Exploring strong interaction in three hadron systems at the LHC

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Technical University of Munich

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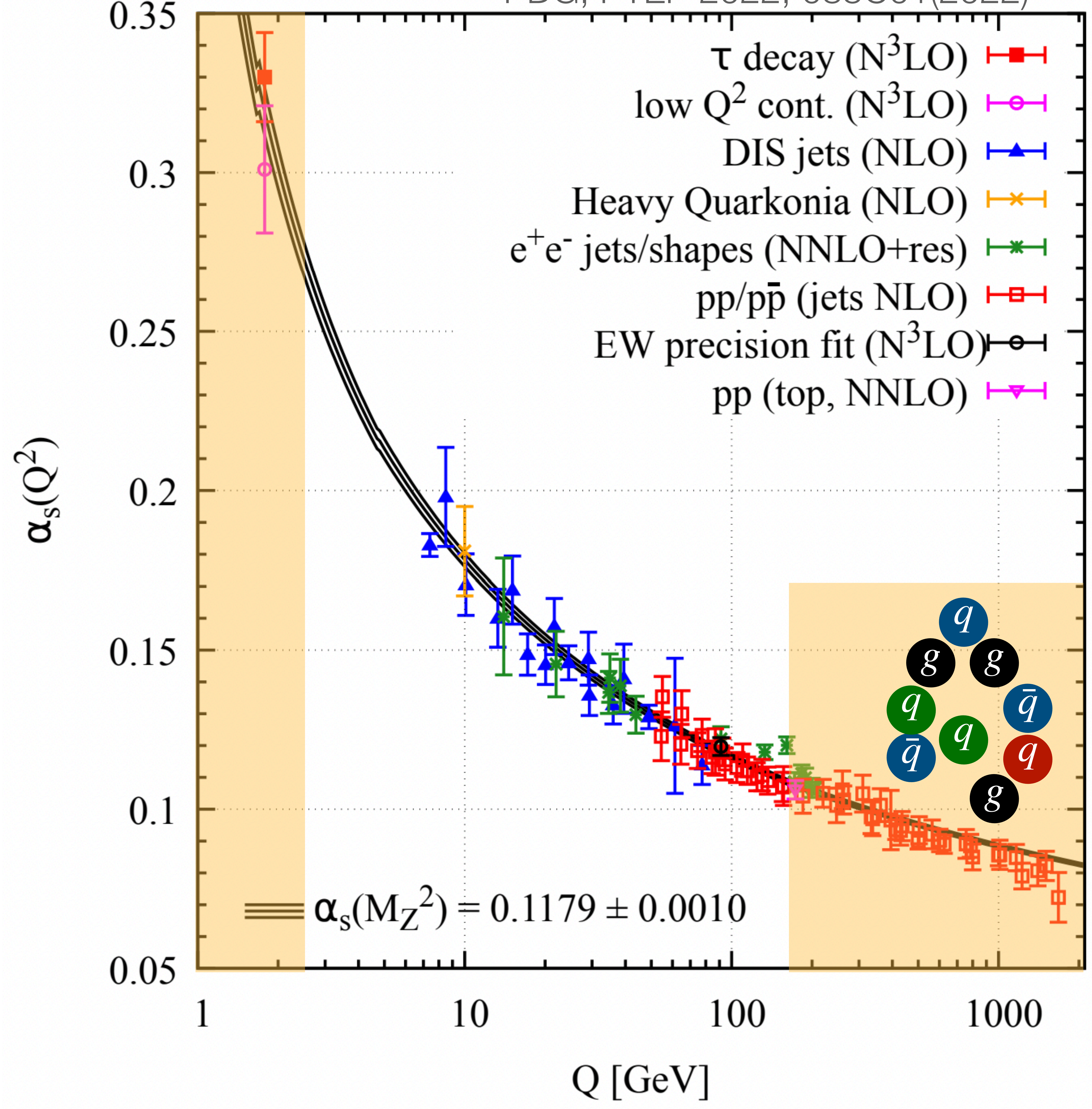
Hadronic interactions and QCD

Understanding how QCD evolves from high-energy to low-energy regime

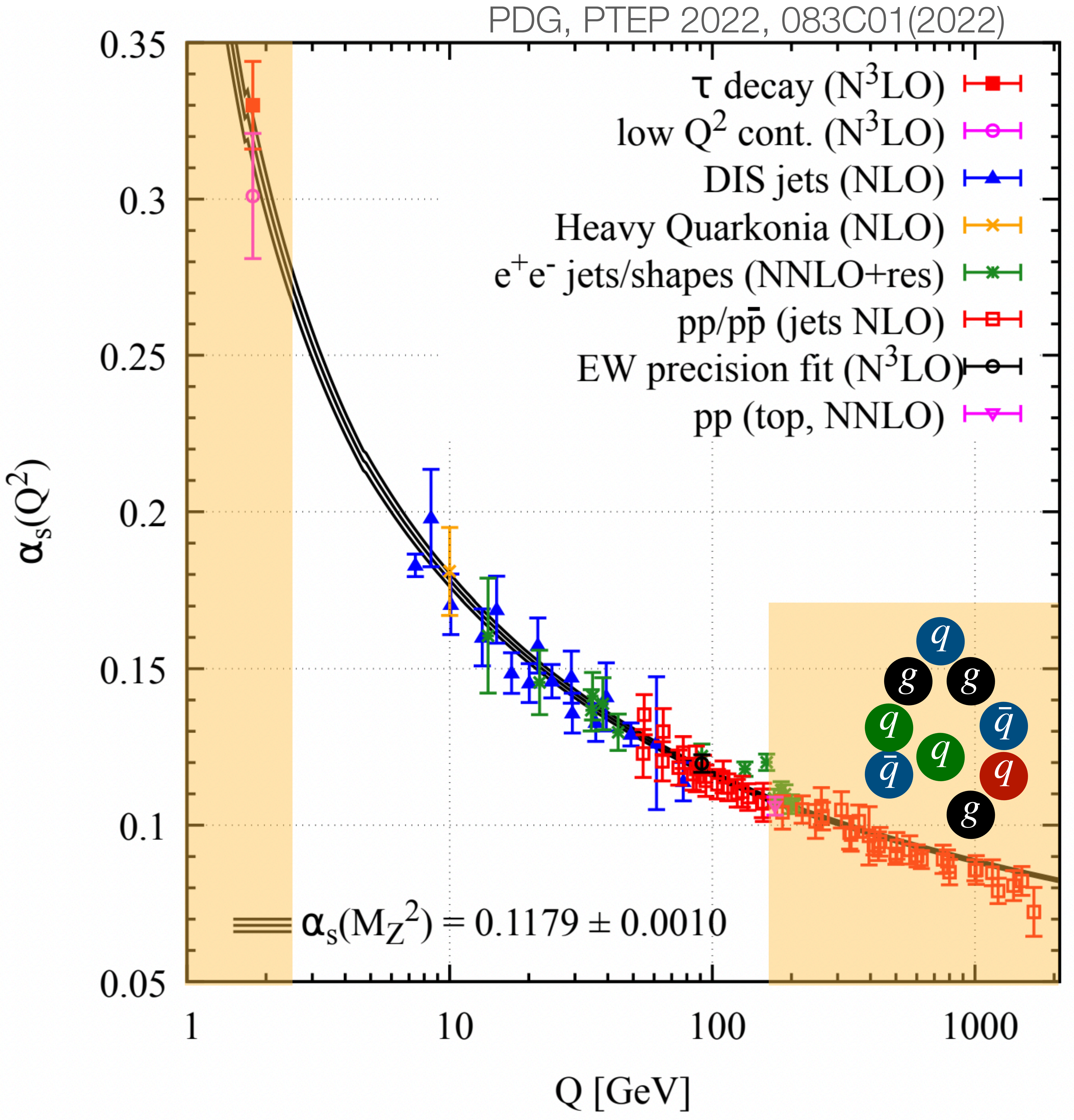
PDG, PTEP 2022, 083C01(2022)



Hadronic interactions and QCD

Understanding how QCD evolves from high-energy to low-energy regime

Non-perturbative QCD $\rightarrow Q \sim 1$ GeV

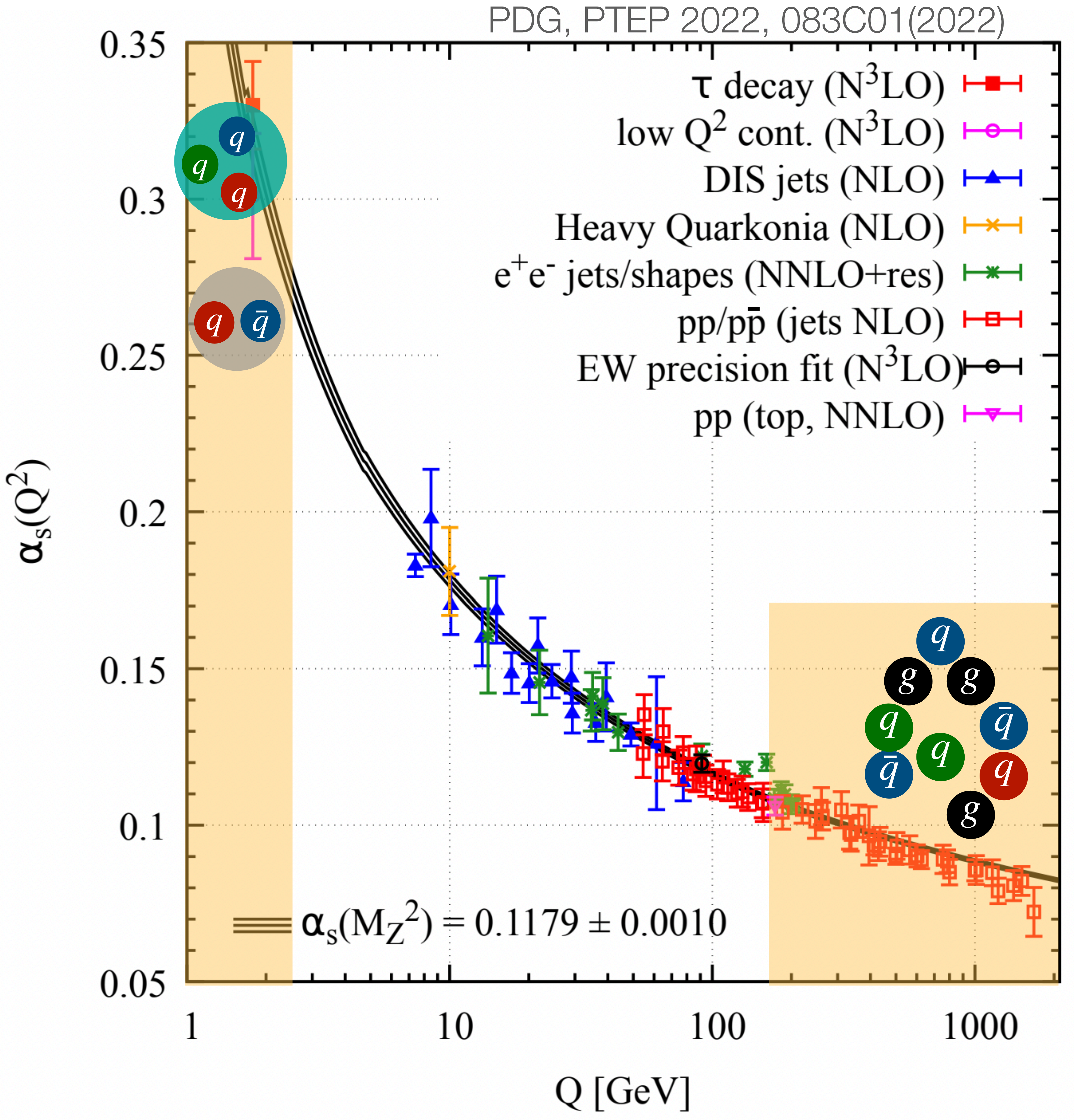


Hadronic interactions and QCD

Understanding how QCD evolves from high-energy to low-energy regime

Non-perturbative QCD $\rightarrow Q \sim 1$ GeV

- Use effective field theories (residual strong interaction)
  - Hadrons as degrees of freedom (baryons, mesons)



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  - Need **experimental data**

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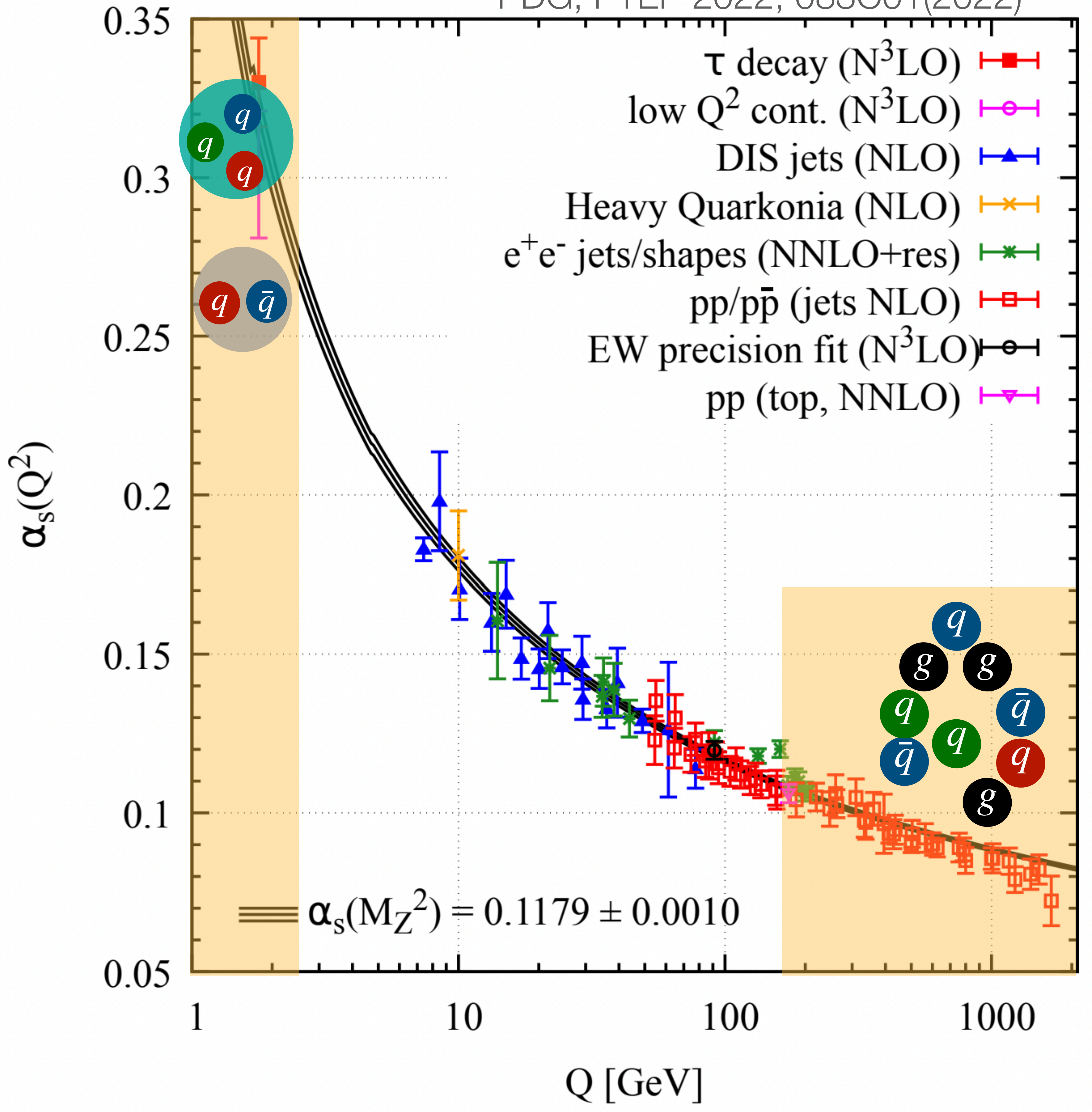


Hadronic interactions and QCD

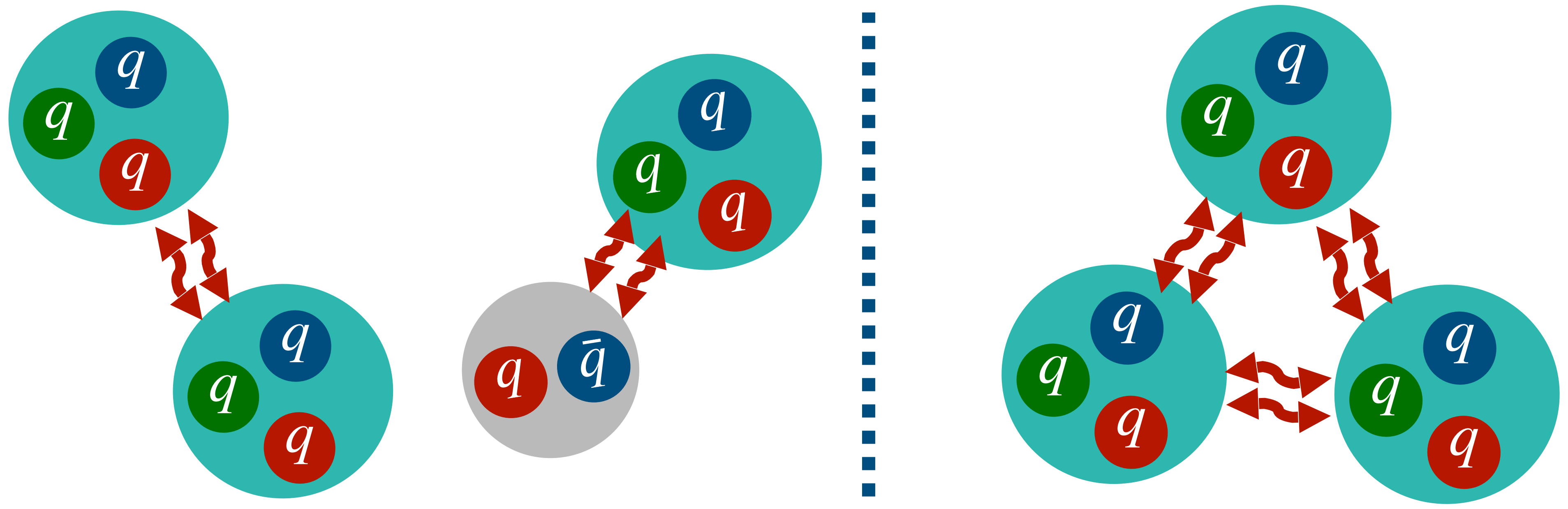
Understanding how QCD evolves from high-energy to low-energy regime

Non-perturbative QCD $\rightarrow Q \sim 1$ GeV

- Use effective field theories (residual strong interaction)
  - Hadrons as degrees of freedom (baryons, mesons)
  - Need **experimental data**
- How do **hadrons** interact?

Two-body interaction

Many-body interaction



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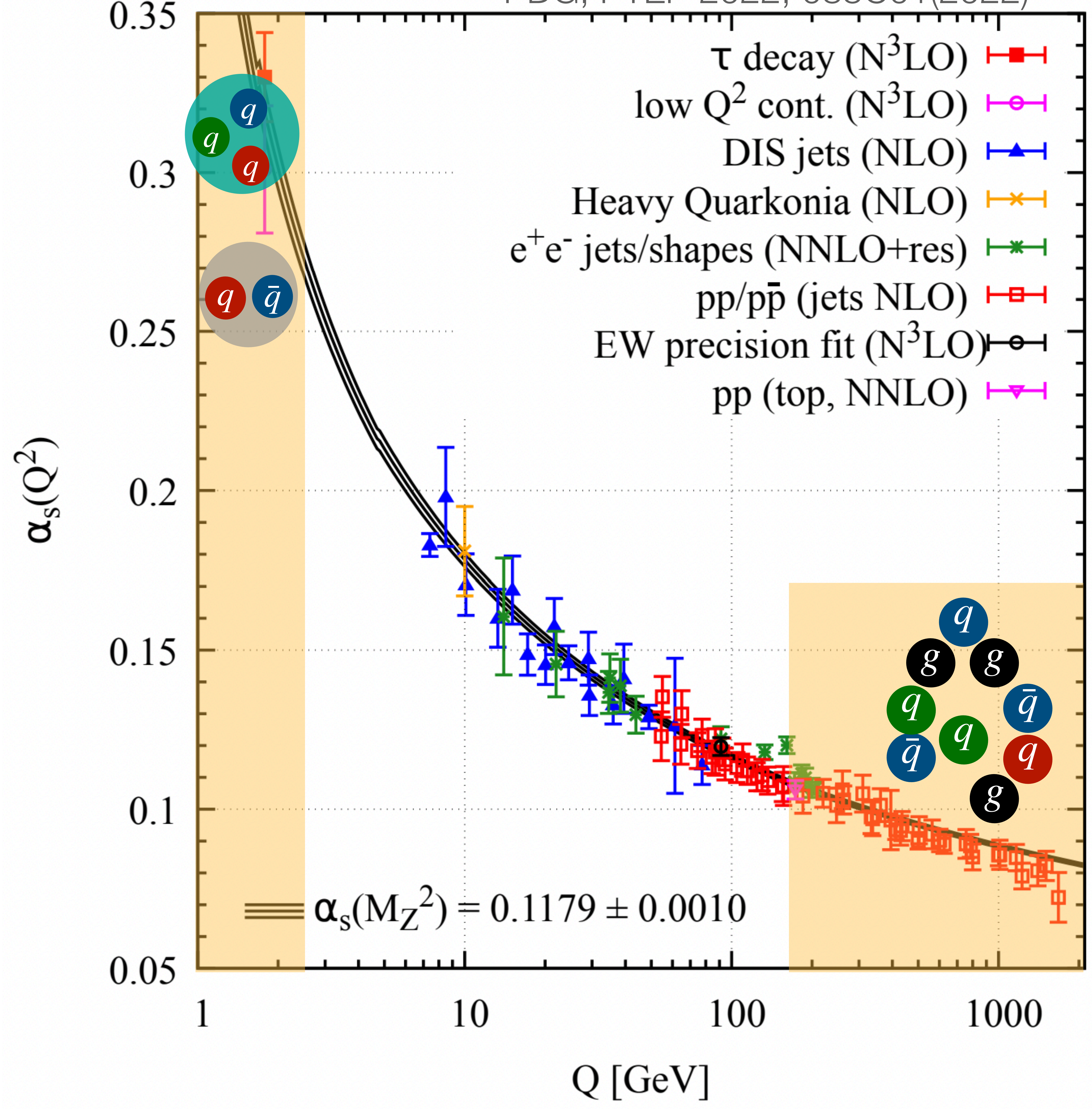
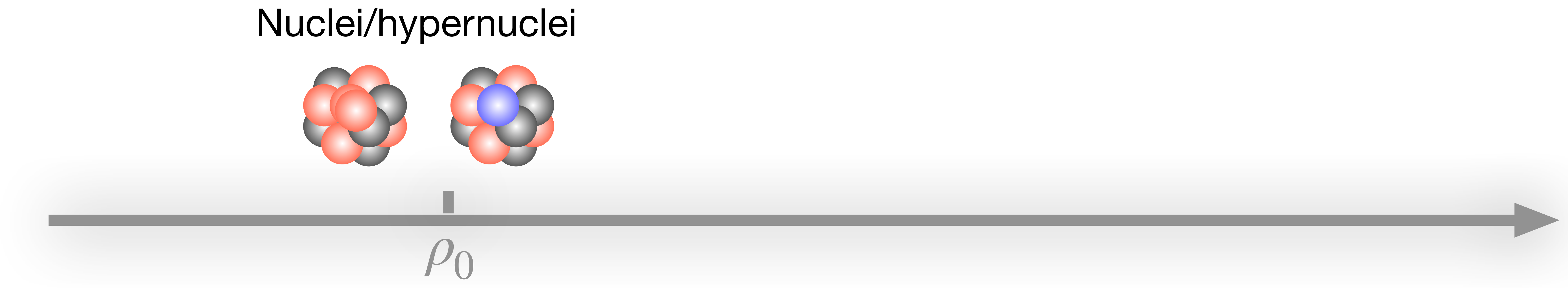
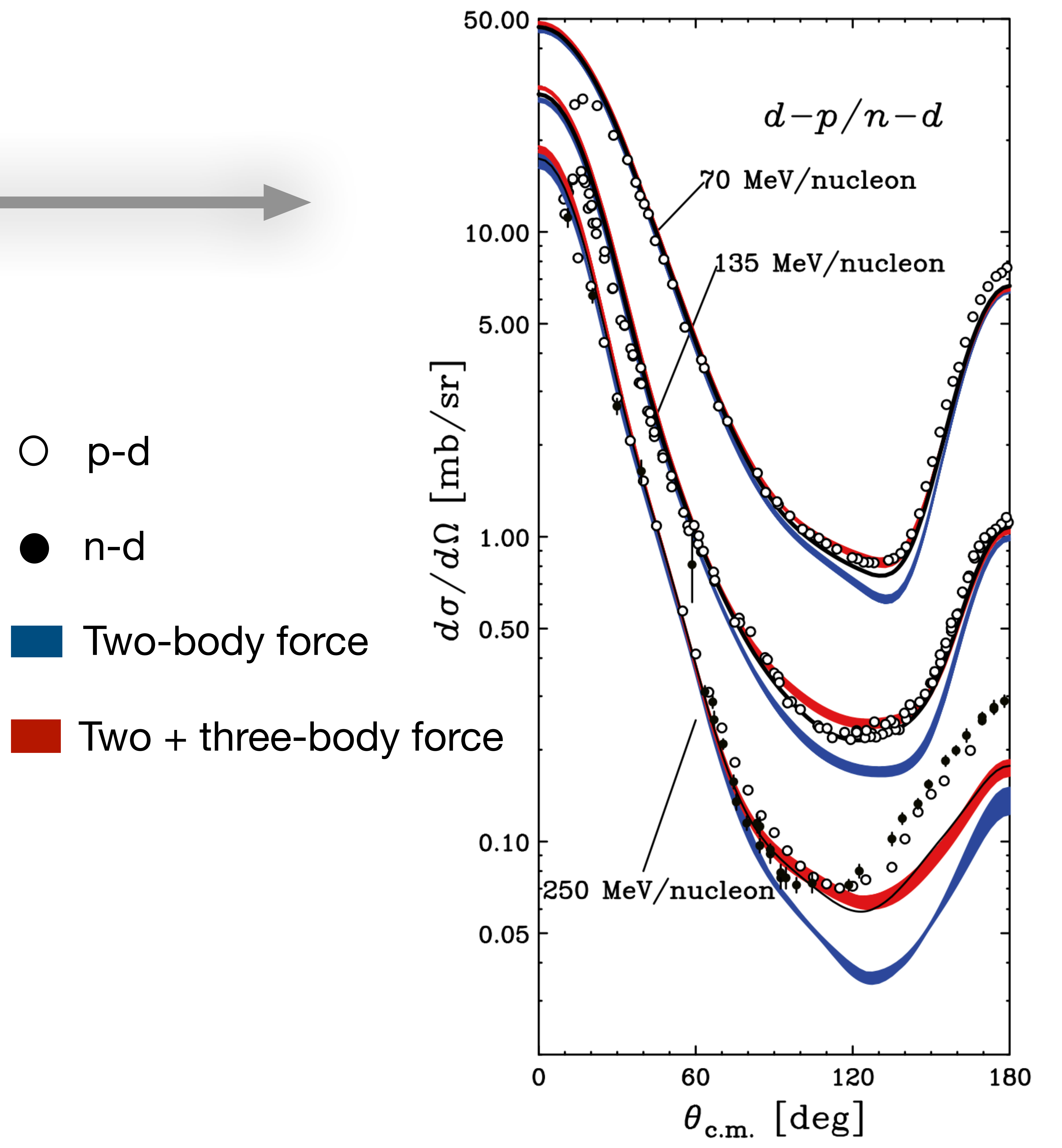
PDG, PTEP 2022, 083C01(2022)





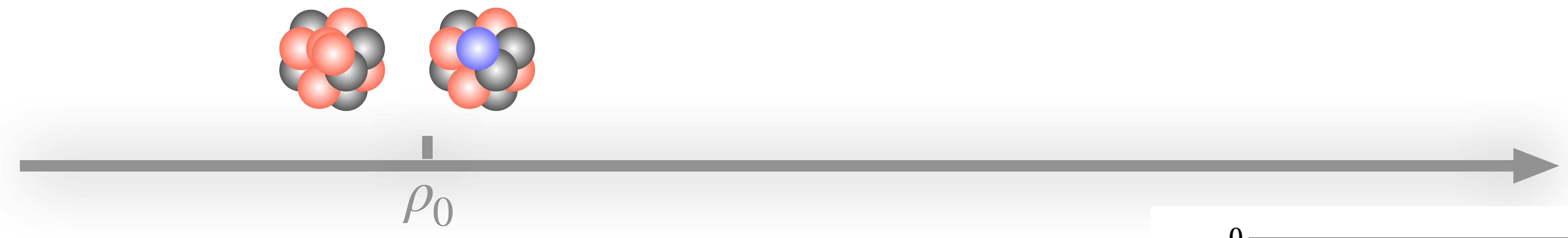
- Neutron-deuteron scattering observables: requires the presence of **three-body interaction**



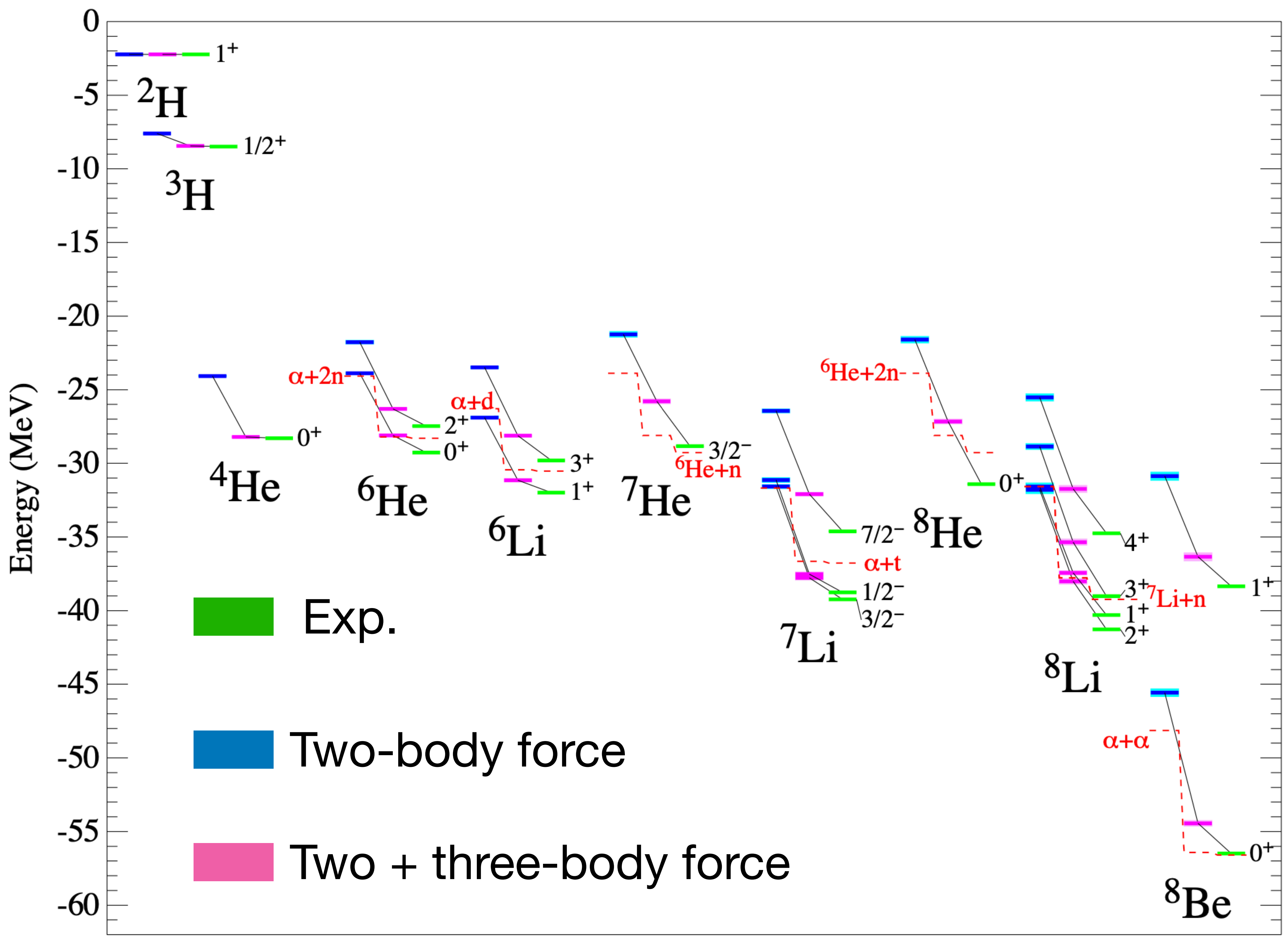
Sekiguchi, K. Few-Body Syst 60, 56 (2019)

Why do we need three-body interaction?

Nuclei/hypernuclei



- Neutron-deuteron scattering observables: requires the presence of **three-body interaction**
- NNN interaction contributes **~10%** to the binding energies of light nuclei



Steven C. Pieper et al, Phys. Rev. C 64, 014001 (2001)

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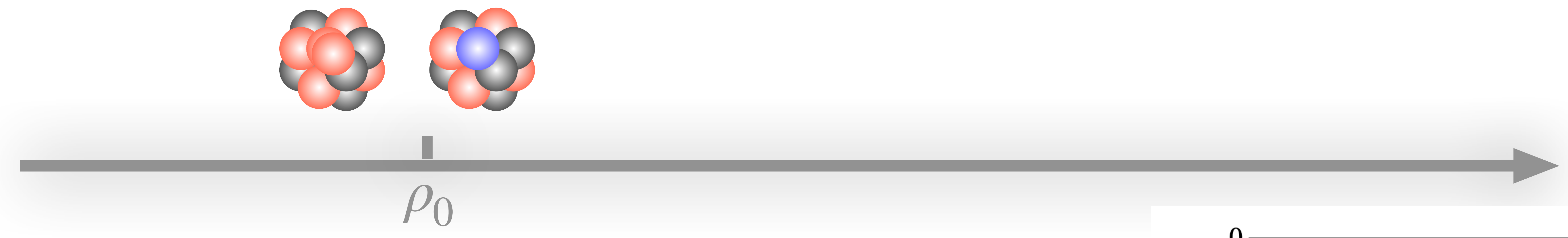

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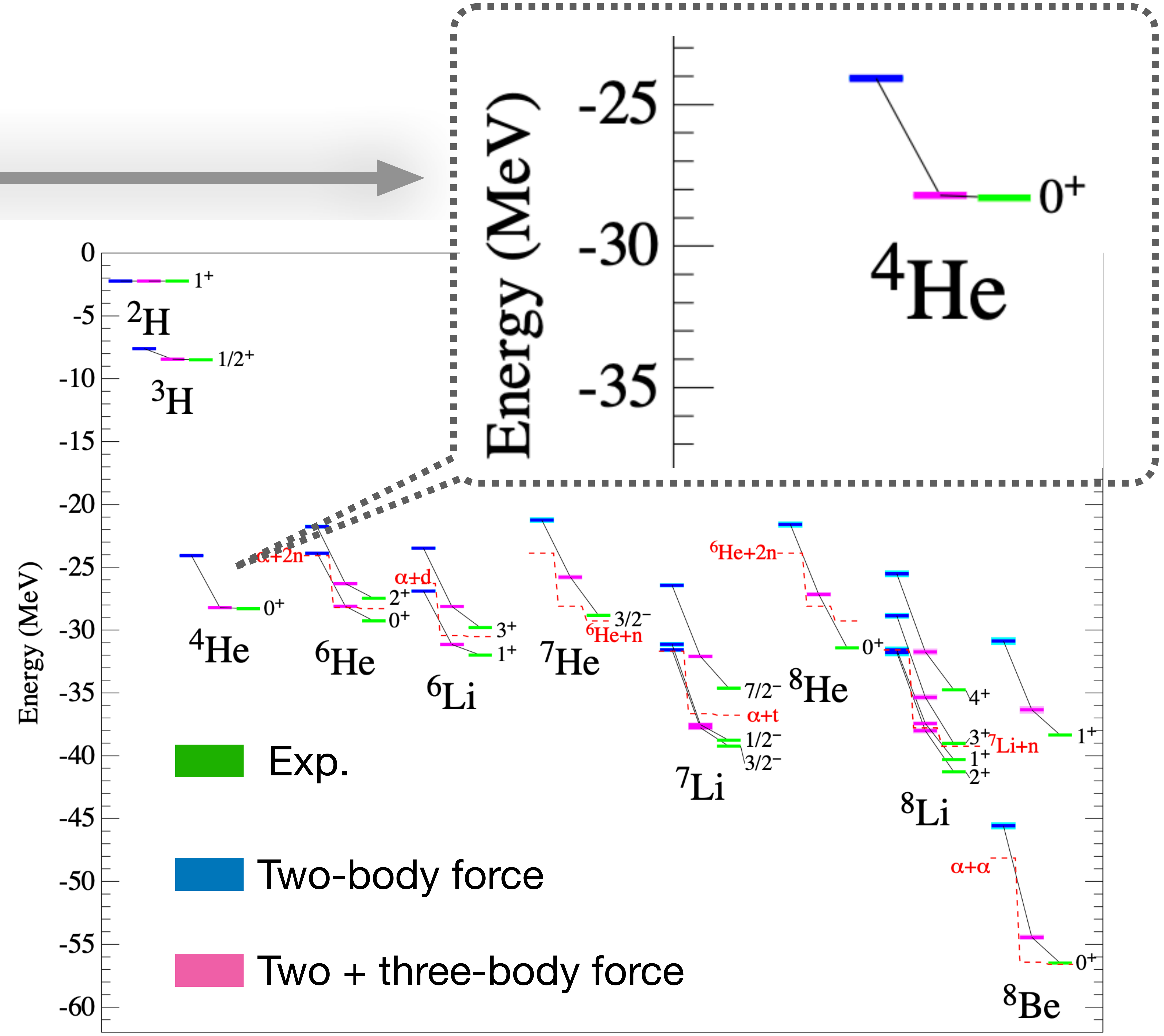

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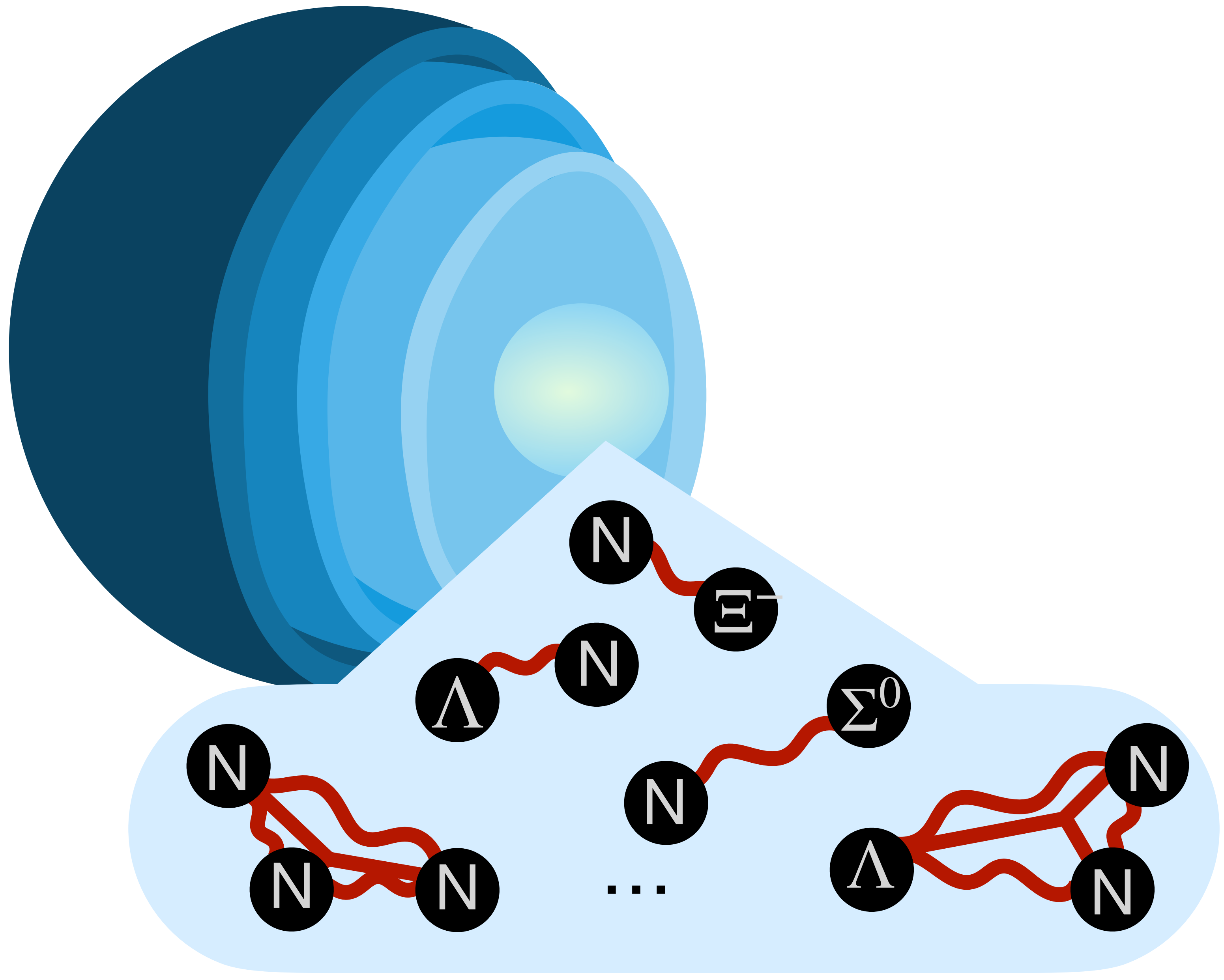
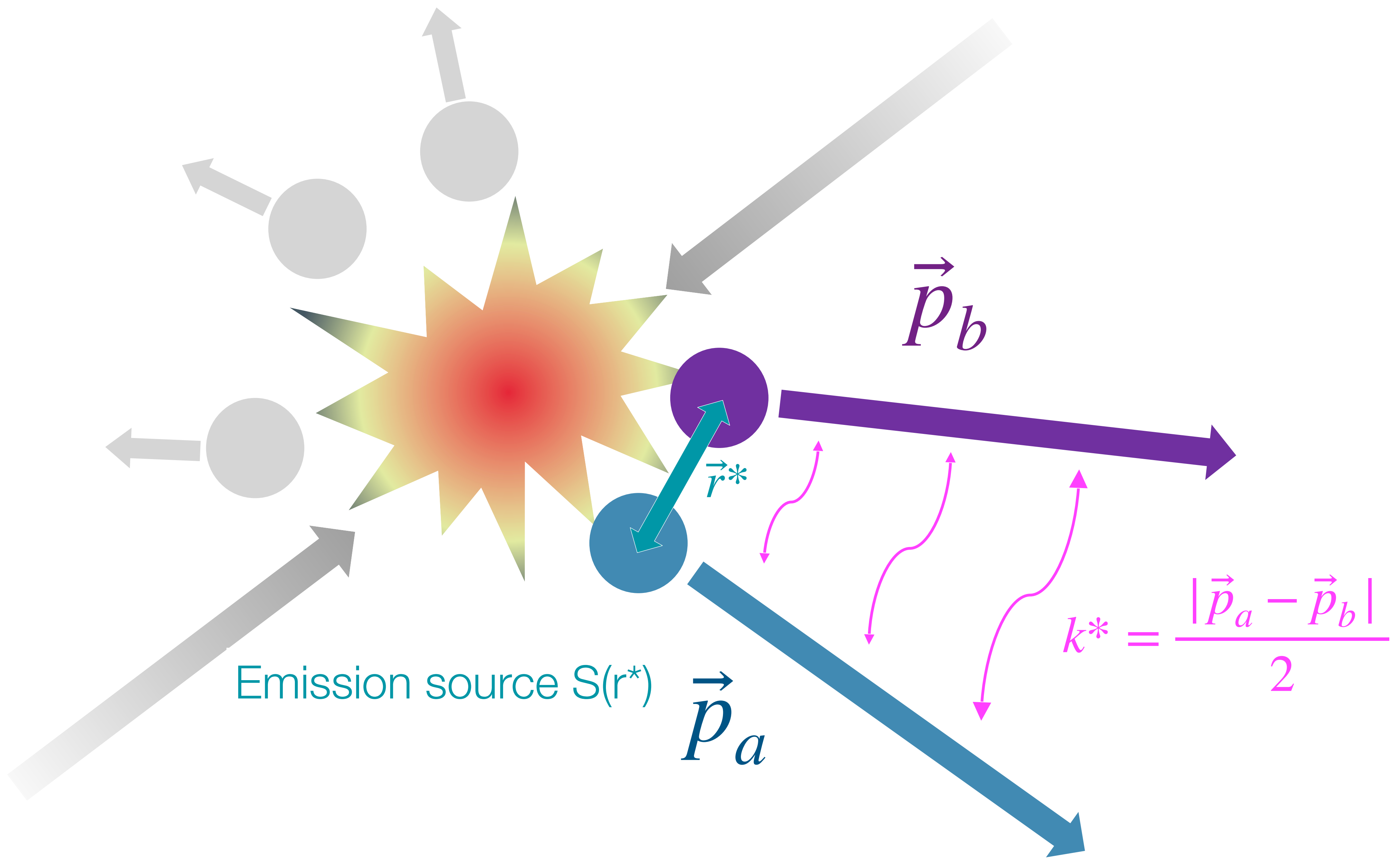
Why do we need three-body interaction?

