Coalescence studies for light nuclei

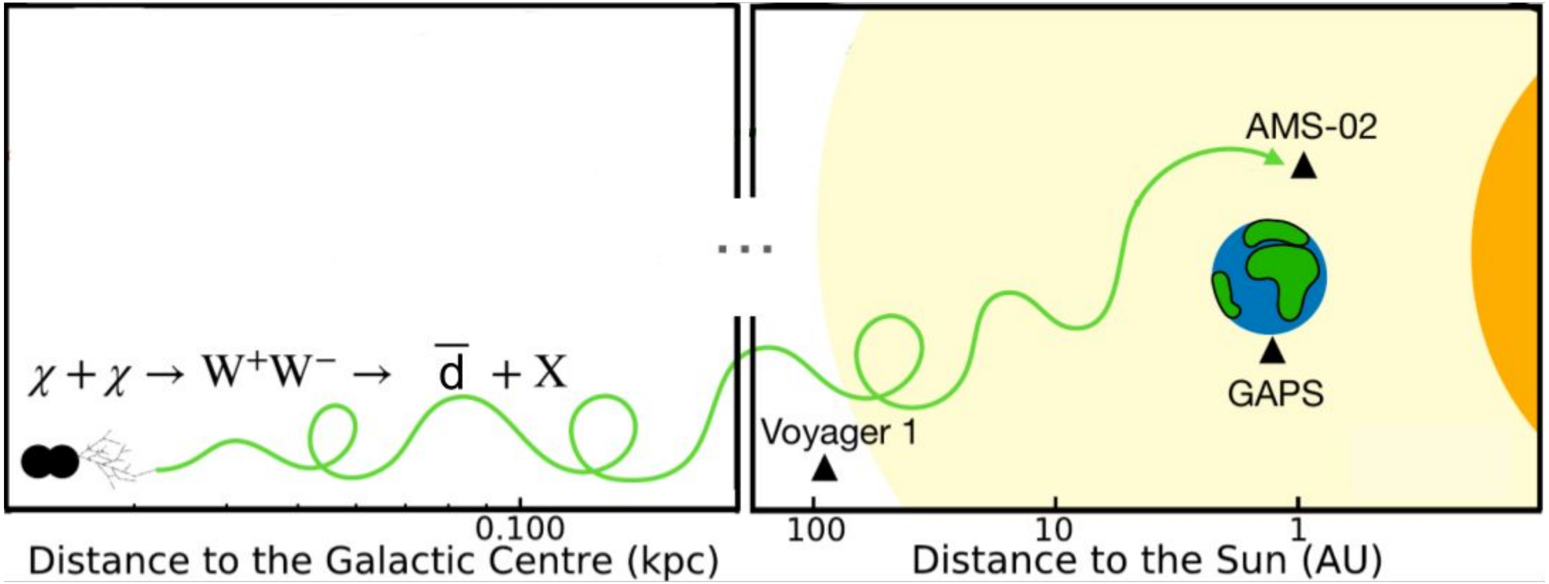
Maximilian Mahlein, Laura Fabbietti, Bhawani Singh, Chiara Pinto, Michele Viviani

Based on: arXiv:2404.03352

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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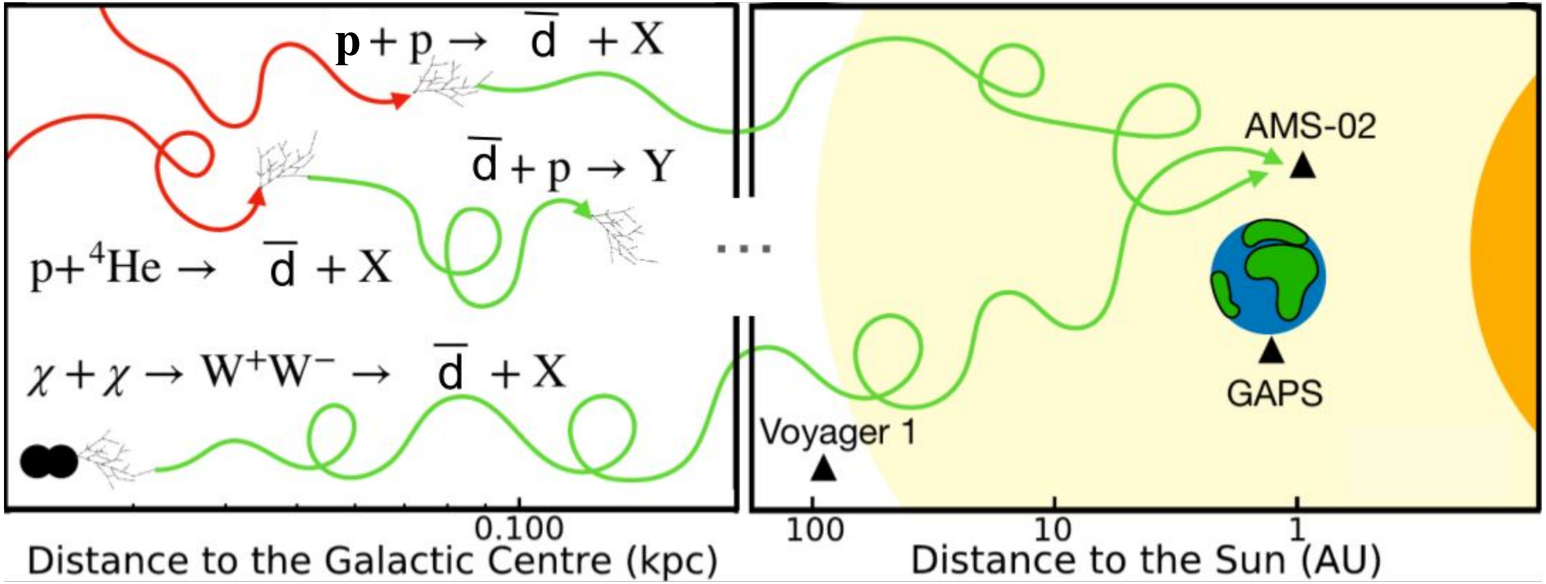

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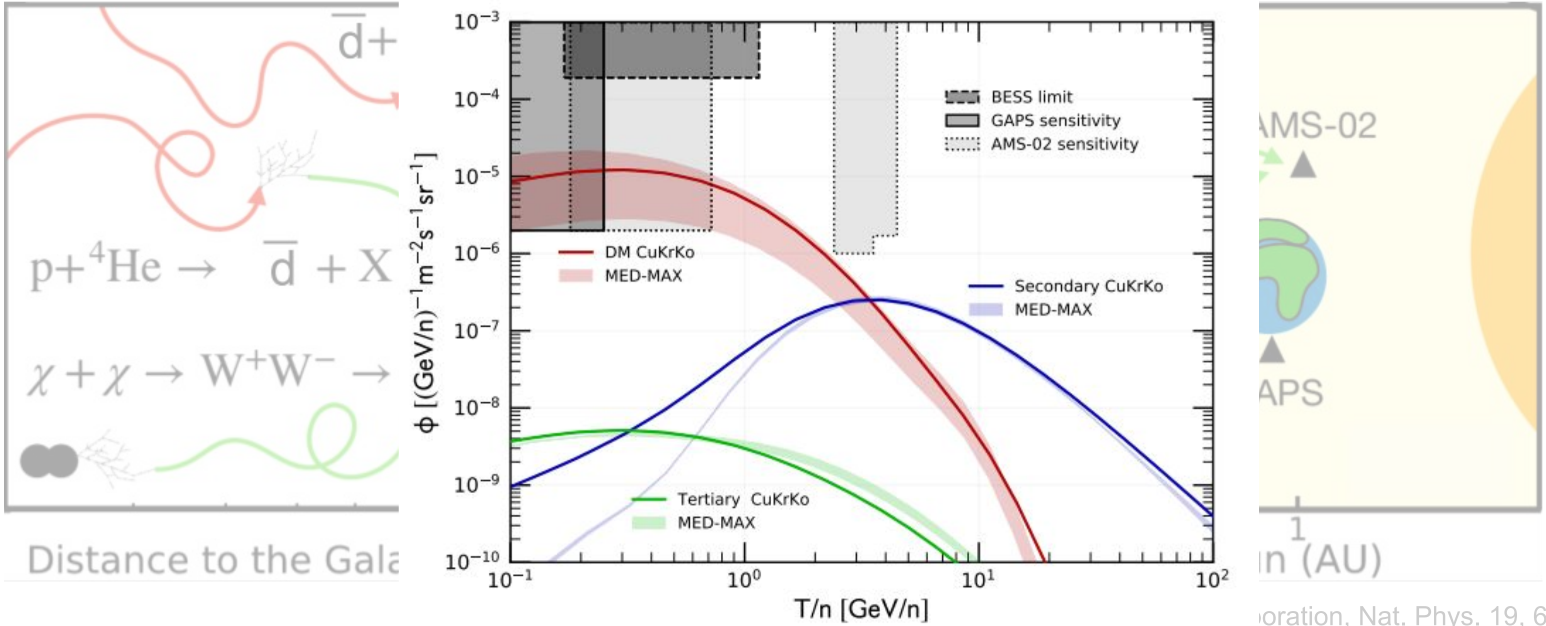

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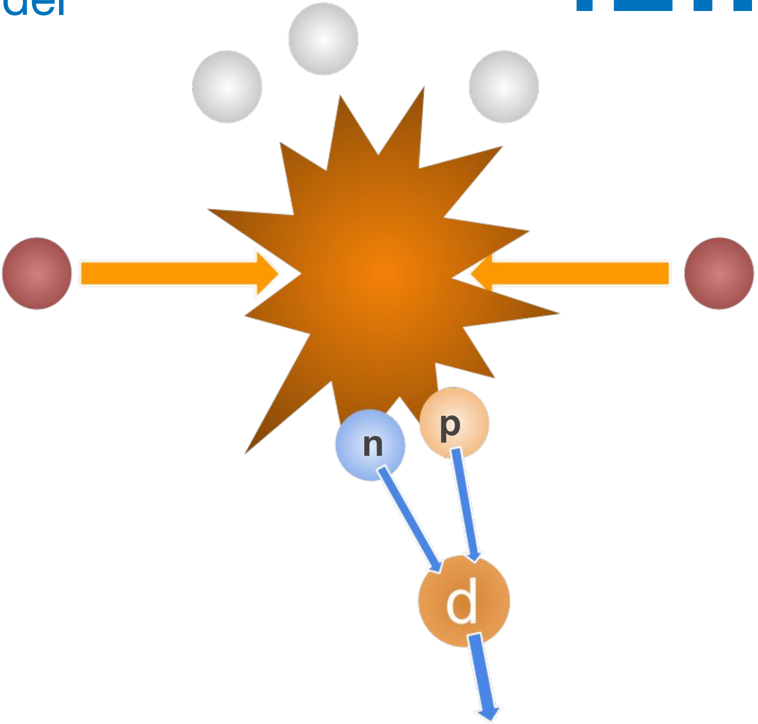
- Antinuclei could be a probe for indirect Dark Matter searches
- However: Astrophysical background from cosmic rays expected
- High Signal/Noise ratio (~10^2-10^4) at low E_{kin} expected by many models!

Modelling (Anti)nuclei Production

The Coalescence Model

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

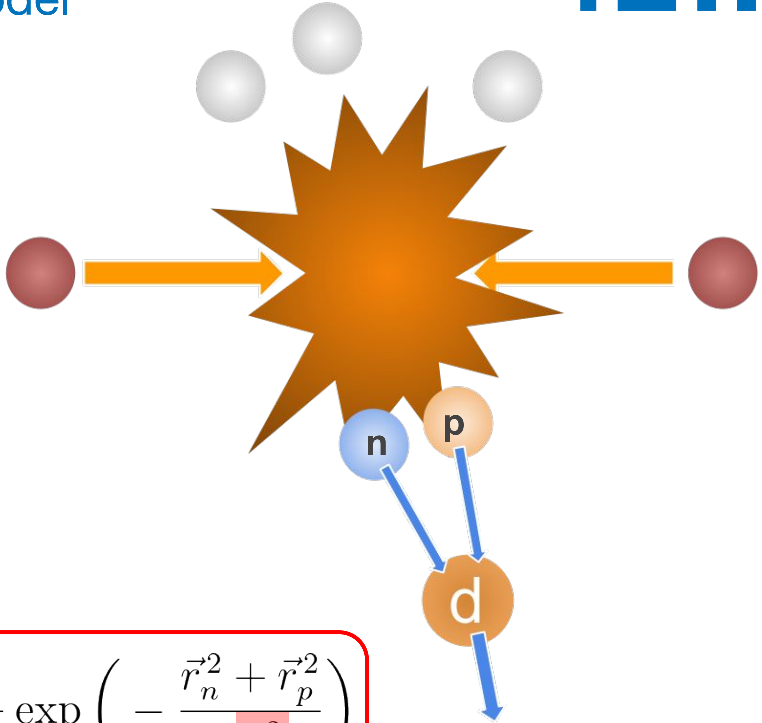


Modelling (Anti)nuclei Production

The Coalescence Model

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

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



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

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

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

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

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$$\times \Psi_d \left(\vec{x}\right.$$

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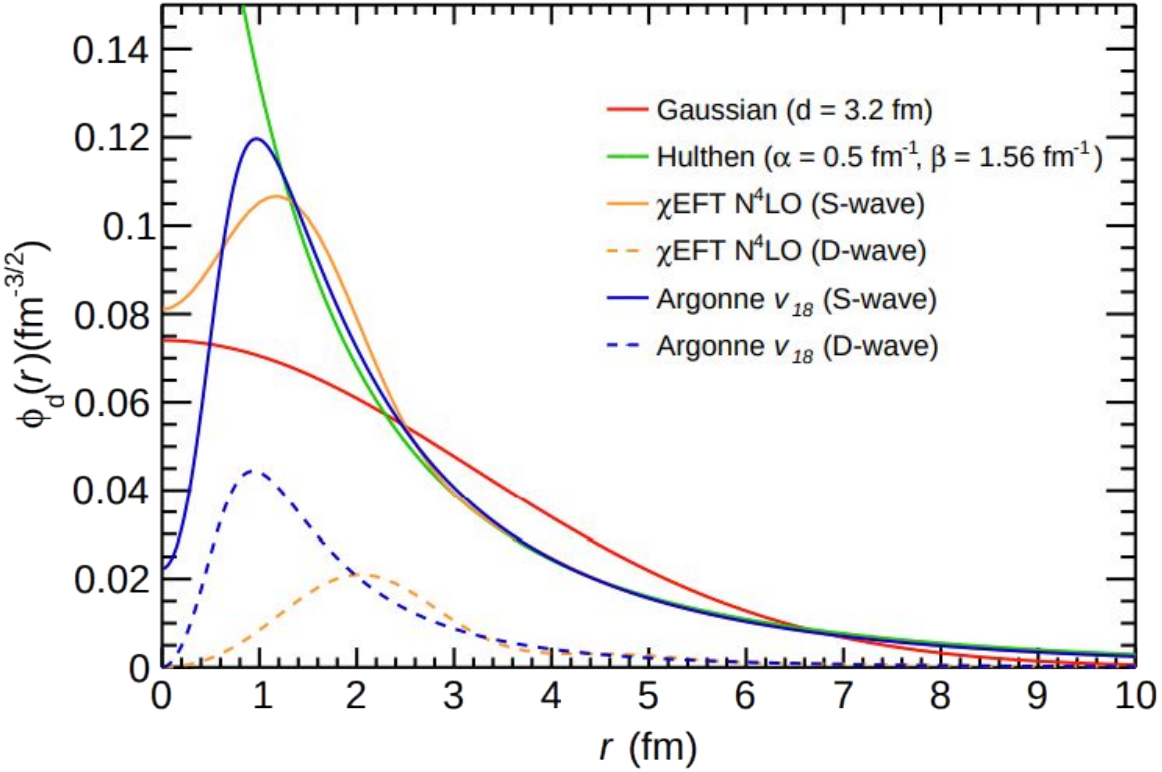

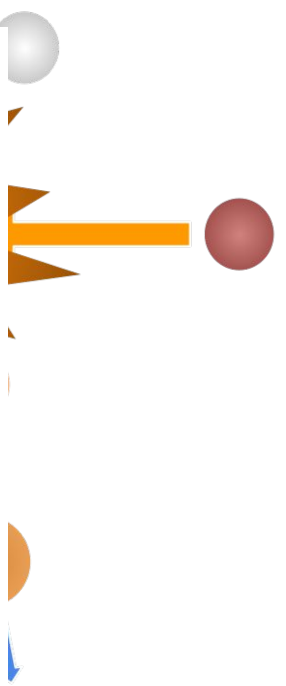

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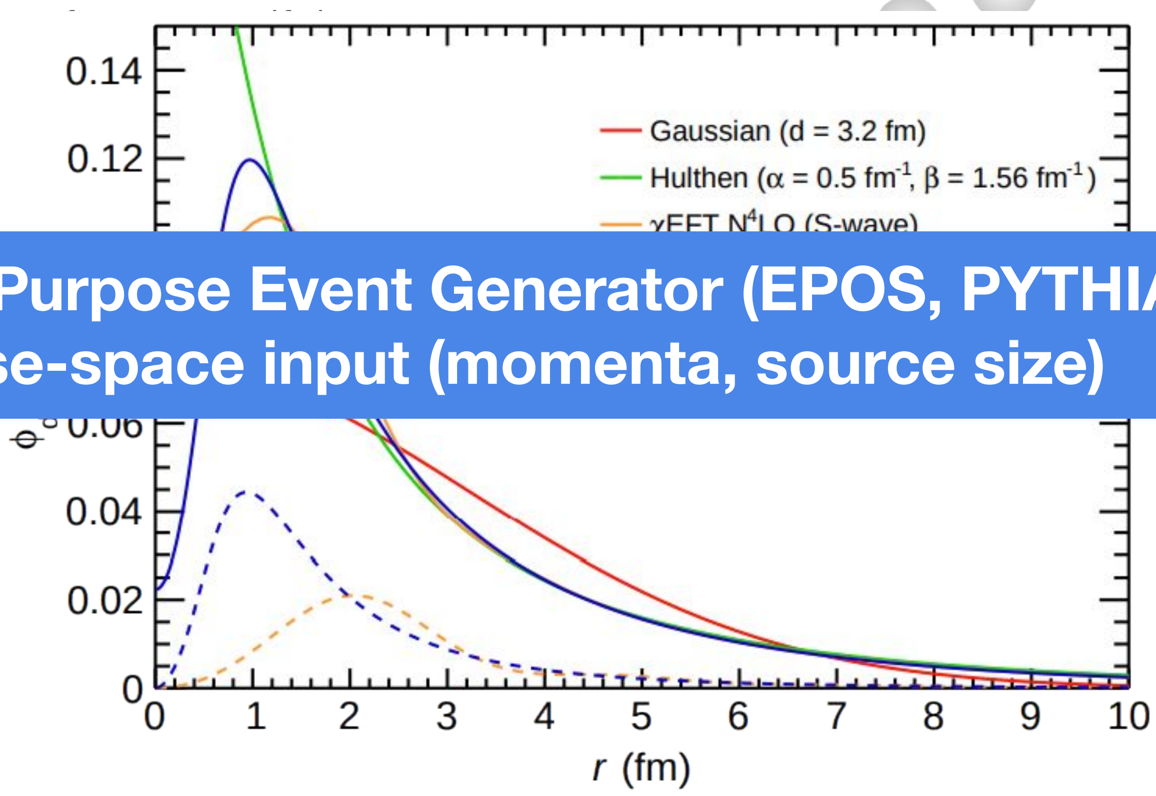

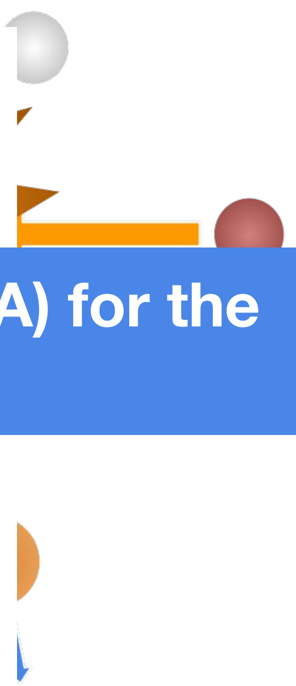

Use a General Purpose Event Generator (EPOS, PYTHIA) for the phase-space input (momenta, source size)

Nucleus wave functi

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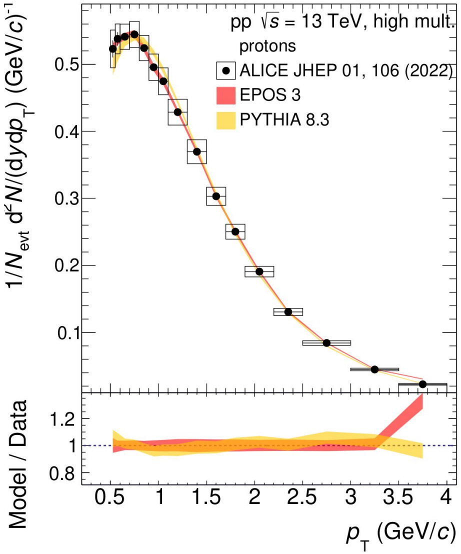
Coalescence Results EPOS & Pythia

