Heavy-baryon decays: Phenomenology

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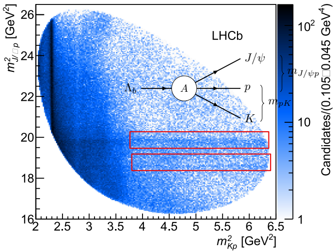
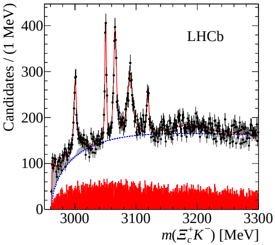
Contents

Polarization for hadron spectroscopy





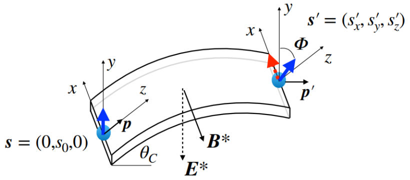
- $\Lambda_b^0 \to J/\psi(\to \mu^+\mu^-)pK^-$ [LHCb]
  - Λ_b^0 is prompt (unpolarized)
  - 2d distribution is sensitive to P_c^+ spin
  - $J/\psi \to \mu^+\mu^-$ adds sensitivity for P_c^+ parity
- $\Xi_b \to J/\psi(\to \mu^+\mu^-)p\Lambda(\to p\pi)$ [LHCb]
  - P_{cs}^0 in $J/\psi\Lambda^0$
  - $\Lambda^0 \to pK^-$ adds sensitivity to the P_{cs} spin

Require further input

- heavy-baryon spectroscopy: $B_b \to B_c K\pi$, with $B_c \in \{\Lambda_c^+, \Sigma_c^+, \Xi_c^+, \Omega_c^0\}$
- pentaquark searches: $\Lambda_b^0 \to \Lambda_c^+(\to pK^-\pi^+)\bar{D}^0 K^-$

Polarization for EDM studies

SELDOM project: Search for the electric dipole moment of strange and charm baryons at LHC

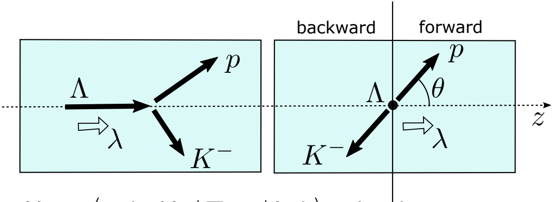


- Fixed target setup
- Production of polarized Λ_c, Ξ_c
- Propagation in the bend cristals changes orientation of the polarization

Recent publication on the progress [Aiola et al., arXiv:2010.11902]

A robust techniques to measure polarization of charm baryons is required.

Polarization and asymmetry parameter



$$H_\lambda = \left\langle p, \lambda; K^- \right| T_{\text{weak}} \left| \Lambda, \lambda \right\rangle : \text{ hardon property}$$

$$\frac{\mathrm{d}N}{\mathrm{d}\cos\theta} = N(1 + \alpha P \cos\theta), \qquad A_{FB} = \alpha P : \text{ asymmerty}$$

- $P = |\vec{P}|$ polarization, for $J = 1/2$, there are just tree d.o.f.
- α is the asymmetry parameter (analysing power of the decay)

$$\Lambda(j^P = 1/2^+) \to p(j^P = 1/2^+)\, K^-(j^P = 0^-):$$

- S-wave – parity violating (PV)
- P-wave – parity conserving (PC)

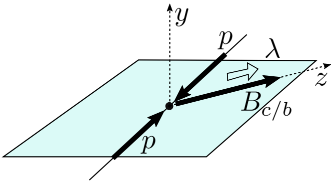
$$\alpha = \frac{|H_+|^2 - |H_-|^2}{|H_+|^2 + |H_-|^2} = -\frac{2\mathrm{Re}(H_S^* H_P)}{|H_S|^2 + |H_P|^2}$$ both PV and PC are needed!

