Accessing strong interaction in three-hadron systems with ALICE

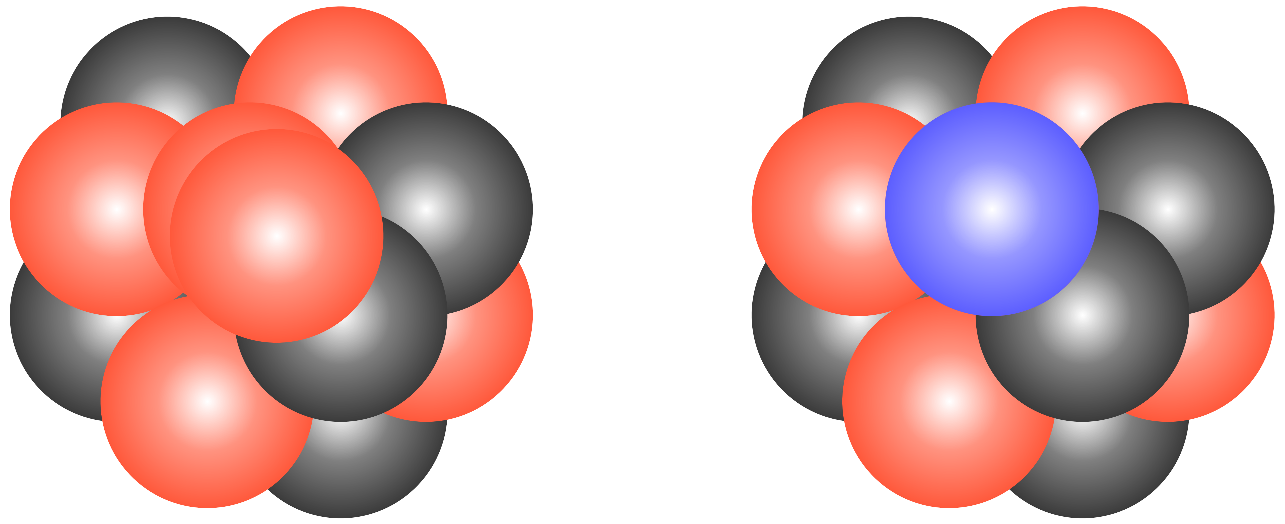
Bhawani Singh

on behalf of the **ALICE Collaboration**

Technical University of Munich

Quark Matter 2023, Houston, Texas

Many-body systems



ρ

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

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

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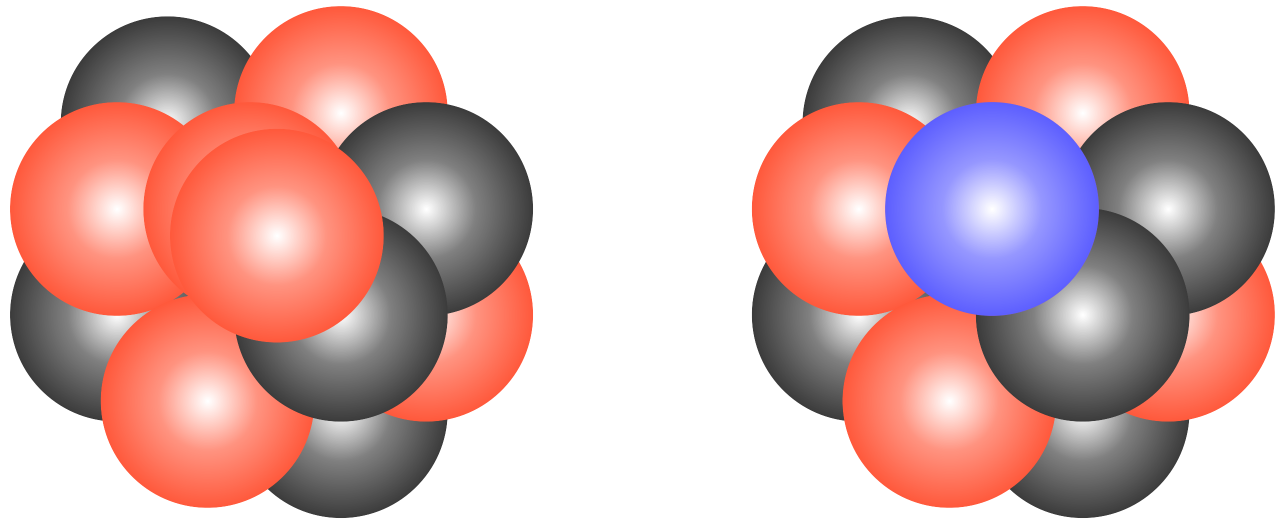

- Description of a dense nuclear matter such as neutron stars requires three-body interactions
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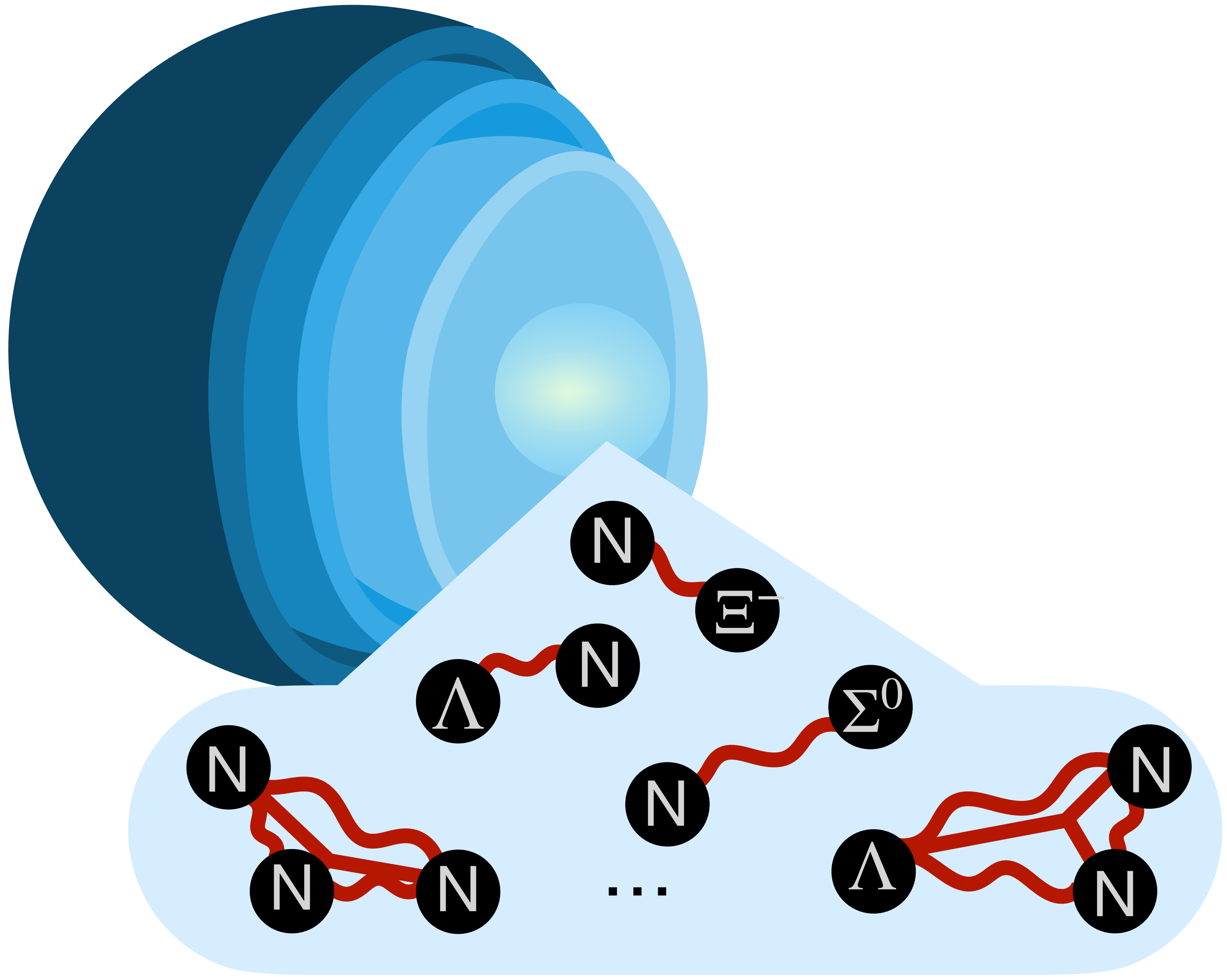

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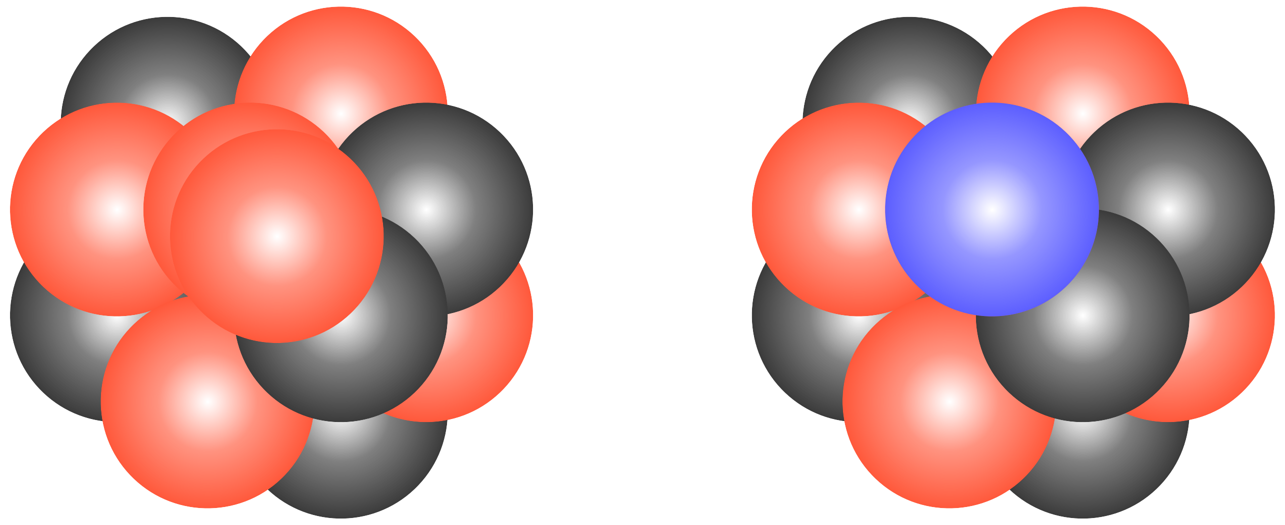

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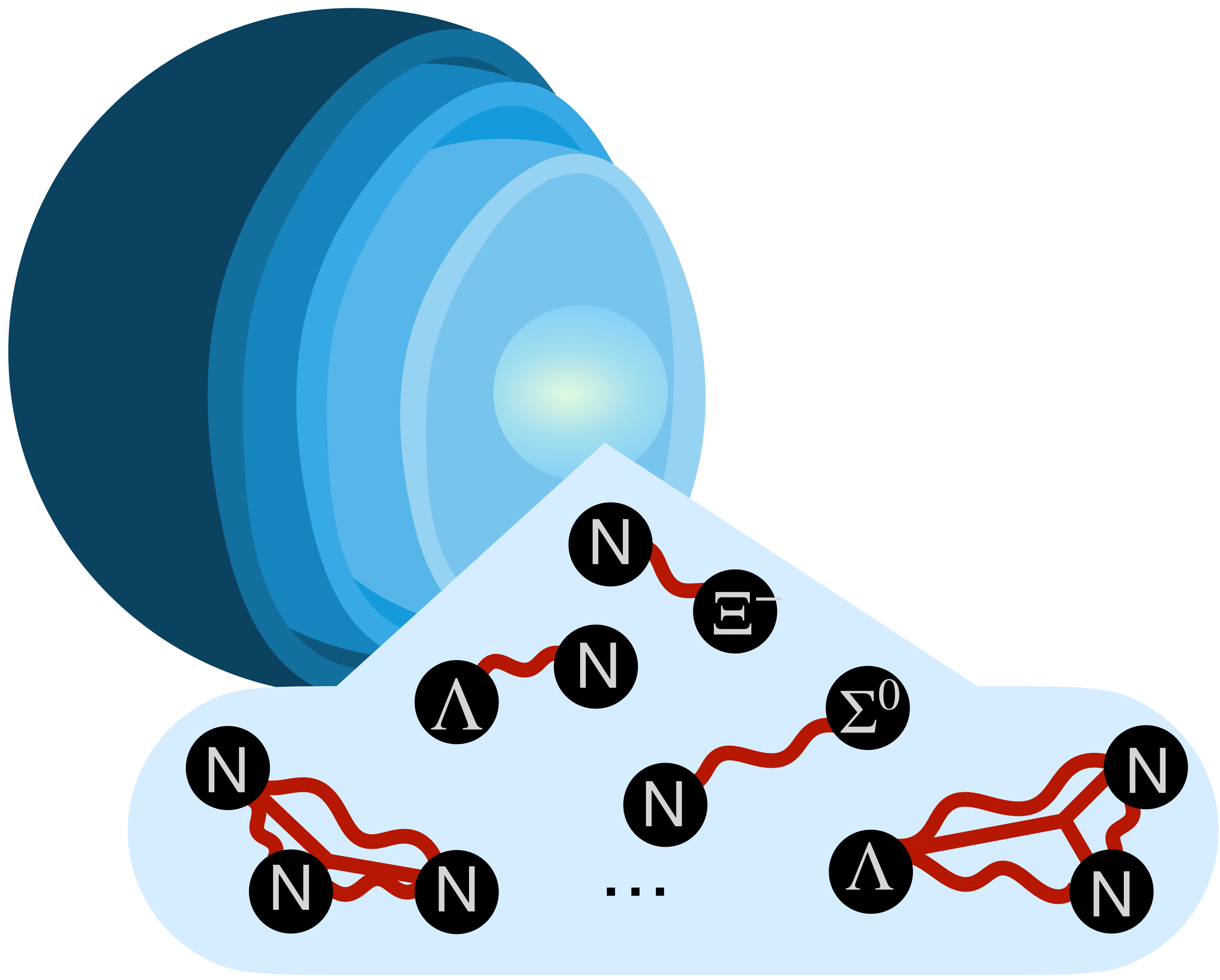
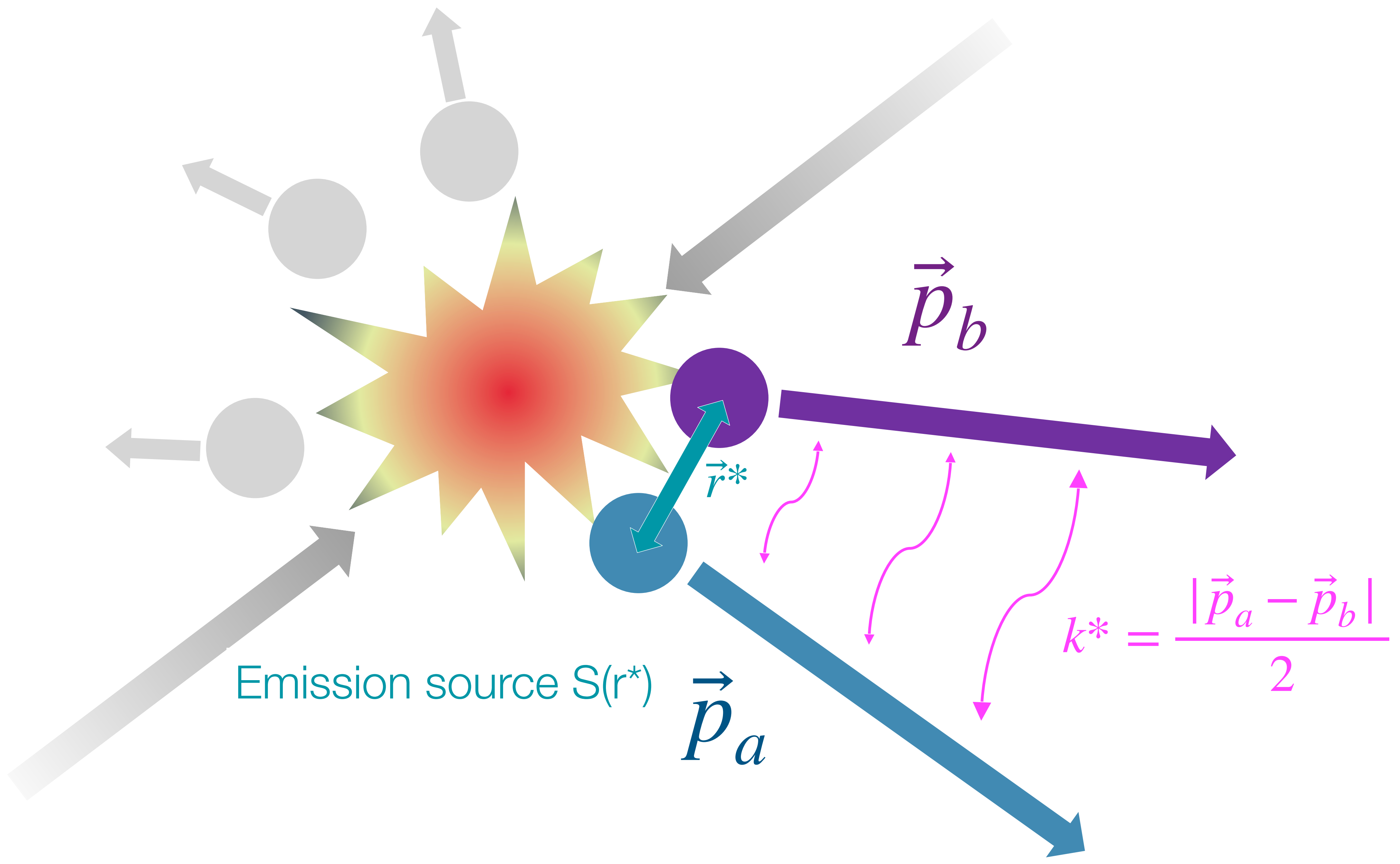


Femtoscopic correlations allow for access to three-body interaction

Femtoscopy with ALICE



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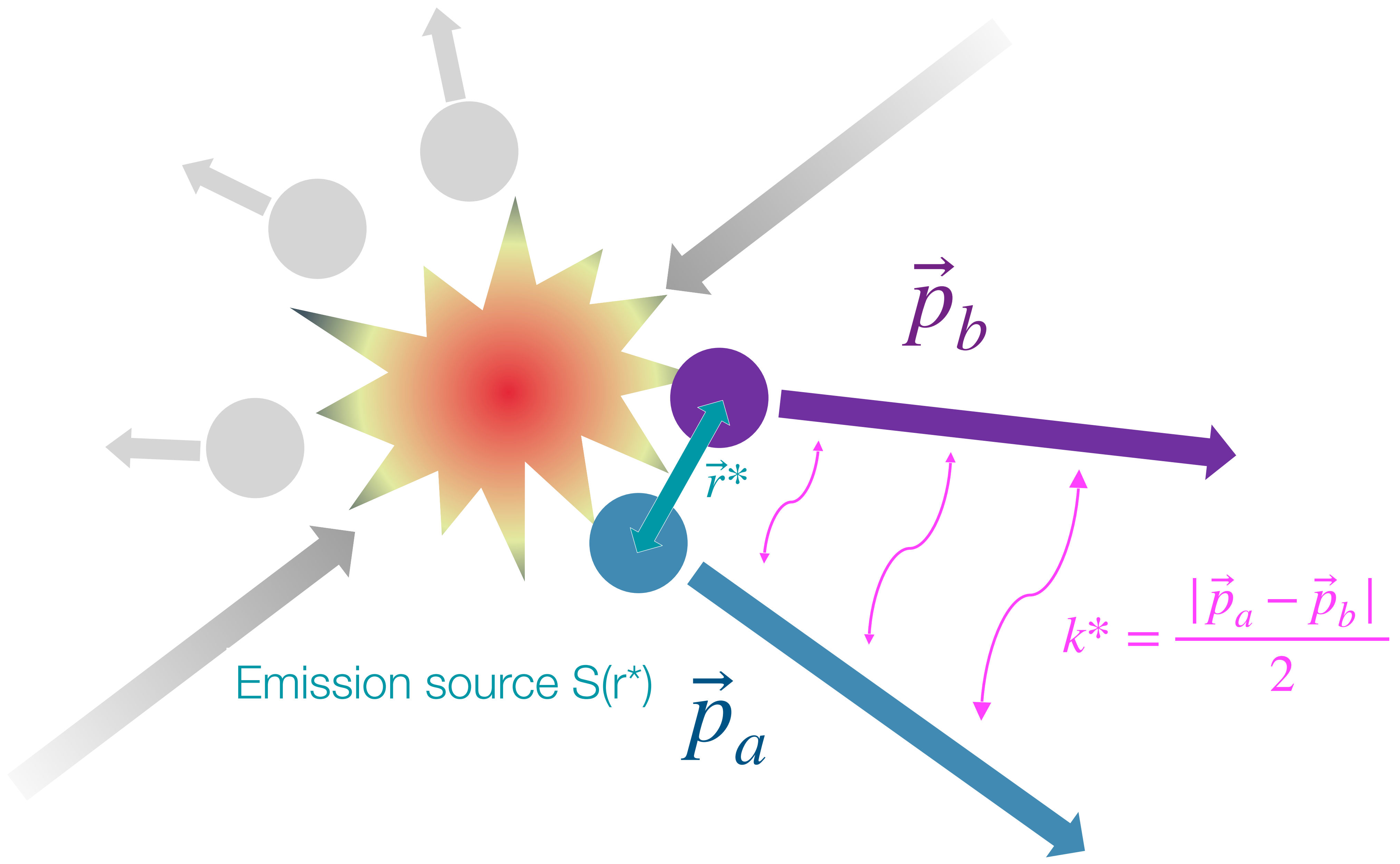

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experimental definition theoretical definition

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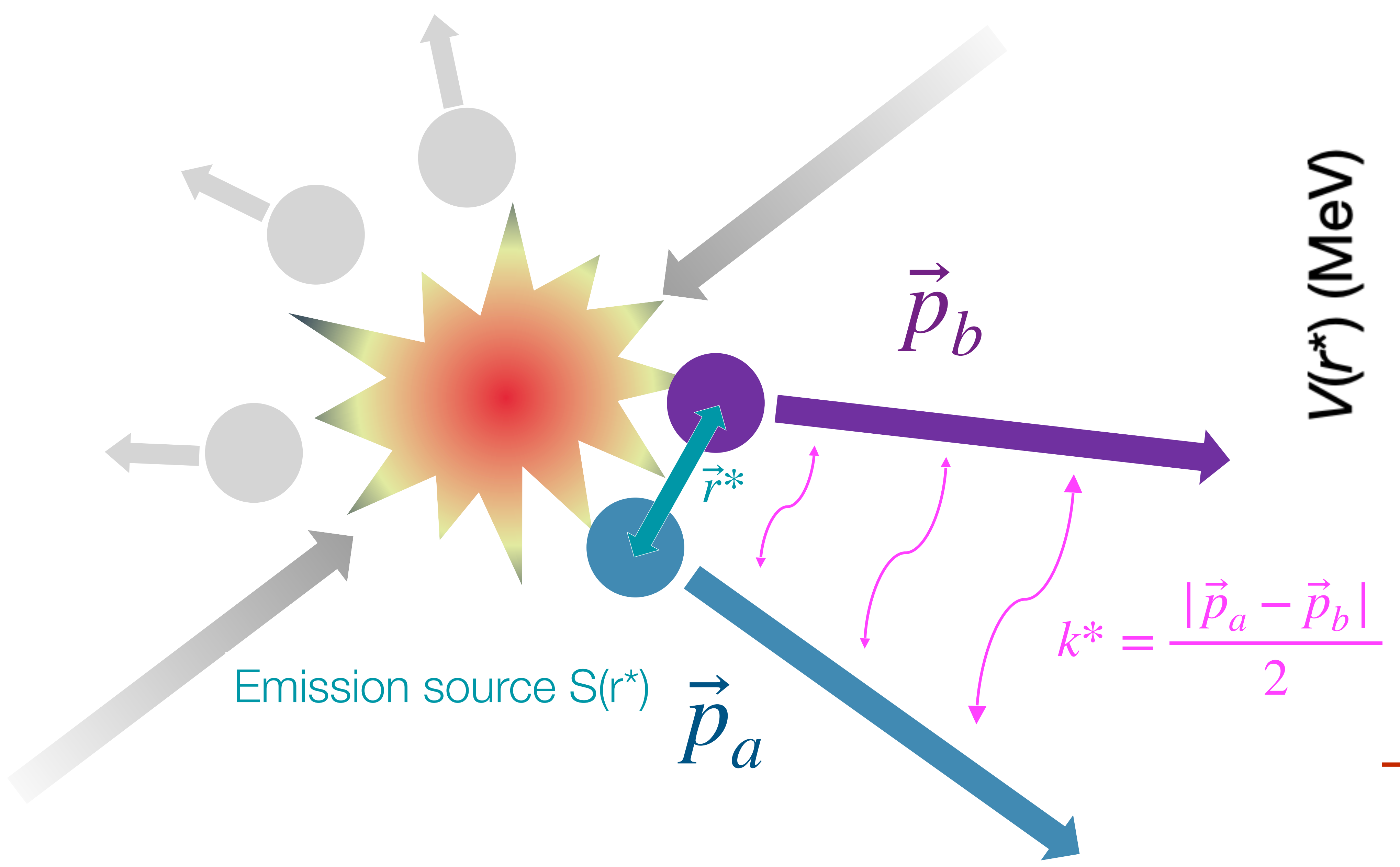
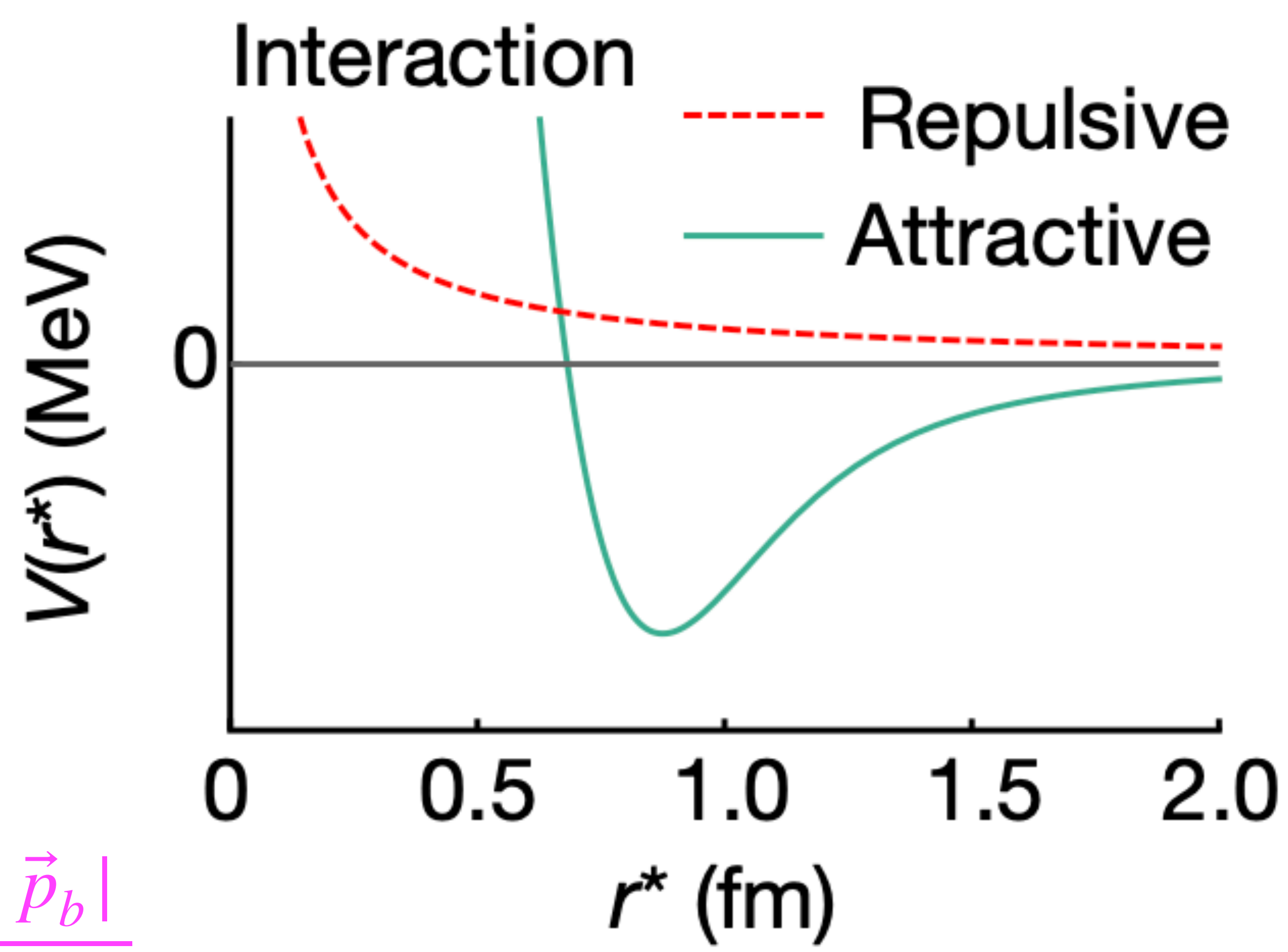
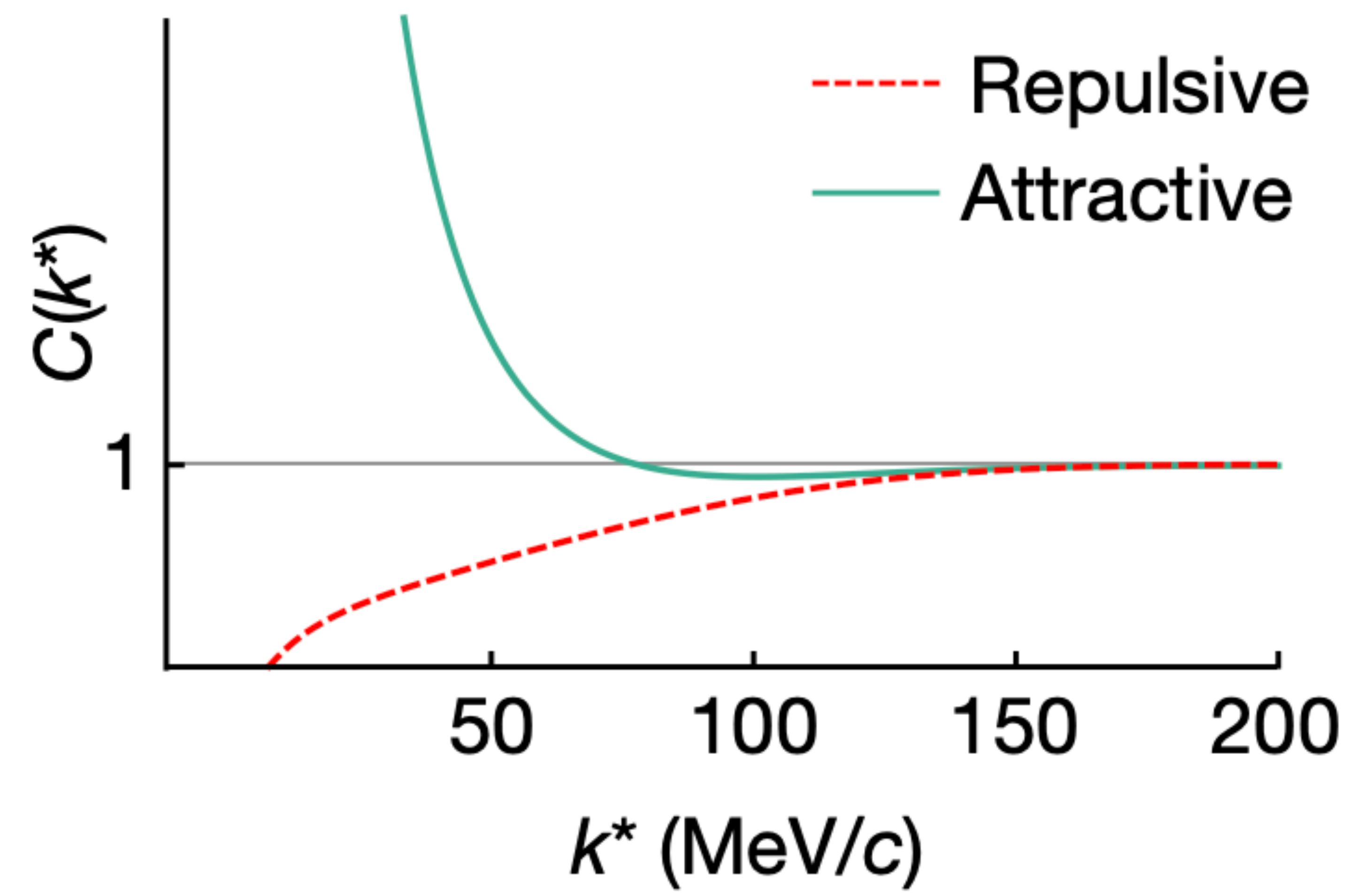




