ALICE determines the scattering parameters of D mesons with light-flavour hadrons

Fabrizio Grosa on behalf of the *ALICE Collaboration*
CERN

QUARK MATTER
KRAKÓW
2022

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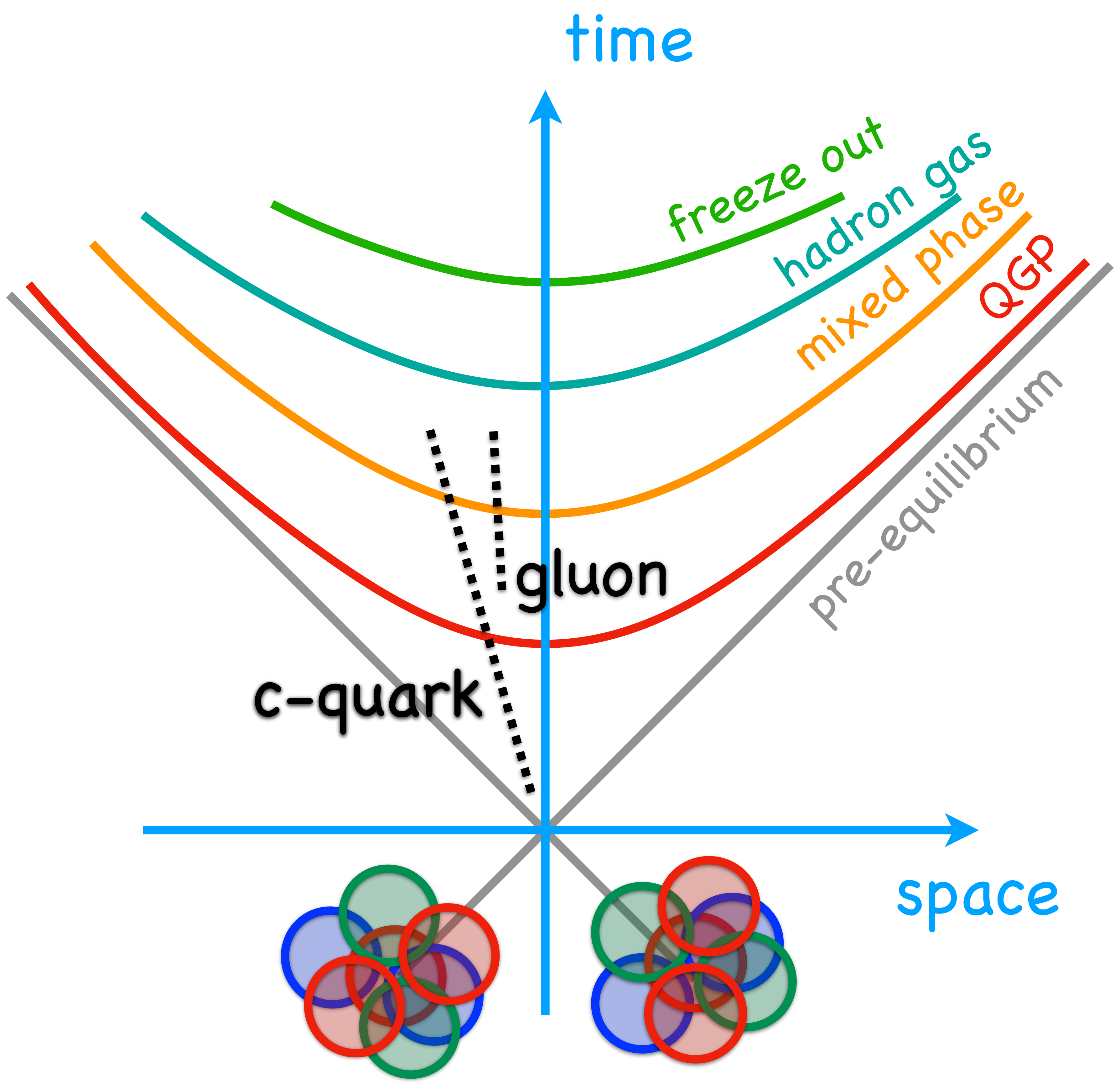
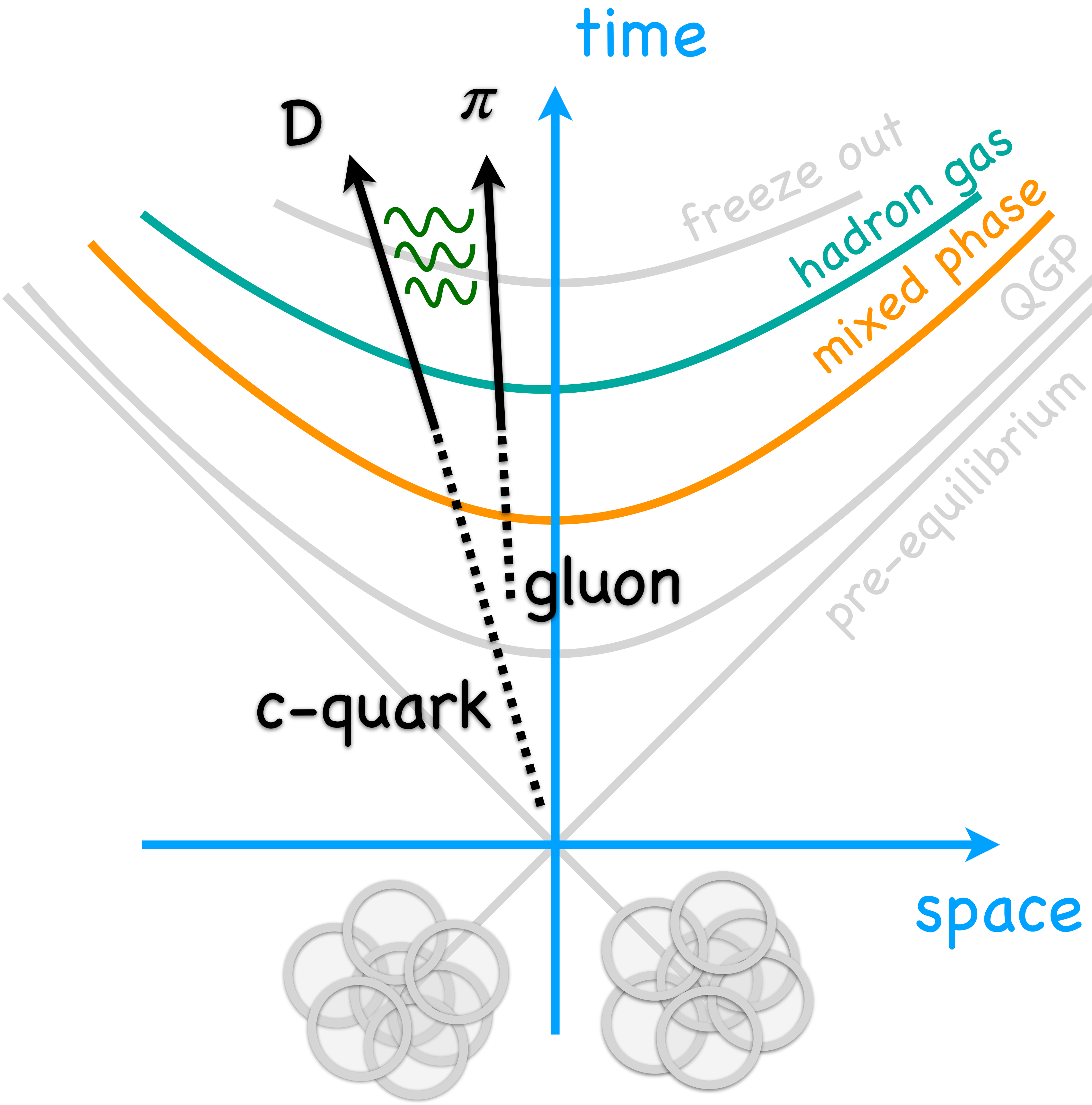


- Charm quarks: produced via hard scattering processes before the formation of the quark–gluon plasma (QGP), subsequently interact with the medium constituents
  ➡ Ideal probes of the QGP



- Charm quarks: produced via hard scattering processes before the formation of the quark–gluon plasma (QGP), subsequently interact with the medium constituents
  - ➡ Ideal probes of the QGP
- After the hadronisation, charm hadrons might still interact with the light hadrons produced
  - ➡ How much hadronic rescatterings influence our observables?

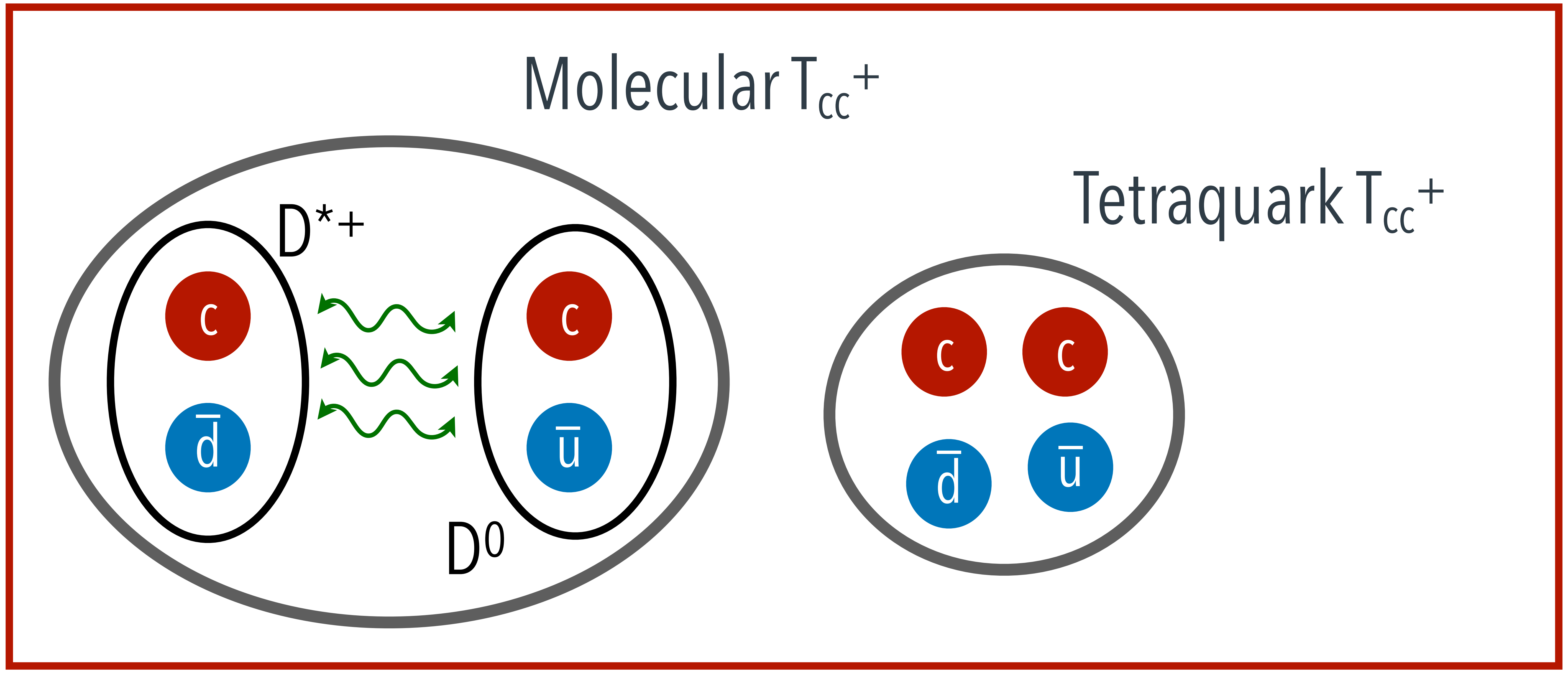
- In the TAMU model the scattering lengths used for πD and $\bar{K}$D are:
  - ➡ $a_{\pi D}(I=3/2) = -0.10$ fm
  - ➡ $a_{\bar{K}D}(I=1) = -0.22$ fm
  - ➡ No experimental constraints

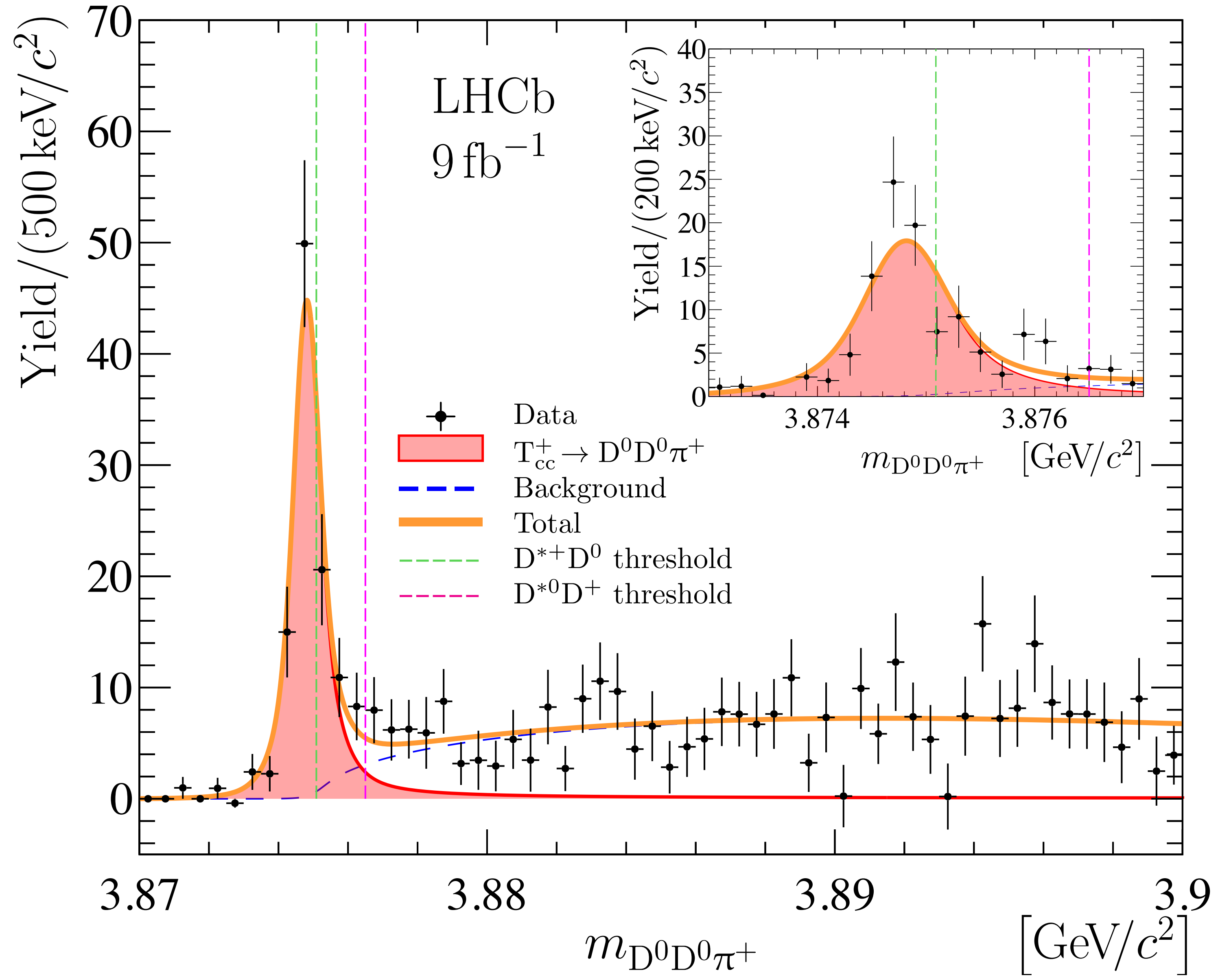
Ralf Rapp et al, Phys. Lett. B 701 (2011) 445–450

- Charm molecules?

System	I ($J^{P(C)}$)	Candidate
np	0 (1^+)	deuteron
ND	0 ($1/2^-$)	$\Lambda_c(2765)$
ND*	0 ($3/2^-$)	$\Lambda_c(2940)$
ND	0 ($1/2^-$)	$\Sigma_c(2800)$
$D^*\bar{D}$	0 (1^{++})	X(3872)
D*D	0 (1^+)	T_{cc}
$D_1\bar{D}$	0 (1^{--})	Y(4260)
$D_1\bar{D}^*$	0 (1^{--})	Y(4360)
$\Sigma\bar{D}$	1/2 ($1/2^-$)	$P_c(4312)$
$\Sigma\bar{D}^*$	1/2 ($1/2^-$)	$P_c(4457)$
$\Sigma\bar{D}^*$	1/2 ($3/2^-$)	$P_c(4440)$

Fang-Zheng Peng et al, Phys. Rev. D 105, 034028 (2022)





- Just below DD* threshold
  - ➡ ideal candidate to be a molecular state

LHCb, arXiv:2109.01038

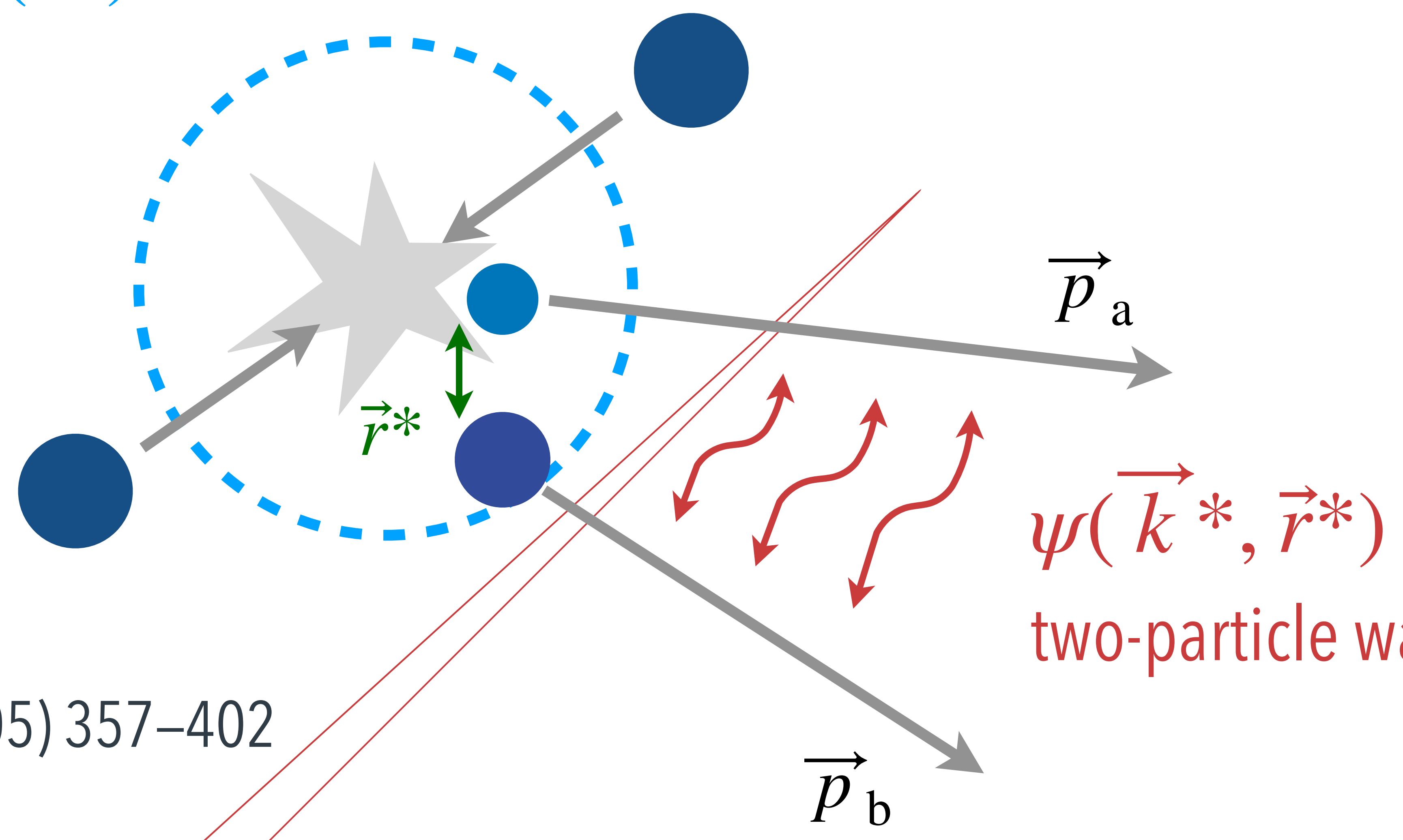
- Femtoscopy technique: based on the *correlation function (CF)*

Experiment | Theory

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

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 ~1 fm

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

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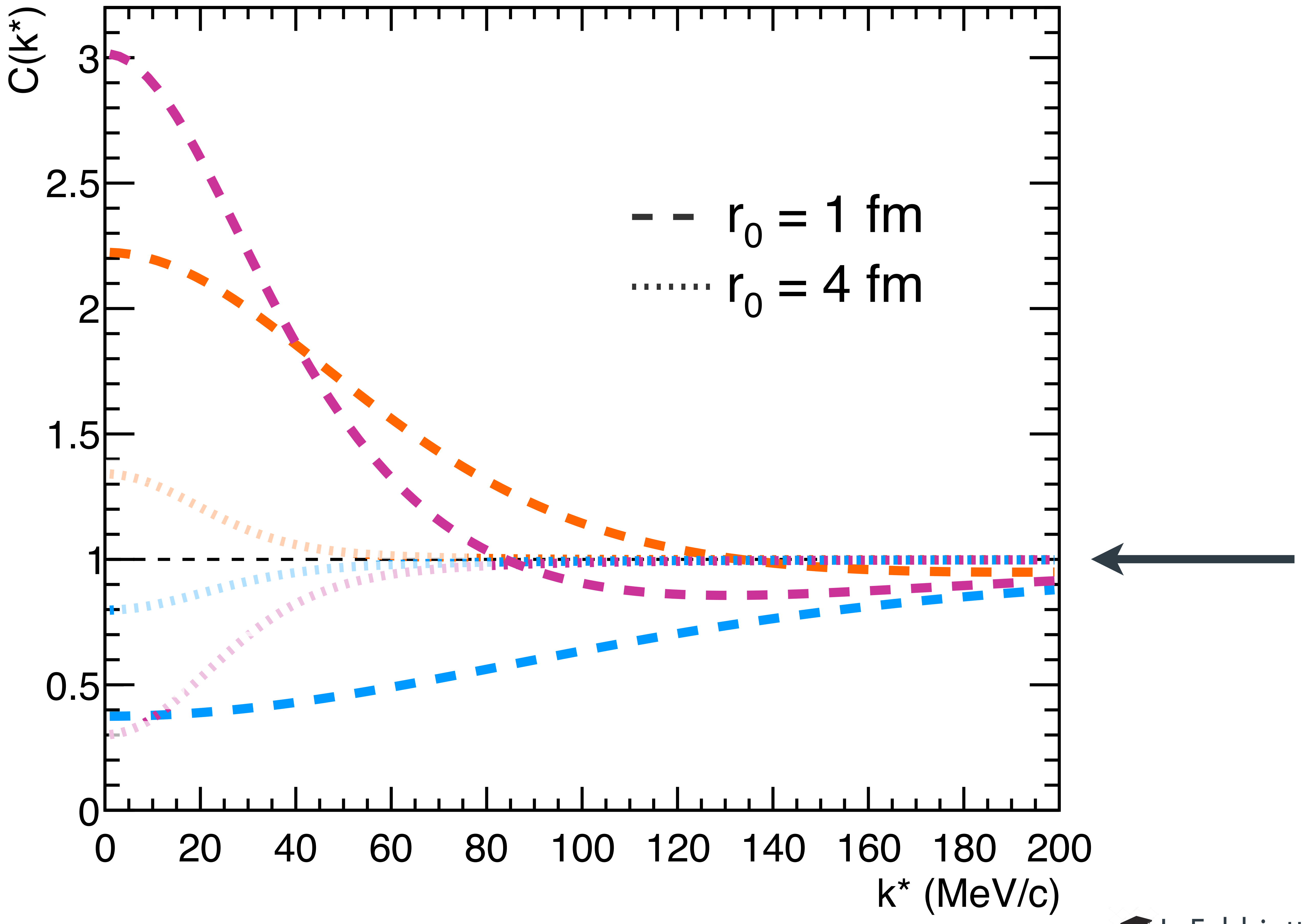
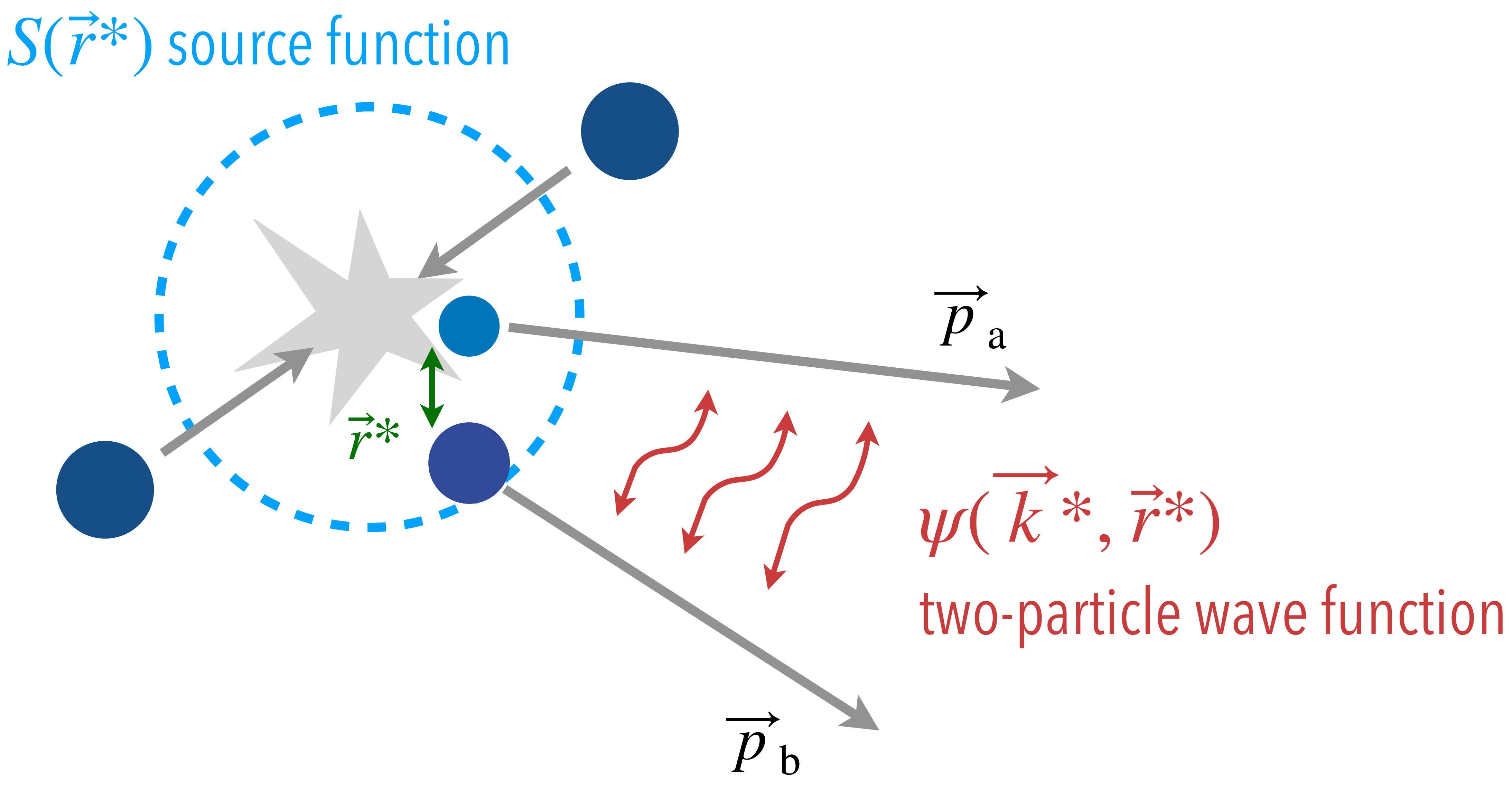
$$C(\vec{k}^*) = \int S(\vec{r}^*)\,|\psi(\vec{k}^*, \vec{r}^*)|^2 \, d^3r^*$$

