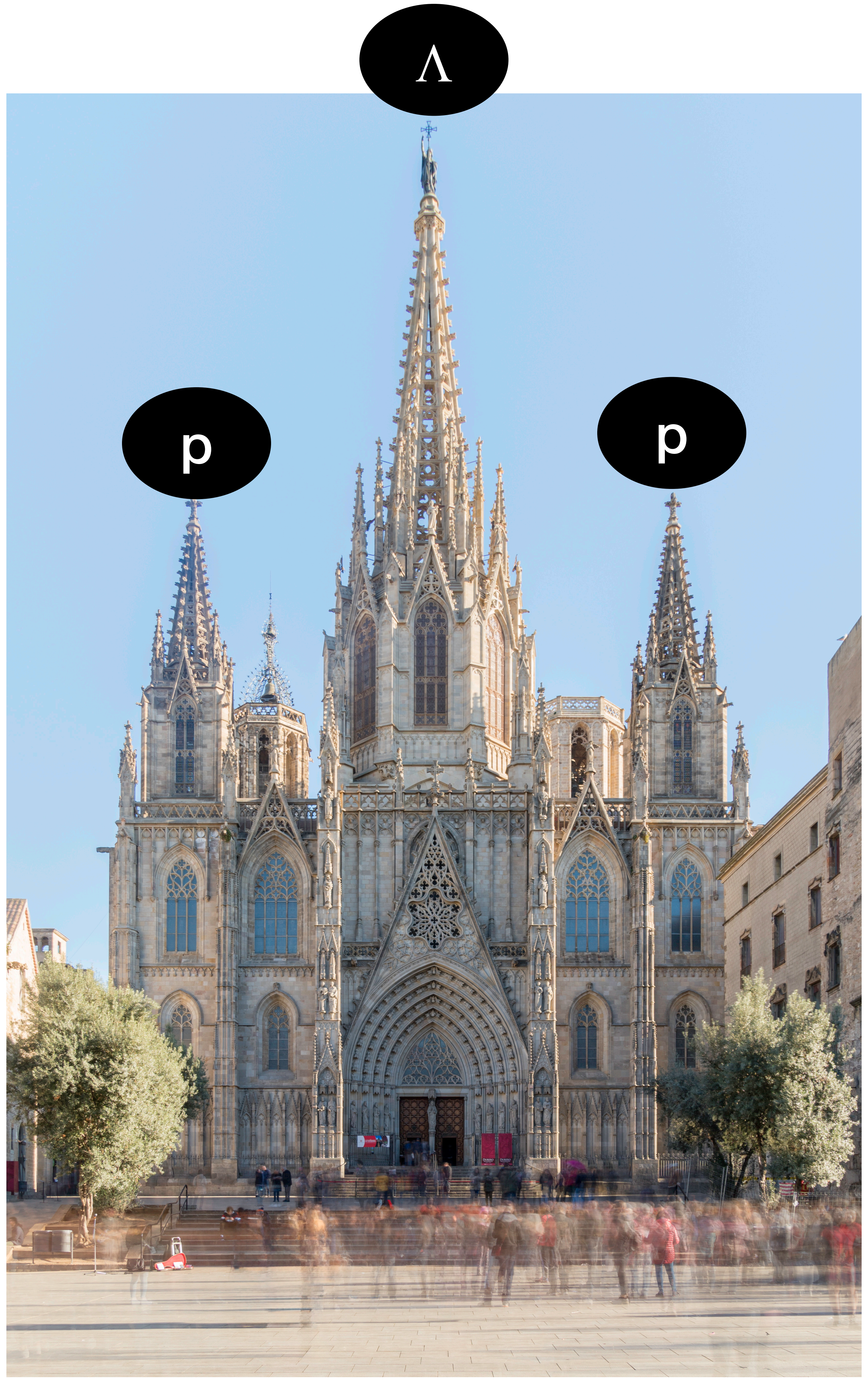


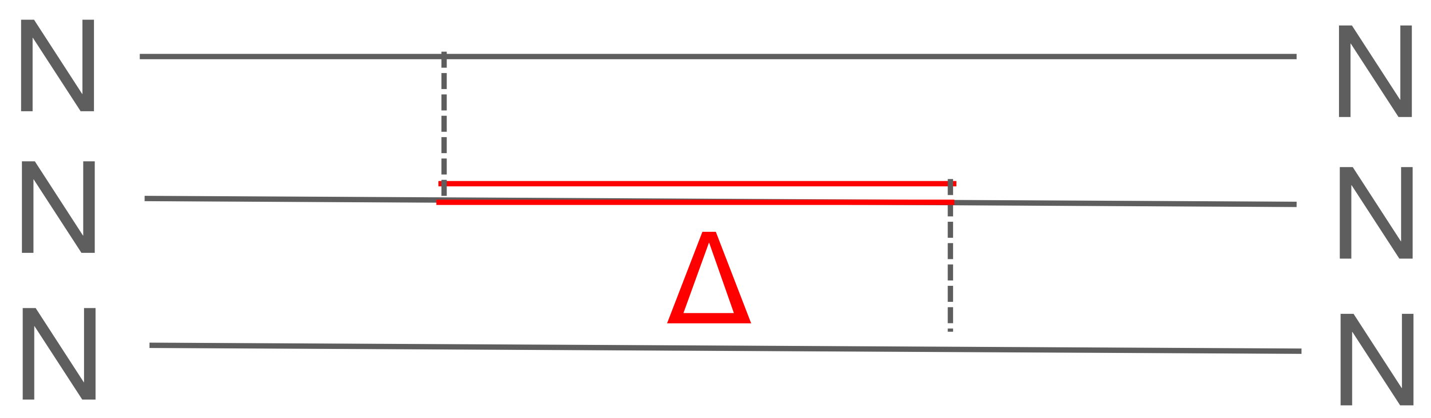
Can we measure genuine three body forces with femtoscopy?

Laura Fabbietti
Technische Universität München

Three-body dynamics

Dynamics of baryons involves formation of hadronic excitations

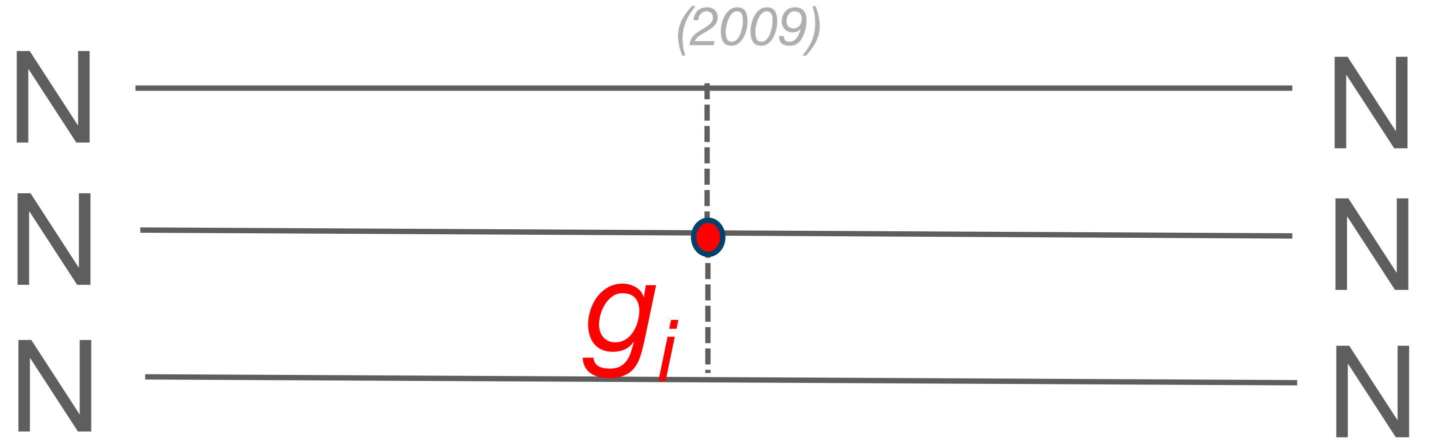
H.-W. Hammer, S. König, U. van Kolck RMP 92 (2020)



Short-range dynamics

Three-body forces in Effective Field Theories

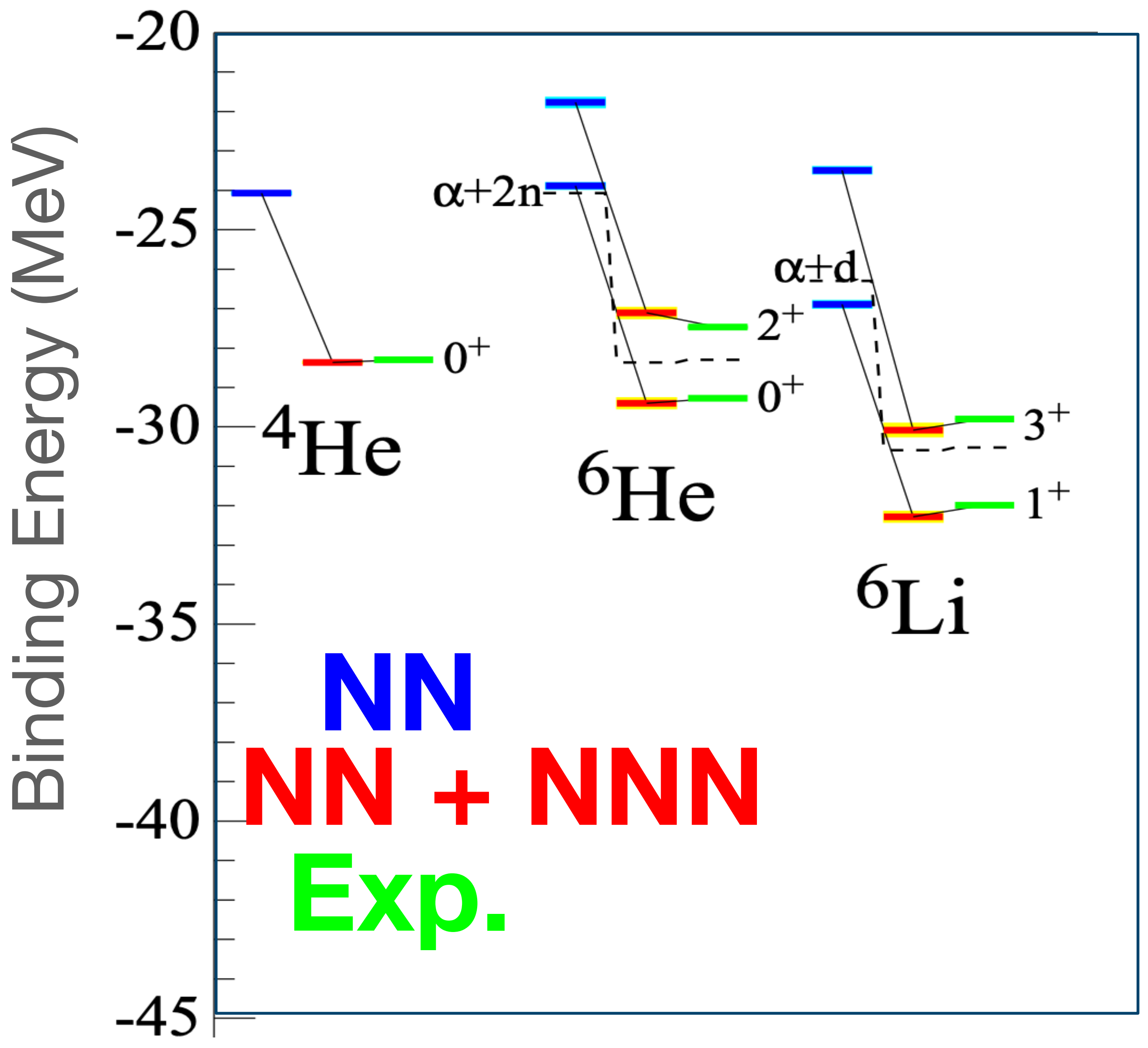
E. Epelbaum, H.-W. Hammer, U.-G. Meißner, RMP 81, 1773 (2009)



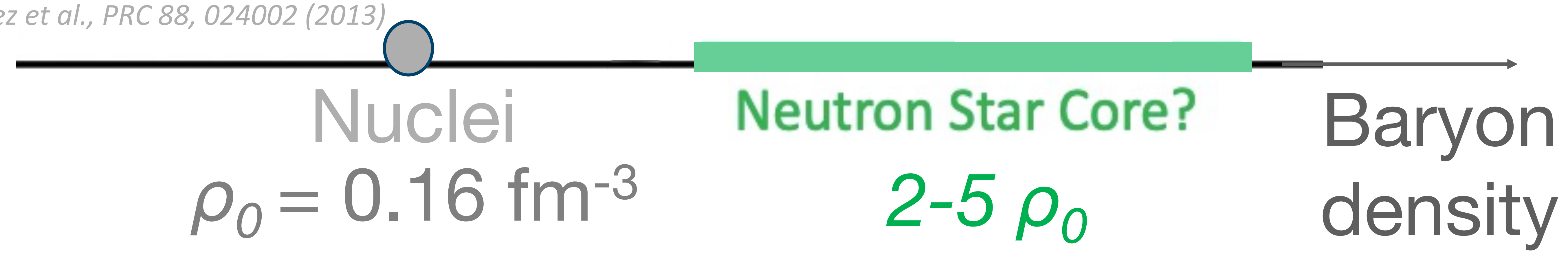
g_i constants to be fixed by the experimental data

Three-body forces

3BFs contribute 10-20% to the binding energies



R. Navarro Perez et al., PRC 88, 024002 (2013)



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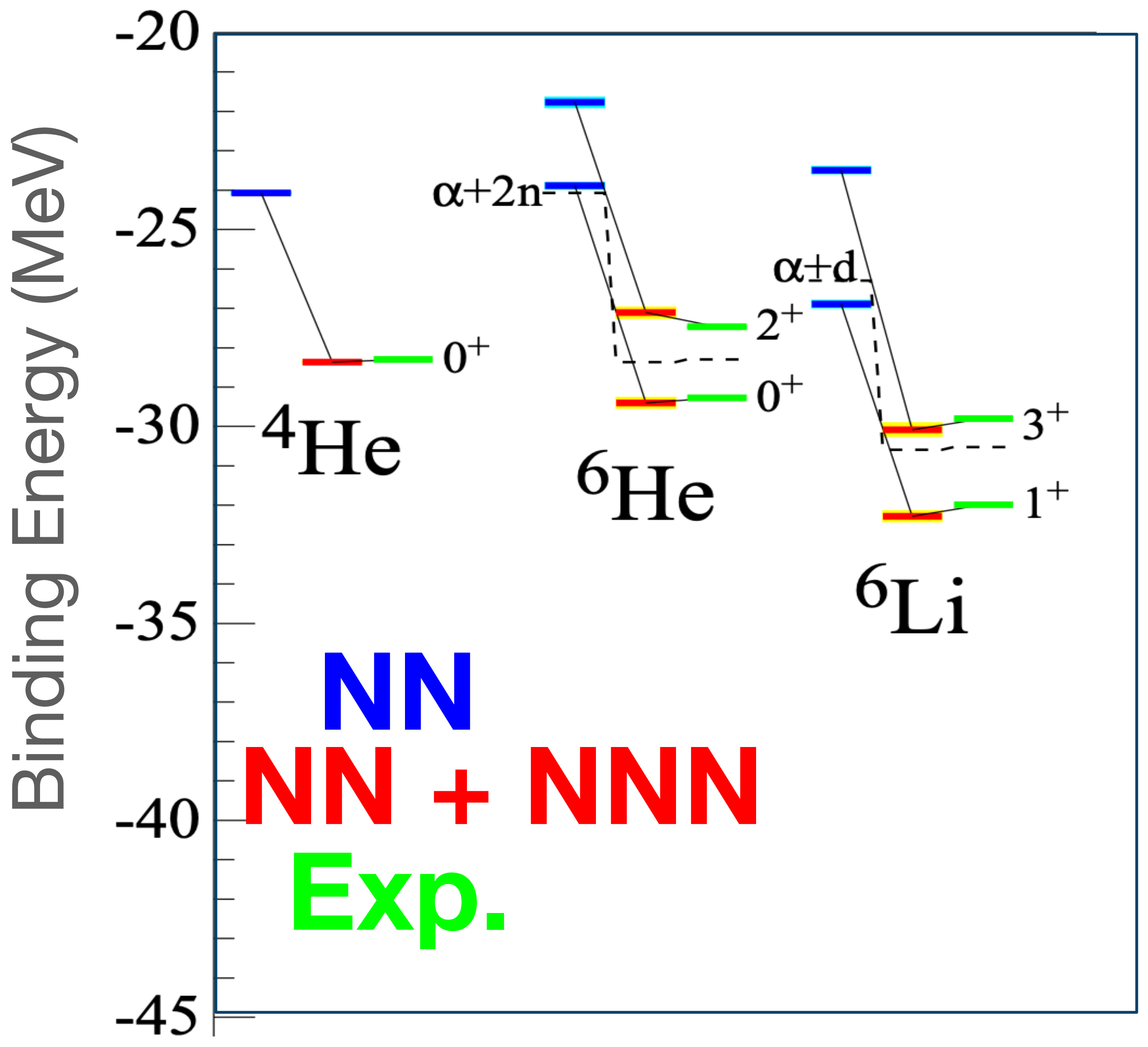
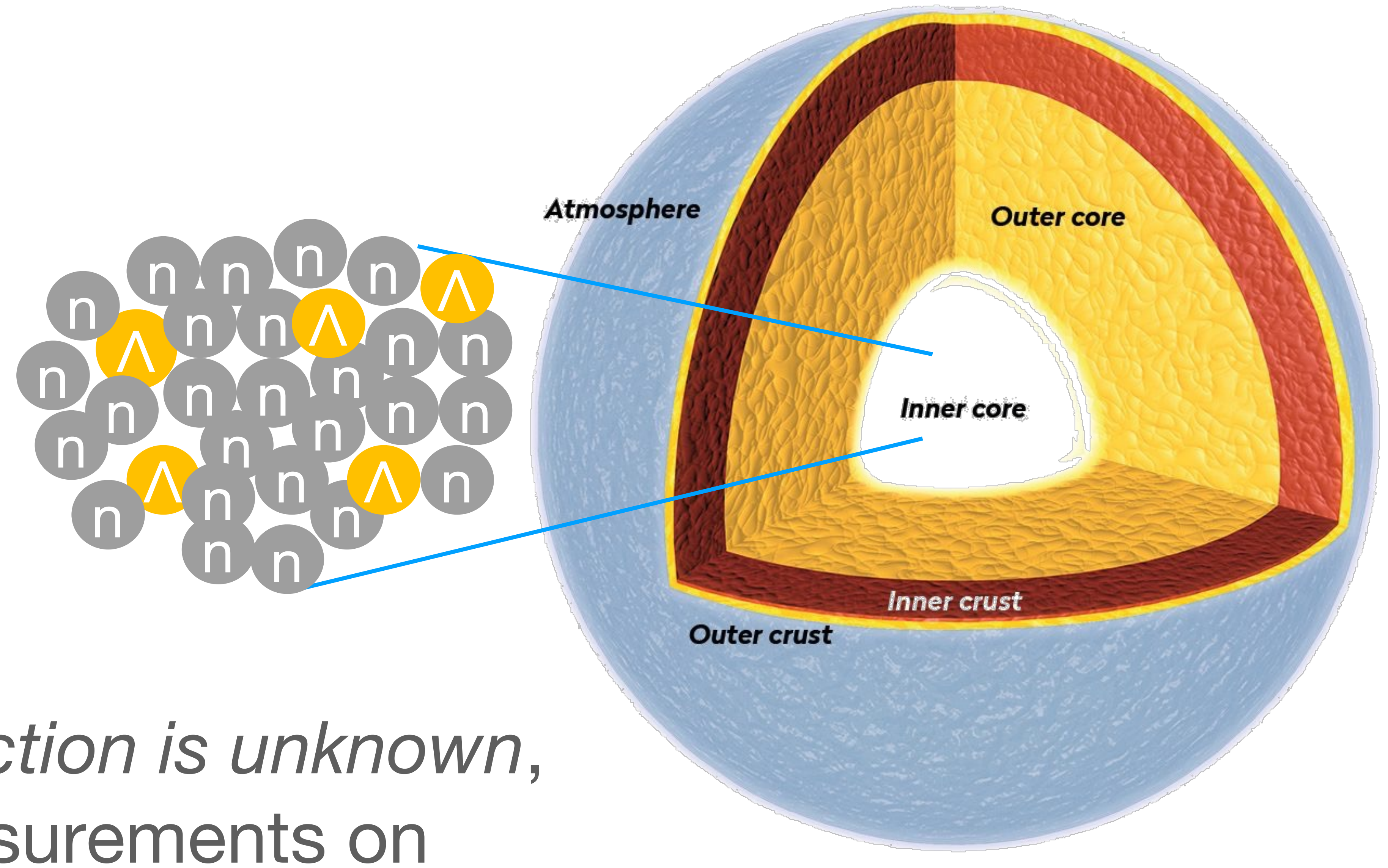


R. Navarro Perez et al., PRC 88, 024002 (2013)

Stronger impact on dense nuclear matter?

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



ΛNN interaction is unknown, 35 measurements on hypernuclei.

Nuclei

$\rho_0 = 0.16\ \text{fm}^{-3}$

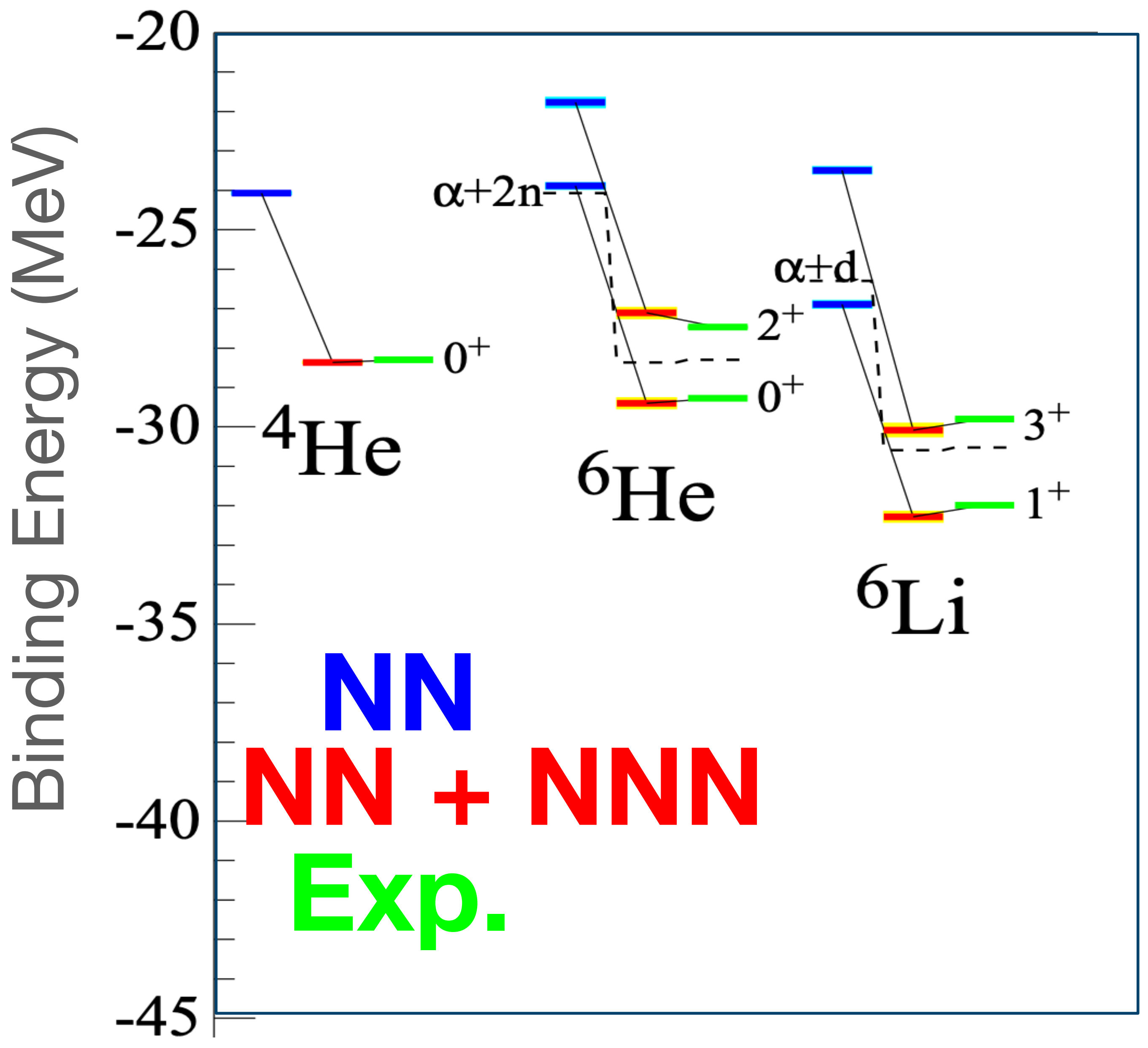
Neutron Star Core?

$2\text{-}5\ \rho_0$

Baryon density

Three-body forces

3BFs contribute 10-20% to the binding energies



R. Navarro Perez et al., PRC 88, 024002 (2013)

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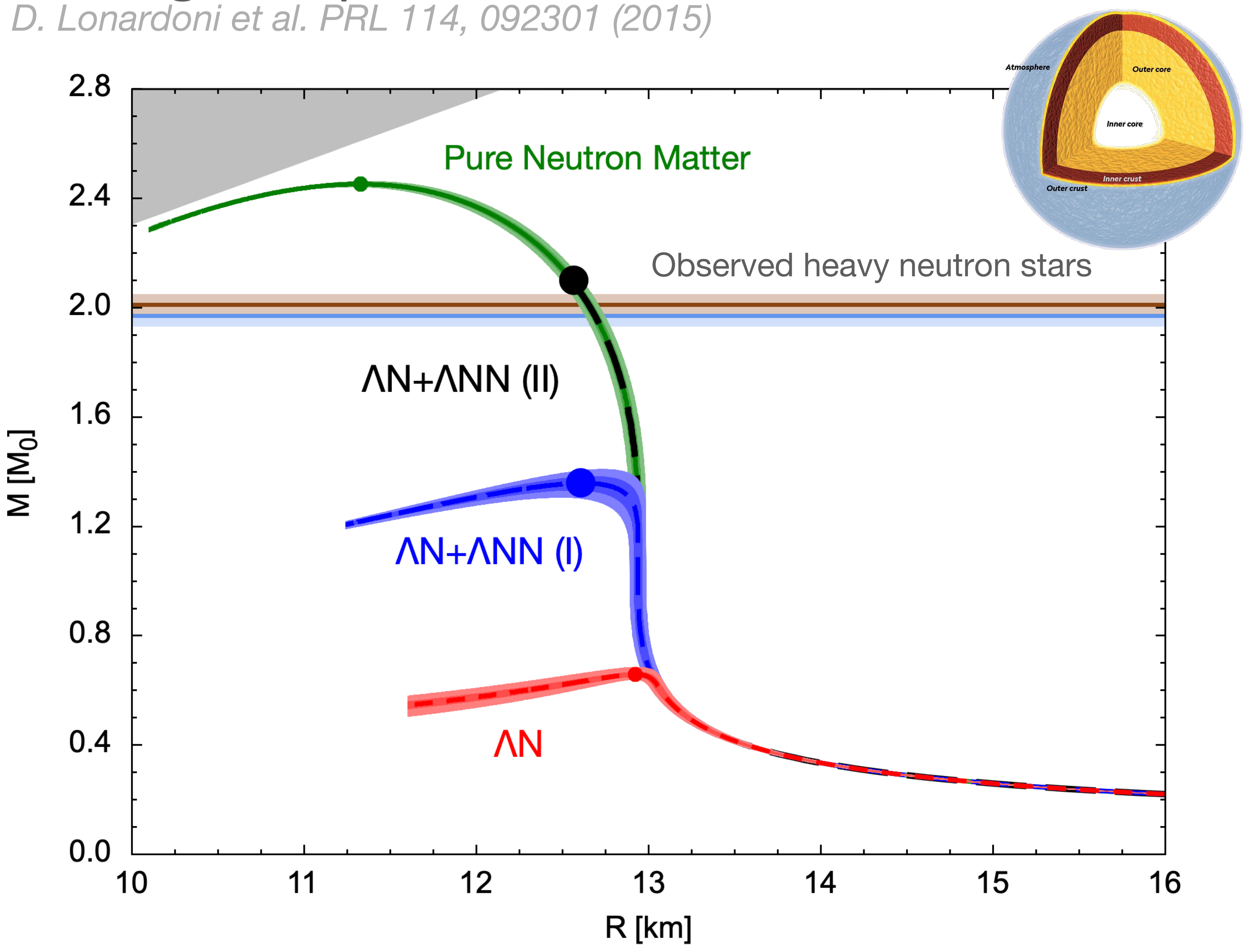

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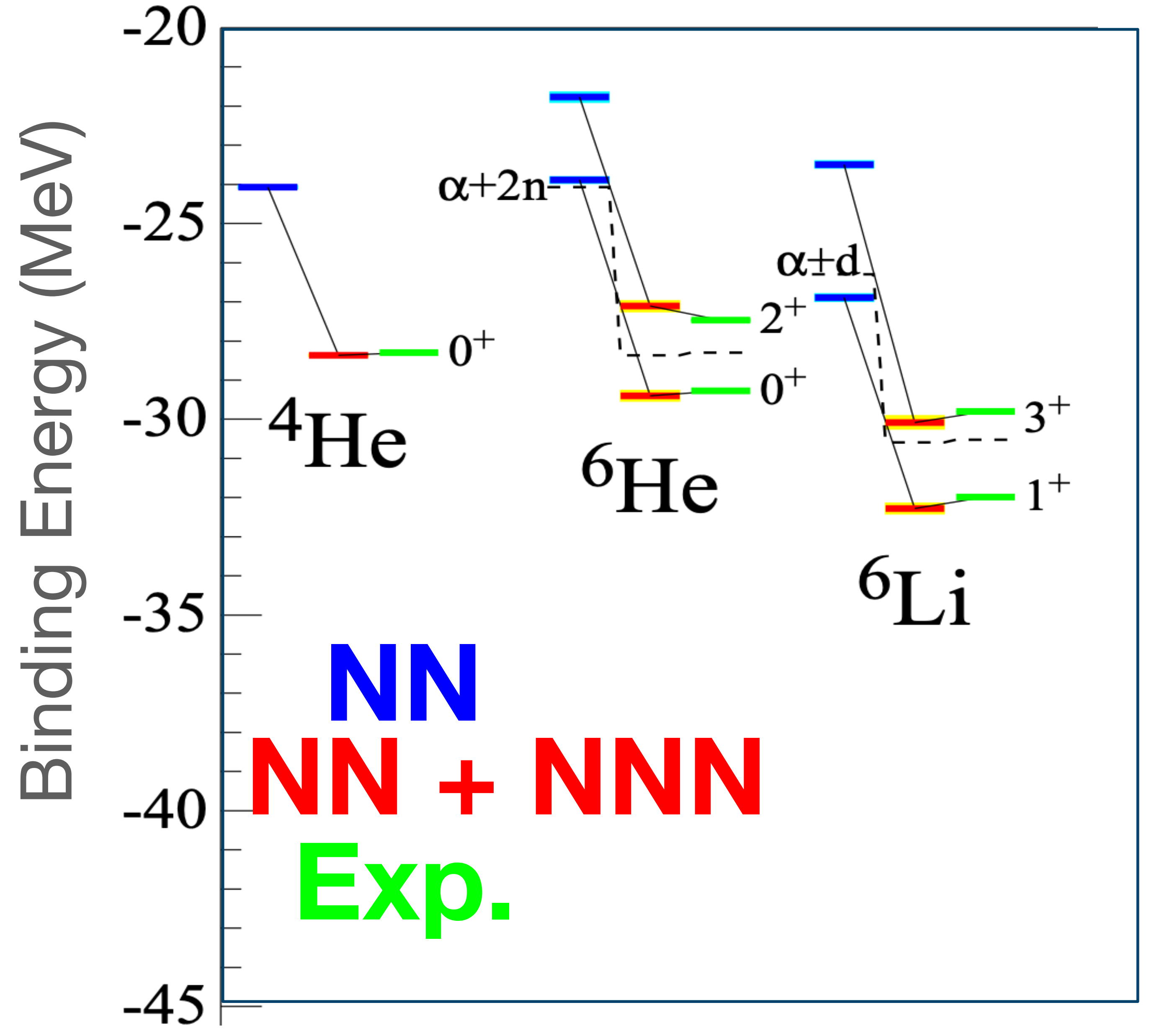

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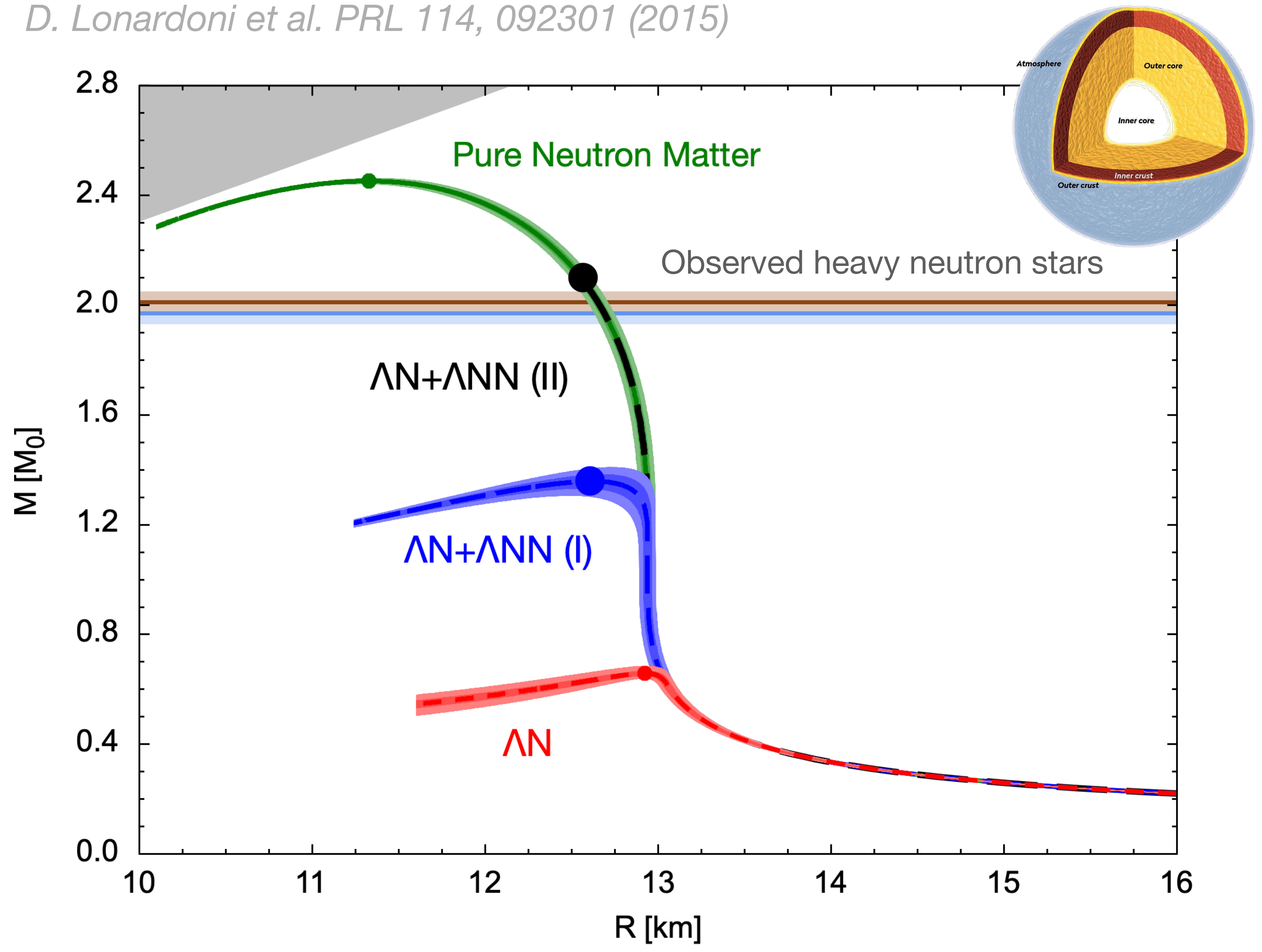


Nuclei

$\rho_0 = 0.16$ fm^{-3}

Neutron Star Core?

2-5 ρ_0

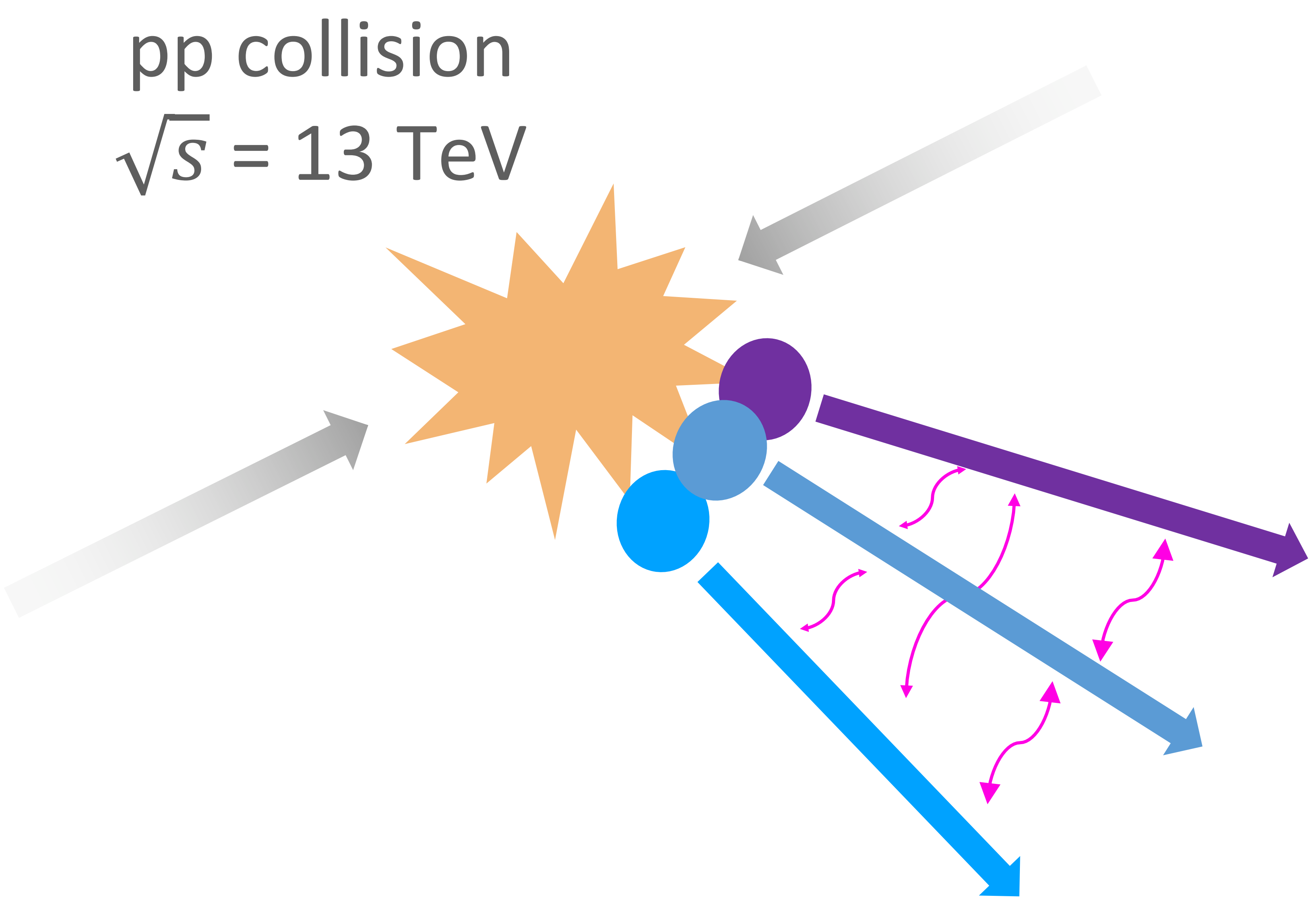
Baryon density

Inter-particle distances

~ 2 fm

~ 0.8-1.0 fm

Three-body scattering at the LHC

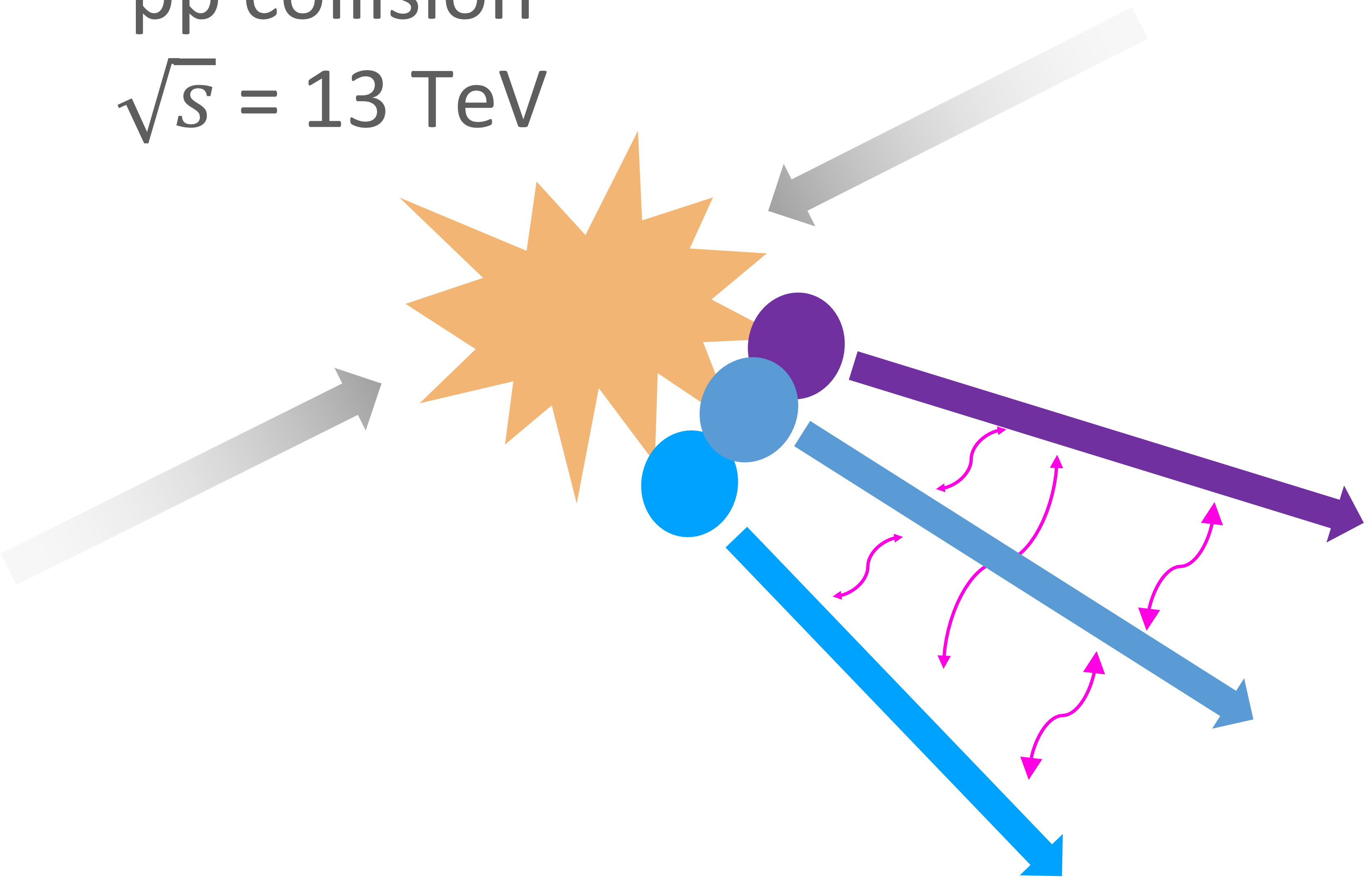


- Scattering of three hadrons are possible
  $$a + b + c \rightarrow a + b + c$$
- Interaction of unstable hadrons can be accessed

Three-body scattering at the LHC

pp collision

$\sqrt{s}$ = 13 TeV



- *Femtoscopy*: Clear relation between the experimental observable and the theory

$$C(Q_3) = \int S(\rho)\left|\psi\,(Q_3, \rho\,)\right|^2 \rho^5\, d\rho$$

Source function

Wave function

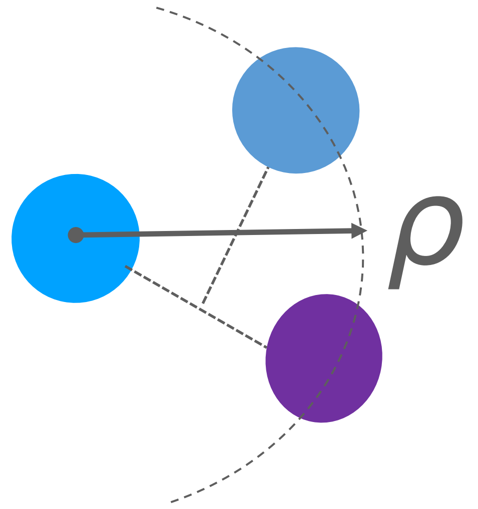
M. A. Lisa, S. Pratt, R. Soltz, and U. Wiedemann, ARNP 55 (2005) 357

