A Realistic Coalescence Model for Deuteron Production

Maximilian Mahlein, Laura Fabbietti, Bhawani Singh, Chiara Pinto

Based on: arXiv:2404.03352

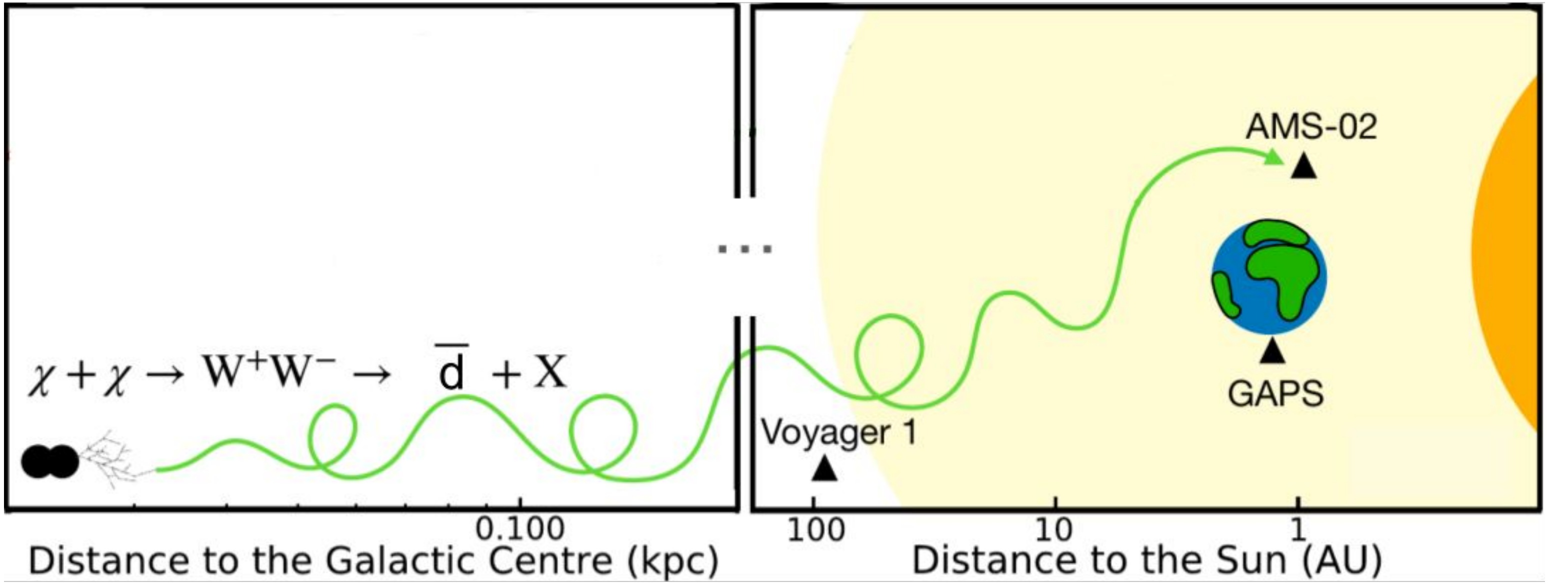
Technical University Munich

Strasbourg 2024

Strangeness in Quark Matter

Cosmic Rays

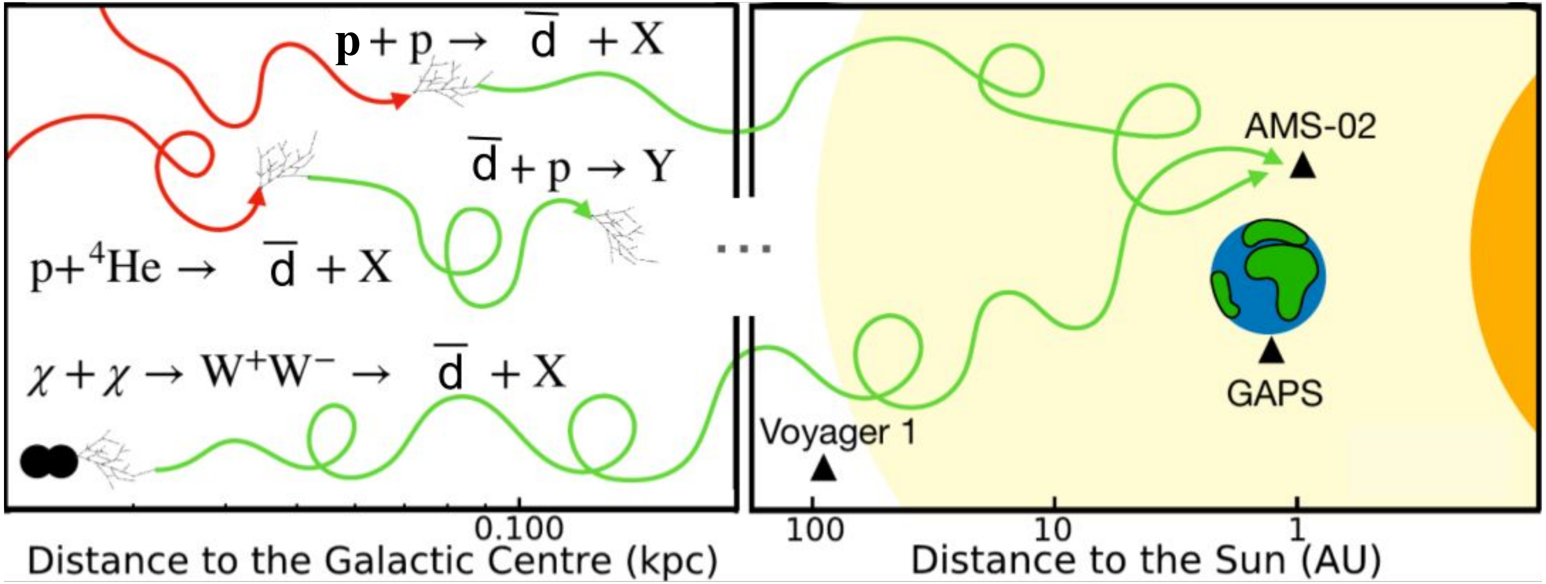
Antinuclei in Cosmic Rays



📚ALICE Collaboration, Nat. Phys. 19, 61–71 (2023)

- Antinuclei could be a probe for indirect Dark Matter searches

Cosmic Rays
Antinuclei in Cosmic Rays

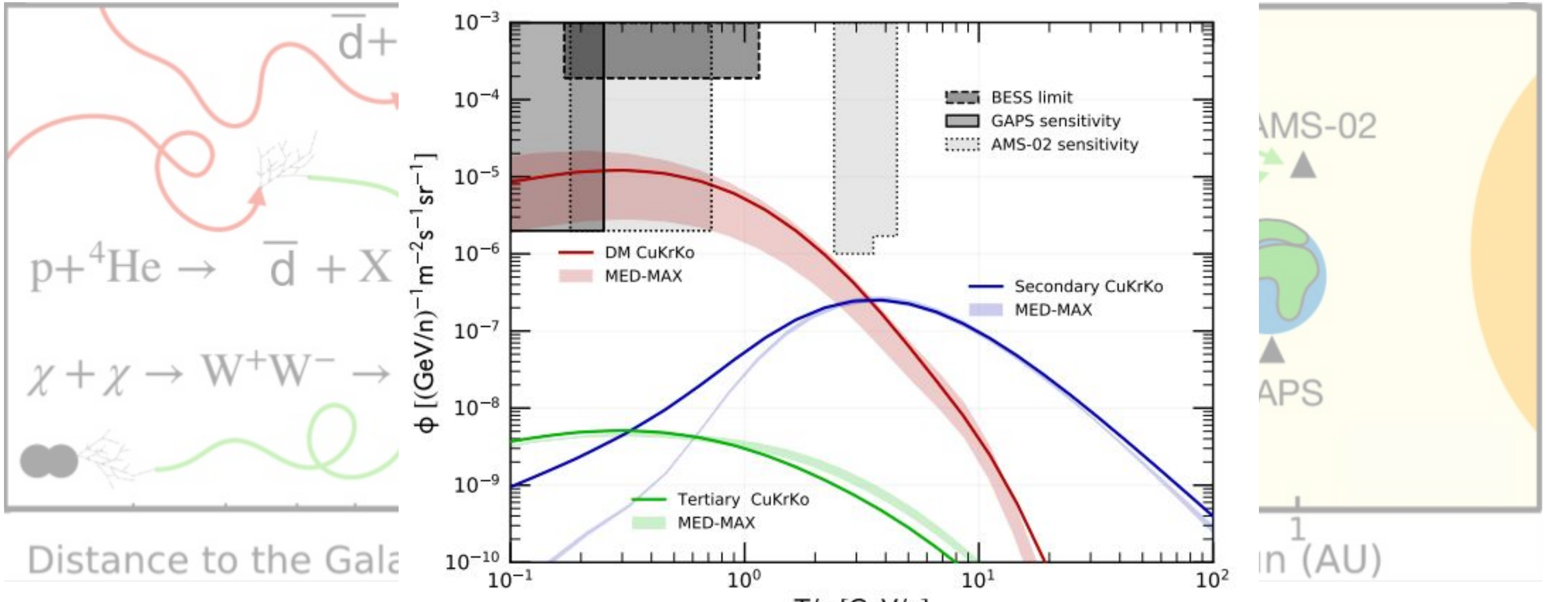


📚ALICE Collaboration, Nat. Phys. 19, 61–71 (2023)

- Antinuclei could be a probe for indirect Dark Matter searches
- However: Astrophysical background from cosmic rays expected

Cosmic Rays

Antinuclei in Cosmic Rays



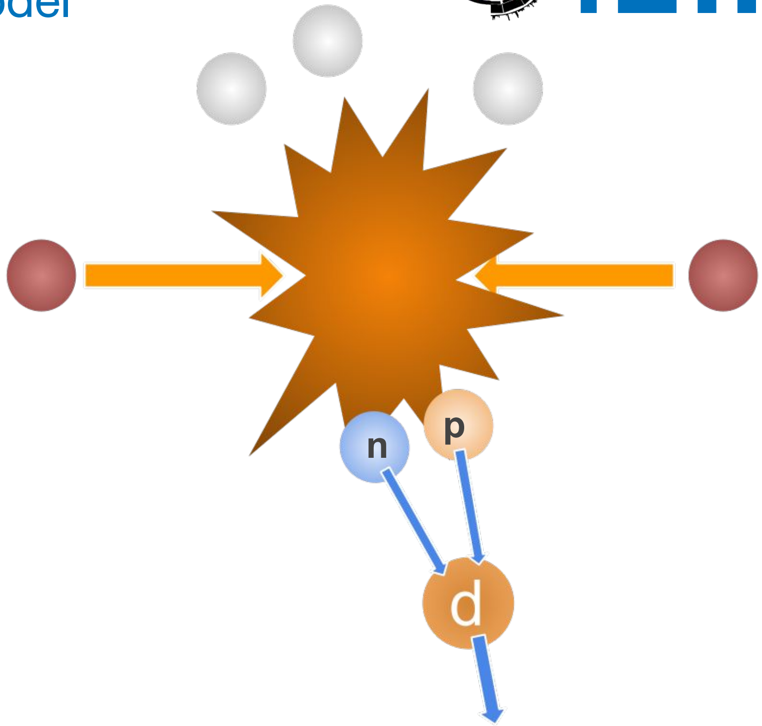
oration, Nat. Phys. 19, 61–71 (2023)

- Antinuclei could be a probe for indirect Dark Matter searches
- However: Astrophysical background from cosmic rays expected
- High Signal/Noise ratio (~10^2-10^4) at low E_{kin} expected by many models!

Modelling (Anti)nuclei Production

The Coalescence Model

- Nucleons bind after freeze-out if they are close in phase-space



Modelling (Anti)nuclei Production

The Coalescence Model

- Nucleons bind after freeze-out if they are close in phase-space
- Wigner function formalism:

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

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

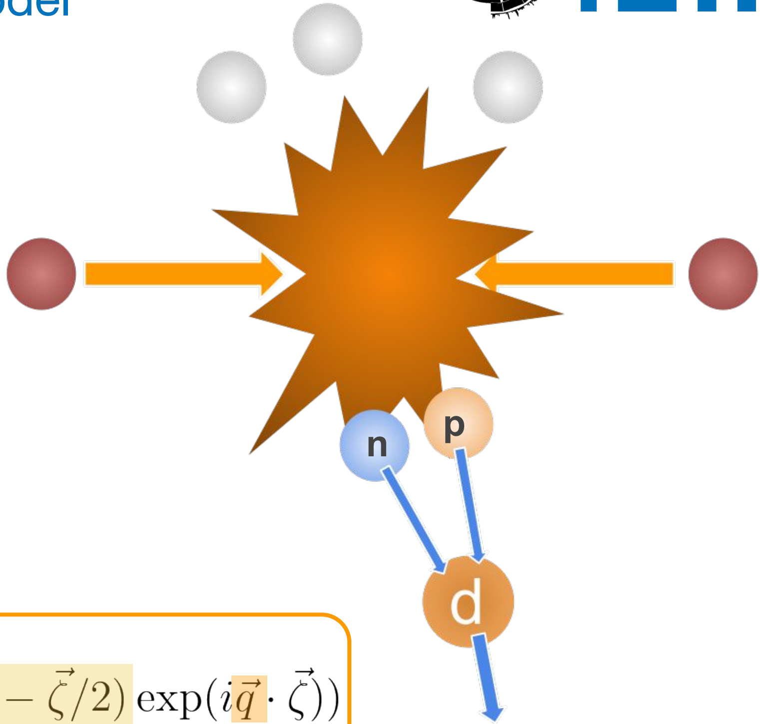
$$= \frac{1}{(2\pi\sigma^2)^3} \exp\left(- \frac{\vec{r}_n^{\,2} + \vec{r}_p^{\,2}}{2\sigma^2} \right)$$

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

Source size

Nucleus wave function

Relative momenta of nucleons



MM et al .Eur.Phys.J.C 83 (2023) 9, 804

Modelling (Anti)nuclei Production

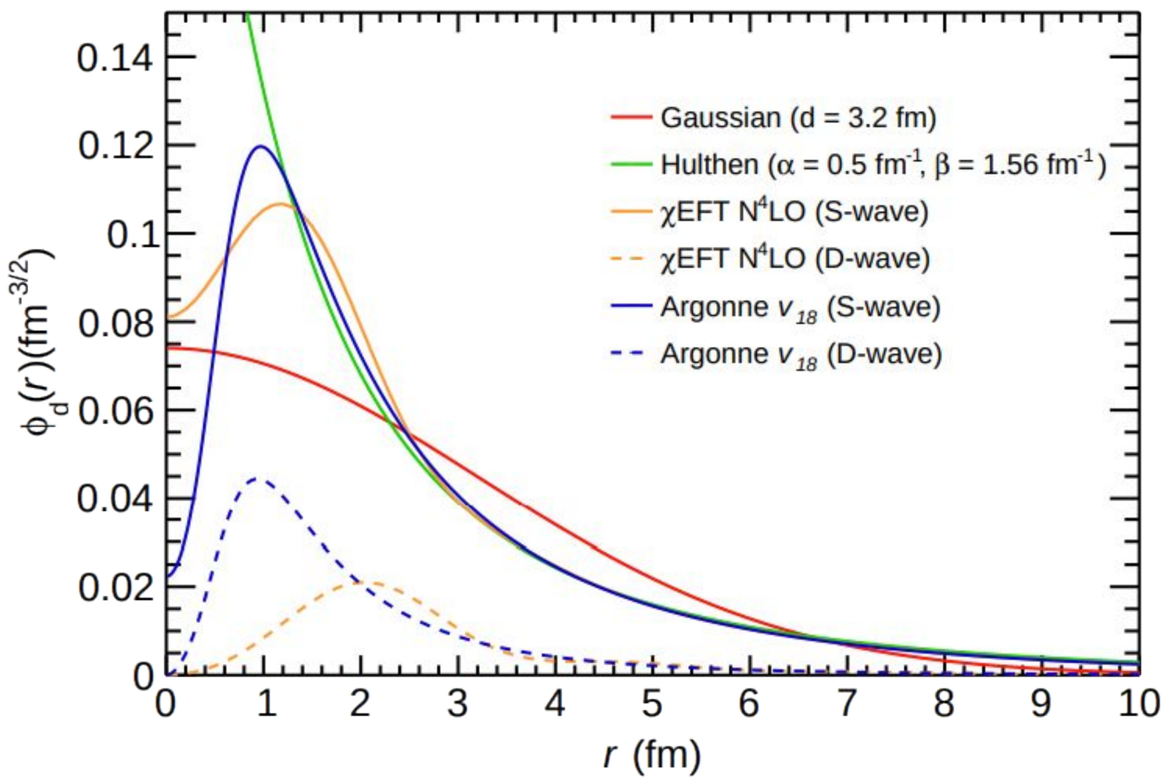
The Coalescence Model

- Nucleons bind
  are close in pha
- Wigner functio

$$p(\sigma, q) = \int d$$

$$= \frac{1}{(2\pi\sigma^2)^3} \exp\left(- \right.$$

So



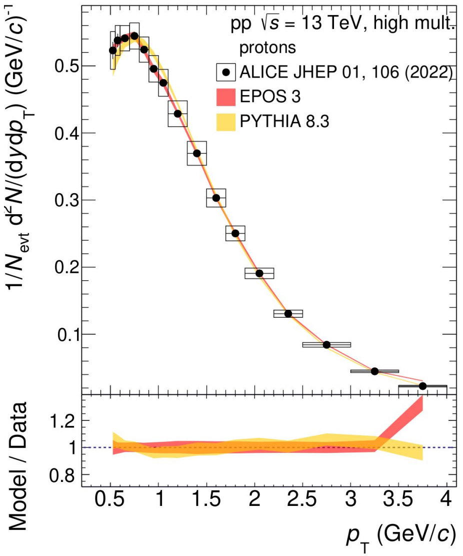
MM et al .Eur.Phys.J.C 83 (2023) 9, 804

Coalescence Results EPOS

Deuteron spectra

📚MM et al .Eur.Phys.J.C 83 (2023) 9, 804

- Corrections to Protons, Source, Multiplicity
- Wavefunctions: Gaussian,Hulthén and Argonne v_{18}
- v_{18} reproduces data to ~10%

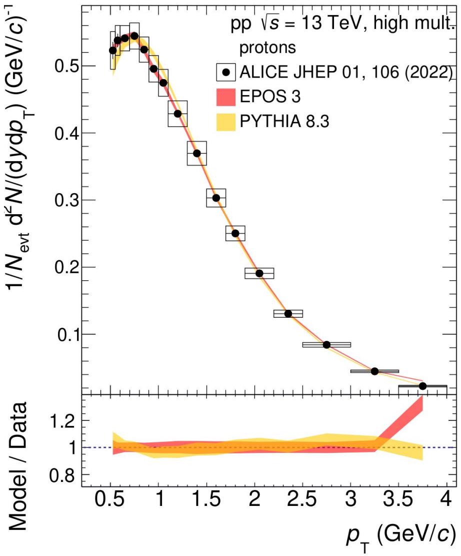


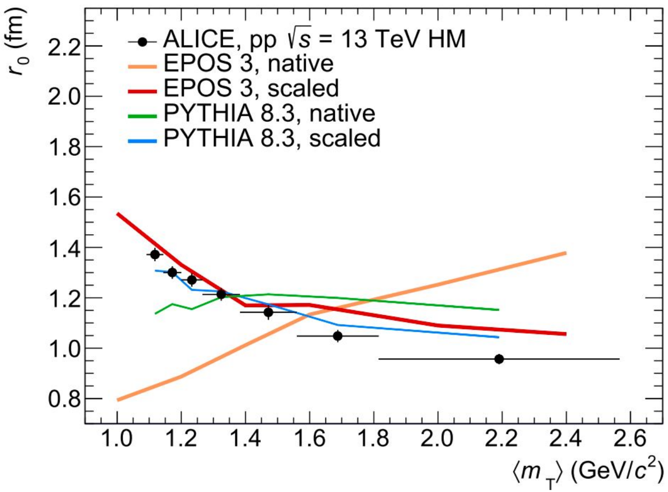
Coalescence Results EPOS

Deuteron spectra

📚MM et al .Eur.Phys.J.C 83 (2023) 9, 804

- Corrections to Protons, Source, Multiplicity
- Wavefunctions: Gaussian,Hulthén and Argonne v_{18}
- v_{18} reproduces data to ~10%



