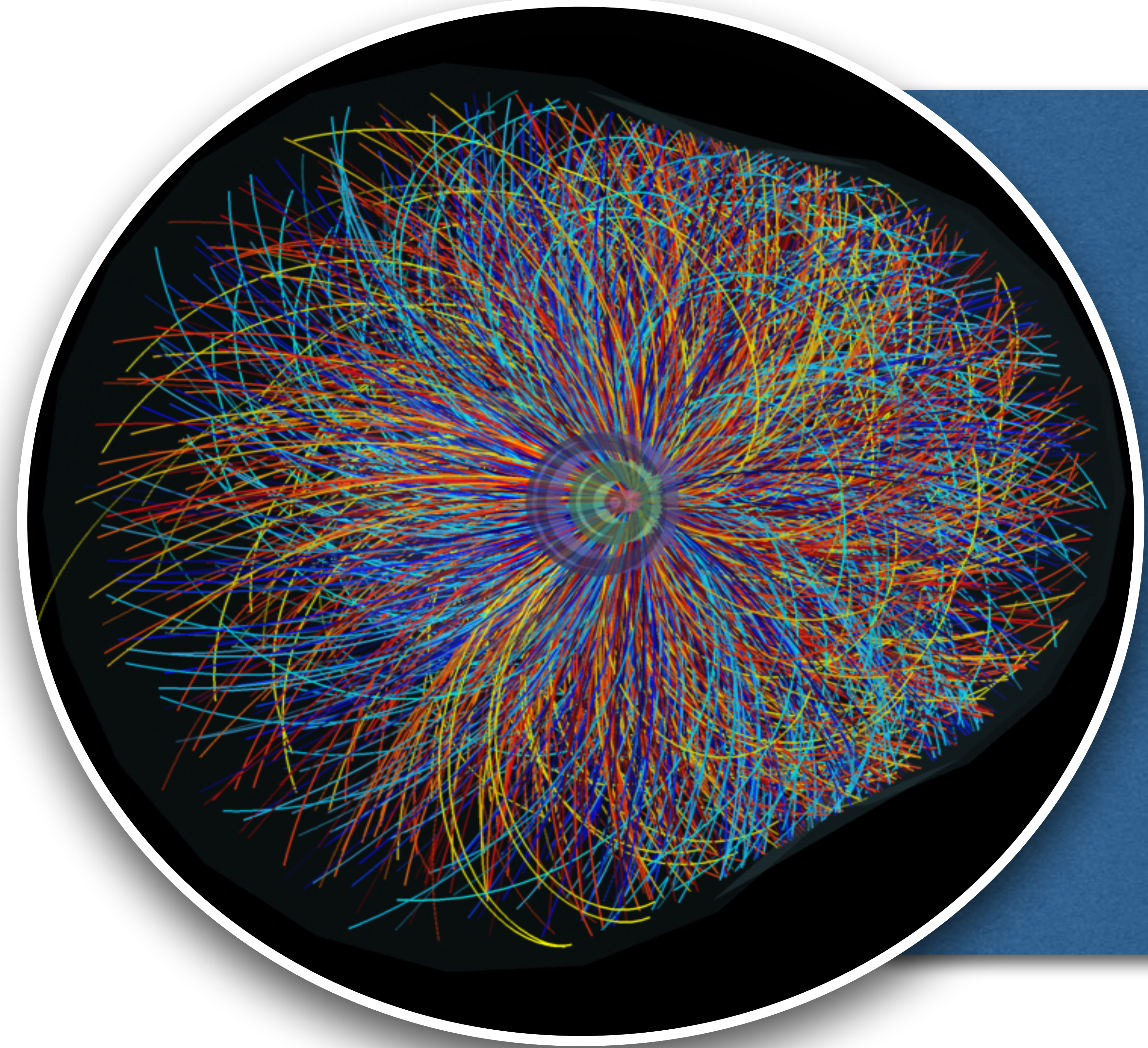


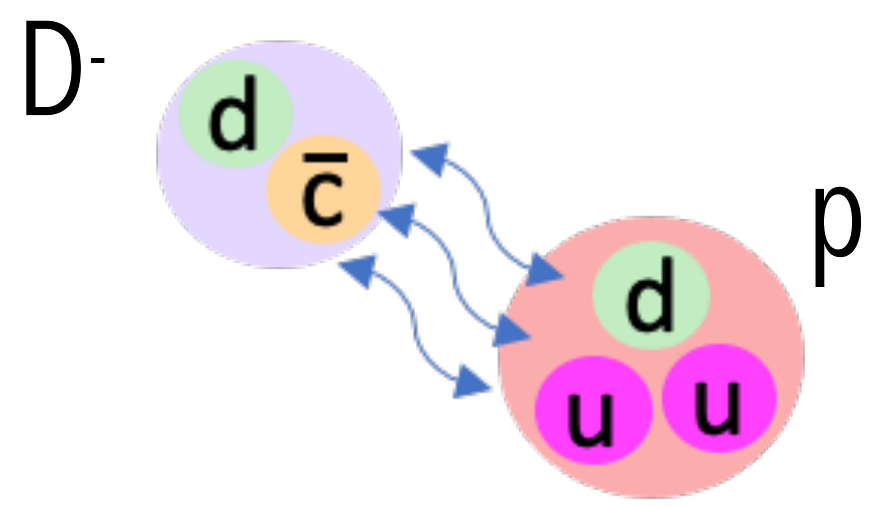
D meson scattering parameters with light-flavor hadrons

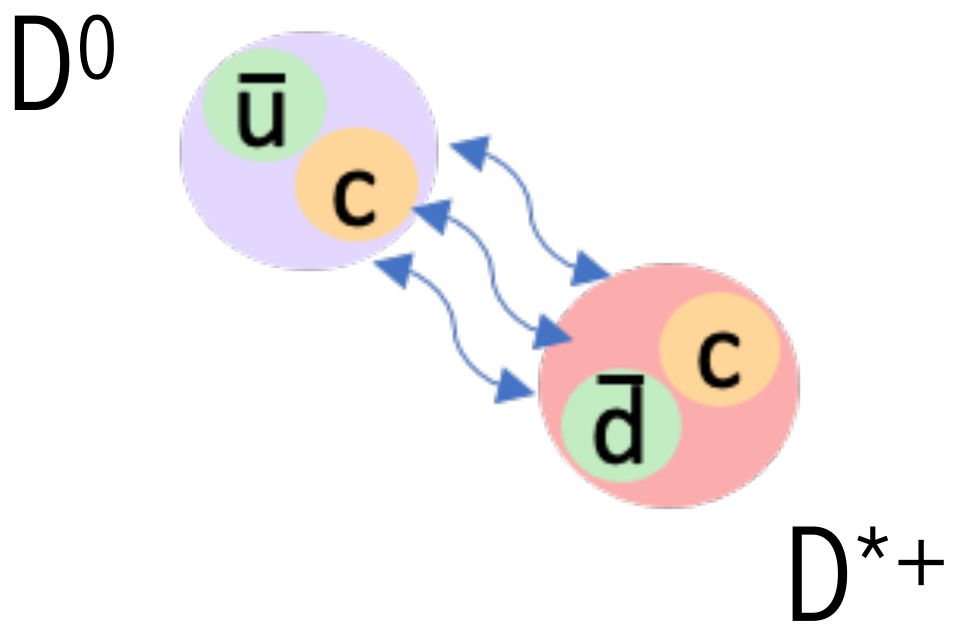
Laura Fabbietti, Fabrizio Grosa, Emma Chizzali and Daniel Battistini

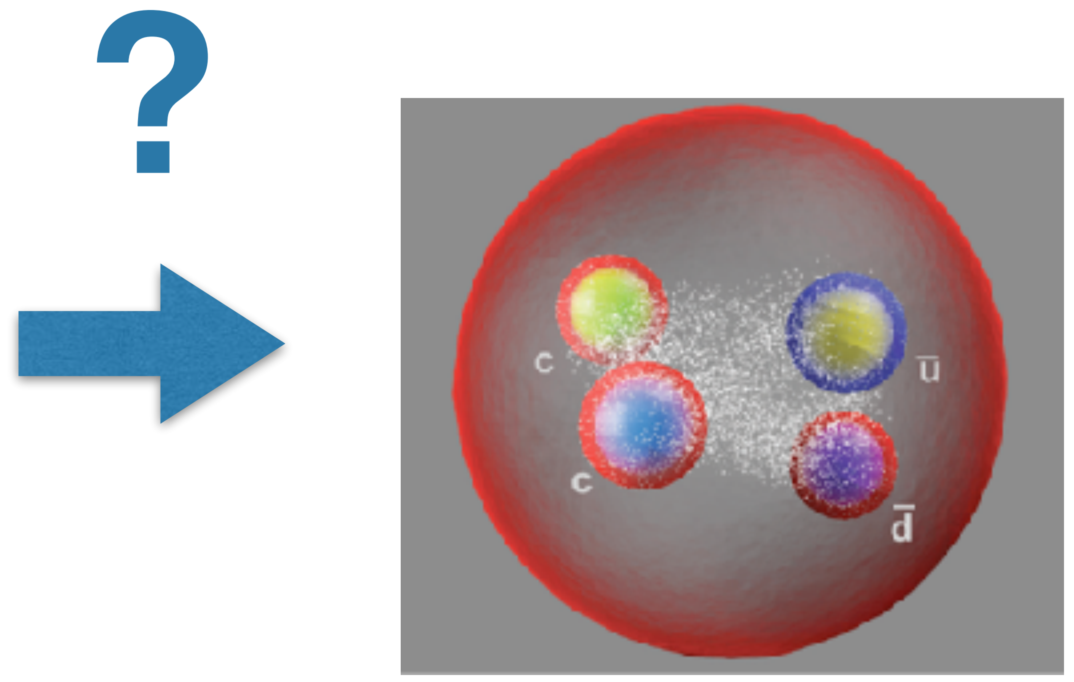
HFwiNC 2020

Residual strong interaction among charmed hadrons

- The residual strong interaction among hadrons is rather well known for NN, less known for YN and barely known for Charmed hadrons-light hadrons combination

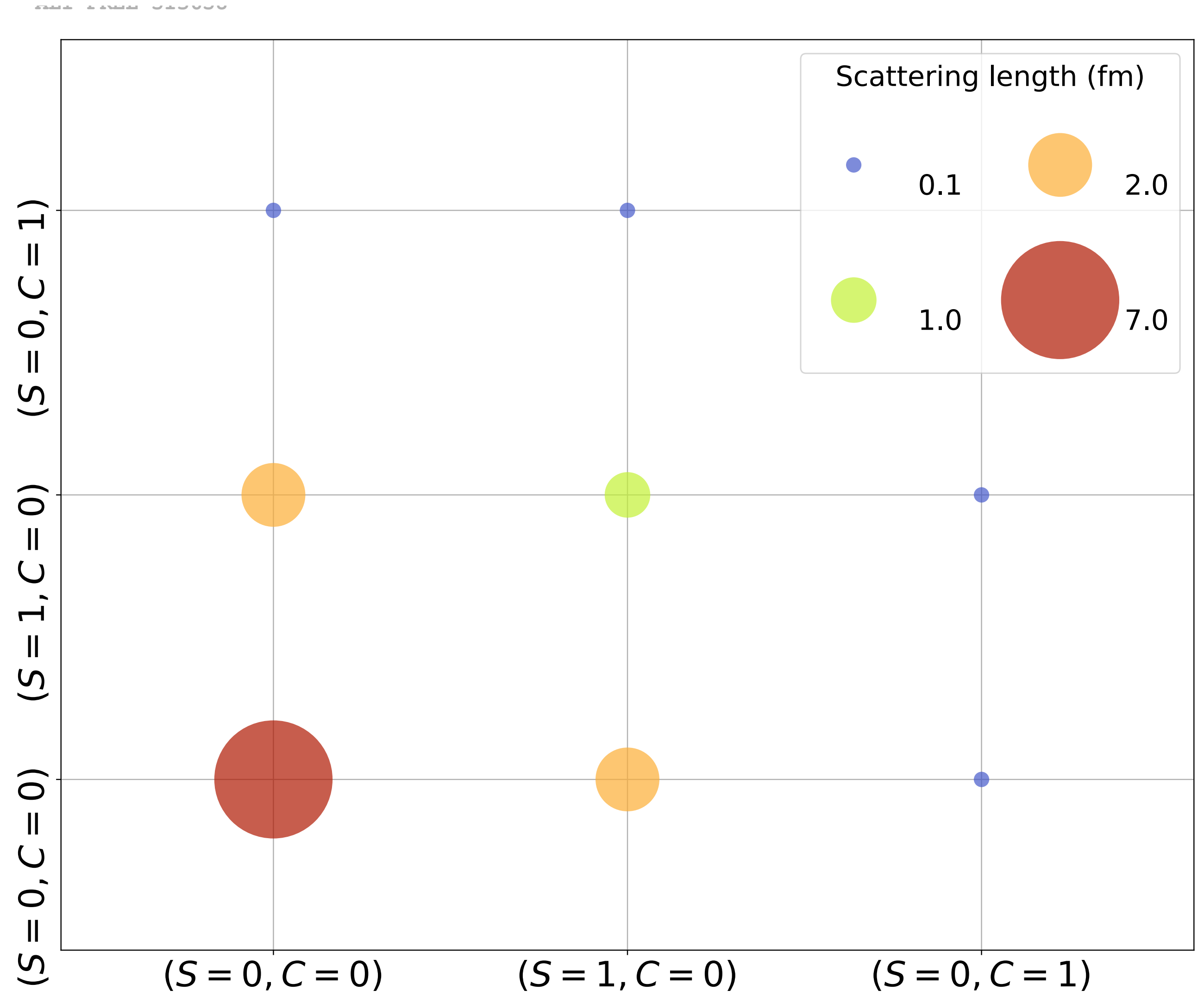






- Determine the hierarchy of the hadron-hadron coupling for all quark flavours

M. He et al, PLB 701 (2011) 445–450

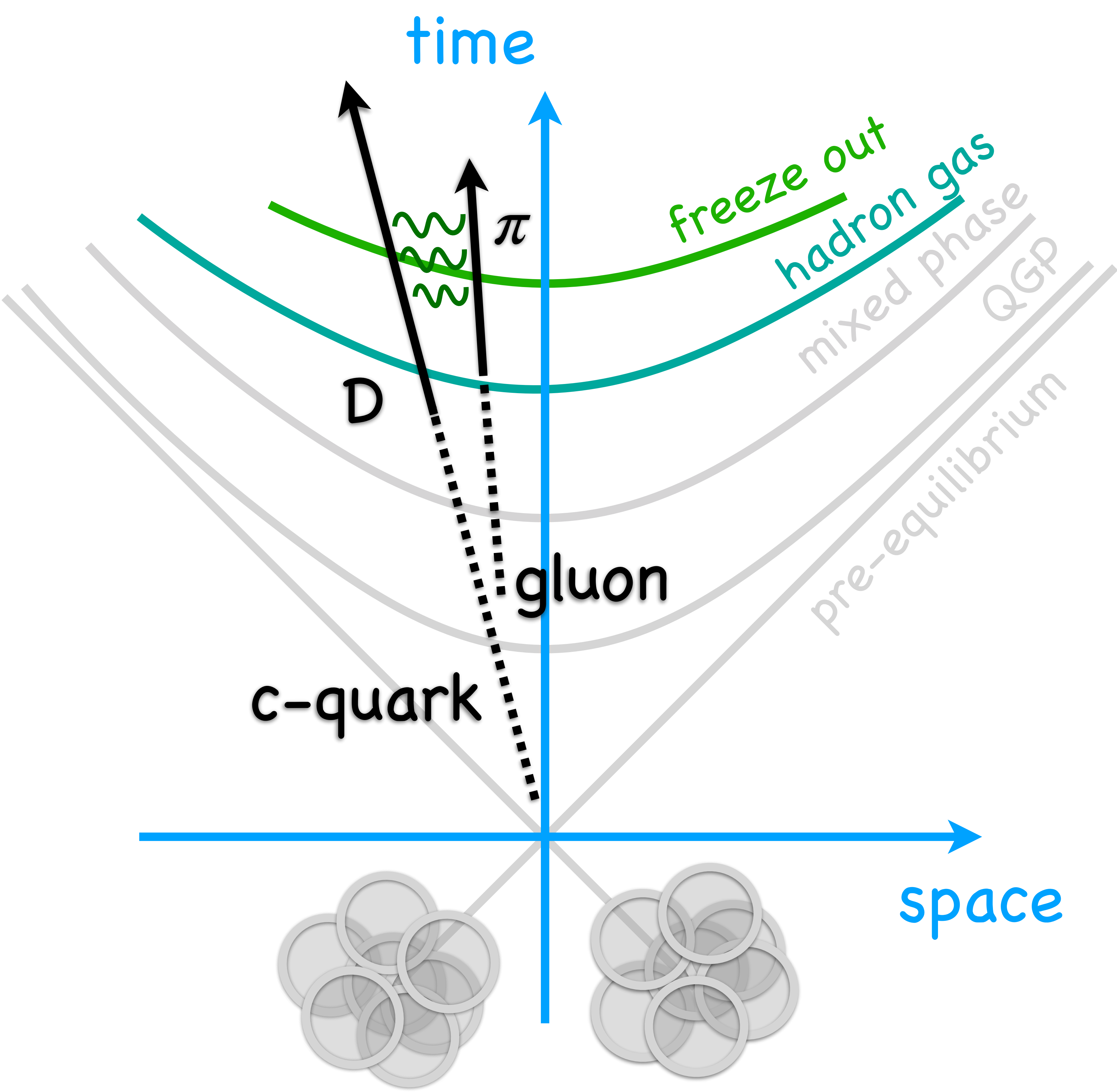


- Determine the scattering parameters among charmed hadrons as a tool to study molecular states with charm content

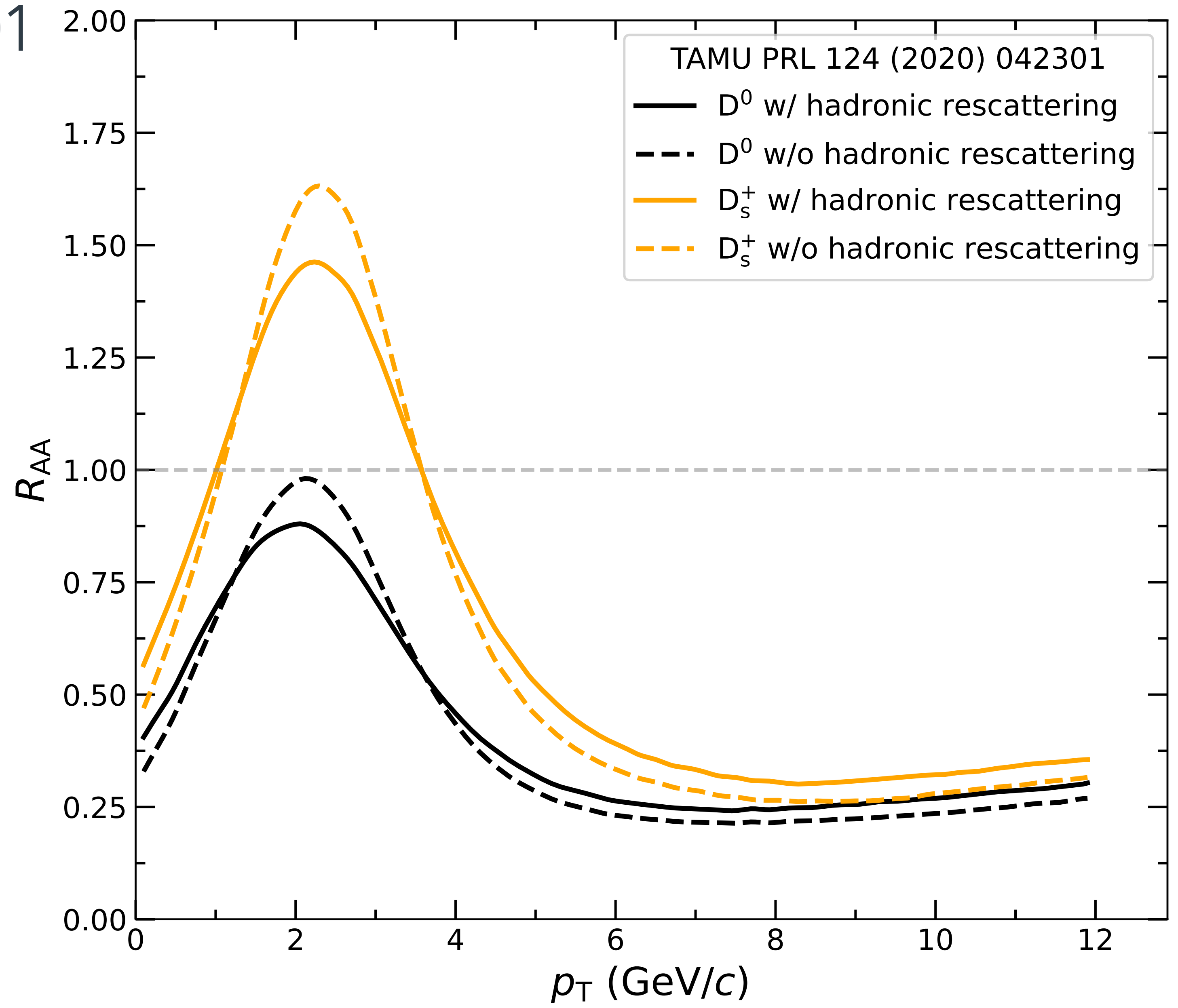
Heavy-flavour hadrons in the hadronic phase

- After the hadronisation, heavy-flavour hadrons might still interact with the light hadrons produced
  - ➡ How much does the hadronic phase influence the heavy–ion observables?

