FINAL STATE INTERACTIONS AND EXOTICS WITH ALICE

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RHIC BEAM ENERGY SCAN AND BEYOND
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Outline

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Introduction

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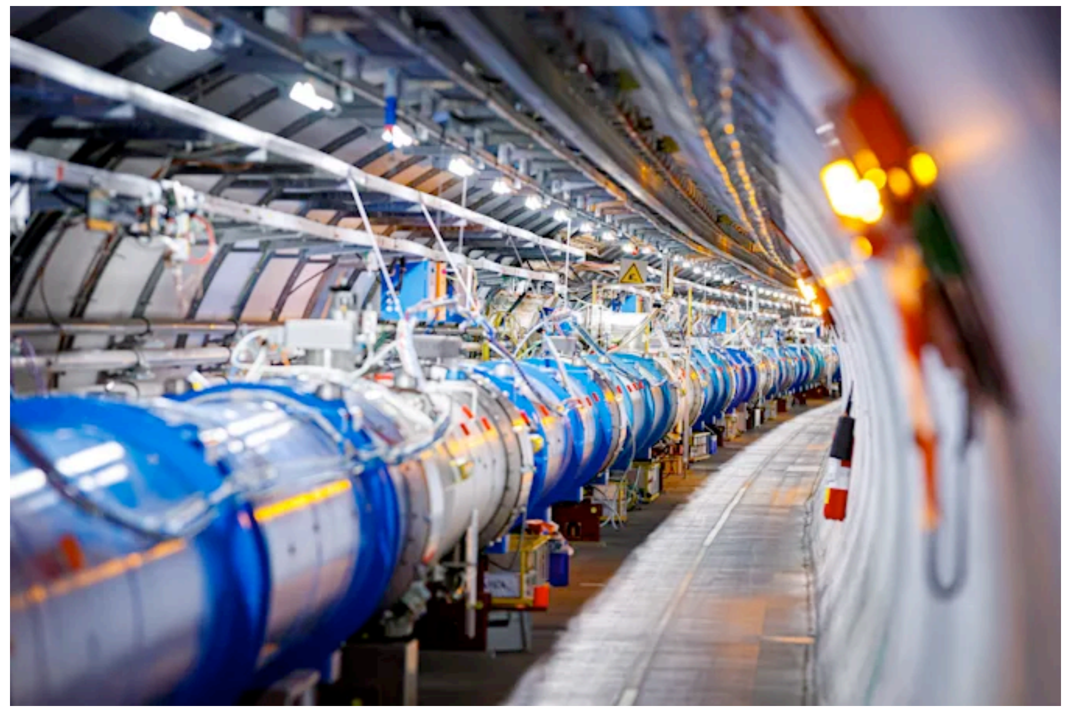
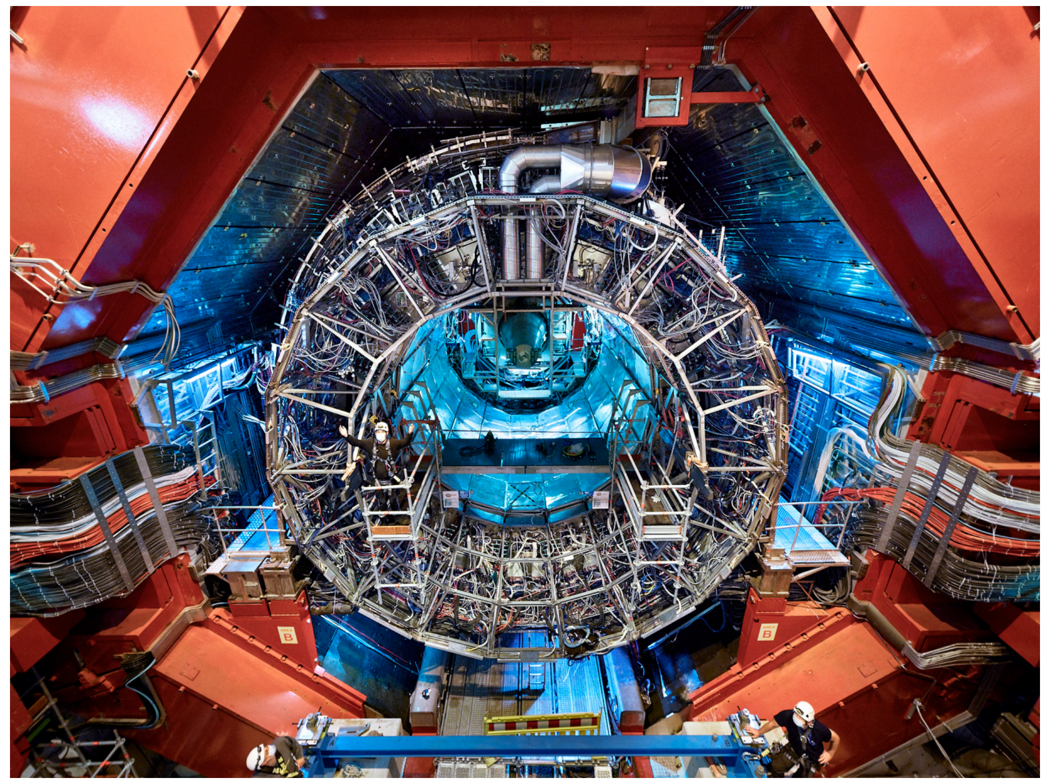
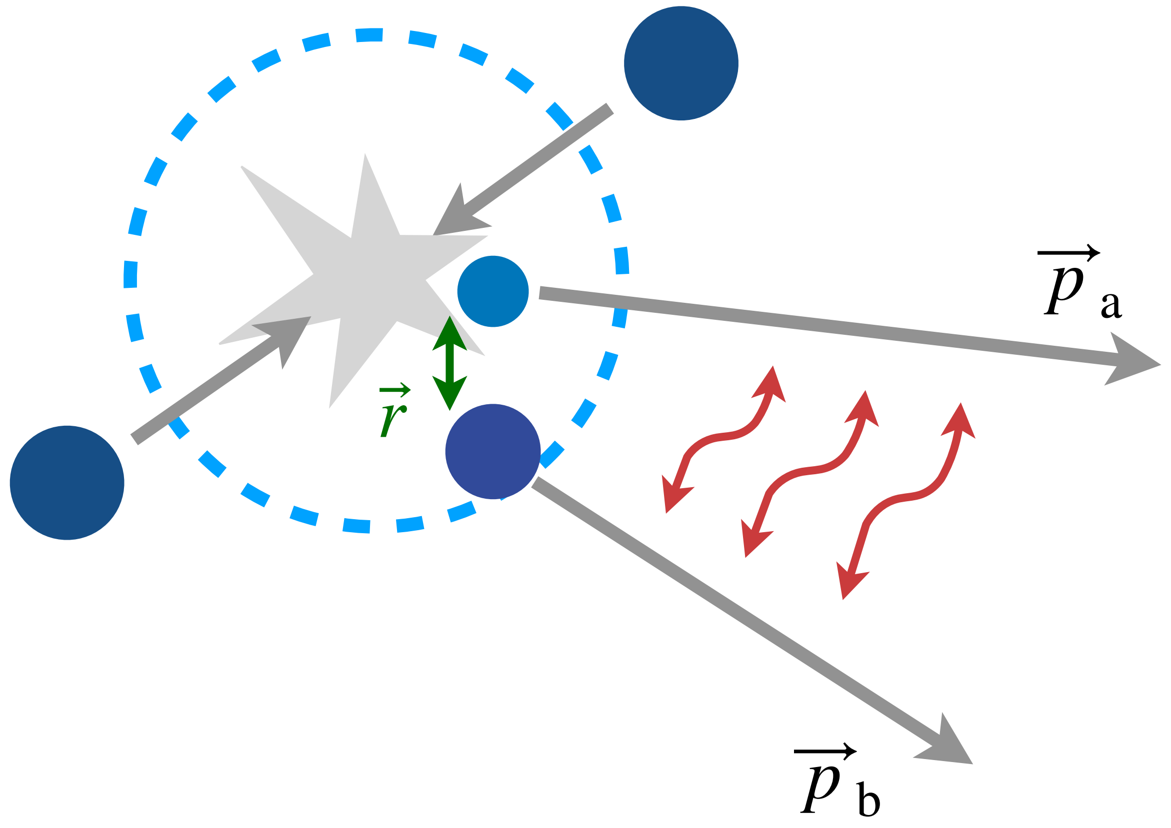
- Exploit high-energy physics accelerators - CERN Large Hadron Collider

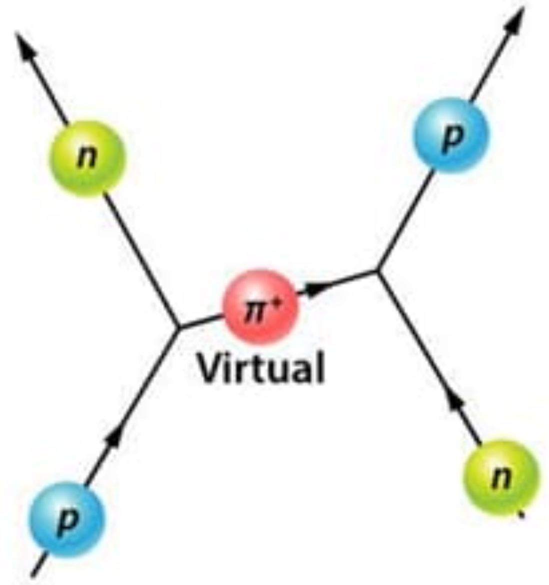


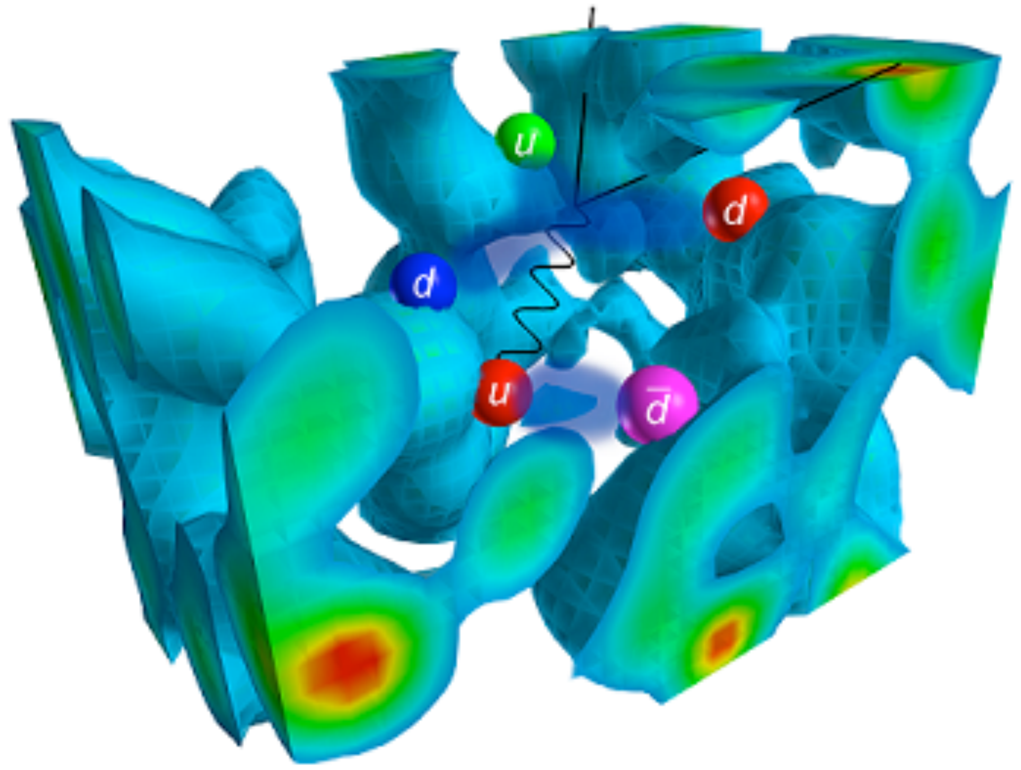
- Measure interaction among hadrons produced in the collisions with the ALICE detector





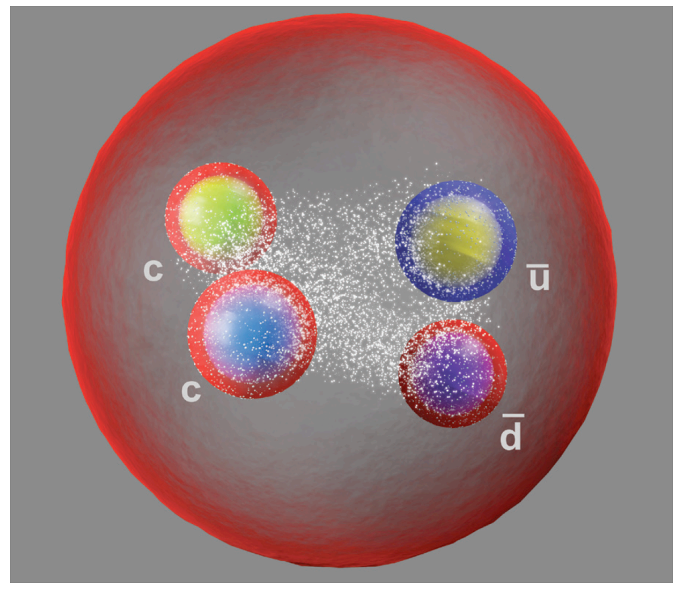
- Study fundamental interactions
  - ➡ Constrain low-energy QCD / chiral effective field theory





➡ Test lattice QCD (lQCD)

- Search for bound states



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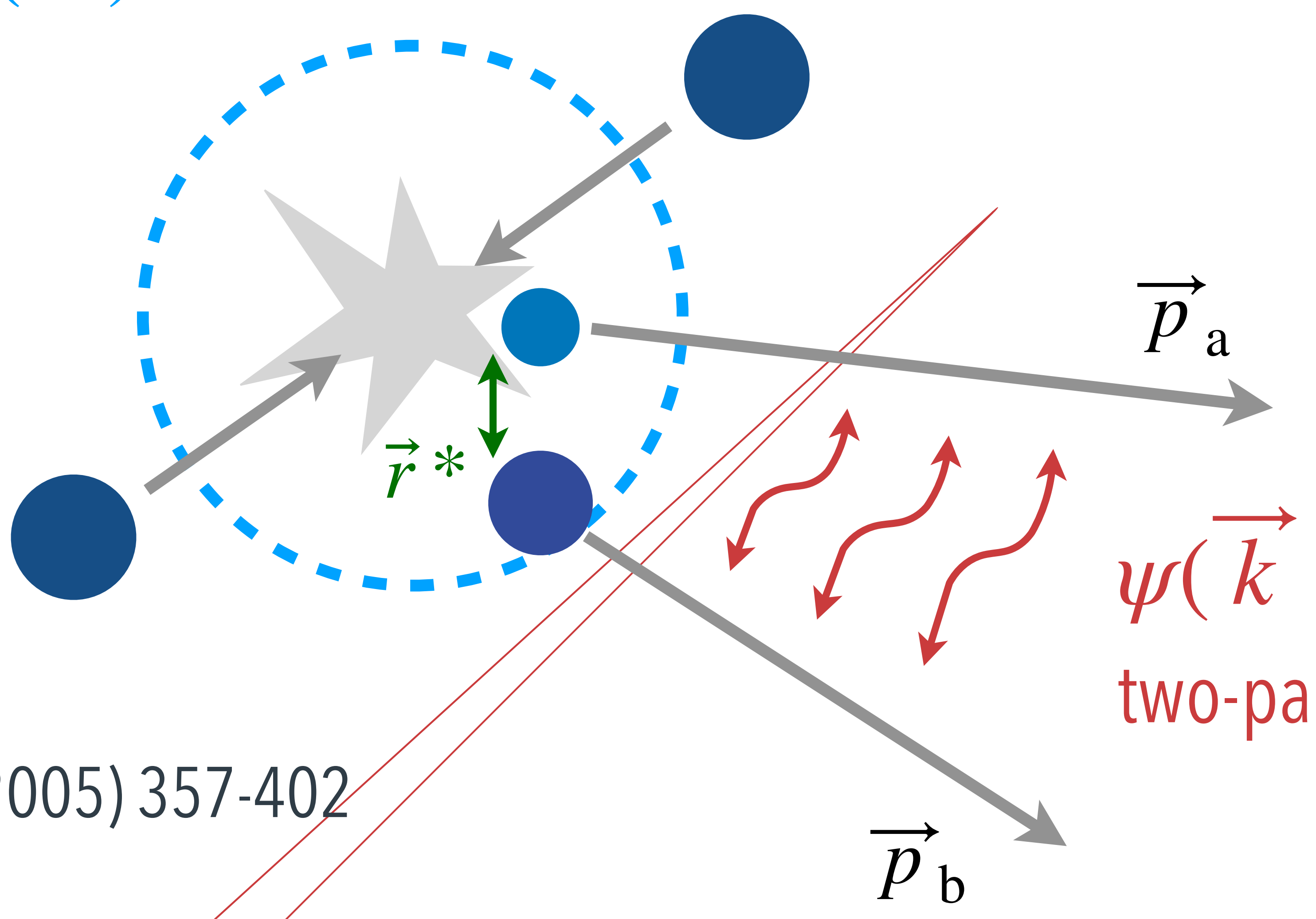
- Femtoscopy technique: based on the *correlation function (CF)*

Experiment | Theory

$$C(\vec{k}^*) = \mathcal{N}\frac{N^{\mathrm{pairs}}_{\mathrm{same}}(k^*)}{N^{\mathrm{pairs}}_{\mathrm{mixed}}(k^*)} = \int S(\vec{r}^*)\,|\psi(\vec{k}^*,\vec{r}^*)|^2\,\mathrm{d}^3r^*$$

➡ Koonin-Pratt equation

M.Lisa, S. Pratt et al, Ann.Rev.Nucl.Part.Sci. 55 (2005) 357-402



where $\vec{k}^* = \frac{\vec{p}_a^* - \vec{p}_b^*}{2}$ is in the rest frame of the particle pair

➡ Relative wave function sensitive to interaction potential

➡ Emitting source: hypersurface at kinematic freeze-out of final-state particles

➡ CF sensitive to strong interaction when the source size ~1fm

CF computed in ALICE using *CATS* (Correlation Analysis Tool using the Schrödinger equation)