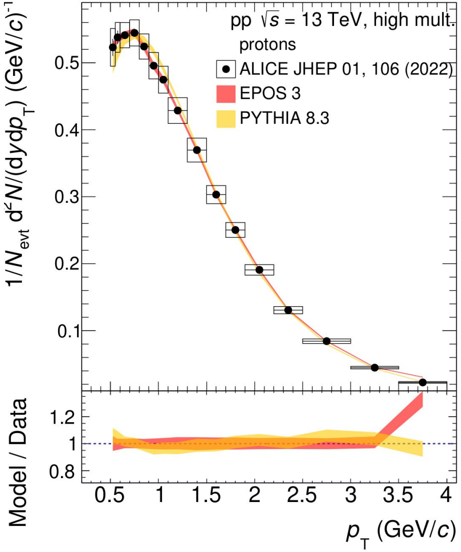


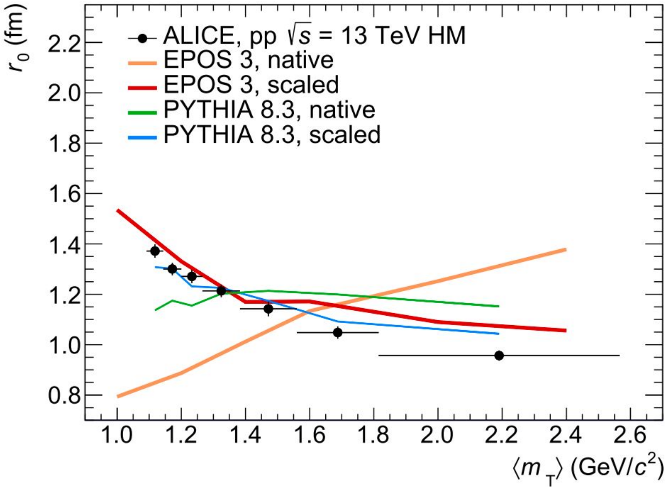
Coalescence Results EPOS

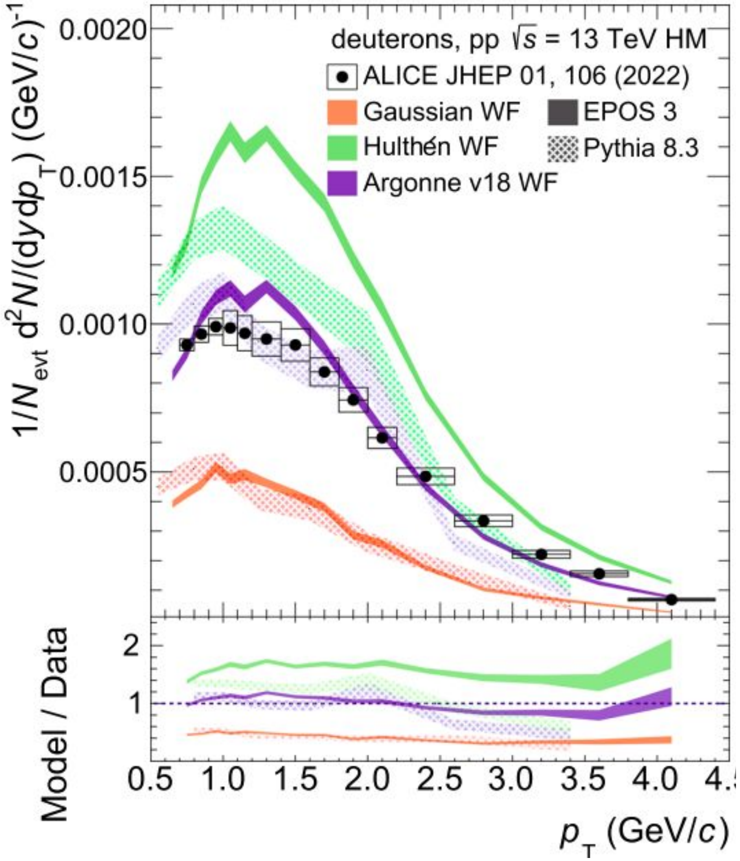
Deuteron spectra

📚MM et al .Eur.Phys.J.C 83 (2023) 9, 804

- Corrections to Protons, Source, Multiplicity
- Wavefunctions: Gaussian,Hulthén and Argonne v_{18}
- v_{18} reproduces data to ~10%





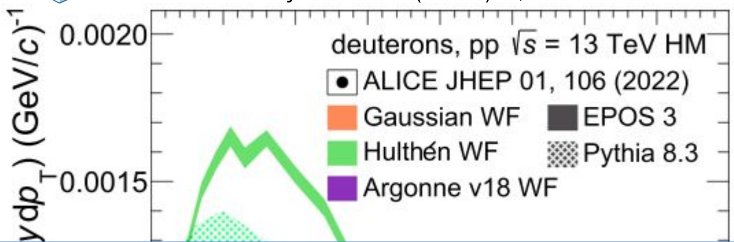


Coalescence Results EPOS

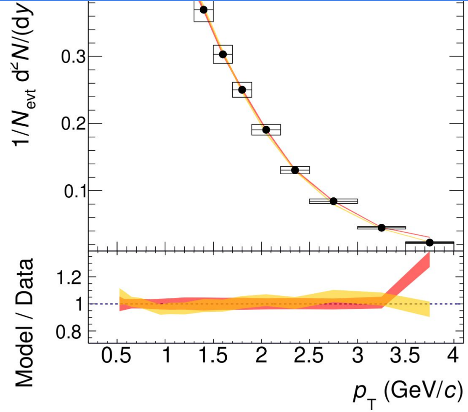
Deuteron spectra

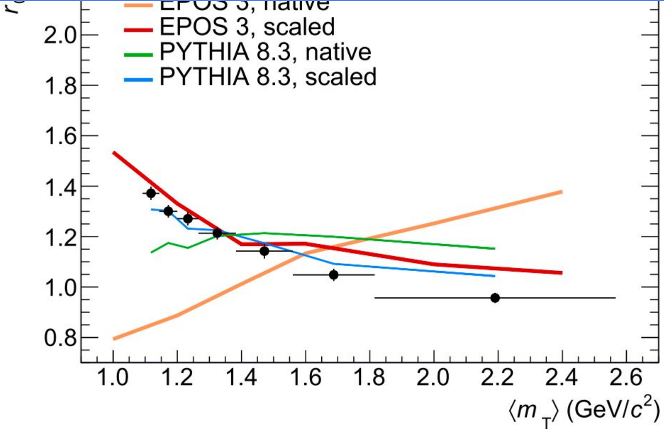
📚MM et al .Eur.Phys.J.C 83 (2023) 9, 804

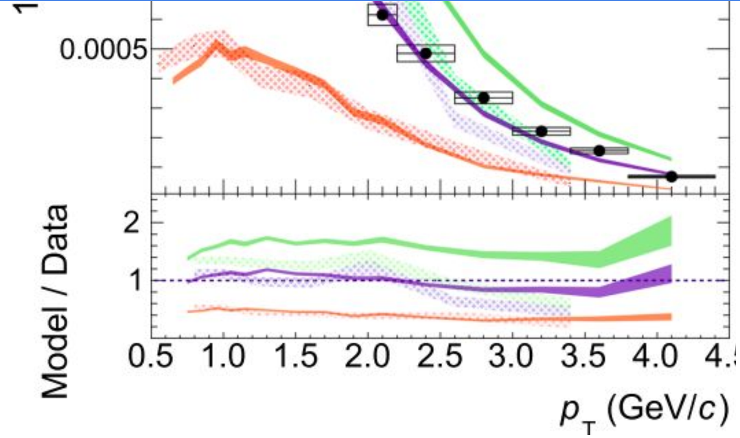
- Corrections to Protons, Source, Multiplicity
- Wavefunctions: Gaussian,Hulthén and Argonne v_{18}
- v_{18} reproduces data to ~10%



Most advanced coalescence model with realistic wave function!





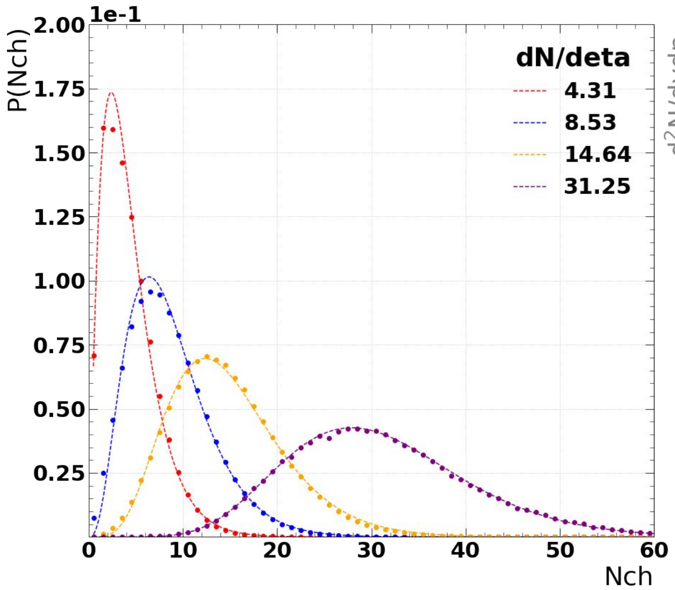


The ToMCCA Model

A Toy Monte Carlo Coalescence Afterburner

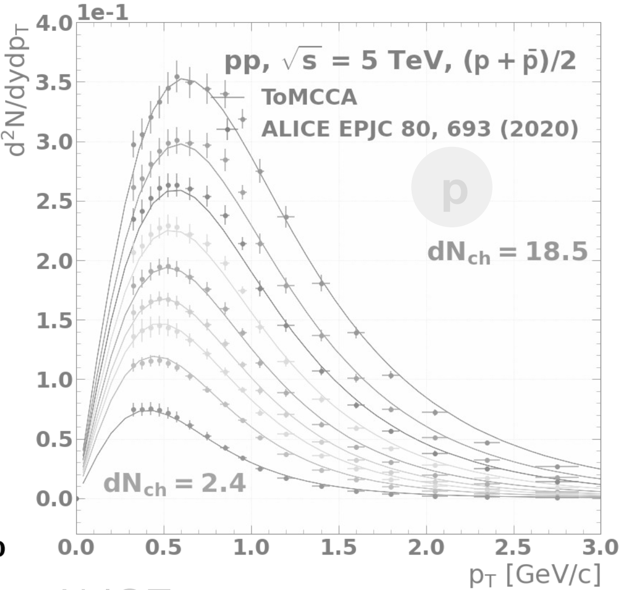
Main Inputs: Multiplicity, momentum distributions, source size

Multiplicity



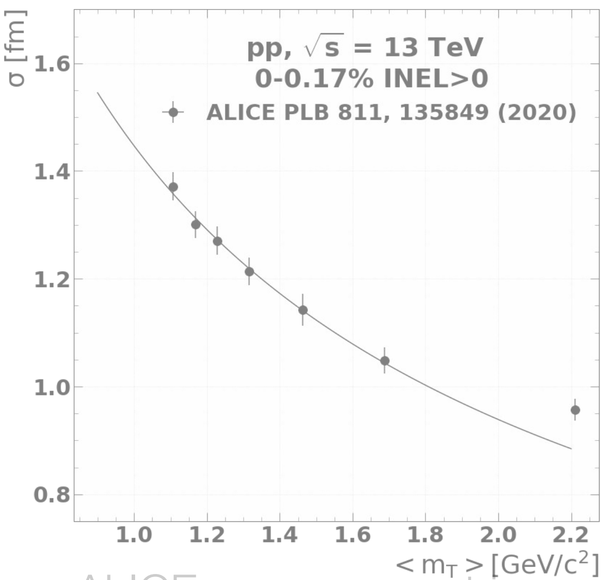
Erlang distribution fitted to EPOS3 simulations

Momentum distribution



ALICE measurements over a large multiplicity range

Source size



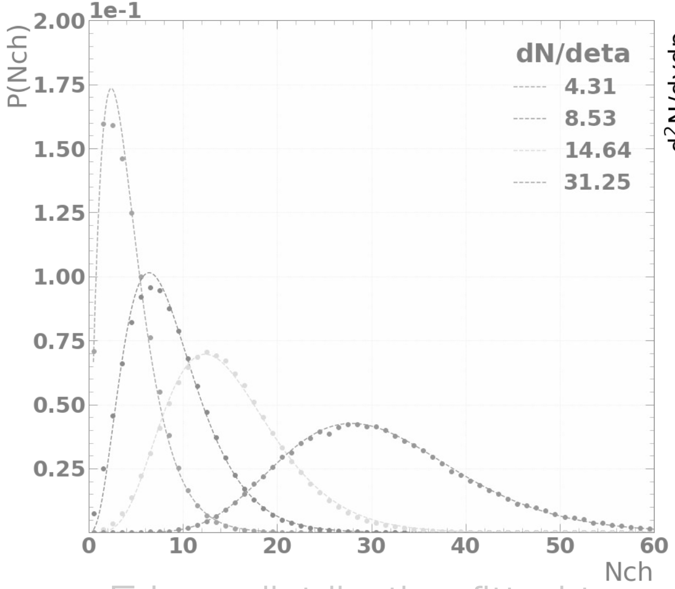
ALICE measurement in high-multiplicity collisions

The ToMCCA Model

A Toy Monte Carlo Coalescence Afterburner

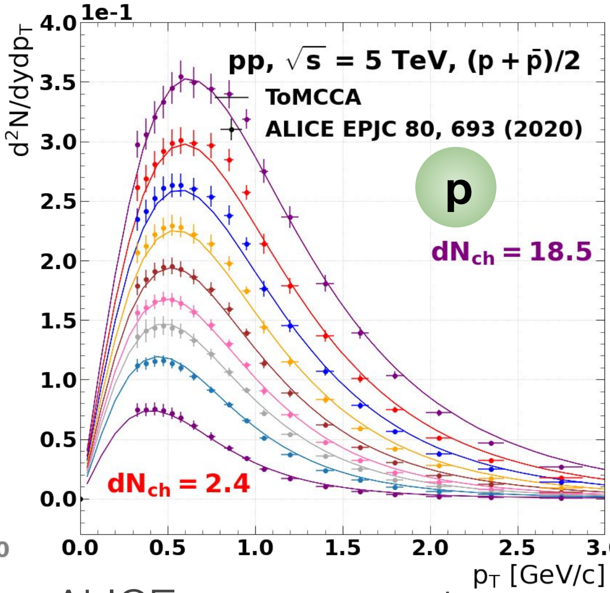
Main Inputs: Multiplicity, momentum distributions, source size

Multiplicity



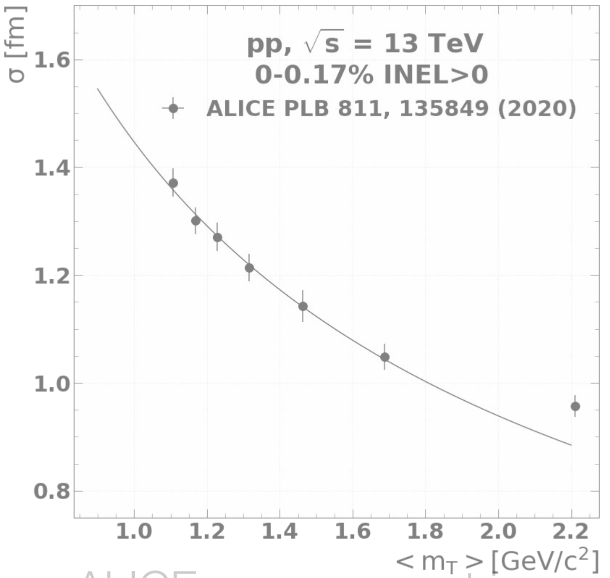
Erlang distribution fitted to EPOS3 simulations

Momentum distribution



ALICE measurements over a large multiplicity range

Source size



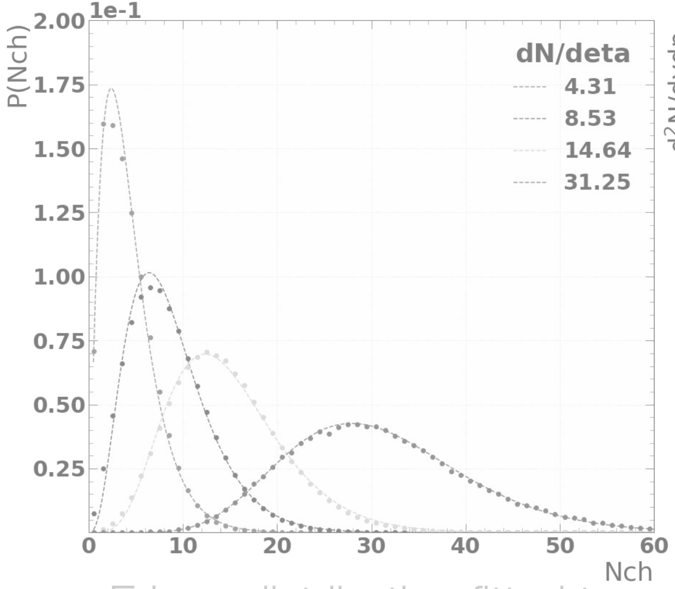
ALICE measurement in high-multiplicity collisions

The ToMCCA Model

A Toy Monte Carlo Coalescence Afterburner

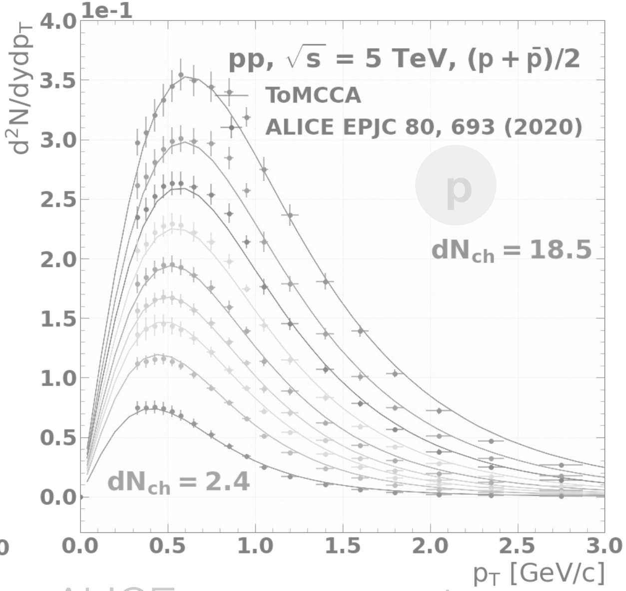
Main Inputs: Multiplicity, momentum distributions, source size

Multiplicity



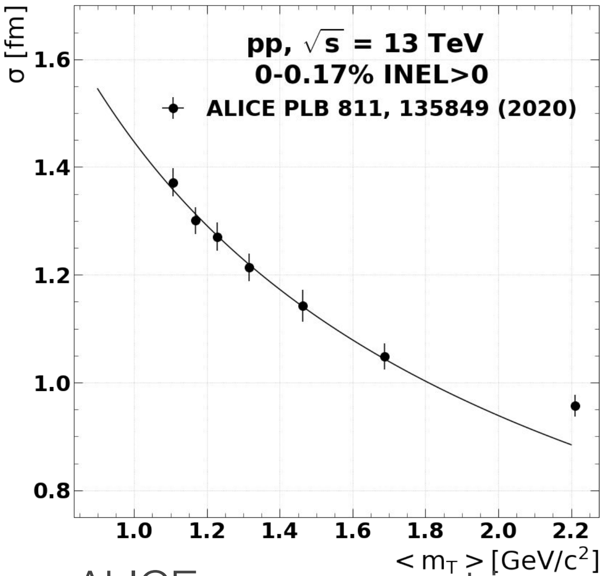
Erlang distribution fitted to EPOS3 simulations

Momentum distribution



ALICE measurements over a large multiplicity range

Source size



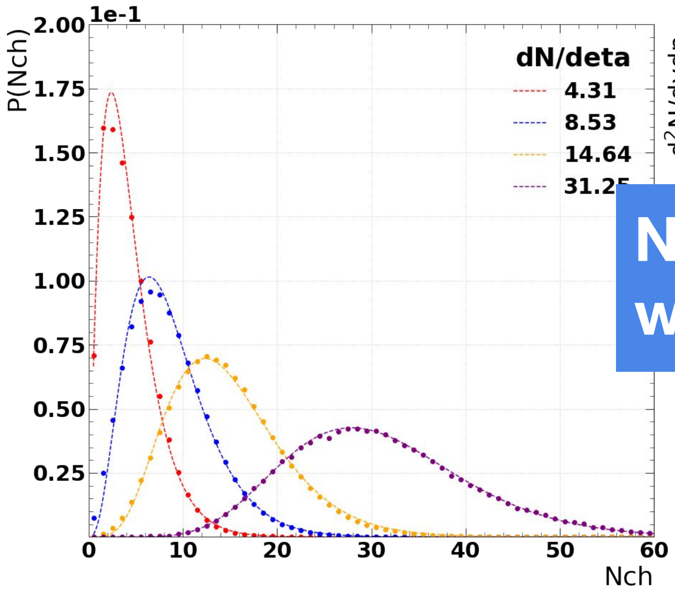
ALICE measurement in high-multiplicity collisions

The ToMCCA Model

A Toy Monte Carlo Coalescence Afterburner

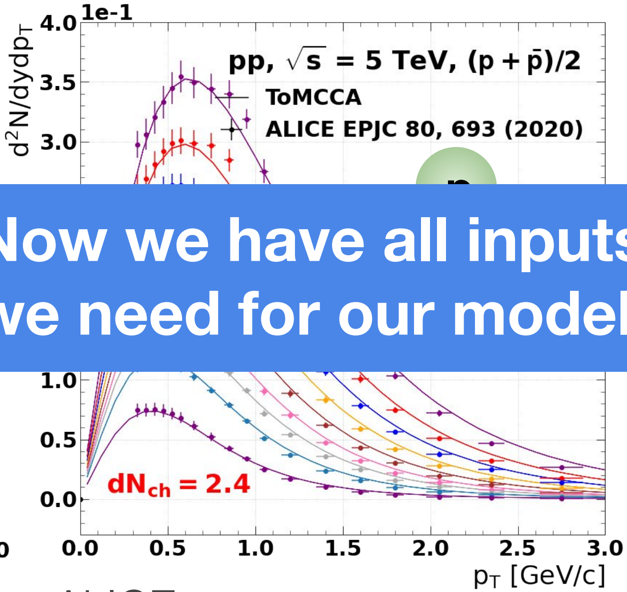
Main Inputs: Multiplicity, momentum distributions, source size

Multiplicity



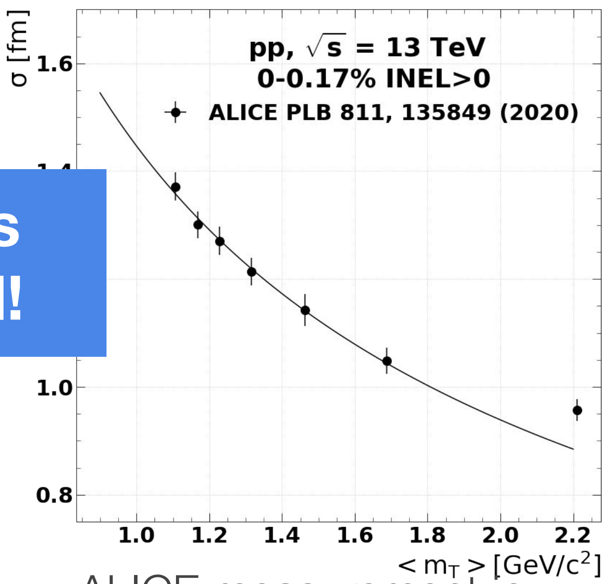
Erlang distribution fitted to EPOS3 simulations

Momentum distribution



ALICE measurements over a large multiplicity range

Source size



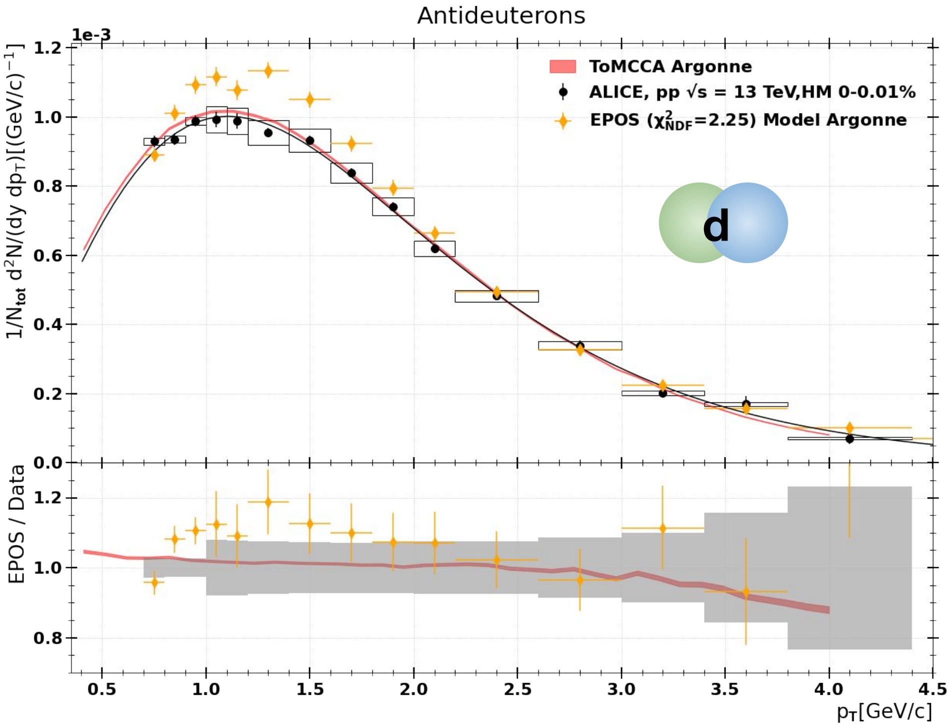
ALICE measurement in high-multiplicity collisions

Now we have all inputs we need for our model!