Schrödinger equation
Two-particle wave function
$\psi(\vec{k}^*, \vec{r}^*)$



Correlation function $C(k^*)$

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

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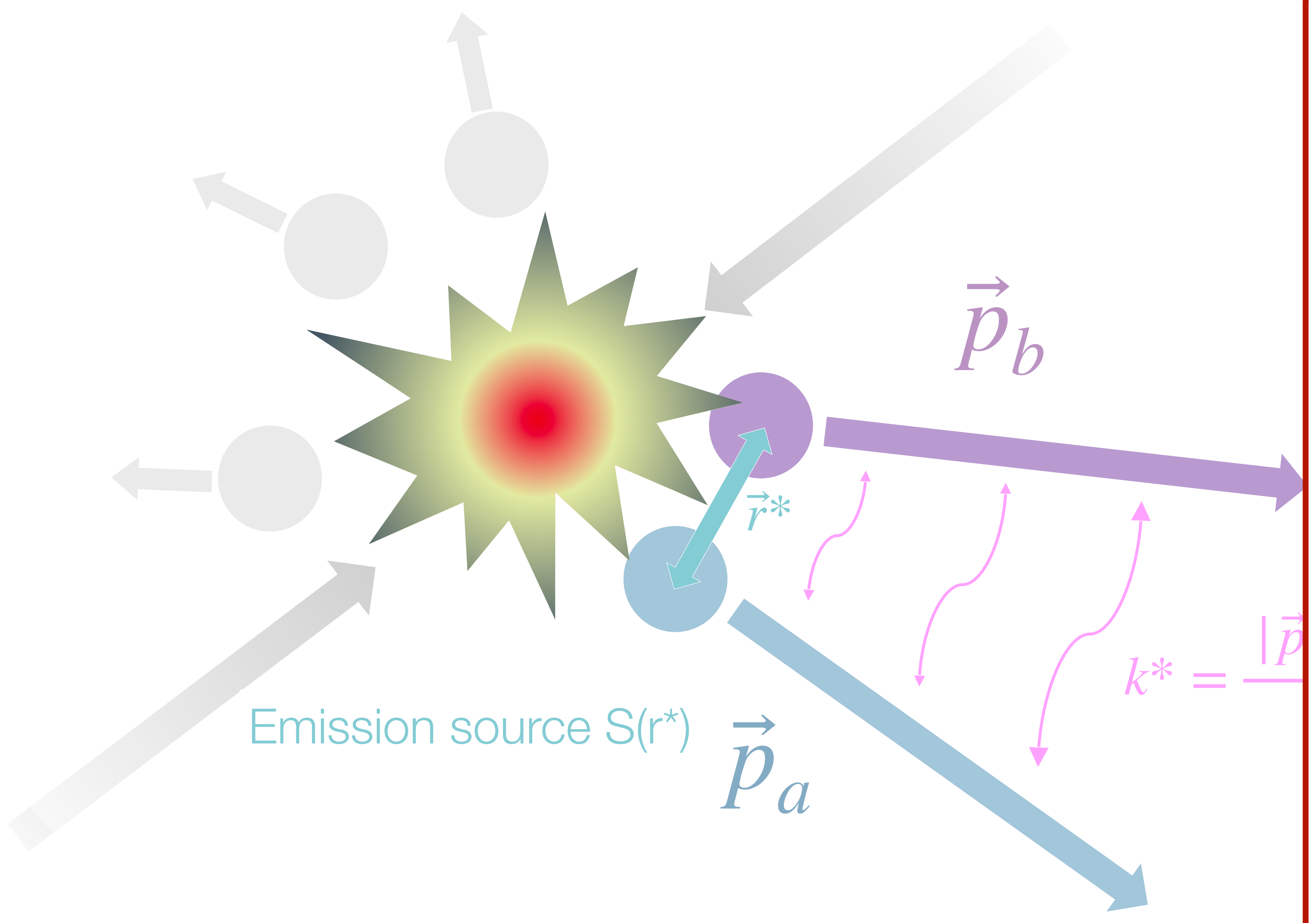
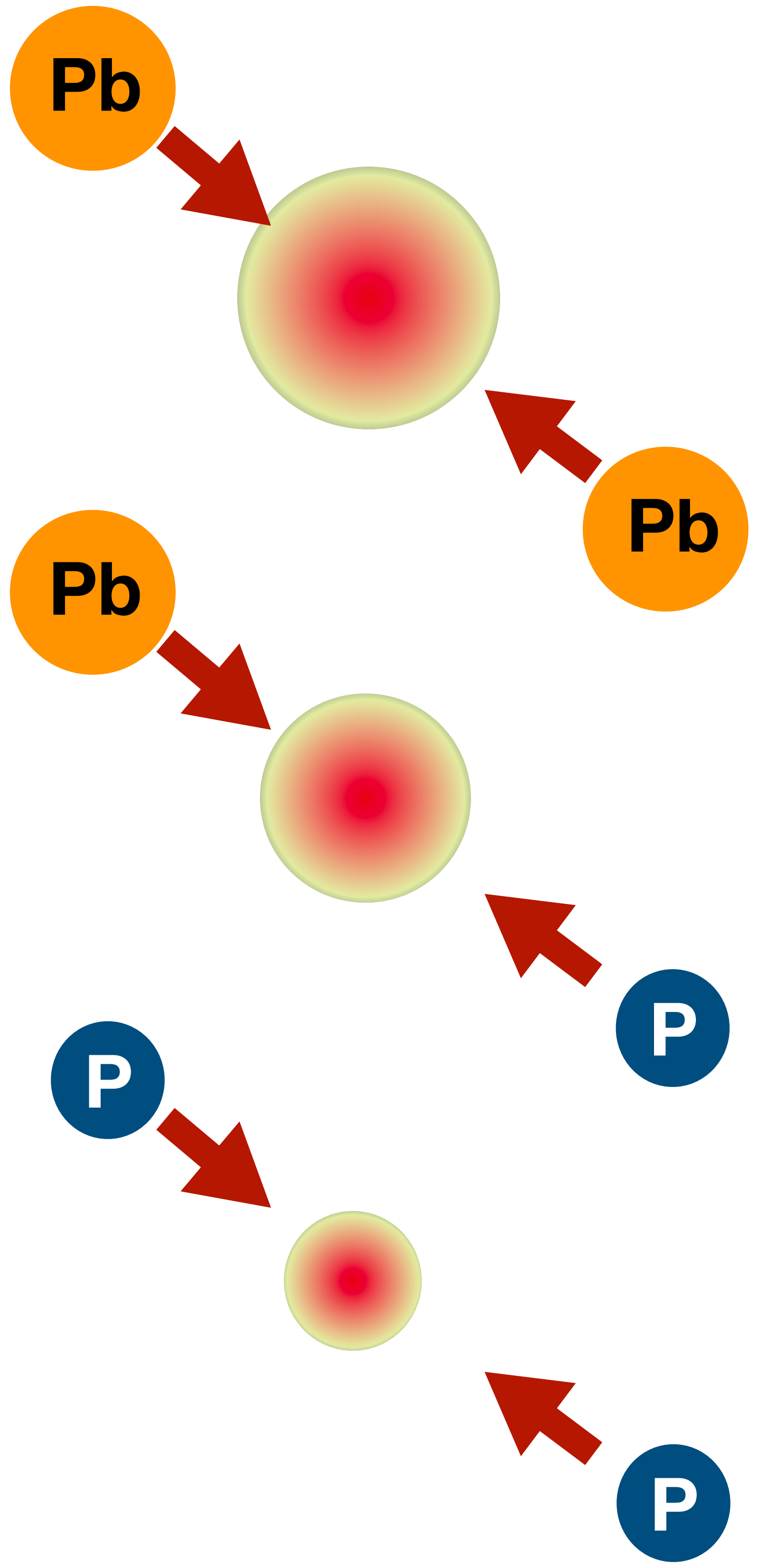


Collisions system sizes

Pb–Pb: 5–10 fm

p–Pb: 2–4 fm

pp: 1–1.5 fm



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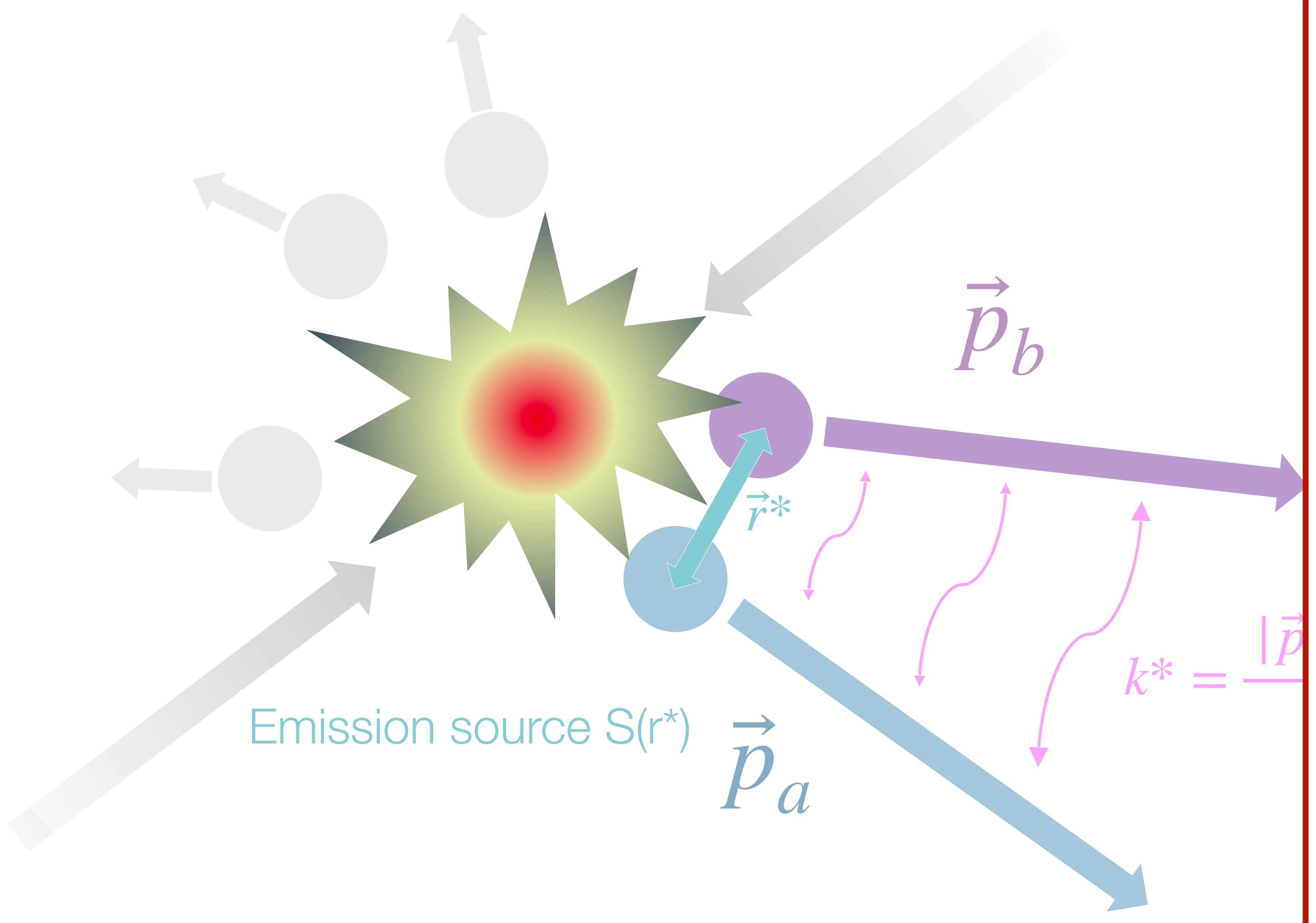

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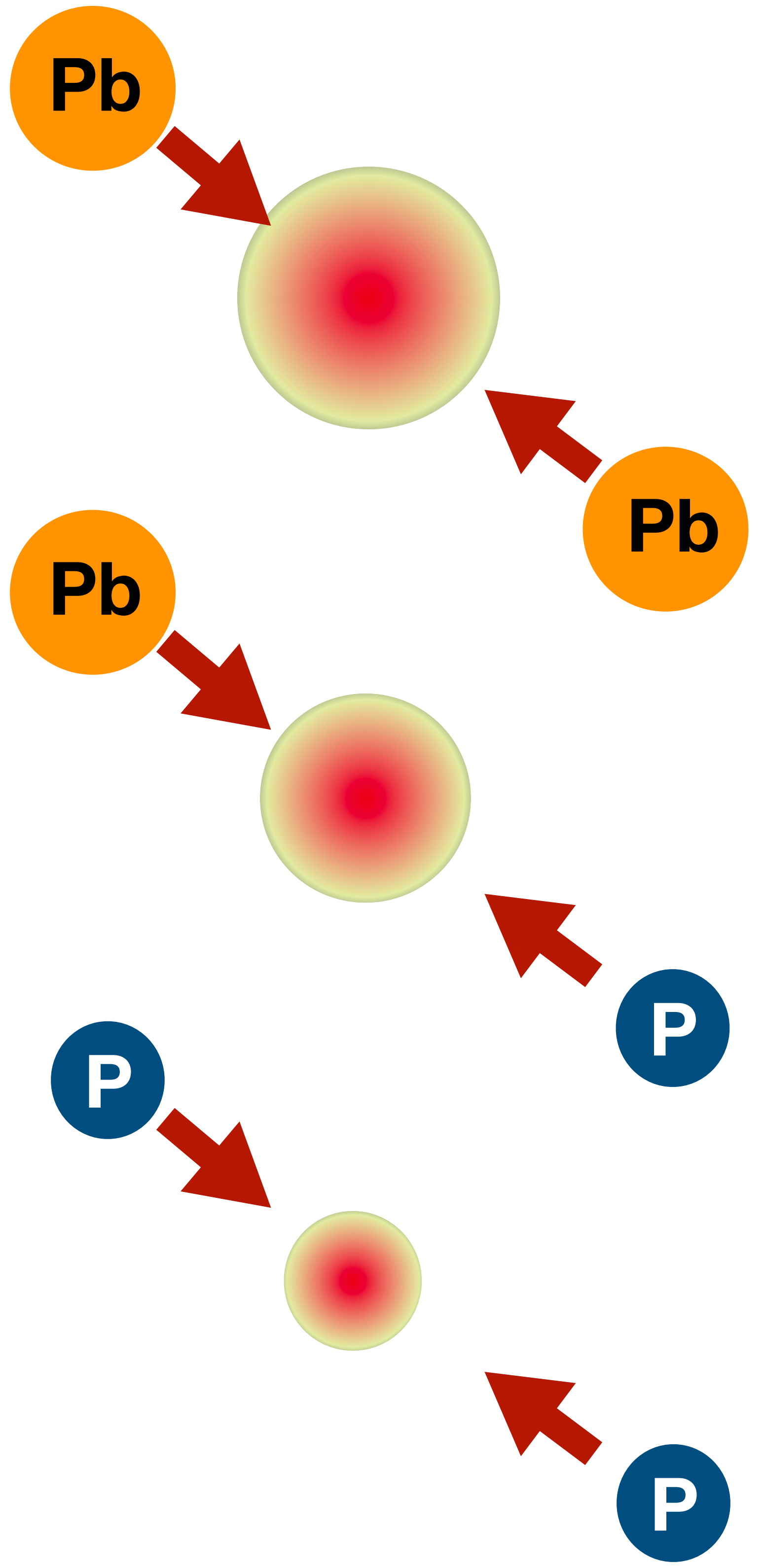

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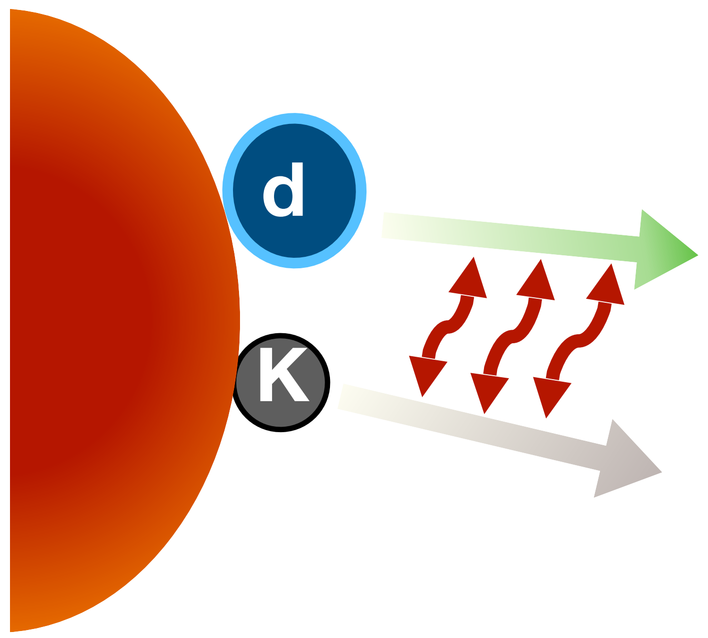
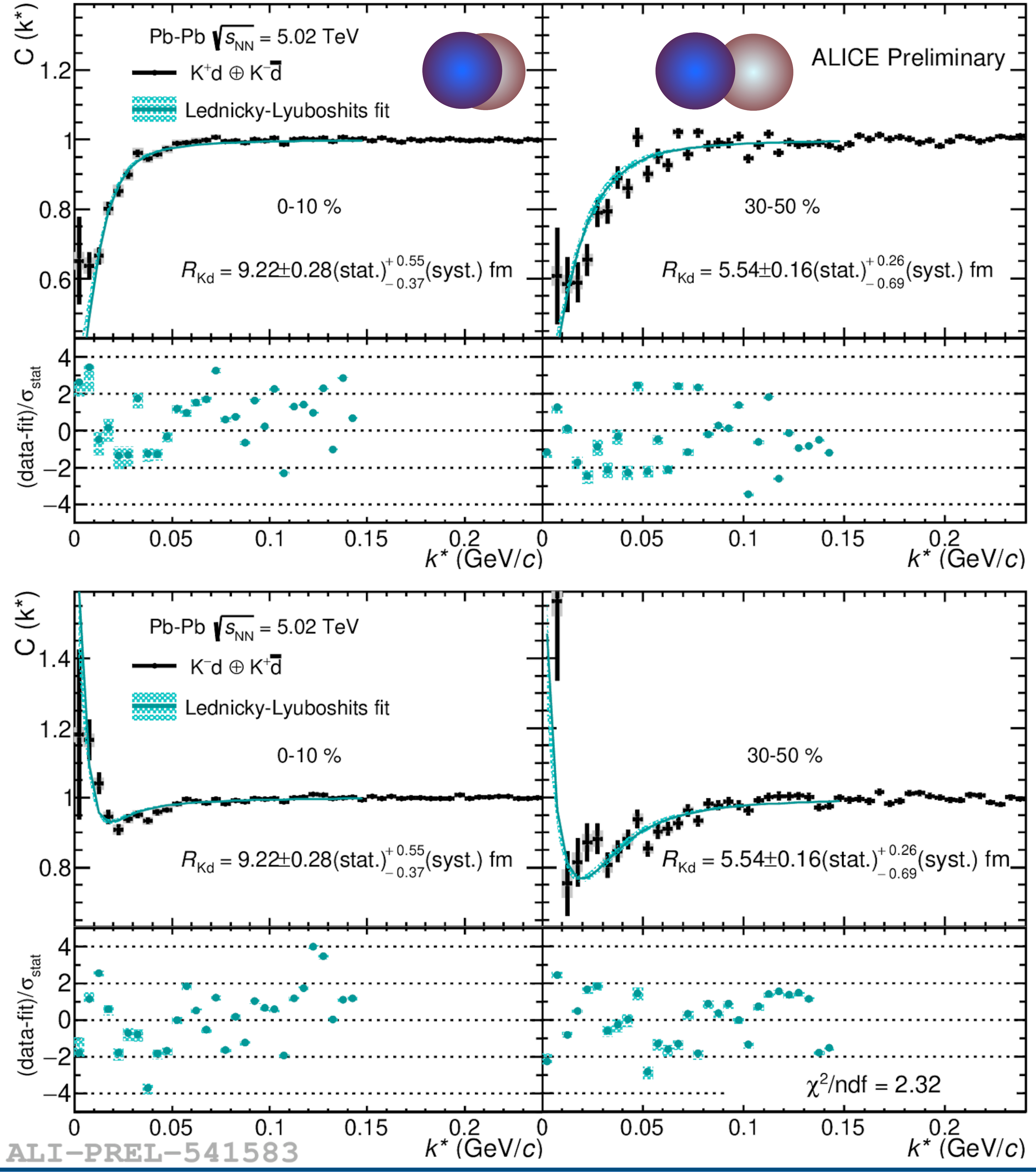
Kaon–deuteron system in Pb–Pb collisions

- **$K^{\pm}$–d correlation functions** in Pb–Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV
  - 3 centrality intervals: 0–10%, 10–30%, and 30–50%

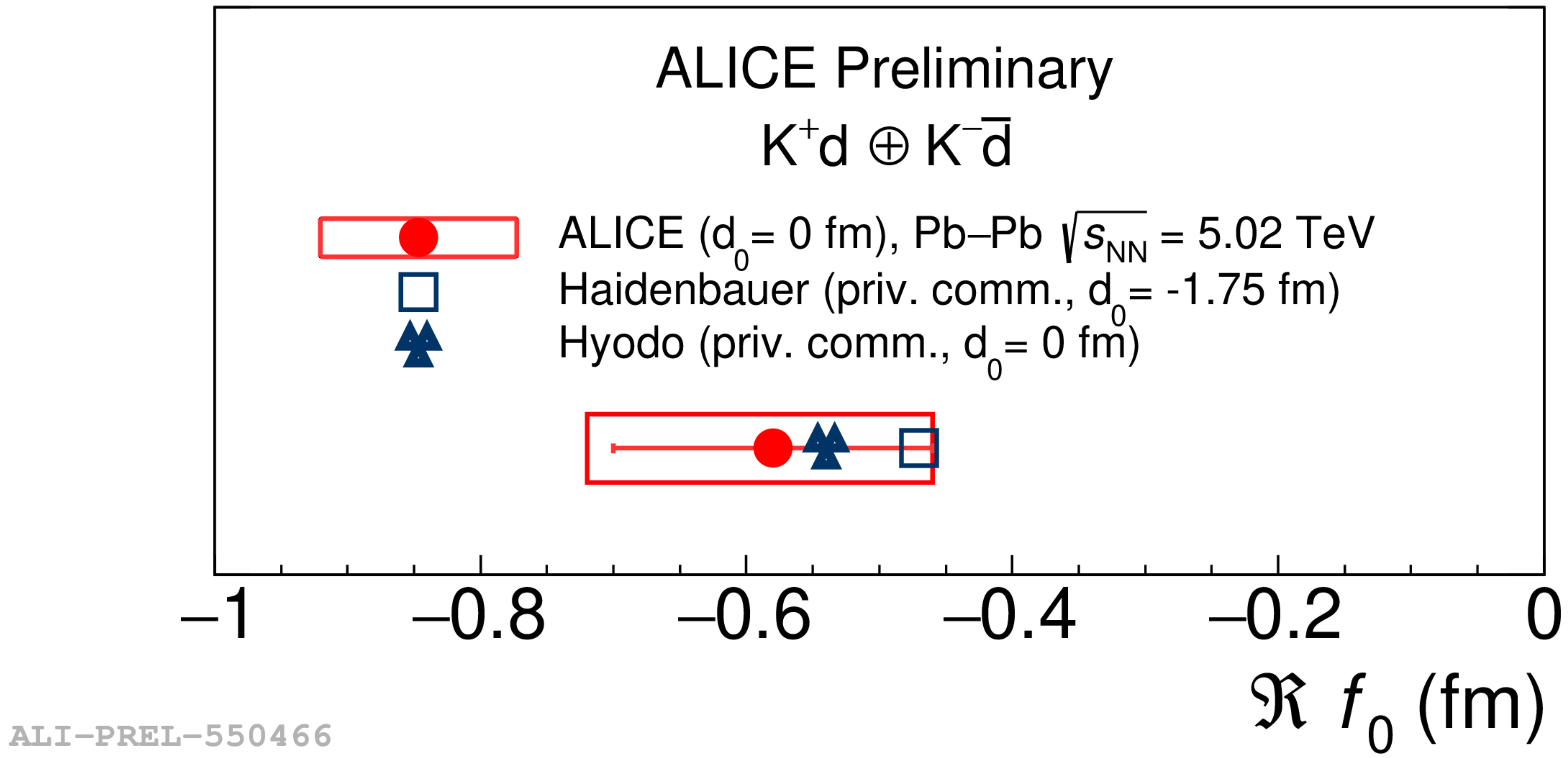
- **Lednický-Lyuboshits approach**
  - Coulomb effects + strong interaction (via scattering parameters)
  - 6 simultaneous fits to extract scattering parameters