R. Del Grande et al, EPJC 82 (2022)

A. Kievsky, **R. Del Grande** et al., Phys. Rev. C 109 (2023)

Q_3 = momentum coordinate

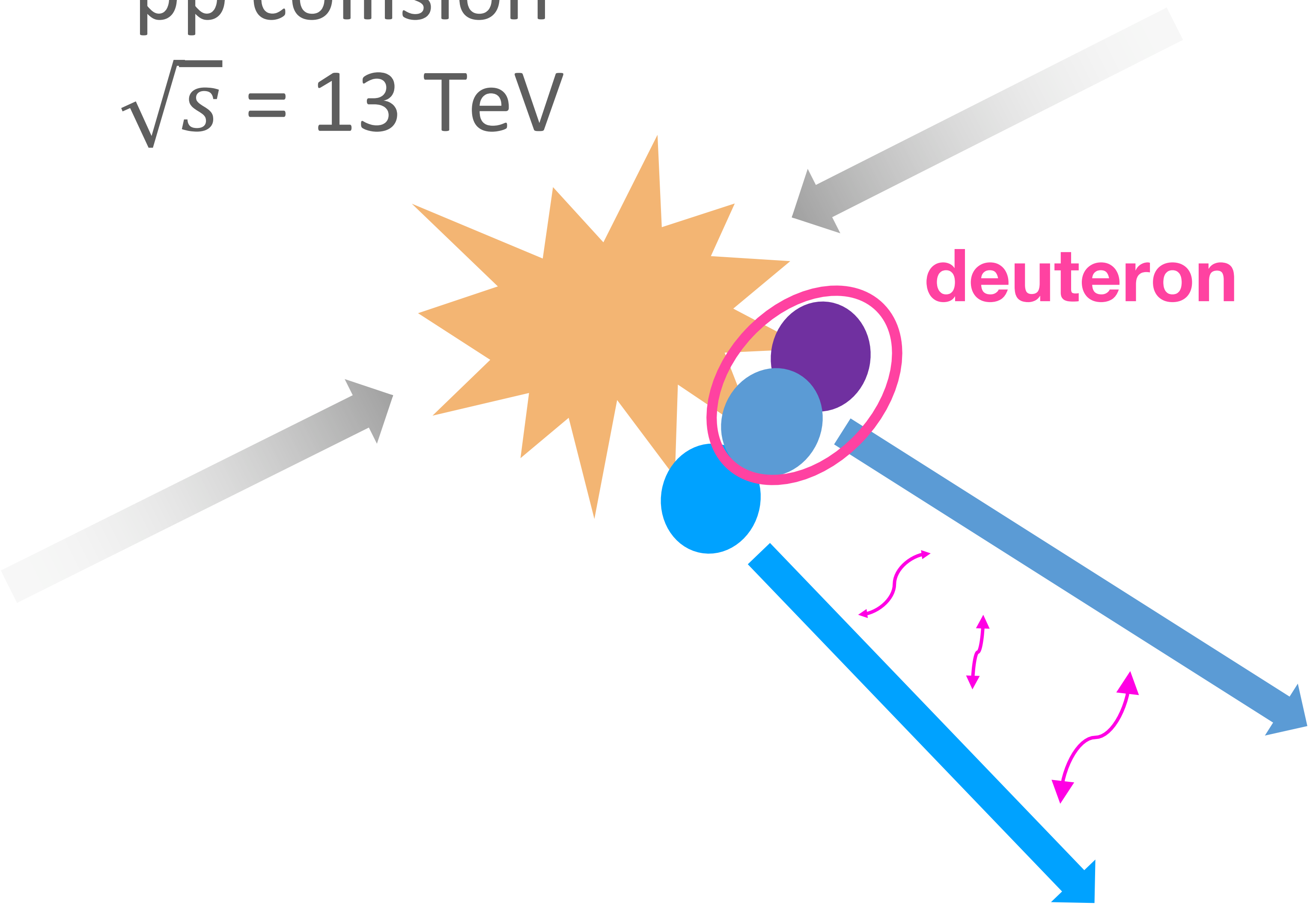
ρ = spatial coordinate



$$Q_3 = \sqrt{-q_{ij}^2 - -q_{ik}^2 - q_{kj}^2}$$

Three-body scattering at the LHC

pp collision
$\sqrt{s}$ = 13 TeV



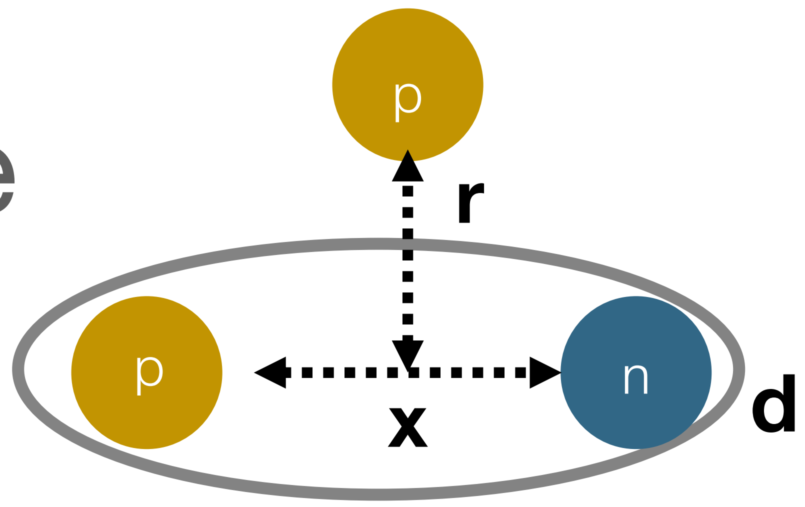
➢ *Femtoscopy*: Clear relation between the experimental observable and the theory

$$C(k^*) = \int S(r)\left|\psi(k^*, r)\right|^2 4\pi r^2\, dr$$

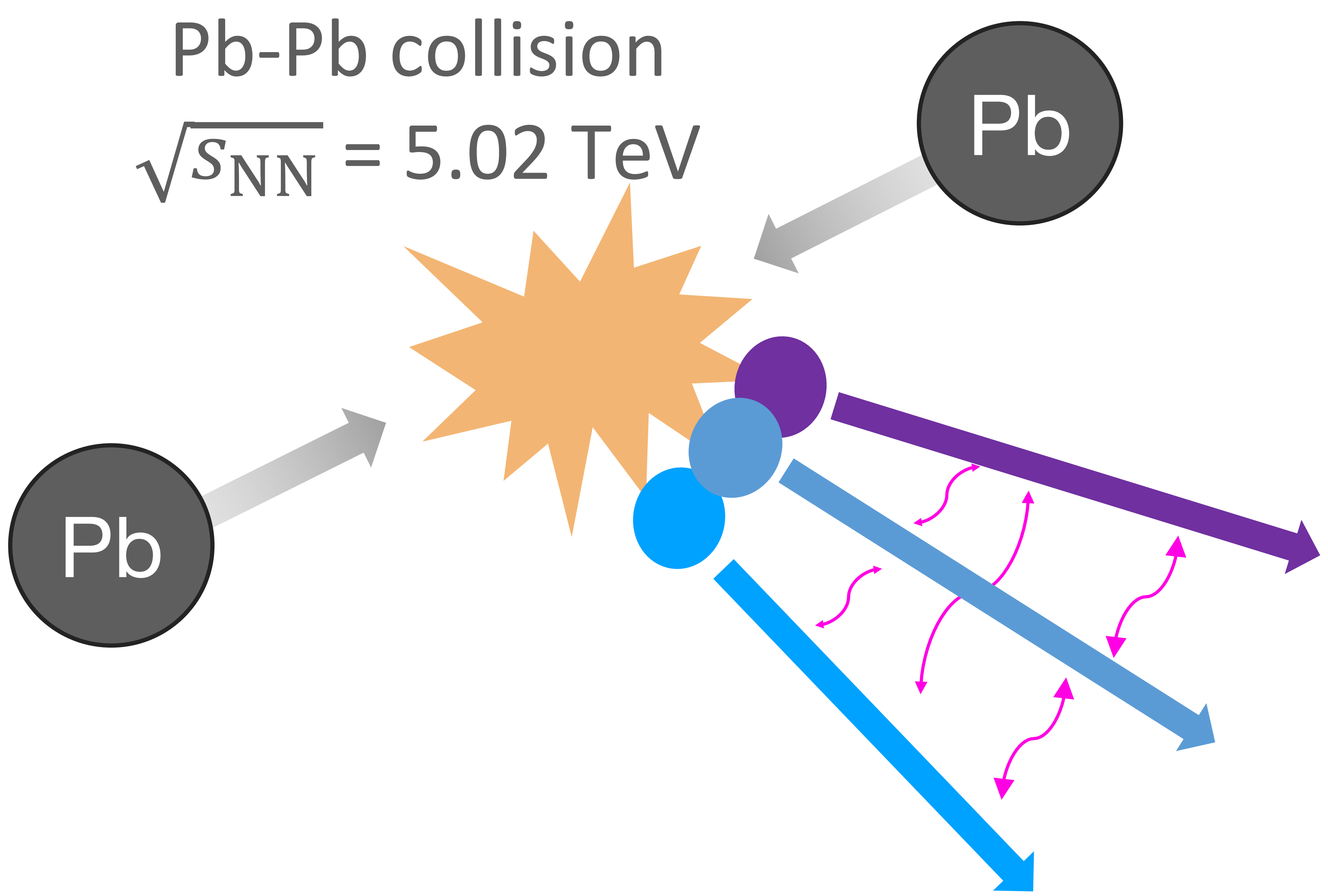
Source function   Wave function

M. A. Lisa, S. Pratt, R. Soltz, and U. Wiedemann, ARNP 55 (2005) 357
D. Mihaylov et al. Eur.Phys.J.C 78 (2018) 5, 394

k^* = relative momentum in the pair reference frame
r = spatial coordinate

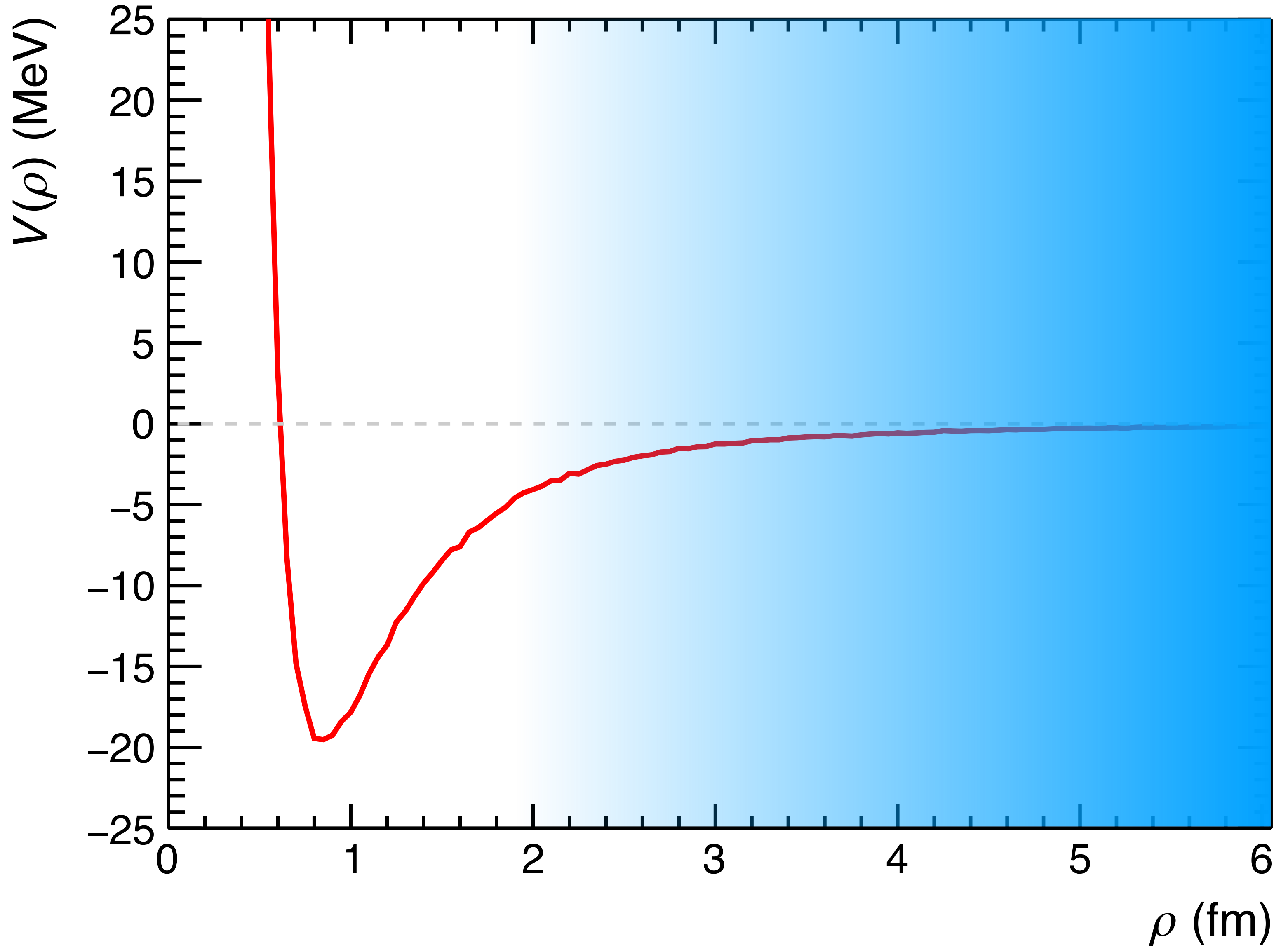


Accessing the distance dependence

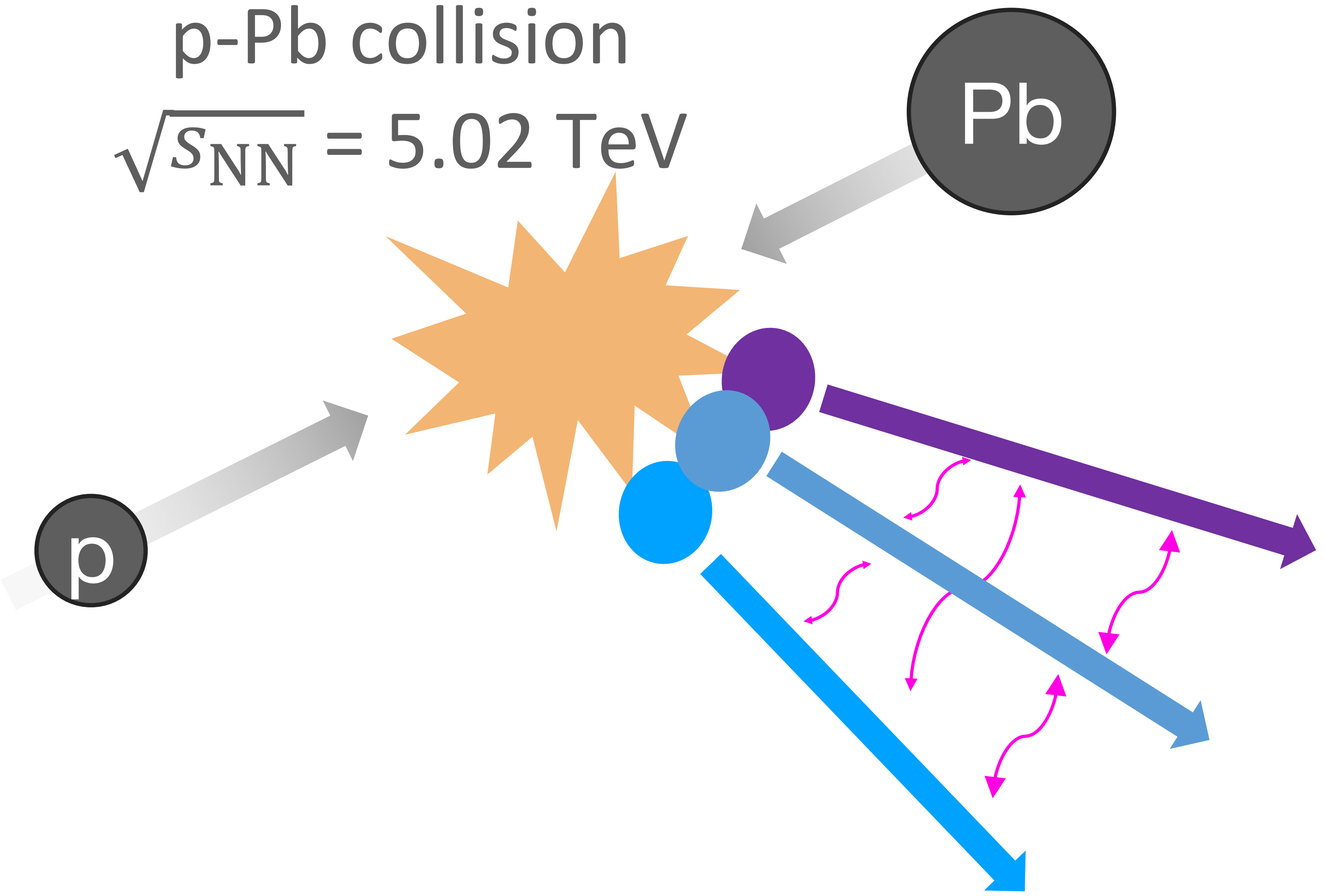


- Explore different system size

Collisions	Source size
Pb-Pb	1.8 – 10 fm

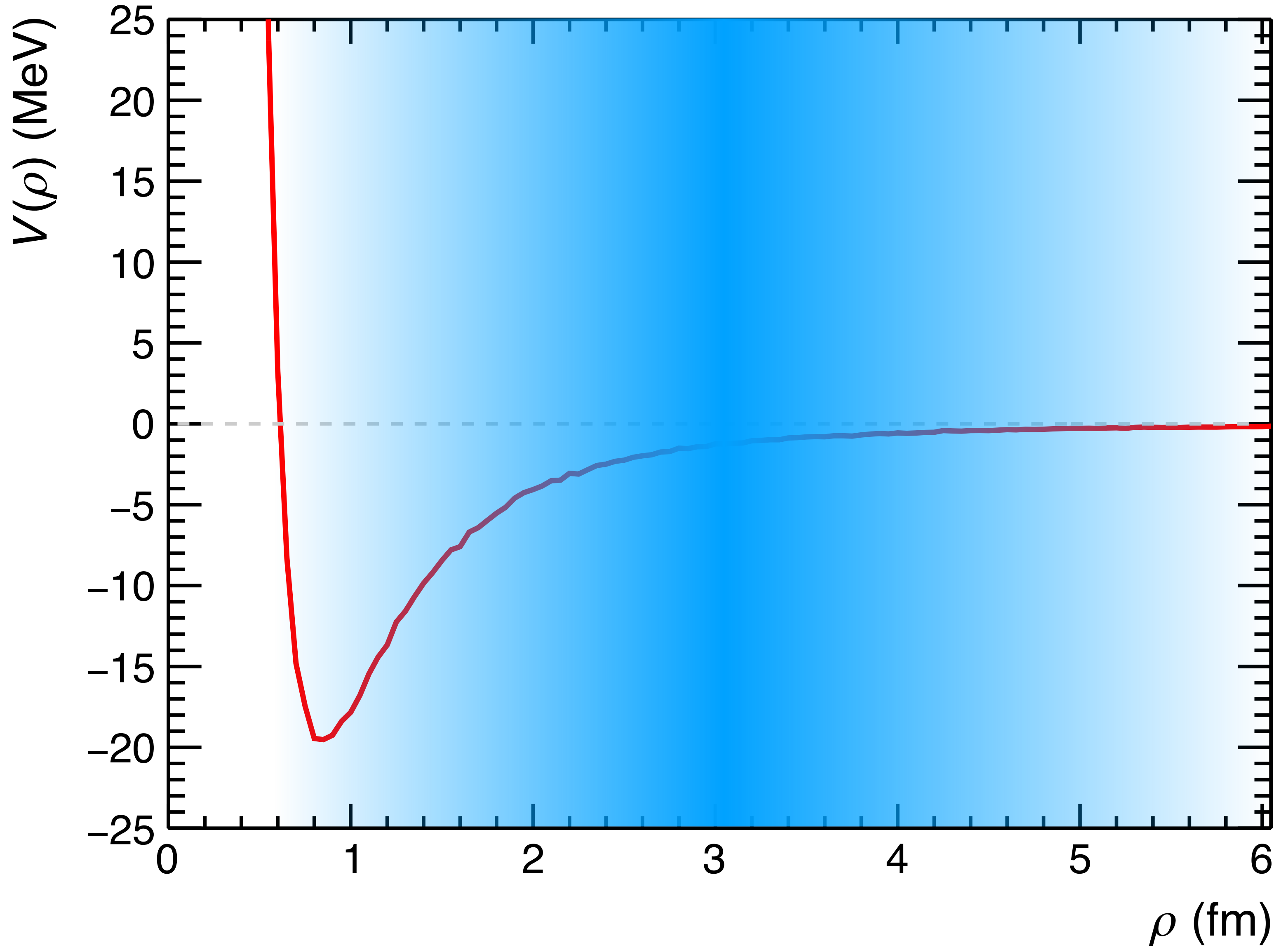


Accessing the distance dependence

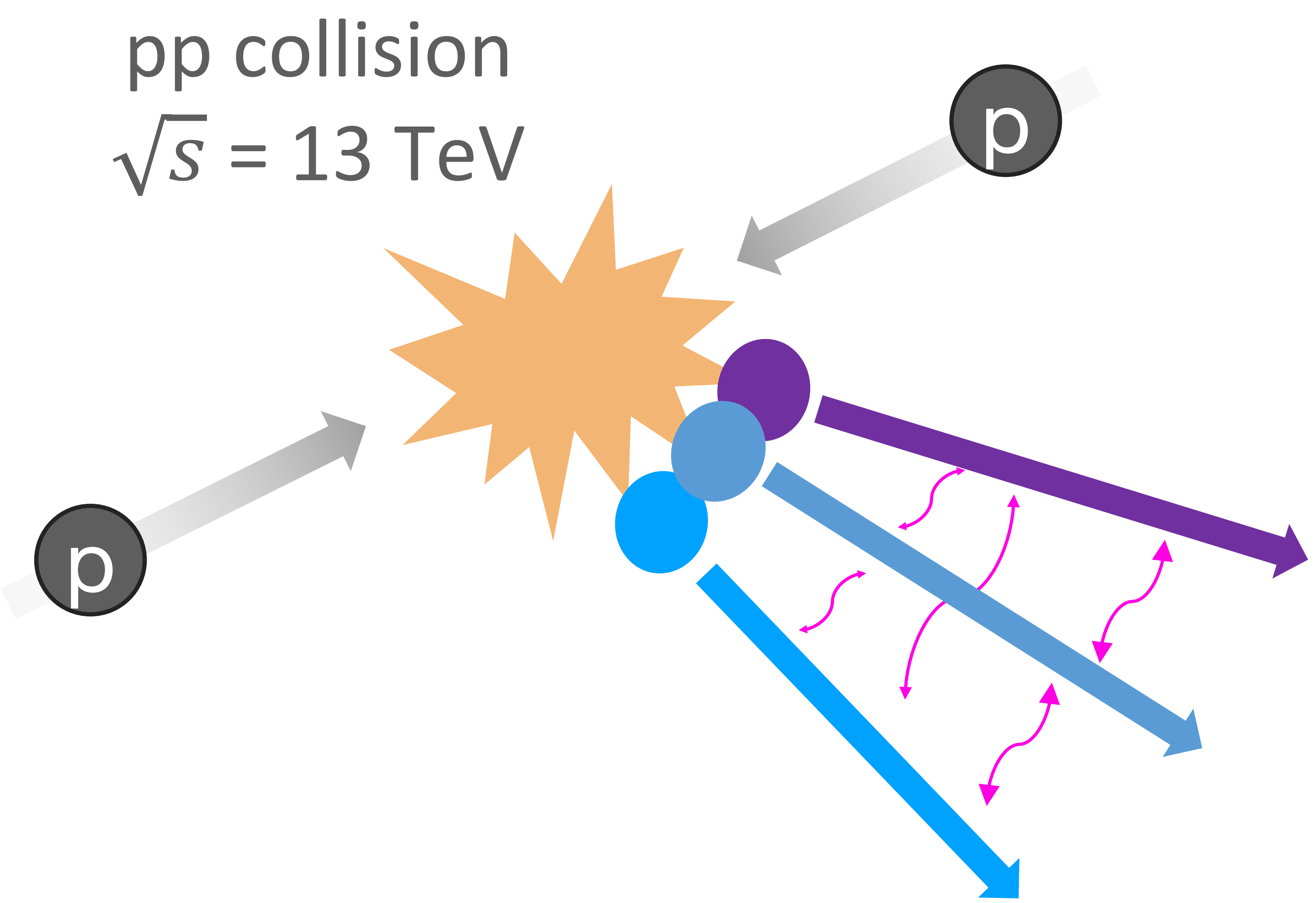


- Explore different system size

Collisions	Source size
Pb-Pb	1.8 – 10 fm
p-Pb	1.4 – 1.8 fm

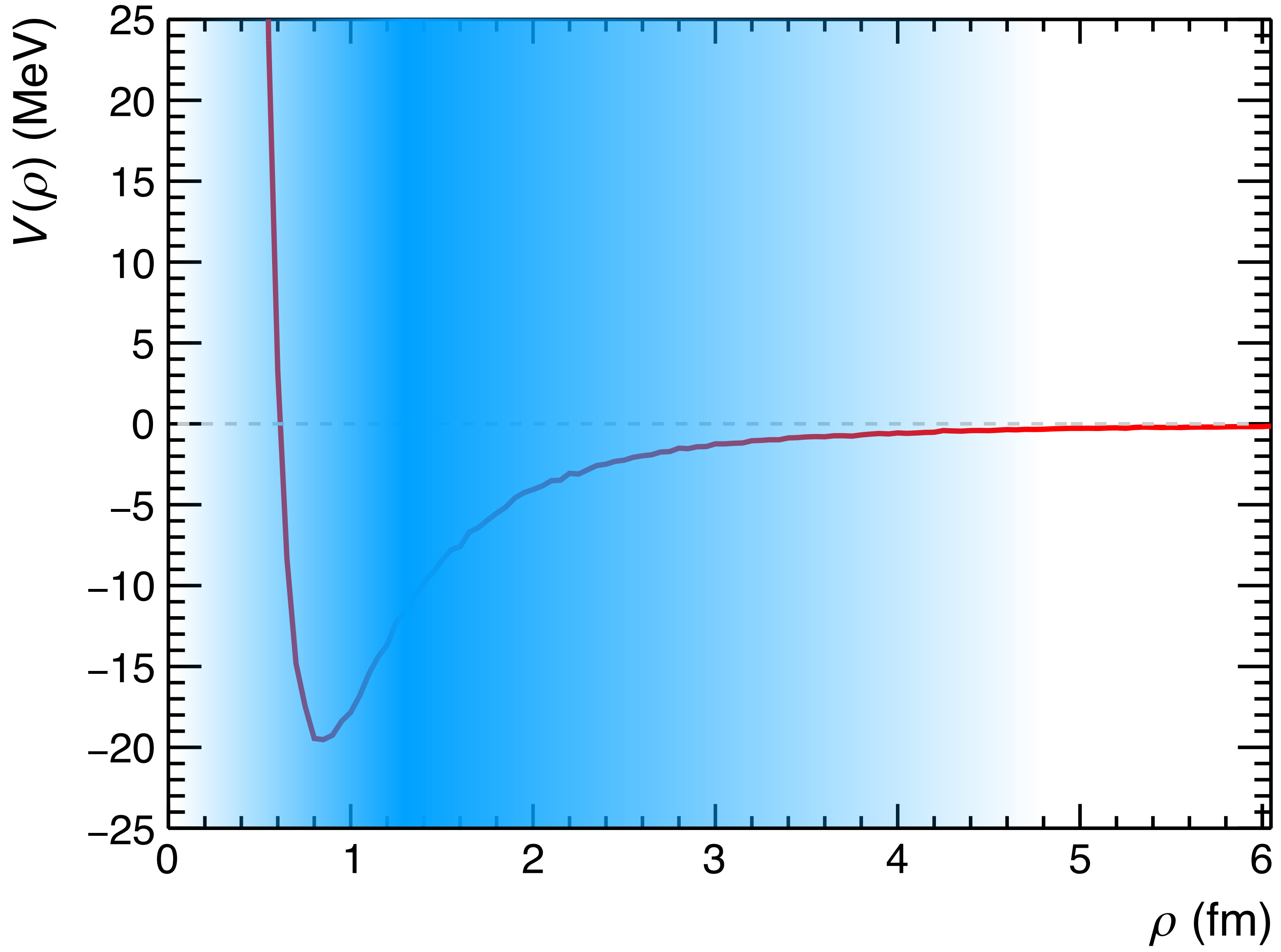


Accessing the distance dependence



- Explore different system size

Collisions	Source size
Pb-Pb	1.8 – 10 fm
p-Pb	1.4 – 1.8 fm
pp	0.8 – 1.4 fm



ALICE detector

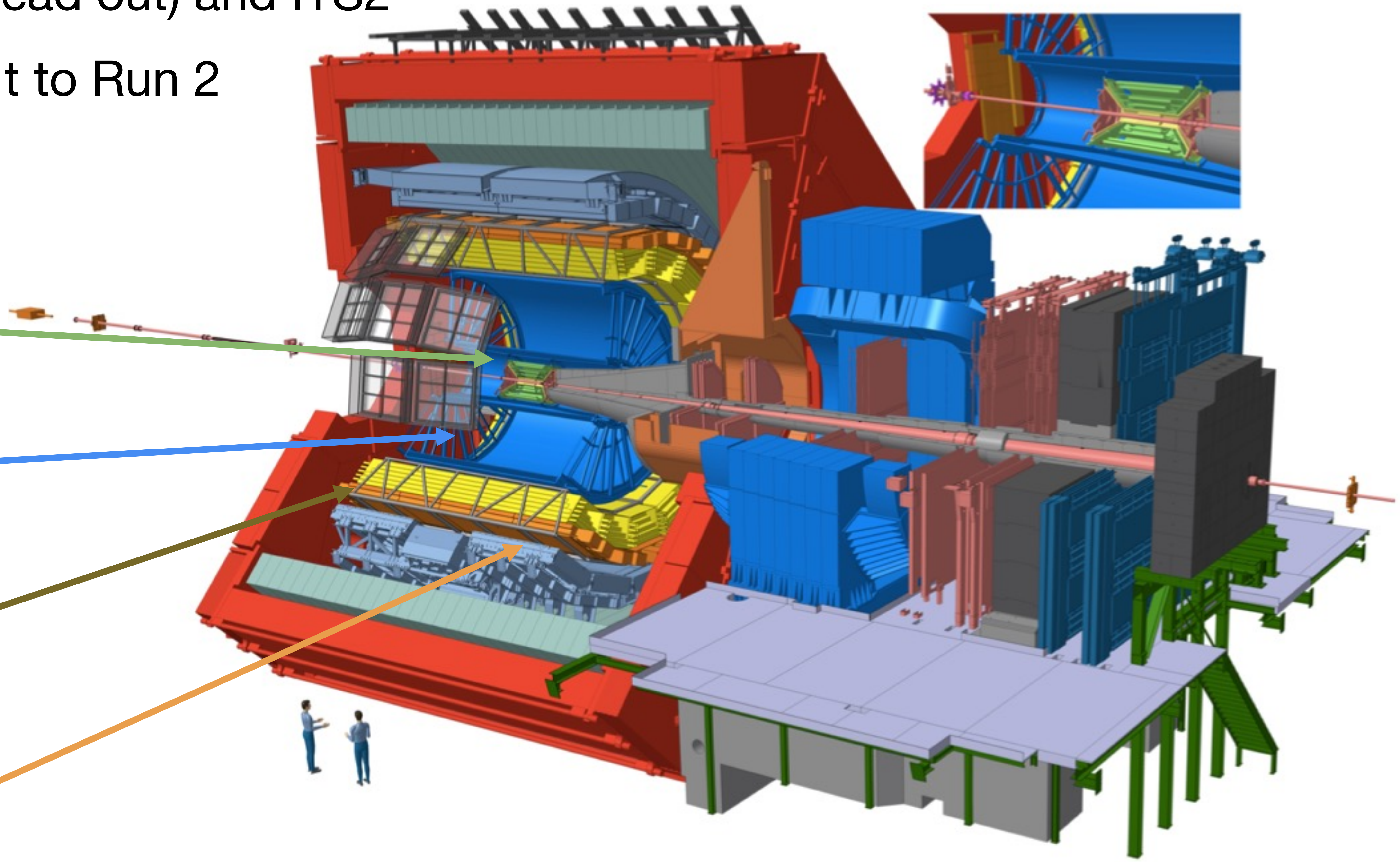
- Excellent tracking and particle identification (PID) capabilities
- Most suitable detector at the LHC to study (anti-)nuclei production and annihilation
- Major upgrade of the TPC (GEM read out) and ITS2
- Factor 100 in data taking rate w.r.t to Run 2
- Run 3 started in 2022-(2025)

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

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

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

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



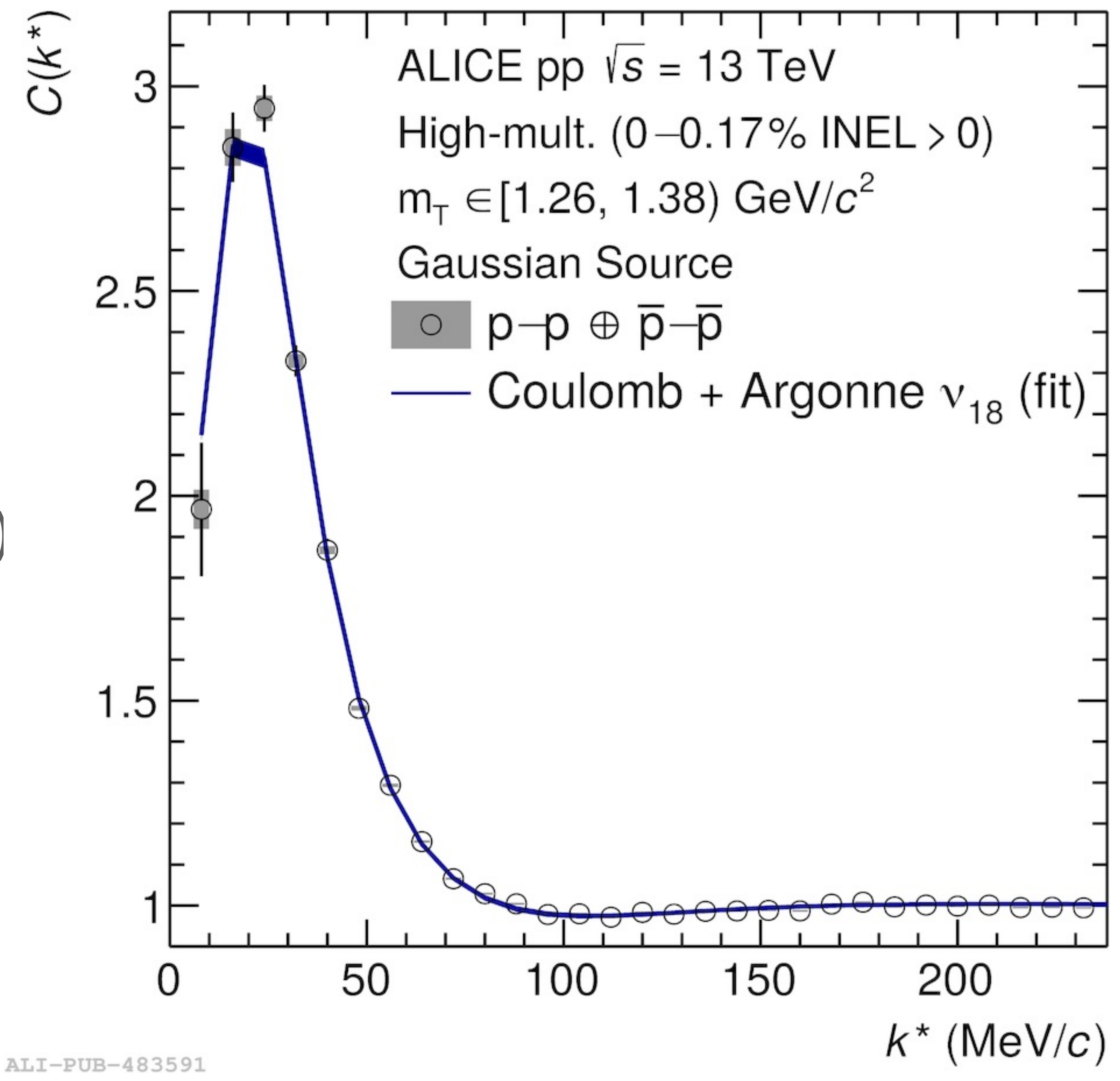
Source function in pp collisions at the LHC

- Emitting source function anchored to p-p correlation function

$$\underbrace{C(k^*)}_{\text{measured}} = \int S(\vec{r}\,)\underbrace{\left|\psi(\vec{k}^*,\vec{r}\,)\right|^2}_{\text{known interaction}} d^3\vec{r}$$

- Gaussian parametrization

$$S(r) = \frac{1}{(4\pi r_{core}^2)^{3/2}} \exp\left(-\frac{r^2}{4r_{core}^2}\right) \times$$ Effect of short lived resonances (cτ ~ 1 fm)



ALICE Coll., PLB, 811 (2020)

Source function in pp collisions at the LHC

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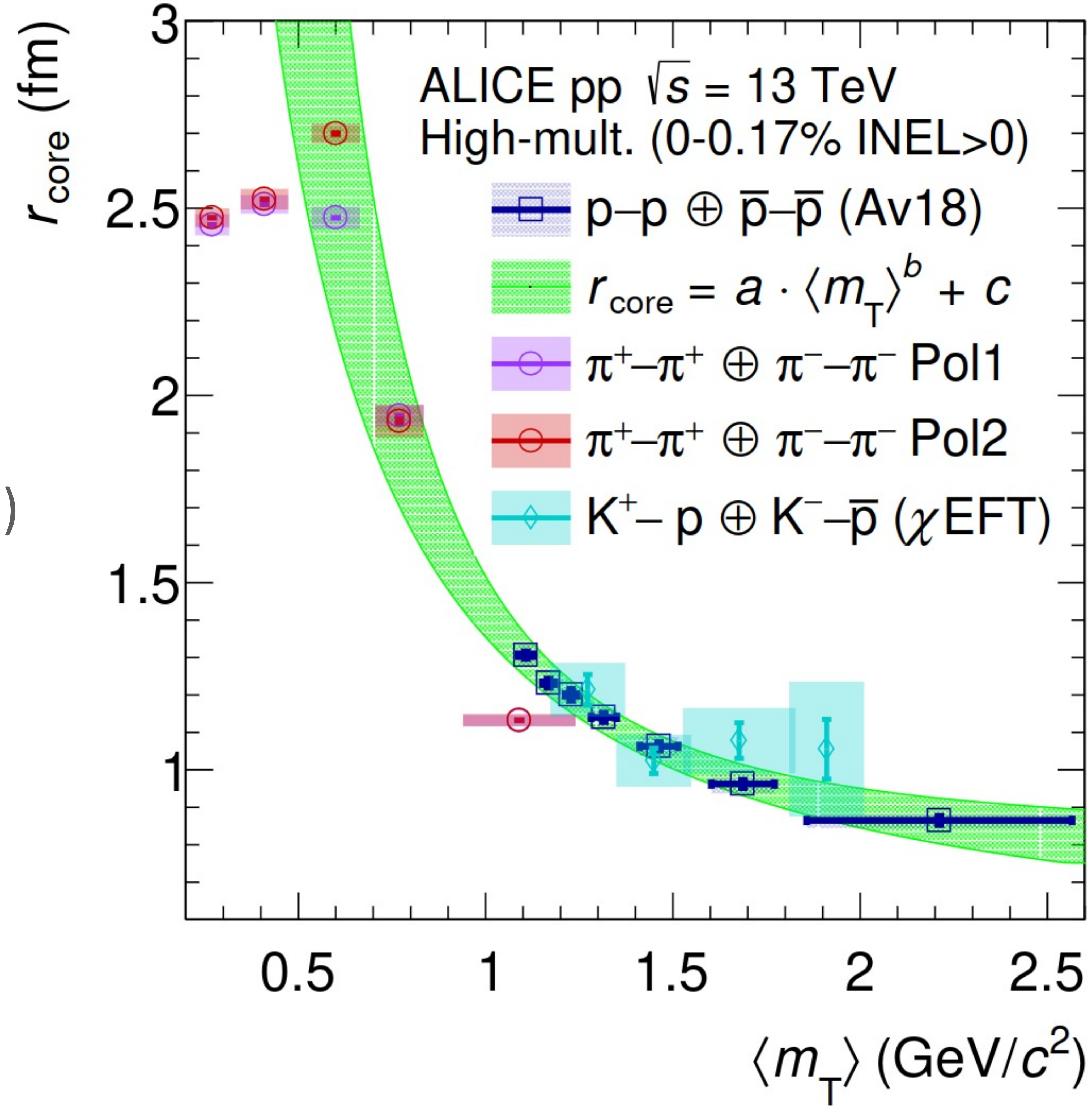
- Gaussian parametrization

$$S(r) = \frac{1}{(4\pi r_{core}^2)^{3/2}} \exp\left(-\frac{r^2}{4r_{core}^2}\right) \times \text{Effect of short lived resonances } (c\tau \sim 1 \text{ fm})$$

- One universal source for all hadrons (cross-check with K⁺-p, π-π, p-Λ, p-π)
- **Small particle-emitting source created in pp collisions at the LHC**
- **Currently the two-body source is used also for three-body calculations!**

ALICE Coll., PLB, 811 (2020), 135849; ALICE Coll., arXiv:2311.14527



Kaon/Proton-deuteron correlation

- Effective two-body system
  - Coulomb + Strong interactions via Lednický model; only s-wave
  - Anchored to scattering experiments
  - Emission source: from m_T scaling

R. Lednický, Phys. Part. Nucl. 40, 307(2009)

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);

System	Spin averaged a_0(fm)	Spin averaged d_0(fm)	$S=1/2$ a_0(fm)	$S=1/2$ d_0(fm)	$S=3/2$ a_0(fm)	$S=3/2$ d_0(fm)
p–d			$1.30^{+0.20}_{-0.20}$	—	$11.40^{+1.80}_{-1.20}$	$2.05^{+0.25}_{-0.25}$
			$2.73^{+0.10}_{-0.10}$	$2.27^{+0.12}_{-0.12}$	$11.88^{-0.10}_{+0.40}$	$2.63^{+0.01}_{-0.02}$
			4.0	—	11.1	—
			0.024	—	13.8	—
			$-0.13^{+0.04}_{-0.04}$	—	$14.70^{+2.30}_{-2.30}$	—
K^+–d	−0.470	1.75				
	−0.540	0.0				

**R. Lednicky and V. L. Lyuboshits Sov. J. Nucl. Phys. 35 (1982)

S = spin state

d_0^S = effective range

f_0^S = scattering length

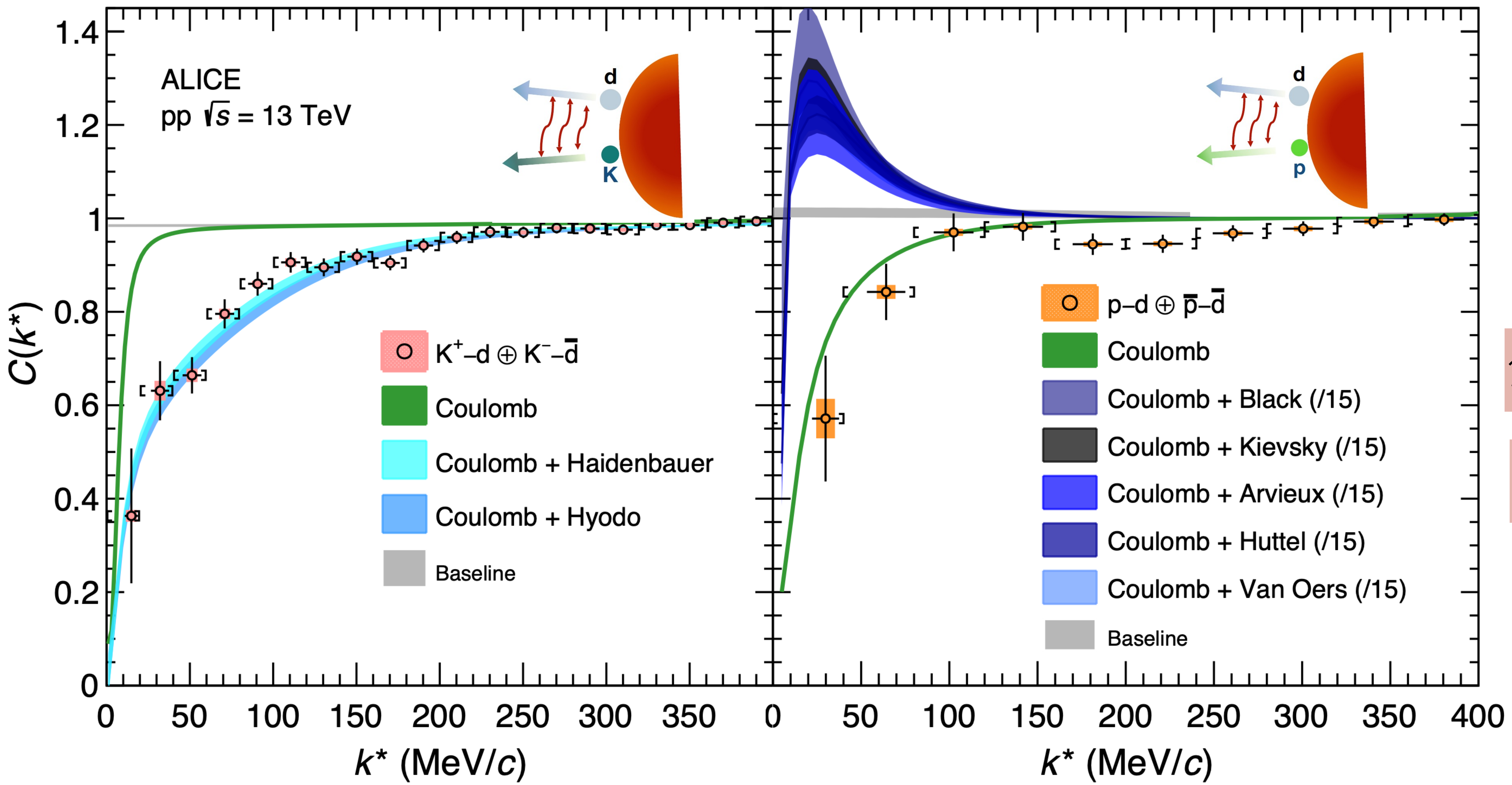
$$f(k^*)^S = \left(\frac{1}{f_0^S} + \frac{1}{2} d_0^S k^{*2} - ik^*\right)^{-1}$$

$$C(k^*) = 1 + \sum_S \rho_S \left[\frac{1}{2}\left|\frac{f(k^*)^S}{r_0}\right|^2 \left(1 - \frac{d_0^S}{2\sqrt{\pi} r_0}\right) + \frac{2\Re f(k^*)^S}{\sqrt{\pi} r_0} F_1(2k^* r_0) - \frac{2\Im f(k^*)^S}{\sqrt{\pi} r_0} F_2(2k^* r_0)\right]$$

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

Kaon/Proton-deuteron correlation

ALICE Coll., arXiv:2308.16120 (2023)



$r_{\text{eff}}^{\text{Kd}} = 1.41^{+0.03}_{-0.06}$ fm

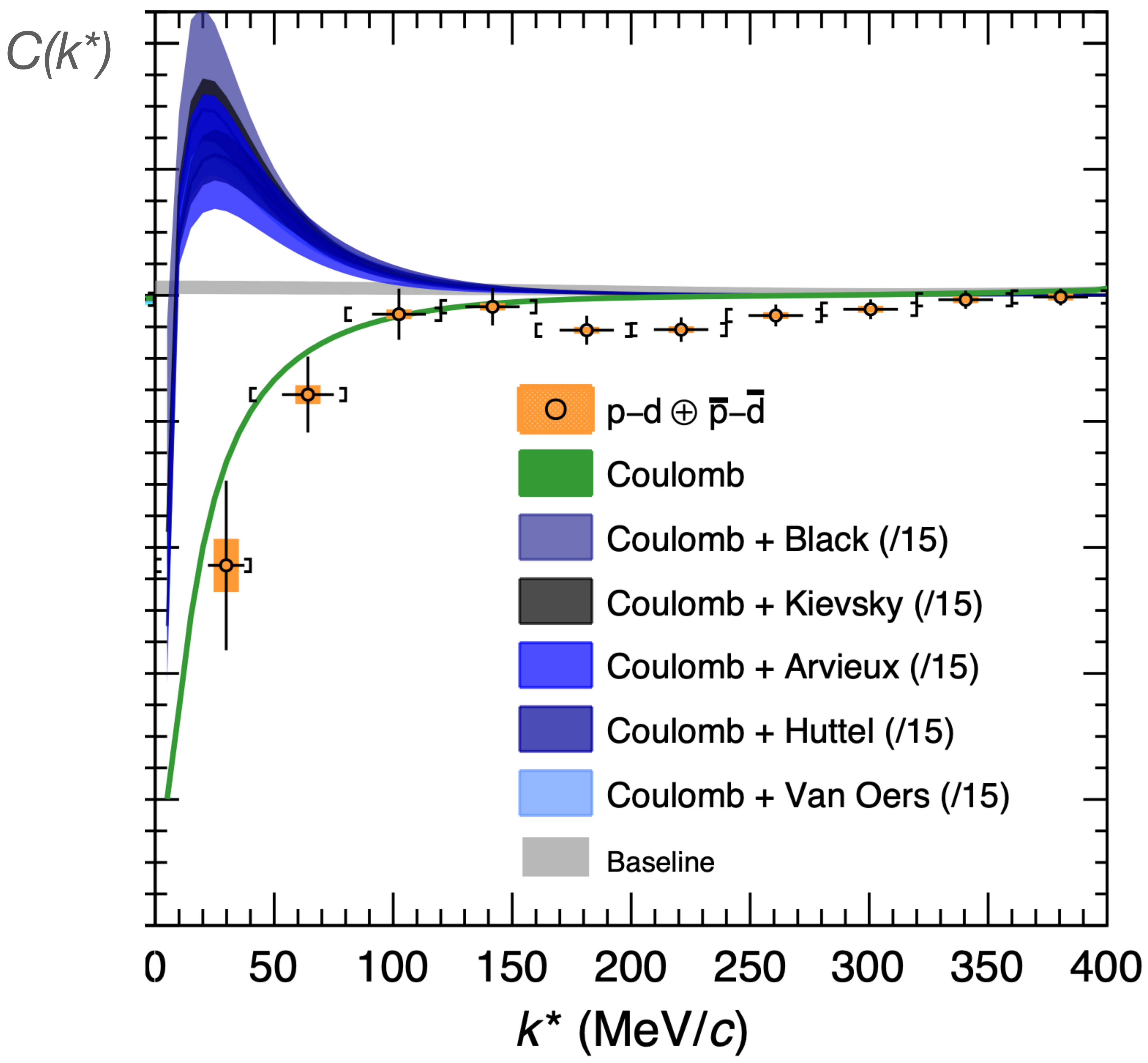
$r_{\text{eff}}^{\text{pd}} = 1.059^{+0.04}_{-0.04}$ fm

