Status and challenges of the coalescence model

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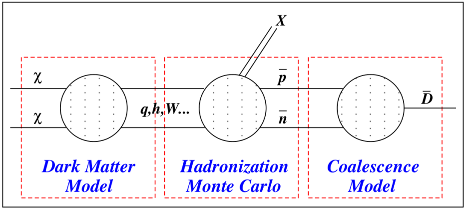
Based on 1209.5539 (JCAP '13) and 1301.3820 (PRD '13)
in collaboration with Alejandro Ibarra

Production of antideuterons

[Figure from Baer, Profumo (2005)]



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$\chi\,\chi \to W^+ W^-$, $\chi\,\chi \to b\,\bar{b}$, $\ldots$, or $p\,p \to$ anything

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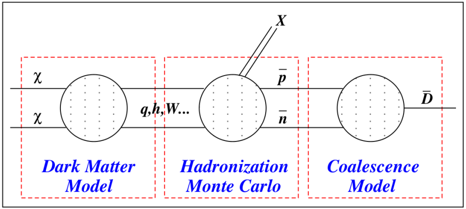

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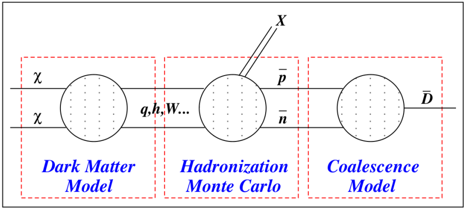

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3) Physics of the formation of an antideuteron out of a $\bar{p} - \bar{n}$ pair:
   - **Coalescence model**
   - (or something else?)

The coalescence model

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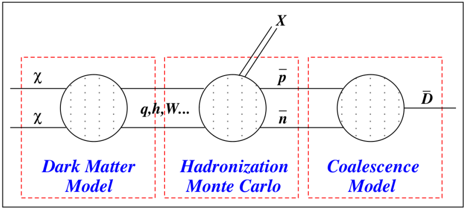

Formation of an antideuteron out of a $\bar{p}$-$\bar{n}$ pair: **Coalescence model**
[Butler, Pearson 1963; Csernai, Kapusta 1983; Kadastik, Raidal, Strumia 2009]

$$\bar{d} \text{ forms if } \left|\vec{k}_{\bar{p}} - \vec{k}_{\bar{n}}\right| \leq p_0 = \mathcal{O}\left(100\,\mathrm{MeV}\right)$$

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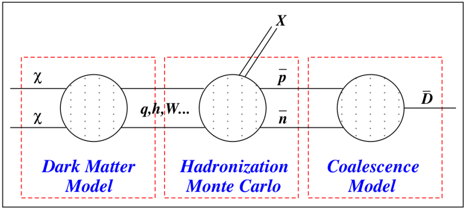

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Central questions which I want to address here:

1) How can this simple model be validated?
2) What is the value of the **coalescence momemtum** p_0?
3) Physically, one expects the coalescence momentum p_0 to be **universal**
   $\hookrightarrow$ Is this supported by experimental data?

Factorized coalescence model

Coalescence model: $\left|\vec{k}_{\bar{p}} - \vec{k}_{\bar{n}}\right| \leq p_0$

$$\Downarrow$$

$$\gamma_{\bar{d}} \frac{\mathrm{d}N_{\bar{d}}}{\mathrm{d}^3 k_{\bar{d}}} \left(\vec{k}_{\bar{d}}\right) \simeq \frac{1}{8} \cdot \frac{4}{3}\pi p_0^3 \cdot \gamma_{\bar{p}}\gamma_{\bar{n}} \frac{\mathrm{d}N_{\bar{p}}\mathrm{d}N_{\bar{n}}}{\mathrm{d}^3 k_{\bar{p}}\mathrm{d}^3 k_{\bar{n}}} \left(\frac{\vec{k}_{\bar{d}}}{2}, \frac{\vec{k}_{\bar{d}}}{2}\right)$$

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Factorized coalescence model: postulation of $\frac{\mathrm{d}N_{\bar{p}}\mathrm{d}N_{\bar{n}}}{\mathrm{d}^3 k_{\bar{p}}\mathrm{d}^3 k_{\bar{n}}} = \frac{\mathrm{d}N_{\bar{p}}}{\mathrm{d}^3 k_{\bar{p}}} \cdot \frac{\mathrm{d}N_{\bar{n}}}{\mathrm{d}^3 k_{\bar{n}}}$

- Used in many works up to ~ 2009
- In particular, the factorized coalescence model has been **tested** against experimental data
  [Chardonnet et. al. 97, Duperray et. al. '05]

Event-by-event coalescence model

State of the art:

Direct, i.e. **event-by-event** implementation of the coalescence condition $\left|\vec{k}_{\bar{p}} - \vec{k}_{\bar{n}}\right| \leq p_0$

[Kadastik, Raidal, Strumia 2009]

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- Importance of **spatial separation**: [Ibarra, SW 2013, Fornengo et. al. 2013]
  $\rightarrow$ exclude antinucleons originating from weak decays ($\bar{\Lambda}$, $\bar{\Sigma}^{\pm}$, ...),
  as they have a spatial separation $\Delta r \gg$ fm, and hence cannot coalesce

