

π -d correlation function and the origin of nuclei

Maximilian Mahlein

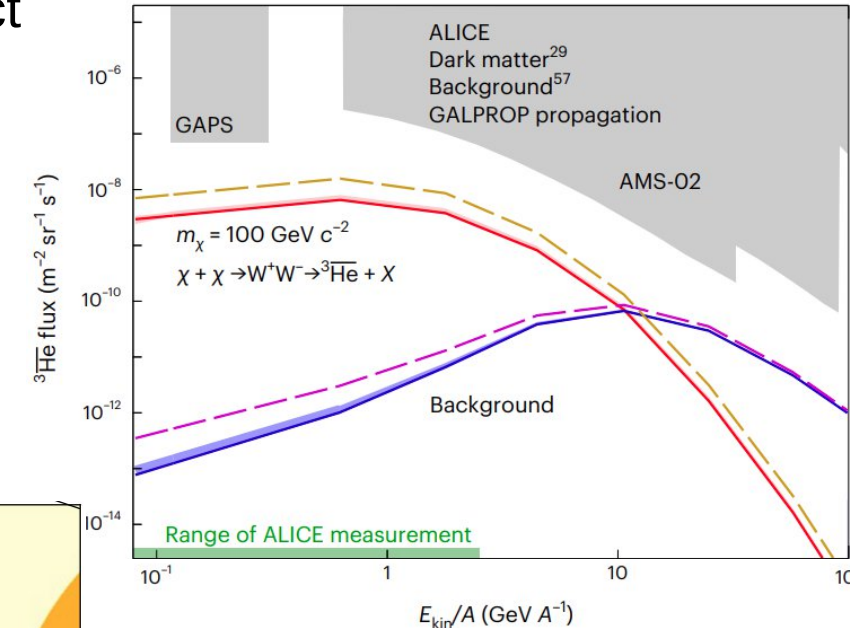
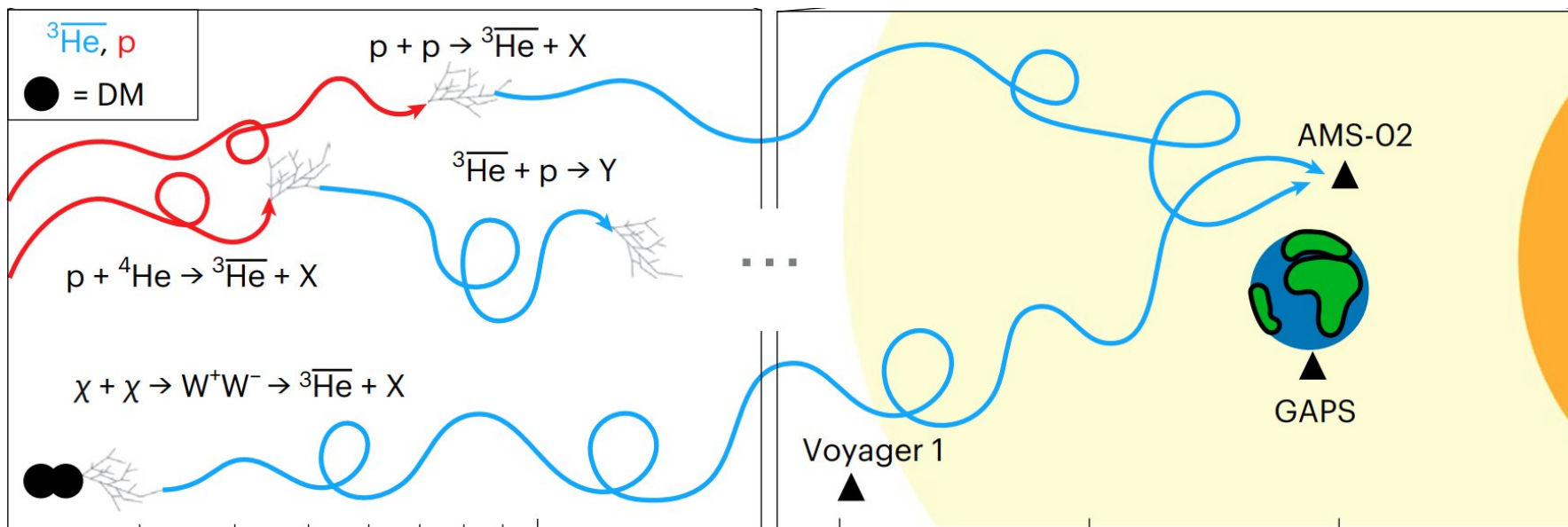
Technical University of Munich

5th EMMI Workshop on Anti-Matter, Hyper-Matter and Exotica
Based on arXiv:2504.02393 (Acc. by Nature)



Antinuclei and cosmic rays

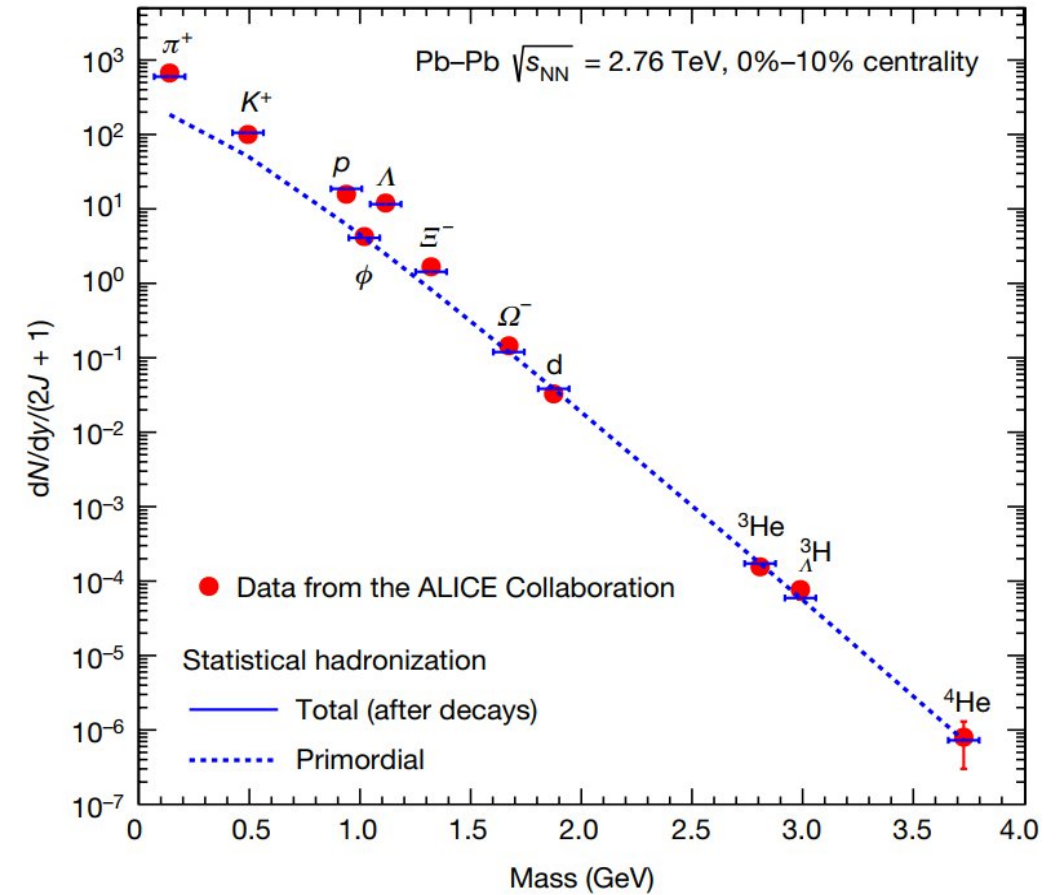
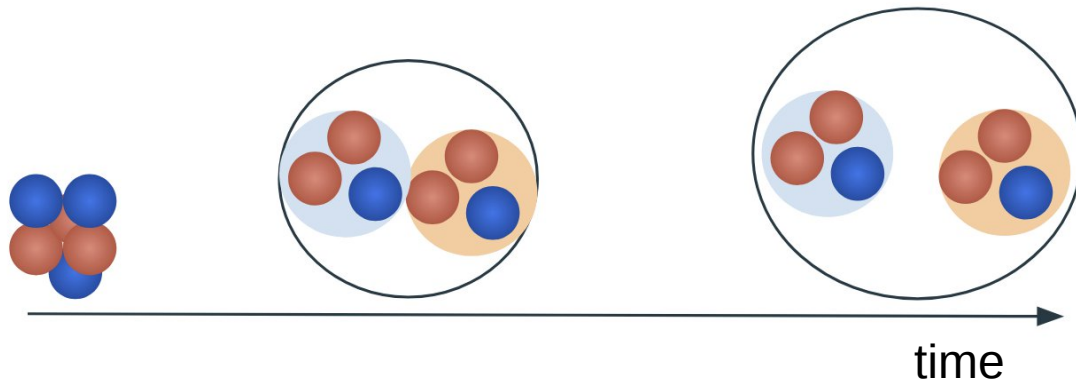
- Detection of antinuclei in cosmic rays is a golden channel for indirect dark matter detection
- However: Astrophysical standard model background
- Large Signal/Background at low E_{kin}
- Still large uncertainties on production



Nuclei production: Thermal Model

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

Deuteron production as 6 quark bag [2]

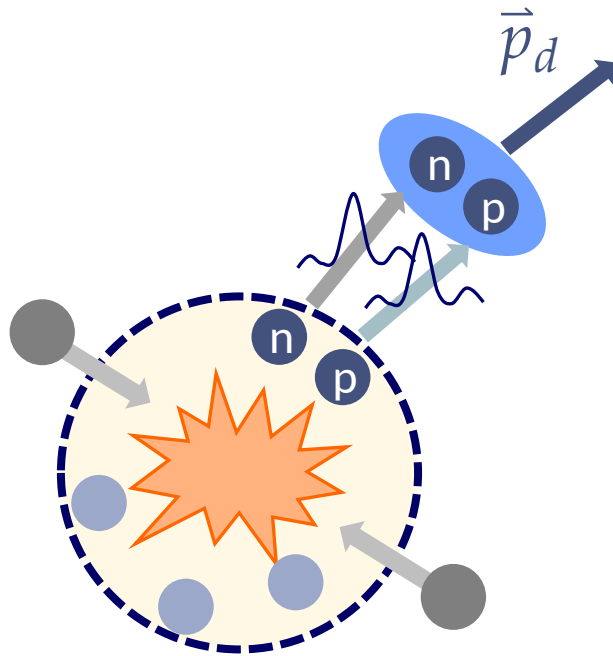


[1] A. Andronic et al., *Nature*, 561, p. 321–330 (2018)

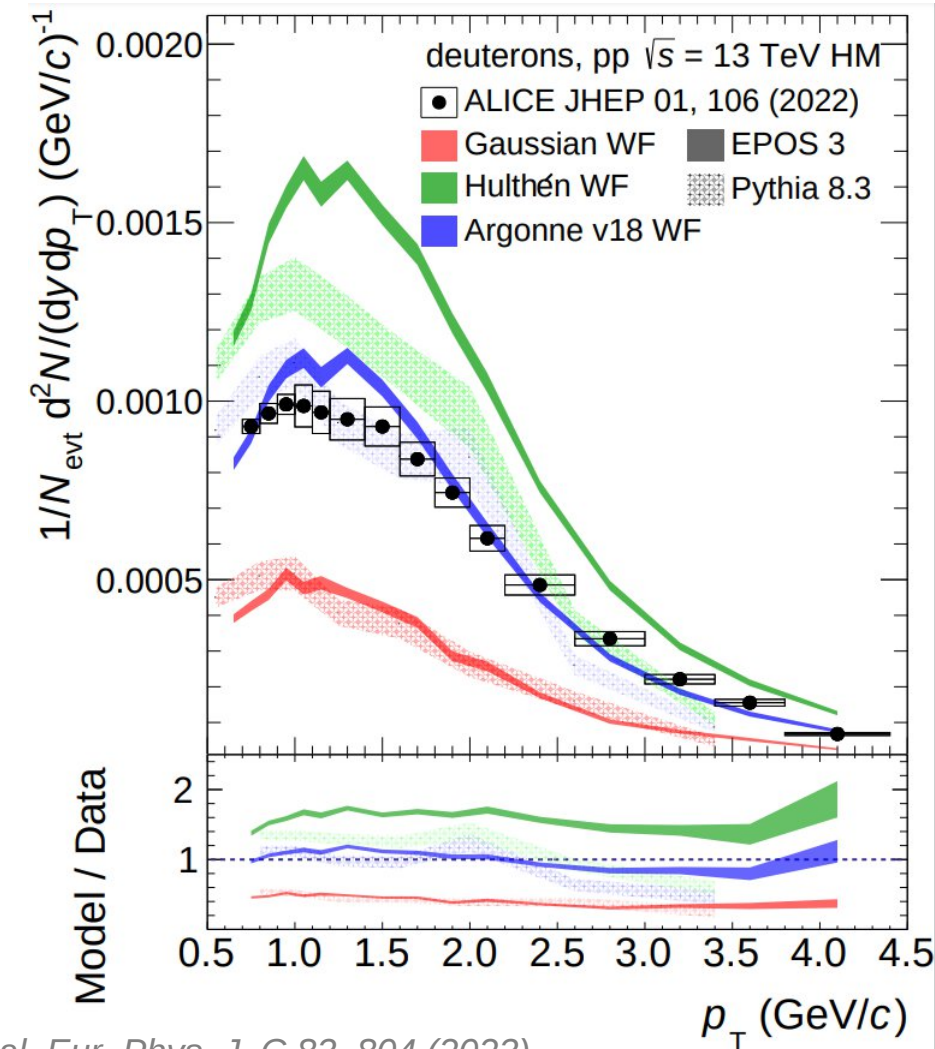
[2] A. Chodos et al.: *PRD* 9, 3471 (1974)

Nuclei production: Coalescence Models

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



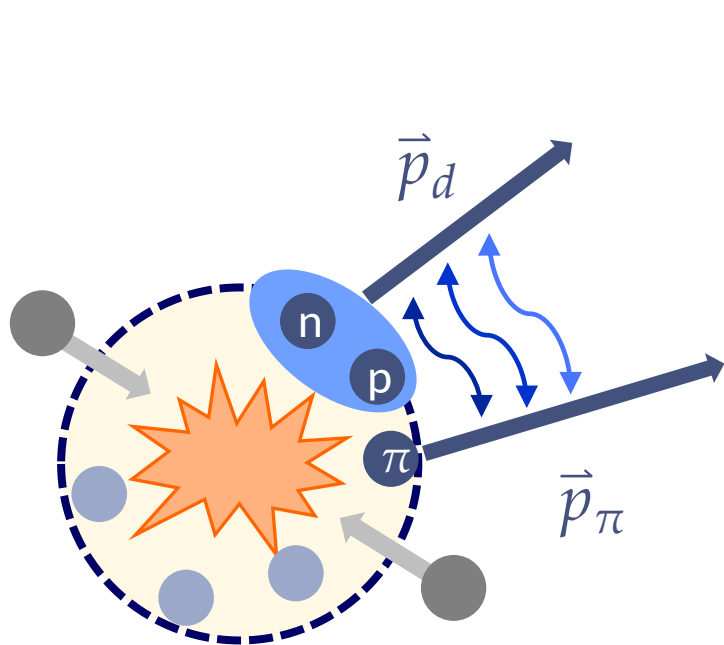
- Current state-of-the-art coalescence model [3] is able to reproduce light (anti)(hyper)nuclei spectra and yields



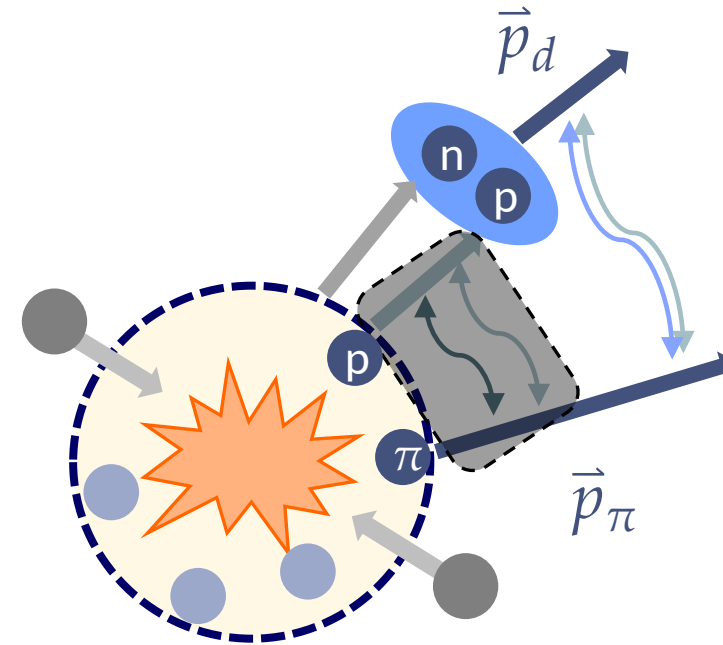
[3] MM et al. Eur. Phys. J. C 83, 804 (2023)

Searching for insights of deuteron formation

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



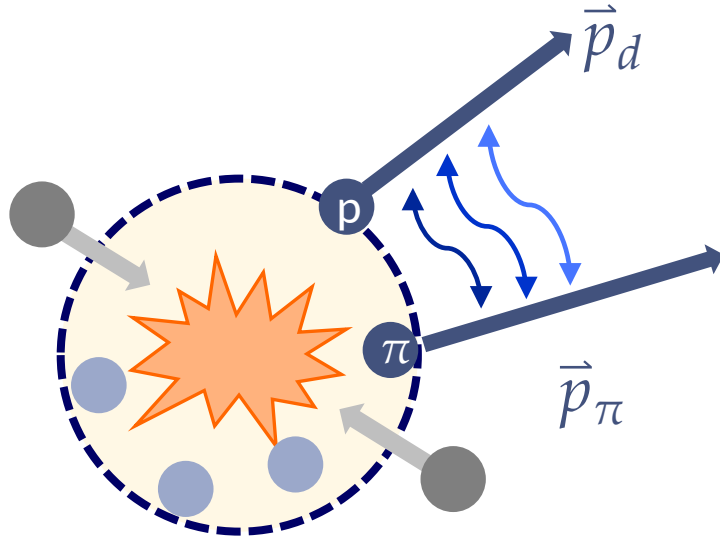
Thermal production of deuterons:
direct interaction/correlation between the π and the d



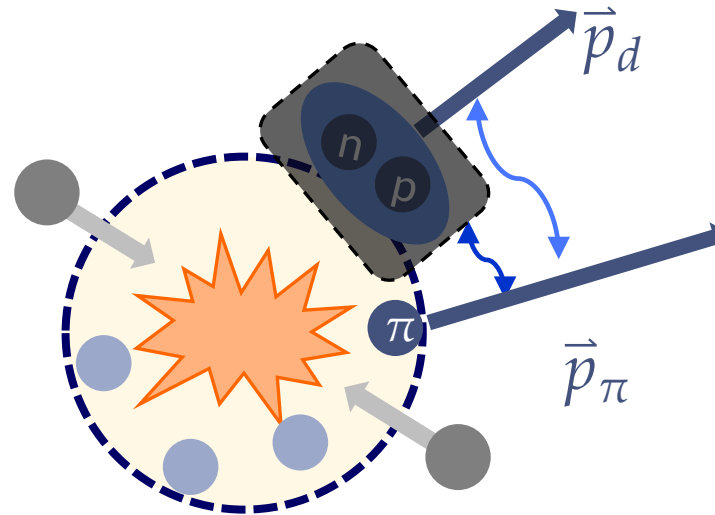
Coalescence of nuclei:
 π -d system might *inherit* any kind of residual correlation that was present between π and any of the two nucleons

Searching for insights of deuteron formation

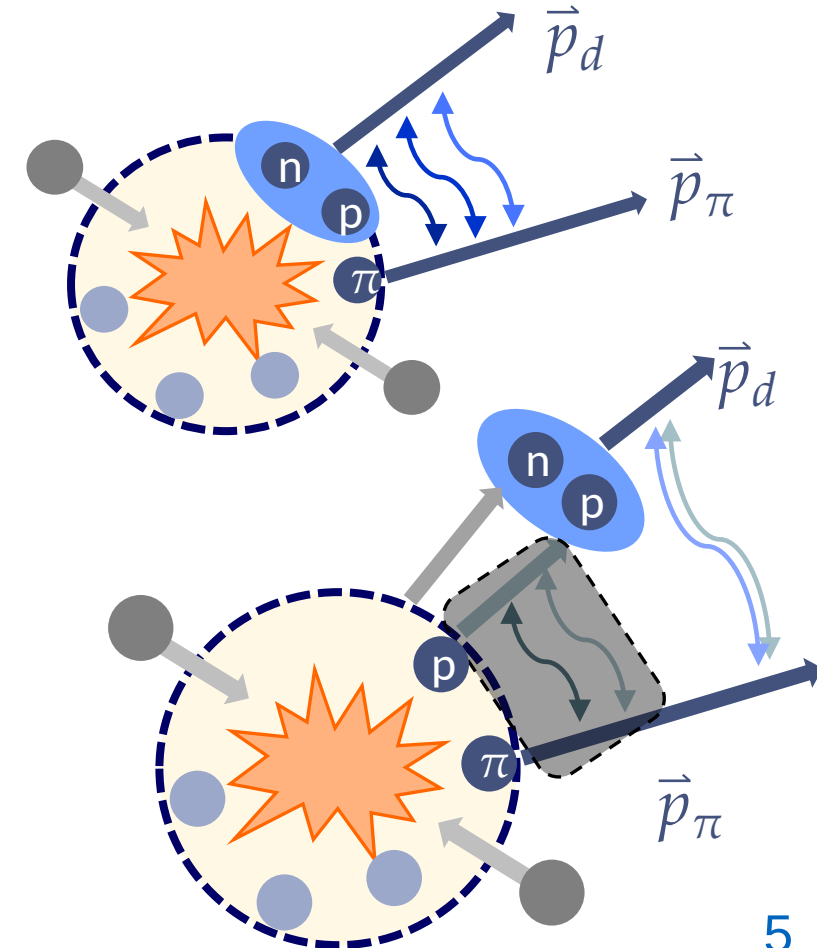
I. Study p – π correlations

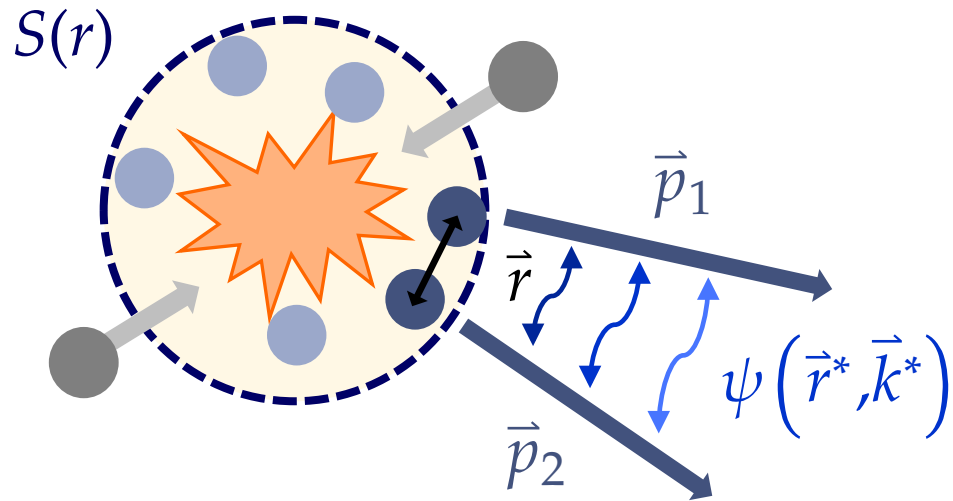


II. Study d – π correlations



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

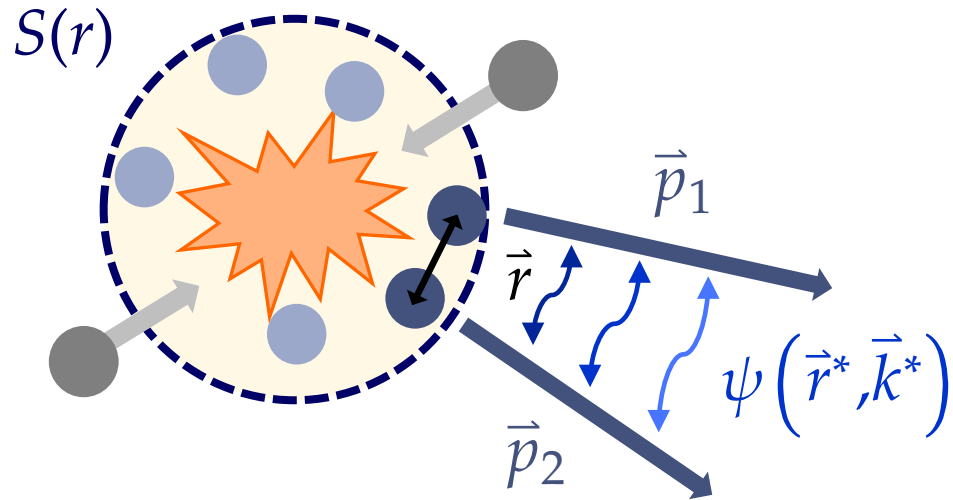




$$C(k^*) = \underbrace{\int S(r^*) \left| \psi(\vec{k}^*, \vec{r}^*) \right|^2 d^3 \vec{r}^*}_{\text{theoretical definition [4,5]}} = \underbrace{\mathcal{N} \frac{N_{\text{same}}(k^*)}{N_{\text{mixed}}(k^*)}}_{\text{experimental definition}}$$

