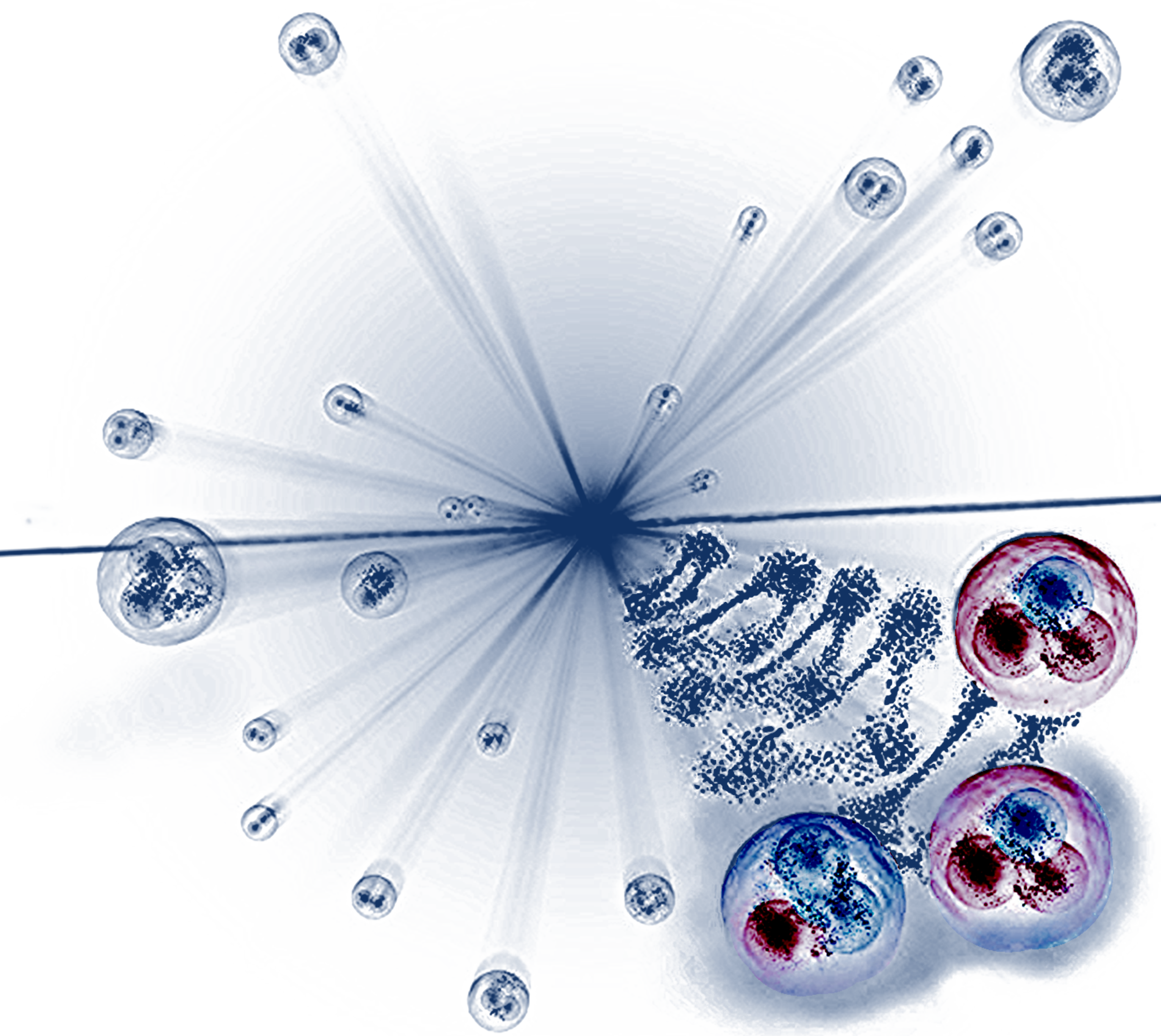


Accessing the strong interaction in three-hadron systems with ALICE

Bhawani Singh
Technical University of Munich (TUM), Germany
On behalf of the ALICE Collaboration (based on Phys. Rev. X 14, 031051 (2024))

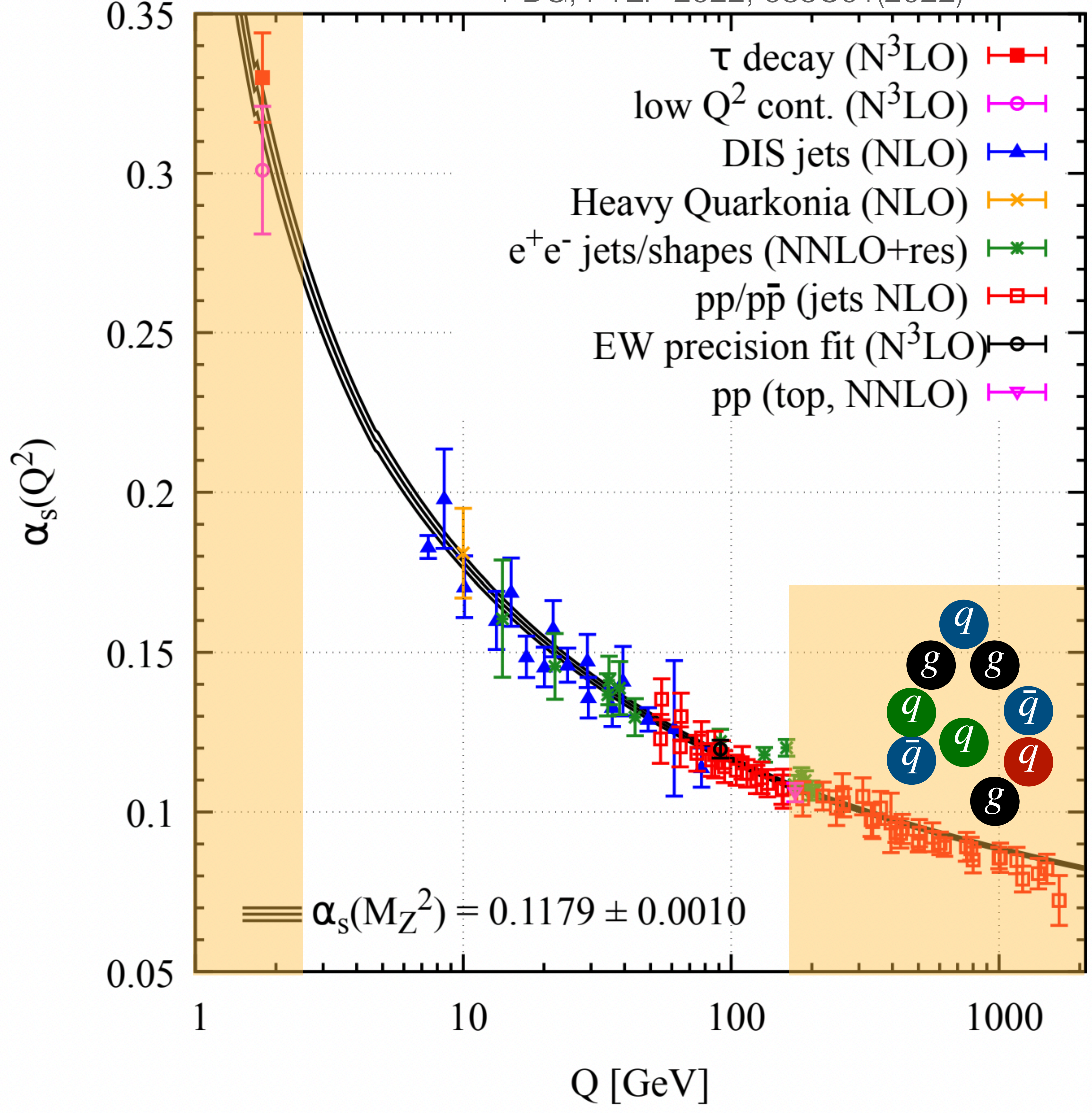
LHC Seminar, 26.11.2024

bhawani.singh@cern.ch

Hadronic interactions and QCD

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

PDG, PTEP 2022, 083C01(2022)



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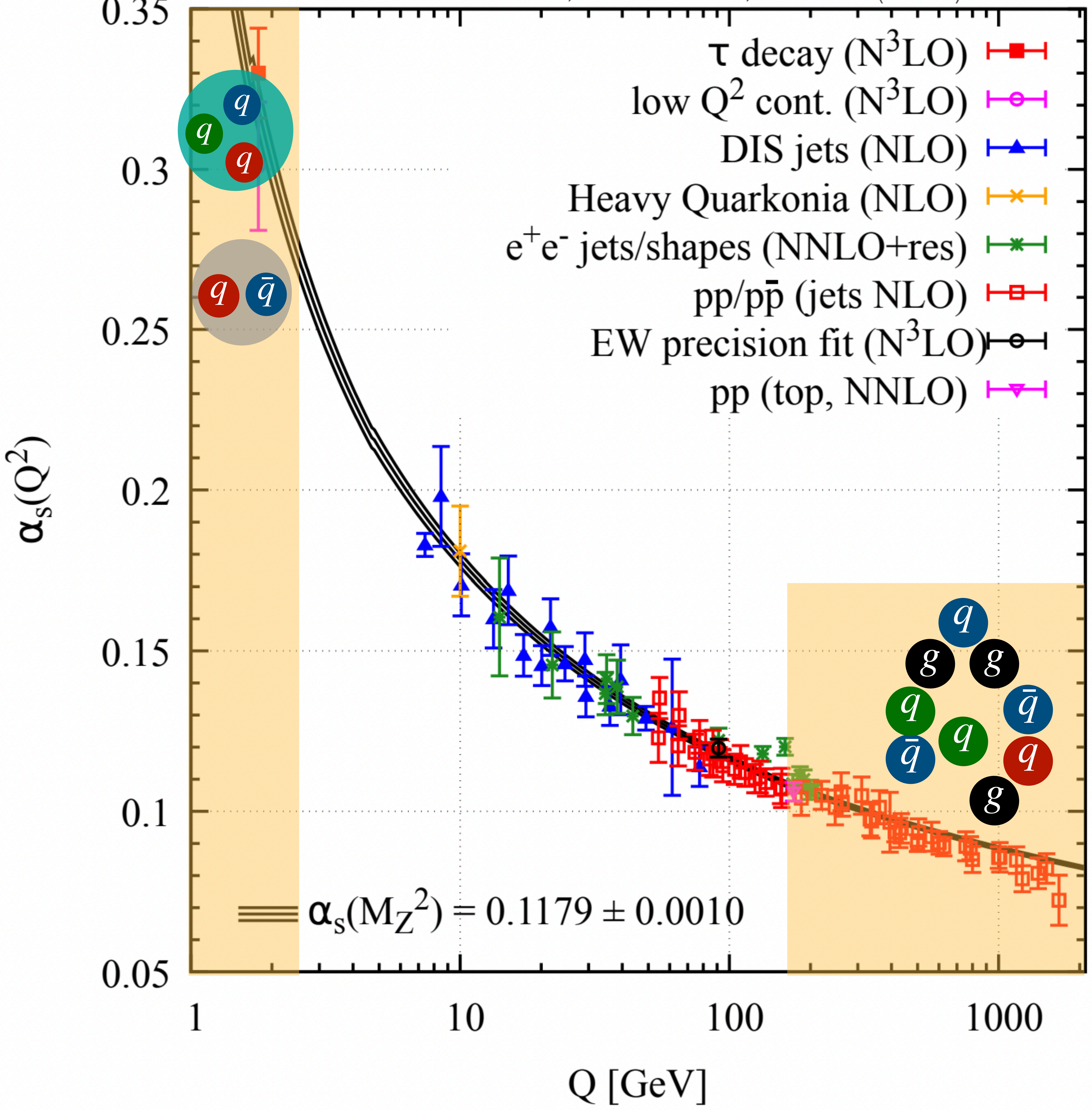
- Use effective field theories (residual strong interaction)
  - Hadrons as degrees of freedom (baryons, mesons)

PDG, PTEP 2022, 083C01(2022)



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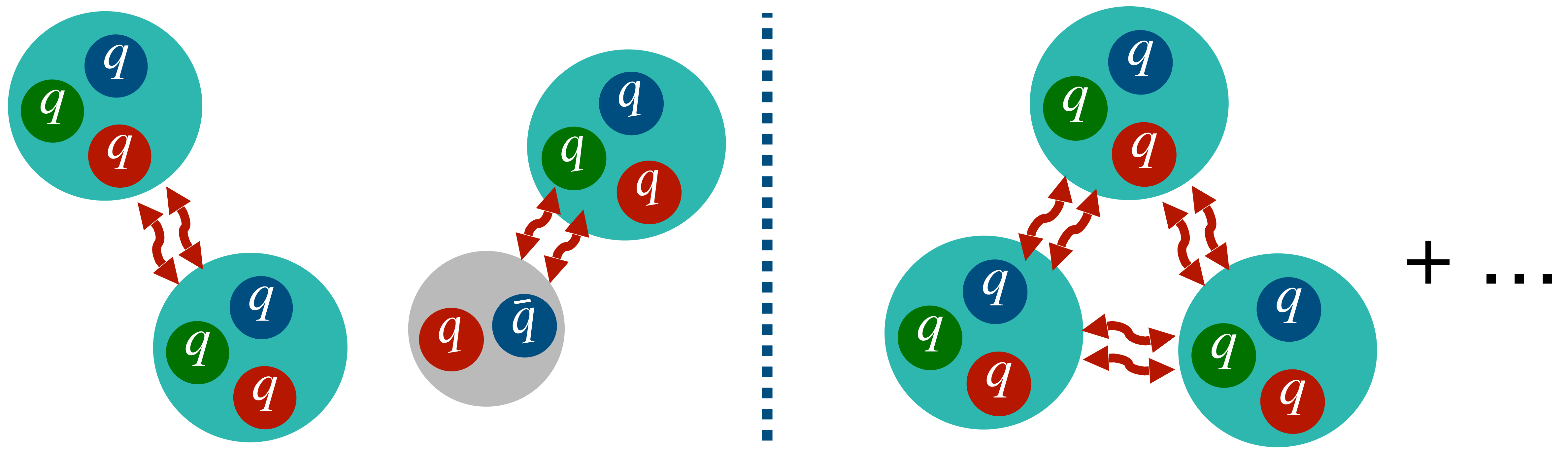
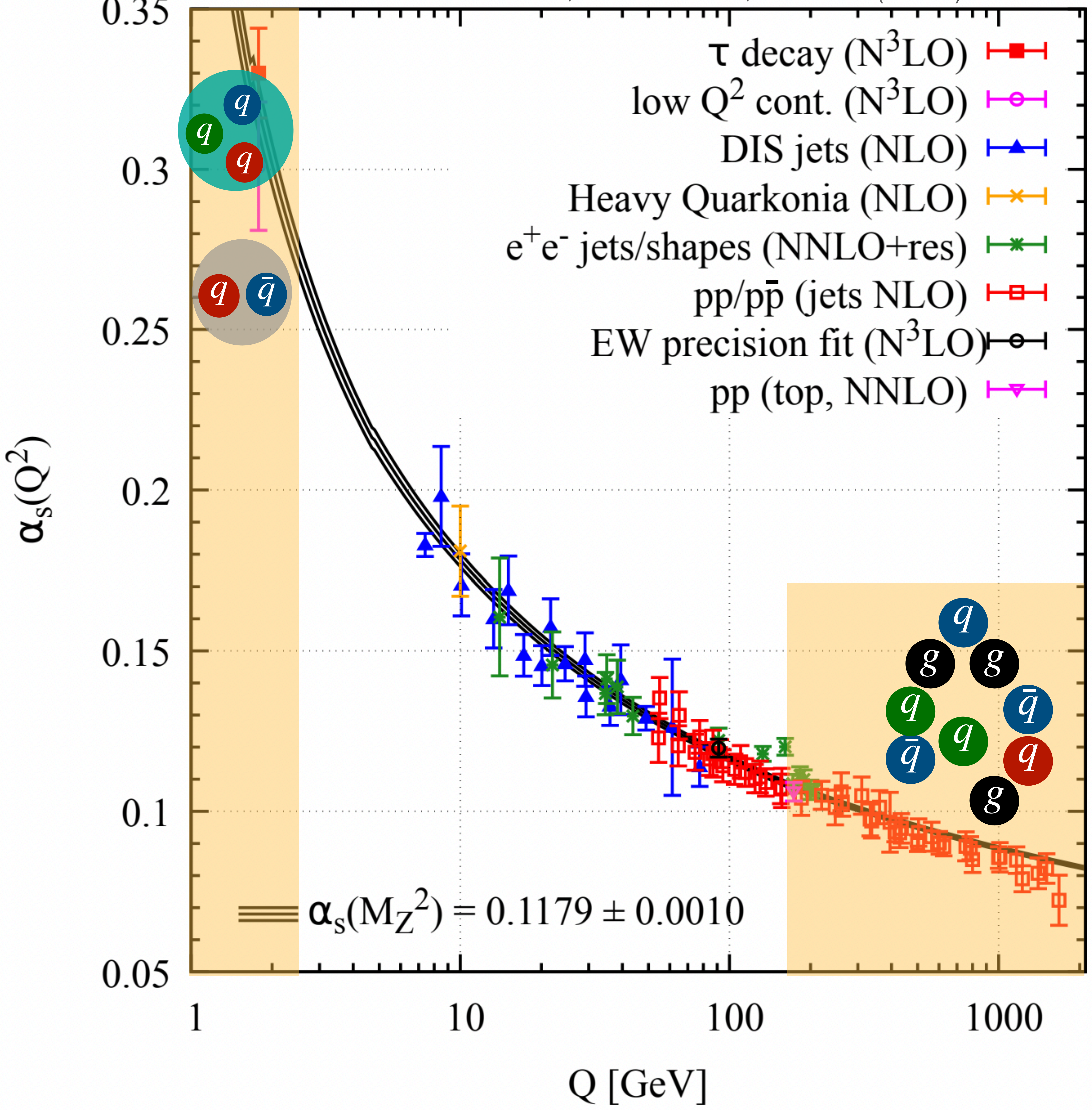
Two-body interaction | Many-body interaction



PDG, PTEP 2022, 083C01(2022)



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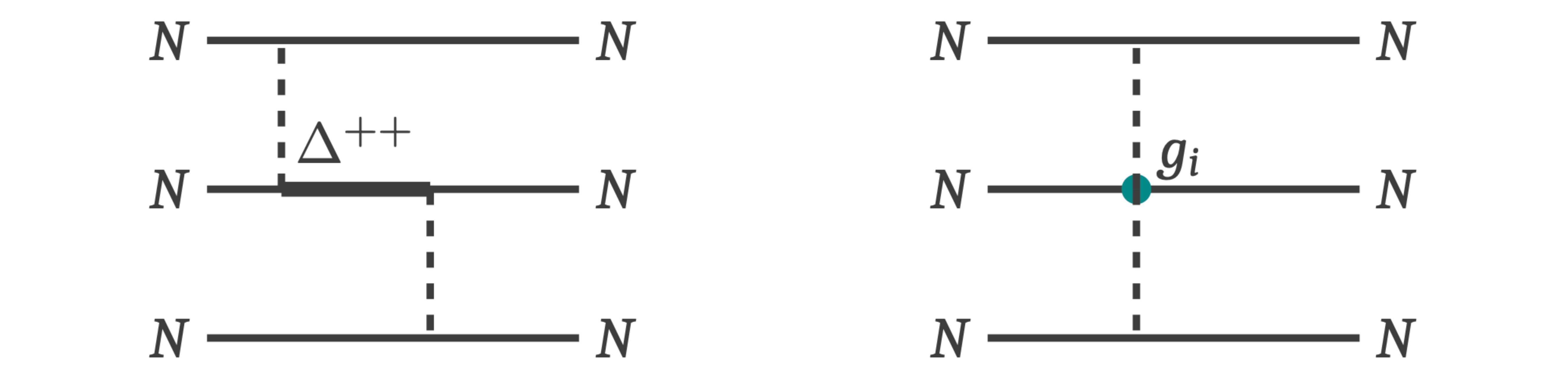

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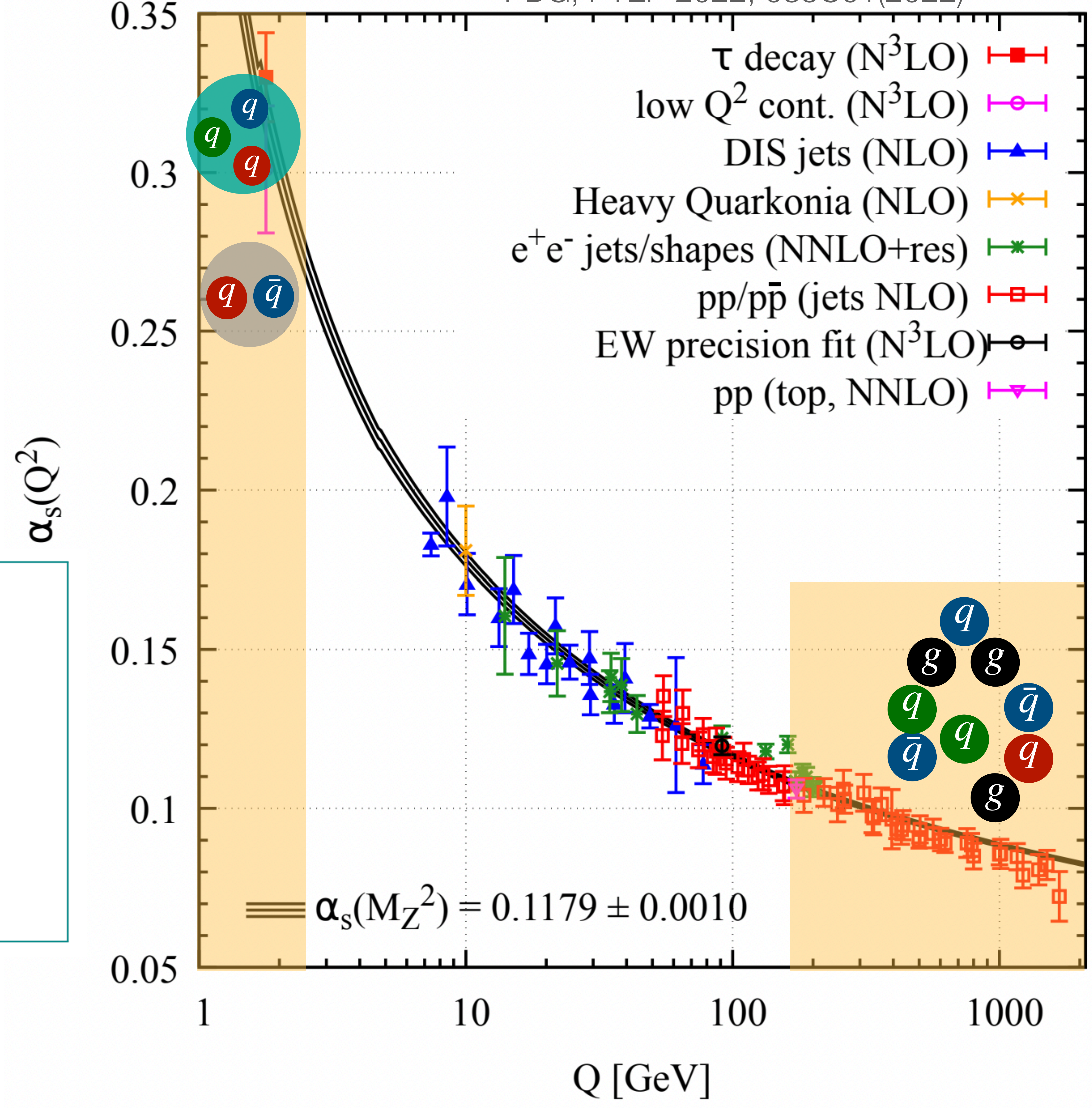

Need for many-body hadronic interaction

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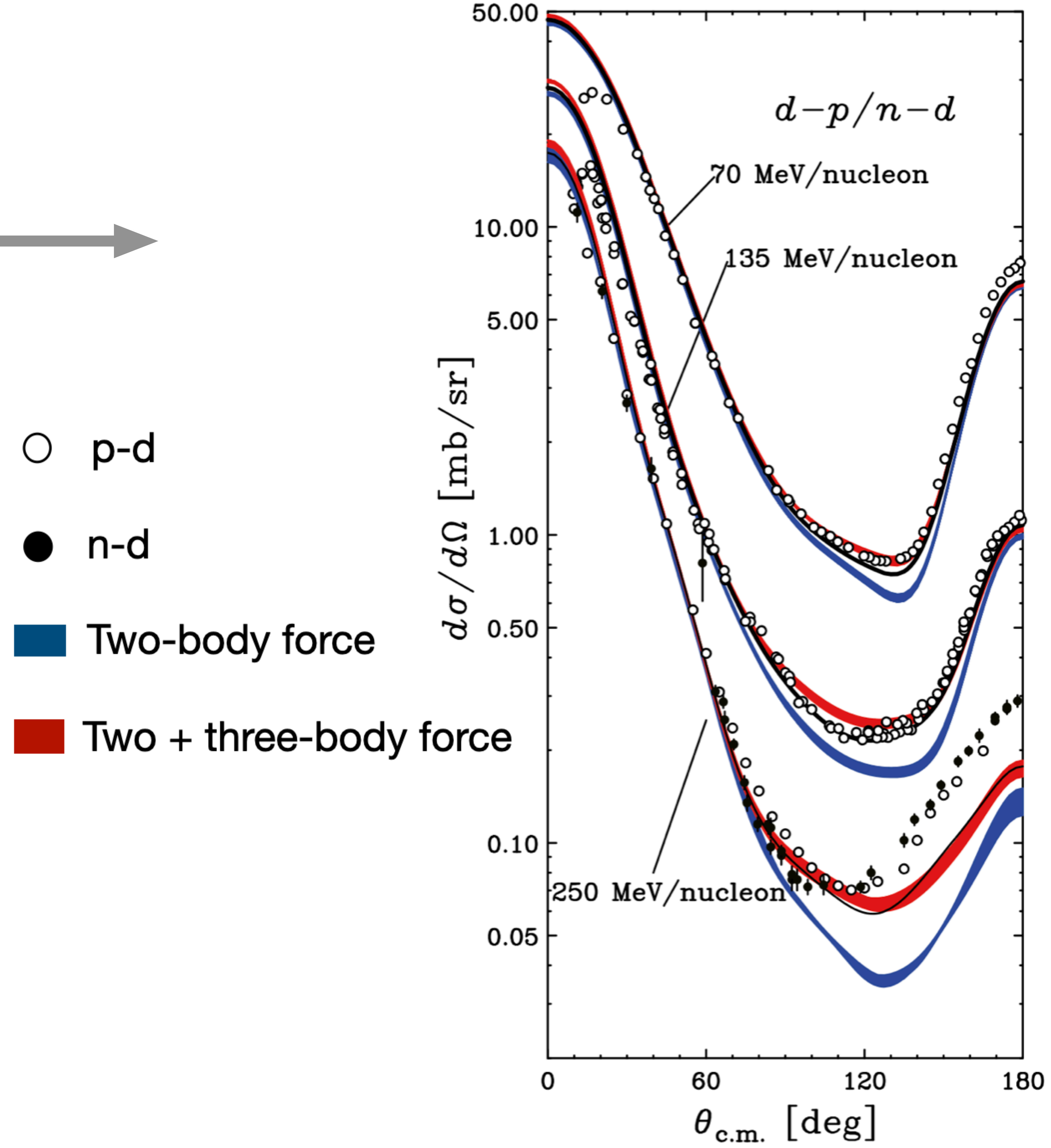

[1] K. Sekiguchi, Few-Body Syst 60, 56 (2019)

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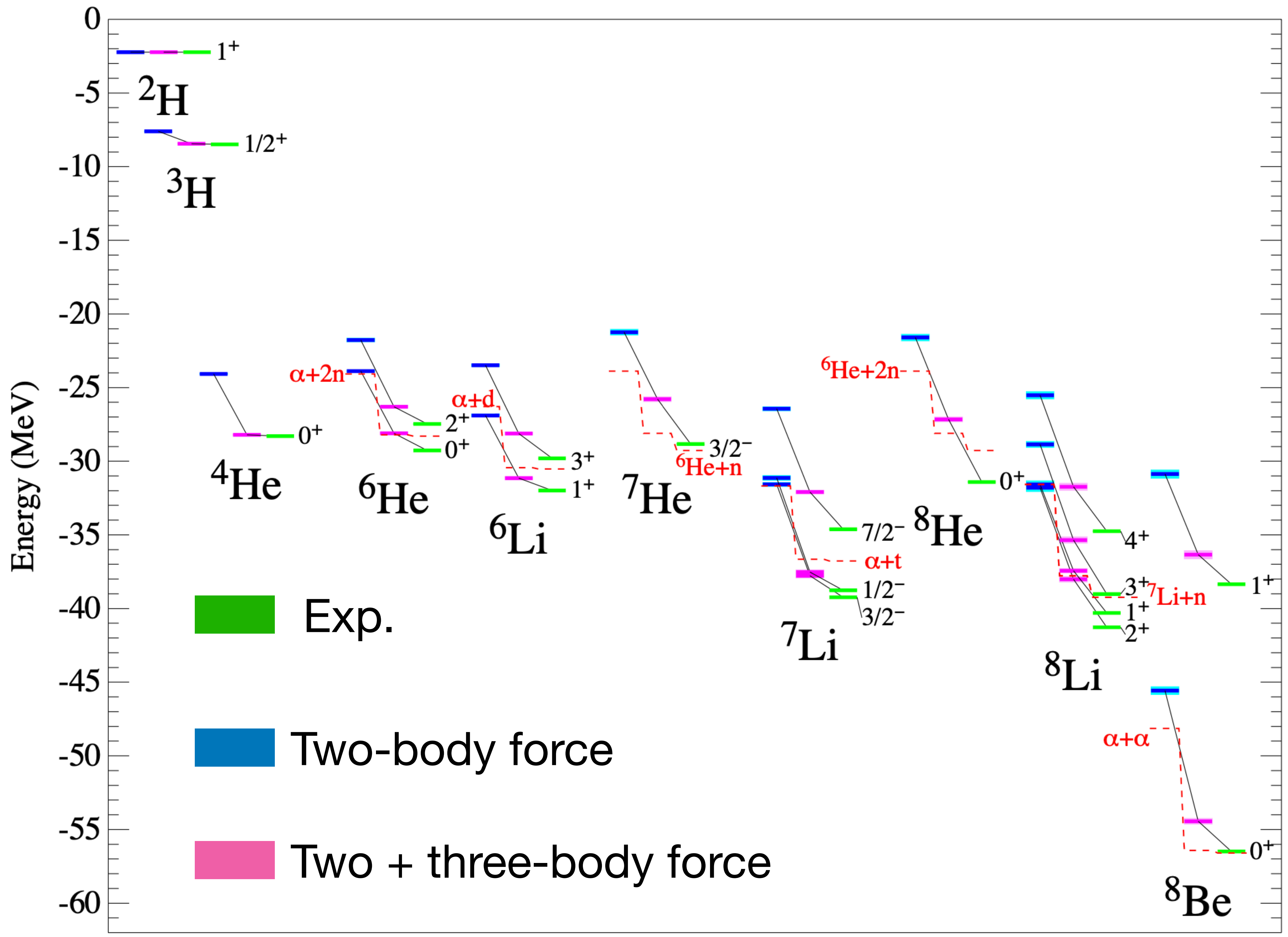

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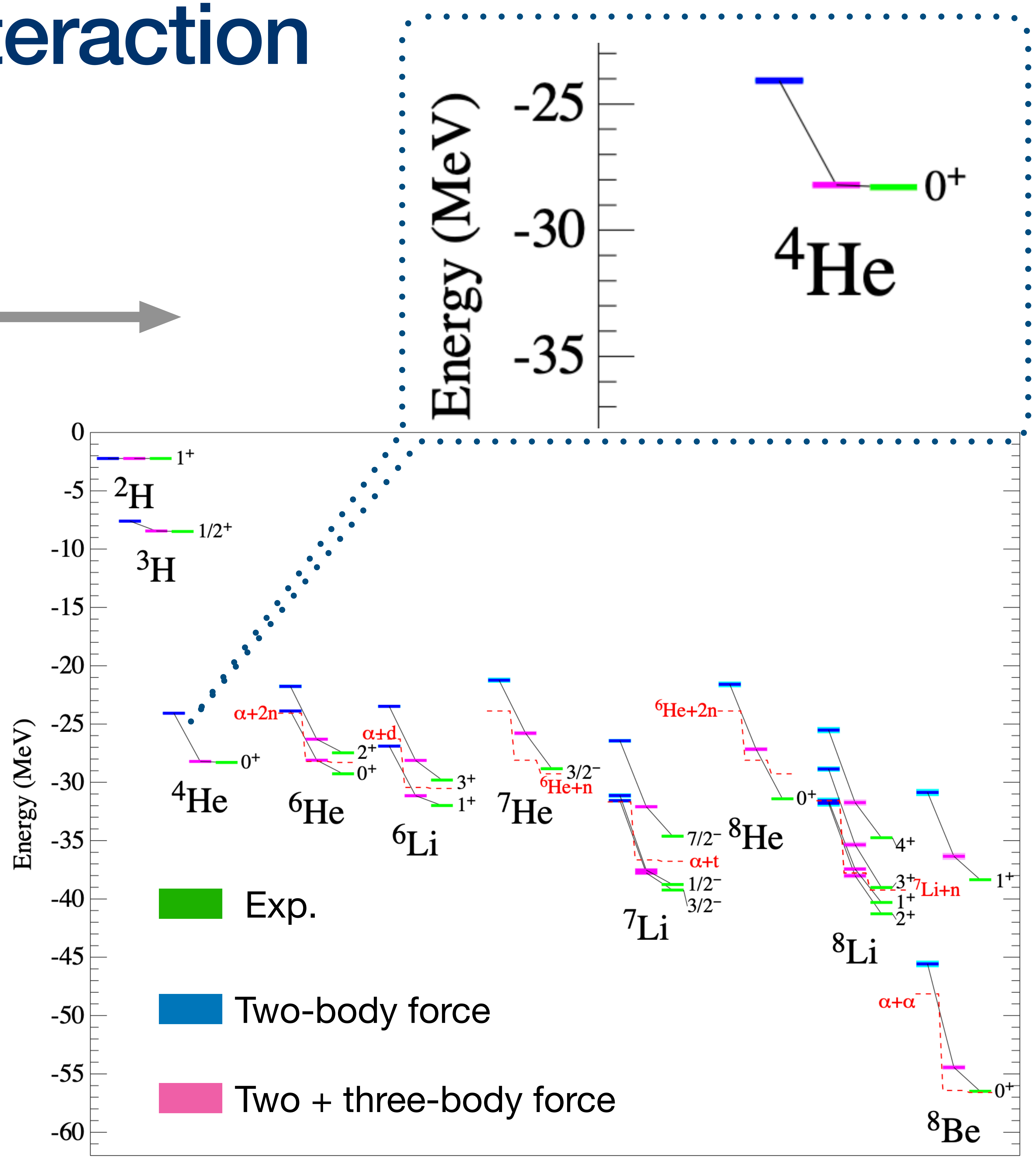

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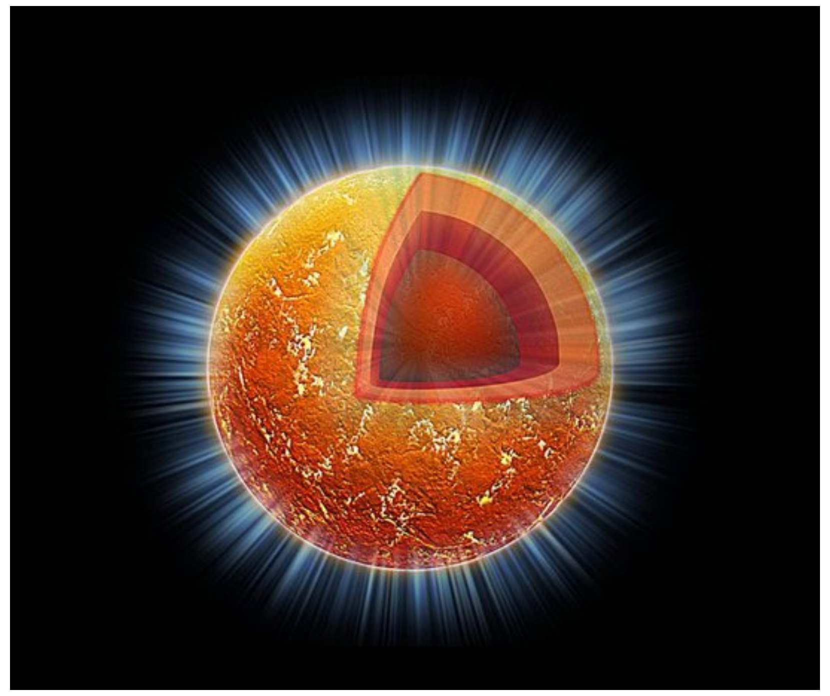

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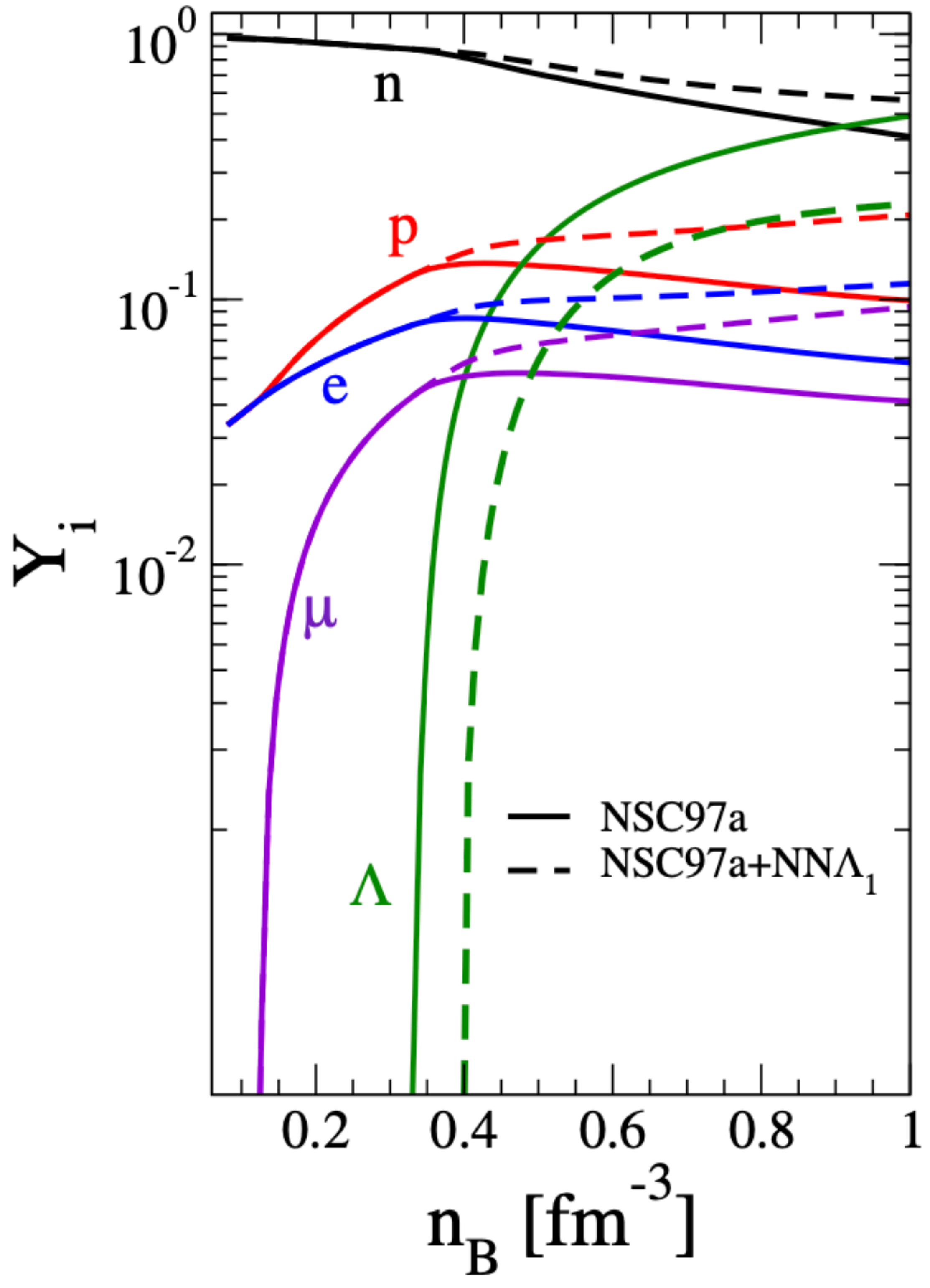

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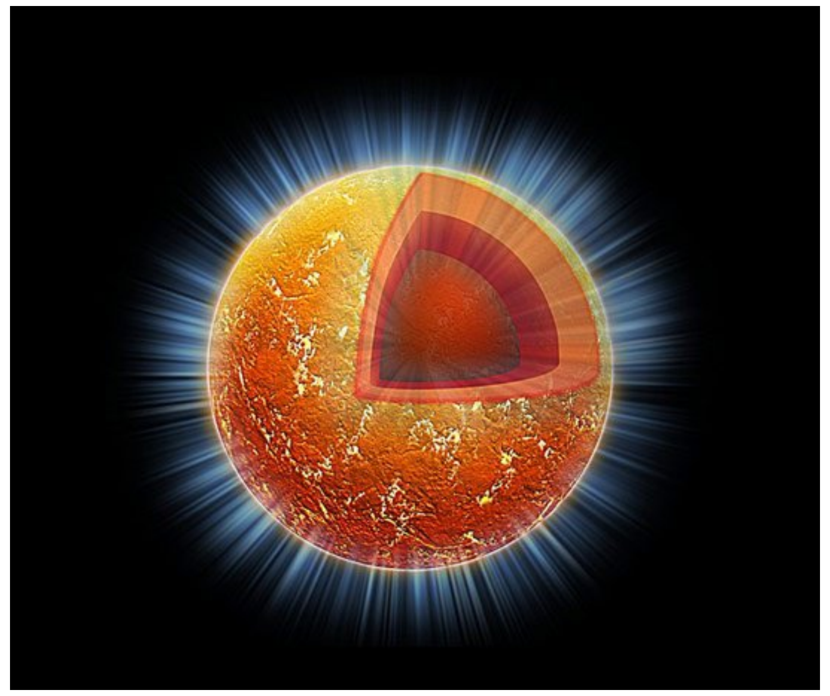

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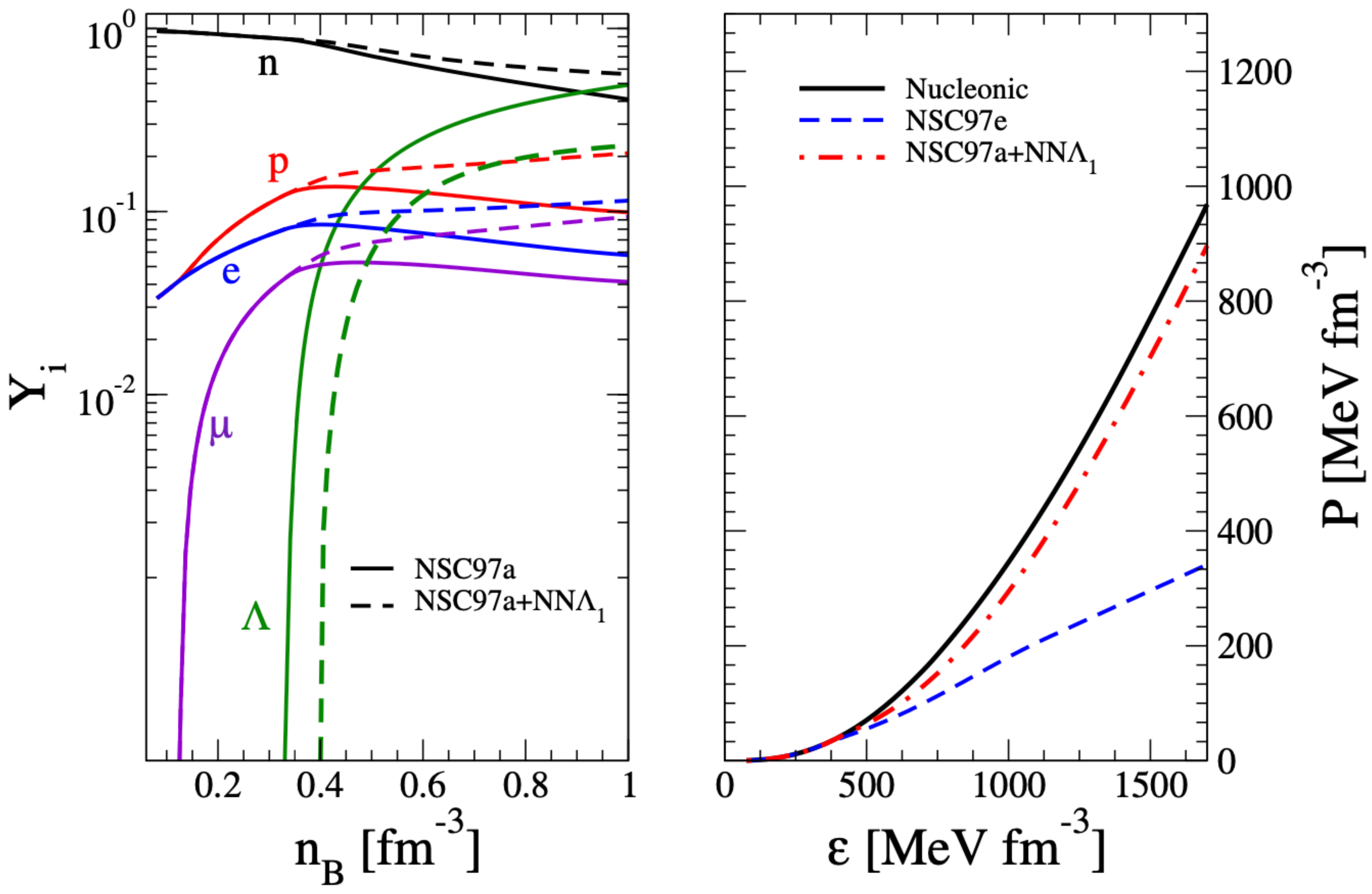

