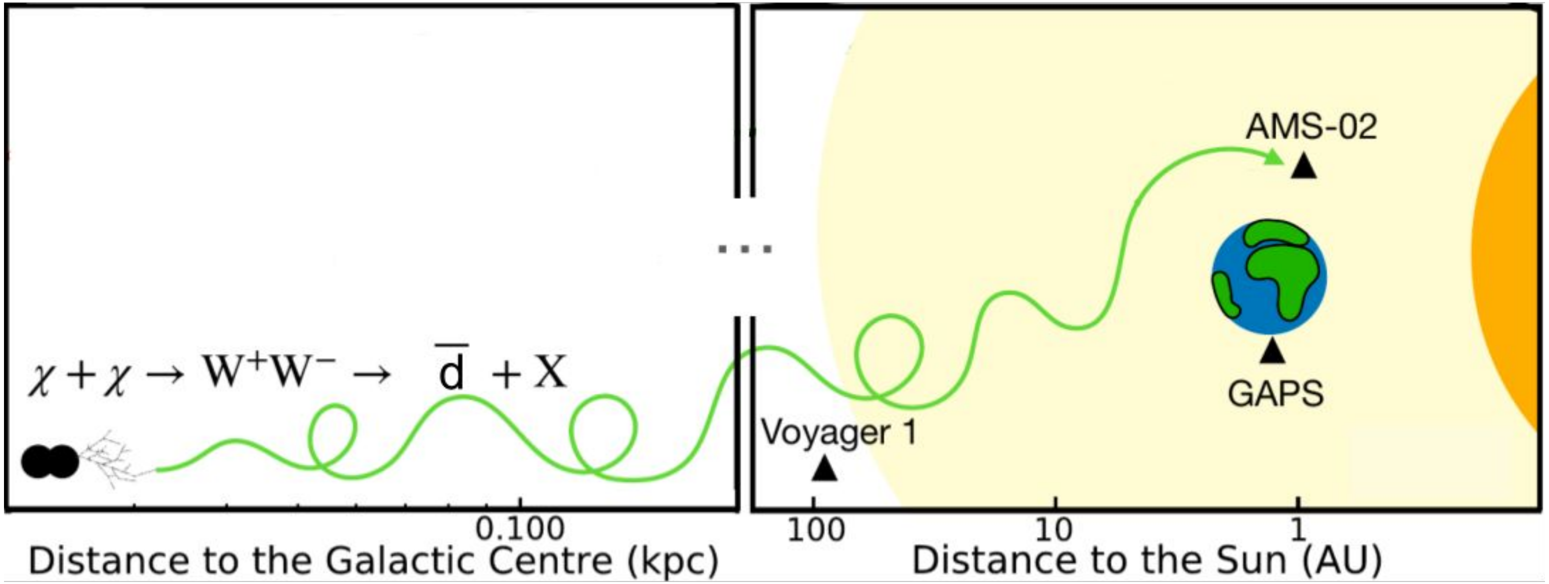
Coalescence studies for light nuclei

Maximilian Mahlein, Laura Fabbietti, Bhawani Singh, Chiara Pinto, Michele Viviani

Based on: arXiv:2404.03352 (accepted by EPJC)

Technical University Munich

Cosmic Rays
Antinuclei in Cosmic Rays



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

- Antinuclei could be a probe for indirect Dark Matter searches

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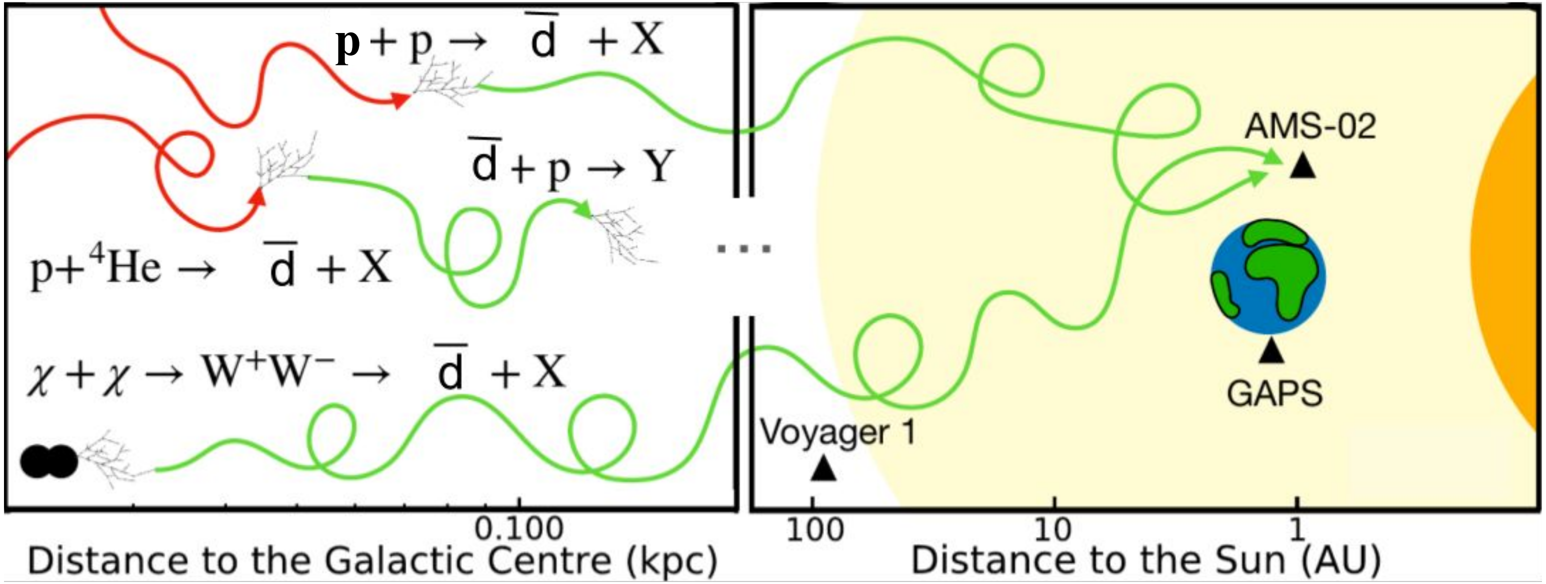

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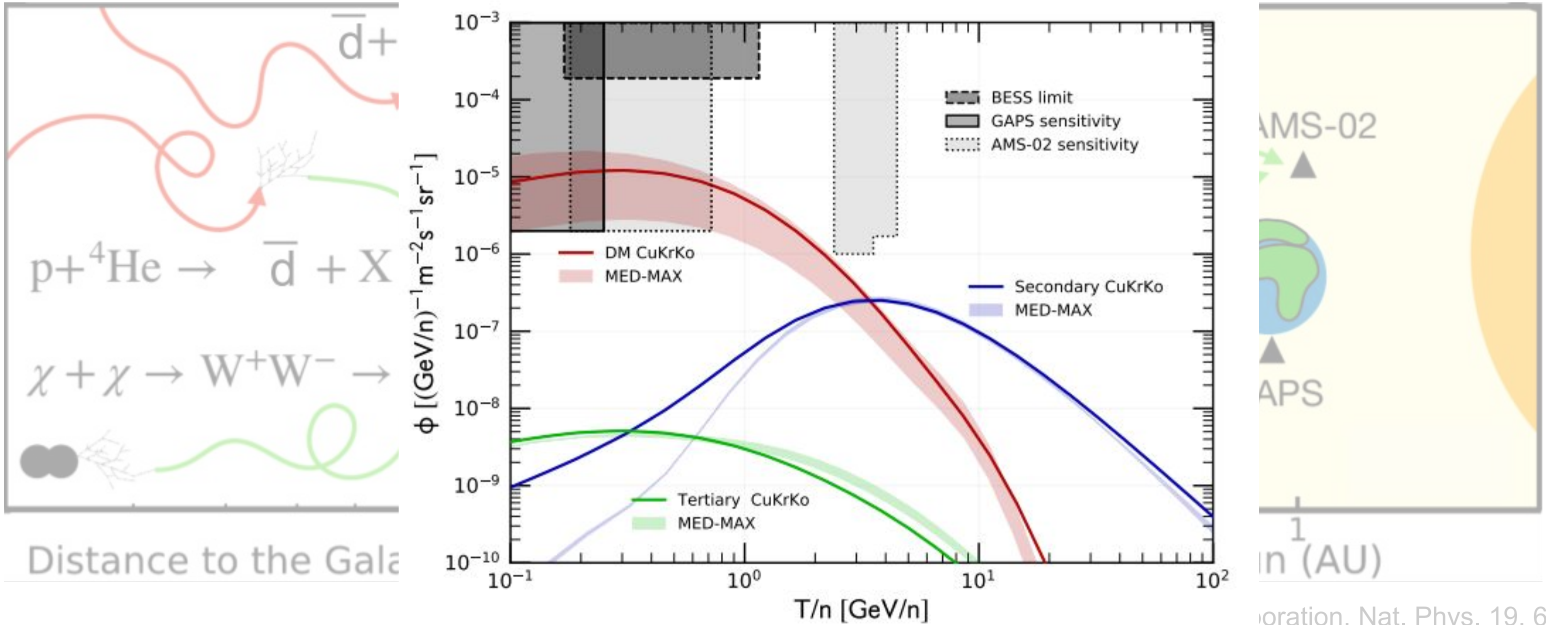

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- High Signal/Noise ratio (~10^2-10^4) at low E_{kin} expected by many models!

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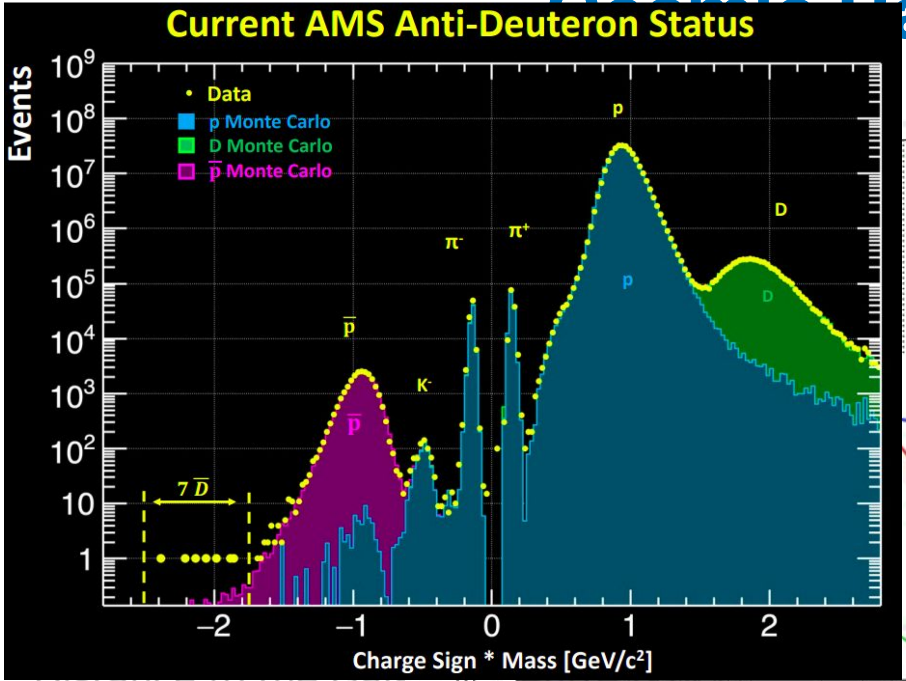

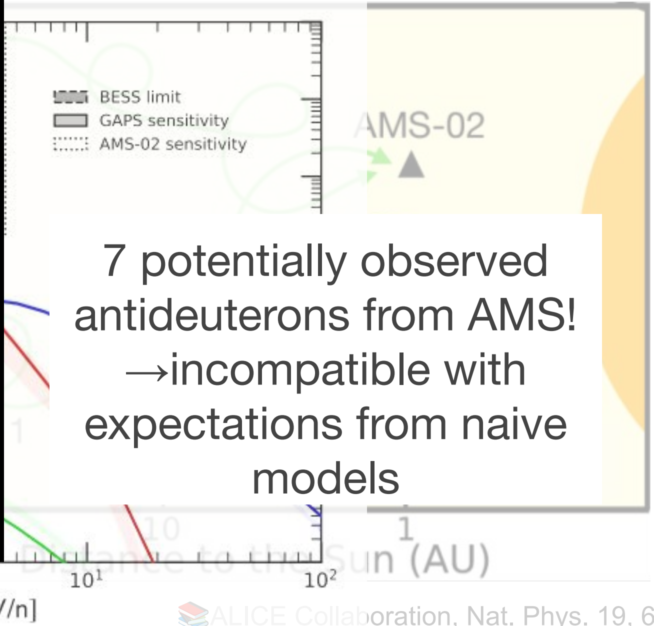

7 potentially observed antideuterons from AMS!
→incompatible with expectations from naive models

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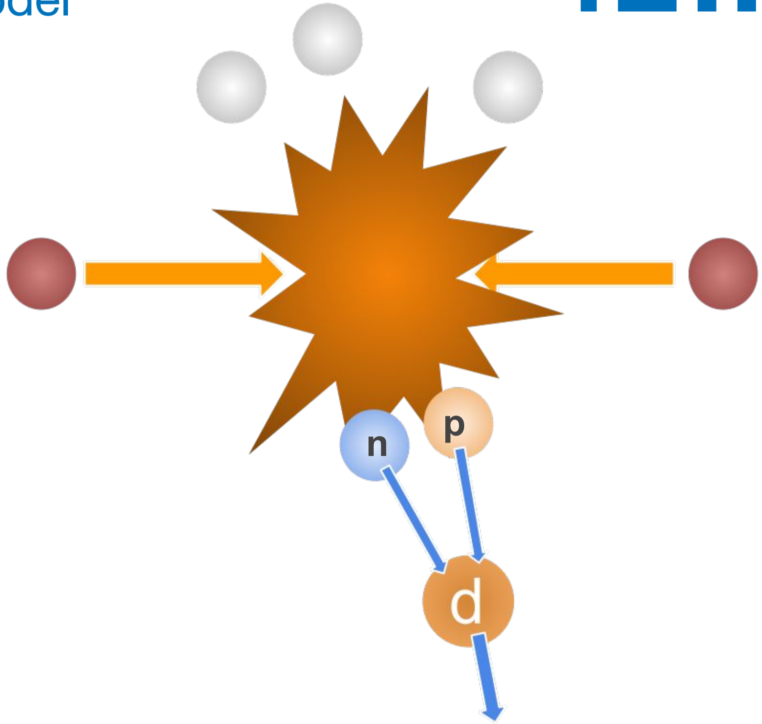
Modelling (Anti)nuclei Production

The Coalescence Model

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

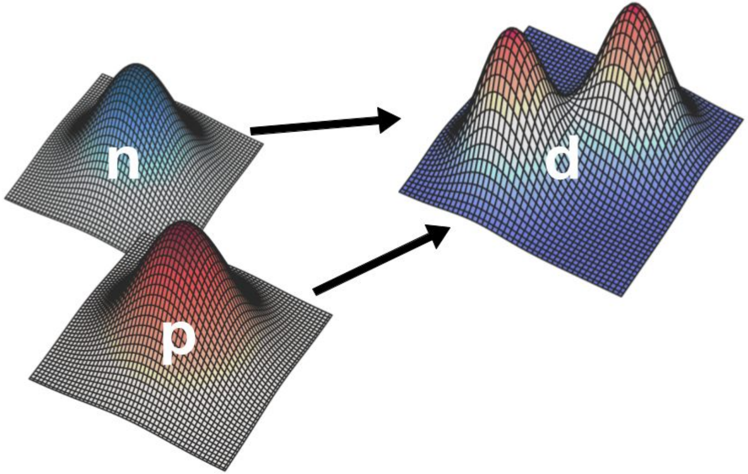


Modelling (Anti)nuclei Production

The Coalescence Model

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

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



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

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

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

Nucleus wave function — Relative momenta of nucleons — Source size

Kachelriess et al EPJA (2020)56: 4, 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…

