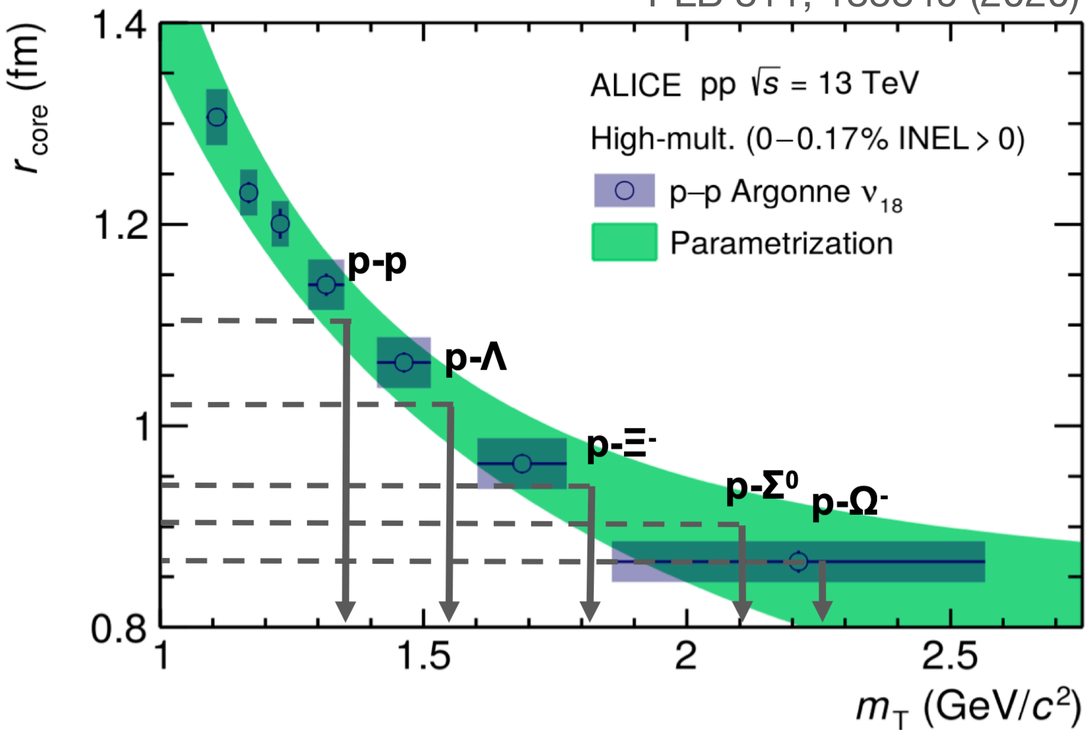
Time **O**f **F**light detector
PID (TOF measurement)

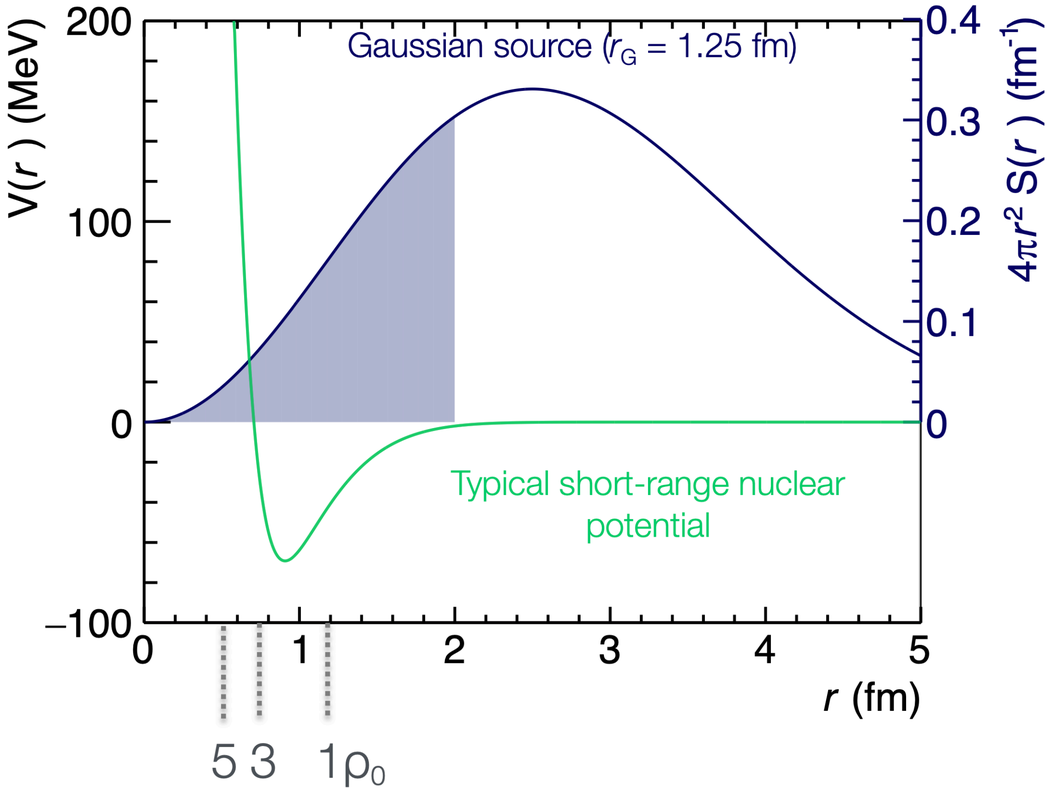


Emission source

- Two main contributions:
  - general: Collective effects result in Gaussian core
  - specific: Decaying resonances require source correction