➡ Relative wave function sensitive to interaction potential





➡ Absence of interaction $C(k^*) = 1$

L. Fabbietti, V. Mantovani Sarti, O. Vázquez Doce, Annu. Rev. Nucl. Part. Sci. (2021) 71:377–402

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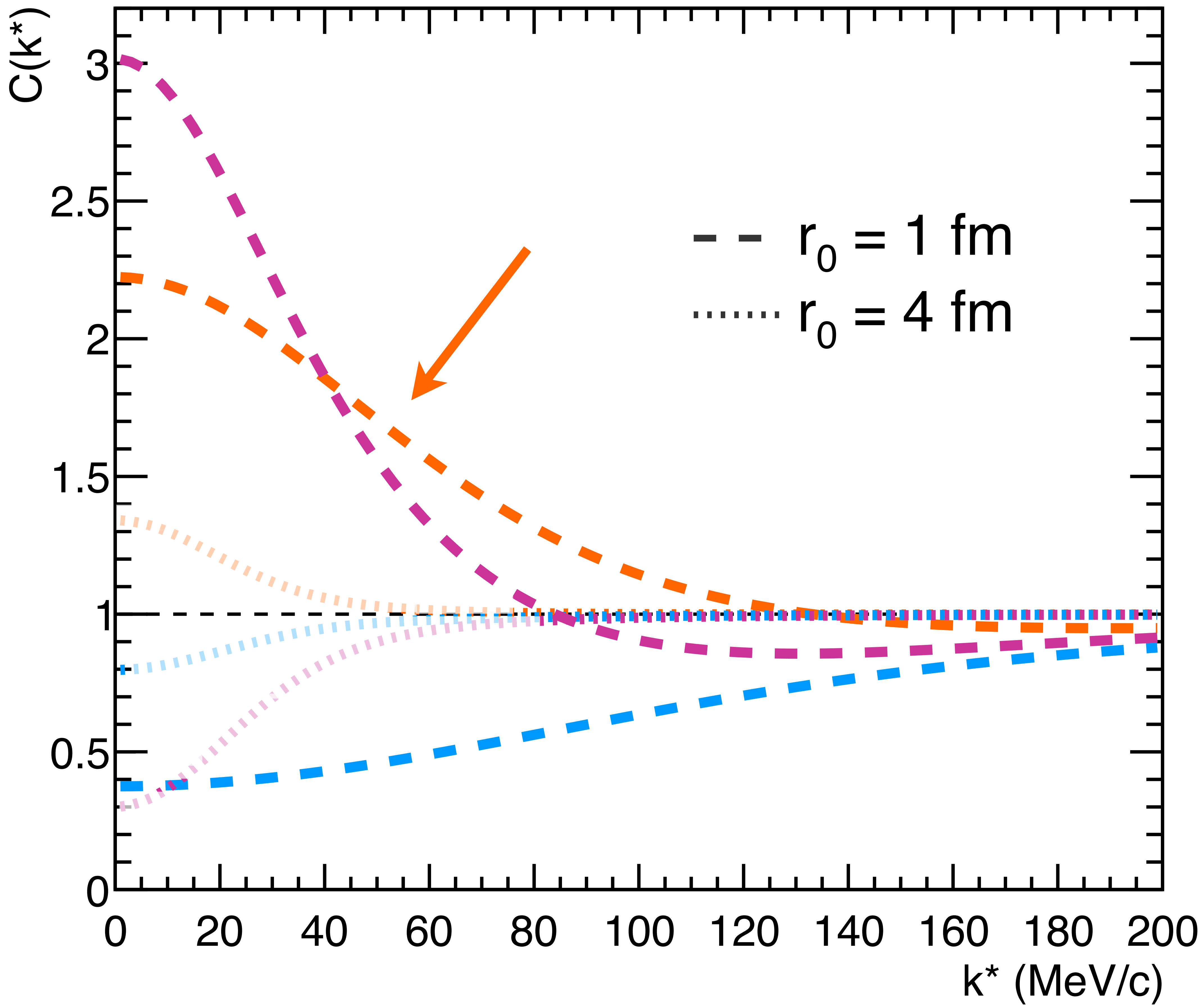

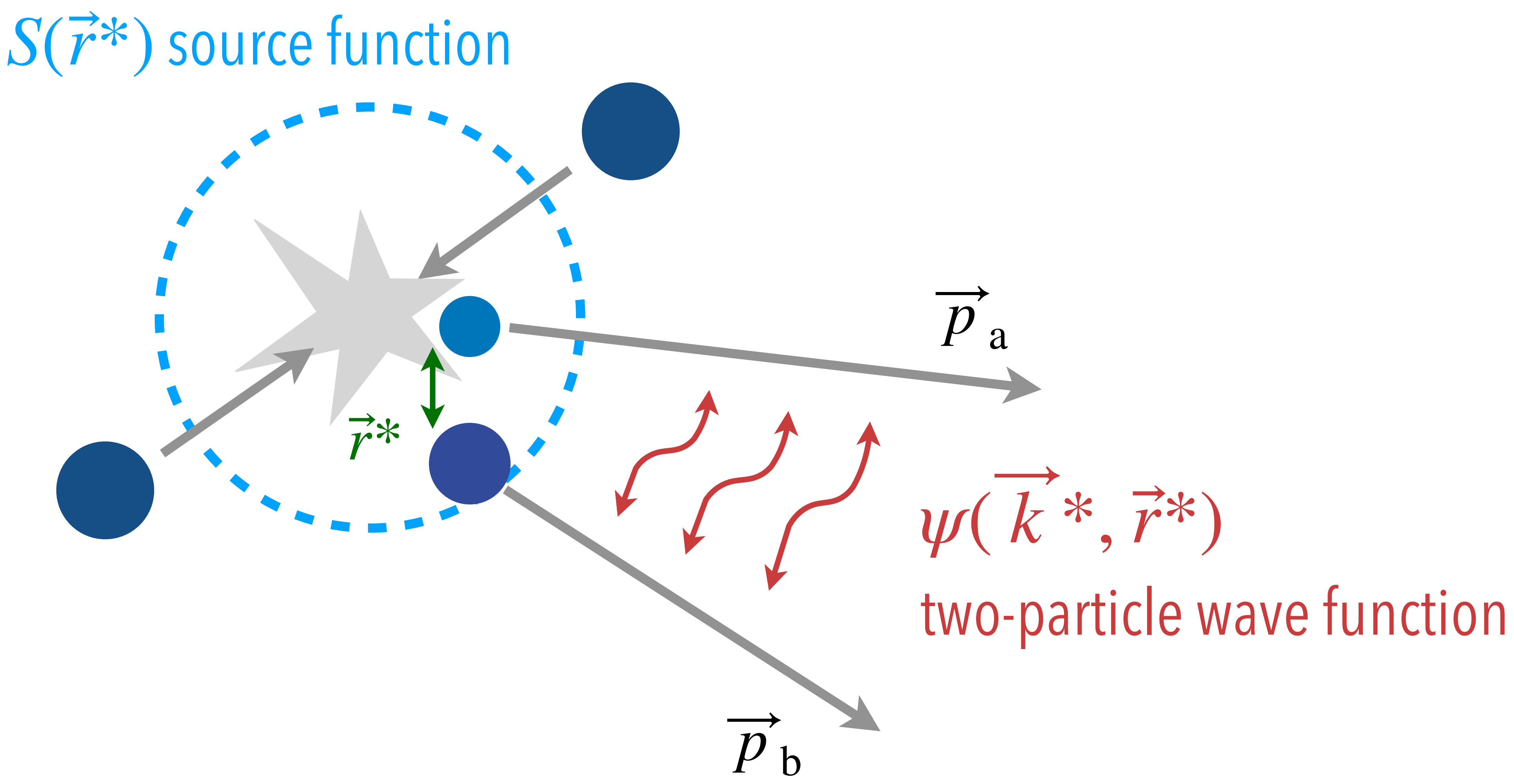

➡ Absence of interaction $C(k^*) = 1$

➡ Attractive potential $C(k^*) > 1$

L. Fabbietti, V. Mantovani Sarti, O. Vázquez Doce, Annu. Rev. Nucl. Part. Sci. (2021) 71:377–402

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

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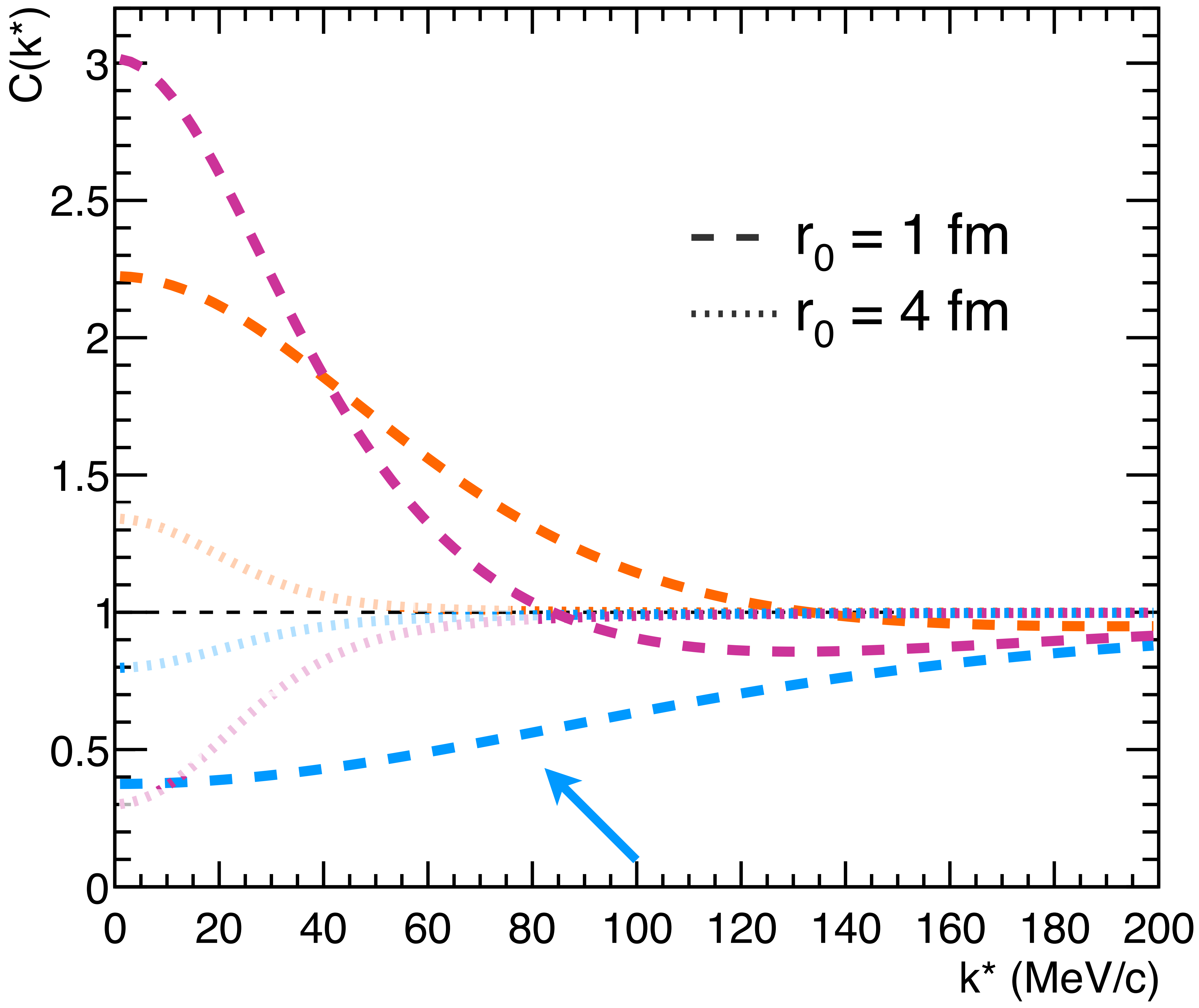

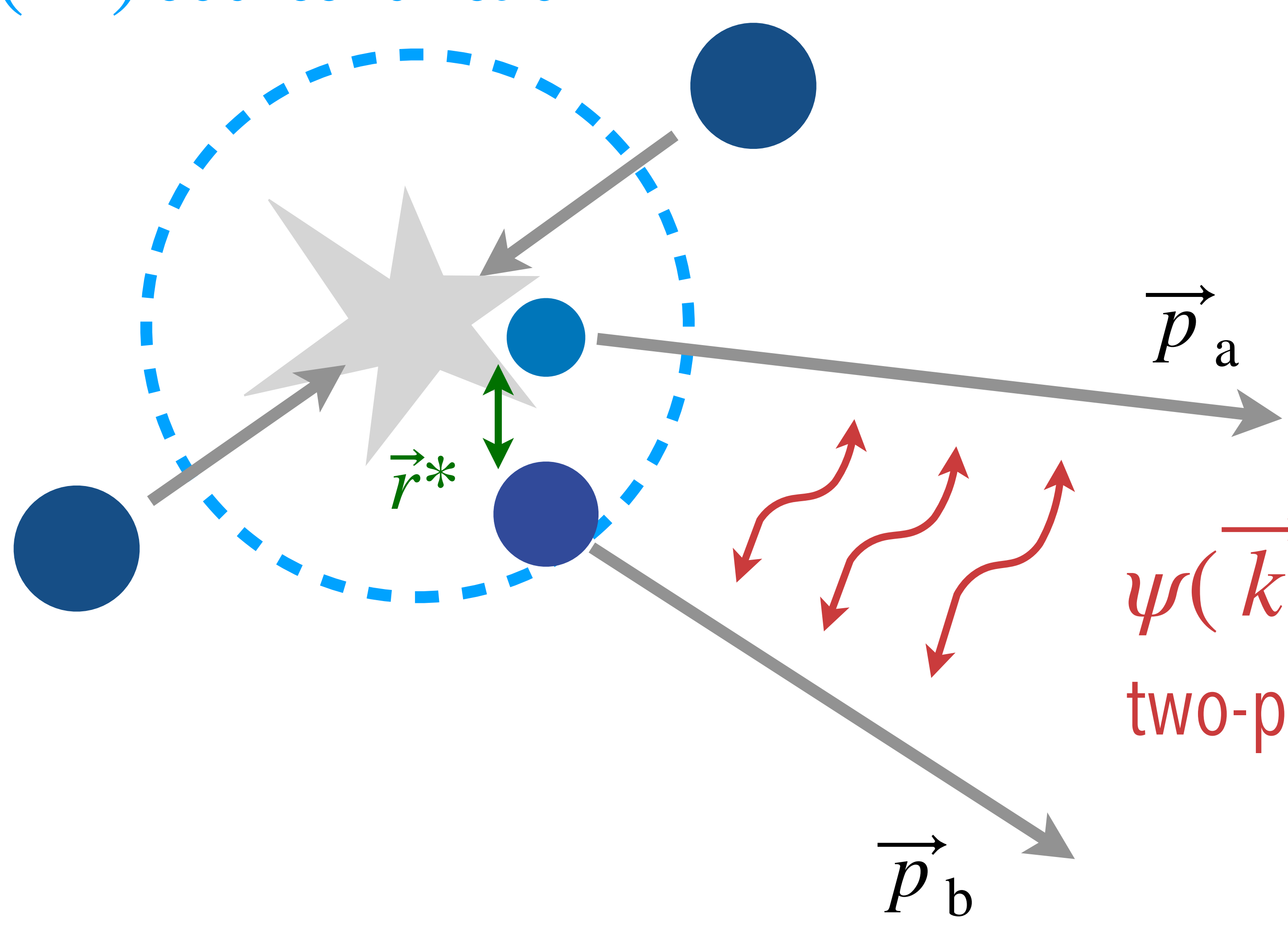

➡ Absence of interaction $C(k^*) = 1$

➡ Attractive potential $C(k^*) > 1$

➡ Repulsive potential $C(k^*) < 1$

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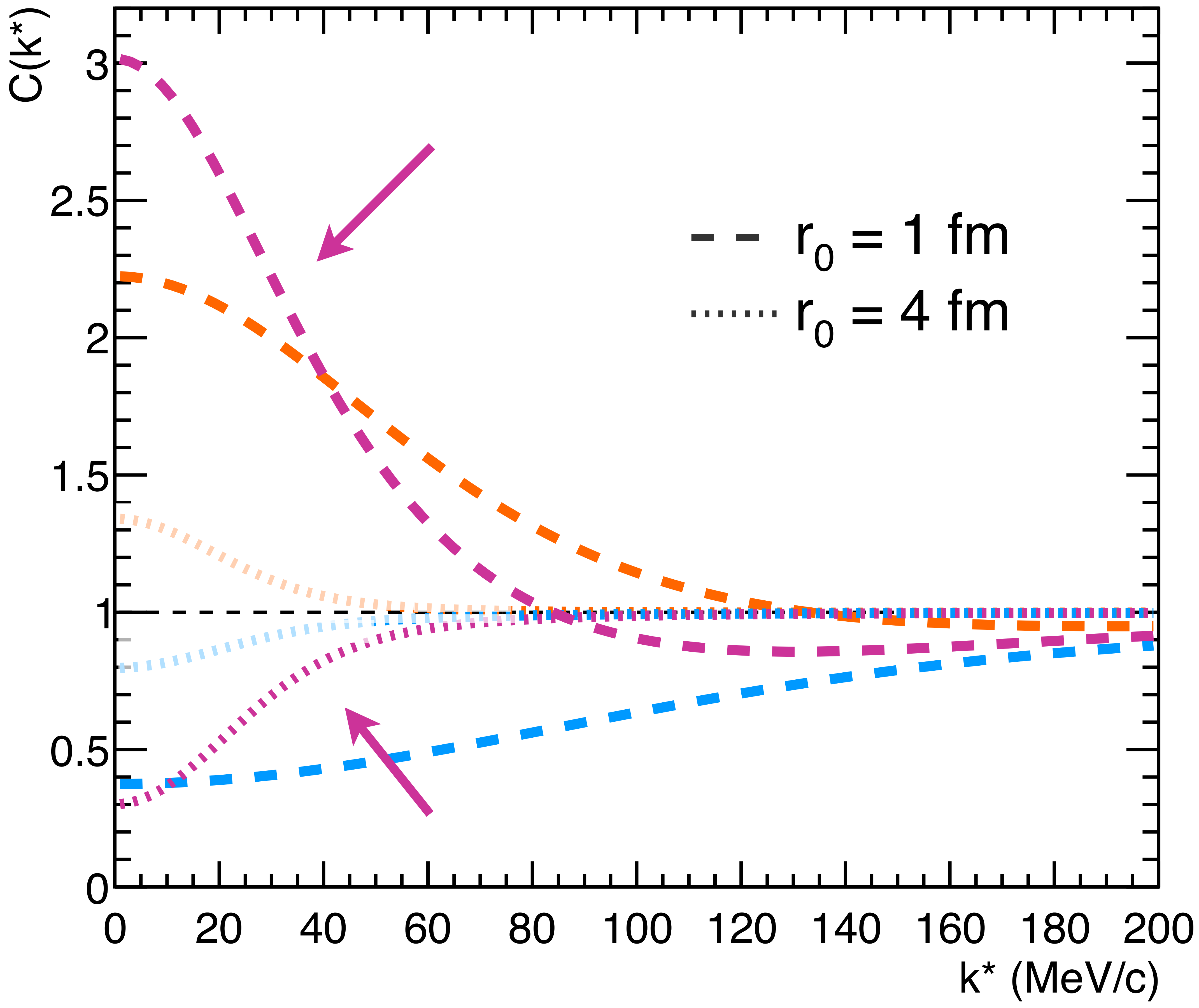
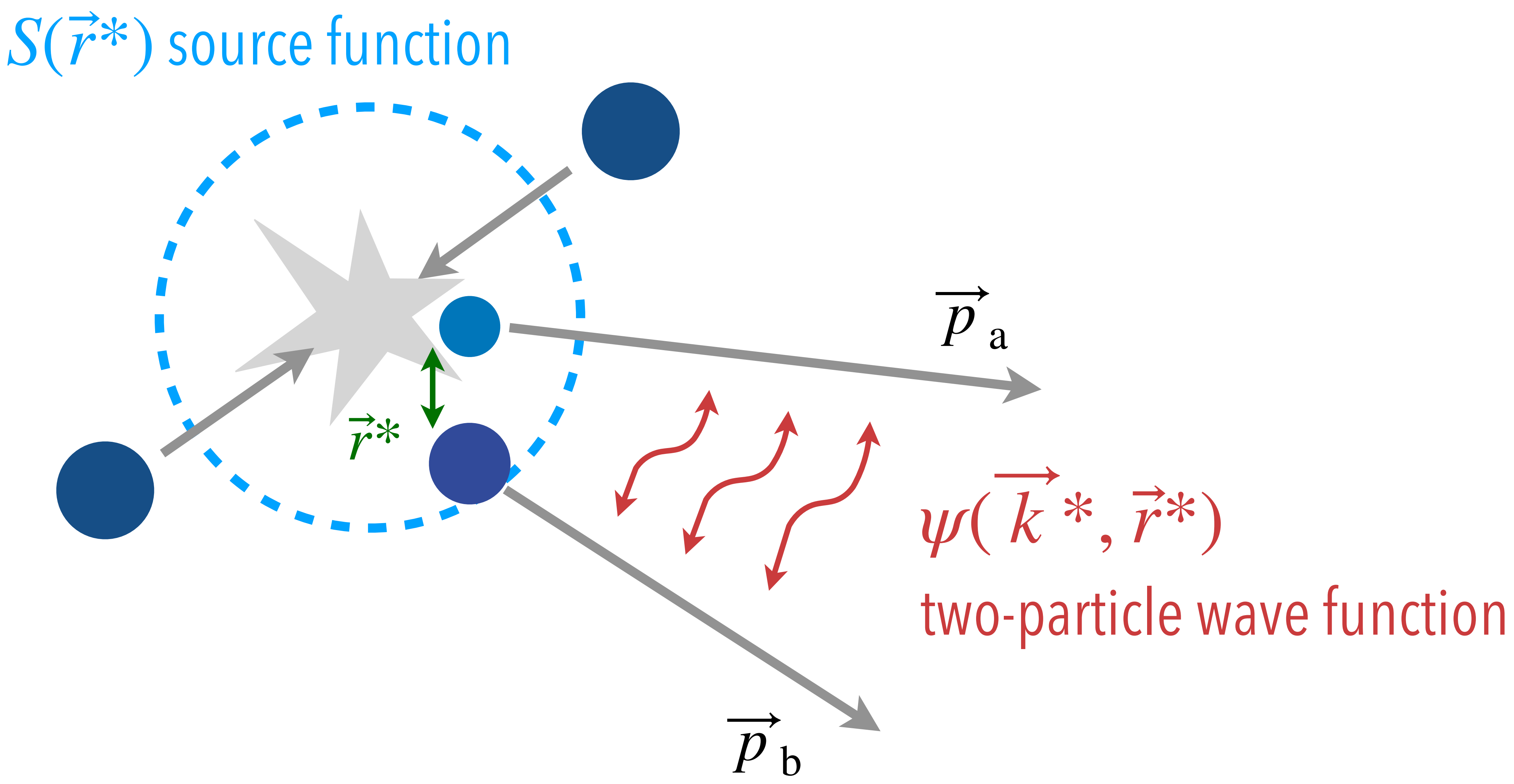




➡ Absence of interaction $C(k^*) = 1$

➡ Attractive potential $C(k^*) > 1$

➡ Repulsive potential $C(k^*) < 1$

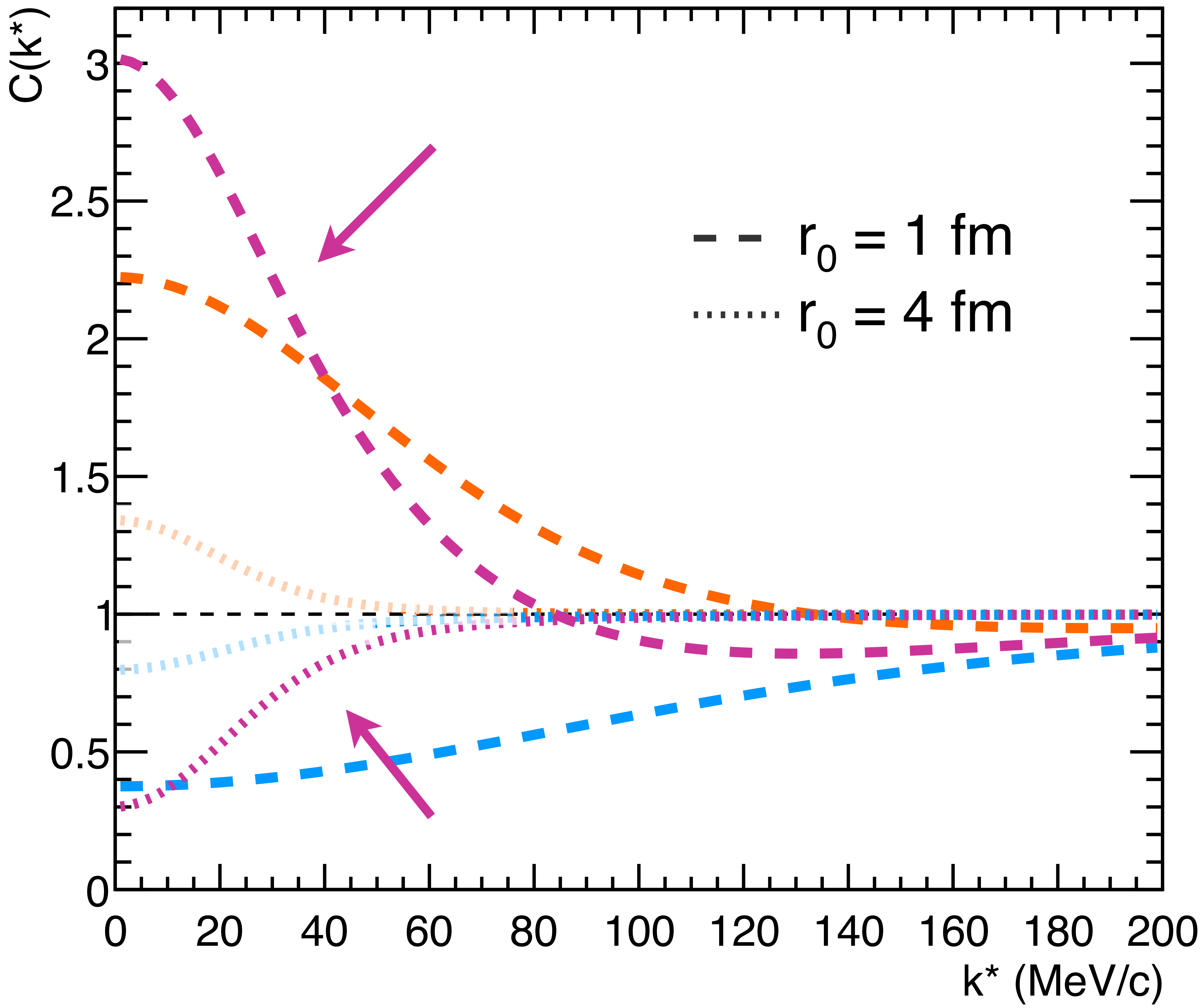
➡ Bound-state formation $C(k^*) <> 1$

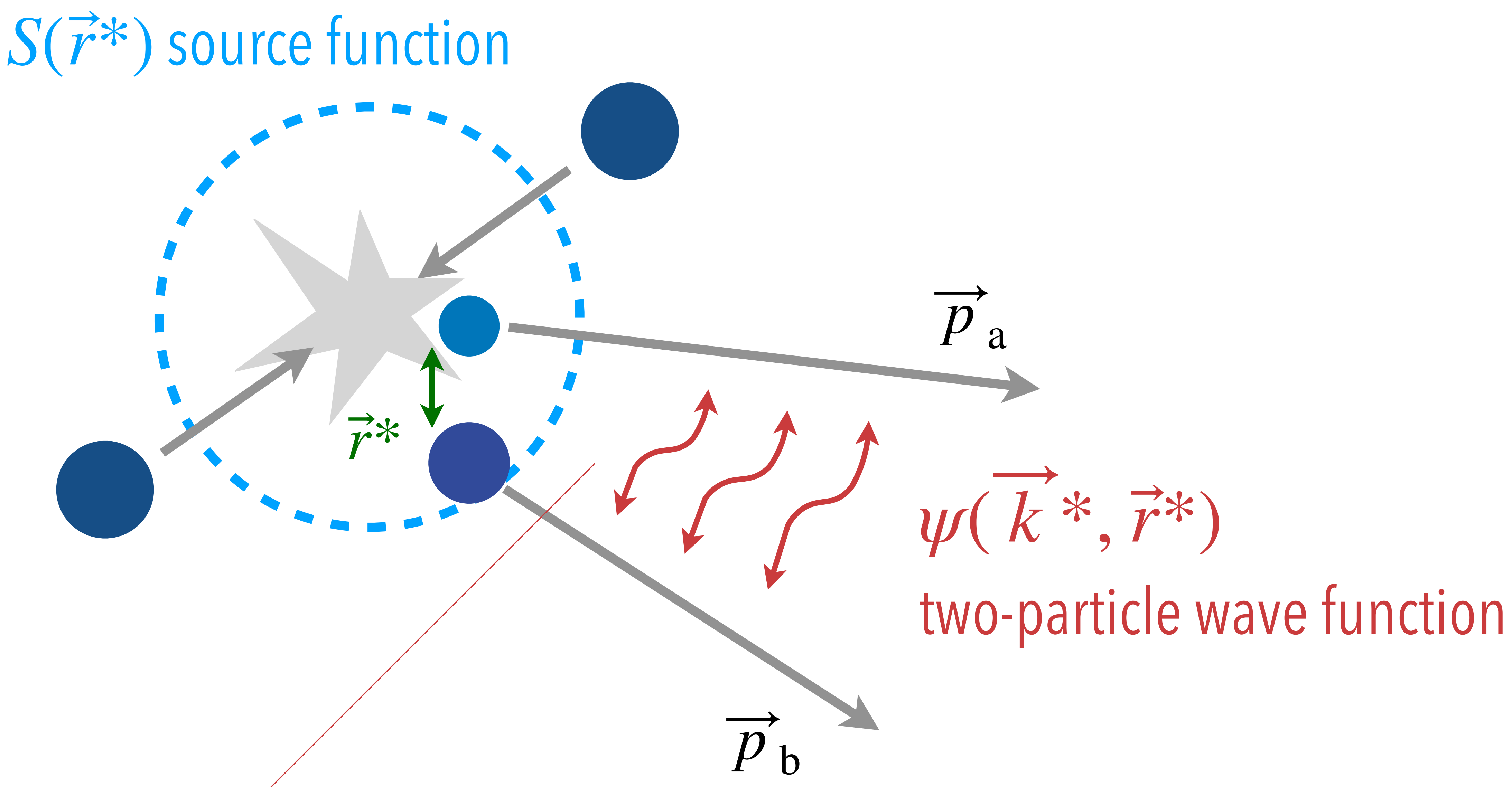
L. Fabbietti, V. Mantovani Sarti, O. Vázquez Doce, Annu. Rev. Nucl. Part. Sci. (2021) 71:377–402