Deuteron spectra

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

- Corrections to Protons



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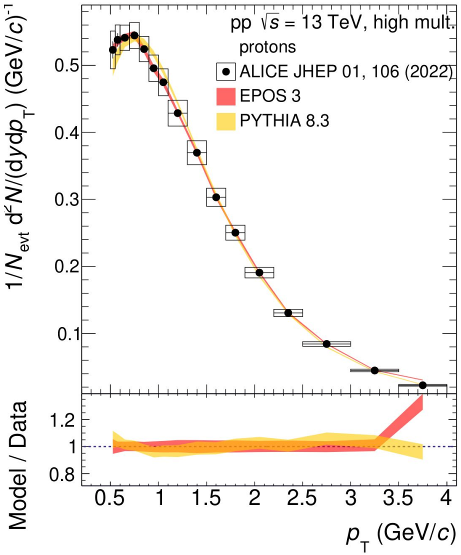

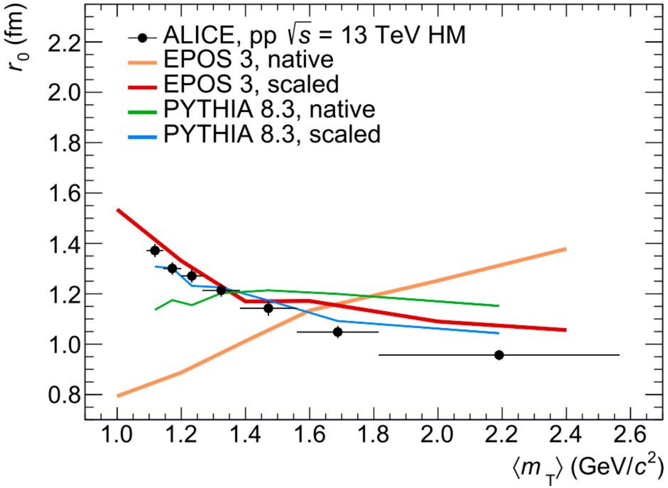

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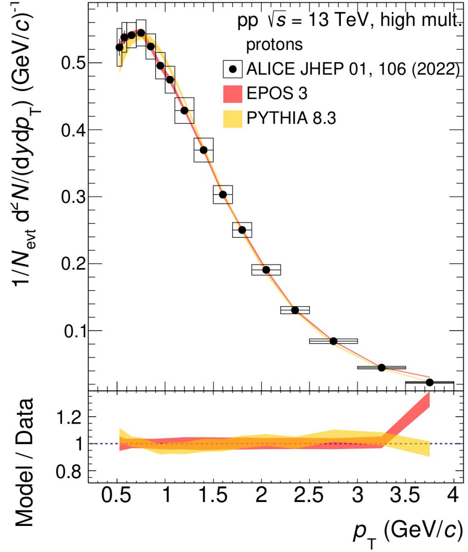
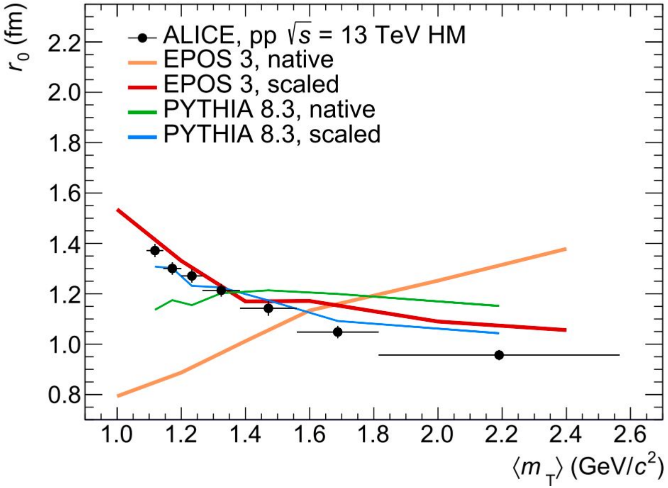
- Wavefunctions: Gaussian,Hulthén and Argonne v_{18}
- AV_{18} reproduces data to ~10%





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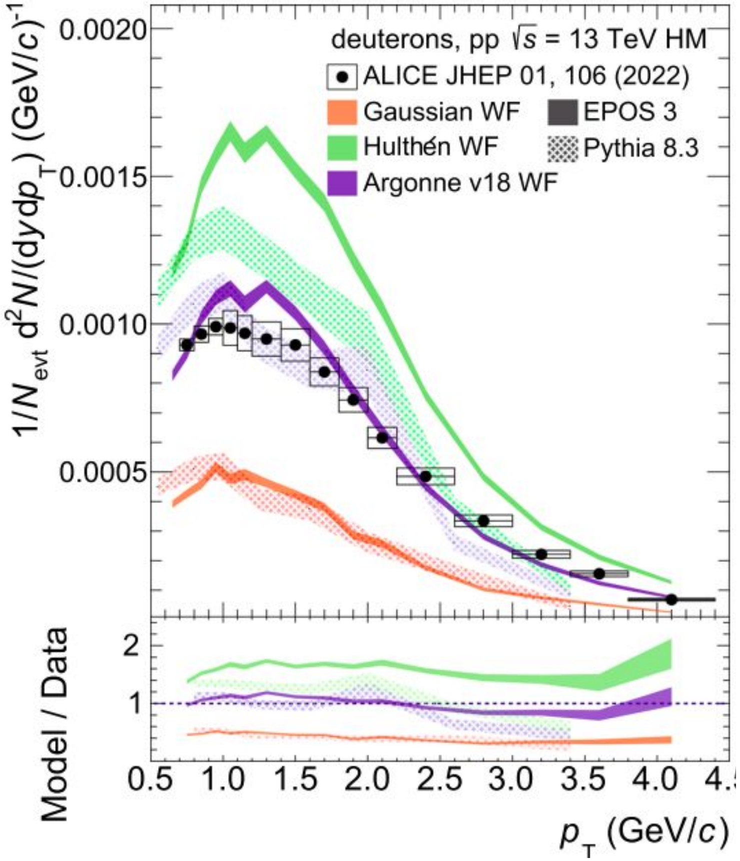

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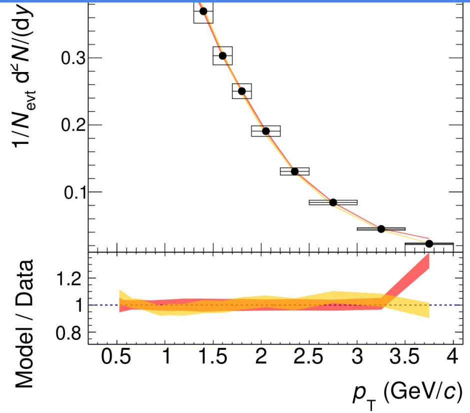
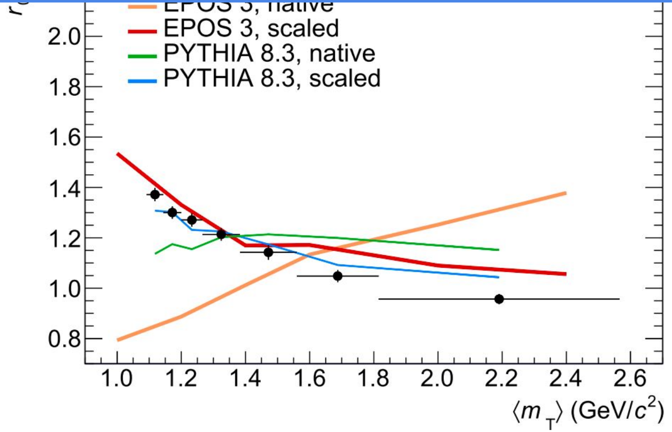
First event-by-event coalescence model with realistic wave function!





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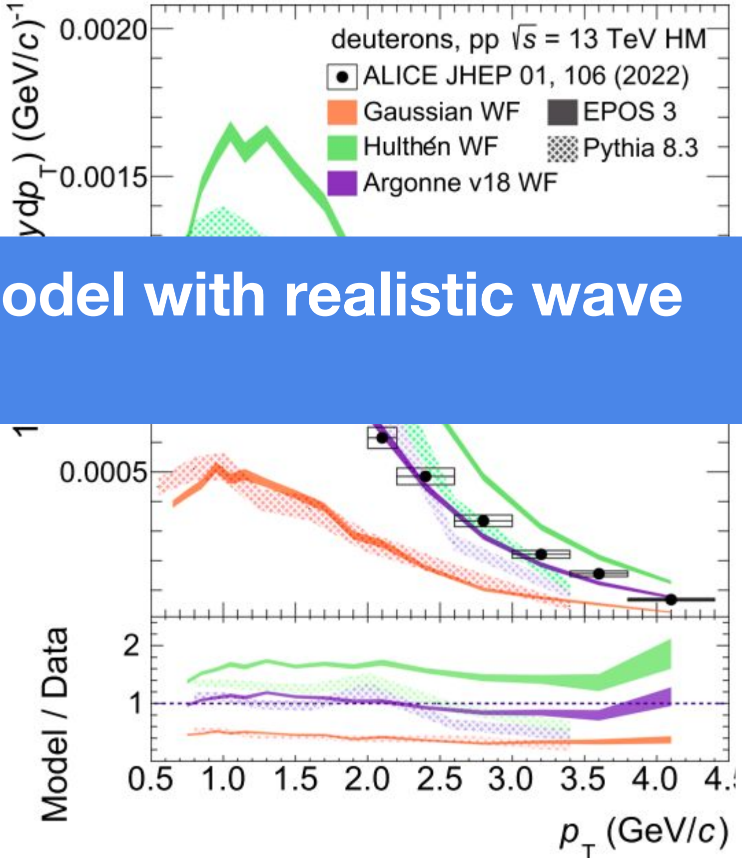

Comment on Event Generators

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

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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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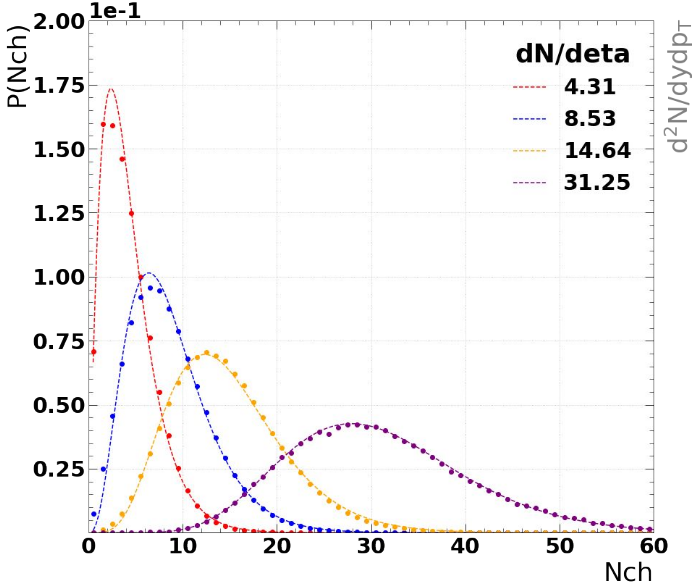
The ToMCCA Model

A Toy Monte Carlo Coalescence Afterburner

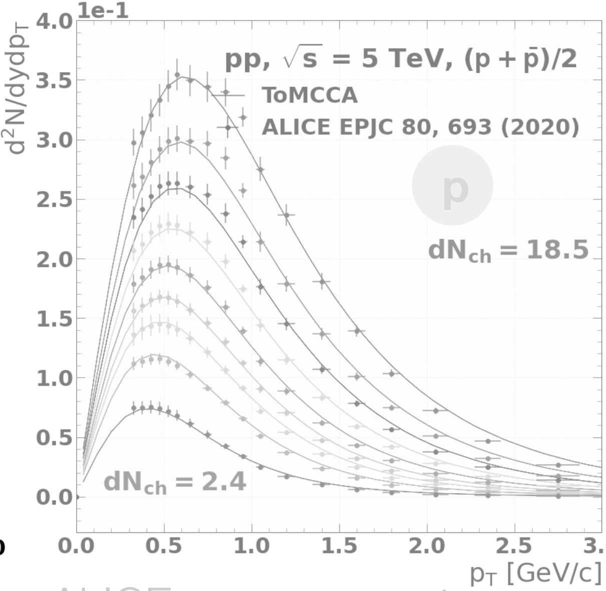
Main Inputs: **Multiplicity, momentum distributions, source size**

Multiplicity



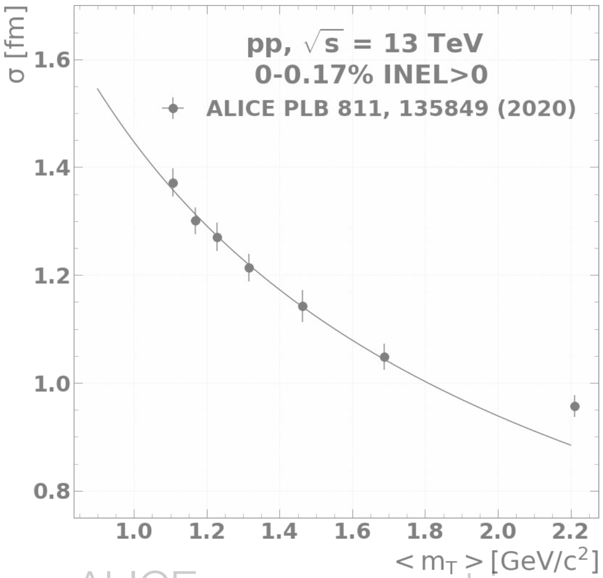
Erlang distribution fitted to EPOS3 simulations

Momentum distribution



ALICE measurements over a large multiplicity range

Source size



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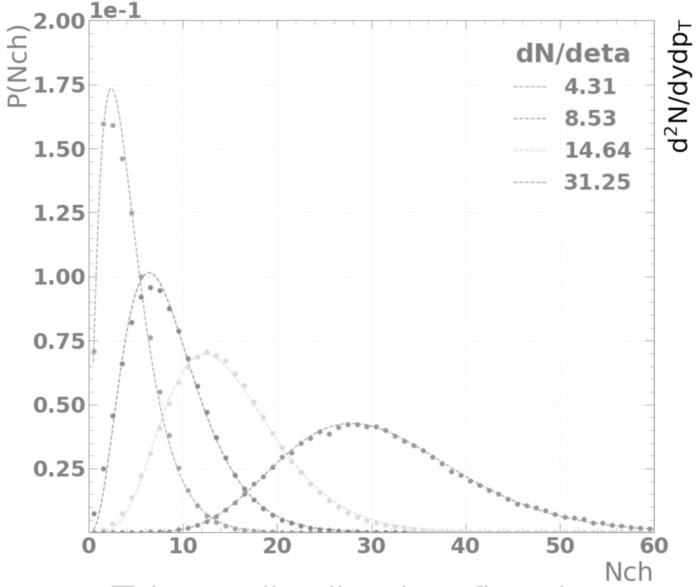

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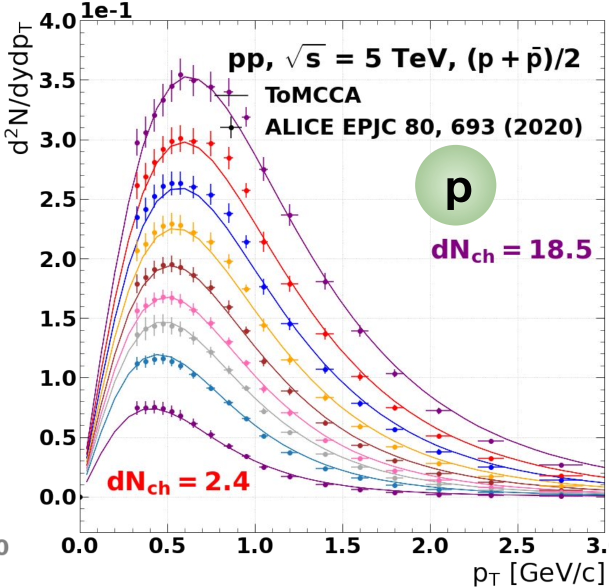

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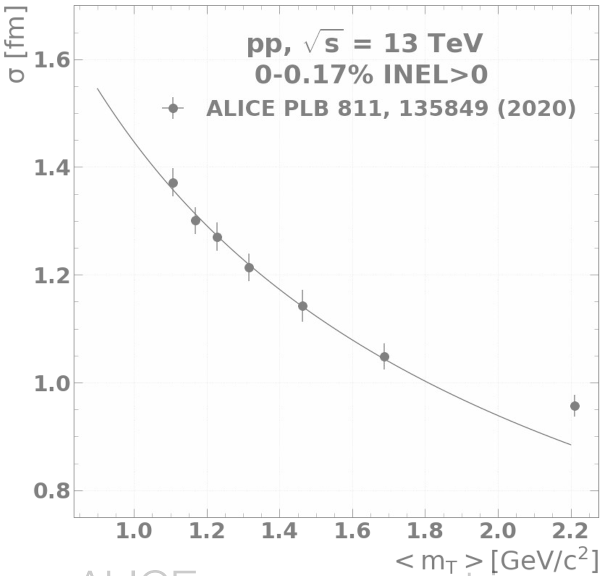

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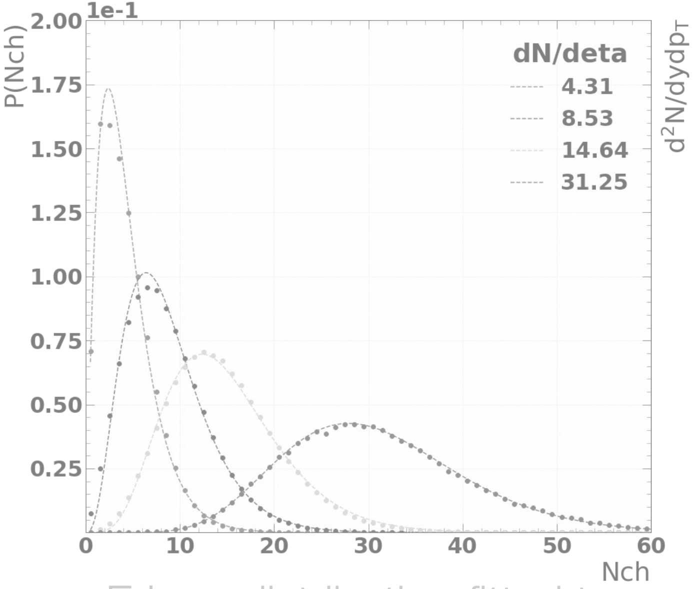

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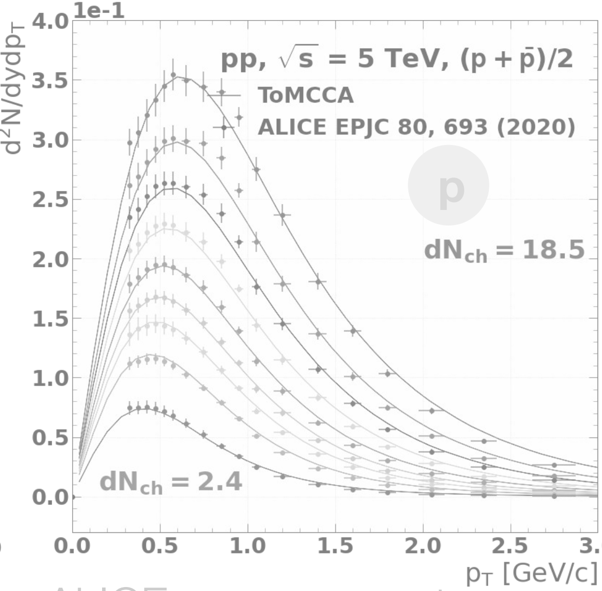

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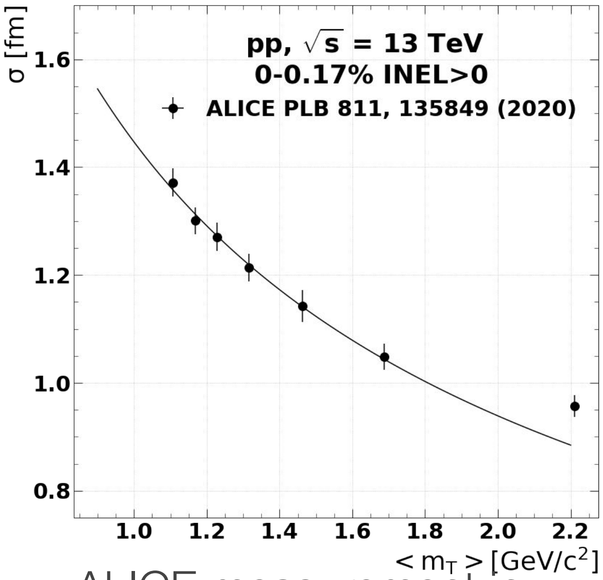

