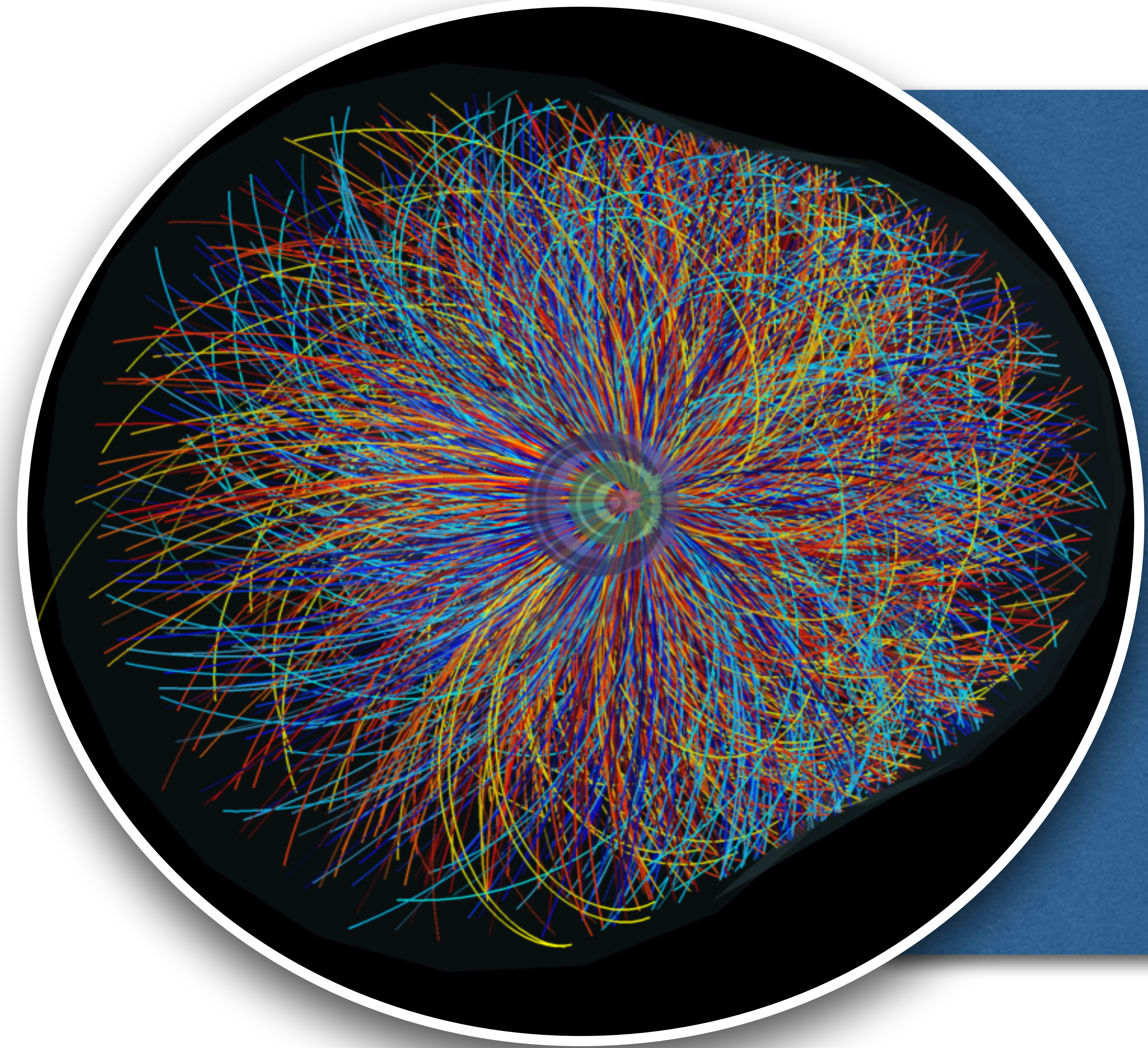


Study of the strong interaction between heavy flavour hadrons

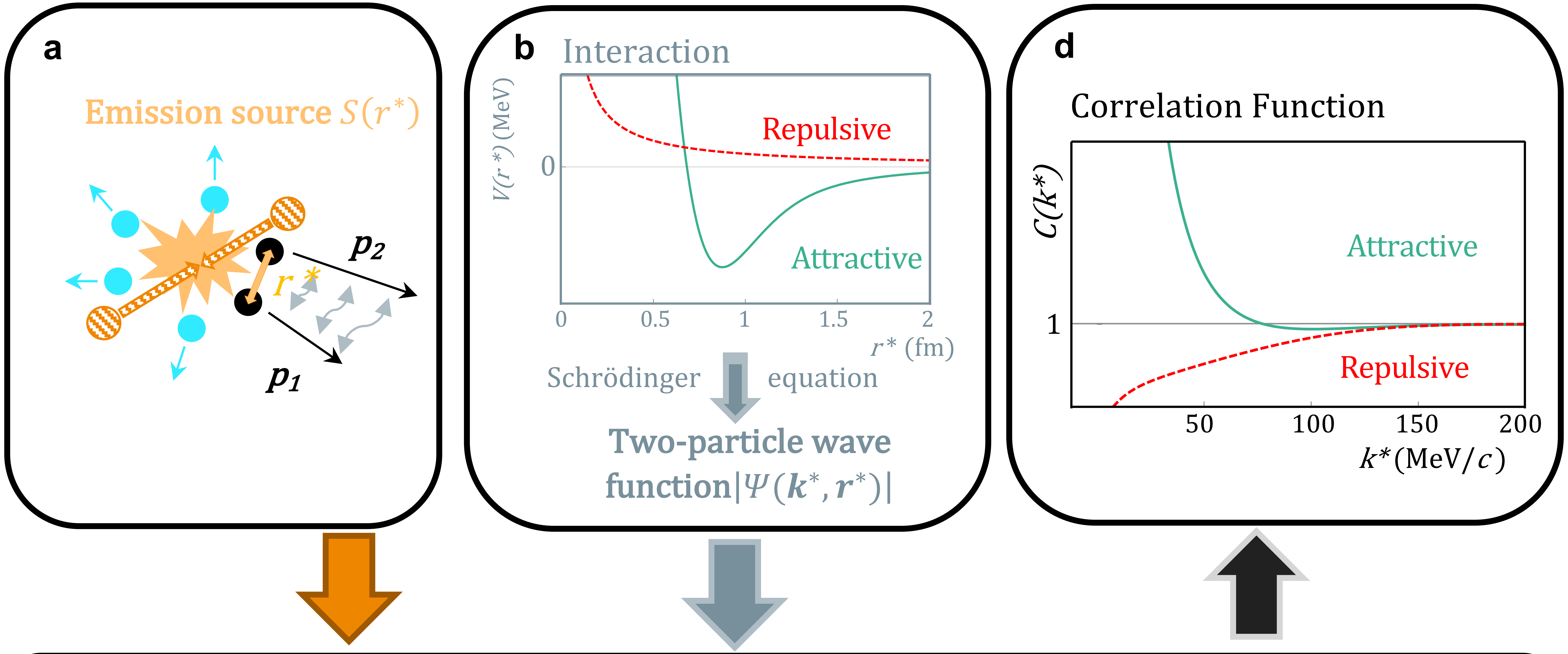
ALICE 3

Laura Fabbietti

18/10/2021

Hadron-hadron interactions studied with femtoscopy the LHC

ALICE coll., Nature 588 (2020) 232–238



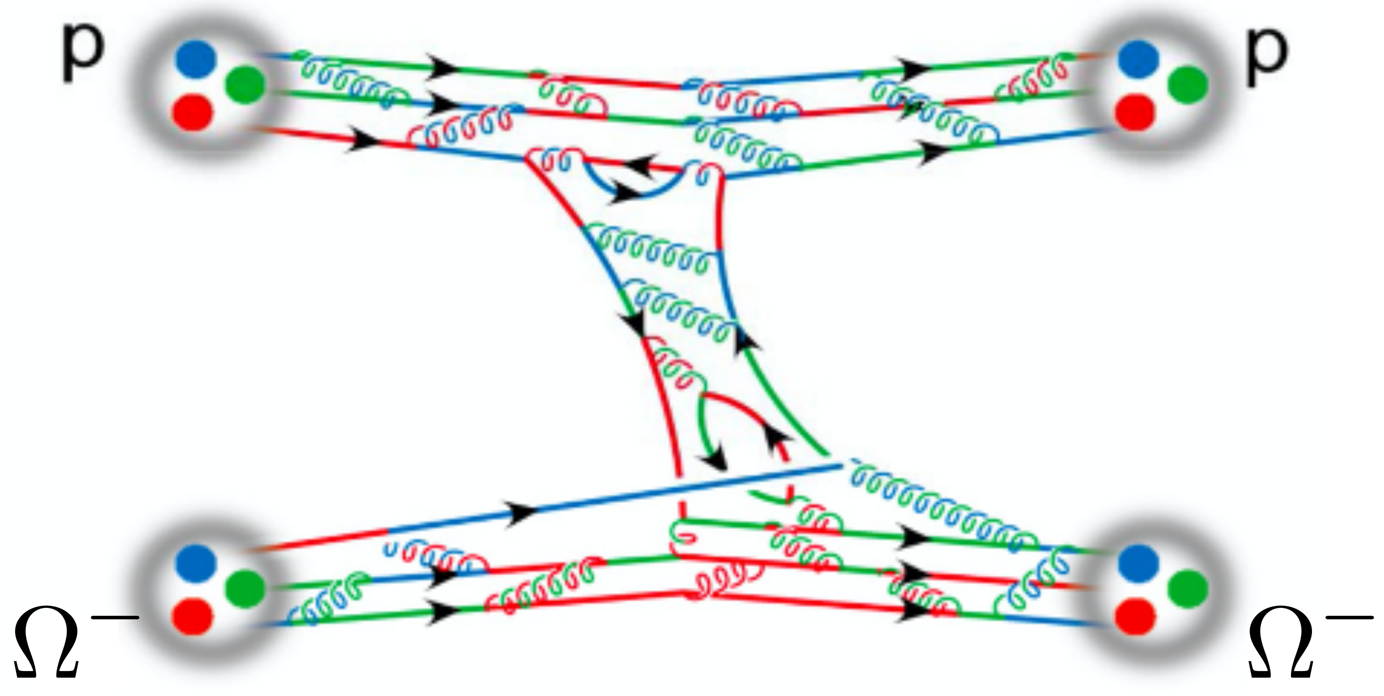
c

$$C(k^*) = \int S(r^*) \; |\Psi(\mathbf{k}^*, \mathbf{r}^*)|^2 \, d^3r^* = \xi(k^*) \otimes \frac{N_{\mathrm{same}}(k^*)}{N_{\mathrm{mixed}}(k^*)}$$

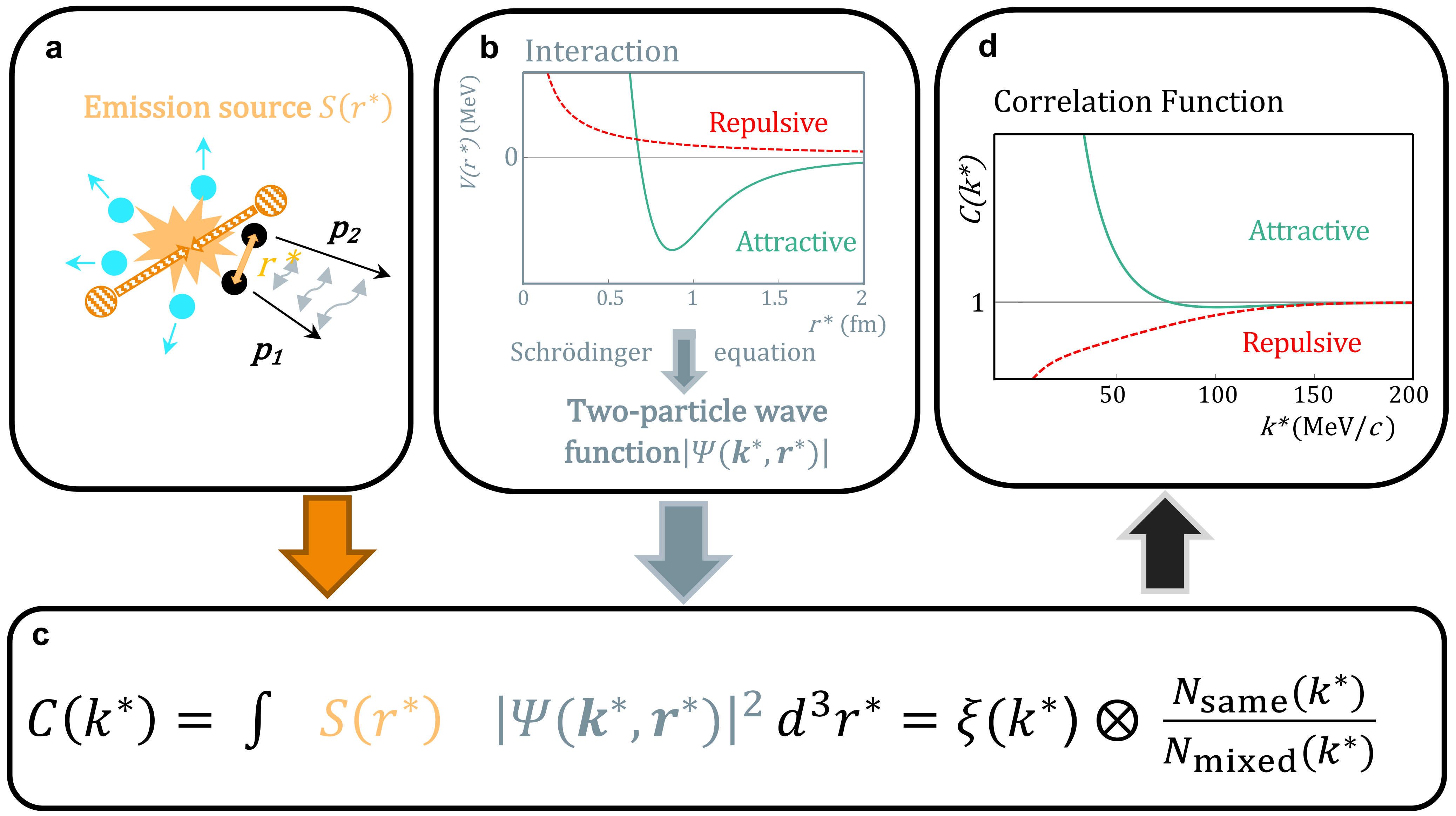
Hadron-hadron interactions studied with femtoscopy the LHC