➡ Developed at Technische Universität München

➡ Provides exact solution of Schrödinger equation for wave function

D. L. Mihaylov et al, Eur. Phys. Journal C 78 (2018) 394

$$C(\vec{k}^*) = \int S(\vec{r}^*)\,|\psi(\vec{k}^*,\vec{r}^*)|^2\,d^3r^*$$

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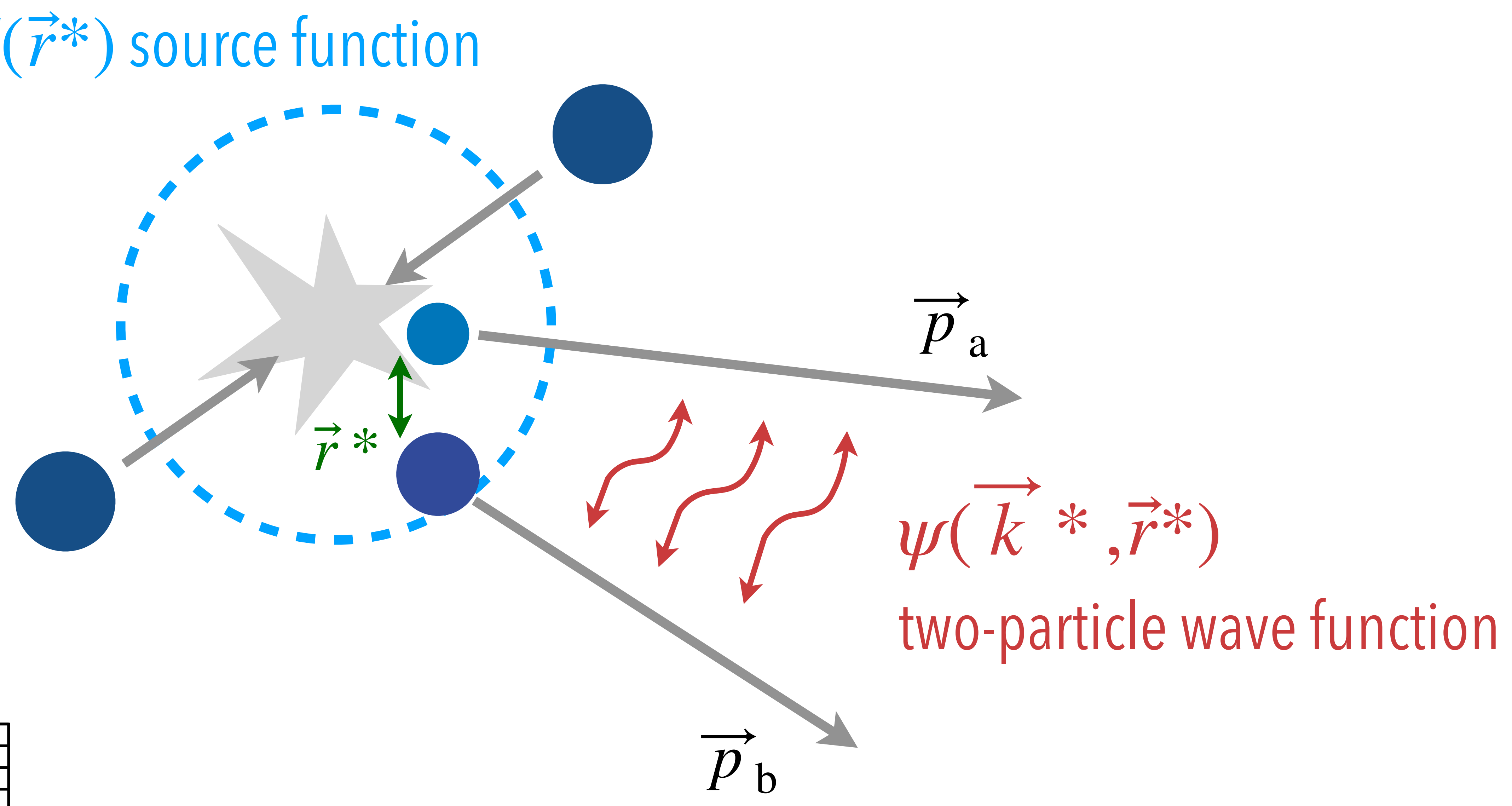
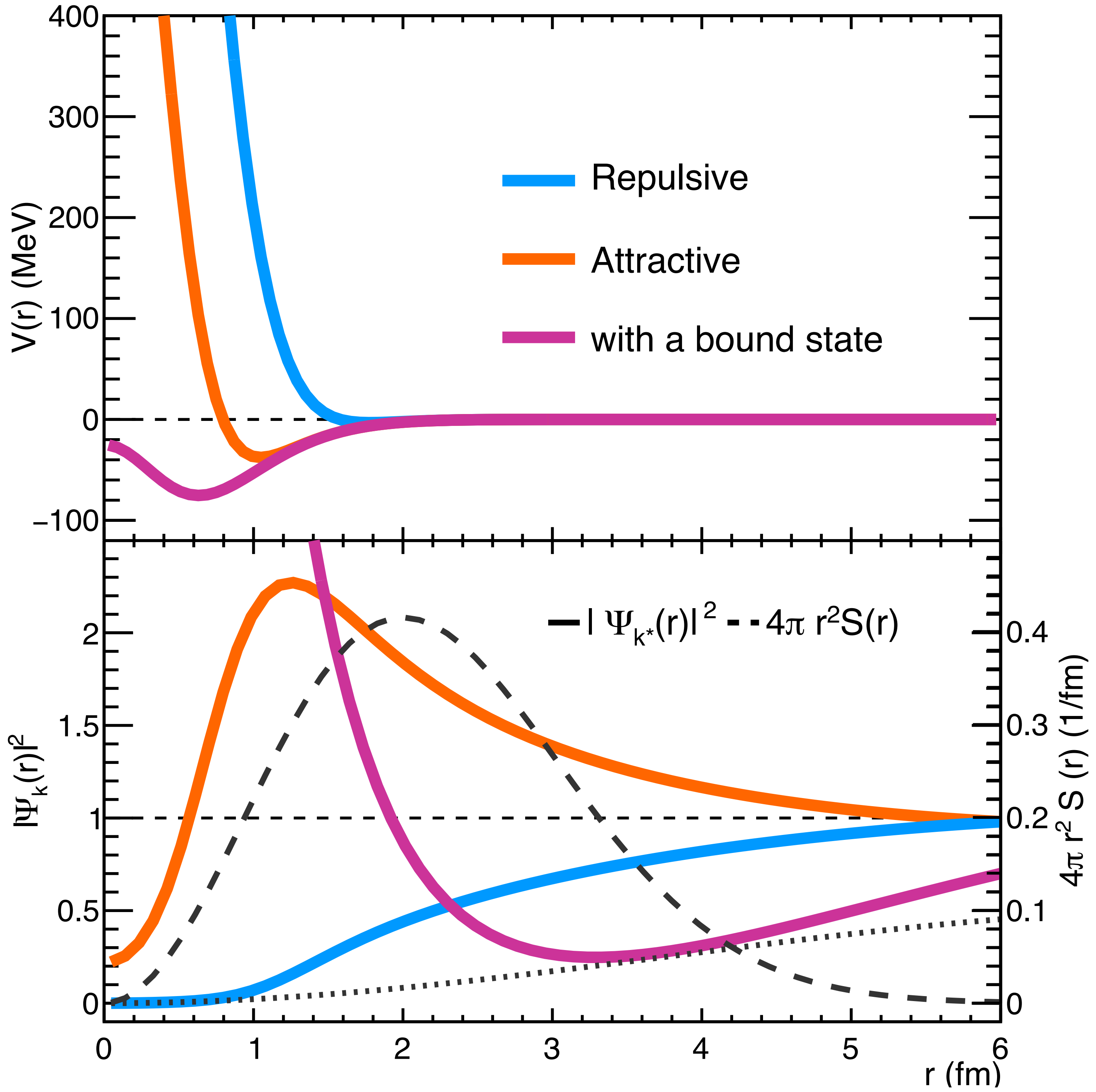
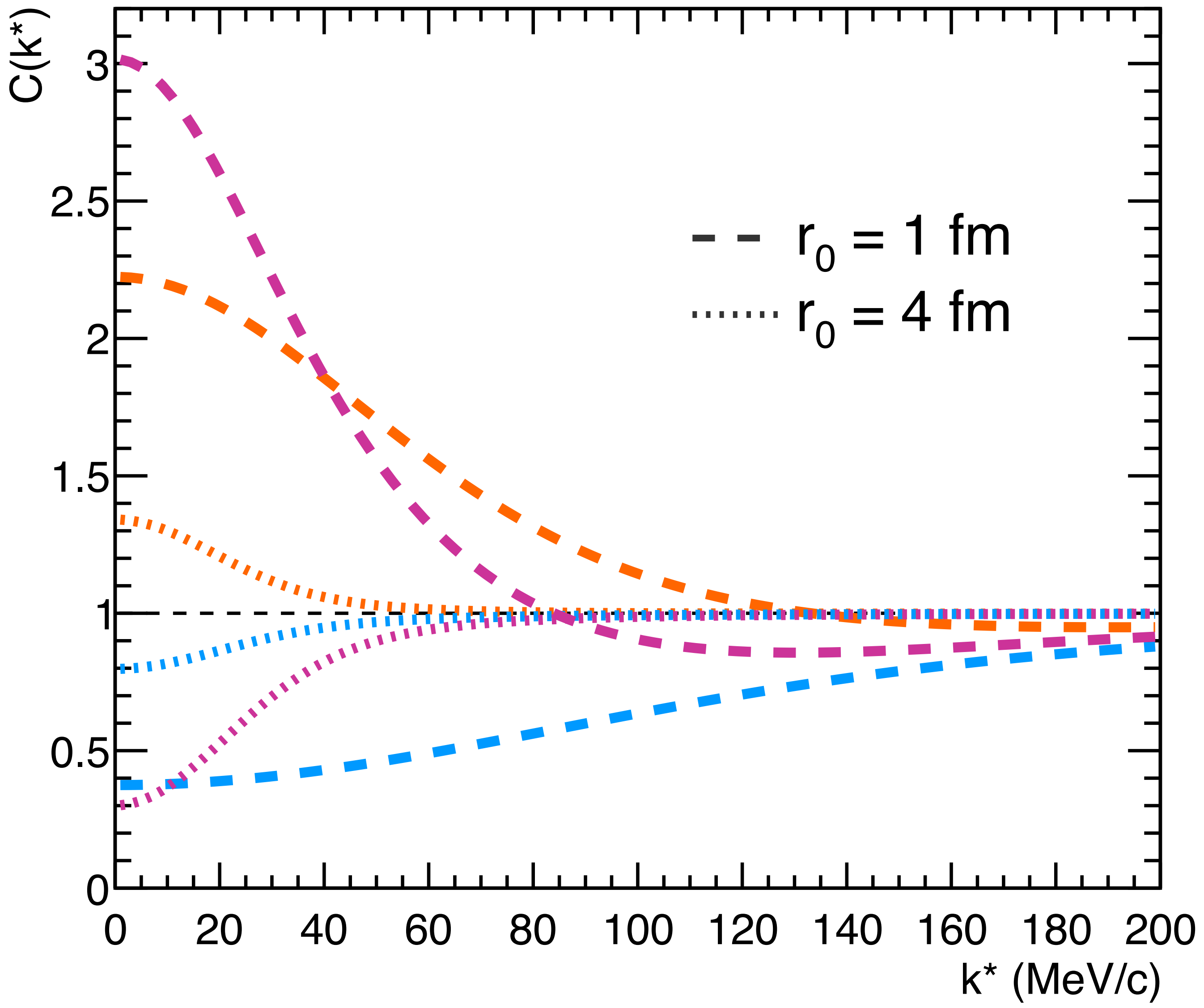






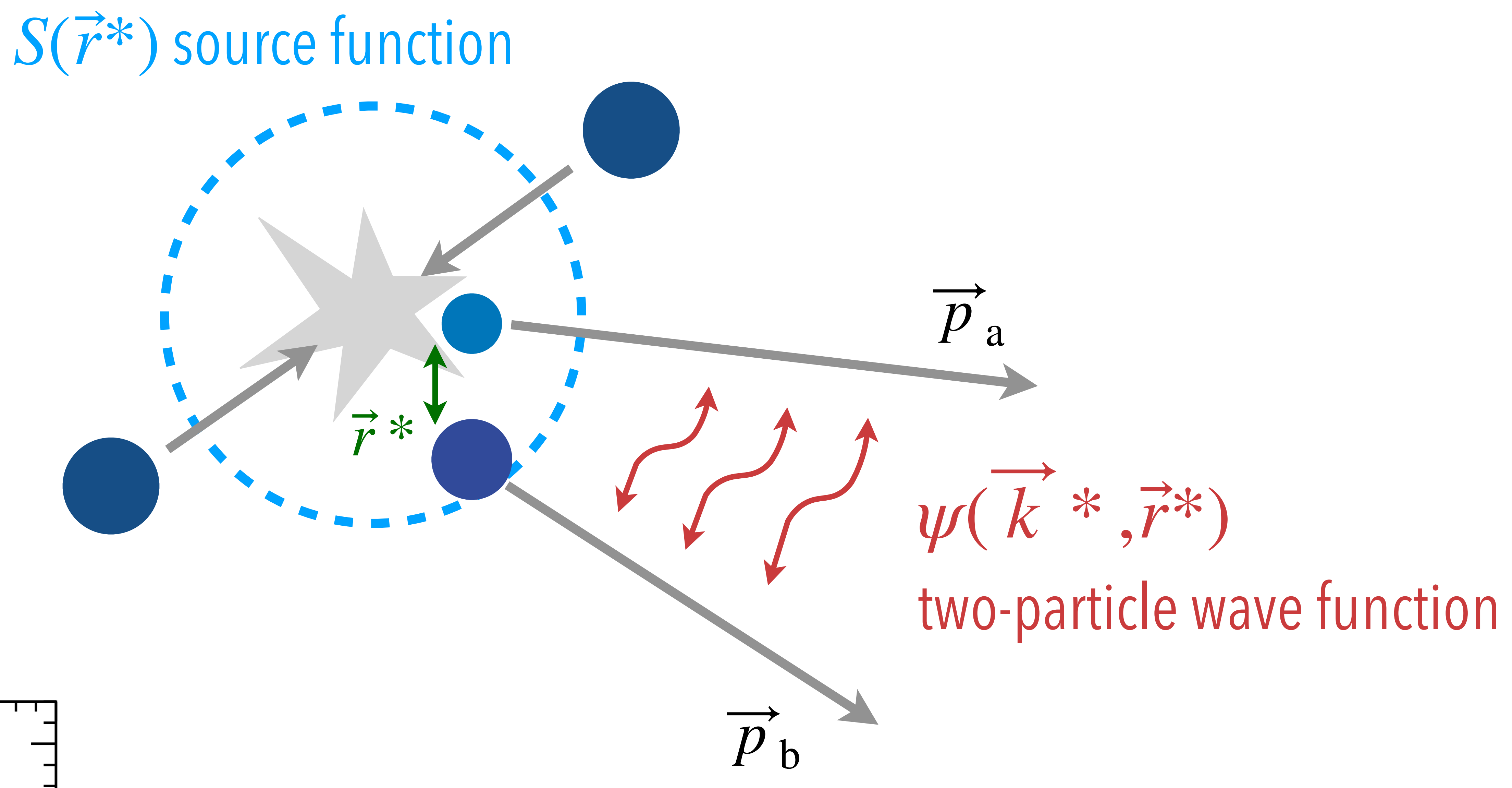
➡ Absence of interaction $C(k^*) = 1$

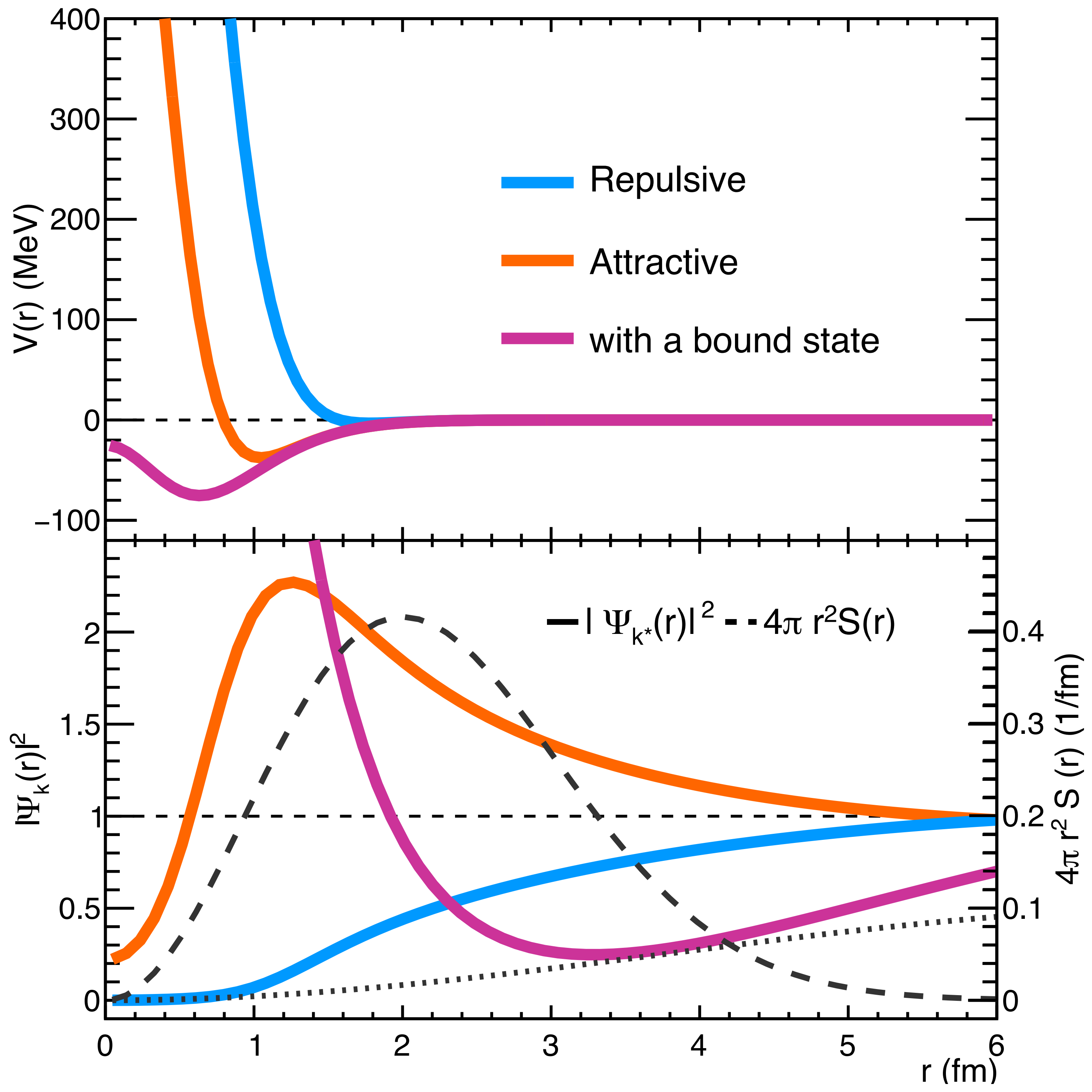
L. Fabbietti, V. Mantovani Sarti, O. Vázquez Doce, arXiv:2012.09806

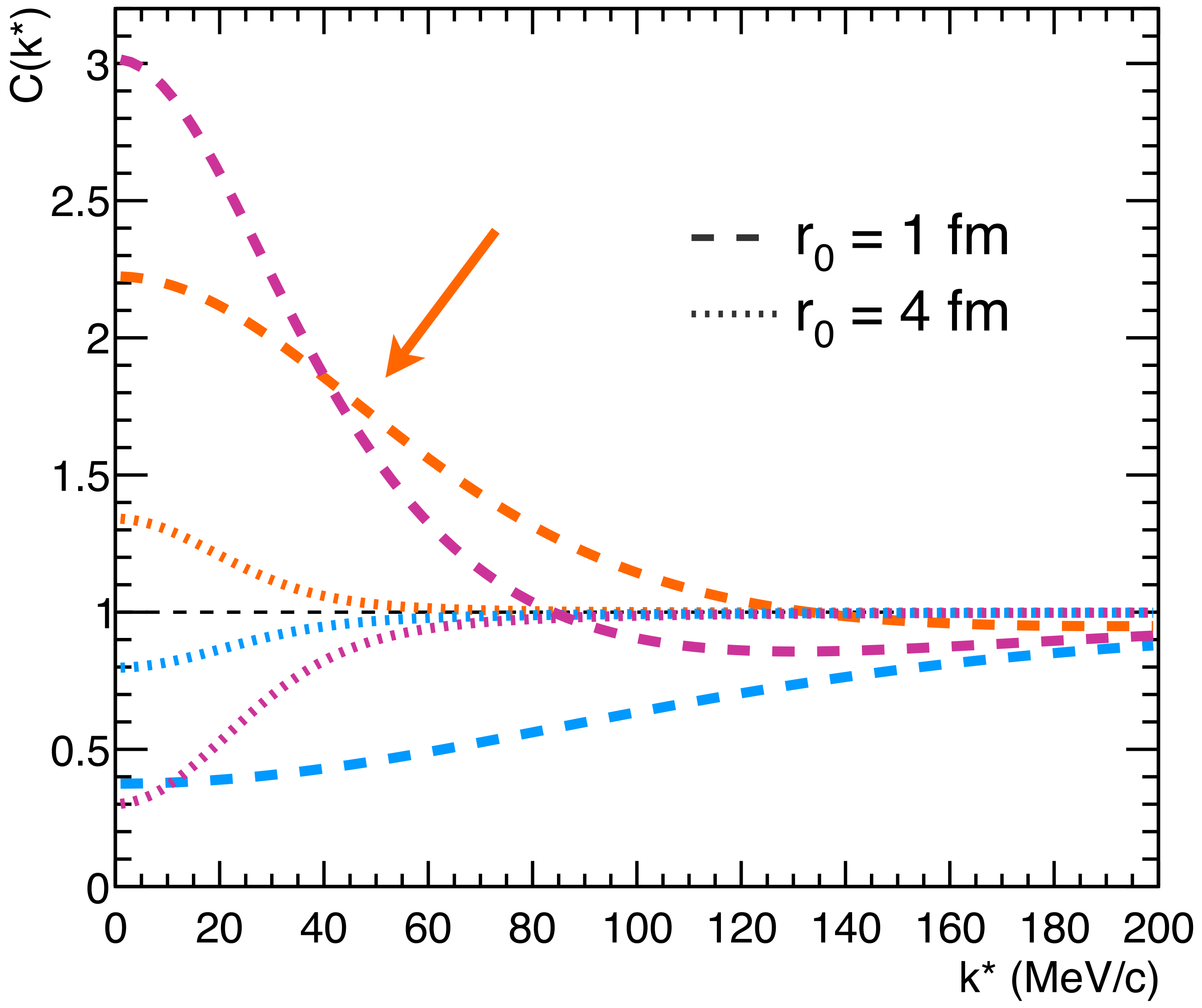
Effect of the interactions on the correlation function

$$C(\overrightarrow{k}^*) = \int S(\vec{r}^*)\,|\psi(\overrightarrow{k}^*,\vec{r}^*)|^2\,d^3r^*$$

