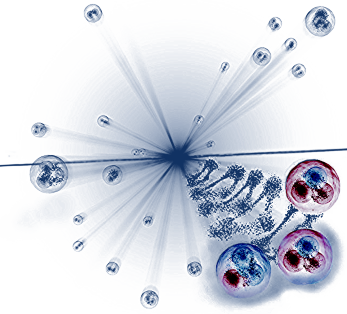


Accessing the strong interaction in three-hadron systems via proton-deuteron femtoscopy

17th Workshop on Particle Correlations and Femtoscopy, WPCF 2024

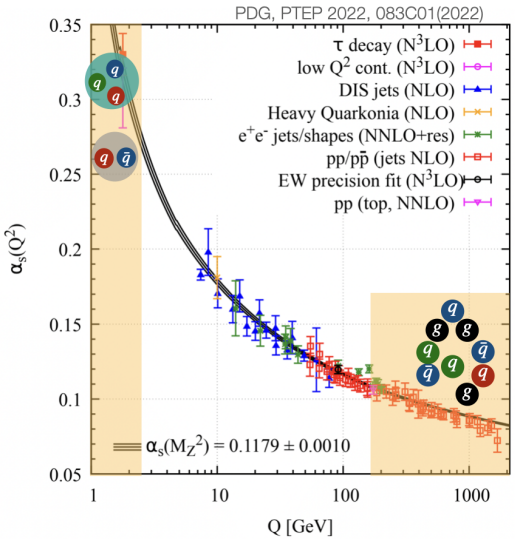
Bhawani Singh (Collaborators: ALICE, O. Vazquez, L. Fabbietti, S. König, PISA group (M. Viviani, A. Kievsky, L. Marcucci))

Technical University of Munich (TUM), Germany

November 6, 2024

Hadronic interactions and QCD

- Non-perturbative nature of QCD $Q \sim 1$ GeV
- Use Effective Field Theories (residual strong interaction)
  - Hadrons as degrees of freedom (baryons, mesons)



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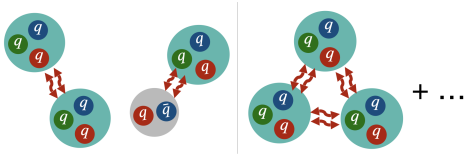

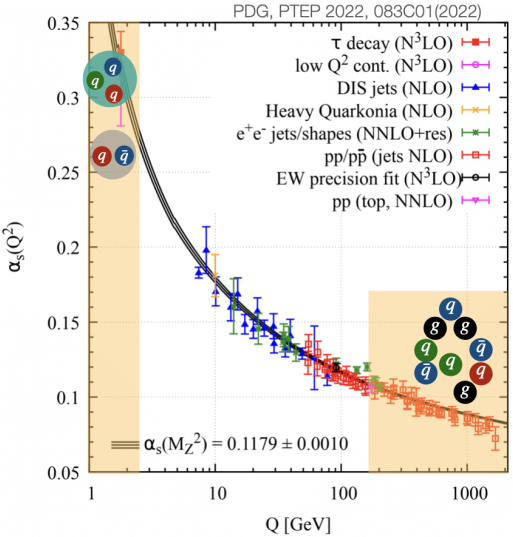

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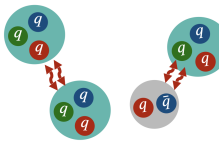
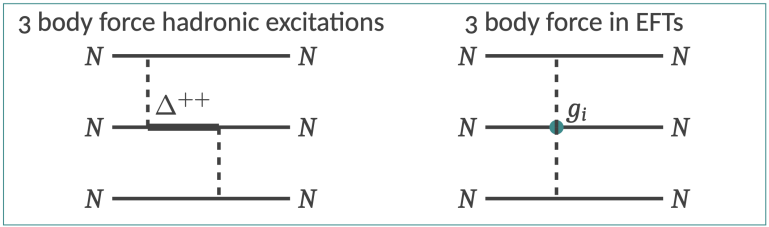
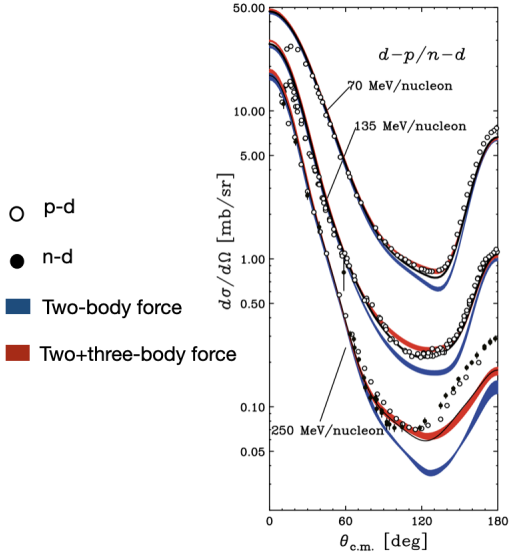




Need for many-body hadronic interaction

- N-d scattering observables: requires the presence of three-body interaction [1]



[1] K. Sekiguchi, Few-Body Syst 60, 56 (2019)

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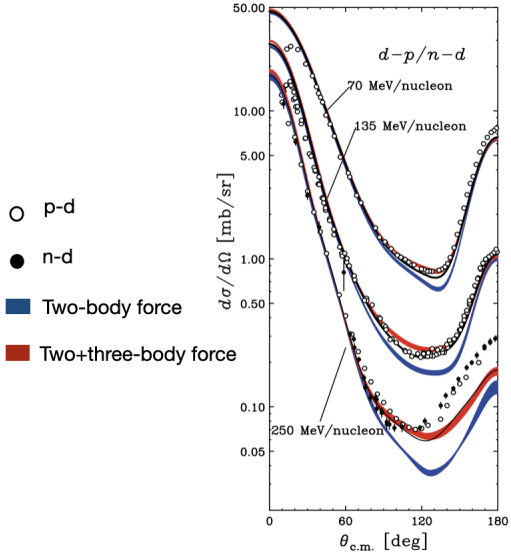

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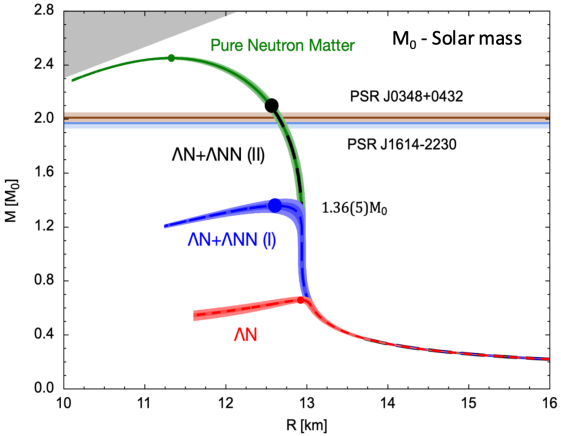
- **Need new tools to study hadronic interactions!**

