Indirect DM detection using cosmic antideuterons: challenges and prospects

Sebastian Wild
Physics Department, TU München

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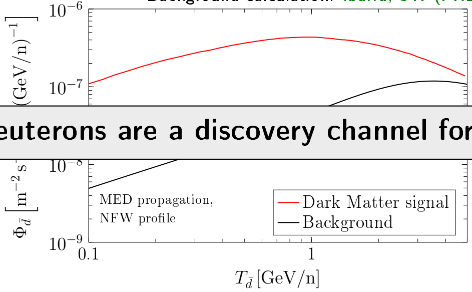
in collaboration with **A. Ibarra**

Indirect DM detection with antideuterons

- Why using **antideuterons** $\bar{d} = [\bar{p}\bar{n}]$ for indirect DM detection?
  - Kinematically suppressed $\bar{d}$ background flux from cosmic ray spallations at low kinetic energies $T_{\bar{d}} \lesssim 1\,\mathrm{GeV/n}$
  - In many models, the expected Dark Matter contribution to the $\bar{d}$ flux exceeds the spallation background (Donato et. al., PRD '00)
  - "Vanilla example": $\chi\chi \to b\bar{b}$, $m_\chi = 100\,\mathrm{GeV}$, $\langle\sigma v\rangle = 3 \cdot 10^{-26}\,\mathrm{cm}^3/\mathrm{s}$

Background calculation: Ibarra, SW (PRD '13)



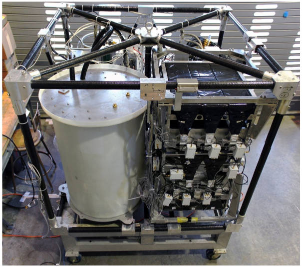
Antideuterons are a discovery channel for DM!

Current experimental situation

→ Up to now, no antideuteron has been found in cosmic rays!

AMS-02 is currently taking data

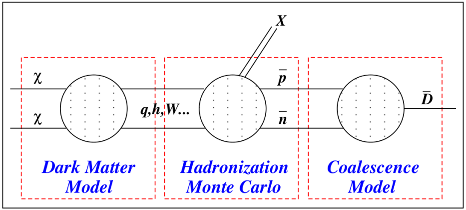
GAPS is a balloon-borne experiment
↪ first science flight ∼2017



The experimental situation on cosmic antideuterons
will change in the near future!

Production of antideuterons in DM annihilations

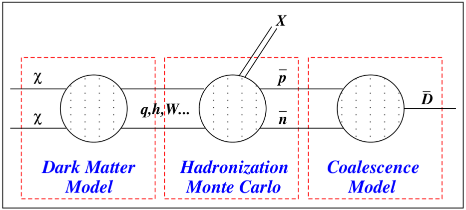
Figure from Baer, Profumo (JCAP '05)



- Dark Matter Model: anything with hadronic final states (W,Z,b,u,...)
- Hadronization: Simulated with e.g. PYTHIA
  ↪ production of a $\bar{p}$ - $\bar{n}$ pair in some events
- Coalescence Model:
  Calculate the probability of forming an $\bar{d}$ out of an $\bar{p}$ - $\bar{n}$ pair
  ↪ Not included in the MC event generators!

The coalescence model

Figure from Baer, Profumo (JCAP '05)



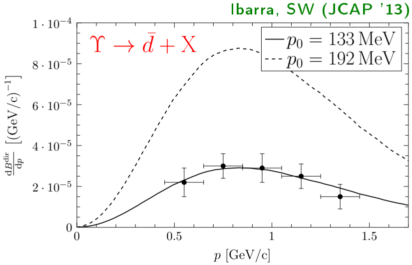
State of the art: **Coalescence Model** on an event-by-event basis

- $\bar{d}$ forms if $\left|\vec{k}_{\bar{p}} - \vec{k}_{\bar{n}}\right| \leq p_0 = \mathcal{O}(100\,\mathrm{MeV})$
- The usually adopted value of the coalescence momentum p_0 is obtained from a measurement of antideuterons in **Z decays** at LEP:
  - ↪ $(5.9 \pm 1.8 \pm 0.5) \times 10^{-6}$ $\bar{d}$ per hadronic Z decay
  - ↪ This number is reproduced by choosing $p_0 = (192 \pm 30)\,\mathrm{MeV}$

Determination of the coalescence momentum p_0 (1)

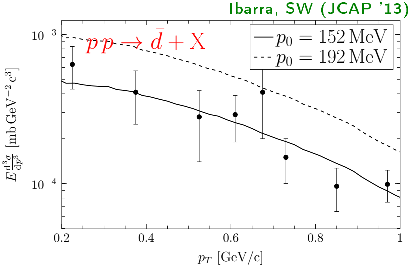
Can we safely use $p_0 = 192\,\mathrm{MeV}$ for $\bar{d}$ production in DM annihilations (or spallation processes)?