➡ Relative wave function sensitive to interaction potential







➡ Absence of interaction $C(k^*) = 1$

➡ Attractive potential $C(k^*) > 1$

L. Fabbietti, V. Mantovani Sarti, O. Vázquez Doce, arXiv:2012.09806

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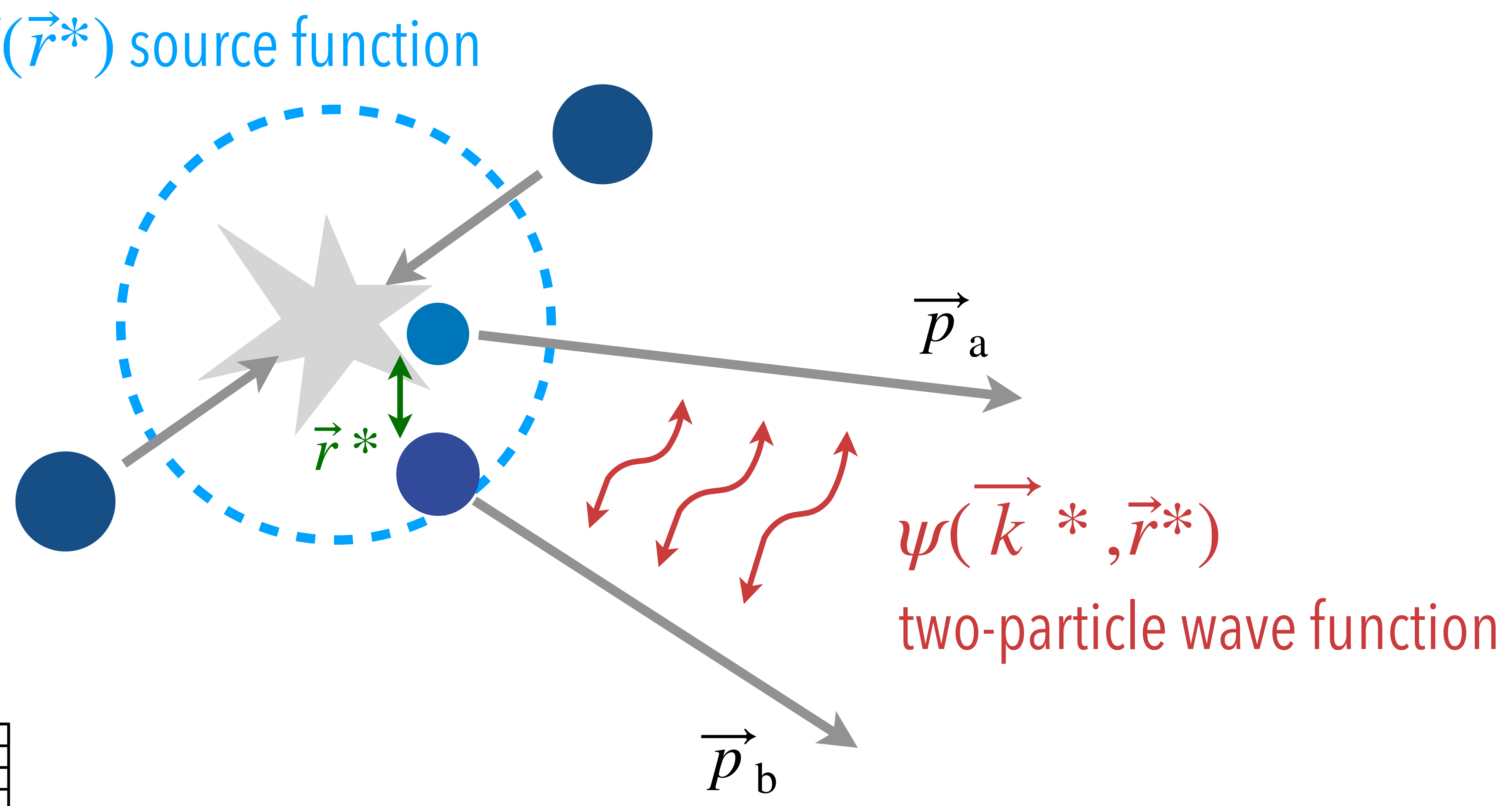
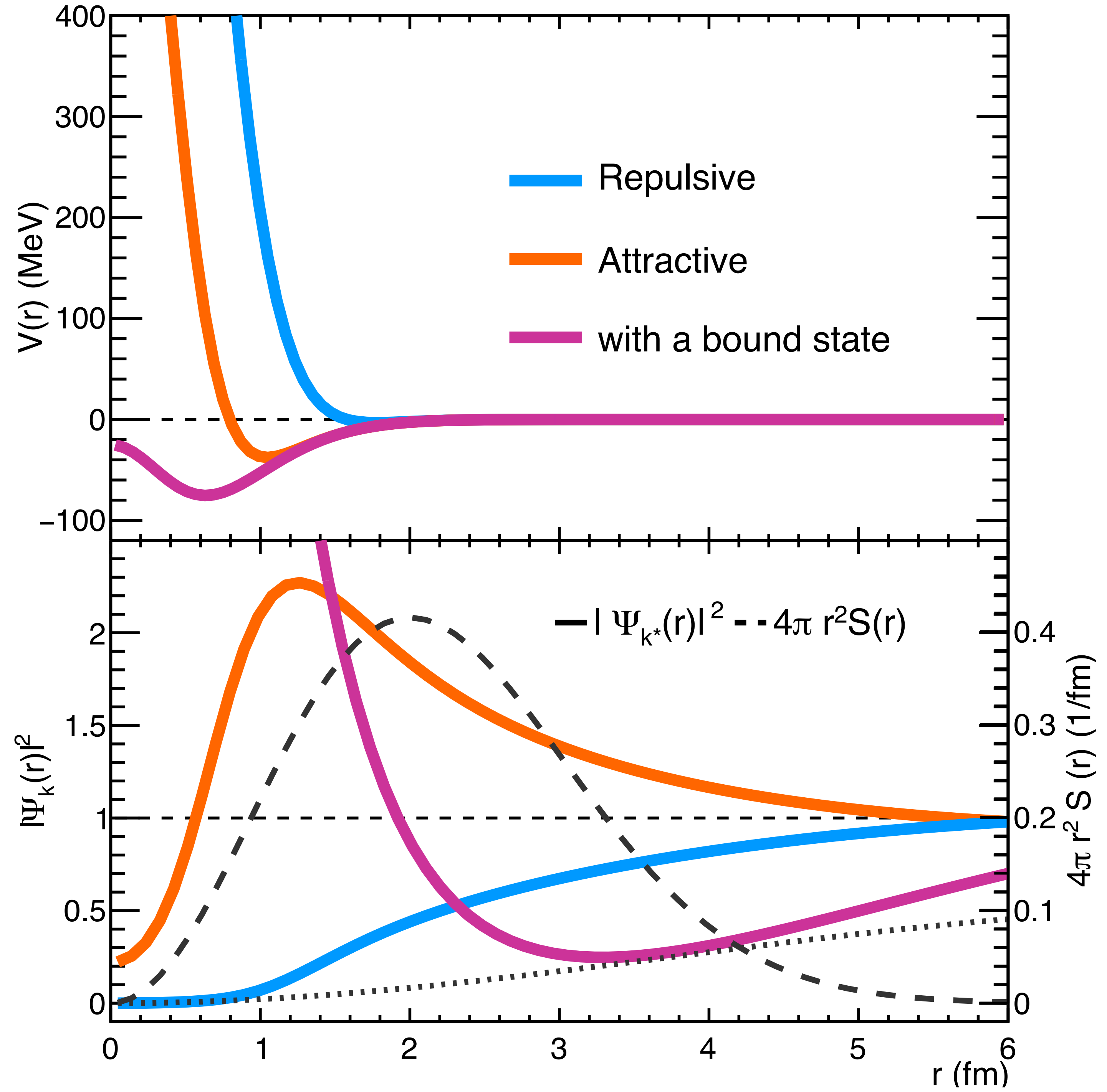
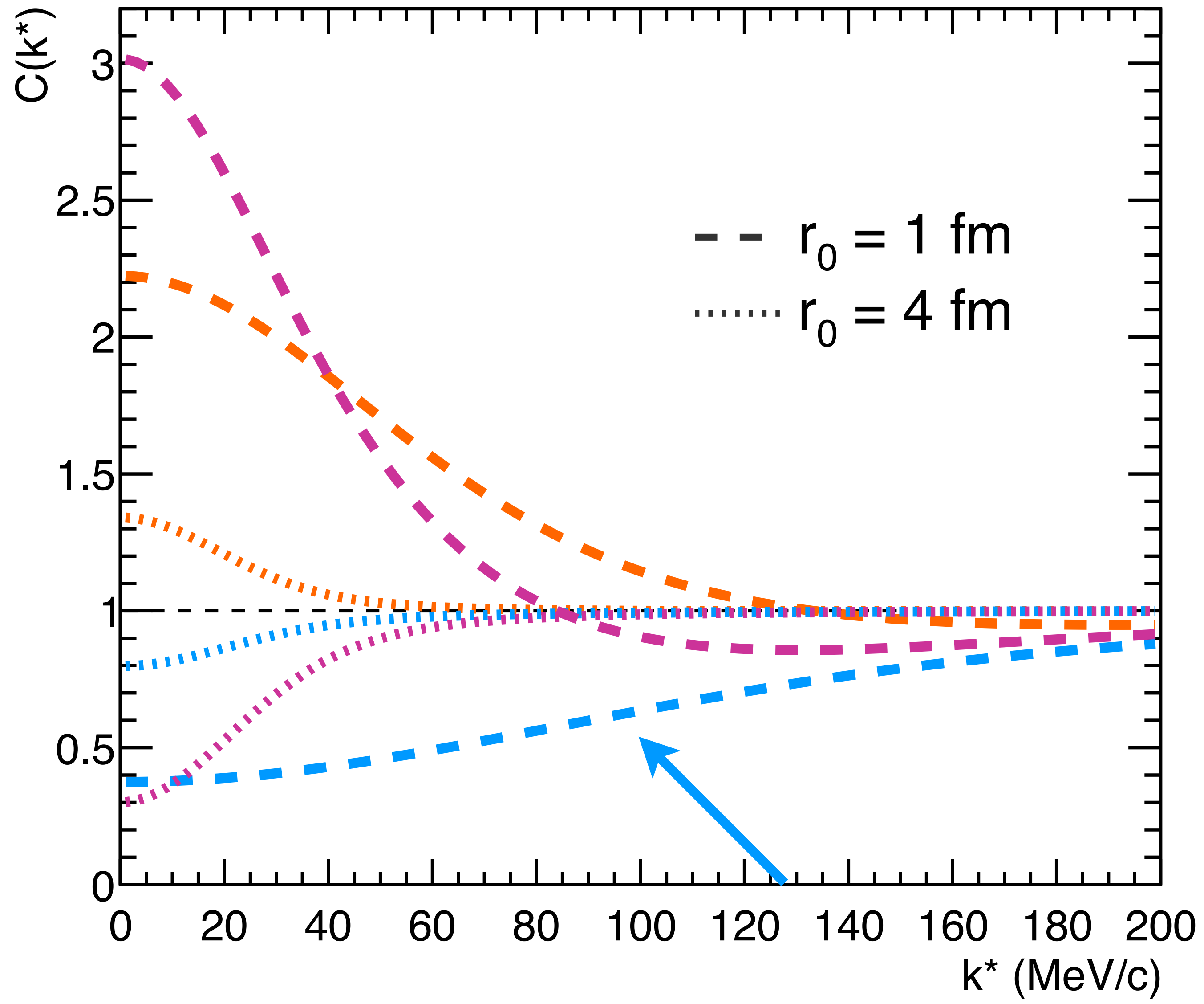
$$C(\overrightarrow{k}^*) = \int S(\vec{r}^*)\,|\psi(\overrightarrow{k}^*,\vec{r}^*)|^2 \mathrm{d}^3 r^*$$

➡ Relative wave function sensitive to interaction potential







➡ Absence of interaction $C(k^*) = 1$

➡ Attractive potential $C(k^*) > 1$

➡ Repulsive potential $C(k^*) < 1$

L. Fabbietti, V. Mantovani Sarti, O. Vázquez Doce, arXiv:2012.09806

Effect of the interactions on the correlation function

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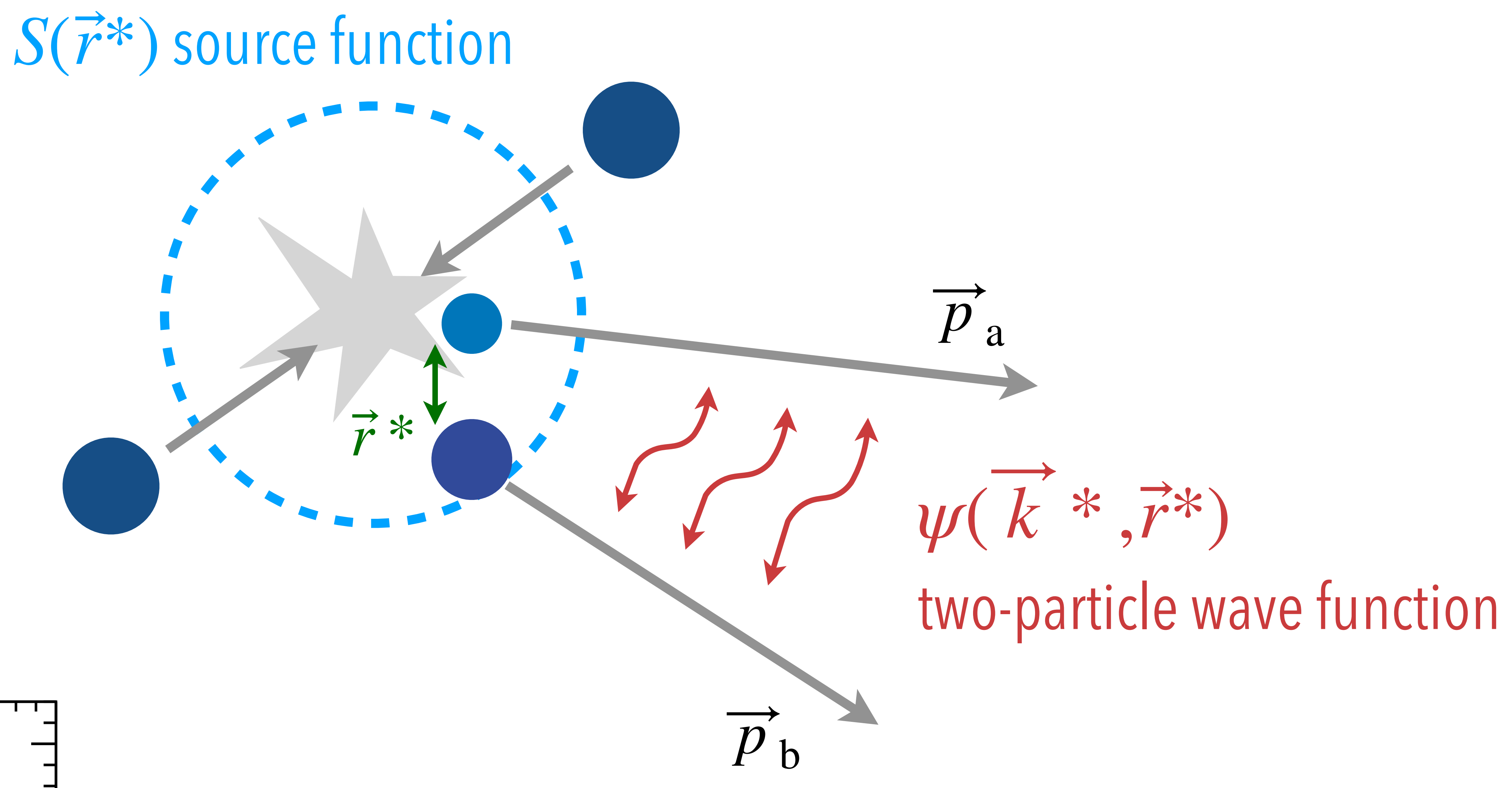
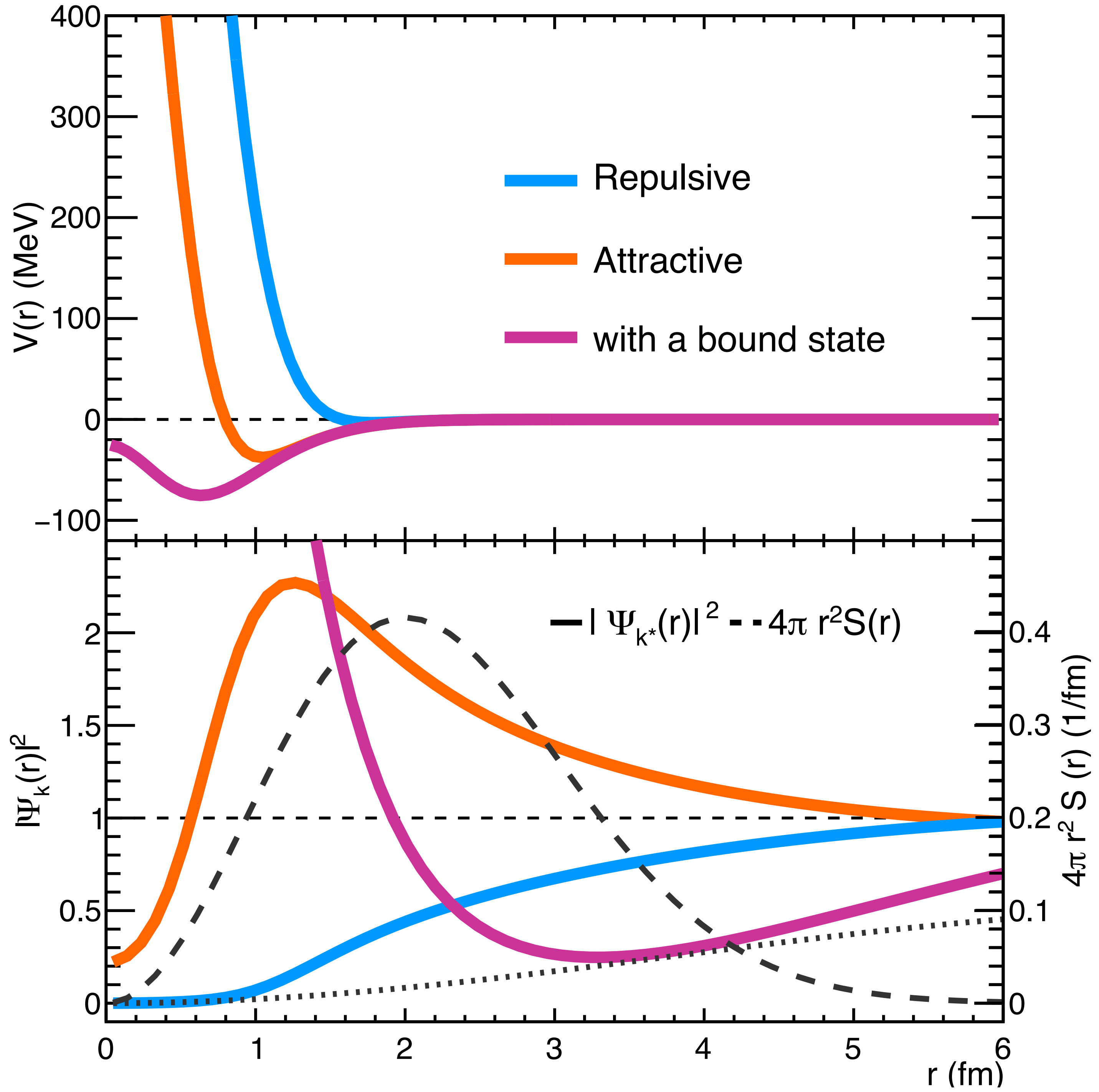
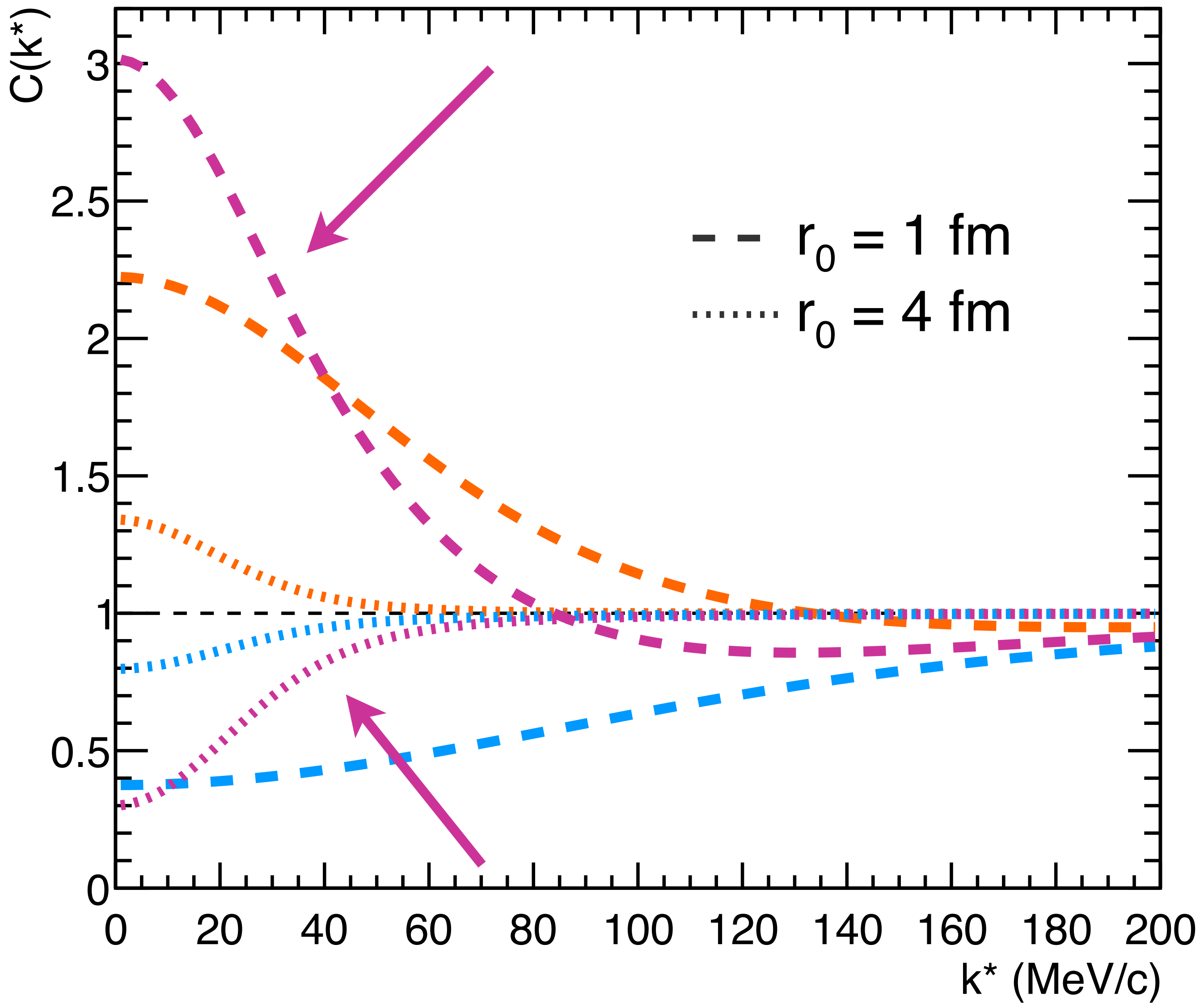
$$C(\vec{k}^*) = \int S(\vec{r}^*)\,|\psi(\vec{k}^*,\vec{r}^*)|^2\,d^3r^*$$