Deuteron Spectra

ToMCCA Model in HM pp Collisions

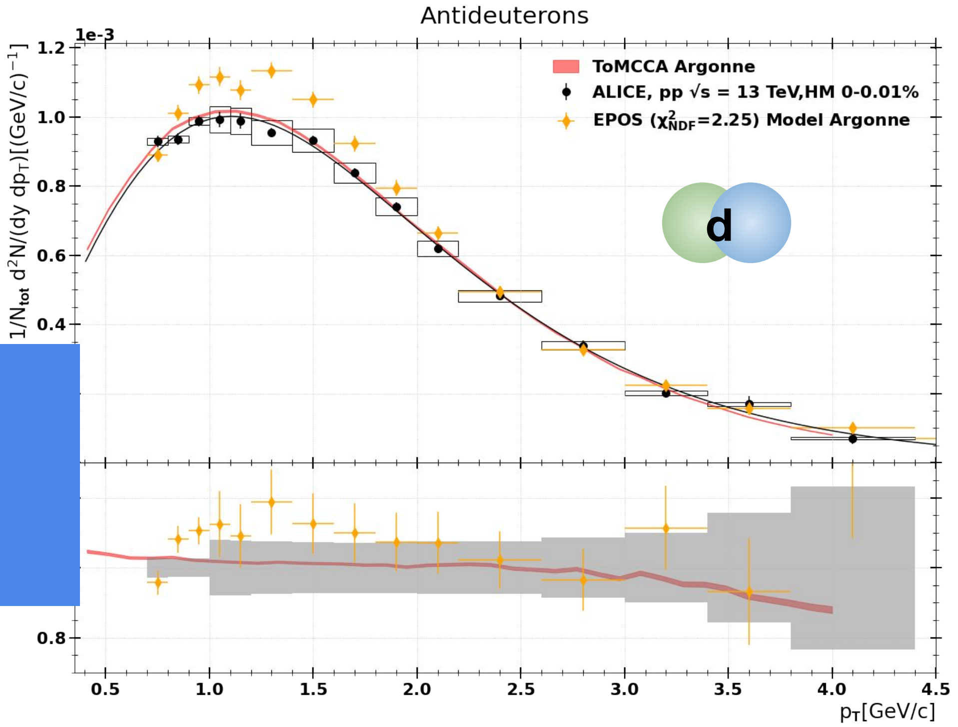
- Using ToMCCA for 13 TeV HM collisions ($(dN_{ch}/d\eta)_{|\eta|<0.8}$~31) we can reproduce measured spectra
- No free parameters!



Deuteron Spectra

ToMCCA Model in HM pp Collisions

- Using ToMCCA for 13 TeV HM collisions ($(dN_{ch}/d\eta)_{|\eta|<0.8}$~31) we can reproduce measured spectra
- No free parameters!

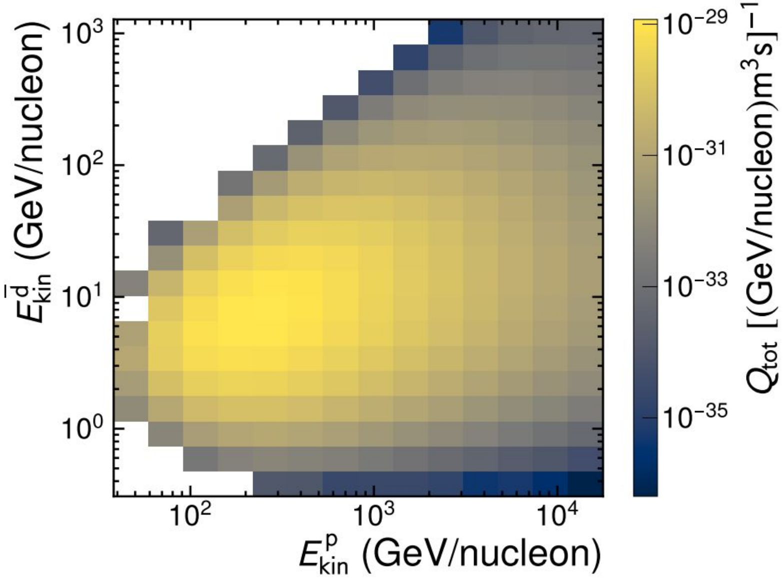


Does this help us in predicting Cosmic Ray fluxes?

Cosmic Rays

Production energy of antinuclei

- Antideuteron production predominantly for protons of E_{kin}~200-500 GeV ($\sqrt{s}$ ~ **19-30 GeV** for p-H)

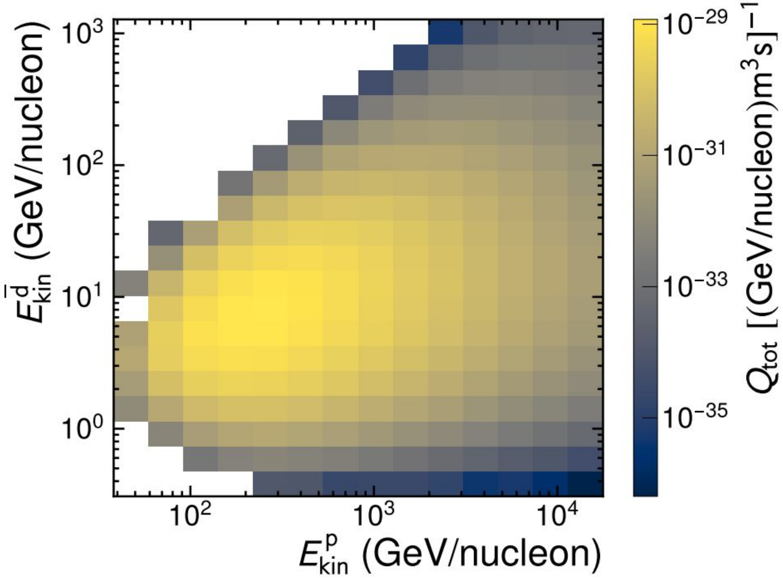


📚Šerkšnytė, et al. PRD 105, 083021 (2022)

Cosmic Rays

Production energy of antinuclei

- Antideuteron production predominantly for protons of E_{kin}~200-500 GeV ($\sqrt{s}$ ~ **19-30 GeV** for p-H)

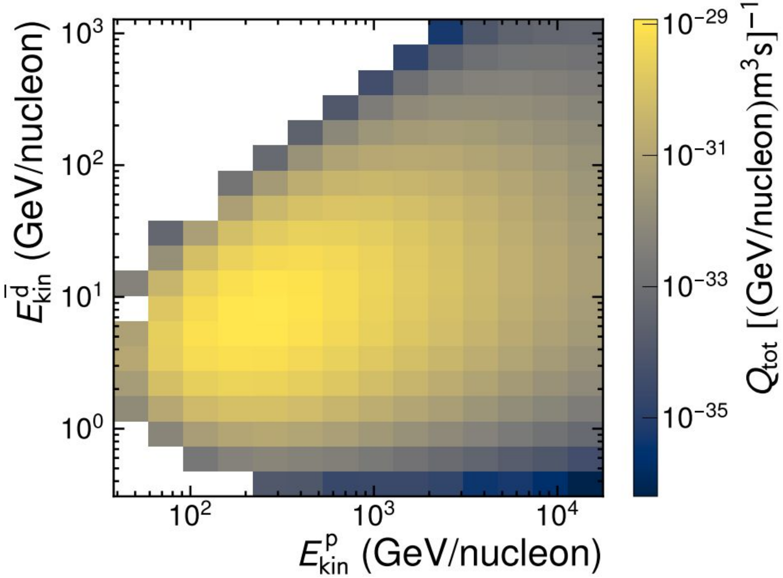


📚Šerkšnytė, et al. PRD 105, 083021 (2022)

- Extrapolation to lower energies via event multiplicity

Cosmic Rays
Production energy of antinuclei

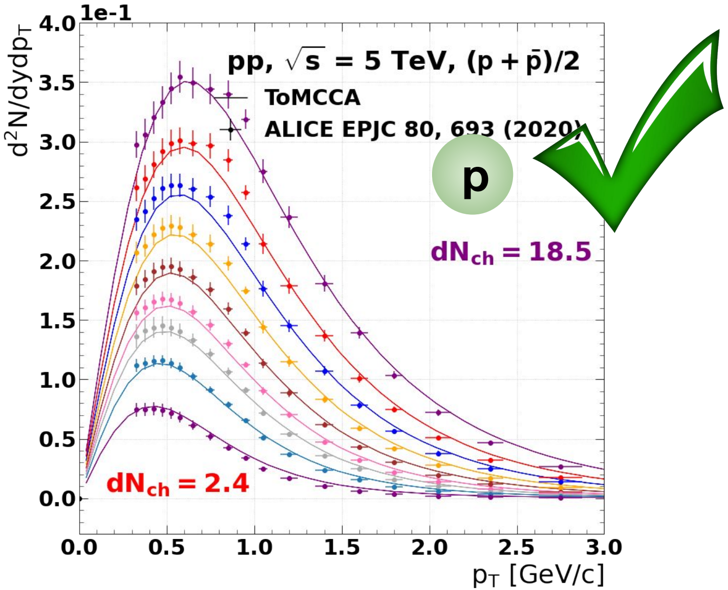
- Antideuteron production predominantly for protons of E_{kin}~200-500 GeV ($\sqrt{s}$ ~ **19-30 GeV** for p-H)



📚Šerkšnytė, et al. PRD 105, 083021 (2022)

- Extrapolation to lower energies via event multiplicity

Momentum distribution

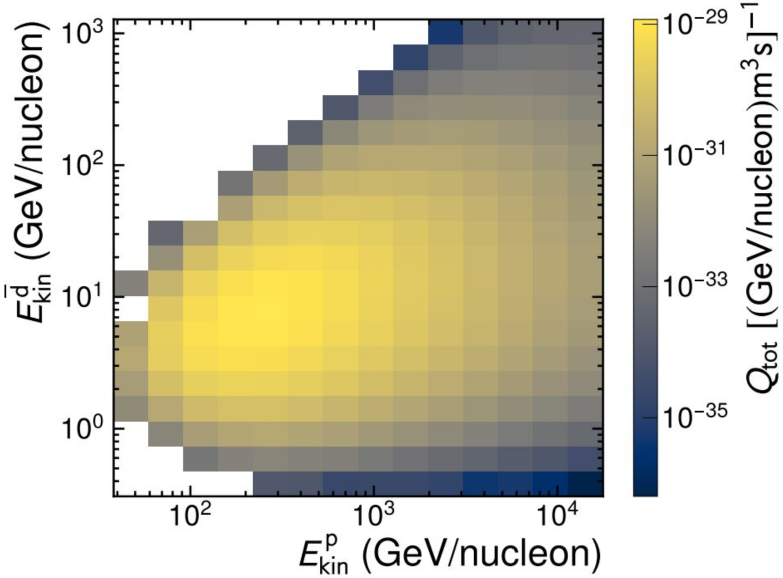


ALICE measurements over a large range in multiplicity

Cosmic Rays

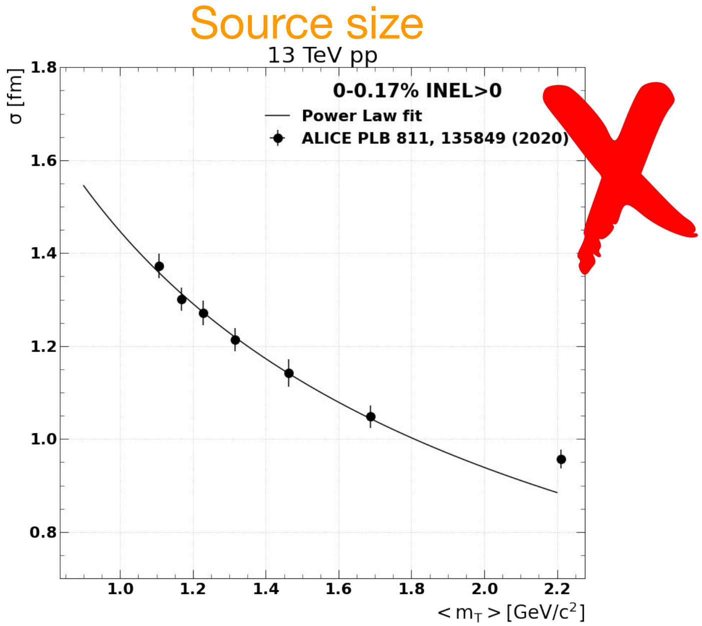
Production energy of antinuclei

- Antideuteron production predominantly for protons of E_{kin}~200-500 GeV ($\sqrt{s}$ ~ **19-30 GeV** for p-H)



📚Šerkšnytė, et al. PRD 105, 083021 (2022)

- Extrapolation to lower energies via event multiplicity

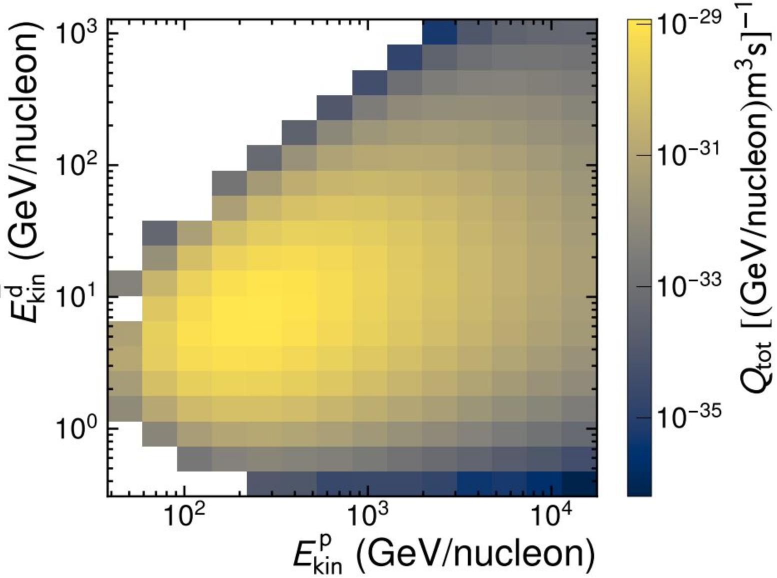


ALICE measurement in high-multiplicity collisions

Cosmic Rays

Production energy of antinuclei

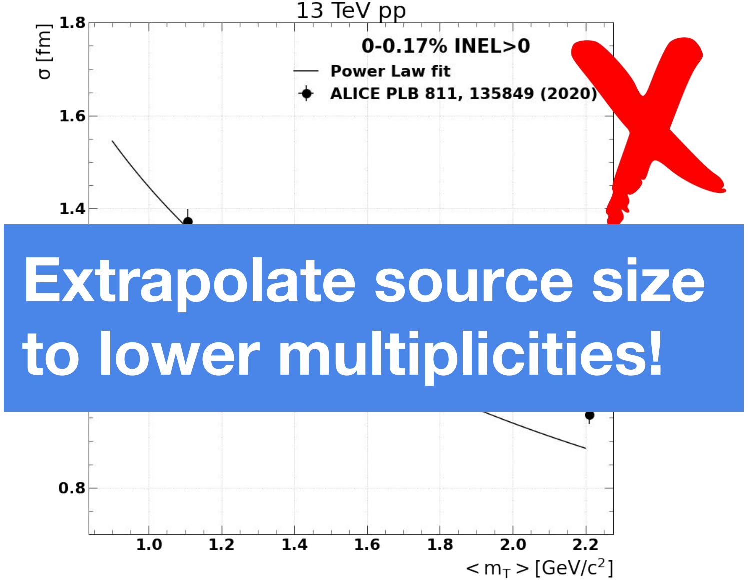
- Antideuteron production predominantly for protons of E_{kin}~200-500 GeV ($\sqrt{s}$ ~ **19-30 GeV** for p-H)



Šerkšnytė, et al. PRD 105, 083021 (2022)

- Extrapolation to lower energies via event multiplicity

Source size

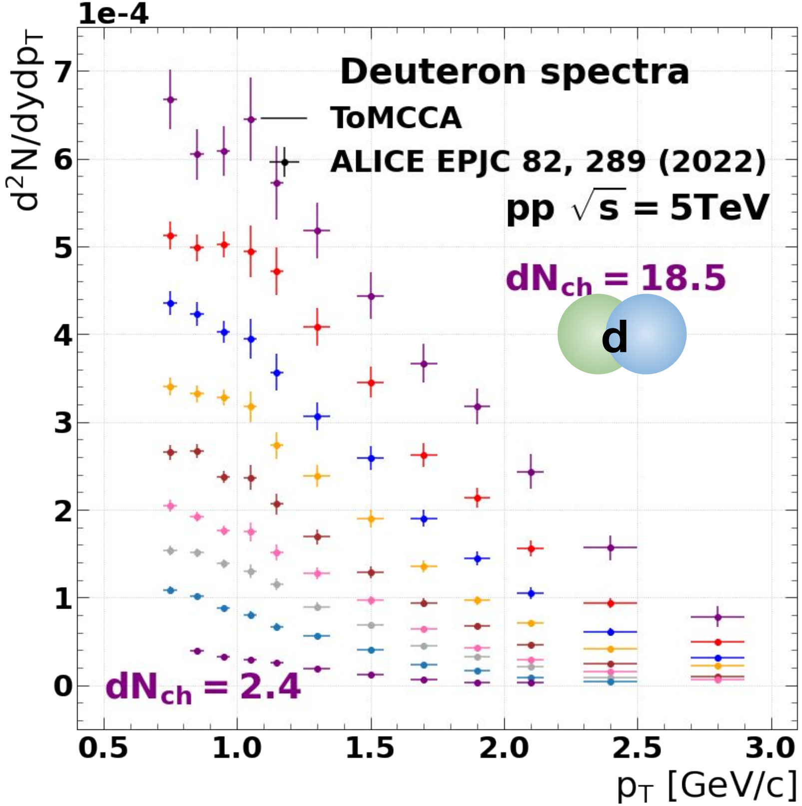


ALICE measurement in high-multiplicity collisions

Extrapolating the Source

Using ToMCCA as a fitting tool

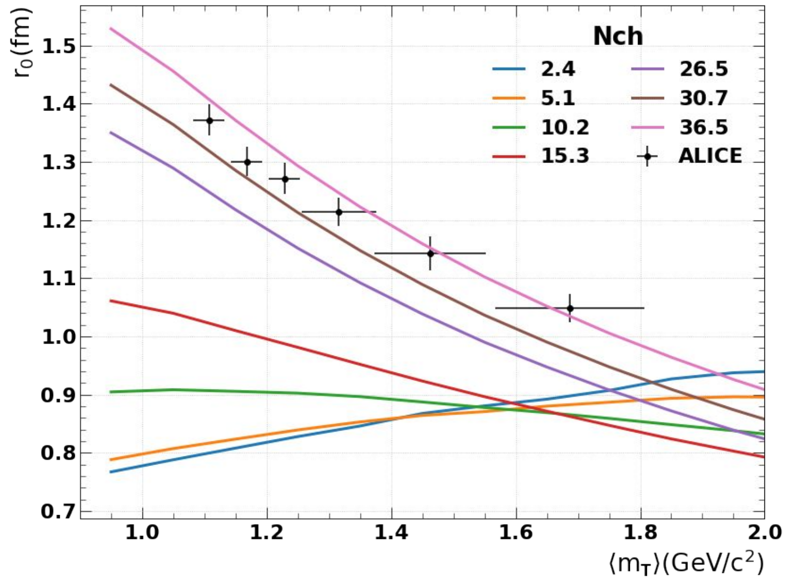
- Deuterons were also measured by ALICE Collab. for different multiplicities
- Fit source size and scaling with m_T to measured data
- Cross check at different energies

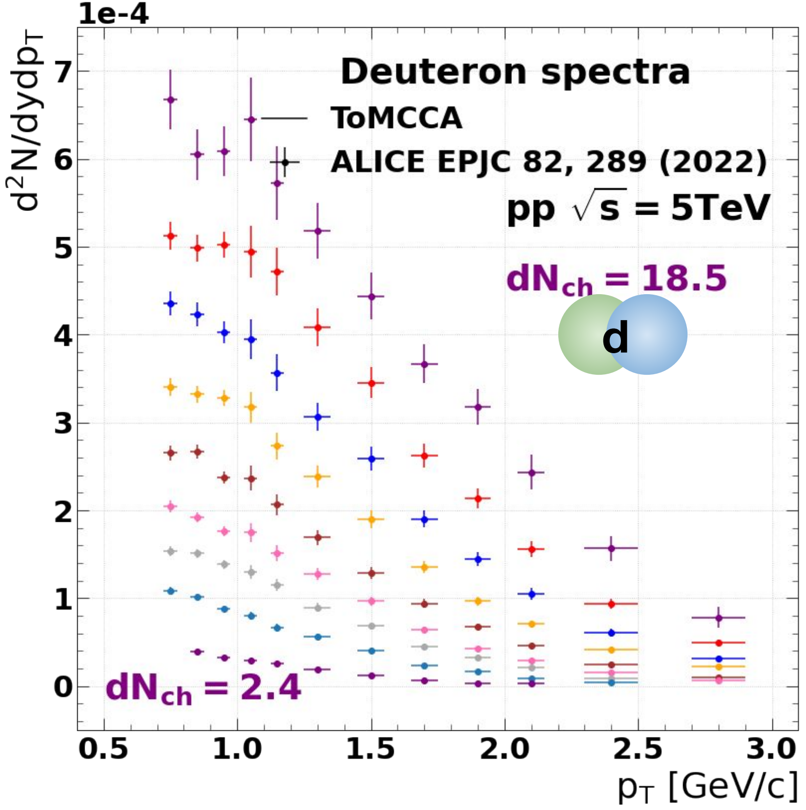


Extrapolating the Source

Using ToMCCA as a fitting tool

- Deuterons were also measured by ALICE Collab. for different multiplicities
- Fit source size and scaling with m_T to measured data
- Cross check at different energies