Equation of state $\rightarrow$ Mass-Radius relation [3]



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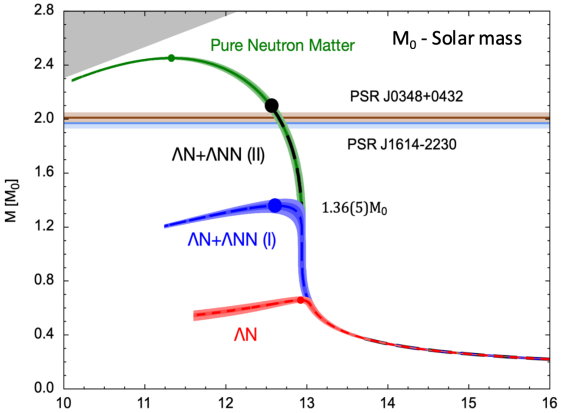

Marcel Lesch (Friday, 14:00)

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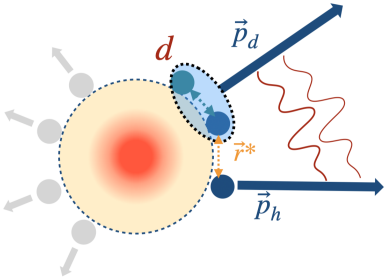
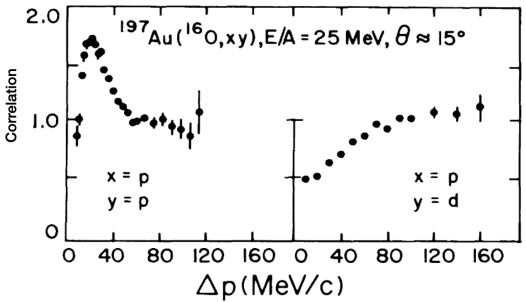
Hadron-deuteron correlations

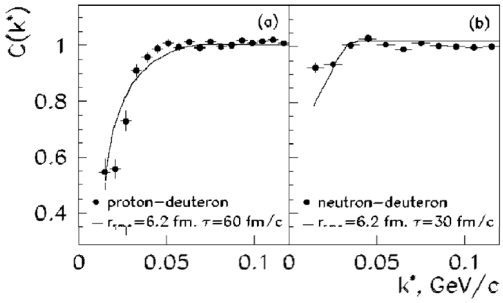


hadron-deuteron correlation functions!

So far...

- p-d correlation from fixed target studies



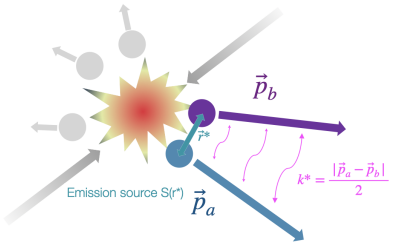


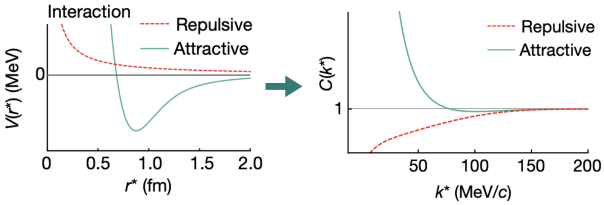
- Already signal of Final State Interaction (FSI) at low energy experiments (MSU (left) and GANIL (right)

[1] C. B. Chitwood et al, PRL 54, 302 (1985)
[2] J. Pochodzalla et al, PRC 35, 1695 (1986)
[2] J. Pochodzalla et al, PLB 175 (1986)
[3] K. Wosińska et al, EPJA 32, 55–59 (2007)

Femtoscopy: a new approach to study hadronic interaction

2 Three-hadron systems





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

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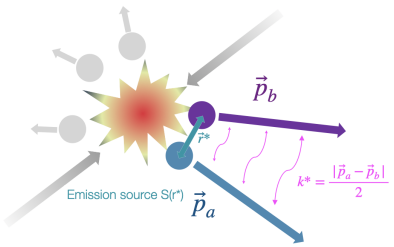
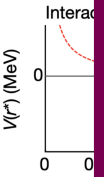
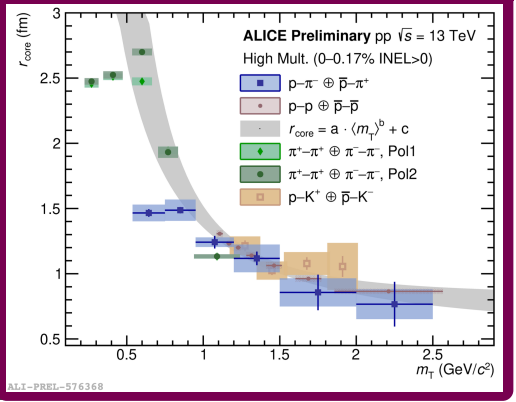




Common source for all hadron-hadron pairs!



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[3] ALICE, PLB 811 (2020)
[3] ALICE, arXiv:2311.14527 (2024)

Kaon-deuteron correlations

- Source size for $r^{\mathrm{K^+-d}} = 1.35^{+0.04}_{-0.05}$ fm
- $\mathrm{K^+}$–d as an effective two-body system: **Lednický-Lyuboshits (LL)** approach [1]
- Strong interaction in $\mathrm{K^+}$–d system
  - Effective-Range Approx. (ER) [2]: $a_0 = -0.47$ fm, $d_0 = -1.75$ fm
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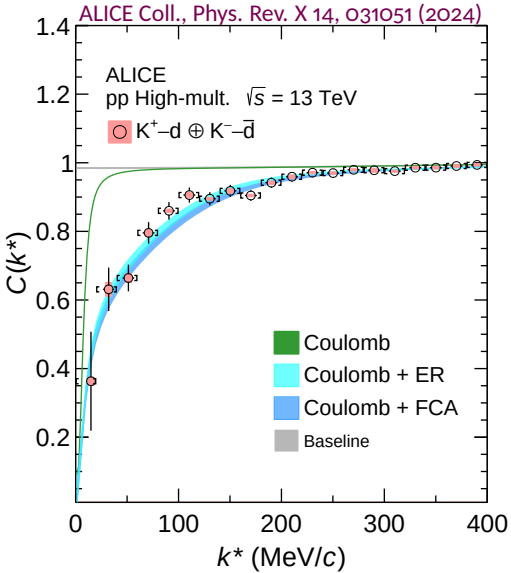

