EXPERIMENTAL ANALYSIS OF Λ^0 BARYONS IN PROTON-PROTON COLLISIONS AT LHCb

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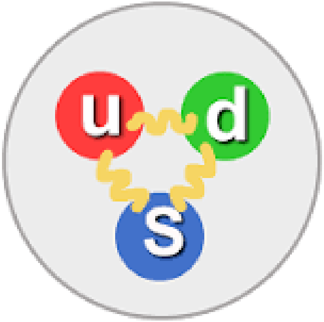
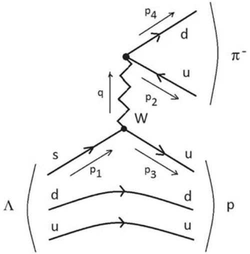


Objectives

Properties of the **Lambda** Λ:

- Invariant mass
- Lifetime
- Transverse polarization



Citation: S. Navas *et al.* (Particle Data Group), Phys. Rev. D **110**, 030001 (2024) and 2025 update

Λ BARYONS
$(S = -1, I = 0)$

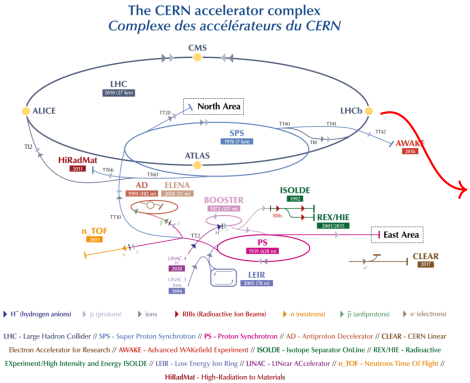
$\Lambda^0 = uds$

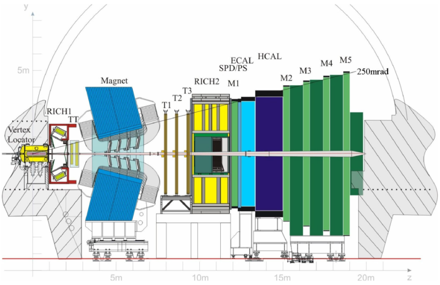
$\boxed{\Lambda}$ $\qquad I(J^P) = 0(\frac{1}{2}^+)$

Mass $m = 1115.683 \pm 0.006$ MeV
$(m_\Lambda - m_{\overline{\Lambda}}) / m_\Lambda = (-0.1 \pm 1.1) \times 10^{-5}$ (S = 1.6)
Mean life $\tau = (2.617 \pm 0.010) \times 10^{-10}$ s (S = 1.5)
$(\tau_\Lambda - \tau_{\overline{\Lambda}}) / \tau_\Lambda = (0.9 \pm 3.2) \times 10^{-3}$
$c\tau = 7.845$ cm
Magnetic moment $\mu = -0.613 \pm 0.004\ \mu_N$
Electric dipole moment $d < 1.5 \times 10^{-16}$ $e$cm, CL = 95%

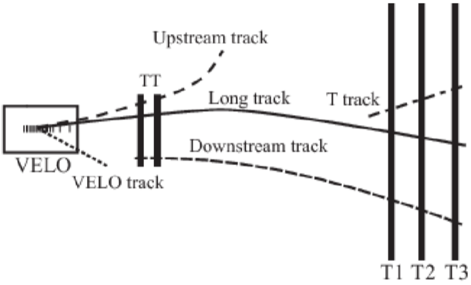
Λ DECAY MODES		Fraction (Γ_i/Γ)	Confidence level	p (MeV/c)
$p\pi^-$		(64.1 ± 0.5) %		101
$n\pi^0$		(35.9 ± 0.5) %		104
$n\gamma$		$(8.3 \pm 0.7) \times 10^{-4}$		162
$p\pi^-\gamma$	[n]	$(8.5 \pm 1.4) \times 10^{-4}$		101
$pe^-\overline{\nu}_e$		$(8.34 \pm 0.14) \times 10^{-4}$		163
$p\mu^-\overline{\nu}_\mu$		$(1.51 \pm 0.19) \times 10^{-4}$		131

The LHCb Experiment





Tracking System



Track types used

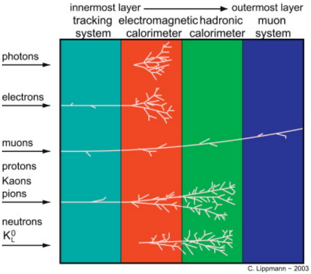
- **Long track**
  $\rightarrow$ Reconstructs position and momentum with the best resolution.
- **Downstream track**
  $\rightarrow$ Lower resolution, but characteristic of the long lifetime of Λ.

