Anti-deuteron measurements at LHCb

Sophie Baker
on behalf of the LHCb collaboration

Imperial College London

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Motivation

Attempting to measure deuterons, d, produced in pp collisions at the LHC using the LHCb detector.

Measurements of anti-deuterons in high energy physics can be used to estimate the background of secondary anti-nuclei in indirect dark matter searches [Aramaki (2015), Korsmeier (2017)].

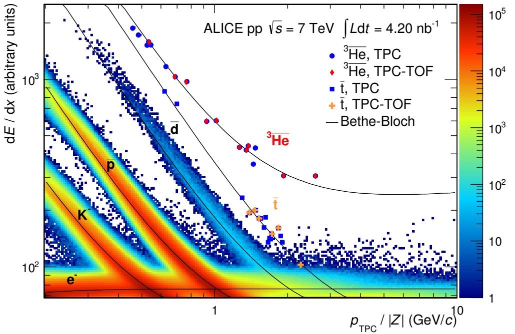
No convincing e^+ or $\overline{p}$ excess has been seen in indirect DM searches. These light antiparticles have high backgrounds, which are reduced for heavier antimatter.

ALICE measurement

Deuterons and other heavy nuclei have been measured at the LHC using the ALICE detector, which was designed for the study of heavy ions.

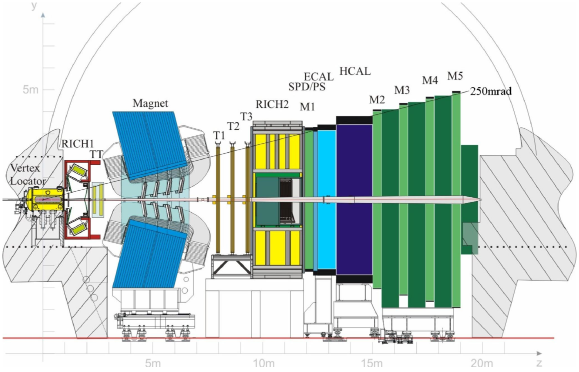
A time projection chamber is used to identify charged particles with energies of a few GeV, in the central rapidity region, $|\eta| < 0.9$, where equal abundances of matter and anti-matter are seen.

LHCb has coverage for particles with energies up to $100\,\mathrm{GeV}$ in the region $1.9 < \eta < 4.9$.



[Phys. Rev. C 97 (2018) 024615]

LHCb



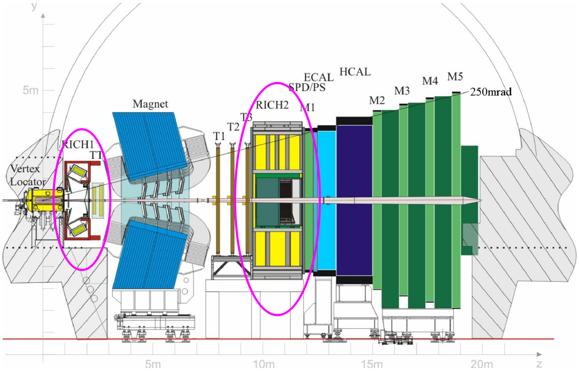
[Int. J. Mod. Phys. A 30 (2015) 1530022]

A forward single-arm spectrometer designed for the study of b-hadron decays from pp collisions.

Unique in its geometry and in its particle identification (PID) capabilities.

PID of e, μ, π, K and p using a combination of ring-imaging Cherenkov (RICH) detectors, calorimeters, and muon stations.

LHCb



[Int. J. Mod. Phys. A 30 (2015) 1530022]

For d identification, the RICH detectors are the most important, each with different kinematic coverage:

RICH 1: $2 < p_\pi < 40\,\text{GeV}/c$
RICH 2: $15 < p_\pi < 100\,\text{GeV}/c$.