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  $\rightarrow$ exclude antinucleons originating from weak decays ($\bar{\Lambda}$, $\bar{\Sigma}^{\pm}$, $\ldots$),
  as they have a spatial separation $\Delta r \gg$ fm, and hence cannot coalesce
  $\rightarrow$ this affects...
  (a) the value of p_0 itself when tuning it do data
  (b) the predicted $\bar{d}$ yield from DM annihilations or spallation processes
  $\rightarrow$ has to be included self-consistently!
  $\rightarrow$ [**Side remark**: be careful when comparing different values of p_0:
  some works include this effect, some not]

Validating the event-by-event coalescence model

Using the event-by-event coalescence model requires some assumptions...:

- correctness of the physical idea of the event-by-event coalescence condition
- correctness of the $\bar{p}$-$\bar{n}$ correlations as they are predicted by Monte Carlo event generators

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$$\Downarrow$$

These assumptions underlying the event-by-event coalescence model have to be tested against data as much as possible!

- This issue is closely related to the determination of the coalescence momentum p_0

What is the value of p_0?

- In absence of a detailed underlying theoretical description, the only way of getting p_0 is **tuning its value to available data**
- Method employed in (almost) all works: **Multiplicity** of antideuterons from Z boson decay measured by ALEPH
  - ↪ We use an event-by-event analysis with PYTHIA 8 to determine p_0 according to this measurement
  - ↪ Result: $p_0 = (192 \pm 30)$ MeV

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  - ↪ Result: $p_0 = (192 \pm 30)$ MeV
- Note that this is a fit of *one* parameter to *one* data point
  - ↪ this does of course **not validate** the correctness and applicability of the event-by-event coalescence model
  - ↪ in particular, it does **not** prove the existence of a universal p_0

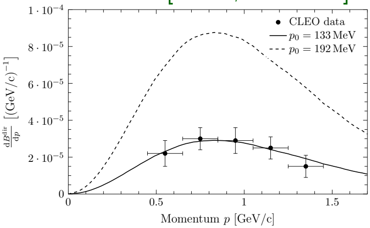
$$\Downarrow$$

Hence, we tried to fit p_0 to all available data sets on antideuteron production

Using all available data sets for obtaining p_0

$$\boxed{\Upsilon(1S) \to \bar{d} + X} \quad \left(\sqrt{s} = m_{\Upsilon(1S)} = 9.46 \text{ GeV}\right)$$

[Ibarra, SW 2013]



- **Momentum spectrum** of $\bar{d}$ produced in $\Upsilon(1S) \to ggg, gg\gamma$ decays, measured by CLEO.
- Best fit: $p_0 = 133$ MeV (PYTHIA 8) $\hookrightarrow$ extremely good fit ($\chi^2/\text{df} = 0.15$)
- $p_0 = (192 \pm 30)$ MeV from Z decay measurement is **in tension** with the data

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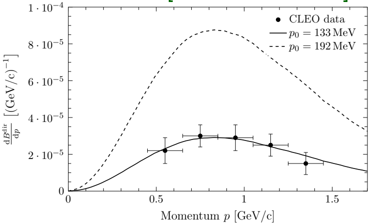

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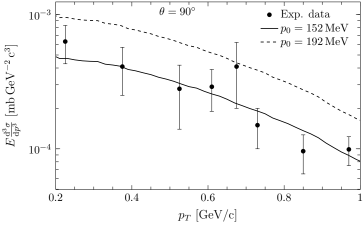
- p_0 only changes the normalization of the $\bar{d}$ spectrum, hence it is a non-trivial result that the *spectrum* is reproduced by the coalescence model!

Using all available data sets for obtaining p_0

$$\boxed{pp \to \bar{d} + X} \quad (\sqrt{s} = 53 \text{ GeV})$$

[Ibarra, SW 2013]



- pp collisions at ISR at $\sqrt{s} = 53$ GeV, $\bar{d}$ spectrum measured at $\theta = 90°$
- Best fit: $p_0 = 152$ MeV (PYTHIA 8)
  $\hookrightarrow$ extremely good fit (χ^2/df $= 0.6$)
- $p_0 = (192 \pm 30)$ MeV from Z decay measurement is compatible with the data

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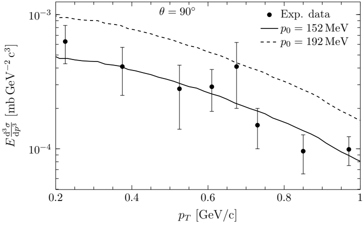

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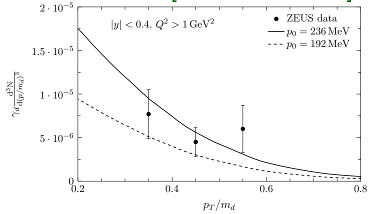
- This is precisely the process mainly responsible for the $\bar{d}$ spallation background, but with $\sqrt{s} \gg \sqrt{s}_{\text{spallation}} \simeq 8 - 10$ GeV
  $\hookrightarrow$ we use $p_0 = 152$ MeV for our calculation of the $\bar{d}$ background [Ibarra, SW 2014]

