Motivation for Deuteron Cross-sections Measurements at the SPD

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Proposal for Measurement

Measurements of deuteron cross-sections in unpolarized $p + p$ data at both stage I and stage II (possibly also anti-deuterons)

Context

- Deuterons (d) as a component of the cosmic rays (CR) are of interest to the astrophysics community
- Ratios of elements (H/He, B/C etc.) give information about composition of CR, density of interstellar medium (ISM), galactic transport etc.
- Ratios of isotopes ($d/H, {}^3He/{}^4He$) are of particular interest as they give information about production mechanism (nucleosynthesis, or beyond-SM-processes)
- Antiparticles ($e^+, \bar{p}$ etc.) are of even more interest as excess of antiparticles could indicate productions from annihilation of Dark Matter (indirect detection)
- $e^+, \bar{p}$ fux so far are inconclusive, but anti-nuclei (i.e. $\bar{d}$) would be 'smoking gun' signatures as SM background are heavily suppressed - $\sim 10^{-3}$ for every added nucleon

Cosmic Rays

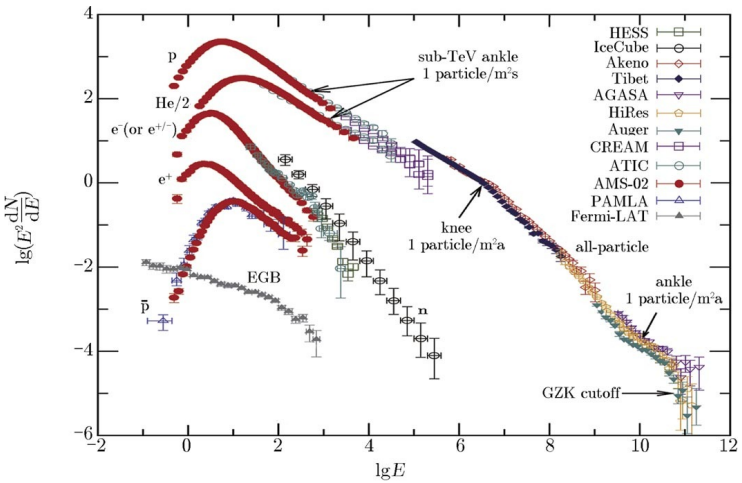

Figure 1: Energy distributions of the cosmic rays (Chinese A & A 43, 327-341 2019)

- CR : practically 90% H (proton p) and rest 10% essentially He. All heavier elements combine to ~ 1%
- CR pass through and interact with ISM which also is composed of 89% H and 10% He
- $p + p$ are 9 times more likely than $p + He$ and 80 times more likely than $He + He$
- Secondary productions of elements in $p + p$ processes are significant and therefore, important
- CR+ISM interactions are like fixed target exp. with CR as beam and ISM as target (σ are plotted as function of CR kinetic energy T)

Interest in Deuteron Productions

- Secondary d production from CR+ISM interaction has two sources : (1) fragmentation of He ($p + He \rightarrow d + X$) and (2) from $p + p \rightarrow d + X$
- Below $T = 1$ GeV, resonance production $p + p \rightarrow d + \pi^+$ dominates
- Above 1 GeV, He-fragmentation dominates - $\sigma \sim$ 2-3 orders of magnitude higher than from $p + p$ but it can still be significant given the abundance of $p + p$ (CR+ISM) scattering

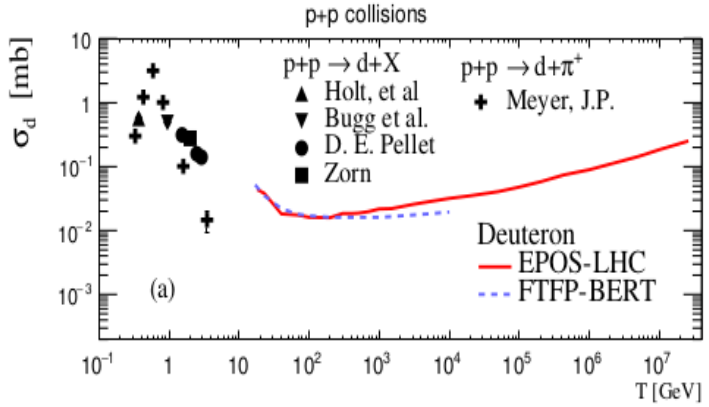

Figure 2: Deuteron productions in $p + p$ interactions : resonance production in low energies and coalescence model prediction at high energies (Phys. Rev. D 98, 023012 2018)

