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**

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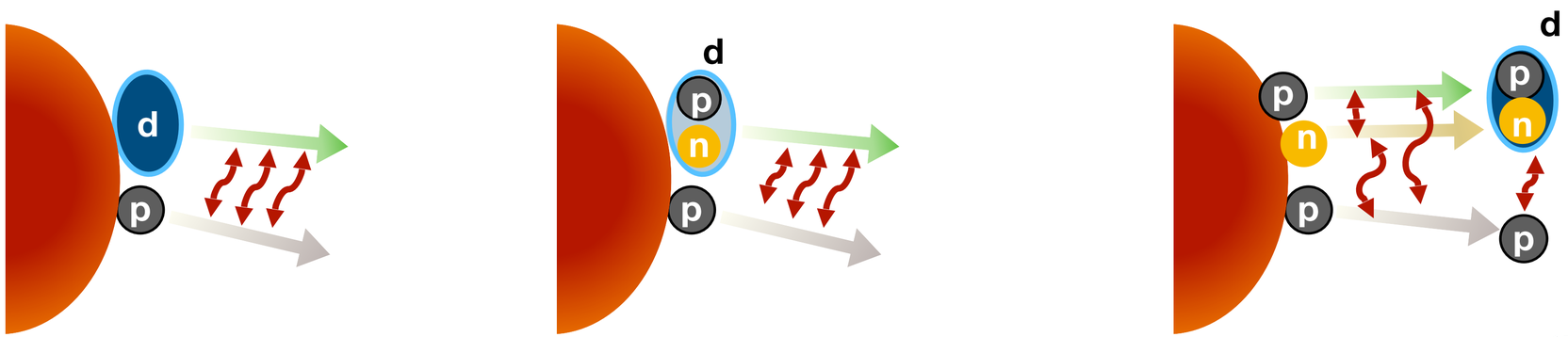
Motivation

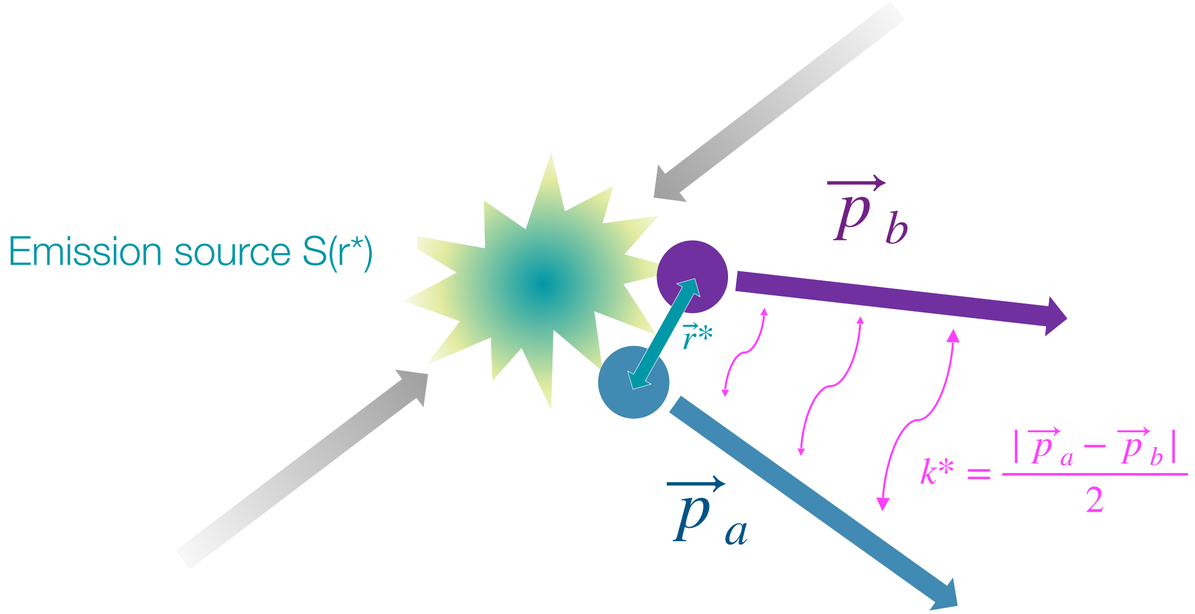
- **Proton-deuteron (p—d) interaction**
  - Three-nucleon force: doorway to probe short distances
  - p—d interaction can be constrained from the scattering experiments
- **Production mechanism of light nuclei not understood:**
  - Models: information on single particle, Statistical Hadronisation Model[1,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



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

Femtoscopy at the LHC

- **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

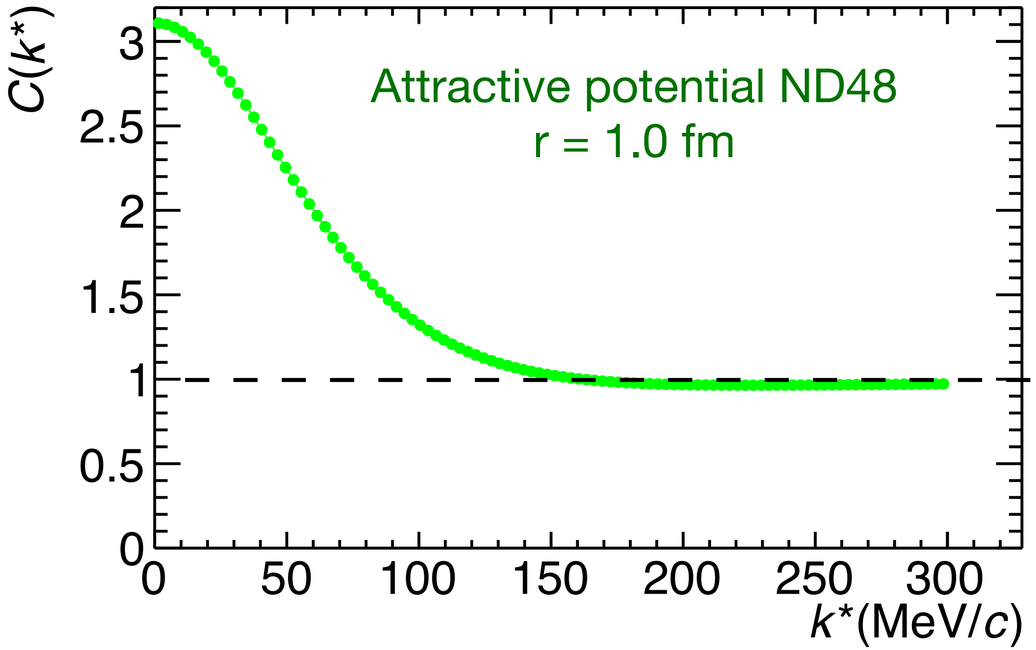
$$C(k^*) = \int S(\vec{r}^*) \left| \psi(\vec{k}^*, \vec{r}^*) \right|^2 d^3\vec{r}^* = \mathcal{N} \frac{N_{\text{same}}(k^*)}{N_{\text{mixed}}(k^*)} \xrightarrow{k^* \to \infty} 1$$

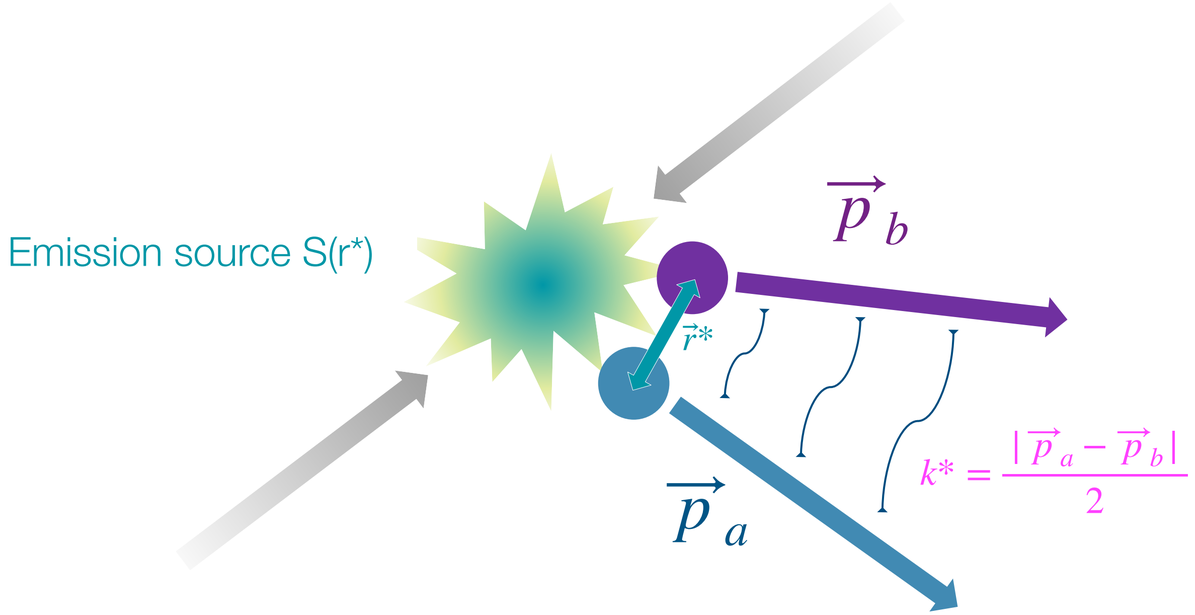
theoretical definition — experimental definition