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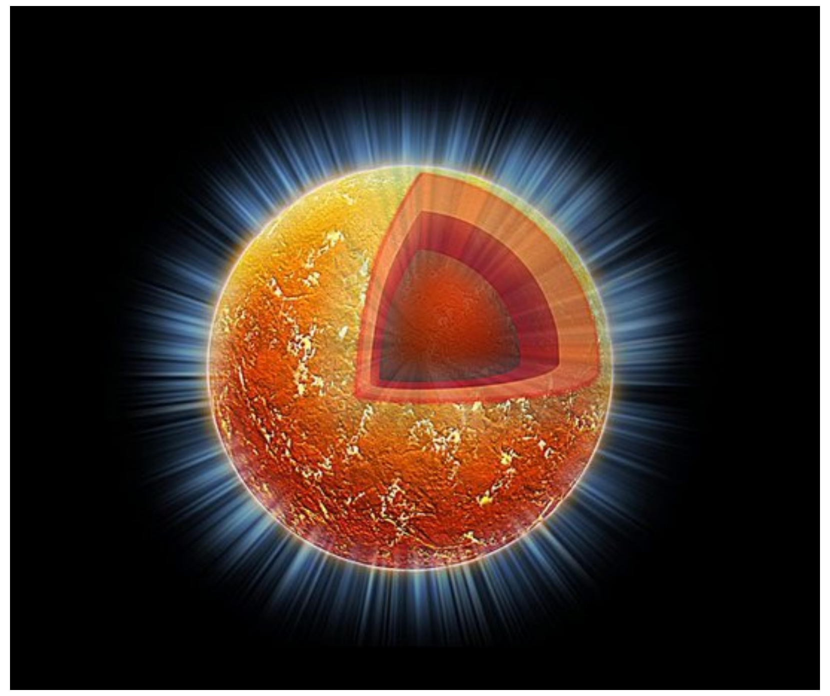

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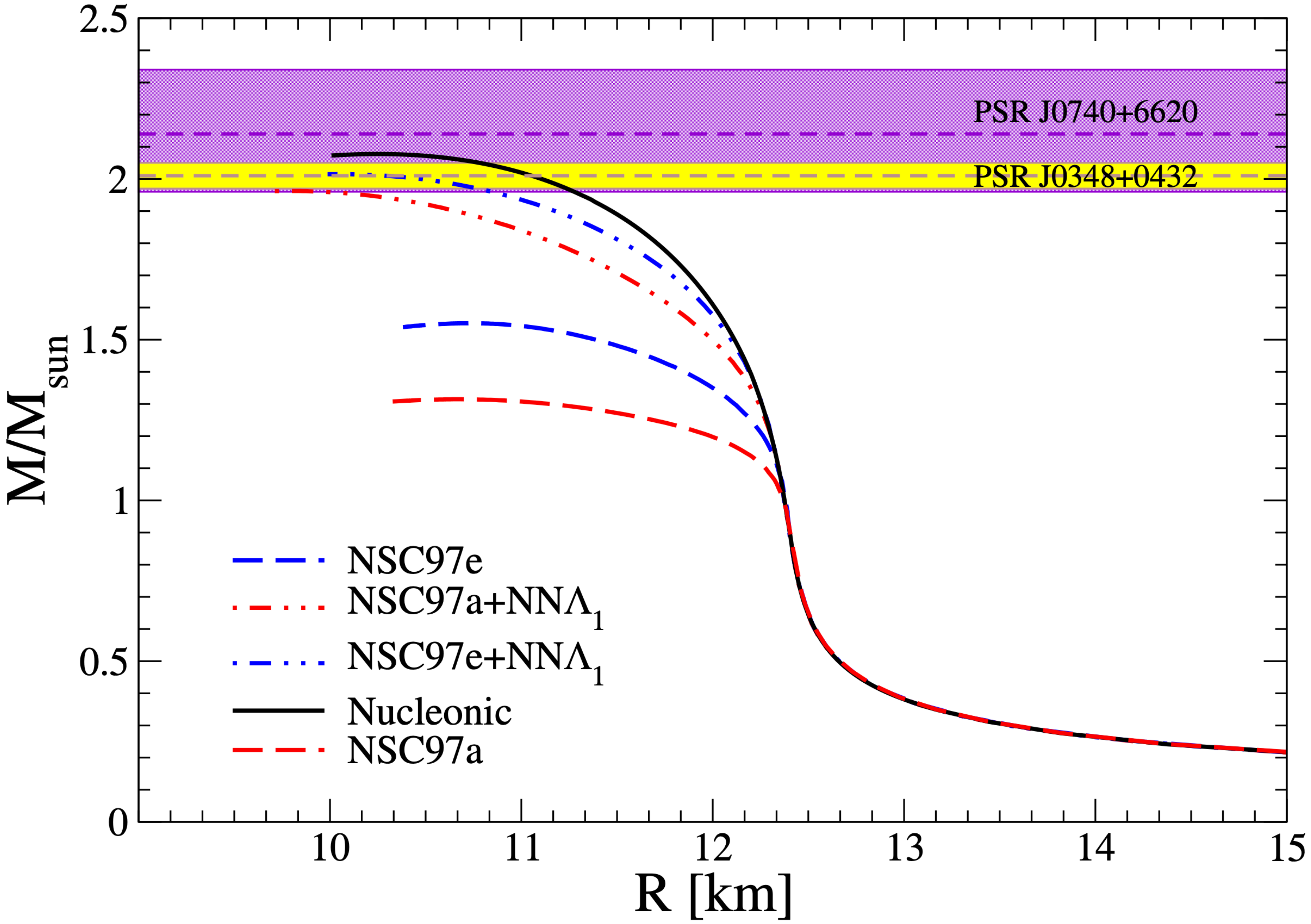
- We need new tools to study three-body hadronic interaction



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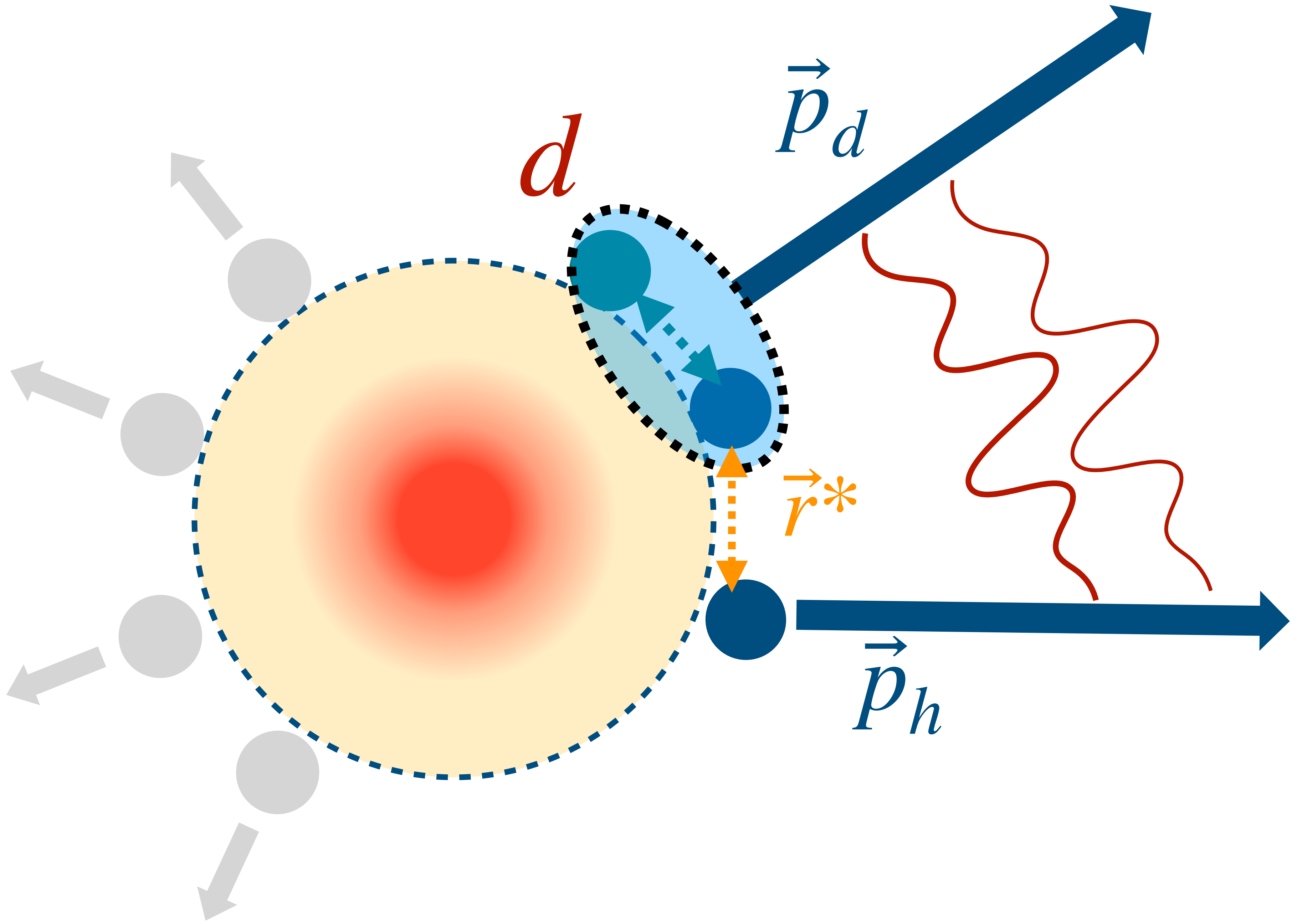
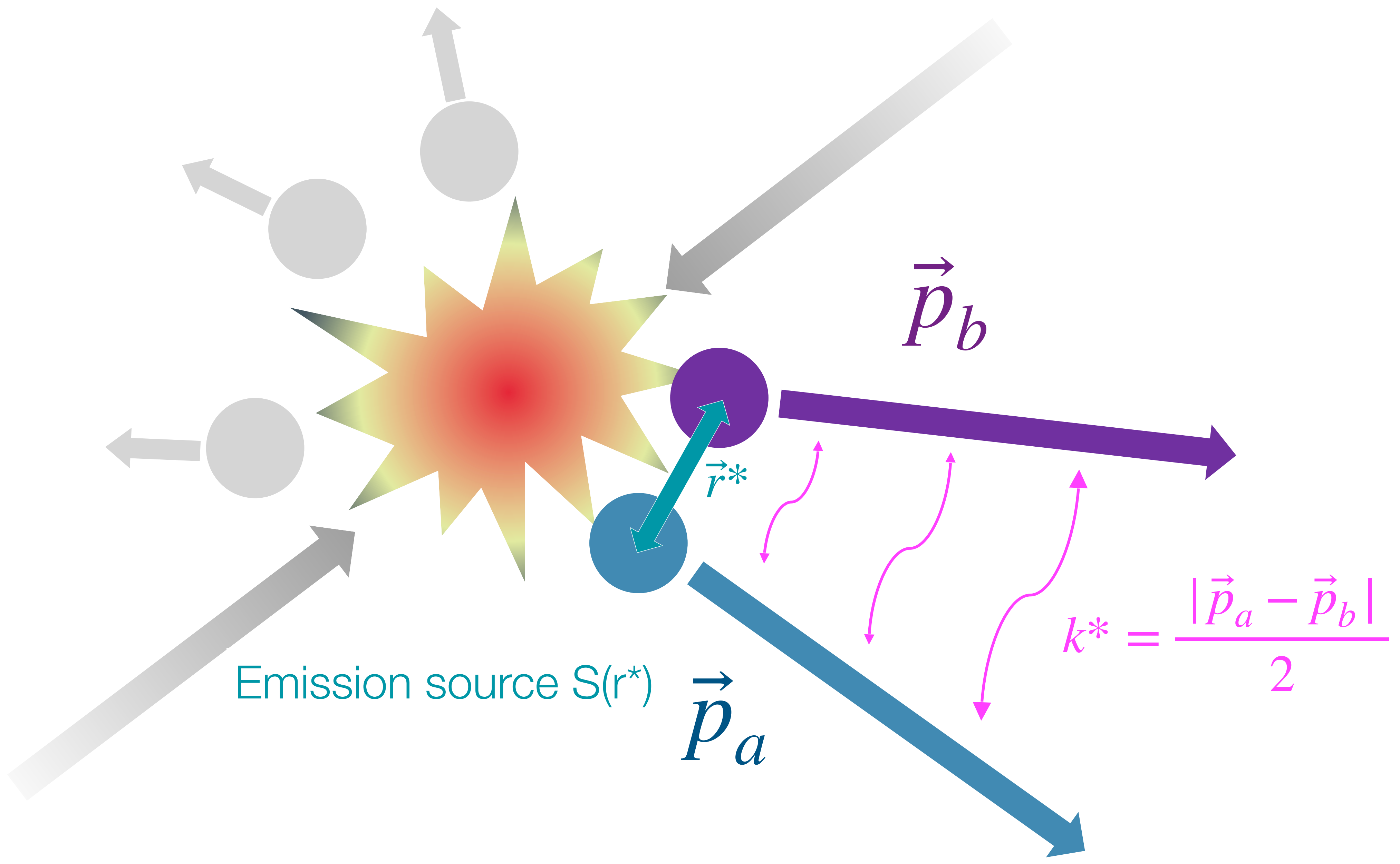


Access interaction three-hadron system with hadron-deuteron correlation

Femtoscopy: momentum space correlations



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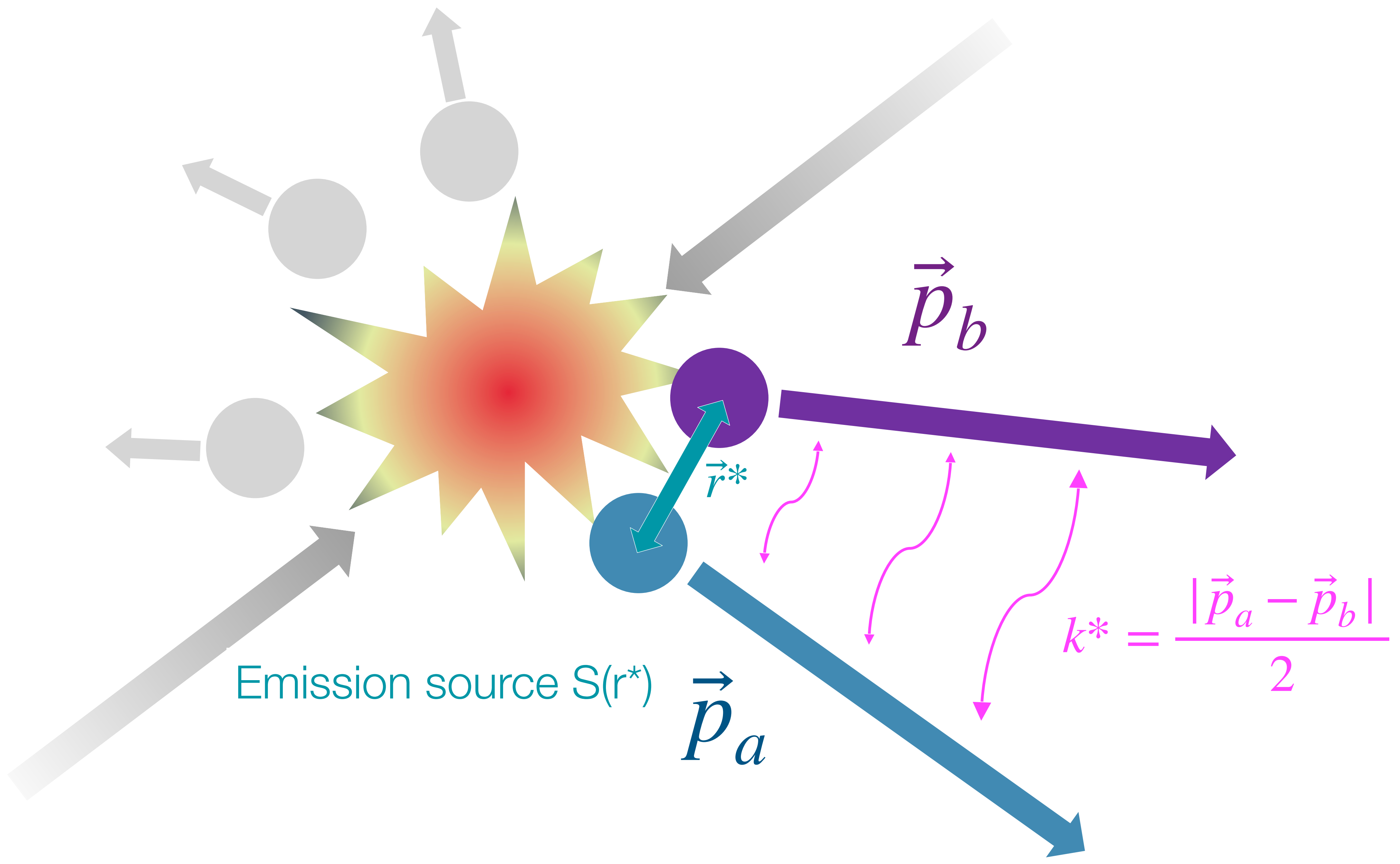

$$C(k^*) = \mathcal{N} \frac{N_{\text{same}}(k^*)}{N_{\text{mixed}}(k^*)} = \int S(\vec{r}^*) \left| \psi(\vec{k}^*, \vec{r}^*) \right|^2 d^3 r^* \xrightarrow{k^* \to \infty} 1$$

experimental definition — theoretical definition

S.E. Koonin et al, Phys. Lett. B 70 43 (1977)
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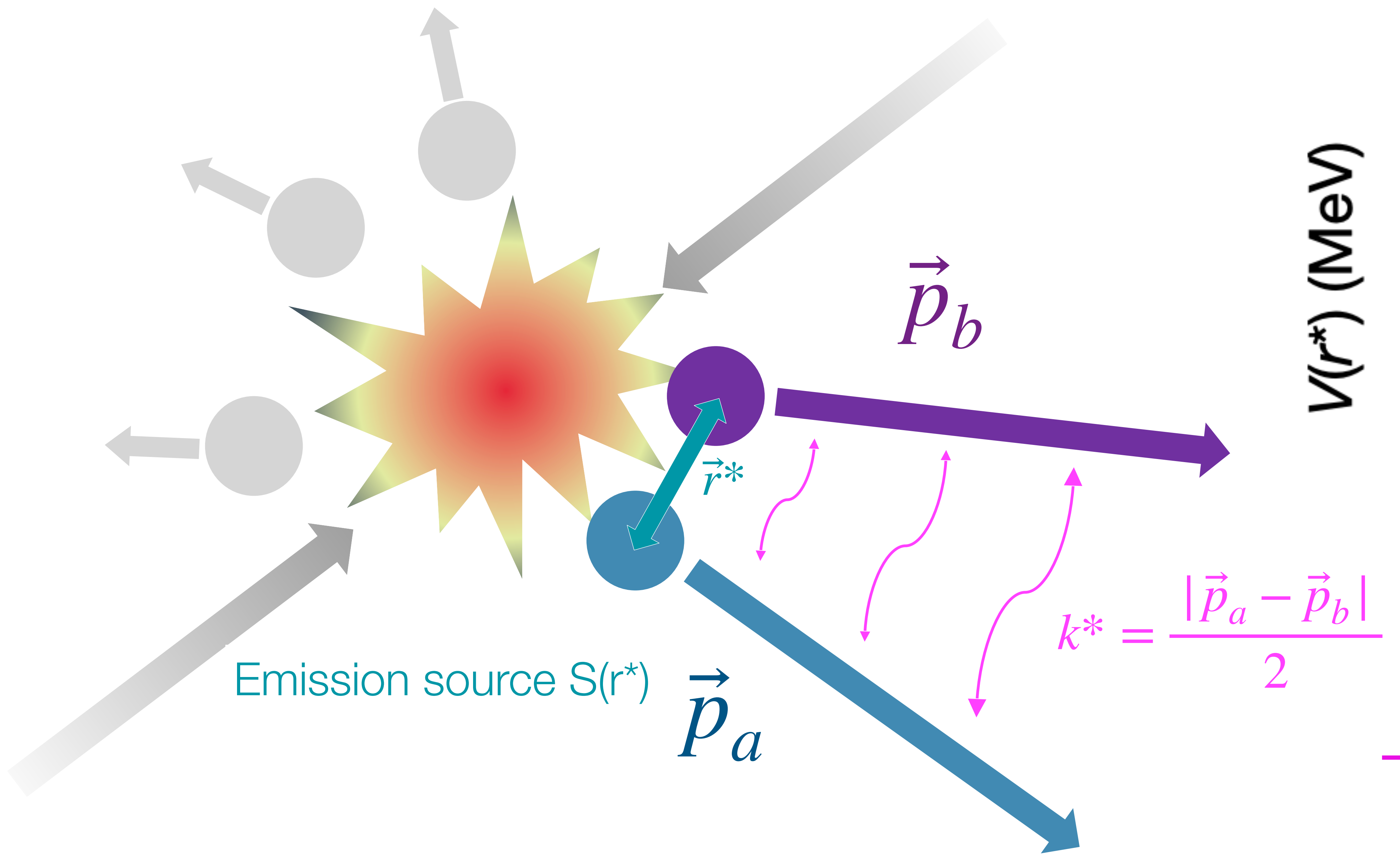
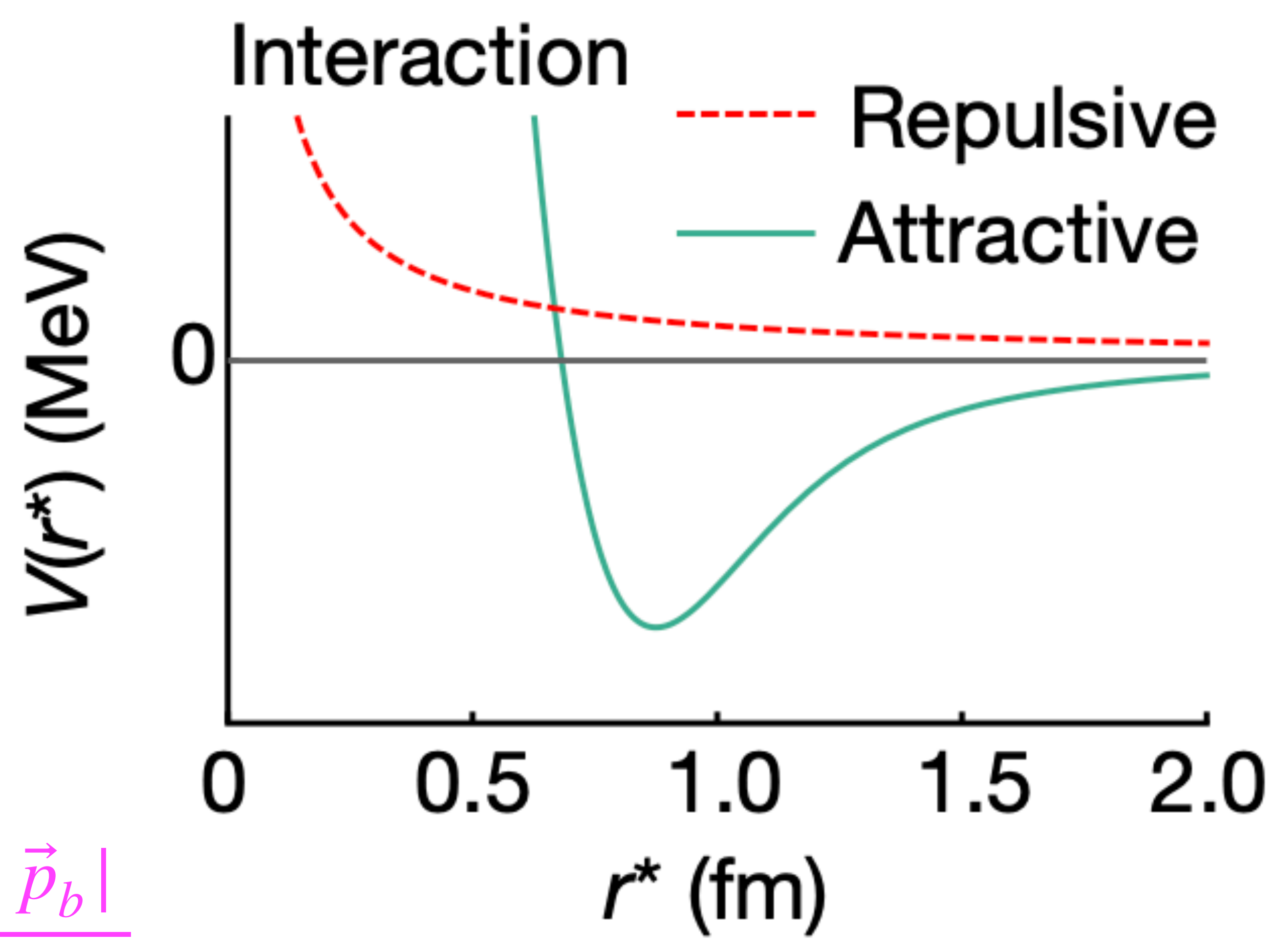
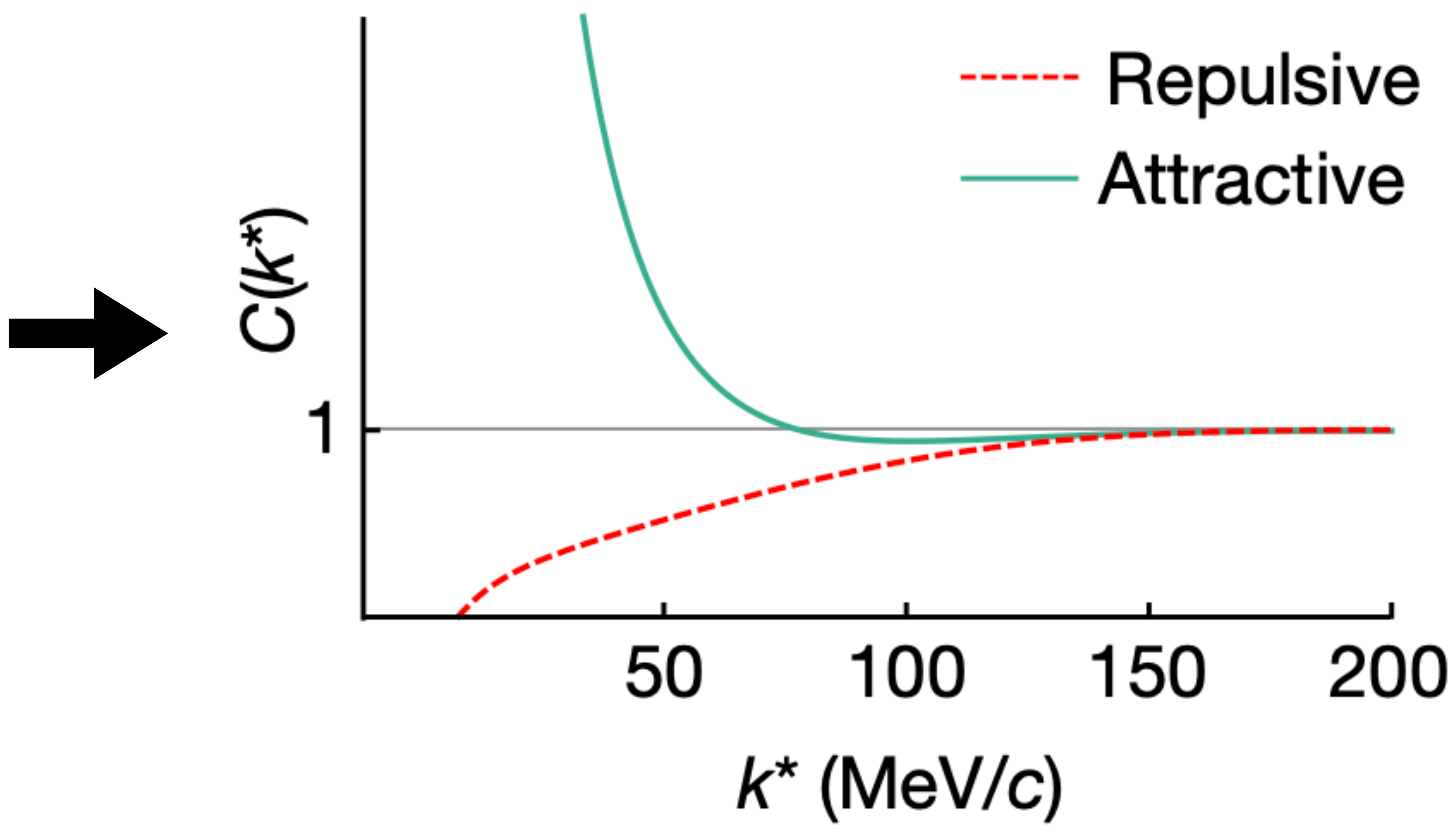




Schrödinger equation

Two-particle wave function

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



Correlation function $C(k^*)$

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

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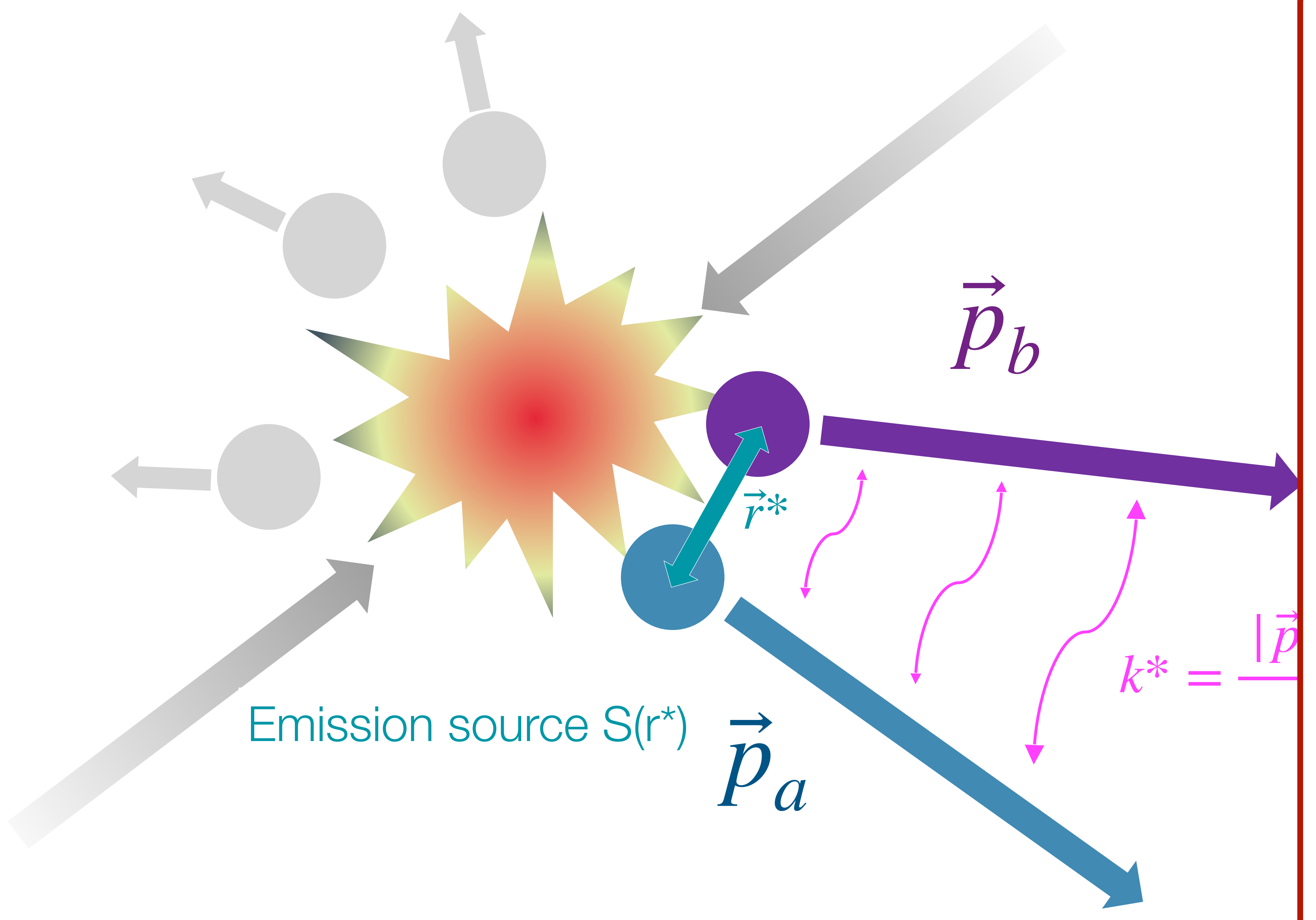
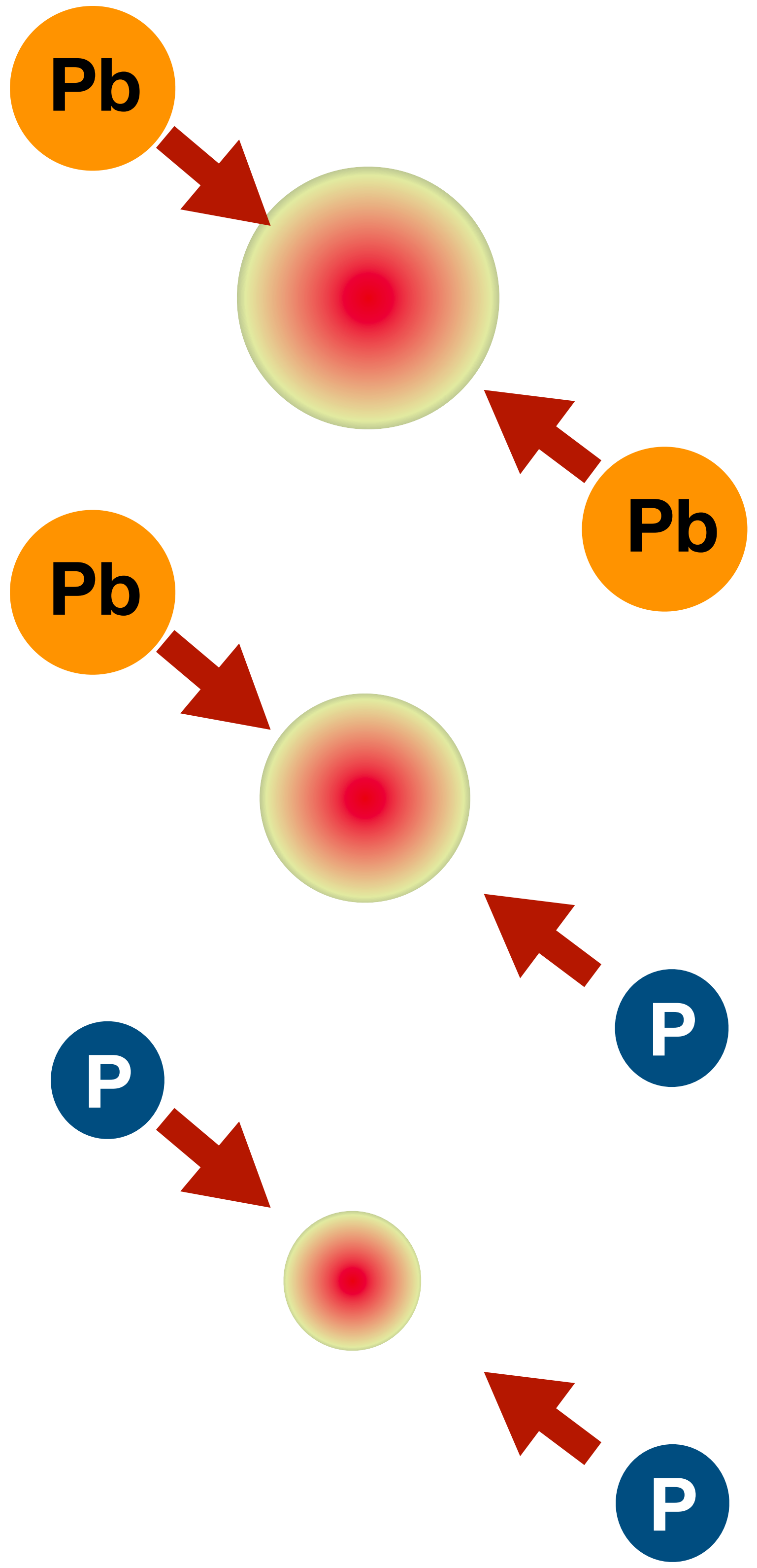


Collisions system sizes

Pb–Pb: 5–10 fm

p–Pb: 2–4 fm

pp: 1–1.5 fm



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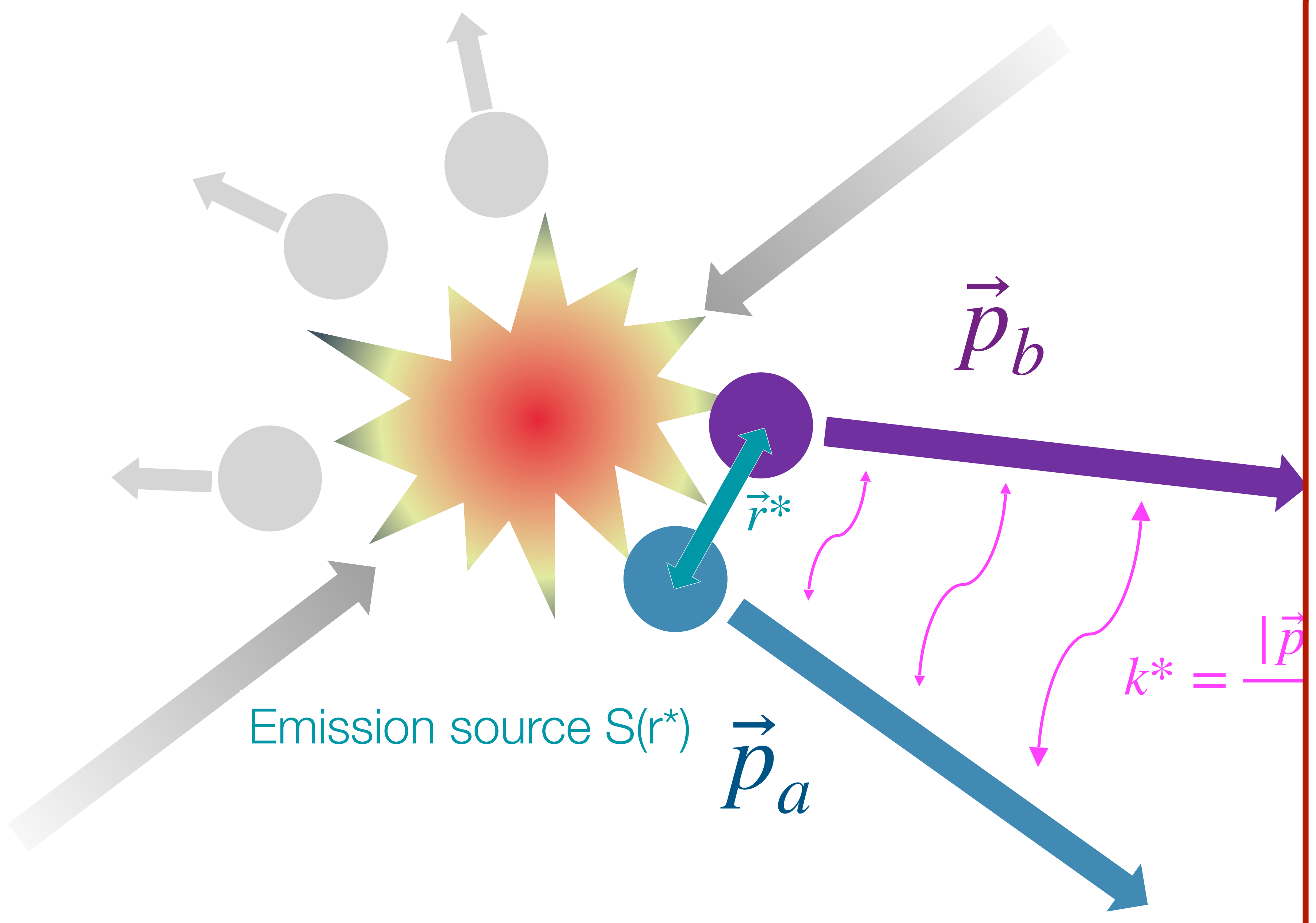

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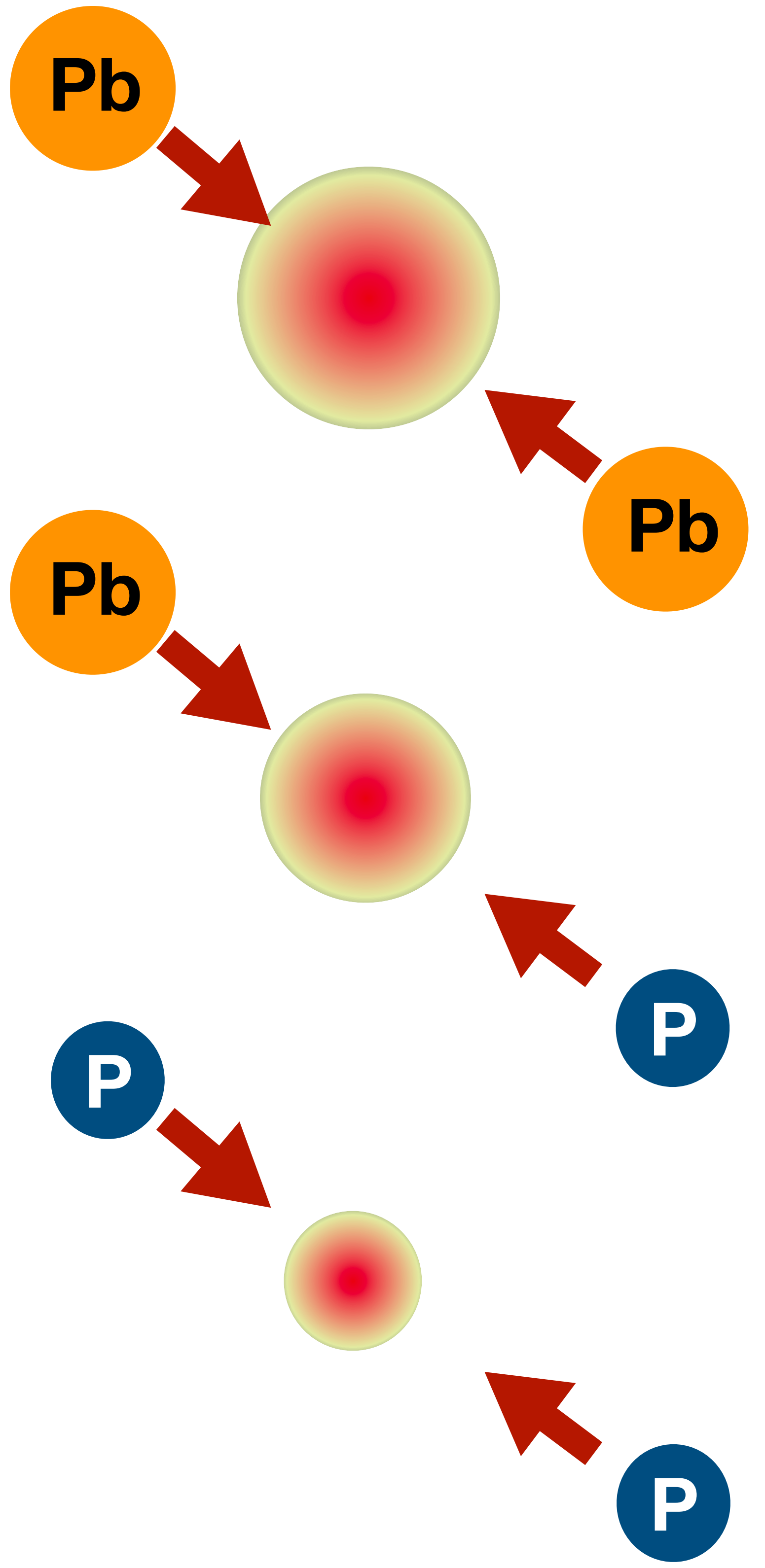

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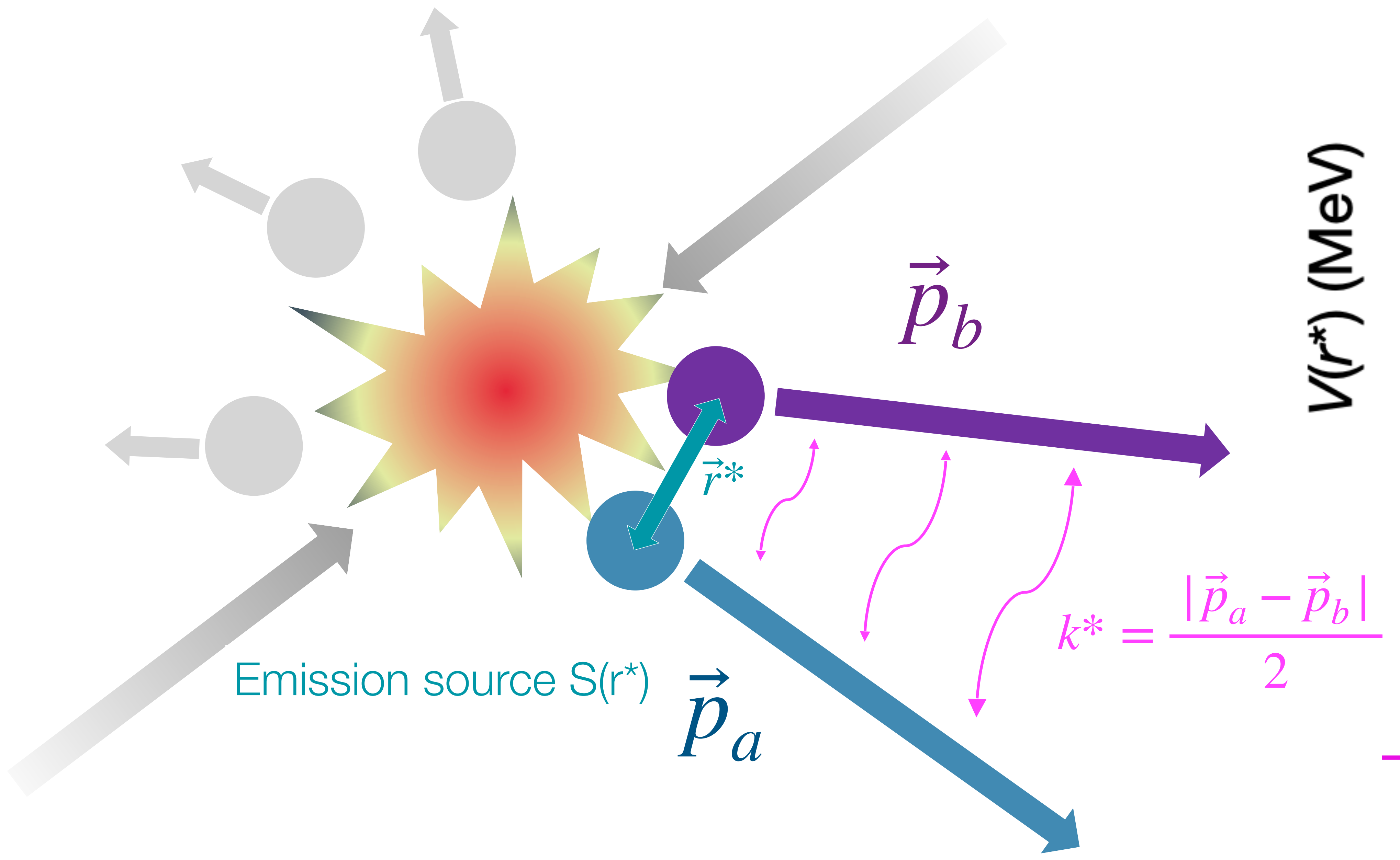

