First observation of (anti)deuteron formation from resonance-decay nucleons

Maximilian Mahlein

on behalf of the ALICE collaboration

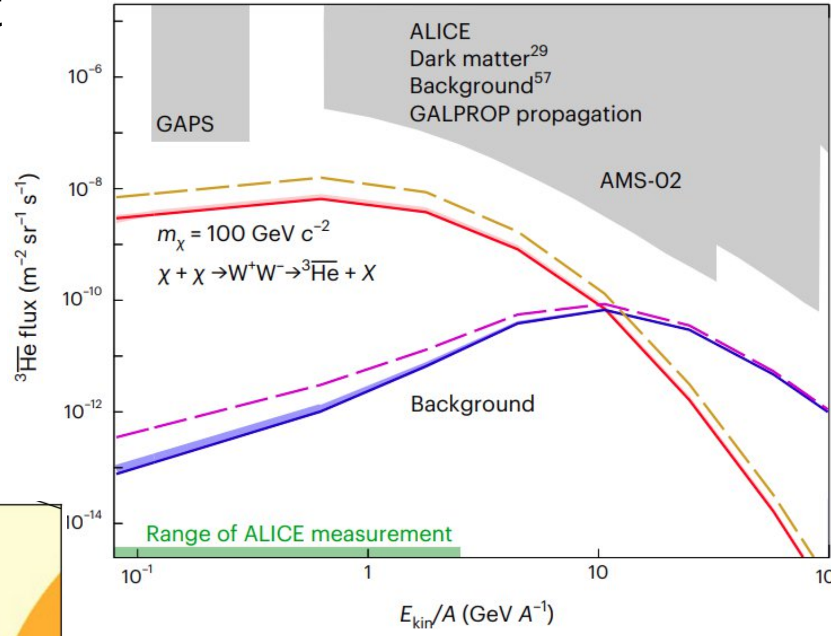
Based on: *Nature volume 648, pages: 306–311 (2025)*

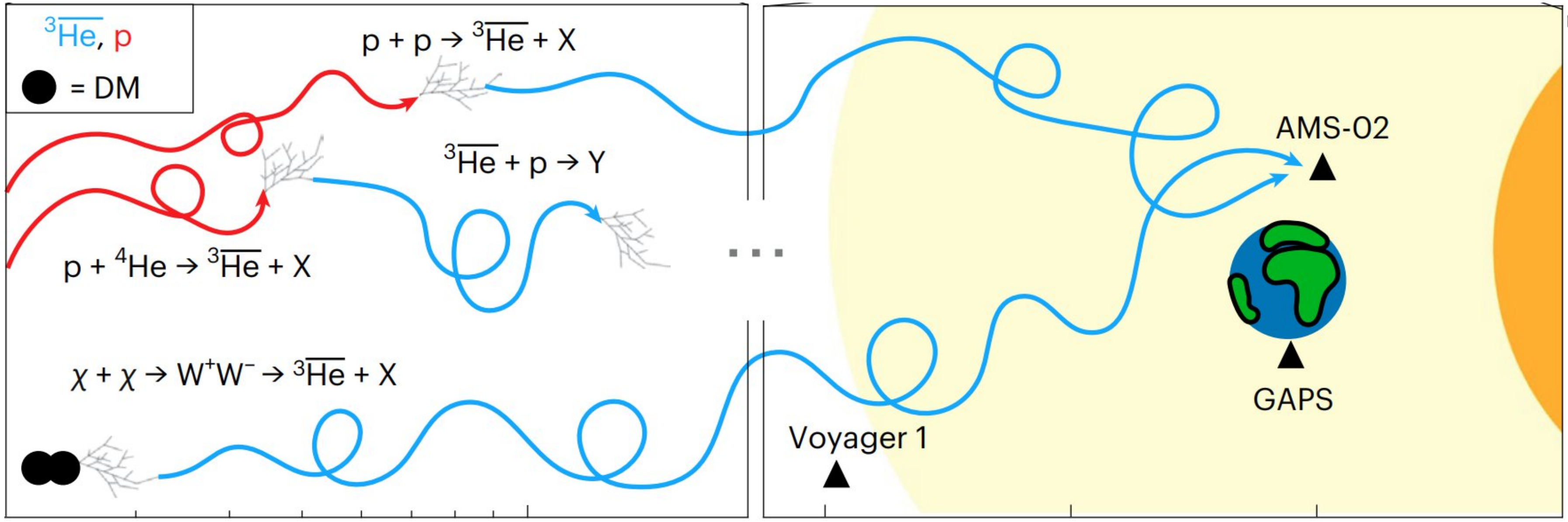
Technical University of Munich

62nd international winter meeting on nuclear physics

Antinuclei and cosmic rays

- Detection of antinuclei in cosmic rays is a golden chanel for indirect dark matter detection
- However: Astrophysical standard model background
- Large Signal/Background at low E_{kin}
- Still large uncertainties on production



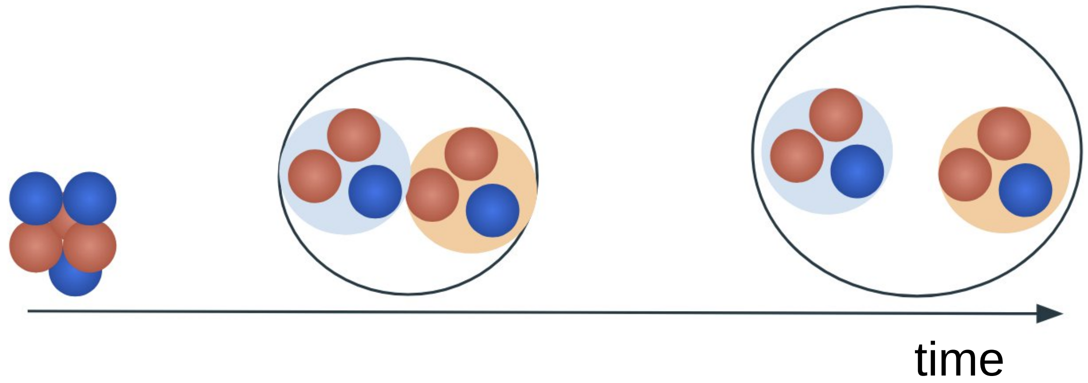


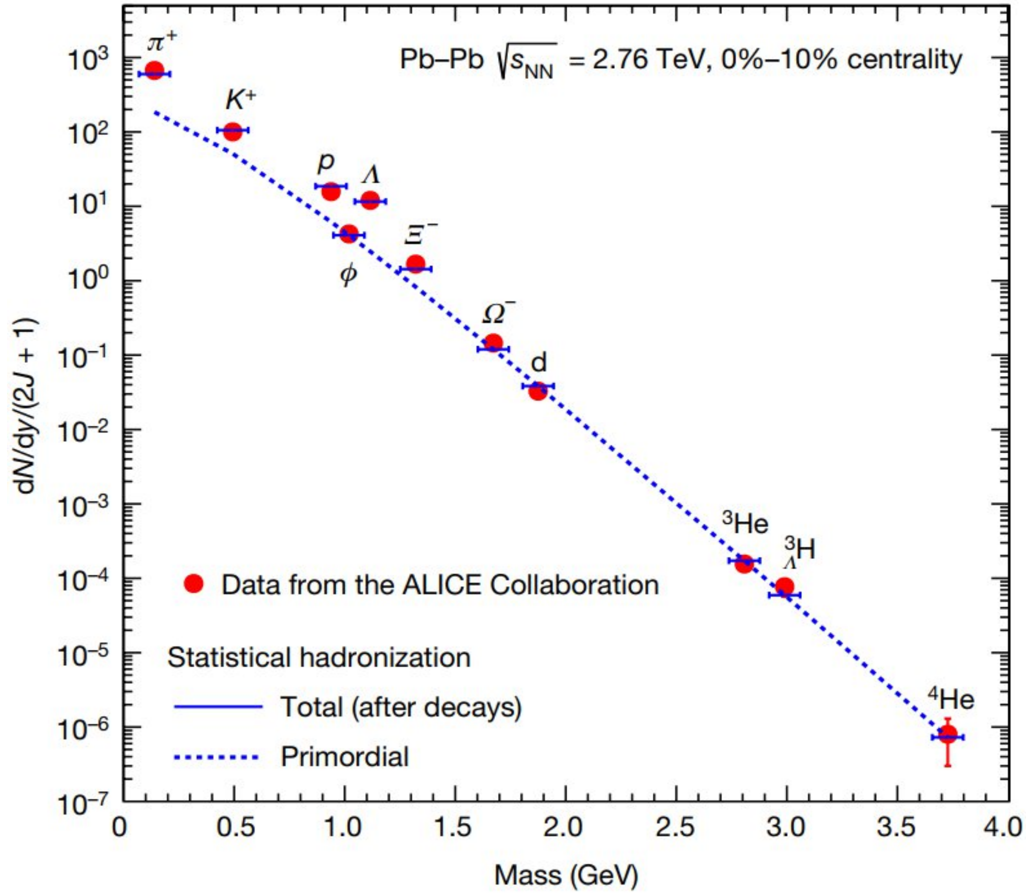
ALICE Collaboration: Nat. Phys. 19, 61 (2023)

Nuclei production: Thermal Model

- Hadron/nuclei emitted statistically from a thermalized source in local equilibrium
- Yields: $dN/dy \propto \exp(-m/T_{chem})$, $T_{chem} \approx 156$ MeV [1]
- Can light nuclei (E_B~2 MeV) survive high temperatures?

Deuteron production as 6 quark bag [2]

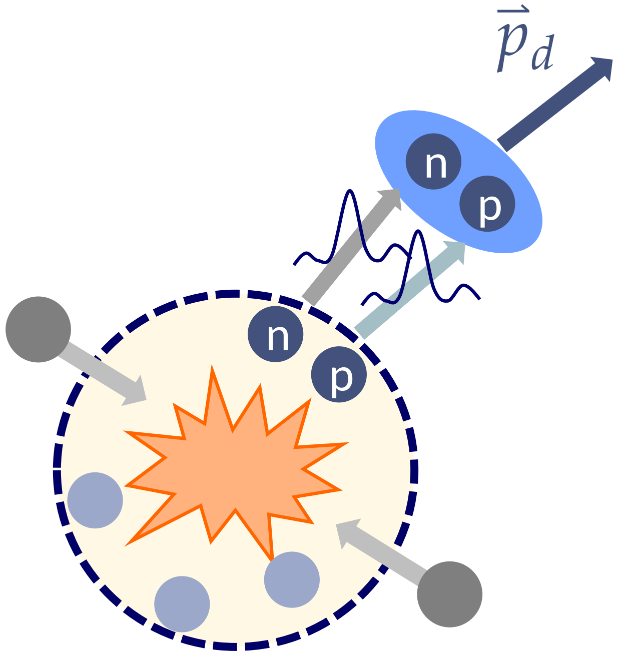


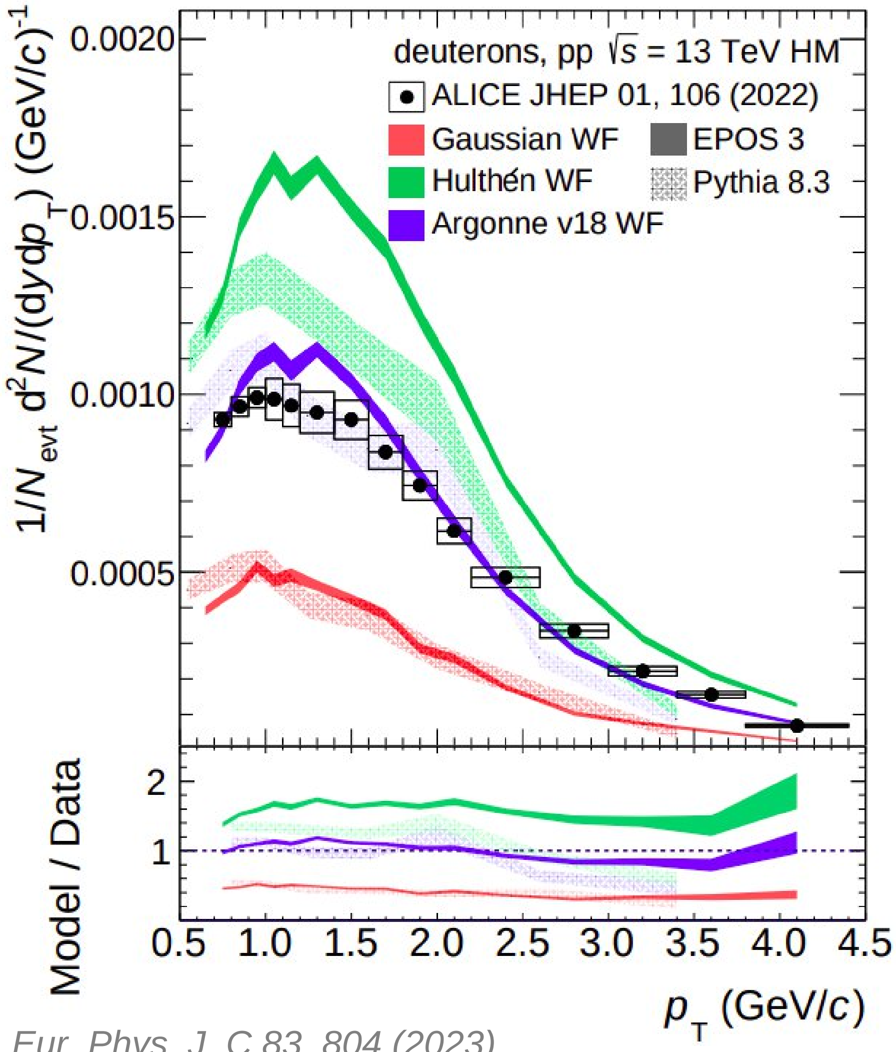


[1] A. Andronic et al., Nature, 561, p. 321–330 (2018)
[2] A. Chodos et al.: PRD 9, 3471 (1974)

Nuclei production: Fusion Models

- Nucleons close in the phase-space after chemical freeze-out can fuse together



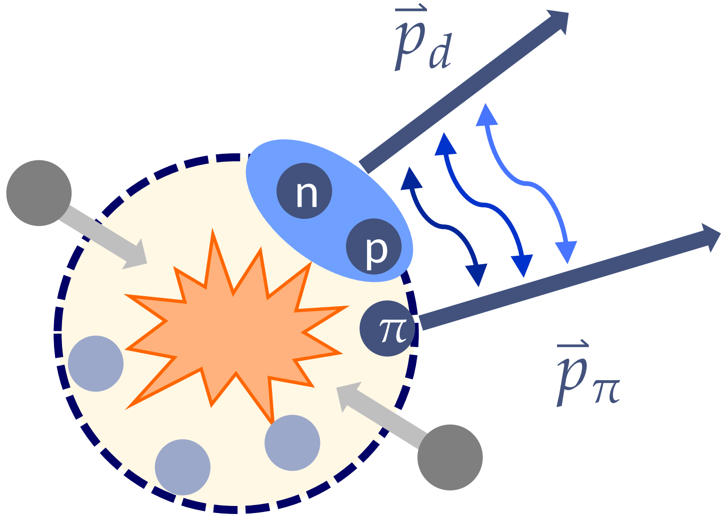


- Current state-of-the-art Coalescence model [3] (realisitc deuteron wave function and Wigner function formalism)

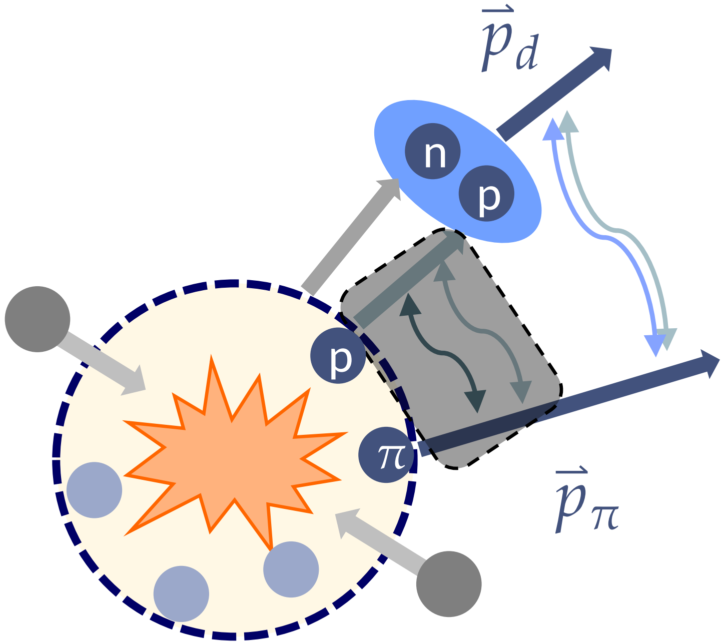
[3] MM et al. Eur. Phys. J. C 83, 804 (2023)

Searching for insights of deuteron formation

- Deuteron is a composite object of one proton and one neutron



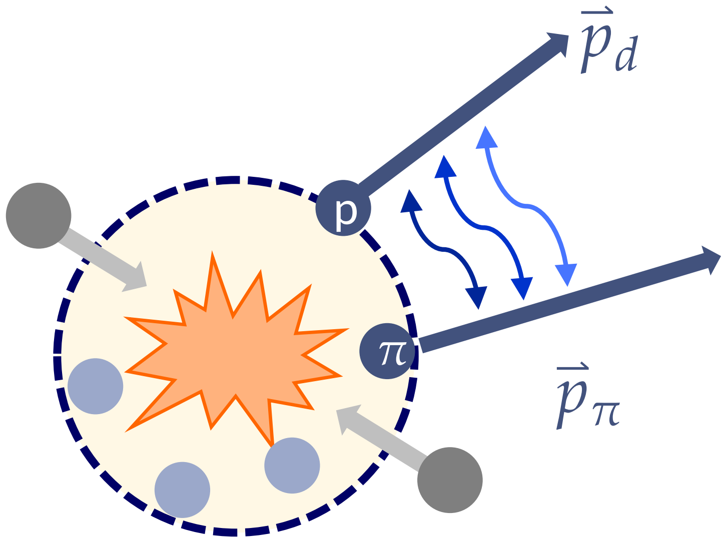
Thermal production of deuterons:
direct interaction/correlation between the π and the d



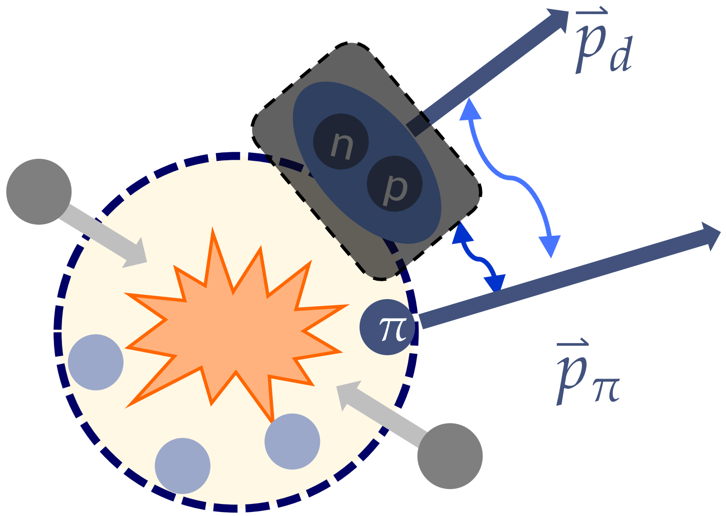
Fusion of nuclei:
π-d system might *inherit* residual correlation that was present between π and any of the two nucleons