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

Femtoscopy at the LHC

- Correlation rises above 1 for attractive potentials





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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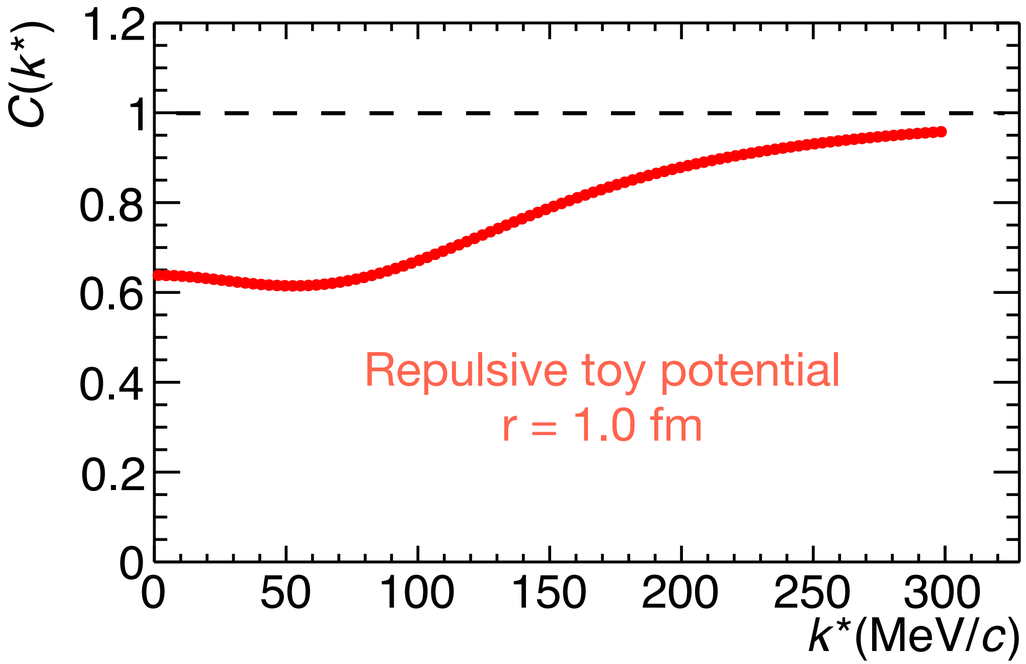
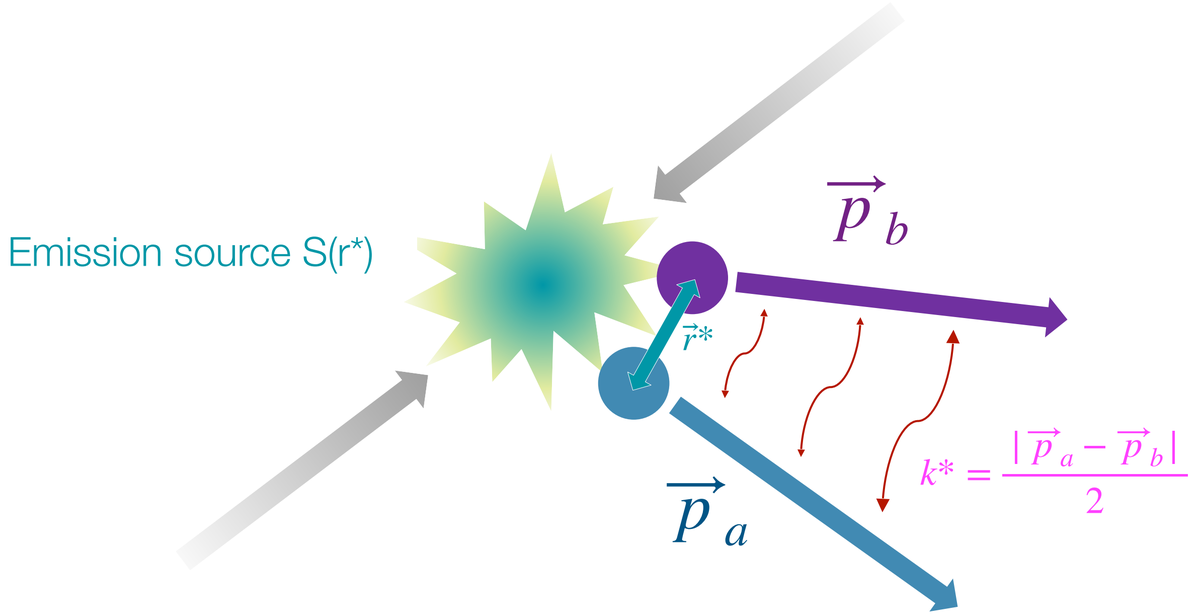
Femtoscopy at the LHC

- Repulsive interaction brings correlation below 1





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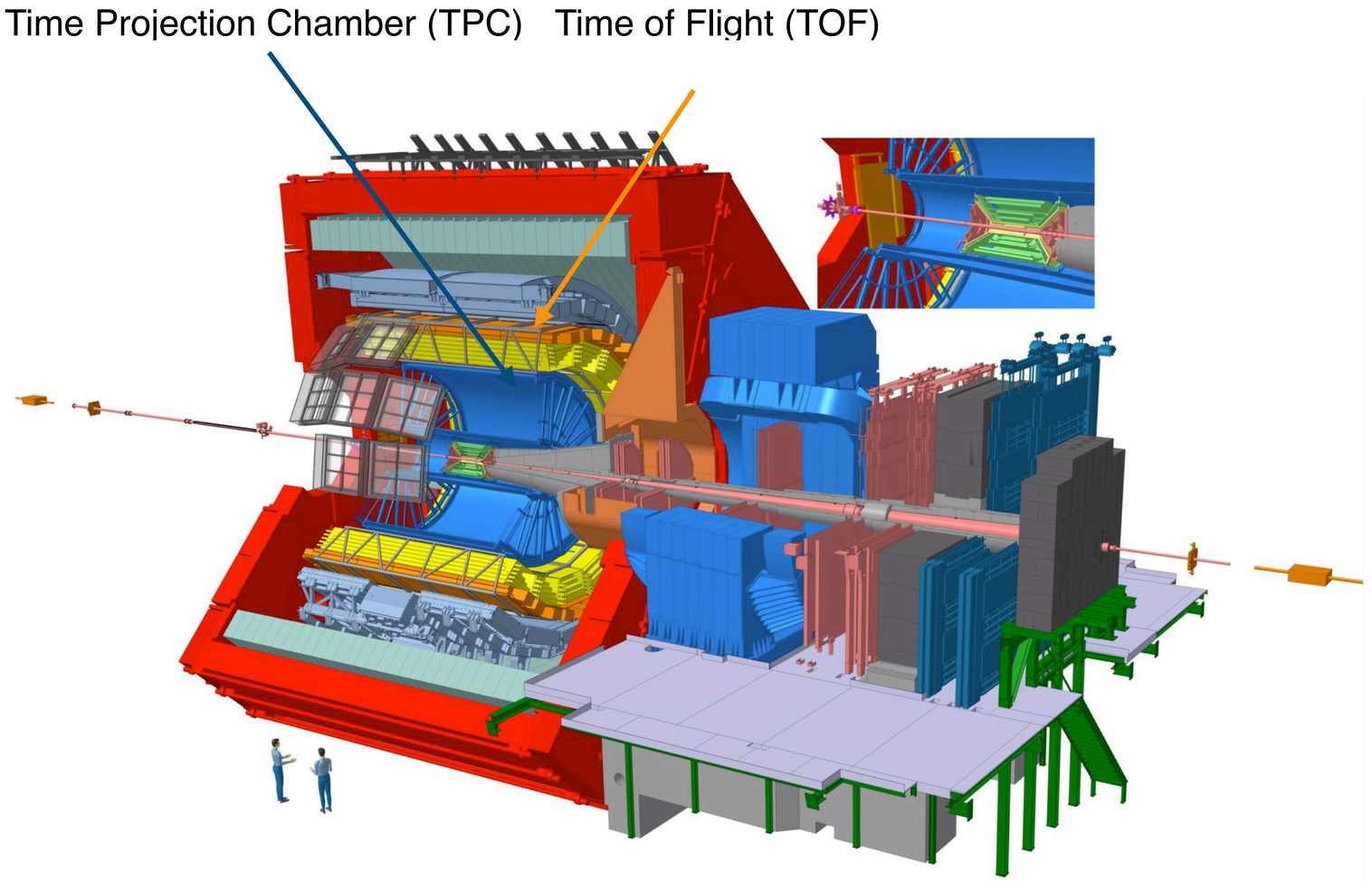
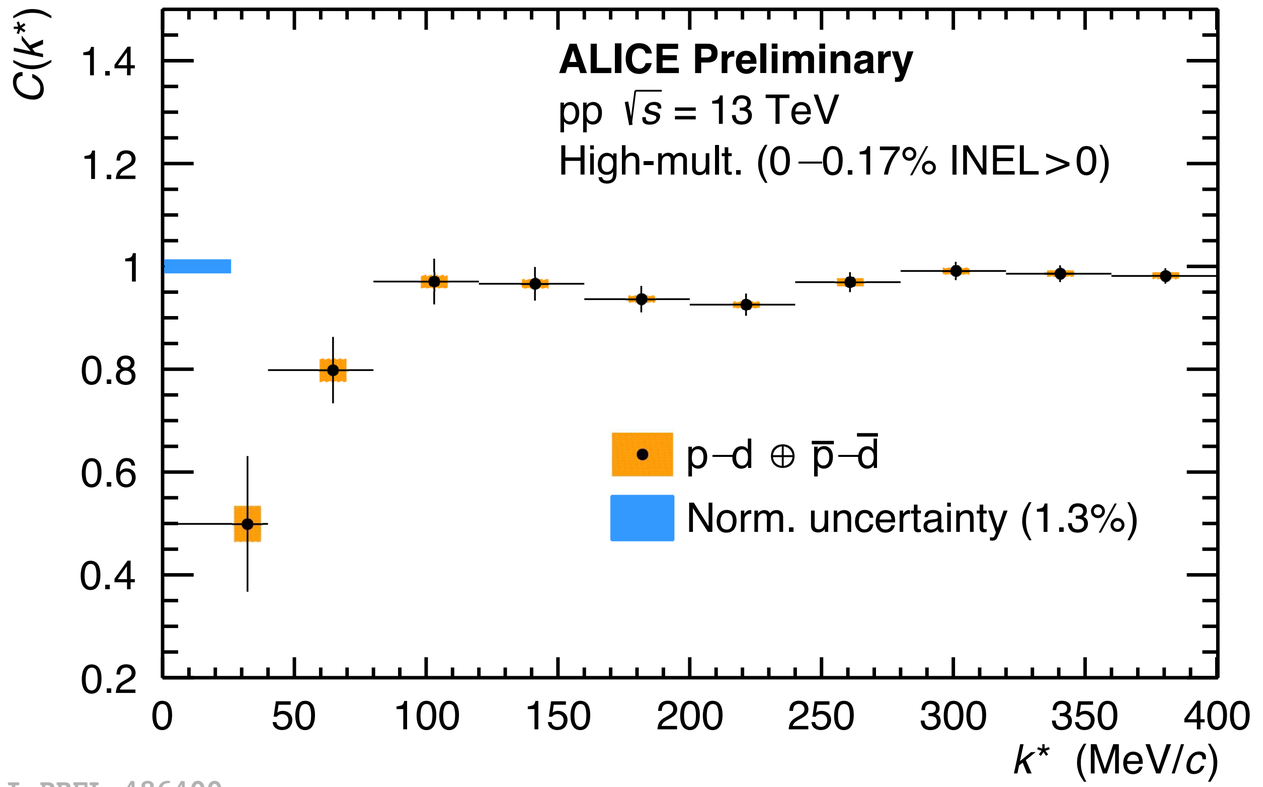
ALICE Experiment