Effect of the interactions on the correlation function

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

➡ 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 $C(k^*) <> 1$

Strange-particle femto, V. Mantovani Sarti talk T08 06/04 10:00
Three-body interactions, R. Del Grande talk T08 06/04 15:00

L. Fabbietti, V. Mantovani Sarti, O. Vázquez Doce, Annu. Rev. Nucl. Part. Sci. (2021) 71:377–402

Reconstruction of strange and charm hadron decays in ALICE

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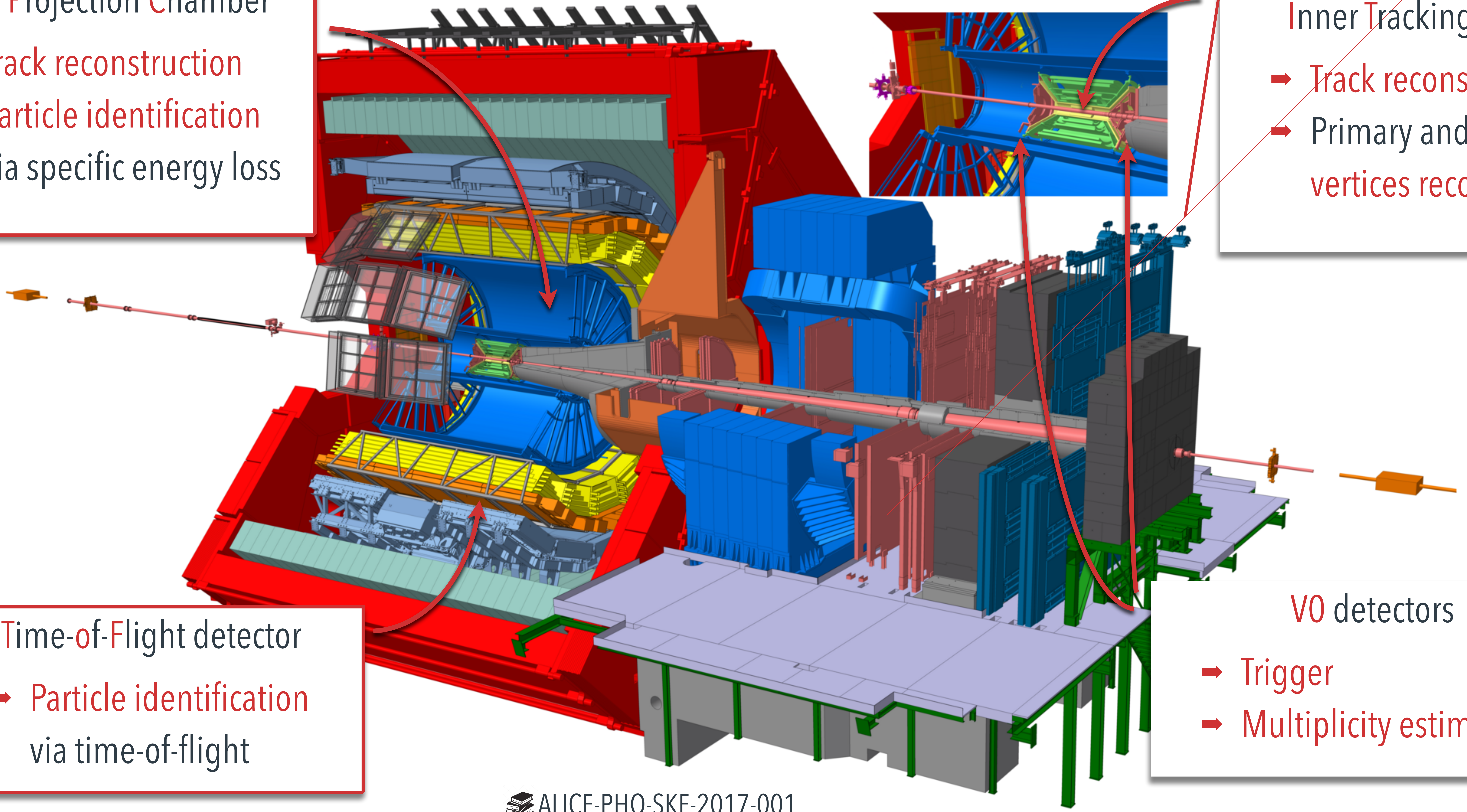
Time Projection Chamber
- ➡ Track reconstruction
- ➡ Particle identification via specific energy loss

Inner Tracking System
- ➡ Track reconstruction
- ➡ Primary and decay vertices reconstruction



Time-of-Flight detector
- ➡ Particle identification via time-of-flight

V0 detectors
- ➡ Trigger
- ➡ Multiplicity estimation

ALICE-PHO-SKE-2017-001

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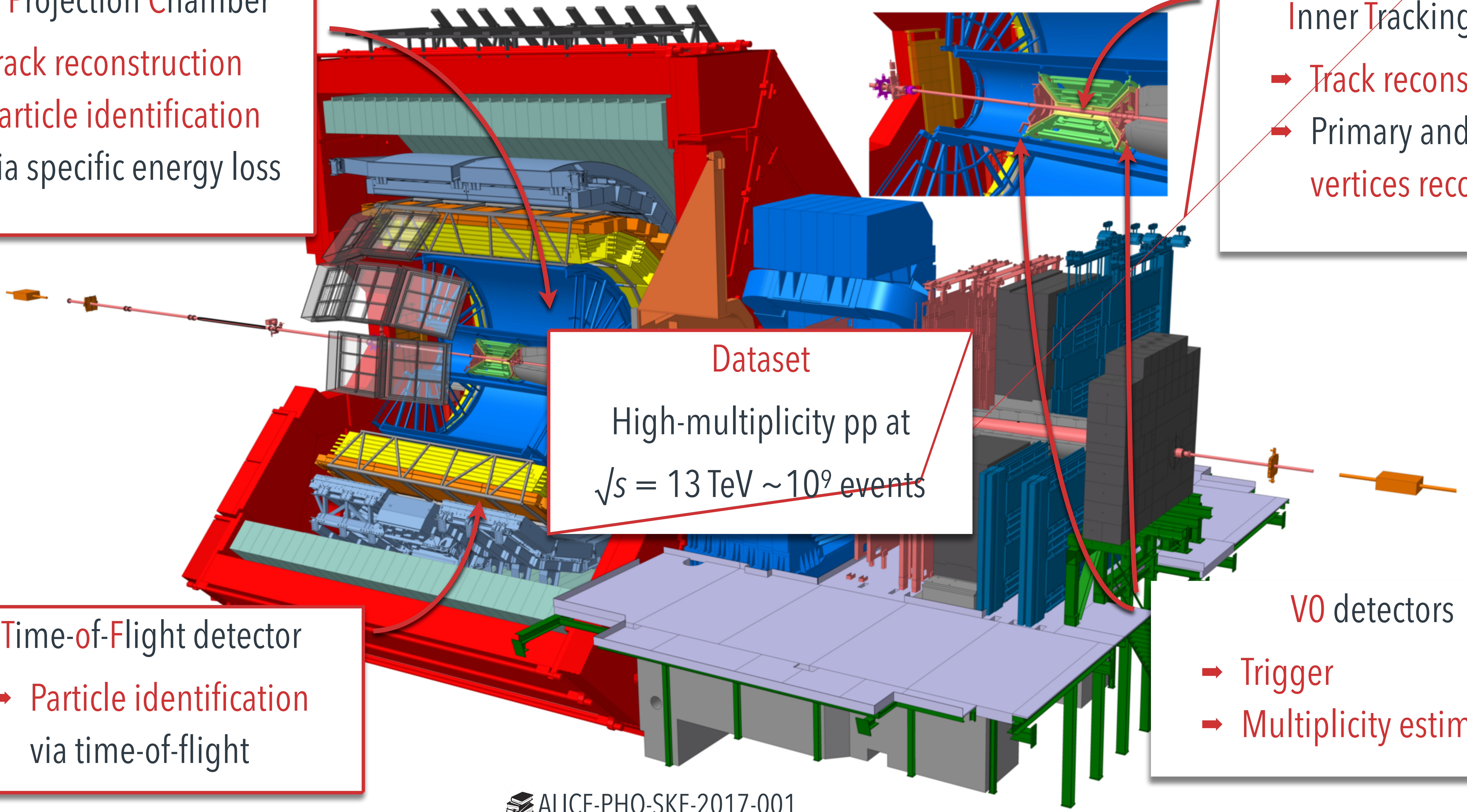

Dataset

High-multiplicity pp at $\sqrt{s}$ = 13 TeV ~10^9 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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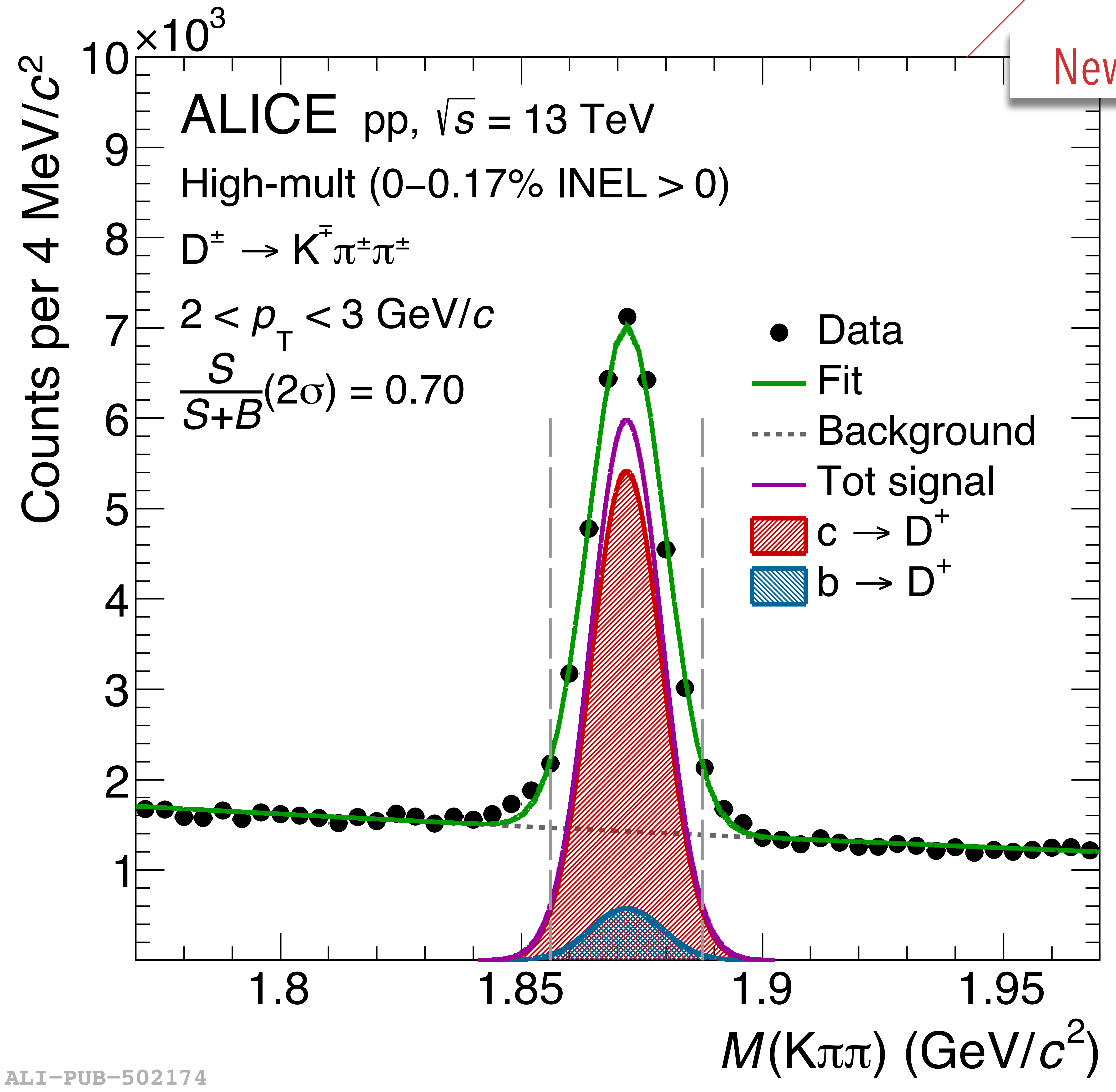
- Decay channel:
  - ➡ $D^{\pm} \to K^{\mp}\pi^{\pm}\pi^{\pm}$
  - ➡ BR = (9.38 ± 0.16)%
    - PDG, Prog. Theor. Exp. Phys. 2020 083C01
- Fully reconstruct decay topologies ($c\tau \approx 312\ \mu$m)
  - ➡ Purity of about 70%, non-prompt contribution about 7%
- Contributions:
  - ➡ Prompt:
    - ▸ from c hadronisation
    - ▸ from D* decays
  - ➡ Non-prompt: from b decays

New on arXiv



arXiv: 2201.05352

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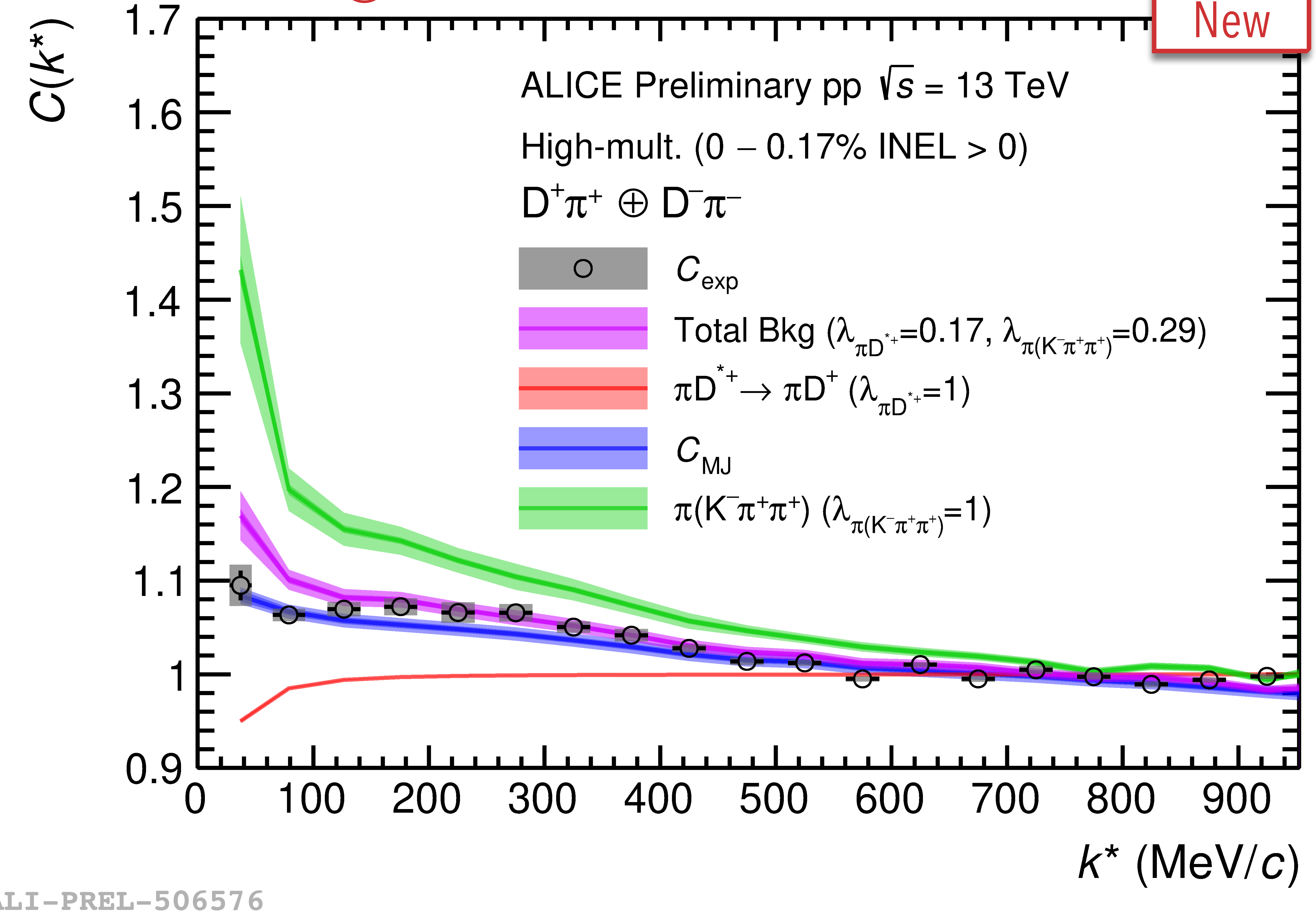
$D^+\pi^+ \oplus D^-\pi^-$

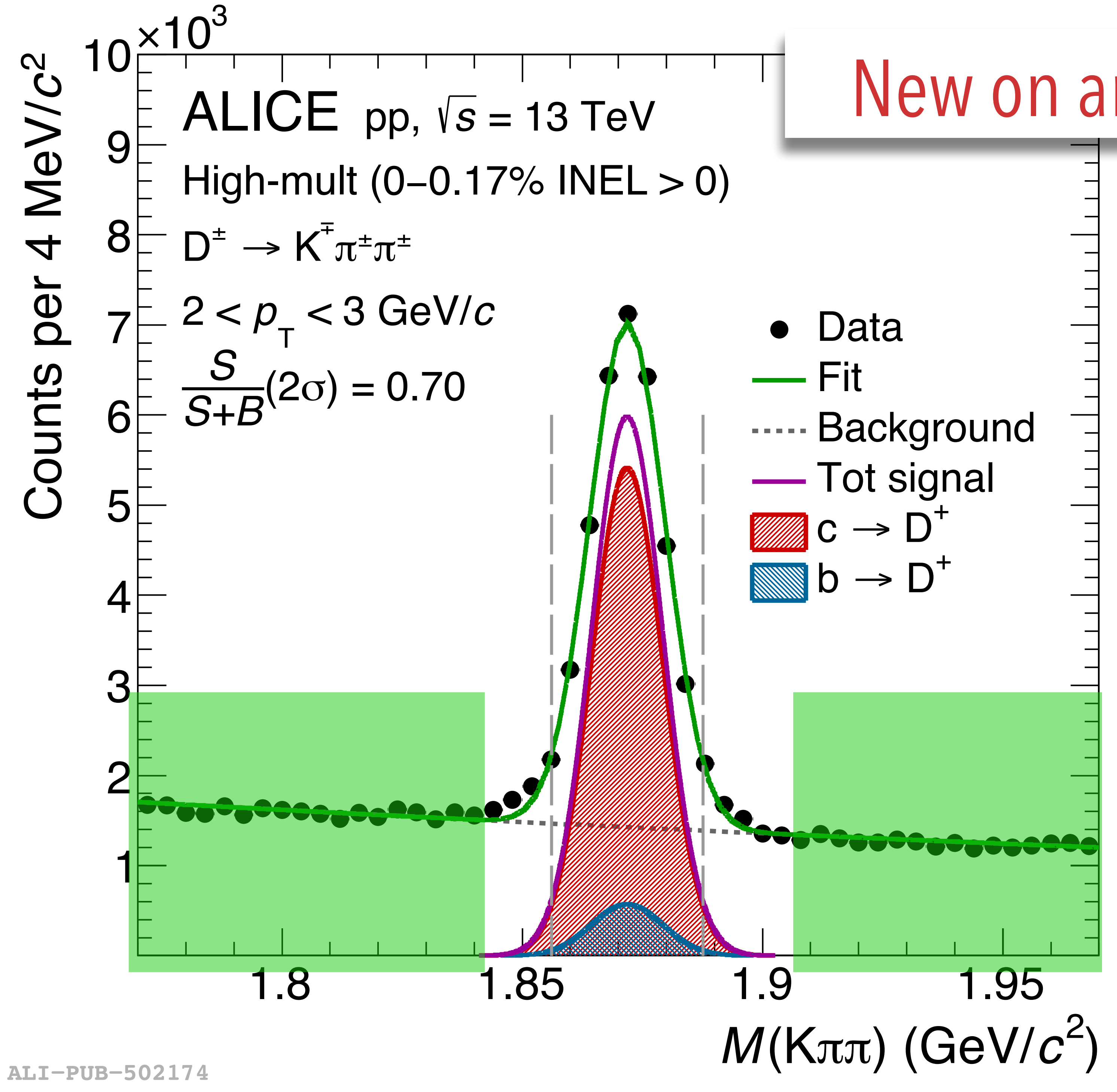
New



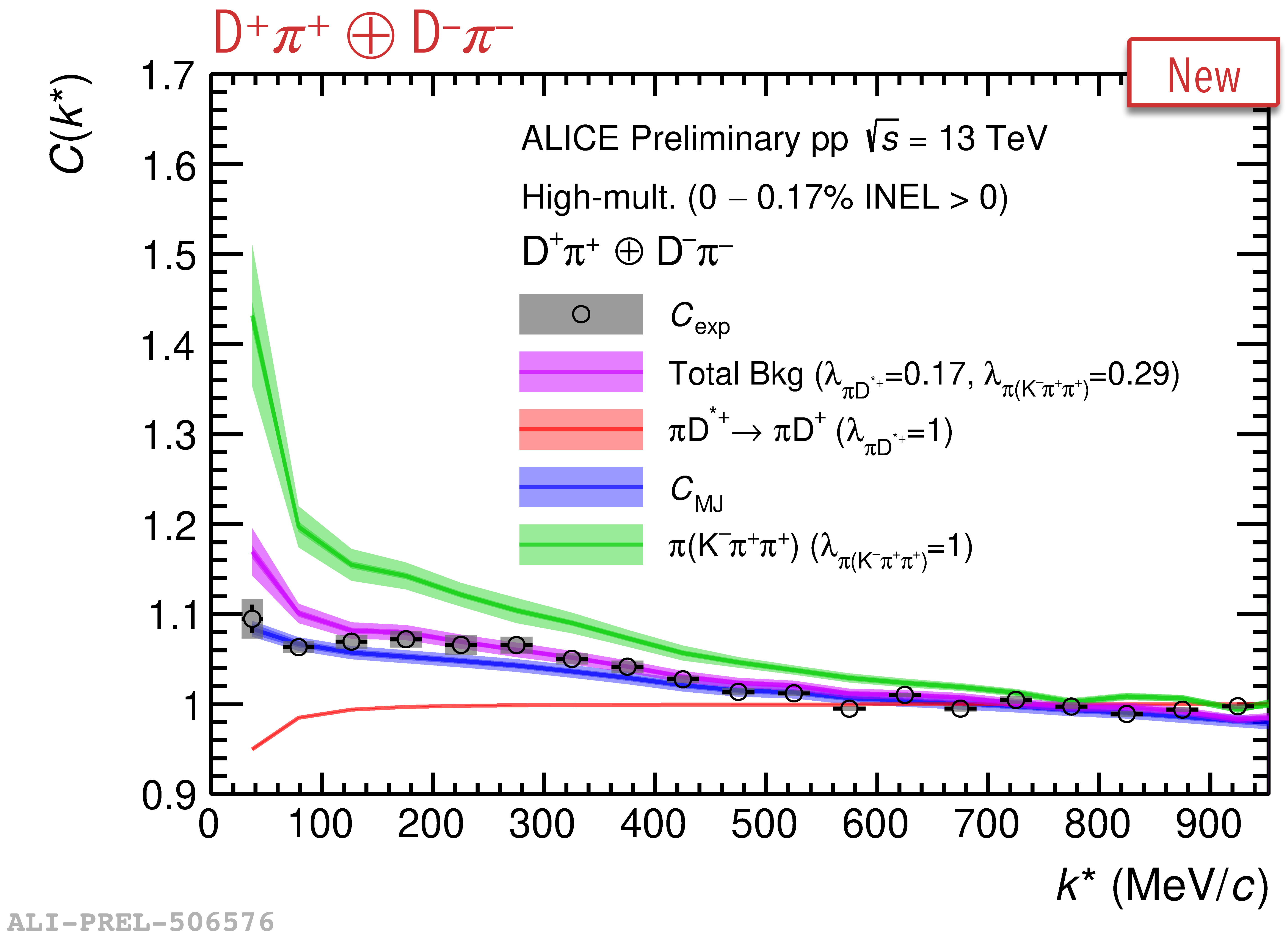
- Raw correlation function includes different sources of backgrounds

   i. Combinatorial background
   estimated from D-meson sidebands

New on arXiv



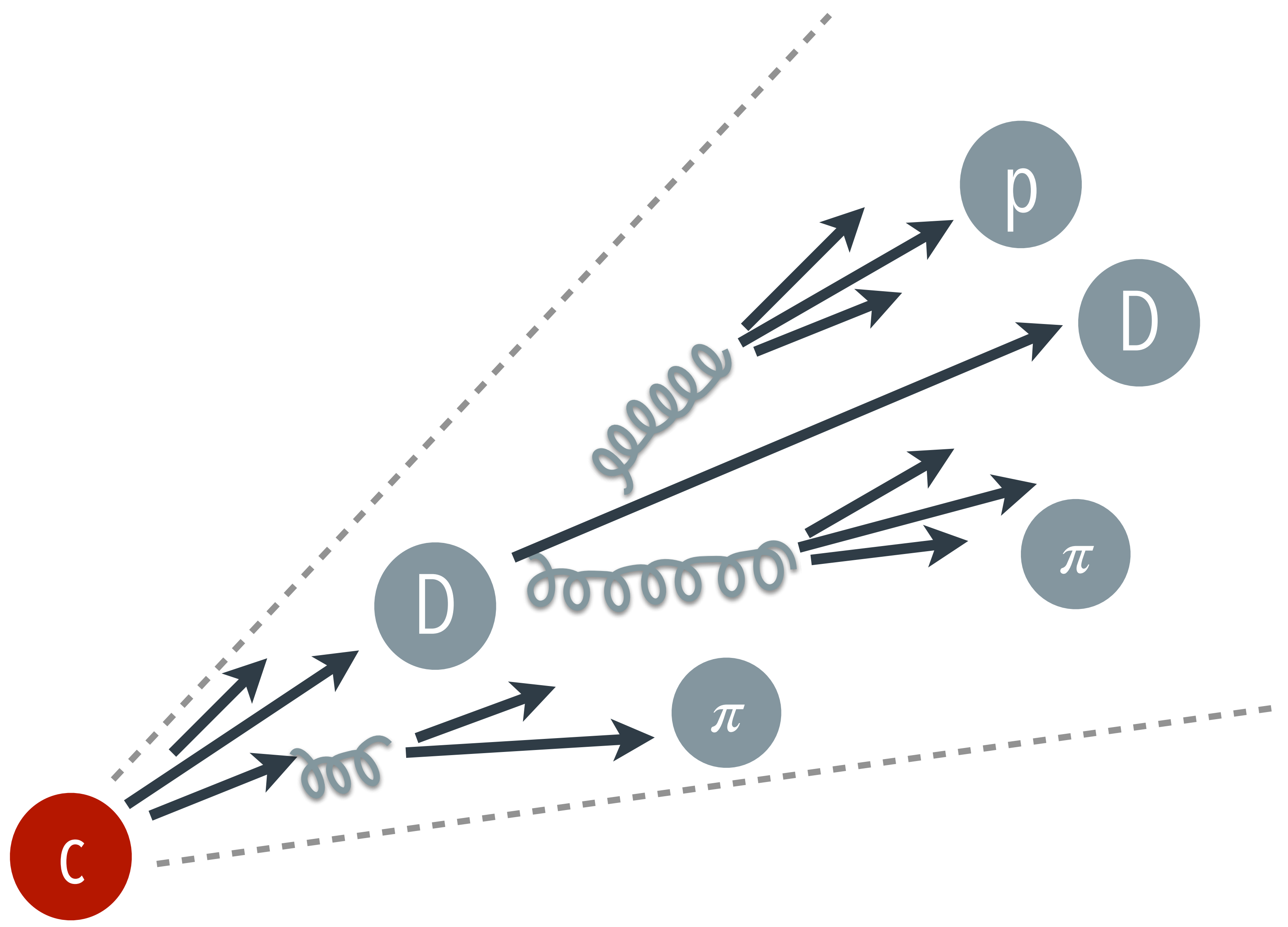
Correction of raw correlation function



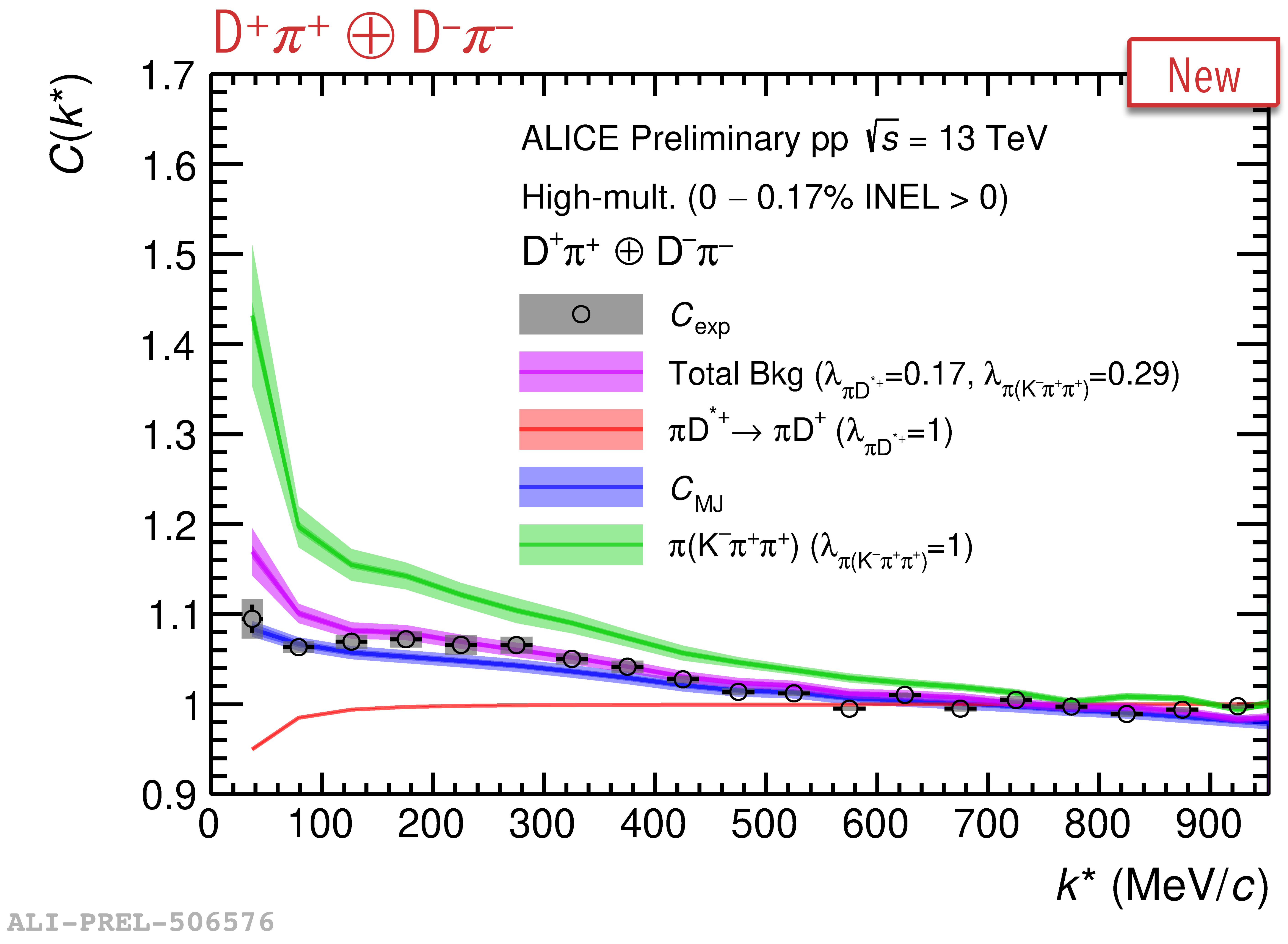
- Raw correlation function includes different sources of backgrounds