It works very well for k-d since this interaction is only repulsive and there are no features of the interaction that appears only at short distances. The asymptotic description is sufficient

Proton-deuteron correlation

- The picture of two point-like particles does not work for p-d
  - the deuteron is a composite object
  - Pauli blocking at work for p-(pn) at short distances
  - The asymptotic interaction is different from the short distance one
  - One need a full-fledged three-body calculation

ALICE Coll., arXiv:2308.16120 (2023)



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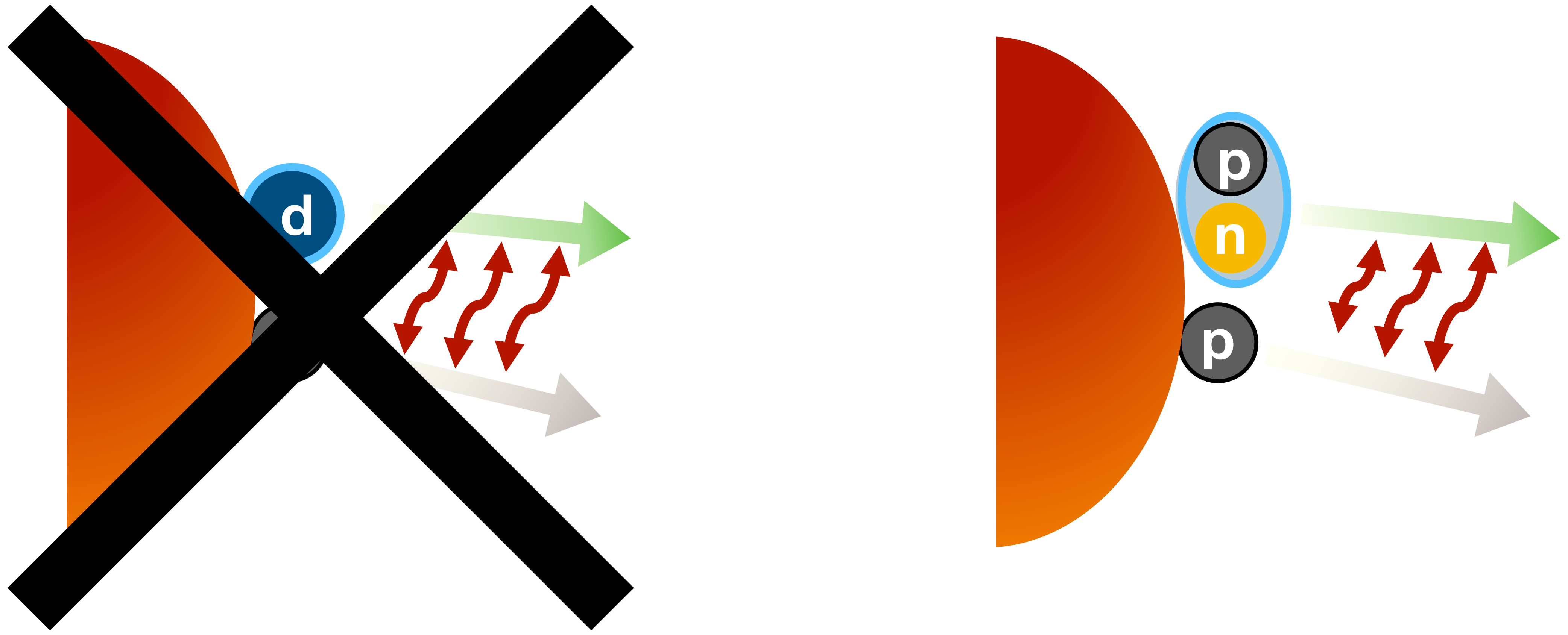
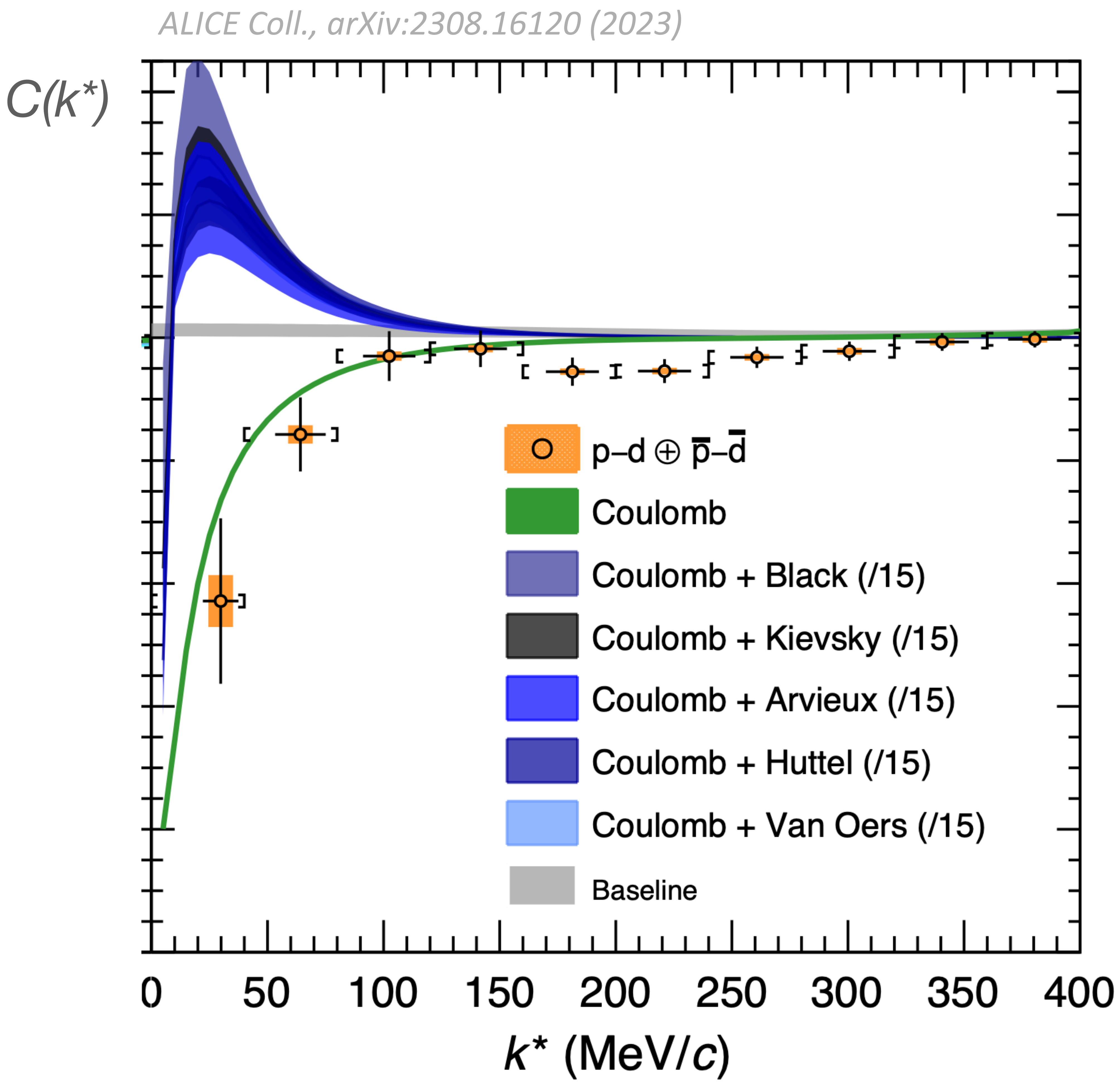




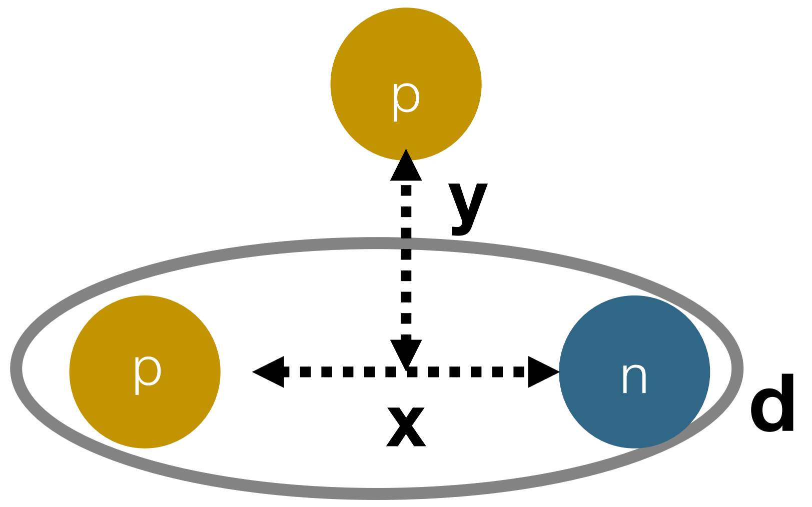
Pisa model: p-d as three-body system

- **Starting with the p-p-n state that goes into p-d state**:
  - Nucleons with the Gaussian sources distributions

Single-particle Gaussian emission source

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

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



Calculation done by PISA theory group: Michele Viviani, Alejandro Kievsky and Laura Marcucci

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

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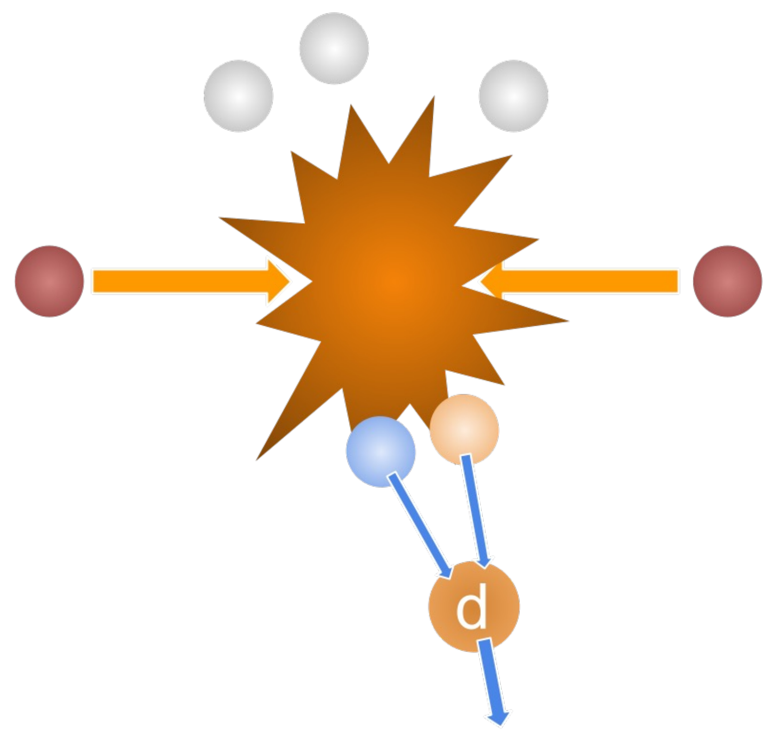
  - $\Psi_{m_2,m_1}(x,y)$ three-nucleon wave function asymptotically behaves as p–d state
  - A_d is the deuteron formation probability using deuteron wavefunction



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

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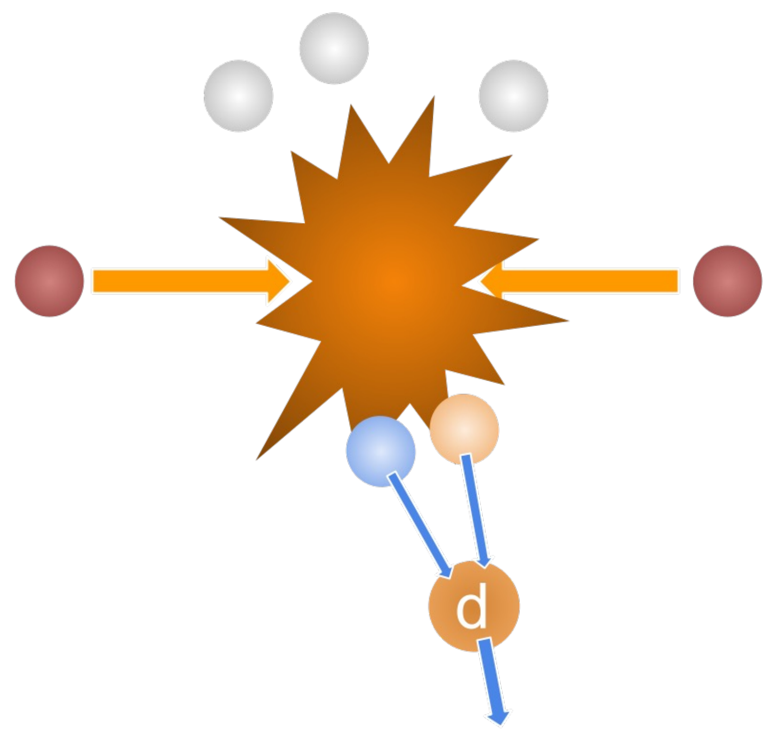
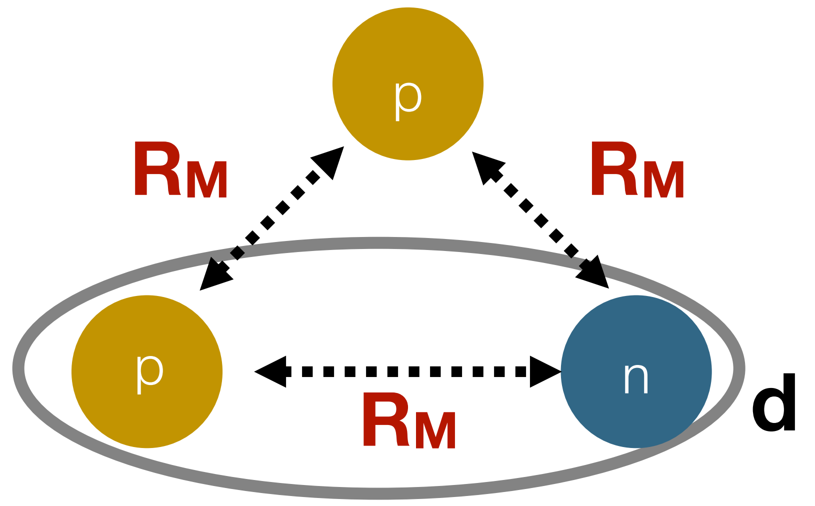


- $\Psi_{m_2,m_1}(x,y)$ three-nucleon wave function asymptotically behaves as p–d state
- A_d is the deuteron formation probability using deuteron wavefunction
- Final definition of the correlation with p–p source size R_M :

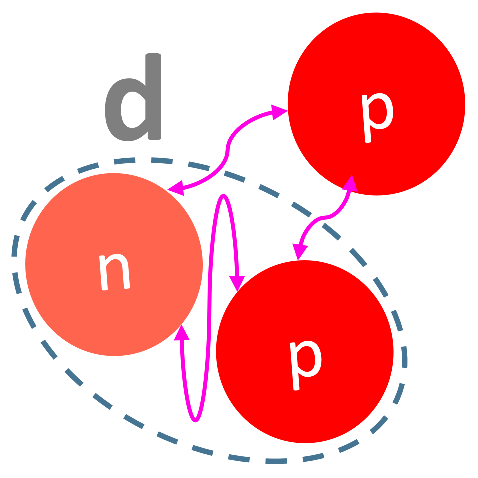
$$A_d C_{pd}(k) = \frac{1}{6}\sum_{m_2,m_1}\int \rho^5 d\rho d\Omega\, \frac{e^{-\rho^2/4R_M^2}}{(4\pi R_M^2)^3}|\Psi_{m_2,m_1}|^2 \,.$$

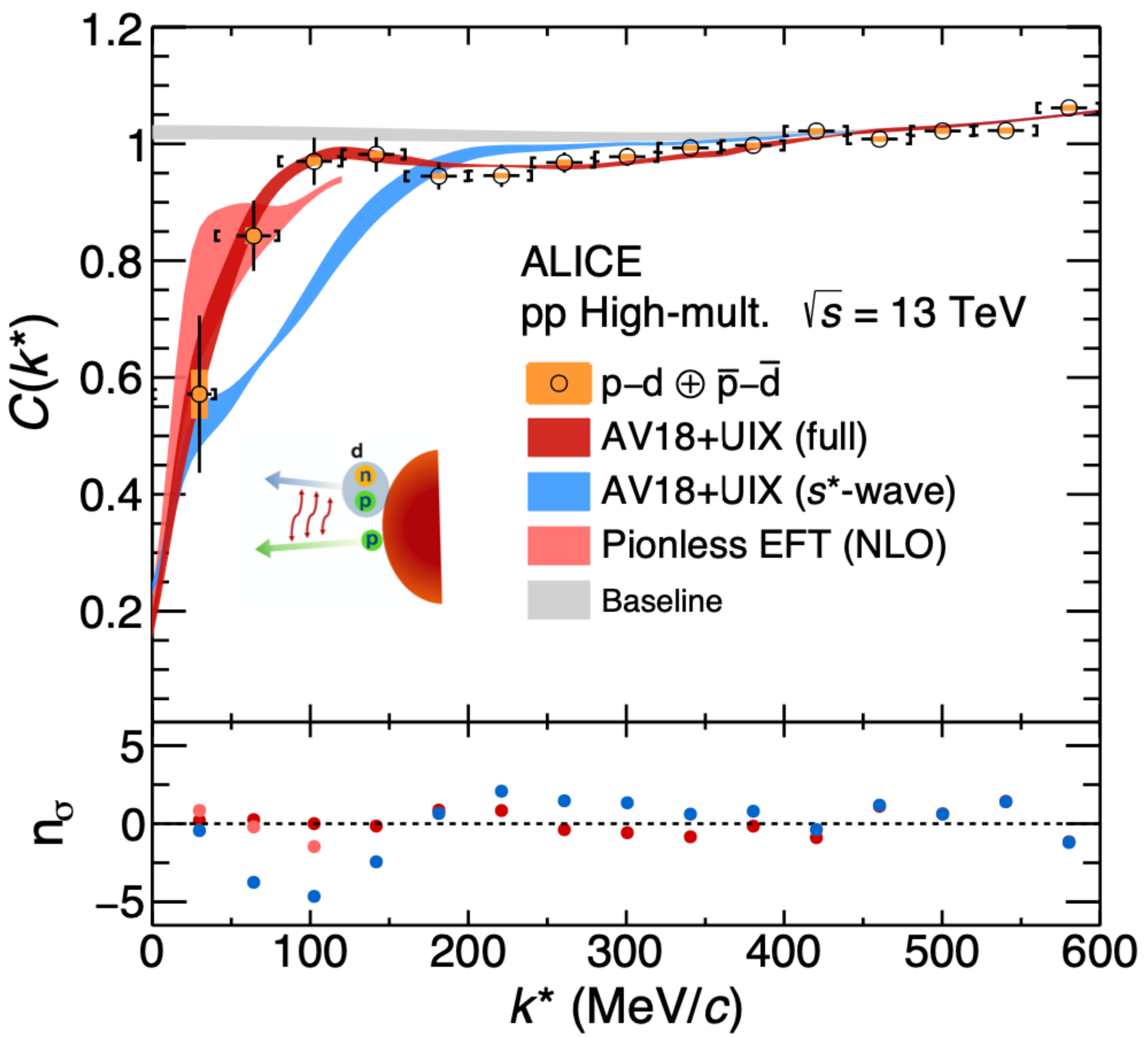


Mrówczyński et al *Eur. Phys. J. Special Topics 229, 3559 (2020)*

NNN using proton-deuteron correlations

- Full three-body calculations are required (NN + NNN + Quantum Statistics)
- Hadron-nuclei correlations at the LHC can be used to study many-body dynamics



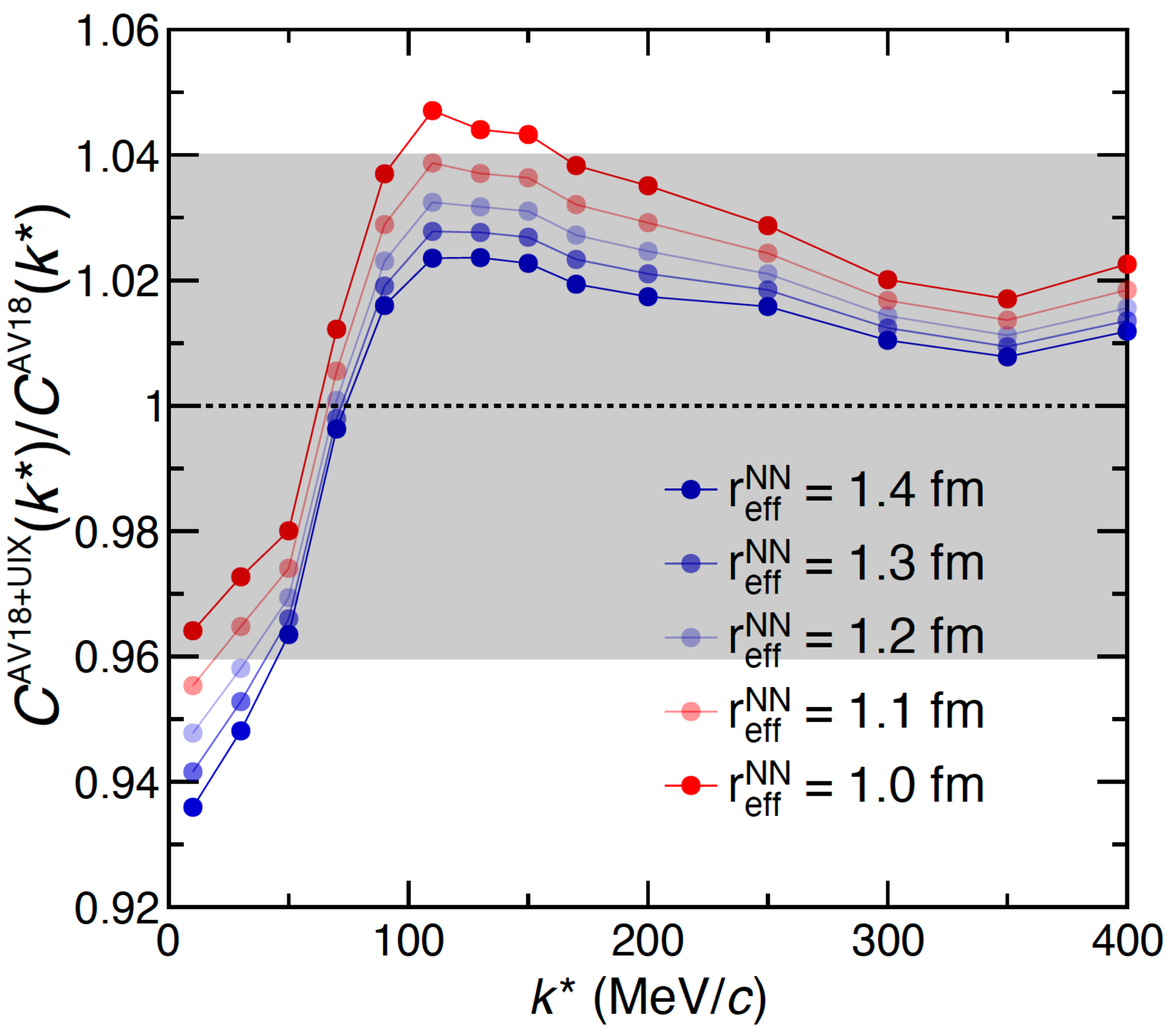


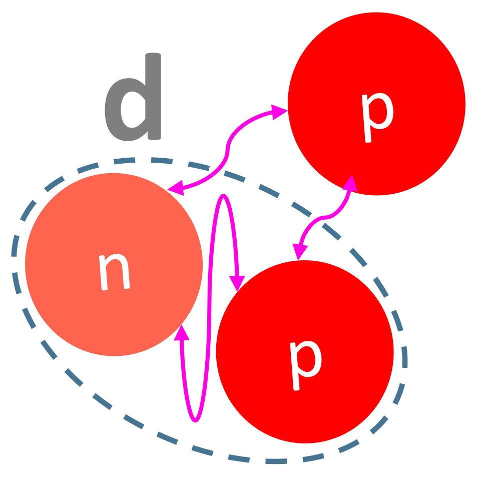
ALICE Coll., arXiv:2308.16120 (2023)

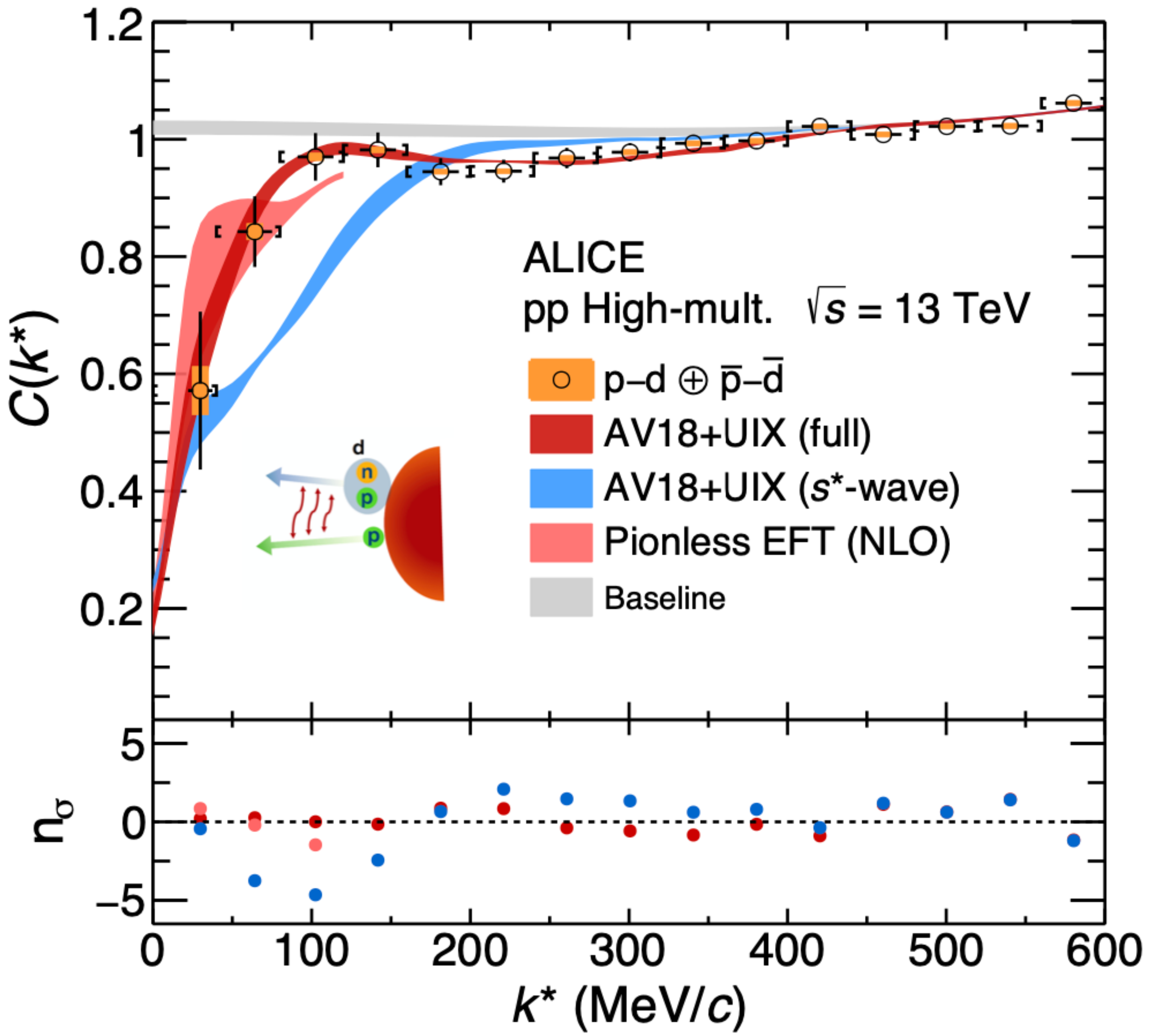
M. Viviani et al, Phys.Rev.C 108 (2023) 6, 064002

NNN using proton-deuteron correlations

- Full three-body calculations are required (NN + NNN + Quantum Statistics)
- Hadron-nuclei correlations at the LHC can be used to study many-body dynamics
- Sensitivity to three-body forces up to 5%





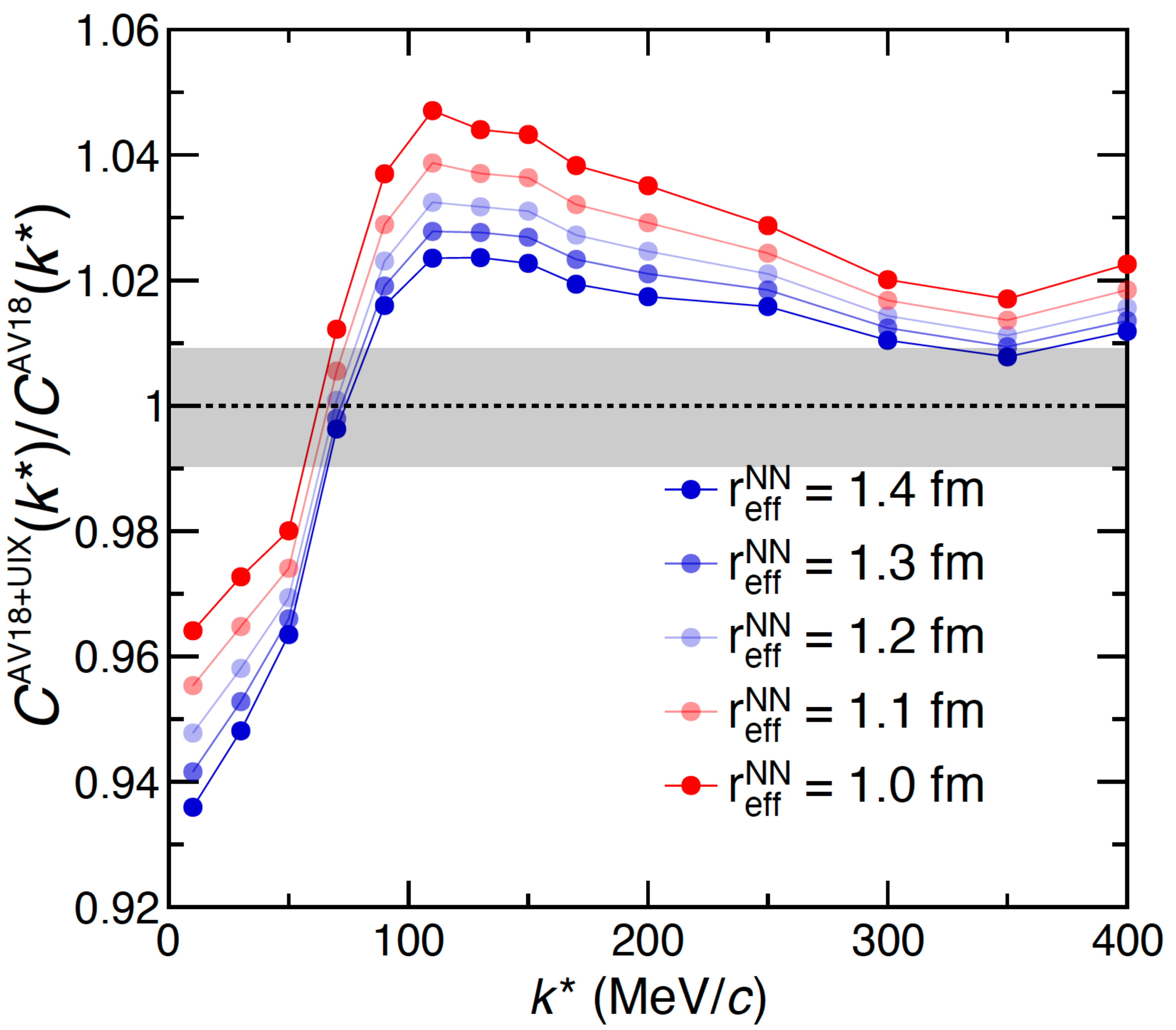


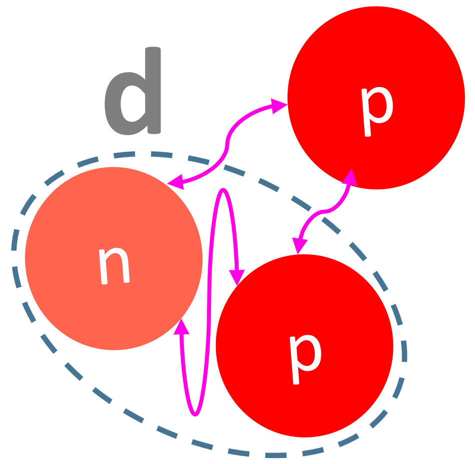
ALICE Coll., arXiv:2308.16120 (2023)

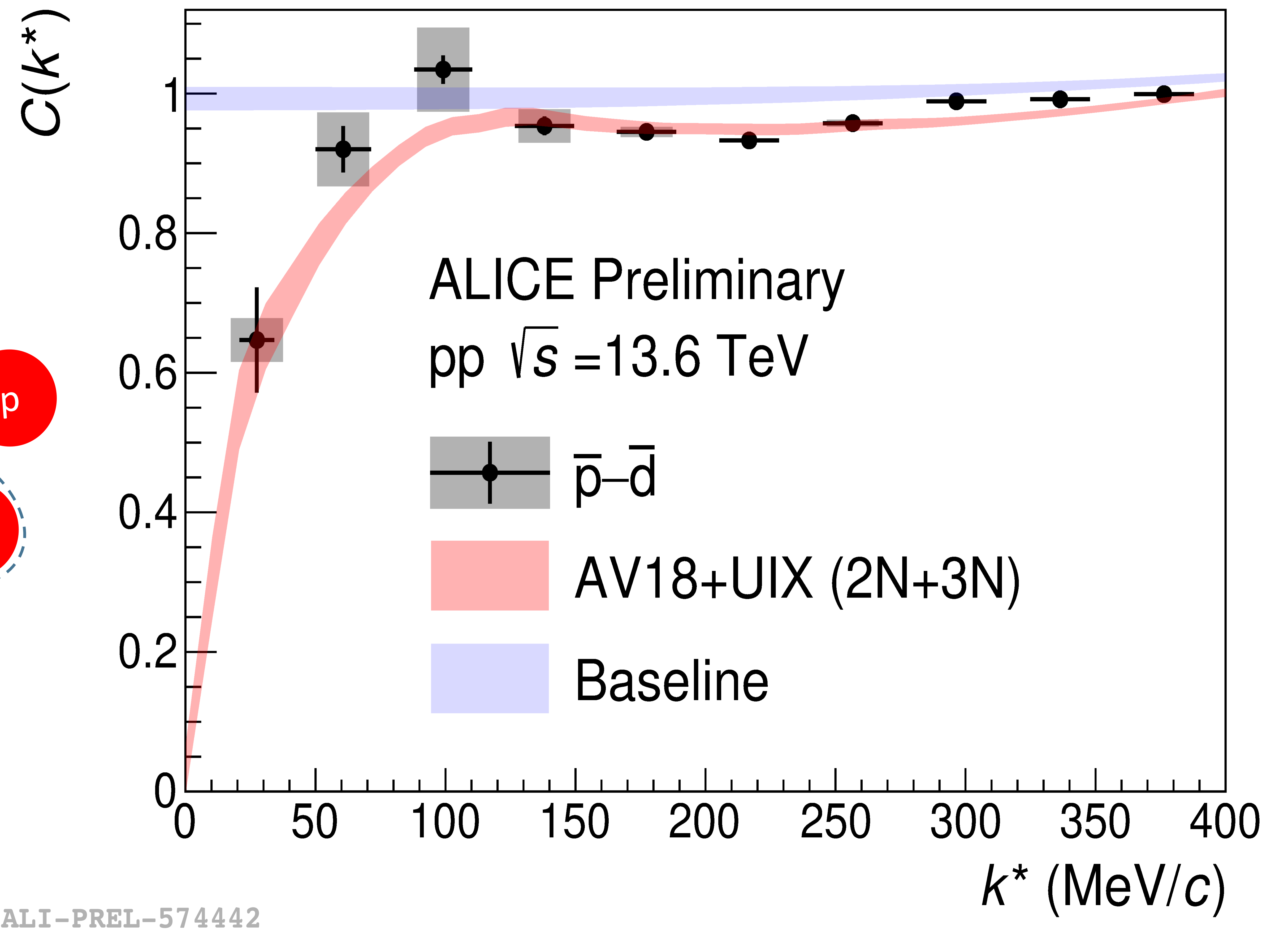
M. Viviani et al, Phys.Rev.C 108 (2023) 6, 064002

NNN using proton-deuteron correlations

- Full three-body calculations are required (NN + NNN + Quantum Statistics)
- Run 3 data from 2022 already analysed and results are promising!
- In Run 3 expected uncertainty of 1%

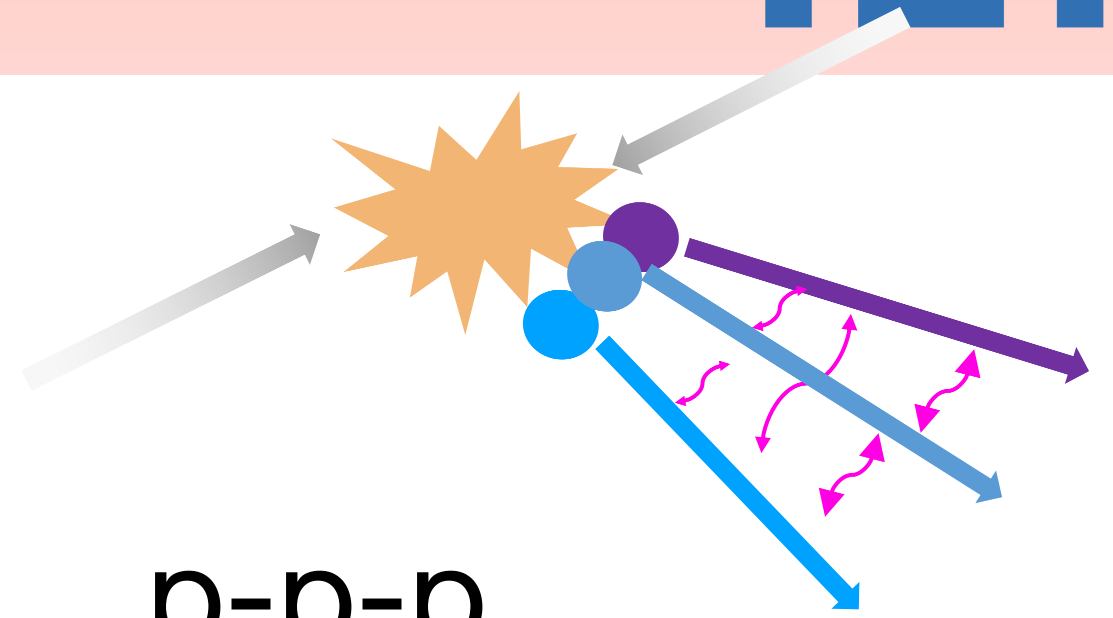






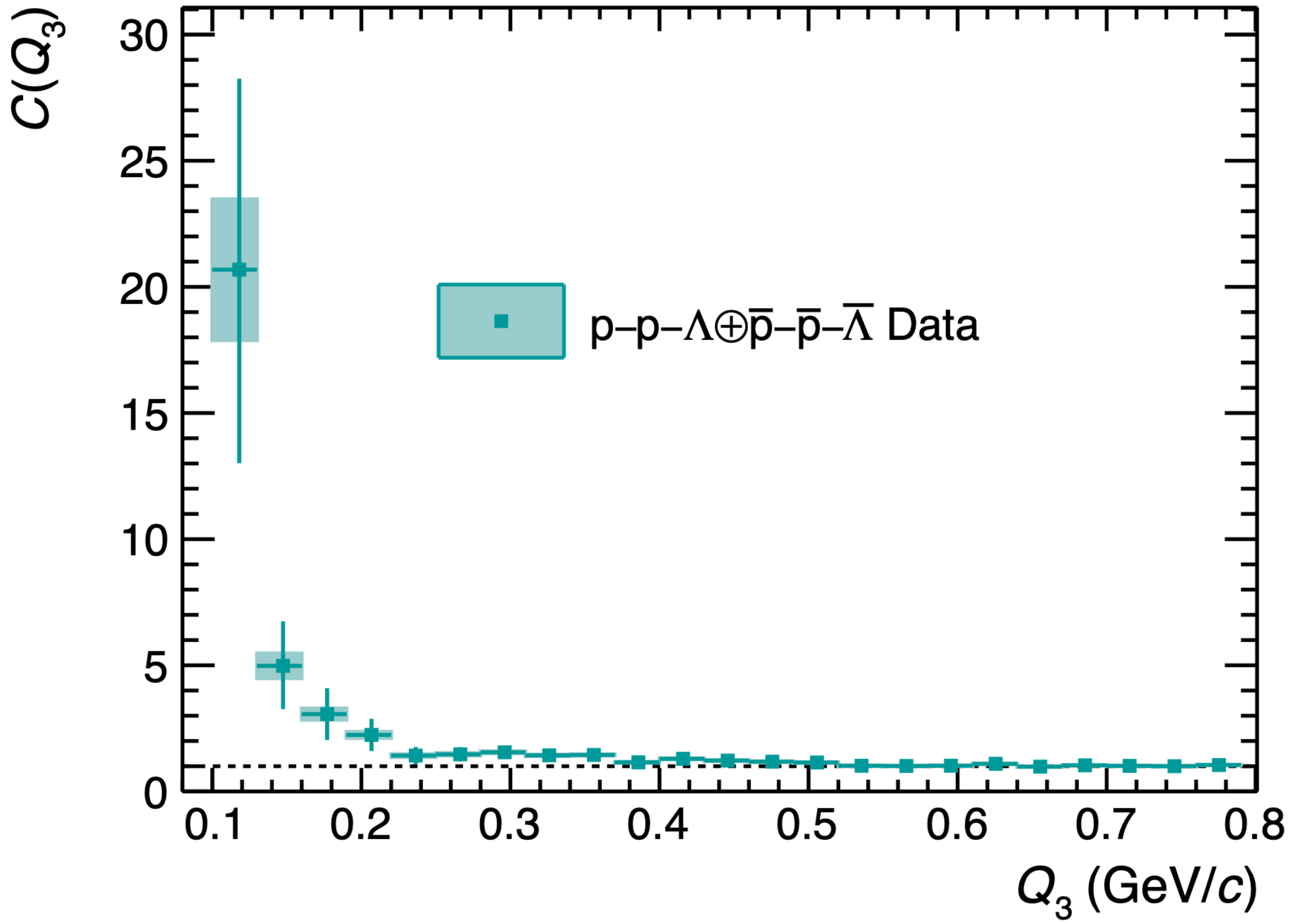
Measured three-body correlation functions

