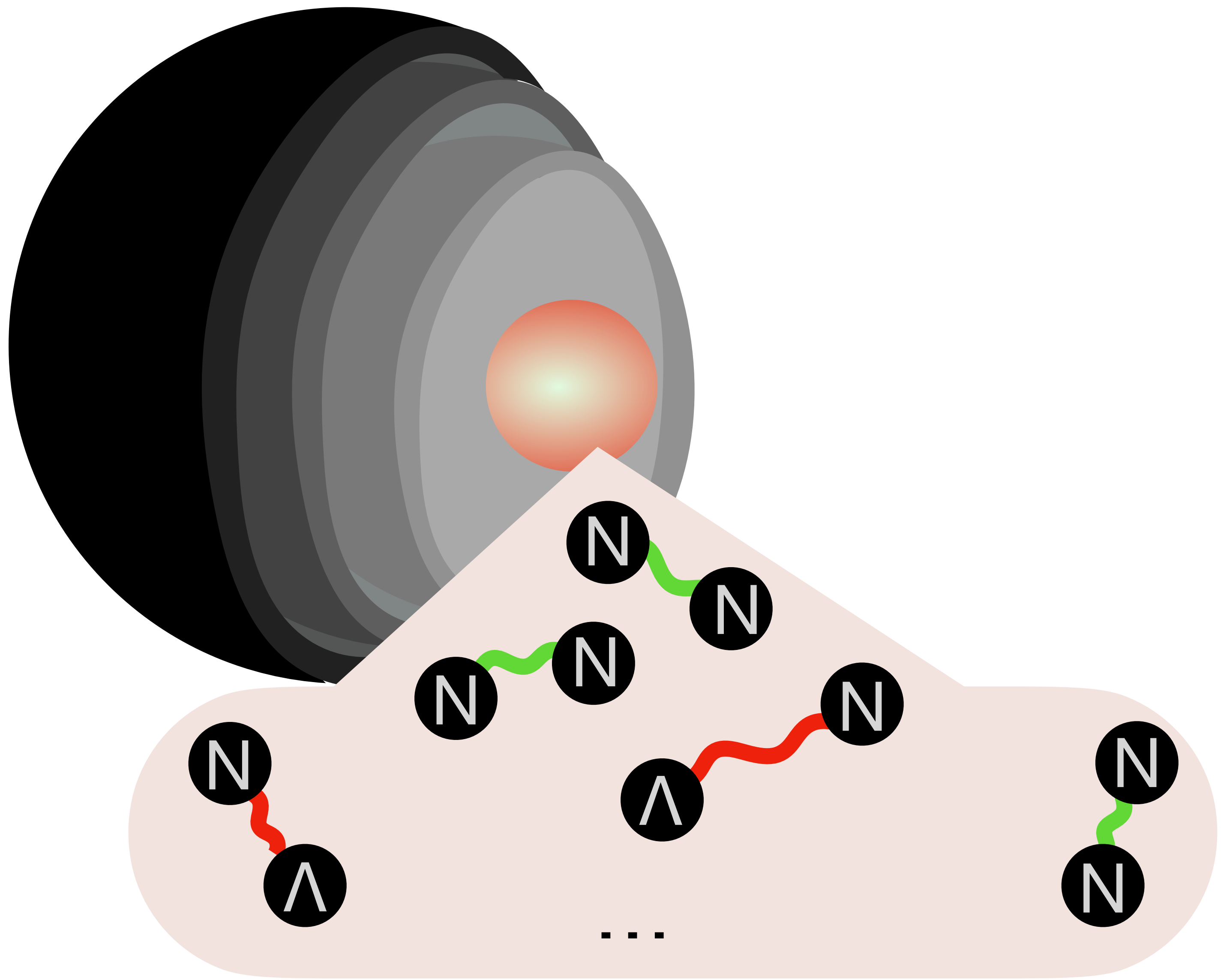
# Shedding light on strong interactions in three-baryon systems with ALICE Run 3 data

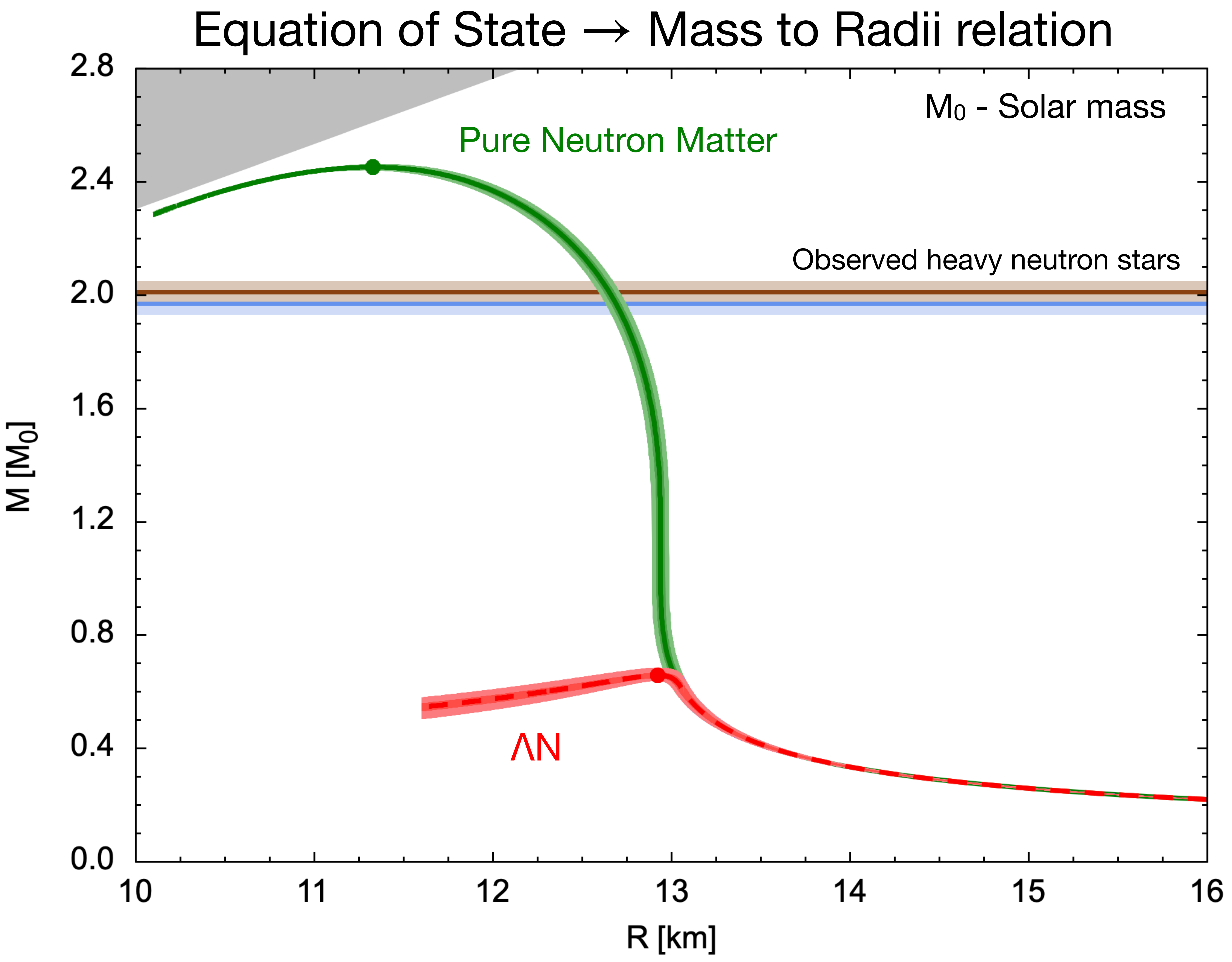
Laura Šerkšnytė on behalf of the ALICE Collaboration
Technical University of Munich

SQM 2024

# Motivation

- Neutron star density > $2\rho_0$
- Hyperons might appear in the system

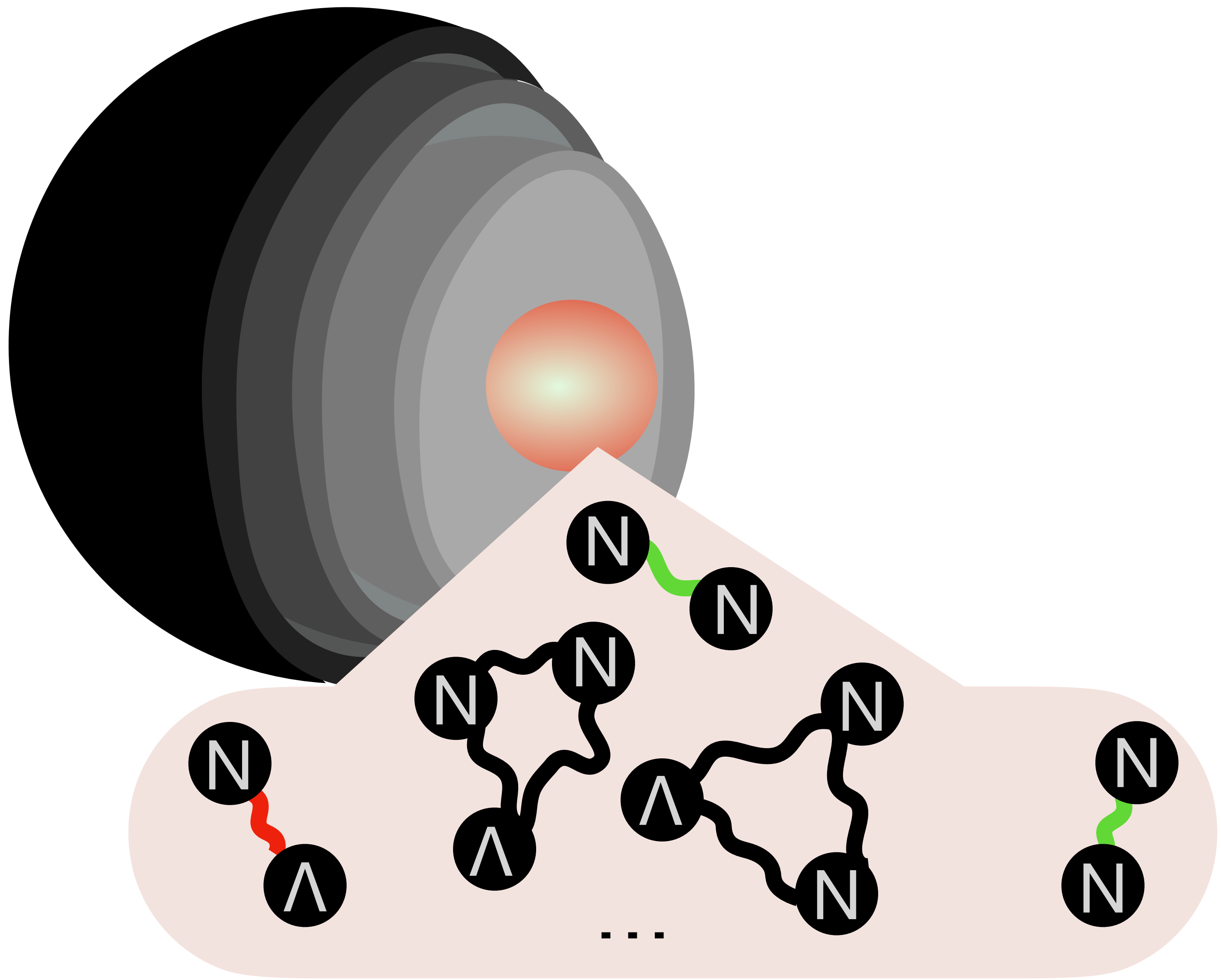


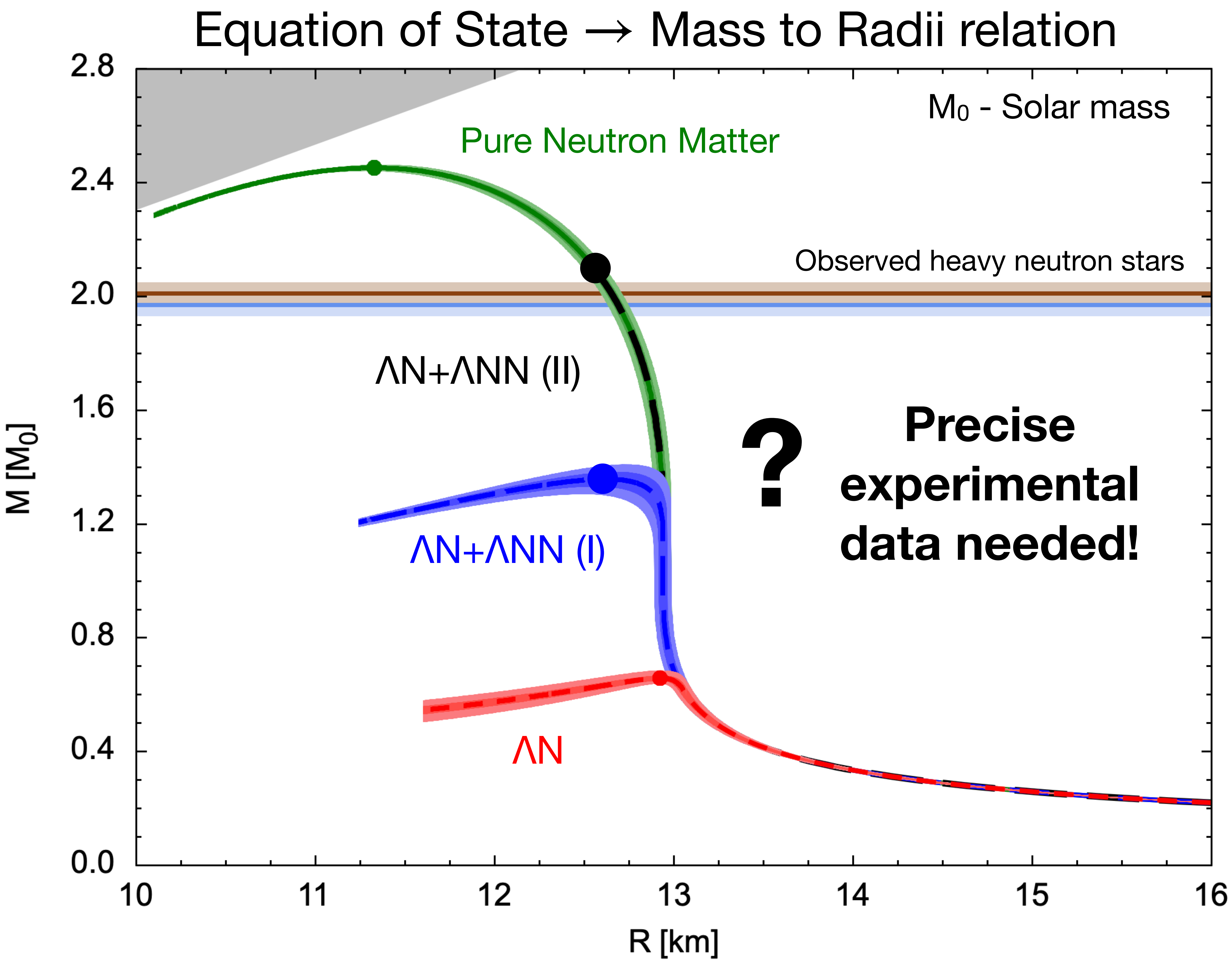

Adapted from D. Lonardoni et al., PRL 114, 092301 (2015)