Searching for insights of deuteron formation

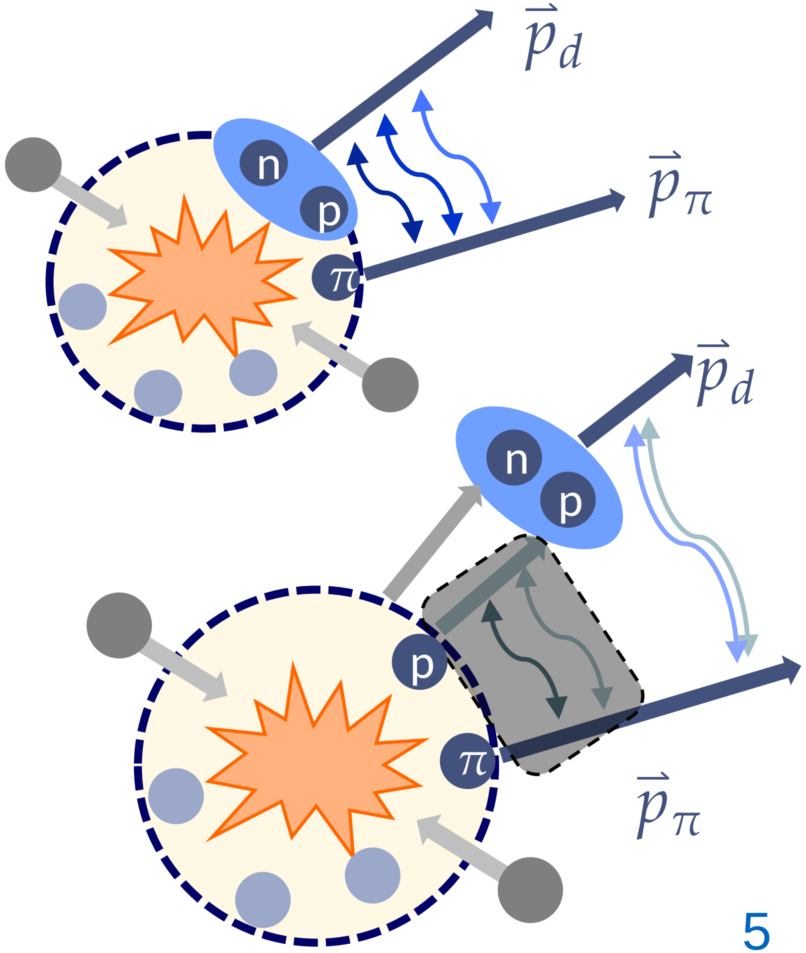
I. Study p–π correlations



II. Study d–π correlations

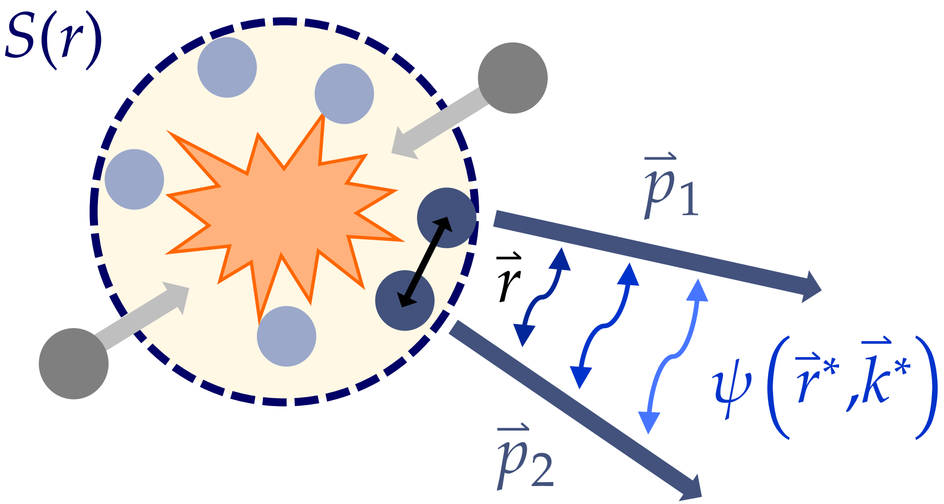


III. Check if any correlations from p–π are inherited.
Learn about nuclei production



Two-body femtoscopy

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



More Femtoscopy Talks:
V. Mantovani Sarti (Wed 9:45)
M. Korwieser (Mon - Poster)

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

theoretical definition [4,5] — experimental definition

Relative momentum $\vec{k}^* = \frac{1}{2} \mid \vec{p}_1^* - \vec{p}_2^* \mid$ and $\vec{p}_1^* + \vec{p}_2^* = 0$

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[4] S. Pratt, Phys. Rev. D 33 (1986) 1314
[5] M. Lisa et al., Ann. Rev. Nucl. Part. Sci. 55 (2005) 357

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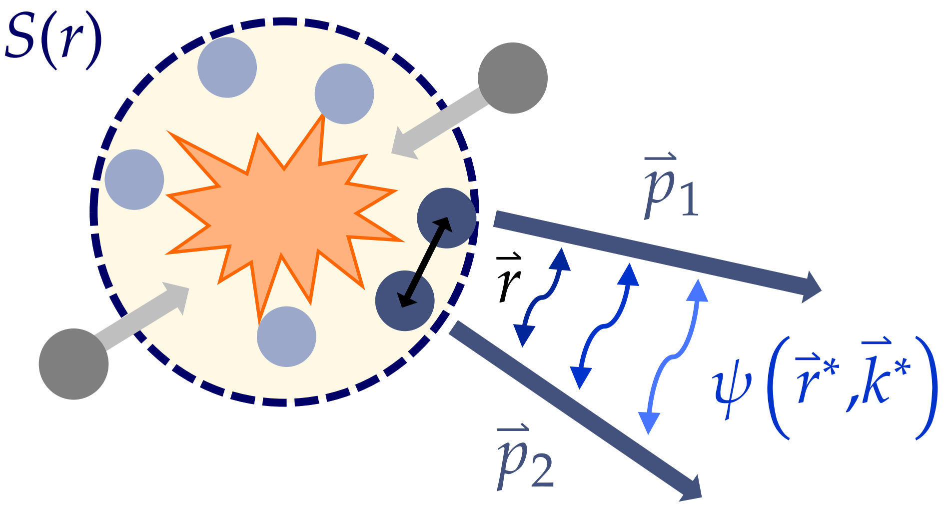

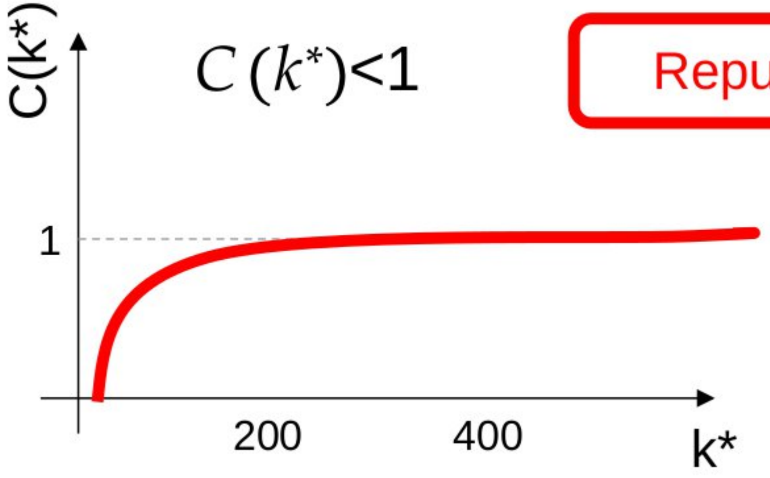

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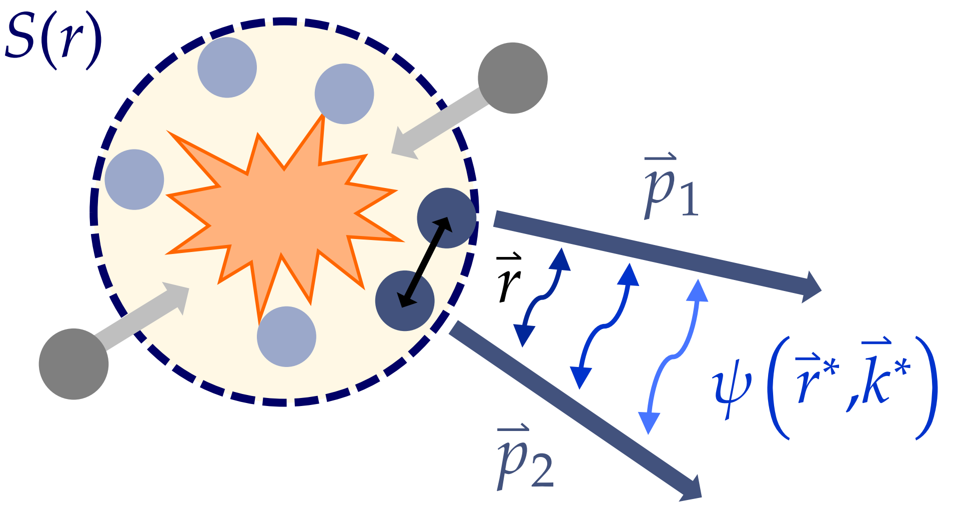

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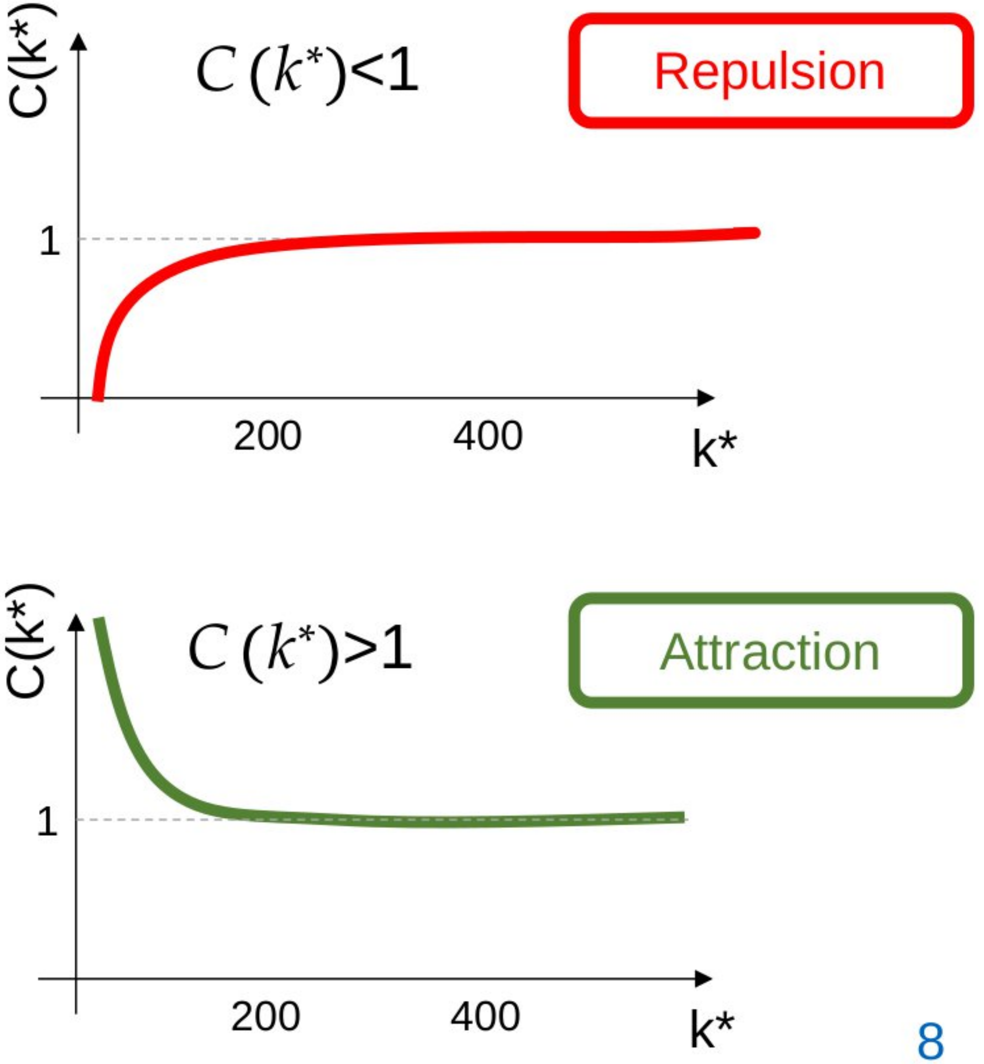

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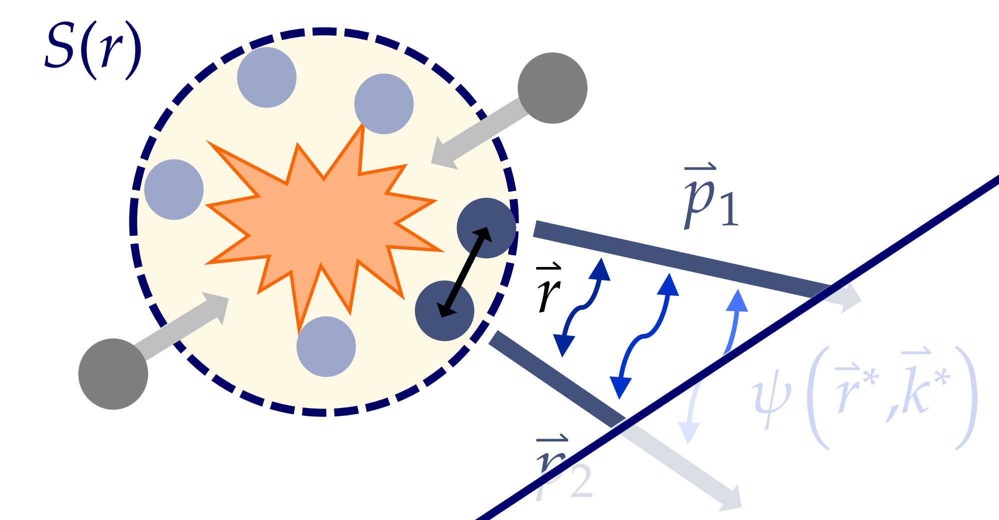

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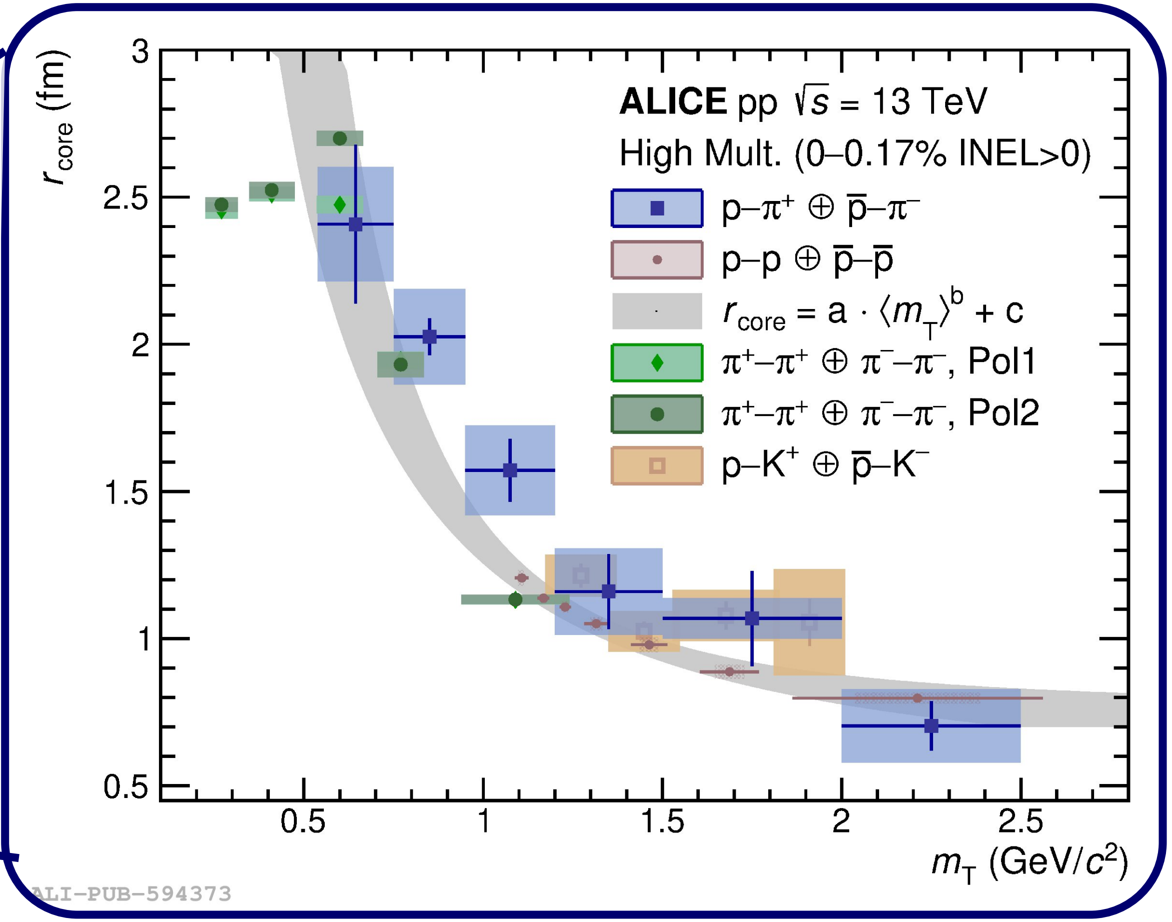


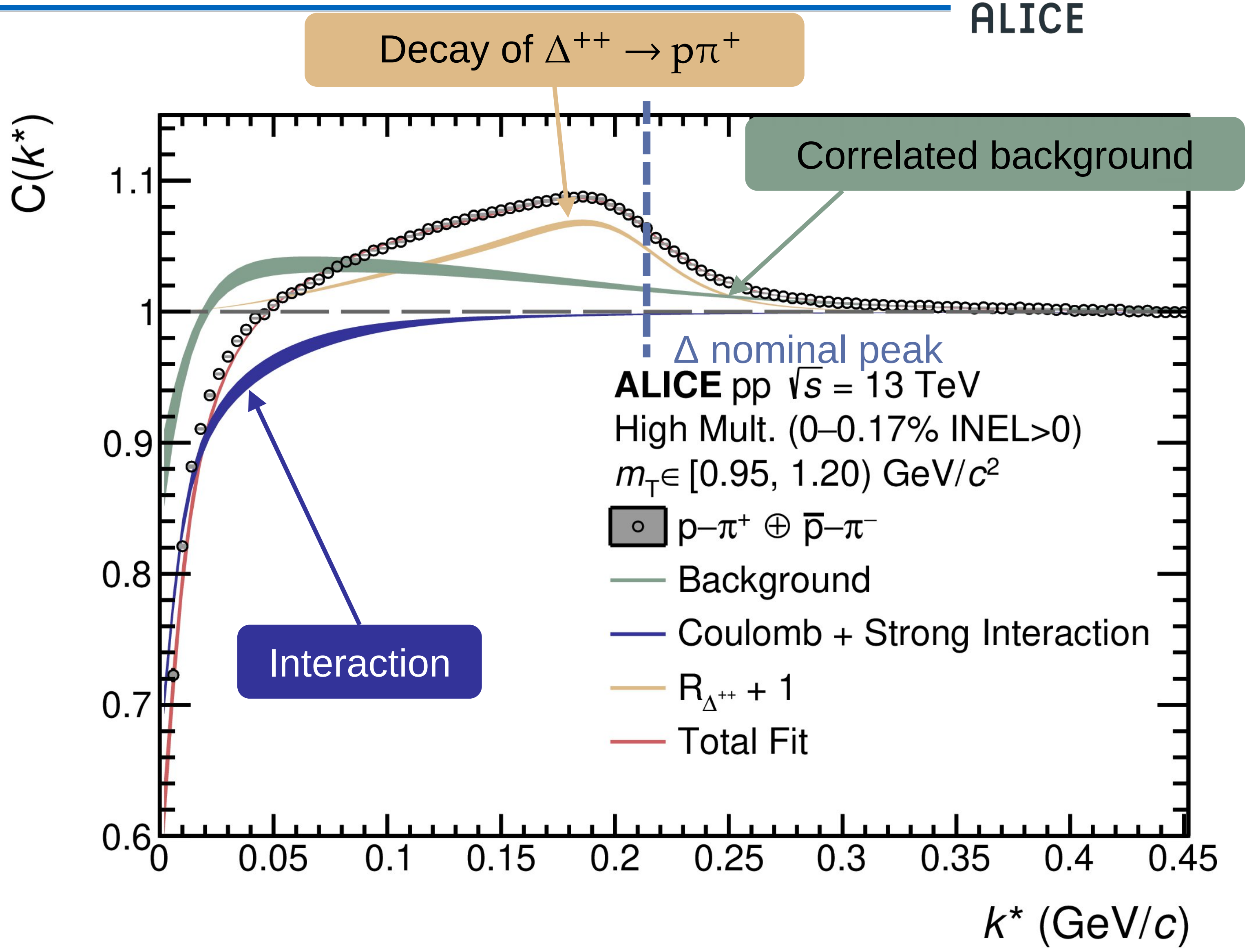
Transverse mass: $m_T = \sqrt{\left(\frac{m_1+m_2}{2}\right)^2 + \left(\frac{p_{T,1}+p_{T,2}}{2}\right)^2}$

p-π: arxiv: 2502.20200, p-p: PLB 811, 135849(2020),
π-π&p-K⁺: arxiv: 2311.14527, D-π: PRD 110, 032004 (2024)
p-Ω: Nature 588, 232 (2020), p-p-p&p-p-Λ: EPJA 59, 298 (2023)

