Modelling the source for coalescence in small systems

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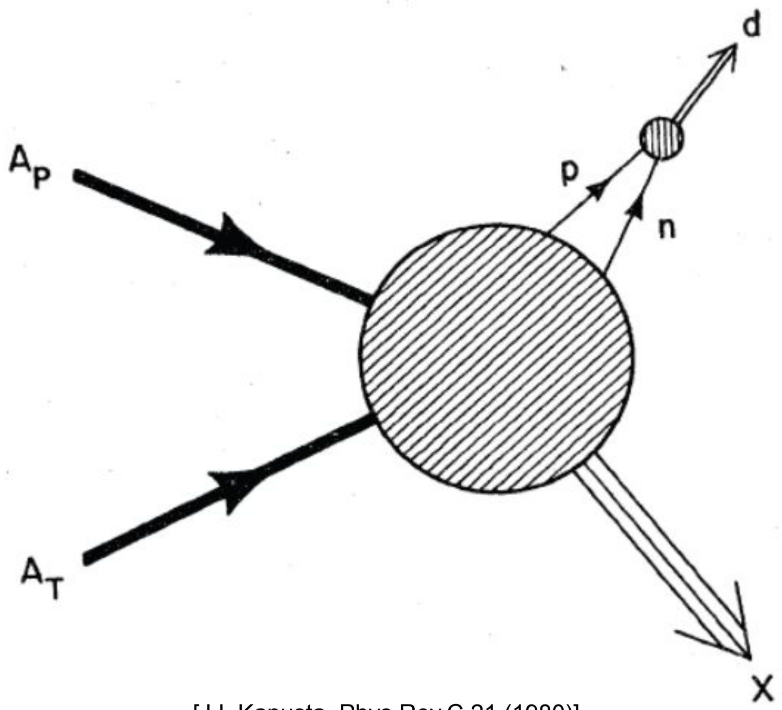
Technische Universität München

The coalescence model

Spherical approximation

- A proton and a neutron form a deuteron if they are close in phase-space after the collision



[J.I. Kapusta, Phys.Rev.C 21 (1980)]

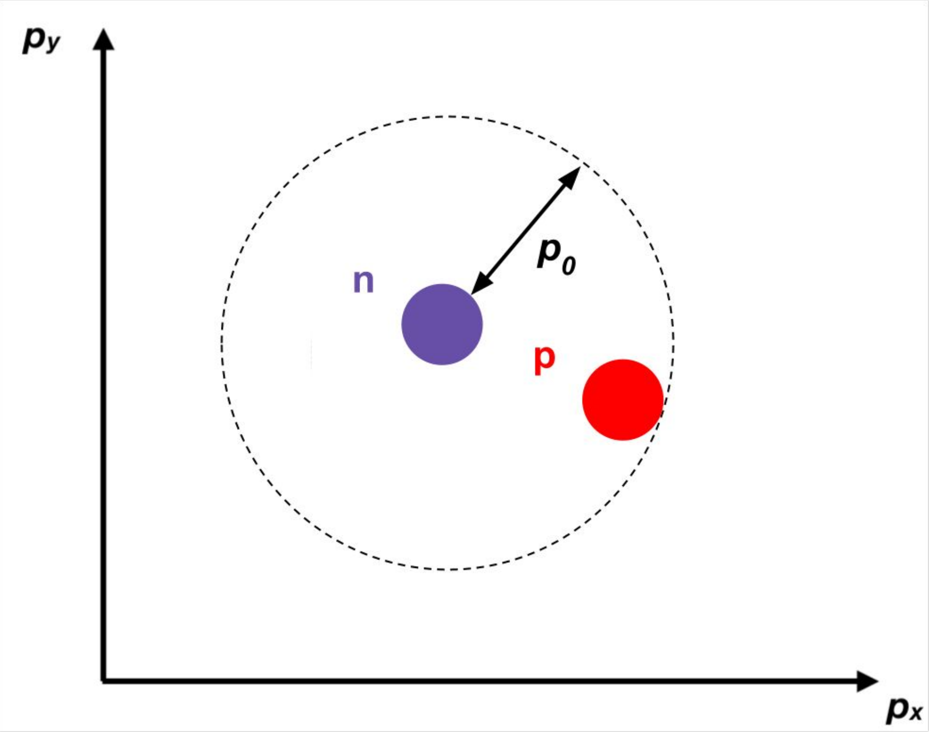
The coalescence model

Spherical approximation

- A proton and a neutron form a deuteron if they are close in phase-space after the collision
- Simplest implementation:

  Spherical approximation

- If relative momentum is less than some p_0 the nucleons will coalesce



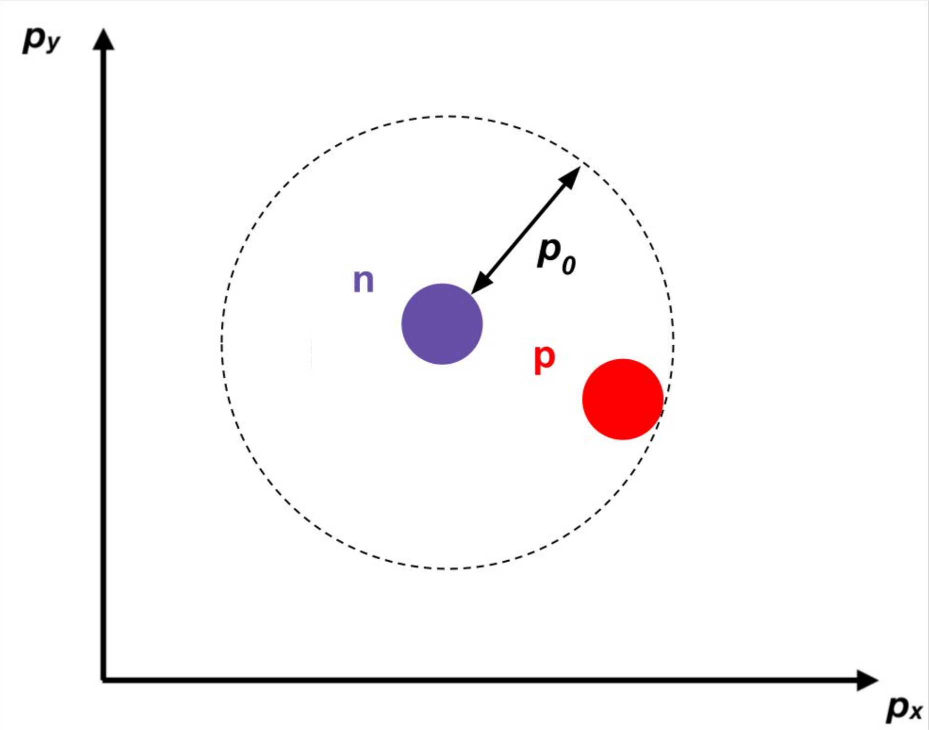
The coalescence model

Spherical approximation

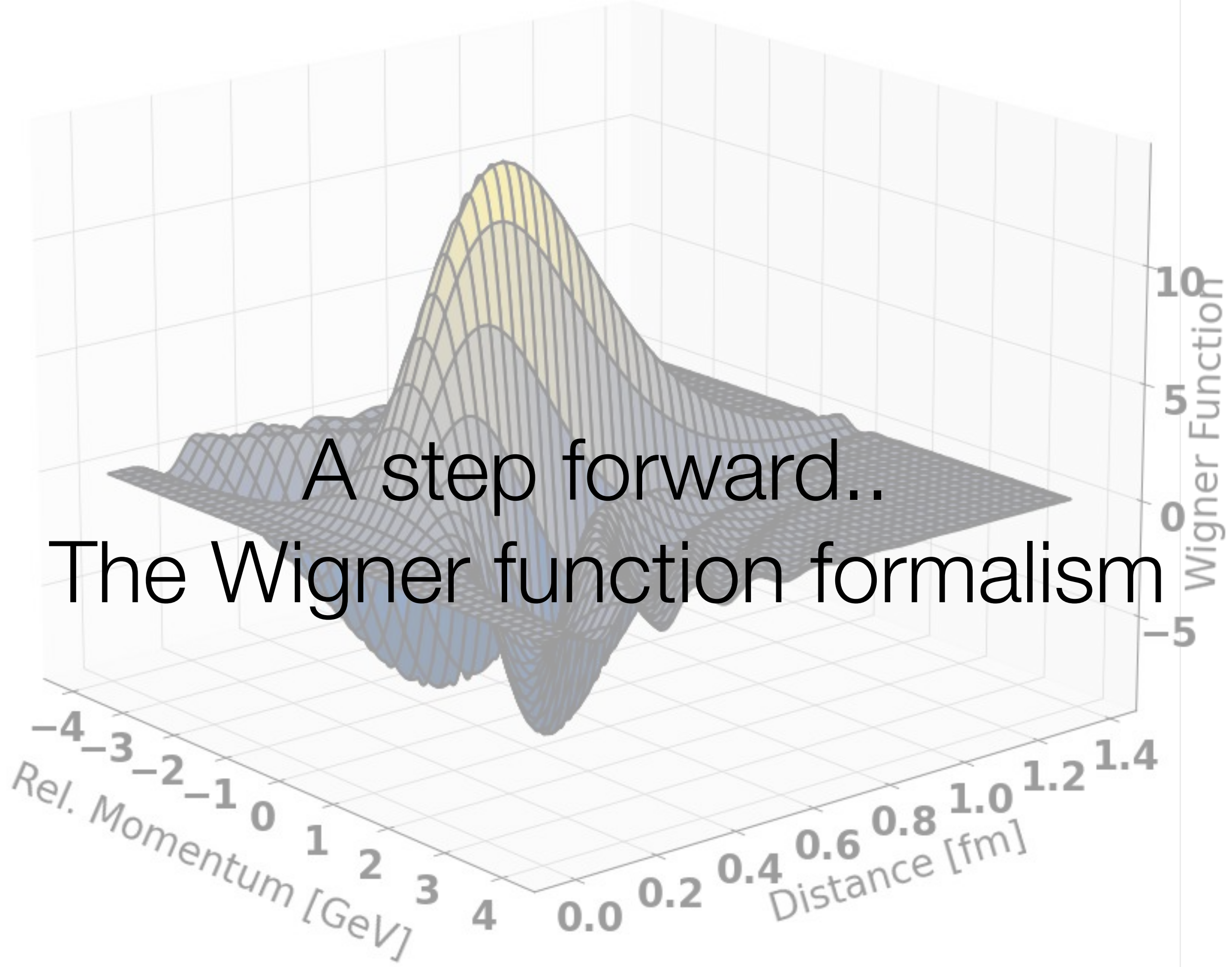
- A proton and a neutron form a deuteron if they are close in phase-space after the collision
- Simplest implementation:

  Spherical approximation

- If relative momentum is less than some p_0 the nucleons will coalesce
- Problem: spatial distances and QM Effects are not taken into account
- No Predictive power!!



A step forward..
The Wigner function formalism



The coalescence model

The Wigner function

- In recent years an effort has been made to incorporate QM effects into coalescence

- Wigner function:

$$W(x,p) = \frac{1}{\pi\hbar}\int_{-\infty}^{\infty} \psi^*(x+y)\psi(x-y)e^{2ipy/\hbar}\,dy$$

The coalescence model

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Wavefunction of the deuteron!

What is the wavefunction of the deuteron?