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$$\times\Psi_d\,(\vec{x}$$

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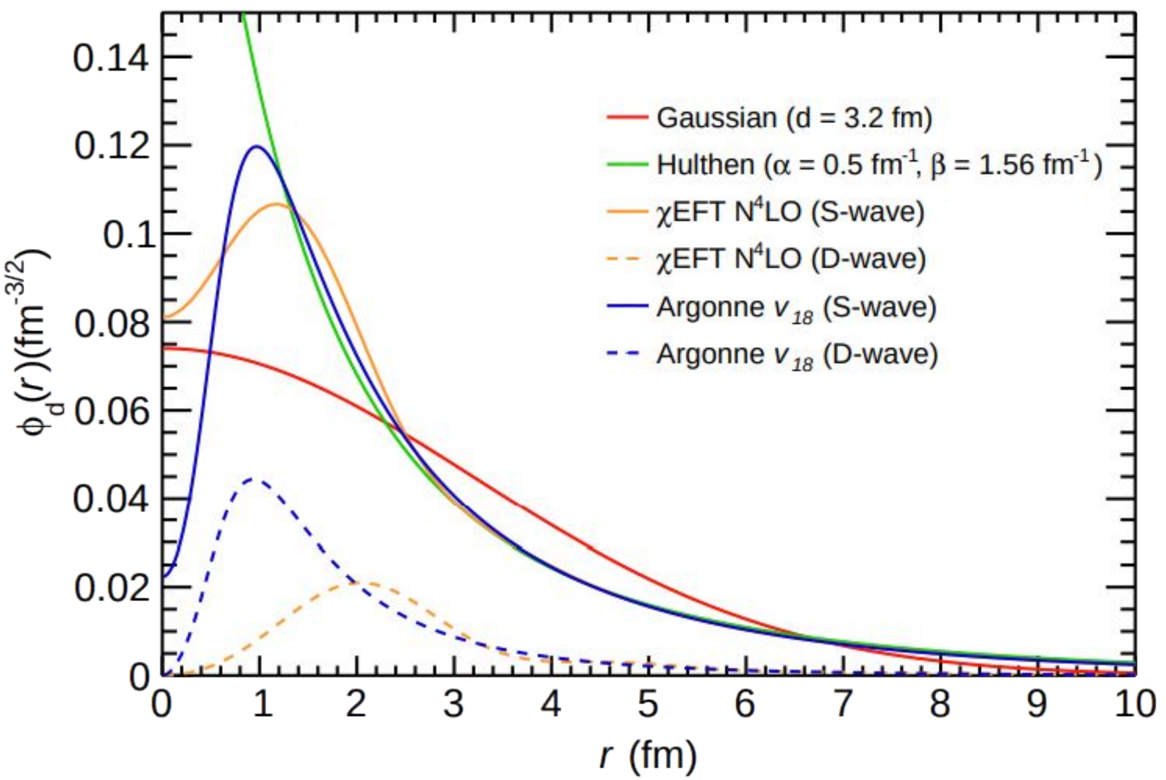
Nucleus wave functio…



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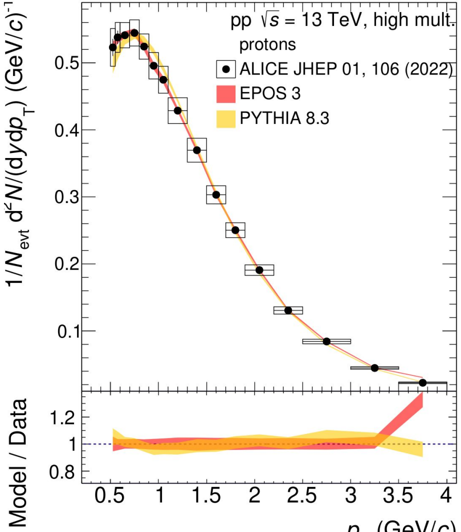
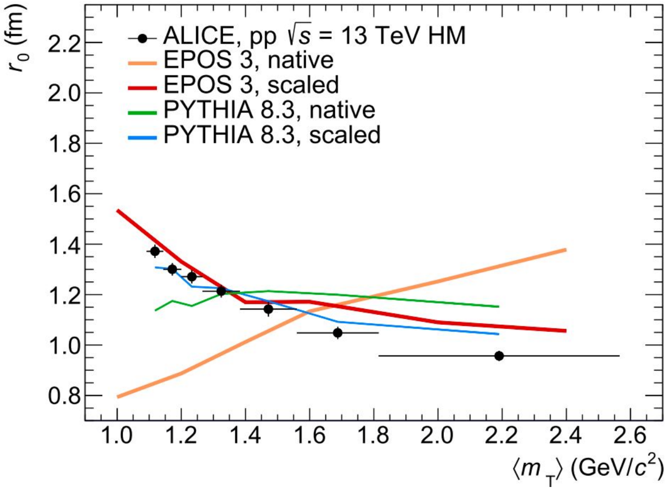
Coalescence Results EPOS & Pythia

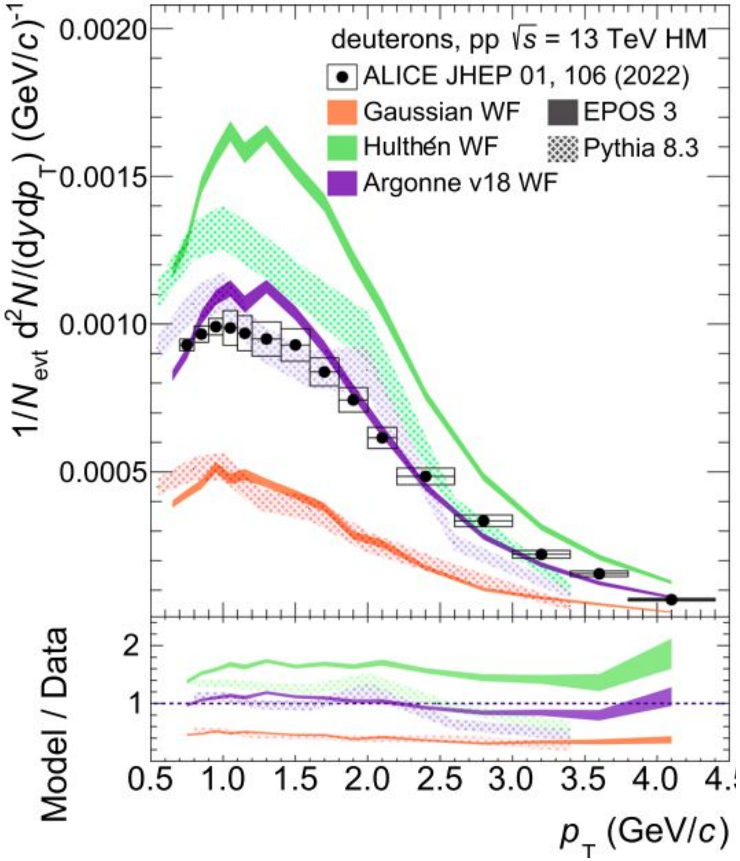
Deuteron spectra

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

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







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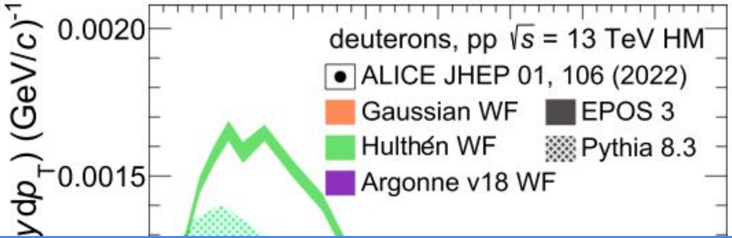
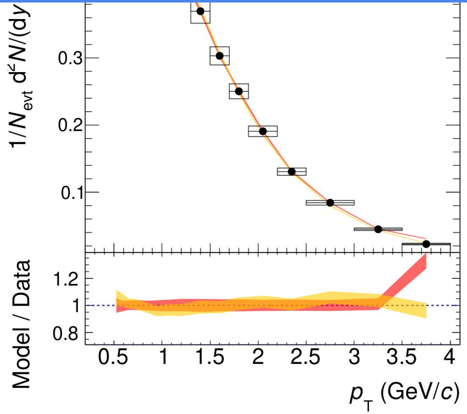
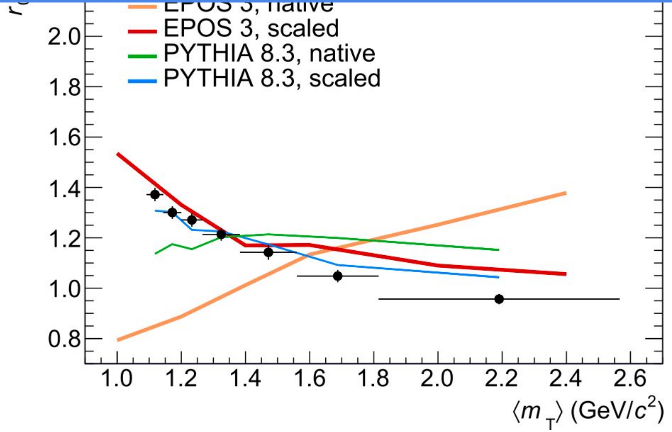
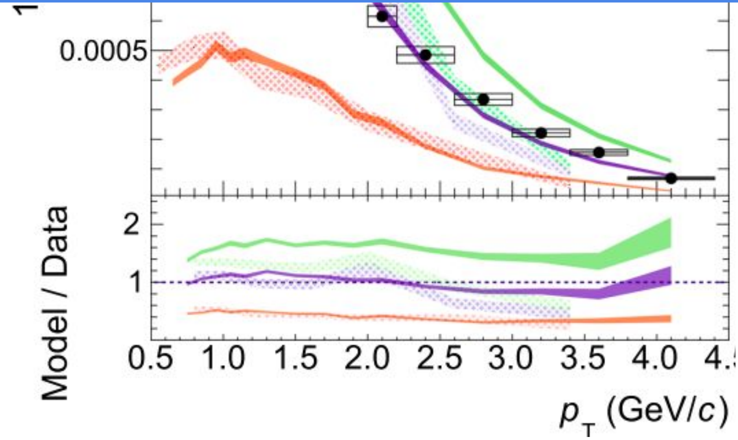


Develop a purpose built Event Generator to apply this model







The ToMCCA Model

A Toy Monte Carlo Coalescence Afterburner

Main Inputs: Multiplicity, momentum distributions, source size

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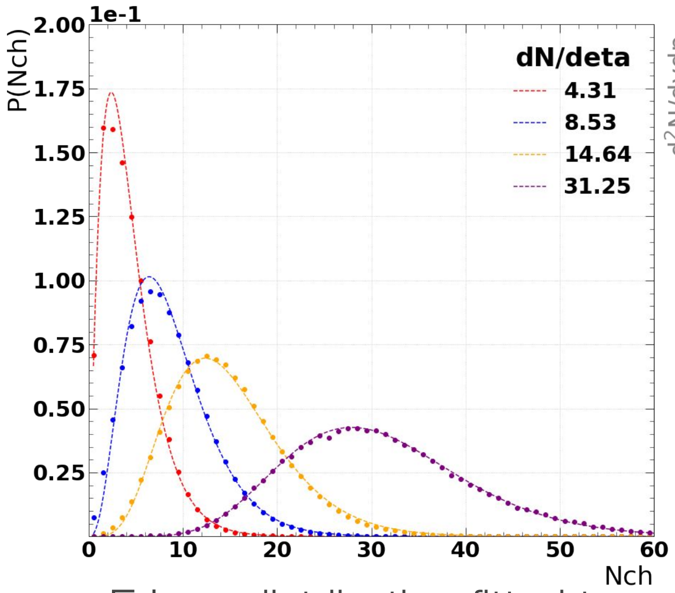
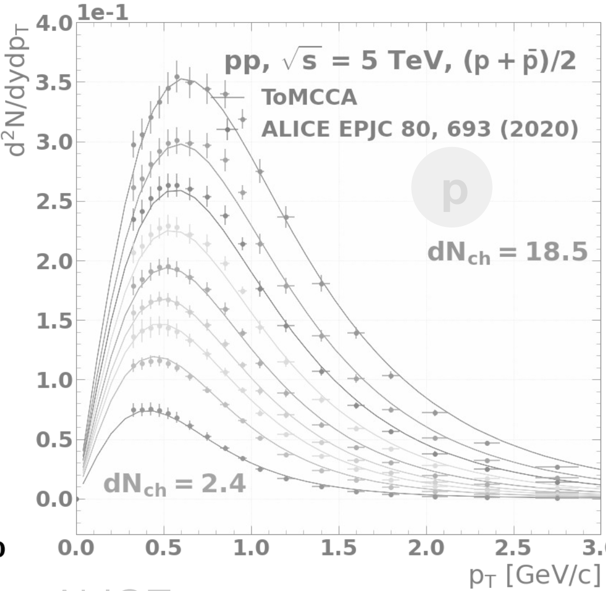


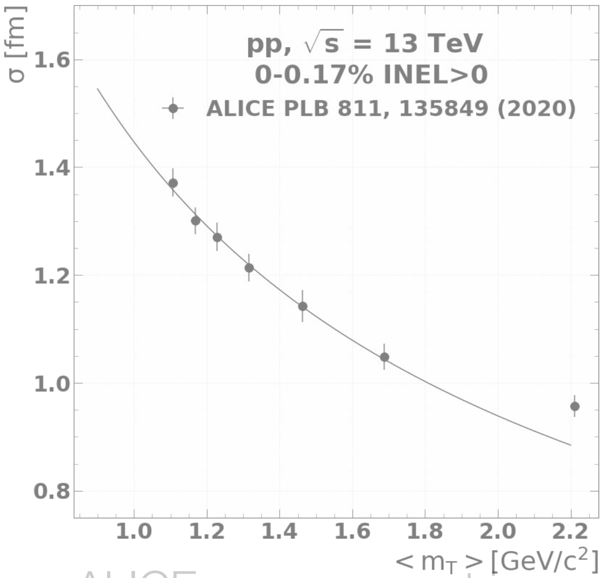
Erlang distribution fitted to EPOS3 simulations

Momentum distribution



ALICE measurements over a large multiplicity range

Source size



ALICE measurement in high-multiplicity collisions

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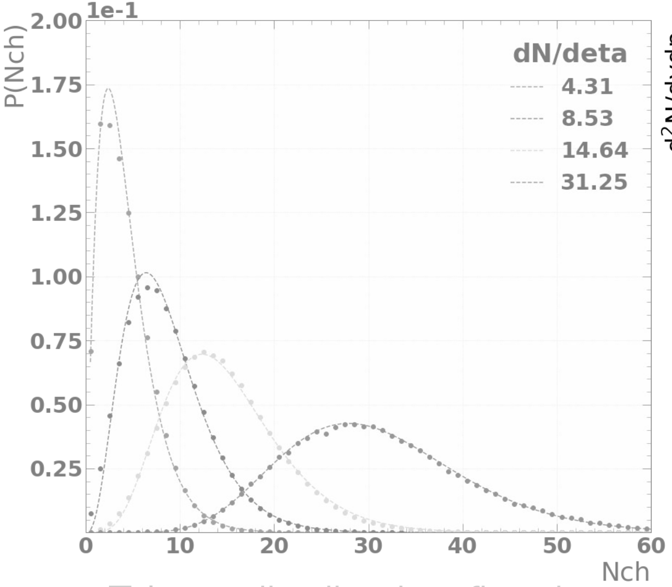

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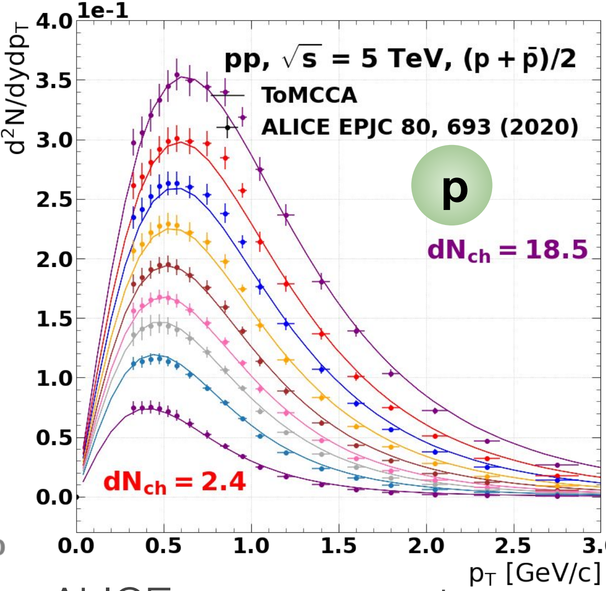

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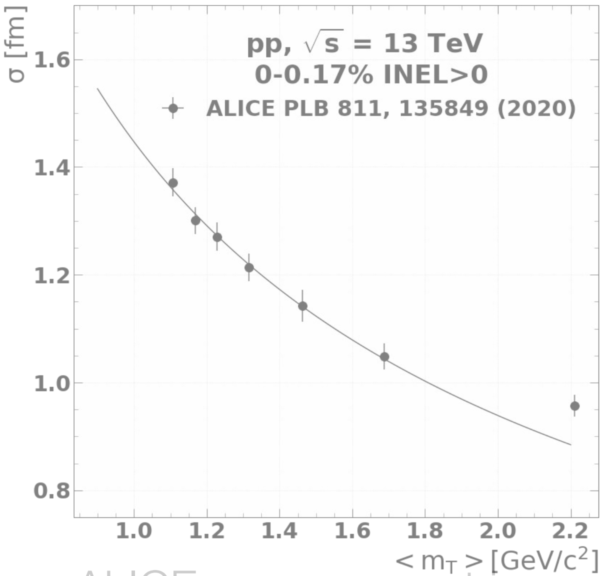