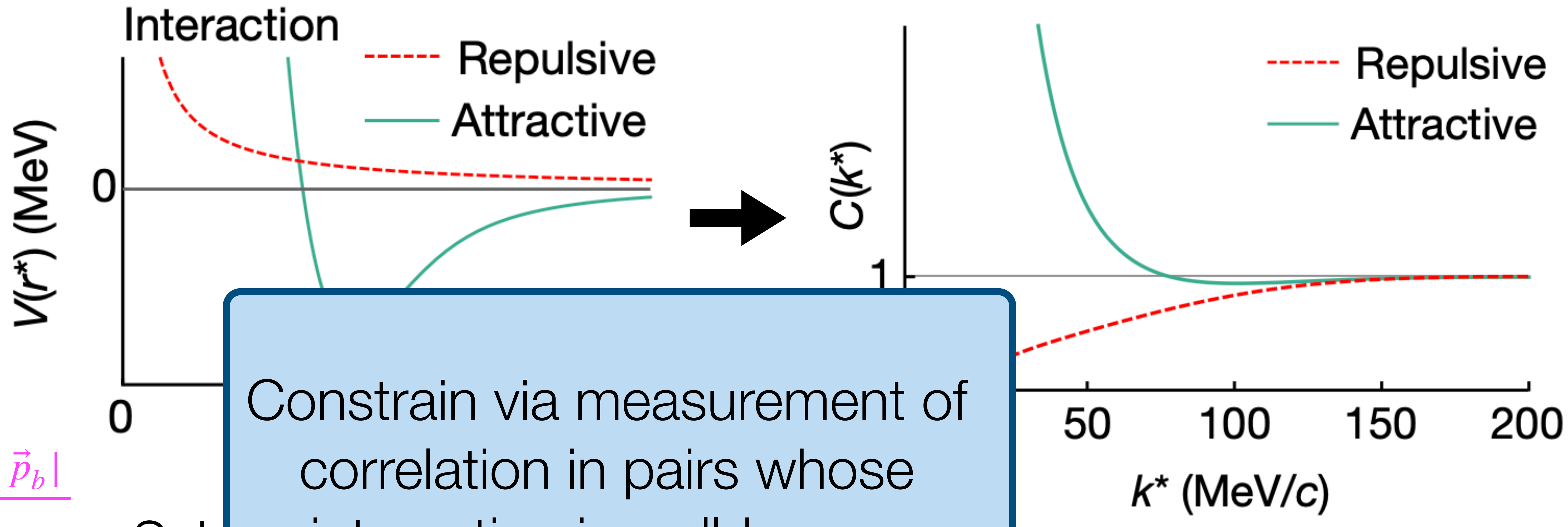

Sch… …ation function $C(k^*)$

Two… …ticle wave function

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

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

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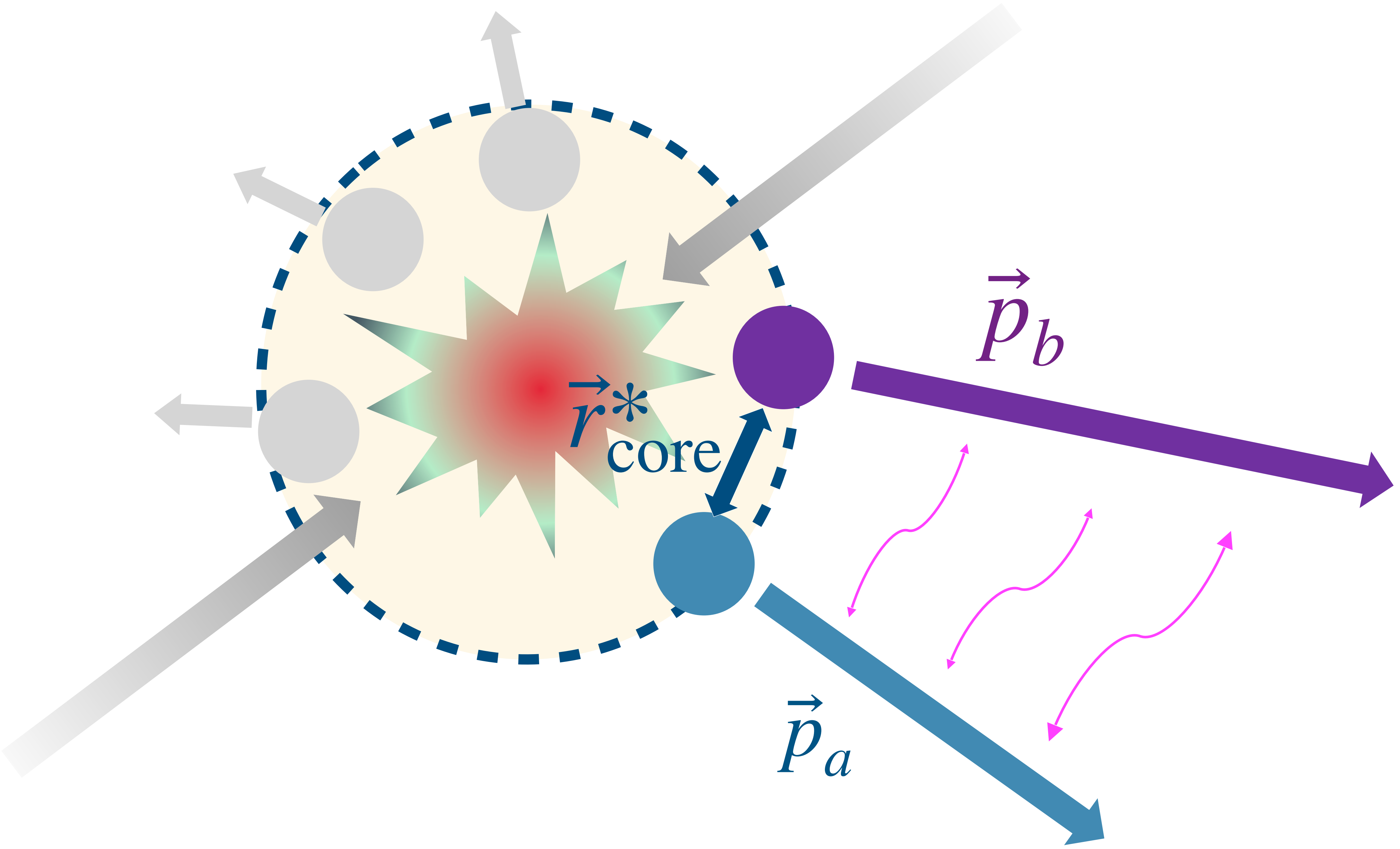
The emission source in pp collisions

- Source modeling is based on
  - Emission of all primordial particles (Gaussian)

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

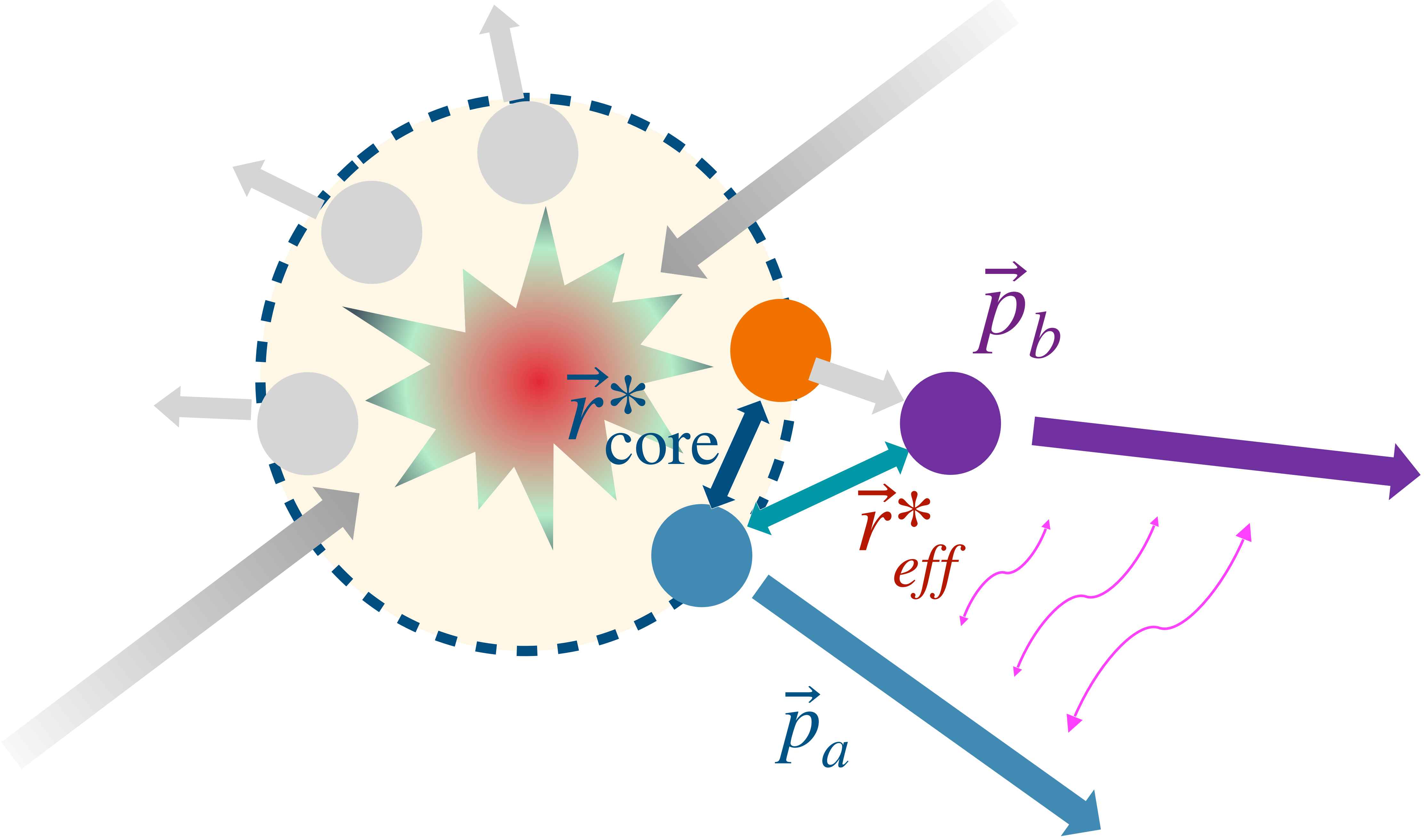


Gaussian core source

The emission source in pp collisions

- Source modeling is based on
  - Emission of all primordial particles (Gaussian)
  - Short-lived resonances ($c\tau \sim 1$ fm : Δ, N^*, Σ^*)

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



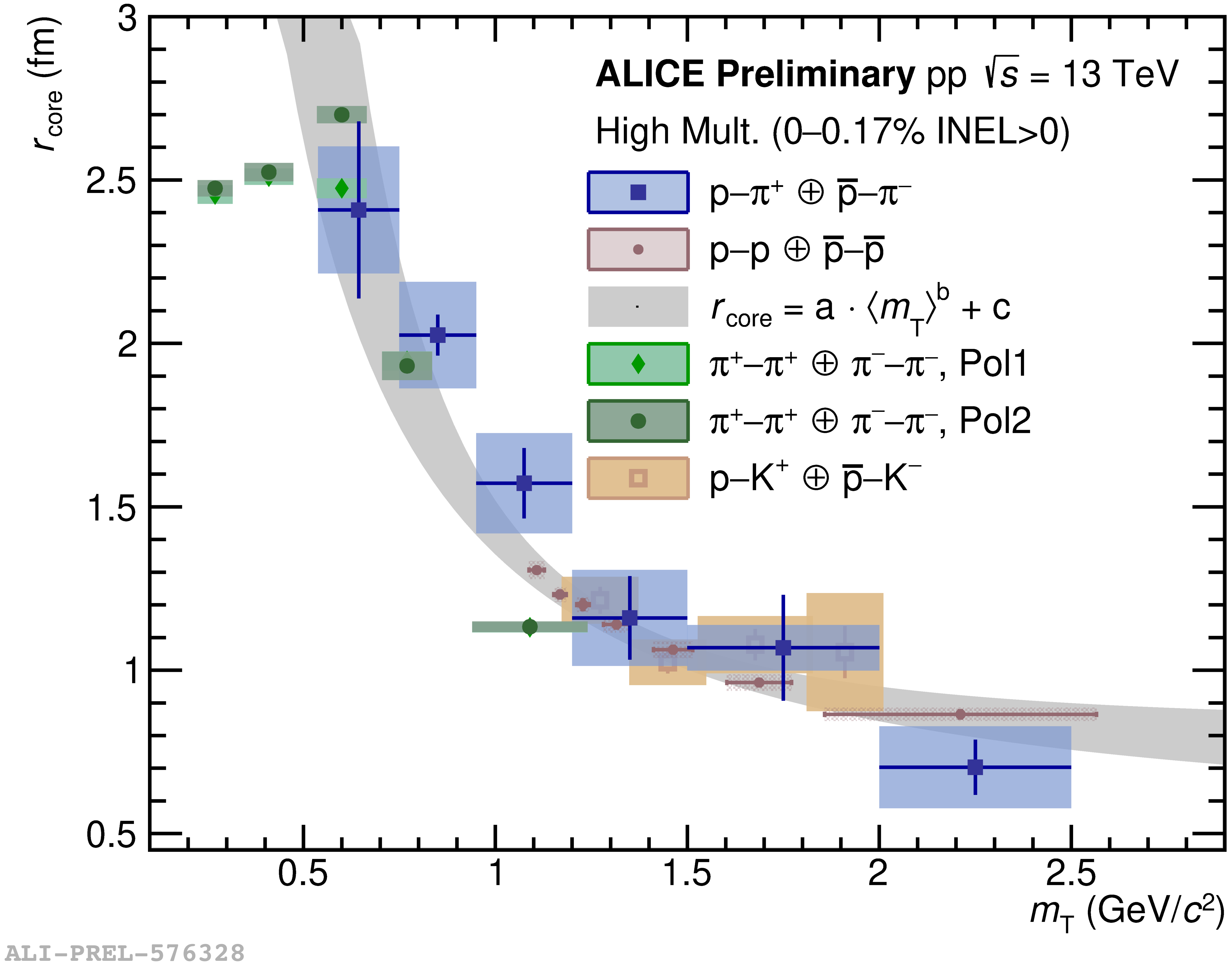
Gaussian core $\oplus$ resonance contributions

- Resonance contributions
  - Dependent on the particle species
  - Fixed from the statistical hadronization model[1] and EPOS[2]
  - r_{core} : particle-emitting source can be studied using particle pairs with known interaction

[1] V. Vovchenko et al, Comput. Phys. Comm. 244 (2019)
[2] T. Pierog et al, Phy. Rev. C 92, 034906 (2015)

A common source for all hadrons in pp collisions

- Particle-emitting sources studied with
  - well-known hadronic interaction
  - p–p ALICE, Phys. Lett. B 811 135849 (2020)
  - p–K^{+} ALICE, arXiv:2311.14527
  - $\pi^{\pm}$–$\pi^{\pm}$ ALICE, arXiv:2311.14527
  - p–$\pi^{\pm}$ (paper in preparation)



$$m_{\mathrm{T}} = \sqrt{\bar{m}^2 + k_{\mathrm{T}}^2} \text{ and } \vec{k}_{\mathrm{T}} = \frac{1}{2}\left(\vec{p}_{\mathrm{T},1} + \vec{p}_{\mathrm{T},2}\right)$$

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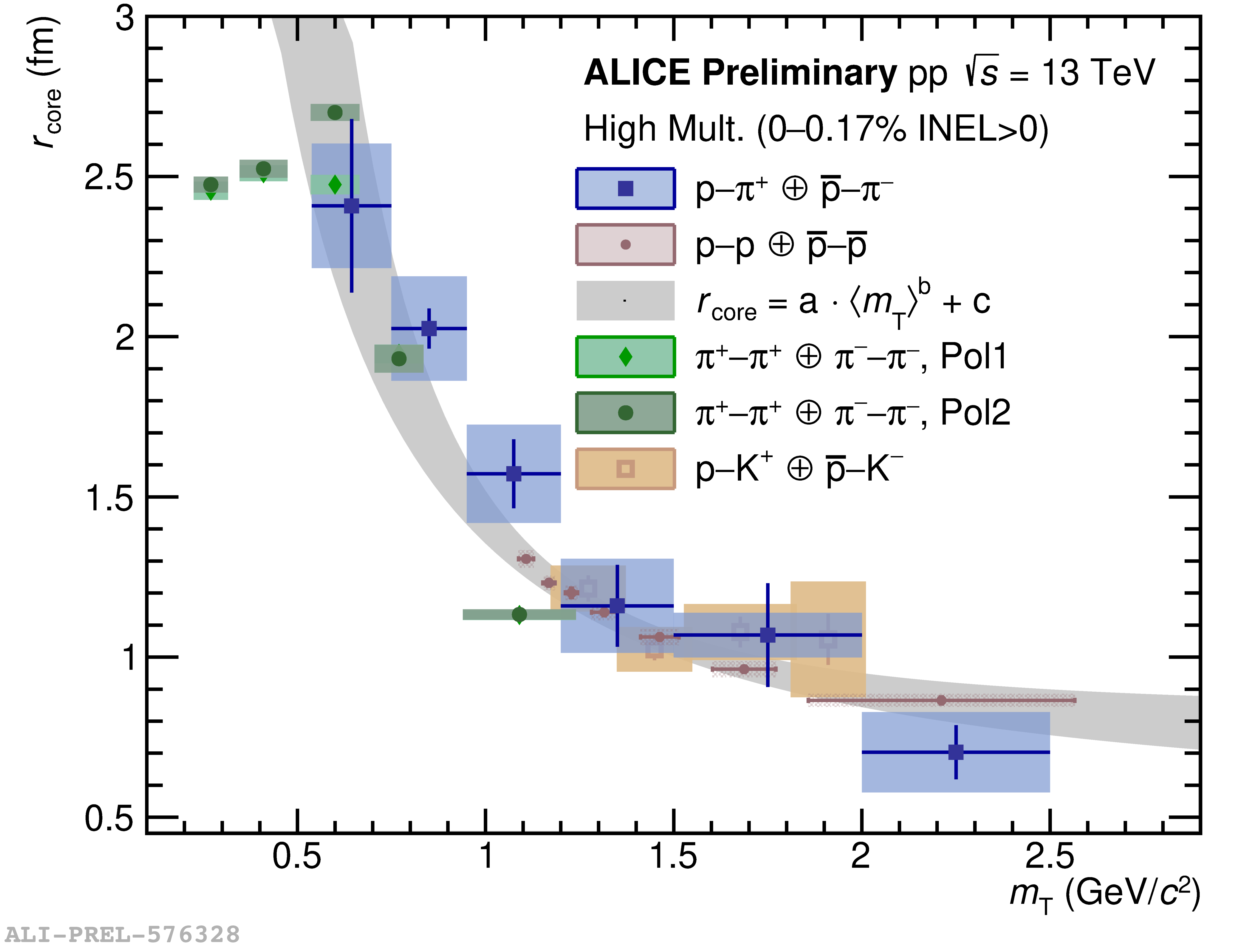
- **A common primordial source for all hadrons in high-multiplicity pp collisions!**
- Use the source size for particle pairs with unknown interaction
- Possibility to study interaction for exotic pairs



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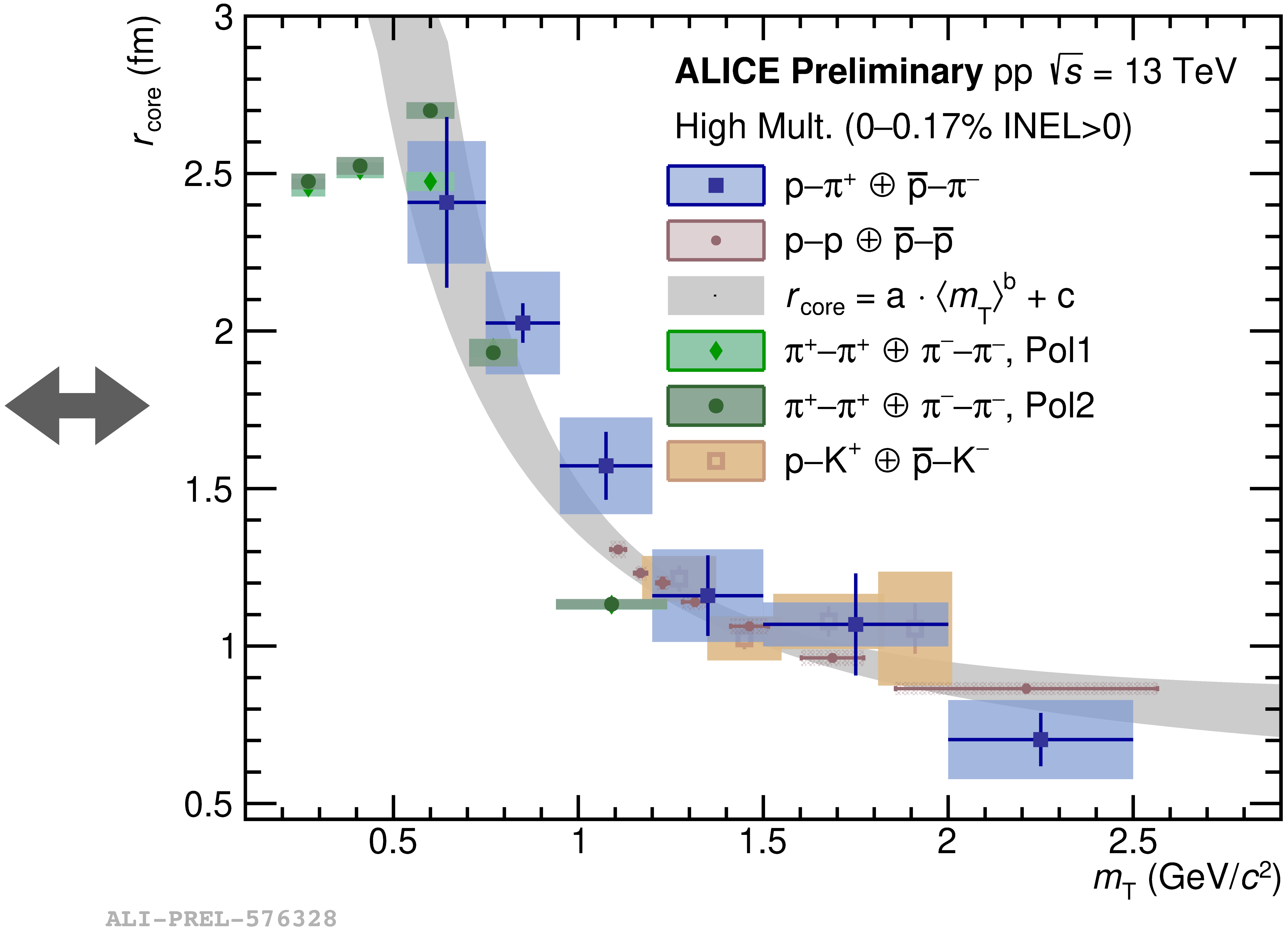
A common source for all hadrons in pp collisions

Recent ALICE femtoscopy measurements

PRC 99 (2019) 2, 024001	p–p, p–Λ, Λ–Λ (methods)
PLB 797 (2019), 134822	Λ–Λ
PRL 123 (2019), 112002	p–Ξ
PRL 124 (2020) 092301	p–K
PLB 805 (2020), 135419	p–Σ^0
PLB 811 (2020), 135849	p–p, p–Λ
Nature 588 (2020) 232-238	p–Ξ, p–Ω
PRL 127 (2021), 172301	p–ϕ
PLB 822 (2021) 136708	p–K
PRC 103 (2021) 5, 055201	Λ–K
PLB 833 (2022), 137272	p–Λ
PLB 829 (2022), 137060	baryon–(anti)baryon
PRD 106 (2022) 5, 052010	p–D
PLB 833 (2022) 137335	K^0–K^0, K^{ch}–K^0
PLB 844 (2022), 137223	Λ–Ξ
EPJA 59 (2023) 7, 145	**p–p–p, p–p–Λ**
EPJA 59 (2023) 12, 298	p–p–K
EPJC 83 (2023) 4, 340	p–K
PLB 845 (2023), 138145	Λ–K
PRD 110, 032004	K/π –D
PRX 14 (2024) 3, 031051	**p–d, K–d**

- Possibility to study interaction for exotic pairs



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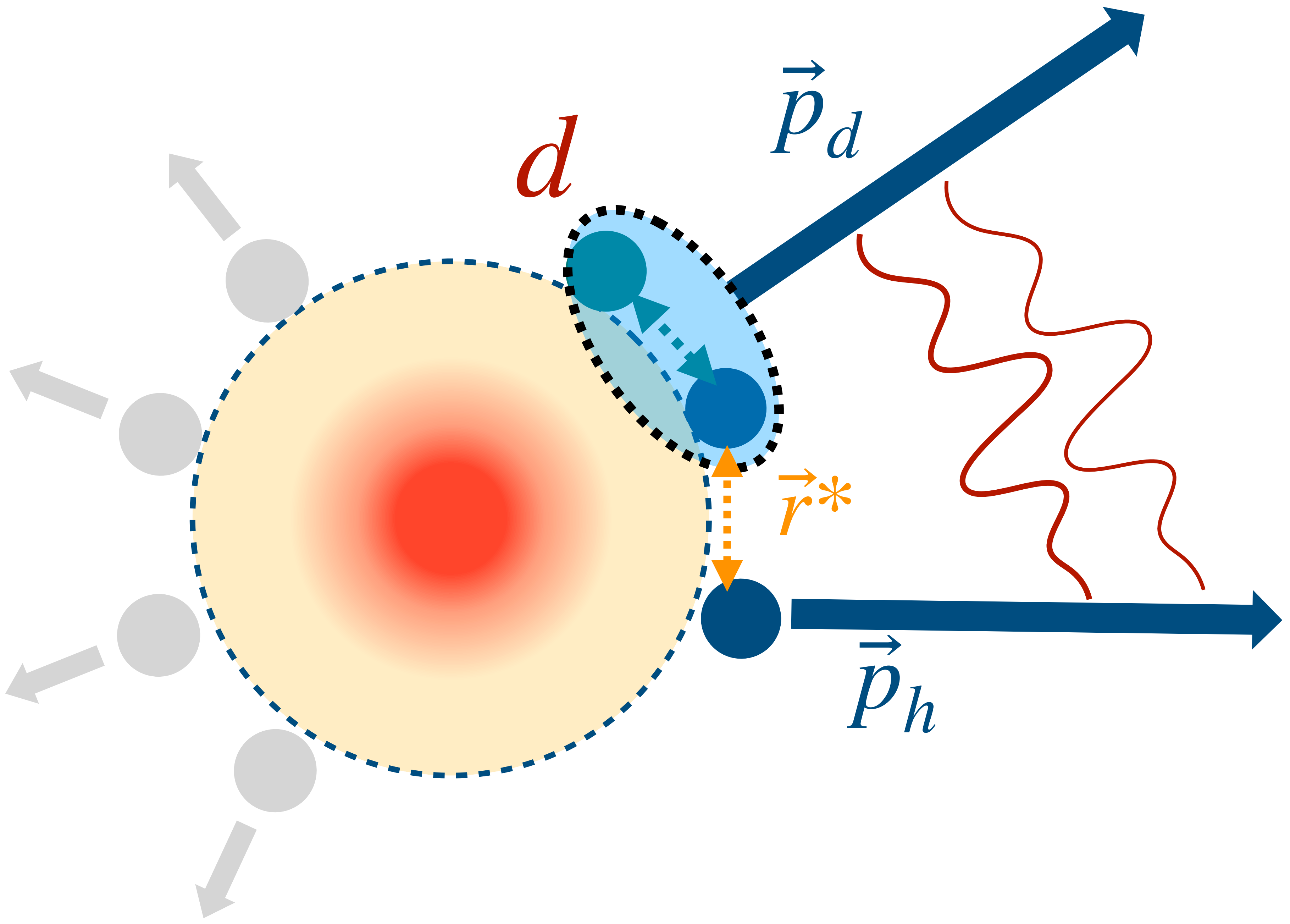
Today: three-hadron systems

- Hadron-deuteron correlations provide an indirect way to study the strong interaction in system of three hadrons

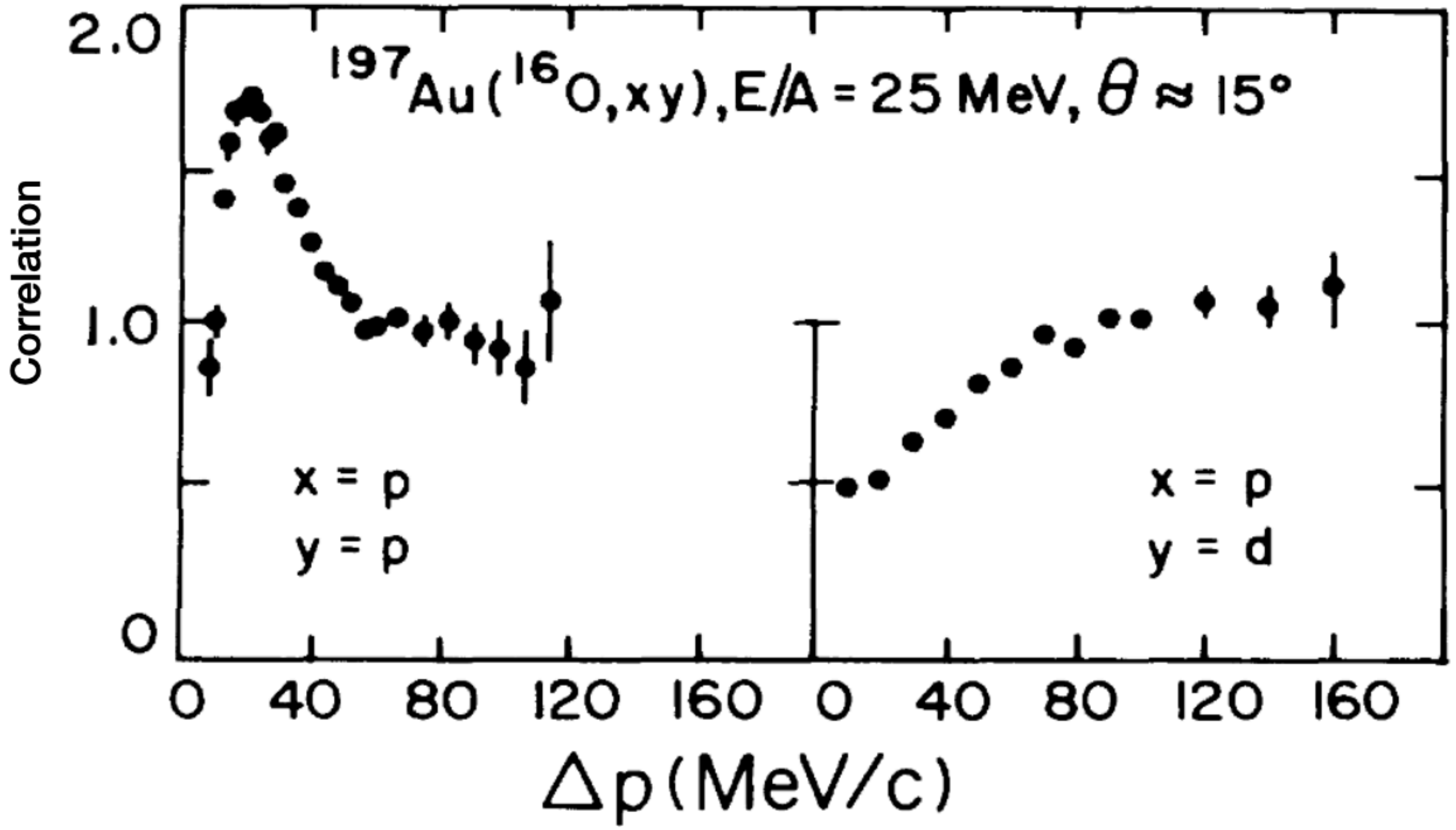


K$^+$–d and p–d systems

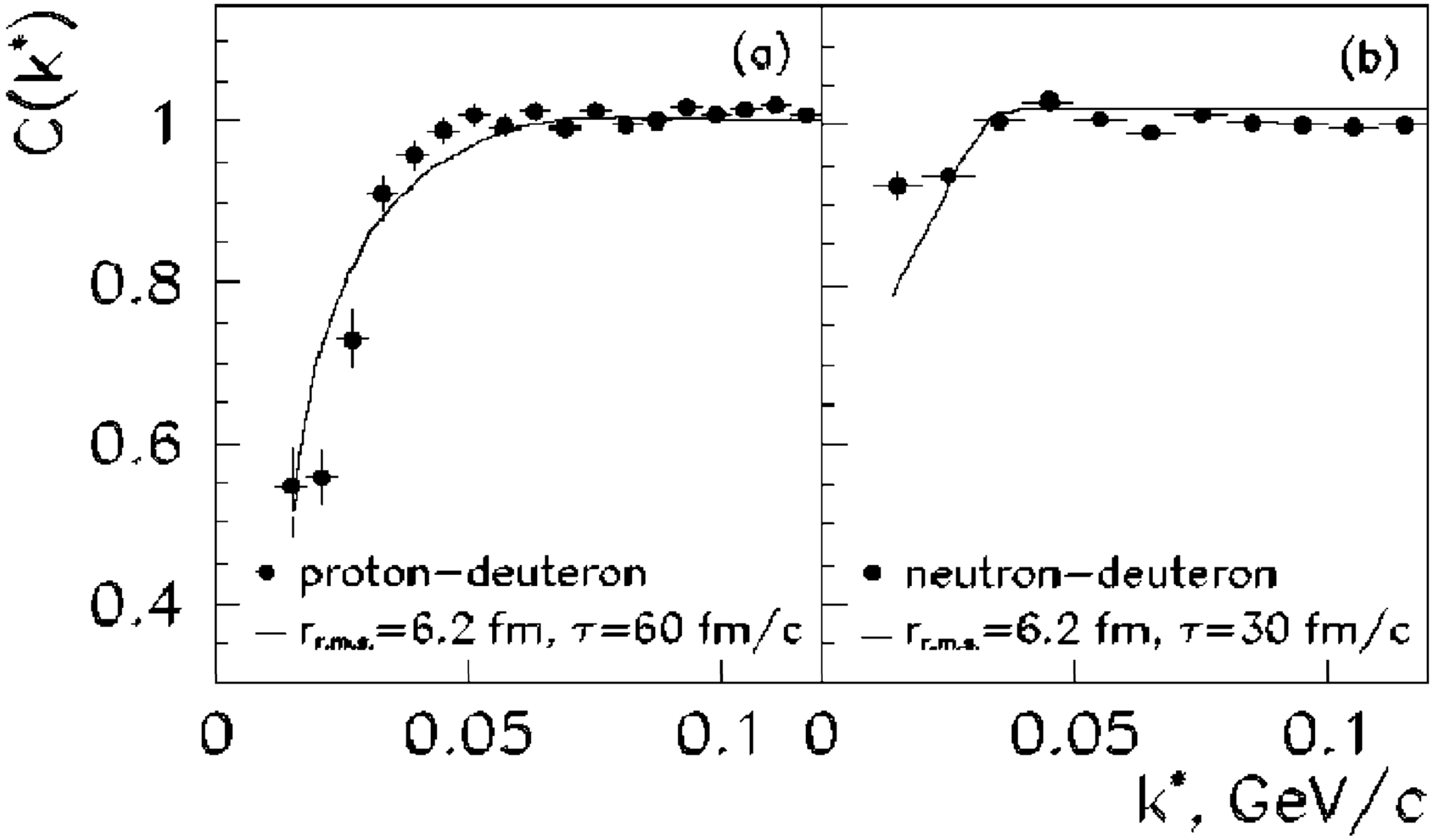
So far… hadron-deuteron correlations

- At very low energy (~ GeV beam energy), fixed target experiments[1-4]

Michigan State University (C. B. Chitwood et al., PRL 54, 302 (1985))



GANIL (K. Wosinska et al., EPJA 32, 55–59 (2007))



[1] C. B. Chitwood et al, Phys. Rev. Lett. 54, 302 (1985)
[2] J. Pochodzalla et al, Phys. Rev. C 35, 1695 (1986)
[3] J. Pochodzalla et al, Phys. Lett. B 175 (1986)
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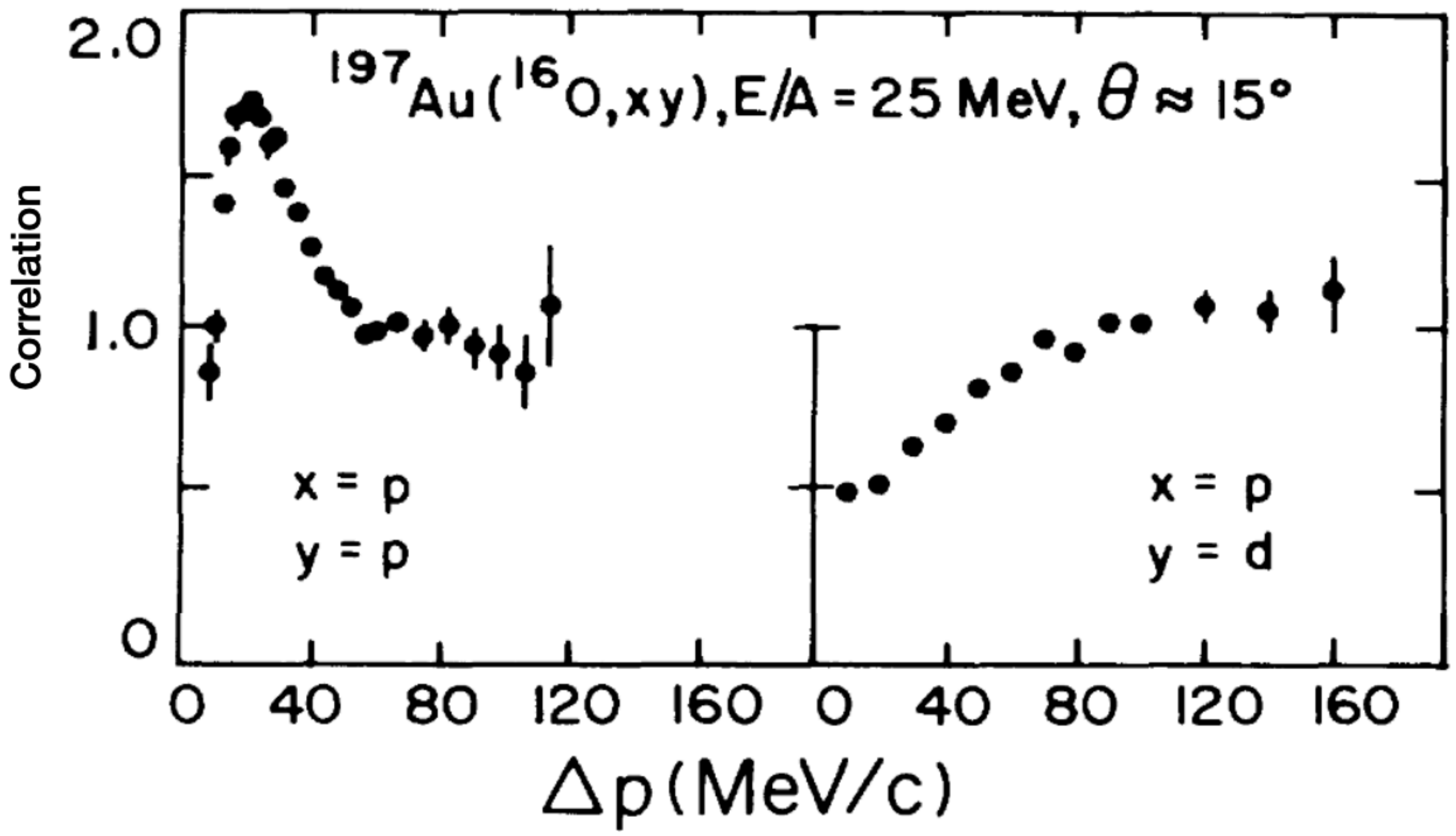

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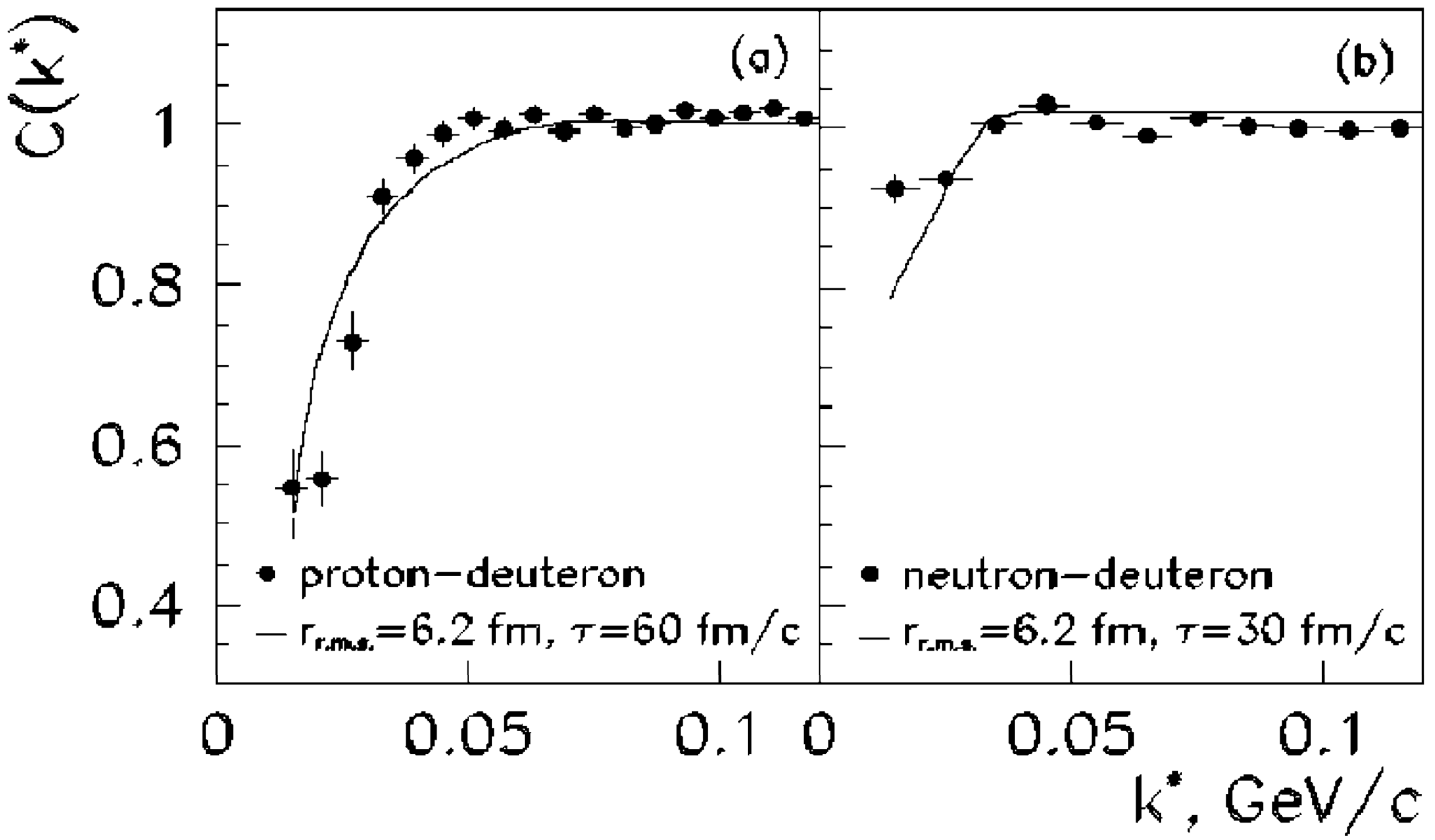

- Large source size ➡ dominant Coulomb interaction
- No **full-fledged calculations** and unconstrained source distributions

[1] C. B. Chitwood et al, Phys. Rev. Lett. 54, 302 (1985)
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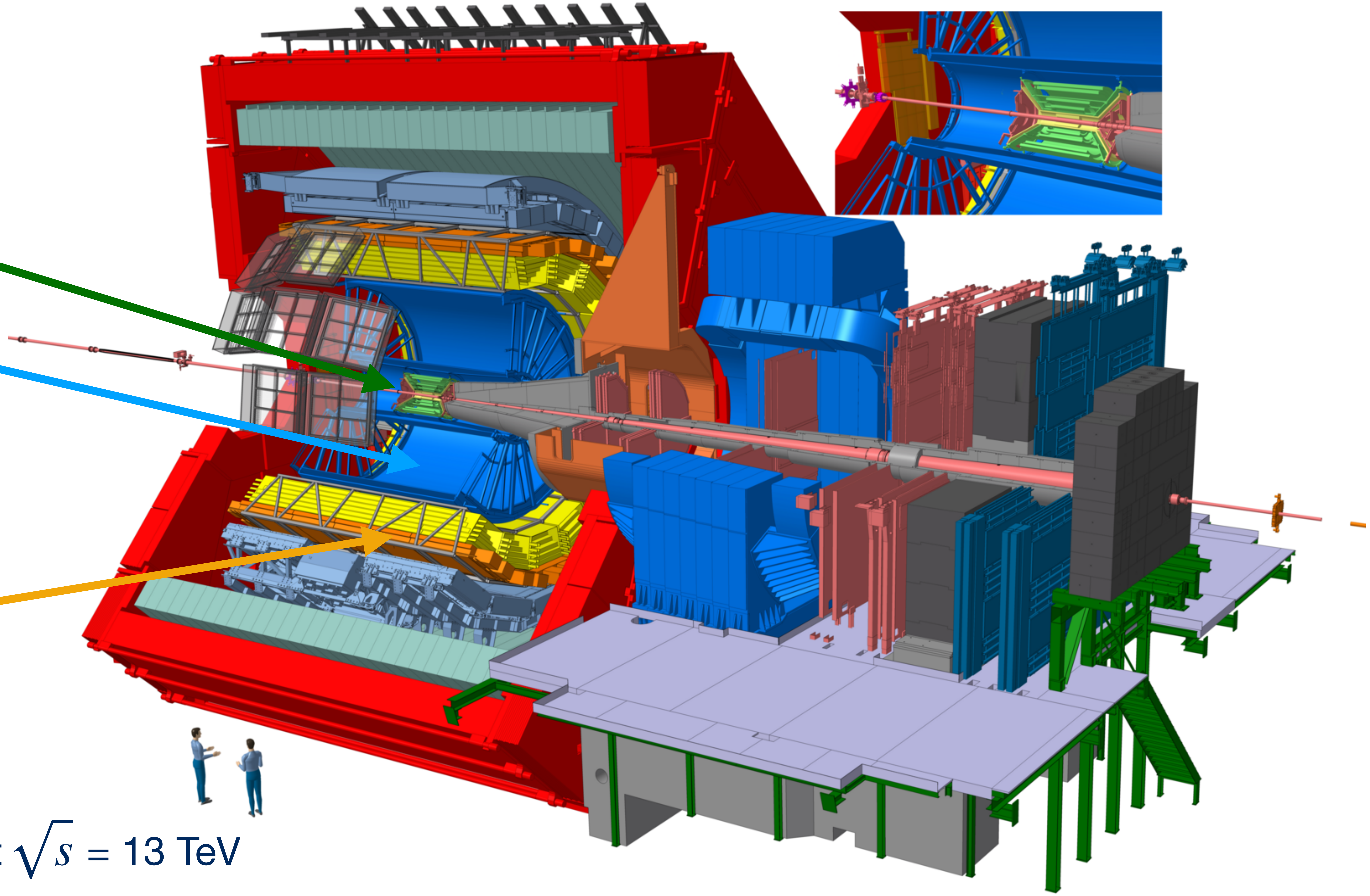
A Large Ion Collider Experiment

