Extending the ALICE strong-interaction studies to nuclei: measurement of proton-deuteron correlations in pp collisions at $\sqrt{s}$ =13 TeV

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on behalf of the **ALICE Collaboration**

SQM2022
The 20th International Conference on Strangeness in Quark Matter
13-17 June 2022
Busan, Republic of Korea

ALICE

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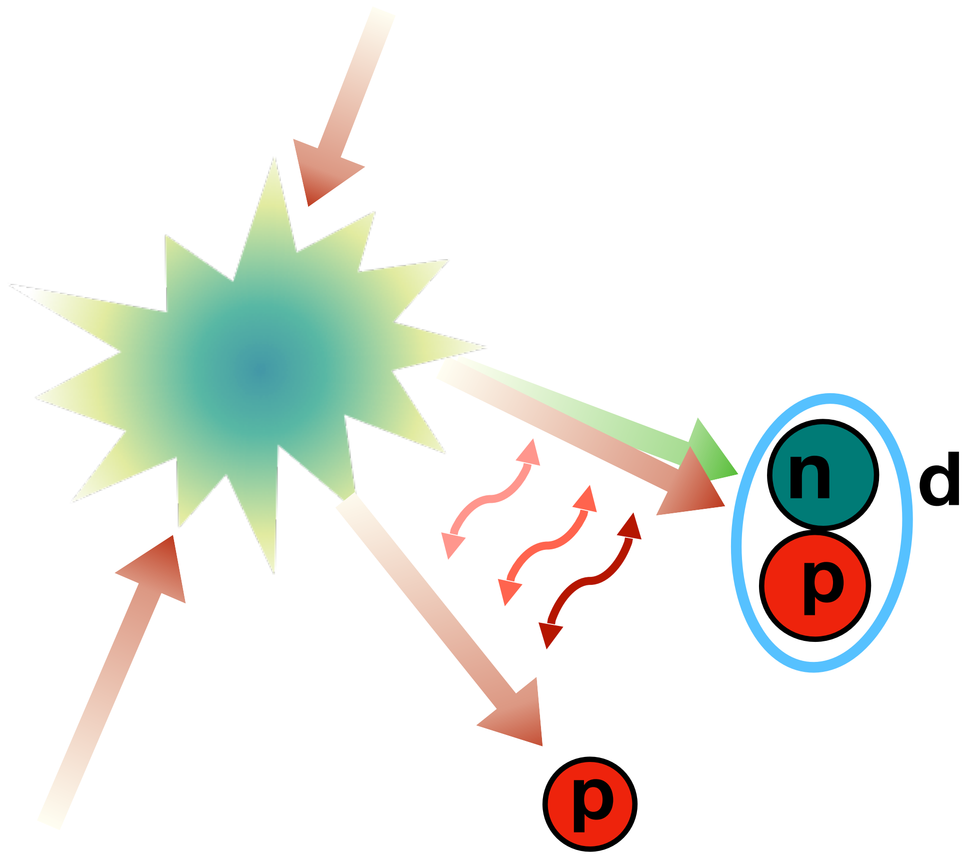
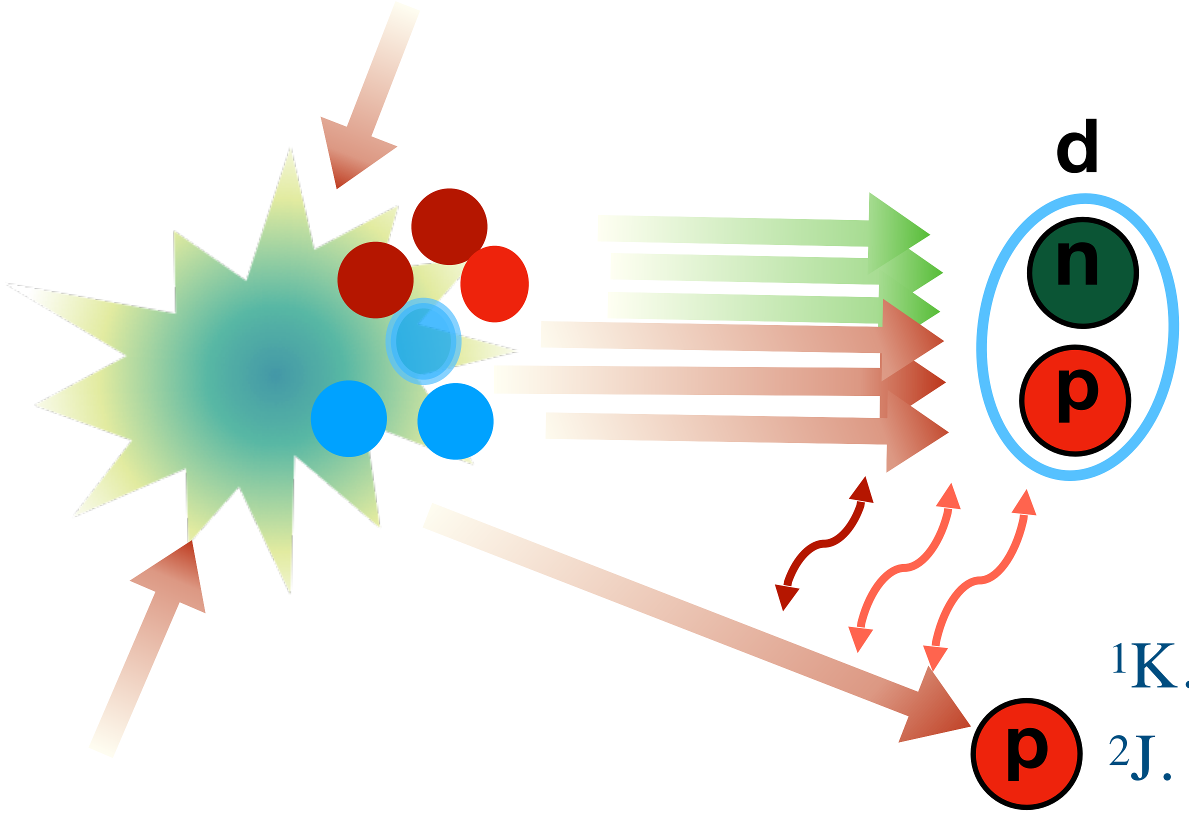
Motivation

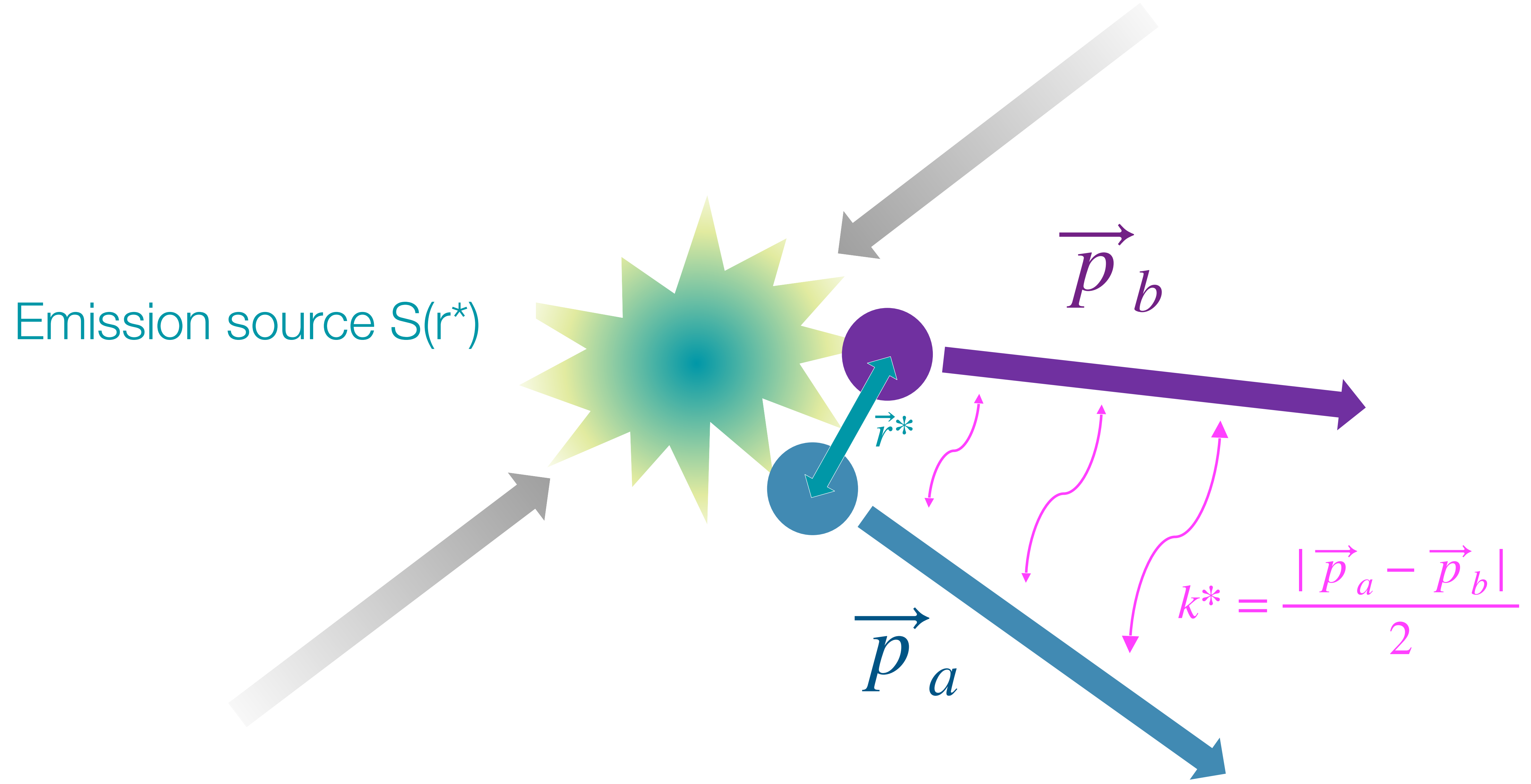
- **Proton-deuteron (p—d) interaction**
  - Three-nucleon force: doorway to probe short distances
  - p—d interaction can be constrained from the scattering experiments
- **Production mechanism of light nuclei not understood:**
  - Models: information on single particle, Statistical Hadronisation Model[2,3] or Coalescence Model[1]
  - Final-state interactions: probe the formation time of deuterons (antideuterons)





[1]K. Blum et al, Phys. Rev. C 99, 04491(2019)
[2]J. Cleymans et al, Phys. Rev. C 74, 034903 (2006),
[3]J. Cleymans et al Z. Phys. C 57, 135–147 (1993)

- **Main observable:** correlation in the relative momentum k* distribution of a particle pair
  - Emitting source: hypersurface of kinematic freeze-out for final-state particles, in pp collision the source size ~ 1 fm (Gaussian profile)
  - Two-particle relative wave function: expresses the interaction between particles



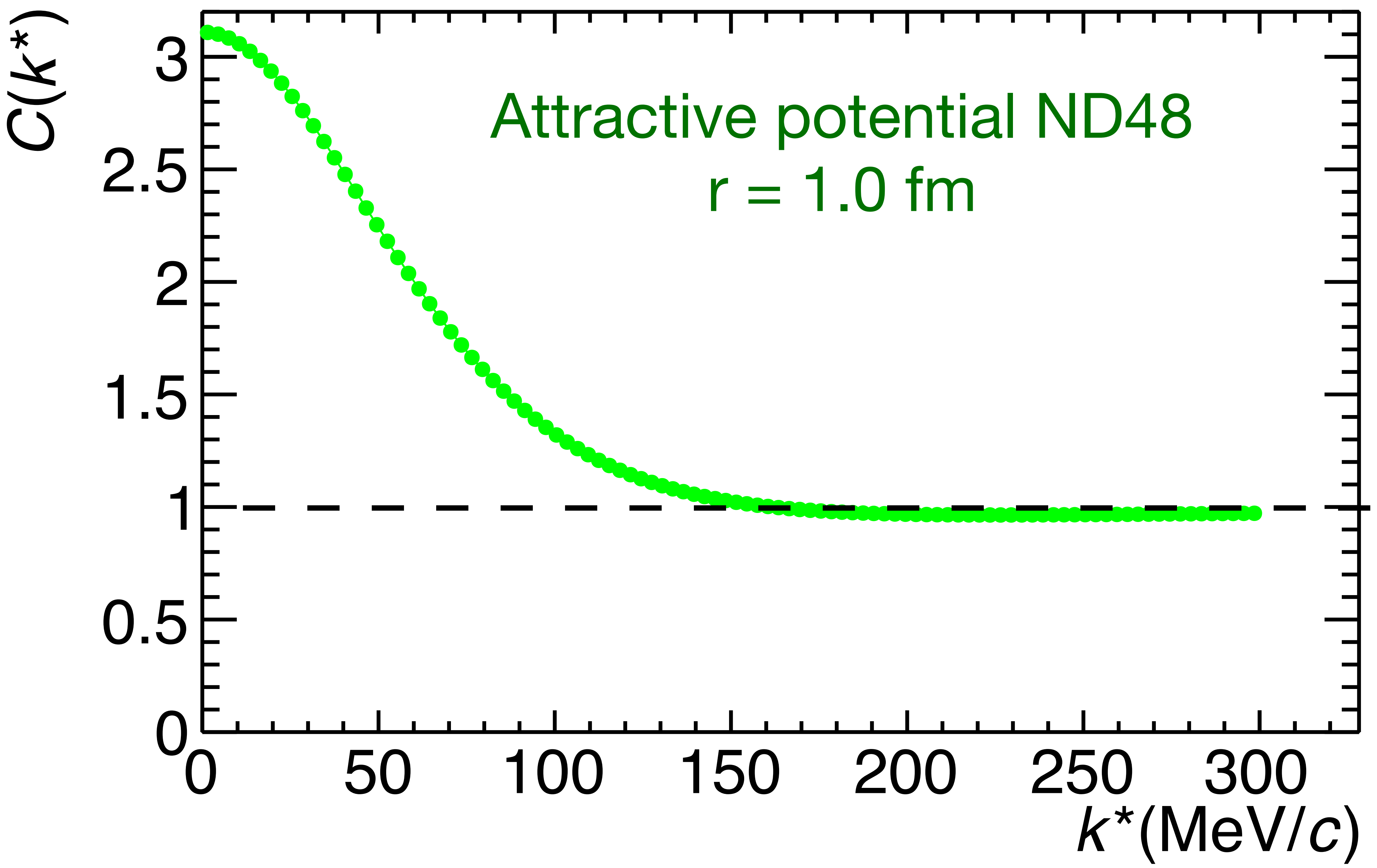
- Study the emission source if the interaction among the particle pair is known
- Or study the interaction among the particles if emission source is known