- Neutron-deuteron scattering observables: requires the presence of **three-body interaction**
- NNN interaction contributes **~10%** to the binding energies of light nuclei
- NNN and NNΛ interactions used in the modeling of the equation of the state of neutron stars



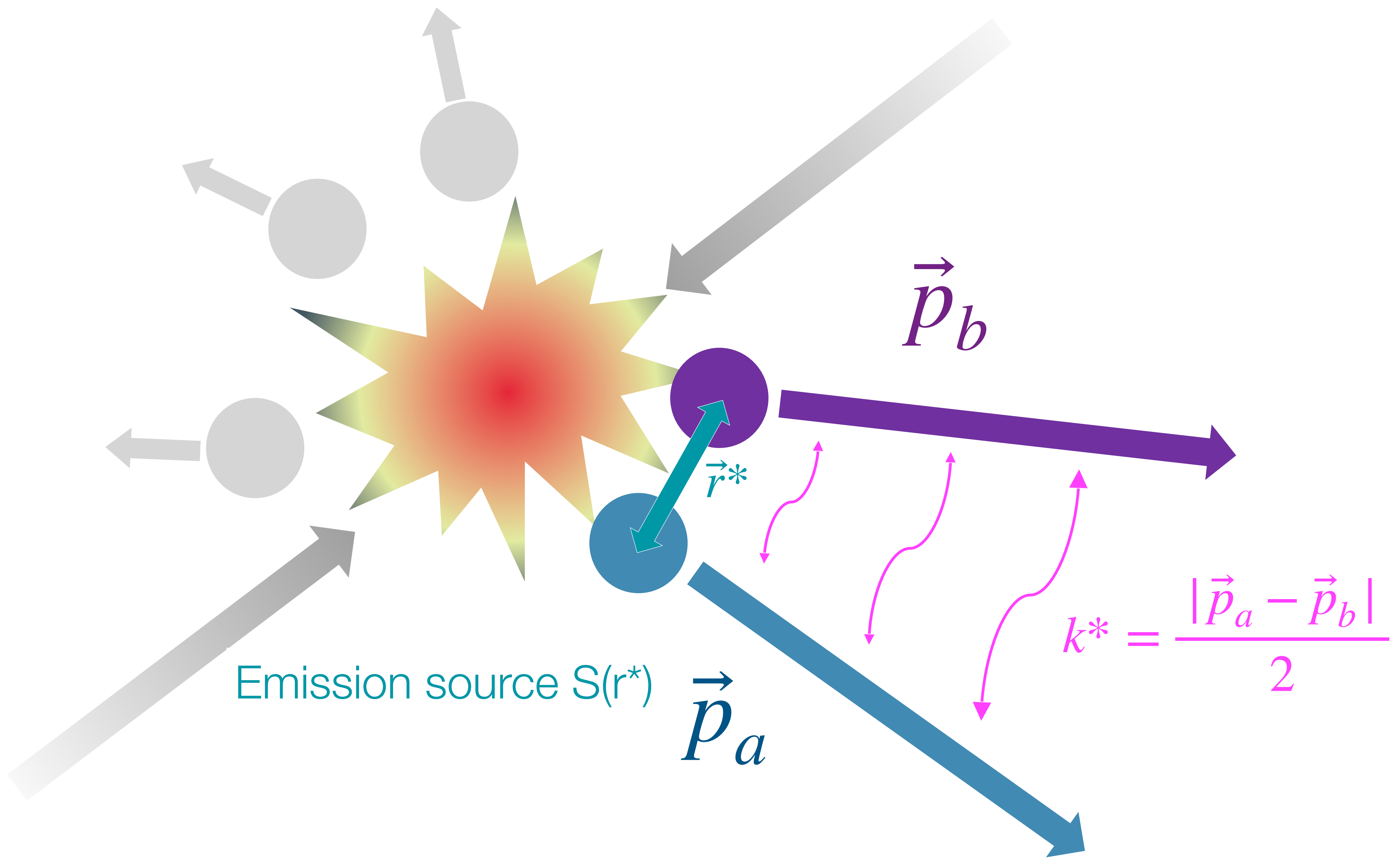
D. Lonardoni et al, PRL 114, 092301 (2015)
J. Schaffner-Bielich et al, NPA 835 (2010)

Femtoscopy with ALICE



S.E. Koonin, PLB 70 43 (1977)
L. Fabbietti et al, Ann. Rev. Nucl. Part.Sci. 71 (2021) 377-402

Femtoscopy with ALICE



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

experimental definition

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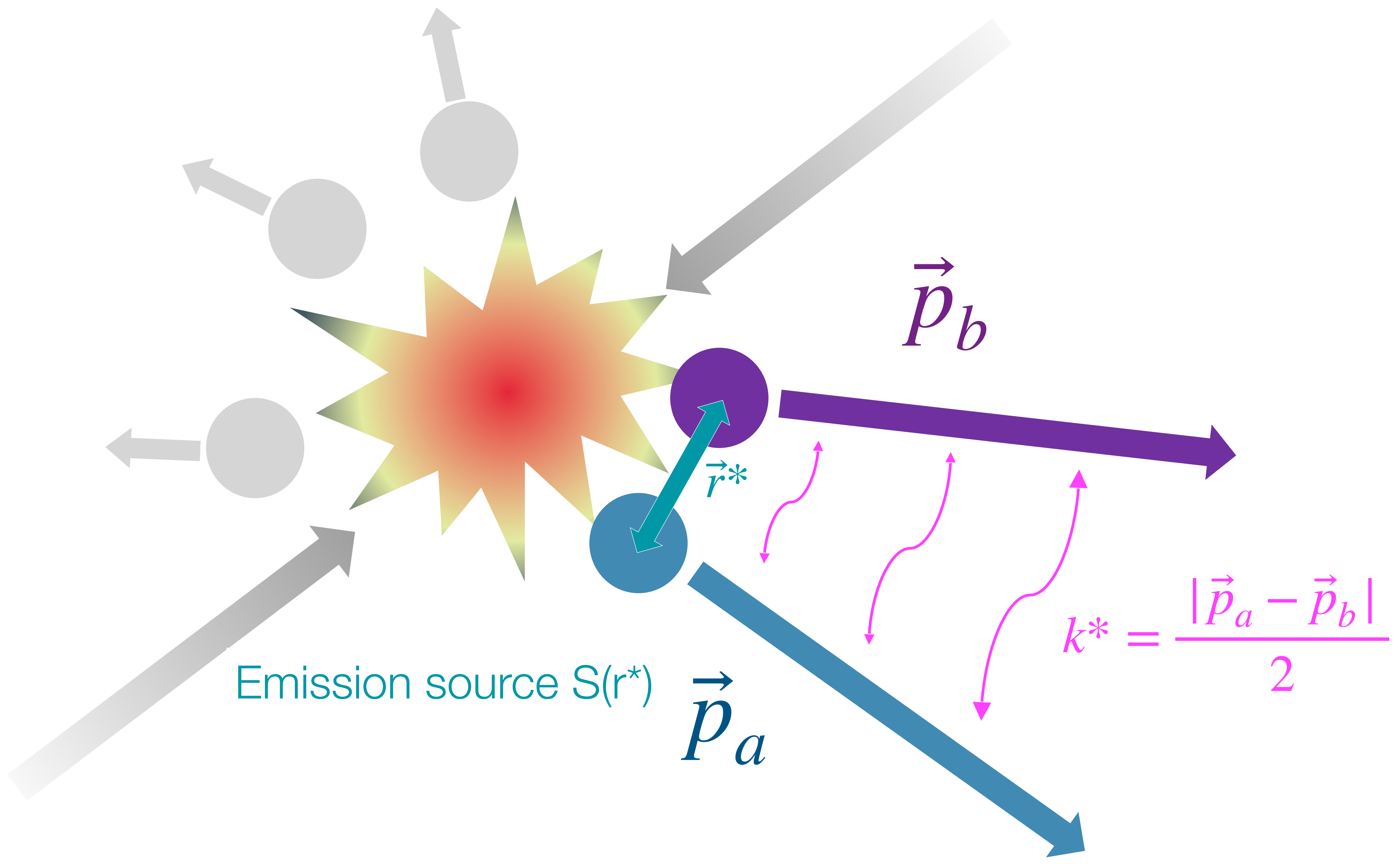

$$C(k^*) = \mathcal{N}\frac{N_{\mathrm{same}}(k^*)}{N_{\mathrm{mixed}}(k^*)} = \int S(\vec{r}^*)\left|\psi(\vec{k}^*, \vec{r}^*)\right|^2 d^3r^* \xrightarrow{k^*\to\infty} 1$$

experimental definition   theoretical definition

S.E. Koonin, PLB 70 43 (1977)
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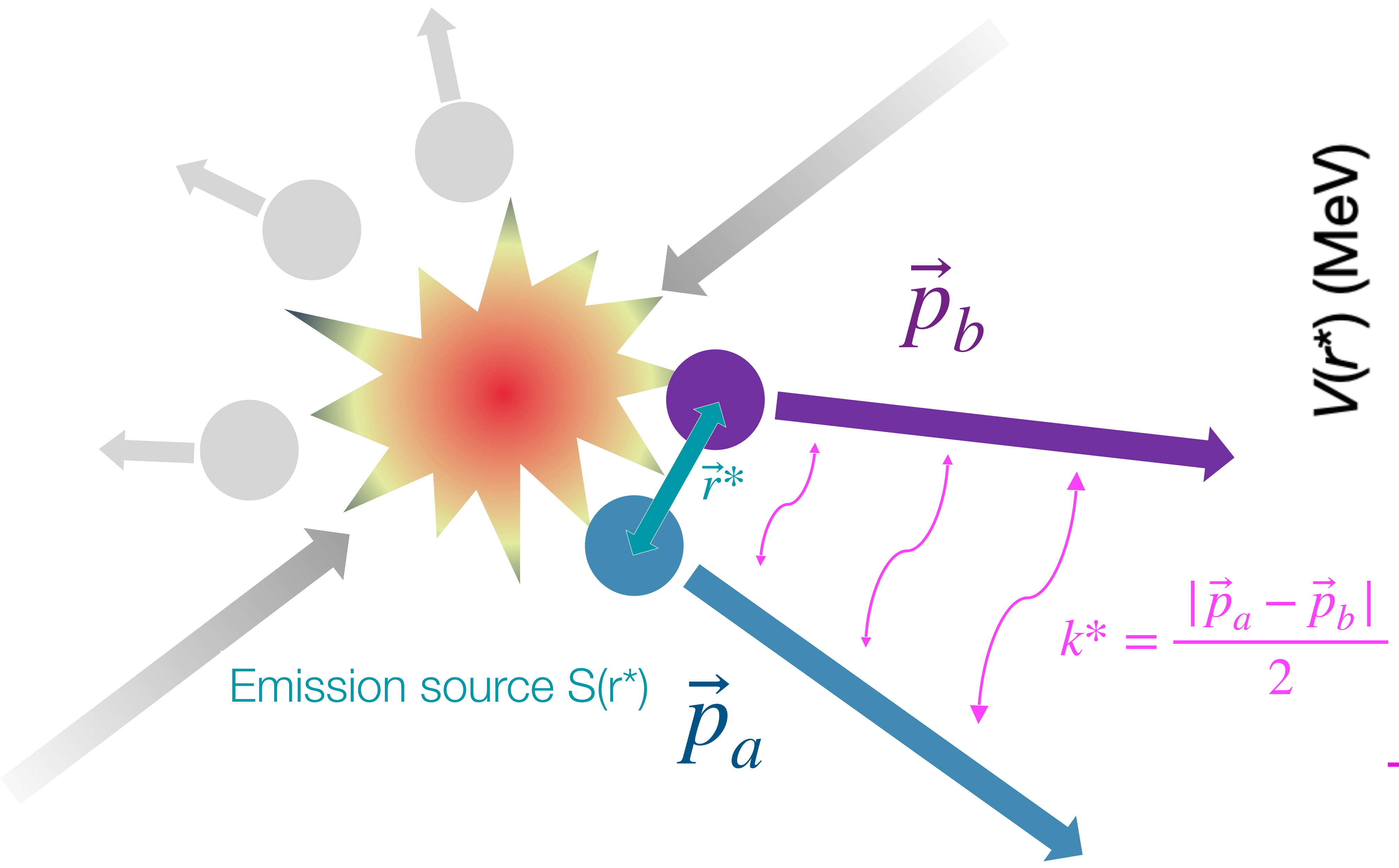
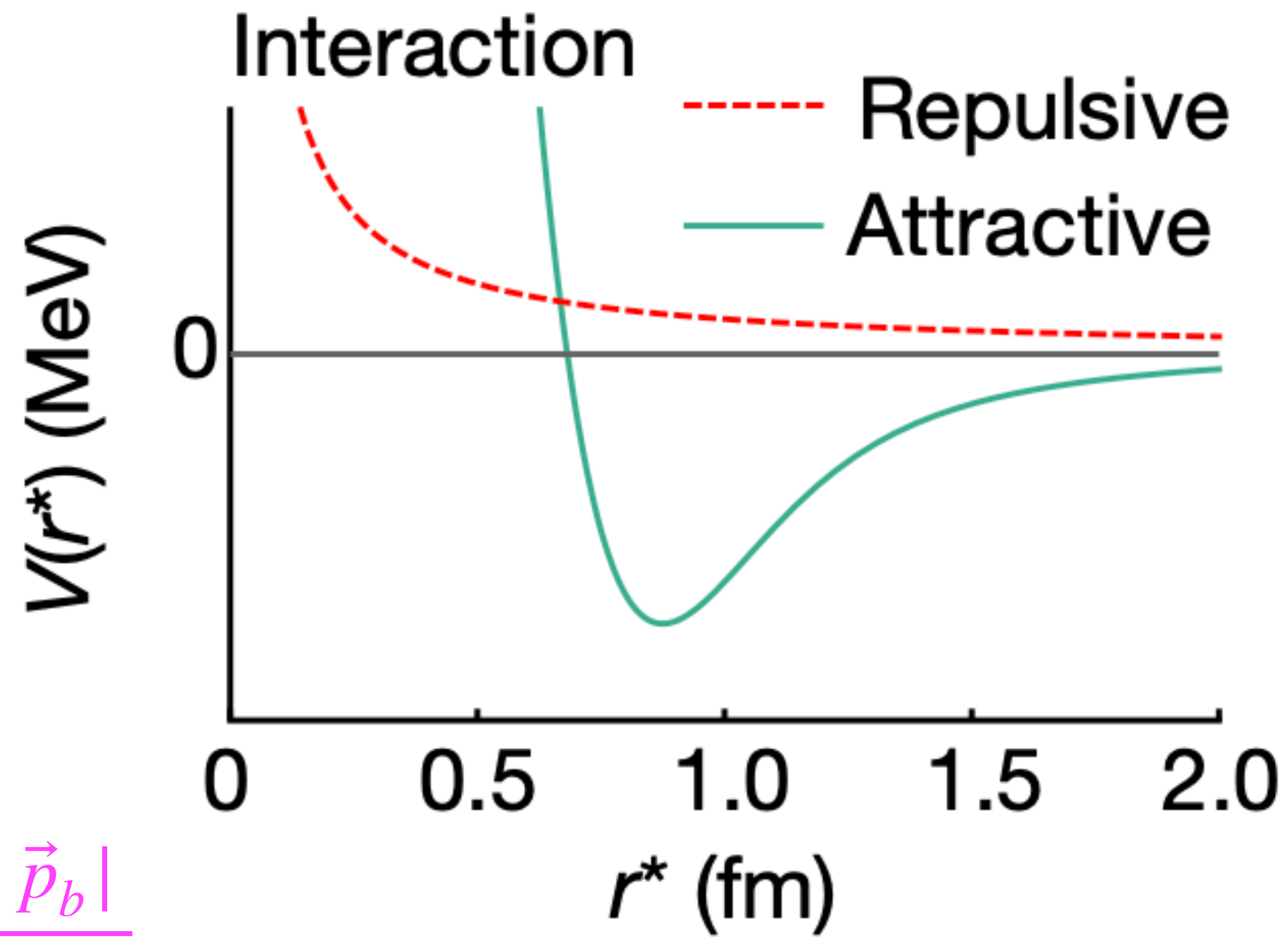
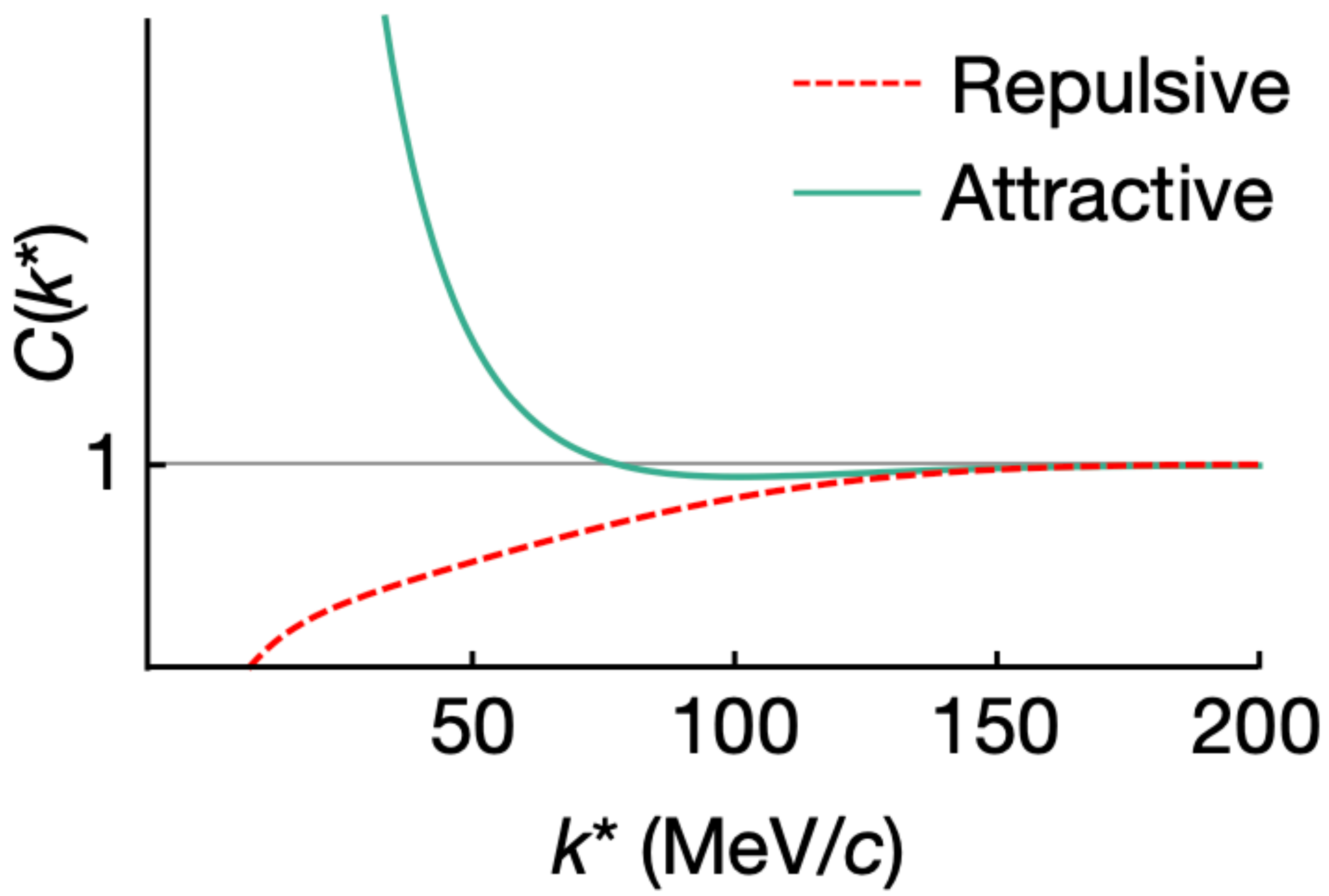




Schrödinger equation

Two-particle wave function

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



Correlation function $C(k^*)$

$$C(k^*) = \mathcal{N} \frac{N_{\text{same}}(k^*)}{N_{\text{mixed}}(k^*)} = \int S(\vec{r}^*) \left| \psi(\vec{k}^*, \vec{r}^*) \right|^2 d^3 r^* \xrightarrow{k^* \to \infty} 1$$

experimental definition theoretical definition

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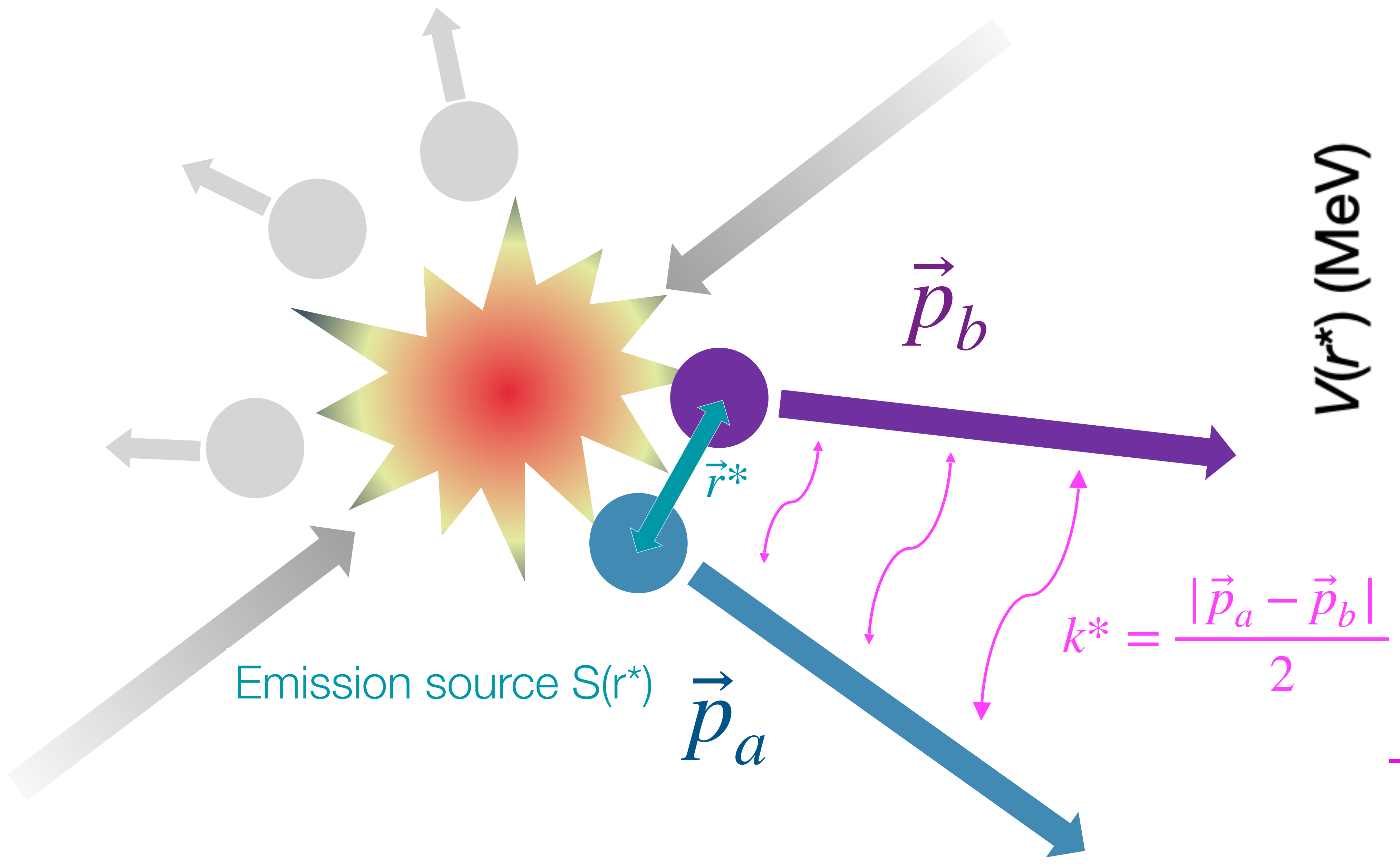
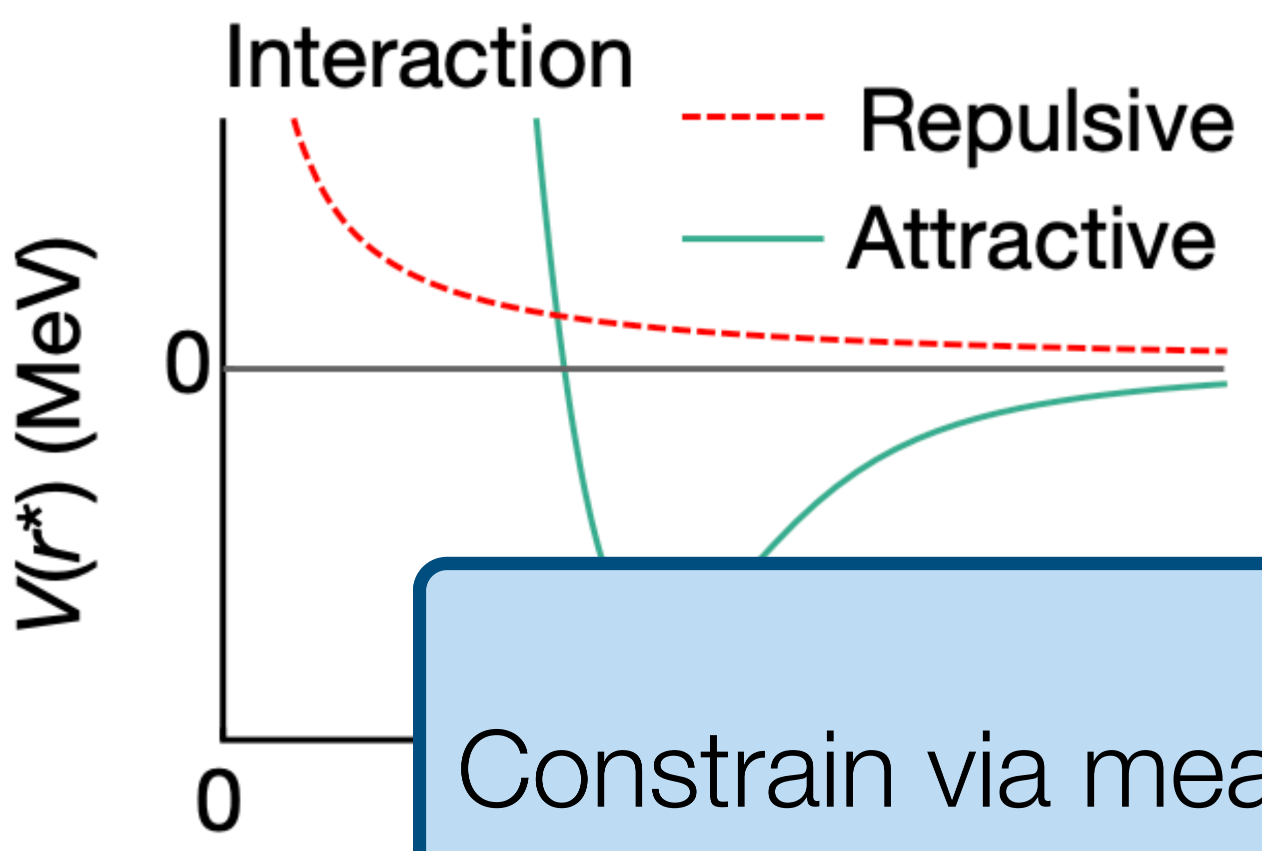
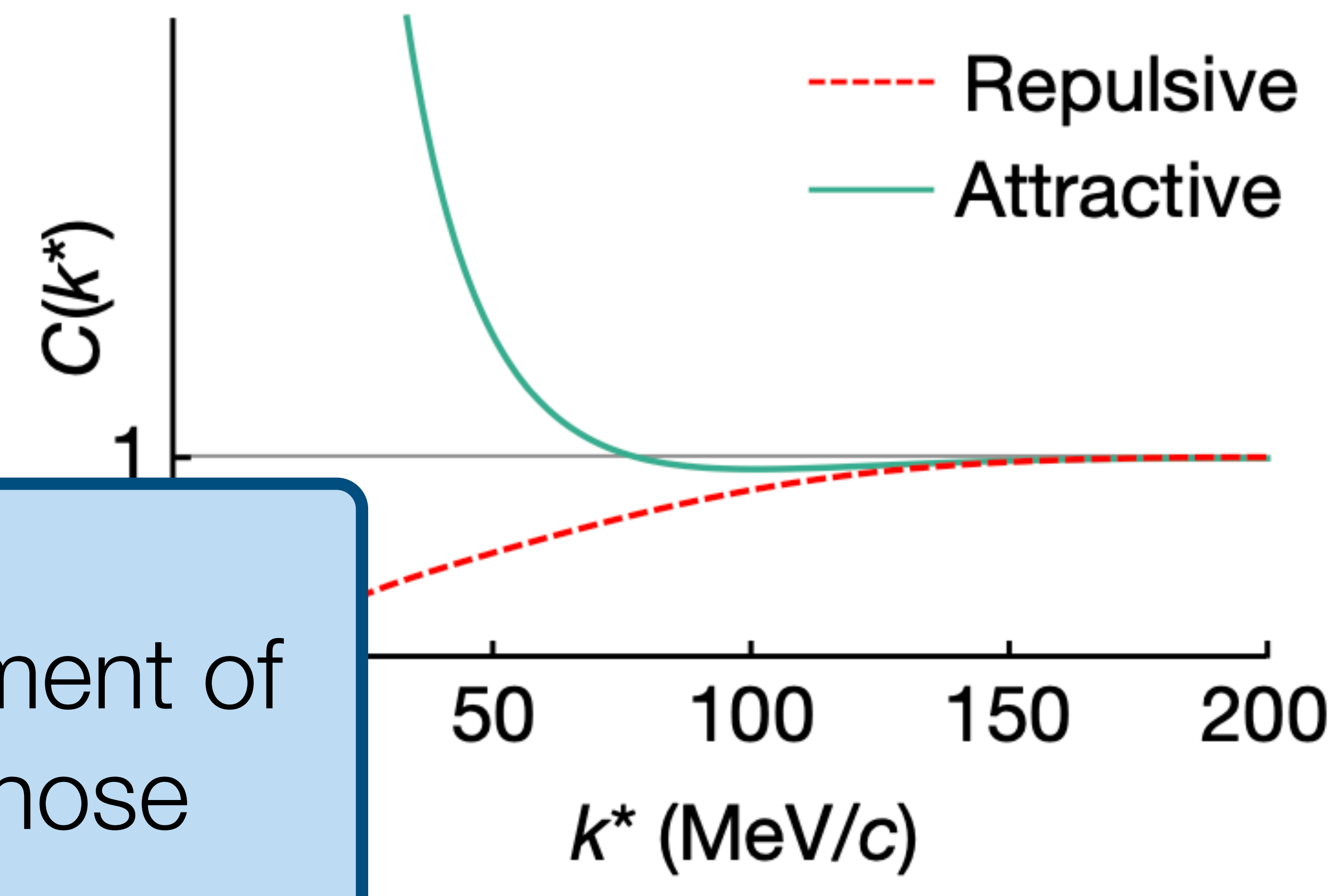
Femtoscopy with ALICE





Sch



ation function $C(k^*)$

Two

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

Constrain via measurement of correlation in pairs whose interaction is well known

$$C(k^*) = \mathcal{N}\frac{N_{\text{same}}(k^*)}{N_{\text{mixed}}(k^*)} = \int S(\vec{r}^*)\left|\psi(\vec{k}^*, \vec{r}^*)\right|^2 d^3r^* \xrightarrow{k^*\to\infty} 1$$

experimental definition theoretical definition

S.E. Koonin, PLB 70 43 (1977)
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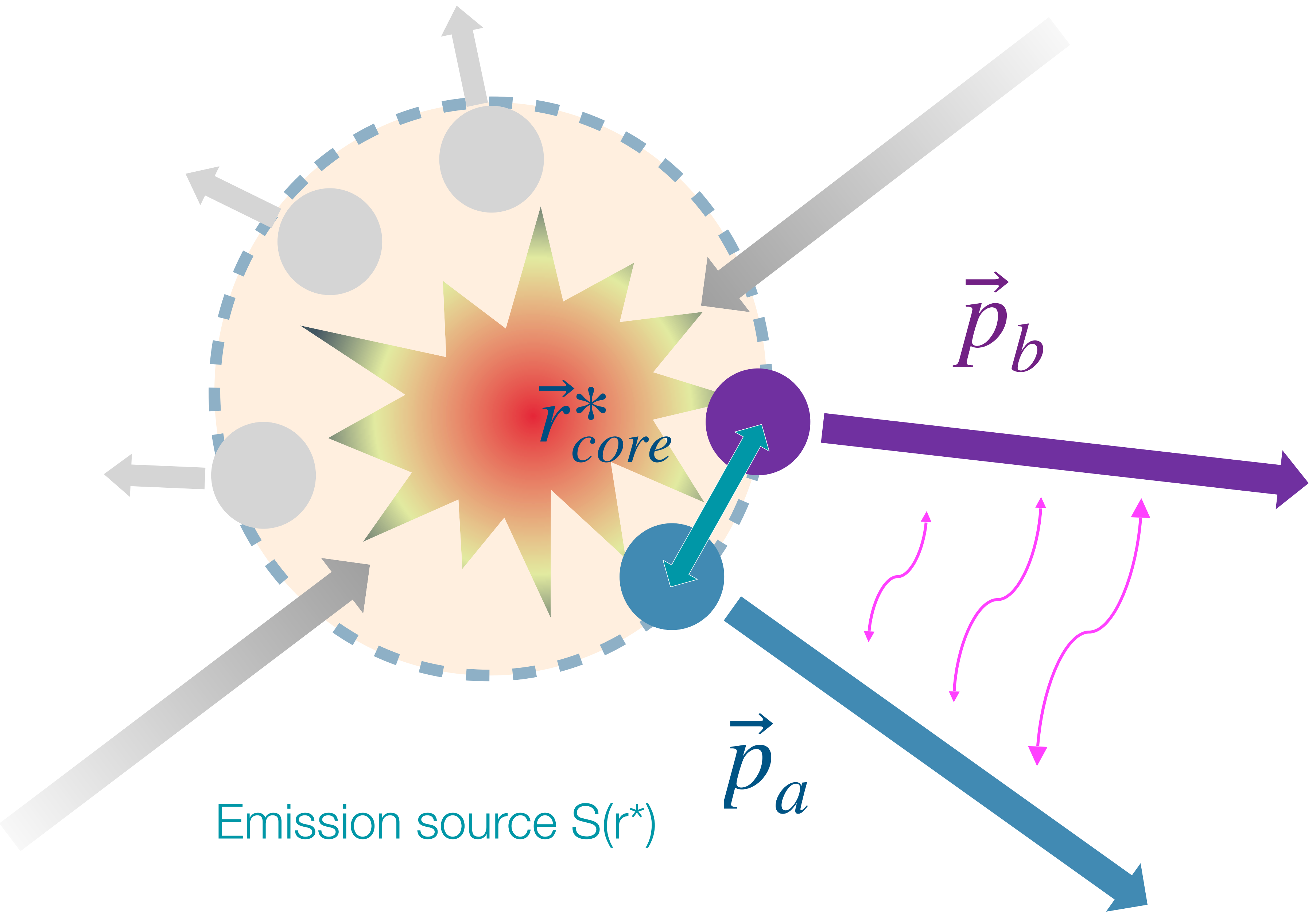
Constraining the source in pp collisions

- Common emission profile for **all hadron pairs**

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



Gaussian core source

ALICE Coll, PLB 811 (2020)

Constraining the source in pp collisions

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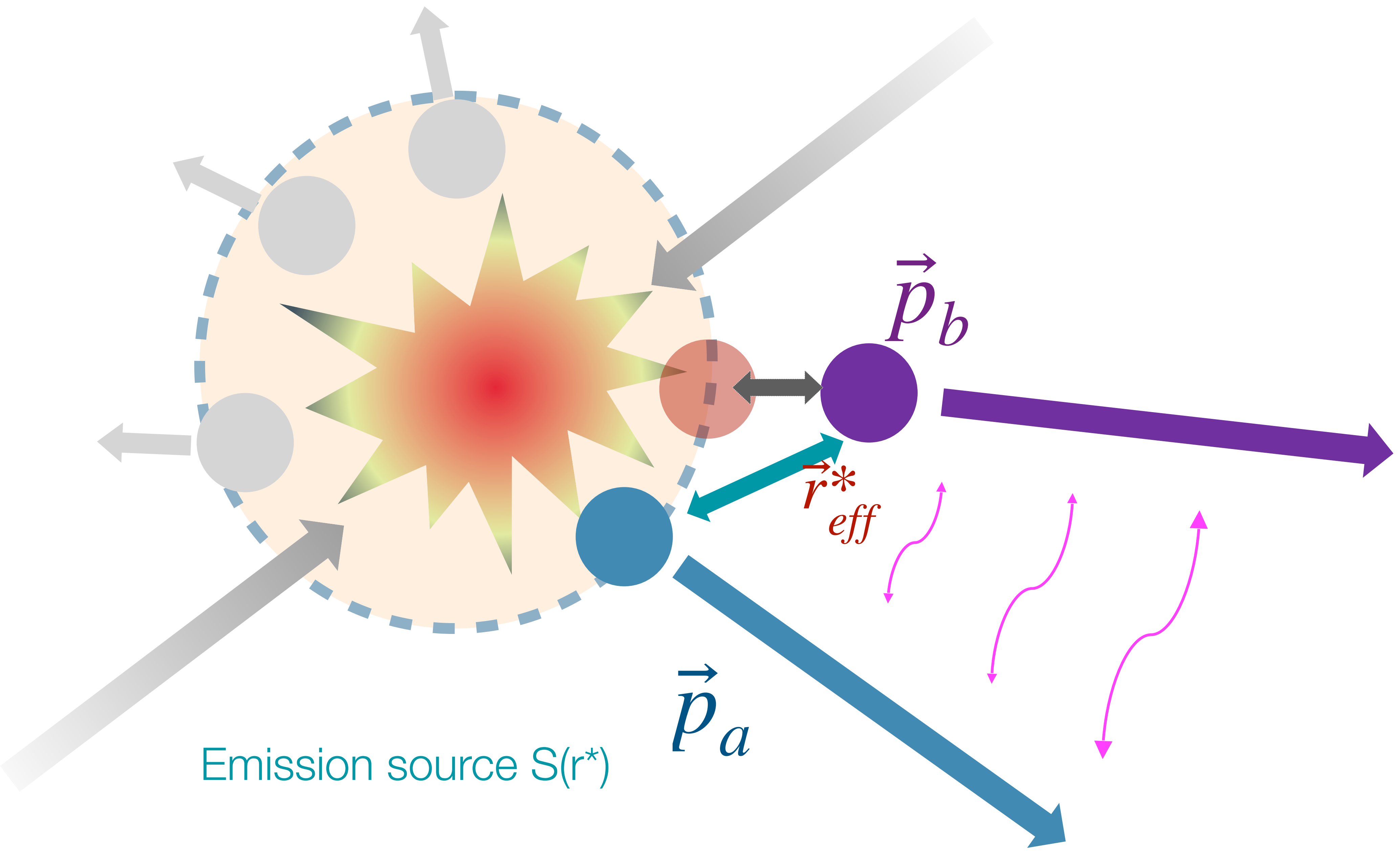
$$S(r^*) = \frac{1}{(4\pi\, r_{core}^2)^{3/2}} exp\left(-\frac{r^{*2}}{4\, r_{core}^2}\right)$$

- Include **short-lived strongly decaying** resonances
  - Life time
    $c\tau \sim r_{core} \sim$ 1fm (Δ^{++},N^*,Σ^*)
  - Yields are constrained using the thermal fist