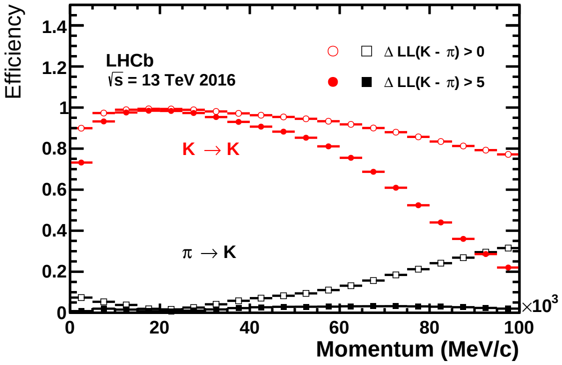
The RICH algorithm links rings of Cherenkov photons to tracks of charged particles, where the size of the ring and the momentum of the track, as measured in the tracking stations, are compared to mass hypotheses for charged particles.

LHCb

Each track is assigned a log-likelihood value, $\Delta\mathrm{LL}$, for each mass hypothesis, and tracks of a given particle type can be selected using these.

Data samples of control channels, such as $K^0_\mathrm{S} \to \pi^+\pi^-$ and $D_s^+ \to \phi(K^+K^-)\pi^+$, can be used to find the efficiency of selecting charged particles.

Cuts are applied to the log-likelihoods, and the efficiencies are the number of tracks passing the cuts, divided by the total number of tracks.



Efficiency for K to be selected as K, and for π to be misidentified as K.

[Eur. Phys. J. C (2013) 73:2431]

Making a deuteron measurement at LHCb

To make the measurement, select charged tracks in data that 'look' like d, then compare the yield to the expected signal and background.

Use minimum bias data samples, which have very loose trigger requirements, of pp collisions at centre-of-mass energy $\sqrt{s} = 13\ \mathrm{TeV}$ from 2016 and 2017.

Three key ingredients:

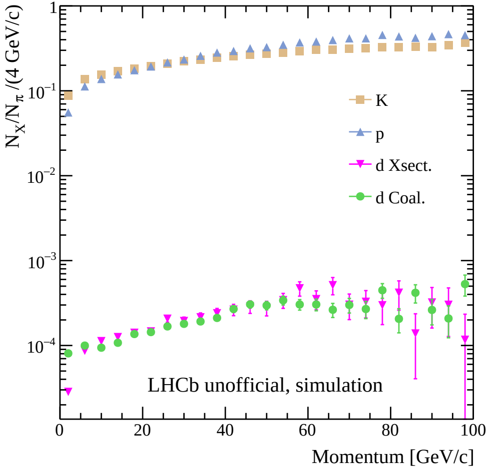
- estimate of the deuteron yield
- efficiency of deuteron identification
- level of background

Simulation of deuteron production

Generate d in pp collisions using two different production models: 'coalescence' and 'cross-section'.

Compare pp, pn and nn pairs and decide whether they should bond based on their momentum separation.

Relative d yield compared to π yield is low, $\mathcal{O}(10^{-4})$.



ID efficiency of deuterons

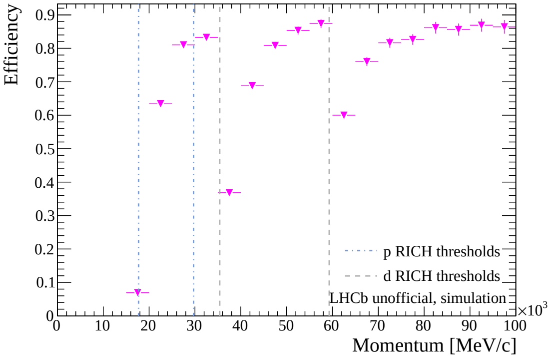
In order to see a deuteron signal, select tracks from pp collisions that 'look' like d according to the mass hypothesis log-likelihood values, $\Delta\mathrm{LL}(d-\pi)$, $\Delta\mathrm{LL}(d-K)$, $\Delta\mathrm{LL}(d-p)$.