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

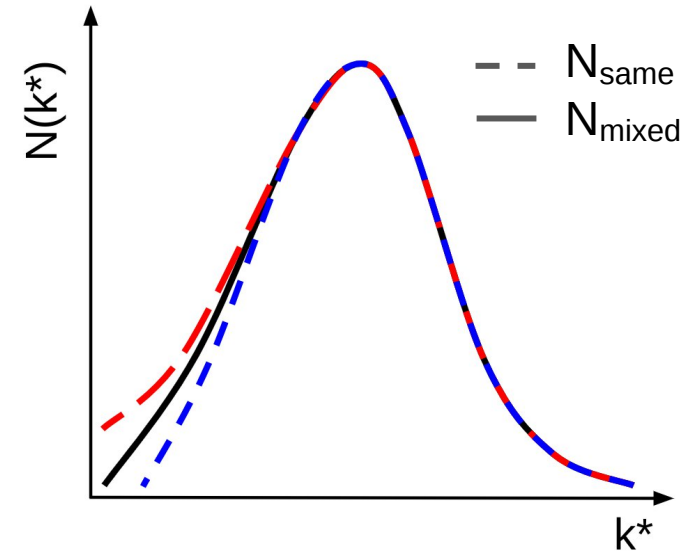
Relative distance $\vec{r}^* = \vec{r}_1^* - \vec{r}_2^*$



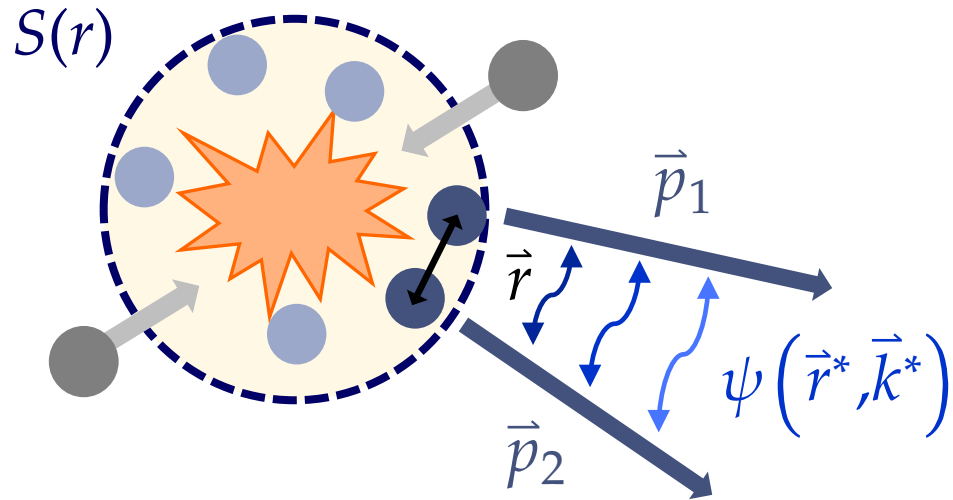
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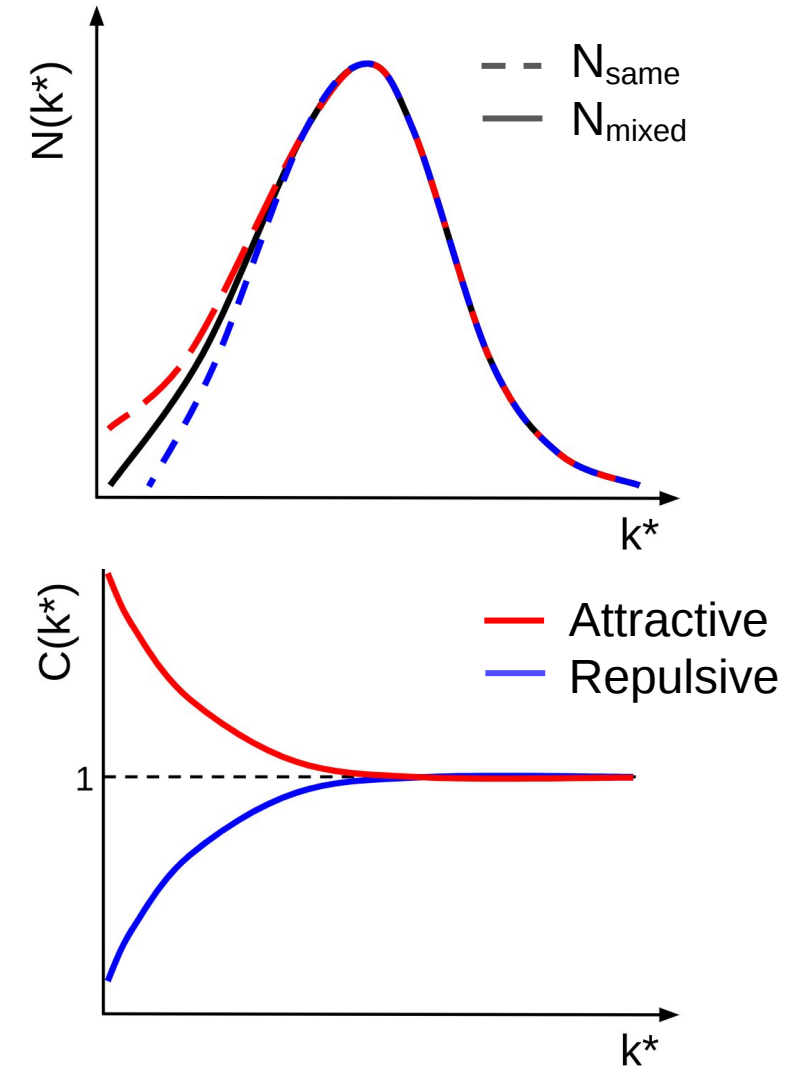
Two-body femtoscopy



$$\boxed{C(k^*)} = \underbrace{\int S(r^*) \left| \psi(\vec{k}^*, \vec{r}^*) \right|^2 d^3 \vec{r}^*}_{\text{theoretical definition [4,5]}} = \underbrace{\mathcal{N} \frac{N_{\text{same}}(k^*)}{N_{\text{mixed}}(k^*)}}_{\text{experimental definition}}$$

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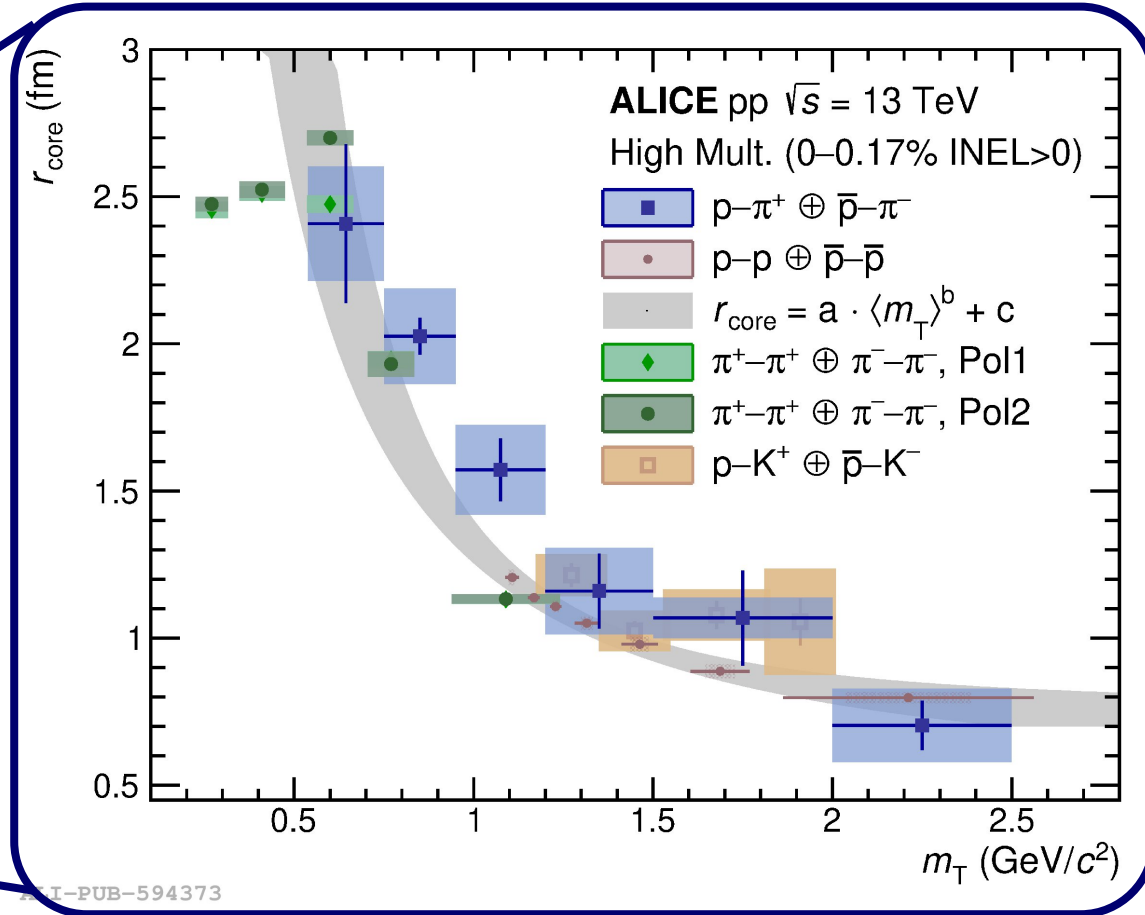
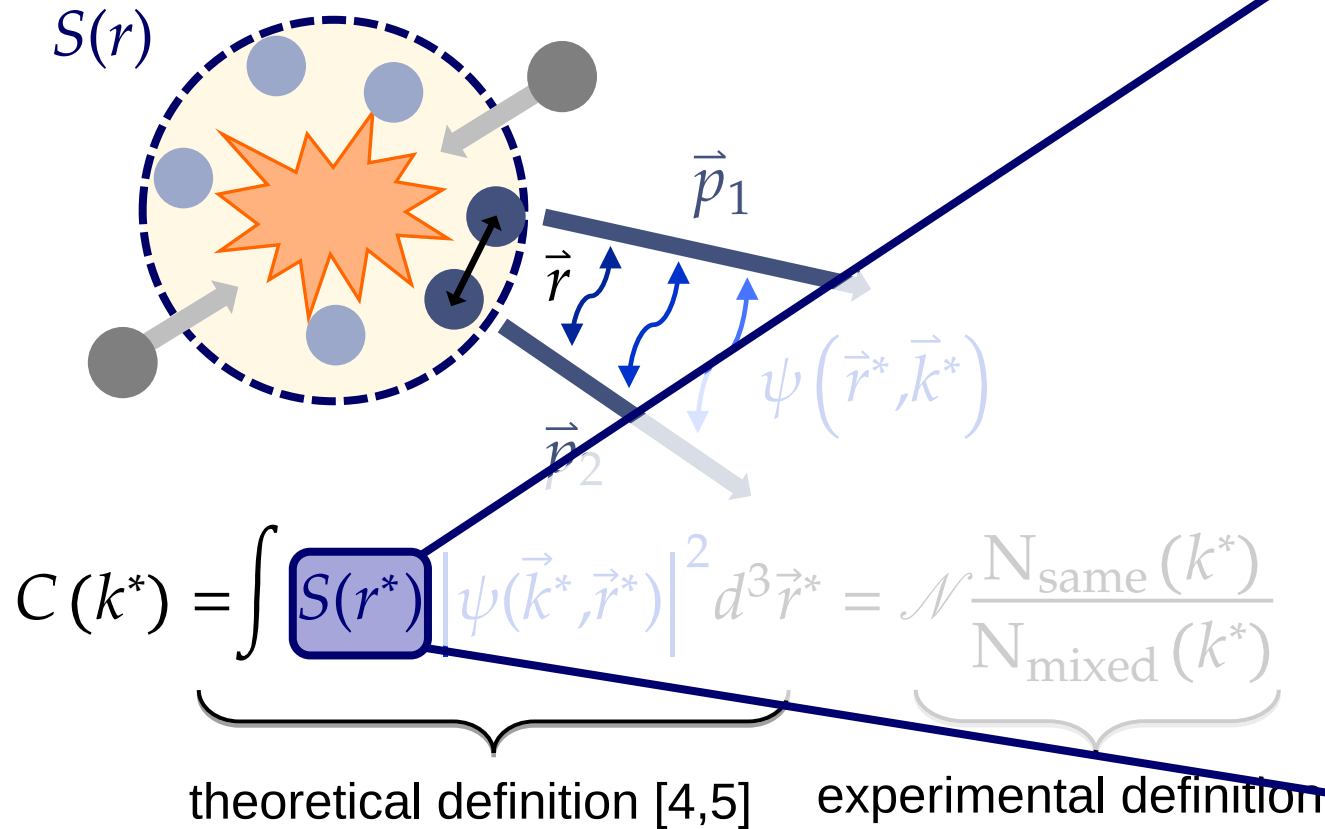


[4] S. Pratt, Phys. Rev. D 33 (1986) 1314

[5] M. Lisa et al., Ann. Rev. Nucl. Part. Sci. 55 (2005) 357

Two-body femtoscopy

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

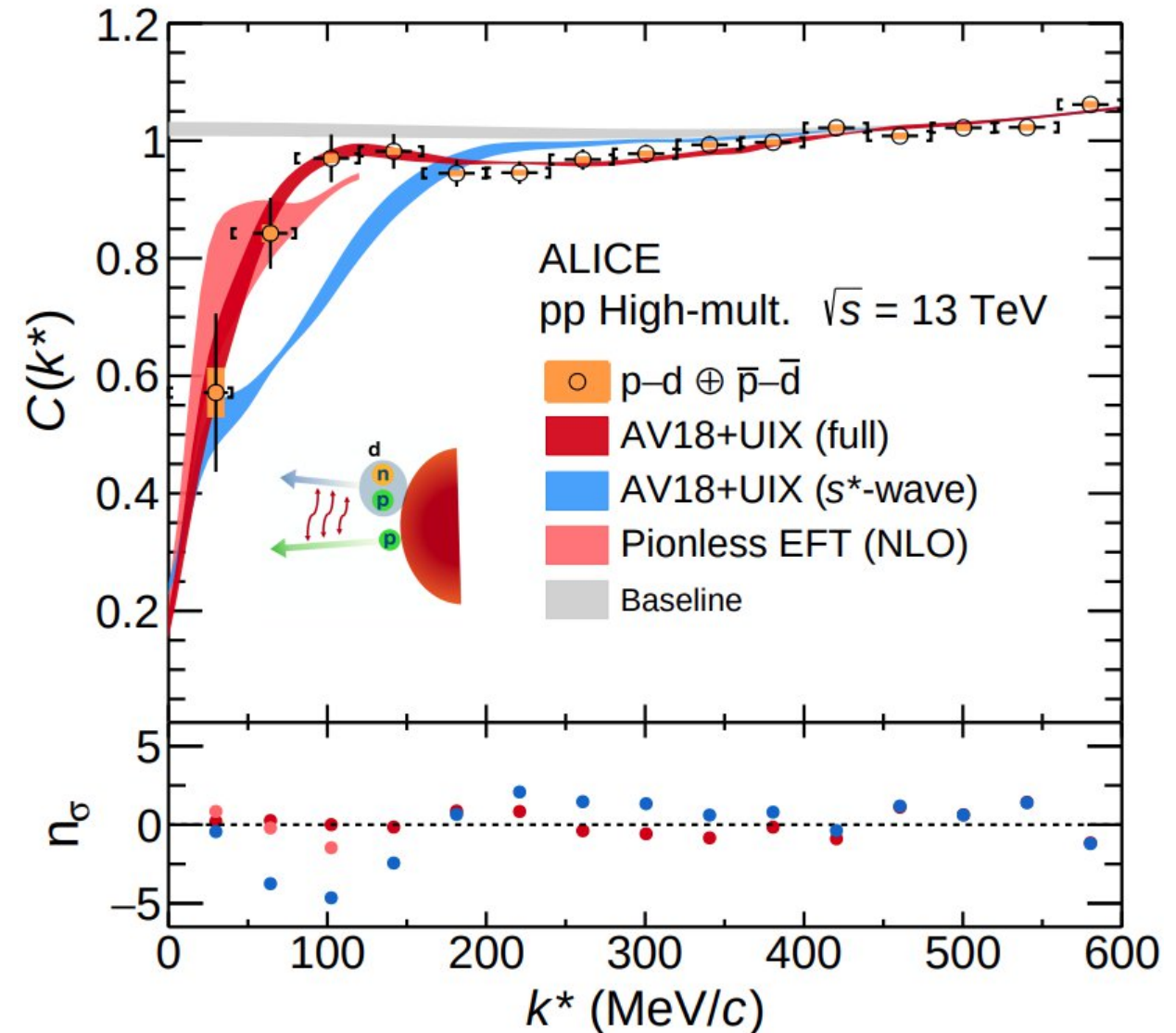
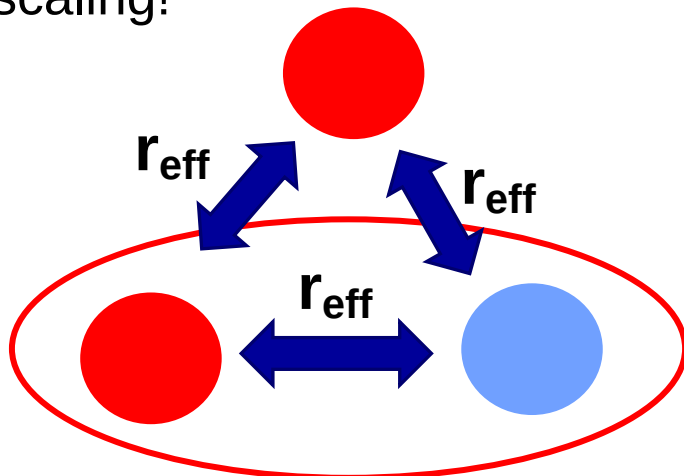


Transverse mass: $m_T = \sqrt{\left(\frac{m_1+m_2}{2}\right)^2 + \left(\frac{p_{T,1}+p_{T,2}}{2}\right)^2}$

$p-\pi$: arxiv: 2502.20200, $p-p$: PLB 811, 135849(2020),
 $\pi-\pi$ & $p-K^+$: arxiv: 2311.14527, $D-\pi$: PRD 110, 032004 (2024)
 $p-\Omega$: Nature 588, 232 (2020), $p-p$ - p & $p-p-\Lambda$: EPJA 59, 298 (2023)

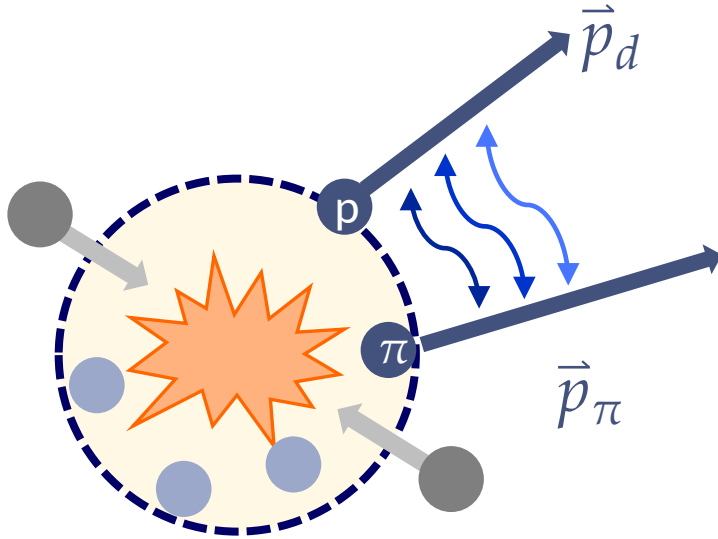
Deuteron femtoscopy in pp collisions

- 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 ($r_{\text{eff}}=1.08$ fm)
- Even deuterons follow the same source size scaling!