  i. Combinatorial background
     estimated from D-meson sidebands

  ii. Jet-like correlations
     estimated with PYTHIA 8



Correction of raw correlation function



- Raw correlation function includes different sources of backgrounds

  i. Combinatorial background
  estimated from D-meson sidebands

  ii. Jet-like correlations
  estimated with PYTHIA 8

  iii. $D^{*\pm} \rightarrow D^\pm + X$
  modelled with Coulomb-only interactions

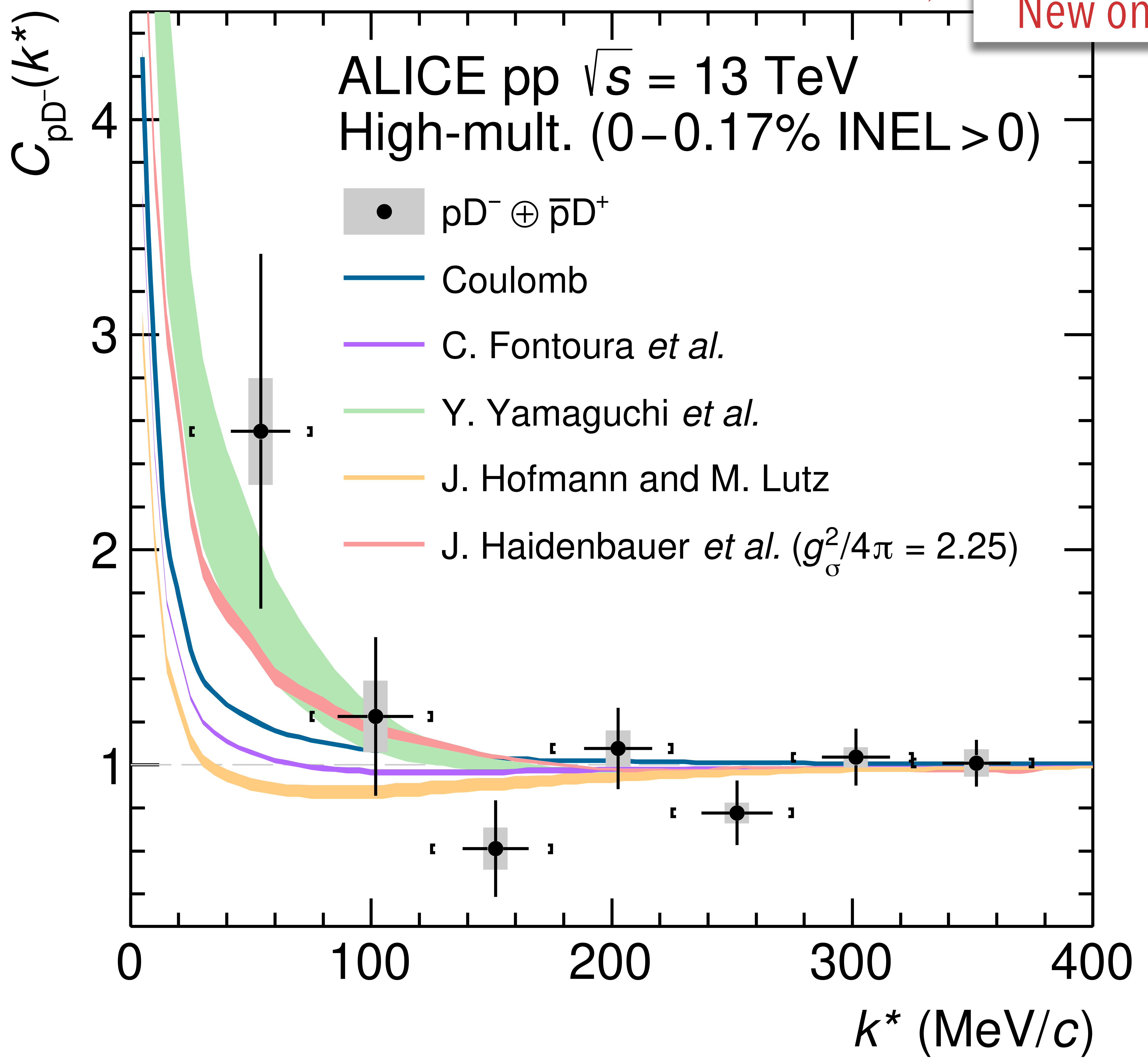
- Total background well describes CF for large k^*

$N\bar{D}$ interaction

- pD^-
  - ➡ Typically very small compared to other interactions (light-light ~ 7-8 fm, light-strange ~ 1.5 fm)
  - ➡ Most of the models predict repulsive interaction
  - ➡ Possible bound state formation (Yamaguchi et al)
- Data compatible with Coulomb only interaction, but comparison slightly improved when also attractive strong interaction is considered

$pD^- \oplus \bar{p}D^+$

New on arXiv



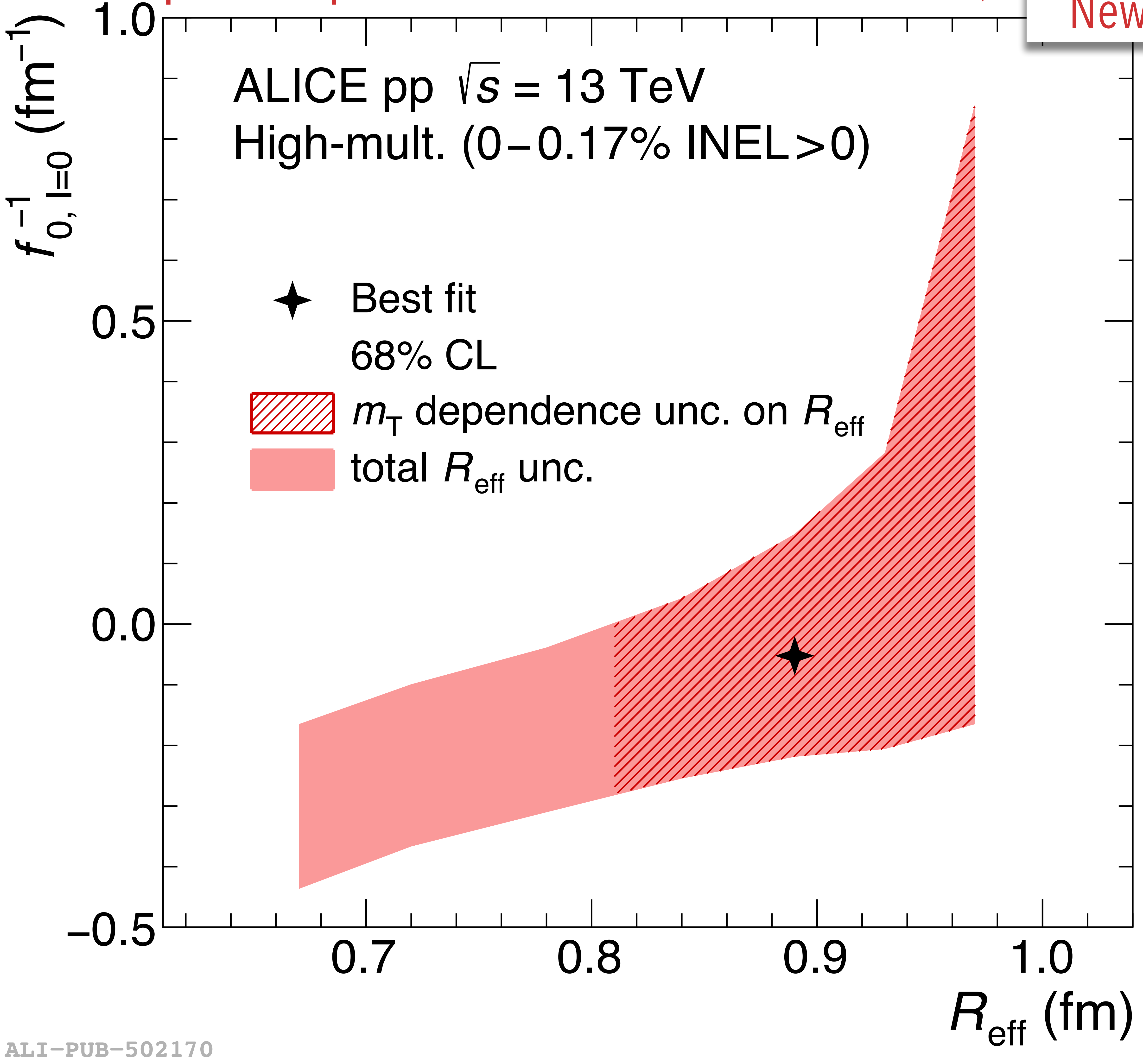
ALI-PUB-502166

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
Yamaguchi et al, Phys. Rev. D84 (2011) 014032
arXiv: 2201.05352

- Confidence interval of scattering length for isospin I=0 channel evaluated by comparing data with CF computed using a Gaussian potential modelled with ρ-meson exchange
  - ➡ Assuming I=1 negligible
  - ➡ First constrain to scattering length for I=0
  - ➡ Indicates either rather shallow attractive interaction or strong attractive interaction with formation of a bound state

$pD^- \oplus \bar{p}D^+$

New on arXiv



arXiv: 2201.05352

πD and KD interactions

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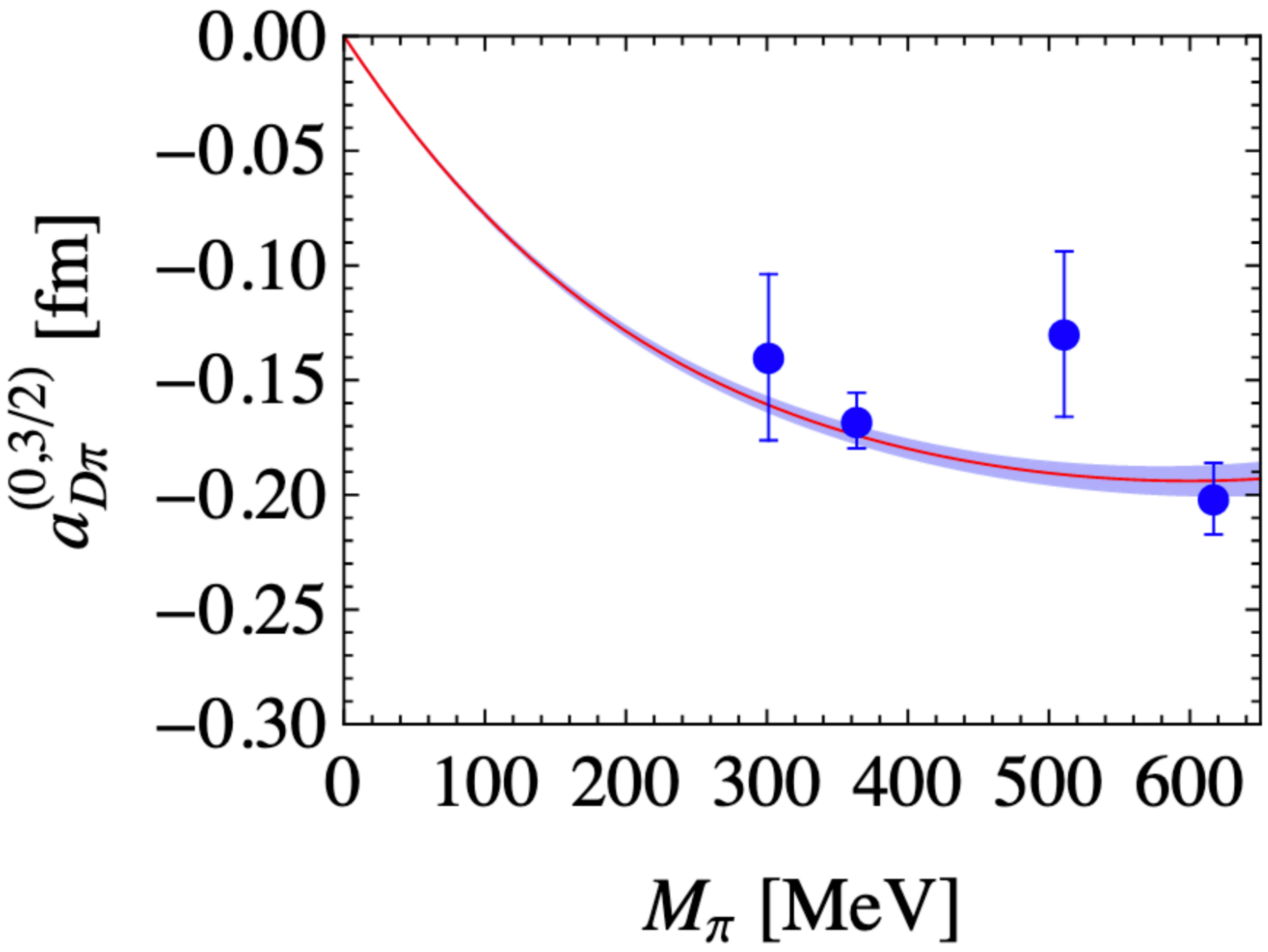
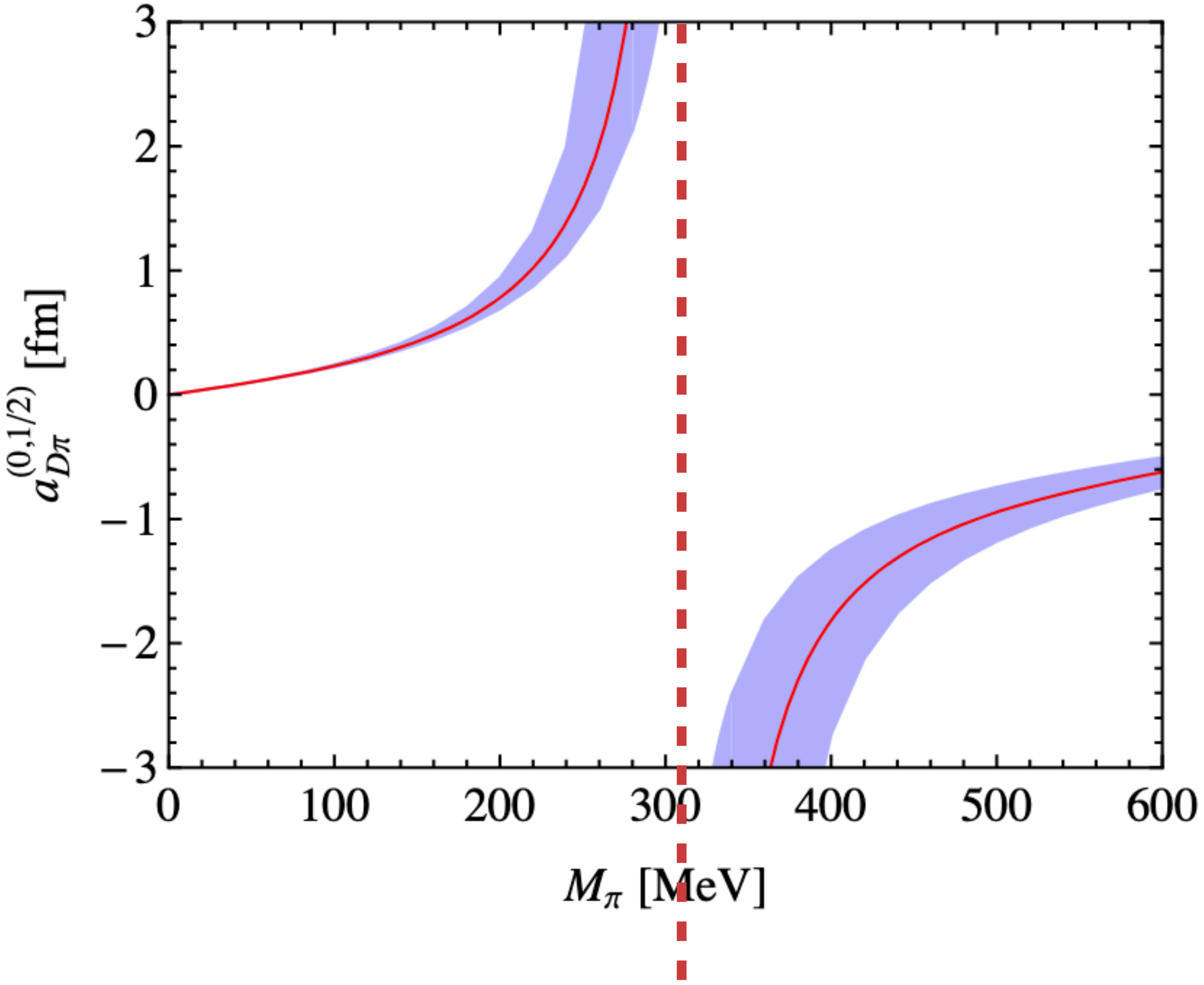
- Predictions of scattering lengths derived from lattice QCD calculations
  - ➡ ~0.1-0.5 fm: very small compared to other interactions (light-light ~ 7-8 fm, light-strange ~ 1.5 fm)
  - ➡ No constraints from data
  - ➡ For pions I=3/2 channel more constrained than I=1/2 channel

X.-Y. Guo et al, Phys. Rev. D 98 (2018) 014510

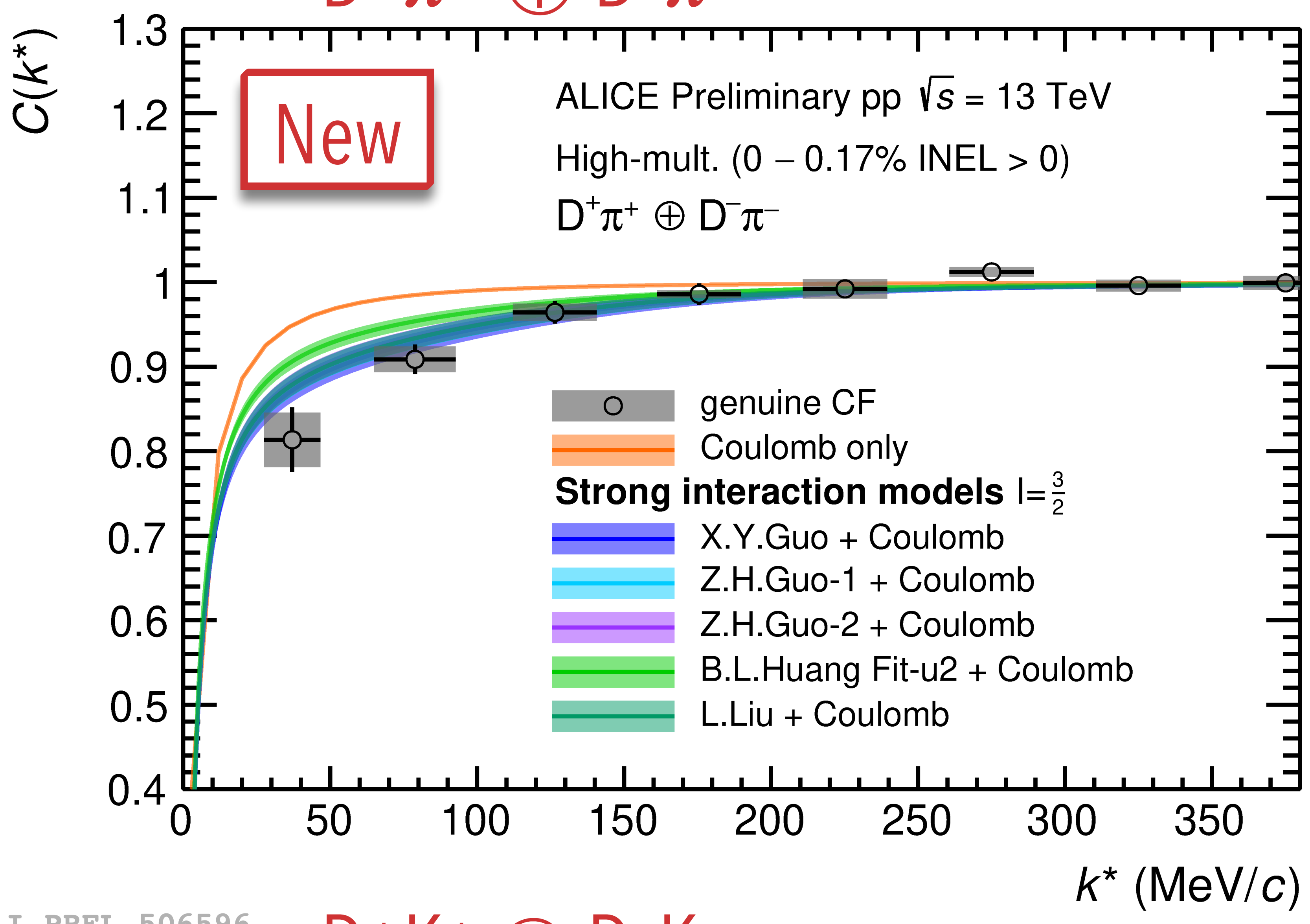




Bound-state pole formation corresponding to D_{s0}*(2317)