Answer: no!



$\bar{d}$'s in Υ decay:

$p_0^{\text{best fit}} = 133\,\mathrm{MeV}$



$\bar{d}$'s in pp collisions at $\sqrt{s} = 53\,\mathrm{GeV}$:

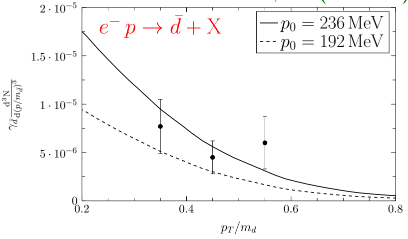
$p_0^{\text{best fit}} = 152\,\mathrm{MeV}$

Determination of the coalescence momentum p_0 (1)

Can we safely use $p_0 = 192\,\mathrm{MeV}$ for $\bar{d}$ production in DM annihilations (or spallation processes)?

Answer: no!

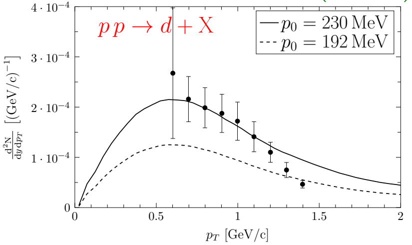
Ibarra, SW (JCAP '13)



$\bar{d}$'s in $e^- p$ collisions at $\sqrt{s} = 318\,\mathrm{GeV}$:

$p_0^{\text{best fit}} = 236\,\mathrm{MeV}$

Ibarra, SW (JCAP '13)



d's in pp collisions at $\sqrt{s} = 7\,\mathrm{TeV}$:

$p_0^{\text{best fit}} = 230\,\mathrm{MeV}$

Determination of the coalescence momentum p_0 (2)

Results:

- Coalescence model **is** able to reproduce measured $\bar{d}$ spectra, **but**:

Apparently, p_0 depends on underlying process and $\sqrt{s}$

$$133\,\mathrm{MeV} \lesssim p_0 \lesssim 236\,\mathrm{MeV}$$

- This dependence is **not understood** and needs further investigation
  - $\hookrightarrow$ Coalescence model too simplistic? Problem with PYTHIA?
  - $\hookrightarrow$ Induced uncertainty on $N_{\bar{d}} \propto p_0^3$: factor of ~ 5.5 (or more?)

Prospects for antideuteron detection at AMS-02 and GAPS in light of the PAMELA $\bar{p}/p$ constraints

Calculating constraints on the maximally allowed $\bar{d}$ flux

PAMELA $\bar{p}/p$ data puts stringent limits
on DM with hadronic annihilation products

Model independent method:

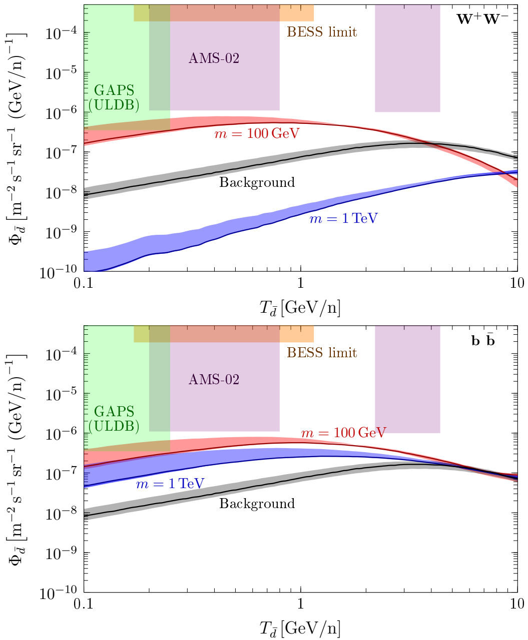
- We analyze annihilations into W^+W^- and $b\bar{b}$
- For fixed m_χ, we calculate upper limits (95 % C.L.) on $\langle\sigma v\rangle$ from the $\bar{p}/p$ data
- Then we use this value of $\langle\sigma v\rangle$ to get the **maximally allowed** $\bar{d}$ flux

Remarks:

→ We use a semi-analytical solution of the standard two-zone diffusion model for propagation of $\bar{p}$ and $\bar{d}$

→ Propagation and Halo uncertainties almost cancel out in the upper limit on the $\bar{d}$ flux

→ Due to our partial ignorance, we use $p_0 = 192\,\mathrm{MeV}$ ($\approx$ central value)