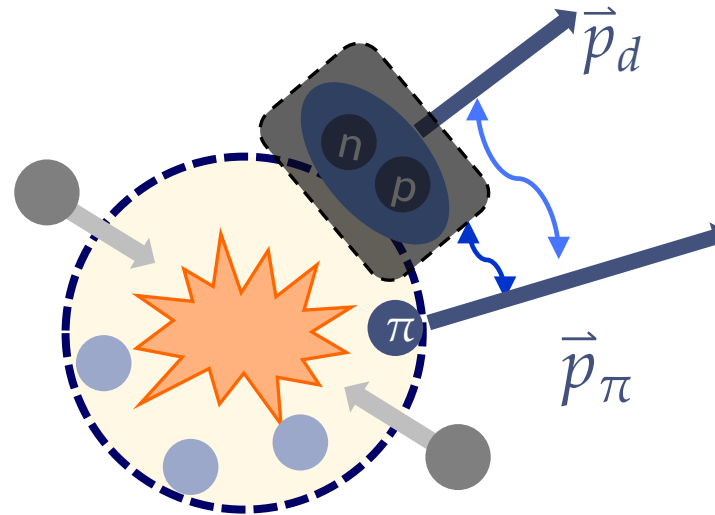


Searching for insights of deuteron formation

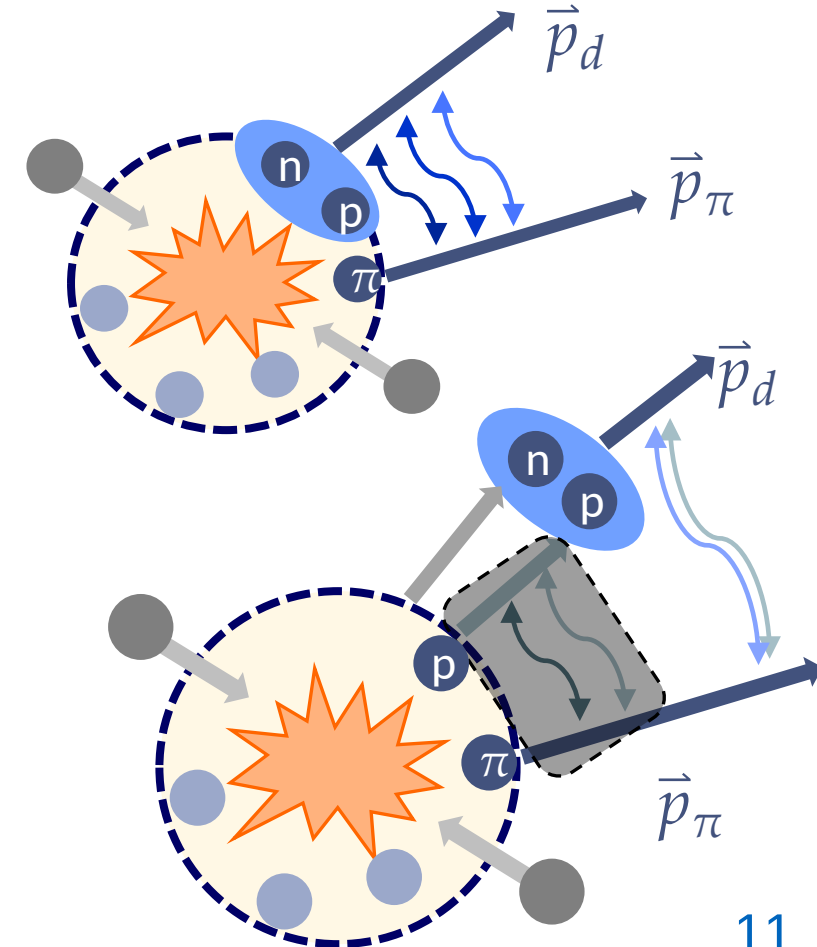
I. Study p – π correlations and see which features appear



II. Study π – d correlations



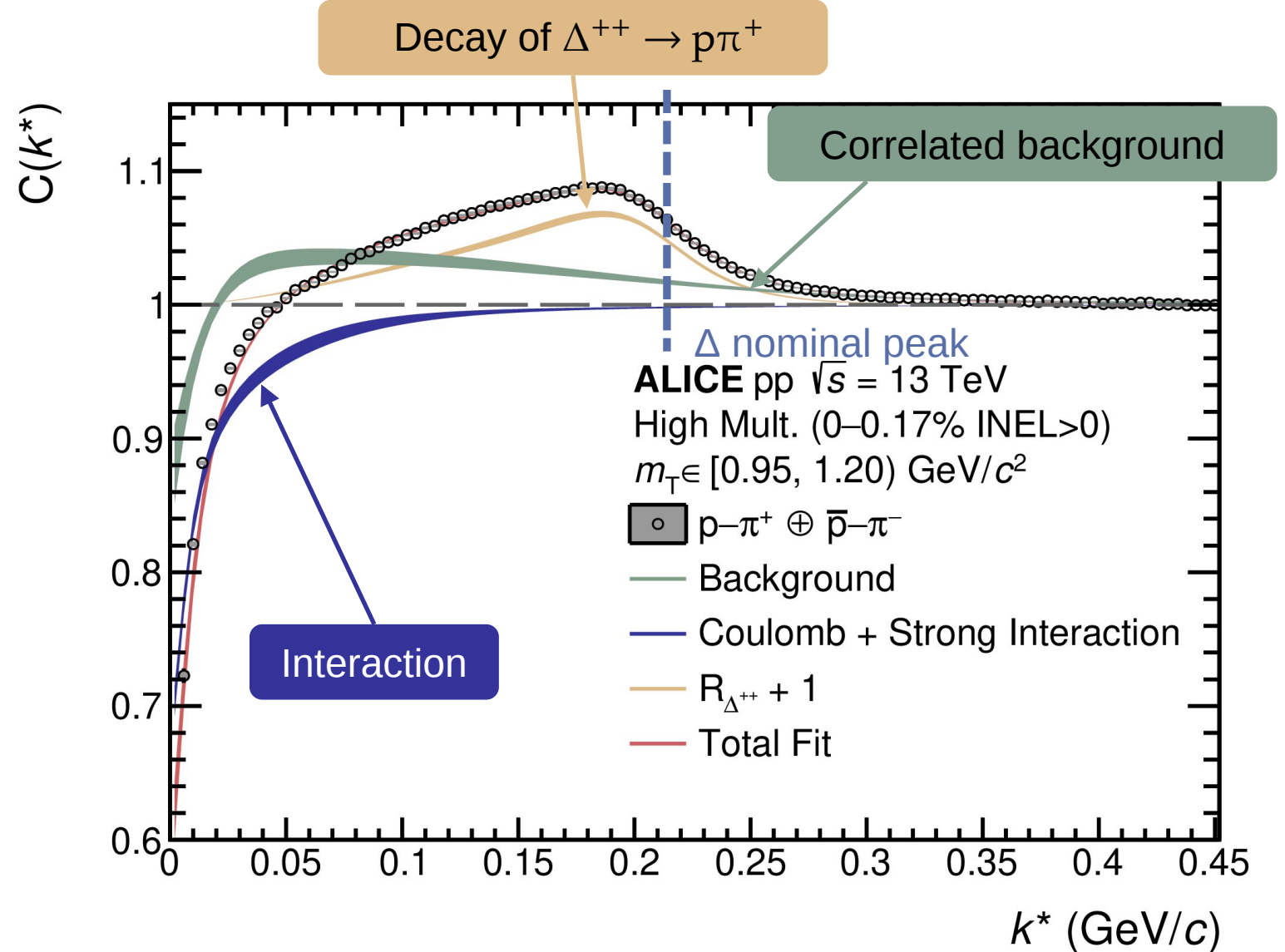
III. Check if any correlations from p – π are inherited.
Learn about nuclei production



Fitting of the $p-\pi^+$ correlation function

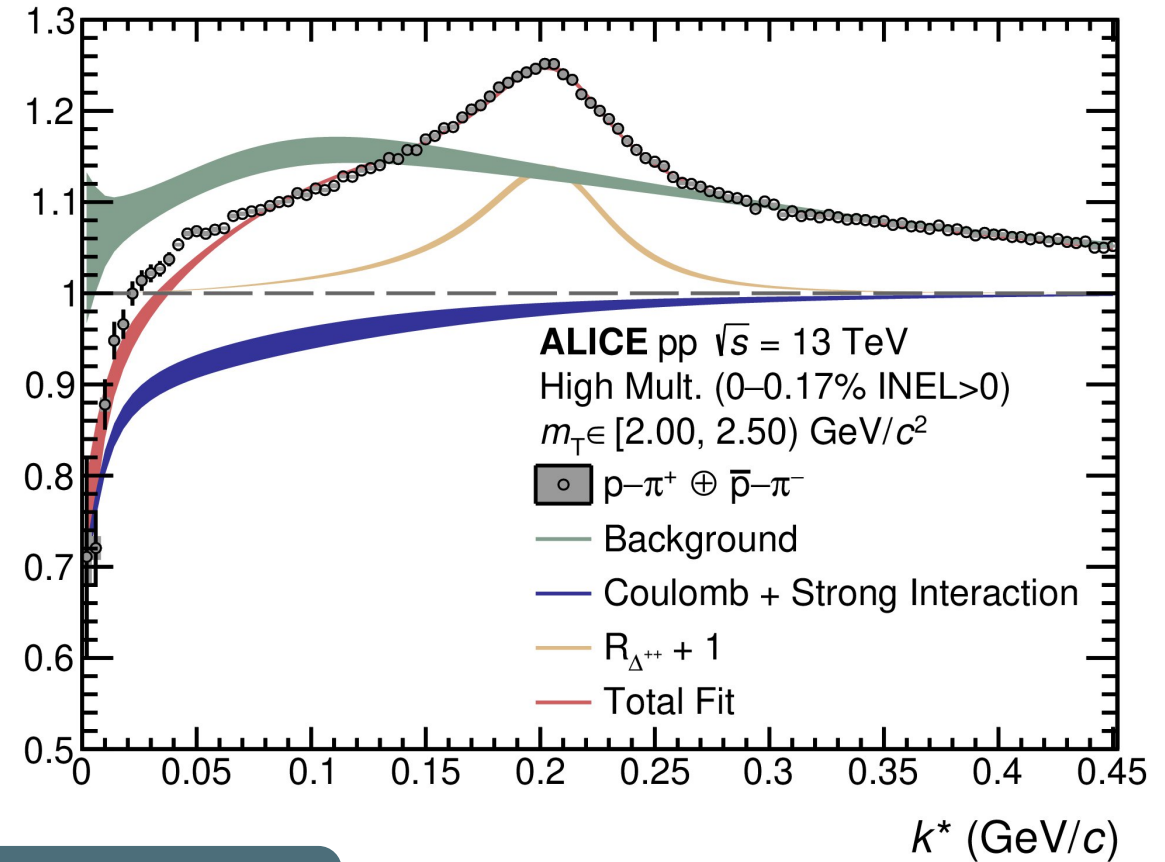
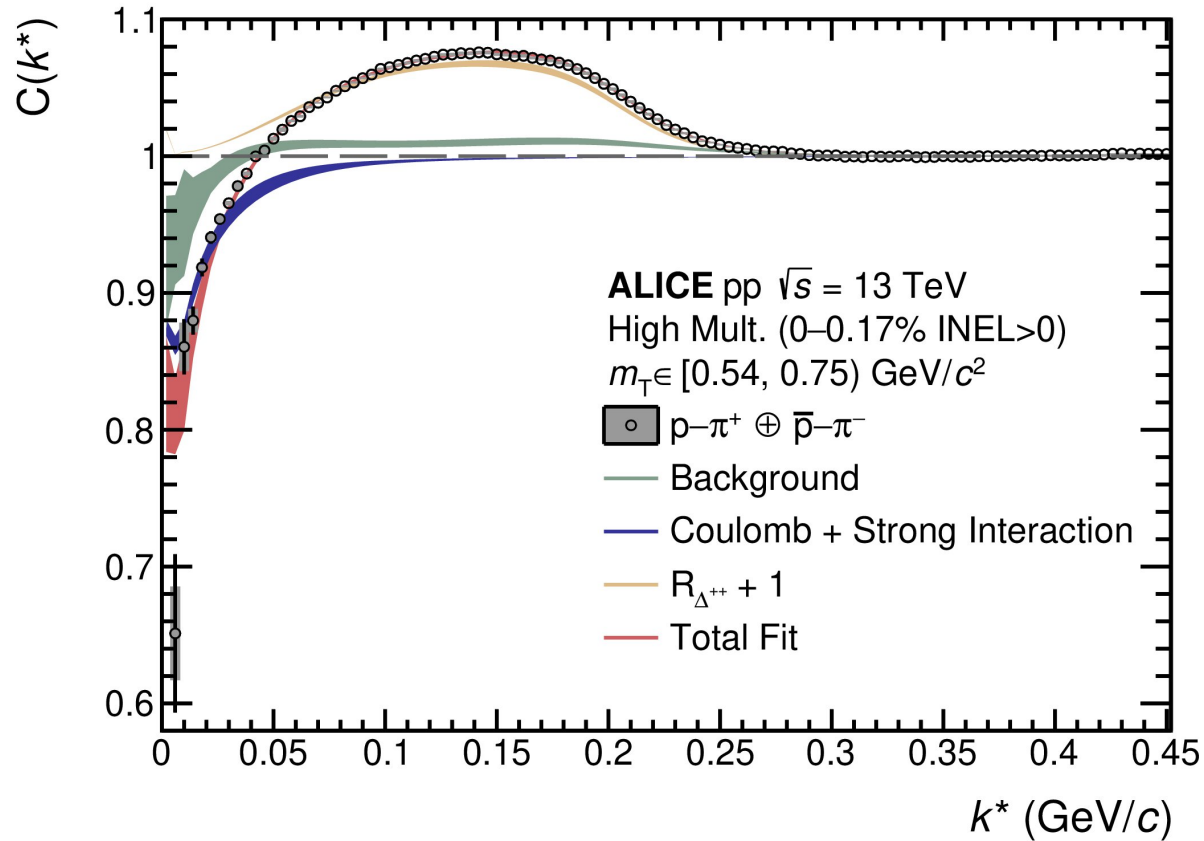
- Good understanding of $p-\pi$ correlation
- The Δ spectral shape is distorted compared to a typical Breit Wigner due to rescattering of the daughter particles
- modeled using a phase space factor (PS)

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



About the life of the Δ^{++}

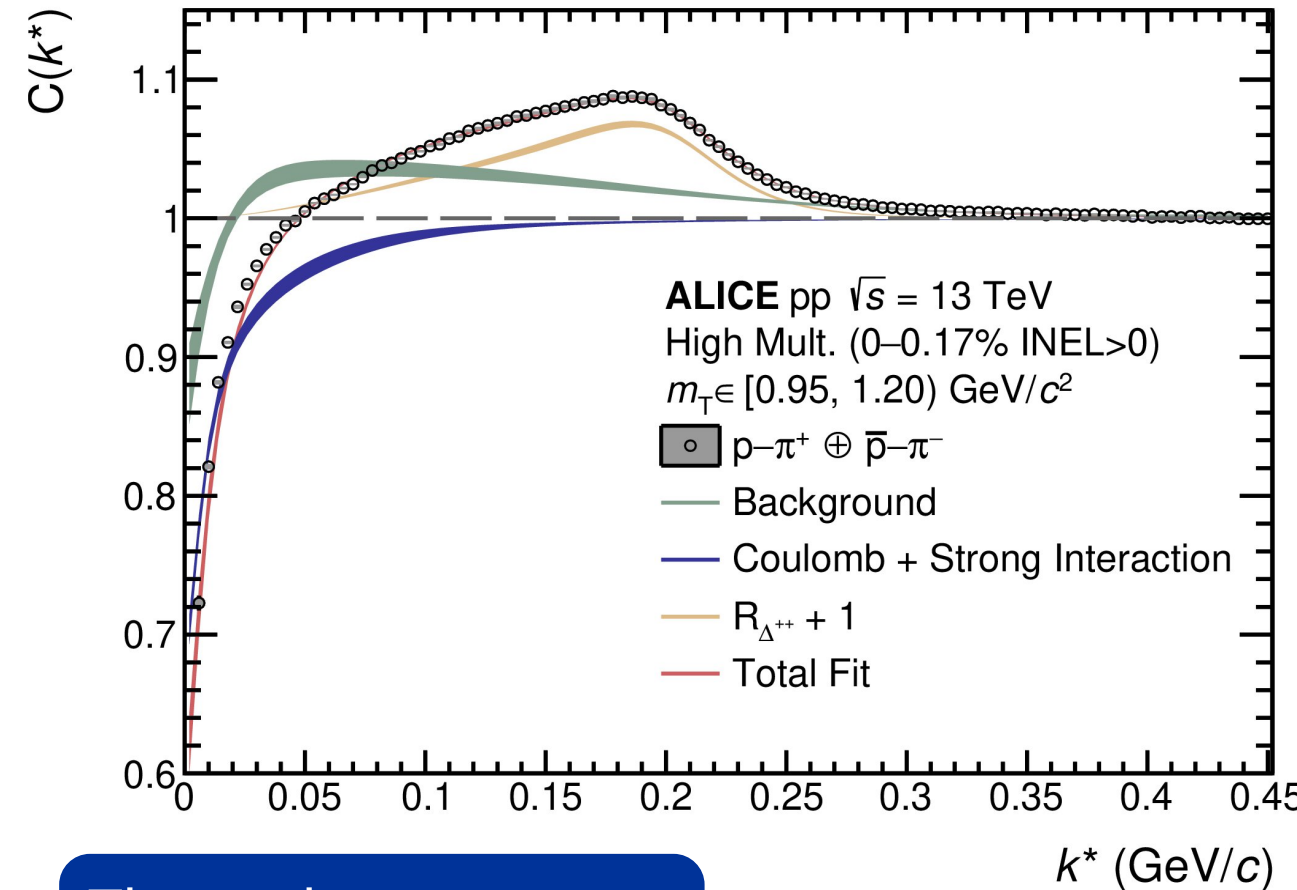
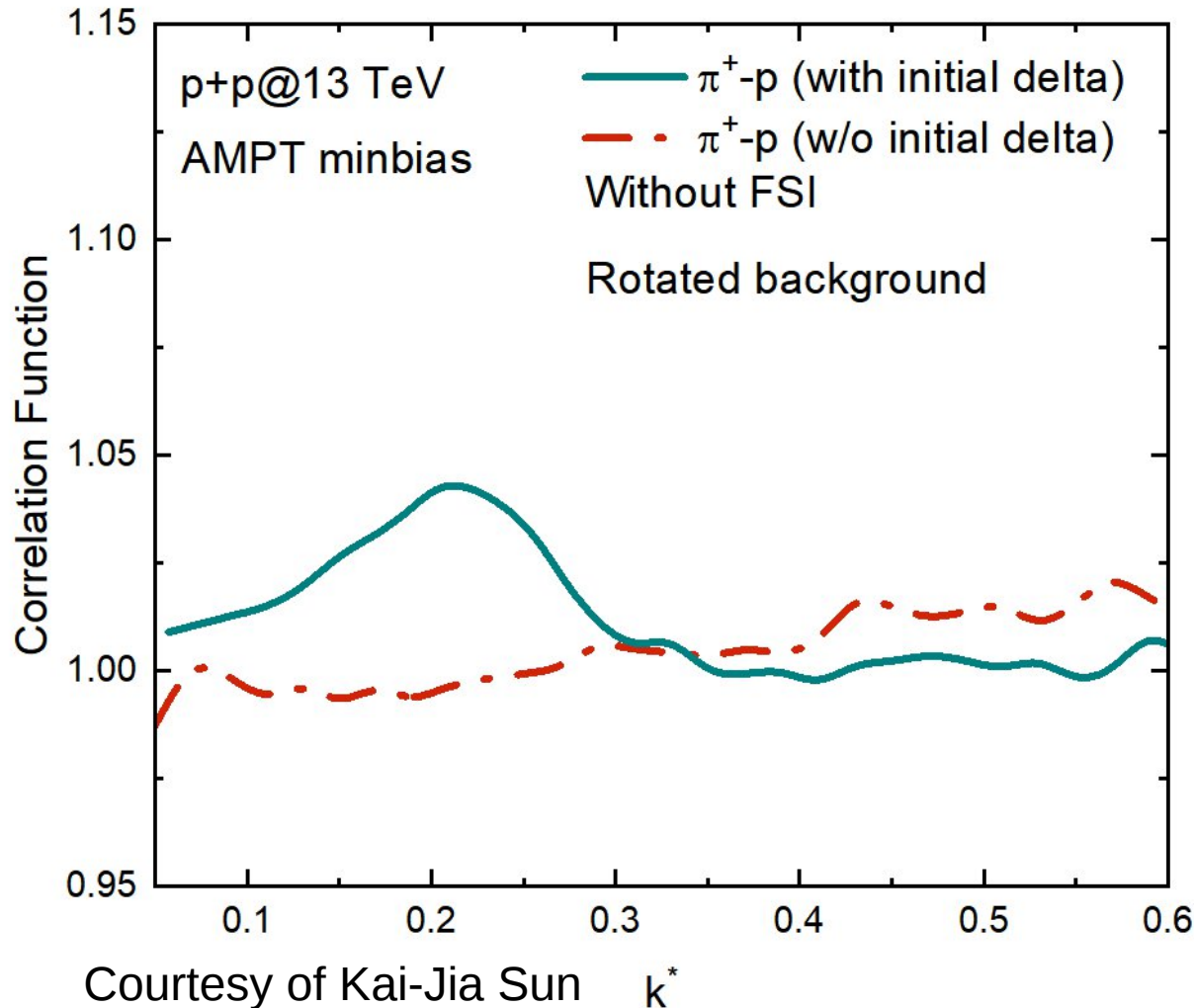
Increasing p_T of the Δ resonance



Increasing distortion of the Δ spectral shape

ALI-PUB-594333

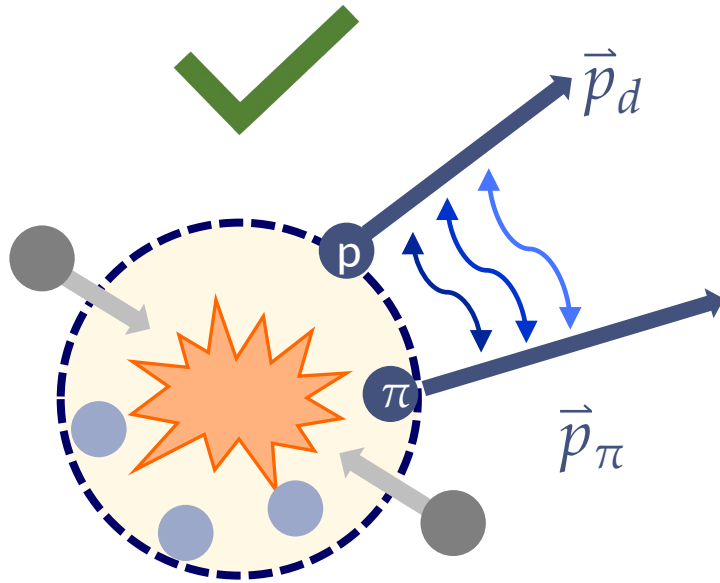
Origin of the Delta peak



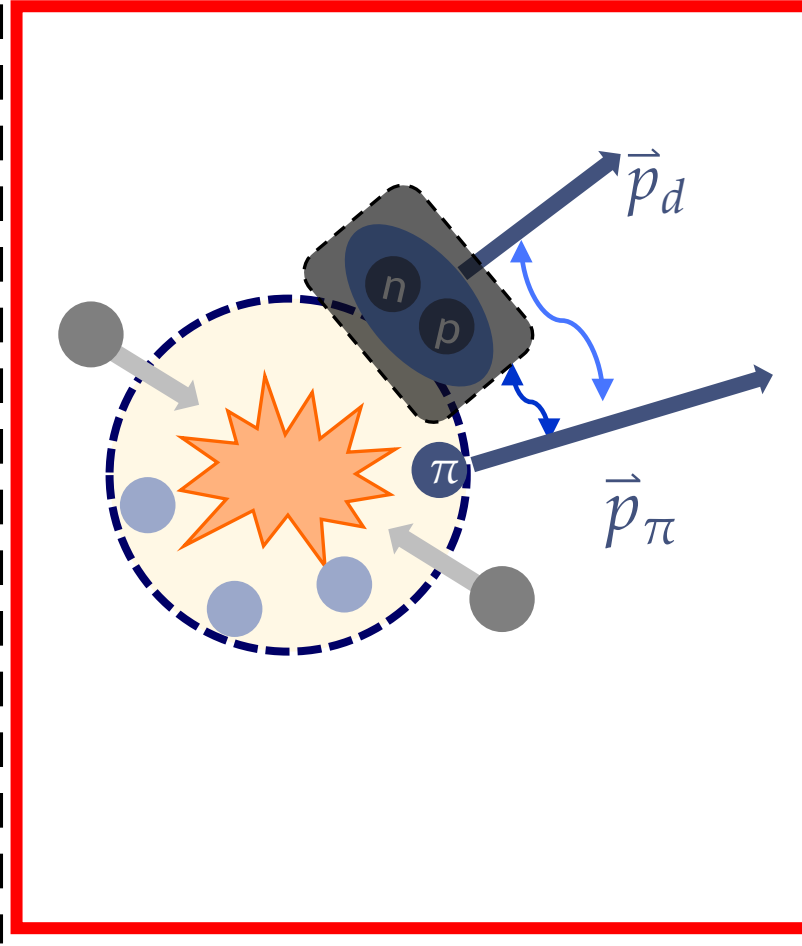
The peak must come from decays of Deltas