The coalescence model

The deuteron wavefunction

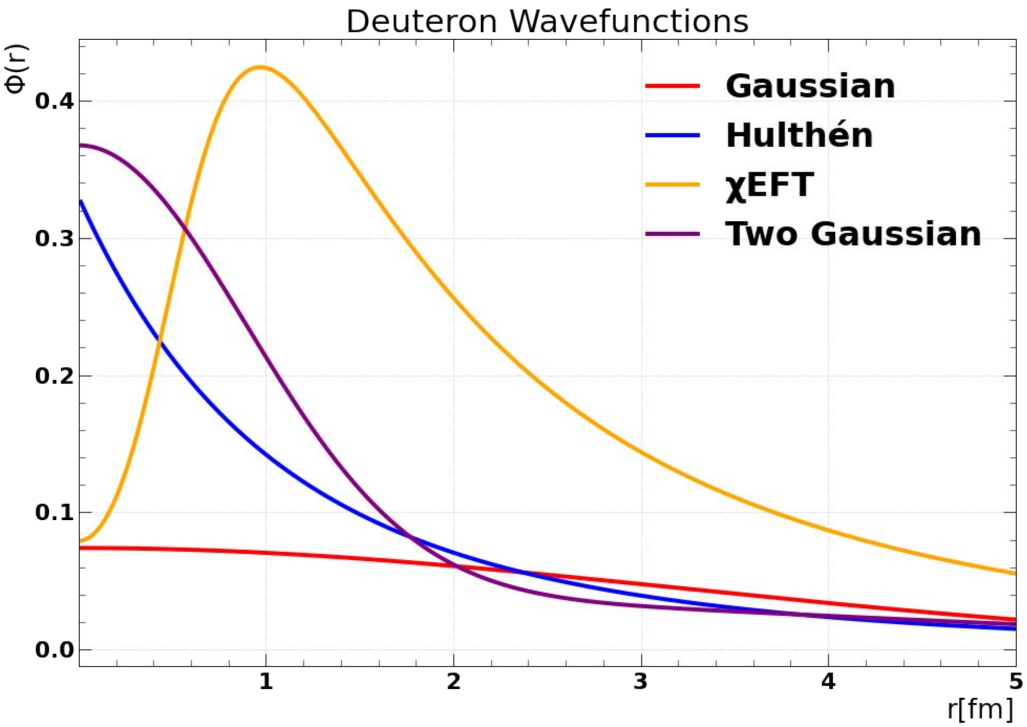
- There are multiple models for the deuteron wave function
- Simplistic:

  Single Gaussian
- Experimental data ('50s):

  Two Gaussian
- From *pion field theory* ('50s):

  Hulthén
- From modern χ_{EFT}:

  Argonne ν_{18}



The coalescence model

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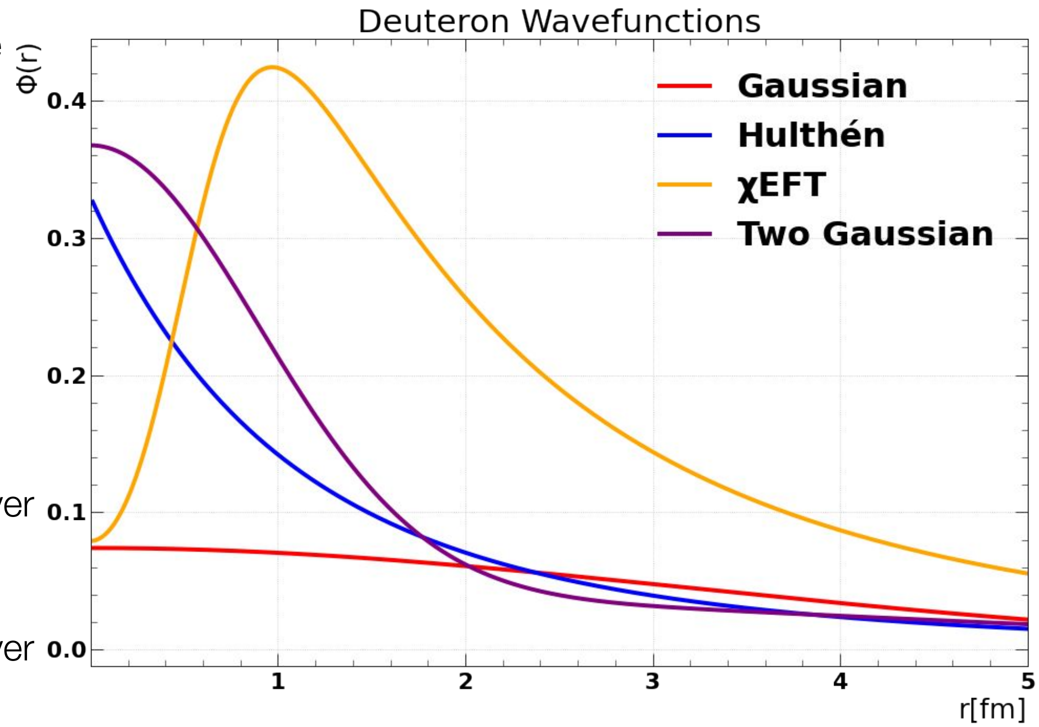
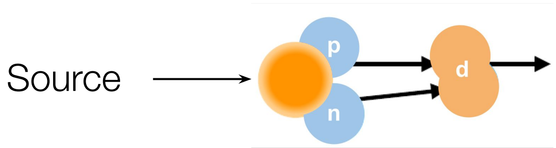


The coalescence model

The Wigner function formalism

(from: Kachelriess et al. Eur.Phys.J.A 56 (2020))

What do we need for coalescence?



p,n-pair ⇨ deuteron

The coalescence model

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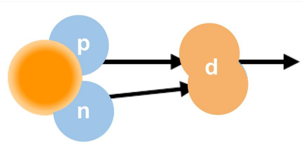

p,n-pair ⇨ deuteron

Quantum mechanics: $d^3N/dP^3 = Tr(\rho_d \rho_{Nucl})$

The coalescence model

The Wigner function formalism

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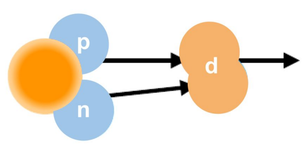

p,n-pair ⇨ deuteron

Quantum mechanics: $d^3N/dP^3 = \mathrm{Tr}(\rho_d \rho_{Nucl})$

$d^3N/dP^3 = \int d^3q \int d^3r_p \int d^3r_n$ *Deuteron Density* *Nucleon Density*

The coalescence model

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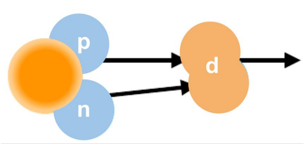


p,n-pair ⇨ deuteron

Quantum mechanics: $d^3N/dP^3 = Tr(\rho_d \rho_{Nucl})$

$d^3N/dP^3 = \int d^3q \int d^3r_p \int d^3r_n$ *Deuteron Density* *Nucleon Density*

$d^3N/dP^3 = S \int d^3q \int d^3r_p \int d^3r_n W(q,r) \; W_{np}(p_n,p_p,r_n,r_p)/(2\pi)^6$

Spin-Isospin statistics factor
(=⅜ for deuterons)

The coalescence model

The Wigner function formalism

(from: Kachelriess et al. Eur.Phys.J.A 56 (2020))

$$d^3N/dP^3 = S \int d^3q \int d^3r_p \int d^3r_n W(q,r)\; W_{np}(p_n,p_p,r_n,r_p)/(2\pi)^6$$

Assume no space-momentum correlations!

Assume uncorrelated emission of protons and neutrons!

- We can decompose $W_{np} = G_{np}(p_p,p_n)\; H_{np}(r_n,r_p) = G_{np}(p_p,p_n)\; h(r_n)\, h(r_p)$
- If we assume a Gaussian source h(r) we can calculate a coalescence probability

Gaussian wave function!

$$d^3N/dP^3 = S \int d^3r_p \int d^3r_n W(q,r)\; h(r_n)h(r_p) = 3\zeta \exp(-q^2d^2) \qquad \zeta=(d^2/(d^2+r^2))^{3/2}$$

depending on the rel. momentum ***q***, the source size ***r*** and deuteron size ***d***=3.2fm

The coalescence afterburner in EPOS 3

The coalescence afterburner

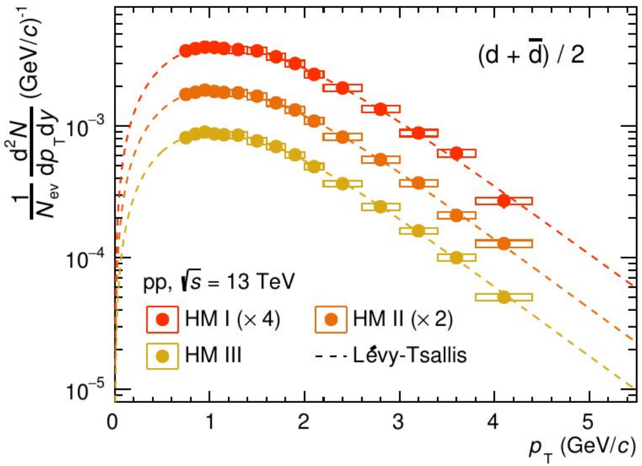
Deuteron data

- Light nuclei are not produced in event generators
- Use p,n pairs produced in the generator and apply Wigner function formalism to predict deuteron yields

Important quantities for coalescence:

  - Charged-particle multiplicity
  - Spatial distribution
  - Momentum distribution

ALICE Collab.: JHEP 01 (2022) 106

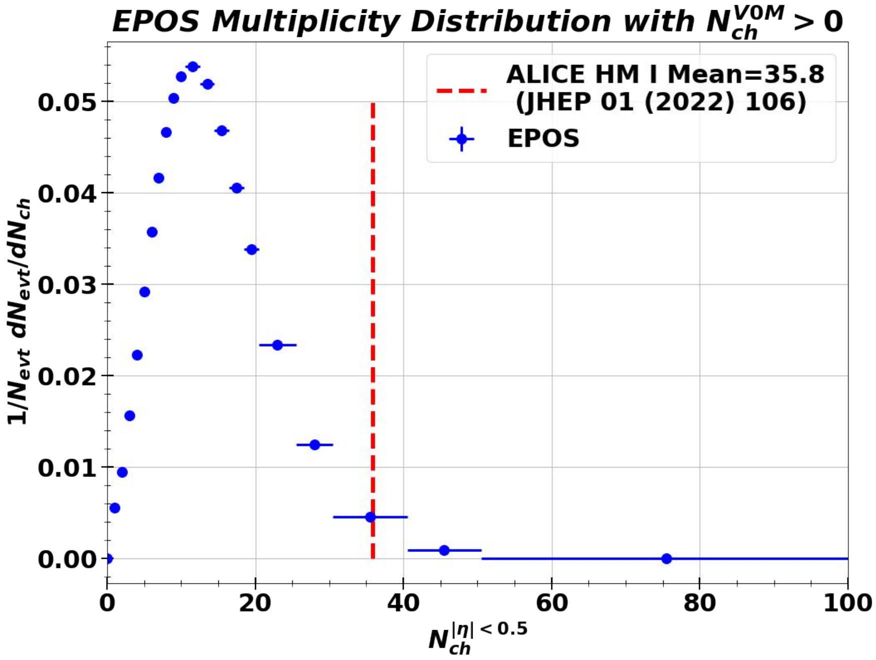


➡ All of these quantities were measured by ALICE for pp @ $\sqrt{s}$ = 13 TeV with high-multiplicity (HM) trigger including d and p spectra

The coalescence afterburner

Multiplicity distribution

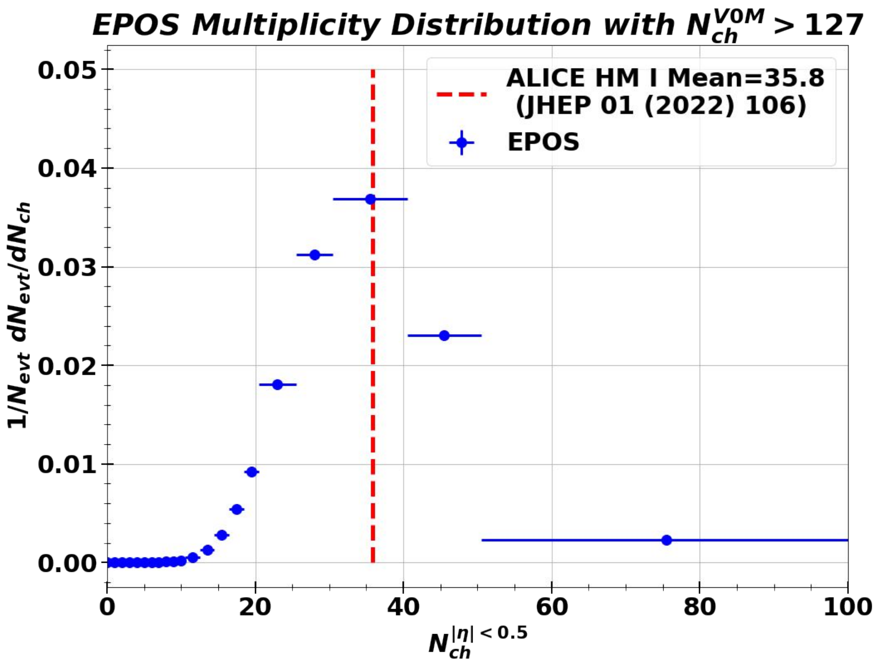
- Massive differences when comparing to HM I (0-0.01%) multiplicity class



The coalescence afterburner

Multiplicity distribution

- Massive differences when comparing to HM I (0-0.01%) multiplicity class
- After tuning the EPOS simulation we obtain the correct multiplicity distribution
- Tuning is done by triggering on forward and backward rapidity multiplicities