$K^{\pm}$–d scattering parameter: first measurement ever

- K^{+}–d system
  - Measured scattering parameters $\Re f_0$ in agreement with the calculations



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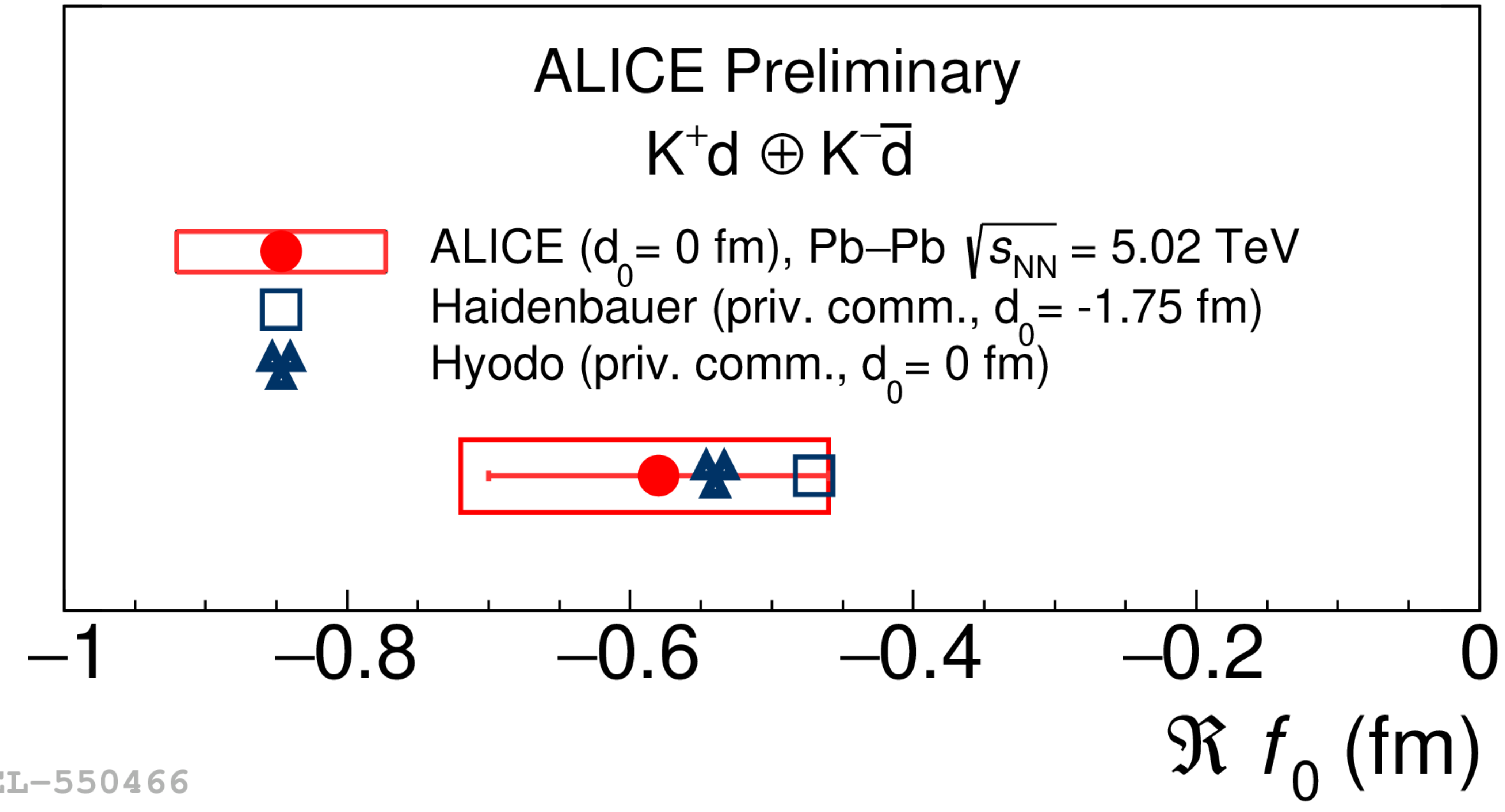
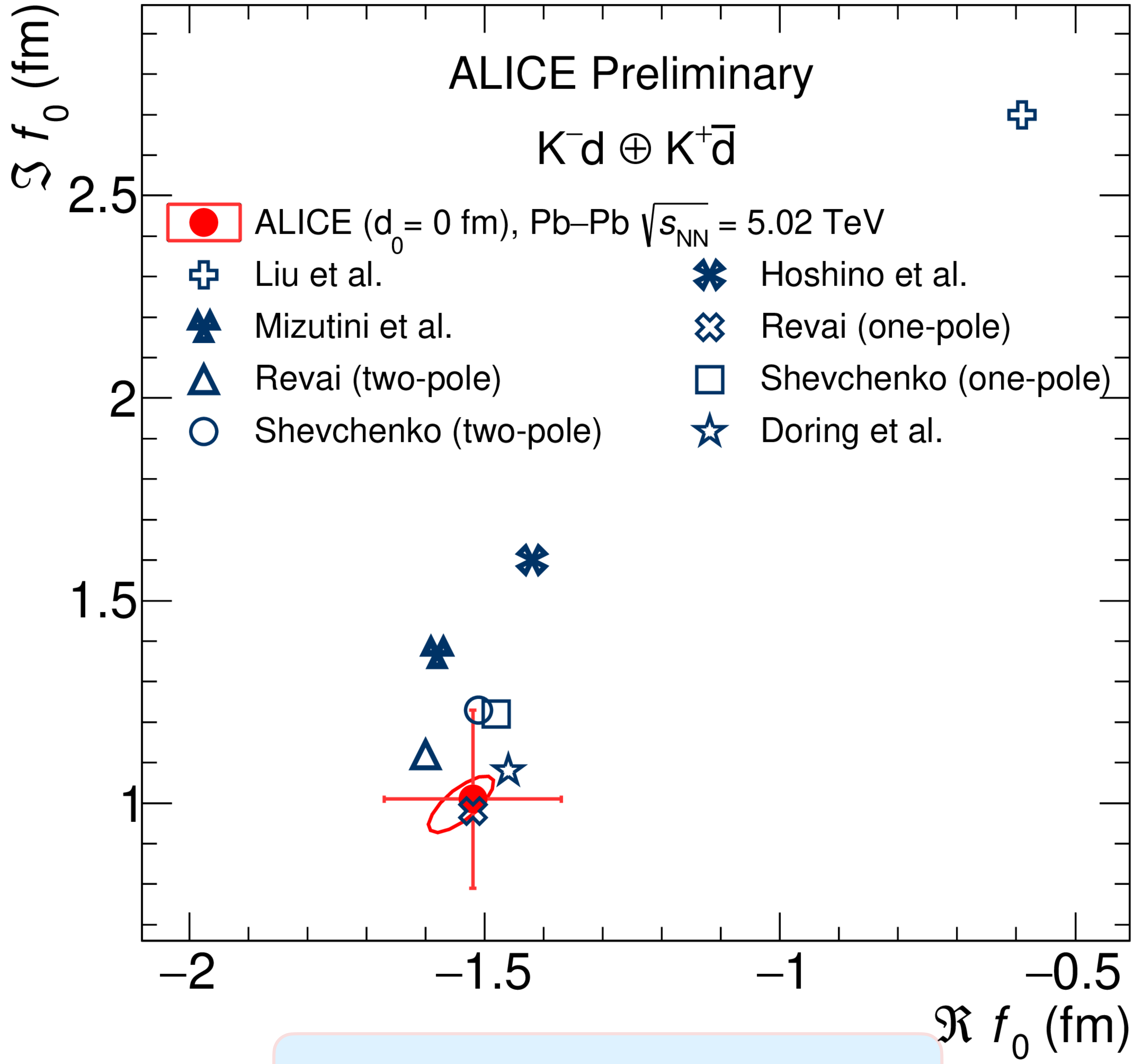
- K^{-}–d system
  - Obtained $\Re f_0$ and $\Im f_0$ agree with most of the available calculations



ALI-PREL-550466



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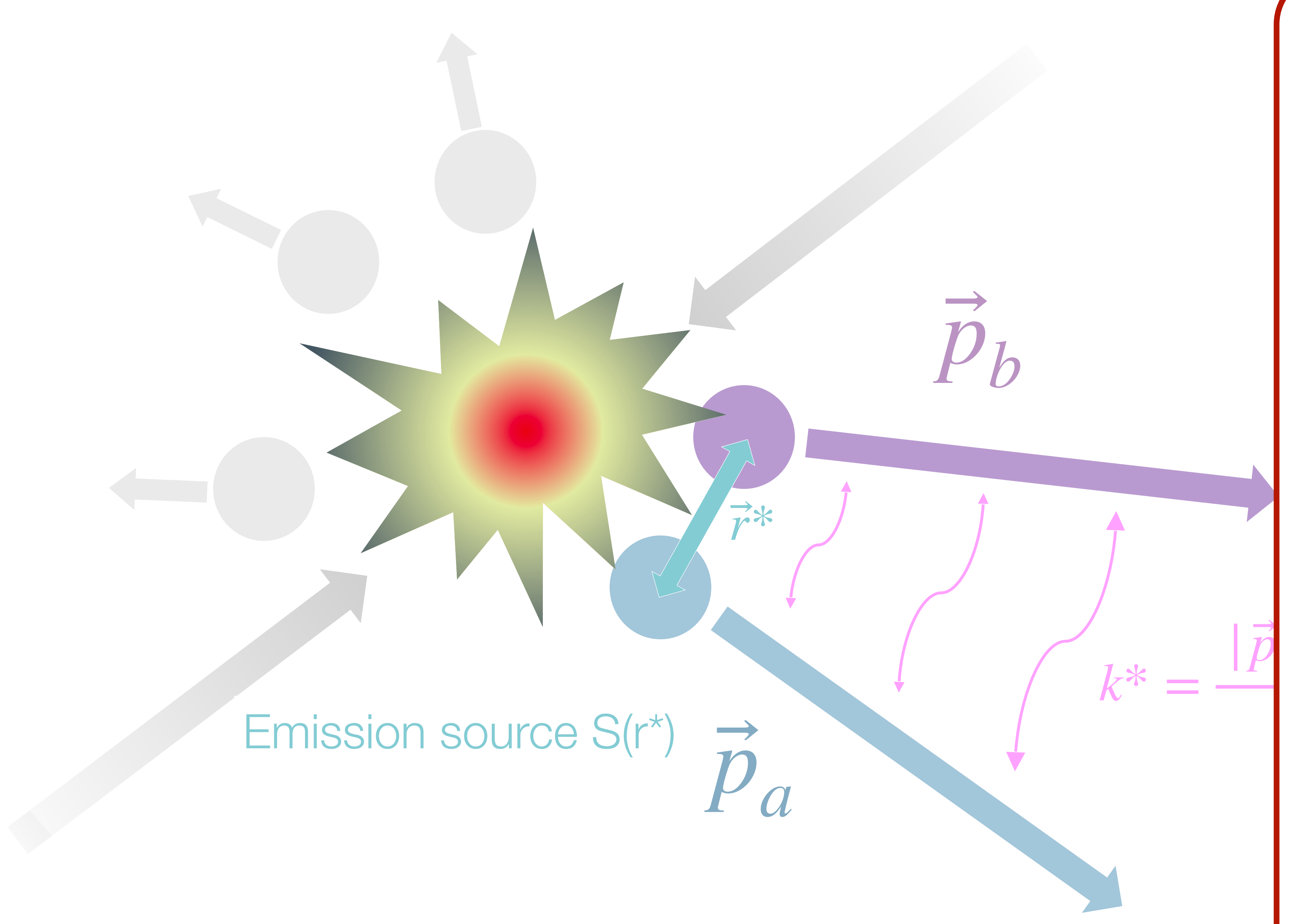
Poster 462 by Wioleta Rzesa

Femtoscopy in pp collisions



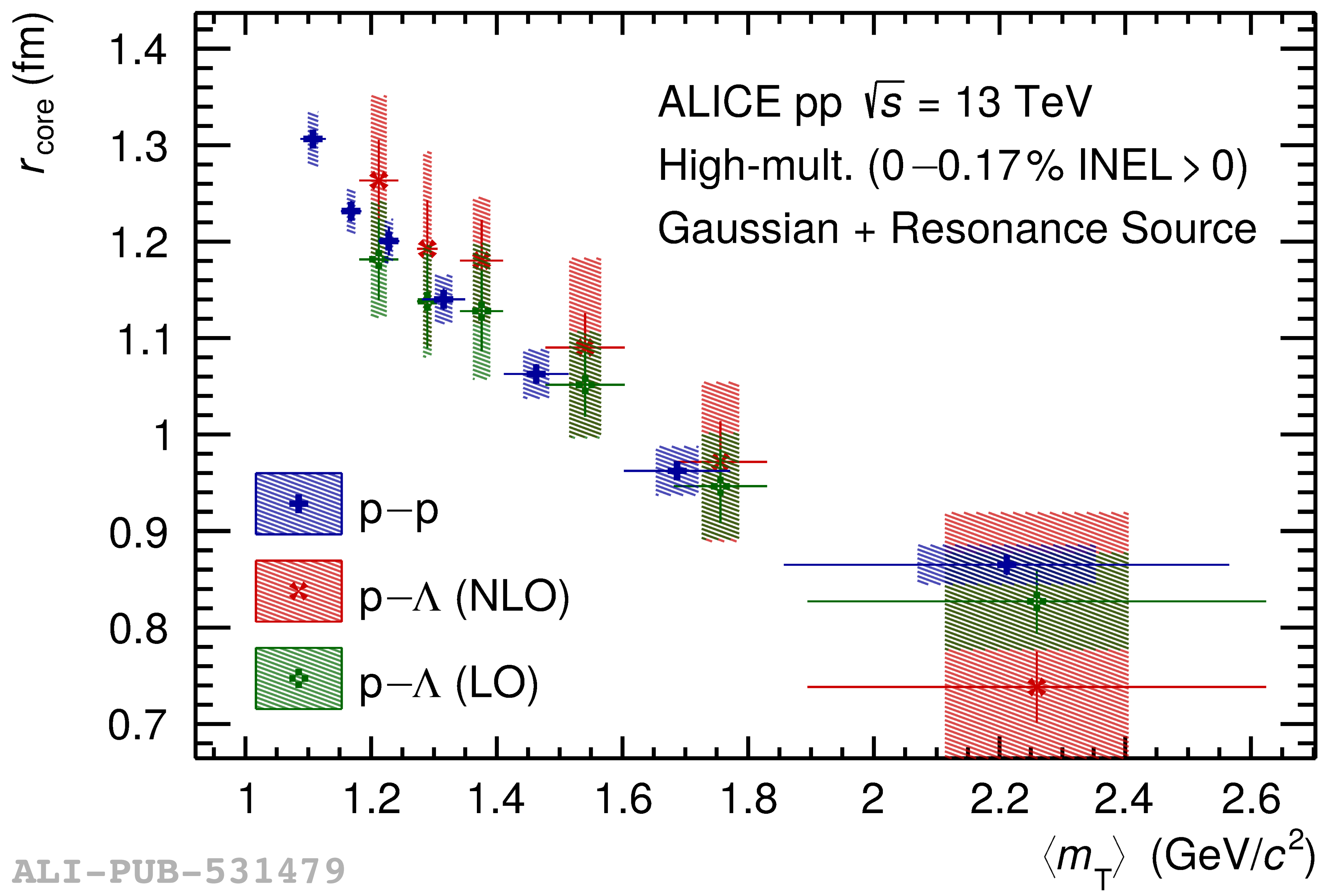
Source common for all baryon–baryon pairs in pp collisions

- Using p–p and p–Λ pairs where interaction is constrained well

$$m_{\mathrm{T}} = \sqrt{k_{\mathrm{T}}^2 + \langle m \rangle^2}$$

$$k_{\mathrm{T}} = \frac{1}{2}\left|\vec{p}_{\mathrm{T},1} + \vec{p}_{\mathrm{T},2}\right|$$

ALICE Collab, PLB 811, 135849 (2020)



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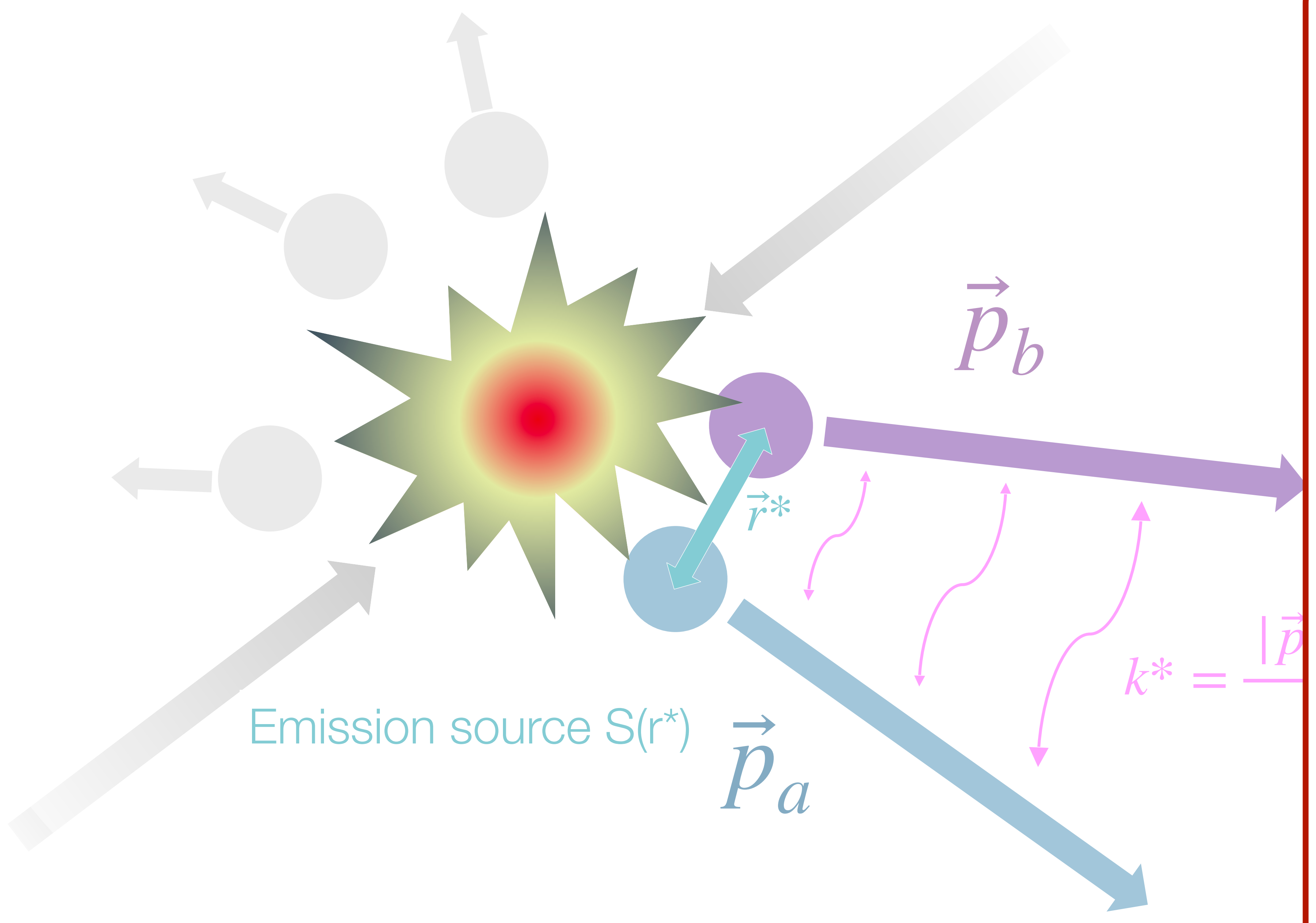

Source common for all baryon–baryon pairs in pp collisions

- Constrain source with common m_T scalling

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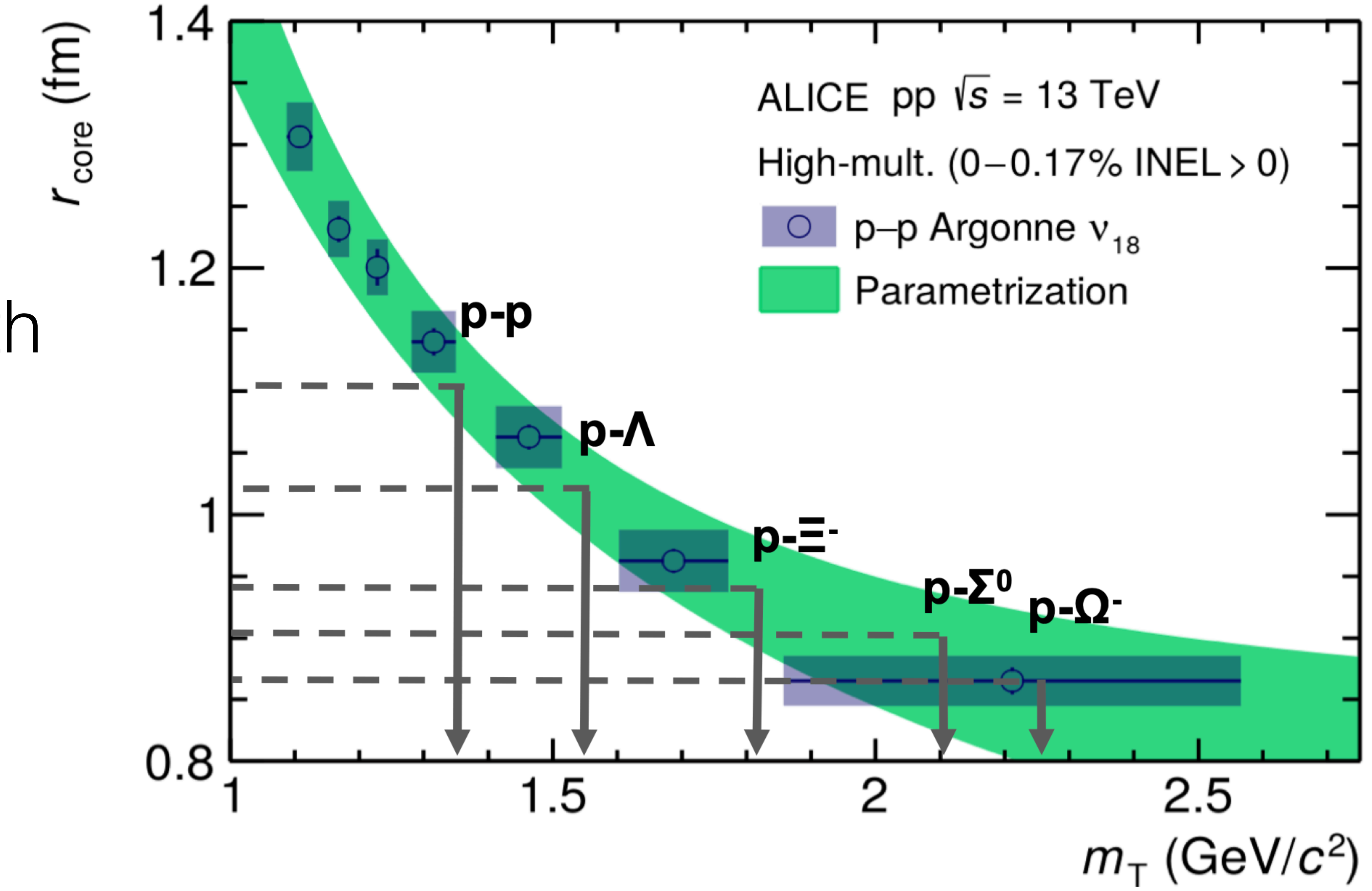

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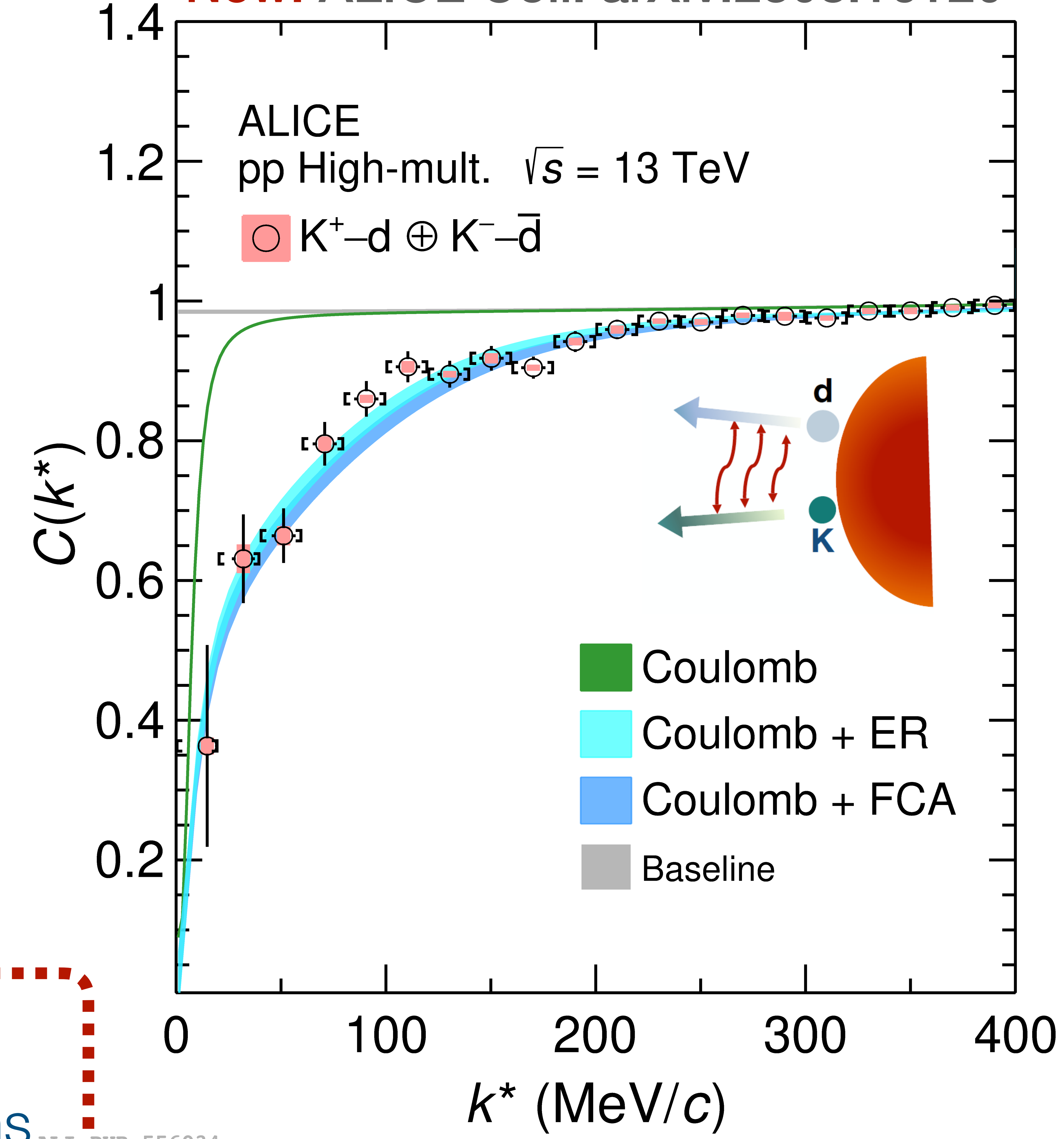
K^+–d correlation in pp collisions

- K^+–d as an **effective two-body** system: Lednický-Lyuboshits approach[1]
- Source size: $1.35^{+0.04}_{-0.05}$ fm
- K^+–d scattering parameters
  - ER (effective-range approximation):
    $a_0 = -0.47$ fm, $d_0 = -1.75$ fm[2]
  - FCA (fixed-center approximation):
    $a_0 = -0.54$ fm, $d_0 = 0$ fm[3]