Ibarra, SW (JCAP '13)

- Red and blue curves: Maximally allowed $\bar{d}$ fluxes ($m_\chi = 100\,\mathrm{GeV}/1\,\mathrm{TeV}$)

$\Downarrow$

The observation of $\bar{d}$'s at AMS-02 and GAPS will be challenging

- However, the DM induced $\bar{d}$ flux can still be **well above the background**

Conclusions

Coalescence Model:

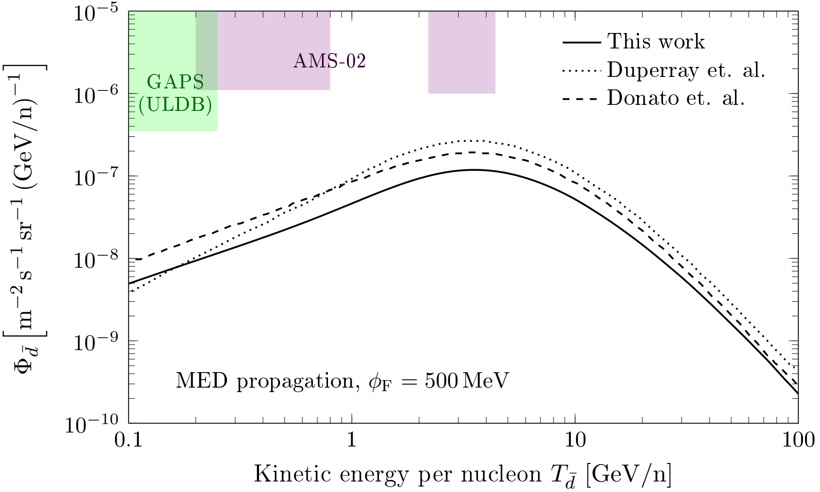
- We find that the coalescence momentum p_0 can **vary significantly** from process to process
  $\hookrightarrow$The formation process of antideuterons in high-energy collisions has to be better understood

Prospects for AMS-02 and GAPS:

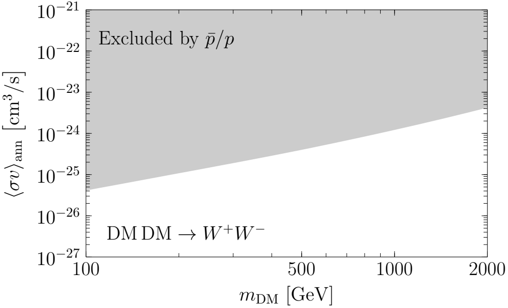
- Non-observation of an excess in antiprotons puts **severe constraints** on the possibility of a $\bar{d}$ signal from DM annihilations:
  - at **AMS-02**: $\bar{d}$ signal is unlikely, independent of the propagation parameters or halo profile
  - at **GAPS (ULDB)**: $\bar{d}$ signal is marginally possible for specific propagation setups, small enough m_χ and for saturation of the PAMELA $\bar{p}/p$ limits

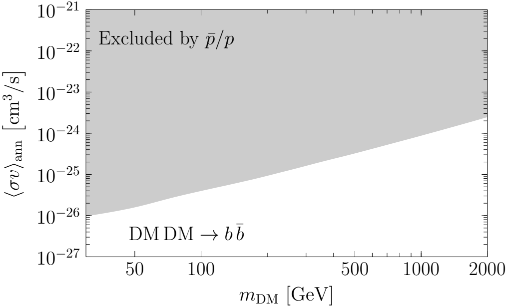
$\Rightarrow$ More sensitive experiments for antideuterons are necessary

Backup slides

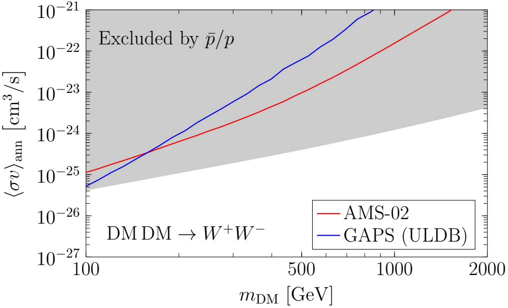


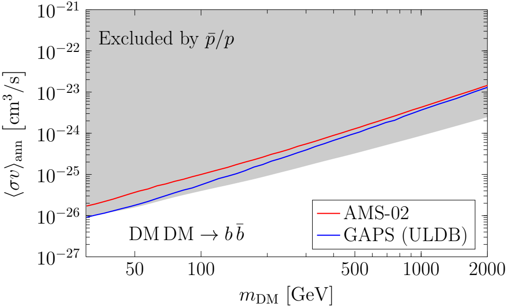
We use, for the first time, an **event-by-event** analysis for calculating the $\bar{d}$ production cross section in spallation processes