# Motivation

- Neutron star density > $2\rho_0$
- Hyperons might appear in the system
- Three-body forces necessary

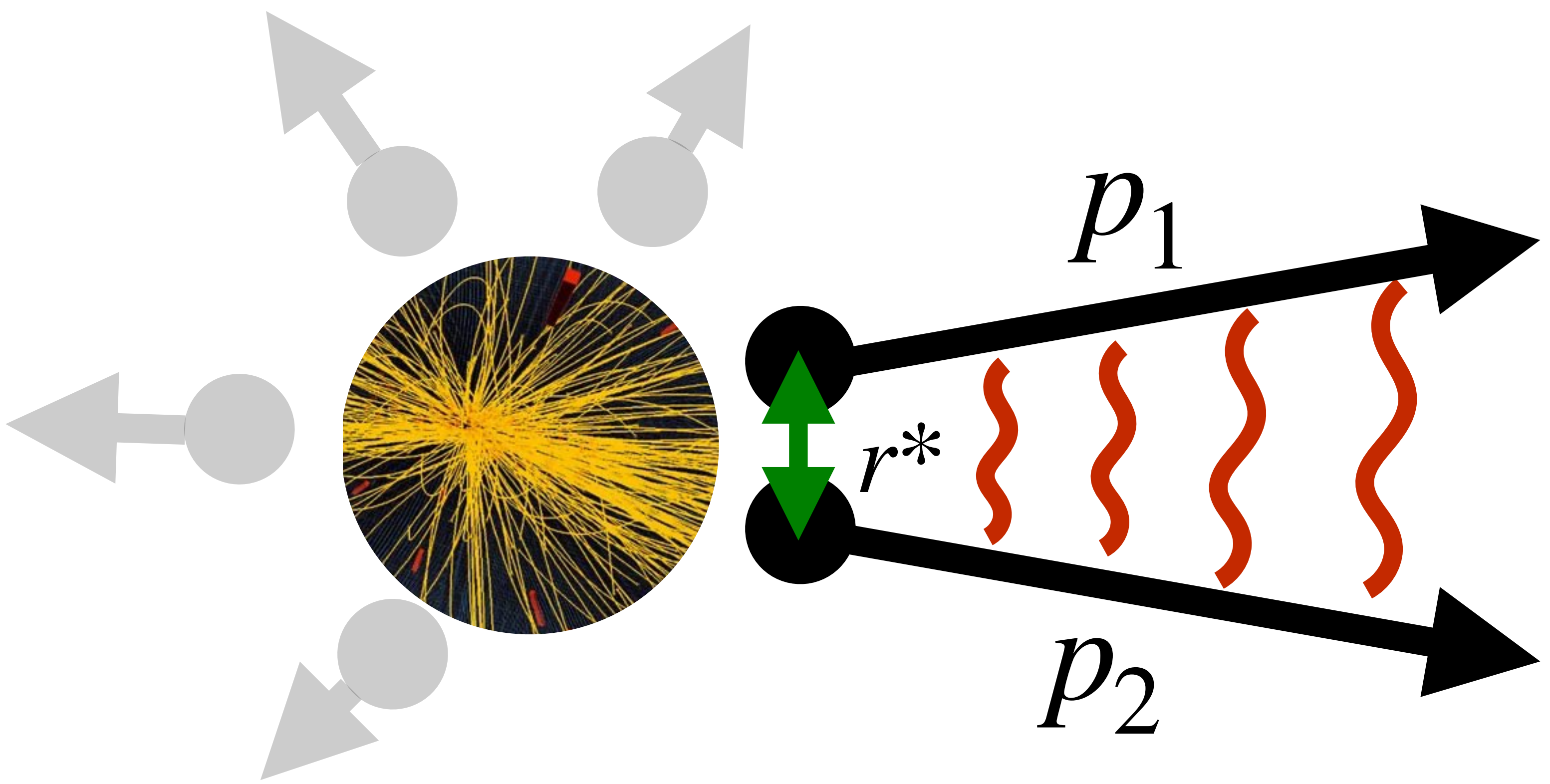



Novel way to access three-hadron systems: femtoscopy

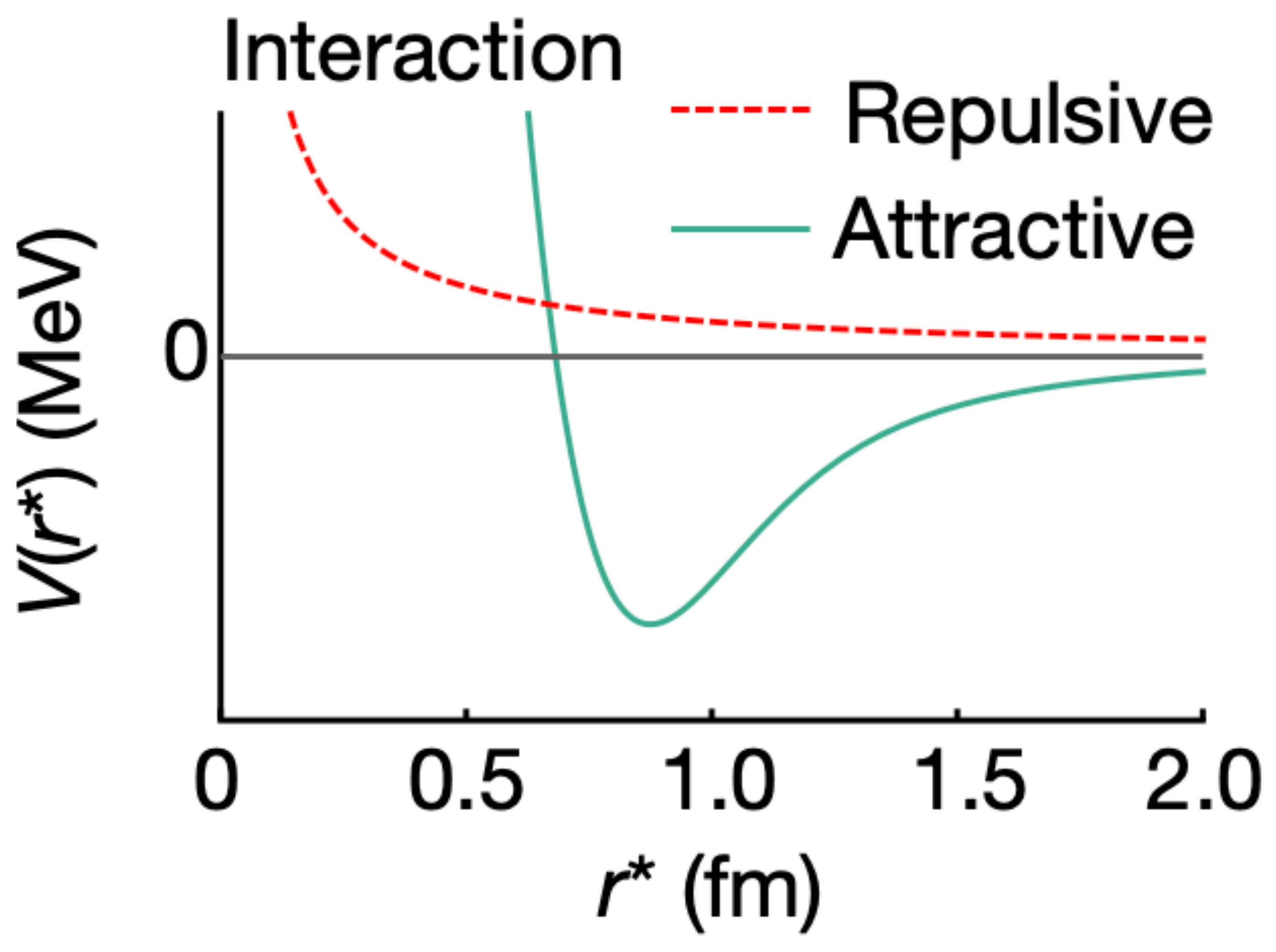



Adapted from D. Lonardoni et al., PRL 114, 092301 (2015)

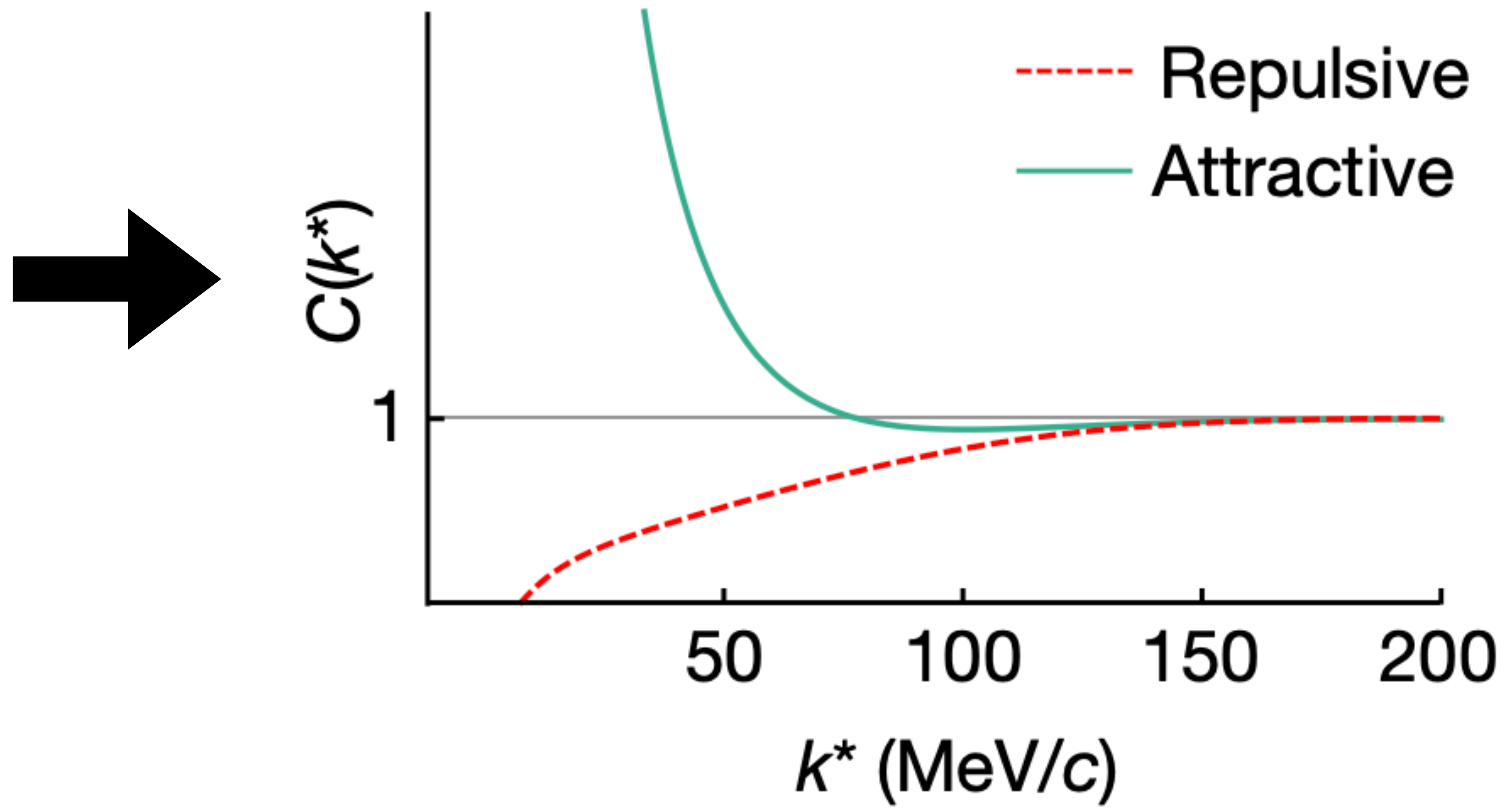
# Two-body femtoscopy




Emission source *S(r*)*




Schrödinger equation
Two-particle wave function
$\left|\psi(\mathbf{k}^*, \mathbf{r}^*)\right|$