First measurement in pp collisions

Deuterons are produced in shorter distances together with hadrons

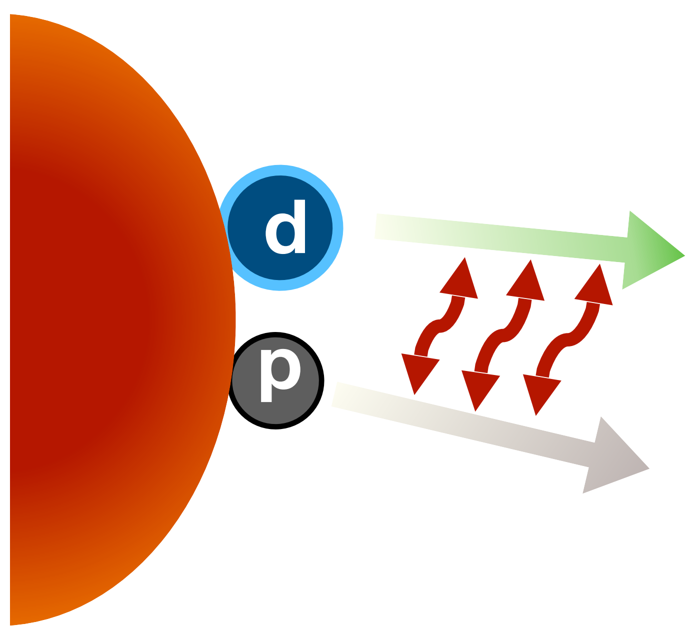
New: ALICE Coll. arXiv:2308.16120



[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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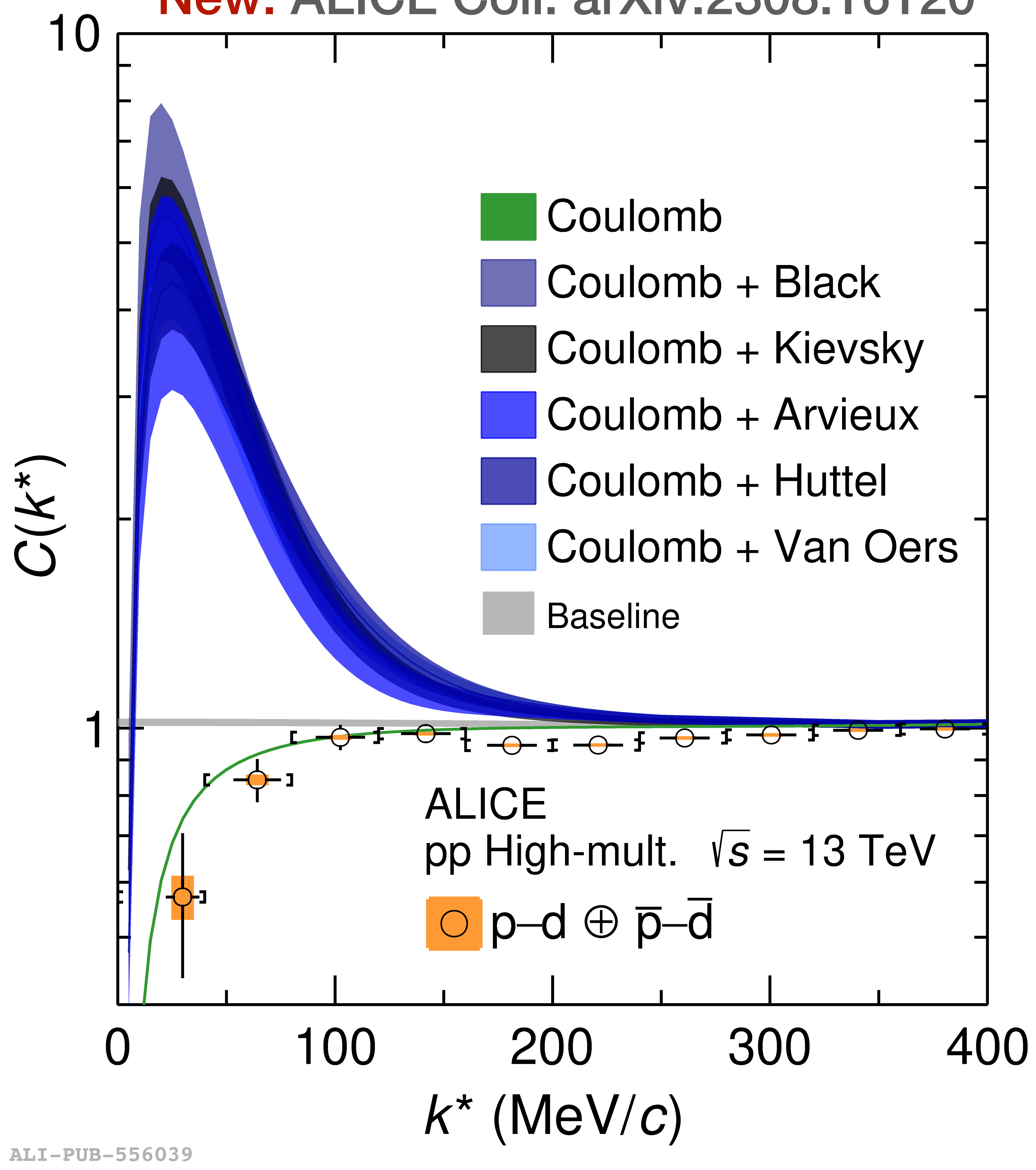

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- Source size: $1.08^{+0.06}_{-0.06}$ fm
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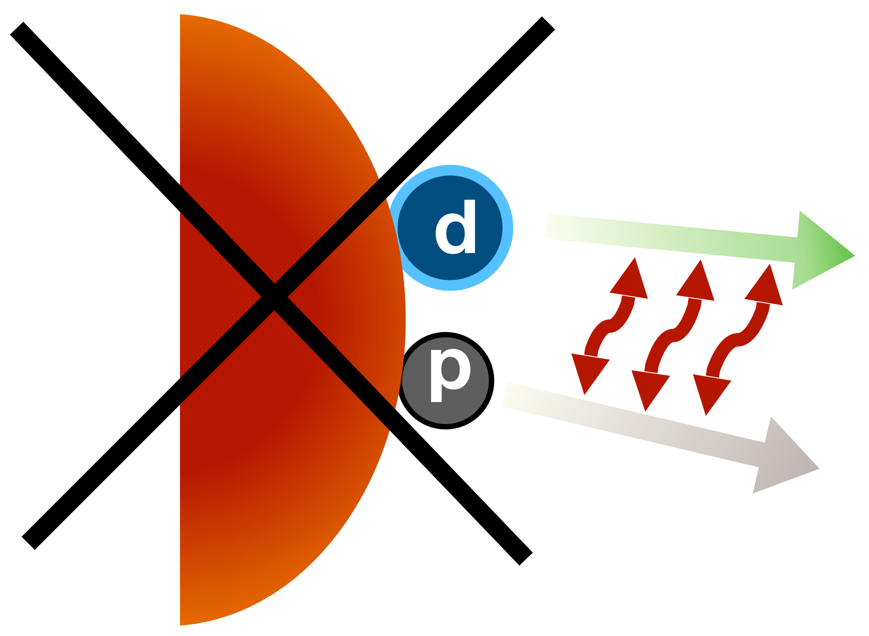
  - Pauli blocking at work for p–(pn) at short distances
  - Asymptotic strong interaction: not sufficient for distances ~1 fm



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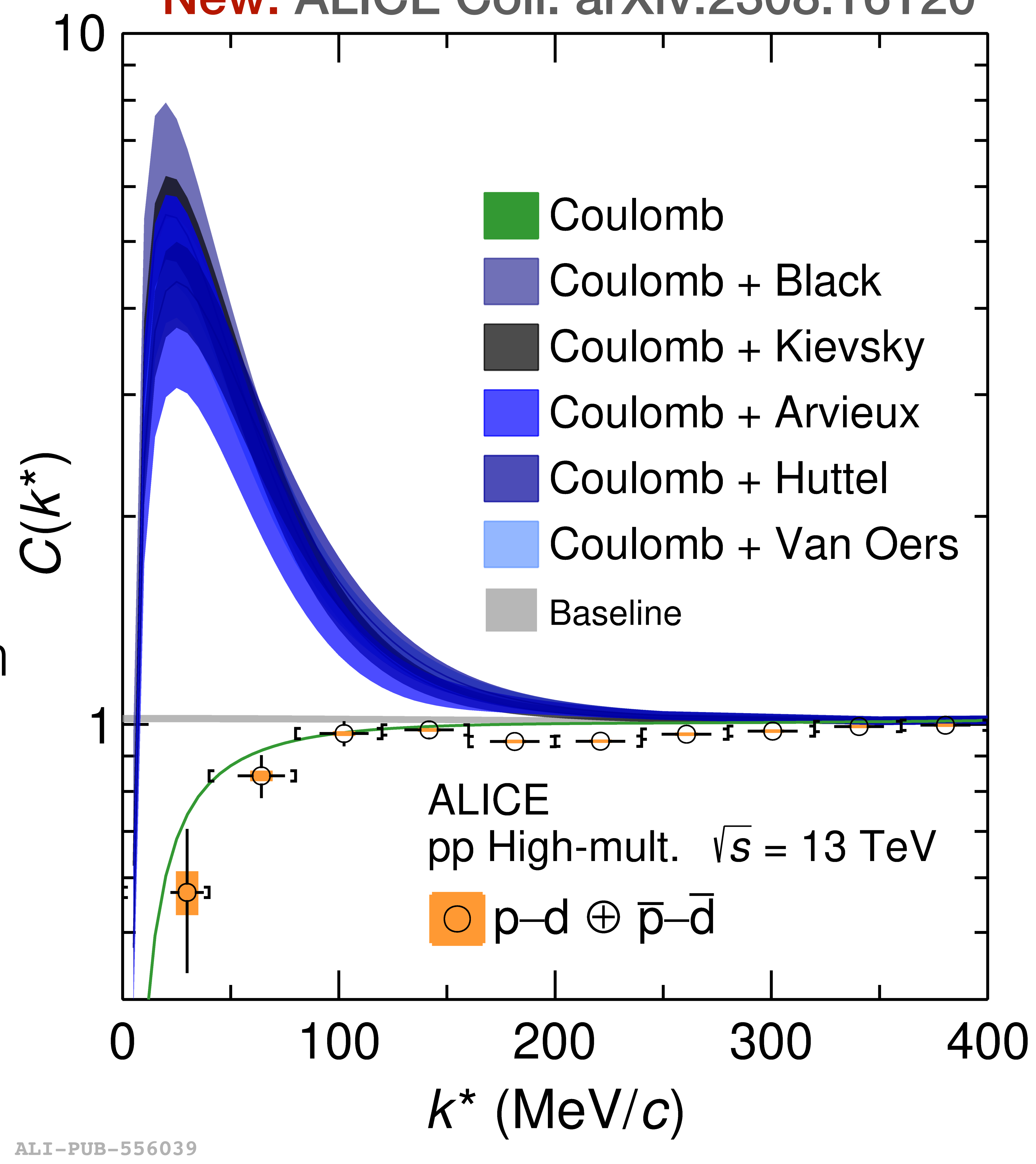

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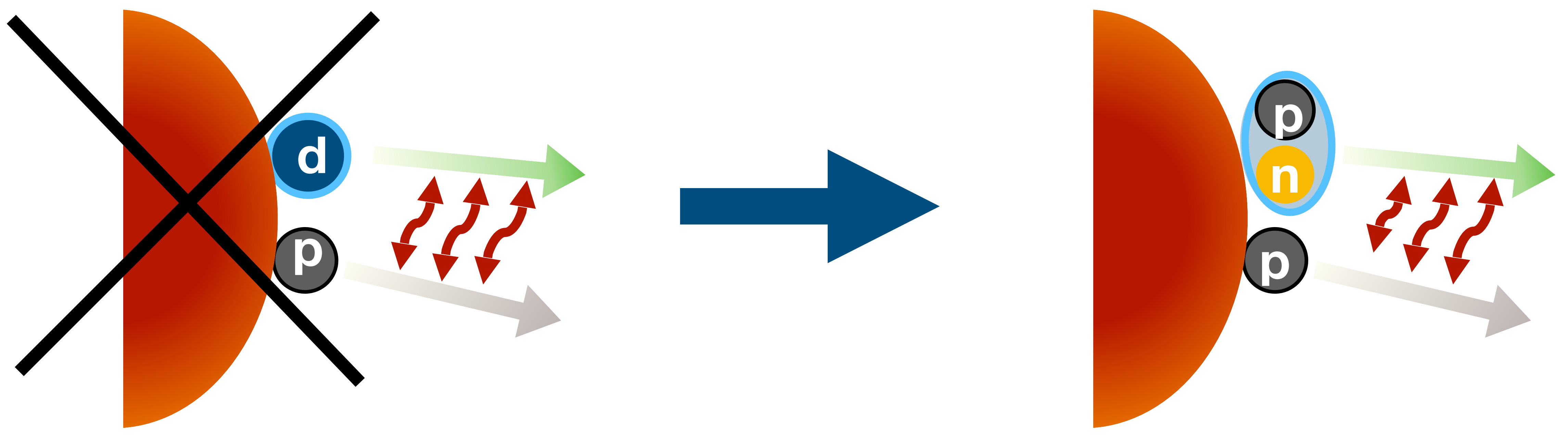

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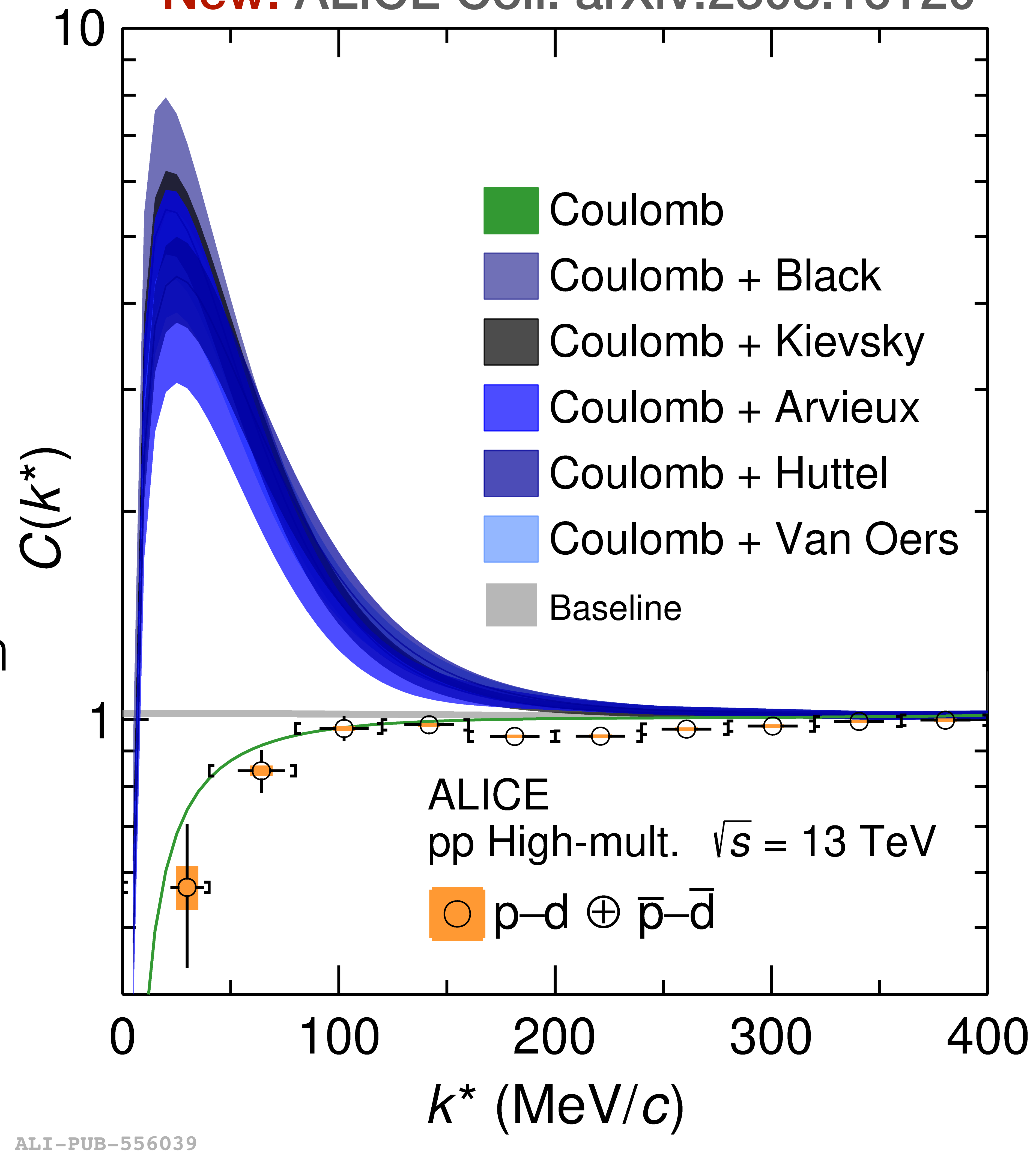

Need for three-body calculations accounting for p-pn dynamics!

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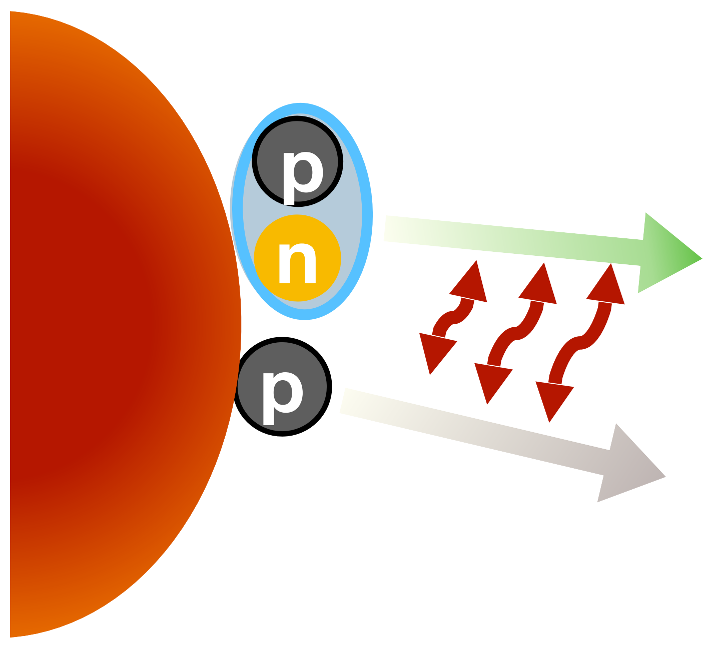
p–d as three-body system



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

$$C_{pd}(k^*) = \frac{1}{16\,A_d} \sum_{m_2,m_1} \int \rho^5 d\rho\, d\Omega \left| \Psi_{m_2,m_1\vec{k}^*} \right|^2 \frac{e^{-\rho^2/4R_M^2}}{(4\pi R_M^2)^3}$$

  - $\Psi_{m_2,\, m_1\, \vec{k}^*}$ the three-nucleon wave function, p–(pn) to p–d state asymptotically

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

Calculations: theory collaborators
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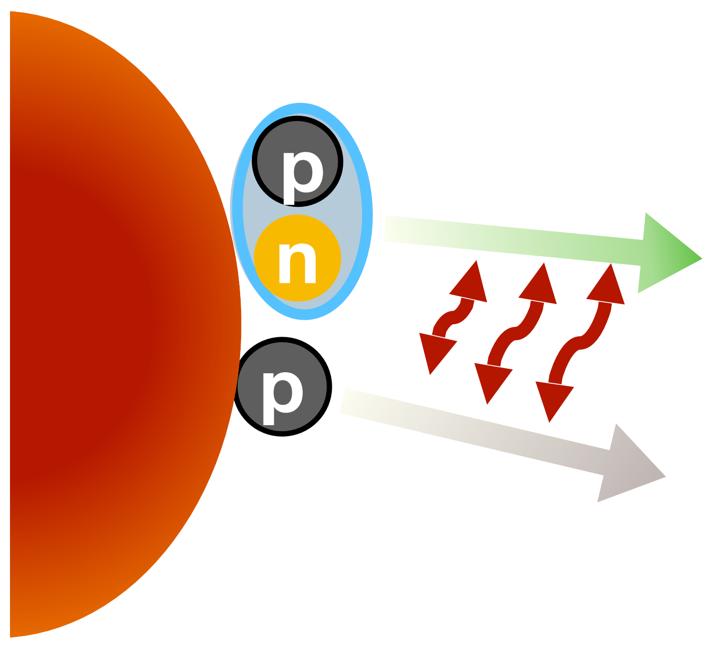

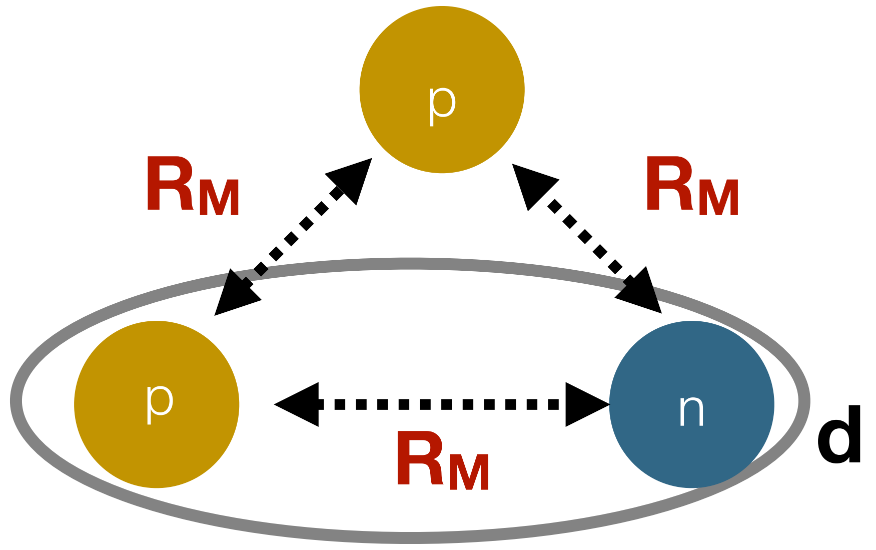

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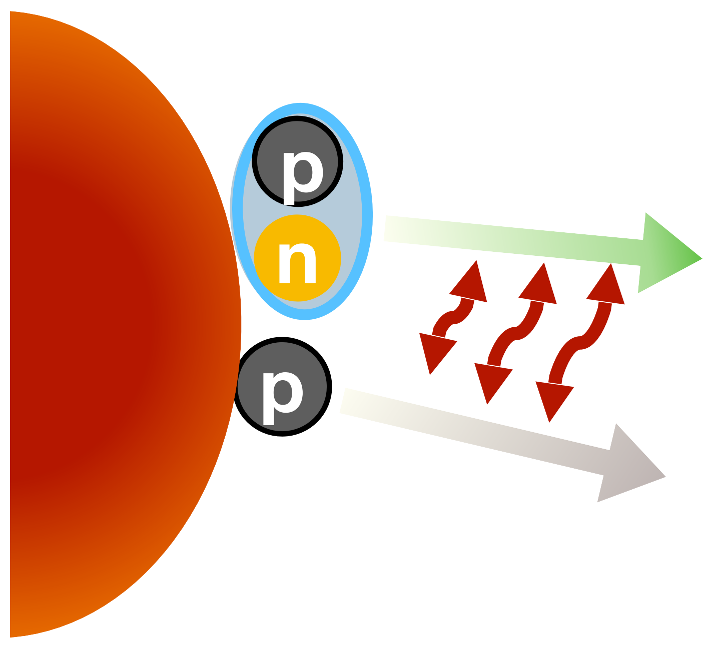
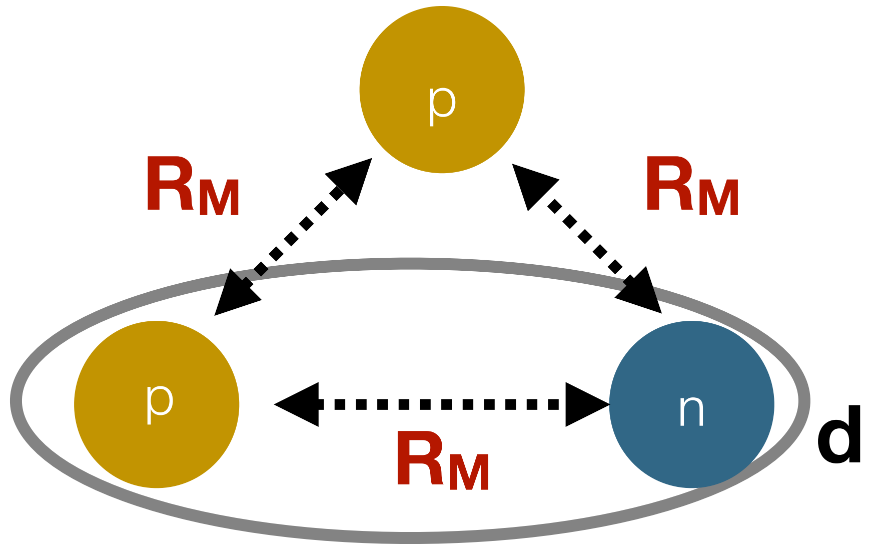
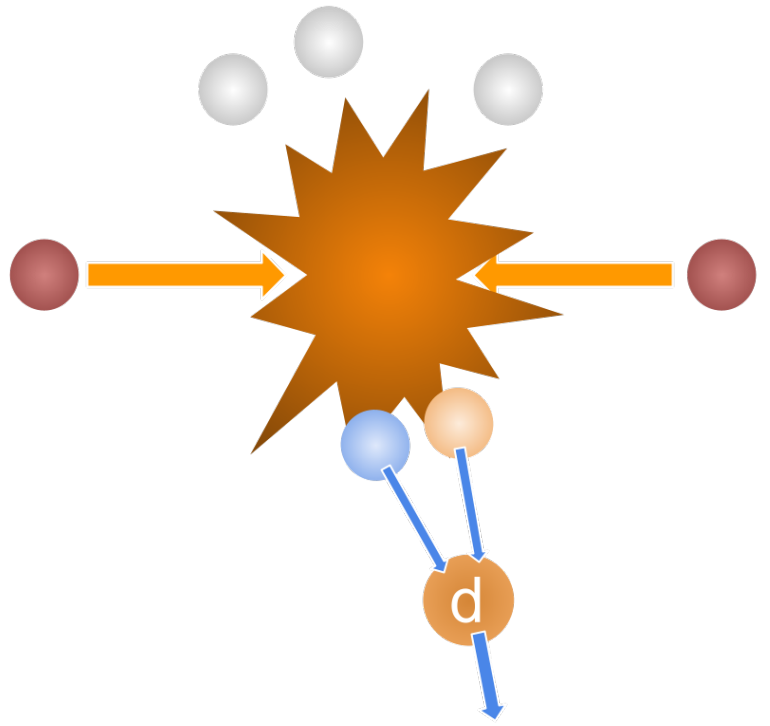
- A_d is the deuteron formation probability using deuteron wave function







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p–d as three-body system

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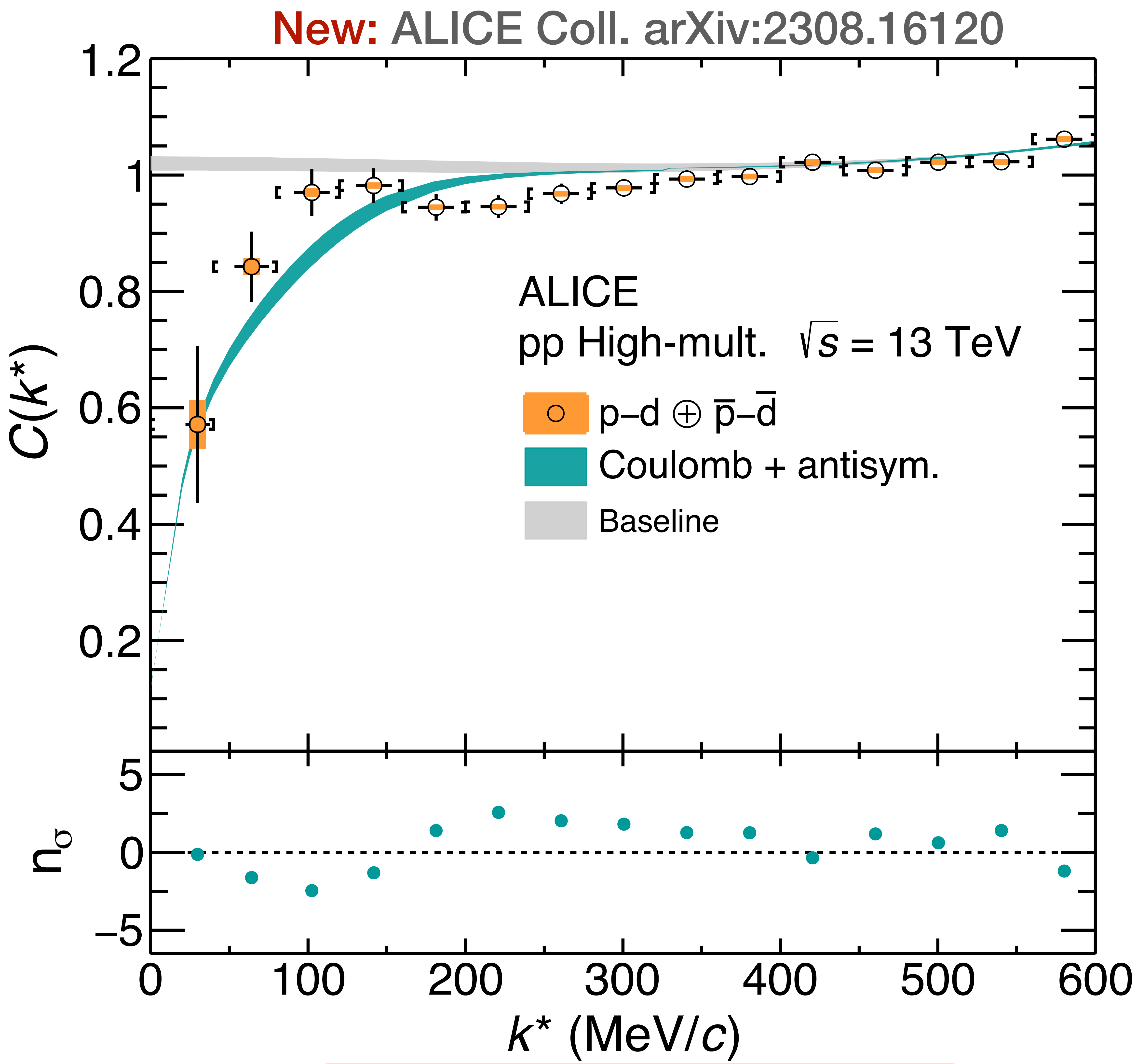