- Excellent tracking and particle identification (PID) capabilities

Inner Tracking System (ITS)
Tracking, vertex

Time Projection Chamber (TPC)
Tracking, PID (dE/dx)

Time Of Flight detector (TOF)
PID (TOF measurement)



- Run 2 data-set
  - 10^9 high-multiplicity pp collisions at $\sqrt{s}$ = 13 TeV

ALICE : ITS and TPC upgrades

Int.J.Mod.Phys.A 29 (2014) 1430044
JINST 3 (2008) S08002

A Large Ion Collider Experiment

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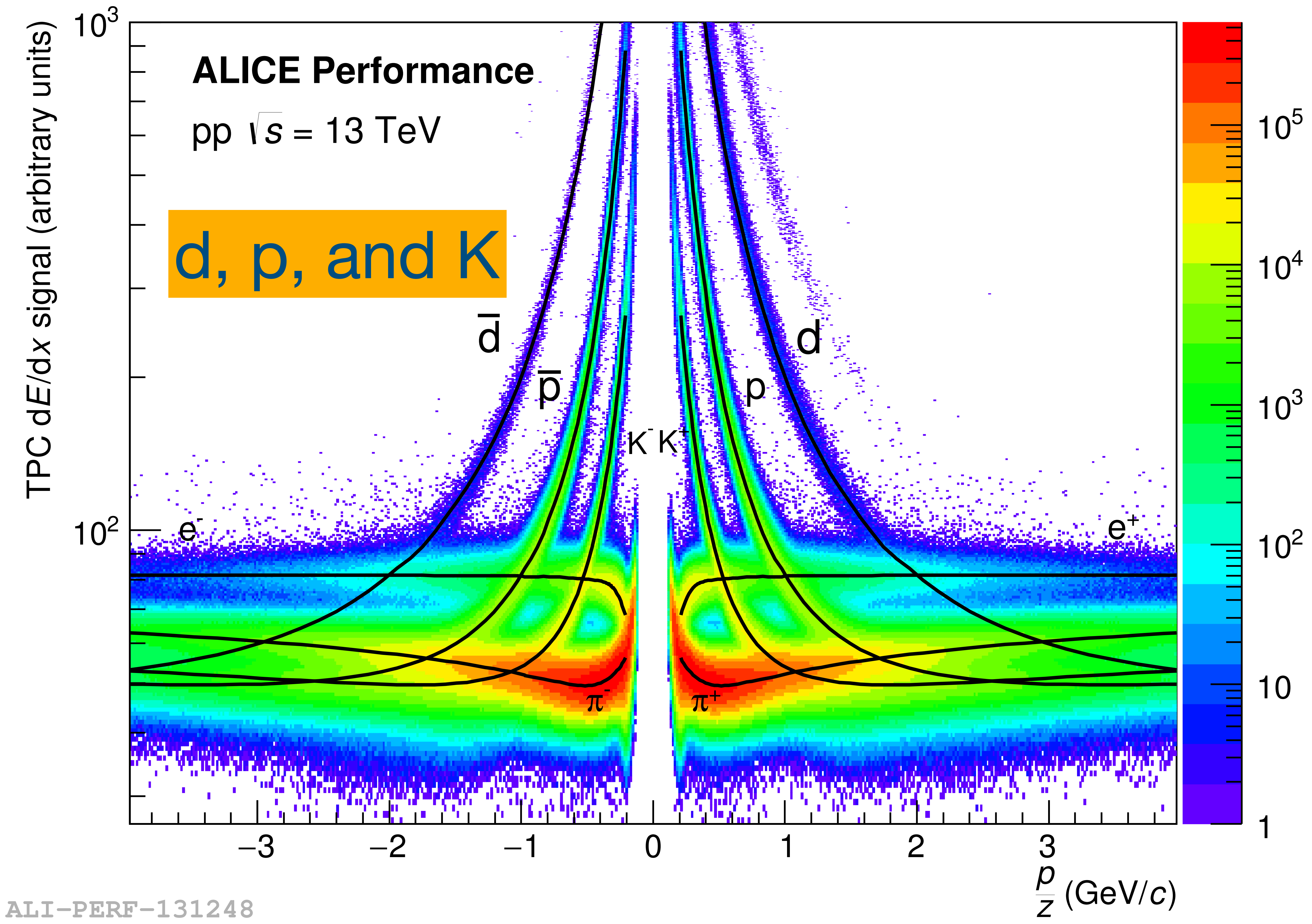
Inner Tracking System (ITS)
Tracking, vertex

Time Projection Chamber (TPC)
Tracking, PID (dE/dx)

Transition Radiation Detector (TRD)

Time Of Flight detector (TOF)
PID (TOF measurement)

- Run 2 data-set
  - 10^9 high-multiplicity pp collisions at $\sqrt{s}$ = 13 TeV



A Large Ion Collider Experiment

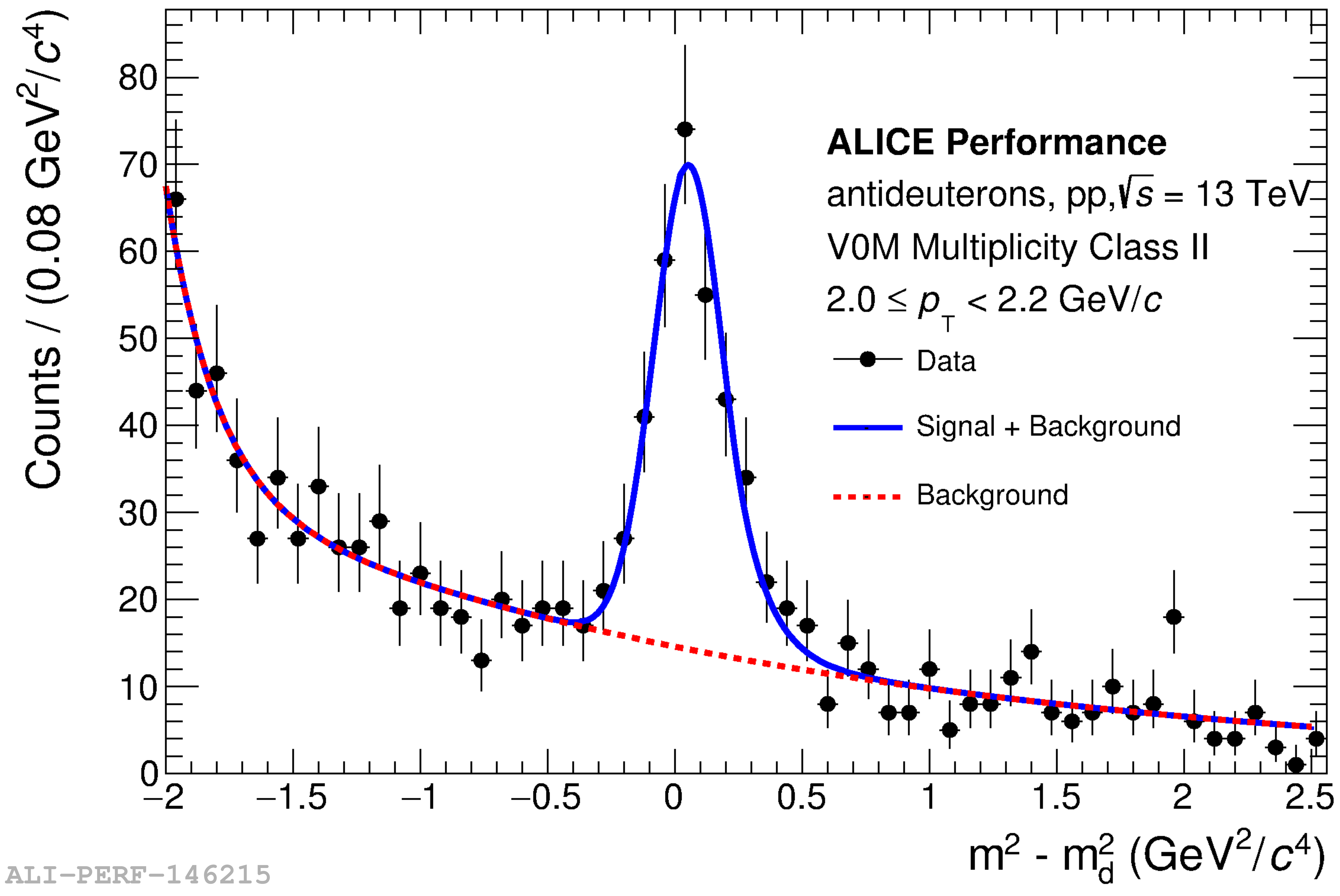
- Excellent tracking and particle identification (PID) capabilities

Inner Tracking System (ITS)
  Tracking, vertex

Time Projection Chamber (TPC)
  Tracking, PID (d*E*/d*x*)

Transition Radiation Detector (TRD)

Time Of Flight detector (TOF)
  PID (TOF measurement)



- Run 2 data-set
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Hadron-deuteron correlations in pp collisions at LHC

- First measurements of p–d and K^+–d correlation functions at the LHC

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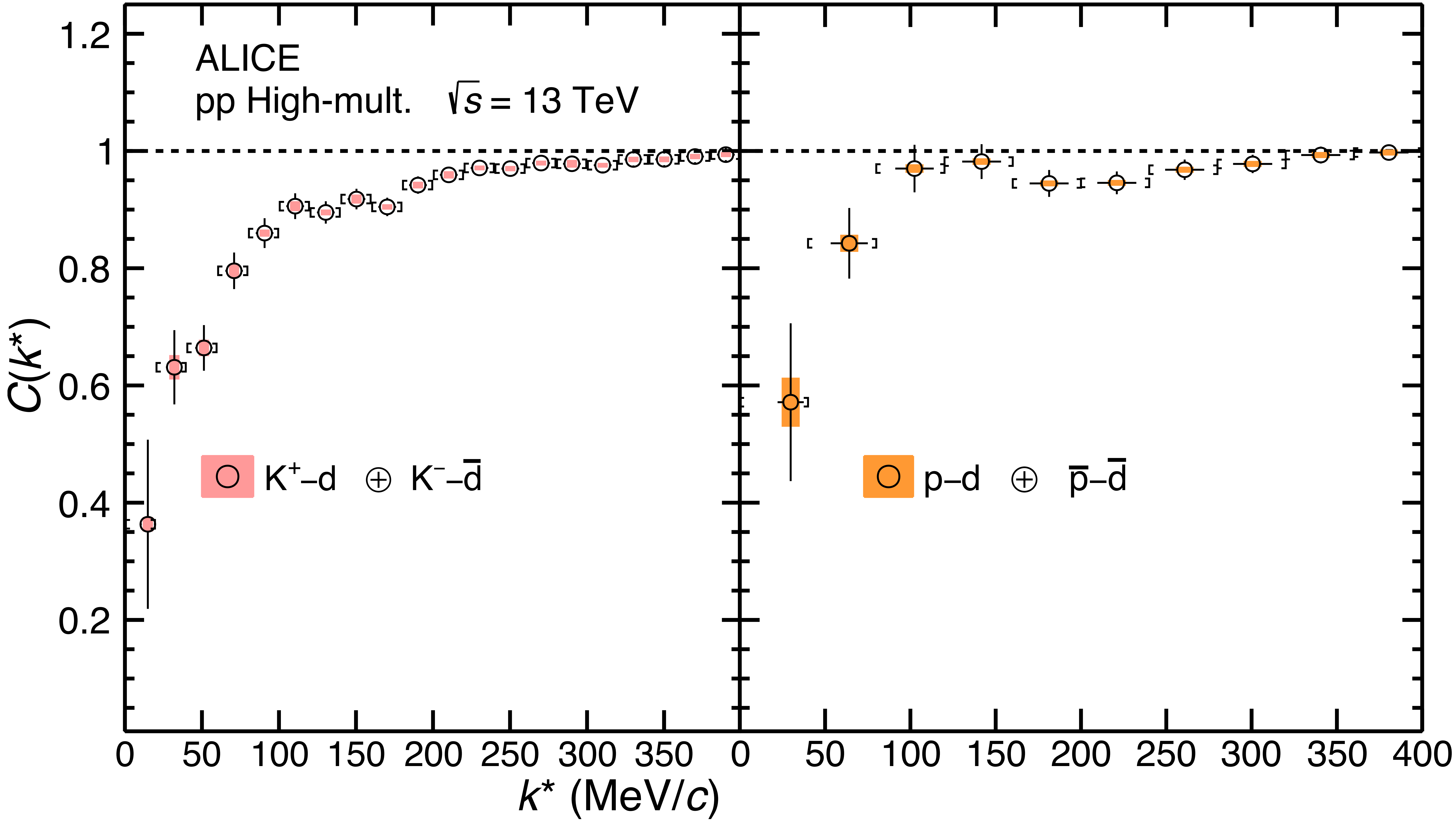

Femtoscopic correlations and modeling

- The femtoscopic correlation consists of various contributions[1-2]

$$C_{\mathrm{femto}}(k^*) = \lambda_{\mathrm{gen}}\, C_{\mathrm{gen}}(k^*) \oplus \lambda_{\mathrm{feed}}\, C_{\mathrm{feed}}(k^*) \oplus \lambda_{\mathrm{misid}}\, C_{\mathrm{misid}}(k^*) \oplus \ldots$$

[1] D. Mihaylov et al. Eur. Phys. J. C78 (2018) 394

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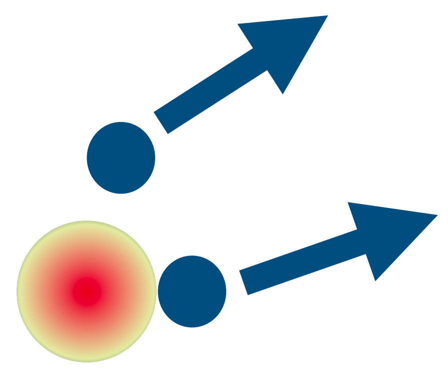

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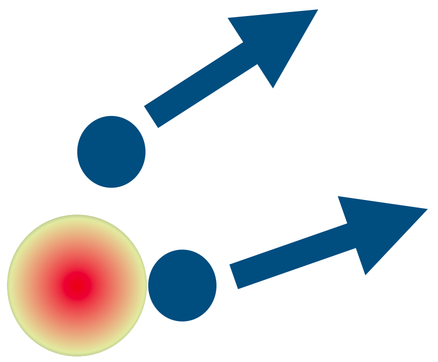

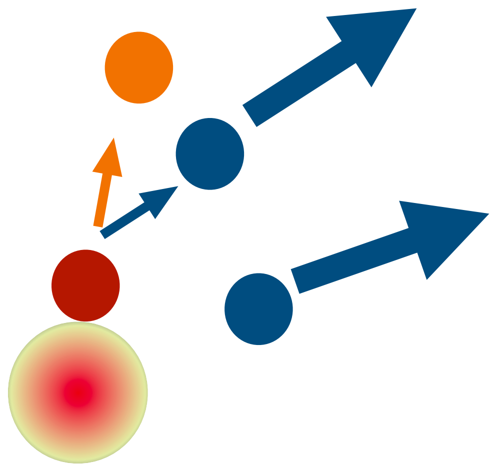

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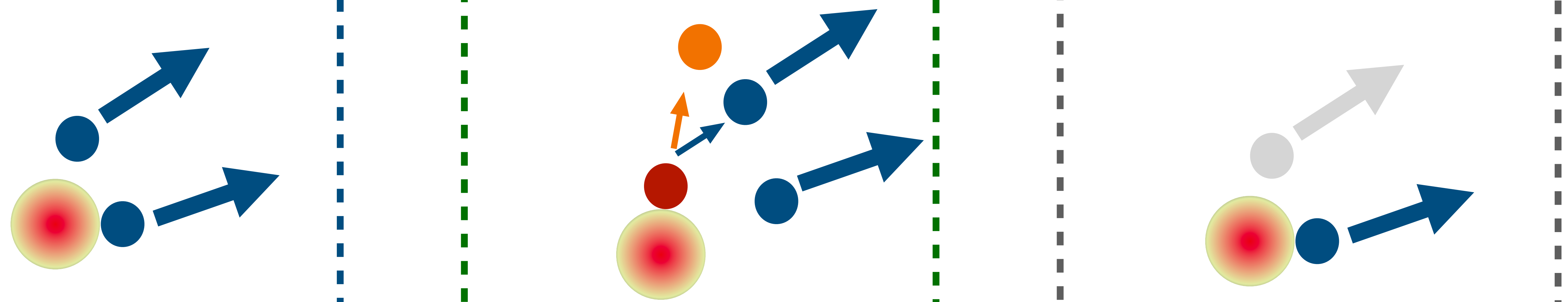

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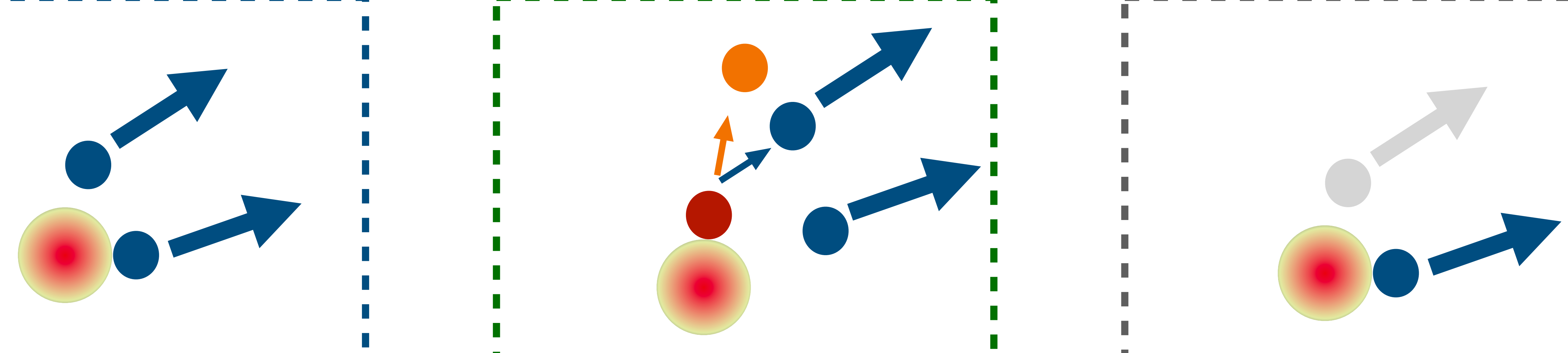

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- A data-driven approach to quantify contributions (lambda parameters $\lambda_{ij} = \mathscr{P}_i . f_i \times \mathscr{P}_j . f_j$ with $\sum_{ij} \lambda_{ij} = 1$)
  - Purity of the individual particles ($\mathscr{P}_i$) and feed-down fractions (f_i)

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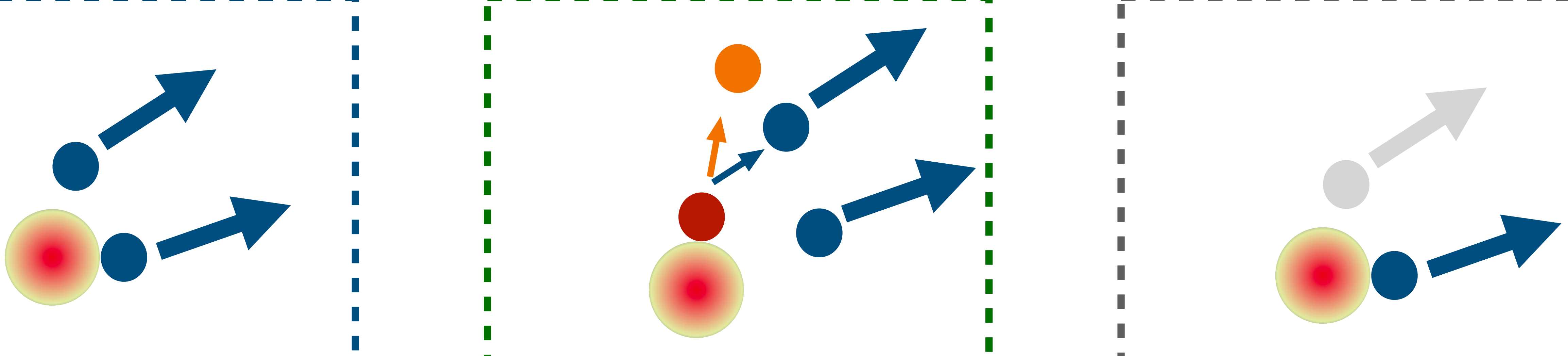

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Genuine interaction: input to theory

Negligible ~unity

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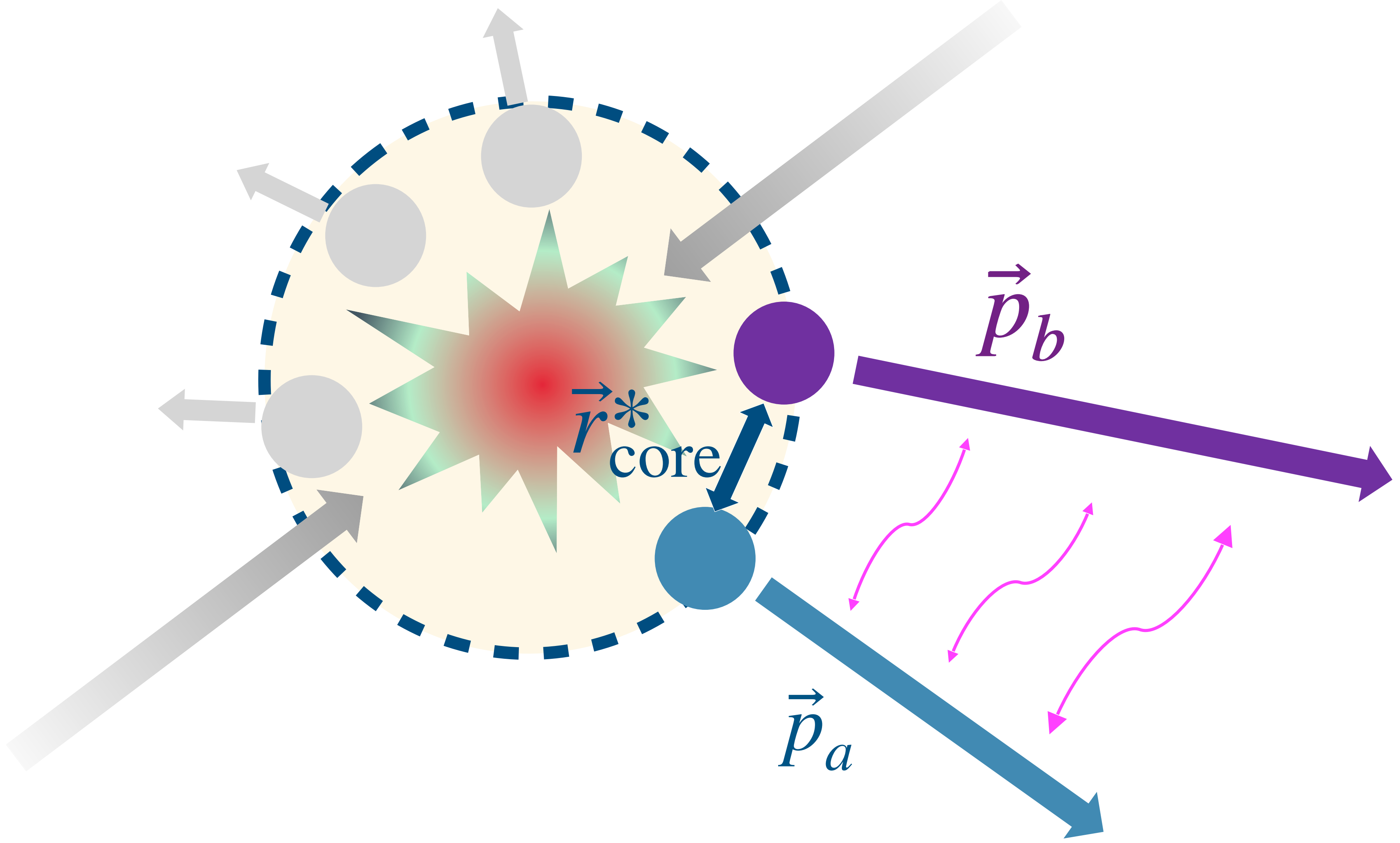
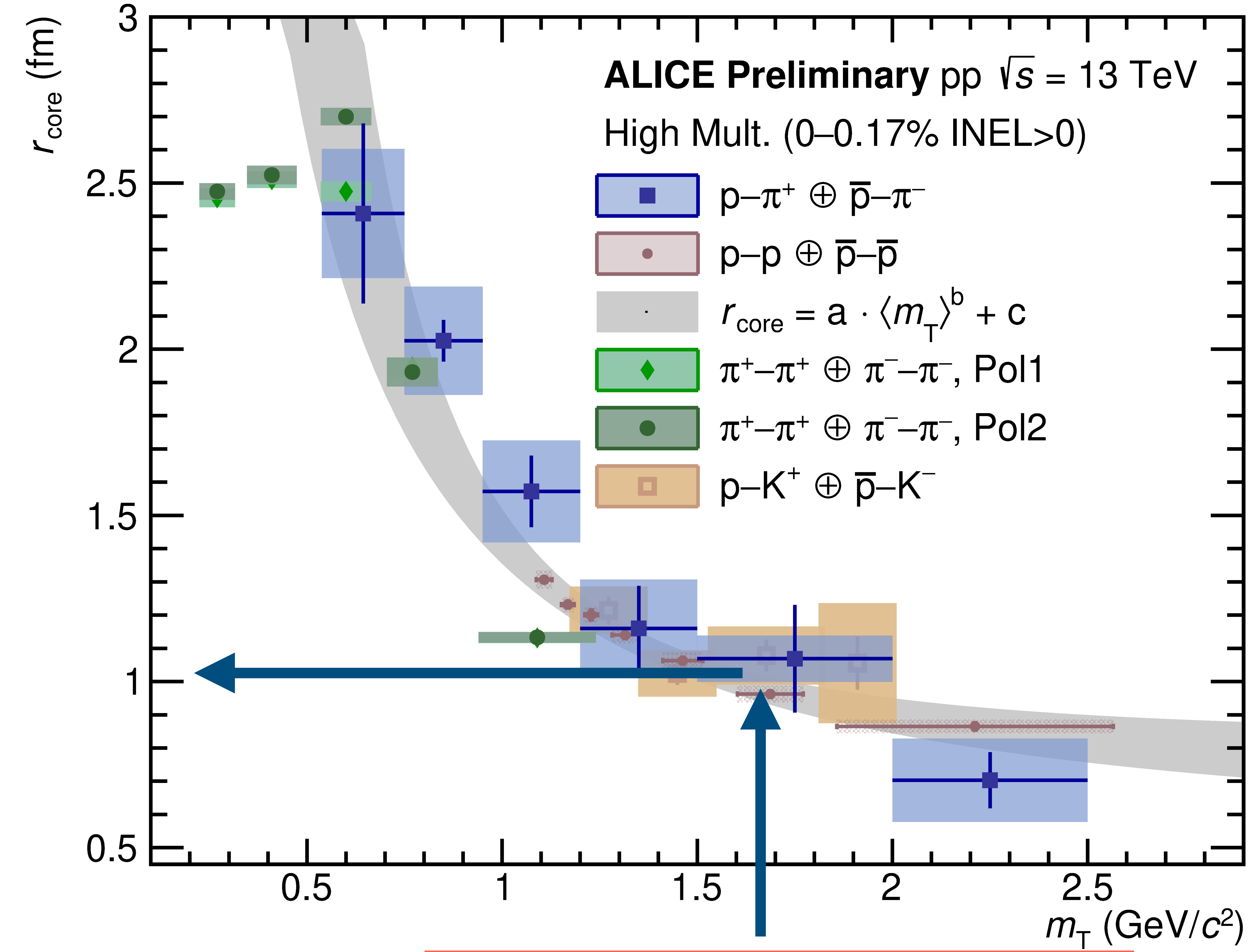
Source for kaon-deuteron and proton-deuteron pairs

- Primordial source size for K^+–d and p–d systems



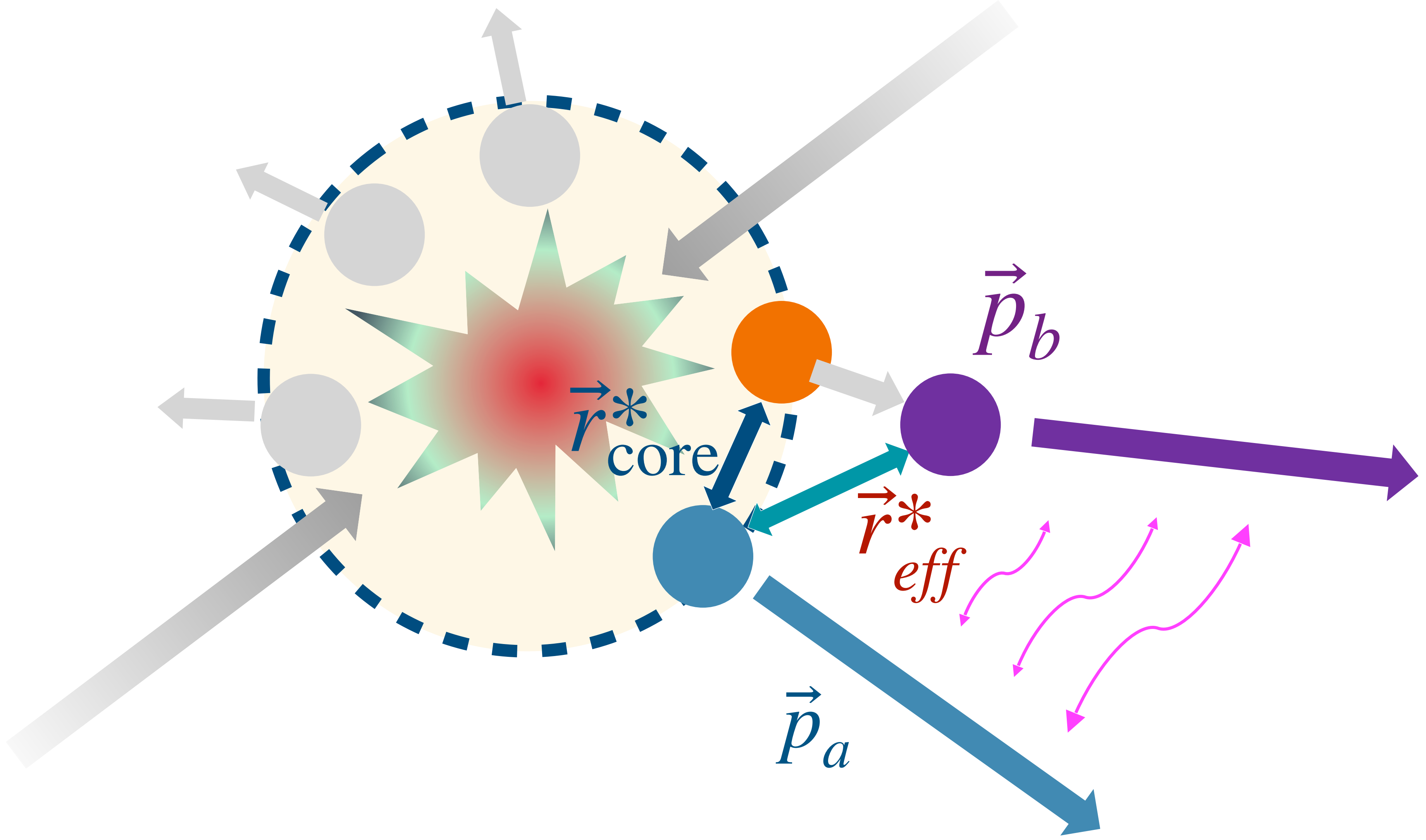
Source size	mean value: p–d	mean value: K^+–d
r_{core}	0.99±0.05 fm	1.04±0.04 fm



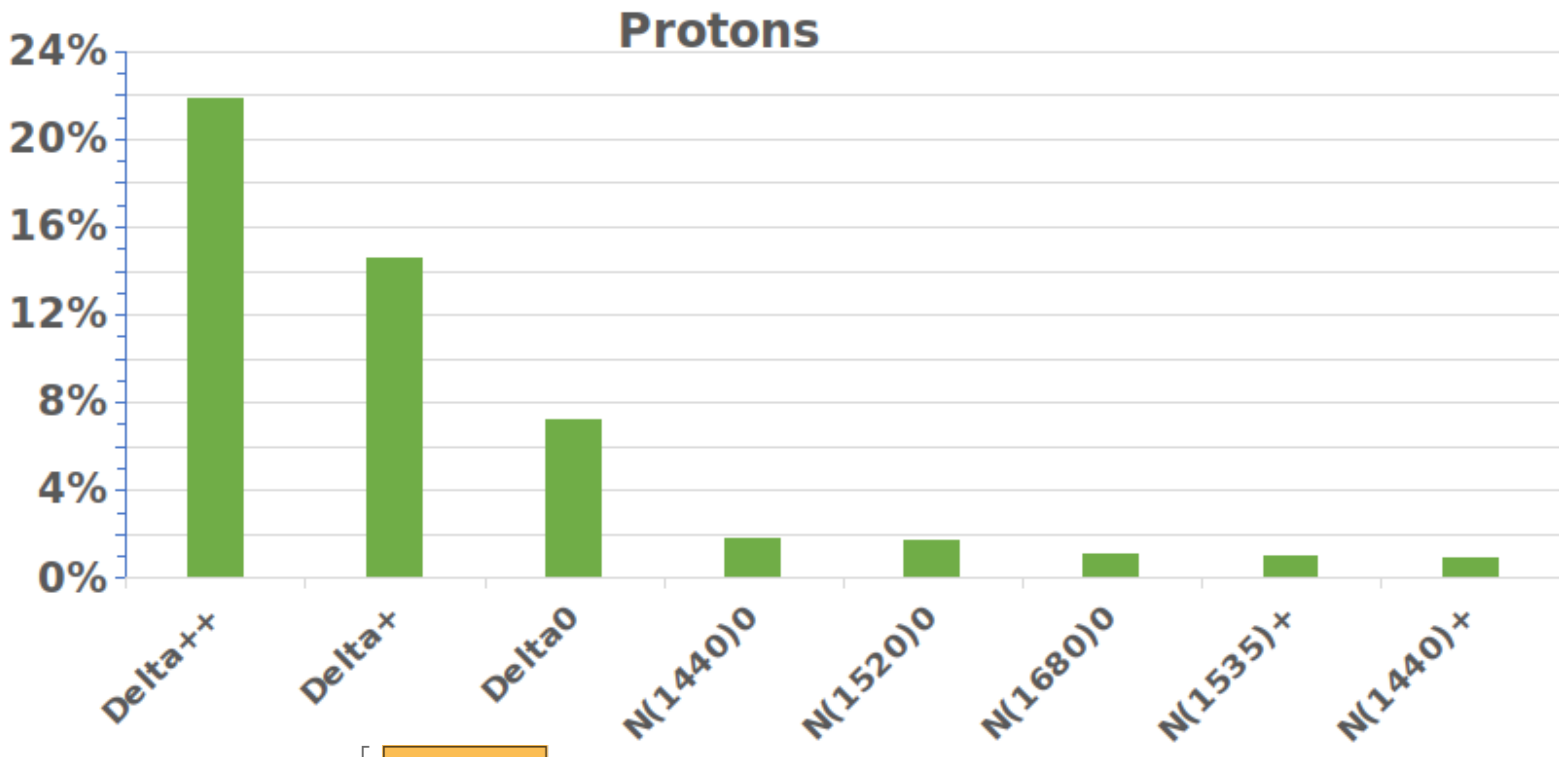
$\langle m_T \rangle_{p\text{-}d\,/K\text{-}d} = 1.64/1.50\ \mathrm{GeV}/c^2$

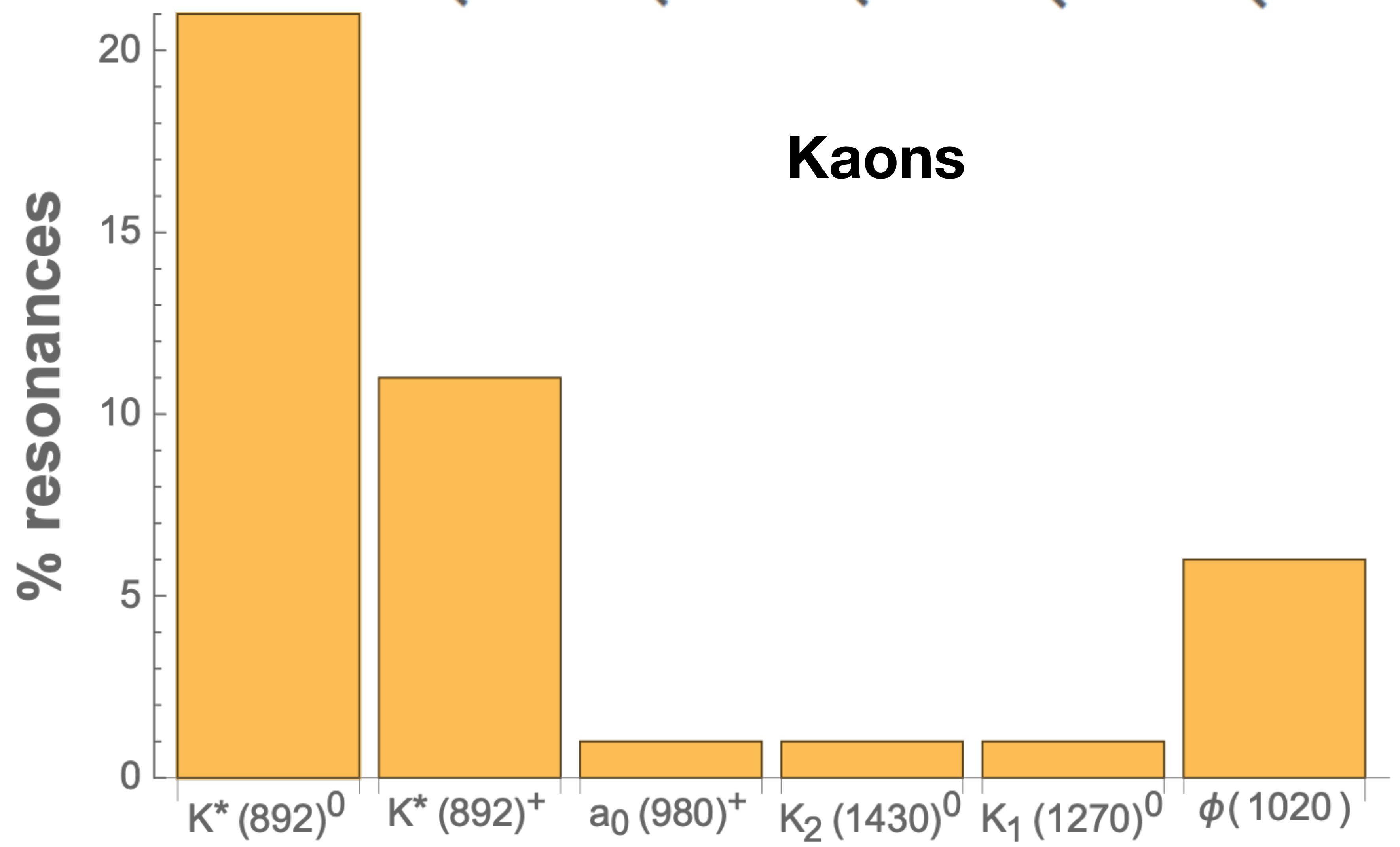
Source for kaon-deuteron and proton-deuteron pairs

- Primordial source size for K^+–d and p–d systems
- Source radius is effectively increased by **short-lived strongly decaying resonance**



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±0.05 fm





ϕ(1020) corrected as feed-down

Theoretical approach correlation functions

- Potential approach: solve Schrödinger equation for the two-hadron system[1]

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  - Only **s-wave** two-particle relative wave function
  - Considers Coulomb effects

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

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- f_c Coulomb normalized scattering amplitude for strong interaction, F and $\tilde{G}$ are Coulomb functions
  - a_0: scattering length
  - d_0: effective range

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Kaon-deuteron correlation function

- Assuming m_T-scaling holds for d, r_{eff} = 1.35±0.05 fm
- Coulomb potential: disagree

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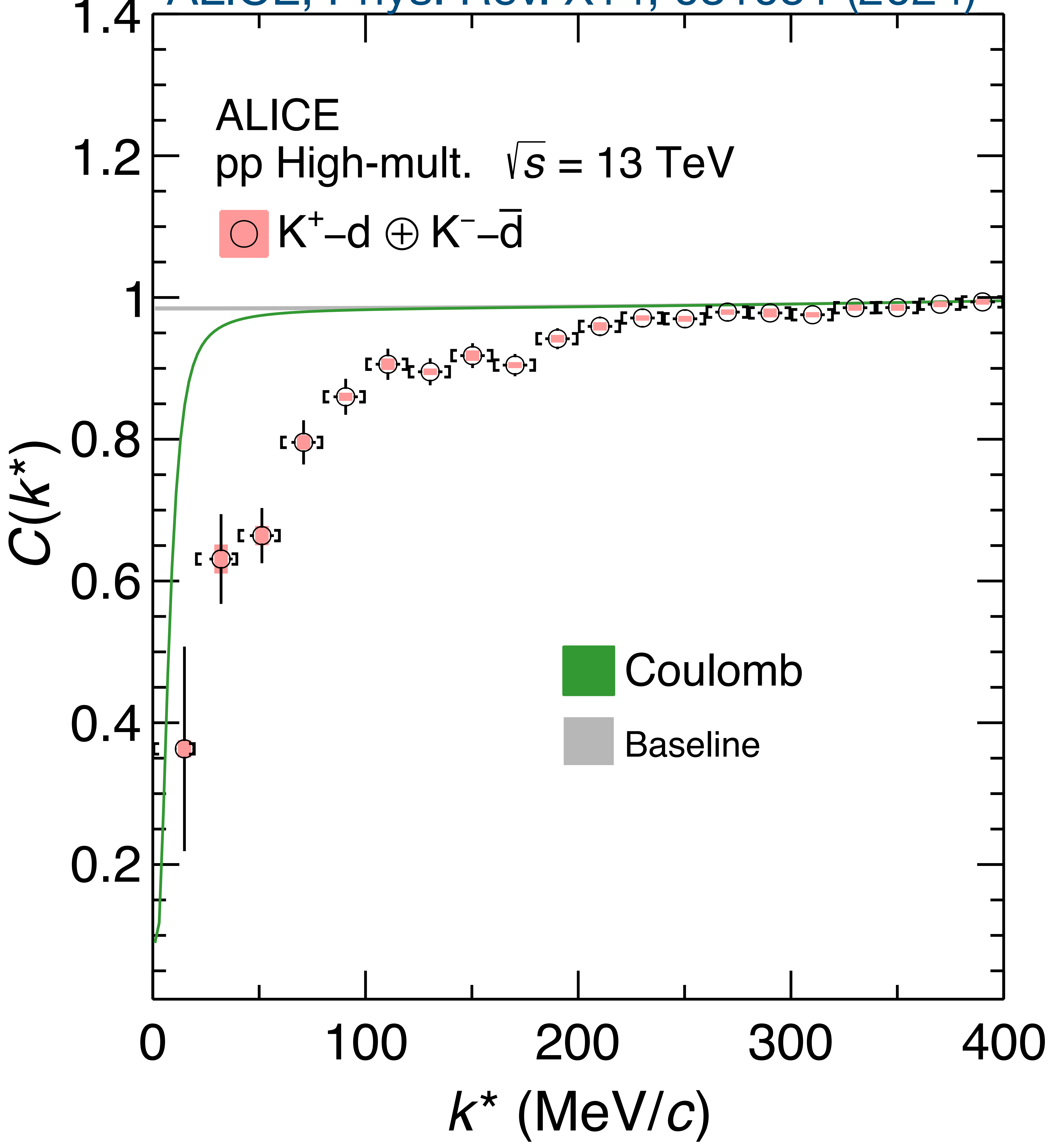

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- Strong interaction in K^+–d as an **effective two-body** system: Lednický-Lyuboshits approach[1]
  - Effective-Range approx. (ER): $a_0 = -0.47$ fm, $d_0 = -1.75$ fm[2]
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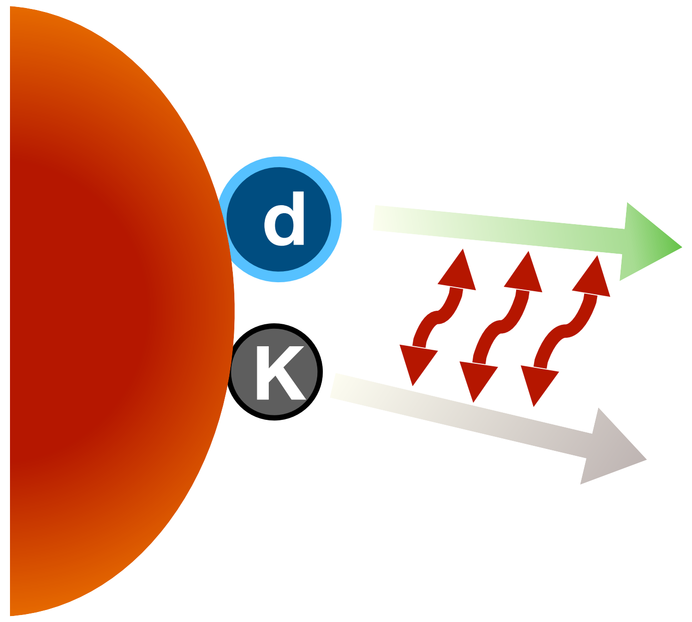