[1] R. Lednický, Phys. Part. Nuc. 40, (2009)
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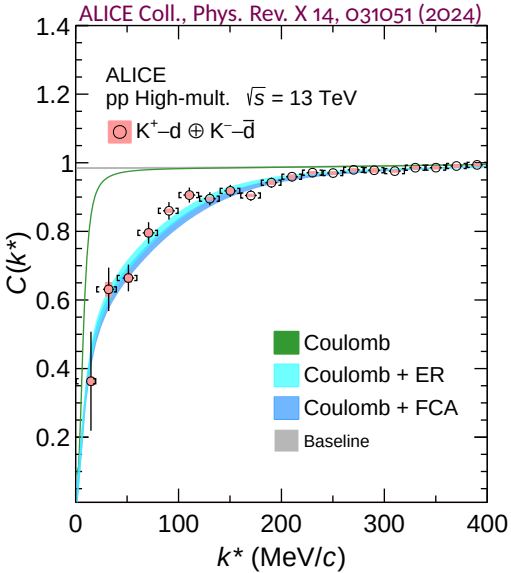
- Deuterons follow the same m_{T}-scaling as other hadrons



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Proton-deuteron correlations

- p–d as effective two-body system with **LL** approach [1]
- Source size $r_{\text{eff}} = 1.08^{+0.006}_{-0.006}$ fm
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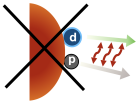
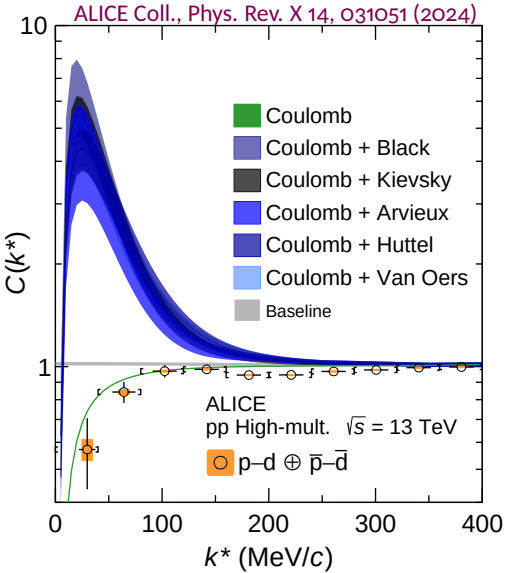
- Two point-like particles picture does not work
  - Pauli-blocking for p-(pn) system
  - Asymptotic strong interaction cant describe p-d at $\sim$1 fm





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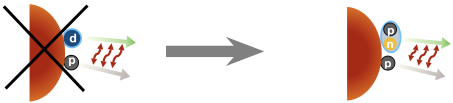

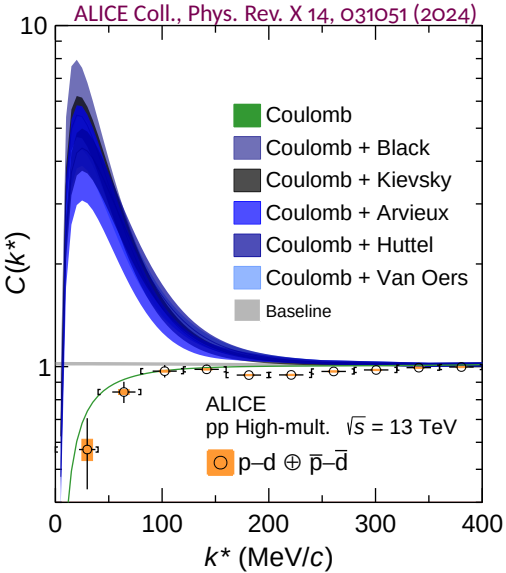

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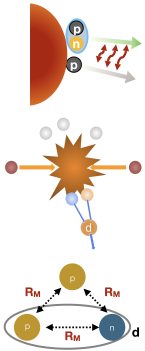
Full three-body calculations for p-d

- Start from p-(pn) system that form p-d state:

$$C_{pd}(k^*) = \frac{1}{6\,A_d} \sum_{m_1,m_2} \int d^3r_1 d^3r_2 d^3r_3 S_1(r_1)\, S_1(r_2)\, S_1(r_3) \left|\Psi_{m_1,m_2,k^*}\right|^2$$

$$= \frac{1}{16\,A_d} \int S(\rho, R_M)\, \left|\Psi(k^*,\rho)\right|^2\, \rho^5\, d\rho\, d\Omega$$



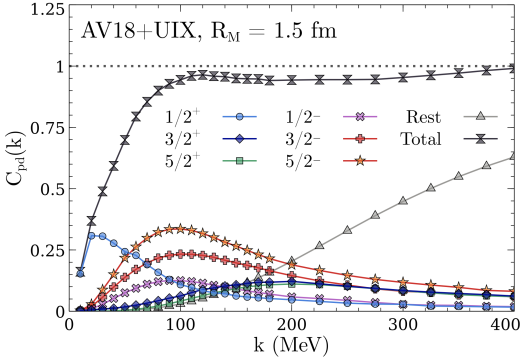
- A_d is the deuteron formation probability [1]
- $R_M = 1.43 \pm 0.16$ fm nucleon-nucleon source size in p-d (obtained from analysis)
  - Accounts for three-body dynamics

M. Viviani, **B. Singh** et al. PRC108,064002 (2023)
INFN PISA [Michele Viviani, Alejandro Kievsky, and Laura Marcucci], NC State Uni[Sebastian König]

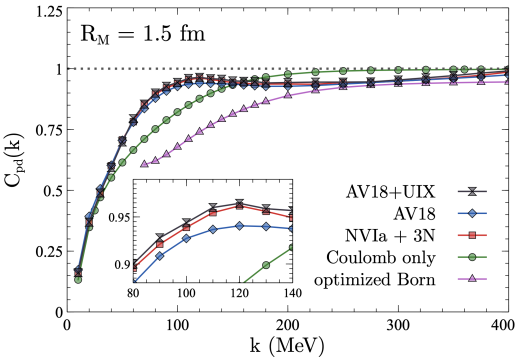
[1] S. Mrowczynski, Acta Physica Polonica B 51, 1739 (2020)