RUN 2

u, d, s - s



p–K: Phys. Rev. Lett. 124 (2020) 092301
p–p, p–Λ, Λ–Λ: PRC 99 (2019) 024001
p–p, p–Λ, Λ–Λ: 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–Σ⁰: Phys. Lett. B 805 (2020) 135419
p–ϕ: arXiv:2105.05578
N–Λ, N–Σ⁰: arXiv:2104.04427

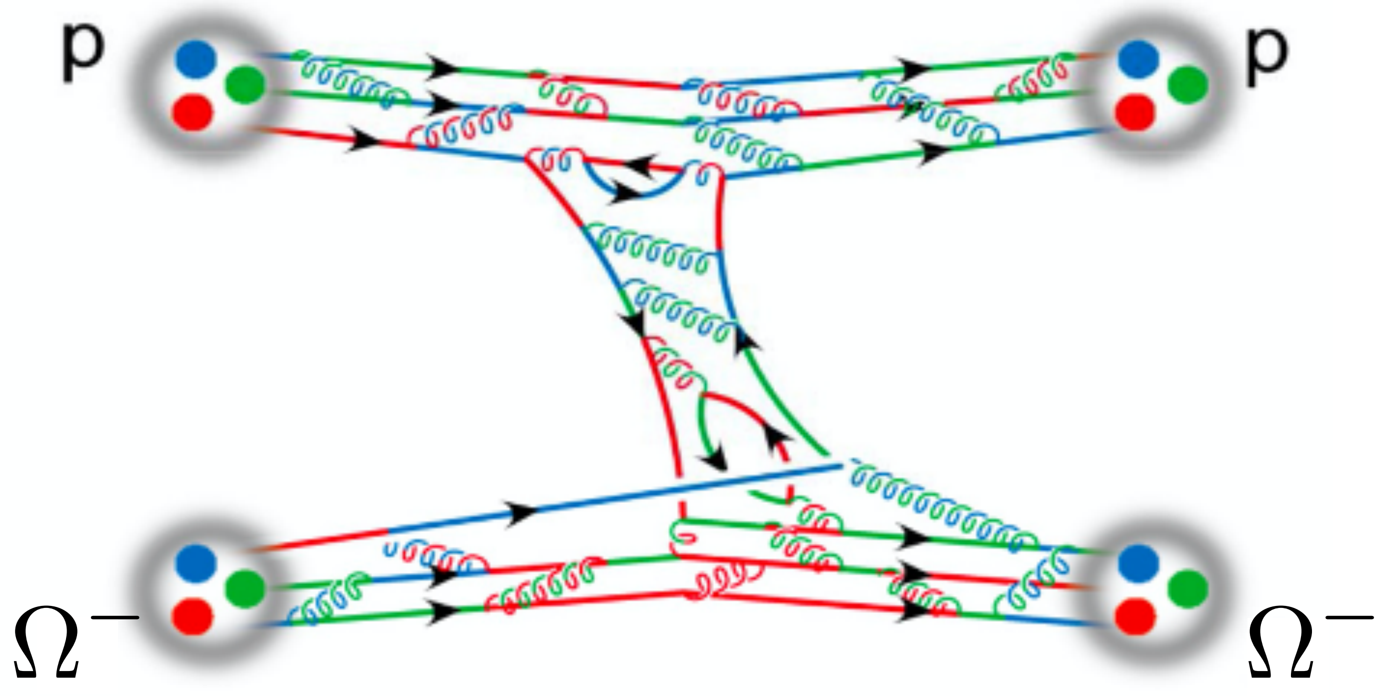


Hadron-hadron interactions studied with femtoscopy the LHC

ALICE

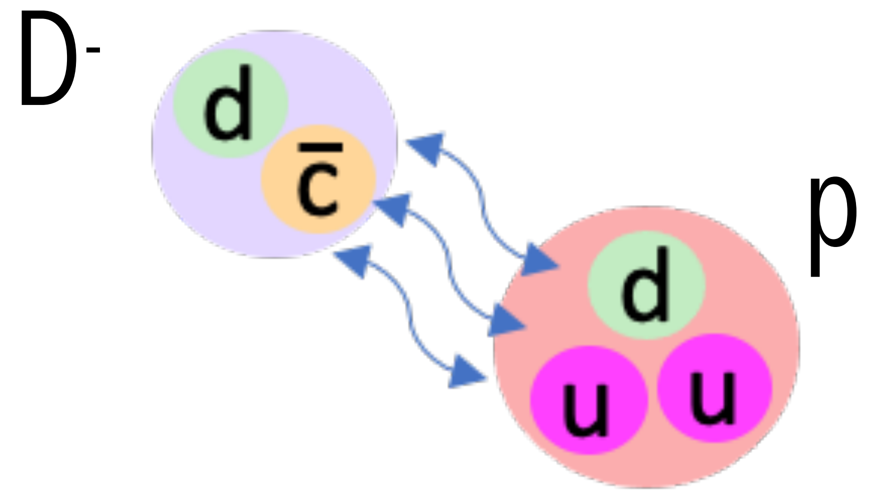
RUN 2

u, d, s - s



RUN 3/4

u, d, s - c



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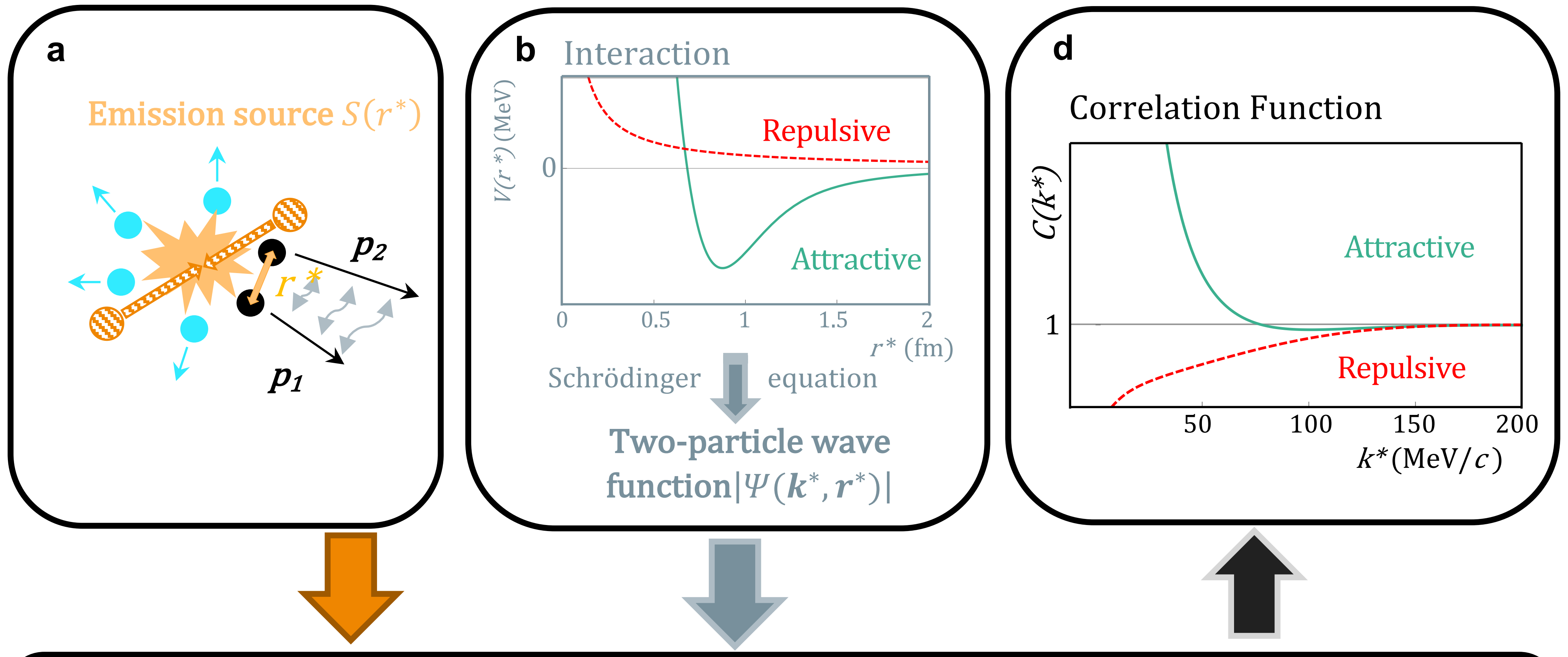

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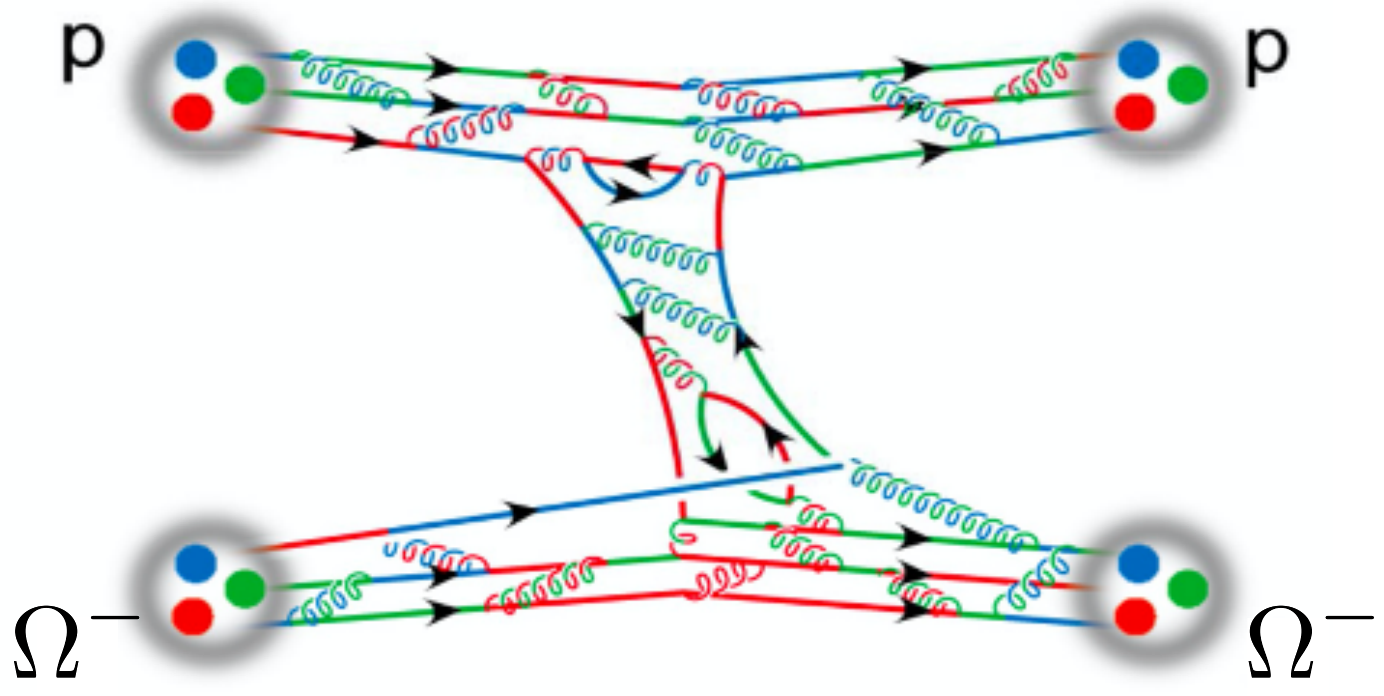
Hadron-hadron interactions studied with femtoscopy the LHC