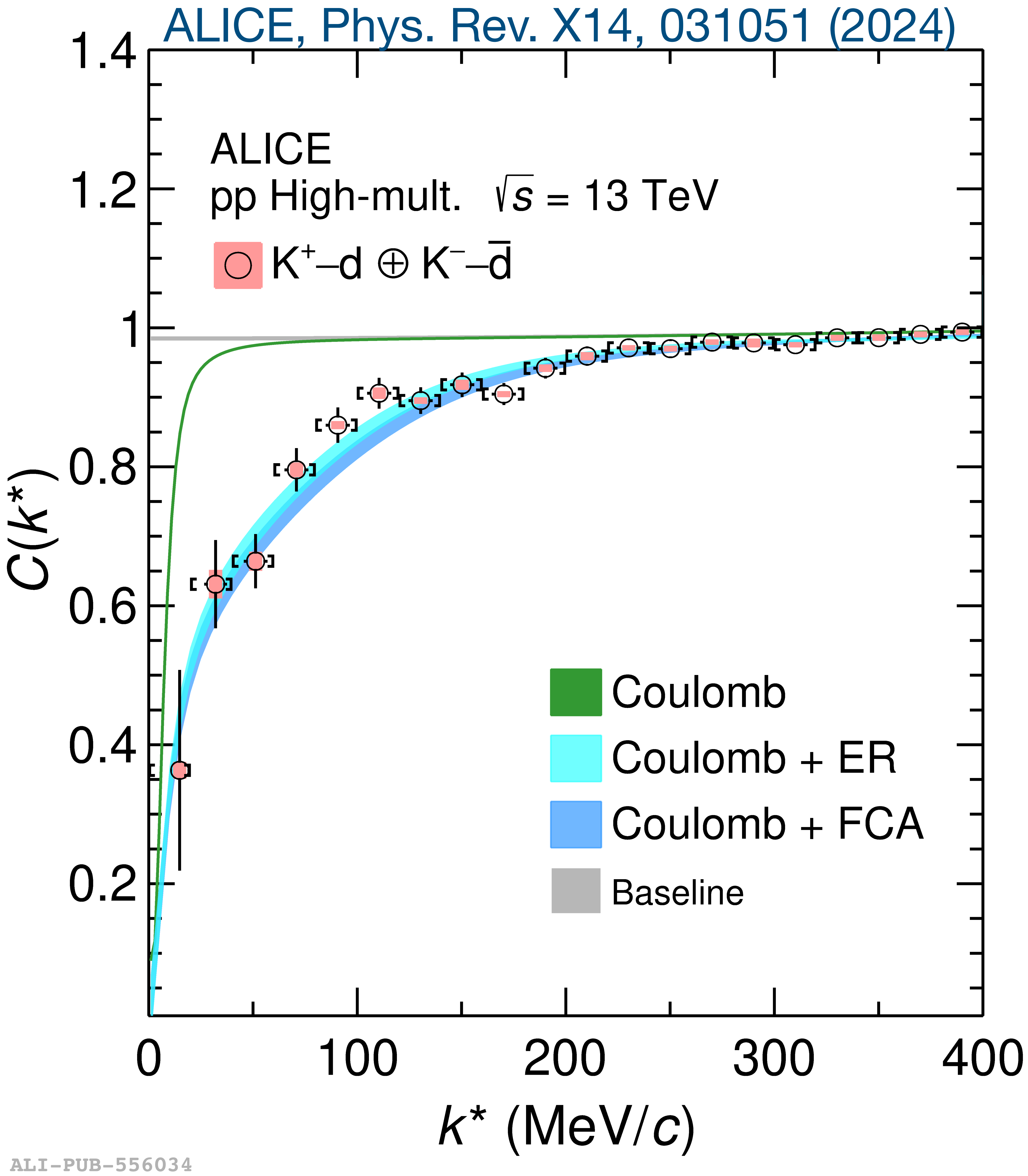

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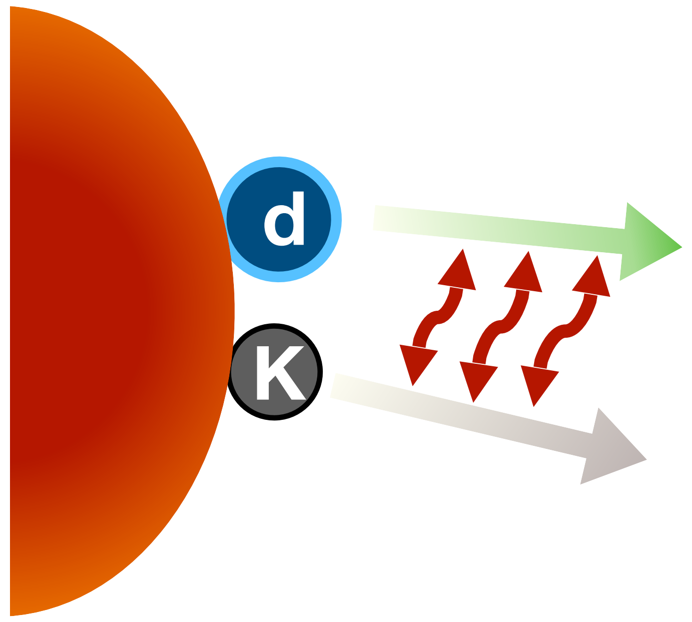
- **Deuterons follow the m_T-scaling, and an effective two-body approach can describe the K$^+$–d system**



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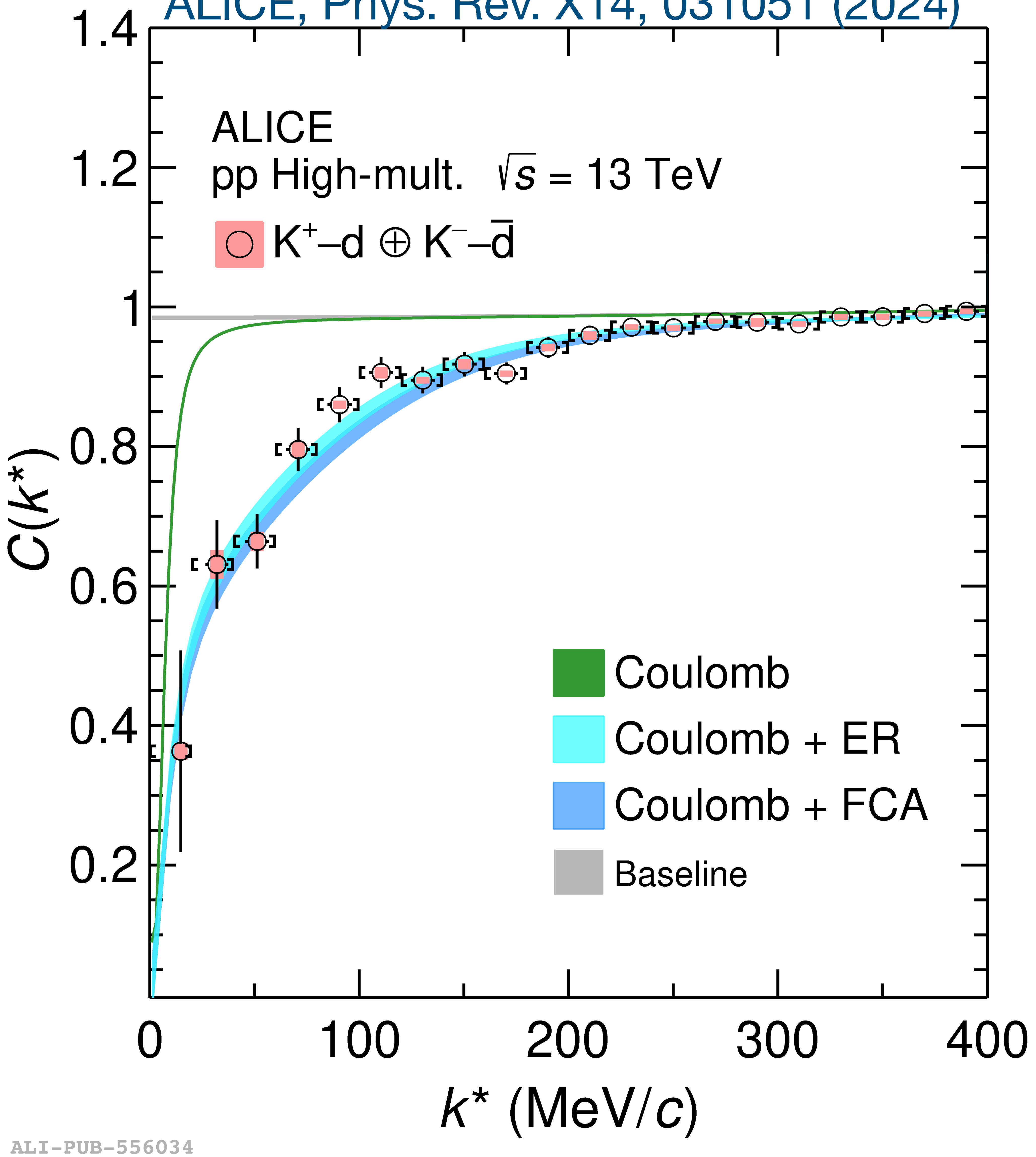

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Proton-deuteron correlation function

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- Source size r_{eff} =1.08±0.06 fm
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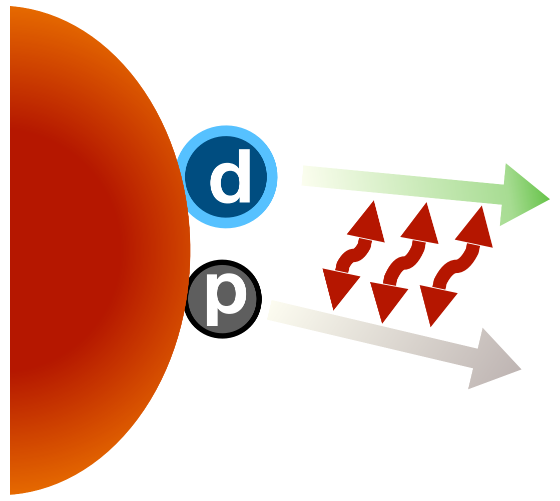

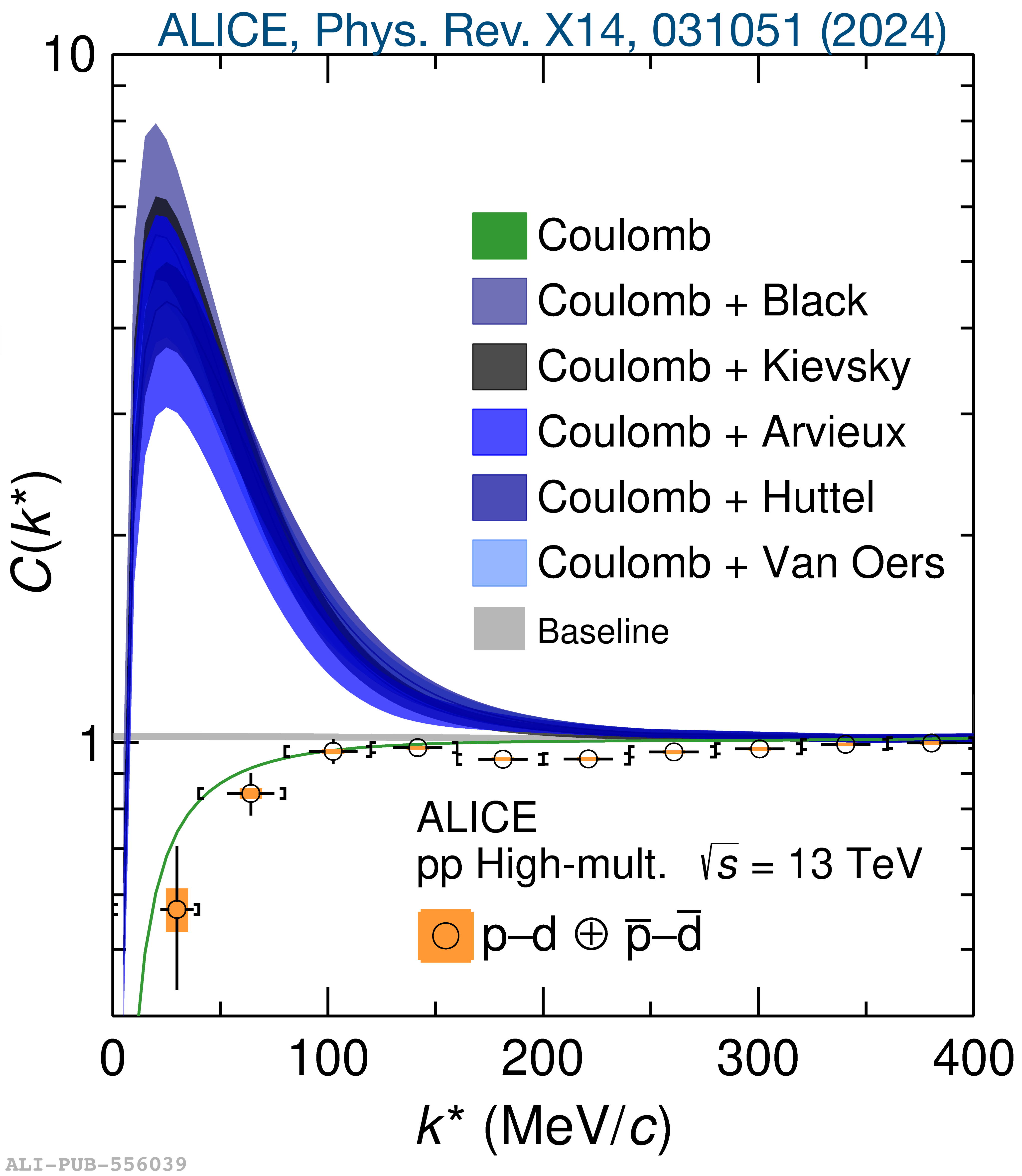

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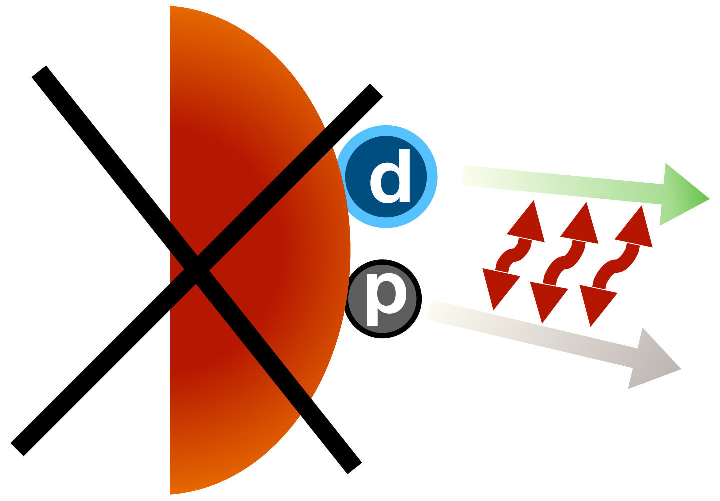

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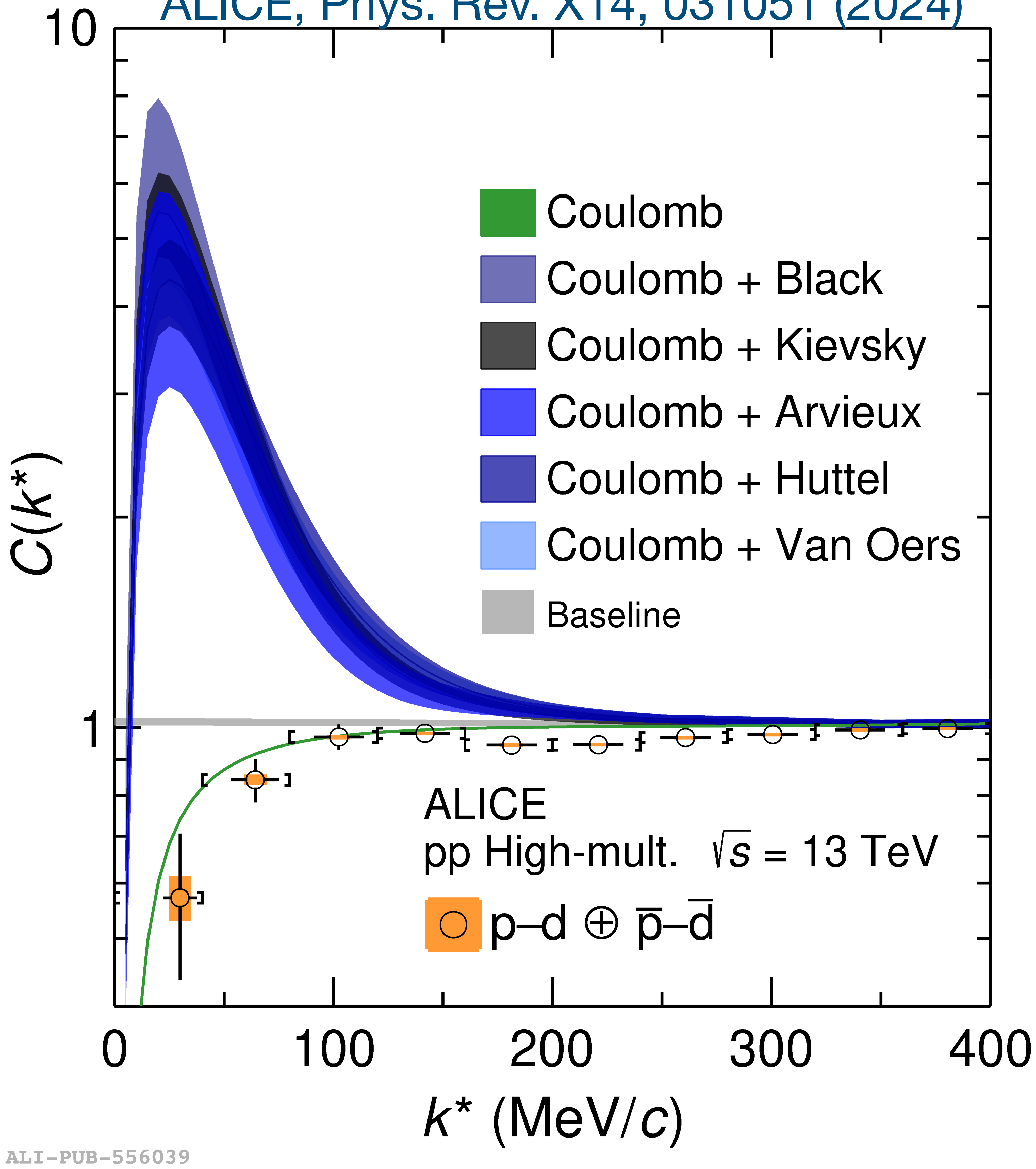

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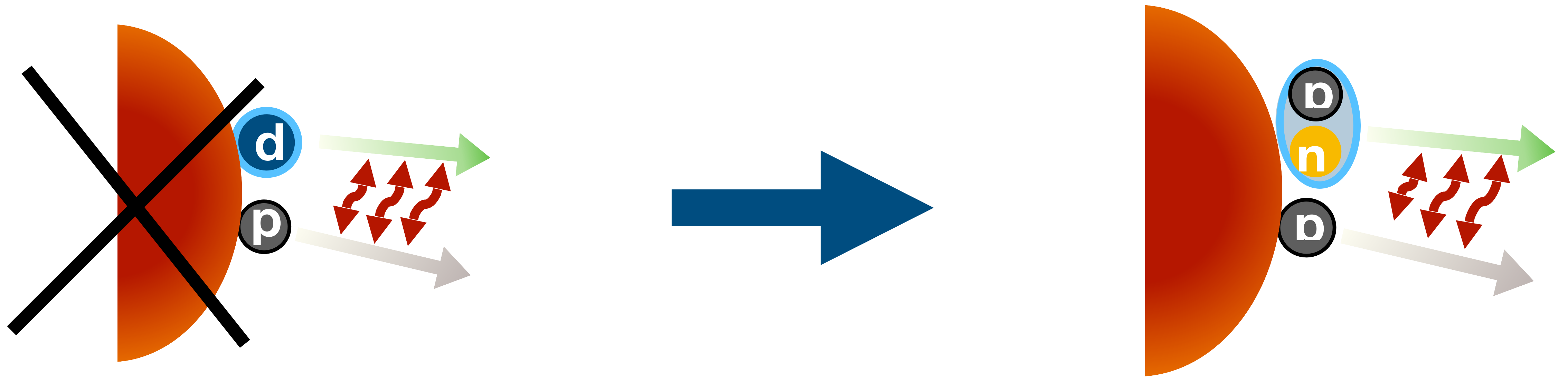

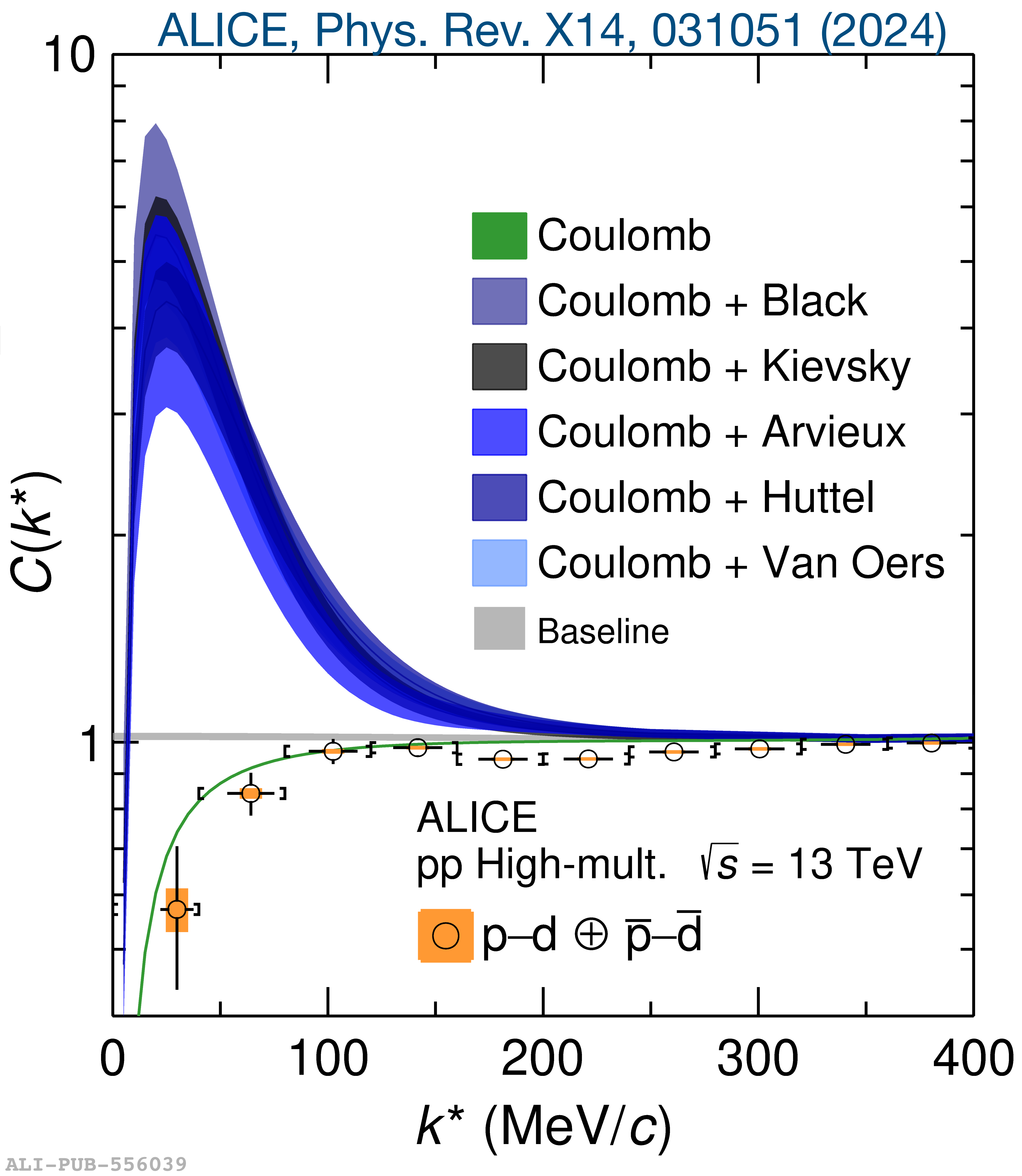

Need for three-body calculations accounting for p–(pn) dynamics

[1] R. Lednicky´, Phys. Part. Nuc. 40, (2009)

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Full three-body treatment for p–d

- Start from p–(pn) system that forms p–d state asymptotically:

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

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M. Viviani, **B. Singh** et al. Phys. Rev. C 108, 064002 (2023)

Michele Viviani, Alejandro Kievsky, and Laura Marcucci from Pisa group
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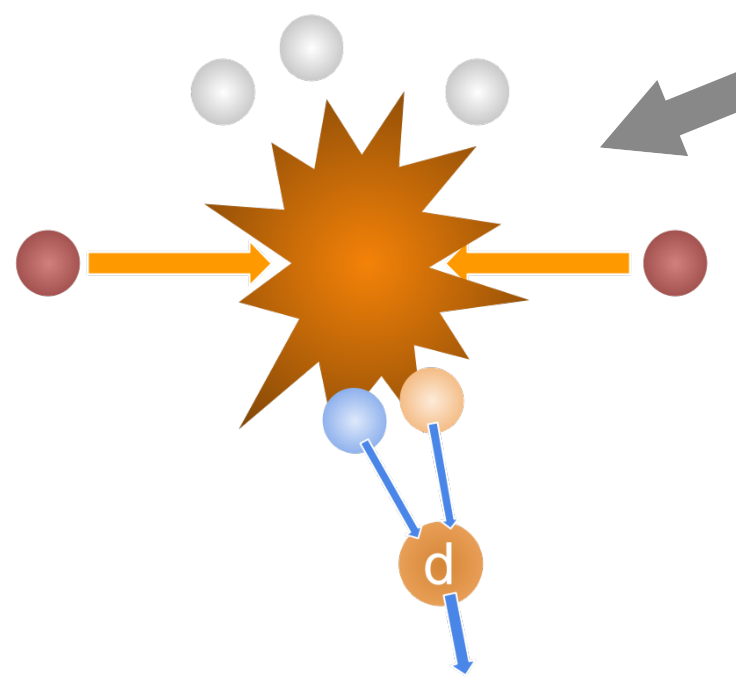

A_d: deuteron formation probability[1]

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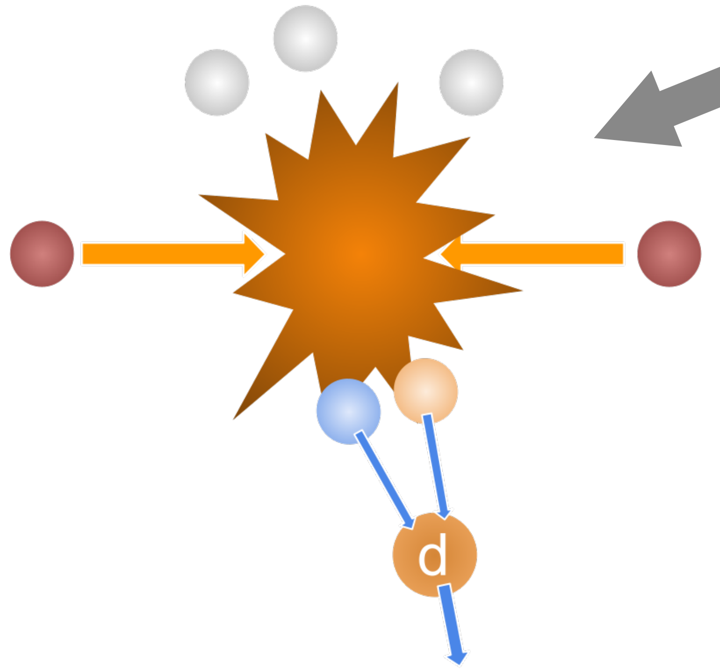

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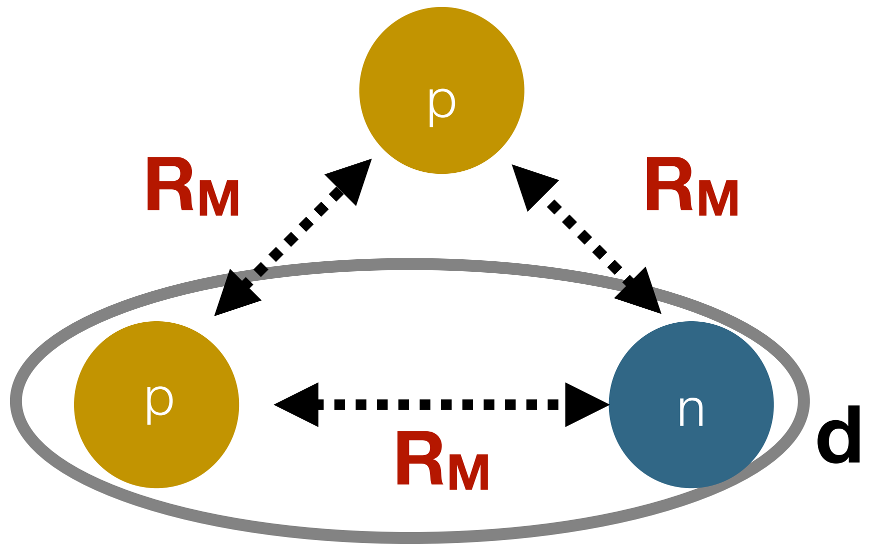

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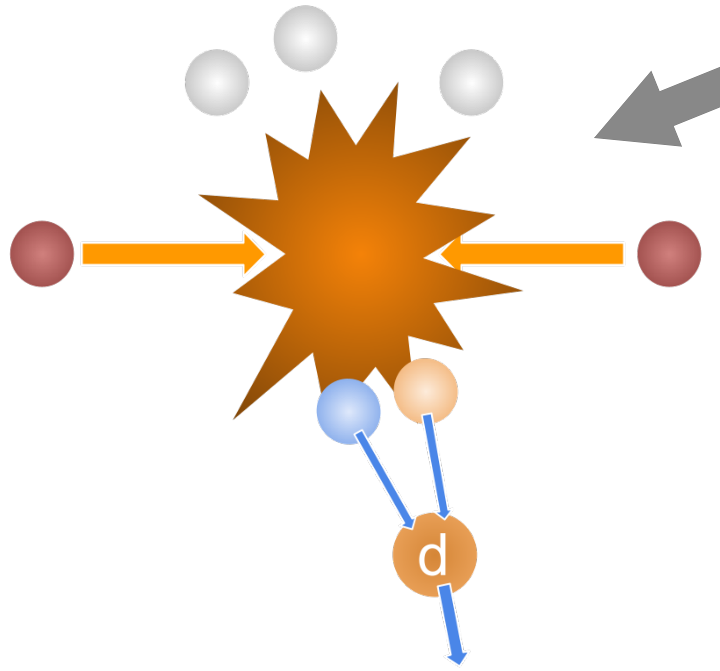

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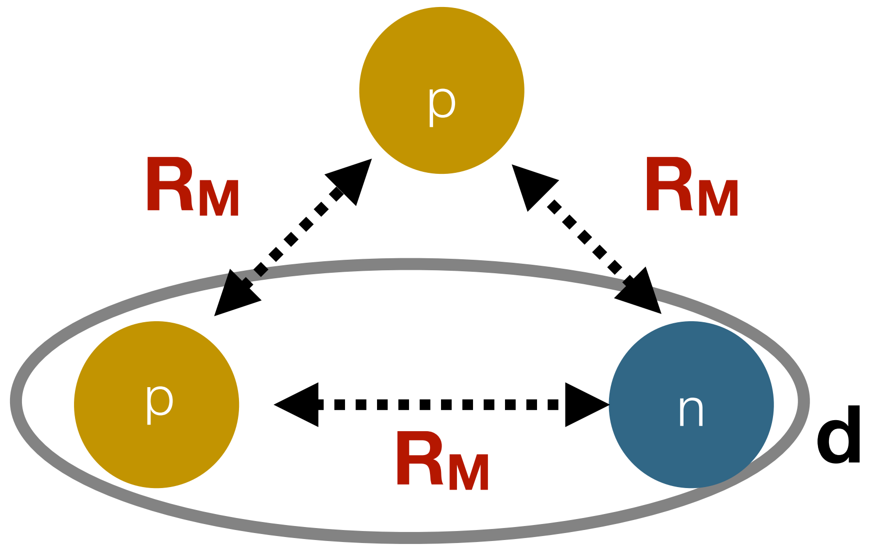

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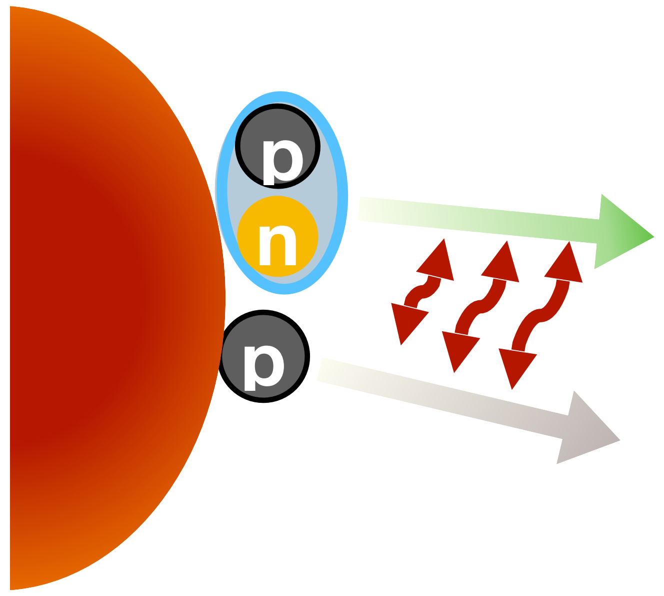

$\Psi(k^*, \rho)$ the three-nucleon wave function

M. Viviani, **B. Singh** et al. Phys. Rev. C 108, 064002 (2023)

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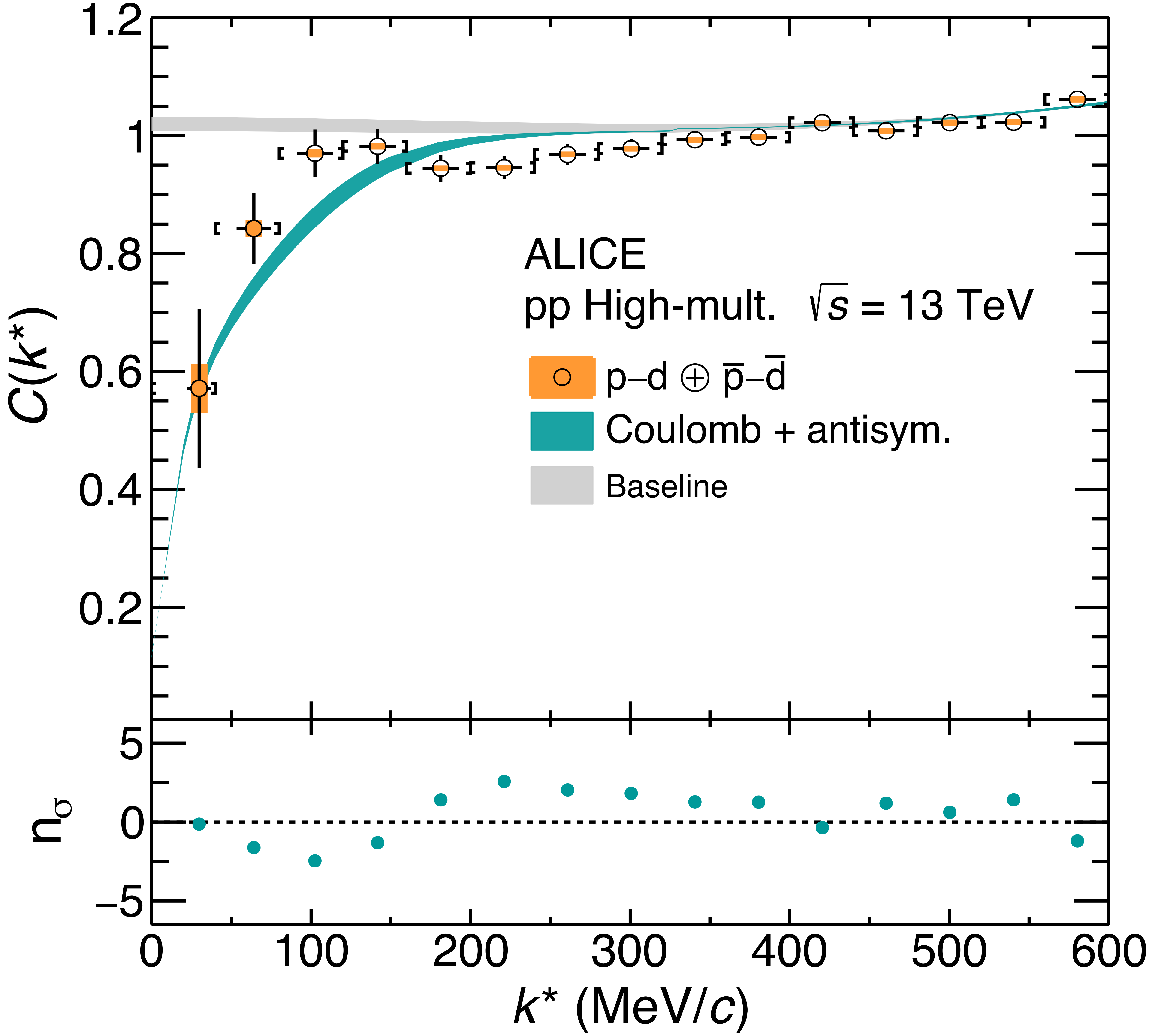
Asymptotic form of strong interaction in p-d system

- Coulomb only: does not describe the data

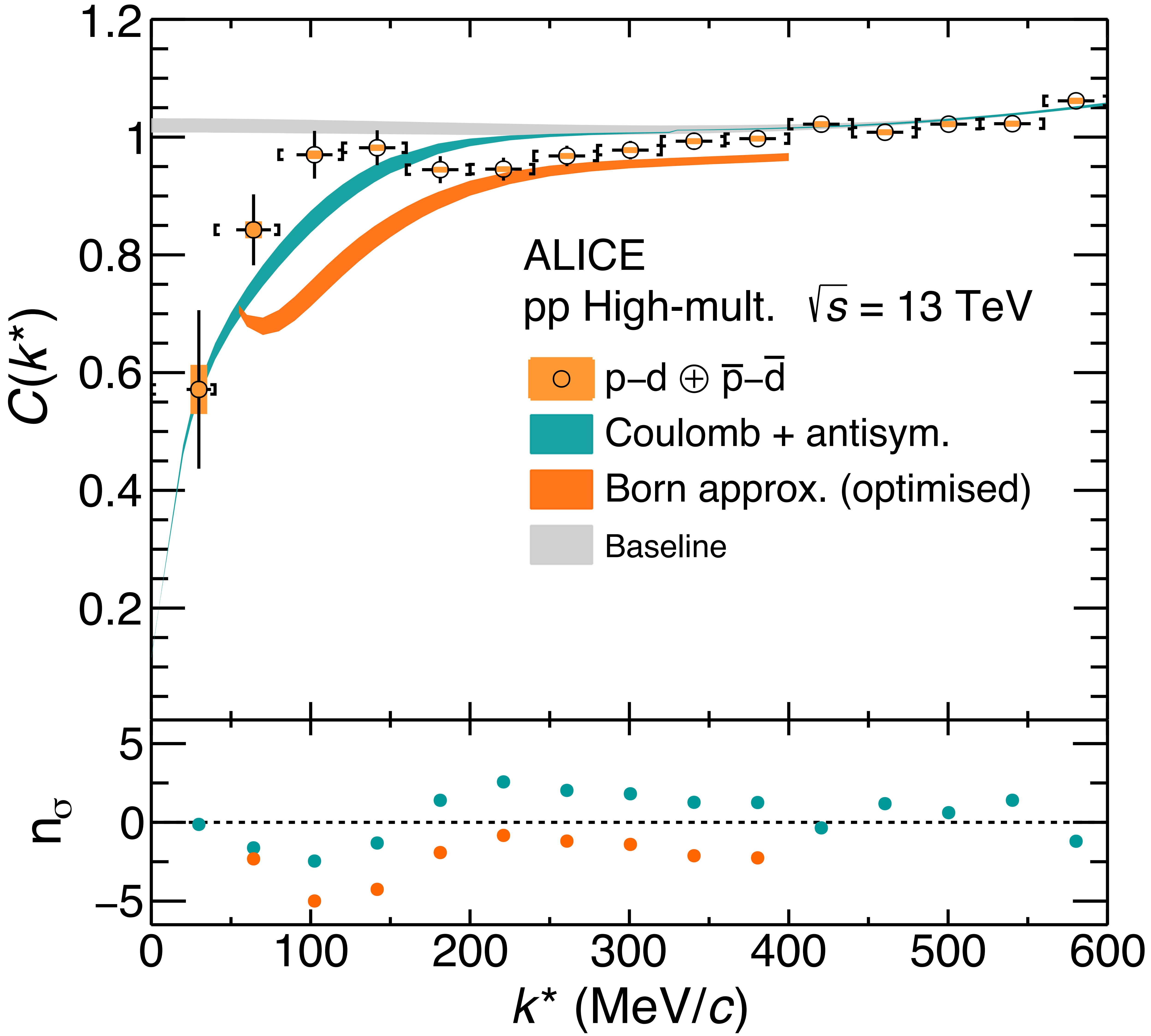
ALICE, Phys. Rev. X14, 031051 (2024)



Asymptotic form of strong interaction in p-d system

- Coulomb only: does not describe the data
- Born approximated wavefunction NN [1-2] NNN potentials[3]
  - Perform antisymmetrization
  - Approximate the wavefunction by ignoring centrifugal core interaction
  - Asymptotic form of strong interaction is insufficient to capture the dynamics of nucleons ~ 1 fm

ALICE, Phys. Rev. X14, 031051 (2024)



[1] M. Viviani, **B. Singh** et al. Phys. Rev. C108,064002 (2023)

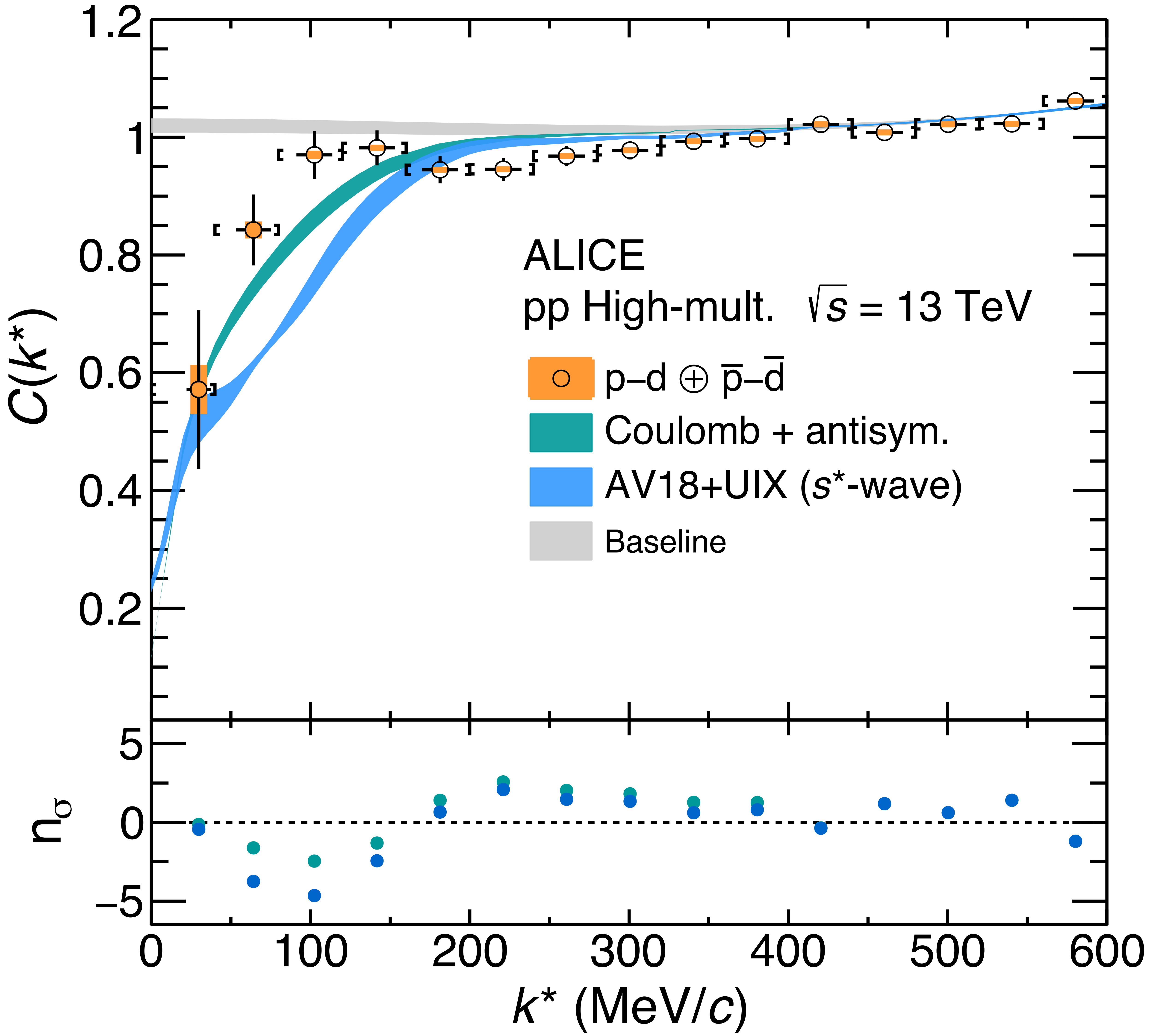
[2] **AV 18 NN potential:** R. B. Wiringa et al. Phys. Rev. C 51, 38 (1995)

[3] **UIX NNN potential:** B. S. Pudliner et al. Phys. Rev. Lett. 74, 4396 (1995)

Two- and three-body interaction at short distance

- Full three-body dynamics at short distances using AV18+UIX potentials[1-3]
  - *s*-wave: undershoots due to repulsion in s-wave

ALICE, Phys. Rev. X14, 031051 (2024)



[1] M. Viviani, **B. Singh** et al. Phys. Rev. C108,064002 (2023)

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[3] **UIX NNN potential:** B. S. Pudliner et al. Phys. Rev. Lett. 74, 4396 (1995)