Gaussian core source +resonance contributions

ALICE Coll, PLB 811 (2020)

Constraining the source in pp collisions

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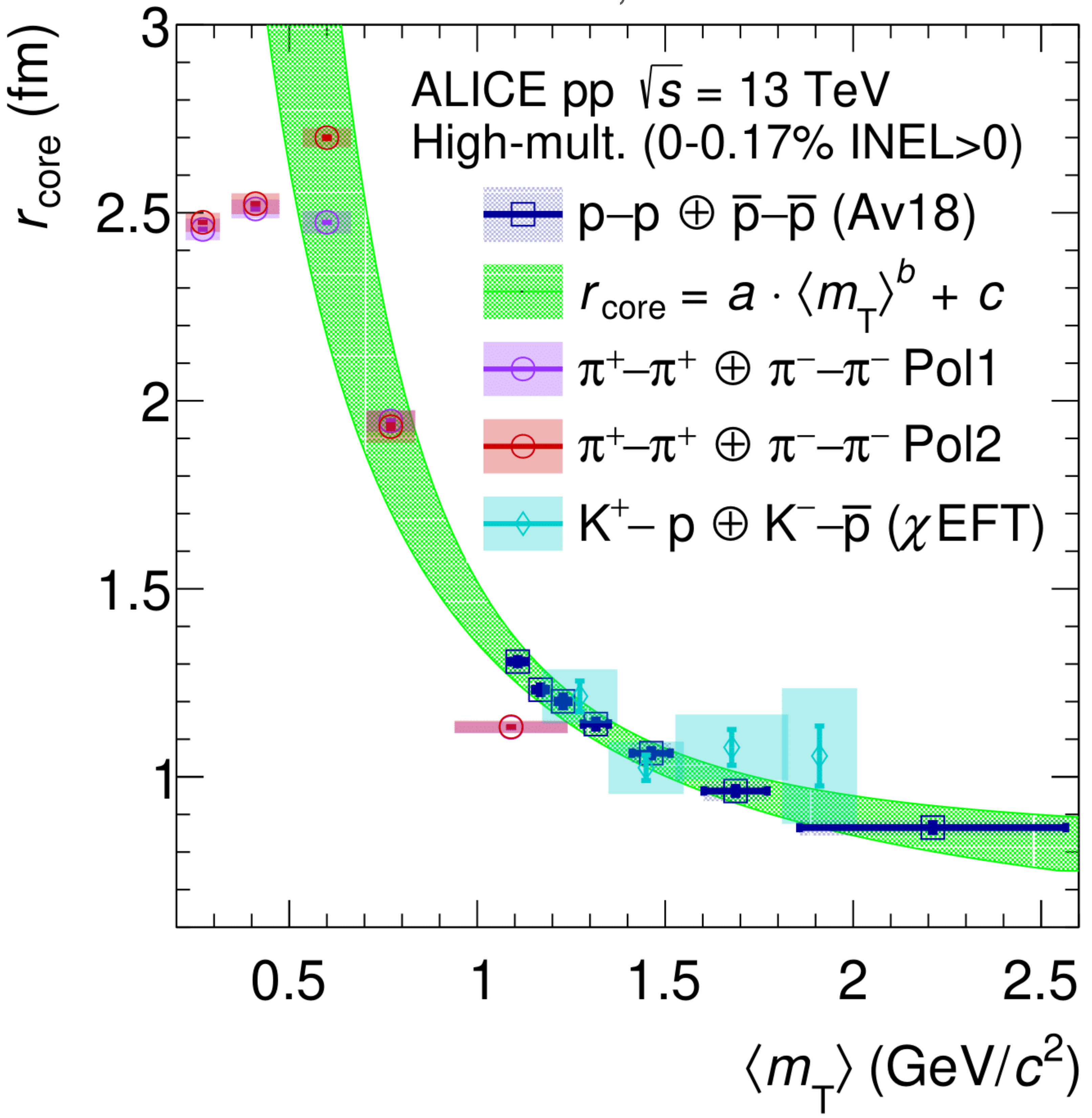
ALICE Coll, arXiv:2311.14527



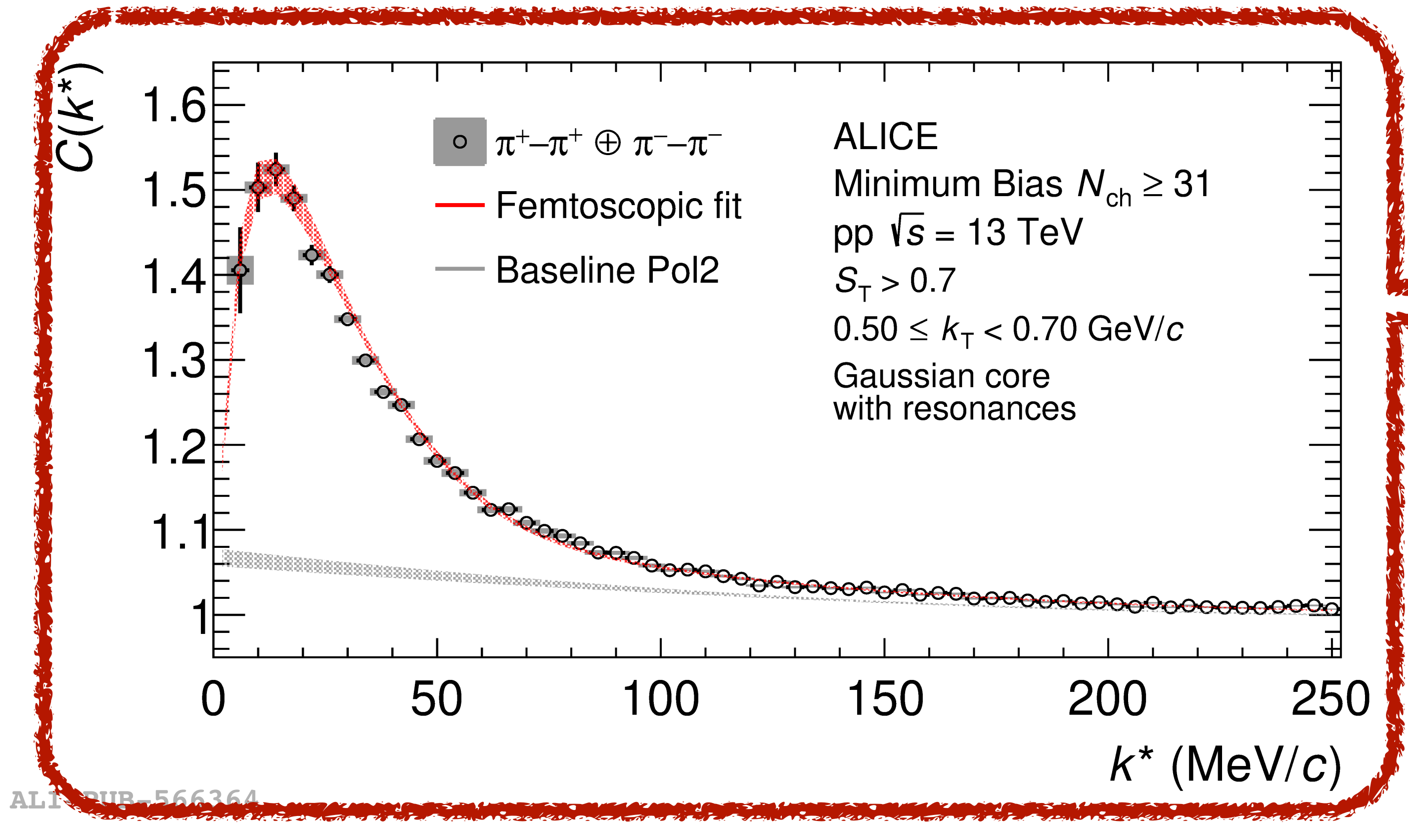
$$k_{\mathrm{T}} = \frac{1}{2}\left|\vec{p}_{\mathrm{T},1} + \vec{p}_{\mathrm{T},2}\right| \qquad m_{\mathrm{T}} = \sqrt{k_{\mathrm{T}}^2 + \langle m \rangle^2}$$

ALICE Coll, PLB 811 (2020)

Constraining the source in pp collisions

- Common emission profile for **all hadron pairs**

π-π (same charge):
Coulomb + quantum statistics



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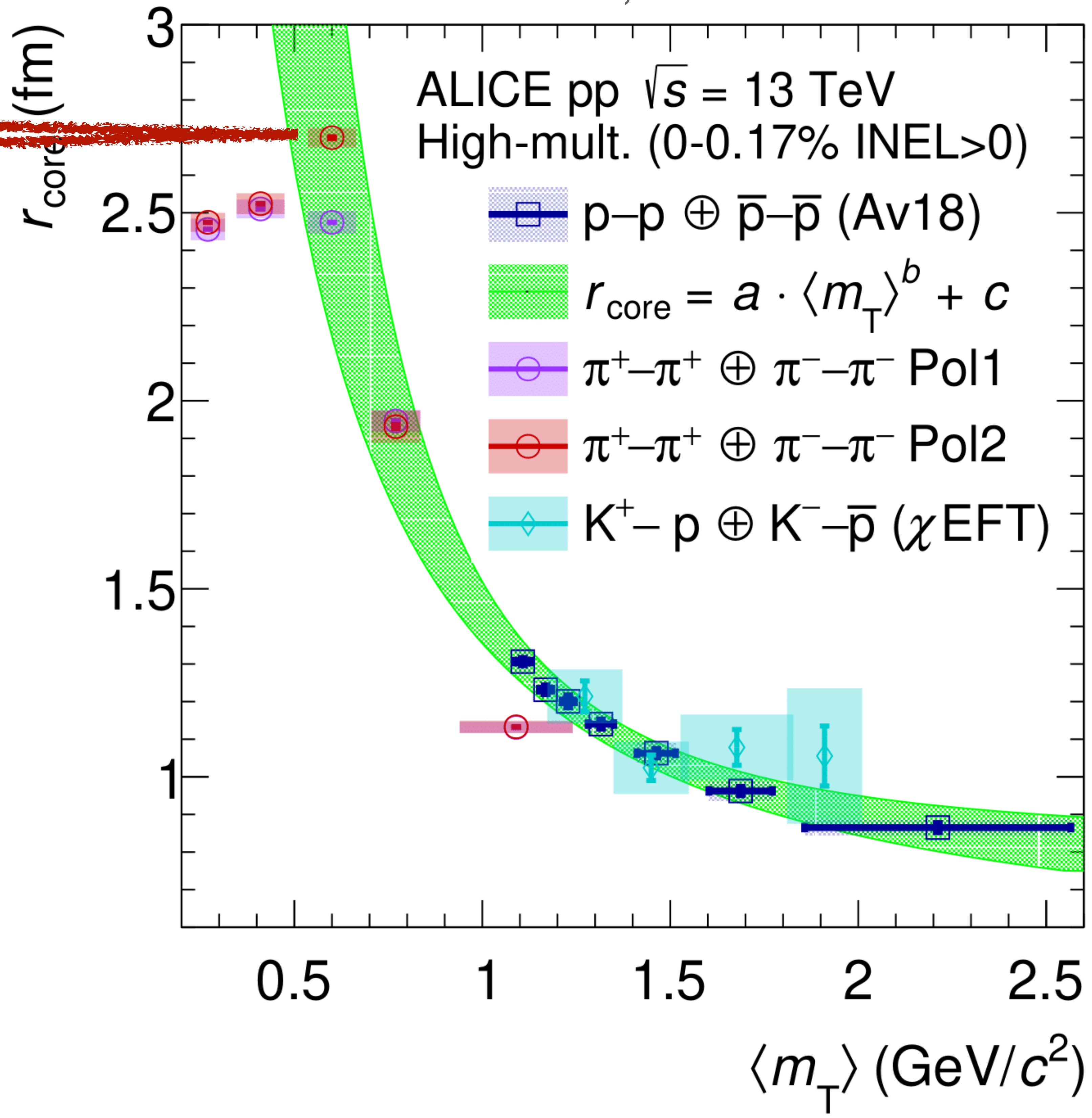

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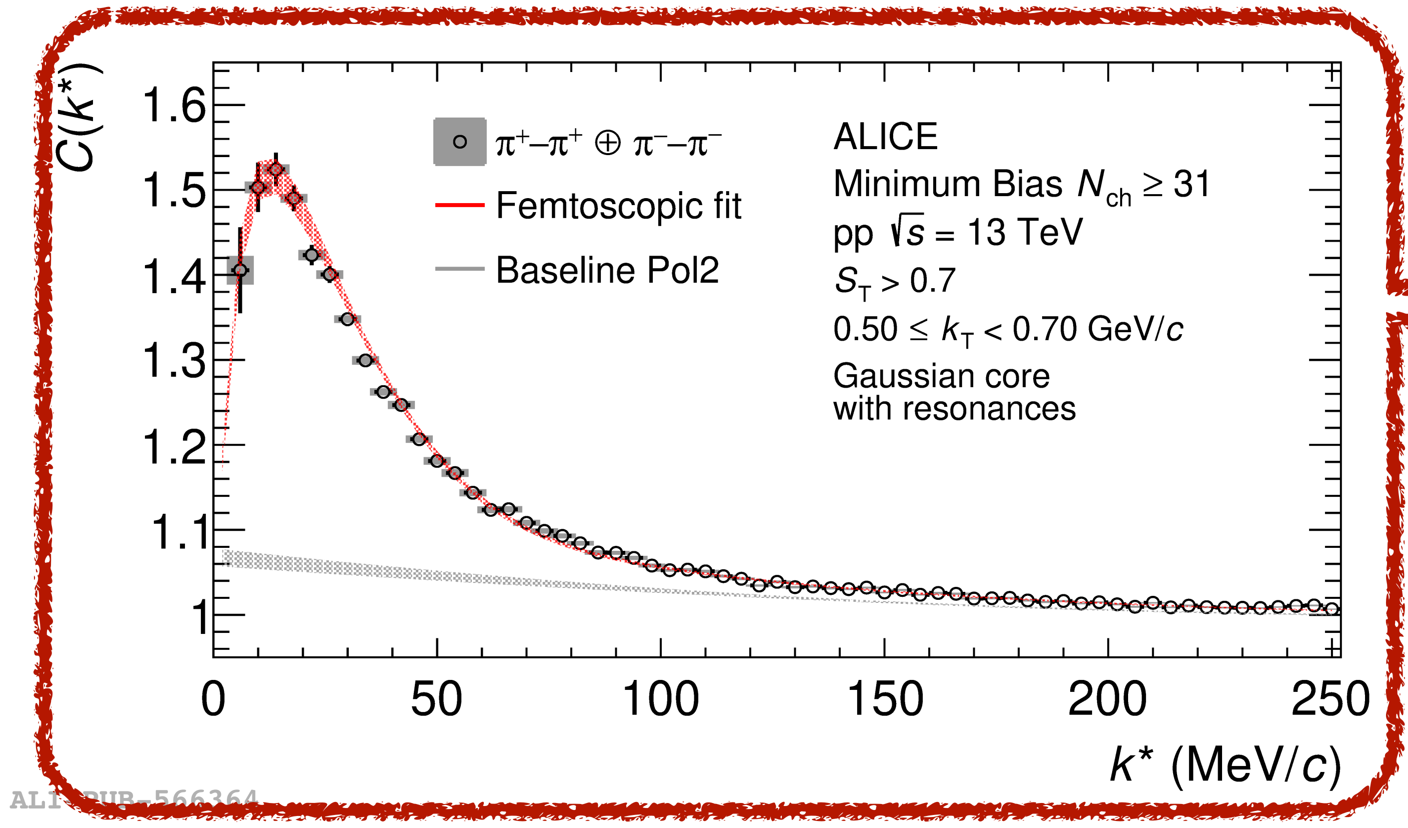

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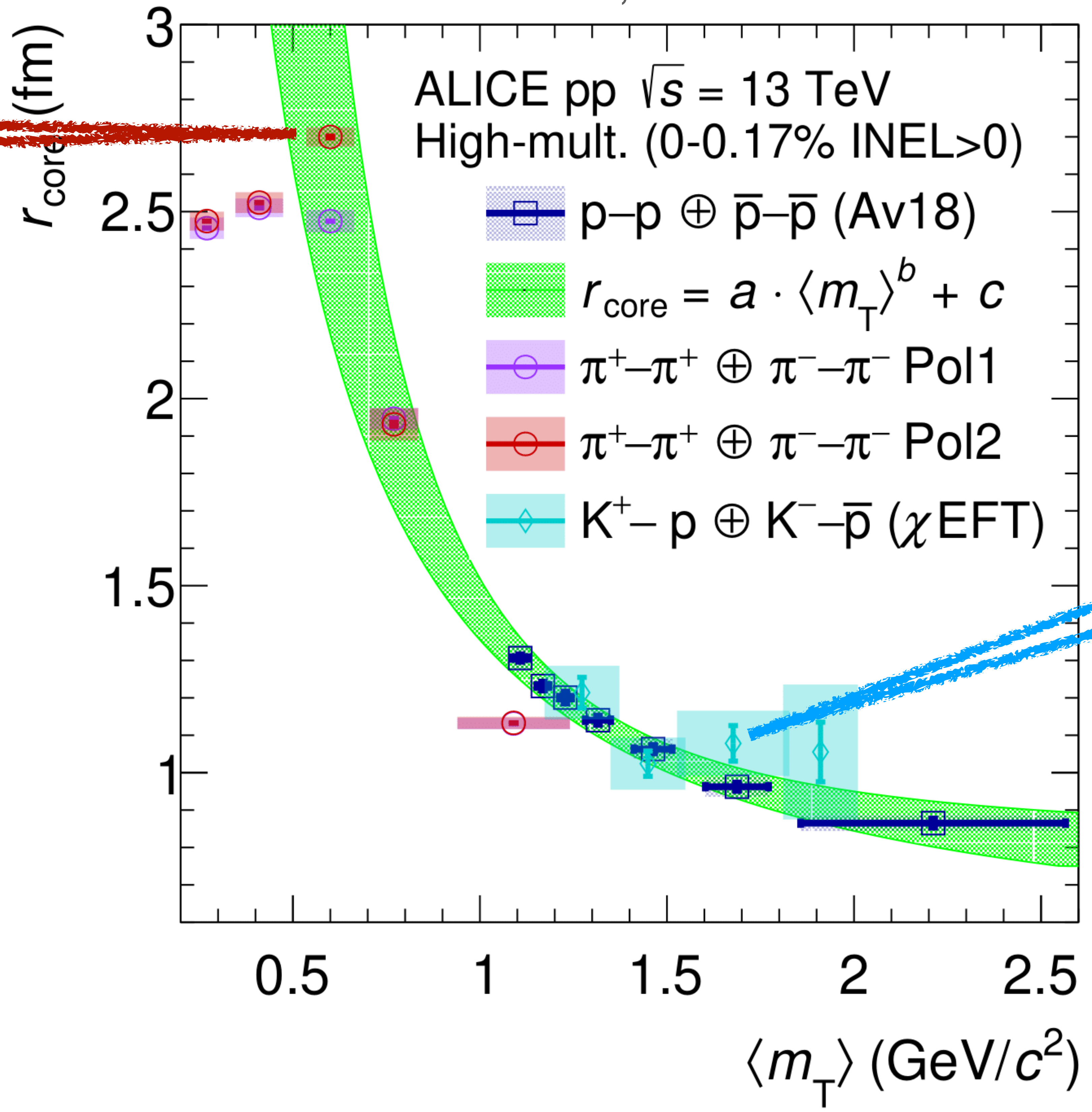
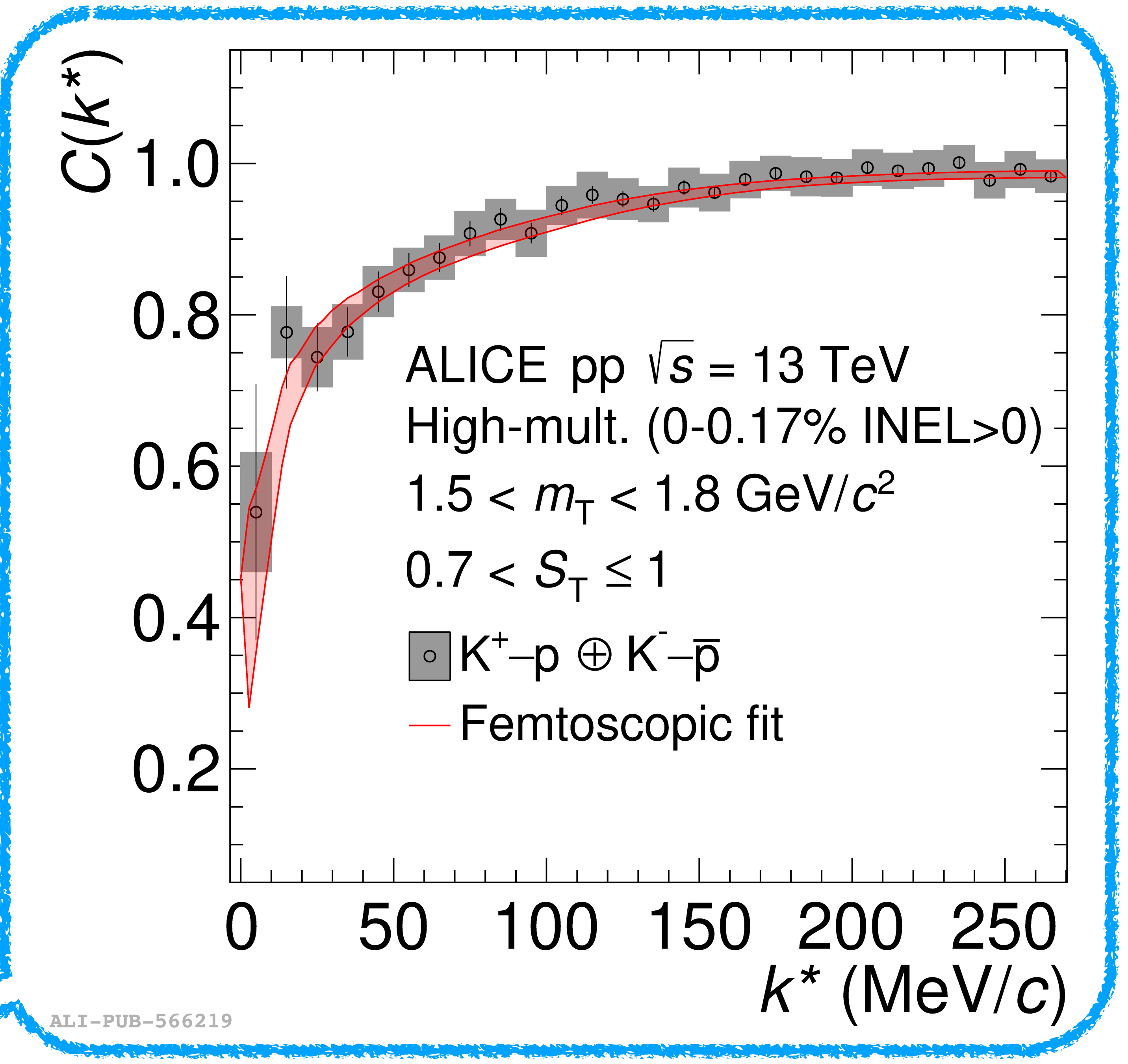


K⁺-p interaction:
Coulomb + KN Chiral potentials



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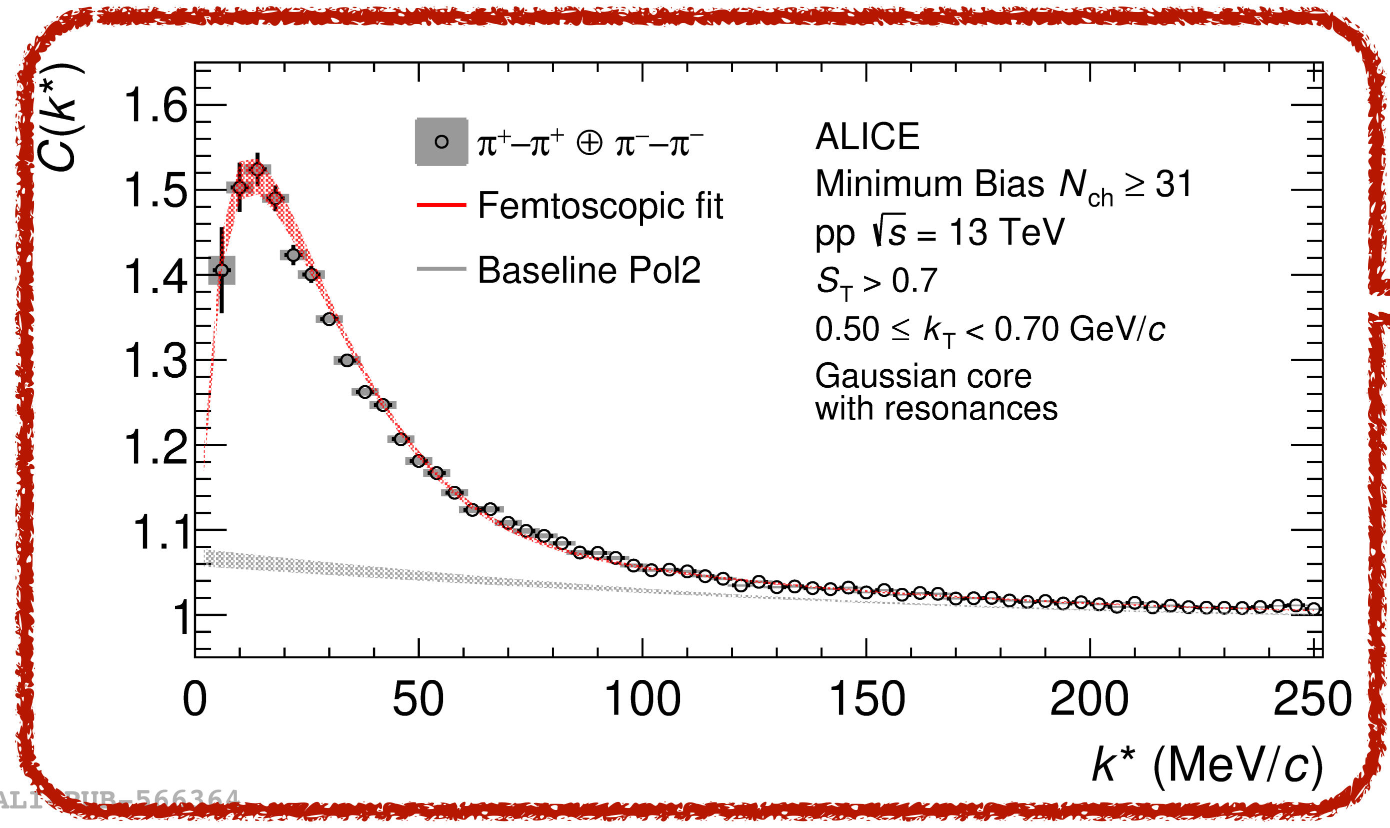
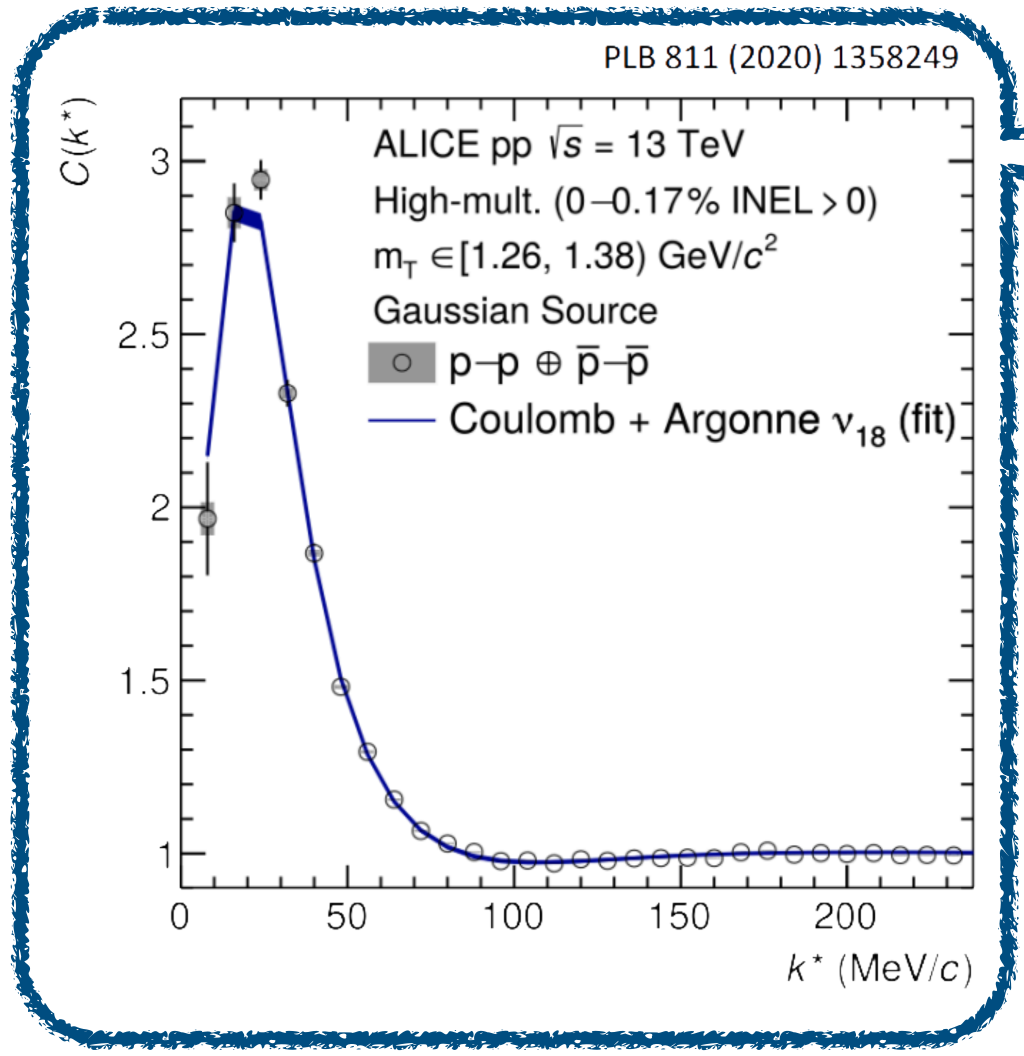


p-p: Coulomb + Argonne v18



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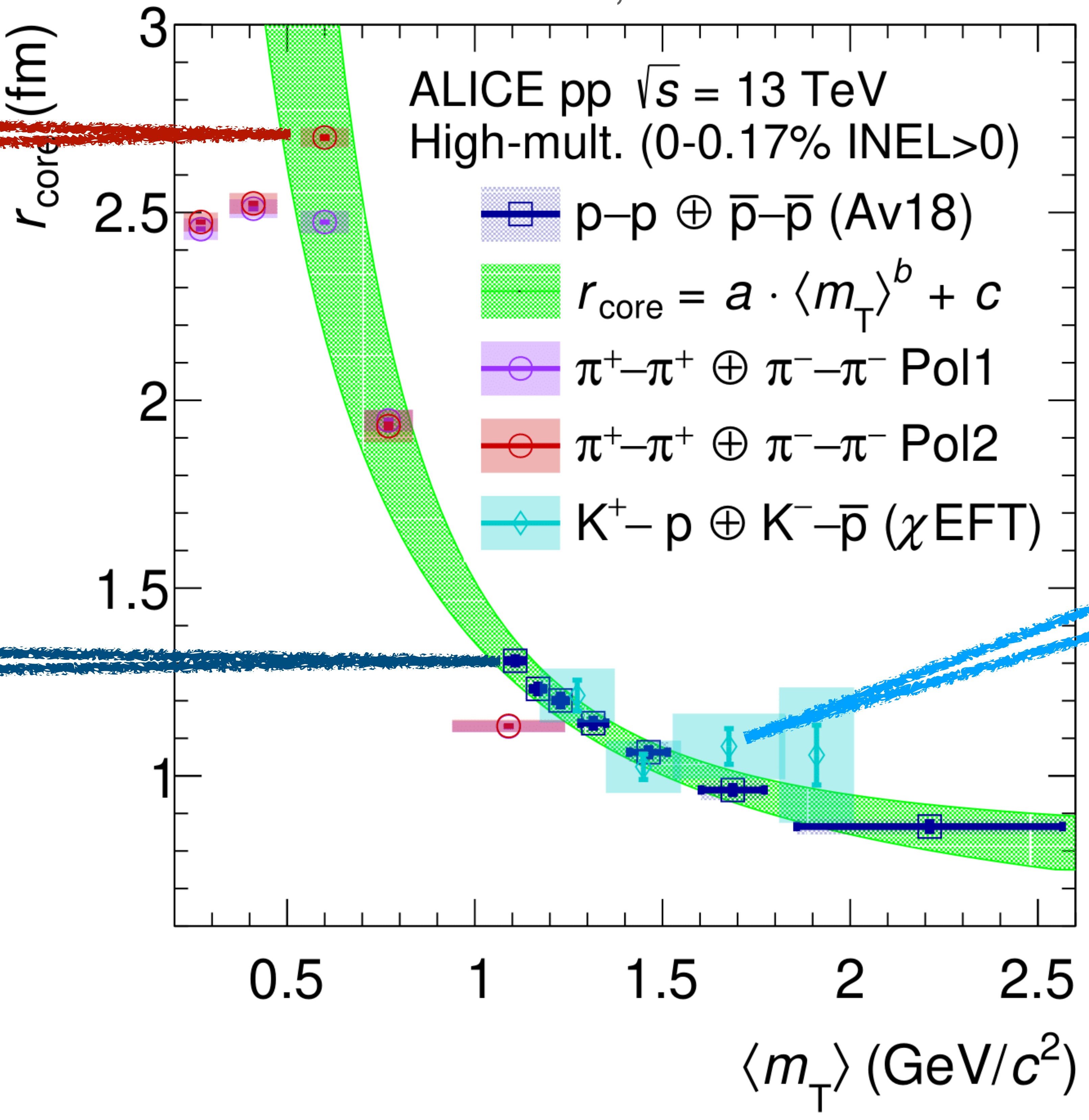

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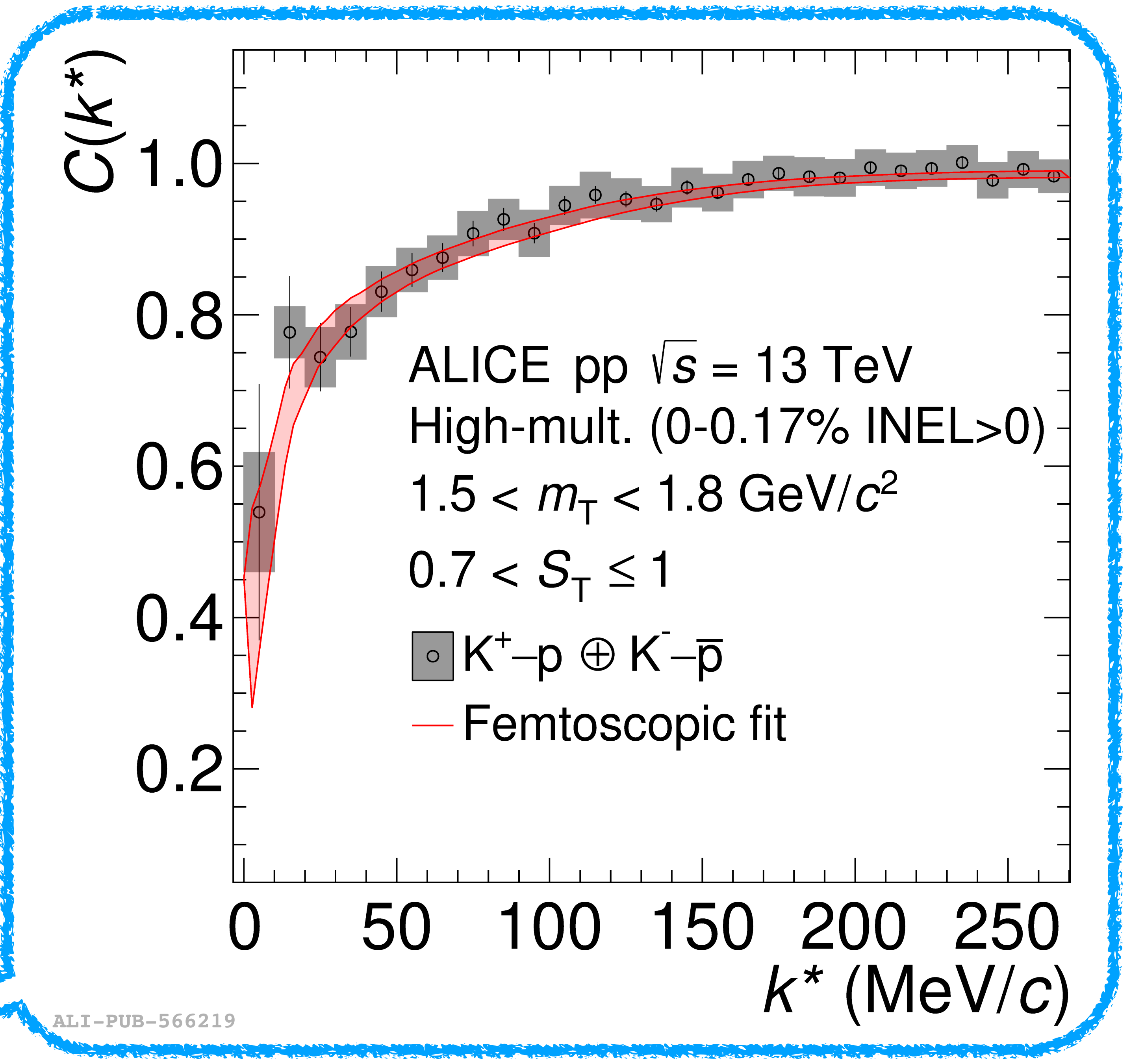

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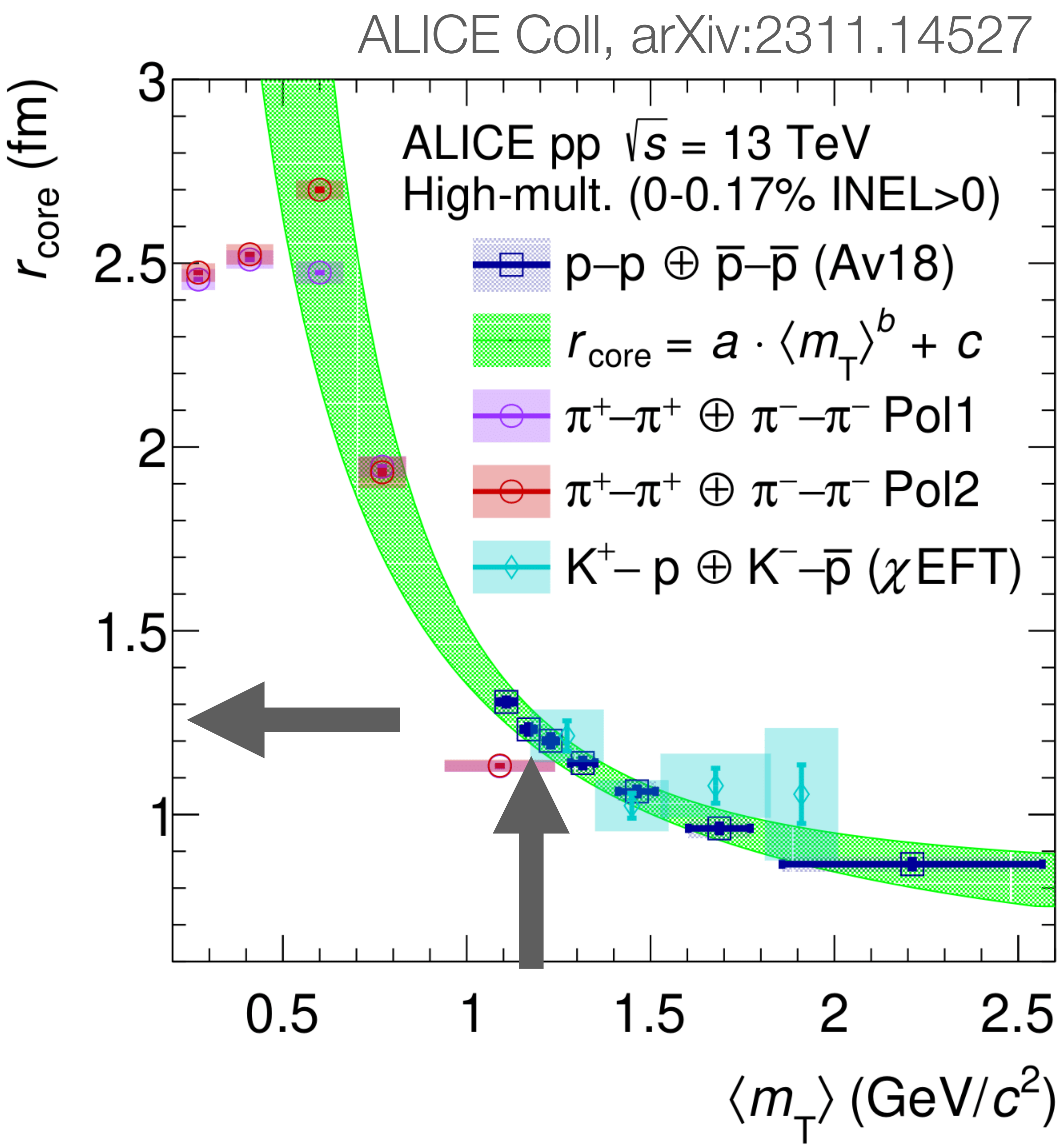
ALICE Coll, PLB 811 (2020)

Constraining the source in pp collisions

- Common emission profile for **all hadron pairs**

Constrained values of $r_{\rm core}$ of the pair



$m_{\rm T}$ of the pair from analysis

ALICE Coll, PLB 811 (2020)