➡ Relative wave function sensitive to interaction potential







➡ Absence of interaction $C(k^*) = 1$

➡ Attractive potential $C(k^*) > 1$

➡ Repulsive potential $C(k^*) < 1$

➡ Bound-state formation $C(k^*) <> 1$

L. Fabbietti, V. Mantovani Sarti, O. Vázquez Doce, arXiv:2012.09806

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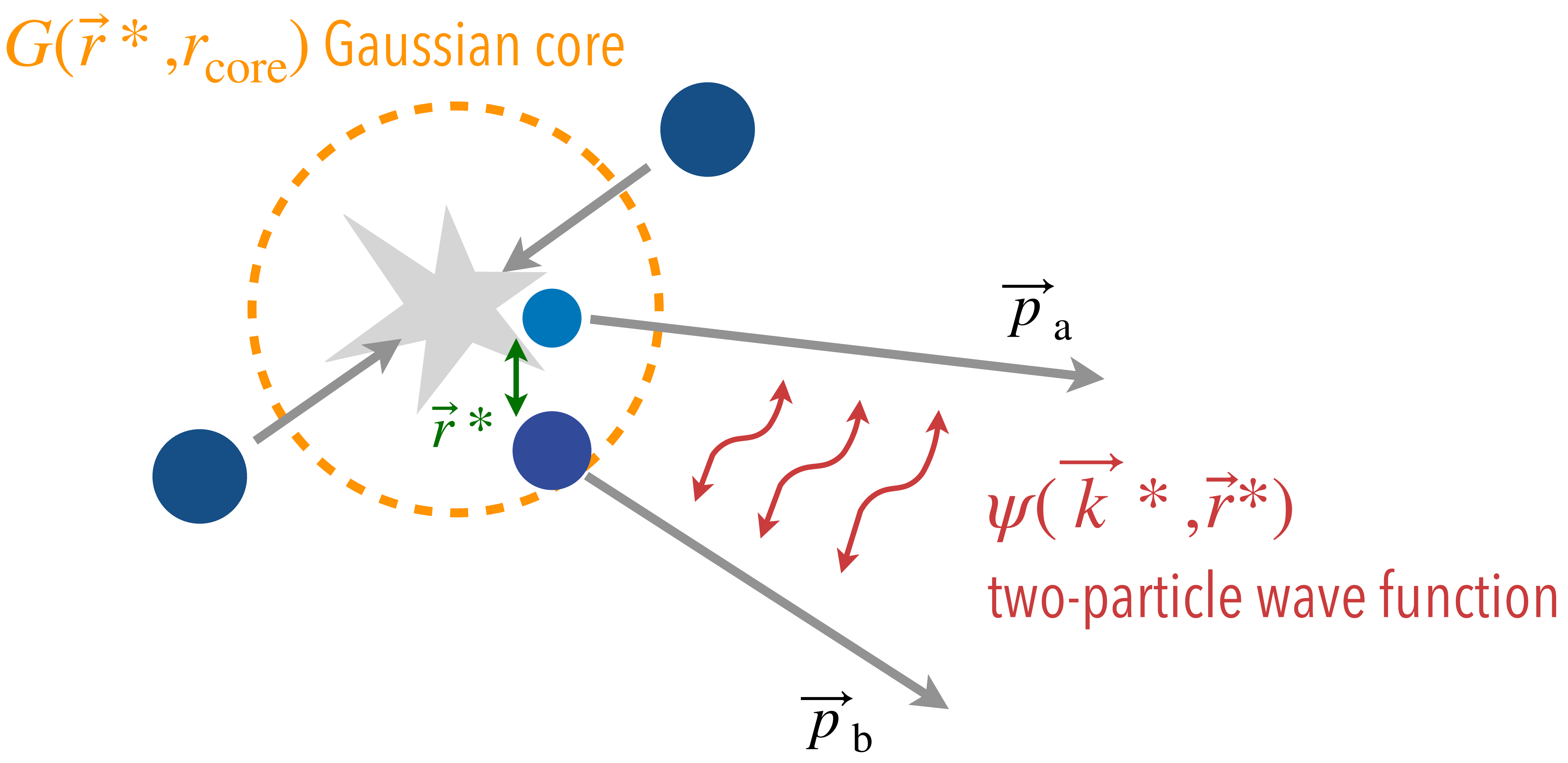
$$C(\vec{k}^*) = \int S(\vec{r}^*)\,|\psi(\vec{k}^*, \vec{r}^*)|^2 \mathrm{d}^3 r^*$$

➡ Emitting source: hypersurface at kinematic freezout of final-state particles



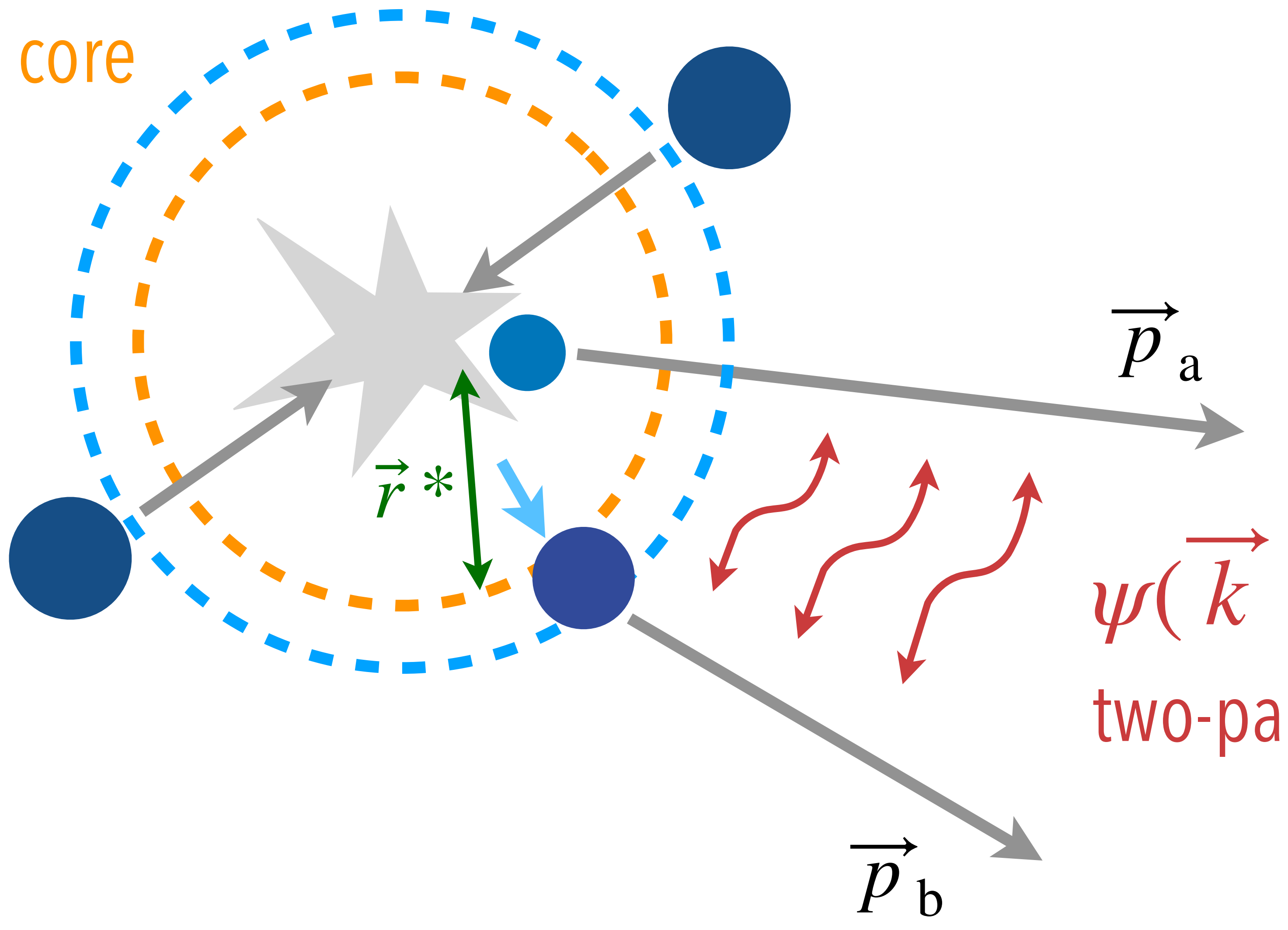
- Described with a Gaussian core

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

The emitting source

$$C(\vec{k}^*) = \int S(\vec{r}^*)\,|\psi(\vec{k}^*, \vec{r}^*)|^2\,\mathrm{d}^3 r^*$$

➡ Emitting source: hypersurface at kinematic freezout of final-state particles



- Described with a Gaussian core

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

- Short-lived strongly decaying resonances effectively enlarge it

$$E(r^*, M_{\mathrm{res}}, \tau_{\mathrm{res}}, p_{\mathrm{res}}) = \frac{1}{s}\exp\left(-\frac{r^*}{s}\right) \quad \text{with} \quad s = \beta\gamma\tau_{\mathrm{res}} = \frac{p_{\mathrm{res}}}{M_{\mathrm{res}}}\tau_{\mathrm{res}}$$

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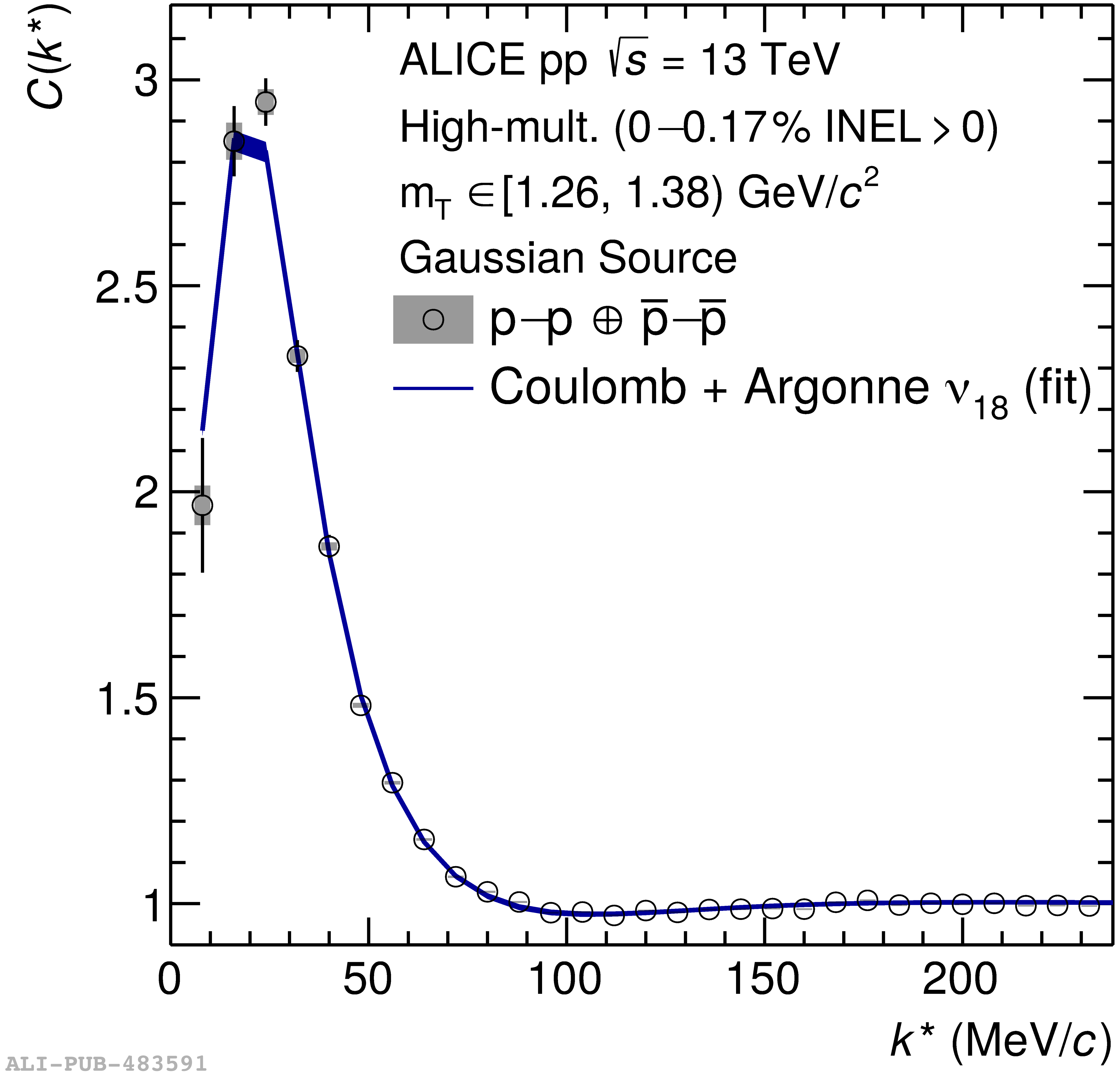
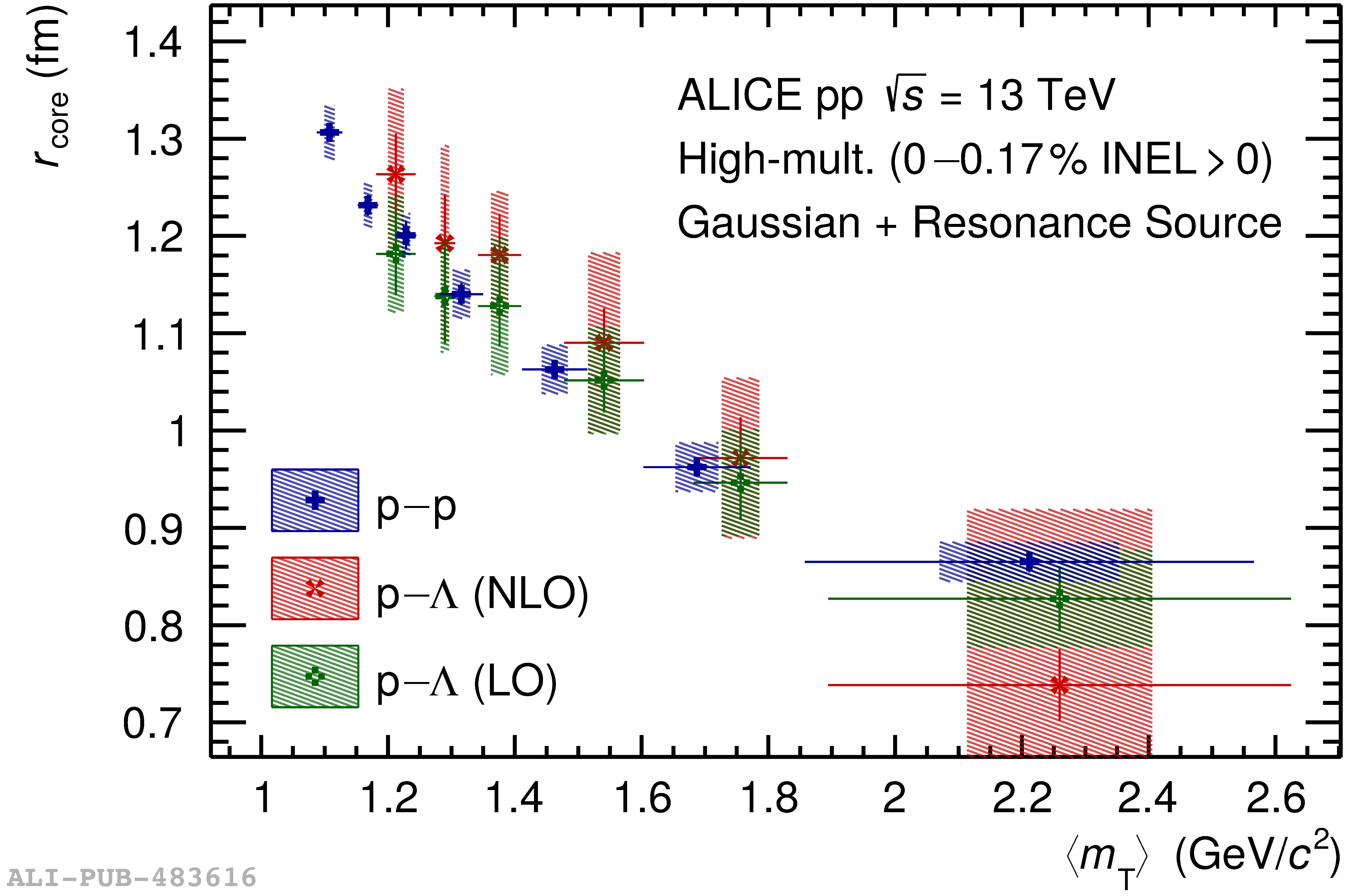
Phys. Lett. B 811 (2020) 135849



- Fit correlation functions of p–p and p–Λ pairs
  - ➡ Interaction precisely described
  - ➡ Gaussian source with radius as free parameter

Phys. Lett. B 811 (2020) 135849



- Source size ~1fm makes the high-multiplicity pp system suitable for the study of hadron–hadron interactions

Reconstruction of strange and charm hadron decays in ALICE

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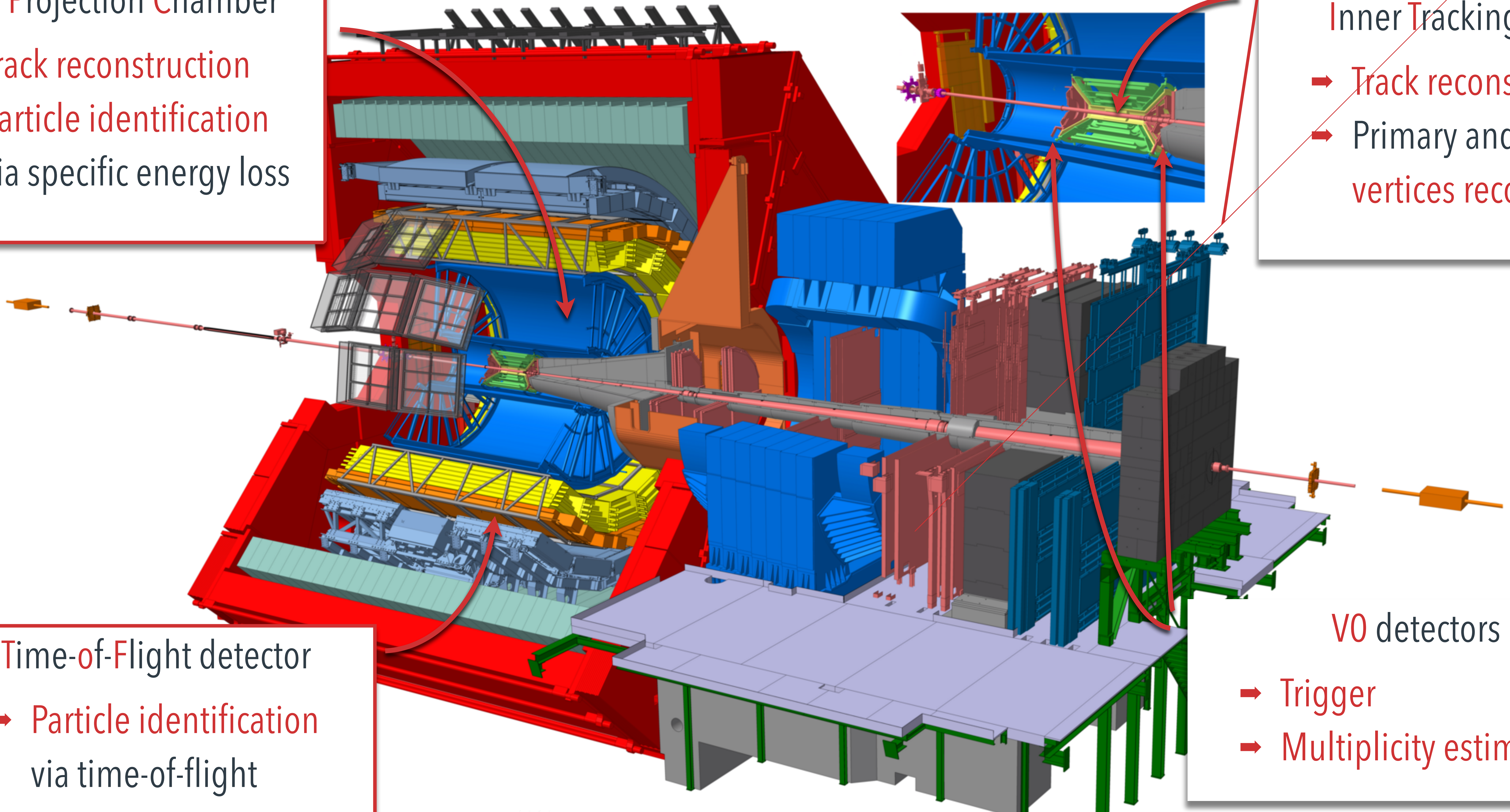
Time Projection Chamber