PLB 811, 135849 (2020)

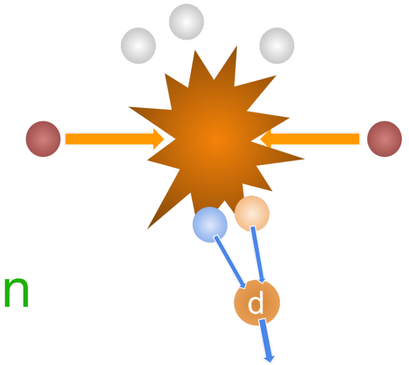




How to access three-body systems?

Three-body dynamics

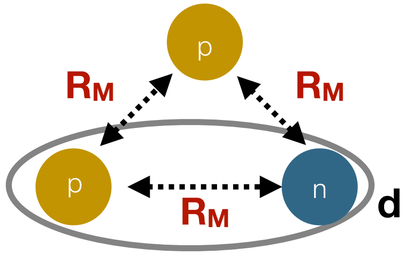
- Start with p-p-n state:
  - single-particle Gaussian emission source
  - three-nucleon wave function asymptotically behaves as p-d state
  - account for the probability to form deuteron employing deuteron wave function



$$C_{pd}(k) = \frac{1}{A_d}\frac{1}{6}\sum_{m_2,m_1}\int d^3r_1 d^3r_2 d^3r_3 S_1\left(r_1\right) S_1\left(r_2\right) S_1\left(r_3\right) \left|\Psi_{m_2,m_1}\right|^2$$

- Rewritten as a function of the known source size R_M constrained by p-p

$$C_{pd}(k) = \frac{1}{A_d}\frac{1}{6}\sum_{m_2,m_1}\int \rho^5 d\rho d\Omega \frac{e^{-\rho^2/4R_M^2}}{\left(4\pi R_M^2\right)^3} \left|\Psi_{m_2,m_1}\right|^2$$



S. Mrówczyński et al., Eur. Phys. J. Special Topics 229, 3559 (2020)

Proton-deuteron wave function

The three body wave function with proper treatment of 2N and 3N interaction at very short distances goes to a p–d state.

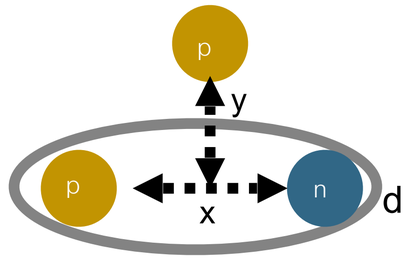
- Three–body wavefunction for p–d: $\Psi_{m_2,m_1}(x,y)$ describing three-body dynamics, anchored to p–d scattering observables.
  - x = distance of p-n system within the deuteron
  - y = p-d distance
  - m2 and m1 deuteron and proton spin

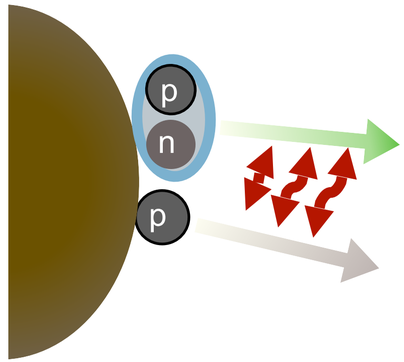
- $\Psi_{m_2,m_1}(x,y)$ three-nucleon wave function asymptotically behaves as p–d state:

$$\Psi_{m_2,m_1}(\boldsymbol{x},\boldsymbol{y}) = \underbrace{\Psi^{(\mathrm{free})}_{m_2,m_1}}_{\text{Asymptotic form}} + \underbrace{\sum_{LSJ}^{J\le\bar{J}} \sqrt{4\pi} i^L \sqrt{2L+1} e^{i\sigma_L} (1 m_2 \tfrac{1}{2} m_1 | S J_z)(L0 S J_z | J J_z) \widetilde{\Psi}_{LSJJ_z}}_{\text{Strong three-body interaction}} .$$

➡ $\widetilde{\Psi}_{LSJJ_z}$ describe the configurations where the three particles are close to each other

➡ $\Psi^{(\mathrm{free})}_{m_1,m_2}$ an asymptotic form of p-d wave function





Kievsky et al, Phys. Rev. C 64 (2001) 024002
Kievsky et al, Phys. Rev. C 69 (2004) 014002
Deltuva et al, Phys. Rev. C71 (2005) 064003