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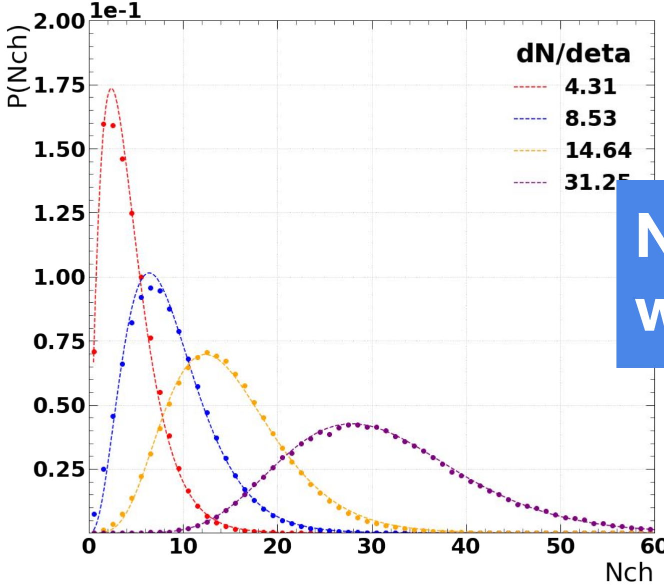

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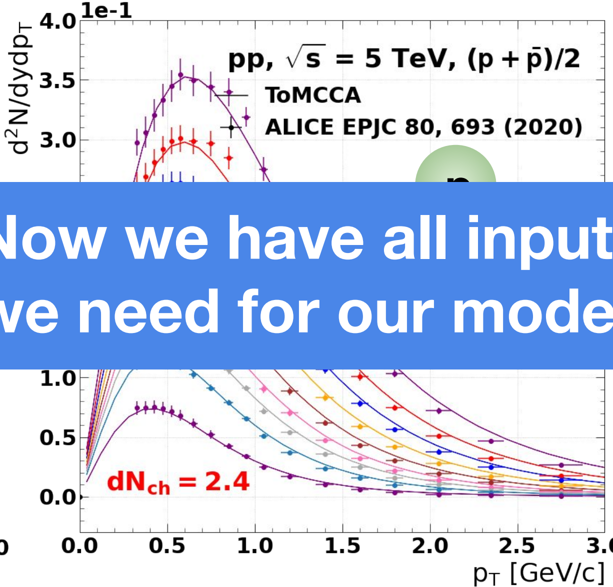

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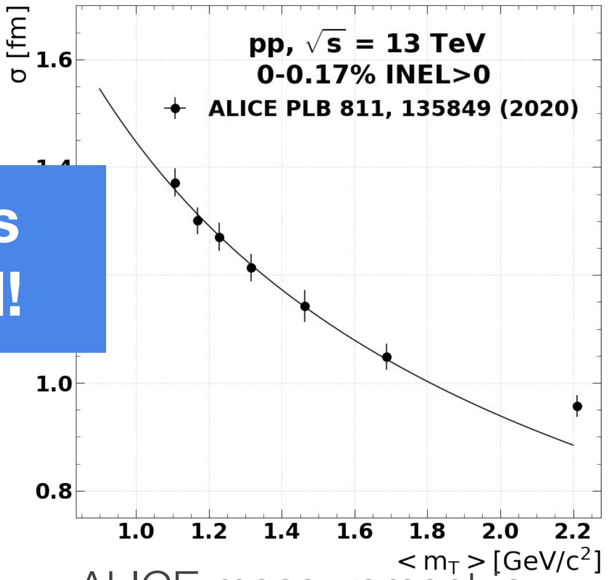


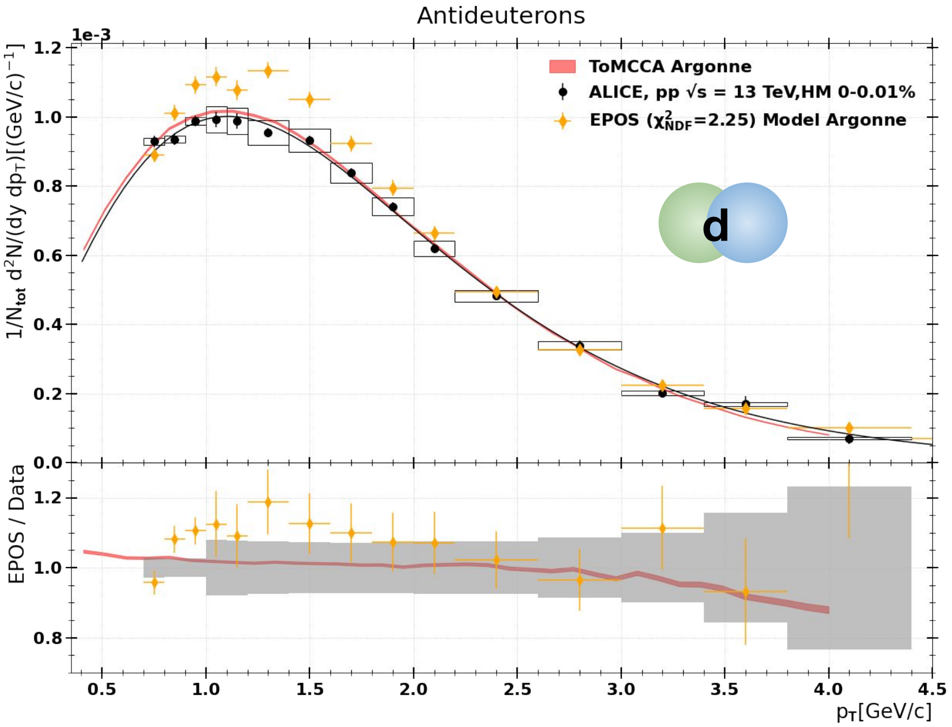
ALICE measurement in high-multiplicity collisions

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!



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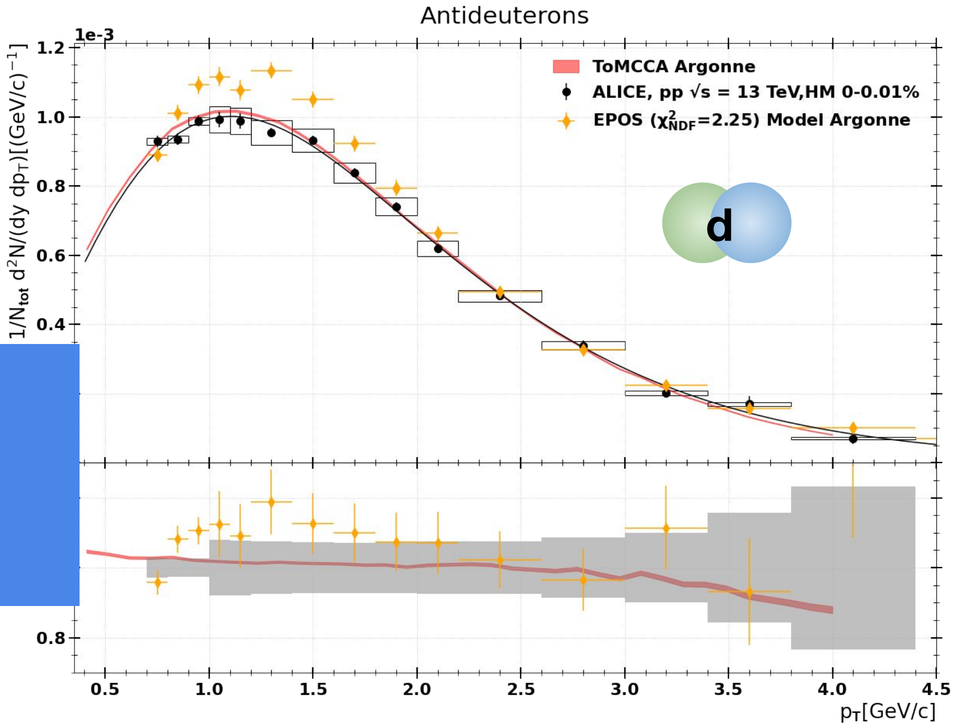
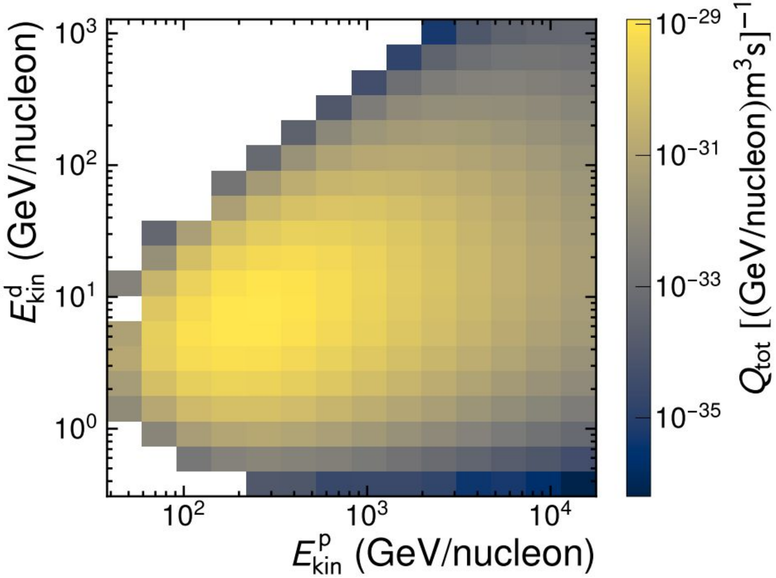


Does this help us in predicting Cosmic Ray fluxes?

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)

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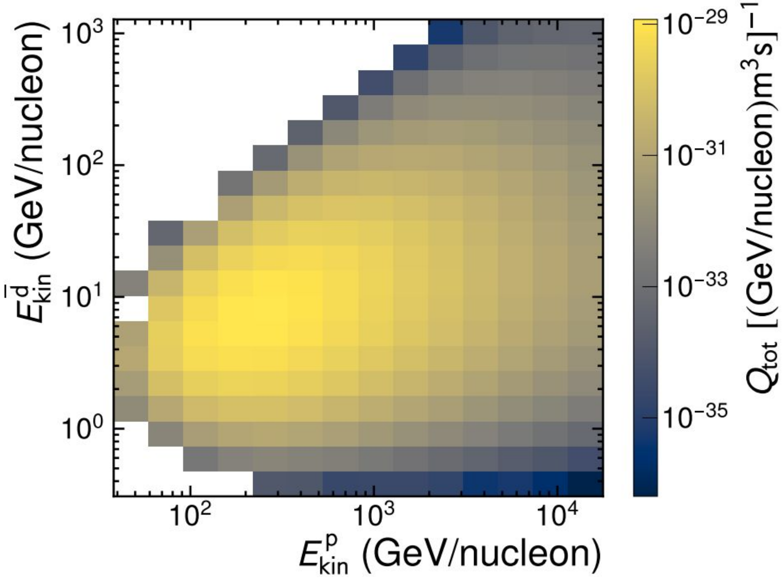

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- Extrapolation to lower energies via event multiplicity

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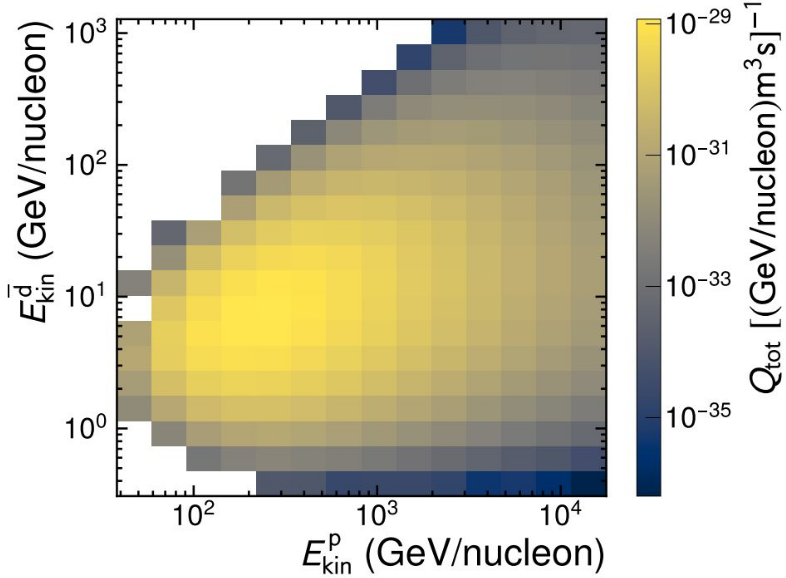

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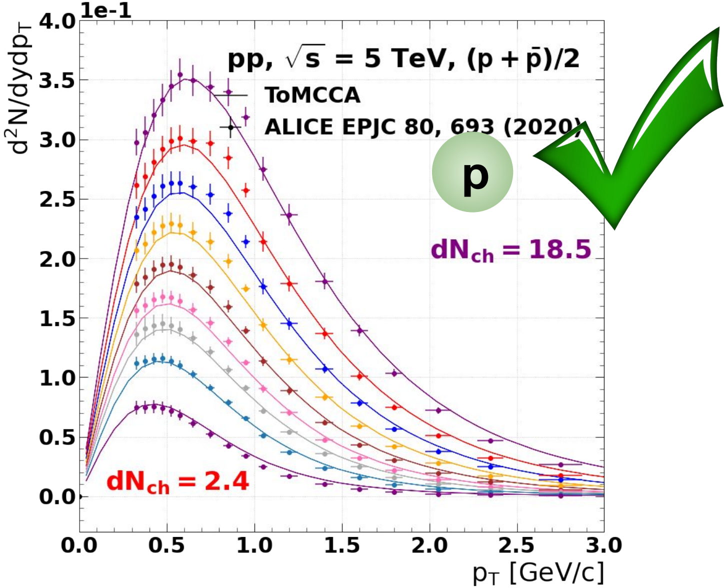

ALICE measurements over a large range in multiplicity

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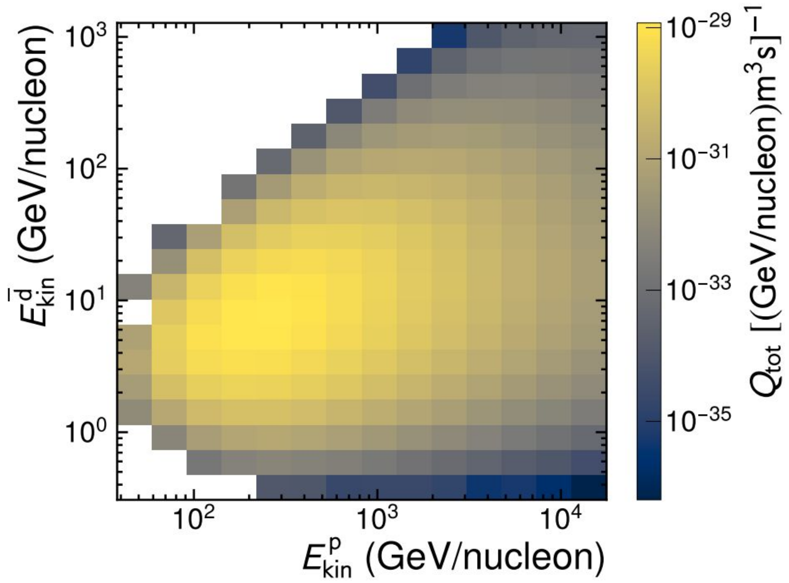

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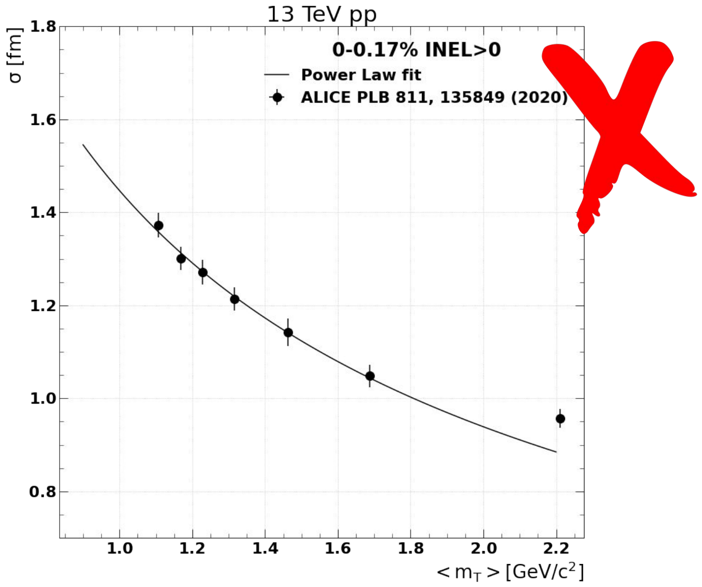
Source size



ALICE measurement in <u>high-multiplicity</u> collisions

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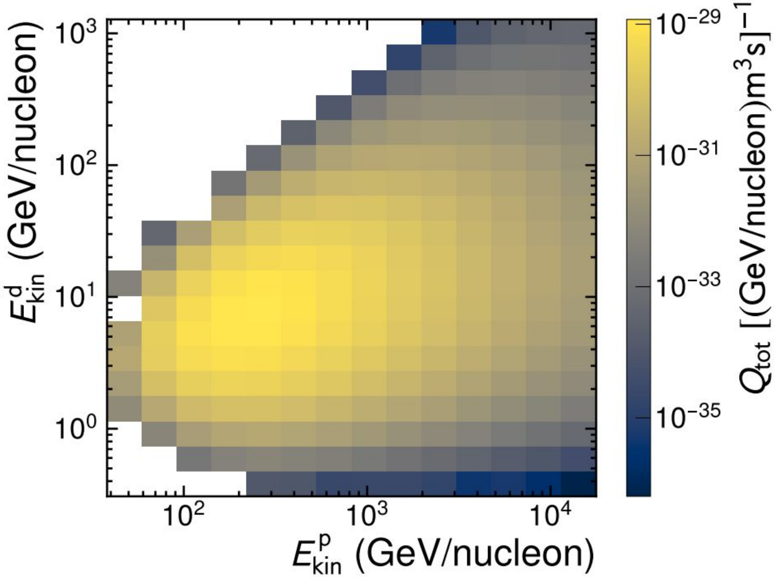

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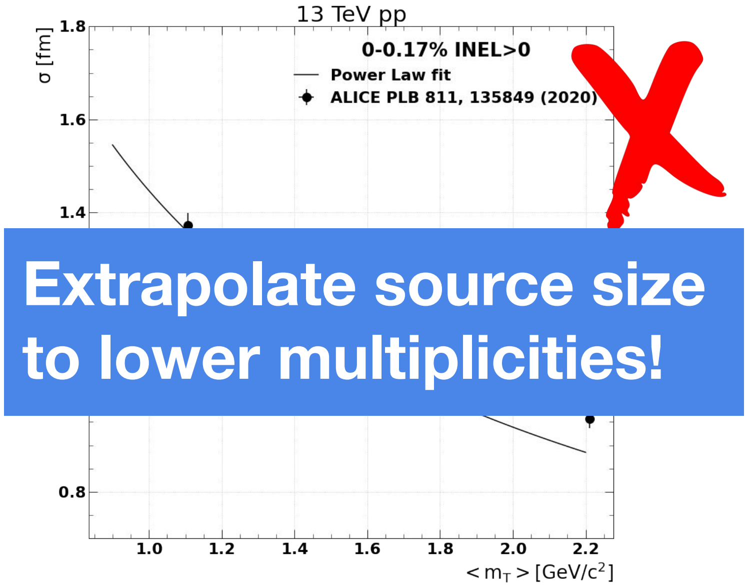


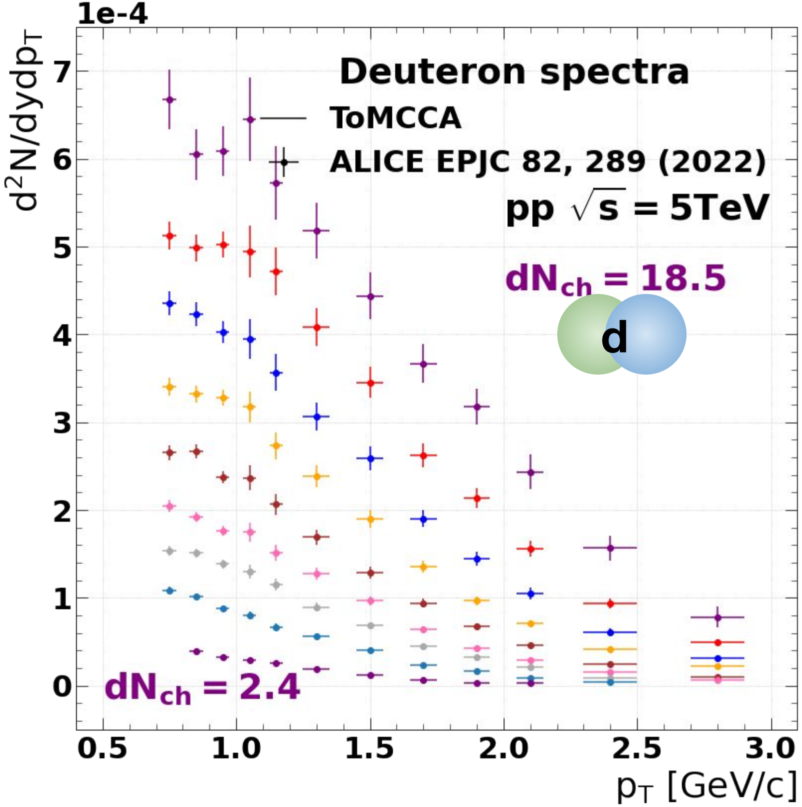
Extrapolate source size to lower multiplicities!