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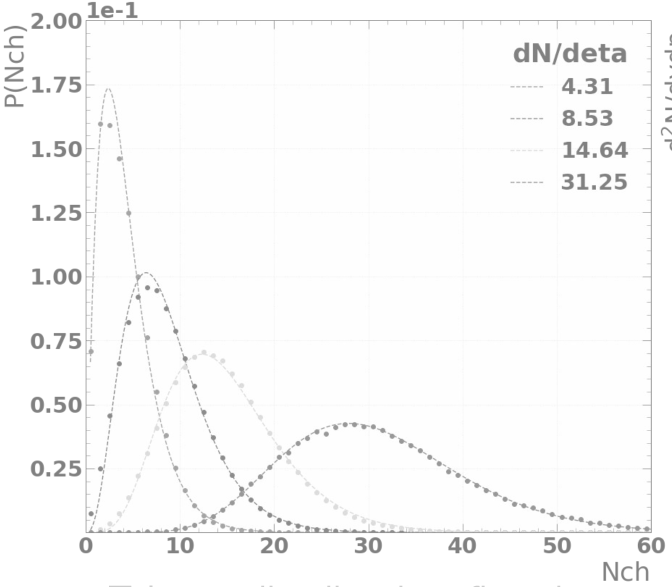

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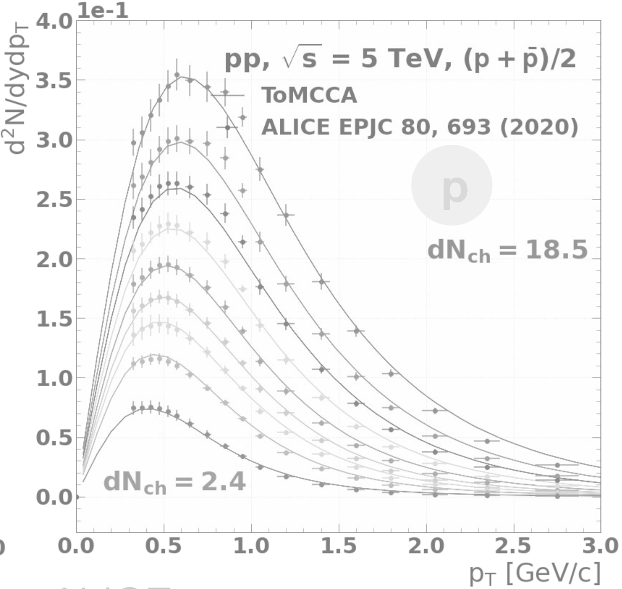

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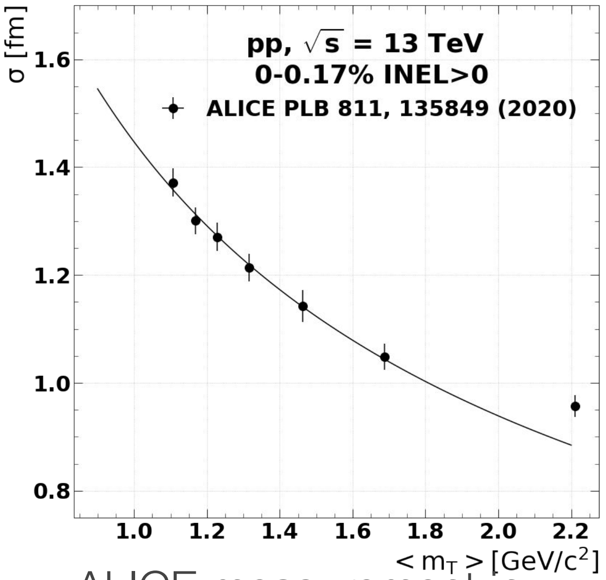

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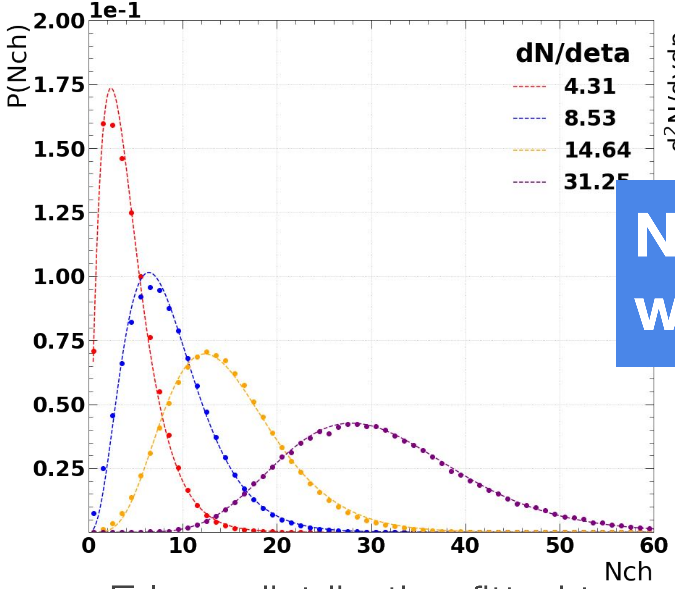

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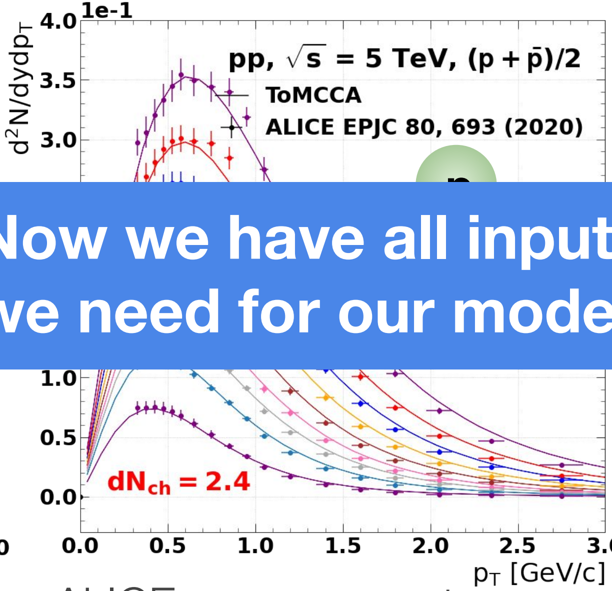
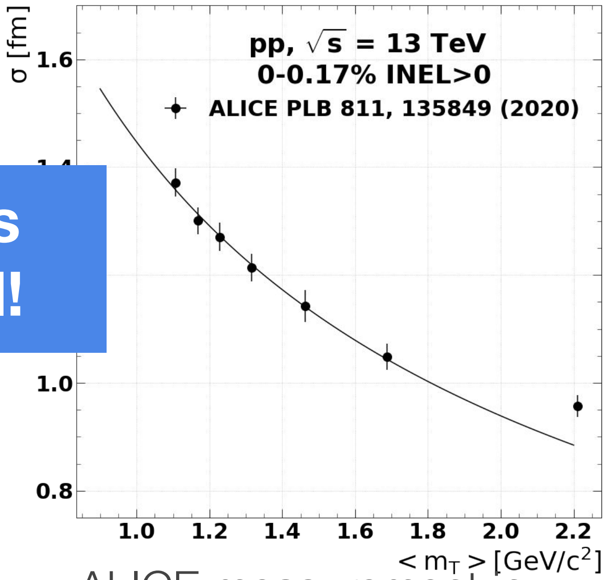


ALICE measurements over a large multiplicity range

Now we have all inputs we need for our model!

Source size

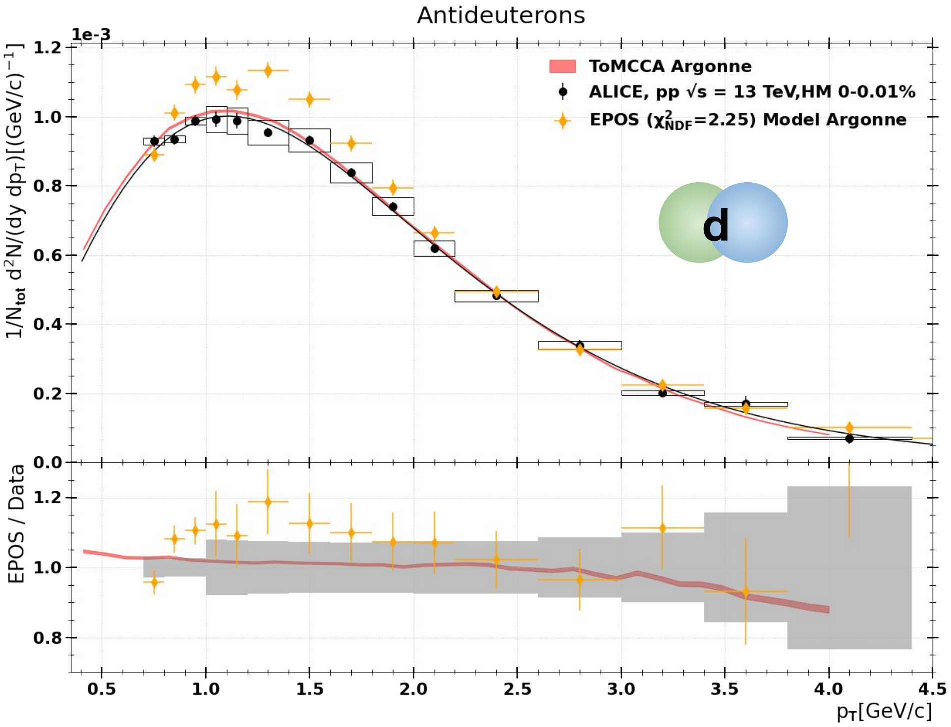


ALICE measurement in high-multiplicity collisions

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!



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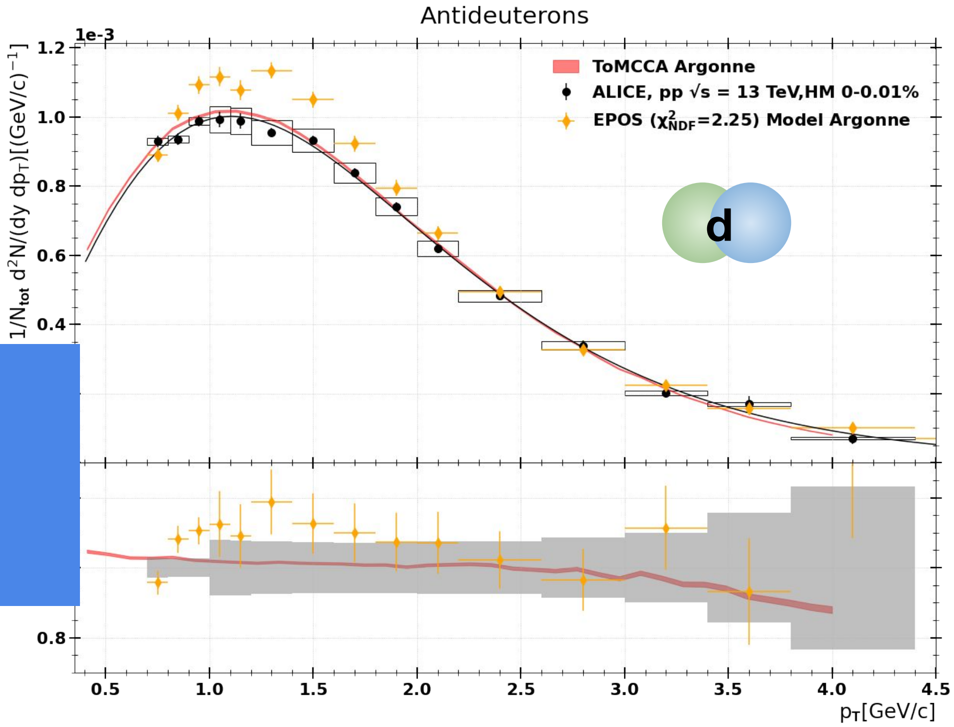
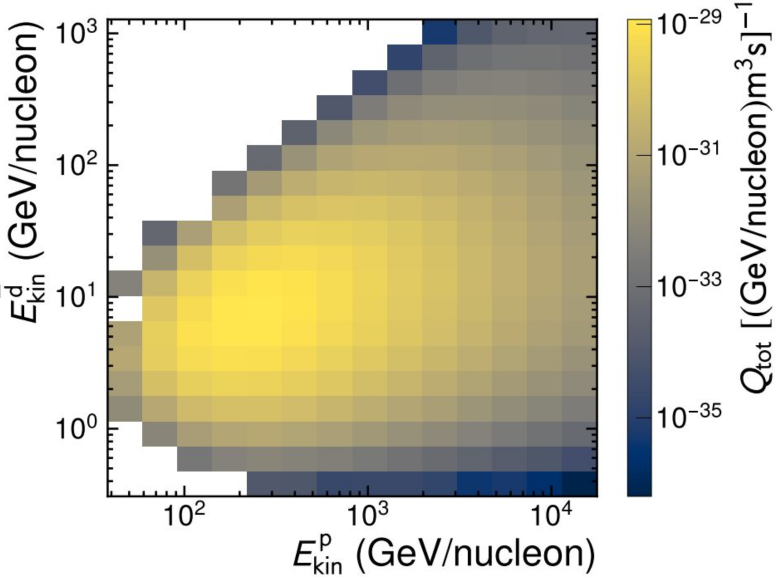


Does this help us in predicting Cosmic Ray fluxes?

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)

- Extrapolation to lower energies via event multiplicity

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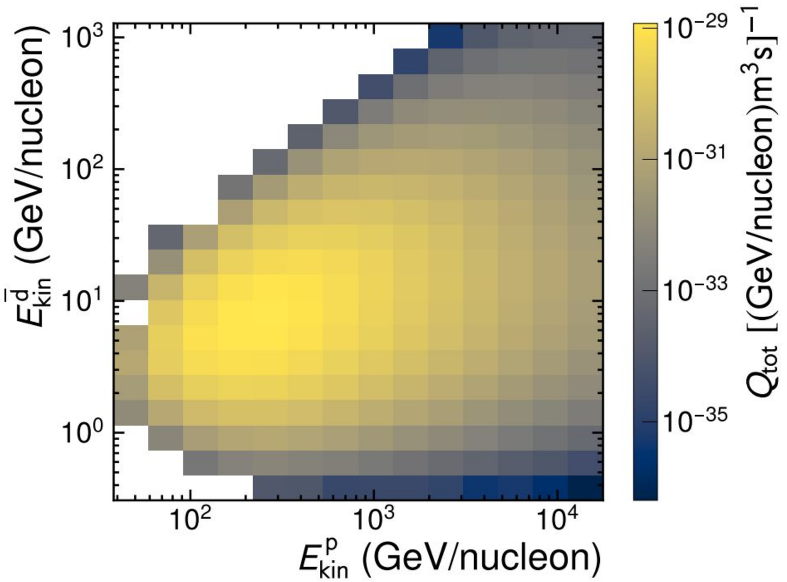

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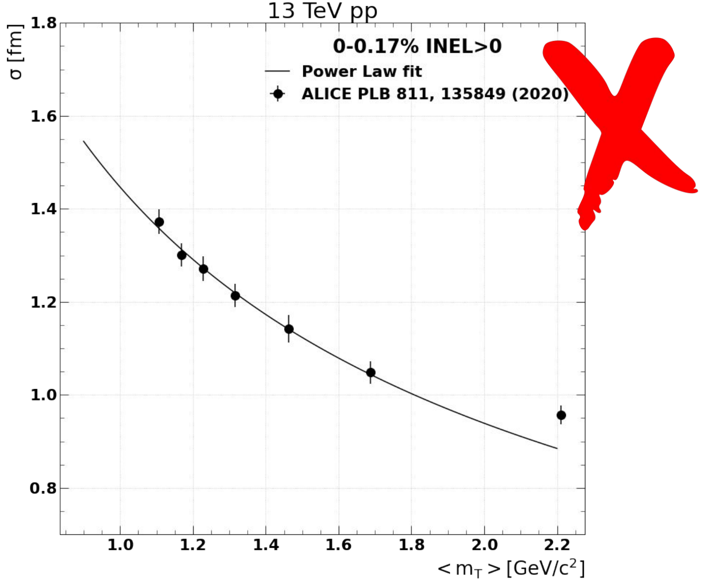

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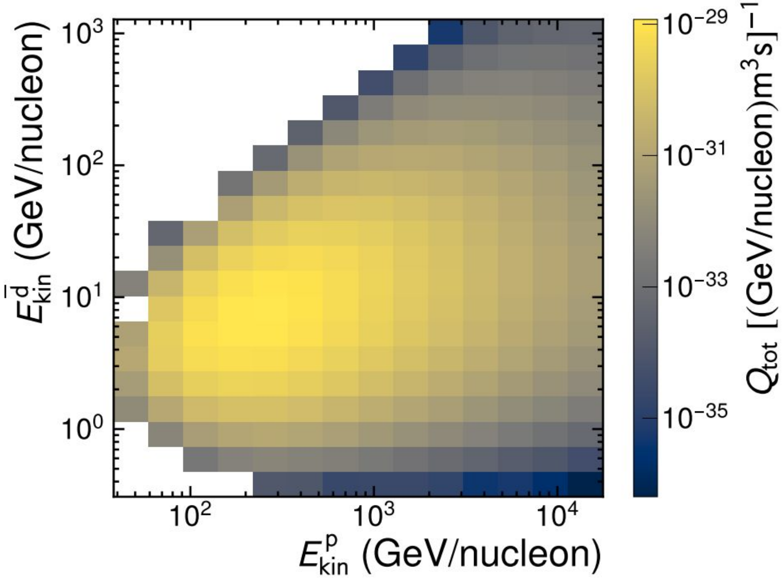