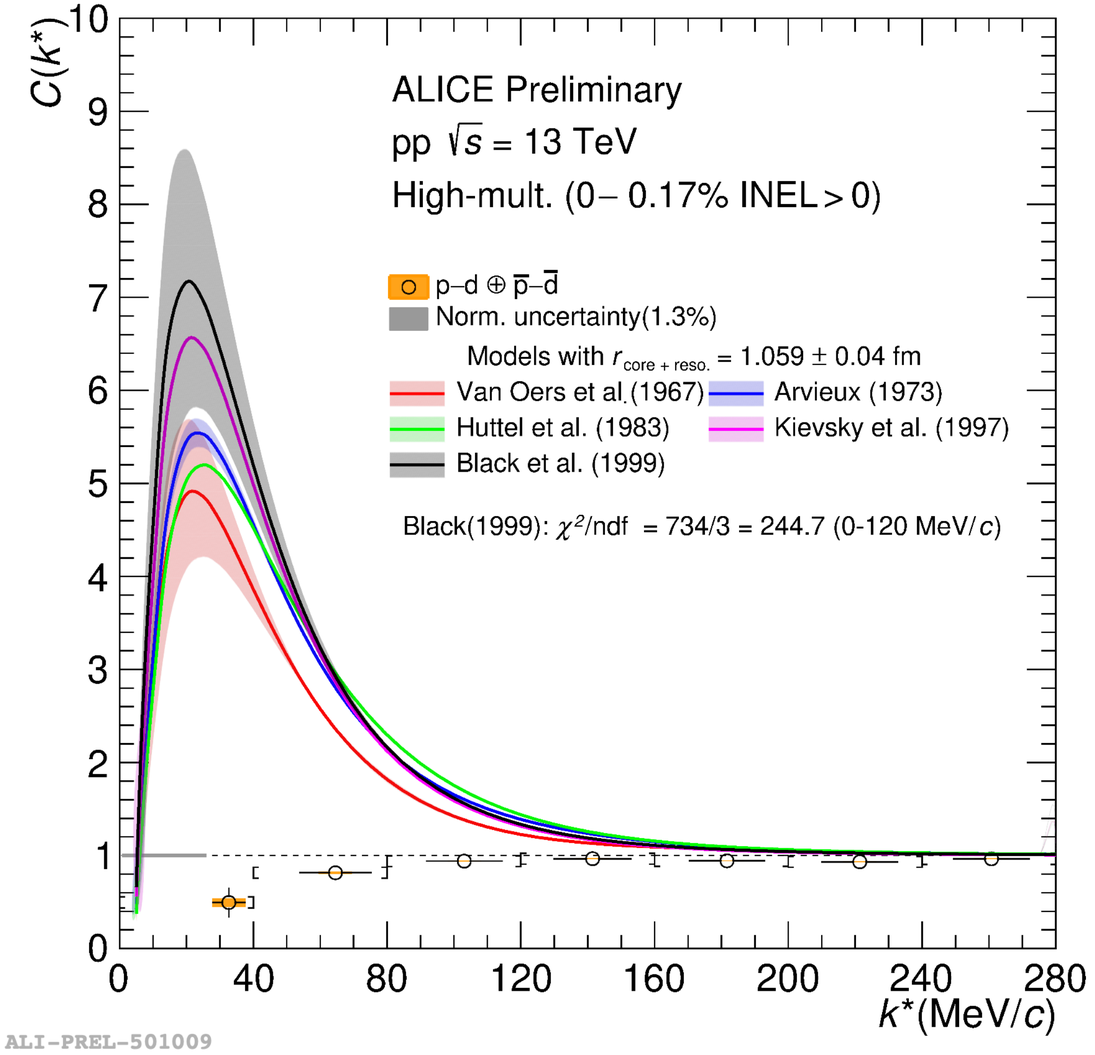
Proton-deuteron correlations

Point-like particle models anchored to scattering experiments

	$S = 1/2$		$S = 3/2$	
	f_0(fm)	d_0(fm)	f_0(fm)	d_0(fm)
Van Oers et al.(1967)	$-1.30^{+0.20}_{-0.20}$	—	$-11.40^{+1.20}_{-1.80}$	$2.05^{+0.25}_{-0.25}$
Arvieux (1973)	$-2.73^{+0.10}_{-0.10}$	$2.27^{+0.12}_{-0.12}$	$-11.88^{+0.10}_{-0.40}$	$2.63^{+0.01}_{-0.02}$
Huttel et al. (1983)	-4.0	—	-11.1	—
Kievsky et al. (1997)	-0.024	—	-13.7	—
Black et al. (1999)	$0.13^{+0.04}_{-0.04}$	—	$-14.70^{+2.30}_{-2.30}$	—

W. T. H. Van Oers, & K. W. Brockman Jr, NPA 561 (1967);
J. Arvieux et al., NPA 221 (1973); E. Huttel et al., NPA 406 (1983);
A. Kievsky et al., PLB 406 (1997); T. C. Black et al., PLB 471 (1999);

- Coulomb + strong interaction using the Lednický model
  Lednický, R. Phys. Part. Nuclei 40, 307–352 (2009)
- Only s-wave interaction
- Source radius evaluated using the hadron-hadron universal m_T scaling