Correlation function *C(k*)*

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

**Thomas Humanic 4 Jun, 09:10**
**Neelima Agrawal 4 Jun, 18:30**
**Anton Riedel 5 Jun, 09:30**
**Valentina Mantovani Sarti 5 Jun, 08:30**
**Raffaele del Grande 6 Jun, 17:30**

Three-body system? Hadron-deuteron correlation

ALICE, Nature 588, 232–238 (2020)

# The source

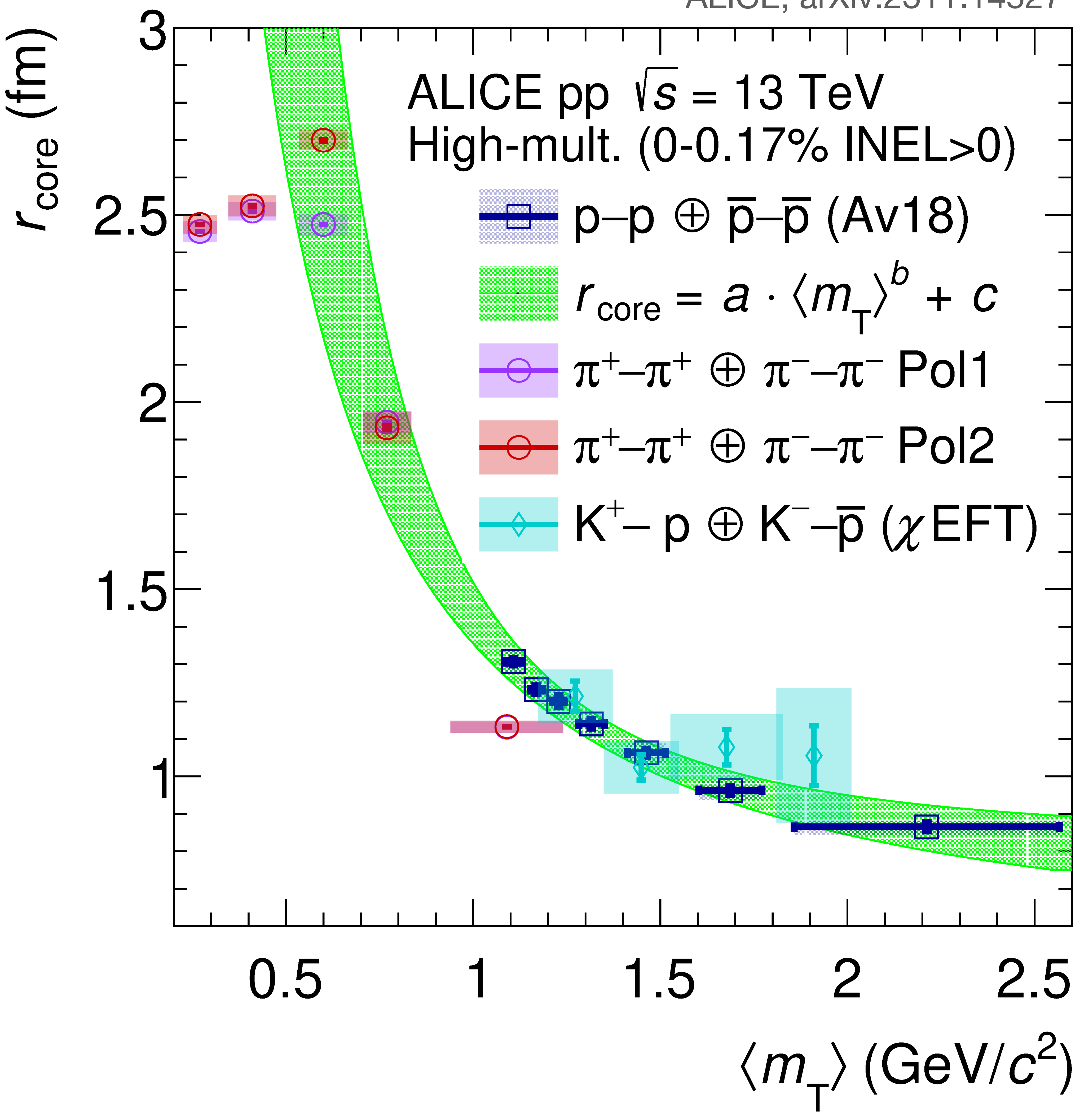
- ***Common Gaussian*** emission source for all hadrons in pp collisions

$$S(r^*) = \frac{1}{\left(2\pi r_{core}^2\right)^{3/2}} e^{-\frac{r^{*2}}{4r_{core}^2}}$$

- Short-living strongly decaying resonances (cτ ~ 1 fm) enhance the source size
  - Different effective source sizes for different pairs

Do deuterons follow the same $m_T$ scaling?

ALICE, arXiv:2311.14527




ALI-PUB-566229

# Kaon-deuteron correlation function

- Source size

$$r_{\mathrm{eff}}^{\mathrm{K^+d}} = 1.35^{+0.04}_{-0.05}\ \mathrm{fm}$$

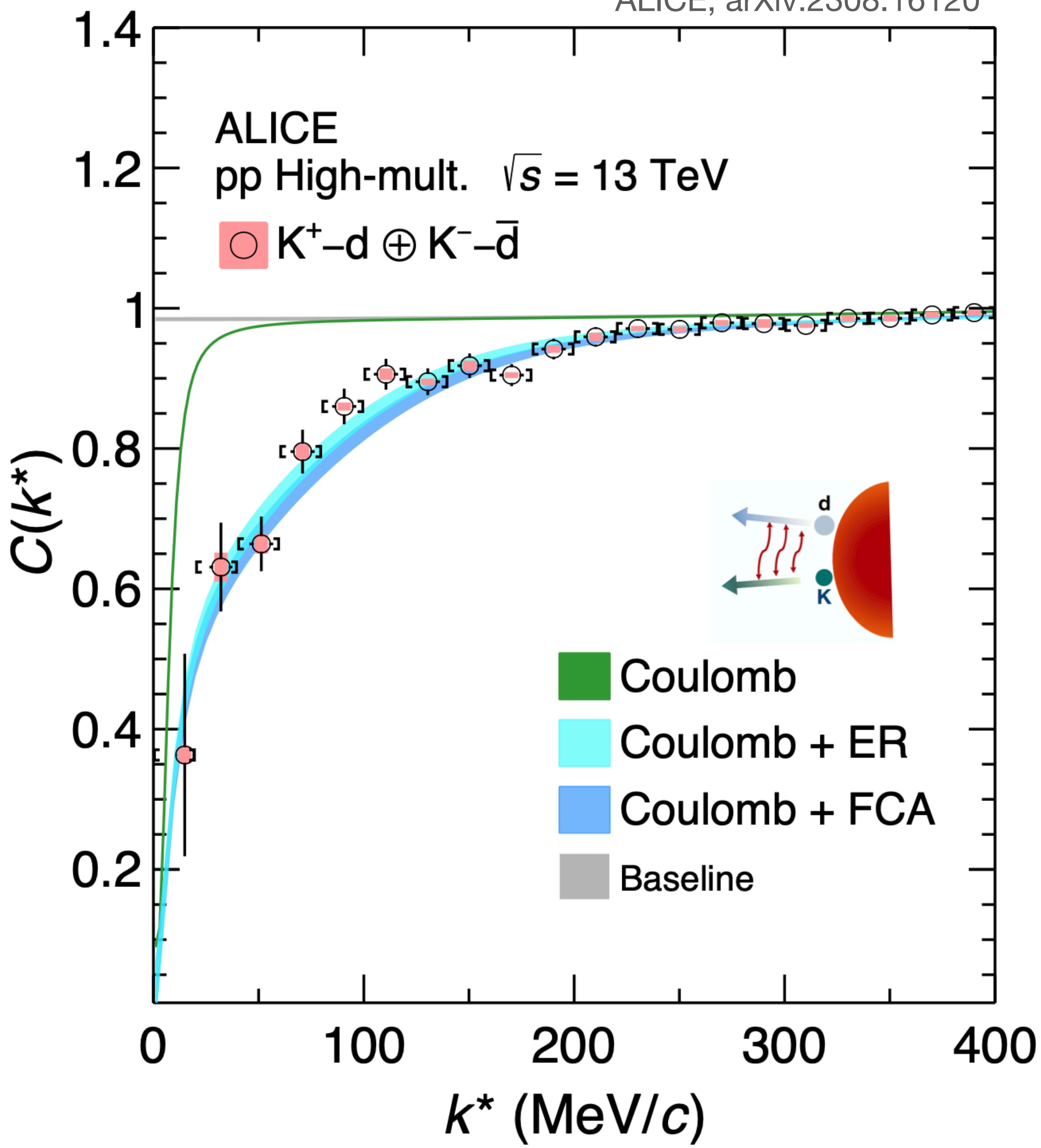
- Modelled as an effective two-body system employing Lednický-Lyuboshits approach

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

- Scattering parameters based on the available scattering data
- Good agreement with data

→ ***deuteron follows the $m_T$ scaling!***

ALICE, arXiv:2308.16120



# Proton-deuteron correlations …

- Source size

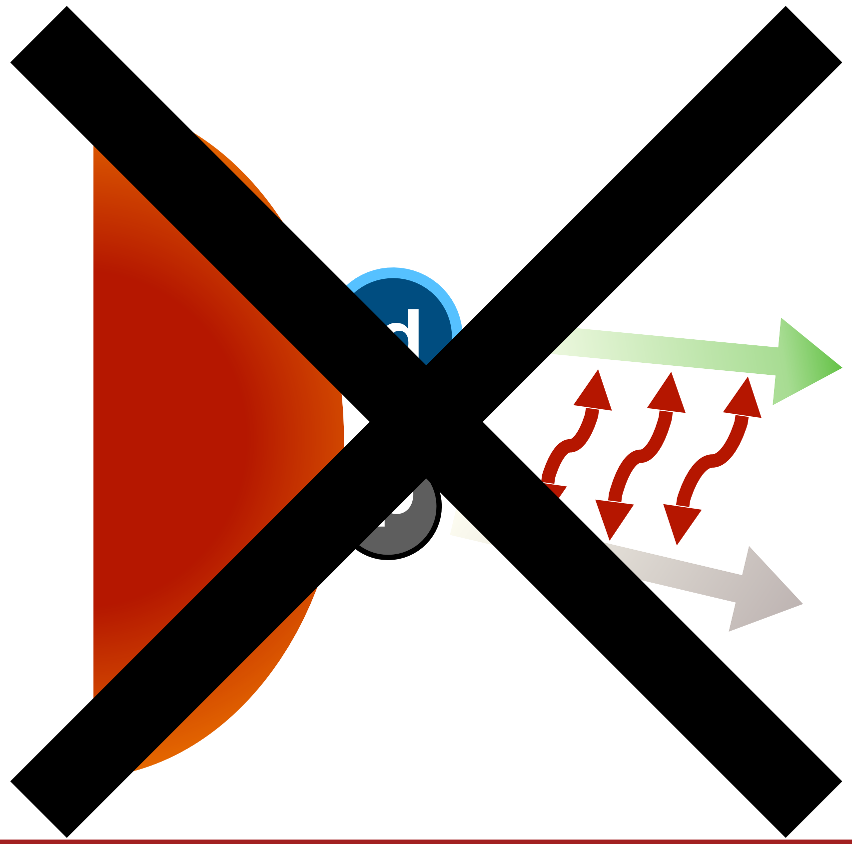
$$r_{\mathrm{eff}}^{\mathrm{pd}} = 1.08^{+0.006}_{-0.006}\ \mathrm{fm}$$

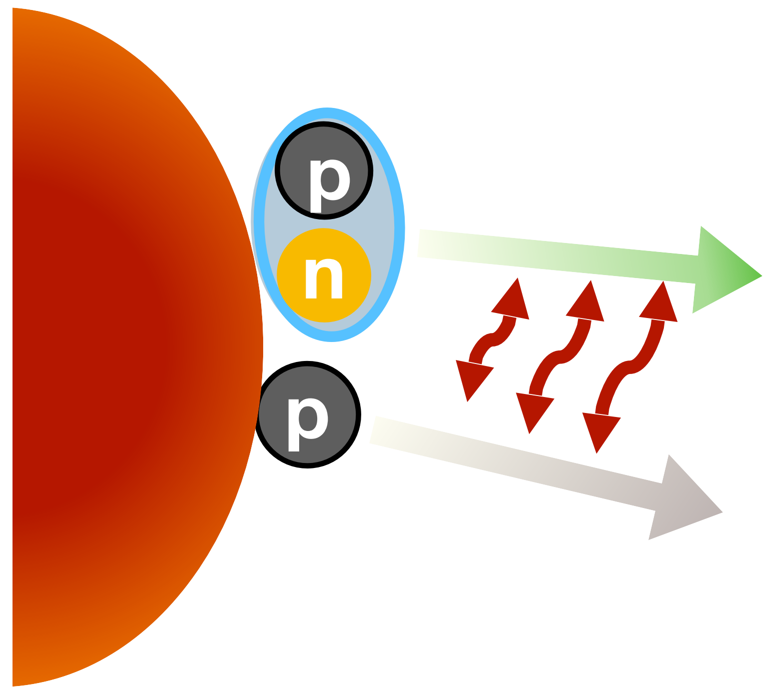
- Modelled as an effective two-body system employing Lednický-Lyuboshits approach