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

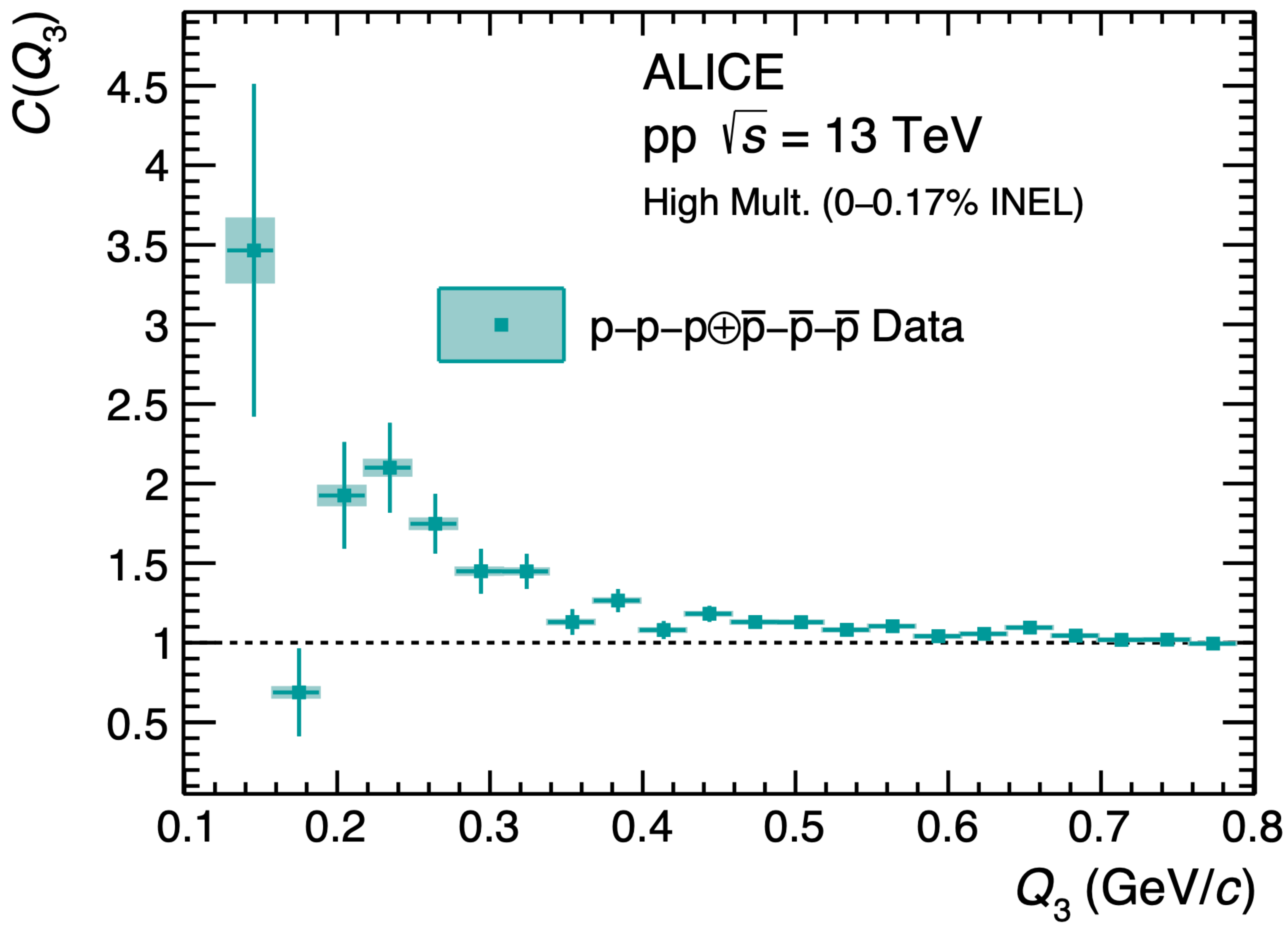


ALICE Coll., Eur.Phys.J.A 59 (2023) 7, 145

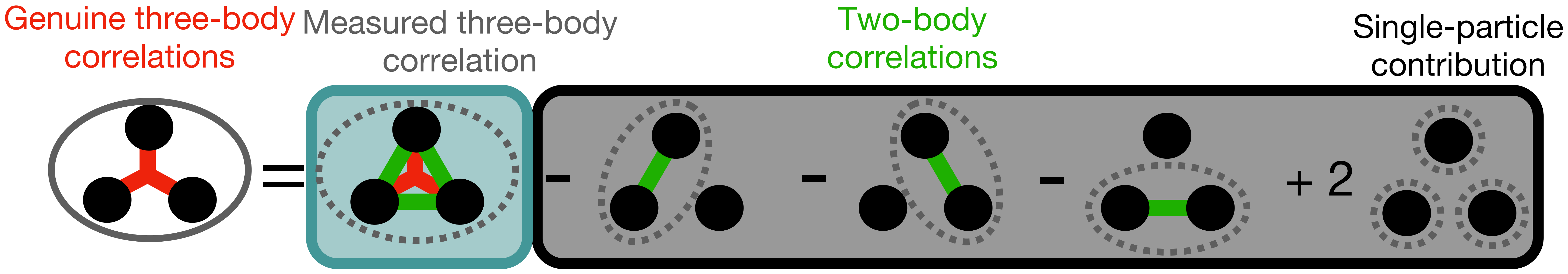
p-p-Λ



p-p-p



Cumulants



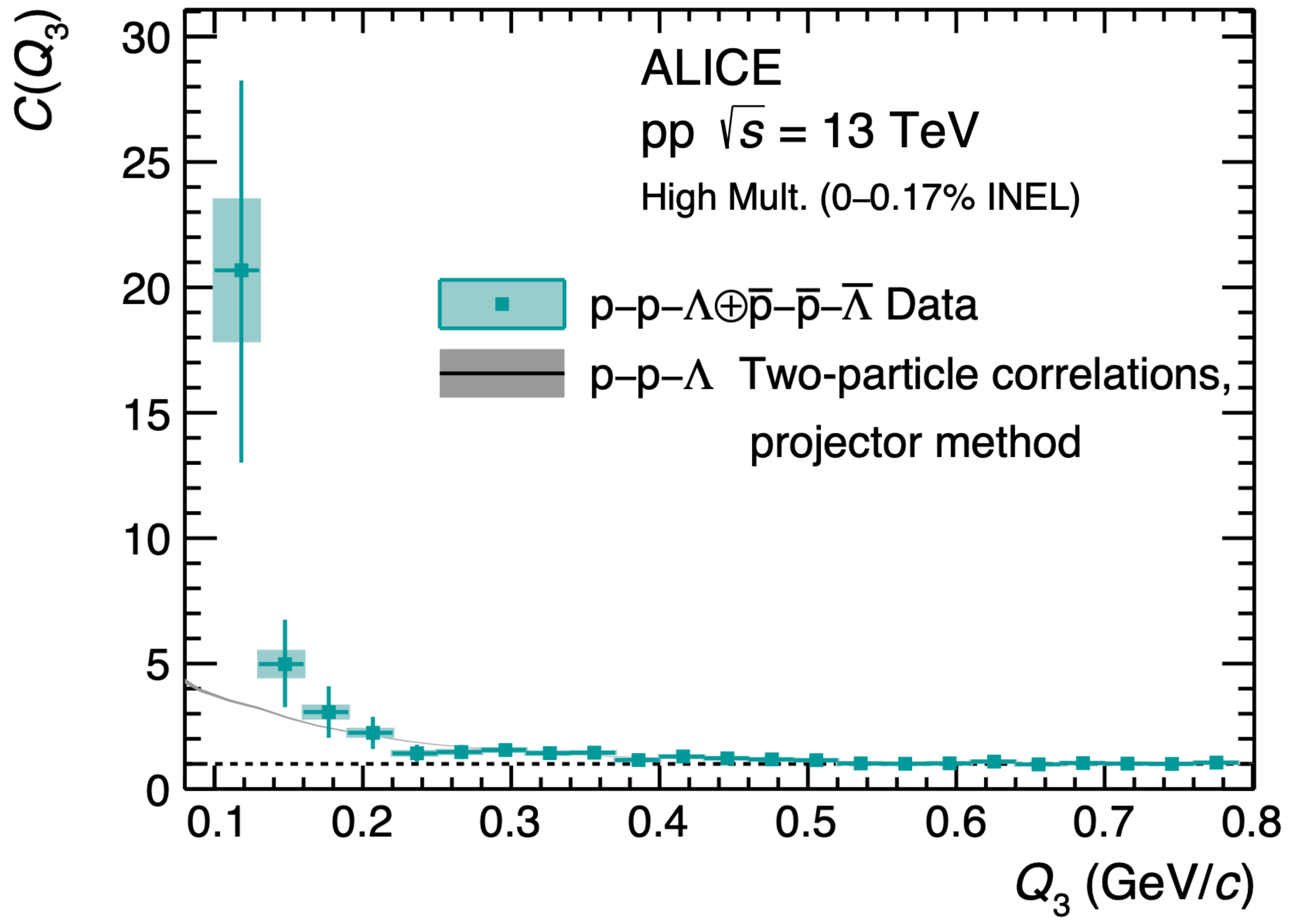
R. Kubo, J. Phys. Soc. Jpn. 17, 1100-1120 (1962)

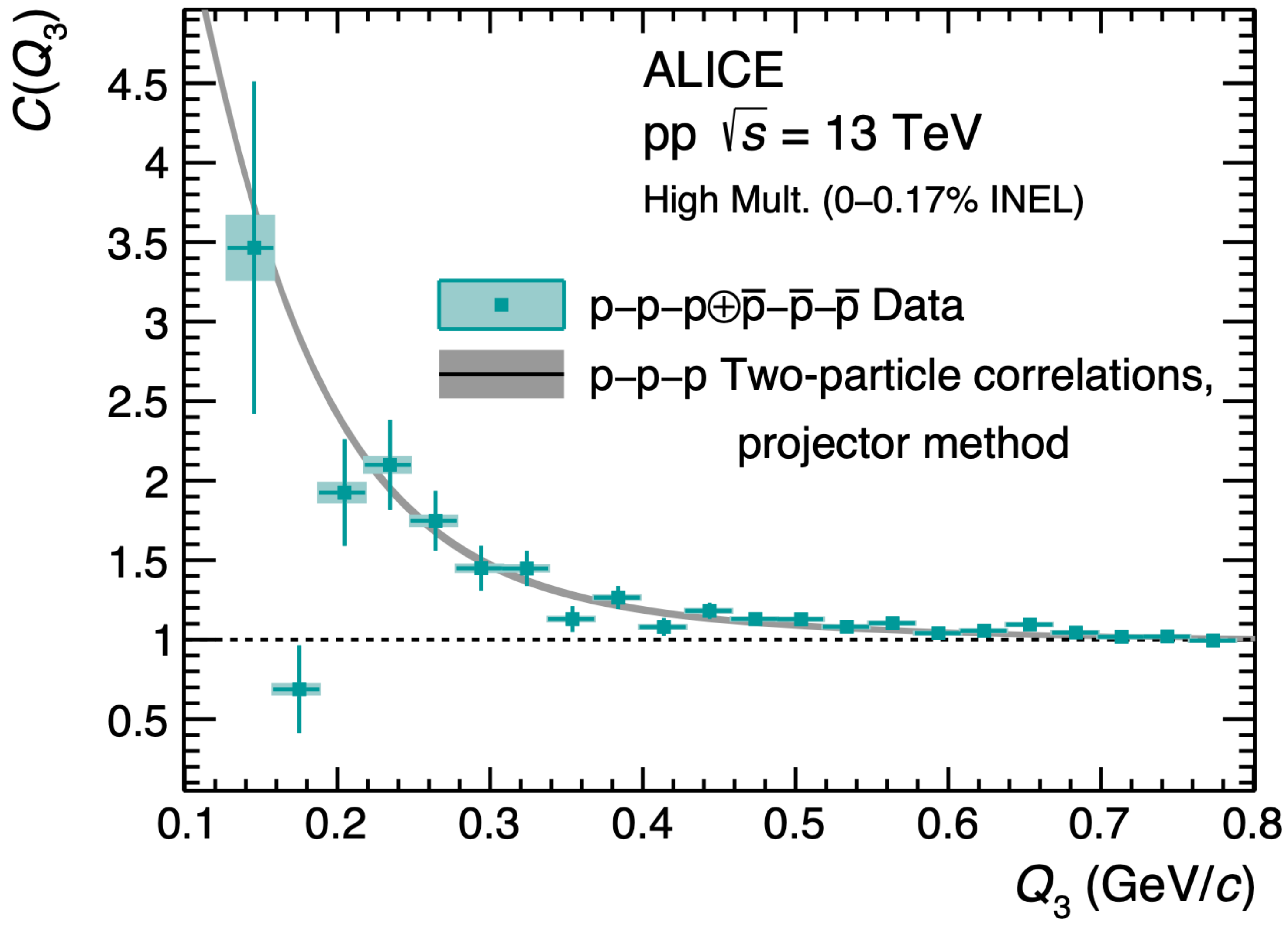
Del Grande et al. EPJC 82 (2022) 244

p-p-Λ

ALICE Coll., Eur.Phys.J.A 59 (2023) 7, 145

p-p-p





Calculation of the p-p-p correlation function

- First ever full three-body correlation function calculations

three-proton wave function

$$C(Q_3) = \int \rho^5 d\rho \, S(\rho, \rho_0) |\Psi(\rho, Q_3)|^2$$

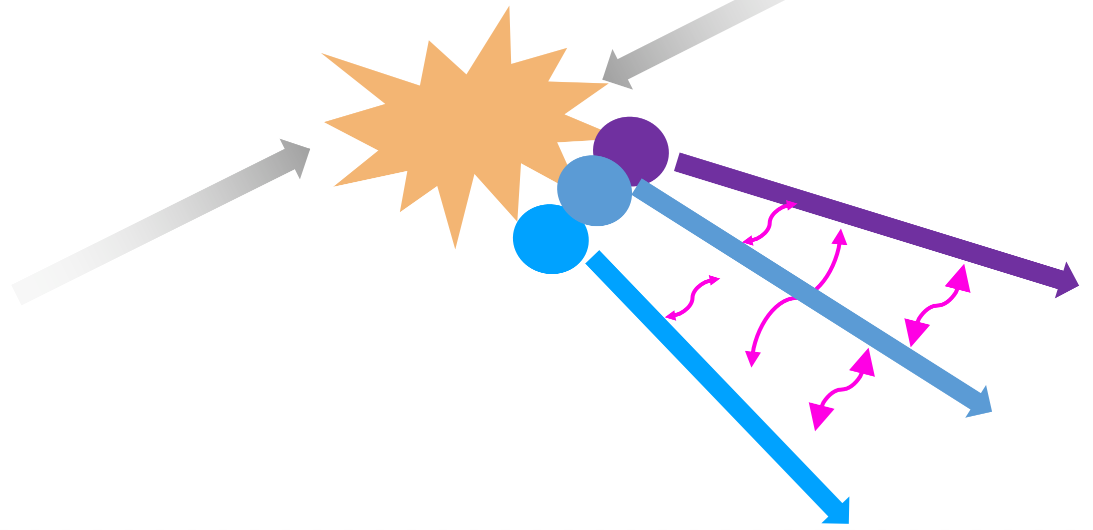
hyperradius

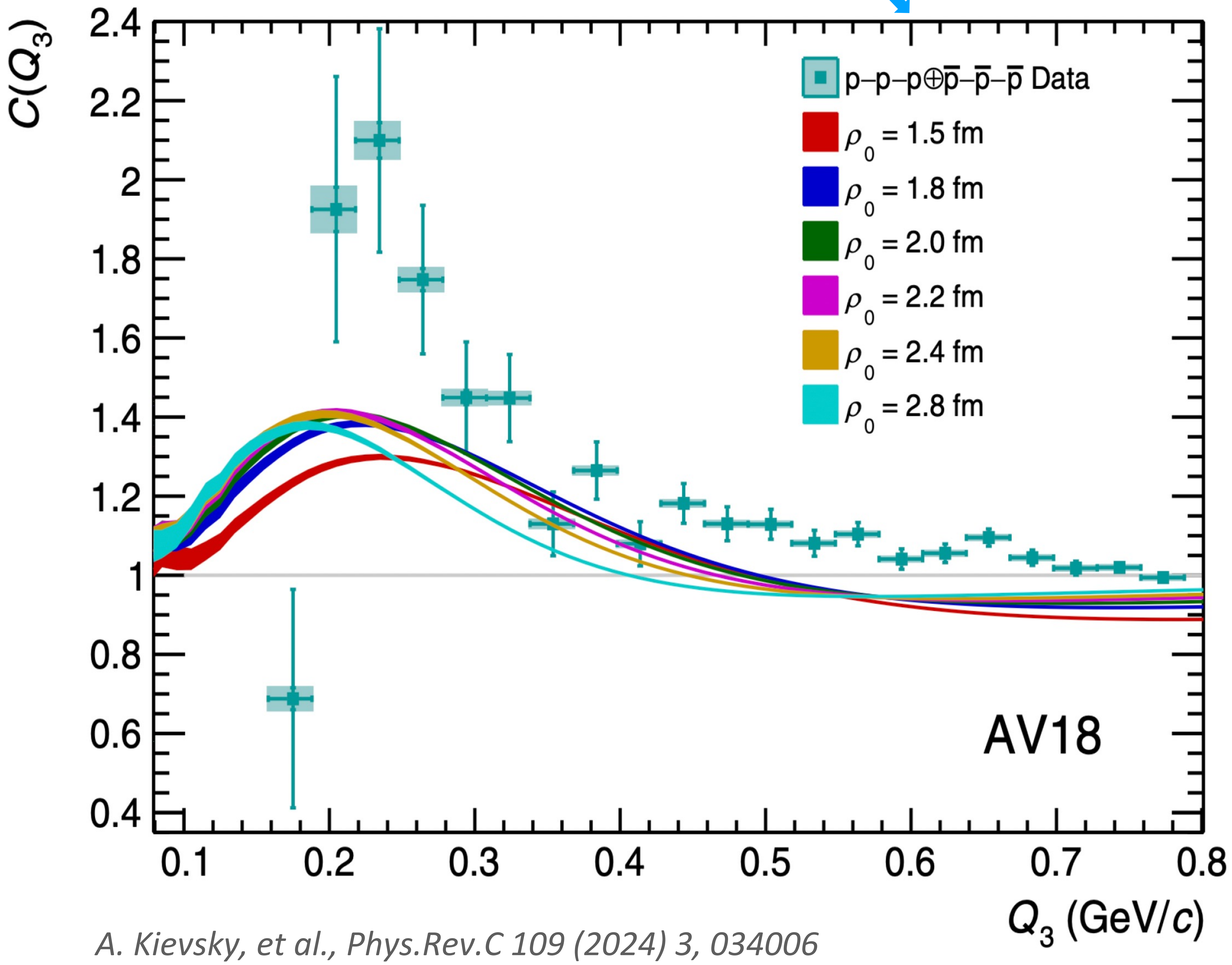
- Wave function via HH:
  - AV18
  - Three-body Coulomb interaction
  - Quantum statistics

A. Kievsky, et al., Phys.Rev.C 109 (2024) 3, 034006

- Negligible contribution from UIX
- Utilise to study three-body source

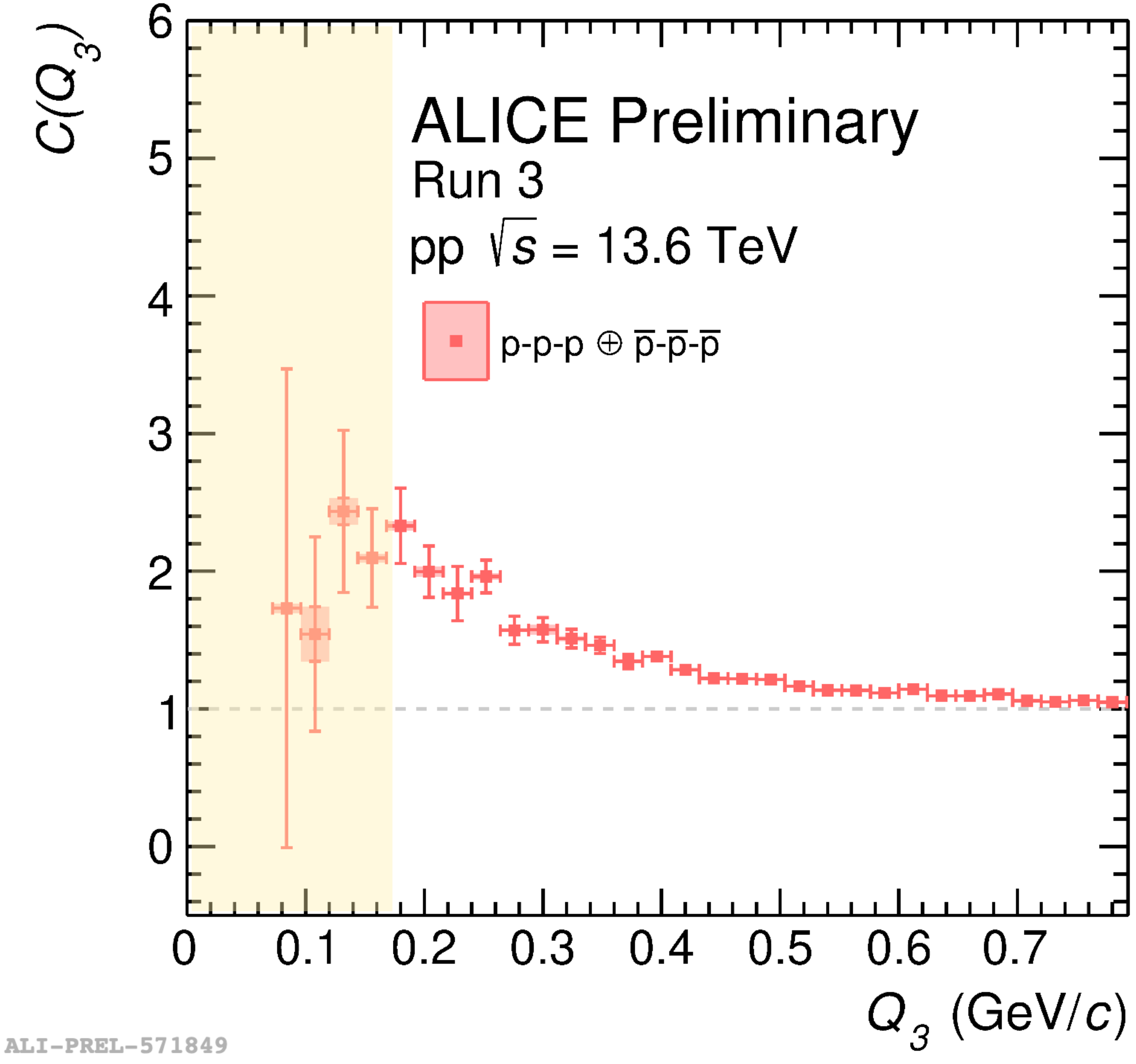
Calculation done by PISA theory group: Michele Viviani, Alejandro Kievsky and Laura Marcucci

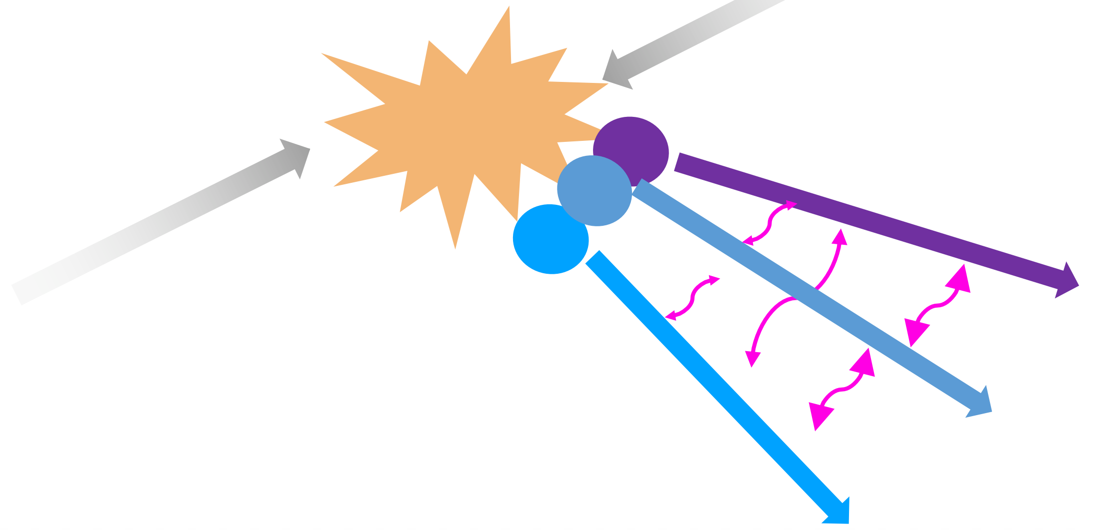


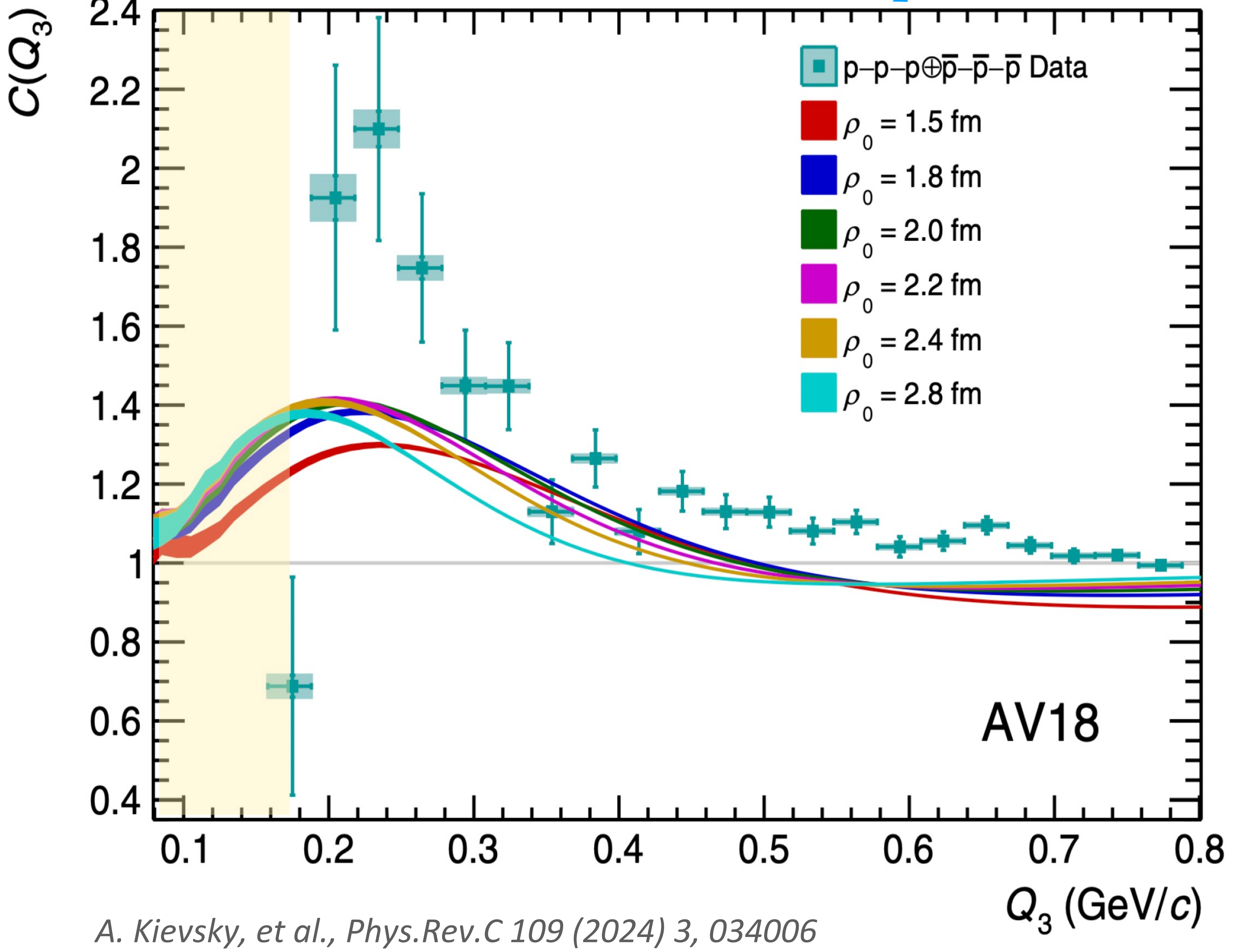


A. Kievsky, et al., Phys.Rev.C 109 (2024) 3, 034006

Calculation of the p-p-p correlation function





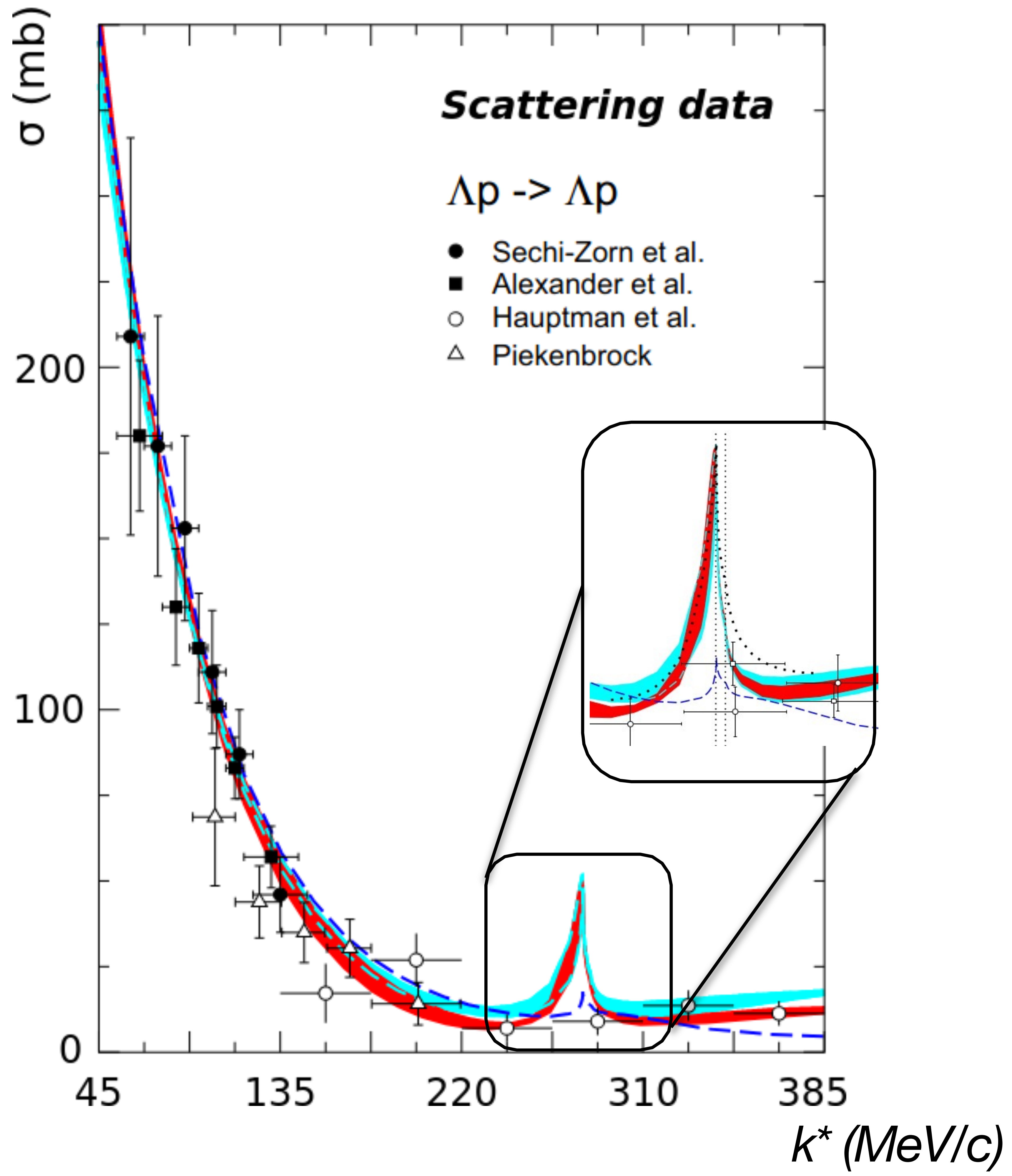


A. Kievsky, et al., Phys.Rev.C 109 (2024) 3, 034006

The pΛ interaction so far…

- Mainly investigated with scattering data
  → High-precision results by CLAS at large momenta
  CLAS coll.PRL 127 (2021), 27, 27230
  → Large uncertainties at low momenta and not available down to threshold

- Cusp structure at ΣN opening
  → Coupling ΛN-ΣN driving the behaviour of Λ at finite ρ
  D. Gerstung et al. Eur.Phys.J.A 56 (2020), 6, 175; J.Haidenbauer, U. Meiβner, EPJA 56 (2020), 3, 91
  → State-of-art chiral potentials with different ΛN-ΣN strength

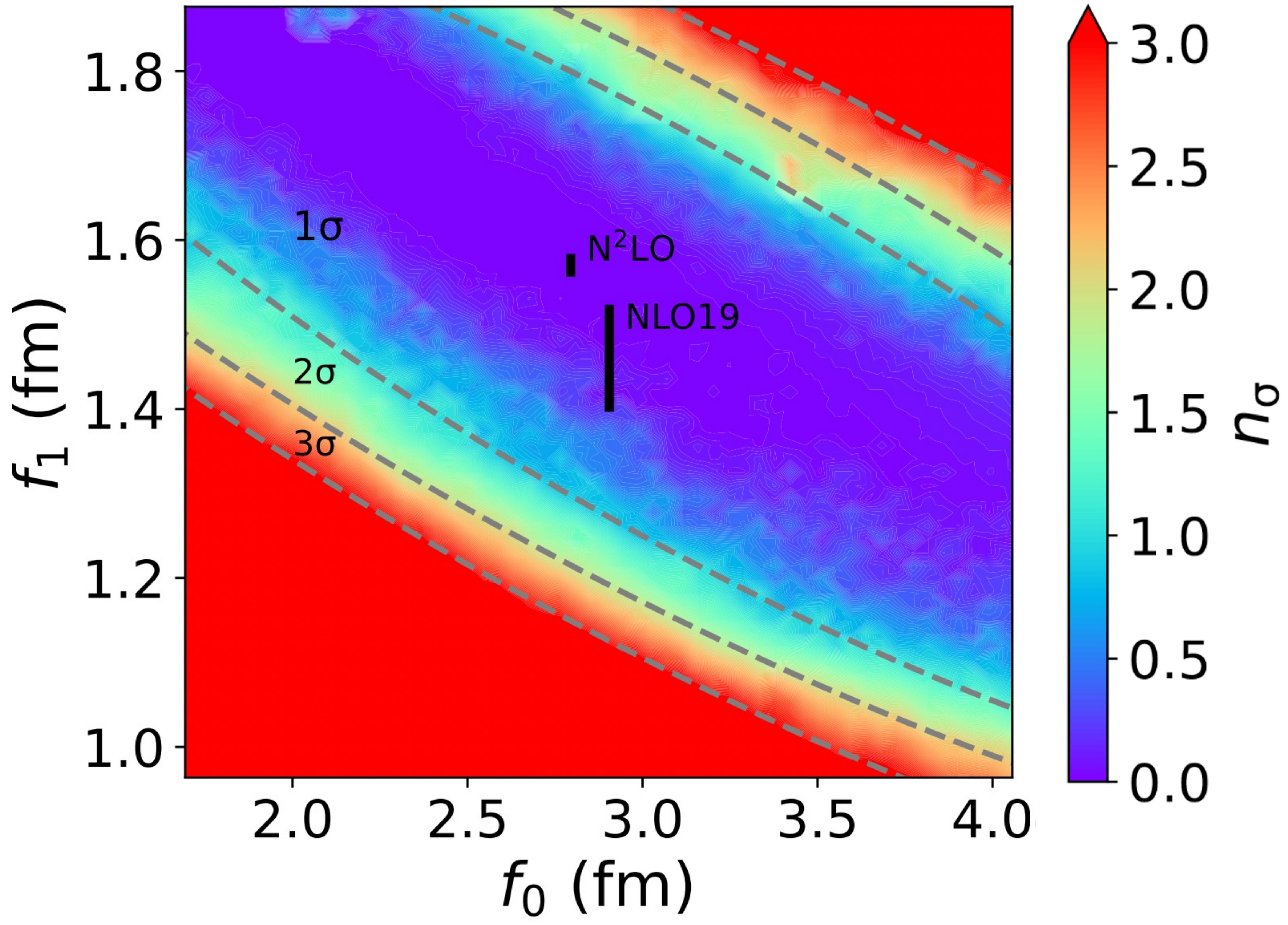


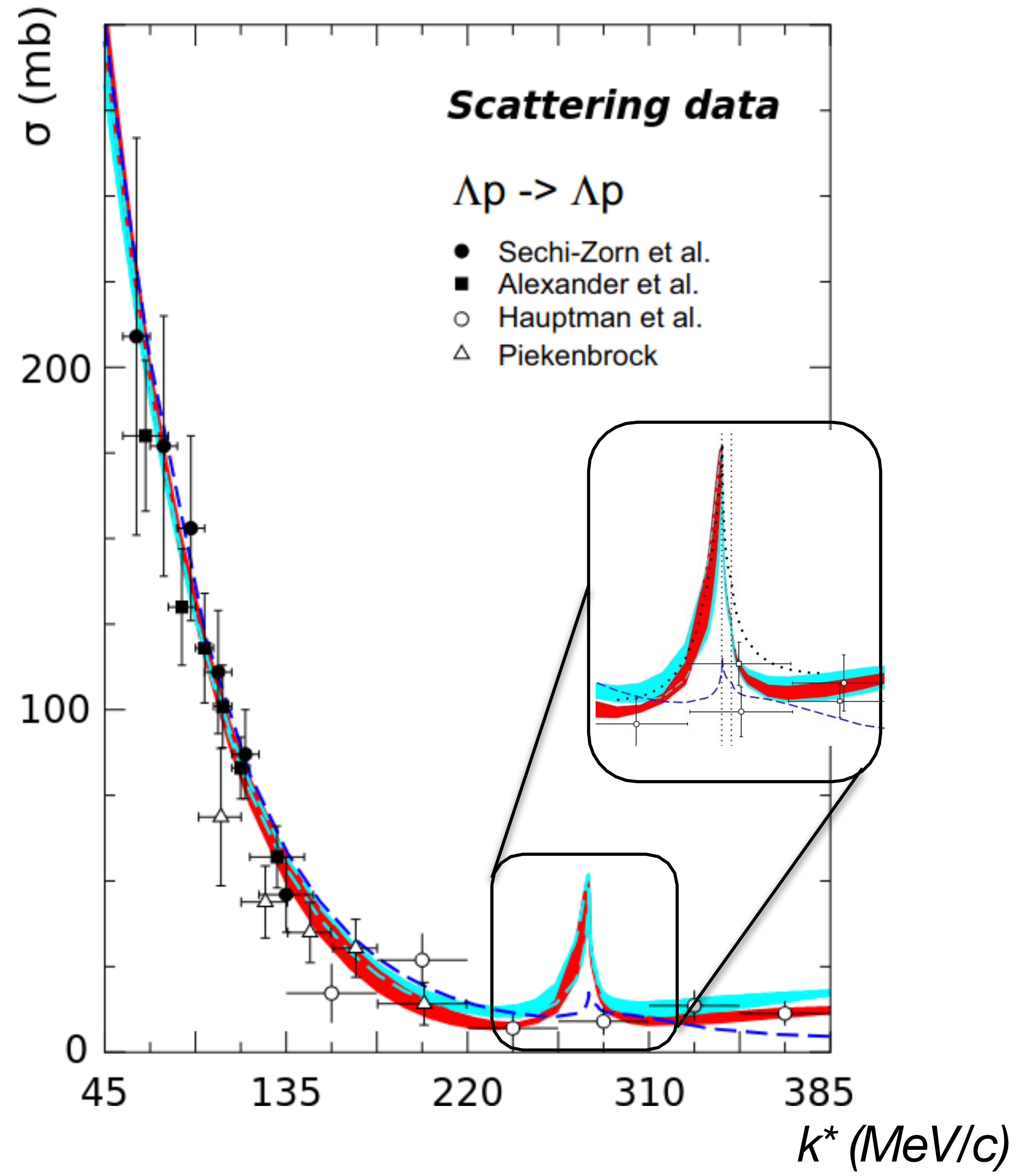
NLO19: J.Haidenbauer, U. Meiβner, EPJA 56 (2020), 3, 91
NLO13: J.Haidenbauer, N.Kaiser et al., NPA 915, 24 (2013)

The pΛ interaction before femtoscopy

- Spin-0 and Spin-1 scattering length from scattering data
- Agreement with N2LO and NLO19

D. Mihaylov, J. Haidenbauer and V. Mantovani Sarti, PLB 850 (2024) 138550



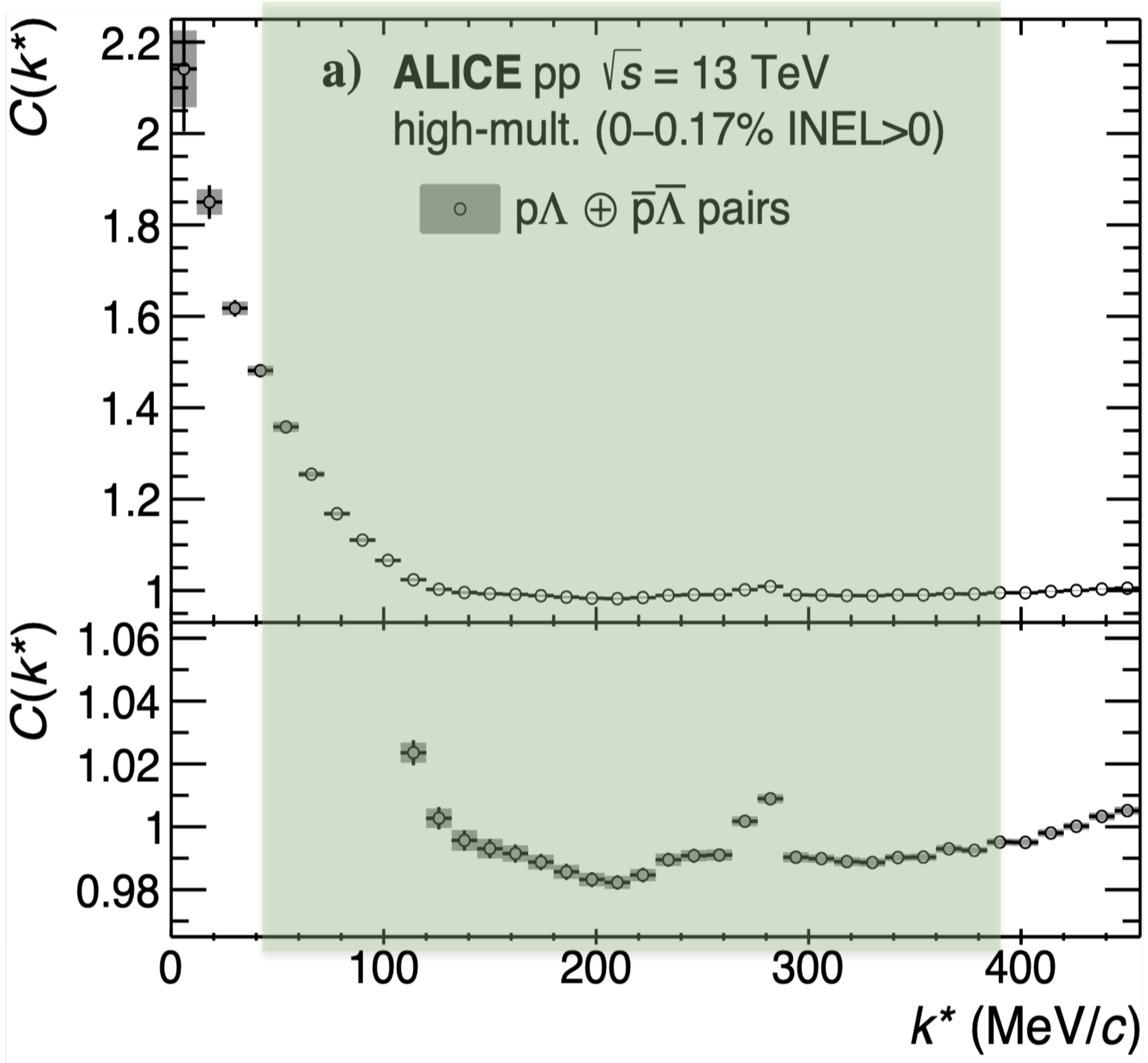


NLO19: J.Haidenbauer, U. Meißner, EPJA 56 (2020), 3, 91

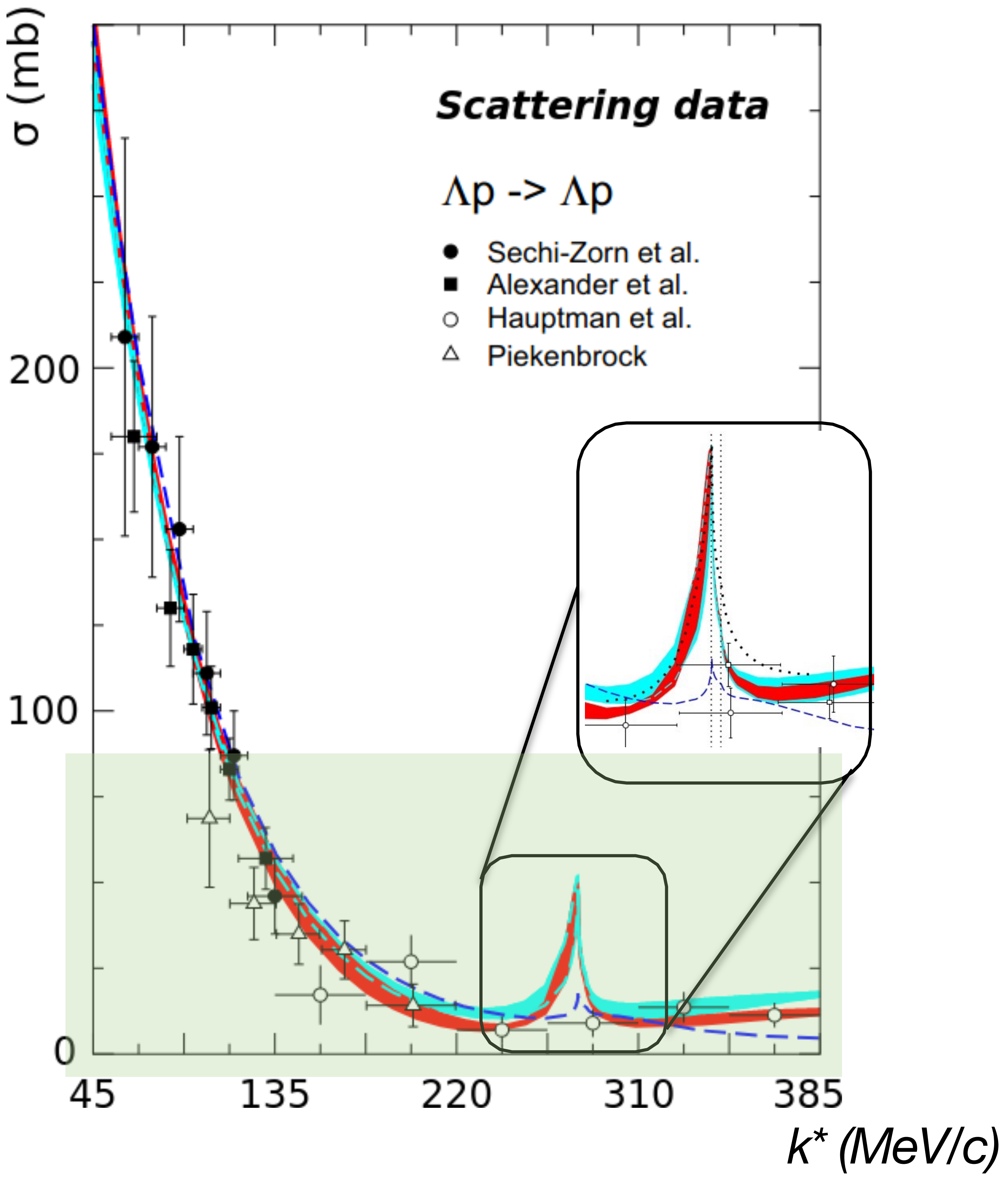
NLO13: J.Haidenbauer, N.Kaiser et al., NPA 915, 24 (2013)

The pΛ interaction in the femtoscopy era

ALICE coll. PLB 833 (2022), 137272



- Measurement down to zero momentum
  - Factor 20 improved precision (<1%)
- First experimental evidence of ΛN-ΣN opening in 2-body channel



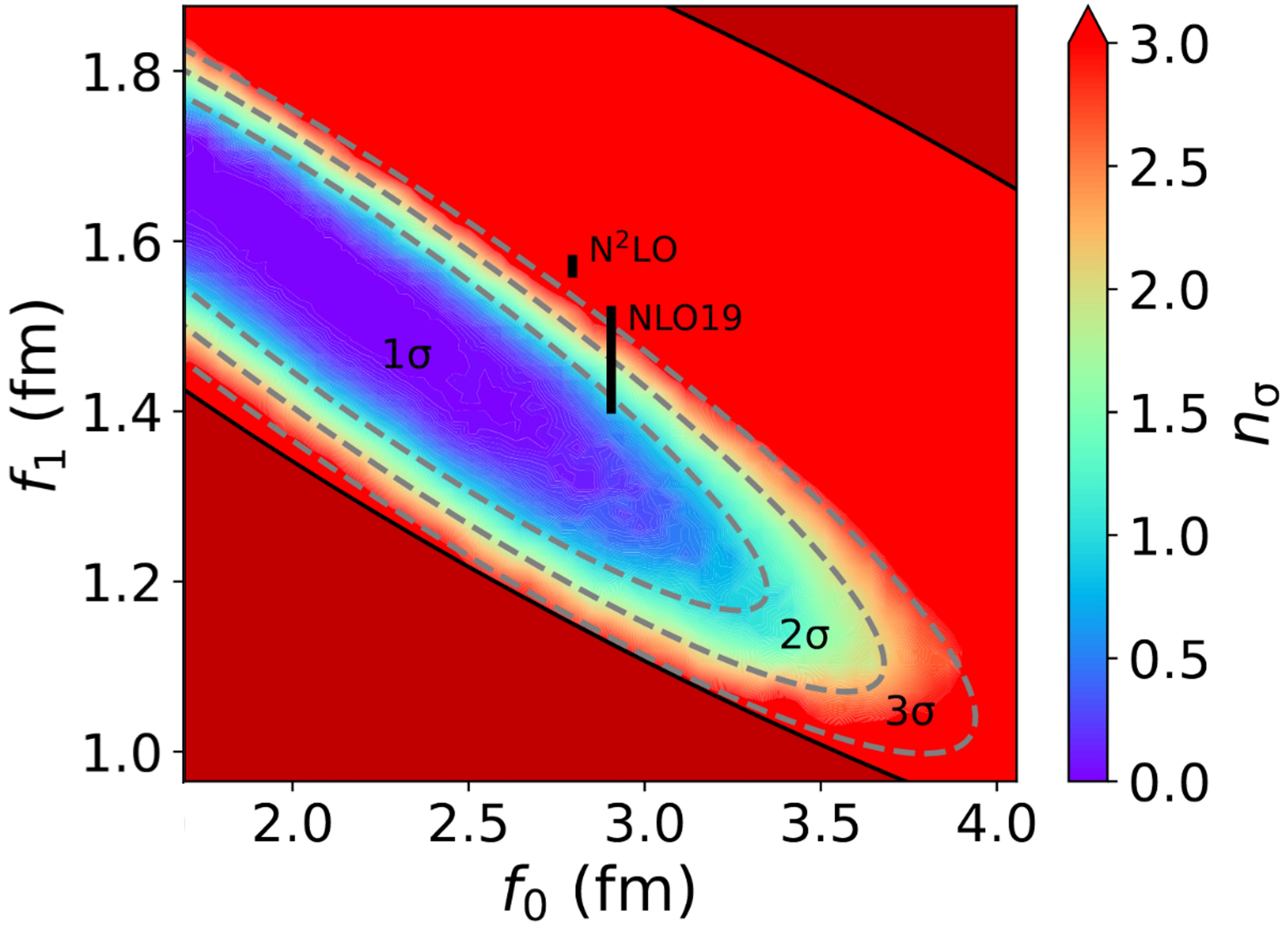
NLO19: J.Haidenbauer, U. Meißner, EPJA 56 (2020), 3, 91