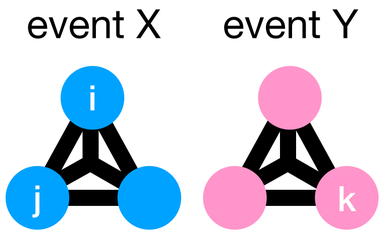


Point-like particle description doesn't work for p-d

Lower-order contributions

Data-driven method

- Use event mixing
- Two particles from the same event and one particle from another:



$$C_{ij}\left(\left[\mathbf{p}_i,\mathbf{p}_j\right],\mathbf{p}_k\right)=\frac{N_2\left(\mathbf{p}_i,\mathbf{p}_j\right)N_1\left(\mathbf{p}_k\right)}{N_1\left(\mathbf{p}_i\right)N_1\left(\mathbf{p}_j\right)N_1\left(\mathbf{p}_k\right)}$$

- Calculate Lorentz-invariant scalar Q_3 for every triplet $\mathbf{p}_i, \mathbf{p}_j, \mathbf{p}_k$ to obtain $C_{ij}(Q_3)$

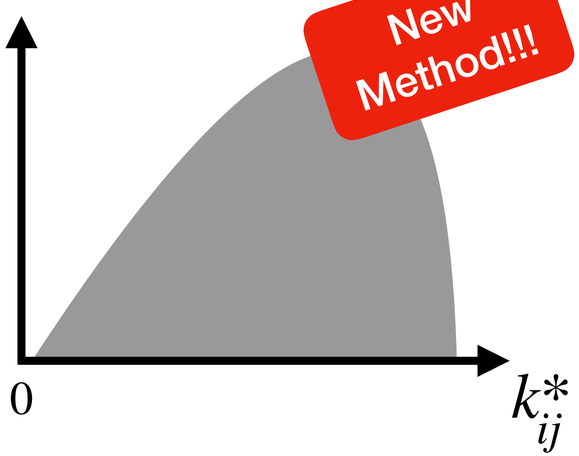
Projector method

- Use two-particle measured or theoretical correlation function $C([\mathbf{p}_i, \mathbf{p}_j])$
- Perform kinematic transformation:

$$C_2\left(k_{ij}^*\right)\rightarrow C_{ij}\left(Q_3\right)$$

k_{ij}^* (pair) $\rightarrow$ Q_3 (triplet)

For one Q_3 value $\rightarrow$



- To obtain the correlation function:

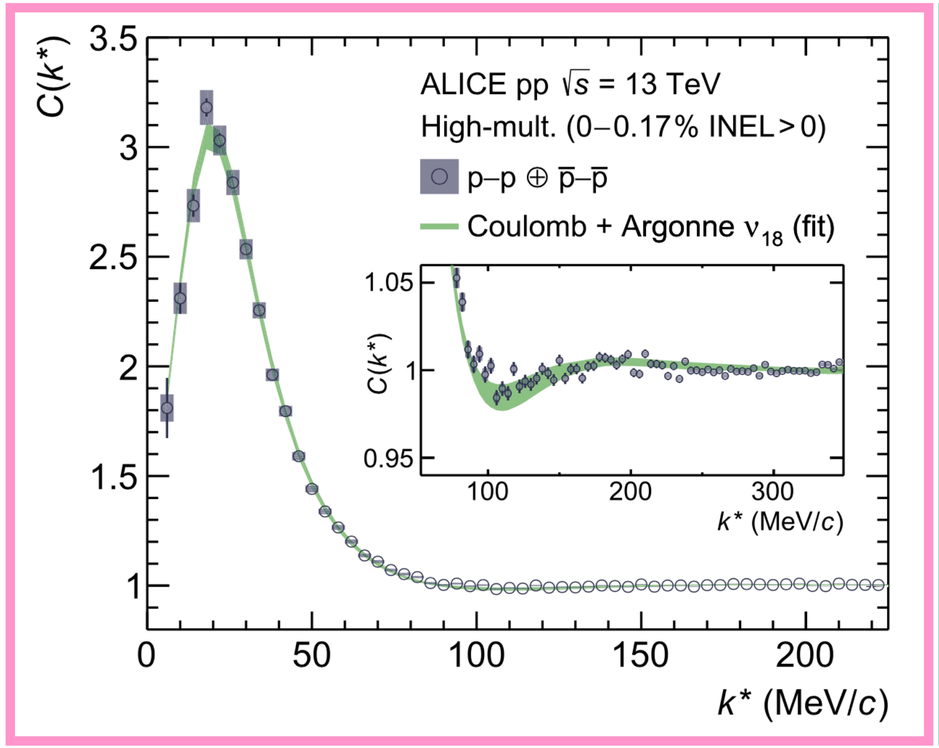
$$C_{ij}(Q_3)=\int C(k_{ij}^*)W_{ij}(k_{ij}^*,Q_3)dk_{ij}^*$$