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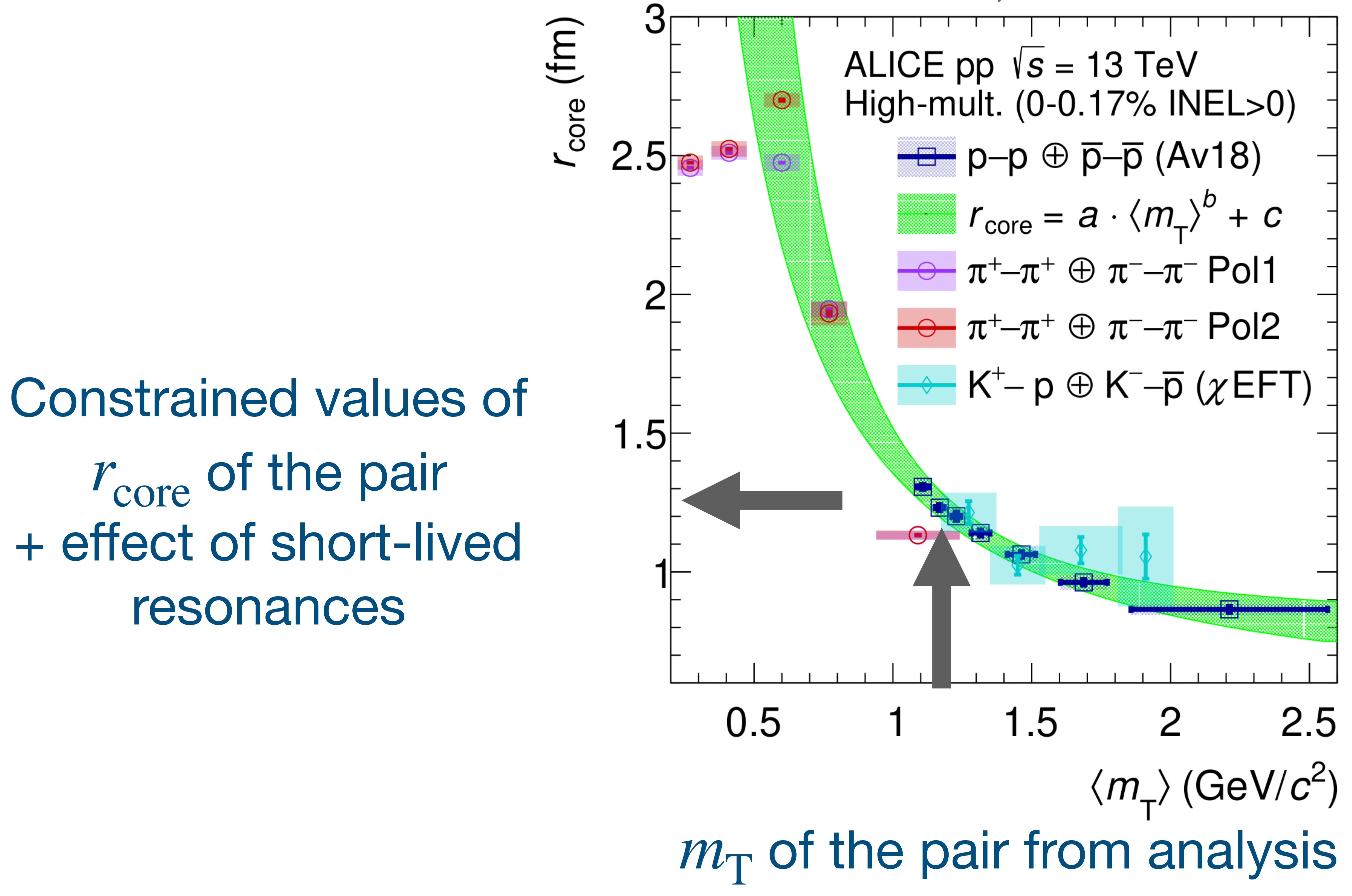

ALICE Coll, PLB 811 (2020)

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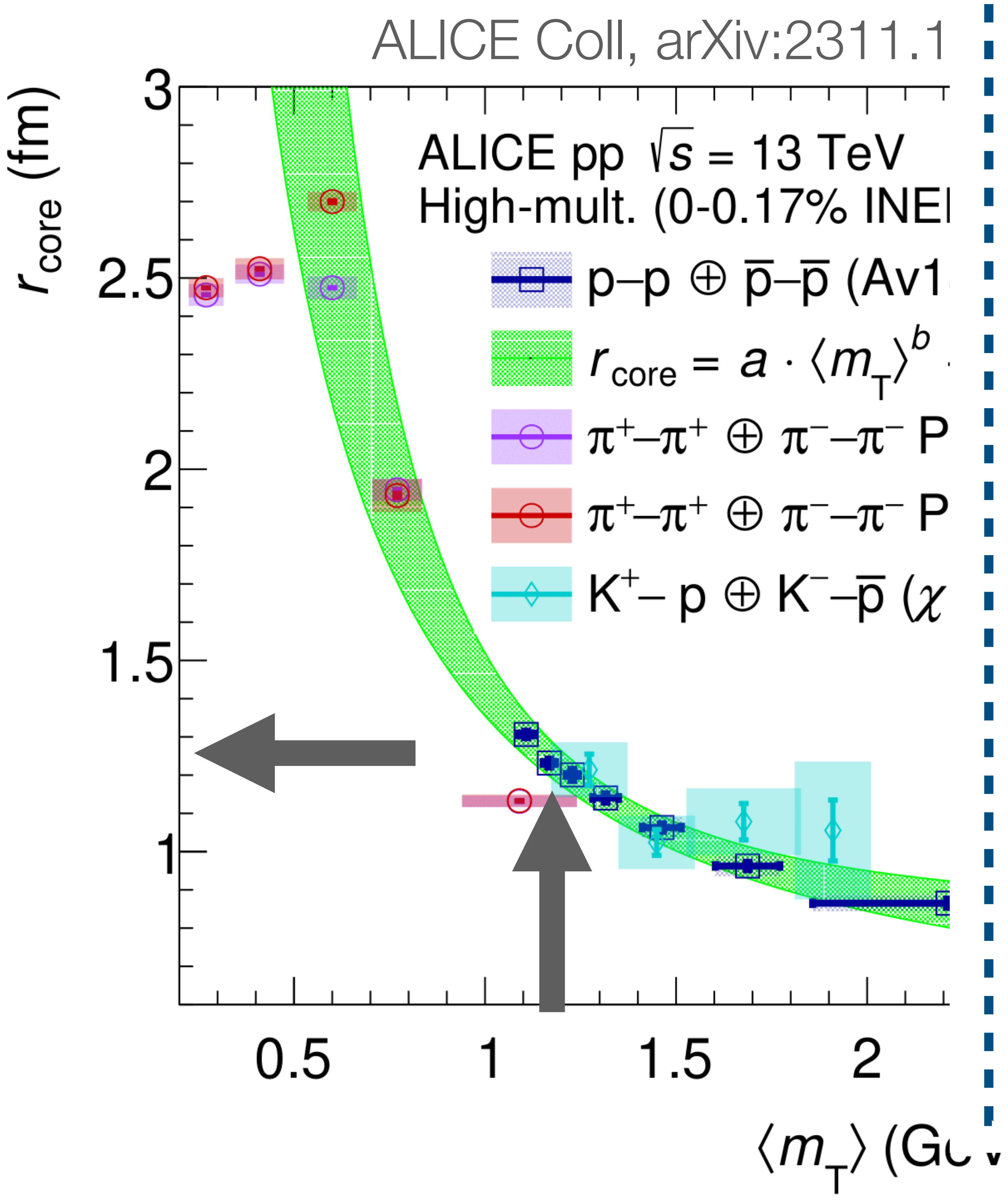
ALICE Collaboration	System
PRC 99 (2019) 2, 024001	p–p, p–Λ
PLB 797 (2019), 134822	Λ–Λ
PRL 123 (2019), 112002	**p–Ξ**
PLB 805 (2020), 135419	p–Σ
PRL 124 (2020) 092301	**p–K**
PLB 811 (2020), 135849	p–p, p–Λ
Nature 588 (2020) 232-238	**p–Ω and p–Ξ**
PRL 127 (2021), 172301	**p–ϕ**
PLB 833 (2022), 137272	p–Λ
PLB 829 (2022), 137060	baryon–(anti)baryon
PRD 106 (2022) 5, 052010	p–D
PLB (2022), 137223	Λ–Ξ
EPJC 83 (2023) 4, 340	K–p
PLB 822 (2021) 136708	p–K
PLB 845 (2023), 138145	Λ–K
PLB 845 (2023), 138145	Λ–K
arxiv 2308.16120	p–d
EPJA 59 (2023) 7, 145	p–p–p, p–p–Λ
arXiv:2303.13448	p–p–K
Not using a universal source	
PRL 124 (2020), 09230	*(anti)K–p*
PLB 822 (2021), 136708	*(anti)K–p*

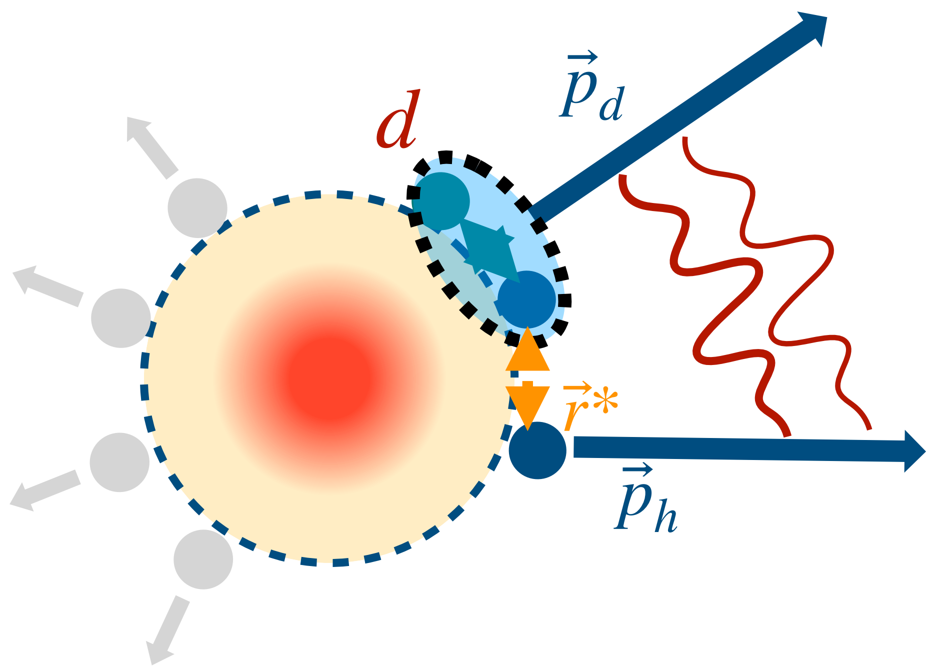


Constrained values of r_{core} of the pair + effect of short-lived resonances

m_{T} of the pair from analysis

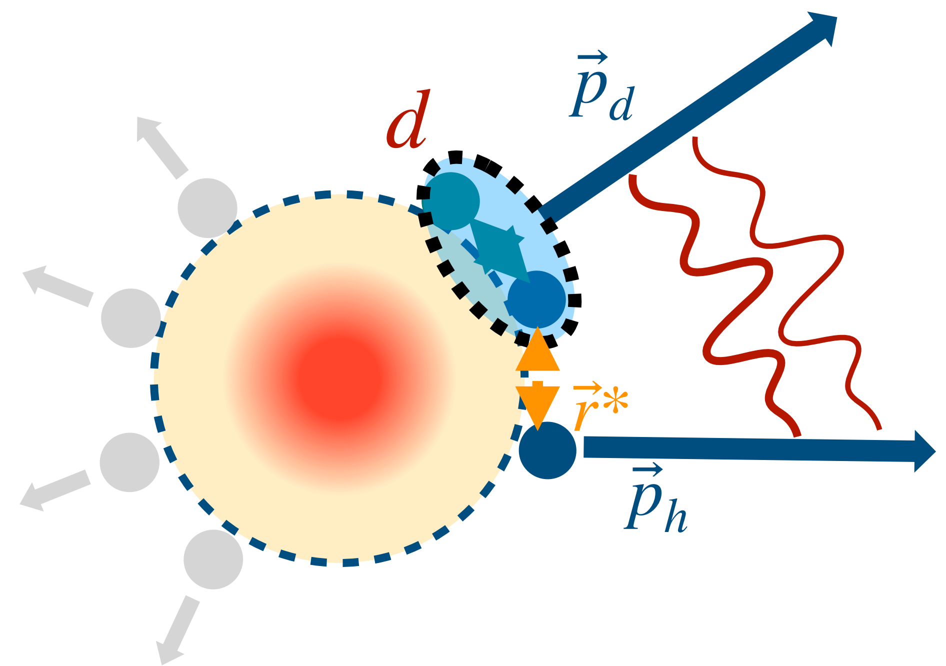
ALICE Coll, PLB 811 (2020)

K^+–d correlation in pp collisions



Deuterons follow hadron-hadron m_T-scaling?

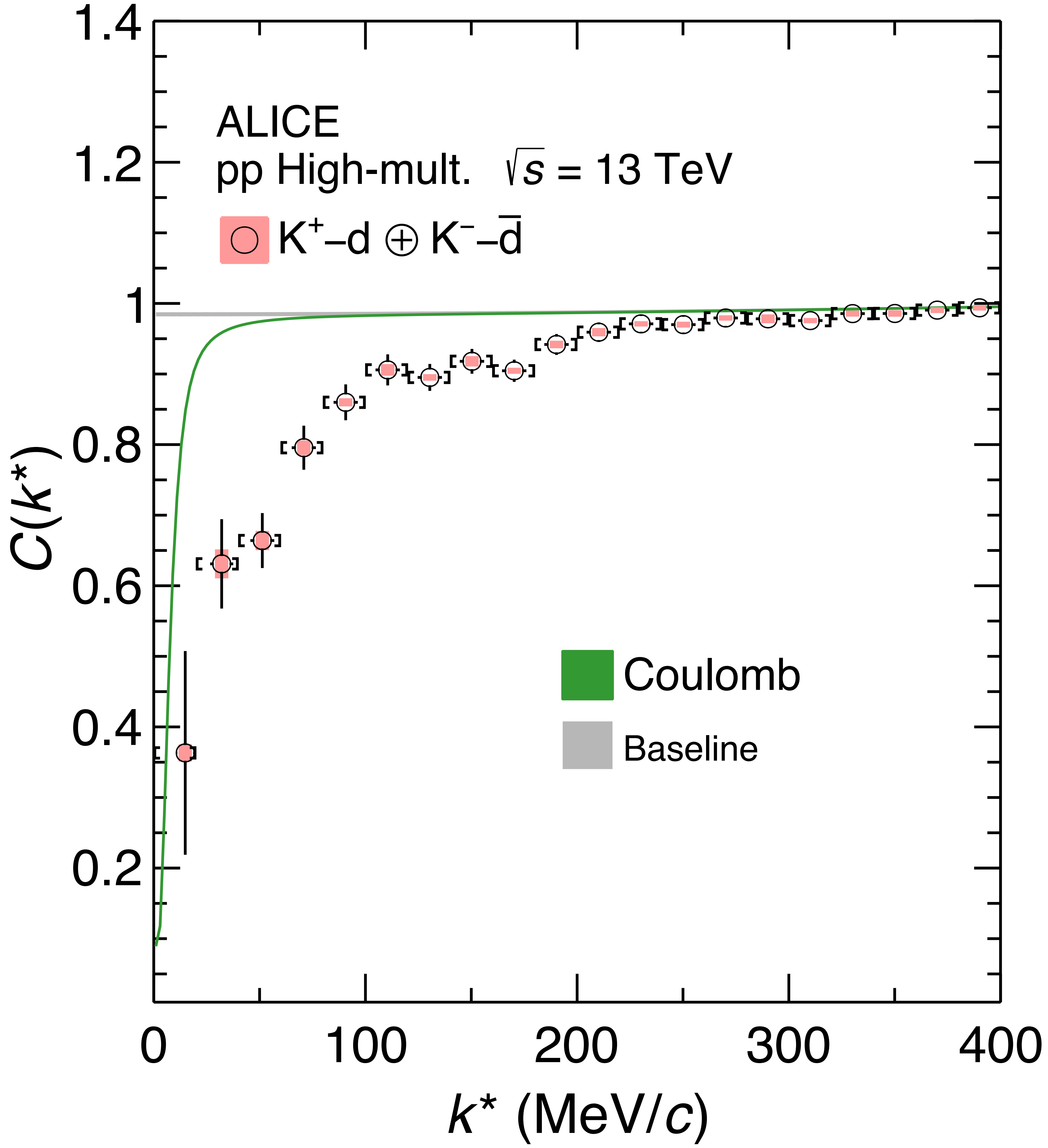
K^+–d correlation in pp collisions



Deuterons follow hadron-hadron m_T-scaling?

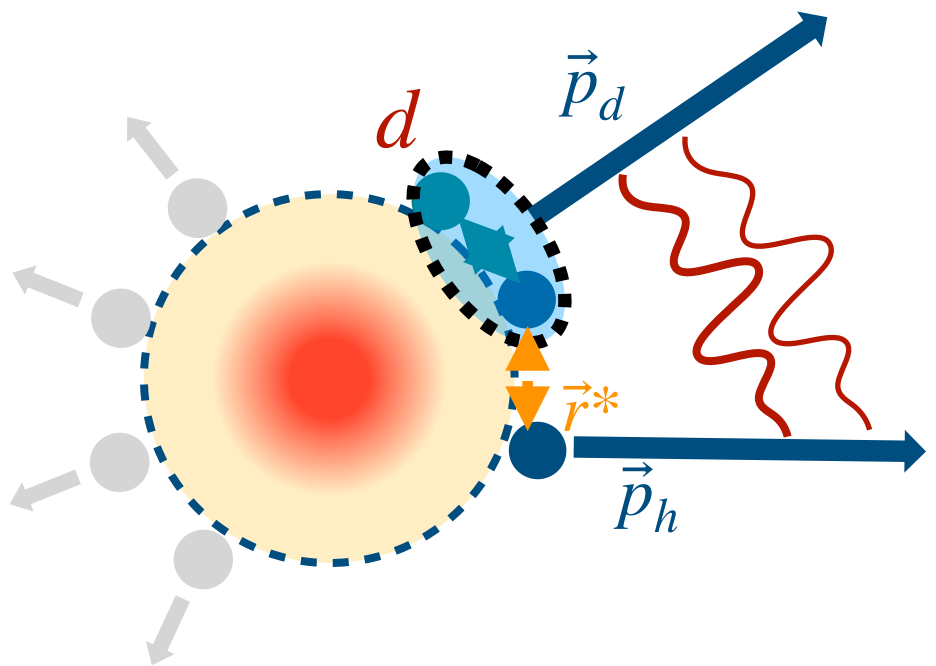
K^+–d source size = $1.35^{+0.04}_{-0.05}$ fm

ALICE Coll. arXiv:2308.16120



- Coulomb potential: disagree

K$^+$–d correlation in pp collisions



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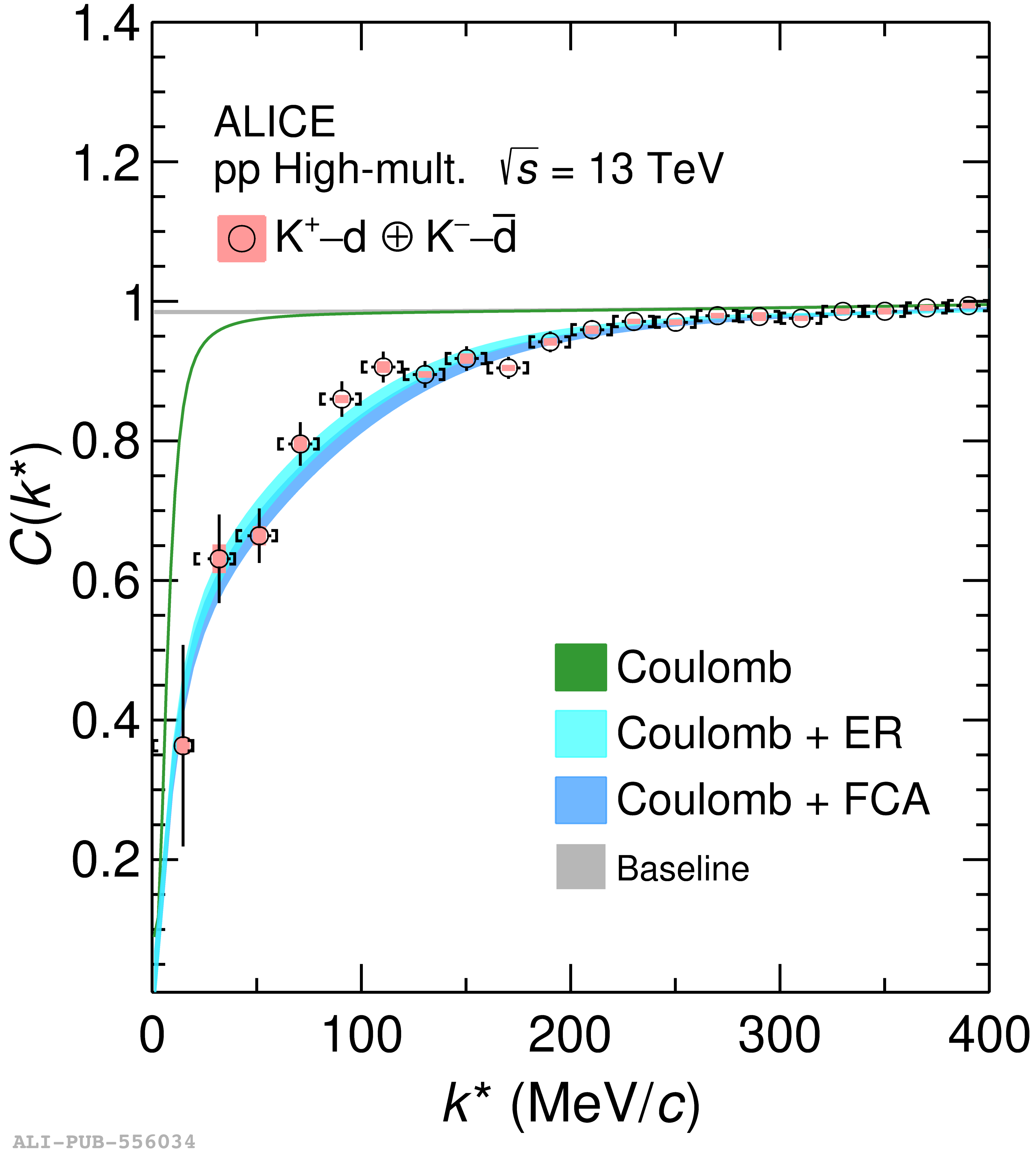


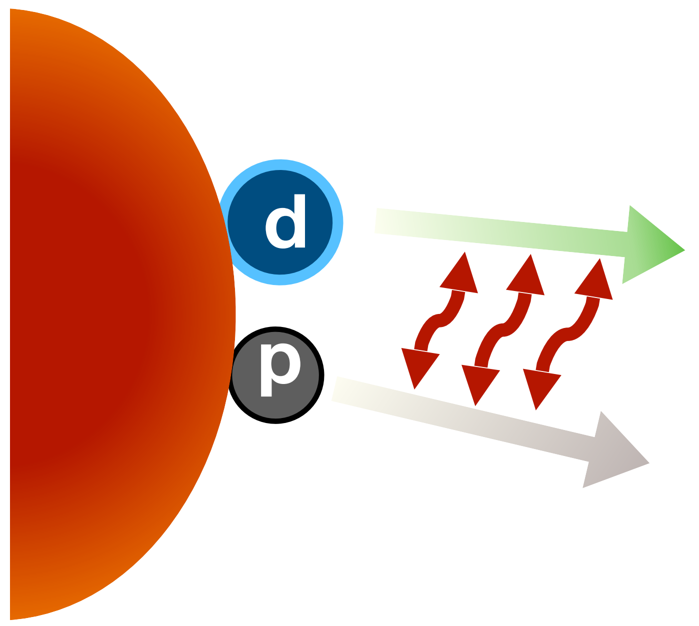
- Coulomb potential: disagree
- K$^+$–d as an **effective two-body** system: Lednický-Lyuboshits approach[1]
- K$^+$–d scattering parameters
  - Effective-Range Approximation (ER):
    $a_0 = -0.47$ fm, $d_0 = -1.75$ fm[2]
  - Fixed-center approximation (FCA):
    $a_0 = -0.54$ fm, $d_0 = 0$ fm[3]

Deuterons follow the same m_T scaling as other hadrons

[1] R. Lednický, Phys. Part. Nuclei 40, 307–352 (2009)
[2] provided by Prof. Johann Haidenbaur
[3] provided by Prof. Tetsuo Hyodo

p–d correlation in pp collisions

- p–d as an **effective two-body**: Lednický-Lyuboshits approach[1]
- Source size: $1.08^{+0.06}_{-0.06}$ fm
- Strong interaction: constrained from the scattering measurements[2]



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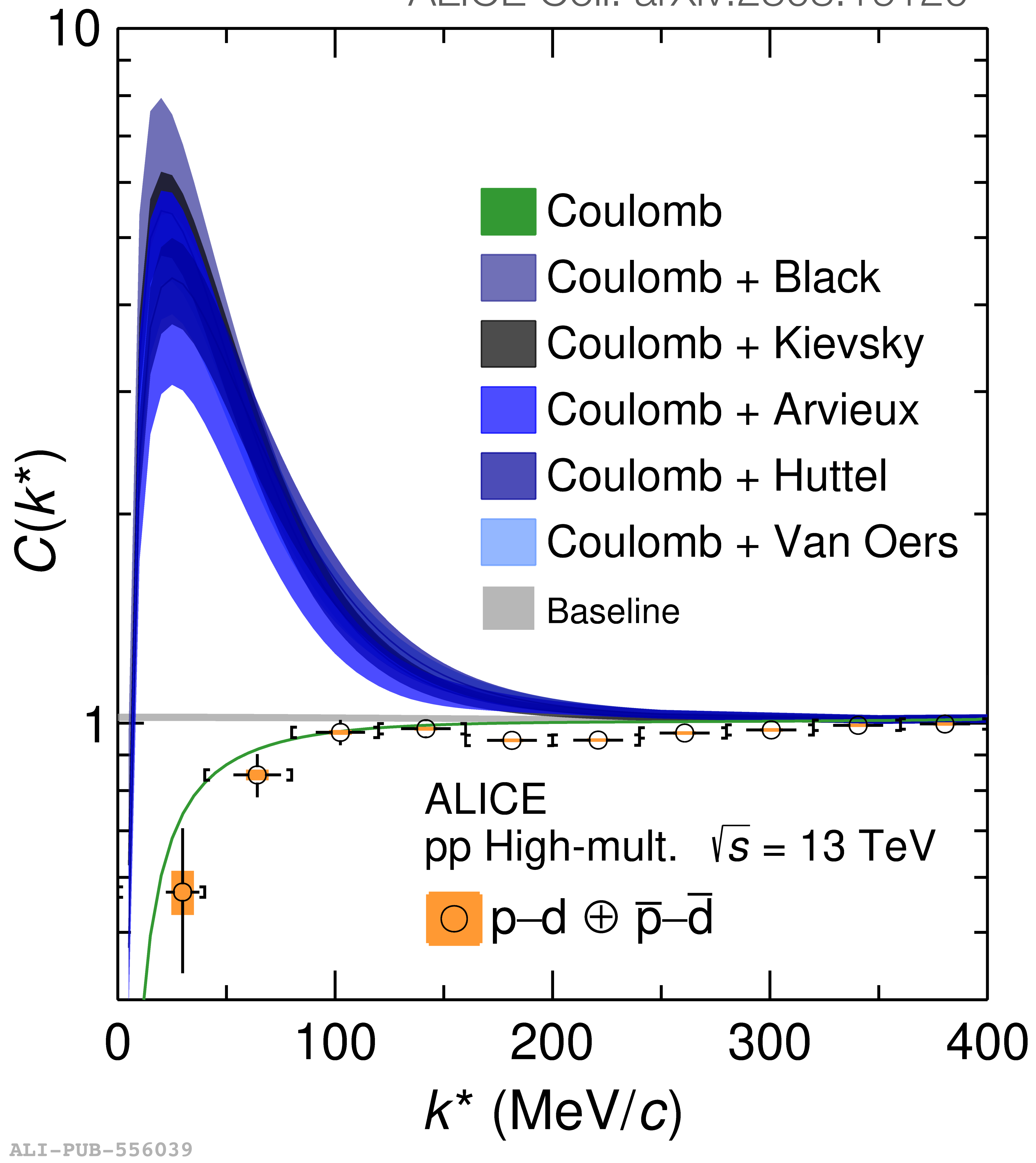
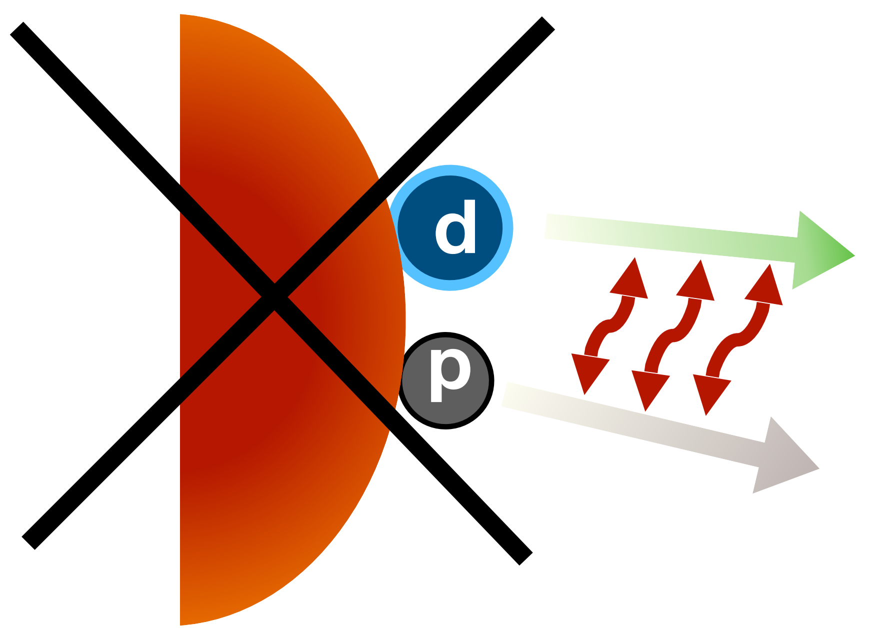


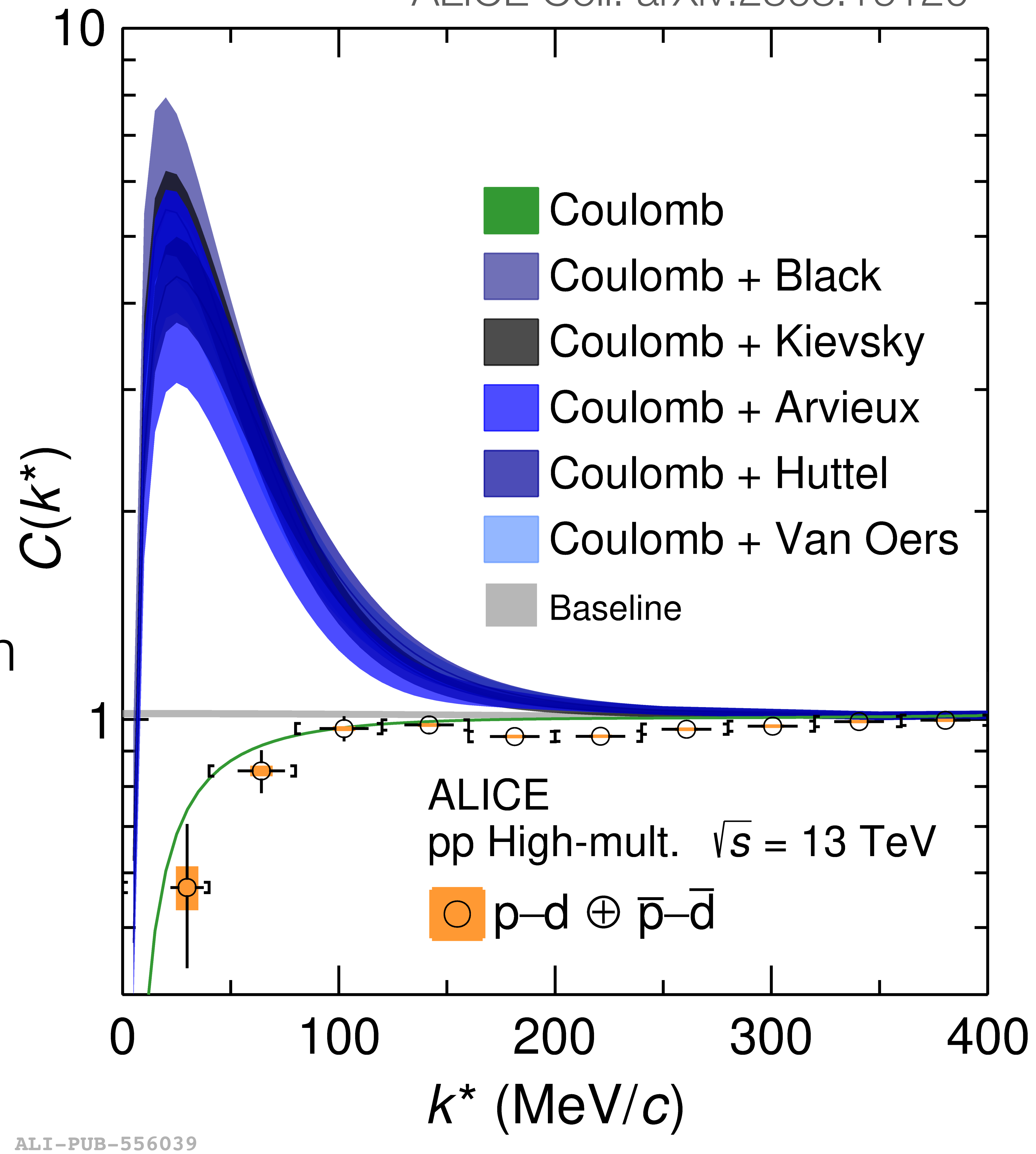
[1] R. Lednický, Phys. Part. Nuclei 40, 307–352 (2009)
[2] Measured scattering parameters of p-d ref in the backup

p–d correlation in pp collisions

- p–d as an **effective two-body**: Lednický-Lyuboshits approach[1]
- Source size: $1.08^{+0.06}_{-0.06}$ fm
- Strong interaction: constrained from the scattering measurements[2]
- The picture of two point-like particles does not work
  - Pauli blocking at work for p–(pn) at short distances
  - Asymptotic strong interaction: does not describe p–d at r ~1 fm



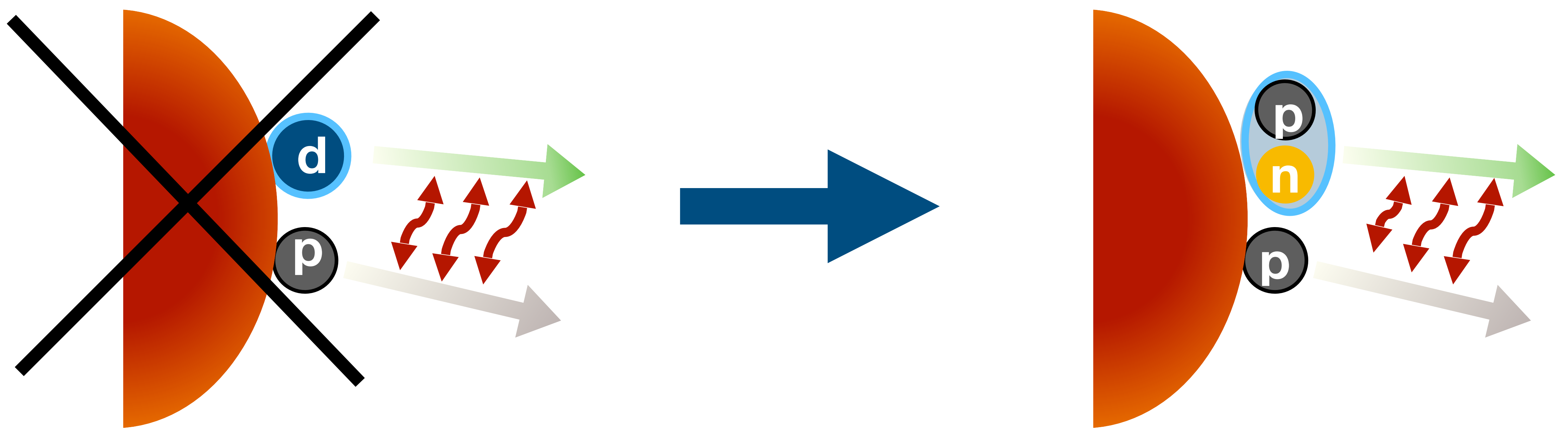
ALICE Coll. arXiv:2308.16120



[1] R. Lednický, Phys. Part. Nuclei 40, 307–352 (2009)
[2] Measured scattering parameters of p-d ref in the backup

p–d correlation in pp collisions

- p–d as an **effective two-body**: Lednický-Lyuboshits approach[1]
- Source size: $1.08^{+0.06}_{-0.06}$ fm
- Strong interaction: constrained from the scattering measurements[2]
- The picture of two point-like particles does not work
  - Pauli blocking at work for p–(pn) at short distances
  - Asymptotic strong interaction: does not describe p–d at r ~1 fm



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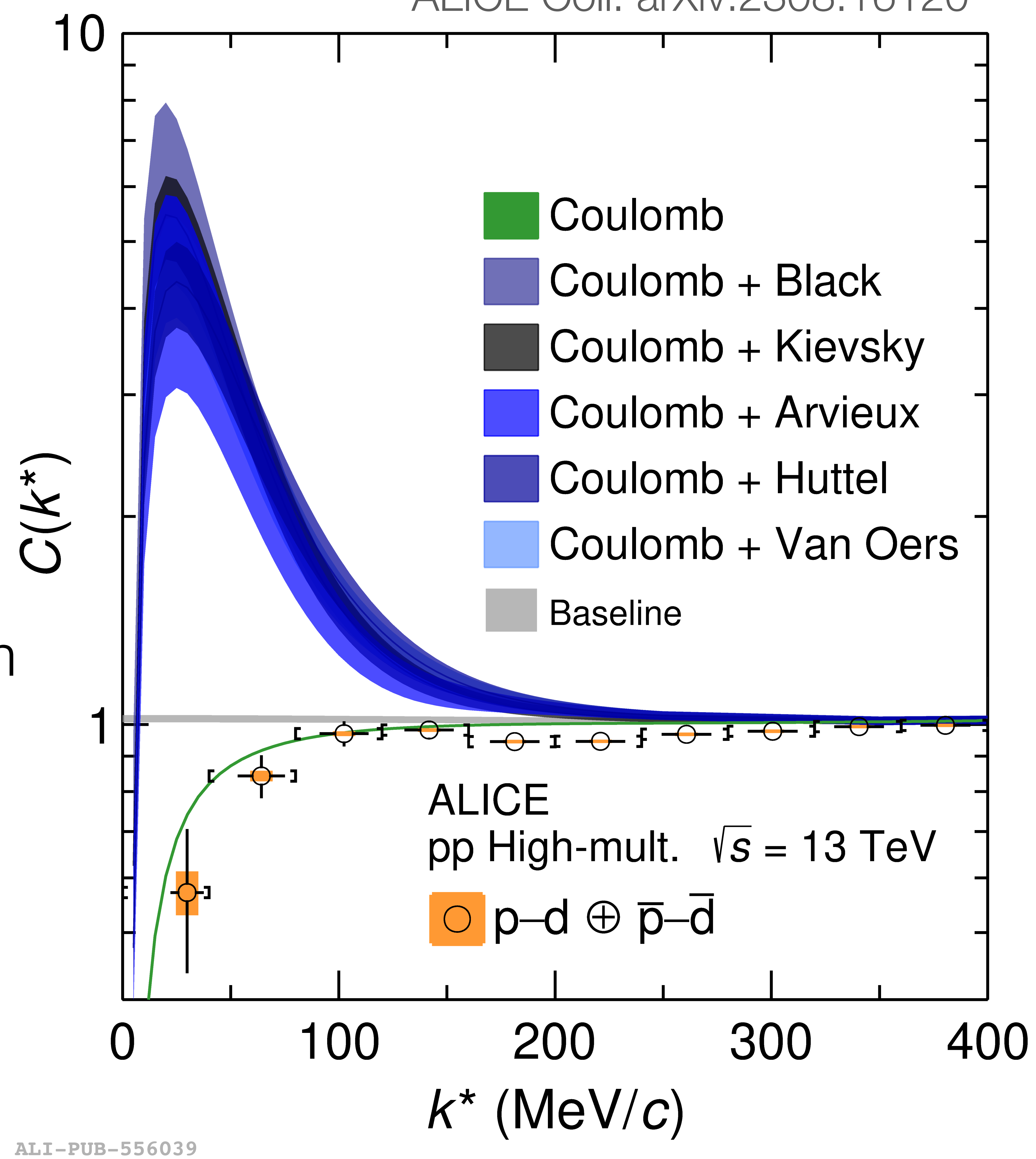

Need for three-body calculations accounting for p-(pn) dynamics

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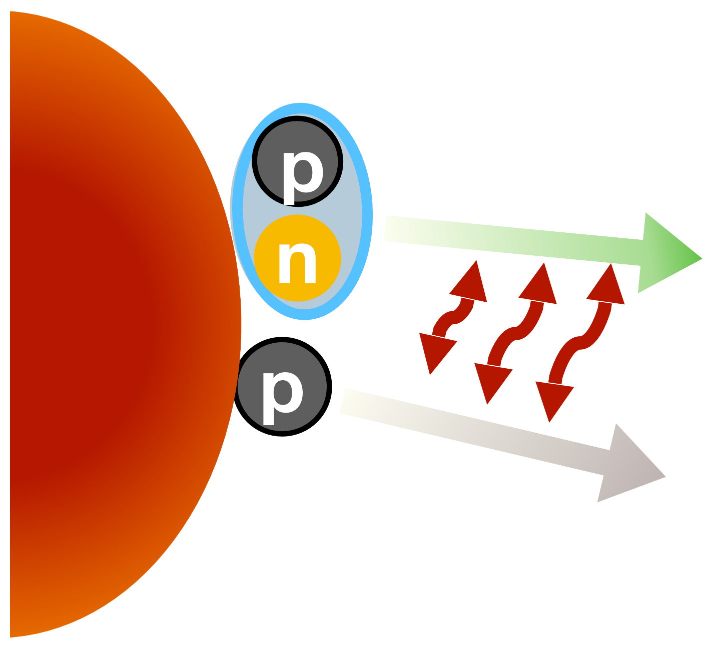
p–d as three-body system



- **Start from p–(pn) system that form p–d state**:

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

  - $\Psi(k^*, \rho)$ the three-nucleon wave function, p–(pn) to p–d state asymptotically

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

Calculations: theory collaborators

Michele Viviani, Alejandro Kievsky, and Laura Marcucci from Pisa group
Sebastian König from NC state University