Searching for insights of deuteron formation

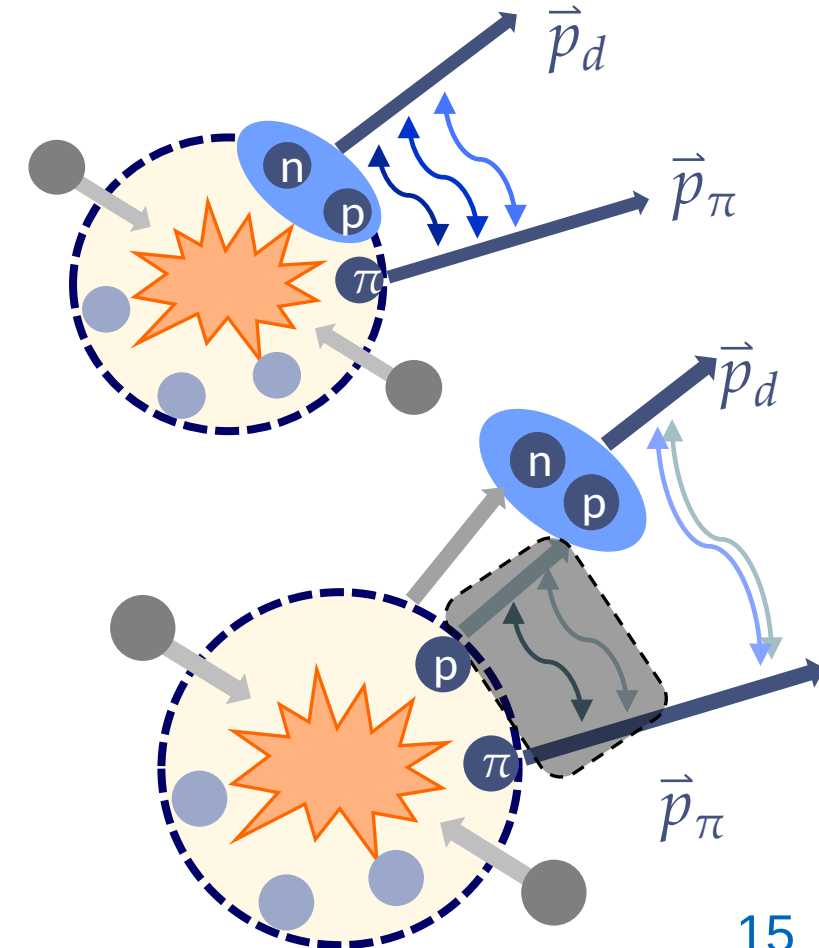
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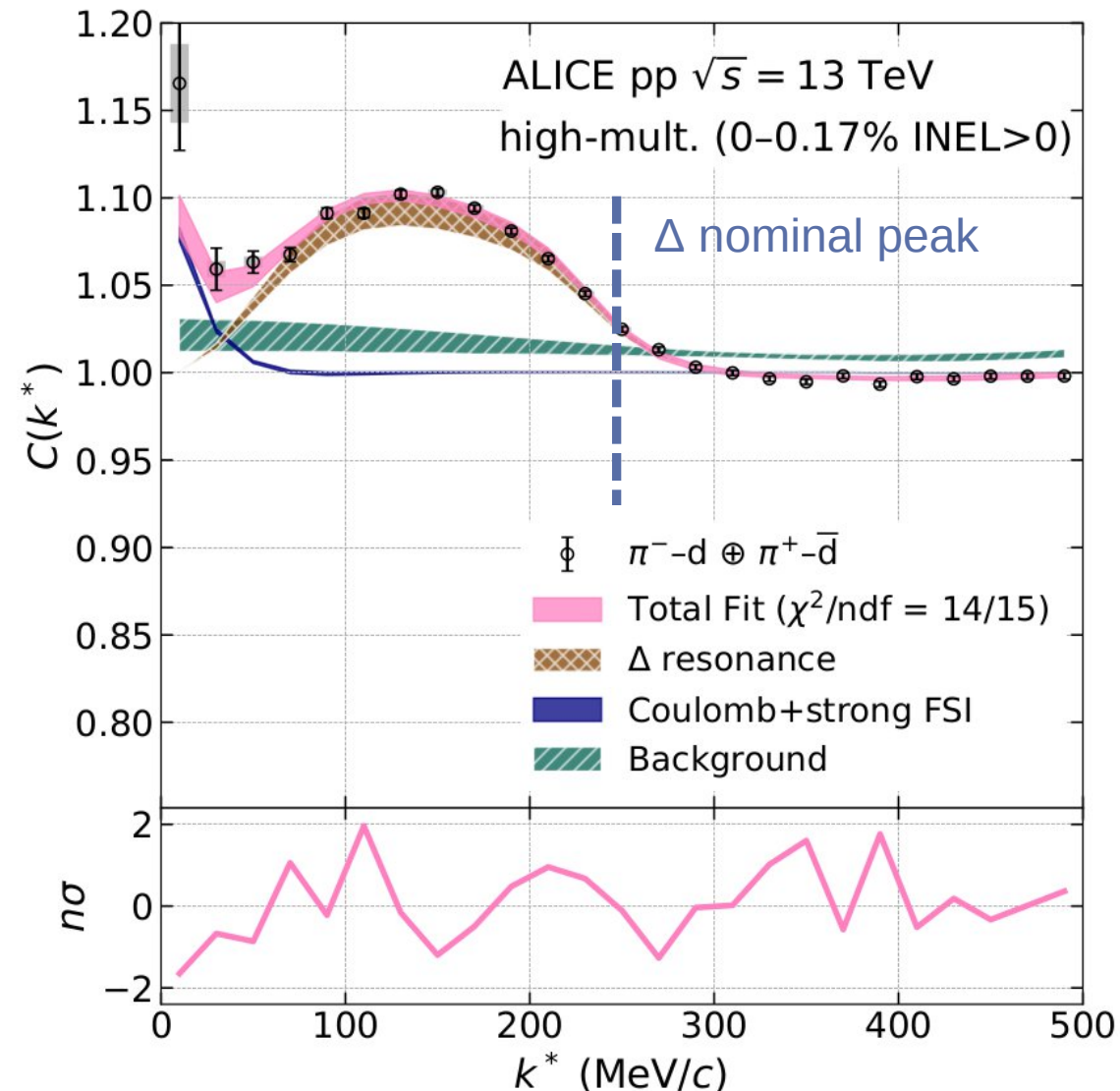


III. Check if any correlations from p – π are inherited.
Learn about nuclei production



$\pi^\pm$ -d Correlations

- 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 $\text{Re}(f_0)$ used in fit
- Coulomb+strong interaction modeled with CATS [7]

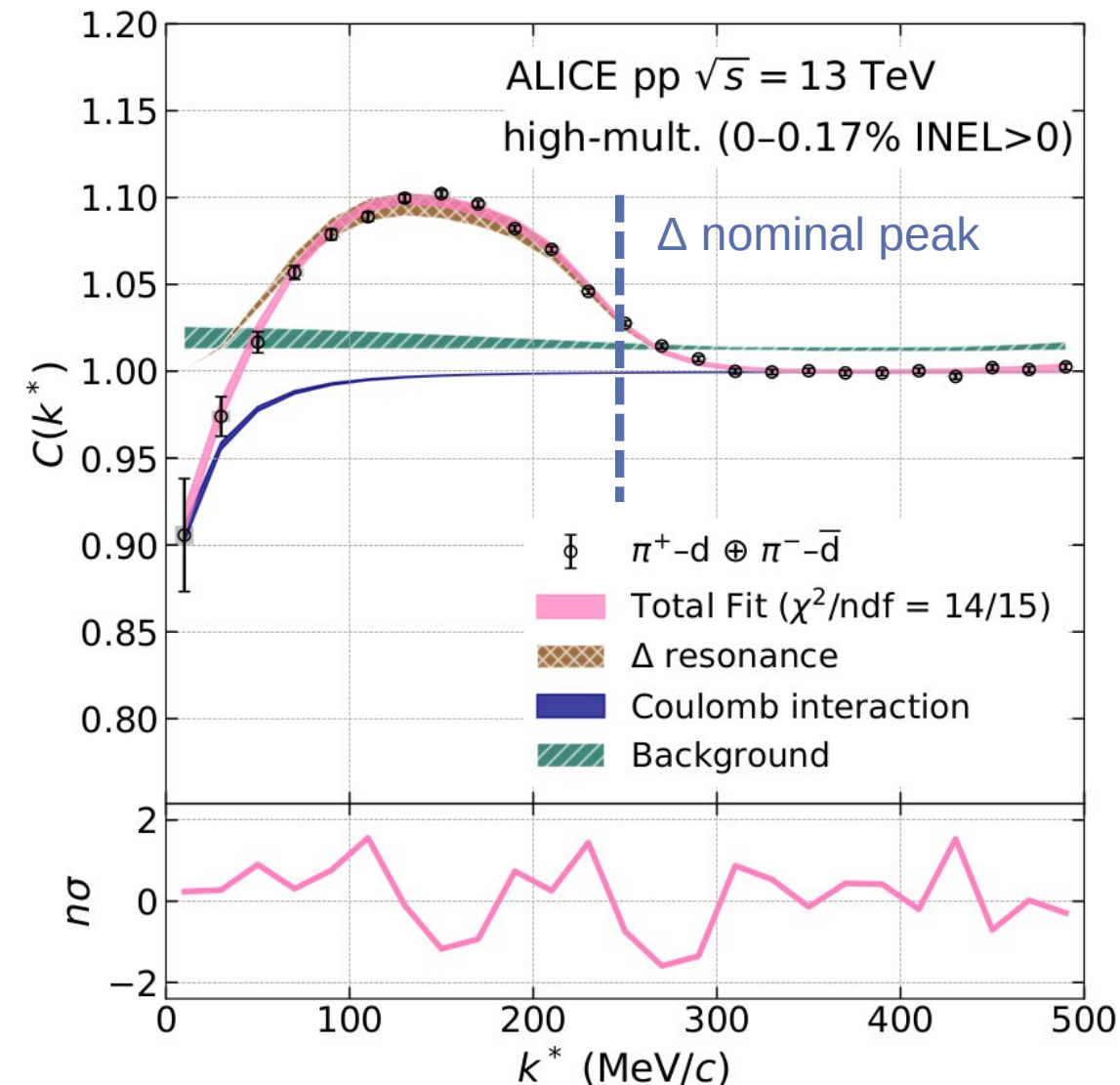


[6] P. Hauser et al, PRC 58, R1869, 1998

[7] D. L. Mihaylov et al.: EPJC 78, 394 (2018)

$\pi^\pm$ -d Correlations

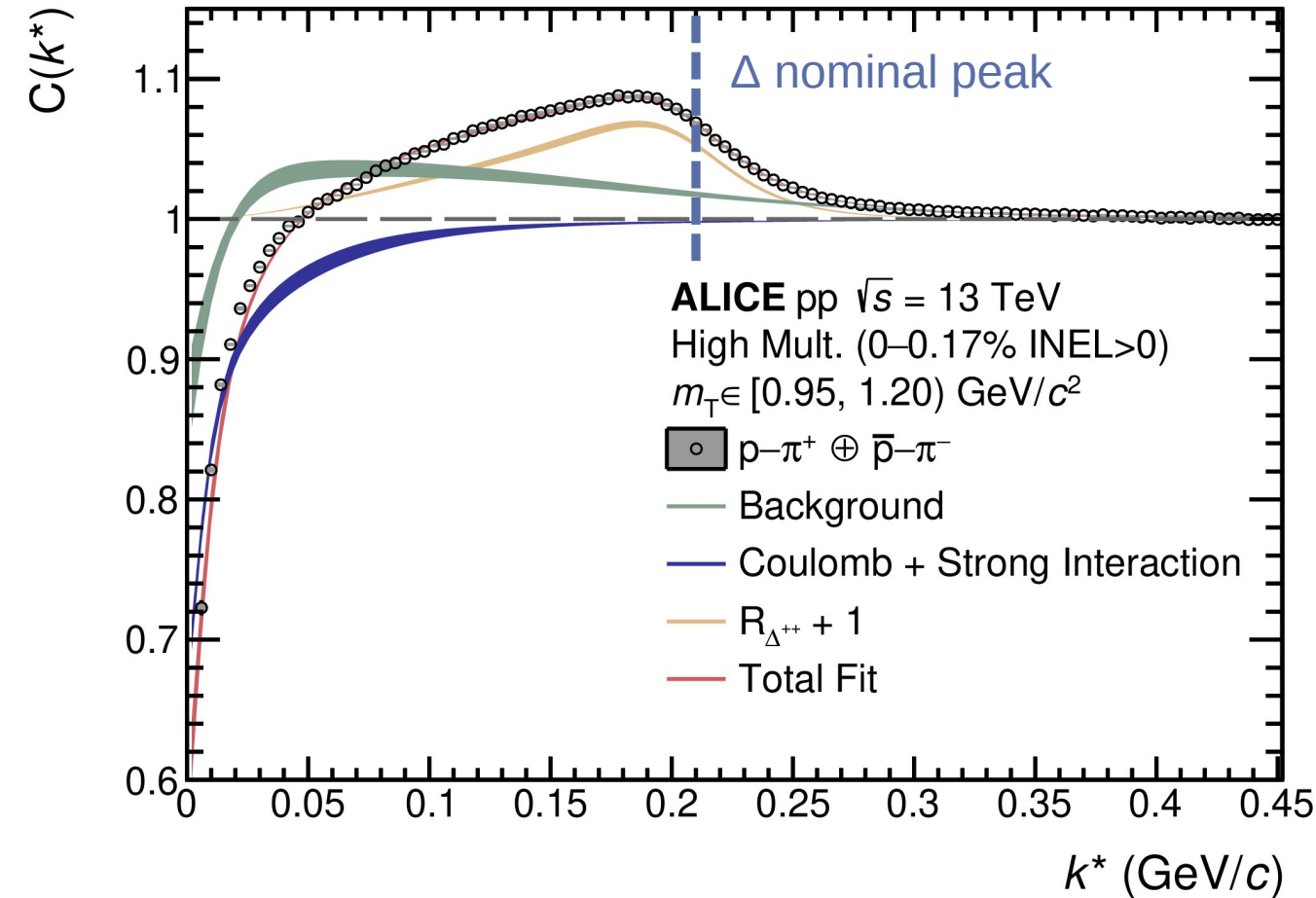
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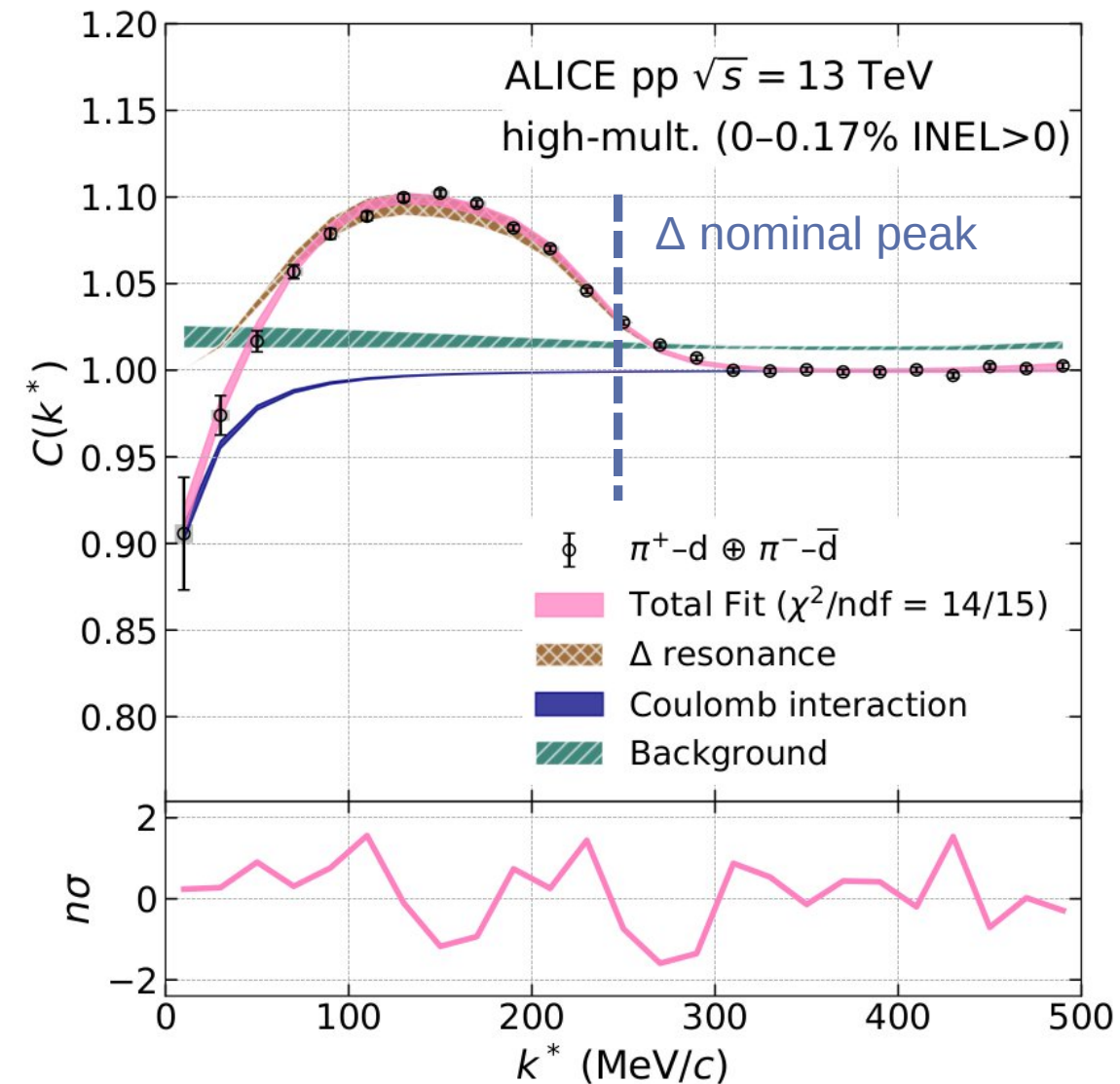
[6] P. Hauser et al, PRC 58, R1869, 1998

[7] D. L. Mihaylov et al.: EPJC 78, 394 (2018)

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

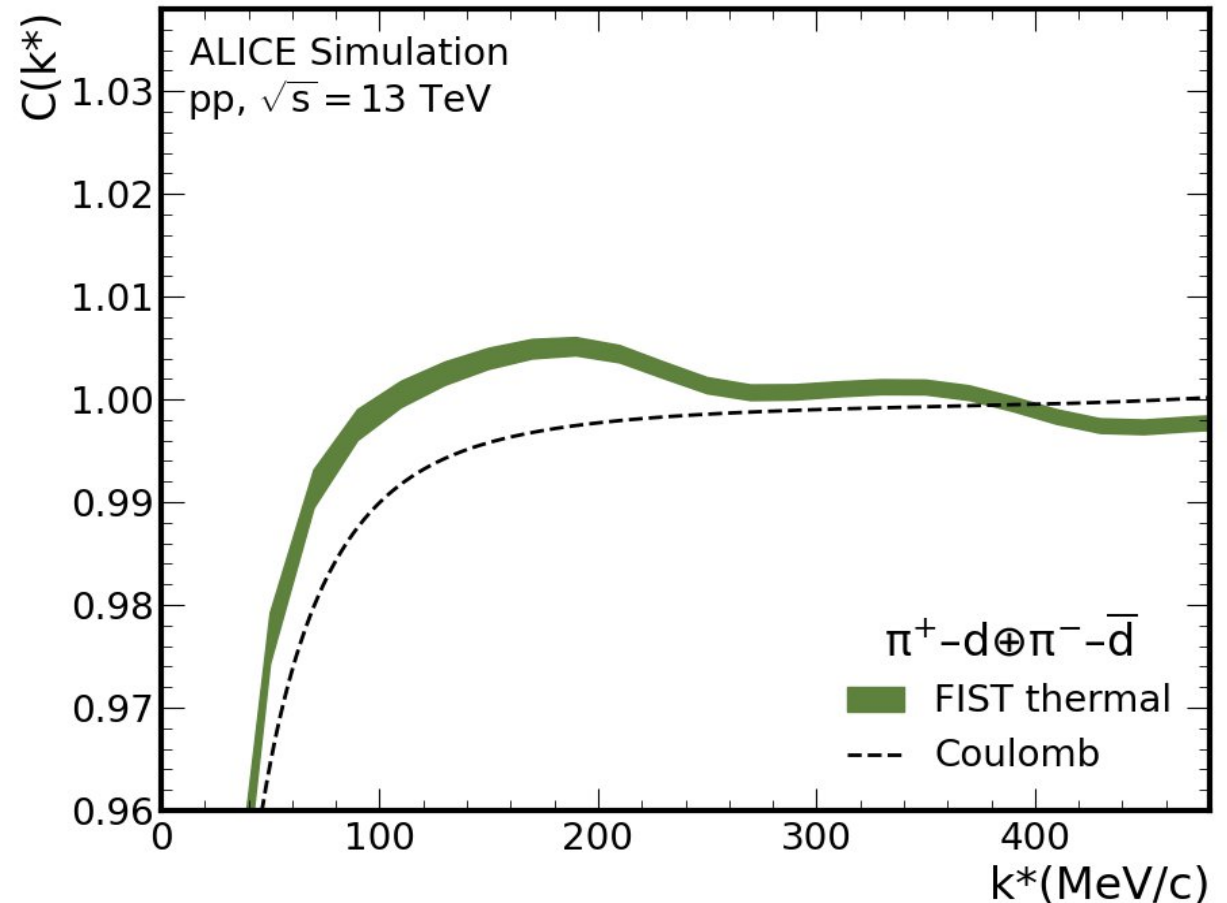
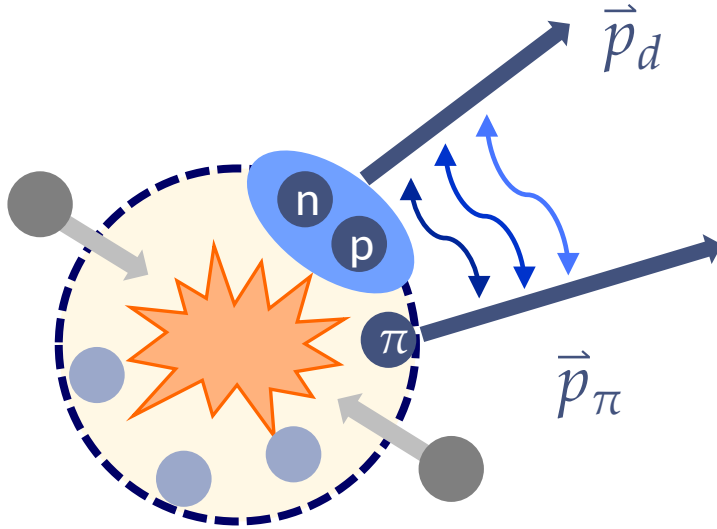


Looks a lot like the Δ peak measured in $p\pi$ correlations!
→ Are deuterons formed after the Δ decays?