- Track reconstruction
- Particle identification via specific energy loss

Inner Tracking System

- Track reconstruction
- Primary and decay vertices reconstruction



ALICE-PHO-SKE-2017-001

Time-of-Flight detector

- Particle identification via time-of-flight

V0 detectors

- Trigger
- Multiplicity estimation

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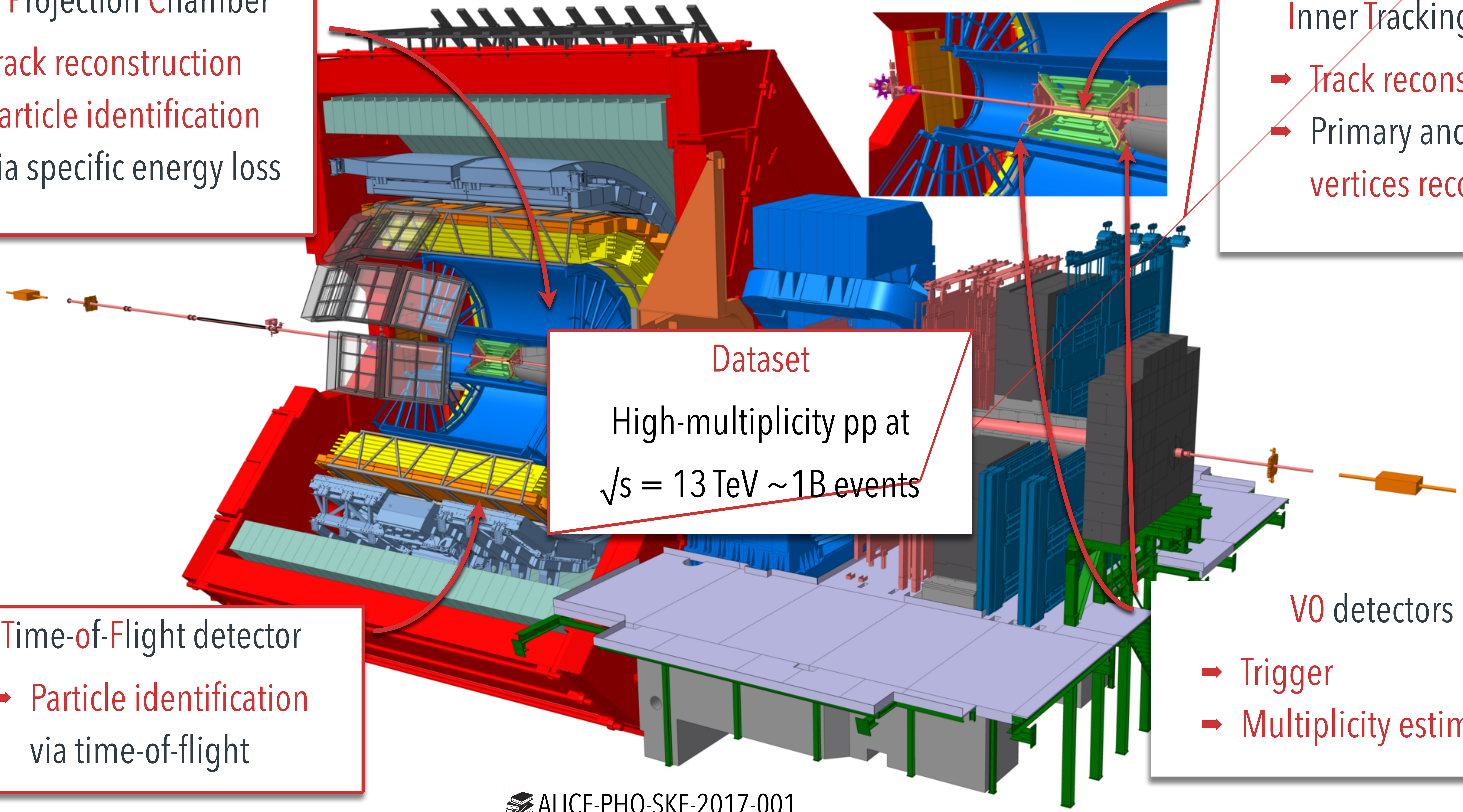

Dataset

High-multiplicity pp at $\sqrt{s}$ = 13 TeV ~1B events

Time-of-Flight detector

- ➡ Particle identification via time-of-flight

V0 detectors

- ➡ Trigger
- ➡ Multiplicity estimation

ALICE-PHO-SKE-2017-001

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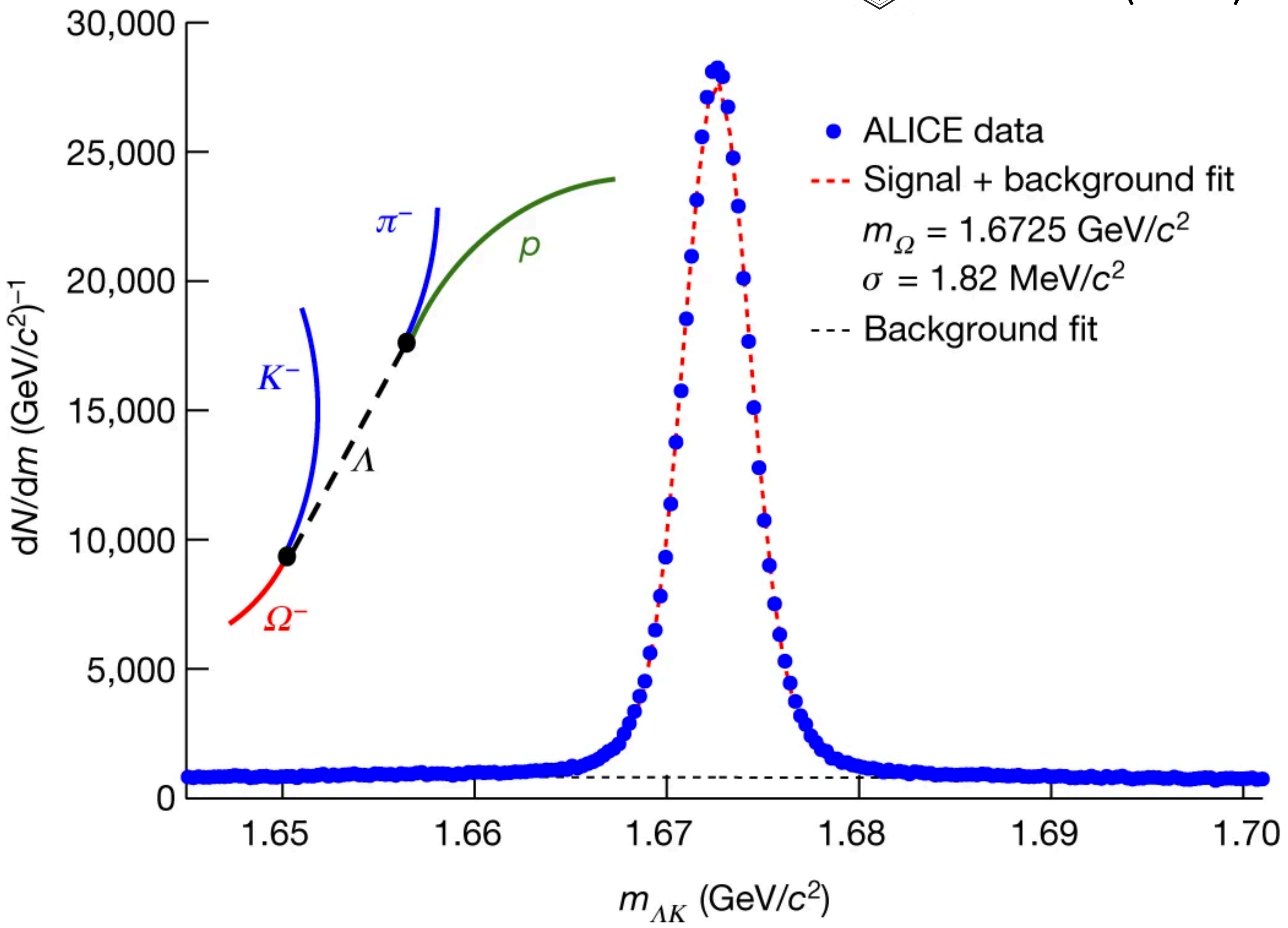
PDG2020, Prog. Theor. Exp. Phys. (2020) 083C01

hadron	decay channel	$c\tau$ (cm)	BR (%)
Λ^0	$p\,\pi^-$	7.89	63.9
Ξ^-	$\Lambda^0\,\pi^-$	4.91	99.9
Ω^-	$\Lambda^0\,K^-$	2.46	67.8
Σ^0	$\Lambda^0\,\gamma$	4.43	100
ϕ	$K^+\,K^-$	Strong decay	48.9
D^-	$K^+\,\pi^-\,\pi^-$	0.0311	9.38

Nature 588 (2020) 232–238



- Strange and charm hadrons reconstructed from their decay products
- Selections on decay-vertex topologies and PID of decay tracks to reduce background
  - ➡ very high purity achieved (>90% for Λ, Ξ^-, Ω^- and >60% for D^-)

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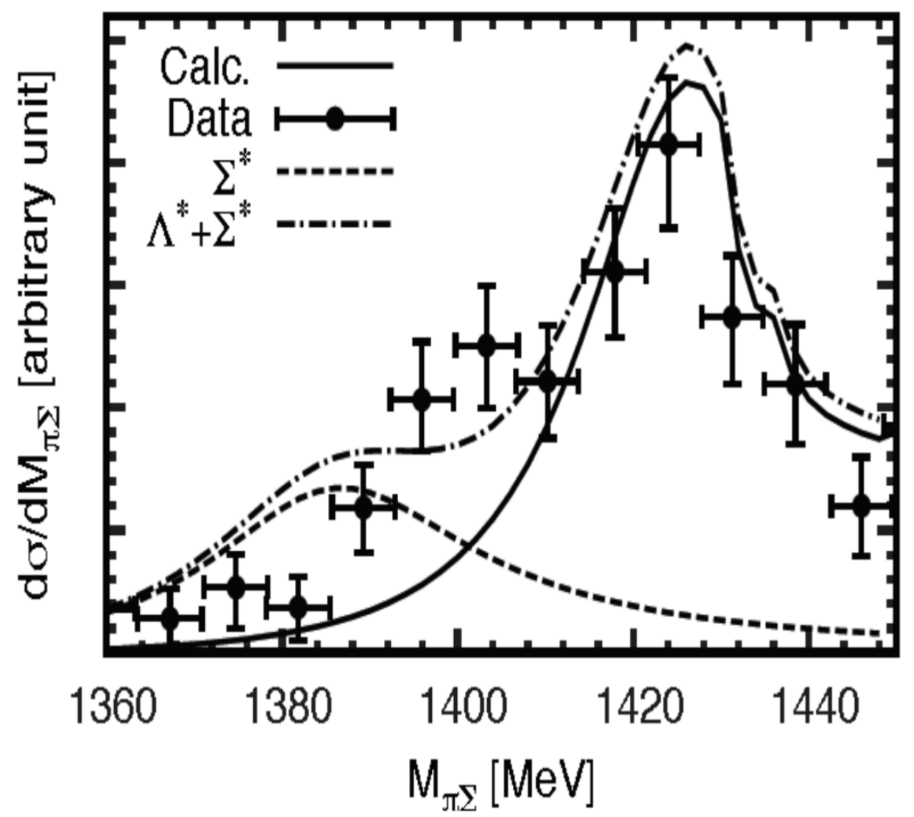
- Λ(1405): $\bar{K}$N–Σπ molecular state
  - ➡ Mass analysis of Σπ: appearance of the Λ(1405) below threshold

Λ(1405)→Σπ



  - ➡ p–K⁻ scattering and kaonic hydrogen data used to constrain the amplitude above threshold (limited precision)

M. Bazzi et al., Phys. Lett. B 704 (2011) 113
M. Bazzi et al., Nucl. Phys. A 881 (2012) 88

p–K⁻ interaction

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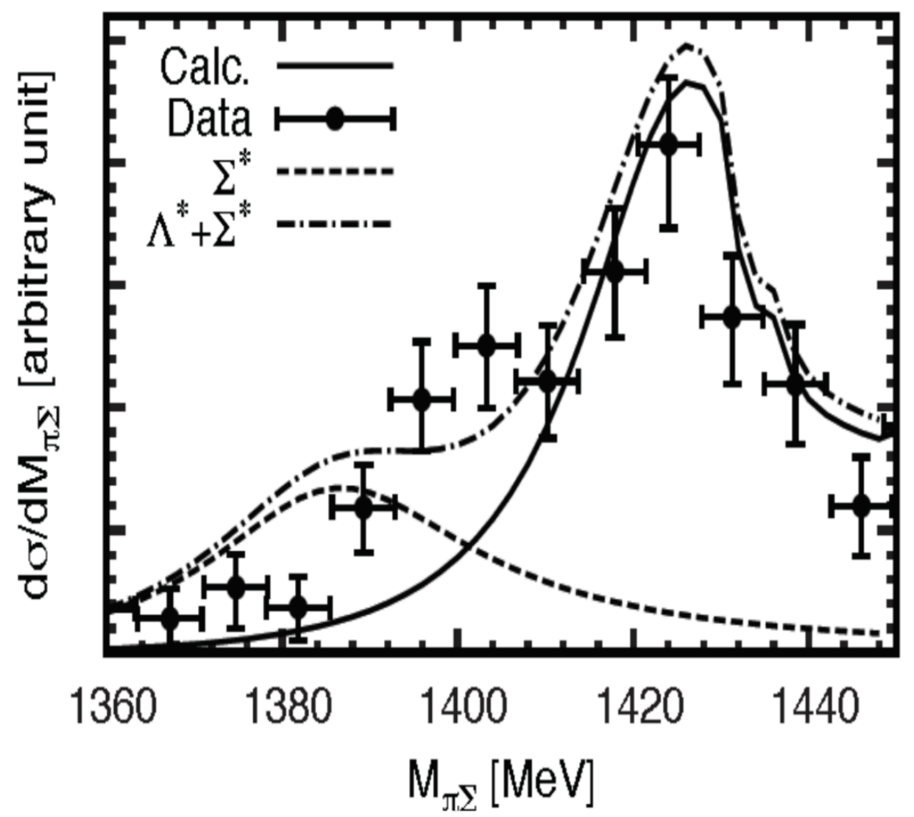

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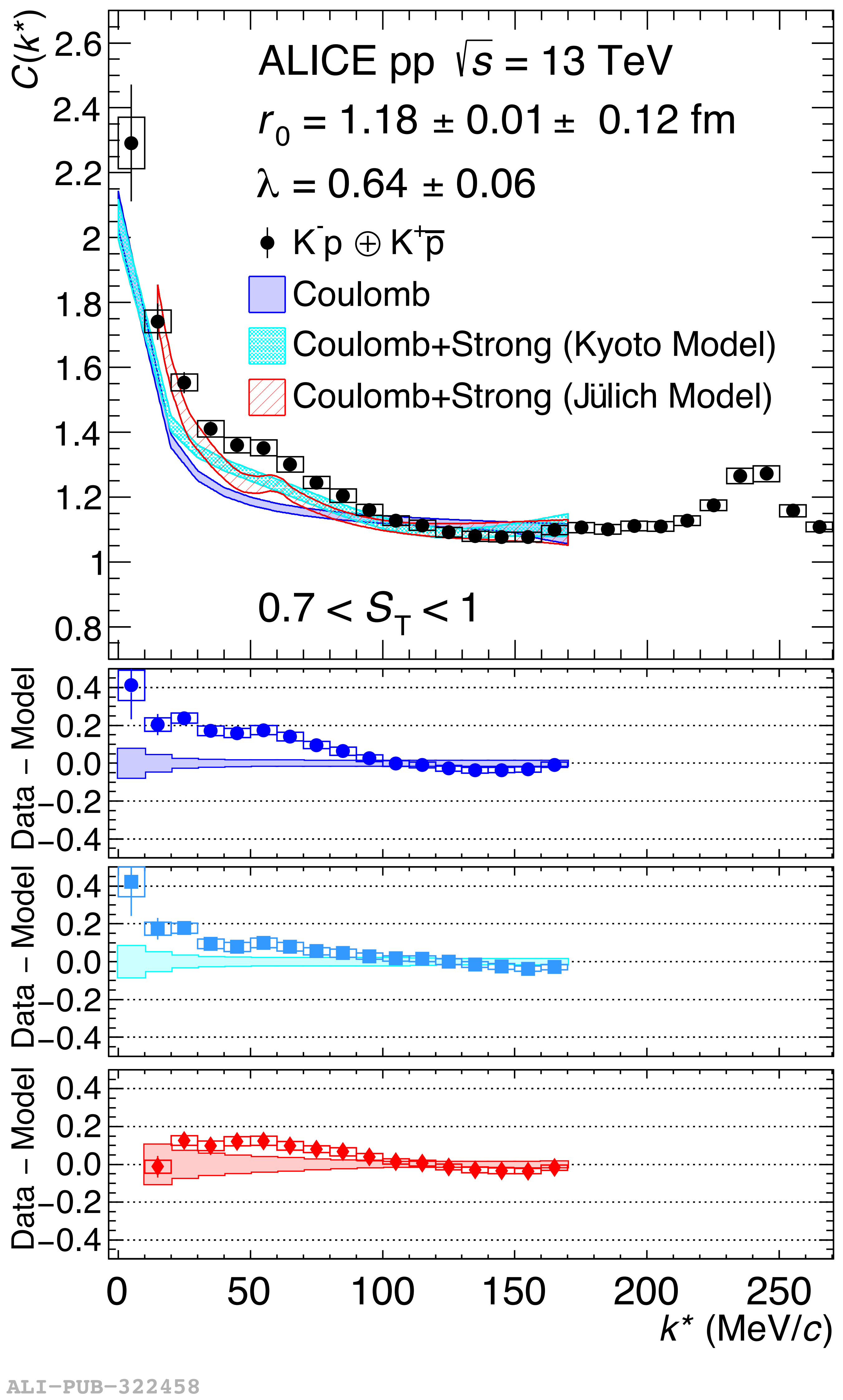
Phys. Rev. Lett. 124 (2020) 092301



- Very precise data from ALICE
  - ➡ Used by theory groups to constrain scattering parameters
- Structure around the n–$\bar{K}^0$ threshold (~58 MeV/c)
  - ➡ First experimental observation of the opening of the n–$\bar{K}^0$ isospin breaking channel

Kyoto Model: Phys. Rev. C93 no. 1, (2016) 015201
Jülich Model: Nucl. Phys. A 981 (2019) 1-16

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S = 0	S = -1	S = -2	S = -3	S = -4	S = -5	S = -6
NN	NΛ, NΣ	ΛΛ, ΛΣ, ΣΣ, NΞ	ΛΞ, ΣΞ, NΩ	ΞΞ, ΛΩ, ΣΩ	ΞΩ	ΩΩ

Experiment ⟵⟶ Better S/N of lattice QCD (lQCD)

- p–K: Phys. Rev. Lett. 124 (2020) 092301
- p–p, p–Λ, Λ–Λ: Phys. Rev. C 99 (2019) 024001
- p–$\bar{p}$, p–$\bar{\Lambda}$, Λ–$\bar{\Lambda}$: arXiv:2105.05190
- Λ–Λ: Phys. Lett. B 797 (2019) 134822
- p–Ξ^-: Phys. Rev. Lett. 123 (2019) 112002
- p–Ξ^-, p–Ω^-: Nature 588 (2020) 232–238
- p–Σ^0: Phys. Lett. B 805 (2020) 135419
- p–ϕ: arXiv:2105.05578
- N–Λ, N–Σ^0: arXiv:2104.04427