ALICE measurement in <u>high-multiplicity</u> 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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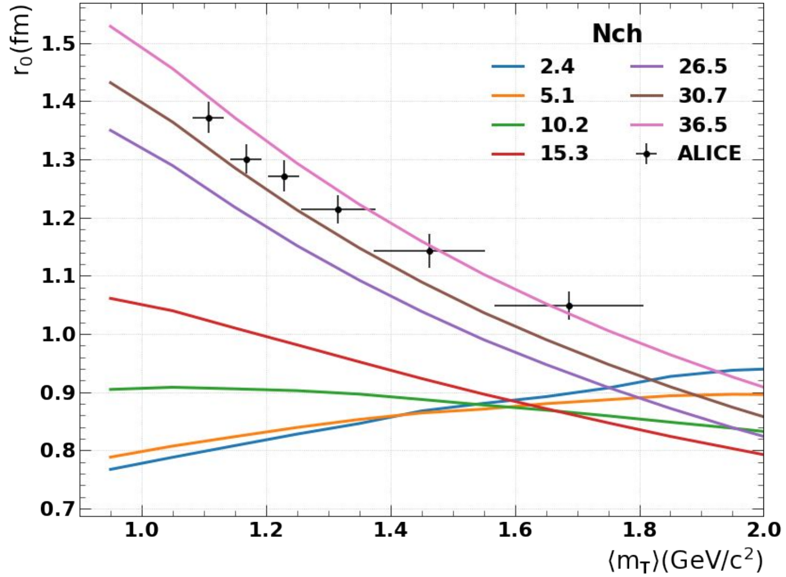

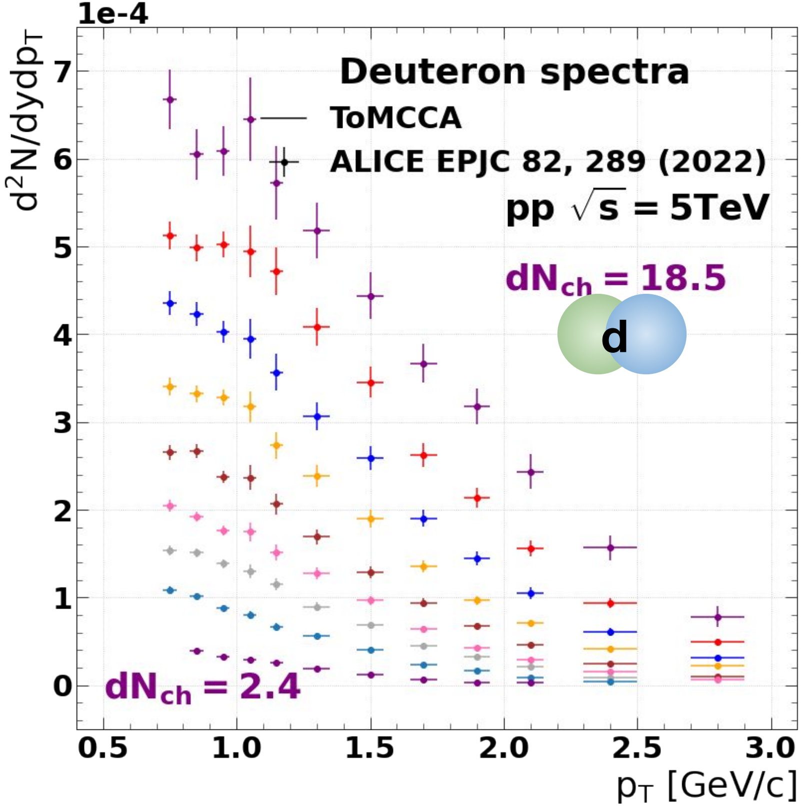

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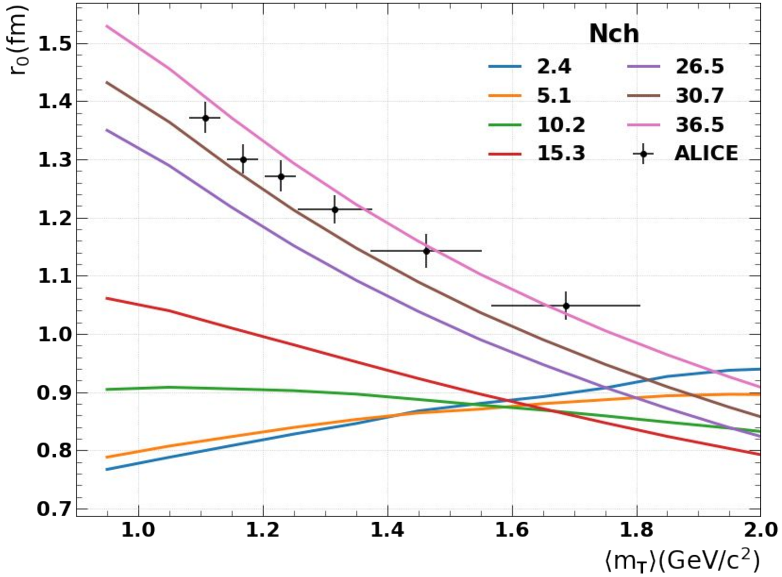

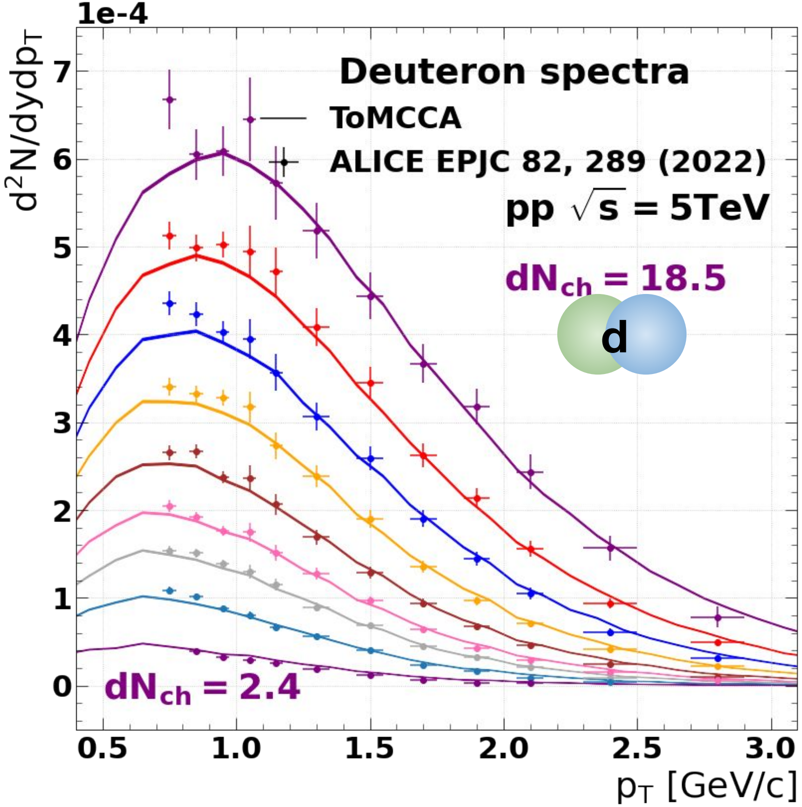

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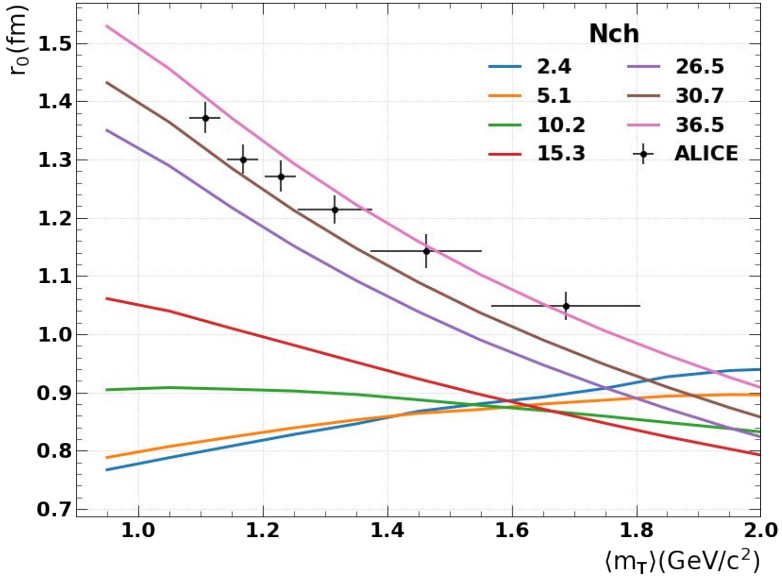
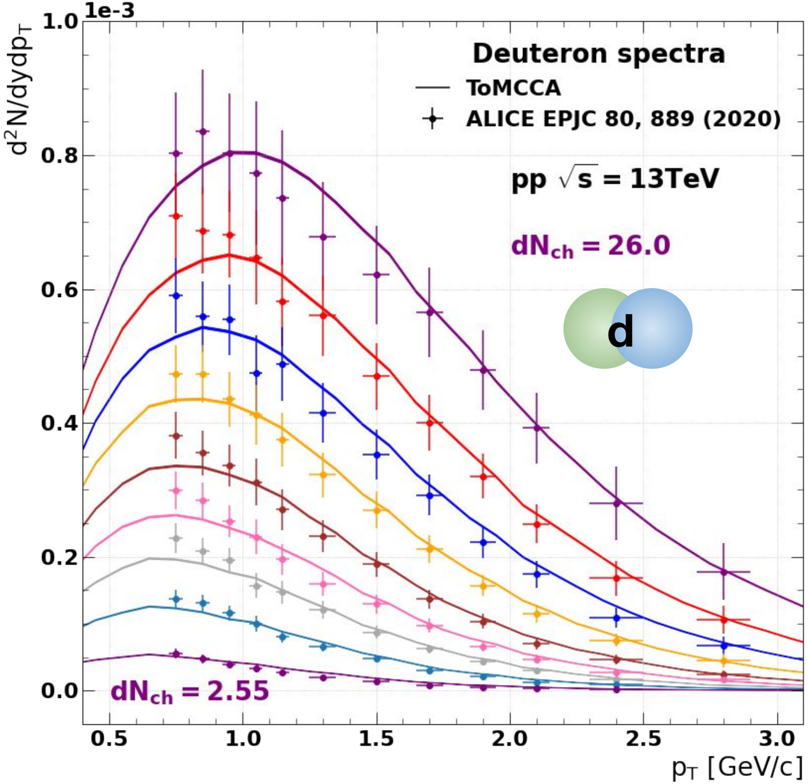
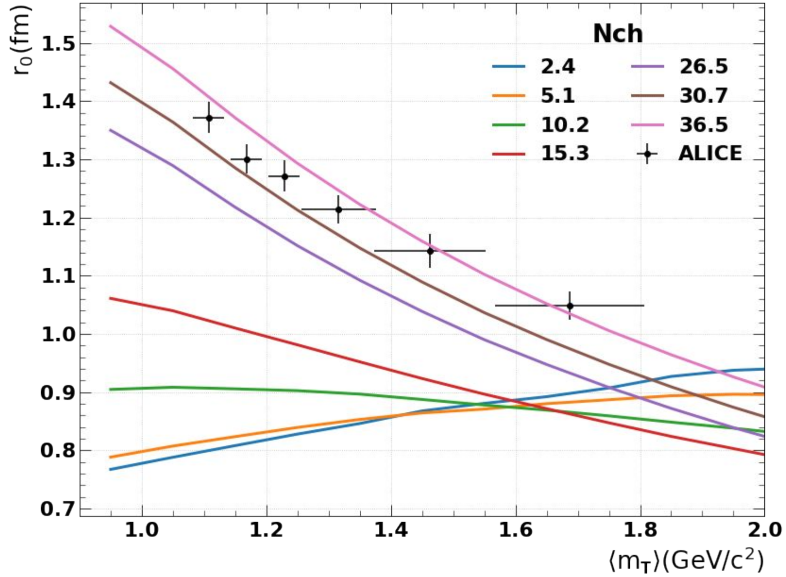


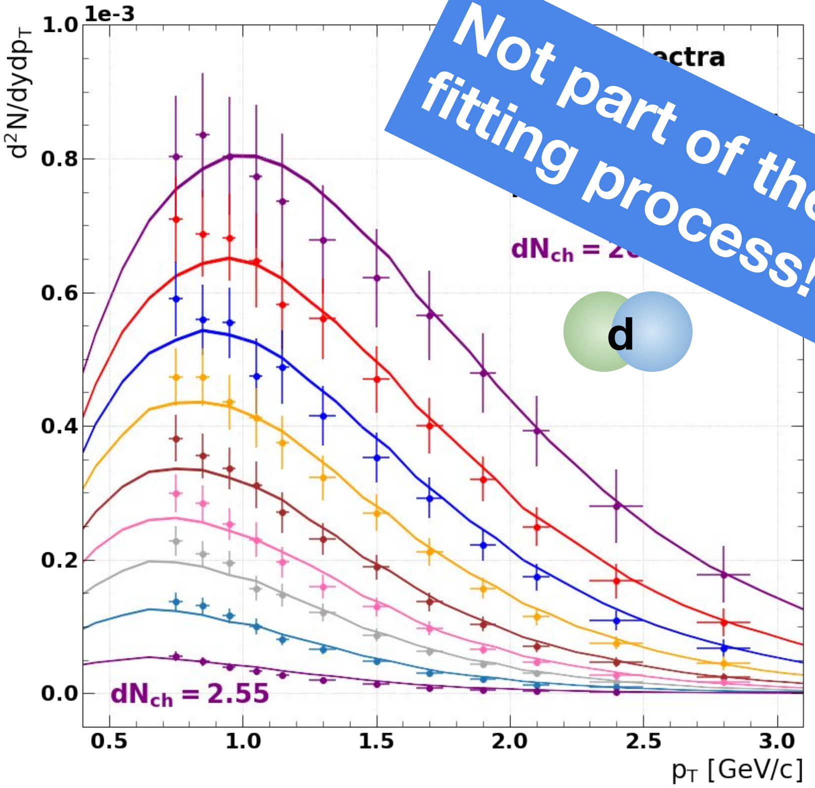


Extrapolating the Source

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



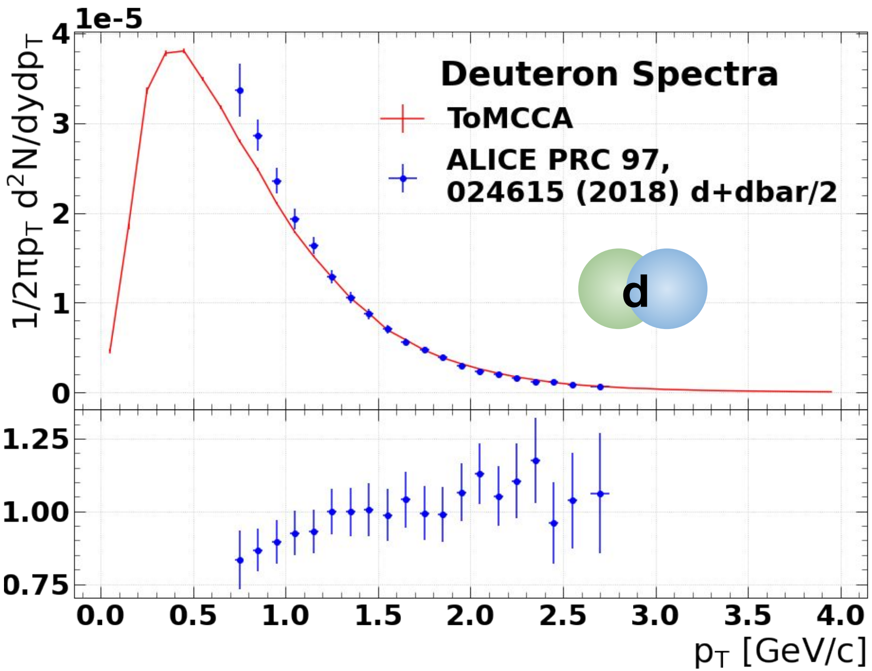


Not part of the fitting process!

Deuteron results

Minimum bias 7 TeV

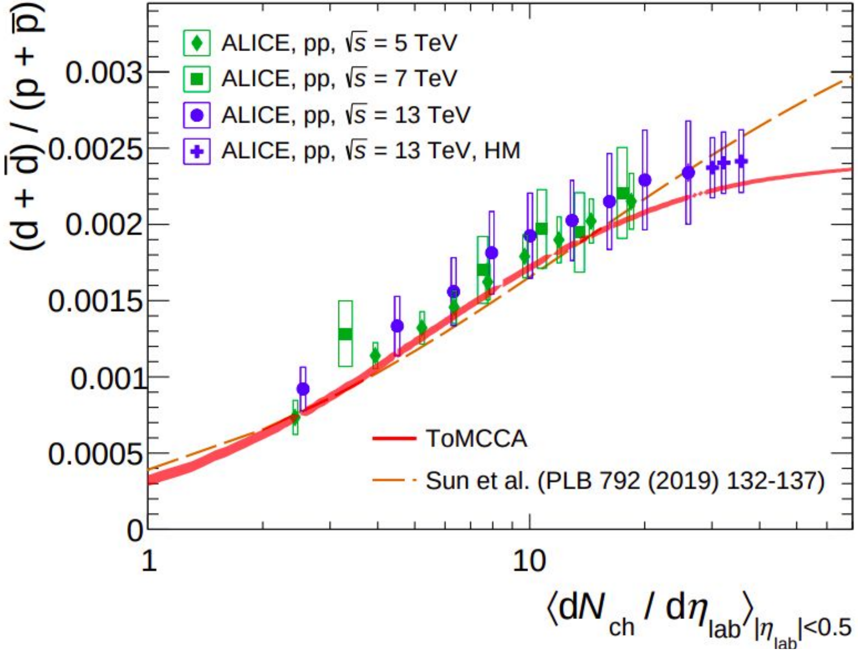
- Deuterons were also measured by ALICE Collab. for different multiplicities
- Fit source size and scaling with m_T to measured data
- Cross check at different energies
- Minimum Bias works well



Deuteron results

d/p ratio

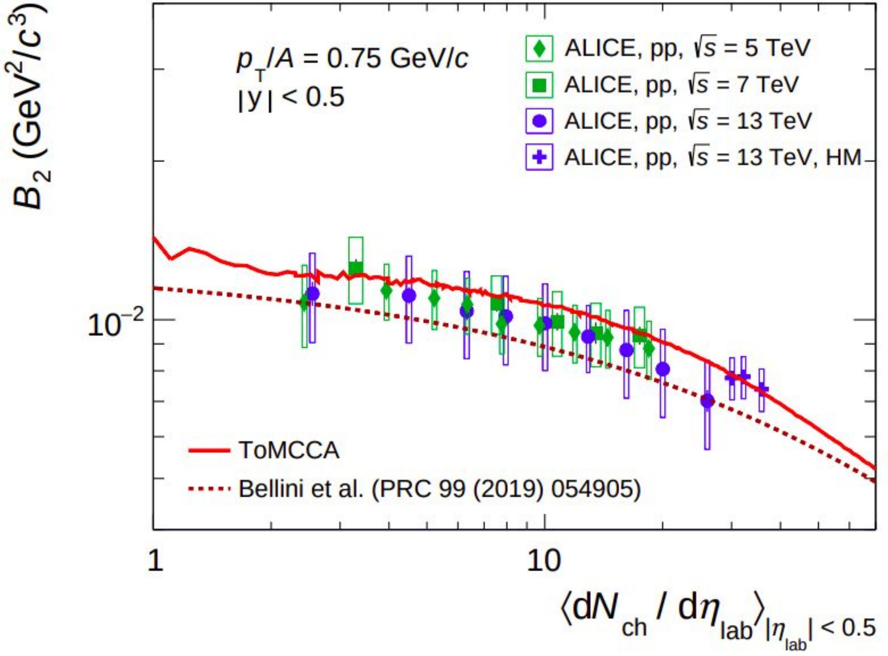
- Deuterons were also measured by ALICE Collab. for different multiplicities
- Fit source size and scaling with m_T to measured data
- Cross check at different energies
- Minimum Bias works well
- d/p ratio reproduces data well, tension to previous predictions at high multiplicity