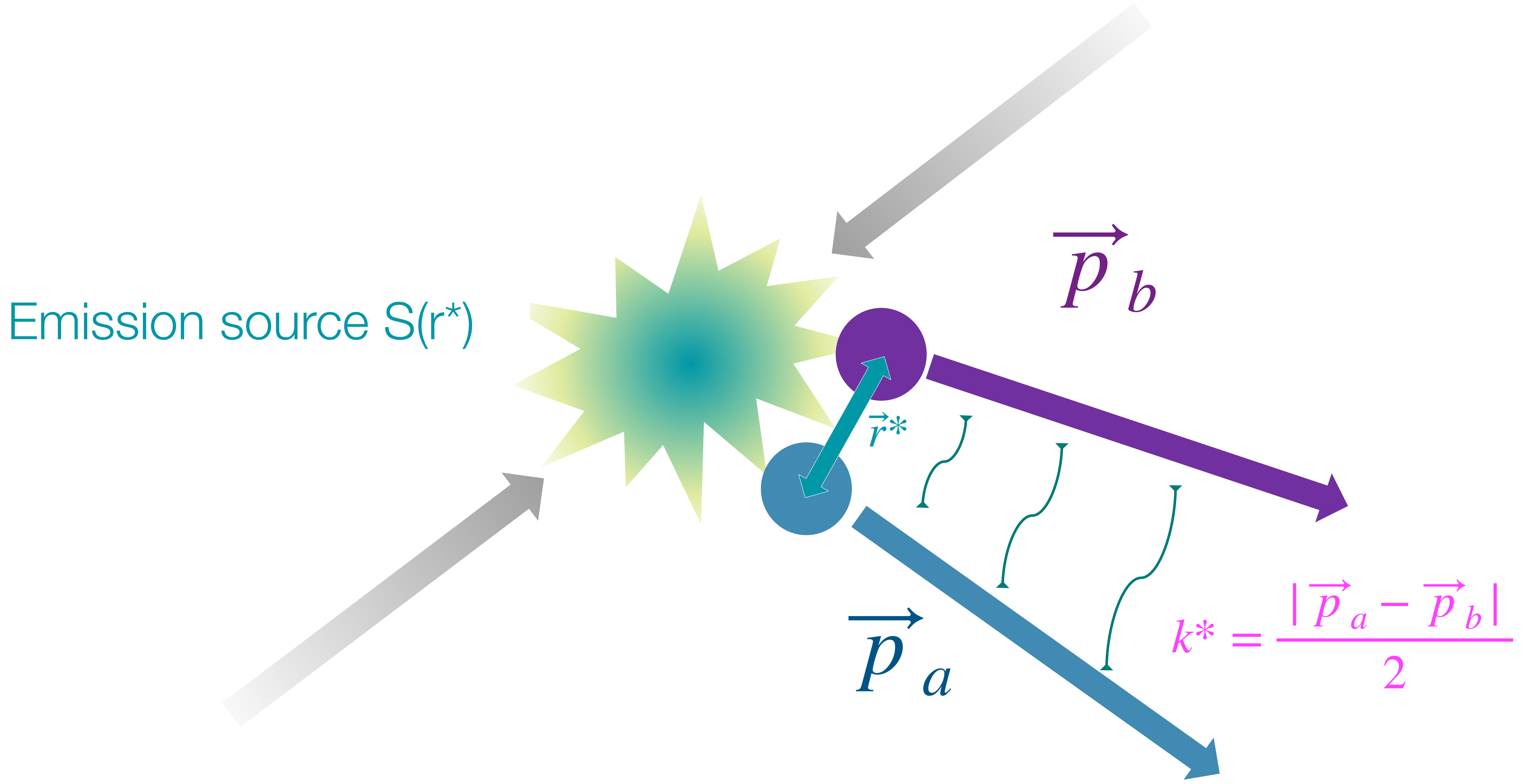
Koonin-Pratt Equation

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

CATS Framework: D. Mihaylov et al., EPJ. C78 (2018) 394
S.E. Koonin PLB 70 43 (1977)

- Correlation rises above 1 for attractive potentials





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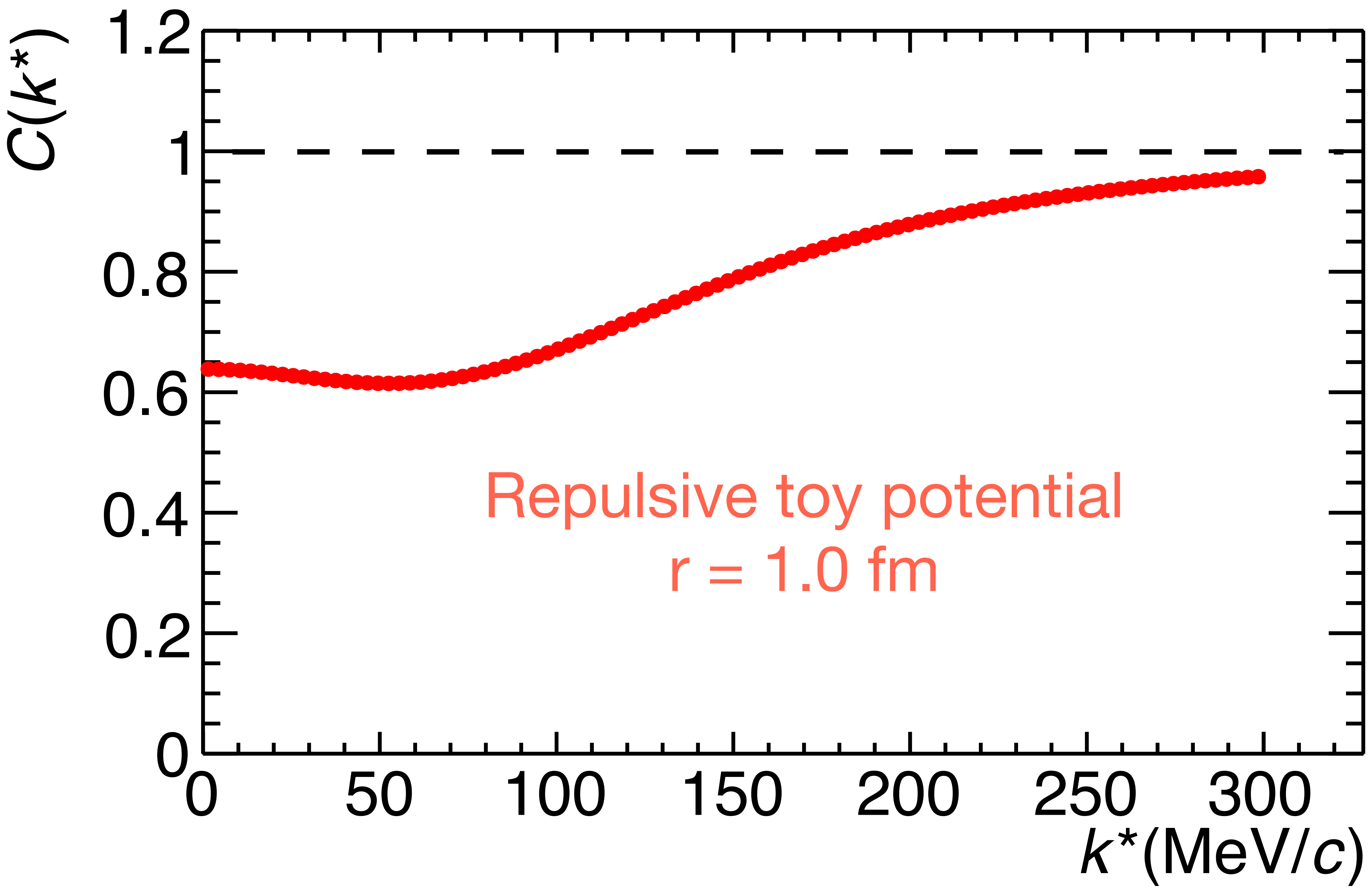
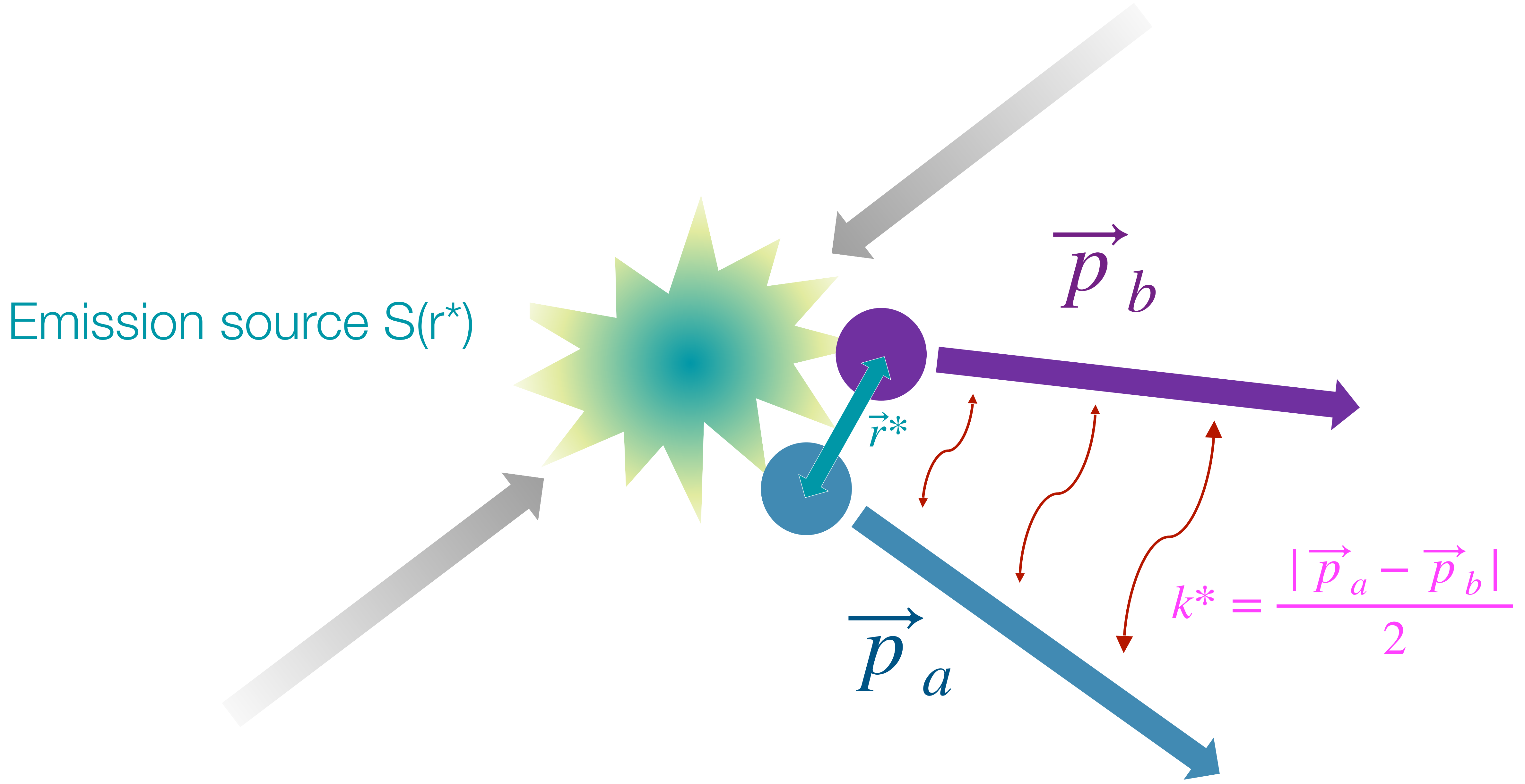
Femtoscopy at the LHC

- Repulsive interaction brings correlation below 1





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theoretical definition — experimental definition

CATS Framework: D. Mihaylov et al., EPJ. C78 (2018) 394
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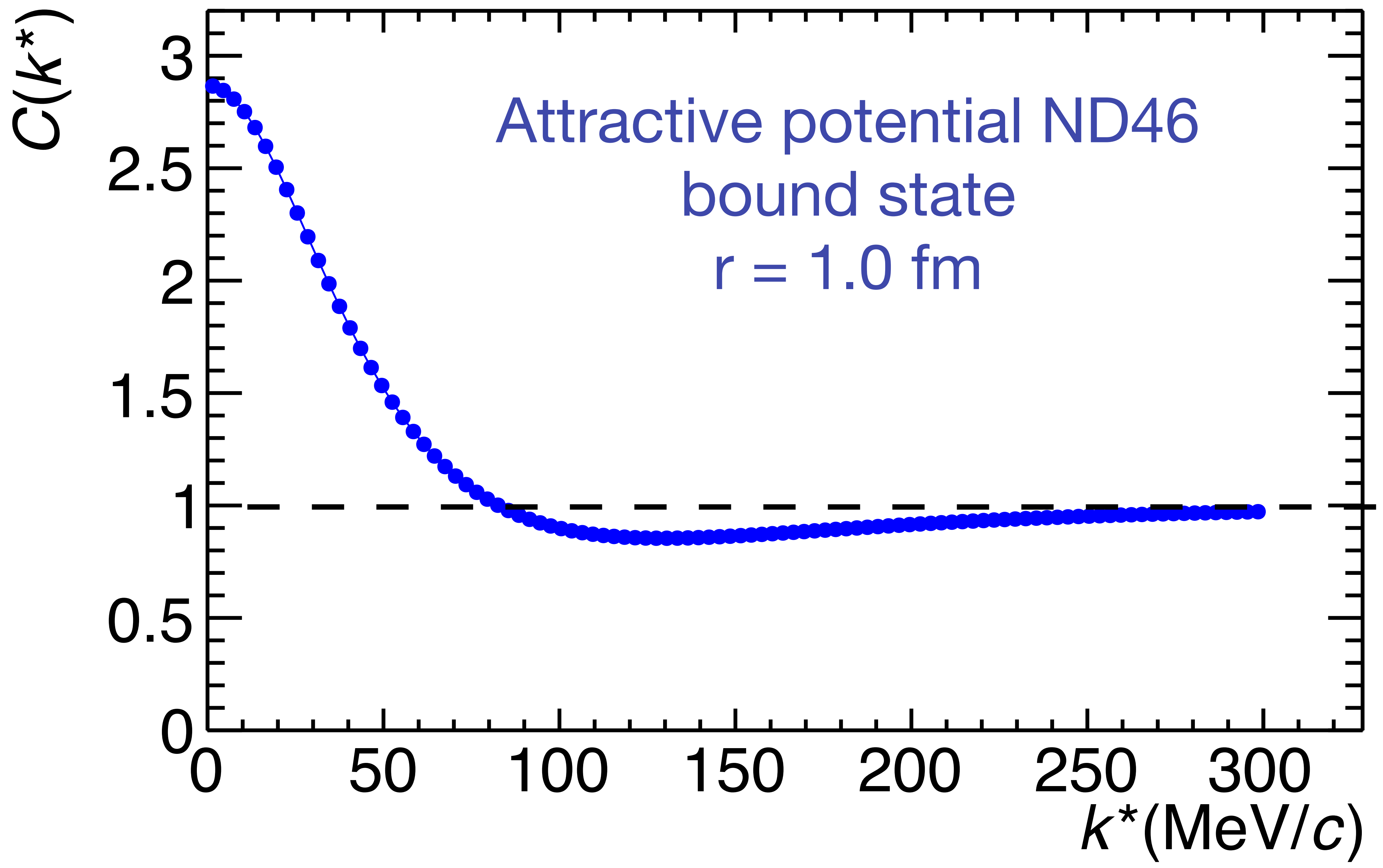
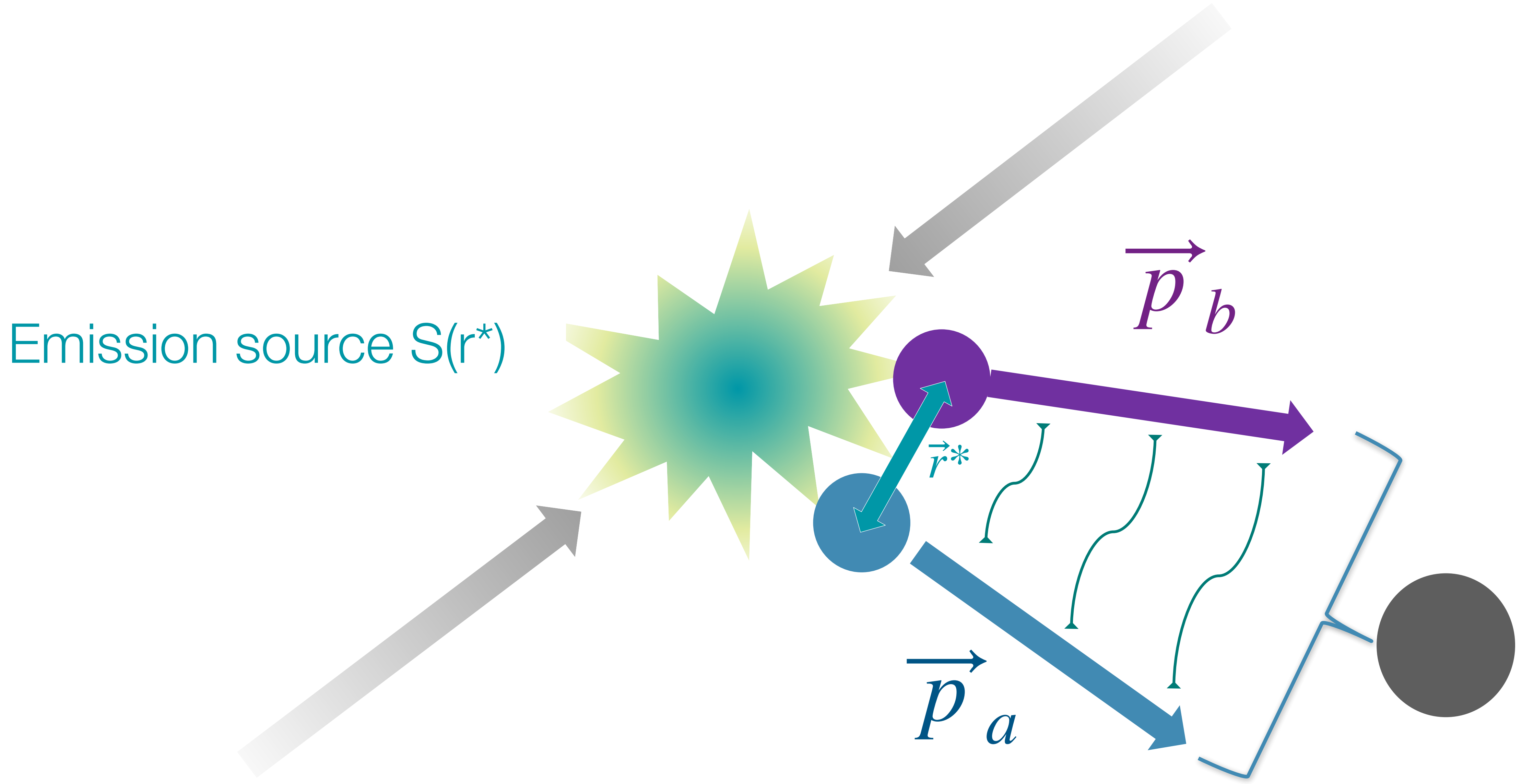
Femtoscopy at the LHC