Two- and three-body interaction at short distance

- Full three-body dynamics at short distances using AV18+UIX potentials[1-3]
  - *s*-wave: undershoots due to repulsion in s-wave
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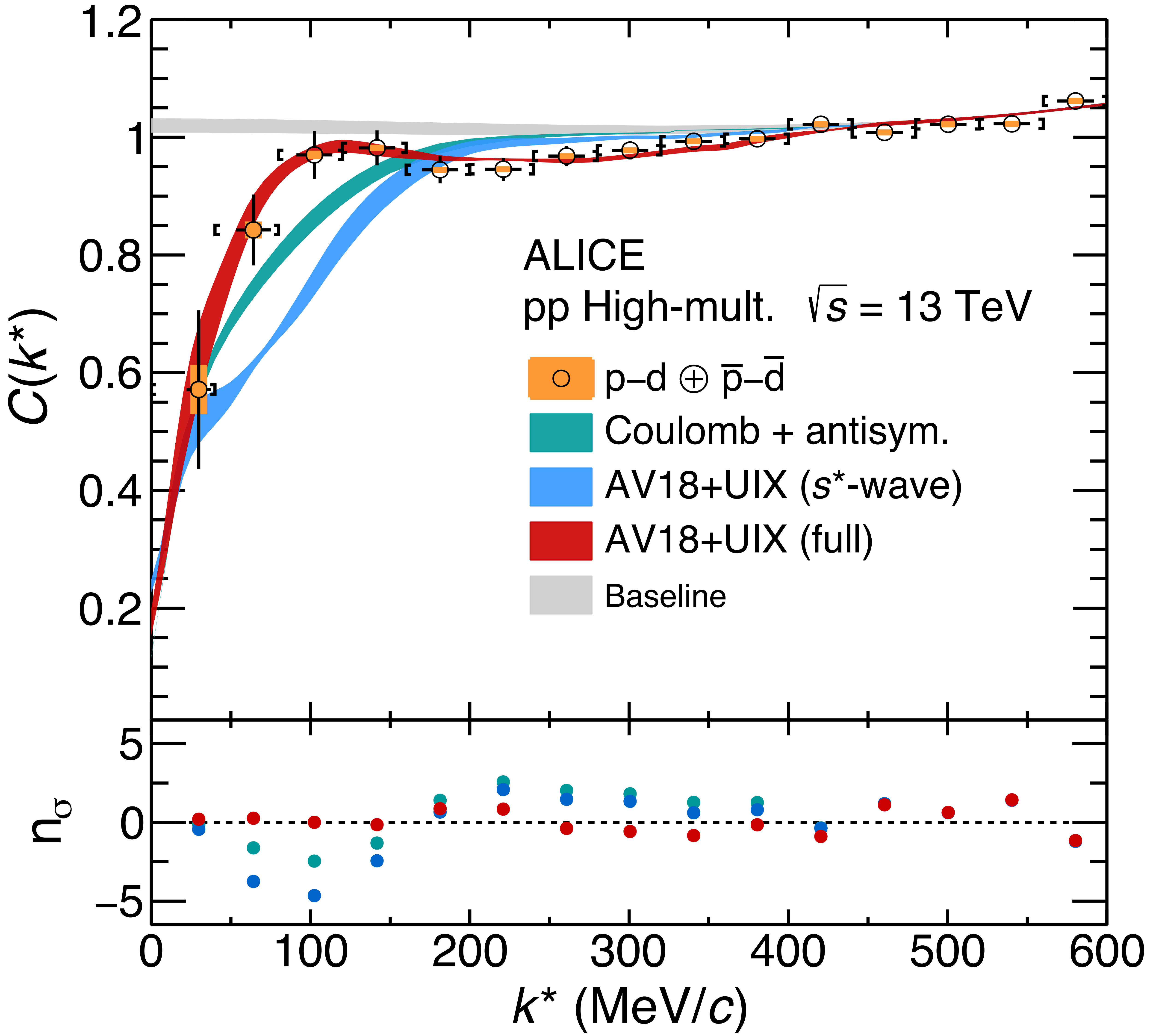

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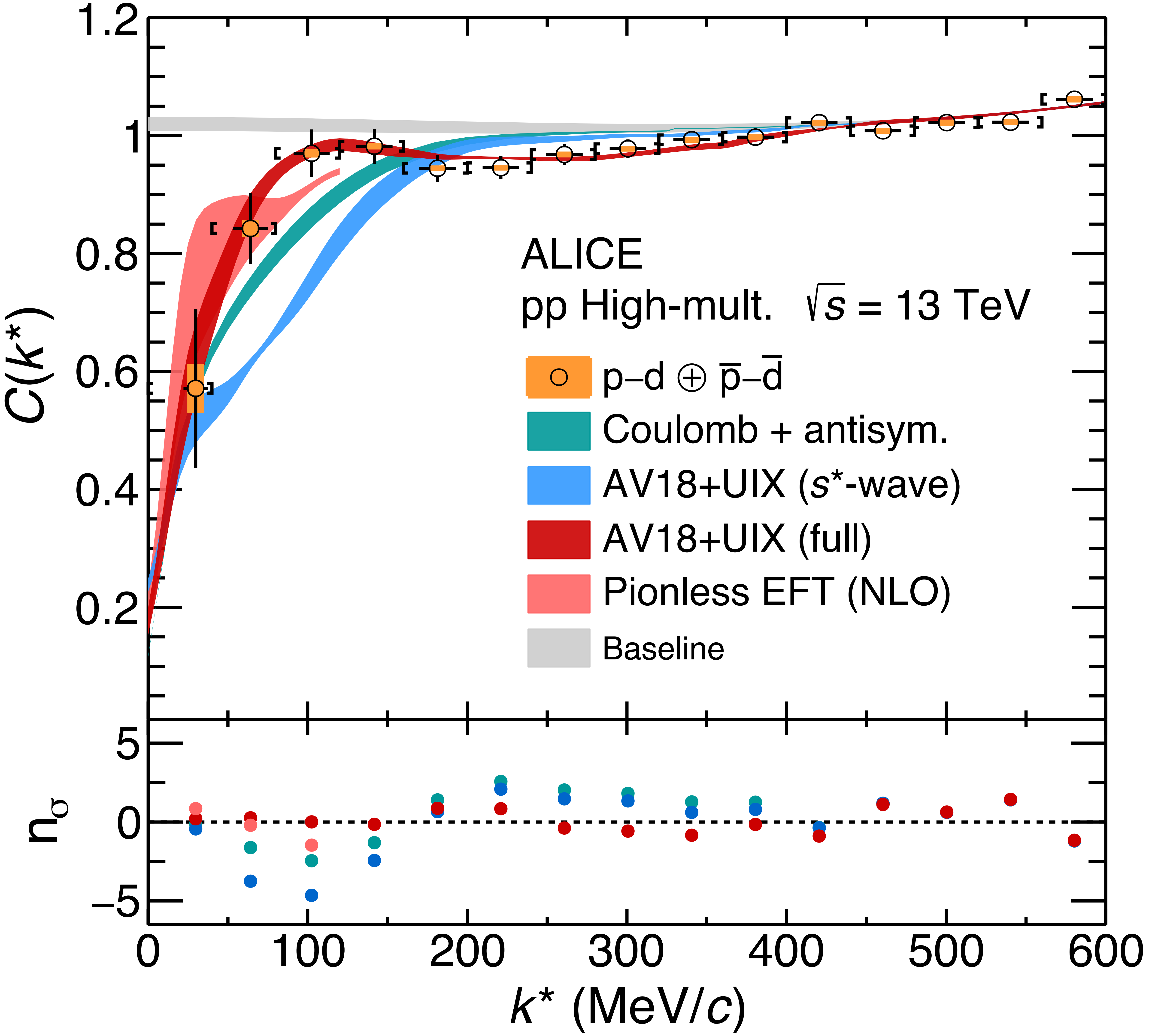
  - All partial waves up to *d*-waves: excellent description ($n\sigma$ ~1 for k^* up to 400 MeV/c)
- Pionless EFT NLO (s+p+d waves):
  - Agree with data within n_σ ~2 for k^* < 120 MeV/c

ALICE, Phys. Rev. X14, 031051 (2024)



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

[1] M. Viviani, **B. Singh** et al. Phys. Rev. C108,064002 (2023)

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Sensitivity to genuine three-body force

- Genuine three-body strong interaction effects:
  - Ratio of CF with and without UIX potential[1]
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  - LHC Run 2: limited statistics

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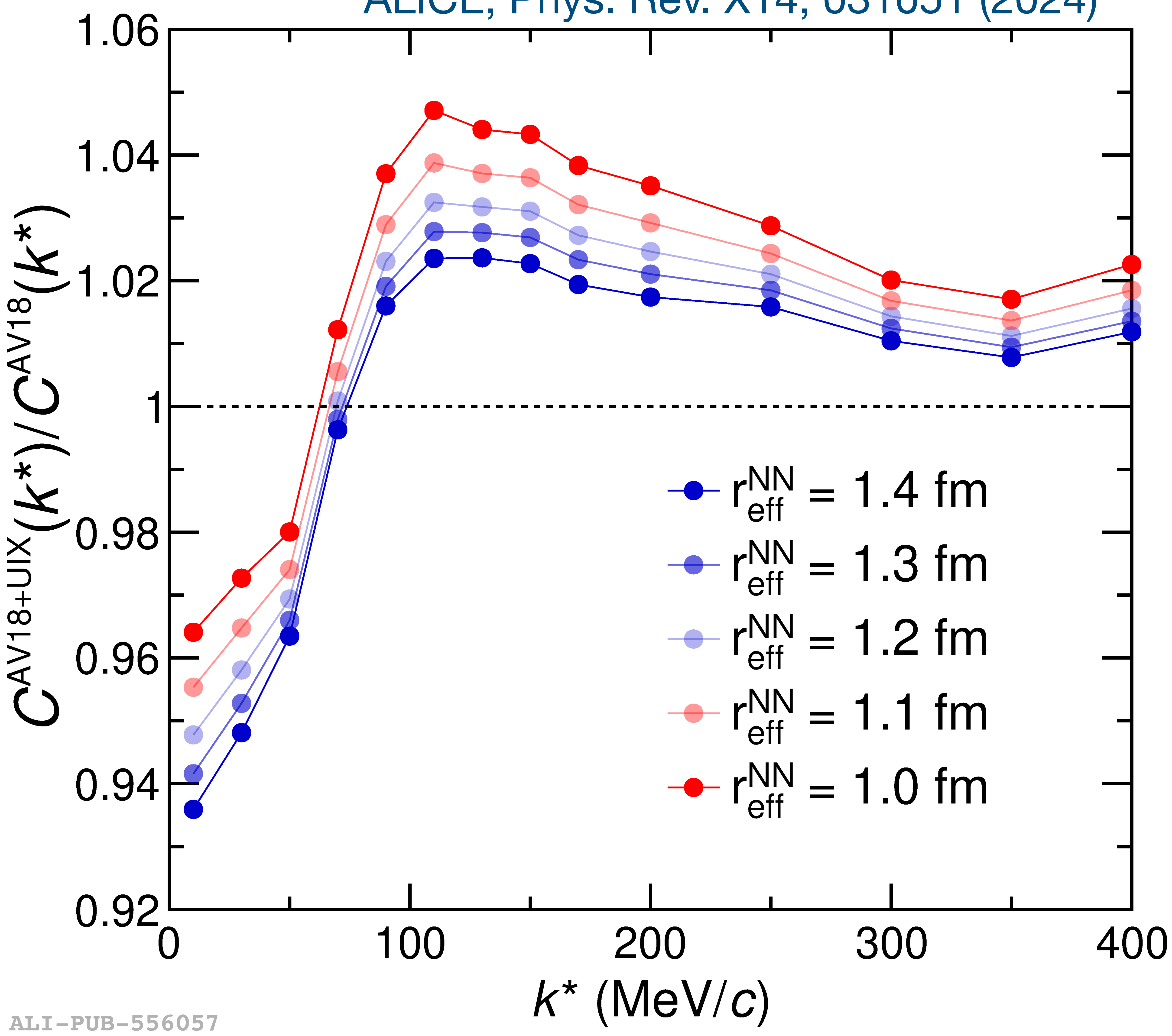

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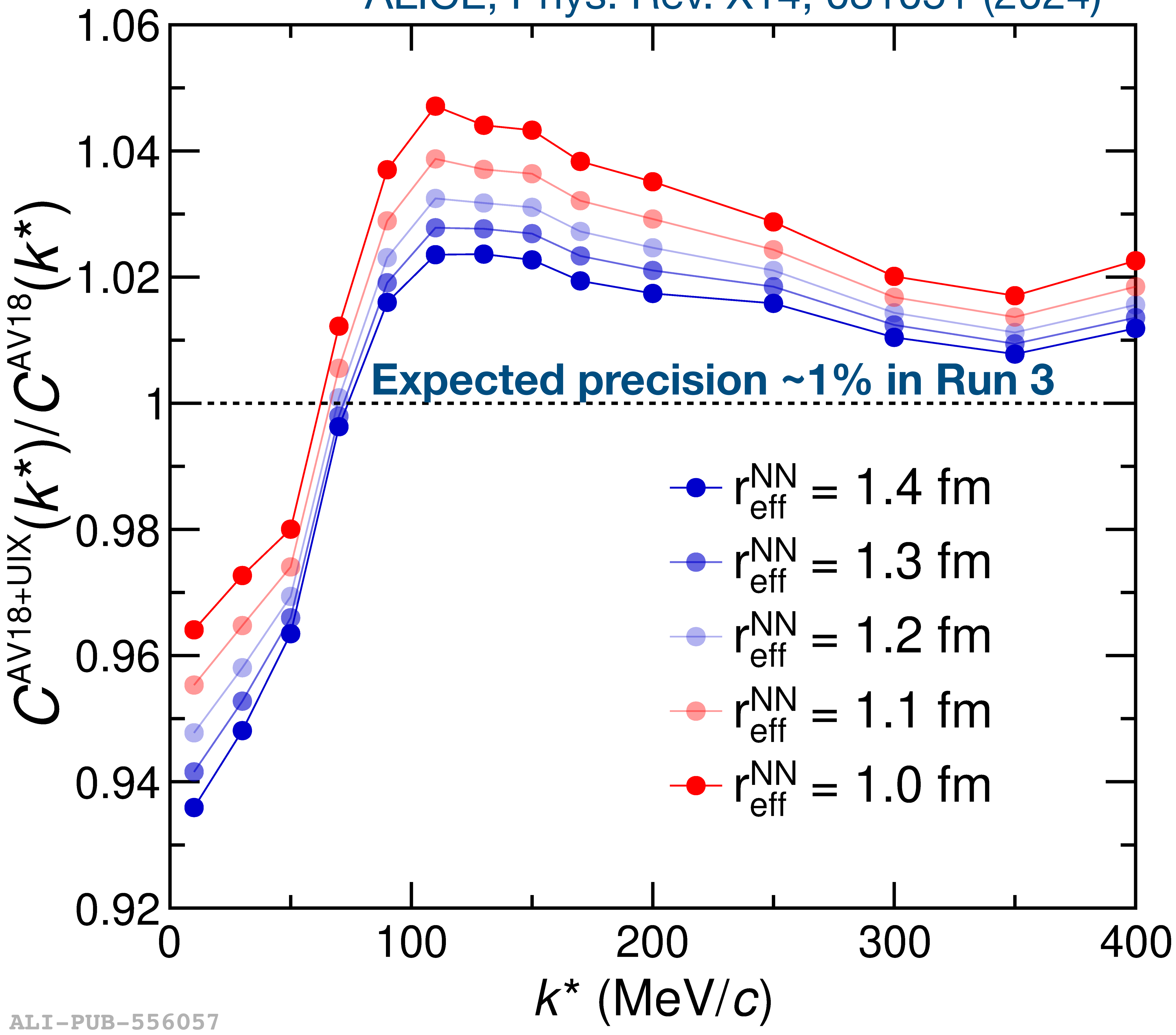
  - Possibility to perform m_T differential analysis

ALICE, Phys. Rev. X14, 031051 (2024)



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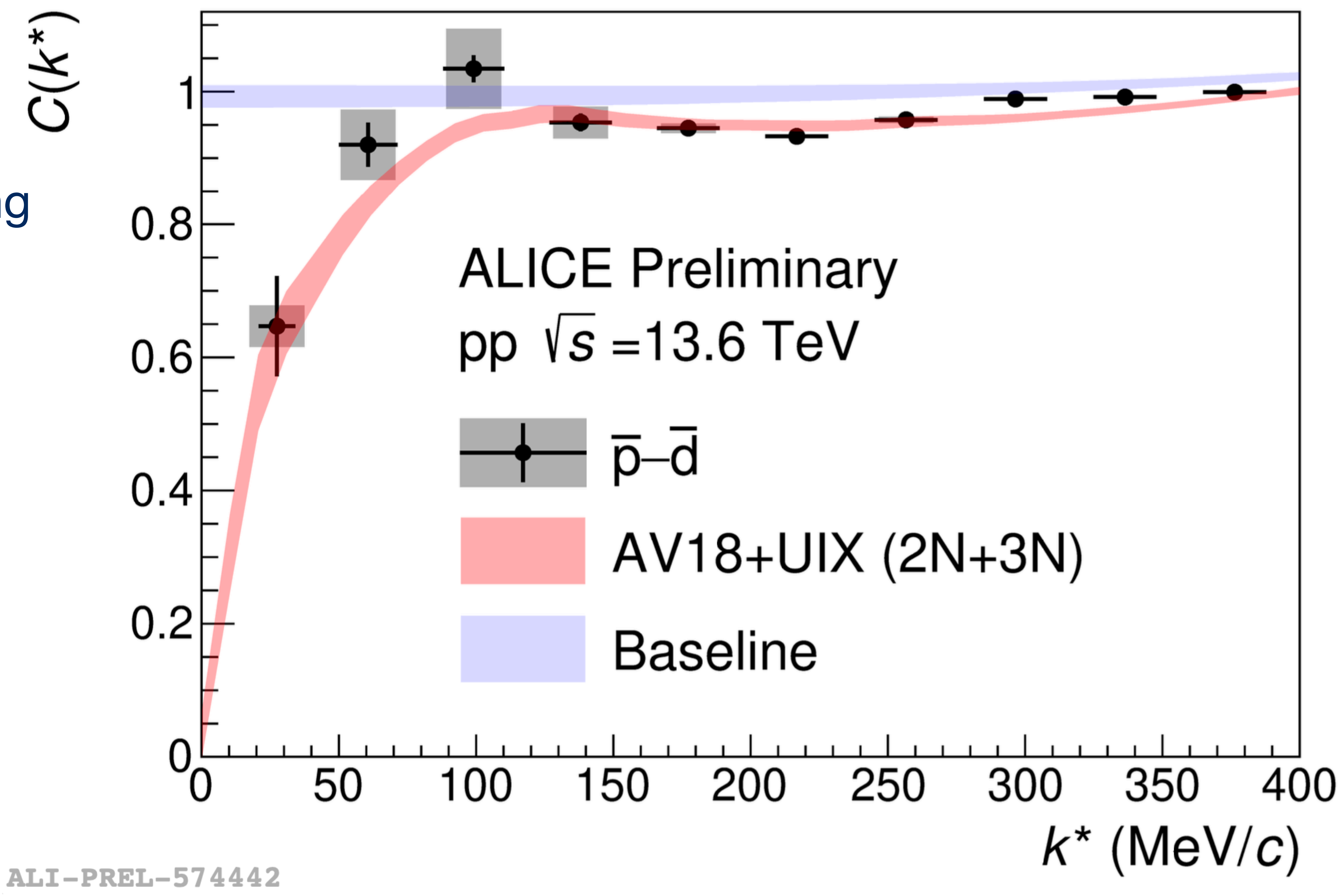

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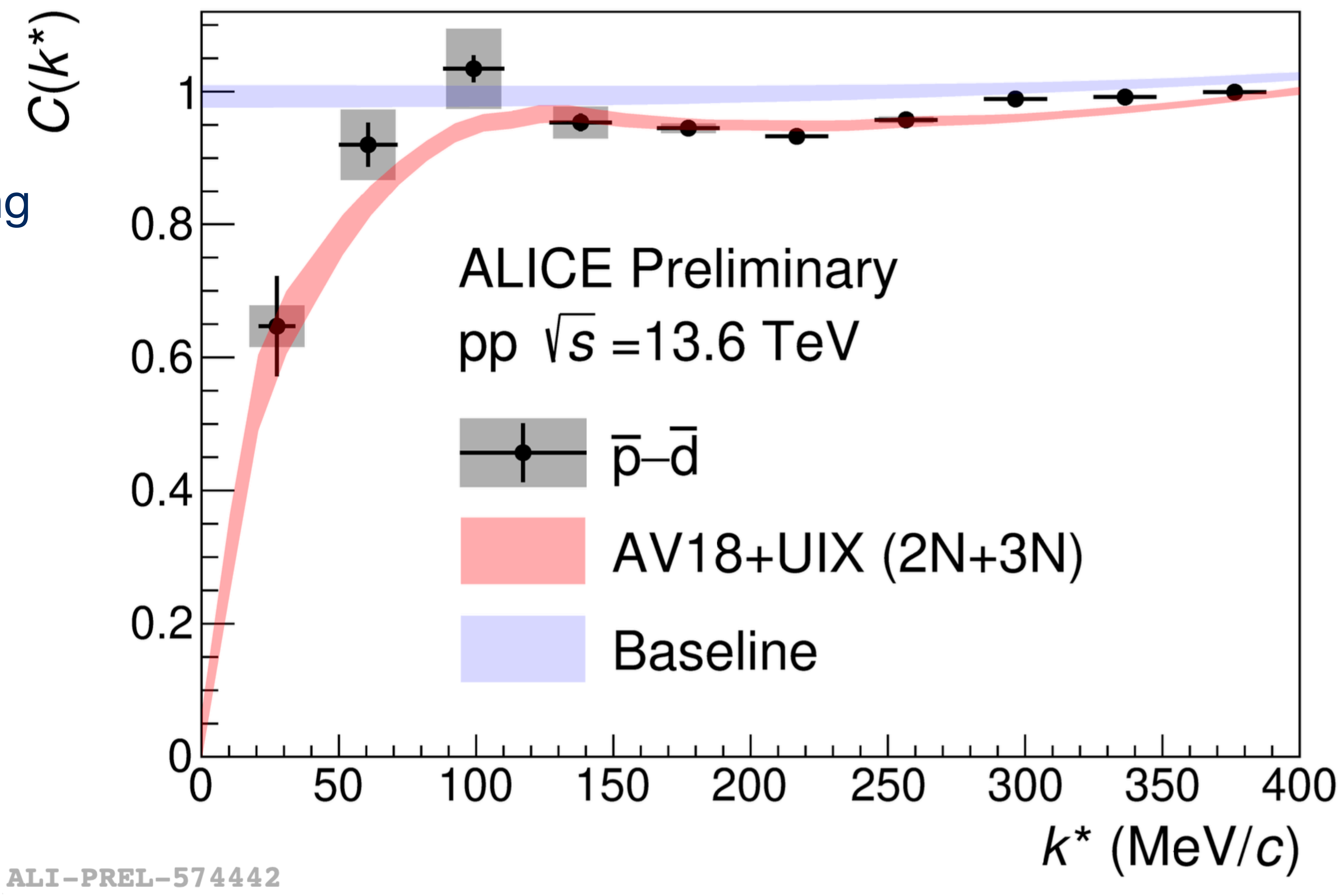
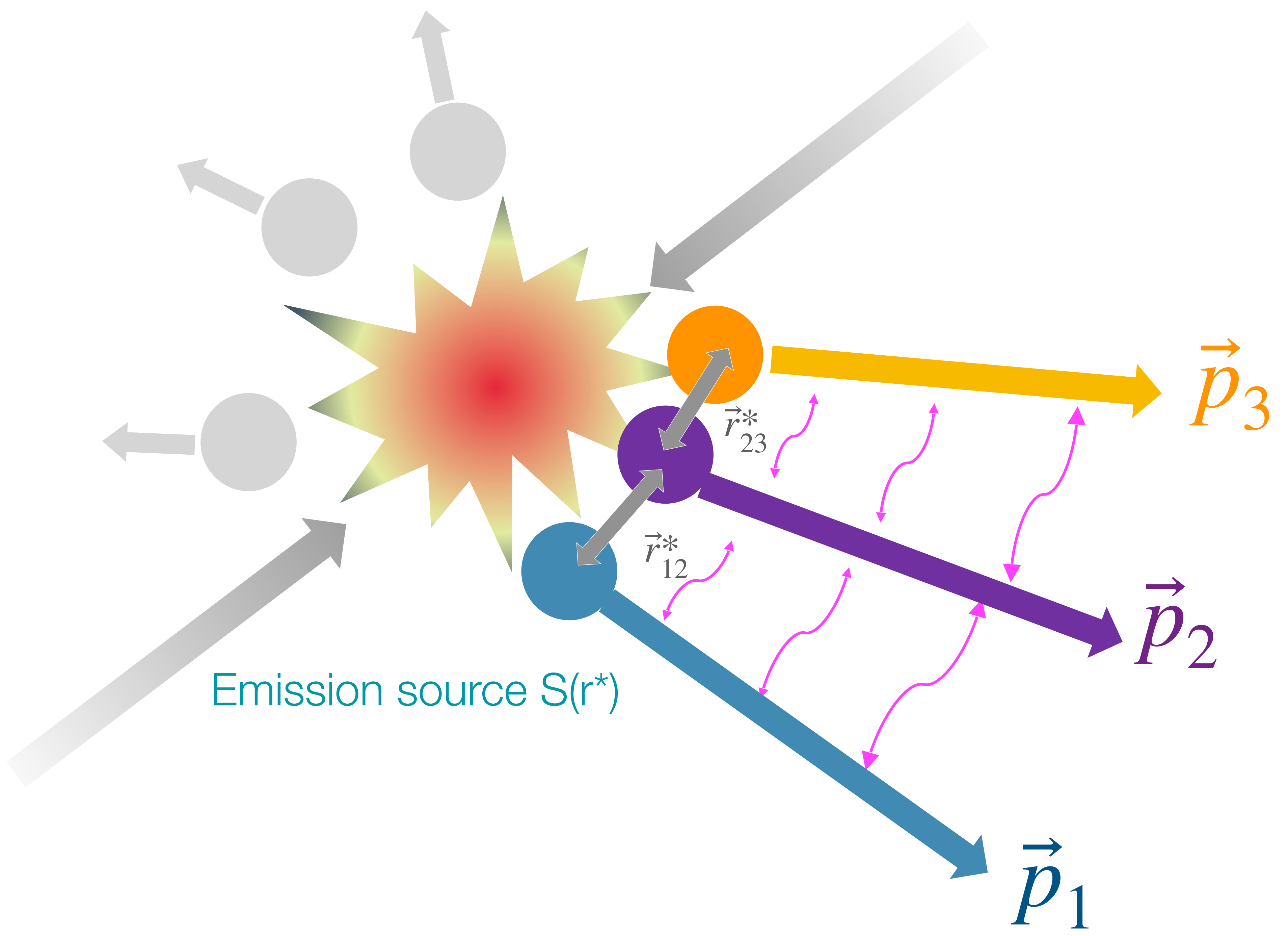


Avenue for the study of hadron–deuteron systems, including charm and strange hadrons!

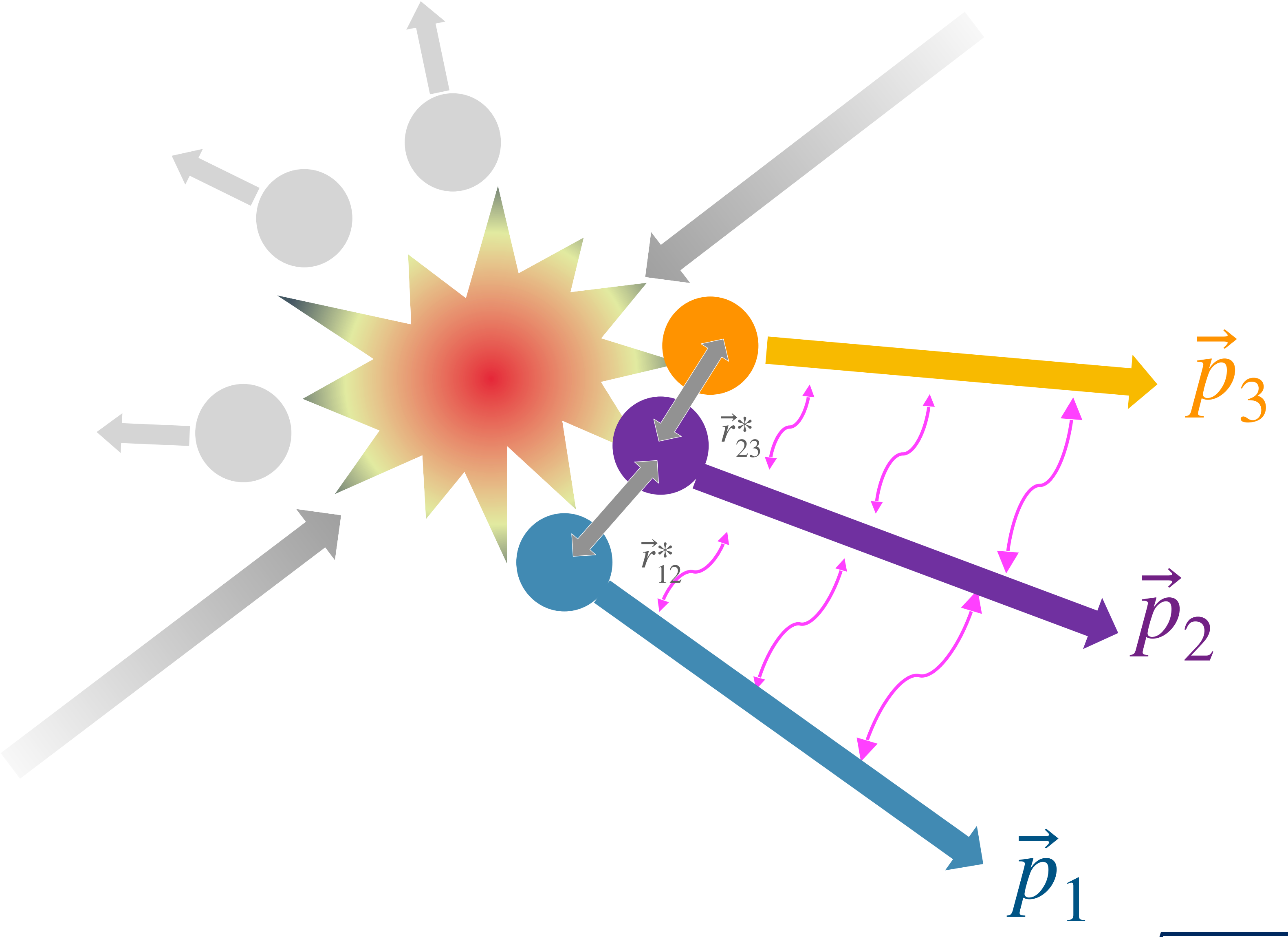
[1] M. Viviani, **B. Singh** et al. Phys. Rev. C108,064002 (2023)



Study correlations among three unbound hadrons
(3 to 3 scattering process)

Three-body femtoscopy

- Study interaction in hadron-triplets via three-particle correlations



- Use Lorentz-invariant hyper-momentum $Q_3 = \sqrt{-q_{12}^2 - q_{23}^2 - q_{13}^2}$

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

experimental definition [1-2]

$$C\left(Q_3\right) = \int S(\rho) \left| \Psi \left(Q_3, \rho\right) \right|^2 \rho^5 \, \mathrm{d}\rho$$

theoretical definition [3]

$$\rho = 2\sqrt{r_{12}^2 + r_{23}^2 + r_{31}^2}$$

[1] ALICE Coll, Eur. Phys. J. A 59, 145 (2023)
[2] R. Del Grande et al, Eur. Phys. J. C 82 (2022) 244
[3] A. Kievsky et al, Phys. Rev. C 109 (2024) 3, 034006

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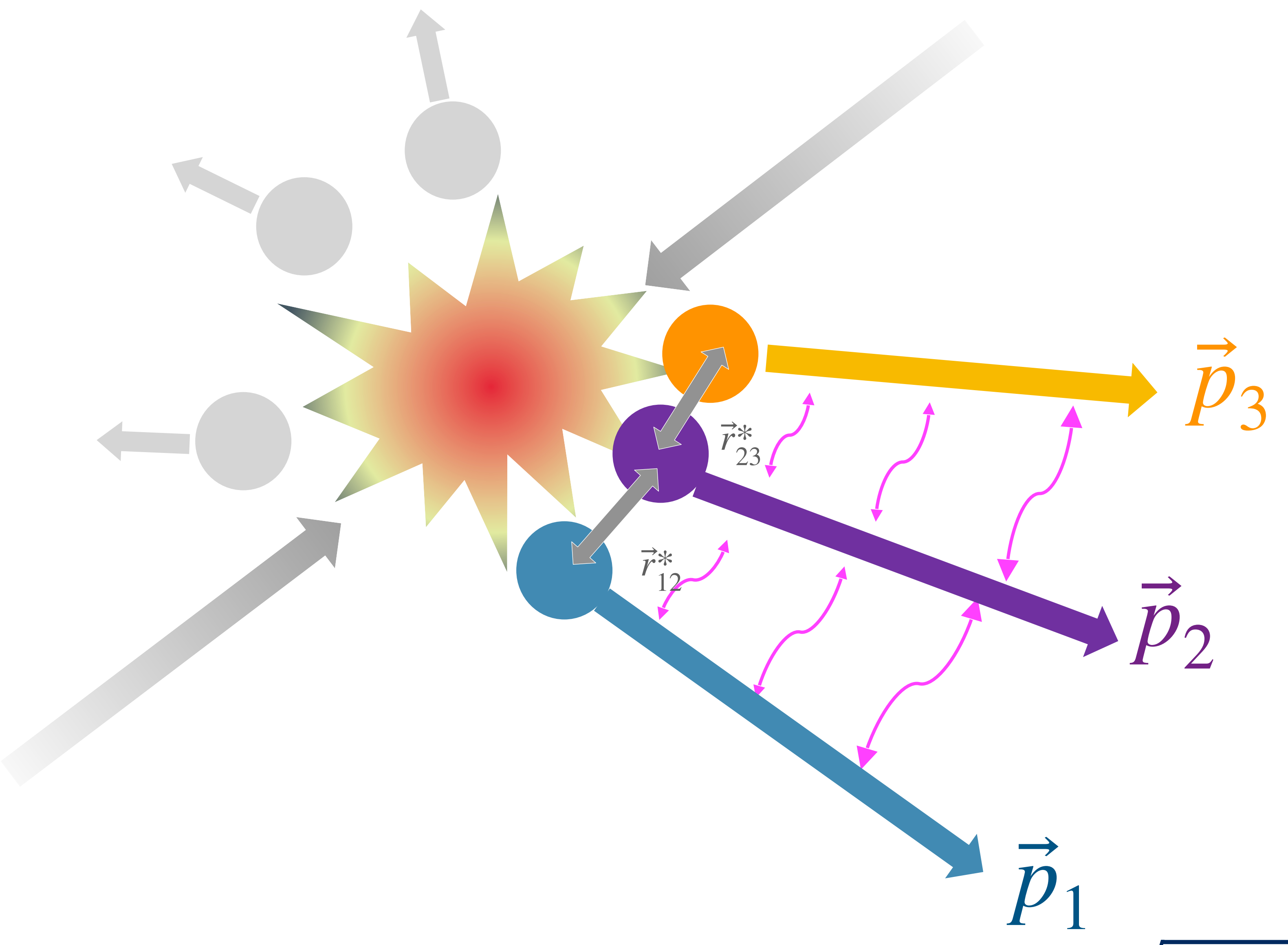

Exp:

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

ALICE Coll., EPJ A 59, 298 (2023)

Theory (Munich and PISA group)

R. Del Grande et al. EPJC 82 (2022) 244

M. Viviani et al, PRC 108 (2023) 6, 064002

A. Kievsky, et al., PRC 109 (2024) 3, 034006

B. E. Garrido et al., arXiv: 2408.01750 (2024)

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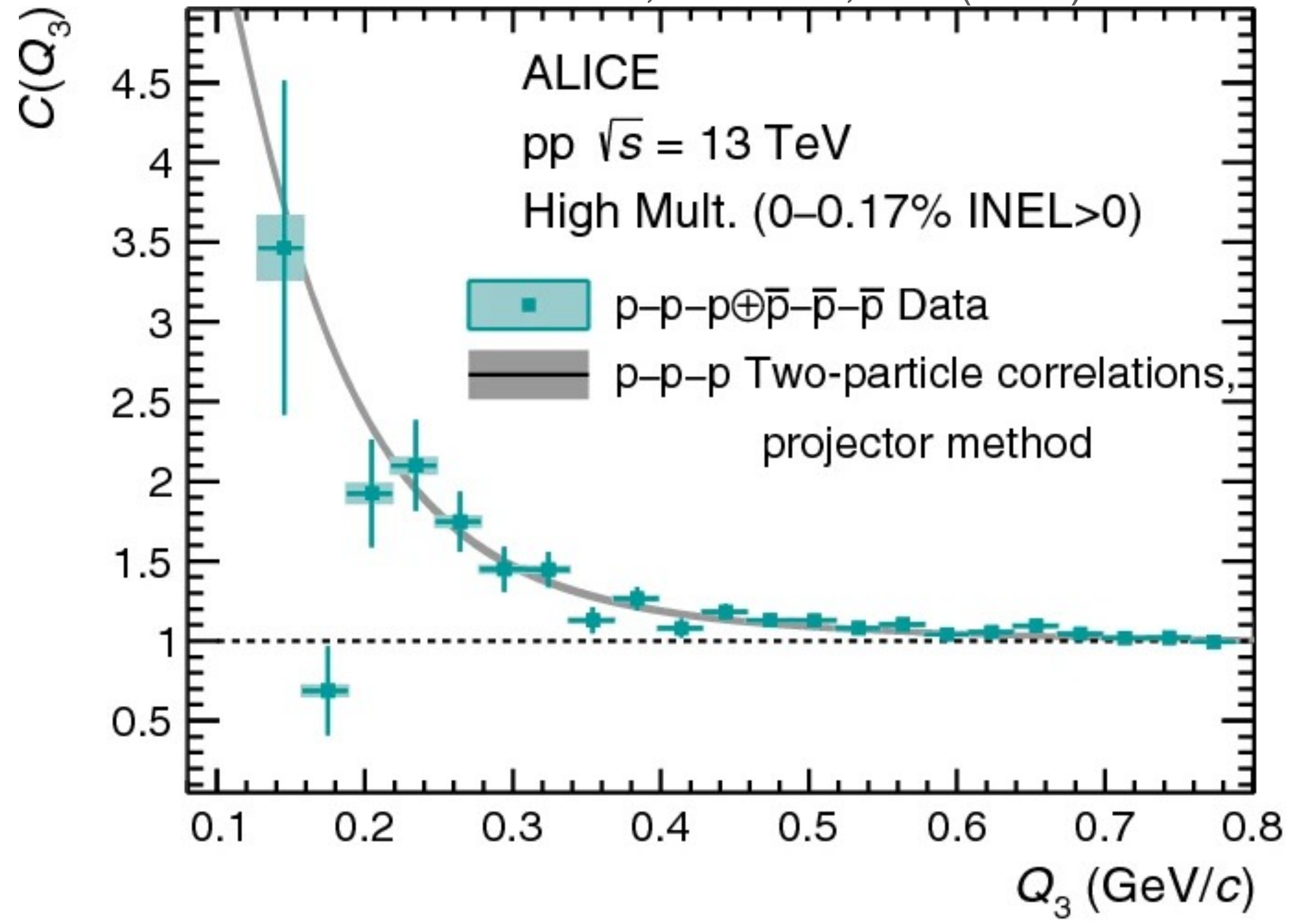
Three-body femtoscopy with ALICE

- Hadron-triplets via three-particle correlations: p–p–p and p–p–Λ

ALICE Coll, EPJA 59, 145 (2023)



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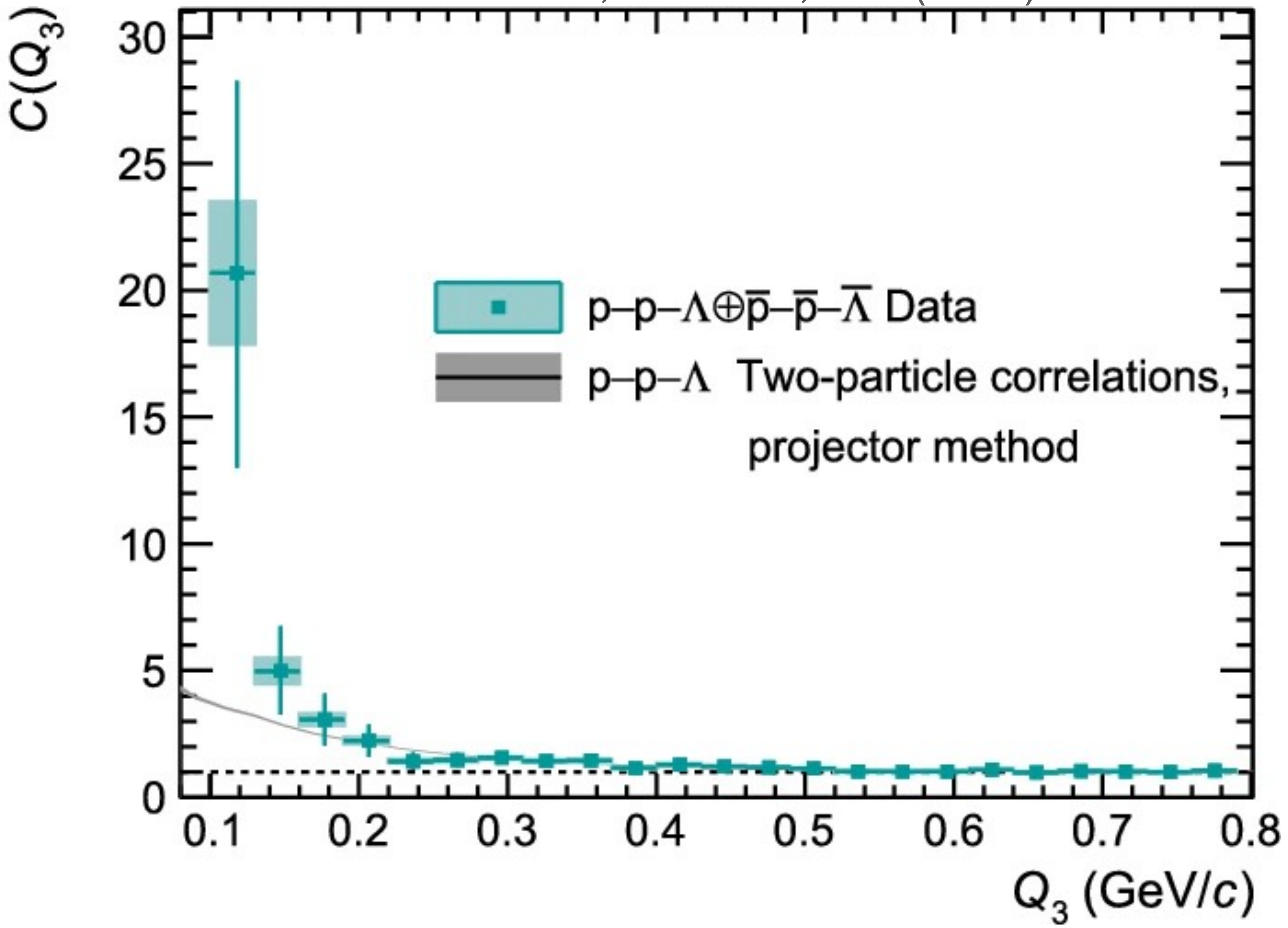

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Projector: Del Grande et al, Eur. Phys. J. C 82, 244 (2022)

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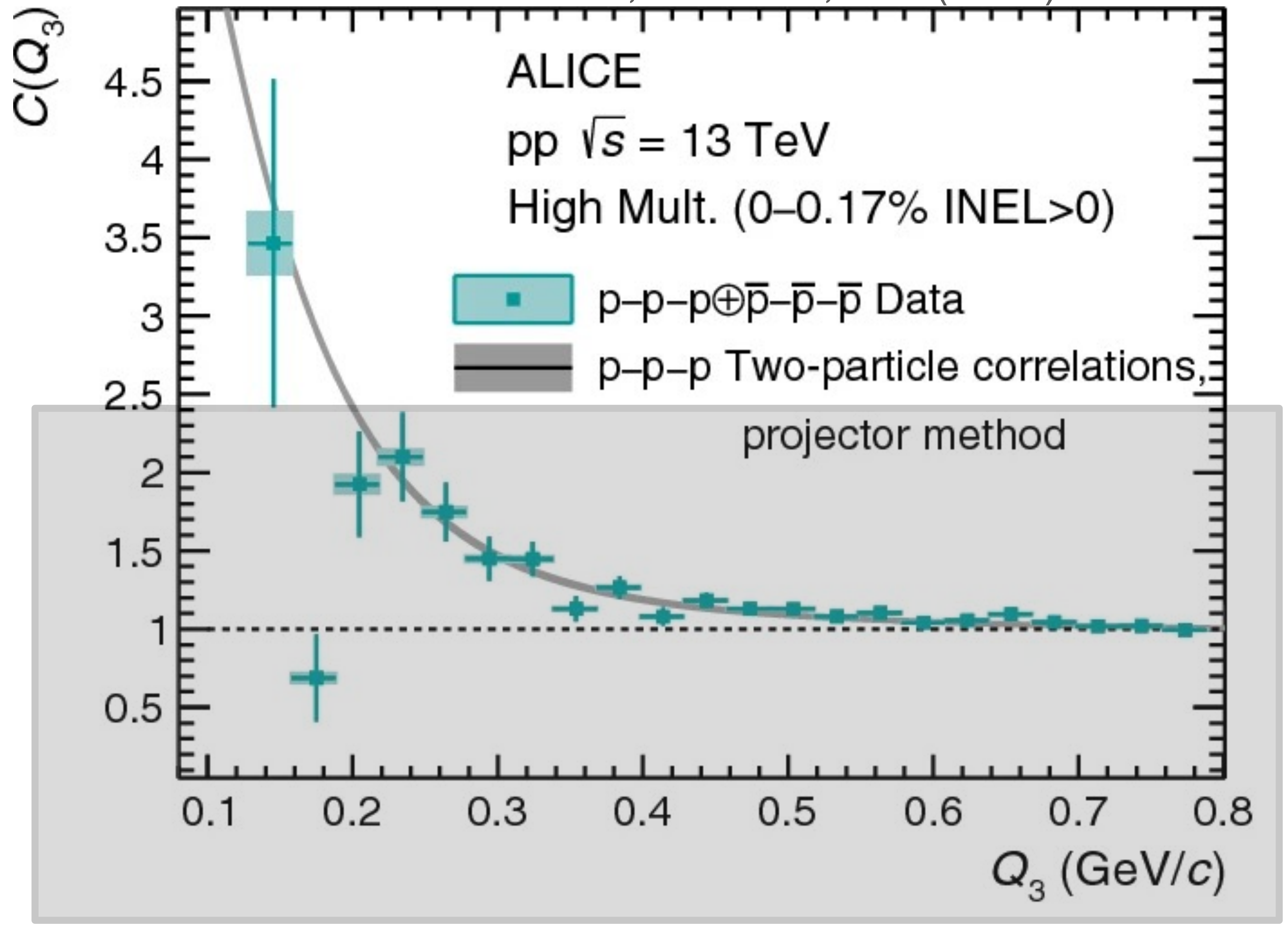