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

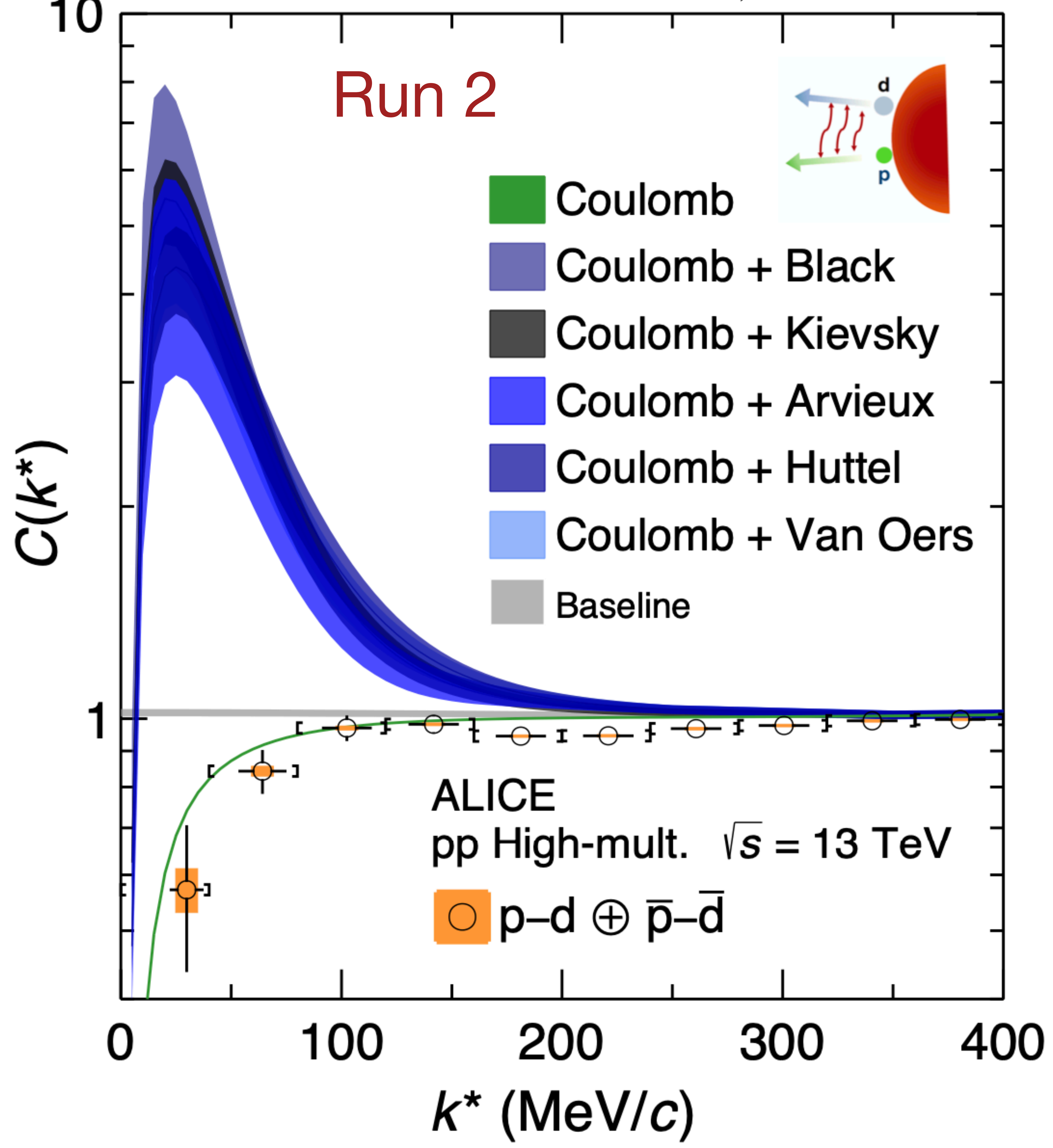
- Scattering parameters based on the available scattering data

- Bad agreement with data: Pauli blocking missing, asymptotic strong interaction not sufficient






ALICE, arXiv:2308.16120



# … as a three-body system

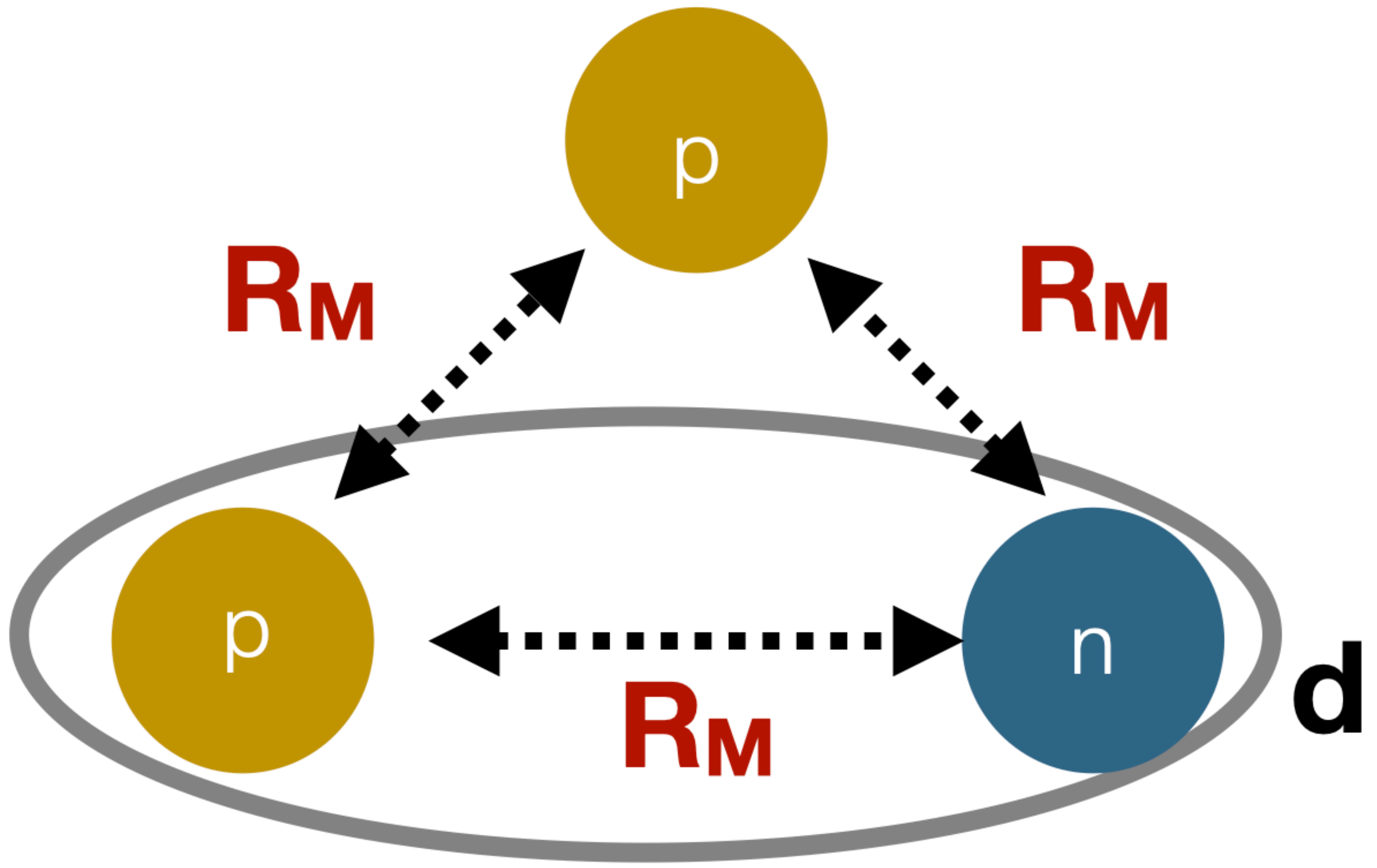
- Full three-body calculations necessary
  M. Viviani et al, Phys.Rev.C 108 (2023) 6, 064002

three-nucleon wave function

$$C_{pd}\left(k^*\right) = \frac{1}{16A_d}\int S\left(\rho, R_M\right)\left|\Psi\left(k^*, \rho\right)\right|^2 \rho^5 d\rho d\Omega$$

nucleon-nucleon source size in pd

- Source size $R_M = 1.43 \pm 0.16 \text{ fm}$



# … as a three-body system

- Full three-body calculations necessary

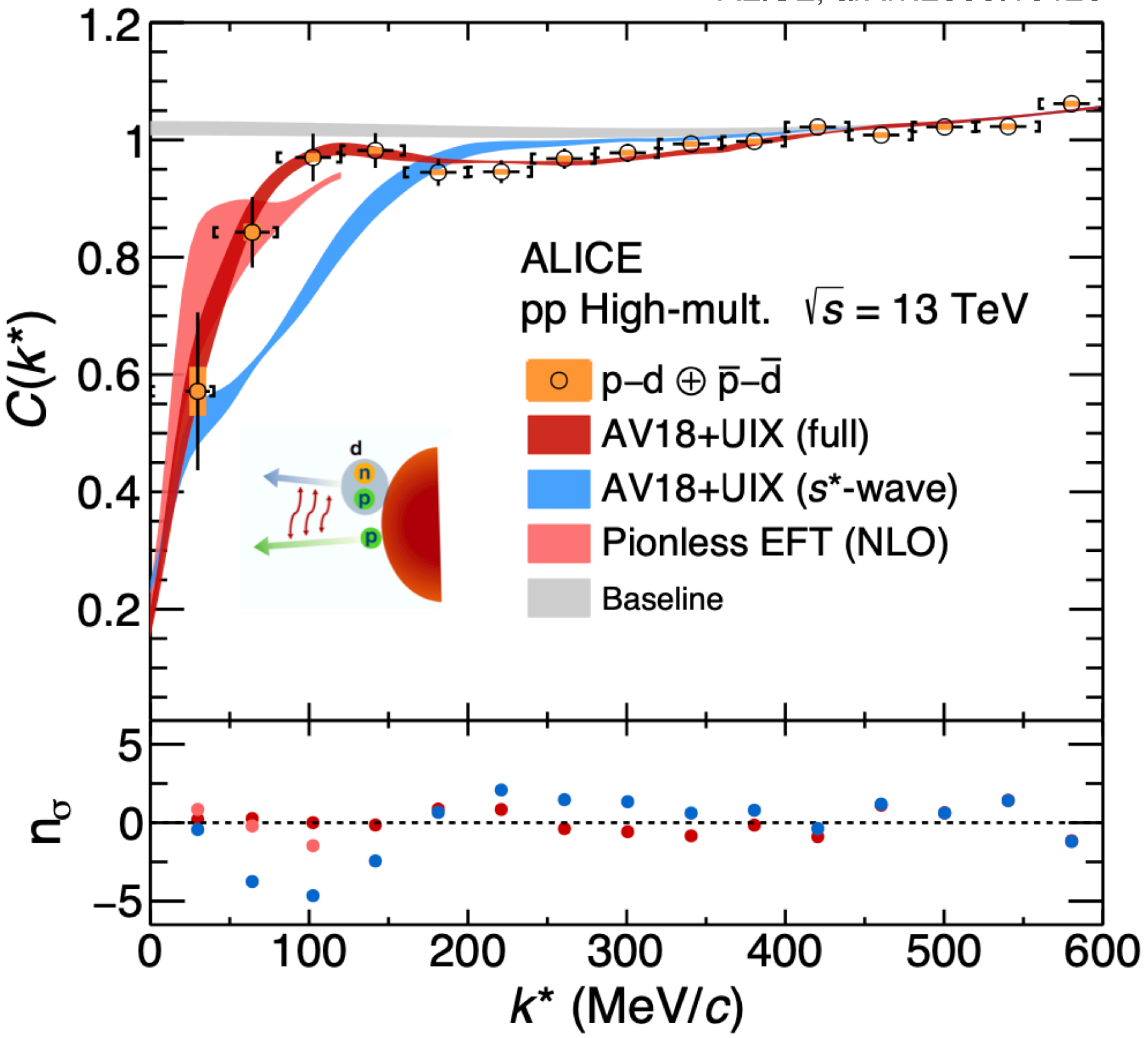
M. Viviani et al, Phys.Rev.C 108 (2023) 6, 064002

three-nucleon wave function

$$C_{pd}\left(k^*\right) = \frac{1}{16A_d}\int S\left(\rho, R_M\right) \left|\Psi\left(k^*, \rho\right)\right|^2 \rho^5 d\rho d\Omega$$

