NA61/SHINE and NA61++ measurements for the understanding of cosmic antinuclei

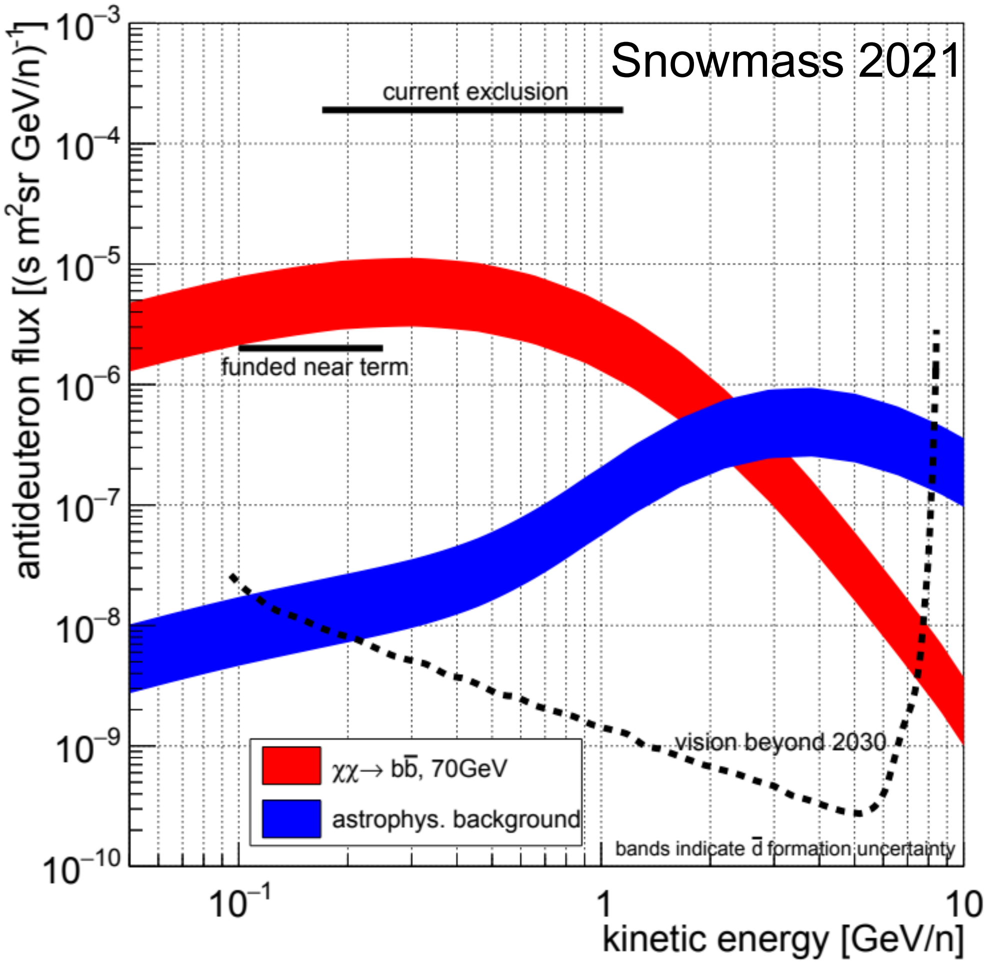
NA61++

Philip von Doetinchem

philipvd@hawaii.edu
Department of Physics & Astronomy
University of Hawai'i at Mānoa
http://www.phys.hawaii.edu/~philipvd

Status cosmic antinuclei searches

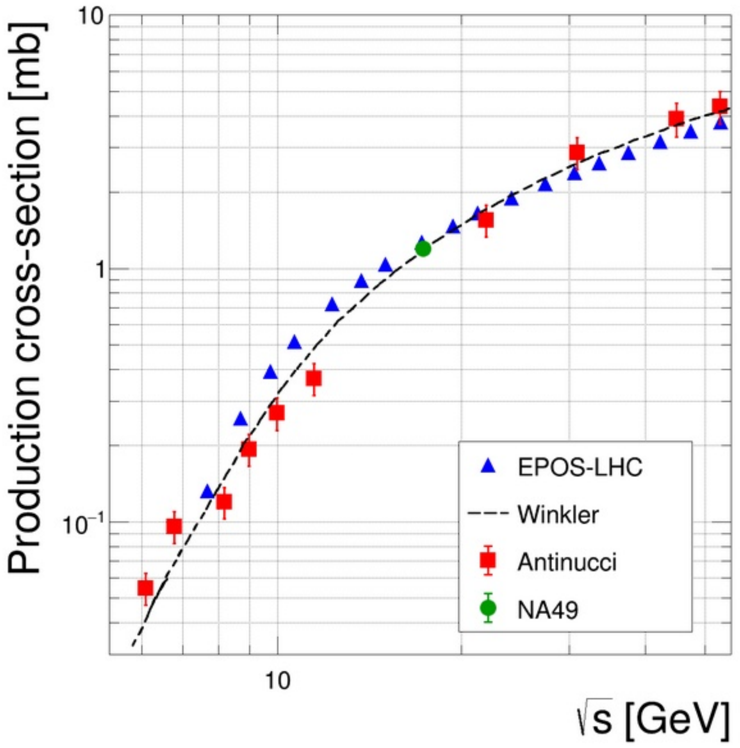
- **Potential $\bar{p}$ excess** in AMS-02 data above secondary background predictions at *R*~10 GV was found in various studies → significance level unclear
- **Low-energy antideuterons are essentially free of astrophysics background**
  - Sensitivity to a wide range of dark matter models, e.g.:
    - Braeuninger et al. Physics Letters B 678, 20–31 (2009)
    - Cui et al, JHEP 1011, 017 (2010)
    - Hryczuk et al., JCAP 1407, 031 (2014).
    - Korsmeier et al., Physical Review D 97, 103011 (2018)
    - Randall & Xu, JHEP (2020)
- AMS-02 reported the observation of **antihelium candidates (~1/year)**
- **Search for antinuclei with independent technique is critical**
- Review based on 2nd Cosmic-ray Antideuteron Workshop "Cosmic-ray Antinuclei as Messengers of New Physics: Status and Outlook for the New Decade" [JCAP08(2020)035, arXiv:2002.04163]