Model Studies with Coalescence and Stat. Hadronization

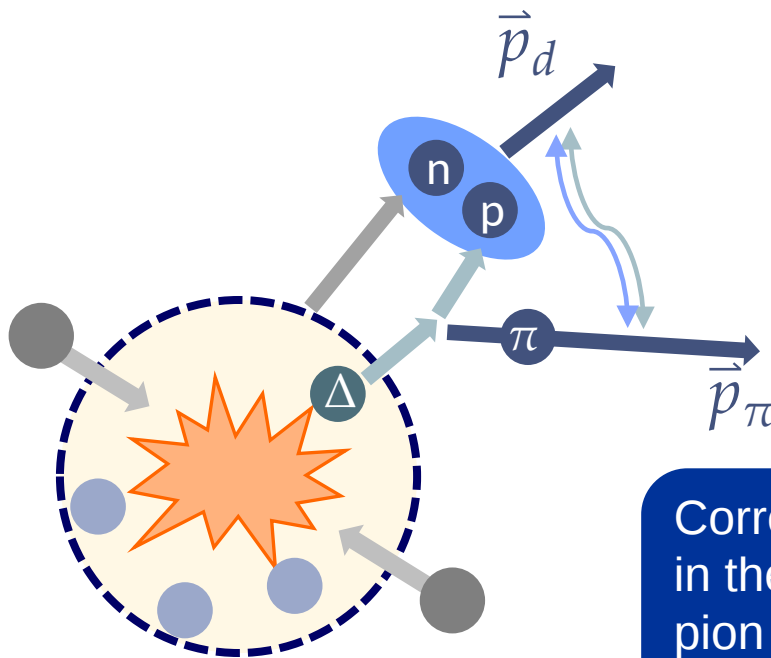
- **Thermal FIST[8]** gives only a trivial baseline



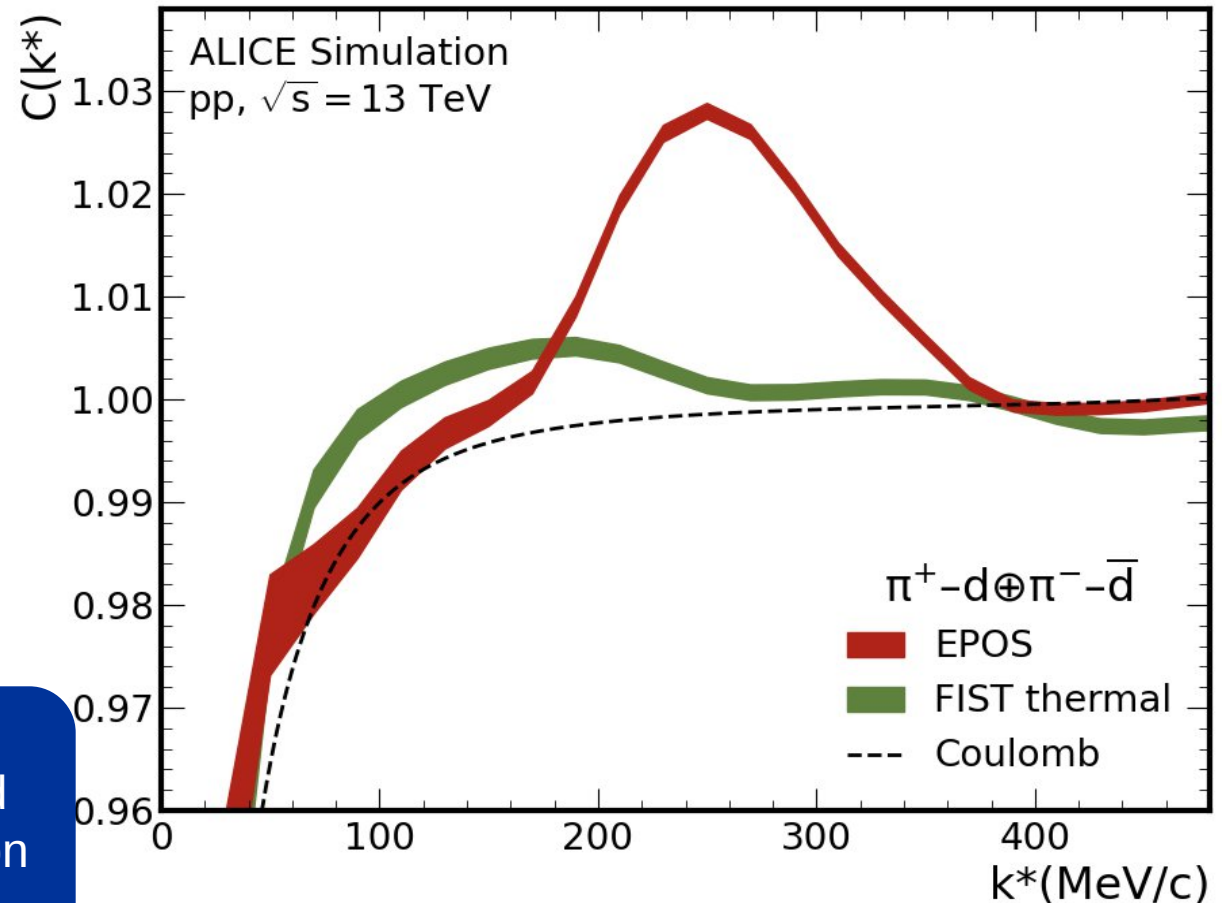
[8] V.Vovchenko et al., *Comput. Phys. Commun.* 244, 295 (2019)

Model Studies with Coalescence and Stat. Hadronization

- **Thermal FIST[8]** gives only a trivial baseline
- **Coalescence[9]** shows a clear bump



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

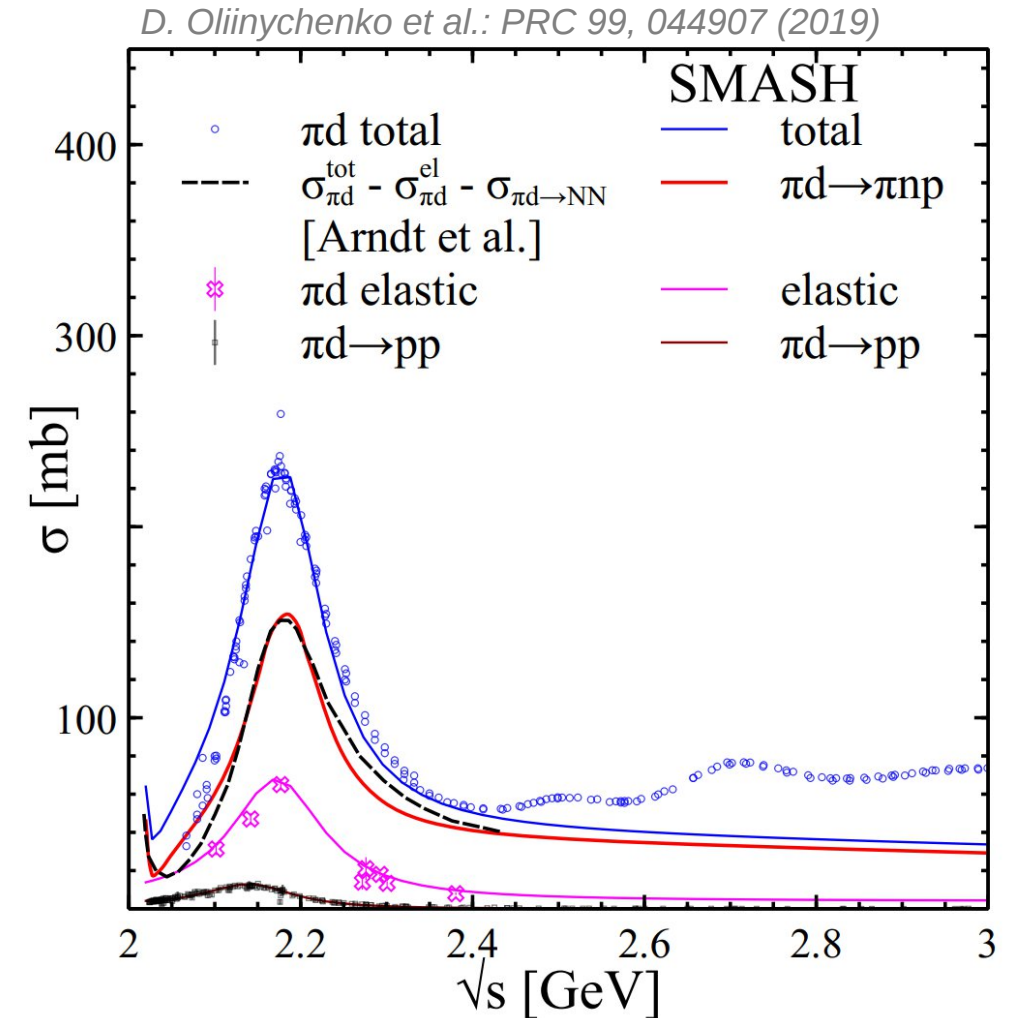
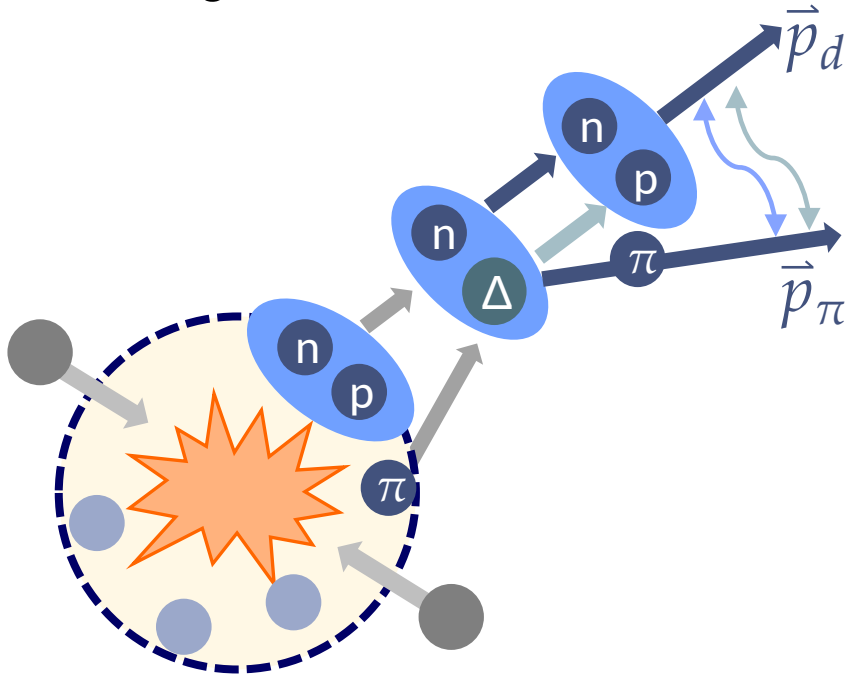


[8] V.Vovchenko et al., *Comput. Phys. Commun.* 244, 295 (2019)

[9] MM et al., *EPJC* 83 (2023) 9, 804

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!

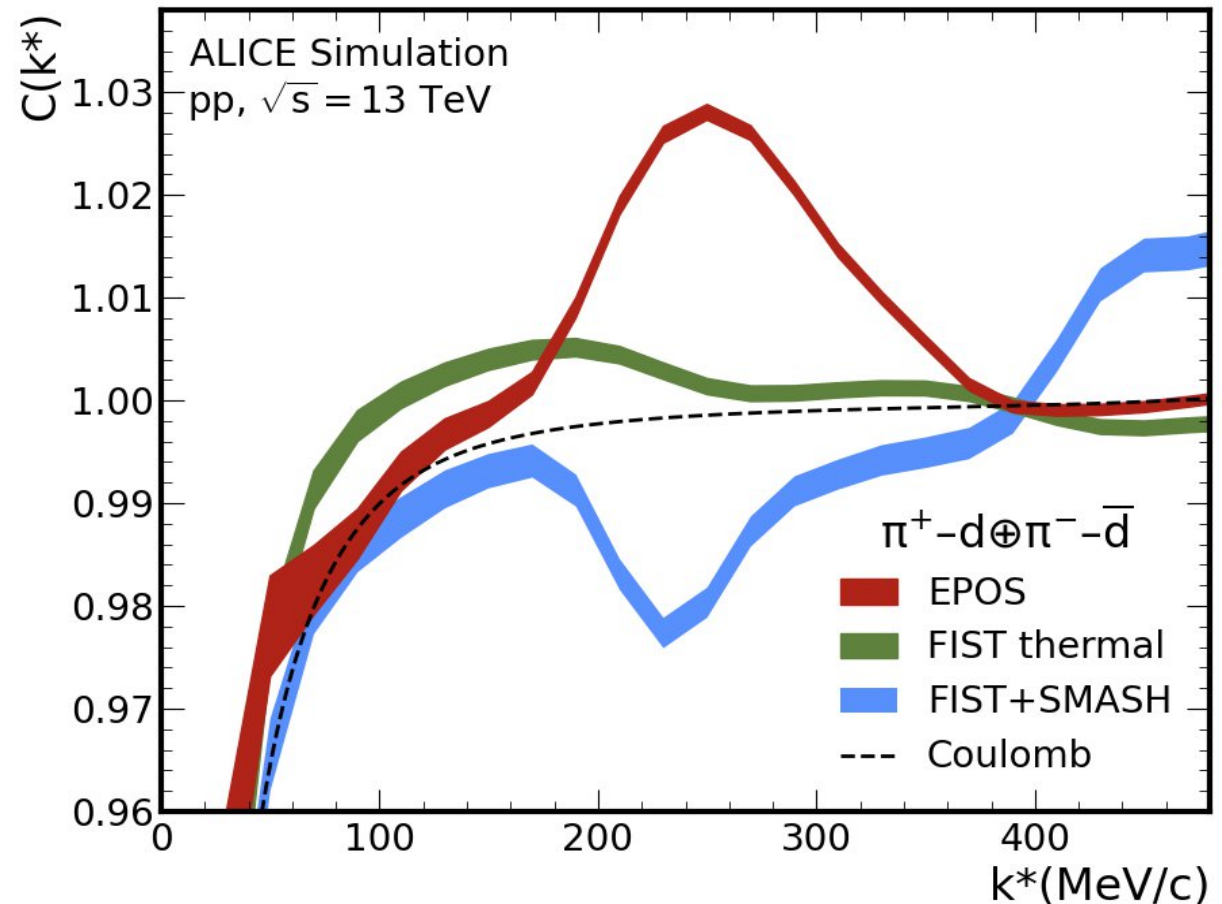
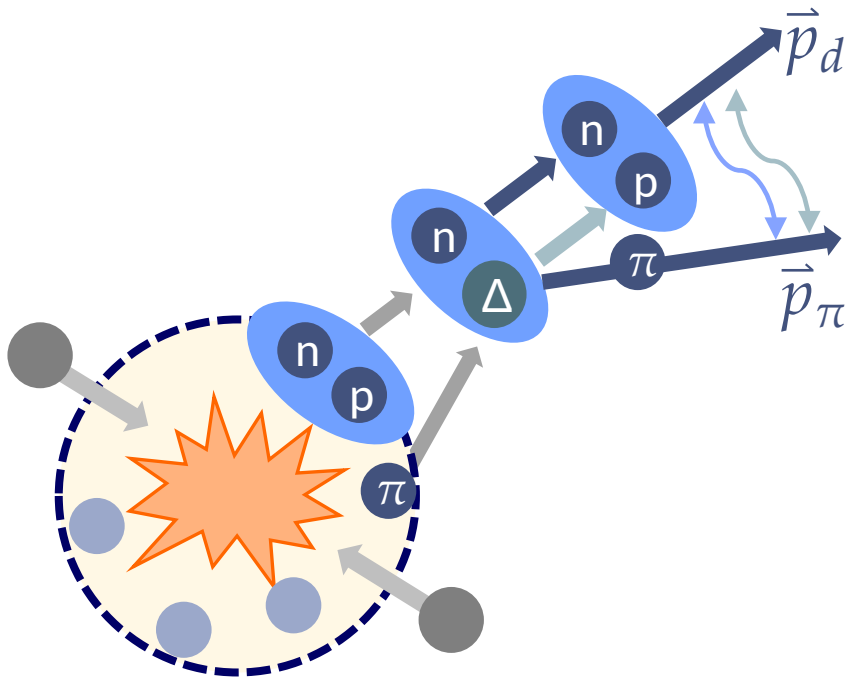


[8] V.Vovchenko et al., *Comput. Phys. Commun.* 244, 295 (2019)

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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**

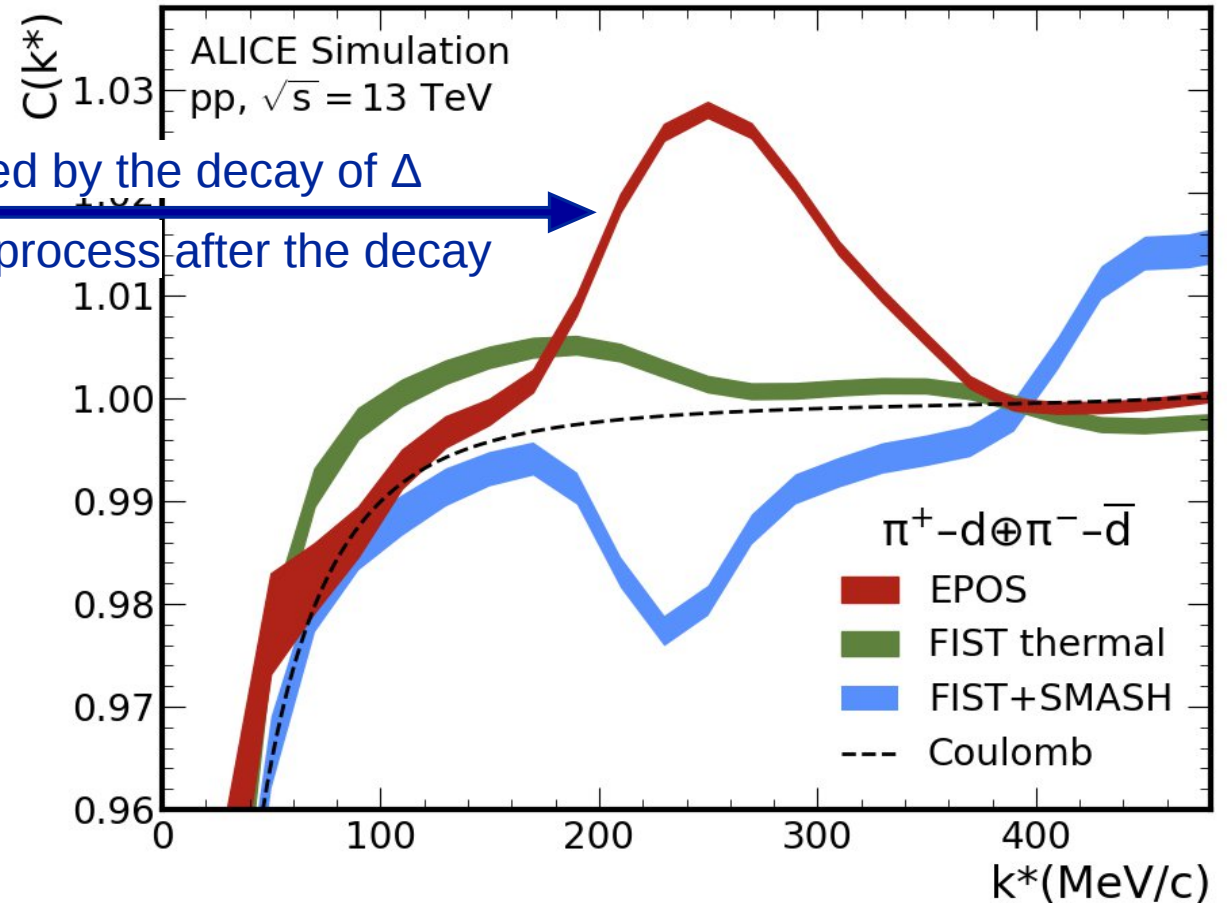
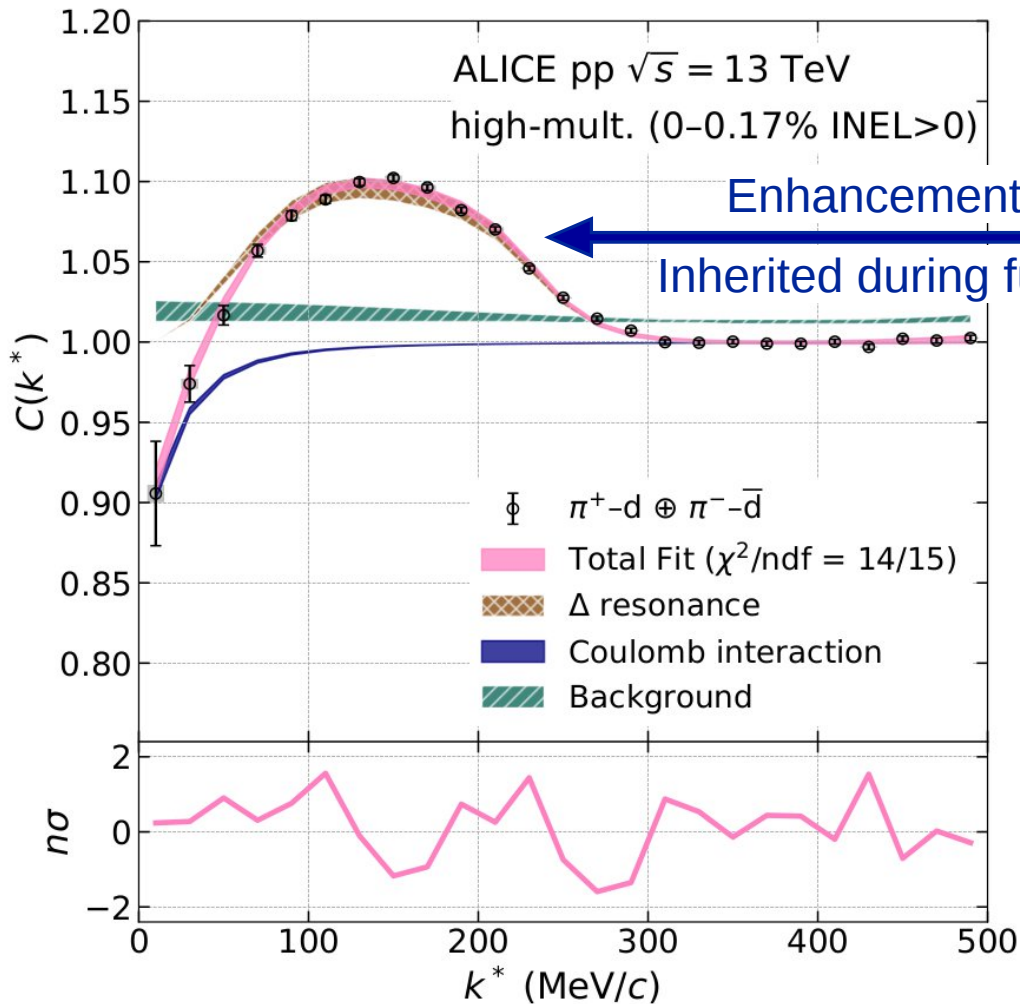


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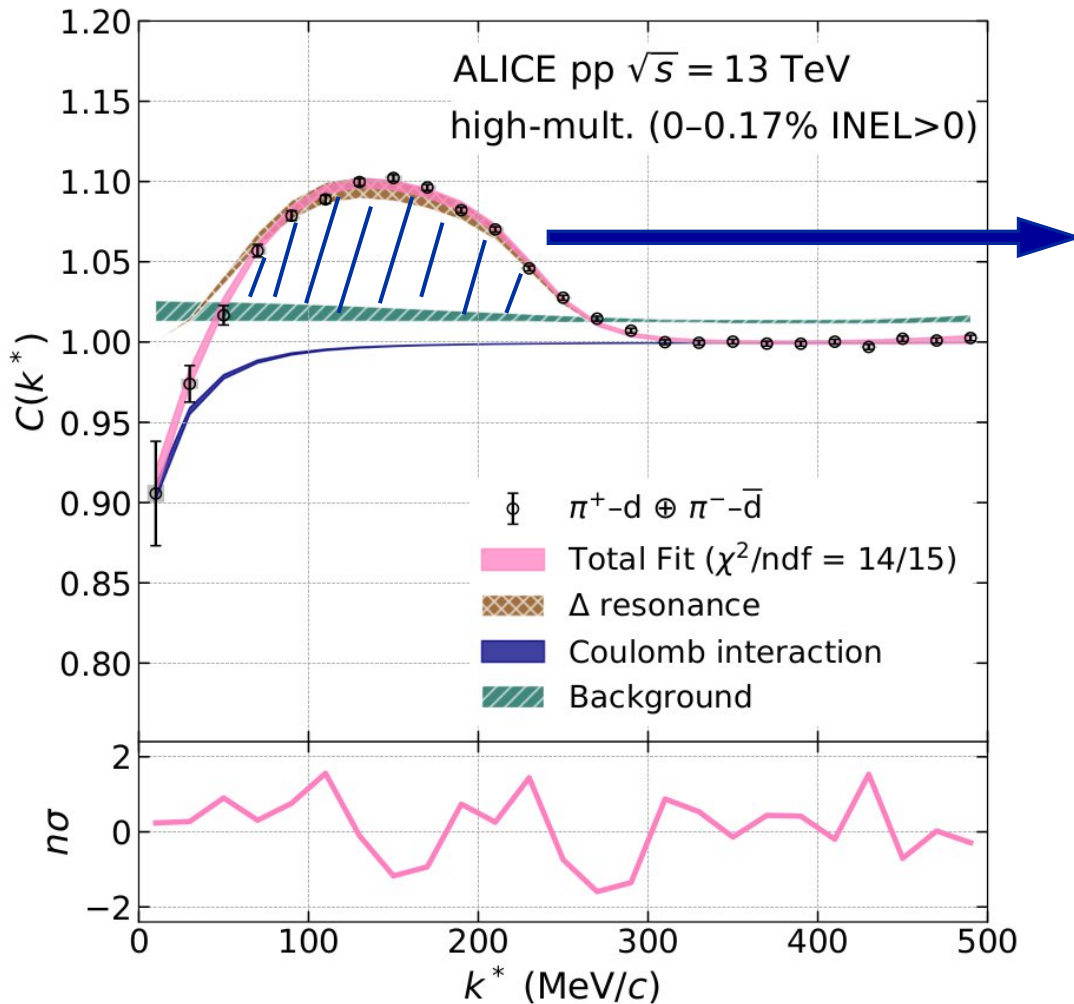
[9] MM et al., *EPJC* 83 (2023) 9, 804