- Depletion due to the loss of particle pairs





$$k^* = \frac{|\vec{p}_a - \vec{p}_b|}{2}$$

Koonin-Pratt Equation

$$C(k^*) = \underbrace{\int S(\vec{r}^*) \left|\psi(\vec{k}^*, \vec{r}^*)\right|^2 d^3\vec{r}^*}_{\text{theoretical definition}} = \underbrace{\mathcal{N} \frac{N_{\text{same}}(k^*)}{N_{\text{mixed}}(k^*)}}_{\text{experimental definition}} < 1$$

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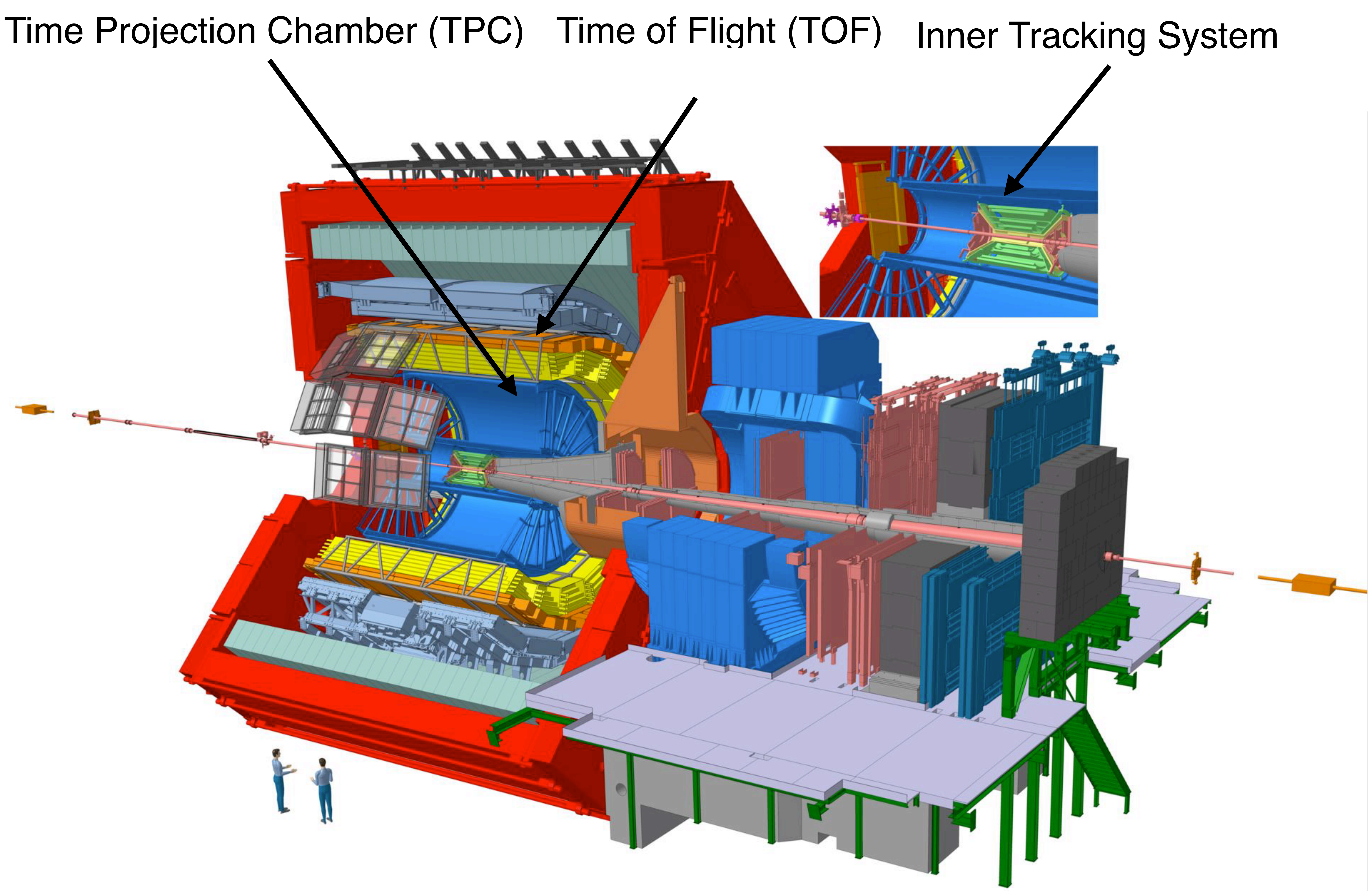
ALICE Experiment

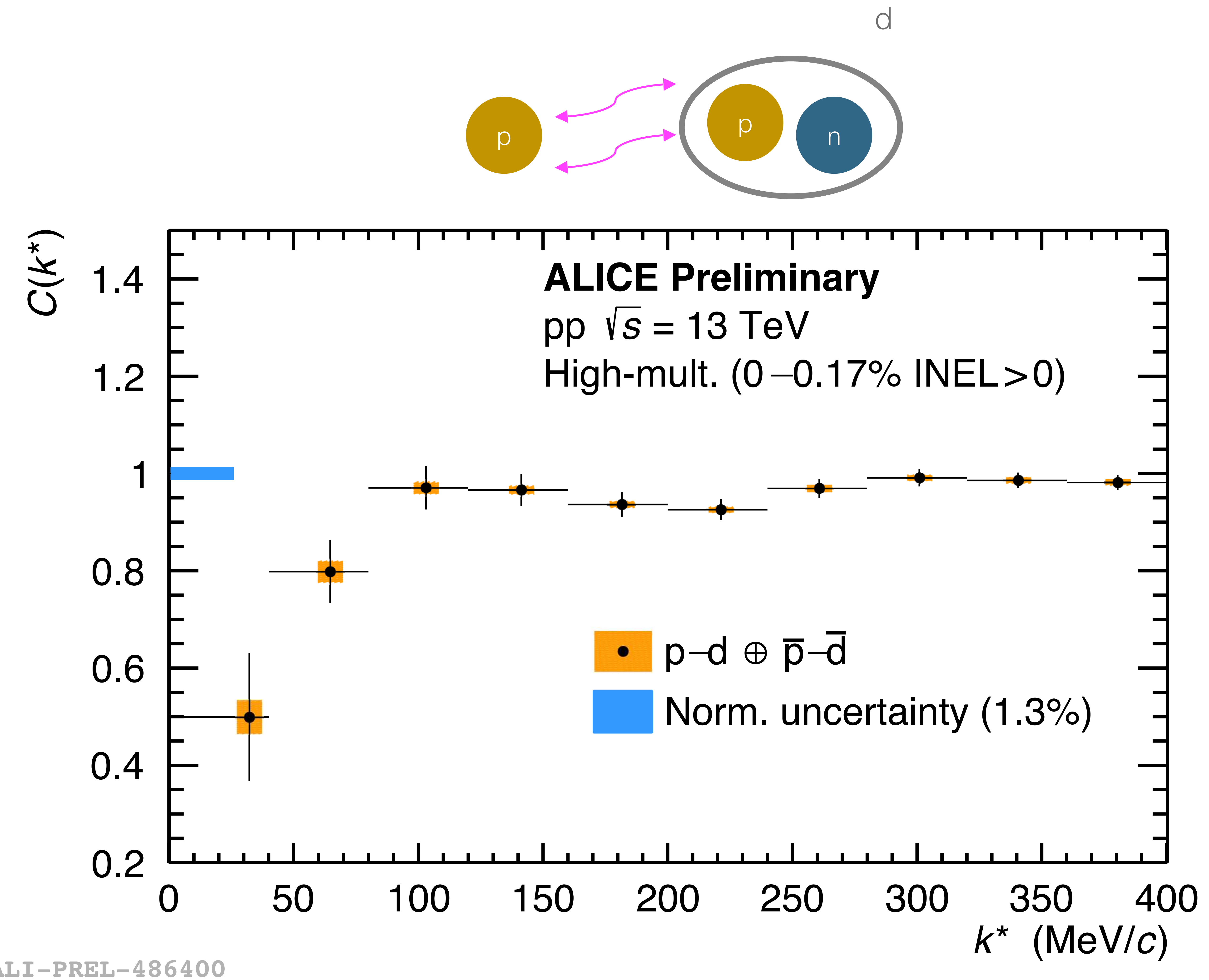
- General purpose heavy-ion experiment
  - Excellent particle identification (PID)
  - Most suited LHC experiment for studying femtoscopic correlations
- Run 2 high-multiplicity data
- Number of events: ~1 x10^9
- Particle selection with TPC +TOF
  - p(anti-p) : **98.30% (98.76%)**
  - d(anti-d) : ~**100%**



3D ALICE Schematic Run 2

First measurement of proton-deuteron

- p—d ⊕ $\bar{p}$—$\bar{d}$ correlation
  - Measured p-d correlation not flat, shows depletion at low *k**
  - Repulsive type of interaction
  - Accessing spin-isospin dependence of NNN
- Pairs below *k**< 200 MeV/*c*
  - p—d: 1747
  - $\bar{p}$—$\bar{d}$: 1250



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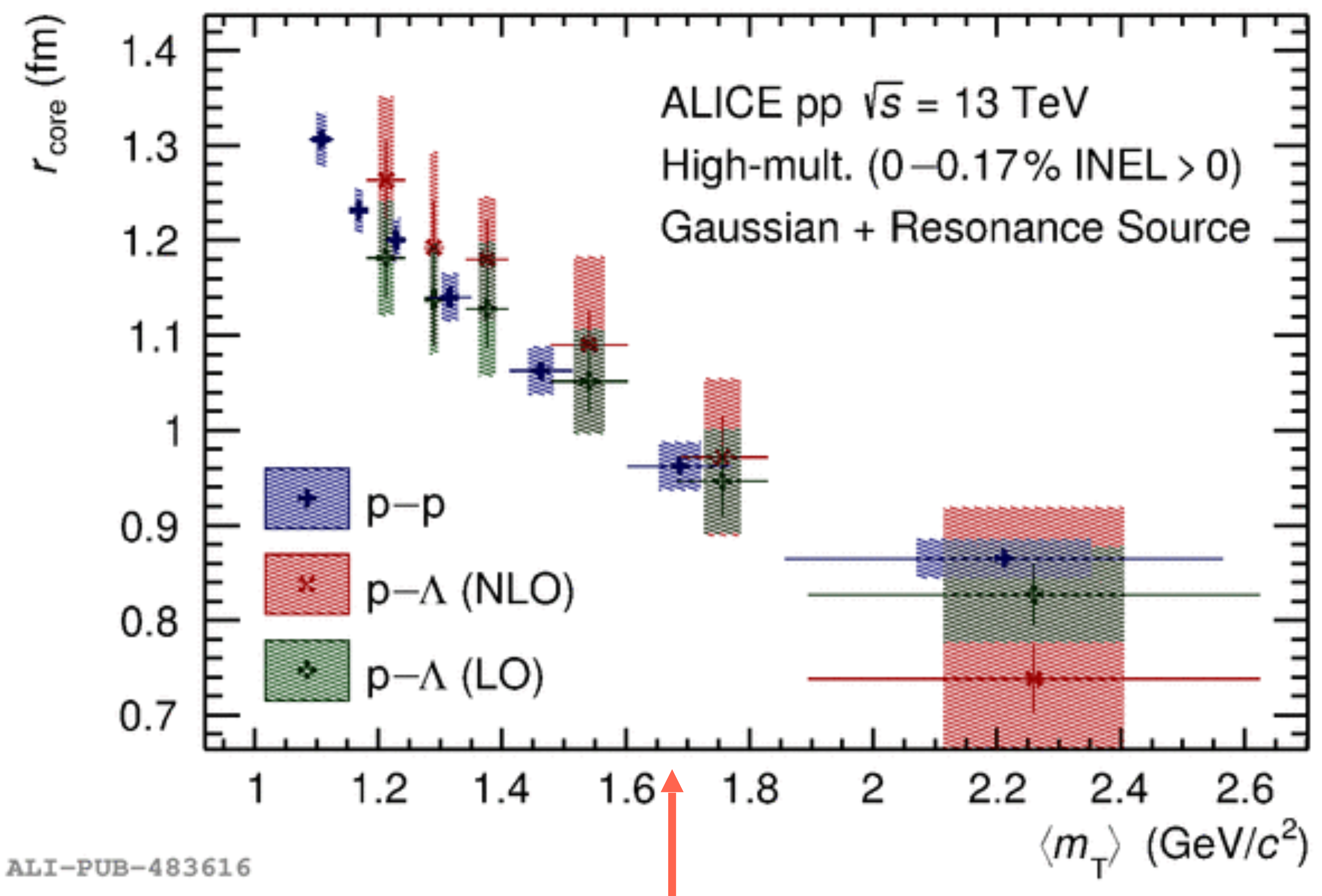
The source