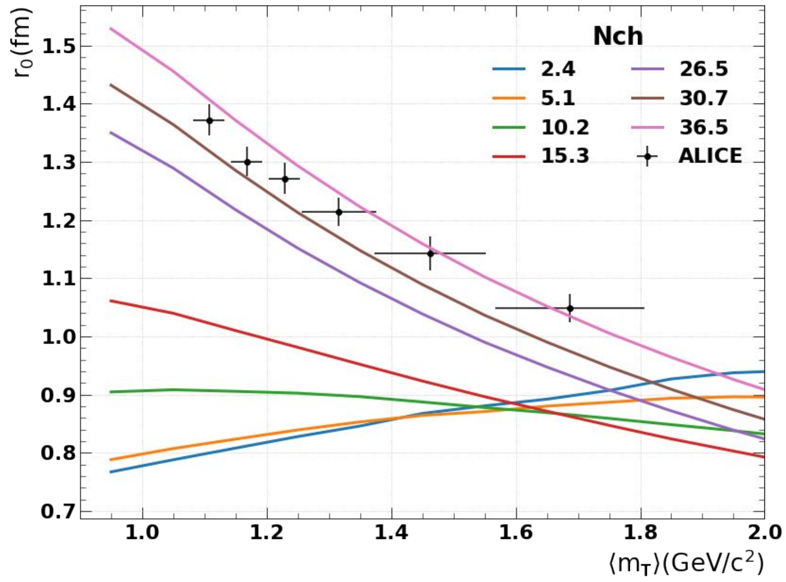


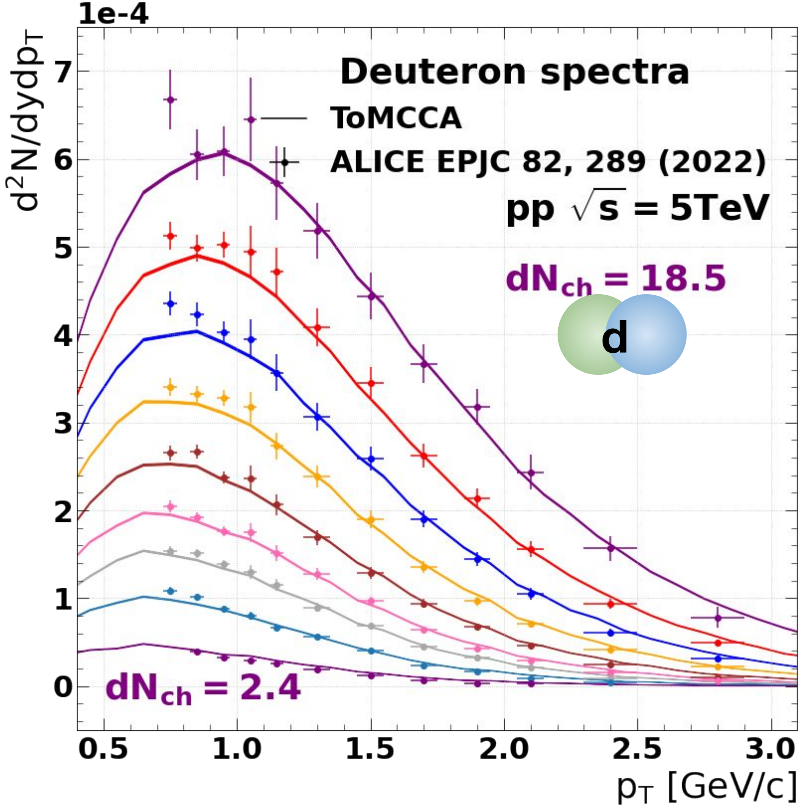


Extrapolating the Source

Using ToMCCA as a fitting tool

- Deuterons were also measured by ALICE Collab. for different multiplicities
- Fit source size and scaling with m_T to measured data
- Cross check at different energies

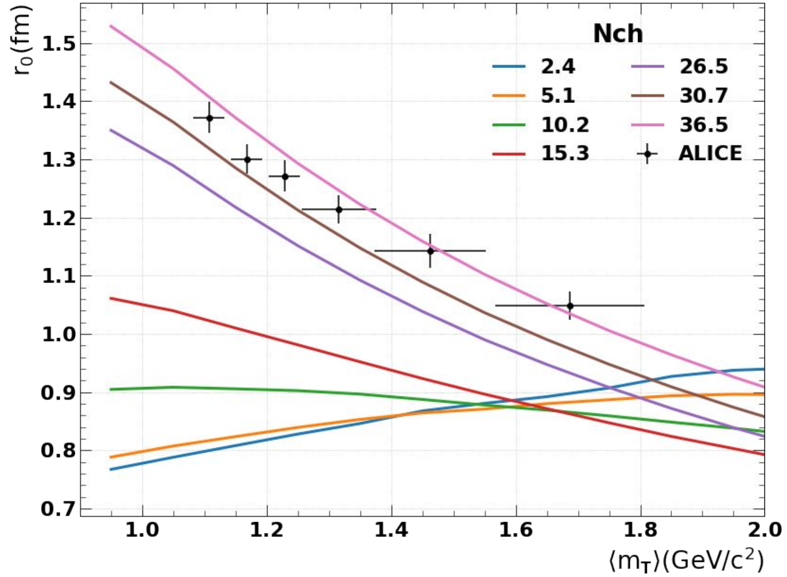


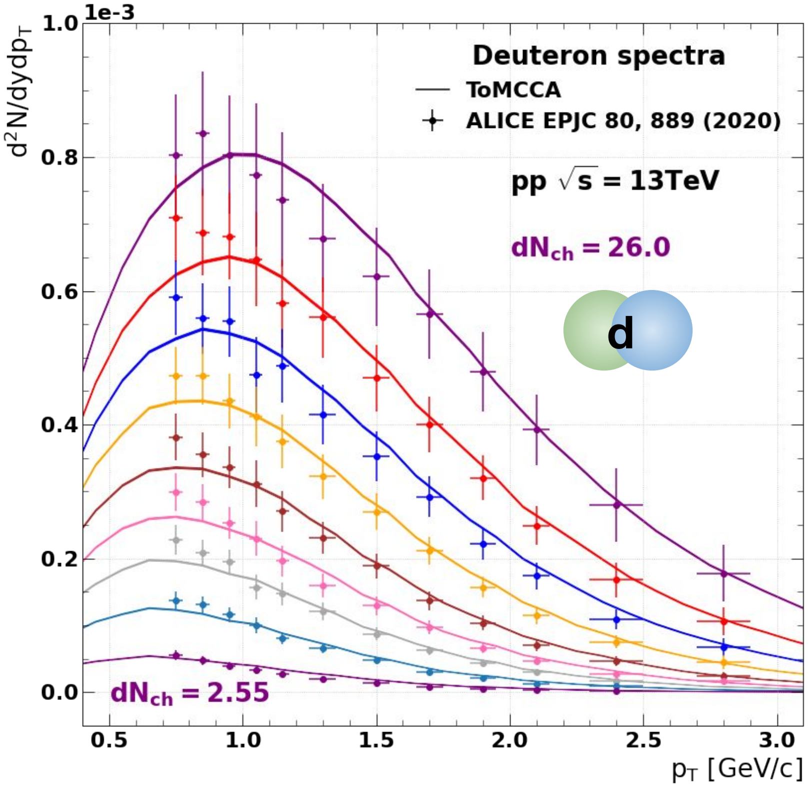


Extrapolating the Source

Using ToMCCA as a fitting tool

- Deuterons were also measured by ALICE Collab. for different multiplicities
- Fit source size and scaling with m_T to measured data
- Cross check at different energies

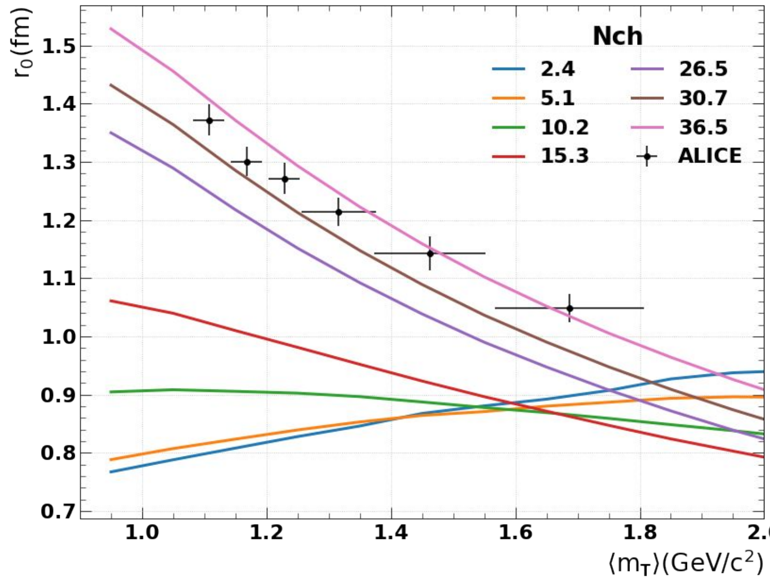


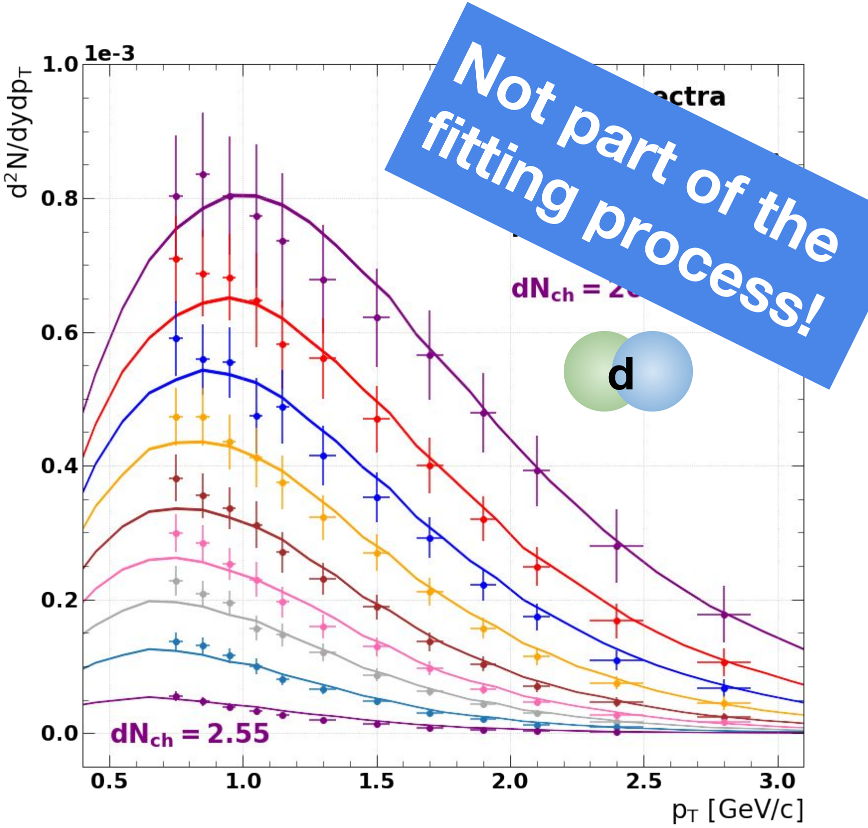


Extrapolating the Source

Using ToMCCA as a fitting tool

- Deuterons were also measured by ALICE Collab. for different multiplicities
- Fit source size and scaling with m_T to measured data
- Cross check at different energies

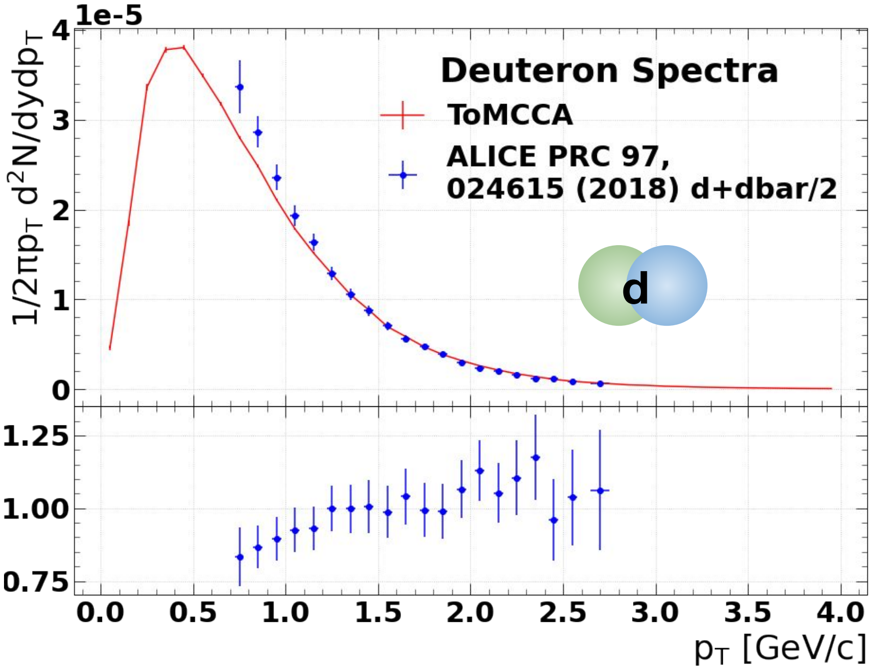




Deuteron results

Minimum bias 7 TeV

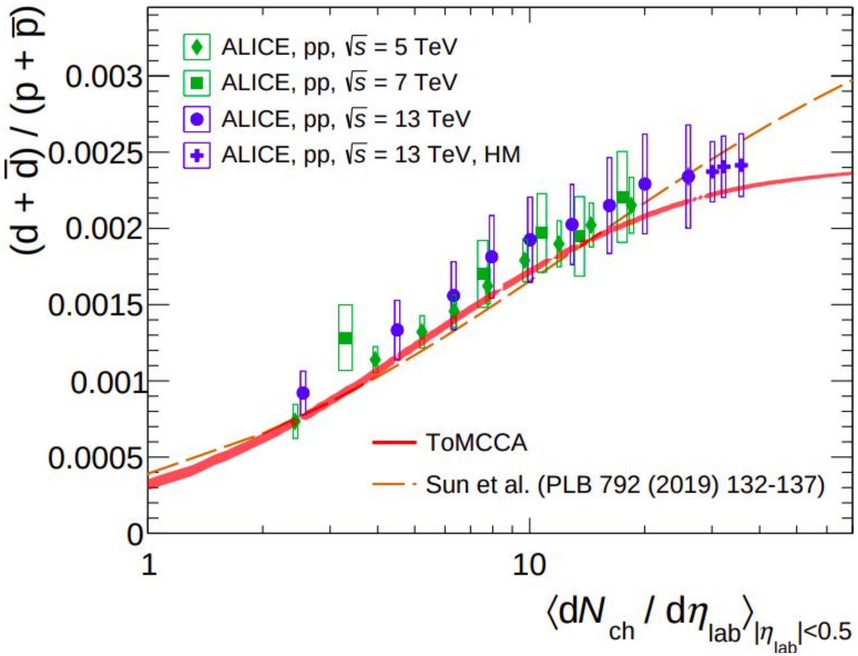
- Deuterons were also measured by ALICE Collab. for different multiplicities
- Fit source size and scaling with m_T to measured data
- Cross check at different energies
- Minimum Bias works well



Deuteron results

d/p ratio

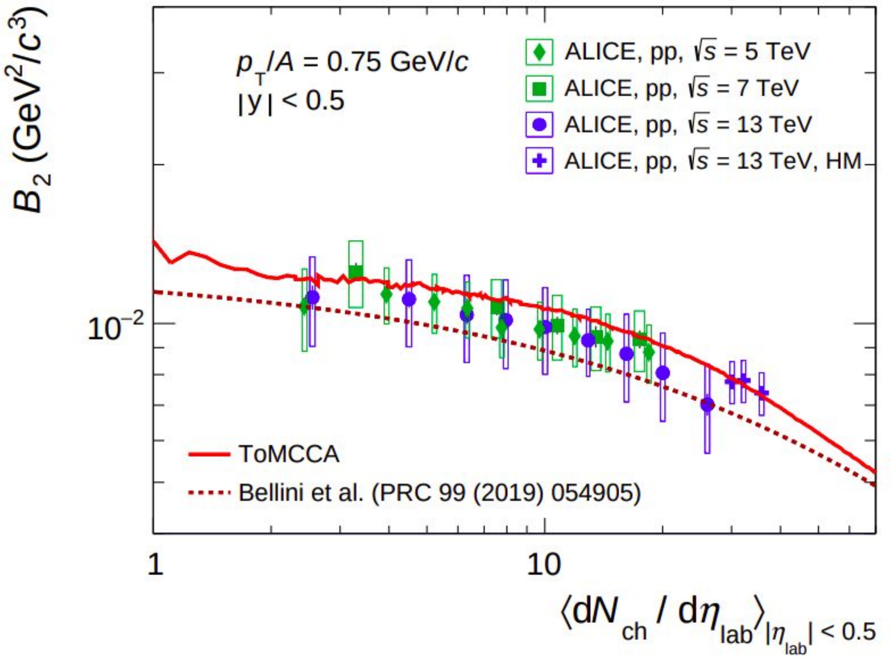
- Deuterons were also measured by ALICE Collab. for different multiplicities
- Fit source size and scaling with m_T to measured data
- Cross check at different energies
- Minimum Bias works well
- d/p ratio reproduces data well, tension to previous predictions at high multiplicity



Deuteron results

B_2 parameter

- Deuterons were also measured by ALICE Collab. for different multiplicities
- Fit source size and scaling with m_T to measured data
- Cross check at different energies
- Minimum Bias works well
- d/p ratio reproduces data well, tension to previous predictions at high multiplicity
- B_2 also reproduced well



$$B_A(p_T^p) = E_A \frac{d^3 N_A}{dp_A^3} \Big/ \left(E_p \frac{d^3 N_p}{dp_p^3} \right)^A$$

Extension to A=3

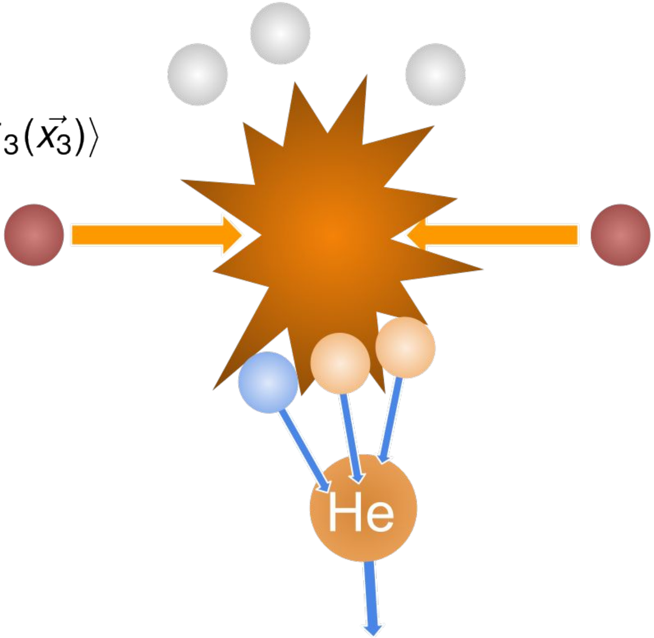
Add 3rd particle to basic formalism

$$\frac{dN_{He}}{d^3P} = S_{\text{He}} \int d^3x_1 \int d^3x_2 \int d^3x_3 \int d^3x_1' \int d^3x_2' \int d^3x_3'$$

$$\times\, \Psi^*_{\text{He}}\left(\vec{x_1}', \vec{x_2}', x_3'\right) \Psi_{\text{He}}\left(\vec{x_1}, \vec{x_2}, \vec{x_3}\right) \langle \Psi_3^\dagger(\vec{x}_3')\Psi_2^\dagger(\vec{x}_2')\Psi_1^\dagger(\vec{x}_1')\Psi_1(\vec{x}_1)\Psi_2(\vec{x}_2)\Psi_3(\vec{x}_3)\rangle$$

Similarly the probability can be expressed as

$$\mathcal{P}(k_1, q_1, \sigma, b) = \frac{S_{\text{He}}}{(2\pi)^3 2^9 \sigma^6} \int d^3r_1\, d^3r_2\, \mathcal{D}(\vec{q}_1, \vec{k}_1, \vec{r}_1, \vec{r}_2) e^{-\frac{r_1^2 + r_2^2}{4\sigma^2}}$$