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

Model Studies with Coalescence and Stat. Hadronization



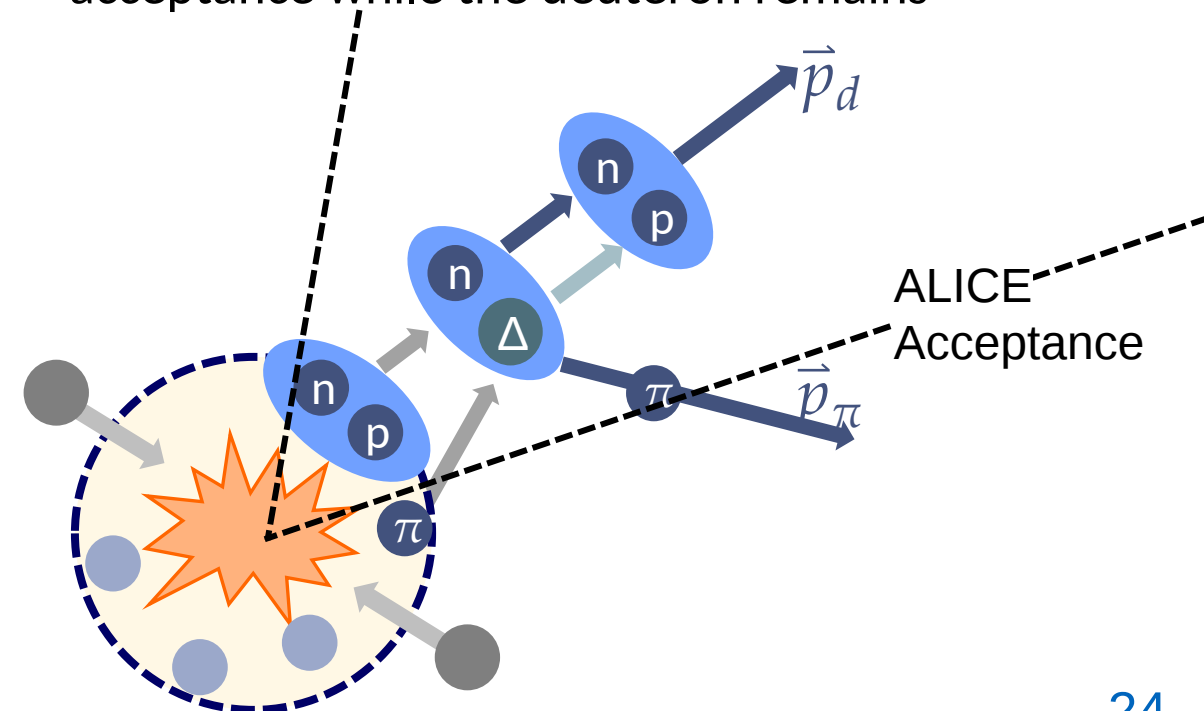
Deuteron fraction from Resonances



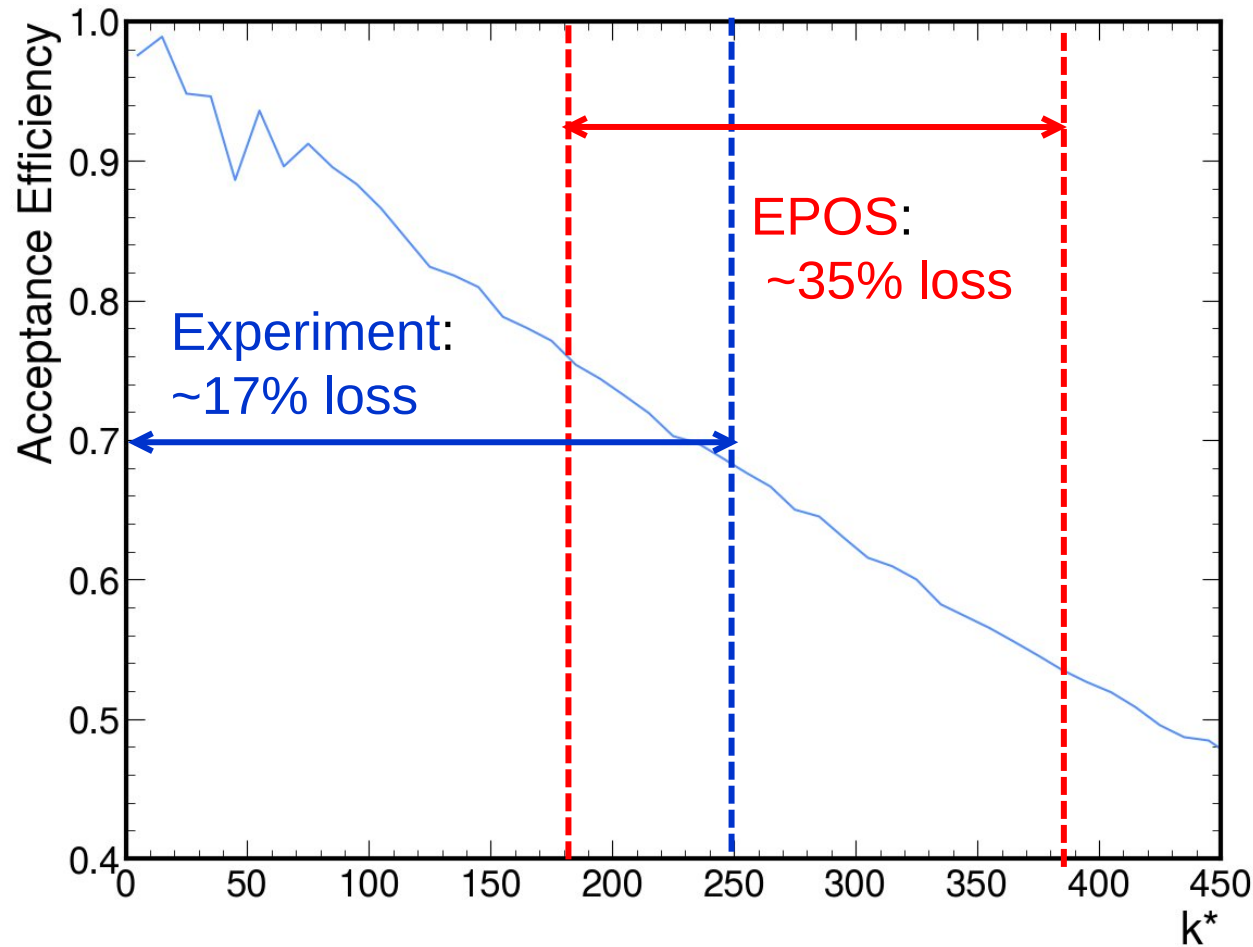
- By counting pairs under the peak we can estimate the fraction of deuterons from Δ decays

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

- Pair can be lost due to the pion escaping the acceptance while the deuteron remains



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

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

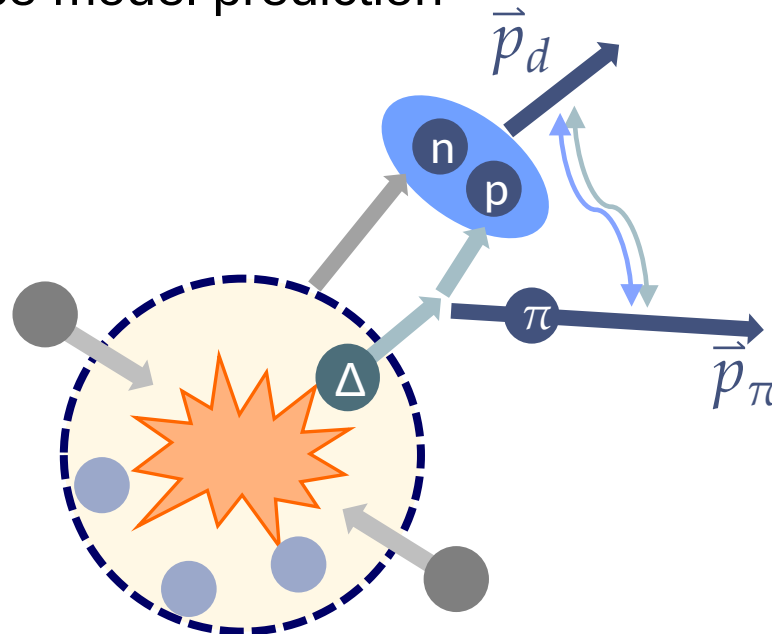
- The equivalent value from **EPOS**

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

What to take home



- Residual $p-\pi$ correlation from Δ -decay with exactly the same shape in $\pi-d$ correlation function
- Only scenario compatible with this residual correlation is nuclear formation by fusion processes
- Obtained fraction of deuterons from resonances compatible with coalescence model prediction



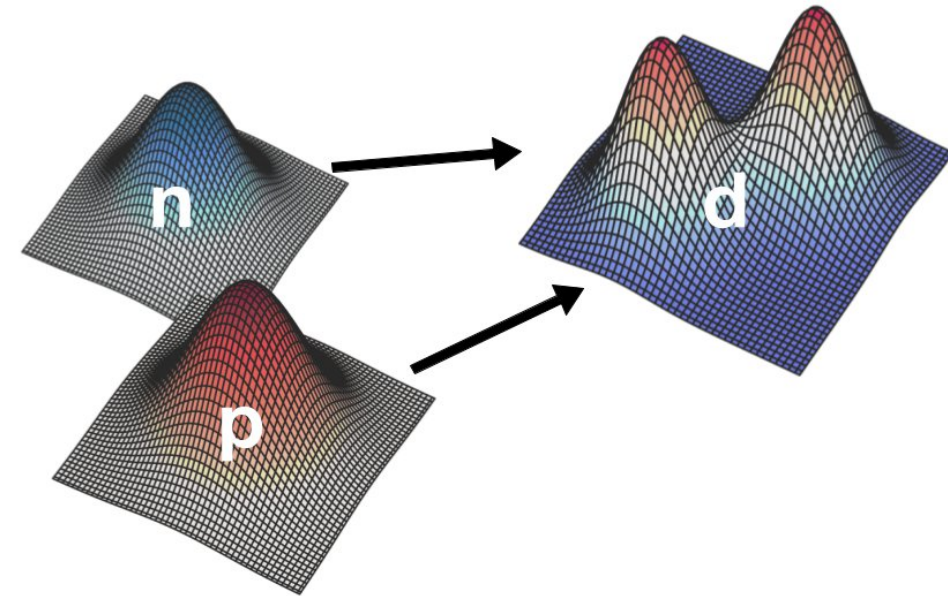
Backup

Coalescence models: Wigner function formalism

- Nucleons close in the phase-space after chemical freeze-out can fuse together
- Wigner function formalism:

$$\frac{dN_d}{d^3P} = S_d \int d^3x_1 \int d^3x_2 \int d^3x'_1 \int d^3x'_2 \Psi_d^*(\vec{x}'_1, \vec{x}'_2) \Psi_d(\vec{x}_1, \vec{x}_2) \times \langle \Psi_2^\dagger(\vec{x}'_2) \Psi_1^\dagger(\vec{x}'_1) \Psi_1(\vec{x}_1) \Psi_2(\vec{x}_2) \rangle$$

$$\mathcal{P}(q, \sigma) = \frac{S_2}{(2\pi)^3 \sigma^6} \int d^3r_p d^3r_n D(q, r) e^{-\frac{r_p^2 + r_n^2}{2\sigma^2}}$$

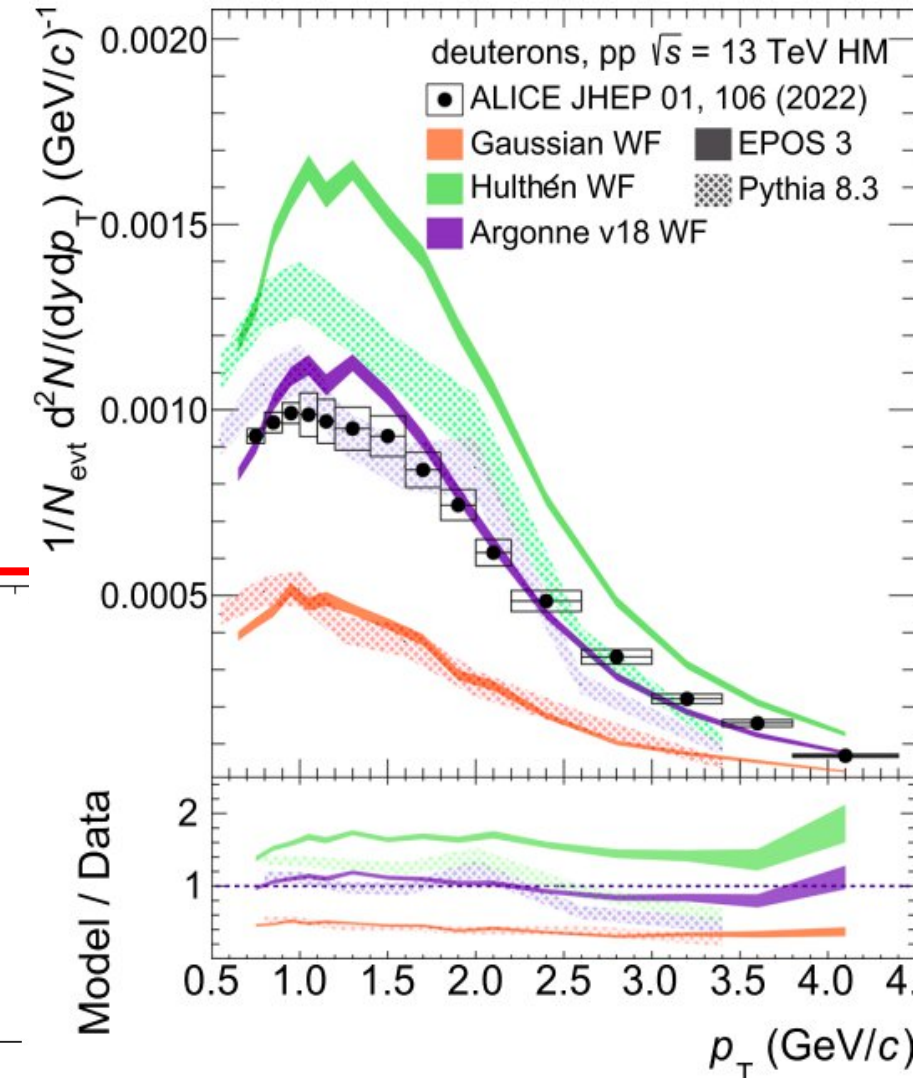
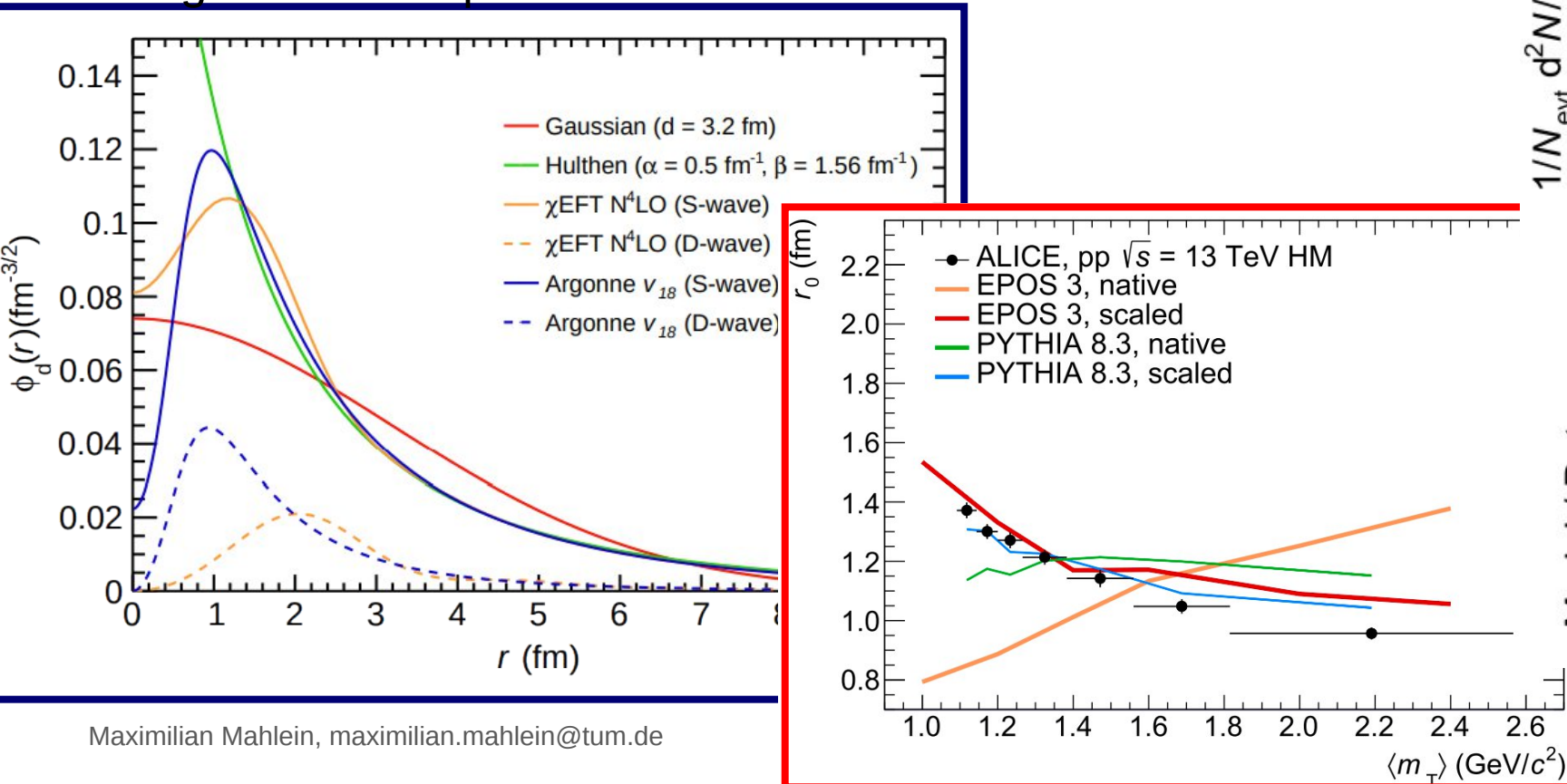


$$= \int d^3\zeta \Psi(\vec{r} + \vec{\zeta}/2) \Psi^*(\vec{r} - \vec{\zeta}/2) \exp(i\vec{q} \cdot \vec{\zeta})$$

$$= \frac{1}{(2\pi\sigma^2)^3} \exp\left(-\frac{\vec{r}_n^2 + \vec{r}_p^2}{2\sigma^2}\right)$$

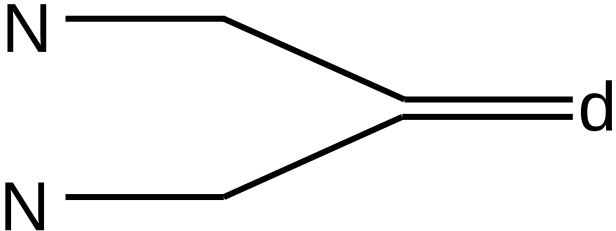
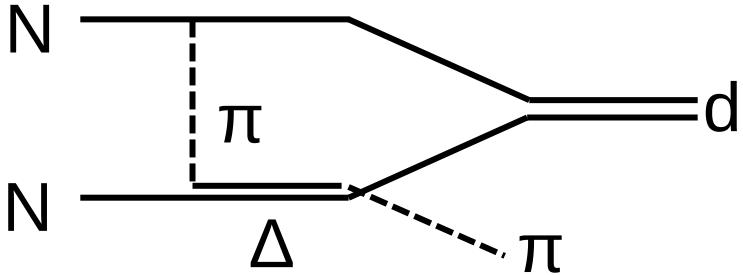
Coalescence models: Wigner function formalism

- EPOS + PYTHIA event generators pp@ $\sqrt{s}=13$ TeV
- Tuned Protons, **Source** & Multiplicity
- **Wavefunctions**: Gaussian, Hulthén and Argonne v18
- Argonne v18 reproduces ALICE data to $\sim 10\%$



Fusion Models: Energy conservation

- Since $m_d < m_n + m_p$ the fusion reaction violates energy and momentum conservation

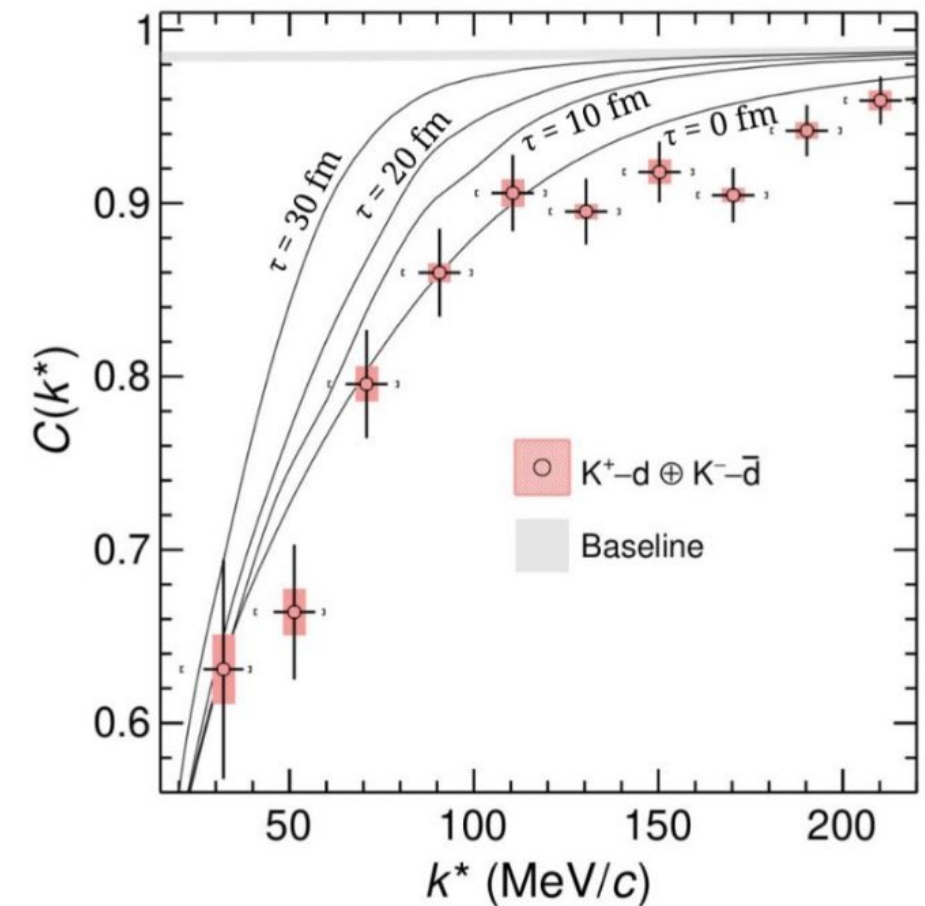
Coalescence		$p+n \rightarrow d+\gamma$ $p+n+\pi \rightarrow d+\pi$ $p^*+n \rightarrow d$
Reactions		dynamic excitation of a Δ resonance

Previous femto studies into deuteron formation

- Using the CECA source model and the measured K^+ -d correlation 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 2.25 fm/c