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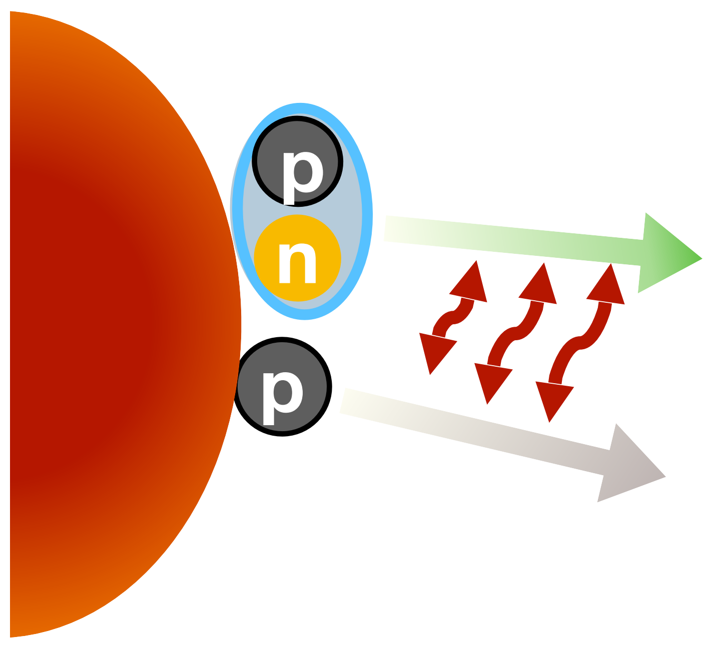

- $\Psi(k^*,\rho)$ the three-nucleon wave function, p–(pn) to p–d state asymptotically
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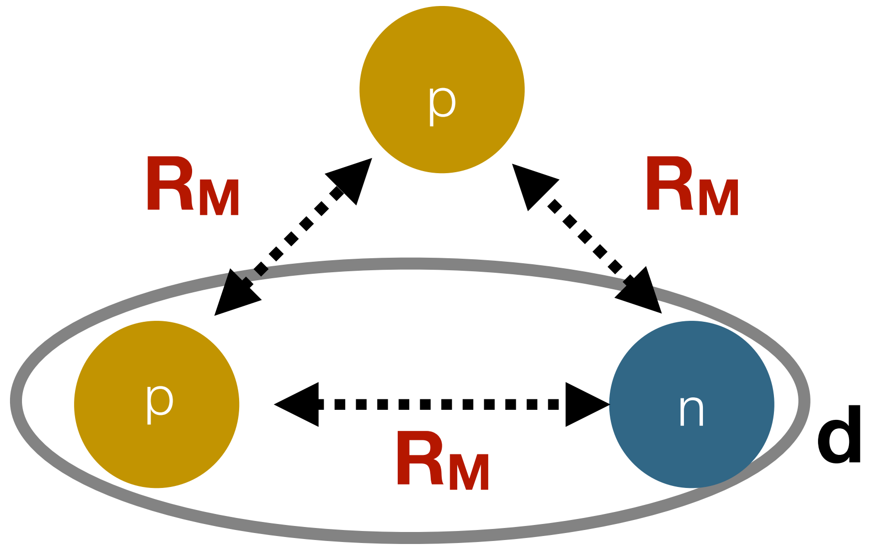

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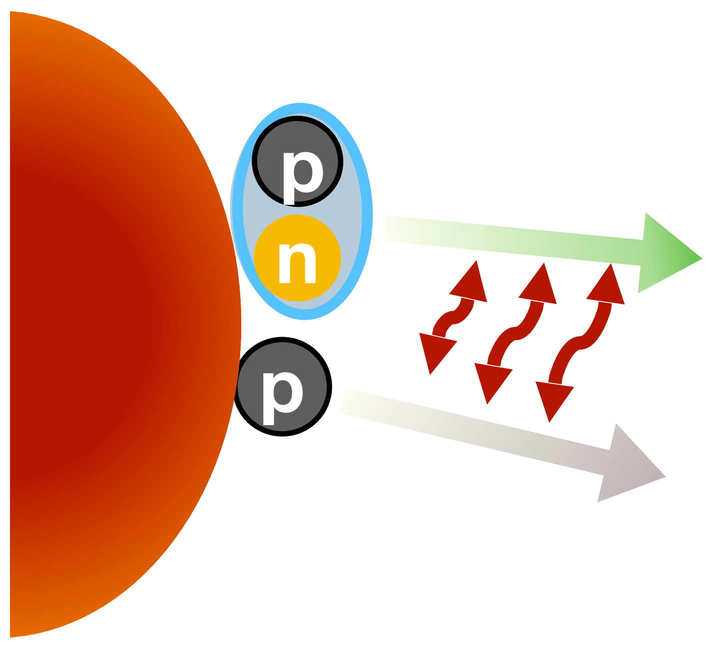

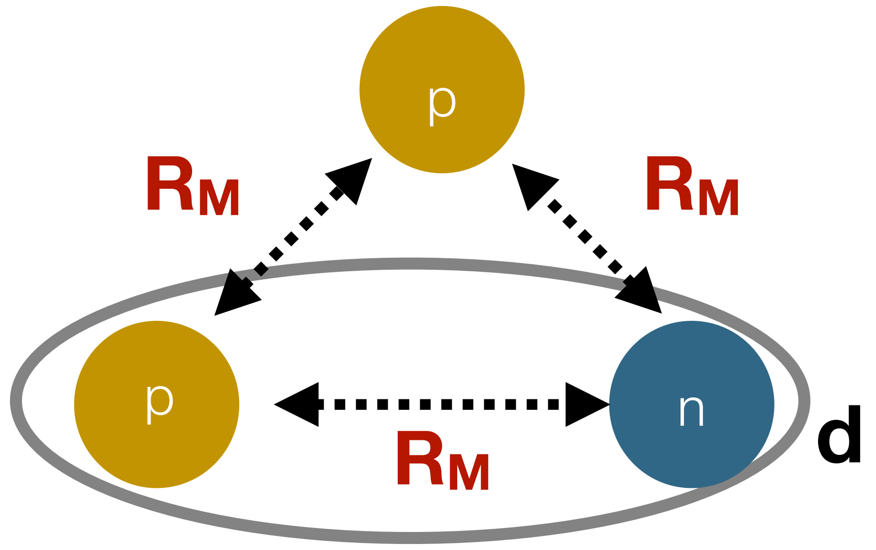

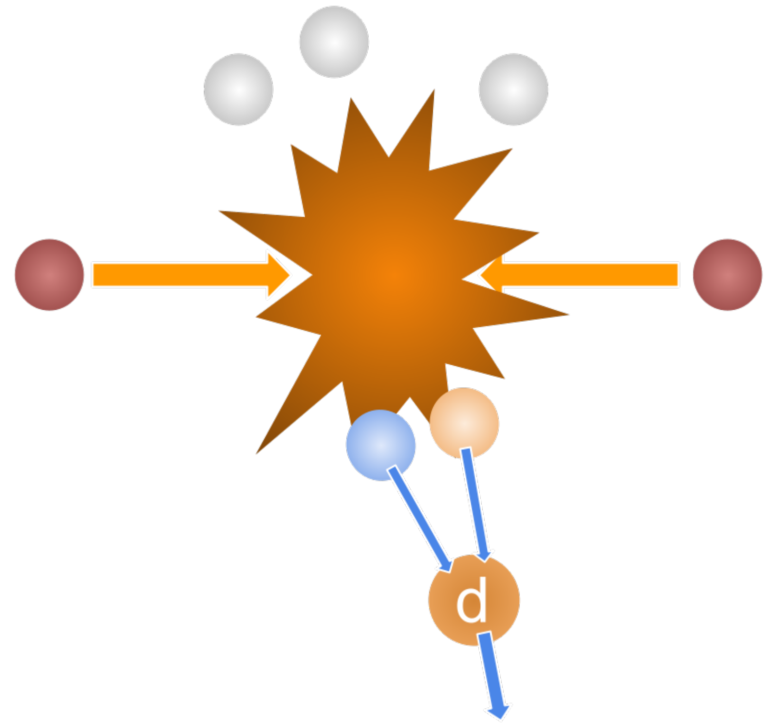

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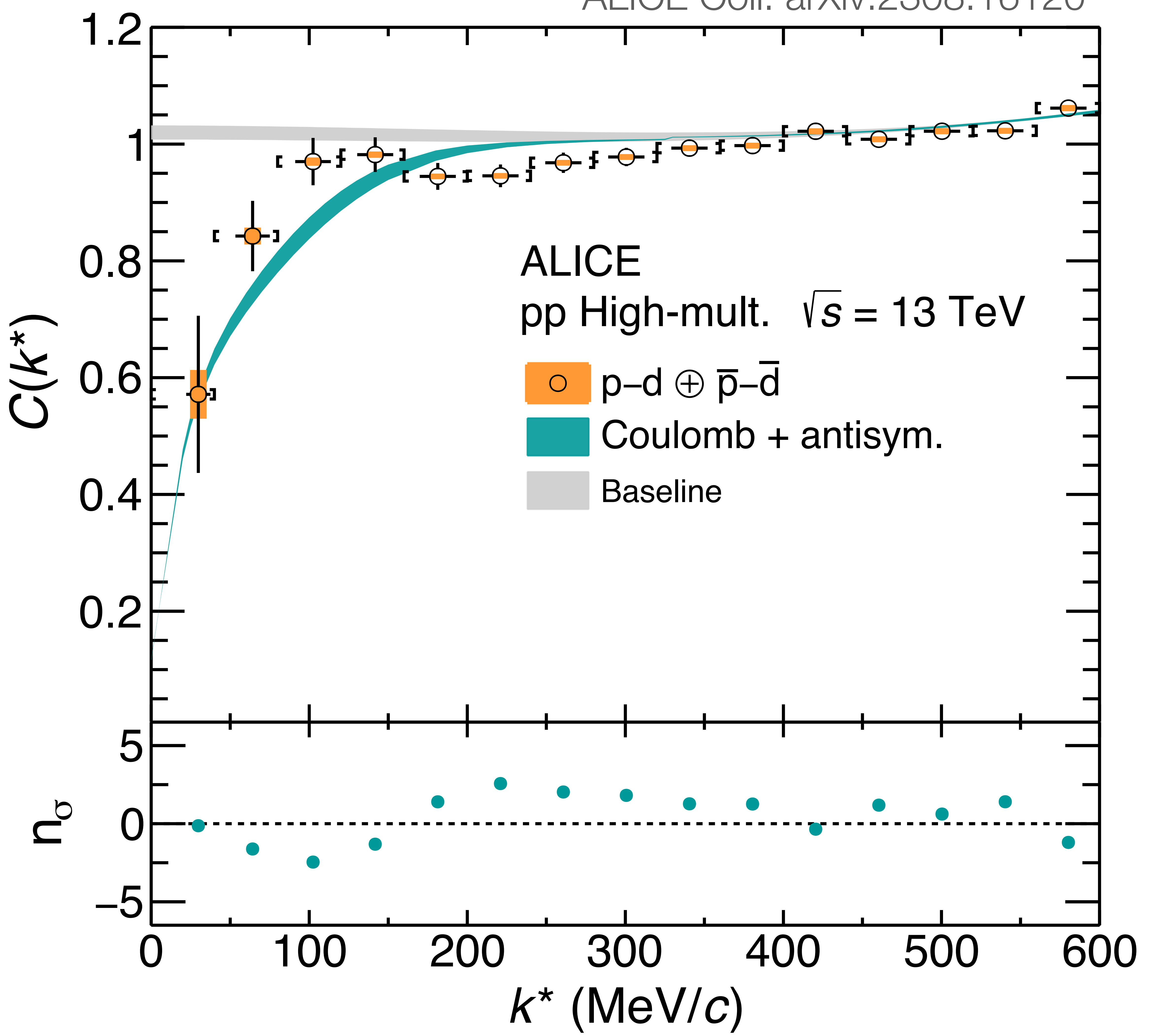
ALICE Coll. arXiv:2308.16120



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  - **s-wave** only: **more repulsion**

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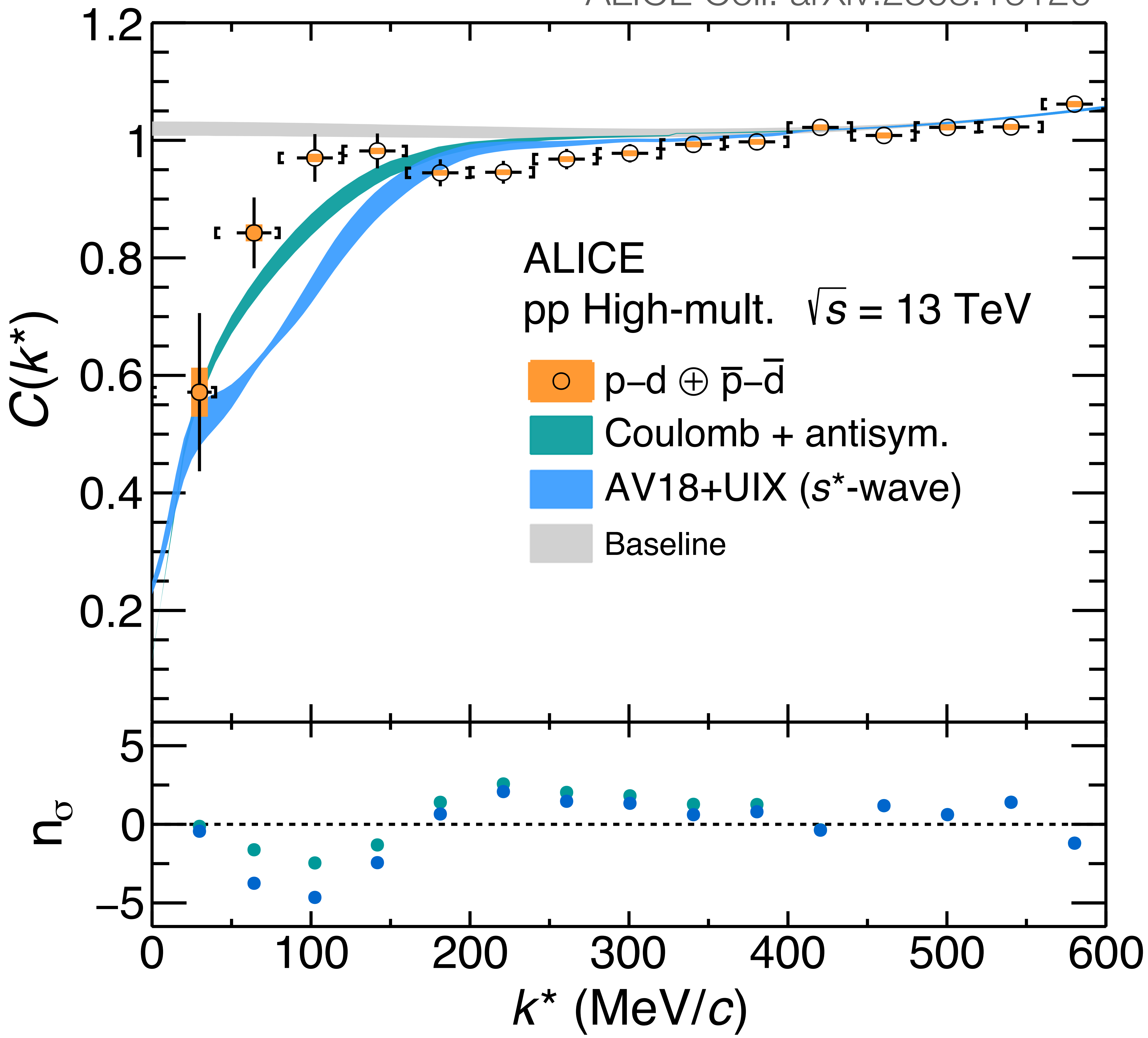

[1] B. R. B. Wiringa et al. Phys. Rev. C 51, 38

[2] B. S. Pudliner et al. Phys. Rev. Lett. 74, 4396

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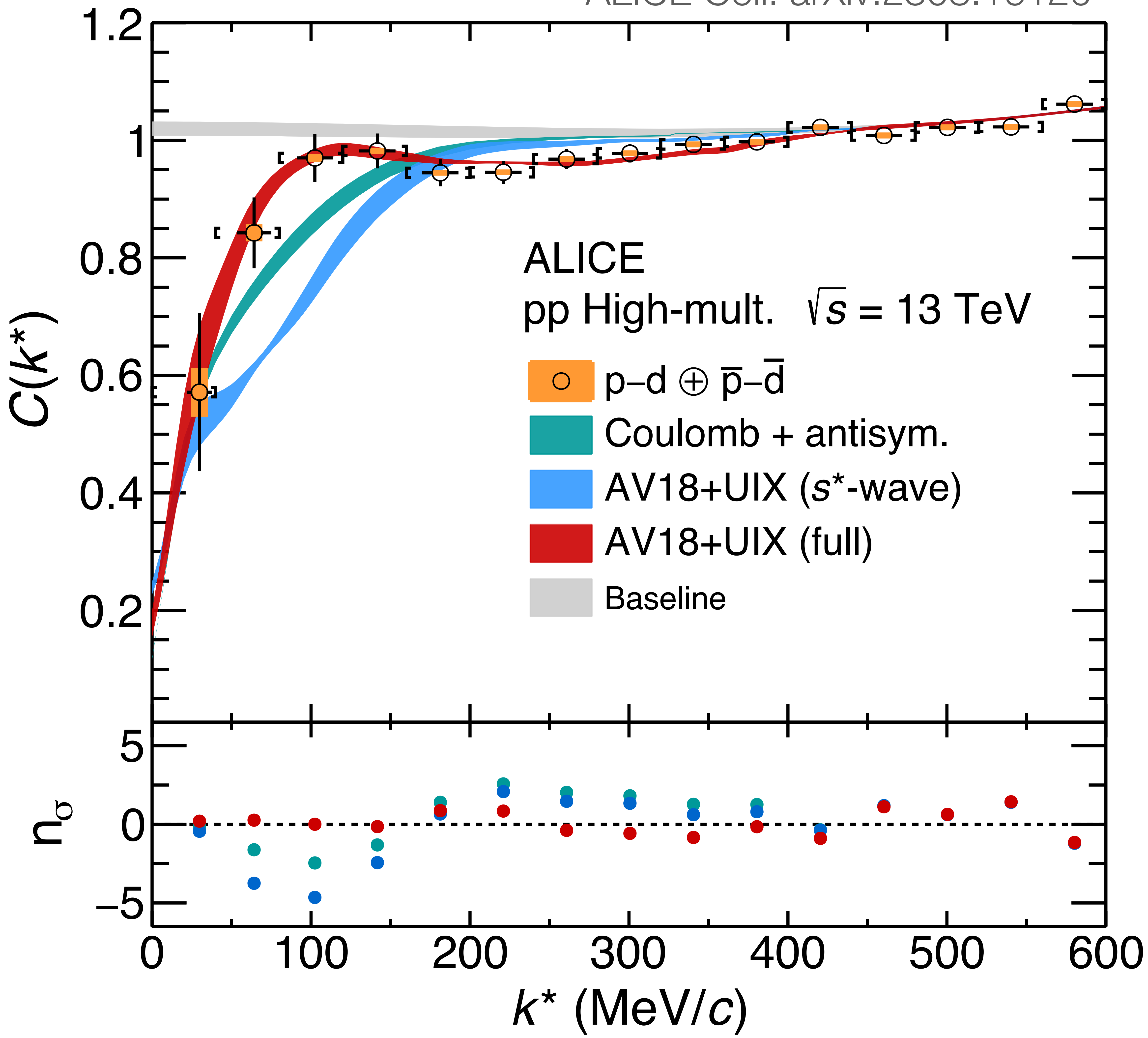

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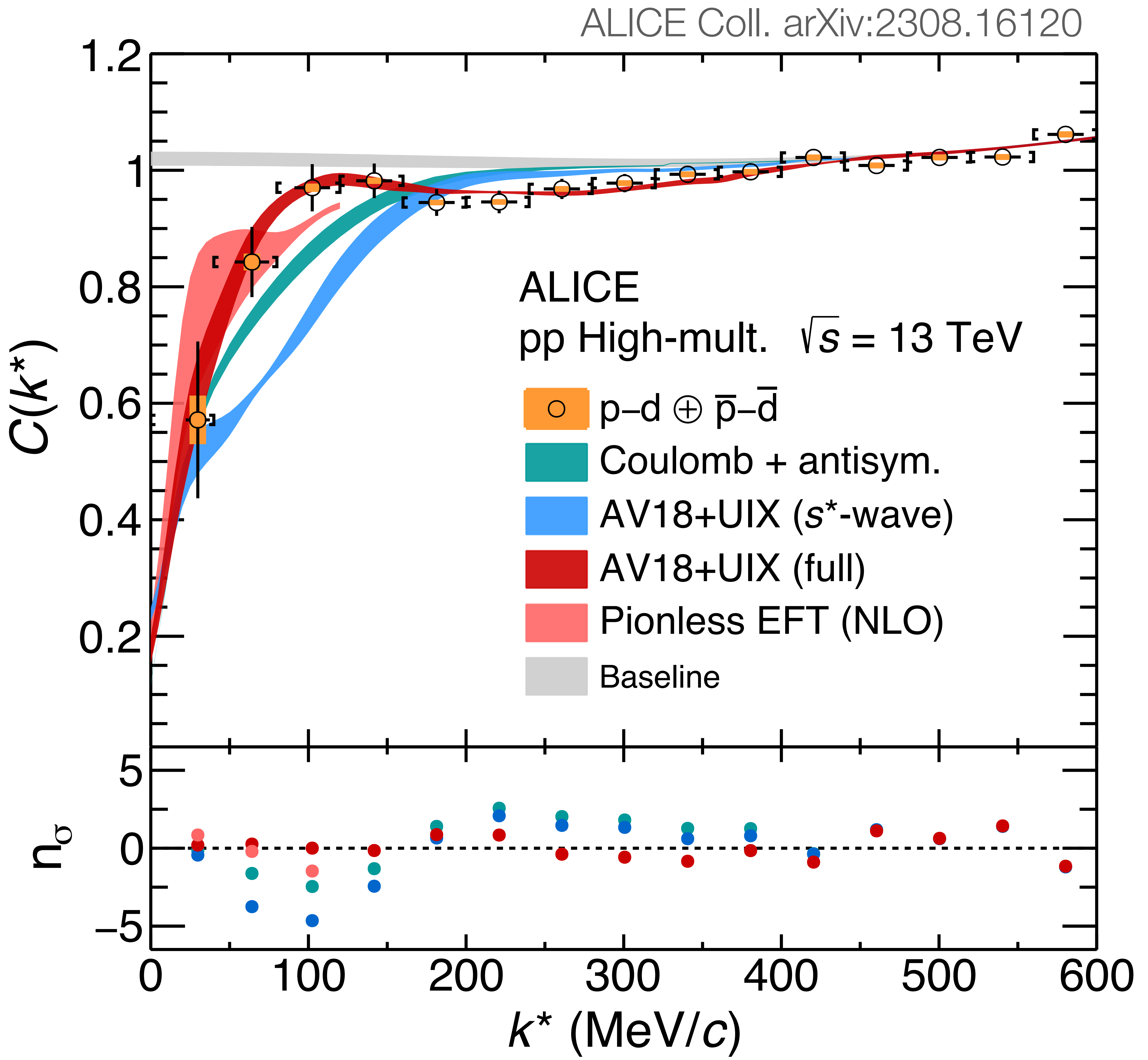

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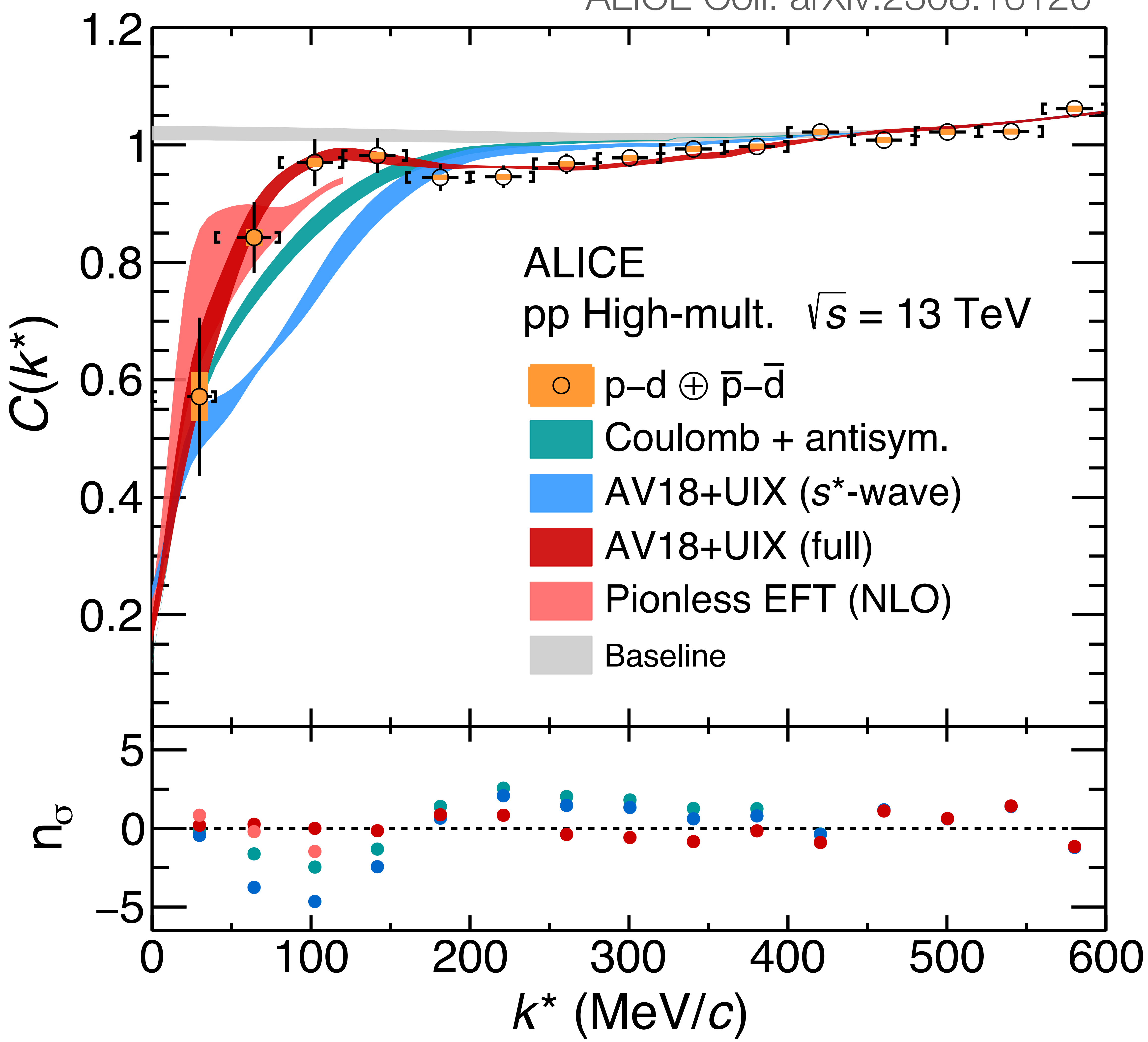
- Dynamics of the three-body p–(pn) system at short distances!
- Inclusion of the higher partial waves

ALICE Coll. arXiv:2308.16120



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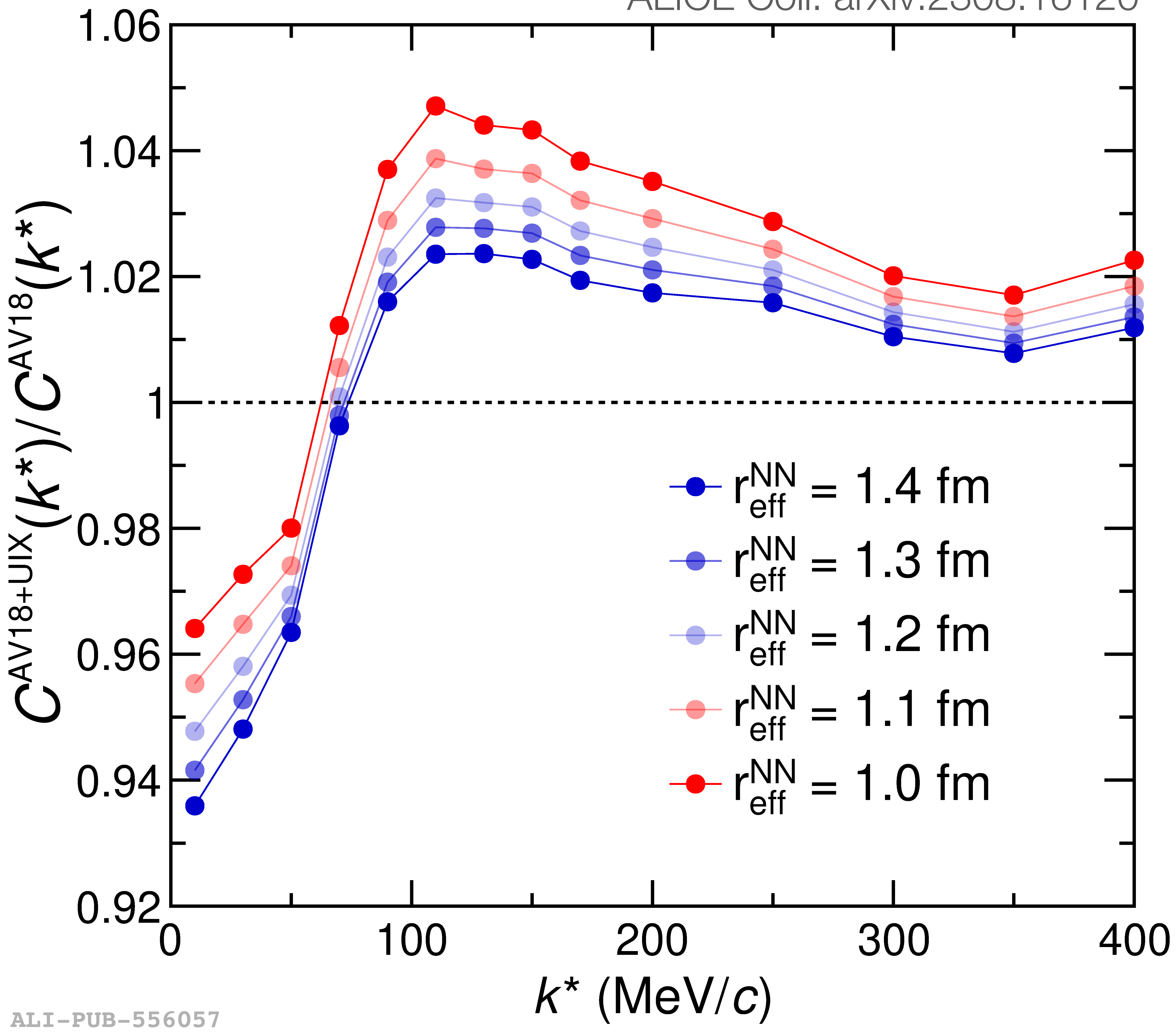
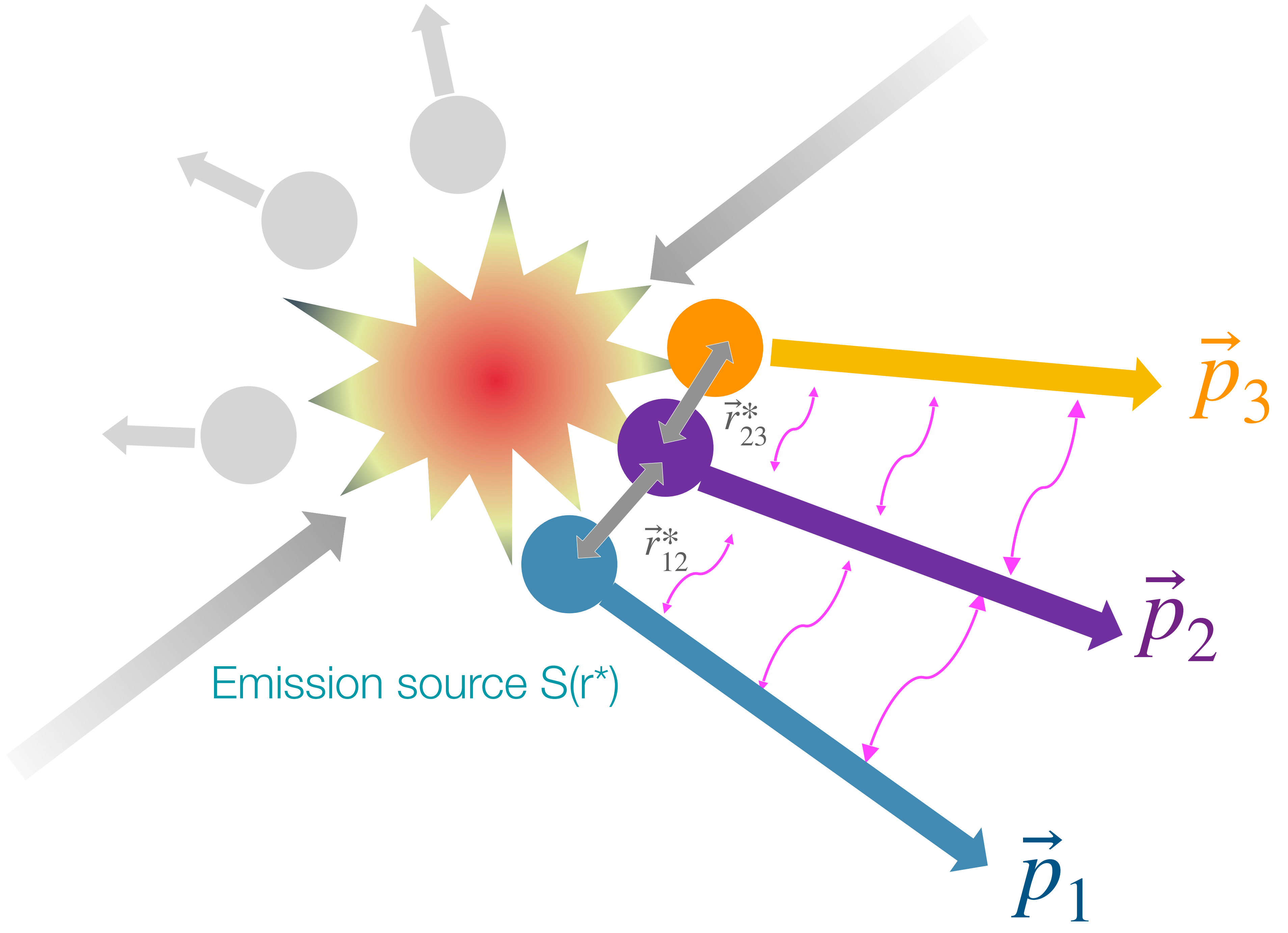
Sensitivity to genuine three-body force

- **Computed correlation function with and without genuine three-body force**
  - Up to 5% effect of genuine three-body interaction
  - Run 2: limited statistics does not allow for resolution to see the effect of three-body force
- **LHC Run 3:** ~2 orders of magnitude increase in pair statistics
  - Possibility to perform m_T differential analysis

ALICE Coll. arXiv:2308.16120



Avenue for the study of hadron–deuteron systems, including charm and strange hadrons!



Femtoscopy opens the door for the study of interactions in unbound system of three hadron (3 to 3 scattering process)

Three-body femtoscopy with ALICE

- Extending femtoscopy to three-particle correlations: p-p-p and p-p-Λ[1]
- Study interaction in hadron-triplets

$$C(Q_3) = N \frac{N_{\text{same}}(Q_3)}{N_{\text{mixed}}(Q_3)} \qquad Q_3 = \sqrt{-q_{12}^2 - q_{23}^2 - q_{13}^2}$$

[1] ALICE Coll., EPJ A 59, 145 (2023)

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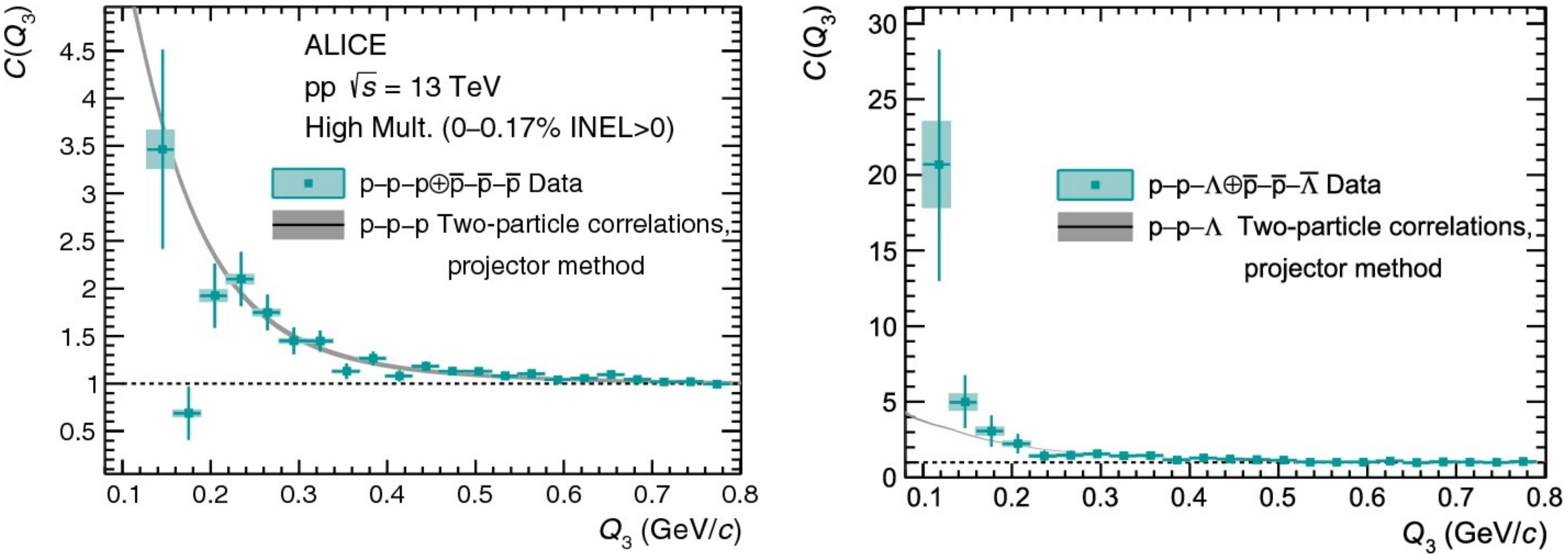


- Effects beyond two-body contributions[2]

[1] ALICE Coll, EPJA 59, 145 (2023)
[2] Del Grande et al, EPJC 82, 244 (2022)

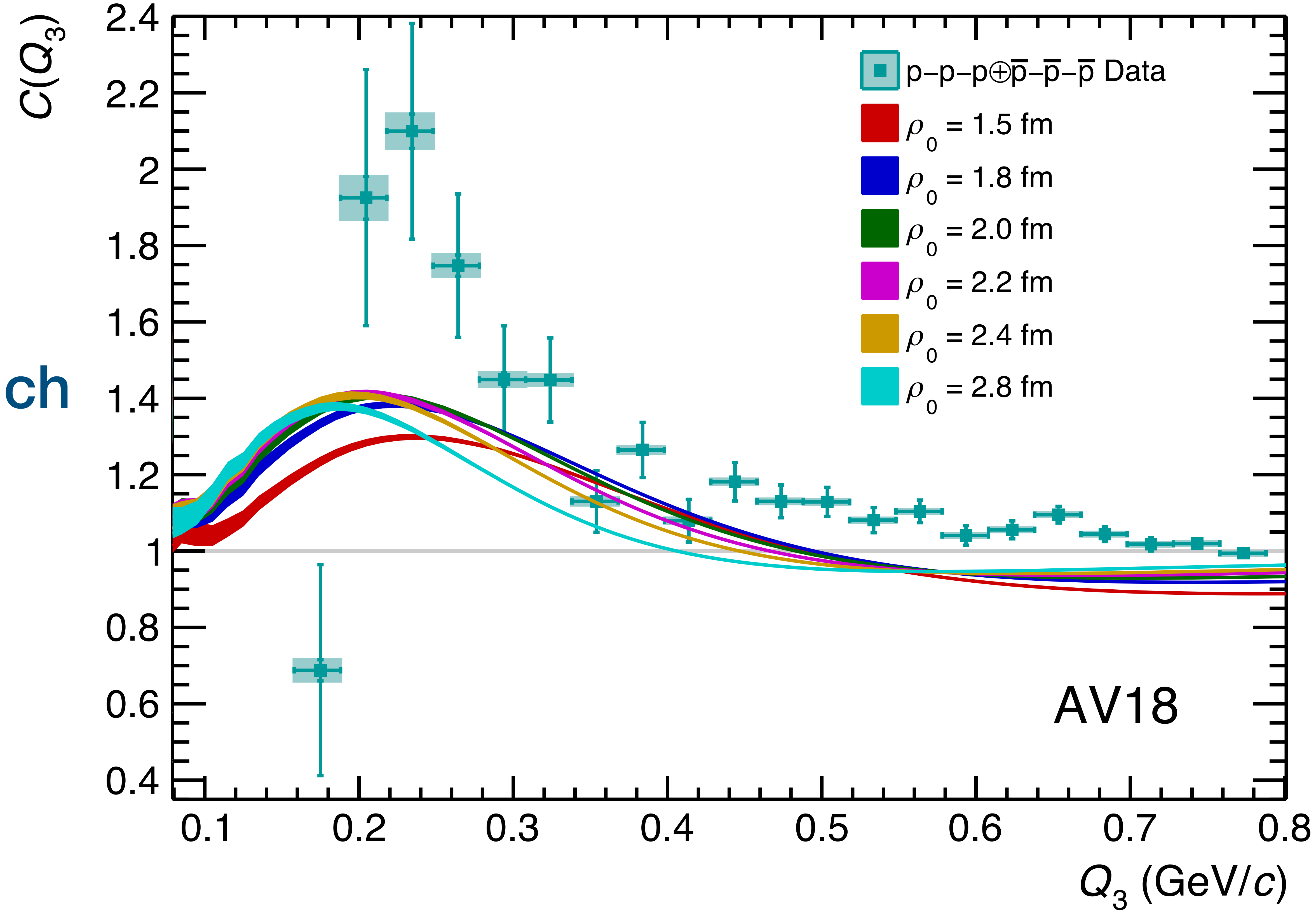
p-p-p correlation using AV18 potential

- Three-body correlation function with HH approach[1]

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

Work of Laura Šerkšnyte, and Raffaele Del Grande (**Munich group**) in collaboration with **INFN PISA group**

- $\Psi(Q_3, \rho)$ computed using pp AV18 strong interaction, Coulomb corrections, and quantum statistics
- Attractive AV18 interaction: results peak
- Pauli-blocking: depletion in $C(Q_3)$