For d, the efficiencies for passing the selection are found using MC samples,

$$\mathrm{Efficiency}(p) = \frac{N_{d\to d}(p)}{N_d(p)}.$$

Cherenkov thresholds in RICH 1 and RICH 2 for d are 35.4 and $59.3\,\mathrm{GeV}/c$.
For p they are 17.7 and $29.7\,\mathrm{GeV}/c$.

$$\Delta\mathrm{LL}(d-\pi) > 5 \;\&\; \Delta\mathrm{LL}(d-K) > 5 \;\&\; \Delta\mathrm{LL}(d-p) > 5$$



Mis-ID efficiency of background

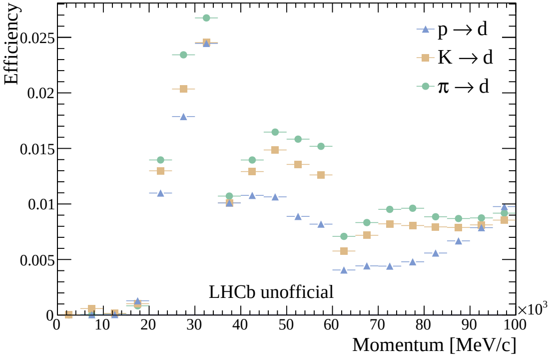
From data samples, find the efficiencies for p, K and π to pass the same d selection cuts, *e.g.*

$$\text{Efficiency}_\pi(p) = \frac{N_{\pi\to d}(p)}{N_\pi(p)}.$$

The high statistics of the control channels means that these efficiencies are well known.

In order to see d signal, need very low efficiencies for these.

$\Delta\text{LL}(d-\pi) > 5$ & $\Delta\text{LL}(d-K) > 5$ & $\Delta\text{LL}(d-p) > 5$



ID efficiency comparison

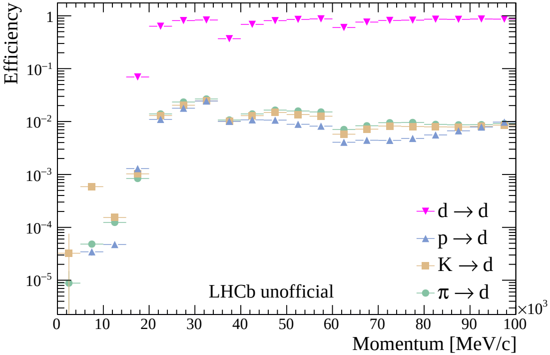
A high ID efficiency and a low mis-ID efficiency will allow for a significant d signal.

Remember that the signal to background level is predicted to be 1:10,000, so the selection needs to be optimised for this.

For harder cuts on $\Delta\mathrm{LL}$, the mis-ID efficiencies for π, K and p can be reduced to $< 10^{-4}$.

With full 2017 data set and given the knowledge of the background, we can expect sensitivity to a d signal, if the predicted d yield and the MC efficiencies are accurate.

$\Delta\mathrm{LL}(d-\pi) > 5$ & $\Delta\mathrm{LL}(d-K) > 5$ & $\Delta\mathrm{LL}(d-p) > 5$



Deuterons from b–baryon decays

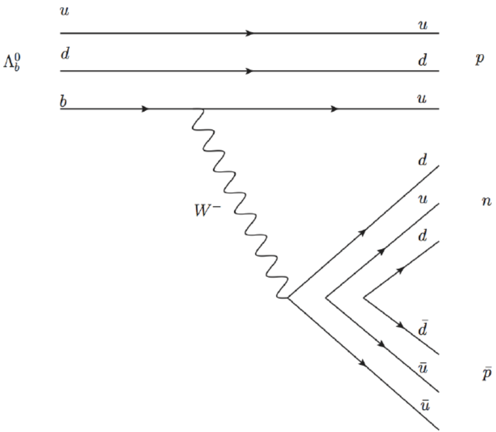
Many DM models predict that DM will annihilate favourably to $b\bar{b}$, which will hadronise, and may decay to $\bar{d}$ and appear in indirect DM searches. Observation of anti-deuterons from b-baryon decays in HE experiments can help to parametrise this process and lead to more meaningful DM results.

Measurements are being made of the channels $\Lambda_b^0 \to d\bar{p}$ and $\Lambda_b^0 \to d\bar{p}\pi^+\pi^-$.

These will be the first measurements of d from b-baryon decays.