- Short distances in pp and p—Pb collisions
- Particle emission from **Gaussian core** source

Source size	mean value
r_{core}	0.97±0.04 fm

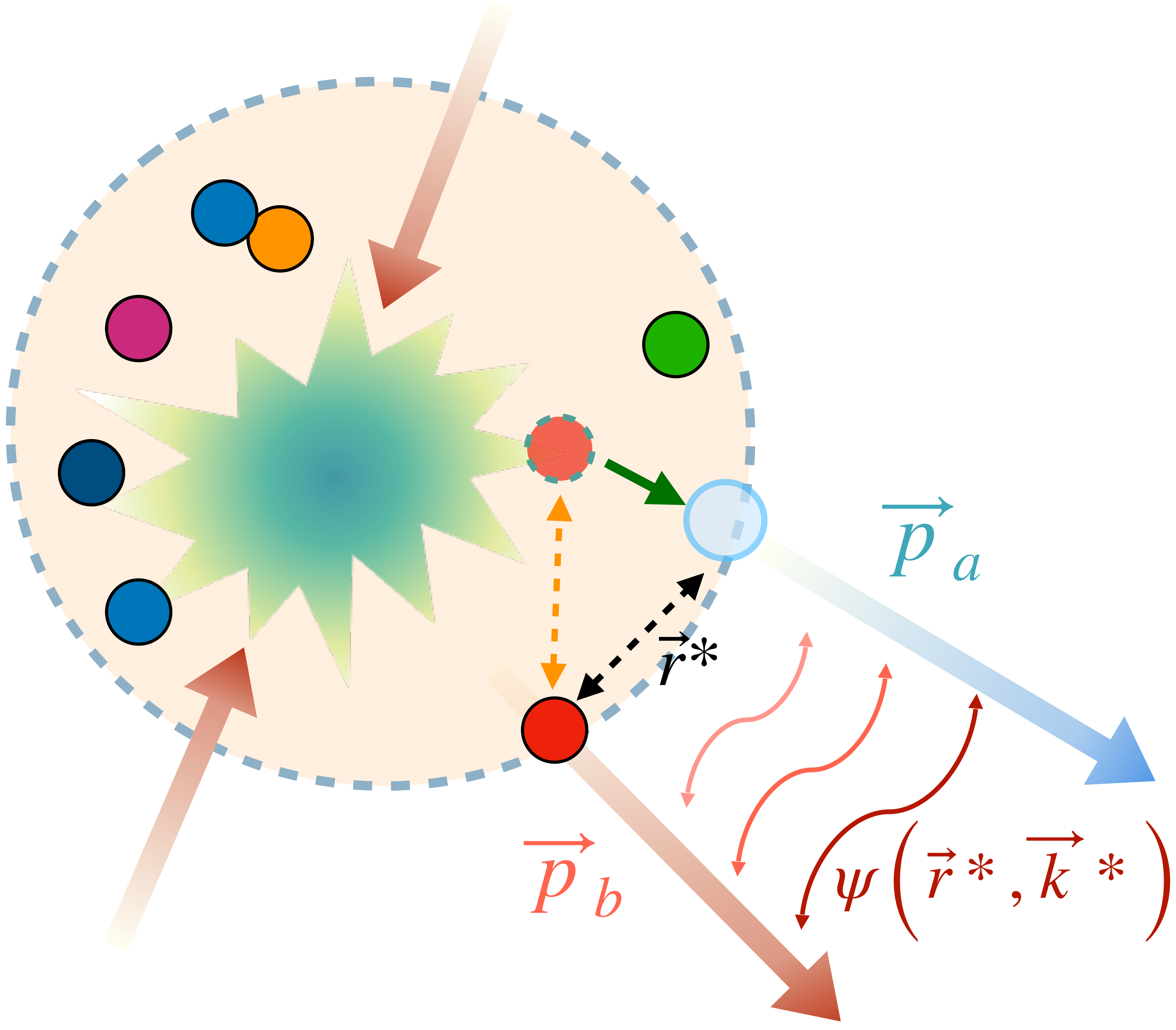


$<m_{T,\,p\text{-}d}> = 1.65$ GeV/c^2

ALICE Coll. PLB 811 135849 (2020)

The source

- Short distances in pp and p—Pb collisions
- Particle emission from **Gaussian core** source
- The source radius is effectively increased by **short-lived strongly decaying resonances** ($c\tau \approx r_{\text{core}}$) e.g. Δ-resonances in case of protons



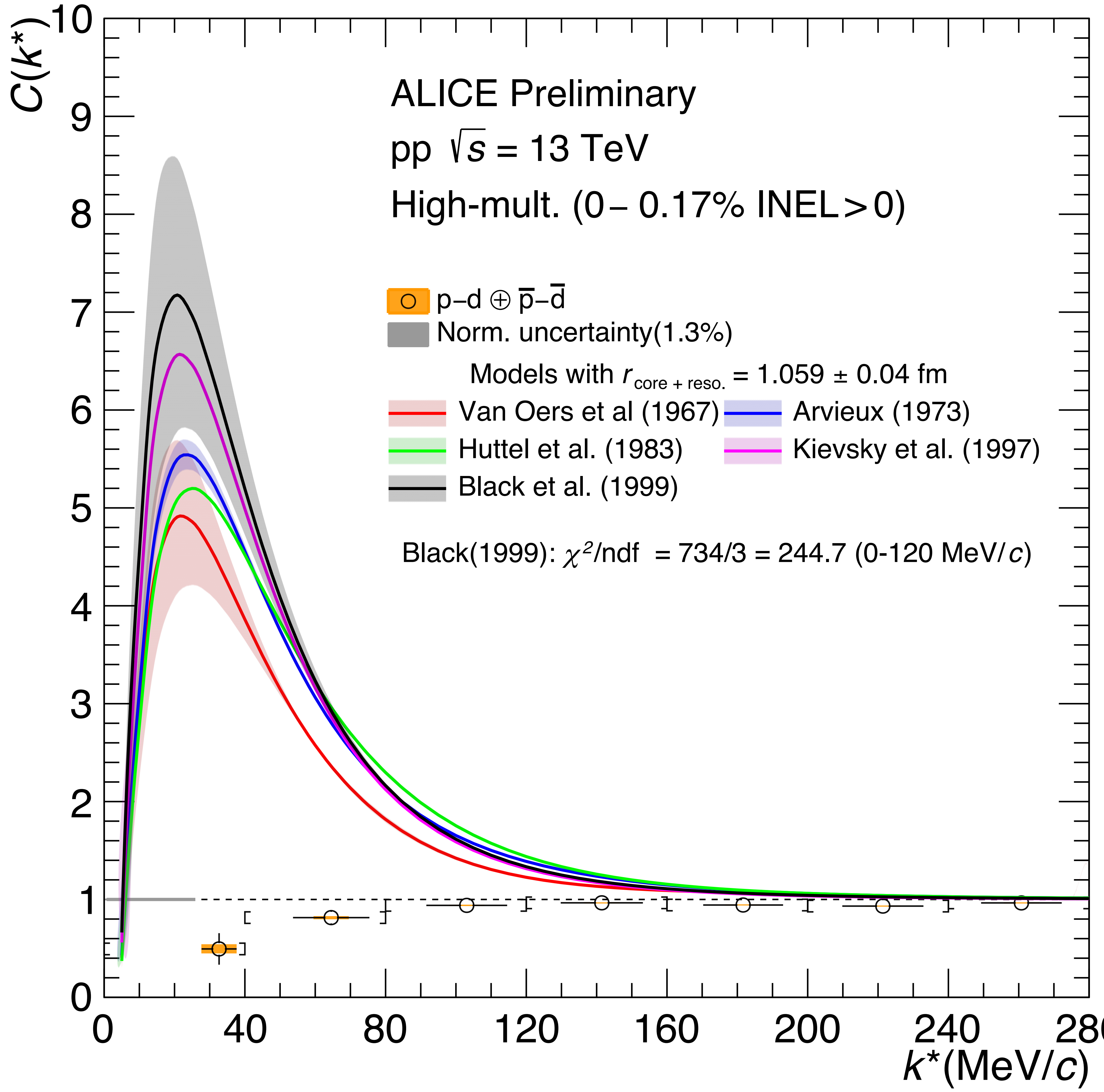
Source size	mean value
r_{core}	0.97±0.04 fm
r_{eff}	1.06±0.04 fm

ALICE Coll. PLB 811 135849 (2020)

Theoretical models and data

- Two-particle s-wavefunction accounting for Coulomb and strong interaction[1]
  - Coulomb + strong interaction (S = 1/2 and S = 3/2)
  - Assumption: p and d are point-like particles!
  - Theoretical model constrained to scattering p—d experiments

Ref	Quartet $^4S_{3/2}$	Doublet $^2S_{1/2}$
Oers, Brockmann et al.(1967)	$11.4^{+1.8}_{-1.2}$	$1.2^{+0.2}_{-0.2}$
Arvieux et al.(1973)	$11.88^{+0.4}_{-0.1}$	$2.73^{+0.1}_{-0.1}$
Huttel et al.(1983)	11.1	4.0
Kievsky et al.(1997)	13.8	0.024
Black et al. (1999)	$14.7^{+2.3}_{-2.3}$	$-0.13^{+0.04}_{-0.04}$



Van Oers,Brockmann et al. Nucl. Phys. A 561-583 (1967)
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[1]R. Lednicky, Phys. Part. Nuclei 40, 307–352 (2009)

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Model and data disagree for source size = 1.06±0.04 fm!

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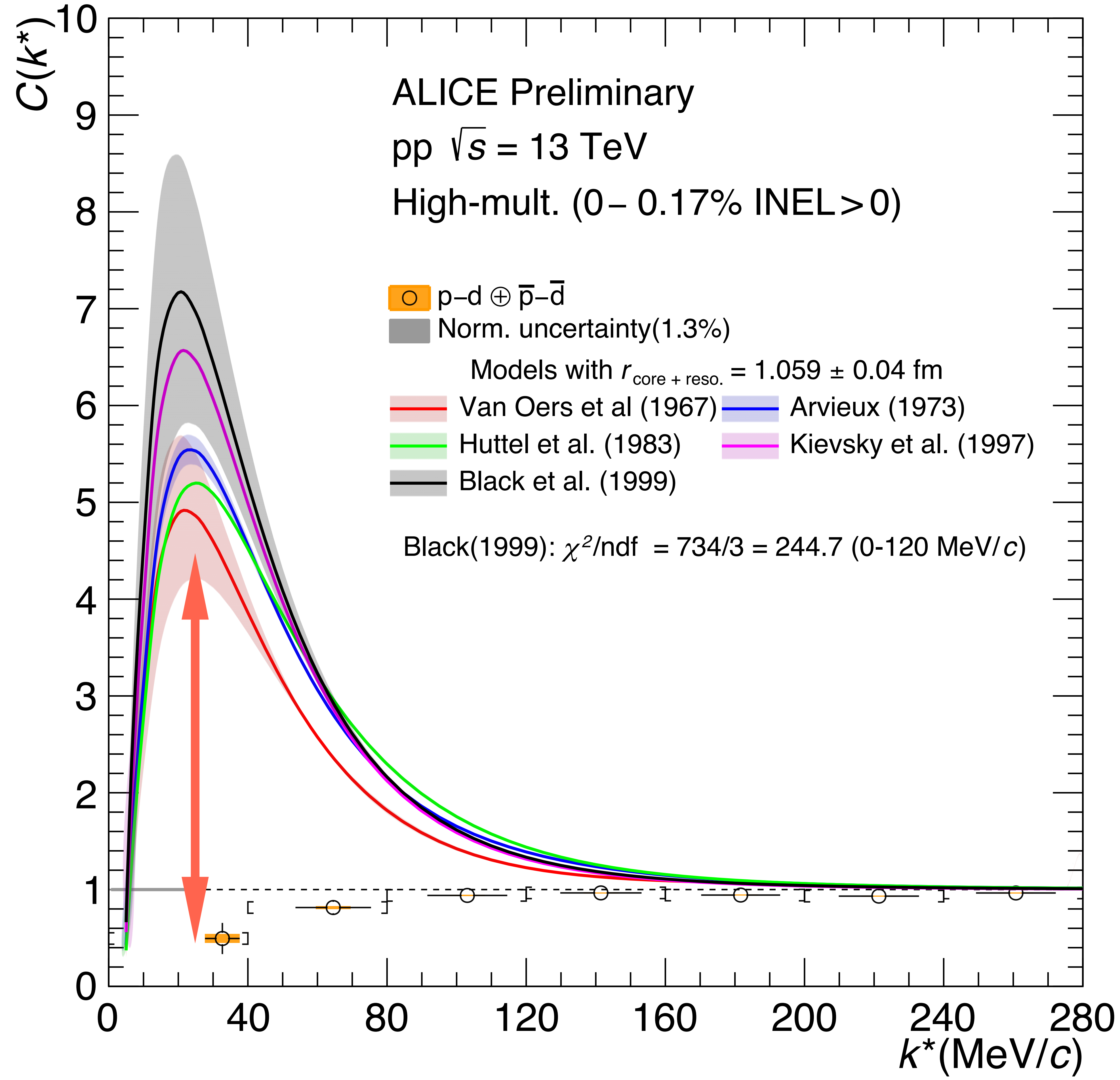