nucleon-nucleon source size in pd

ALICE, arXiv:2308.16120



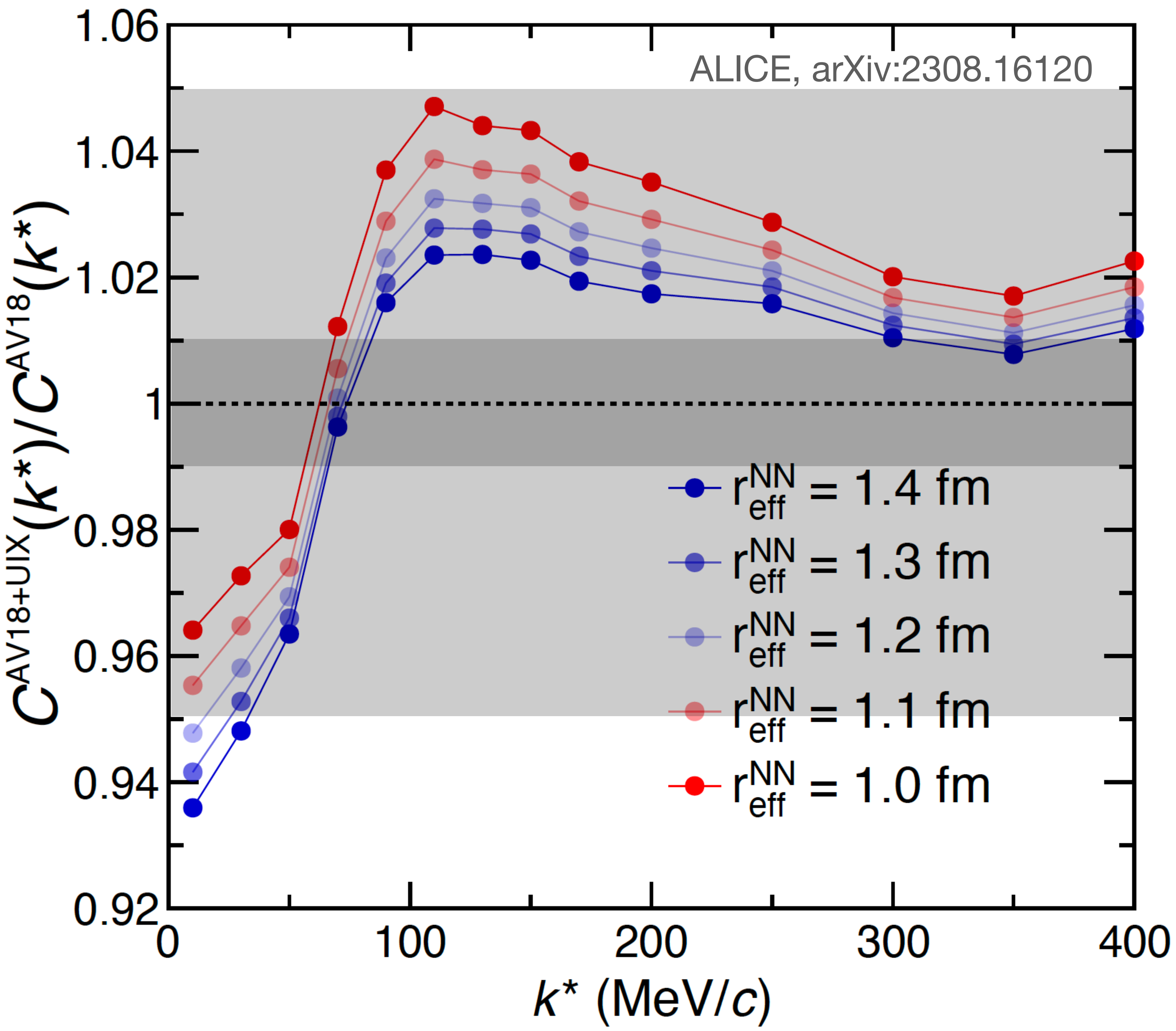

- Wave function:
  - Hyperspherical harmonic (HH) approach with Argonne V18 (AV18) + Urbana IX (UIX) potentials
  - Pionless EFT NLO

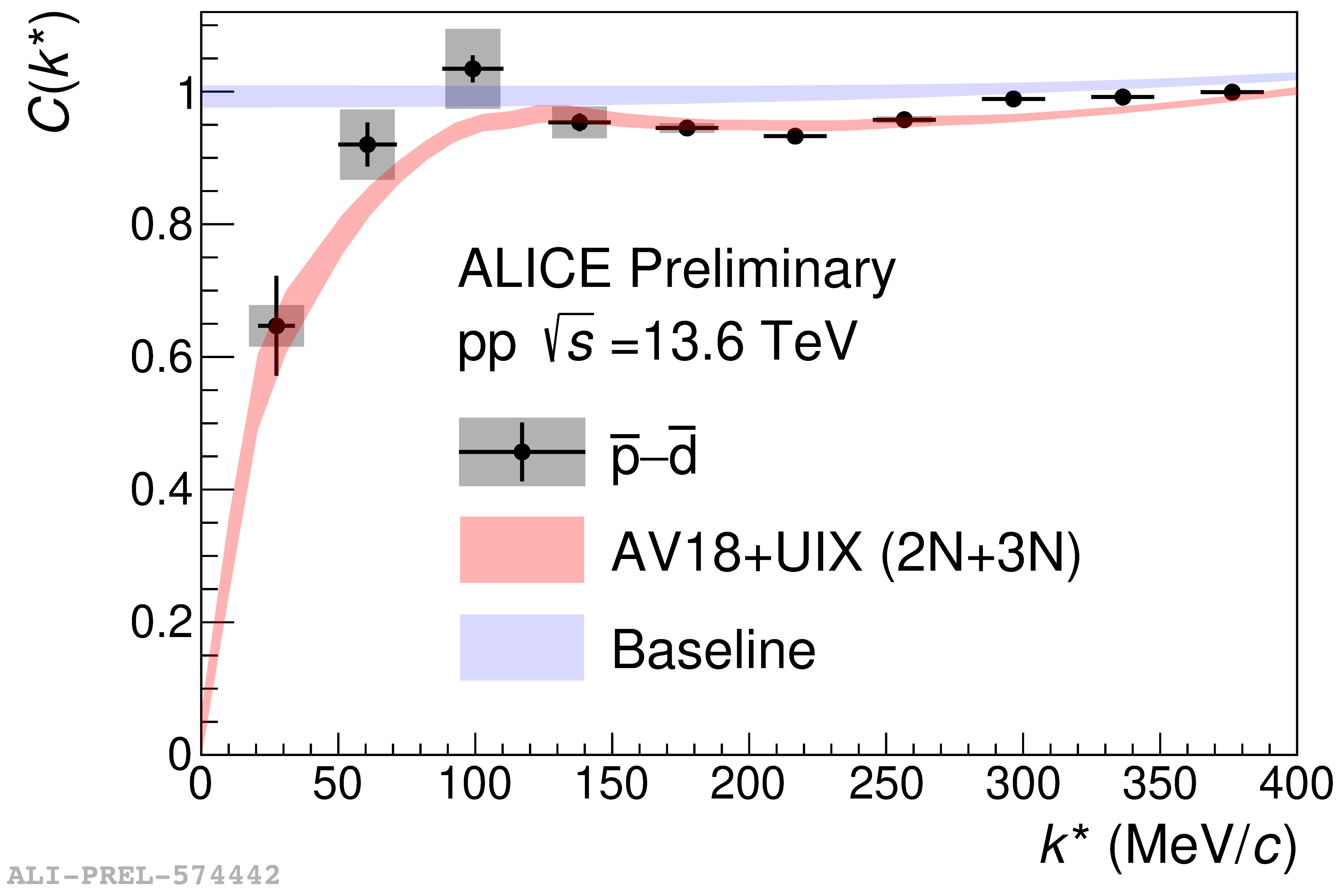
Sensitive to the three-body dynamics and interaction!

# Sensitivity to three-body interaction

- Sensitivity to three-body forces up to 5% - no sensitivity with Run 2

New!



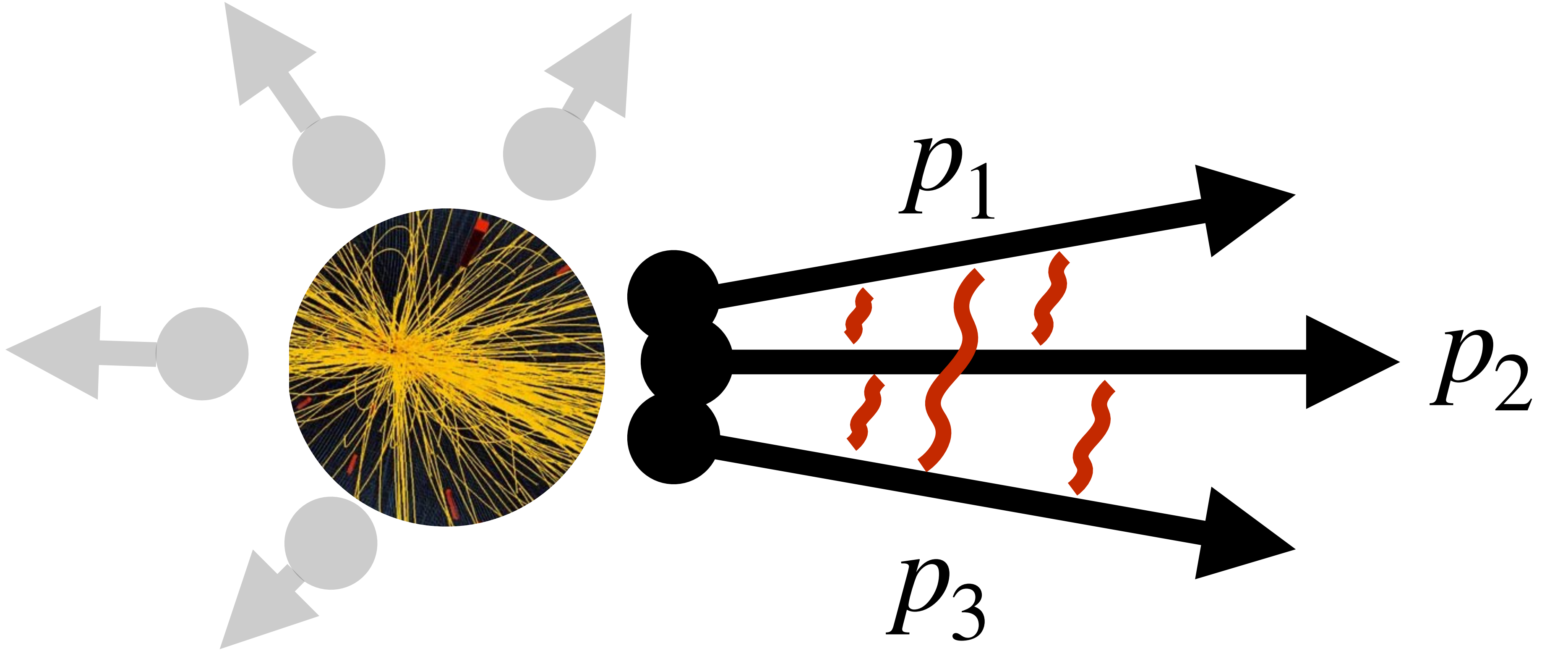



# Three-body femtoscopy

- Experimental definition

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

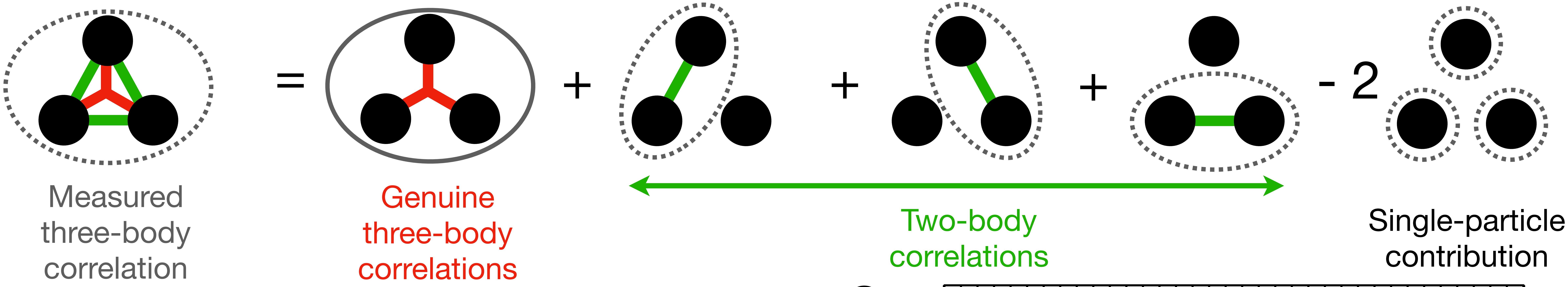
$$Q_3 = \sqrt{-q_{ij}^2 - q_{jk}^2 - q_{ki}^2}$$




- Theoretical three-particle correlation function
  - Two-body interactions
  - ***Three-body interaction***

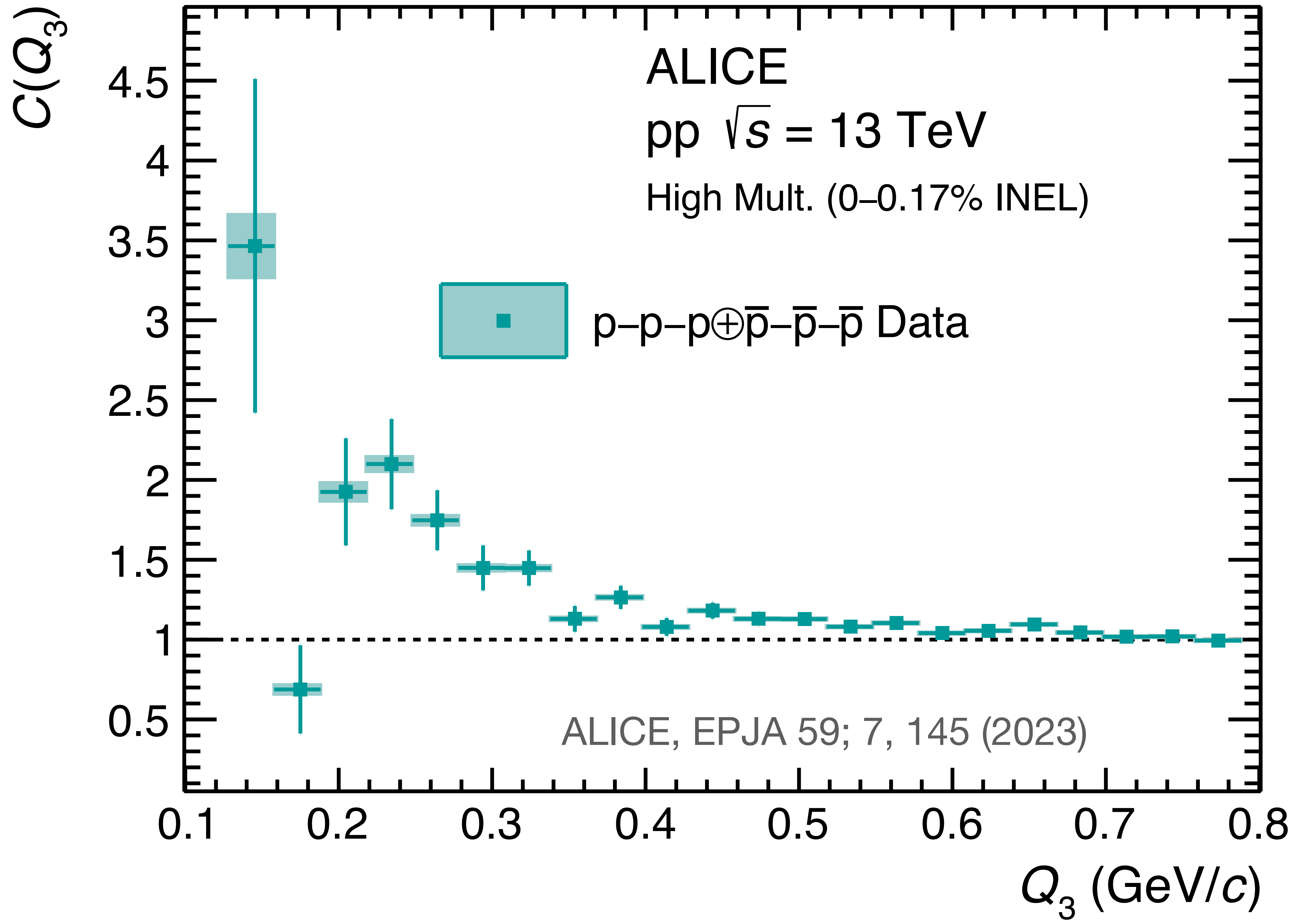
$$C_3(\mathbf{p}_1, \mathbf{p}_2, \mathbf{p}_3) = \iiint S_3(\mathbf{r}_1, \mathbf{r}_2, \mathbf{r}_3)\left|\Psi(\mathbf{r}_1, \mathbf{r}_2, \mathbf{r}_3, \mathbf{p}_1, \mathbf{p}_2, \mathbf{p}_3)\right|^2 d^3\mathbf{r}_1 d^3\mathbf{r}_2 d^3\mathbf{r}_3$$