RUN 2

u, d, s - s



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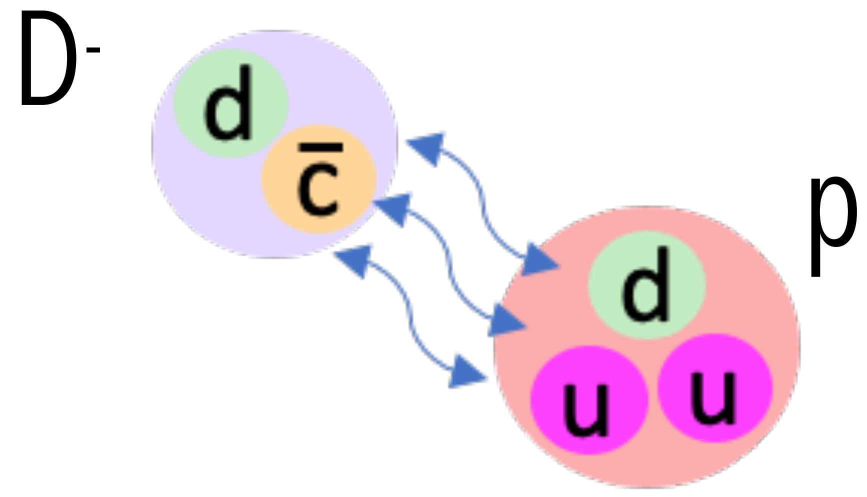
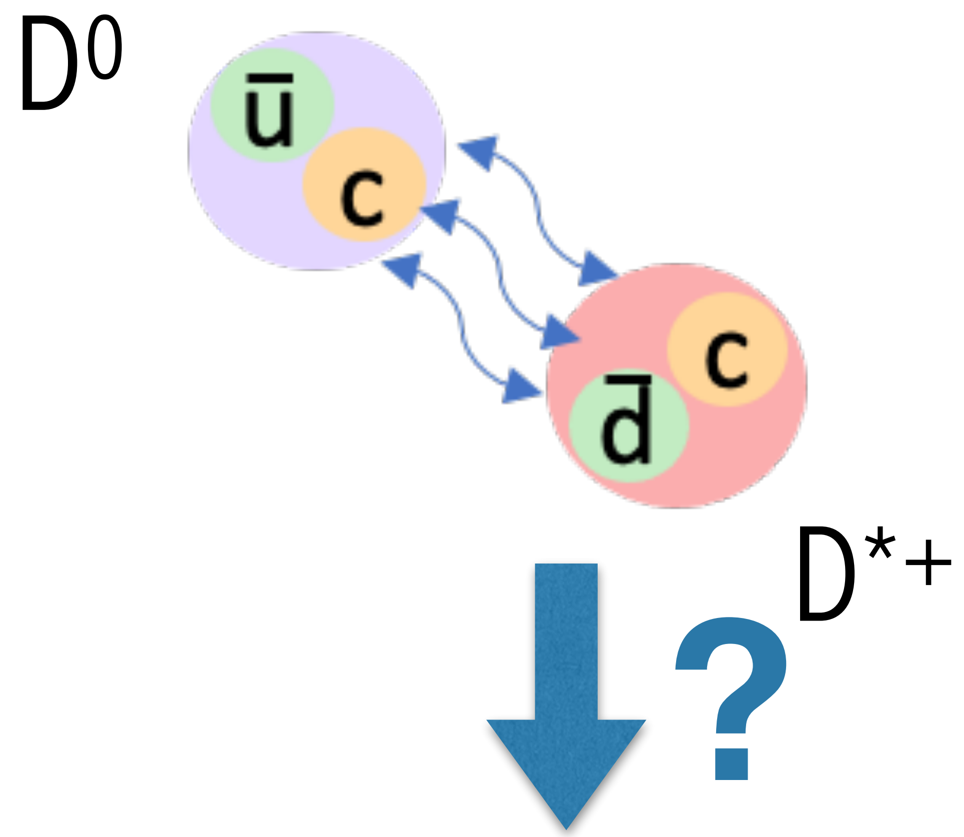
RUN 3/4

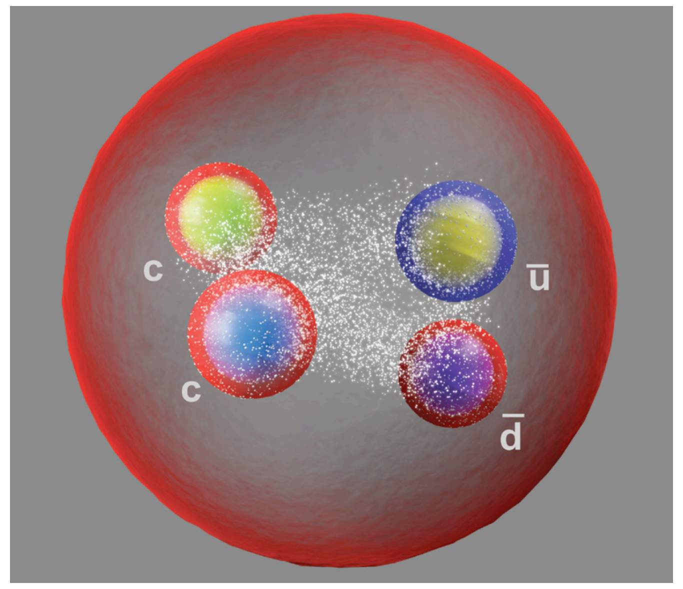
u, d, s - c

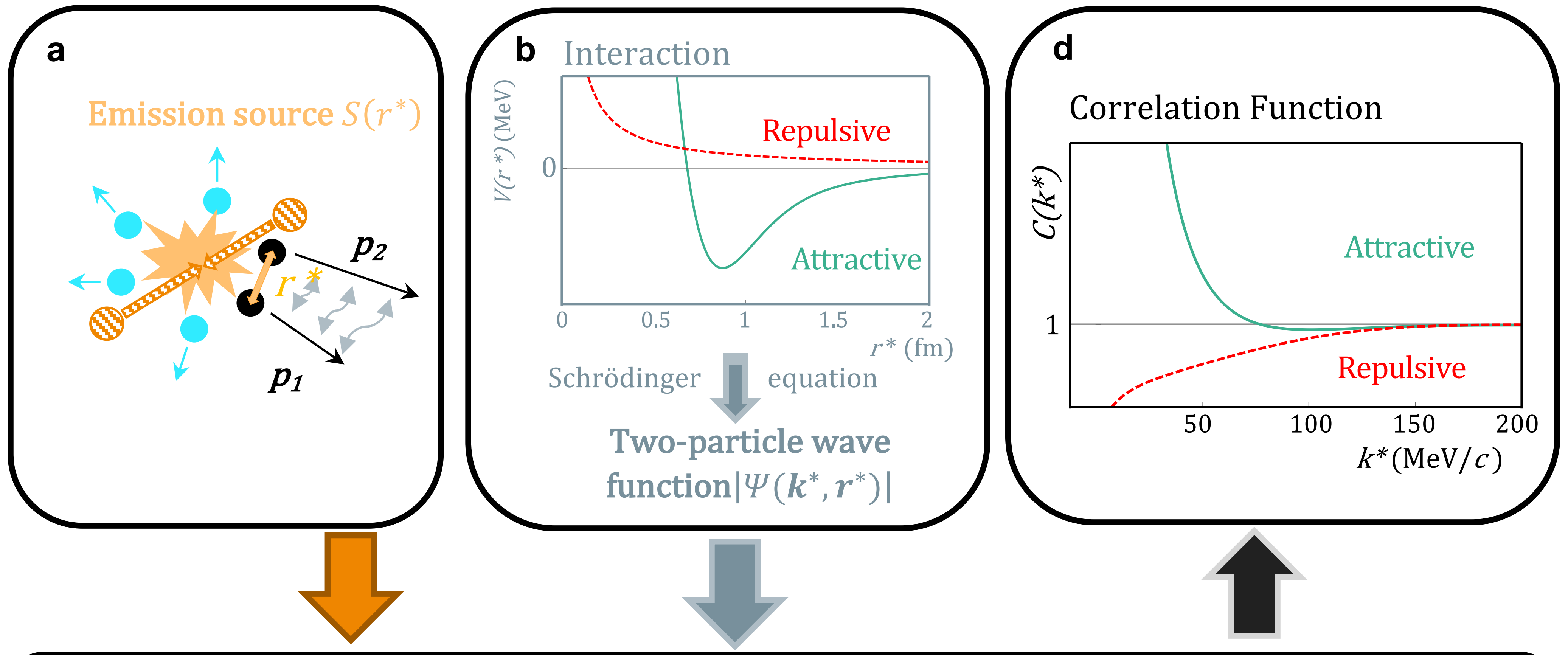


ALICE 3

u, d, s, c, b - c, b







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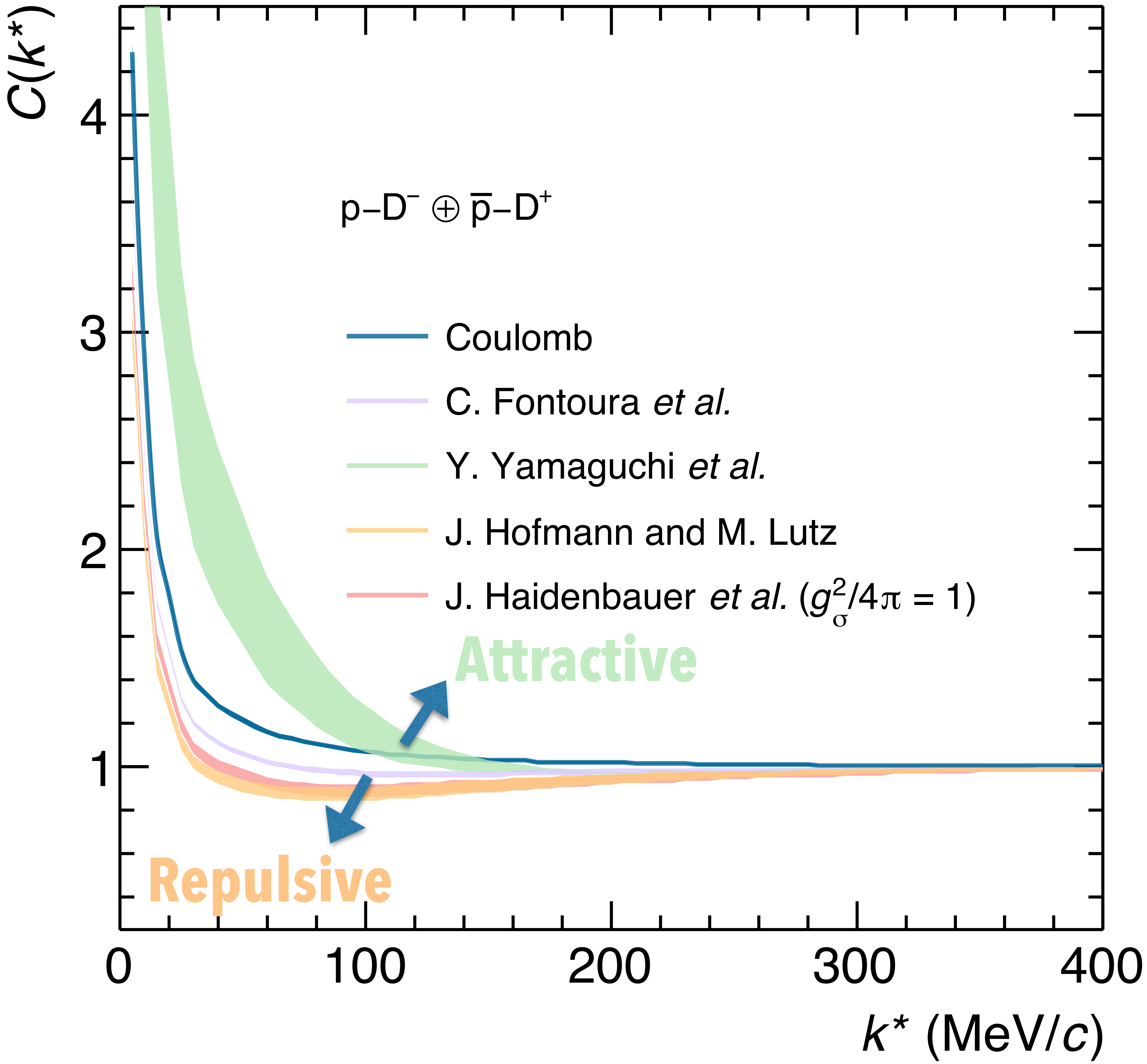
p-D$^-$ correlation function