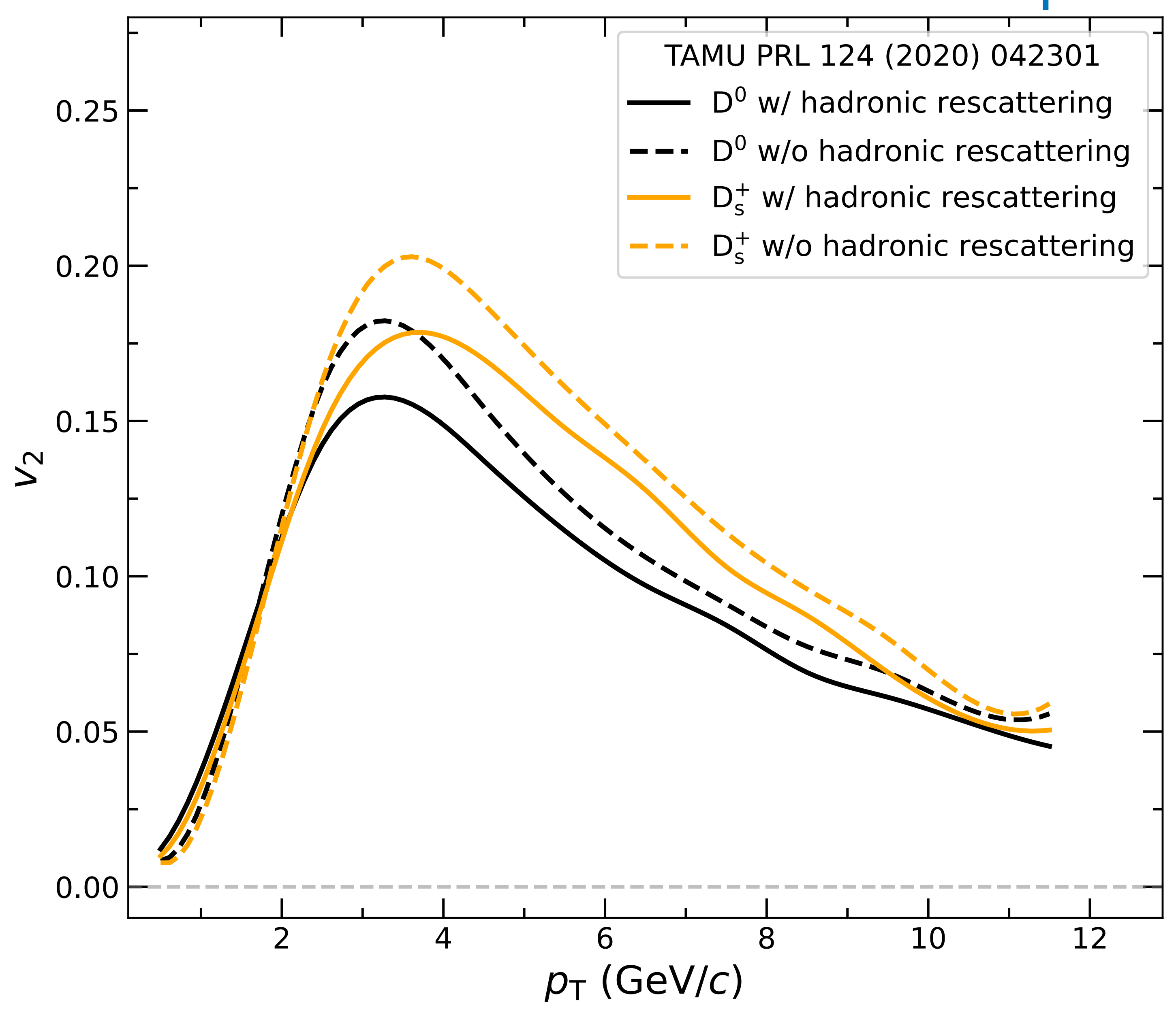
M. He, R. Rapp, PRL 124 (2020) 042301



Nuclear modification factor R_{AA}



Azimuthal anisotropies



- In the TAMU model the scattering lengths used for πD and KD are:
  - ➡ $a_{\pi D}(I=3/2) = -0.10$ fm
  - ➡ $a_{KD}(I=1) = -0.22$ fm

M. He et al, PLB 701 (2011) 445–450

The study of the residual strong interactions

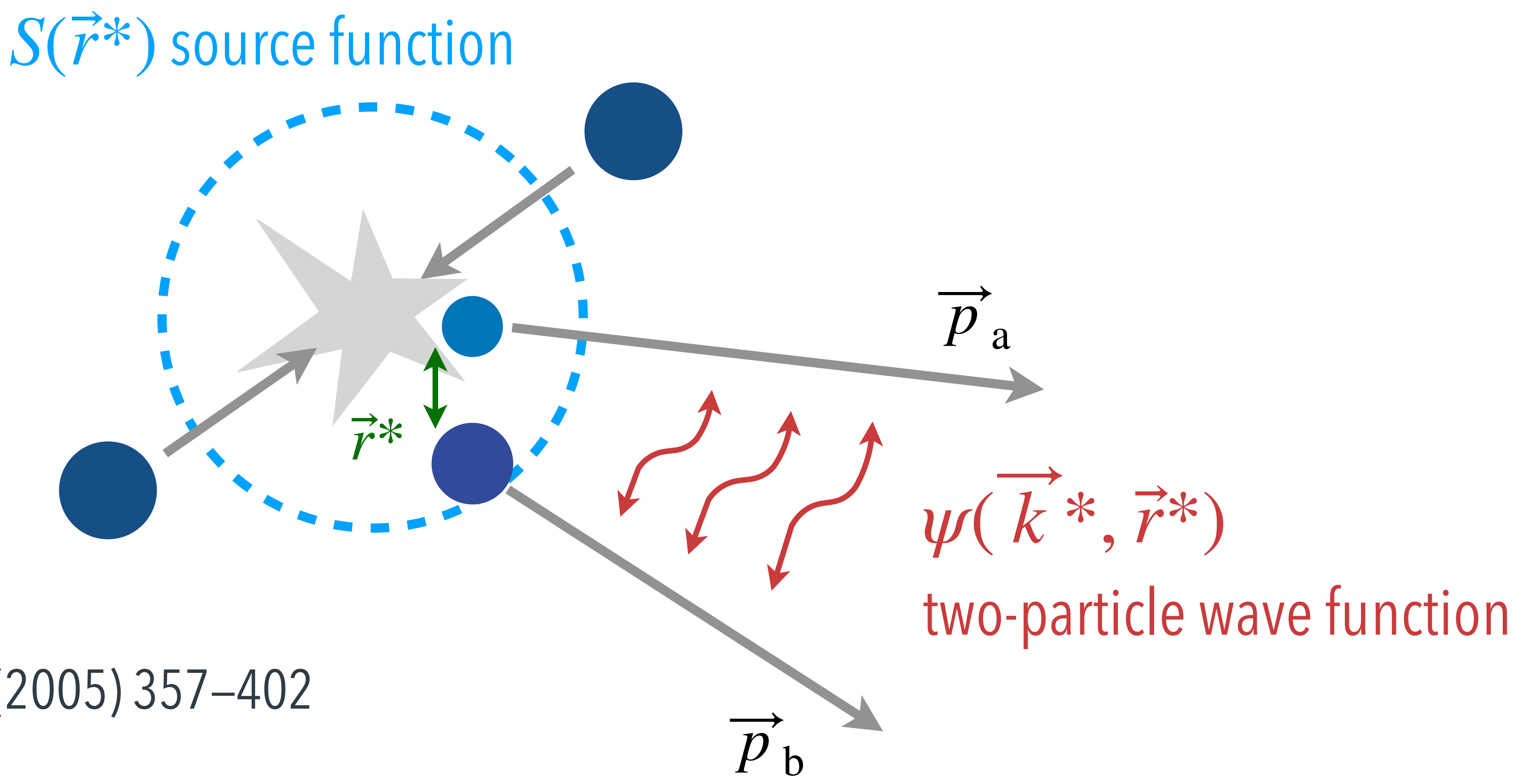
- Femtoscopy technique: based on the correlation function (CF)

Experiment | Theory

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

Koonin-Pratt equation

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

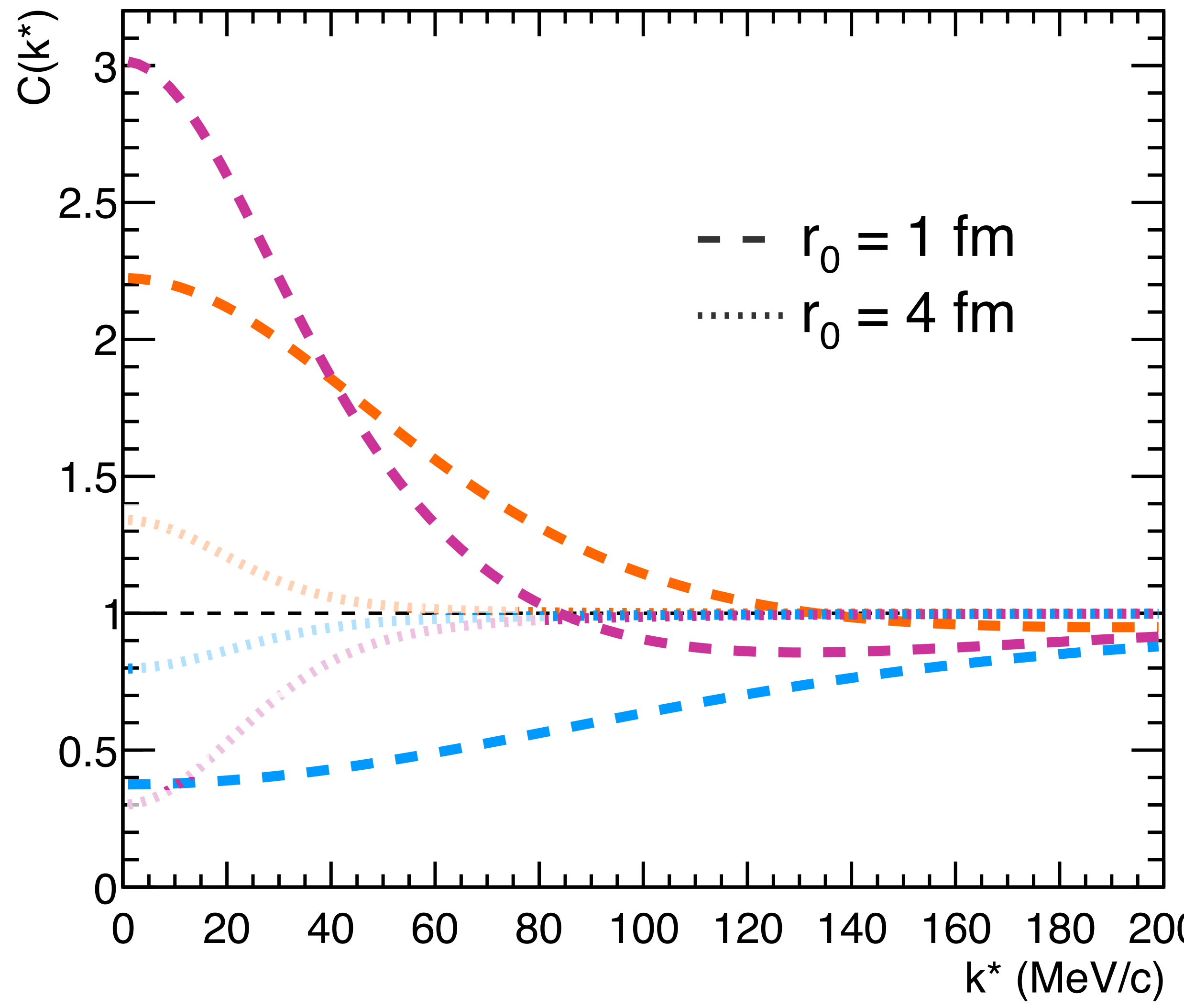


where $\vec{k}^* = \dfrac{\vec{p}^*_{\mathrm{a}} - \vec{p}^*_{\mathrm{b}}}{2}$ is in the rest frame of the particle pair

➡ Relative wave function sensitive to interaction potential

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

➡ $C(k^*)$ most sensitive to strong interaction when the source size ~1 fm



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

Attractive potential $C(k^*) > 1$

Repulsive potential $C(k^*) < 1$

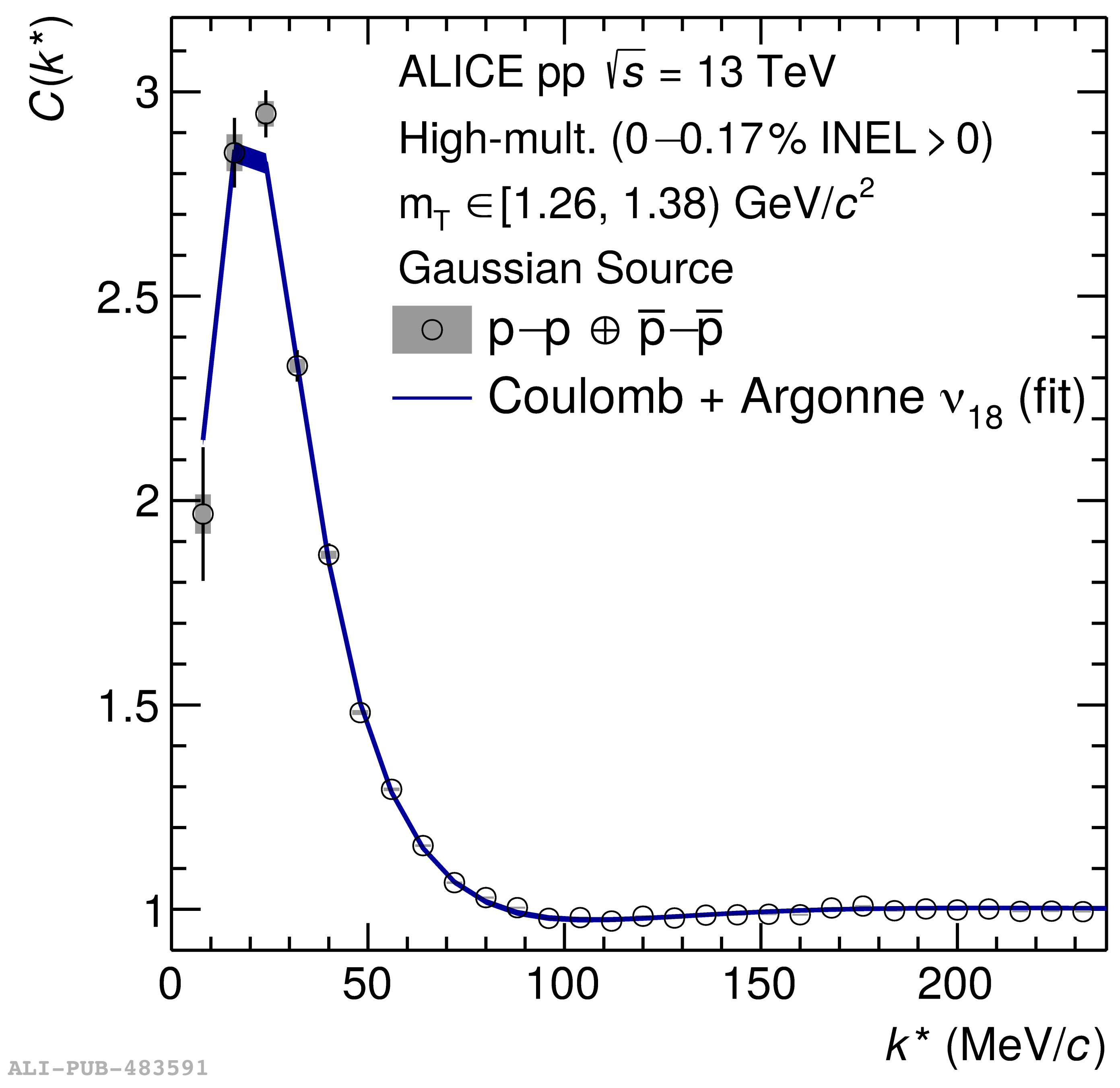
Bound-state formation $C(k^*) <> 1$

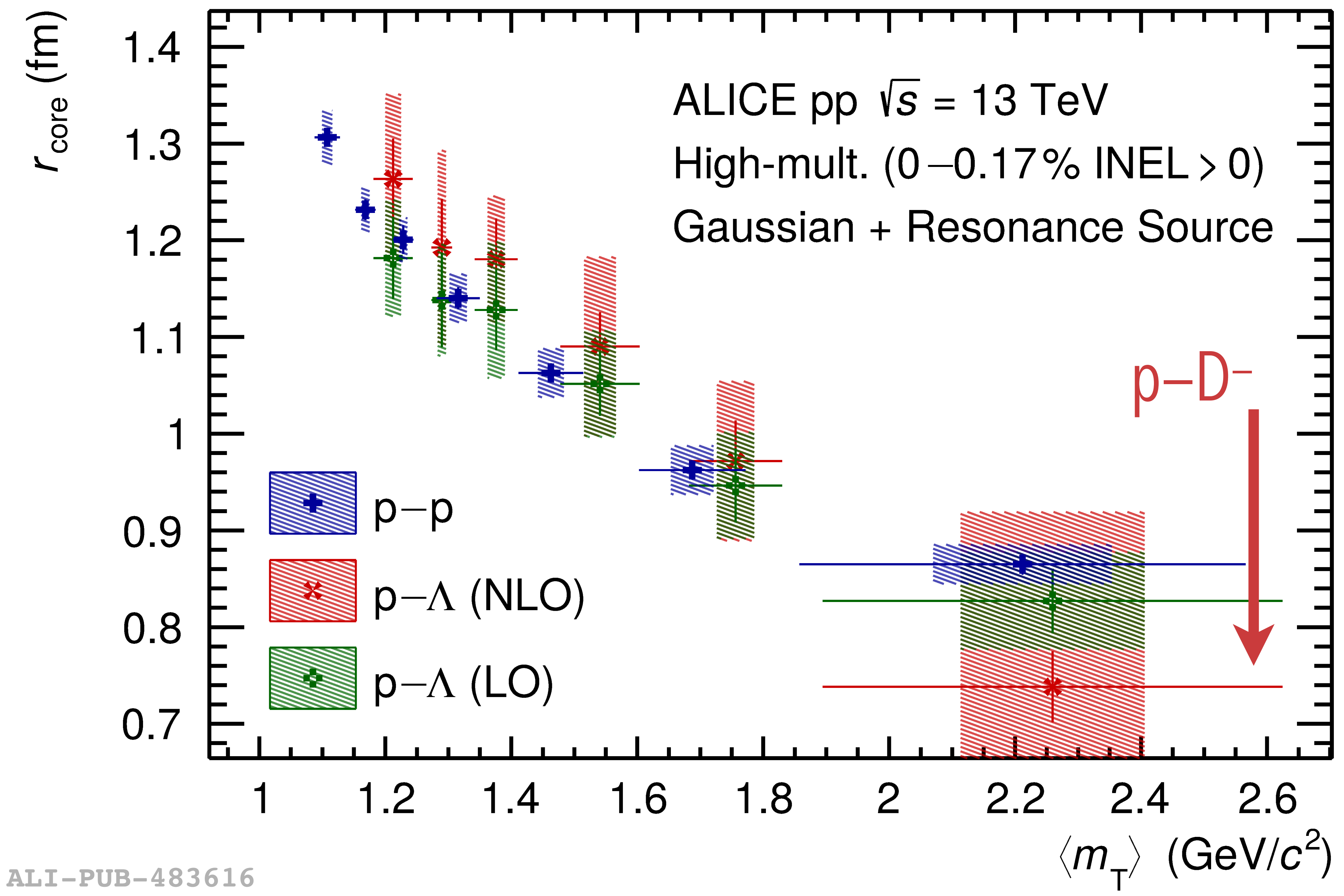
L. Fabbietti, V. Mantovani Sarti, O. Vázquez Doce, Annu. Rev. Nucl. Part. Sci. (2021) 71:377–402

Calibrating the emitting source

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

ALICE, PLB 811 (2020) 135849





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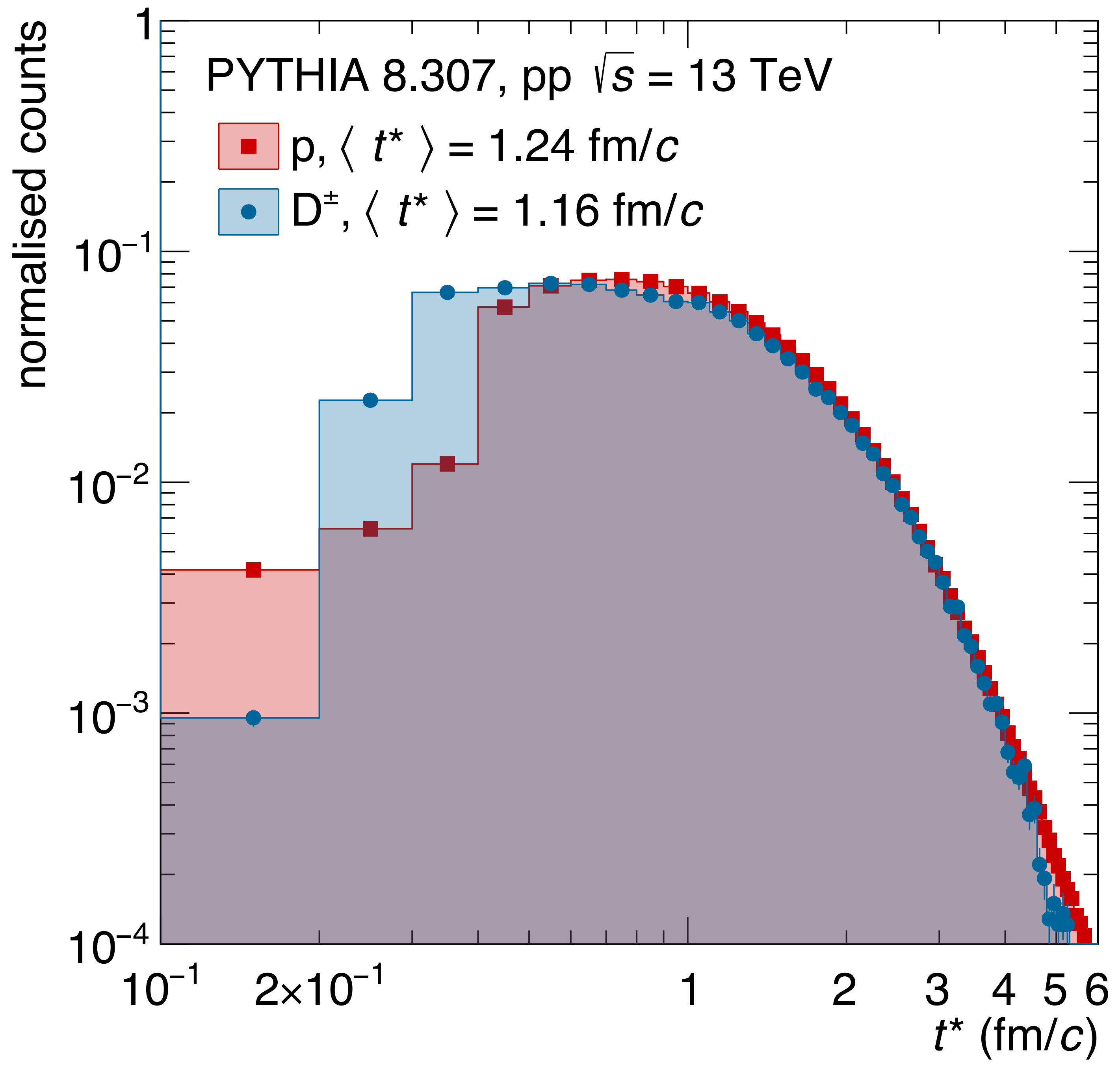
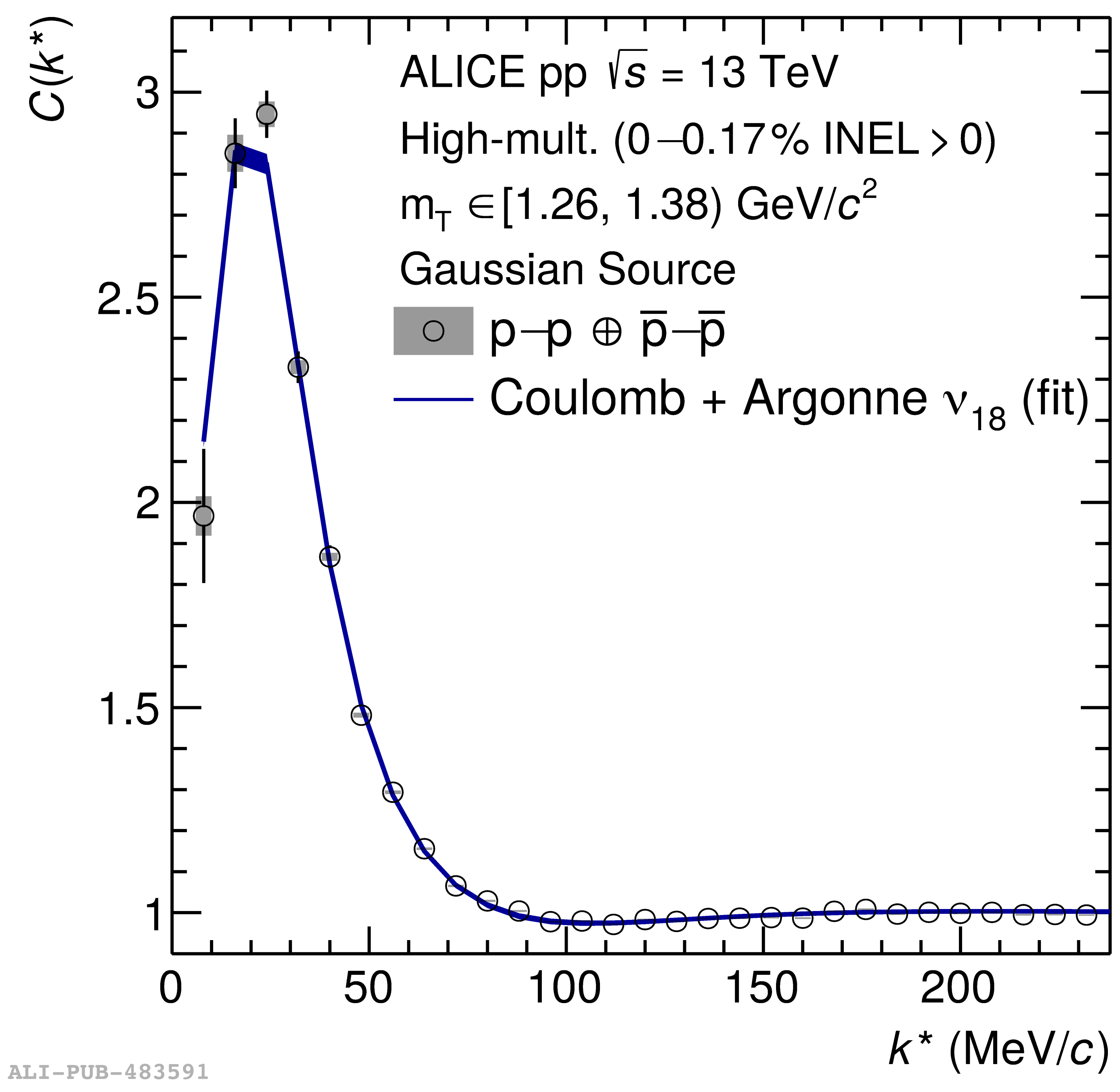
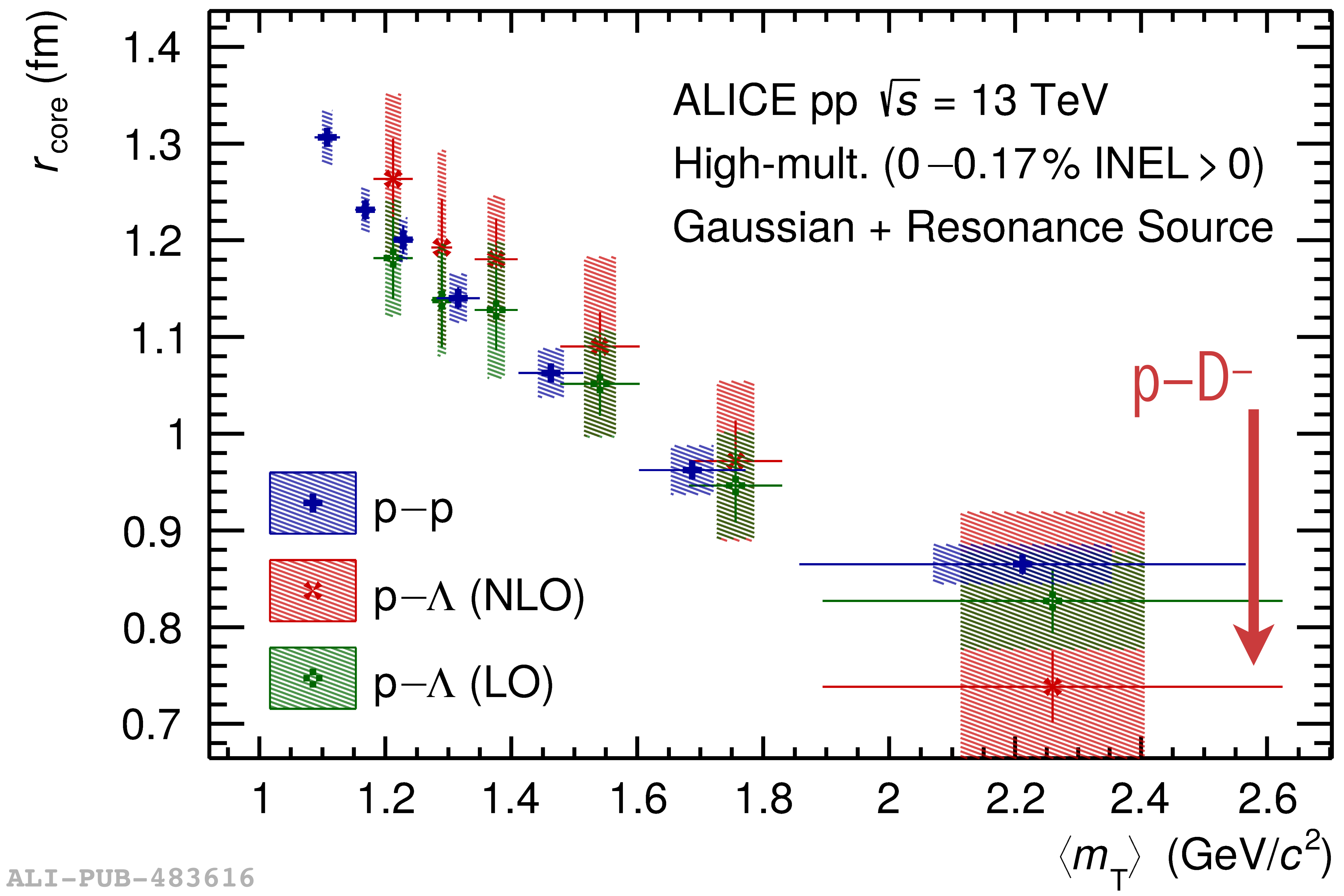