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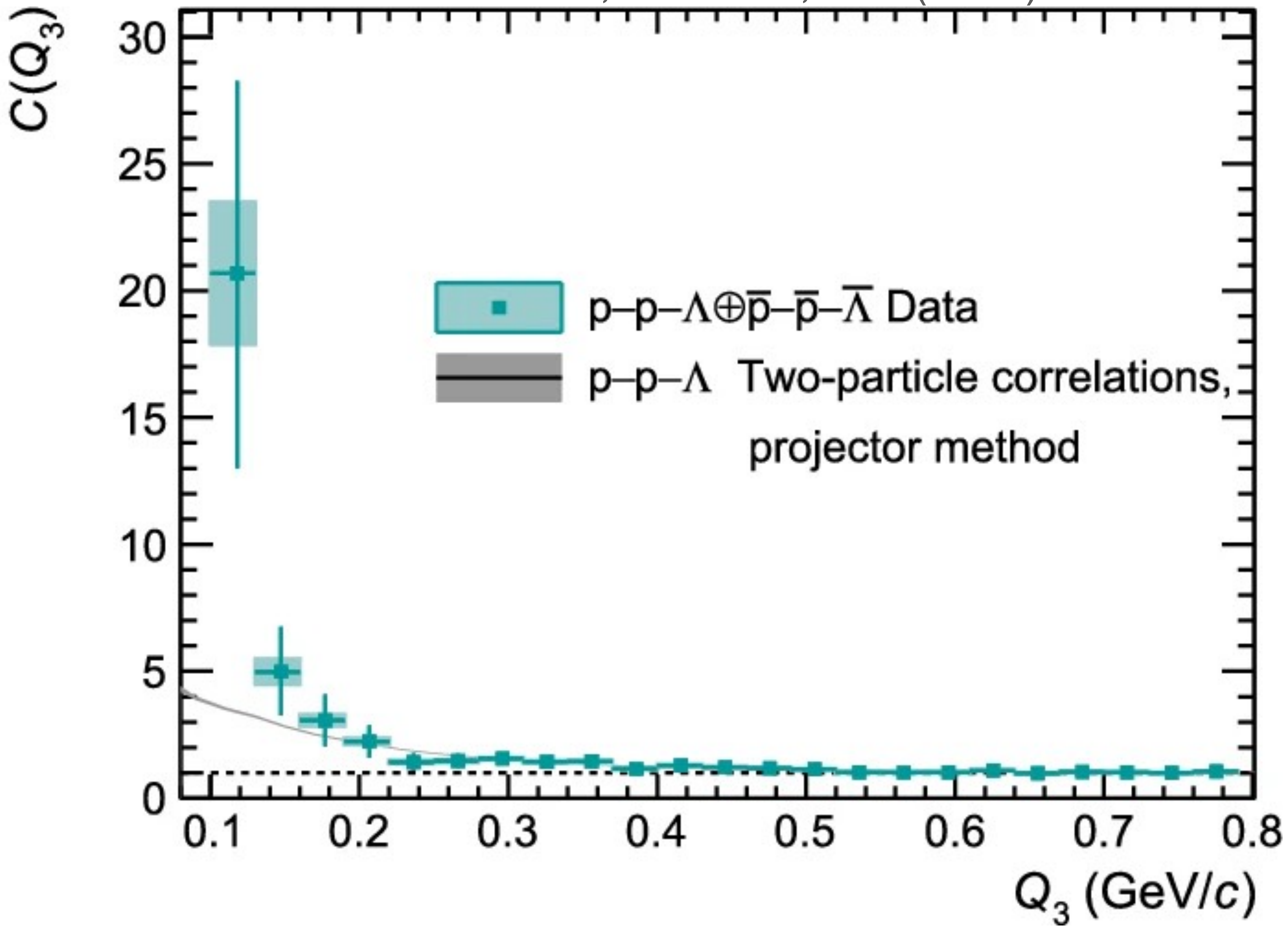

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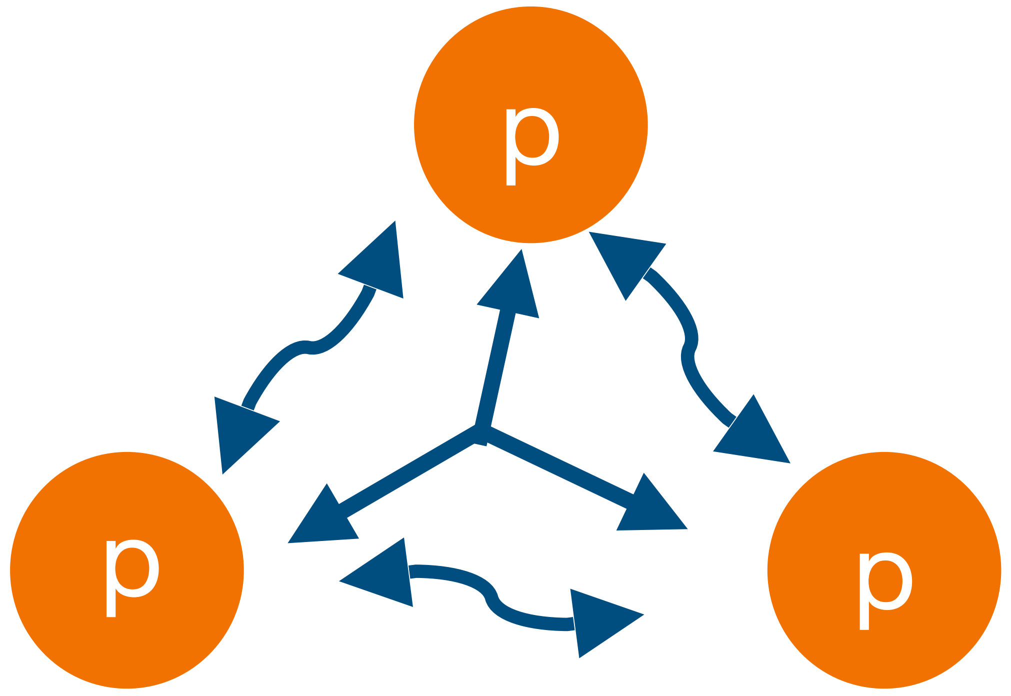
p–p–p correlation using AV18 potential

- Three-body correlation function AV18 and UIX potential[1]

$$C\left(Q_3\right) = \int S(\rho)\left|\Psi\left(Q_3,\rho\right)\right|^2 \rho^5\,\mathrm{d}\rho$$

- $\Psi(Q_3,\rho)$ computed using **only pp AV18** strong interaction, Coulomb corrections, and quantum statistics
- Negligible contribution from NNN (via UIX) found < 1%
- Attractive AV18 interaction: results peak
- Pauli-blocking: depletion in $C(Q_3)$



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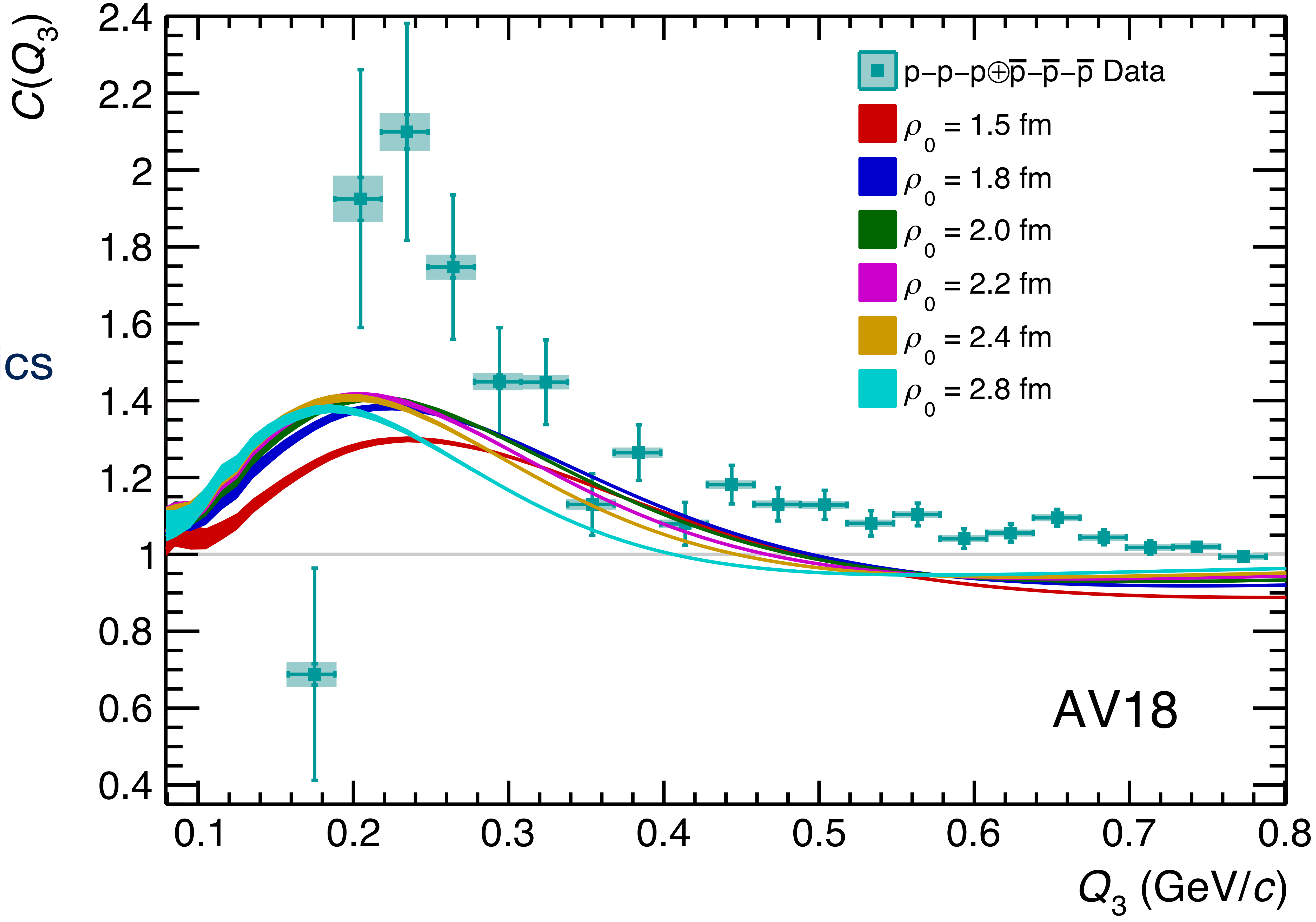
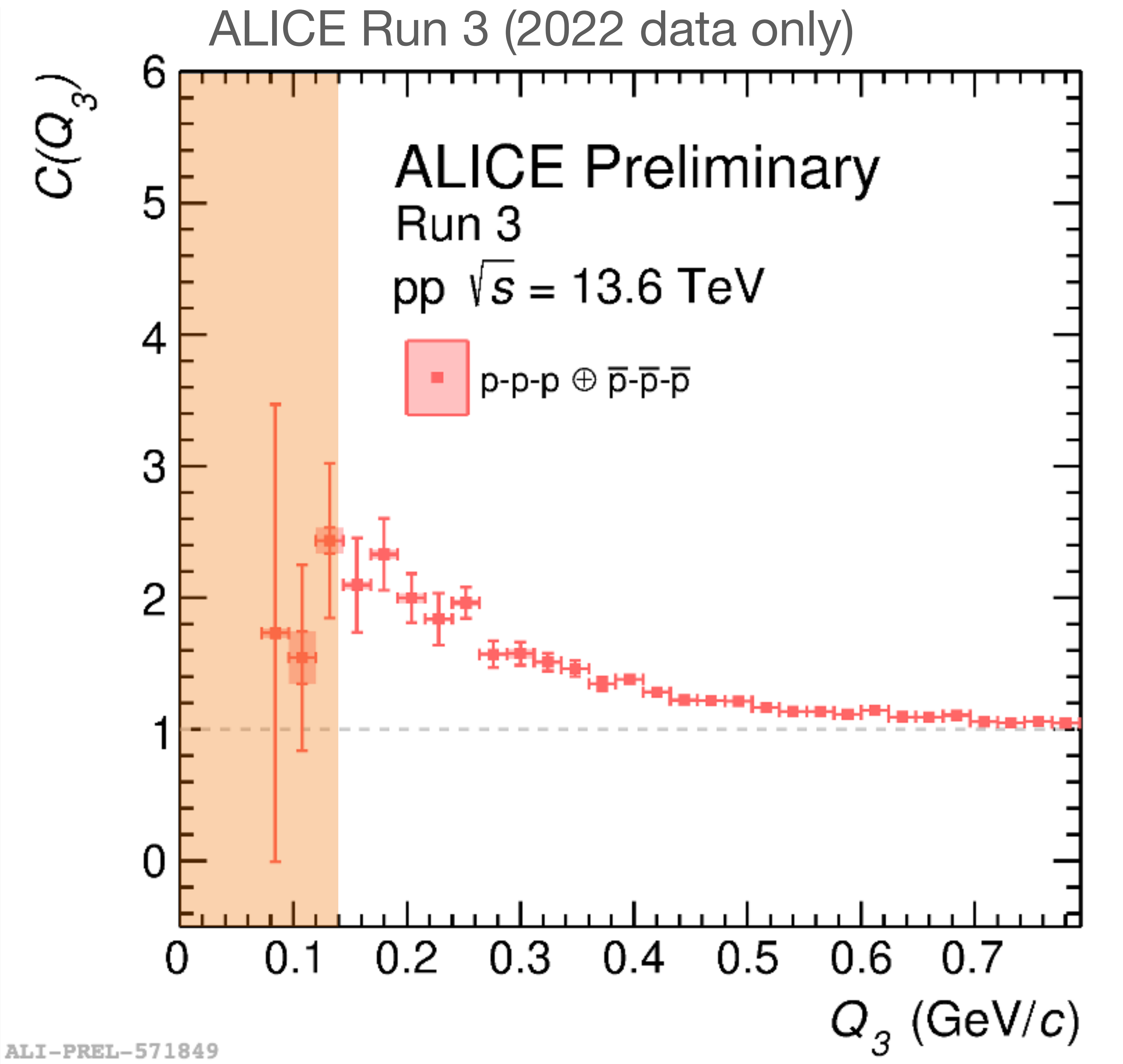
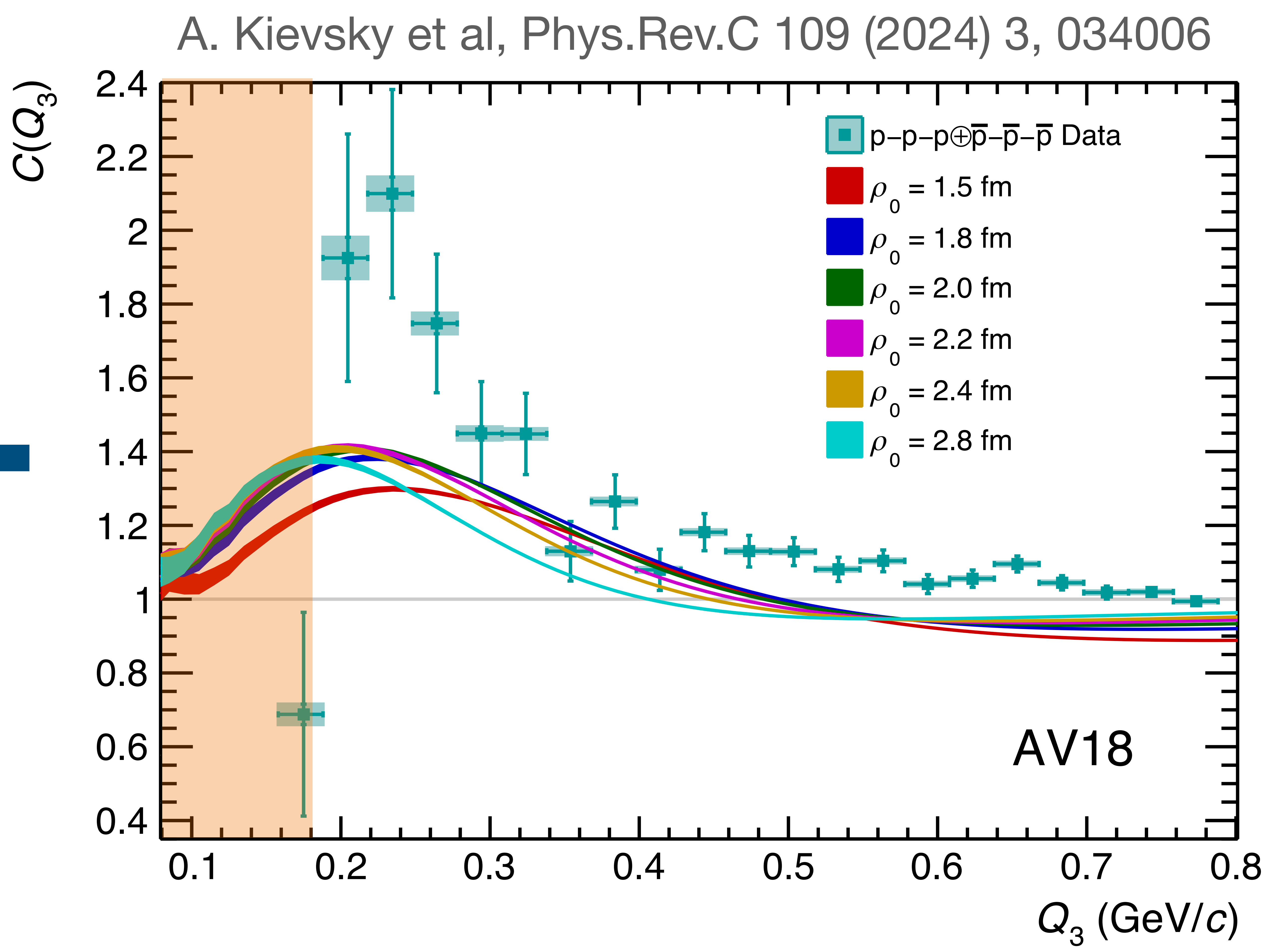


[1] A. Kievsky et al, Phys. Rev. C 109 (2024) 3, 034006

p–p–p correlation in Run 3



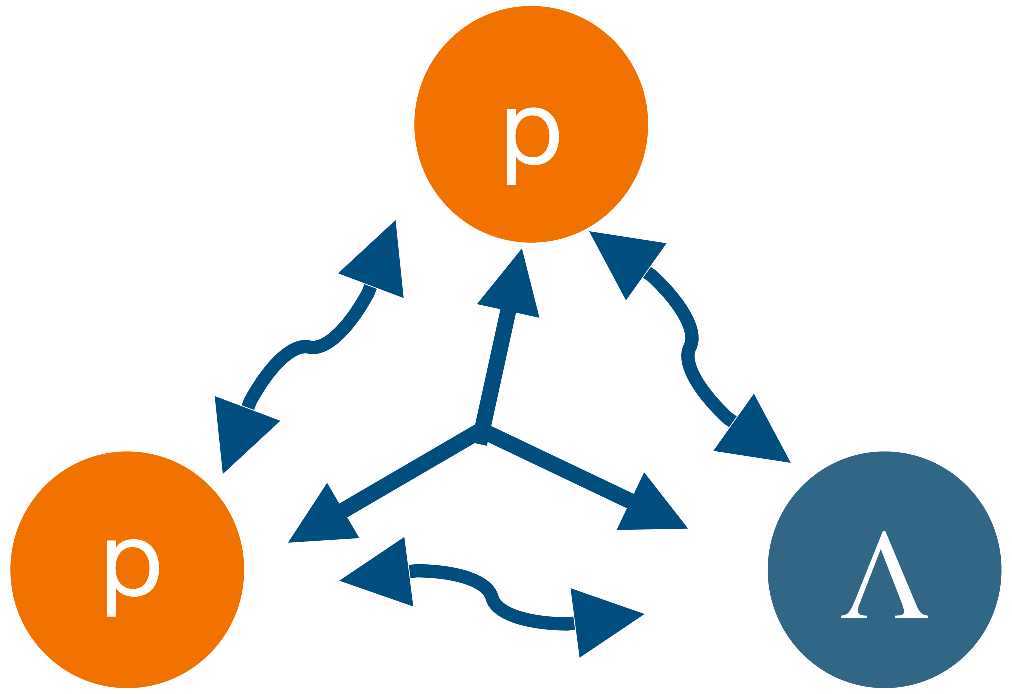


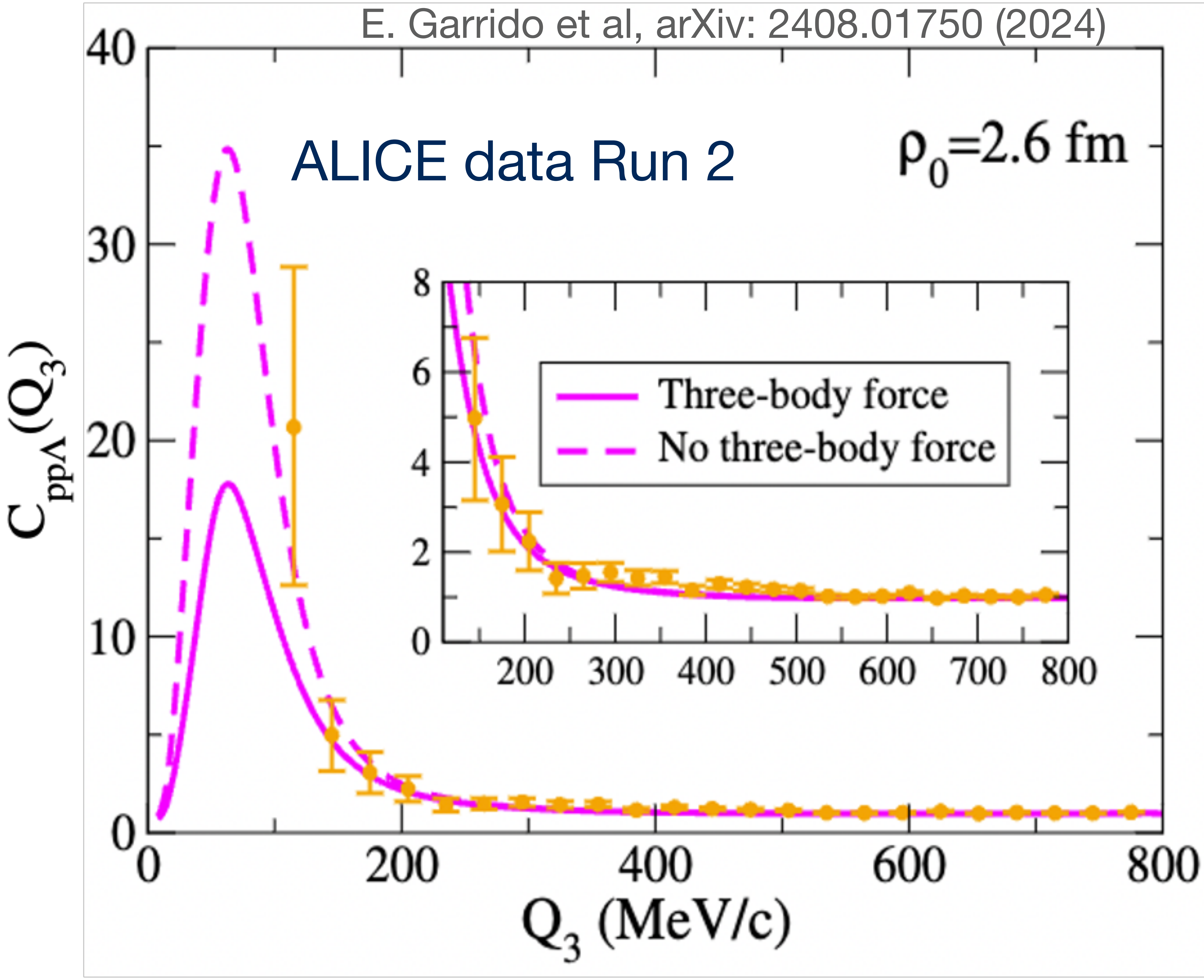
[1] A. Kievsky et al, Phys. Rev. C 109 (2024) 3, 034006

By the end of Run 3, 100 times more triplets w.r.t Run 2 statistics, estimated with dedicated software triggers!

Theoretical p–p–Λ correlation

- Three-particle emission source modeled as three single-particle emitters constrained to data [1]
- Modeling includes experimental corrections (e.g. feed-down)





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- Three-particle emission source modeled as three single-particle emitters constrained to data [1]
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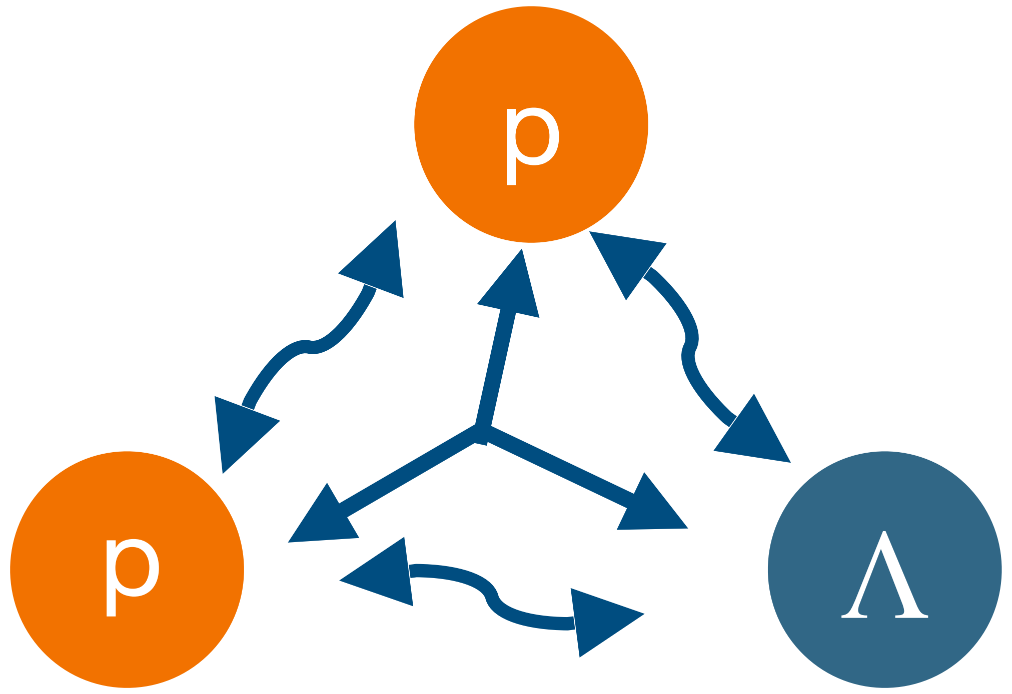
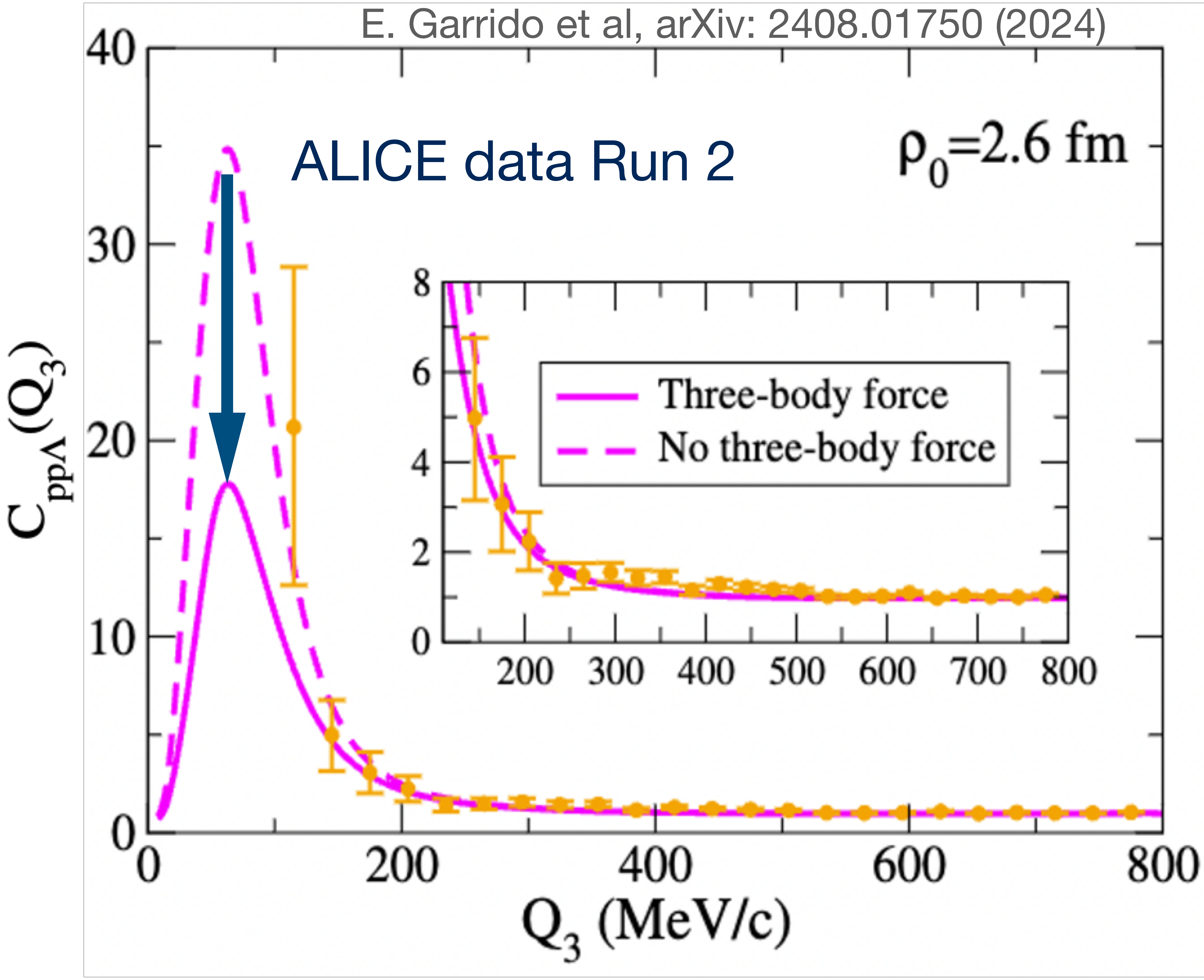
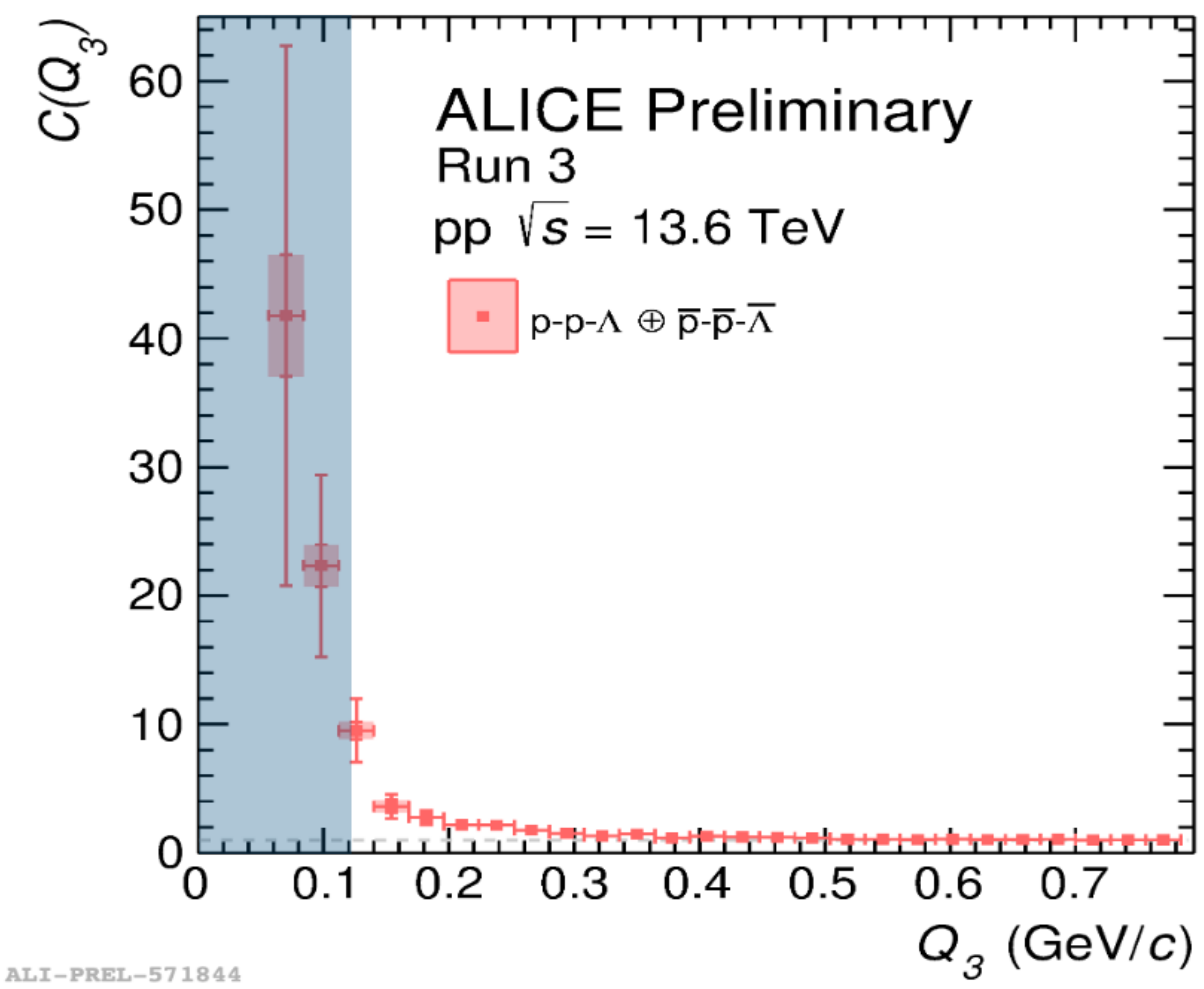
- The most interesting region $Q_3 < 100$ MeV/c not yet accessed by data



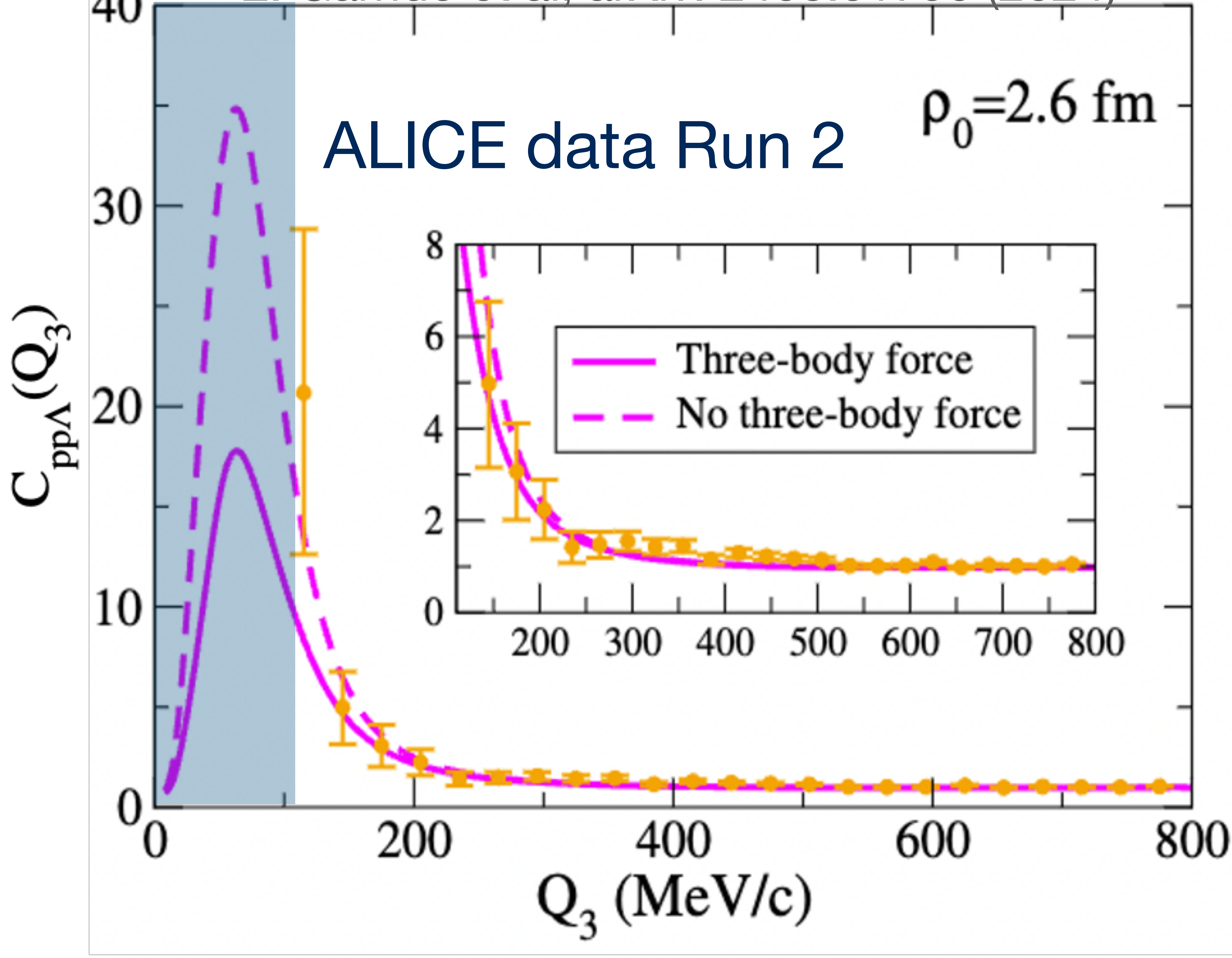


Theoretical p–p–Λ correlation

ALICE Run 3 (2022 data only)



E. Garrido et al, arXiv: 2408.01750 (2024)



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Conclusions and Outlook

- **K^+–d:** deuterons follow source size scaling for all hadrons in pp collisions
- **p–d**
  - Access to three-body strong interaction
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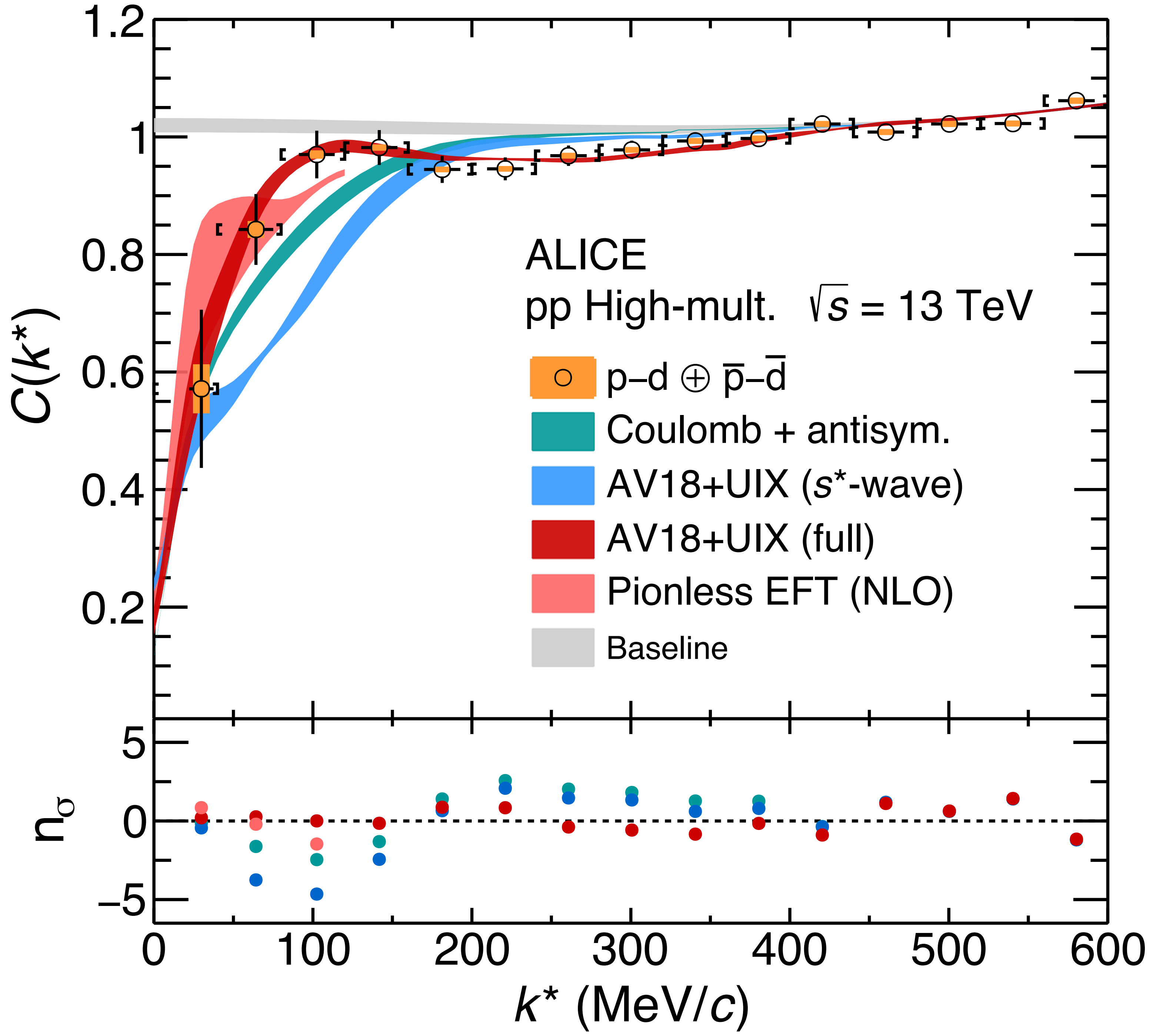

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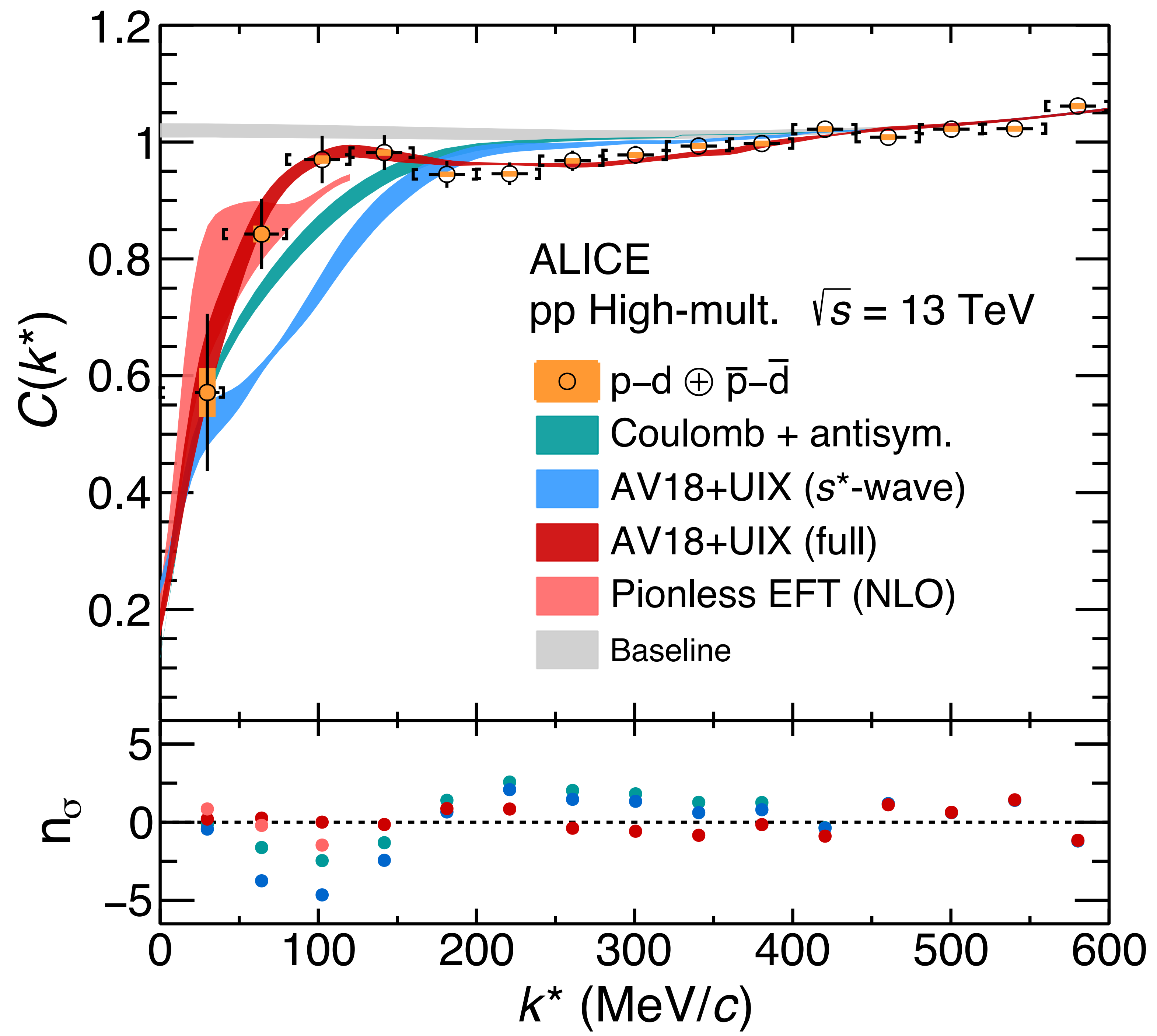