Production of polarizaion

Prompt production in the strong (electromagnetic) process

$pp \to B_{c/b} + X$. Polarization matrix

$$\boxed{\rho^{(B_{c/b})}_{\lambda,\lambda'} = \frac{1}{2I}\sum_{\{\nu\}} A_{\lambda,\{\nu\}} A^*_{\lambda',\{\nu\}} = \frac{1}{2}(1 + P_x\sigma_1 + P_y\sigma_2 + P_z\sigma_3)}$$



the production amplitude $A_{\lambda,\{\nu\}}$:

- $\{\nu\}$ is for all other helicities

From parity conservation:

$$A_{-\lambda,\{-\nu\}} = \boxed{\text{phase}}\, A_{\lambda,\{\nu\}}$$

$$\rho^{(B_{c/b})}_{-\lambda,-\lambda'} = \rho_{\lambda,\lambda'}$$

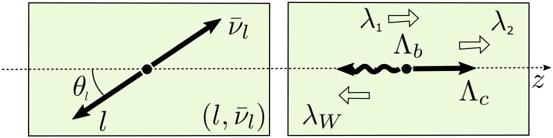
I.e. $P_x = P_z = 0$

$$\rho^{(B_{c/b})} = \frac{1}{2}\begin{pmatrix} 1 & P \\ P & 1 \end{pmatrix}$$

- $\vec{P}\ \perp$ the reaction plane ($\uparrow\uparrow \vec{y}$)
- $|\vec{P}|$ is small for pp colliders

Polarization in the weak decay

$\Lambda_b^0 \to \Lambda_c^+(l^-\bar{\nu}_l)$ is the most theoretically studied



$$H_{\lambda_2,\lambda_W} = \langle \Lambda_c; \lambda_2 | V_\mu - A_\mu | \Lambda_b; \lambda_1 \rangle \, \epsilon^\mu(\lambda_W)$$

- Known current V-A, unknown hadron wave functions ($\Lambda_{c/b}$)
- Predicted in HQET, e.g [PRD49, 2363 (1994)]:
  - $\alpha_{\Lambda_b^0 \to \Lambda_c^+(l^-\bar{\nu}_l)} = -0.77$ (HQET)
  - $\alpha_{\Lambda_b^0 \to \Lambda_c^+(l^-\bar{\nu}_l)} = -0.81$ (FQD)
- Polarization in the decay is equal to asymmetry parameter α: $P_{\text{daughter}} = \alpha_{\text{mather}}$
- Λ_c is produced with large longitudinal polarization!

Detection of polarization

Two-body decays: $\Lambda_c^+ \to$ Baryon Pseudoscalar

Two methods to determine α

Recent BESIII measurements [PRD 100 (2019) 7, 072004] $e^+e^- \to \Lambda_c^+\Lambda_c^-$

1) Sequence of two weak decays

$\Lambda_c^+ \to \Lambda^0\pi^+$, $\Lambda_c^+ \to \Sigma^+\pi^0$, and $\Lambda_c^+ \to \Sigma^0\pi^+$.

- Asymmetry parameter becomes longitudinal polarization of Λ/Σ
- Knowing $\alpha_{\Lambda\to\pi p}$, $\alpha_{\Sigma^+\to p\pi^0}$, and $\alpha_{\Sigma^0\to\Lambda\gamma}$
- One finds Λ_c from FB asymmetry. In Λ/Σ decay:

- $\alpha_{\Lambda\pi^+} = -0.80 \pm 0.08$
- $\alpha_{\Sigma^+\pi^0} = -0.57 \pm 0.10$
- $\alpha_{\Sigma^0\pi^+} = -0.73 \pm 0.17$
- $\alpha_{pK_S} = -0.18 \pm 0.43$
- 2.1σ significance of initial Λ_c^+ polarization.

2) Check FB asymmetry with polarized Λ_c

- One can look directly to the Λ_c decay
- The only option for $\Lambda_c^+ \to pK_S$.