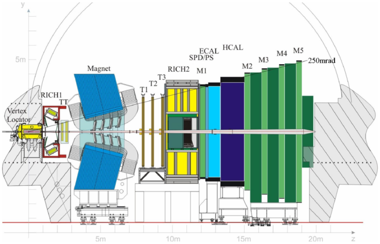
$\Rightarrow$ **Only Long track and Downstream track of the daughter particles from Λ decay are used.**

Particle Identification (PID) System

Phenomena:

- Cherenkov radiation
- Particle shower





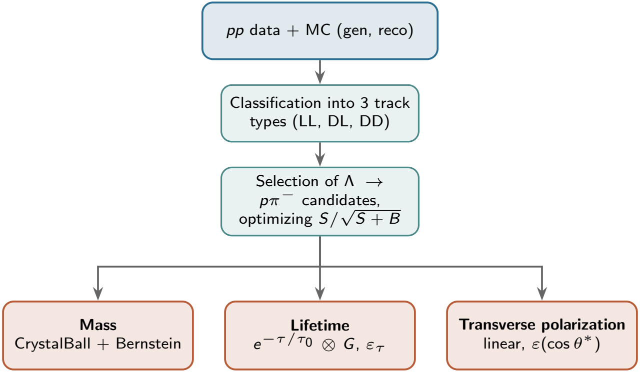
LHCb PID detector:

- 2 RICH detectors
- Calorimeters (ECAL & HCAL)
- 5 Muon stations

Dataset and Analysis Pipeline

pp collisions at $\sqrt{s} = 7\,\text{TeV}$, integrated luminosity $\mathcal{L} = 1.042\ \text{fb}^{-1}$.

- **Real data**
- **MC simulation**, comprising two levels: *gen* (before acceptance) and *reco* (after acceptance).



Selection Criteria and Event Yields

Selection criteria

Category	Variable	Threshold
Mass	$\lvert M(p\pi) - M_{\mathrm{PDG}} \rvert$	< 30 MeV
Geometry	$z_{\mathrm{OWNPV}}(\Lambda)$ $\mathrm{FD}_{\mathrm{OWNPV}}$ cos(DIRA) $\eta(p, \pi)$	$[-180; 180]$ mm $< 800/2400$ mm > 0.99996 $[2; 4.9]$
Track & IP	$\chi^2_{\mathrm{track}}/\mathrm{ndof}$ FisherIP $\nu(\text{Fisher } \chi^2_{\mathrm{IP}})$	< 3 > 1 > 2
Kinematics	$p_T(\Lambda)$ $x_F(\Lambda)$	$[150; 8000]$ MeV $[0; 0.05]$
Arm.–Pod.	p_T^{AP} $\lvert \alpha_{\mathrm{AP}} \rvert$	$[20; 125]$ MeV > 0.5
PID	PIDp(p) PIDK(p) ProbNNp(p) ProbNNghost(p)	> 0 > -10 > 0.1 < 0.8

Event yields

	Track	After	Retained
MC reco	LL	207,368	2.57%
	DL	333,656	13.03%
	DD	320,765	13.03%
	Total	**861,789**	**6.59%**
Data	LL	454,436	11.31%
	DL	1,597,035	1.62%
	DD	2,125,596	1.56%
	Total	**4,177,067**	**1.75%**

Total candidates before selection: 1.3×10^7 (MC reco) and 2.4×10^8 (real data).

$\rightarrow$ The criteria remove most of the background, retaining prompt Λ events.