Hyperon–nucleon and hyperon–hyperon interactions with lQCD

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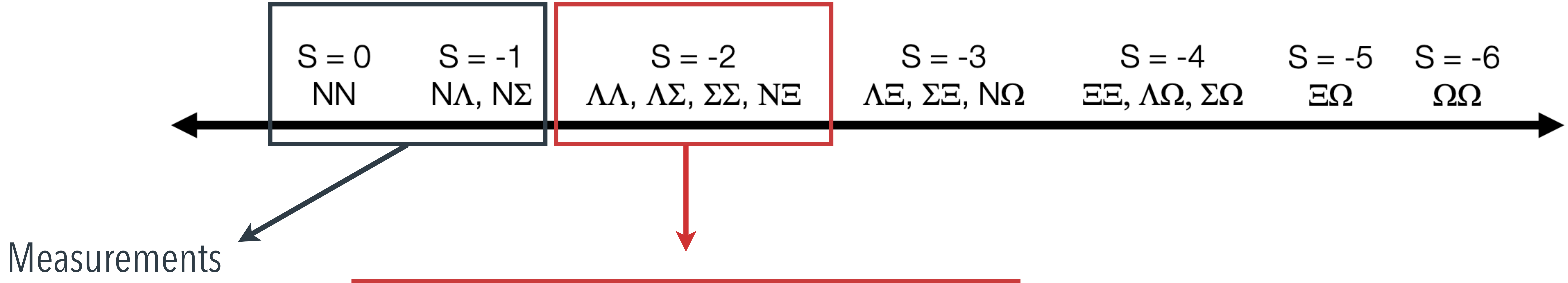

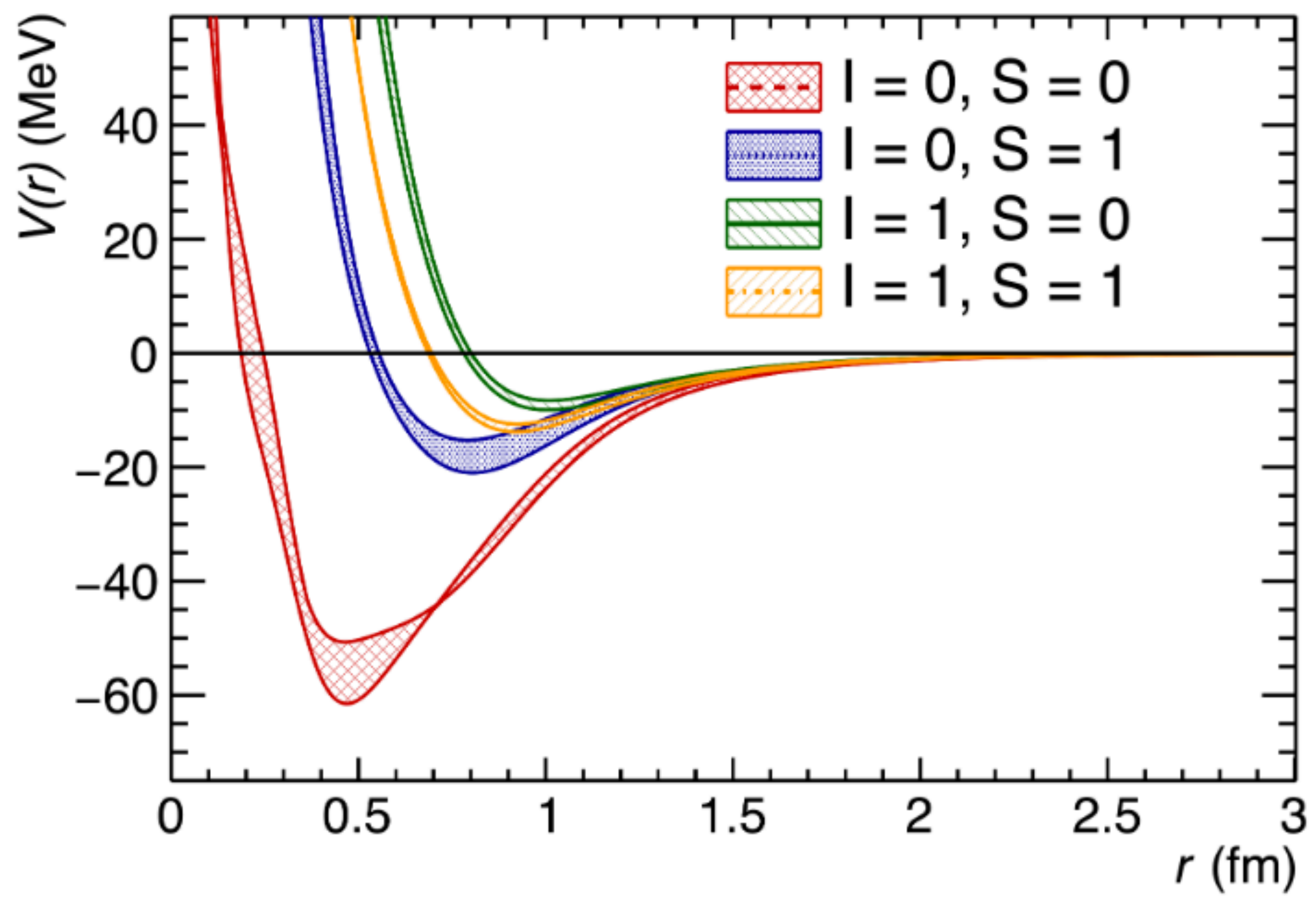

HAL QCD, Nuclear Physics A 998 (2020) 121737

- p–Ξ^- interaction in 4 isospin (I) and (S) states

Hyperon–nucleon and hyperon–hyperon interactions with lQCD

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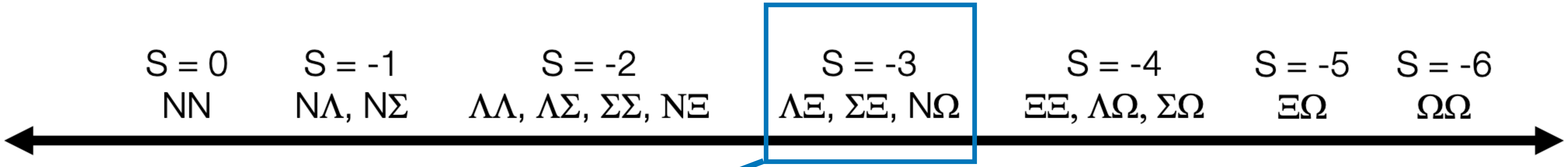
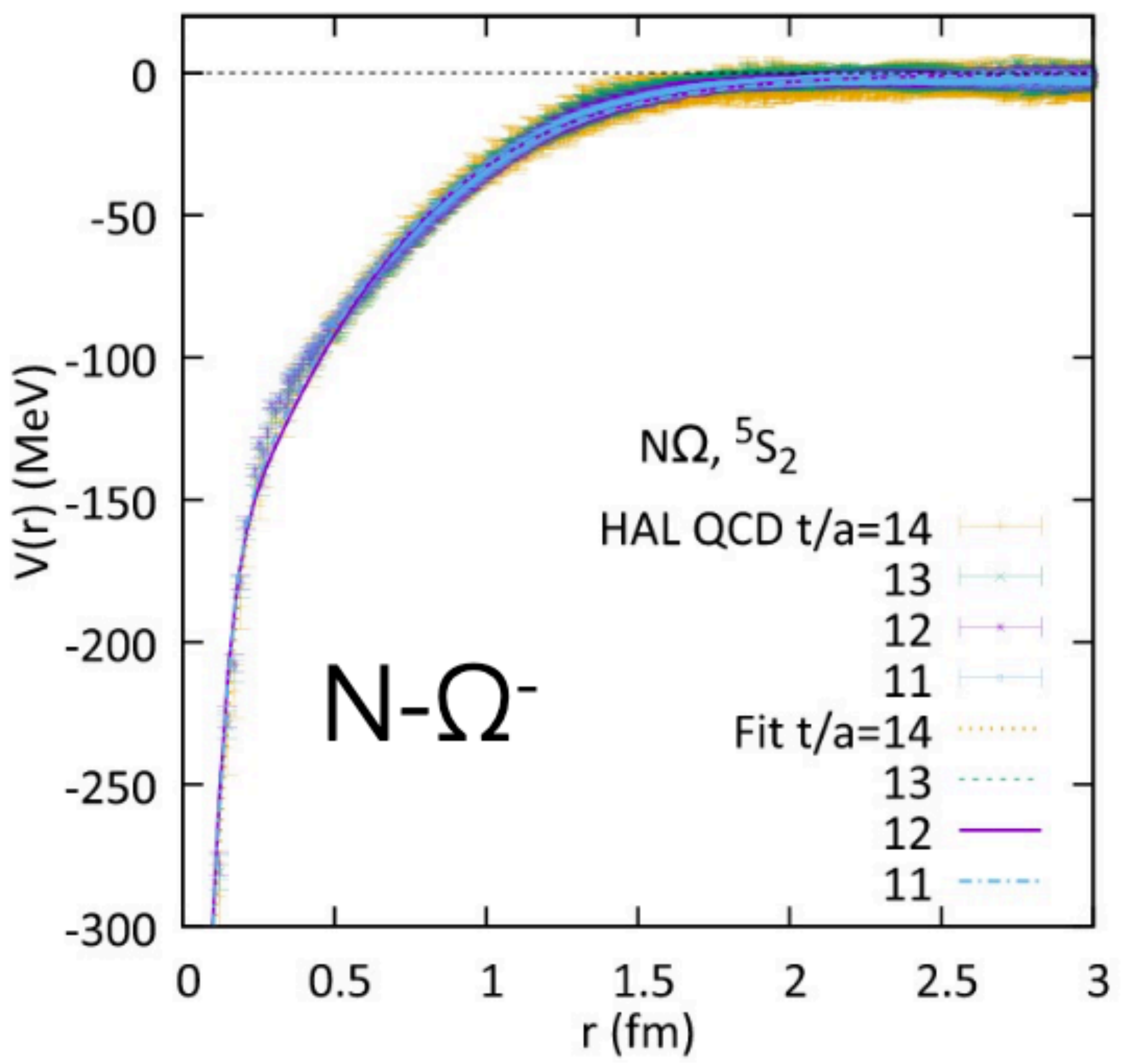


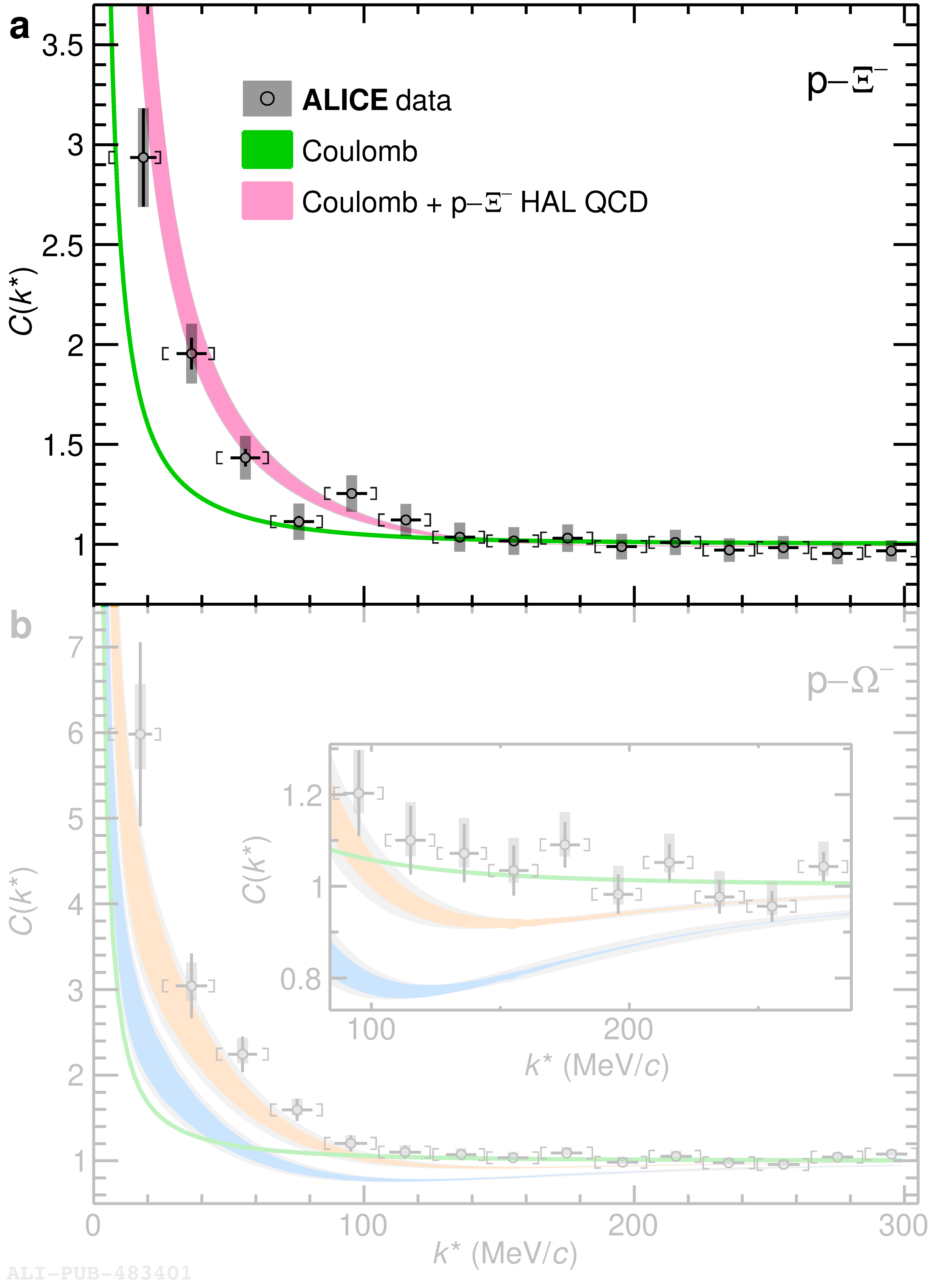


HAL QCD, Phys. Rev. C 101 (2020) 015201

- p–Ω^-: two spin states $^5S_2$ and $^3S_1$ with absorption to Λ–Ξ^- and Σ^0–Ξ^-
  - ➡ Absorption processes in $^3S_1$ not yet calculated in lQCD
  - ➡ Attraction in $^5S_2$ results in a bound state with B.E. = 1.54 MeV

p–Ξ⁻ and p–Ω⁻ interactions

Nature 588,232–238 (2020)

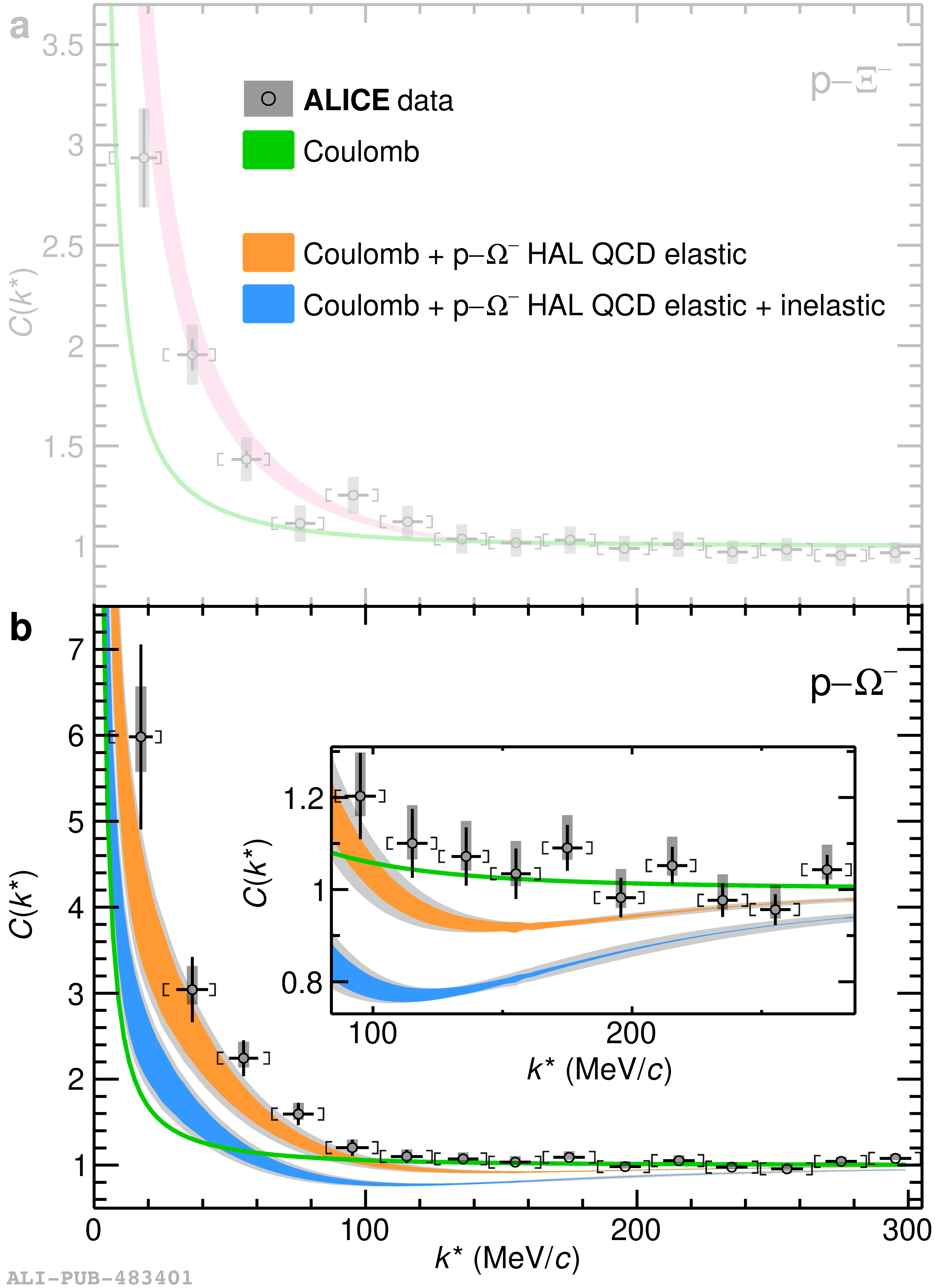


- Overall attractive interaction
- Enhancement above Coulomb interaction
  - ➡ Attractive strong interaction
- Very well described by lQCD calculations

HAL QCD, Nucl. Phys. A 998 (2020) 121737

p–Ξ⁻ and p–Ω⁻ interactions

Nature 588,232–238 (2020)



- Overall attractive interaction
- Enhancement above Coulomb interaction
  - ➡ Attractive strong interaction

- Missing potential of the $^3S_1$ channel
  - ➡ Test of two cases:
    - ▸ Inelastic channels dominated by absorption
    - ▸ Neglecting inelastic channels
  - ➡ Data more precise than lattice calculations
  - ➡ So far, no indication of a bound state