Fitting of the p–π$^+$correlation function

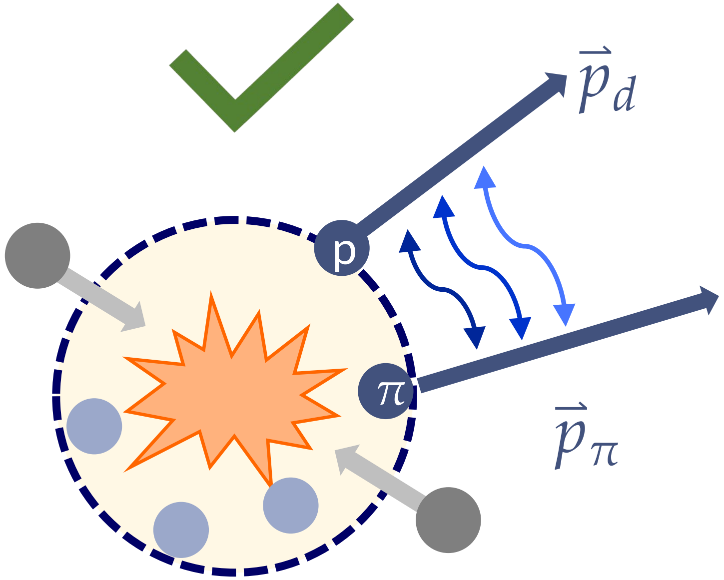
- Good understanding of p–π correlation
- The Δ spectral shape is distorted compared to a typical Breit Wigner due to rescattering of the daughter particles
- modeled using a phase space factor (PS)

$$PS(p_\mathrm{T},T) \propto \frac{m}{\sqrt{m^2+p_\mathrm{T}^2}} \times \exp\left(-\frac{\sqrt{m^2+p_\mathrm{T}^2}}{T}\right)$$



Searching for insights of deuteron formation

I. Study p–π correlations and see which features appear



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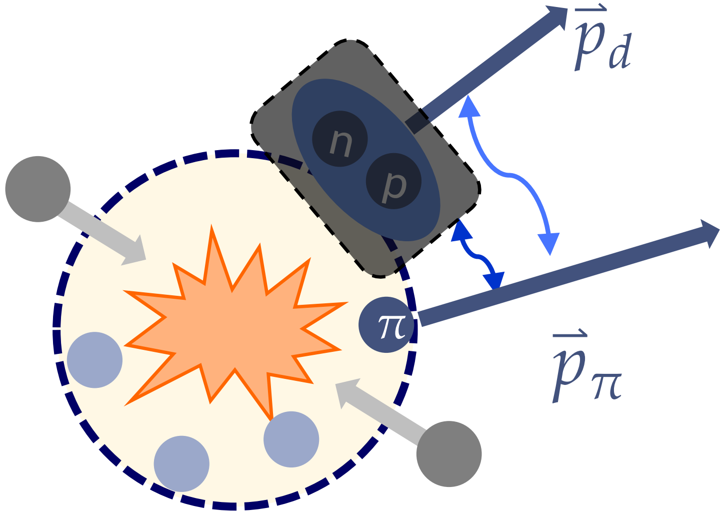

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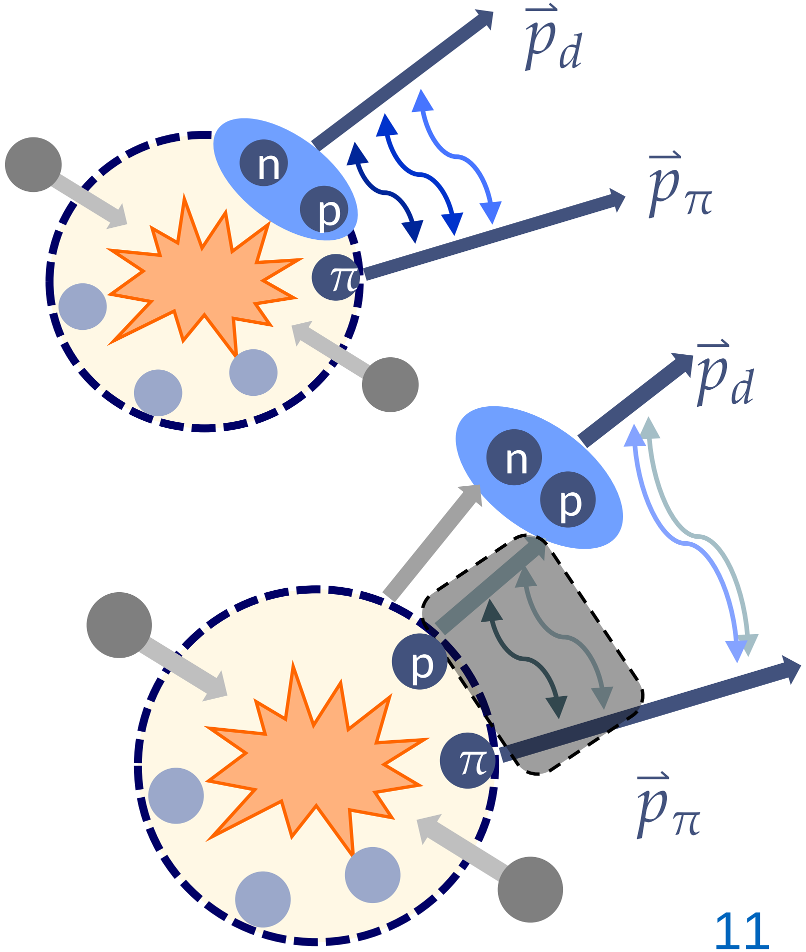
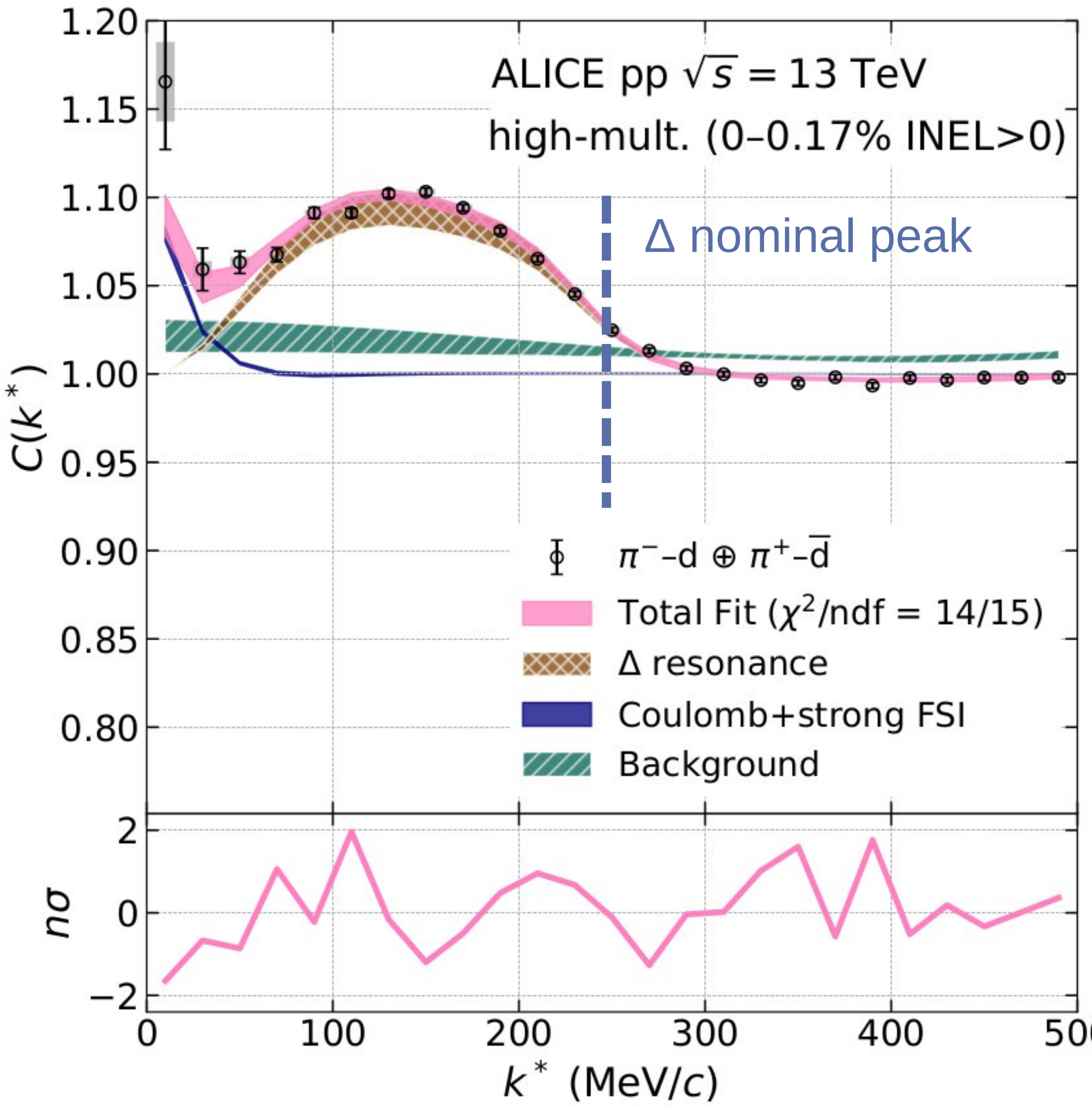


π^-–d Correlation function

- Effect of final state interaction at low *k** which is dominated by Coulomb interaction
  - Attractive for π^-–d
  - Repulsive for π^+–d
- Large bump present centered around 150 MeV/*c*
- π^-–d: Repulsive strong interaction [6]
  f_0 = -0.037 + i 0.008 fm
- Only Re(f_0) used in fit
- Coulomb+strong interaction modeled with CATS[7]



[6] P. Hauser et al, PRC 58, R1869 ,1998
[7] D. L. Mihaylov et al.: EPJC 78, 394 (2018)

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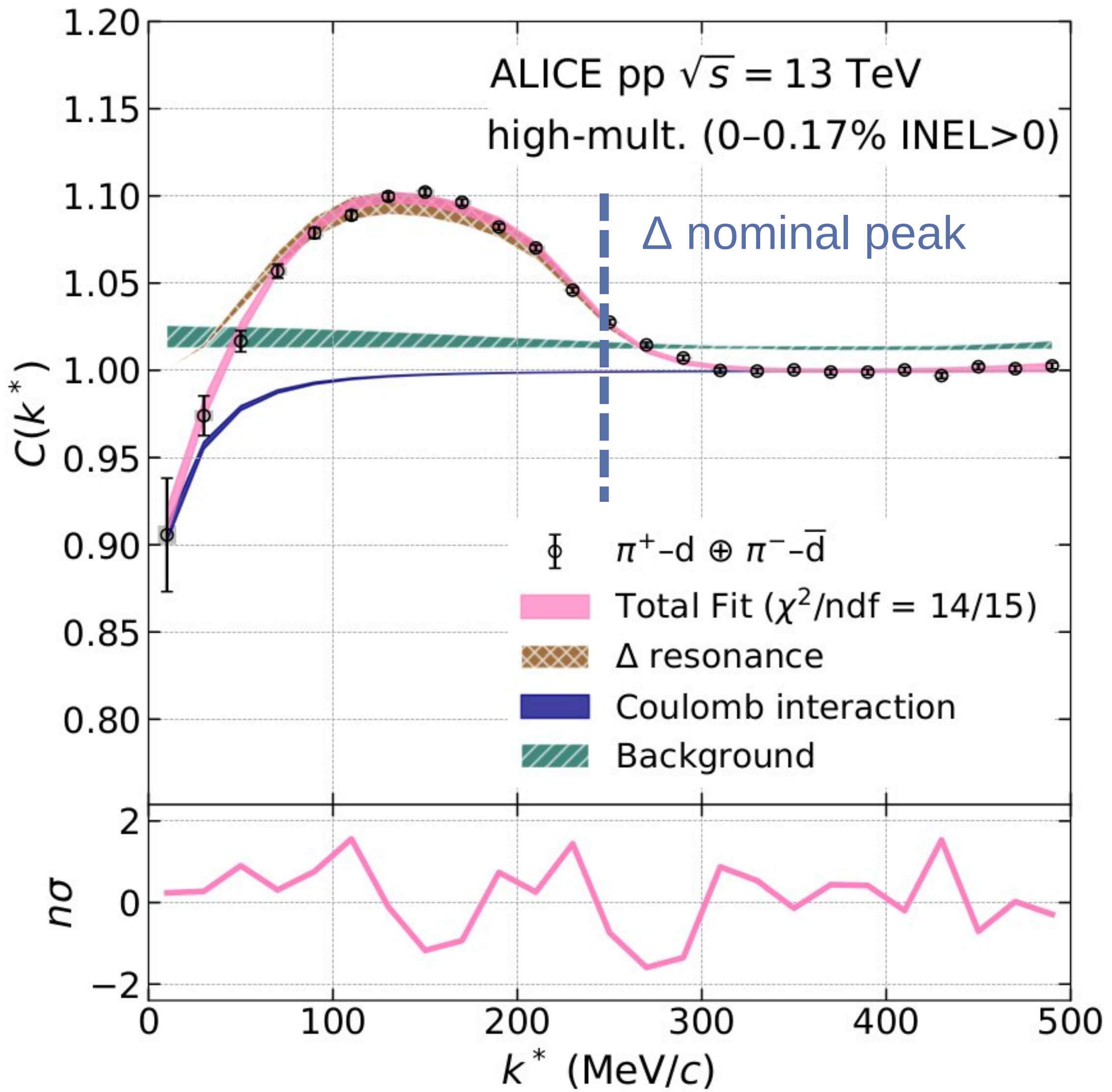

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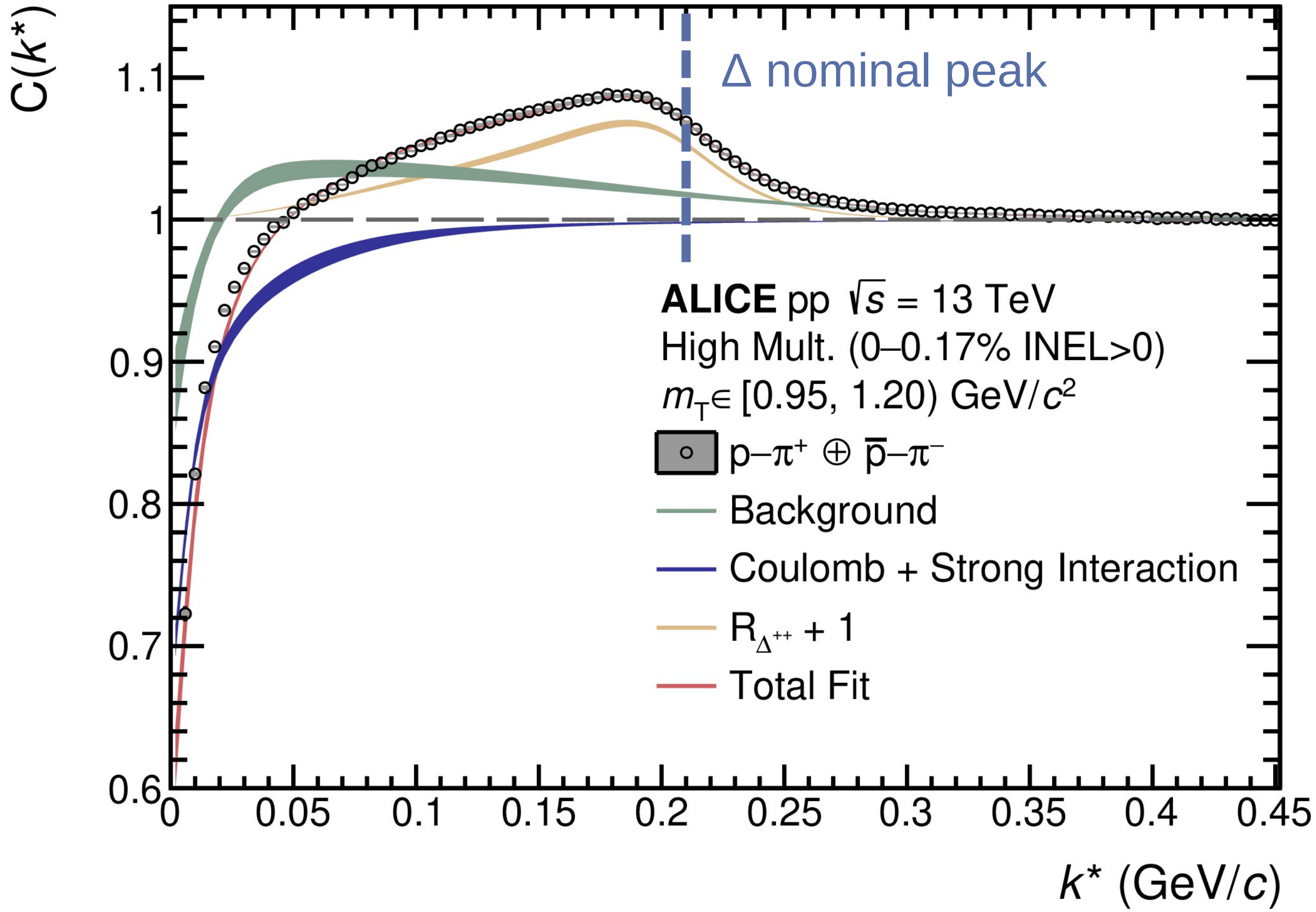
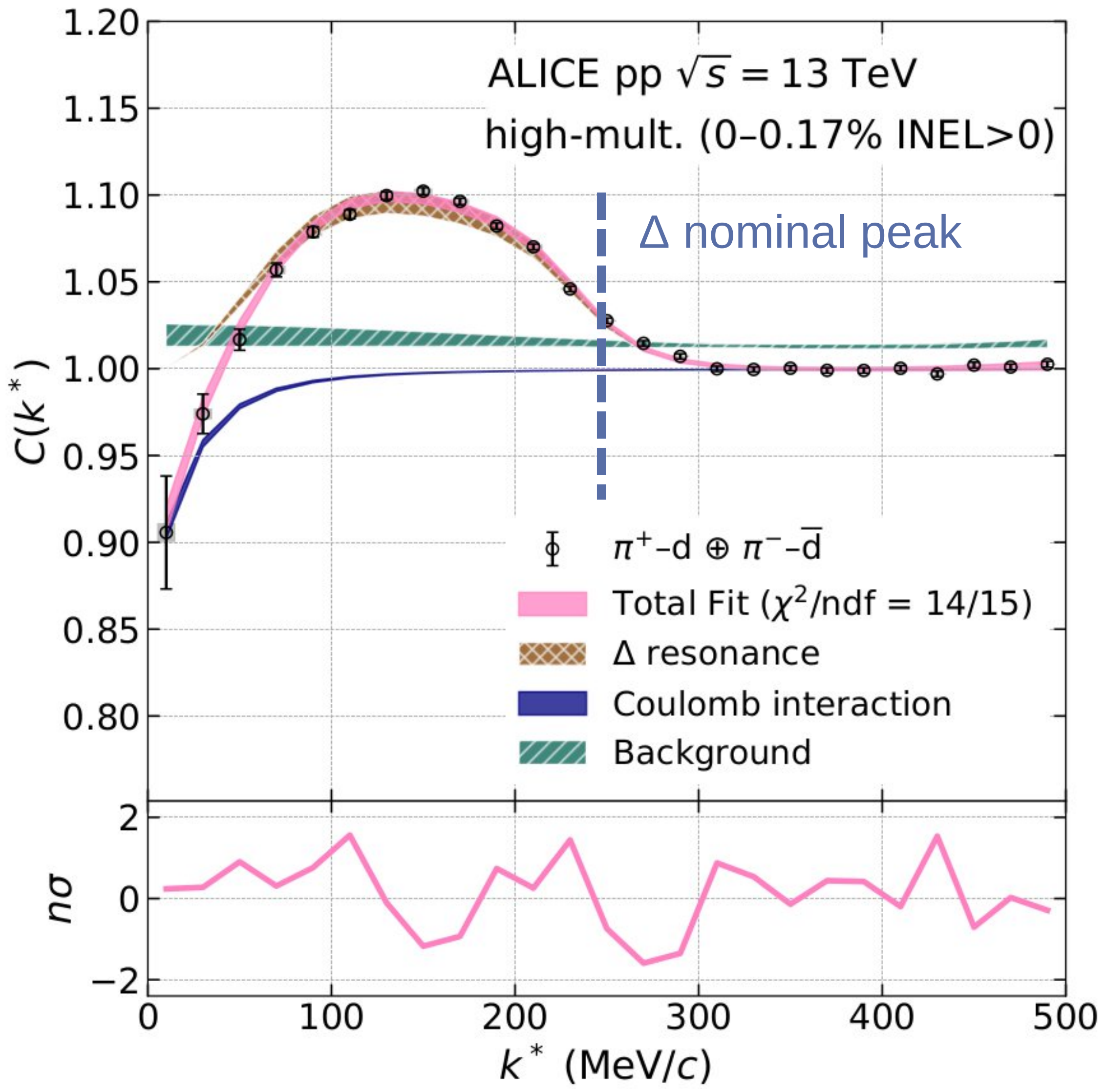
Δ resonance in $\pi^{\pm}$– d and p–$\pi^{\pm}$?