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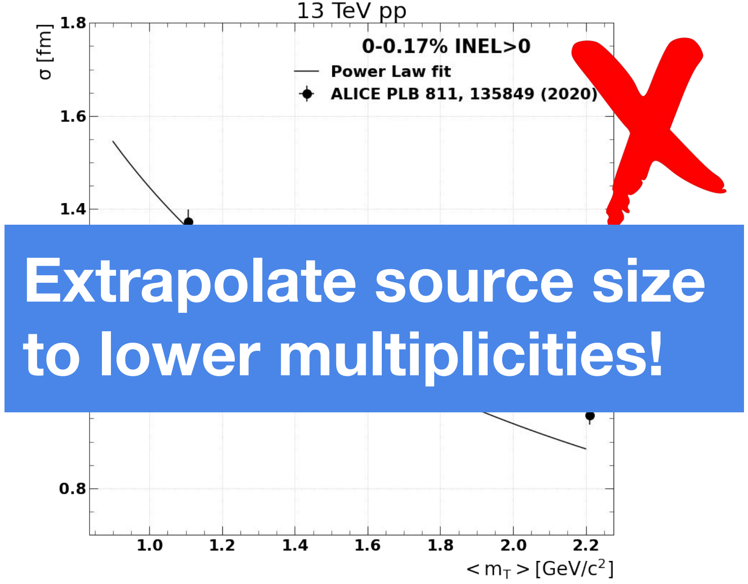
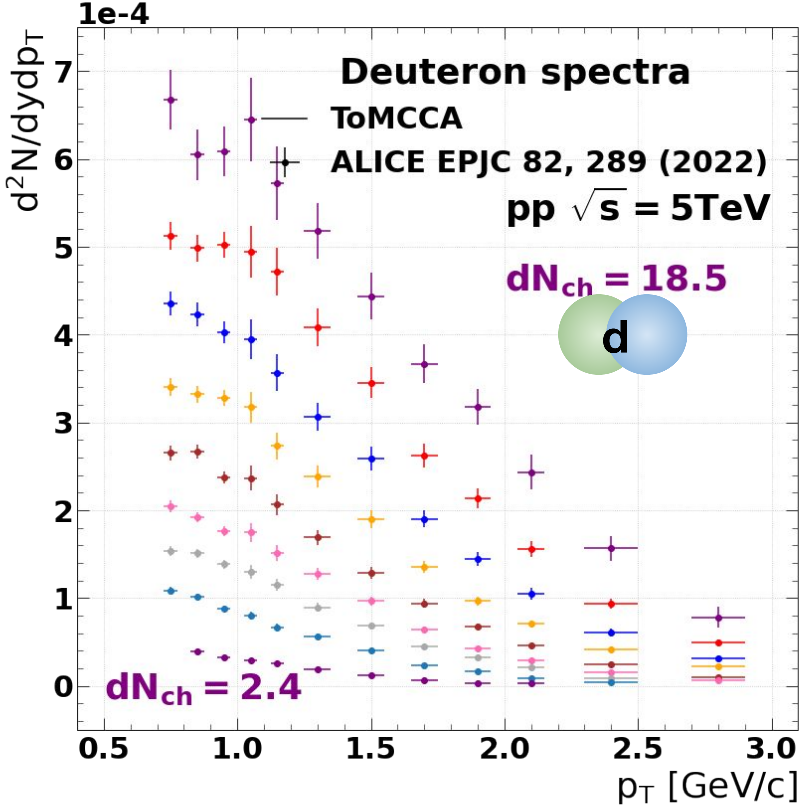


ALICE measurement in high-multiplicity collisions

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



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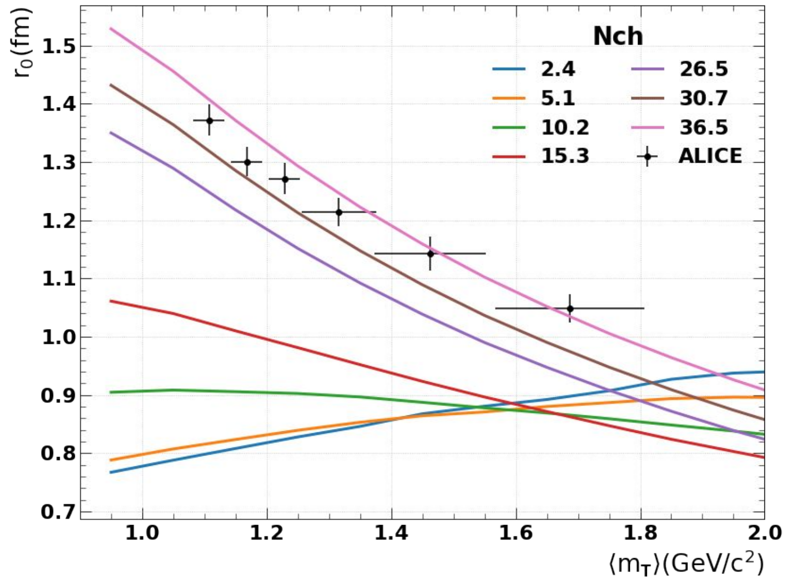

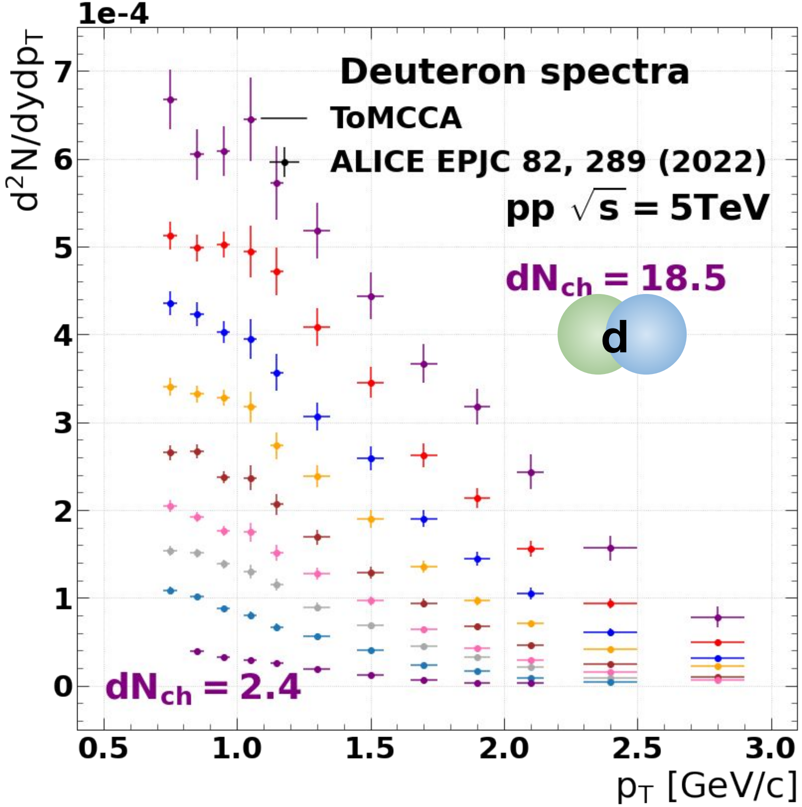

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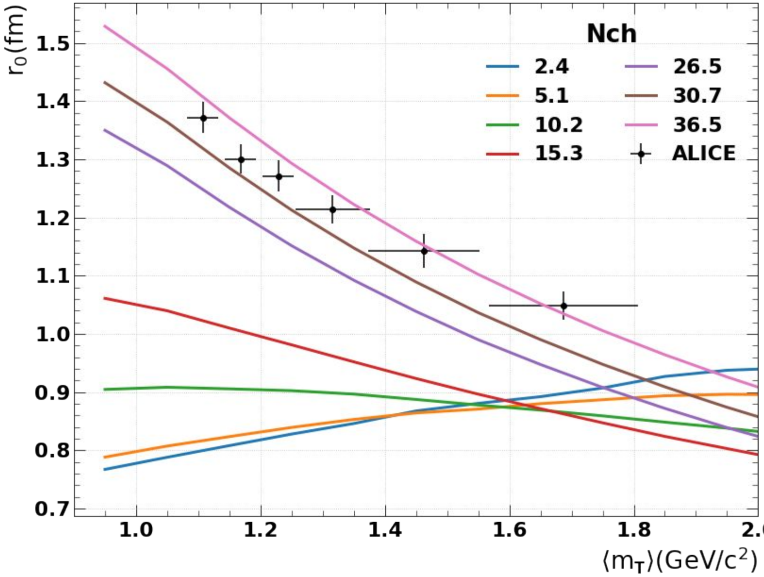

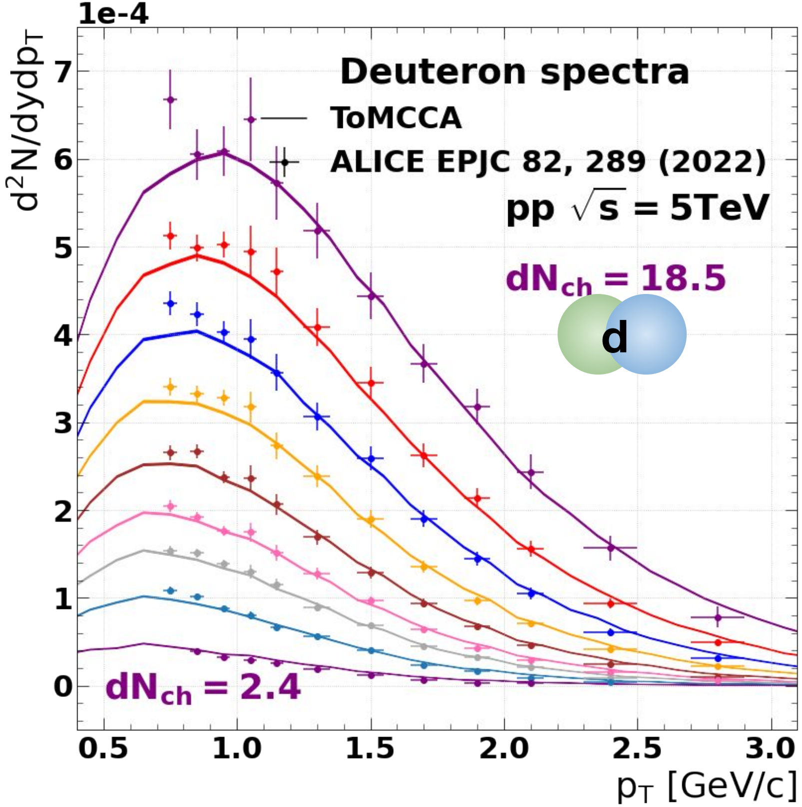

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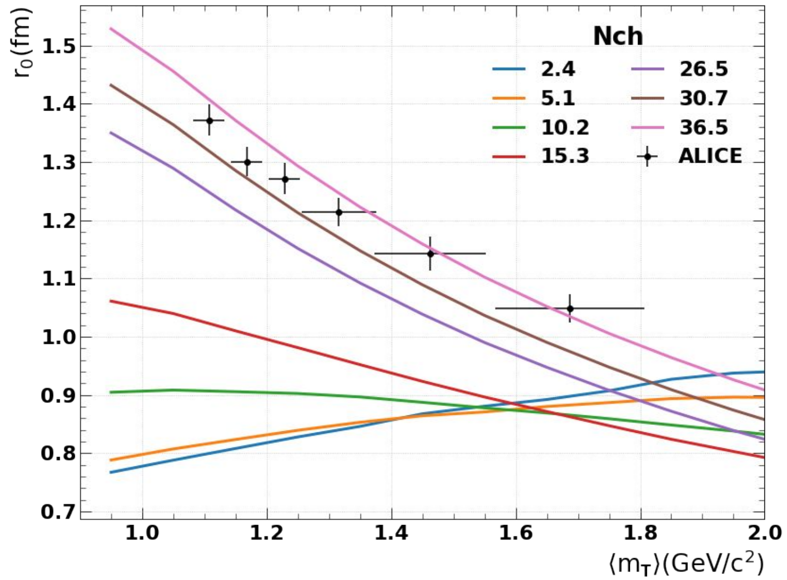