- 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%**



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
  - p—d: 1250

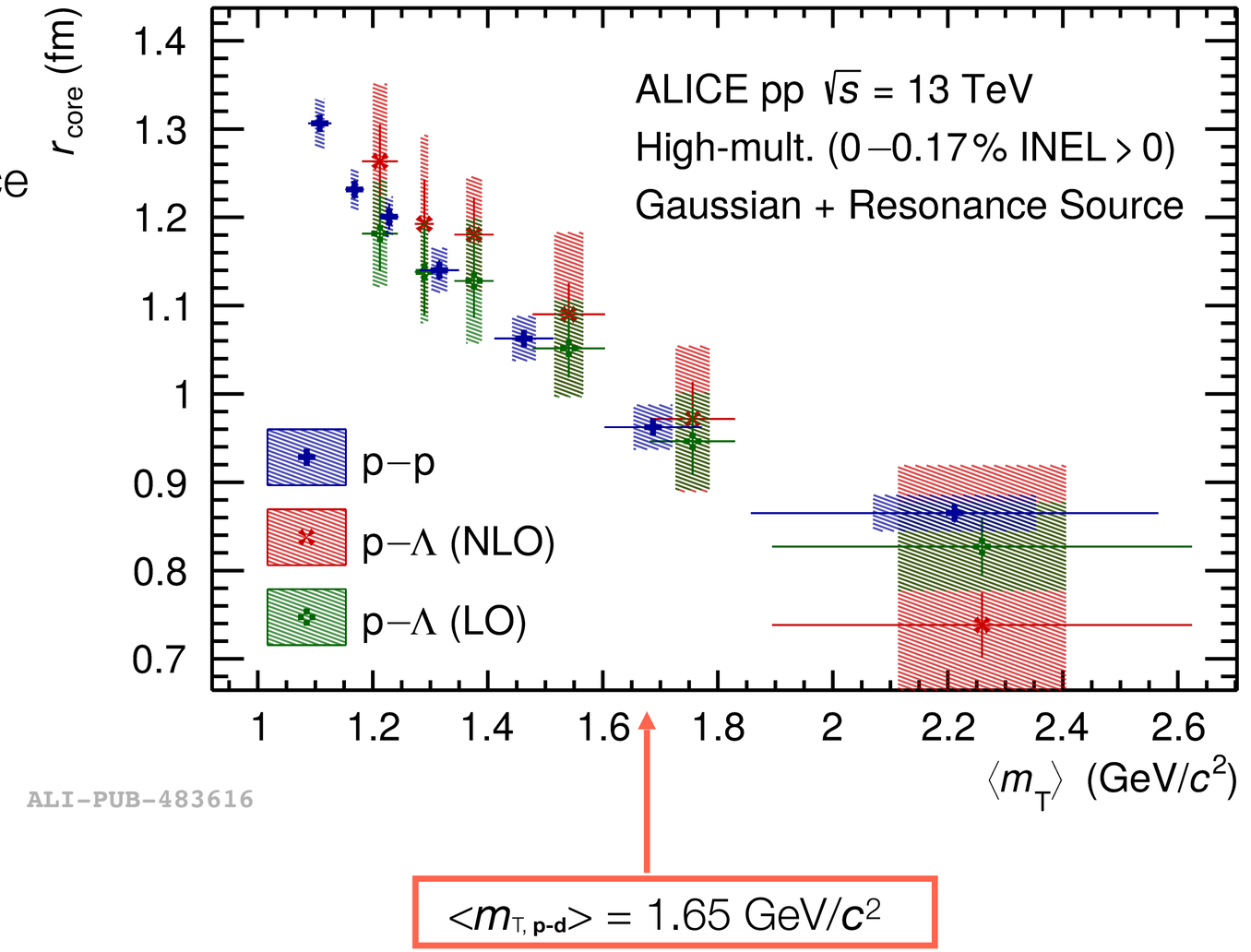


ALI-PREL-486400

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

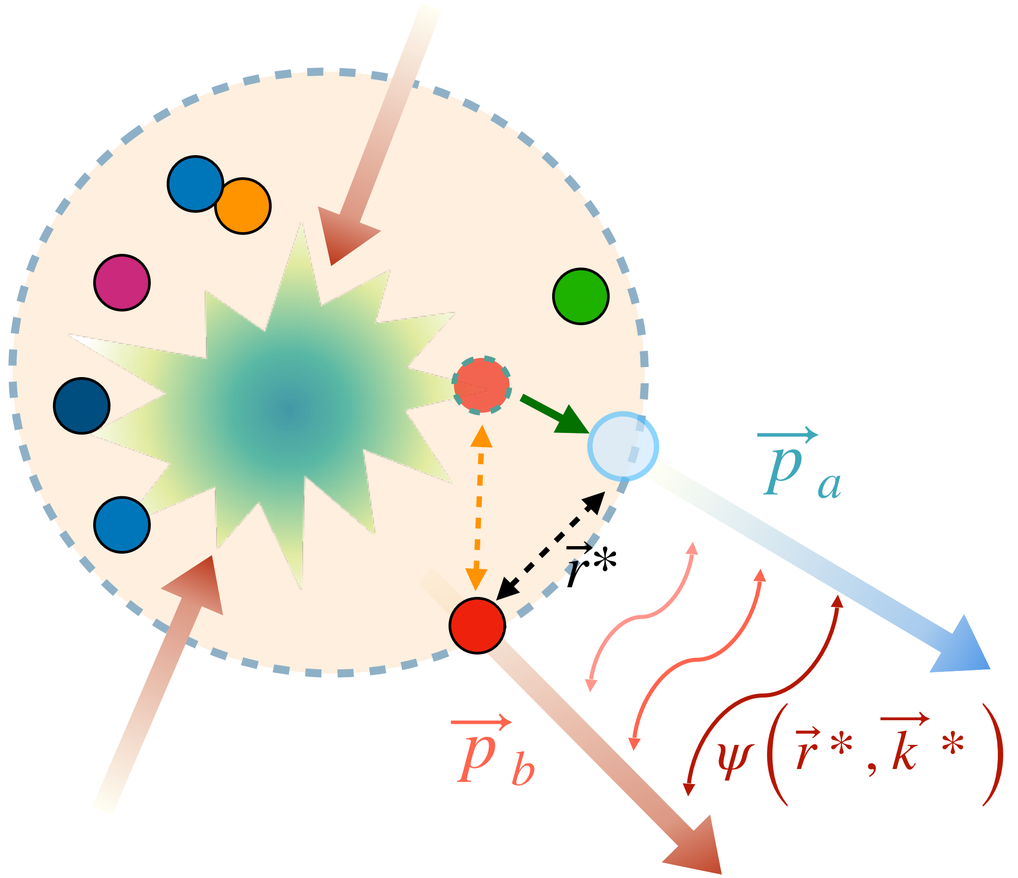


ALICE Coll. PLB 811 135849 (2020)

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** ($c\tau \approx r_{core}$) 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

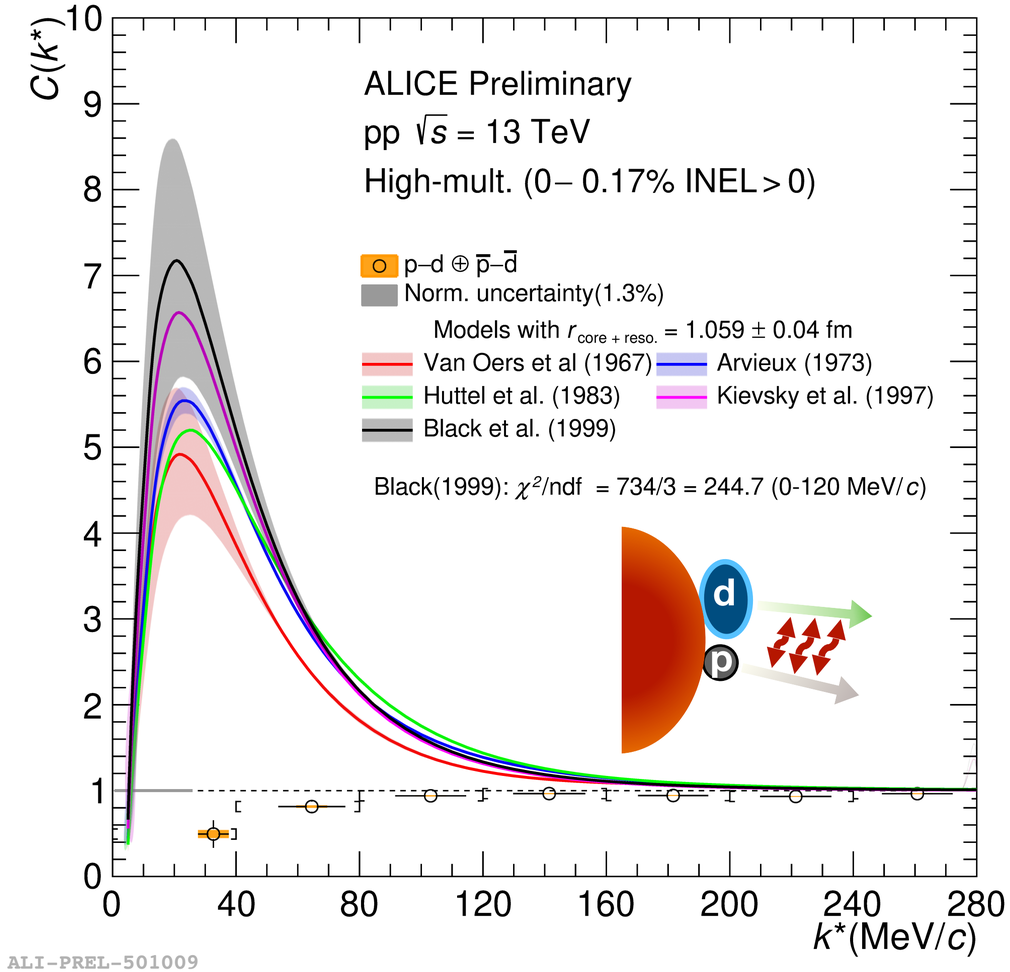


ALICE Coll. PLB 811 135849 (2020)