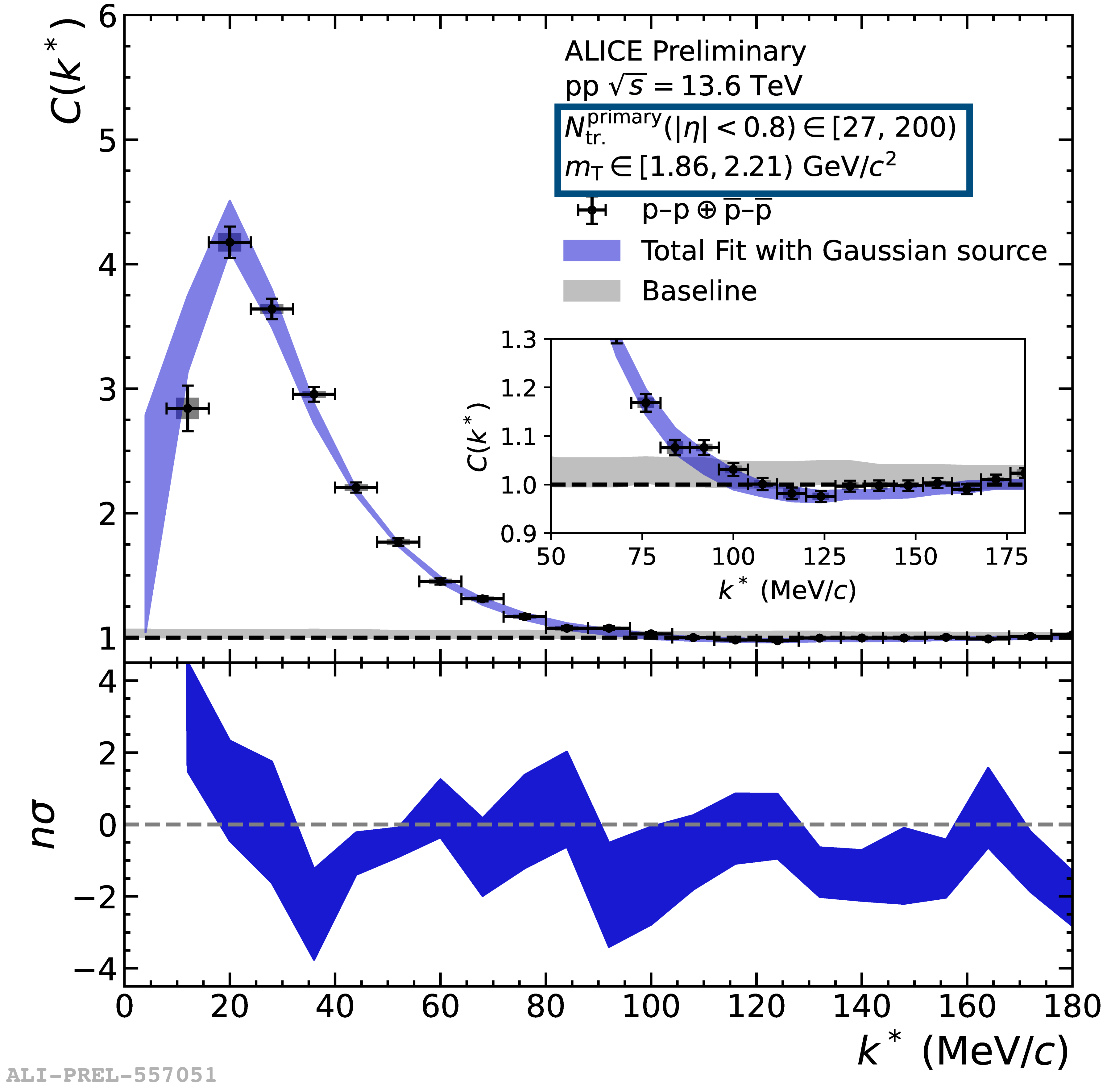


p-p-Λ: theoretical work in progress

[1] A Kievsky et al, arXiv:2310.10428 (accepted by PRC)

Femtoscopy towards LHC Run 3

- LHC Run 3 pp collisions at 13.6 TeV: 2 orders of magintude increased p–p pair statistics
- Fixed source for all interaction studies using femtoscopy



p–p correlation function measured in m_T and multiplicity differential

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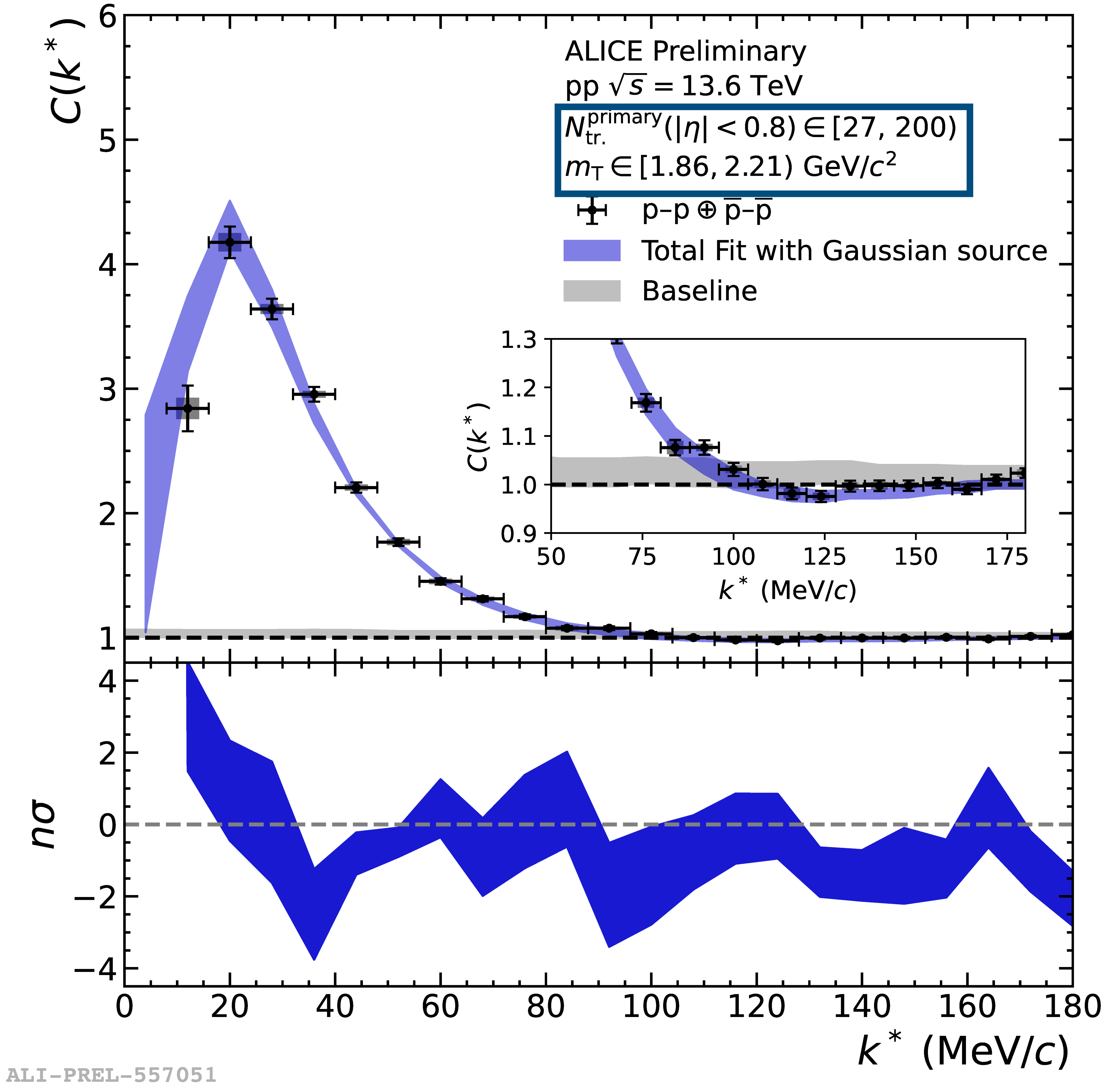

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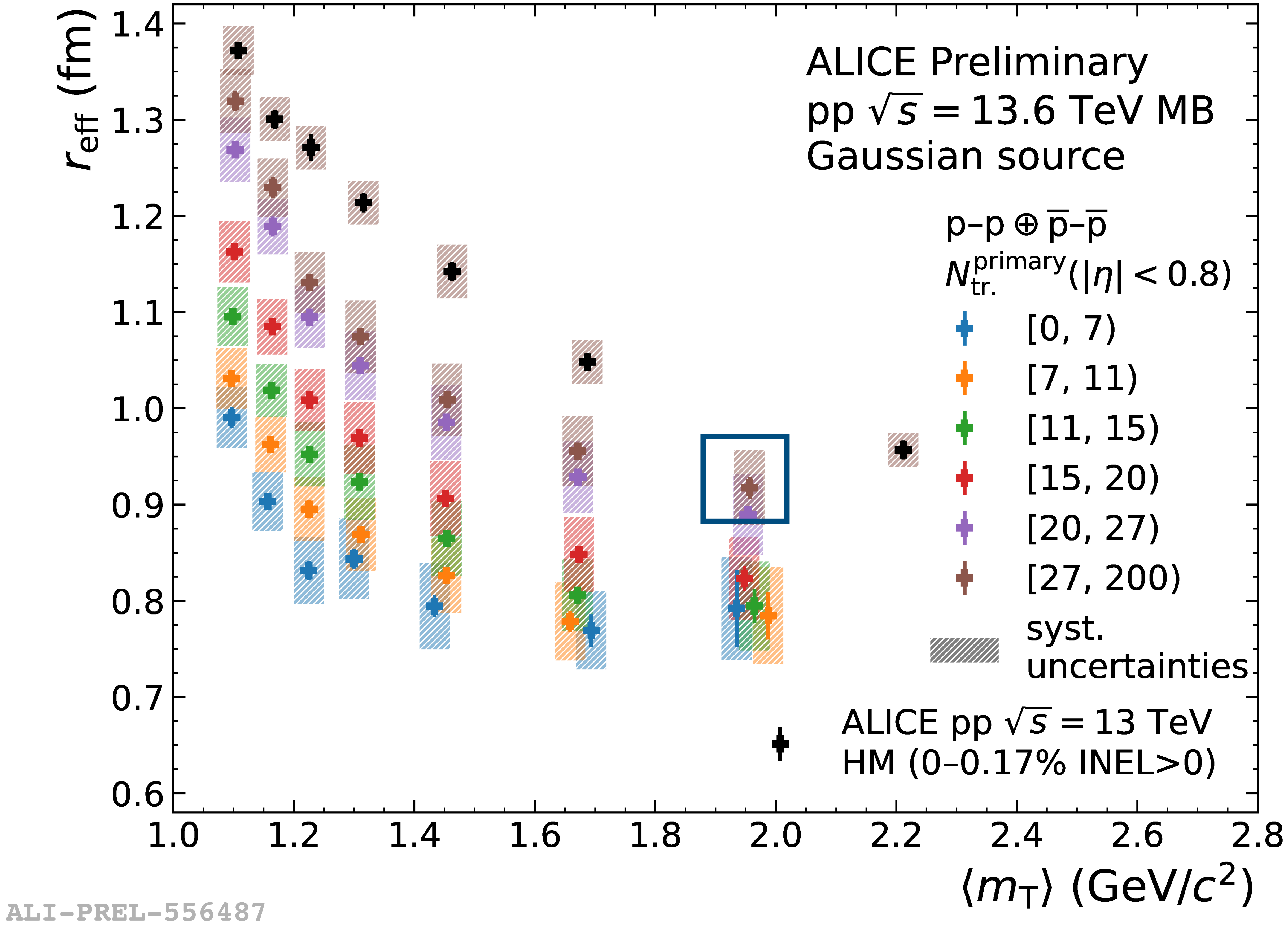
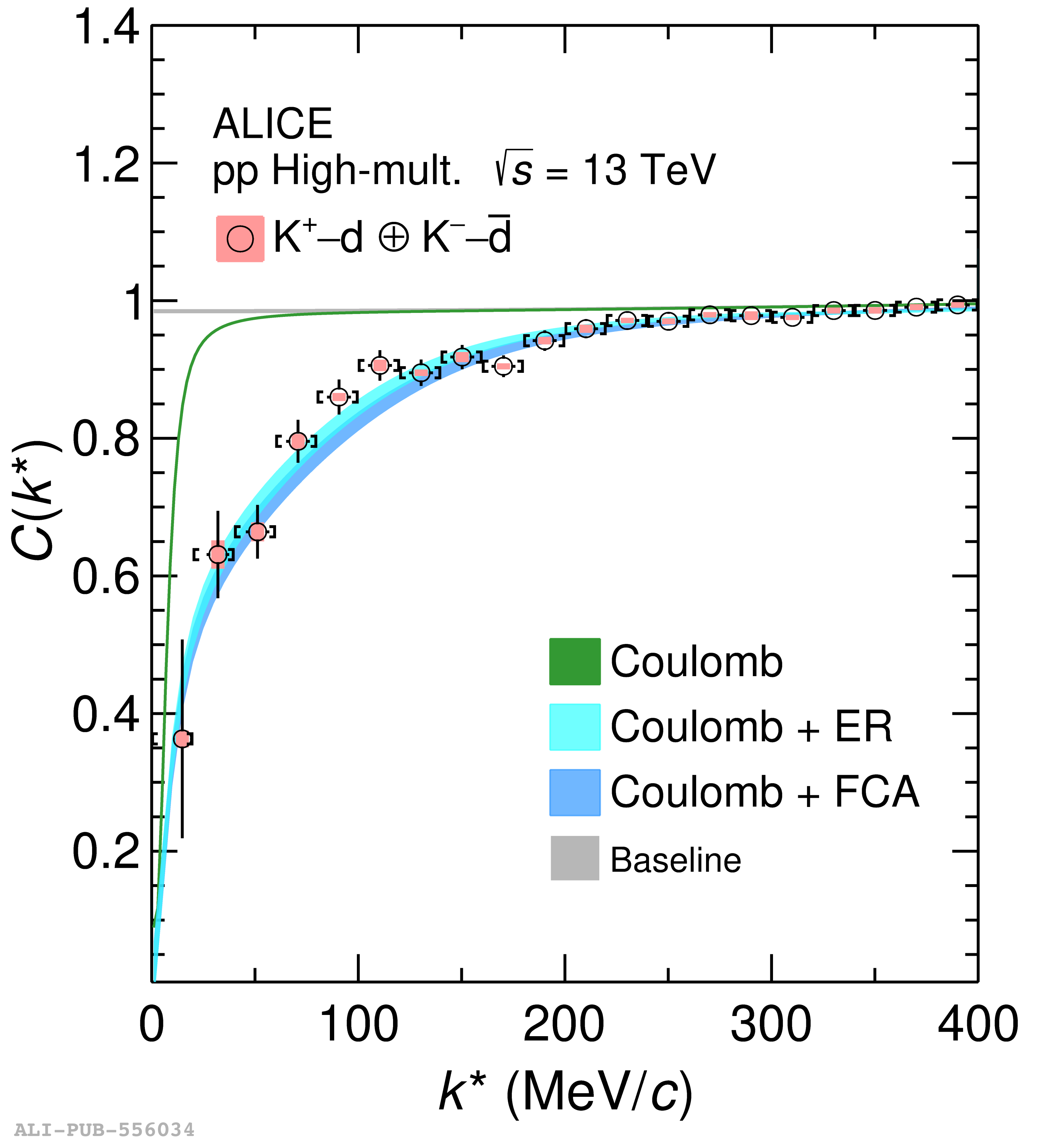


m_T-scaling of the effective source size for p–p pairs in different multiplicity classes

Summary

Summary:

- **K–d in pp in the first measurement ever**
  - Deuterons follow source size scaling common for all baryon–baryon pairs in pp collisions



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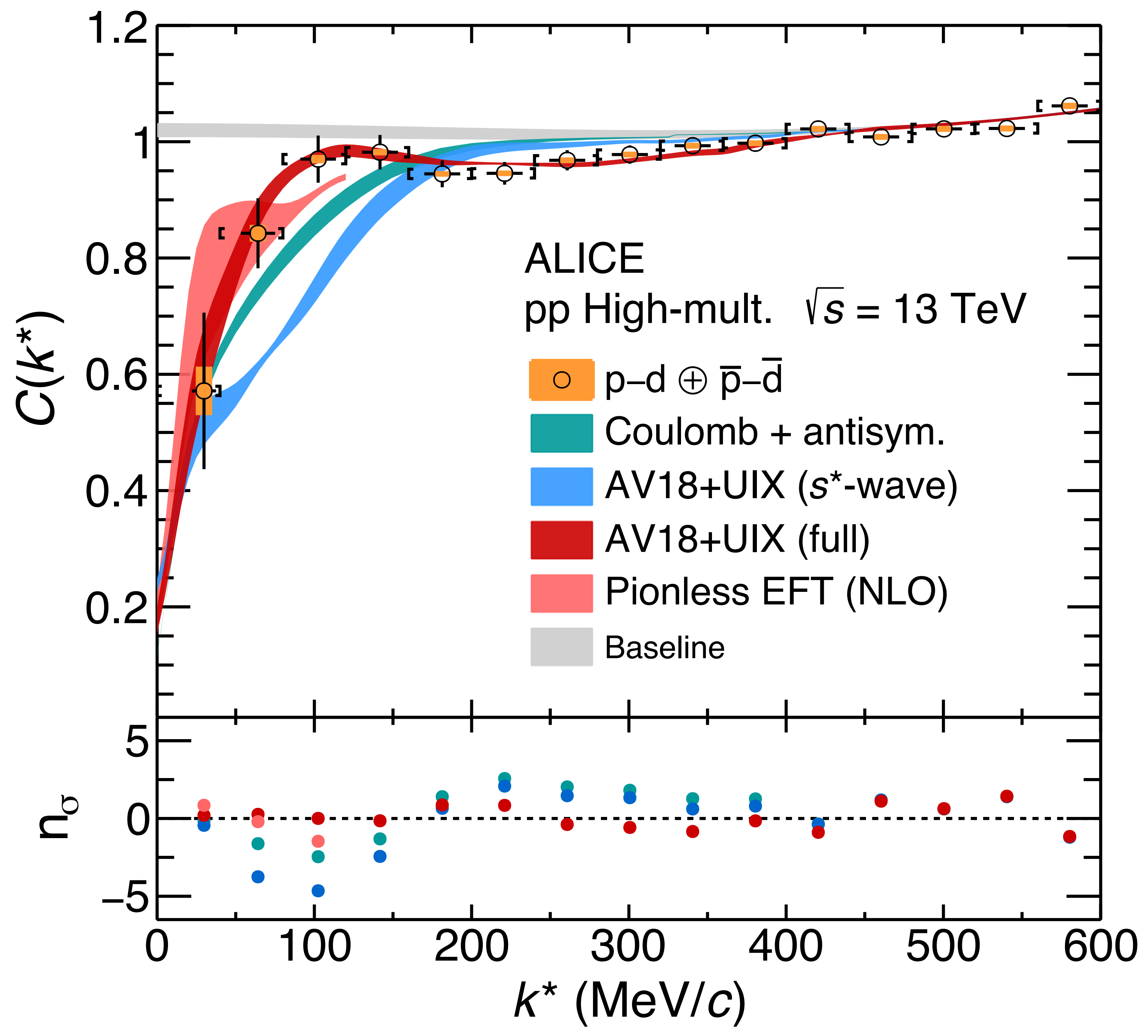

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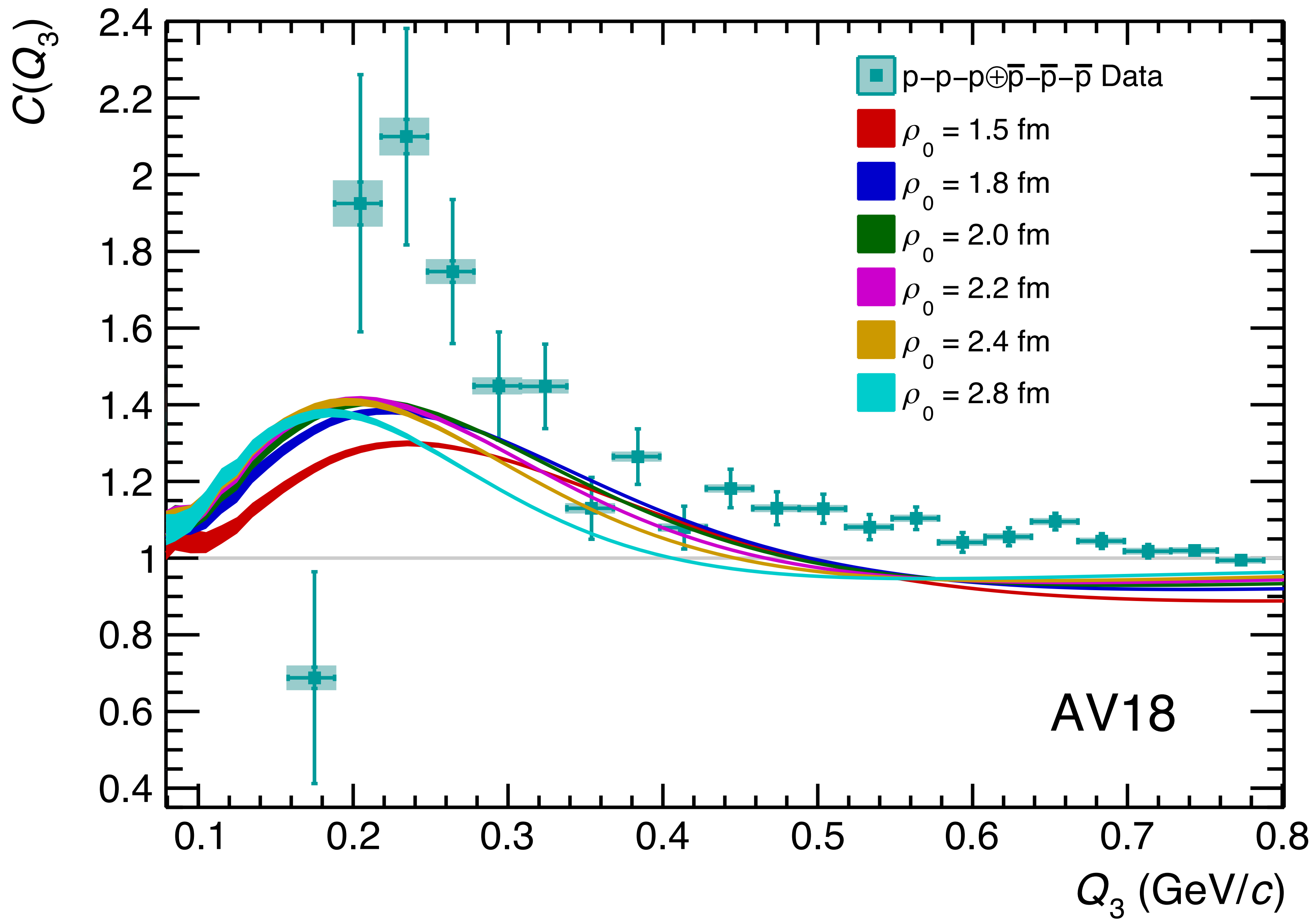

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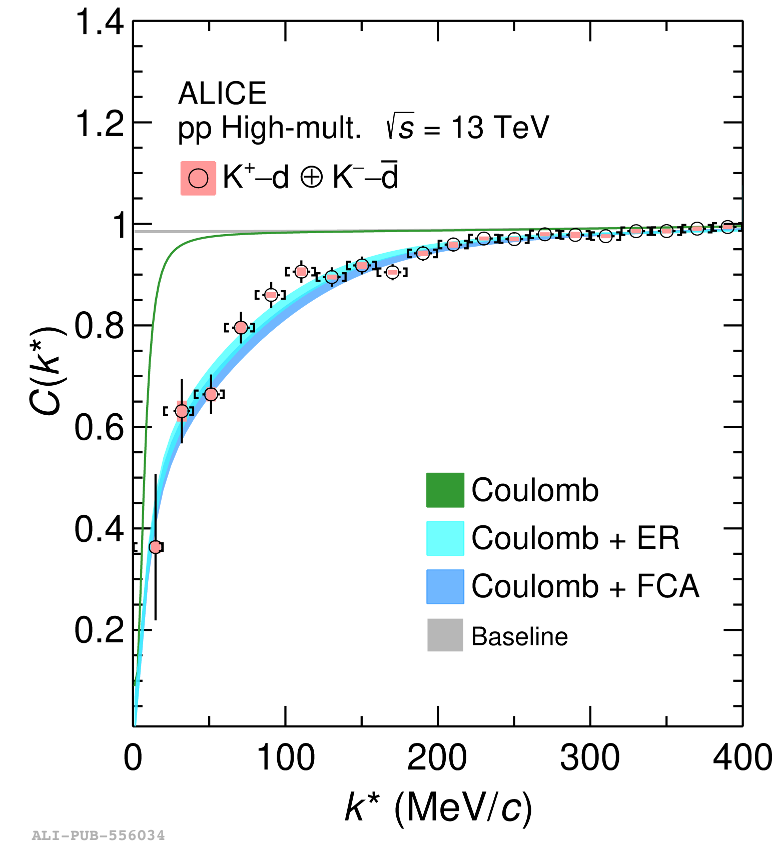

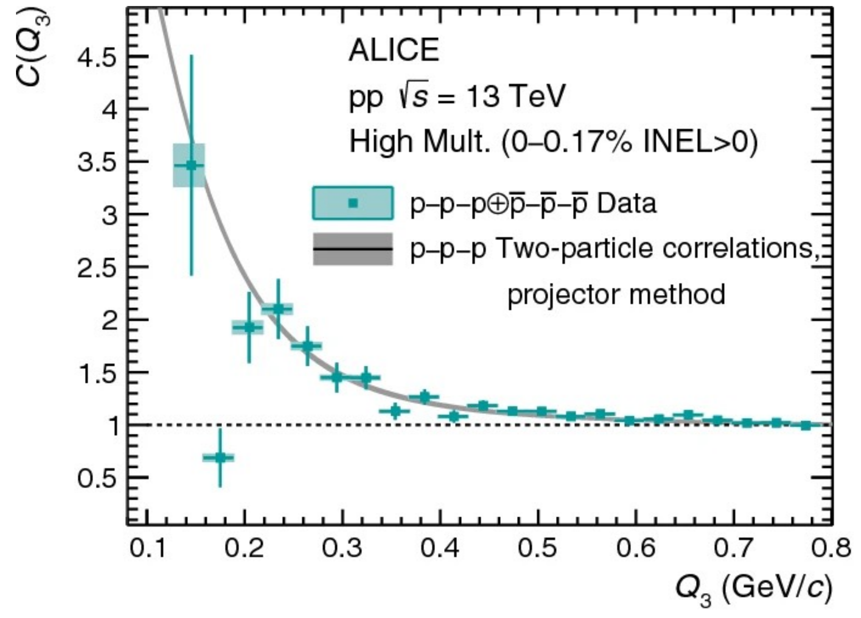

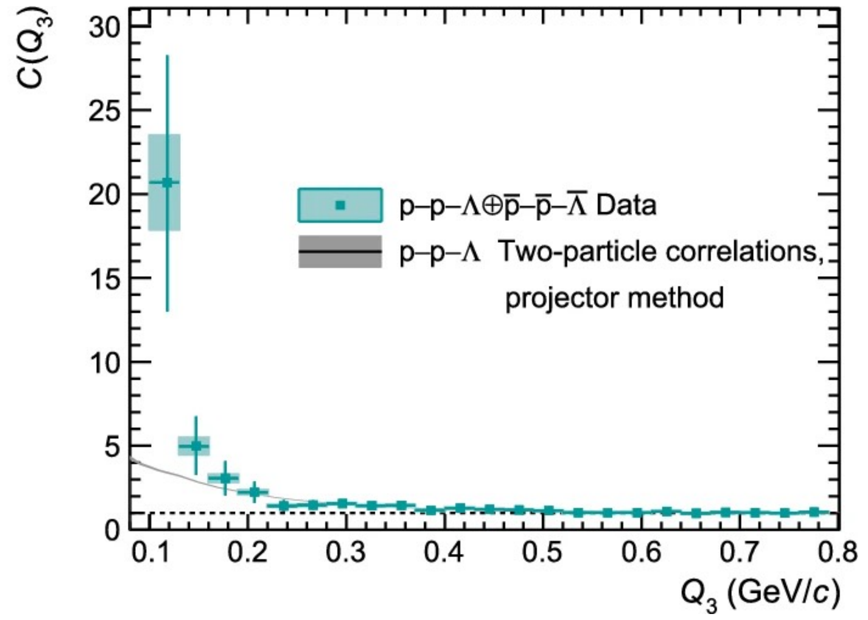

Outlook: Large statistics of LHC run 3 and run 4

- **p–p correlation** in LHC run 3: source constrained for all interaction studies
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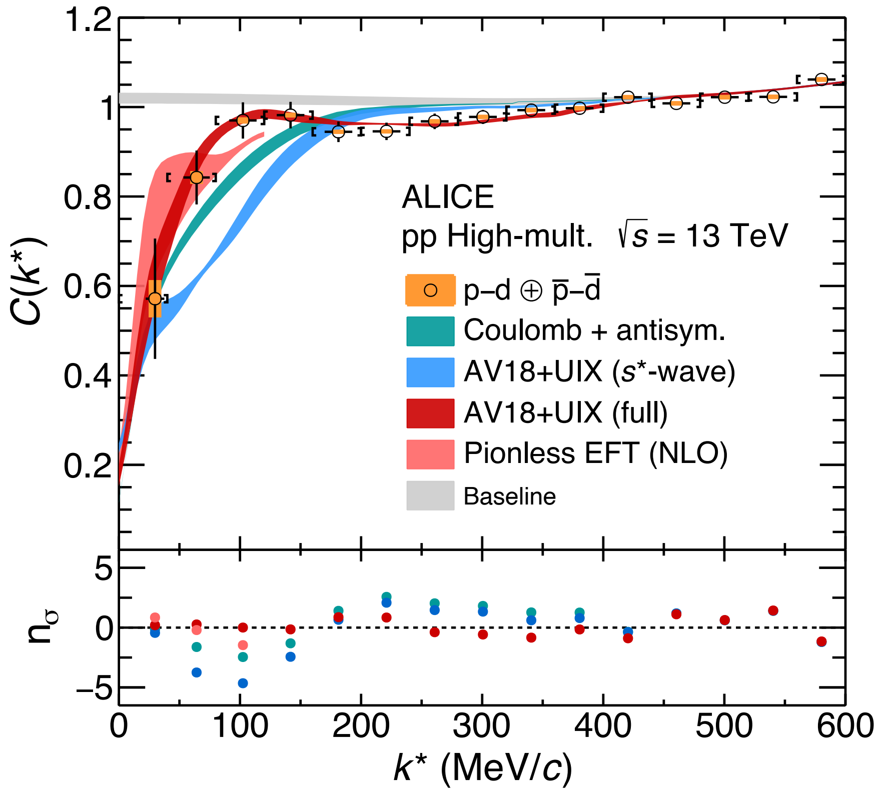

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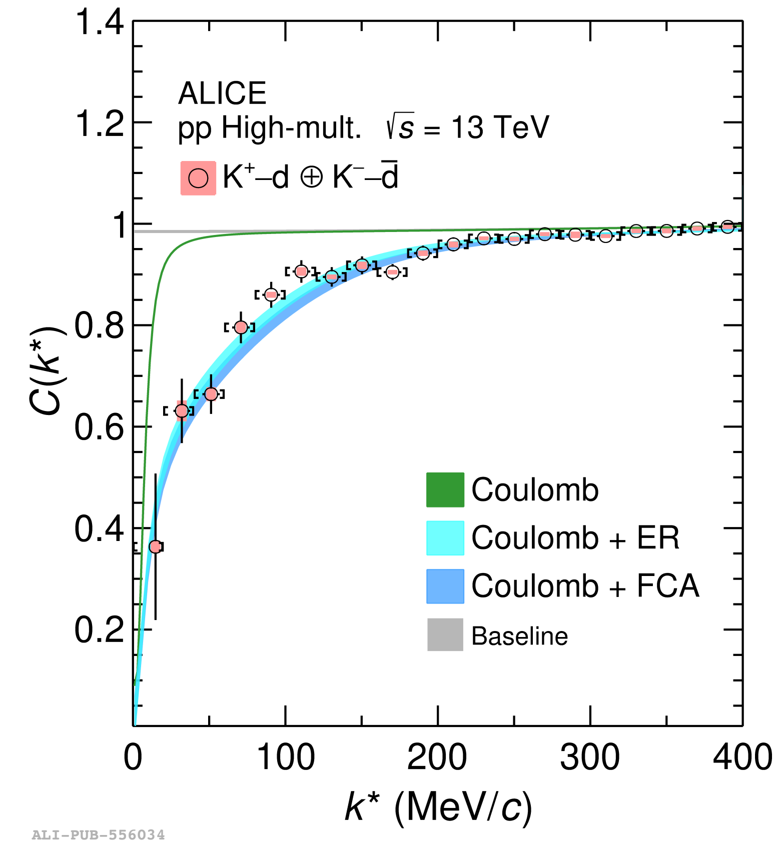

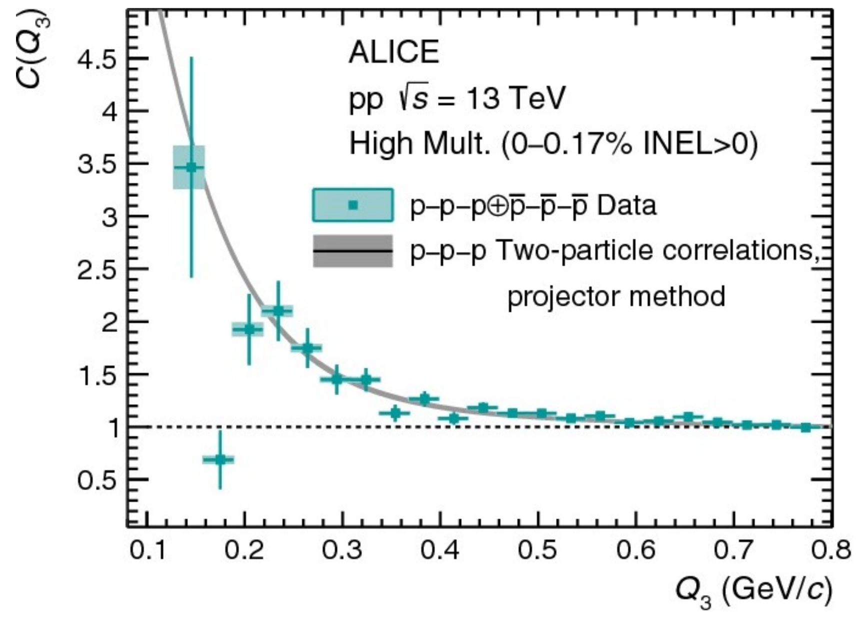

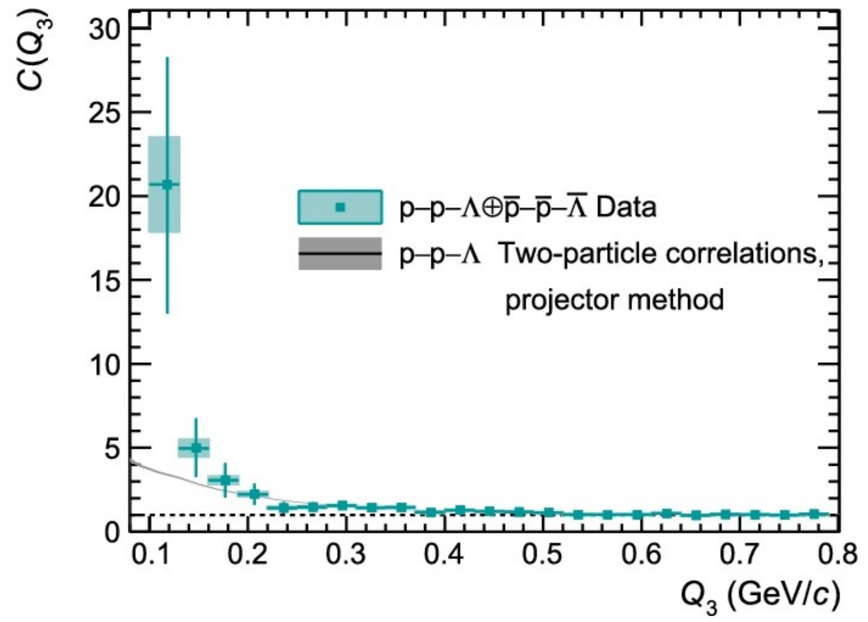

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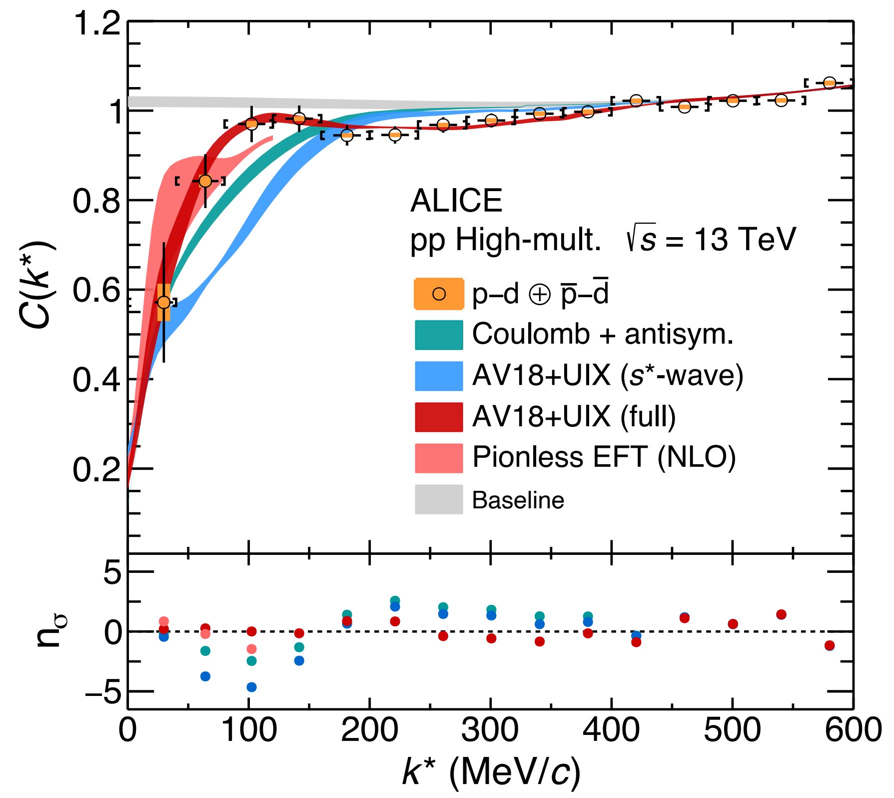
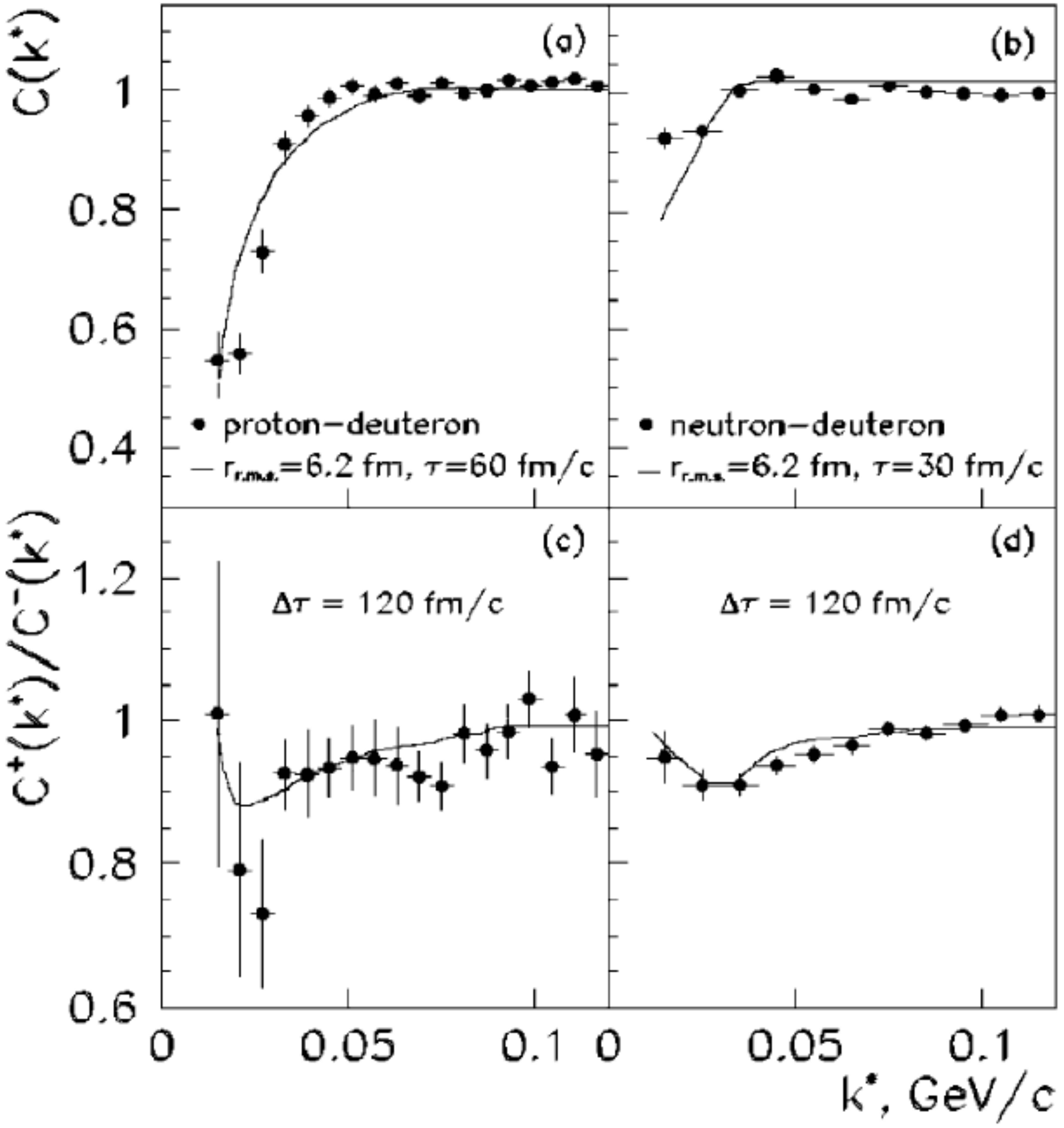


Thank you for your attention!