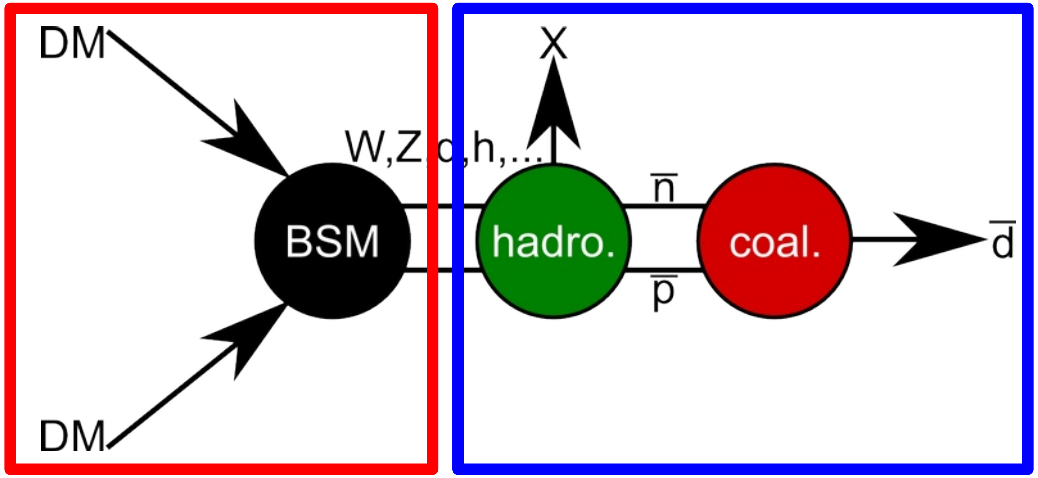
Uncertainties and NA61/SHINE

- **Cosmic-ray propagation**:
  - Fits of cosmic-ray nuclei data are very important to constrain cosmic-ray propagation models (e.g., B/C, d/α, Li/C, Li/O, Be/C, Be/O, B/O) and models depend on production cross sections of primary cosmic rays with the interstellar medium → **NA61/SHINE measurements are important**
  - Inelastic interactions of antinuclei in the Galaxy
    → ALICE conducted cross section measurements
- **Antinuclei formation** process breaks the degeneracy between heavier antinuclei and antiprotons:
  - Antiproton production cross section not very well known
  - Coalescence: $\bar{d}$ can be formed by an $\bar{p}$-$\bar{n}$ pair if relative momentum is small compared to coalescence momentum p_0
  - Thermal model: Antinuclei directly formed at hadronization stage
  - Wigner-function based, semi-classical model has been developed

  → **NA61/SHINE measurements are important**



(Anti)nuclei coalescence



dark matter

conventional production (e.g., p+ISM) & dark matter

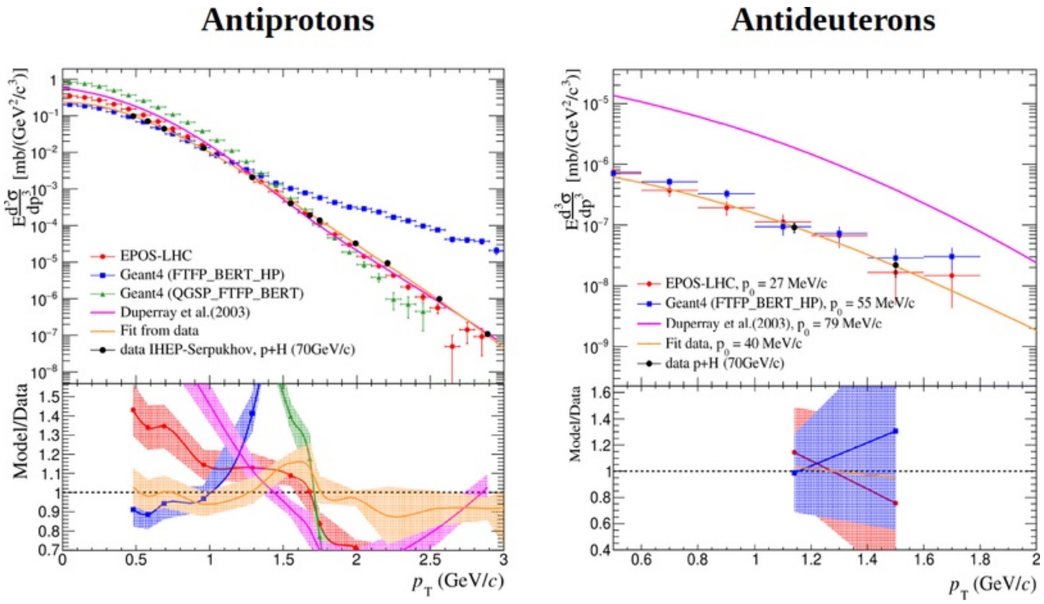
- (Anti)nuclei yield:

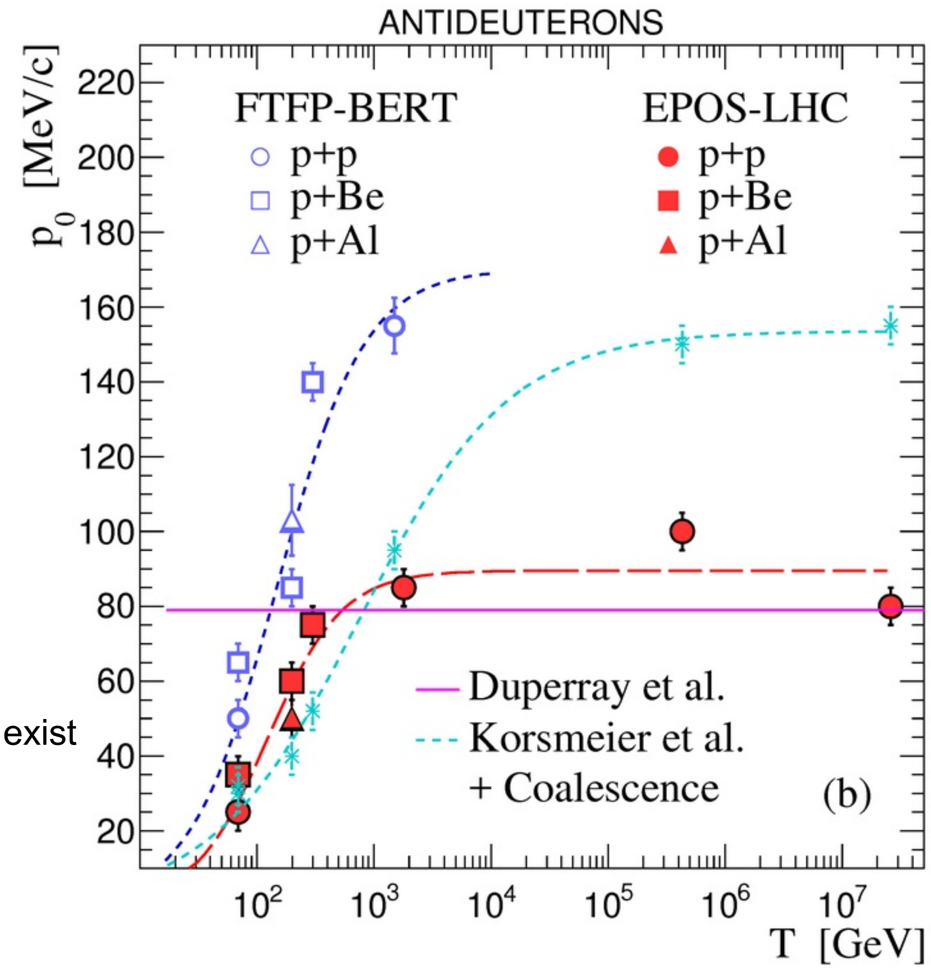
$$E_A \frac{\mathrm{d}^3 N_A}{\mathrm{d}p_A^3} = B_A \left(E_p \frac{\mathrm{d}^3 N_p}{\mathrm{d}p_p^3} \right)^Z \left(E_n \frac{\mathrm{d}^3 N_n}{\mathrm{d}p_n^3} \right)^N \quad \text{with } B_A = A \left(\frac{4\pi}{3} \frac{p_0^3}{m_p} \right)^{A-1}$$

- use an event-by-event coalescence approach with hadronic generators

Coalescence modeling

D. Gomez-Coral et al., Phys Rev D 98, 023012 (2018)





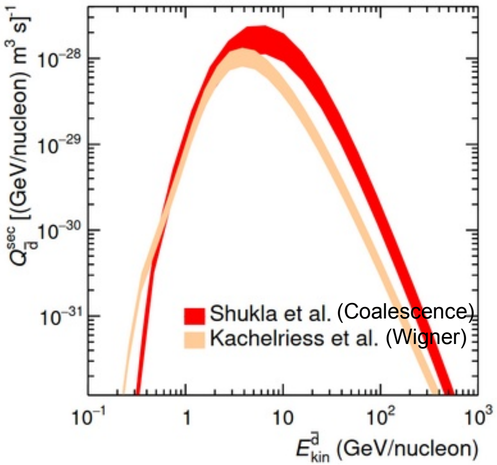
- Event-by-event approach with hadronic generators
- find p_0 for each data set where antiproton and antideuteron results exist
- p_0 show strong energy depedence in the range most important for cosmic rays
- **more high-statistics p-p data needed to constrain antinuclei formation models**