HAL QCD, Phys. Rev. C 101 (2020) 015201

Λ–Ξ⁻ interaction

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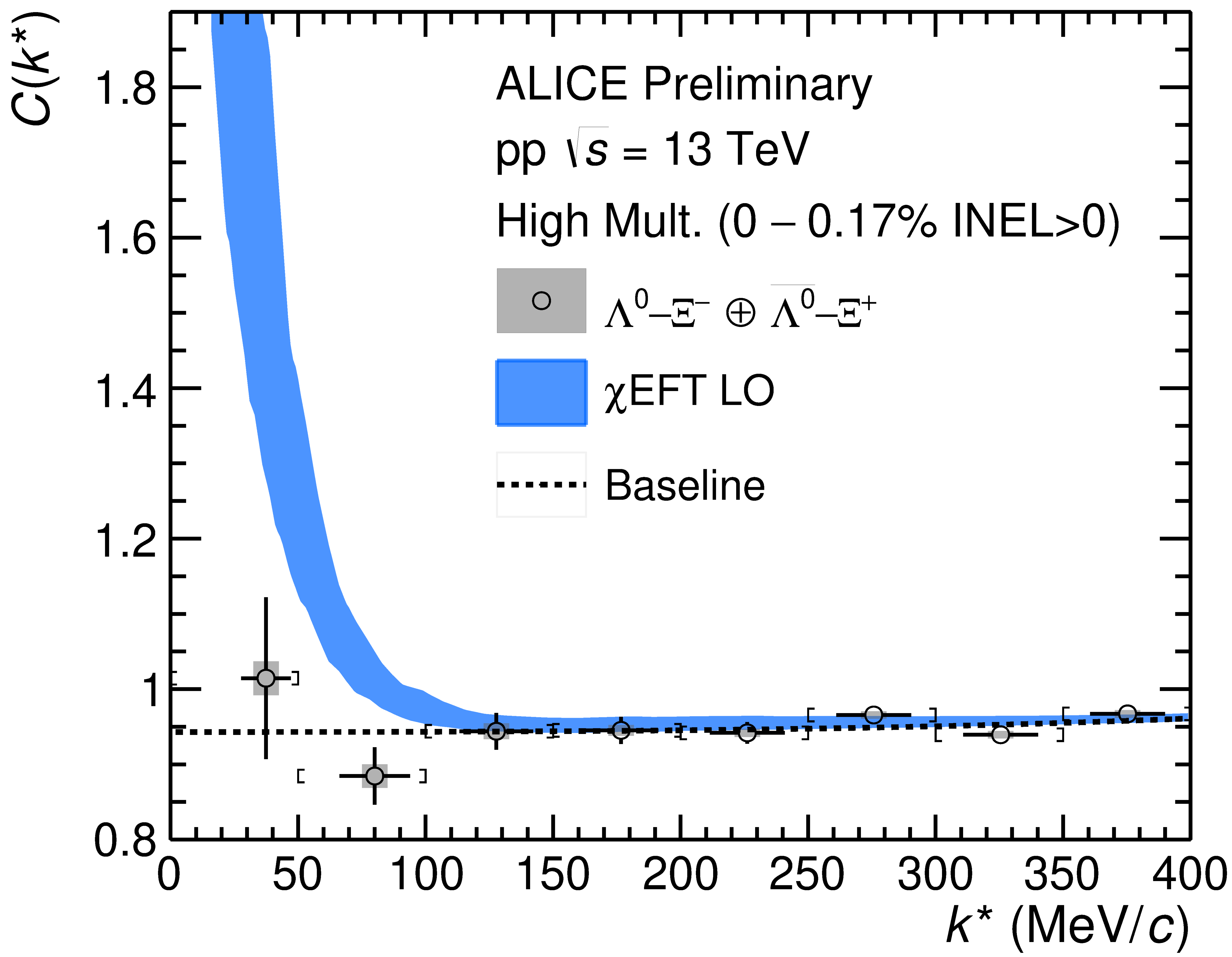
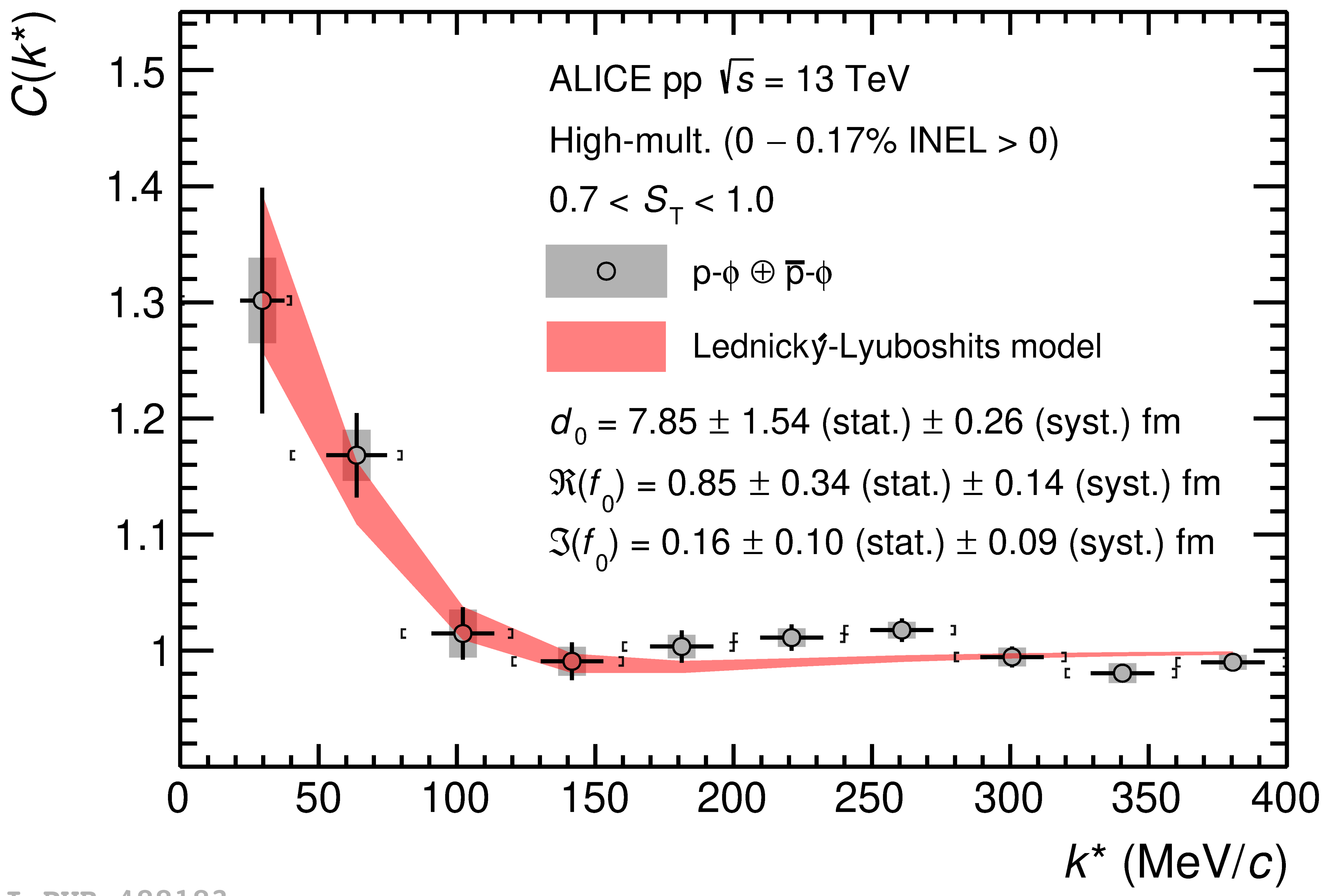
- More insights about hyperon–hyperon interaction can be accessed via the Λ–Ξ⁻
- Coupled channel in p–Ω⁻
  - ➡ Shallow interaction
  - ➡ Negligible coupling to p–Ω⁻
  - ➡ No lQCD calculations available
  - ➡ Chiral effective field theory to leading order

    J. Haidenbauer, U.-G. Meissner, Phys. Lett. B 684 (2010) 275–280
    - ▸ Large scattering parameters
    - ▸ Does not describe the data



arXiv:2105.05578



ALI-PUB-488183

- Hidden-strange content → direct coupling to u and d quarks expected to be OZI suppressed
  - ➡ Expected small interaction
- N–ϕ OZI-allowed processes can proceed via couplings to particle pairs with same quantum numbers (e.g. K–Λ)

- Attractive interaction
- Scattering parameters obtained by comparing the data with a model based on the Lednický-Lyuboshits approach

R. Lednicky and V.L. Lyuboshits, Sov. J. Nucl. Phys. 53 (1982) 770

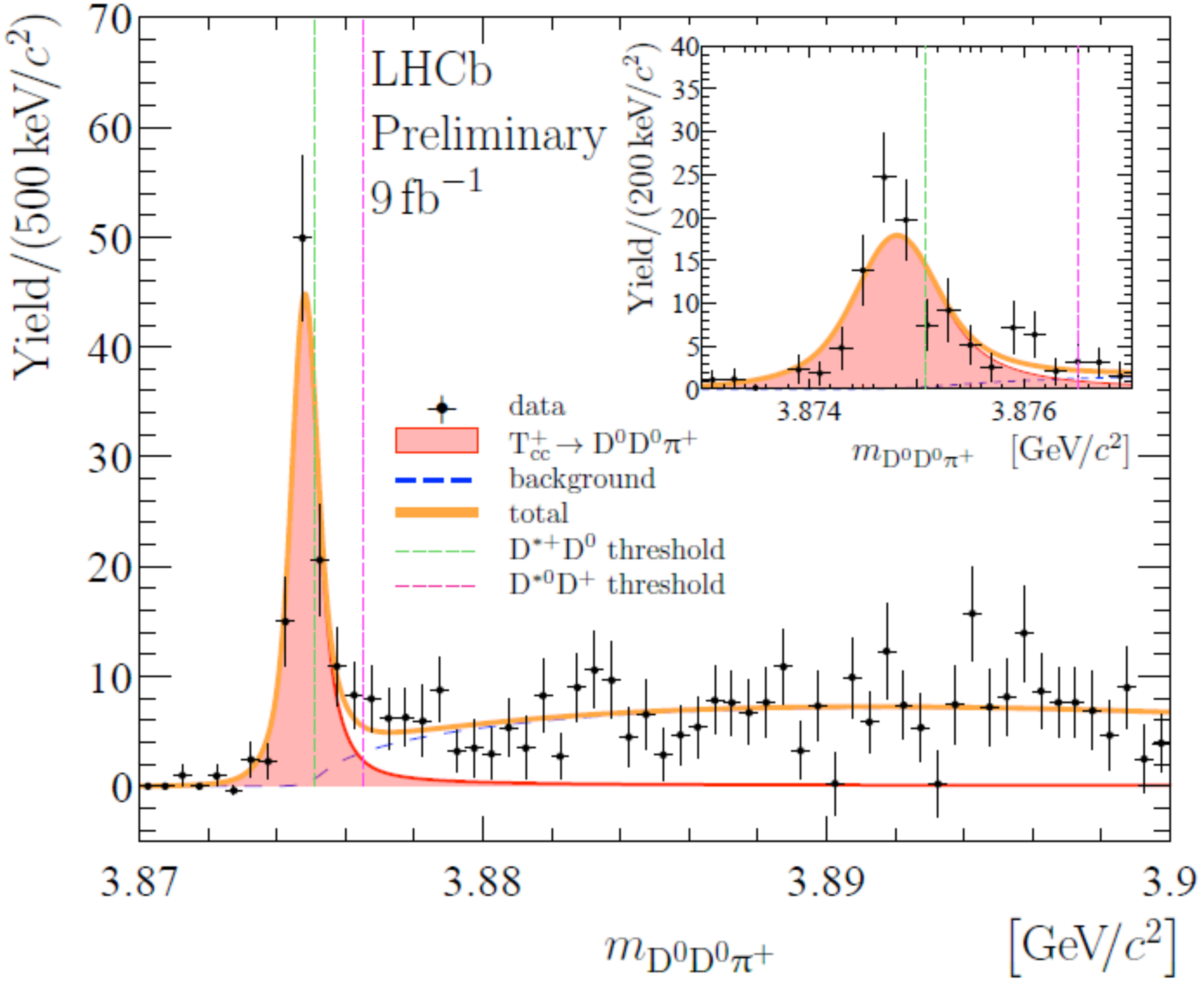
➡ N–ϕ coupling constant can be related to the hyperon–hyperon interaction: $g_{\Lambda-\phi} \propto g_{N-\phi}$

S. Weissborn et al., Nucl. Phys. A, 881 (2012) 62-77

- Study of interaction of hadrons involving charm quarks is of great interest for hadronic physics
  - ➡ Similarly to the case of Λ(1405), also in the charm sector the knowledge of hadron–hadron potentials gives the possibility to discriminate between molecular or multi-quark states
    - ▸ e.g. X(3872), $T_{cc}{}^{+}$, P_c(4450), P_c(4380)

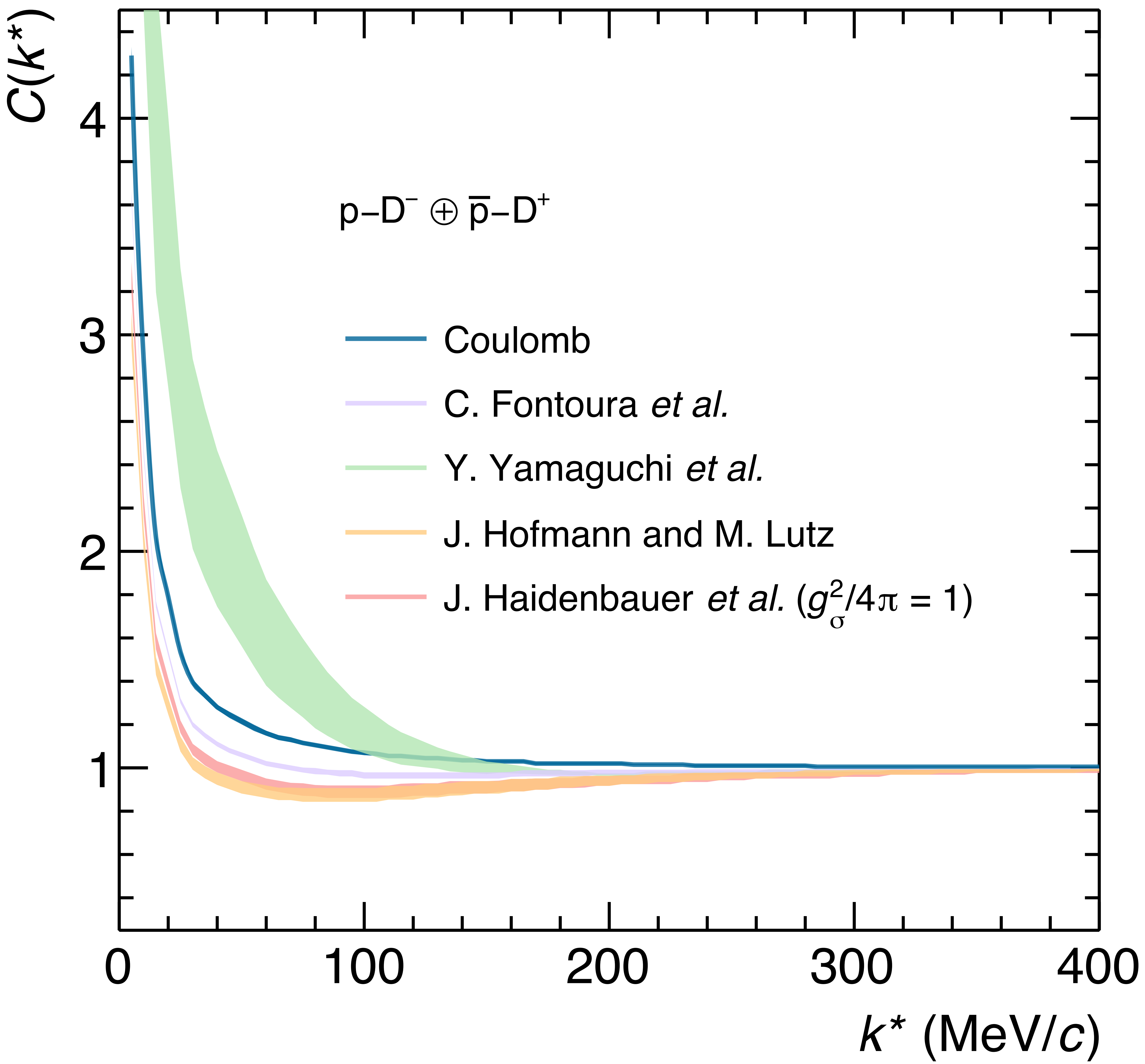
E. S. Swanson, Phys. Rept. 429 (2006) 243-305
F.-K. Guo et al, Rev. Mod. Phys. 90 (2018) 1, 015004

EPS2021, Recent LHCb results on exotic meson candidates



First look at p–D⁻ interaction

- "Simplest" system: p–D⁻
  - ➡ Most of the models predict repulsive interaction
  - ➡ Attraction might arise from 2-pion exchange
  - ➡ Possible pentaquark Θ_c (c-ud-ud) resonance
    - H1, Phys. Lett. B588:17,2004
  - ➡ Potential calculable with lattice QCD (not yet available)



J. Haidenbauer et al, Eur. Phys. J. A33 (2007) 107-117
J. Hofmann and M. Lutz, Nucl. Phys. A 763 (2005) 90-139
Fontura et al, Phys. Rev. C 87 (2013) 025206
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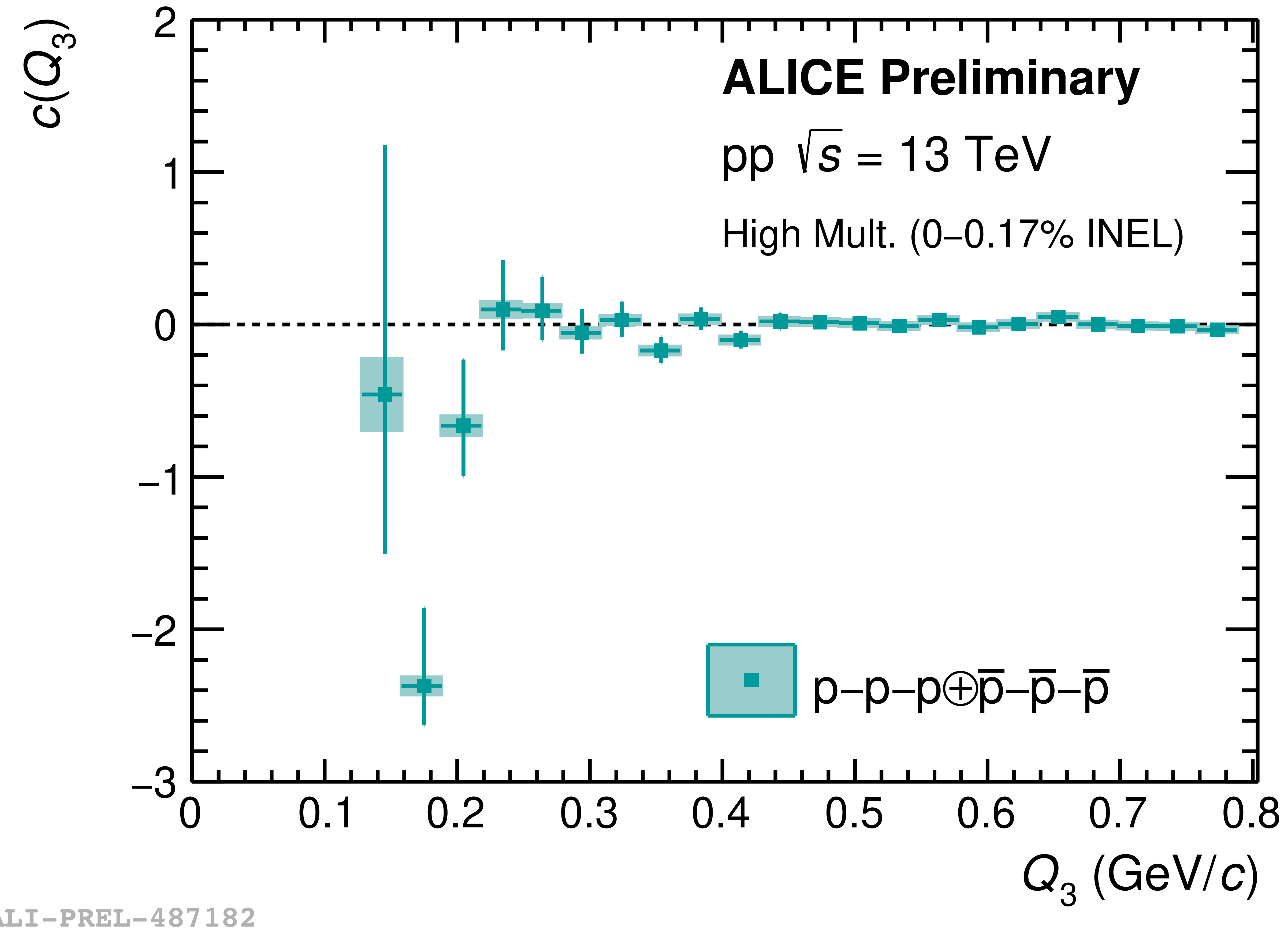
- Femtoscopy technique can be used to provide unprecedented constraints on hadron–hadron interactions
  - ➡ Constrain low-energy QCD effective field theories
  - ➡ Test QCD calculations on the lattice
  - ➡ Search and study bound states

- Many more measurements foreseen for the future with LHC Run 3 and 4, e.g:
  - ➡ Multi-body interactions
  - ➡ Interactions involving nuclei
  - ➡ Interactions among hadrons containing charm quarks

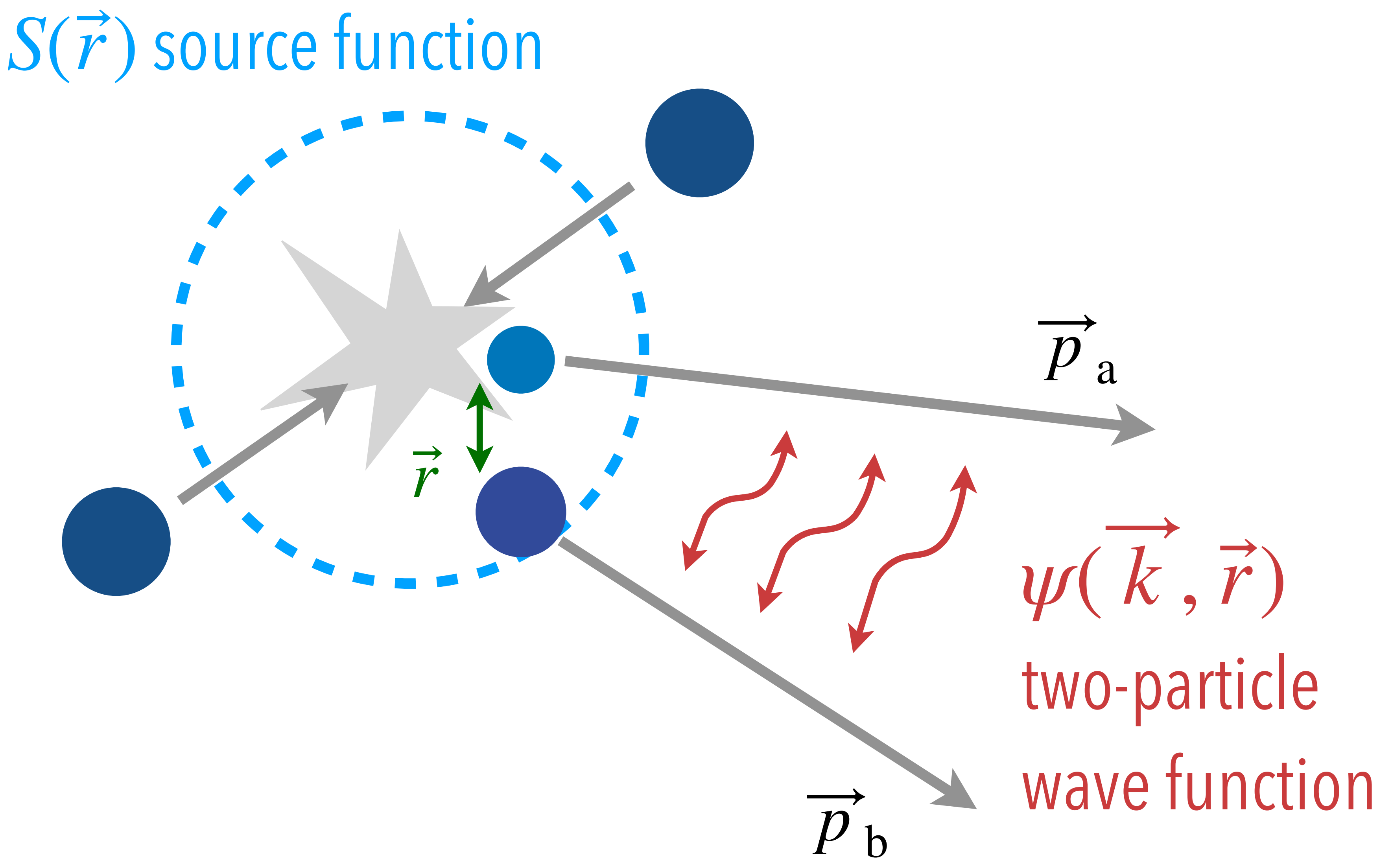


Thanks to the whole ALICE group at the Technische Universität München for the fruitful discussions and the inputs!