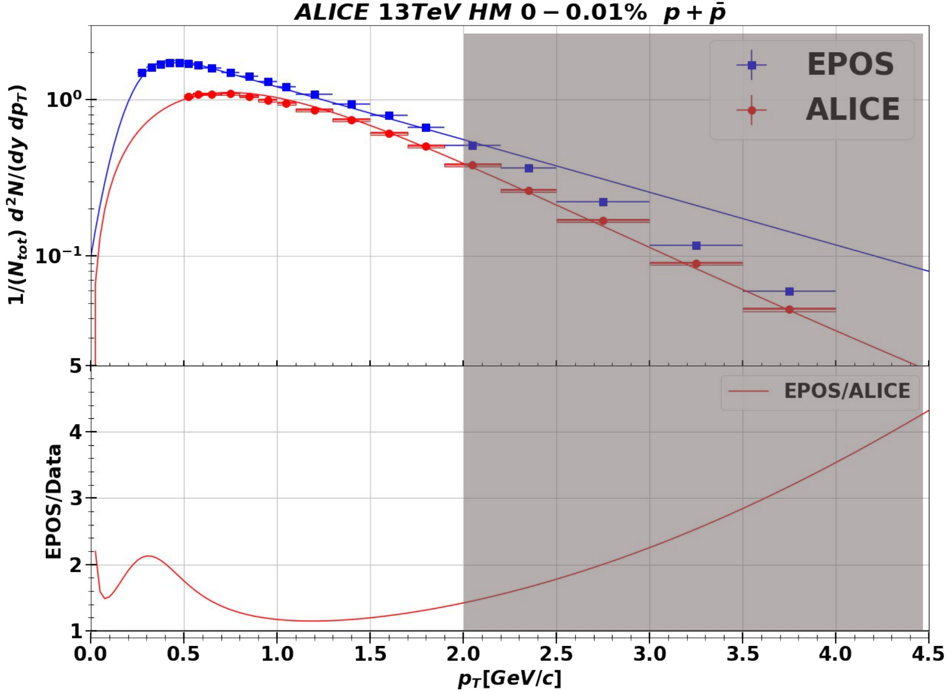
The coalescence afterburner

Momentum distribution

Correct momentum distribution

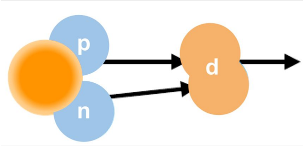
- Compare EPOS with measured ALICE HM data
- HM trigger for EPOS included
- Use their ratio as a correction function on an event-by-event basis
- Region $p_T > 2$ GeV not interesting for data comparison

ALICE Collab.: JHEP 01 (2022) 106



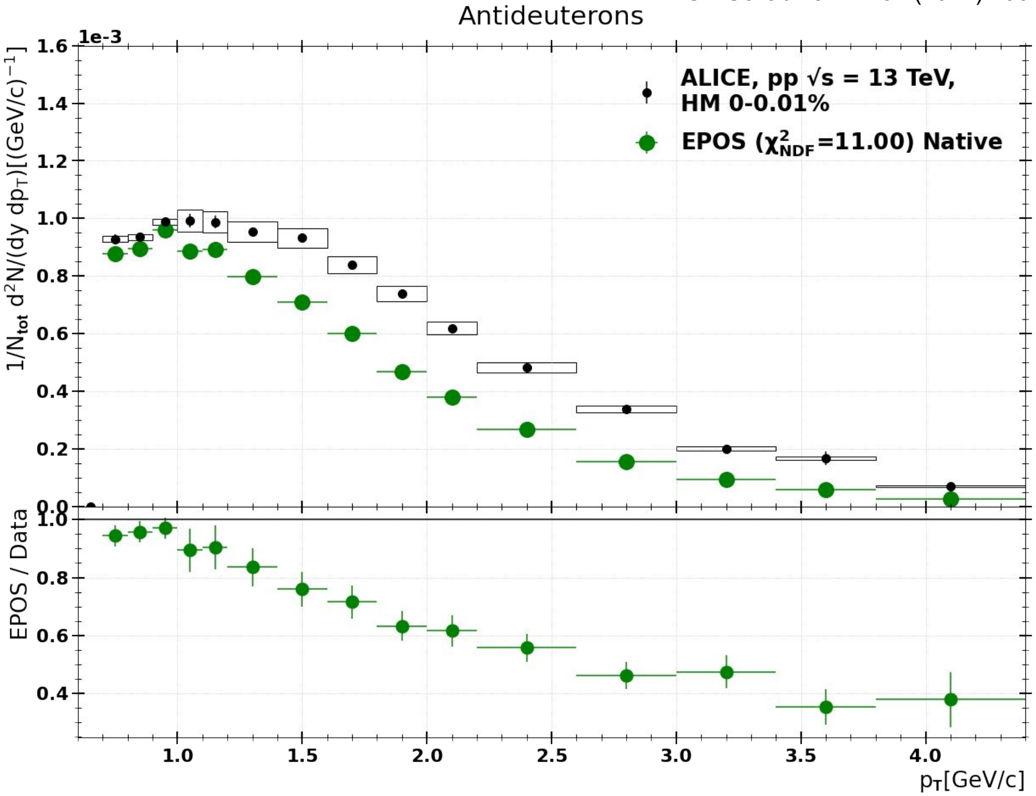
Deuteron spectra

Source model comparison



- For each p-n pair in each event simulated by EPOS we calculate the coalescence probability
- Reweight each nucleon according to p_T
- Gaussian wave function
- *Double Gaussian:* Yields are Factor 5-10 too large (not shown)

ALICE Collab.: JHEP 01 (2022) 106



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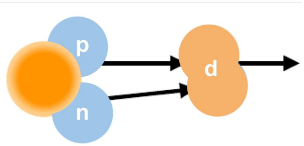
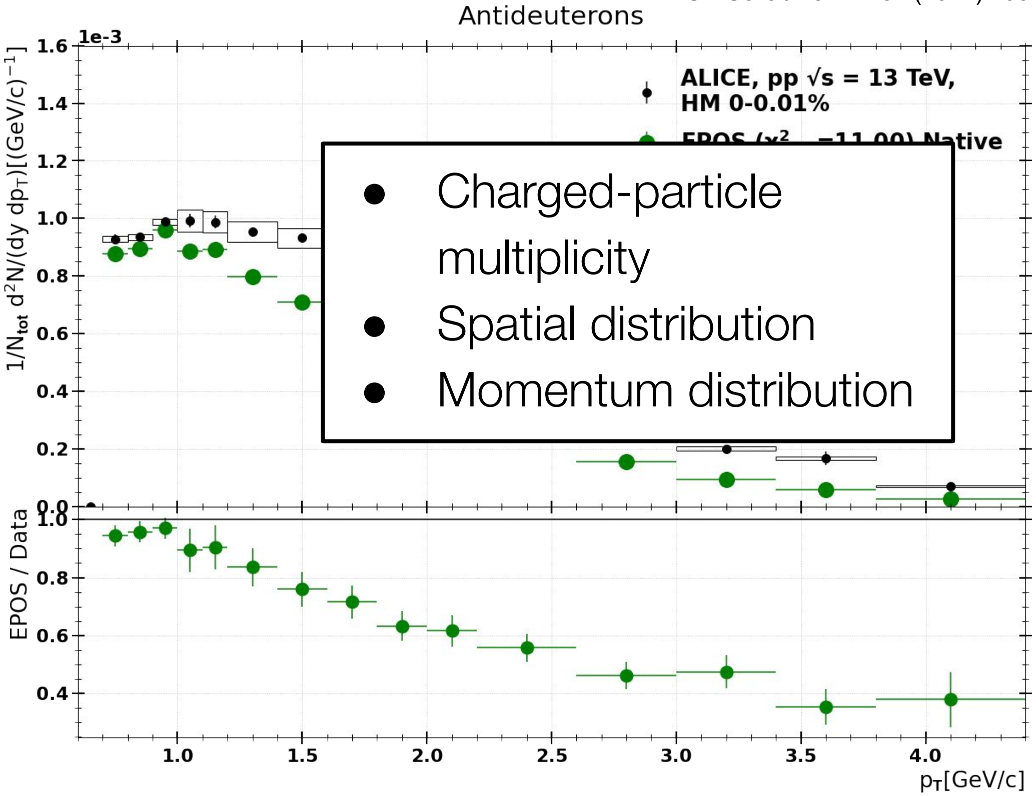


- For each p-n pair in each event simulated by EPOS we calculate the coalescence probability
- Reject events using HM trigger
- Reweight each nucleon according to p_T

ALICE Collab.: JHEP 01 (2022) 106



- Charged-particle multiplicity
- Spatial distribution
- Momentum distribution

Deuteron spectra

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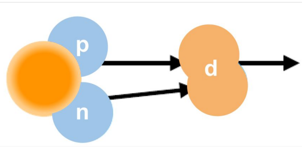

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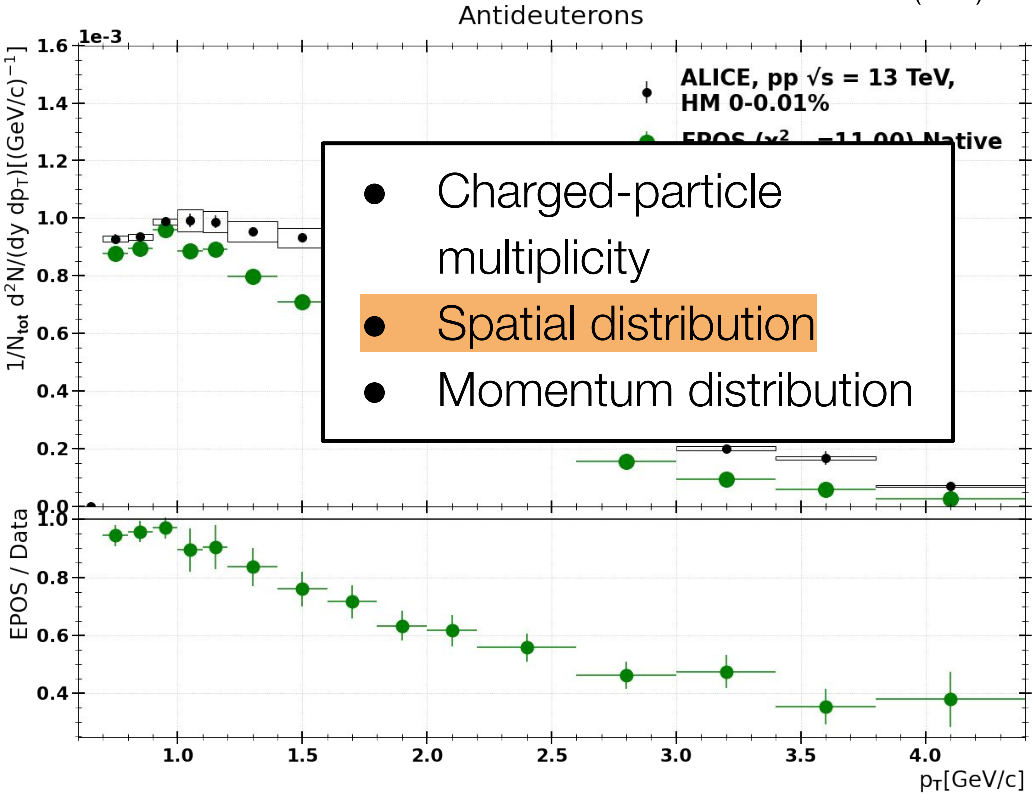
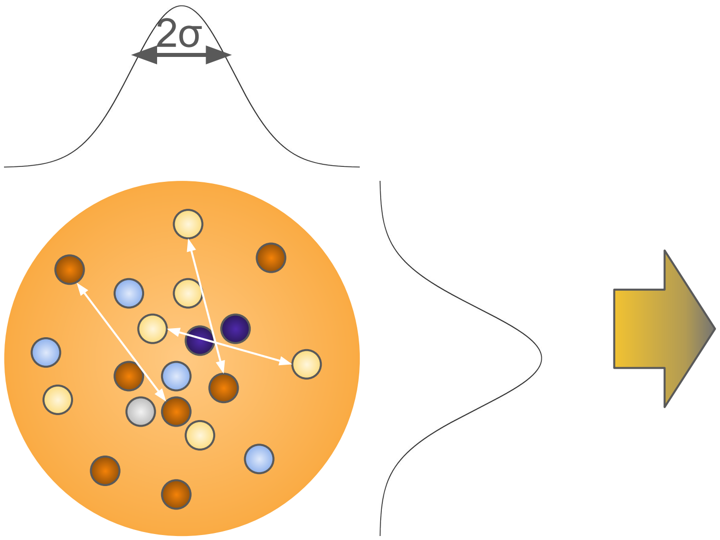