Del Grande, Šerkšnytė et al. EPJC 82 (2022) 244

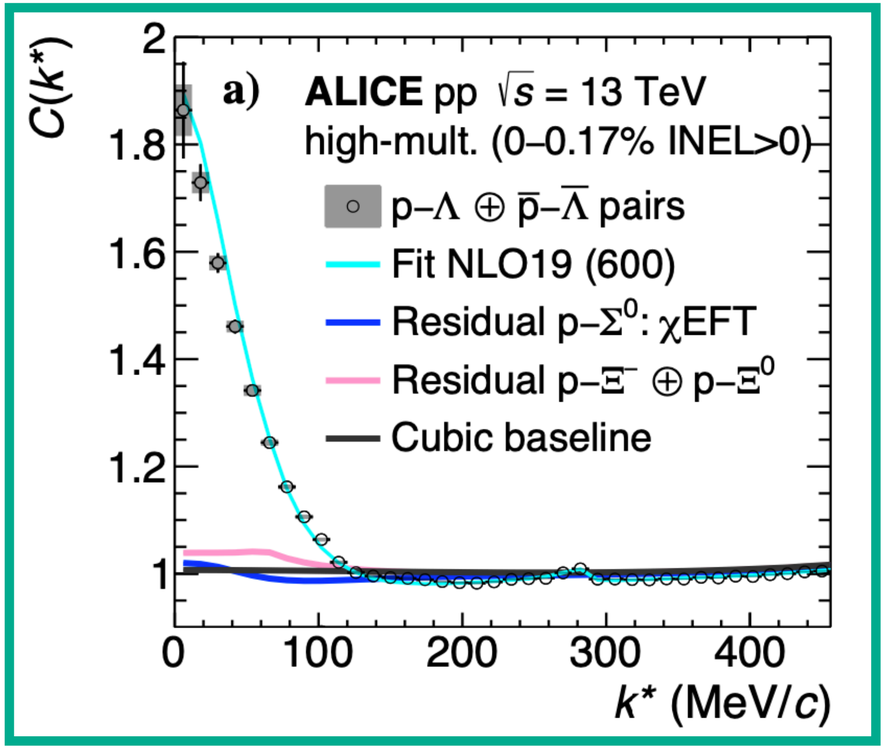
Two-body measurements

- Many different two-body interactions measured successfully!

p ? p



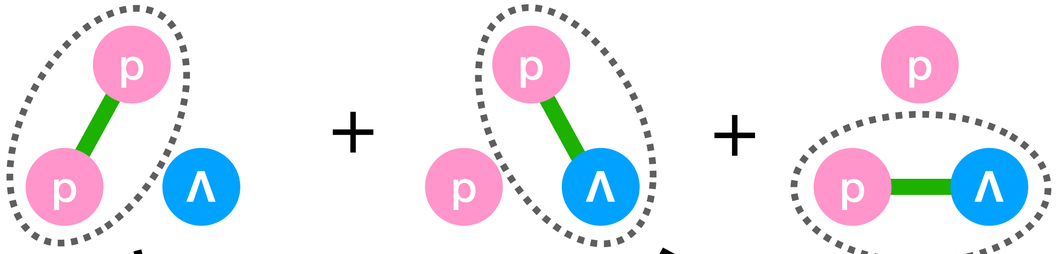
p ? Λ



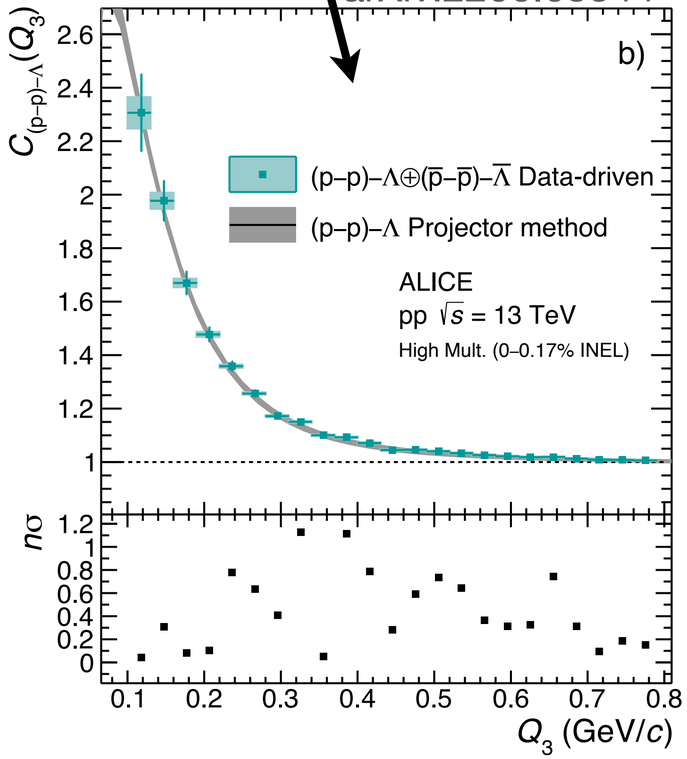
TUM Group:
EPJC 78 (2018) 394
arXiv:2107.10227

ALICE:
PRC 99 (2019) 024001
PLB 797 (2019) 134822
PRL 123 (2019) 112002
PRL 124 (2020) 09230
PLB 805 (2020) 135419
PLB 811 (2020) 135849
Nature 588 (2020) 232-238
arXiv:2104.04427
arXiv:2105.05578
arXiv:2105.05683
arXiv:2105.05190