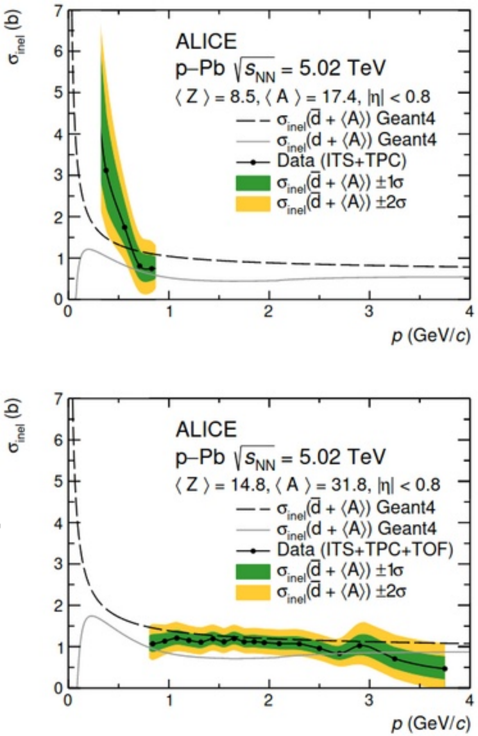
From production to flux at Earth

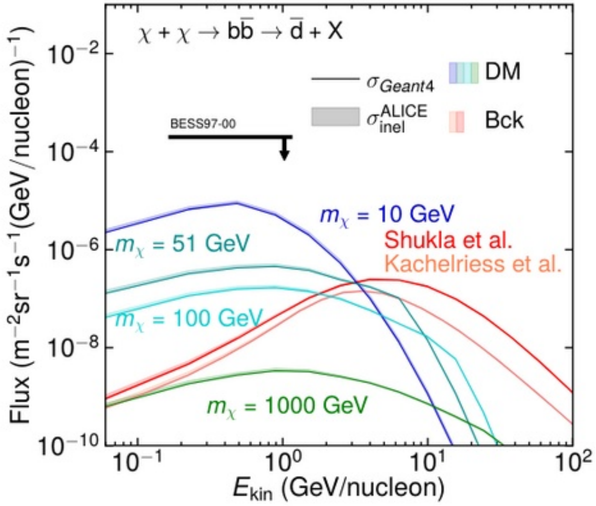
Šerkšnytė et al., Phys. Rev. D 105, 083021 (2022)

Propagation equation:

$$\frac{\partial \psi}{\partial t} = Q(\boldsymbol{r}, p) + \mathbf{div}(D_{\mathrm{xx}}\mathbf{grad}\psi - \boldsymbol{V}\psi) + \frac{\partial}{\partial p}p^2 D_{\mathrm{pp}}\frac{\partial}{\partial p}\frac{\psi}{p^2} - \frac{\partial}{\partial p}\left[\psi\frac{\mathrm{d}p}{\mathrm{d}t} - \frac{p}{3}(\mathbf{div}\cdot\boldsymbol{V})\psi\right] - \frac{\psi}{\tau},$$