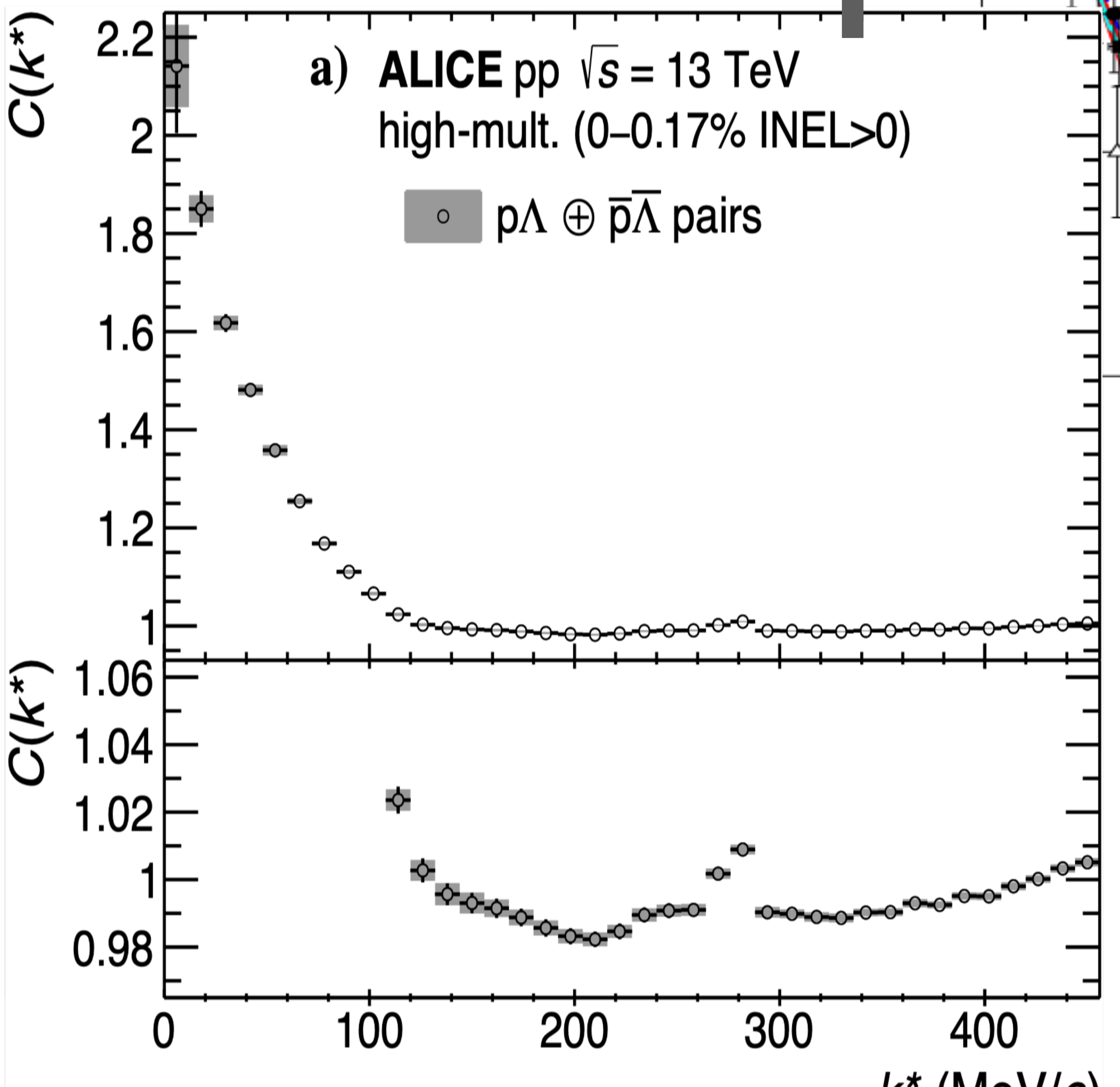
NLO13: J.Haidenbauer, N.Kaiser et al., NPA 915, 24 (2013)

The pΛ interaction in the femtoscopy era

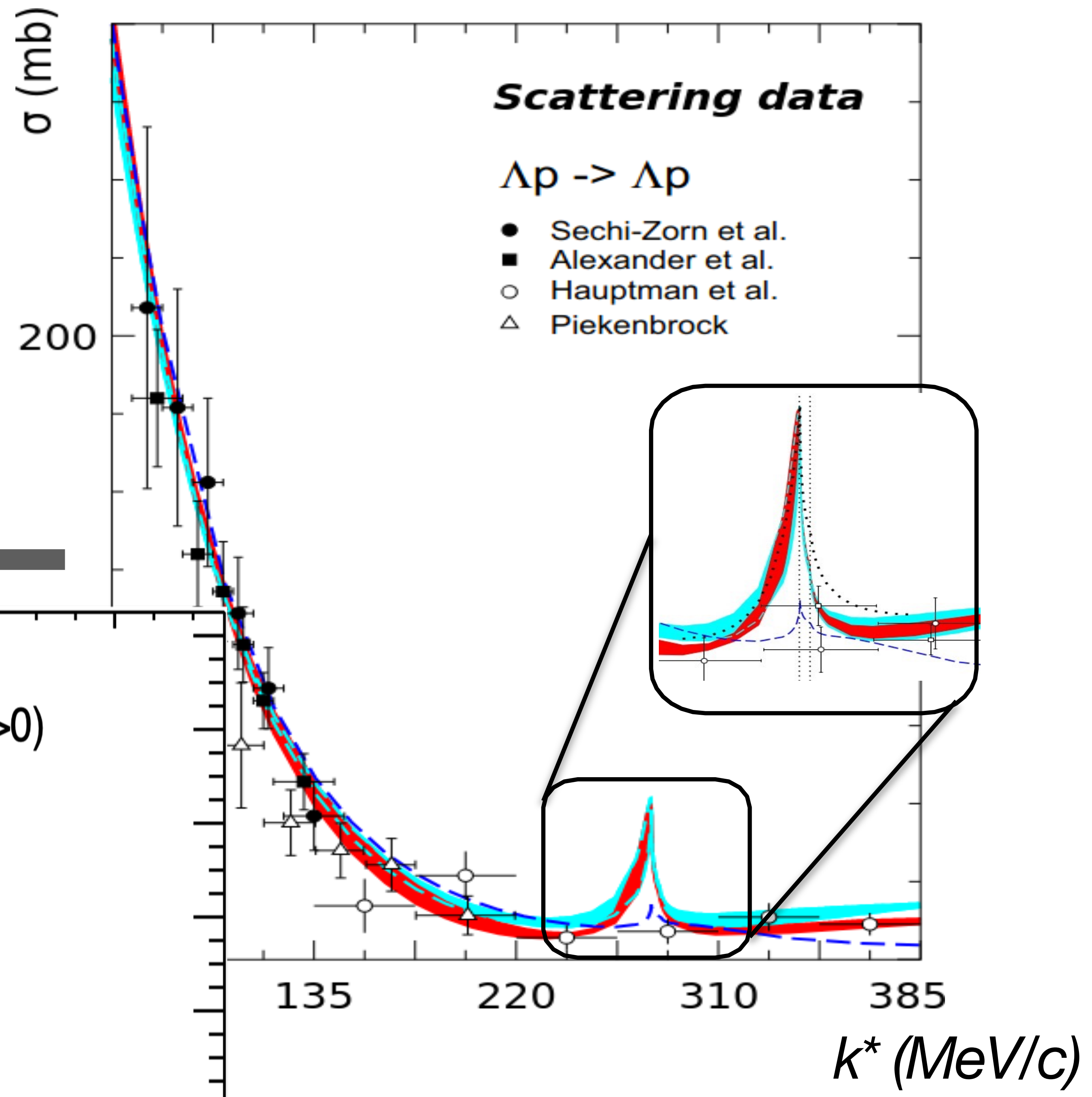
- **NEW**: combined analysis of femtoscopic and scattering data

D. Mihaylov, J. Haidenbauer and V. Mantovani Sarti, PLB 850 (2024) 138550





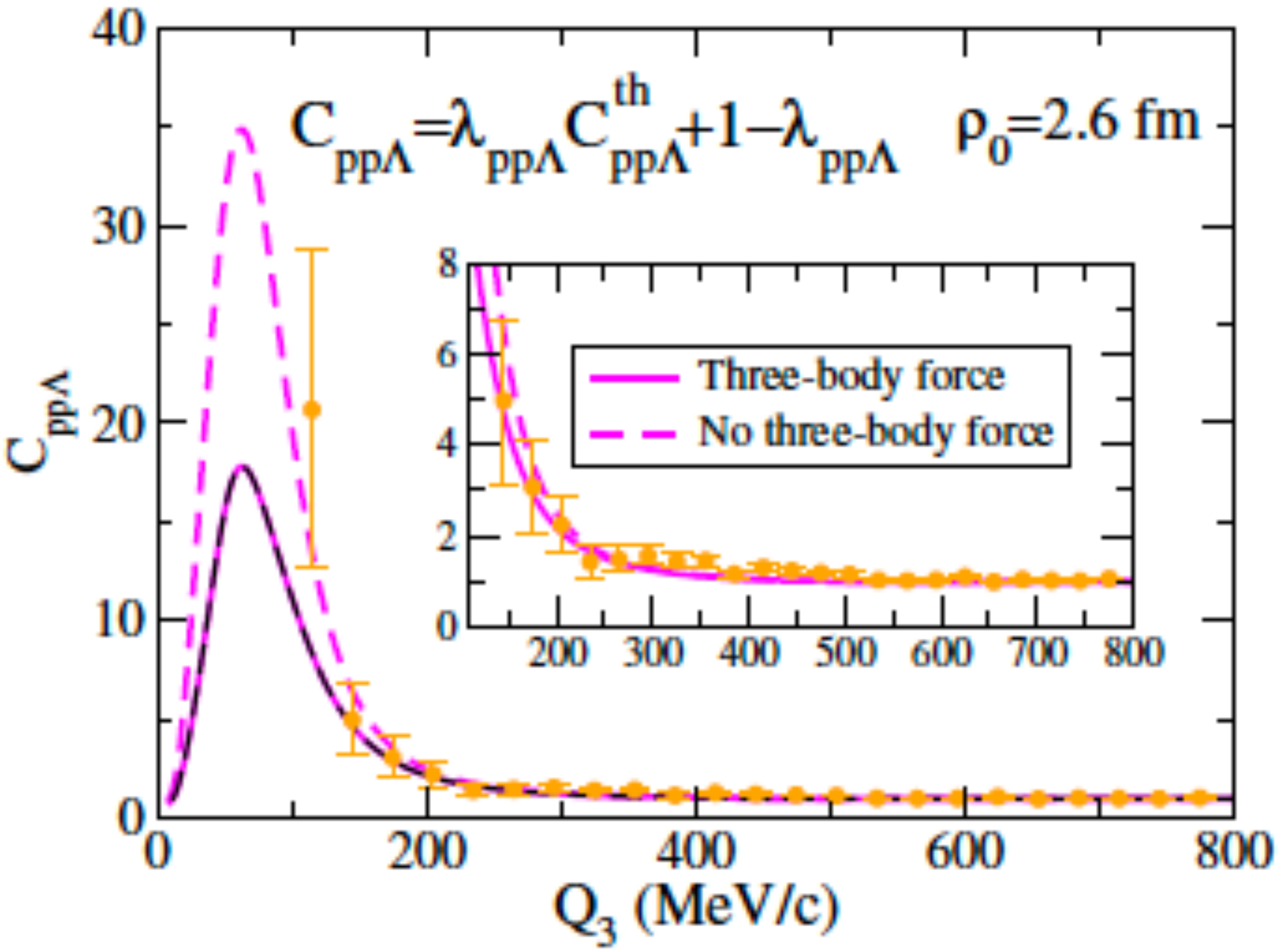
ALICE coll. PLB 833 (2022), 137272



p-p-Λ correlation function

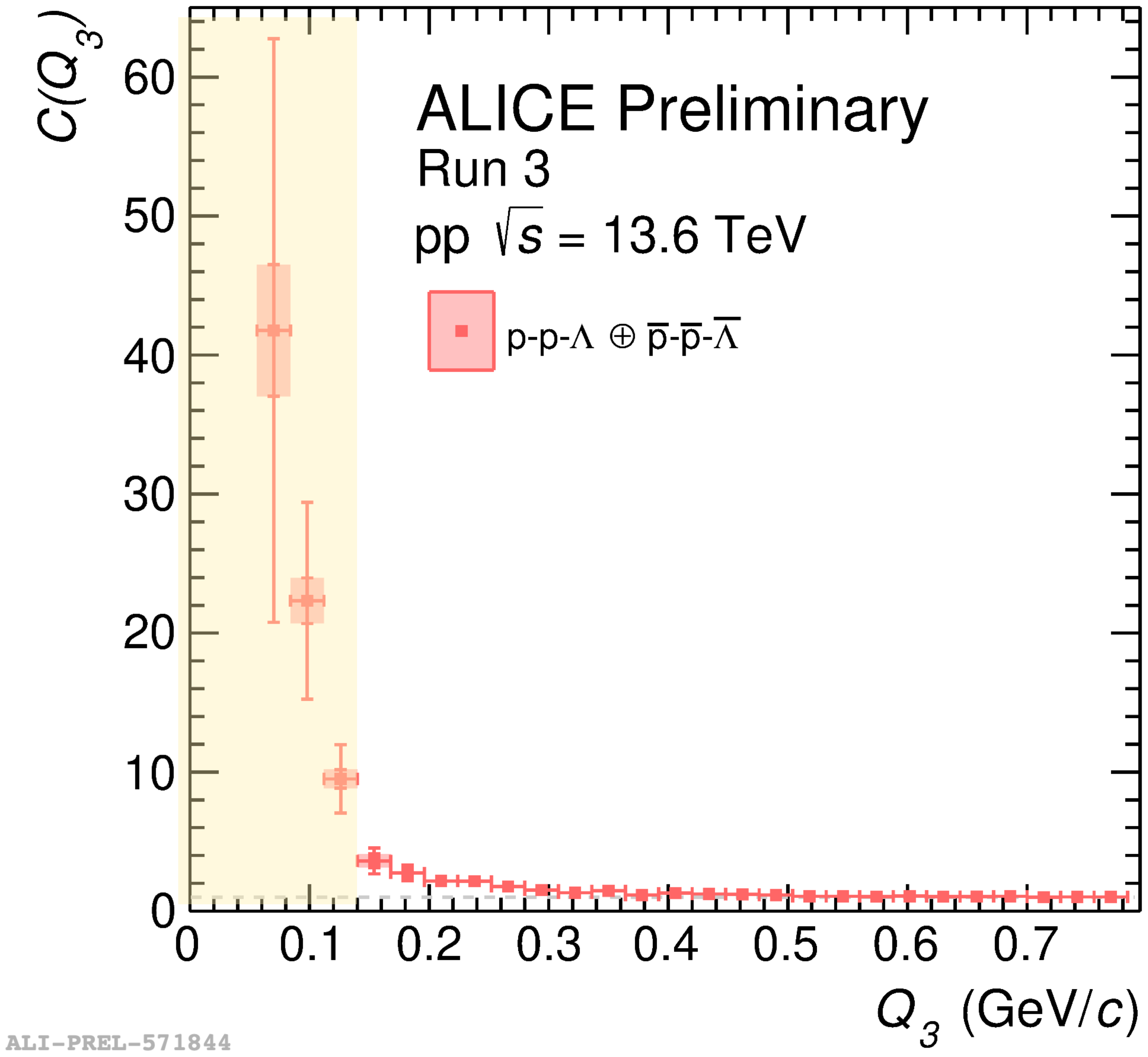
A. Kievsky and E. Garrido, Gattobigio, R. Del Grande, LF paper in preparation
ALICE Coll., EPJA 59, 145 (2023)

- First theoretical predictions:
  → NΛ interaction from NLO19
  → NNΛ interaction fixed to hypertrition BE



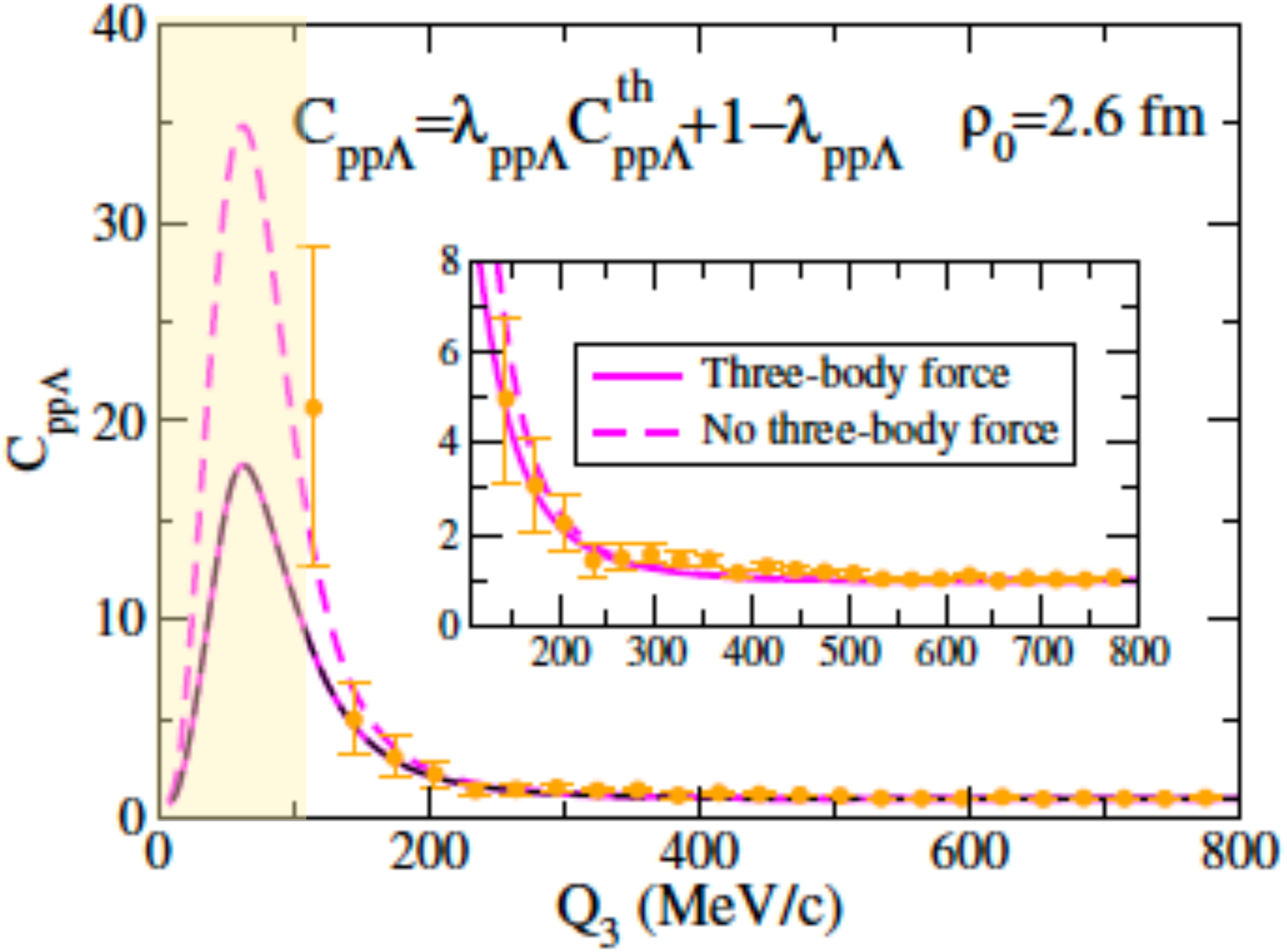
Calculation done by Alejandro Kievsky, Edoardo Garrido, Mario Gattobiglio, Raffaele Del Grande

p-p-Λ correlation function



A. Kievsky and E. Garrido, Gattobigio, R. Del Grande, LF paper in preparation

ALICE Coll., EPJA 59, 145 (2023)



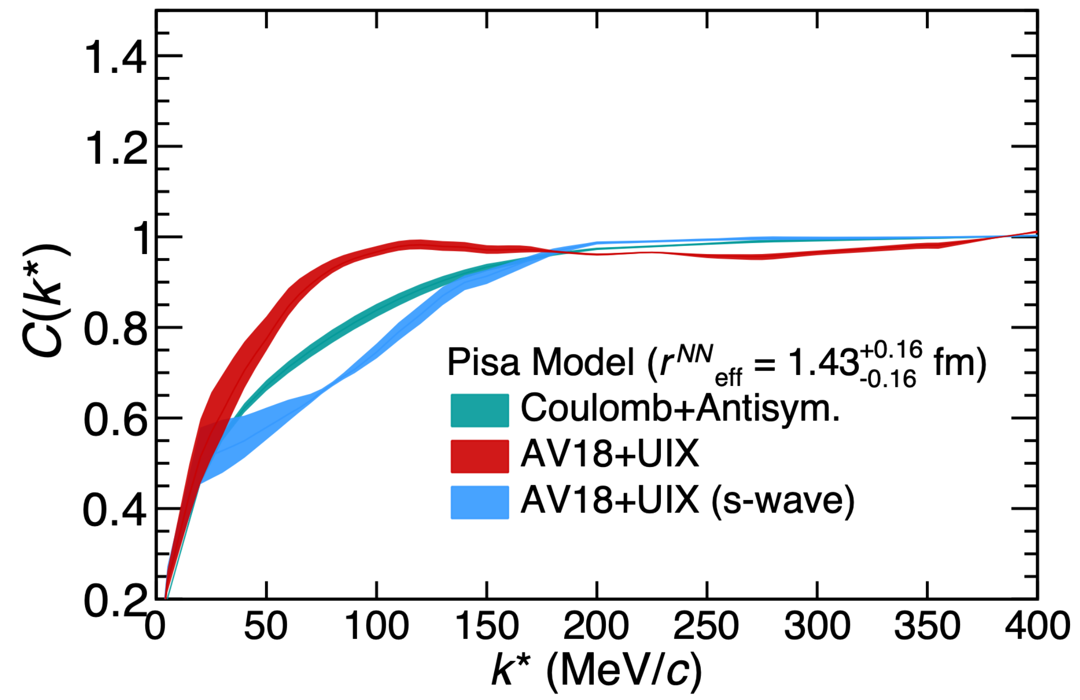
- **New data by ALICE** (Run 3 2022 data)
- By the end of Run 3: 150 times larger statistical triplets sample expected compared to Run 2 due to developed software triggers!

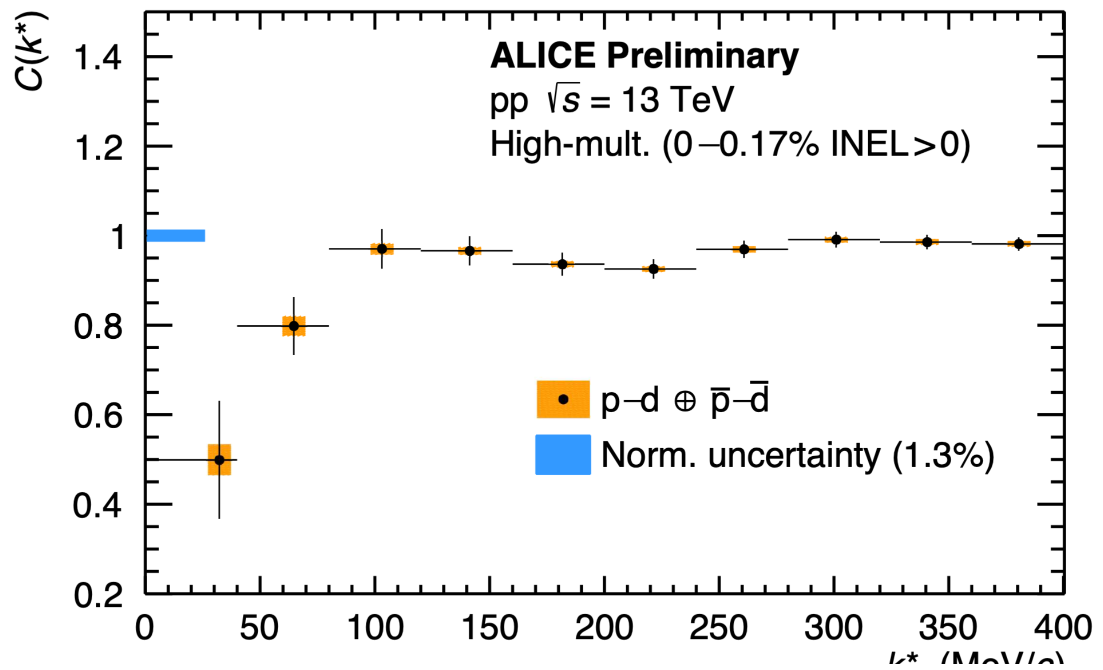
Conclusions

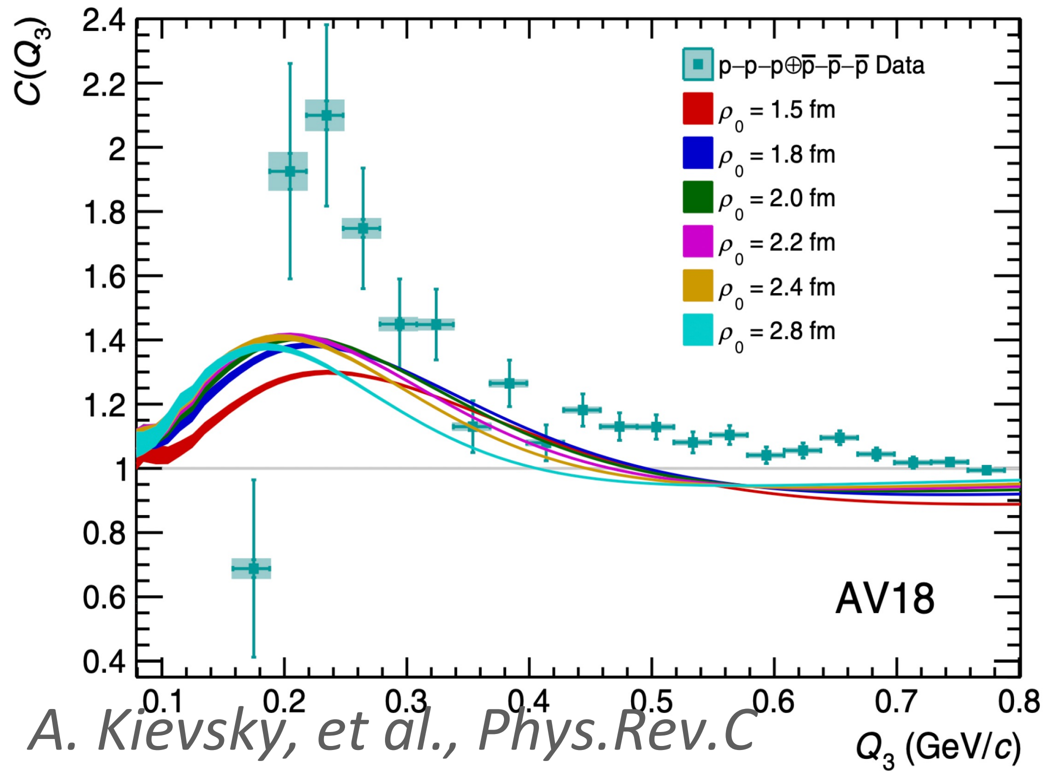
First measurements tackling the problem of genuine three-body interactions using femtoscopy!

- **p-d**: can be described with full three-body calculations
- **p-p-p**: towards a precision measurement as a benchmark
- **p-p-Λ: first measurement and first calculation**

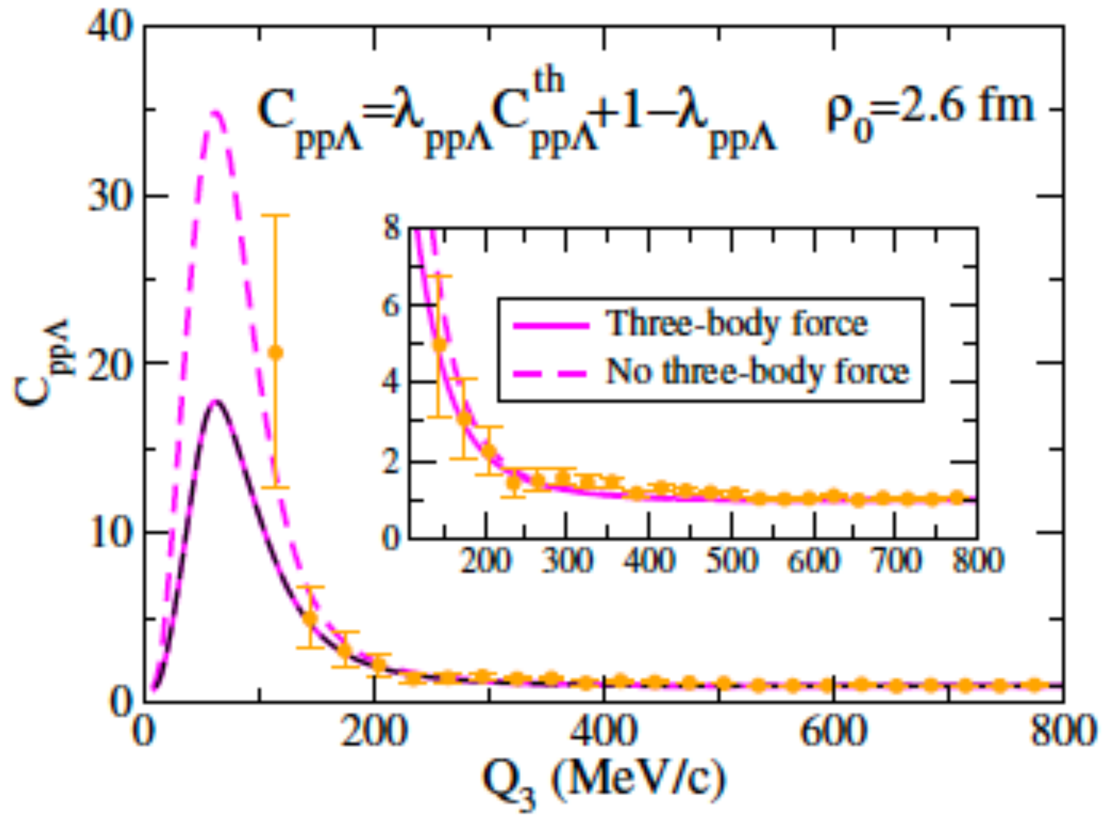
Final constraints on three-body interactions will arrive with Run 3 data!







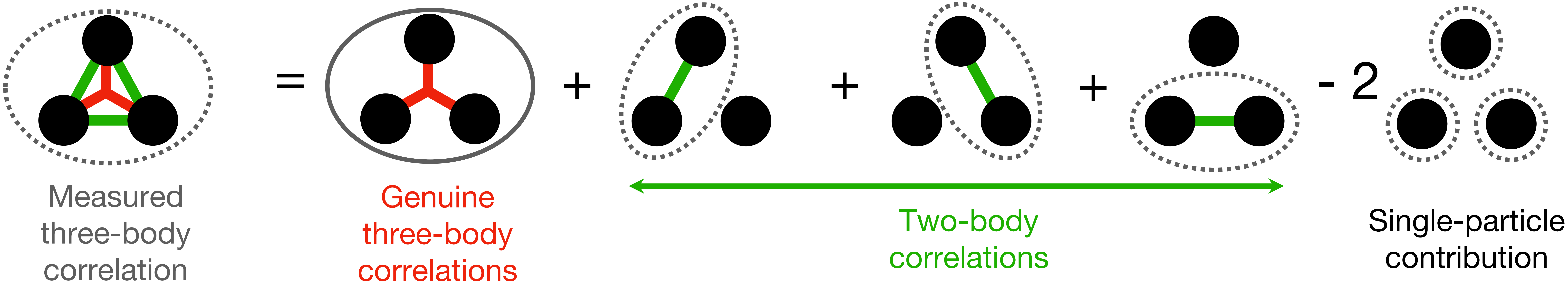
A. Kievsky, et al., Phys.Rev.C 109 (2024) 3, 034006



Back-up

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:

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

Lower-order contributions

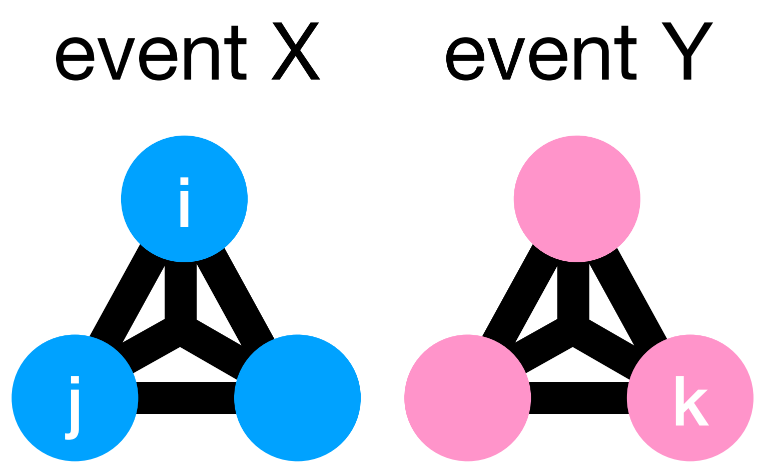
[1] R. Kubo, J. Phys. Soc. Jpn. 17, 1100-1120 (1962)

Lower-order contributions

Data-driven method

- Use event mixing

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



Lower-order contributions

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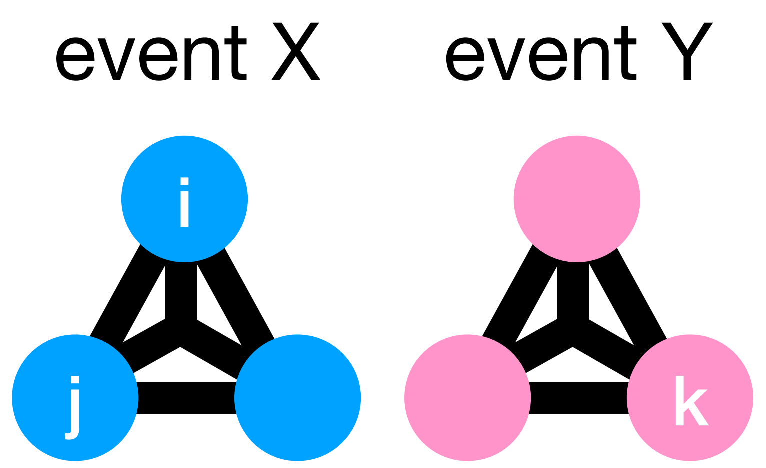
- Two particles from the same event and one particle from another:



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

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

Lower-order contributions

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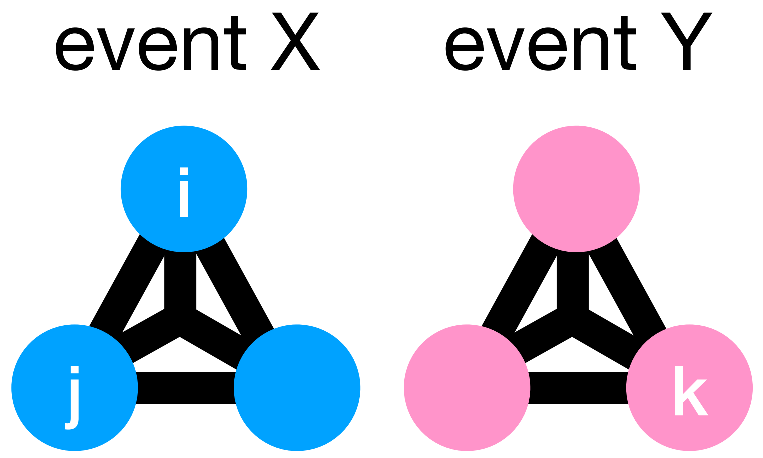
- Use event mixing
- Two particles from the same event and one particle from another:



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

- 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:

$$C_2(k^*_{ij}) \rightarrow C_{ij}(Q_3)$$

$$k^*_{ij}\,(pair) \rightarrow Q_3\,(triplet)$$

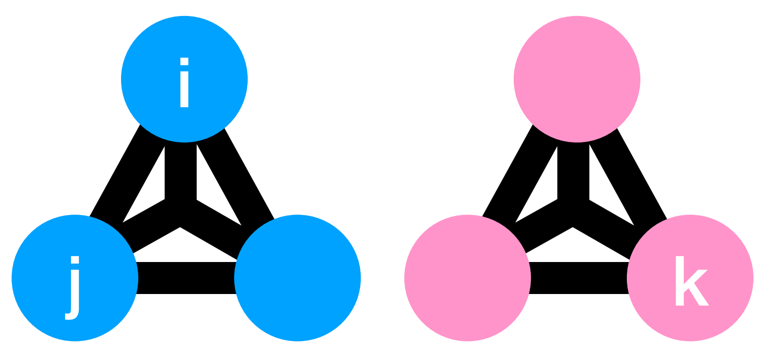
For one Q_3 value ➡

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

Lower-order contributions

Data-driven method

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



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

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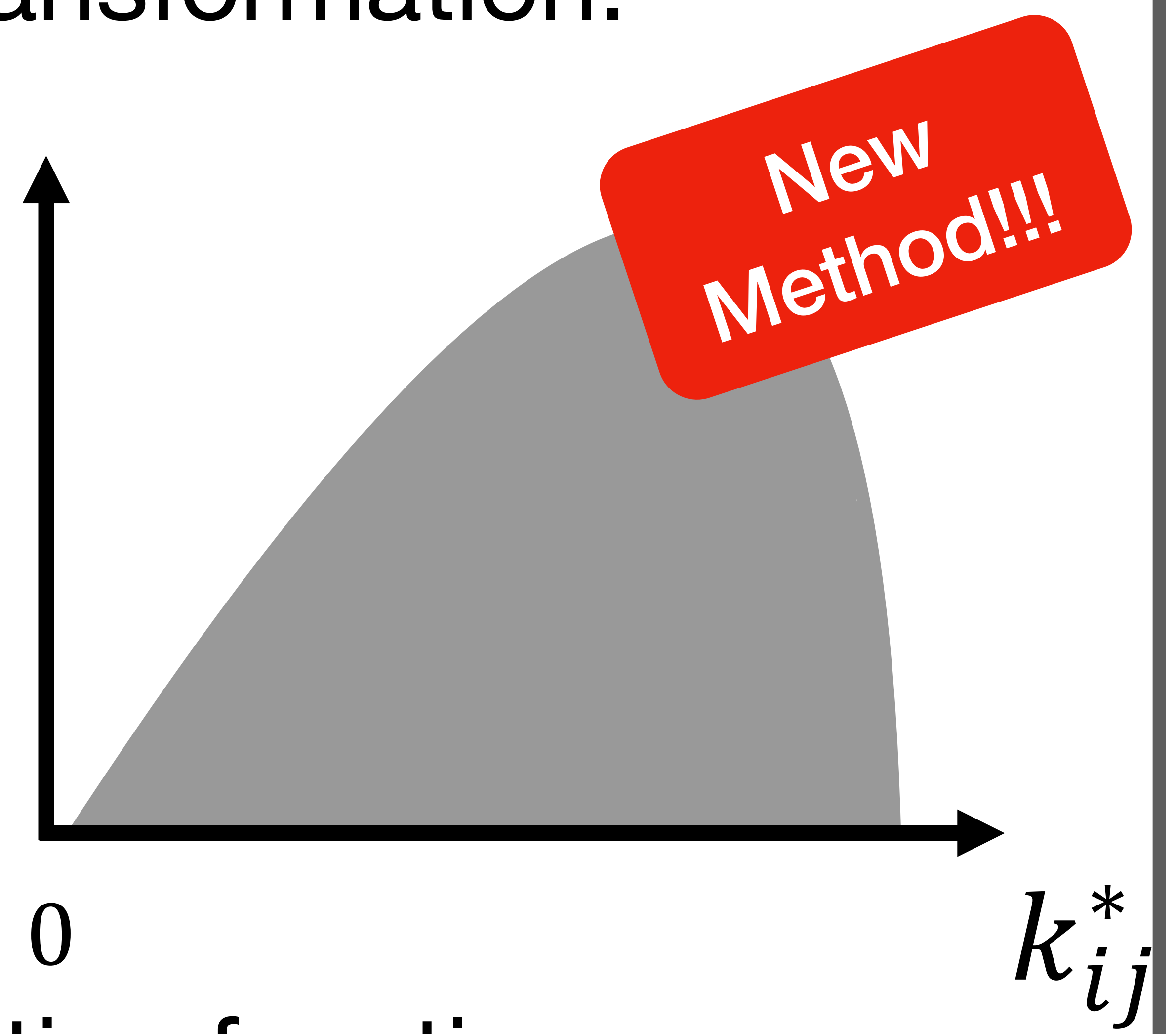
For one Q_3 value



- To obtain the correlation function:

Caption

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

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

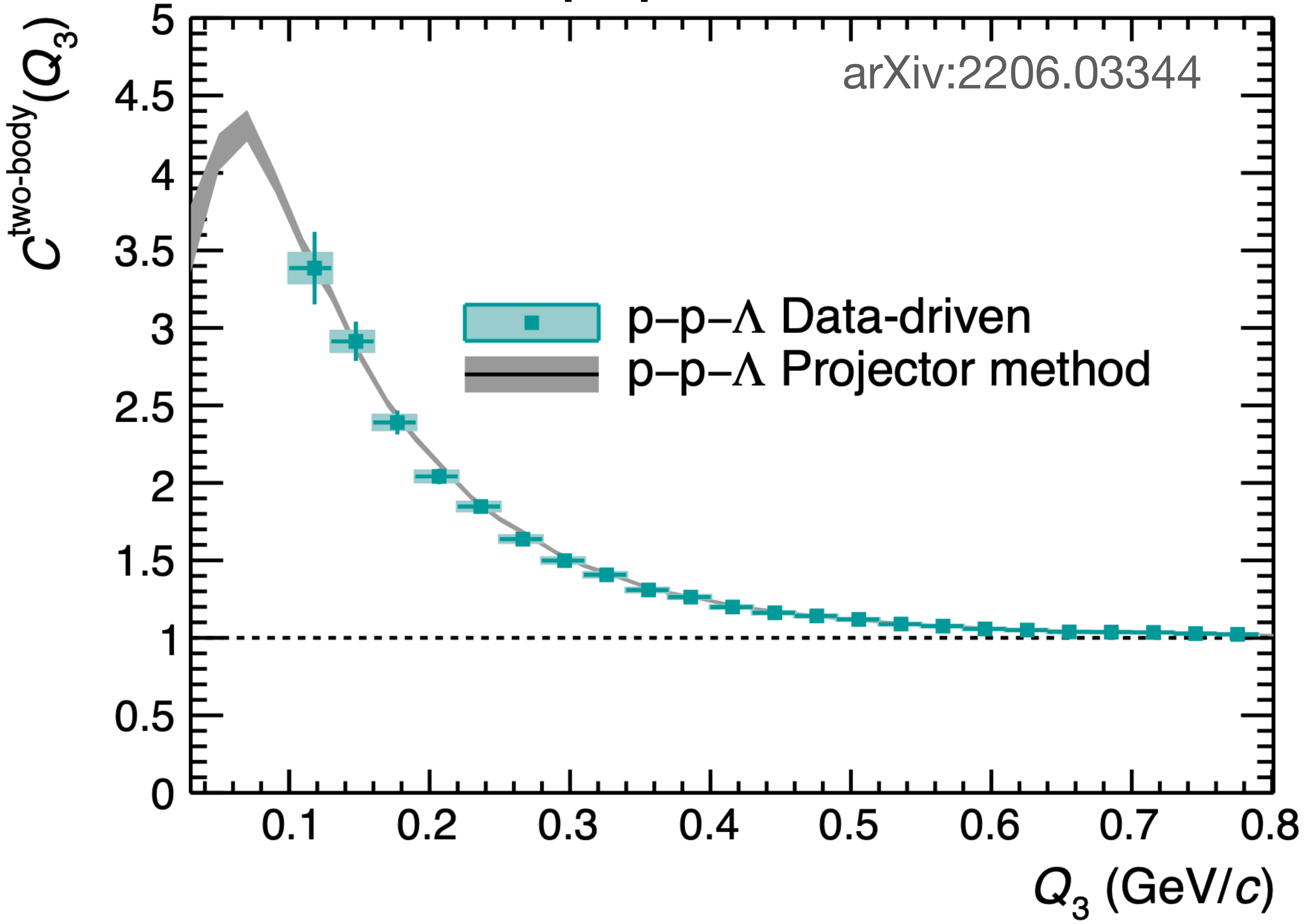
Lower-order contributions

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

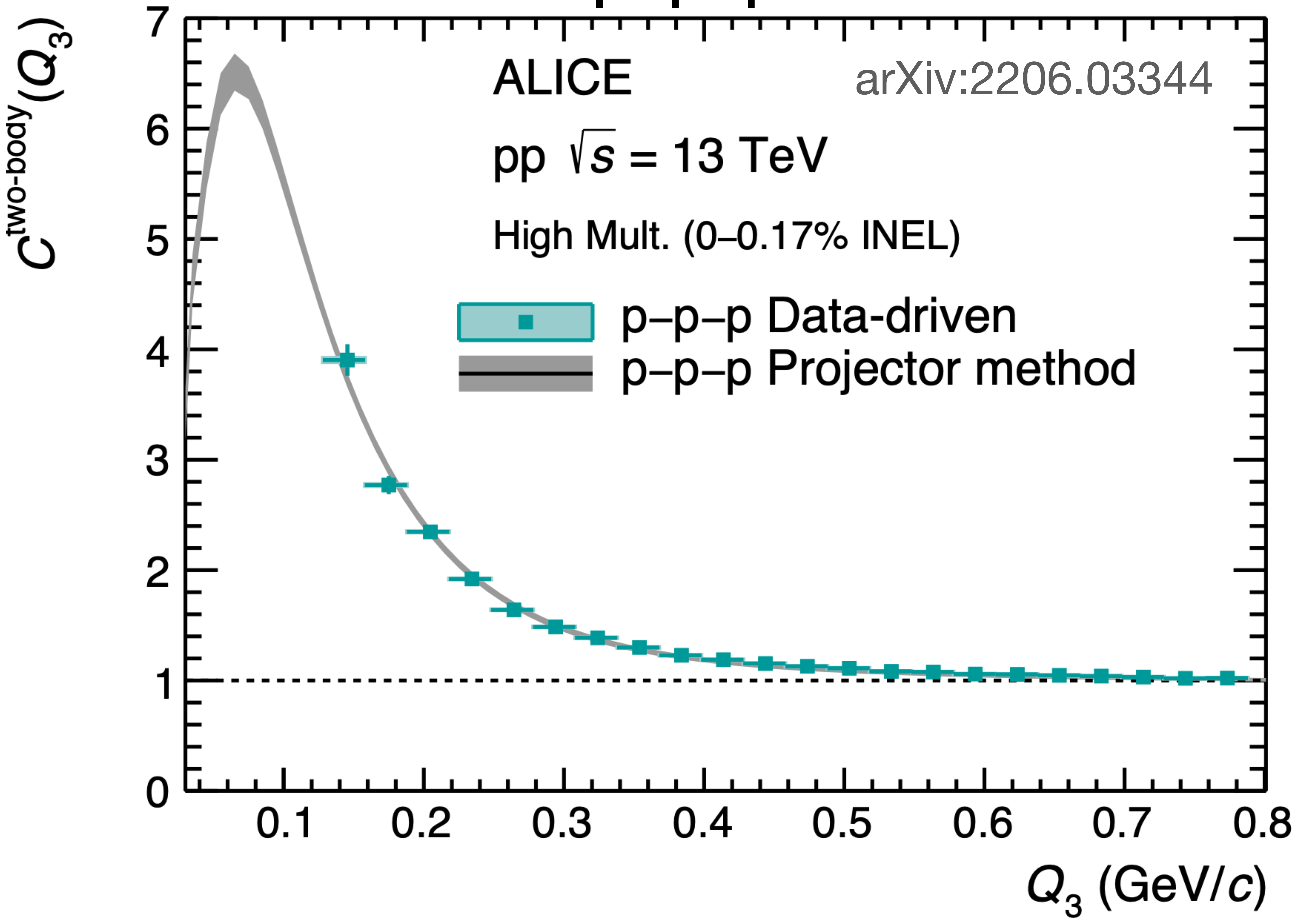
Lower-order contributions under control!