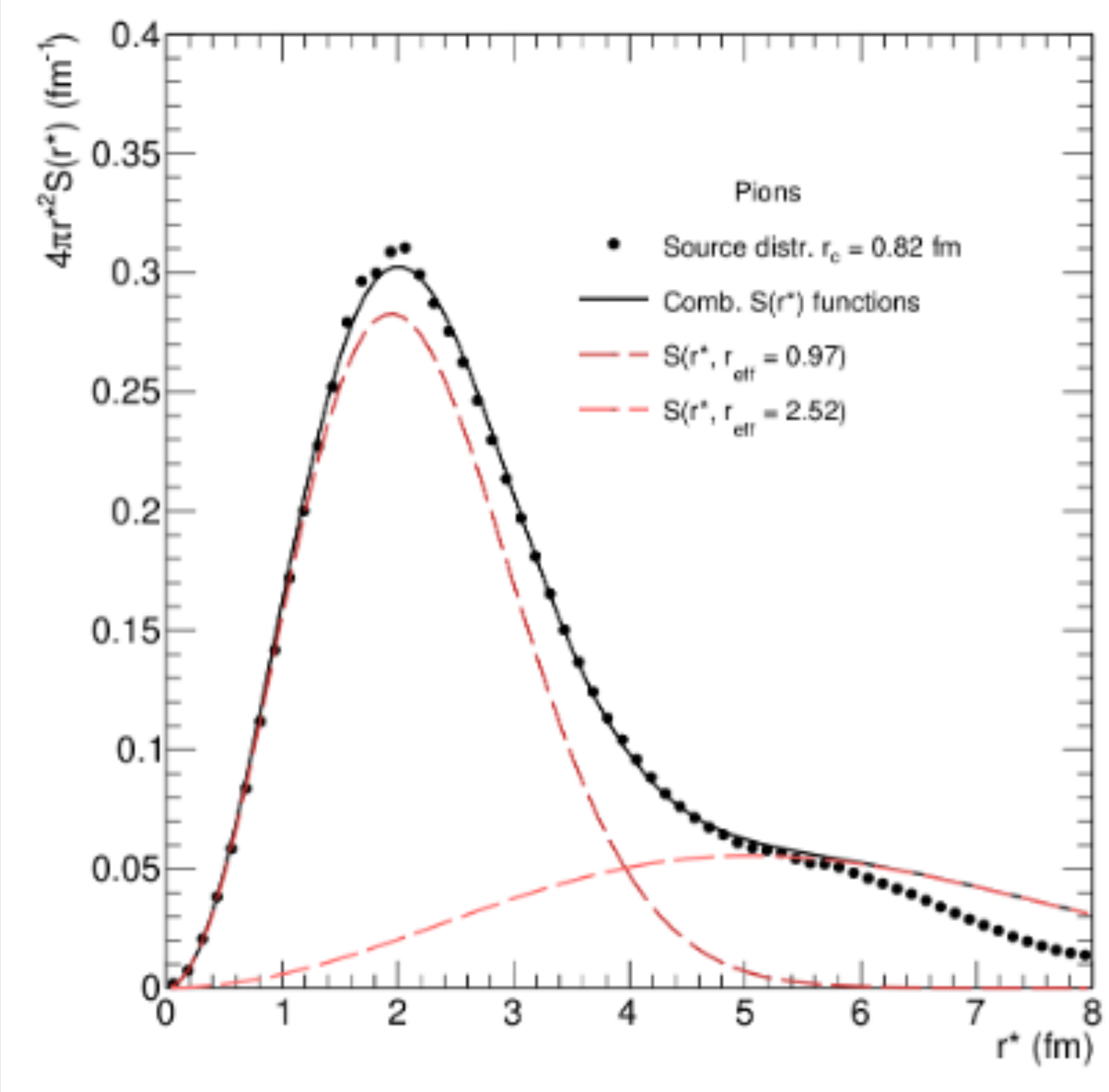


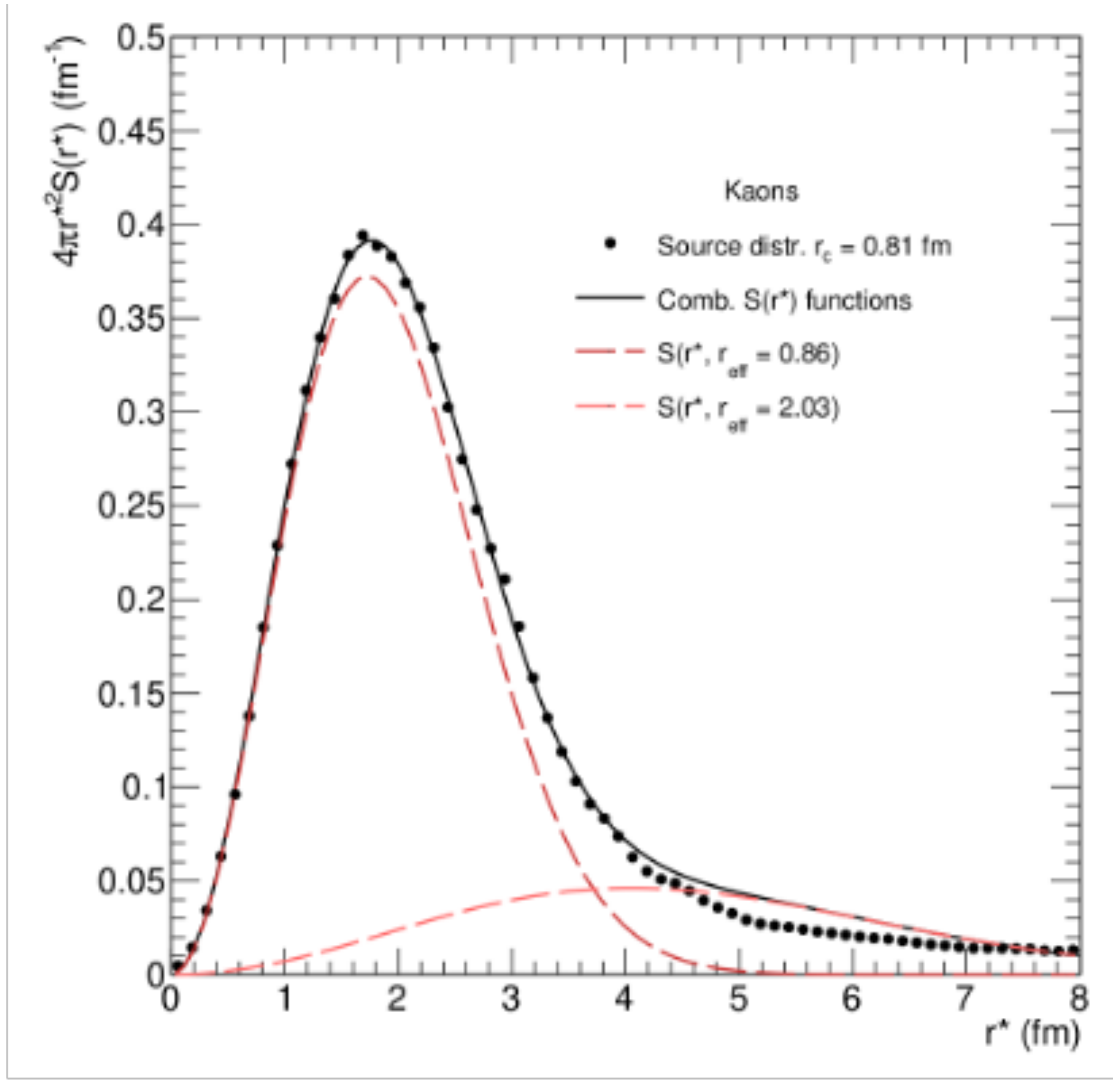
ALICE, PLB 811 (2020) 135849



- Is the source the same also for charm hadrons?
  - ➡ Charm-hadrons produced slightly earlier in MC generators (PYTHIA 8)
  - ➡ Charm-light interaction starts only when other light particle produced, hence similar emitting source expected
  - ➡ **Data-driven studies of emitting source crucial**

D-π and D-K source

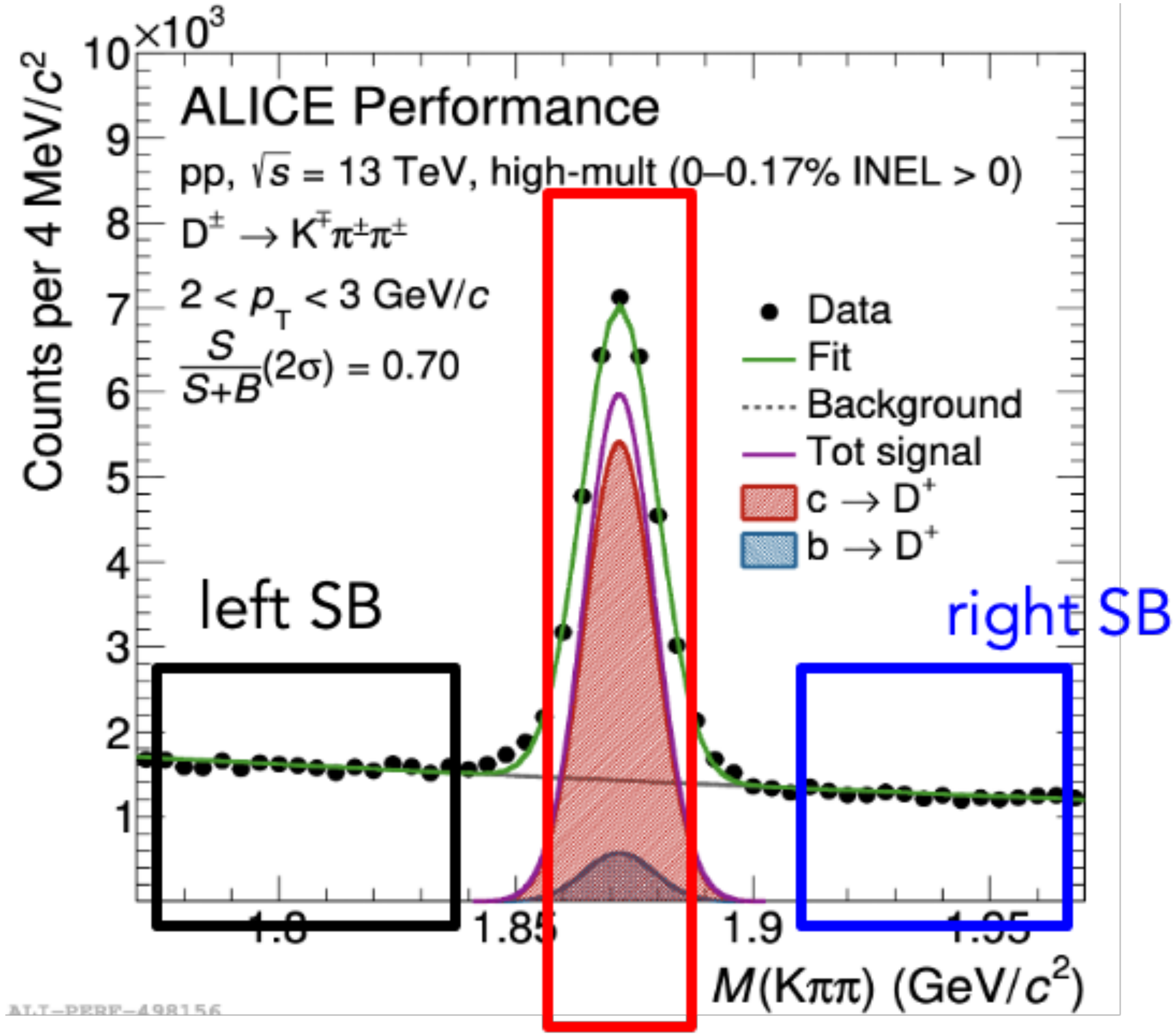




- Gaussian core, effectively enlarged by short-live strongly decaying resonances
  - ➡ Resonances yield from statistical hadronisation model
  - ➡ Resonances propagated with EPOS

Pair	w_1	r^1_{eff} [fm]	r^2_{eff} [fm]
KD	$0.78^{+0.02}_{-0.01}$	$0.86^{+0.09}_{-0.07}$	$2.03^{+0.19}_{-0.12}$
πD	$0.66^{+0.03}_{-0.02}$	$0.97^{+0.09}_{-0.08}$	$2.52^{+0.36}_{-0.20}$

D mesons in Run 2



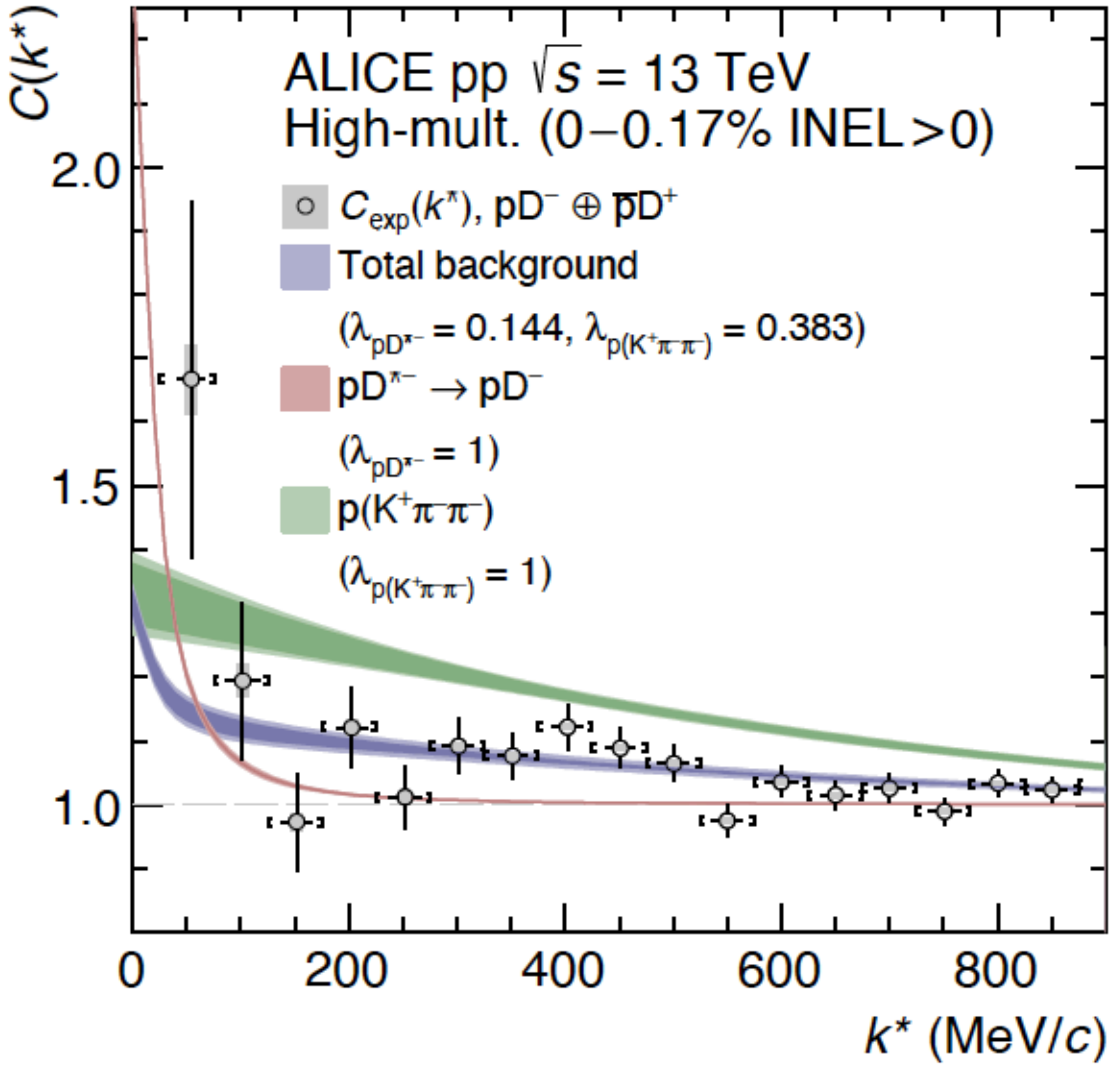
- Relevant sources of background
  1. Uncorrelated ($K^+ \pi^- \pi^-$) background candidates
     - ➡ Parametrised from the measured C(k*) computed with D^- candidates in the sidebands
  2. D^- from D^{*-} decays (~30% of D^-)
     - ➡ p– D^{*-} strong interaction not known, only Coulomb considered

- All these contributions must be considered for the interpretation of the correlation function

$N\bar{D}$ raw correlation function

$$C_{\rm exp}(k^*) = \lambda_{\rm pD^-} \times C_{\rm pD^-}(k^*) + \lambda_{\rm p(K^+\pi^-\pi^-)} \times C_{\rm p(K^+\pi^-\pi^-)}(k^*) + \lambda_{\rm pD^{*-}} \times C_{\rm pD^{*-}}(k^*) + \lambda_{\rm flat} \times C_{\rm flat}.$$

