Coalescence studies

meeting @ cern, 6 May 22

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for the TUM group

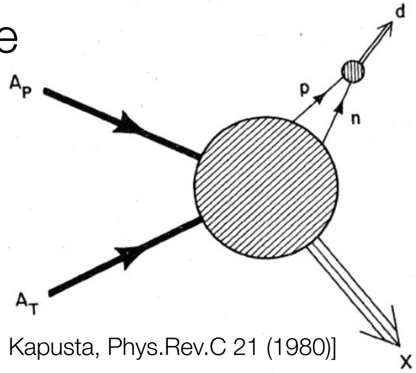
What have we done so far

Coalescence Parameter

Nucleons close in phase-space can form a nucleus by coalescence

Coalescence Parameter B_A (A = target nucleus mass) is defined as

$$E_A \frac{d^3 N_A}{dp_A^3} = B_A \left(E_{p,n} \frac{d^3 N_{p,n}}{dp_{p,n}^3} \right)^A \Bigg|_{\vec{p}_p = \vec{p}_n = \frac{\vec{p}_A}{A}}$$

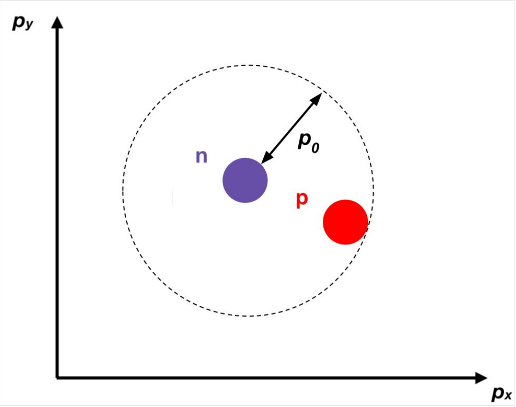


[J.I. Kapusta, Phys.Rev.C 21 (1980)]

Most simple implementation: *spherical approximation*

A proton and a neutron coalesce if they are *within a sphere of radius p_0*

$$\Delta p < p_0$$

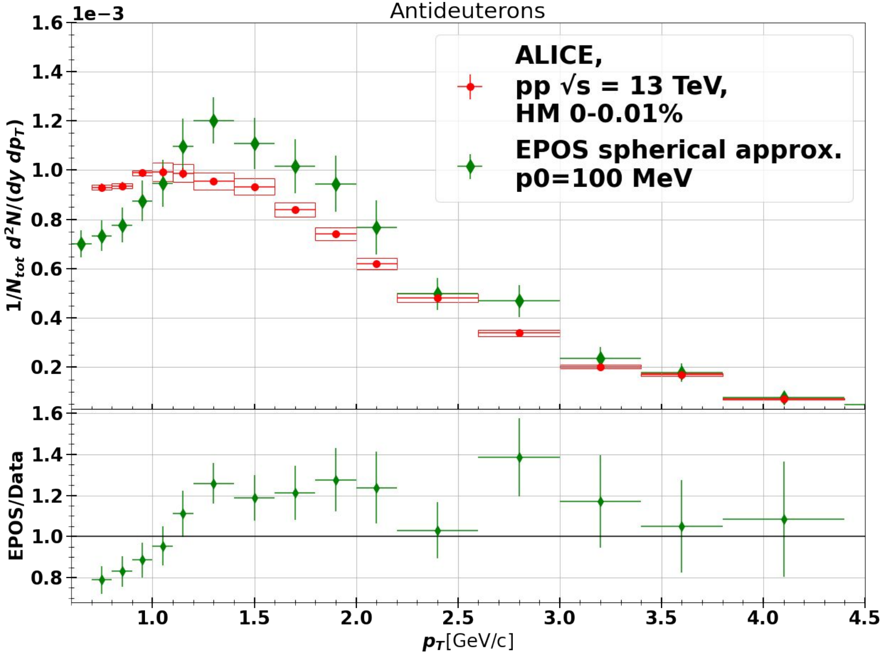


What have we done so far

Spherical approximation

Idea: study coalescence on an event-by-event basis using event generators (EPOS, Pythia,..)

This works fine for small to medium source sizes (e^+e^-, pp)



https://doi.org/10.1007/JHEP01%282022%29106

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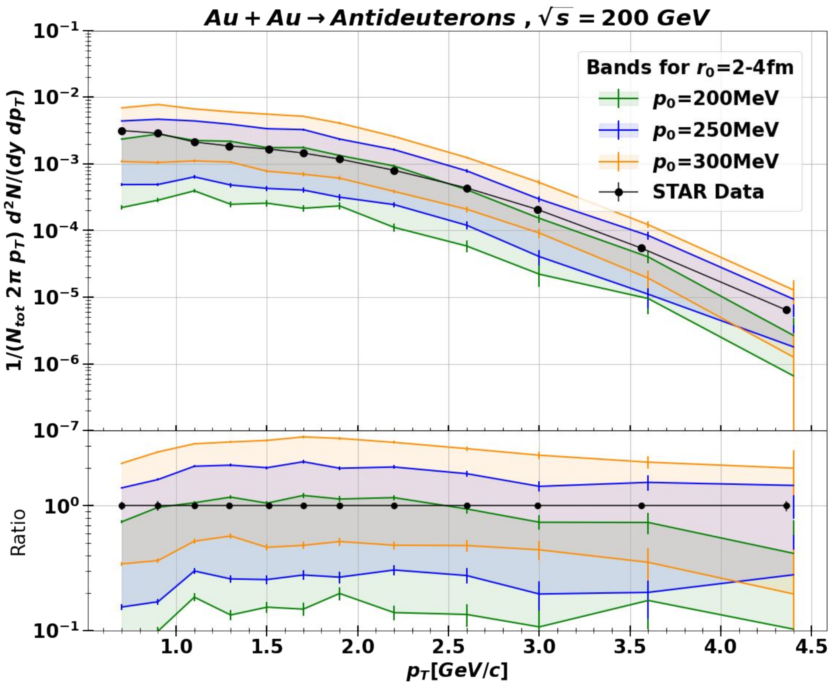
For Heavy Ion: additionally add an r_0 condition

Problem: the p_0/r_0 parameters need to be obtained from fitting and/or parameterizations



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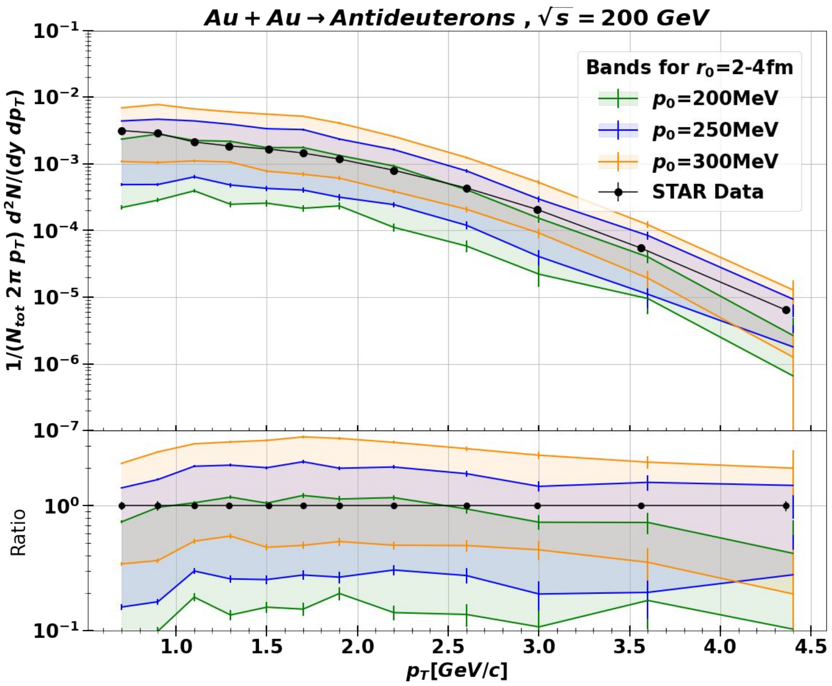
Work with an improved coalescence model!



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What have we done so far

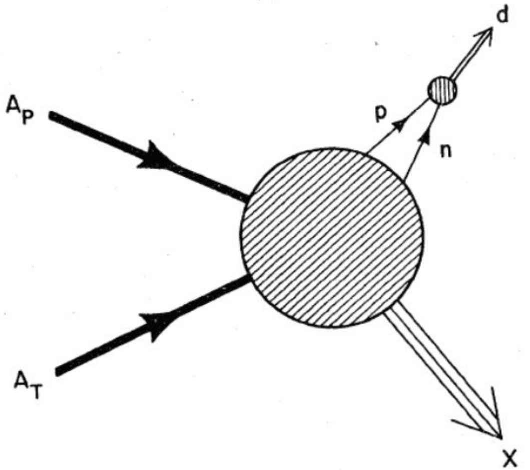
State-of-the-art coalescence

State-of-the-art coalescence models → take into account quantum-mechanical properties of the nucleons and of the final-state nucleus

Bellini & Kalweit: B_A as a function of source size

https://doi.org/10.1103/PhysRevC.99.054905

$$B_A = \frac{2J_A+1}{2^A}\frac{1}{\sqrt{A}}\frac{1}{m_T^{A-1}}\left(\frac{2\pi}{R^2+(\frac{r_A}{2})^2}\right)^{\frac{3}{2}(A-1)}$$



