First measurement of anti-deuteron nuclear inelastic cross-section with ALICE

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Introduction

Low-energy cosmic-ray antideuterons - unique probe for indirect Dark Matter searches

- Low background from secondary production is expected
- Vital to determine precisely primary and secondary anti-deuteron flux!

![Diagram showing cosmic rays and antideuterons](image_url)
A long way to the detectors

Basic ingredients for anti-deuteron flux calculation:
• Propagation: common for all (anti-)particles
• Annihilation in interstellar medium, Earth’s atmosphere, …
• Production of anti-deuterons in pp, p\bar{p}, p-He, \bar{p}-He…
A long way to the detectors

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• Propagation: common for all (anti-)particles
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Precise nuclear inelastic cross-sections are needed to reduce large uncertainties from nuclear physics!
Status of $\bar{p}$ and $\bar{d}$ nuclear inelastic cross-sections

Anti-deuteron inelastic cross-section is poorly known at low energies

• No experimental data below $p = 13.3$ GeV/c [2]

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• Use ALICE to study anti-deuteron absorption in detector material!

Anti-protons [1]

Anti-deuterons [2]

(Anti-)deuterons on carbon

Within ALICE reach

LHC as an anti-matter factory

At LHC energies, particles and anti-particles are produced in almost equal amounts

*Primordial* anti-matter to matter ratio approaches unity with increasing $\sqrt{s}$

\[ \frac{d}{d} \text{ and } (\bar{p}/p)^2 \text{ ratios vs } p_T [1] \]

\[ \frac{\bar{p}}{p} \text{ ratio at mid-rapidity vs } \sqrt{s} [1] \]

This talk: results from p-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV, ~300 M events

Extrapolations for $\sqrt{s_{NN}} = 5.02$ TeV:

- $\bar{p} / p$: $R = 0.984 \pm 0.015$
- $\rightarrow \bar{d} / d$: $R = 0.968 \pm 0.030$

(assuming $\bar{d} / d \sim (\bar{p} / p)^2$)

More details about (anti-)nuclei production at LHC energies:

- E. Bartsch, Tue 05.11 15:40 [Collective dynamics and FSI]
- L. Barioglio, Wed 06.11 11:00 [Small systems]

... and ALICE detector material as a target

Material budget at mid-rapidity [1]:

• Beam pipe (~0.3% $X_0$)
• ITS (~8% $X_0$)
• TPC (~4% $X_0$)
• TRD (~25% $X_0$)
• Space frame (~20% $X_0$ between TPC and TOF detectors)

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Idea: analyse raw reconstructed anti-particle to particle ratios ($\bar{p} / p$ and $\bar{d} / d$)

- No correction due to detector efficiency or absorption in detector material
- Correct for secondary (anti-)particles from weak decays or spallation processes
- Constrain $\sigma_{\text{inel}}(\bar{d})$ via comparison with detailed Monte Carlo simulations based on Geant4

Particle identification in TPC and TOF

Complementary information from TPC and TOF detectors allows to select high-purity (anti-)particles

TPC: $dE/dx$ in gas (Ar/CO$_2$)

![Graph showing $dE/dx$ in ALICE TPC](image)

Particle identification in TPC and TOF

Complementary information from TPC and TOF detectors allows to select high-purity (anti-)particles

TPC: $dE/dx$ in gas (Ar/CO$_2$)

TOF measurements: $\beta = v/c$

• $p = \gamma \beta m \rightarrow \text{mass}$

$\frac{dE}{dx}$ in ALICE TPC [1]

TOF $\beta$

Particle identification in TPC and TOF

Complementary information from TPC and TOF detectors allows to select high-purity (anti-)particles.

TPC: dE/dx in gas (Ar/CO₂)

TOF measurements: \( \beta = v/c \)

- \( p = \gamma \beta m \rightarrow \text{mass} \)
- Extract yields using fits to TOF \( m^2 \)

\[
\text{dE/dx in ALICE TPC [1]} \\
\text{TOF } \beta
\]


Anti-deuteron inelastic cross-section with ALICE  |  I. Vorobyev  |  QM 2019 Wuhan  |  06.11.2019
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TPC: $dE/dx$ in gas (Ar/CO$_2$)