[btw] Great option for LHCb with $\Lambda_b^0 \to \Lambda_c^+\pi^-$, $\Lambda_b^0 \to \Lambda_c^+(l^-\bar{\nu}_l)$

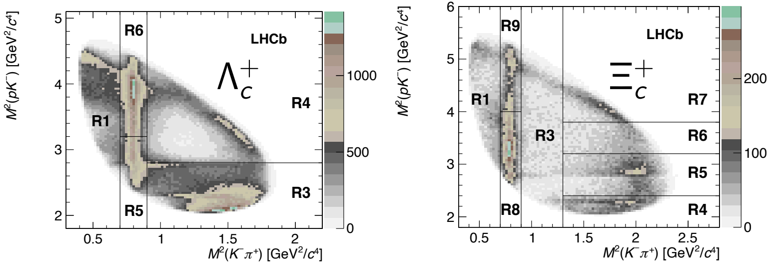
$\Lambda_c^+ \to pK^-\pi^+$, the "darling channel" [König et al., PRD 49 (1994)]

- largest hadronic decay mode (6.24 ± 0.32 [PDG])
- Convenient experimentally, three charge tracks

AmAn: By E791 (fixed target at Fermilab) is based in 1k events [PLB 471 (2000)]

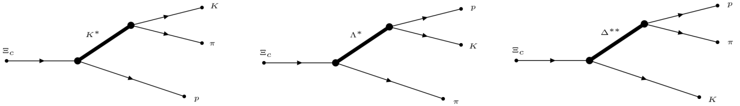
- Measured $K^*(19.5 \pm 2.6\%)$, $\Lambda^{*0}(18 \pm 3\%)$, $\Delta^{*++}(7.7 \pm 1.8\%)$, with NR(55%)
- Significant polarization is measured, up to $P = 0.67$ at high p_T.
- Problem in the formalism (interference terms)

New data are available [LHCb EPJC 80 (2020)]. Refinement of the analysis method is



needed.

$\Lambda_c^+/\Xi_c^+ \to pK^-\pi^+$ dynamics



- Decays via intermediate resonances
  1. $\Lambda_c^+ \to \Lambda^{*0}(\to pK^-)\pi$
  2. $\Lambda_c^+ \to \Delta^{++}(\to p\pi^-)K^-$
  3. $\Lambda_c^+ \to K^{*0}(\to K^-\pi^+)p$
- Different decay chains interfere(!)

One still can write for longetudional polatization:

$$\frac{\mathrm{d}N}{\mathrm{d}\cos\beta_i} = N(1 + P\alpha_i \cos\beta_i), \quad i = 1, 2, 3$$

But:

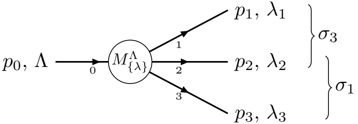
- Different $\cos\beta$ for every chain
- Various chains influence each other, changing α-s.

The Dalitz-Plot decomposition

[MM et al.(JPAC), arXiv:1910.04566]

Reformulation of the helicity approach

General expression of the decay amplitude:



$$= \sum_{\nu} \underbrace{D^{J*}_{\Lambda\nu}(\alpha, \beta, \gamma)}_{\text{Decay-plane orientation}} \times \underbrace{O^{\nu}_{\{\lambda\}}(m_{12}^2, m_{23}^2)}_{\text{Dalitz-plot function}}$$

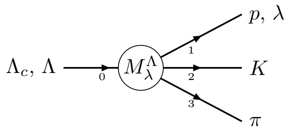
Model-independent factorization of the overall rotation:

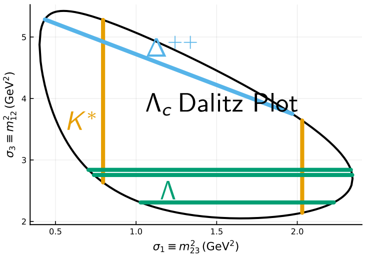
- Exploits properties of the Lorentz group (orientation – just three Euler angles)
- Dalitz-plot function depends entirely on 2 variables, m_{12}^2, and m_{23}^2
- $O^{\nu}_{\{\lambda\}}$ is hadronic dynamic function (to be measured once).

Impacted range of analyses

- Pentaquark analysis, Λ_b/Λ_c polarionation measurements, Baryonic decay chains,. . .