# p-p-p correlation function

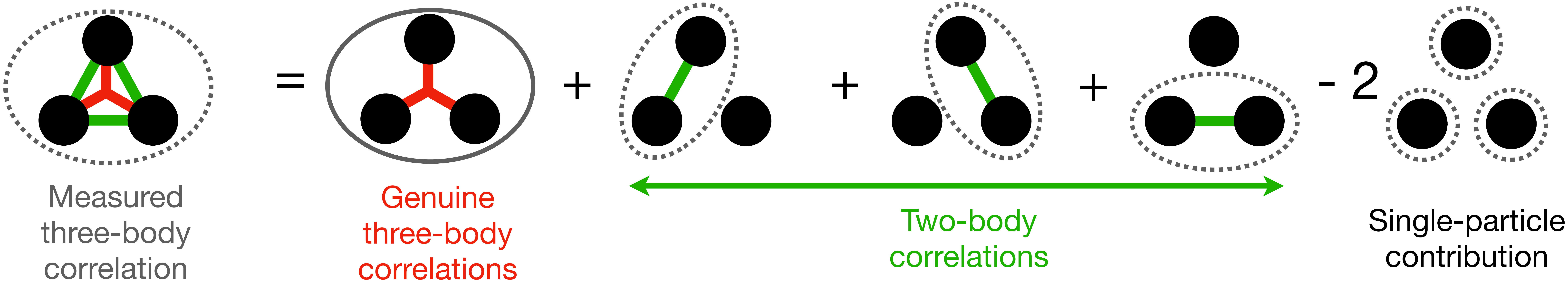



- Kubo's cumulant method provides first hint of effects beyond two-body correlations

R. Kubo, J. Phys. Soc. Jpn. 17, 1100-1120 (1962)
Del Grande, LS et al. EPJC 82 (2022) 244



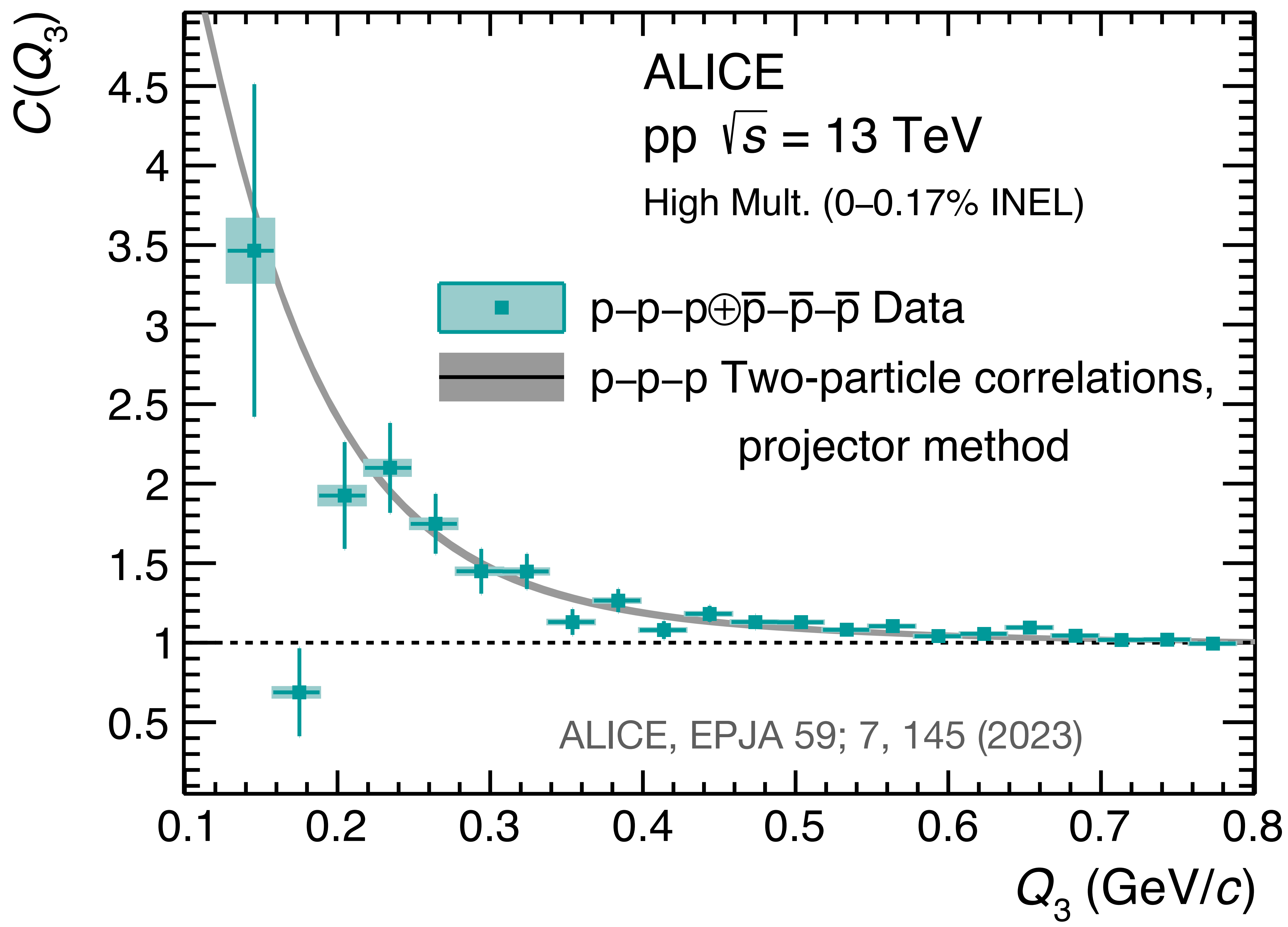
# p-p-p correlation function




- Cumulant method provides first hint of effects beyond two-body correlations

  R. Kubo, J. Phys. Soc. Jpn. 17, 1100-1120 (1962)
  Del Grande, LS et al. EPJC 82 (2022) 244

- A deviation of nσ = 6.7 from lower-order contributions
- Theoretical predictions necessary to further understand the origin of the deviation further



# p-p-p correlation function

- First ever full three-body correlation function calculations
  A. Kievsky, LS, et al., Phys.Rev.C 109 (2024) 3, 034006

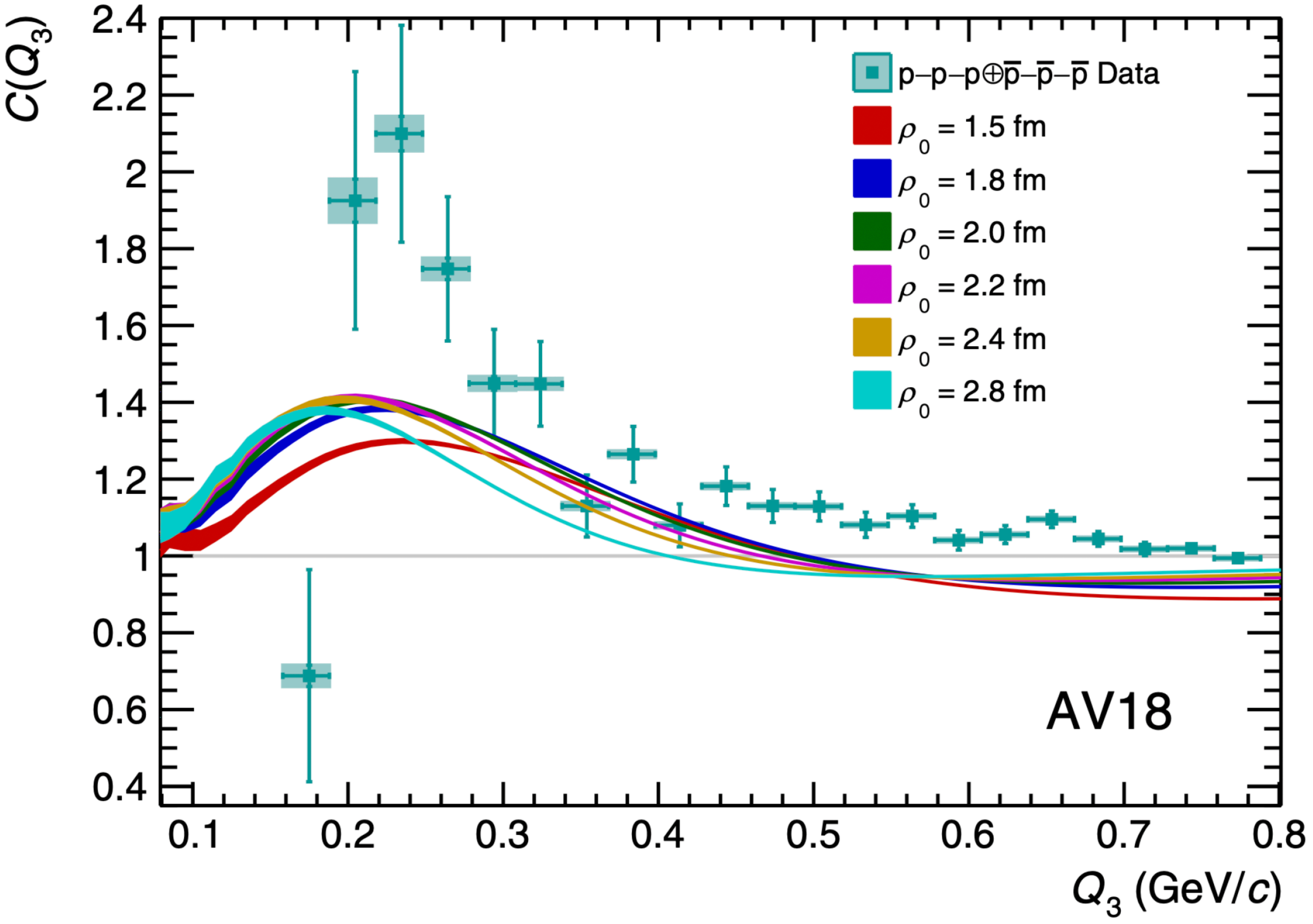
three-proton wave function

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

hyperradius

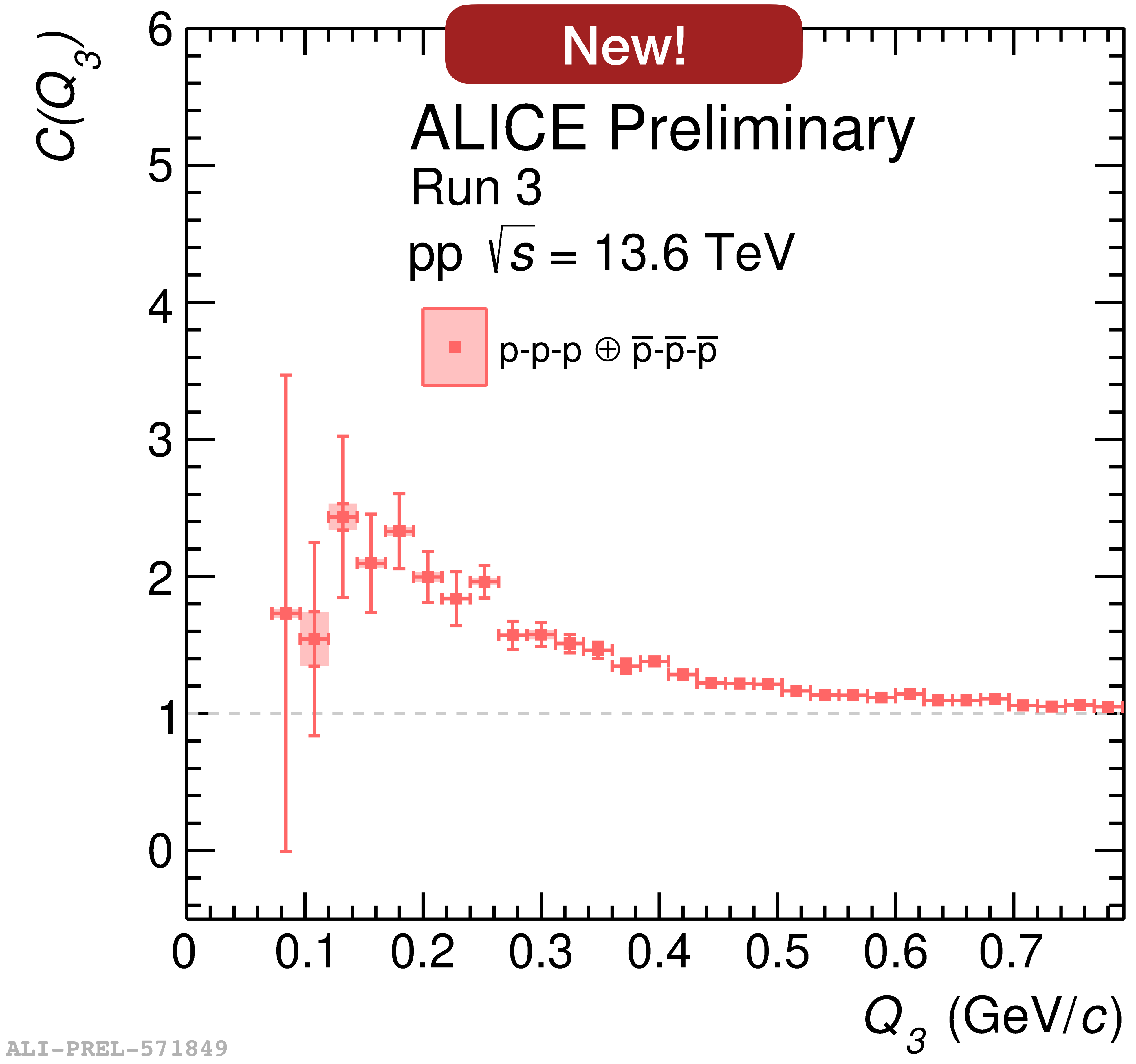
- Wave function via HH:
  - AV18
  - Three-body Coulomb interaction
  - Quantum statistics
- Negligible contribution from UIX
  - Utilise to study three-body source
- Only shape of the theory and data should be compared.