TOF measurements: $\beta = v/c$

$\bullet \quad p = \gamma \beta m \rightarrow$ mass

$\bullet \quad$ Extract yields using fits to TOF $m^2$

(anti-)protons:

\[
\begin{align*}
\text{TPC: } & \frac{dE}{dx} \text{ in ALICE TPC [1]} \\
\text{TOF: } & \text{TOF measurements: } \beta = \frac{v}{c} \\
\text{Extract yields using fits to TOF } m^2 \\
\end{align*}
\]

(anti-)deuterons:
Raw ratio of primary (anti-)protons

Raw $\bar{p} / p$ ratio compared to ALICE Monte Carlo simulations

- Higher loss of anti-protons in detector material
- Step at $p = 0.7$ GeV/c due to additional detector material between TPC and TOF (TRD, space frame)

Monte Carlo data: detailed simulation of ALICE detector performance
- Propagation of (anti-)particles and interaction with matter with Geant
Raw ratio of primary (anti-)protons

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Monte Carlo data: detailed simulation of ALICE detector performance
- Propagation of (anti-)particles and interaction with matter with Geant

Vary $\sigma_{\text{inel}}(\bar{p})$ in Geant4-based simulations until MC ratio is $\pm 1\sigma$ or $\pm 2\sigma$ away from experimental ratio $\rightarrow$ constraints on $\sigma_{\text{inel}}(\bar{p})$

Raw $\bar{p}/p$ ratio

ALICE Preliminary $p$–$\text{Pb} \setminus s_{\text{NN}} = 5.02$ TeV

Data
- ITS+TPC analysis
- ITS+TPC+TOF analysis
- ±$1.5\%$ global unc. not shown

Monte Carlo
- Geant3
- Geant4
Constraints for $\sigma_{\text{inel}} (\bar{p})$ with ALICE material

Several measurements available for $\sigma_{\text{inel}}(\bar{p})$ on different materials [1, 2]

In ALICE, $\sigma_{\text{inel}}(\bar{p})$ has been estimated for an “averaged element” of detector material

• $\langle Z \rangle = 11.9$, $\langle A \rangle = 25.5$ (from primary collision vertex to the TOF detector)
• Good agreement with Geant4 parameterisations as expected

Raw ratio of primary (anti-)deuterons

Raw $\bar{d}/d$ ratio compared to ALICE Monte Carlo simulations

*Geant4-based simulations are in much better agreement with experimental data*
Constraints for $\sigma_{\text{inel}}(\bar{d})$ with ALICE material

High $p$ region (TOF analysis): good agreement with Geant4 parameterisations

**Raw $\bar{d}/d$ ratio**

- ALICE Preliminary
- $p$--$Pb \ \sqrt{s_{\text{NN}}} = 5.02$ TeV

**$\sigma_{\text{inel}}(\bar{d})$ on averaged ALICE material**

- ALICE Preliminary
- $p$--$Pb \ \sqrt{s_{\text{NN}}} = 5.02$ TeV
  - $\langle Z \rangle = 11.9$, $\langle A \rangle = 25.5$
  - $\sigma_{\text{inel}}(\bar{d})$ Geant4
  - $\sigma_{\text{inel}}(\bar{d})$ ALICE $\pm 1\sigma$
  - $\sigma_{\text{inel}}(\bar{d})$ ALICE $\pm 2\sigma$
Constraints for $\sigma_{\text{inel}}(\bar{d})$ with ALICE material

High $p$ region (TOF analysis): good agreement with Geant4 parameterisations
Low $p$ region (ITS-TPC analysis): hint for steeper rise of $\sigma_{\text{inel}}(\bar{d})$ than predicted by Geant4
• Energy loss in detector material - inelastic interaction at $p$ lower than $p$ at primary vertex
Constraints for $\sigma_{\text{inel}}(\bar{d})$ with ALICE material

High $p$ region (TOF analysis): good agreement with Geant4 parameterisations

Low $p$ region (ITS-TPC analysis): hint for steeper rise of $\sigma_{\text{inel}}(\bar{d})$ than predicted by Geant4

*First experimental information on $\sigma_{\text{inel}}(\bar{d})$ at low momentum!*

Raw $\bar{d}$ / d ratio

$\sigma_{\text{inel}}(\bar{d})$ on averaged ALICE material / $\sqrt{A}$
Summary and outlook

ALICE Experiment at CERN LHC as a tool to study anti-deuteron absorption in detector material