Poster 368 by
Oton Vazquez Doce

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

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

p–d as three-body system

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- Argonne v18(2N) + Urbana IX (**genuine three-body force**) potentials[1,2]
  - **s-wave** only: **not sufficient!**

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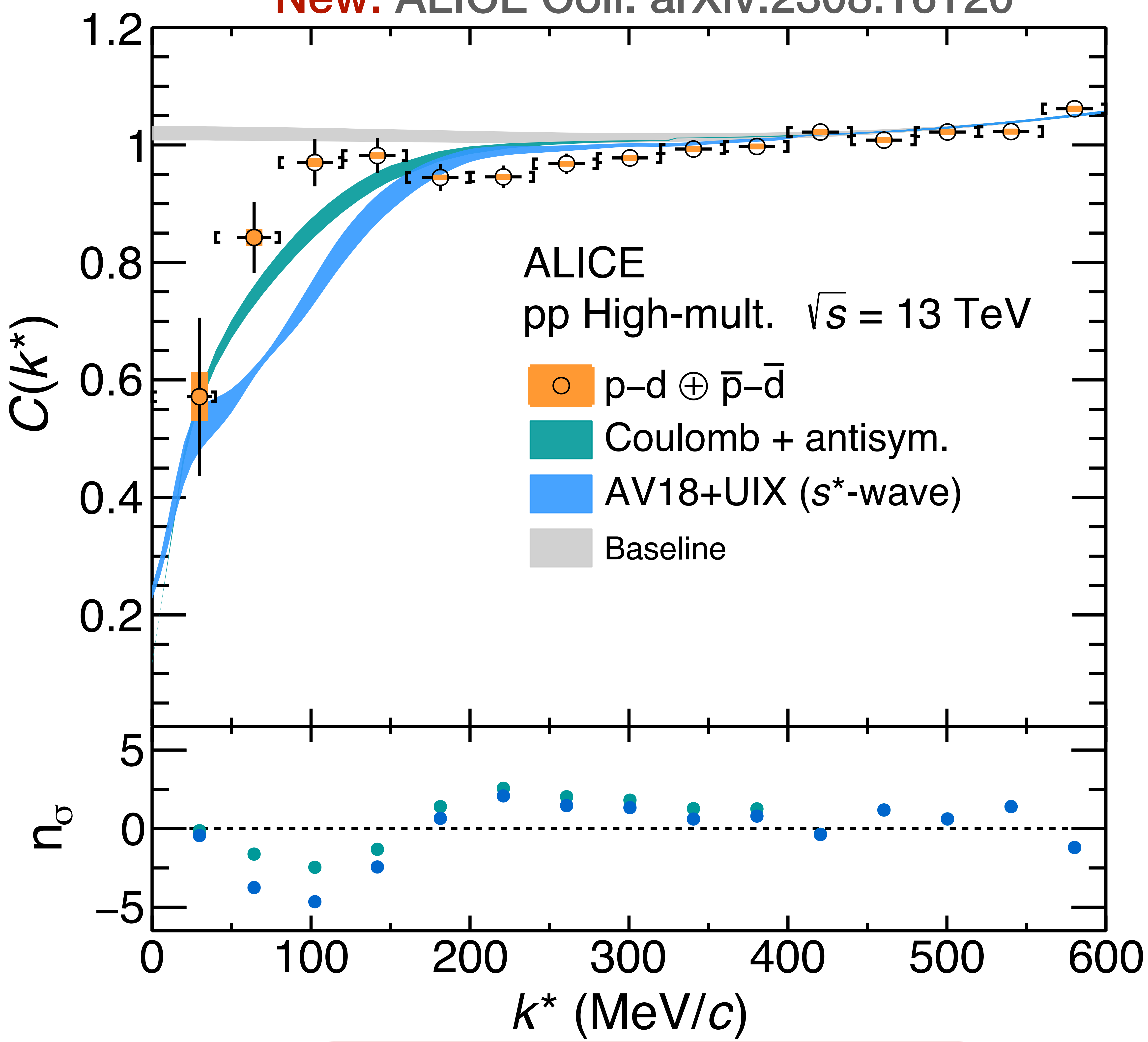

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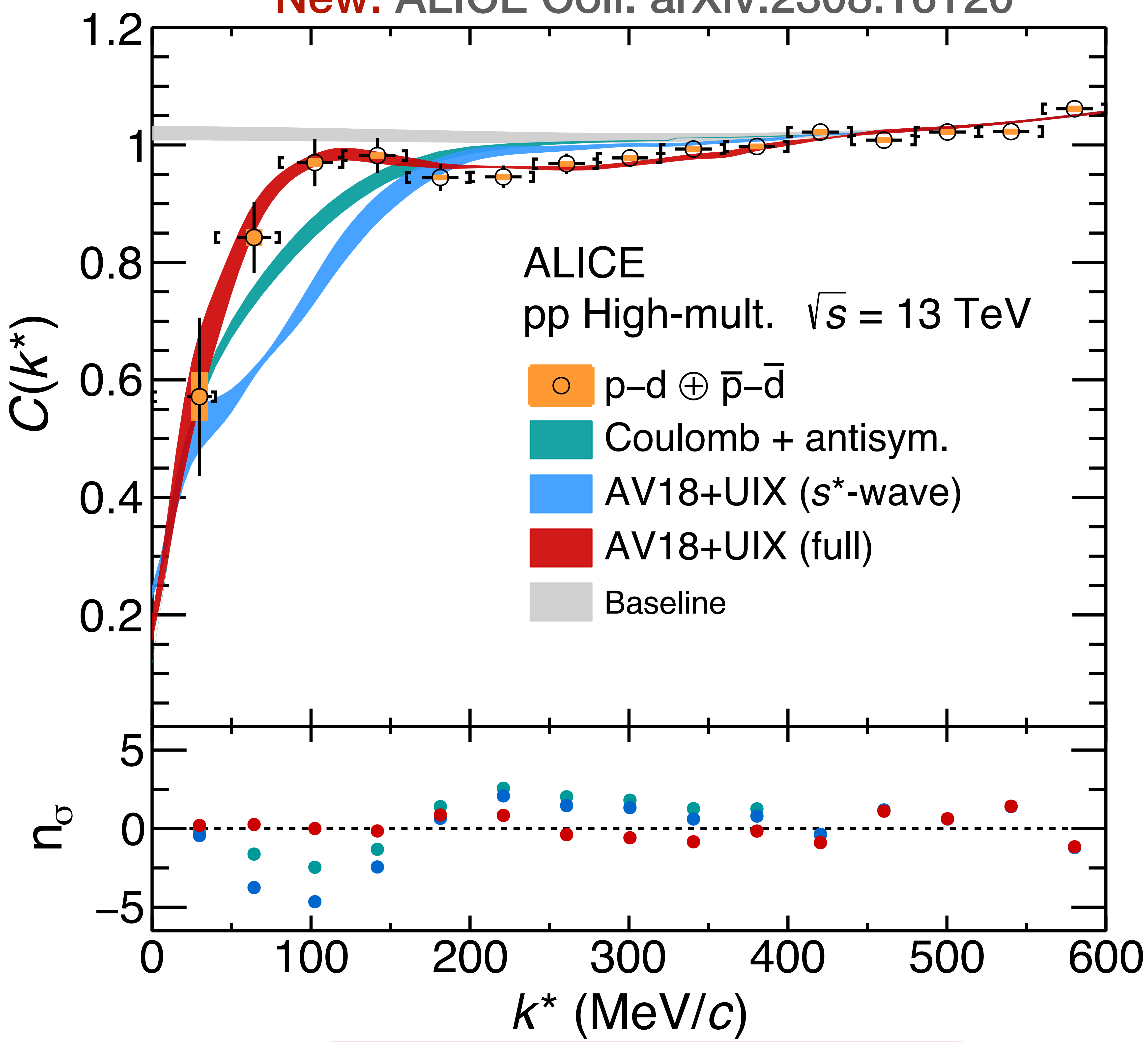

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- **Pionless EFT NLO (s+p+d waves):**
  - Agree with data within n_σ ~2.5 for k^* < 120 MeV/c

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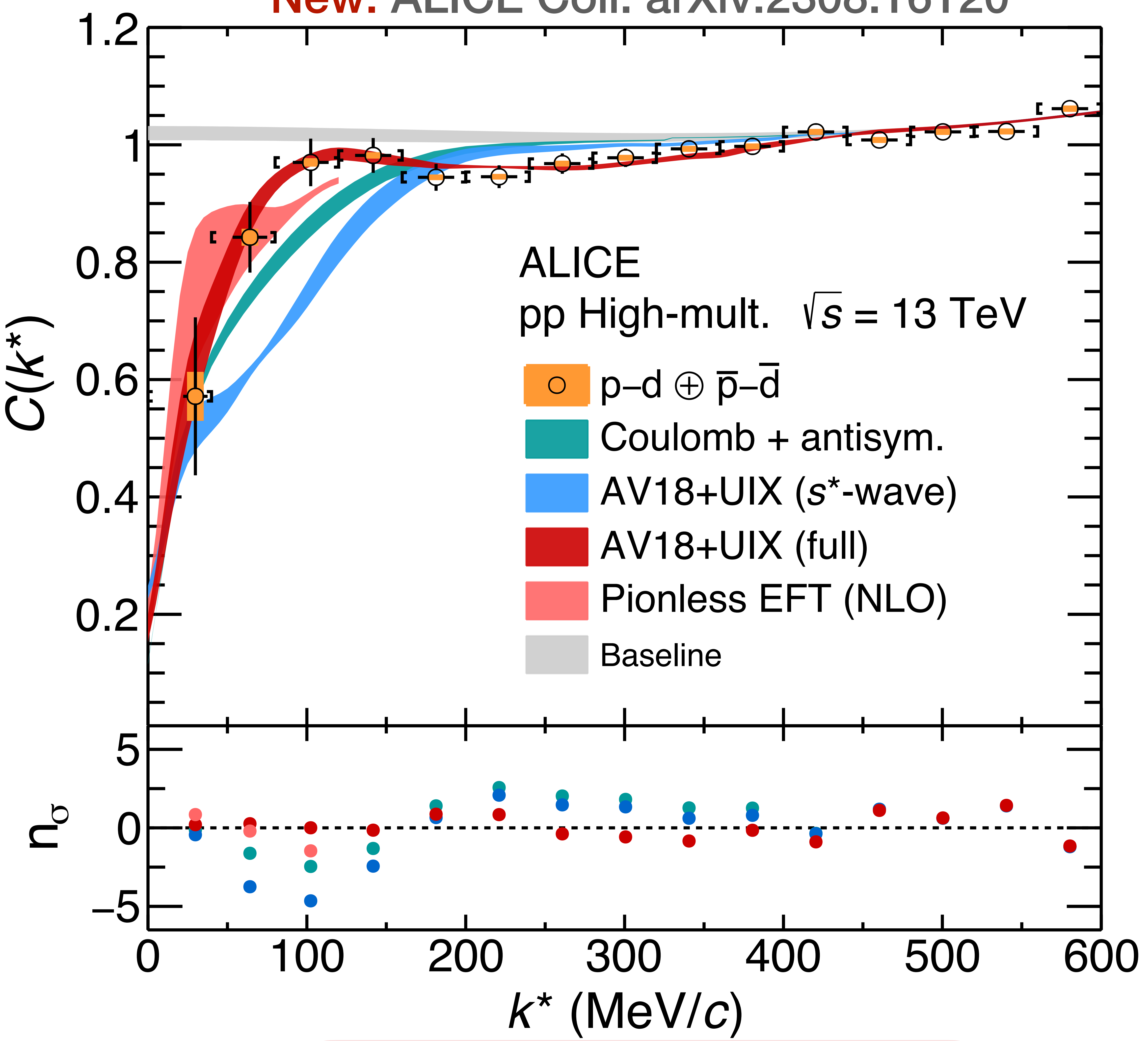

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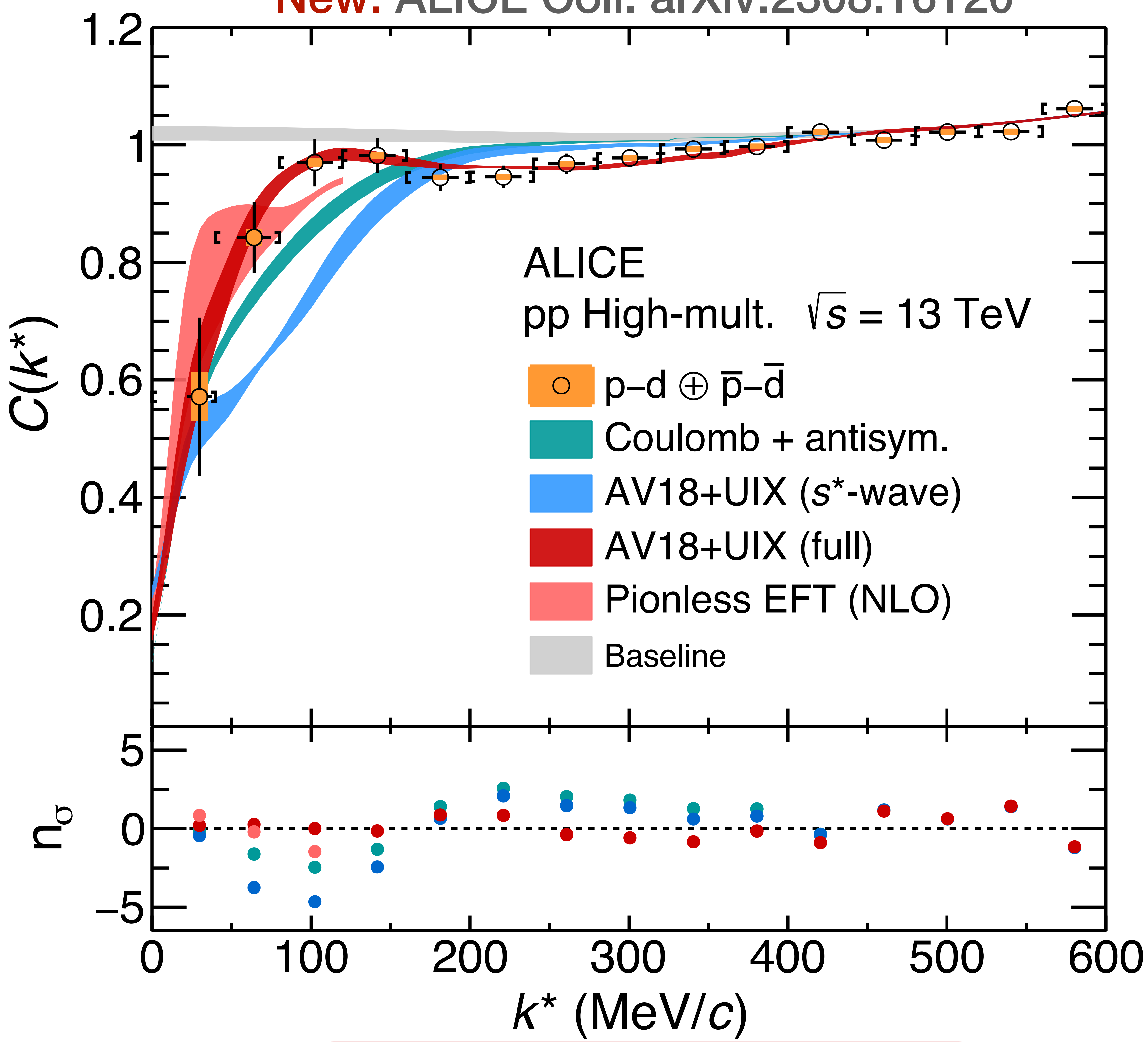
  - **s-wave** only: **not sufficient!**
  - **All partial waves up to d-waves:** describes data within n_σ ~1 for k^* up to 400 MeV/c
- **Pionless EFT NLO (s+p+d waves):**
  - Agree with data within n_σ ~2.5 for k^* < 120 MeV/c

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

New: ALICE Coll. arXiv:2308.16120



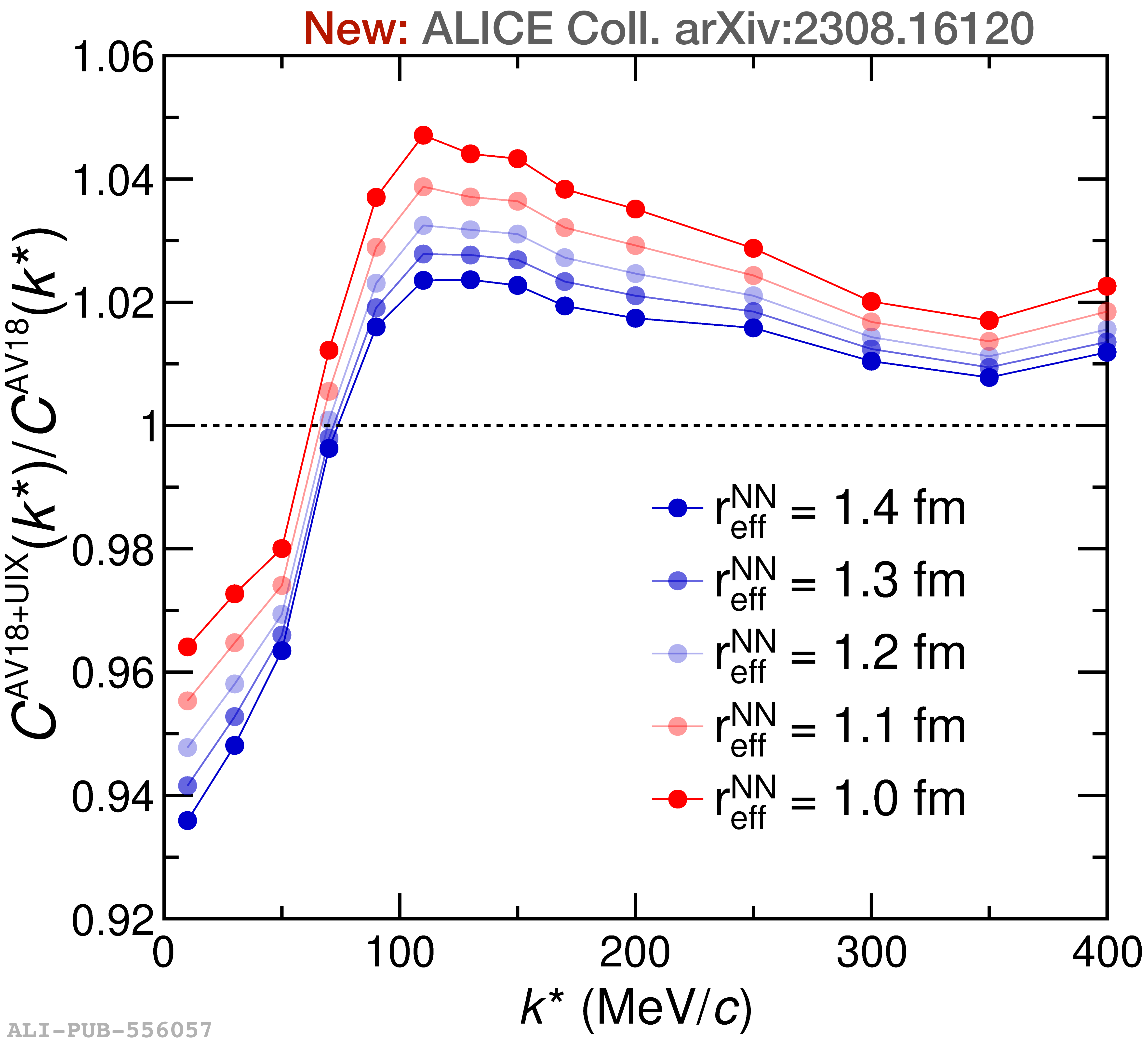
Poster 368 by Oton Vazquez Doce

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

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

Role of 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 in the measurement
- **LHC Run 3:** ~2 orders of increase in pair statistics
  - Possibility to perform m_T differential analysis

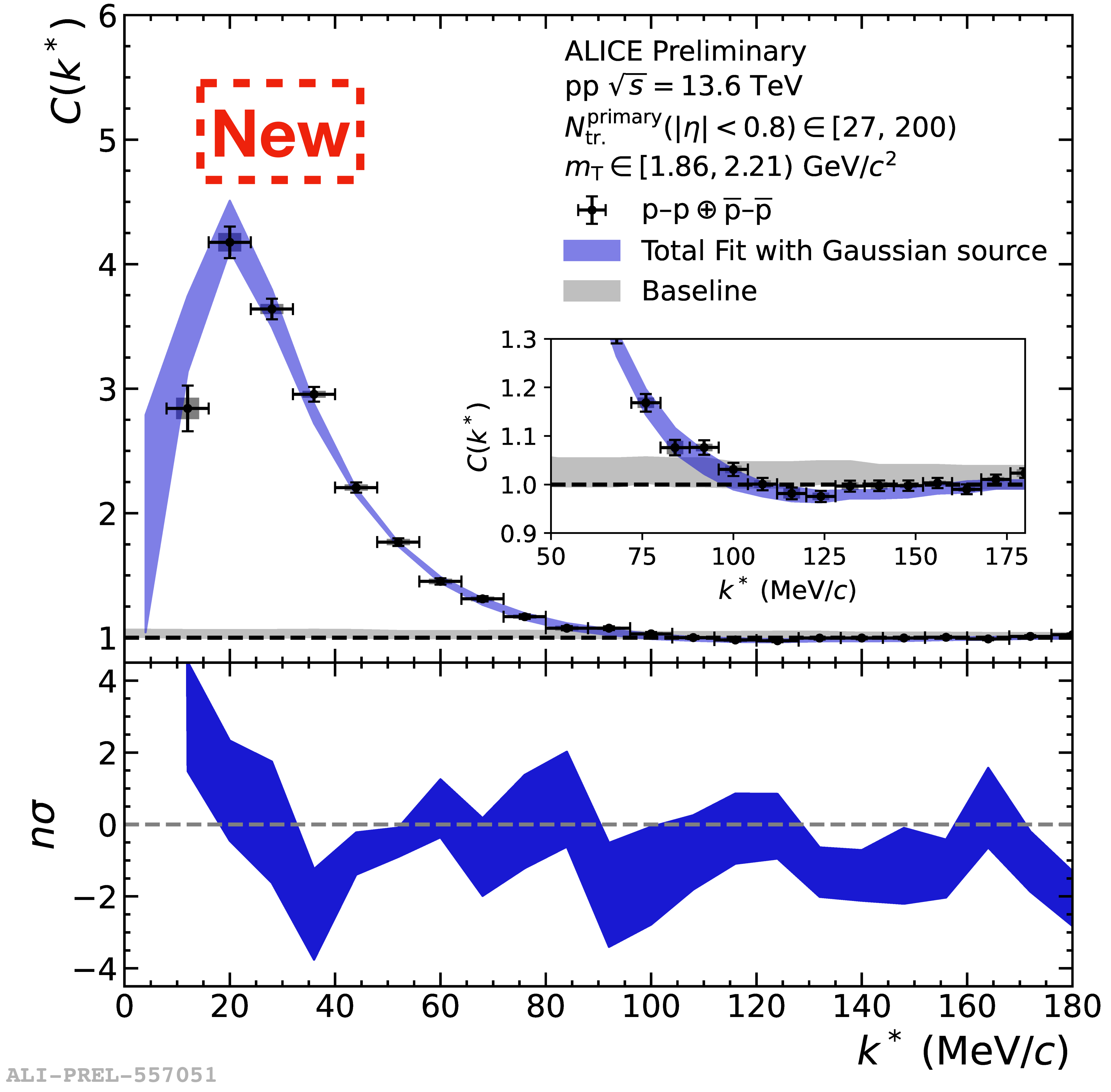


Avenue for the study of hadron–deuteron systems, including charm and strange hadrons!

p–p correlation: LHC Run 3

- LHC Run 3 pp collisions at 13.6 TeV: 50 times increased p–p pair statistics
- Fixed source for all interaction studies using femtoscopy

Poster 462 by Anton Riedel



p–p correlation function measured in m_T and multiplicity differential

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

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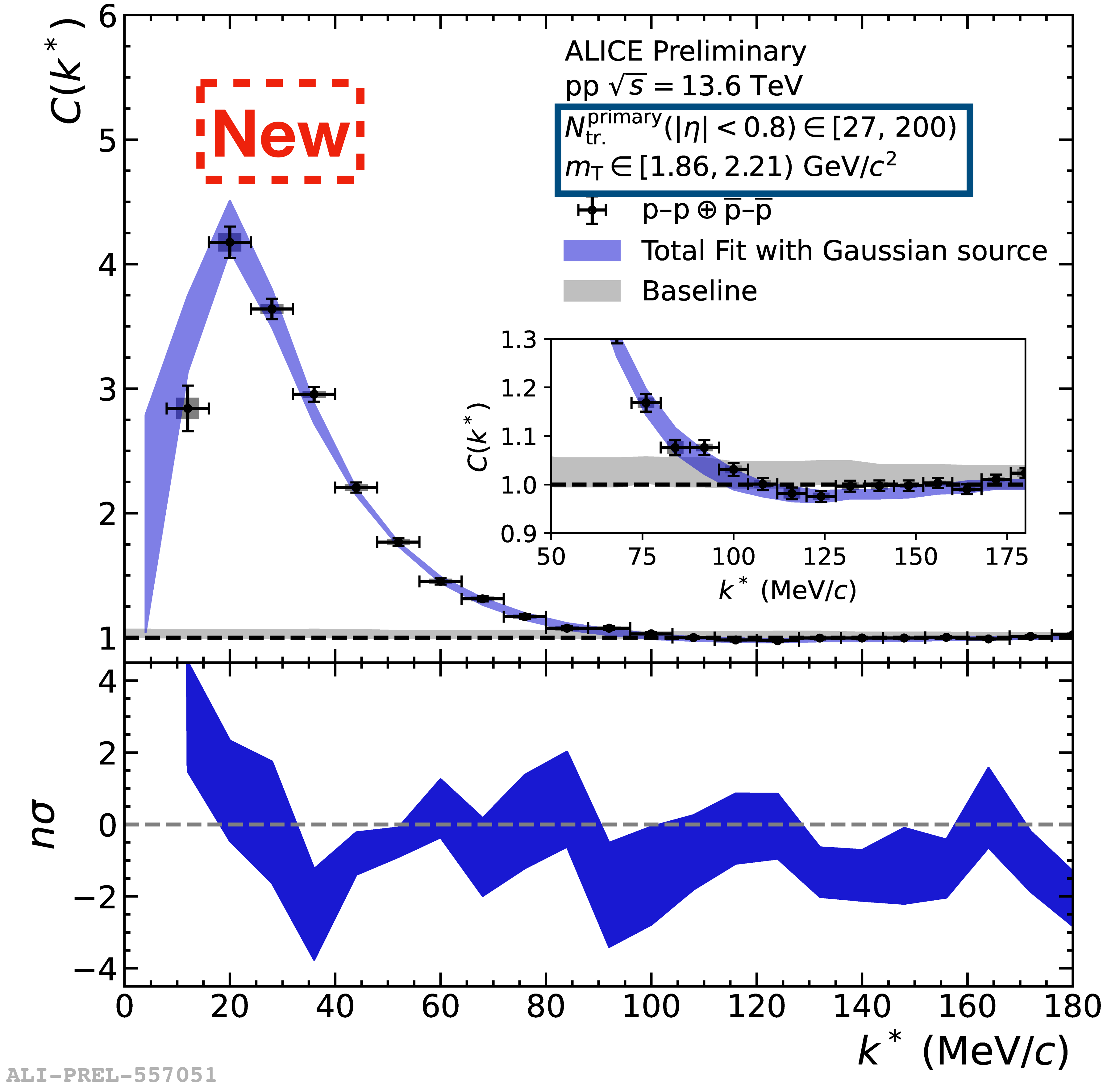
Poster 462 by Anton Riedel