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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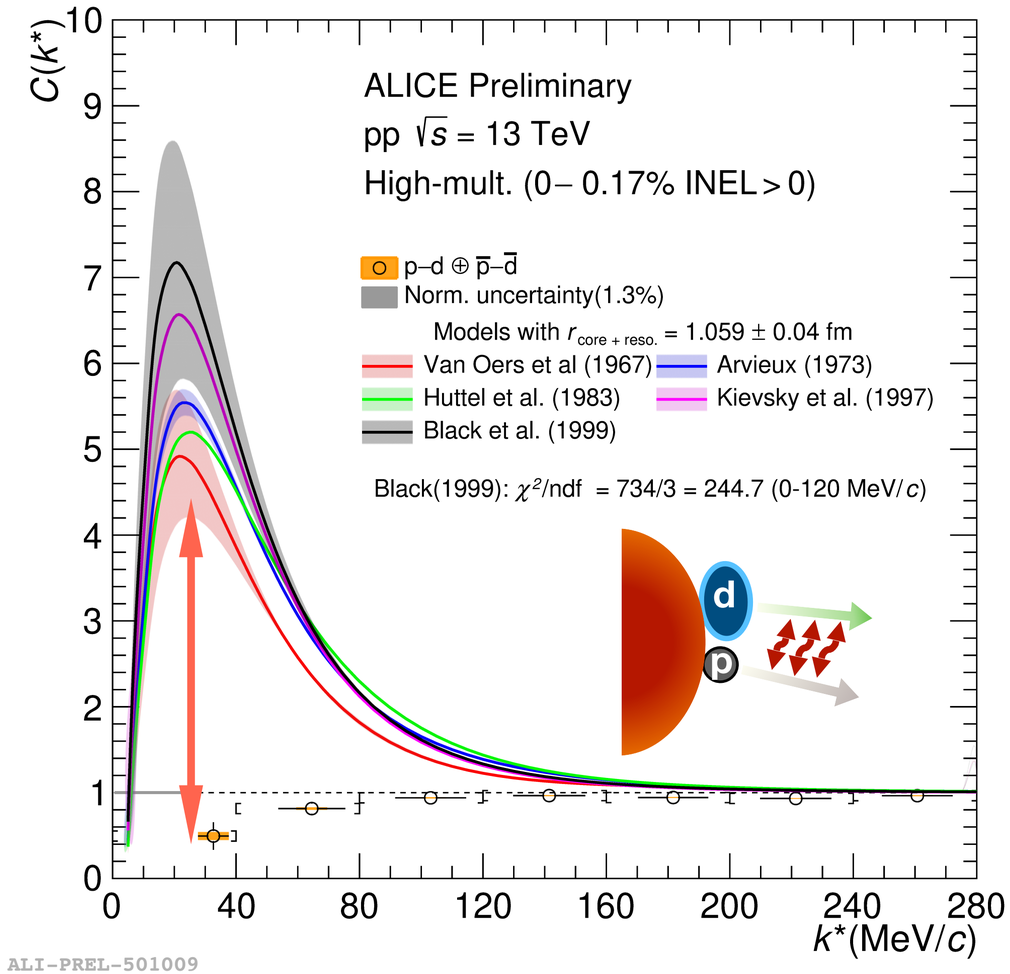

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Van Oers,Brockmann et al. Nucl. Phys. A 561-583 (1967)
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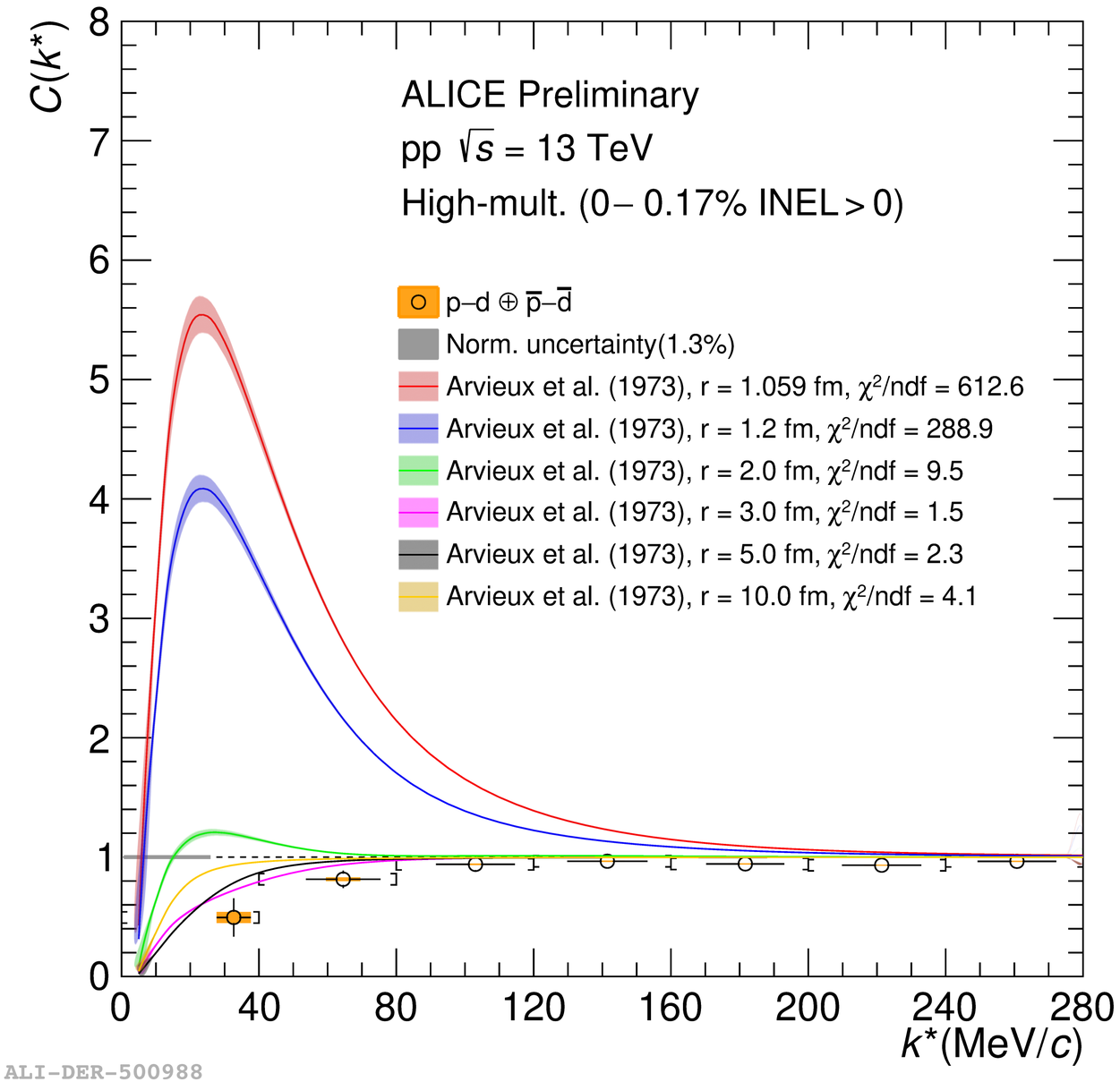
Increased source size deuteron(antideuteron)

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

Assumptions

➡ Model does not account for p-(p-n) interaction

➡ Deuteron as point like particle



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Increased source size deuteron(antideuteron)

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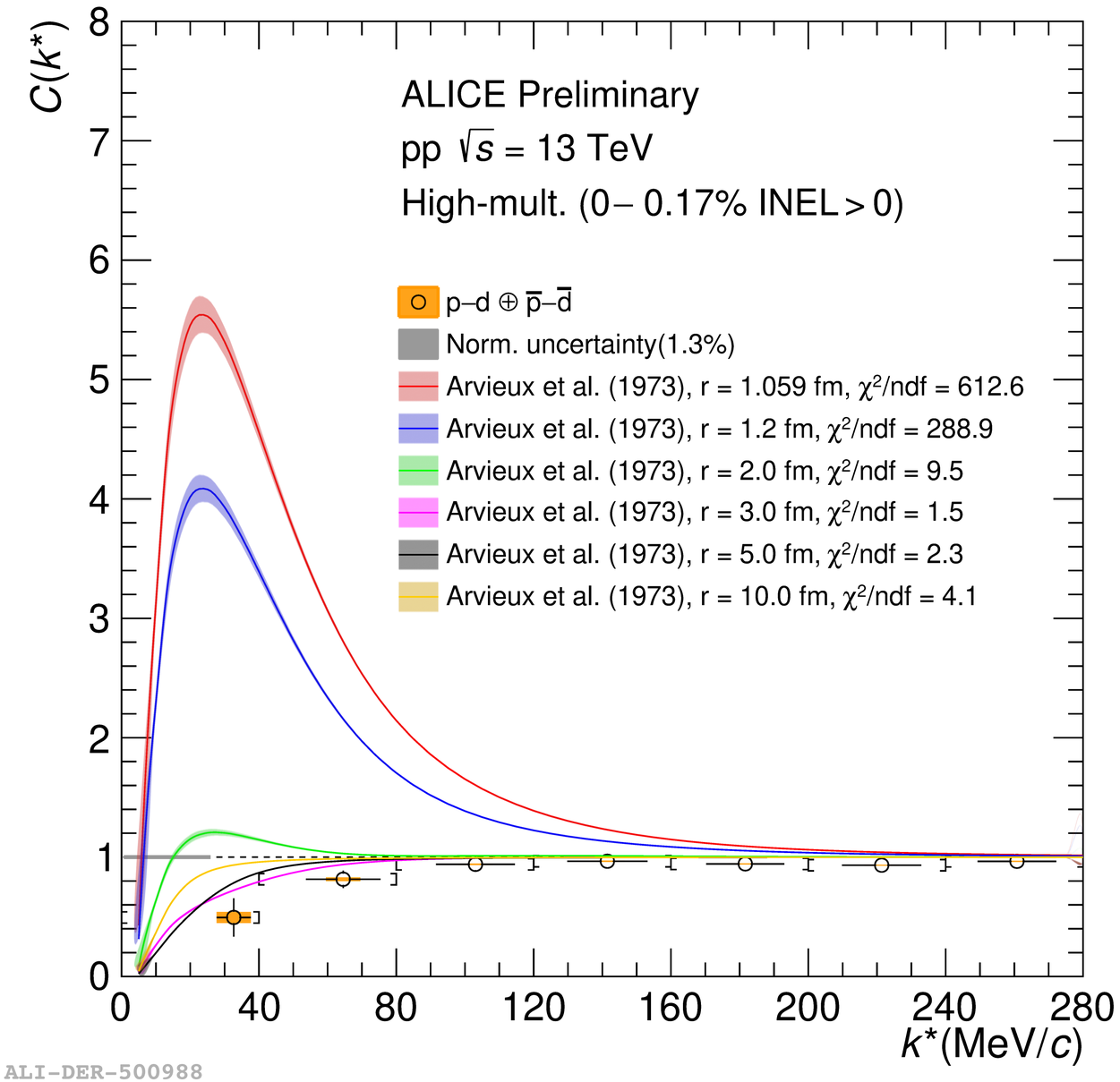
Assumptions