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

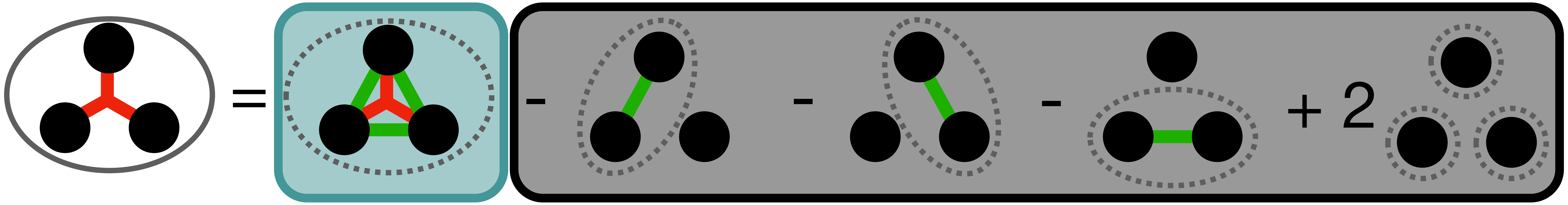
p-p-Λ



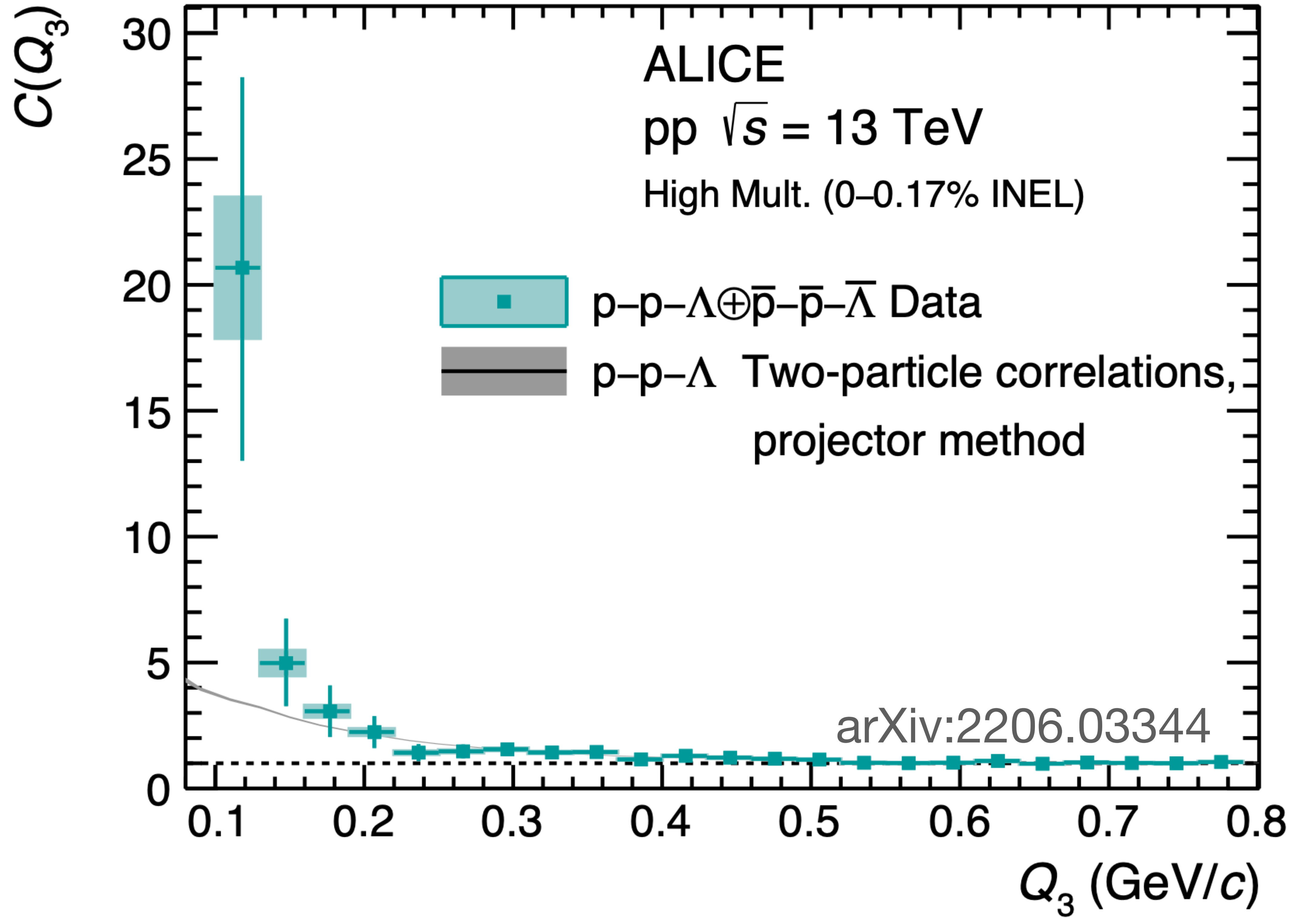
p-p-p



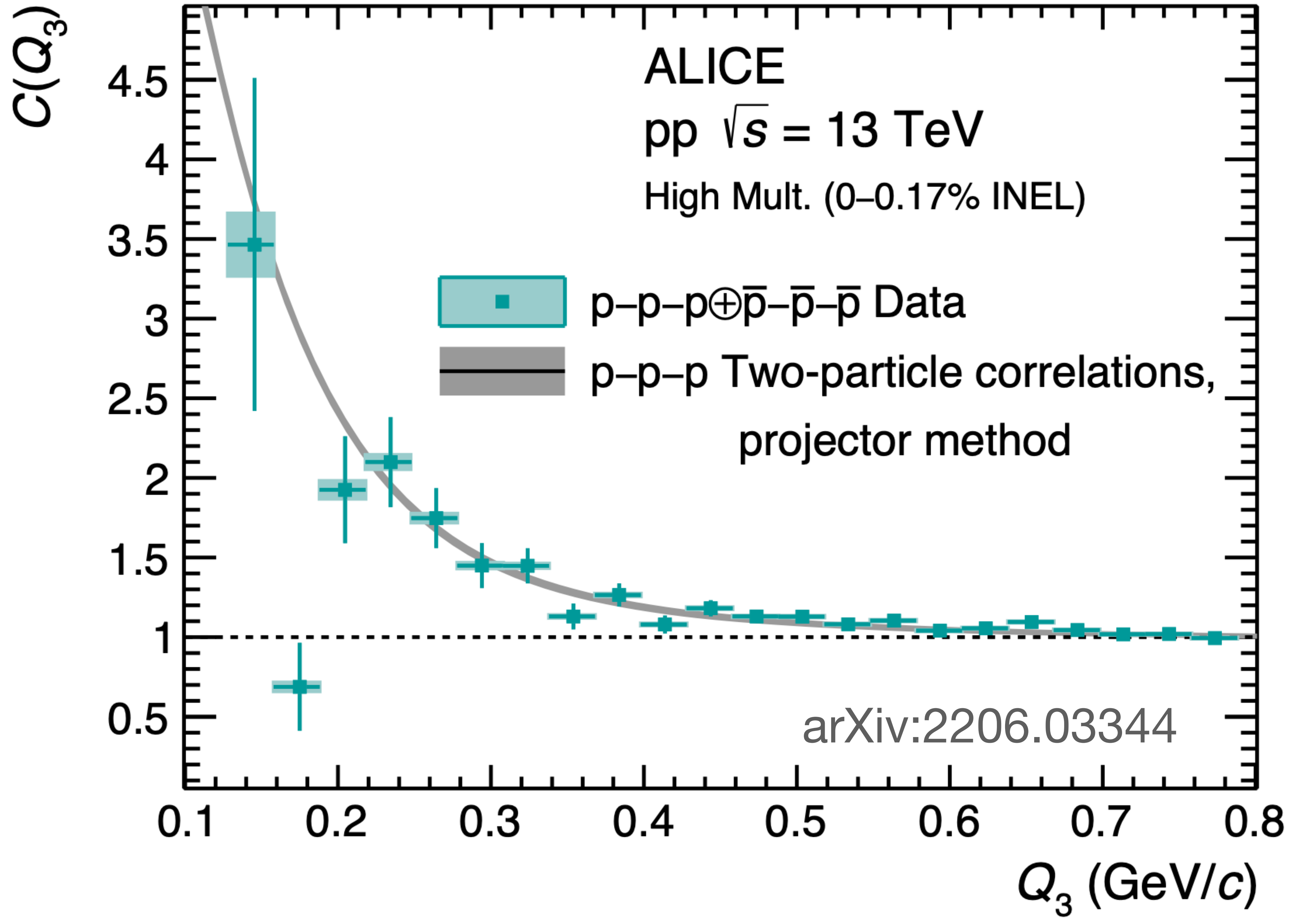
p-p-Λ and p-p-p correlation functions



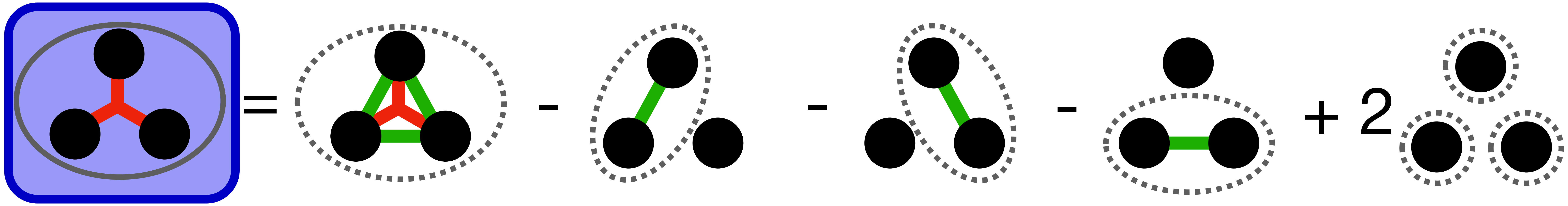
p-p-Λ



p-p-p



p-p-p cumulant



Negative cumulant for p-p-p

Possible forces at play:

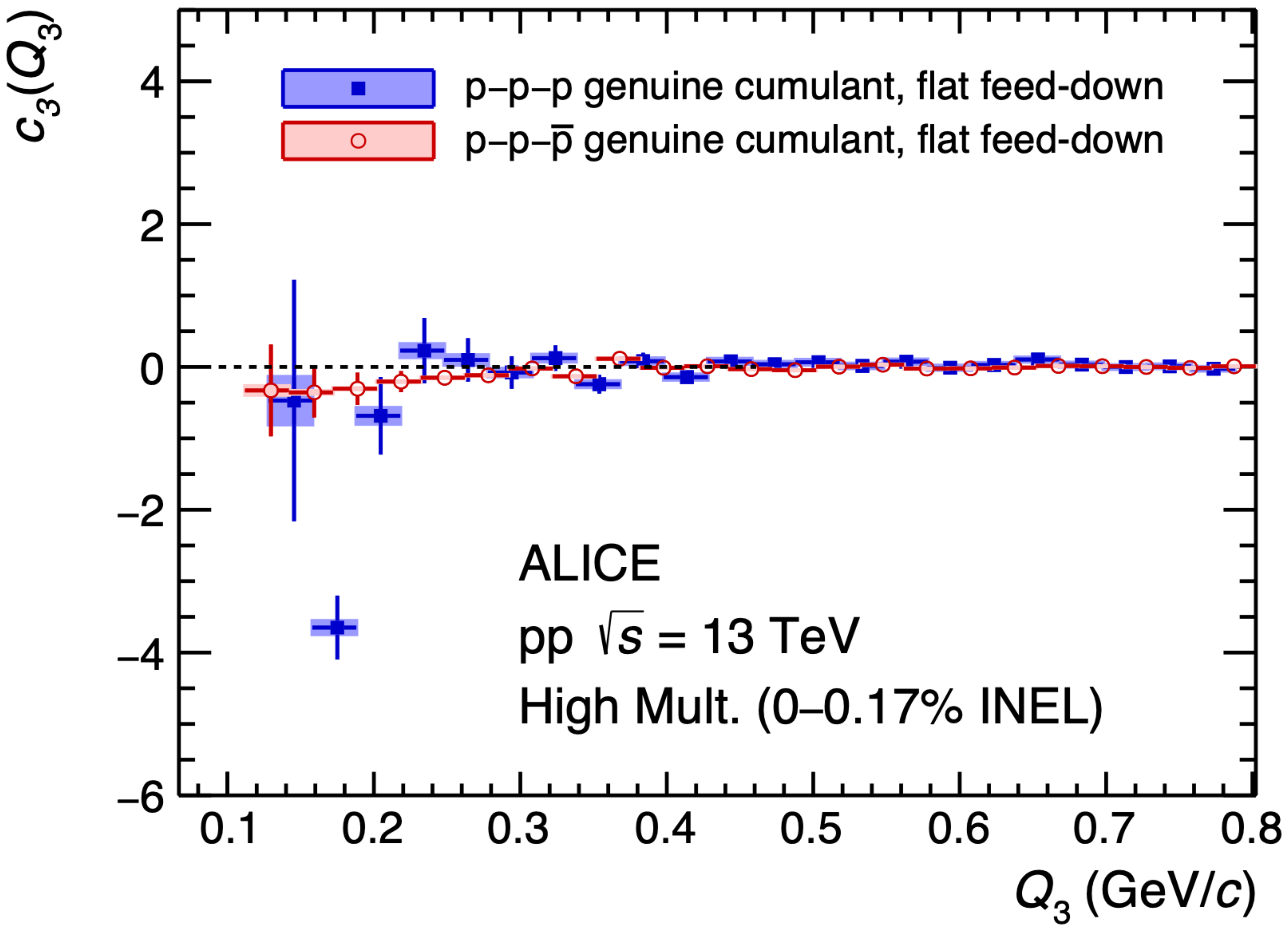
- *Pauli blocking at the three-particle level*
- three-body strong interaction
- long-range Coulomb

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

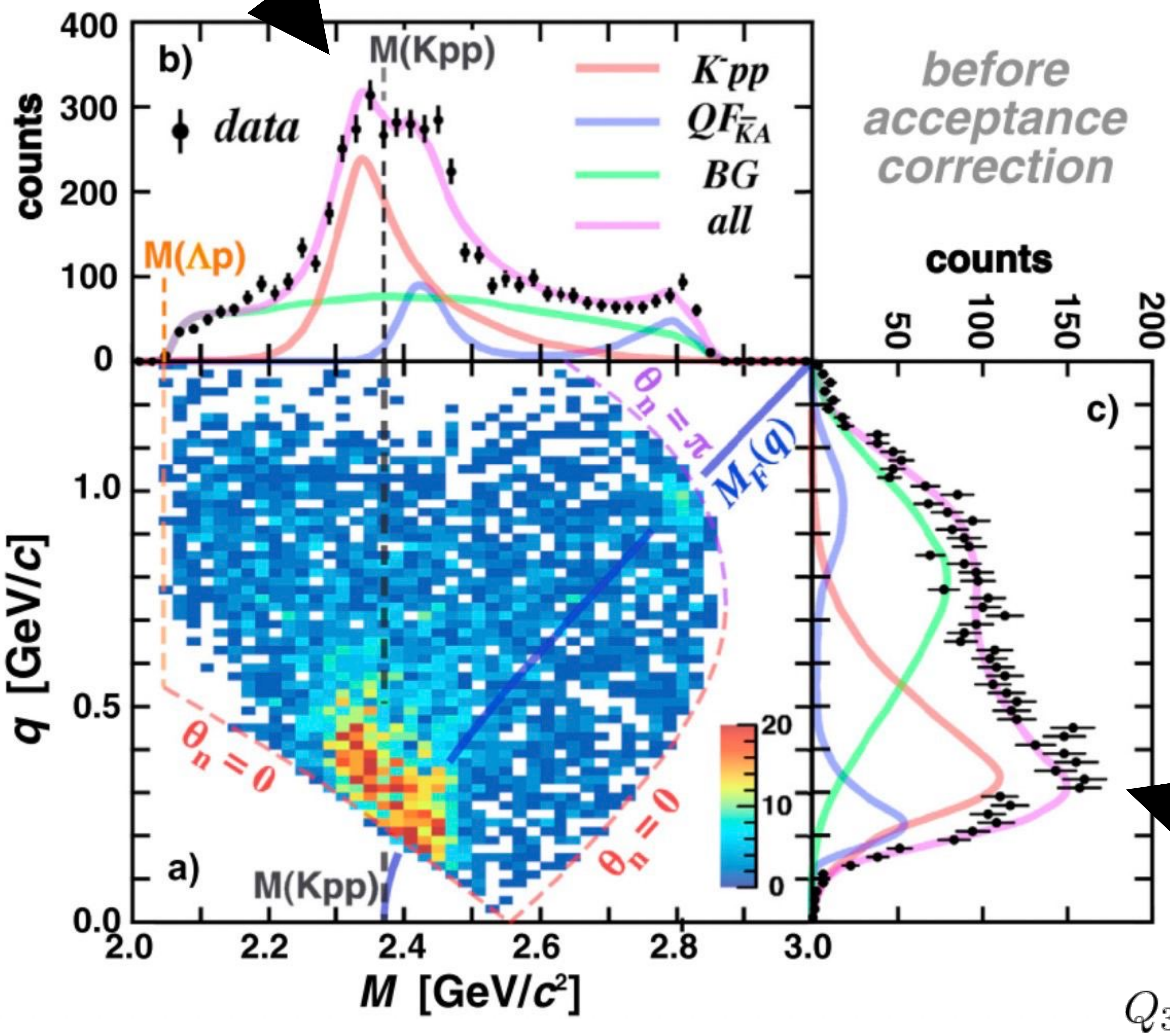
arXiv:2206.03344



Test with mixed-charge particles, cumulant negligible.

Kaonic bound state measured by E15

E15 Coll., PLB 789 (2019) 620



The E15 collaboration measured the bound state via the following decay:

$$K^- + p + p \rightarrow \Lambda + p$$

The Λp momentum distribution has a peak at

$$q = p_\Lambda + p_p \approx 0.35\ \mathrm{GeV}/c$$

Using the momentum conservation:

$$p_{K^-} + p_p + p_p \approx 0.35\ \mathrm{GeV}/c$$

The protons are at-rest → $p_K \approx 0.35\ \mathrm{GeV}/c$

In terms of Q_3 we have

$$Q_3 = 2\sqrt{k_{\rm pK}^2 + k_{\rm pK}^2 + k_{\rm pp}^2} = 2\sqrt{2}\,k_{\rm pK} = 4/3\sqrt{2}\,p_K < 0.5\,\mathrm{GeV}/c$$

Many-body systems

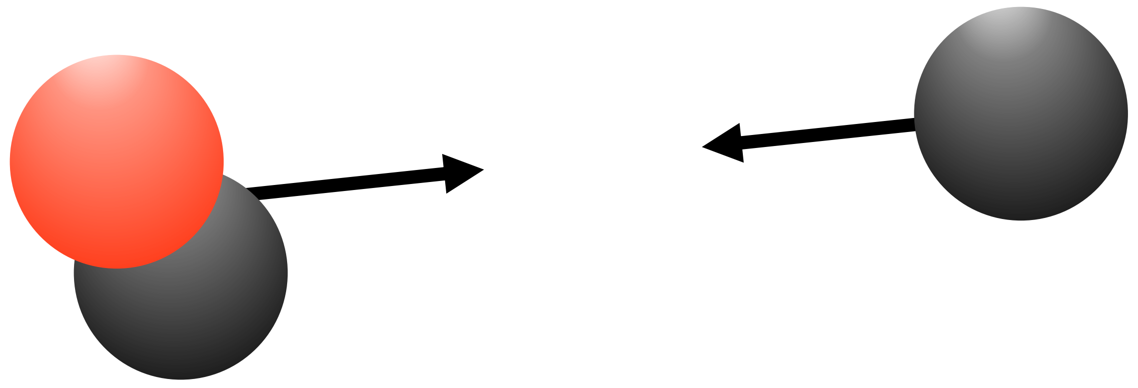
- Description of the N-d elastic scattering requires inclusion of three-body interactions

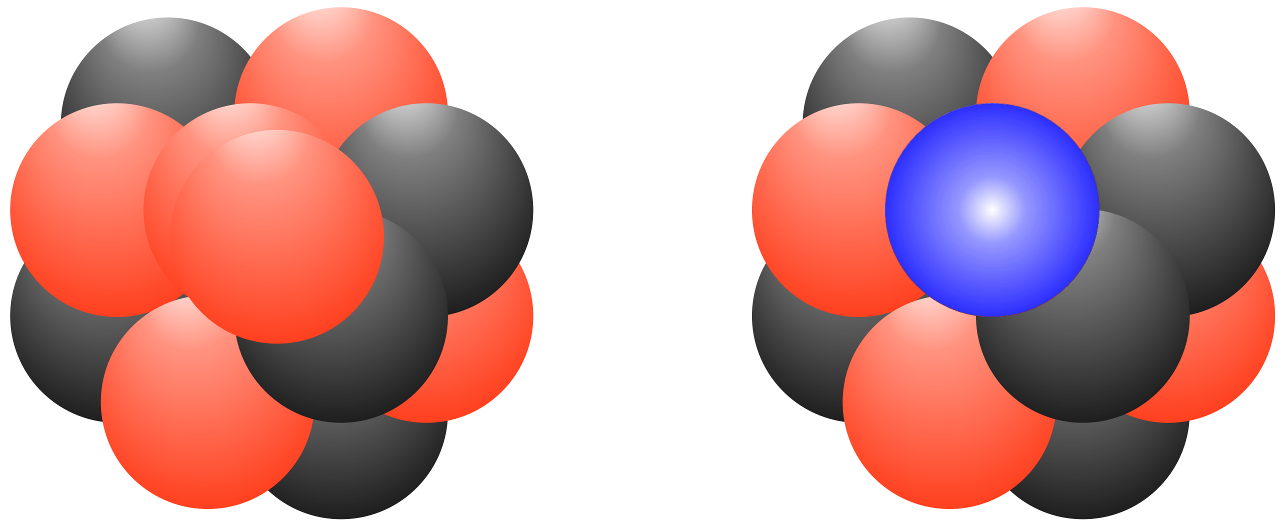
  L.E. Marcucci et al., Front. Phys. 8, 69 (2020)

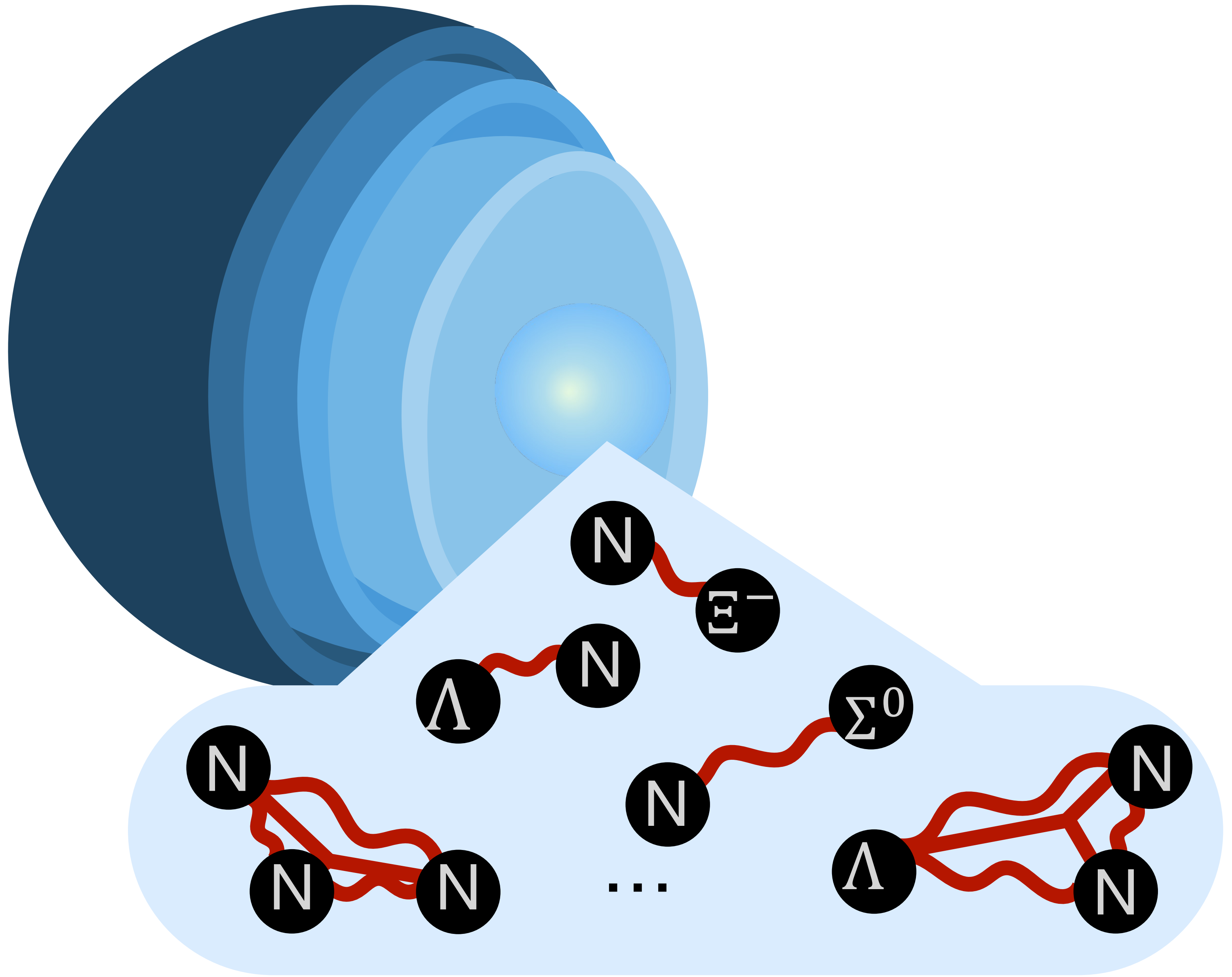
- Properties of nuclei and hypernuclei cannot be described satisfactorily with two-body forces only

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

ρ



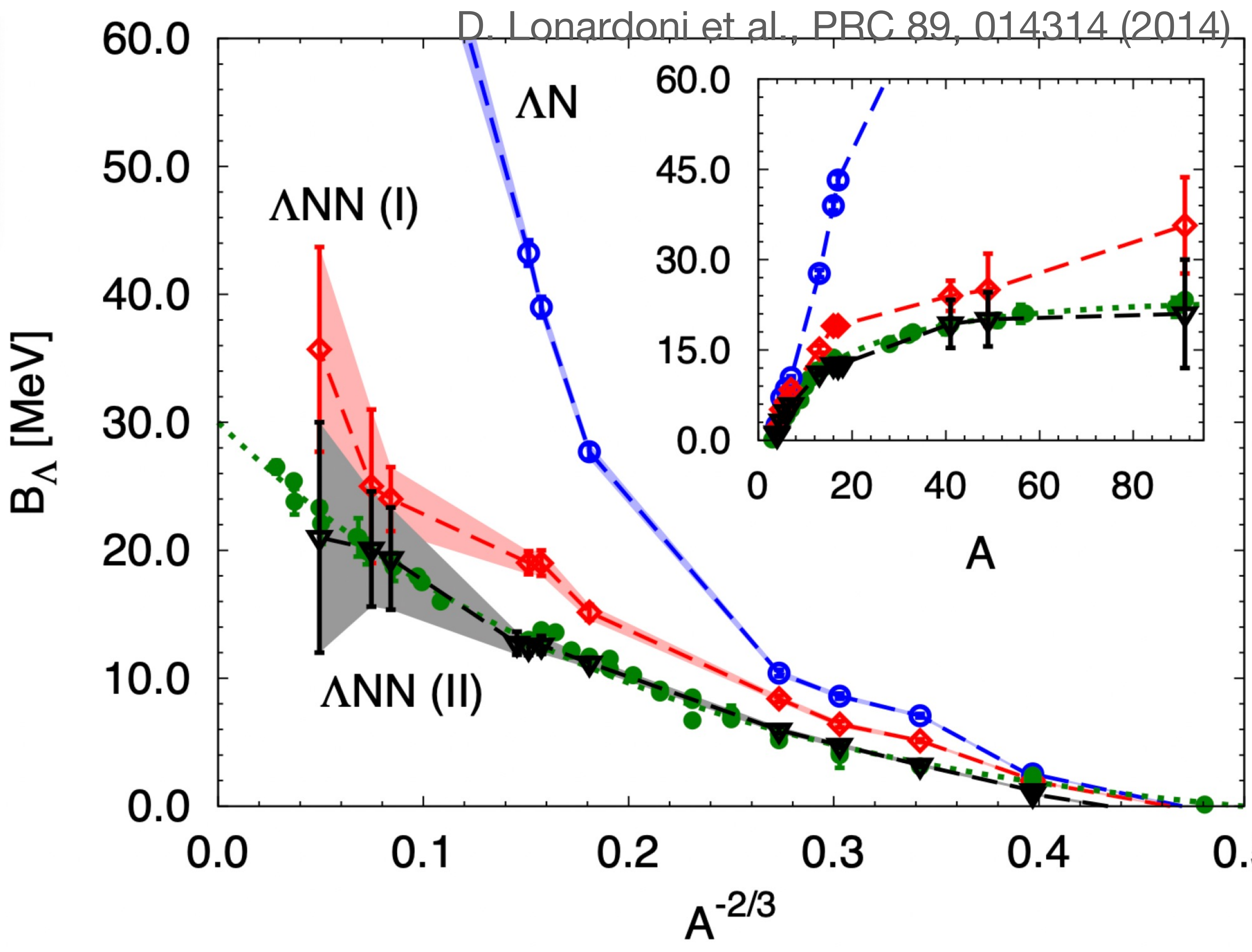




How to constrain three-body forces?

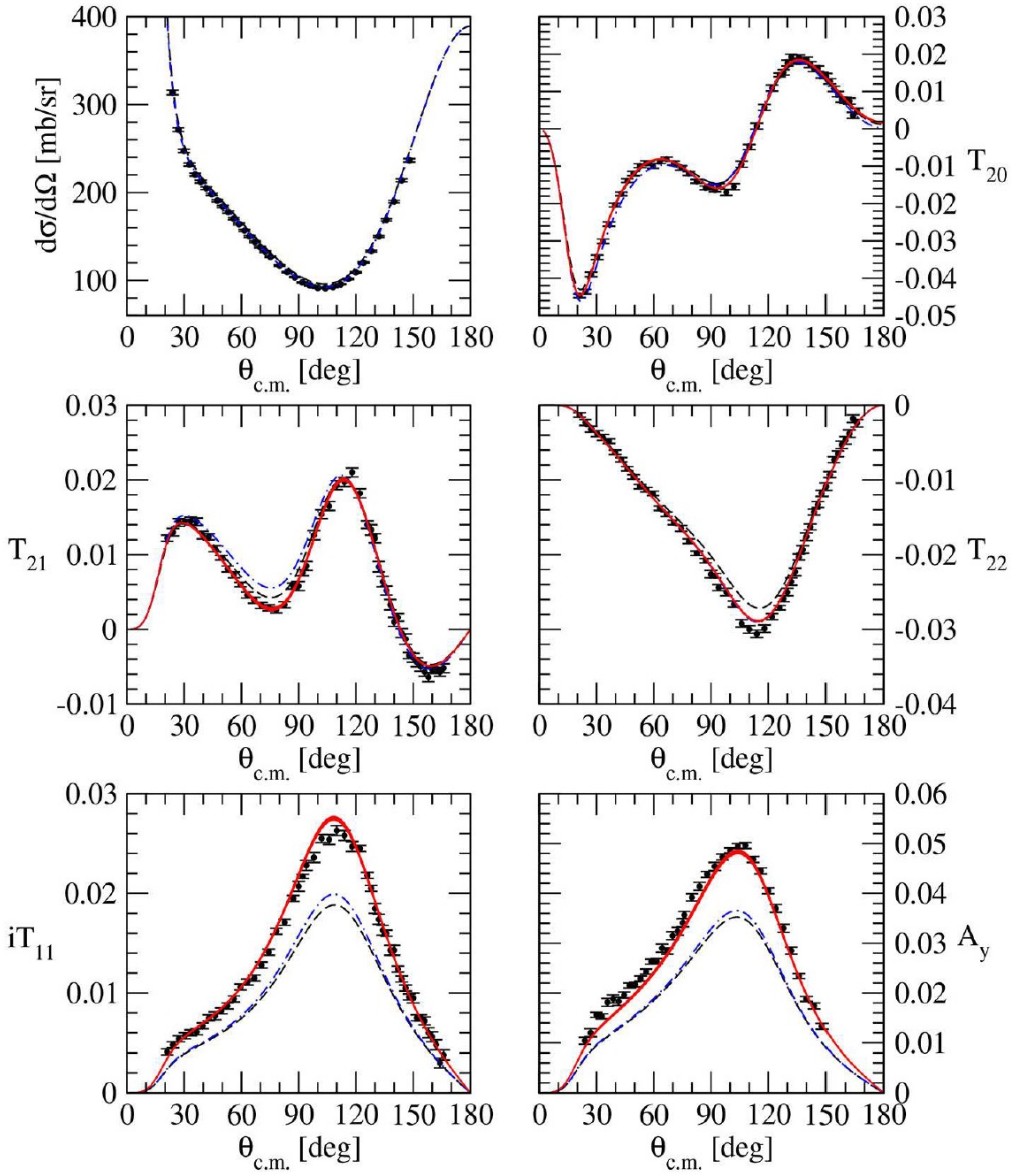
- Models are fitted to reproduce measured (hyper)nuclei properties
  - Access only to nuclear densities
  - Strongly dependent on the assumed two-body and many-body interactions
  - Different parametrisations of three-body forces describe better different nuclei

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)



p-d scattering

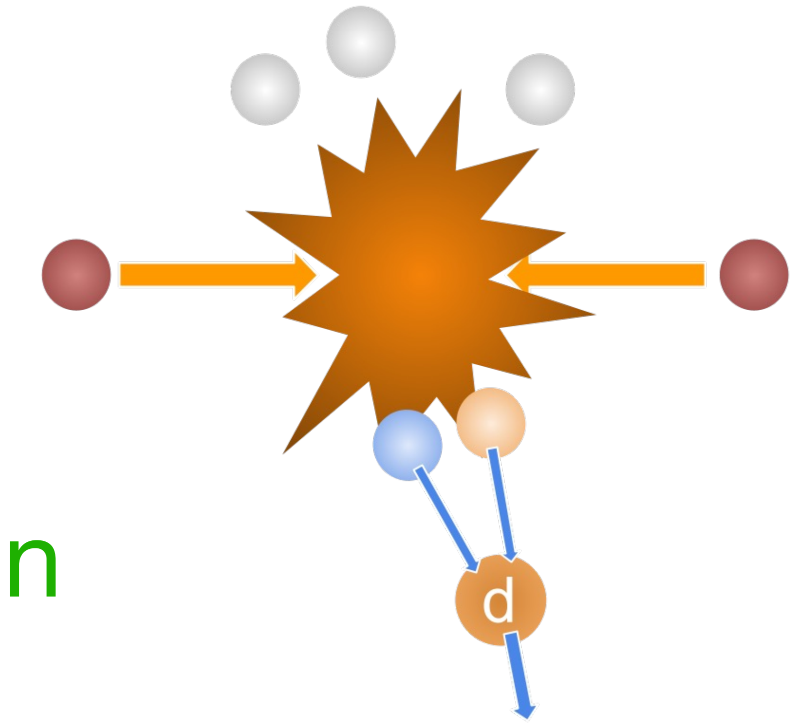
- Three body interactions are required to reproduce scattering data



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

Three-body dynamics

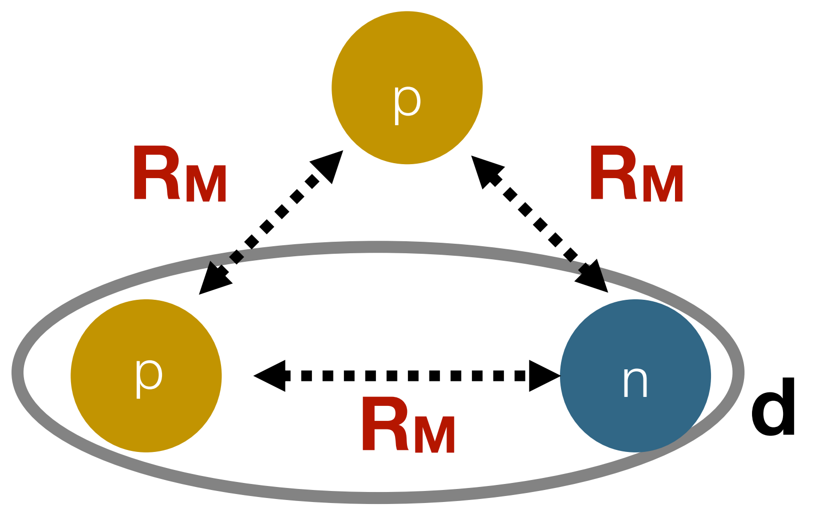
- Start with p-p-n state:
  - single-particle Gaussian emission source
  - three-nucleon wave function asymptotically behaves as p-d state
  - account for the probability to form deuteron employing deuteron wave function



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

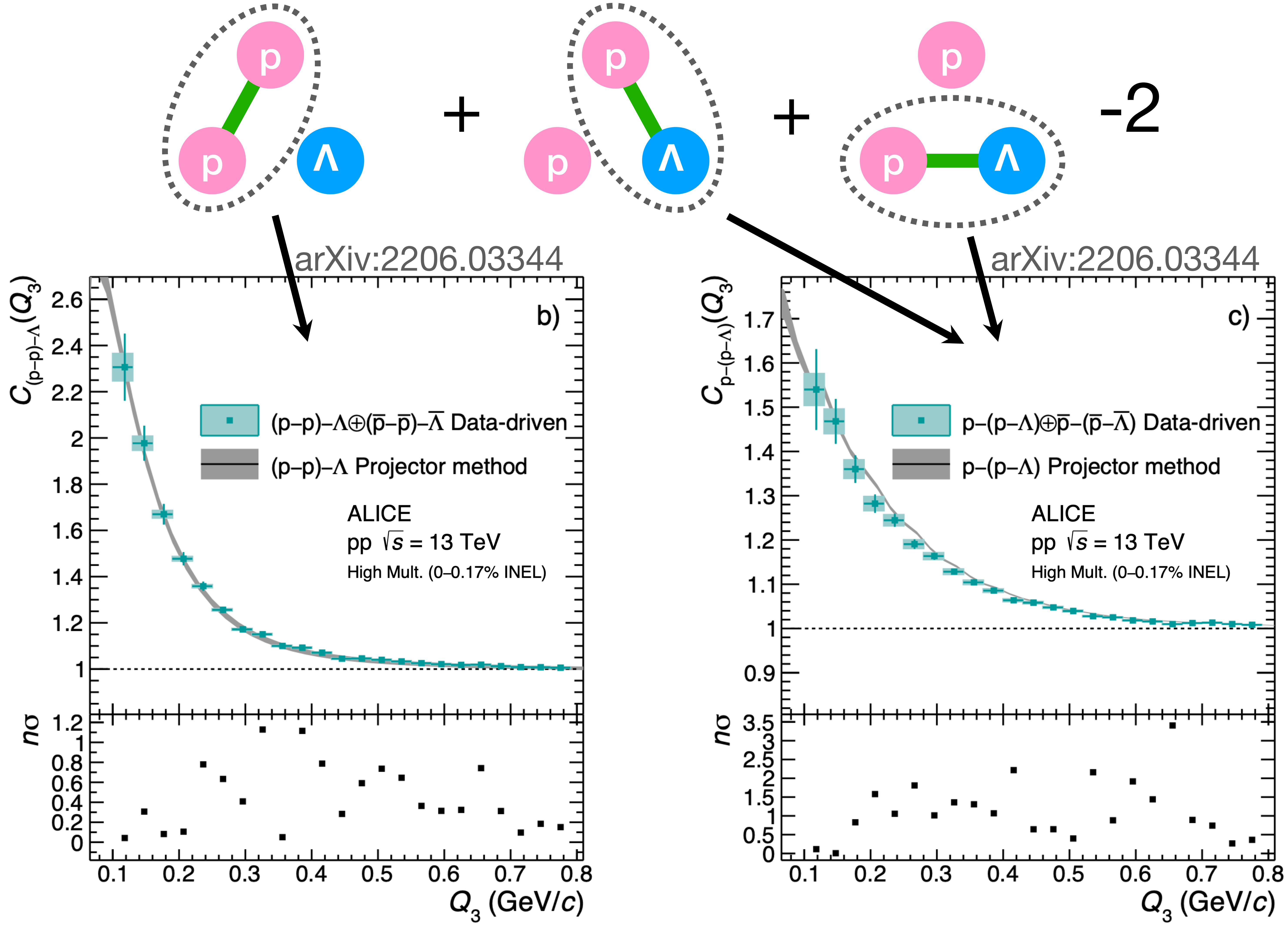
- Rewritten as a function of the known source size R_M constrained by p-p

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

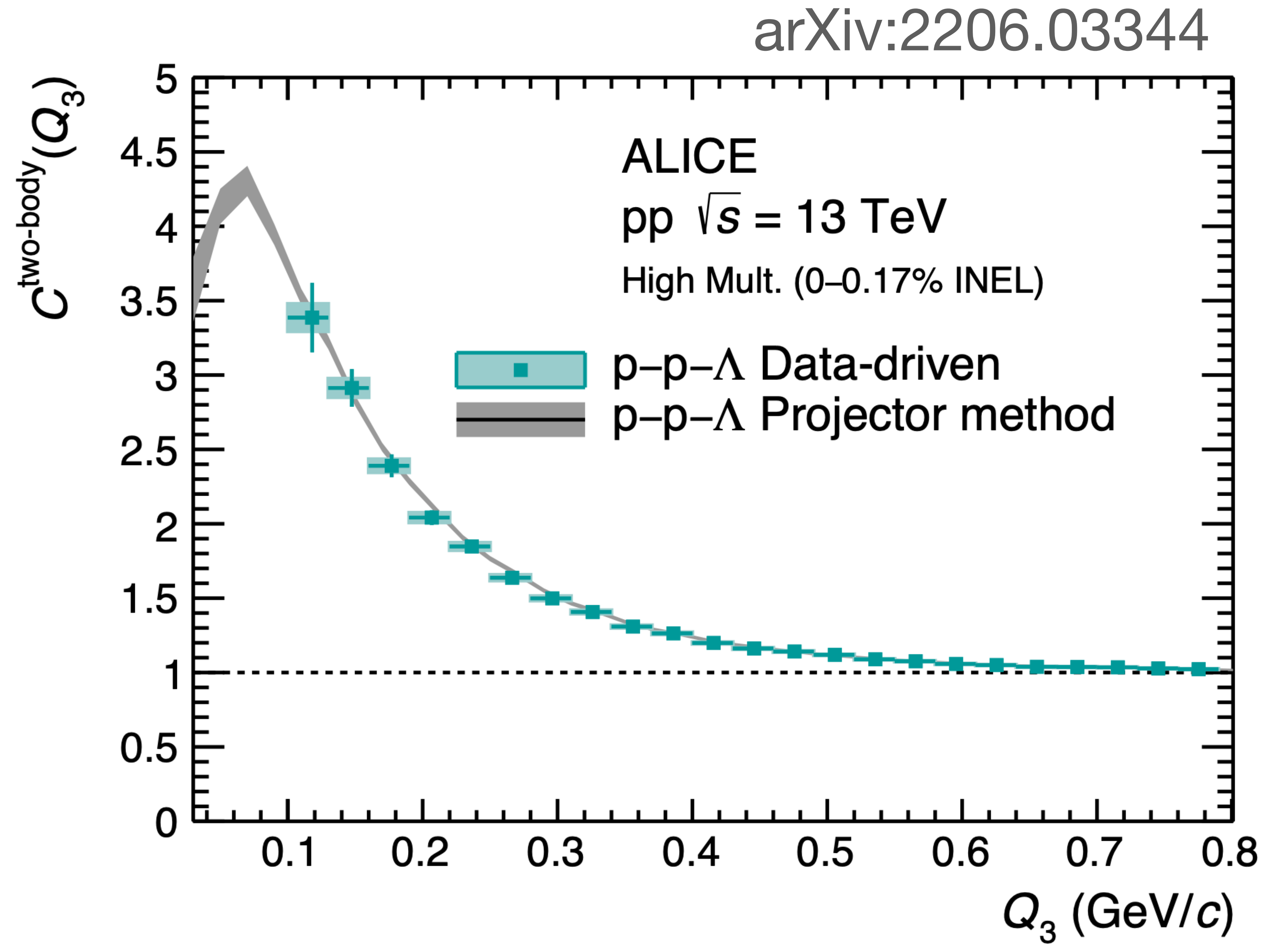


S. Mrówczyński et al., Eur. Phys. J. Special Topics 229, 3559 (2020)

Lower-order contributions: p-p-Λ



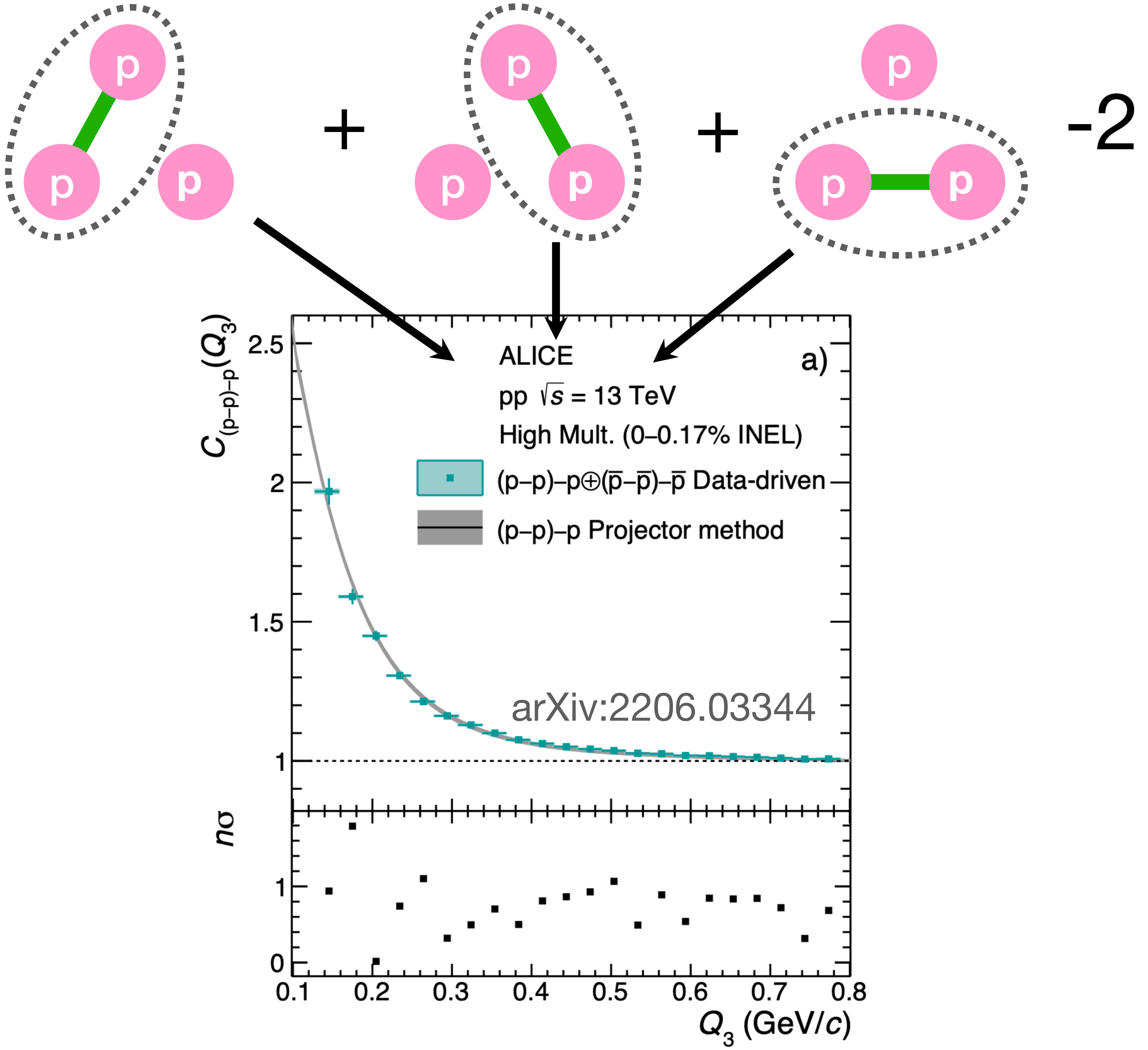
Total lower-order contributions



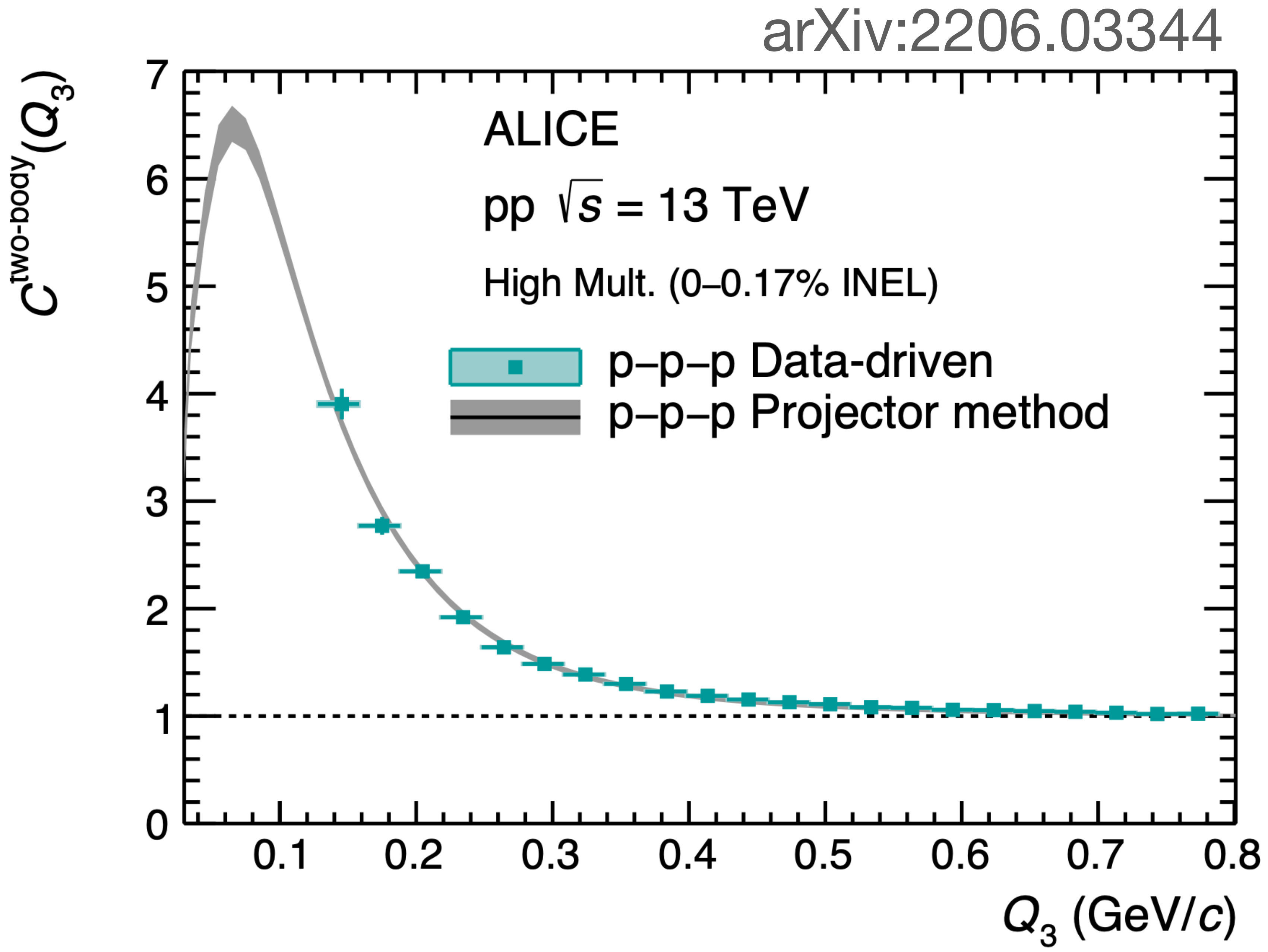
Already measured p-p [1] and p-Λ [2] correlation functions used for projection

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

Lower-order contributions: p-p-p



Total lower-order contributions



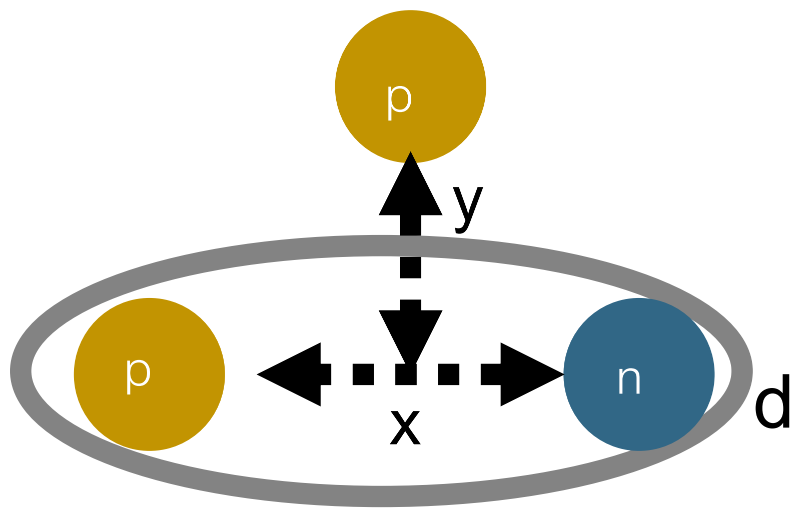
Already measured p-p [1] correlation function used for projection.