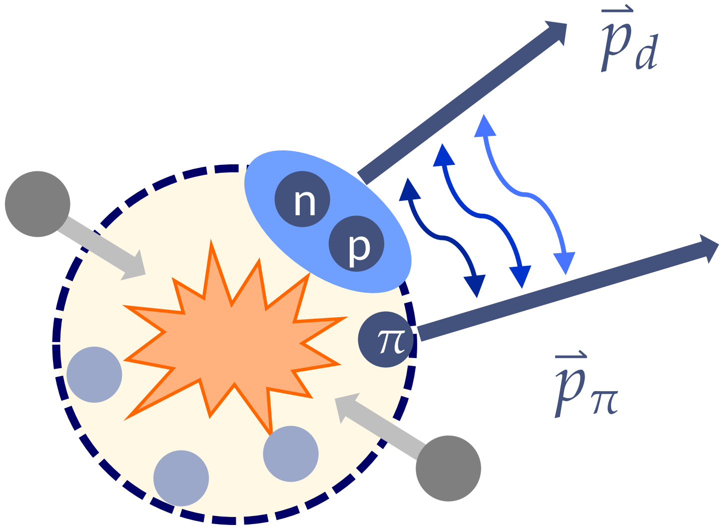


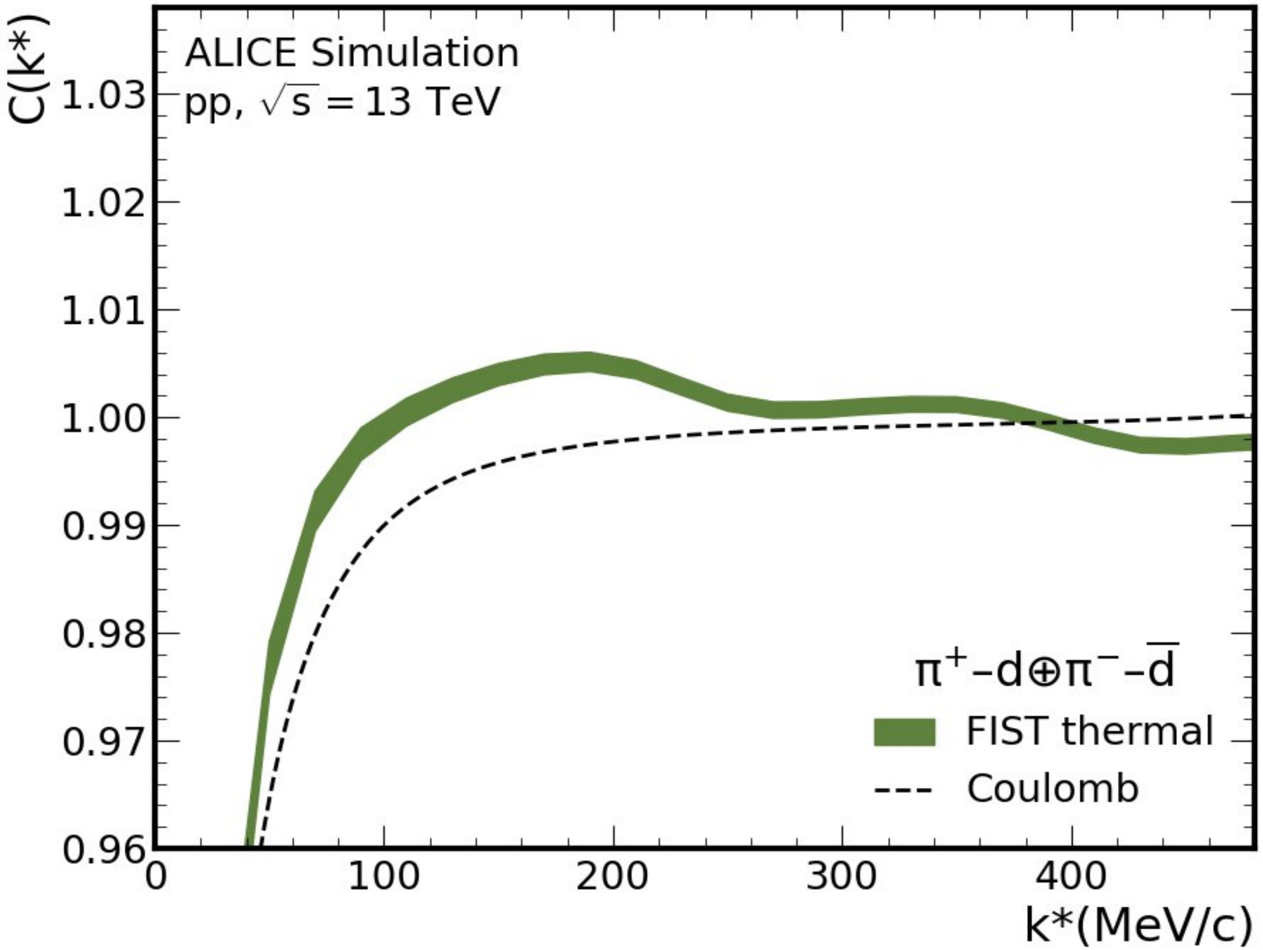
Looks a lot like the Δ peak measured in pπ correlations!
⟶ Are deuterons formed after the Δ decays?

p-π: arxiv: 2502.20200

Model Studies with Coalescence and Stat. Hadronization

- **Thermal FIST[8]** gives only a trivial baseline





[8] V.Vovchenko et al., Comput. Phys. Commun. 244, 295 (2019)

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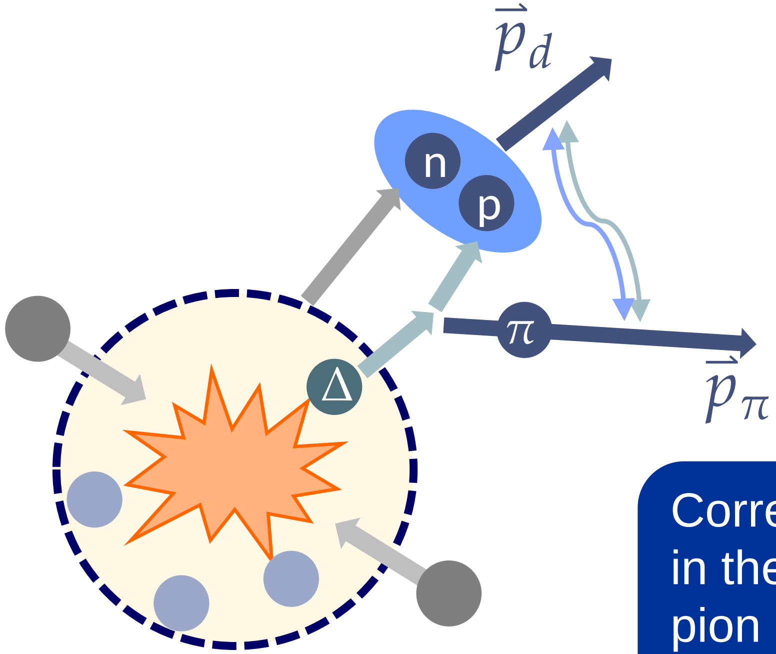
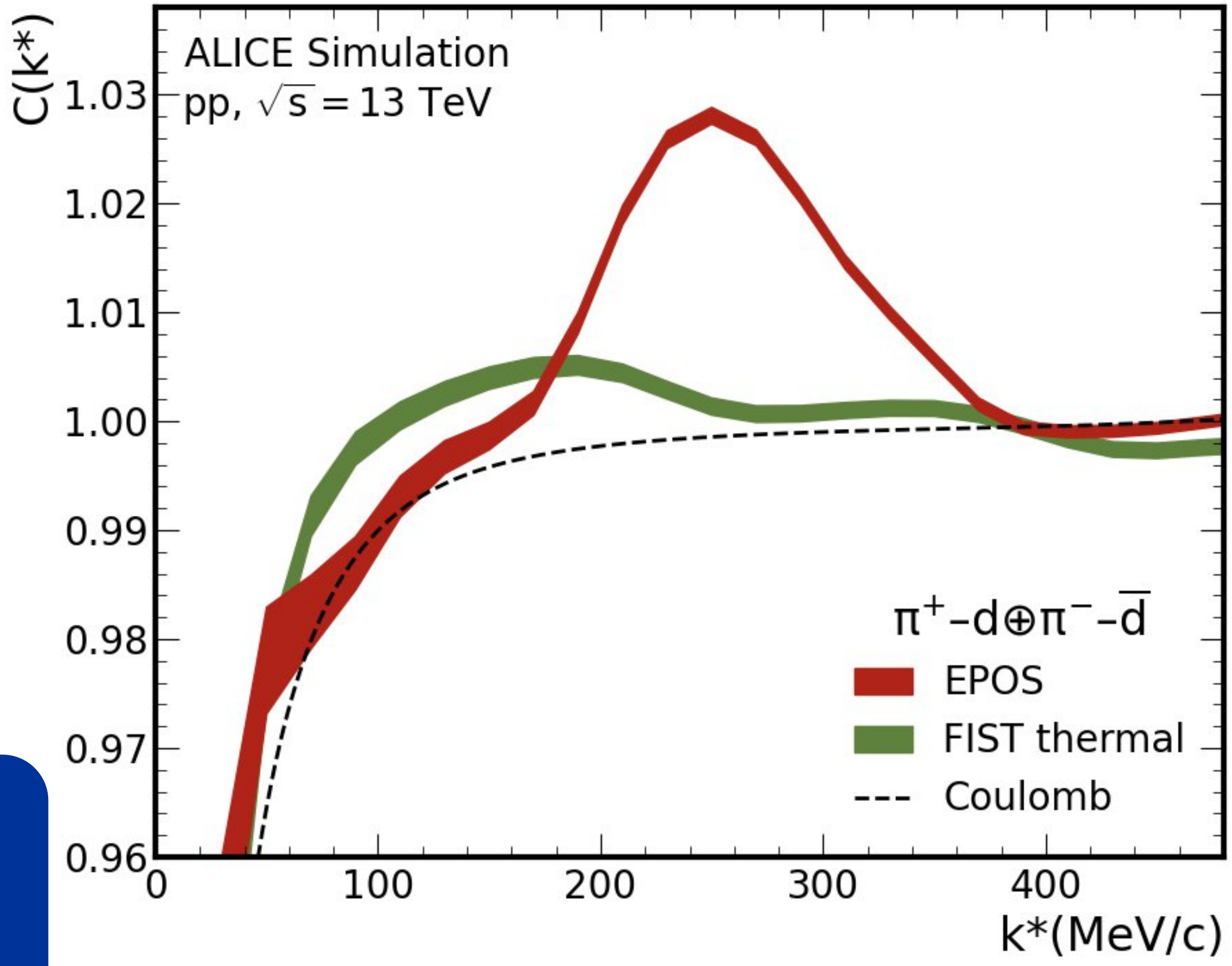


Correlated nucleon in the deuteron and pion due to common Δ mother



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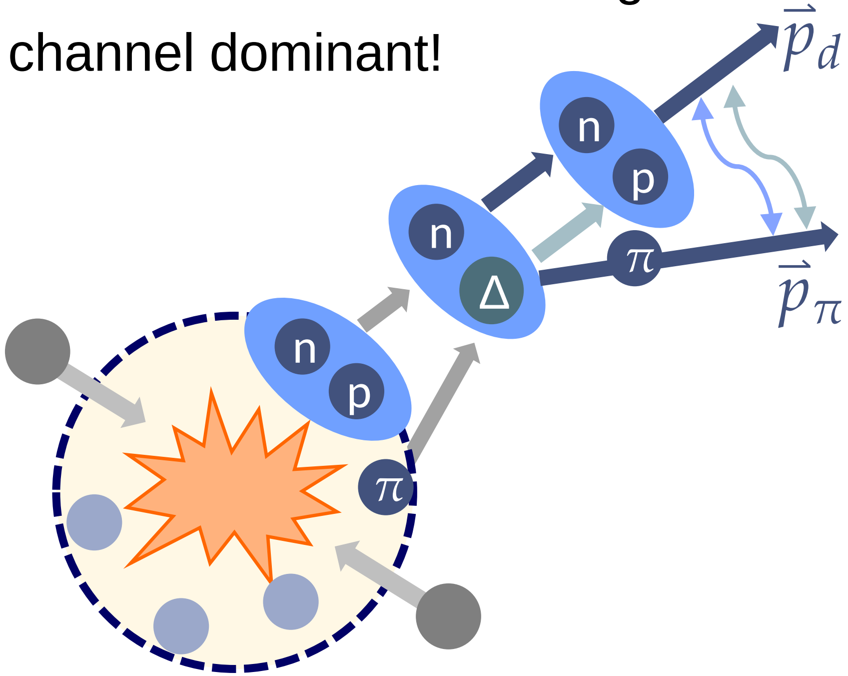
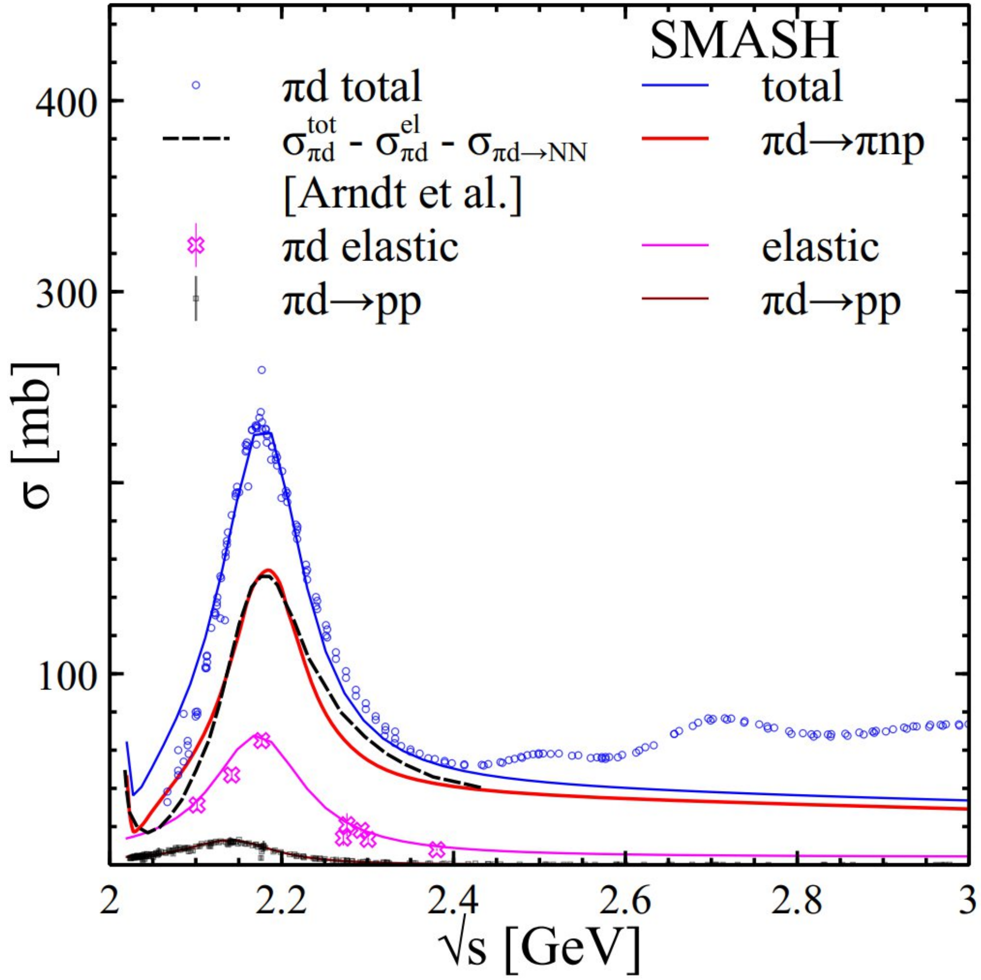
Model Studies with Coalescence and Stat. Hadronization

- **Thermal FIST[8]** gives only a trivial baseline
- **Coalescence[9]** shows a clear bump
- Cross-section measurement + **inelastic**/**elastic** modelling → **inelastic** channel dominant!