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What have we done so far

State-of-the-art coalescence

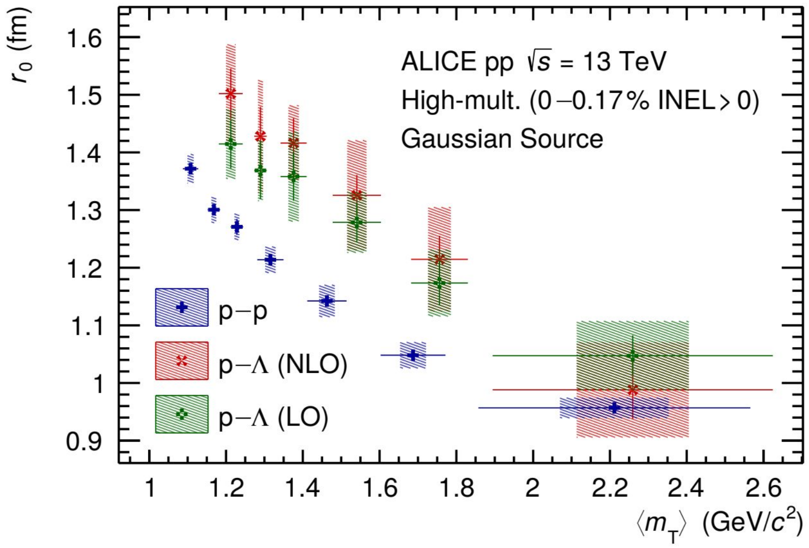
B_A predictions for pp collisions based on the nucleus wave function and the measured source size

$$B_2(p) \approx \frac{3}{2m} \int d^3q\, D(\vec{q})\, \mathscr{C}_2^{\mathrm{PRF}}(\vec{p},\vec{q})$$

$$\mathscr{C}_2^{\mathrm{PRF}}(\vec{p},\vec{q}) = e^{-R^2 q^2}$$

$$D(\vec{q}) = \int d^3r\, |\phi_d(\vec{r})|^2 e^{-i\vec{q}\times\vec{r}}$$

https://doi.org/10.1103/PhysRevC.99.044913

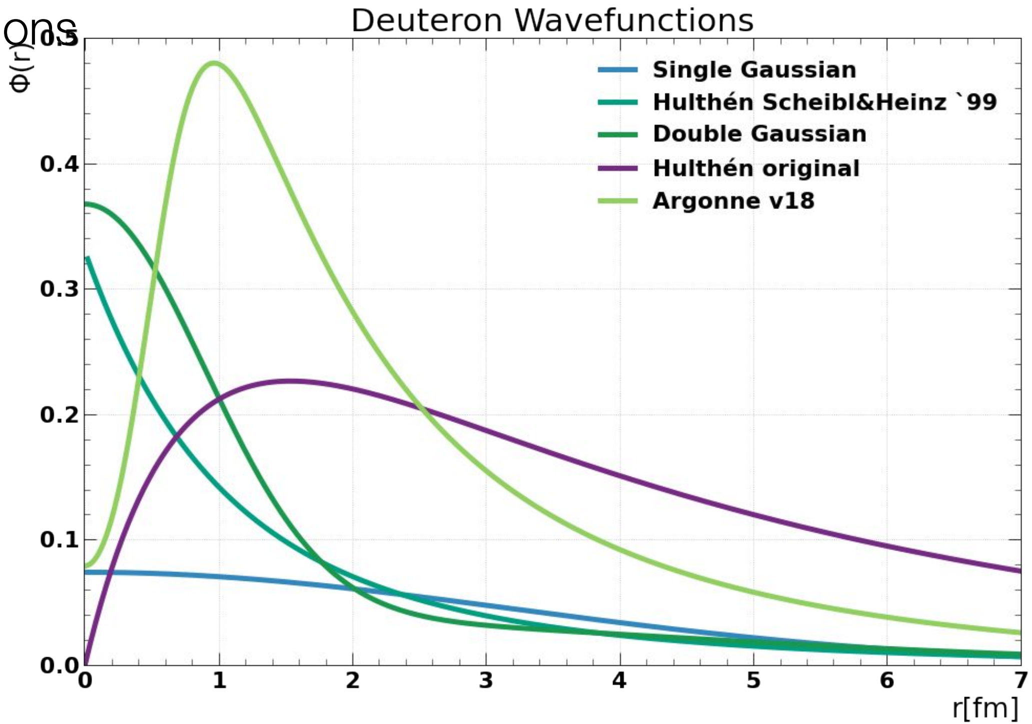


What have we done so far

Deuteron wave function

There are several possible wave functions for the deuteron

- Simplistic:
  Single Gaussian
- Experimental data (‘50s):
  Double Gaussian
- From *pion field theory* (‘50s):
  Hulthén
- From modern χ_{EFT}:
  Argonne ν_{18}



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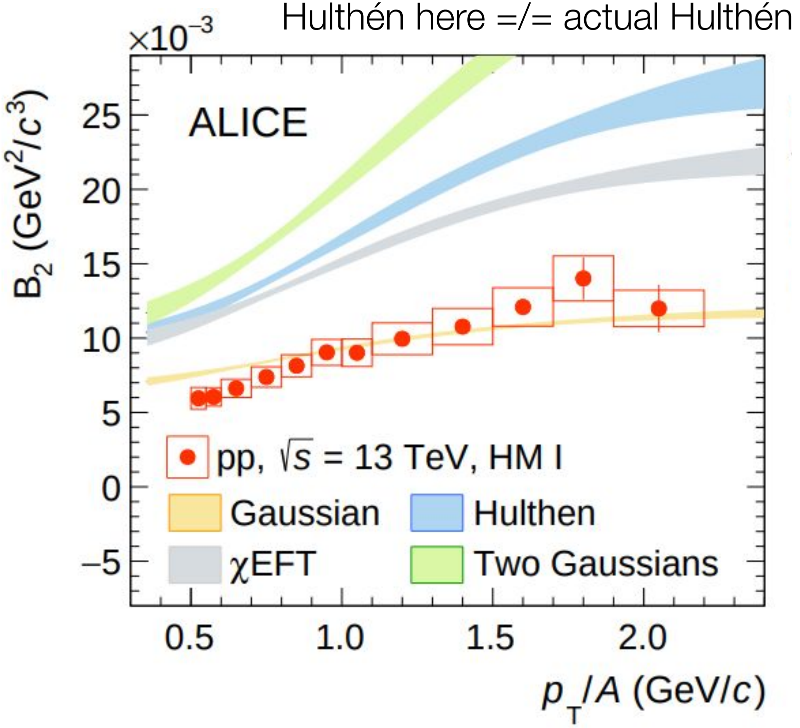
Hulthén here =/= actual Hulthén



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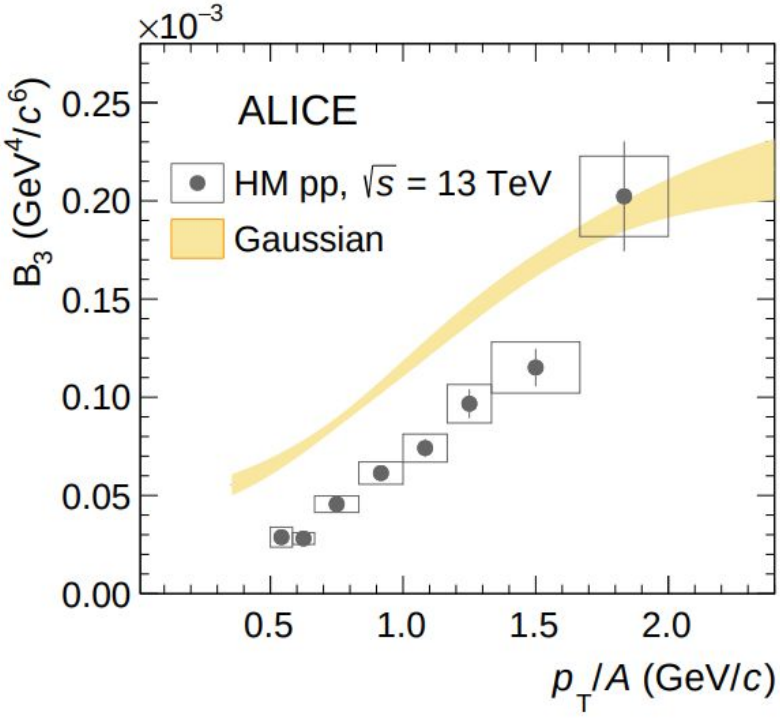
(same as above)



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What have we done so far

Wigner function coalescence formalism

Use the wave function of the Deuteron and calculate its Wigner function

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

Project onto the nucleon-nucleon phase-space

$$\frac{d^3N}{dP^3} = \frac{S}{(2\pi)^3}\int d^3q \int d^3r_n d^3r_p\, W_d(q,r)\cdot W_{np}(p_p, p_n, r_p, r_n)$$

Fold with the source to get a coalescence probability *p(r,q)*

$$p(q,r) = S\int d^3r_n d^3r_p\, W_d(q,r) h(r_n) h(r_p)$$

https://doi.org/10.48550/arXiv.1905.01192

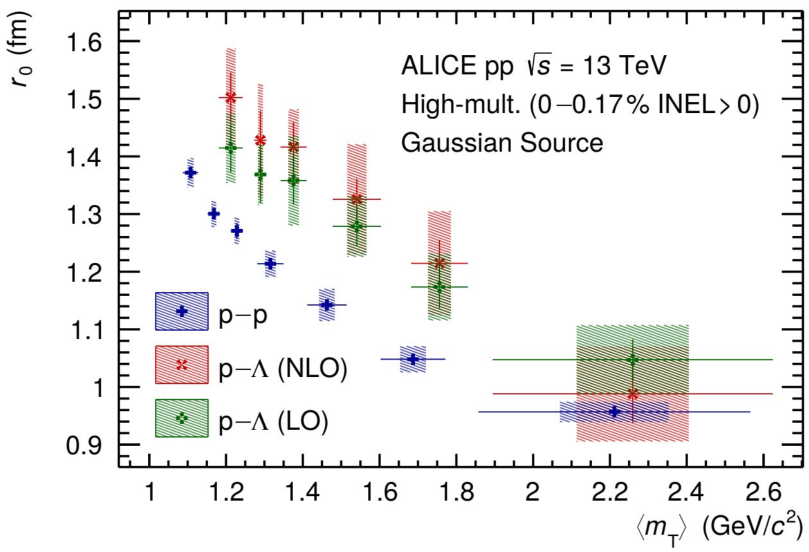
What have we done so far

The Source

The Source is an important ingredient of this coalescence model

There are multiple options:

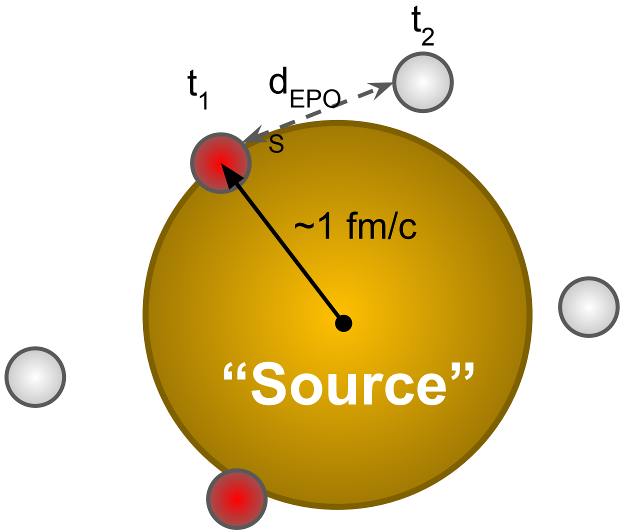
1) Use measured source size as a function of m_T
2) Use external parameterization/toy MC to predict a 3D source distribution
3) Use semi-classical traces in the event generator