Deuteron Flux from AMS-02

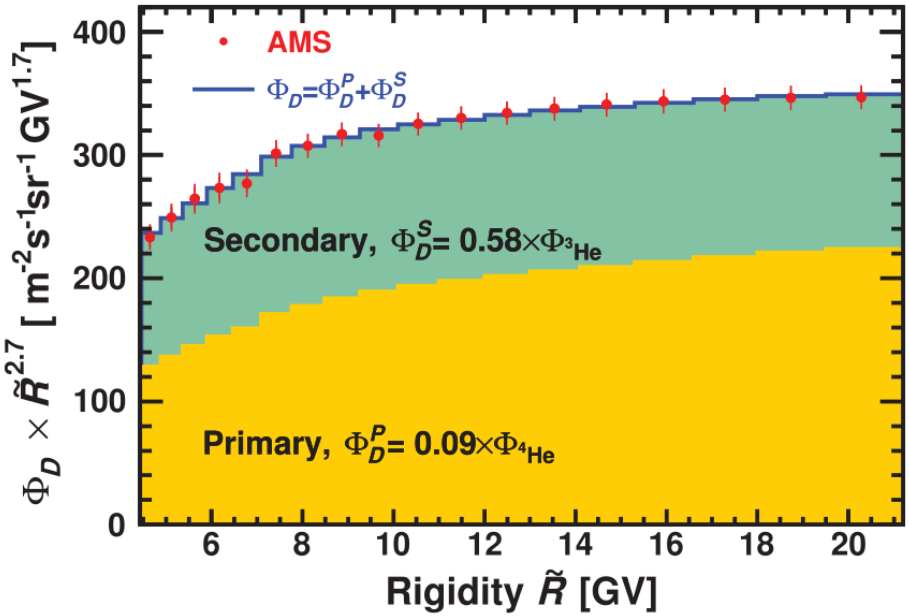

Figure 3: Deuteron flux as function of rigidity measured by AMS-02 (Phys. Rev. Lett. 132, 261001 2024)

- Rigidity $R = p/Q$, also GV instead of GeV is probably cosmic physics community standard jargon
- Nucleosynthesis calculations and subsequent galactic transport predict negligible primary d in CR
- The measurements from AMS-02 (brand new - published in June, 2024) with the fit (primary + secondary) is a surprise - all the more reason to understand d productions in various processes

Anti-deuteron Productions

- Coalescence of p, n into d and $\bar{p}, \bar{n}$ into $\bar{d}$ are essentially equivalent processes
- Studying d coalescence production at high energies also gives information on secondary $\bar{d}$ production from cosmic rays - the main SM background for any $\bar{d}$ signal from Dark Matter annihilation

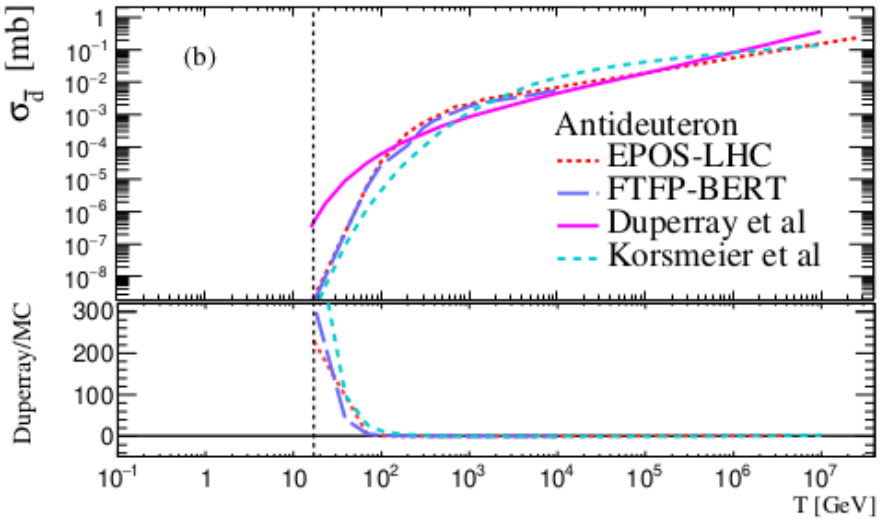

Figure 4: Predictions for anti-deuteron ($\bar{d}$) productions in $p + p$ interactions above threshold (Phys. Rev. D 98, 023012 2018)