➡ Model does not account for p-(p-n) interaction

➡ Deuteron as point like particle

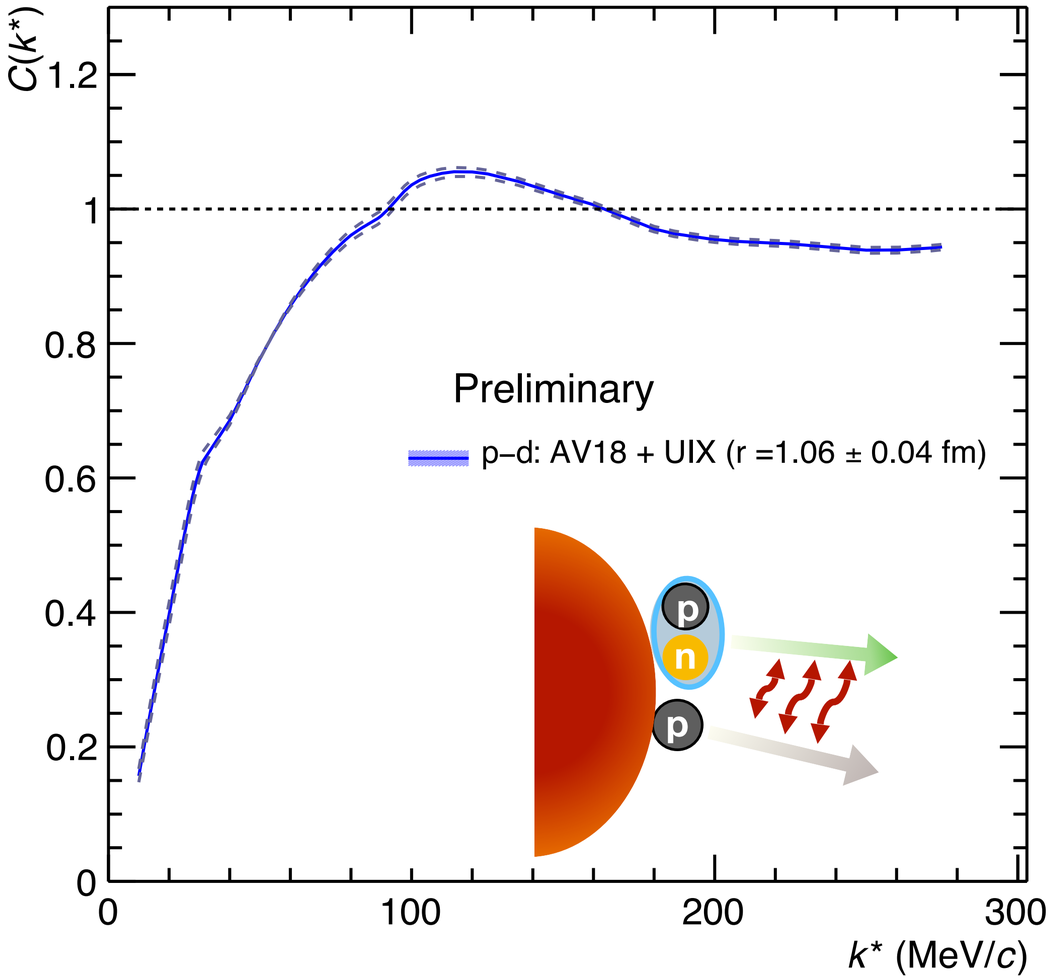
Work in progress: project the pair-wise and genuine three-body interaction of p-(p-n) on the p-d correlations



Theoretical calculations

- **Model:** based on three-body dynamics calculation done by PISA theory group: **Michele Viviani**, **Alejandro Kievesky** and **Laura Marcucci**

- Relevant potentials:
  - Two-body interaction with Argonne V18 (AV18) and three-body interaction using Urbana XI (UIX) potential
  - Used a deuteron wavefunction from AV18 NN interaction
  - Demanding that deuteron is formed at the same time as the proton



Calculation: provided in a private communication

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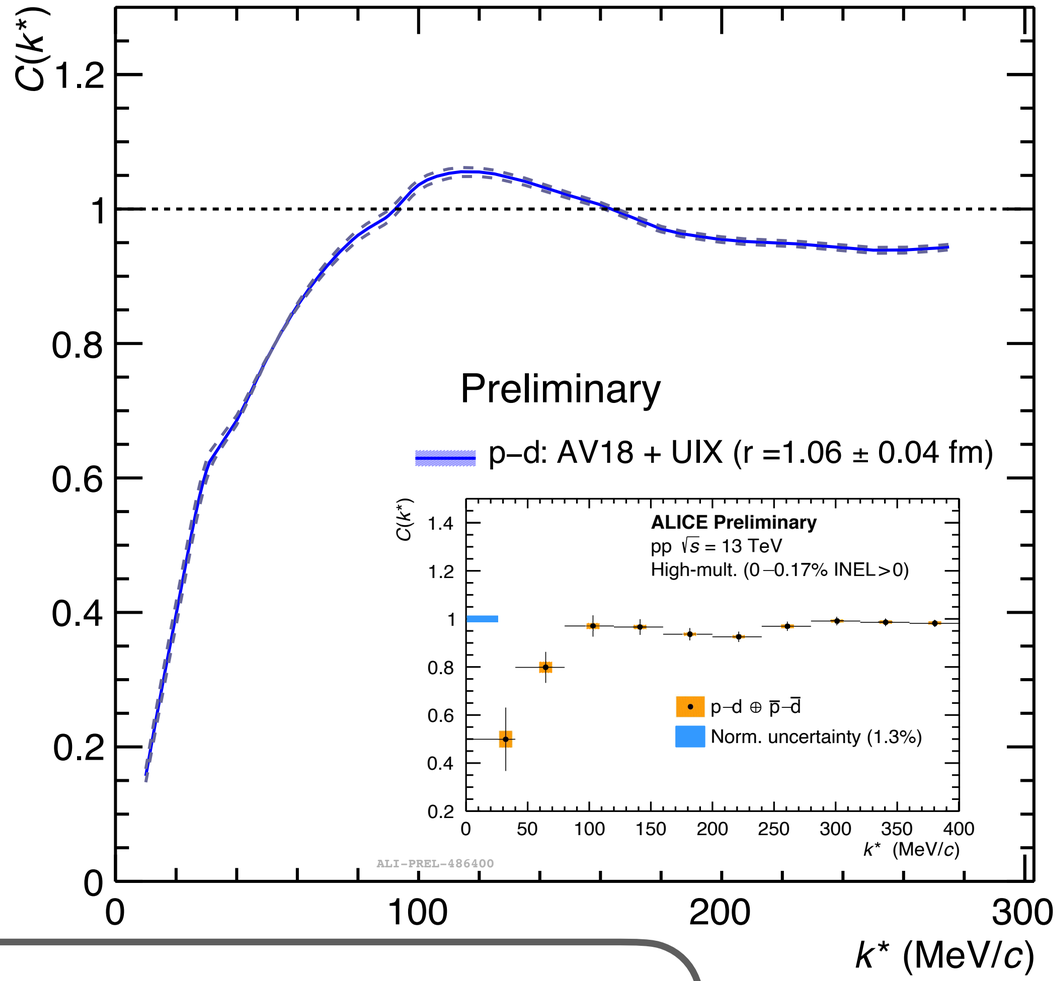
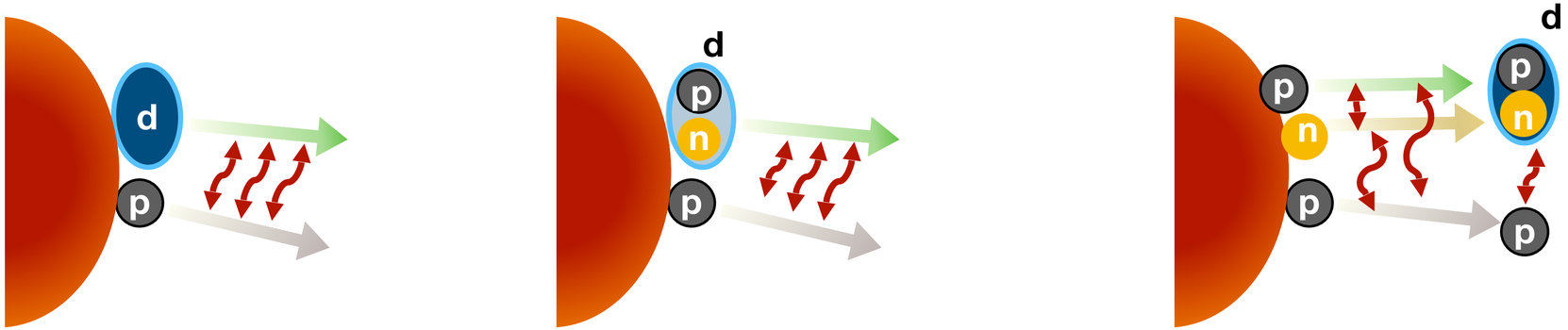


➡ **Model calculation qualitatively reproduces the data**

➡ **The p-d correlation should be affected by two + three-body p-p-n interactions!**

Summary & Outlook



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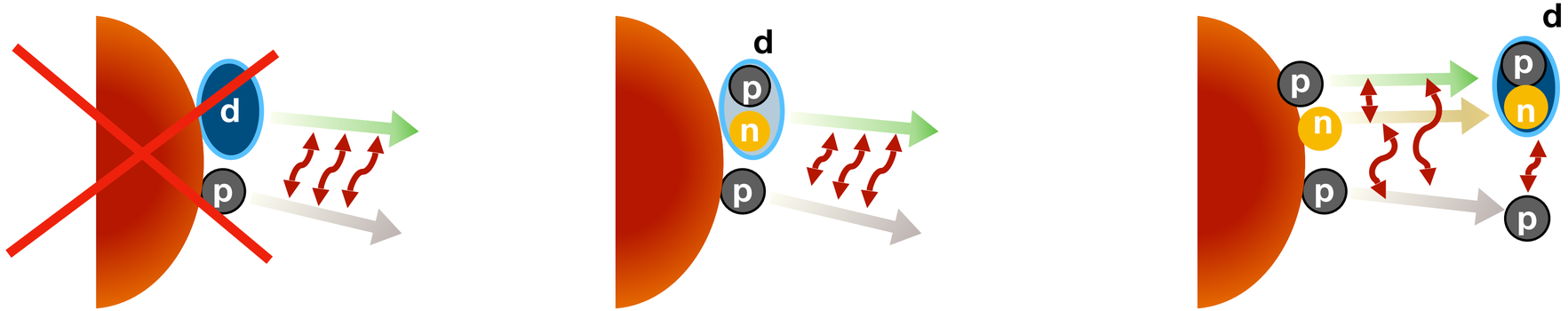
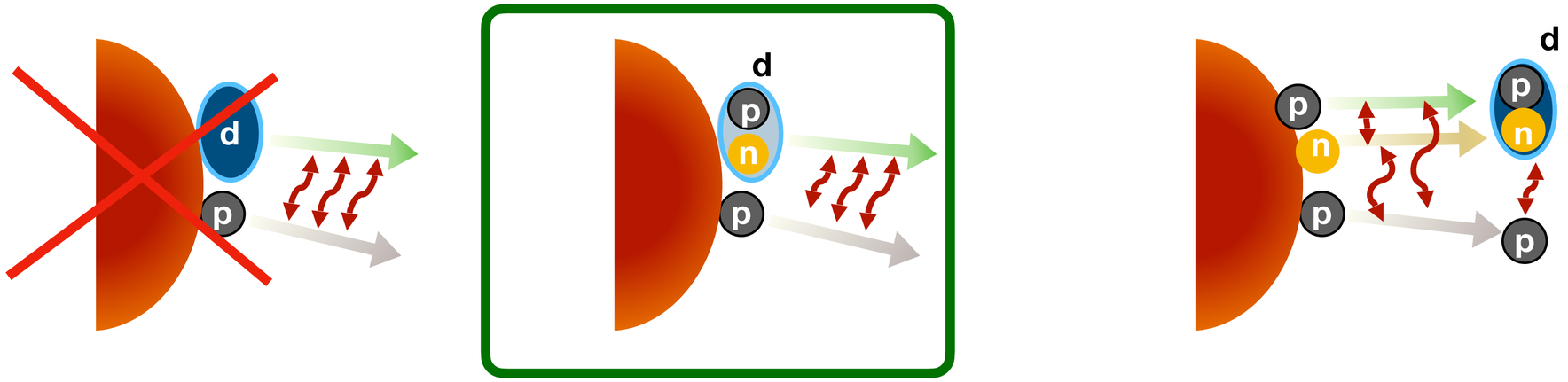


Summary & Outlook

Looks promising!