What have we done so far

EPOS improved source model

1) EPOS produces particles at different times



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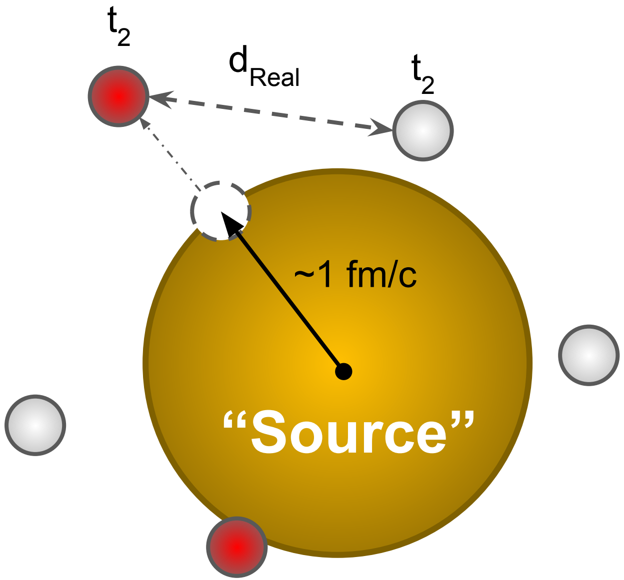
EPOS improved source model

1) EPOS produces particles at different times
2) Propagate particles to equal times to evaluate the true distance



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EPOS improved source model

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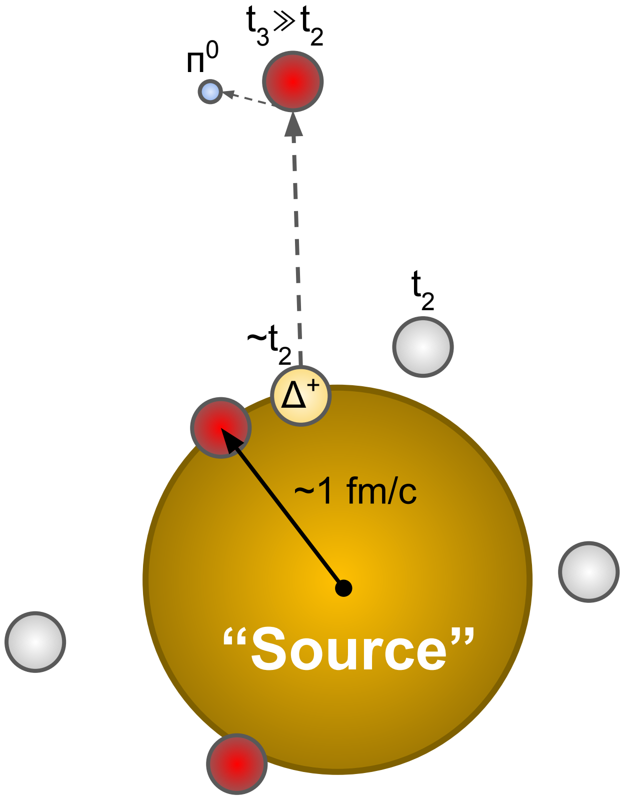
2) Propagate particles to equal times to evaluate the true distance
3) Especially important for resonances



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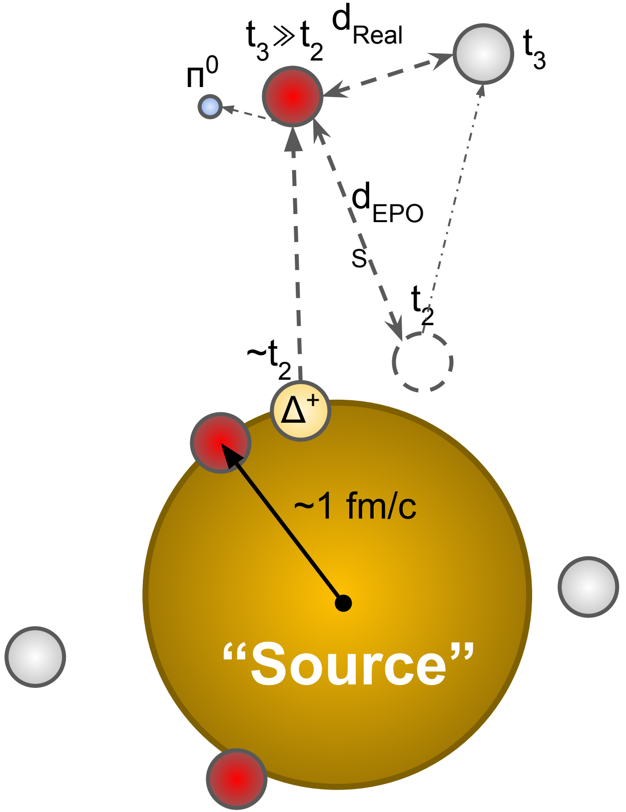
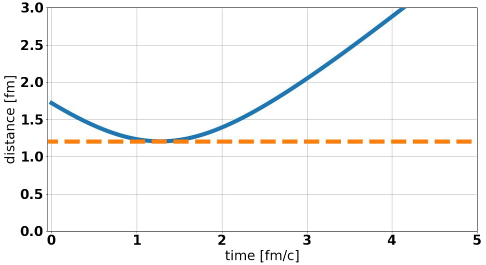


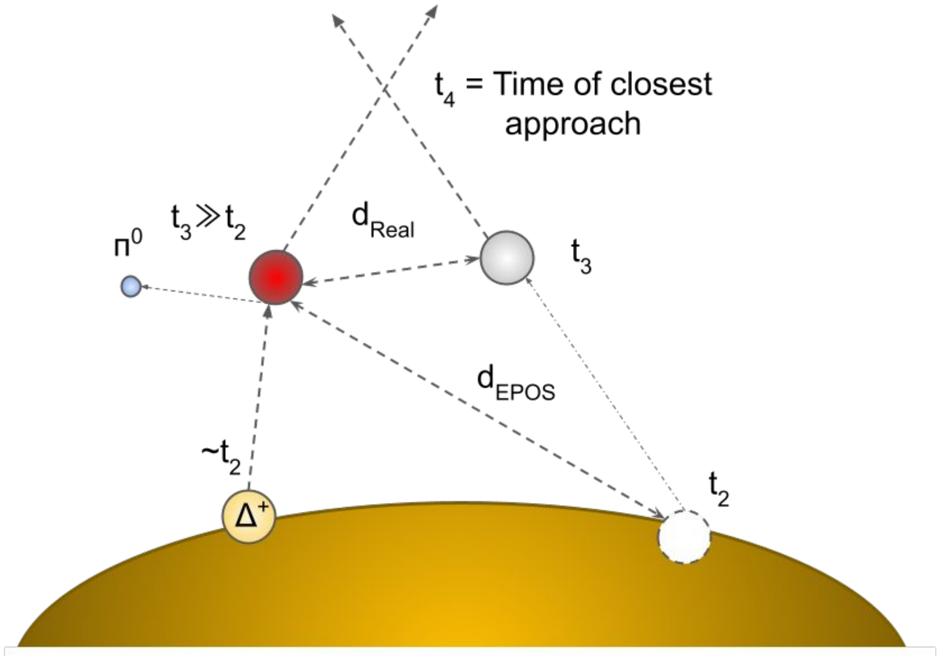
What have we done so far

EPOS improved source model

1) EPOS produces particles at different times
2) Propagate particles to equal times to evaluate the true distance
3) Especially important for resonances
4) Propagate particles further to evaluate a distance of closest approach



d_{CA}



What have we done so far

EPOS tuning

To limit biases by the event generator and properly probe only the coalescence model one needs to tune the event generator

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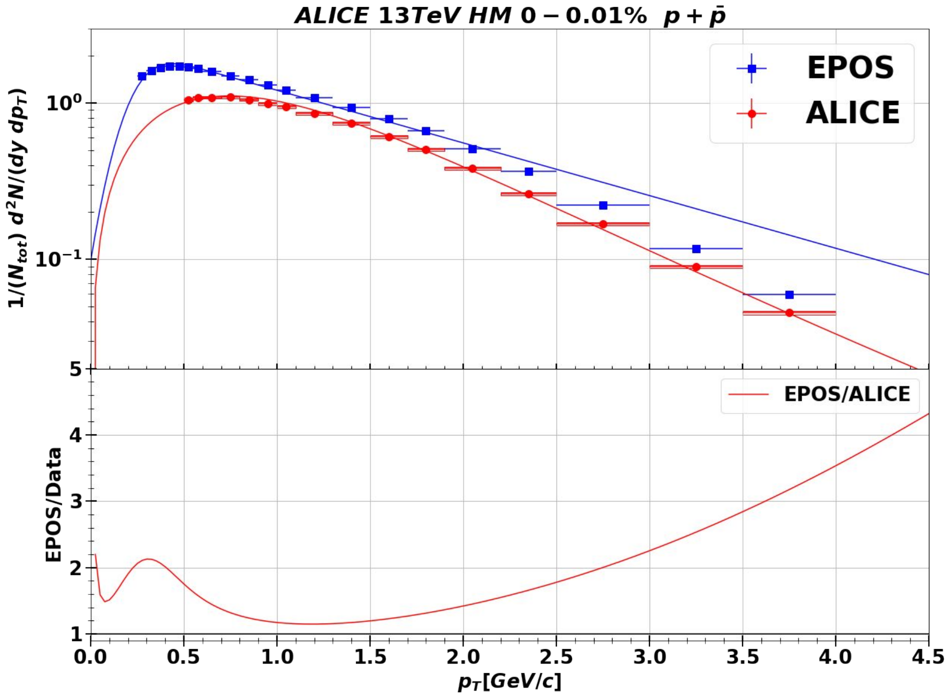
1) Reweight nucleons to reproduce the measured p_T spectrum (N_p/N_n = 1)

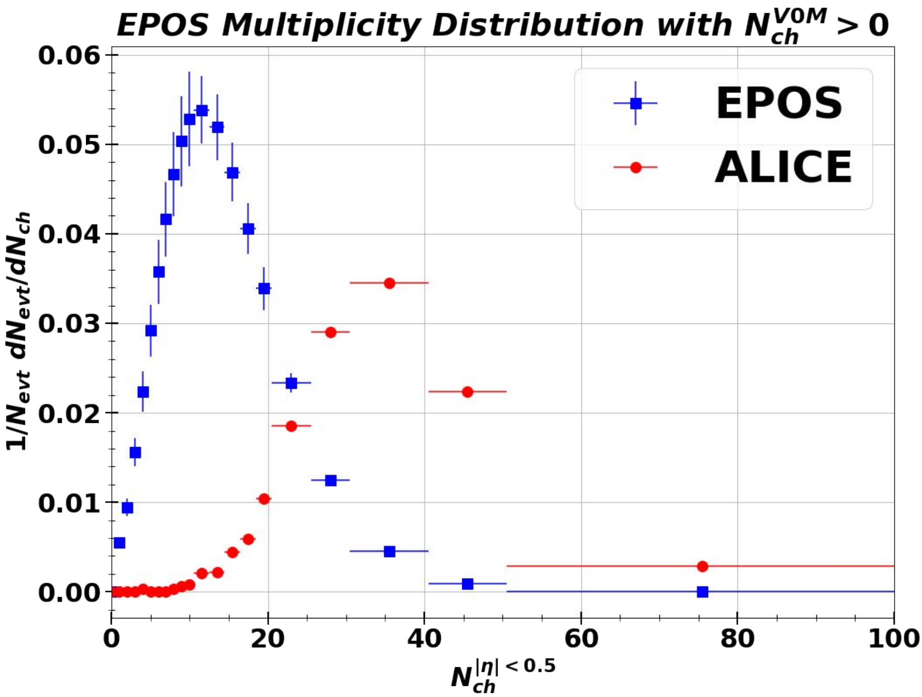


What have we done so far

EPOS tuning

To limit biases by the event generator and properly probe only the coalescence model one needs to tune the event generator