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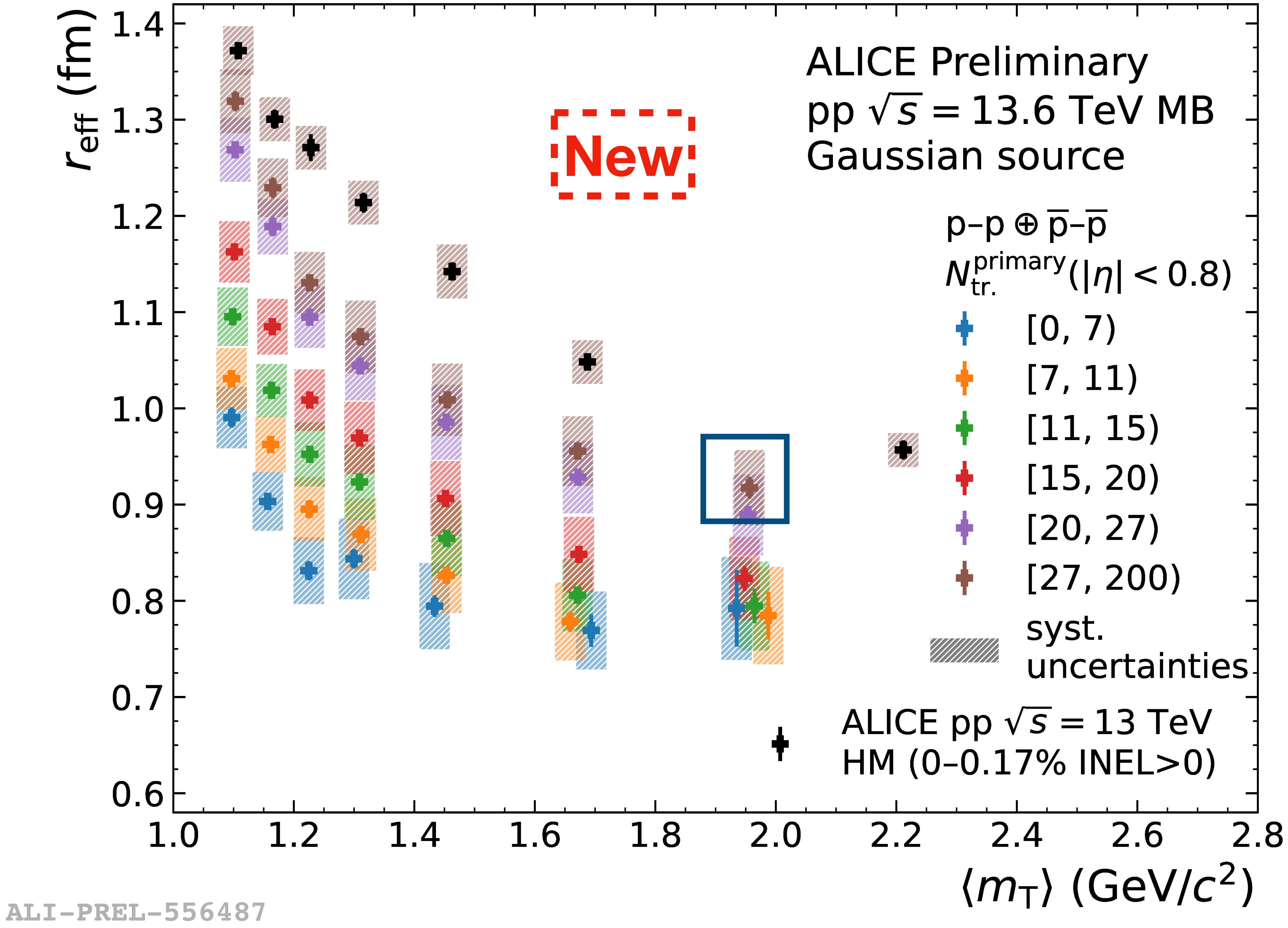

m_T-scaling of the effective source size for p–p pairs in different multiplicity classes

Summary and outlook

Summary:

- **K–d in pp and Pb–Pb collisions: the first measurement ever**
  - Deuterons follow source size scaling common for all baryon–baryon pairs in pp collisions
  - Provide constraints on $K^{+/-}$–d interaction => useful to study kaonic bound-states
- **p–d: can be described with full three-body calculations**
  - Correlation of deuteron–proton: access to three-body system
- **p–p correlation in Run 3 LHC**
  - Femtoscopic source constrained for all interaction studies

Outlook: more data more physics!

- Deuterons can be combined to other hadrons to study many-body interaction
- Final constraints on three-body interactions will arrive in Run 3 and Run 4!

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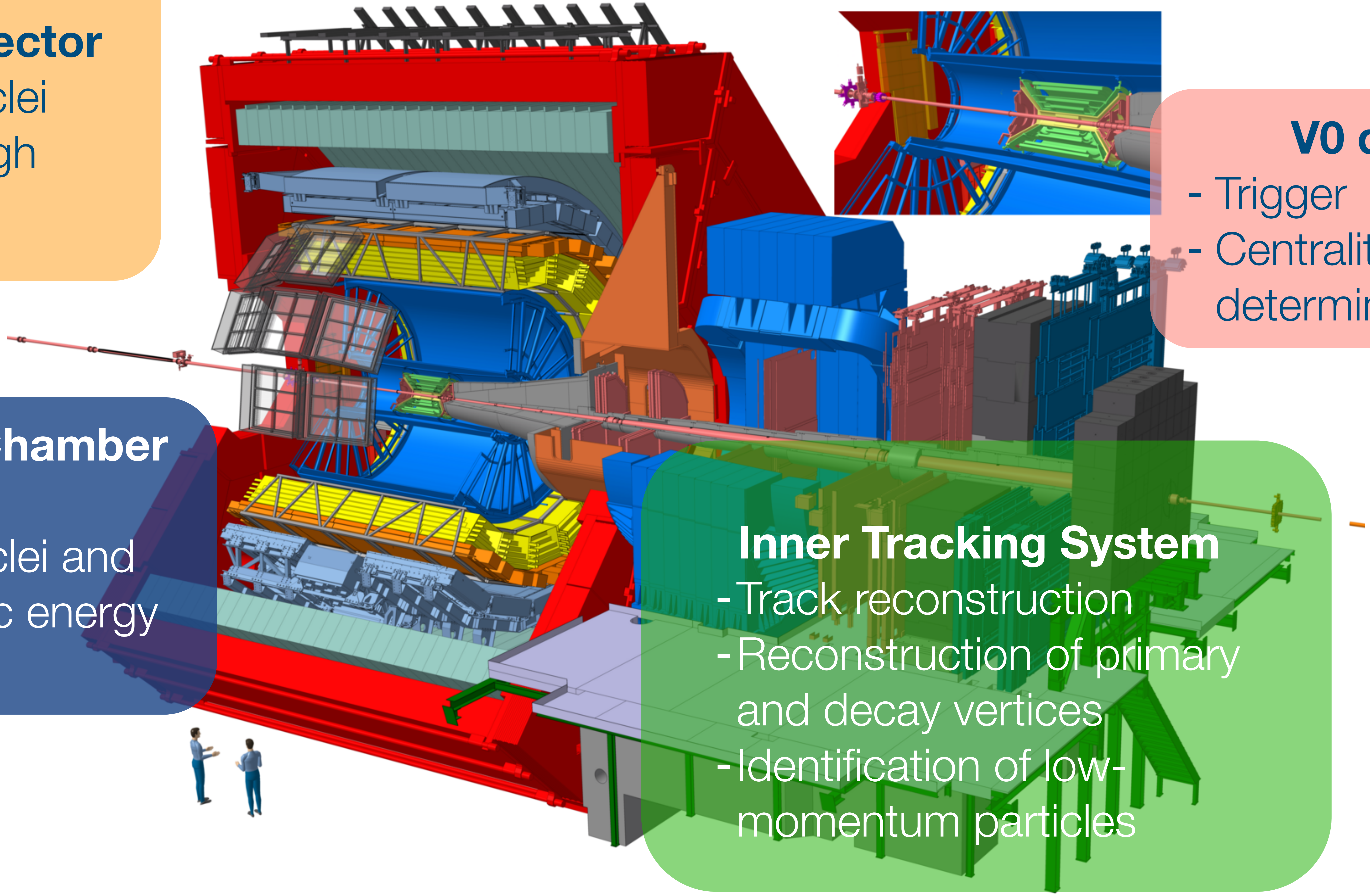
Thanks for your time!

additional slides

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



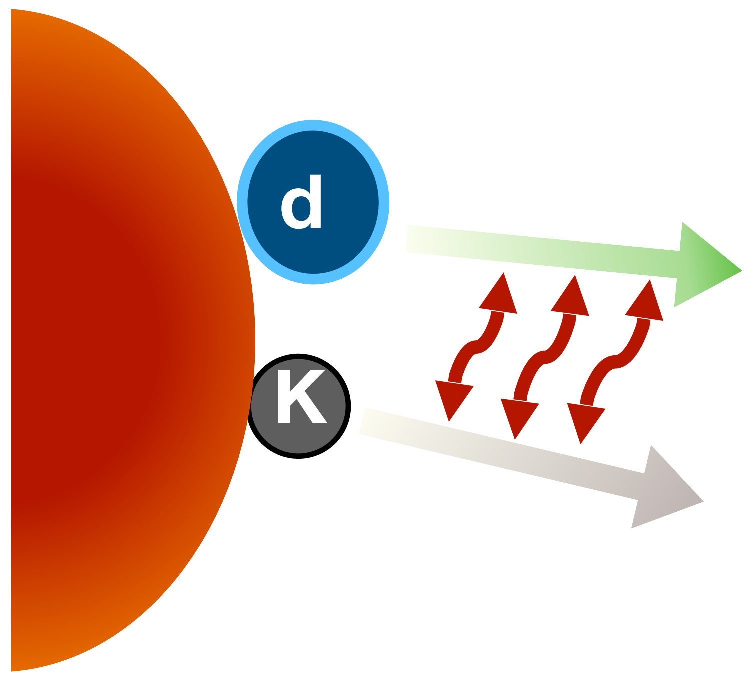
V0 detectors
- Trigger
- Centrality/multiplicity determination

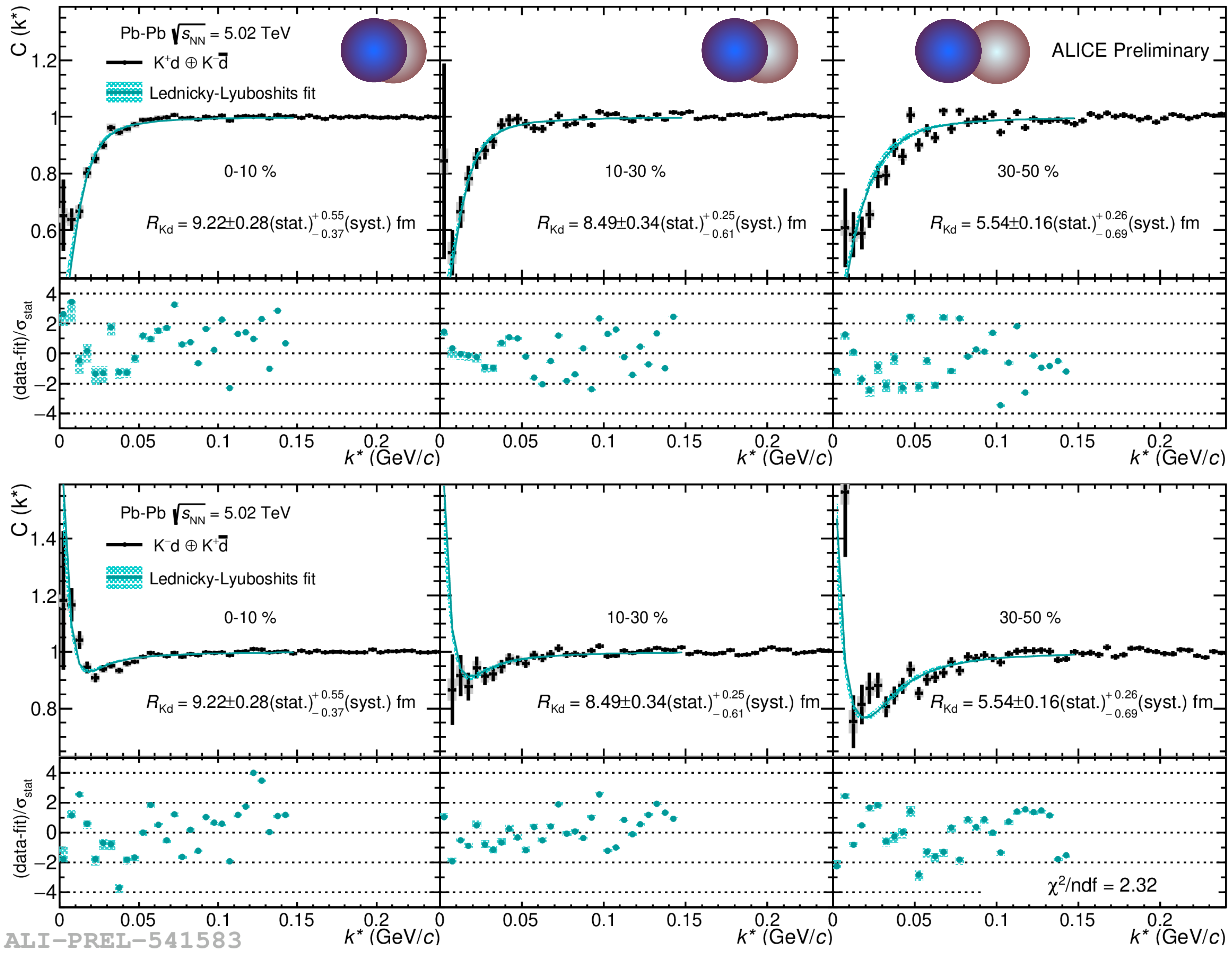
Inner Tracking System
- Track reconstruction
- Reconstruction of primary and decay vertices
- Identification of low-momentum particles

ALICE : ITS and TPC upgrades

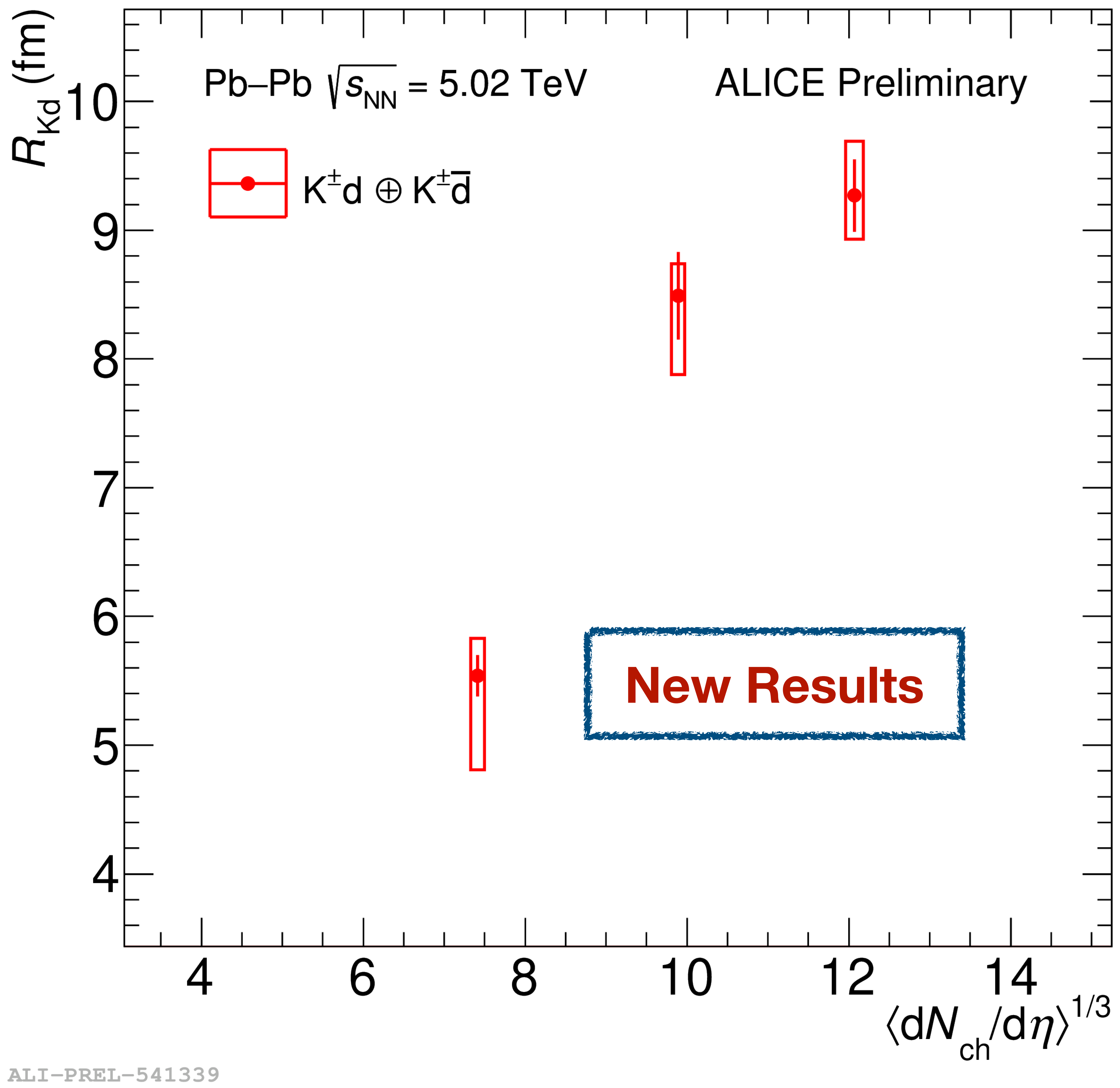
Kaon–deuteron system in Pb–Pb collisions

- **$K^{\pm}$–d correlation functions** in Pb–Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV
  - 3 centrality intervals: 0–10%, 10–30%, and 30–50%
- **Lednický-Lyuboshitz approach**
  - Coulomb effects + strong interaction (via scattering parameters)





$K^{\pm}d$ source size in Pb–Pb

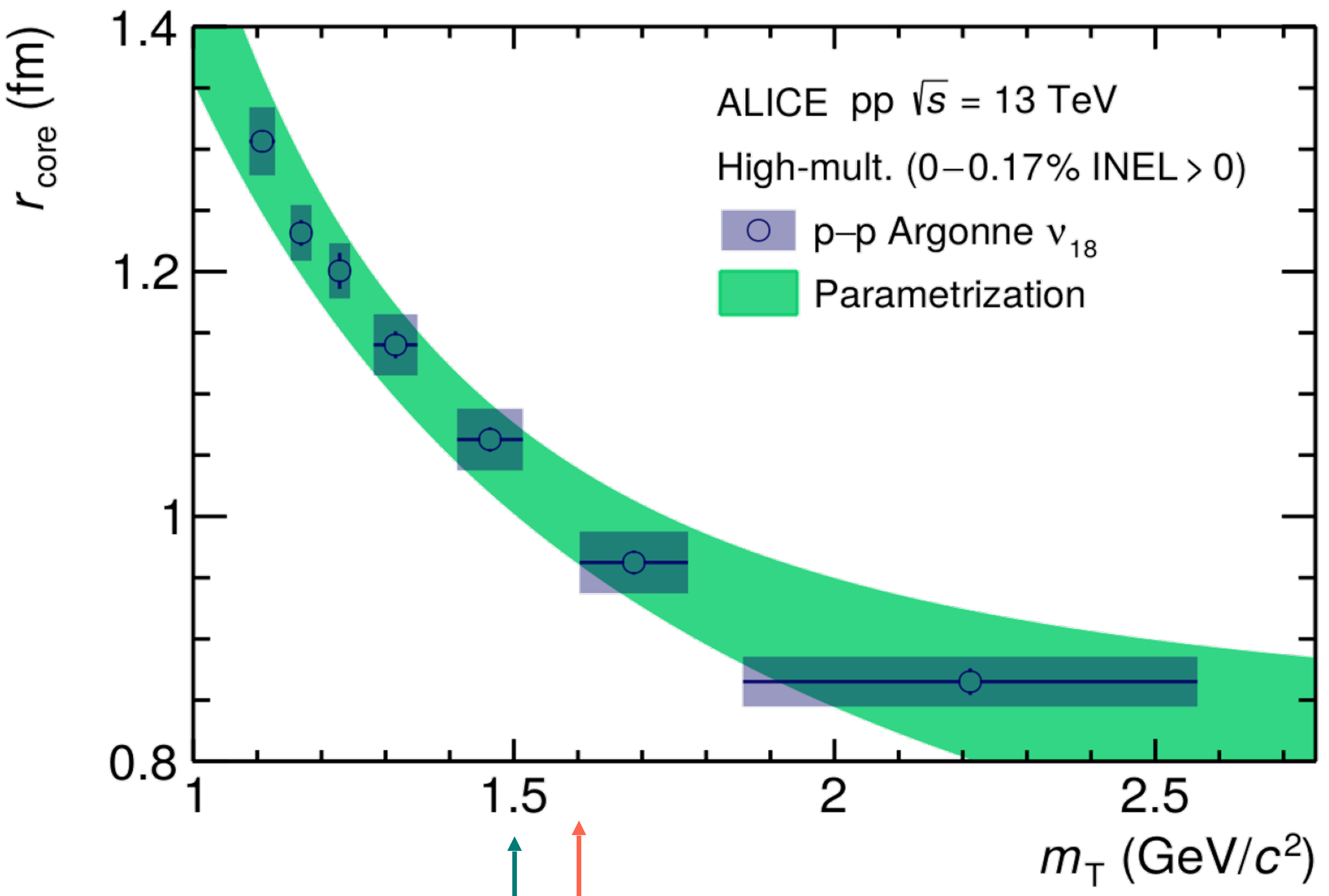


- 3 radii as a function of centrality
  - for 3 centralities (the same radius for all particle pairs)
- Source size increases with multiplicity!

Source size for p–d and K⁺–d pairs

- Two main contributions:
  - Collective effects: results in a core emission profile **Gaussian core** source (constrained theoretical p-p correlation with **AV18 interaction** with Fermi-Dirac statistics, Coulomb, and strong interaction)
  - Increase: strongly decaying resonances require source correction

Source size	mean value:p–d	mean value:K^+–d
r_{core}	0.99±0.05 fm	1.04±0.04 fm



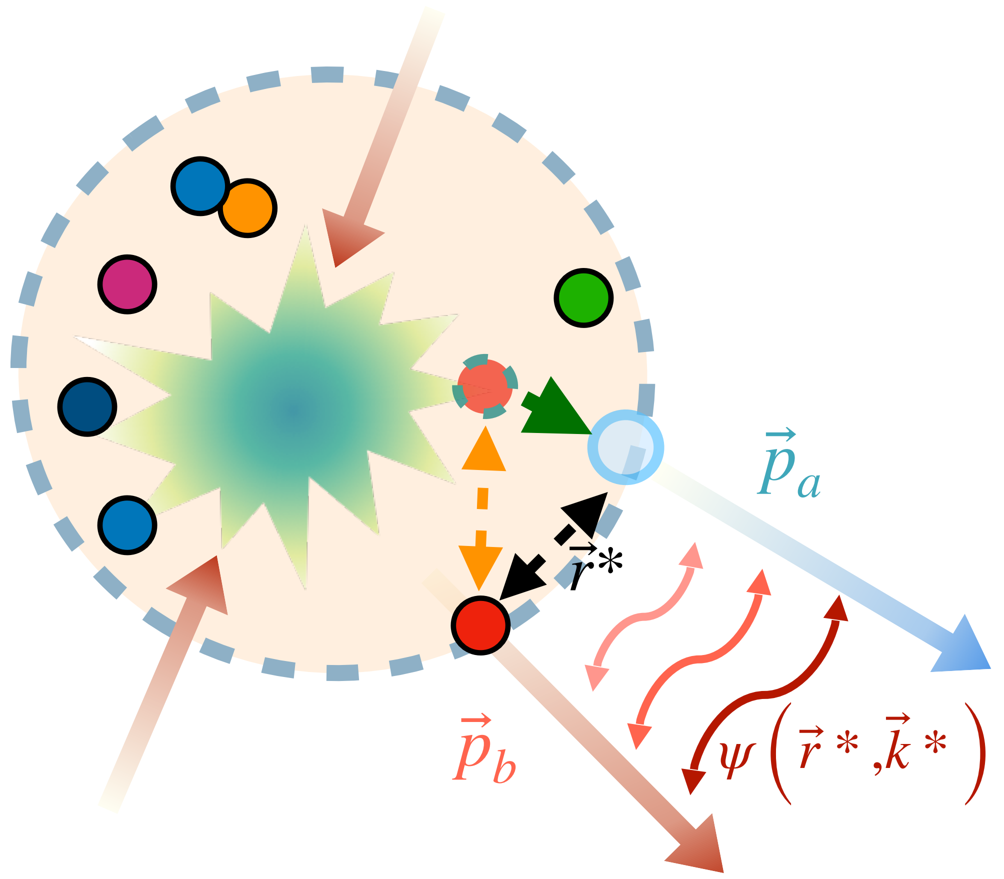
$\langle m_T, p-d \rangle = 1.64$ GeV/c^2

$\langle m_T, K^+-d \rangle = 1.50$ GeV/c^2

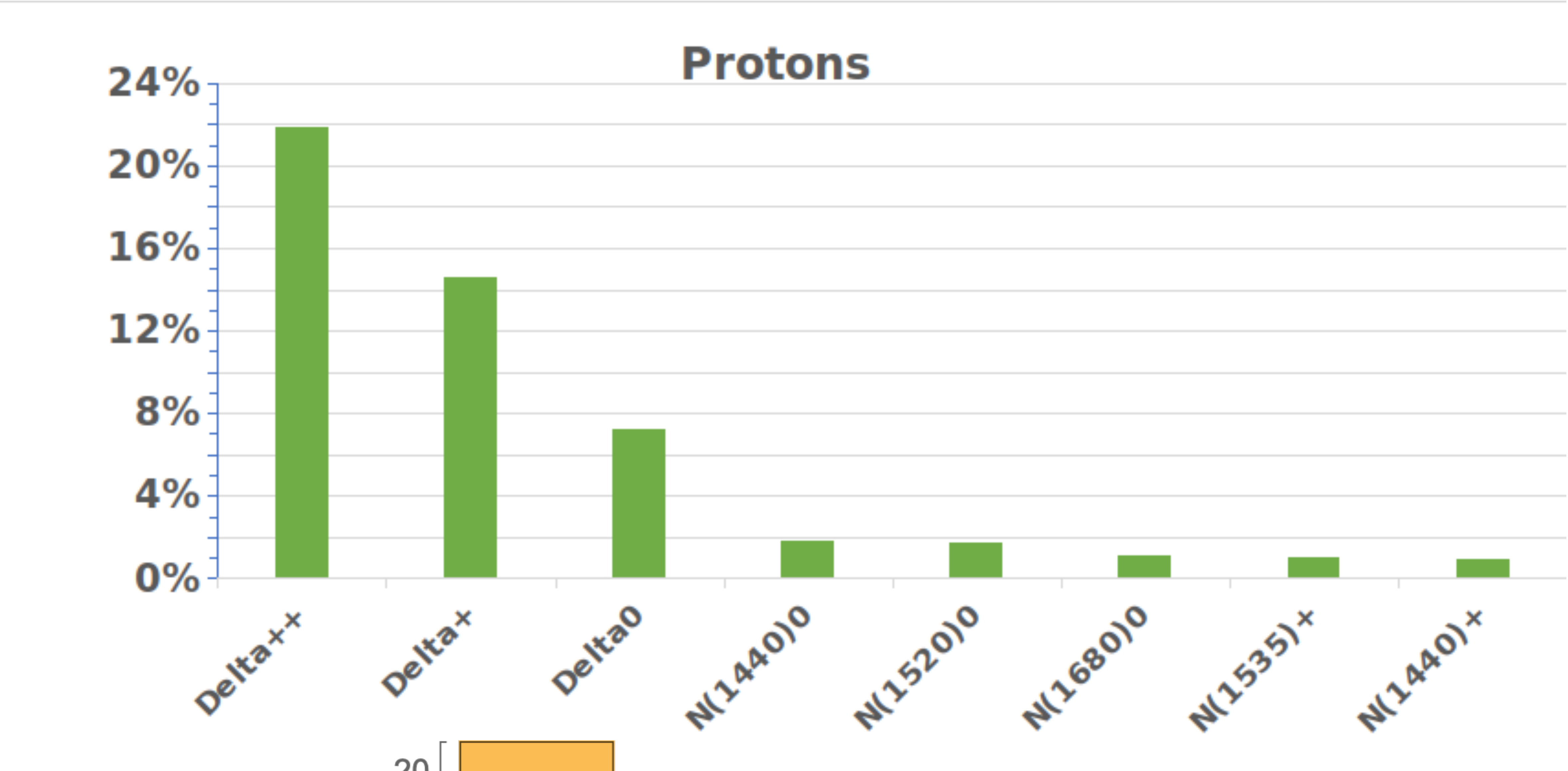
ALICE Coll. PLB 811 135849 (2020)