Invariant Mass of Λ

The invariant mass of Λ is reconstructed from the energy-momentum of the two daughter particles p and π^- (using $E^2 = p^2 + m^2$):

Invariant mass

$$M_\Lambda = \sqrt{(E_p + E_{\pi^-})^2 - (\boldsymbol{p}_p + \boldsymbol{p}_{\pi^-})^2}$$

- The M_Λ distribution is fitted to separate signal from background $\Rightarrow$ peak mass m_Λ and resolution σ.
- Fit function:
  - **Signal:** Double-sided Crystal Ball - a Gaussian core combined with two power-law tails, describing detector resolution and energy loss
  - **Background:** first-order Bernstein polynomial

Lifetime of Λ

Decay time in the laboratory frame $t = L/|\boldsymbol{v}|$

Proper lifetime (rest frame of Λ)

$$\tau = \frac{t}{\gamma} = \frac{L\, M_\Lambda}{|\boldsymbol{p}_\Lambda|},$$

Fitting the above distribution with an exponential function $N(\tau) = N_0\, e^{-\tau/\tau_0}$ gives the lifetime τ_0 to be determined.

Realistic Lifetime Fit Function

Accounting for detector resolution

Single track type:

$$N_{\text{reco}}(\tau) = N_0 \left[e^{-\frac{\tau}{\tau_0}} \otimes G(\mu_{\text{res}}, \sigma_{\text{res}}) \right]$$

Combined tracks (LL, DL, DD):

$$N_{\text{reco}}^{\text{all}}(\tau) = N_1 \left[e^{-\frac{\tau}{\tau_0}} \otimes G_1 \right] + (N_0 - N_1) \left[e^{-\frac{\tau}{\tau_0}} \otimes G_2 \right]$$

G_1, G_2: Gaussian resolution functions for LL and DL/DD tracks.

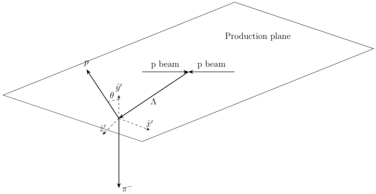
Reconstruction efficiency correction ε_τ

Using MC simulation to obtain the unbiased distribution from the detector:

$$N_{\text{real}}(\tau) = \frac{N_{\text{reco}}(\tau)}{\varepsilon_\tau}, \qquad \varepsilon_\tau = \frac{N_{\text{reco}}^{\text{MC}}(\text{truth})}{N_{\text{gen}}^{\text{MC}}(\text{truth})}$$

Transverse Polarization of Λ

Based on **parity violation** in the weak decay $\Lambda \to p\pi^-$: polarization is revealed through the angular distribution of the decay proton.



Normal vector of the production plane:

$$\hat{\boldsymbol{y}}' = \frac{\boldsymbol{p}_{\text{beam}} \times \boldsymbol{p}_{\Lambda}}{|\boldsymbol{p}_{\text{beam}} \times \boldsymbol{p}_{\Lambda}|}.$$

θ^*: angle between the proton momentum (in the Λ rest frame) and $\hat{\boldsymbol{y}}'$.

Decay asymmetry parameter:

$$\alpha_{\Lambda} = 0.749 \pm 0.008, \quad \alpha_{\bar{\Lambda}} = -0.758 \pm 0.005.$$

Theoretical angular distribution

$$\frac{dN}{d\cos\theta^*} = \frac{N}{2}\left(1 + \alpha_{\Lambda} P \cos\theta^*\right)$$

Transverse Polarization Fit Function

The normalized $\cos\theta^*$ distribution is fitted with a linear function including efficiency:

Fit function

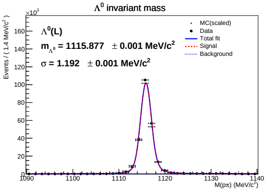
$$N(\cos\theta^*) = C_1\left(1 + C_2\cos\theta^*\right)\varepsilon(\cos\theta^*), \qquad C_2 = \alpha_h P_y$$

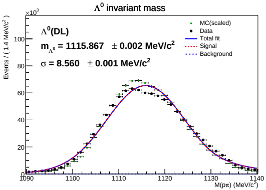
Reconstruction efficiency

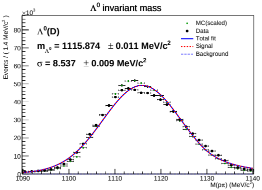
$$\varepsilon(\cos\theta^*) = \frac{N^{\mathrm{MC}}_{\mathrm{reco}}(\cos\theta^*)}{N^{\mathrm{MC}}_{\mathrm{gen}}(\cos\theta^*)}$$

- Fitted in bins of x_F and p_T $\Rightarrow$ transverse polarization $P_y = C_2/\alpha_h$.