Backup

p-d correlation in the past

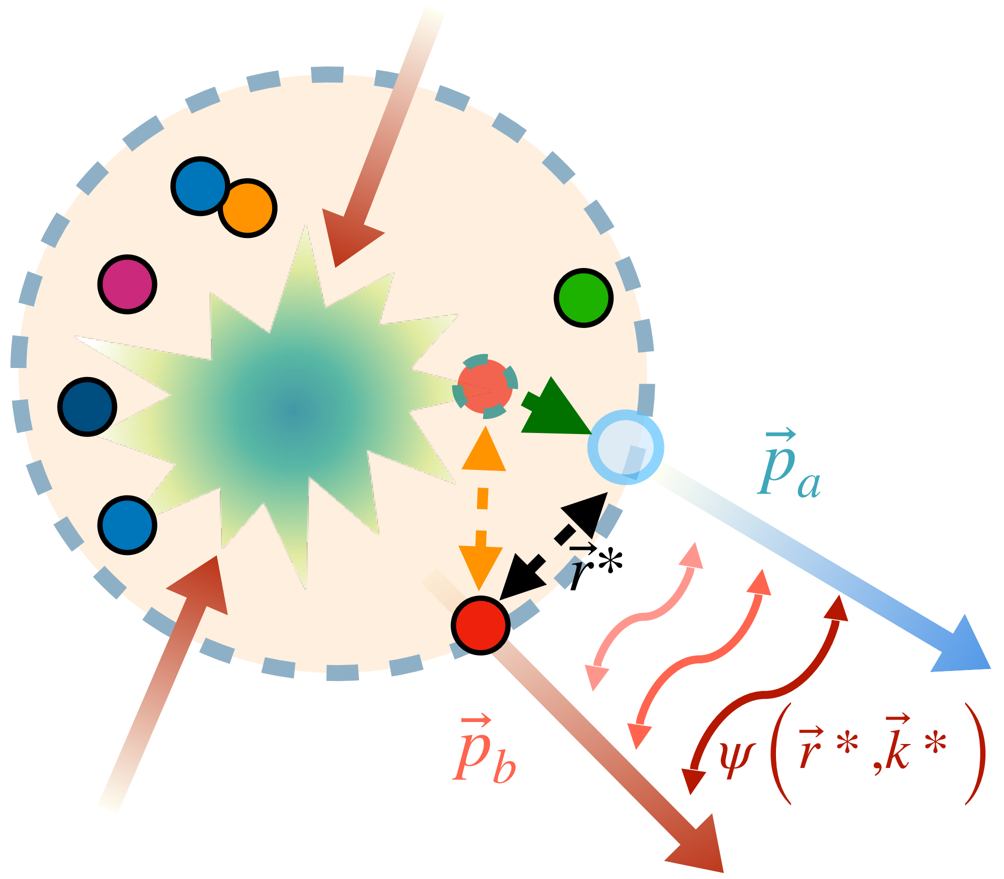
- Interpreted using the LL approach
- Measurement performed at AGS



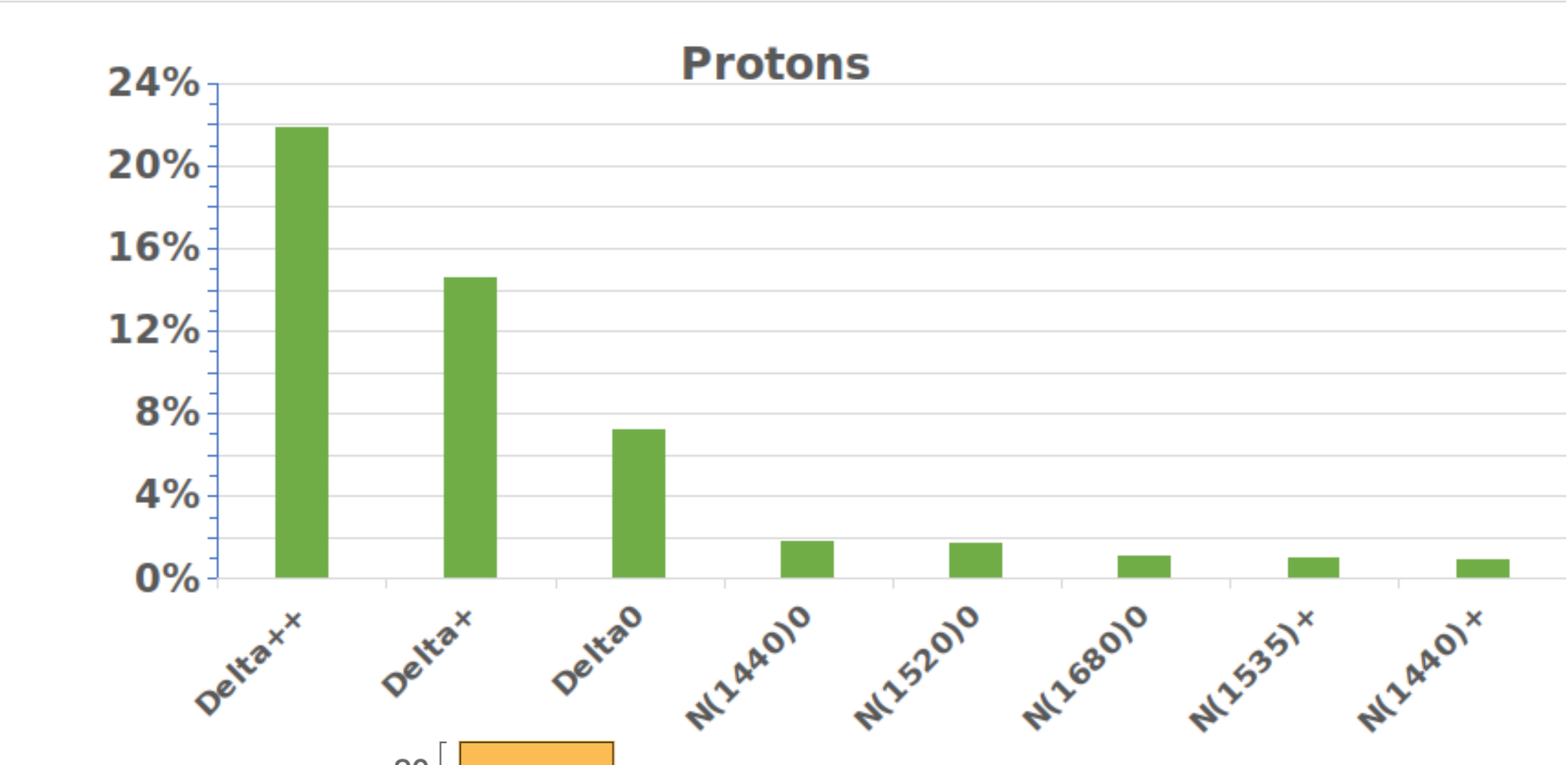
[1] Wosińska, K., Pluta, J., Hanappe, F. *et al. Eur. Phys. J. A* 32, 55–59 (2007)

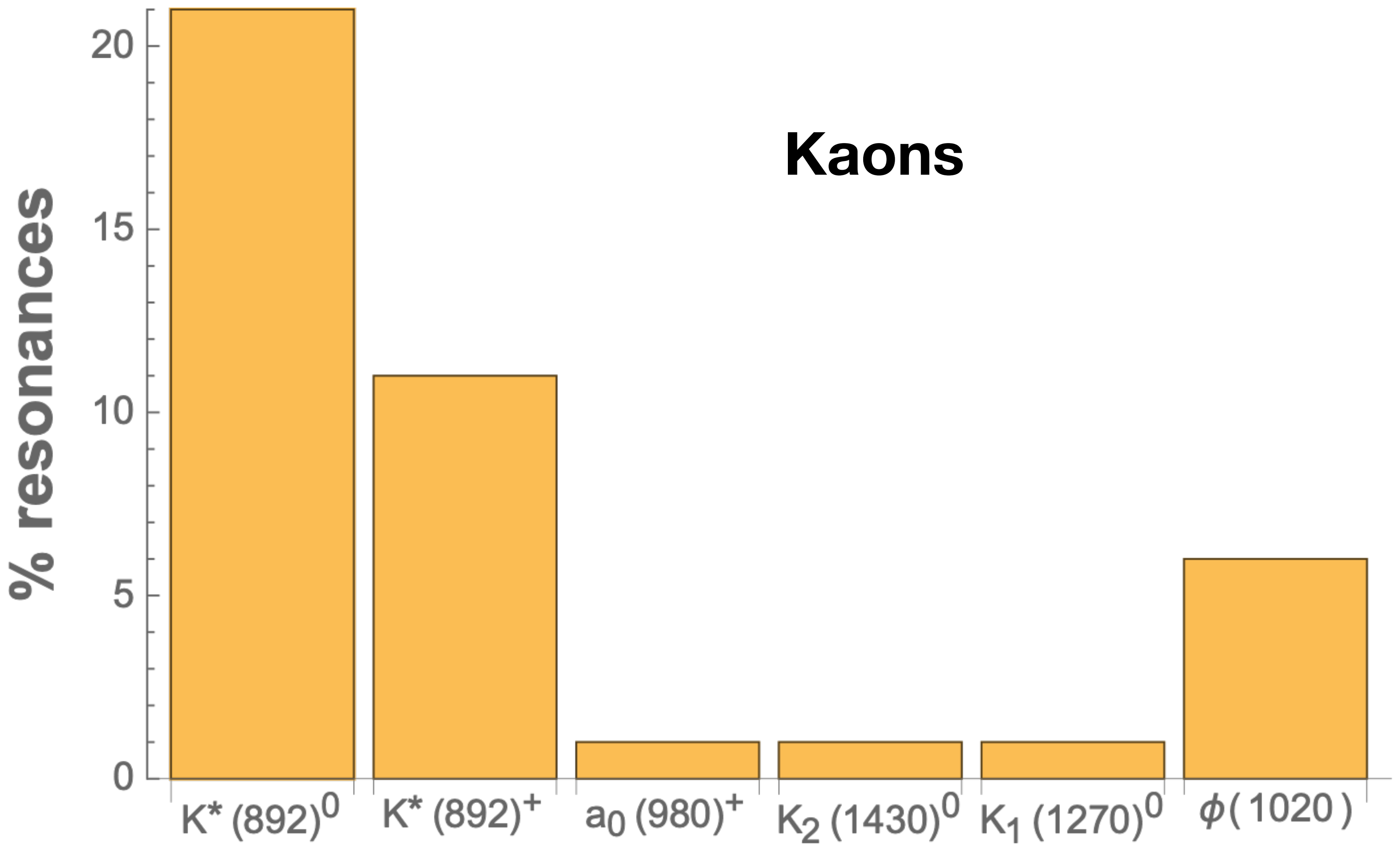
Source size for p–d and K⁺–d pairs

- The source radius is effectively increased by **short-lived strongly decaying resonances ($c\tau \approx r_{core}$)** e.g. Δ-resonances in case of protons



Source size	mean value:p–d	mean value:K⁺–d
r_{core}	0.99±0.05 fm	1.04±0.04 fm
r_{eff}	1.08±0.06 fm	$1.35^{+0.04}_{-0.05}$ fm





Hadron-deuteron pairs are created at very small distances in pp collisions at the LHC!

(1) ϕ(1020) corrected as feed-down

Total wavefunction for p-d system

$$\Psi_{LSJJ_z} = \sum_{n,\alpha} \frac{u_{n,\alpha}(\rho)}{\rho^{5/2}} \mathcal{Y}_{n,\alpha}(\Omega)$$
$$+ \frac{1}{\sqrt{3}} \sum_{\ell}^{\text{even perm.}} \left\{ Y_L(\hat{\boldsymbol{y}}_\ell) \left[\varphi^d(i,j)\chi(\ell) \right]_S \right\}_{JJ_z} \frac{F_L(\eta, ky_\ell)}{ky_\ell}$$
$$+ \sum_{L'S'} T^J_{LS,L'S'} \frac{1}{\sqrt{3}} \sum_{\ell}^{\text{even perm.}} \left\{ Y_{L'}(\hat{\boldsymbol{y}}_\ell) \left[\varphi^d(i,j)\chi(\ell) \right]_{S'} \right\}_{JJ_z}$$
$$\times \frac{\overline{G}_{L'}(\eta, ky_\ell) + iF_{L'}(\eta, ky_\ell)}{ky_\ell} \; .$$

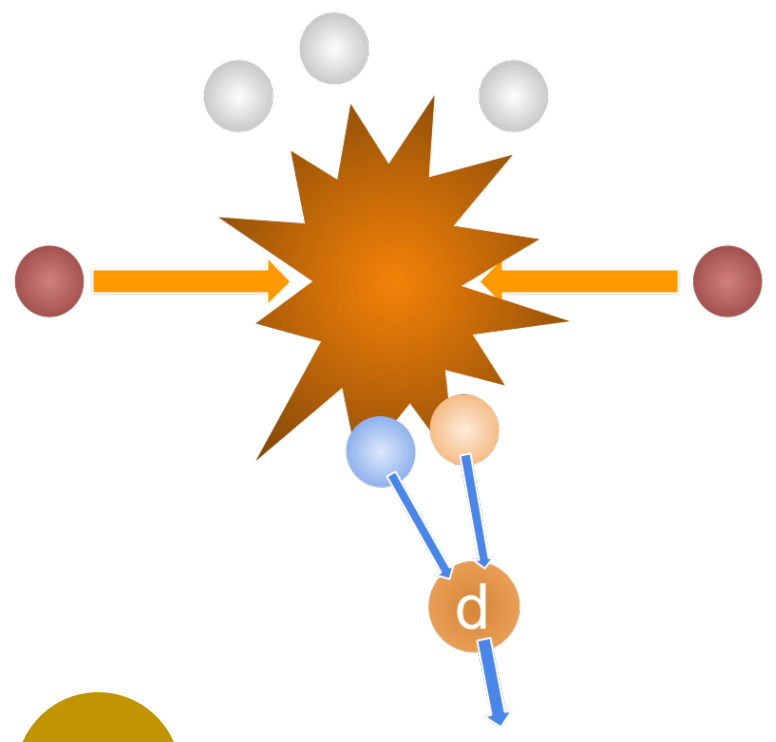
p–d as three-body system

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

- **p–pn correlation to form p–d state**:
  - Nucleons with the Gaussian sources distributions

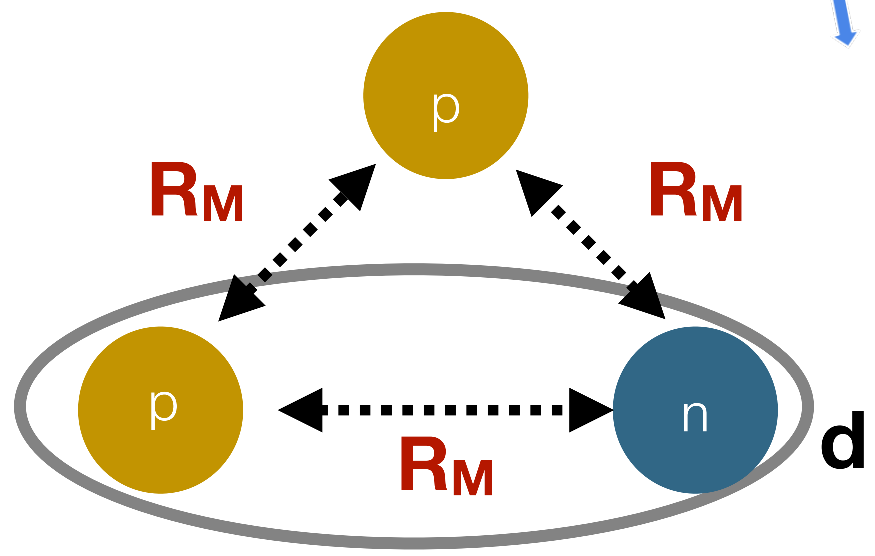
Single-particle Gaussian emission source

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



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

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



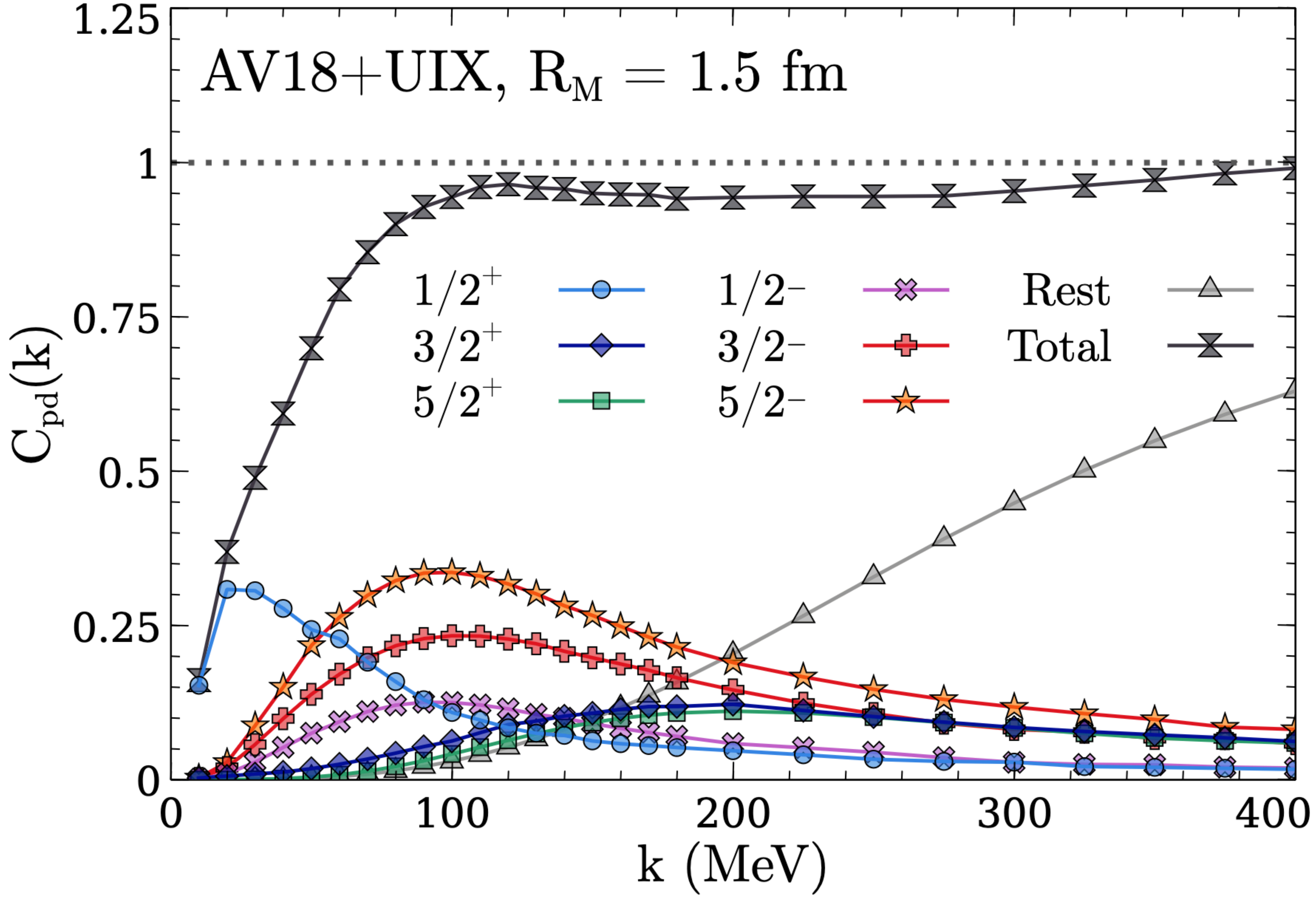
M. Viviani et al arXiv:2306.02478v1 [nucl-th] (2023) (submitted to PRC)

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

Partial wave decomposition of p-d

- Precise calcualtion using AV18+UIX as well NVIa3/3N chiral potentials

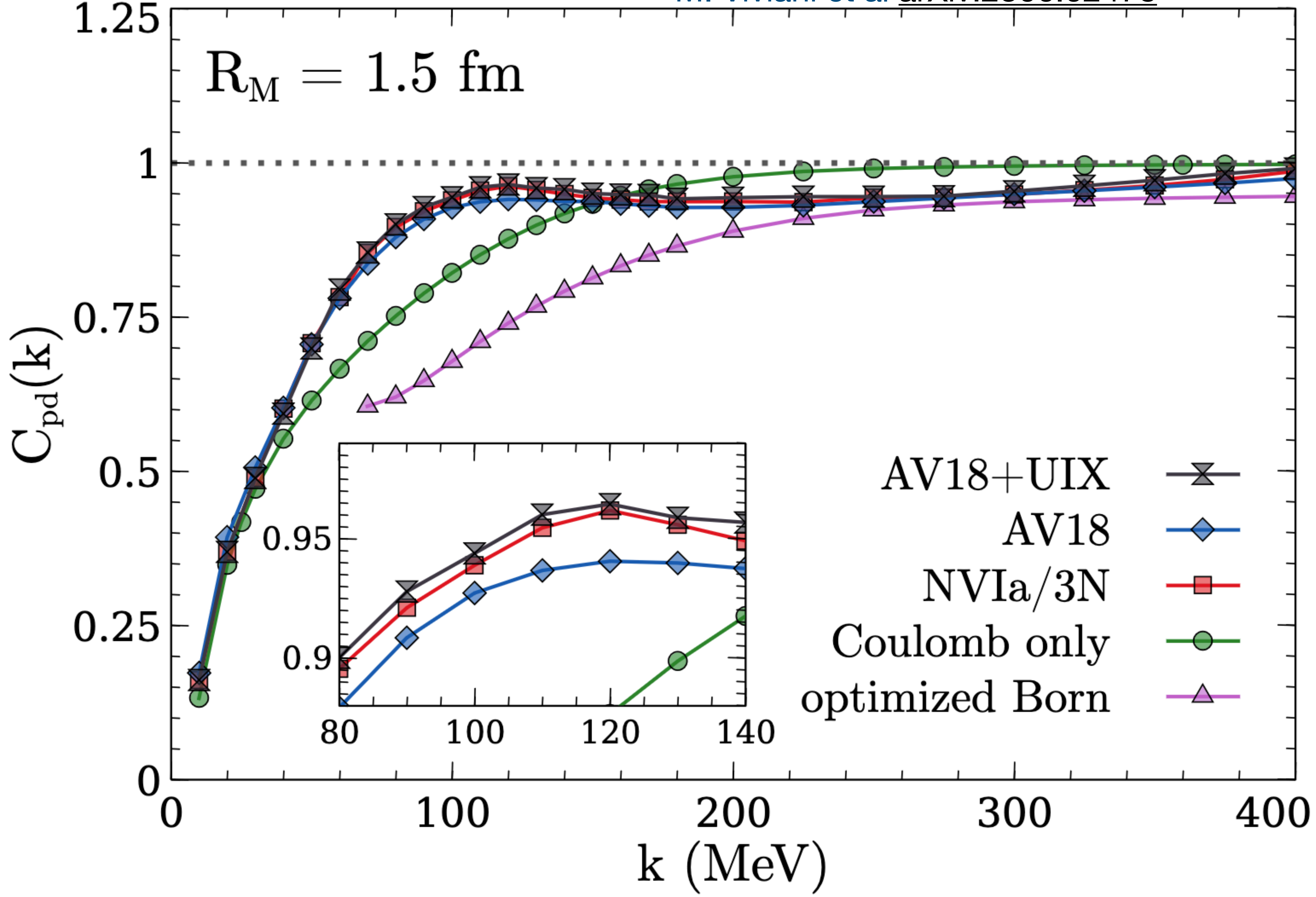
M. Viviani et al arXiv:2306.02478



AV18+UIX vs NVIa3 3N Chiral potentials

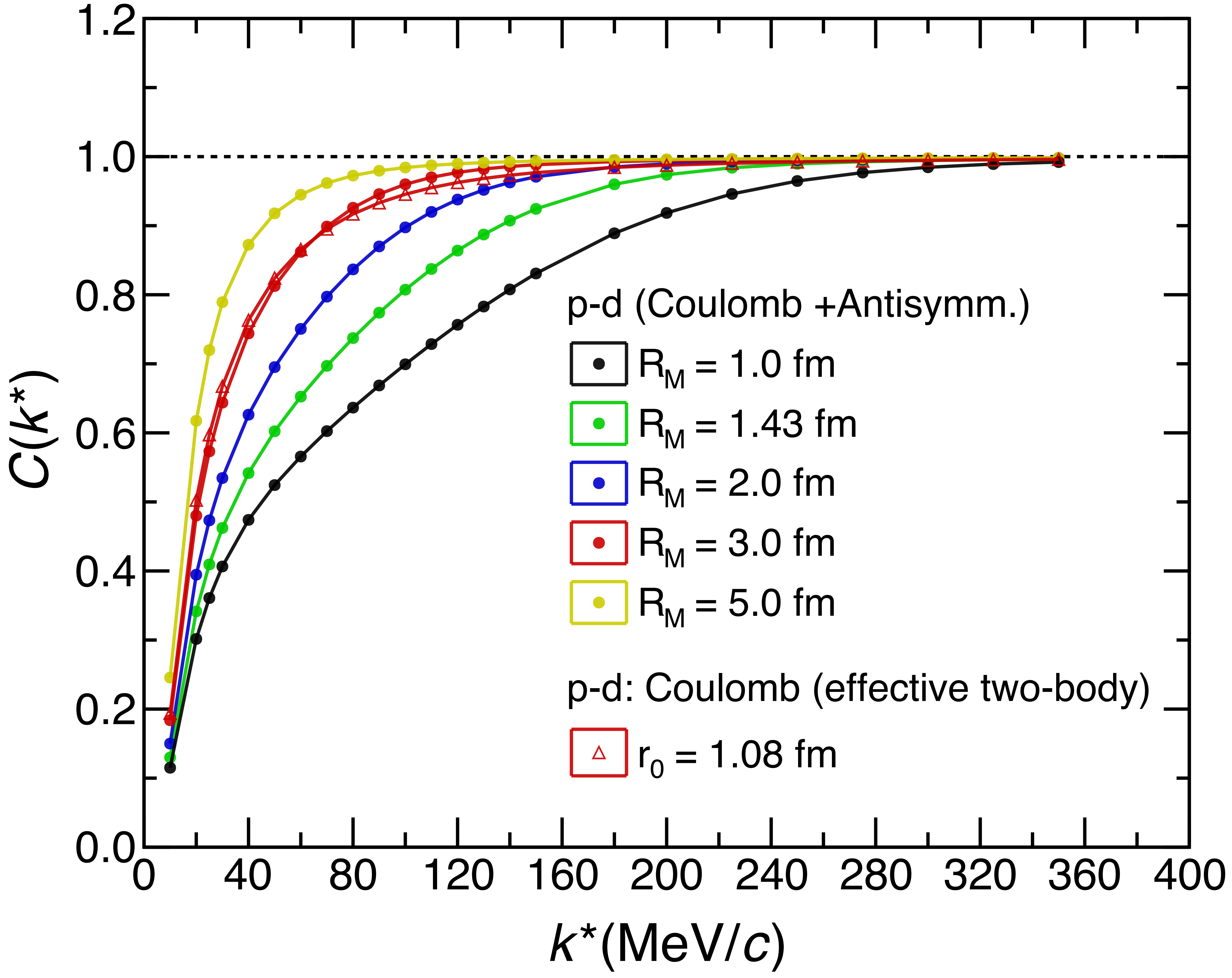
- Precise calcualtion using AV18+UIX as well NVIa3/3N chiral potentials

M. Viviani et al arXiv:2306.02478



Coulomb only

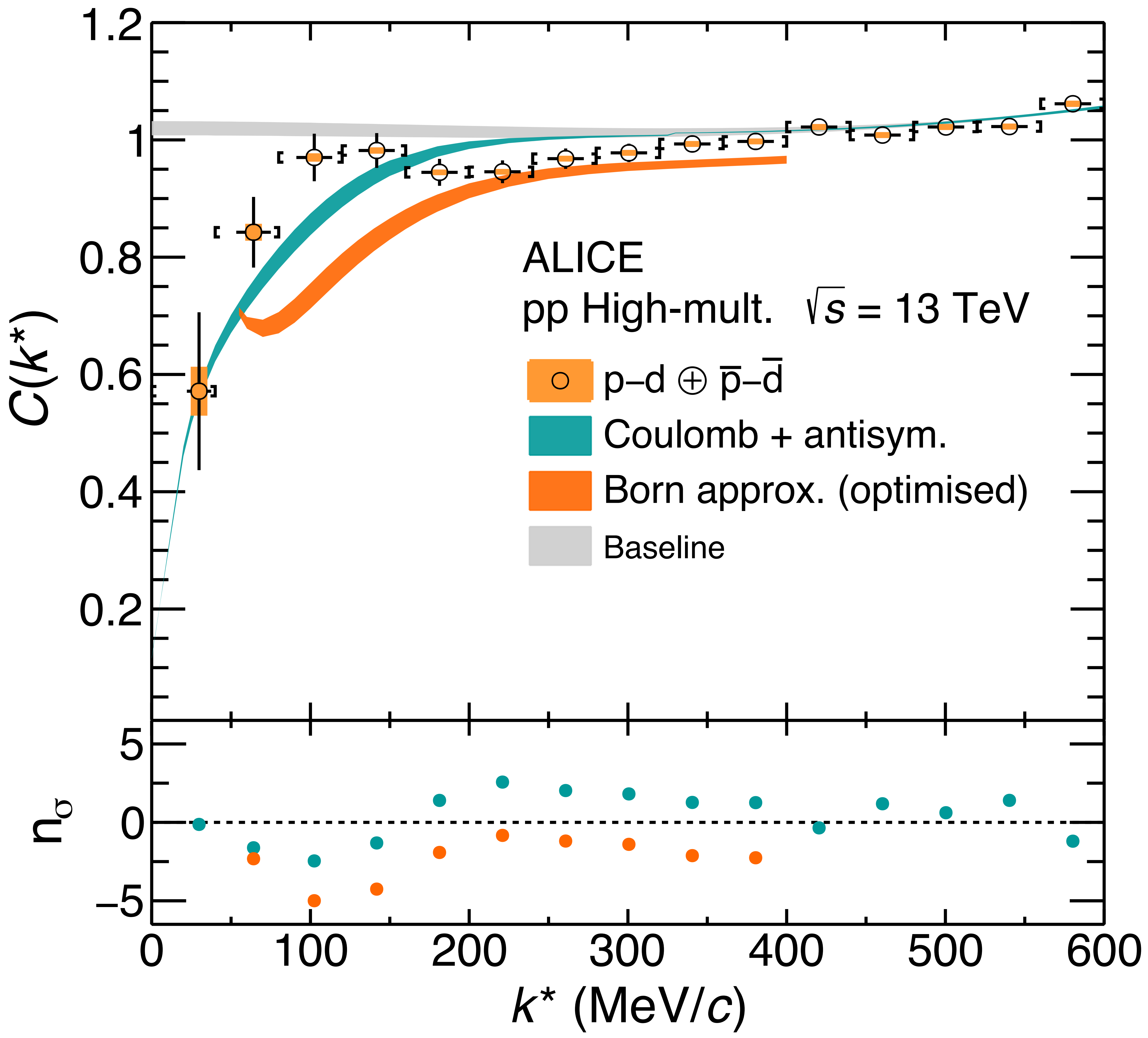
- Complete p–pn dynamics, but the strong interaction is **absent** at very short-range!
  - **r^{NN}_{eff} =1.43±0.16** fm (nucleon-nucleon distance)
- In the case of the two-body picture Coulomb-only interaction differs from the one using the p-(pn) dynamics
  - **r^{pd}_{eff} =1.08±0.06** fm (proton-deuteron distance)
  - More repulsion due to the Pauli-blocking



Sensitivity to the dynamics of the three-body p–(pn) system even for Coulomb case

Born approximation effective two-body

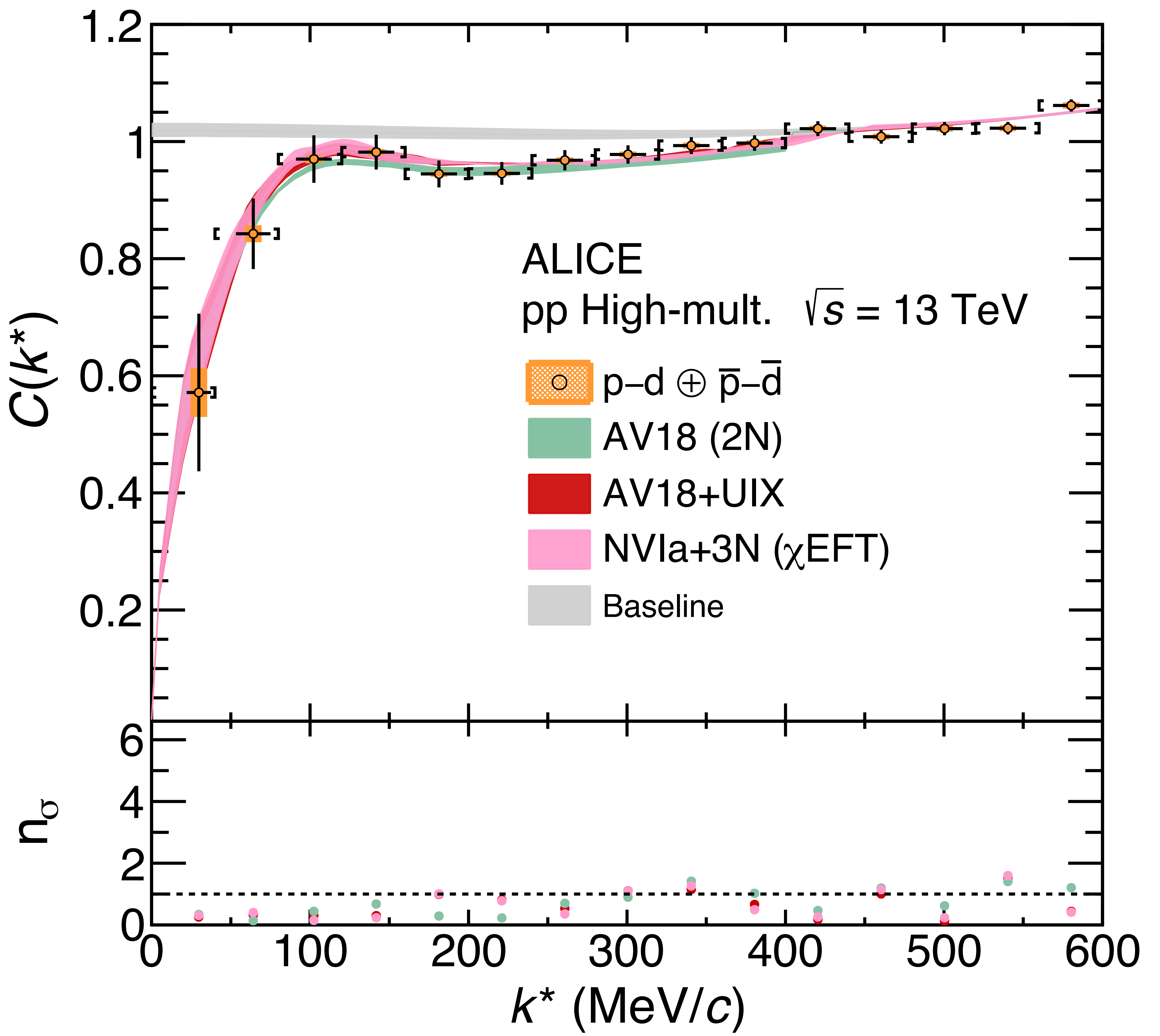
- Complete p–pn dynamics, but the strong interaction is **absent** at very short-range!
  - r^{NN}_{eff} **=1.43±0.16** fm (nucleon-nucleon distance)
  - Coulomb-only interaction coincidently appears in the data (despite the large scattering lengths)
  - Coulomb+strong interaction using **Born approximation (neglecting short-range strong interaction)** and proper p–pn dynamics



Sensitivity to the dynamics of the three-body p–(pn) system at short distance

Chiral potentials calculation: NVIa+3N

- Comparisition with Chiral potentials (**Full three-body dynamics)**[1]
- Argonne v18+Urbana IX interaction[2,3]
  - **All partial waves upto d-waves:** describes data within $n_\sigma \sim 1$ for k^* up to 400 MeV/c
- Calculations using chiral potential from NVIa+3N
  - Very good agreement with AV18+UIX
- AV18 alone: just two-body NN interaction
  - Current data cannot resolve the effect of three-body force



Both AV18+UIX and NVIa+3N calculations provide an excellent agreement with the measurement

Femtoscopic correlation

- The femtoscopic correlation may have background/contributions from
  - Particles from weak decays
  - Particles from material knock-outs
  - Misidentifications

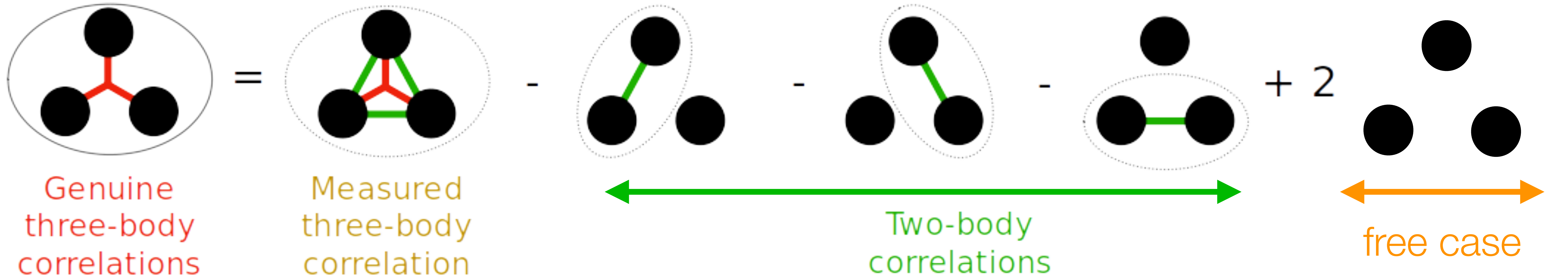
$$C_{femto}(k^*) = \lambda_0 C_0 \oplus \lambda_1 C_1 \oplus \lambda_2 C_2 \oplus \ldots$$

Contributions from: genuine feed-down misidentifications

- Quantification of the contributions to the pairs done by the lambda parameters $\lambda_{ij} = \mathscr{P}_i . f_i \times \mathscr{P}_j . f_j$
  - Purity of the individual particles ($\mathscr{P}_i$)
  - Feed-down fractions (f_i)

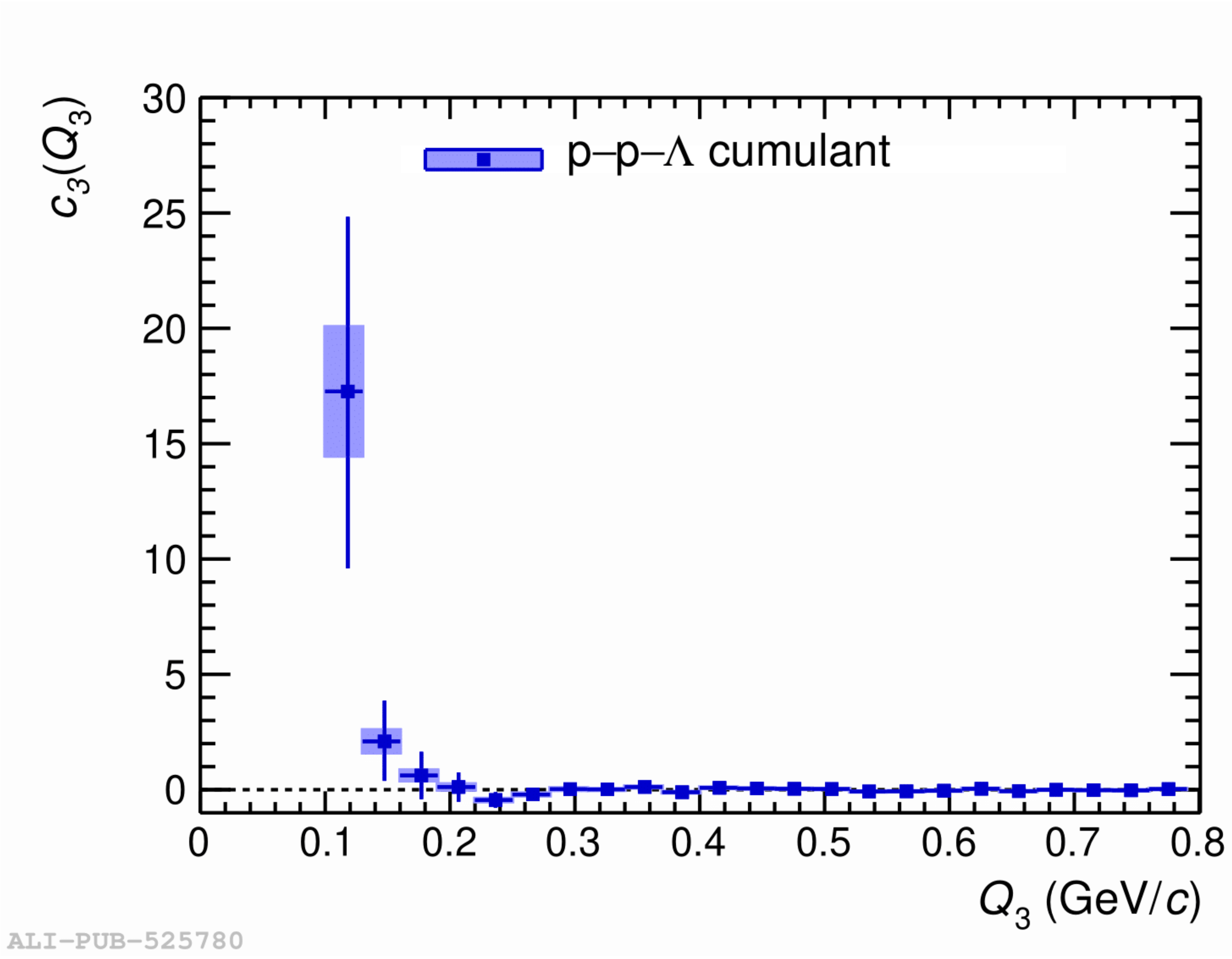
Cumulant: measure for three-body effects