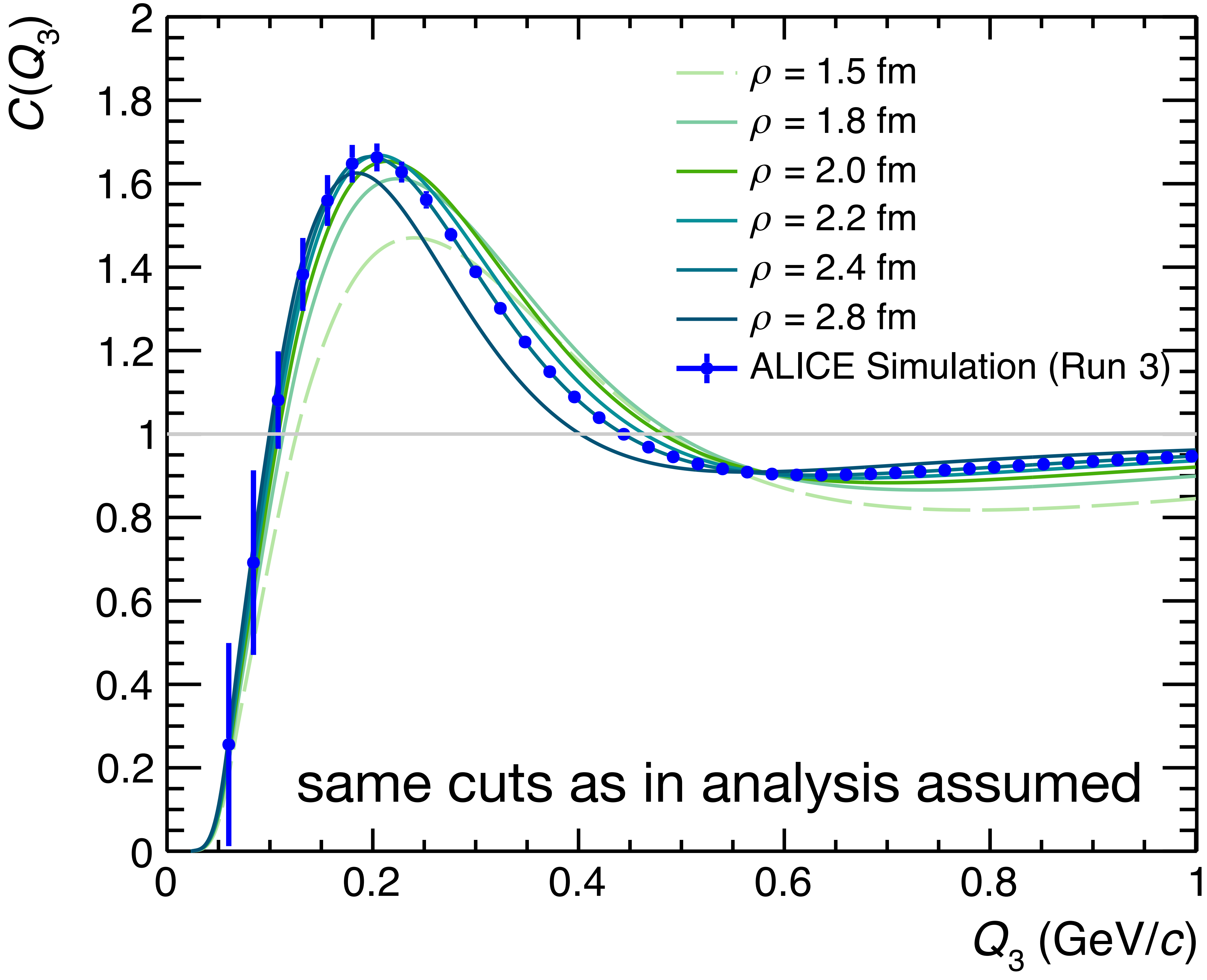
A. Kievsky, LS, et al., Phys.Rev.C 109 (2024) 3, 034006



# What is possible with Run 3?

- Run 3 data from 2022 already analysed and results are promising!
- At the end of Run 3 - 25 times larger statistical sample than 2022 alone



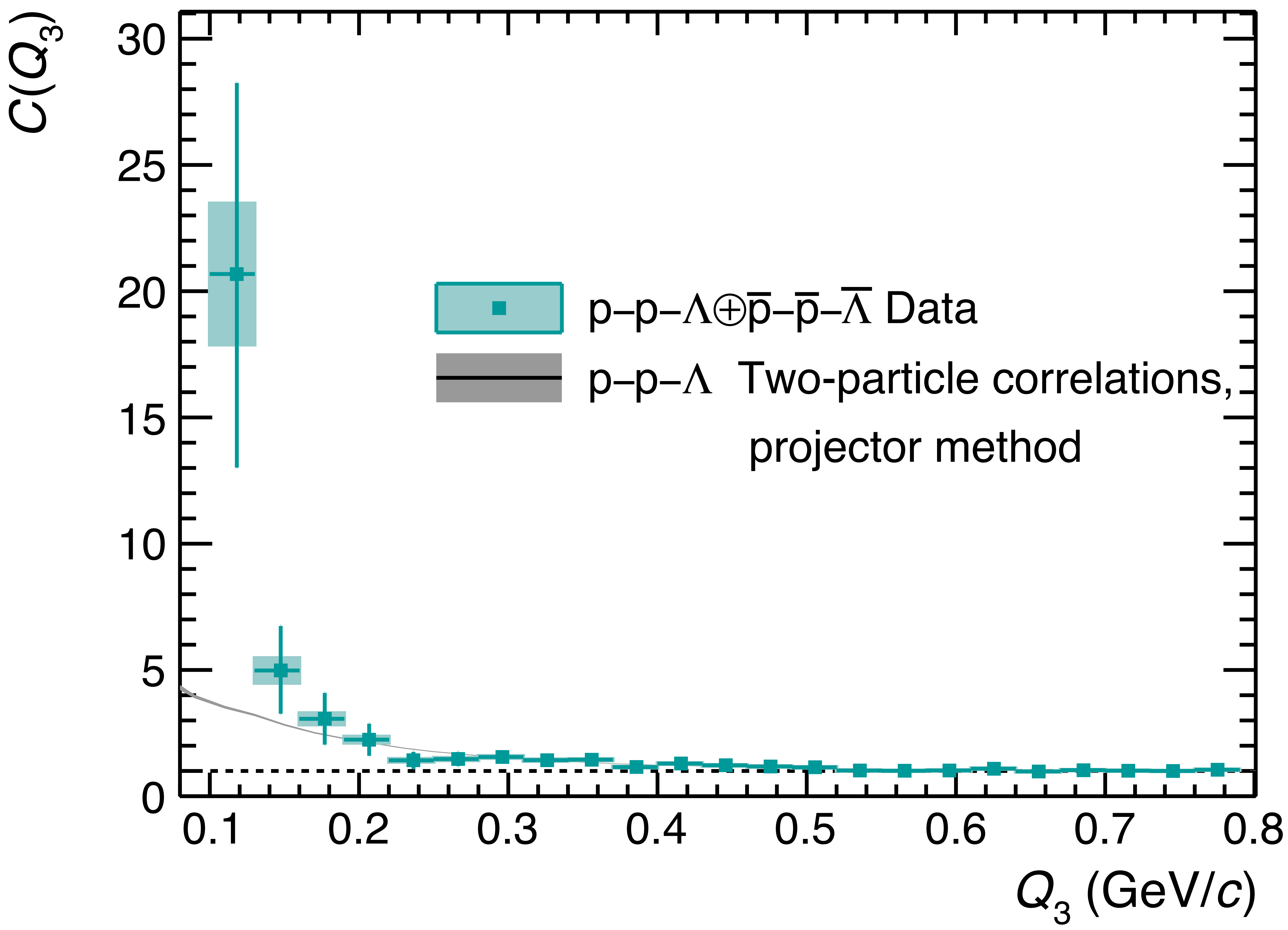




With Run 3 data - expected sensitivity to the source size!

# p-p-Λ correlation function

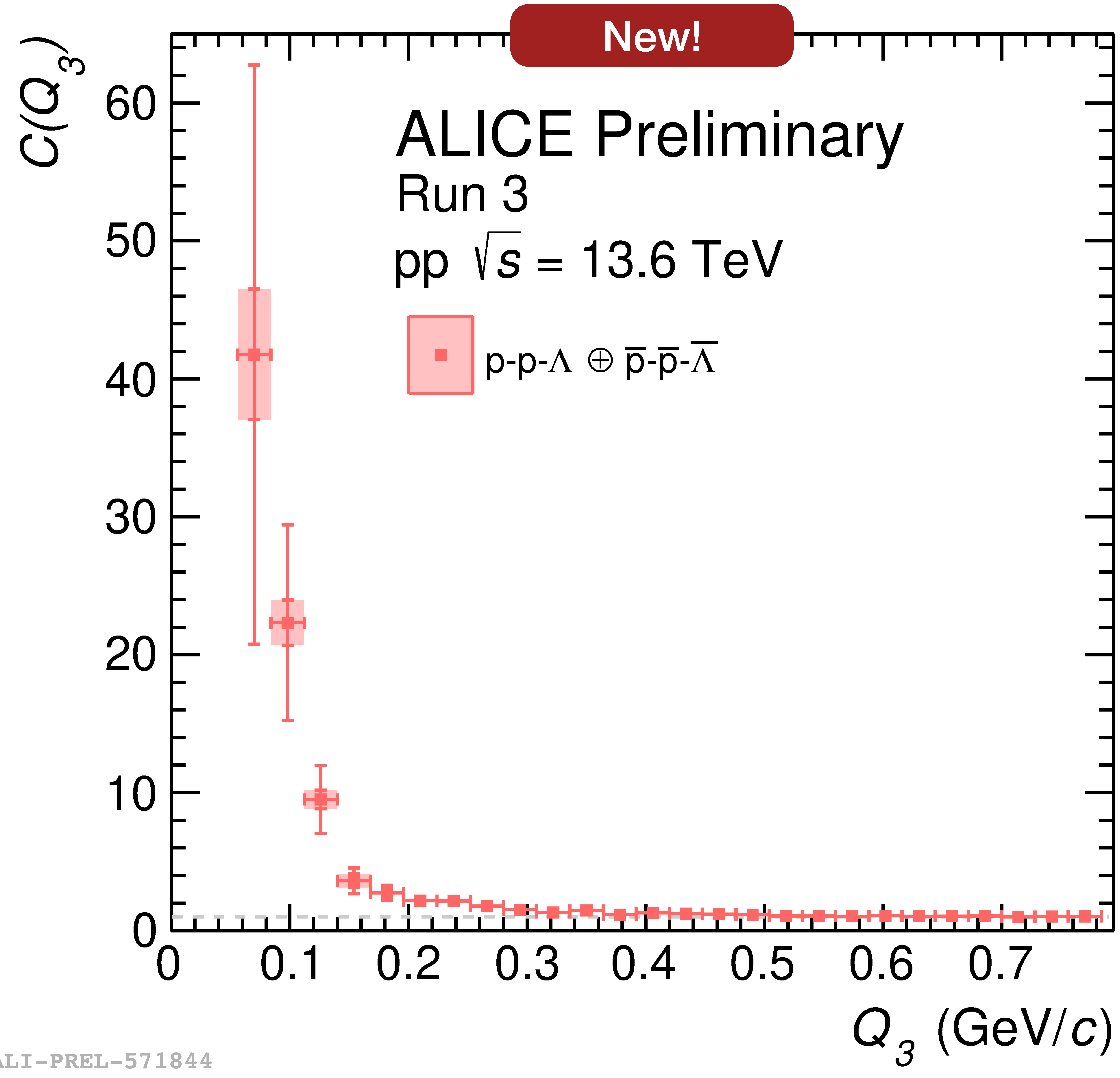
- Run 2: compatible with lower-order contributions (nσ = 0.8)