The measurements will be made with respect to a normalisation channel, $\Lambda_b^0 \to \Lambda_c^+(pK\pi^+)\pi^-$, which has been measured previously at LHCb, has a high yield, and has similar kinematics to the signal channels.

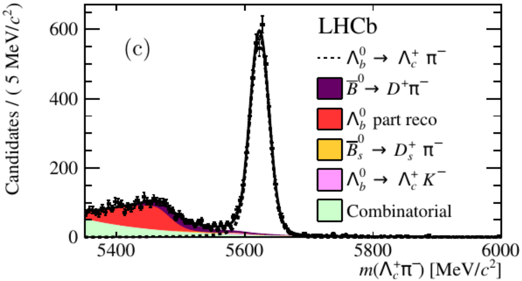
Deuterons from b–baryon decays



$\Lambda_b^0 \to d\bar{p}$ will go as $\Lambda_b^0 \to p\bar{p}n$, where pn bind to form d.

$\Lambda_b^0 \to \Lambda_c^+(pK\pi^+)\pi^-$

$3.05 < \eta(\Lambda_b^0) < 3.2$



[JHEP 08 (2014) 143]

Measurement of normalisation channel using $1\,\text{fb}^{-1}$ of data at centre-of-mass energy of $\sqrt{s} = 7\,\text{TeV}$.

Deuterons from b–baryon decays

$\Lambda_b^0 \to d\overline{p}$ and $\Lambda_b^0 \to d\overline{p}\pi^+\pi^-$ measurements are currently blinded in the Λ_b^0 mass windows.

The selection processes are being optimised, with little background expected, except for combinatorial backgrounds.

After vetoing the normalisation channel, select the signal using boosted decision trees.

Expect to have sensitivity for branching fractions down to $\mathcal{O}(10^{-8})$.

Conclusion

Exciting measurements being made, which push LHCb's particle identification capabilities to their limits.

Hoping for a first observation of deuterons at LHCb in the near future, and the first measurements of deuterons from b-hadron decays, with important outcomes for indirect DM measurements.

Backup: deuteron production models

Coalescence model: [Kapusta (1980)]

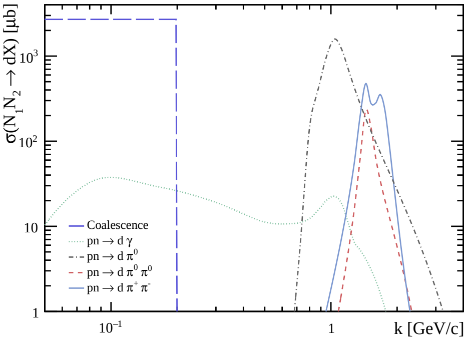
Used to describe data since 1963, but the measured threshold parameter for coalescence is not universal.

Assuming that p and n have the same mass and same p_T spectra, d production given by

$$E_d \frac{\mathrm{d}^3 N_d}{\mathrm{d}p_d^3} = B_d \left(E_p \frac{\mathrm{d}^3 N_p}{\mathrm{d}p_p^3} \right)^2 ,$$

where $B_d = \left(\frac{4\pi}{3m_p} p_0^3 \right)$, with p_0 the radius of the momentum sphere for coalescence.

$pn \to d$



Backup: deuteron production models

'Cross-section' model: [Dal & Raklev (2015)]

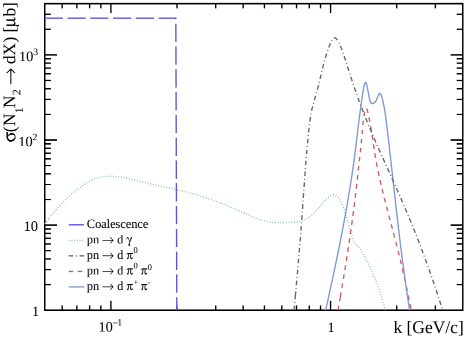
A probabilistic approach based on the momentum separation of the binding pair.