D. Oliinychenko et al.: PRC 99, 044907 (2019)



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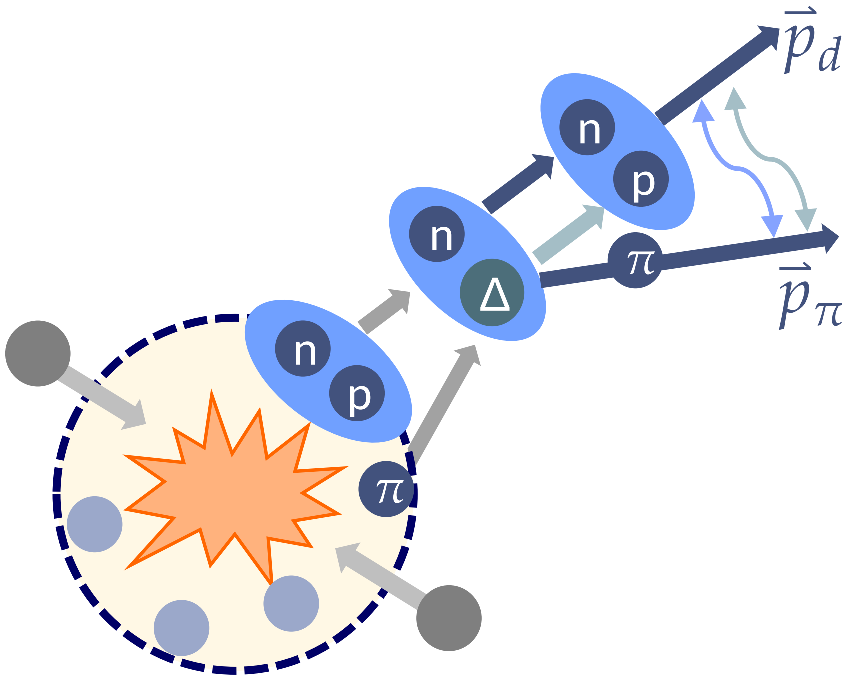
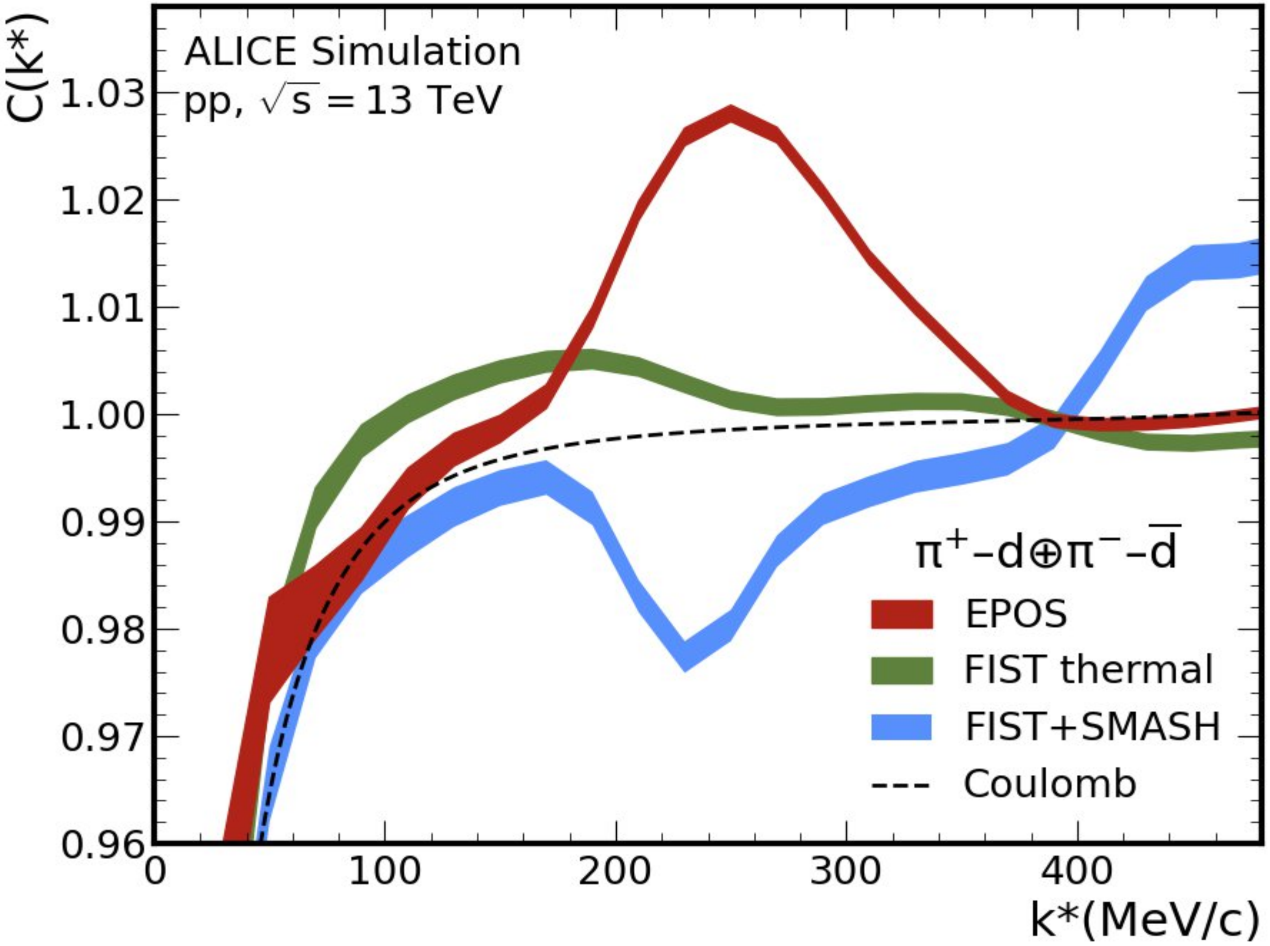
Model Studies with Coalescence and Stat. Hadronization

- **Thermal FIST[8]** gives only a trivial baseline
- **Coalescence[9]** shows a clear bump
- **FIST+SMASH[10]**: massive reduction due to deuteron **destruction**





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[10] J.Weil et al., Phys. Rev. C 94, 054905 (2016)

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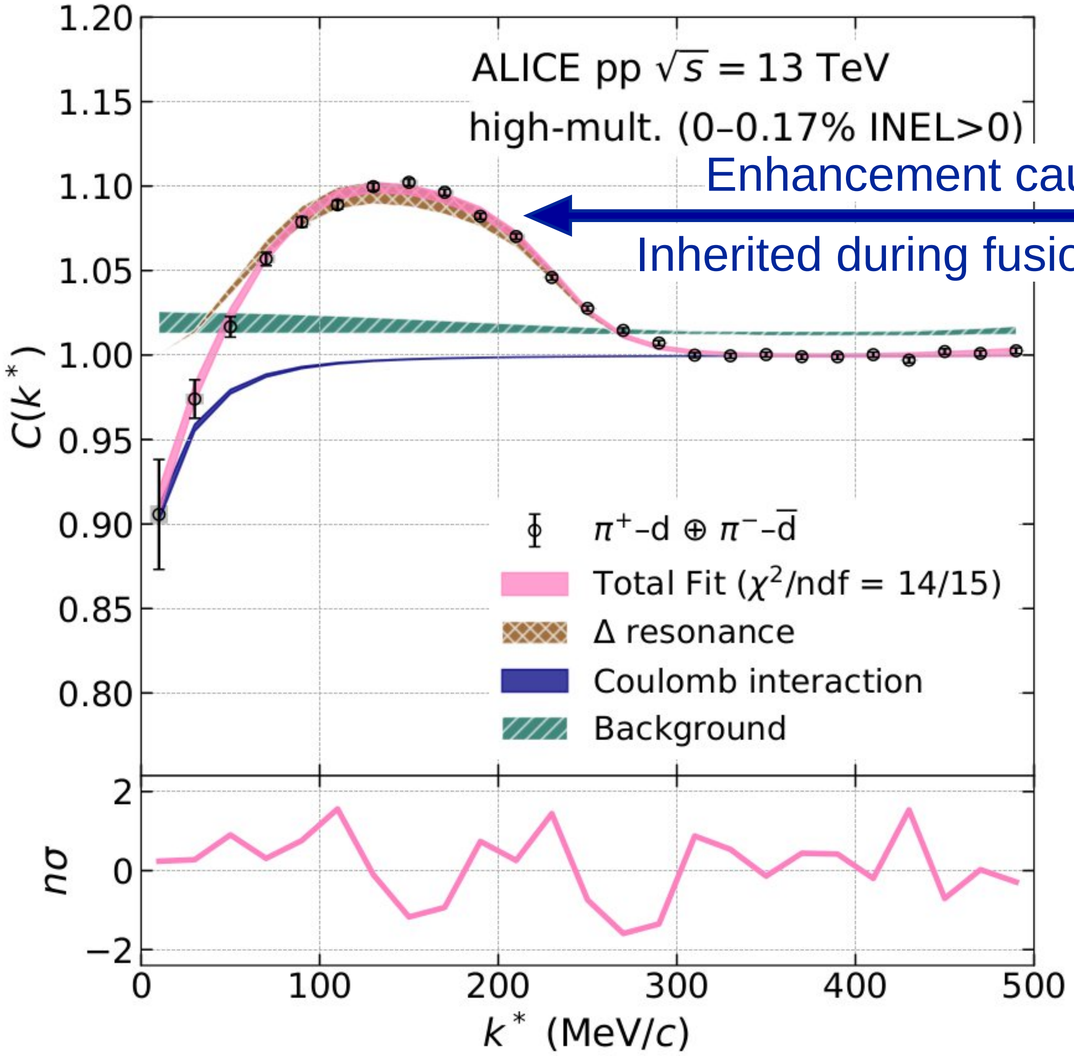
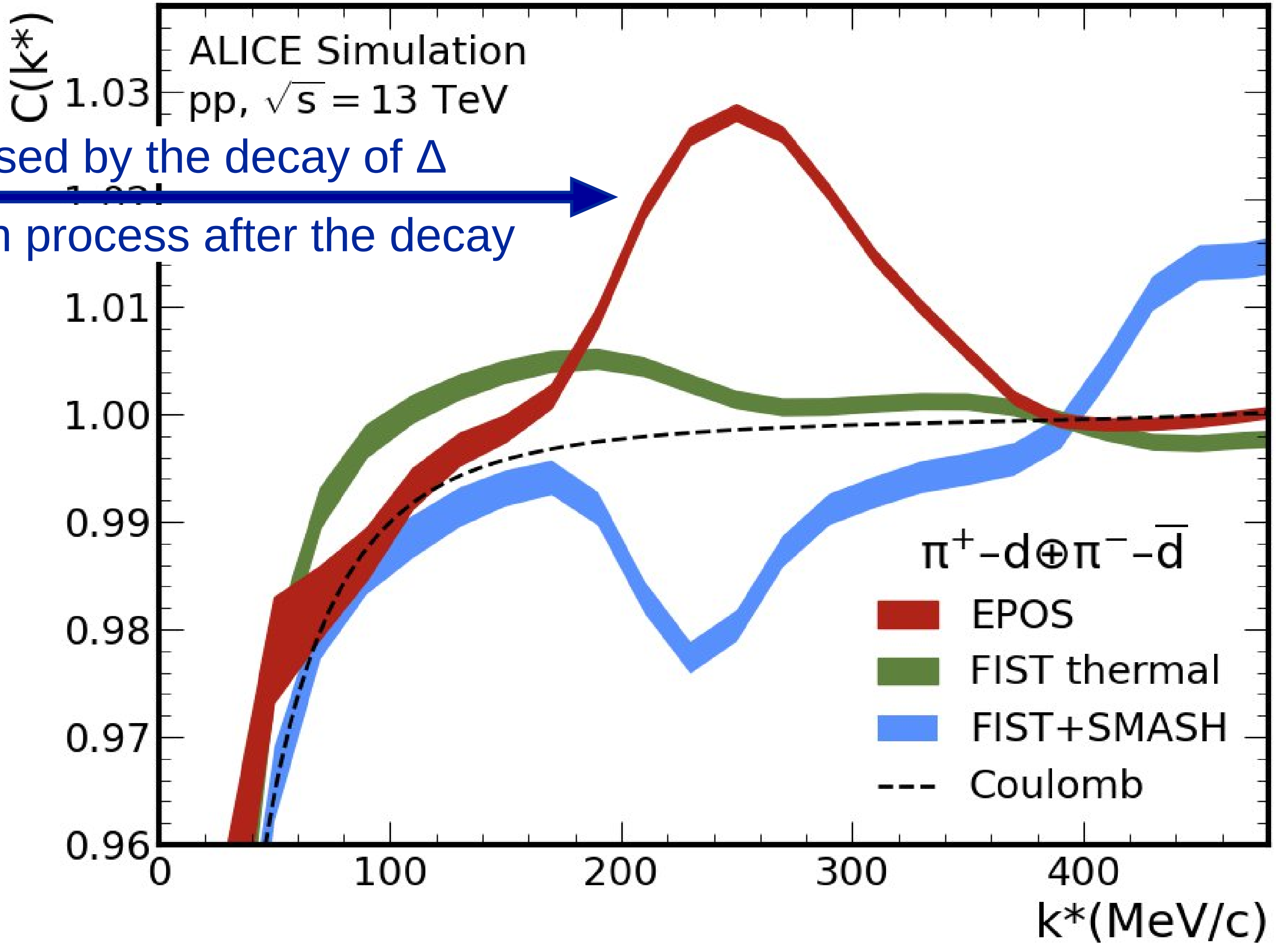
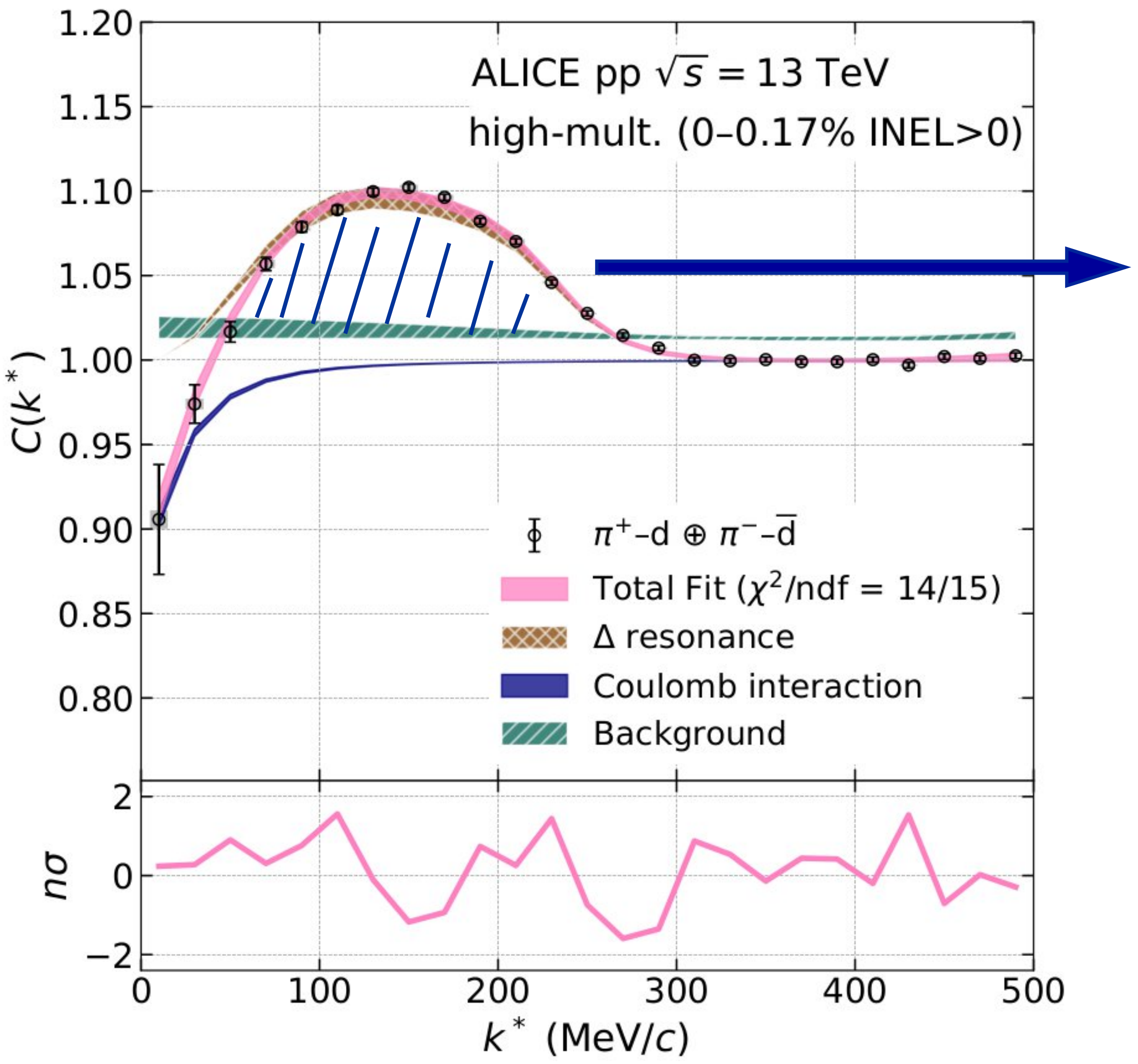


Enhancement caused by the decay of Δ

Inherited during fusion process after the decay



Deuteron fraction from Resonances



- By counting pairs under the peak we can estimate the fraction of deuterons from Δ decays

$$F_{\Delta\rightarrow d} = 61.6 \pm 4.1\%$$

- Extrapolating to all resonances and accounting for acceptance losses we get

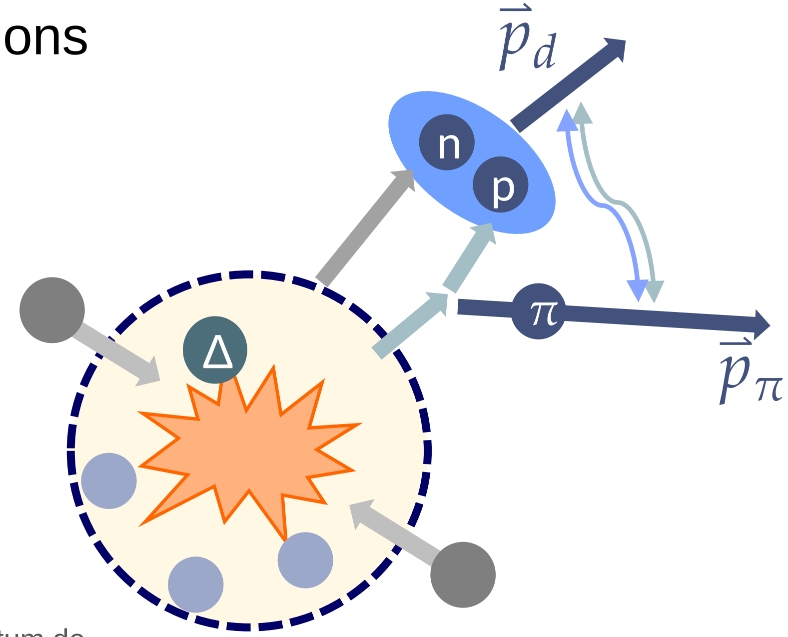
$$\boxed{F_{R\rightarrow d} = 88.9 \pm 6.3\%}$$

- The equivalent value from **EPOS**

$$\boxed{F_{R\rightarrow d} = 89.3 \pm 1.6\%}$$

What to take home

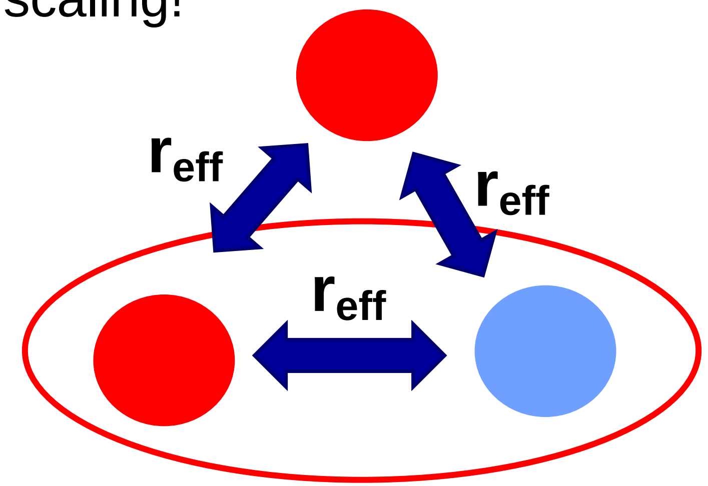
- Residual p–$\pi^{\pm}$ correlation from Δ-decay appears to have exactly the same shape in $\pi^{\pm}$–d correlation function
- The only scenario compatible with this residual correlation is nuclear formation by fusion processes
- The fraction of deuterons originating from resonances, as extracted from the correlation function is compatible with coalescence calculations