1) Reweight nucleons to reproduce the measured p_T spectrum ($N_p/N_n = 1$)
2) Correct multiplicity distribution by implementing a HM trigger



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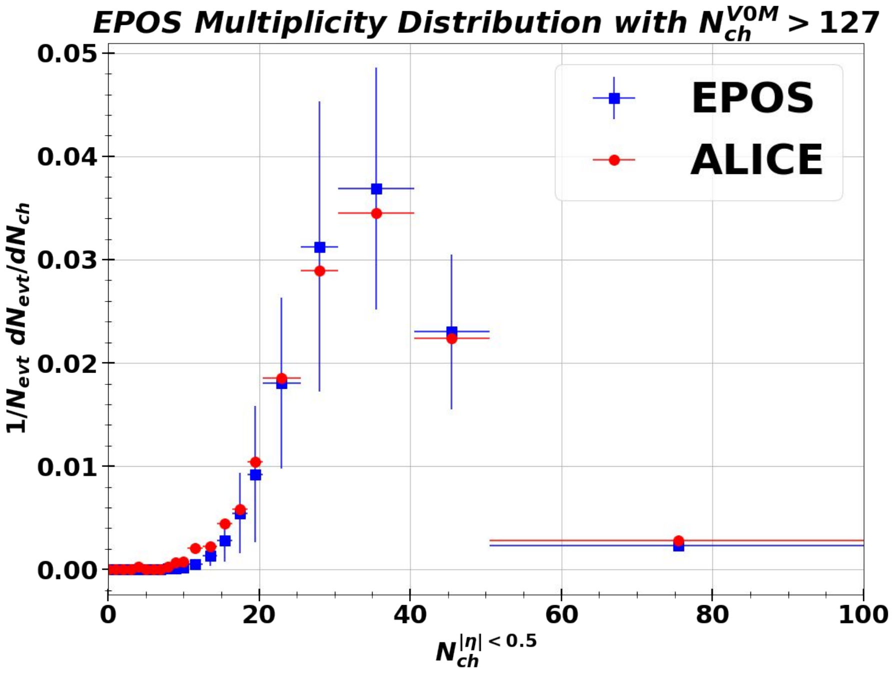

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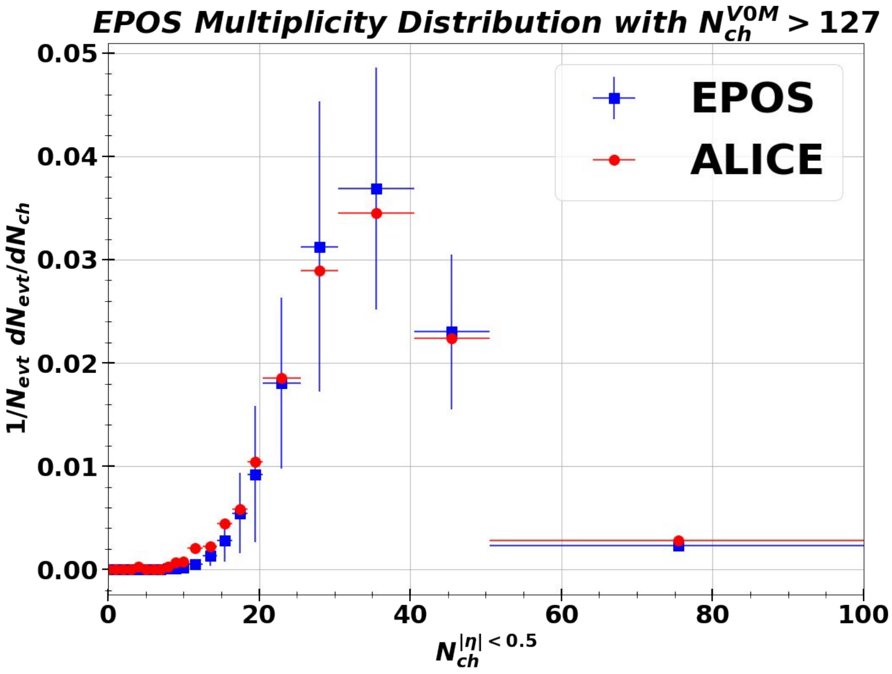
1) Reweight nucleons to reproduce the measured p_T spectrum ($N_p/N_n = 1$)
2) Correct multiplicity distribution by implementing a HM trigger
3) Reweighted the EPOS resonance cocktail to fit the thermal model composition