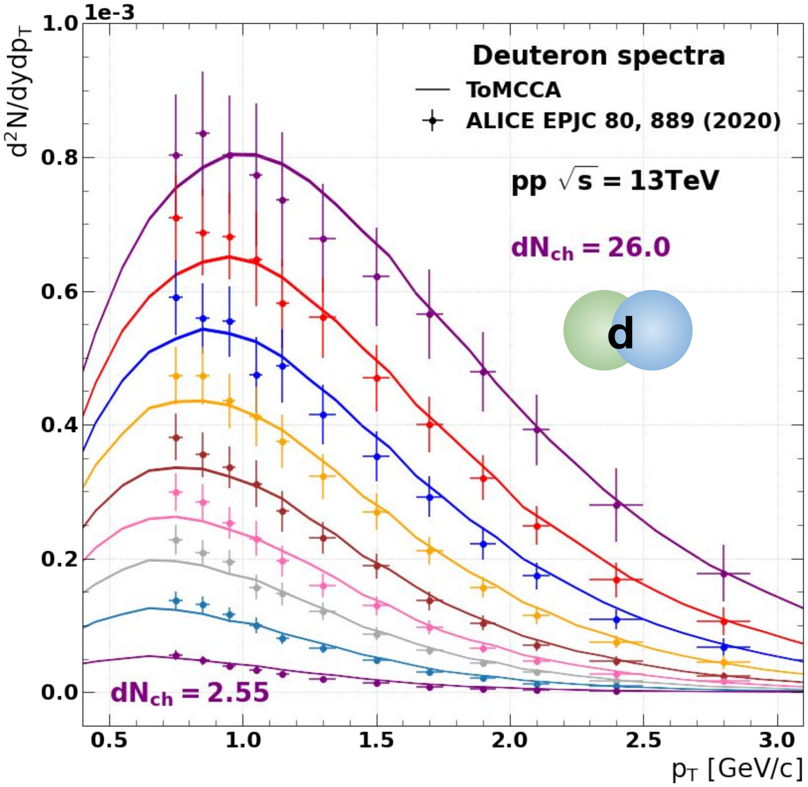

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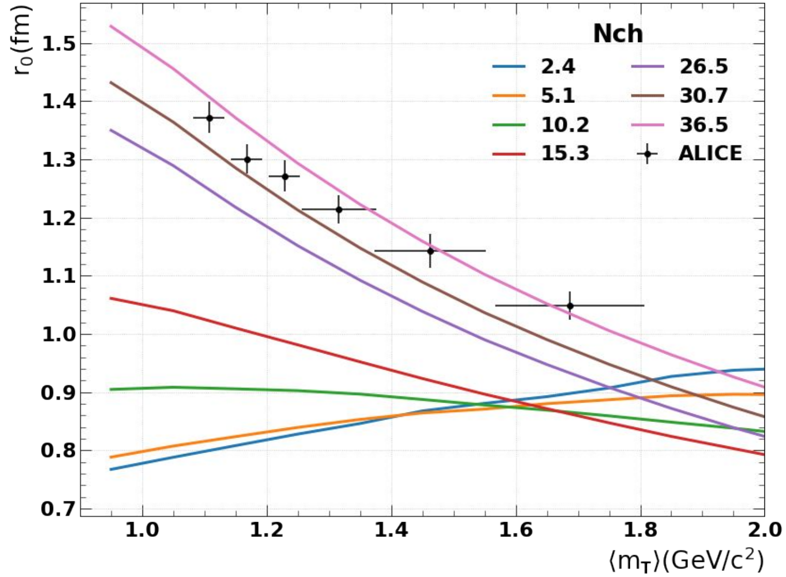
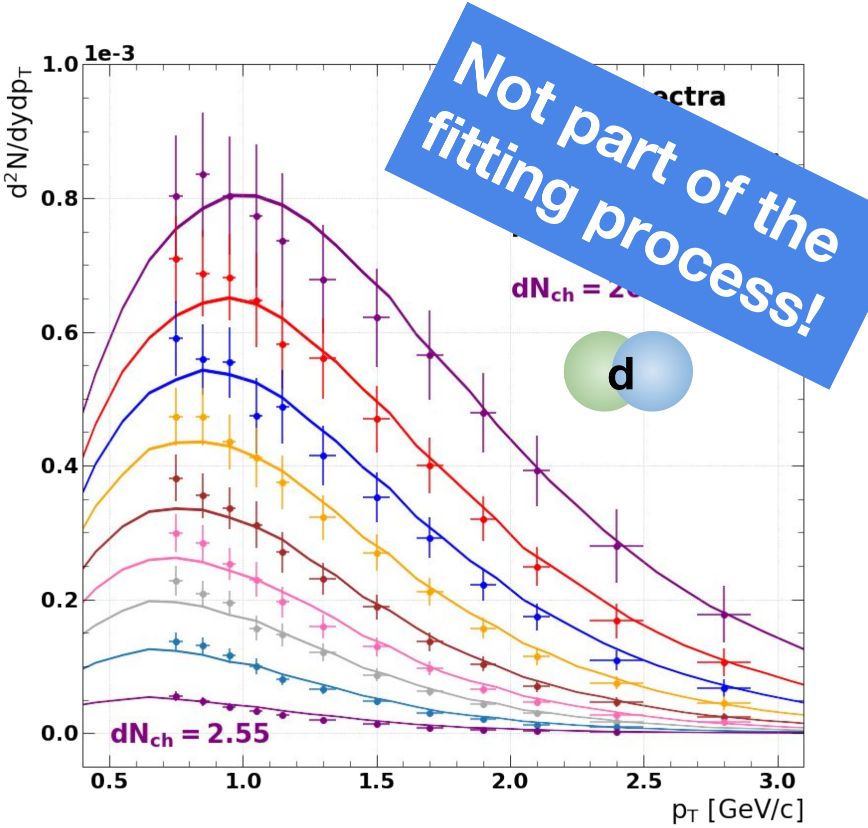
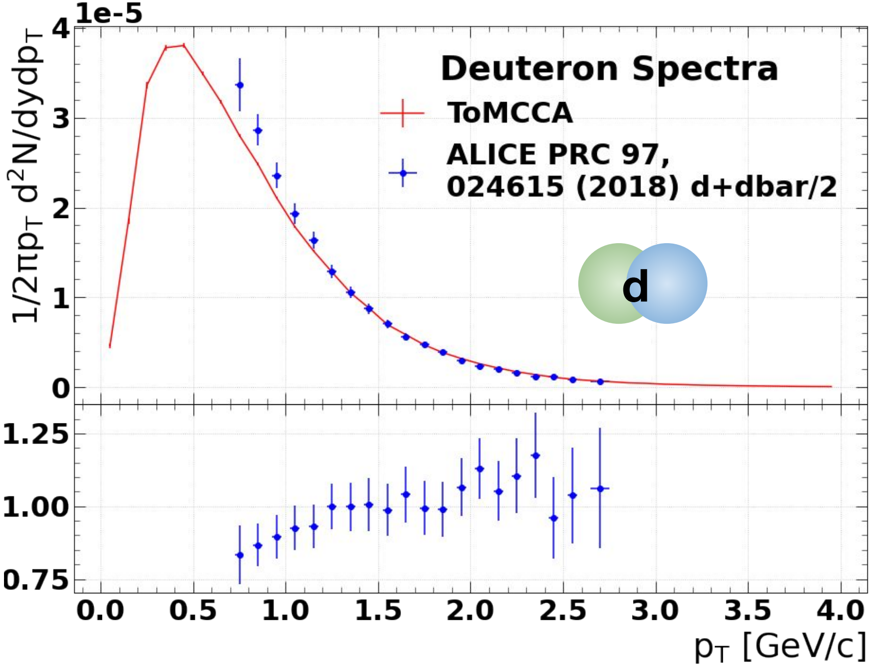




Deuteron results

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

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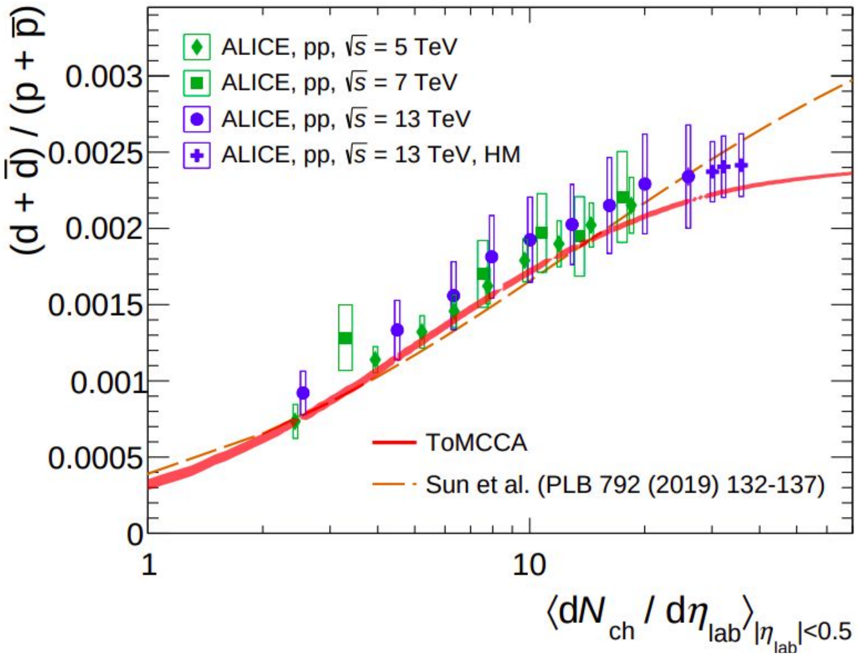
- d/p ratio reproduces data well, tension to previous predictions at high multiplicity



Deuteron results

B_2 parameter

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- Minimum Bias works well
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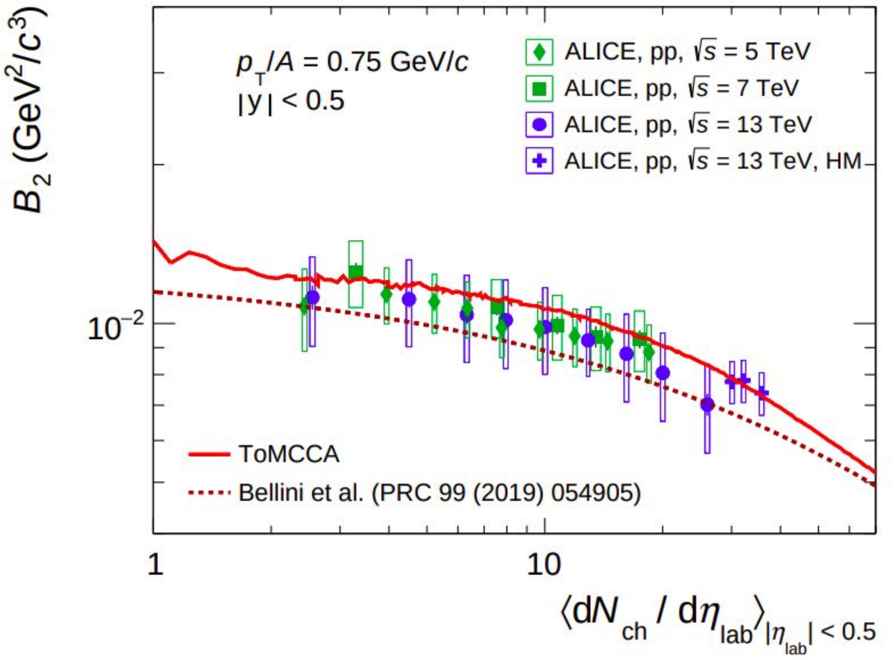
- B_2 also reproduced well



$$B_A(p_{\mathrm{T}}^p) = E_A \frac{d^3 N_{\mathrm{A}}}{dp_{\mathrm{A}}^3} \Bigg/ \left(E_{\mathrm{p}} \frac{d^3 N_{\mathrm{p}}}{dp_{\mathrm{p}}^3} \right)^{\mathrm{A}}$$

Extension to A=3

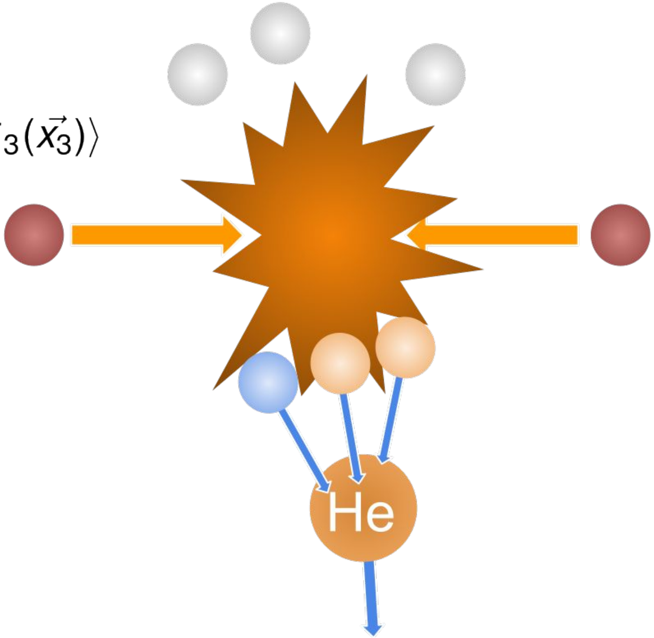
Add 3rd particle to basic formalism

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

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

Similarly the probability can be expressed as

$$\mathcal{P}(q_1, q_2, \sigma) = \frac{S_d}{(2\pi)^3 2^3 \sigma^6} \int d^3r_1 d^3r_2 \mathcal{D}(q_1, q_2, r_1, r_2) e^{-\frac{r_1^2+r_2^2}{4\sigma^2}}$$

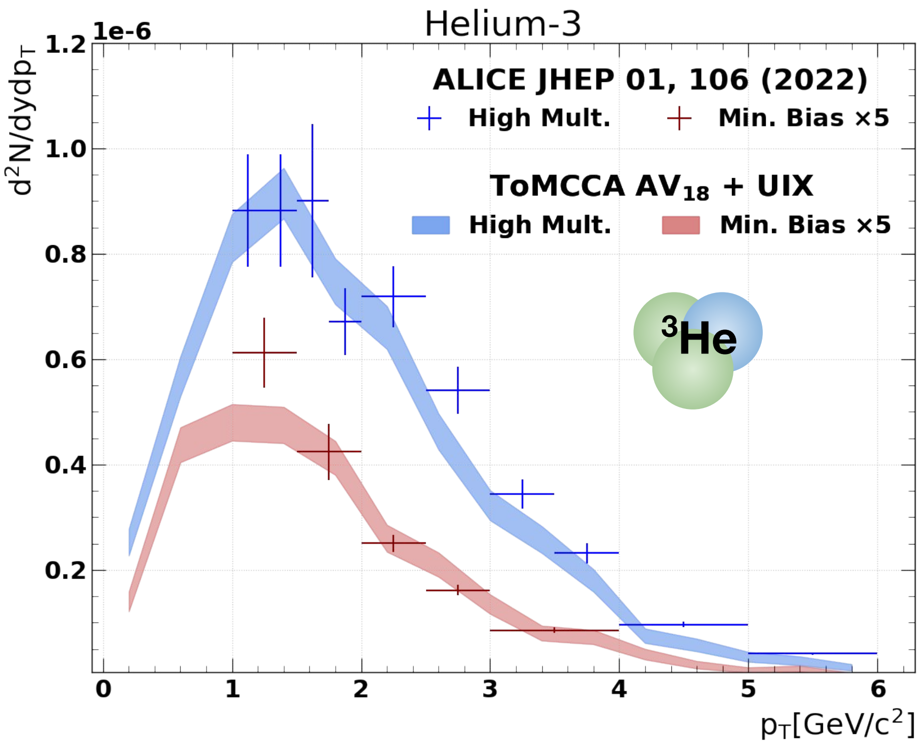


Extension to A=3

Helium-3

Extension to A=3 coalescence

- Use 2-body source size
  - Assign every pair a distance
  - Geometric mean of distance for coalescence probability
- 3-body angular correlations built from 2-body
- Wavefunction based on Argonne v_{18} (2-body) + Urbana IX (3-body)[1]
- Fully numeric calculation of Probability



[1] Provided by Michele Viviani, INFN Pisa

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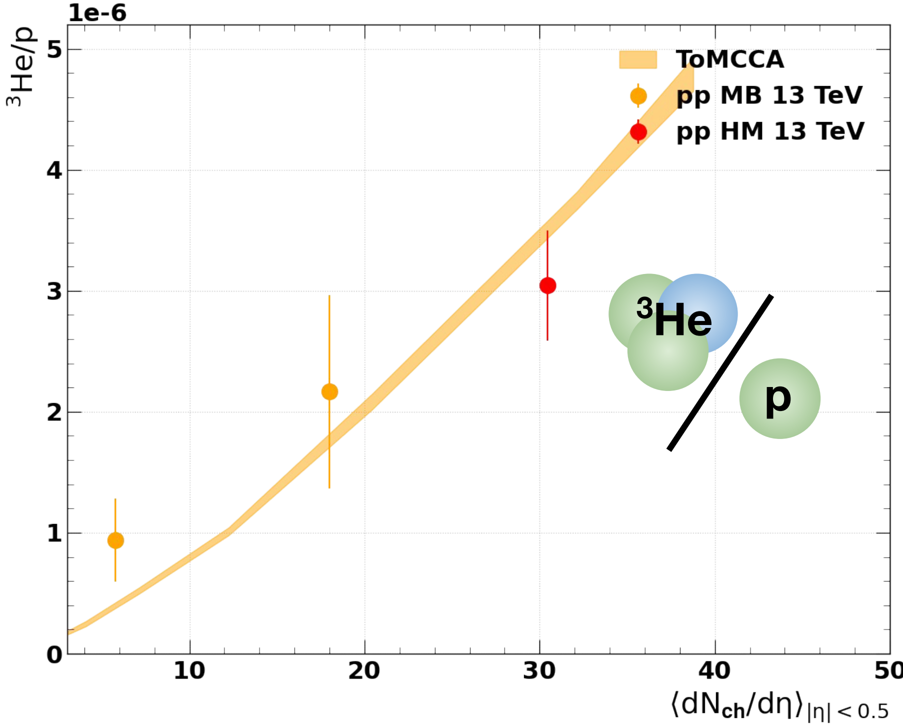
- Fully numeric calculation of Probability



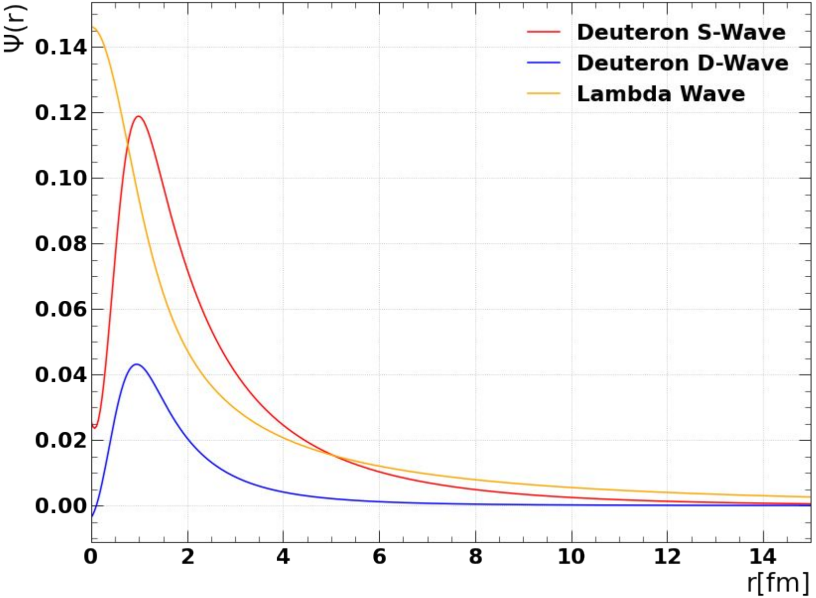
[1] Provided by Michele Viviani, INFN Pisa

Extension to A=3
Hypertriton

- Congleton[1] wavefunction

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

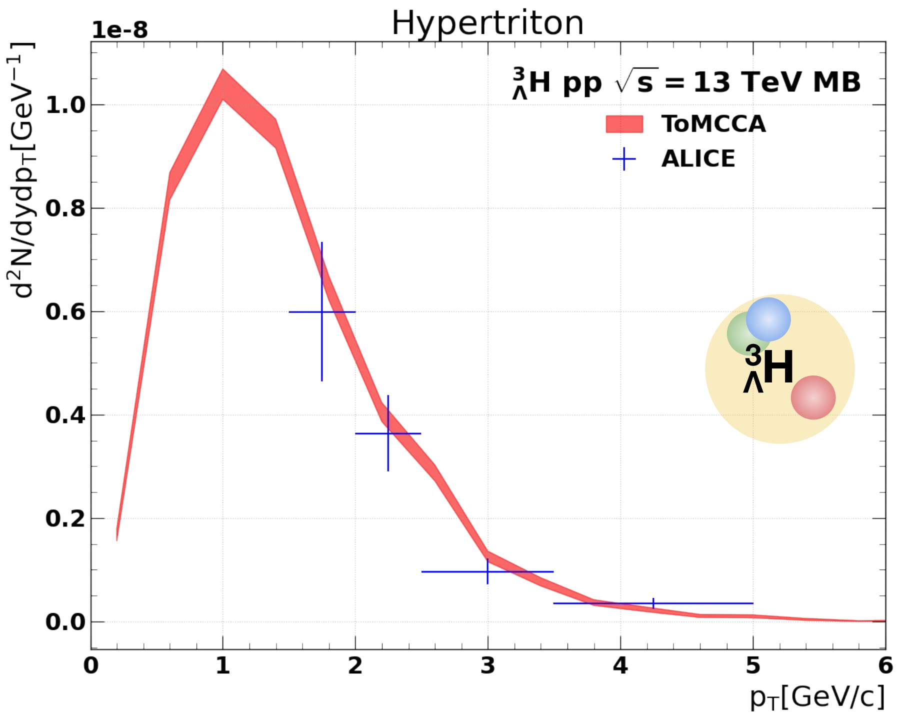
- Assumes factorization of Hypertriton wavefunction into deuteron+Λ
- Scattering parameters retuned to latest Hypertriton formfactor calculations[2] by Hildenbrand & Hammer[3]