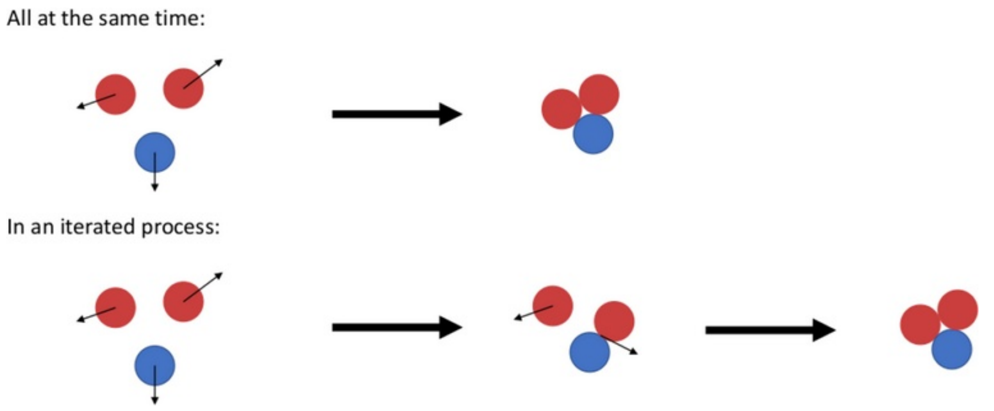




Antideuteron flux at the top of the atmosphere

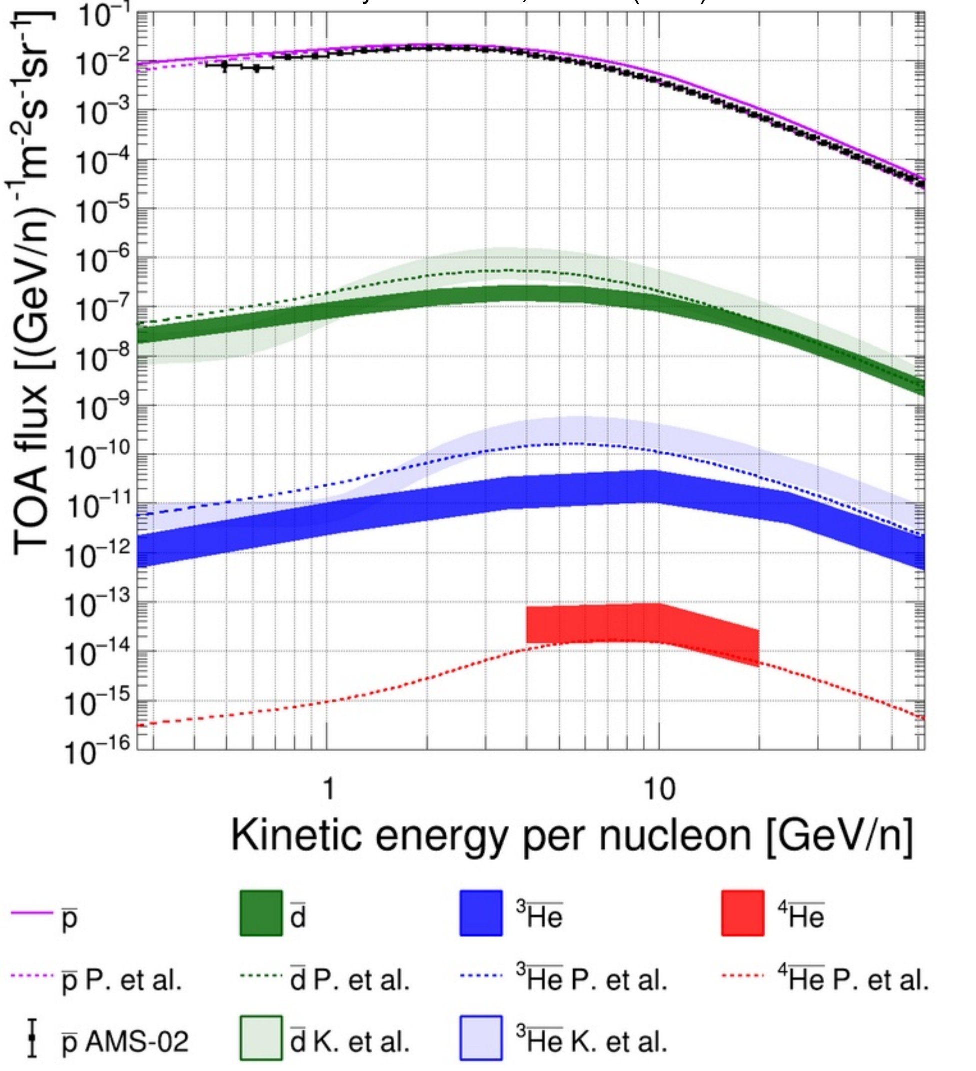
- D_{xx}, V, and D_{pp} are the spatial diffusion coefficient, the convection velocity, and the diffusive re-acceleration coefficient, respectively.
- ψ/τ accounts for particles lost via decay, fragmentation and inelastic interactions in the Galaxy

Antihelium coalescence



- expanded modified MC coalescence model to merging multiple antinucleons from p-p interactions
  → requires quite a bit of computing power (~**5,000 years**)
- use the p_0 behavior from antideuterons
- Very good agreement with ALICE antihelium-3 data (p-p at √s=7TeV)

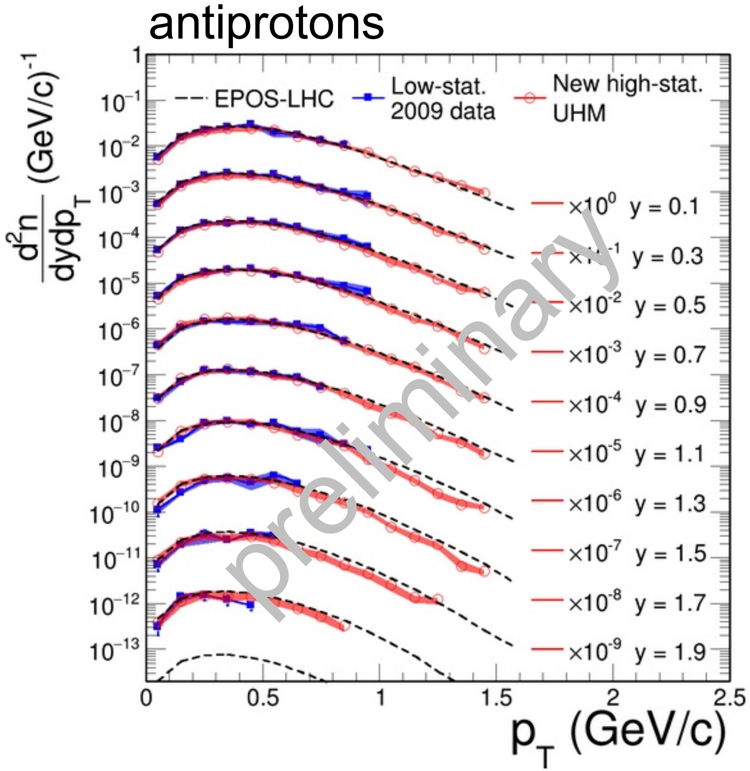
A. Shukla et al. Phys Rev D 102, 063004 (2020)