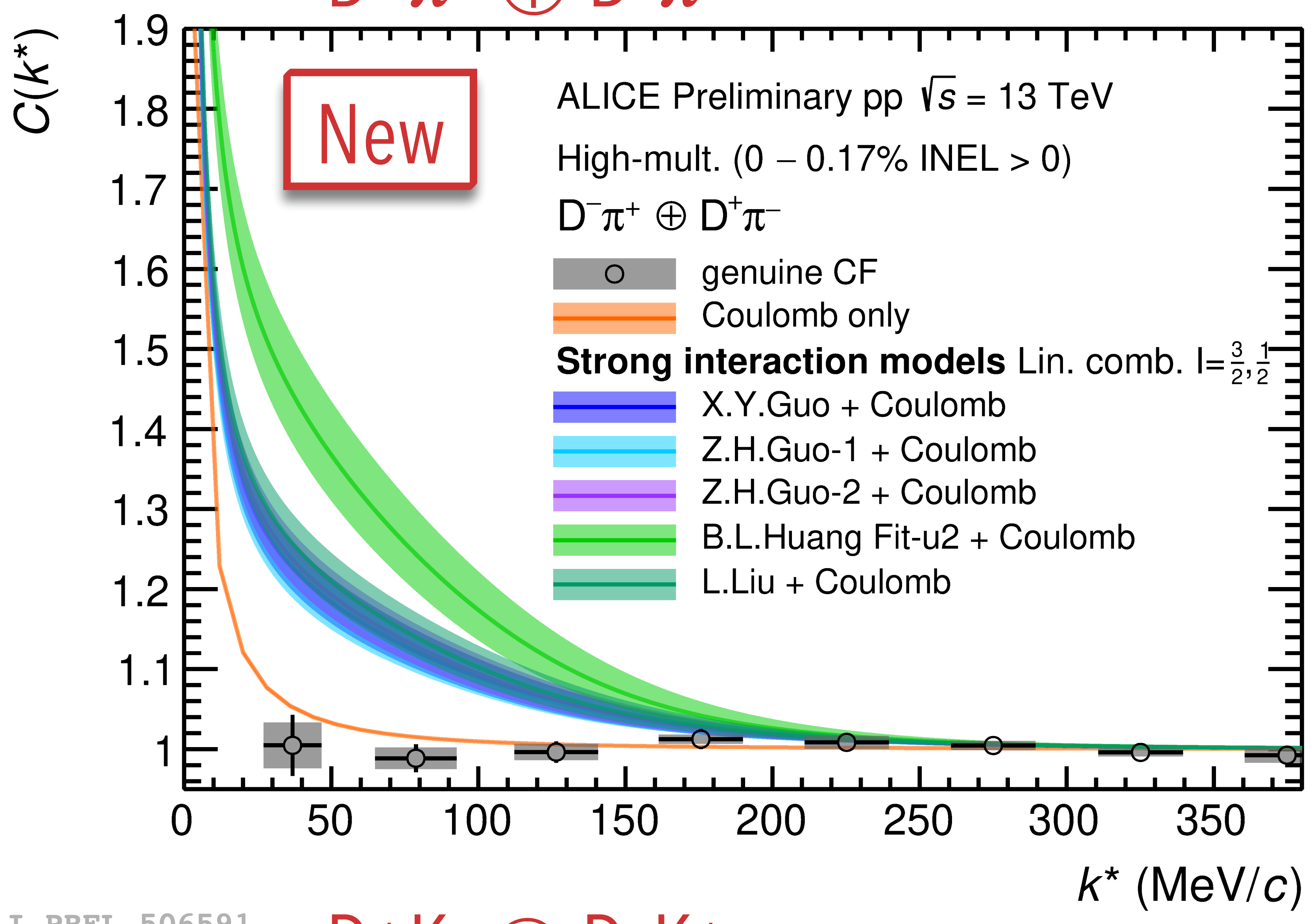
πD and KD interactions

$D^+\pi^+ \oplus D^-\pi^-$



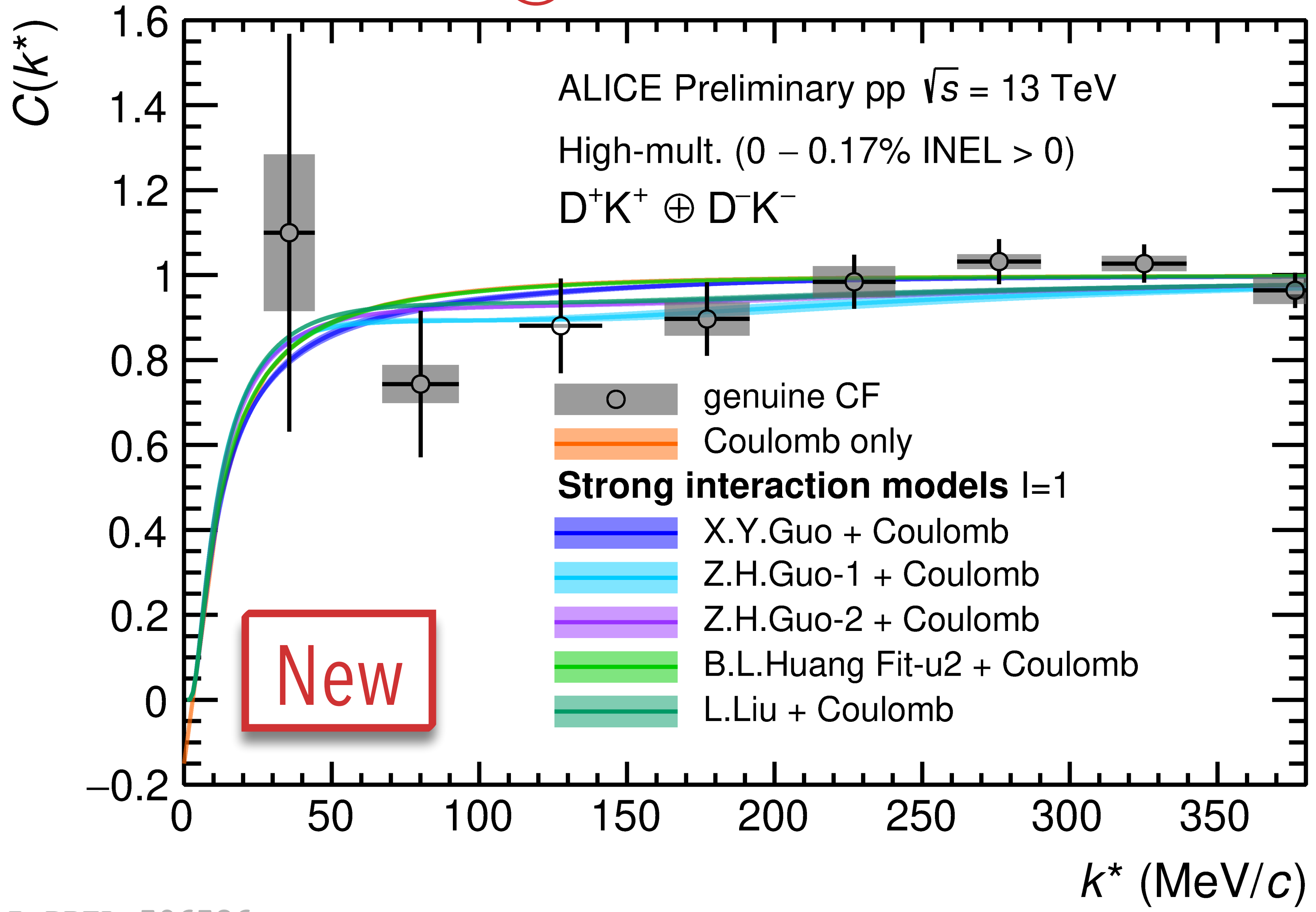
ALI-PREL-506596

$D^+\pi^- \oplus D^-\pi^+$



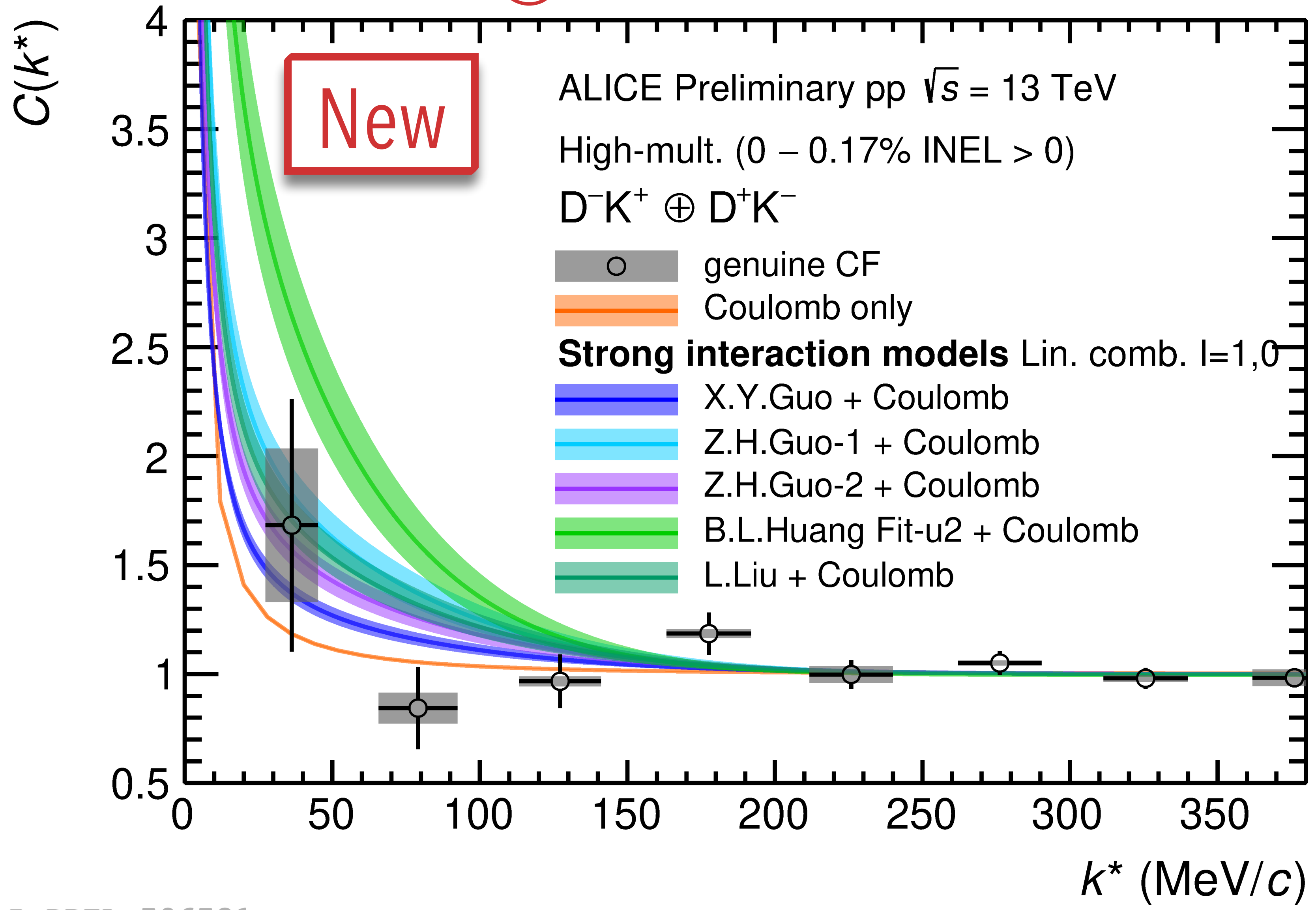
ALI-PREL-506591

$D^+K^+ \oplus D^-K^-$



ALI-PREL-506586

$D^+K^- \oplus D^-K^+$



ALI-PREL-506581

- Models agree with data in case of same-charge CF
- Models overestimate data in case of opposite-charge CF

L. Liu et al, Phys. Rev. D87 (2013) 014508
X.-Y. Guo et al, Phys. Rev. D 98 (2018) 014510
B.-L. Huang et al, Phys. Rev. D 105 (2022) 036016
Z.-H. Guo et al Eur. Phys. J. C 79 (2019) 13

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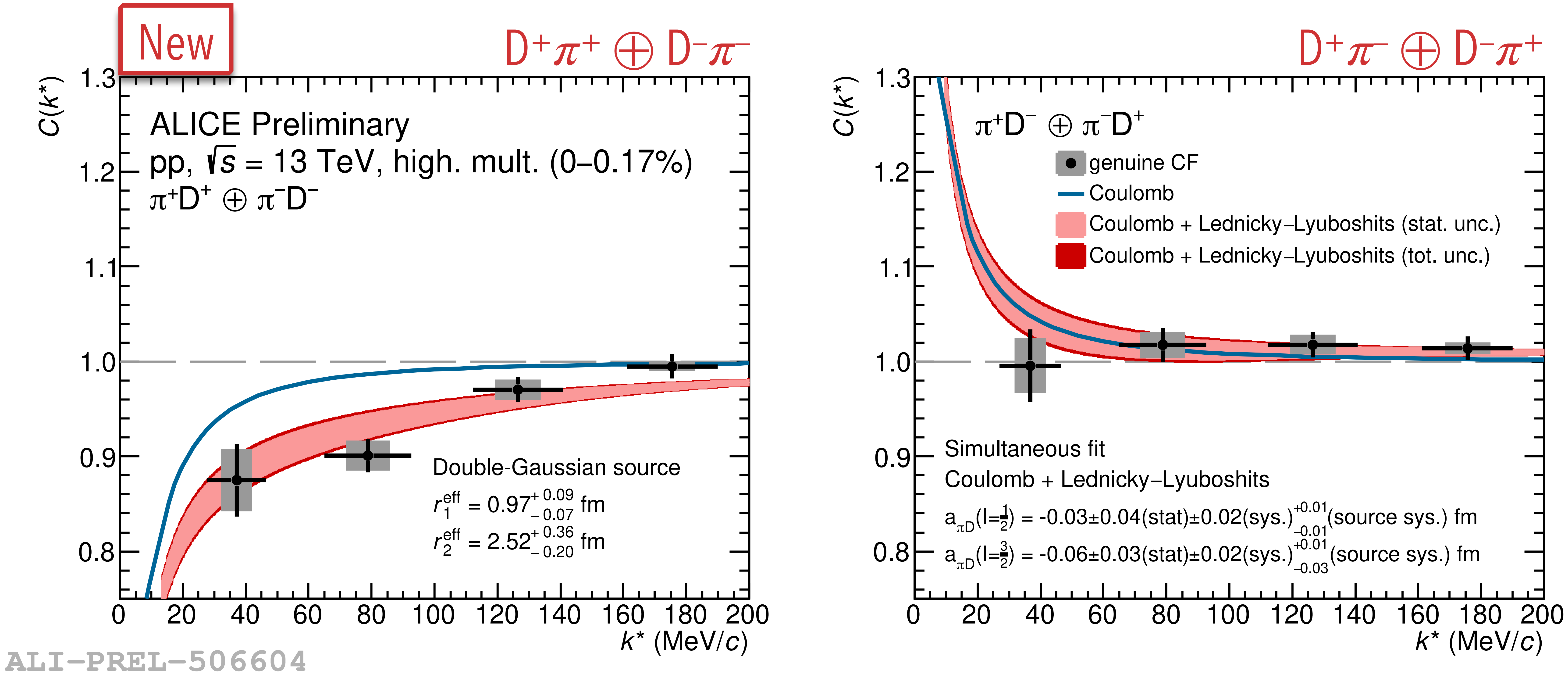
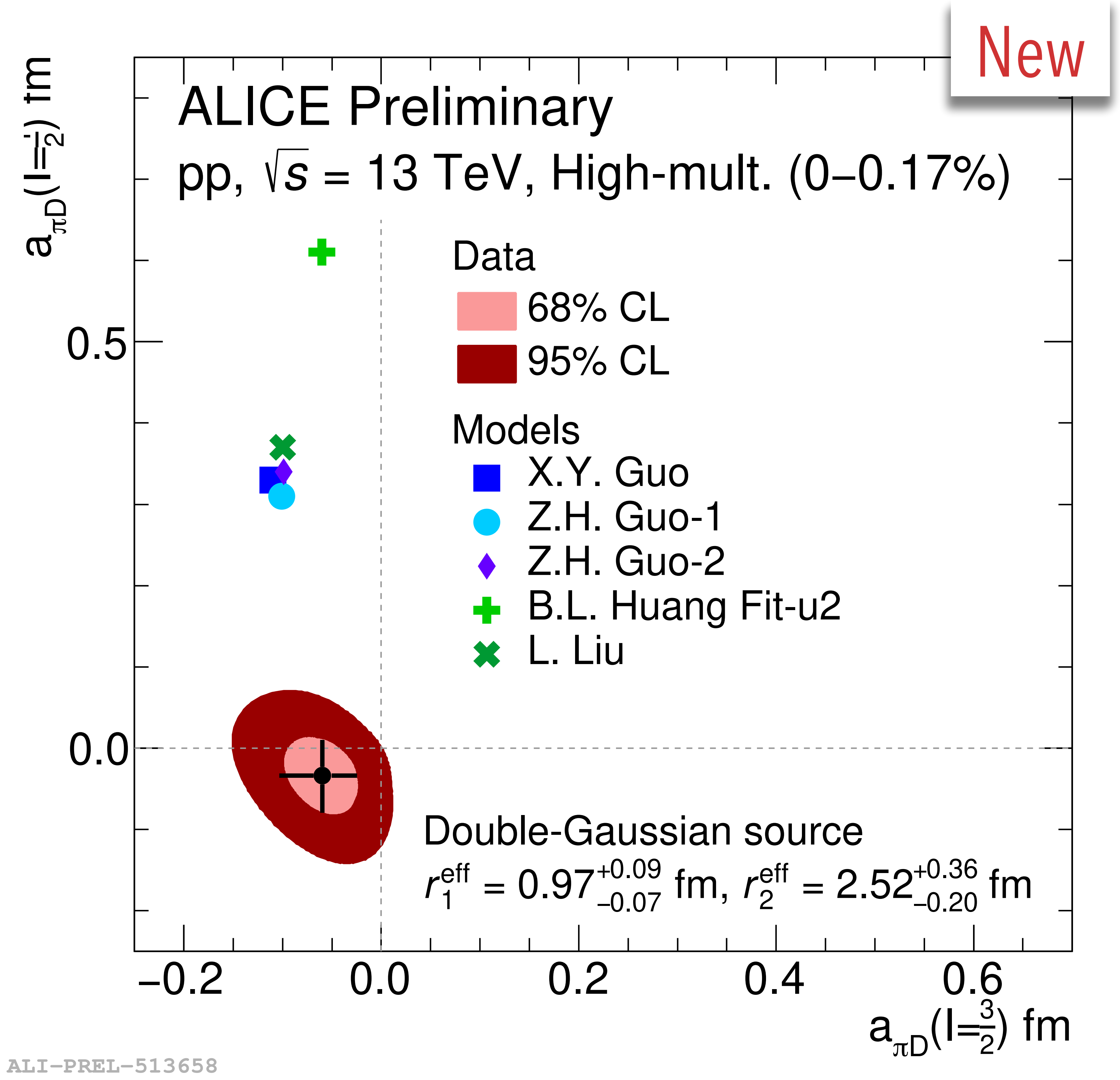


- π^+D^+
  - ➡ I=3/2 channel only
- π^+D^-
  - ➡ I=3/2 (33%)
    I=1/2 (66%)



- The values found indicate a small rescattering of D mesons in the hadronic phase of heavy-ion collisions
- Scattering length for I=3/2 in agreement with models
- Scattering length for I=1/2 significantly smaller than models

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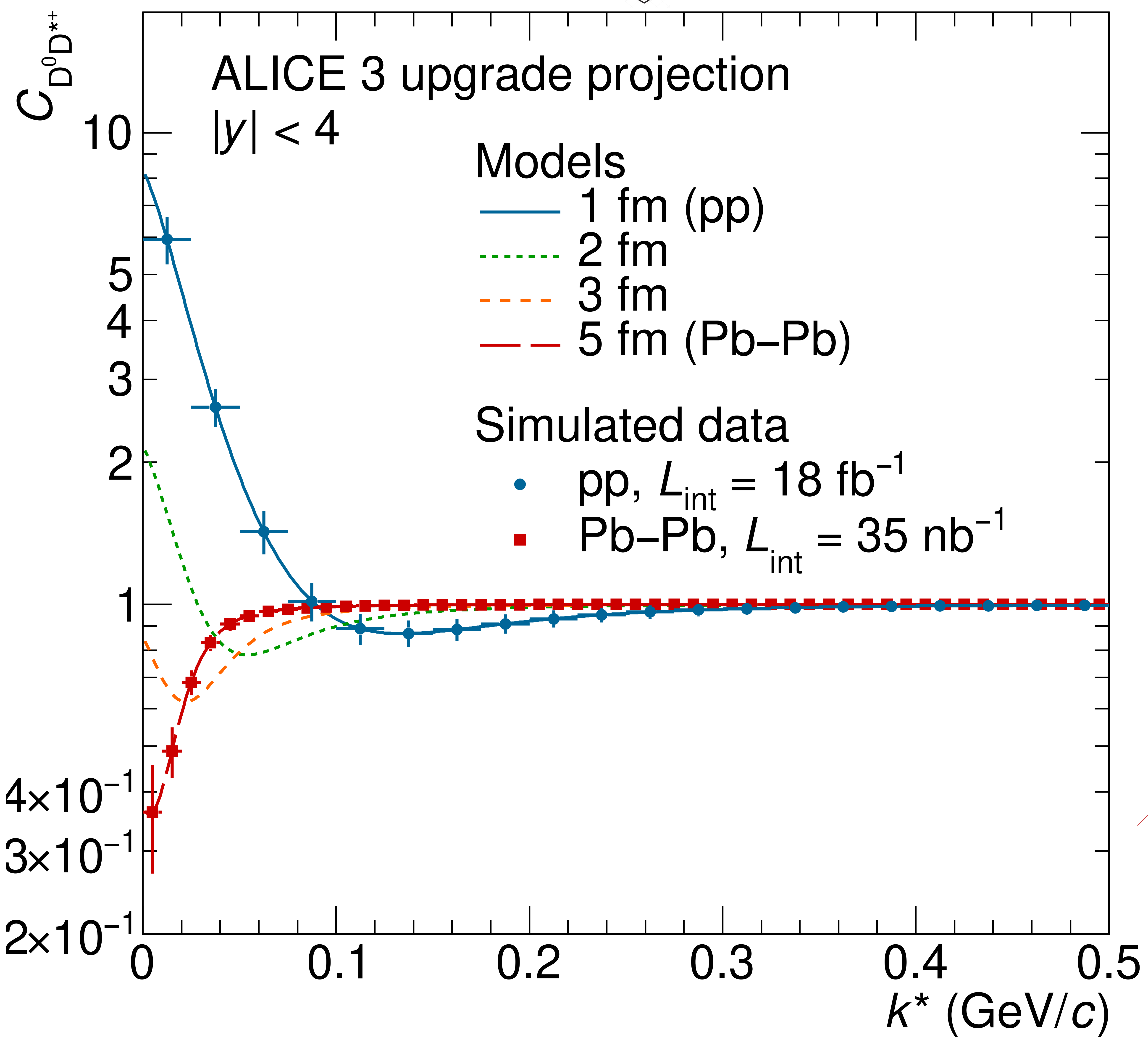
ALICE3 LOI: CERN-LHCC-2022-009



ALI-SIMUL-502575

- ALICE 3: large acceptance, high luminosity, excellent spatial resolution
  - ➡ Run 5: ideal laboratory for the measurement of charm-hadron momentum correlations in different colliding systems
- Interplay between system size and scattering length
  - ➡ size-dependent modification of the correlation function in presence of a bound state

Yuki Kamyia et al, arXiv:2203.13814

ALICE upgrades, H. S. Scheid talk 07/04 2022, 16:00

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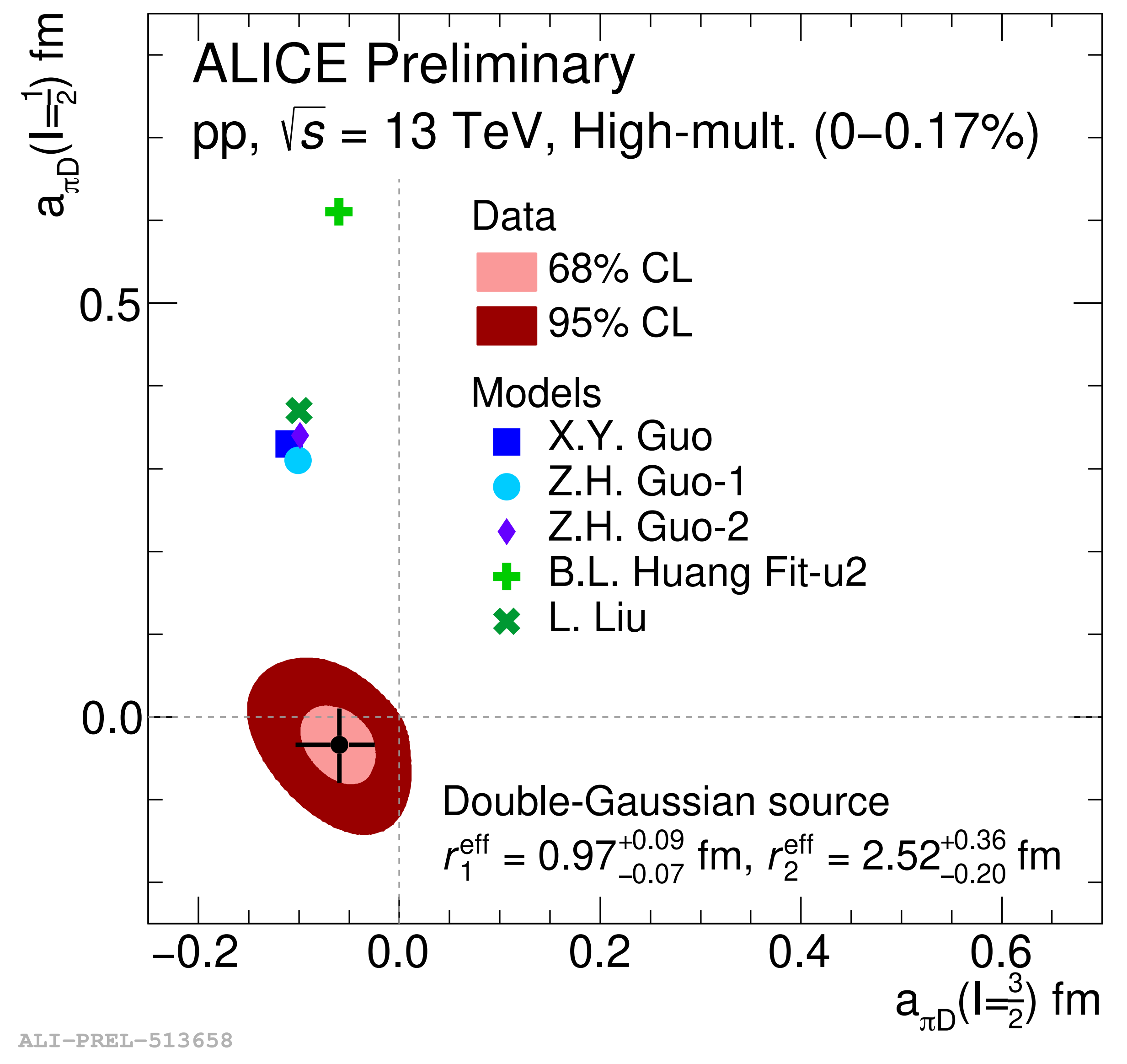
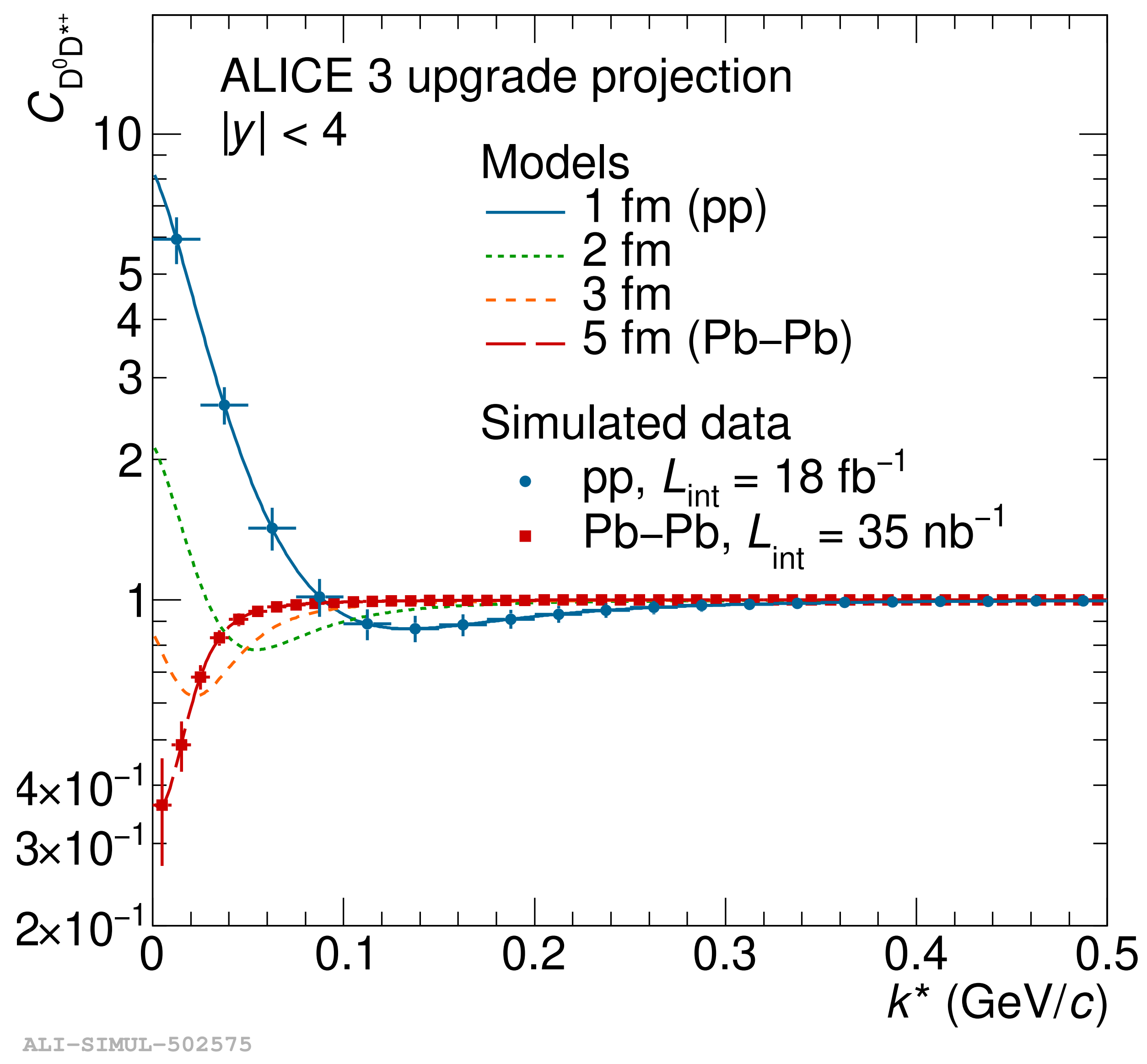
Summary and outlook

- First studies of residual strong interaction between charm and light hadrons performed with Run 2 data
  - ➡ Shallow interaction between charm mesons and light hadrons suggests no important hadronic phase for heavy-flavour hadrons in heavy-ion collisions
  - ➡ Possible formation of bound state in ND interaction not excluded
  - ➡ Significant improvement foreseen with Run 3 data



- ALICE 3 will provide an ideal laboratory for the study of residual strong interaction among charm hadrons and for the search of charm molecular states



ADDITIONAL SLIDES

- Charm molecules?