Full three-body calculations for p-d

- Contributions of partial waves



- Different interaction potentials

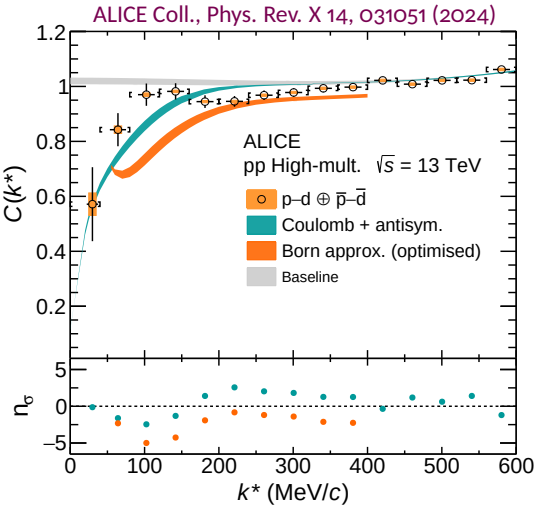


- A robust theoretical framework applicable to other h-d systems

M. Viviani, **B. Singh** et al. PRC108, 064002 (2023)

Born approximation and p-d system

- Coulomb only: does not describe the data
- Born approximated wave function AV18 (2N) [1] UIX (NNN) potentials [2]:
  - Ignore core short-range interaction
  - $\sim 5\sigma$ away from the data
- Asymptotic strong interaction is insufficient due to short-distance dynamics of nucleons



[1] M. Viviani, **B. Singh** et al. Phys. Rev. C108,064002 (2023)
[2] B. R. B. Wiringa et al. Phys. Rev. C 51, 38
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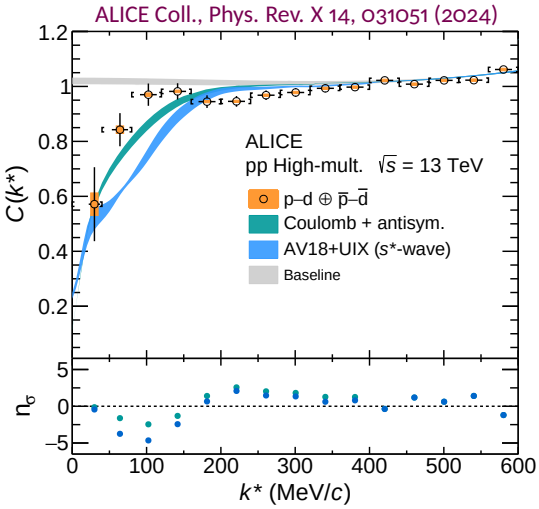
Two- and three-body interaction at short distance

- Coulomb only: does not describe the data
- AV18 + UIX potentials [1-3]
  - *s*-wave only: more repulsion



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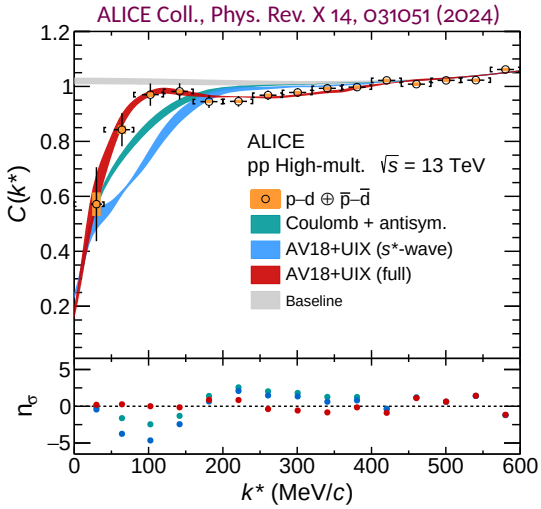

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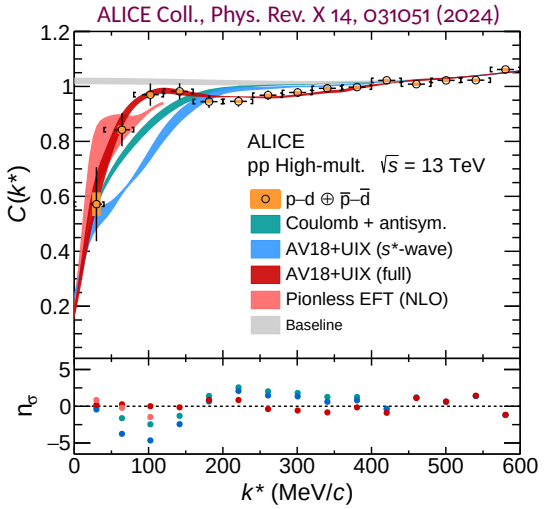

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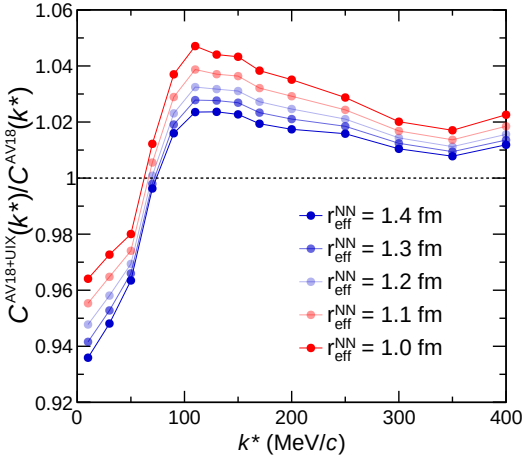
Sensitivity to genuine three-body force

- Three-body interaction effects:
  - Ratio of CF with and without UIX potential
  - Up to 5% effect of genuine three-body interaction
  - Run 2: limited statistics

ALICE Coll., Phys. Rev. X 14, 031051 (2024)



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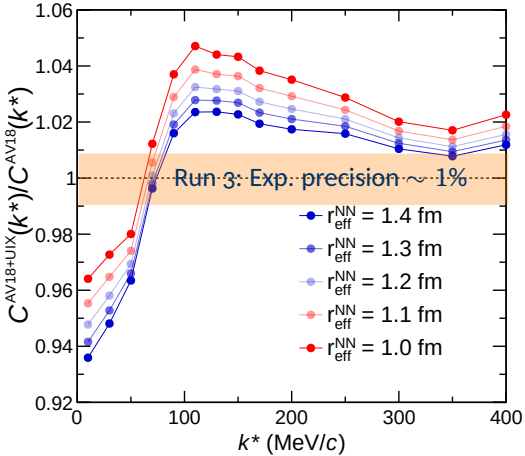

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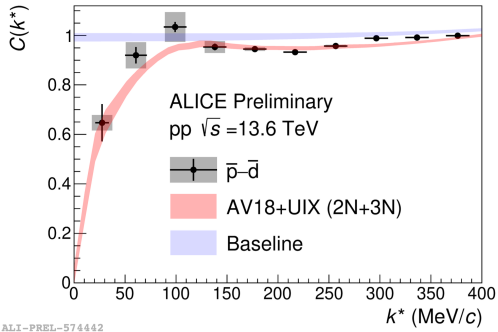
- Avenue for the study of hadron-deuteron systems, including charm and strange hadrons!