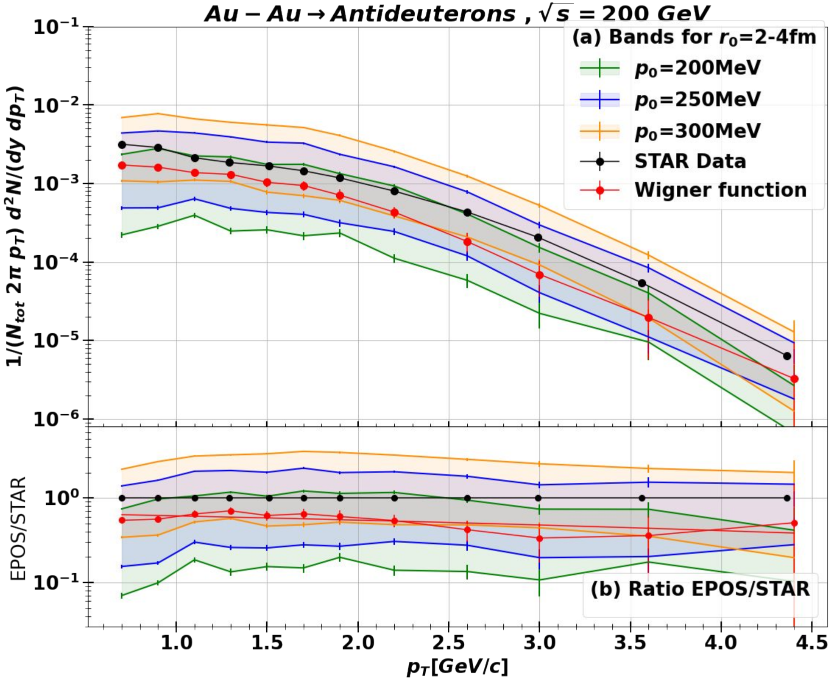


What have we done so far

Results

STAR Au–Au @ 200GeV

Results from “vanilla” EPOS: no corrections except the p_T spectra



https://doi.org/10.1103/PhysRevC.99.064905

What have we done so far

Results for Wigner function coalescence

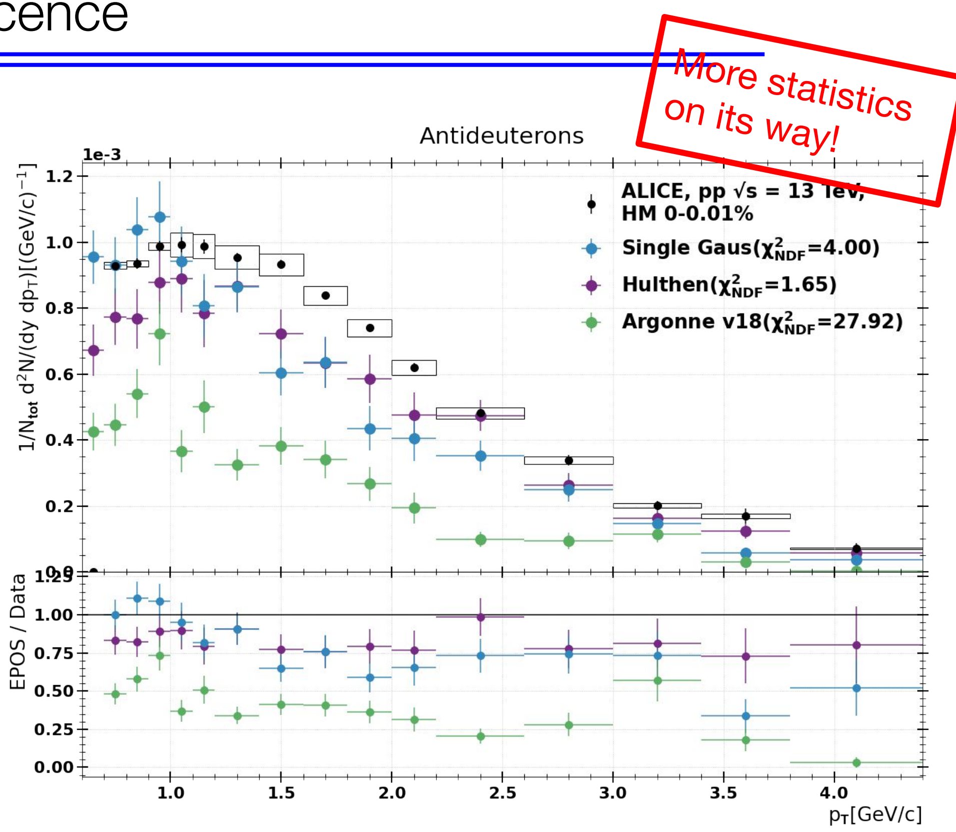
STAR Au–Au @ 200GeV

Results from “vanilla” EPOS: no corrections except the p_T spectra

ALICE pp @ 13TeV HM 0-0.01%

Only showing single Gaussian, Hulthén and Argonne *v*18 wave functions

Double Gaussian factor ~10 too high yield



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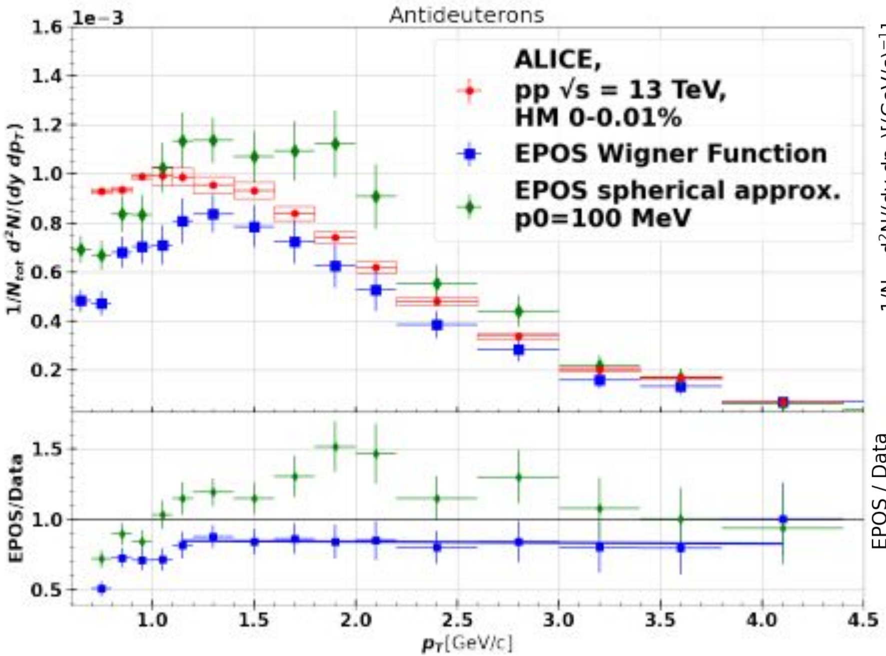
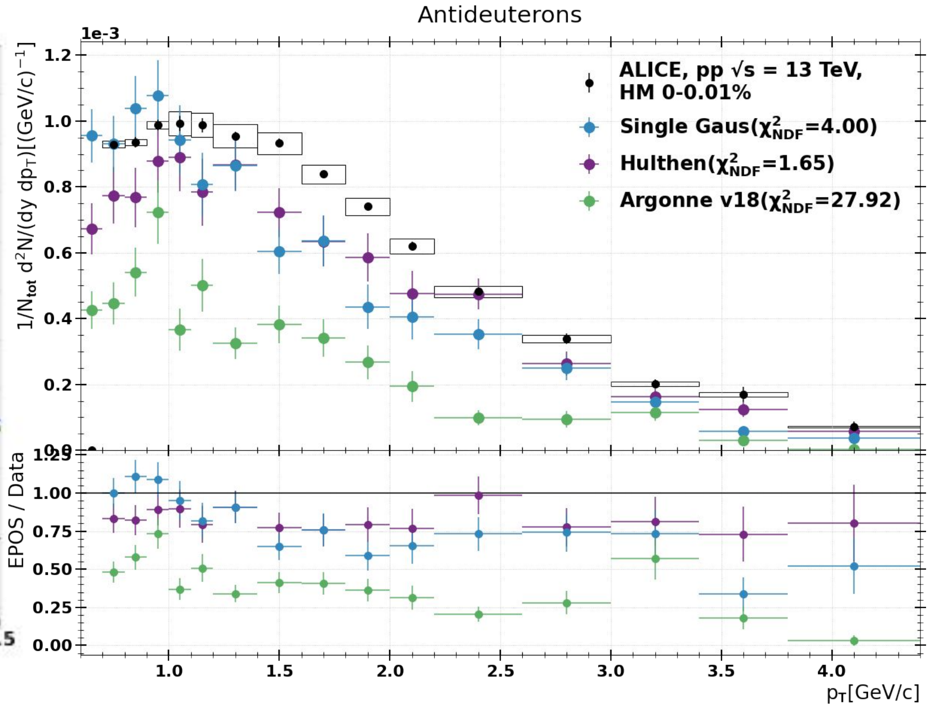

Antideuterons
1e−3
ALICE,
pp √s = 13 TeV,
HM 0-0.01%
EPOS Wigner Function
EPOS spherical approx.
p0=100 MeV
1/N_tot d²N/(dy dp_T)
EPOS/Data
p_T[GeV/c]


Antideuterons
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Single Gaus(χ²_NDF=4.00)
Hulthen(χ²_NDF=1.65)
Argonne v18(χ²_NDF=27.92)
1/N_tot d²N/(dy dp_T)[(GeV/c)⁻¹]
EPOS / Data
p_T[GeV/c]

Additional studies

deuteron production in jets

What have we done so far

Nuclei production in and out of jets

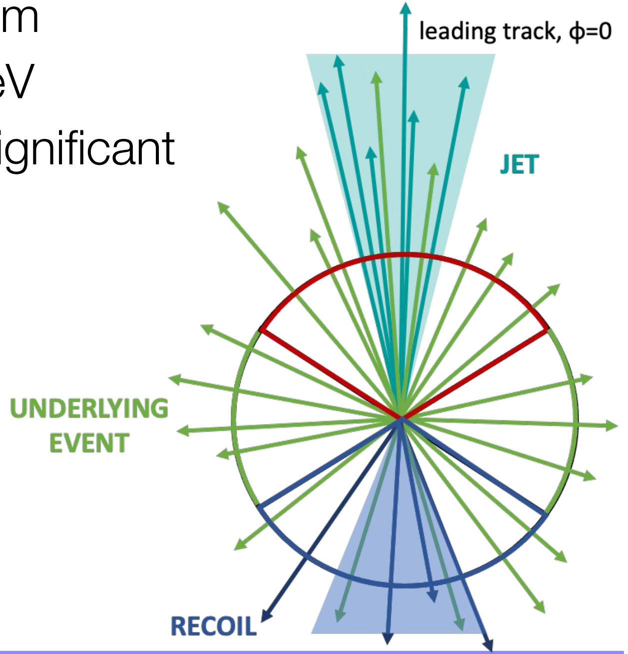
- Production of antideuterons (antihelium-3) in our Galaxy by collisions of CRs with ISM occurs at energies between 17 GeV (31 GeV) and several TeV
- Largest contribution to the antideuteron yield comes from interactions of CRs with kinetic energies around 300 GeV
- Above this energy contribution from jets is particularly significant

3 regions in the event plane wrt leading track (highest p_T):

Toward: $|\Delta\phi| < 60°$

Transverse: $60° < |\Delta\phi| < 120°$

Away: $|\Delta\phi| > 120°$



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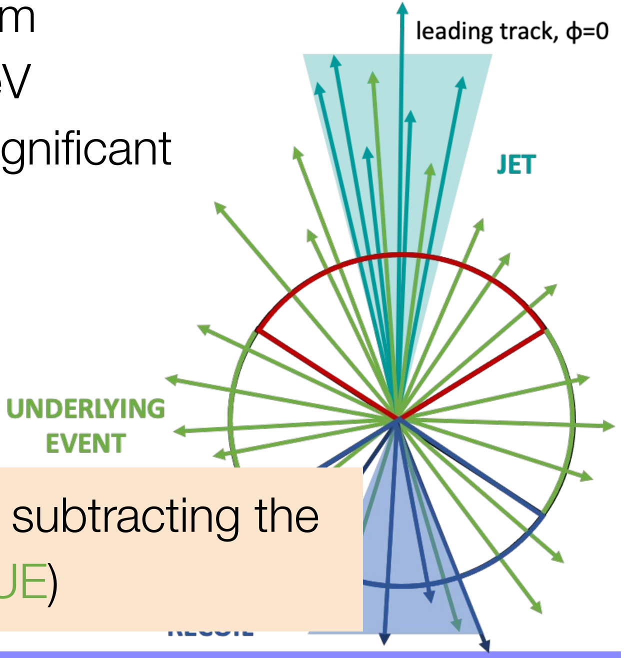
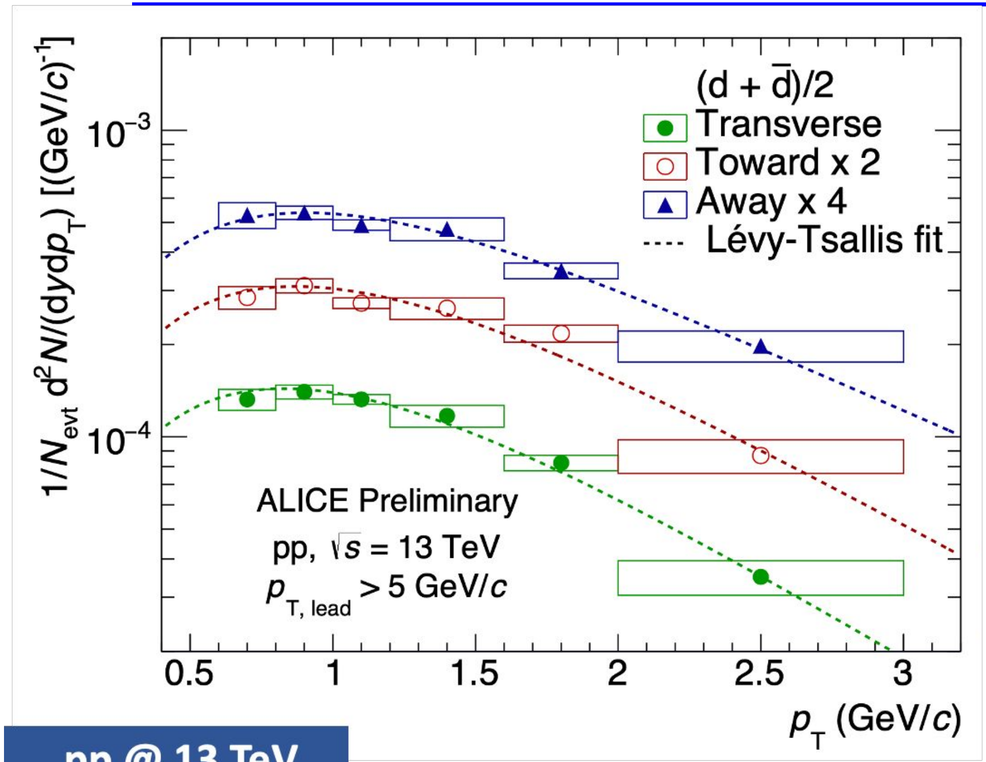


B_2 in jet can be studied in a very simple way by subtracting the UE from the Toward region (Jet + UE)