- Analysis of raw reconstructed \( \bar{p} / p \) and \( \bar{d} / d \) ratios
- Better description of results with Geant4-based simulations
- Constrain \( \sigma_{\text{inel}}(\bar{p}) \) and \( \sigma_{\text{inel}}(\bar{d}) \) via comparison with Geant4-based simulations
  - Results for \( \sigma_{\text{inel}}(\bar{p}) \) in good agreement with existing data
  - First experimental constraints on \( \sigma_{\text{inel}}(\bar{d}) \) in momentum range below \( p = 13 \text{ GeV/c} \)

Work in progress towards the final results

- Paper in preparation

Extend the analysis to heavier anti-nuclei (\(^3\bar{\text{He}}, \ldots\))

*Use results as an input for cosmic ray propagation models!*
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*Use results as an input for cosmic ray propagation models!*

*Thank you for your attention!*
Prospects for DM detection

![Diagram showing antideuteron flux as a function of kinetic energy per nucleon for a 30 GeV neutralino, a 40 GeV extra-dimensional Kaluza–Klein neutrino, and a 50 GeV gravitino [45,46,50,49]. The antideuteron limits from BESS are shown [51], along with the projected sensitivities of AMS-02 for the superconducting-magnet configuration [52] after 5 years of operation and GAPS after three 35-day flights [53,54]. The MED Galactic propagation scenario is assumed (Section 4.1). These predictions use a coalescence momentum that is set to 195 MeV (Section 3) and the Einasto dark matter density profile (Section 4.1.4). For the solar modulation parameters see Section 4.2.]

Fig. 1. Predicted antideuteron flux as a function of kinetic energy per nucleon for a 30 GeV neutralino, a 40 GeV extra-dimensional Kaluza–Klein neutrino, and a 50 GeV gravitino [45,46,50,49]. The antideuteron limits from BESS are shown [51], along with the projected sensitivities of AMS-02 for the superconducting-magnet configuration [52] after 5 years of operation and GAPS after three 35-day flights [53,54]. The MED Galactic propagation scenario is assumed (Section 4.1). These predictions use a coalescence momentum that is set to 195 MeV (Section 3) and the Einasto dark matter density profile (Section 4.1.4). For the solar modulation parameters see Section 4.2.
Prospects for DM detection

Fig. 3. Predicted antideuteron flux for annihilation of dark matter with $m_{\text{DM}} = 5, 10, 20$ TeV [56] (blue lines, top to bottom) into $b\bar{b}$ with enhanced annihilation cross sections $((\sigma v)_{5\text{TeV}} = 3 \times 10^{-22}$ cm$^2$/s, $(\sigma v)_{10\text{TeV}} = 7 \times 10^{-22}$ cm$^2$/s, $(\sigma v)_{20\text{TeV}} = 20 \times 10^{-22}$ cm$^2$/s). The predicted antideuteron flux from pure-Wino dark matter [90] (solid green line) with $m_{\text{DM}} = 0.5$ TeV, $(\sigma v) = 4.82 \times 10^{-25}$ cm$^3$/s with Sommerfeld enhanced annihilations into $W^+W^-$. The MAX propagation model is used for all predictions. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)
A long way to the detectors

Interstellar Medium
- Injection of primary CR
- Production of secondary CR in interstellar matter
- Transport
  - Absorption and (re-)acceleration

Heliosphere
- Solar wind shielding
- Most dominant effects at low momenta
- Time dependency of solar activity

Near-Earth Environment
- Shielding / deflection by Earth’s magnetic field
- Background production and absorption in Earth’s atmosphere

Local interstellar flux
Solar-modulated flux
Flux at experiment
Modelling of cosmic rays propagation

Interstellar Medium | Heliosphere | Near-Earth Environment

Injection spectra (particles) | Propagation in the galaxy | Solar magnetic field | Earth's magnetic field and atmosphere | Cosmic rays at Earth

Galprop¹ | Solarprop² Planetocosmics³

[1] https://galprop.stanford.edu

Thomas Pöschl (TUM) | 03/29/19 | Los Angeles

[1] https://galprop.stanford.edu
Anti-deuteron diffusion equation

\[
\nabla(-K \nabla N_{\bar{d}} + V_c N_{\bar{d}}) + \partial_T \left( b_{\text{tot}} N_{\bar{d}} - K_{EE} \partial_T N_{\bar{d}} \right) + \Gamma_{\text{ann}} N_{\bar{d}} = q_{\bar{d}} + q_{\bar{d}}^{\text{ter}}
\]