ADDITIONAL SLIDES

Source calibration

- Interaction region of the two colliding particles (protons, nuclei) is the emitting source
  - ➡ Measurement of correlation between emitted particles:
    - Infer size of emitting source (r) if interaction between particle is known
    - Study interaction among particles if size of emitting source is known



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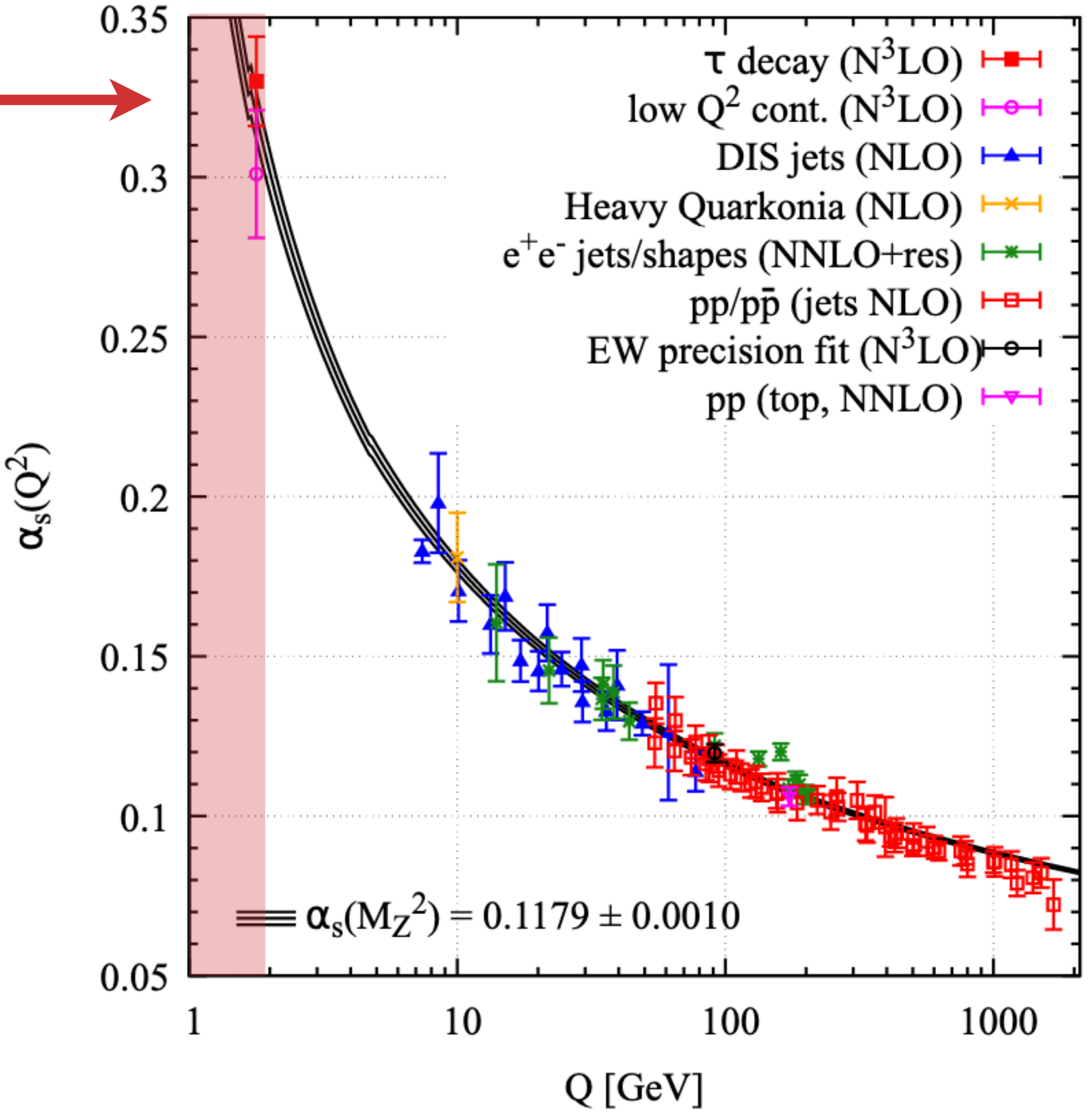
confinement: quarks and gluons are bound in hadrons



asymptotic freedom:
quarks and gluons are asymptotically deconfined

- Typical size of emitting source r ~ 1 fm (Q ~ 1 GeV)
  - ➡ Non-perturbative regime of strong interaction
  - ➡ Effective potentials with hadrons are degree of freedoms
  - ➡ Quantum chromodynamic (QCD) calculations on lattice

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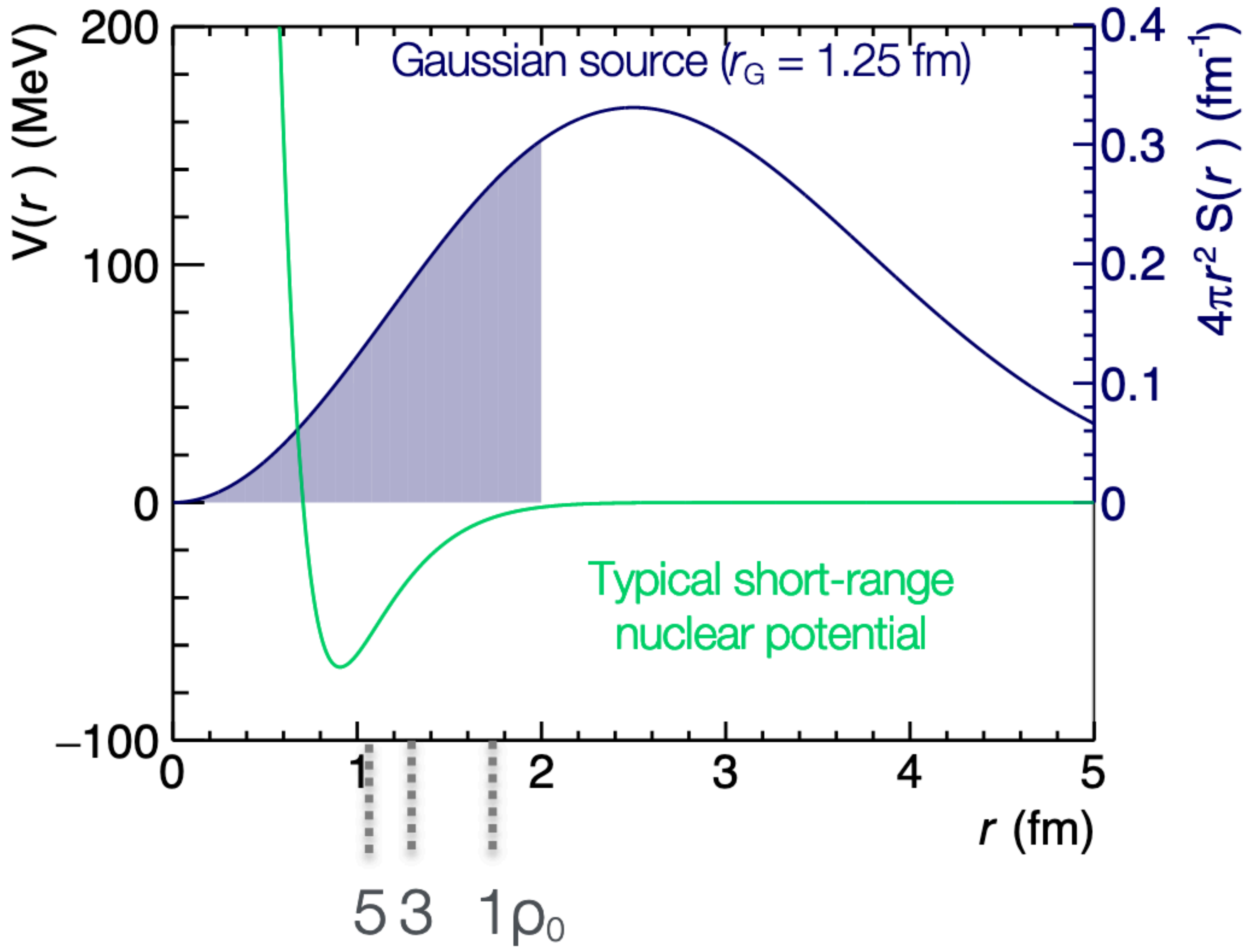
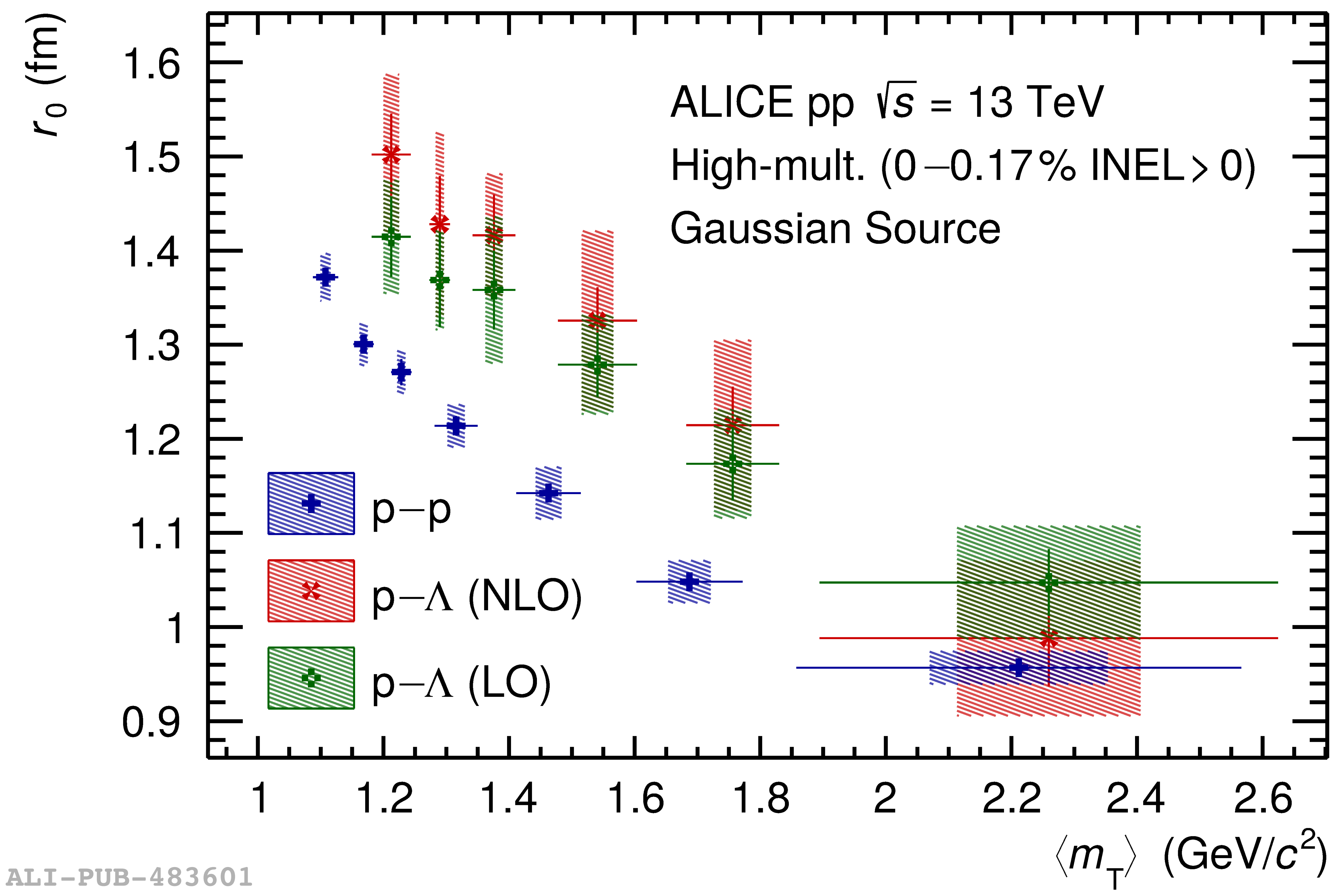


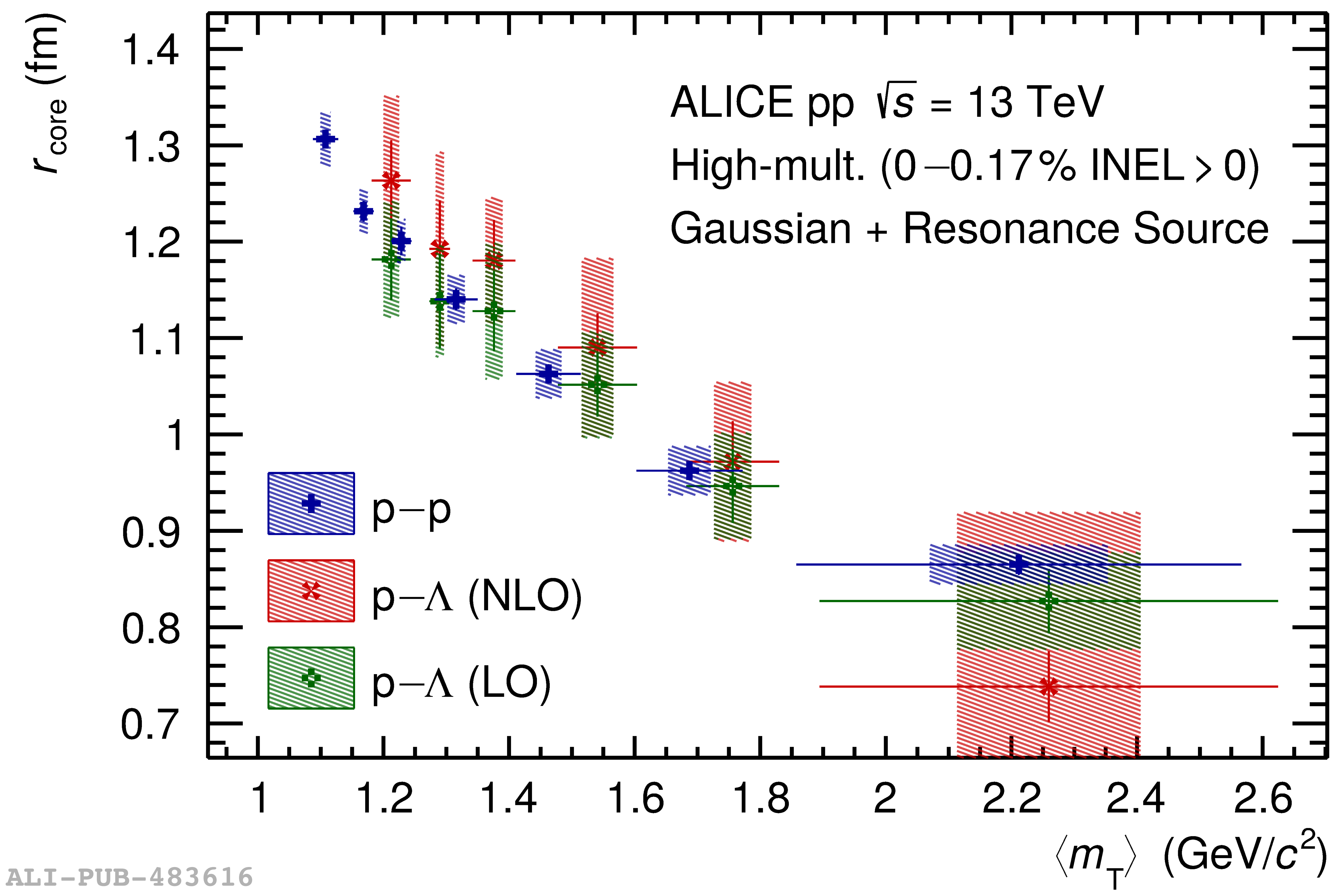
- Typical range of nuclear potential around 1-2 fm
  - ➡ study of strong interaction among hadrons not possible with larger sources
  - ➡ proton–proton and proton–nucleus collisions are the ideal laboratory to study the strong interaction

Emitting source with with and without resonances

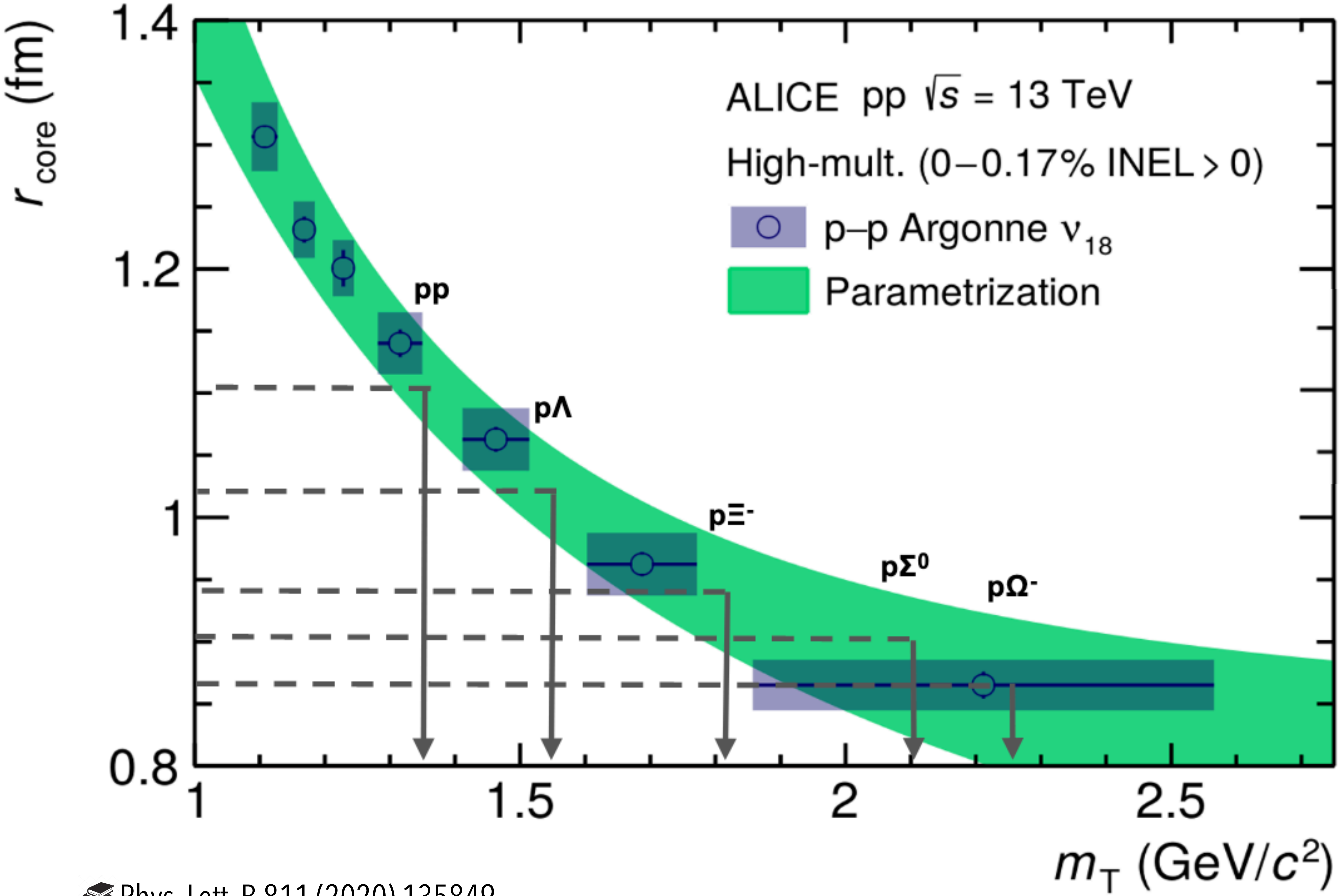
- Without considering resonances



- Considering resonances



Calibration of the emitting source



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- Measurement of source radius obtained from p–p correlation used to obtain the values for other baryon species

Pair	r_{core} (fm)
p–p	1.1
p–Λ	1.0
p–Ξ^-	0.93
p–Ω^-	0.86
p–Σ^0	0.87
p–ϕ	0.89
Λ–Λ	1.1
Λ–Ξ^-	0.89
p–D^-	0.86