System	I ($J^{P(C)}$)	Candidate
np	0 (1^+)	deuteron
ND	0 ($1/2^-$)	$\Lambda_c(2765)$
ND*	0 ($3/2^-$)	$\Lambda_c(2940)$
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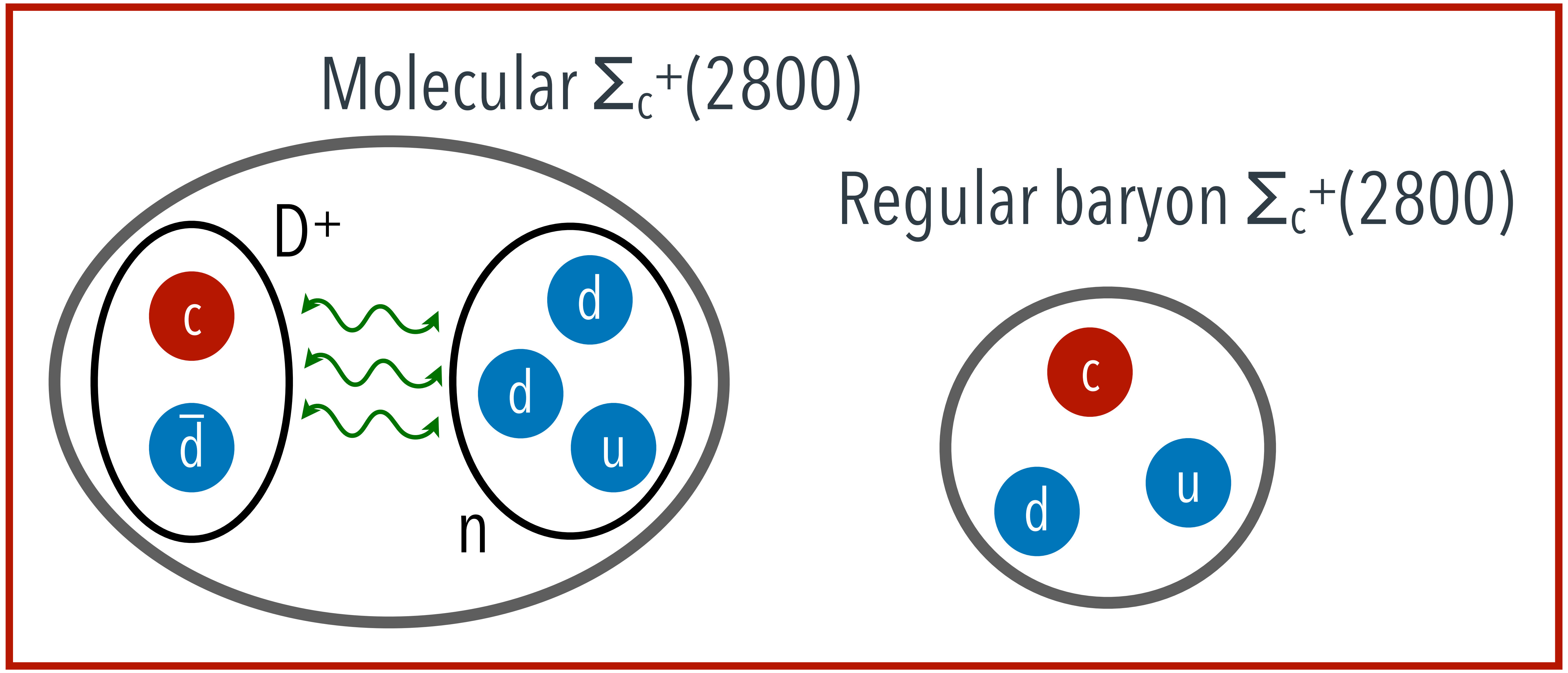
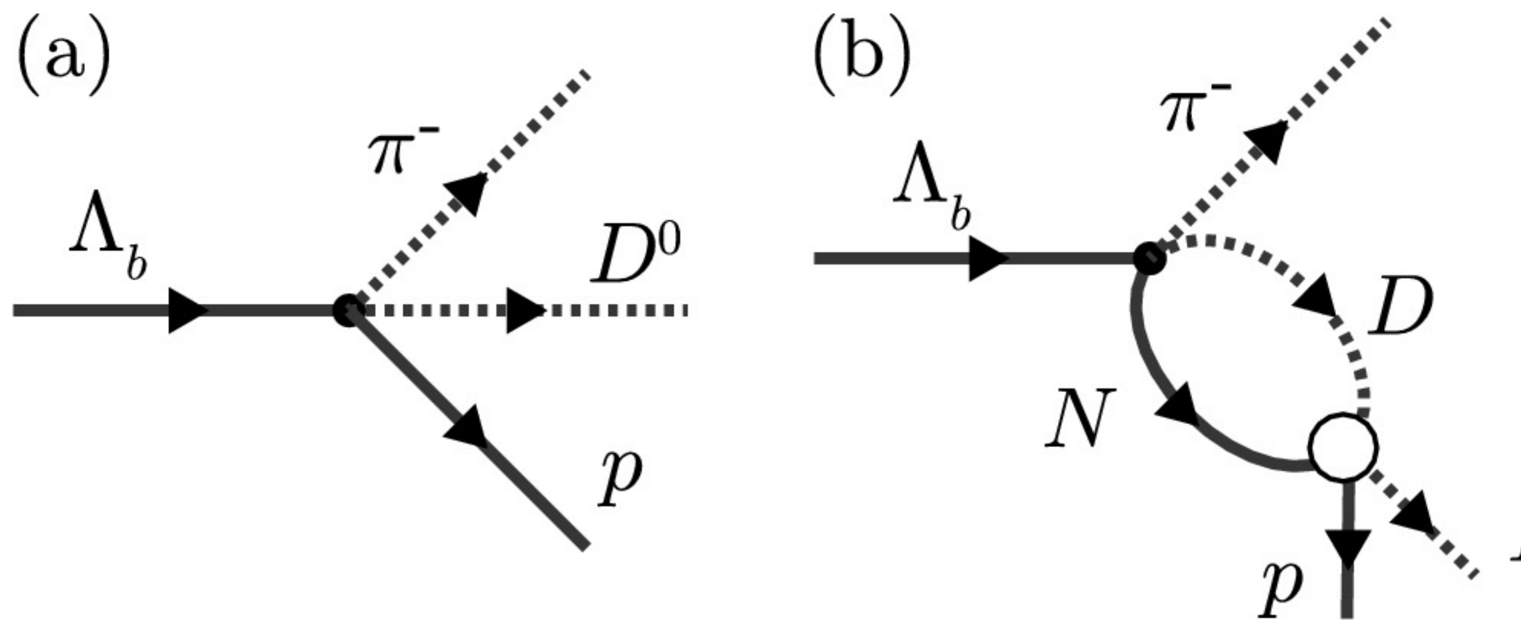
Fang-Zheng Peng et al, Phys. Rev. D 105, 034028 (2022)



- Proposed as molecular state in J. Haidenbauer et al, Eur. Phys. J. A 47, 18 (2011)
  S. Sakai et al, Phys. Lett. B 808 (2020) 135623



- Molecular states also relevant to explain some beauty-hadron decays

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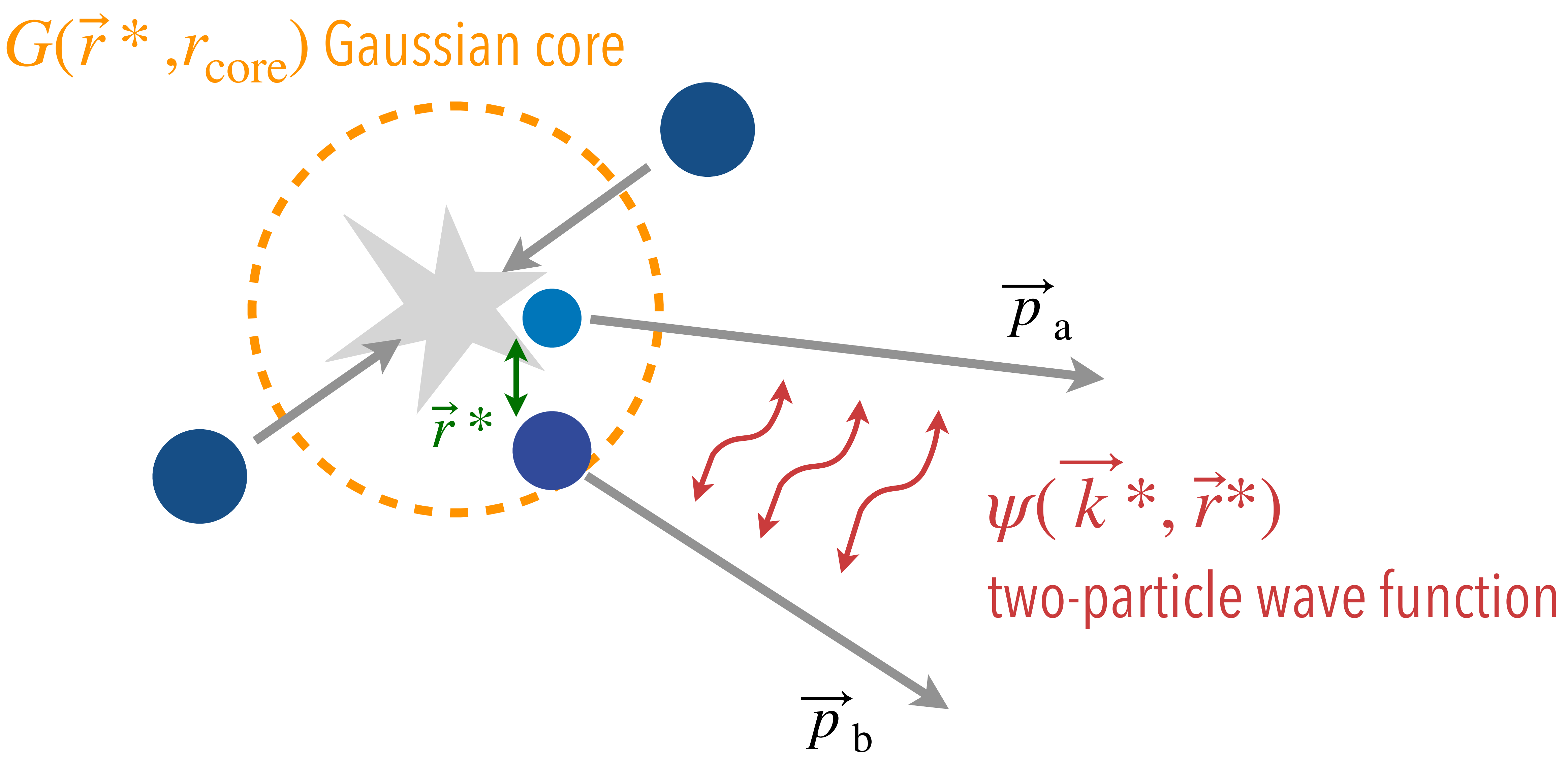
$$C(\vec{k}^*) = \int S(\vec{r}^*)\,|\psi(\vec{k}^*, \vec{r}^*)|^2\, \mathrm{d}^3 r^*$$

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



- Described with a Gaussian core

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

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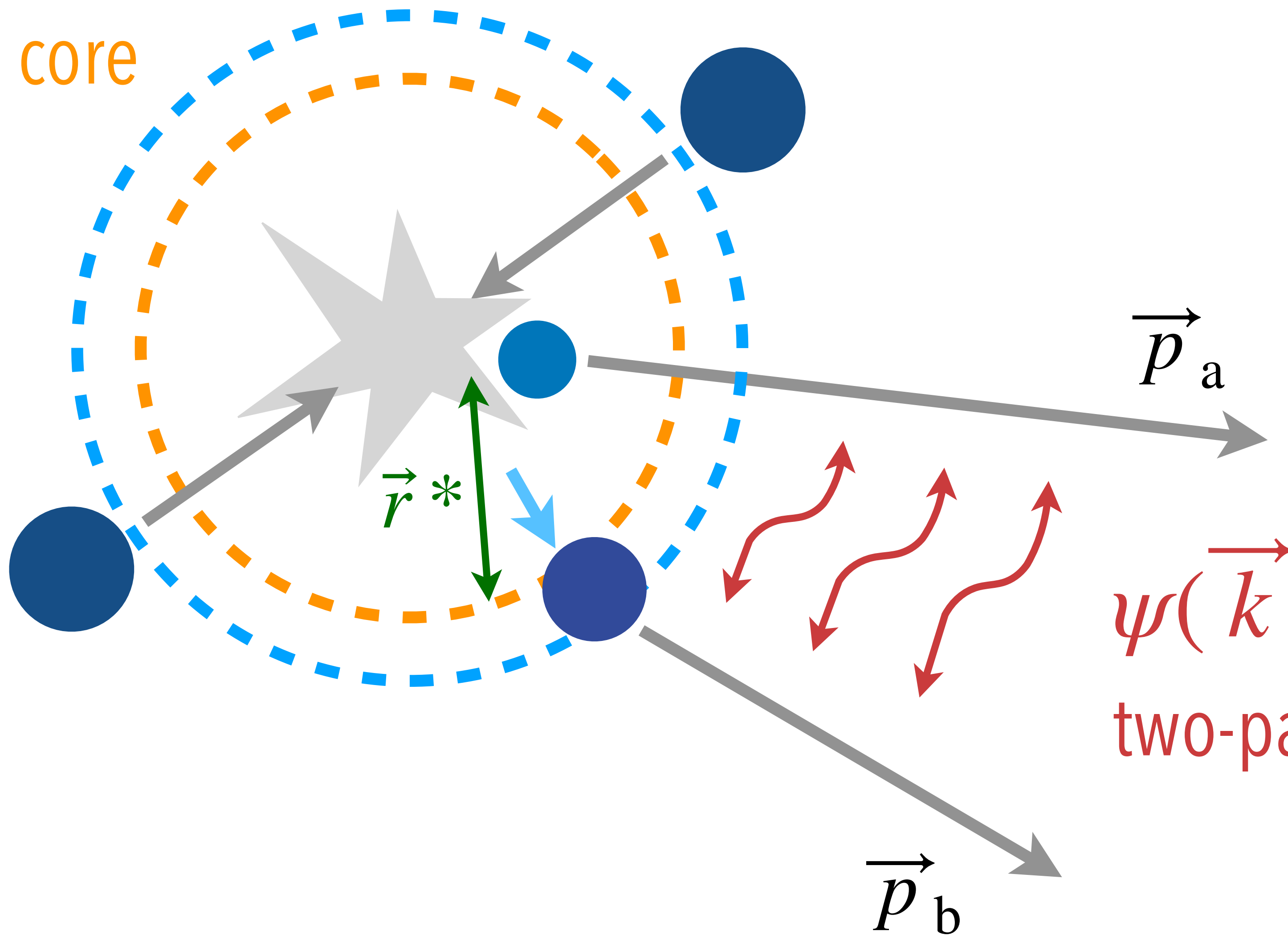
$$C(\vec{k}^*) = \int S(\vec{r}^*)\,|\psi(\vec{k}^*, \vec{r}^*)|^2 \, d^3 r^*$$

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



- Described with a Gaussian core

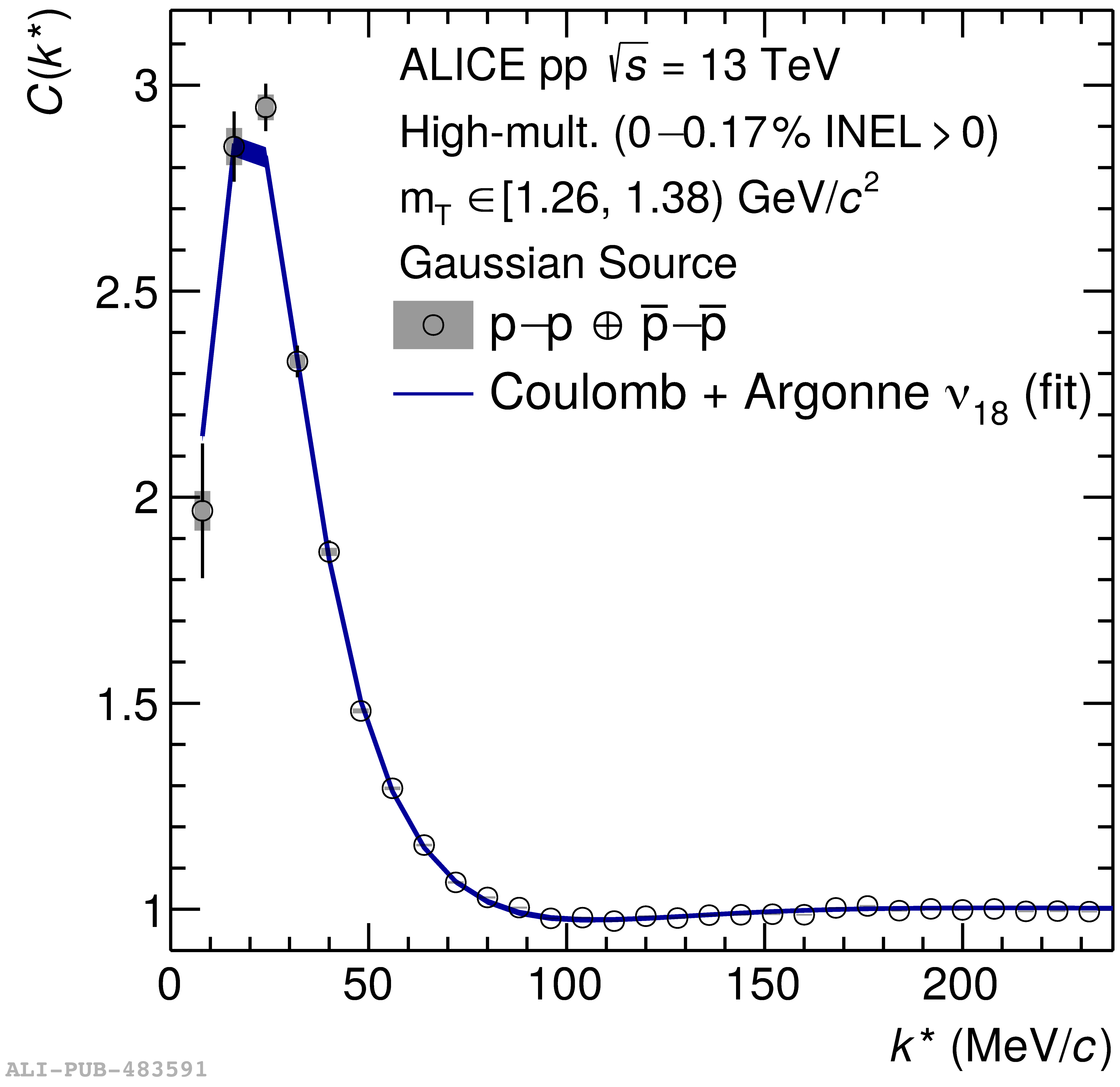
$$G(r^*, r_{core}(m_T)) = \frac{1}{(4\pi r_{core}^2(m_T))^{3/2}} \cdot \exp\left(-\frac{r^{*2}}{4 r_{core}^2(m_T)}\right)$$

- Short-lived strongly decaying resonances effectively enlarge it

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

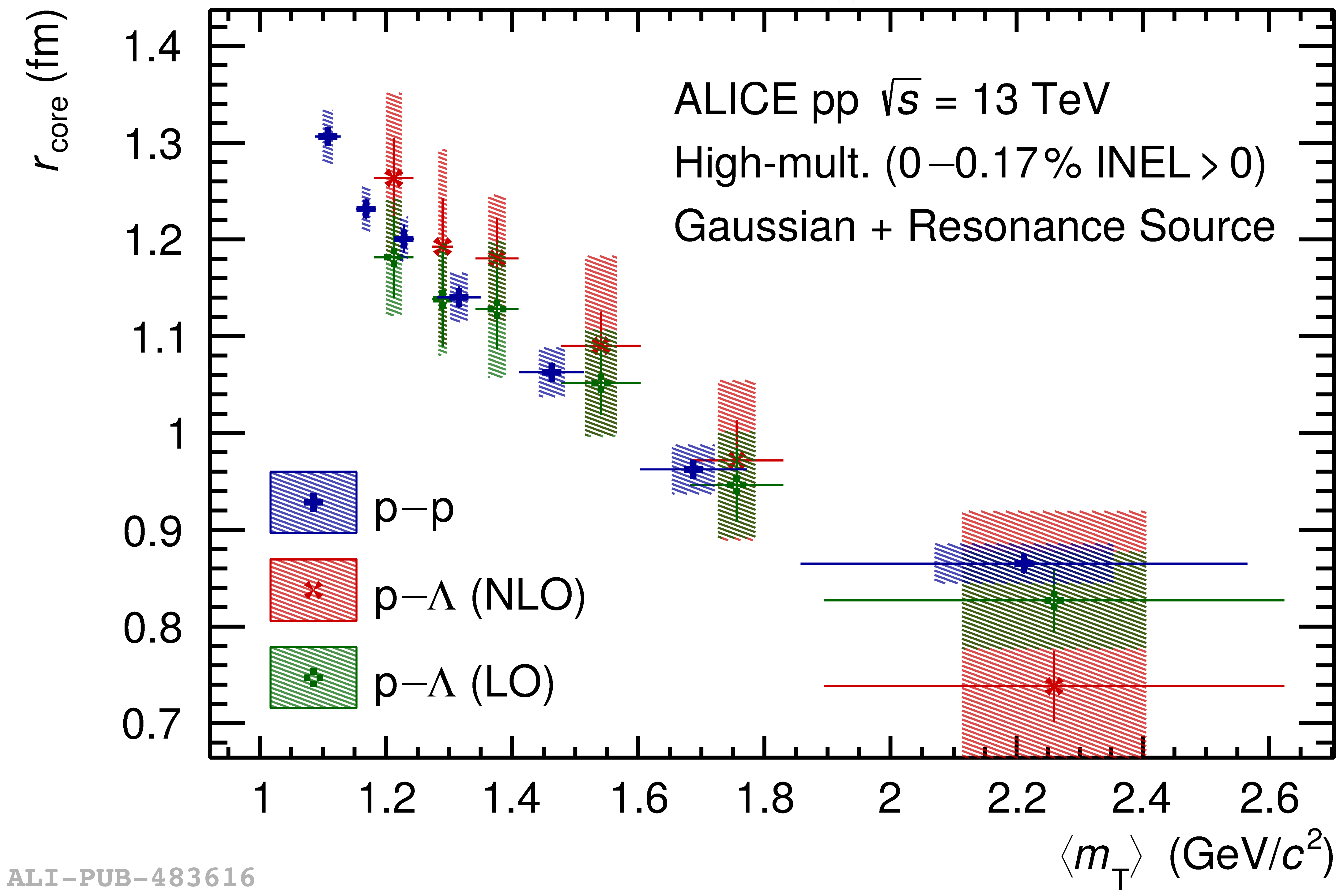
Calibrating the source

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

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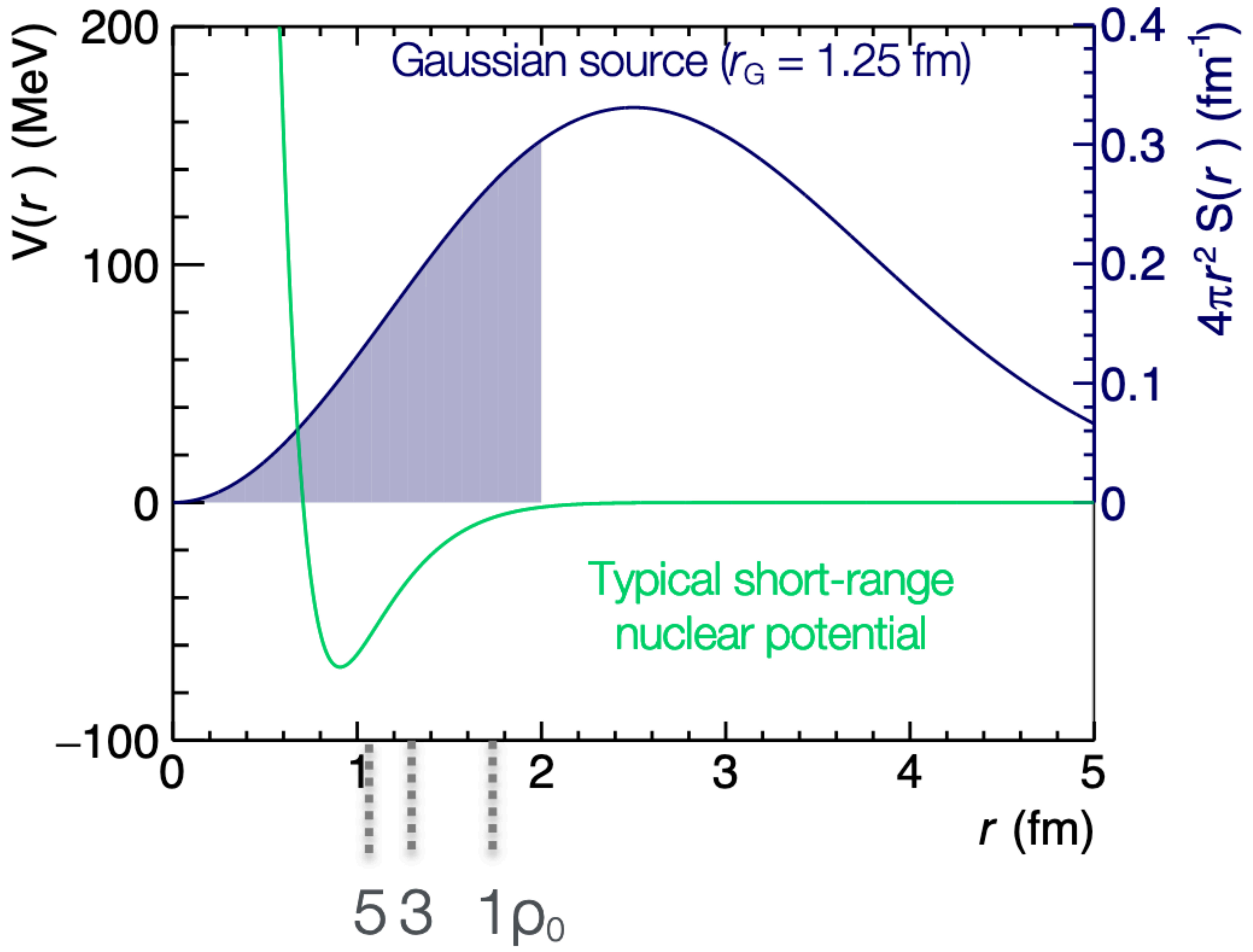

- Typical range of nuclear potential around 1-2 fm
  - ➡ study of strong interaction among hadrons not possible with larger sources
  - ➡ proton–proton and proton–nucleus collisions are the ideal laboratory to study the strong interaction

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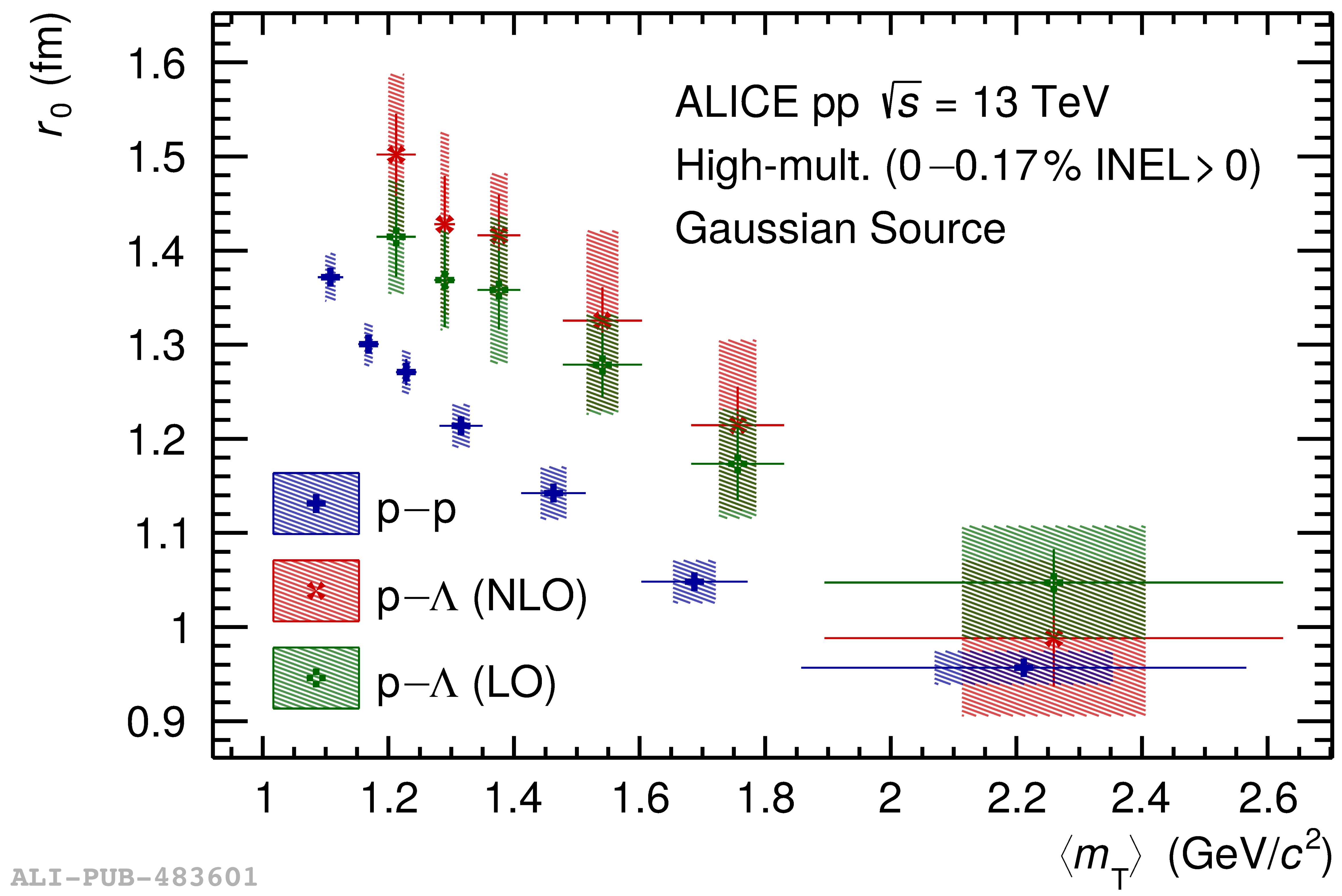
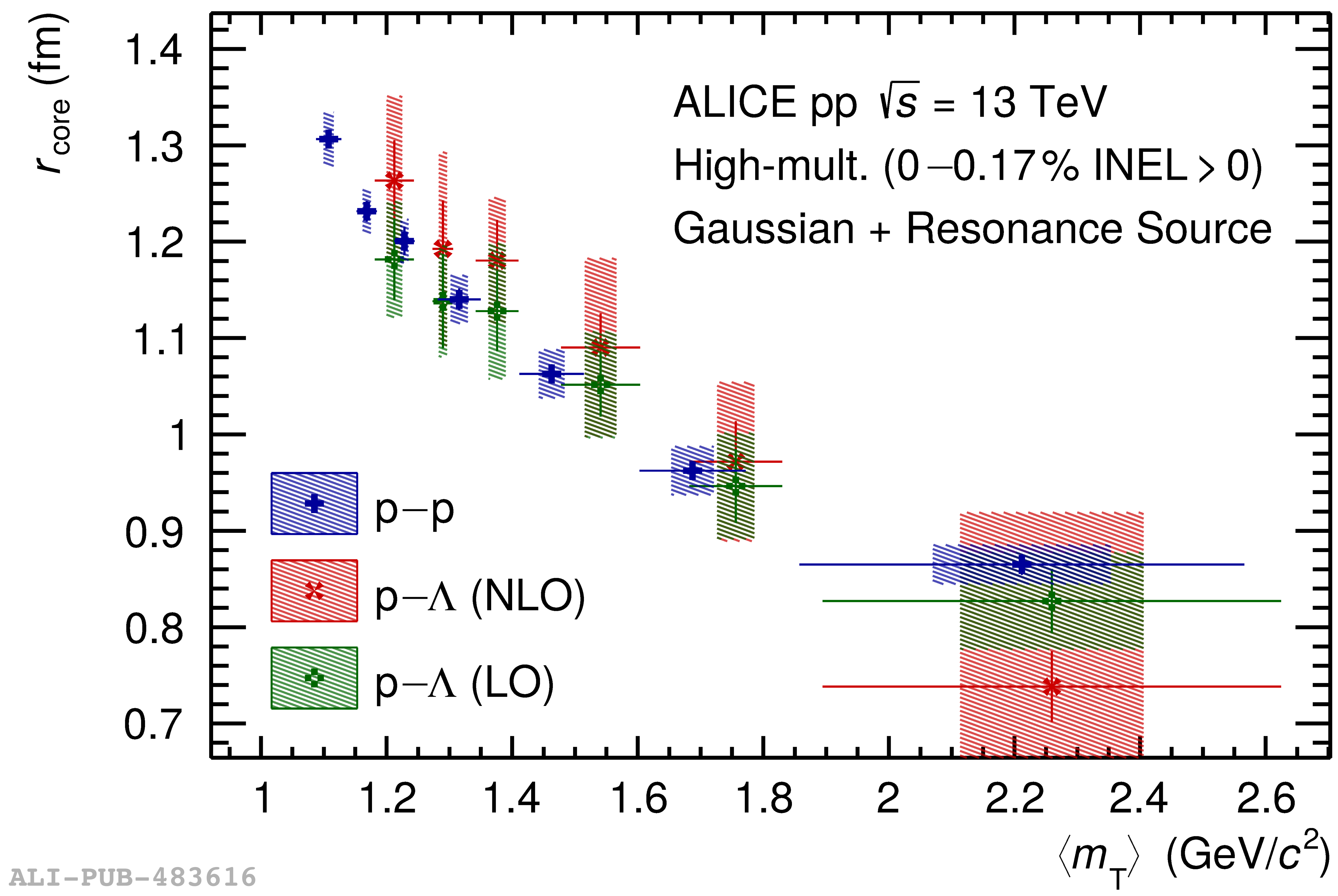
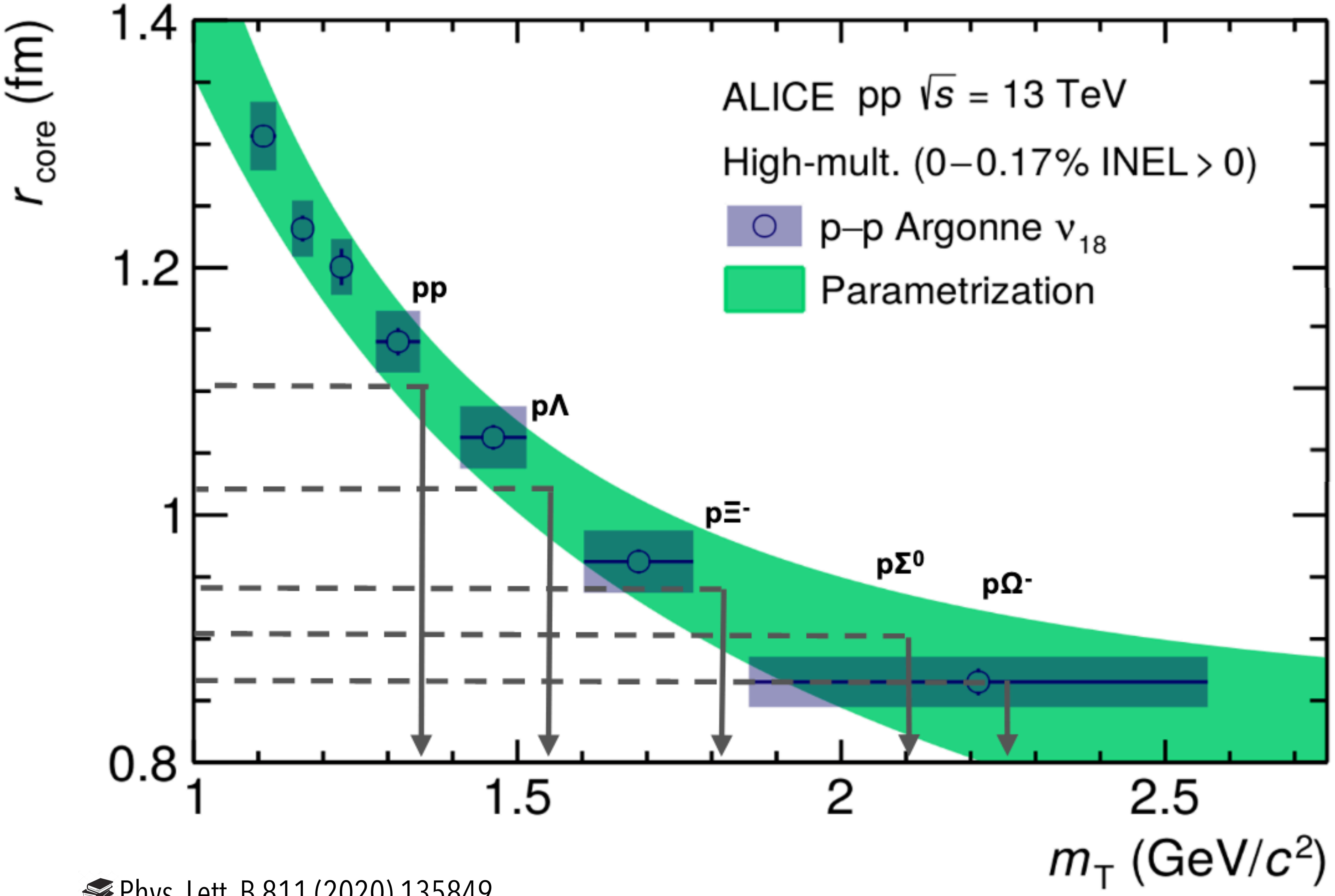
- Without considering resonances