Results: Invariant Mass of $\Lambda/\bar{\Lambda}$



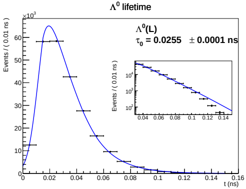


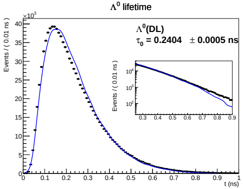


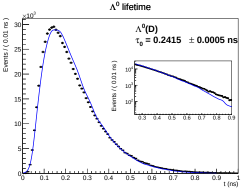
	Track	M (MeV/c^2)	σ (MeV/c^2)
	PDG	1115.683 ± 0.006	
Λ	LL	1115.877 ± 0.001	1.192 ± 0.001
	DL	1115.867 ± 0.002	8.560 ± 0.001
	DD	1115.874 ± 0.011	8.537 ± 0.009
$\bar{\Lambda}$	LL	1115.871 ± 0.002	1.185 ± 0.002
	DL	1115.885 ± 0.011	8.598 ± 0.009
	DD	1115.884 ± 0.012	8.618 ± 0.010

- All track types peak near 1115.87 MeV/c^2, about 0.19 MeV/c^2 ($\sim 0.017\%$) above the PDG value $\Rightarrow$ **systematic uncertainty**.
- $\sigma_{LL} \approx 1.19 \ll \sigma_{DL,DD} \approx 8.5$–$8.6$ (about $7\times$ better) $\Rightarrow$ role of the VELO.

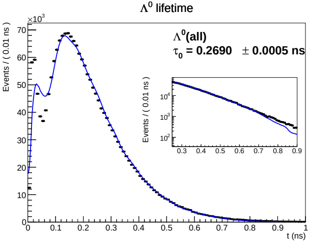
Results: Lifetime of $\Lambda/\bar{\Lambda}$



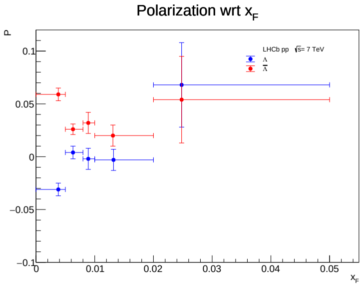




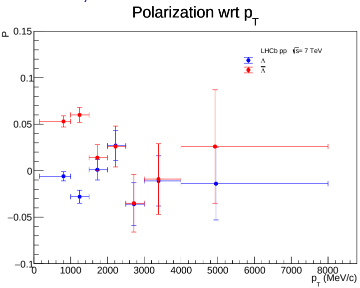
	τ_0 (ns)	
Track	Λ	$\bar{\Lambda}$
LL	0.0255 ± 0.0001	0.0259 ± 0.0001
DL	0.2404 ± 0.0005	0.2522 ± 0.0005
DD	0.2415 ± 0.0005	0.2508 ± 0.0006
All tracks	$\mathbf{0.2690} \pm 0.0005$	$\mathbf{0.2772 \pm 0.0005}$
PDG	0.2617 ± 0.0010	



Results: Transverse Polarization of $\Lambda/\bar{\Lambda}$



Polarization vs. x_F



Polarization vs. p_T

Over the full kinematic range ($\eta \in [2; 4.9]$, $p_T \in [150; 8000]$ MeV, $x_F \in [0; 0.05]$):

$$P_y(\Lambda) = -0.009 \pm 0.004, \qquad P_y(\bar{\Lambda}) = +0.036 \pm 0.004.$$

- Small magnitude, consistent with LHCb's very low x_F range.
- Negative sign for Λ, qualitatively consistent with most other experiments.
- $\bar{\Lambda}$ is more significantly positive than Λ $\rightarrow$ requires further verification.

Thank you!