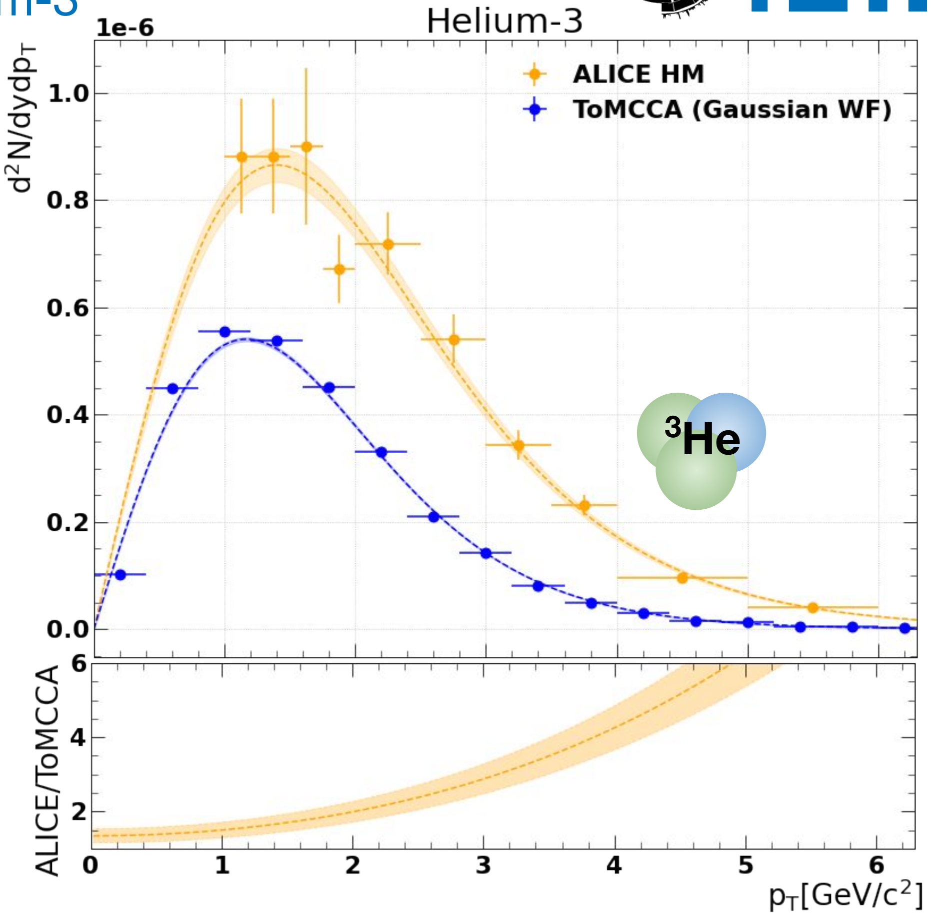
Extension to A=3

Helium-3

Extension to A=3 coalescence

- Use 2-body source size
  - Assign every pair a distance
  - Geometric mean of distance for coalescence probability
- For now only Gaussian wave function:
  - Yield ~*50% lower* than data
  - Shape at large p_T deviates

$$\mathcal{P}(k,q,\sigma) = \frac{S\ 64\ b^6}{(b^2+2\sigma^2)^3} \exp\left[-b^2(k^2+q^2)\right]$$



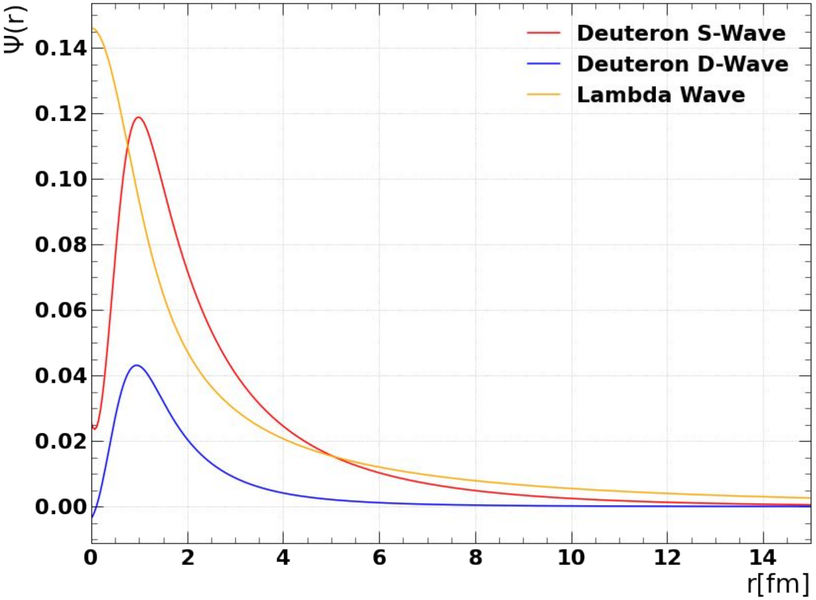
Extension to A=3

Hypertriton

- Congleton[1] wavefunction

$$\Psi_\Lambda(q) = N\frac{exp[-(q/\Lambda)^2]}{q^2 + \alpha^2}$$

- Assumes factorization of Hypertriton wavefunction into deuteron+Λ
- Scattering parameters retuned to latest Hypertriton formfactor calculations[2]



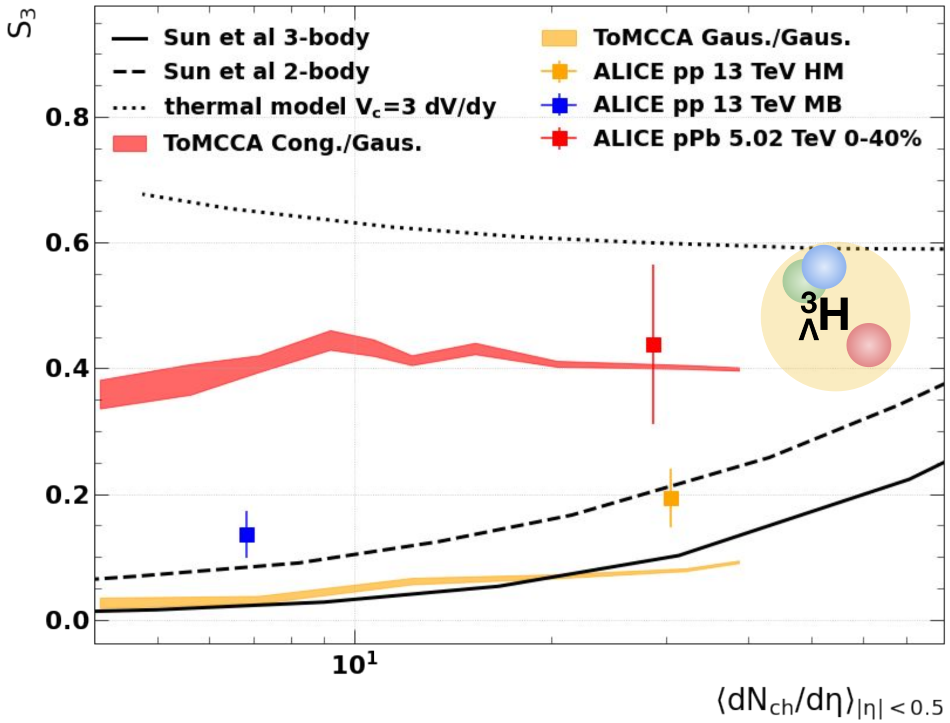
[1] J G Congleton 1992 J. Phys. G: Nucl. Part. Phys. 18 339
[2] F. Bellini et al.: Phys.Rev.C 103, 1 (2021)

Extension to A=3

Hypertriton

- S_3 observable is expected to be very sensitive to production mechanism
- Using Gaussian for LH3 and He-3 gives comparable results to Sun et al.
- Using Congleton for LH3 overestimates S_3

$$S_3 = ({}^3_\Lambda\mathrm{H}/{}^3\mathrm{He})/(\Lambda/p)$$

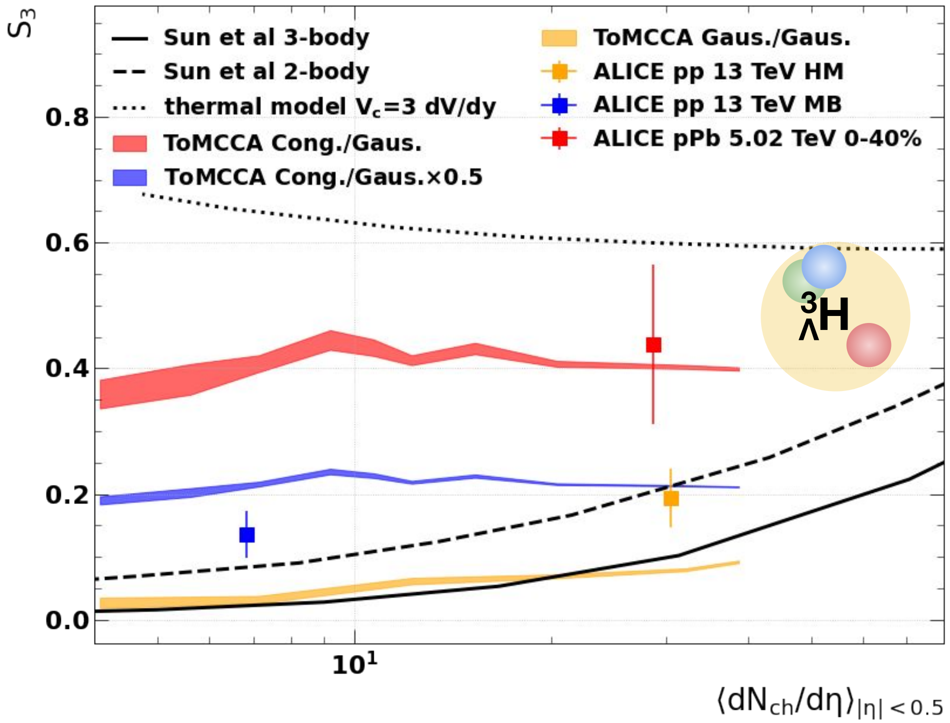


Extension to A=3

Hypertriton

- S_3 observable is expected to be very sensitive to production mechanism
- Using Gaussian for LH3 and He-3 gives comparable results to Sun et al.
- Using Congleton for LH3 overestimates S_3
- He-3 yield is underestimated →Scale by 0.5

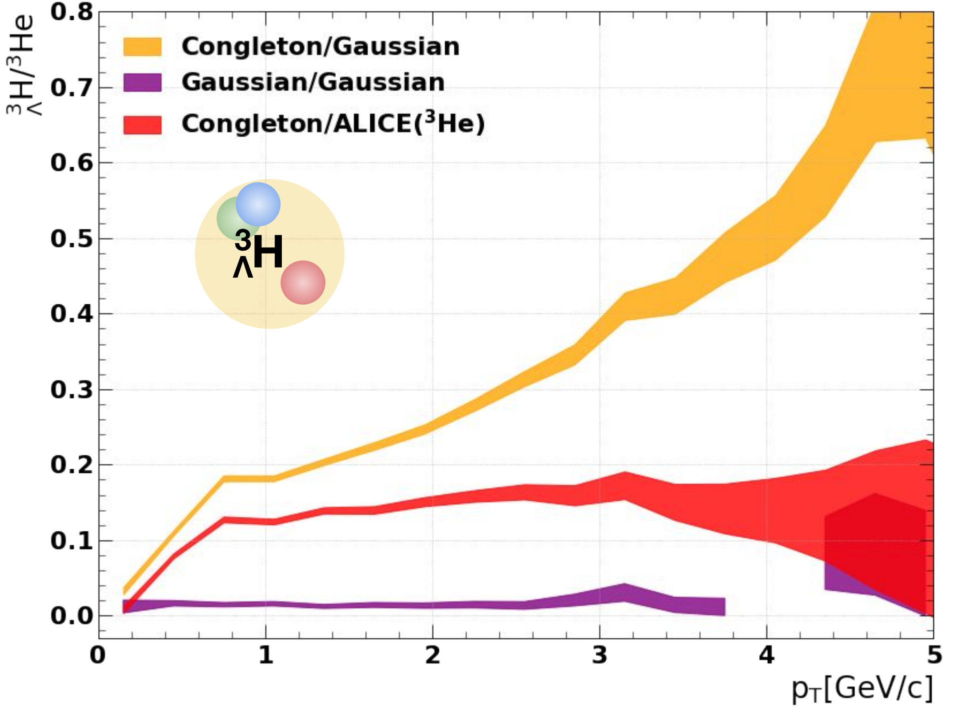
$$S_3 = ({}^3_\Lambda\mathrm{H}/{}^3\mathrm{He})/(\Lambda/p)$$



Extension to A=3

Hypertriton

- S_3 observable is expected to be very sensitive to production mechanism
- Using Gaussian for LH3 and He-3 gives comparable results to Sun et al.
- Using Congleton for LH3 overestimates S_3
- He-3 yield is underestimated →Scale by 0.5
- ${}^{3}_{\Lambda}H/{}^{3}He$ Ratio shows increasing behaviour
- However: ${}^{3}He$ does not reproduce shape of measured spectra
- Flat behaviour when using measured ${}^{3}He$ spectra



Conclusion

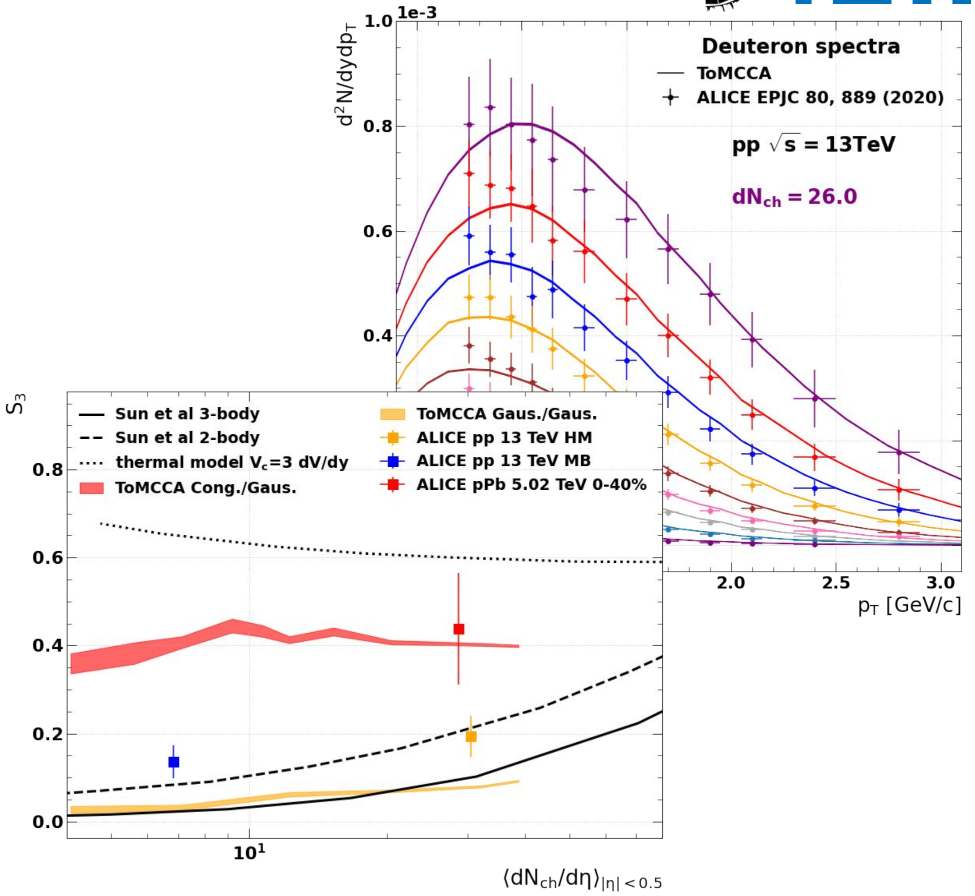
Deuterons:

- Coalescence model reproduces data with no free parameters
- Realistic wavefunction required
- ToMCCA allows for an extension to arbitrary multiplicities

A=3 Coalescence

- Successful extension of the model to A=3
- Nuclei and *Hyper*nuclei
- Realistic wavefunctions required

ToMCCA is available under:
https://github.com/horstma/tomcca-public



Conclusion

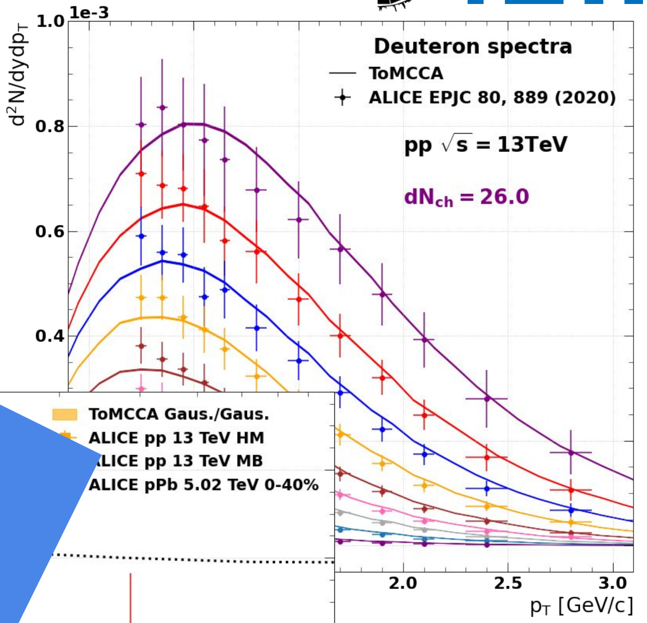
Deuterons:

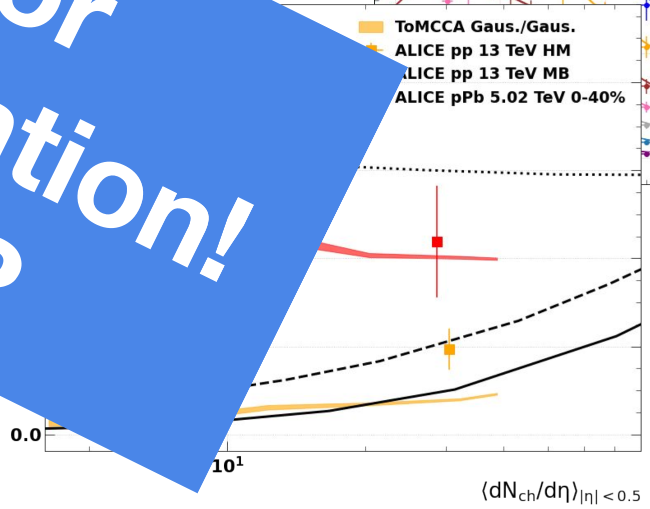
- Coalescence mode[…]ces data with no free para[…]
- Realistic wavefu[…]
- ToMCCA allow[…] arbitrary mult[…]

A=3 Coalescenc[…]

- Successfu[…] A=3
- Nuclei and *Hypern*[…]
- Realistic wavefunctions fo[…]

Thanks for your attention! Questions?





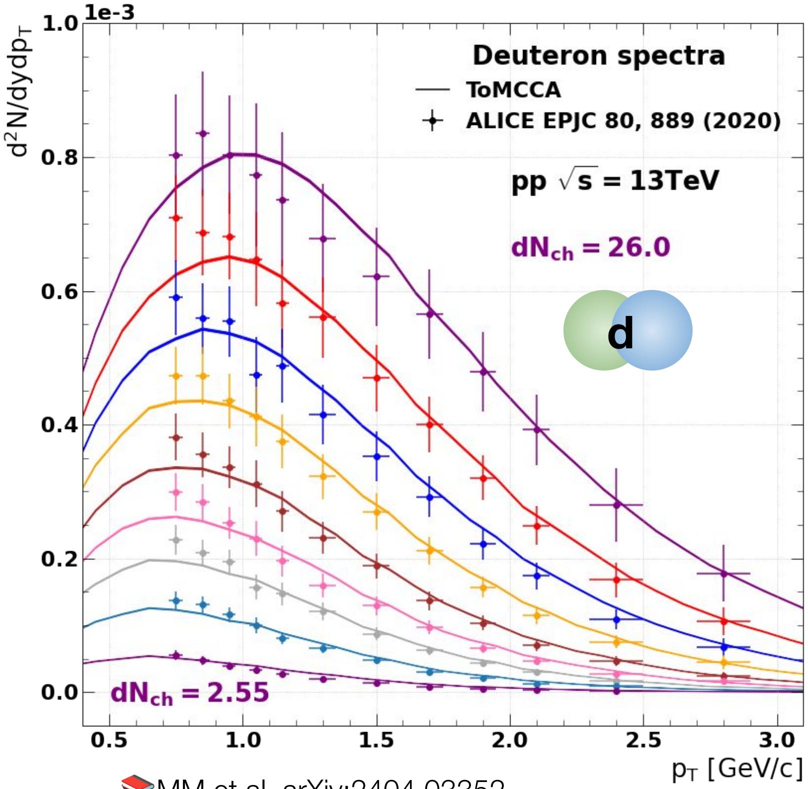
ToMCCA is available under:
https://github.com/horstma/tomcca-public

BACKUP

Conclusion

Deuteron production

- Understanding nuclei formation on earth can open a window to **indirect dark matter** searches
- **Wigner function formalism** can predict nuclei yields with no free parameters
- ToMCCA allows us to extrapolate to arbitrary multiplicities



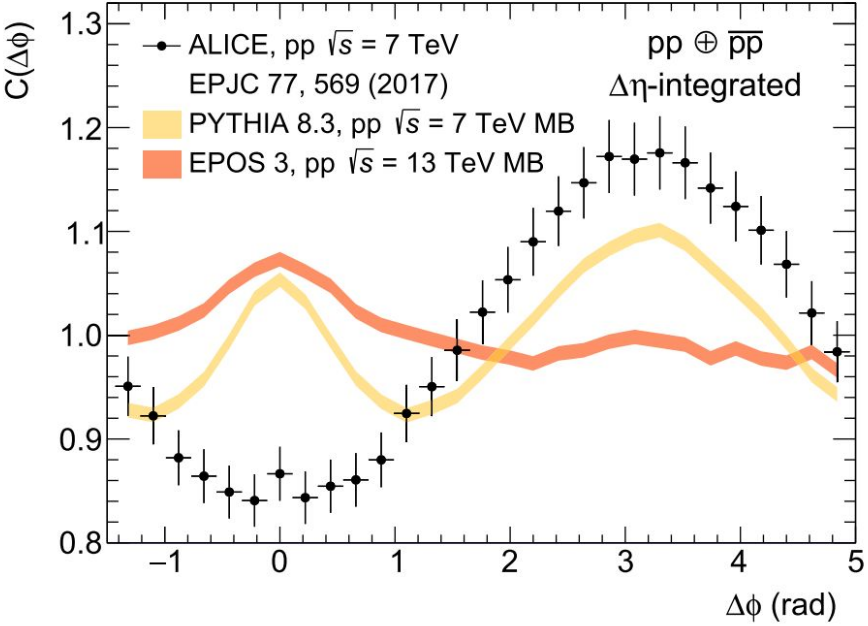
📚MM et al. arXiv:2404.03352

Coalescence Results EPOS

Angular correlations

- $\Delta\phi$ of pp (pn) pairs
- Not reproduced by EPOS or Pythia
- No real control over these behaviours in general purpose event generators