Deuteron spectra in azimuthal regions

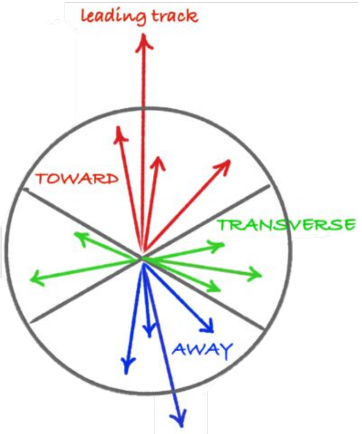


pp @ 13 TeV

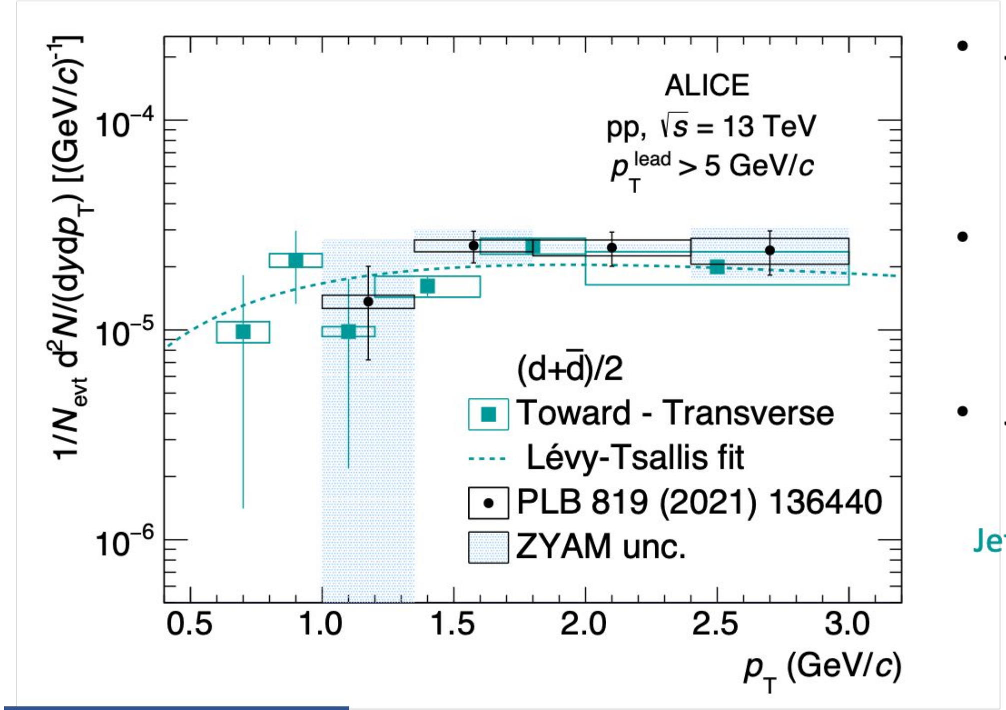
- High-p_T (p_T^{lead} > 5 GeV/c) trigger particle used as jet proxy
- Deuteron spectra in several azimuthal regions
- Lévy-Tsallis fit to guide the eye

Toward region (Jet + UE)

Transverse region (UE)



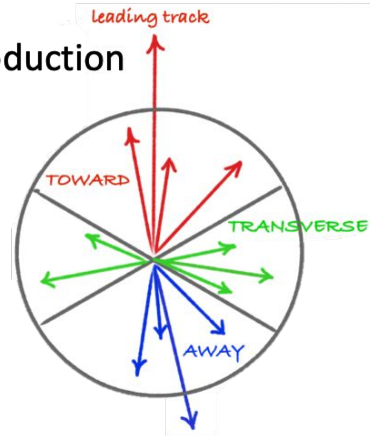
Deuteron spectra in the jet



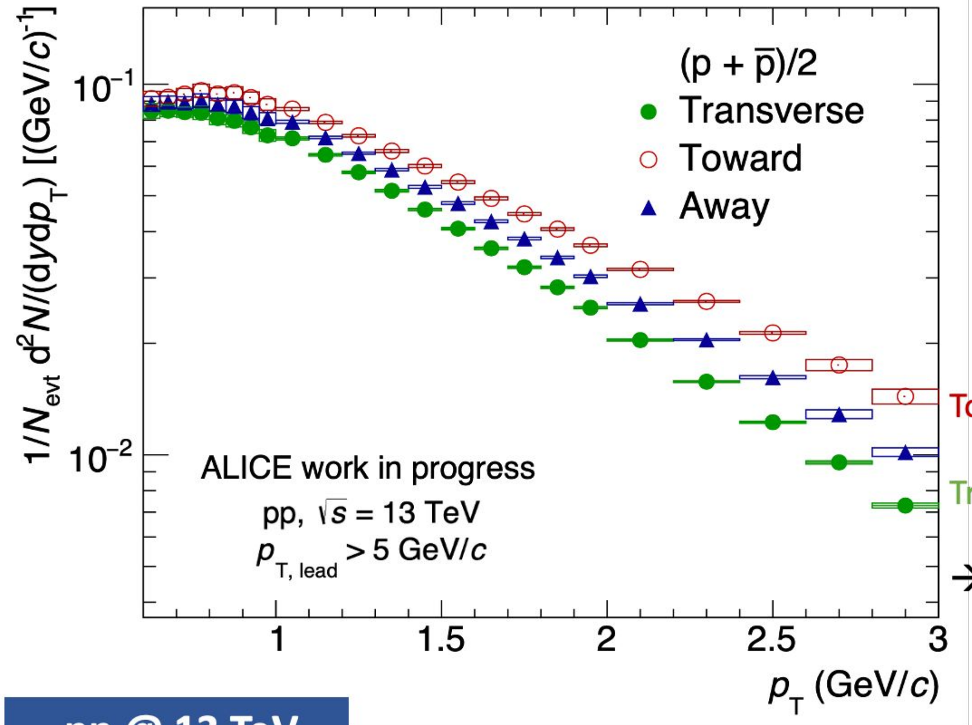
pp @ 13 TeV

- Jet-like spectrum can be easily obtained by subtracting the UE from the Toward region (Jet + UE)
- Results consistent with the the two-particle correlation method [Phys.Lett.B 819 (2021) 136440]
- Jet: ~10% of total production

Jet = Toward – Transverse



Proton spectra in azimuthal regions



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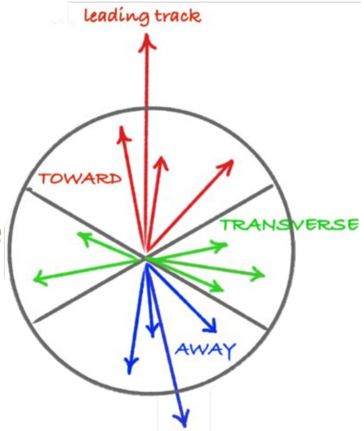
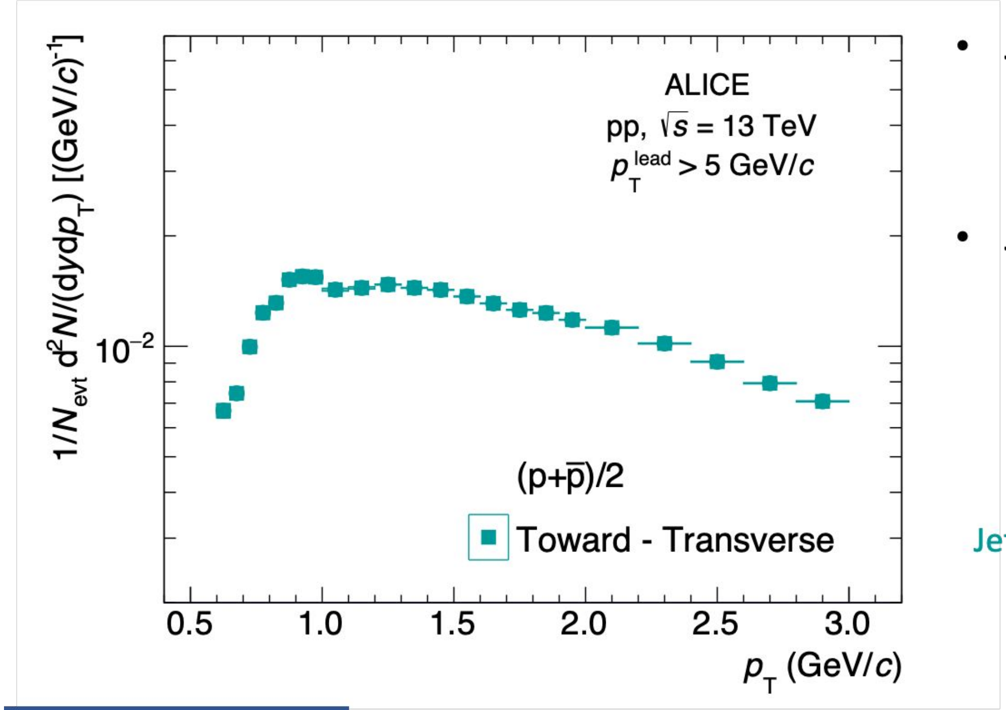
Toward region (Jet + UE)

Transverse region (UE)

→ Jet = Toward – Transverse



Proton spectrum in the jet



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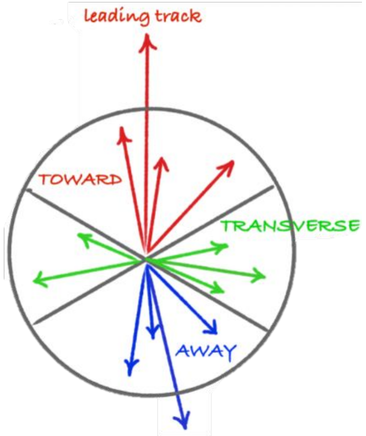
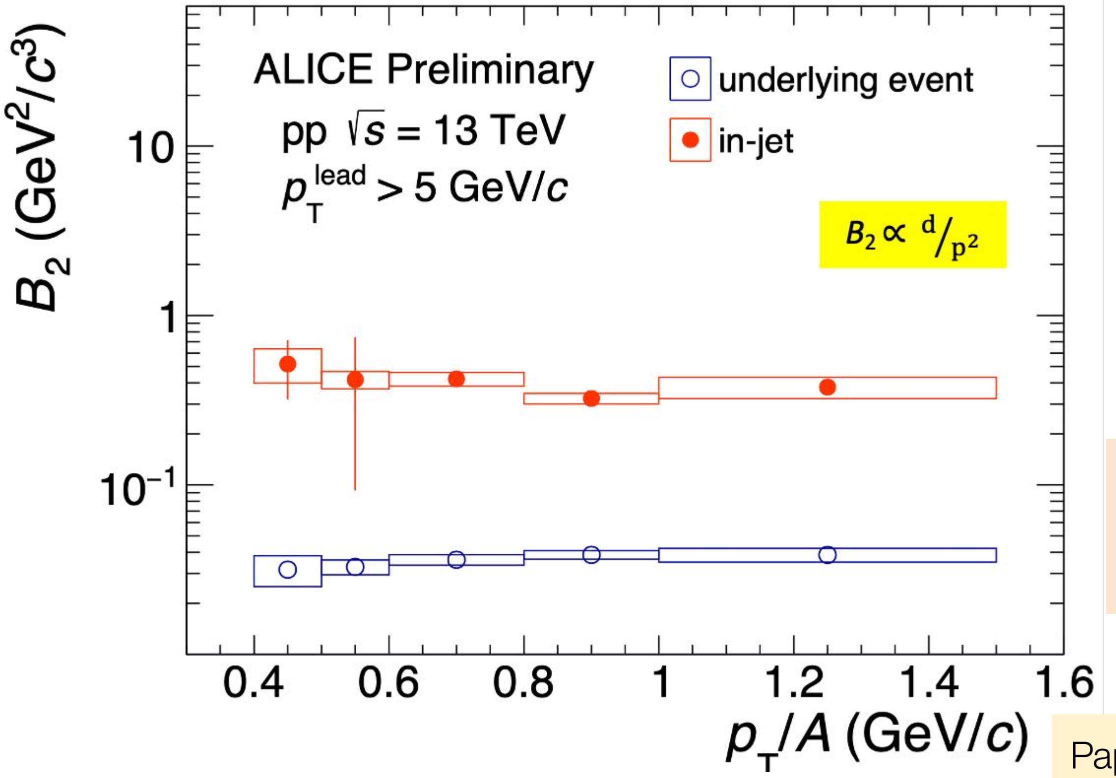


Coalescence parameter in and out of jets



- B_2 parameter flat vs p_T/A → in agreement with simple coalescence
- B_2 in-jet ~ 15 times larger than B_2 in UE (and ~ 30 times than MB)

Coalescence probability is enhanced in the jet wrt the UE by 1 order of magnitude!