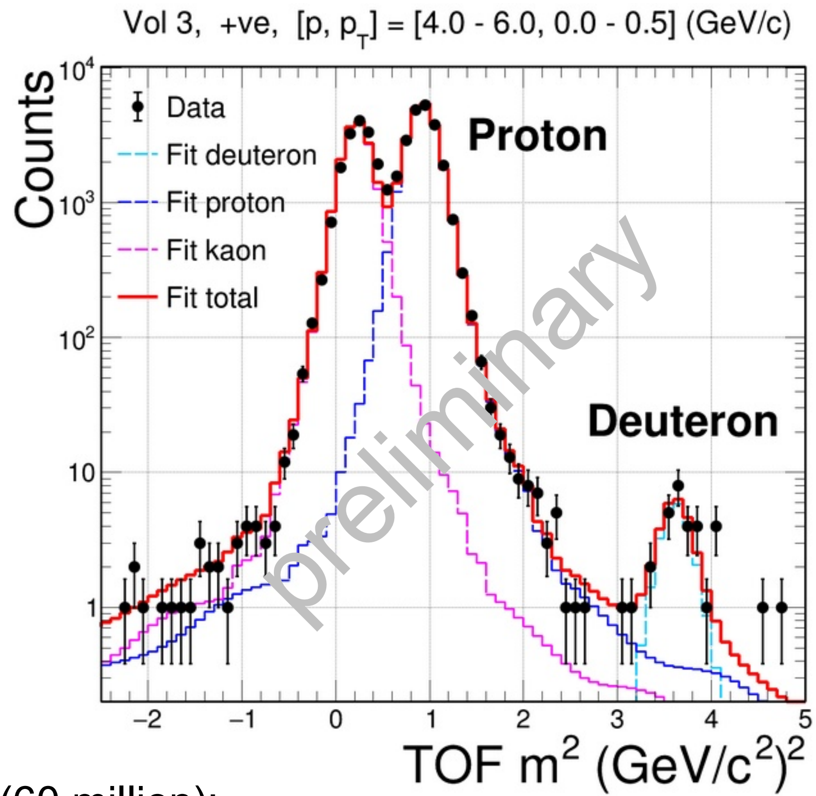


Issues of the coalescence model

- **phase space** for ion production depends on the available energy in the formation interaction
- highly sensitive to **two-particle correlations** between the participating (anti)nucleons
- (anti)neutron spectra are challenging to access experimentally, potential asymmetries should be evaluated
- hadronic generators failing to describe (anti)proton and (anti)neutron spectra automatically result in a shift of p_0
- **spin** is not considered
- not a QM model
- generators not really tuned for antiparticle production
  → use dedicated antiproton, deuteron, and antideuteron data

New NA61/SHINE $\bar{p}$ and d results





- Use of 158GeV/c p-p data from 2009/10/11 (60 million):
  - Significantly extended the $\bar{p}$ phasespace coverage
  - First high-statistics d measurements in p-p in the most-relevant energy range for cosmic rays
  - Will be published soon (including d yield spectra, d/p ratio)

→ tune hadronic generators

Next step: coalescence improvements

- Following the ALICE approach, studiyng two-nucleon correlations in p-p data allows for extracting the size of the formation region $R(p_T)$:

$$\mathcal{C}(k) = \mathcal{N}\frac{N_{\mathrm{same}}(k)}{N_{\mathrm{mixed}}(k)} = \int \mathrm{d}^3 r S(r) |\Psi(r,k)|^2$$

- **Data-driven** quantum-mechanical description of coalescence:

$$B_2(p_T) \approx \frac{3}{2m} \int \mathrm{d}^3 q D(q) \exp\left(-R(p_T)^2 q^2\right) \;\; \text{with} \;\; D(q) = \int \mathrm{d}^3 r |\varphi_d(r)|^2 \exp(-iqr)$$

S: emission source function, ψ 2-(anti)nucleon wave function,
φ internal (anti)deuteron wave function

Future studies and measurements

- Preliminary: current NA61/SHINE p-p data at 158GeV/c contains ~50 antideuteron candidates → ongoing

- Conduct the same analysis with existing p-p 400GeV/c data set

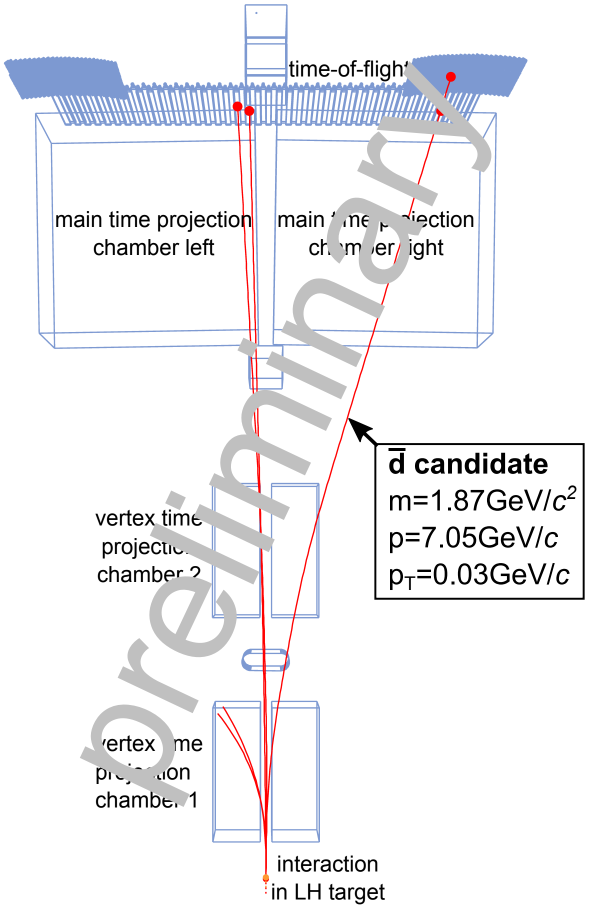
- **More very-high statistics p-p data needed:**

  - Take data with upgraded NA61/SHINE experiment (10-20x faster electronics, better TPC resolution, better TOF, etc.)