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



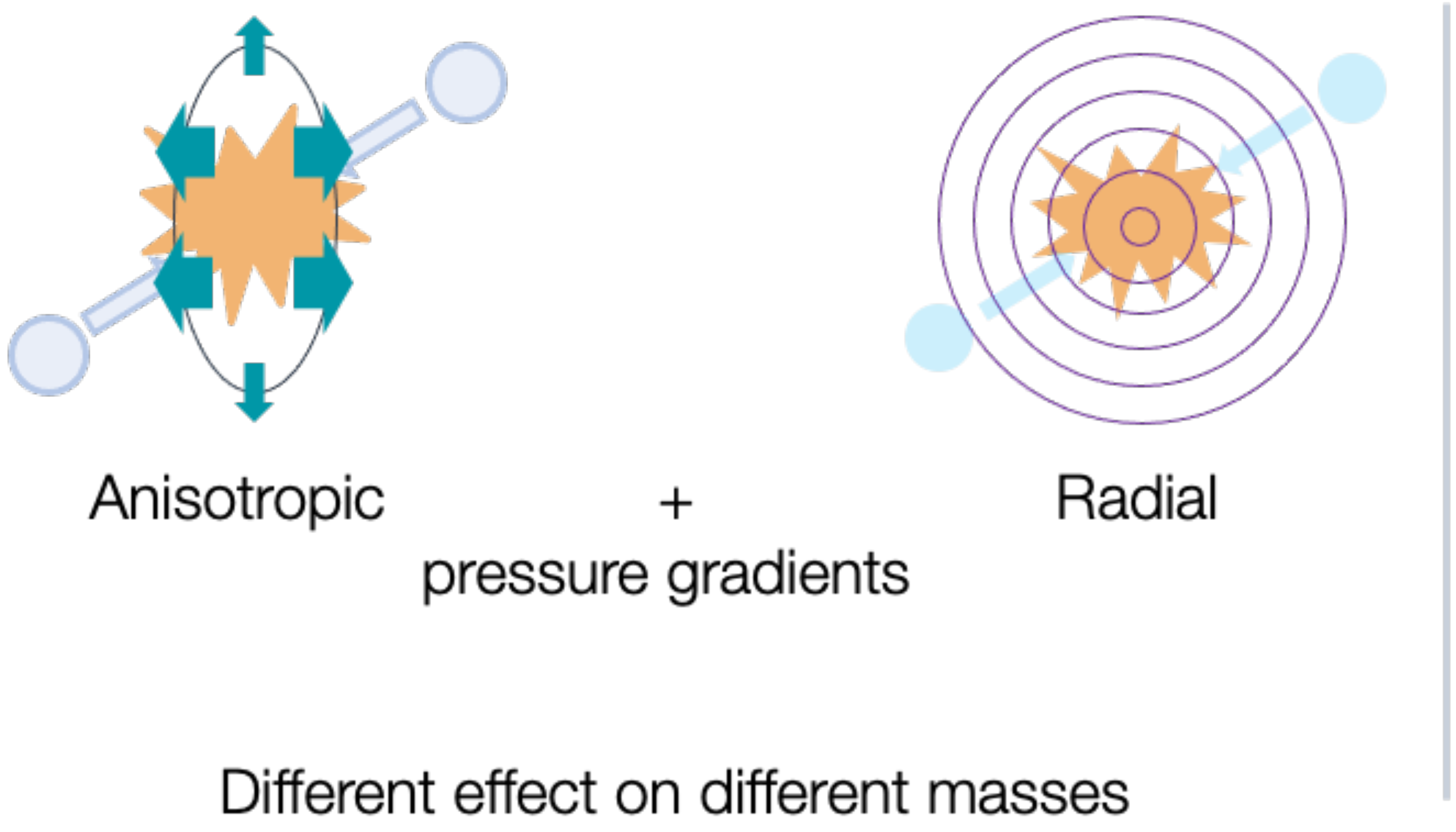
Fontura et al, Phys. Rev. C 87 (2013) 025206
Yamaguchi et al, Phys. Rev. D84 (2011) 014032
J. Hofmann and M. Lutz, Nucl. Phys. A 763 (2005) 90-139
J. Haidenbauer et al, Eur. Phys. J. A33 (2007) 107-117

The emitting source

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

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

$G(\vec{r}^*, r_{\mathrm{core}}, m_T)$ Universal core

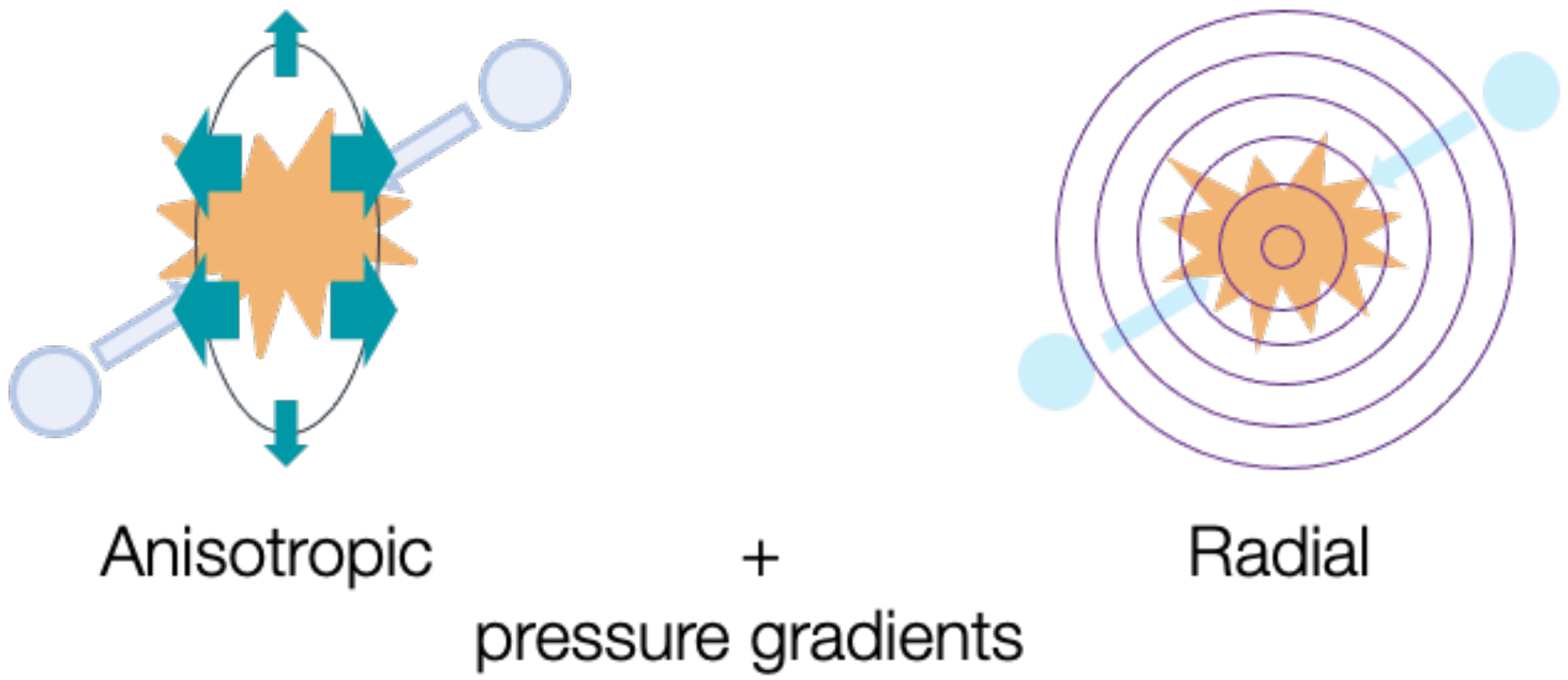


The emitting source

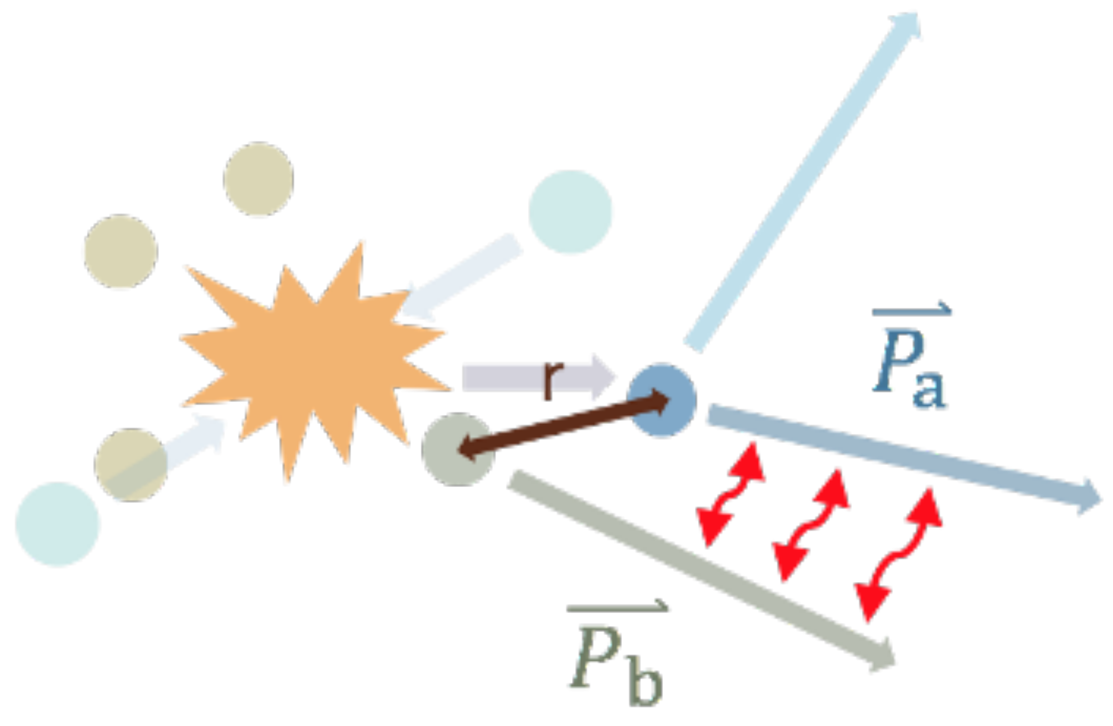
$$C(\vec{k}^*) = \int S(\vec{r}^*)\,|\psi(\vec{k}^*, \vec{r}^*)|^2\, d^3r^*$$

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

$G(\vec{r}^*, r_{core}, m_T)$ Universal core **+** 'Tail' Due to strong resonances