📚MM et al .Eur.Phys.J.C 83 (2023) 9, 804

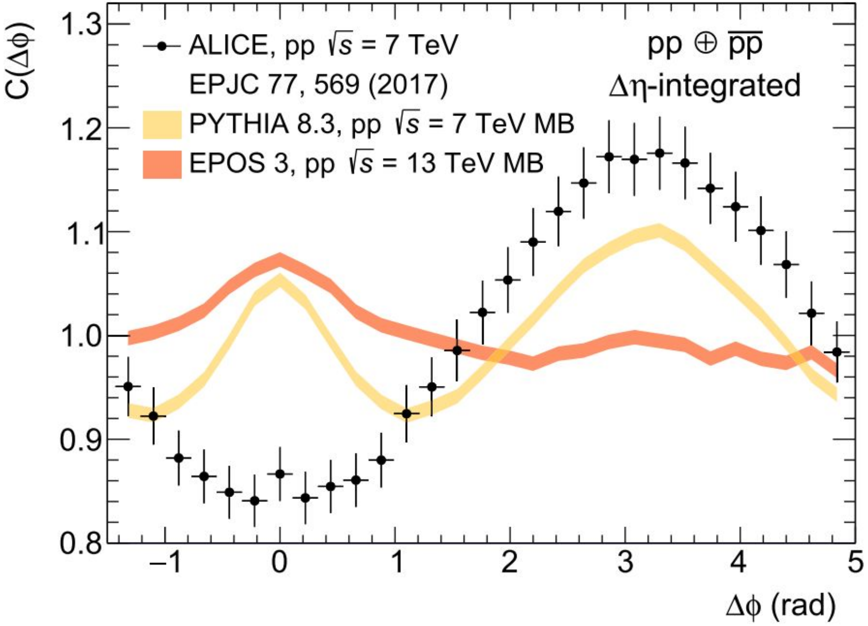


Coalescence Results EPOS

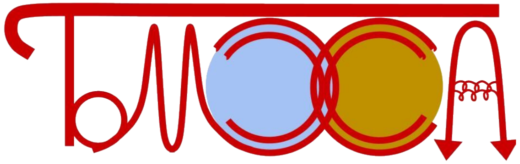
Angular correlations

- Δϕ of pp (pn) pairs
- Not reproduced by EPOS or Pythia
- No real control over these behaviours in general purpose event generators

📚MM et al .Eur.Phys.J.C 83 (2023) 9, 804



Introducing:



Toy **M**onte **C**arlo **C**oalescence **A**fterburner
arXiv:2404.03352

Comparison to previous predictions

- Important observable in accelerator measurements: $\mathbf{B_A}$

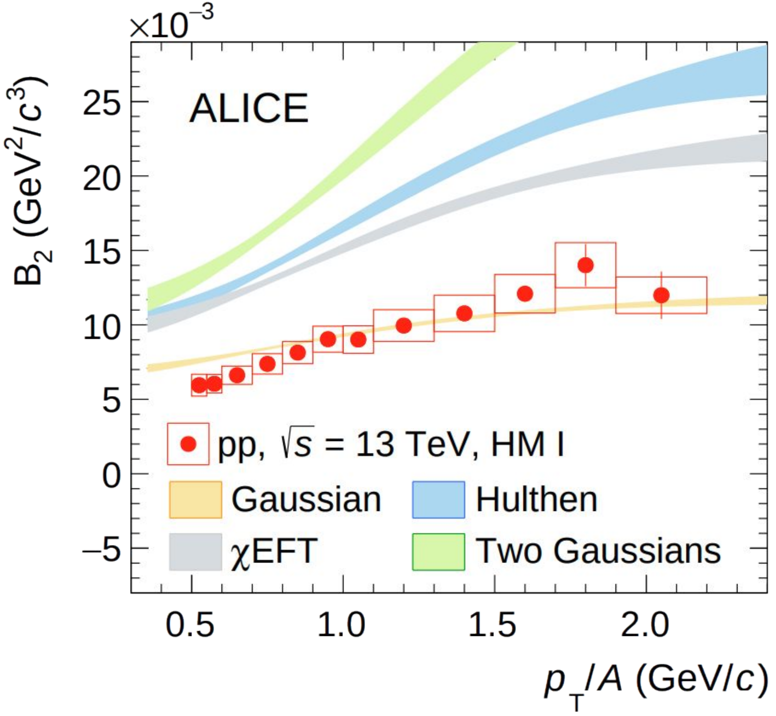
$$B_A(p_T^p) = E_A \frac{d^3 N_A}{dp_A^3} \Big/ \left(E_p \frac{d^3 N_p}{dp_p^3} \right)^A$$

- Theoretical prediction [1]

$$B_2(\vec{p}) \approx \frac{3}{2m} \int d^3 q D(\vec{q}) e^{-R^2(p_T)\ q^2}$$

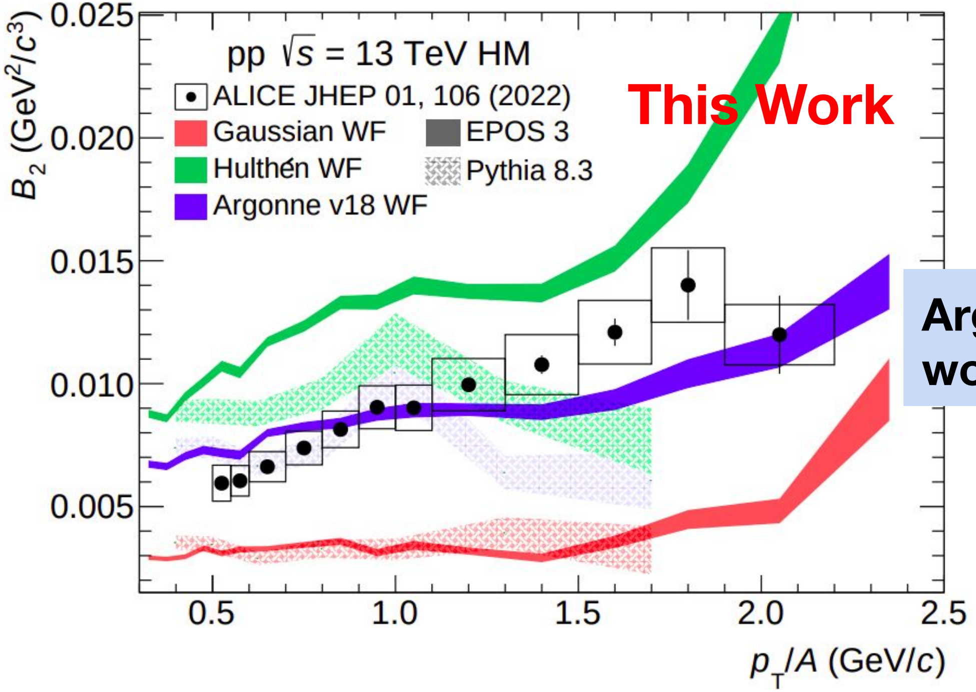
$$D(\vec{q}) = \int d^3 r |\phi_d(\vec{r})|^2 e^{-i\vec{q}\cdot\vec{r}}$$

- This neglects momentum difference between Nucleons
- approximate to 10% in Pb–Pb, factor 2 in pp

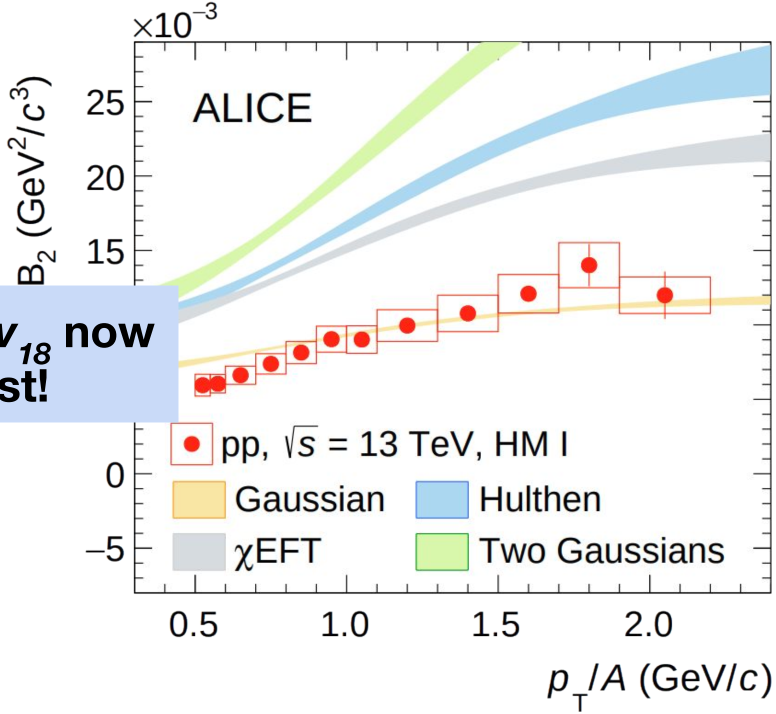


[1] Blum, Takimoto, PRC 99 (2019) 044913

Comparison to previous predictions



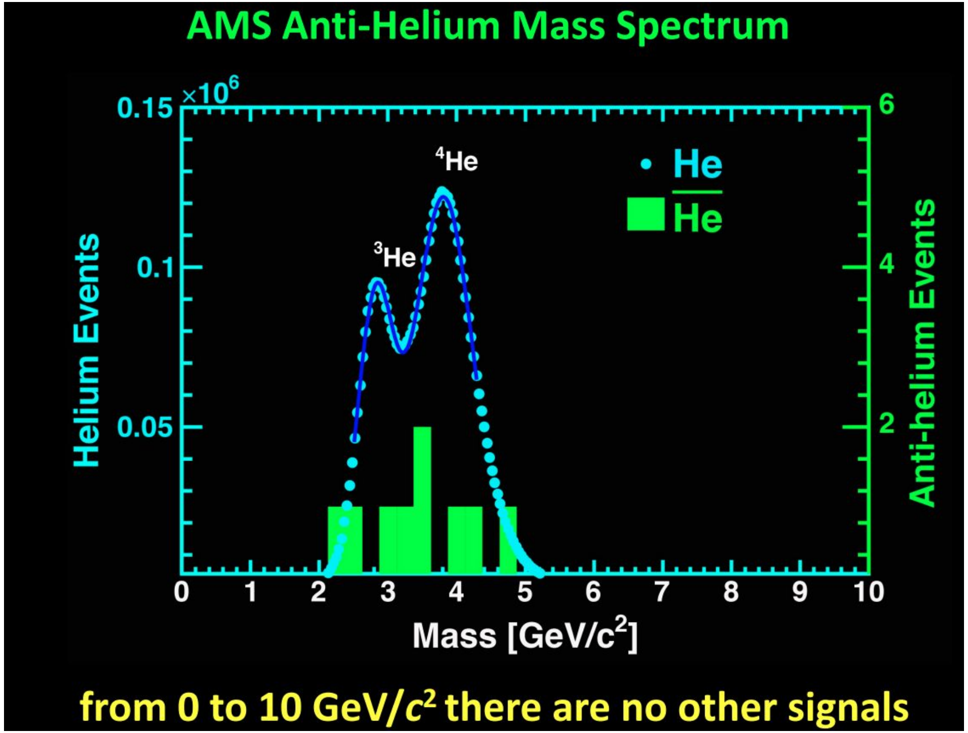
Argonne v_{18} now works best!



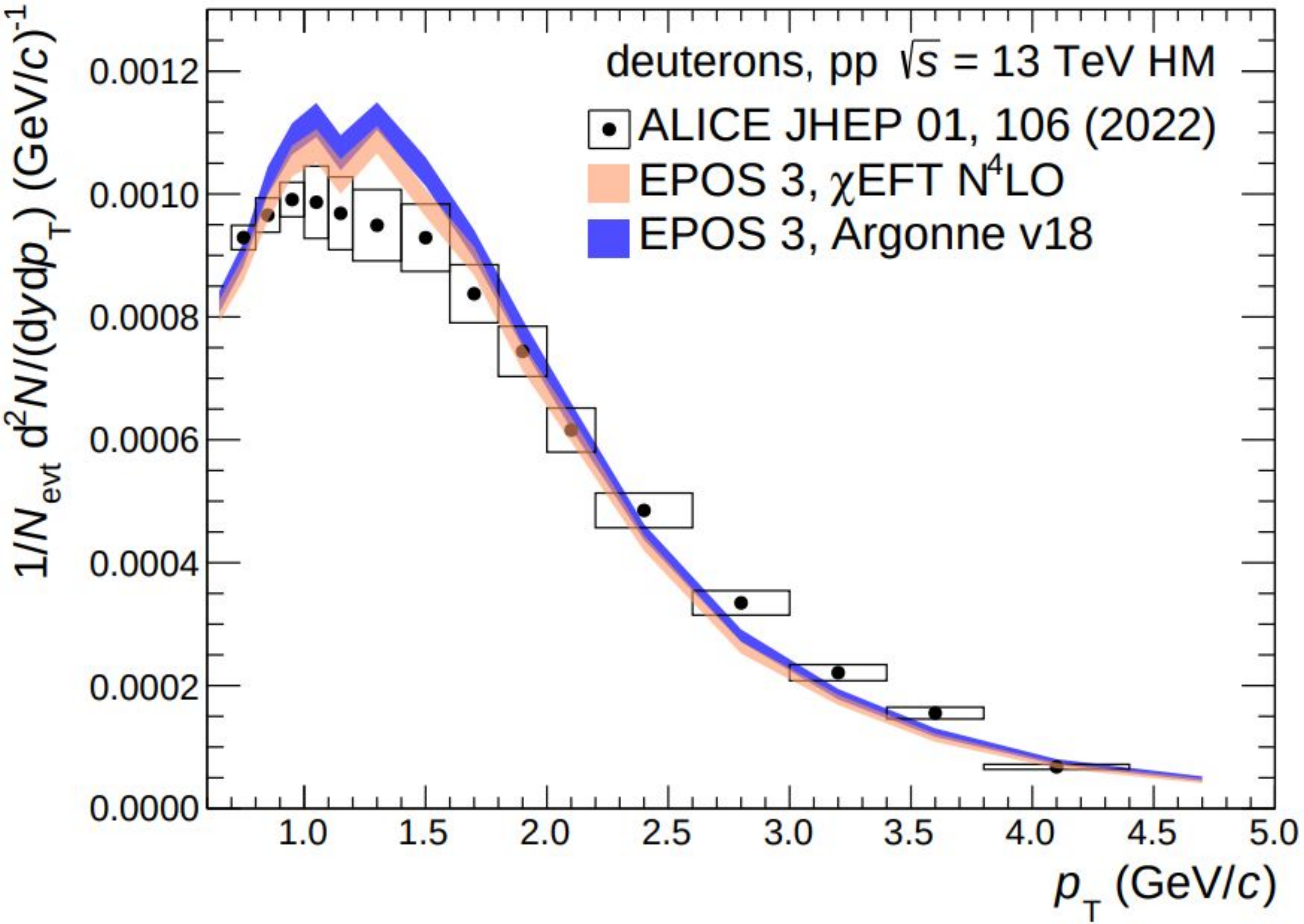
Cosmic Rays

Antinuclei in Cosmic Rays?

- AMS-02 @ ISS has measured 9 **antihelium** candidates
- Not yet published
- What could be the origin of these **antinuclei**?



Pauolo Zuccon for AMS-02 Collaboration at MIAPP workshop 2022



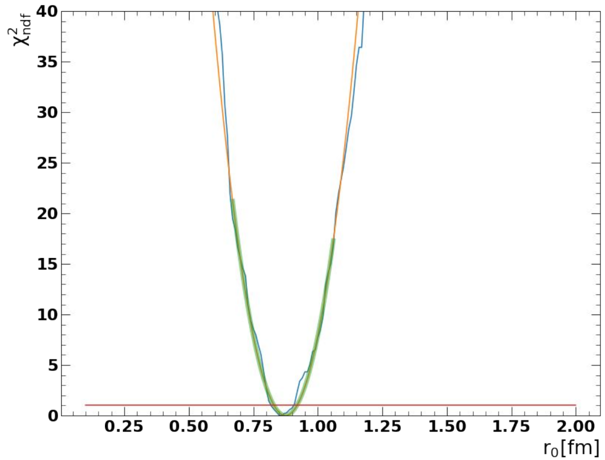
deuterons, pp $\sqrt{s}$ = 13 TeV HM
ALICE JHEP 01, 106 (2022)
EPOS 3, χEFT N⁴LO
EPOS 3, Argonne v18
$1/N_{evt}\, d^2N/(dydp_T)$ (GeV/c)$^{-1}$
p_T (GeV/c)
0.0000
0.0002
0.0004
0.0006
0.0008
0.0010
0.0012
1.0
1.5
2.0
2.5
3.0
3.5
4.0
4.5
5.0

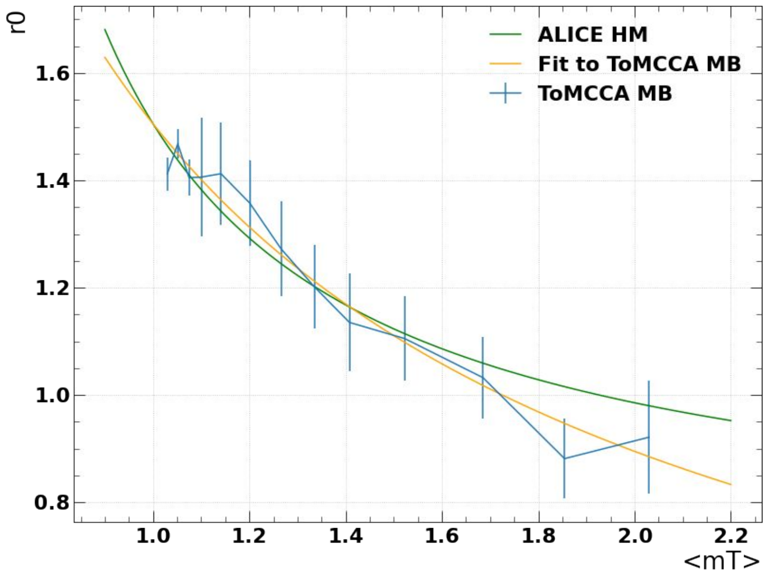
Next generation coalescence Model

Fitting the Source

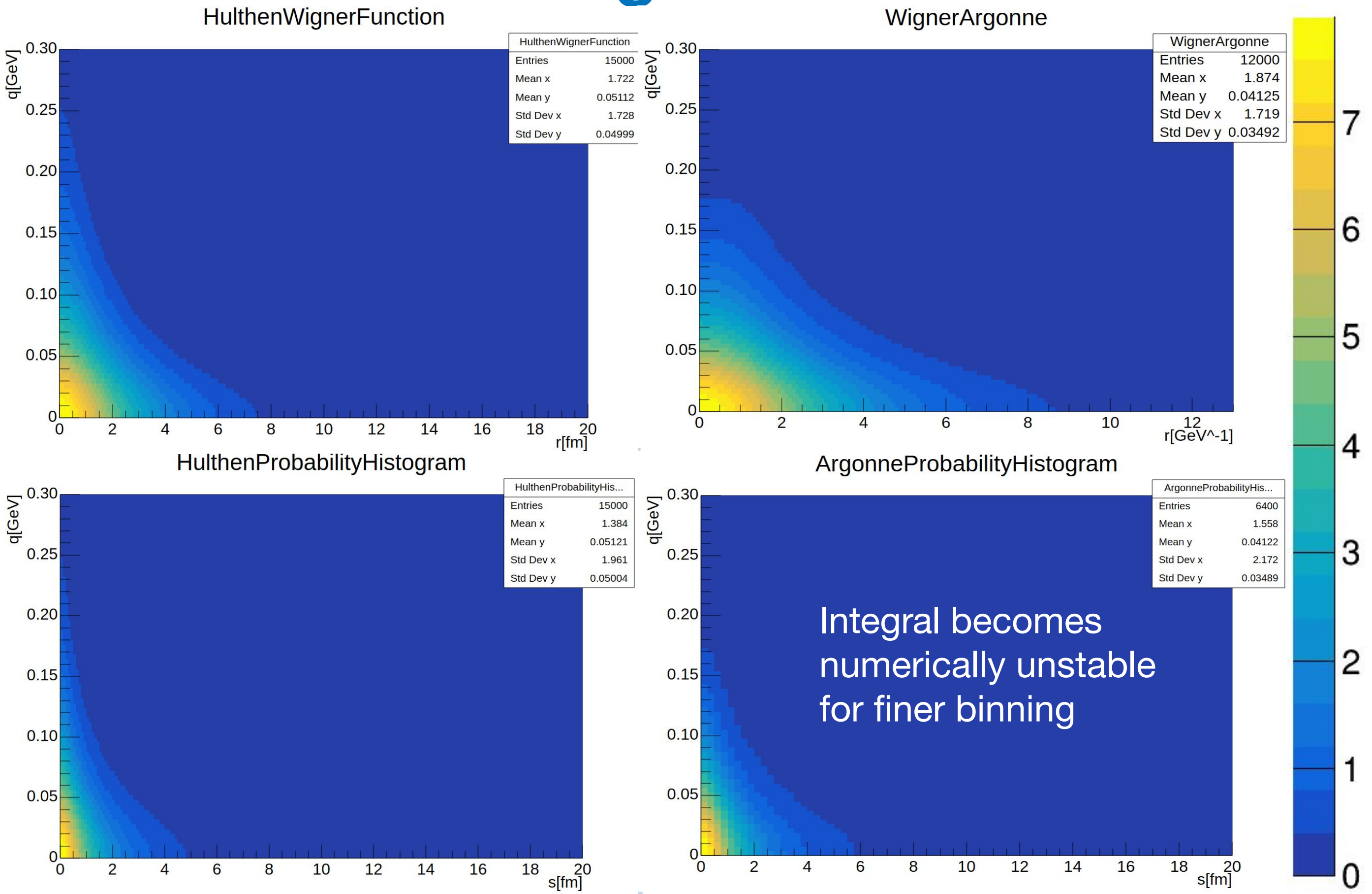
Fitting Procedure:

- Run ToMCCA with a fixed source size (e.g. 1.8 fm, flat in m_T)
- For the resulting deuteron spectra calculate the χ^2 for each bin and save it
- Reduce source size
- Repeat until source size is 0