  - **Goal:** p-p data set on the order of 1-10 billion events

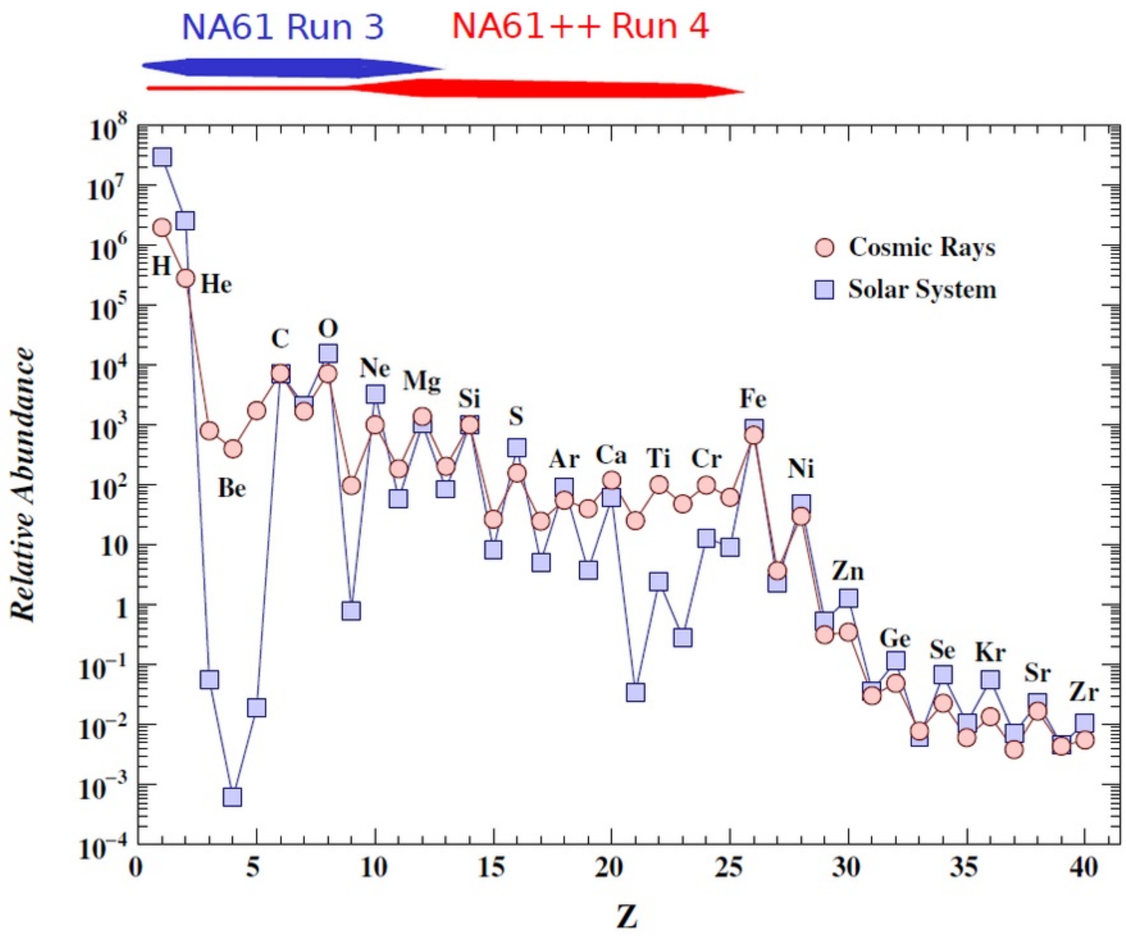
    → high-statistics antideuteron measurements