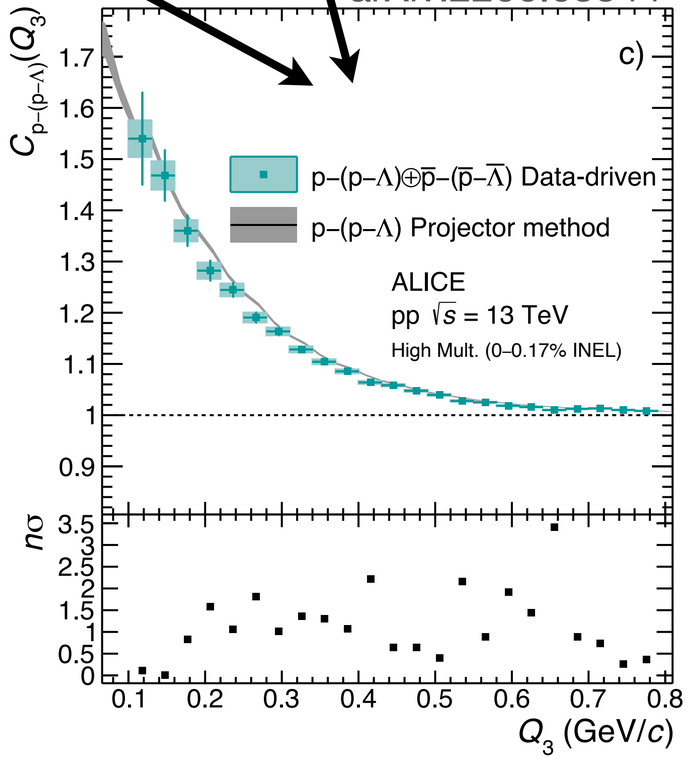
Lower-order contributions: p-p-Λ



arXiv:2206.03344

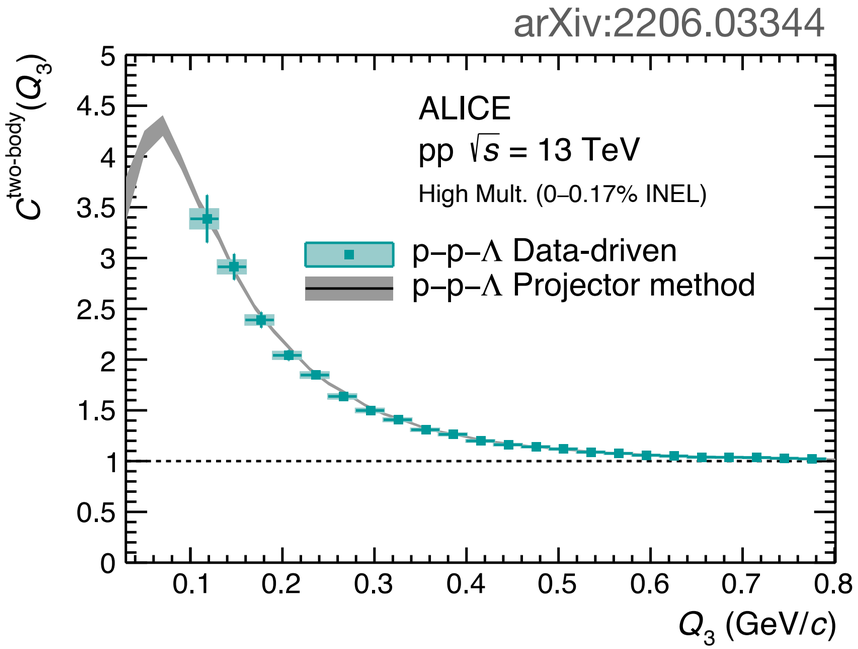


arXiv:2206.03344



Total lower-order contributions

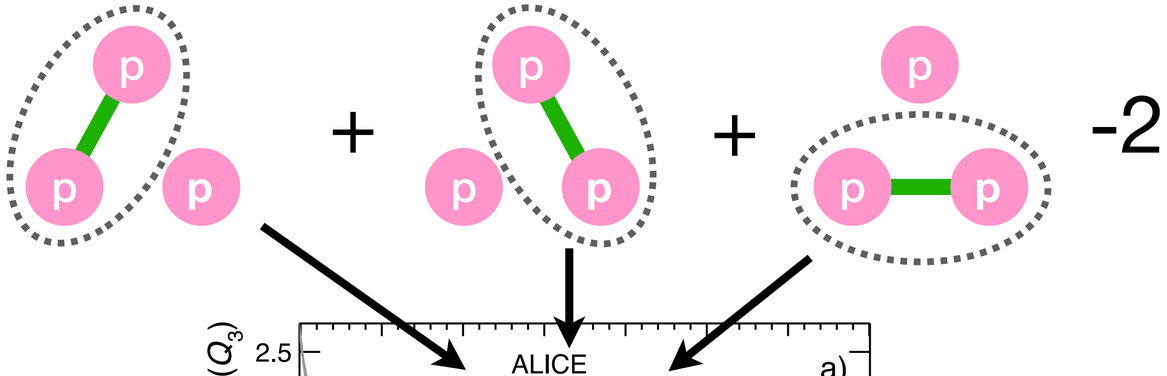
arXiv:2206.03344

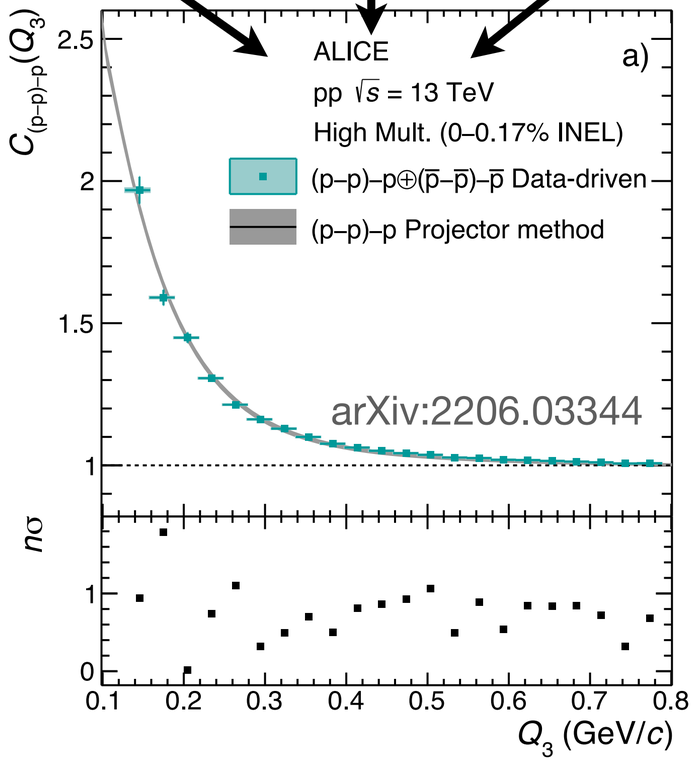


Already measured p-p [1] and p-Λ [2] correlation functions used for projection

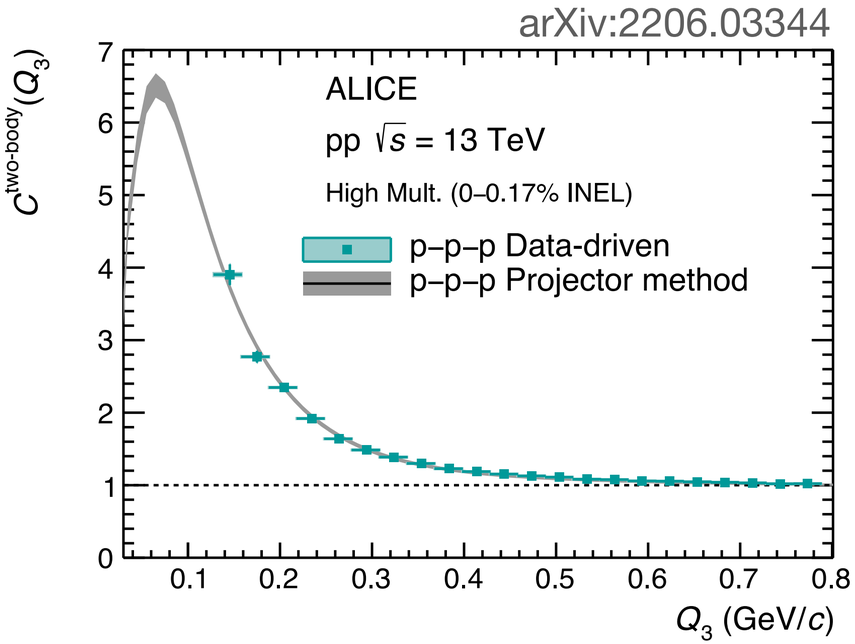
[1] PLB 805 (2020) 135419; [2] arXiv:2104.04427