- Considering resonances





Phys. Lett. B 811 (2020) 135849

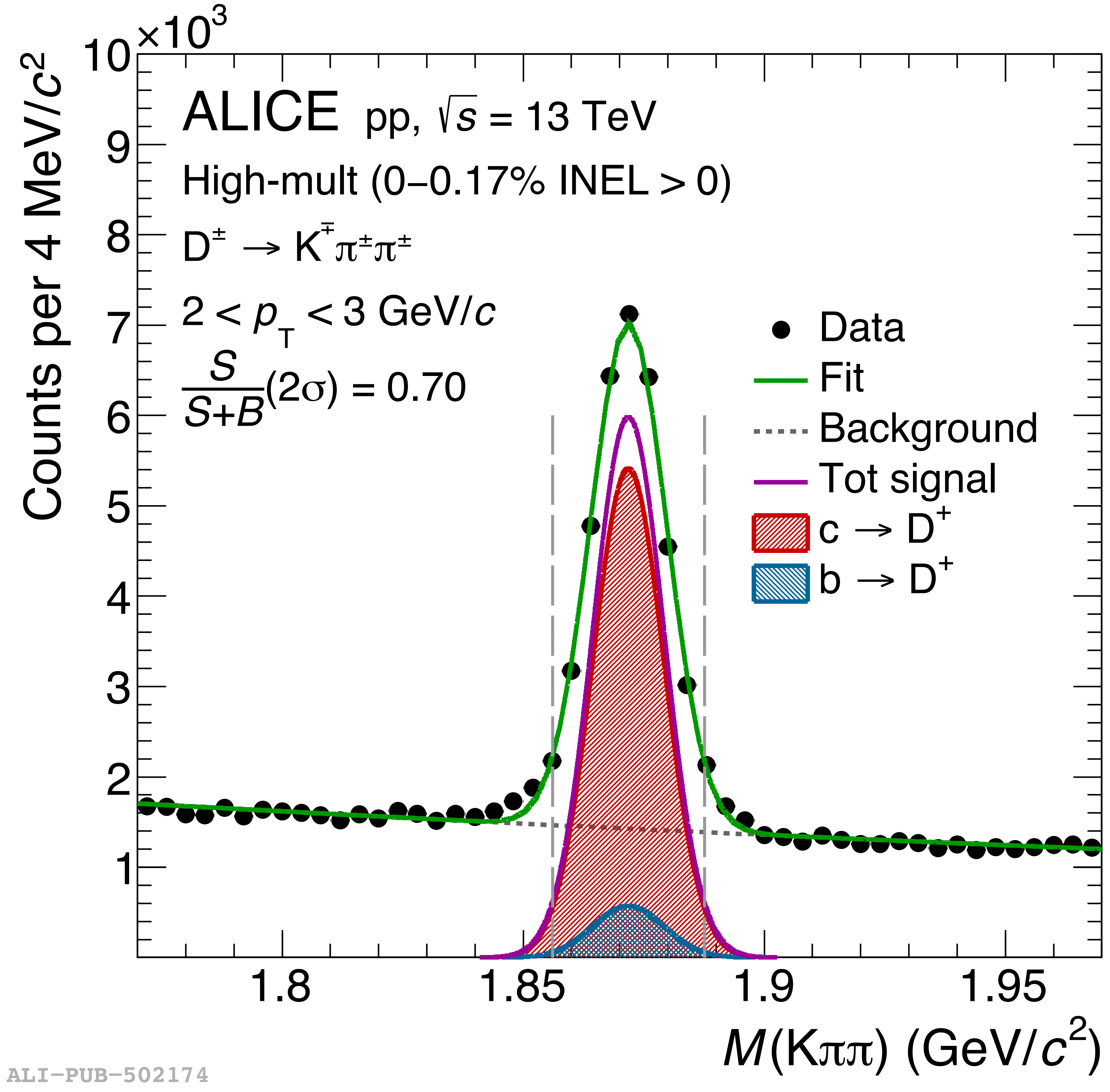
- Measurement of source radius obtained from p–p correlation used to obtain the values for other baryon species

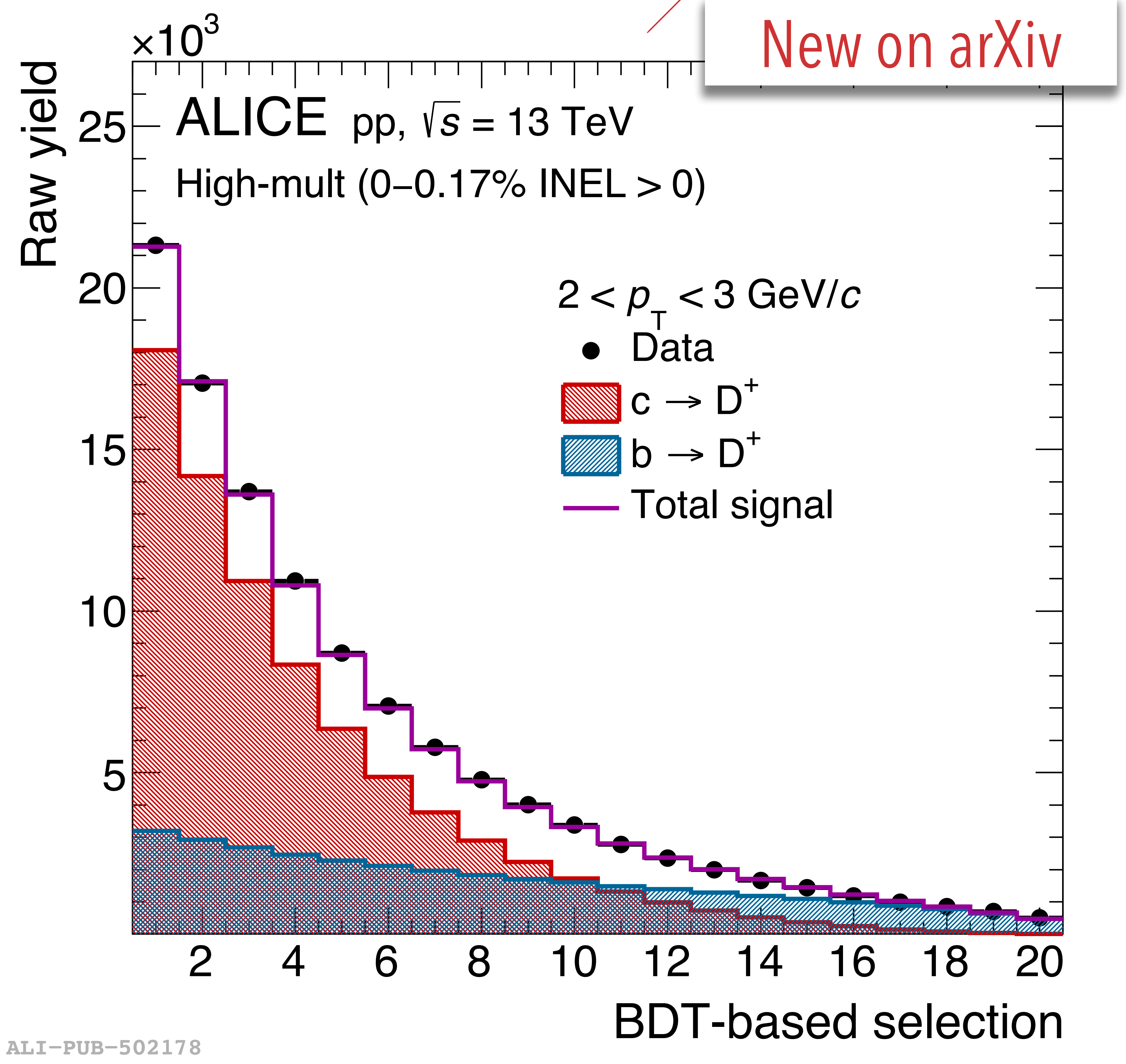
D±-meson reconstruction with ALICE - extended

- Decay channel:
  - ➡ $D^{\pm} \rightarrow K^{\mp}\pi^{\pm}\pi^{\pm}$
  - ➡ BR = (9.38 ± 0.16)%

PDG, Prog. Theor. Exp. Phys. 2020 083C01

- Contributions:
  - ➡ Prompt:
    - from c hadronisation
    - from D* decays
  - ➡ Non-prompt: from b decays





arXiv: 2201.05352

- Fully reconstruct decay topologies ($c\tau \approx 312\ \mu$m)
  - ➡ Multiclass Boosted Decision Trees feed with geometrical, kinematic and PID variables used to reduce combinatorial background and non-prompt contribution
  - ➡ Purity of about 70%, non-prompt contribution about 7%

$N\bar{D}$ interaction - scattering lengths in models

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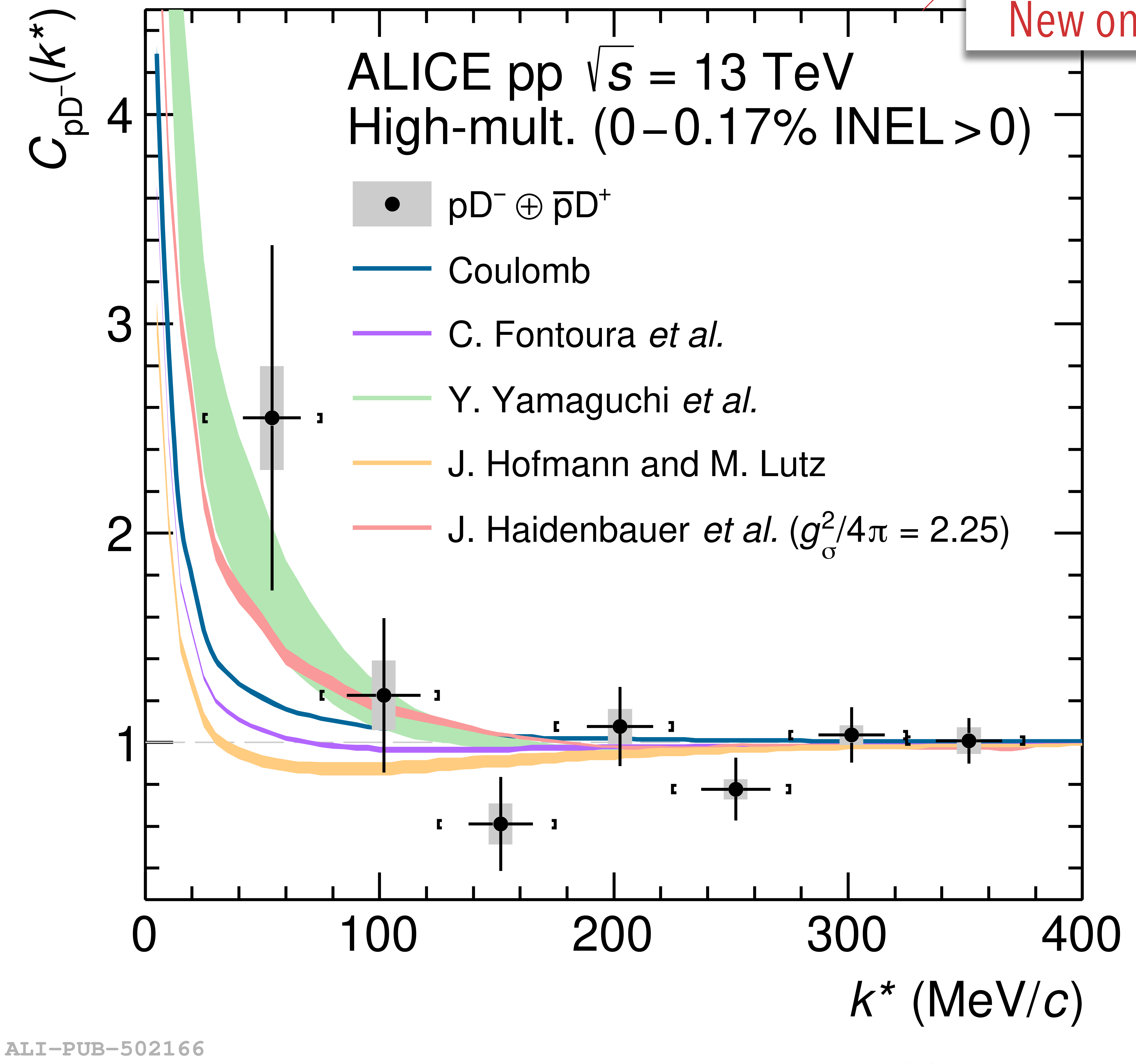
Model	f_0 (I=0) [fm]	f_0 (I=1) [fm]
Haidenbauer $g_\sigma^2/4\pi = 1$ Meson-exchange model	0,14	−0,28
Haidenbauer $g_\sigma^2/4\pi = 2.25$ Meson-exchange model	0,67	0,04
Hofmann and Lutz SU(4) contact interaction	−0,16	−0,26
Yamaguchi meson-exchange on HQ symmetry	−4,38	−0,07
Fontoura Chiral-quark model	0,16	−0,25

New on arXiv



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
Yamaguchi et al, Phys. Rev. D84 (2011) 014032

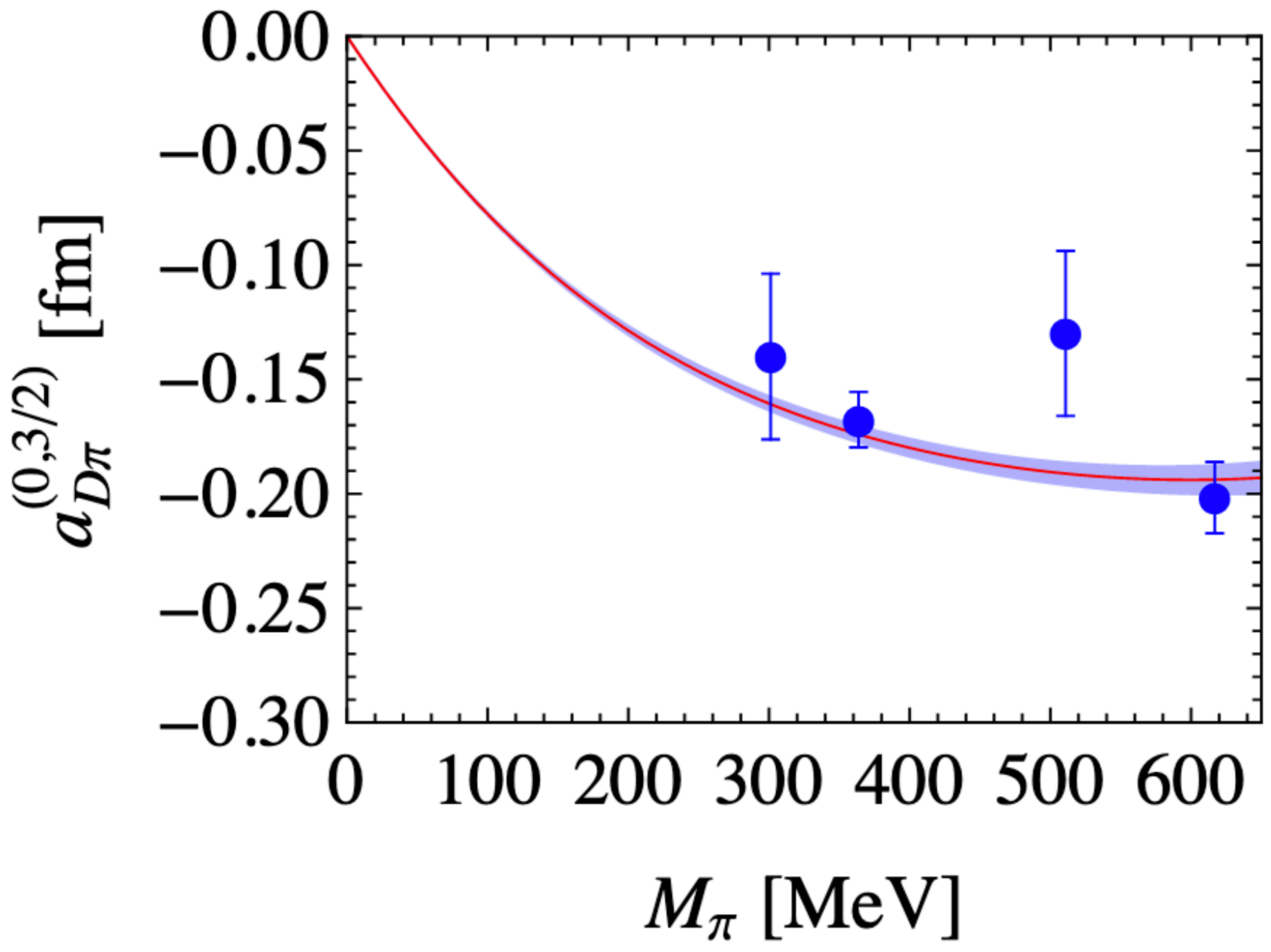
arXiv: 2201.05352

πD and KD interactions - scattering lengths in models

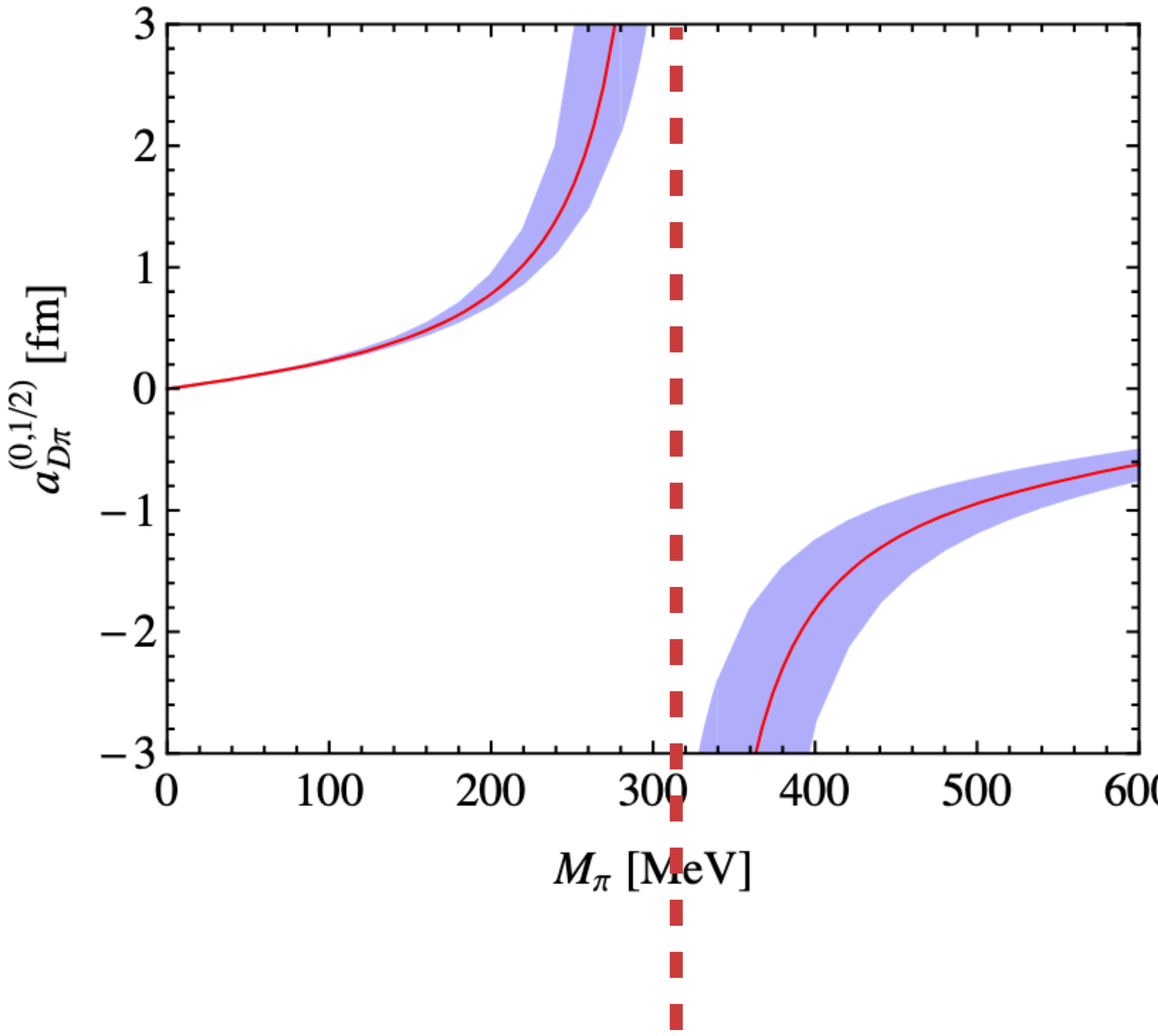
Channel	L. Liu	X.-Y. Guo	Z.-H. Guo-1	Z.-H. Guo-2	B.-L. Huang
Dπ(I=3/2) [fm]	–0,10	–0,11	–0,101	–0,099	–0,06
Dπ(I=1/2) [fm]	0,37	0,33	0,31	0,34	0,61
DK(I=1) [fm]	0,07+i0,17	–0,05	0,06+i0,30	0,05+i0,17	–0,01
D$\bar{K}$(I=0) [fm]	0,84	0,46	0,96	0,68	1,81
D$\bar{K}$(I=1) [fm]	–0,20	–0,22	–0,18	–0,19	–0,24

L. Liu et al, Phys. Rev. D87 (2013) 014508
X.-Y. Guo et al, Phys. Rev. D 98 (2018) 014510
B.-L. Huang et al, Phys. Rev. D 105 (2022) 036016
Z.-H. Guo et al Eur. Phys. J. C 79 (2019) 13

- Predictions of scattering lengths derived from lattice QCD calculations
  - ➡ Typically very small compared to other interactions (light-light ~ 7-8 fm, light-strange ~ 1.5 fm)
  - ➡ No constraints from data
  - ➡ For pions I=3/2 channel more constrained than I=1/2 channel



X.-Y. Guo et al, Phys. Rev. D 98 (2018) 014510



Bound-state pole formation corresponding to D_{s0}*(2317)

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$$C'(k^*) = A_C(k^*)\left\{ 2\left[\frac{1}{4}\left(\frac{|f_C(k^*)|}{r}\right)^2\left[1 - \frac{d_0}{2\sqrt{\pi}r} + \frac{1}{2}(A_C(k^*)-1)^2(1-e^{-4(rk^*)^2})\right] + \right.\right.$$
$$+\mathcal{R}(f_C(k^*))\frac{F_1(2k^*r)}{\sqrt{\pi}r} +$$
$$\left.\left. +\mathcal{I}(f_C(k^*))\left[\frac{F_2(2k^*r)}{2r} + (A_C(k^*)-1)k^*\cos(rk^*)e^{-(rk^*)^2}\right]\right] + 1\right\}$$

Where

$$f_C(k^*) = \left[\frac{1}{a_0} + \frac{1}{2}d_0 k^{*2} - \frac{2}{a_C}h(k^* a_C) - ik^* A_C(k^*)\right]^{-1}$$