📚[1] J G Congleton 1992 J. Phys. G: Nucl. Part. Phys. 18 339
📚[2] F. Bellini et al.: Phys.Rev.C 103, 1 (2021)
📚[3] F. Hildenbrand and H.-W. Hammer: Phys. Rev. C 100, 034002

Extension to A=3
Hypertriton

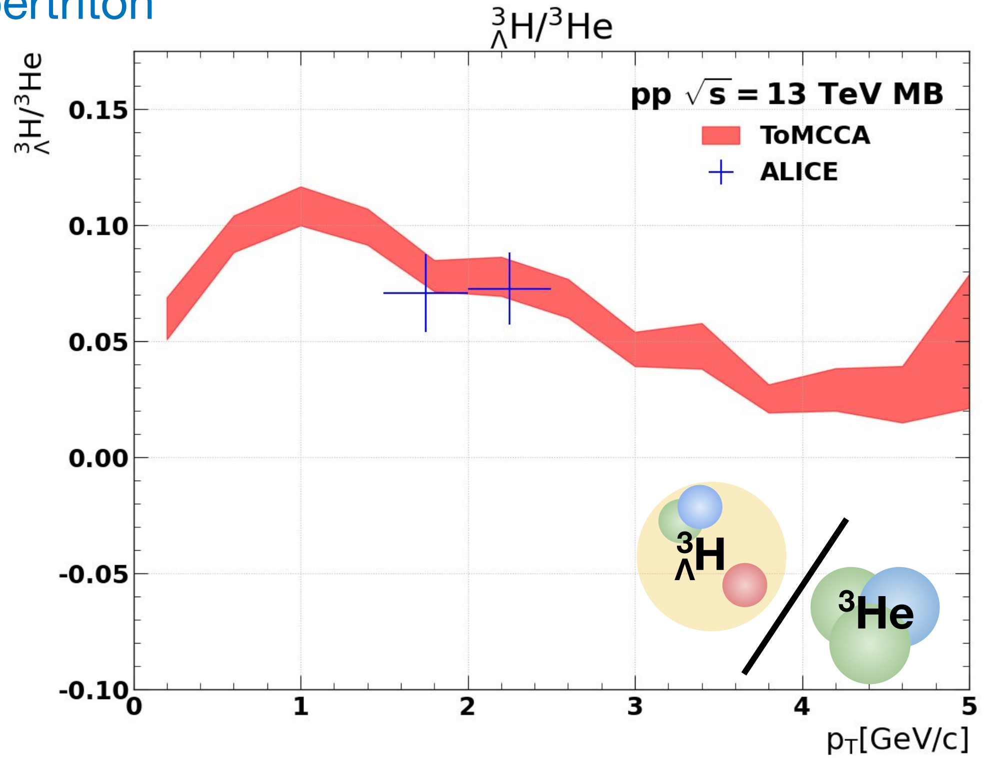
- Latest ALICE measurements of ${}^{3}_{\Lambda}H$ in 13 TeV MB



Extension to A=3

Hypertriton

- Latest ALICE measurements of ${}^{3}_{\Lambda}H$ in 13 TeV MB
- ${}^{3}_{\Lambda}H/{}^{3}He$ Ratio falling off for large p_T



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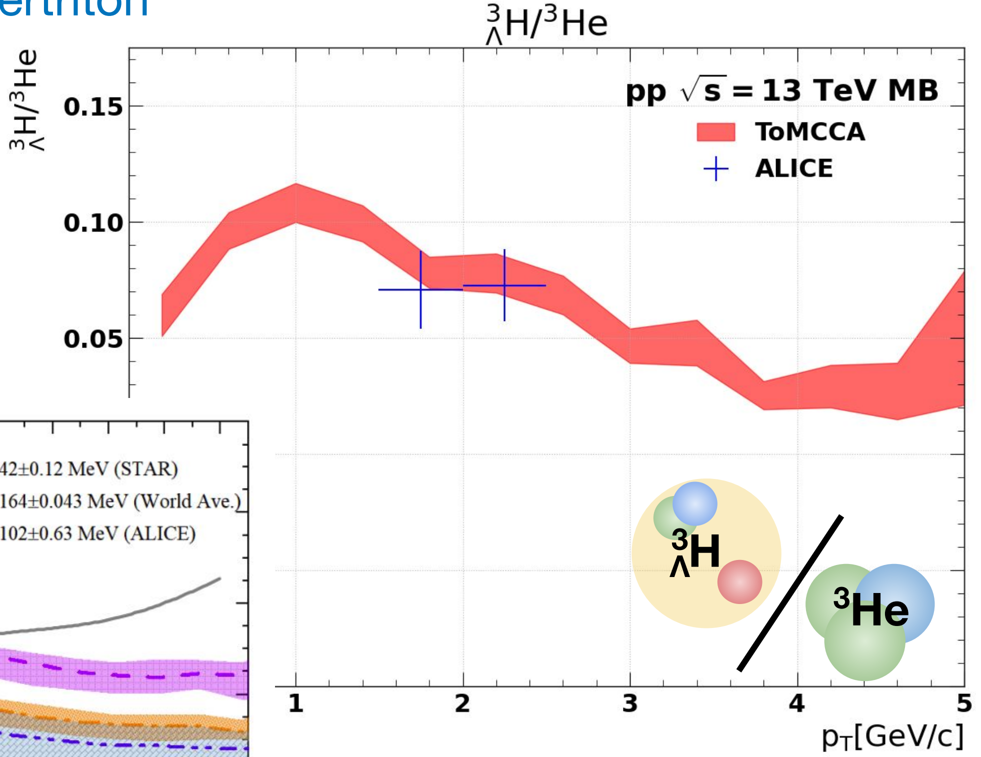
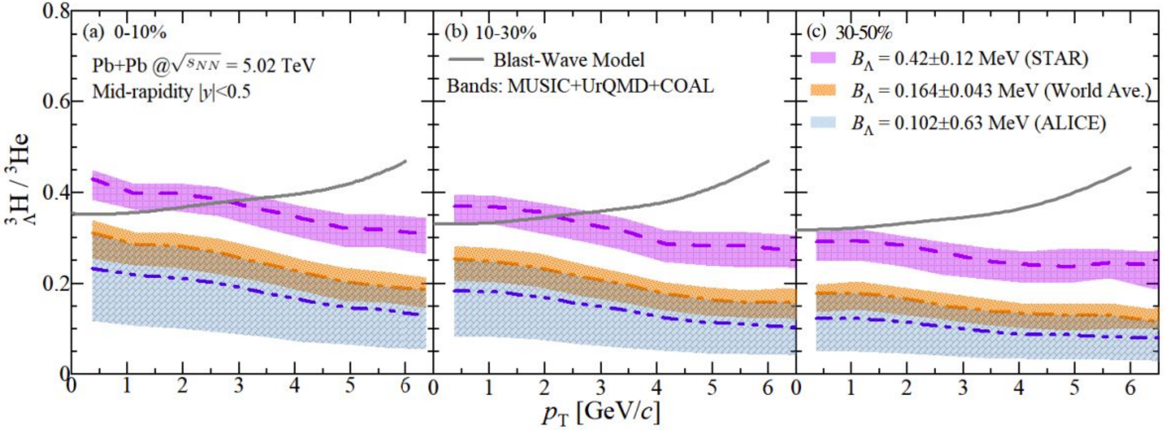


Only available predictions in Heavy Ions[1]:



[1]K.-J. Sun et.al. arXiv:2404.02701

Extension to A=3

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- Latest ALICE measurements of ${}^{3}_{\Lambda}H$ in 13 TeV MB
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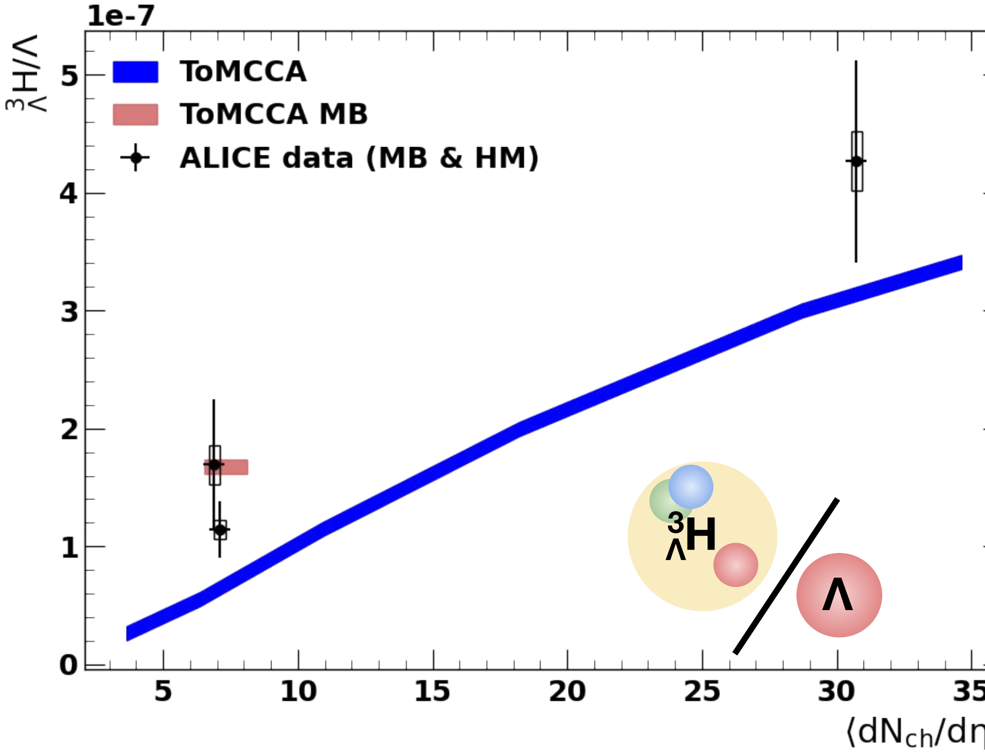


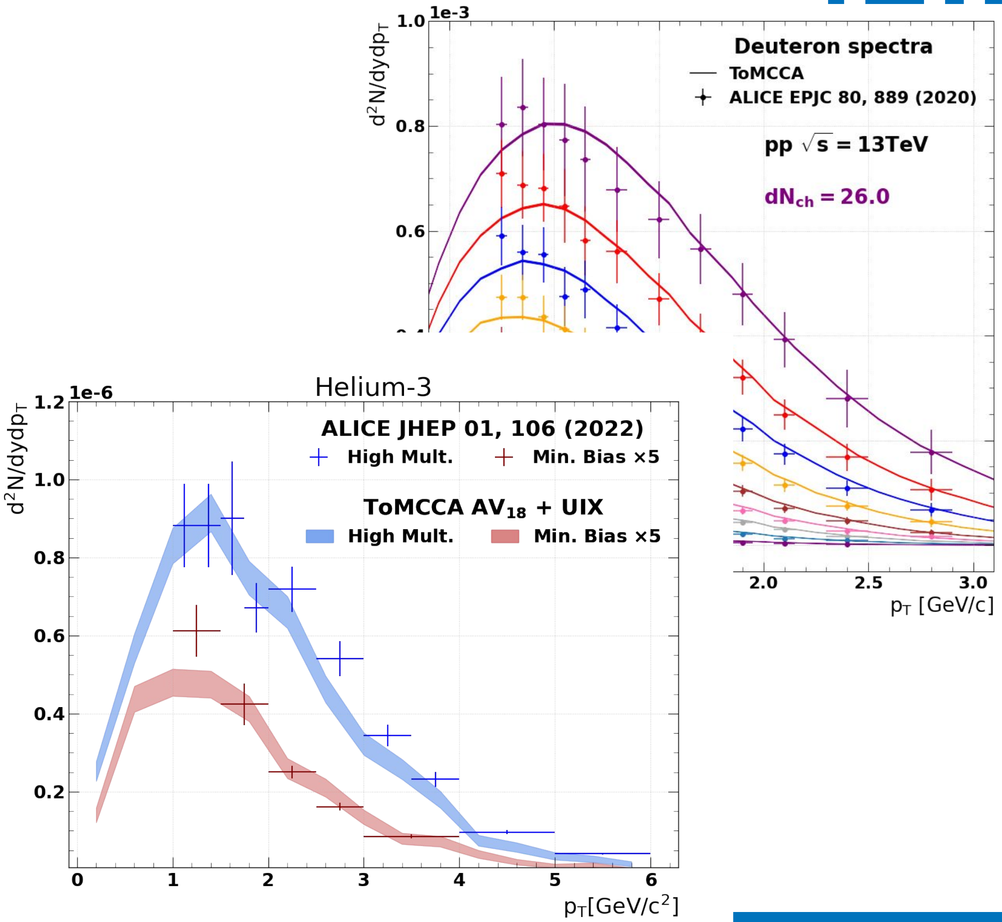
Conclusion

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-publi

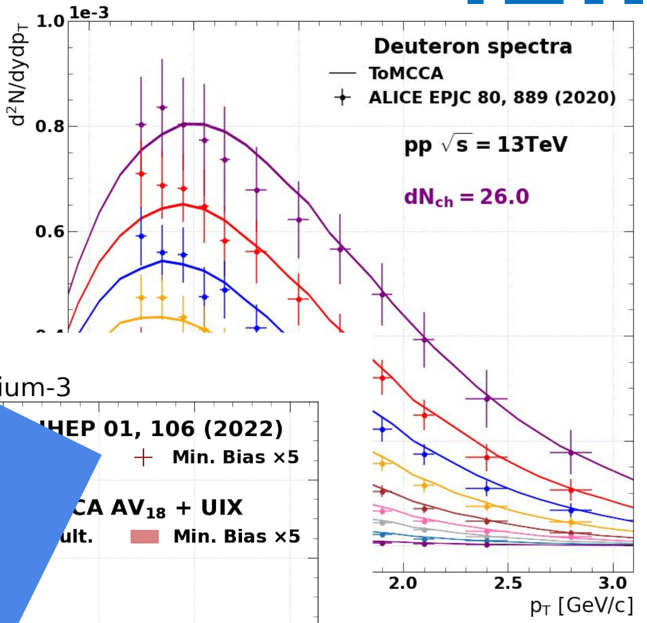
Conclusion

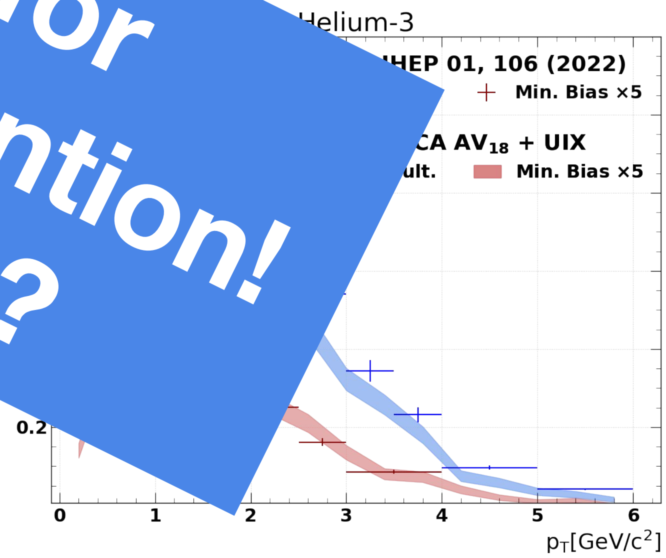
Deuterons:
- Coalescence mod[...]ces data with no free para[...]
- Realistic wavefu[...]
- ToMCCA allow[...] arbitrary mult[...]

A=3 Coalescenc[...]
- Successfu[...] A=3
- Nuclei and *Hypern*[...]
- Realistic wavefunctions [...]

Thanks for your attention!

Questions?