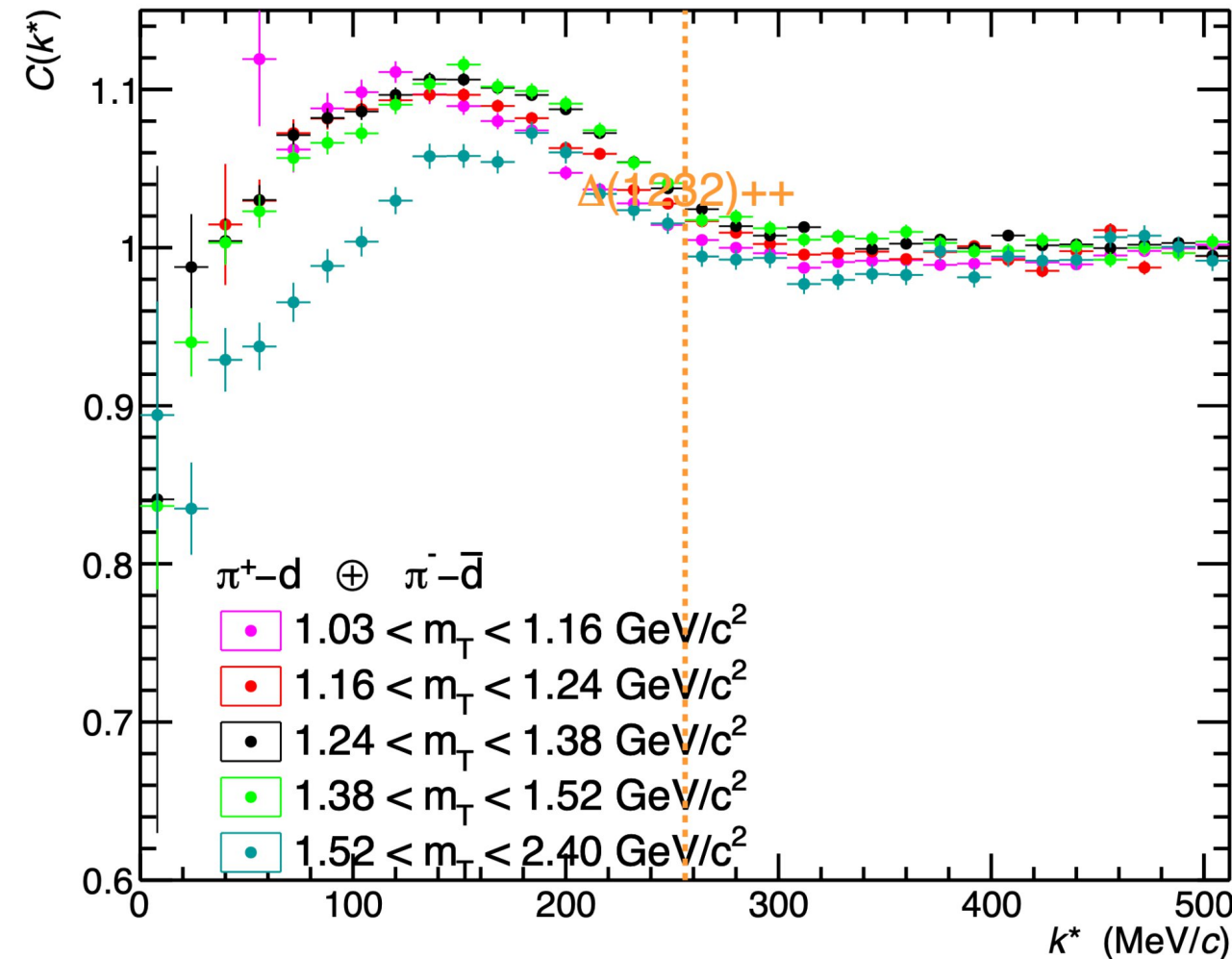
CECA Source model

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



$\pi^\pm$ -d Correlations

- 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 $\text{Re}(f_0)$ 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)

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:

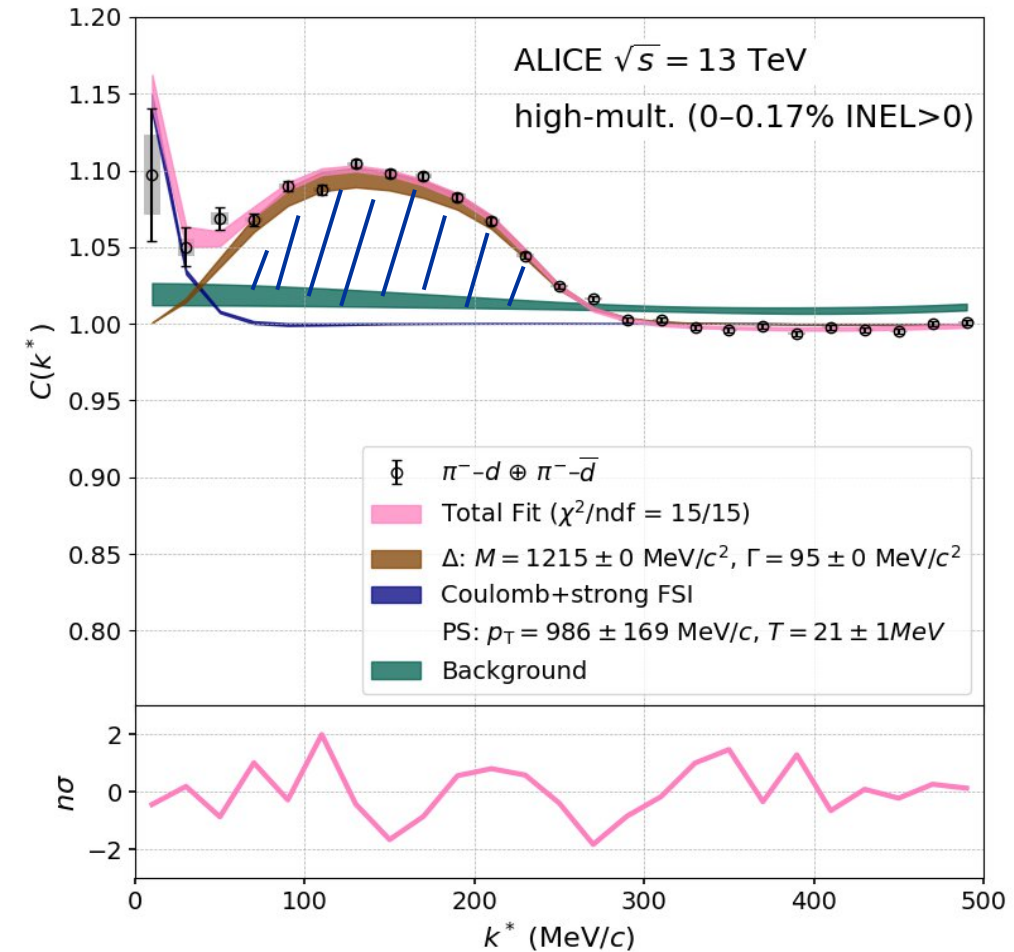
$$F_{\Delta \rightarrow d} = \frac{\text{deuterons from } \Delta}{\text{all } d \text{ candidates}} = 61.6 \pm 4.1\%$$

- Using thermalFIST to extrapolate to all resonances gives

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

- The corresponding number from EPOS¹ is **89.3±1.6%**

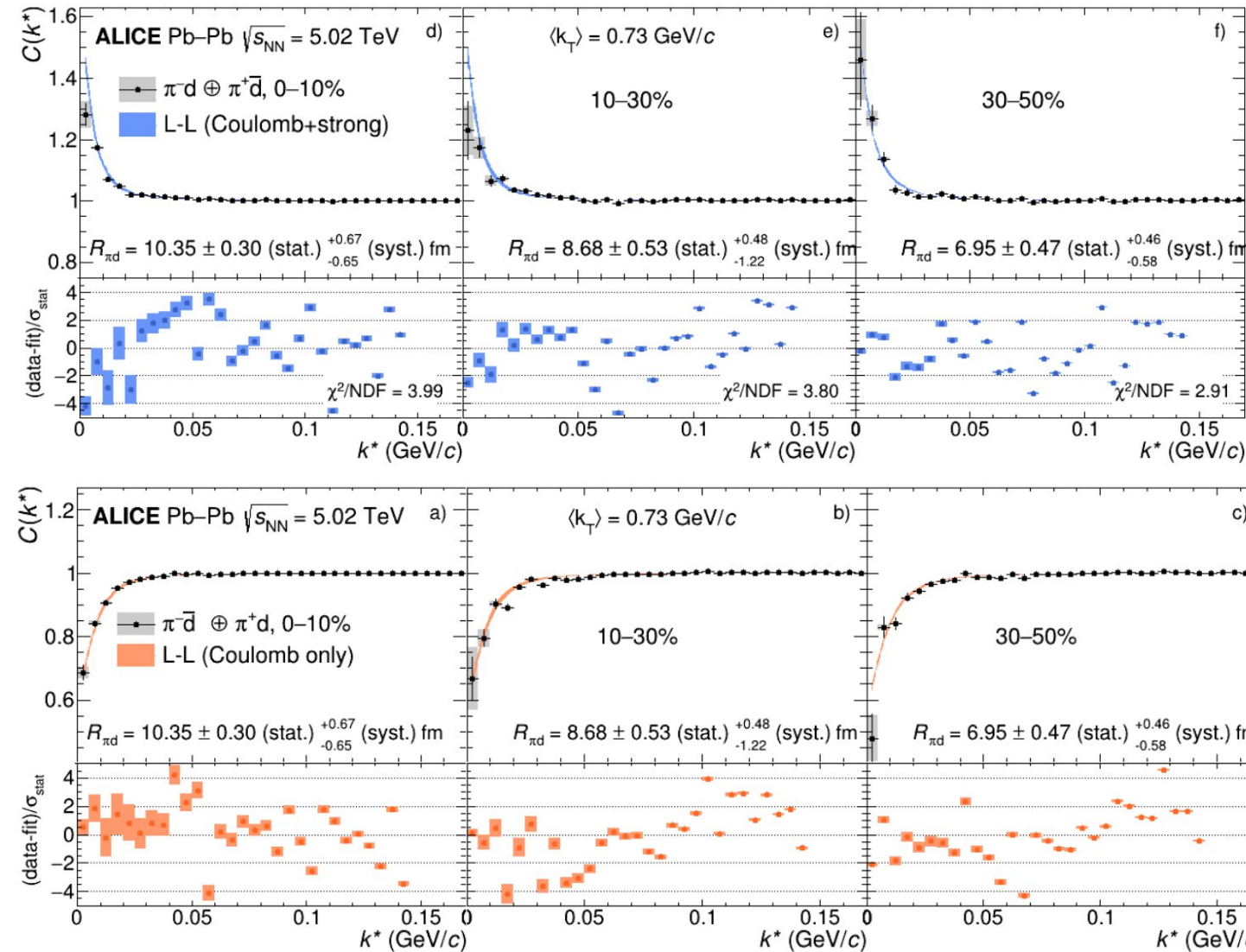
Formation of deuterons from resonances is not only happening, it is the **dominant** contribution!



¹EPOS 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

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

- 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

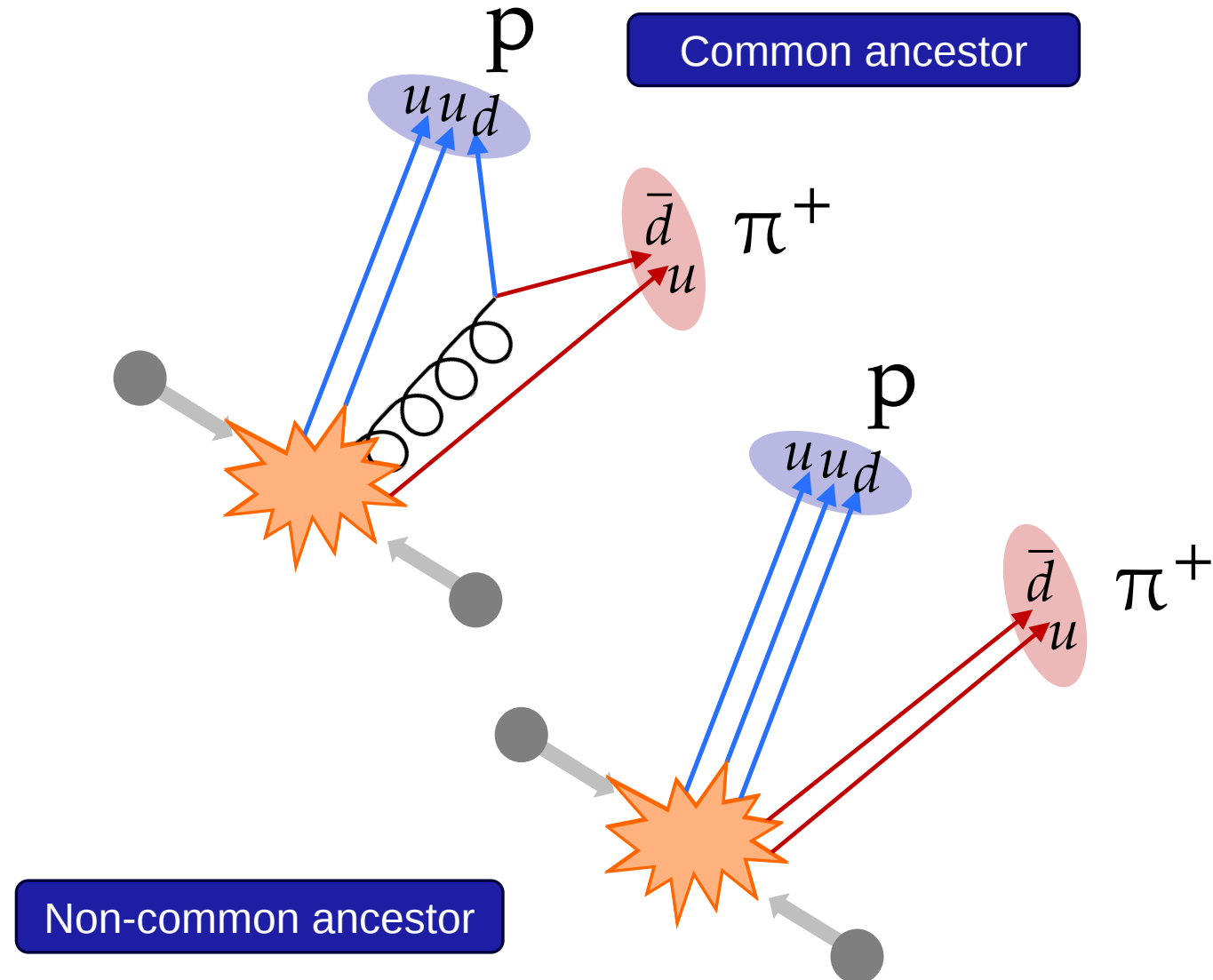
- $PS(p_T, T)$ phase-space factor

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

- 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 $p\pi$, with the parameters extracted from data, to $d\pi$ (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
 - $C_{bckg} = \mathcal{N} \times [w_c C_c + (1-w_c) C_{nc}]$



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
F. Giacosa et al., EPJA 57 (2021) 12
- $PS(p_{\text{T}}, T)$ phase-space factor

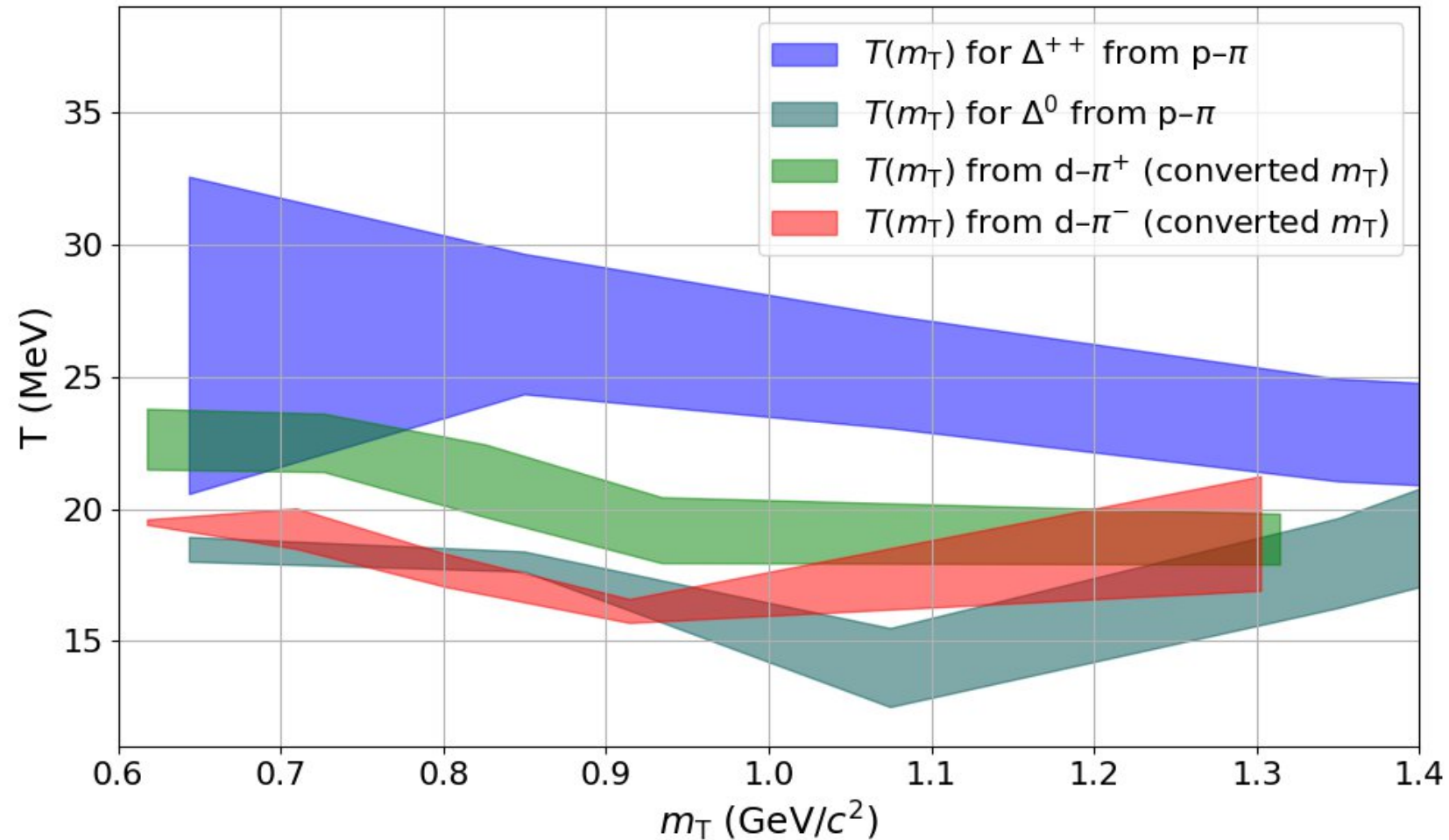
$$PS(p_{\text{T}}, T) \propto \frac{m}{\sqrt{m^2 + p_{\text{T}}^2}} \times \exp\left(-\frac{\sqrt{m^2 + p_{\text{T}}^2}}{T}\right)$$

- Fit between 0 and 450 MeV in k^*

Resonance decoupling temperature

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

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



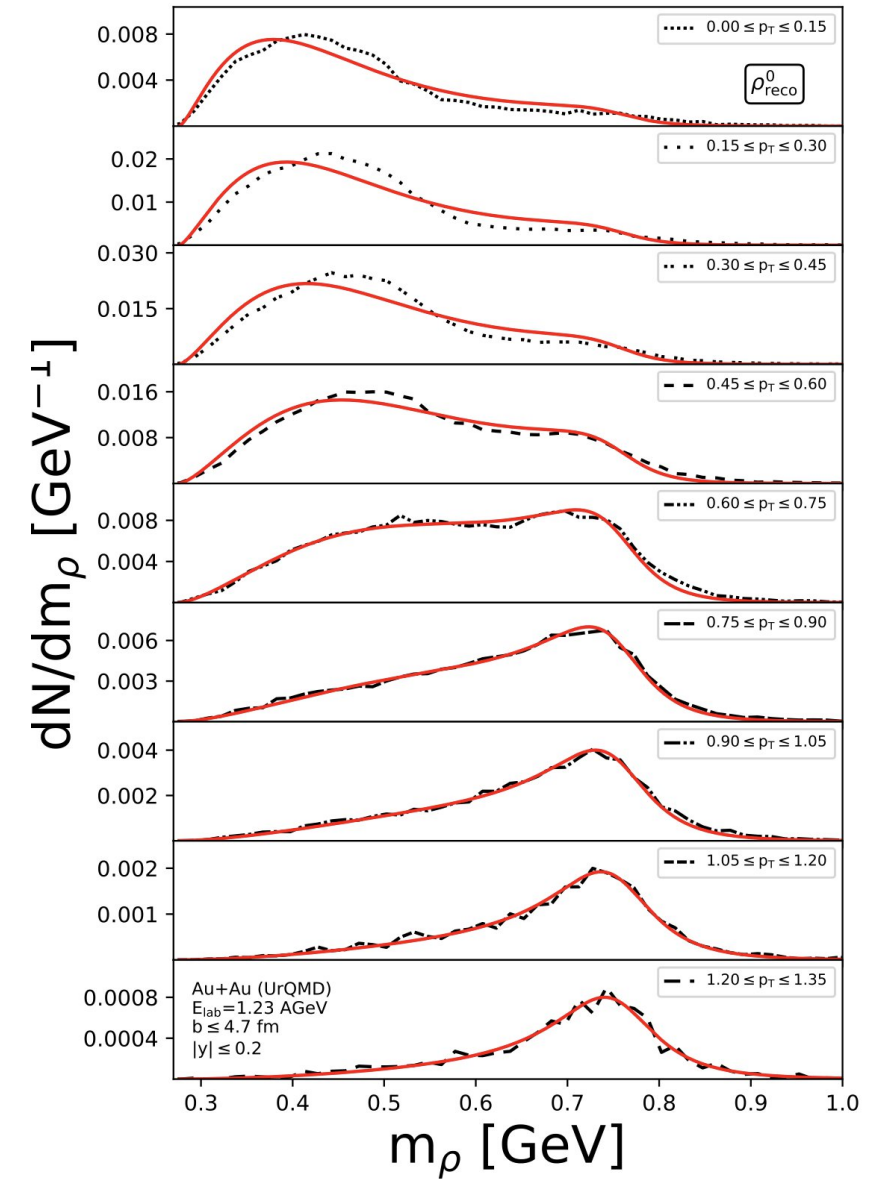
Temperature interpretation

- Temperature related to resonance regeneration $\Delta \leftrightarrow N\pi$ phase
- Lower temperature $\leftrightarrow$ 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
π^+d	Δ^{++}	π^+p (repulsive); -88.1	Shorter
	Δ^+	π^+n (attractive); 84.9	Longer
π^-d	Δ^0	π^-p (attractive); 85.8	Longer
	Δ^-	π^-n (repulsive); -89.0	Shorter