- 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

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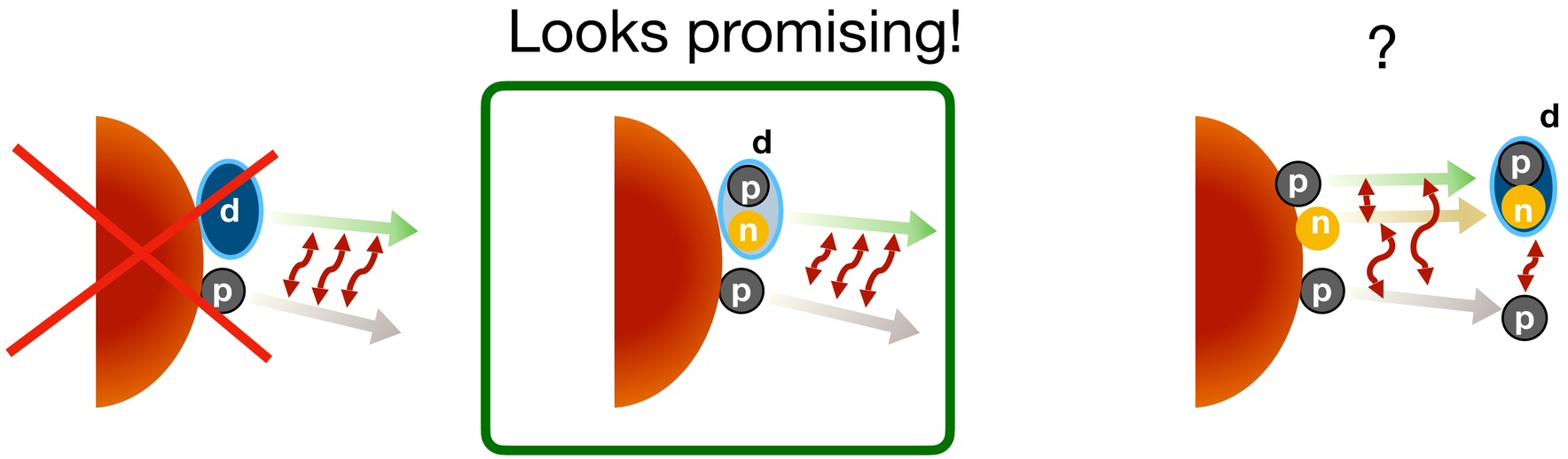

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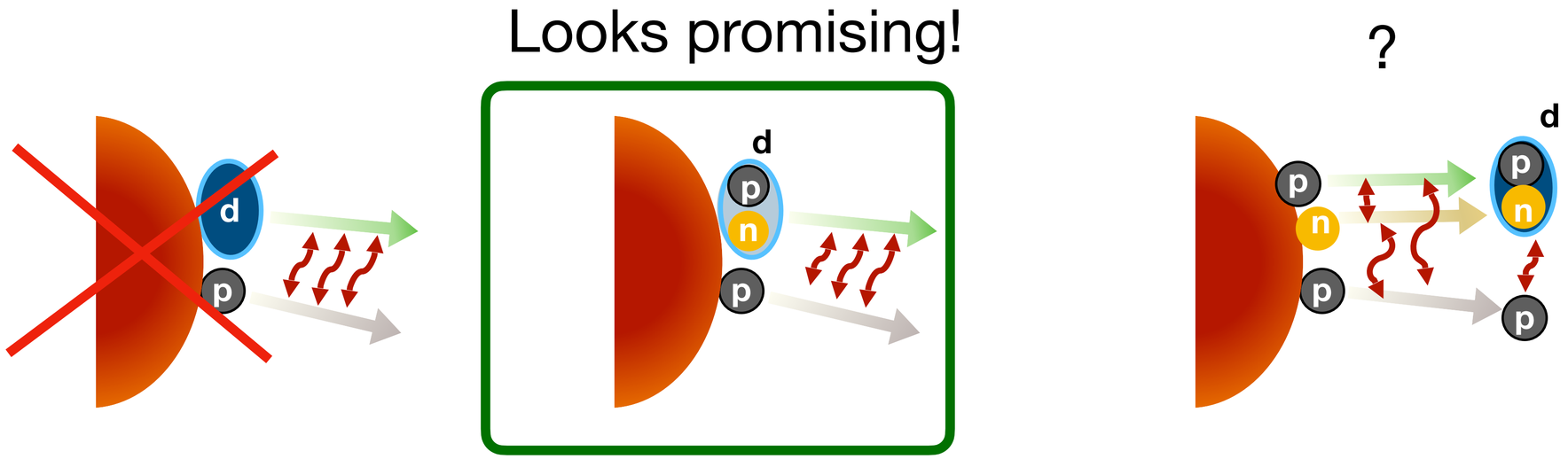

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- Outlook:
  - More precision studies within reach with the large data samples in Run 3

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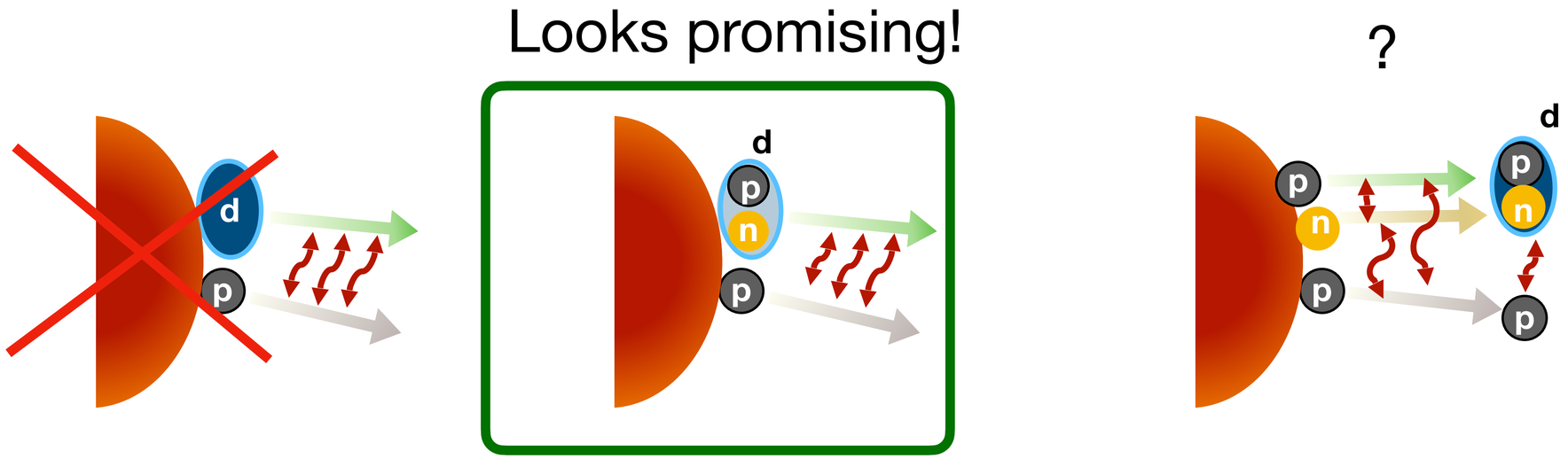

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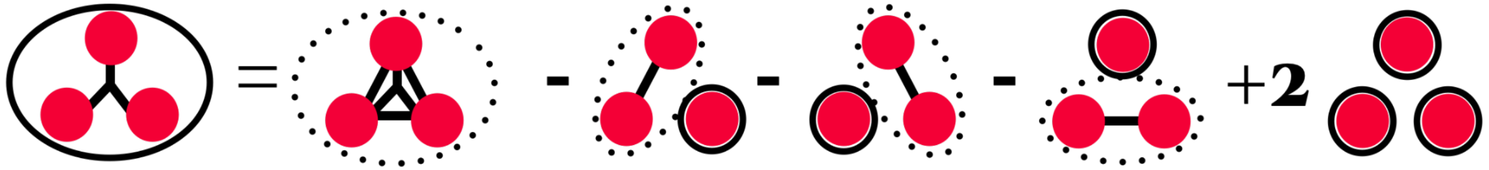
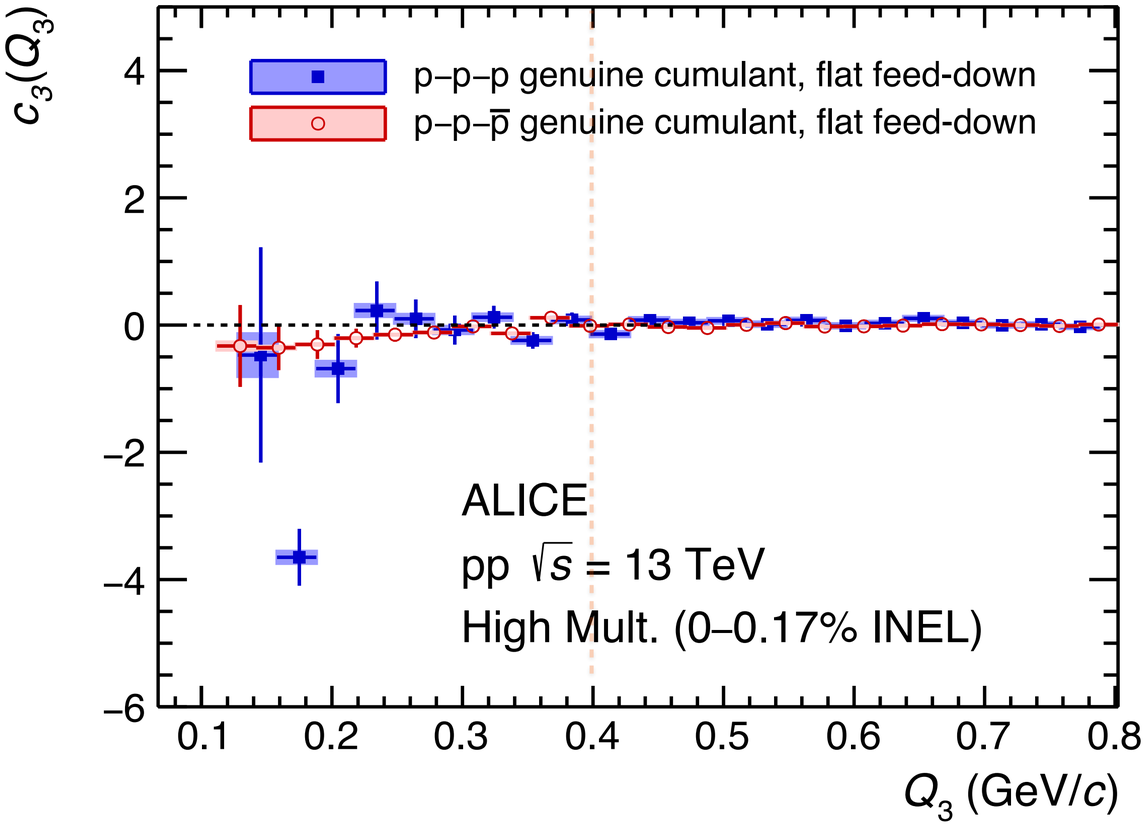
Thank you for your attention!