Lower-order contributions: p-p-p





Total lower-order contributions



Already measured p-p [1] correlation function used for projection.

[1] PLB 805 (2020) 135419

Projector

- Looking at 2-body correlation function in 3-body space requires to account for the phase-space of the particles.

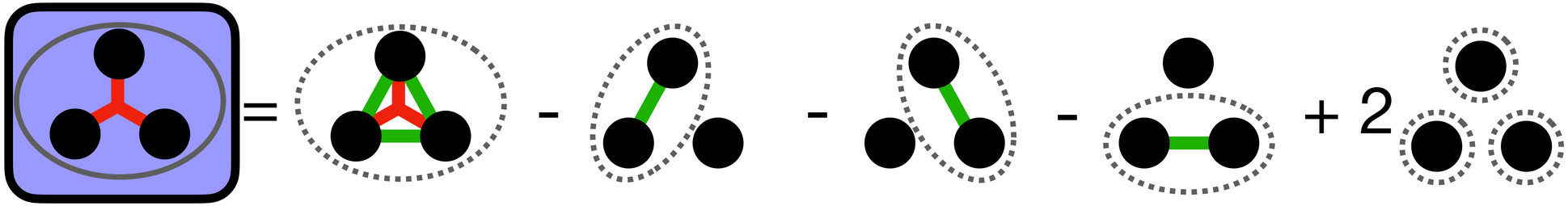
- The projection onto Q_3 is performed by integrating the correlation function over all the configurations in the momentum phase space having the same value of Q_3