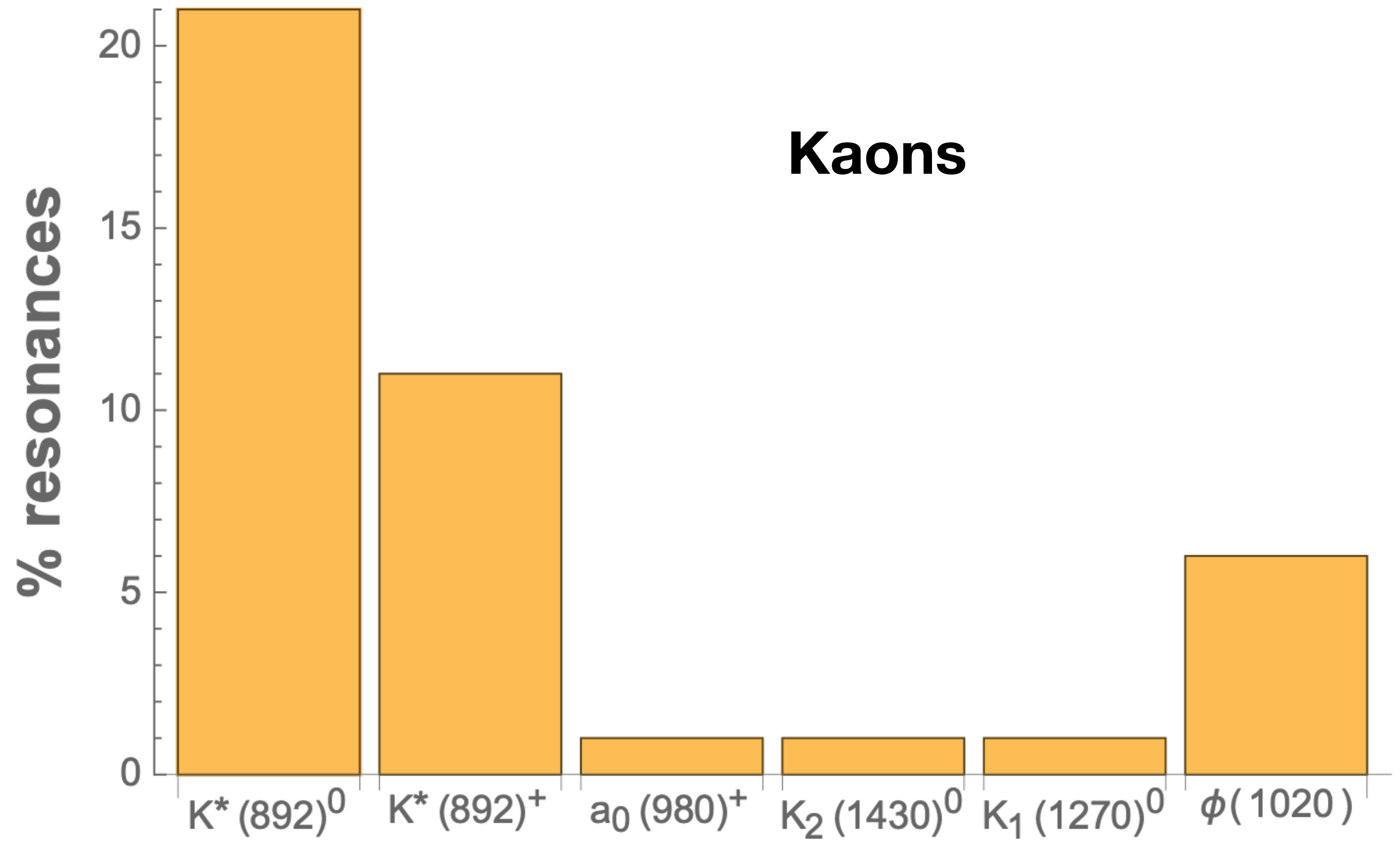
Source size for p–d and K+–d pairs

- The source radius is effectively increased by **short-lived strongly decaying resonances** (cτ ≈ 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

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 (Lednicky): arxiv.org/abs/nucl-th/0501065

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

- f_c : Coulomb normalised 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 behaviour of wavefunction

⇒ to obtain two-particle correlation we can use Koonin-Pratt formula

Effective two-body approach

- **For distinguishable pointlike particles: Lednicky approach**
  - Considers Coulomb effects + strong interaction (via scattering parameters)
  - Only s-wave interaction

- **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[2]
  - FCA (fixed-center approximation): a_0= –0.54 fm, d_0= 0.0 fm[3]

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

Femtoscopic correlation

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

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

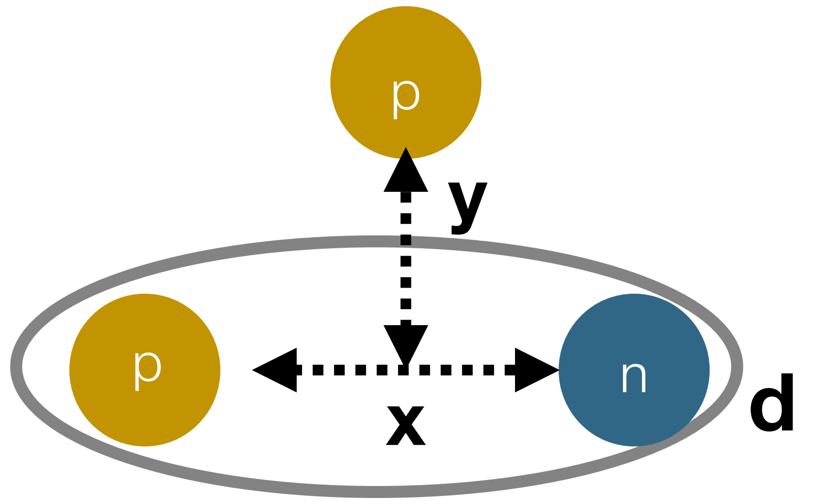
Contributions from: genuine feed-down misidentifications

- 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)

p–d correlation with d as composite object

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

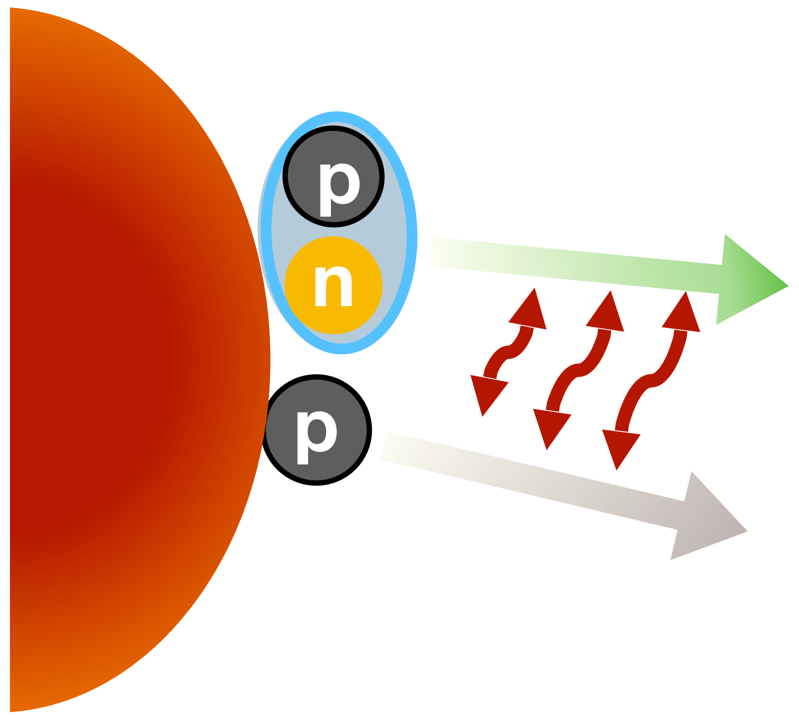
- **Three–body wavefunction for p–d:** $\Psi_{m_2,m_1}(x,y)$ describing three-body dynamics, anchored to p–d scattering observables.
  - x = distance of p-n system within the deuteron, y is the p-d distance
  - m_2 and m_1 deuteron and proton spin



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

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

Asymptotic form   Strong three-body interaction



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

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

New theory paper:
M. Viviani et al arXiv:2306.02478

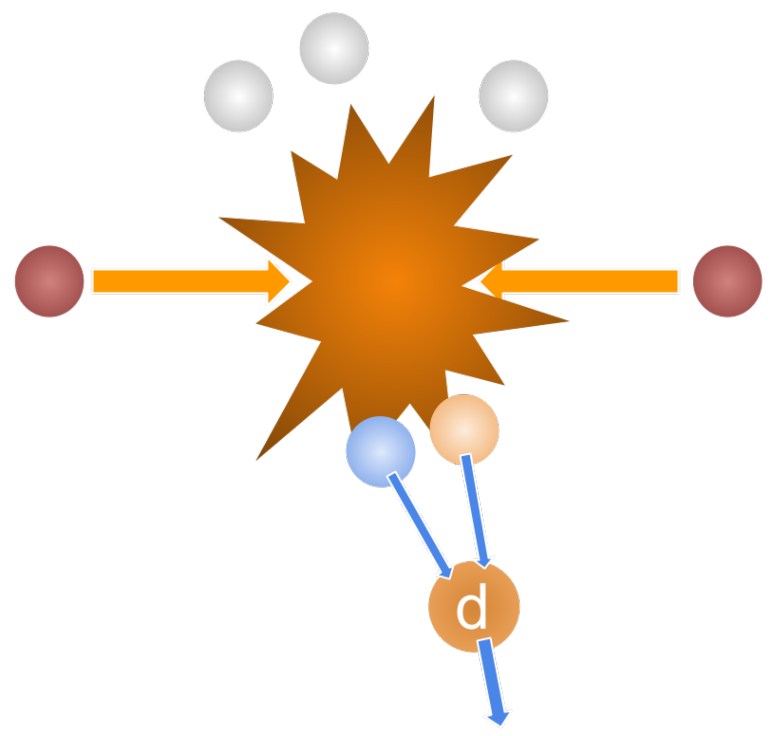
p–d as three-body system

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

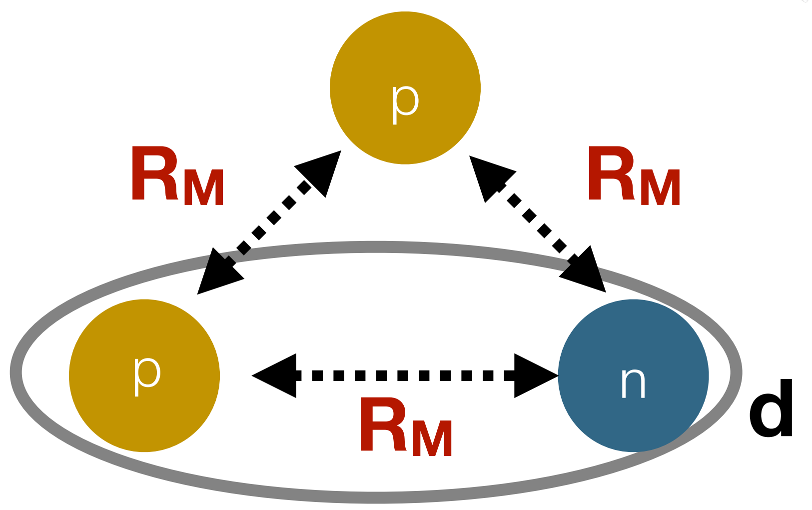
Single-particle Gaussian emission source

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

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



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

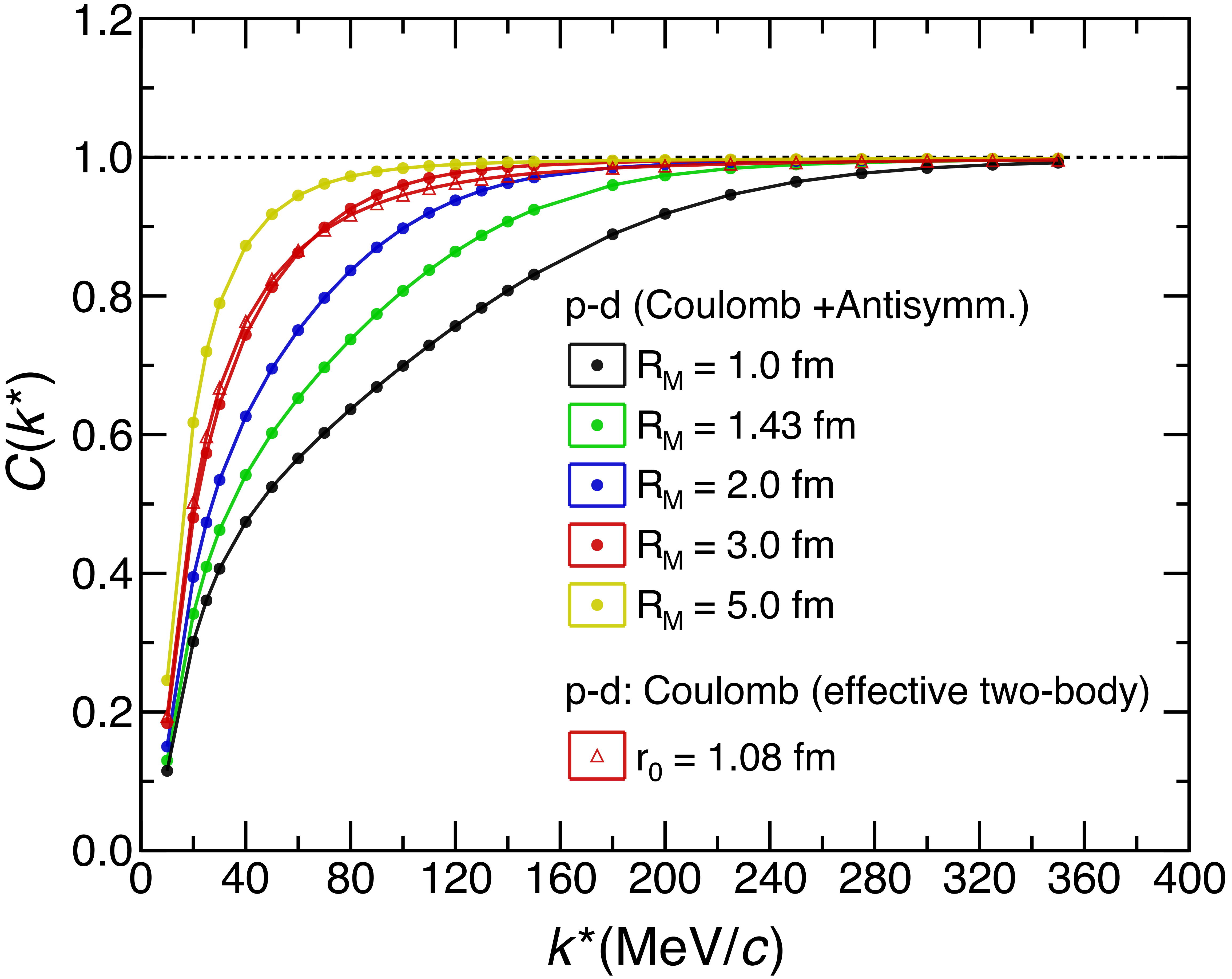


M. Viviani et al arXiv:2306.02478

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

Role p–pn dynamics only in Coulomb case

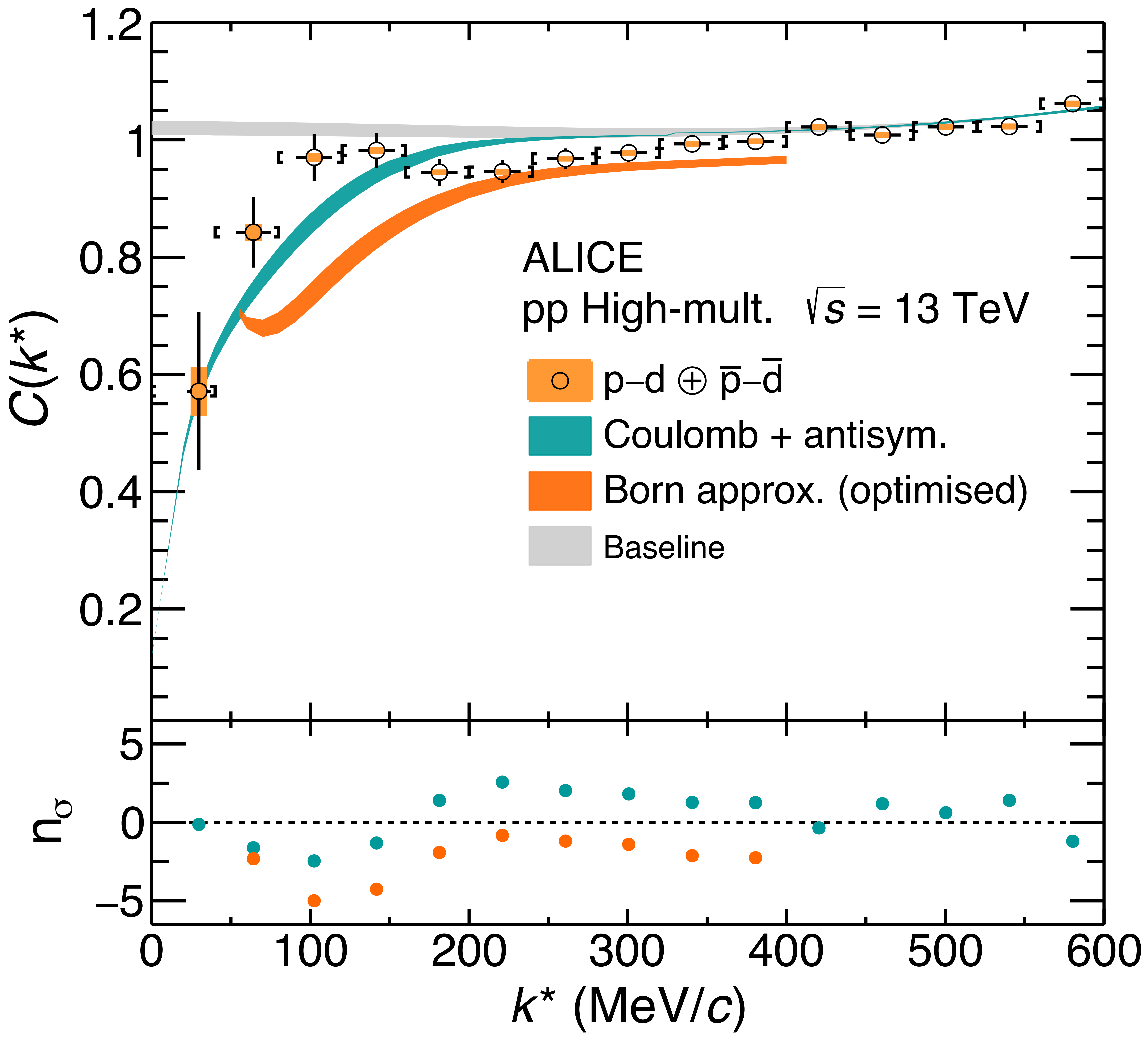
- Complete p–pn dynamics, but the strong interaction is **absent** at very short-range!
  - **r^{NN}_{eff} =1.43±0.16** fm (nucleon-nucleon distance)
- In the case of the two-body picture Coulomb-only interaction differs from the one using the p-(pn) dynamics
  - **r^{pd}_{eff} =1.08±0.06** fm (proton-deuteron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



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

Deuteron as composite object: p–pn dynamics

- 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

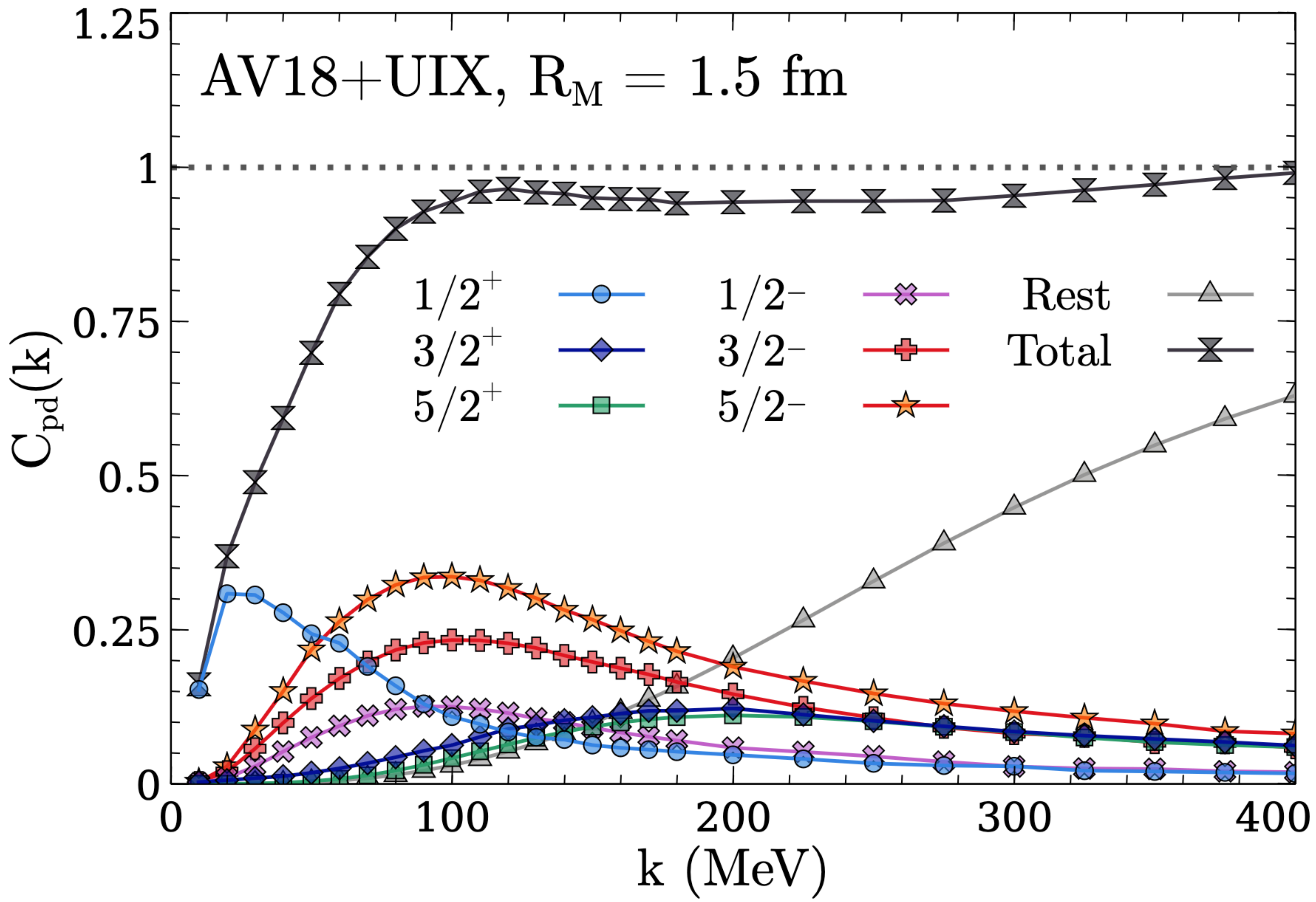


Sensitivity to the dynamics of the three-body p–(pn) system at short distance

Partial wave decomposition of p-d

- Contribution from different partial waves in p-d

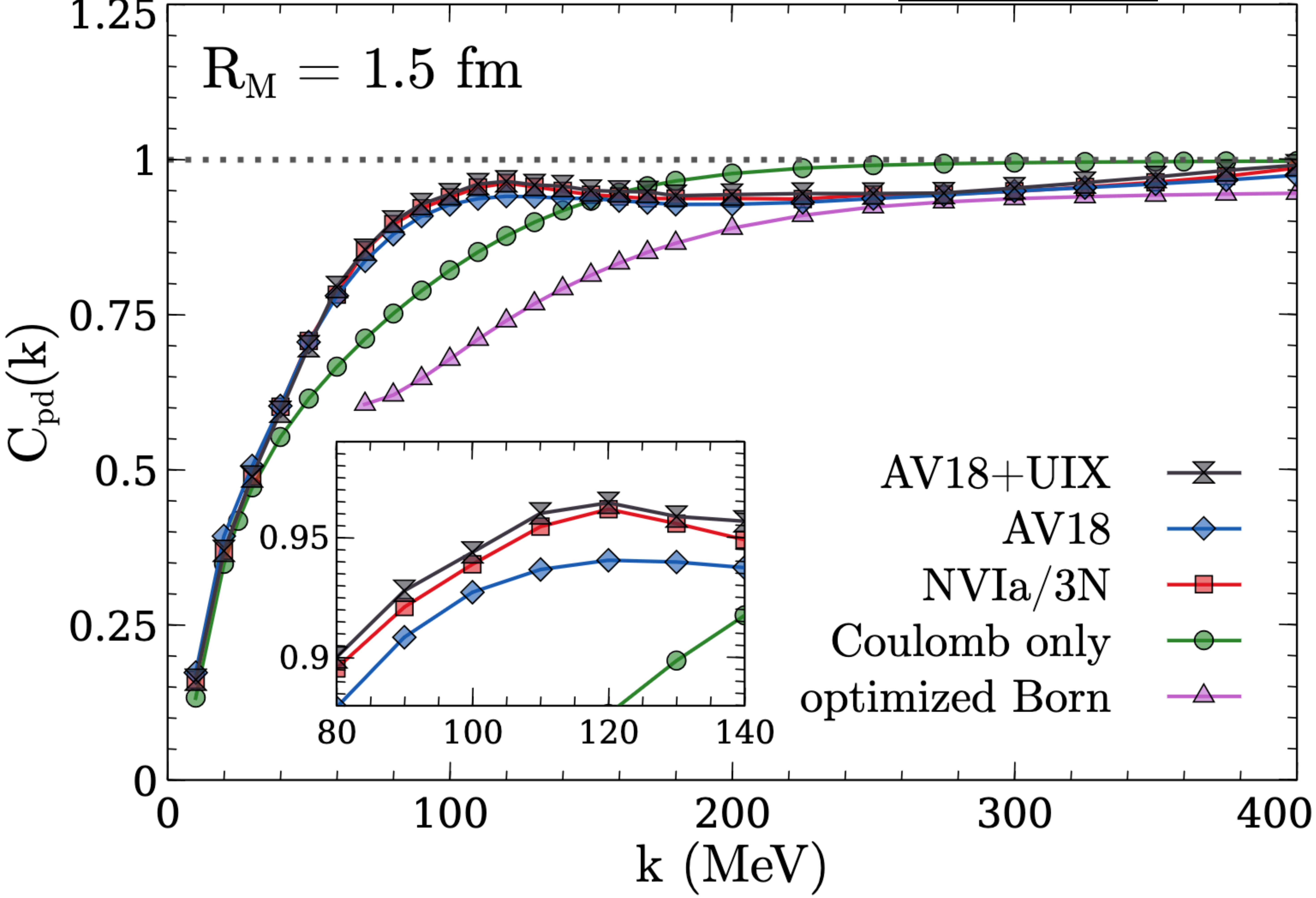
M. Viviani et al arXiv:2306.02478



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



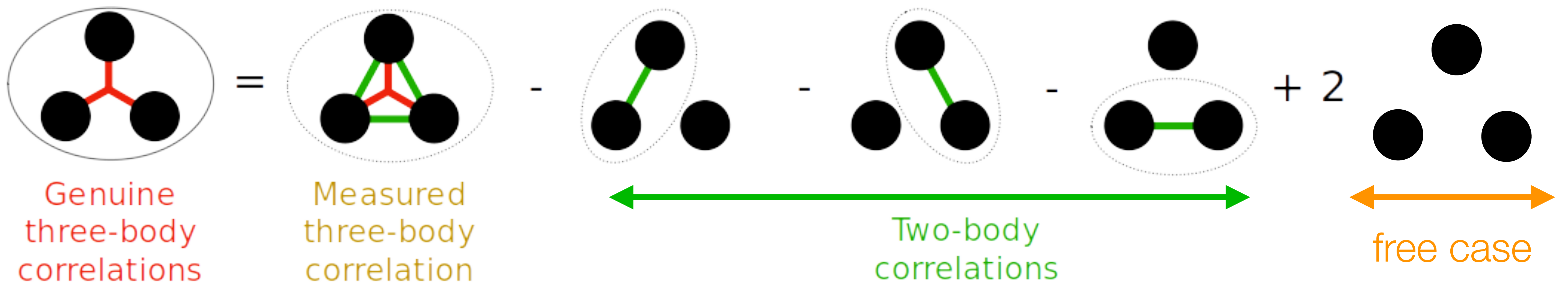
Total wavefunction for p-d system

- Hyperspherical formalism

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

Cumulant: measure for three-body effects

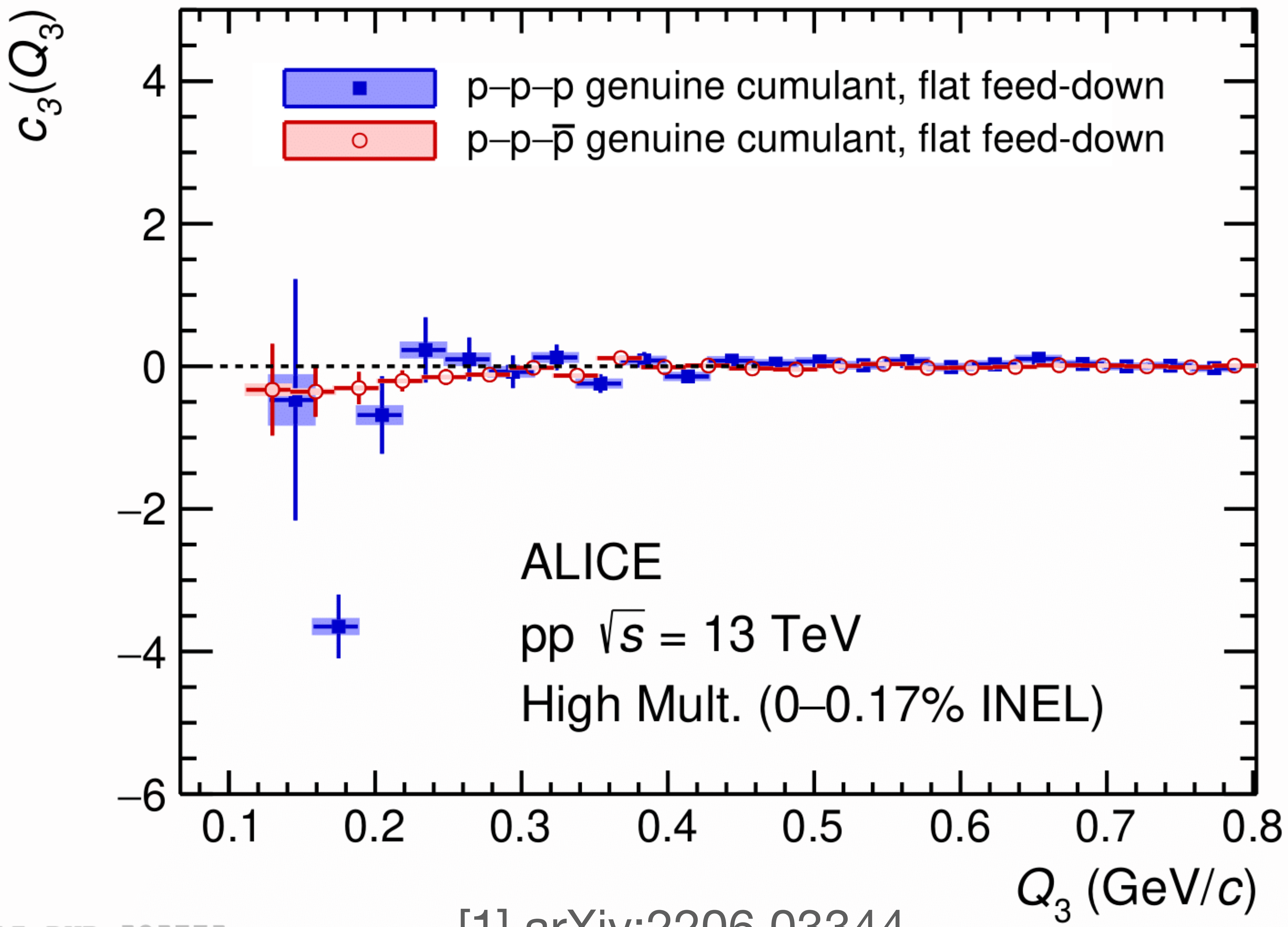
c_3 (Q_3)