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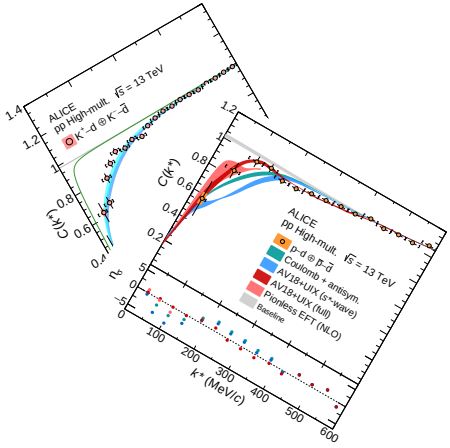
Summary

- $p/\mathrm{K}^{+}-$**d correlations: first measurement in pp**
  - light nuclei follow m_{T}scaling in pp collisions
  - Access strong interaction in three-body systems



Summary

- $p/\mathrm{K}^{+}-\mathrm{d}$ **correlations: first measurement in pp**
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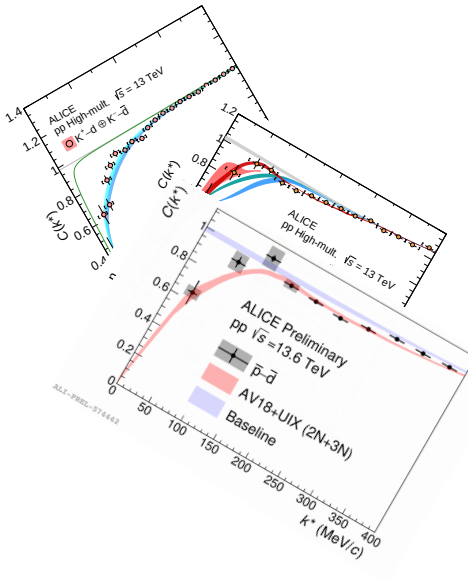
- **More statistics from LHC Run 3 and Run 4**
  - Ongoing studies for p-d, Λ-d, p-p-p, and p-p-Λ



Summary

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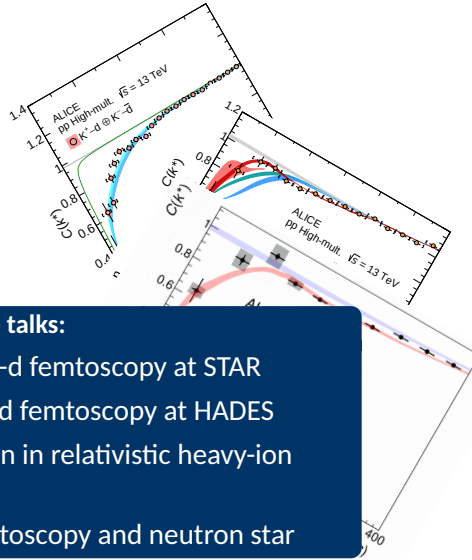


More interesting results in the talks:

Ke Mi (today, 16:20): baryon-baryon, h-d, and d-d femtoscopy at STAR

Diana Paw lowska-Szymańska (today, 14:35): Λ-d femtoscopy at HADES

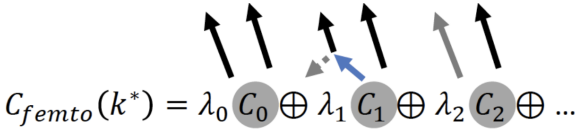
Wioleta Rzesa (tomorrow, 16:20): h-d correlation in relativistic heavy-ion collisions with ALICE

Marcel Lesch (Friday, 14:00): three-particle femtoscopy and neutron star

Accessing the strong interaction in three-hadron systems via proton-deuteron femtoscopy

Thank you for listening!
Time for questions!

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

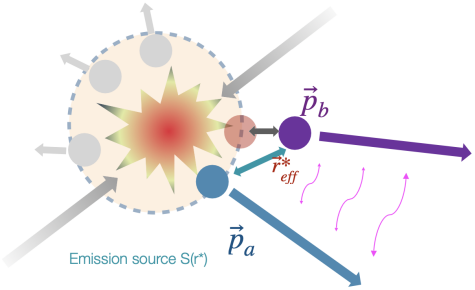


- Quantification of the contributions to the pairs done by the lambda parameters: $\lambda_{ij} = \mathcal{P}_i \times f_i \times \mathcal{P}_j \times f_j$
  - Purity of the individual particles ($\mathcal{P}_j$)
  - Feed-down fractions (f_i)

- Common emission for **all hadrons** in pp collisions [1,2]

$$S(r*) = \frac{1}{(2\pi r_{\text{core}}^2)^{3/2}} e^{-\frac{r*^2}{4r_{\text{core}}^2}}$$

- **Short-living strongly decaying** resonances ($c\tau \sim 1$ fm) enhance the source
  - Particle kinematics from simulations
  - Yields constrained from Statistical Hadronisation Model



[1] ALICE, PLB 811 (2020)
[2] ALICE, arXiv:2311.14527 (2024)

- Common emission for **all hadrons** in pp collisions [1,2]

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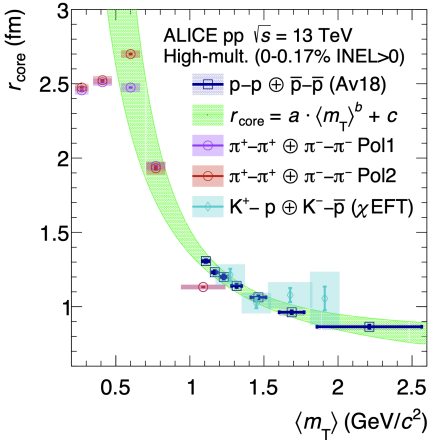
- Common source m_{T} scaling for all hadrons in pp collisions