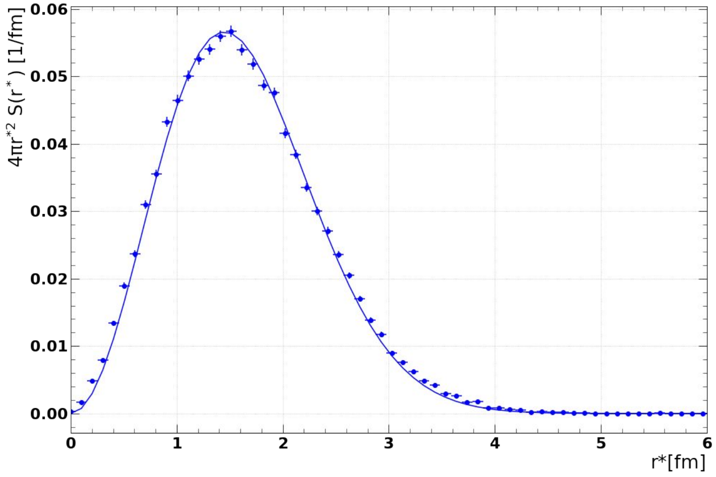
Modelling the source

The emission source

Basics

- The source size is defined by the distance between particle pair
- We assume a gaussian source distribution:





Fit using: $$\frac{4\pi r^{*2}}{(4\pi\sigma^2)^{3/2}} \exp\left(-\frac{r^{*2}}{4\sigma^2}\right)$$

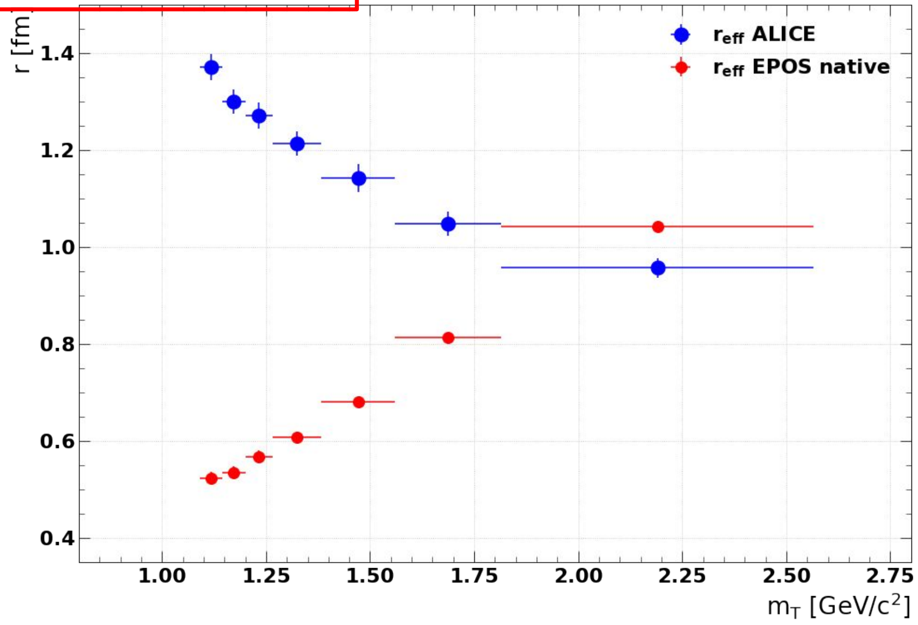
The emission source

Native EPOS results

1. Emissions source in pp HM was measured by ALICE Collab. using Femtoscopy techniques
2. EPOS fails to reproduce the m_T-scaling of the source

(See Chiara Pinto's talk from Monday for details)

ALICE Collab. Physics Letters B 811 (2020) 135849



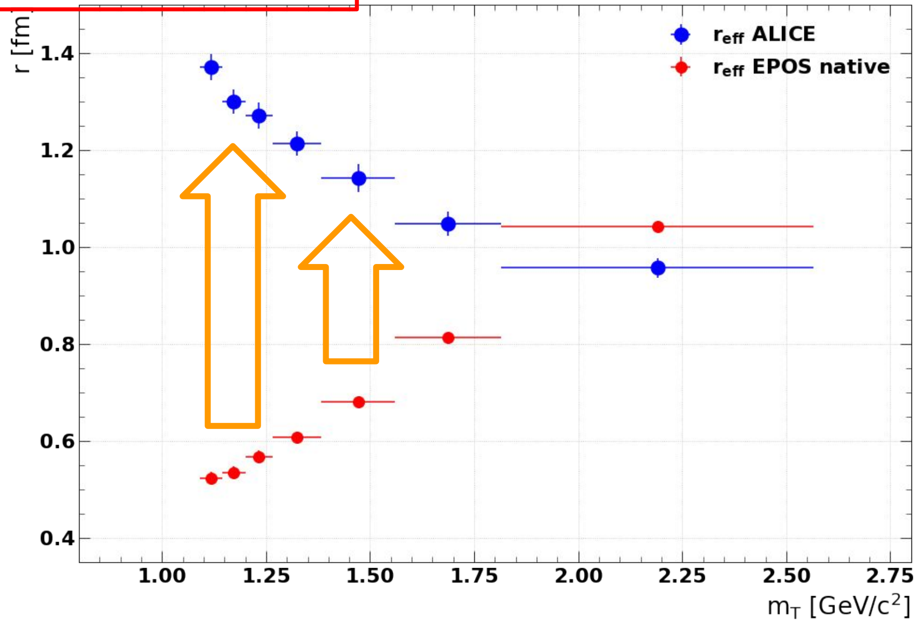
The emission source

Native EPOS results

(See Chiara Pinto's talk from Monday for details)

1. Emissions source in pp HM was measured by ALICE Collab. using Femtoscopy techniques
2. EPOS fails to reproduce the m_T-scaling of the source
3. Simple approach: sample distances from measurement according to the m_T of the pair
4. Advanced approach: Scale the source and propagate particles in EPOS to reproduce the measurement

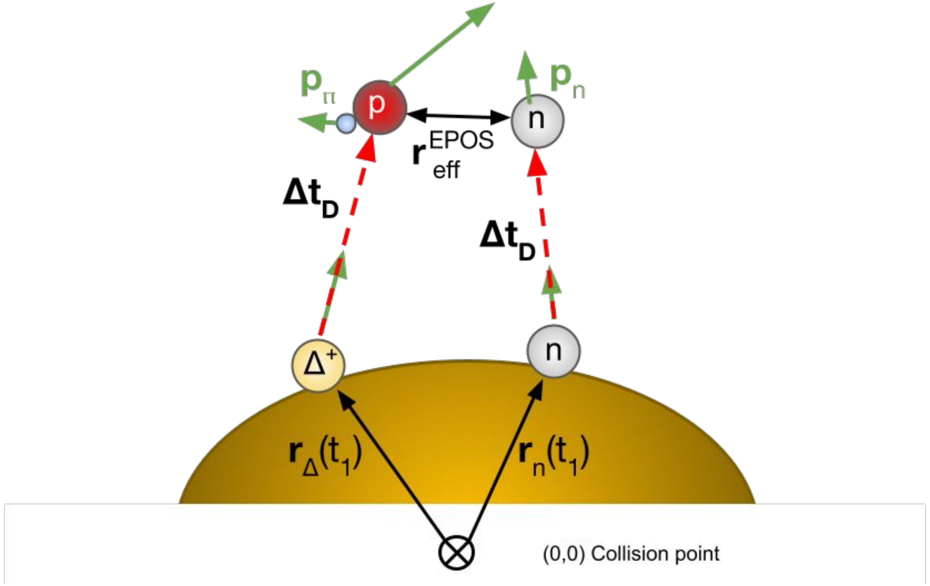
ALICE Collab. Physics Letters B 811 (2020) 135849



The advanced source model in EPOS

Scheme

Propagation scheme:

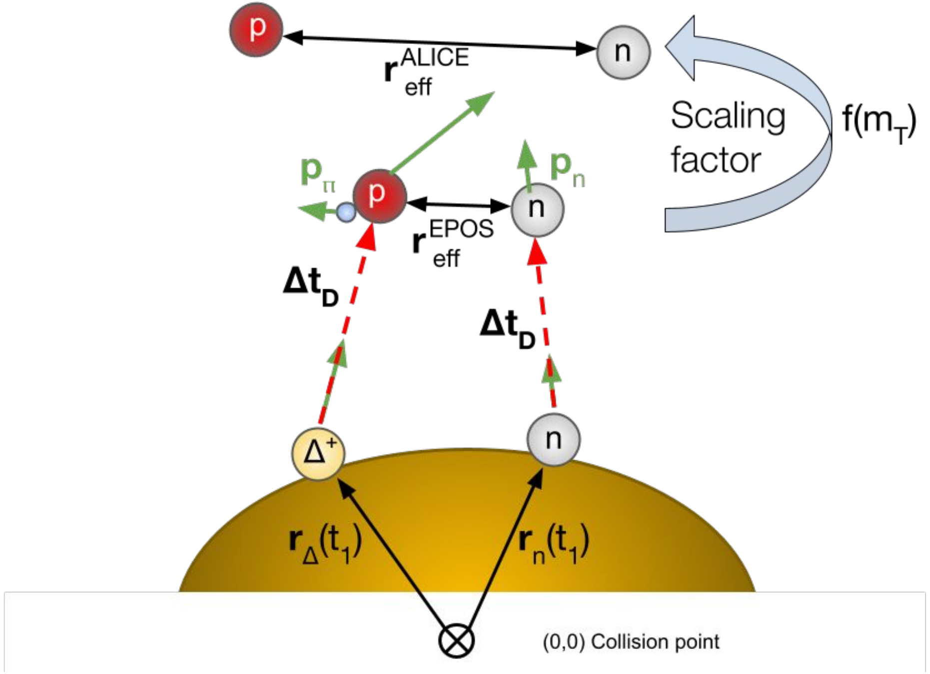


The advanced source model in EPOS

Scheme

Propagation scheme:

- We obtain a scaling factor as a function of m_T from the source size measurement



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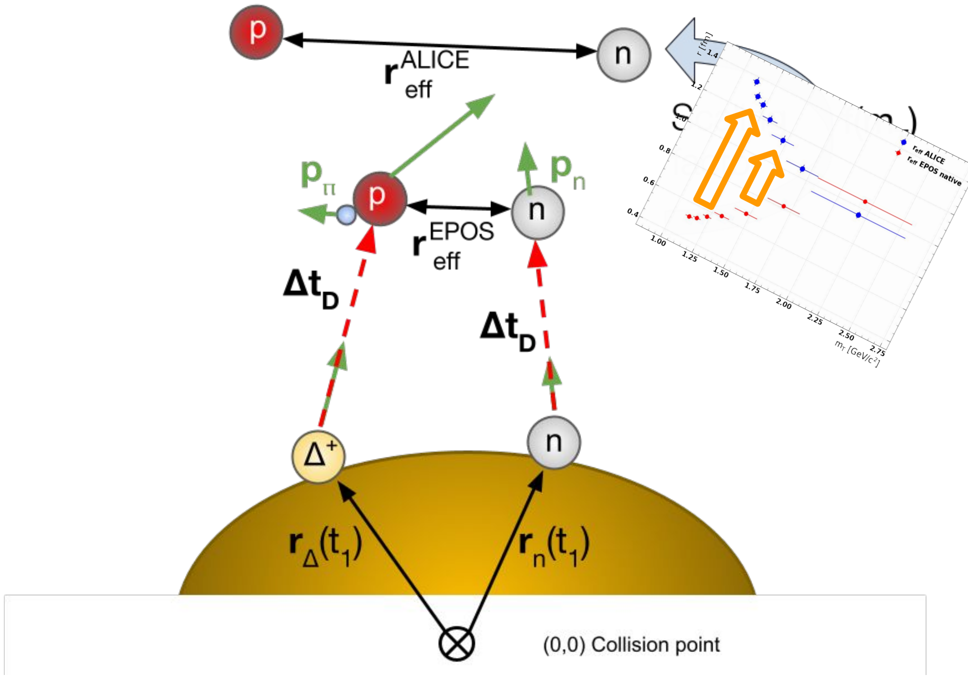
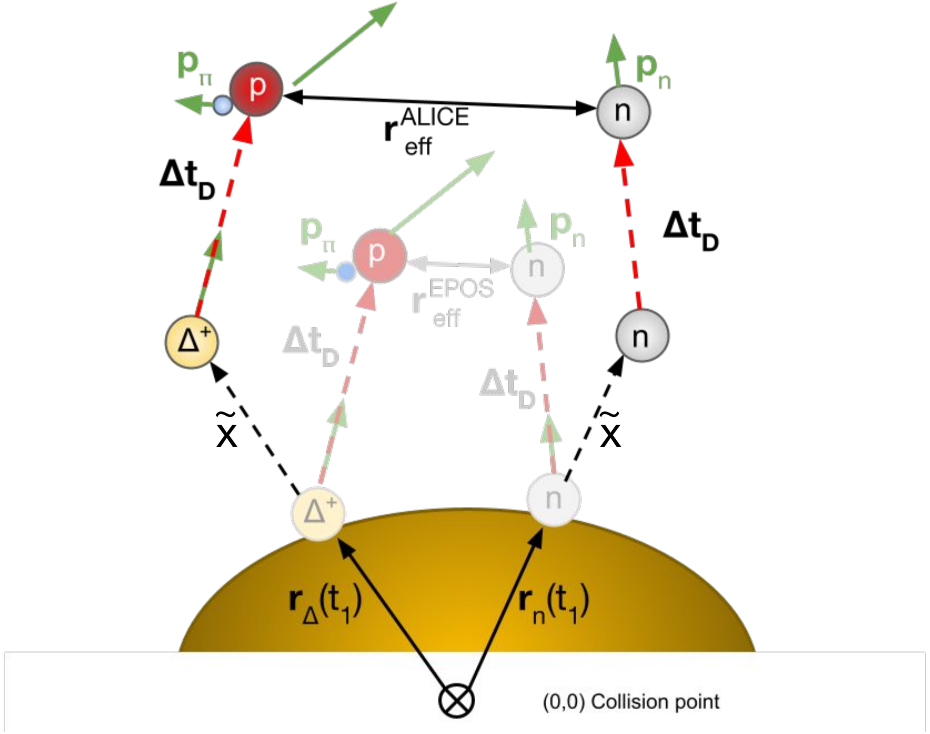