Different effect on different masses

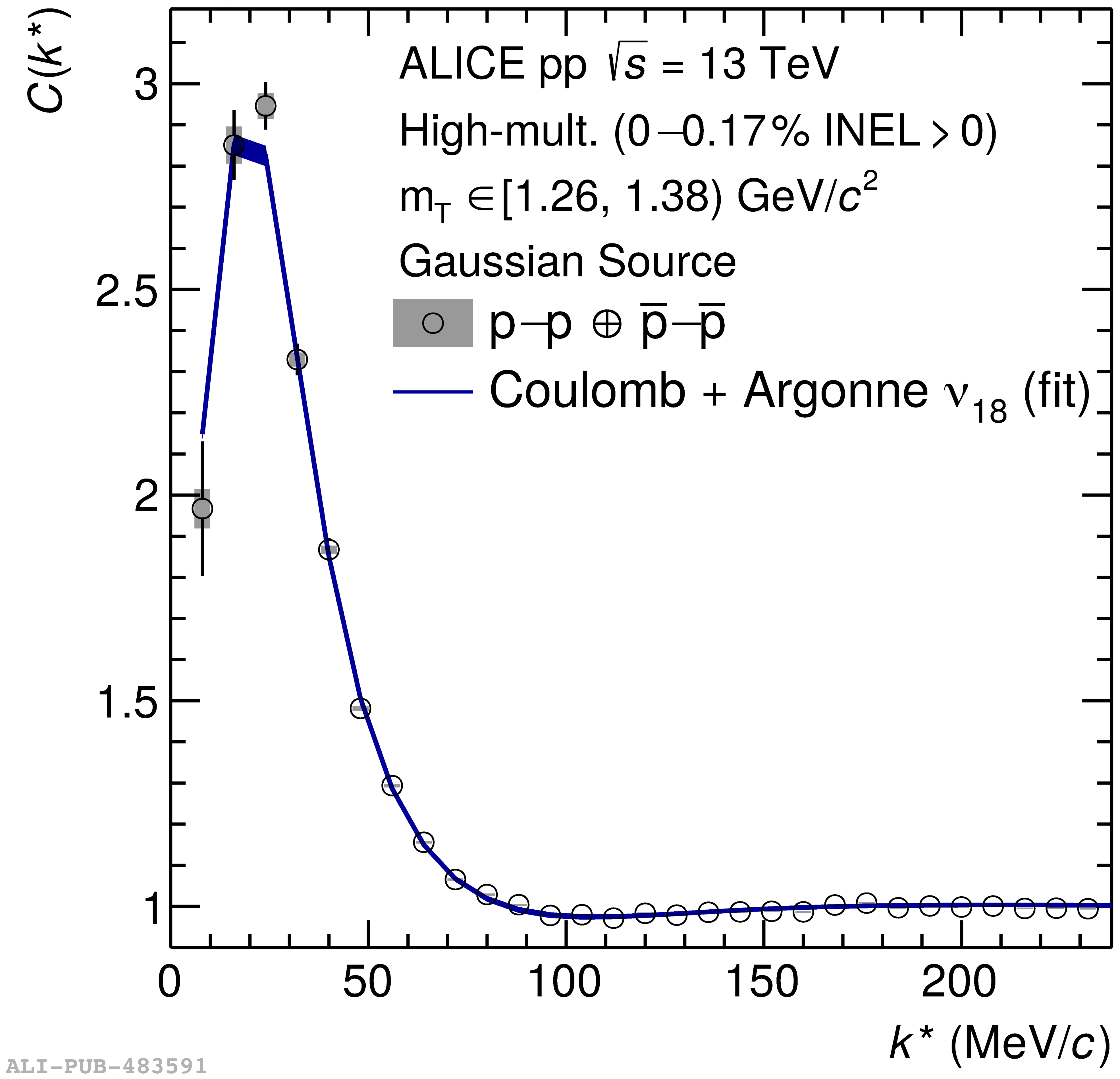


Particle	Primordial fraction	Resonances <cτ>
Proton	33 %	1.6 fm
Lambda	34 %	4.7 fm

U. Wiedemann U. Heinz (PRC56 R610, 1997)

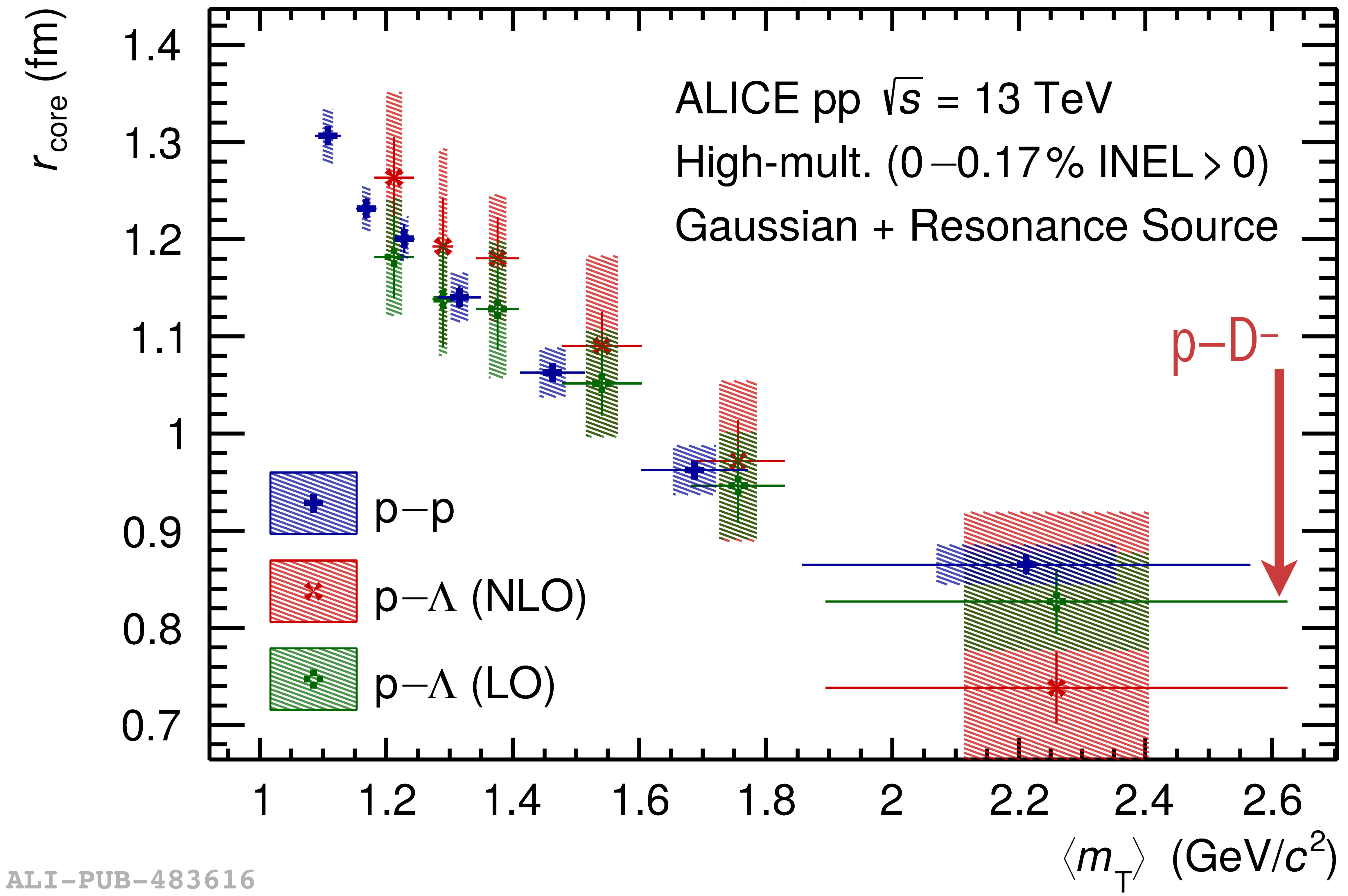
Data-driven modelling of the emitting source

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

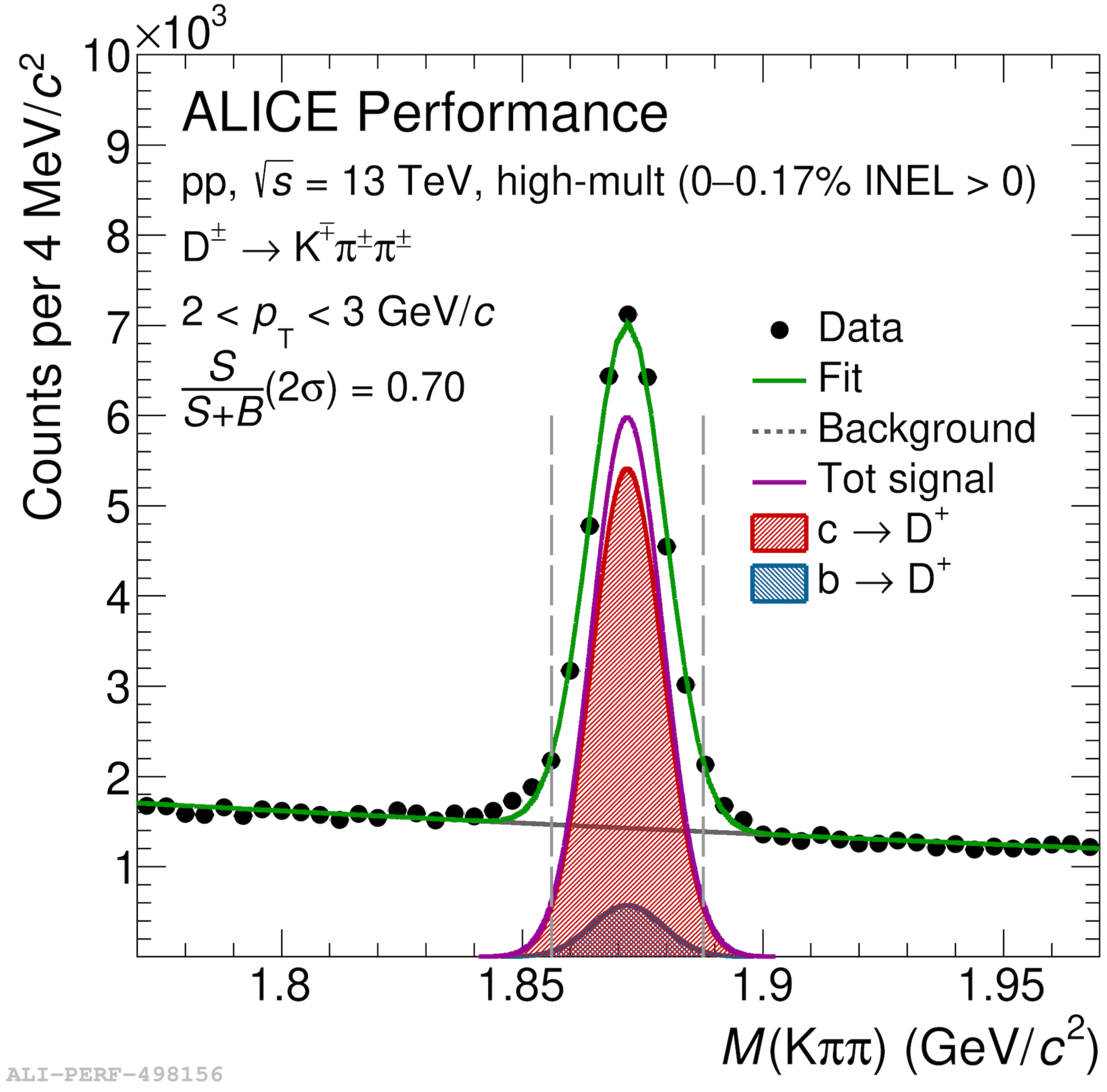


- Source size ~1fm makes the high-multiplicity pp system suitable for the study of hadron–hadron interactions

D- in Run 2

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

hadron	decay channel	$c\tau$ (μm)	BR (%)
D^-	$K^+ \pi^- \pi^-$	312	9,38

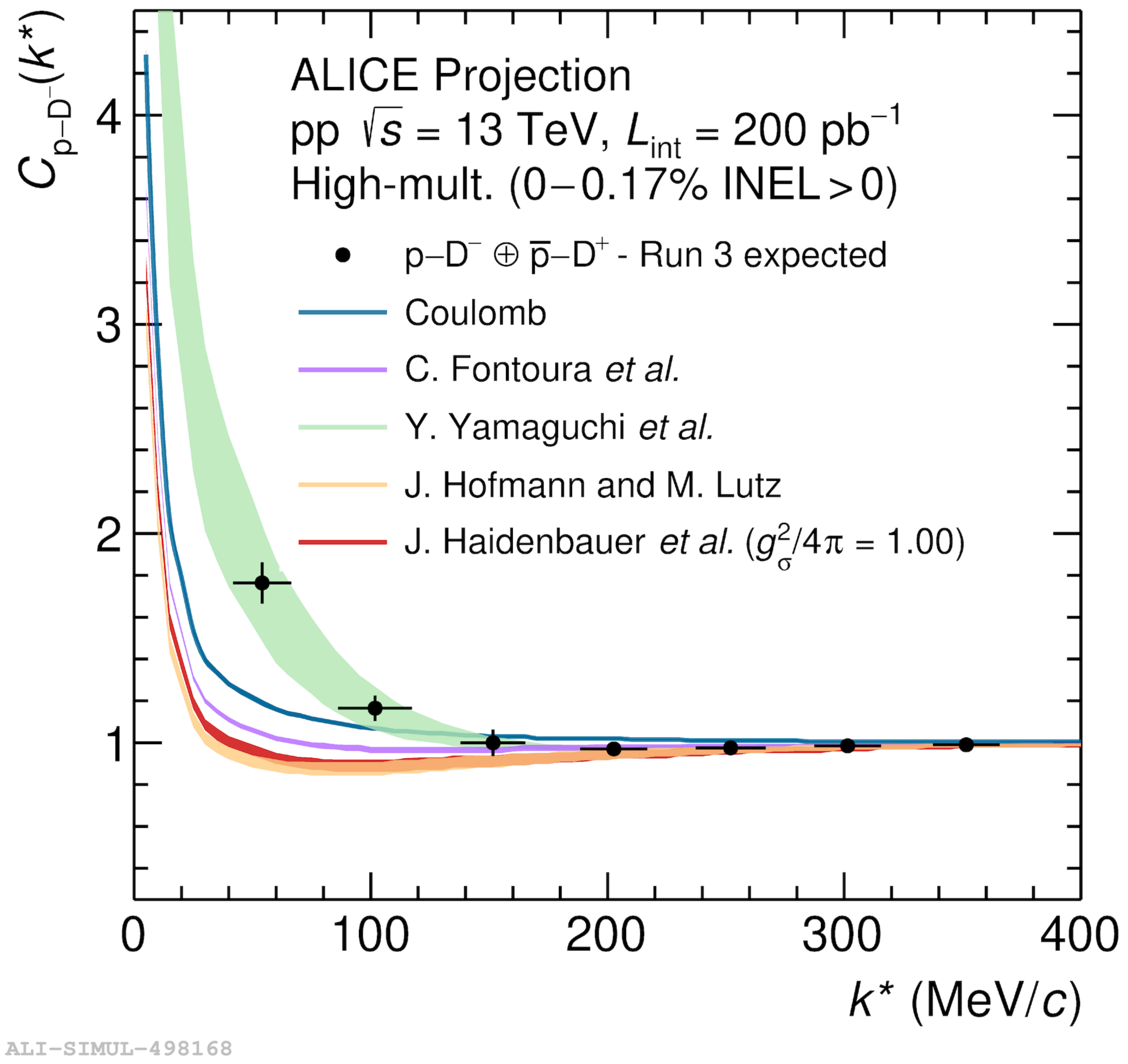


- Excellent identification of D and D*
- Relevant sources of background
  1. Uncorrelated ($K^+ \pi^- \pi^-$) background candidates
     - ➡ Parametrised from the measured C(k*) computed with D^- candidates in the sidebands
  2. D^- from D^{*-} decays (~30% of D^-)
     - ➡ p– D^{*-} strong interaction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

- ⭐ All contributions to the correlation function under control
- ⭐ Statistically at the limit for Run 2 but feasibility demonstrated
- ⭐ Paper in preparation !!