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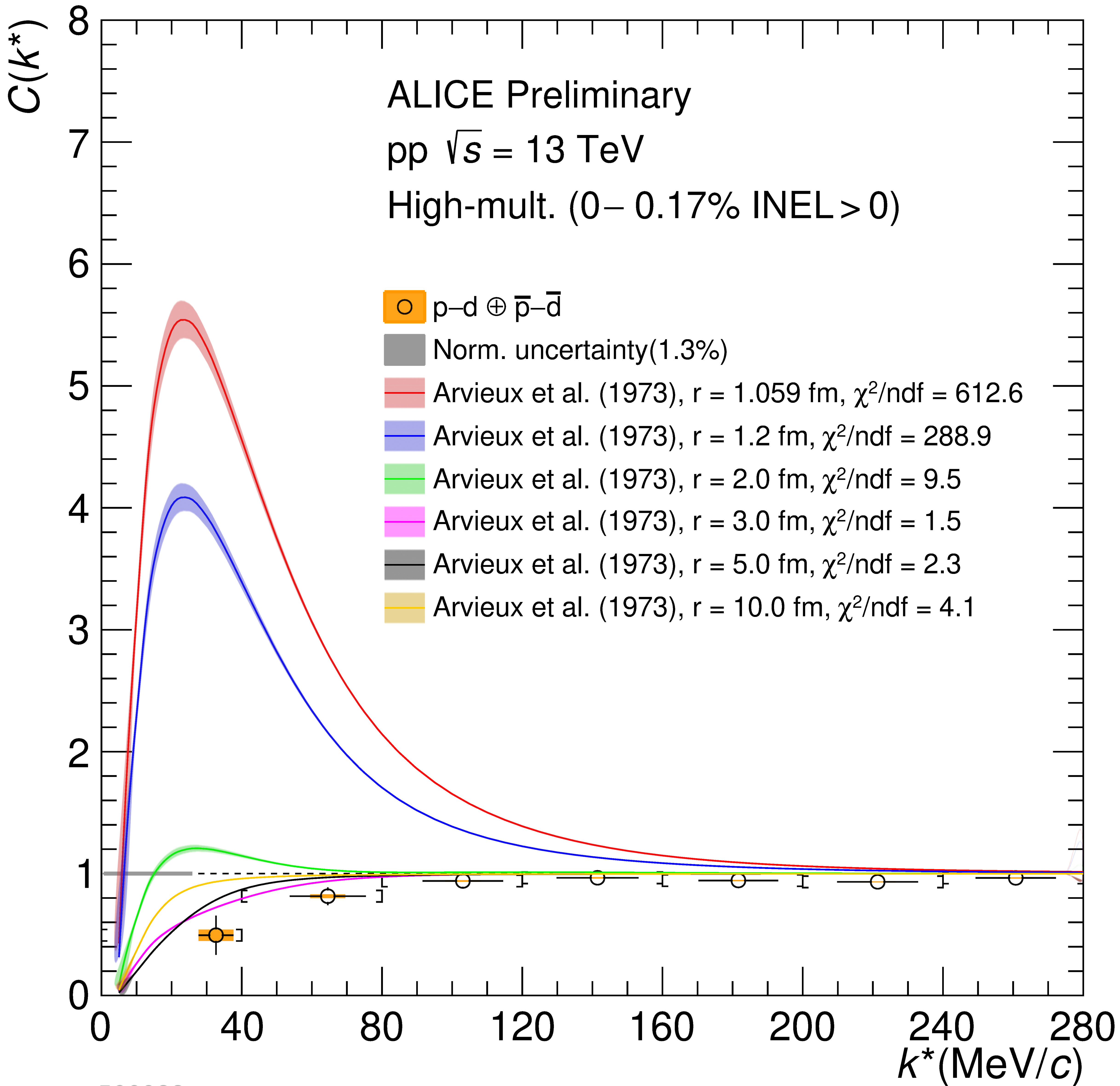
Increased source size deuteron(antideuteron)

- Improved agreement with larger source sizes
- CF becomes flat at larger source size
- The effect of attractive strong interaction in the CF is washed off

Assumption: Model does not account for p-p-n interaction before deuteron is formed



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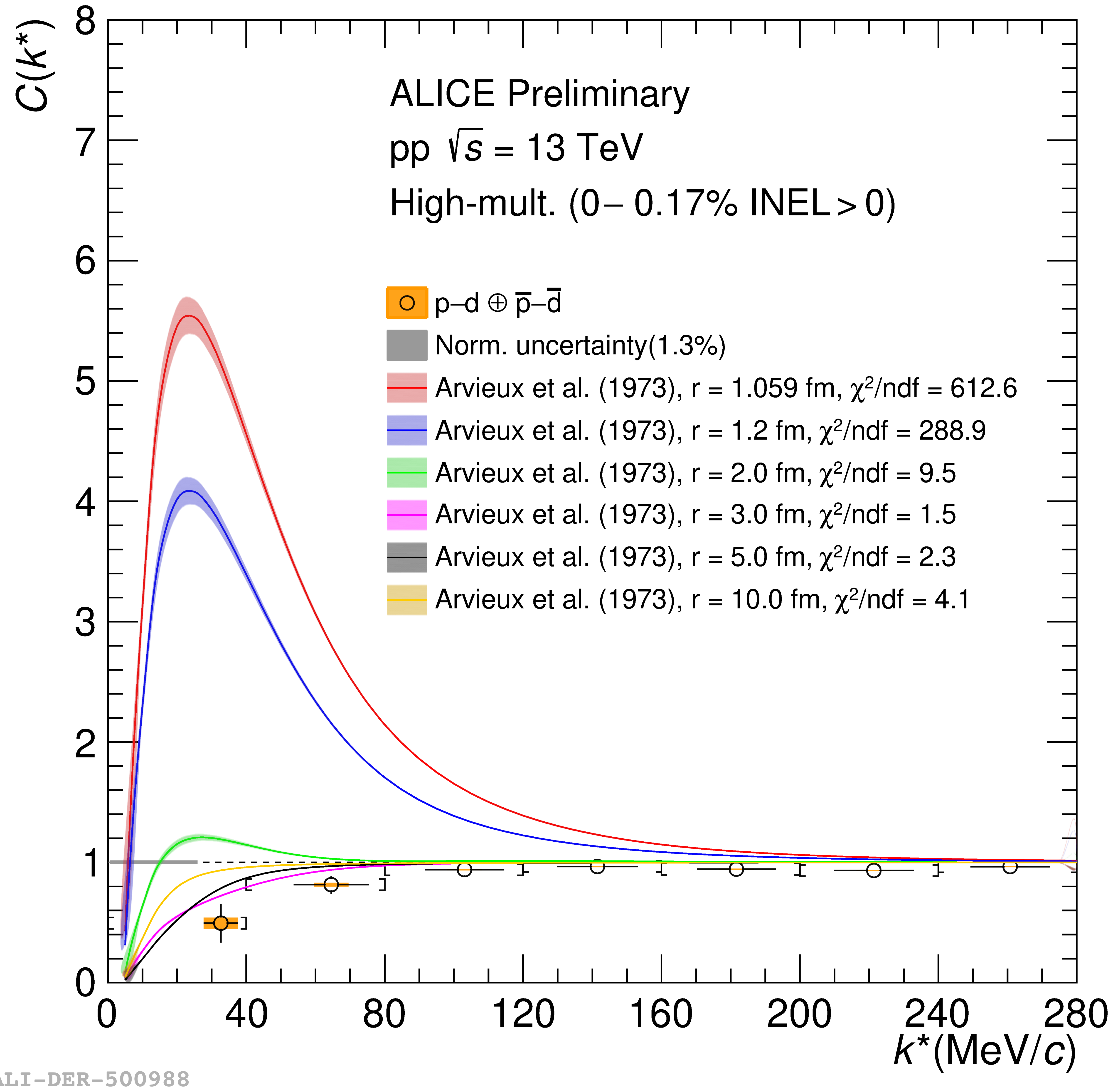
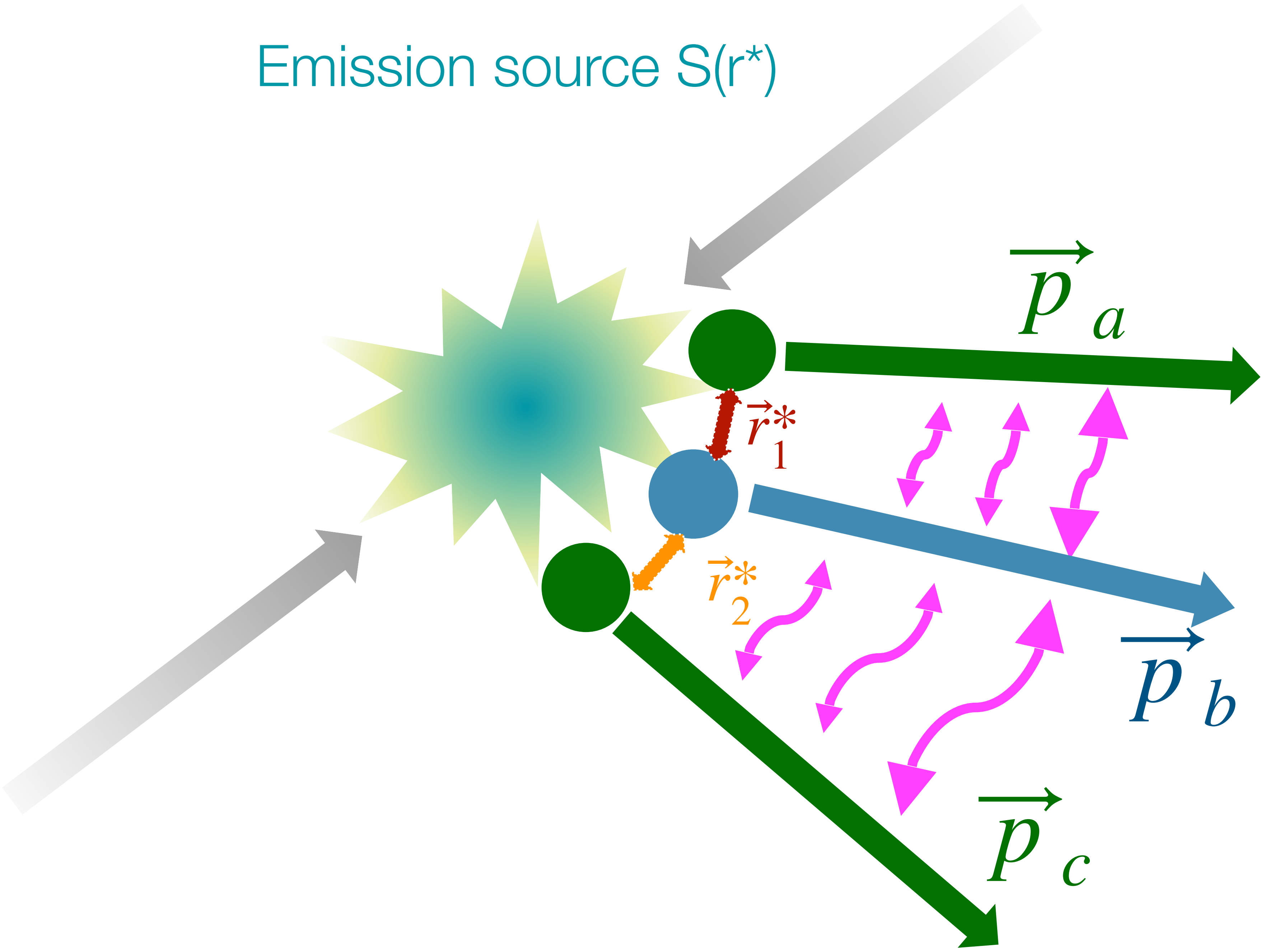
Work in progress: project the pair-wise and genuine three-body interaction of p-p-n on the p-d correlations



Study p-p-p interaction

- The nucleons **formed first** will interact among themselves before forming a pair of **p-d**
- The measured correlation among a triplet of protons can be studied using three-particle correlations



Three-particle correlation

$$C(\vec{p_a}, \vec{p_b}, \vec{p_c}) = \frac{P(\vec{p_a}, \vec{p_b}, \vec{p_c})}{P(\vec{p_a}), P(\vec{p_b}), P(\vec{p_c})} = \xi(Q_3)\frac{SE}{ME}$$

$$Q_3 = \sqrt{-q_{ab}^2 - q_{bc}^2 - q_{ac}^2}$$

$$q_{ij}^{\mu} = (p_i - p_j)^{\mu} - \frac{(p_i - p_j) \cdot P_{ij}}{P_{ij}^2} P_{ij}^{\mu} \qquad P_{ij} = p_i + p_j$$

Contribution of p-p-n interaction

- The nucleons **formed first** will interact among themselves before forming a pair of **p-d**
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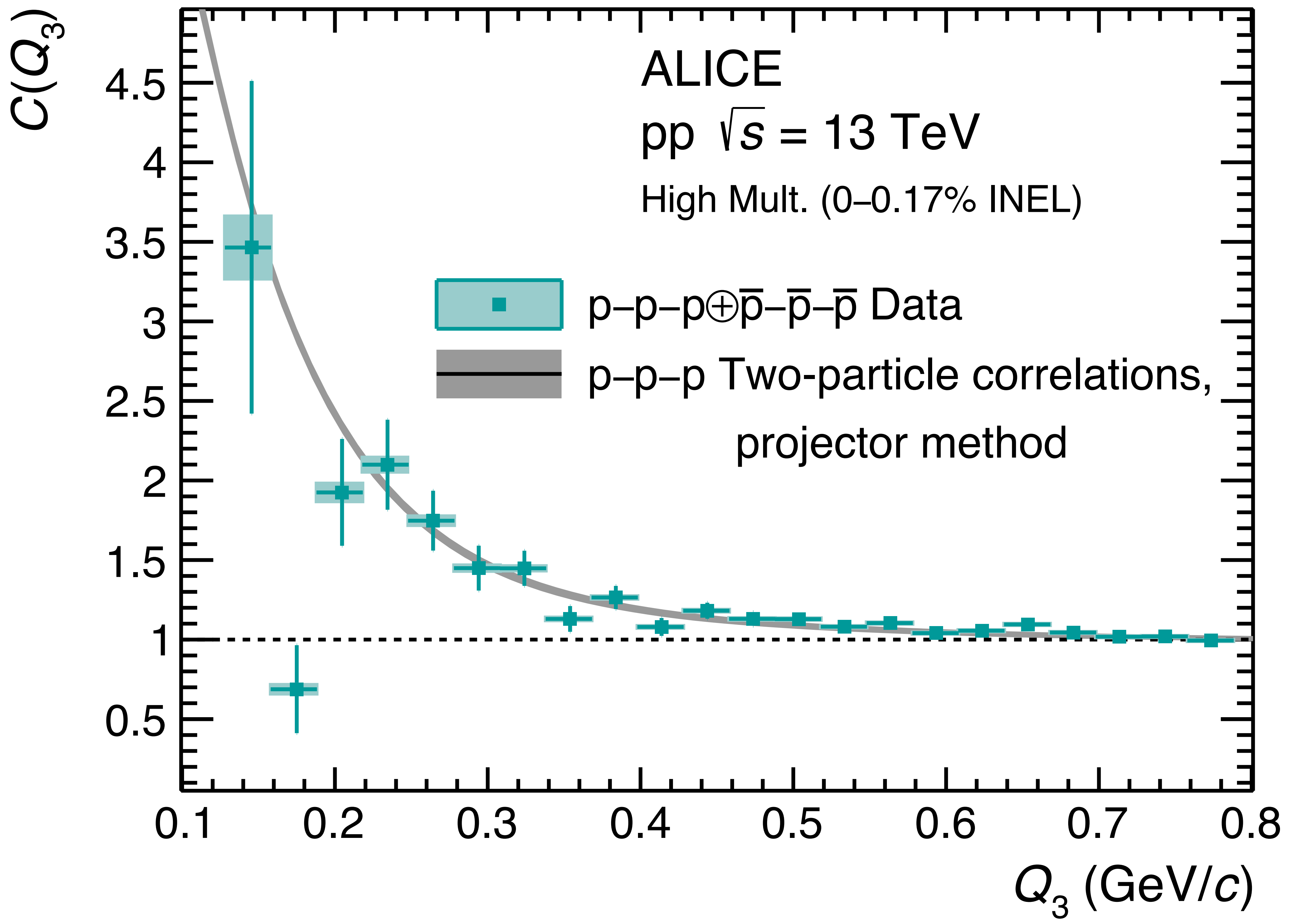