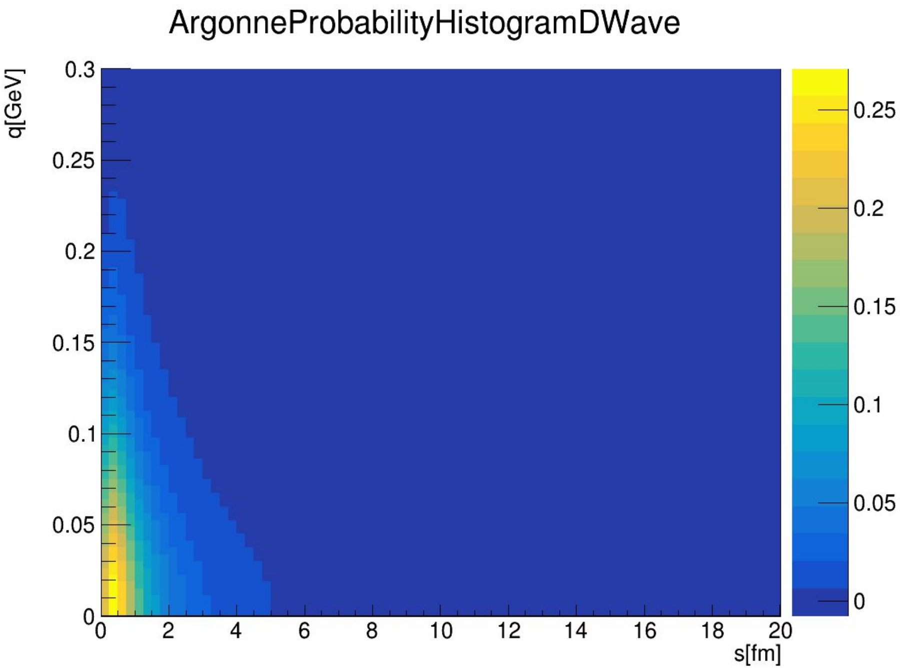


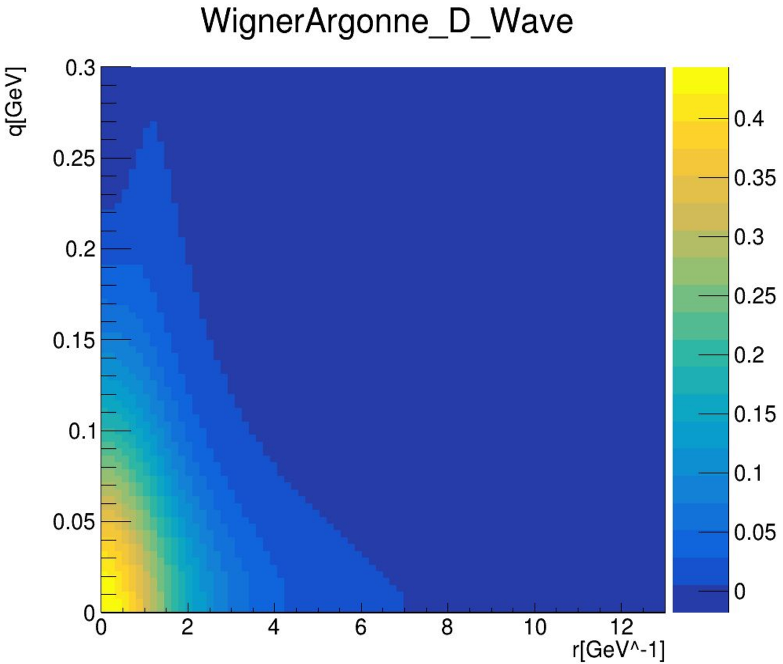
New Wiger functions/Probabilities



Integral becomes numerically unstable for finer binning

Argonne D-State probability



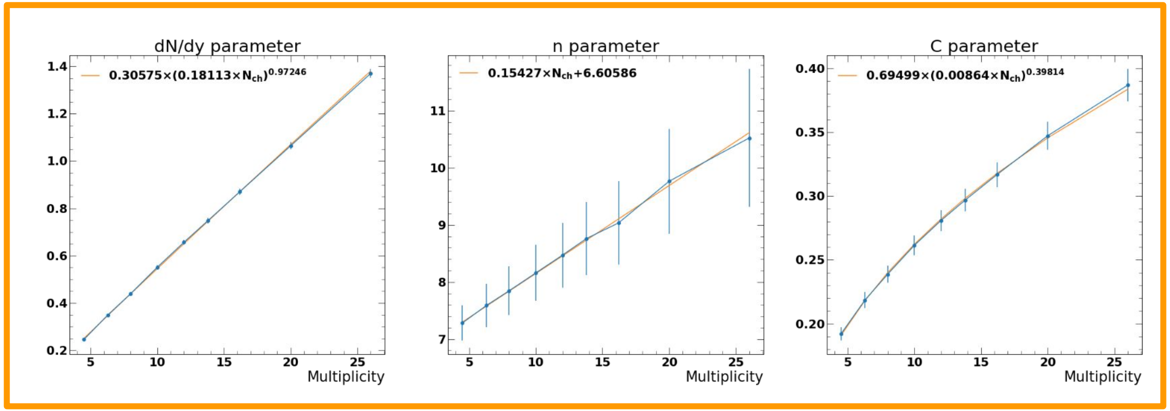


D-State probability is 6% → Maximum ~11% effect

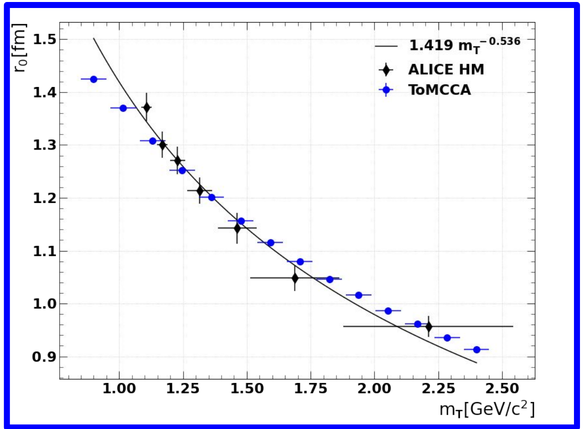
Recap: ToMCCA

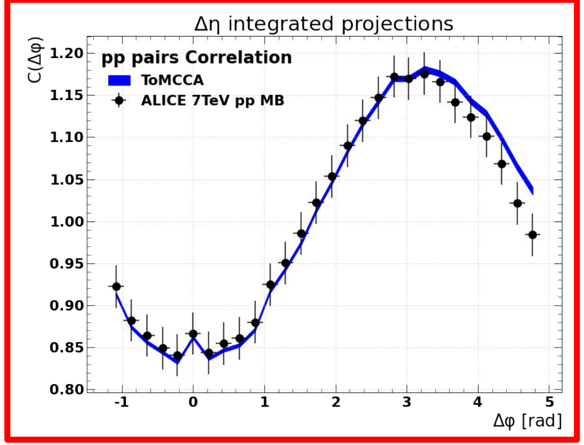
Inputs

- ToMCCA is a Toy Monte Carlo →it requires everything as an ***input***:
  - Momentum distribution →Fully parameterized
  - *Multiplicity* →Poissonian/Event Generator
  - Angular distribution →From Measurement
  - Source Size →ALICE Measurement



$$\frac{d^2N}{dy\,dp_T} = \frac{dN}{dy}\,\frac{p_T(n-1)(n-2)}{nC[nC+m_p(n-2)]}\left(1+\frac{m_T-m_p}{nC}\right)^{-n}$$

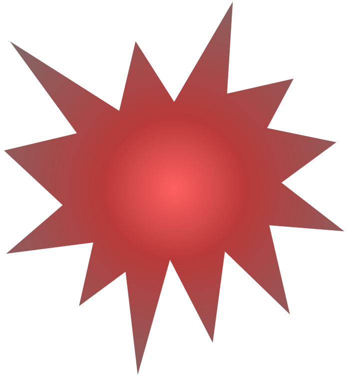




Using a toy MC for Coalescence

Basics of ToMCCA

Event Loop:

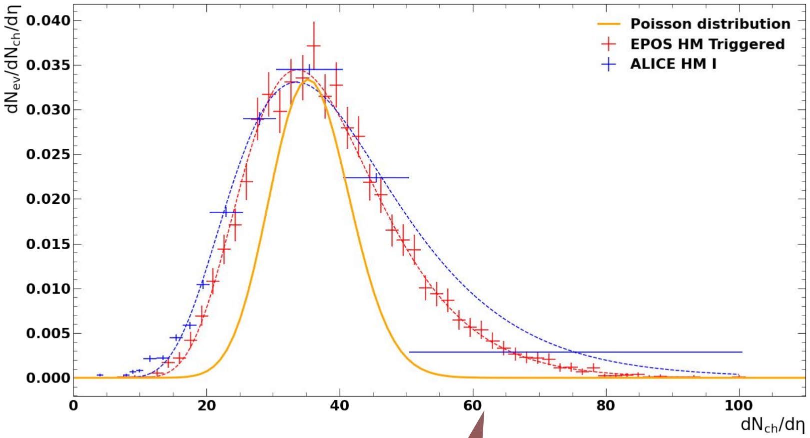


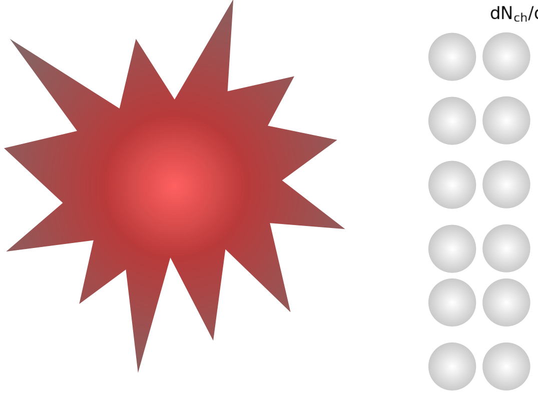
Using a toy MC for Coalescence
Basics of ToMCCA

Event Loop:

Get number of charged particles

1. Poissonian distribution with given mean
2. dN/deta measurements by ALICE
3. Event generator output





Using a toy MC for Coalescence

Basics of ToMCCA

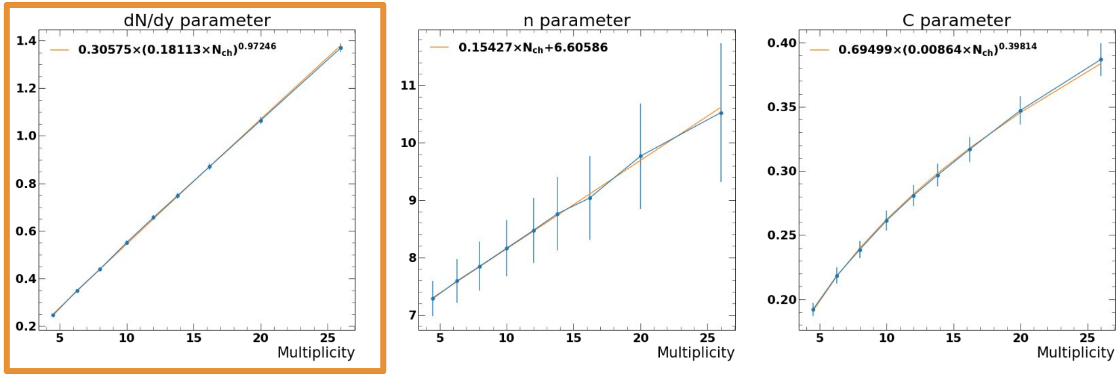
Event Loop:

Get number of charged particles
Get proton yield
Get neutron yield

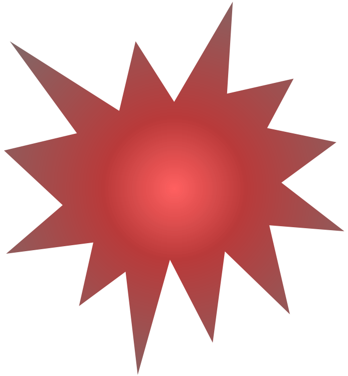
Fit all proton spectra for 13TeV using a Lévy Tsallis:

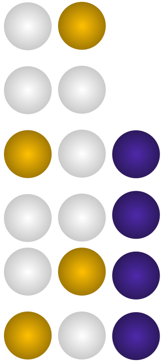
$$\frac{d^2N}{dydp_T} = \frac{dN}{dy}\,\frac{p_T(n-1)(n-2)}{nC[nC+m_p(n-2)]}\left(1+\frac{m_T-m_p}{nC}\right)^{-n}$$

Yield parameter!



Full parameterization as a function of multiplicity



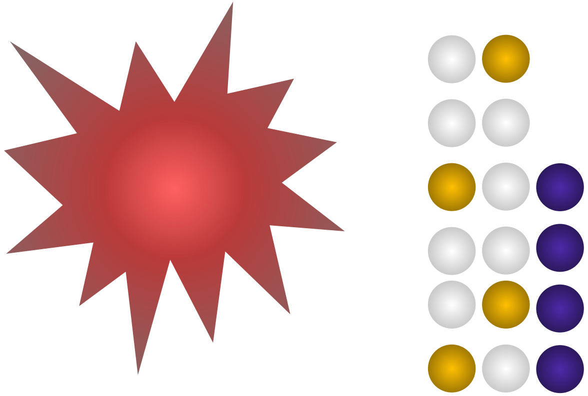


Using a toy MC for Coalescence

Basics of ToMCCA

Event Loop:

- Get number of charged particles
- Get proton yield
- Get neutron yield
- ⟳ Loop over all protons



Using a toy MC for Coalescence

Basics of ToMCCA

Event Loop:

Get number of charged particles

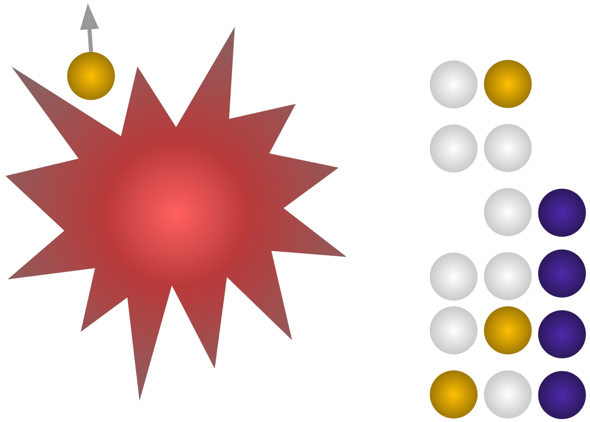
Get proton yield

Get neutron yield

⟳ Loop over all protons

Get 3D momentum of proton

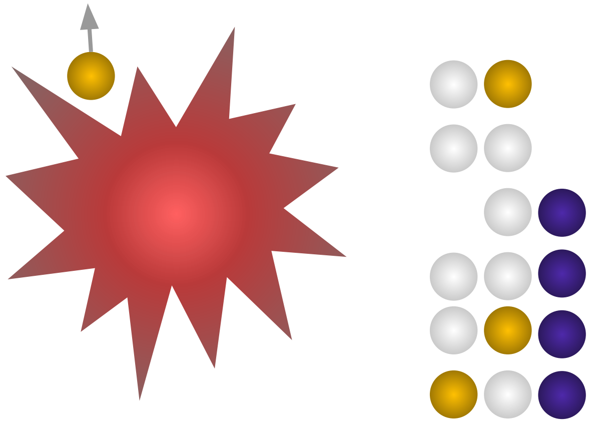
- Draw p_T from parameterization
- Draw flat rapidity y=[-0.5,0.5]
- Draw random ϕ=[0,2π)



Using a toy MC for Coalescence
Basics of ToMCCA

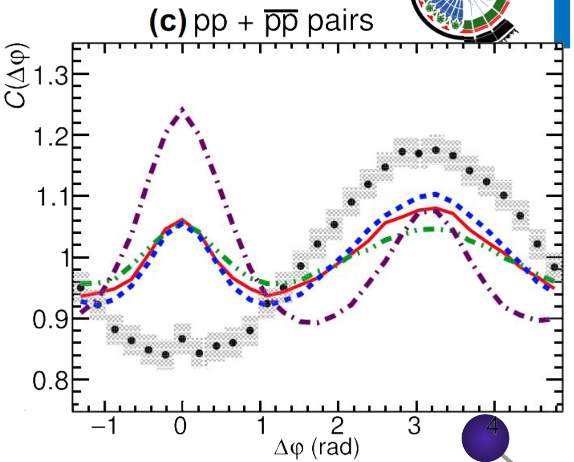
Event Loop:

- Get number of charged particles
- Get proton yield
- Get neutron yield
- ⟳ Loop over all protons
  - Get 3D momentum of proton
  - ⟳ Loop over all neutrons



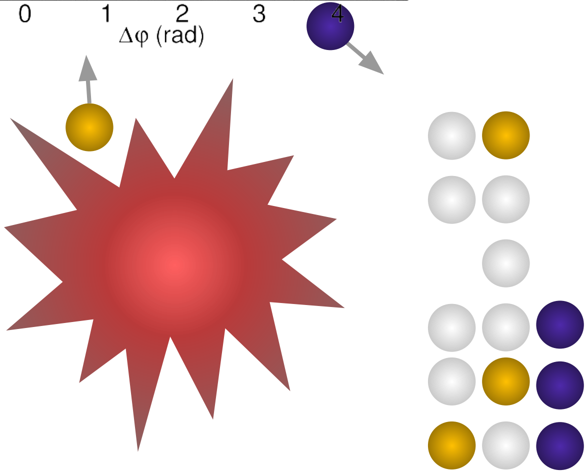
Using a toy MC for Coalescence

Basics of ToMCCA



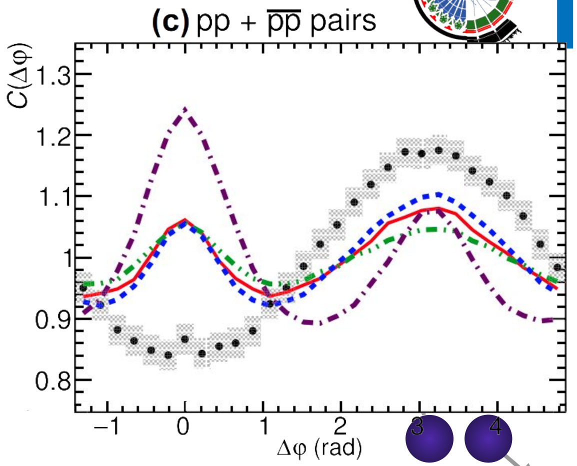
<u>Event Loop:</u>

- Get number of charged particles
- Get proton yield
- Get neutron yield
- ⟳ Loop over all protons
  - Get 3D momentum of proton
  - ⟳ Loop over all neutrons
    - Get 3D momentum of neutron
      - Draw p_T from parameterization
      - Draw flat rapidity y=[-0.5,0.5]
      - Draw random Δϕ from ALICE measurement



Using a toy MC for Coalescence

Basics of ToMCCA



Event Loop:

Get number of charged particles

Get proton yield

Get neutron yield

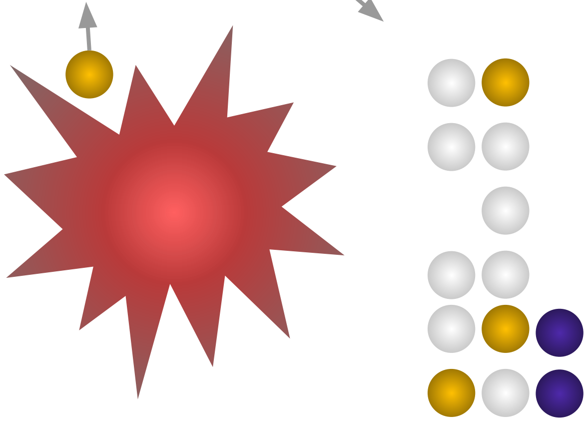
⟳ Loop over all protons

Get 3D momentum of proton

⟳ Loop over all neutrons

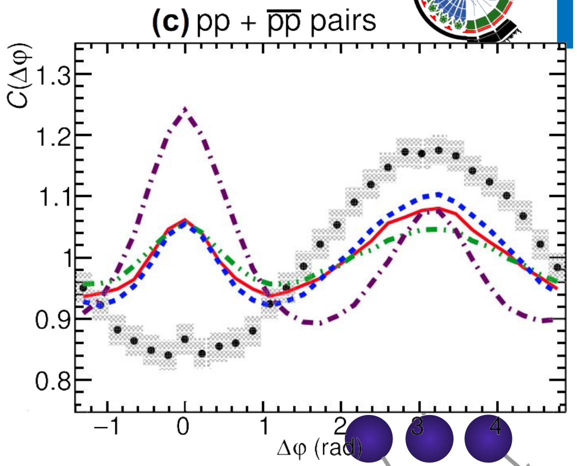
Get 3D momentum of neutron

- Draw p_T from parameterization
- Draw flat rapidity y=[-0.5,0.5]
- Draw random Δϕ from ALICE measurement



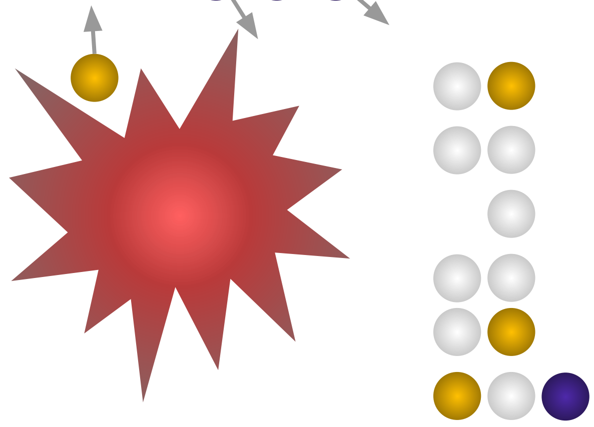
Using a toy MC for Coalescence

Basics of ToMCCA



<u>Event Loop:</u>

Get number of charged particles
Get proton yield
Get neutron yield
⟳ Loop over all protons
    Get 3D momentum of proton
    ⟳ Loop over all neutrons
        Get 3D momentum of neutron
        - Draw p_{T} from parameterization
        - Draw flat rapidity y=[-0.5,0.5]
        - Draw random Δϕ from ALICE measurement