**Propagation term**
- Common for all (anti-)particle species

**Annihilation term**
- Annihilation of anti-deuterons (interstellar medium, Earth’s atmosphere…)

**Source term**
- Production of anti-deuterons in collisions of pp, p\bar{p}, p-He, \bar{p}-He…
Simulation of cosmic ray flux: protons

Modelling of propagation in interstellar medium and in solar magnetic field
- Chain of several MC-based frameworks
- Protons: mostly primaries from supernova remnants
- Boron / carbon ratio to constrain propagation of primary and secondary particles

Calculations can describe nicely the AMS-02 data

[1] L. Šerkšnytė, T. Pöschl, private communication

Solar modulated proton flux [1]
Simulation of cosmic ray flux: anti-protons

Modelling of propagation in interstellar medium and in solar magnetic field
• Chain of several MC-based frameworks
• Most relevant reactions for secondary anti-protons: pp, p-He, He-p, He-He
• No conclusive model which can describe AMS-02 data in whole energy range

Anti-proton production in pp collisions [1]

[1] L. Šerkšnytė, T. Pöschl, private communication
GEANT3/4 cross-sections for (anti-)deuterons

Figure 14: GEANT3 and GEANT4 parameterizations of d-nucleus and d-nucleus data. Solid lines represent the parameterization implemented in GEANT3, dashed lines the GEANT4 approach, symbols are experimental data, blue is for deuterons and red for antideuterons.

Figure 15: GEANT3 parameterization using only d-nucleus data.
**GEANT3 inelastic cross-sections**

Empirical parameterisation based on Moiseev’ formula [1]:

\[
\sigma_R = \left( Z_p \sigma_{pA}^{3/2} + N_p \sigma_{nA}^{3/2} \right)^{2/3} K(A_T)
\]

\[
K(A_T) = C_0 \log(A_T + 2)^{-C_1}
\]

\[
\sigma_{pA} = 45A_T^{0.7} (1 + 0.016 \sin(5.3 - 2.63 \ln A_T)) \left( 1 - 0.62e^{-5E} \sin(1.58E^{-0.28}) \right)
\]

\[
\sigma_{nA} = 43.2A_T^{0.719}
\]

\[
\sigma_{\bar{p}A} = \left( a_0 + a_1 Z_T + a_2 Z_T^2 \right) A_T^{2/3}
\]

where \( a_0 = 48.2 + 19(E - 0.02)^{-0.55} \), \( a_1 = 0.1 - 0.18E^{-1.2} \) and \( a_2 = 0.0012E^{-1.5} \)

\[
\sigma_{\bar{n}A} = (51 + 16E^{-0.4})A_T^{2/3}
\]

GEANT4: Glauber calculations vs data

Lines are Glauber calculations, points are various exp. data [1]

Parameterisations used in GEANT4

Direct Glauber calculations in GEANT4 in a run-time mode are too heavy → parametrise Glauber calculations with [1]:

\[
\sigma_{hA}^{\text{tot}} = 2\pi R_A^2 \ln \left[ 1 + \frac{A\sigma_{hN}^{\text{tot}}}{2\pi R_A^2} \right], \\
\sigma_{hA}^{\text{in}} = \pi R_A^2 \ln \left[ 1 + \frac{A\sigma_{hN}^{\text{tot}}}{\pi R_A^2} \right], \\
\sigma_{BA}^{\text{tot}} = 2\pi \left( R_B^2 + R_A^2 \right) \ln \left[ 1 + \frac{B\sigma_{hN}^{\text{tot}}}{2\pi \left( R_B^2 + R_A^2 \right)} \right], \\
\sigma_{BA}^{\text{in}} = \pi \left( R_B^2 + R_A^2 \right) \ln \left[ 1 + \frac{B\sigma_{hN}^{\text{tot}}}{\pi \left( R_B^2 + R_A^2 \right)} \right],
\]

\( R_A \) cannot be directly connected with known values due to some simplifications

Use equations as a determination of \( R_A \) having calculated \( \sigma_{hA} \) and \( \sigma_{BA} \) with Glauber