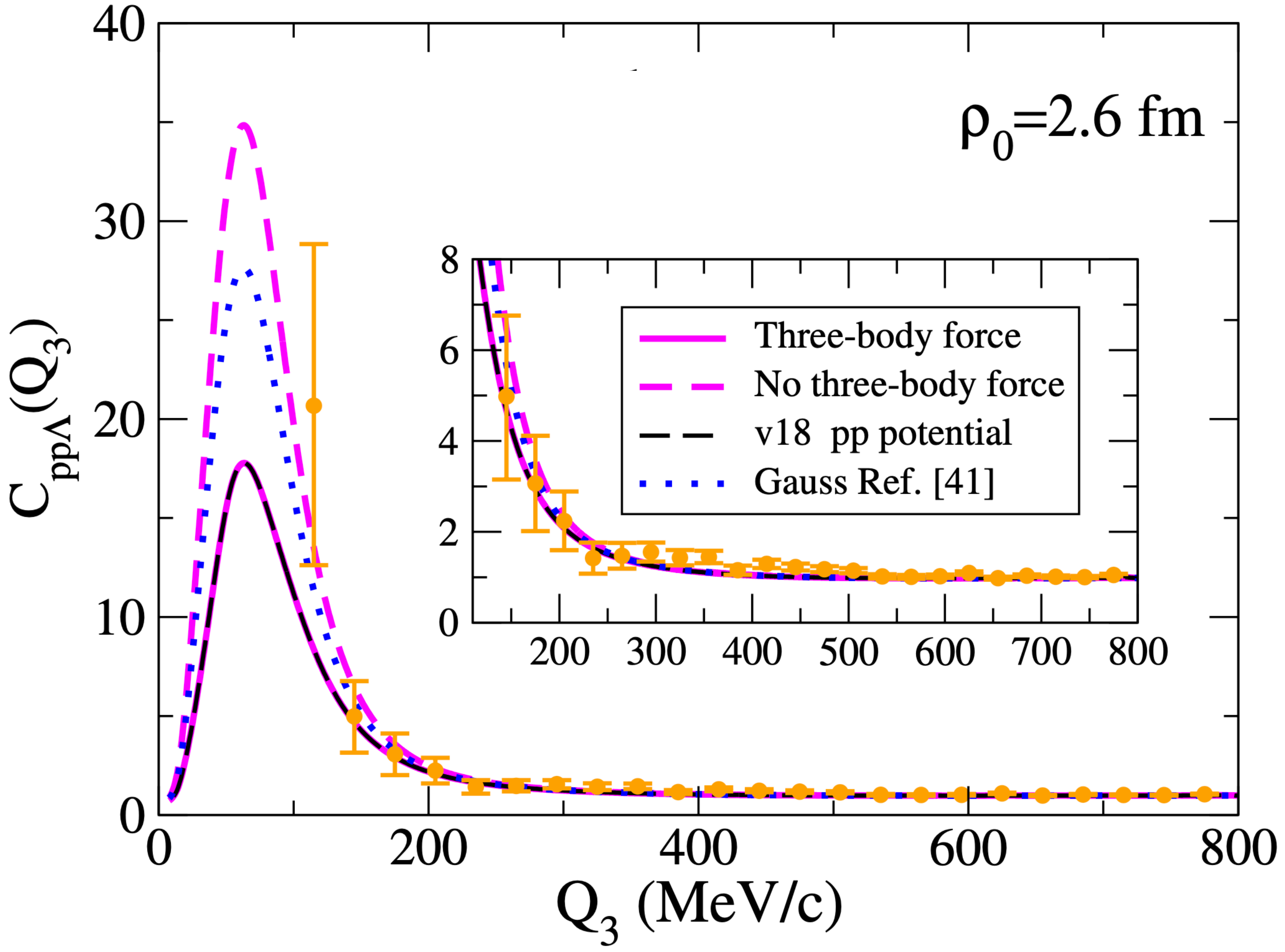

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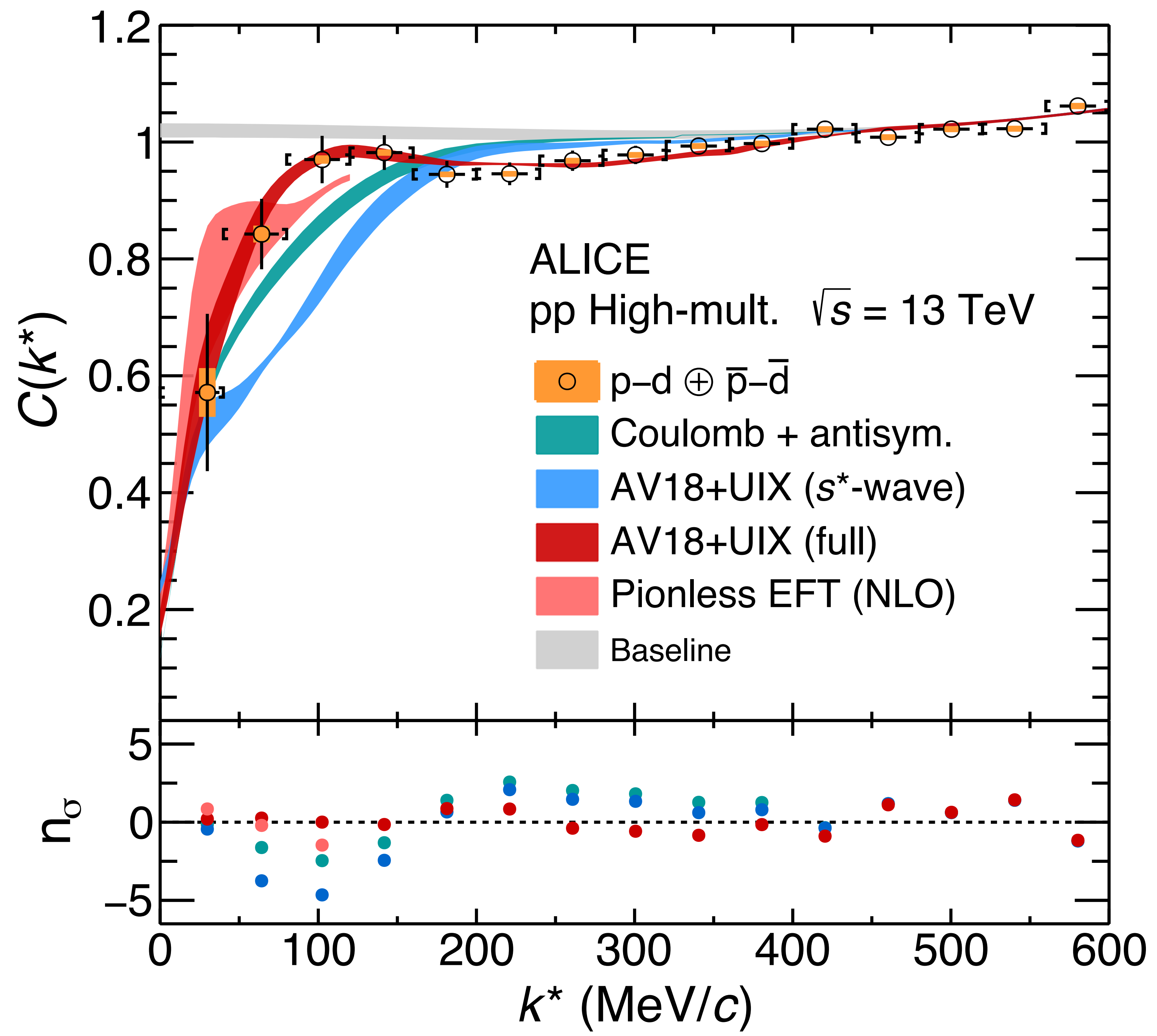
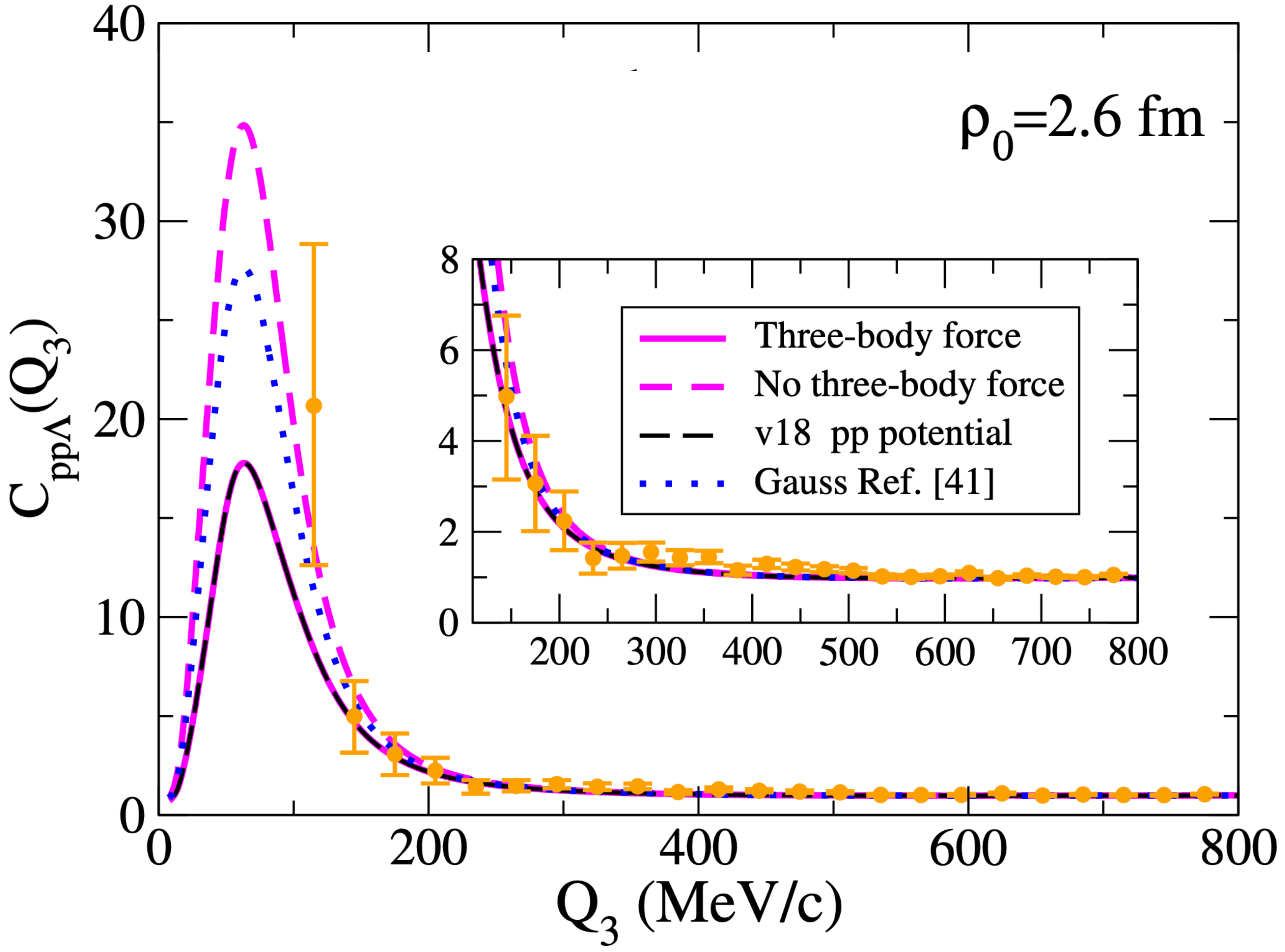
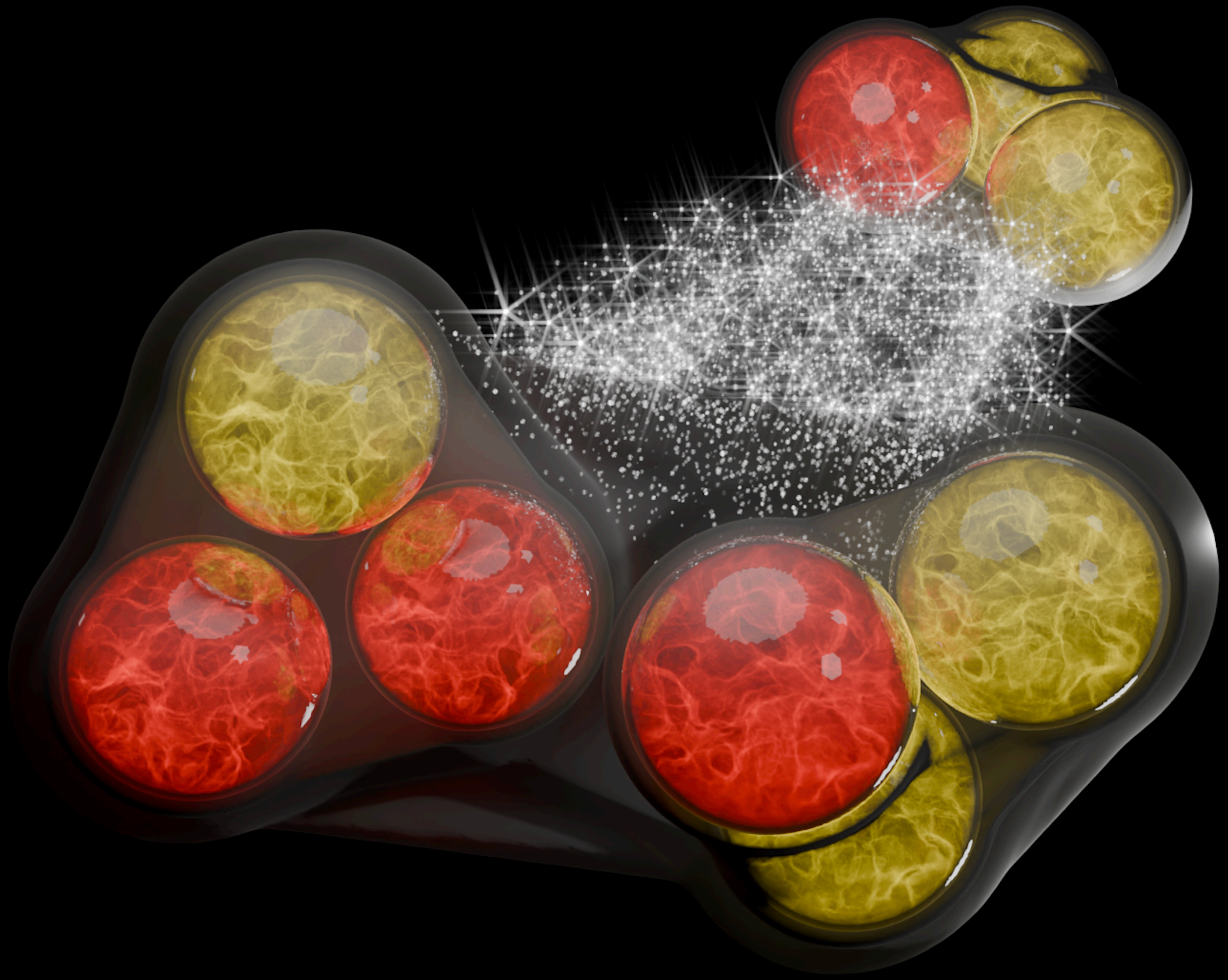
- **p–p–Λ:** 3-body force with strangeness up to 40%
- **Large statistics of LHC Run 3 and Run 4**
  - p–p correlation in LHC Run 3: source constrained for all interaction studies
  - Ongoing studies for p–d, Λ–d, p–p–p, and p–p–Λ from LHC Run 3







Thank you for your attention!

Credit: D. Chinellato, DOI 10.5281/zenodo.13284731

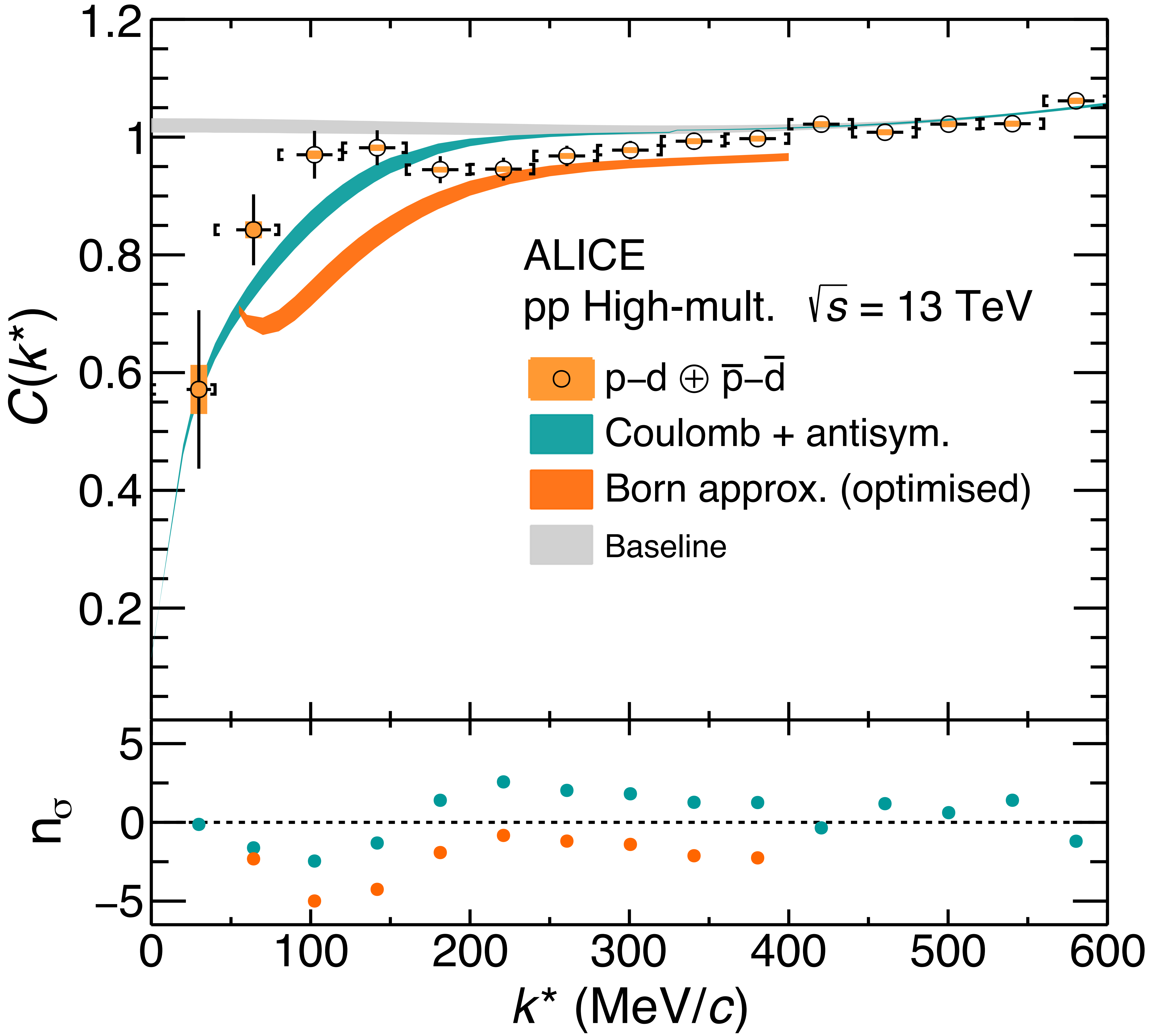
Additional slides

Asymptotic form of strong interaction in p-d system

- Coulomb only: does not describe the data
- Born approximated wavefunction AV18(2N) [1-2] UIX (NNN) potentials [3]
- Asymptotic form of strong interaction is insufficient to capture the dynamics of nucleons ~ 1 fm

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

ALICE, Phys. Rev. X14, 031051 (2024)



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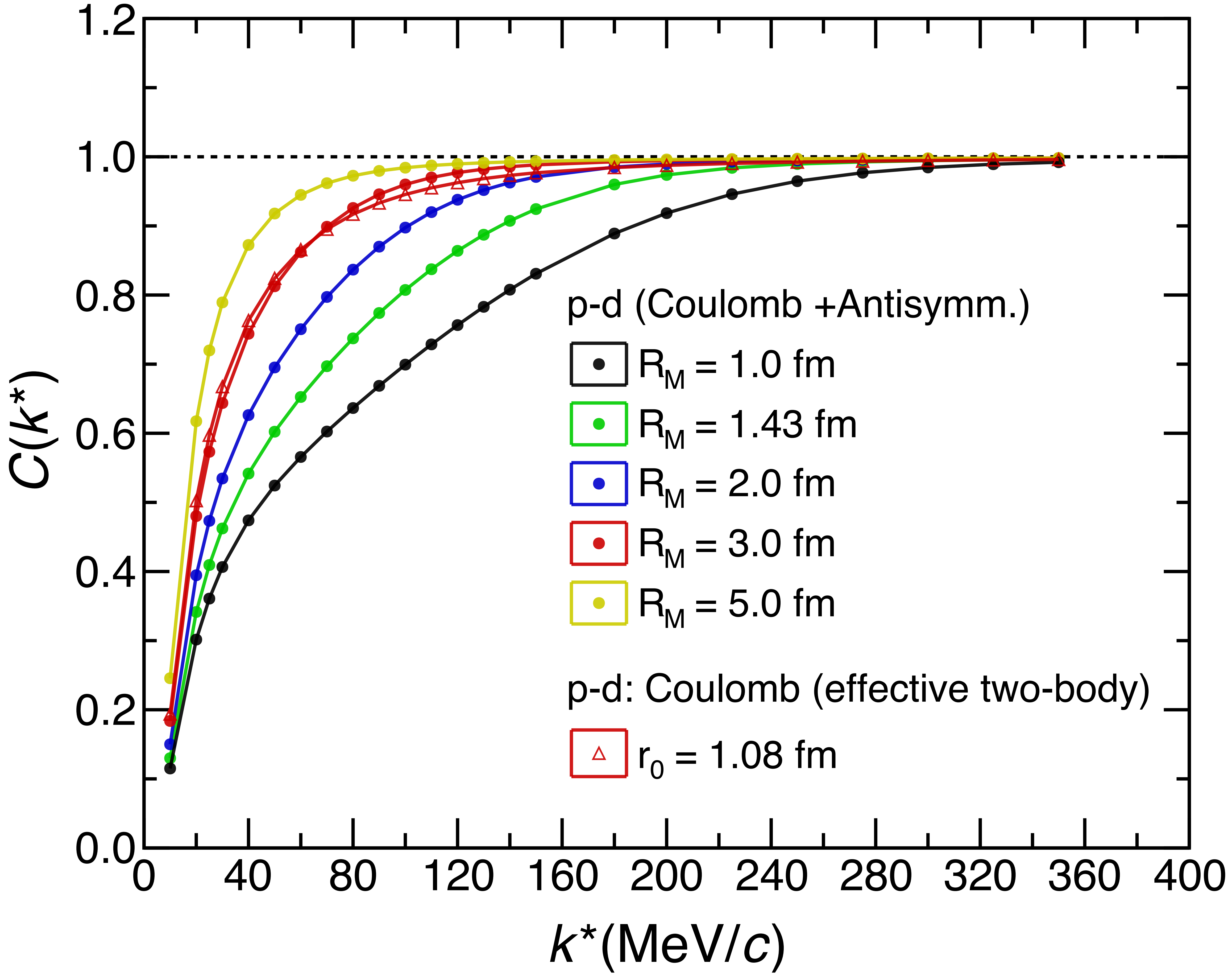
[2] R. B. Wiringa et al. Phys. Rev. C 51, 38 (1995)

[3] B. S. Pudliner et al. Phys. Rev. Lett. 74, 4396 (1995)

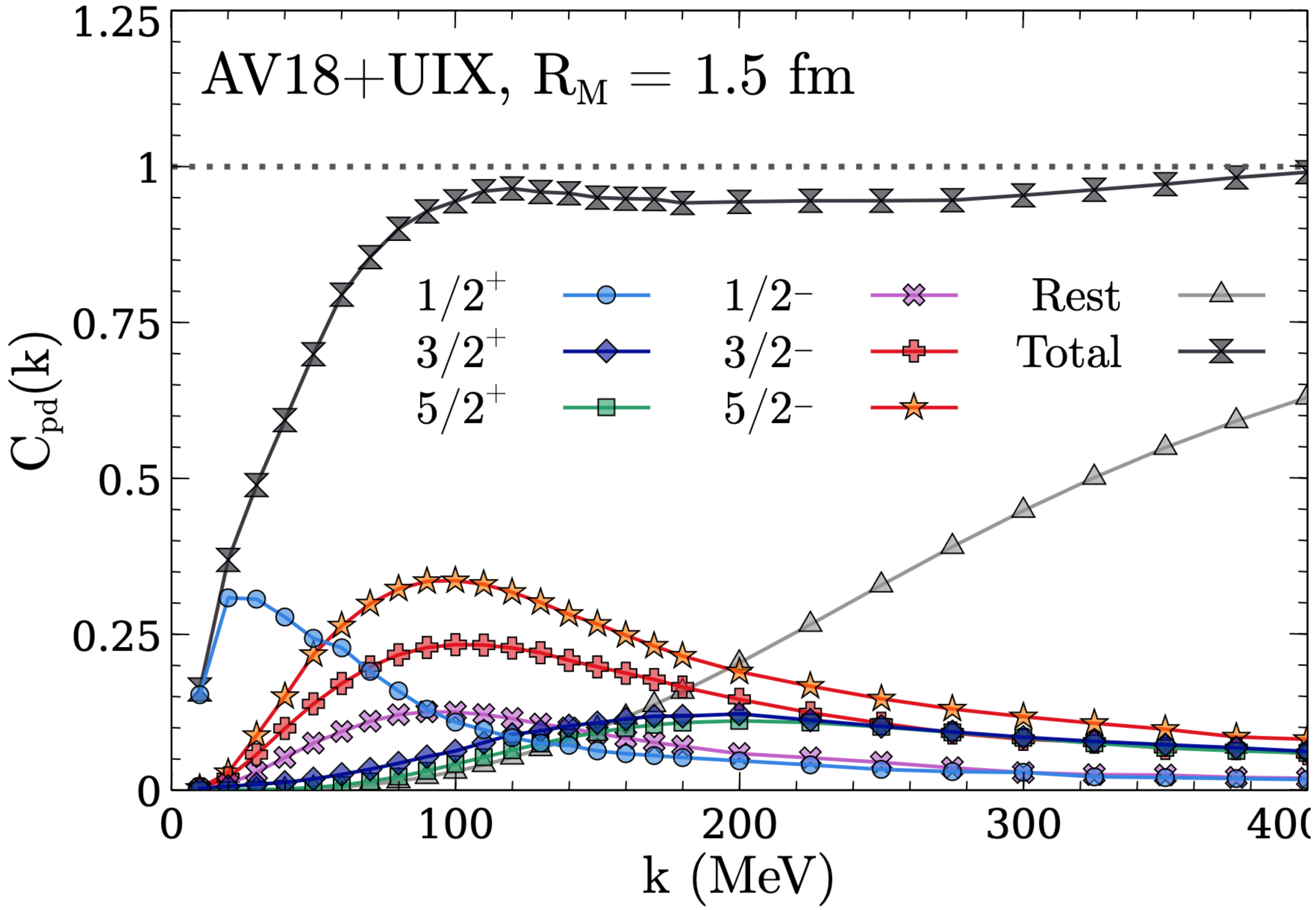
Coulomb interaction in p-d system

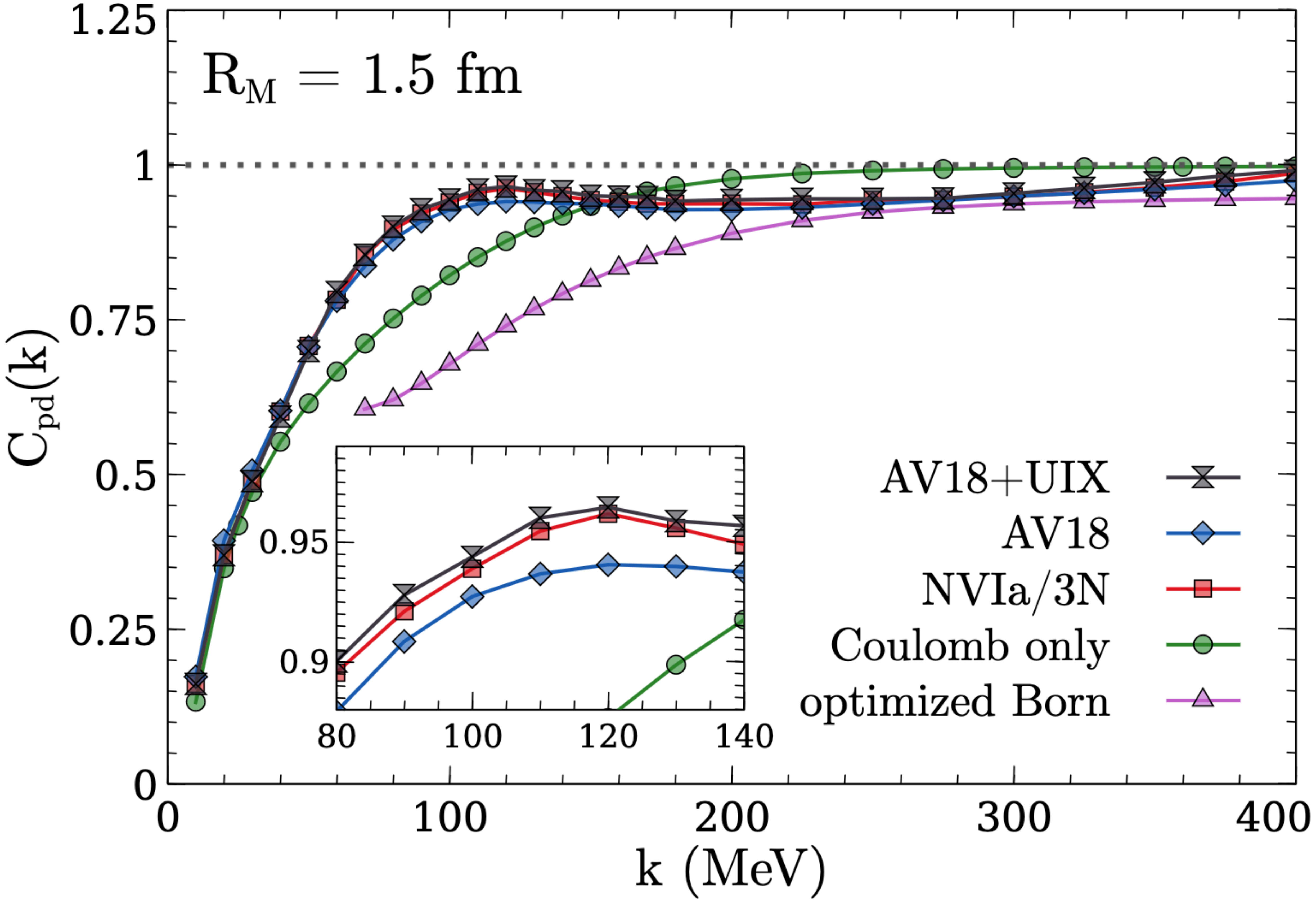
- Complete p–pn dynamics, but the strong interaction is **absent** at very short-range!
  - **r^{NN}_{eff} =1.43±0.16** fm (nucleon-nucleon distance)
- In the case of the two-body picture Coulomb-only interaction differs from the one using the p-(pn) dynamics
- **Two-body source 1.08±0.06** fm (proton-deuteron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



AV18+UIX vs NVIa3 3N Chiral potentials

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





M. Viviani, **B. Singh** et al. Phys. Rev. C 108, 064002 (2023)

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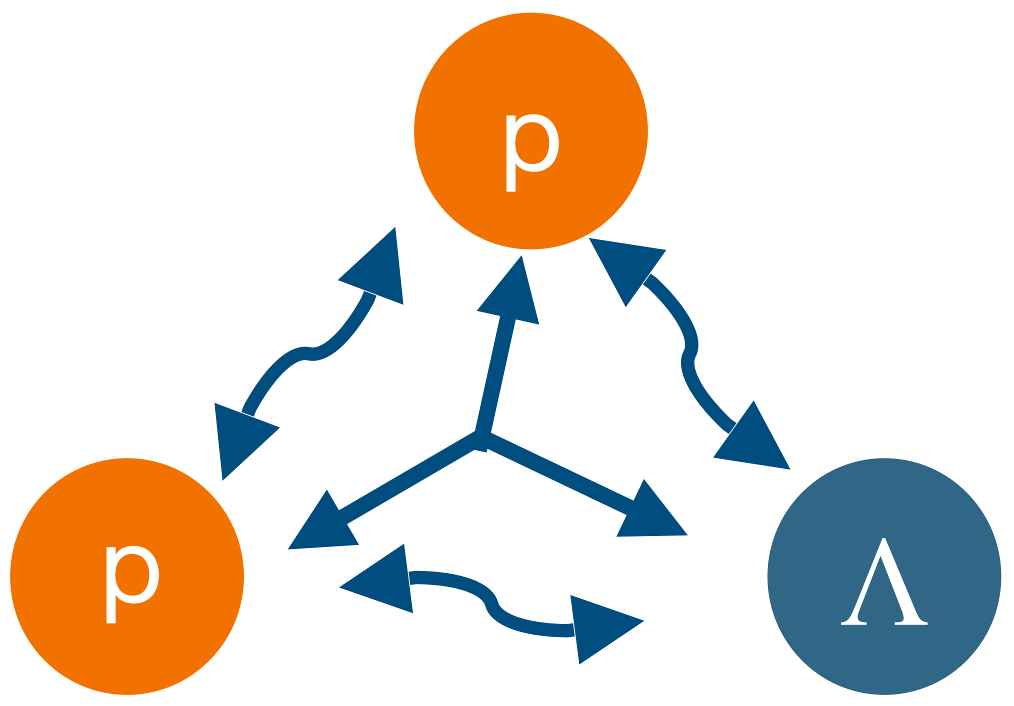

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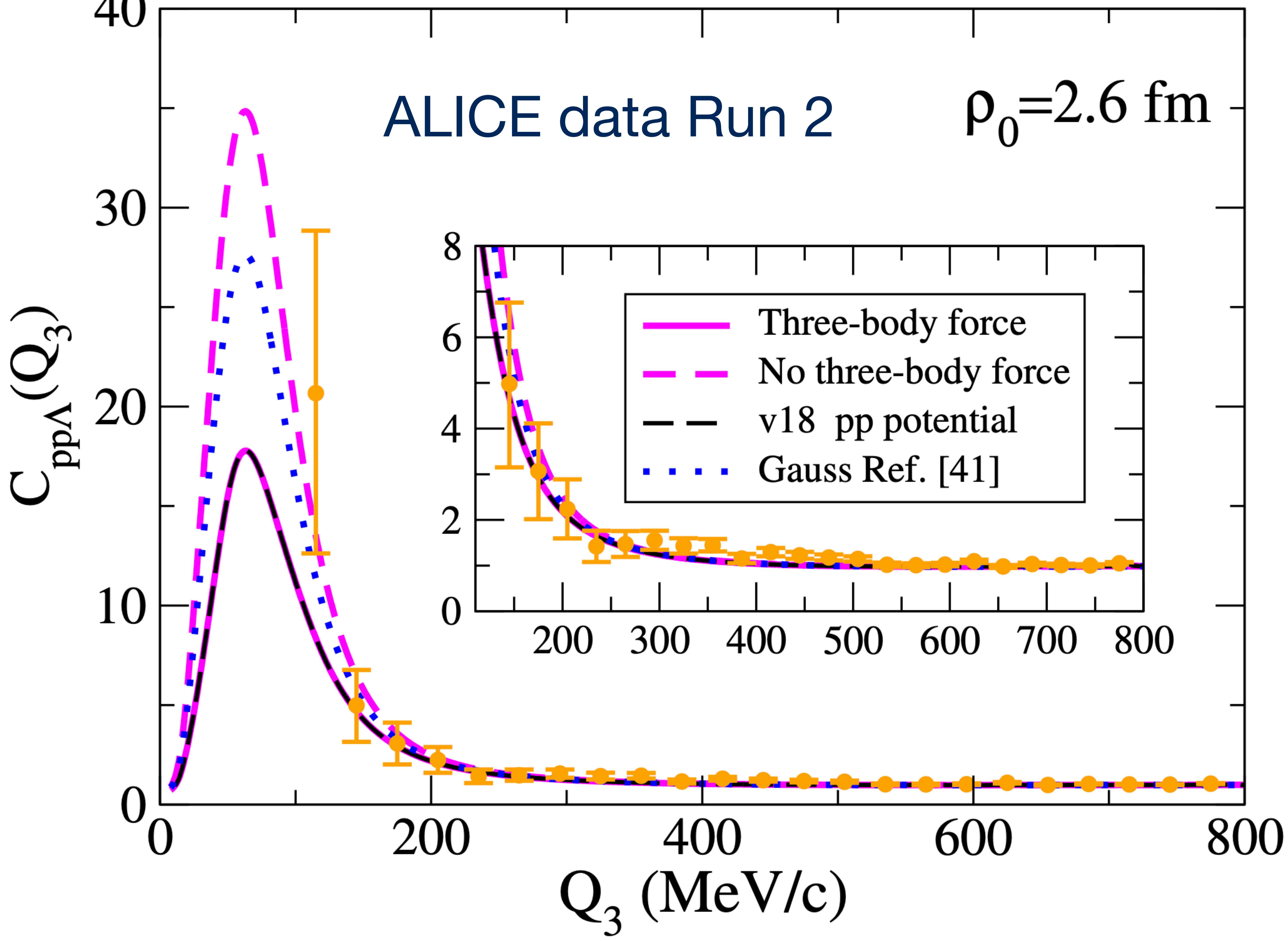
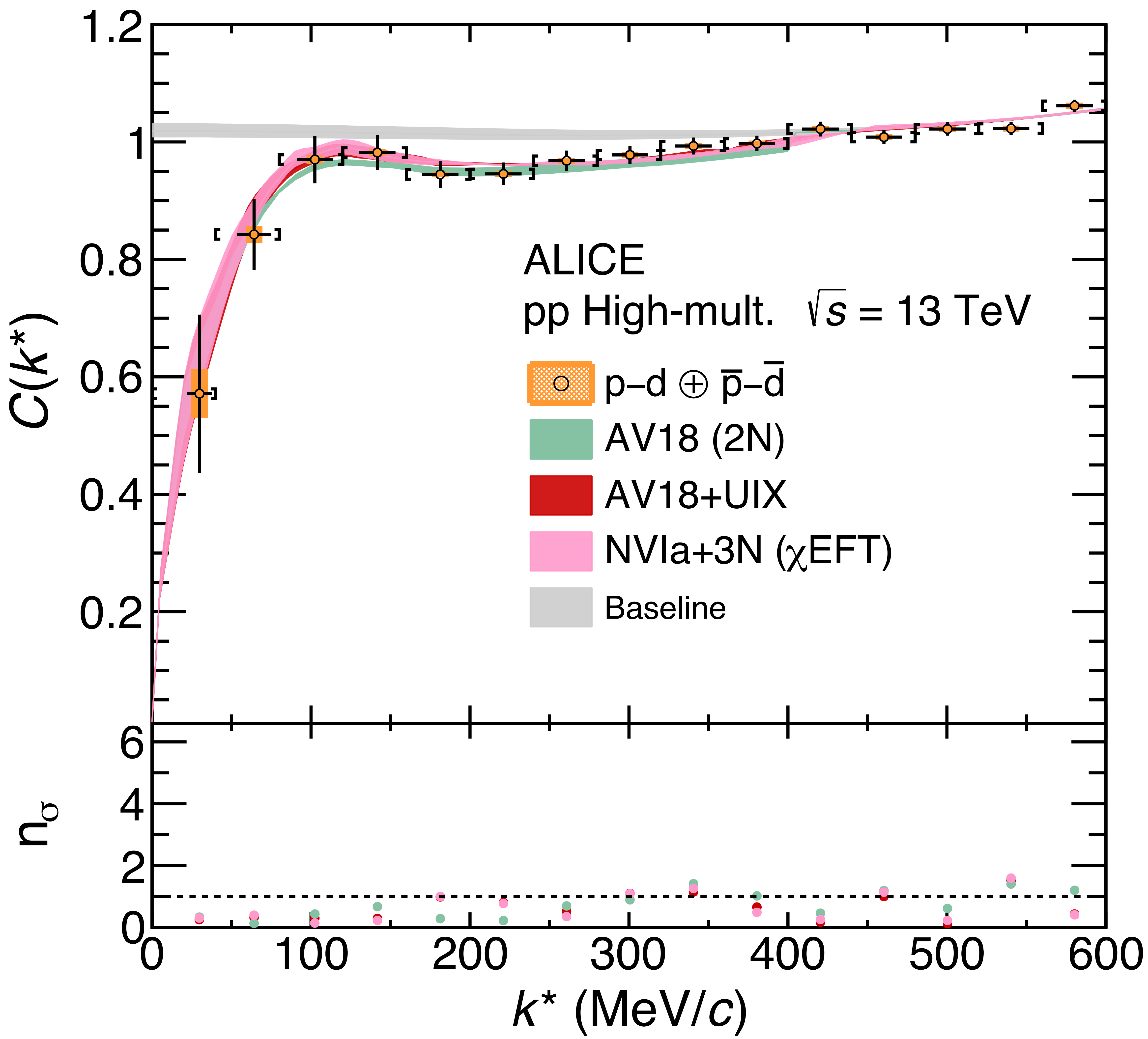


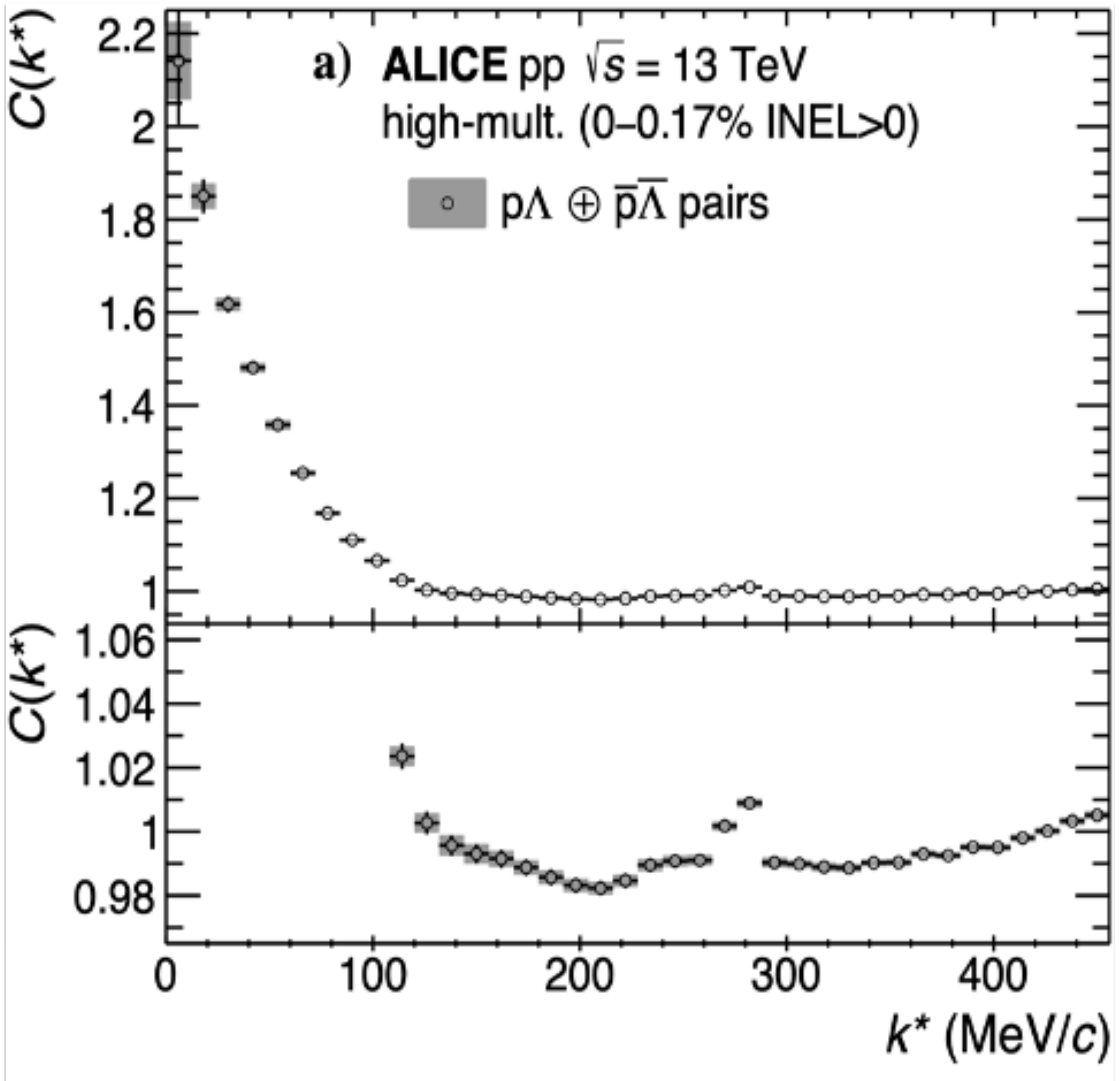
AV18+UIX vs NVIa3 3N Chiral potentials

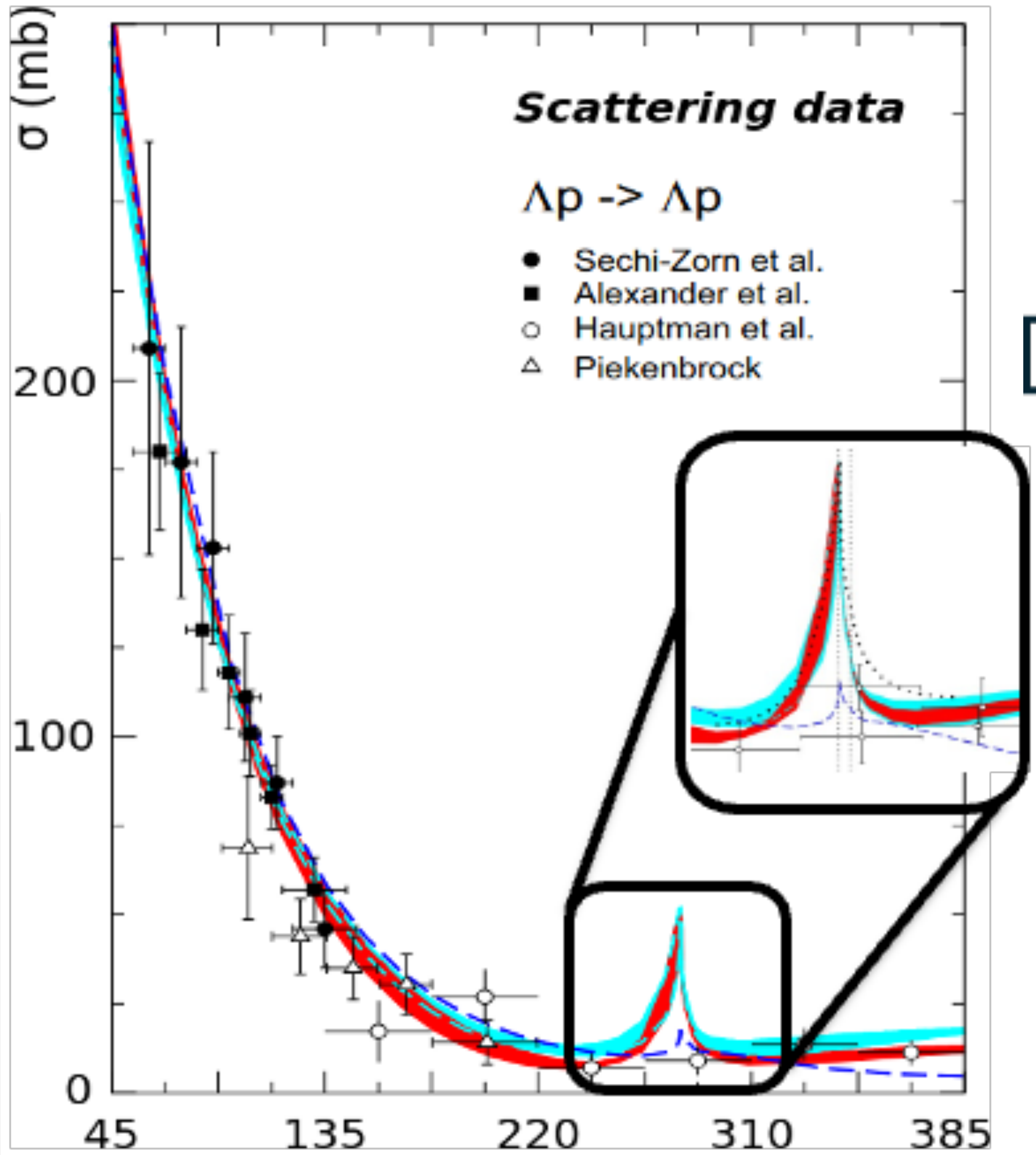
- Comparisition with Chiral potentials (**Full three-body dynamics)**[1]
- Argonne v18+Urbana IX interaction[2,3]
- **All partial waves upto d-waves:** describes data within n_{σ} ~1 for k^* up to 400 MeV/c
- Calculations using chiral potential from NVIa+3N
  - Very good agreement with AV18+UIX
- AV18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



The pΛ interaction in the femtoscopy

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





D. Mihaylov et al PLB 850 (2024) 138550