[1] PLB 805 (2020) 135419

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



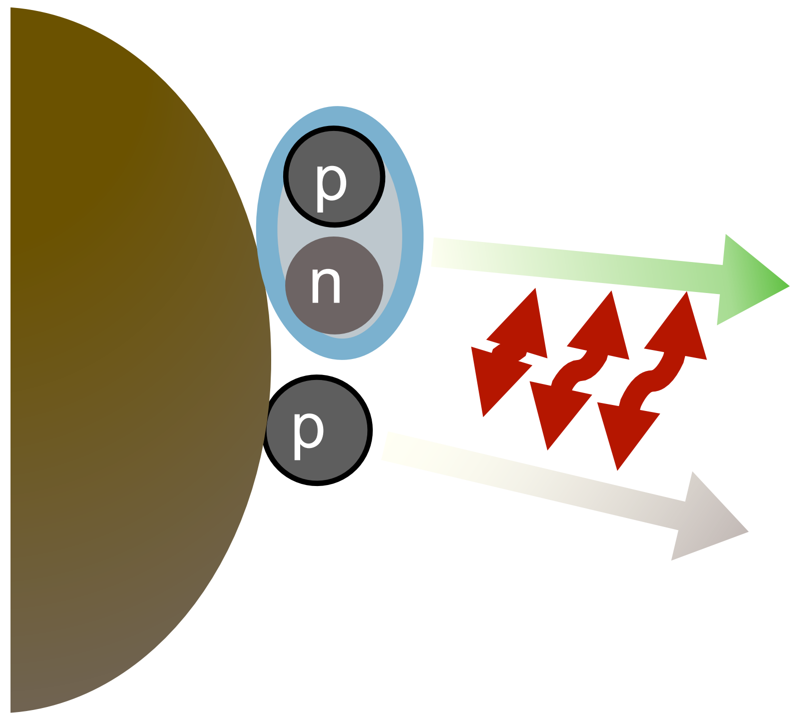
- $\Psi_{m_2,m_1}(x,y)$ three-nucleon wave function asymptotically behaves as p–d state:

$$\Psi_{m_2,m_1}(\boldsymbol{x},\boldsymbol{y}) = \underbrace{\Psi^{(\mathrm{free})}_{m_2,m_1}}_{\text{Asymptotic form}} + \sum_{LSJ}^{J\leq\bar{J}} \sqrt{4\pi} i^L \sqrt{2L+1} e^{i\sigma_L} \underbrace{(1m_2 \tfrac{1}{2} m_1|SJ_z)(L0SJ_z|JJ_z)\widetilde{\Psi}_{LSJJ_z}}_{\text{Strong three-body interaction}} \,.$$

Asymptotic form Strong three-body interaction

$\tilde{\Psi}_{LSJJ_z}$ 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

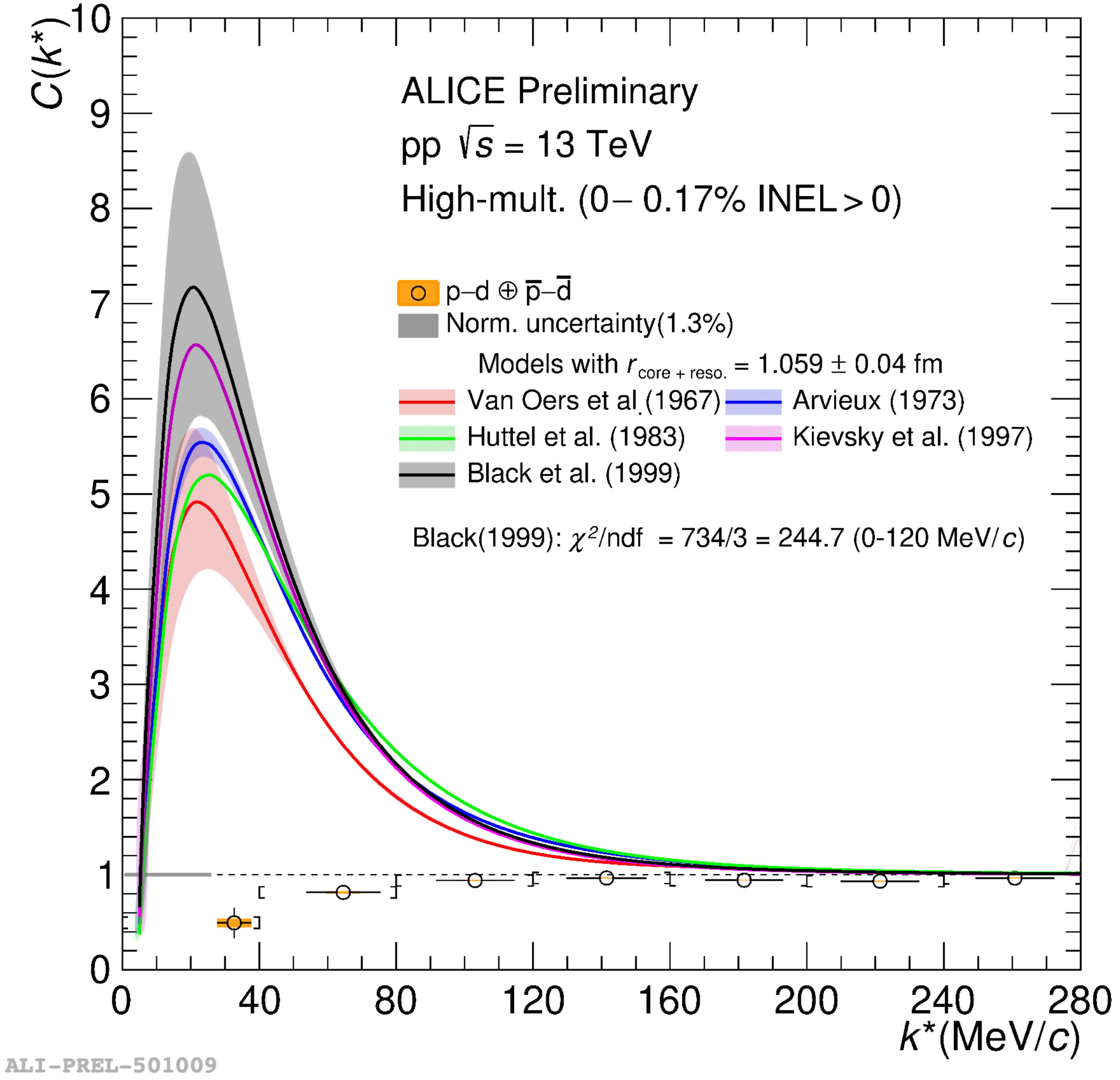
Point-like particle models anchored to scattering experiments

- Van Oers et al (1967)
- Arvieux (1973)
- Huttel et al. (1983)
- Kievsky et al. (1997)
- Black et al. (1999)

$S = 1/2$		$S = 3/2$	
f_0(fm)	d_0(fm)	f_0(fm)	d_0(fm)
$-1.30^{+0.20}_{-0.20}$	—	$-11.40^{+1.20}_{-1.80}$	$2.05^{+0.25}_{-0.25}$
$-2.73^{+0.10}_{-0.10}$	$2.27^{+0.12}_{-0.12}$	$-11.88^{+0.10}_{-0.40}$	$2.63^{+0.01}_{-0.02}$
-4.0	—	-11.1	—
-0.024	—	-13.7	—
$0.13^{+0.04}_{-0.04}$	—	$-14.70^{+2.30}_{-2.30}$	—

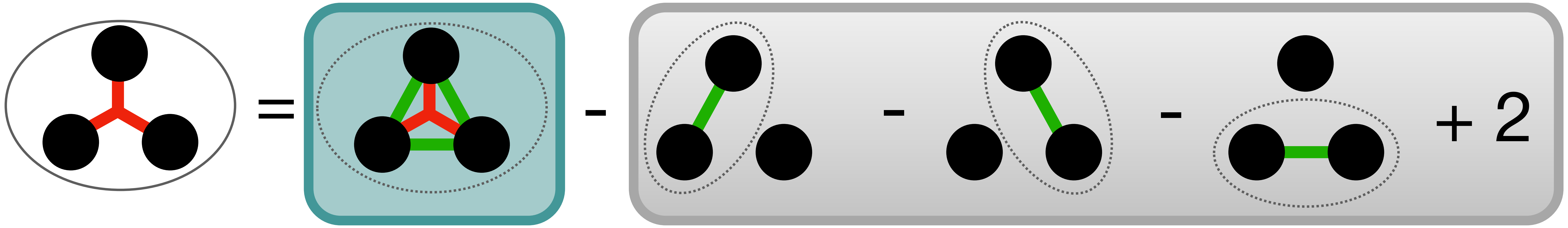
W. T. H. Van Oers, & K. W. Brockman Jr, NPA 561 (1967);
J. Arvieux et al., NPA 221 (1973); E. Huttel et al., NPA 406 (1983);
A. Kievsky et al., PLB 406 (1997); T. C. Black et al., PLB 471 (1999);

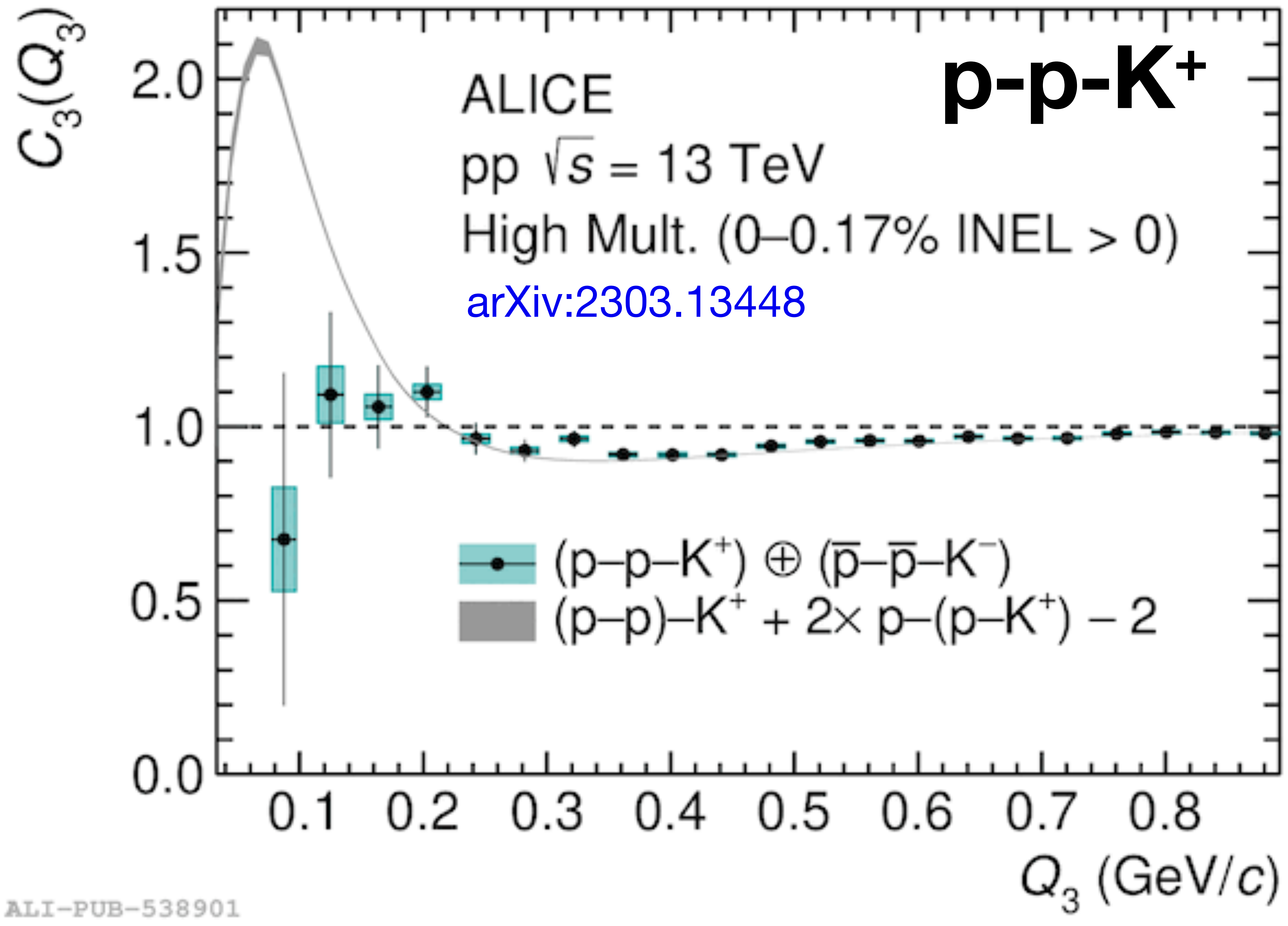
Lednický, R. Phys. Part. Nuclei 40, 307–352 (2009)

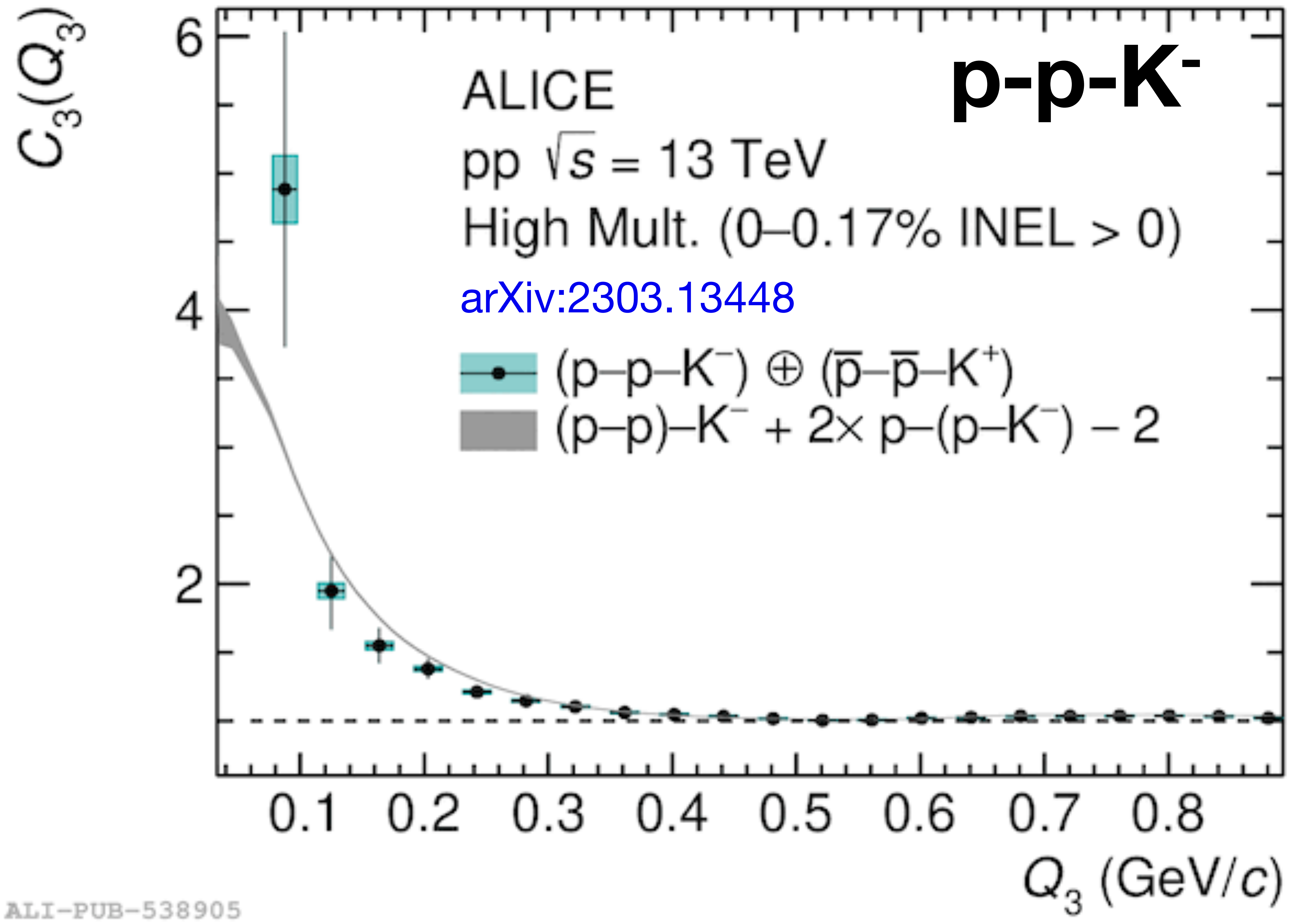


Point-like particle description doesn't work for p-

p-p-K⁺ and p-p-K⁻ correlation functions

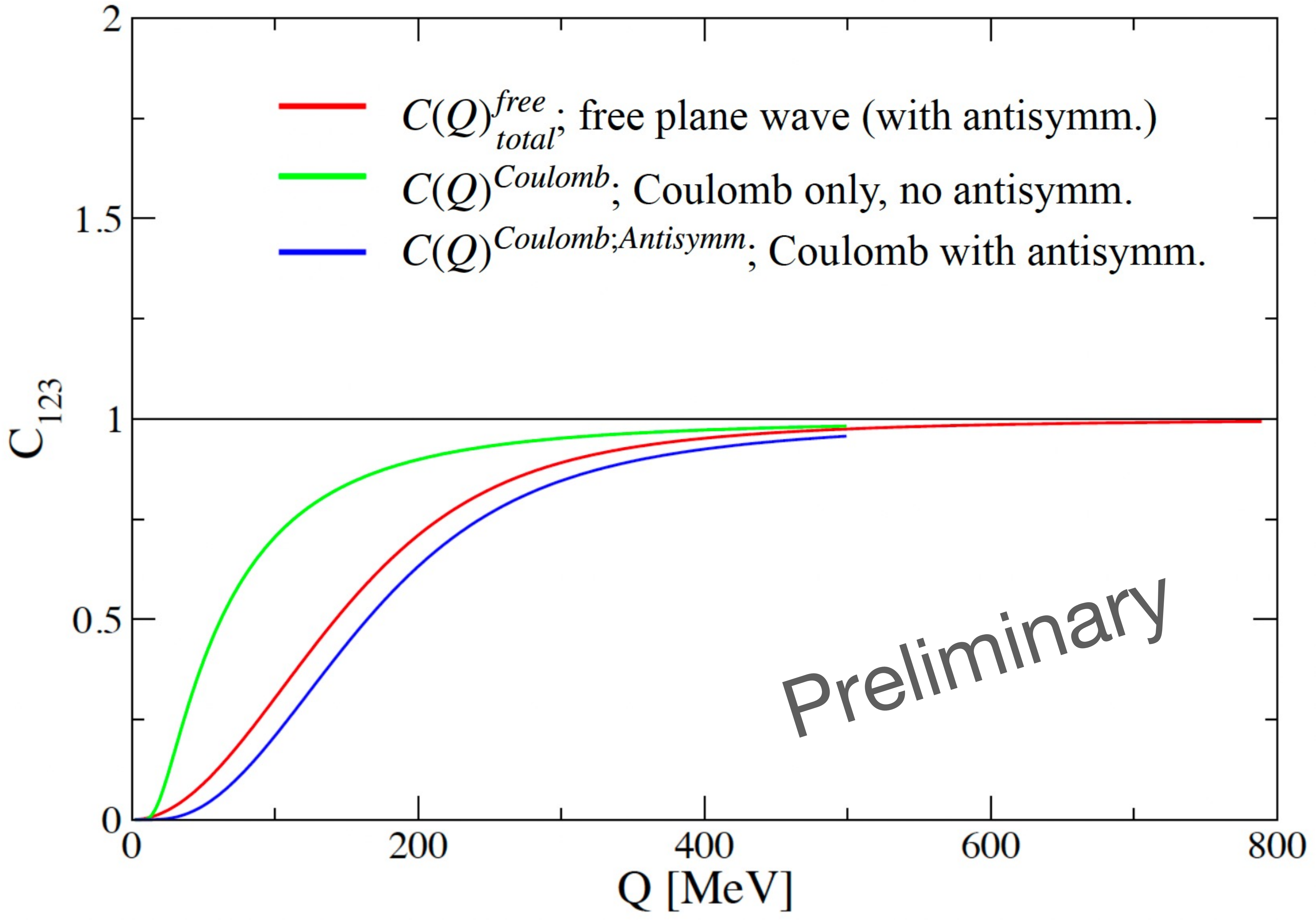


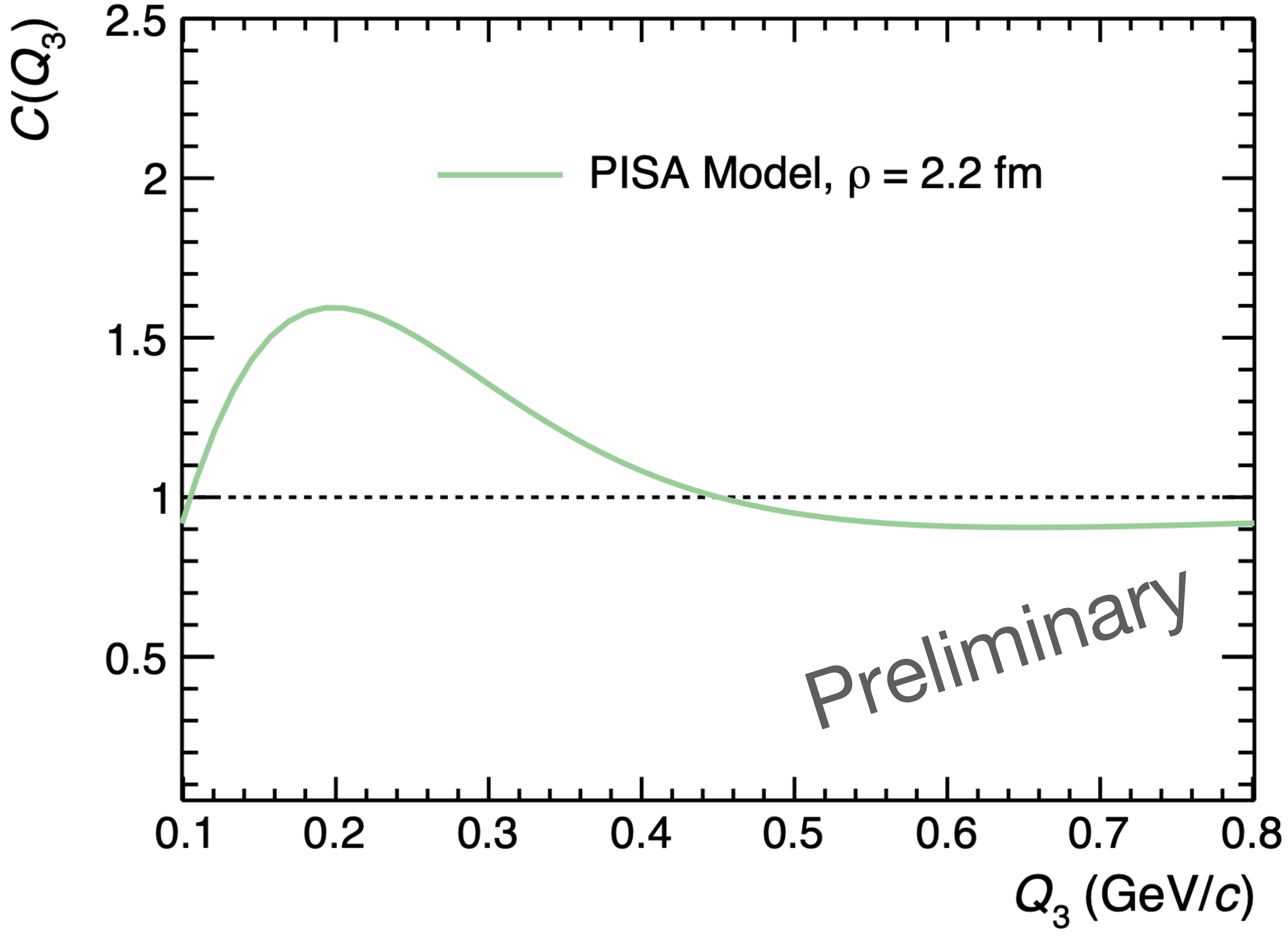




p-p-p calculations (ongoing)

- Calculations performed by Alejandro Kievsky





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

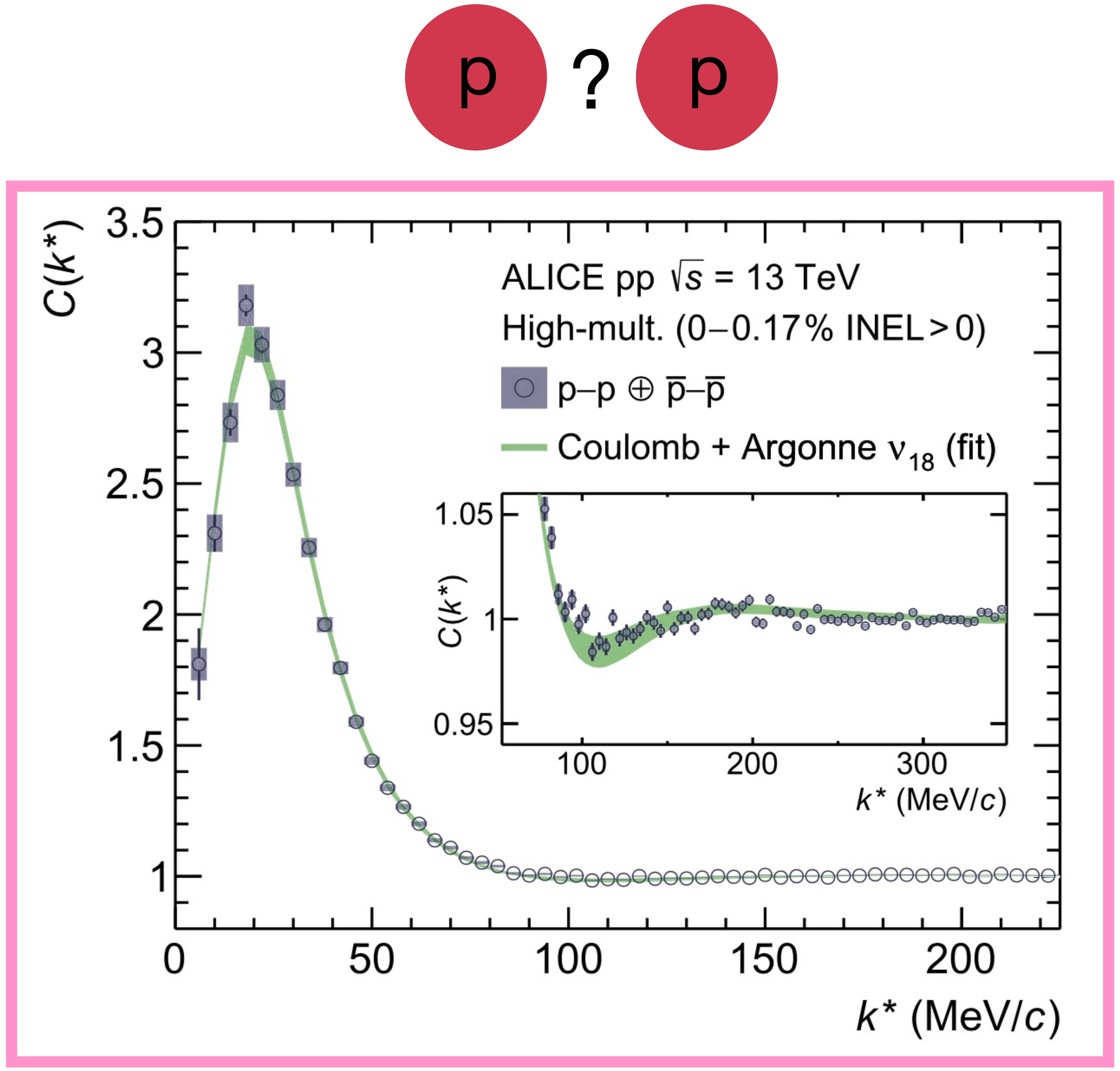
$$C(Q_3) = \iiint_{Q_3=\text{constant}} C([\mathbf{p}_i, \mathbf{p}_j], \mathbf{p}_k) d^3\mathbf{p}_i d^3\mathbf{p}_j d^3\mathbf{p}_k = \int C_2(k^*_{ij}) W_{ij}(k^*_{ij}, Q_3) dk^*_{ij}$$

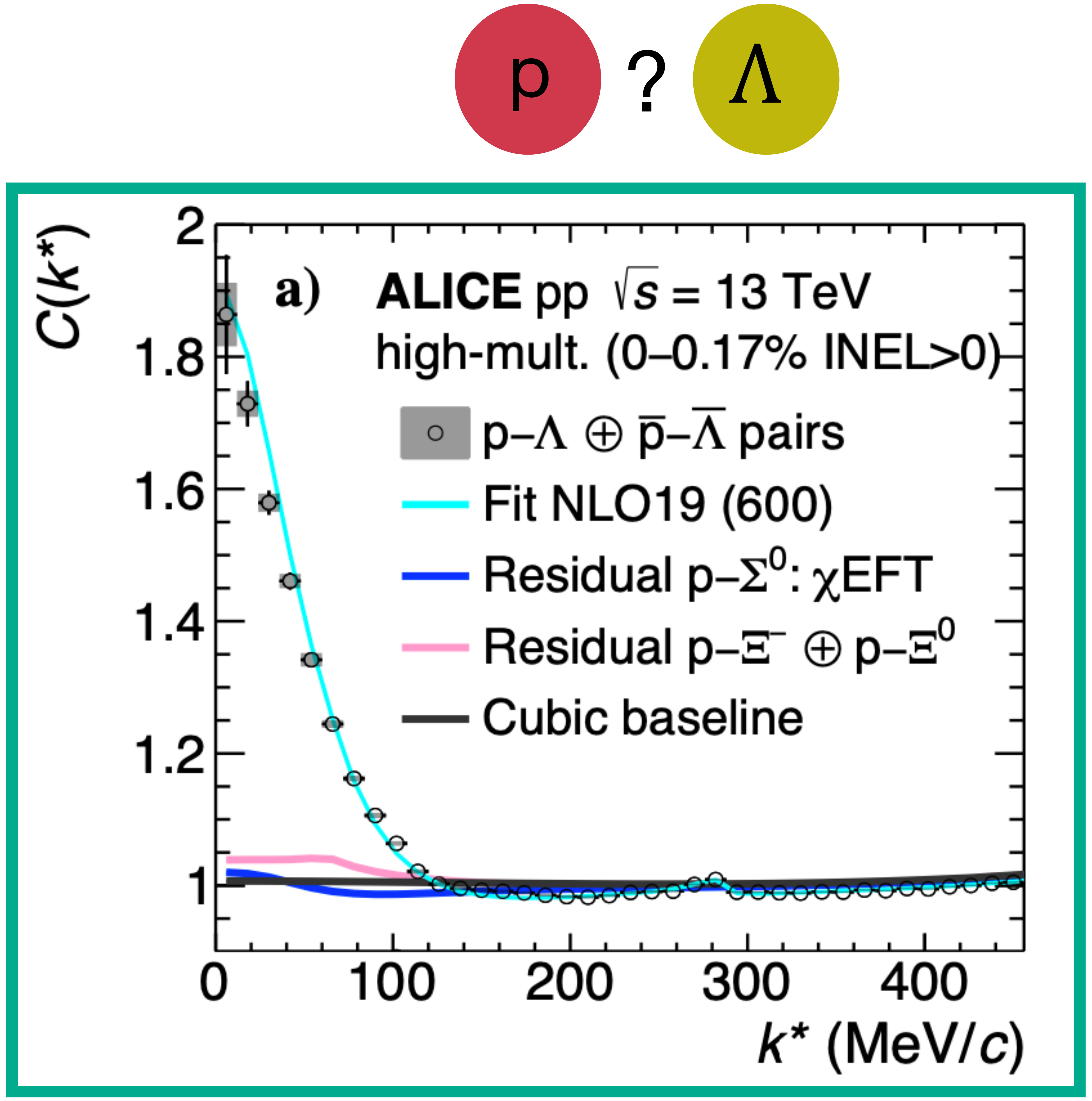
$$W_{ij}(k^*_{ij}, Q_3) = \frac{16(\alpha\gamma - \beta^2)^{3/2} {k^*_{ij}}^2}{\pi\gamma^2 {Q_3}^4} \sqrt{\gamma {Q_3}^2 - (\alpha\gamma - \beta^2){k^*_{ij}}^2}$$

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

Two-body measurements

- Many different two-body interactions measured successfully!



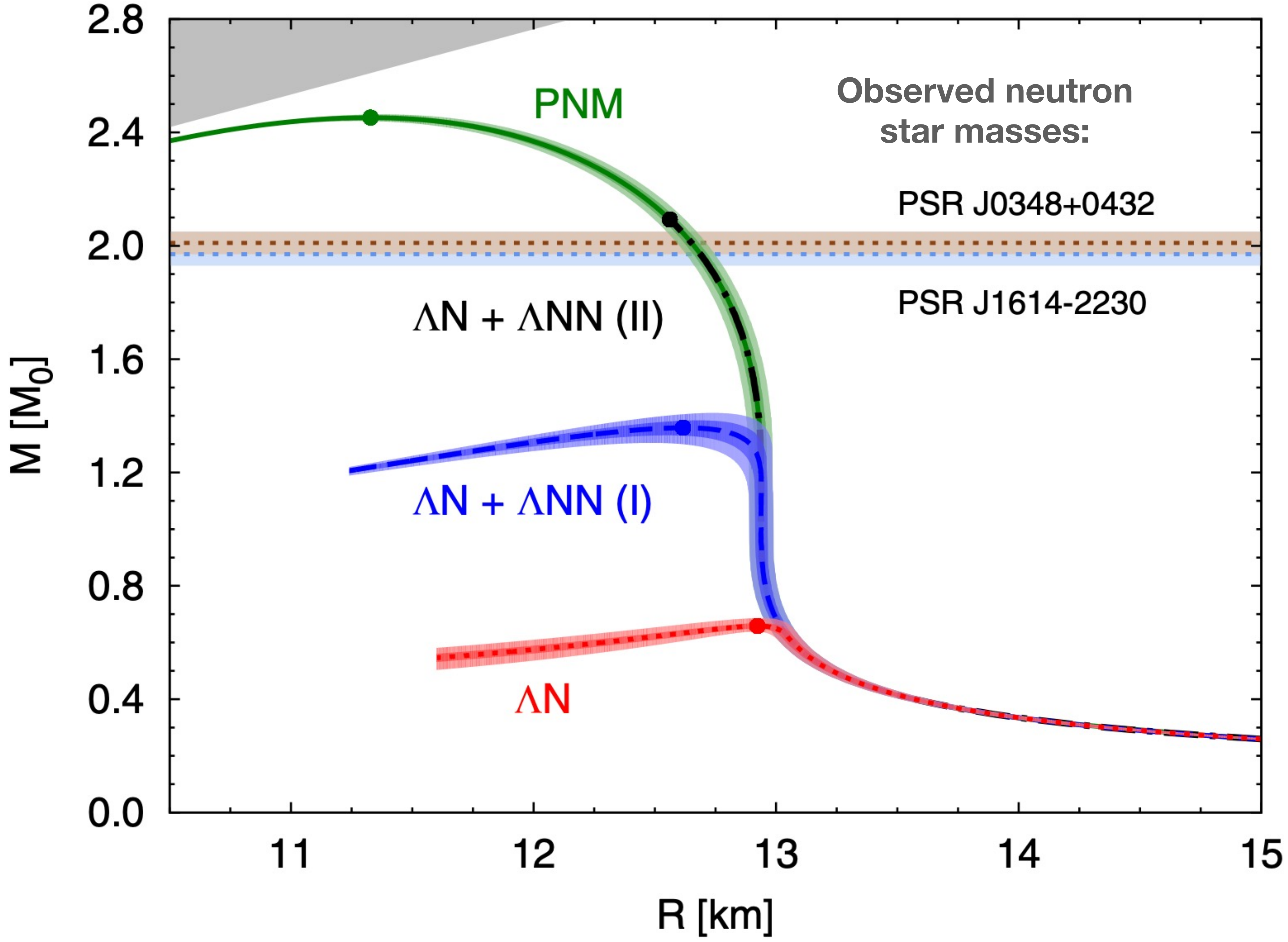


TUM Group:
EPJC 78 (2018) 394
arXiv:2107.10227

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

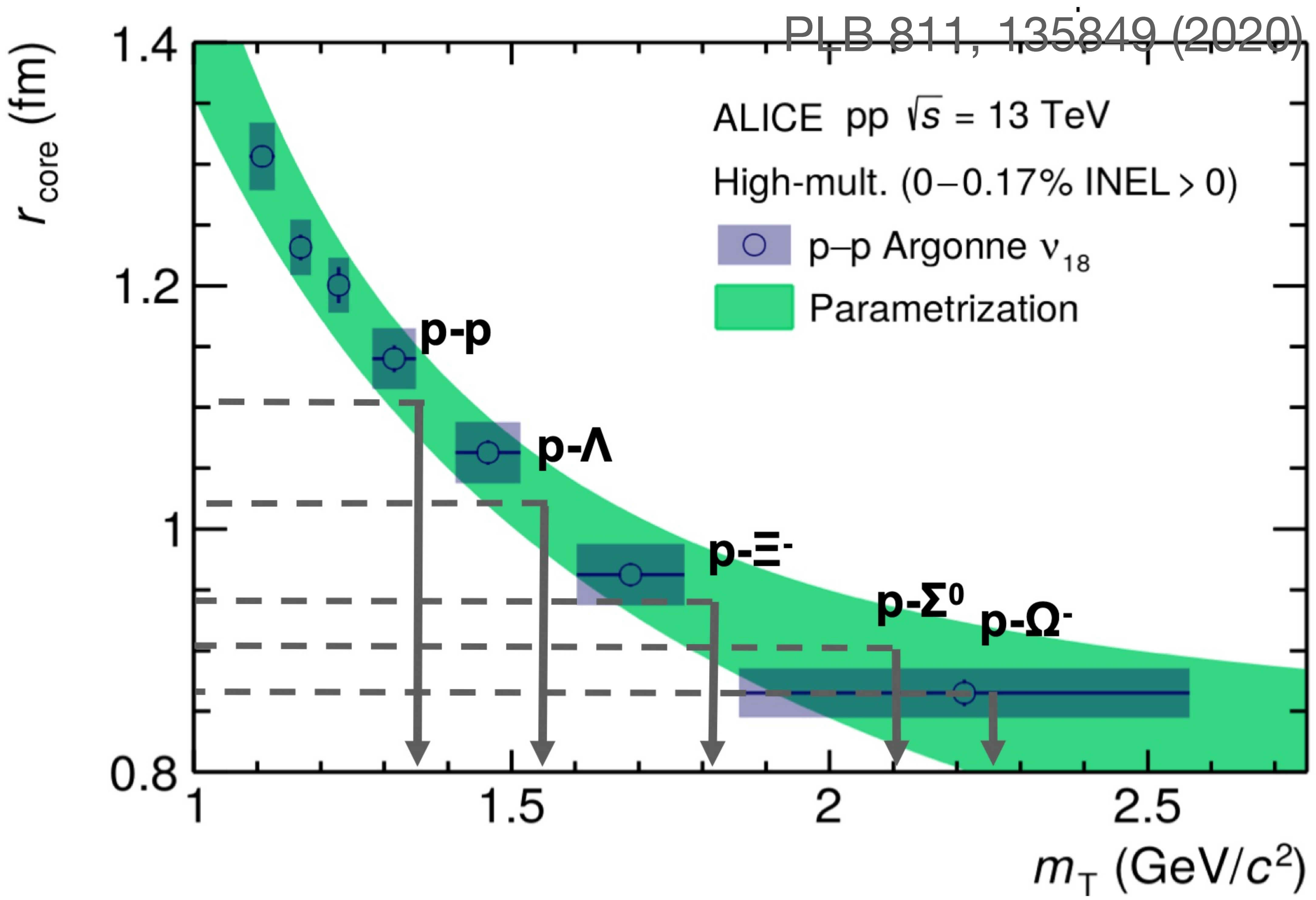
How to constrain three-body forces?