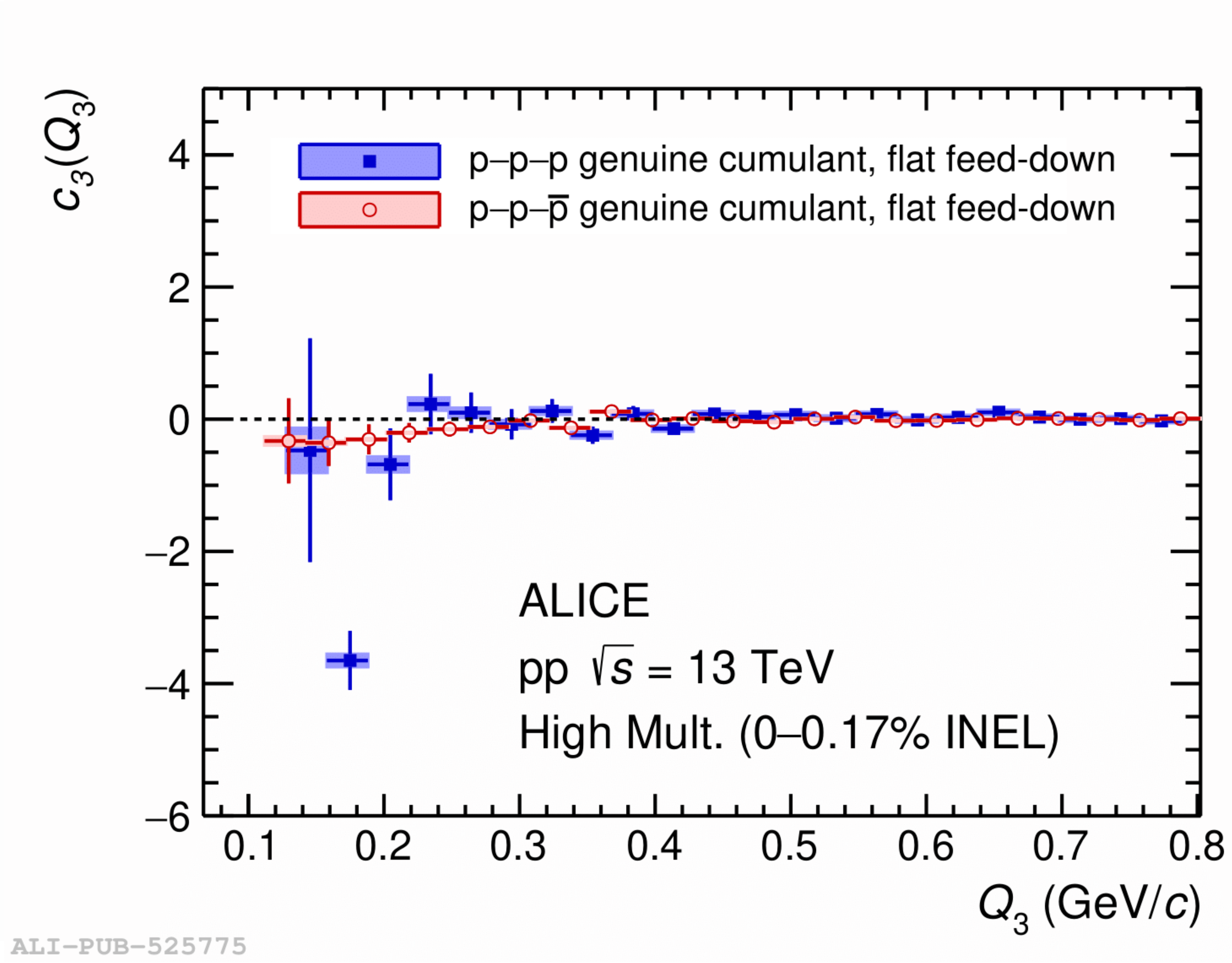
$c_3\,(Q_3)$



Kubo, J. Phys. Soc. Jpn. 177 (1962)

$c_3\,(Q_3)$ allows to isolate effects associated with the genuine three-body interactions





Cumulants (Run 2)

p-p-p and p-p-p̄: nonzero

- Hint of a genuine three-body effect

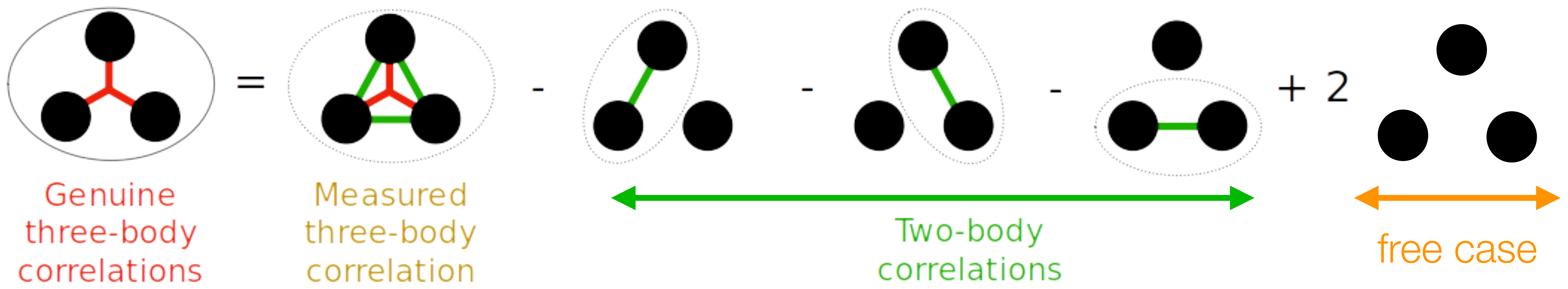
p-p-Λ: compatible with zero

- Strong rise but inclusive due to lack of statistics

Need for large statistics to precisely measure the three-body effects=> Run 3 of LHC

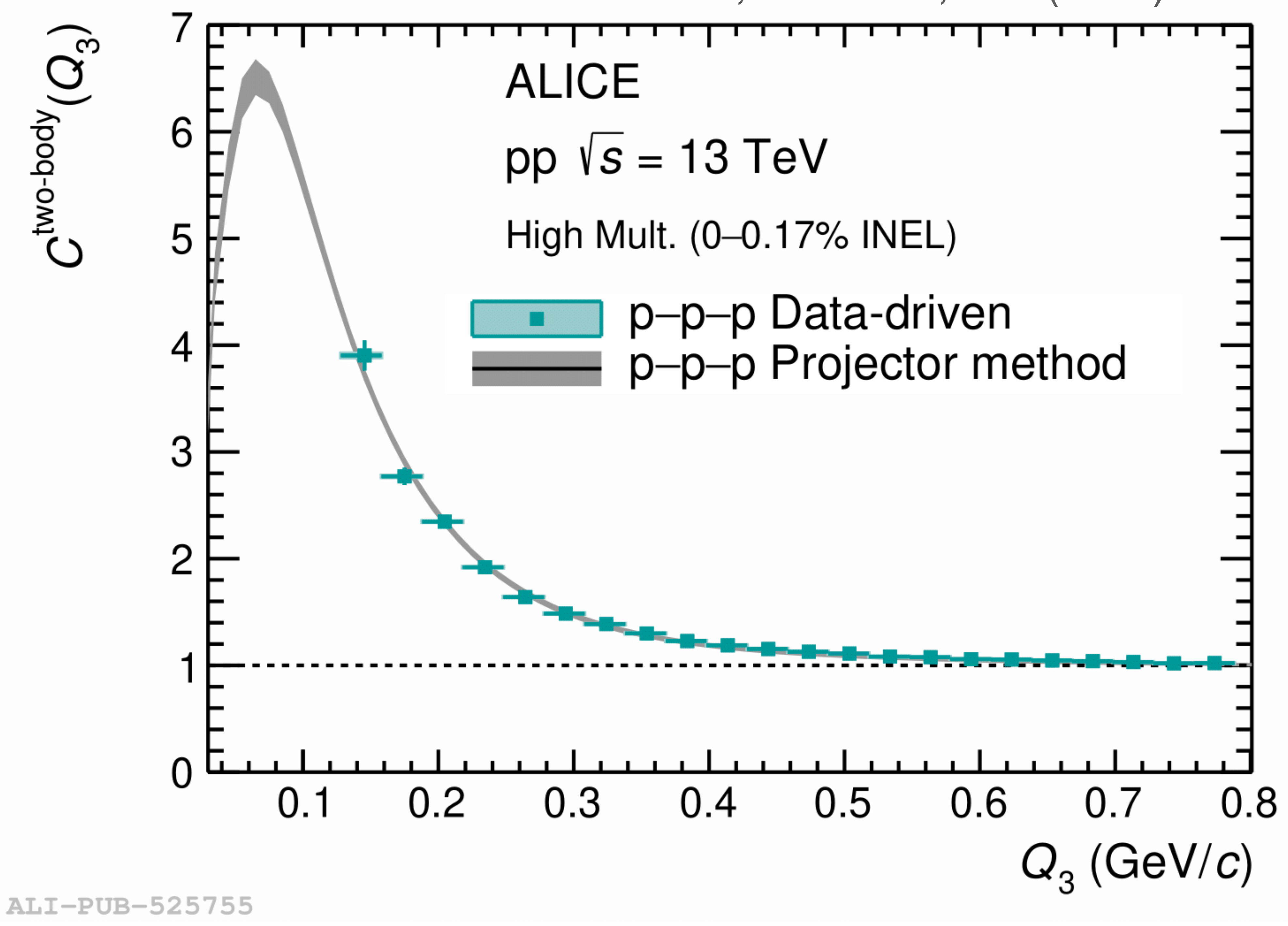
Towards genuine three-body interaction

Kubo's cumulant approach[1]



- First study underlying two body correlations with a **data-driven**[2] and a **phase-space projector**[3] methods

ALICE Coll., EPJ A 59, 145 (2023)



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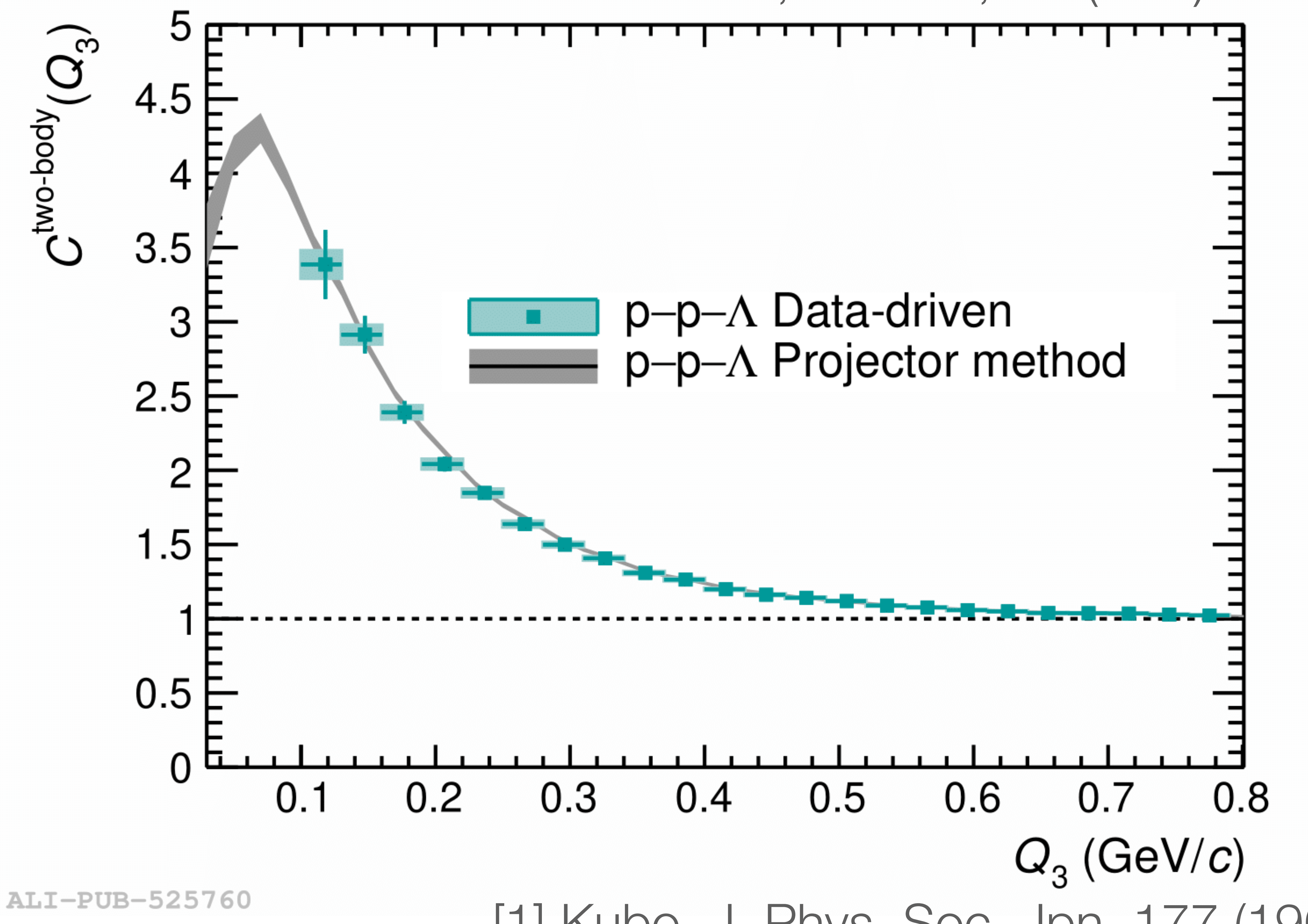
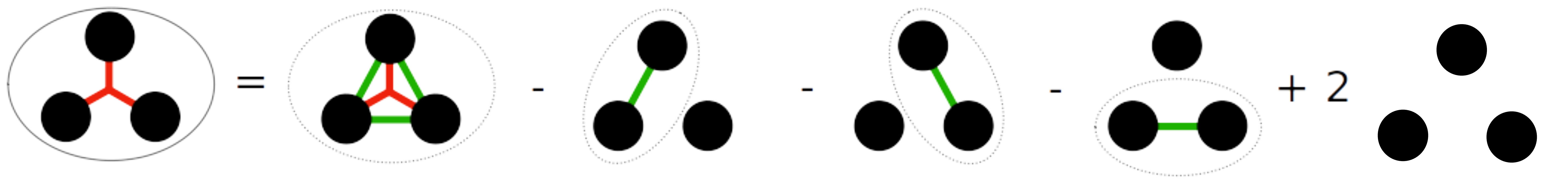


[1] Kubo, J. Phys. Soc. Jpn. 177 (1962)
[2] ALICE Coll., EPJ A 59, 145 (2023)
[3] R. Del Grande et al. EPJC 82 (2022)

Cumulant: measure for three-body effects

Kubo's cumulant approach[1]



c_3 (Q_3) allows to isolate effects associated with the genuine three-body interactions

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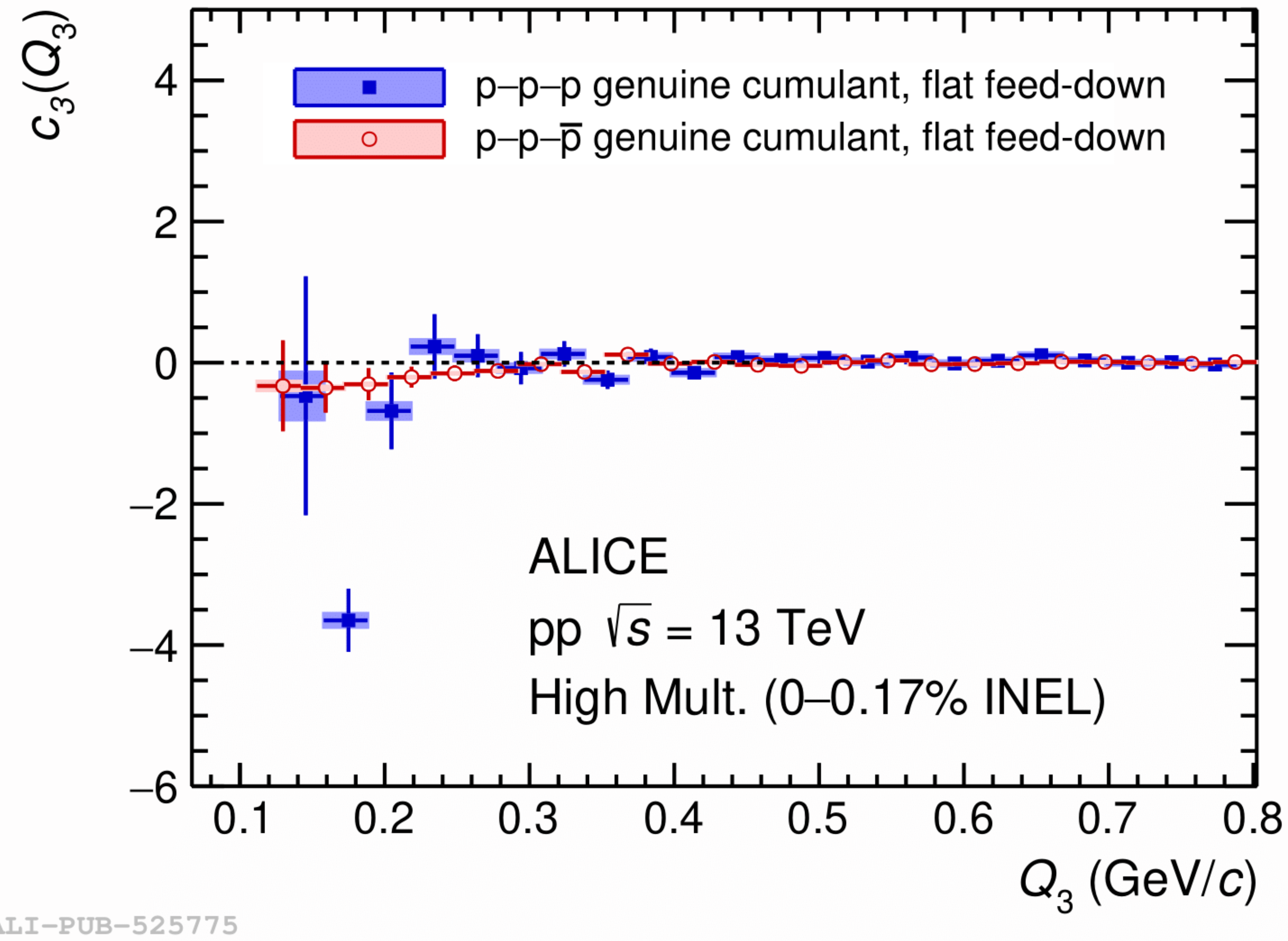


- Negative values of p-p-p and p-p-p̄ cumulants
  - Pauli blocking at the three-particle level
  - Three-body strong interaction

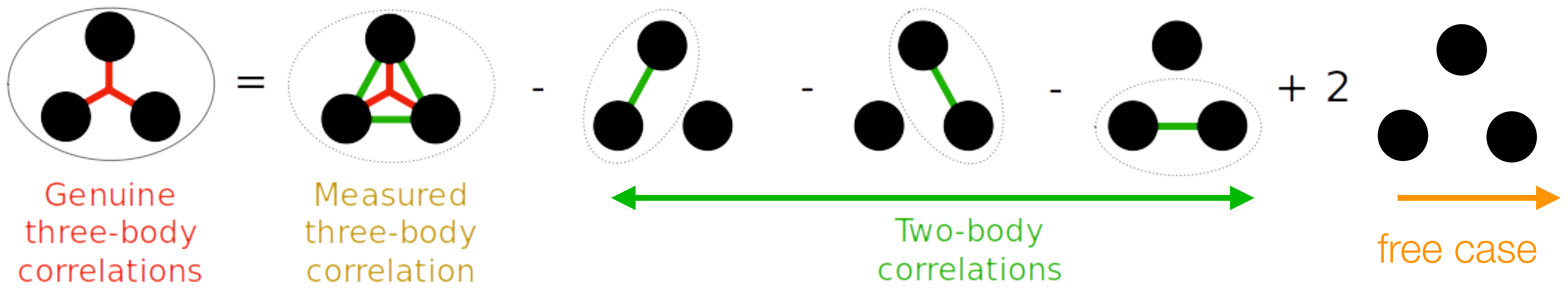
- Statistical significance:

nσ = 6.7 for Q_3 < 0.4 GeV/c

[1] Kubo, J. Phys. Soc. Jpn. 177 (1962)

p-p-Λ cumulant

Kubo's cumulant approach[1]



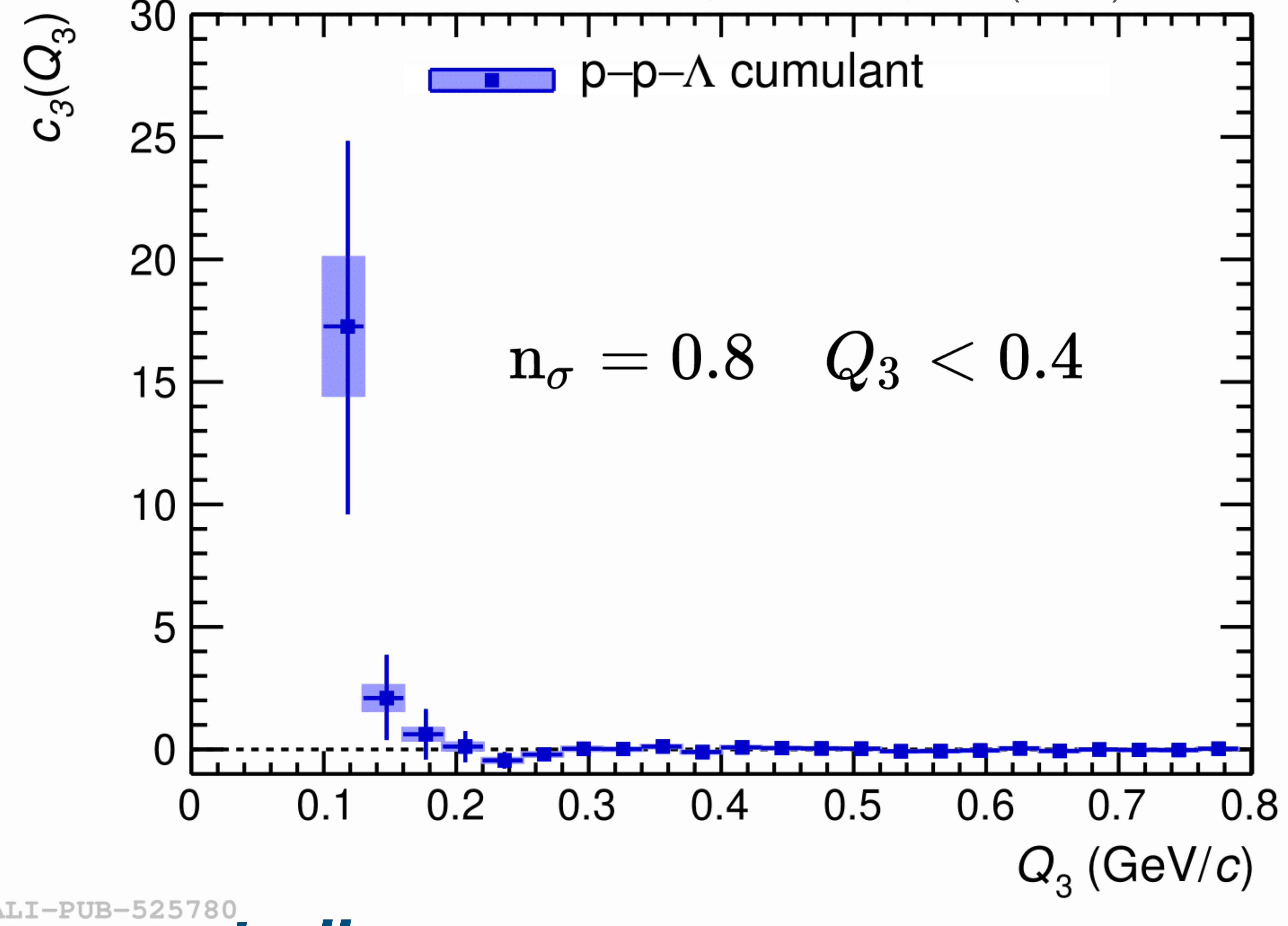
$c_3\,(Q_3)$ allows to isolate effects associated with the genuine three-body interactions

- Positive p-p-Λ cumulant
  - Two identical particle and charged particle
  - Expected dominant contribution from strong interaction

- Statistical significance:

$n\sigma$ = 0.8 for Q_3 < 0.4 GeV/c

ALICE Coll., EPJ A 59, 145 (2023)



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

Lednicky Model

- For distinguishable particles
  - Starting from the scattering parameters ⇒ define the s-wave two-particle relative wave function
  - Considers Coulomb effects

- Coulomb-corrected wave function for final-state interactions in s wave:

$$\psi_{-k^*}(r^*) = e^{i\delta_c}\sqrt{A_c(\eta)}\left[e^{-ik^*r^*}F\left(-i\eta, 1, i\zeta\right) + f_c(k^*)\frac{\tilde{G}(\rho,\eta)}{r^*}\right]$$

- f_c : Coulomb normalized scattering amplitude for strong interaction
- $F(-i\eta, 1, i\zeta)$: confluent hypergeometric function
- $\tilde{G}(\rho,\eta)$: combination of singular and regular Coulomb function, describes asymptotic behavior of wavefunction

⇒ to obtain two-particle correlation: apply Koonin-Pratt formula

Interaction model

- **For distinguishable pointlike particles: Lednicky approach**[1]
  - Starting from the scattering parameters ⇒ define the s-wave two-particle relative wave function
  - Considers Coulomb effects + strong interaction (via scattering parameters)

- **p–d scattering parameters** from constrained to the p-d scattering data

$S = 1/2$		$S = 3/2$	
a_0(fm)	d_0(fm)	a_0(fm)	d_0(fm)
$1.30^{+0.20}_{-0.20}$	—	$11.40^{+1.80}_{-1.20}$	$2.05^{+0.25}_{-0.25}$
$2.73^{+0.10}_{-0.10}$	$2.27^{+0.12}_{-0.12}$	$11.88^{-0.10}_{+0.40}$	$2.63^{+0.01}_{-0.02}$
4.0	—	11.1	—
0.024	—	13.8	—
$-0.13^{+0.04}_{-0.04}$	—	$14.70^{+2.30}_{-2.30}$	—

Van Oers,Brockmann et al. Nucl. Phys. A 561-583 (1967)
J.Arvieux et al. Nucl. Phys. A 221 253-268 (1973)
E.Huttel et al. Nucl. Phys. A 406 443-455 (1983)
A.Kievsky et al. PLB 406 292-296 (1997)
T.C.Black et al. PLB 471 103-107 (1999)

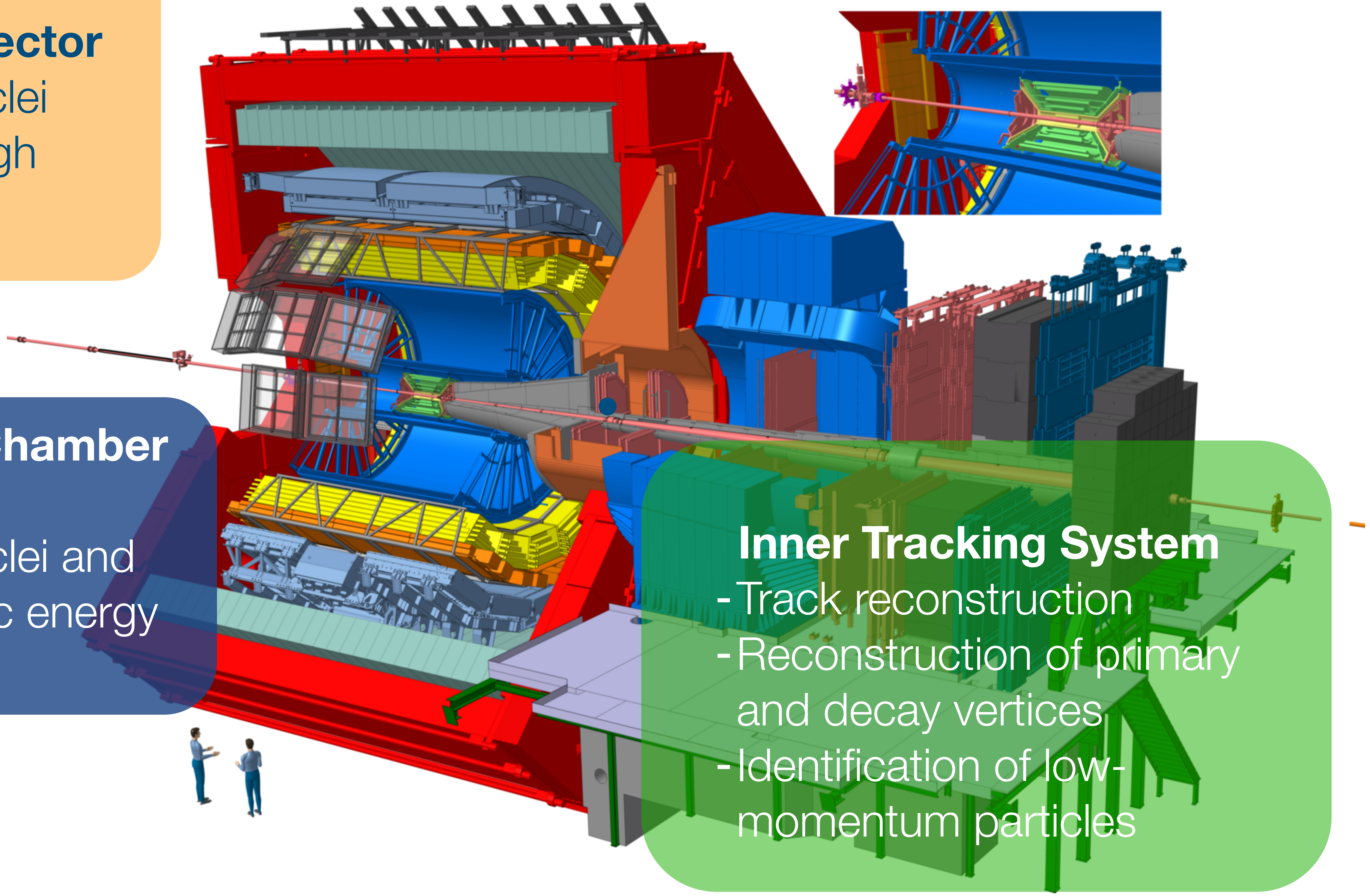
- **K^+–d scattering parameters**
  - ER (effective-range approximation): a_0= –0.47 fm, d_0= –1.75 fm, calculated by Prof. Johann Haidenbaur, based on potential describing K^+d low-energy cross-sections[2]
  - FCA (fixed-center approximation): a_0= –0.54 fm, d_0= 0.0 fm, calculated by Prof. Tetsuo Hyodo starting from Chiral model KN scattering lengths[3]

[1] R. Lednicky, Phys. Part. Nuclei 40, 307–352 (2009)
[2] T. Takaki PRC 81, 055204 (2010)]
[3] K. Aoki and D. Jido, PTEP 2019, 013D01 (2019)

ALICE detector: Run 2

Time-Of-Flight detector
- Identification of nuclei and hadrons through their time-of-flight

Time Projection Chamber
- Tracking
- Identification of nuclei and hadrons via specific energy loss



Inner Tracking System
- Track reconstruction
- Reconstruction of primary and decay vertices
- Identification of low-momentum particles

ALICE : ITS and TPC upgrades

Another calculation at hand

- Hadron-Deuteron Correlations and Production of Light Nuclei in Relativistic Heavy-Ion Collisions: arxiv.org/abs/1904.08320
  - hadron-deuteron correlation function which carries information about the source of the deuterons
  - Allows one to determine whether a deuteron is directly emitted from the fireball or if it is formed afterwards
  - Conclusion:
    - The theoretical p-d correlation function is strongly dependent on the source size

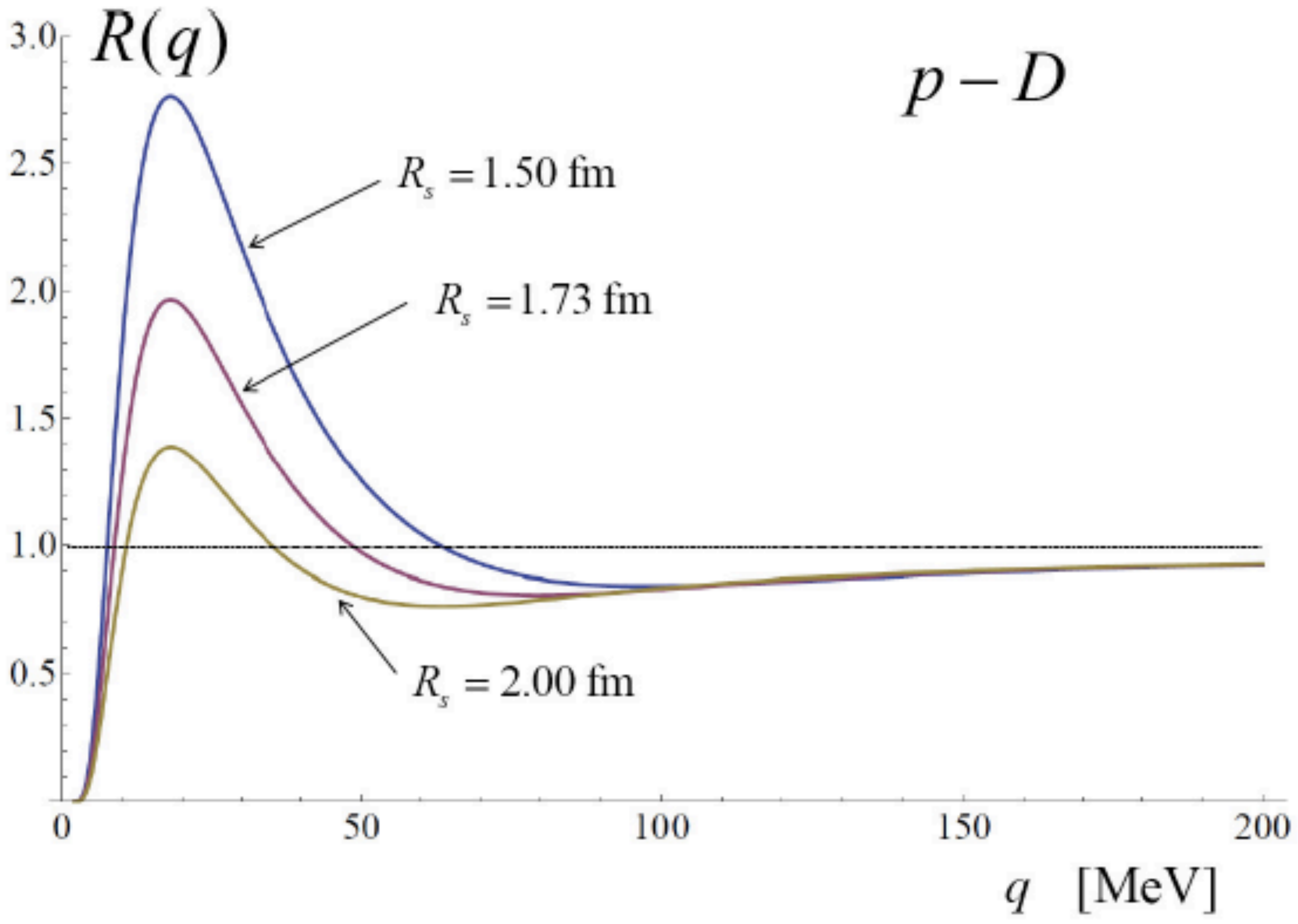
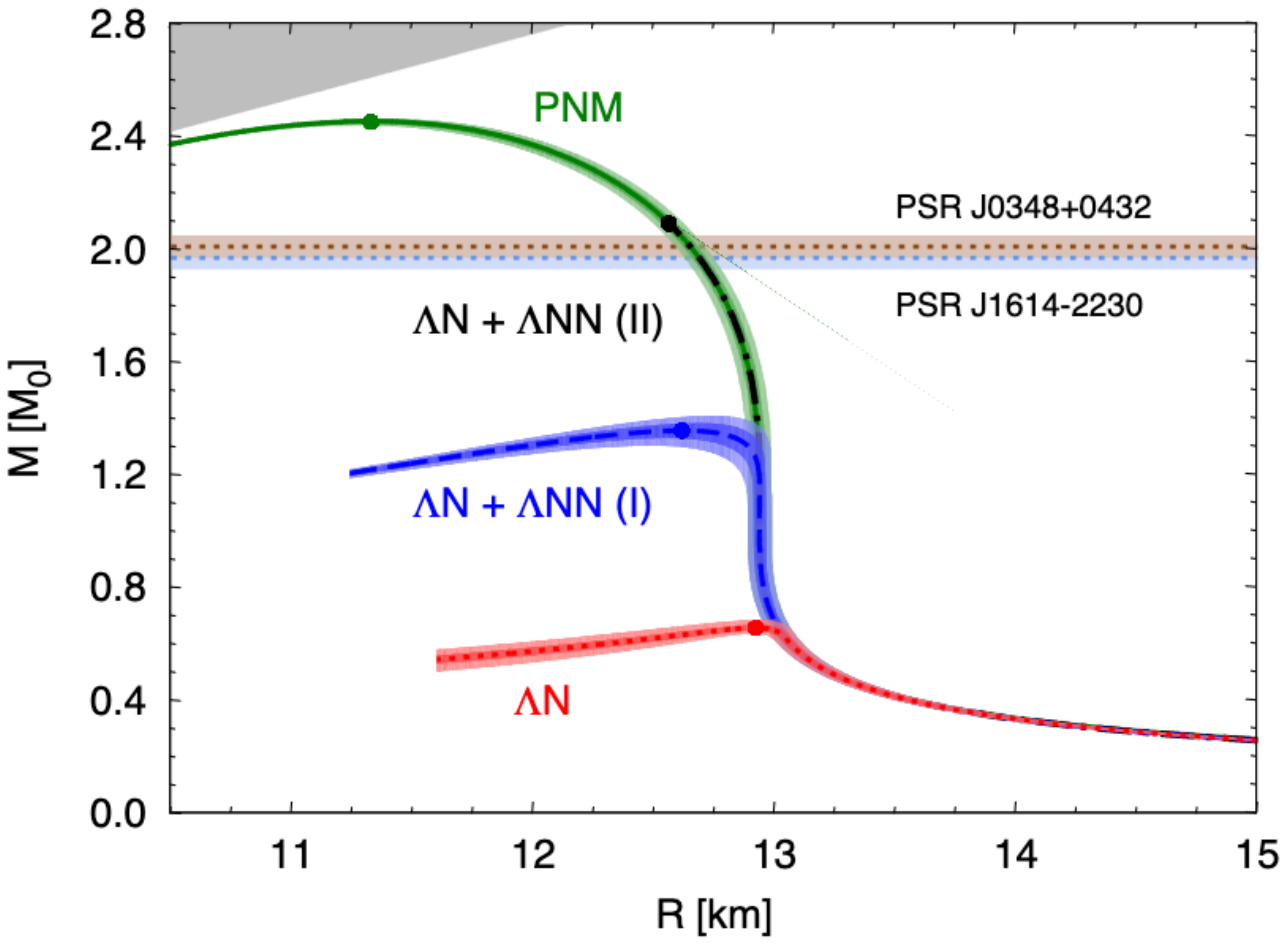
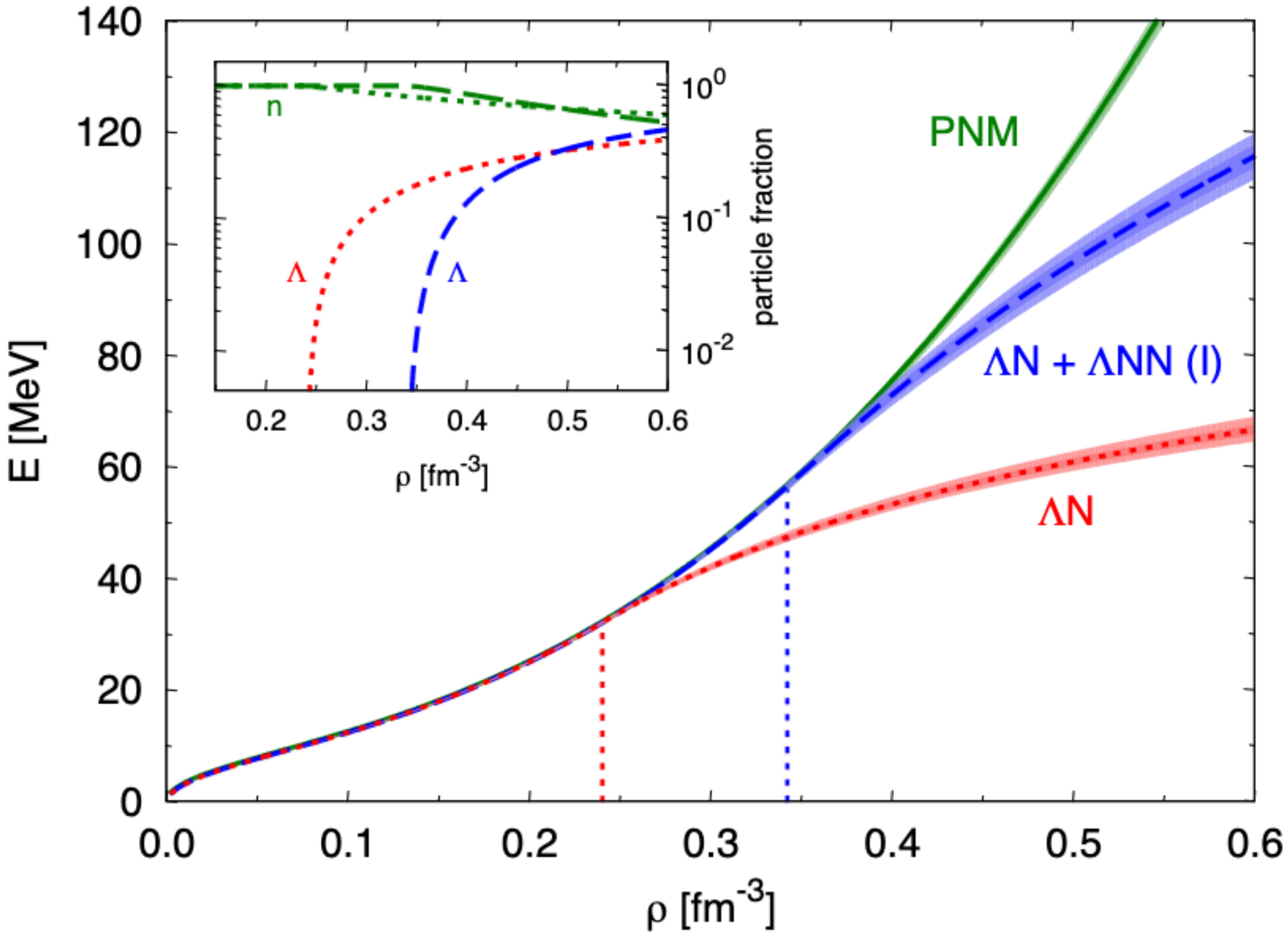


Fig. 2. $p-D$ correlation function

NS





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