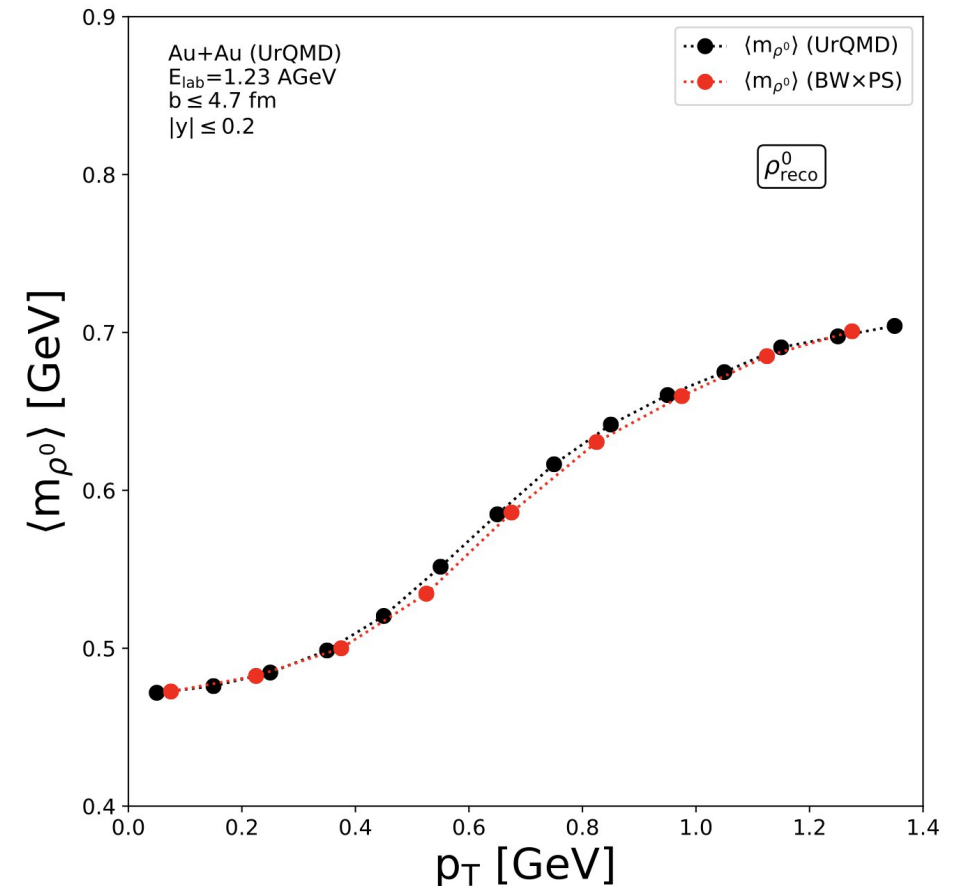
Modification of resonances

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



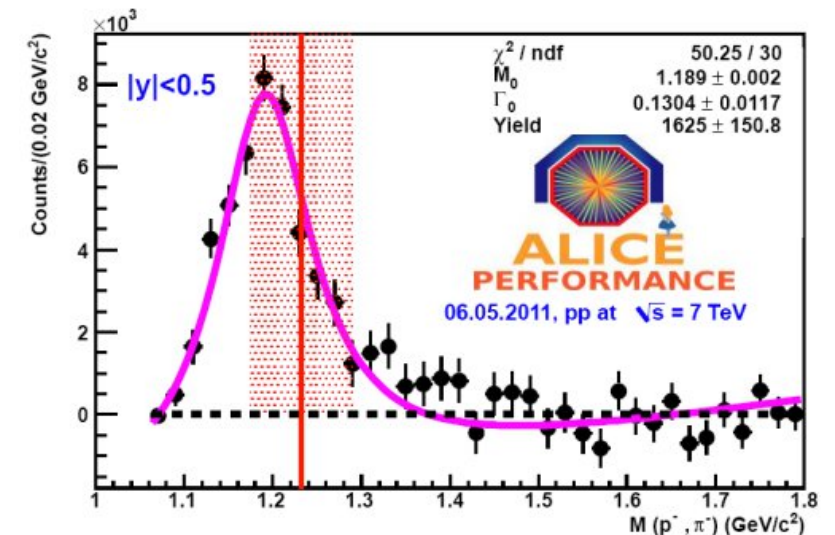
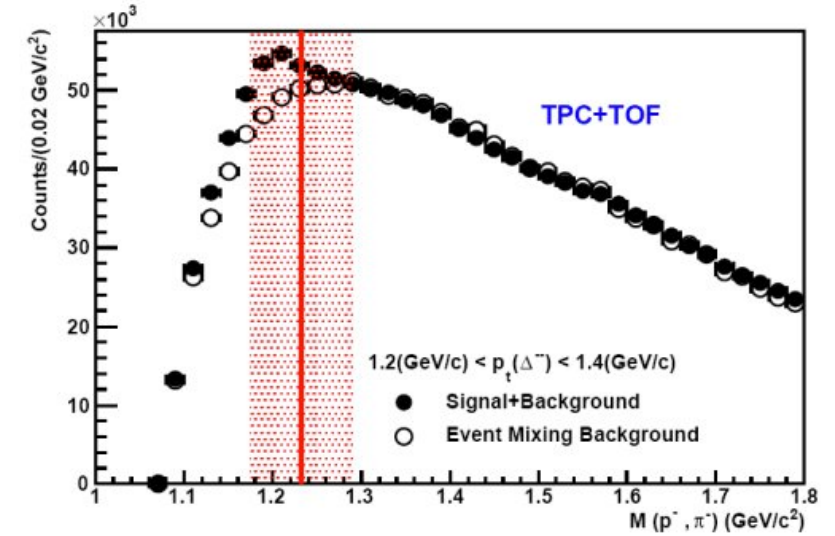
Modification of resonances

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



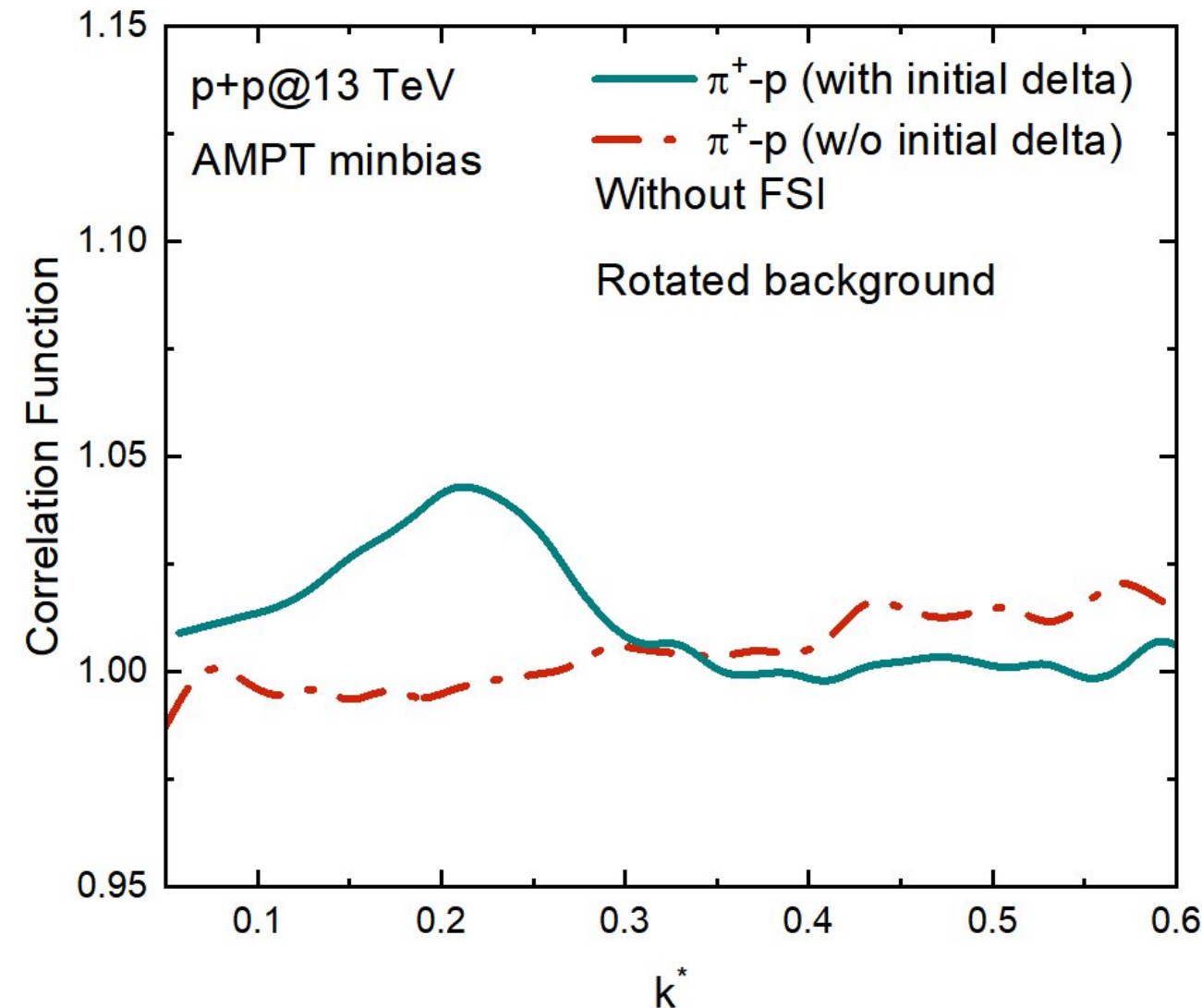
Modification of resonances

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

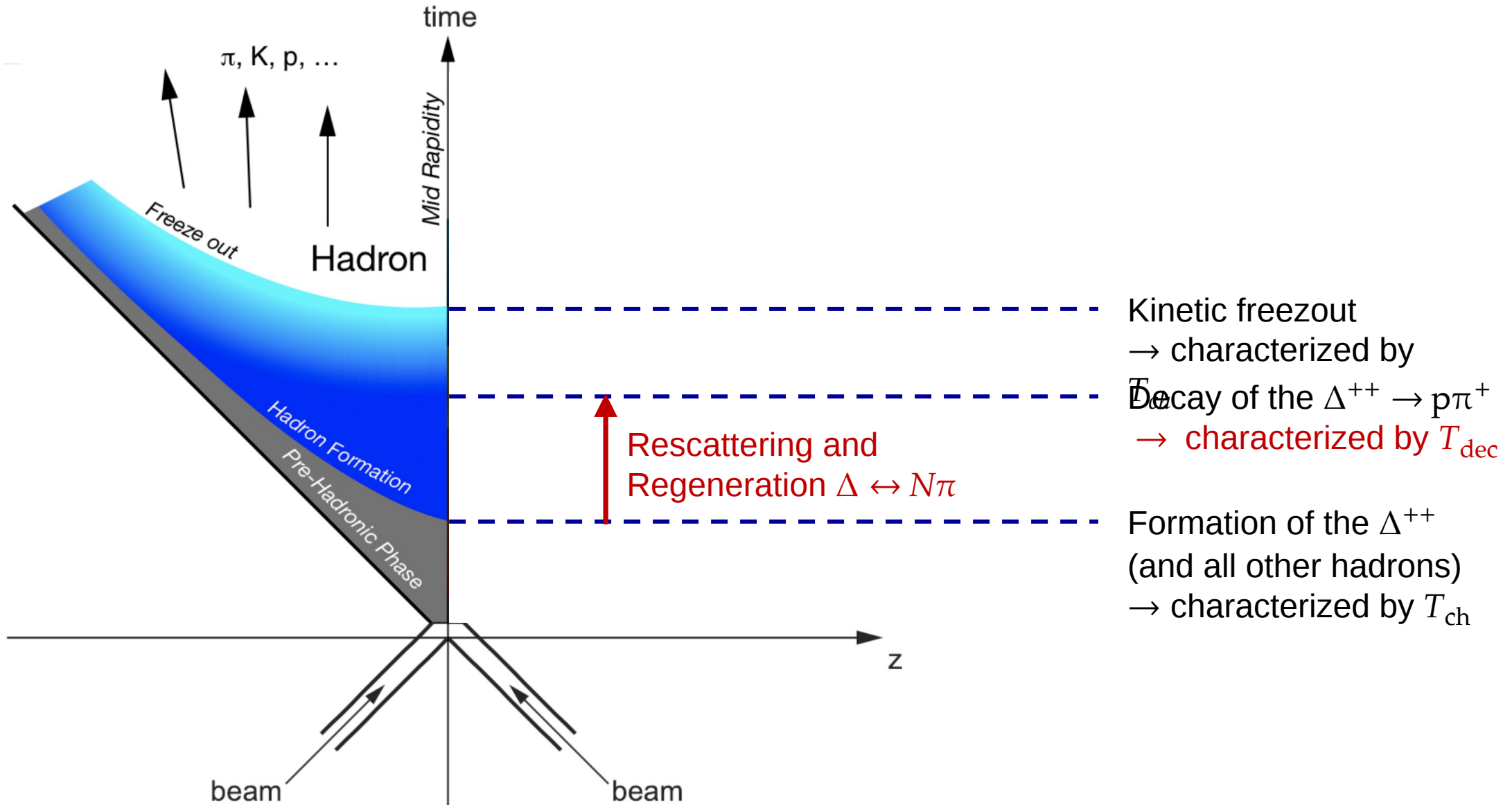


Modification of resonances

- 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



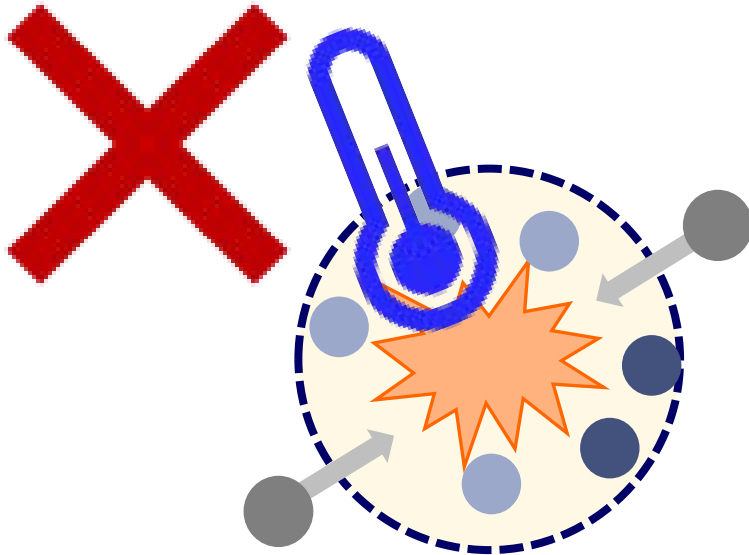
About the life of the Δ^{++}



Kinetic 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 $\Delta \leftrightarrow N\pi$
- hadronic moshpit for the Δ^{++}

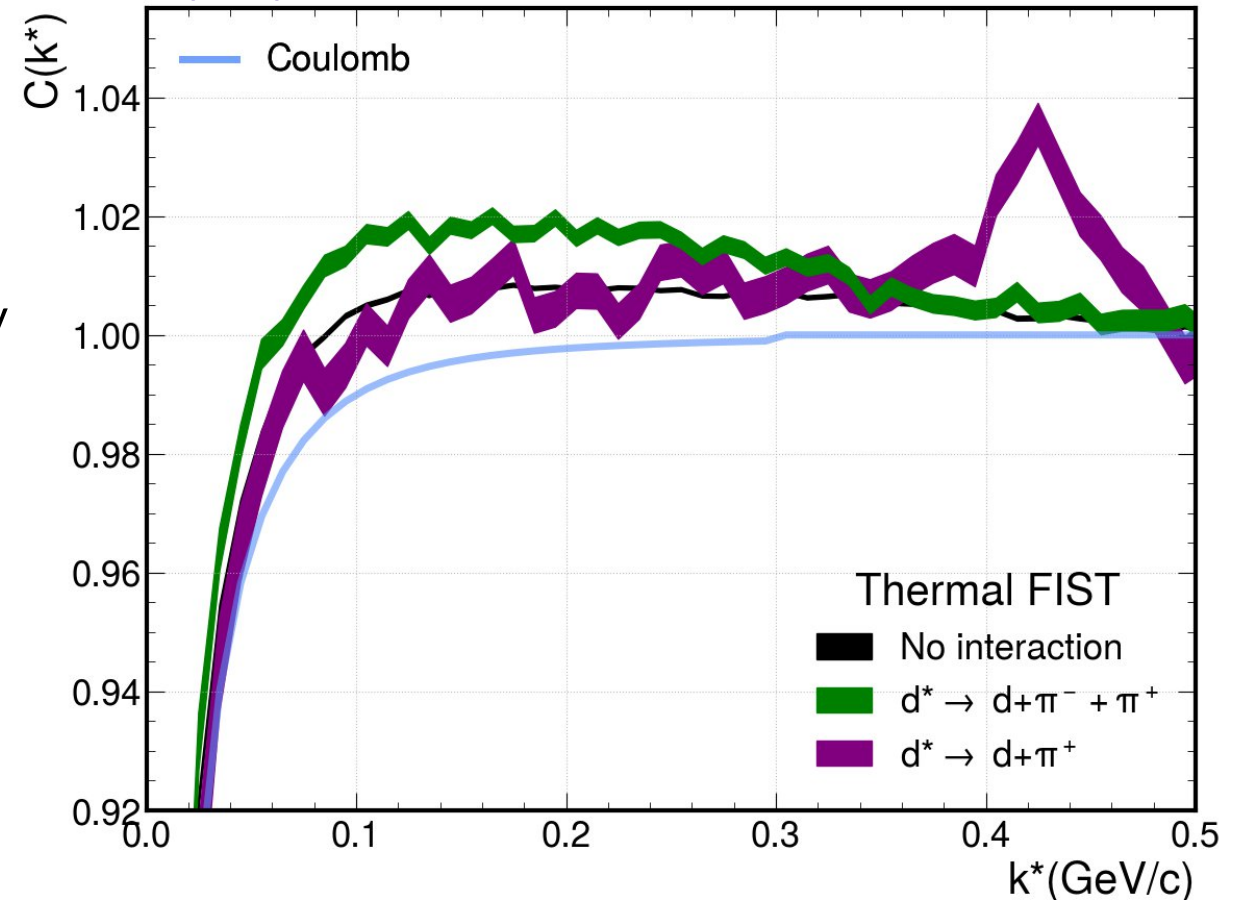
Hadronic Moshpit



$d^*(2380)$ Decay

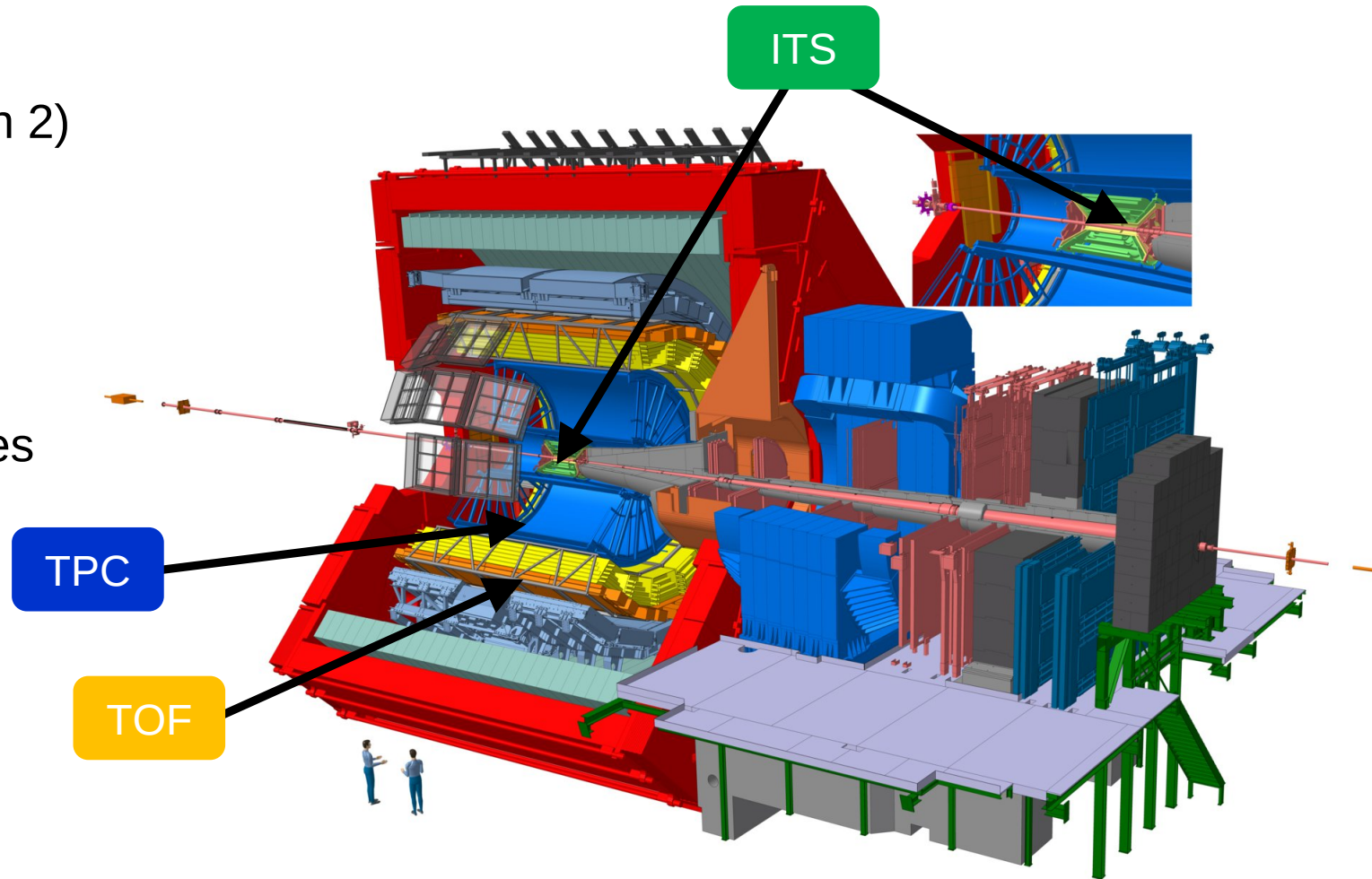
- Evidence of $d^*(2380)$ has been reported by WASA-at-COSY $pn \rightarrow d\pi^0\pi^0$
- $m=2380$ MeV, $\Gamma=70$ MeV, $J=S=3$
- Implement this resonance into ThermalFIST
- Decay channels: $d^* \rightarrow d+\pi^++\pi^-$, $d^* \rightarrow d+\pi^+$
- B.R. 100% $\rightarrow$ get most extreme signal 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%)

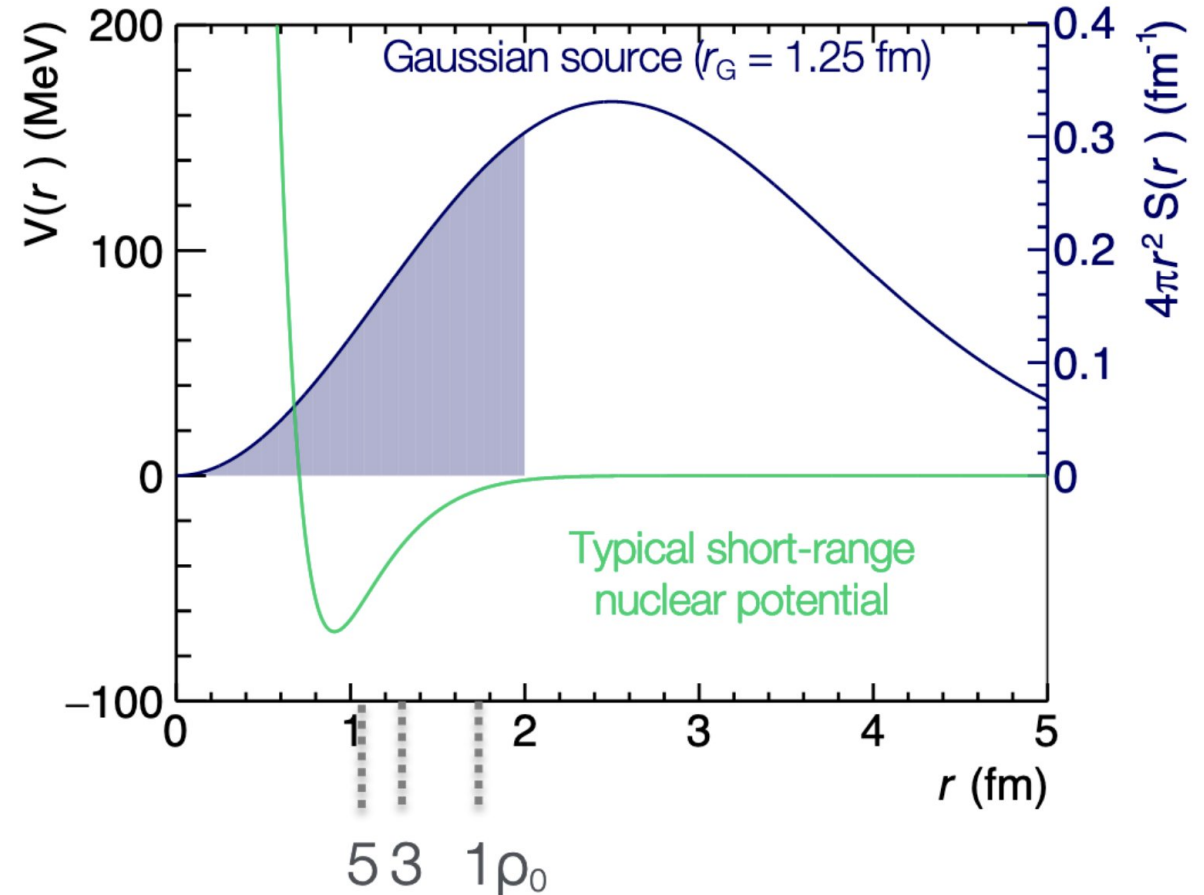


A. Tauro, "ALICE Schematics" (2017), [CERN CDS](#)

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