D^- p correlations in Run 3

Projections without improvement factor due to ITS2



Model	f_0 $(I=0)$	f_0 $(I=1)$
Coulomb		
Haidenbauer *et al.* [13]		
$-g_\sigma^2/4\pi = 1$	0.14	−0.28
$-g_\sigma^2/4\pi = 2.25$	0.67	0.04
Hofmann and Lutz [14]	−0.16	−0.26
Yamaguchi *et al.* [16]	−4.38	−0.07
Fontoura *et al.* [15]	0.03	−0.25

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

J. Haidenbauer et al, Eur. Phys. J. A33 (2007) 107-117
J. Hofmann and M. Lutz, Nucl. Phys. A 763 (2005) 90-139 — Repulsive
Fontura et al, Phys. Rev. C 87 (2013) 025206

In Run 3 we will test with precision the interactions among charm and non charmed hadrons

Which correlations could be of interest ?

State	Mass [MeV]	Width [MeV]	S-wave threshold [MeV]	Coupled Channels
X(3872) [14]	3872 ± 0.17	1.19 ± 0.21	$D^{*0}\bar{D}^0(-0.04)$, $D^{*+}\bar{D}^-(-8.11)$	$\pi^+\pi^- J/\psi$, $\pi^+\pi^-\pi^0 J/\psi$
X(3940) [14]	3942 ± 9	37	$D^*\overline{D}^*$ (-75 ±9)	$D^*\bar{D}$
X(4140) [14]	4147 ± 4.5	83 ± 21	$D_s\overline{D}_s^*$ $(-66^{+4.9}_{-3.2})$	$\phi J/\psi$
X(4274) [14]	4273 ± 8.3	56 ± 11	$D_s\overline{D}_s^*$ $(-49.1^{+19.1}_{-9.1})$	$\phi J/\psi$
$Z_b(10610)$ [14]	10607 ± 2.0	18.4 ± 2.4	$B\overline{B}^*(4 \pm 3.2)$	$\pi^\pm\Upsilon(nS)$ $\pi^\pm h_b(nP)$
$Z_b^\pm(10650)$ [14]	10652.2 ± 1.5	11.5 ± 2.2	$B^*\bar{B}^*(+2.9)$	$\pi^\pm\Upsilon(nS)$ $\pi^\pm h_b(nP)$
$P_c^+(4312)$ [15]	$4311.9 \pm 0.7^{+6.8}_{-0.6}$	$9.8 \pm 2.7^{+3.7}_{-4.5}$	$\Sigma_c\bar{D}(-9.7)$	pJ/ψ
$P_c^+(4440)$ [15]	$4440.3 \pm 1.3^{+4.1}_{-4.7}$	$20.6 \pm 4.9^{+8.7}_{-10.1}$	$\Sigma_c\bar{D}^*(-21.8)$	$pJ/\psi, \Sigma_c\bar{D}\Sigma_c^*\bar{D}$
$P_c^+(4457)$ [15]	$4457.3 \pm 0.6^{+4.1}_{-1.7}$	$6.4 \pm 2.0^{+5.7}_{-1.9}$	$\Sigma_c\bar{D}^*(-4.8)$	$pJ/\psi, \Sigma_c\bar{D}\Sigma_c^*\bar{D}$
T_{cc}^+ [16]	3874.827	0.410	$D^{*+}D^0(-0.273)$, $D^{*0}D^+(-1.523)$	$D^0D^0\pi^+$

Tetraquarks with $c\bar{c}$?

Tetraquarks with $b\bar{b}$?

Pentaquarks with $c\bar{c}$?

Tetraquarks with cc ?

Or all molecular states ?

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

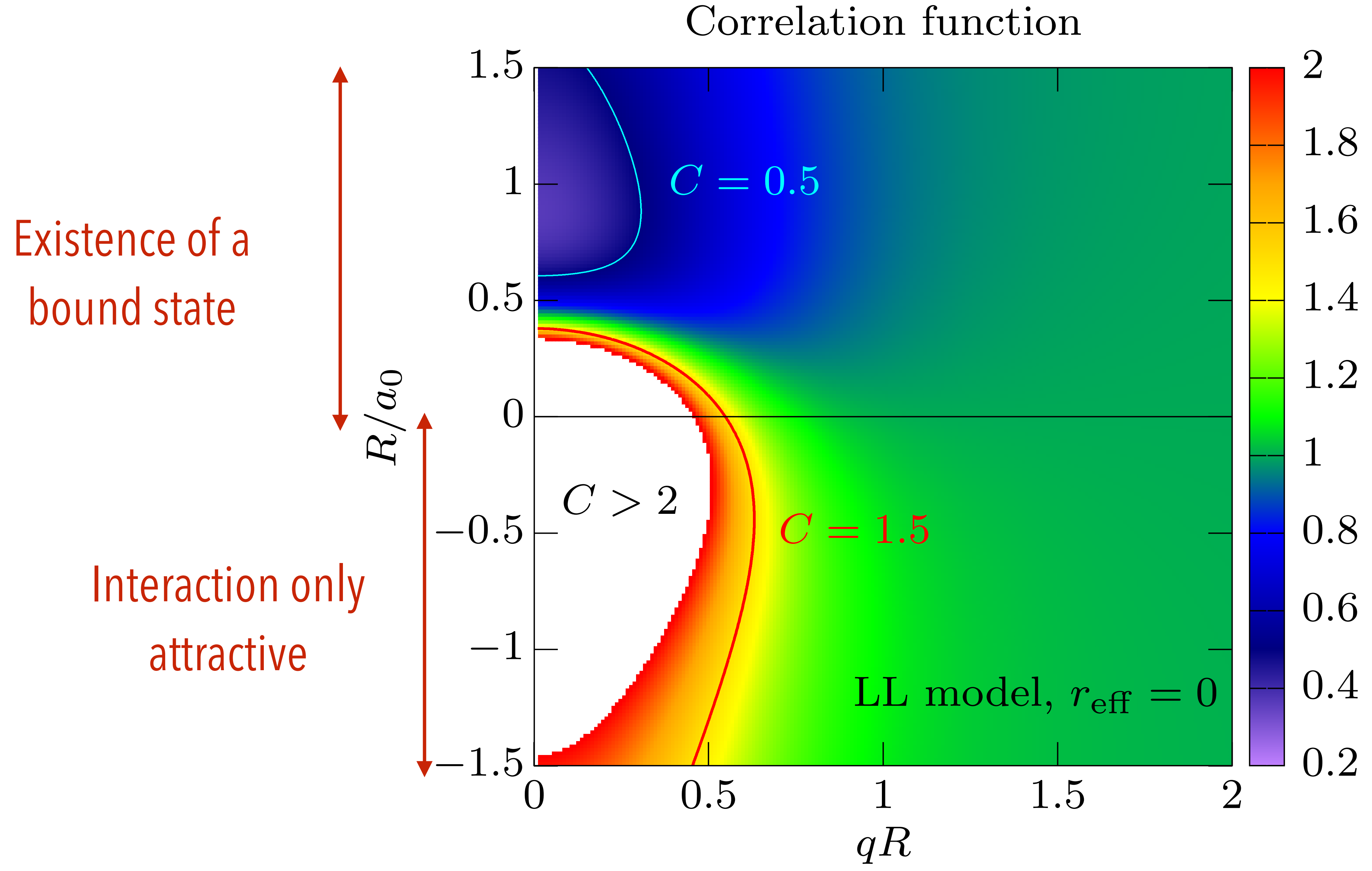
$$x = qR \quad y = \frac{R}{a_0} \qquad C(q) = 1 + \frac{1}{x^2 + y^2}\left[\frac{1}{2} - \frac{2y}{\sqrt{\pi}}\int_0^{2x} dt \frac{e^{t^2-4x^2}}{x} - \frac{(1-e^{-4x^2})}{2}\right]$$