Coalescence Productions

- Number of 'coalesced' composite particle is proportional to the product of number densities of constituents
- $\gamma_d \frac{d^3N_d}{dp_d^3} = \frac{4\pi}{3} p_0^3 (\gamma_p \frac{d^3N_p}{dp_p^3})(\gamma_n \frac{d^3N_n}{dp_n^3})$
- p_0 is the coalescence parameter (unit of momentum)
- Imagine a bubble in momentum phase space within which two constituents have to be to coalesce (it can hide many other effects)
- Extracted values of $p_0 \sim 100$ MeV, implying the difference in momenta of the proton and the neutron should be small

Coalescence (Anti-)Deuteron Productions

Phys. Rev. D 98, 023012 2018

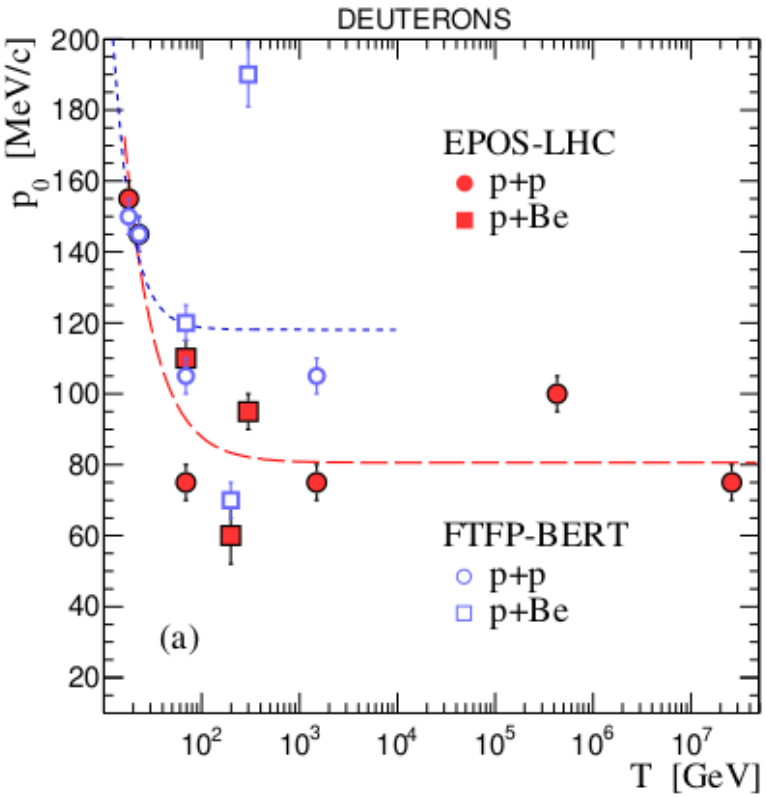

Figure 5: Coalescence parameter extracted from fitting data for d productions

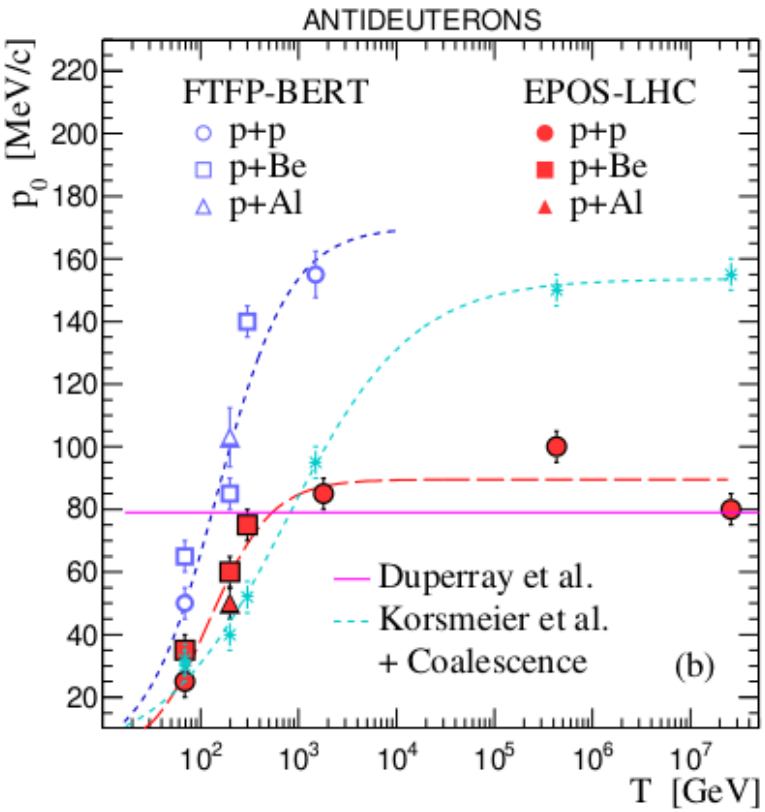

Figure 6: Coalescence parameter extracted from fitting data for $\bar{d}$ productions