    → potential for seeing antihelium-3

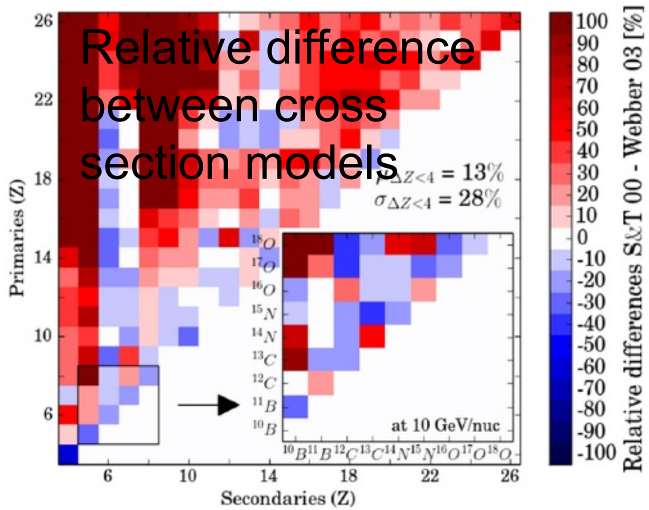


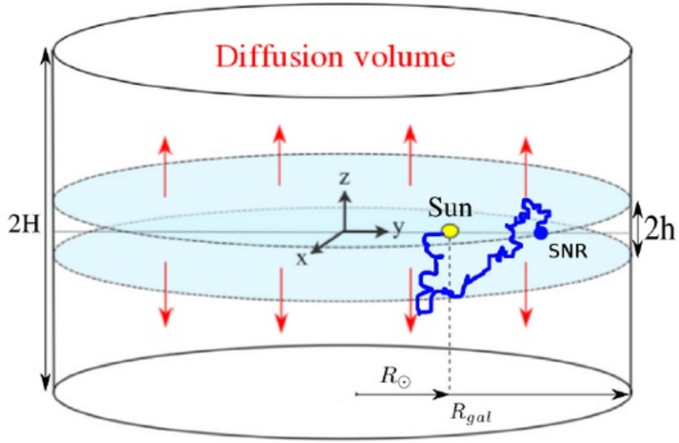
Propagation: High-Mass Nuclei

Slides from M. Unger



Particle Data Group 2022



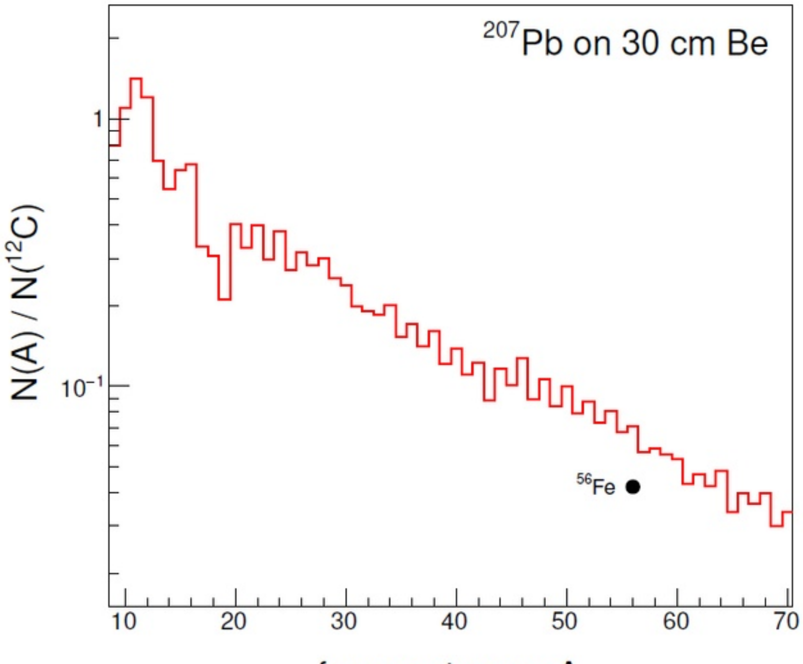


Y. Genolini et al, A&A. 580 (2015) A9 and TAUP 2015

High-Mass Nuclei: Experimental Challenges

Slides from M. Unger

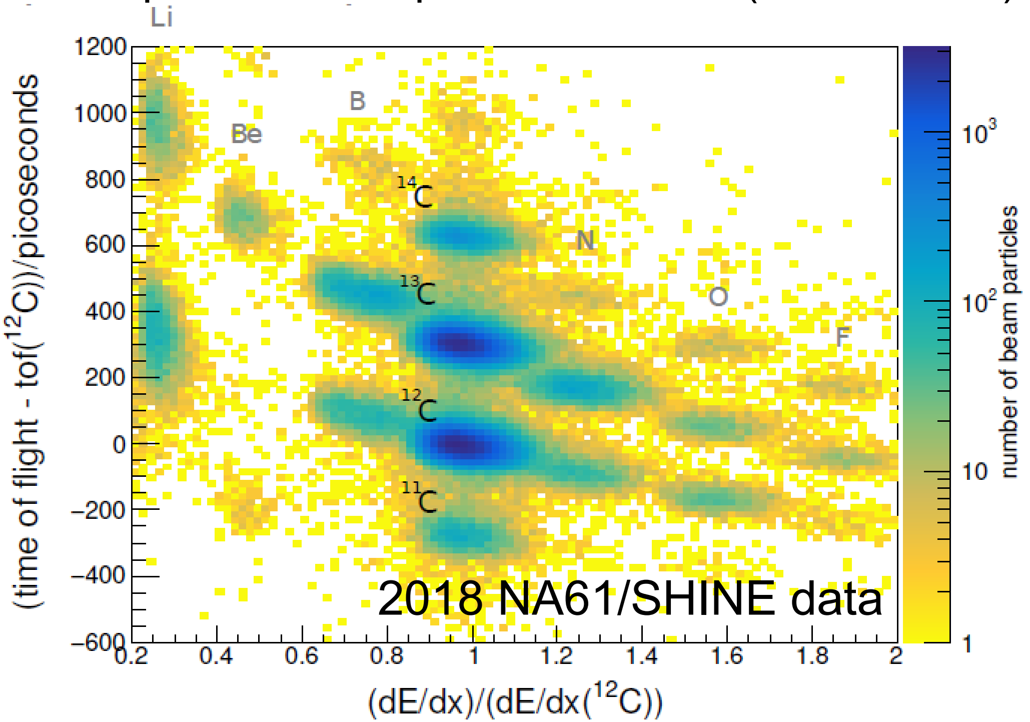
fragmented Pb beam



FLUKA simulation (N. Charitonidis)

- high-mass group (28-56) can saturate DAQ

upstream isotope identification (~240m TOF)



- Pilot run at 14AGeV/c, TOF res. ~30ps
- $\Delta t(^{12}C-^{13}C)$=300ps
- $\Delta t(^{56}Fe-^{57}Fe)$=75ps

→ difficult, but feasible

Summary

- Ideal range for relevant cosmic antinuclei cross section studies is p_{lab}=100-500GeV/c for p-p

- Full QM model for antinuclei formation needs to be further developed and validated

- More high-statistics p-p measurements are needed
  → **upgraded NA61/SHINE ideally suited**