Paper in internal review, to be submitted to PRL

Coalescence parameters in and out of jets

Model comparison

1. Pythia 8.3 (including d production via ordinary reactions, with energy-dependent cross sections parametrized based on data)

- d production in Pythia:

$p + n \rightarrow \gamma + d$

$p + n \rightarrow \pi^0 + d$

$p + n \rightarrow \pi^0 + \pi^0 + d$

$p + n \rightarrow \pi^+ + \pi^- + d$

$p + p \rightarrow \pi^+ + d$

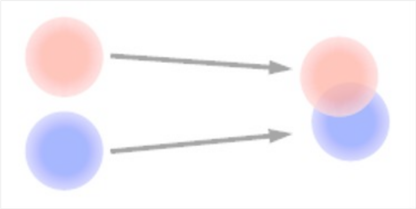
$p + p \rightarrow \pi^+ + \pi^0 + d$

$n + n \rightarrow \pi^- + d$

$n + n \rightarrow \pi^- + \pi^0 + d$

2. Pythia 8 + simple coalescence

- $\Delta p < p_0$



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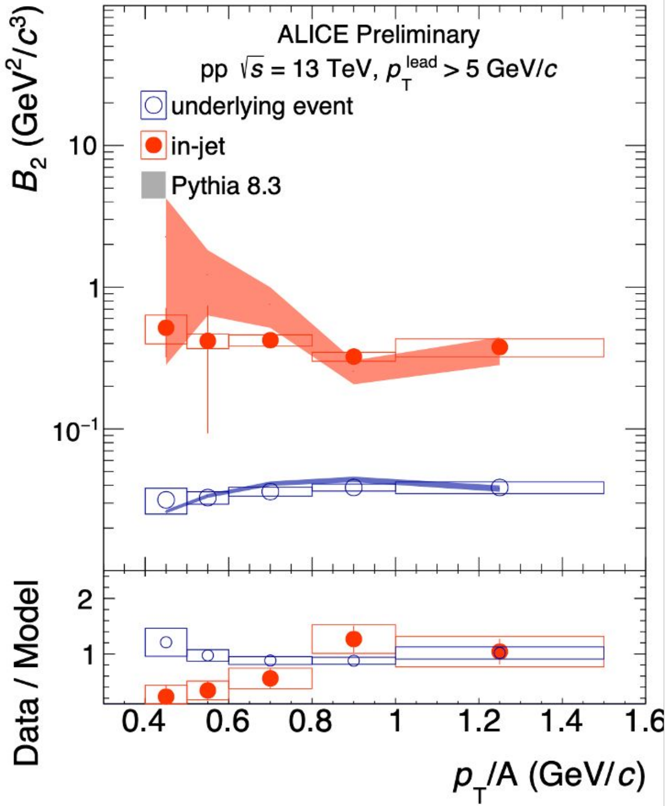

Enhanced production rate in simulations
→ normalization needed

Protons not tuned on data (yet)

B_2 UE Pythia normalized to match the data

B_2 in-jet Pythia reproduces difference between UE and jet

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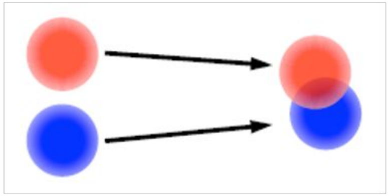
2. Pythia 8 + simple coalescence

- $\Delta p < p_0$



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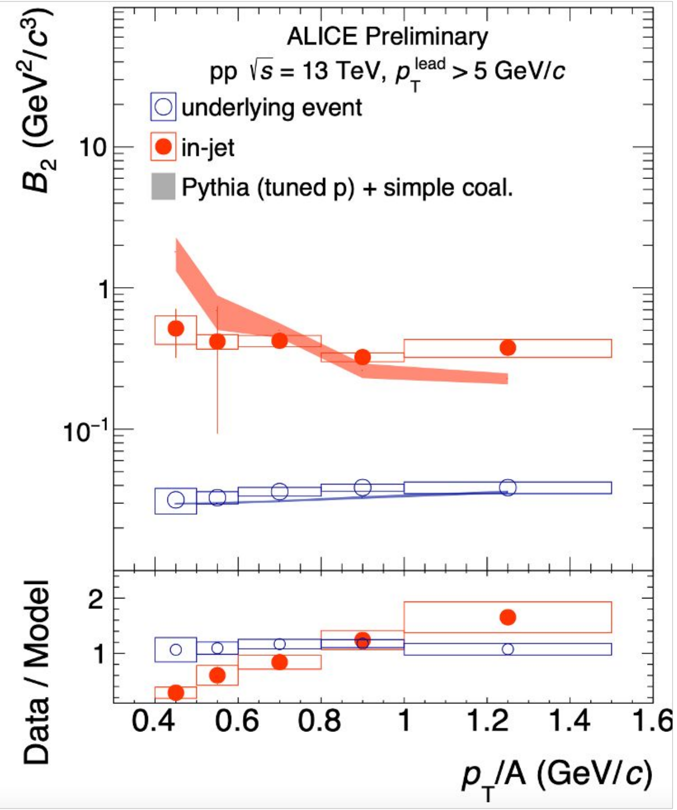


Pythia 8 + simple Coalescence (Δp < 0.285 GeV)

B_2 UE is fairly well reproduced by the model

B_2 in-jet coalescence model gives a decreasing trend vs p_T not observed in data

Paper in internal review, to be submitted to PRL

Coalescence parameters in and out of jets

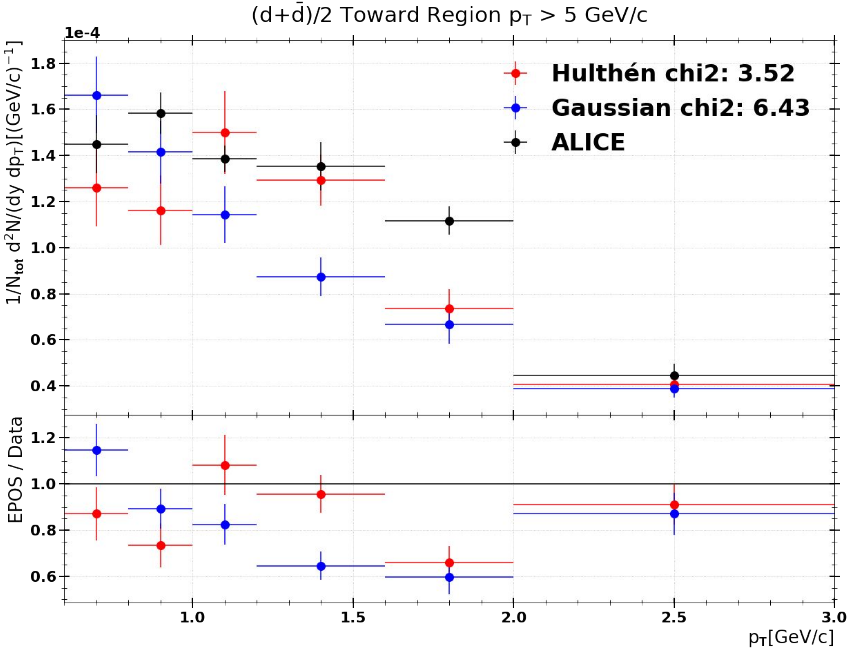
Wigner approach model

The Wigner approach model discussed before can also be used to study coalescence in and out of Jets

Results for Toward region ✅
(more statistics on its way!)

Working on transverse region 🔜

→ Seems quite promising!



Summary

To-do list

1. B_2 prediction for Hulthén wave function
2. Calculate B_2 for EPOS
3. Systematic study of wave function properties
    a. Size
    b. Magnetic moment
    c. Requirement of a "Hard core" from old scattering data
4. ^{3}He coalescence in EPOS
5. Finish the study of coalescence in the Jet in EPOS
    a. Transverse region
    b. B_2 in and out of Jet

Summary

Open points

1. Status of Pythia comparison for Wigner function coalescence of deuterons
2. Status of Pythia tunings
3. Extension of coalescence with Wigner function to ^{3}He
4. Predictions of Jet coalescence with Pythia (as done with EPOS)

Paper structure

General ideas

– Discussion on available published results (see following slide for the list)

– Comparison of deuteron spectra of pp HM 13 TeV with models using different wave functions and different event generators (EPOS, pythia) [done with EPOS]

– Comparison of ^{3}He spectra of pp HM 13 TeV with models using different wave functions and different event generators (EPOS, pythia) [TBD]

– Deuteron spectra and B_2 in and out of jet using the Wigner approach and different event generators (discussion) [working on EPOS, feasible with pythia?]

Published results on (anti)nuclei

- ALICE

1. (anti)deuterons
   - MB pp 13 TeV: Eur. Phys. J. C 80 (2020) 889 https://doi.org/10.1140/epjc/s10052-020-8256-4
   - HM pp 13 TeV: JHEP 01 (2022) 106 https://doi.org/10.1007/JHEP01%282022%29106
   - MB pp 5 TeV: Eur. Phys. J. C 82, 289 (2022) https://doi.org/10.1140/epjc/s10052-022-10241-z
   - pp 0.9, 2.76, 7: Phys. Rev. C 97, 024615 (2018) https://doi.org/10.1103/PhysRevC.97.024615
   - p-Pb 5 TeV: Phys. Lett. B 800 (2020) 135043 10.1016/j.physletb.2019.135043
   - p-Pb 8 TeV: unpublished ☹
2. (anti)^{3}He
   - MB + HM pp 13 TeV: JHEP 01 (2022) 106 https://doi.org/10.1007/JHEP01%282022%29106
   - MB pp 5 TeV: Eur. Phys. J. C 82, 289 (2022) https://doi.org/10.1140/epjc/s10052-022-10241-z
   - pp 0.9, 2.76, 7: Phys. Rev. C 97, 024615 (2018) https://doi.org/10.1103/PhysRevC.97.024615
   - p-Pb 5 TeV: Phys. Rev. C 101 (2020) 4, 044906 10.1103/PhysRevC.101.044906
   - p-Pb 8 TeV: unpublished ☹

Published results on (anti)nuclei

Before ALICE (AGS, SPS, RHIC)

[12] **E878** Collaboration, M. J. Bennett *et al.*, "Light nuclei production in relativistic Au + nucleus collisions," *Phys. Rev. C* **58** (1998) 1155–1164.

[13] **E802** Collaboration, L. Ahle *et al.*, "Proton and deuteron production in Au + Au reactions at 11.6 A-GeV/*c*," *Phys. Rev. C* **60** (1999) 064901.