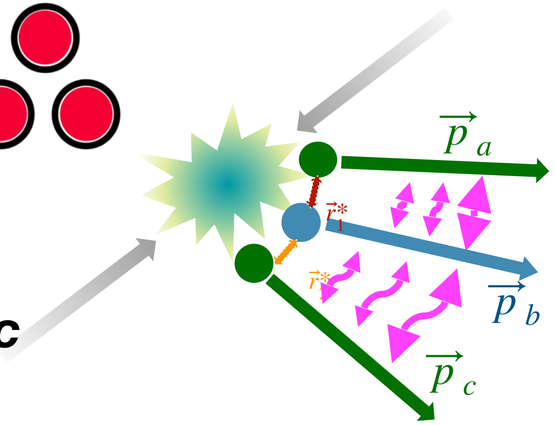
Additional slides

The p-p-p cumulant

Talk: Laura Šerkšnytė
29/06/2022, 11:15







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

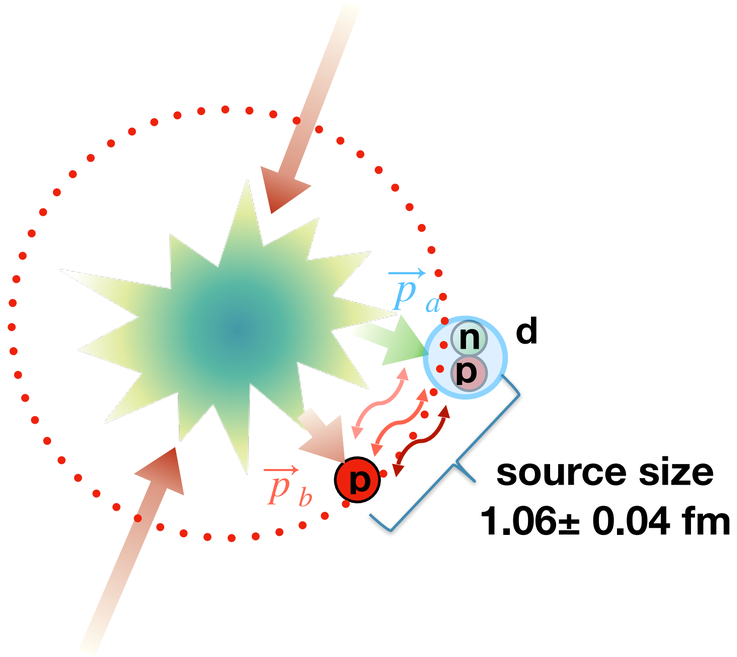
New
arXiv:2206.03344

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

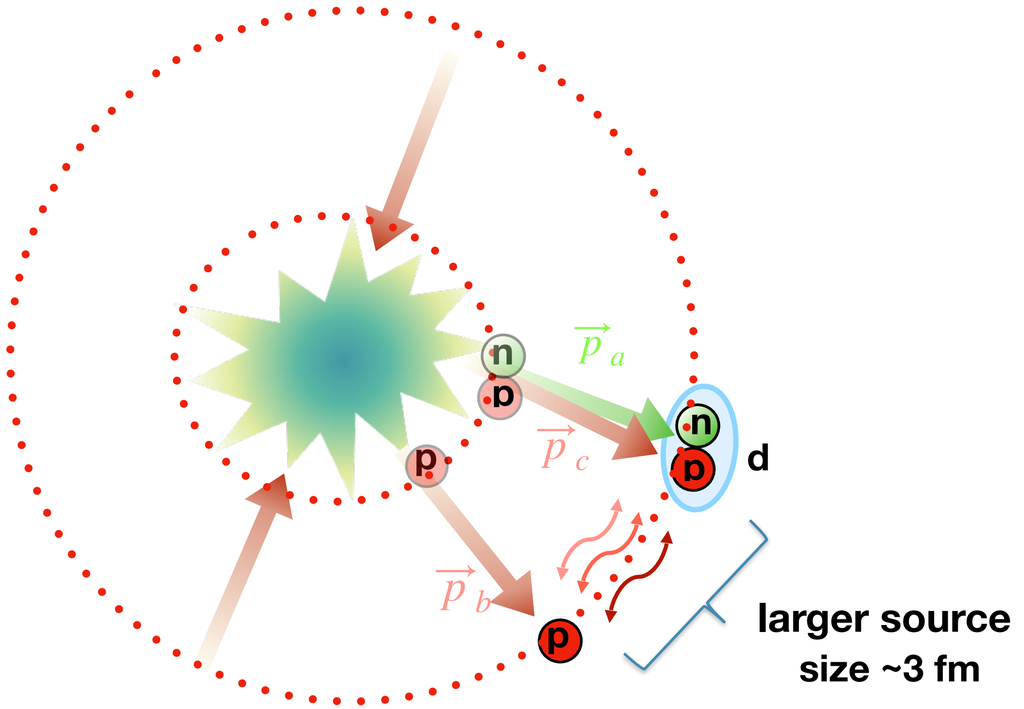
What if the deuteron is formed later?

- 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

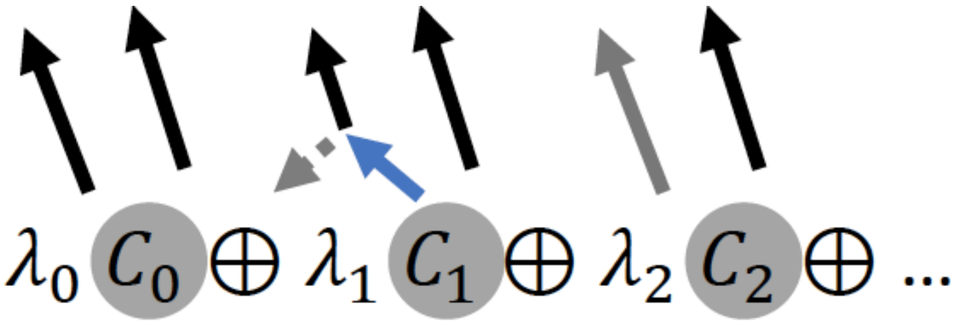


Case II : delayed formation of d



Femtoscopic correlation

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



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

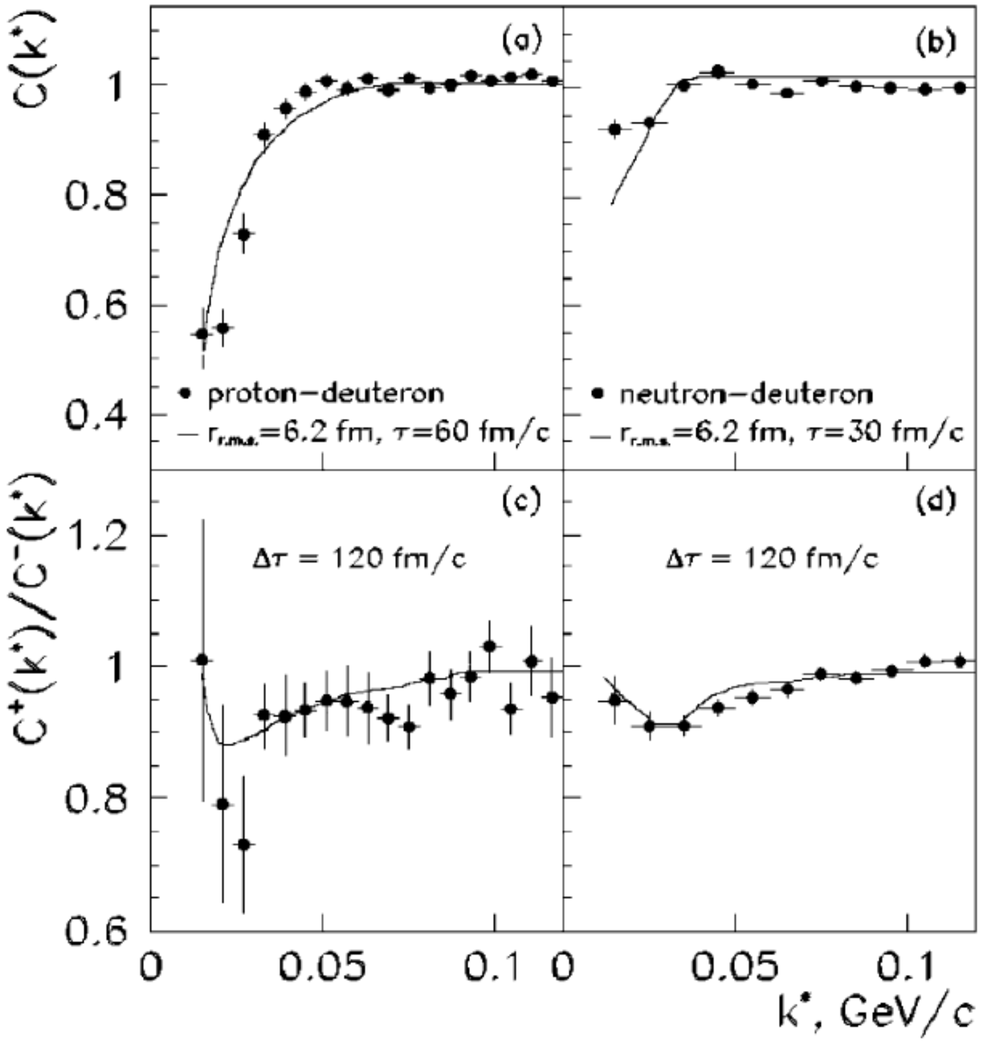
Contributions from: genuine feed-down misidentifications