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

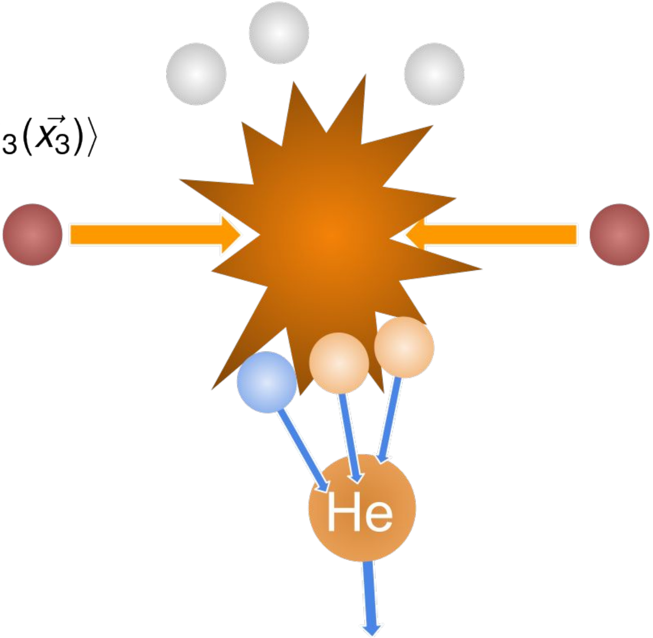
Add 3rd particle to basic formalism

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

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

Similarly the probability can be expressed as

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

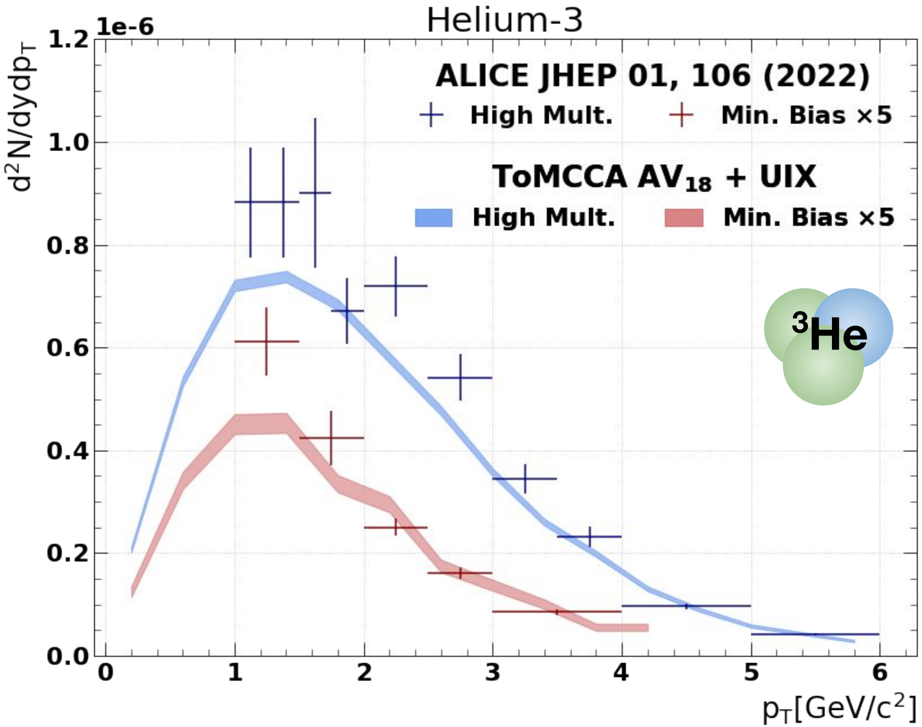


Extension to A=3

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



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[1] Provided by Michele Viviani, INFN Pisa

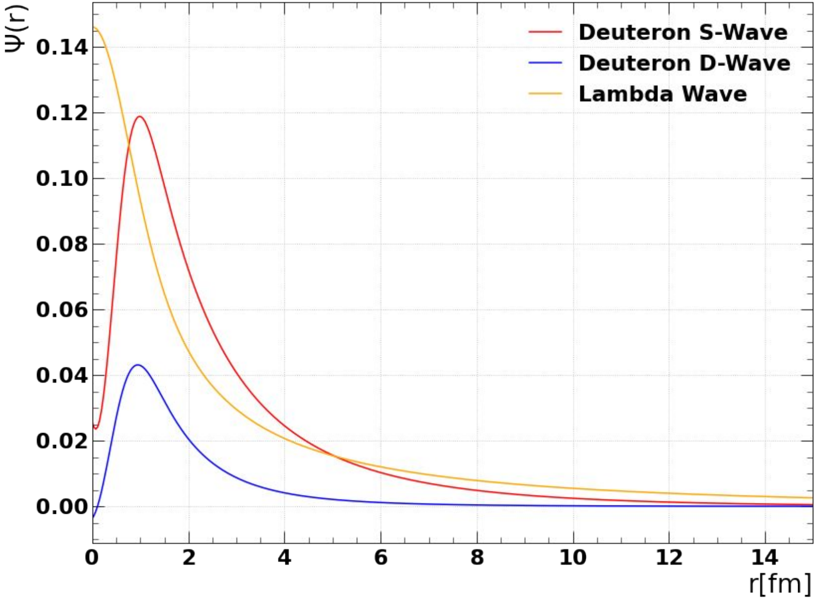
Extension to A=3

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

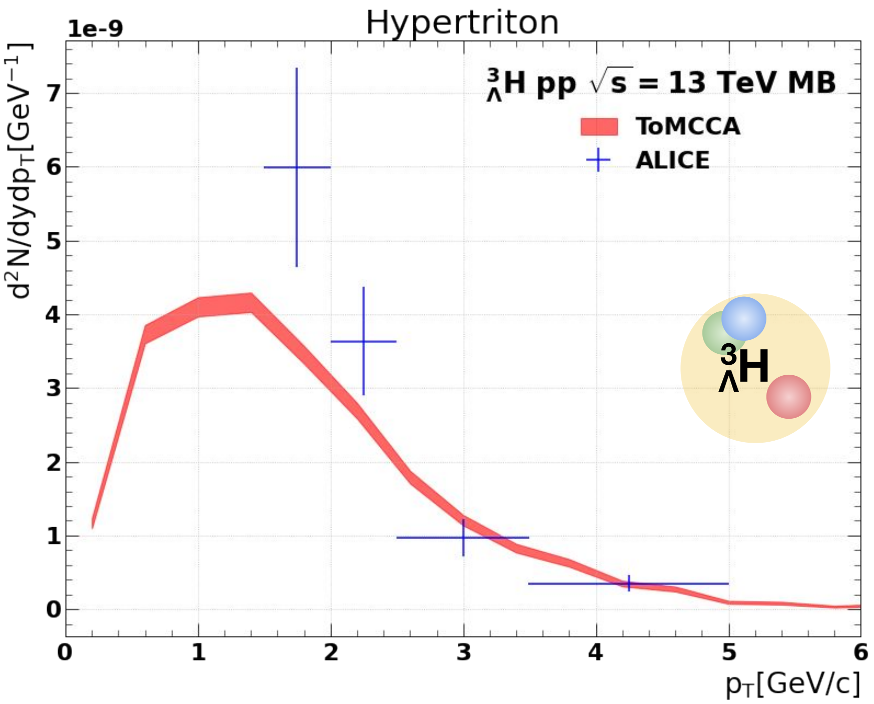
📚[2] F. Bellini et al.: Phys.Rev.C 103, 1 (2021)

📚[3] F. Hildenbrand and H.-W. Hammer: Phys. Rev. C 100, 034002

Extension to A=3

Hypertriton

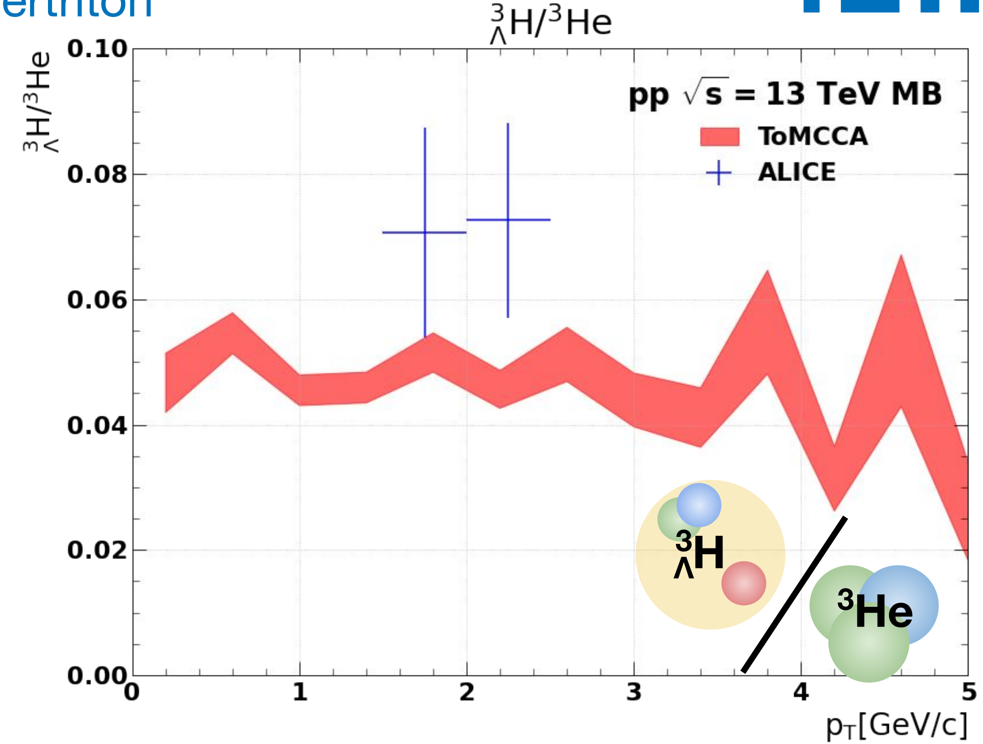
- Latest ALICE measurements of ${}^{3}_{\Lambda}H$ in 13 TeV MB



Extension to A=3

Hypertriton

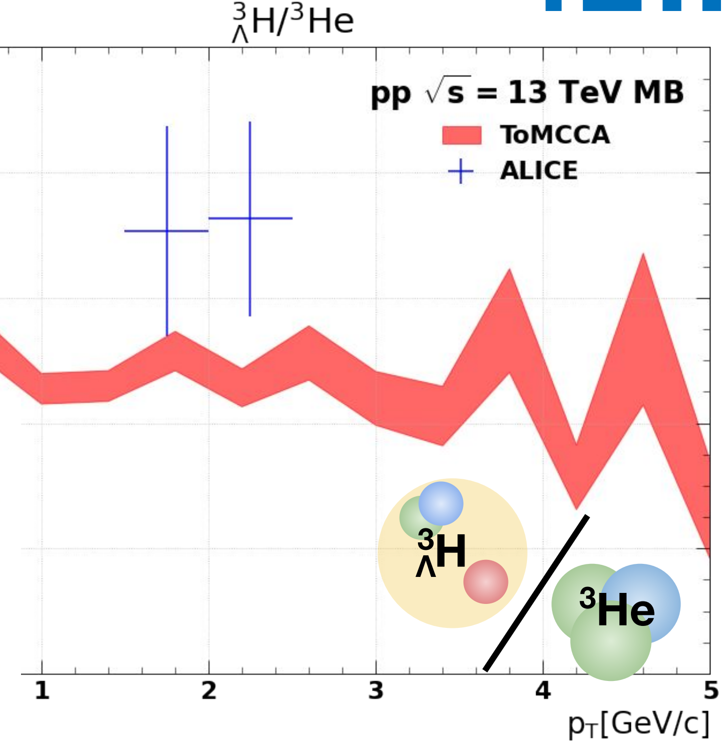
- Latest ALICE measurements of ${}^{3}_{\Lambda}$H in 13 TeV MB
- ${}^{3}_{\Lambda}$H/^{3}He Ratio flat in p_T



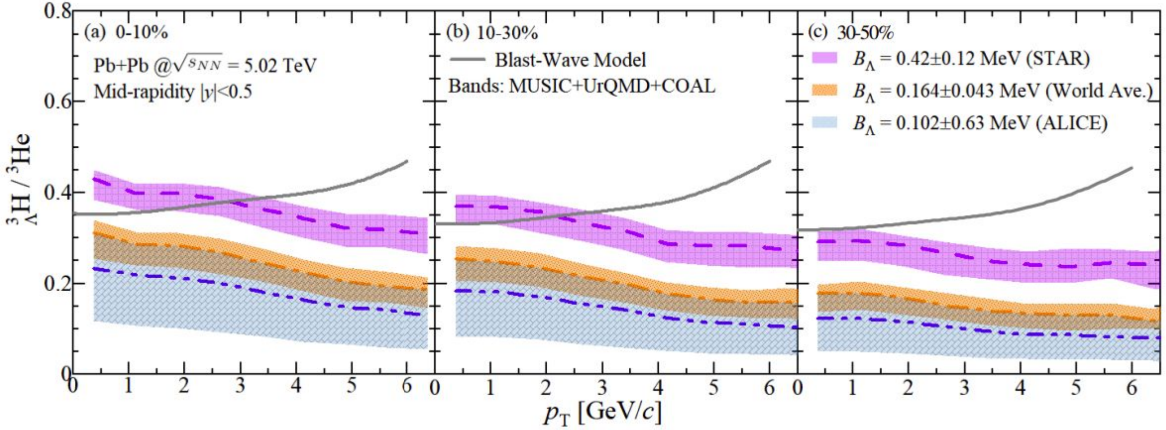
Extension to A=3

Hypertriton

- Latest ALICE measurements of $^{3}_{\Lambda}\mathrm{H}$ in 13 TeV MB
- $^{3}_{\Lambda}\mathrm{H}/^{3}\mathrm{He}$ Ratio flat in p_T



Only available predictions in Heavy Ions[1]:



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

Conclusion

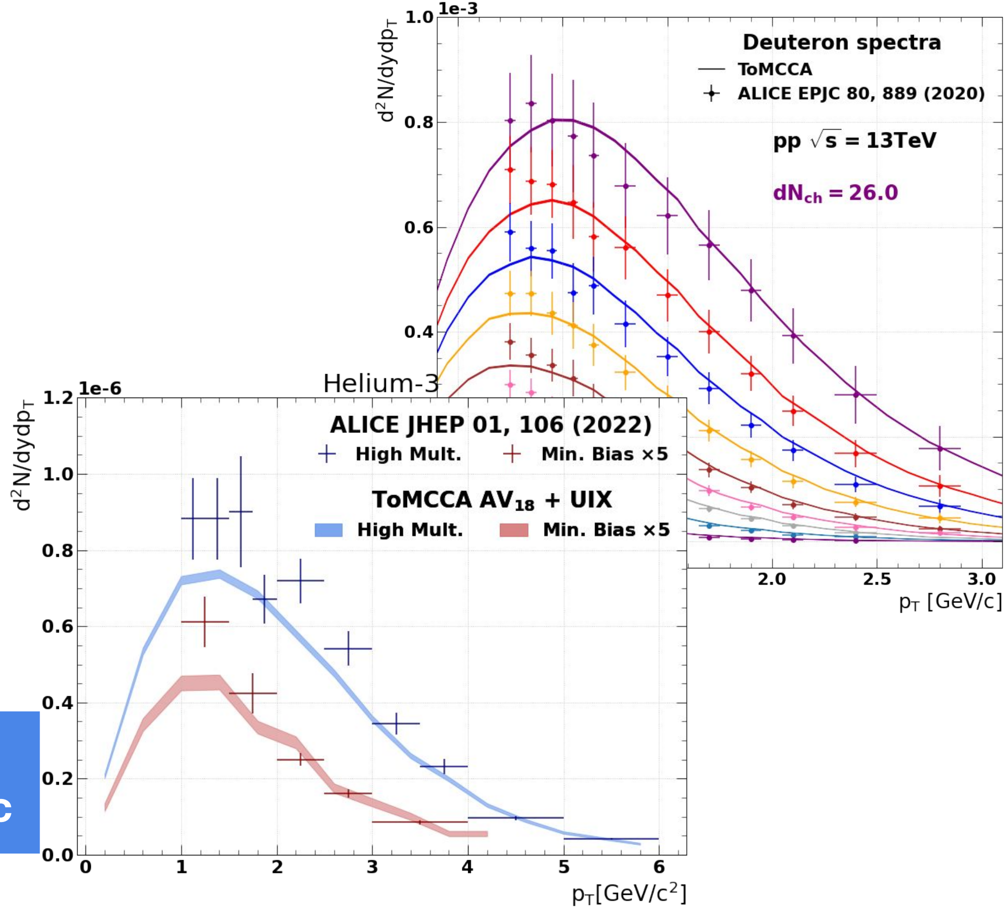
Deuterons:

- 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:

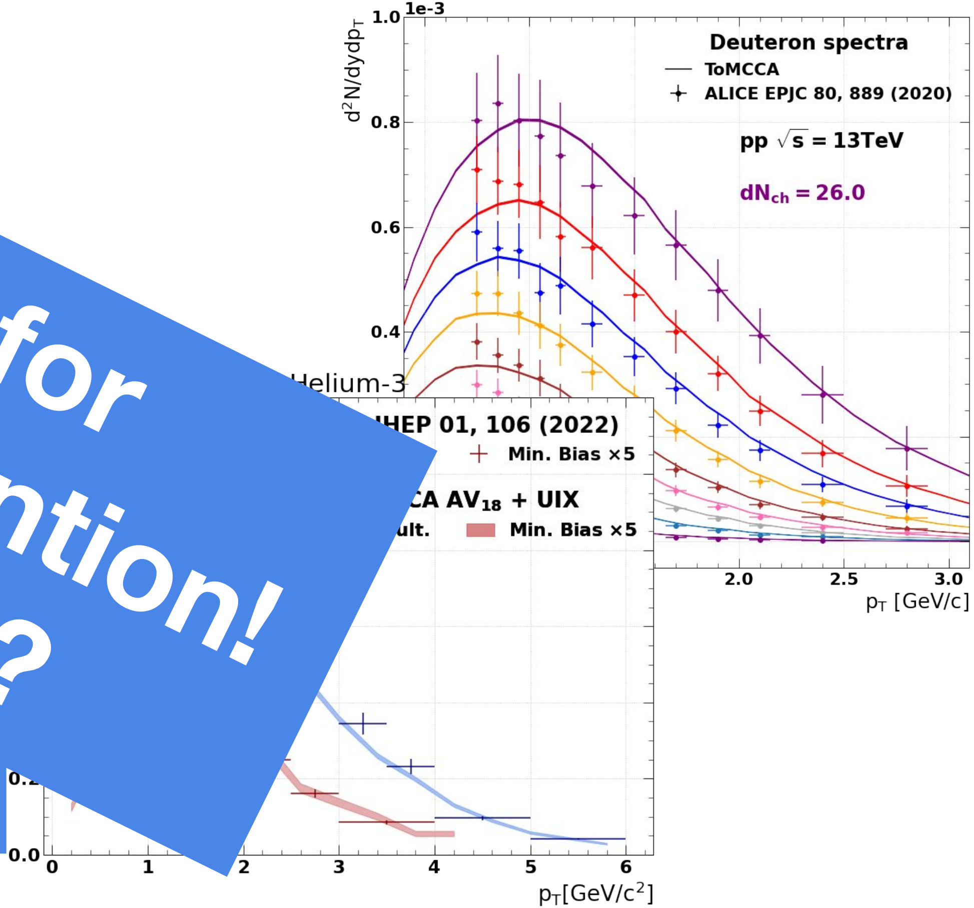
- Coalescence mod ces data with no free parar
- Realistic wavefu
- ToMCCA allow arbitrary mult

A=3 Coalescenc

- Successfu A=3
- Nuclei and *Hypernu*
- Realistic wavefunctions f

Thanks for your attention!

Questions?