The advanced source model in EPOS

Scheme

Propagation scheme:

- We obtain a scaling factor as a function of m_T from the source size measurement
- We move the primordials out radially until we reach the scaled distance
- This distance ($\tilde{x}$) is the same for both primordials of the pair

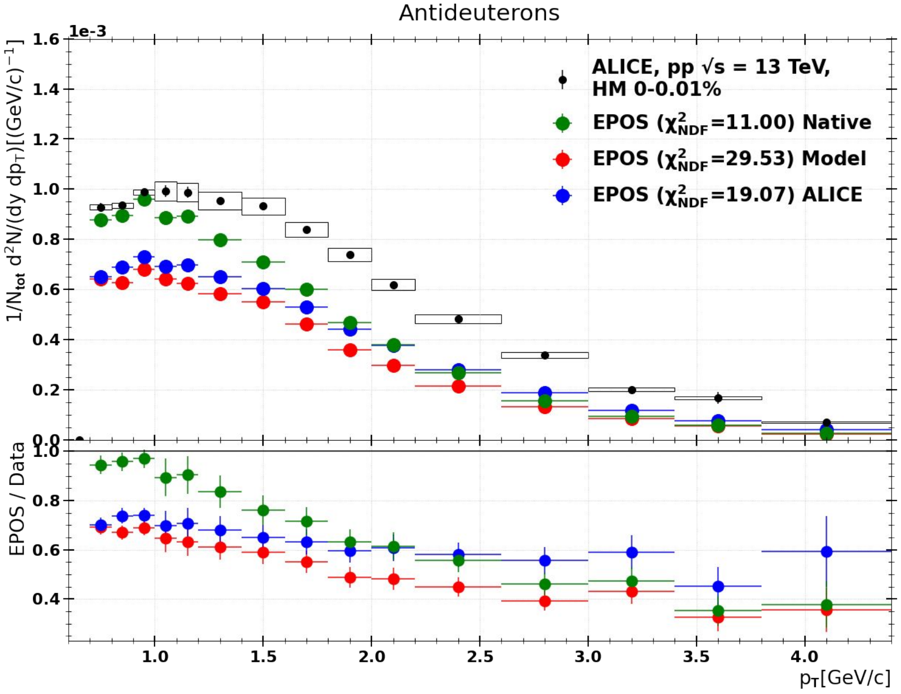


Deuteron spectra with different source models using the Wigner function formalism

Deuteron spectra

Source model comparison

- “Native”: unaltered EPOS source
- “Model”: Source model with propagation scheme
- “ALICE”: Source model sampling from the measurement
- *Double Gaussian:* Yields are Factor 5-10 too large (not shown)

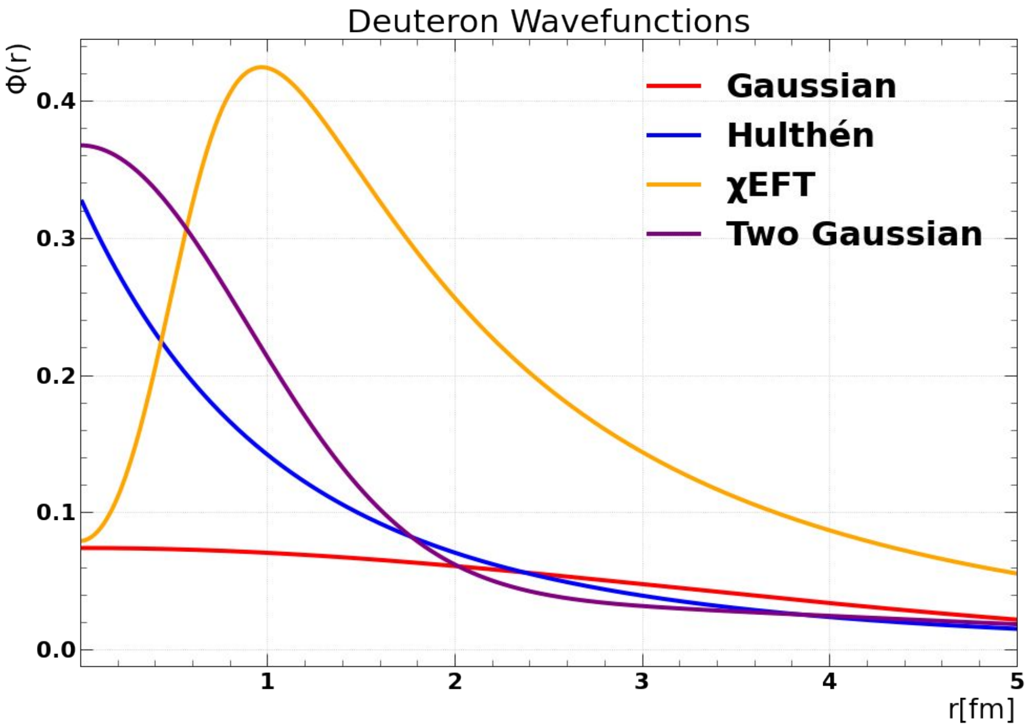


Improving the coalescence results

The coalescence model

The deuteron wavefunction

- There are multiple models for the deuteron wave function
- Simplistic:
  Single Gaussian
- Experimental data ('50s):
  Two Gaussian
- From *pion field theory* ('50s):
  Hulthén
- From modern χ_{EFT}:
  Argonne ν_{18}



The coalescence model

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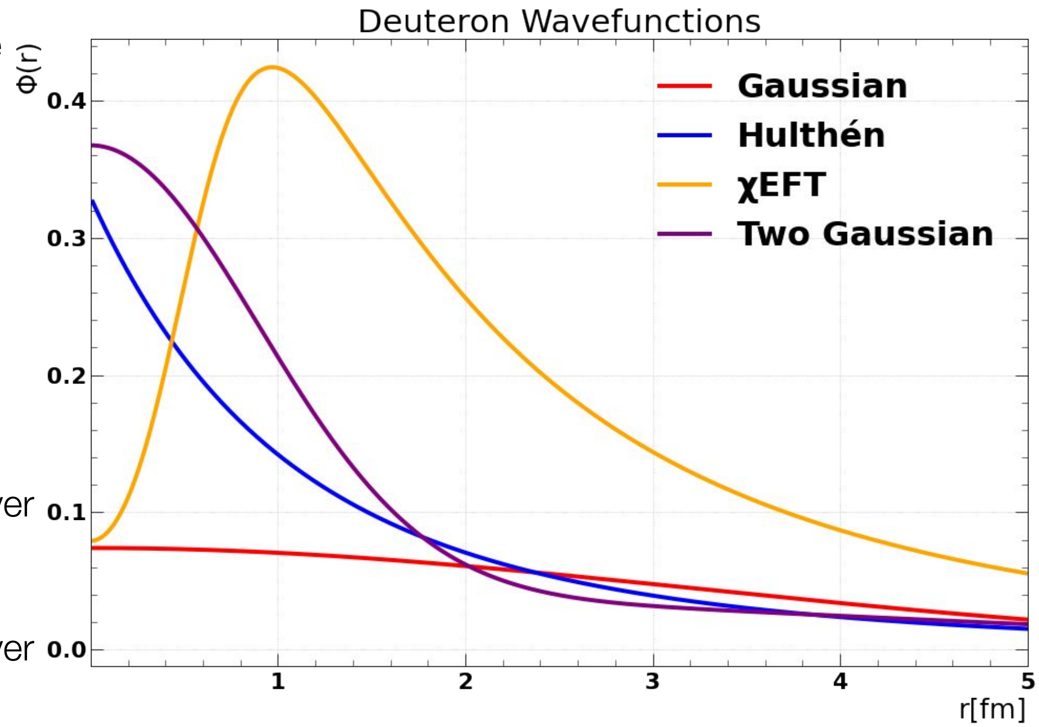

The coalescence model

The deuteron wavefunction

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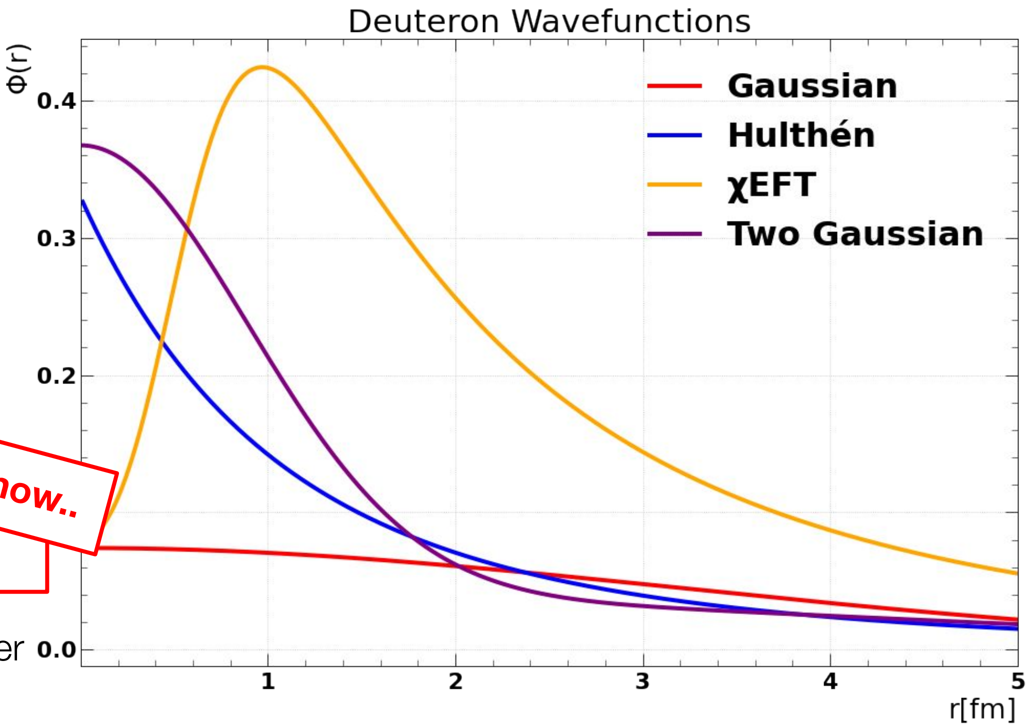
Until now..