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BACKUP

Comment on Event Generators

Advantages:	Disadvantages:
• Model extremely complex phenomena and particle correlations • Easy to use (‘Plug and play’) • Trivial extrapolation to different energies, multiplicities (and Collision systems)	• Convoluted Code, hard to adjust • Hard to distill influence of single mechanism on the final result • Long simulation times • No nuclei production

Comment on Event Generators

Advantages:

- Model extremely complex phenomena and particle correlations
- Easy to use ('Plug and play')
- Trivial extrapolation to different energies, multiplicities (and Collision systems)

Disadvantages:

- Convoluted Code, hard to adjust
- Hard to distill influence of single mechanism on the final result
- Long simulation times
- No nuclei production

⇨ Build Toy Monte Carlo that uses only the necessary mechanisms for nuclei production

Requirements: Fast simulation, easy to adjust to end-users needs

Toy **M**onte **C**arlo **C**oalescence **A**fterburner: ToMCCA

ToMCCA Building principles

Speed:

Slowest parts of Event generators: *Hadronization*, *Hadronic Cascade*

⇨ Fully omit Hadronization, start from a statistical distribution of nucleons (no mesons)

⇨ No Rescattering, Flow, Jets, …

Correlations:

No ab-initio correlations, built in fully by hand

⇨ can be easily deactivated or adjusted

User-Friendly:

All of ToMCCA is ~800 lines of Code

⇨ Easy to find code responsible for specific effect

Run-in-place configuration

⇨ Download (*https://github.com/HorstMa/ToMCCA-Public*) and run immediately

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But a Toy Model needs measured inputs…

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Run-in-place configuration

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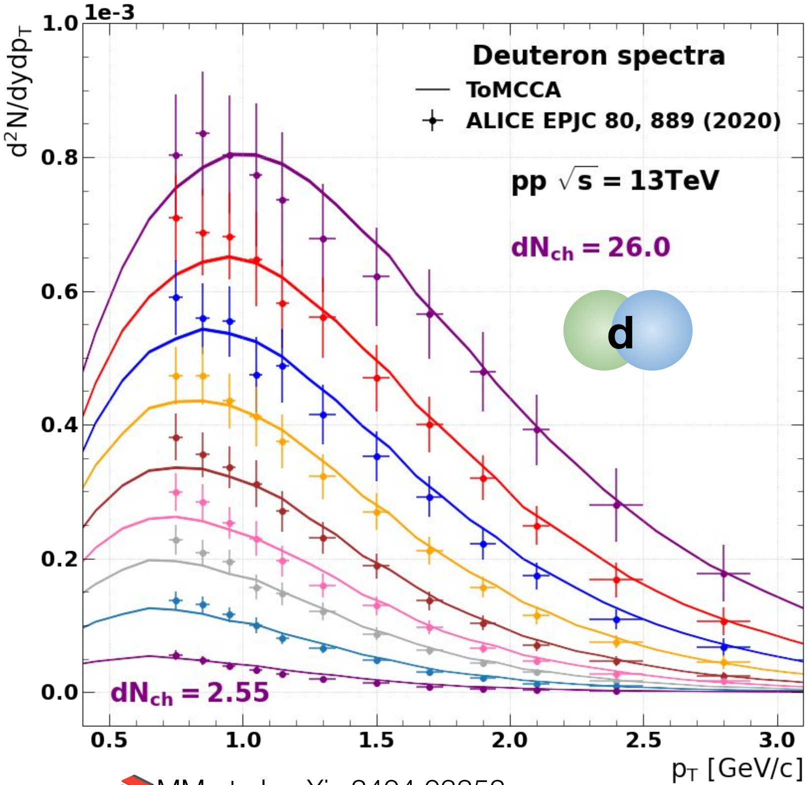
Conclusion

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



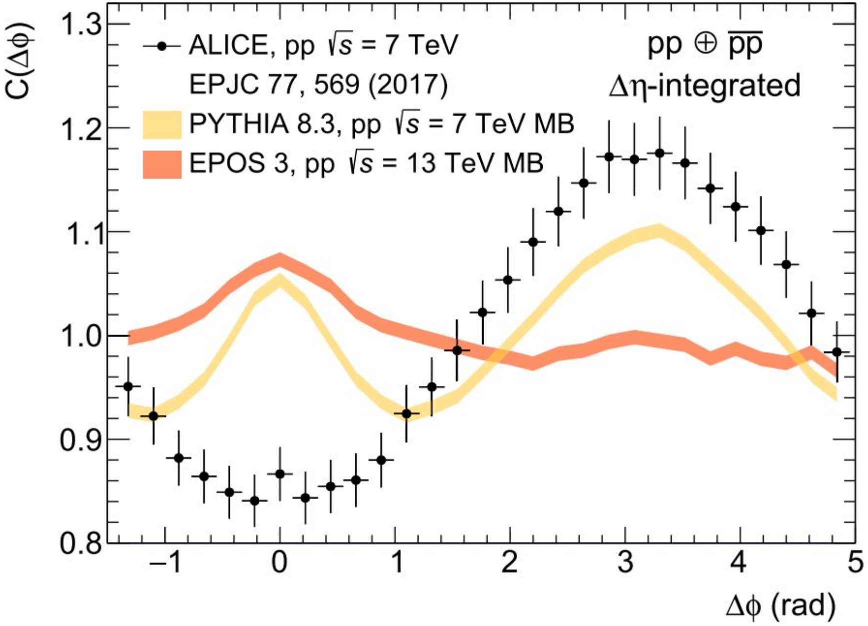
📚MM et al. arXiv:2404.03352

Coalescence Results EPOS

Angular correlations

- 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



Comparison to previous predictions

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

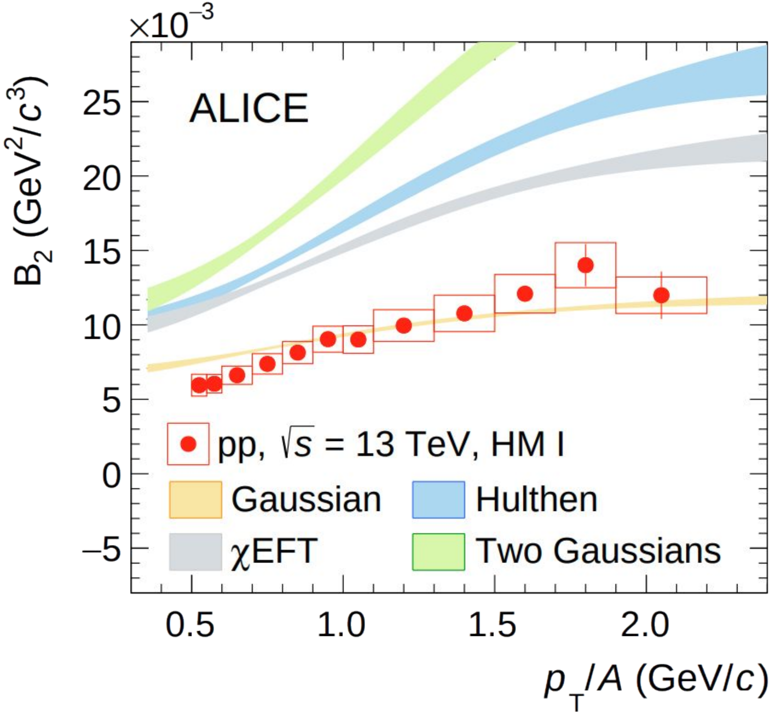
$$B_A(p_T^p) = E_A \frac{d^3N_A}{dp_A^3} \Big/ \left(E_p \frac{d^3N_p}{dp_p^3}\right)^A$$

- Theoretical prediction [1]

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

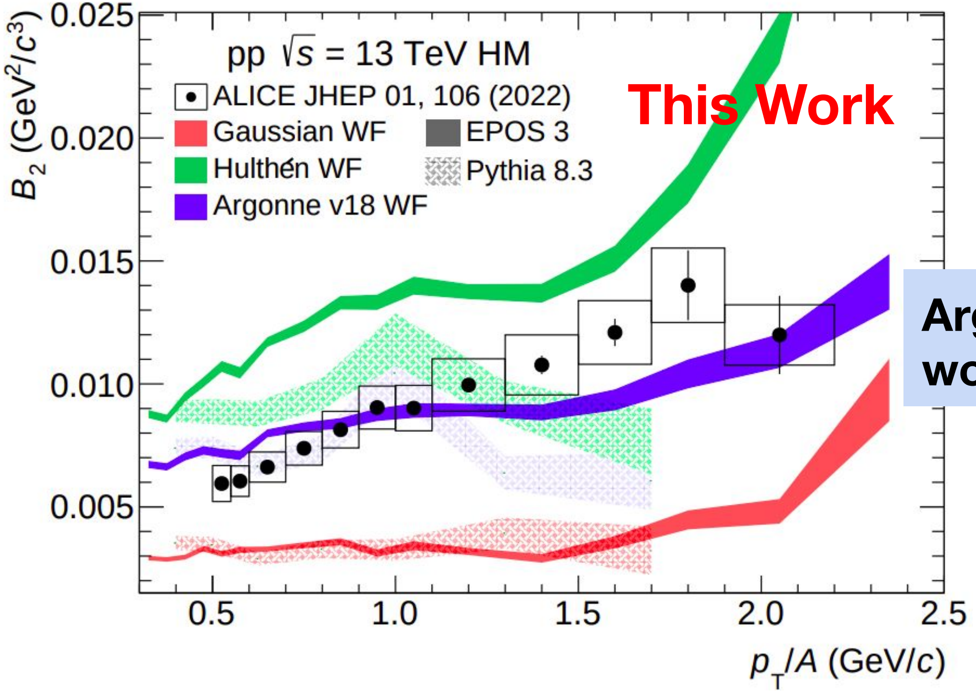
$$D(\vec{q}) = \int d^3r |\phi_d(\vec{r})|^2 e^{-i\vec{q}\cdot\vec{r}}$$

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

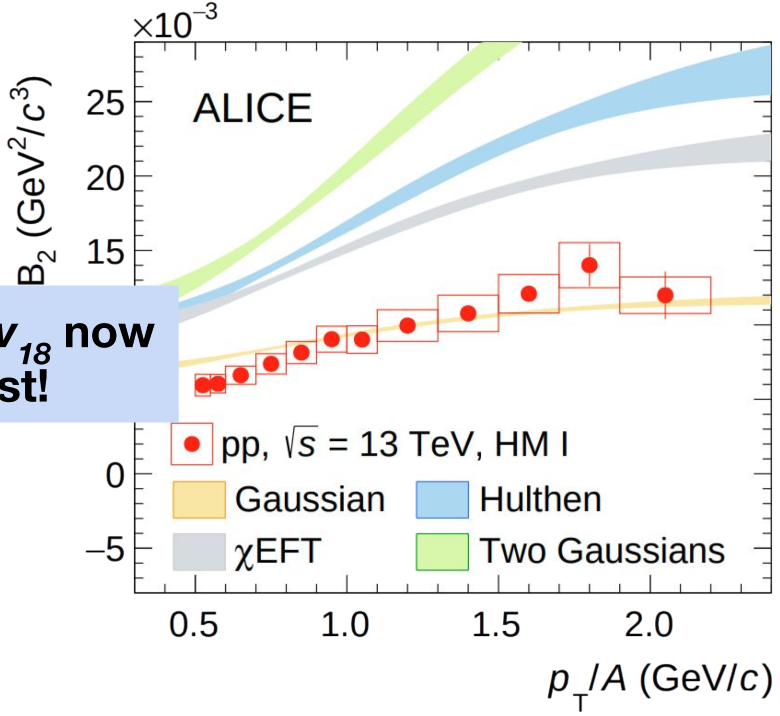


[1] Blum, Takimoto, PRC 99 (2019) 044913

Comparison to previous predictions



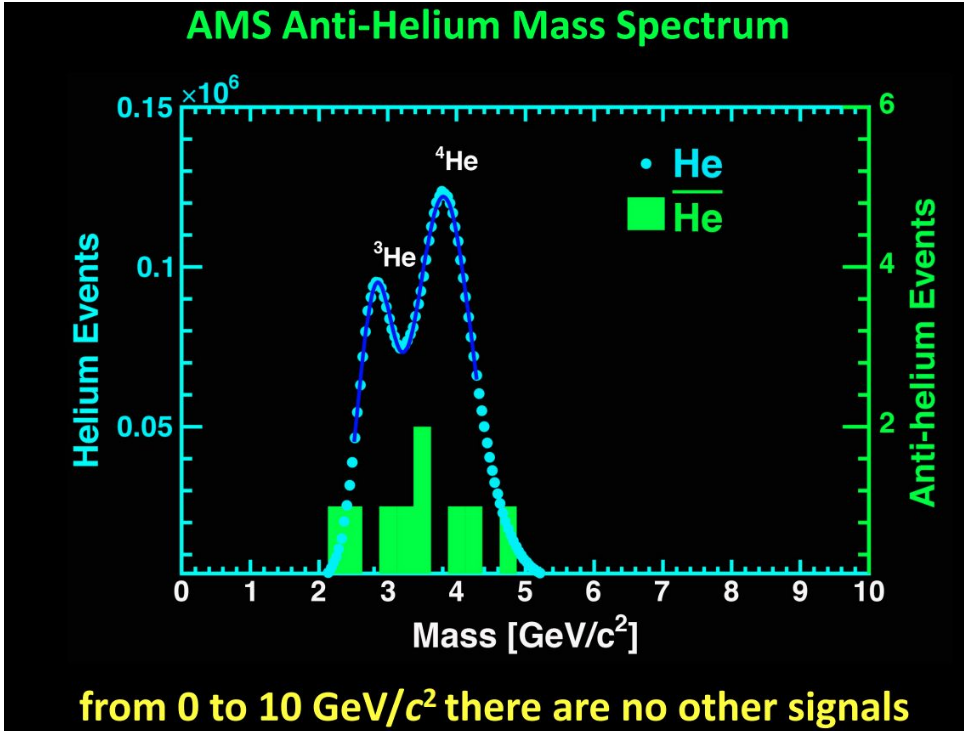
Argonne v_{18} now works best!



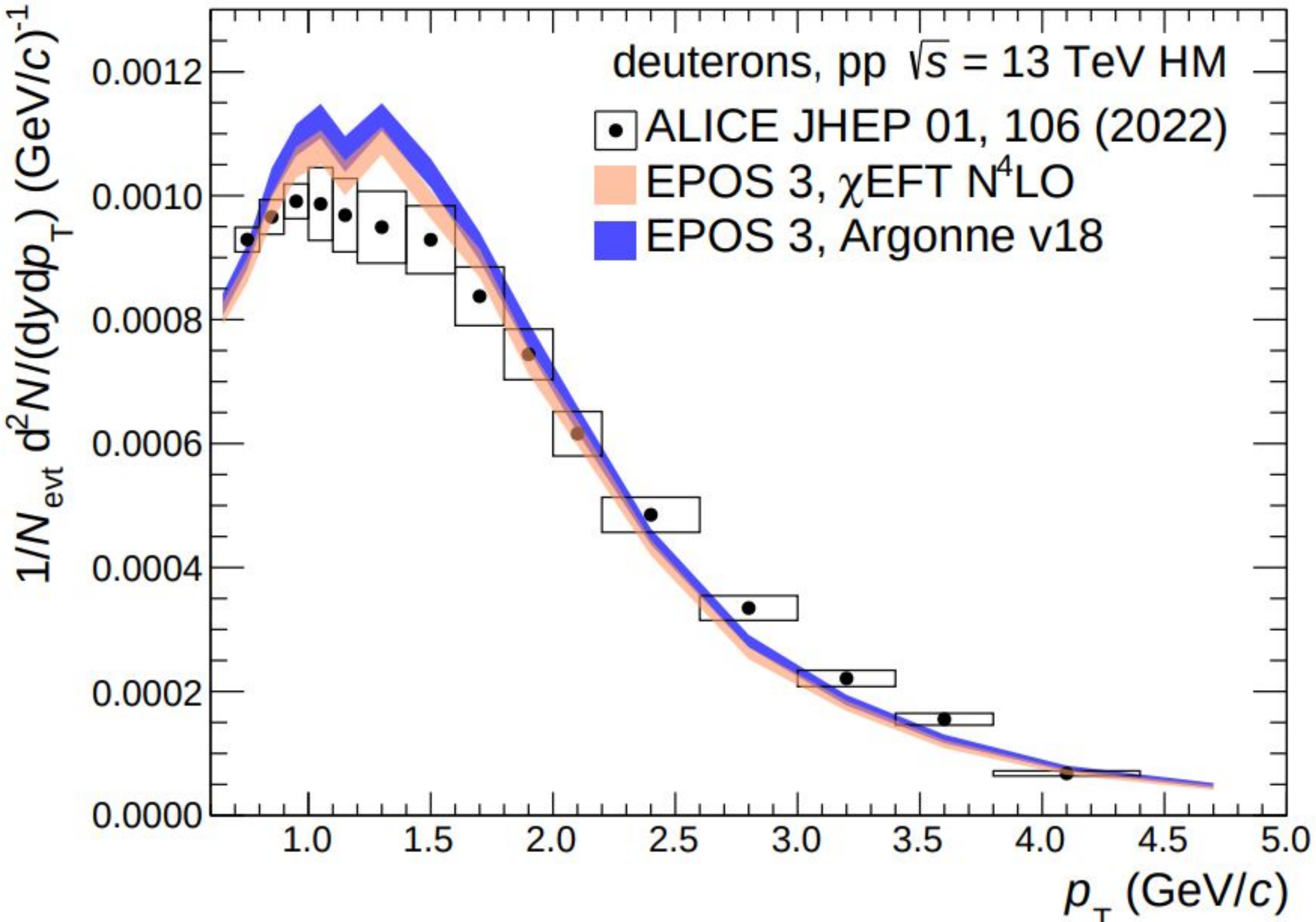
Cosmic Rays

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

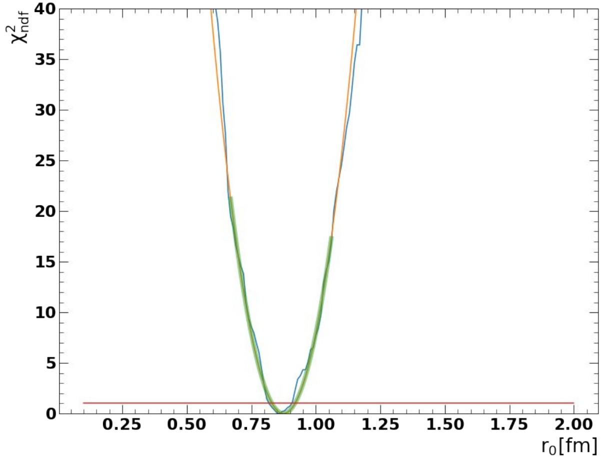

deuterons, pp $\sqrt{s}$ = 13 TeV HM
ALICE JHEP 01, 106 (2022)
EPOS 3, χEFT N⁴LO
EPOS 3, Argonne v18
$1/N_{evt}\ d^2N/(dydp_T)$ (GeV/c)$^{-1}$
0.0012
0.0010
0.0008
0.0006
0.0004
0.0002
0.0000
1.0
1.5
2.0
2.5
3.0
3.5
4.0
4.5
5.0
p_T (GeV/c)