$\Lambda_c^+ \to pK^-\pi^+$ decay amplitude





$$\boxed{M_\lambda^\Lambda = \sum_\nu D_{\Lambda\nu}^{1/2*}(\alpha,\beta,\gamma) O_\lambda^\nu(m_{K\pi}^2, m_{p\pi}^2),}$$

Decay matrix elements: coupling $\times$ d $\times$ coupling
$H(\Lambda_c \to RP)d(\cos)H(R \to PP)$:

$$O_\lambda^{(K^{*0})\nu} = H_{\nu+\lambda,\lambda}^{(K^{*0})}\, d_{\nu,0}^{1}(\theta_{23}) H_{0,0}\, \mathrm{BW}(m_{K\pi}^2),$$

$$O_\lambda^{(\Delta^{**})\nu} = H_{\nu,0}^{(\Delta^{**})}\, d_{\nu,-\lambda}^{1/2}(\theta_{31}) H_{0,\lambda}\, \mathrm{BW}(m_{p\pi}^2),$$

$$O_\lambda^{(\Lambda^{*0})\nu} = H_{\nu,0}^{(\Lambda^{*0})}\, d_{\nu,\lambda}^{1/2}(\theta_{12}) H_{\lambda,0}\, \mathrm{BW}(m_{pK}^2);$$

Spin alignment is taken care when adding chains:

$$O_\lambda^\nu(m_{K\pi}^2, m_{p\pi}^2) = O_\lambda^{(1)\nu} + \sum_{\nu'\lambda'} d_{\nu,\nu'}^{1/2}(\hat\theta_{2(1)}) O_{\lambda'}^{(2)\nu'} d_{\lambda',\lambda}^{1/2}(\zeta_{2(1)}^1) + \sum_{\nu'\lambda'} d_{\nu,\nu'}^{1/2}(\hat\theta_{3(1)}) O_{\lambda'}^{(3)\nu'} d_{\lambda',\lambda}^{1/2}(\zeta_{3(1)}^1)$$

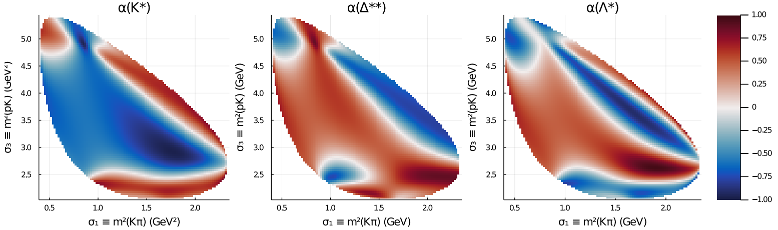
- for every decay chain α can be calculate from $H_{(\cdot,\cdot)}^{(\text{chain})}$
- Incfluence between channels, analysing power should be constructed from whole matrix element

$$\alpha_1(m_{K\pi}^2, m_{p\pi}^2) = \frac{I_{1/2} - I_{-1/2}}{I_{1/2} + I_{-1/2}}, \quad I_\nu = \sum_\lambda |O_\lambda^\nu(m_{K\pi}^2, m_{p\pi}^2)|^2$$

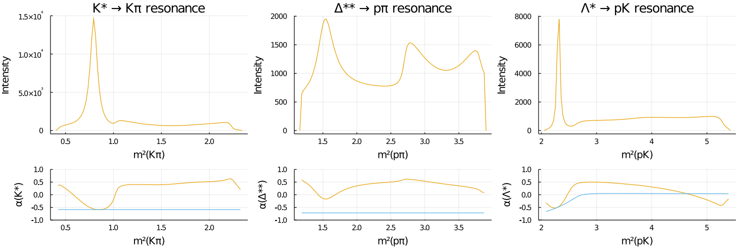
Analysing power in three-body decay (toy model)

$$\alpha_1^{(2d)}(m_{K\pi}^2, m_{p\pi}^2) = \frac{I_{1/2} - I_{-1/2}}{I_{1/2} + I_{-1/2}}, \quad \alpha_1^{(1d)}(m_{K\pi}^2) = \frac{\int I_{1/2}\mathrm{d}m_{p\pi}^2 - \int I_{-1/2}\mathrm{d}m_{p\pi}^2}{\int I_{1/2}\mathrm{d}m_{p\pi}^2 + \int I_{-1/2}\mathrm{d}m_{p\pi}^2}.$$

2d



1d



Can we determine α just from Dalitz Plot?