The Hulthén Wigner function

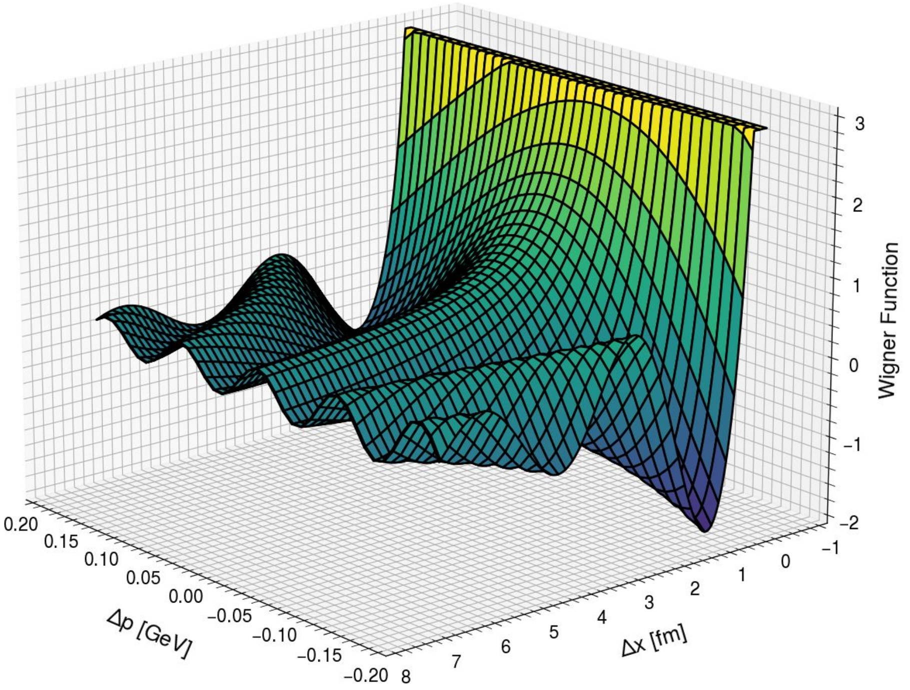
- Hulthén wave function comes from a Yukawa-like potential

$$\varphi_d(r) = \sqrt{\frac{ab(a+b)}{2\pi(a-b)^2)}}\frac{e^{-ar} - e^{-br}}{r}$$

- Wigner function has a *(surprisingly)* simple form

$$\frac{ab(a+b)}{2\pi(a-b)^2} \, 16\pi^2 \frac{\cosh(r(a-b))}{q} \cos(2qr) \exp(-r(a+b))$$

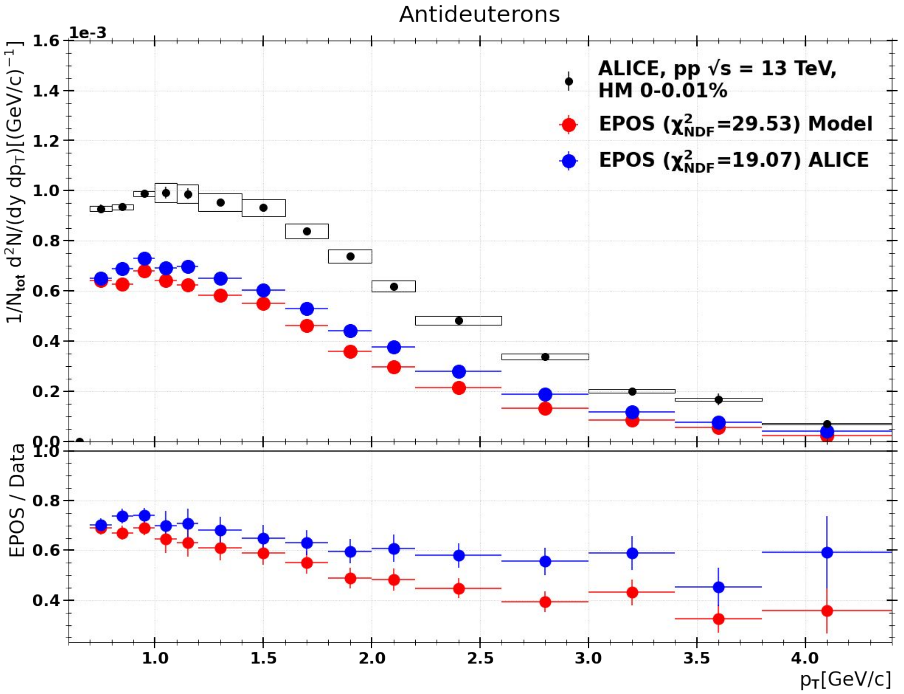
- Calculate probability (so far only numerical integration)



Deuteron spectra with Hulthén wave function and 2 different source models

Coalescence using Hulthén

Deuteron Spectra

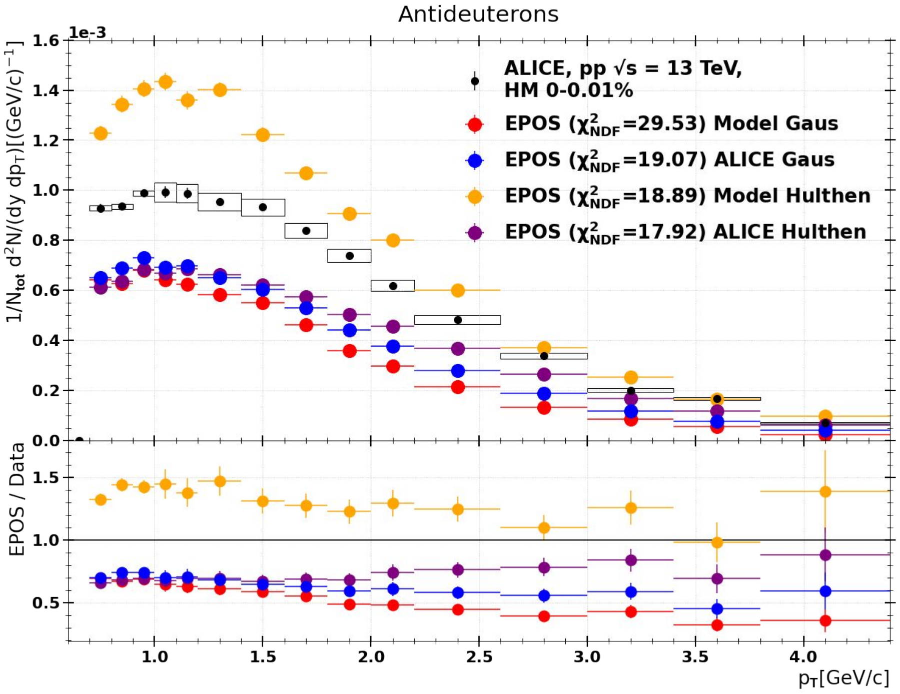


Coalescence using Hulthén

Deuteron Spectra

- "Model": ~45% too high yield
- "ALICE": ~25% too little yield
- Big difference when breaking correlations! (from sampling random distances)

➡ Further study correlations!

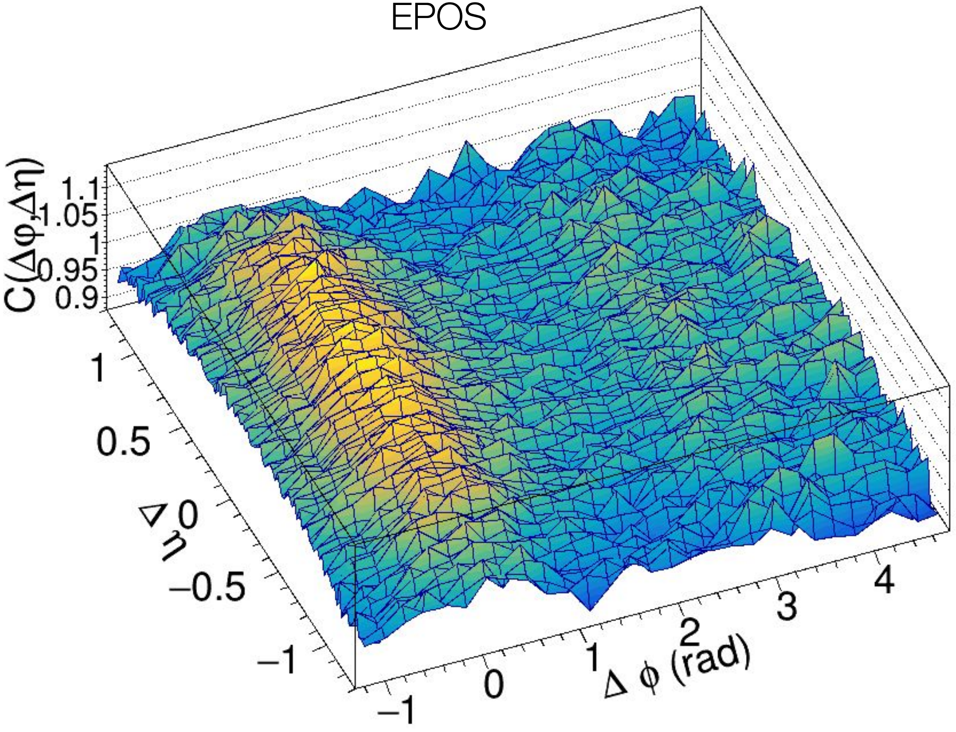


Correcting angular correlations

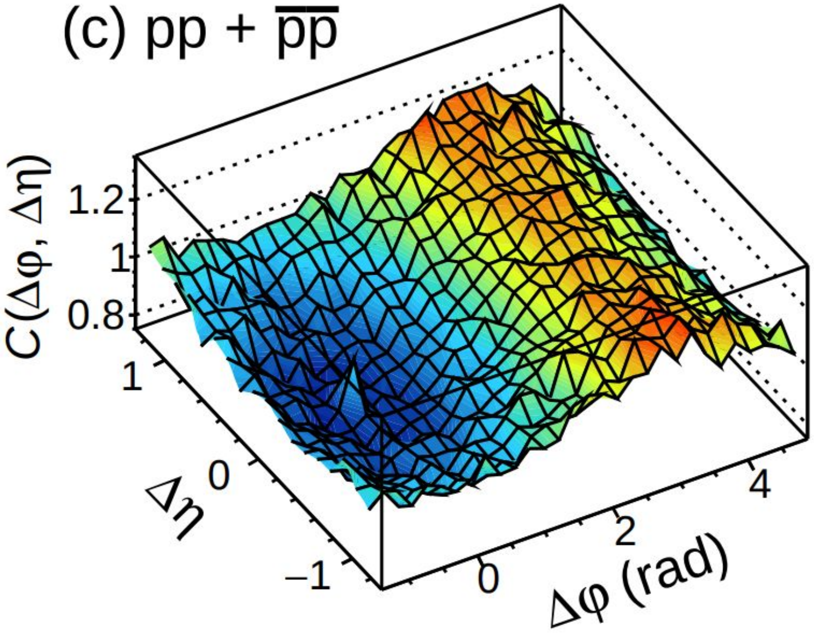
Correlations comparison

Δη-Δφ Correlation function

EPOS



ALICE (*Eur.Phys.J.C* 77 (2017) 8, 569)



Correlations comparison

Δη-Δφ Correlation function

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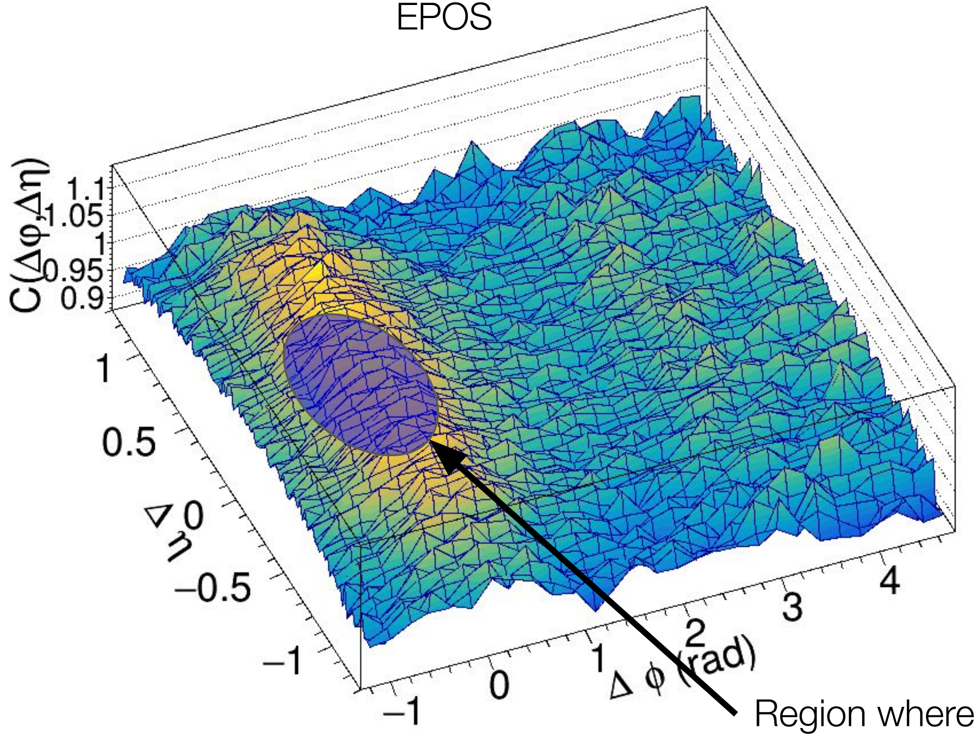