[14] **E864** Collaboration, T. A. Armstrong *et al.*, "Measurements of light nuclei production in 11.5 A-GeV/*c* Au + Pb heavy ion collisions," *Phys. Rev. C* **61** (2000) 064908, arXiv:nucl-ex/0003009.

[15] **E864** Collaboration, T. A. Armstrong *et al.*, "Anti-deuteron yield at the AGS and coalescence implications," *Phys. Rev. Lett.* **85** (2000) 2685–2688, arXiv:nucl-ex/0005001.

[16] **NA52 (NEWMASS)** Collaboration, G. Ambrosini *et al.*, "Baryon and anti-baryon production in lead-lead collisions at 158 A-GeV/*c*," *Phys. Lett. B* **417** (1998) 202–210.

[17] **STAR** Collaboration, C. Adler *et al.*, "$\overline{\mathrm{d}}$ and $^{3}\overline{\mathrm{He}}$ production in $\sqrt{s_{\mathrm{NN}}}$ = 130 GeV Au + Au collisions," *Phys. Rev. Lett.* **87** (2001) 2623011–2623016.

[18] **PHENIX** Collaboration, S. S. Adler *et al.*, "Deuteron and antideuteron production in Au + Au collisions at 200 GeV," *Phys. Rev. Lett.* **94** (2005) 122302, arXiv:nucl-ex/0406004.

[19] **BRAHMS** Collaboration, I. Arsene *et al.*, "Rapidity dependence of deuteron production in Au+Au collisions at $\sqrt{s_{\mathrm{NN}}}$ = 200 GeV," *Phys. Rev. C* **83** (2011) 044906, arXiv:1005.5427 [nucl-ex].

[20] **STAR** Collaboration, H. Agakishiev *et al.*, "Observation of the antimatter helium-4 nucleus," *Nature* **473** (2011) 353, arXiv:1103.3312 [nucl-ex]. [Erratum: Nature 475 (2011) 412].

[21] **STAR** Collaboration, L. Adamczyk *et al.*, "Measurement of elliptic flow of light nuclei at $\sqrt{s_{\mathrm{NN}}}$ = 200, 62.4, 39, 27, 19.6, 11.5, and 7.7 GeV at the BNL Relativistic Heavy Ion Collider," *Phys. Rev. C* **94** no. 3, (2016) 034908, arXiv:1601.07052 [nucl-ex].

[22] **STAR** Collaboration, J. Adam *et al.*, "Beam energy dependence of (anti-)deuteron production in Au + Au collisions at the BNL Relativistic Heavy Ion Collider," *Phys. Rev. C* **99** no. 6, (2019) 064905, arXiv:1903.11778 [nucl-ex].

Backup

What have we done so far

Spherical approximation

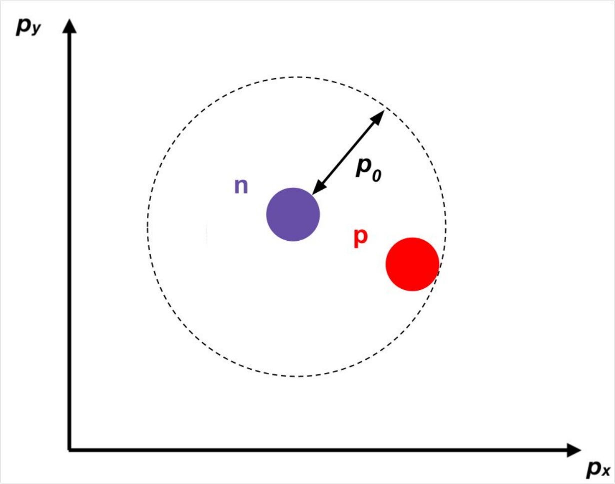
Another approach is to study coalescence on an event-by-event basis using event generators (EPOS, Pythia,..).

Coalesce nucleons *close in phase space*

Most simple implementation: ***spherical approximation***

Coalesce a proton and a neutron if they are *within a sphere of radius p_0*

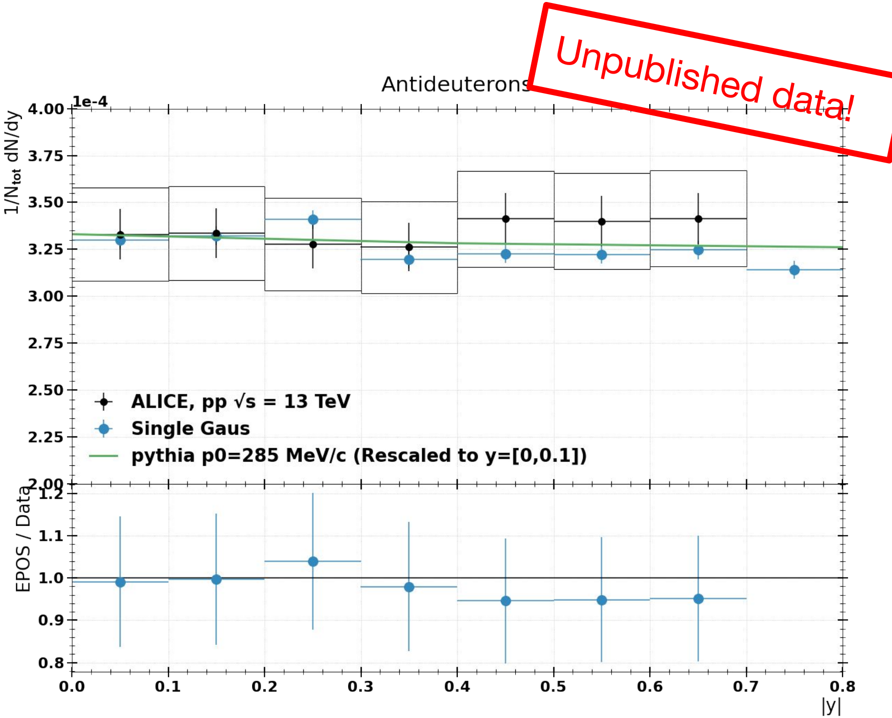
$$\Delta p < p_0$$

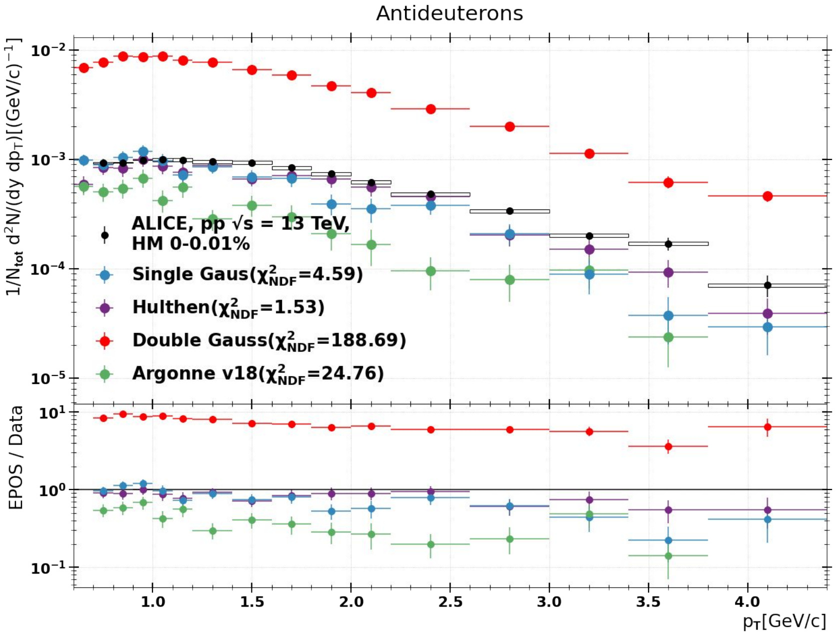


Other studies

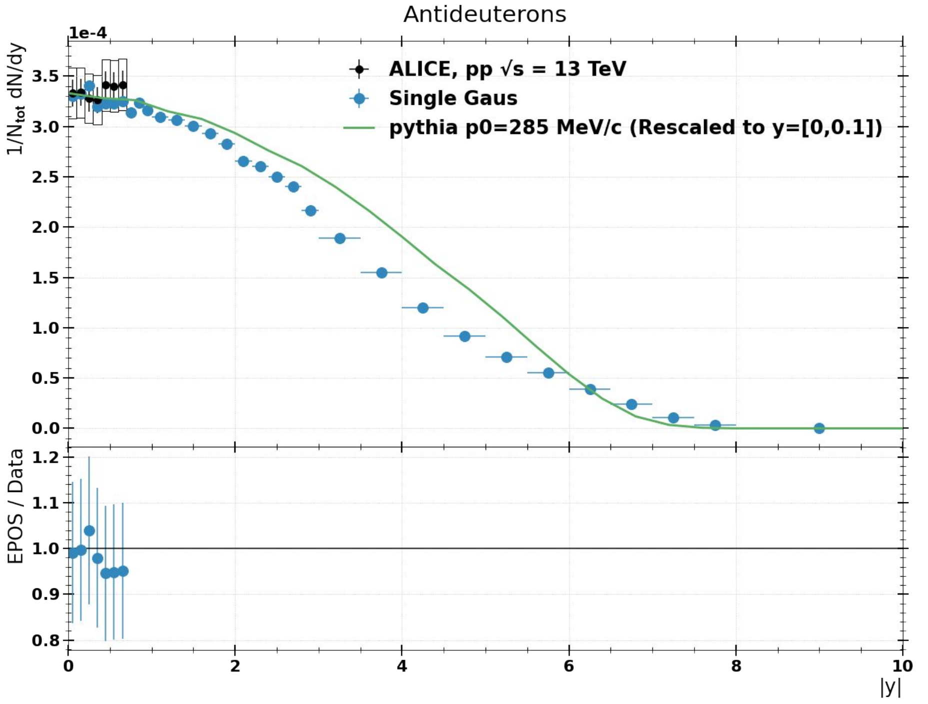
Coalescence in Rapidity

The rapidity dependent production studied by Chiara is perfectly reproduced by the Wigner function coalescence model using a single Gaussian wave function





Antideuterons
$1/N_{tot}\ d^2N/(dy\ dp_T)[(GeV/c)^{-1}]$
EPOS / Data
ALICE, pp √s = 13 TeV,
HM 0-0.01%
Single Gaus(χ^2_{NDF}=4.59)
Hulthen(χ^2_{NDF}=1.53)
Double Gauss(χ^2_{NDF}=188.69)
Argonne v18(χ^2_{NDF}=24.76)
p_T[GeV/c]


Antideuterons
1e-4
1/N_tot dN/dy
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
ALICE, pp √s = 13 TeV
Single Gaus
pythia p0=285 MeV/c (Rescaled to y=[0,0.1])
EPOS / Data
1.2
1.1
1.0
0.9
0.8
0
2
4
6
8
10
|y|