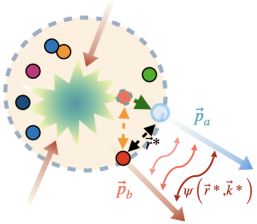
pair transverse mass $m_{\text{T}} = \sqrt{k_{\text{T}}^2 + \langle m \rangle^2}$

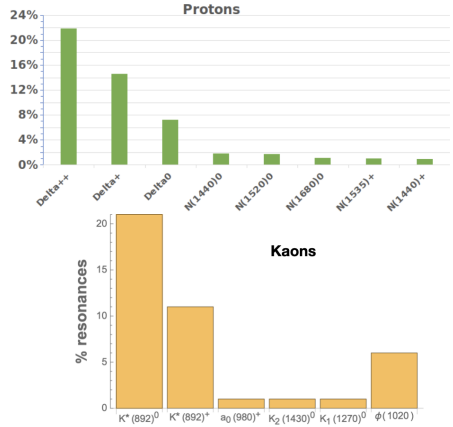
[1] ALICE, PLB 811 (2020)
[2] ALICE, arXiv:2311.14527 (2024)

p–d and K^+–d source

4 Extra

- Contributions for K^+–d and p–d pairs





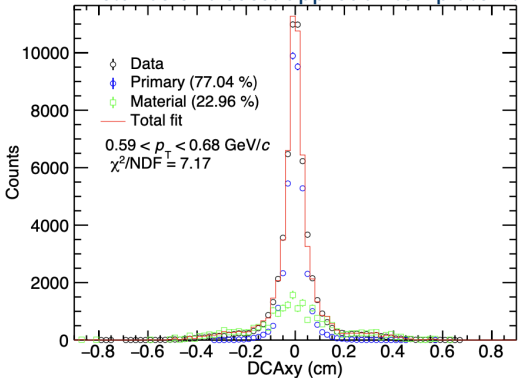
Source size	mean value:p–d	mean value:K^+–d
r_{core}	0.99±0.05 fm	1.04±0.04 fm
r_{eff}	1.08±0.06 fm	$1.35^{+0.04}_{-0.05}$ fm

Candidate primary fractions: (anti-)deuteron

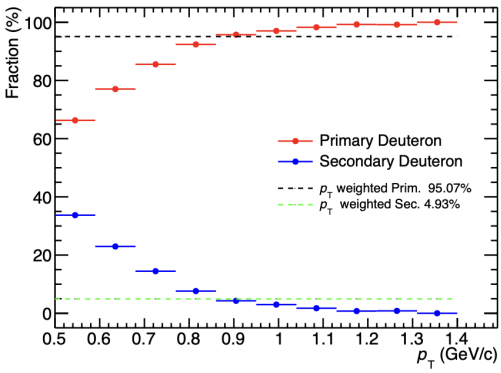
4 Extra

- **(anti)deuteron: candidate fractions [Thesis: B. Singh, CERN-THESIS-2023-199]**

Distance of closest approach template fit



Fractions



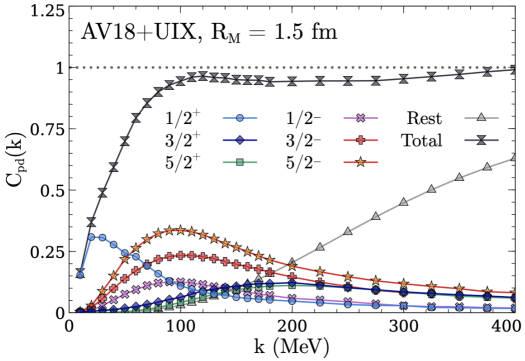
- **95% primary deuteron and 100% antideuteron candidates**

p-d system calculations

4 Extra

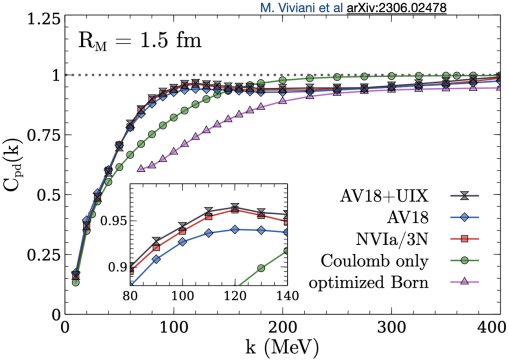
- Calculations for AV18+UIX contributions of partial waves

M. Viviani et al arXiv:2306.02478



- Calculations for different interaction potentials

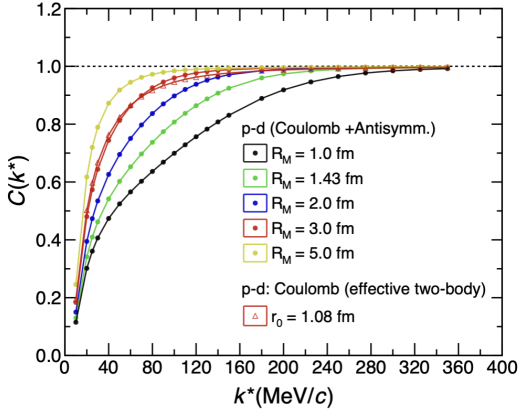
M. Viviani et al arXiv:2306.02478



p-d system two-body vs three-body Coulomb

4 Extra

- Calculations only for Coulomb interactions



p-d system three-body wavefunction

- Full three-body wavefunction in HH approach

$$\Psi_{LSJJ_z} = \sum_{n,\alpha} \frac{u_{n,\alpha}(\rho)}{\rho^{5/2}} \mathcal{Y}_{n,\alpha}(\Omega)$$
$$+ \frac{1}{\sqrt{3}} \sum_{\ell}^{\text{even perm.}} \left\{ Y_L(\hat{\boldsymbol{y}}_\ell) \left[\varphi^d(i,j) \chi(\ell) \right]_S \right\}_{JJ_z} \frac{F_L(\eta, k y_\ell)}{k y_\ell}$$
$$+ \sum_{L'S'} T^J_{LS,L'S'} \frac{1}{\sqrt{3}} \sum_{\ell}^{\text{even perm.}} \left\{ Y_{L'}(\hat{\boldsymbol{y}}_\ell) \left[\varphi^d(i,j) \chi(\ell) \right]_{S'} \right\}_{JJ_z}$$
$$\times \frac{\overline{G}_{L'}(\eta, k y_\ell) + i F_{L'}(\eta, k y_\ell)}{k y_\ell} \, .$$