ALICE, EPJA 59; 7, 145 (2023)



# p-p-Λ correlation function

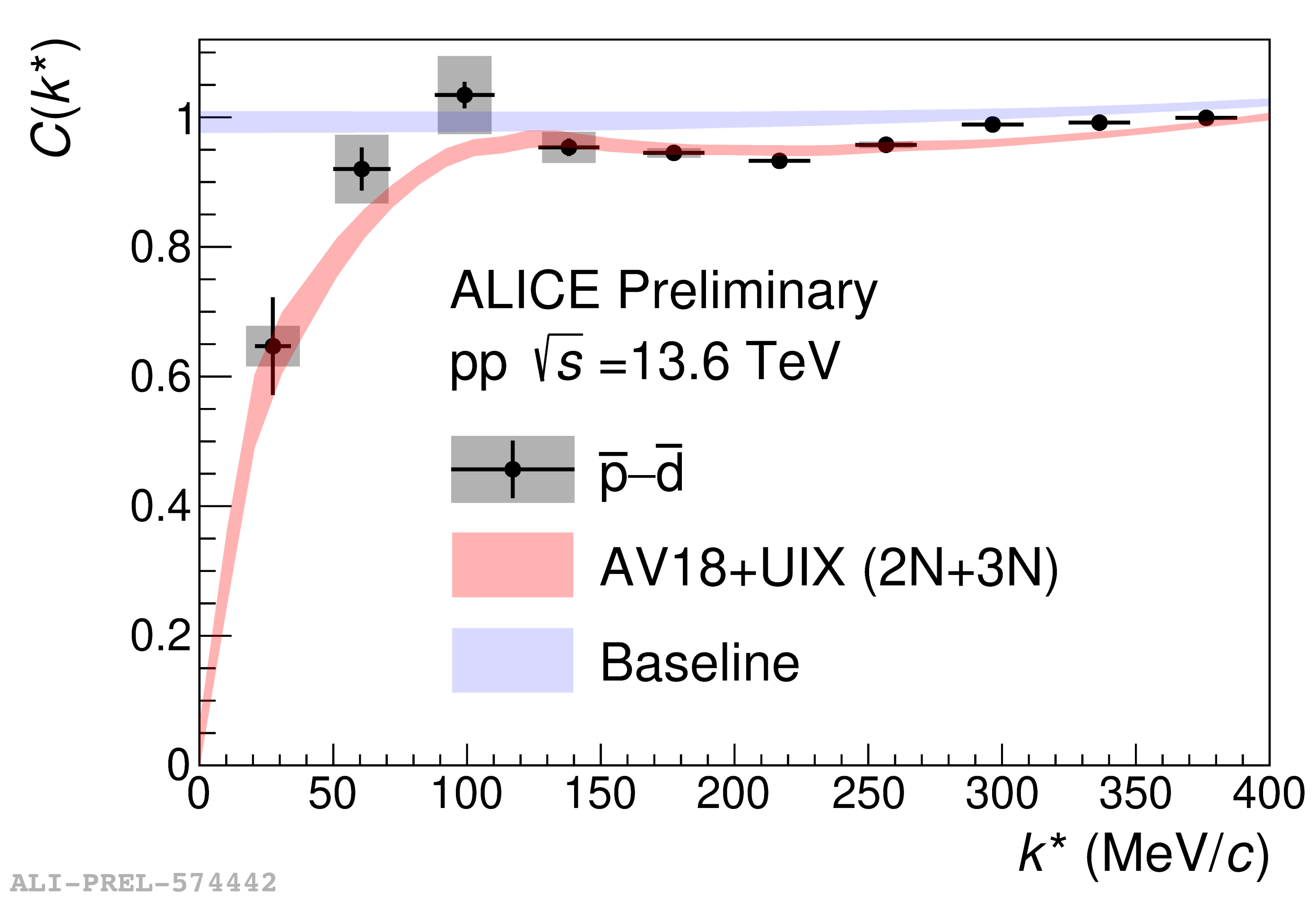
- Run 2: compatible with lower-order contributions (nσ = 0.8)
- Run 3 2022 data confirms observed correlation shape
- By the end of Run 3 - 150 times larger statistical triplets sample expected compared to Run 2 due to developed software triggers!
- Awaiting first theoretical predictions to interpret the available data
  - More on the ppΛ correlation function by Raffaele del Grande on 6 Jun, 17:30!
  - Expected effect - 30%

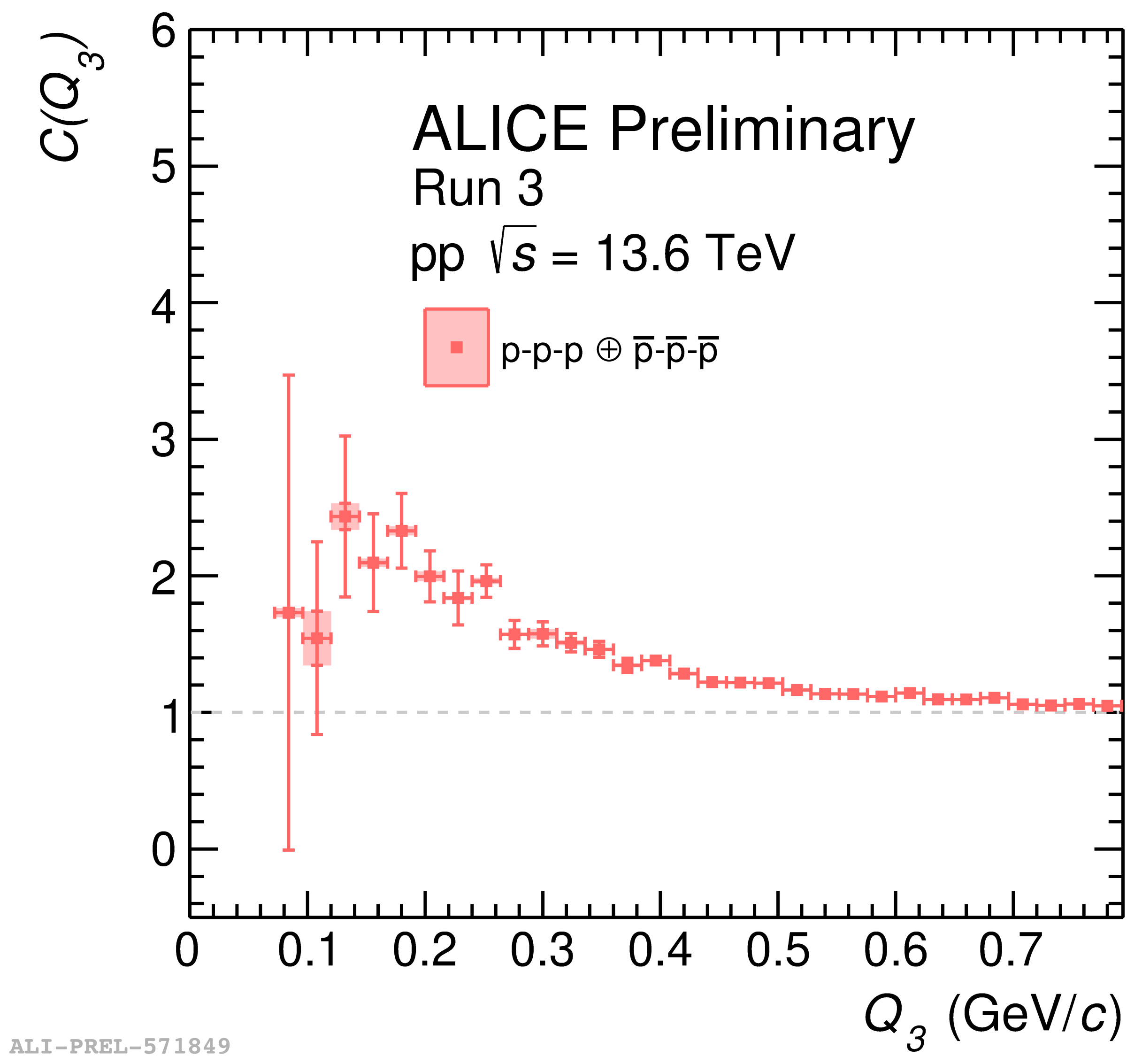


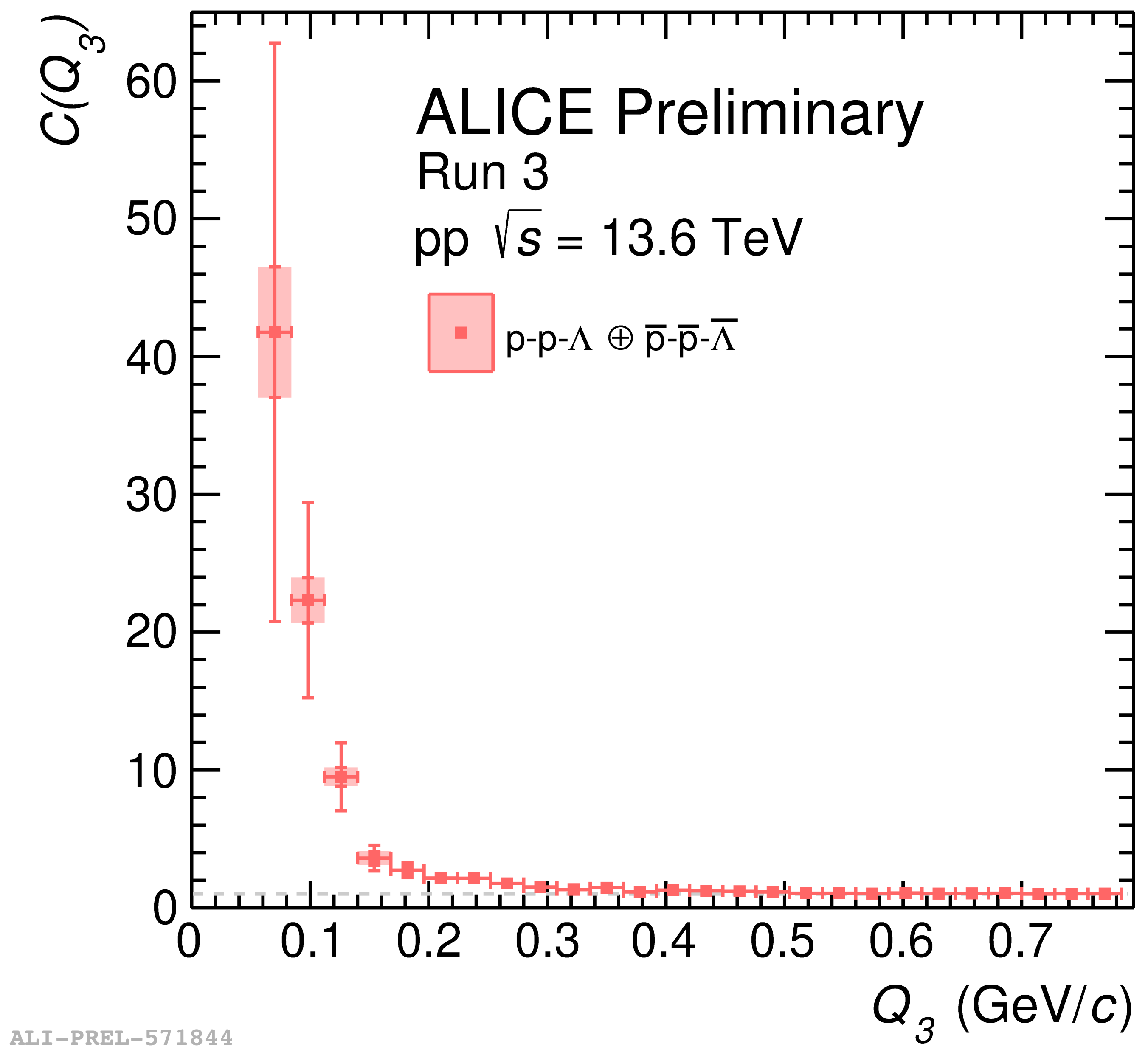

laura.serksnyte@tum.de

# Summary and Outlook

- $K^+d$: deuteron follows the same $m_T$ scaling observed for hadrons
- pd: sensitive to the three-body dynamics and interaction
  - Possible with full Run 3 statistics
- ppp: sensitive to the three-body dynamics but not genuine three-body force
  - Study three-body source which is possible with full Run 3 statistics
- ppΛ: ongoing theoretical studies to interpret the data
  - Full Run 3 will provide 150 times more triplets than Run 2 - very high precision data



# Backup

# Scattering parameters p-d

| 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) | References |
|---|---|---|---|---|---|---|---|
| $K^+$–d | $-0.470$ | 1.75 | — | — | — | — | ER [52] |
| | $-0.540$ | 0.0 | — | — | — | — | FCA [53, 54] |
| p–d | | | $2.73^{+0.10}_{-0.10}$ | $2.27^{+0.12}_{-0.12}$ | $11.88^{-0.10}_{+0.40}$ | $2.63^{+0.01}_{-0.02}$ | Arvieux [55] |
| | | | $1.30^{+0.20}_{-0.20}$ | — | $11.40^{+1.80}_{-1.20}$ | $2.05^{+0.25}_{-0.25}$ | VanOers [56] |
| | | | 4.0 | — | 11.1 | — | Huttel [57] |
| | | | 0.024 | — | 13.8 | — | Kievsky [58] |
| | | | $-0.13^{+0.04}_{-0.04}$ | — | $14.70^{+2.30}_{-2.30}$ | — | Black [59] |

# pd correlation with asymptotic SF

- Coulomb only interaction: does not describe the data
- Argonne v18 (2N) [1] + Urbana IX (NNN) potentials [2] (Born approximation on wave function): cannot describe the data
- Asymptotic strong interaction is insufficient due to dynamics at short-distances (~1-2 fm)

ALICE, arXiv:2308.16120