- 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

Title Text

- **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

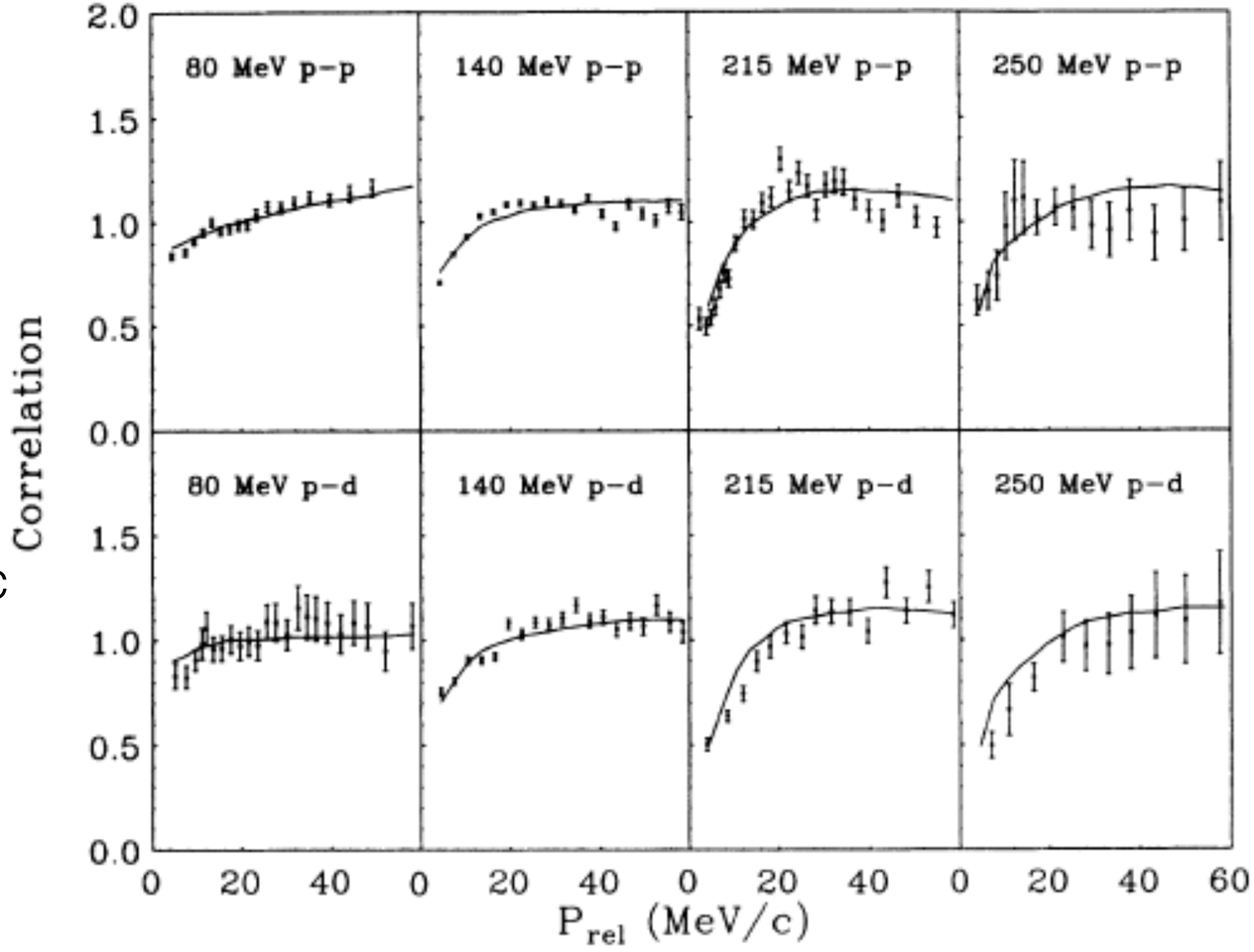


[1] Wosińska, K., Pluta, J., Hanappe, F. *et al. Eur. Phys. J. A* 32, 55–59 (2007)

proton-deuteron correlation measurement so far

Title Text

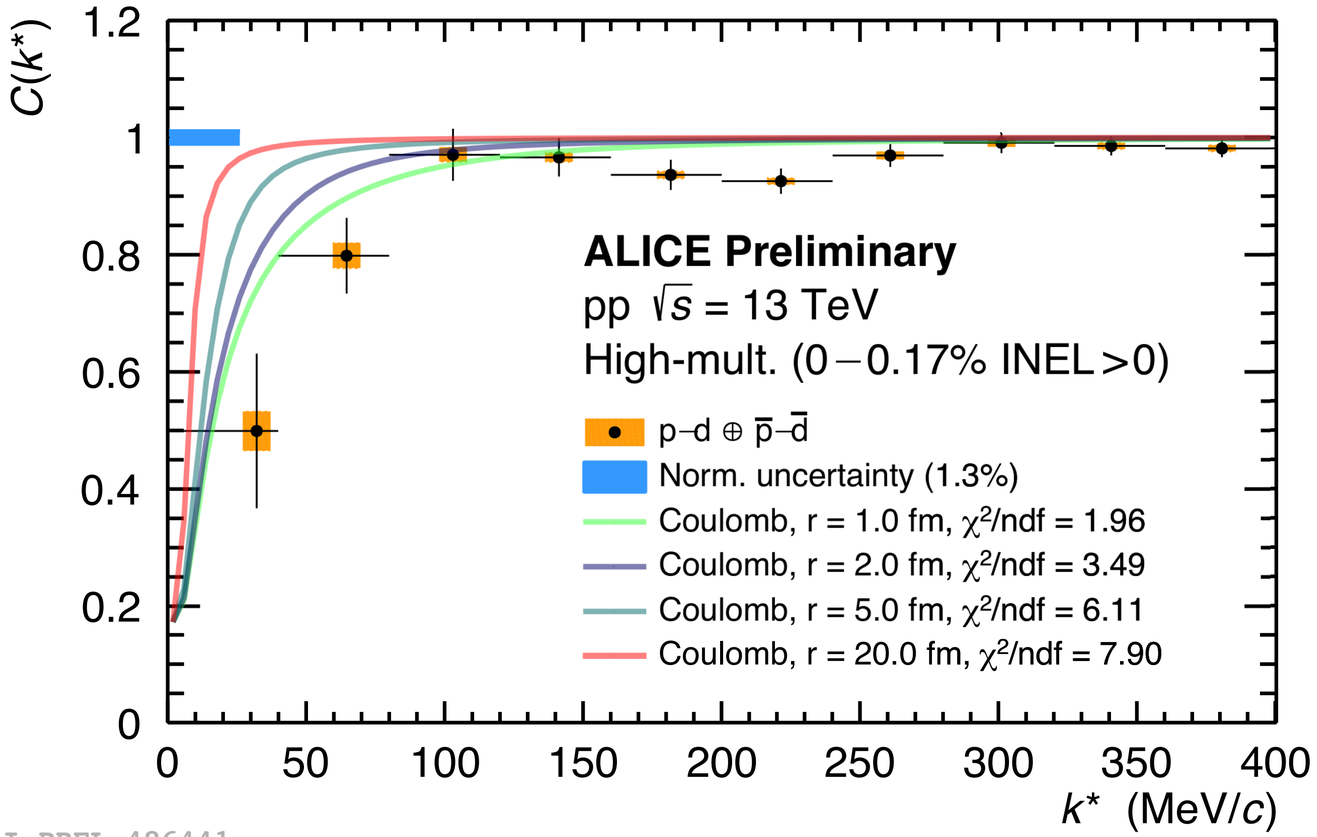
- **Status**: Measurement by *P. A. DeYoung et al* in 1990
  - Measurements for 80 and 140 MeV/c ^{16}O - ^{27}Al reaction were performed at the Stony Brook Linac
  - Measurements for 215 and 250 MeV/c ^{16}O - ^{27}Al reaction were performed at the ATLAS facility of the Argonne National Laboratory.
  - 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



ALI-PREL-486441

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

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

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

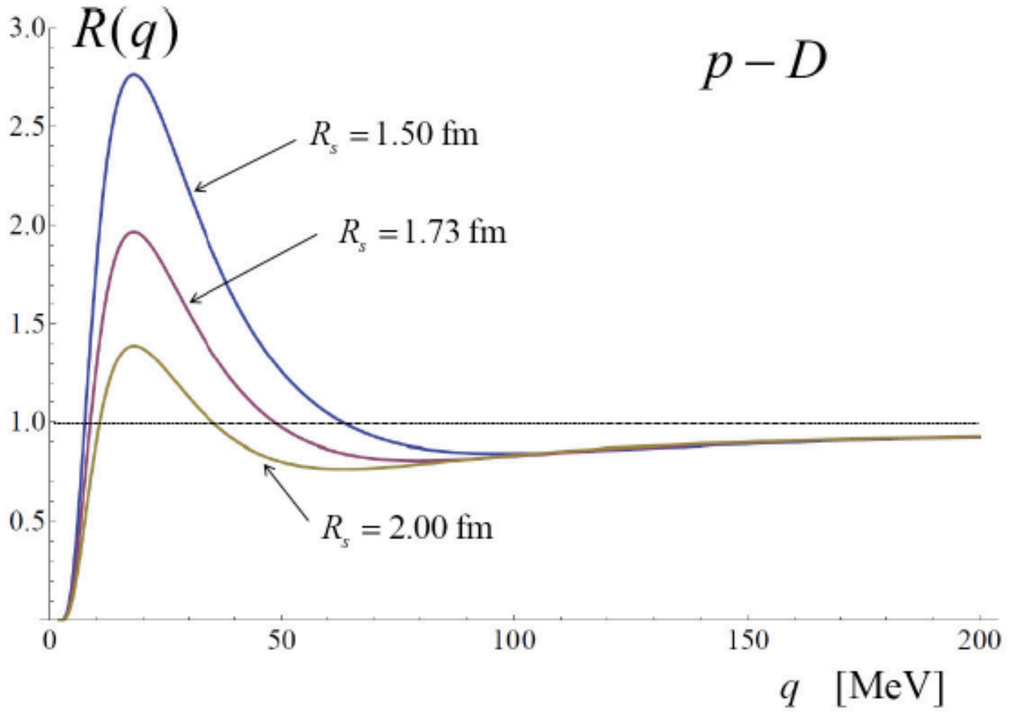


Fig. 2. $p-D$ correlation function