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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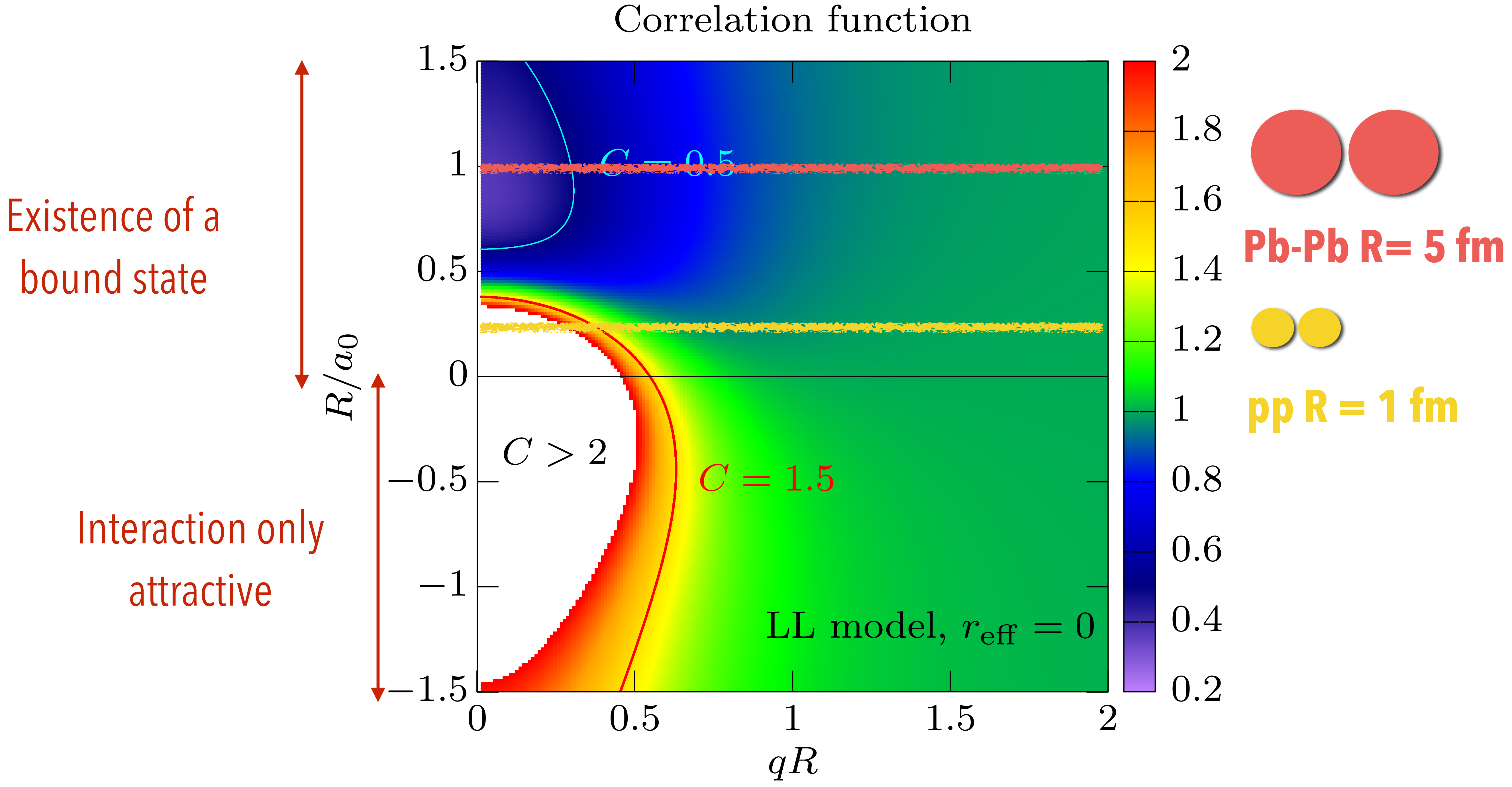
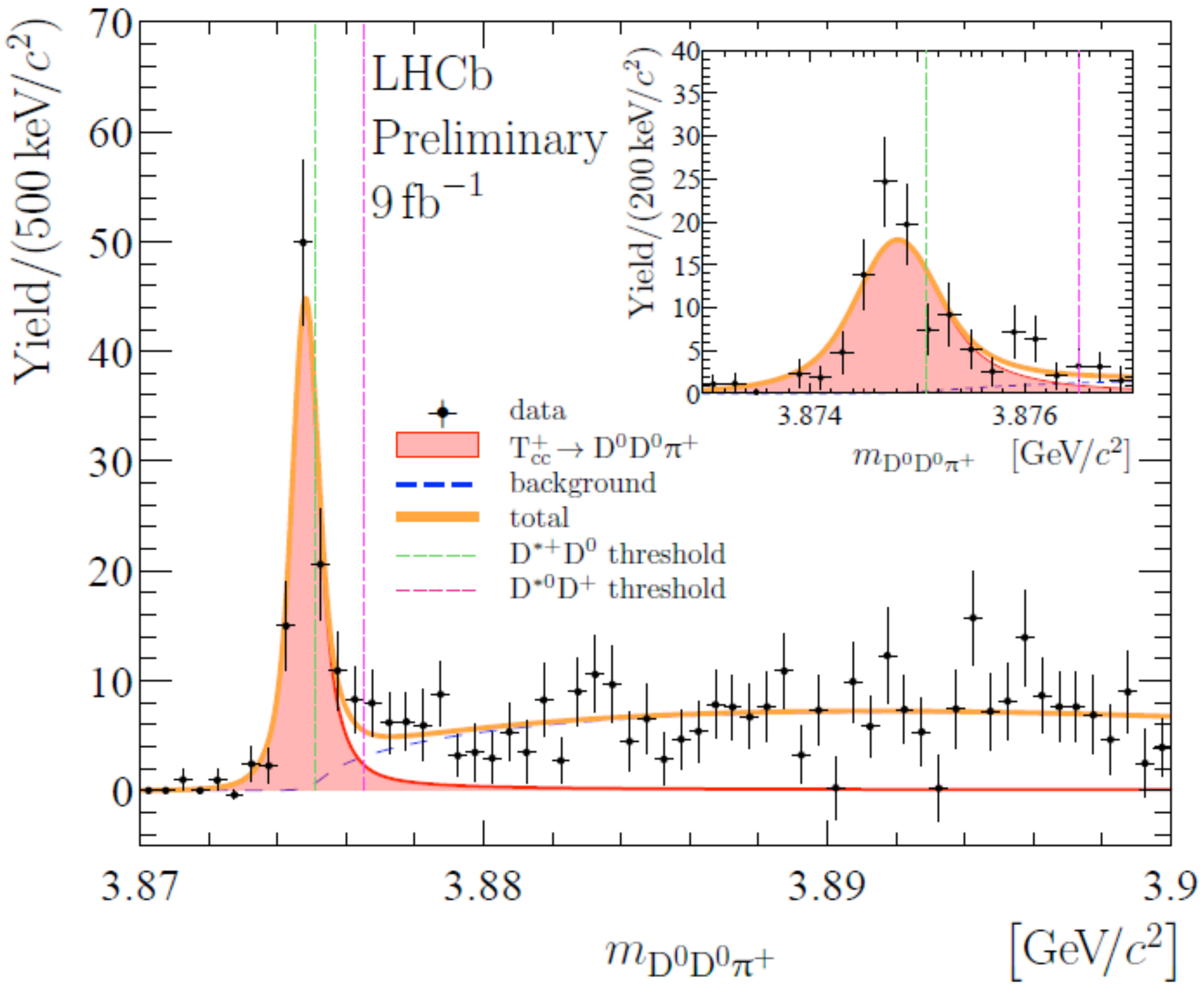
Example: a_0 = 5 fm



Y. Kamiya et al. arXiv:2108.09644v1

The T_{cc}^{+} example

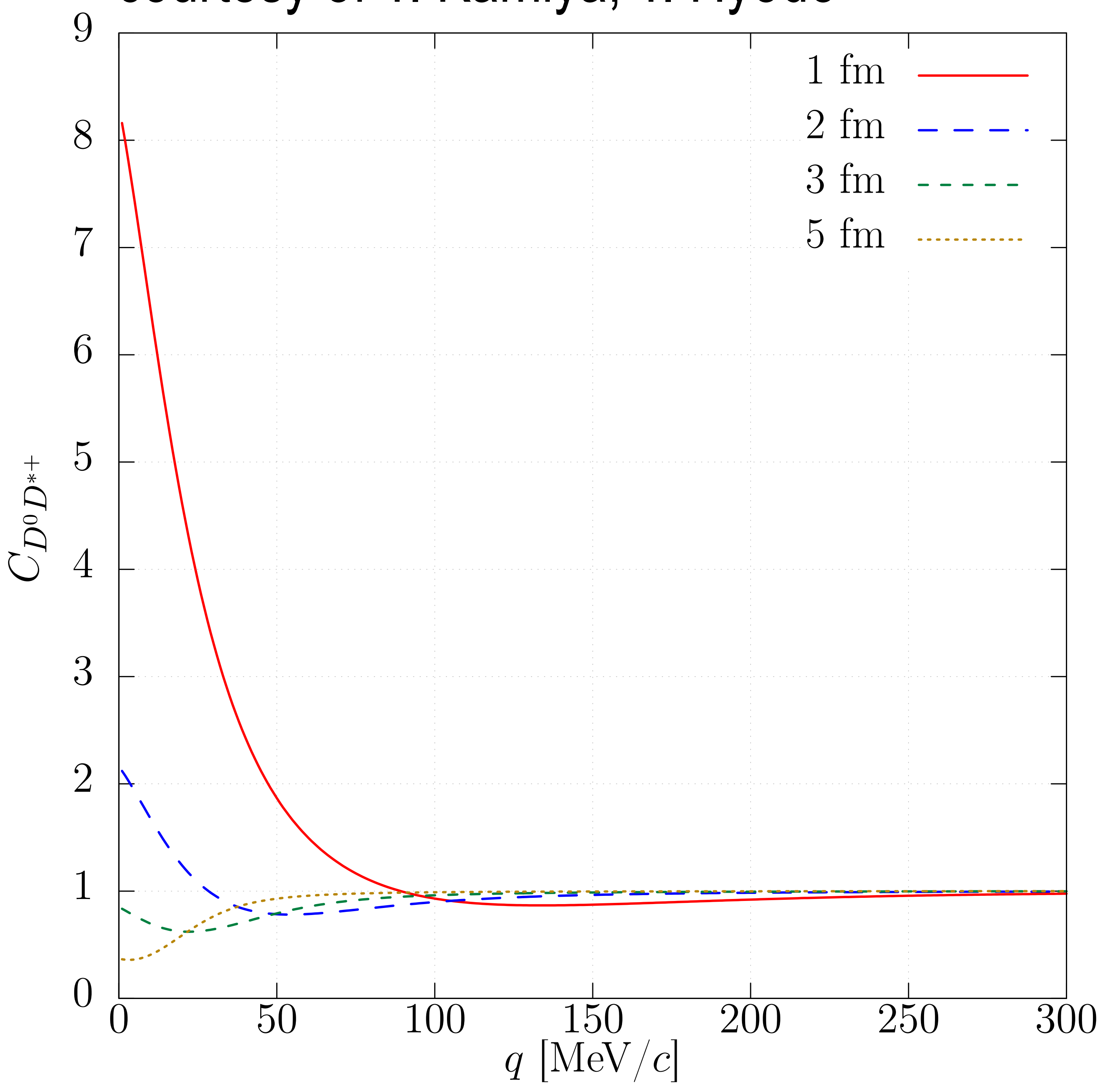
- Recent measurement of a tetraquark candidate by LHCb
  - ➡ Just below D^0D^{*+} and D^+D^{*0} thresholds → candidate to be a molecular state



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

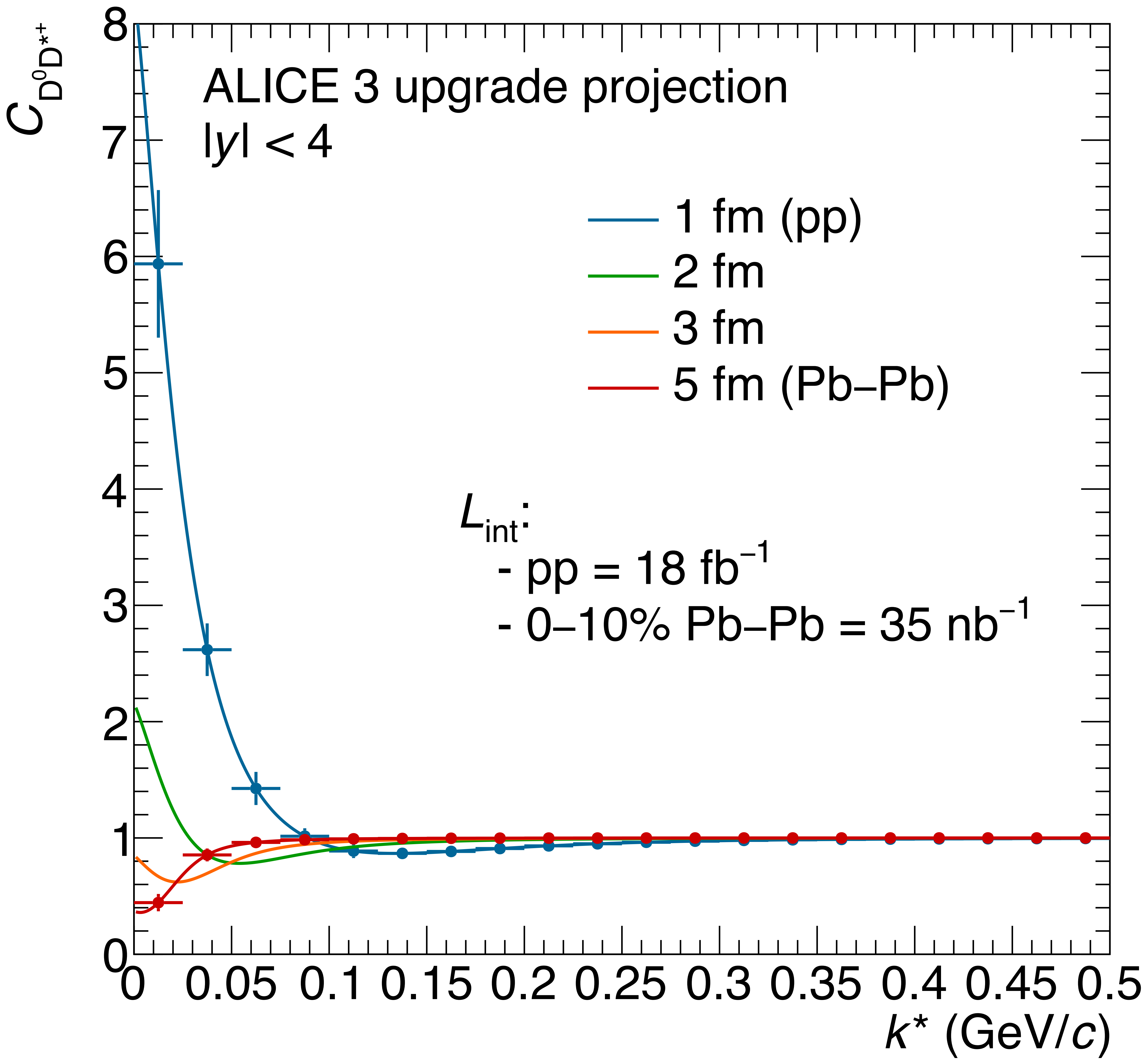
- Its nature can be assessed via the measurement of DD* correlations
  - ➡ In case of a bound state (T_{cc}^{+}) the correlation function is expected to change from smaller to larger than unity for different source sizes

courtesy of Y. Kamiya, T. Hyodo



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

ALICE 3 projections for the $D^{*+}D^0$



- Projection according to 6 years of data taking
- Enough sensitivity to verify/exclude formation of bound state
- Although scan over wide range of source size needed
  - ➡ Necessity to perform measurement from pp to Pb–Pb