Three-particle correlation

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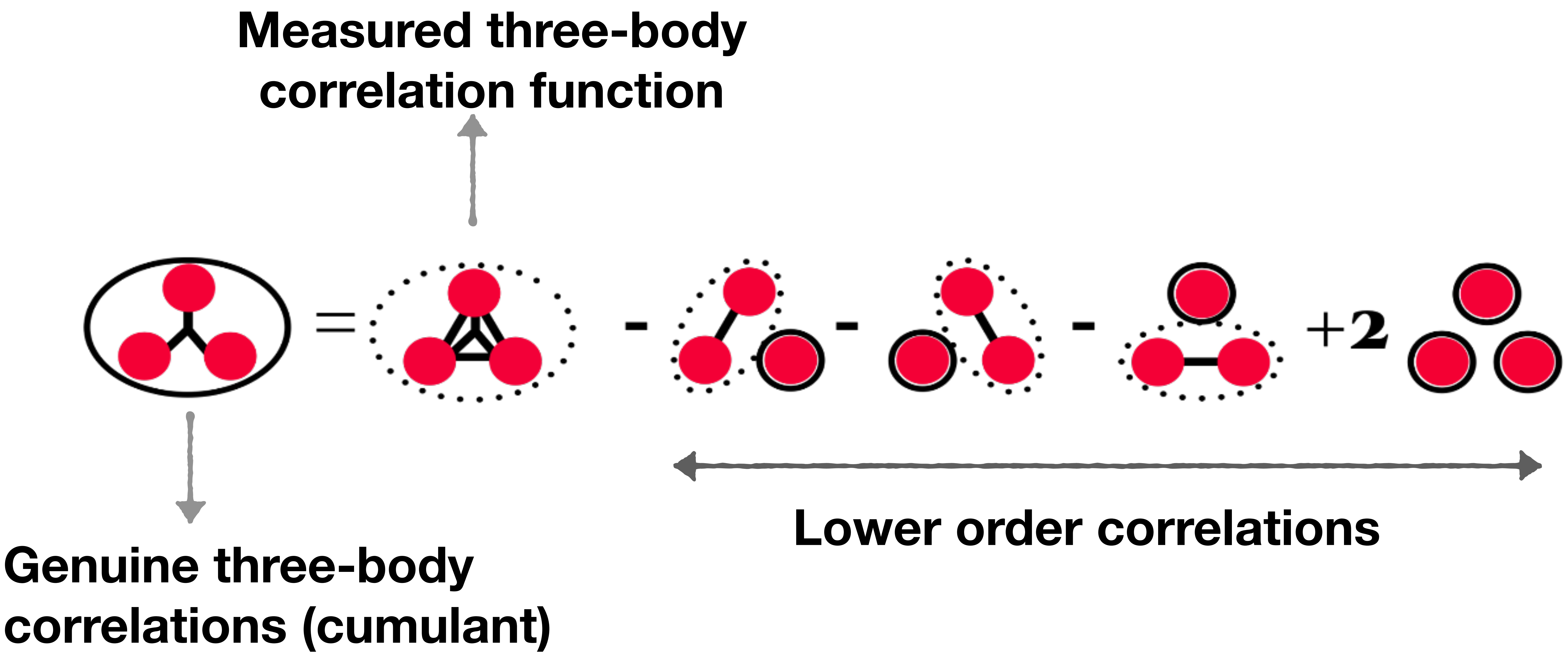
Cumulants

- Genuine three-particle correlations isolated using the Kubo's cumulant expansion method[1]:



[1] R. Kubo, J. Phys. Soc. Jpn. 177 (1962)

Cumulants

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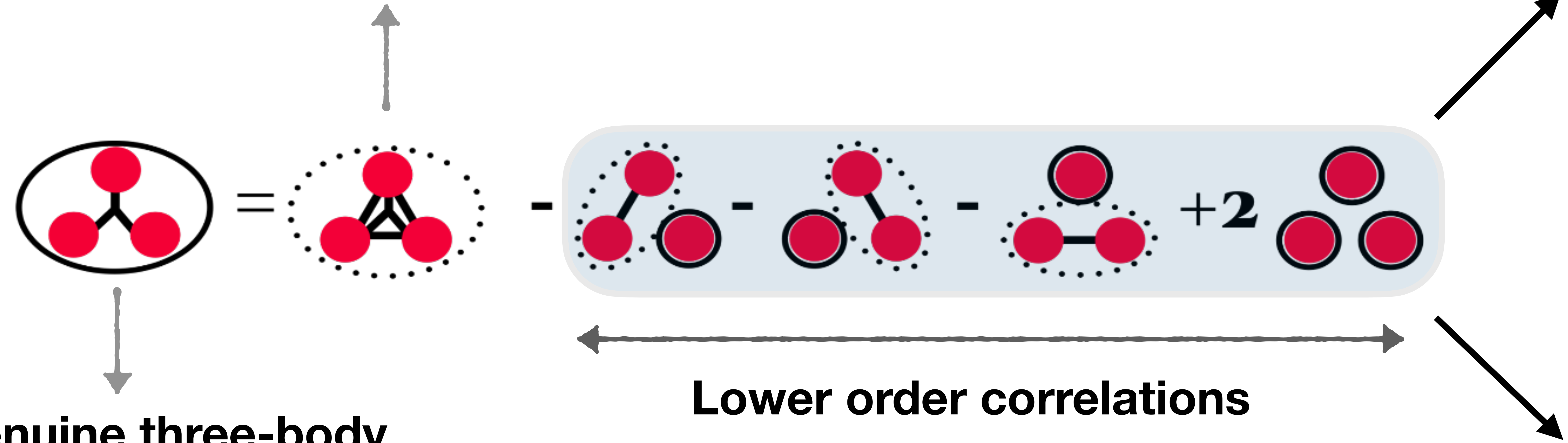
Measured three body correlation function



Genuine three-body correlations (cumulant)

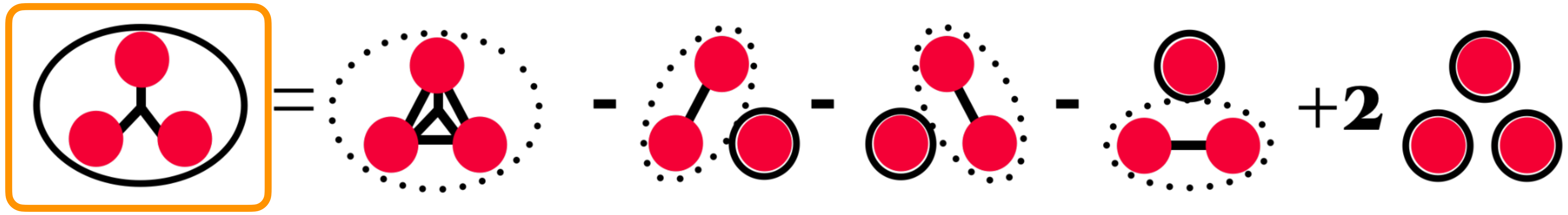
Lower order correlations

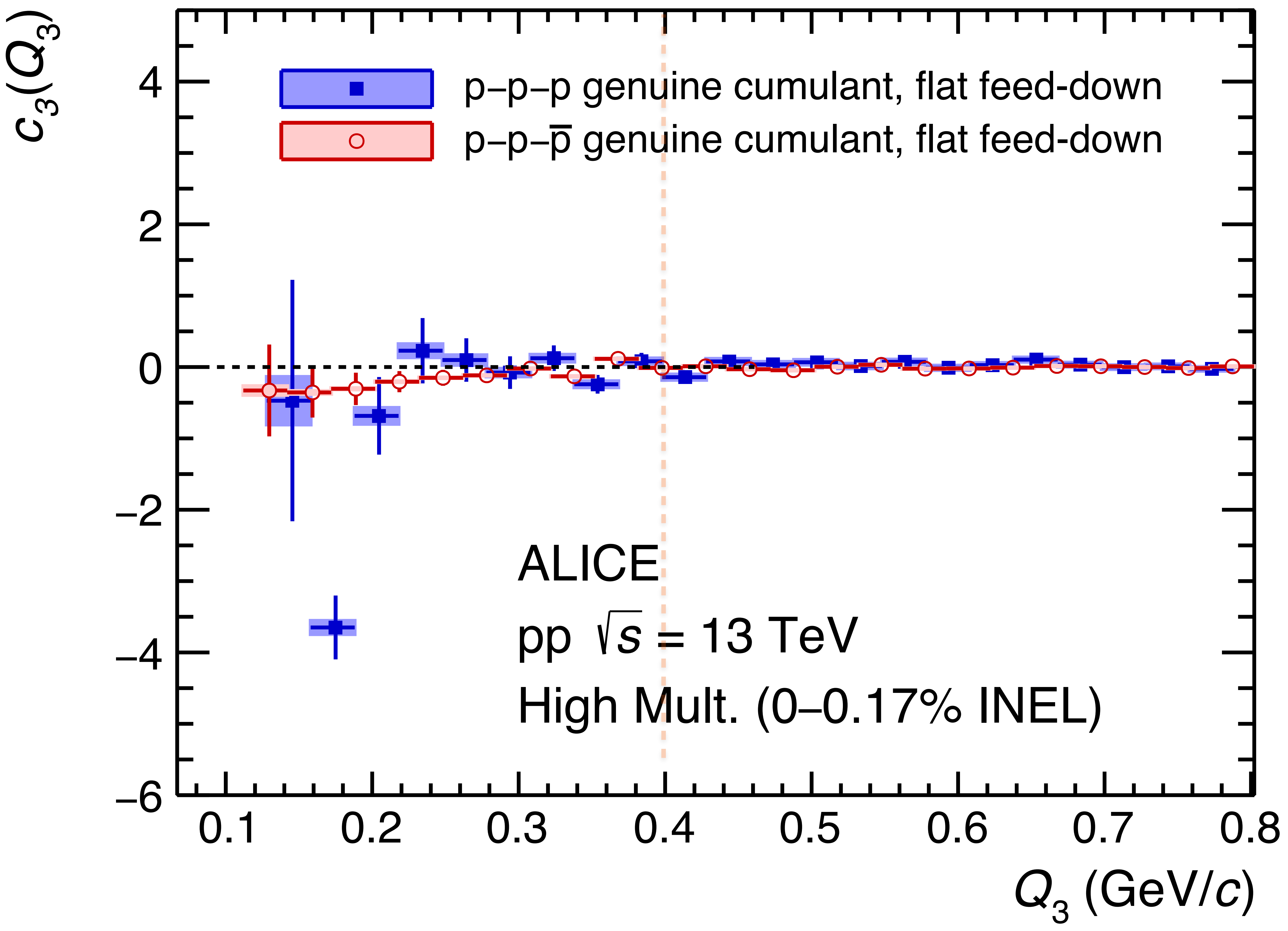
Data driven approach: using two particles from same event and a third from another event.

Projector method: calculate the kinematic projection of the two-body correlation on the three-body state[2].

[1] R. Kubo, J. Phys. Soc. Jpn. 177 (1962)
[2] R. Del Grande, L. Šerkšnytė et al, EPJC 82 (2022) 3, 244

The p-p-p cumulant





Statistical significance:

p-p-p: n_σ = 6.7 for $Q_3 < 0.4$ GeV/c

Conclusion:

Presence of a genuine three-body effect in p-p-p!

Possible interpretations:

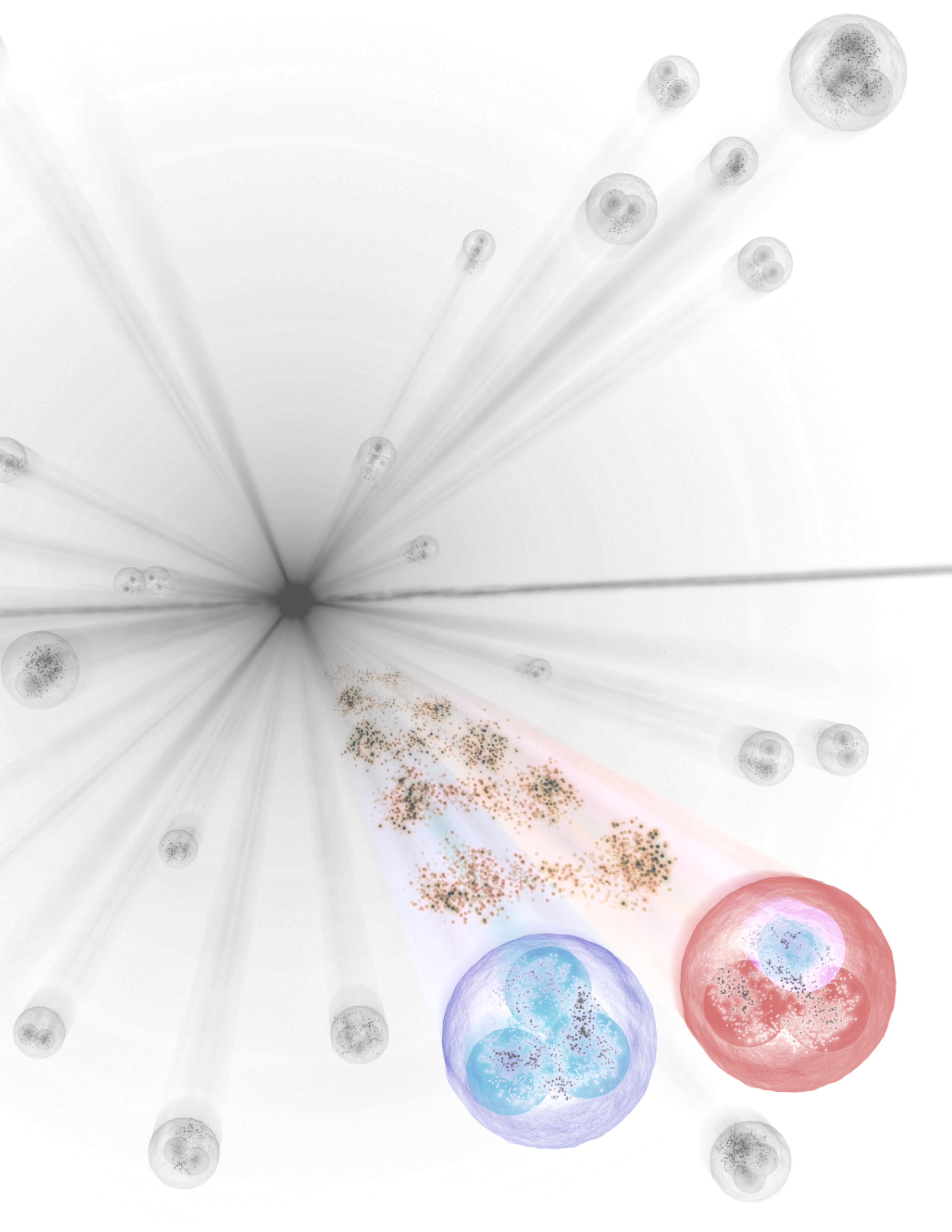
- Pauli blocking at the three-particle level
- long-range Coulomb interaction effects
- three-body strong interaction

New
arXiv:2206.03344

The p-d correlation should be affected by three-body p-p-n interactions!