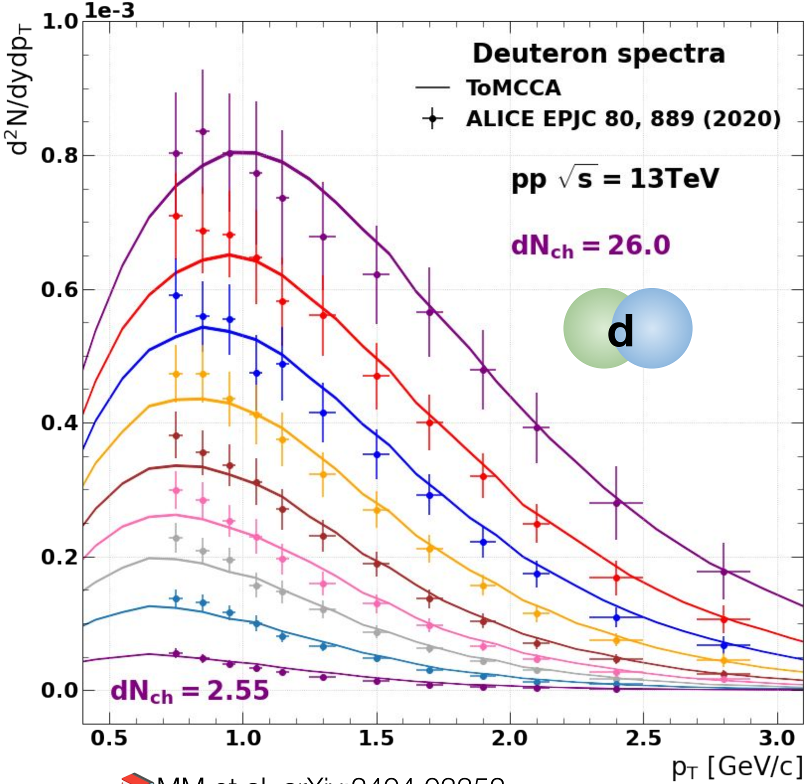
ToMCCA is available under:
https://github.com/horstma/tomcca-public

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



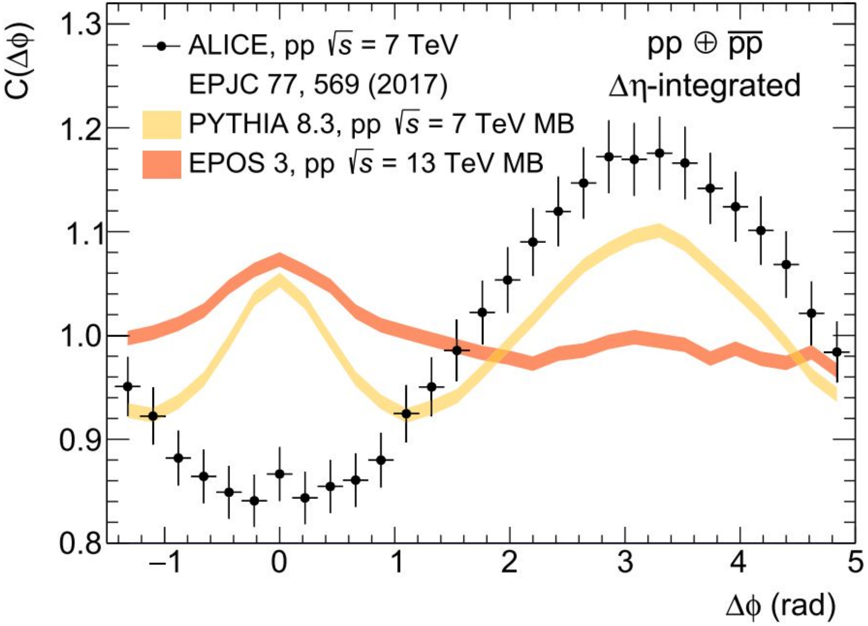
📚MM et al. arXiv:2404.03352

Coalescence Results EPOS

Angular correlations

- 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: **B_A**

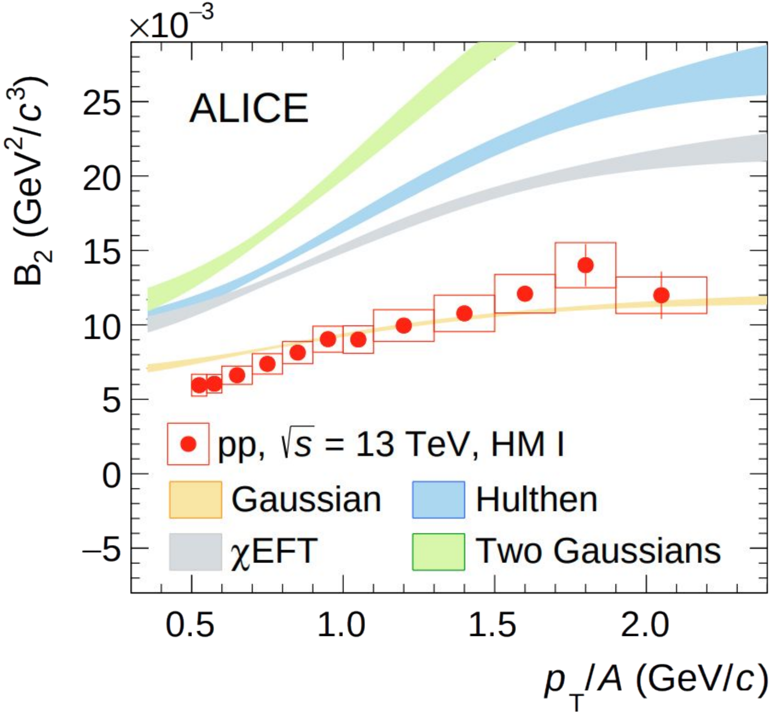
$$B_A(p_T^p) = E_A \frac{d^3 N_A}{dp_A^3} \Big/ \left(E_p \frac{d^3 N_p}{dp_p^3} \right)^A$$

- Theoretical prediction [1]

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

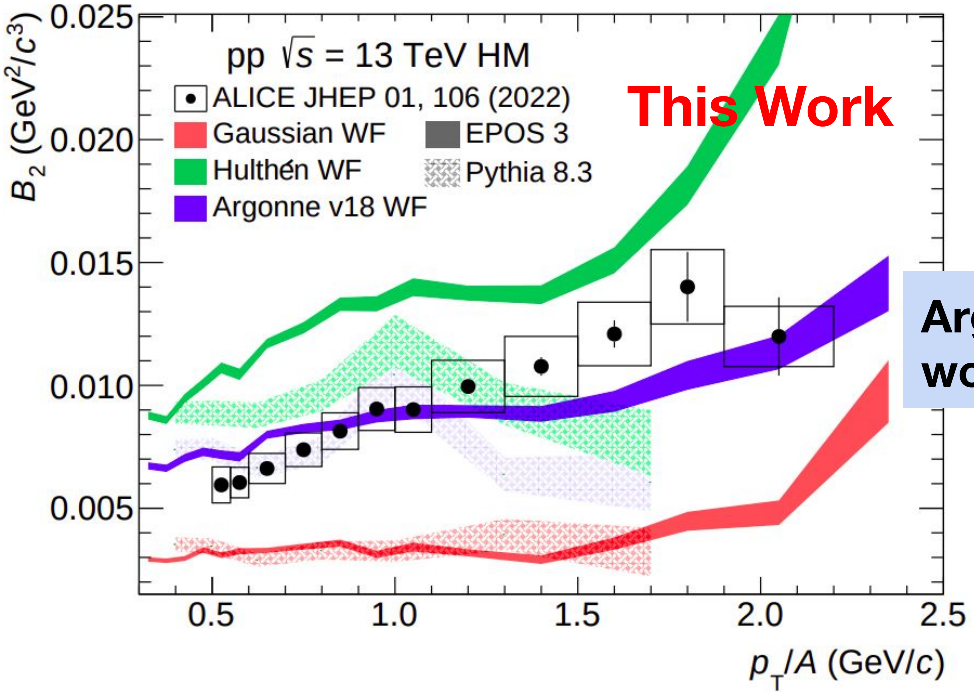
$$D(\vec{q}) = \int d^3 r |\phi_d(\vec{r})|^2 e^{-i\vec{q}\cdot\vec{r}}$$

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



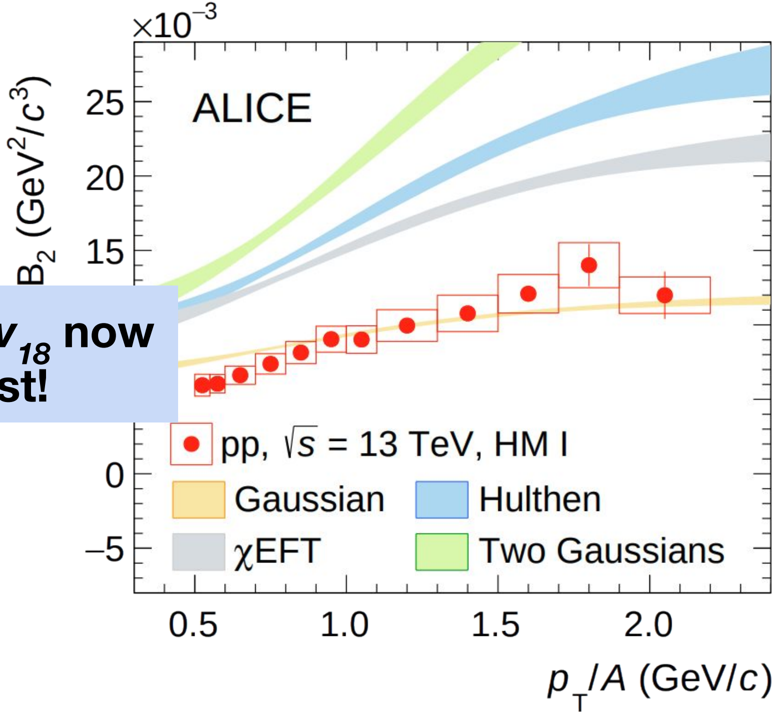
[1] Blum, Takimoto, PRC 99 (2019) 044913

Comparison to previous predictions



This Work

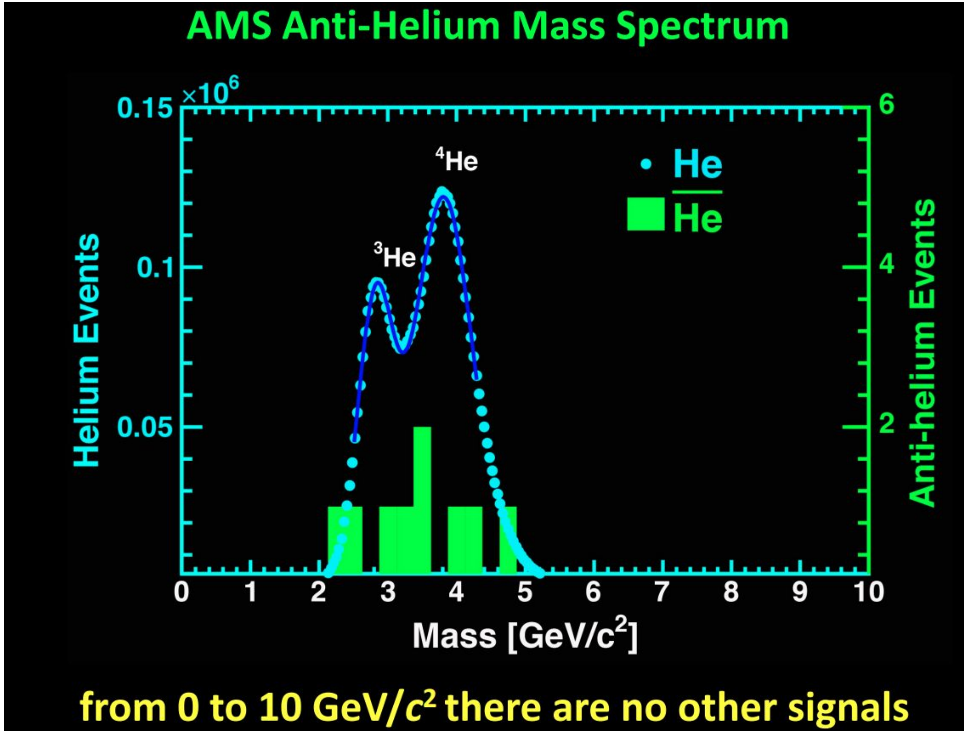
Argonne v_{18} now works best!



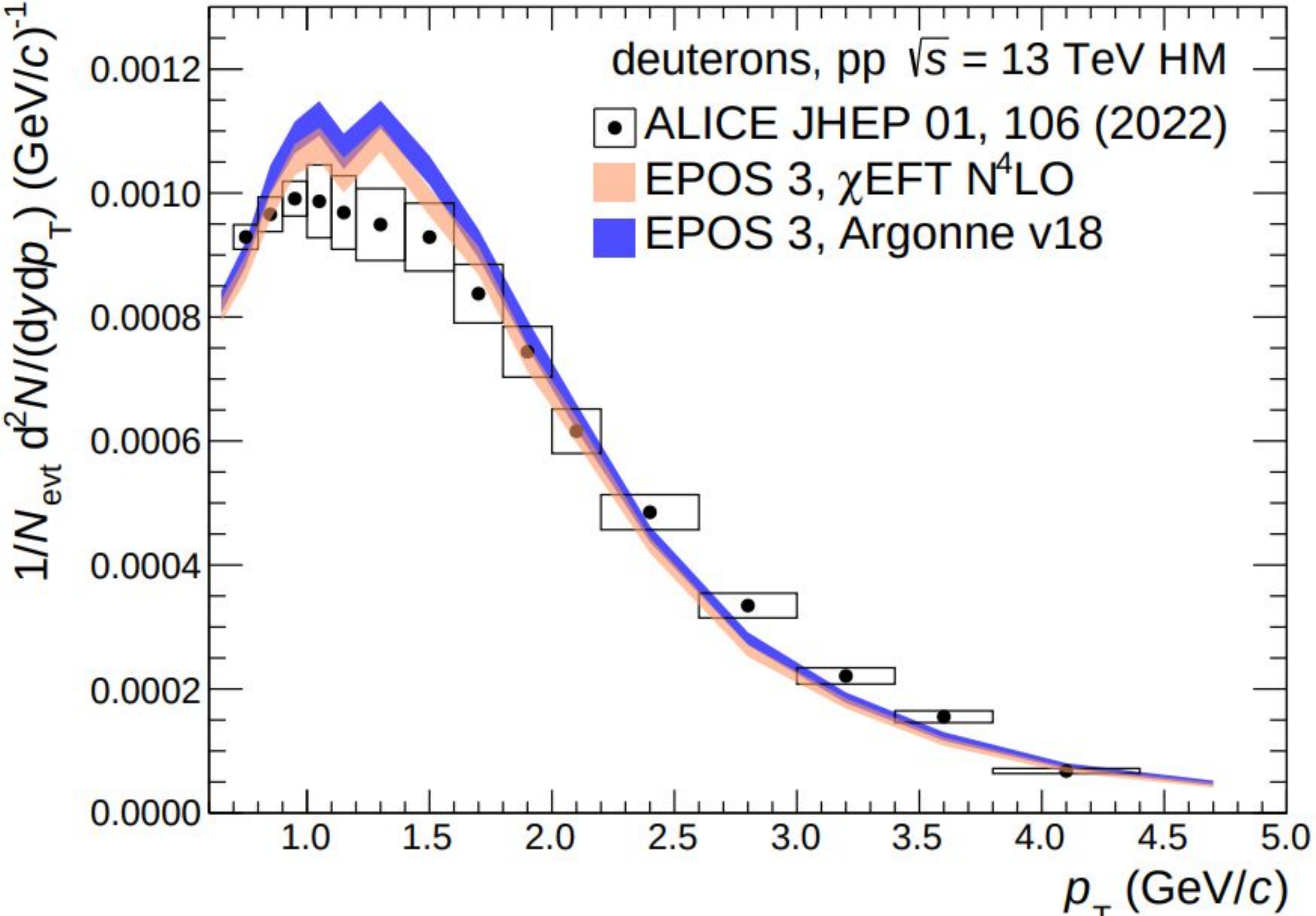
Cosmic Rays

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

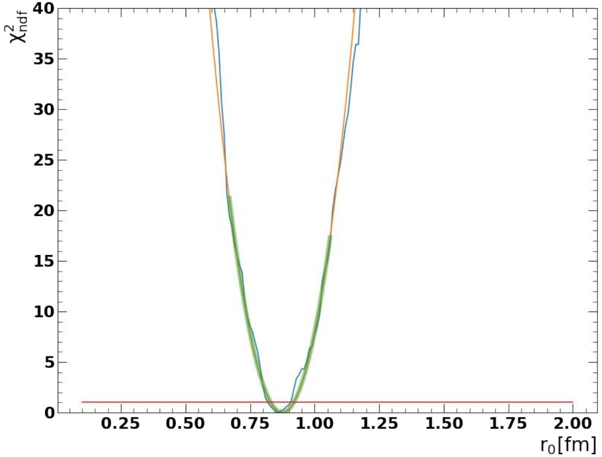

deuterons, pp $\sqrt{s}$ = 13 TeV HM
ALICE JHEP 01, 106 (2022)
EPOS 3, χEFT N⁴LO
EPOS 3, Argonne v18
$1/N_{evt}\ d^2N/(dydp_T)\ (GeV/c)^{-1}$
0.0000
0.0002
0.0004
0.0006
0.0008
0.0010
0.0012
1.0
1.5
2.0
2.5
3.0
3.5
4.0
4.5
5.0
p_T (GeV/c)

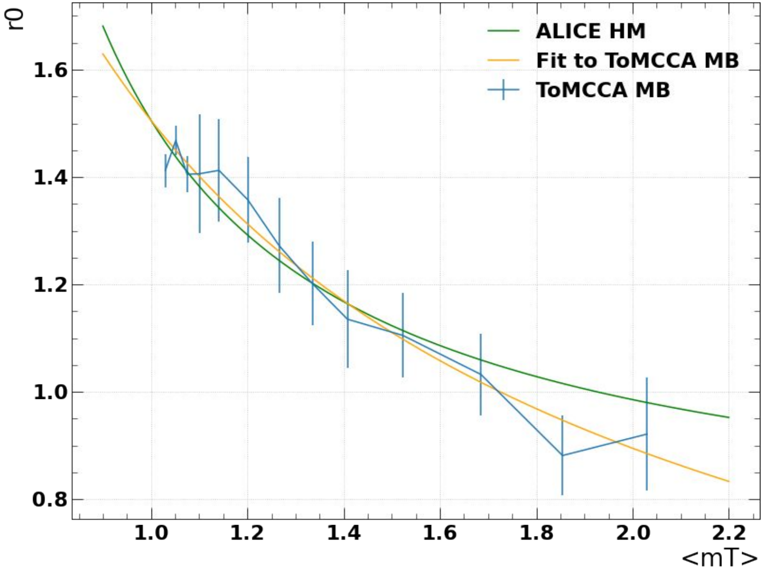
Next generation coalescence Model

Fitting the Source

Fitting Procedure:

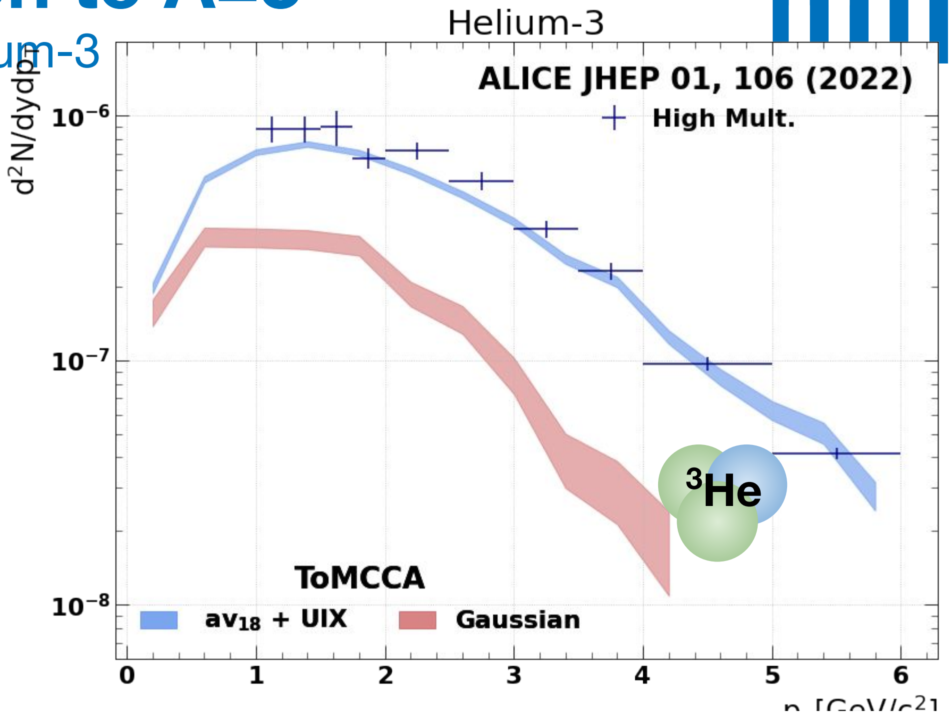
- Run ToMCCA with a fixed source size (e.g. 1.8 fm, flat in m_T)
- For the resulting deuteron spectra calculate the χ^2 for each bin and save it
- Reduce source size
- Repeat until source size is 0





Extension to A=3

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

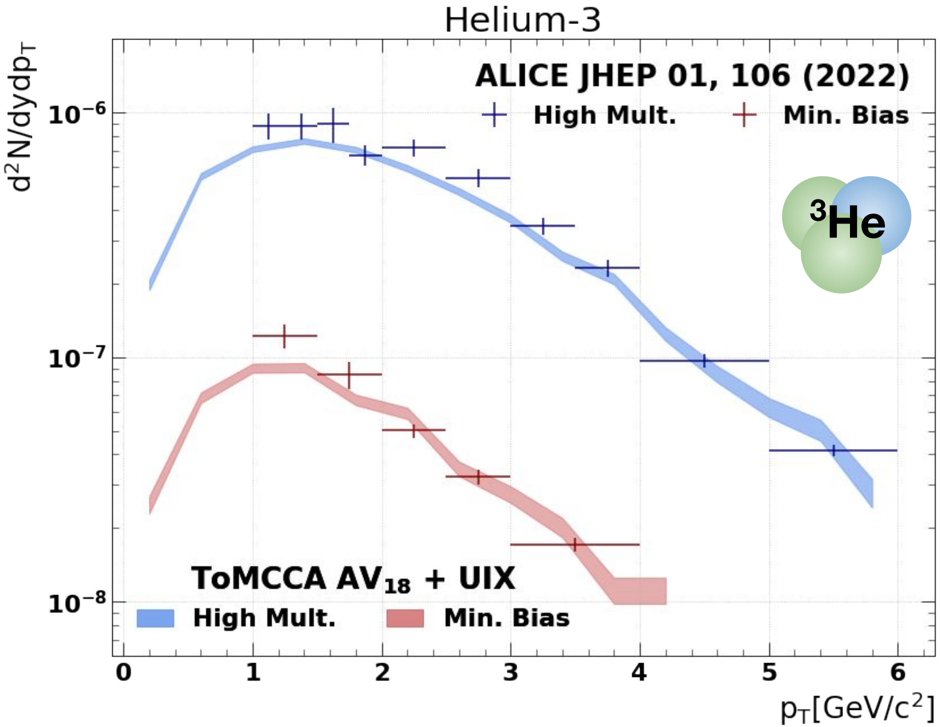
$$\mathcal{P}(k,q,\sigma) = \frac{S\ 64\ b^6}{(b^2+2\sigma^2)^3} \exp\left[-b^2(k^2+q^2)\right]$$