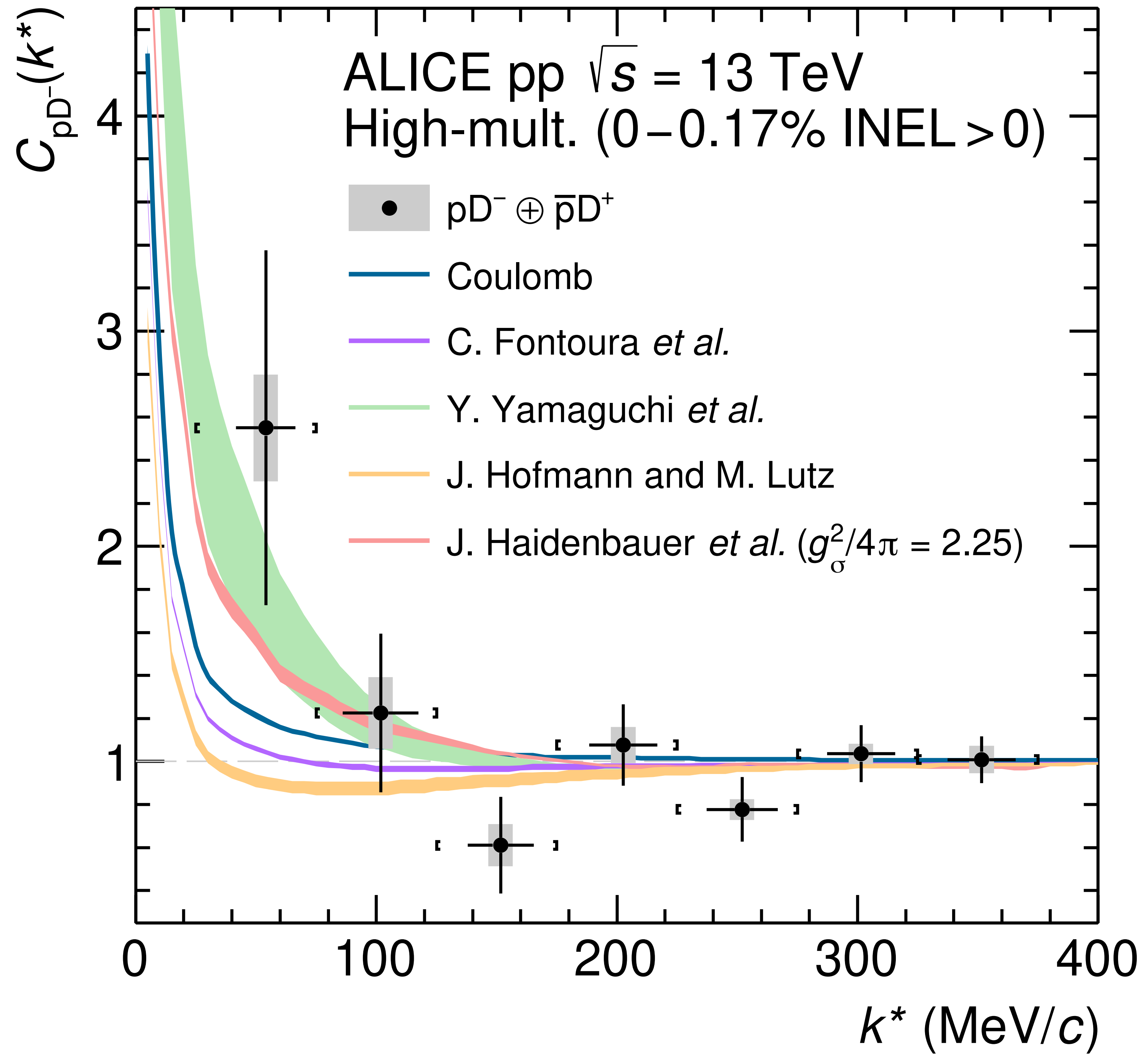
ALICE, arXiv: 2201.05352

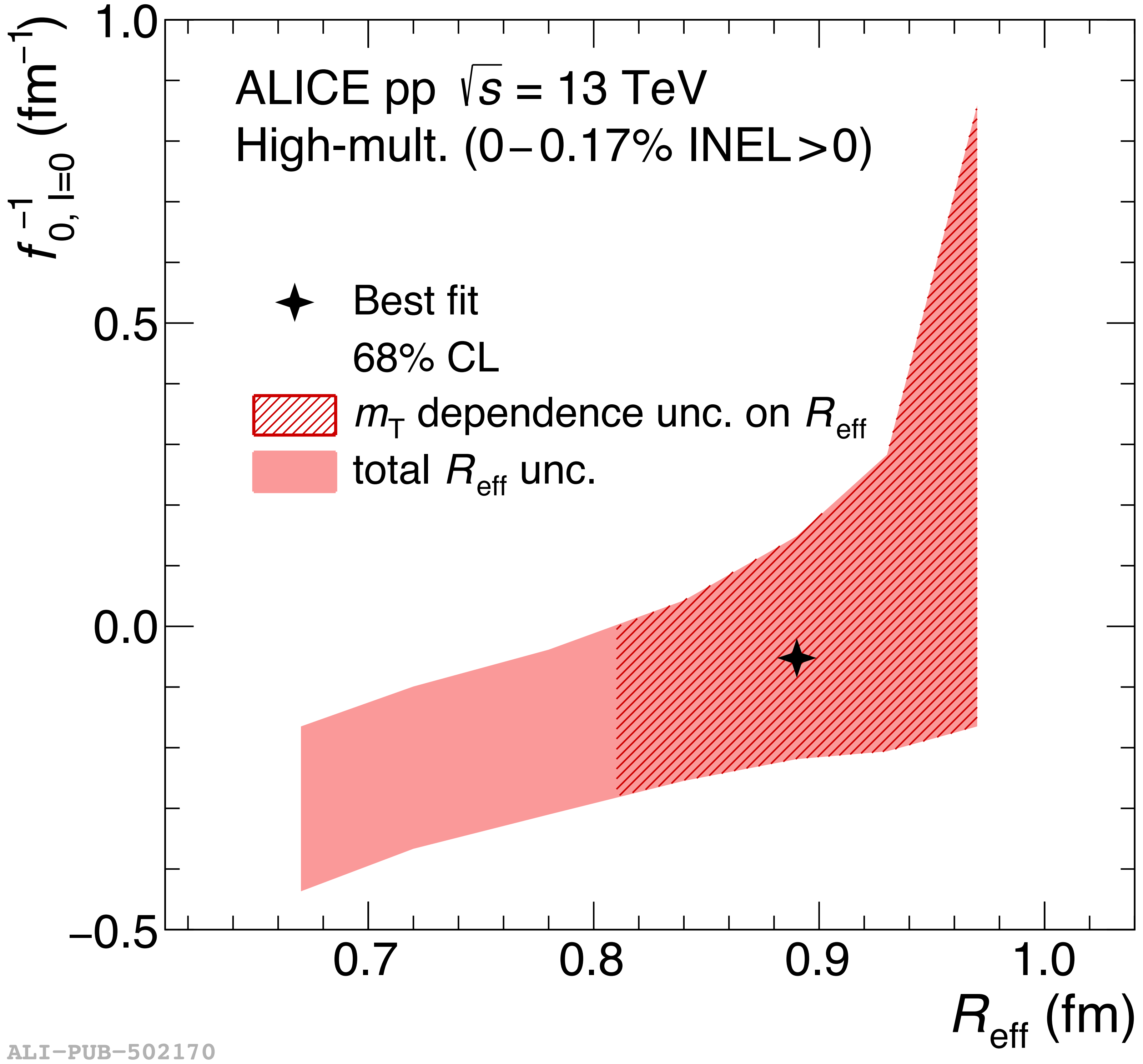


- The different λ parameters are extracted from the weight of the side-bands, the evaluated D* contribution and the purity for the D and p reconstruction
- There is no mini-jets background for the $\bar{D}N$ correlation

N$\bar{\text{D}}$ interaction

- pD⁻ interaction
  - ➡ Small compared to other interactions (scattering lengths light-light ~ 7-8 fm, light-strange ~ 1.5 fm)
  - ➡ Many models predict repulsive interaction
  - ➡ Possible bound state formation (Yamaguchi et al)





ALICE, arXiv: 2201.05352

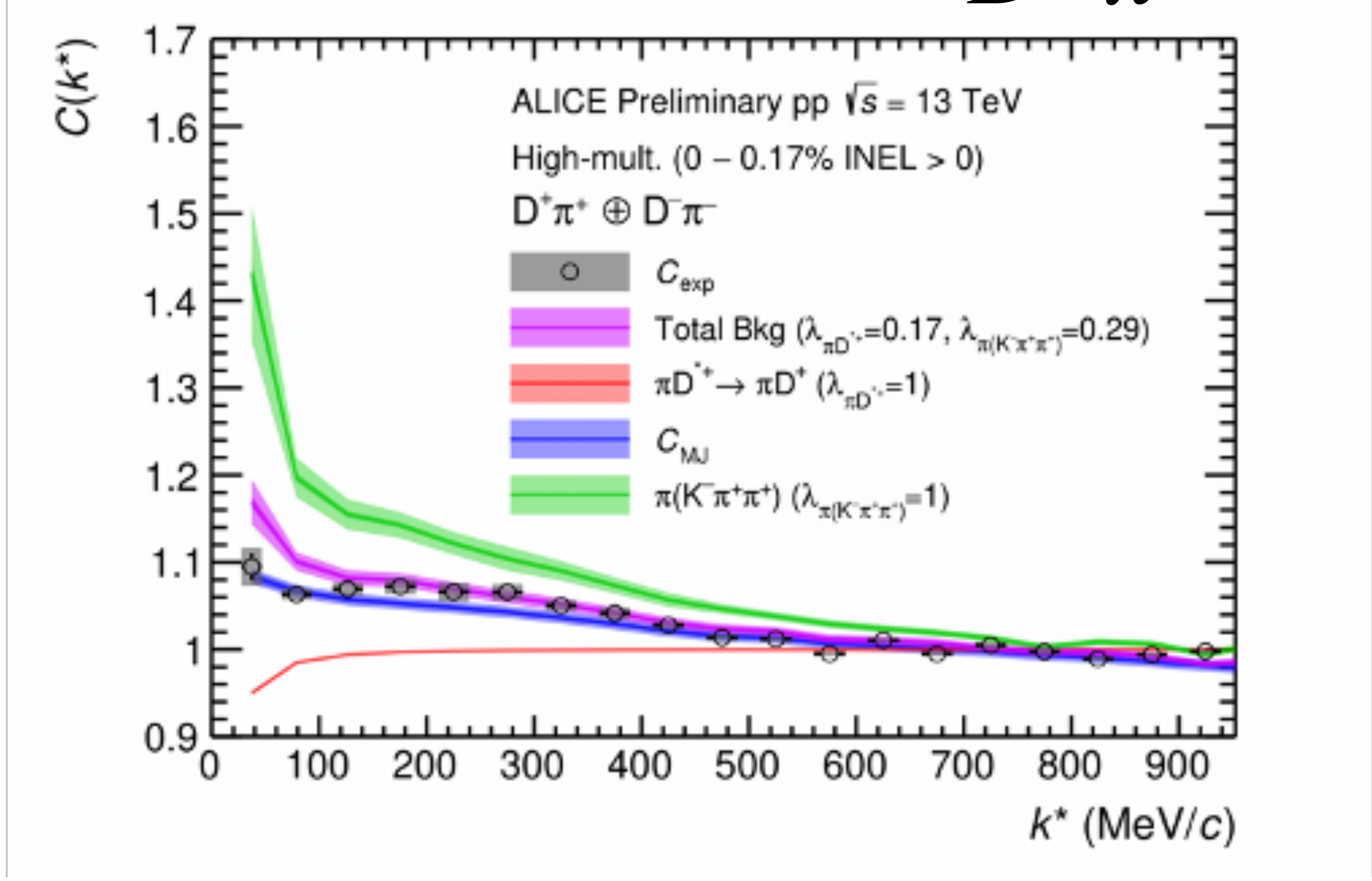
- Interval of scattering length for isospin I=0 at 68% CL indicates either **attractive interaction with or without the formation of a bound state**

J. Haidenbauer et al, EPJA 33 (2007) 107–117
J. Hofmann and M. Lutz, NPA 763 (2005) 90–139
Fontura et al, PRC 87 (2013) 025206
Yamaguchi et al, PRD 84 (2011) 014032

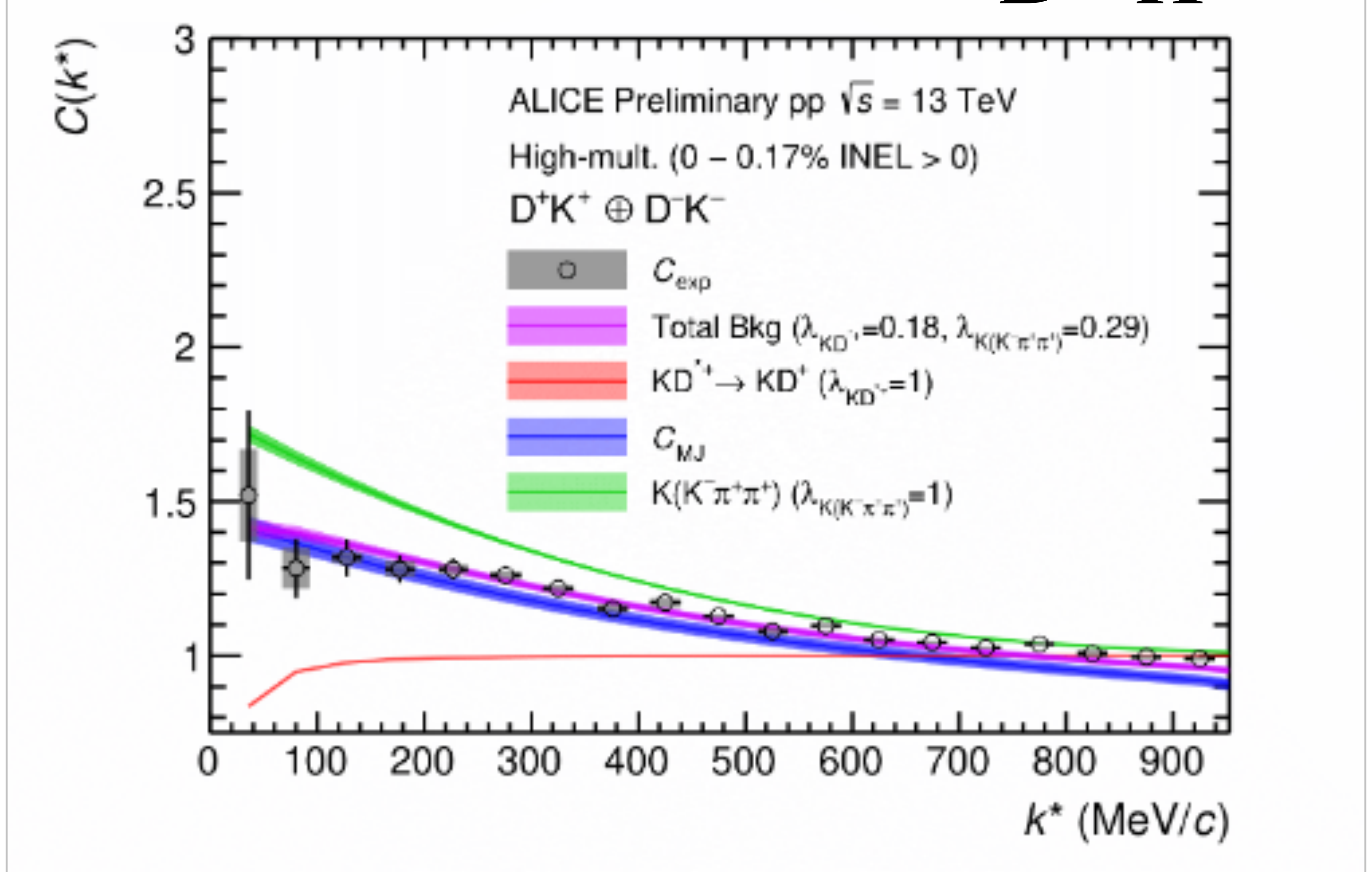
Decomposition of the correlation function

$$C_{\mathrm{raw}} = \lambda_{(\widetilde{\mathrm{D}},\mathrm{K})} C_{(\widetilde{\mathrm{D}},\mathrm{K})} + C_{\mathrm{minijets}} \left[\lambda_{\mathrm{gen}} C_{\mathrm{gen}} + \lambda_{(\mathrm{D}\leftarrow\mathrm{D}^*,\mathrm{K})} C_{(\mathrm{D}\leftarrow\mathrm{D}^*,\mathrm{K})} + \lambda_{\mathrm{flat}} C_{\mathrm{flat}} \right]$$

$D^+\pi^+$



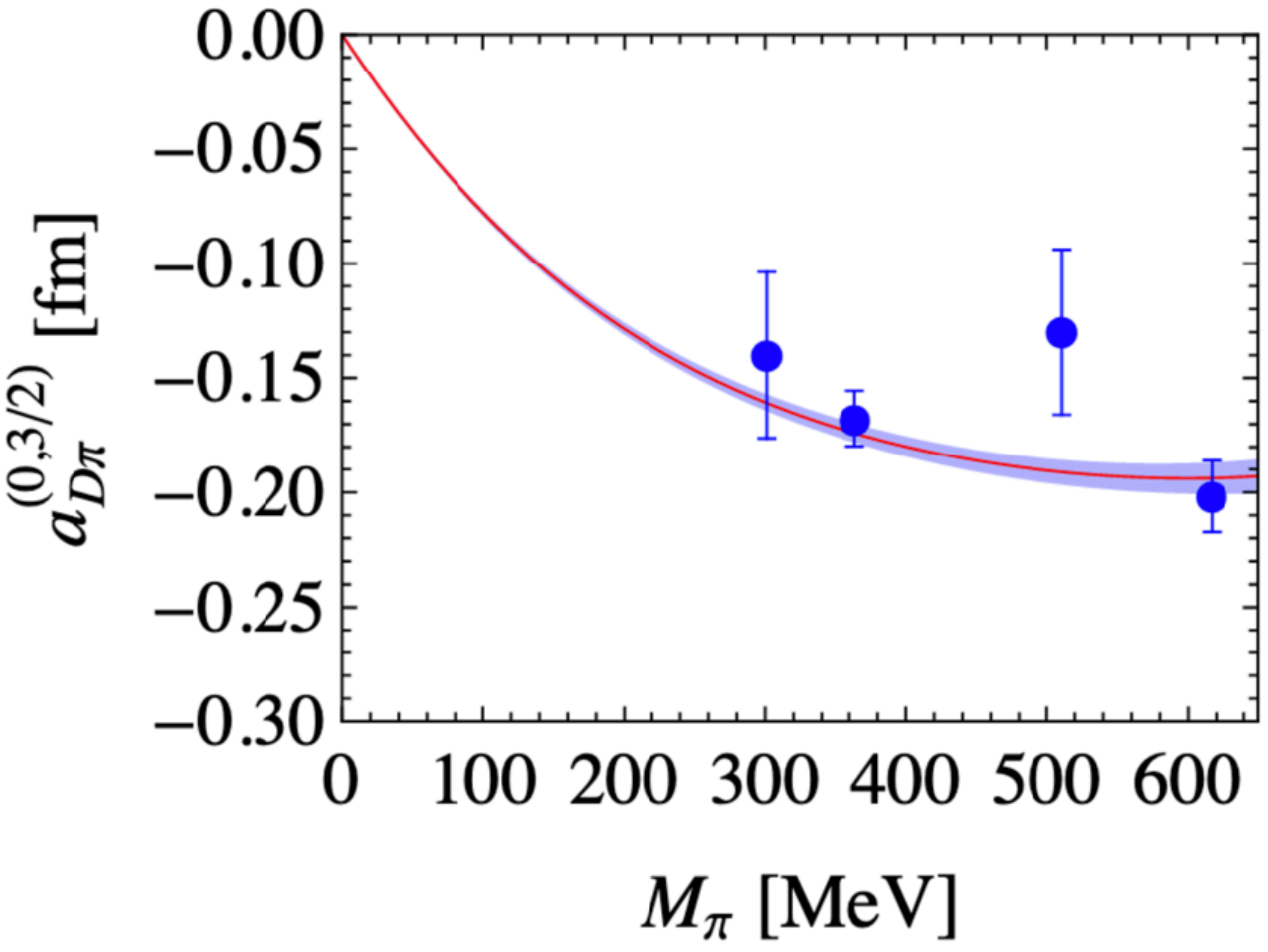
D^+K^+

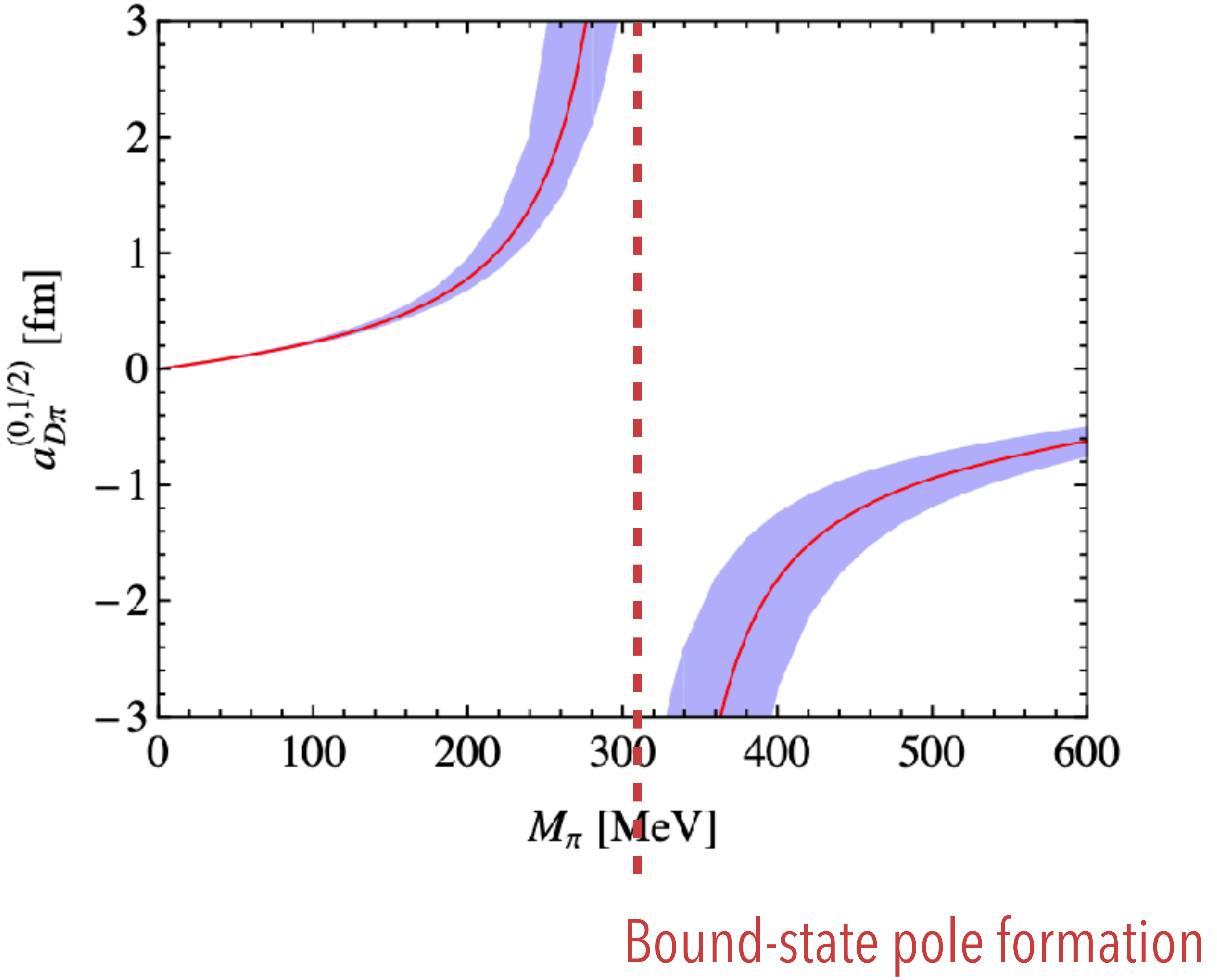


Dπ interactions

- πD interaction: 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, PRD 98 (2018) 014510