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

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

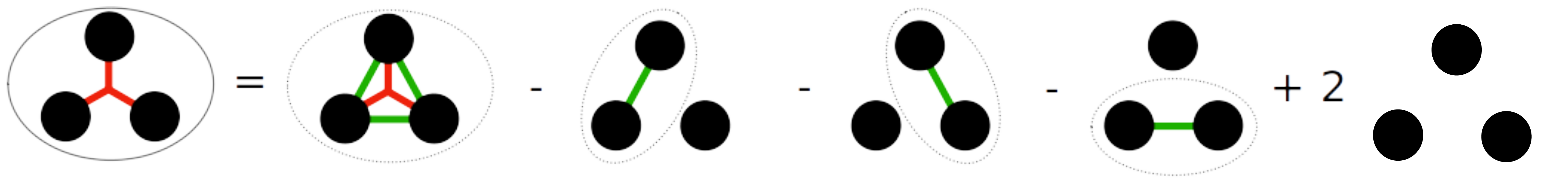
- p-p-p and p-p-p̄ cumulants : nonzero
  - Hint of a genuine three-body effect
- Possible interpretations:
  - Pauli blocking at three-particle level
  - Three-body strong interaction



[1] arXiv:2206.03344

Cumulant: measure for three-body effects

$c_3 (Q_3)$

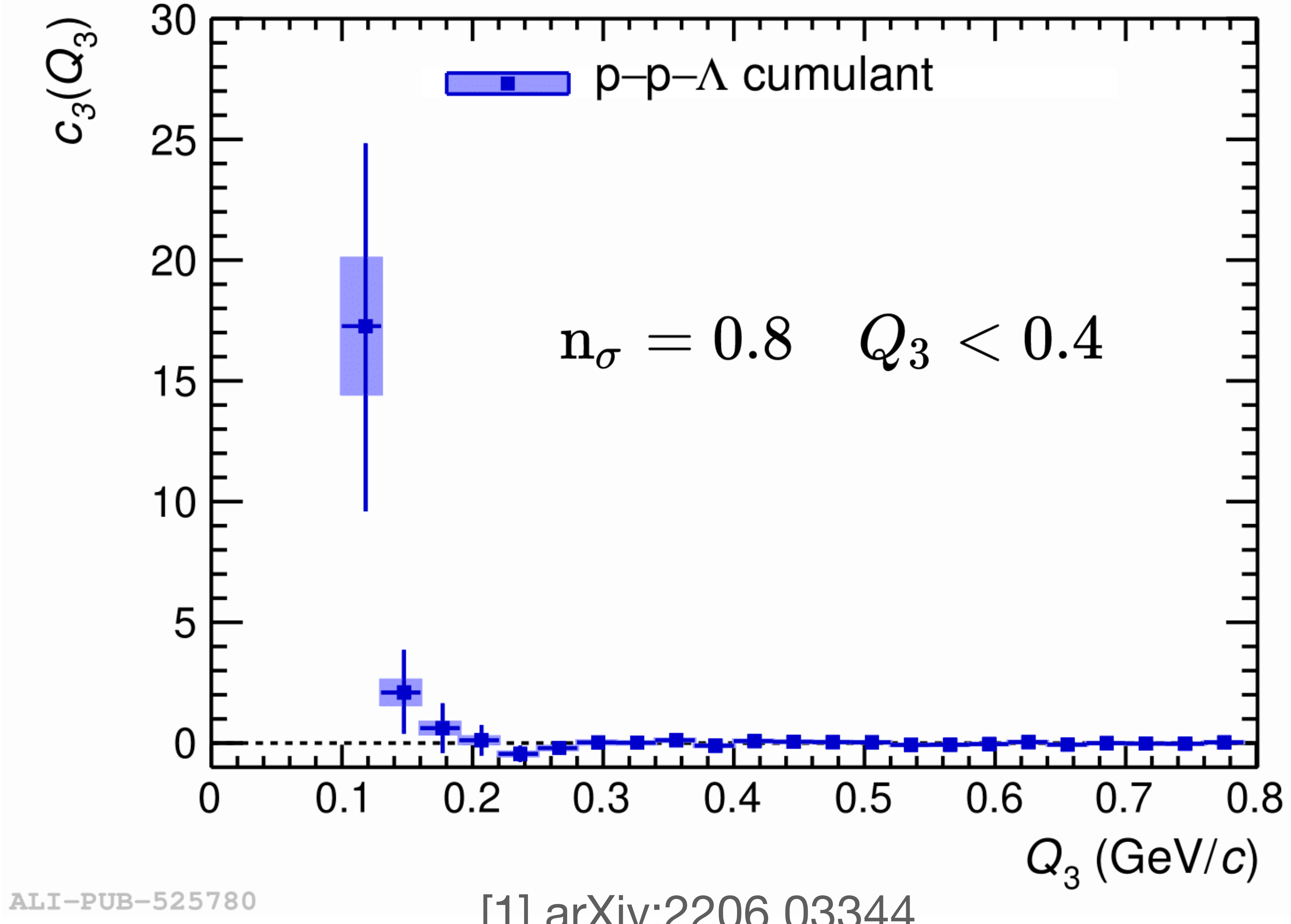


Kubo, J. Phys. Soc. Jpn. 177 (1962)

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

- p-p-Λ cumulants : compatible with zero
  - The ongoing Run 3 and future Run 4 at the LHC with a much larger data sample will allow for precise measurements

➡p-p-Λ interaction plays a crucial role in constrainig the equation of state of the neutron stars[1]

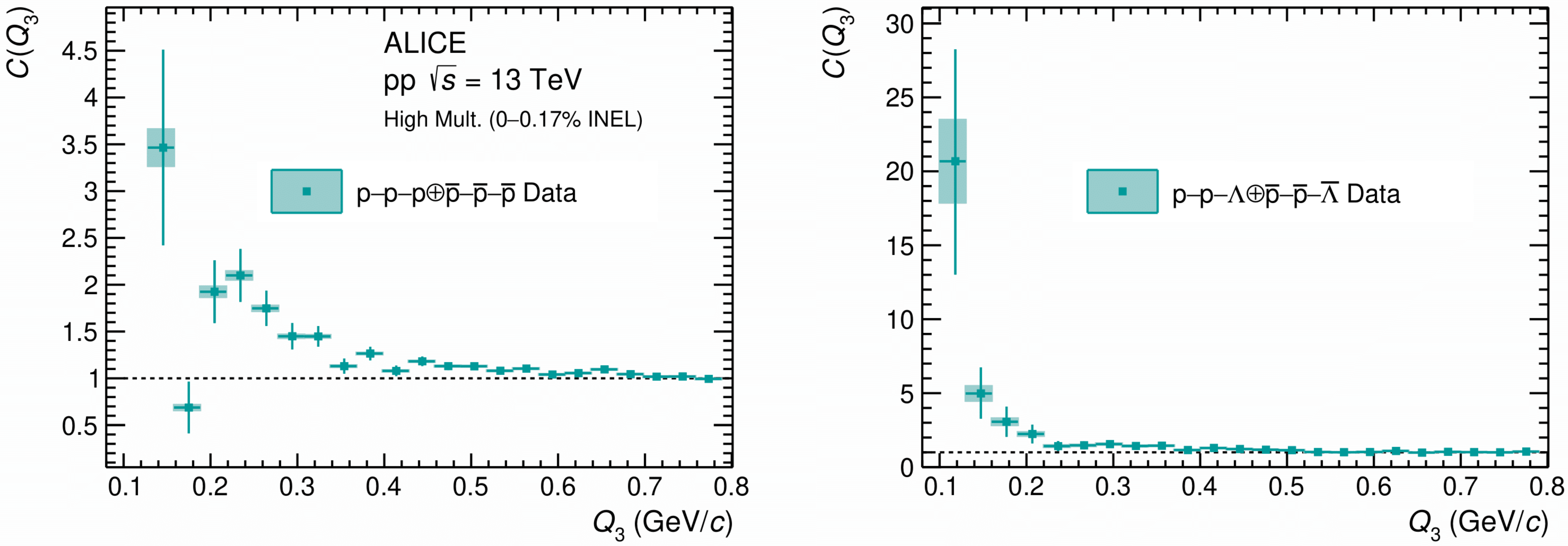


[1] arXiv:2206.03344

Three-body femtoscopy with ALICE

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

$$C(\mathbf{p_1},\mathbf{p_2},\mathbf{p_3}) = \frac{P(\mathbf{p_1},\mathbf{p_2},\mathbf{p_3})}{P(\mathbf{p_1})P(\mathbf{p_2})P(\mathbf{p_3})} = N\frac{N_{same}(Q_3)}{N_{mixed}(Q_3)} \qquad Q_3 = \sqrt{-q_{ij}^2 - q_{jk}^2 - q_{ki}^2}$$



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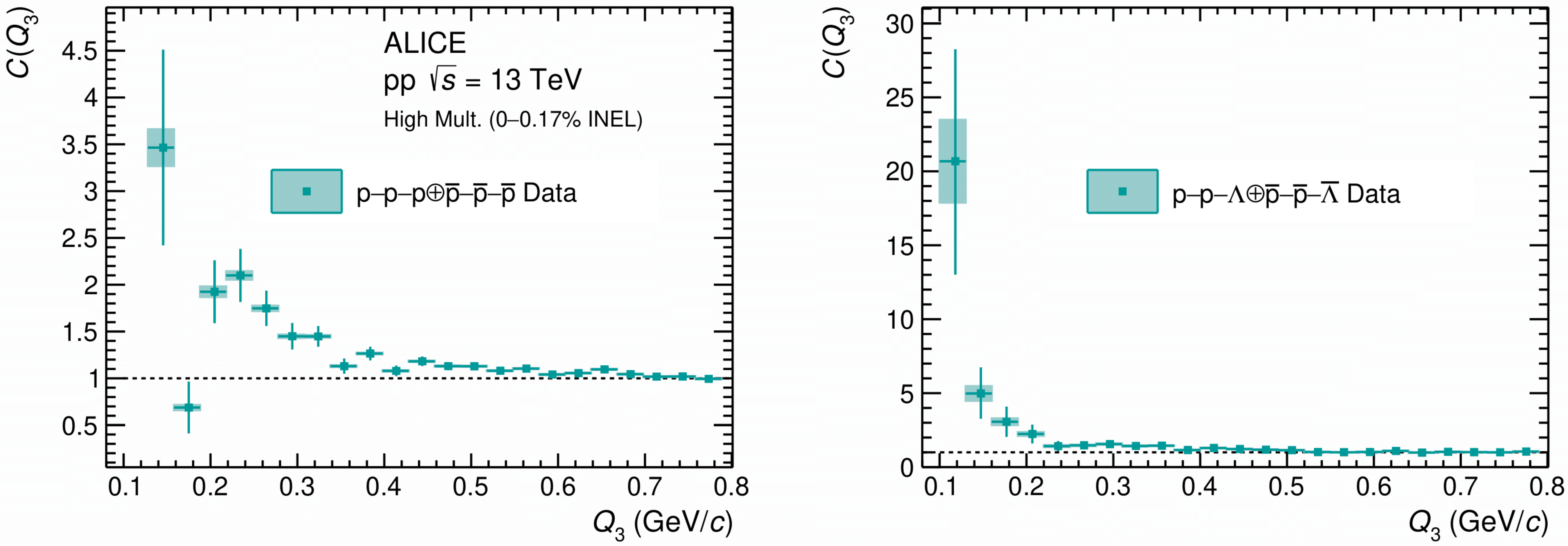
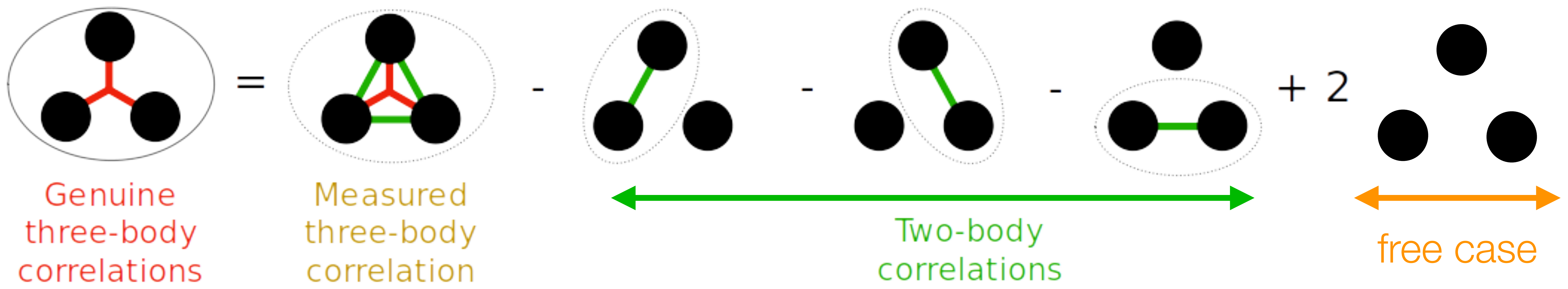


How to interpret the results? Interplay between 2-body and 3-body forces

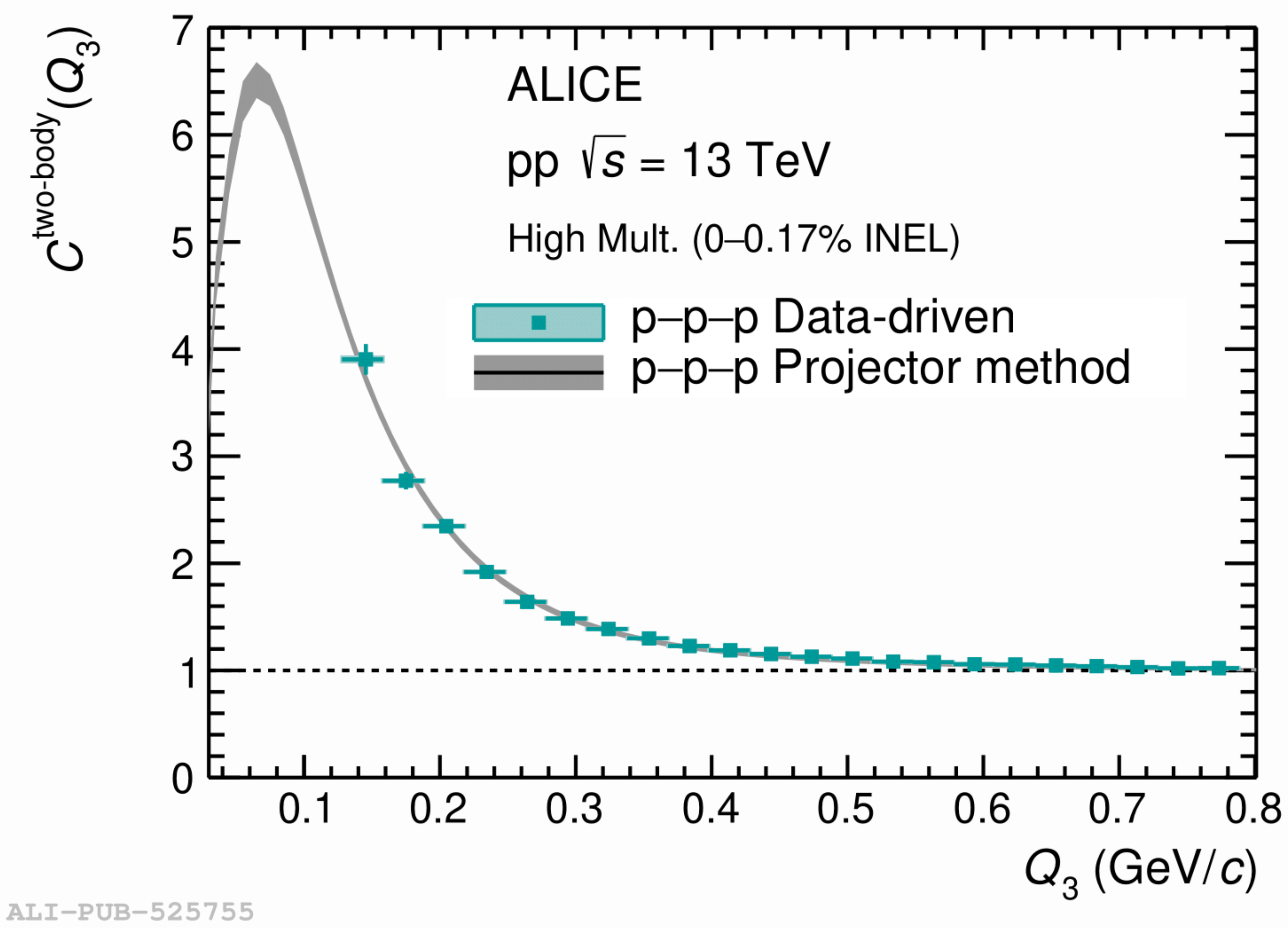
[1] arXiv:2206.03344

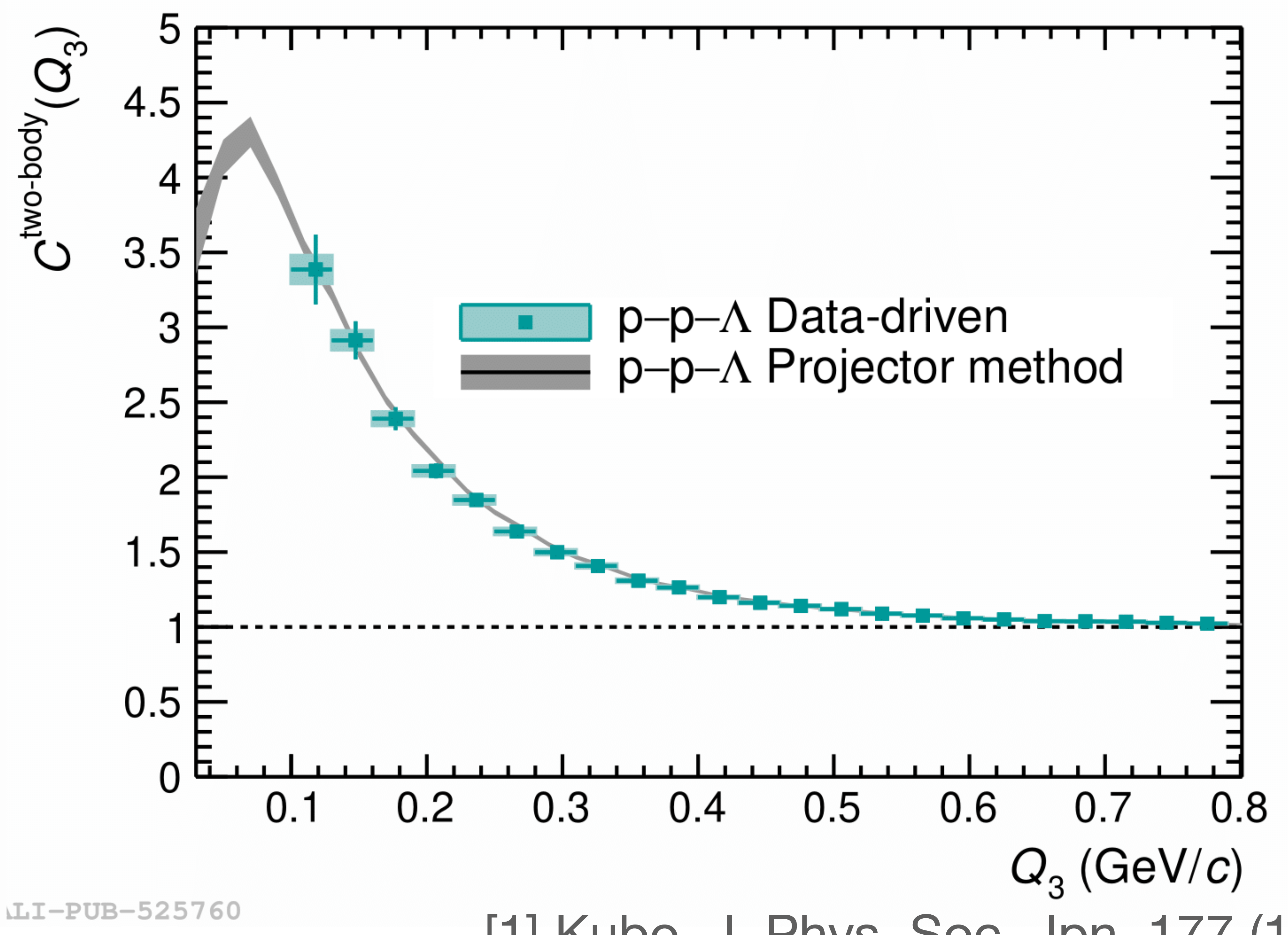
Steps to genuine three-body interaction



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

- First study underlying two body correlations with a data driven and a phase-space projector methods





[1] Kubo, J. Phys. Soc. Jpn. 177 (1962)
[2] arXiv:2206.03344
[3] R. Del Grande et al. EPJC 82 (2022)

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

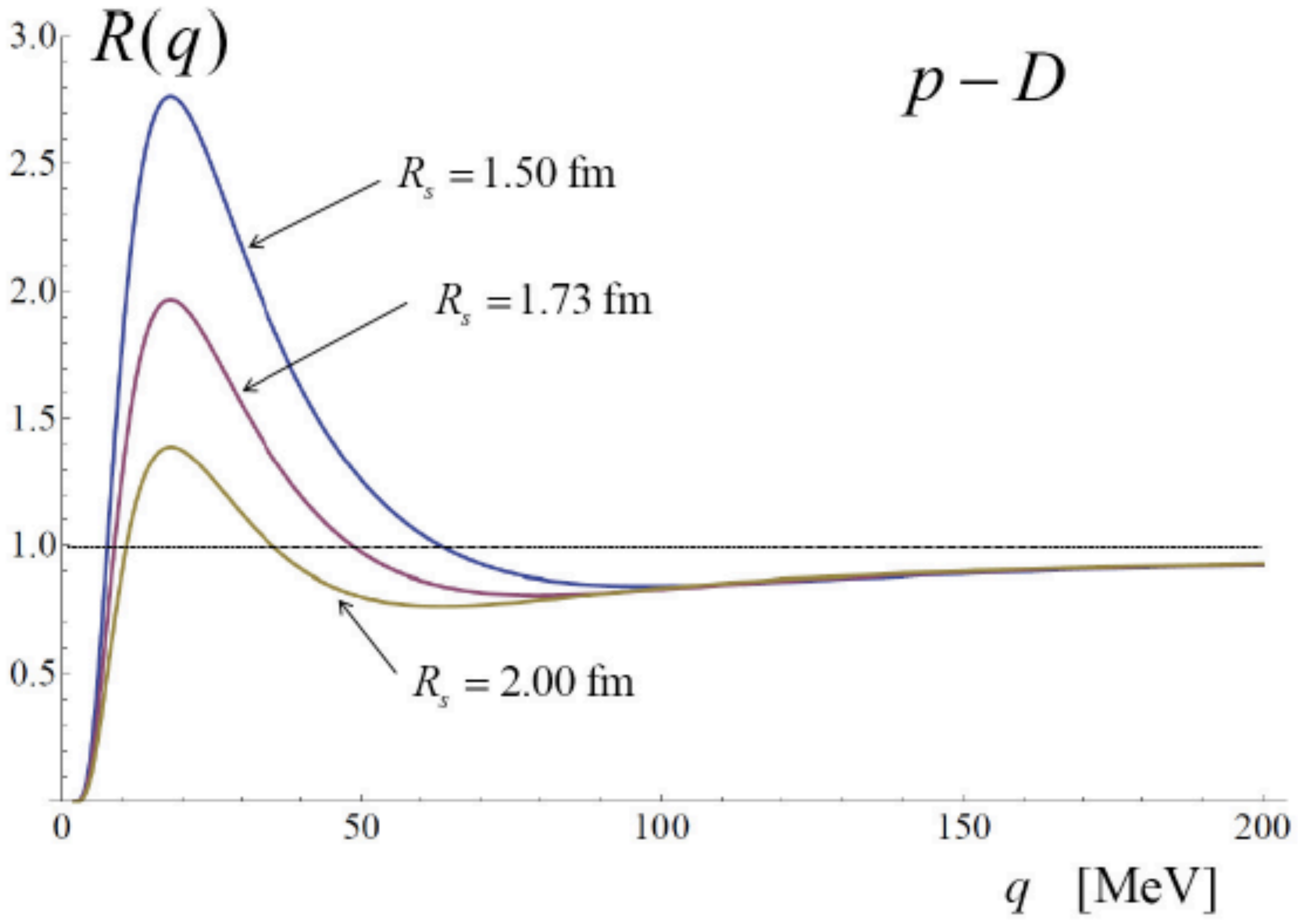


Fig. 2. $p-D$ correlation function