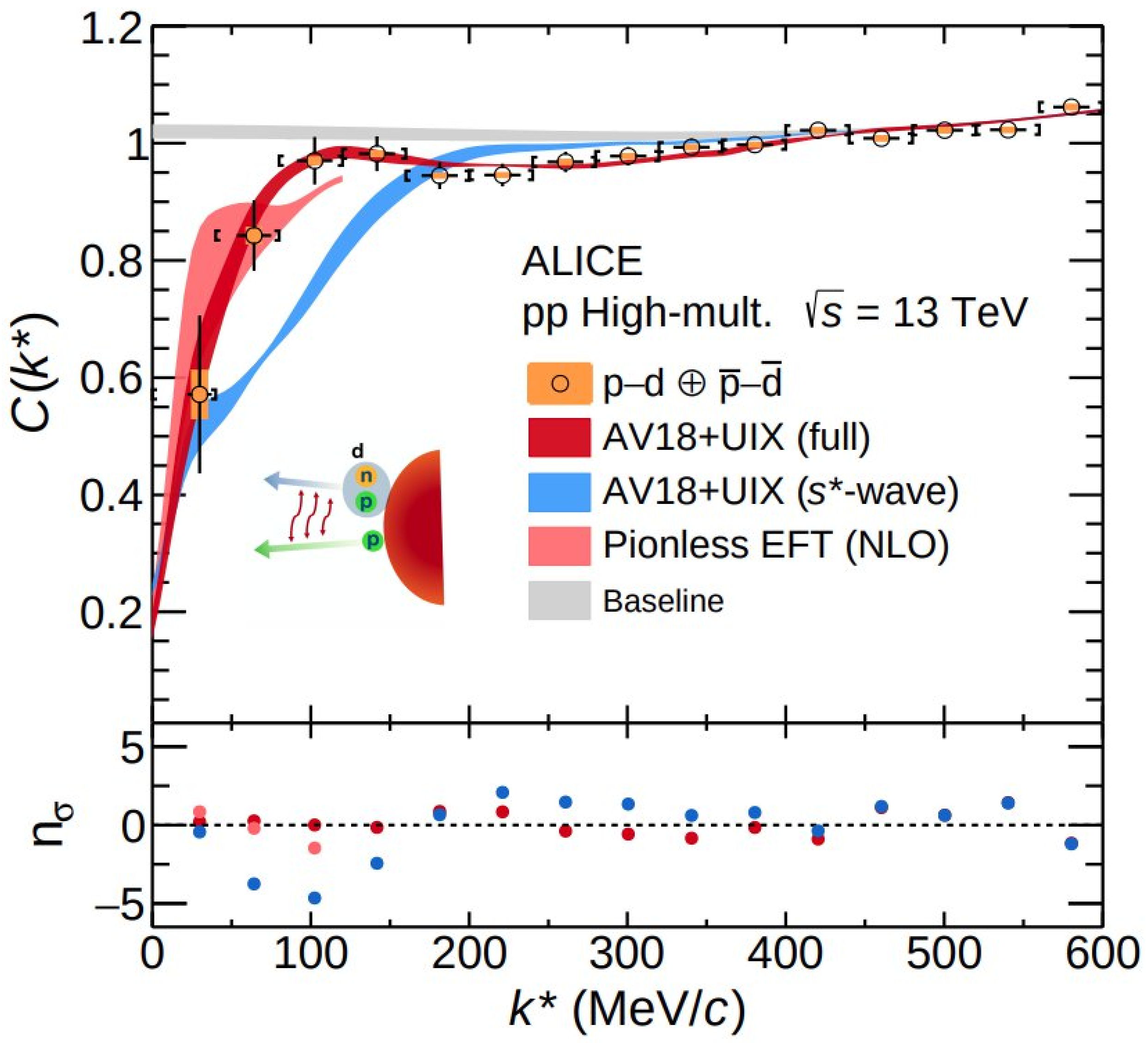


Backup

Deuteron femtoscopy in pp collisions

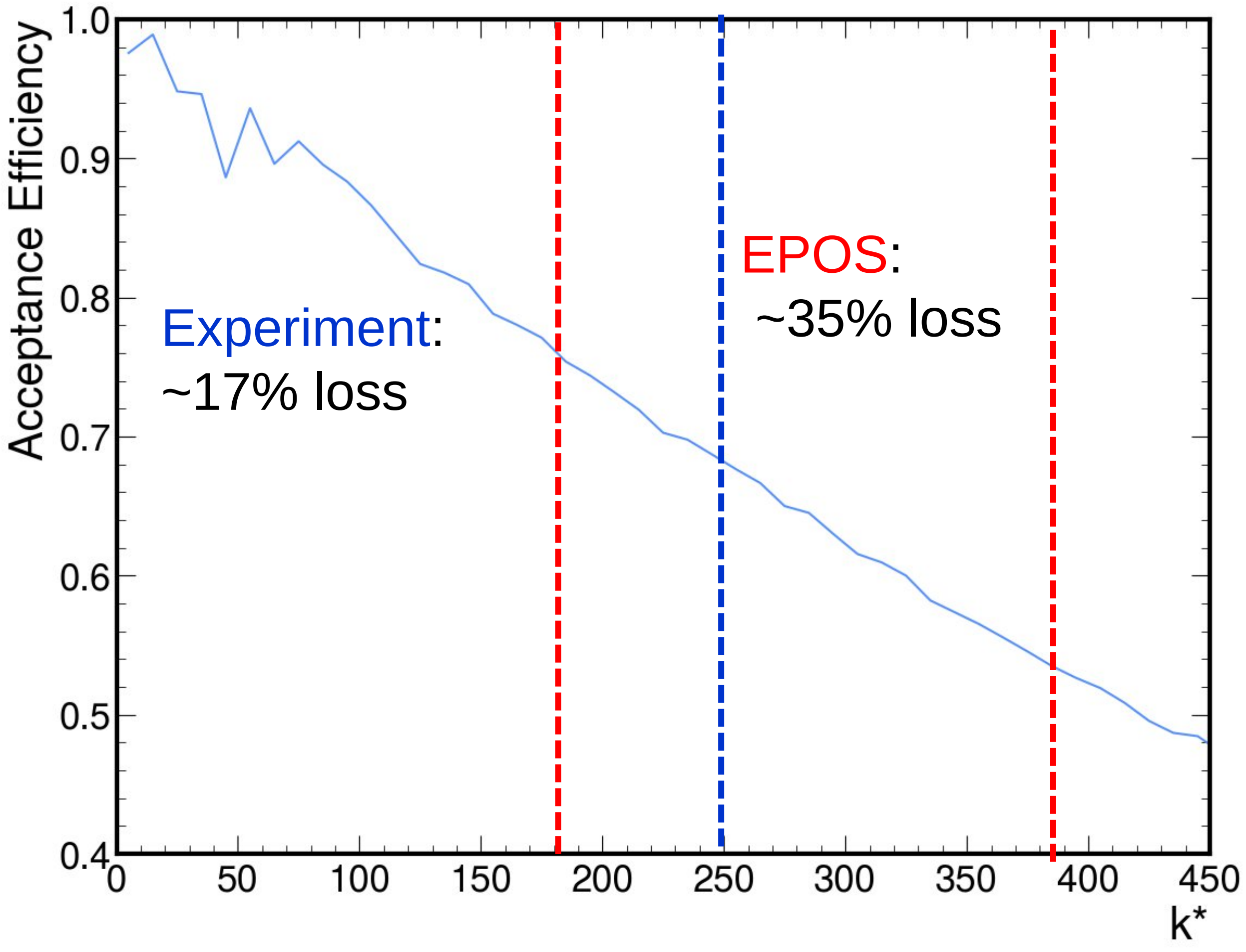
- p-d correlation function in pp collisions
- Fit using full-fledged calculation based on Argonne v_{18} (2-body) and Urbana IX (3-body) potentials
- Source size obtained from common source scaling (r_{eff}=1.08 fm)
- Even deuterons follow the same source size scaling!





p-d: PRX 14, 031051 (2024)

Deuteron fraction from Resonances



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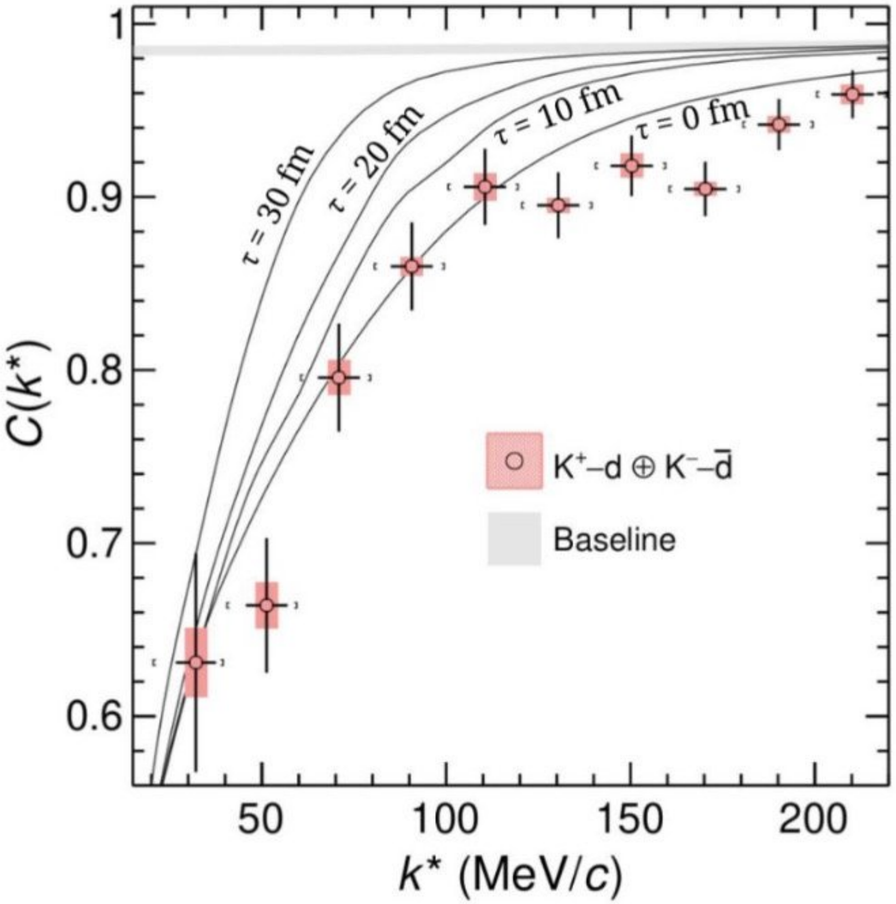
Previous femto studies into deuteron formation

- Using the CECA source model and the measured K^+-d correlaction function an upper limit of the deuteron formation time was determined
- If the deuteron is primordial the upper limit is 4.75 fm/*c*
- if the deuteron stems from resonances it is 2.25fm/*c*



CECA Source model
D. Mihaylov, J. Gonzalez-Gonzalez Eur.Phys.J.C 83 (2023) 7, 590

ALICE Collaboration: Nat. Phys. 19, 61 (2023)

Deuteron fraction

- Count **number of πd pairs** under the peak (**π^+-d & π^--d** simultaneously)
- Add the contributions from all final (including π^0)
- Finally, we evaluate:

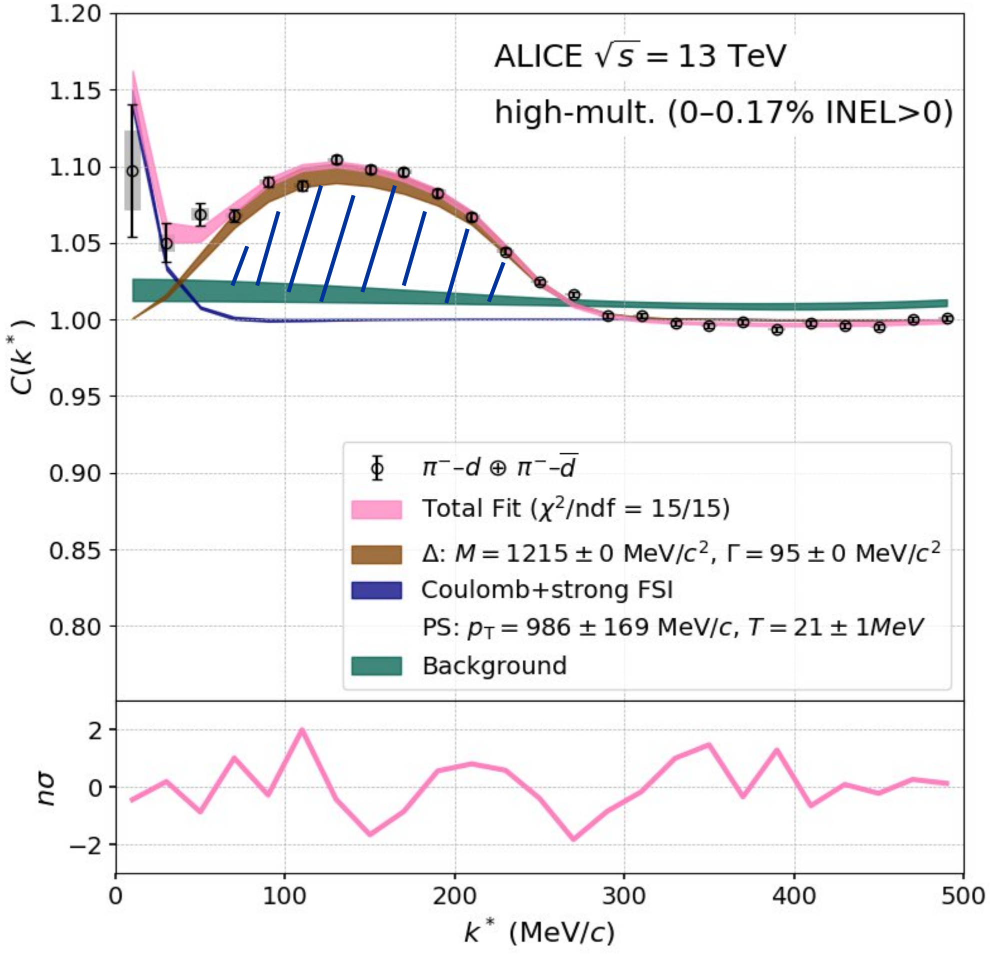
$$F_{\Delta\to d} = \frac{deuterons\ from\ \Delta}{all\ d\ candidates} = 61.6 \pm 4.1\%$$

- Using thermalFIST to extrapolate to all resonances gives

$$F_{R\to d} = \mathbf{79.5 \pm 5.5\%}$$

- The corresponding number from EPOS[1] is **89.3±1.6%**

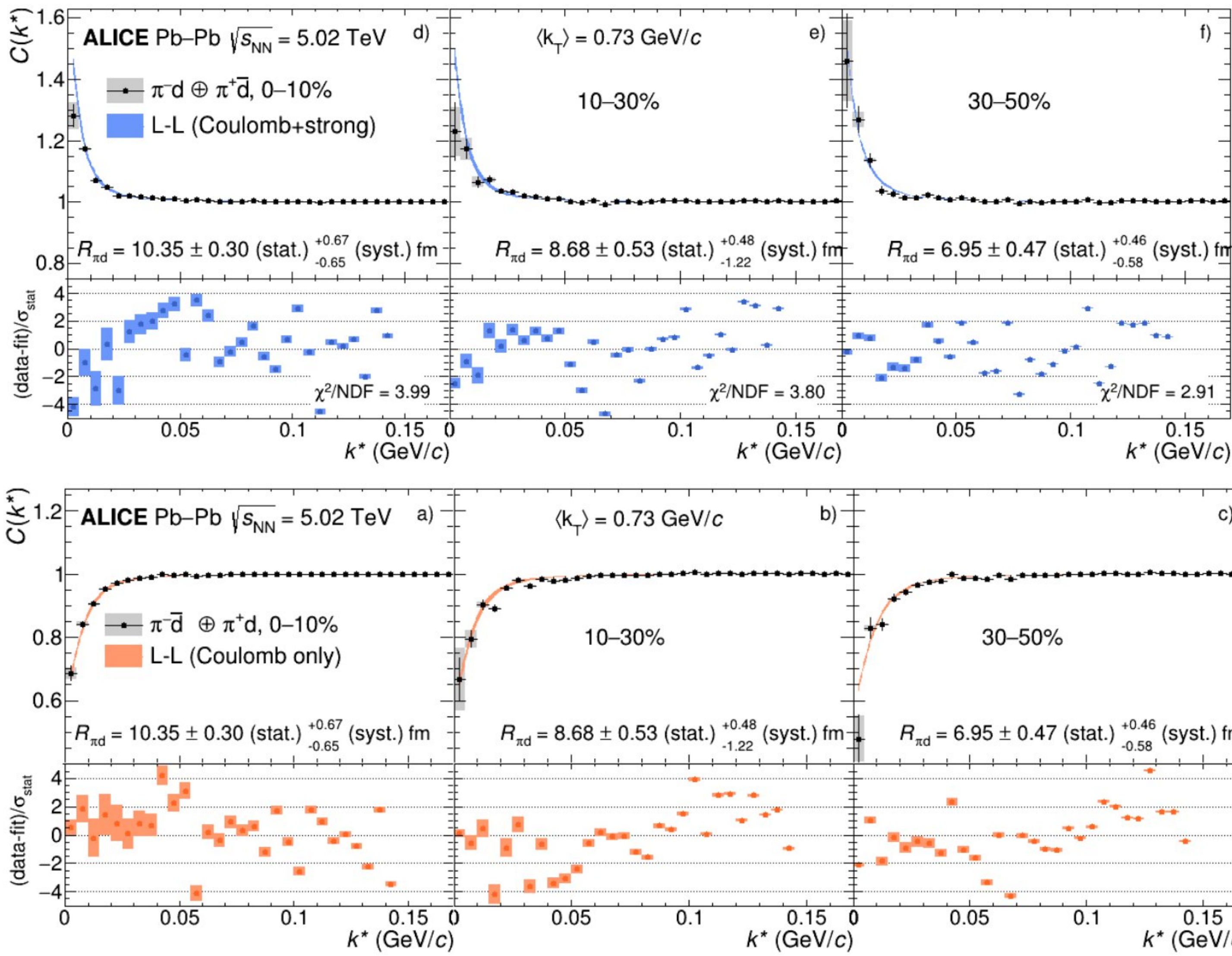
Formation of deuterons from resonances is not only happening, it is the **dominant** contribution!



[1]EPOS resonance fractions were tuned to thermalFIST

$\pi^{\pm}$–d in Pb–Pb collisions

- Same analysis done in Pb–Pb collisions
- No visible peak
- Combinatorial background overshadows any signal



Modelling of d$\pi^{\pm}$ Correlation Function

$$C_{\text{total}} = \mathcal{N} \times C_{\text{baseline}} \times [\lambda_{\text{Gen}} C_{\text{gen}} \times (\ (1-F_{\Delta}) + F_{\Delta} N_{\Delta} PS\,(p_{\text{T}},T) \times Sill(M_{\Delta},\Gamma_{\Delta})) + (1-\lambda_{\text{Gen}})]$$

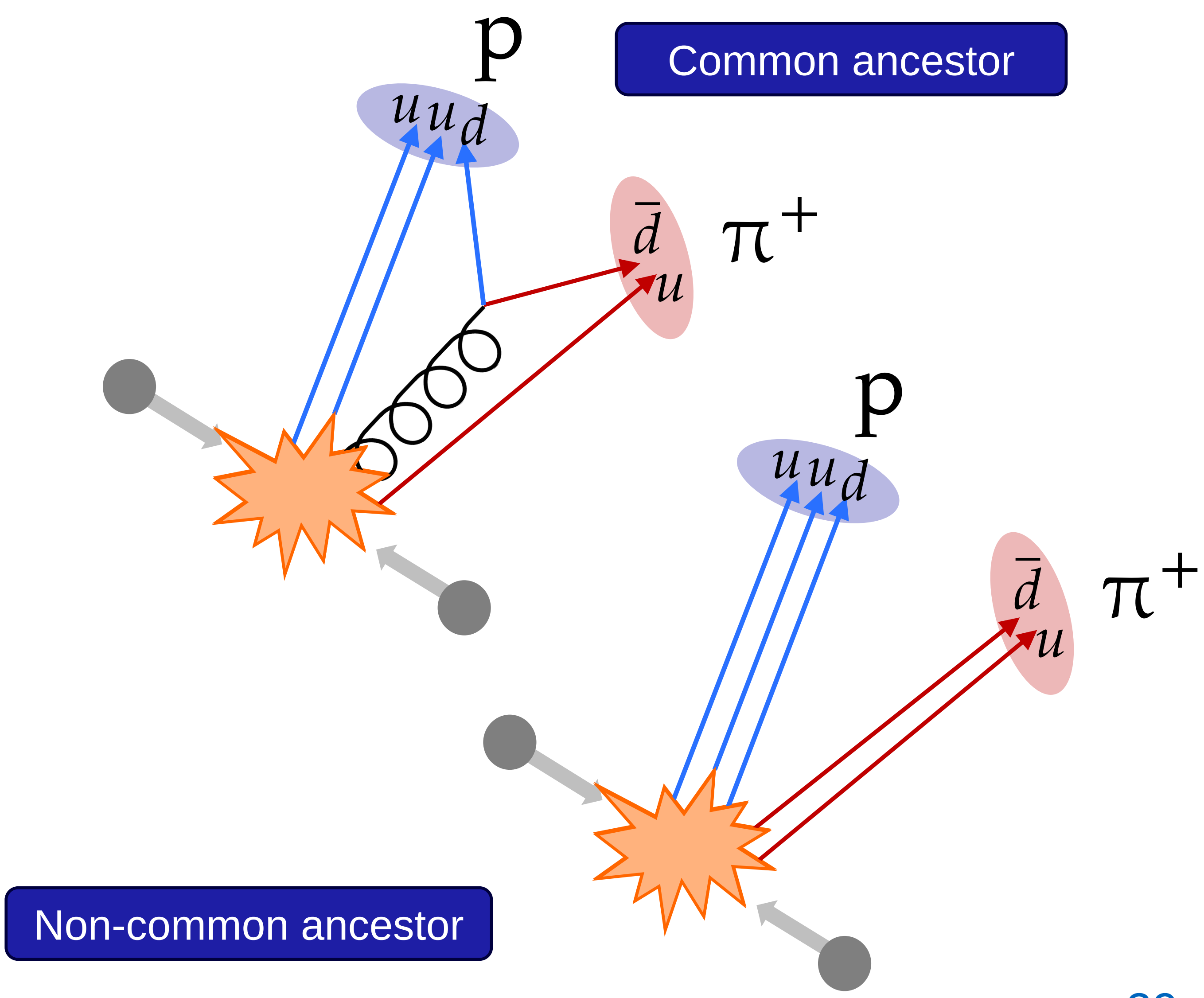
- Baseline C_{baseline} modelled via pol3
- Final State Interaction C_{gen} Coulomb
- Resonance description: Sill distribution $Sill(M_{\Delta},\Gamma_{\Delta})$, M_{Δ} fixed to 1215 MeV
  F. Giacosa et al., EPJA 57 (2021) 12
- $PS\,(p_{\text{T}},T)$ phase-space factor

$$PS\,(p_{\text{T}},T) \propto \frac{m}{\sqrt{m^2+p_{\text{T}}^2}} \times \exp\left(-\frac{\sqrt{m^2+p_{\text{T}}^2}}{T}\right)$$