For total cross-section:
\[
\tilde{\rho} A R_A = 1.34 A^{0.23} + 1.35/A^{1/3} \text{ (fm)}, \\
\tilde{d} A R_A = 1.46 A^{0.21} + 1.45/A^{1/3} \text{ (fm)}, \\
\tilde{t} A R_A = 1.40 A^{0.21} + 1.63/A^{1/3} \text{ (fm)}, \\
\tilde{\alpha} A R_A = 1.35 A^{0.21} + 1.10/A^{1/3} \text{ (fm)}.
\]

For inelastic cross-section:
\[
\tilde{\rho} A R_A = 1.31 A^{0.22} + 0.90/A^{1/3} \text{ (fm)}, \\
\tilde{d} A R_A = 1.38 A^{0.21} + 1.55/A^{1/3} \text{ (fm)}, \\
\tilde{t} A R_A = 1.34 A^{0.21} + 1.51/A^{1/3} \text{ (fm)}, \\
\tilde{\alpha} A R_A = 1.30 A^{0.21} + 1.05/A^{1/3} \text{ (fm)}.
\]

Geant4: antih-A and antiB-A cross-sections

Points are Glauber calculation, lines are GEANT4 parametrisation [1]

The ALICE Experiment at the CERN LHC
General-purpose (heavy-ion) experiment at Large Hadron Collider

- Excellent tracking and particle identification (PID) capabilities
- Most suitable detector at the LHC to study the physics of (anti-)nuclei

**Inner Tracking System**
- Tracking, vertex, PID (dE/dx)

**Time Projection Chamber**
- Tracking, PID (dE/dx)

**Time Of Flight detector**
- PID (TOF measurement)

**Transition Radiation Detector**
LHC as an anti-matter factory

At LHC energies, particles and anti-particles are produced in almost equal amounts at mid-rapidity

- Protons and deuterons: only ~5% and ~0.005% of all charged particles
- Penalty factor of ~1000 to produce one additional nucleon (in pp collisions)

(Anti-)deuteron momentum spectra in pp collisions [1]

Integrated yield at mid-rapidity [1]
ALICE detector material as a target

Material budget at mid-rapidity [1]:

- **Beam pipe (~0.3% X₀):** beryllium
- **ITS (~8% X₀):** silicon detectors, carbon supporting structures
- **TPC (~4% X₀):** Ar/CO₂ gas (88/12), nomex field cage
- **TRD (~25% X₀):** carbon/polypropylene fibre radiator, Xe/CO₂ gas, carbon supporting structures
- **Space frame (~20% X₀ between TPC and TOF detectors):** stainless steel

Deuterons from spallation processes


About 80% of all deuterons at $p_T = 0.85$ GeV/c are from spallation reactions and not of primary origin. This background source is not present in antinuclei.
Simple Geant4-based model

Standalone Geant4 simulation to investigate ratios in more details

- (Anti-)proton and (anti-)deuteron source + a target made of ALICE detector materials
- Loss of (anti-)particles due to inelastic processes in detector material
  - low \( p \): beam pipe, ITS, TPC (\( <Z> = 7.4, <A> = 14.8 \))
  - high \( p \): beam pipe, ITS, TPC, TRD, SF (\( <Z> = 11.9, <A> = 25.5 \))
- Loss of (anti-)particles due to scattering effects in ITS, TPC and TRD material
  - Multiple coulomb and hadron elastic scattering

Detailed ALICE simulation

Simple Geant4 setup

Same materials as for the full ALICE simulation

p, d, \( \bar{p}, \bar{d} \)
**Simple Geant4-based model**

Standalone Geant4 simulation to investigate ratios in more details

• (Anti-)proton and (anti-)deuteron source + a target made of ALICE detector materials
• Loss of (anti-)particles due to inelastic processes in detector material
  • low $p$: beam pipe, ITS, TPC ($<Z> = 7.4$, $<A> = 14.8$)
  • high $p$: beam pipe, ITS, TPC, TRD, SF ($<Z> = 11.9$, $<A> = 25.5$)
• Loss of (anti-)particles due to scattering effects in ITS, TPC and TRD material
  • Multiple coulomb and hadron elastic scattering

![Graphs showing ALICE Simulation p→Pb $\sqrt{s_{NN}} = 5.02$ TeV]
Variations of $\sigma_{\text{el}}$ with simple Geant4 model