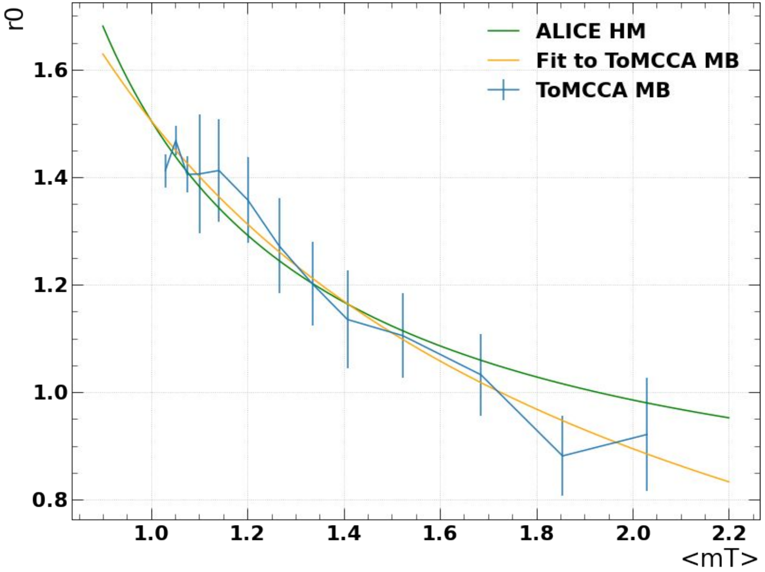
Next generation coalescence Model

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

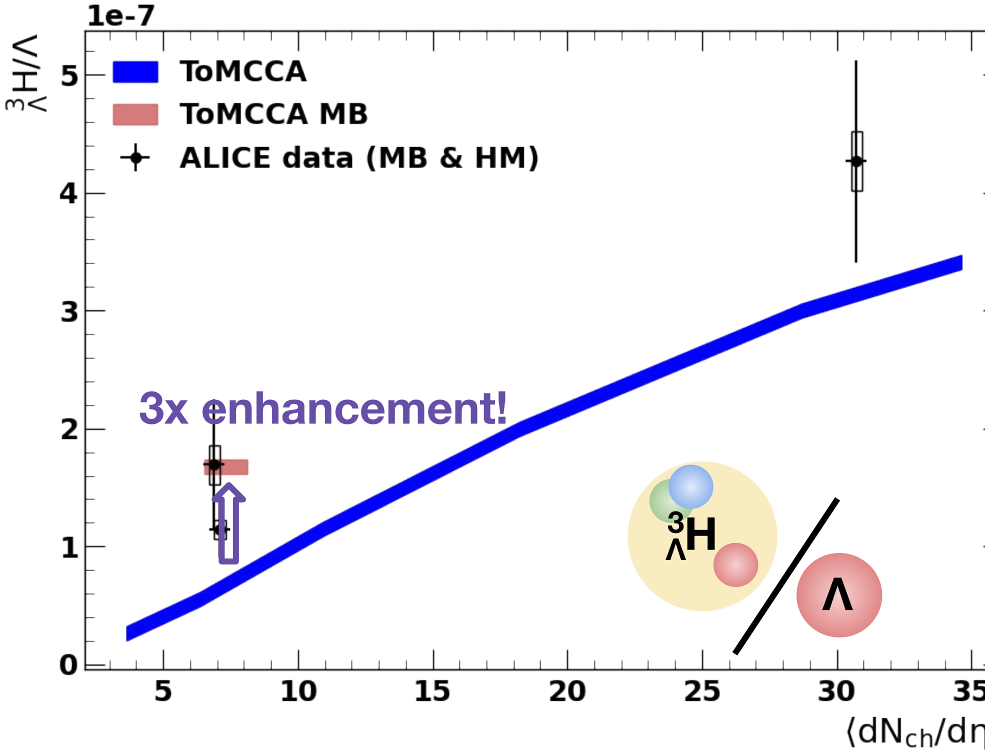




Extension to A=3

Hypertriton

- Latest ALICE measurements of ${}^{3}_{\Lambda}H$ in 13 TeV MB
- ${}^{3}_{\Lambda}H/{}^{3}He$ Ratio falling off for large p_T
- ${}^{3}_{\Lambda}H/\Lambda$ Ratio as a function of Multiplicity
- Important Note:
  Minimum Bias Data is not comparable this way! *3x enhancement from wide multiplicity distribution*

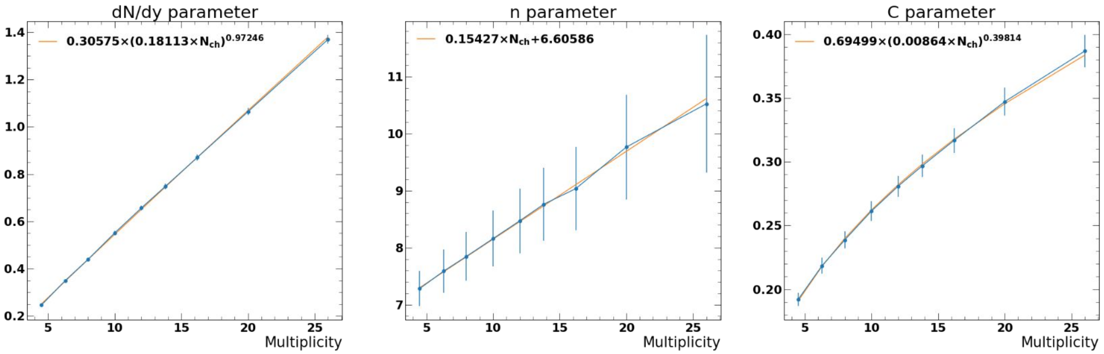


📚[1]K.-J. Sun et.al. arXiv:2404.02701

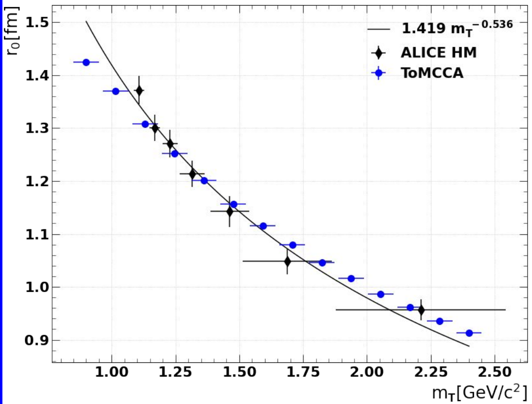
Recap: ToMCCA

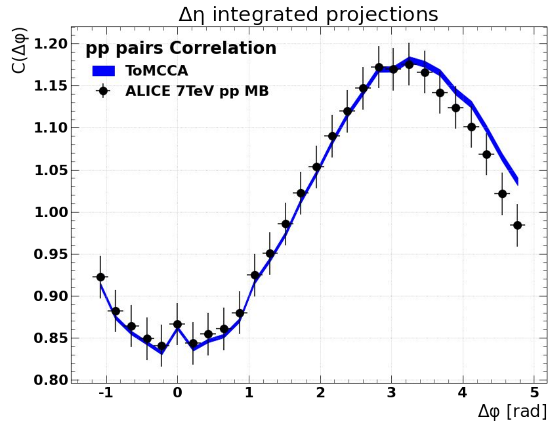
Inputs

- 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

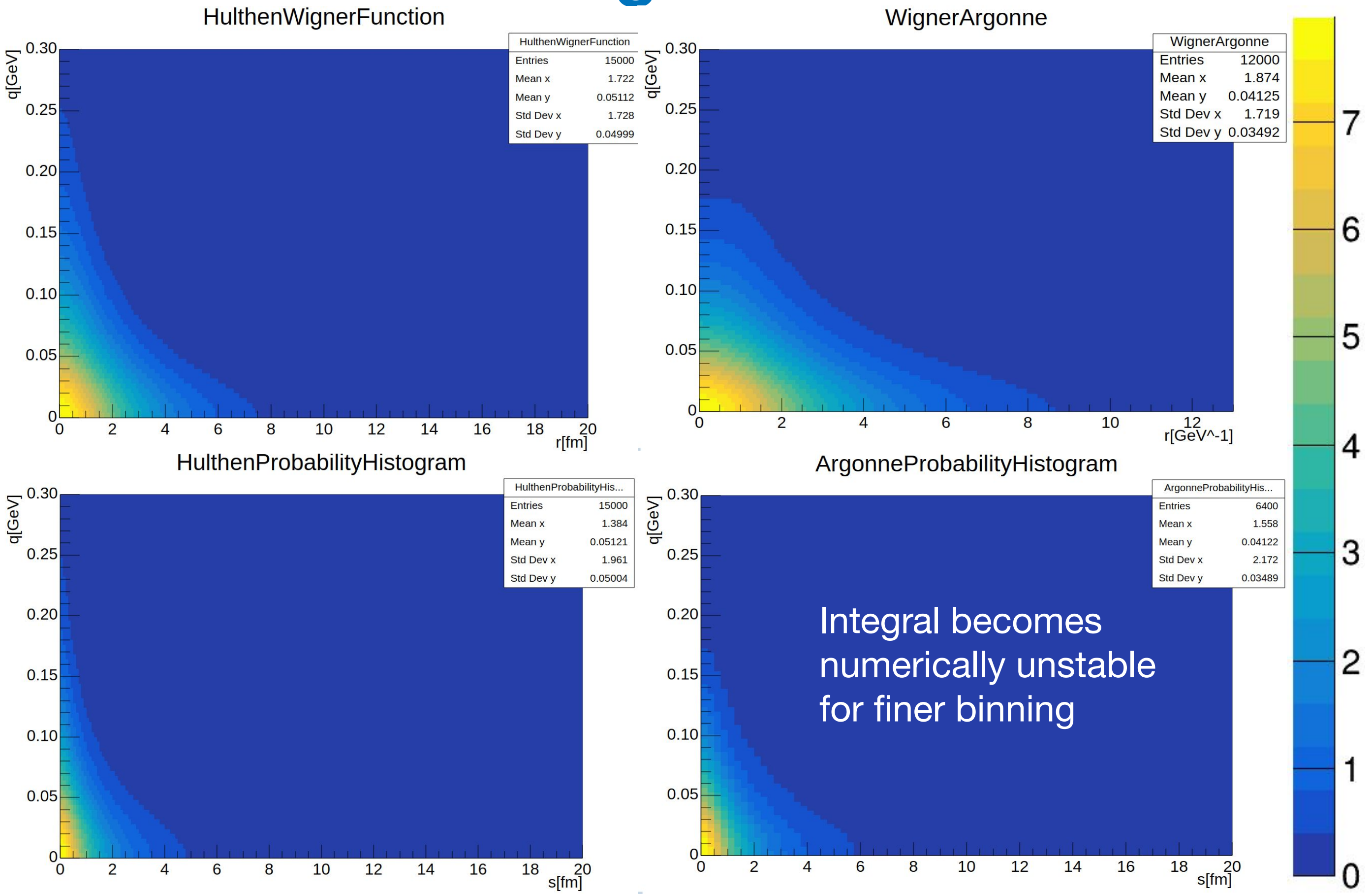


$$\frac{d^2N}{dydp_T} = \frac{dN}{dy}\,\frac{p_T(n-1)(n-2)}{nC[nC+m_p(n-2)]}\left(1+\frac{m_T-m_p}{nC}\right)^{-n}$$



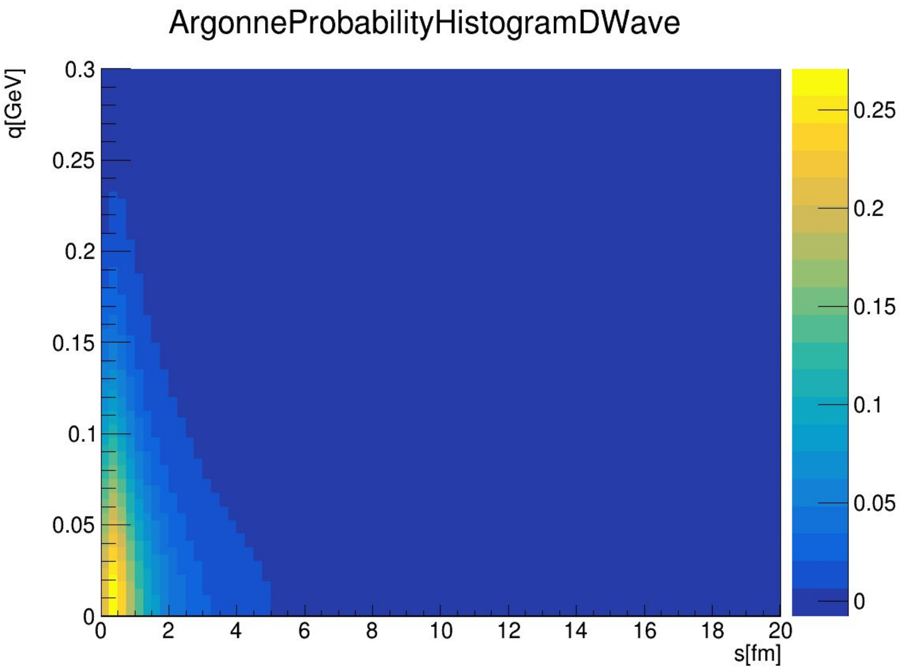


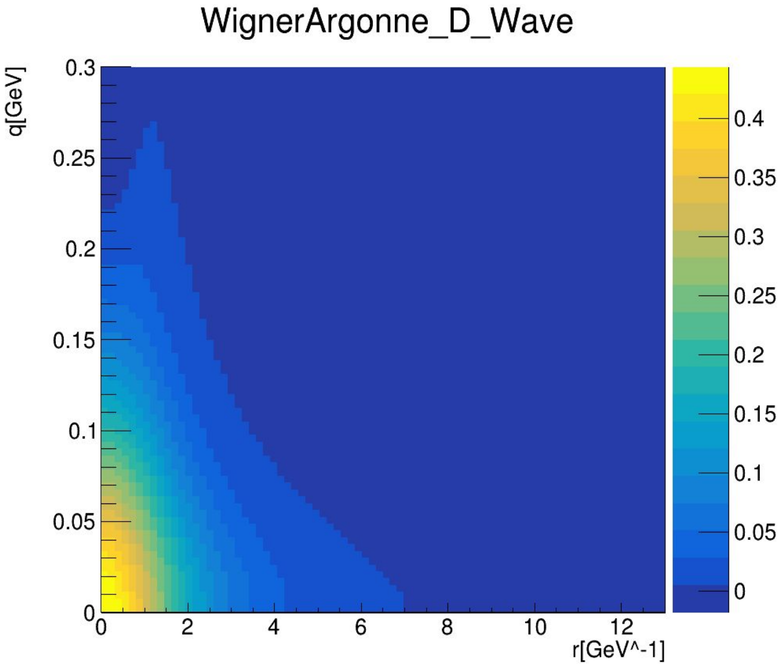
New Wiger functions/Probabilities



Integral becomes numerically unstable for finer binning

Argonne D-State probability





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