- F_{Δ} is the fraction of πd pairs with a d stemming from a Δ, compared to all πd pairs.
- Resonance shape is evaluated by transforming the Δ peak seen in pπ, with the parameters extracted from data, to dπ (except of the temperature)

Background contribution

- Correlated background due to “mini-jet” contribution from hadronization process
- Background modelled with MC simulations using Pythia:
  - Obtain MC correlation function for pairs with common and non-common partonic origin (ancestors) separately
  - Use common C_{c} and non-common C_{nc} as templates to build the background
  - $C_{\mathrm{bckg}} = \mathcal{N} \times [w_{\mathrm{c}} C_{\mathrm{c}} + (1 - w_{\mathrm{c}})\, C_{\mathrm{nc}}]$



Modelling of $p\pi^+$data

$$C_{\text{total}} = \mathcal{N} \times C_{\text{bckg}} \times [\lambda_{\text{Gen}} C_0 + (1-\lambda_{\text{Gen}})] + N_\Delta PS(p_{\text{T}},T) \times Sill(M_\Delta,\Gamma_\Delta)$$

- Background C_{bckg} via MC templates, controlled by w_{c}
- Interaction $C_0(r_{\text{core}})$ Coulomb + strong interaction (fixed from scattering lengths)
  M. Hoferichter et al., Phys.Rept. 625 (2016) 1–88
  M. Hennebach et al., EPJA 50 (2014) 12, 190
- Resonance description: Sill distribution $Sill(M_\Delta,\Gamma_\Delta)$, M_Δ fixed to 1215 MeV
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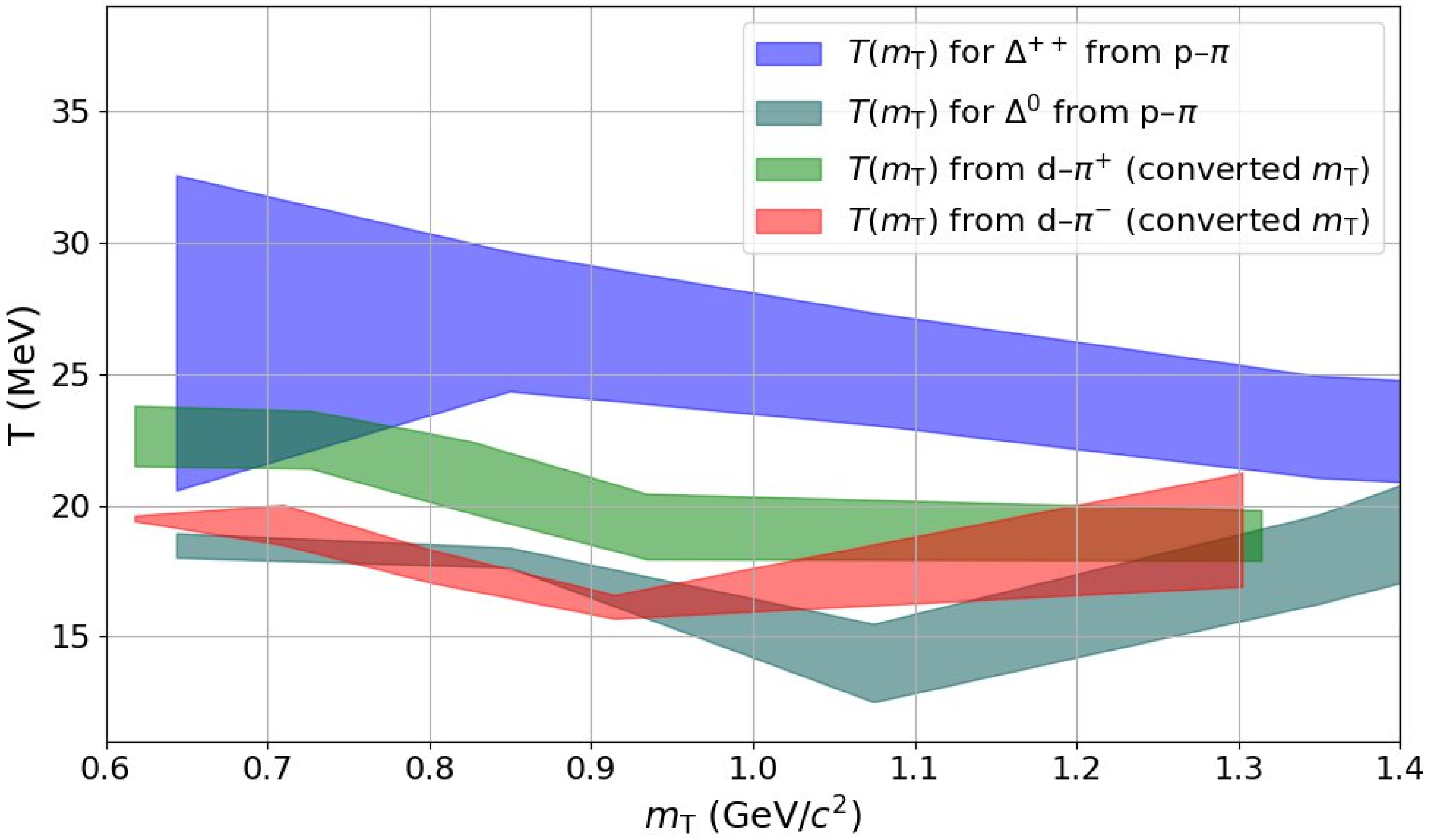
- Fit between between 0 and 450 MeV in *k**

Resonance decoupling temperature

- Similarly low kinetic decoupling temperature obtained in $\mathrm{d}\pi^{\pm}$ as in $\mathrm{p}\pi^{\pm}$
- Slight differences as the resonance signal in $\mathrm{d}\pi^{\pm}$ is mixed

System	Resonances
$\mathrm{p}\pi^{+}$	Δ^{++}
$\mathrm{p}\pi^{-}$	Δ^{0}
$\mathrm{d}\pi^{+}$	Δ^{++} and Δ^{+}
$\mathrm{d}\pi^{-}$	Δ^{0} and Δ^{-}



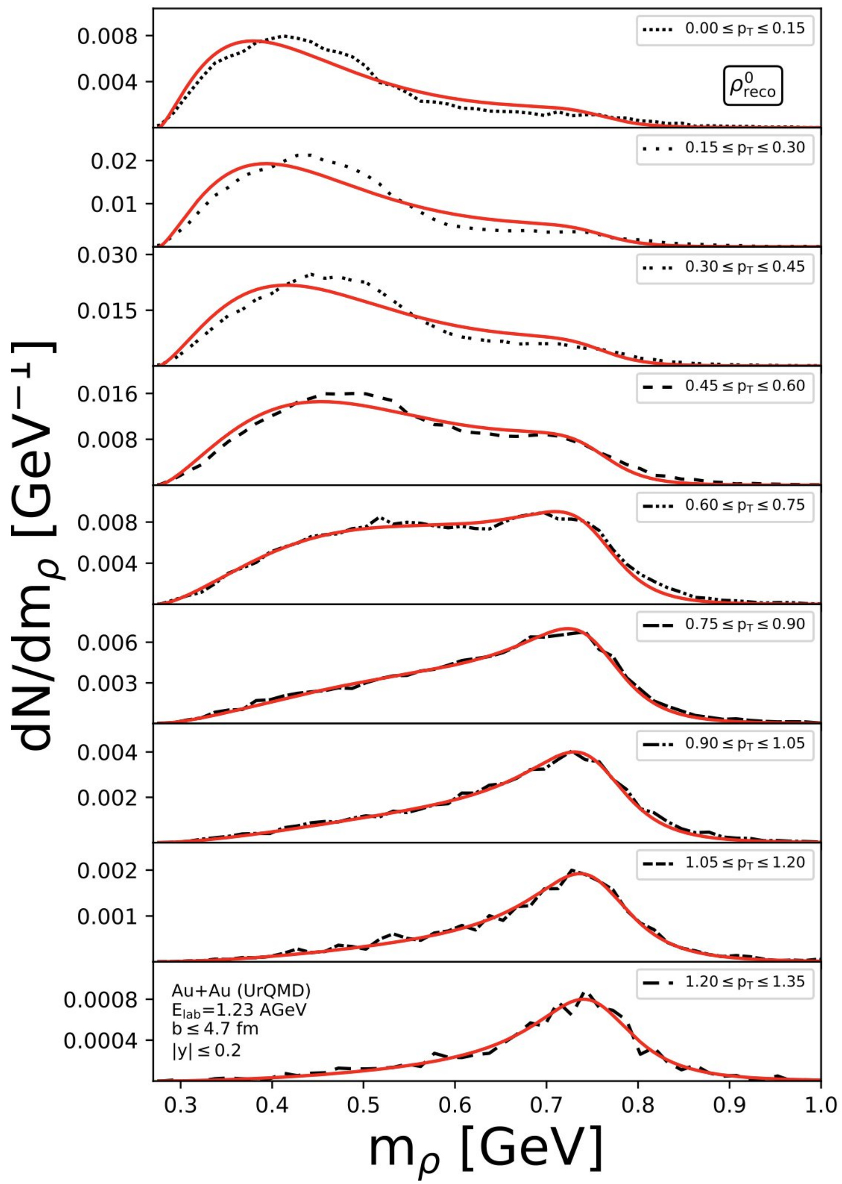
Temperature interpretation

- Temperature related to resonance regeneration $\Delta \leftrightarrow N\pi$ phase
- Lower temperature ↔ longer lasting regeneration phase (more phase space modification)
- Attractive interactions can give longer lasting regeneration (lower temperature) while repulsive interactions should lead to shorter regeneration phases (higher temperature)

Channel	Resonance	Relevant decay & scattering length in $10^{-3} m_{\pi}^{-1}$	Length of resonance regeneration phase
$\pi^{+}d$	Δ^{++}	$\pi^{+}p$ (repulsive); -88.1	Shorter
	Δ^{+}	$\pi^{+}n$ (attractive); 84.9	Longer
$\pi^{-}d$	Δ^{0}	$\pi^{-}p$ (attractive); 85.8	Longer
	Δ^{-}	$\pi^{-}n$ (repulsive); -89.0	Shorter

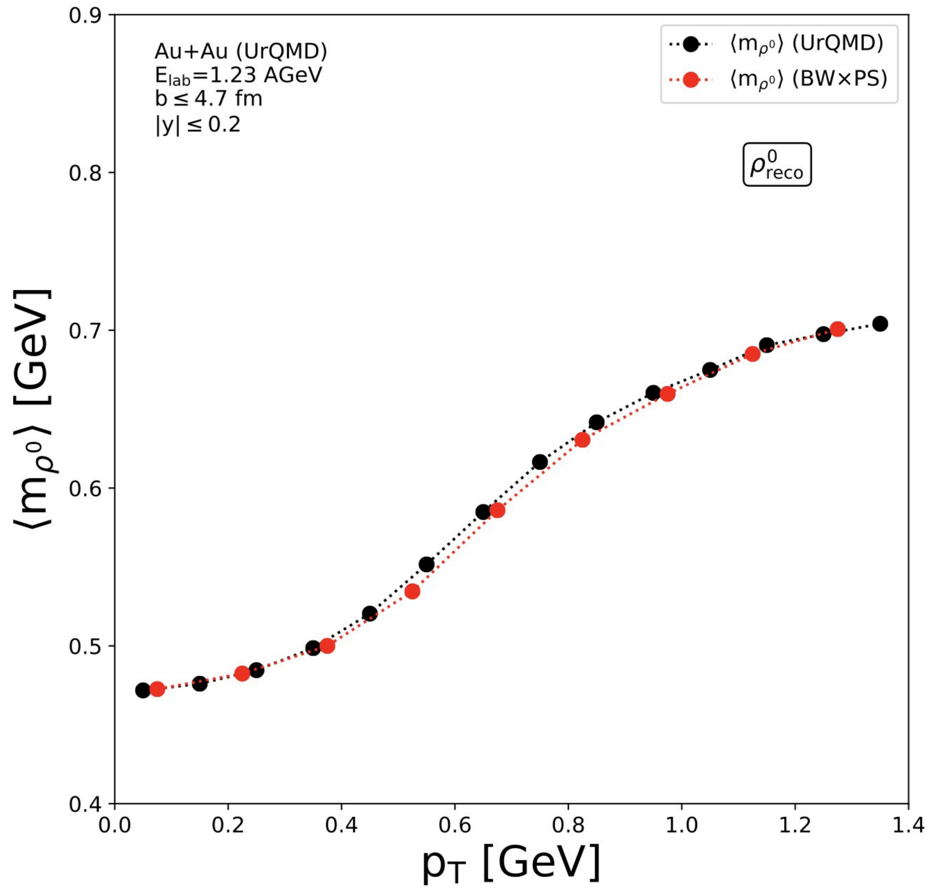
Modification of resonances

- Paper: Tom Reichert, Marcus Bleicher, [Nucl.Phys.A 1028 (2022) 122544]
- Study of kinetic mass shifts of ρ(770) and K*(892) in Au+Au reactions at E_{beam} = 1.23 AGeV with UrQMD
- Fitting of Data with PS x BW
- However: Temperature not fixed to chemical freezout but free parameter



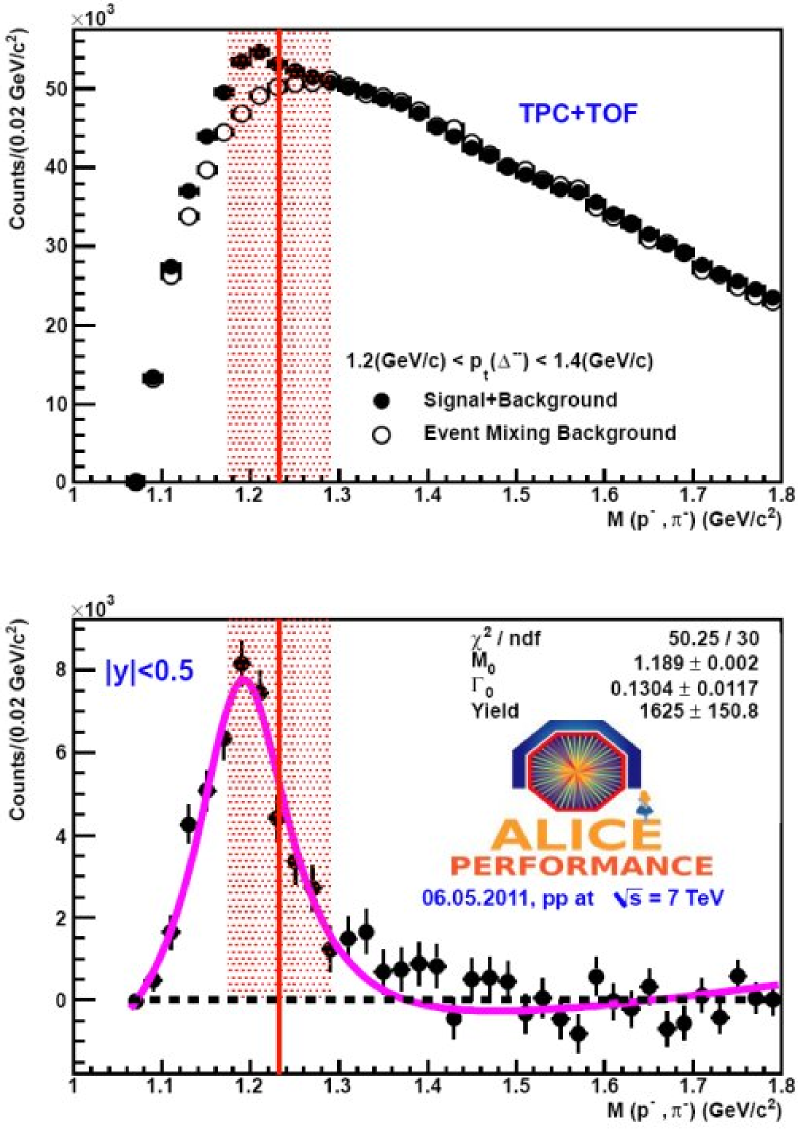
Modification of resonances

- Paper: Tom Reichert, Marcus Bleicher, Nucl.Phys.A 1028 (2022) 122544
- Study of kinetic mass shifts of ρ(770) and K*(892) in Au+Au reactions at E_{beam} = 1.23 AGeV with UrQMD
- Fitting of Data with PS x BW
- However: Temperature not fixed to chemical freezout but free parameter (“Kinetic Decoupling Temperature”)
  → good agreement between UrQMD and fit



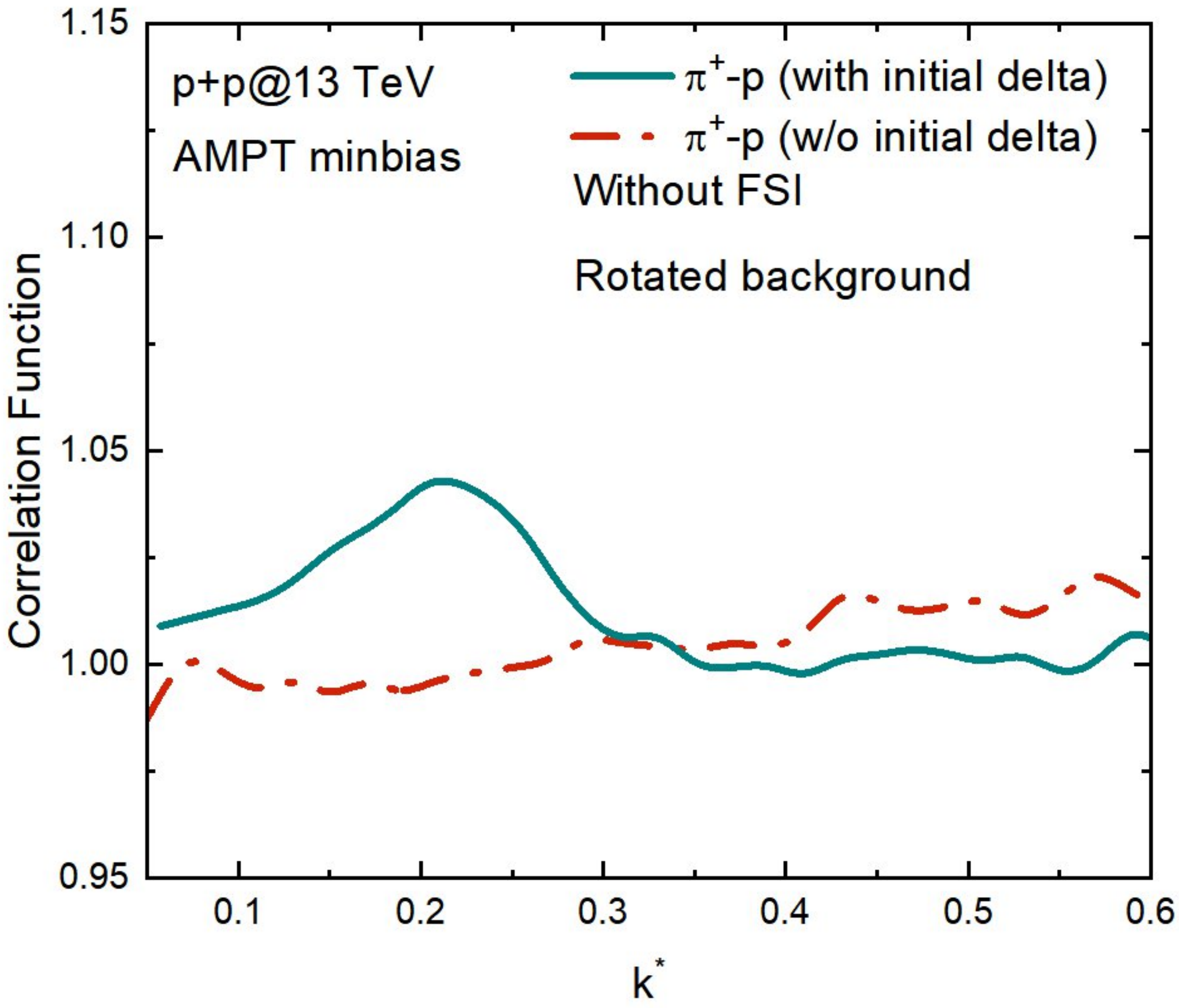
Modification of resonances

- Measurement by ALICE in Run-1 pp collisions @ 7 TeV
- Clear shift of the Delta towards lower masses