M. Gmitro, J. Kvasil, R. Lednicky, and V.L. Lyuboshits, Czech. J. Phys. B (1986) 36:1281

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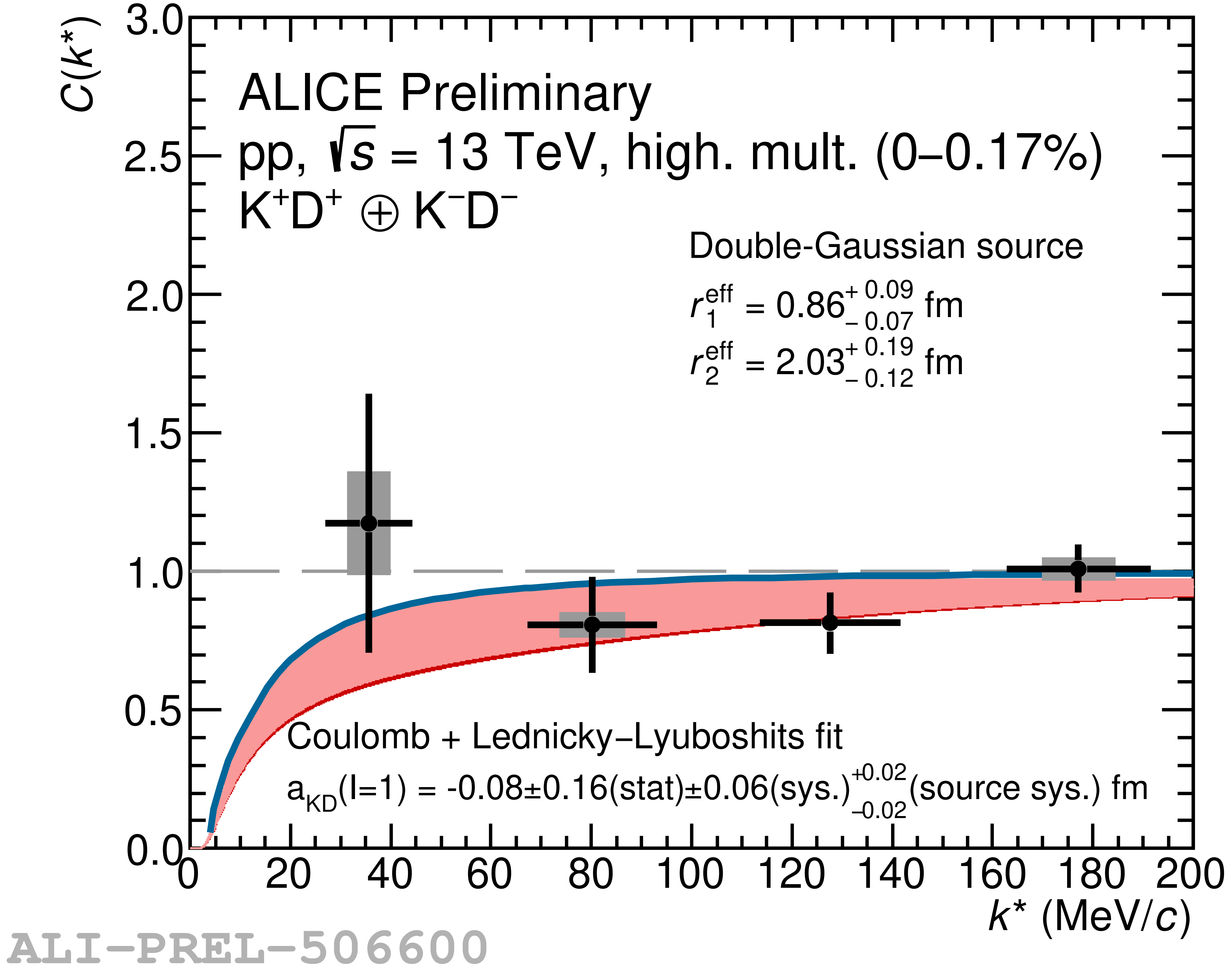
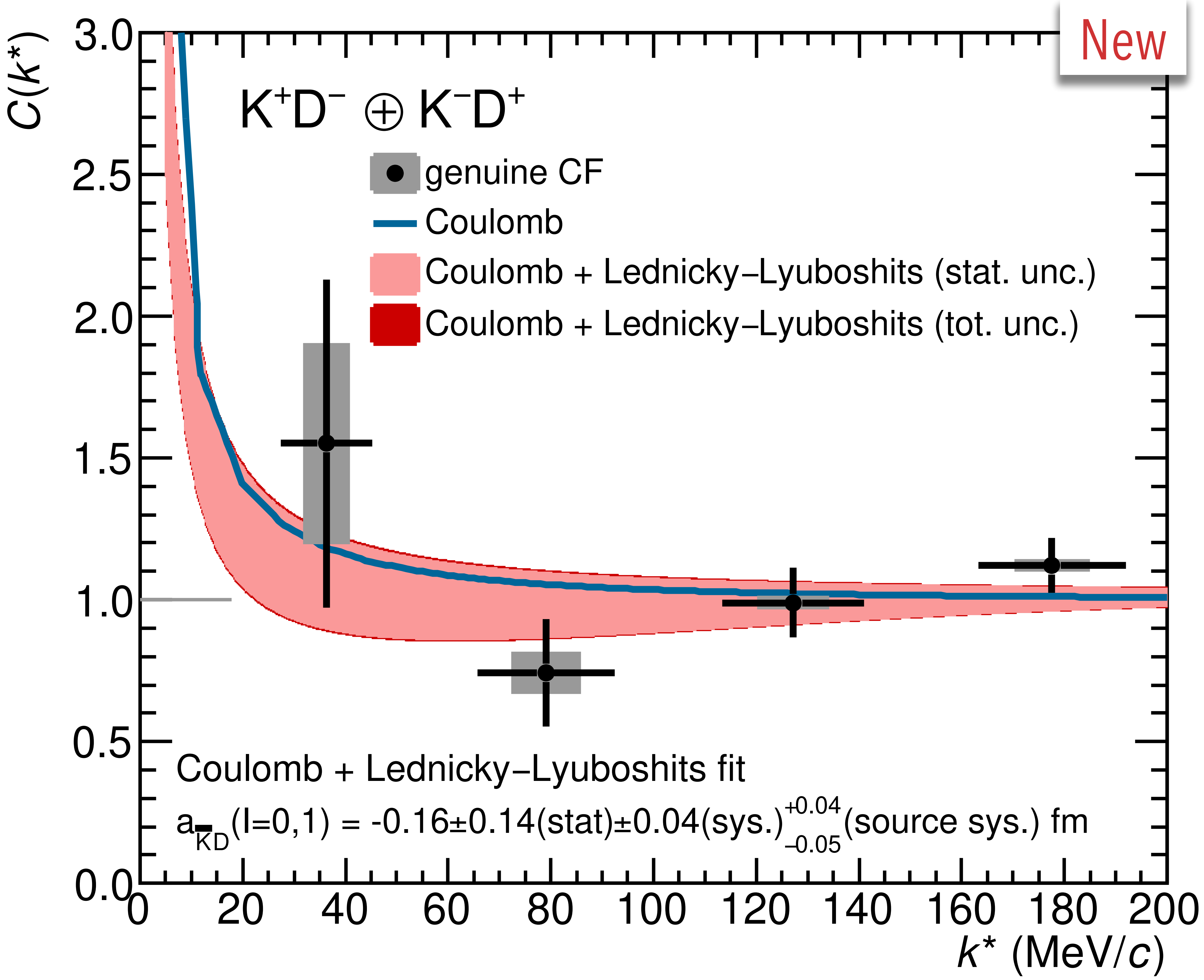
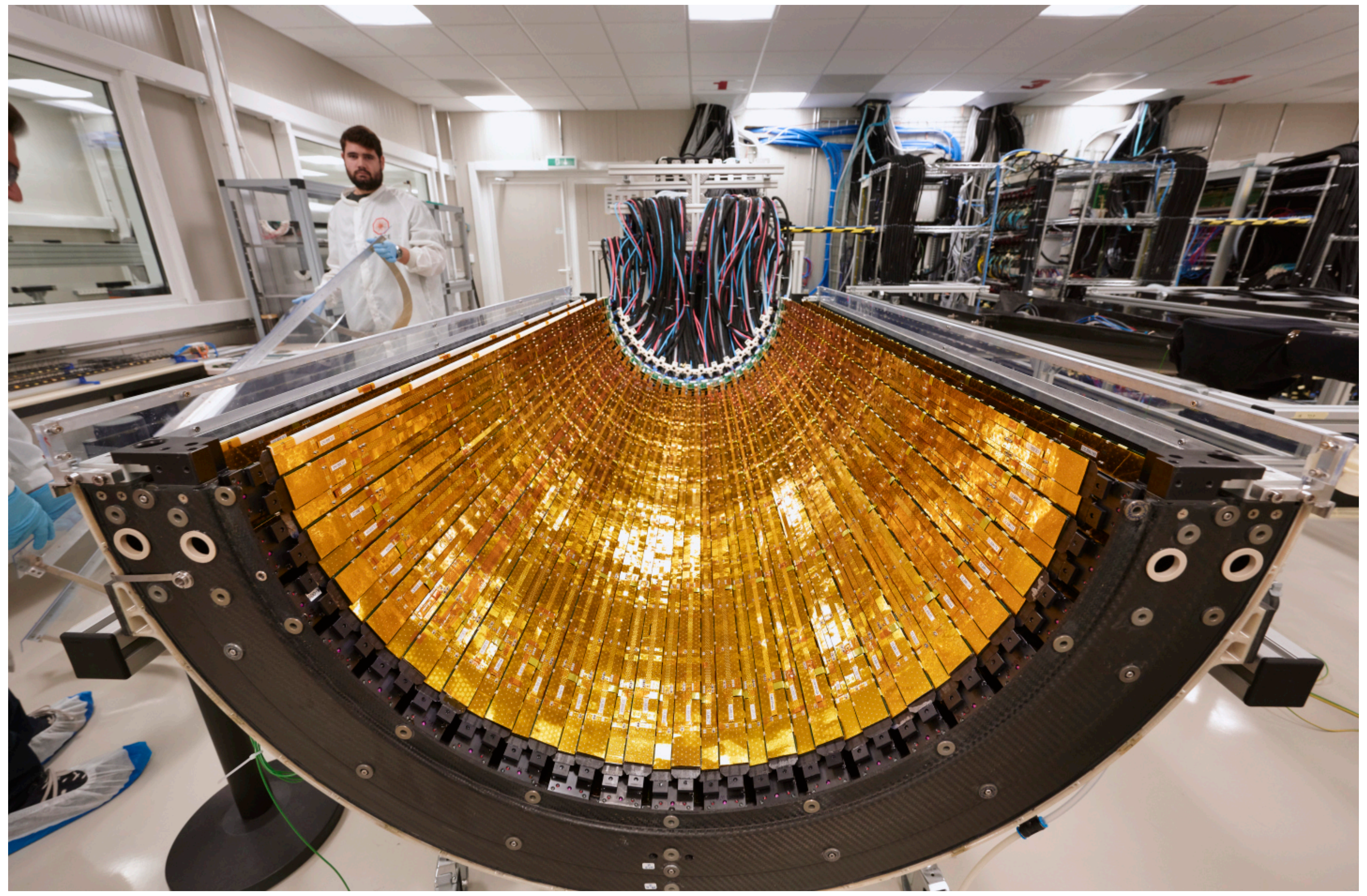
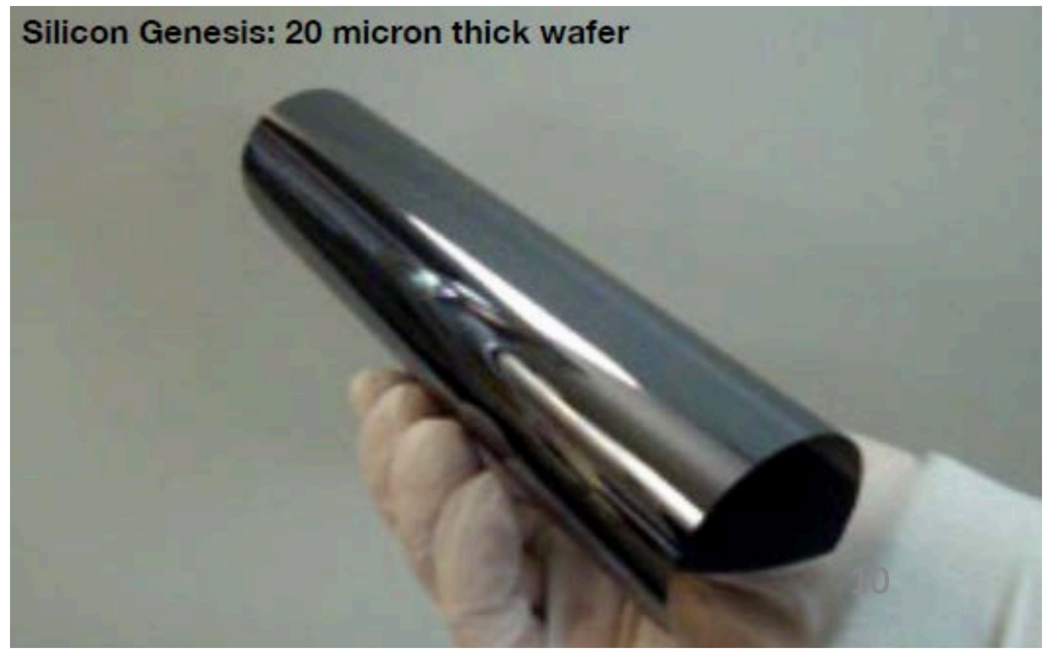




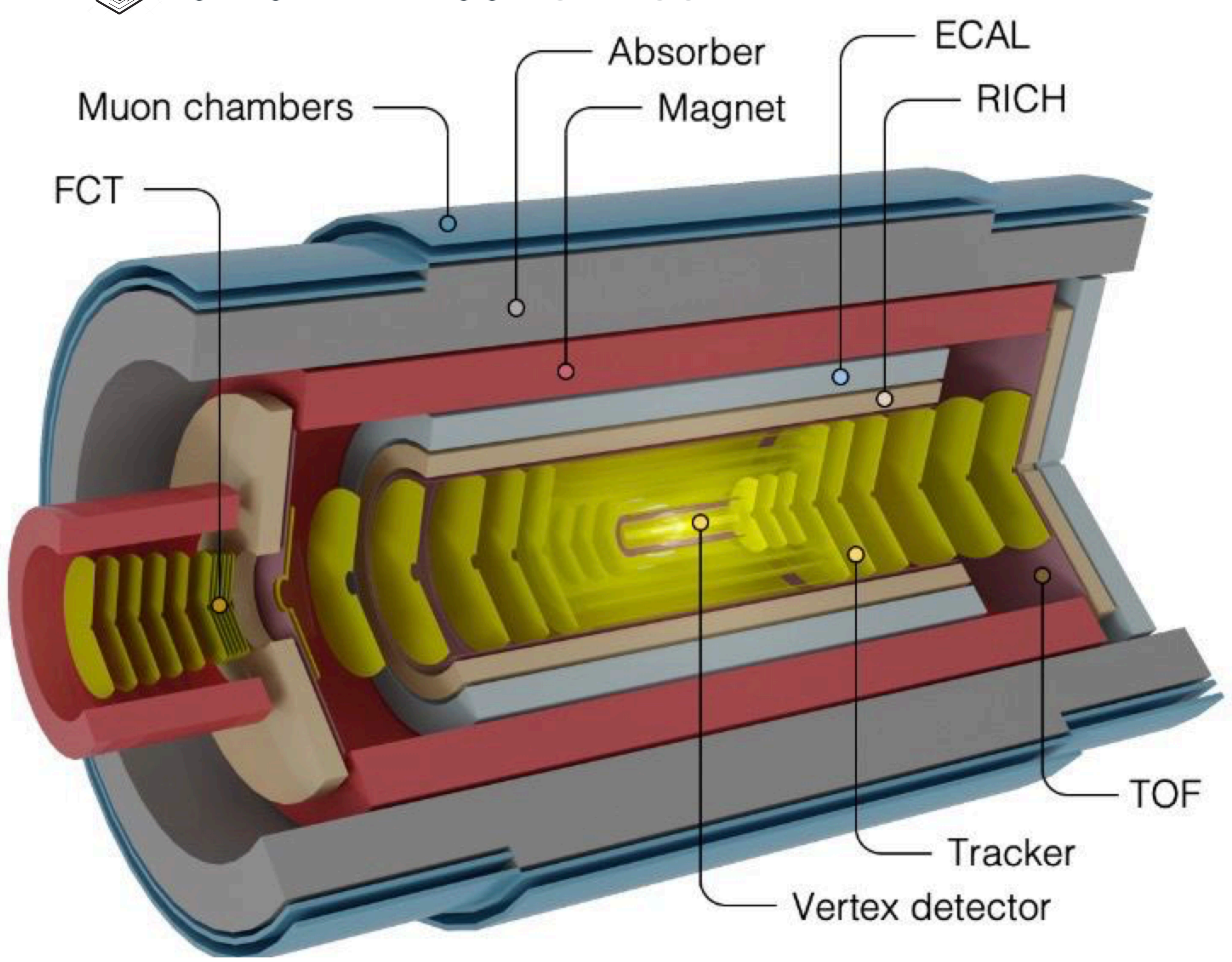
- K^+D^+
  - ➡ I=1 channel only
- K^+D^-
  - ➡ I=0 (50%)
  - ➡ I=1 (50%)



- Wide ALICE upgrade program for LHC Run 3 and 4 crucial for HF
  - ➡ increase collected Pb-Pb luminosity by more than one order of magnitude
  - ➡ new silicon Inner Tracking System
    - Run 3: ITS2 TDR: CERN-LHCC-2013-024
    - Run 4: ITS3 LOI: CERN-LHCC-2019-018
  - ➡ Run5: all silicon ultra-light detector



LOI: CERN-LHCC-2022-009



- New / more precise HF measurements down to low p_T
  - ➡ Precise measurements of charm mesons and baryons
  - ➡ Access to measurements of beauty-strange meson and beauty-baryon production and azimuthal anisotropy
  - ➡ Run 5: multi-charm baryon production in heavy-ion collisions and charm-charm momentum correlations

System-size dependence of CF in case of bound-state formation

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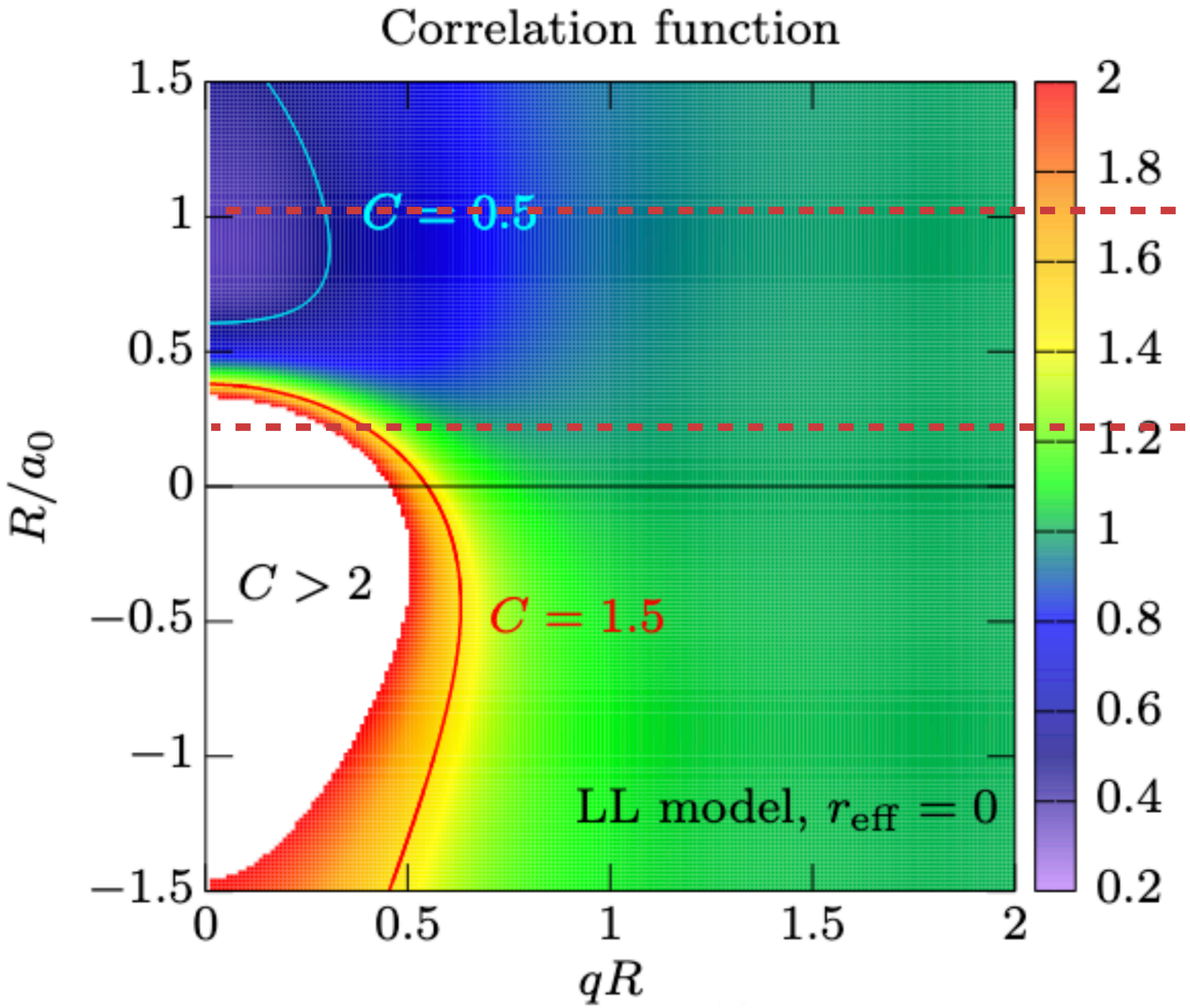

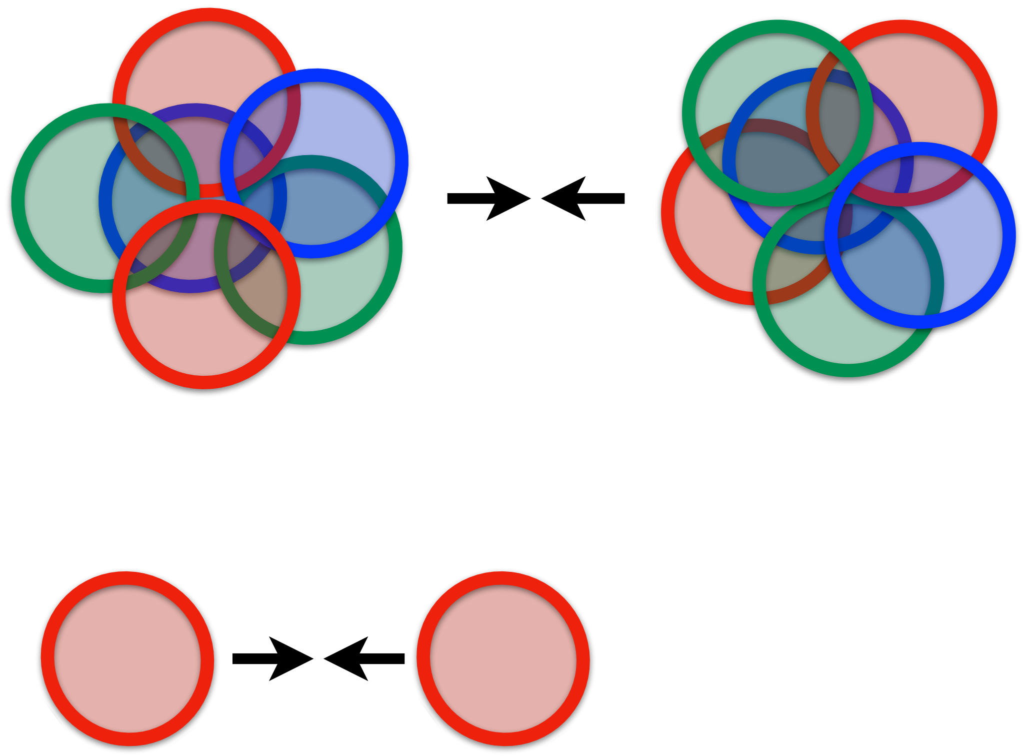

Yuki Kamyia et al, arXiv:2108.0964

- Interplay between system size and scattering length
  - ➡ size-dependent modification of the correlation function in presence of a bound state

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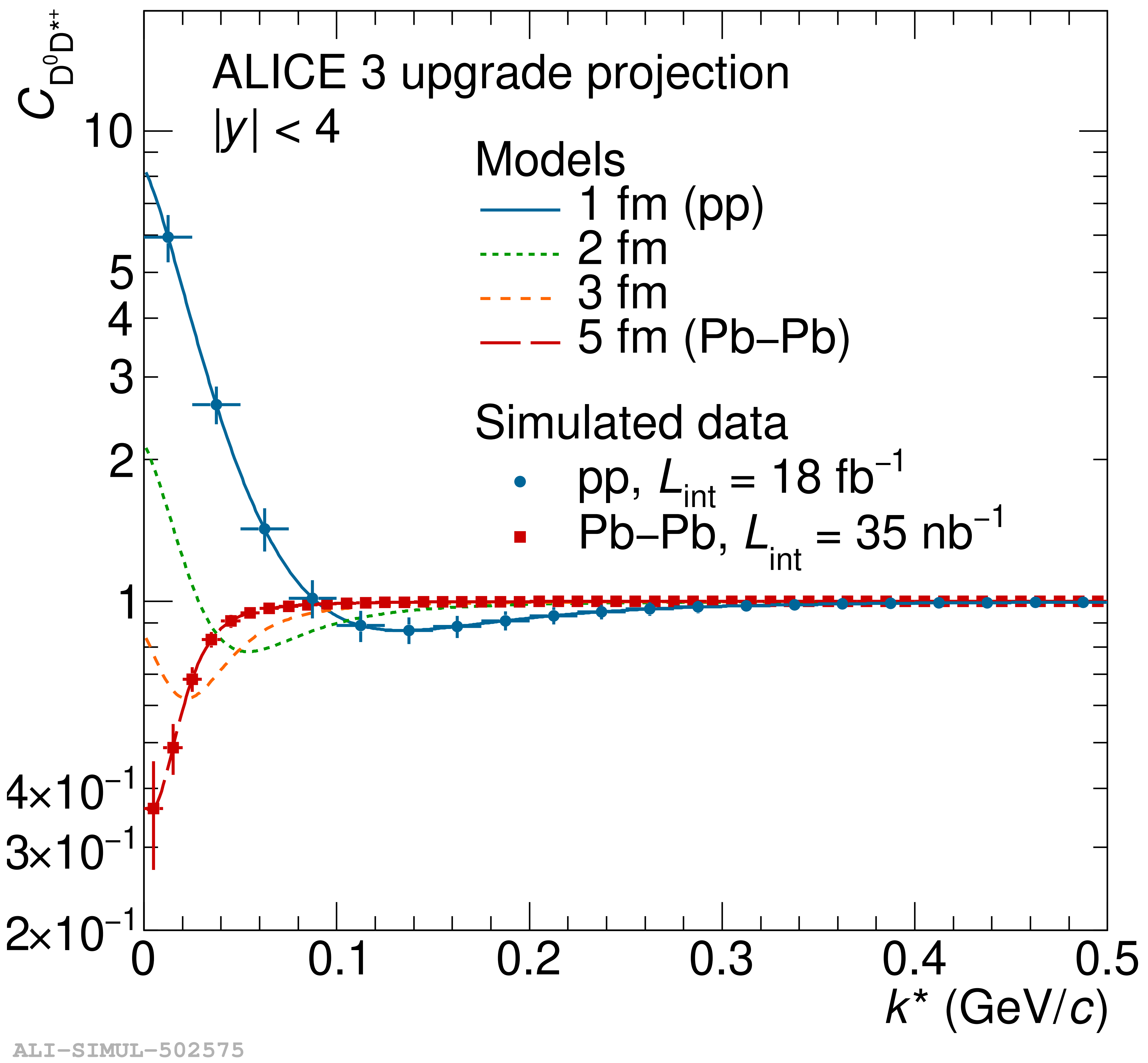

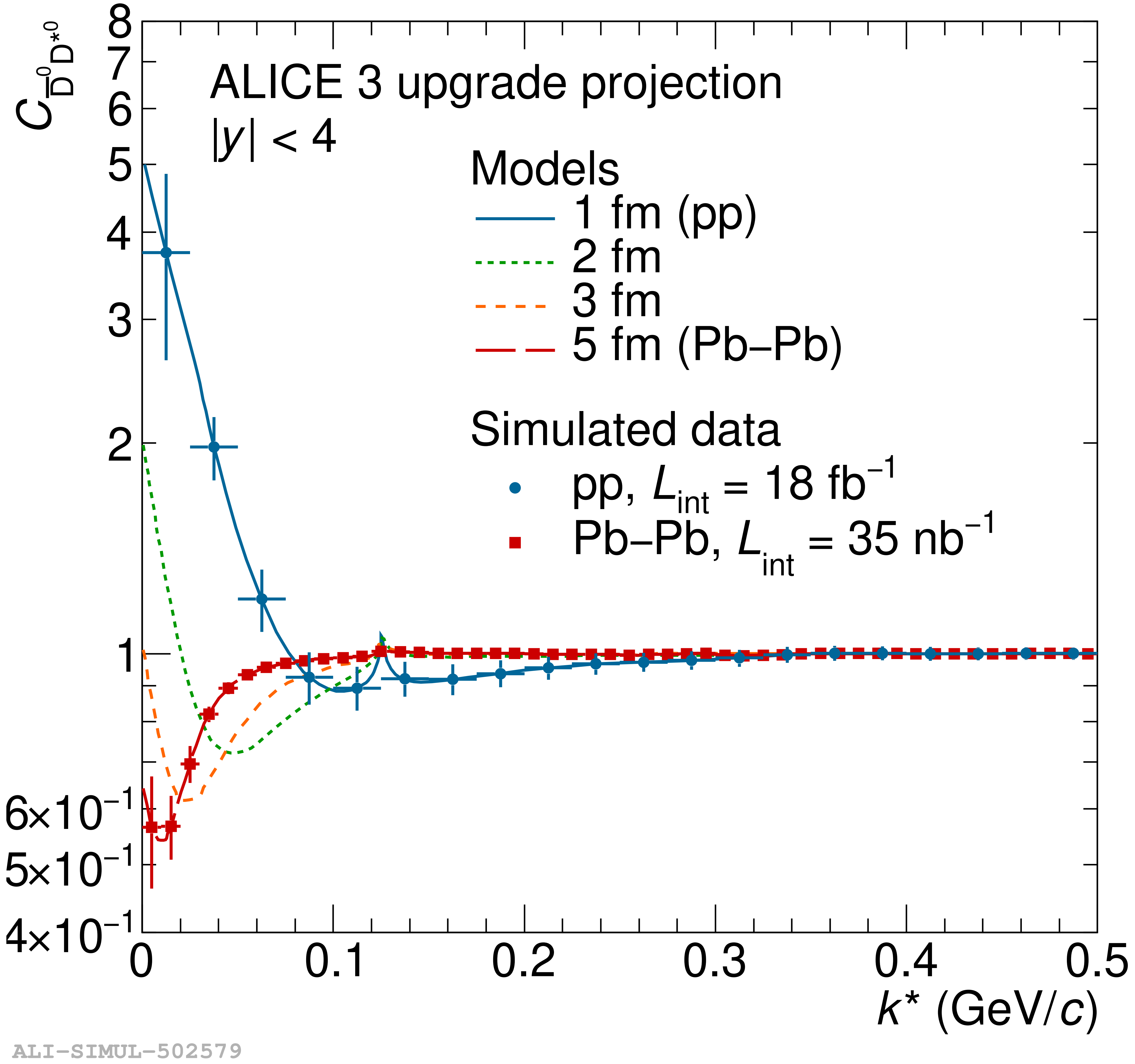

- Expected precision enough to observe different behaviour of the CF in pp and Pb–Pb collisions in case T_{cc}^+ and X(3872) are bound states of D mesons