$$C(Q_3) = \iiint_{Q_3=\text{constant}} C([\mathbf{p}_i, \mathbf{p}_j], \mathbf{p}_k)\; d^3\mathbf{p}_i\; d^3\mathbf{p}_j\; d^3\mathbf{p}_k \quad = \quad \int \; C_2(k^*_{ij})\; W_{ij}(k^*_{ij}, Q_3)\; dk^*_{ij}$$

$$W_{ij}(k^*_{ij}, Q_3) = \frac{16(\alpha\gamma - \beta^2)^{3/2} {k^*_{ij}}^2}{\pi\gamma^2 {Q_3}^4} \sqrt{\gamma {Q_3}^2 - (\alpha\gamma - \beta^2){k^*_{ij}}^2}$$

- The α, β, γ depend only on the masses of the three particles.

p-p-K+ cumulant

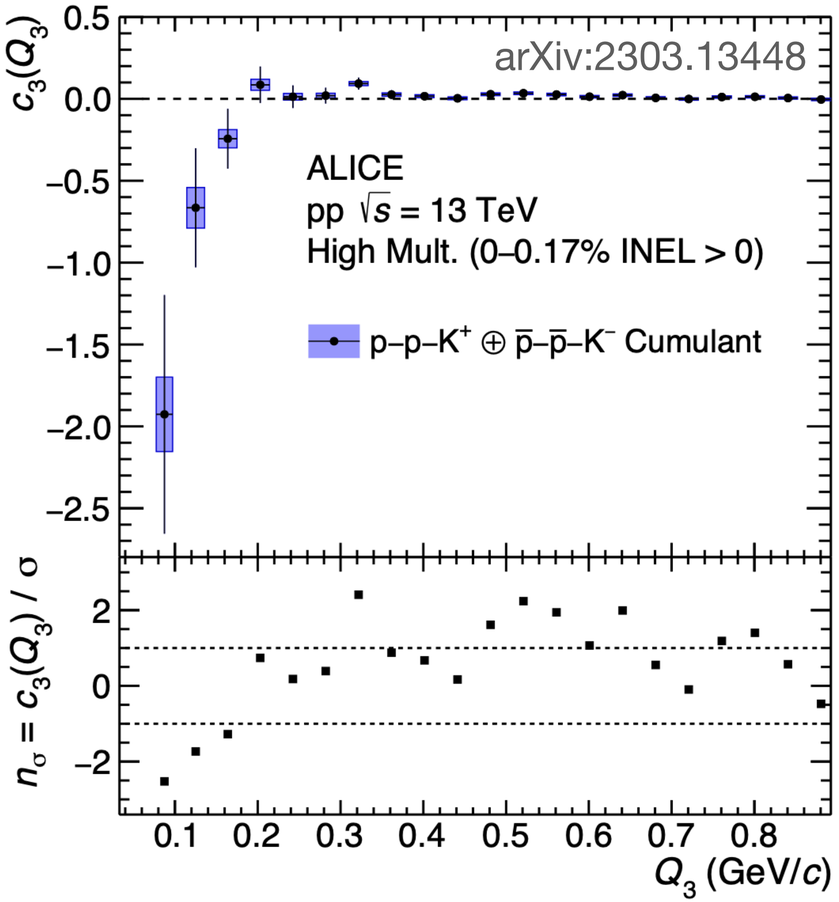


Hint of a negative cumulant for p-p-K+

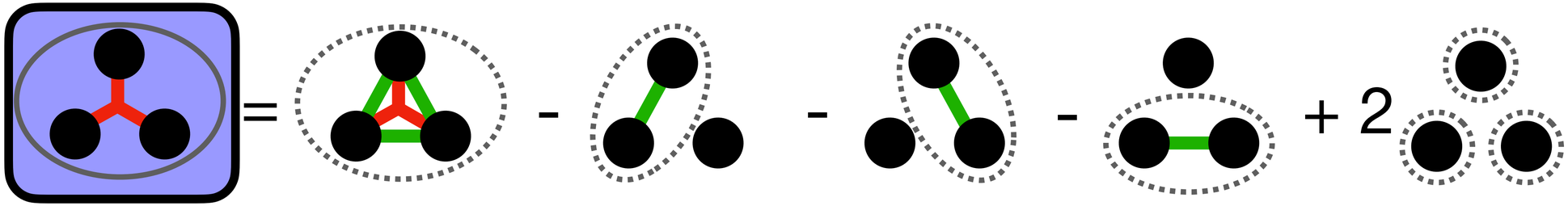
Statistical significance:

n_σ= 2.3 for Q_3 < 0.4 GeV/c

Conclusion: the measured cumulant is compatible with zero within the uncertainties



p-p-K$^-$ cumulant



Zero cumulant for p-p-K$^-$

Statistical significance:

n_σ= 0.5 for Q_3 < 0.4 GeV/c

Conclusion: the measured cumulant is compatible with zero within the uncertainties

p-p-K$^-$ system shows only two-body interactions.

✔ The measurement confirms that three-body strong interaction should not be relevant in the formation of exotic kaonic bound states!