Dπ interactions

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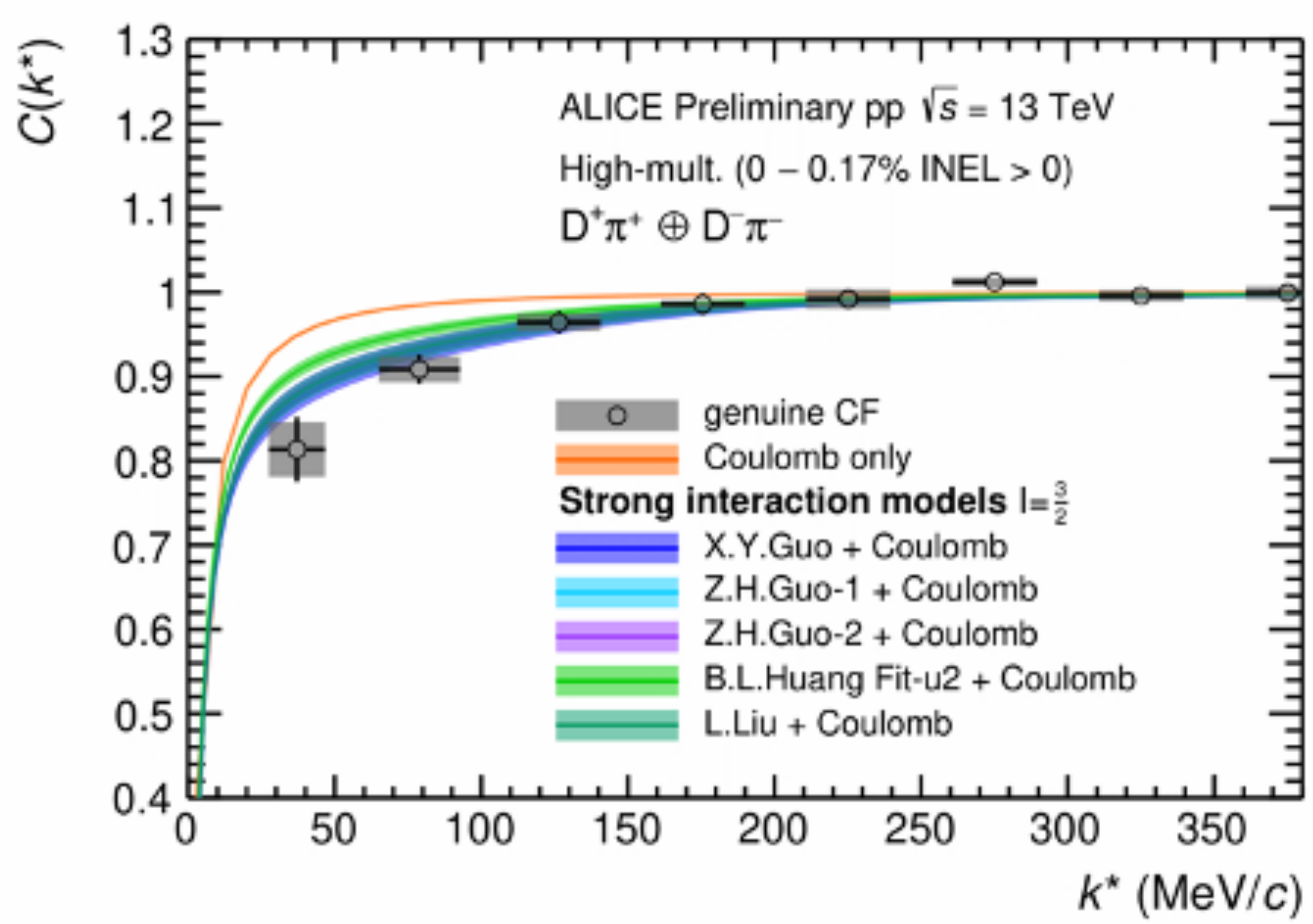
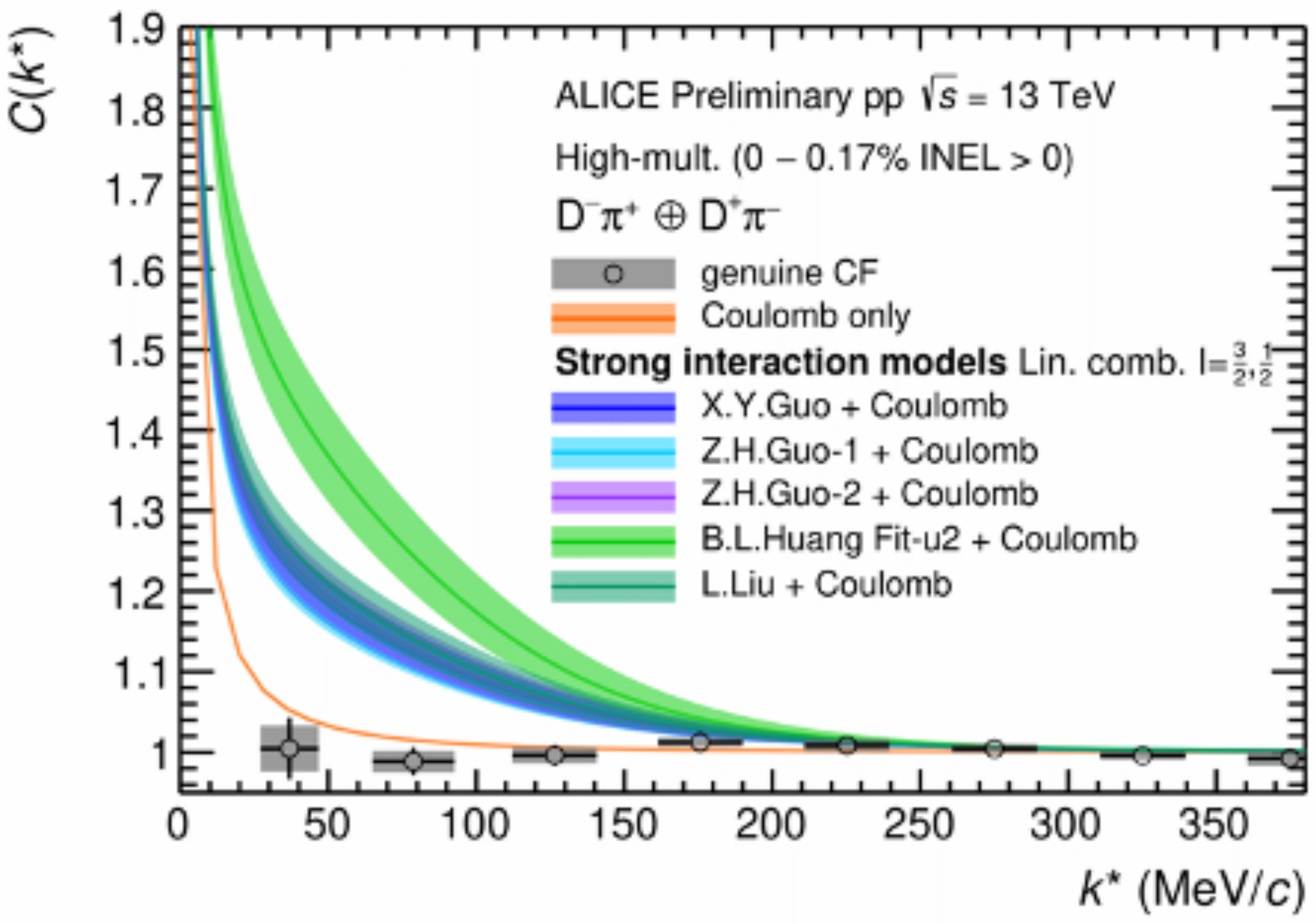
  - ➡ No constraints from data
  - ➡ For pions I=3/2 channel more constrained than I=1/2 channel
- Model correlation functions obtained from Gaussian-type potential, tuned to reproduce theoretical scattering lengths
- Depending on charge combination different isospin states contribute to total correlation function

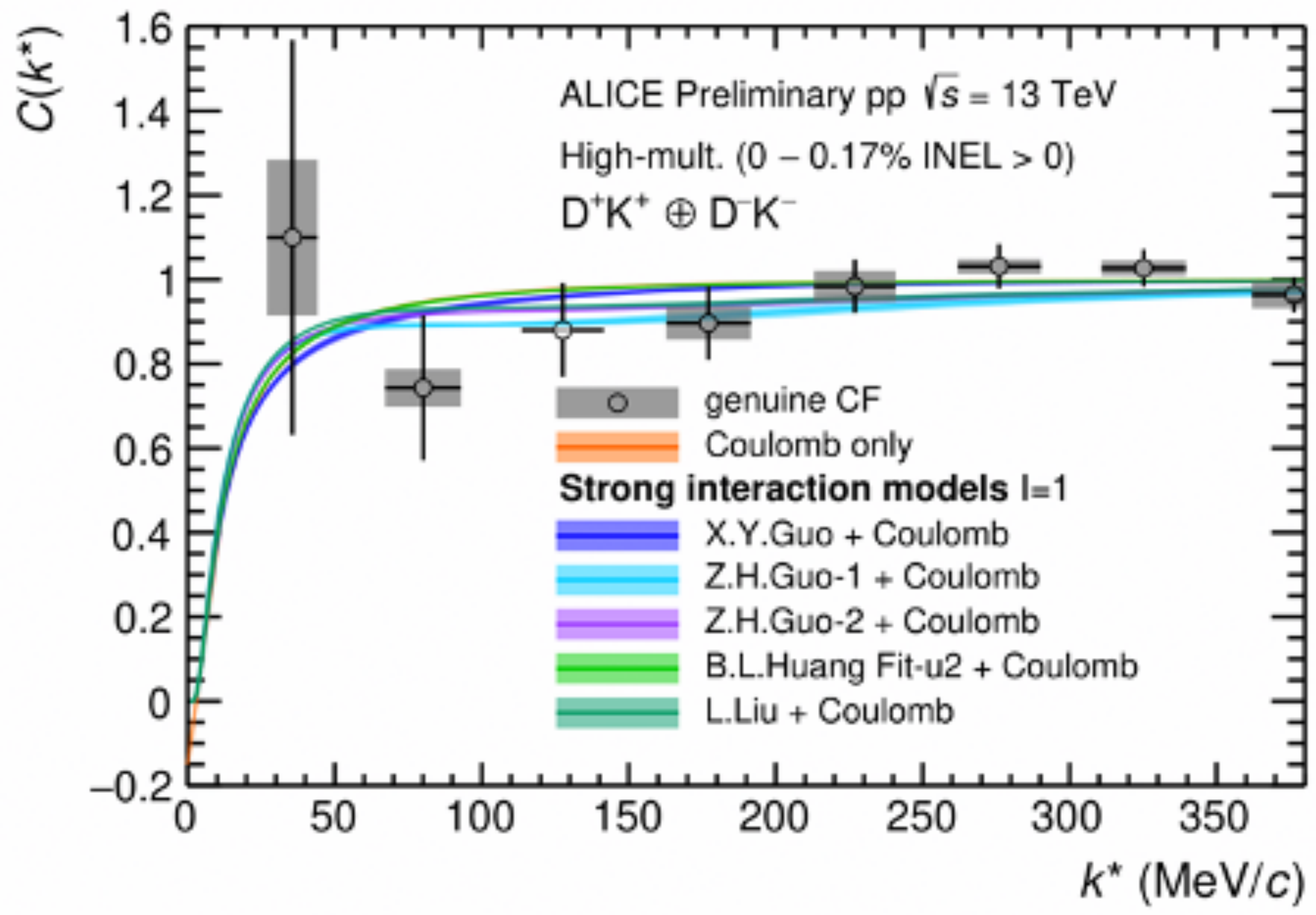
Channel	(S,I)	L. Liu	X.-Y. Guo	B.-L. Huang	Z.-H. Guo - 1	Z.-H. Guo - 2
Dπ	(0,3/2)	-0.10 fm	-0.11 fm	-0.06 fm	-0.101 fm	-0.099 fm
	(0,1/2)	0.37 fm	0.33 fm	0.61 fm	0.31 fm	0.34 fm
DK	(1,1)	0.07+i0.17 fm	-0.05 fm	-0.01 fm	0.06+i0.30 fm	0.05+i0.17 fm
D$\bar{K}$	(-1,0)	0.84 fm	0.46 fm	1.81 fm	0.96 fm	0.68 fm
	(-1,1)	-0.20 fm	-0.22 fm	-0.24 fm	-0.18 fm	-0.19 fm

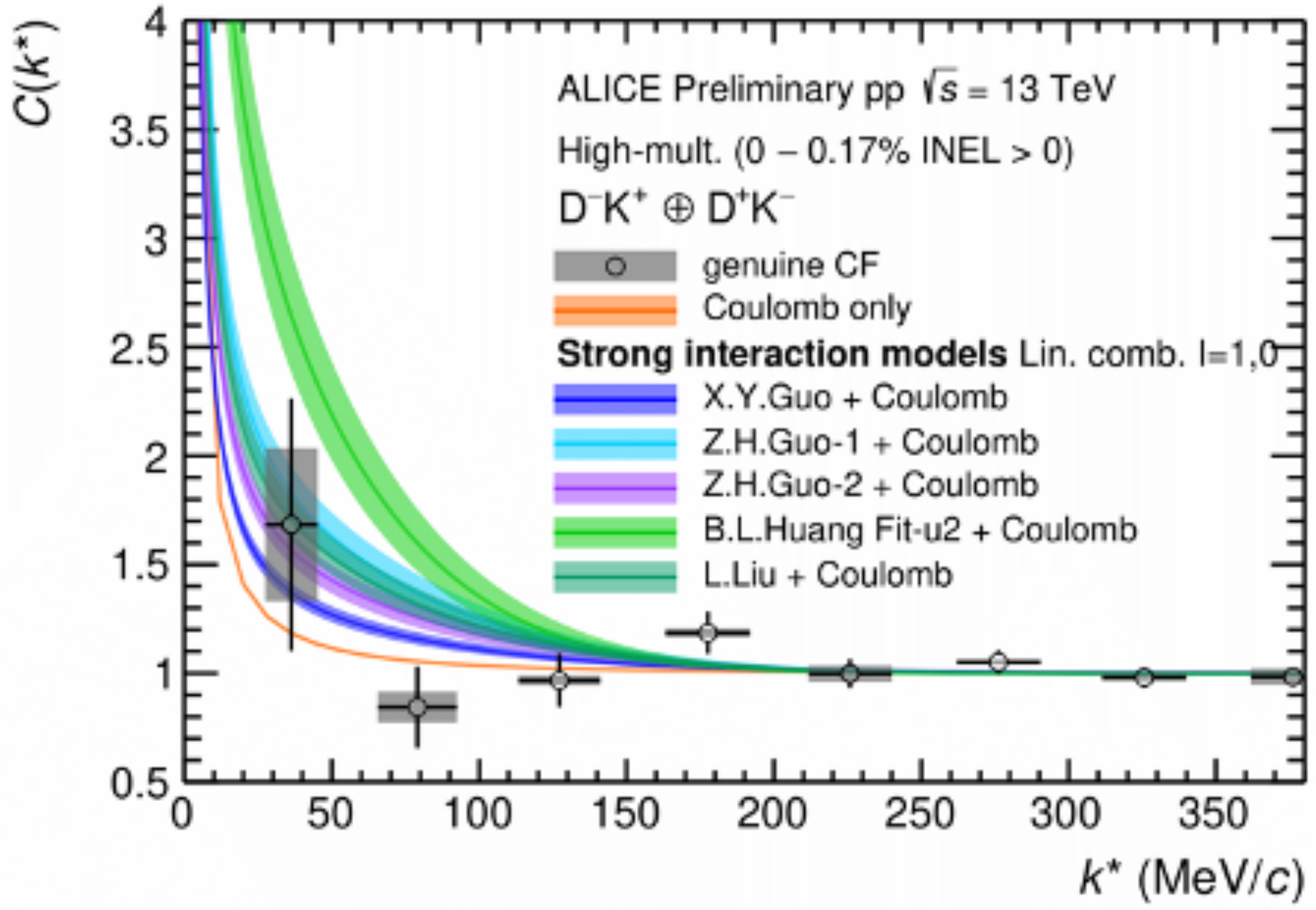
X.-Y. Guo et al, PRD 98 (2018) 014510
Z.-H. Guo et al, *Eur. Phys. J. C* **79** (2019) 13
B.-L. Huang et al, *Phys. Rev. D* **105** (2022) 036016
L. Liu et al, *Phys. Rev. D* **87** (2013) 014508