Extension to A=3

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



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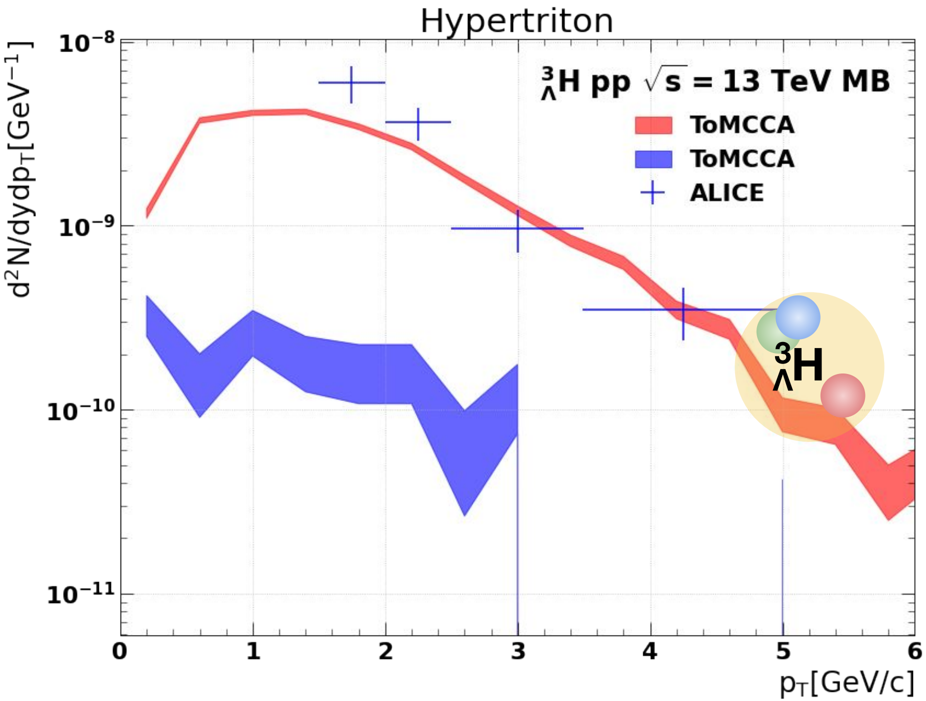
[1] Provided by Michele Viviani, INFN Pisa

Extension to A=3

Hypertriton

- Latest ALICE measurements of LH3 in 13 TeV MB

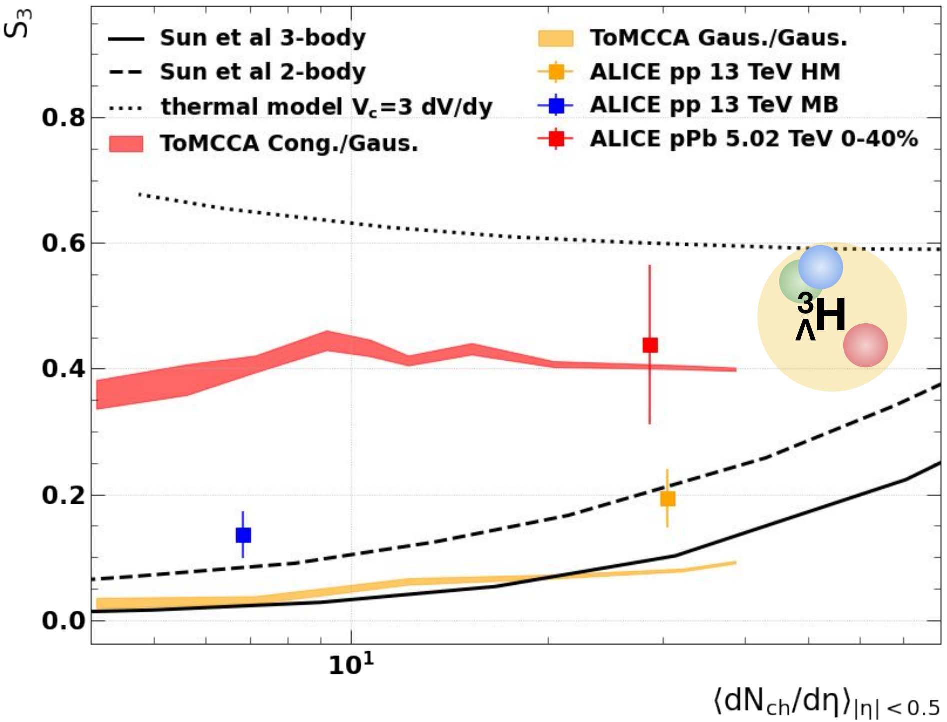


Extension to A=3

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

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

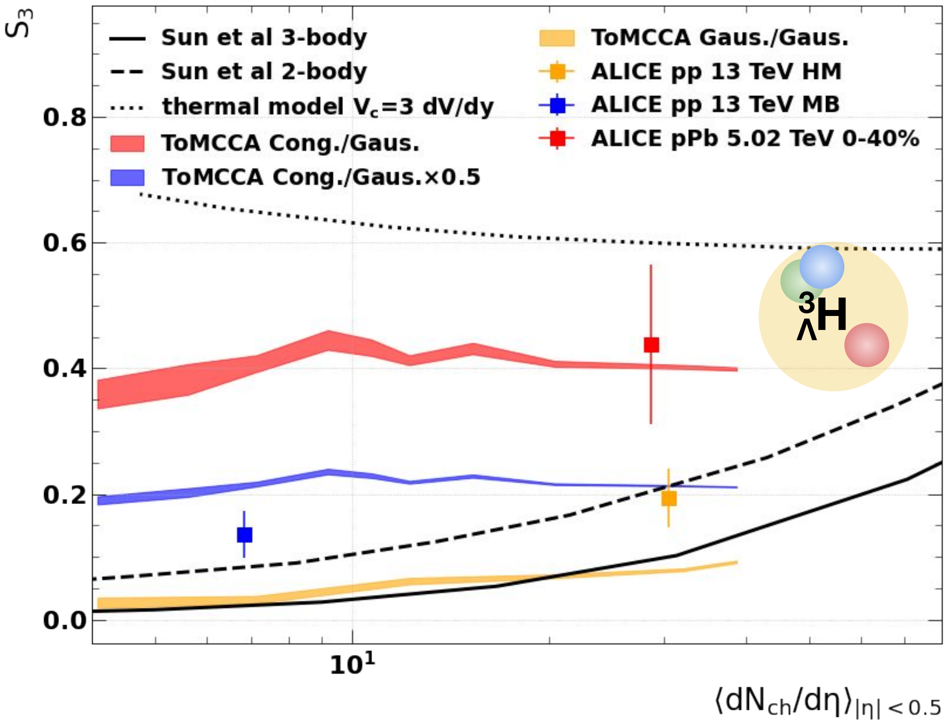


Extension to A=3

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

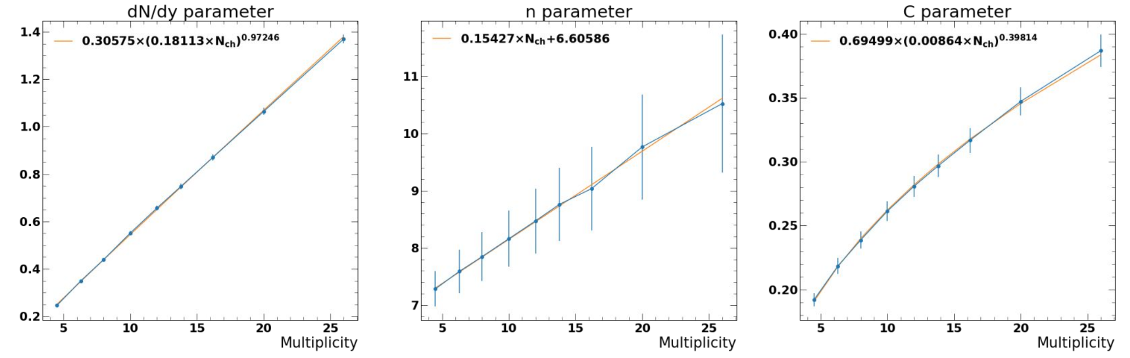
$$S_3 = ({}^{3}_{\Lambda}\mathrm{H}/{}^{3}\mathrm{He})/(\Lambda/p)$$



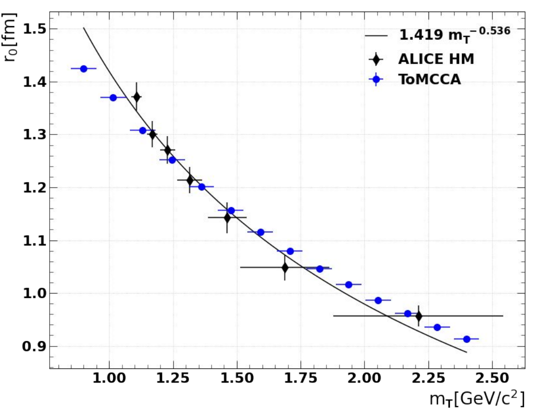
Recap: ToMCCA

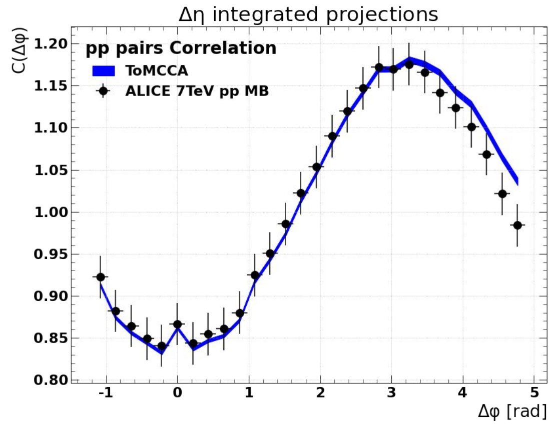
Inputs

- 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



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

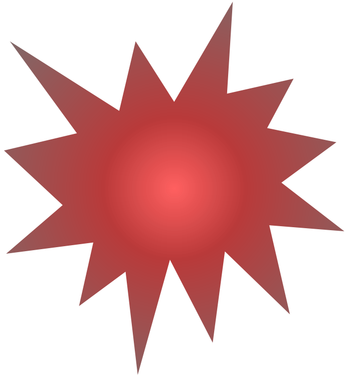




Using a toy MC for Coalescence

Basics of ToMCCA

Event Loop:



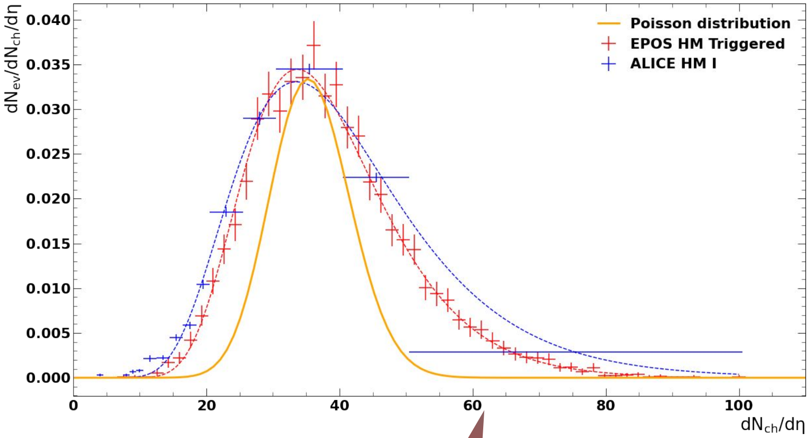
Using a toy MC for Coalescence

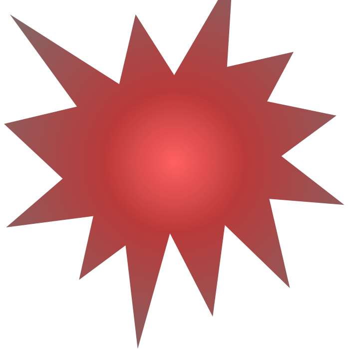
Basics of ToMCCA

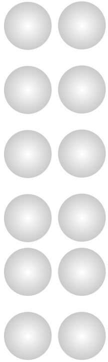
<u>Event Loop:</u>

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

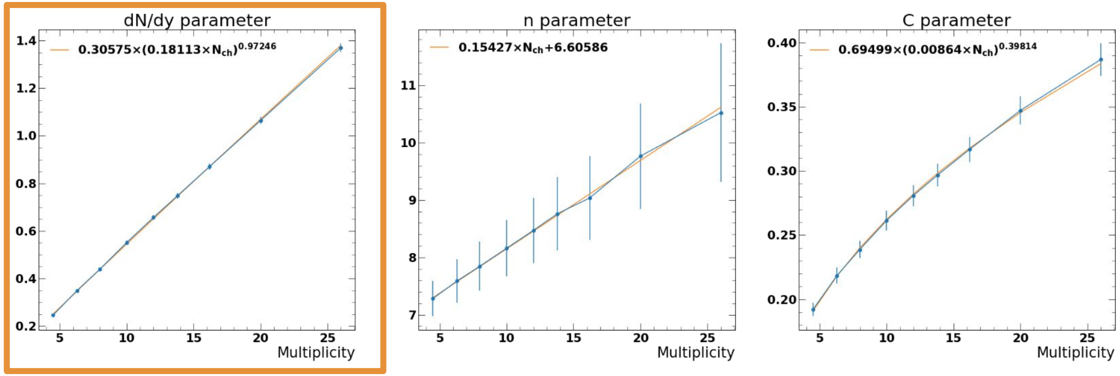
Event Loop:

Get number of charged particles
Get proton yield
Get neutron yield

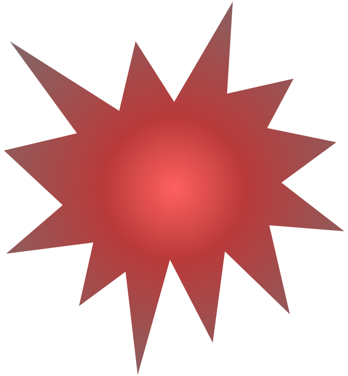
Fit all proton spectra for 13TeV
using a Lévy Tsallis:

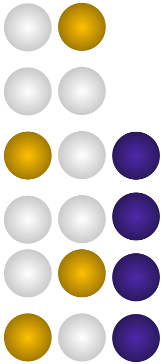
$$\frac{d^2N}{dydp_T} = \frac{dN}{dy}\,\frac{p_T(n-1)(n-2)}{nC[nC+m_p(n-2)]}\left(1+\frac{m_T-m_p}{nC}\right)^{-n}$$

Yield parameter!



Full parameterization as a function of multiplicity



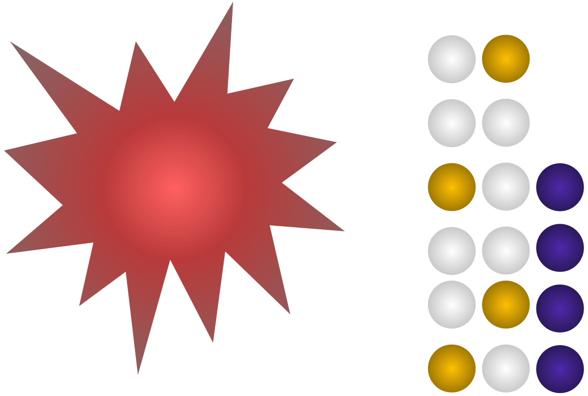


Using a toy MC for Coalescence

Basics of ToMCCA

Event Loop:

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

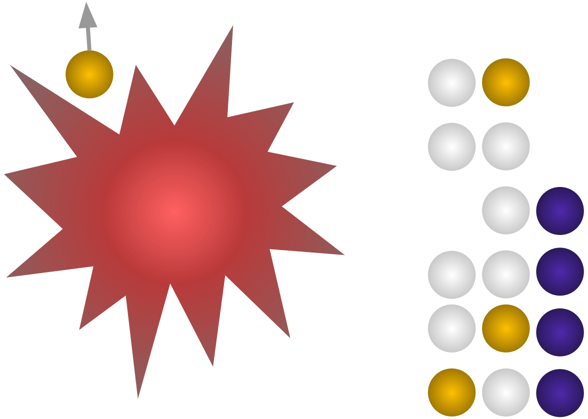


Using a toy MC for Coalescence

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)
```

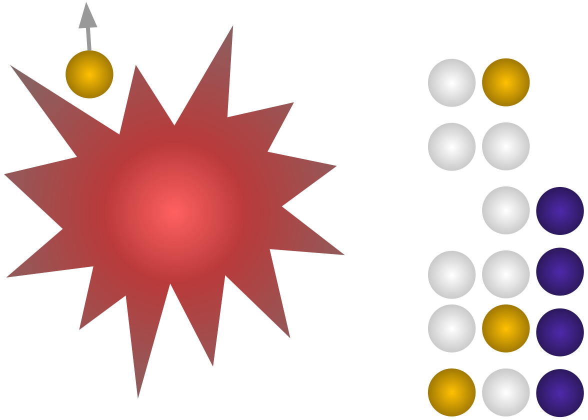


Using a toy MC for Coalescence

Basics of ToMCCA

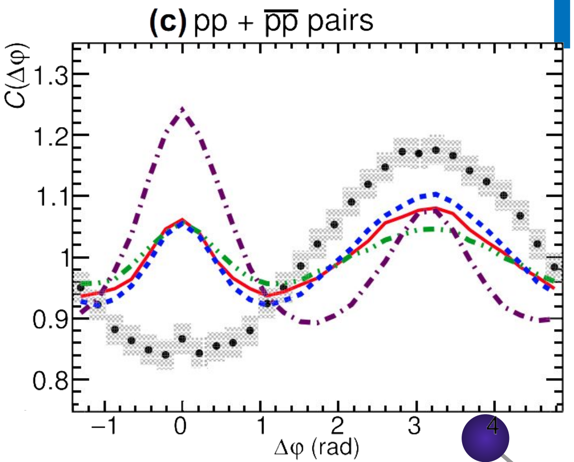
Event Loop:

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



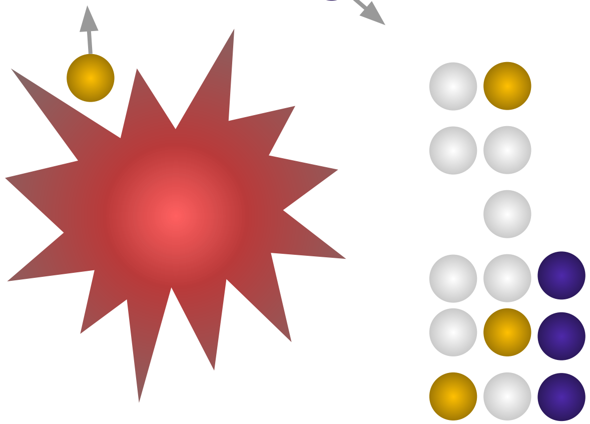
Using a toy MC for Coalescence

Basics of ToMCCA



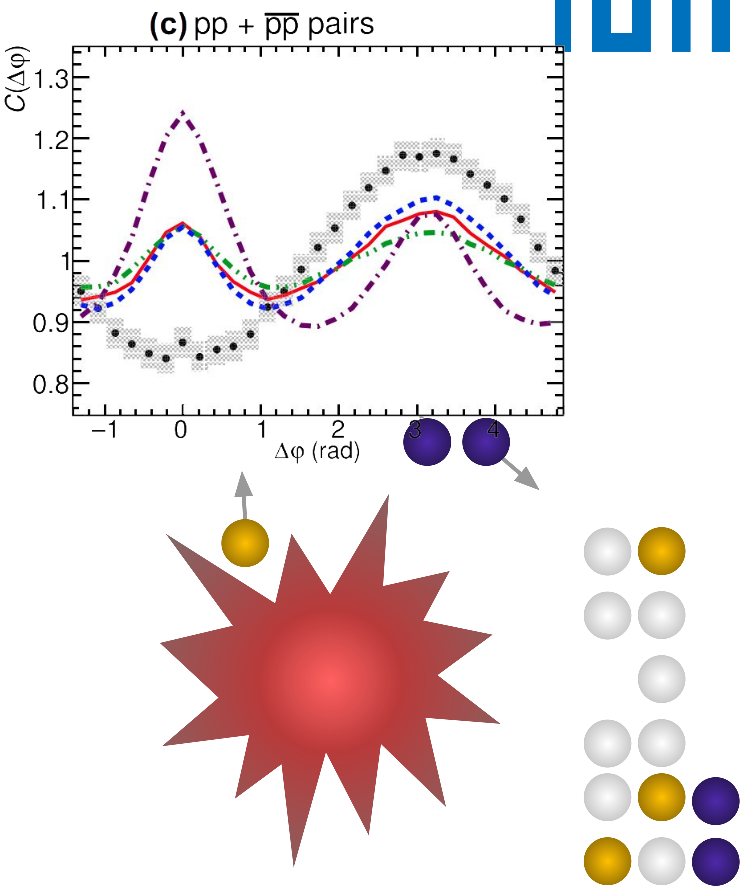
Event Loop:

```
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



Event Loop:

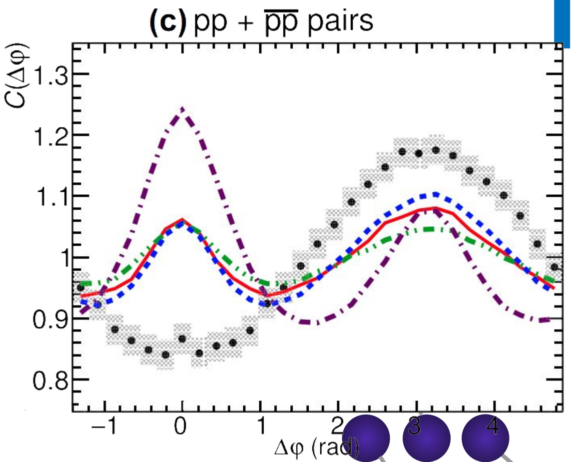
```
Get number of charged particles
Get proton yield
Get neutron yield
⟳ Loop over all protons
    Get 3D momentum of proton
    ⟳ Loop over all neutrons
        Get 3D momentum of neutron
        ● Draw $p_T$ from parameterization
        ● Draw flat rapidity y=[-0.5,0.5]
        ● Draw random Δϕ from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

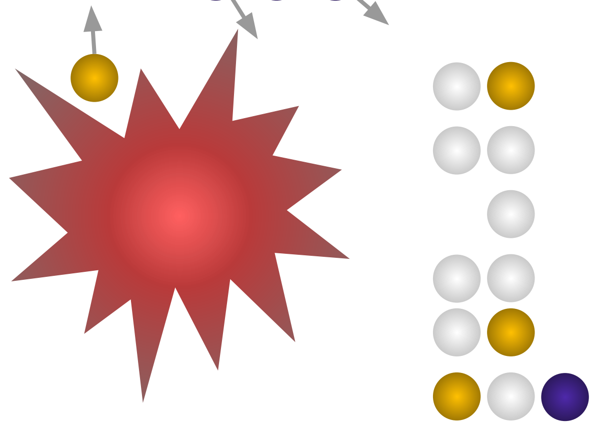
Using a toy MC for Coalescence

Basics of ToMCCA

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





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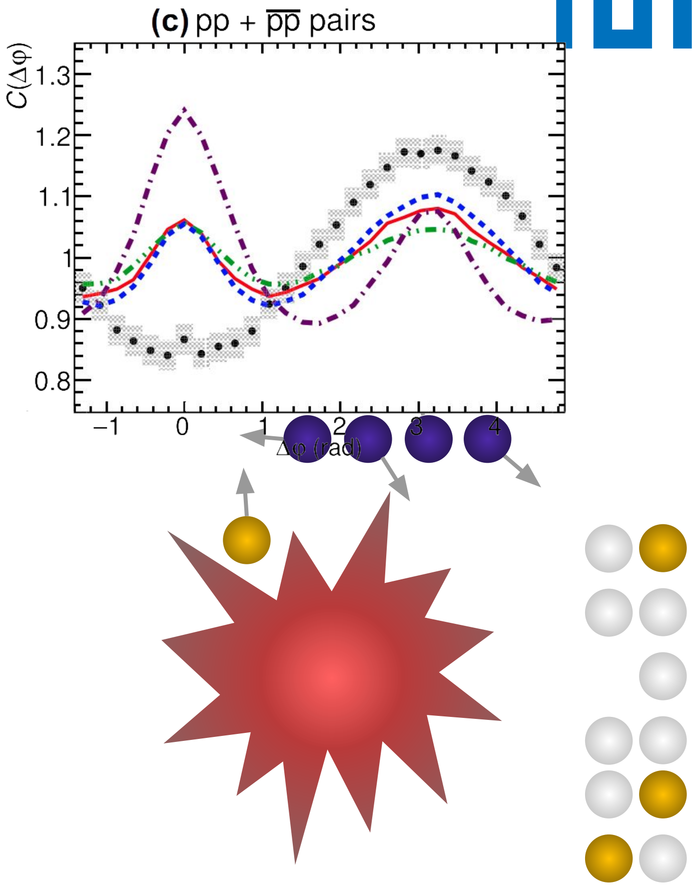

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    Get number of charged particles
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    ⟳ Loop over all protons
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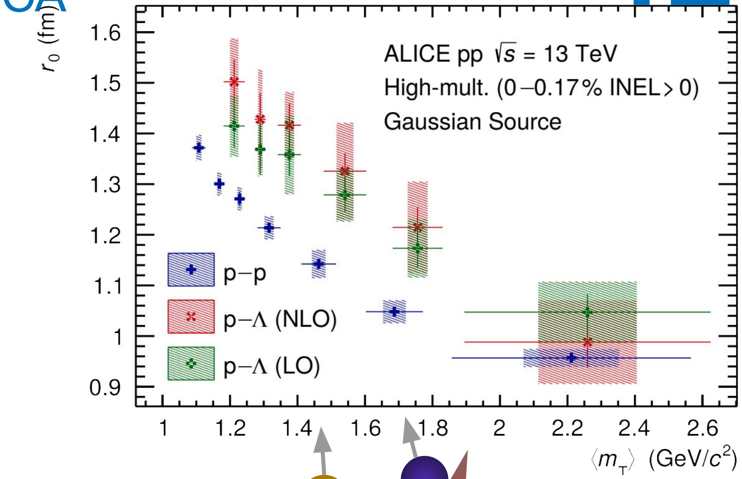
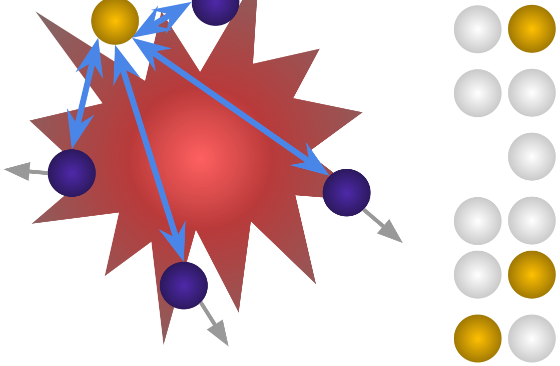
        ⟳ Loop over all neutrons
            Get 3D momentum of neutron
            Get source size
```





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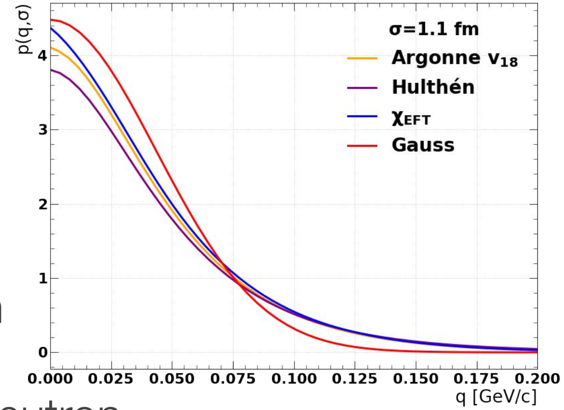
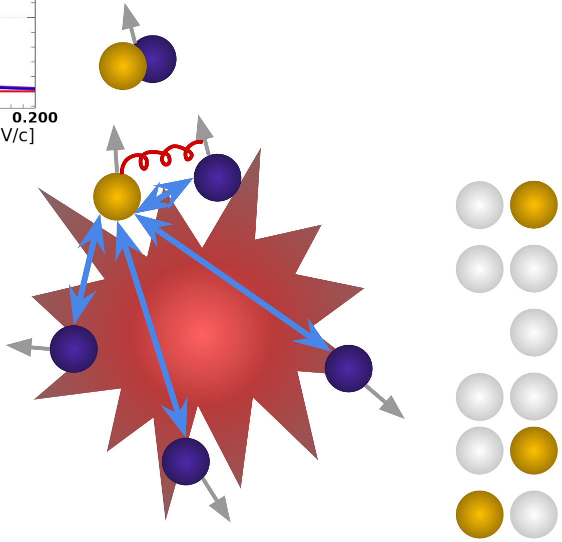
    - Apply coalescence condition





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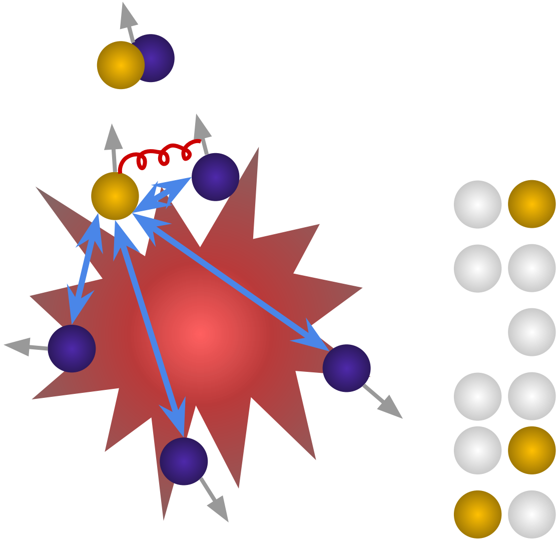

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            ❎ try next neutron
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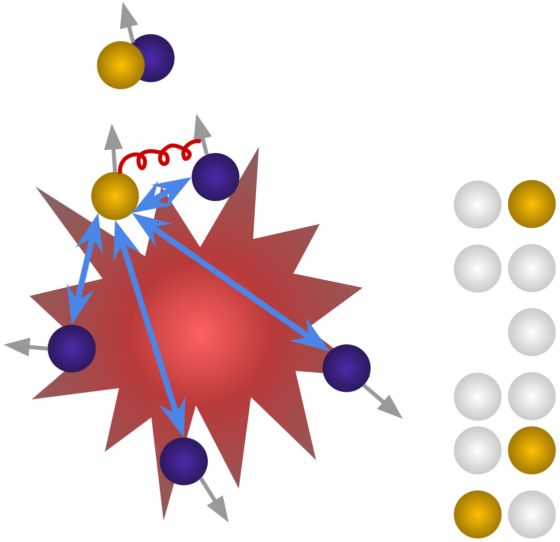

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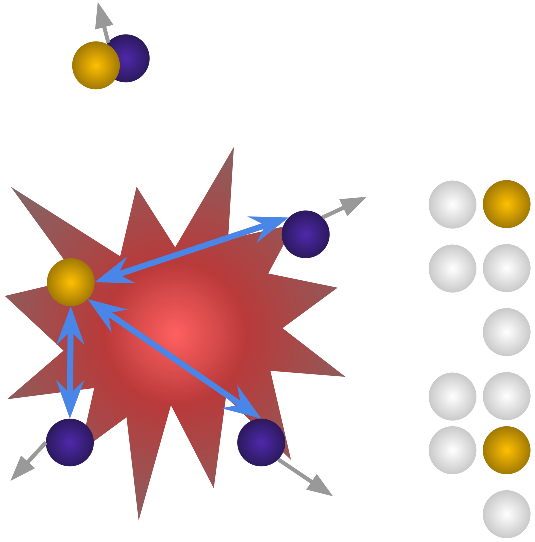

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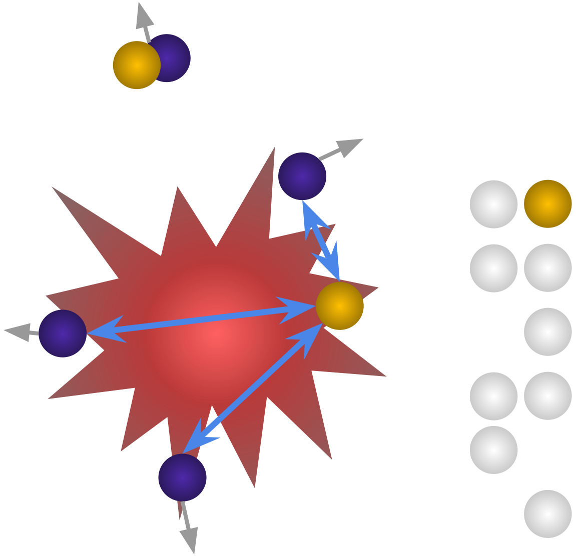

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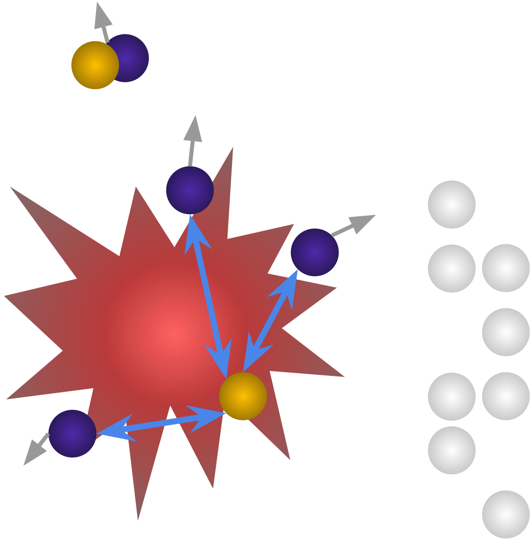

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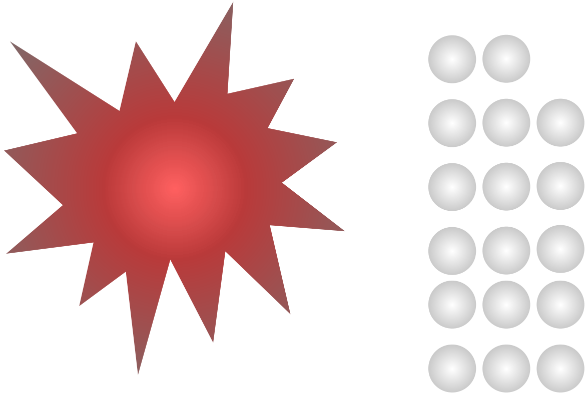
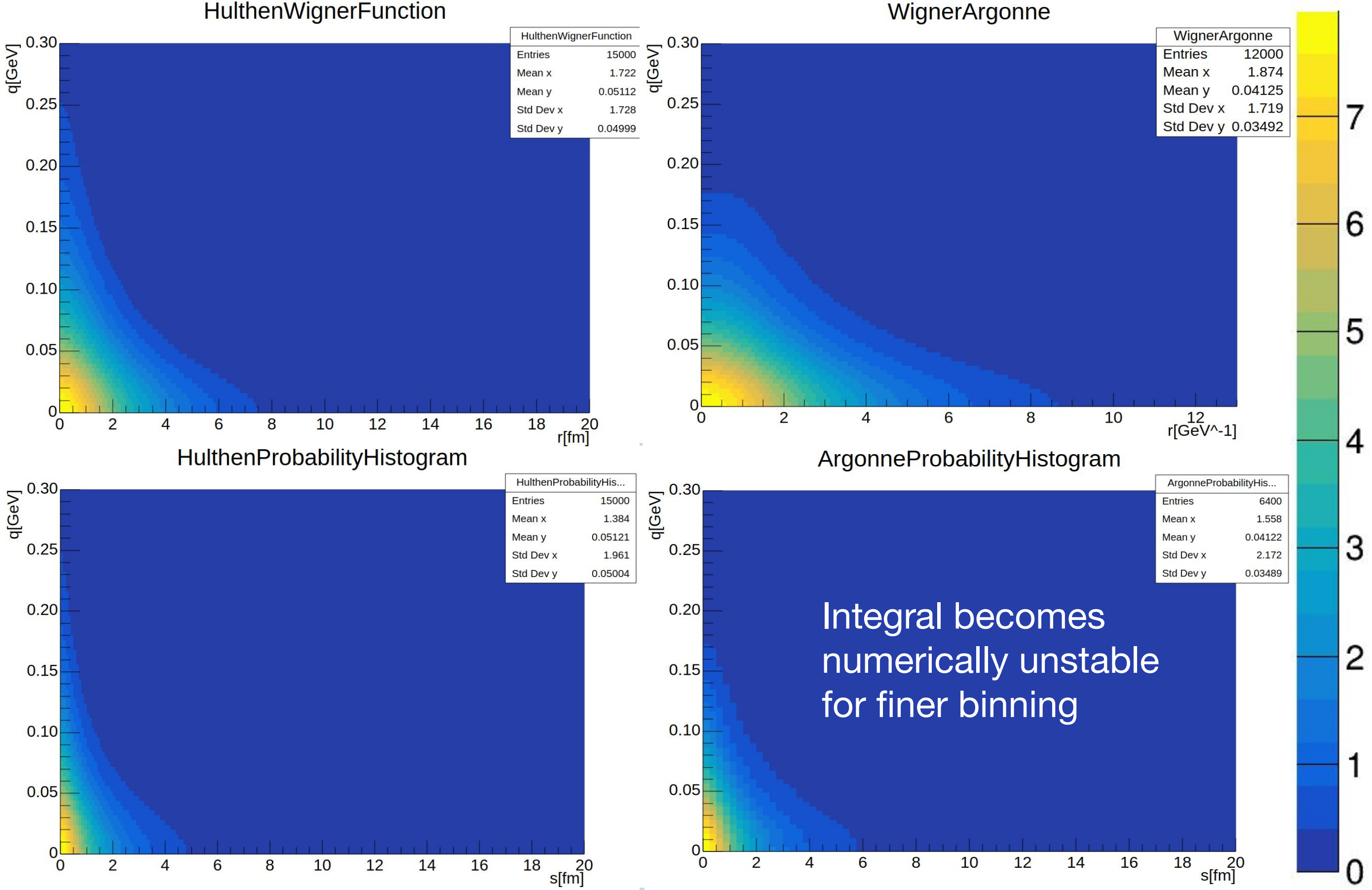


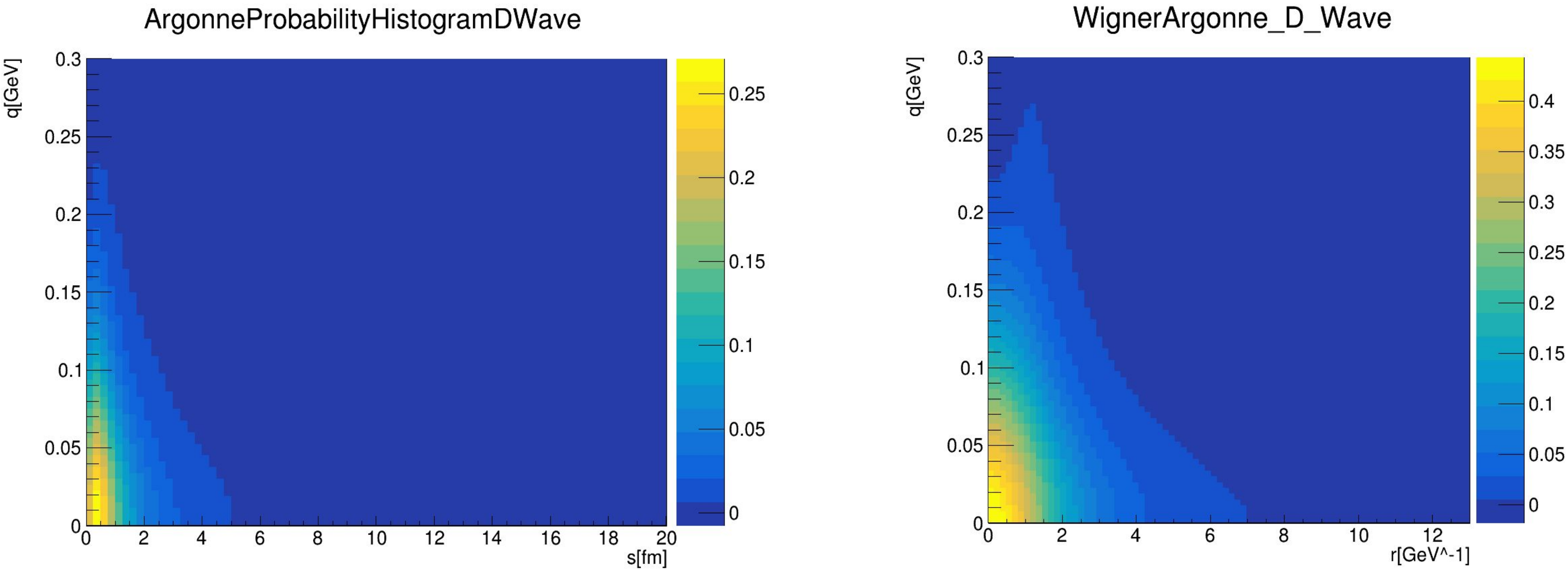
Next Event..

New Wiger functions/Probabilities



Integral becomes numerically unstable for finer binning

Argonne D-State probability



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