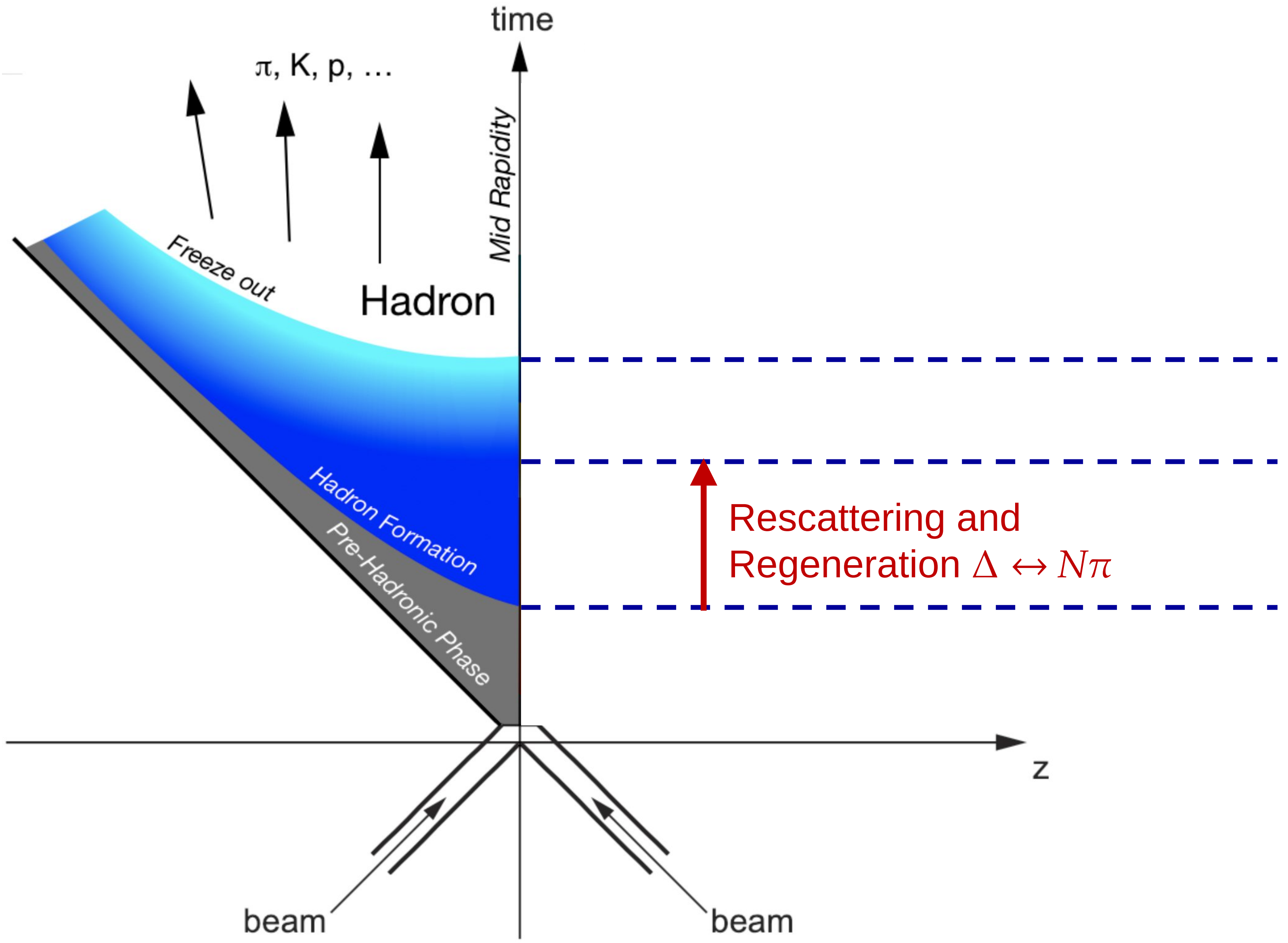


Modification of resonances

- AMPT simulation with and without Deltas in initial state
- Rescattering simulation done by Kai-Jia Sun
- No peak without initial Delta
- Peak in CF and Invariant Mass comes only from initially produced Deltas



About the life of the Δ^{++}



Kinetic freezout
$\rightarrow$ characterized by T

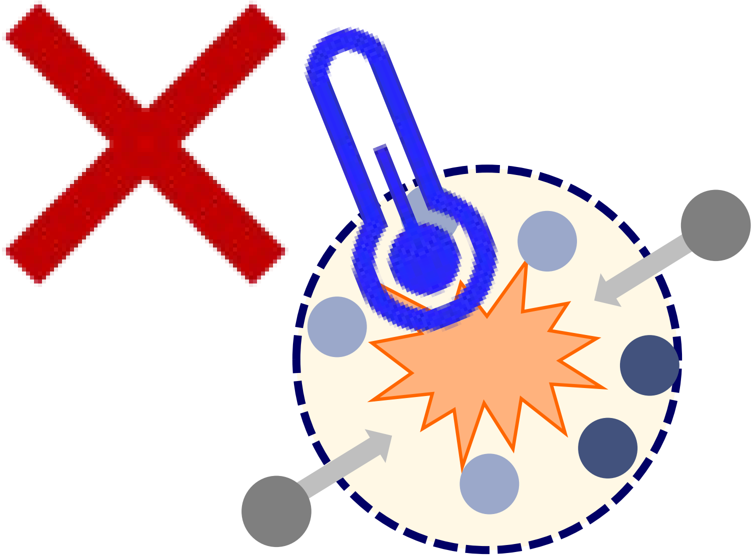
Decay of the $\Delta^{++} \rightarrow \mathrm{p}\pi^{+}$
$\rightarrow$ characterized by T_{dec}

Formation of the Δ^{++}
(and all other hadrons)
$\rightarrow$ characterized by T_{ch}

Kinetic decoupling temperature Δ^{++}

- Low "decoupling temperature" of about 25 MeV
- This does not mean that pp collisions are cold!
- We see a modification of the phase space of resonance due to regeneration phase $\Delta \leftrightarrow N\pi$

$\rightarrow$ hadronic moshpit for the Δ^{++}

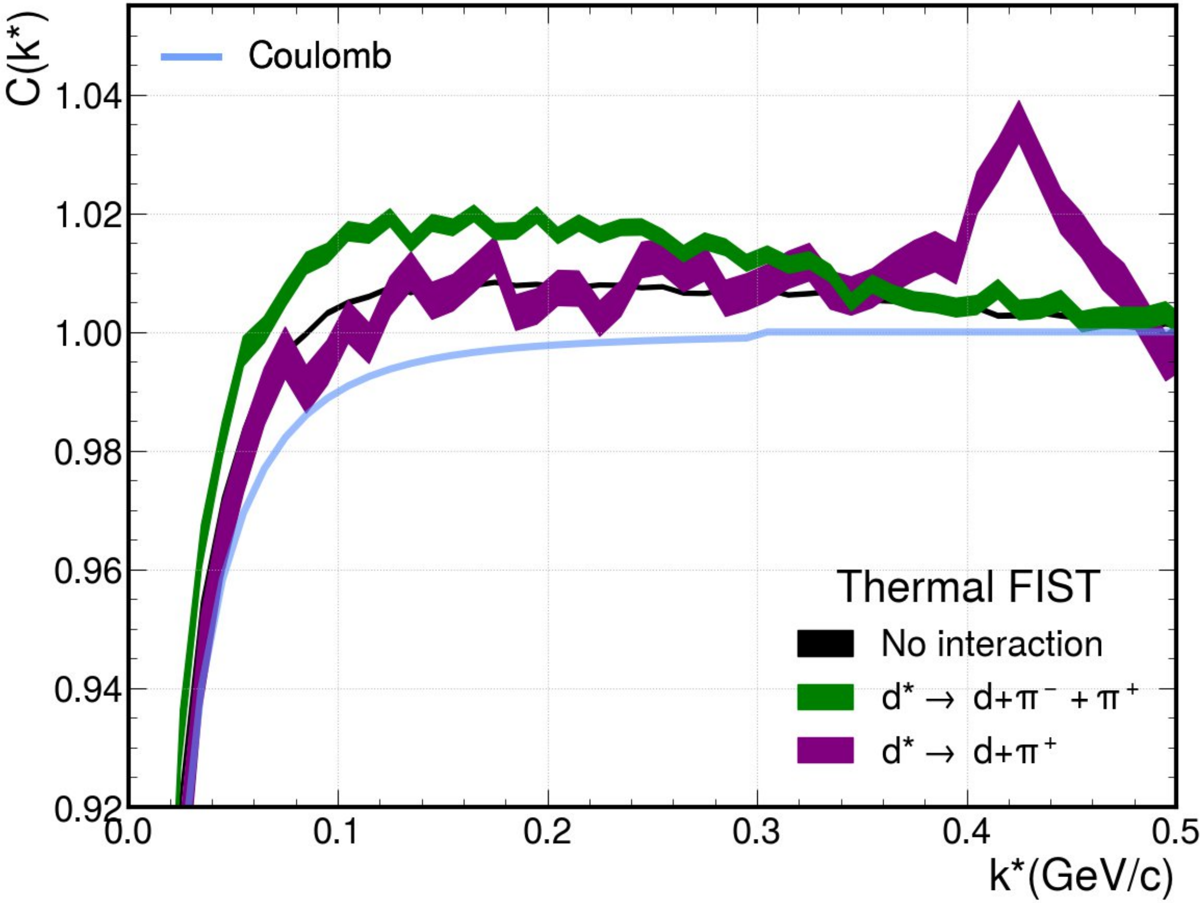


Hadronic Moshpit

d*(2380) Decay

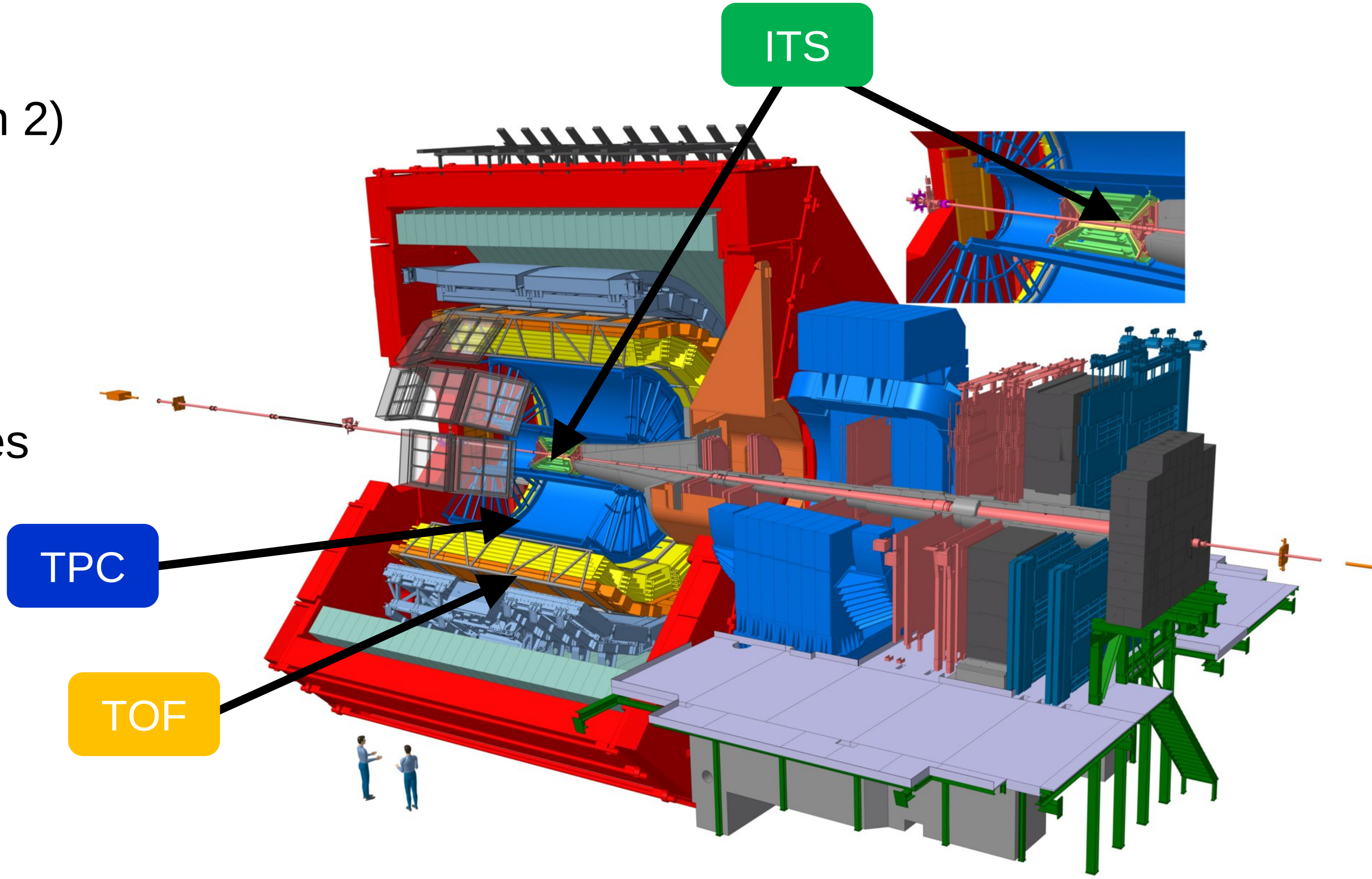
- Evidence of d*(2380) has been reported by WASA-at-COSY $pn \rightarrow d\pi^0\pi^0$
- m=2380 MeV, Γ=70 MeV, J=S=3
- Implement this resonance into ThermalFIST
- Decay channels: **$d^* \rightarrow d+\pi^+ + \pi^-$**, **$d^* \rightarrow d+\pi^+$**
- B.R. 100% →get most extreme signal possible!
- No evidence of a peak structure in 3-body decay
- Peak ~420 MeV/*c* for 2-body decay
- Not compatible with observed signal

[1] M.Bashkanov, Acta Physica Polonica B 47(2016)



ALICE - A Large Ion Collider Experiment

- pp at $\sqrt{s} = 13$ TeV
- 10^9 high-multiplicity (HM) events (Run 2)
- Direct detection of charged particles (protons, kaons, pions, deuterons)
- Very good PID capabilities of the detector resulting in very pure samples (deuterons~ 99%, pions 100%)

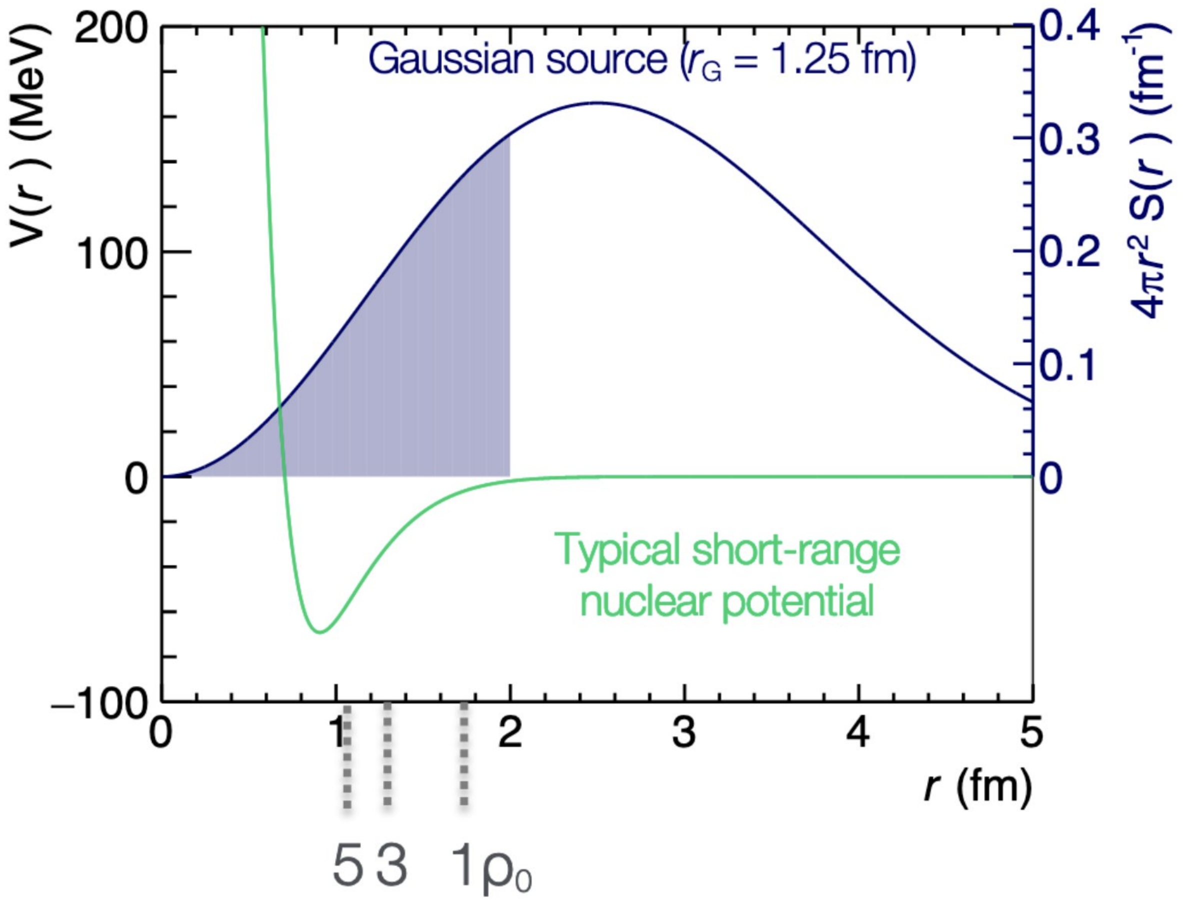


A. Tauro, "ALICE Schematics" (2017), CERN CDS

Source in pp Collisions

- Nuclear force with short range of a few fm
- Emission of particle pairs in pp collisions at close distances

→ **Ideal for studying the short-ranged strong interaction**



The source in pp collisions

- Source modelling involves
  - core source of primordial particles (Gaussian)
  - contributions from short-lived resonances

$$S(r) = \frac{1}{(4\pi r_{core}^2)^{3/2}} \exp\left(-\frac{r^2}{4r_{core}^2}\right) \otimes (\text{Resonance contributions})$$

ALICE, PLB 811 135849, 2020

- Resonance contributions
  - dependent on the particle species
  - **fixed** from statistical hadronization model and EPOS
- Particle-emitting source can be studied using particle pairs with known interaction