$D\pi$ and DK and comparison to models



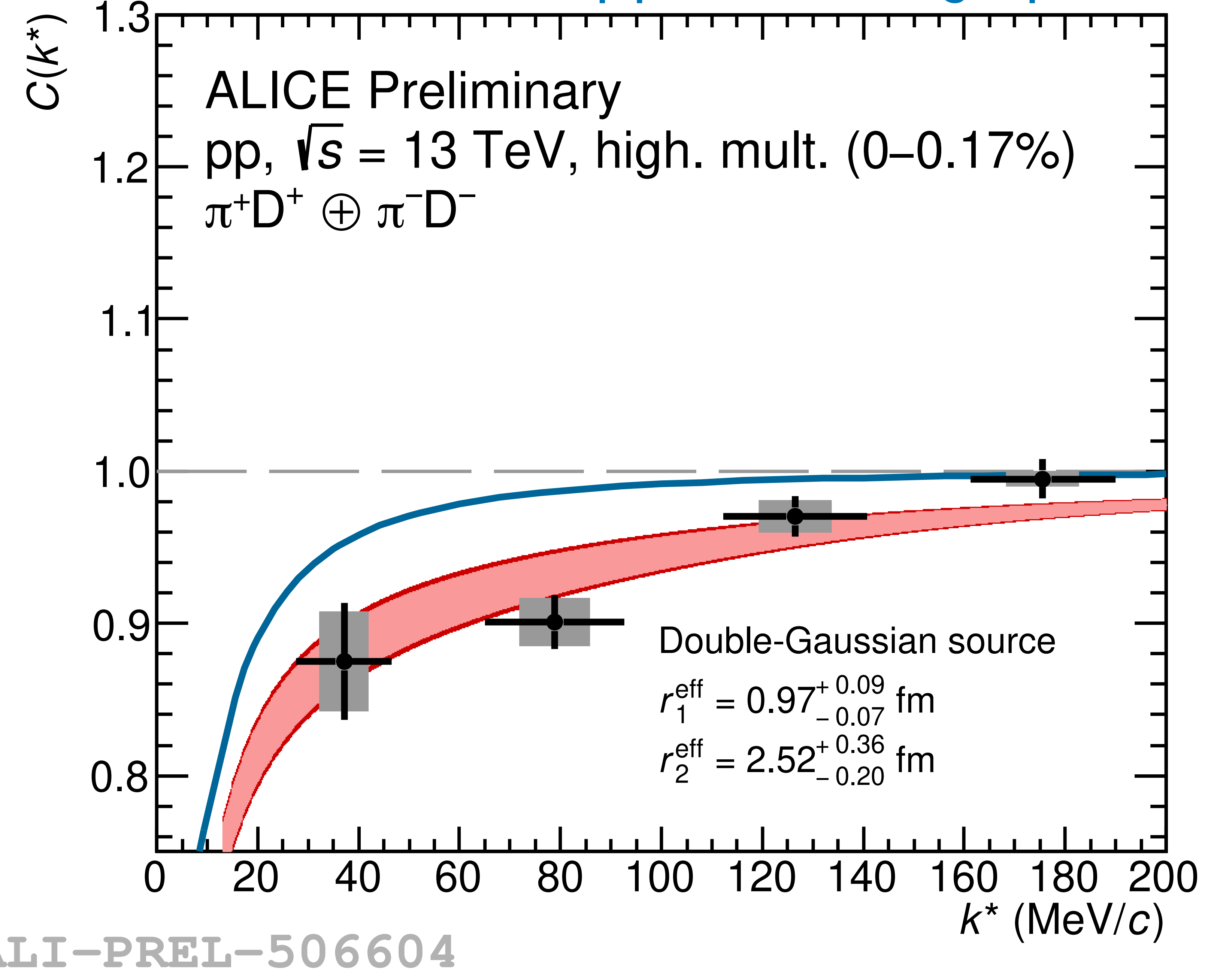




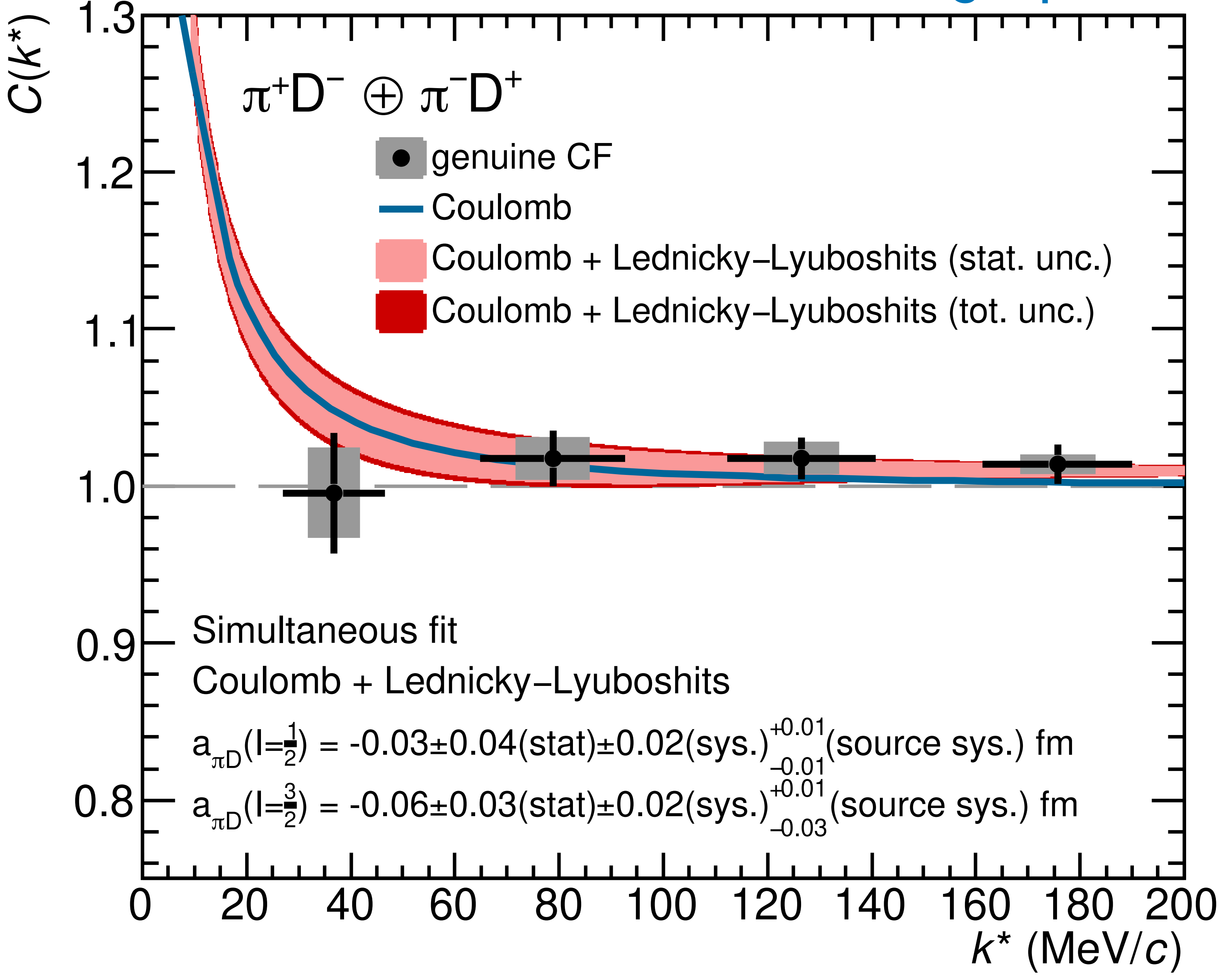


πD interaction: fit with Lednický-Lyuboshits formula

Opposite-charge pairs



Same-charge pairs

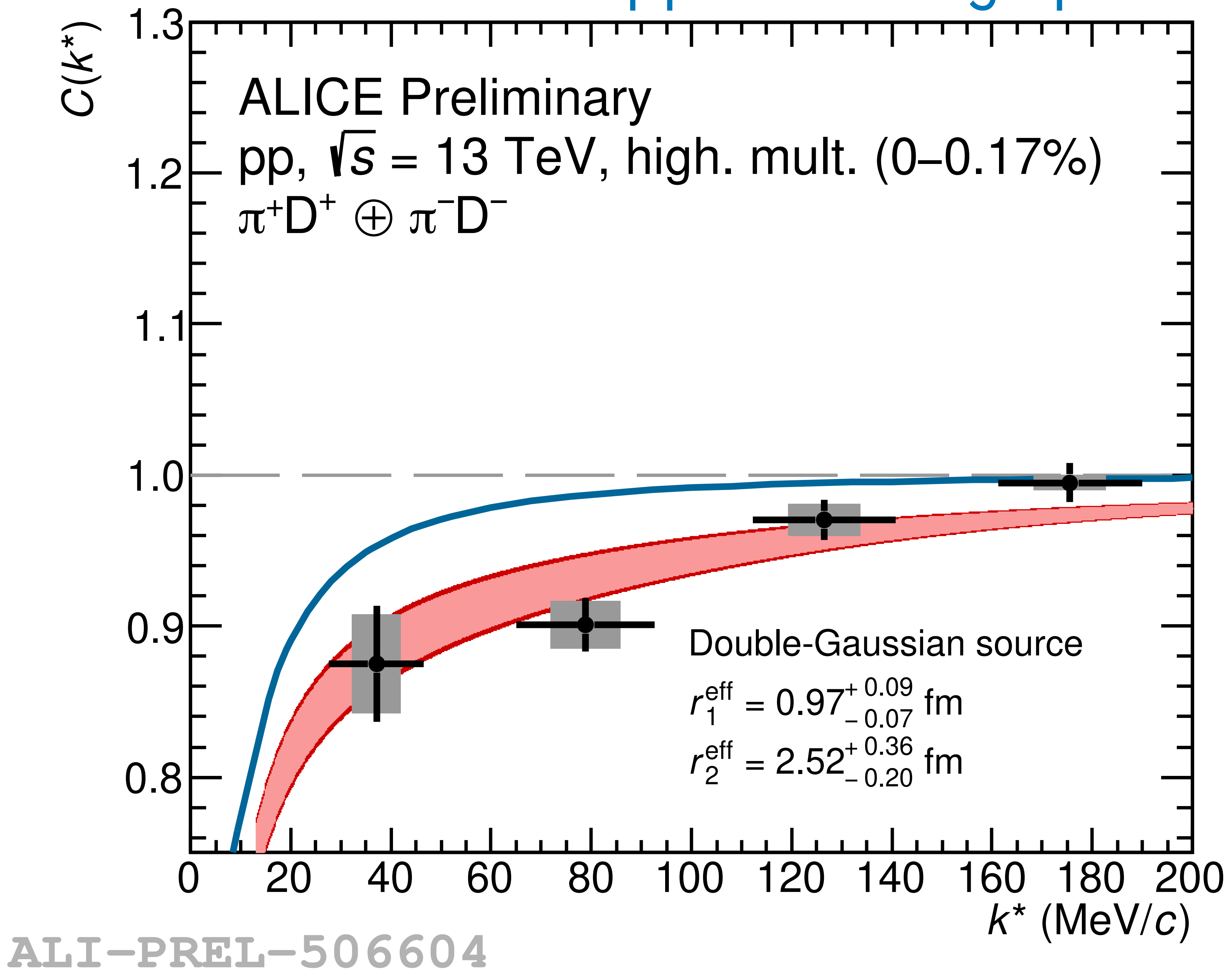


ALICE preliminary

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

πD interaction: fit with Lednický-Lyuboshits formula

Opposite-charge pairs



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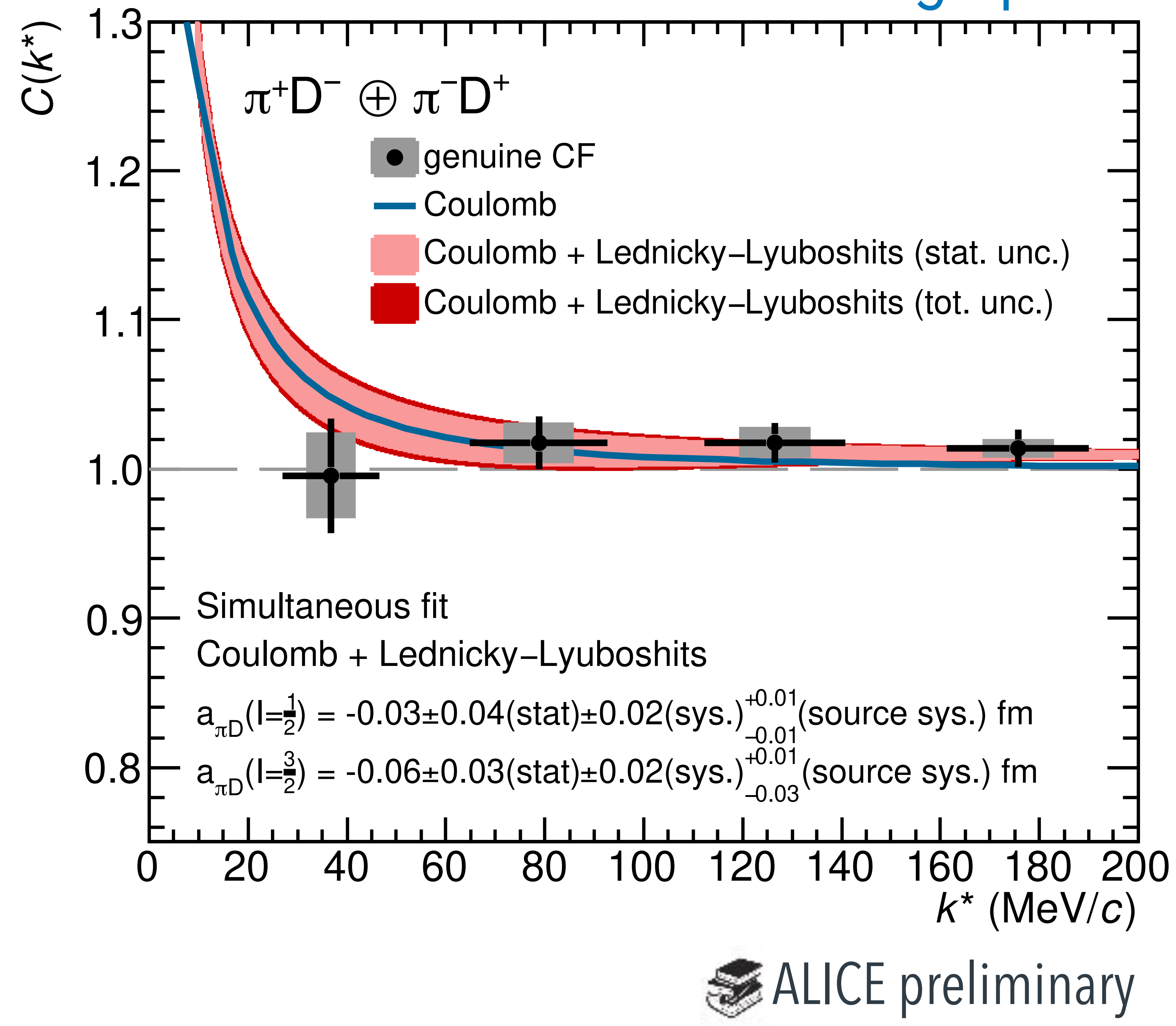

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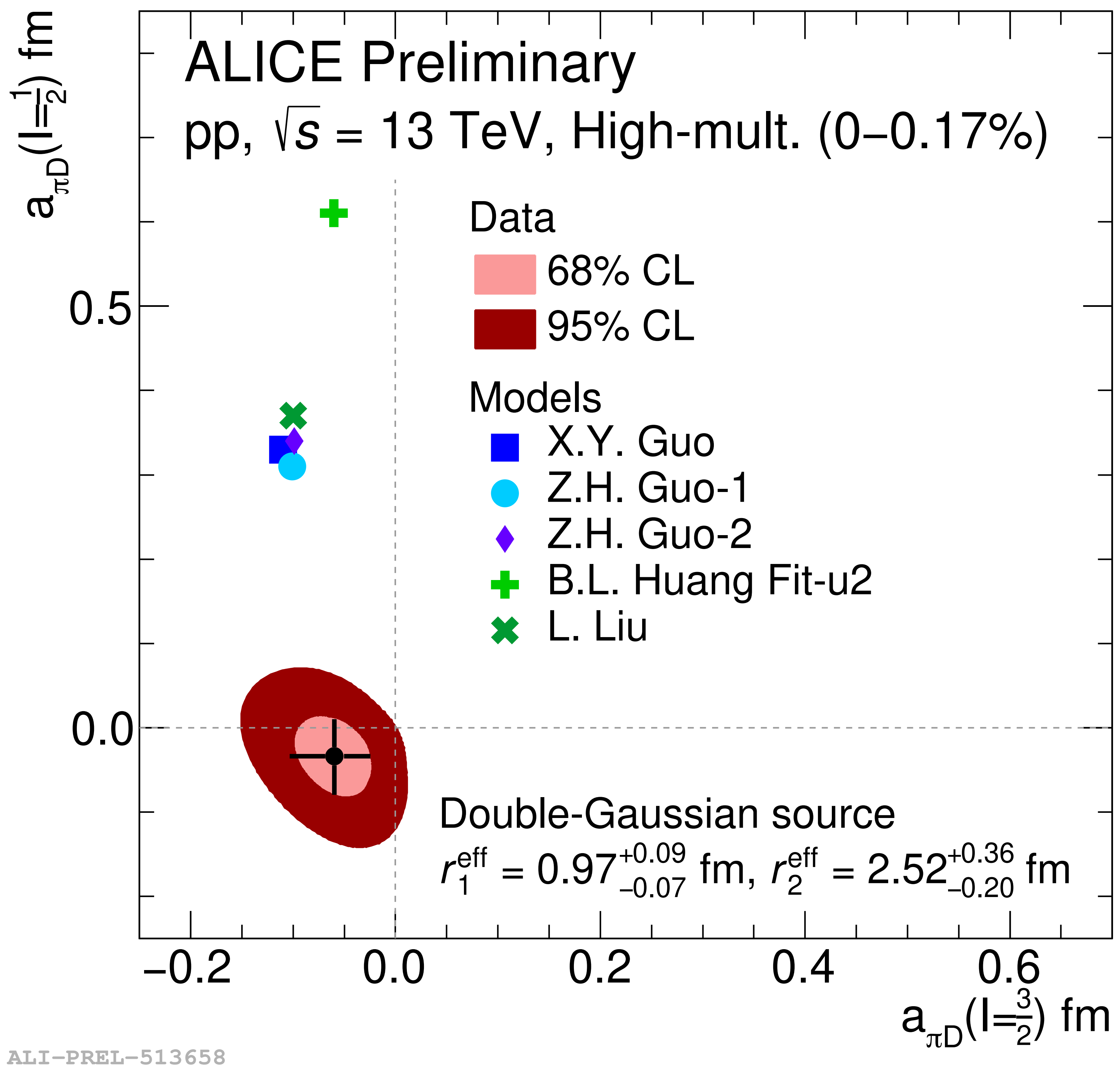
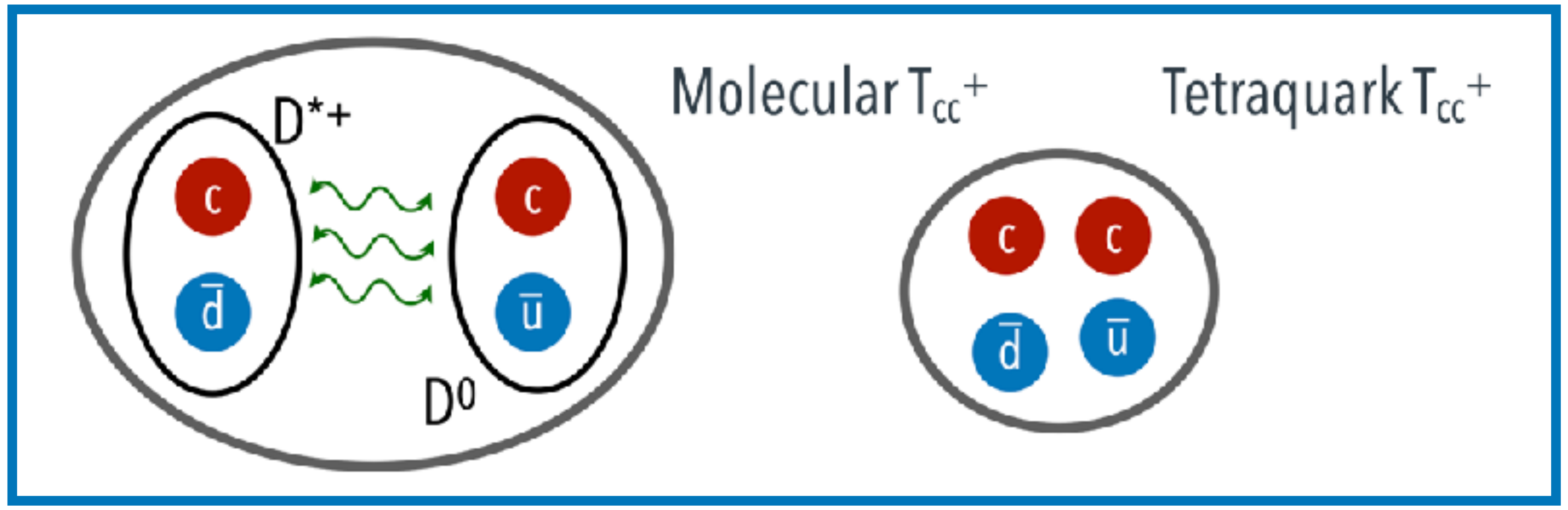


- Scattering length for I=3/2 in agreement with models
- Scattering length for I=1/2 significantly smaller than models
- The values found indicate a **small rescattering of D mesons in the hadronic phase of heavy-ion collisions**

Charm-charm hadron interaction: hadronic physics

- 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)

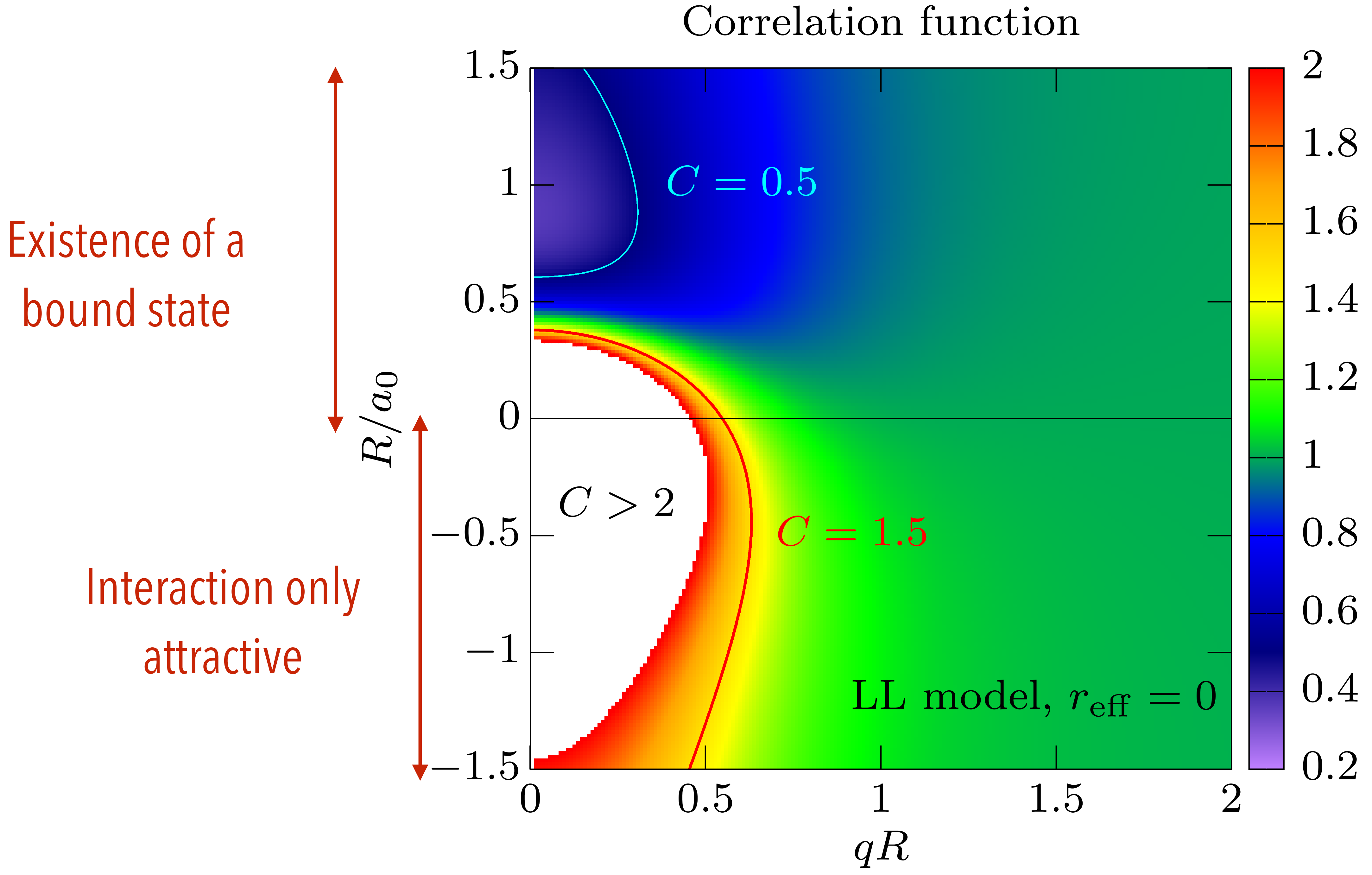
Correlation functions and bound states

- Correlation functions can be used to study the existence of bound states
- Interplay between system size and scattering length can lead to a size-dependent modification of the correlation function in presence of a bound state

$$x = qR \quad y = \frac{R}{a_0} \qquad\qquad C(q) = 1 + \frac{1}{x^2+y^2}\left[\frac{1}{2} - \frac{2y}{\sqrt{\pi}}\int_0^{2x} dt \frac{e^{t^2-4x^2}}{x} - \frac{(1-e^{-4x^2})}{2}\right]$$

R= source size
q= invariant relative momentum
a_0= scattering length

- A single measurement at fixed R does not suffice
- A systematic measurements of different sizes is necessary :
  - pp (R= 1 fm), p-Pb(R= 1. 5 fm), Pb-Pb (R= 2-6 fm)



Y. Kamiya et al. arXiv:2108.09644v1

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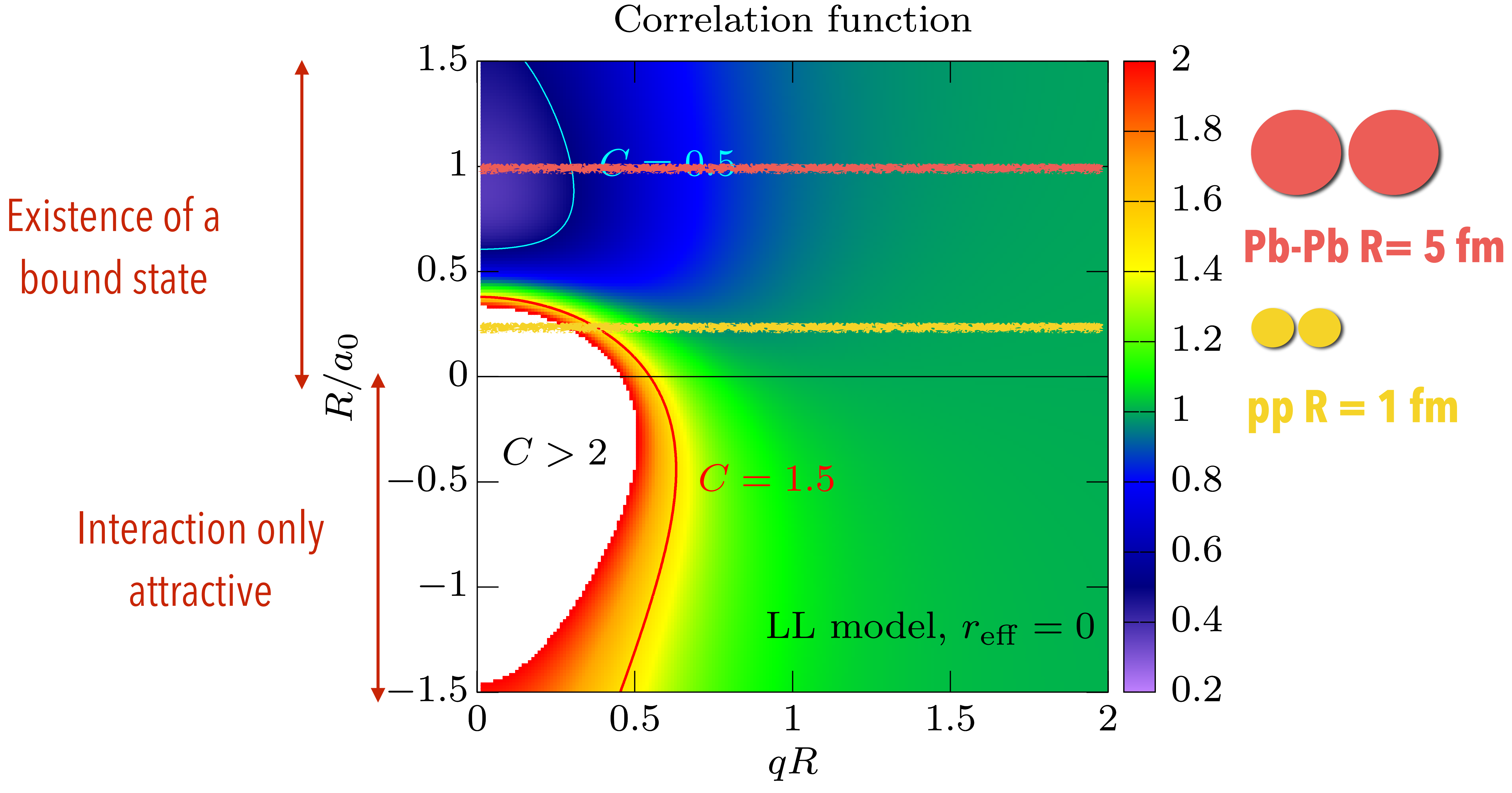
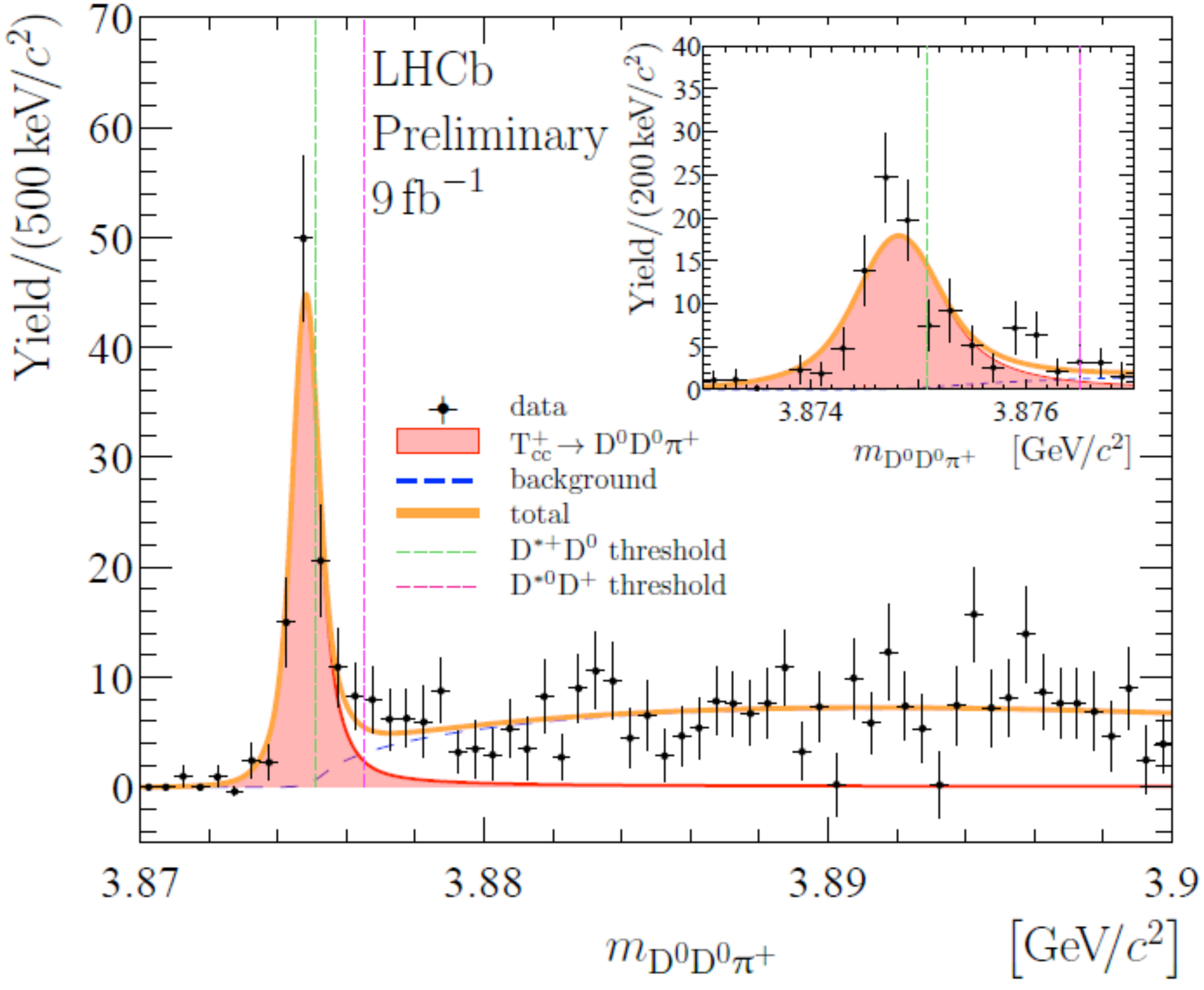