Summary & Outlook

- Summary:
  - First measurement of proton-deuteron correlations in high-multiplicity pp collisions at $\sqrt{s}$ = 13 TeV
  - In contrast to the data, the simple model based on scattering parameters show a huge peak at low k^*
- Work in progress:
  - Include the projections of the contributions of pair-wise and genuine three-body p-p-n interactions to the p-d correlation
  - p-d potential models based on three-body dynamics.
- Outlook:
  - More precision studies within reach with the large data samples in Run 3



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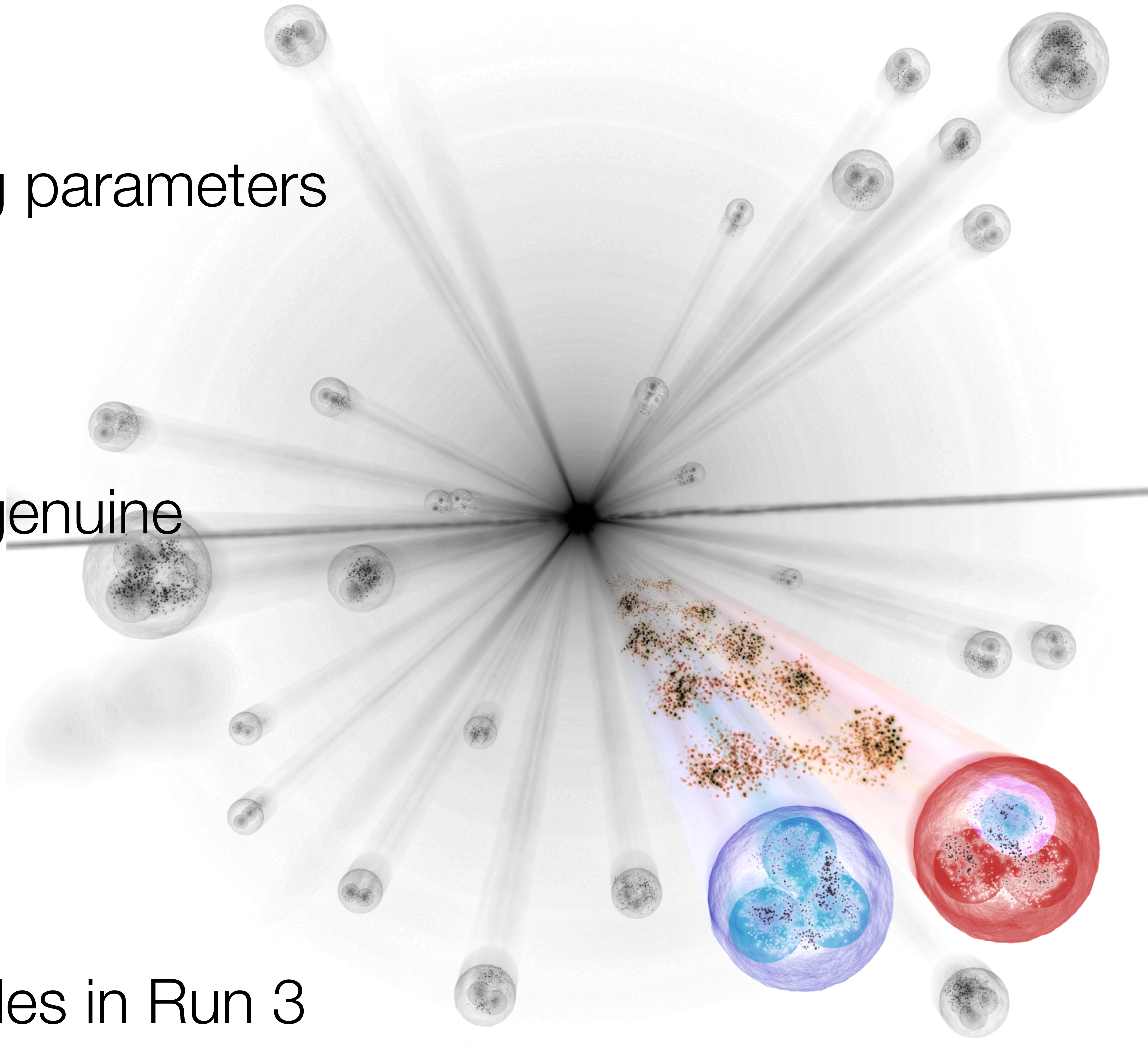


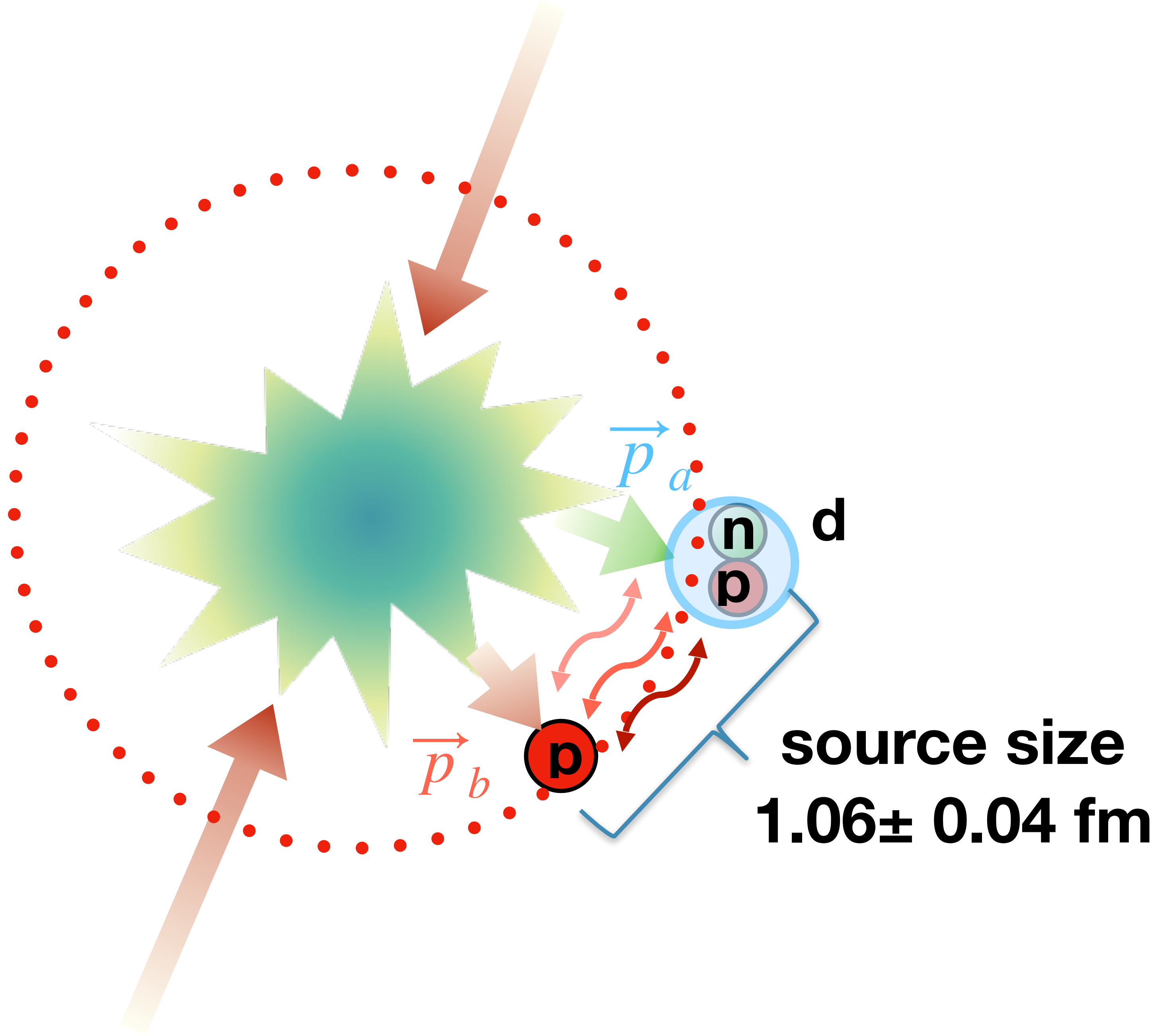
Thank you for your attention!

Additional slides

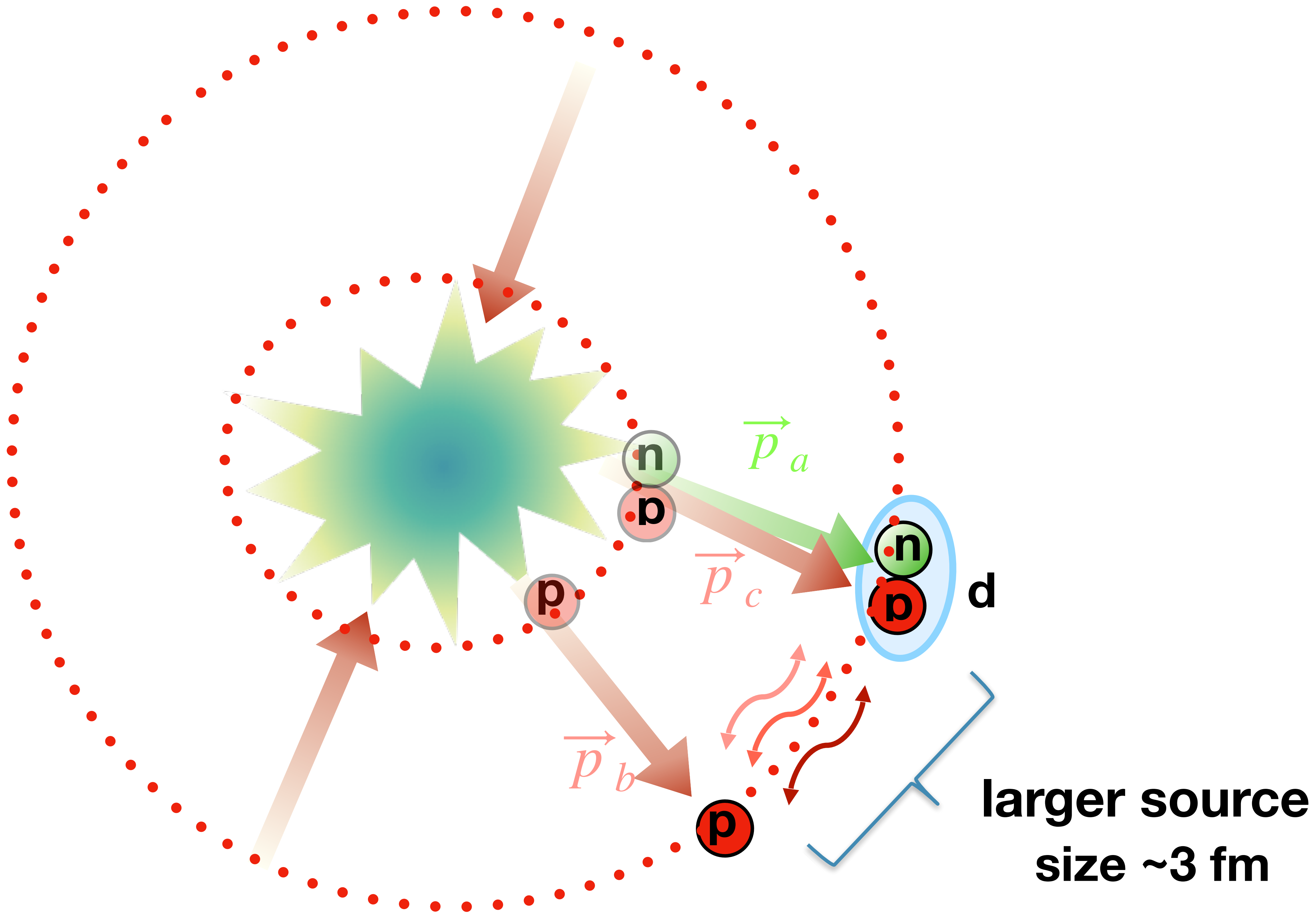
What if the deuteron is formed later?

- Source size increases due to **late formation** of deuteron
  - As a result the measured interaction between proton and deuteron weakens

Case I : p and d are formed at the same time



Case II : delayed formation of d



Femtoscopic correlation

- The femtoscopic correlation may have background/contributions from
  - Particles from weak decays
  - Particles from material knock-outs
  - Misidentifications

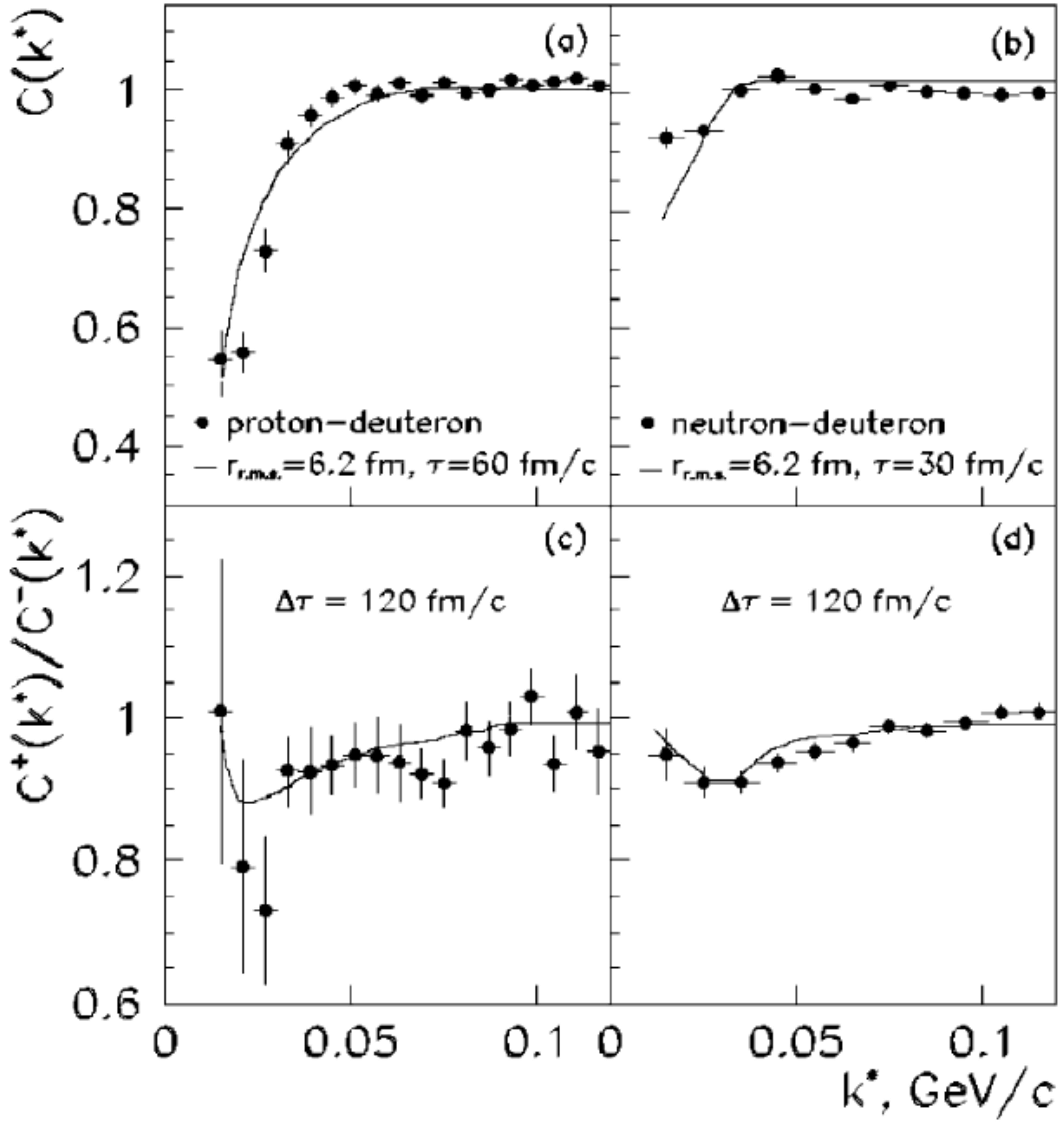
$$C_{femto}(k^*) = \lambda_0 C_0 \oplus \lambda_1 C_1 \oplus \lambda_2 C_2 \oplus \ldots$$