Fixed Target and Collider Energies

- $\sqrt{s} = 5$ GeV at SPD would correspond to $T = 12.5$ GeV CR
- $\sqrt{s} = 10$ GeV at SPD would correspond to $T = 52.4$ GeV CR
- $\sqrt{s} = 27$ GeV at SPD would correspond to $T = 387.7$ GeV CR
- SPD measurements of d cross-sections may be able to add multiple high precision data points, helping to reduce experimental uncertainties in galactic propagation parameters and also contribute towards better understanding of coalescence productions of light nuclei

Summary

- SPD stage I physics paper already suggests anti-proton measurements in aid of DM search. This will be a complementary measurement towards the same goal
- Important for astrophysics and cosmic ray physics community but not connected to spin physics
- Meaningful measurement and publication for both stage I and stage II data from recorded hard scattering data
- At stage I, PID from ST energy deposition and at stage II, ST + TOF might be enough to make decent cross-section measurements
- Simulation study required to see what sort of precision we can achieve - on that note, any group with a young member willing to do simulation studies? ☺

Thank You

Backup

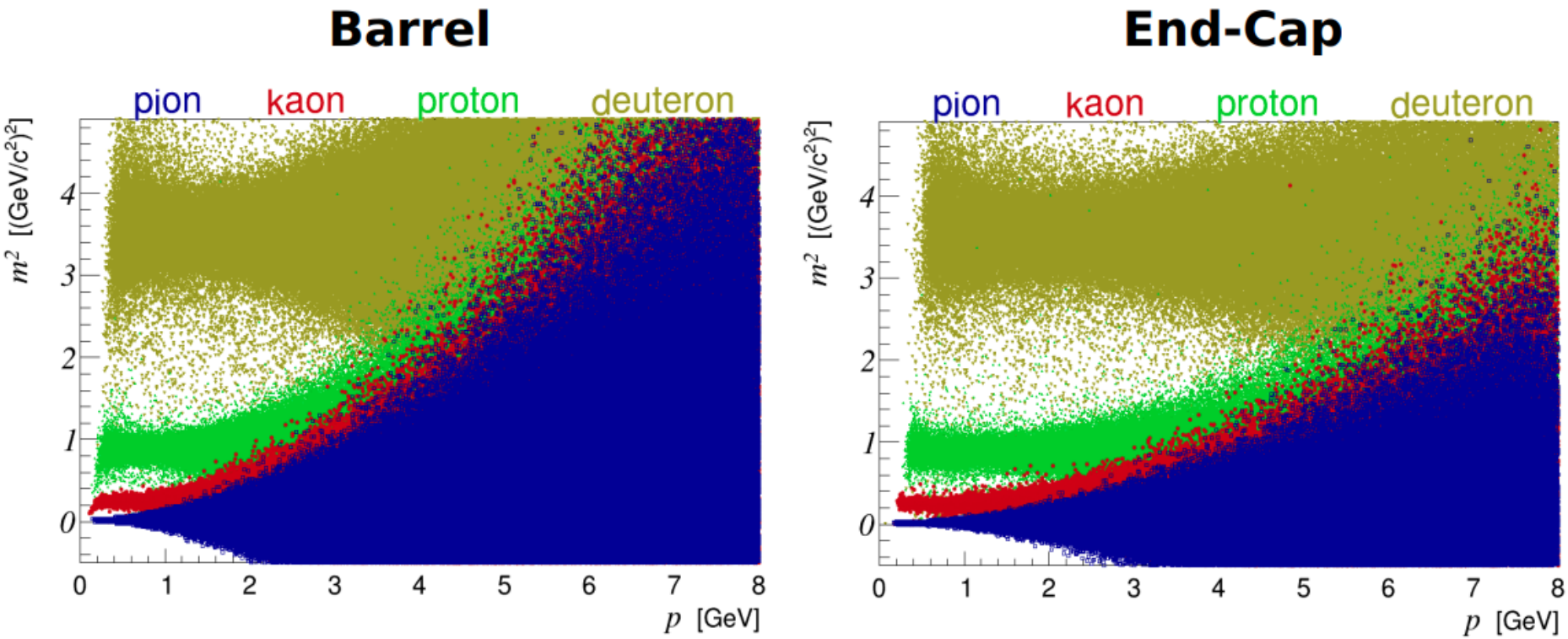

Figure 7: PID from Time of Flight detector - Artem Ivanov