Vary each $\sigma_{\text{el}}$ by ±20% in all combinations and check the final ratio

- $\sigma_{\text{el}}$ contributes to scattering effects in ITS, TPC and TRD material
- Only a minor effect on the ratio ($\lesssim 1\%$ for $\bar{p} / p$, $\lesssim 2\%$ for $\bar{d} / d$)

For final results: cross-check the variations with full ALICE MC simulations
Variations of $\sigma_{\text{inel}}$ with simple Geant4 model

Ratios are sensitive to the variations of $\sigma_{\text{inel}}(\bar{p})$ and $\sigma_{\text{inel}}(\bar{d})$

Re-scale $\sigma_{\text{inel}}(\bar{p})$ and $\sigma_{\text{inel}}(\bar{d})$ to be $\pm 1\sigma / \pm 2\sigma$ away from experimentally measured ratio

$1\sigma =$ uncertainties added in quadrature:
- Stat. and syst. uncertainties of the data
- Uncertainty from primordial ratio ($1.5\%$ for $\bar{p}/p$, $3\%$ for $\bar{d}/d$)
- Unc. from variations of $\sigma_{\text{inel}}(p)$ and $\sigma_{\text{inel}}(d)$ within precision of Geant4 parameterisations
- Uncertainty from variations of elastic cross-sections
Comparison of ALICE results with existing data

Anti-proton inelastic interaction cross-section as a function of $A$ for fixed momentum

- ALICE results correspond to $\pm 1\sigma$ limits (blue lines)

\[ \sigma_{\text{inel}}(p) \]
Uncertainty due to $\sigma_{\text{inel}}$ (proton)

How precise $\sigma_{\text{inel}}$ (proton) is described by Geant4?

- Check available experimental data (Be, B, C, O, Al, Fe, Cu, Ge, Sn, Pb)
- Vary Geant4 parametrisation, calculate $\chi^2$ for all data points
- Minimum $\chi^2$ and $\pm 1\sigma$: $0.9925 \pm 0.0375$ – 0.0325

Scaling factor for Geant4 $\sigma_{\text{inel}}$ (proton)
Uncertainty due to $\sigma_{\text{inel}}$ (deuteron)

How precise $\sigma_{\text{inel}}$ (deuteron) is described by Geant4?

• Check available experimental data (Be, C, O, Si, Sn, Pb)
• Vary Geant4 parametrisation, calculate $\chi^2$ for all data points
• Minimum $\chi^2$ and $\pm 1\sigma$ : $1.0175^{+0.0625}_{-0.0475}$

Scaling factor for Geant4 $\sigma_{\text{inel}}$ (proton)
Raw $\bar{d}/d$ ratios

TOF analysis from $p = 1.4$ GeV/c

TOF analysis from $p = 0.9$ GeV/c

ALICE Preliminary
$p$–$Pb \ \sqrt{s_{NN}} = 5.02$ TeV

Data
- ITS+TPC analysis
- ITS+TPC+TOF analysis
- Monte Carlo
- Geant3
- Geant4

$\pm 3.0\%$ global unc. not shown

TOF analysis

Data / MC

$\bar{d}/d$

$p$ (GeV/c)
Constraints on $\sigma_{\text{inel}}(\bar{d})$

TOF analysis from $p = 1.4$ GeV/c

TOF analysis from $p = 0.9$ GeV/c
Estimation of $p^*$ for anti-deuterons

Energy loss in detector material: inelastic interaction happens at momentum $p^*$ which is lower than $p$ at primary event vertex

Momentum transformation matrices: $p^* / p$ vs $p$

- Black points/errors: profile of 2d map (mean ± RMS)

**ITS-TPC analysis**

![ITS-TPC Analysis Graph]

**TOF analysis**

![TOF Analysis Graph]
Estimation of $p^*$: anti-protons

Energy loss in detector material: inelastic interaction happens at momentum $p^*$ which is lower than $p$ at primary event vertex

Momentum transformation matrices: $p^*/p$ vs $p$

- Black points/errors: profile of 2d map (mean ± RMS)

**ITS-TPC analysis**

**TOF analysis**

Entries: 702259
Mean x: 1.135
Mean y: 0.9374
RMS x: 0.5207
RMS y: 0.1405

Entries: 1249956
Mean x: 1.36
Mean y: 0.9739
RMS x: 0.3738
RMS y: 0.0539