Contributions from: genuine feed-down misidentifications

- Quantification of the contributions to the pairs done by the lambda parameters $\lambda_{ij} = \mathscr{P}_i . f_i \times \mathscr{P}_j . f_j$
  - Purity of the individual particles ($\mathscr{P}_i$)
  - Feed-down fractions (f_i)

proton-deuteron correlation measurement so far

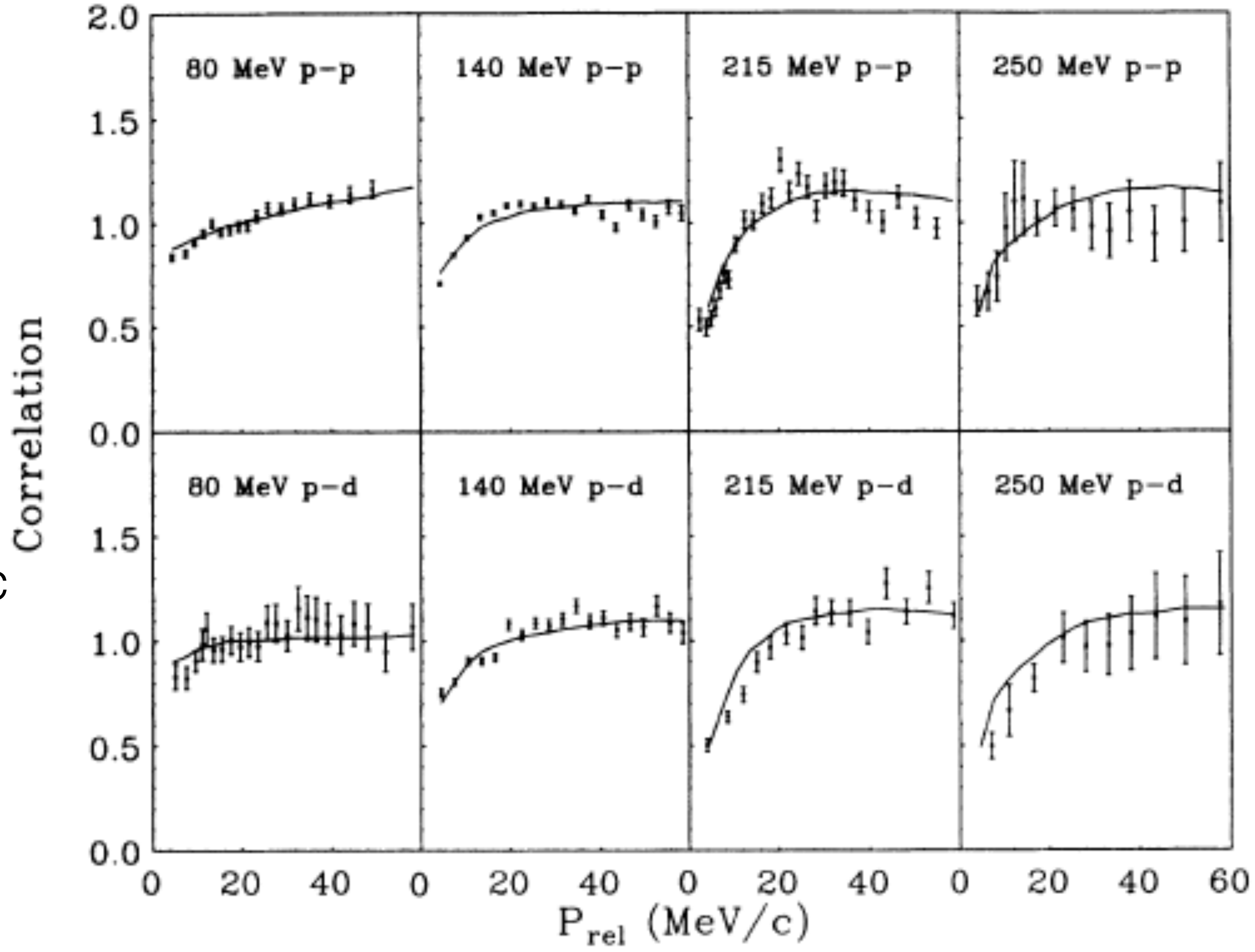
- **Status**:
  - p-d correlation function from 2006
  - GANIL(Grand Accélérateur National d'Ions Lourds):
    - ^{40}Ar-^{58}Ni reaction at 77 MeV/u
    - Show a clear depletion
    - Only unto 100 MeV/c in relative momentum



[1] Wosińska, K., Pluta, J., Hanappe, F. *et al. Eur. Phys. J. A* 32, 55–59 (2007)

proton-deuteron correlation measurement so far

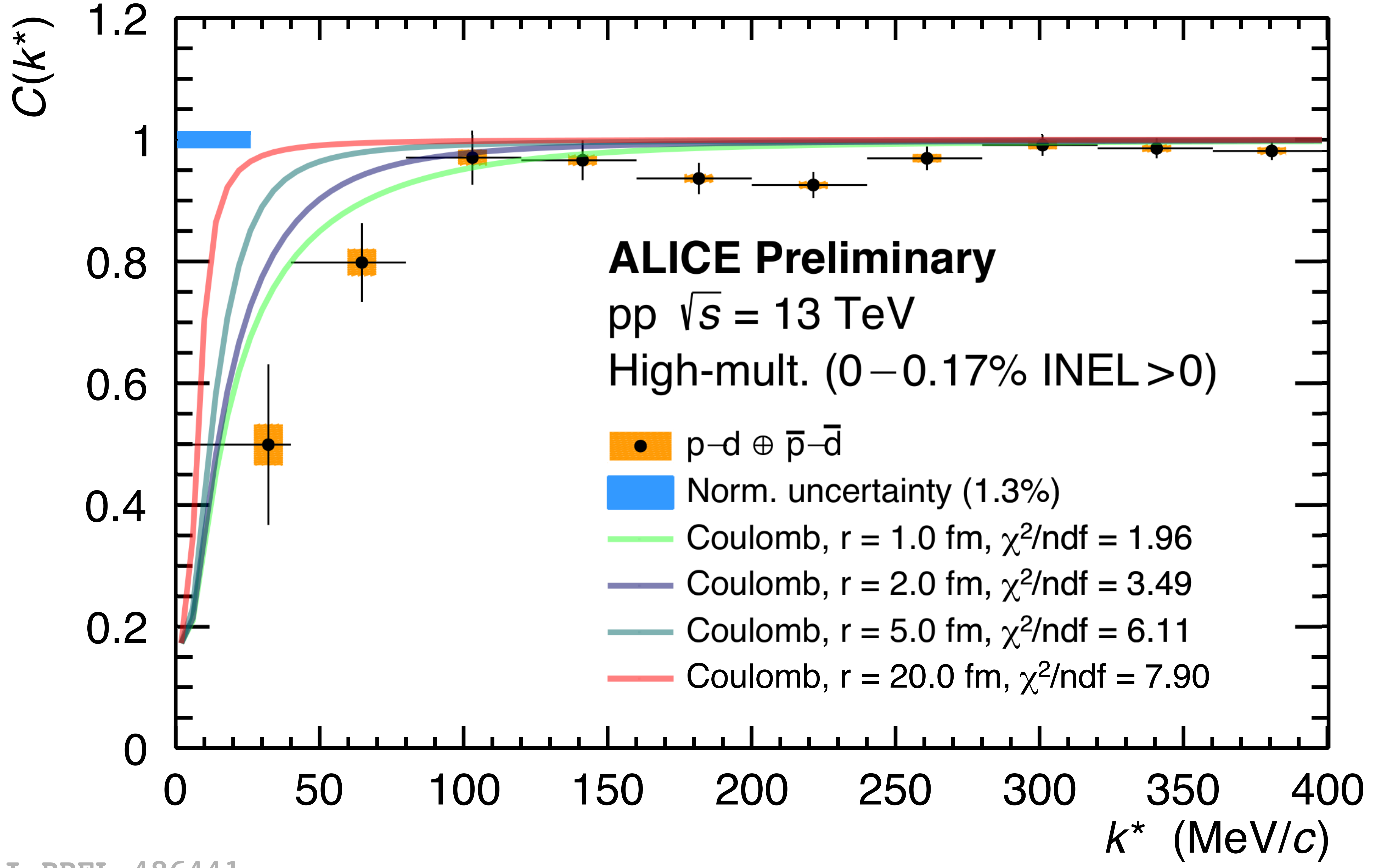
- **Status**: Measurement by *P. A. DeYoung et al* in 1990
  - Measurements for 80 and 140 MeV/c ^{16}O - ^{27}Al reaction were performed at the Stony Brook Linac
  - Measurements for 215 and 250 MeV/c ^{16}O - ^{27}Al reaction were performed at the ATLAS facility of the Argonne National Laboratory.
  - In the relative momentum range [0-60] MeV/c
  - Show a clear depletion
  - Solid line coulomb prediction from Koonin model



P. A. DeYoung et al. PRC ***41,*** *R1885* (1990)

Theoretical models and data

- Coulomb-corrected wave function for charged particles Lednický, R. *Phys. Part. Nuclei* 40, 307–352 (2009)
  - Coulomb + strong interaction (S = 1/2 and S = 3/2)
  - Only for s wave interaction
  - Theoretical models constrained to scattering p—d experiments
  - Coulomb-interaction only does not describe the data



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Lednicky model

- Coulomb-corrected wave function for final-state interactions (Lednicky): arxiv.org/abs/nucl-th/0501065

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

  - f_c is the Coulomb-corrected strong scattering amplitude
  - $F(-i\eta, 1, i\zeta)$ is the confluent hypergeometric function and $\tilde{G}(\rho,\eta)$ is the regular Coulomb function

- It is an approximated wave function for two near-threshold charged particles:

- The two-particle correlation: we can use Koonian-Pratt formula

$$C(k) = \int S(\mathbf{r}) \mid \psi_k(\mathbf{r}) \mid^2 \mathrm{d}^3 r,$$ with source function $$S(r) = \frac{1}{(4\pi r_0^2)^{3/2}} \exp\left(-\frac{r^2}{4r_0^2}\right)$$

Another calculation at hand

- Hadron-Deuteron Correlations and Production of Light Nuclei in Relativistic Heavy-Ion Collisions: arxiv.org/abs/1904.08320
  - hadron-deuteron correlation function which carries information about the source of the deuterons
  - Allows one to determine whether a deuteron is directly emitted from the fireball or if it is formed afterwards
  - Conclusion:
    - The theoretical p-d correlation function is strongly dependent on the source size

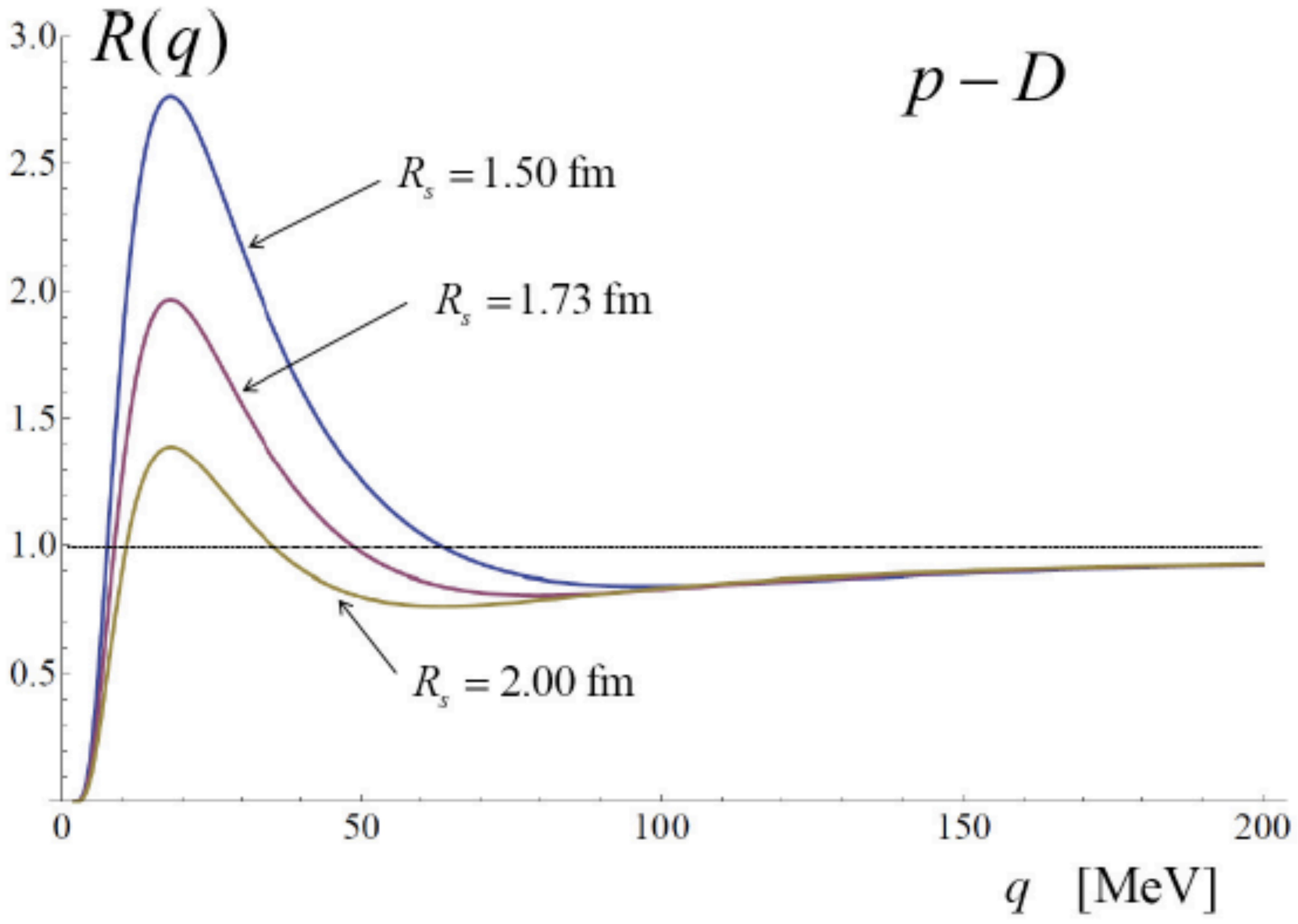

Fig. 2. $p-D$ correlation function