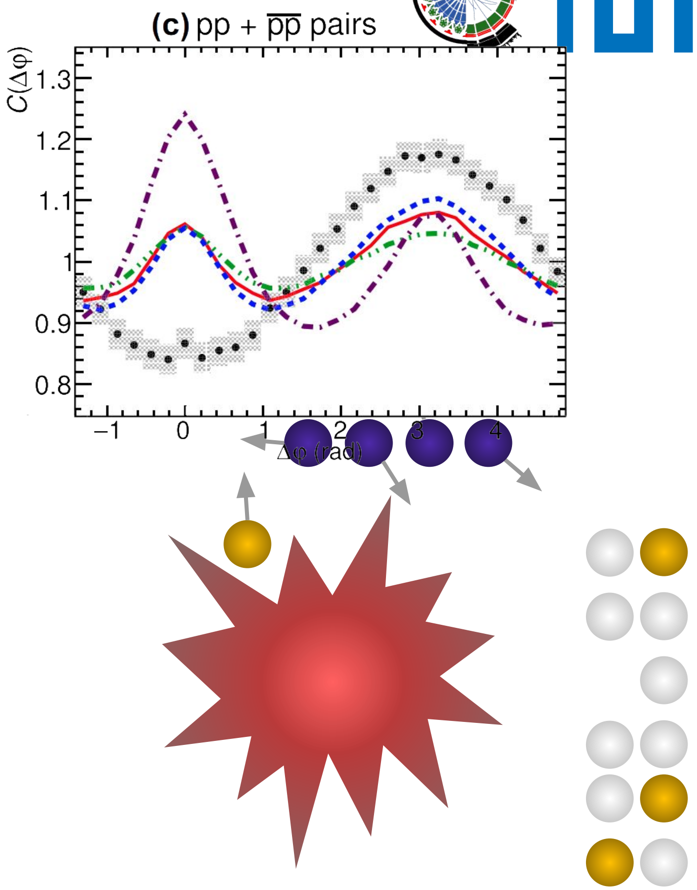


Using a toy MC for Coalescence

Basics of ToMCCA

<u>Event Loop:</u>

- Get number of charged particles
- Get proton yield
- Get neutron yield
- ⟳ Loop over all protons
    - Get 3D momentum of proton
    - ⟳ Loop over all neutrons
        - Get 3D momentum of neutron
            - Draw p_T from parameterization
            - Draw flat rapidity y=[-0.5,0.5]
            - Draw random Δϕ from ALICE measurement

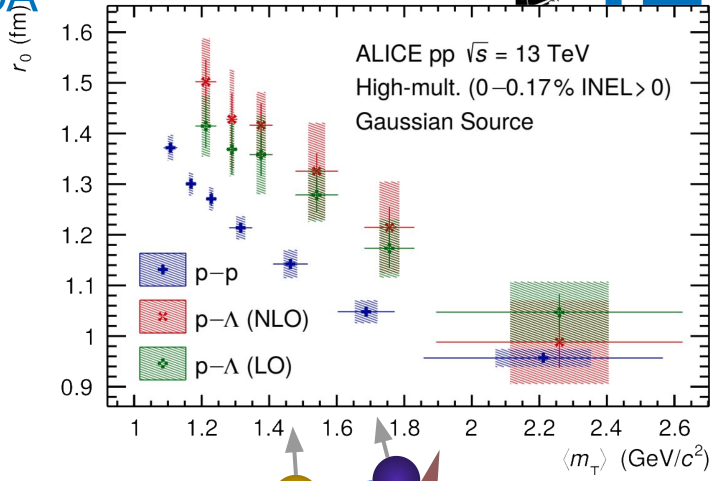


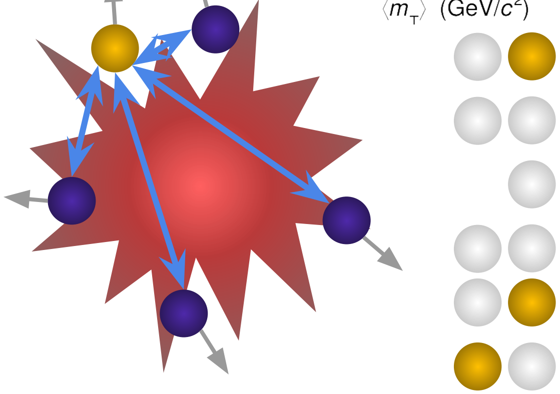
Using a toy MC for Coalescence

Basics of ToMCCA

<u>Event Loop:</u>

- Get number of charged particles
- Get proton yield
- Get neutron yield
- ⟳ Loop over all protons
  - Get 3D momentum of proton
  - ⟳ Loop over all neutrons
    - Get 3D momentum of neutron
    - Get source size



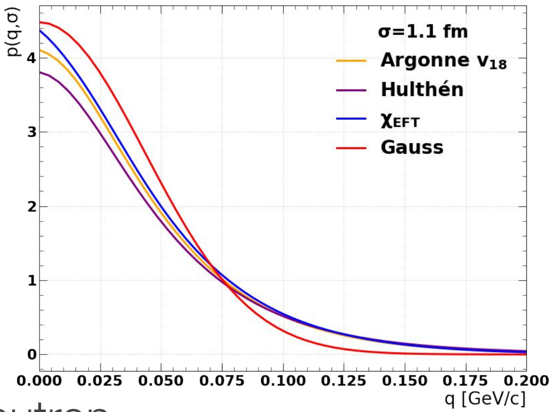


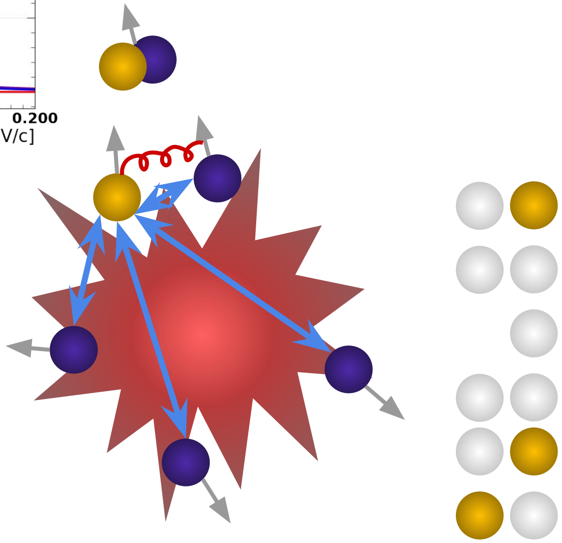
Using a toy MC for Coalescence

Basics of ToMCCA

Event Loop:

Get number of charged particles
Get proton yield
Get neutron yield
⟳ Loop over all protons
  Get 3D momentum of proton
  ⟳ Loop over all neutrons
    Get 3D momentum of neutron
    Get source size
    Apply coalescence condition





Using a toy MC for Coalescence

Basics of ToMCCA

Event Loop:

Get number of charged particles

Get proton yield

Get neutron yield

⟳ Loop over all protons

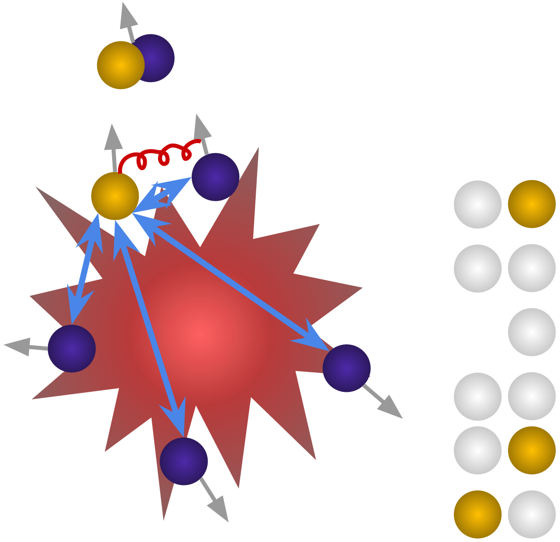
Get 3D momentum of proton

⟳ Loop over all neutrons

Get 3D momentum of neutron

Get source size

Apply coalescence condition

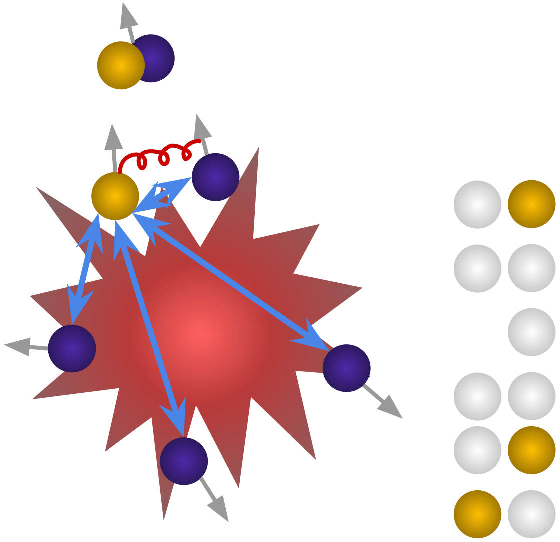


Using a toy MC for Coalescence

Basics of ToMCCA

Event Loop:

- Get number of charged particles
- Get proton yield
- Get neutron yield
- ⟳ Loop over all protons
  - Get 3D momentum of proton
  - ⟳ Loop over all neutrons
    - Get 3D momentum of neutron
    - Get source size
    - Apply coalescence condition
      - ✅ make deuteron, number of neutrons -1
      - ❎ try next neutron

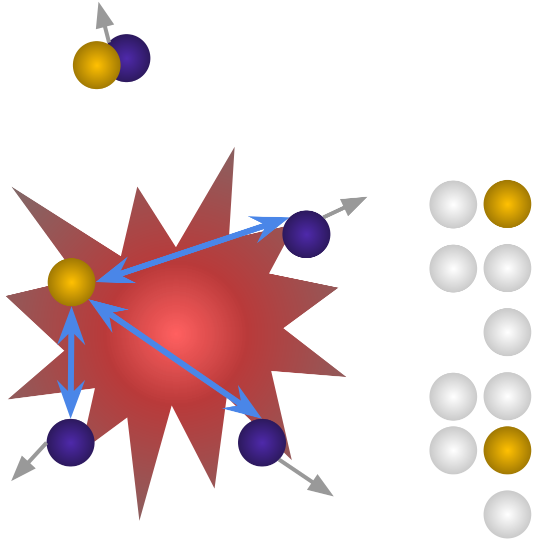


Using a toy MC for Coalescence

Basics of ToMCCA

Event Loop:

Get number of charged particles
Get proton yield
Get neutron yield
⟳ Loop over all protons
  Get 3D momentum of proton
  ⟳ Loop over all neutrons
    Get 3D momentum of neutron
    Get source size
    Apply coalescence condition
      ✅ make deuteron, number of neutrons -1
      ❎ try next neutron

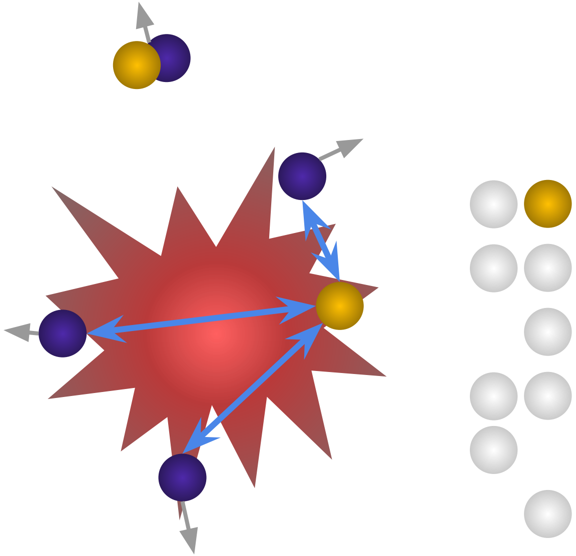


Using a toy MC for Coalescence

Basics of ToMCCA

Event Loop:

- Get number of charged particles
- Get proton yield
- Get neutron yield
- ⟳ Loop over all protons
  - Get 3D momentum of proton
  - ⟳ Loop over all neutrons
    - Get 3D momentum of neutron
    - Get source size
    - Apply coalescence condition
      - ✅ make deuteron, number of neutrons -1
      - ❎ try next neutron

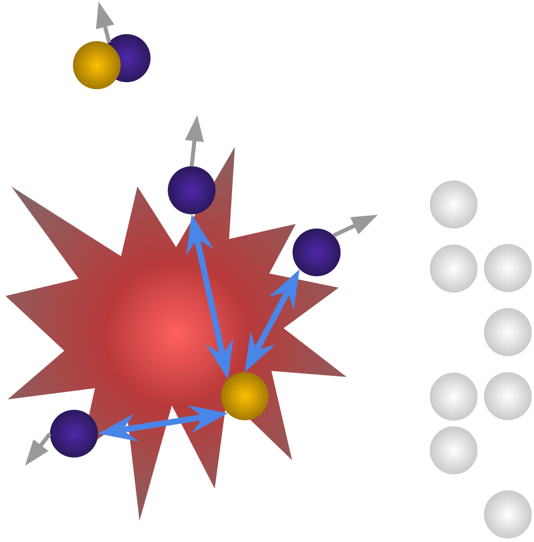


Using a toy MC for Coalescence

Basics of ToMCCA

Event Loop:

Get number of charged particles
Get proton yield
Get neutron yield
⟳ Loop over all protons
    Get 3D momentum of proton
    ⟳ Loop over all neutrons
        Get 3D momentum of neutron
        Get source size
        Apply coalescence condition
            ✅ make deuteron, number of neutrons -1
            ❎ try next neutron



Using a toy MC for Coalescence

Basics of ToMCCA

Event Loop:

Get number of charged particles

Get proton yield

Get neutron yield

⟳ Loop over all protons

Get 3D momentum of proton

⟳ Loop over all neutrons

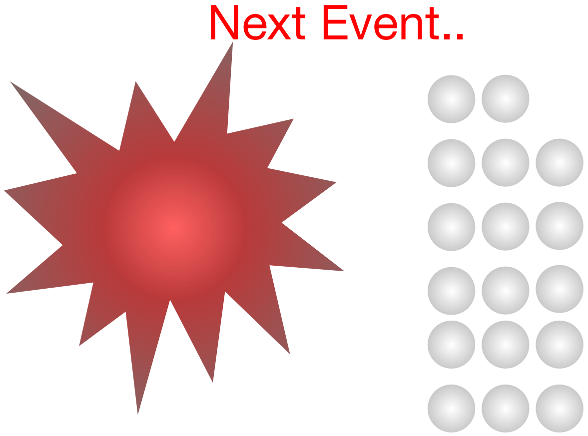
Get 3D momentum of neutron

Get source size

Apply coalescence condition

✅ make deuteron, number of neutrons -1

❎ try next neutron



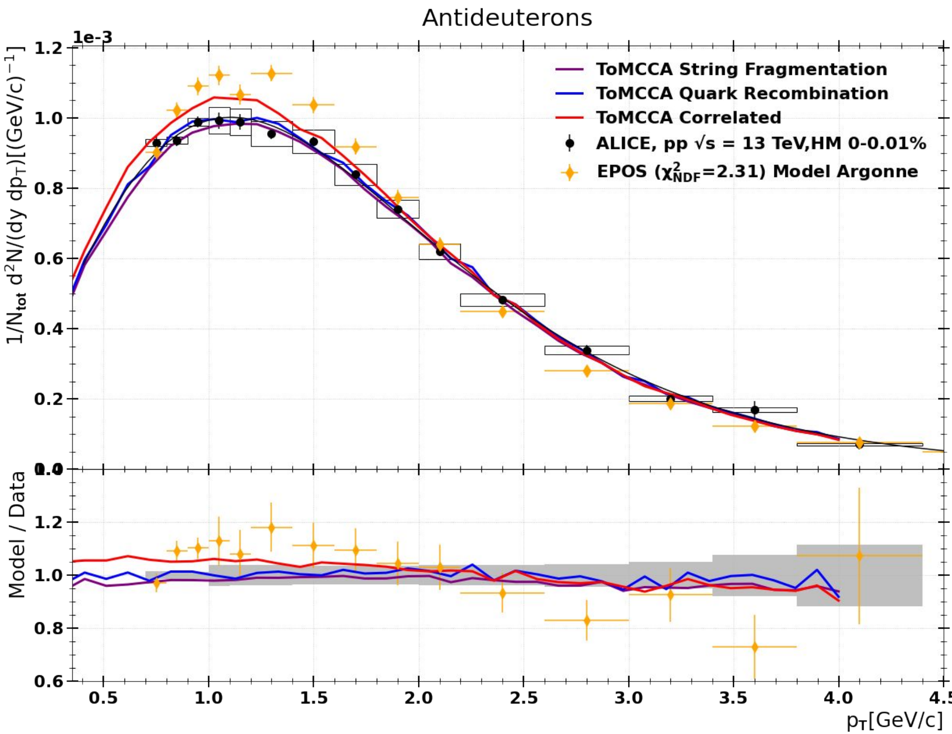
Verifying the Model

Comparison to ALICE deuteron Spectra

Comparison of ToMCCA and EPOS to ALICE deuteron spectra 13 TeV pp with a HM trigger

- EPOS reproduces spectra within ~20%
- EPOS does not reproduce the Δφ measurement by ALICE
- ToMCCA with string fragmentation and quark recombination mode reproduces the measurement perfectly
- ToMCCA with correlated emission overshoots data at lower pT

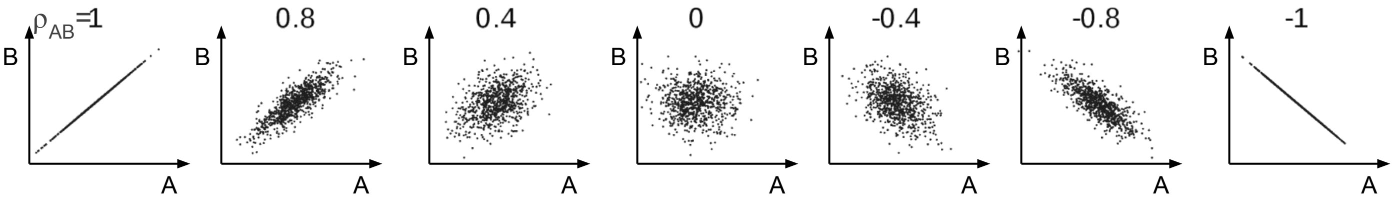
⇨ Model reproduces the data, with no free parameters!



Deuteron number fluctuations

Introduction

- To shed a light on the nuclei production mechanism measure more differential observables and test them against the common models (CSM, coalescence)
- Rationale:
  a. In the CSM deuterons and protons are produced independently ("poissonian")
  b. In the coalescence model a deuteron is formed from two independent nucleons →combination of two poissonian distributions does not yield a poissonian distribution
- The observables:
  a. $\kappa_1 = \langle n \rangle$ the mean number of particles per event
  b. $\kappa_2 = \langle (n - \langle n \rangle)^2 \rangle$ the variance of the number distribution
  c. $\rho_{pd} = \langle (n_p - \langle n_p \rangle)(n_d - \langle n_d \rangle) \rangle / \sqrt{\kappa_{2p} \kappa_{2d}}$ The pearson correlation coefficient



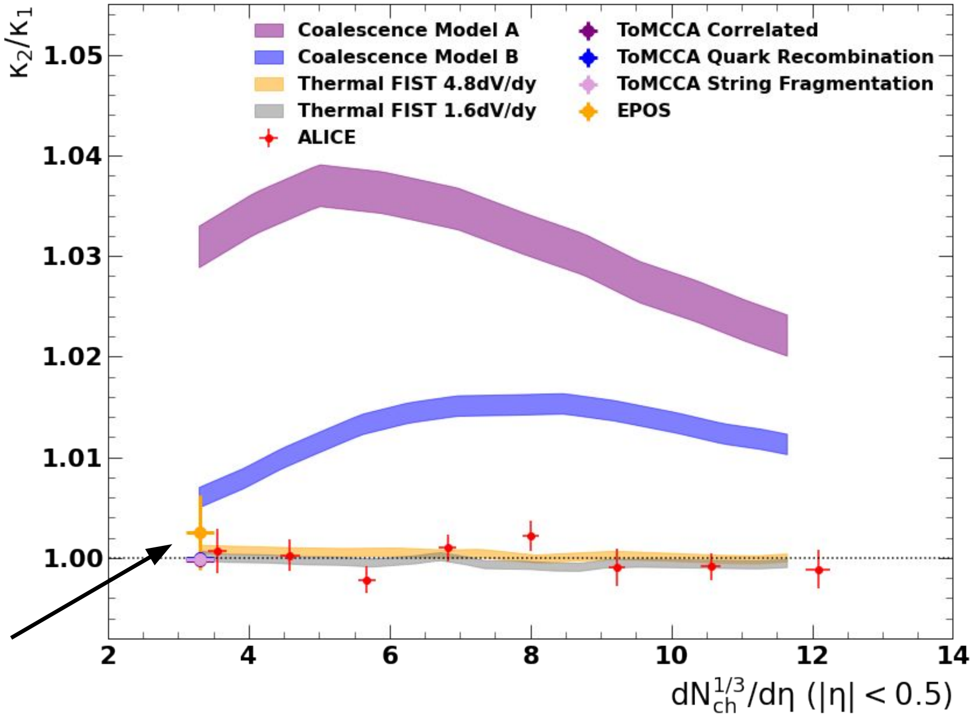
Deuteron number fluctuations

Results κ_2/κ_1

κ_2/κ_1: Data is consistent with 1

- This implies a poissonian fluctuation of the deuteron number
- This is expected in the *CSM* since protons and deuterons are emitted independently (barring canonical suppression)
- *Coalescence* model shows a (positive) deviation of *O*(1%) indicating a deviation from the poissonian baseline
- All 3 versions of ToMCCA reproduce the κ_2/κ_1=1
- EPOS reproduces data with in large uncertainty

Data translated from Centrality to mean multiplicity (using https://twiki.cern.ch/twiki/bin/viewauth/ALICE/ReferenceMult)



We can only work with pp 13 TeV HM 1 (Mult ~36)

Deuteron number fluctuations

Results ρ_{pd}

ρ_{pd}: Data shows a negative pearson coefficient $O(0.1\%)$

Data translated from Centrality to mean multiplicity (using https://twiki.cern.ch/twiki/bin/viewauth/ALICE/ReferenceMult)

- This implies that deuteron and proton numbers are negatively correlated
- In the *CSM* this can be achieved by including canonical suppression (Baryon number conservation)
- In the *coalescence* model there are two effects at play:
  a. Deuterons "take away" protons in the formation process *(d↑ → p↓)*
  b. Non-linear formation relation between protons and deuterons *(p↑ → d↑↑)*
- String fragmentation and Quark recombination come close to data
- Correlated emission and EPOS too high