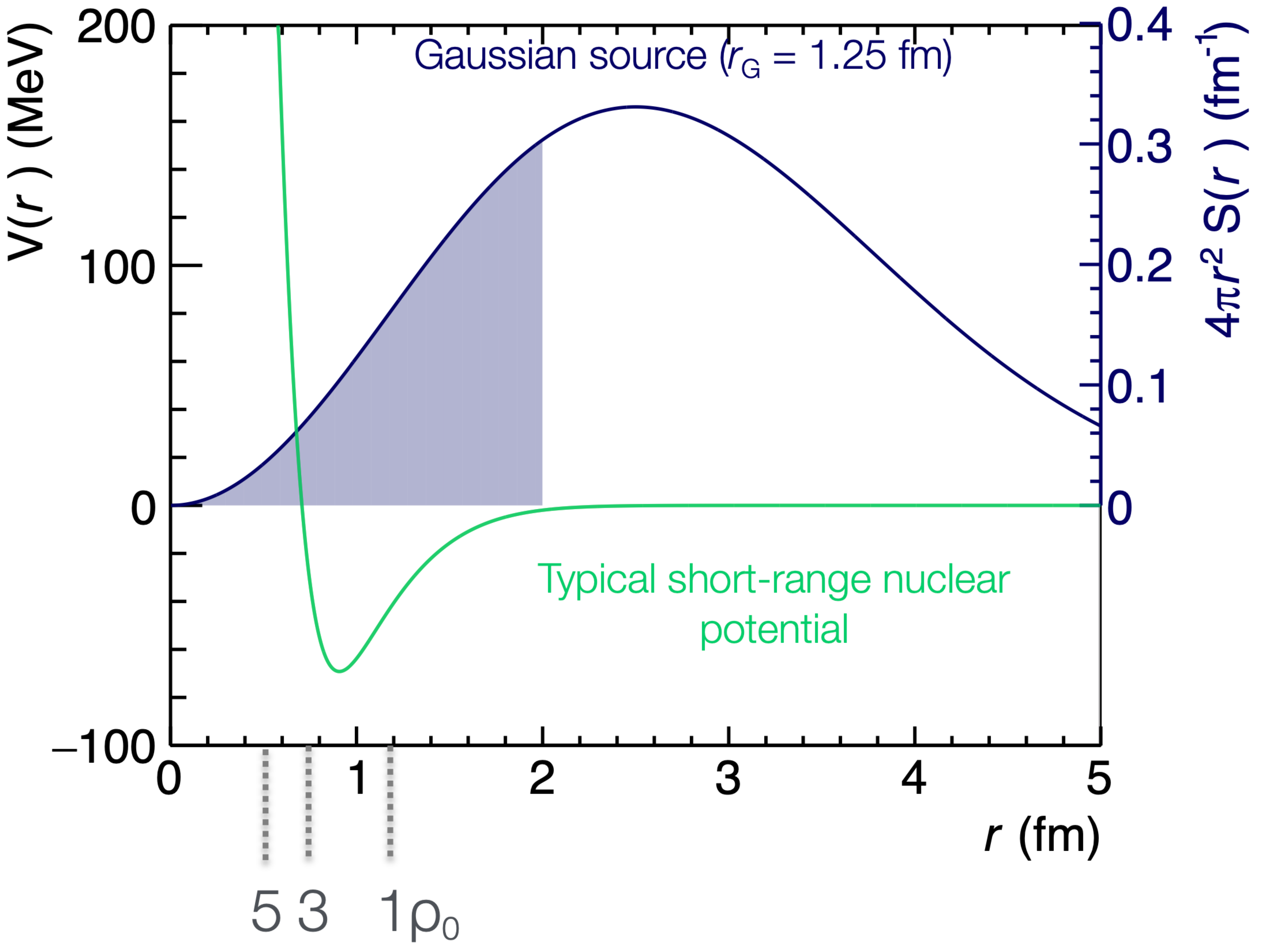
- Models are fitted to reproduce measured (hyper)nuclei properties
  - Access only to nuclear densities
  - Strongly dependent on the assumed two-body and many-body interactions
  - Different parametrisations of three-body forces describe better different nuclei



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

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



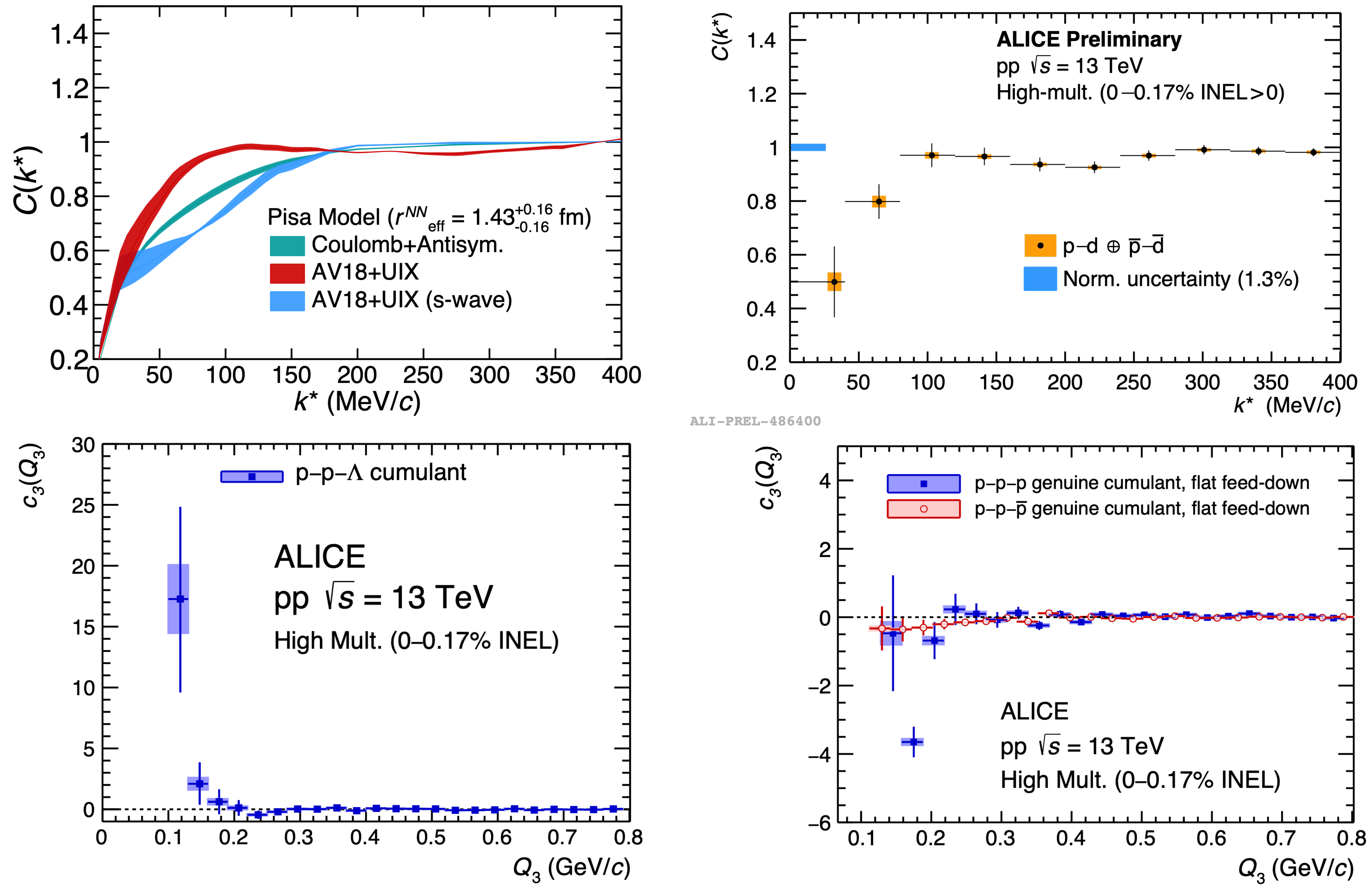


How to access three-body systems?

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!

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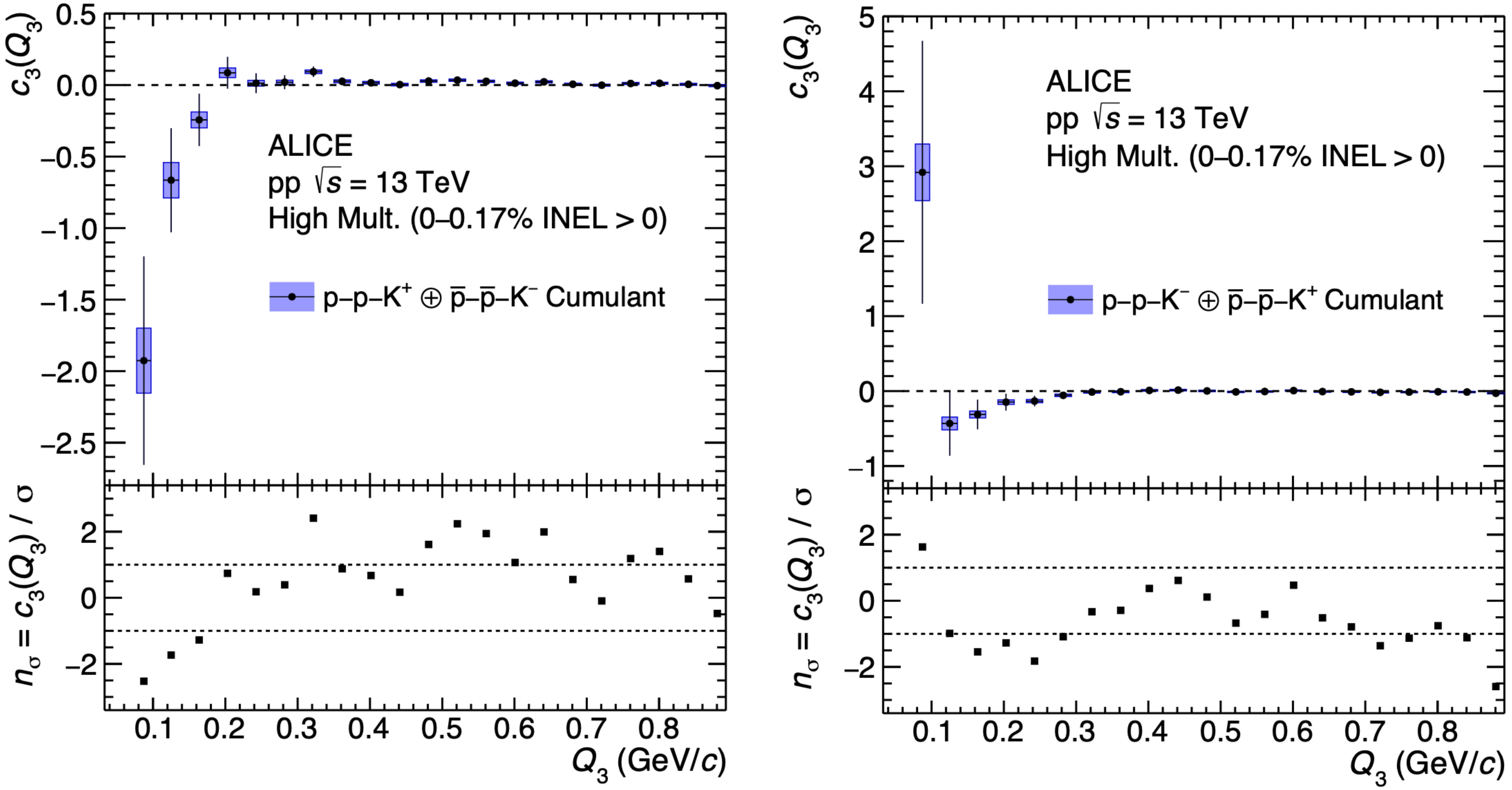
- **p-p-K⁺** and **p-p-K⁻**: cumulants compatible with 0, no evidence of a genuine three-body force

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

New paper: arXiv:2303.13448



Conclusions

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

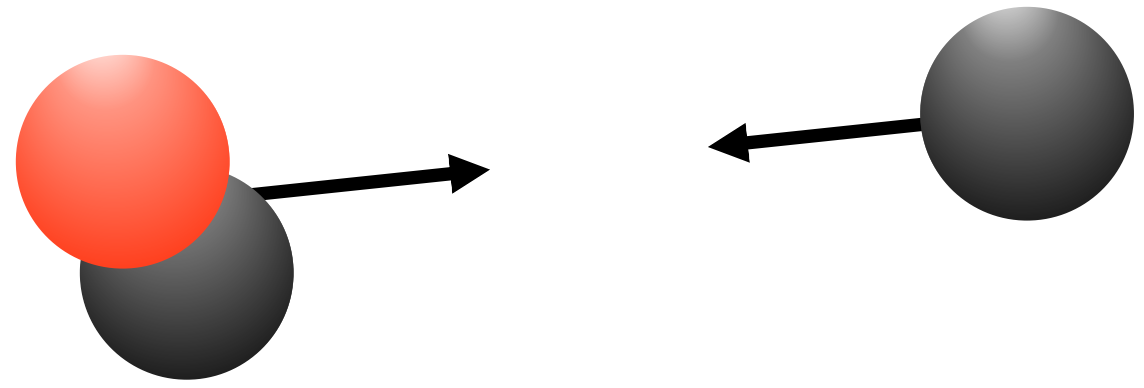
Valentina Mantovani Sarti 5 Jun 2023, 14:30
Dimitar Mihaylov 5 Jun 2023, 17:40
Wioleta Rzęsa 7 Jun 2023, 14:24
Marcel Lesch 8 Jun 2023, 15:12
Ramona Lea 8 Jun 2023, 15:42

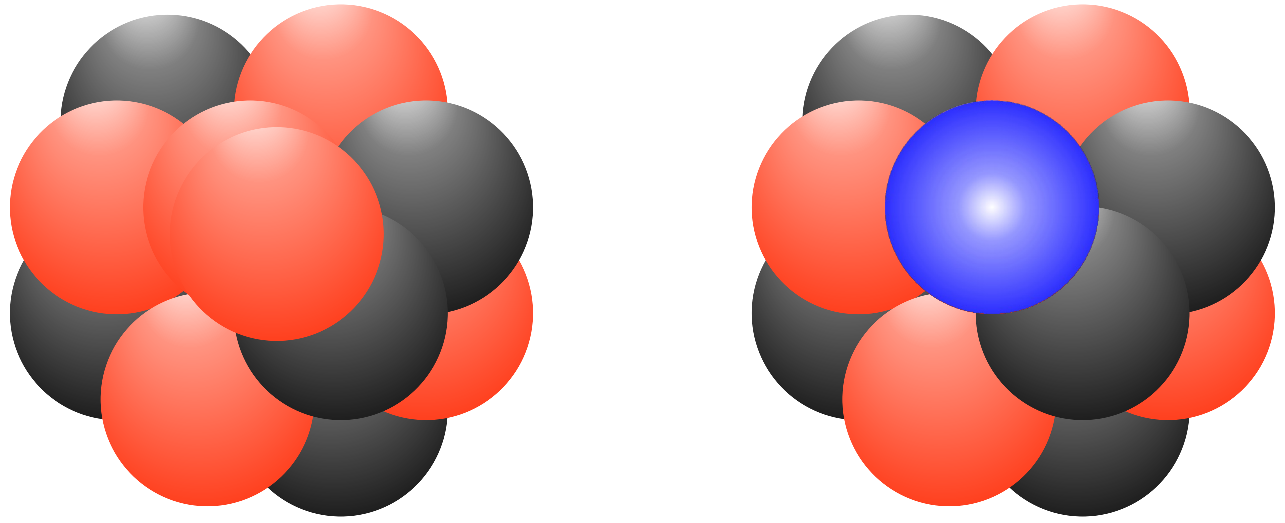
Many-body systems

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

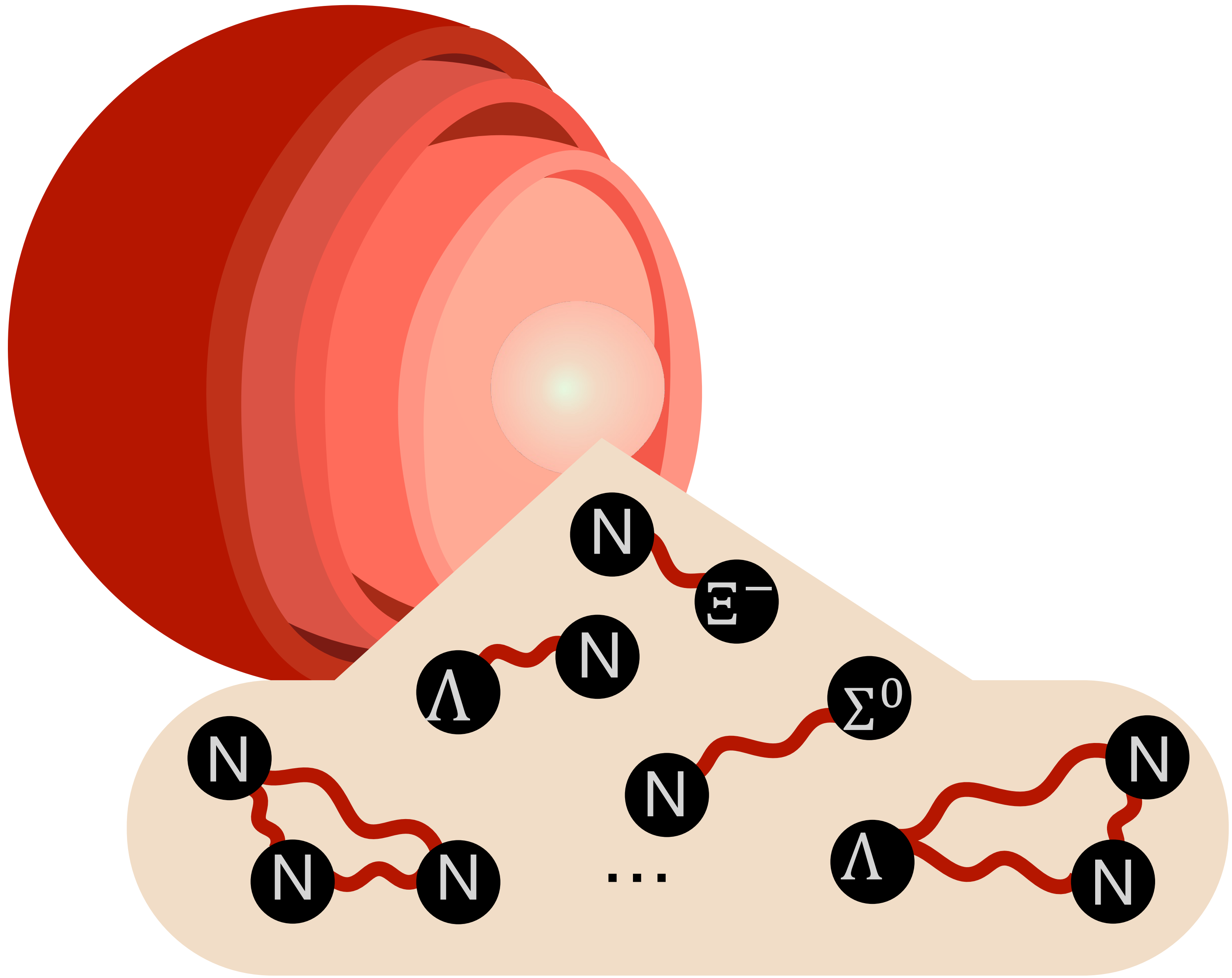
L.E. Marcucci et al., Front. Phys. 8, 69 (2020)

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





ρ


N
Ξ⁻
Λ
N
Σ⁰
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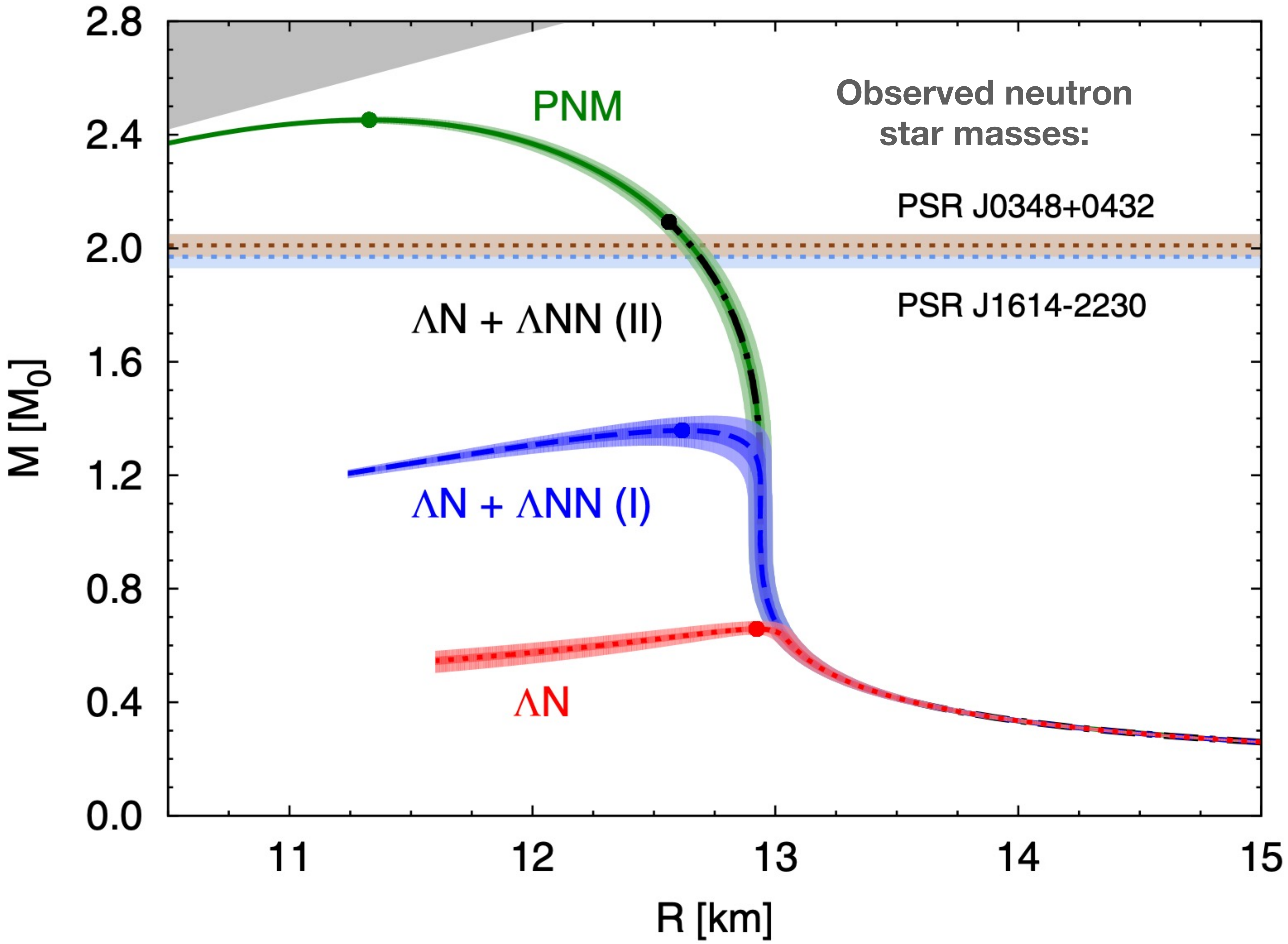
N
N
N
N
Λ
N
N
...

Neutron stars and three-body forces

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

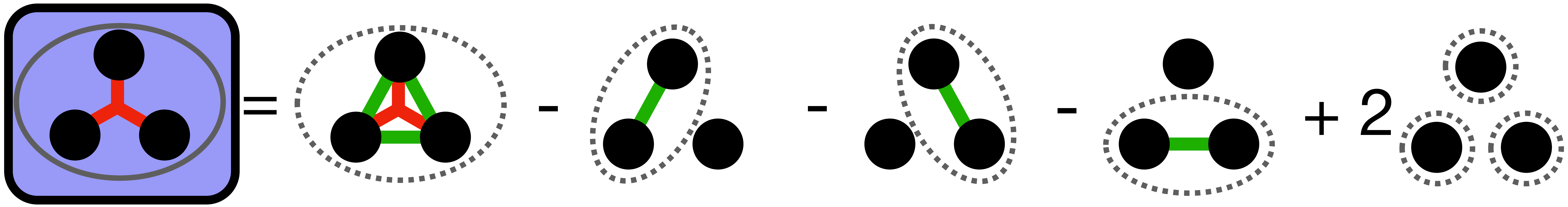
- Large difference in the equation of state at large densities

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



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

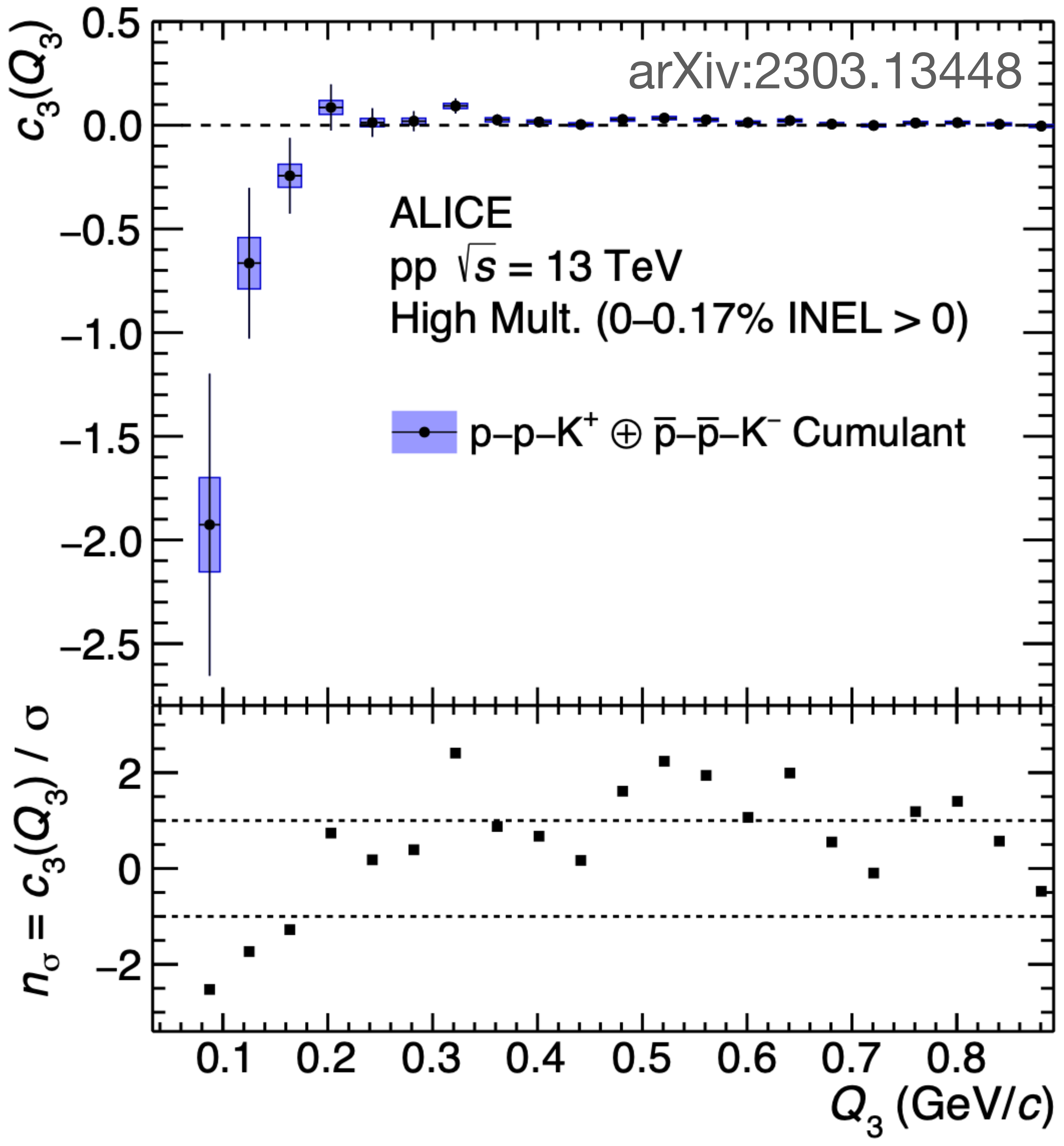
p-p-K⁺ cumulant



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

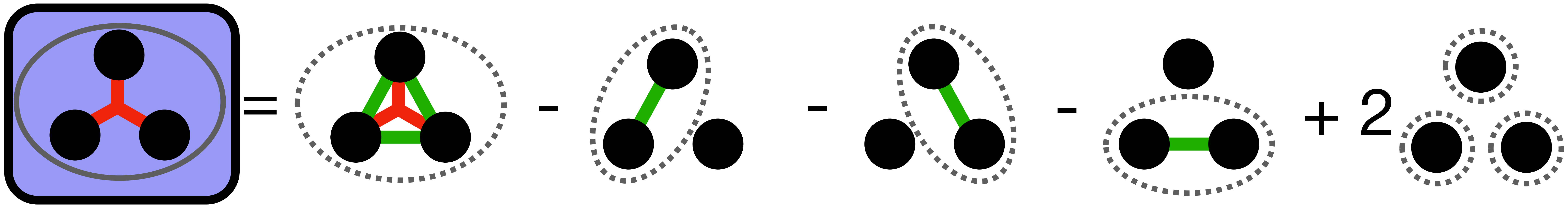
Statistical significance:

n_σ= 2.3 for Q_3 < 0.4 GeV/c



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

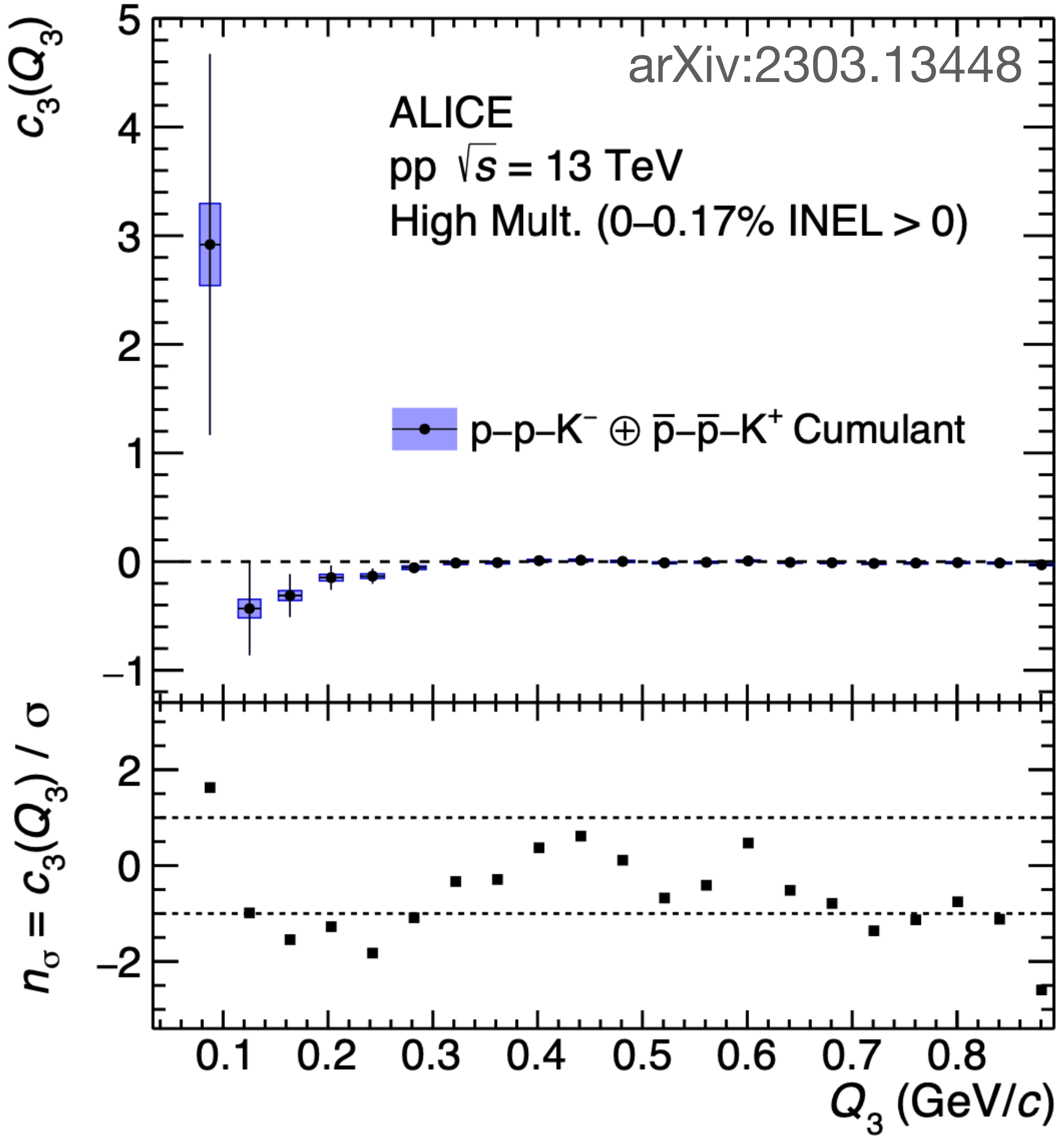
p-p-K$^-$ cumulant



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!

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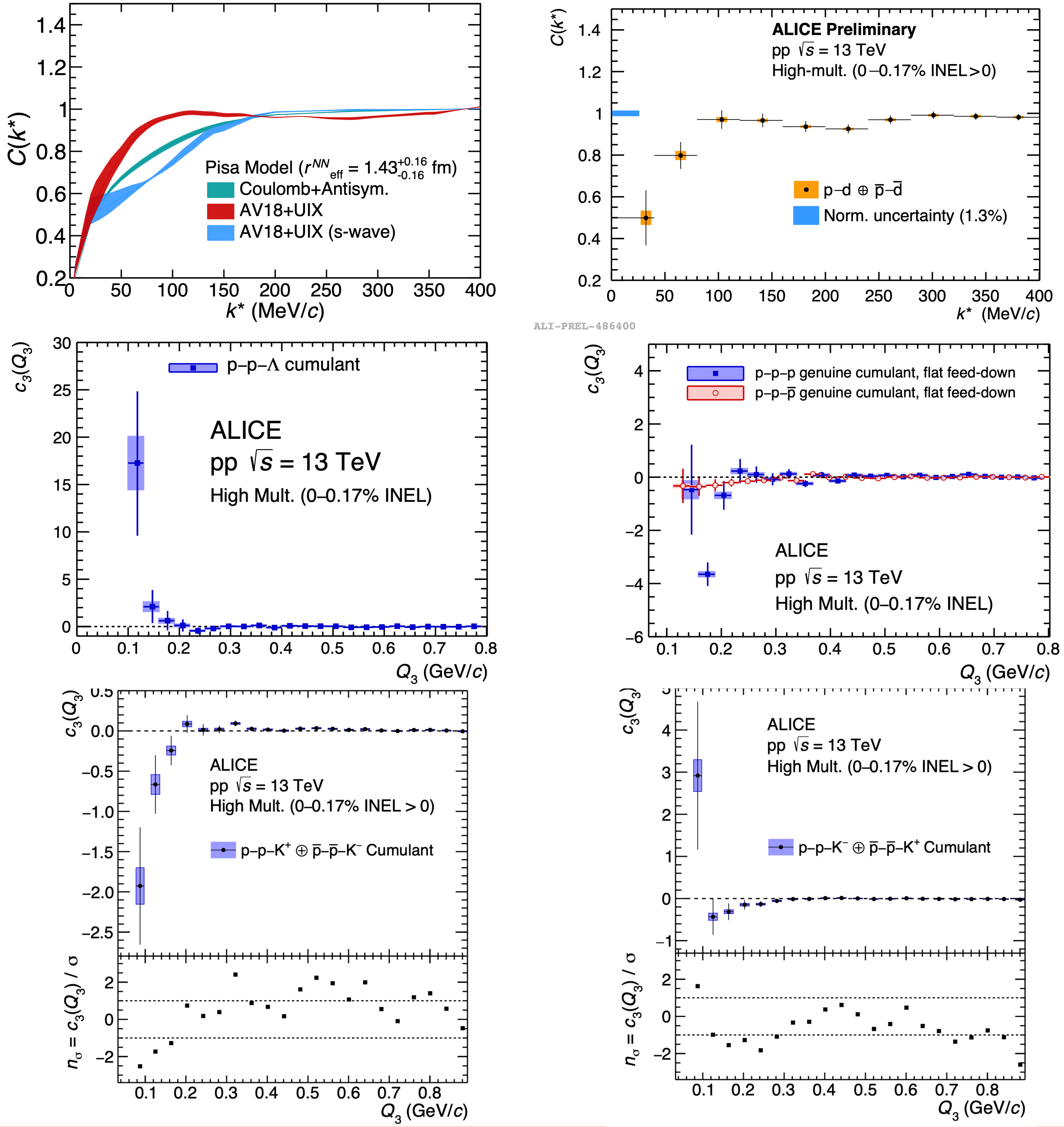

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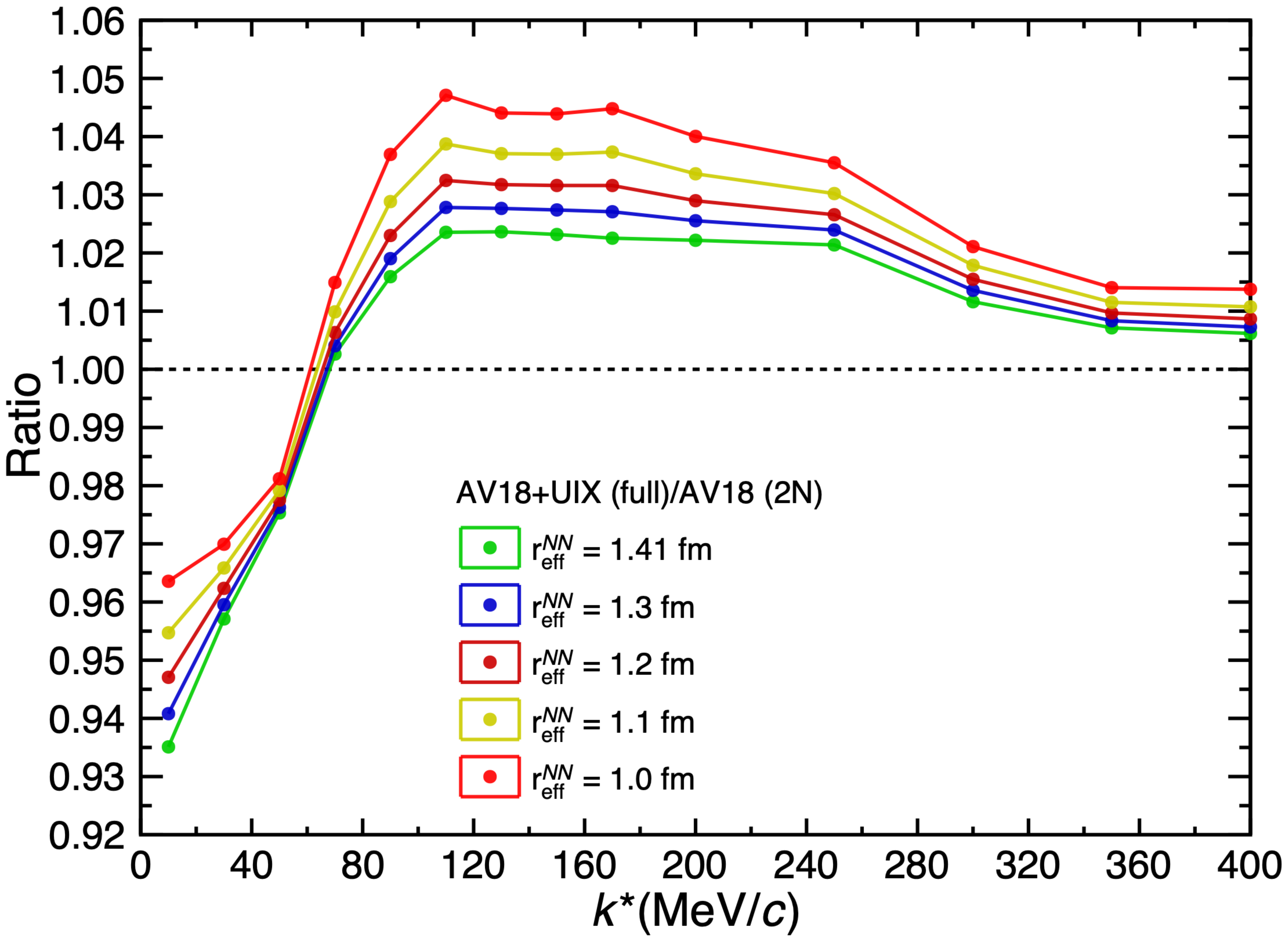
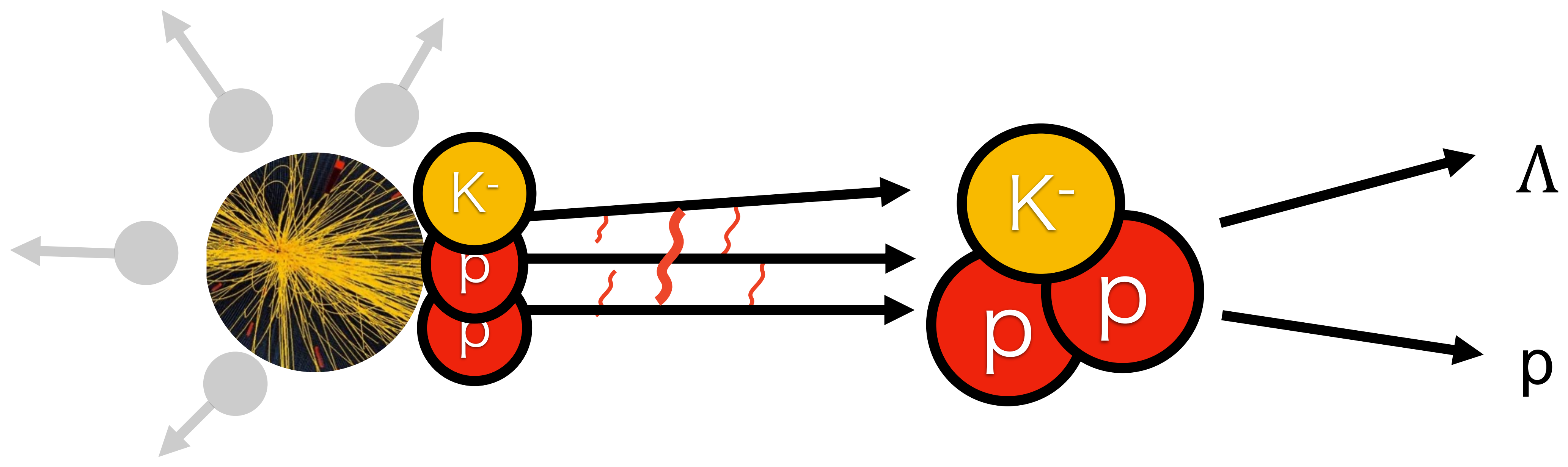
Effect of genuine three body forces



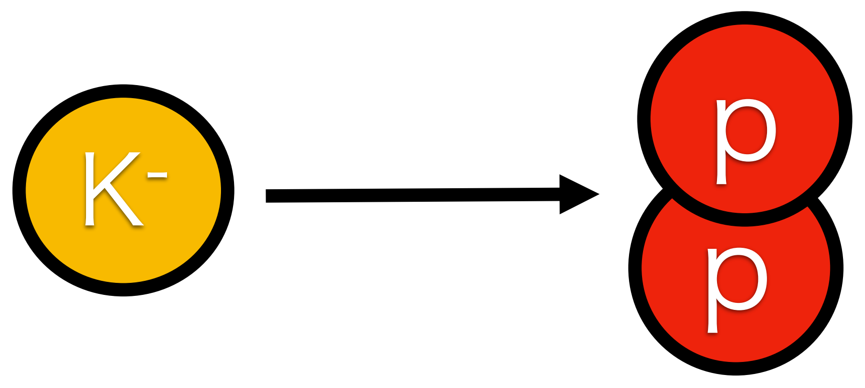
Current precision and radius size does not allow sensitivity to genuine three body forces yet
More differential measurement (mT scaling!!) are needed

p-p-K^- cumulant

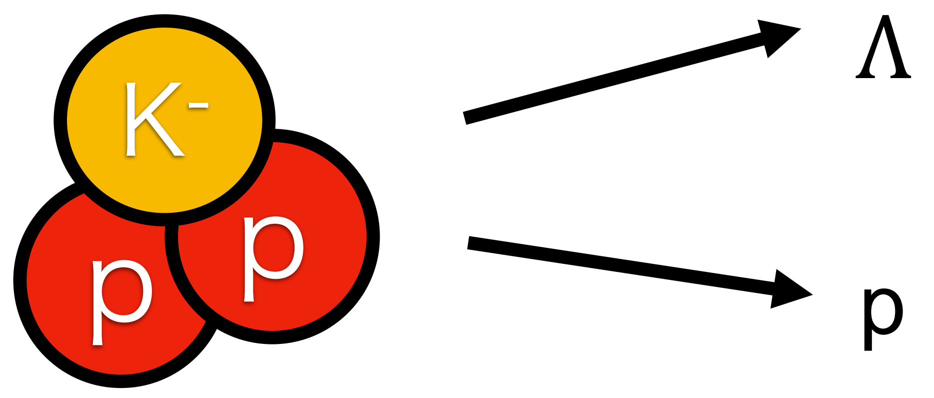


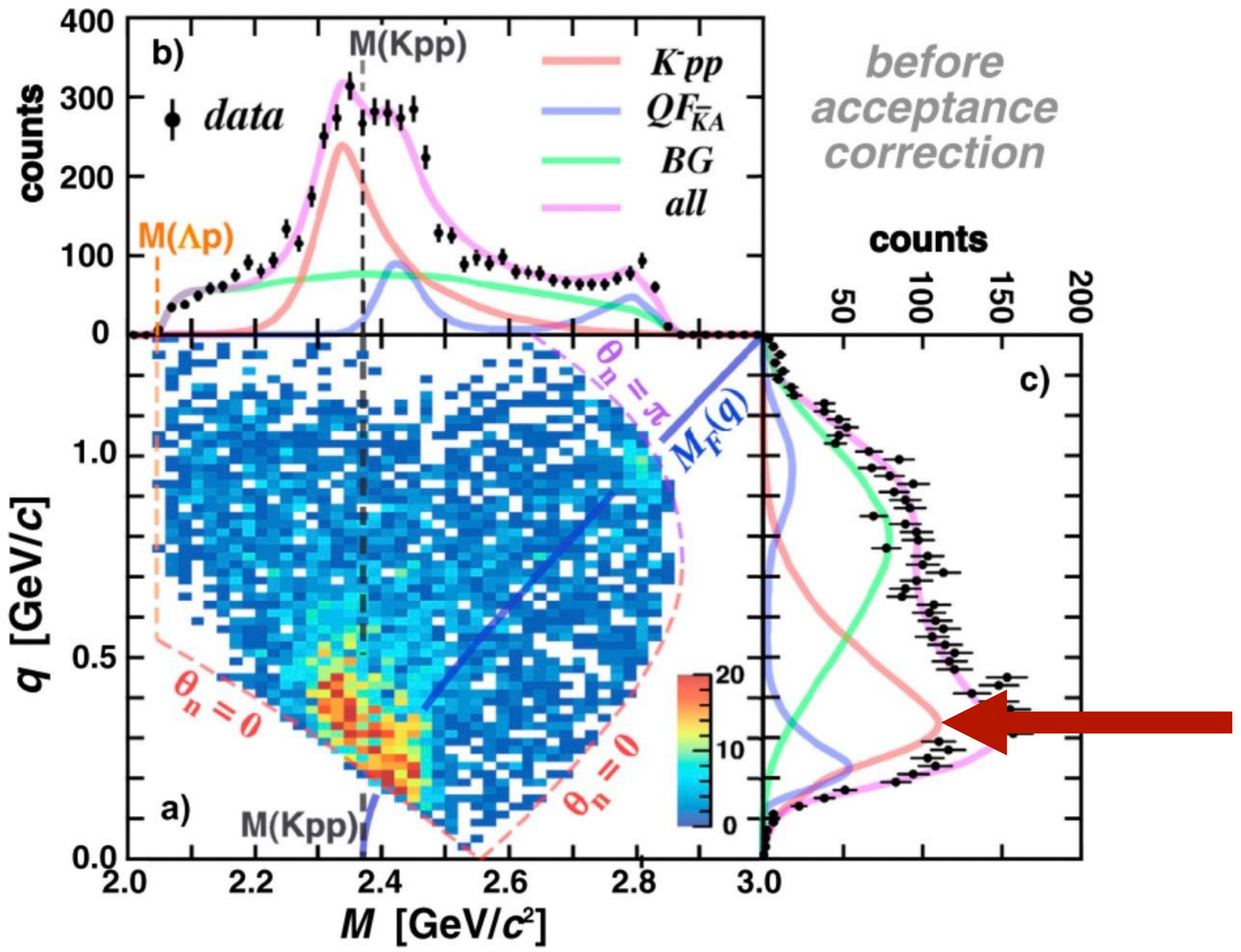
Which is the Q_3 of the p-p-K^- triplets?

If we believe in the measurement by E15, the bound state is compact (R ~ 0.6 fm) and the transfer momentum by the K^- on the two rest protons is q_X ~ 0.3 GeV/c.



Transfer momentum
$q_X = p_K$ ~ 0.3 GeV/c





Q_3 is Lorentz-invariant —> we can choose the rest frame of the two-protons

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

$$q_{ij}^{\mu} = 2\left(\frac{m_j E_i}{m_i + m_j} - \frac{m_i E_j}{m_i + m_j}, \frac{m_j}{m_i + m_j}\mathbf{p}_i - \frac{m_i}{m_i + m_j}\mathbf{p}_j\right)$$