Y. Kamiya et al. arXiv:2108.09644v1

The T_{cc}^{+} example

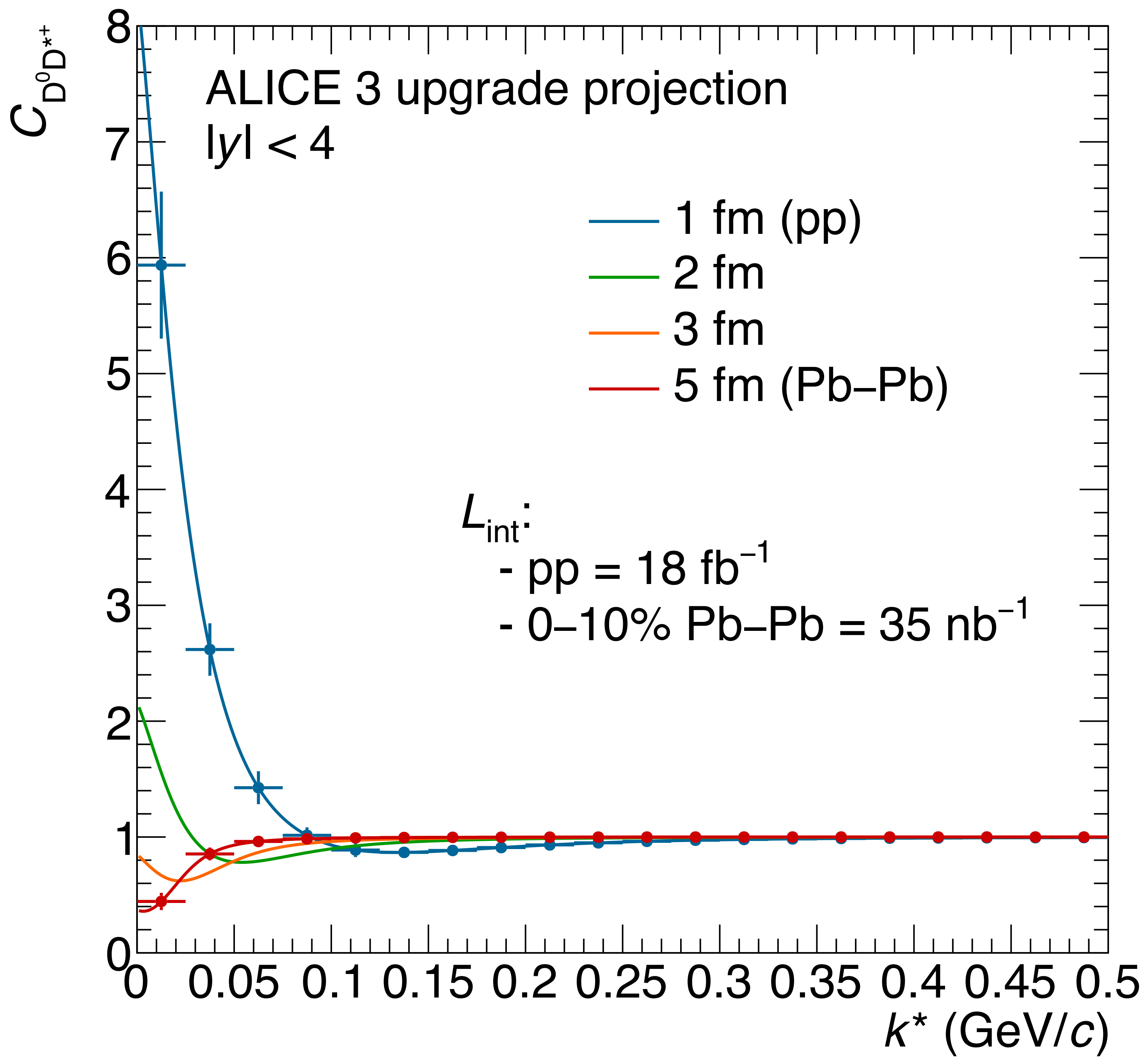
- Recent measurement of a tetraquark candidate by LHCb
  - ➡ Just below D^0D^{*+} and D^+D^{*0} thresholds → candidate to be a molecular state



E. S. Swanson, Phys. Rept. 429 (2006) 243-305

- Its nature can be assessed via the measurement of DD* correlations
  - ➡ In case of a bound state (T_{cc}^{+}) the correlation function is expected to change from smaller to larger than unity for different source sizes

ALICE3 LOI, CERN-LHCC-2022-009



- ➡ Scan from pp to AA collisions needed
- ➡ ALICE3 is the ideal detector for acceptance and purity for the heavy flavour signal

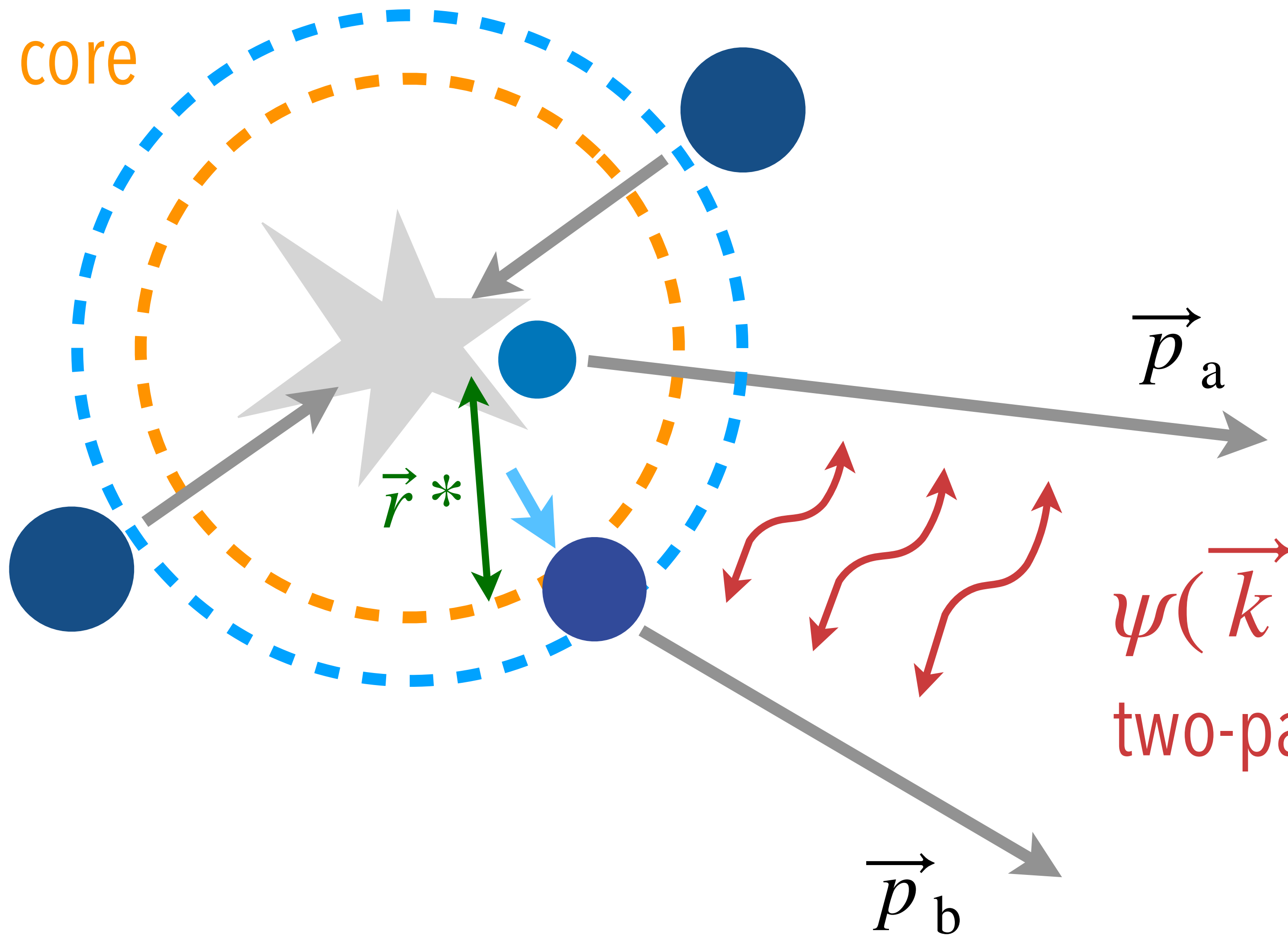
Summary and Outlook

- D- light hadron scattering parameters estimated for the first time
- D-pion: disagreement with theory prediction for I=1/2 channel
- On going work on simultaneous fit of all correlation function to improve precision on the scattering parameter
- DD* correlation can be used as a tool to study molecular state candidates with charm content
- such measurements can be carried out with ALICE3

The emitting source of hadrons

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

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



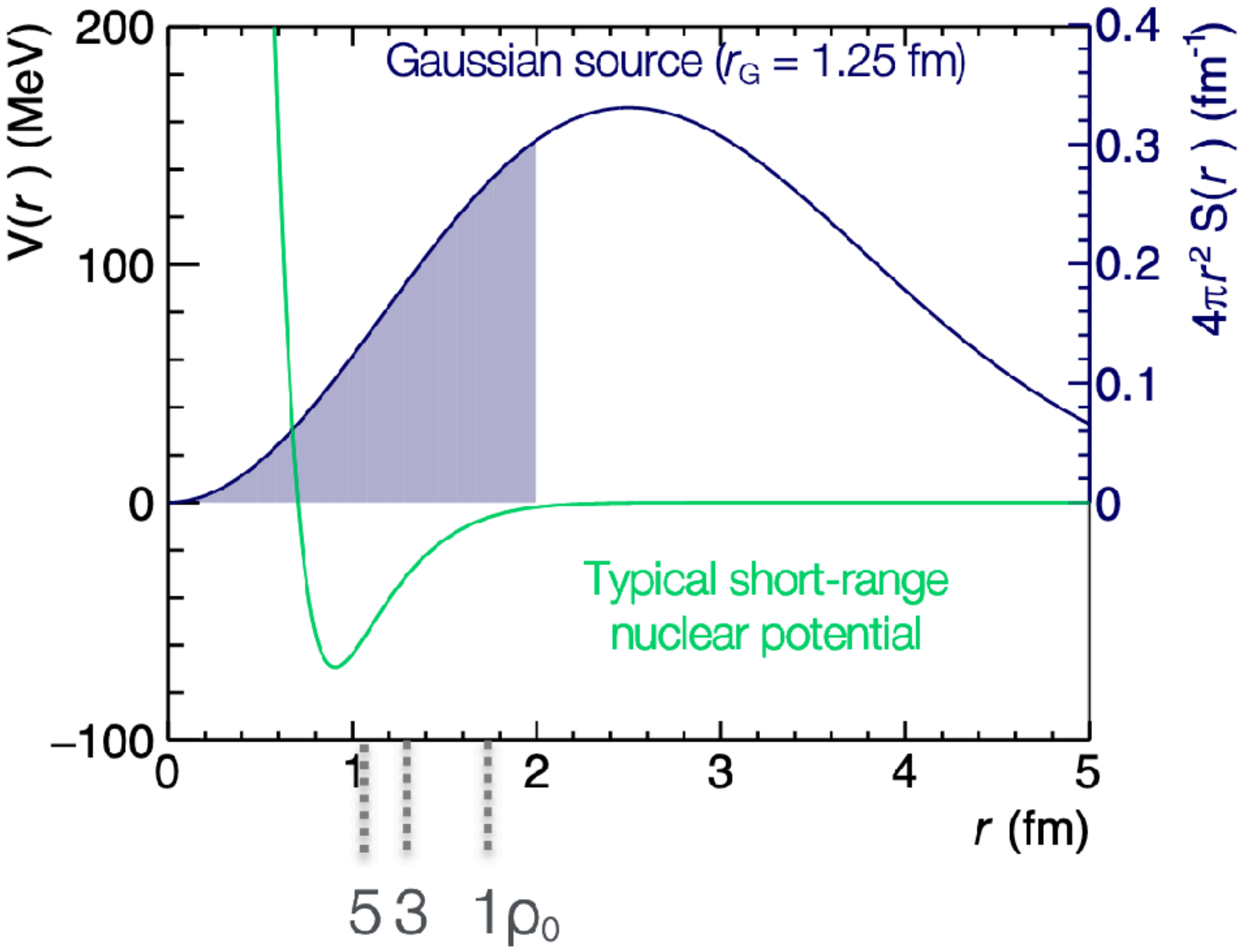
- Described with a Gaussian core

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

- Short-lived strongly decaying resonances effectively enlarge it

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

Femtoscopy with small emitting sources

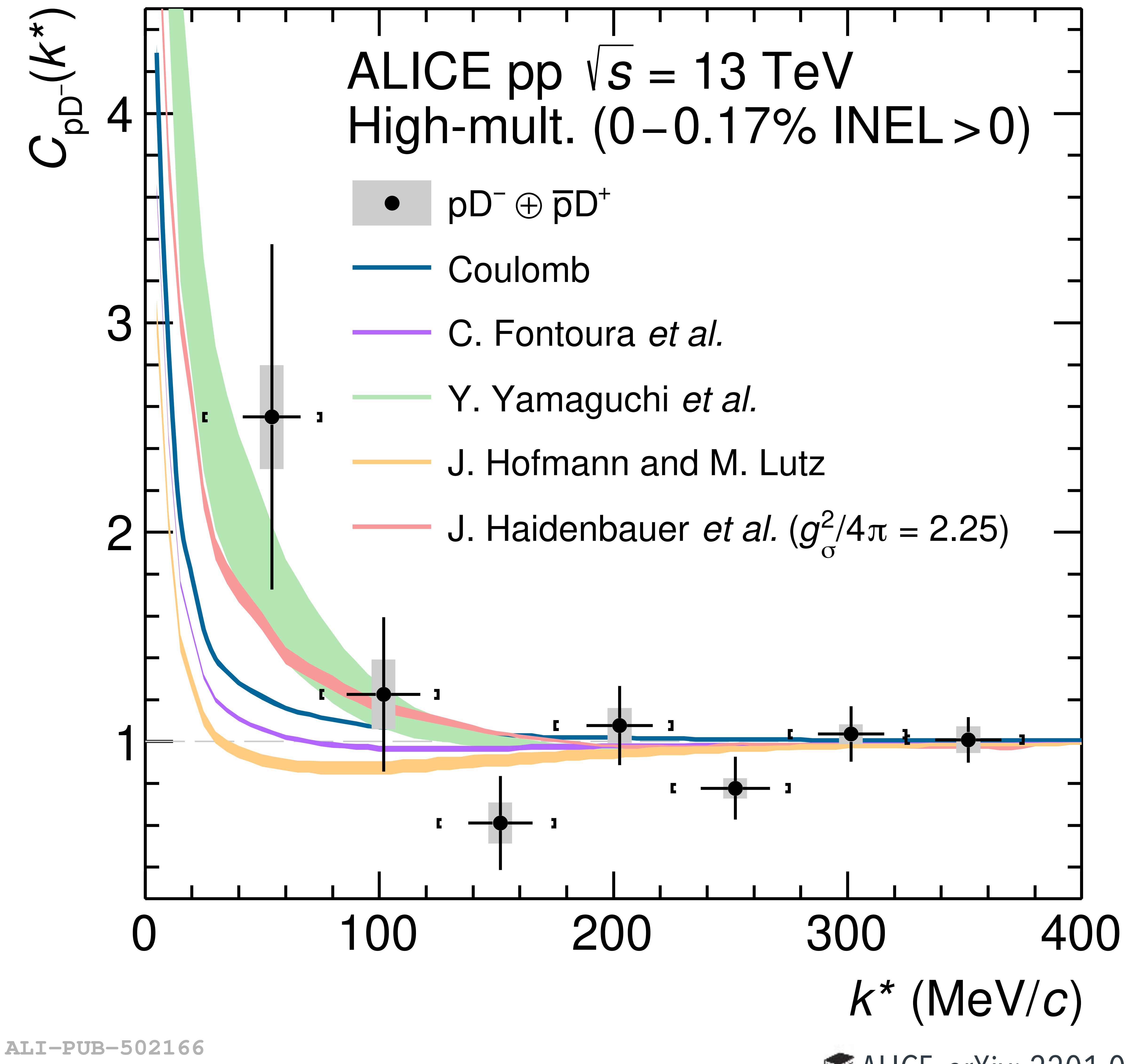


- Typical range of nuclear potential around 1-2 fm
  - ➡ study of strong interaction among hadrons not possible with larger sources
  - ➡ proton–proton and proton–nucleus collisions are the ideal laboratory to study the strong interaction

N$\bar{\text{D}}$ 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)

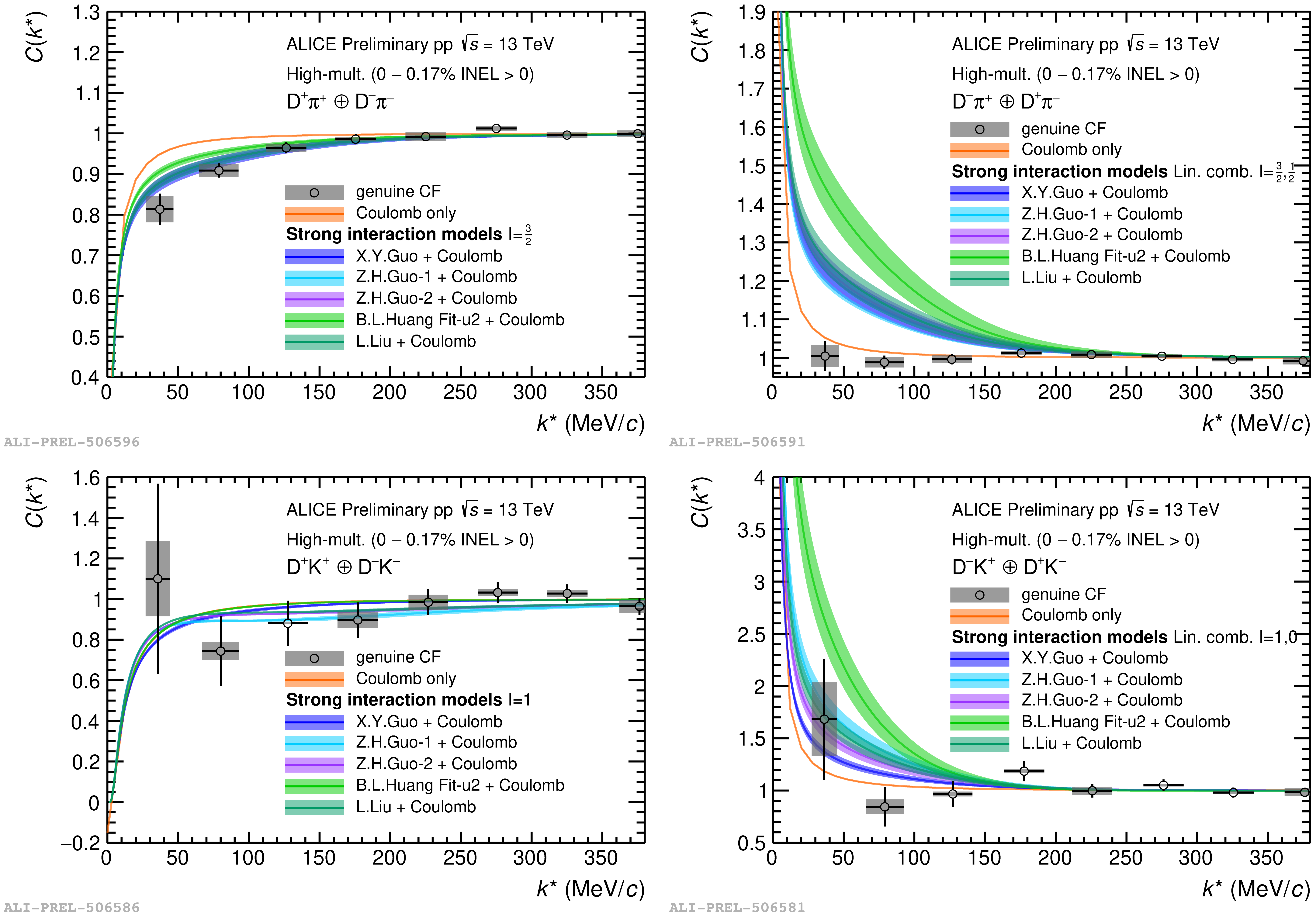
- Data compatible with Coulomb only interaction, but comparison slightly improves when also attractive strong interaction is considered



ALICE, arXiv: 2201.05352

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

πD and KD interactions



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

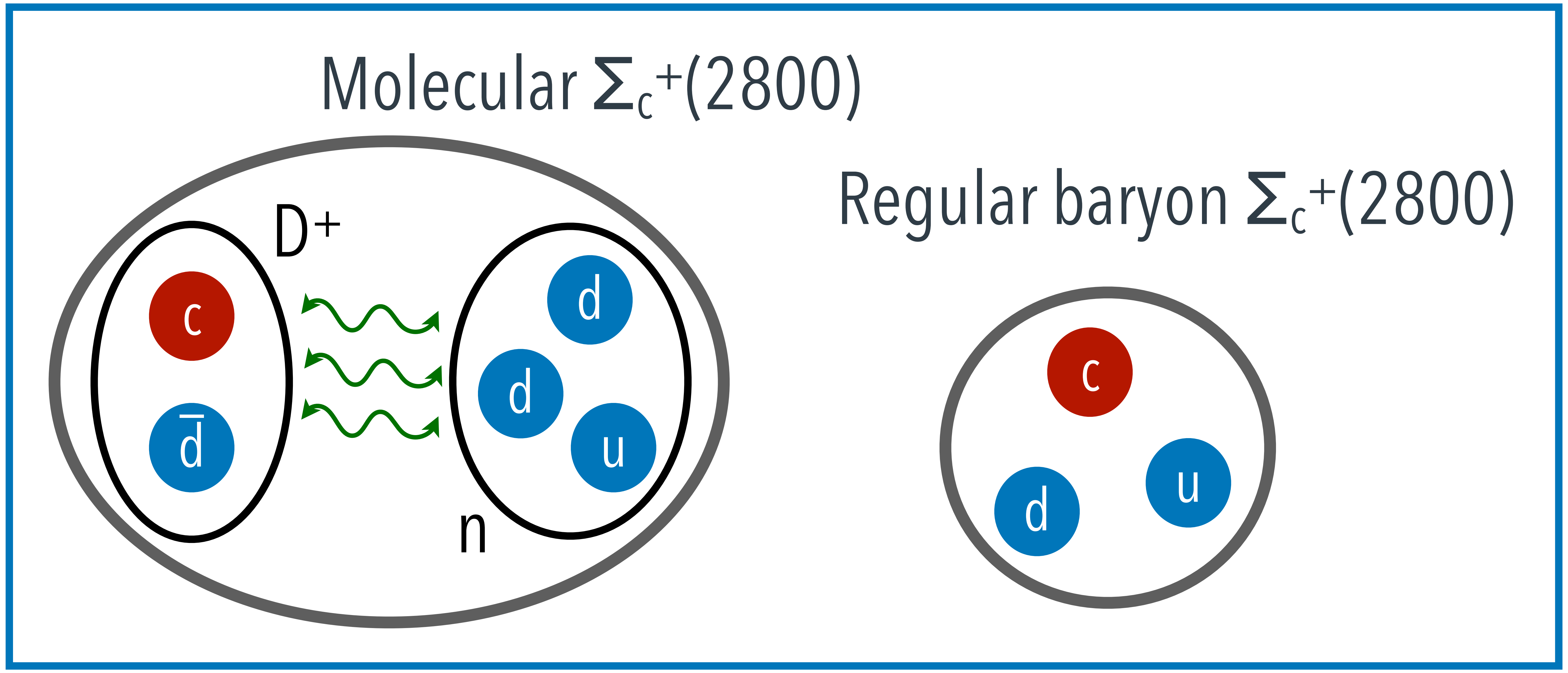
L. Liu et al, Phys. Rev. D87 (2013) 014508
X.-Y. Guo et al, Phys. Rev. D 98 (2018) 014510
B.-L. Huang et al, Phys. Rev. D 105 (2022) 036016
Z.-H. Guo et al Eur. Phys. J. C 79 (2019) 13

Charm-light hadron interaction: hadronic physics

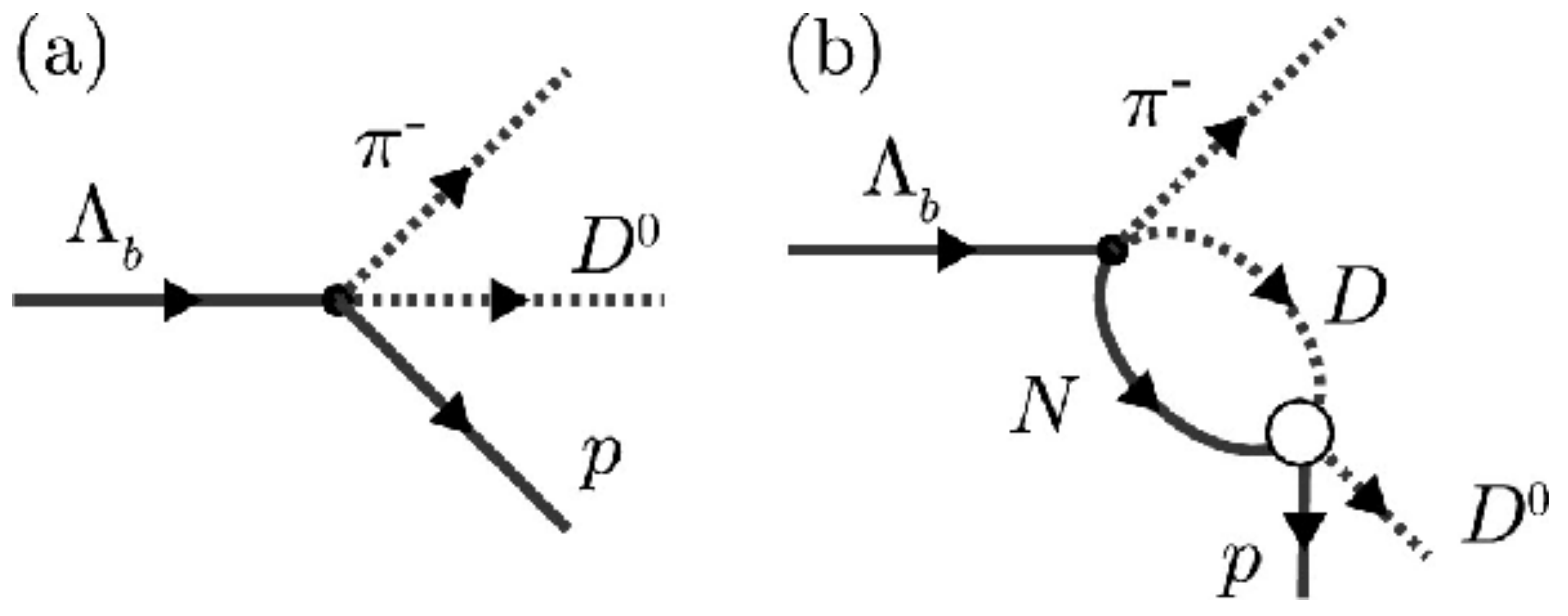
- Charm molecules?