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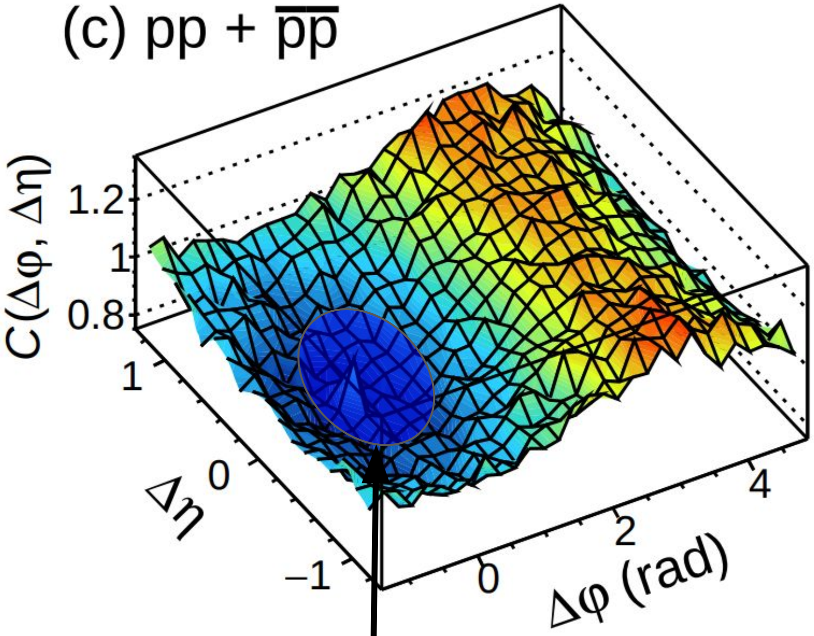


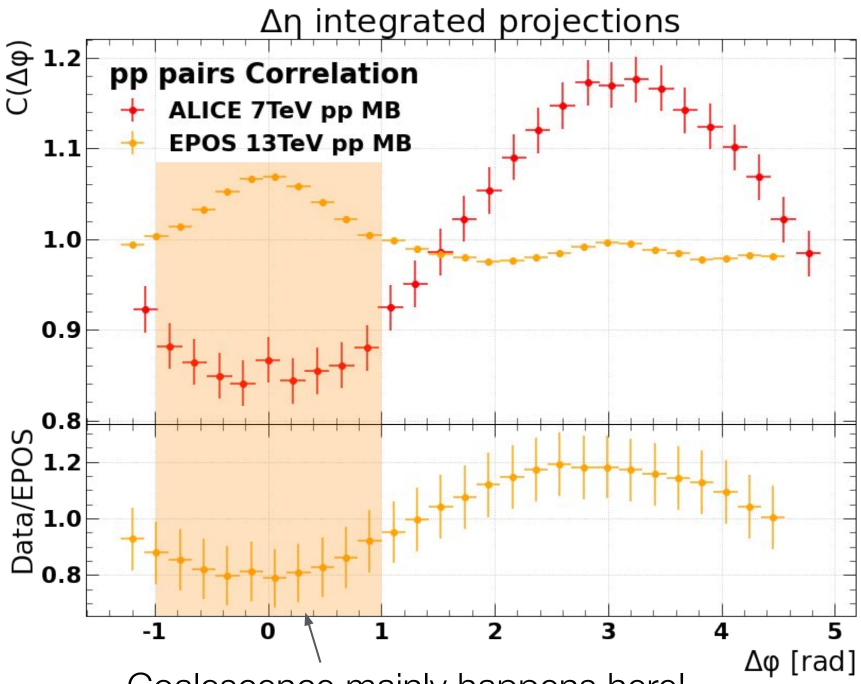
Region where coalescence happens!

Angular correlations

Δη-integrated $\Delta\varphi$ Correlation function

- Comparison between 7TeV MB pp by ALICE and 13 TeV MB in EPOS
- No 13 TeV HM data published
- Big differences in the region of interest!

ALICE Collab. (*Eur.Phys.J.C* 77 (2017) 8, 569)

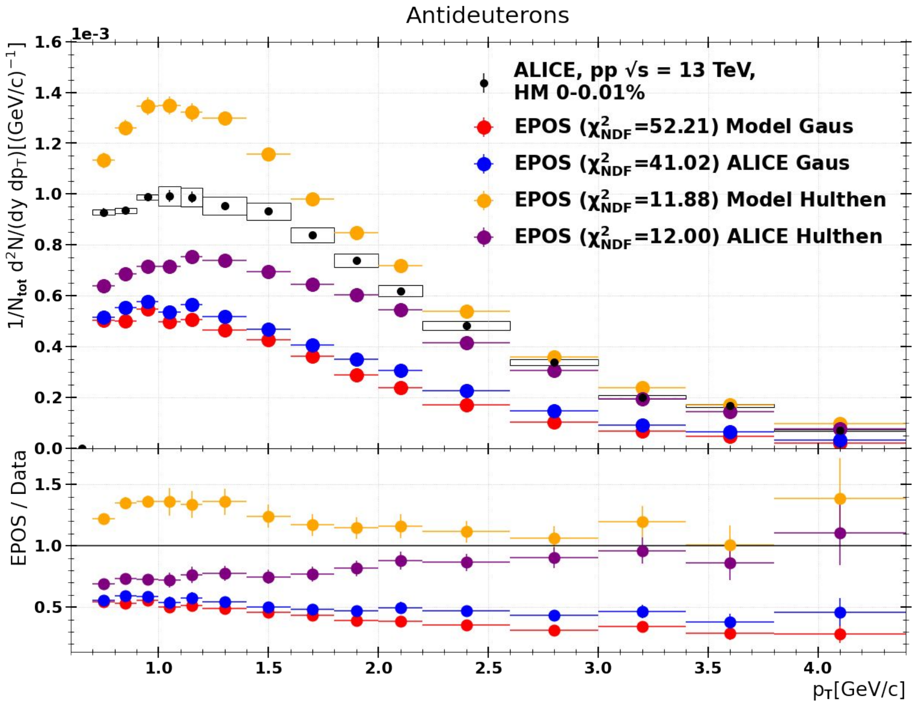


Coalescence mainly happens here!

Deuteron spectra

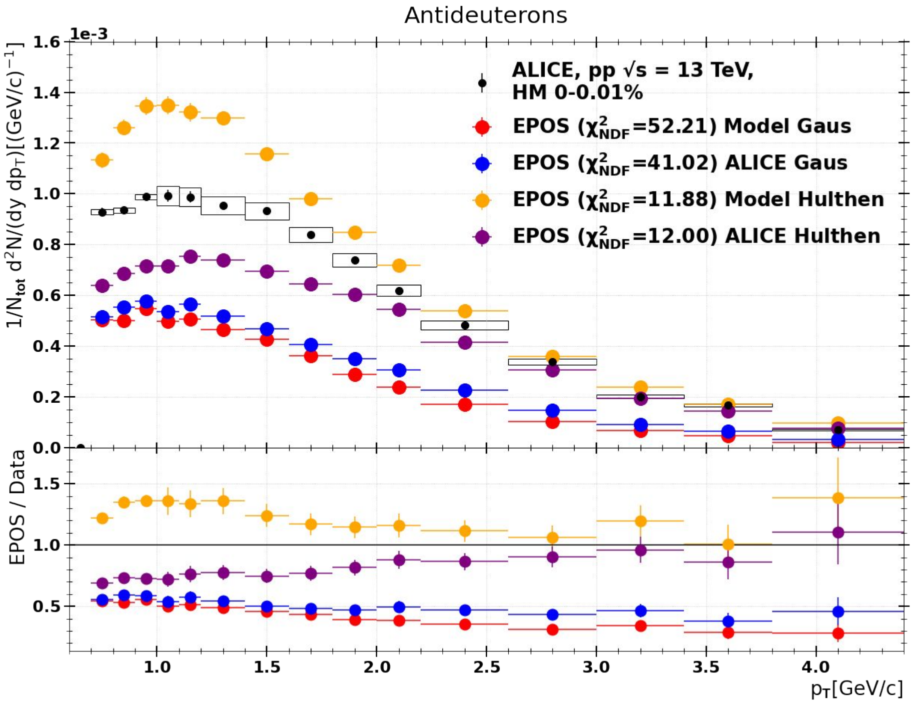
$\Delta\varphi$ Reweighting

- Improvement of the Hulthen + Model (45%->30%)
- In future improvement with 2D Δη-$\Delta\varphi$ correlation



Summary

- Event generators need to be tuned and improved a lot to get a realistic description
- Hulthén wave function working much better than Gaussian
- Two-particle correlations have a huge impact on coalescence predictions

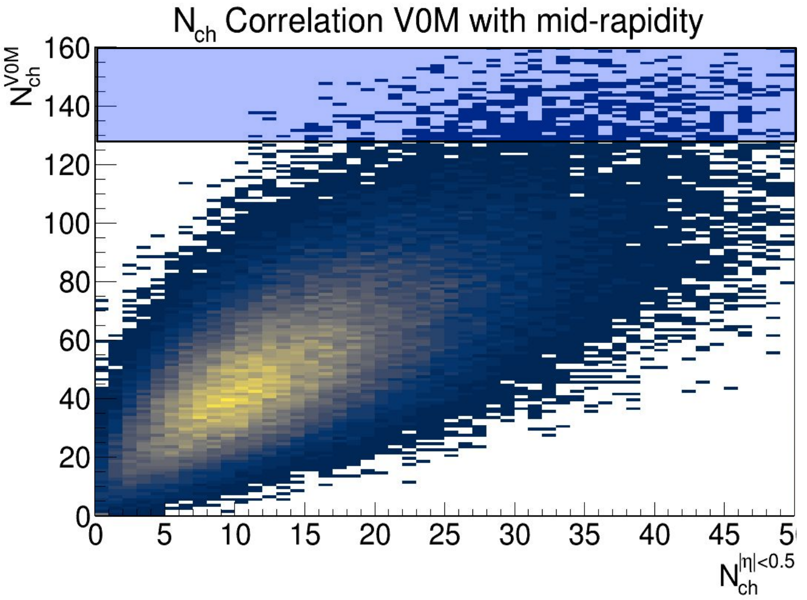



Event Generators
need to improve
CHANGE MY MIND
imgflip.com

Backup slides

High multiplicity trigger in EPOS

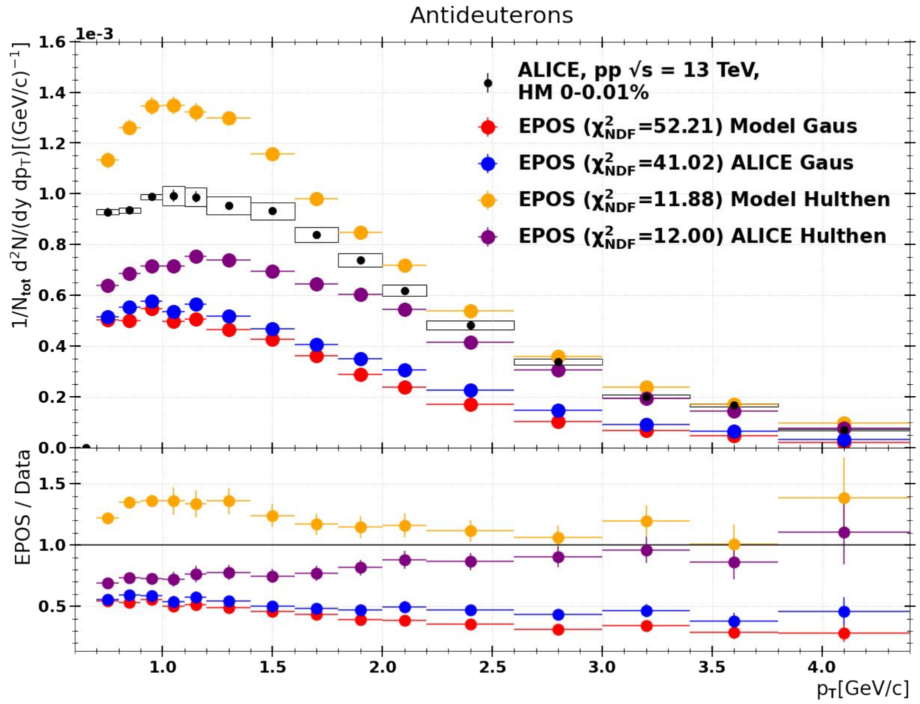
- **Approach**: follow ALICE method closely
- Correlate charged particle multiplicities in V0M region with mid-rapidity
- Trigger for different V0M multiplicities and compare mid-rapidity to ALICE measurement