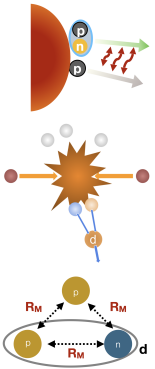
Full three-body calculations for p-d

4 Extra

- Start from p-(pn) system that form p-d state:

$$C_{pd}(k^*) = \frac{1}{16\,A_d} \int S(\rho, R_M)\ |\Psi(k^*, \rho)|^2\ \rho^5\, d\rho\, d\Omega$$

- A_d is the deuteron formation probability [1]
- $R_{\mathrm{M}} = 1.43 \pm 0.16$ fm nucleon-nucleon source size in p-d (obtained from analysis)
- $\Psi(k^*, \rho)$: the three-body wave function
  - Accounts for three-body dynamics

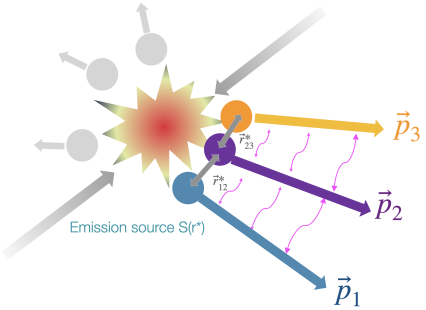


M. Viviani, **B. Singh** et al. PRC108,064002 (2023)

INFN PISA [Michele Viviani, Alejandro Kievsky, and Laura Marcucci], NC State Uni[Sebastian König]

[1] S. Mrowczynski, Acta Physica Polonica B 51, 1739 (2020)

Femtoscopy opens the door for the study of interactions in unbound system of three hadron (3 to 3 scattering process)

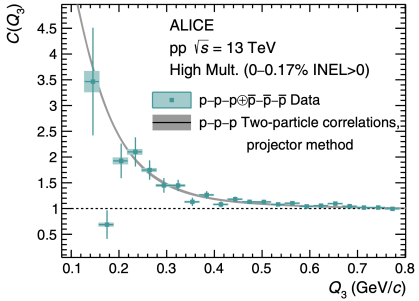


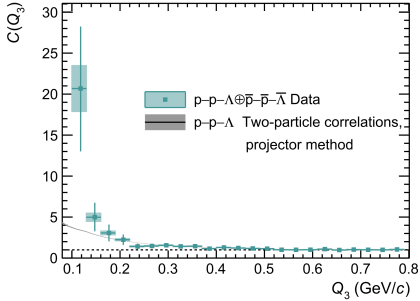
Three-body femtoscopy with ALICE

4 Extra

- Extending femtoscopy to three-particle correlations: p-p-p and p-p-Λ at the LHC [1]

$$C(Q_3) = N\frac{N_{\text{same}}(Q_3)}{N_{\text{mixed}}(Q_3)} \qquad \text{with hypermomentum} \quad Q_3 = \sqrt{-q_{12}^2 - q_{23}^2 - q_{13}^2}$$





- Effects beyond two-body contributions [2]

[1] ALICE Coll., EPJA 59, 145 (2023)
[2] Del Grande et al, EPJC 82, 244 (2022)

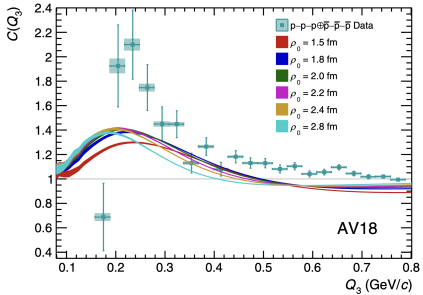
Three-body femtoscopy with ALICE

4 Extra

- First three-body calculations for unbound system of three protons

$$C(Q_3) = \int S(\rho, \rho_0) \left|\Psi_{ppn}(\rho, Q_3)\right|^2 \rho^5 d\rho$$

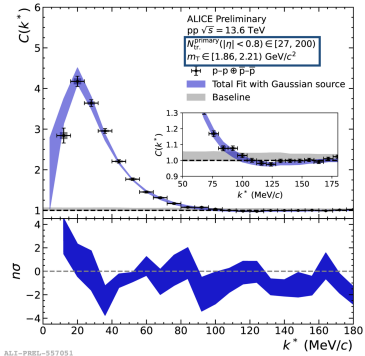
- **Kievsky et al PRC 109, 034006(2023)** Munich group and INFN PISA group
- With AV18 strong interaction, Coulomb corrections, and quantum statistics
- Ongoing work for ppΛ system



[1] ALICE Coll., EPJA 59, 145 (2023)
[2] Del Grande et al, EPJC 82, 244 (2022)

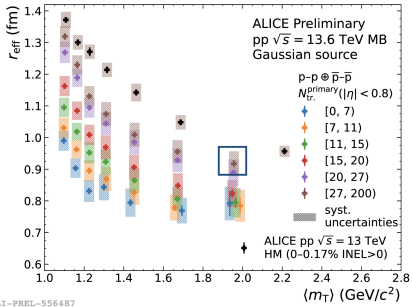
- LHC Run 3 pp collisions at 13.6 TeV: 2 orders of magnitude increased p-p pair statistics

p-p CF in m_T and multiplicity bins



ALI-PREL-557051

m_T-scaling of the source size for p-p pairs



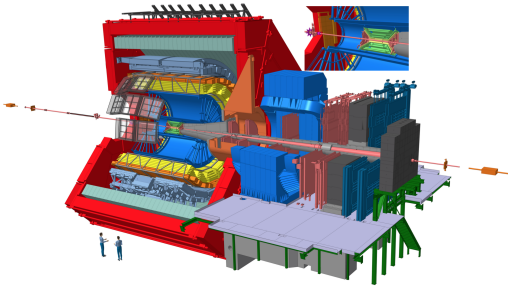
ALI-PREL-556487

Opens door for all hadronic interactions studies in LHC Run 3

Particle identification: protons, Kaons, and deuterons

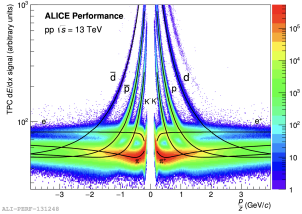
4 Extra

- **ALICE Detector in RUN 2:** Unique tracking and PID capabilities to perform femtoscopic studies at the LHC energies!