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)
$\Sigma_c\bar{D}$	1/2 $(1/2^-)$	$P_c(4312)$
$\Sigma_c\bar{D}^*$	1/2 $(1/2^-)$	$P_c(4457)$
$\Sigma_c\bar{D}^*$	1/2 $(3/2^-)$	$P_c(4440)$

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



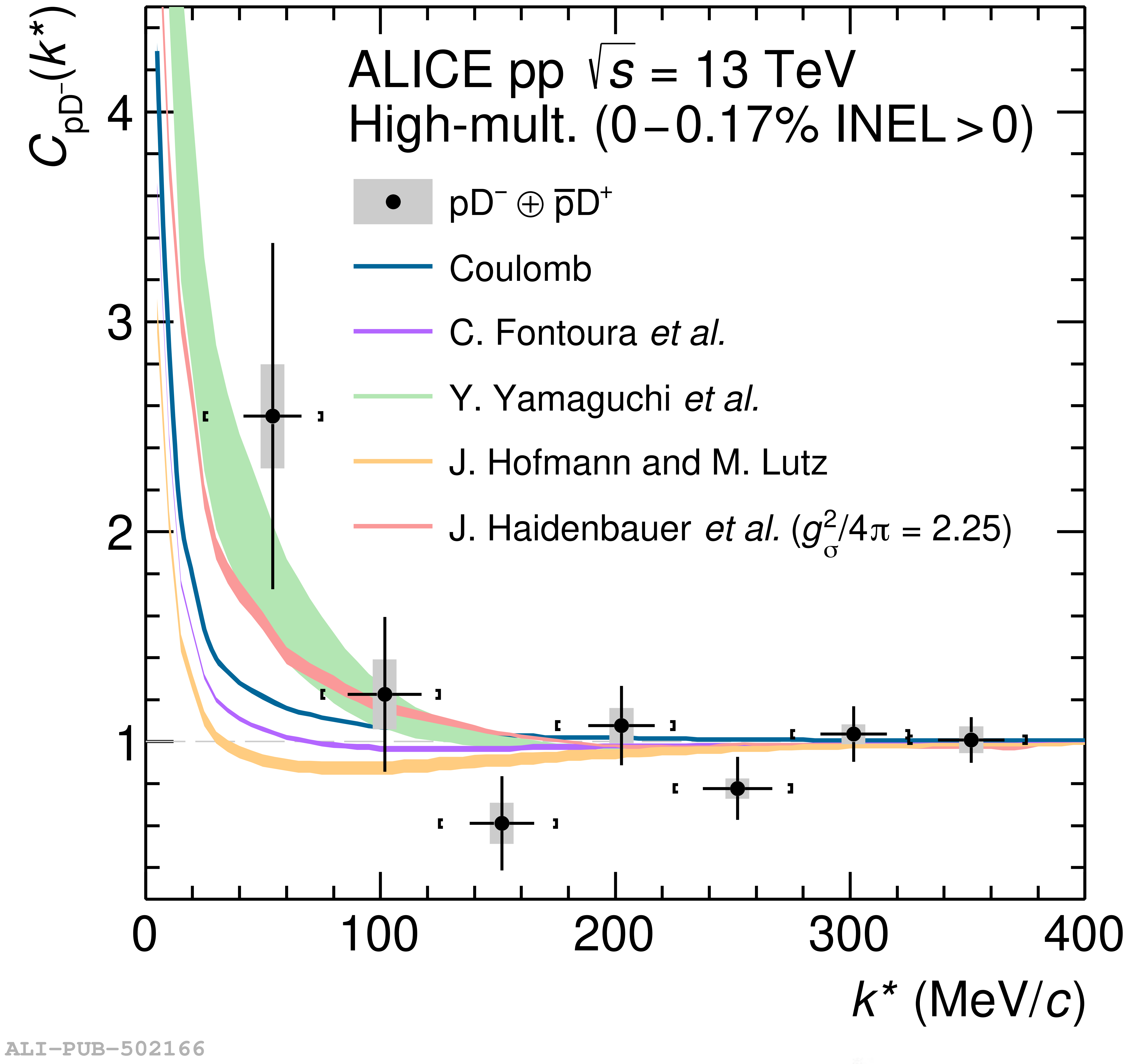
- Proposed as molecular state in J. Haidenbauer et al, Eur. Phys. J. A 47, 18 (2011)
  S. Sakai et al, Phys. Lett. B 808 (2020) 135623



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

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

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



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

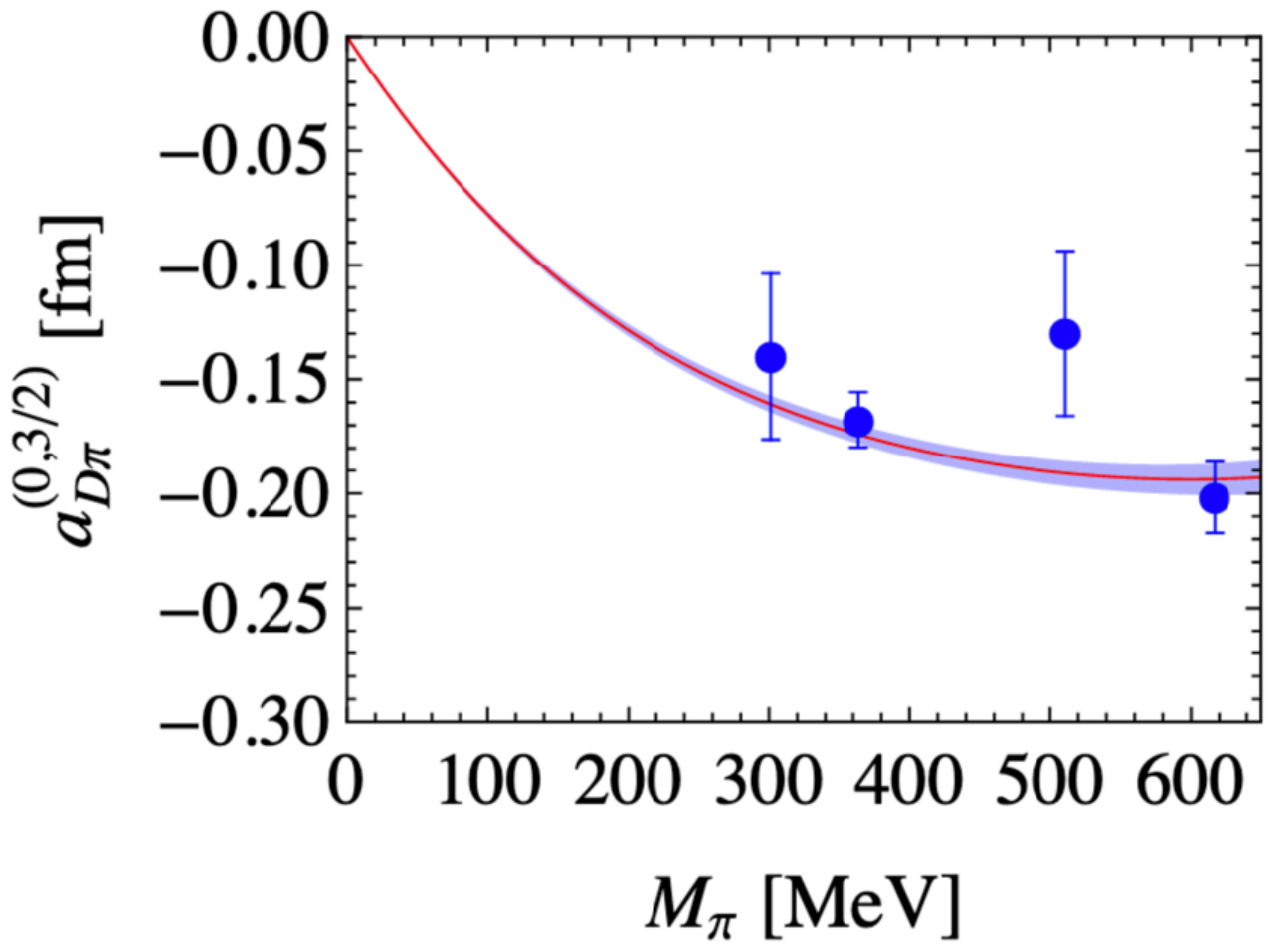
ALICE, arXiv: 2201.05352

πD and KD interactions - scattering lengths in models

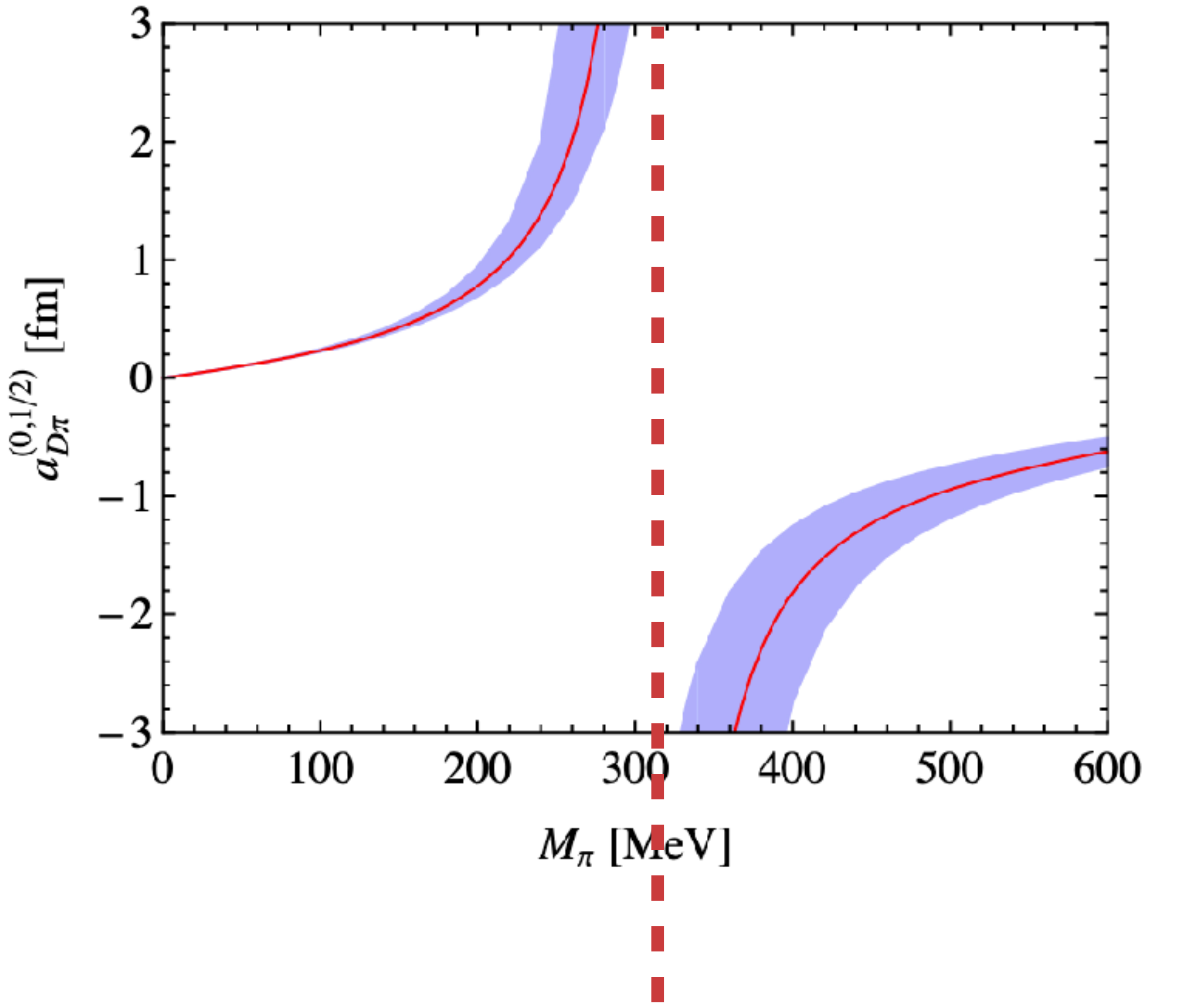
Channel	L. Liu	X.-Y. Guo	Z.-H. Guo-1	Z.-H. Guo-2	B.-L. Huang
Dπ(I=3/2) [fm]	−0,10	−0,11	−0,101	−0,099	−0,06
Dπ(I=1/2) [fm]	0,37	0,33	0,31	0,34	0,61
DK(I=1) [fm]	0,07+i0,17	−0,05	0,06+i0,30	0,05+i0,17	−0,01
D$\bar{\text{K}}$(I=0) [fm]	0,84	0,46	0,96	0,68	1,81
D$\bar{\text{K}}$(I=1) [fm]	−0,20	−0,22	−0,18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

Lednický-Lyuboshits formula

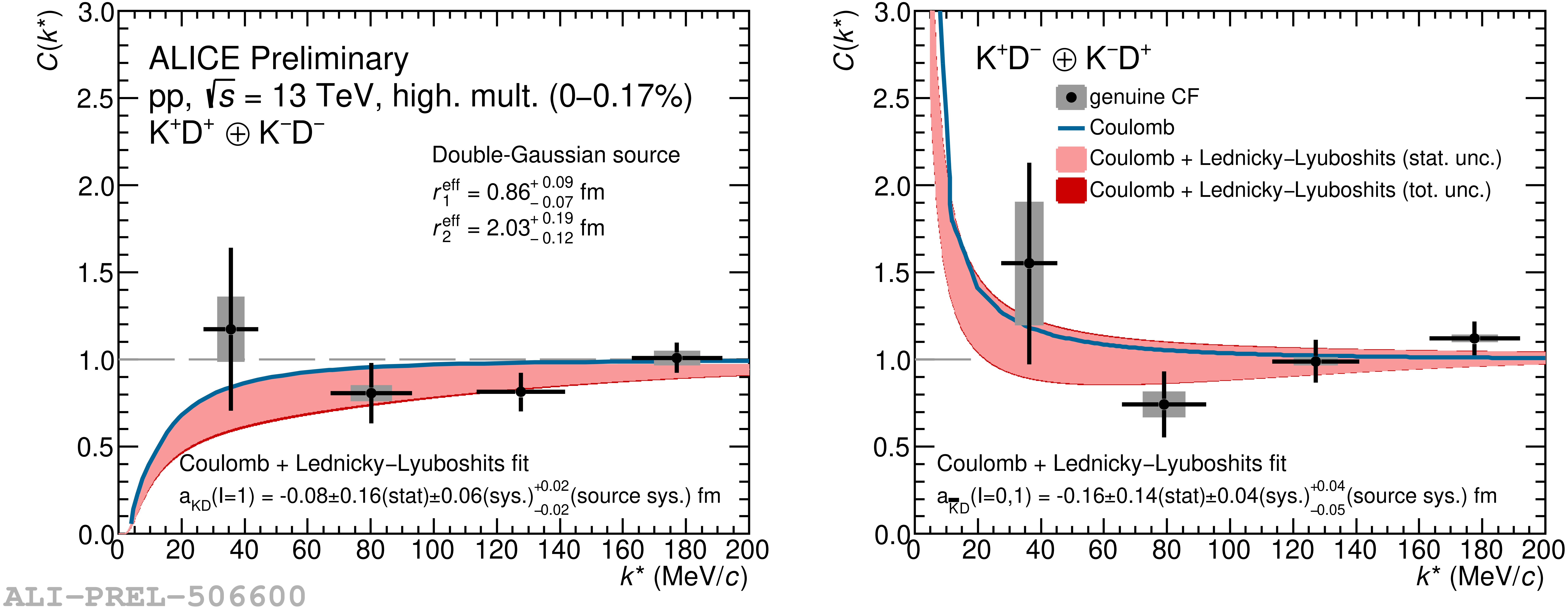
$$C'(k^*) = A_C(k^*)\left\{ 2\left[\frac{1}{4}\left(\frac{|f_C(k^*)|}{r}\right)^2\left[1-\frac{d_0}{2\sqrt{\pi}r}+\frac{1}{2}(A_C(k^*)-1)^2(1-e^{-4(rk^*)^2})\right]+\right.\right.$$
$$+\mathcal{R}(f_C(k^*))\frac{F_1(2k^*r)}{\sqrt{\pi}r}+$$
$$\left.\left.+\mathcal{I}(f_C(k^*))\left[\frac{F_2(2k^*r)}{2r}+(A_C(k^*)-1)k^*\cos(rk^*)e^{-(rk^*)^2}\right]\right]+1\right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

Where

$$f_C(k^*) = \left[\frac{1}{a_0}+\frac{1}{2}d_0k^{*2}-\frac{2}{a_C}h(k^*a_C)-ik^*A_C(k^*)\right]^{-1}$$

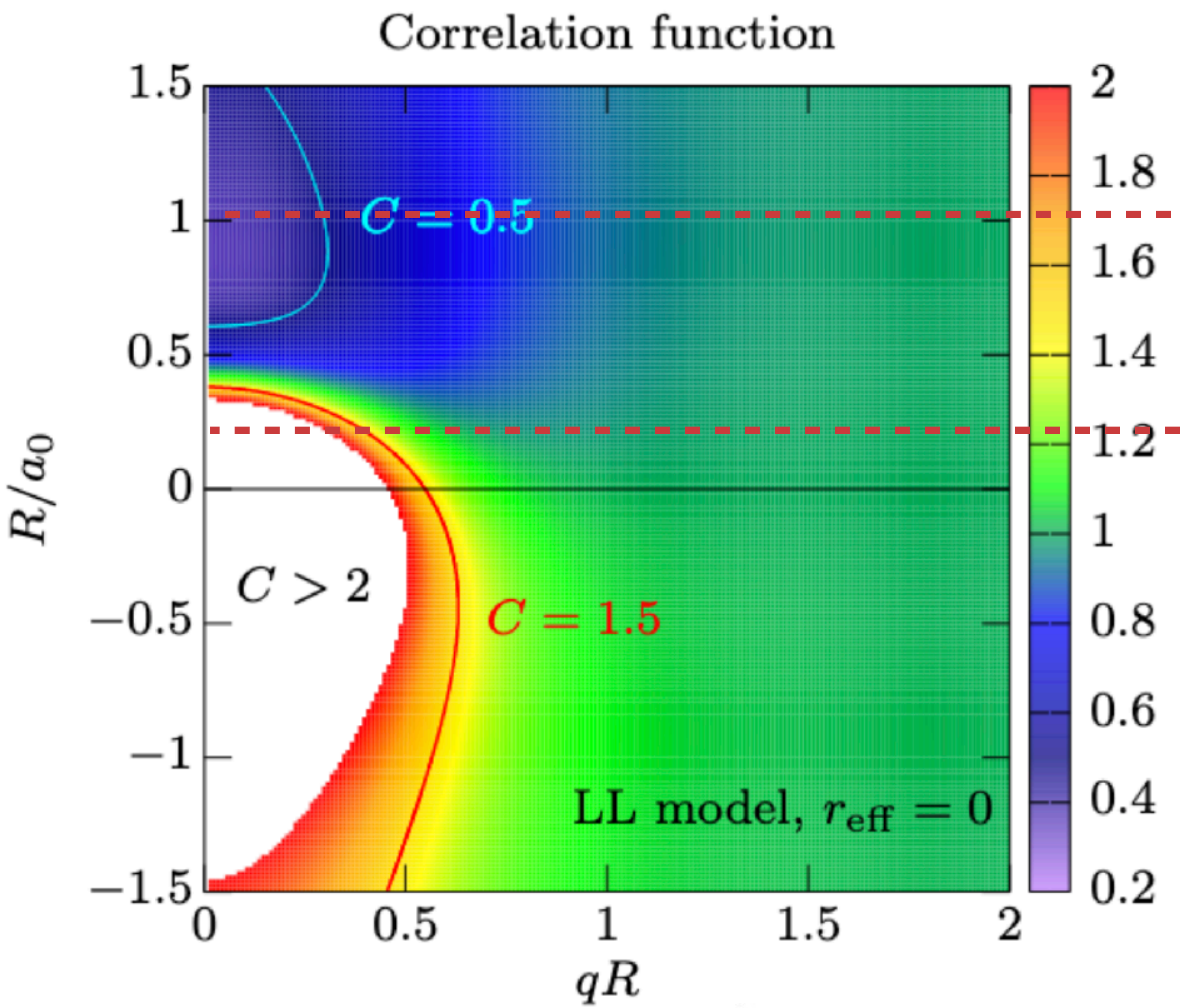
M. Gmitro, J. Kvasil, R. Lednicky, and V.L. Lyuboshits, Czech. J. Phys. B (1986) 36:1281

KD interaction: fit with Lednický-Lyuboshits formula

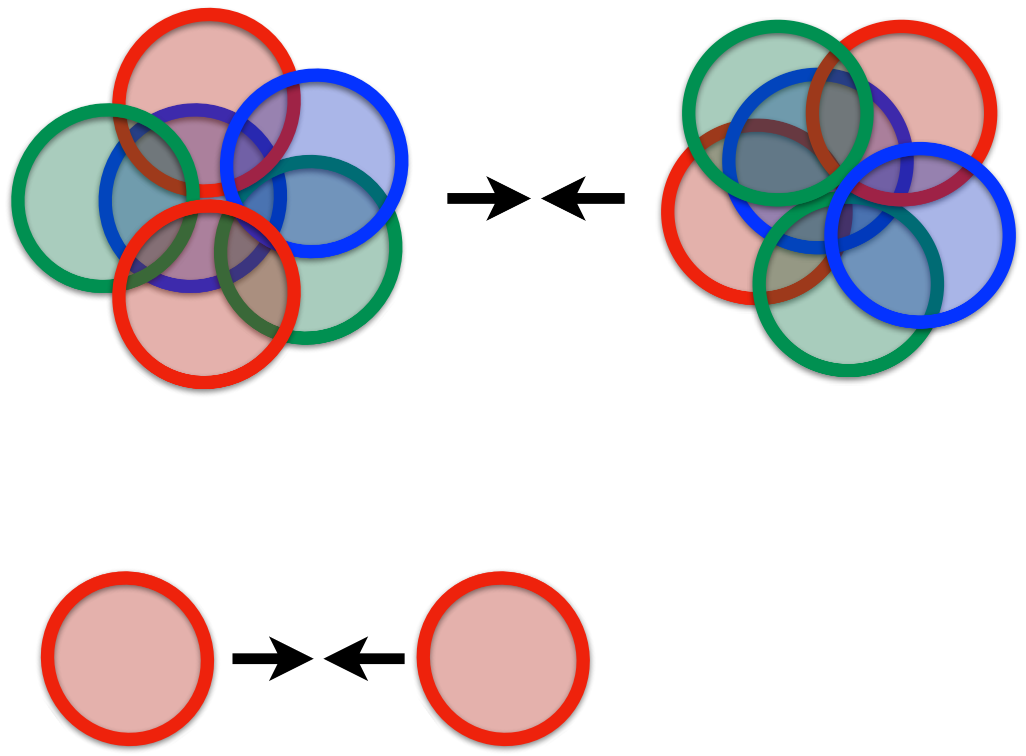


- K^+D^+
  - ➡ I=1 channel only
- K^+D^-
  - ➡ I=0 (50%)
  - ➡ I=1 (50%)

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



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