Reminder:

A comprehensive measurement of the correlations among proton, hyperons and kaons is necessary to pin down the source properties

Summary of the strong interaction studies between heavy flavour hadrons

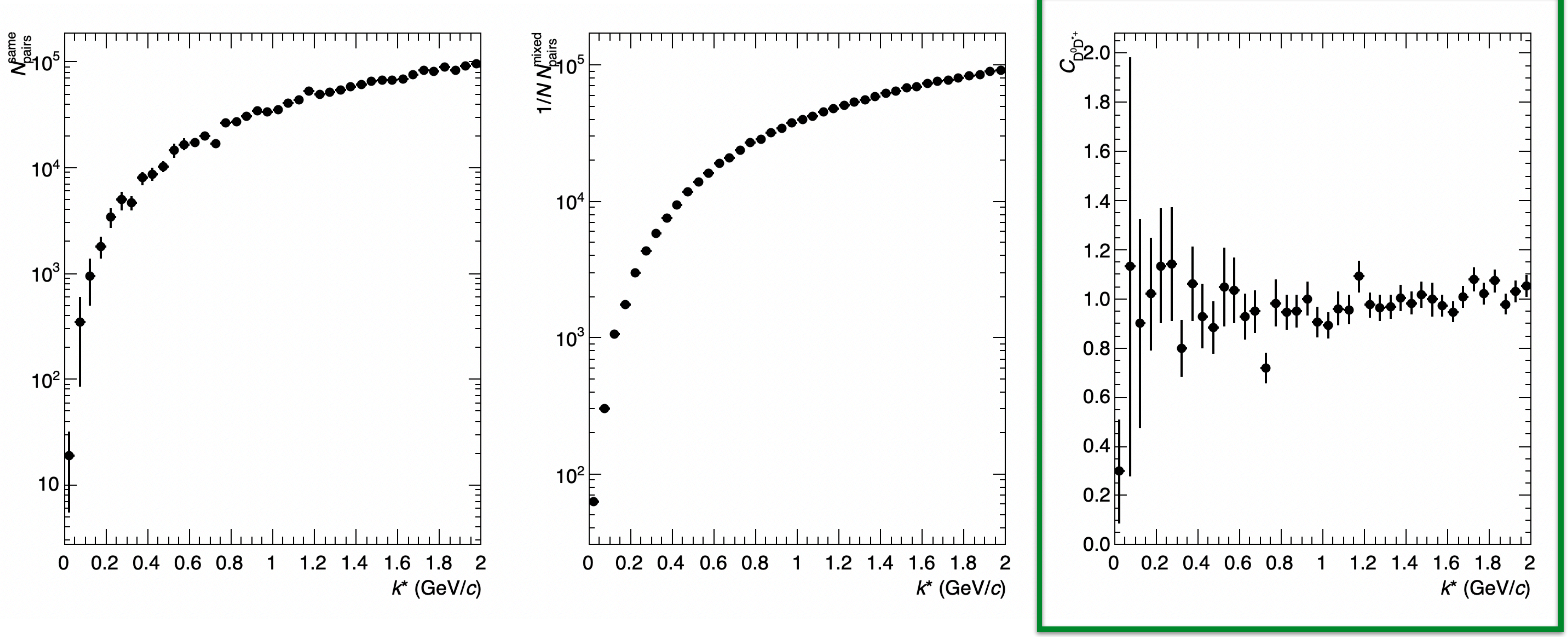
- Femtoscopy at the LHC has been established as a solid technique to study the residual strong interaction among hadrons
- Run 2: the (almost) complete set of interaction u,d,s-s has been measured!
- Run 3: all the interactions among u,d,s -c,s will be accessed with high precision
- ALICE3: c-c, b-b correlations will be measured in different colliding system to test residual strong interaction and study molecular state
- ALICE3 unique detector for its large geometrical acceptance and vertexing resolution for charm and beauty hadron and strange weak decays

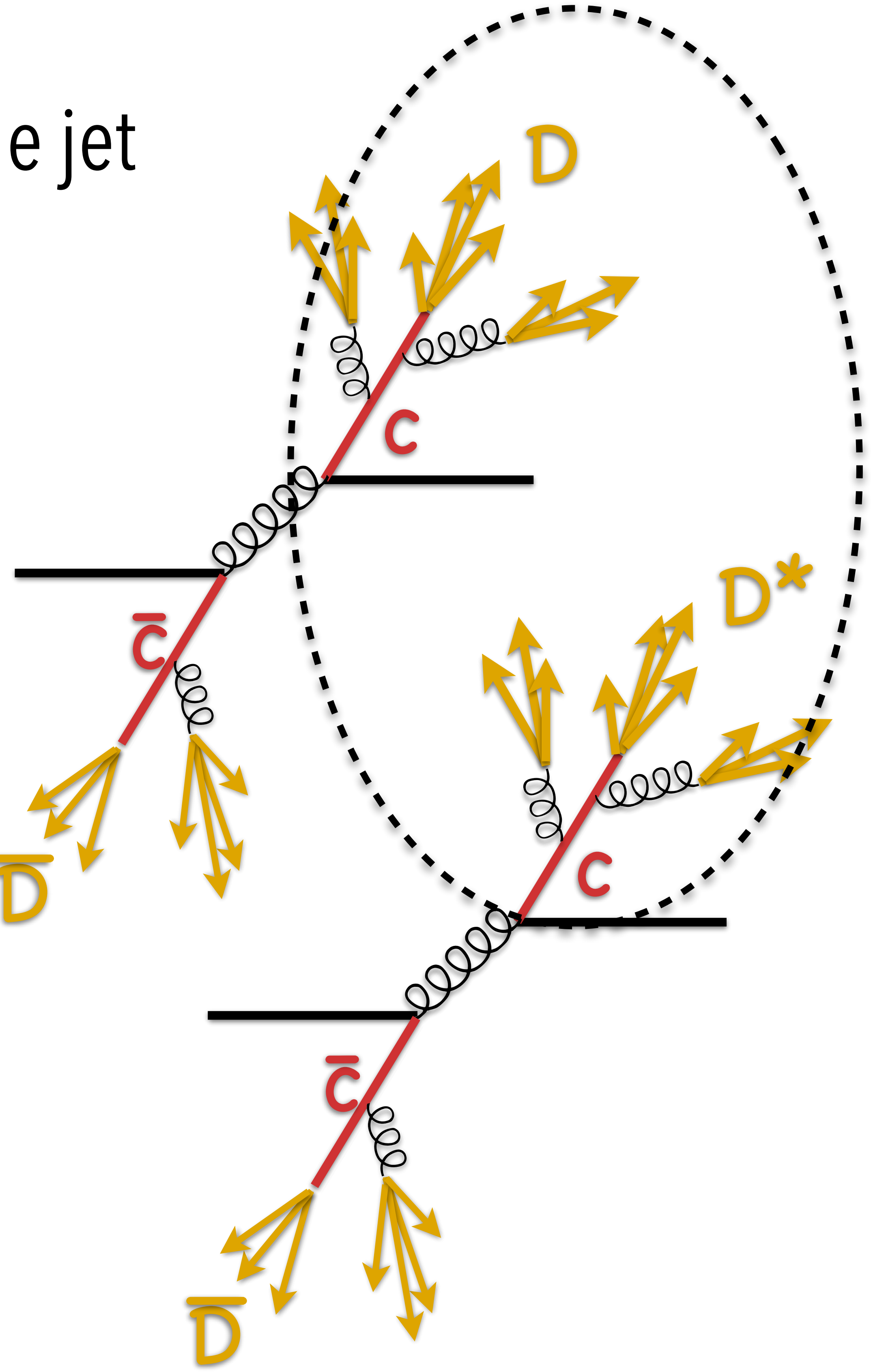
BACKUP

D^0D^{*+} correlation function in Pythia

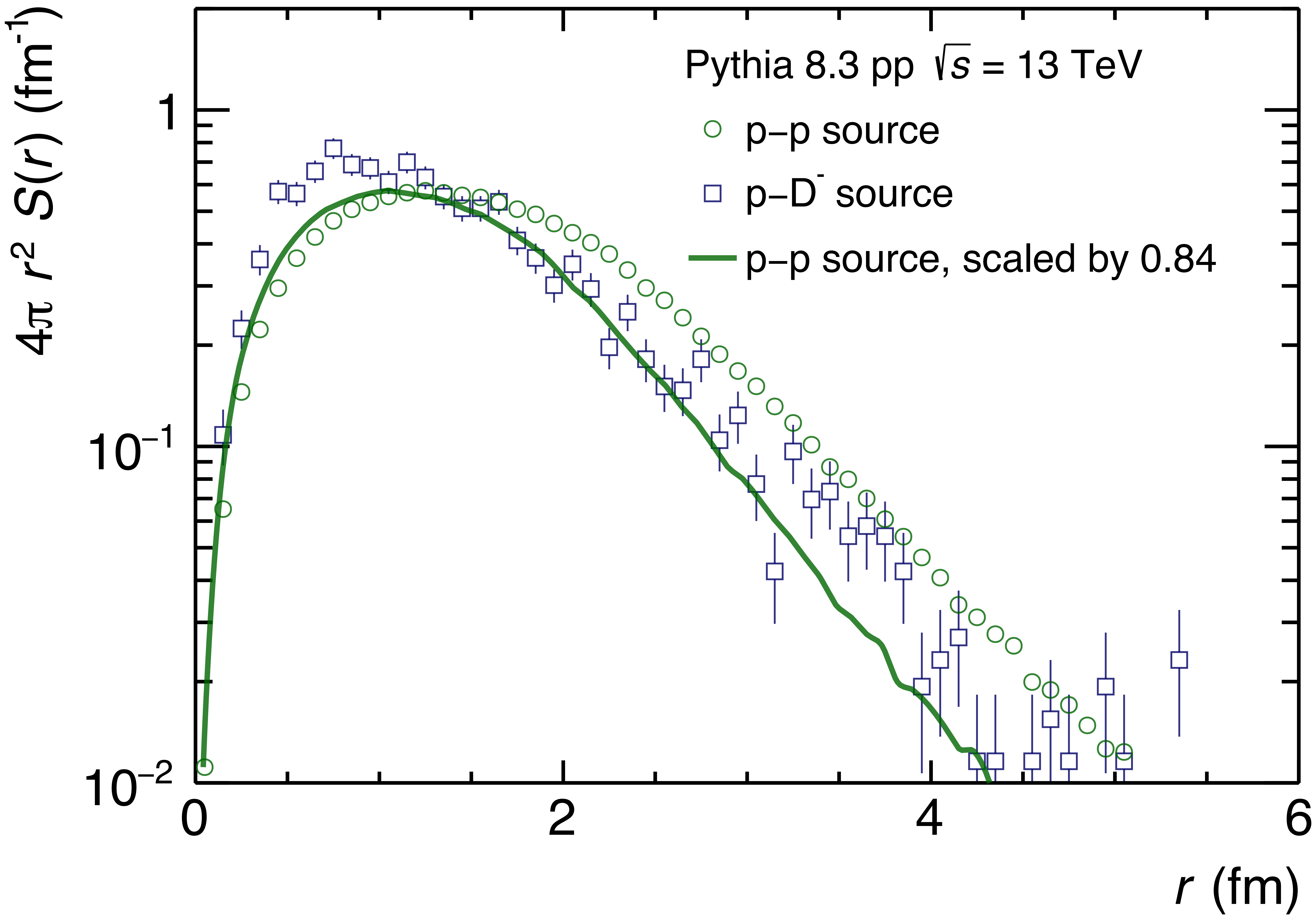
$$C(\overrightarrow{k}^*) = \mathcal{N}\frac{N^{\text{pairs}}_{\text{same}}(k^*)}{N^{\text{pairs}}_{\text{mixed}}(k^*)}$$

- 500M Pythia8 (CR mode2) events simulated
- NB: D^0 from D^{*+} decays are excluded because would probe D^{*+} D^{*+} interaction instead
- Flat at unity also for low k^* → D^0 and D^{*+} cannot come from same jet





Calibrating the p-D⁻ source



- Source size not necessarily the same for charm hadrons (depends on hadronisation)
  - ➡ Study performed with PYTHIA8.3 indicates that the source might be 25% lower than the p–p source for the corresponding <m_T>
  - ➡ Added as systematic uncertainty

$D^0\overline{D}^{*+}$ correlation function in Pythia

$$C(\vec{k}^*) = \mathcal{N}\frac{N^{\text{pairs}}_{\text{same}}(k^*)}{N^{\text{pairs}}_{\text{mixed}}(k^*)}$$

- Rising trend because charm and anti-charm quarks mostly come from same hard scattering