- Shaded regions: 95% C.L. exclusion from PAMELA $\bar{p}/p$
  $\hookrightarrow$ using NFW profile,
  MED propagation parameters

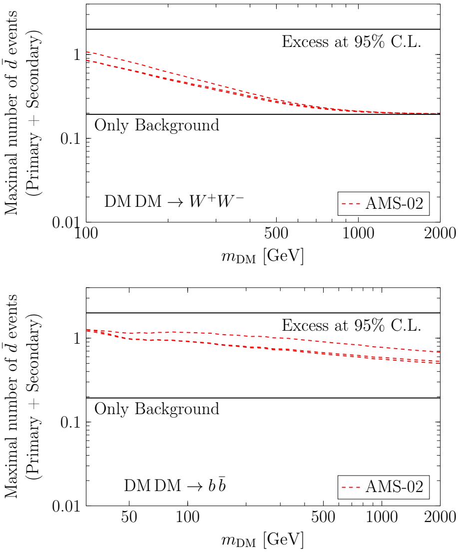




- Shaded regions: 95% C.L. exclusion from PAMELA $\bar{p}/p$
  ↪ using NFW profile, MED propagation parameters

- Red and blue: cross sections necessary for an expectation of a primary $\bar{d}$ signal at 95% C.L.

Maximimal number of $\bar{d}$ events at AMS-02

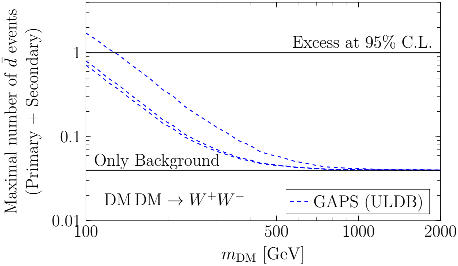


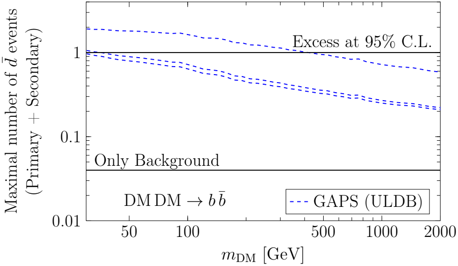
- Red curves:
  Maximal number of $\bar{d}$ at AMS-02 compatible with $\bar{p}/p$ constraints (MIN, MED, MAX)
- Propagation uncertainties largely cancel out (similar for halo profile uncertainties)

↓

Excess at 95% C.L. (= 2 events) is in **strong tension** with $\bar{p}/p$ constraints!

Maximimal number of $\bar{d}$ events at GAPS (ULDB)



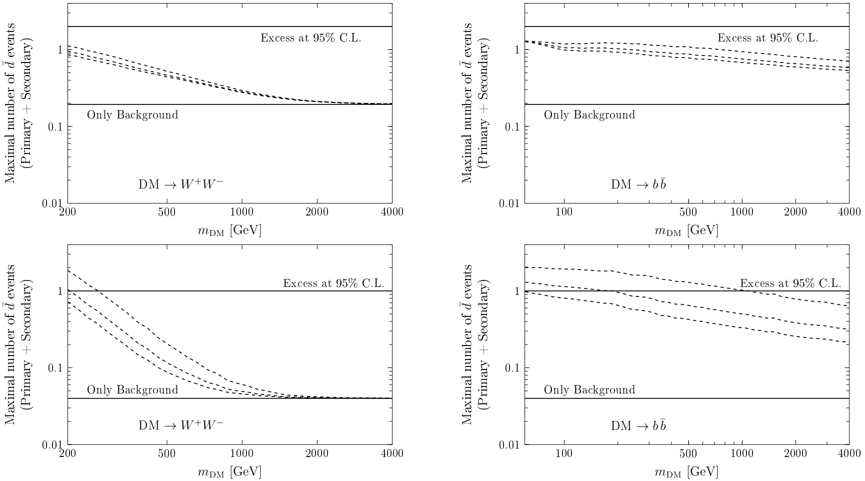


- Blue curves:
  Maximal number of $\bar{d}$ at GAPS (ULDB) compatible with $\bar{p}/p$ constraints (MIN, MED, MAX)

  ↓

  Excess at 95% C.L. (= 1 event) **only possible** for MAX propagation and
  $m_\chi < 125\,\mathrm{GeV}\ (W^+W^-)$
  $m_\chi < 400\,\mathrm{GeV}\ (b\bar{b})$

Maximal number of events for decaying Dark Matter



Upper panel: AMS-02, lower panel: GAPS (ULDB)