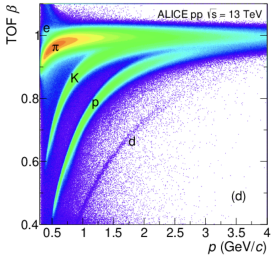


ALICE, Nucl. Part. Phys. 41 087002

Time Projection Chamber (TPC): dEdx

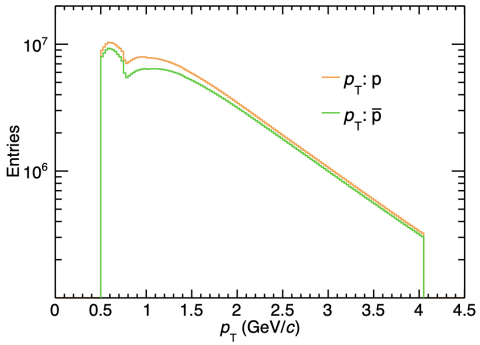


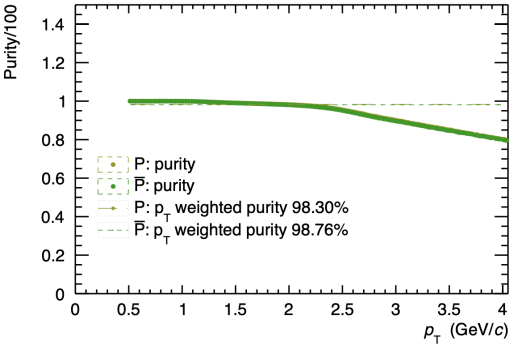
Time-Of-Flight detector (TOF): velocity



Candidate purity: (anti-)protons

- (anti)proton: candidate purities [Thesis: B. Singh, CERN-THESIS-2023-199]





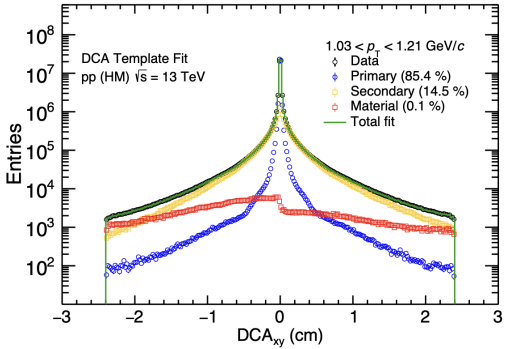
- Very high purity sample with $\sim$ 100% pure (anti)proton candidates

Candidate primary fractions: (anti-)protons

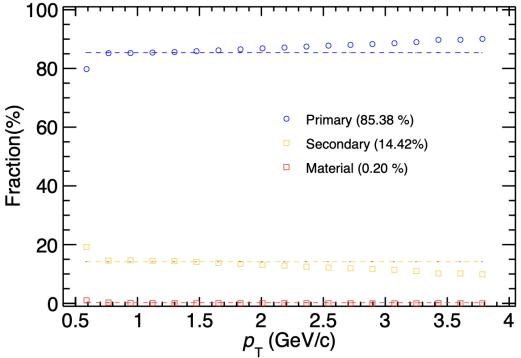
4 Extra

- **(anti)proton: candidate fractions [Thesis: B. Singh, CERN-THESIS-2023-199]**

Distance of closest approach template fit



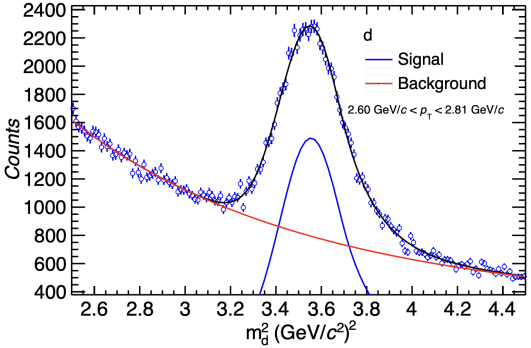
Fractions

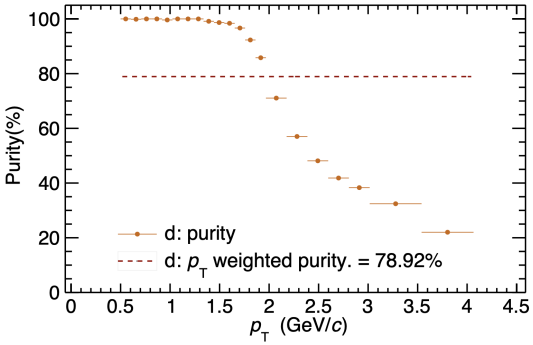


- $\sim$ **85% primary (anti-)proton candidates**
- **Similar approach was used for (anti)Kaon candidates, more than 99% pure**

Candidate purity: (anti-)deuteron

- **(anti)deuteron: candidate purities [Thesis: B. Singh, CERN-THESIS-2023-199]**

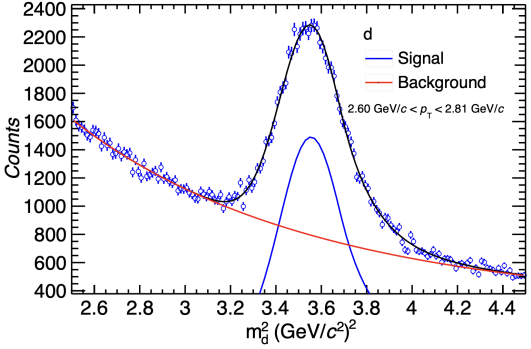


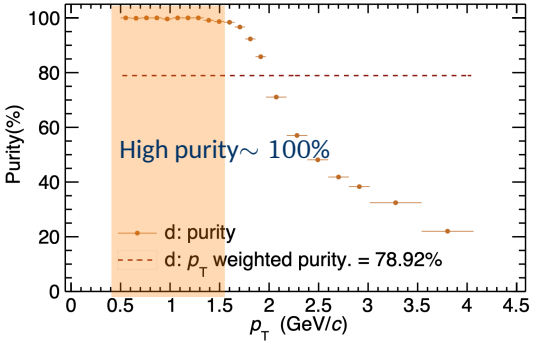


- Drastic decrease in the purity leads to artificial signal in the p-d correlations

Candidate purity: (anti-)deuteron

- **(anti)deuteron: candidate purities [Thesis: B. Singh, CERN-THESIS-2023-199]**





- Drastic decrease in the purity leads to artificial signal in the p-d correlations
- **Restricted (anti)deuteron selections to obtain very high purity sample with ∼ 100%**