Using all available data sets for obtaining p_0

$$\boxed{e^- p \to \bar{d} + X} \; (\sqrt{s} = 318 \text{ GeV})$$

[Ibarra, SW 2013]

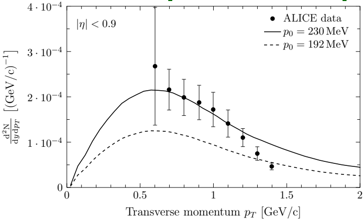


- Antideuteron production in deep inelastic $e^- p$ scattering at $\sqrt{s} = 318$ GeV measured by ZEUS.
- Best fit: $p_0 = 236$ MeV (PYTHIA 6)
  $\hookrightarrow$ good fit ($\chi^2/\text{df} = 1.0$), but not very conclusive data set due to only three data points

Using all available data sets for obtaining p_0

$$\boxed{pp \to d + X} \quad (\sqrt{s} = 7 \text{ TeV})$$

[Ibarra, SW 2013]



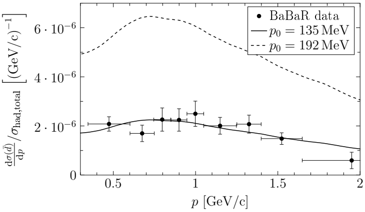
- Momentum spectrum of **deuterons** produced in pp collisions at $\sqrt{s} = 7$ TeV, measured by ALICE (preliminary data).
- Best fit: $p_0 = 230$ MeV (PYTHIA 8) $\hookrightarrow$ rather poor fit ($\chi^2/\text{df} = 2.8$)
- $p_0 = (192 \pm 30)$ MeV from Z decay measurement is (also) in tension with the data

Using all available data sets for obtaining p_0

$$\boxed{e^+e^- \to q\bar{q} \to \bar{d} + X} \quad (\sqrt{s} = 10.58 \text{ GeV})$$

New results, not published! See also the talk by Brian Hamilton

[not published]



- Momentum spectrum of $\bar{d}$ produced in $e^+e^- \to q\bar{q}$ at $\sqrt{s} = 10.58$ GeV, measured by BaBaR.
- Best fit: $p_0 = 135$ MeV (PYTHIA 8) $\hookrightarrow$ very good fit ($\chi^2/\text{df} = 0.89$)
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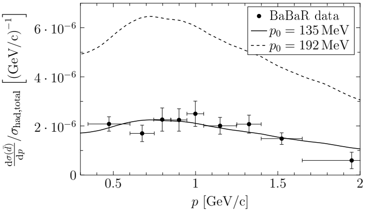

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This data set is **particularly interesting**, as it directly resembles a $\simeq 10$ GeV dark matter particle annihilating into a "mixed" $q\bar{q}$ state
$\hookrightarrow$ relevant channel for AMS-02 and GAPS!

Fitting p_0 to data: interpretation

Interpretation of these results: (within PYTHIA)

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  $\hookrightarrow$ Confirmation of the $\bar{p} - \bar{n}$ correlations in PYTHIA?

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  $\hookrightarrow$ Confirmation of the $\bar{p} - \bar{n}$ correlations in PYTHIA?
- Note that data from pA and AA collisions can not be used within the event-by-event approach

Fitting p_0 to data: interpretation

Tempting interpretation:

> Event-by-event coalescence is valid,
> but p_0 depends on underlying process and $\sqrt{s}$

- This dependence is **not understood** and needs further investigations
  $\hookrightarrow$ Induced uncertainty on $N_{\bar{d}} \propto p_0^3$: (at least?) a factor of ~ 5.5

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Alternative explanations:

- Problem within PYTHIA?
  $\hookrightarrow$ $\bar{p}$-$\bar{n}$ correlations are not part of the tuning in PYTHIA
  $\hookrightarrow$ see talk by Lars Dal for a similar analysis using Herwig
- Coalescence model itself too simplistic?
  $\hookrightarrow$ classical description not applicable?

Summary & Conclusions

- State-of-the-art method for calculating $\bar{d}$ formation:
  event-by-event coalescence model
  ↪ this in principle captures all (anti-)correlations of $\bar{p}$ and $\bar{n}$ production
- However, this relies on a Monte Carlo event generator for simulating the production of $\bar{p} - \bar{n}$ pairs
  ↪ e.g. PYTHIA is in principle not tuned for this task

Hence, one **has to check** the combination of the Monte Carlo generator plus the event-by-event coalescence model using all available data!

- We did this using PYTHIA, and found that **no choice of** p_0 can simultaneously fit all data sets
  ↪ however, the individual spectra can be reproduced quite successfully
- **How could this situation be improved?**
  a) More experimental data is needed, in particular at low $\sqrt{s}$
  b) Tuning of Monte Carlo generators?
  c) Better understanding of $\bar{d}$ formation from the nuclear physics side