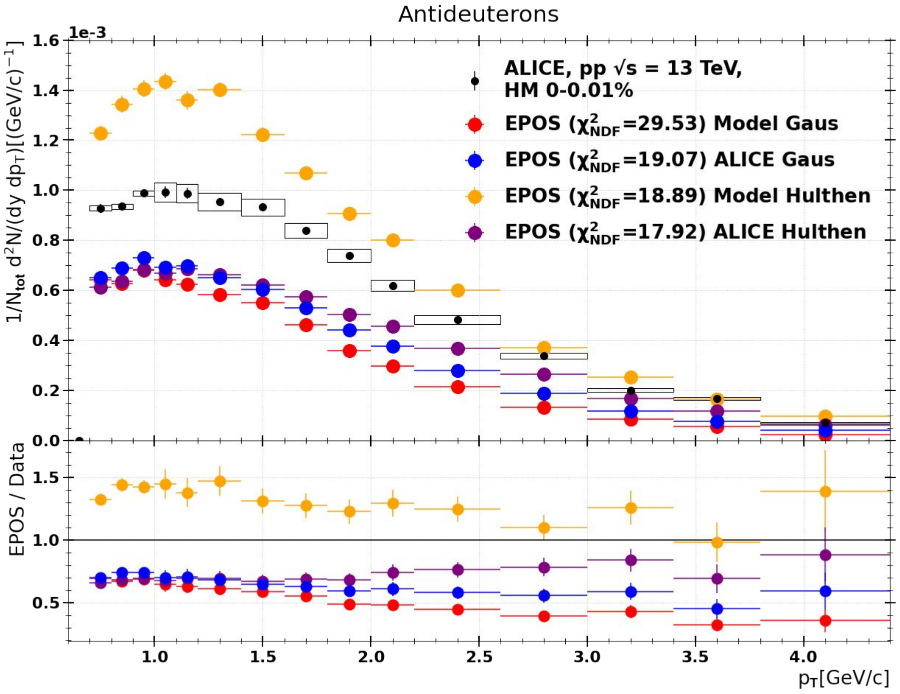


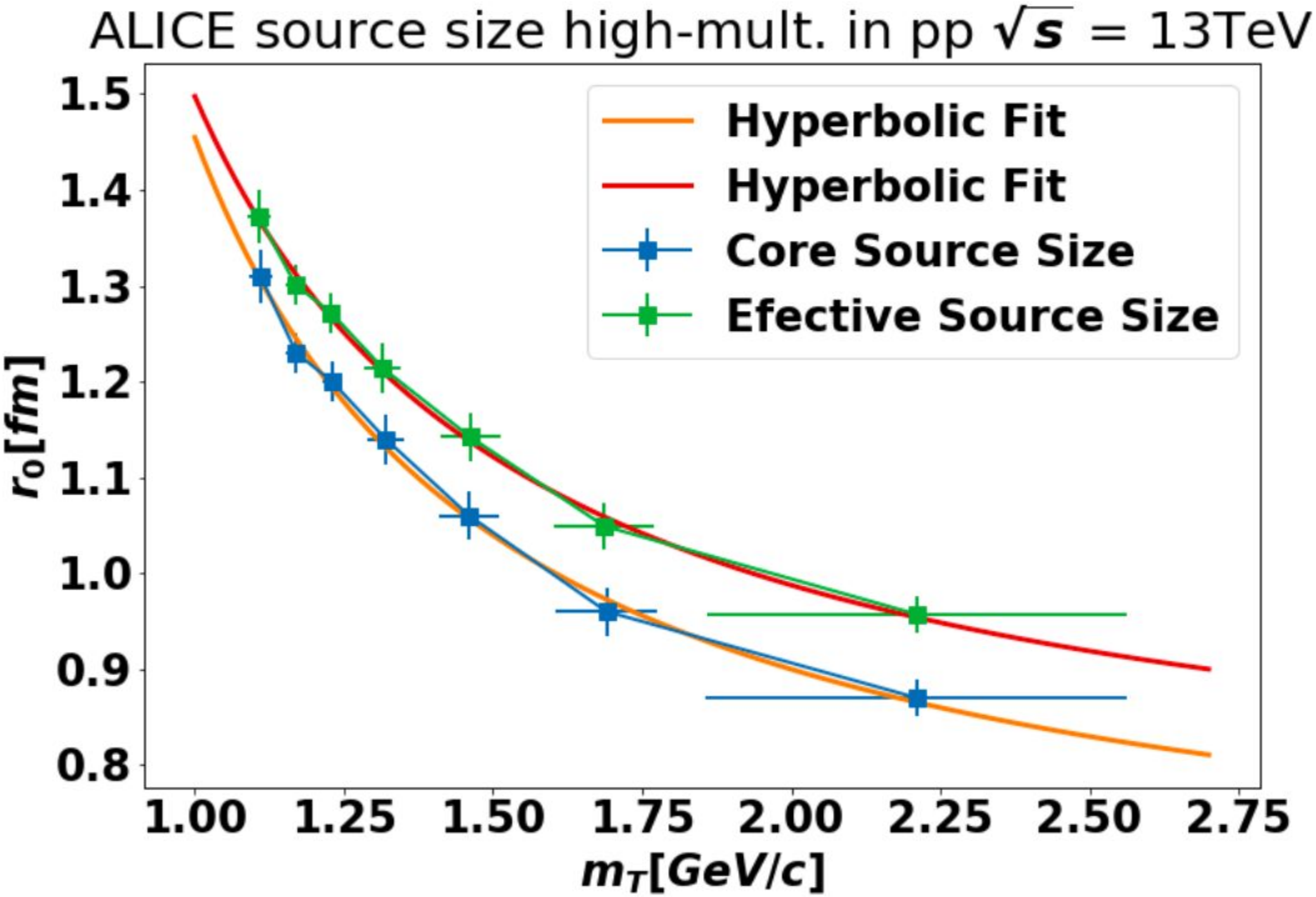
V0M: $-3.7 < \eta < -1.7$ and $2.8 < \eta < 5.1$

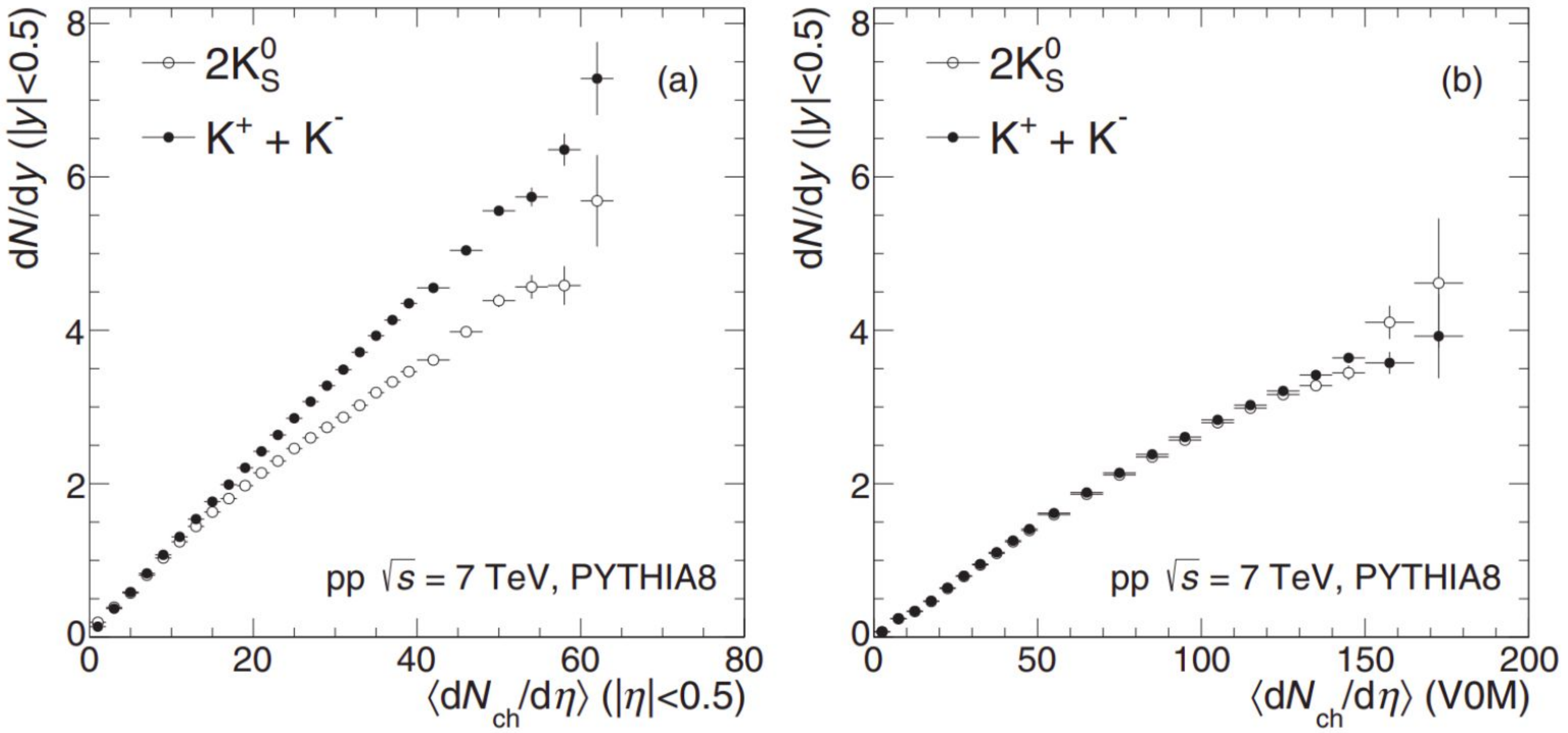
mid-rapidity: $-0.5 < \eta < 0.5$

Comparison with and without Δη-Δφ Correlation

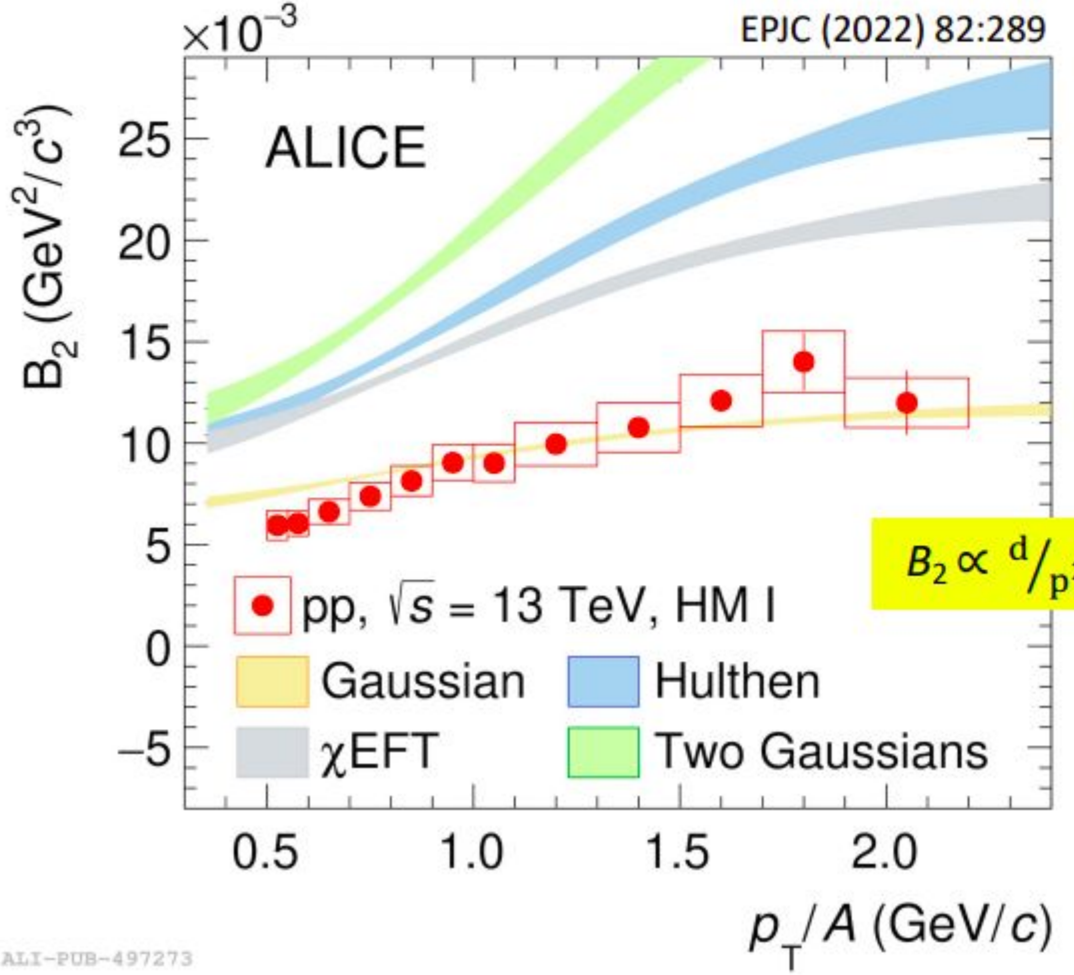





ALICE source size high-mult. in pp $\sqrt{s}$ = 13TeV
1.5
1.4
1.3
1.2
1.1
1.0
0.9
0.8
$r_0[fm]$
1.00
1.25
1.50
1.75
2.00
2.25
2.50
2.75
$m_T[GeV/c]$
Hyperbolic Fit
Hyperbolic Fit
Core Source Size
Efective Source Size



dN/dy (|y|<0.5)
$2K^0_S$
$K^+ + K^-$
(a)
pp $\sqrt{s}$ = 7 TeV, PYTHIA8
⟨dN_{ch}/dη⟩ (|η|<0.5)
(b)
⟨dN_{ch}/dη⟩ (V0M)



$B_2 \propto {}^{d}/_{p^2}$