Production cross-section as function of CoM momentum difference, k,

$$\sigma(k) = \frac{ak^b}{(c - exp(dk))^2 + e},$$

where a, b, c, d, e are best fit parameters given in the paper.

$$pn \rightarrow d\gamma,\ pn \rightarrow d\pi^0,\ pn \rightarrow d\pi^0\pi^0,$$
$$pn \rightarrow d\pi^+\pi^-$$
$$pp \rightarrow dX,\ nn \rightarrow dX$$



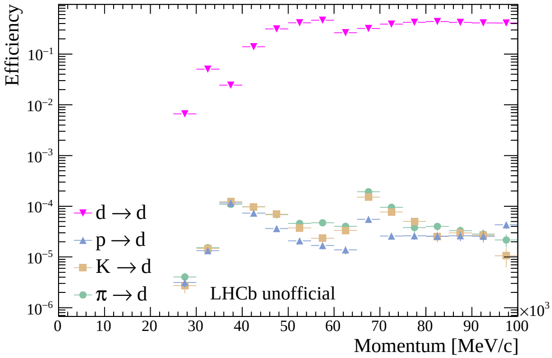
Backup: ID efficiency comparison

For very hard cuts on the ΔLL values, the mis-ID efficiencies of p, K and π can be reduced to the level of 10^{-4}.

The efficiencies for d found from MC are also reduced when doing this.

More study of this is needed in order to accurately know the uncertainties on the signal and background, and to find the optimal cuts in ΔLL.

$\Delta\text{LL}(d-\pi) > 30\ \&\ \Delta\text{LL}(d-K) > 30\ \&\ \Delta\text{LL}(d-p) > 30$

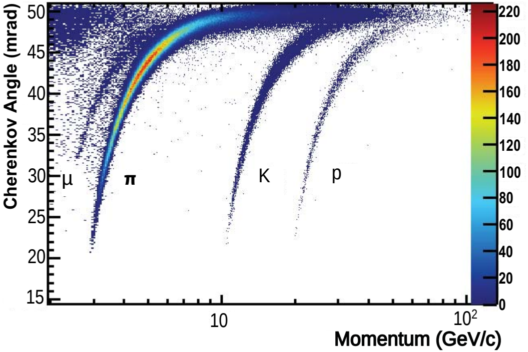


Backup: Cherenkov signal

Instead of using the RICH PID output, what if we try to look for the Cherenkov signal directly?

The d signal should appear as a curve to the right of the p signal in the θ_C vs. p plot. Why can't we see it there already?

Cherenkov angle not readily available in data, so make simplified study using MC.



[Eur. Phys. J. C (2013) 73:2431]

Backup: Cherenkov signal

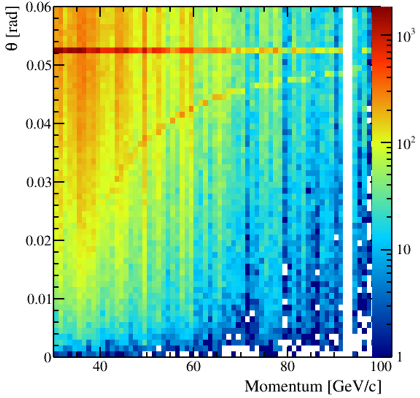
Want to judge whether the deuteron signal would be seen above the background of other Cherenkov photons, which comes mainly from π.

1. Take all d and π that are above the Cherenkov thresholds in an event
2. For each, generate Cherenkov photons in a cone about their track
3. Plot the angle between every photon track with each d and π track in the event, vs. momentum

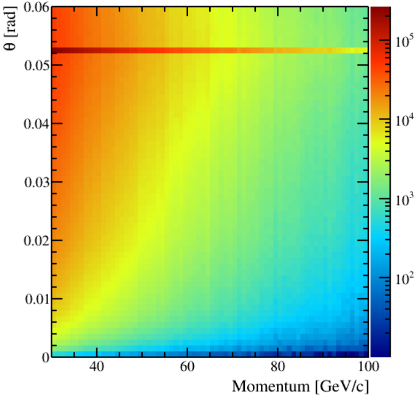
This last step estimates the background of photons paired with wrong particle tracks.

Backup: Cherenkov signal

d exclusive events



All events



There could be room for a statistical observation of d using this method, given enough data.