Recap of the methods to measure α:

- Look at polarization of the decay product $P_{\text{daughter}} = \alpha_{\text{mather}}$
- Look at the case with initial polarization
- (!!) Explore interference between decay chains in three-body decay

$+$ asymmetry parameter arise from the interplay between PC and PC.

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$+$ asymmetry parameter arise from the interplay between PC and PC.

Decay channel correlation matrix:

$$\begin{array}{l} \mathrm{PC}: K^* \\ \mathrm{PC}: \Delta^{*++} \\ \mathrm{PC}: \Lambda^{*0} \\ \mathrm{PV}: K^* \\ \mathrm{PV}: \Delta^{*++} \\ \mathrm{PV}: \Lambda^{*0} \end{array} \begin{pmatrix} 100 & {\color{red}14+5i} & {\color{red}-0.8i} & & & \\ 14-5i & 100 & {\color{red}0.7+2i} & & & \\ 0.8i & 0.7-2i & 100 & & & \\ & & & 100 & {\color{red}-10-10i} & {\color{red}0.2+0.2i} \\ & & & -10+10i & 100 & {\color{red}-5-2i} \\ & & & 0.2-0.2i & -5+2i & 100 \end{pmatrix}$$

- PC and PV do not interfere with each other whatsoever
- Resonance interfere differently within each the PV and PC sectors
- It might give a handle to distriguish the sectors

How difficult is it?

Very difficult!

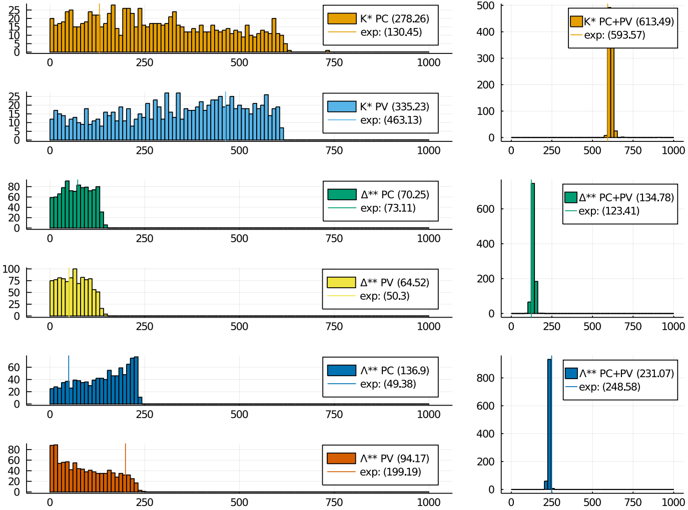
[V.Dedu, MM, Alex Pearce, CERN-STUDENTS-Note-2020-031]

We run toys (1k events):

- PV and PC with different couplings
- Fit model is the same as generation model (!!)

and found:

- Intensities of the resonances are **well** constrained in the fit $|PC|^2 + |PV|^2$
- Individualy the sectors **cannot** be distinguised with present statistics



Significantly larger interference between decay chains is needed for the method to work

Conclusions

- Asymmetry parameters are fundamental hadronic quantities (measure once, use forever)
- Including decay dimension increase sensitivity of angular analysis
- Polarization manifests as asymmetry in weak decays
- The effect is an interplay of PC ($j^P = 1/2^+$) and PV ($j^P = 1/2^-$) transitions. **One needs both!**

Three-body decays:

- α becomes a function of the dalitz-plot variables (m_{12}^2, m_{23}^2)
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- PV and PC are distinguished only by resonances lineshape and interference (a tiny effect)

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Measurements of asymmetries requires, ether:

- Measurements of final state polarization, e.g. $\Lambda_c^+ \to \Lambda^0(\to p\pi)\pi^+$
- Polarized initial state: $\Lambda_b^0 \to \Lambda_c^+(l^-\bar{\nu})$, or $\Lambda_b \to \Lambda_c\pi$
- Large interference on the Dalitz plot (no ambiguities are not guaranteed)