Heavy-baryon decays: Phenomenology

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December 16th, 2019
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Polarization for hadron spectroscopy

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

Require further input

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

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 \( \Lambda_c, \Xi_c \)
- Propagation in the bend crystals 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

\[ H_\lambda = \langle p, \lambda; K^- | T_{\text{weak}} | \Lambda, \lambda \rangle : \text{hadron property} \]

\[
\frac{dN}{d \cos \theta} = N(1 + \alpha P \cos \theta), \quad A_{FB} = \alpha P : \text{asymmetry}
\]

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

\[ \Lambda(j^P = 1/2^+) \rightarrow p(j^P = 1/2^+) K^- (j^P = 0^-) : \]

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

\[
\alpha = \frac{|H_+|^2 - |H_-|^2}{|H_+|^2 + |H_-|^2} = - \frac{2 \text{Re}(H_S^* H_P)}{|H_S|^2 + |H_P|^2}
\]

both PV and PC are needed!
Production of polarization
Prompt production in the strong (electromagnetic) process

\[ pp \rightarrow B_{c/b} + X. \] Polarization matrix

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

From parity conservation:

\[ A_{-\lambda,\{-\nu\}} = \text{phase} A_{\lambda,\{\nu\}} \]

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

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

$Λ_b^0 → Λ_c^+(l^- \bar{ν}_l)$ is the most theoretically studied

$H_{λ_2,λ_W} = \langle Λ_c; λ_2 | V_μ - A_μ | Λ_b; λ_1 \rangle \epsilon^μ(λ_W)\$

- Known current V-A, unknown hadron wave functions ($Λ_c/b$)
- Predicted in HQET, e.g [PRD49, 2363 (1994)]:
  - $α_{Λ_b^0 → Λ_c^+(l^- \bar{ν}_l)} = -0.77$ (HQET)
  - $α_{Λ_b^0 → Λ_c^+(l^- \bar{ν}_l)} = -0.81$ (FQD)
- Polarization in the decay is equal to asymmetry parameter $α$:
  - $P_{\text{daughter}} = α_{\text{mather}}$
- $Λ_c$ is produced with large longitudinal polarization!
Detection of polarization
Two-body decays: $\Lambda_c^+ \rightarrow$ Baryon Pseudoscalar

Two methods to determine $\alpha$

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

1) Sequence of two weak decays

<table>
<thead>
<tr>
<th>Decay Sequence</th>
<th>Asymmetry Parameter</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Lambda_c^+ \rightarrow \Lambda^0 \pi^+$</td>
<td>$\alpha_{\Lambda^0 \pi^+} = -0.80 \pm 0.08$</td>
</tr>
<tr>
<td>$\Lambda_c^+ \rightarrow \Sigma^+ \pi^0$</td>
<td>$\alpha_{\Sigma^+ \pi^0} = -0.57 \pm 0.10$</td>
</tr>
<tr>
<td>$\Lambda_c^+ \rightarrow \Sigma^0 \pi^+$</td>
<td>$\alpha_{\Sigma^0 \pi^+} = -0.73 \pm 0.17$</td>
</tr>
</tbody>
</table>

Asymmetry parameter becomes longitudinal polarization of $\Lambda/\Sigma$

Knowing $\alpha_{\Lambda^0 \rightarrow \pi p}$, $\alpha_{\Sigma^+ \rightarrow \pi^0 p}$, and $\alpha_{\Sigma^0 \rightarrow \Lambda \gamma}$

One finds $\Lambda_c$ from FB asymmetry. In $\Lambda/\Sigma$ decay:

2) Check FB asymmetry with polarized $\Lambda_c$

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

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

Three-body decays

\[ \Lambda_c^+ \rightarrow pK^-\pi^+ \], the “darling channel” [König et al., PRD 49 (1994)]

- largest hadronic decay mode \((6.24 \pm 0.32 \text{ [PDG]})\)
- 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.
Detection of polarization

Three-body decays

$\Lambda_c^+ / \Xi_c^+ \rightarrow pK^−\pi^+$ dynamics

- Decays via intermediate resonances
  1. $\Lambda_c^+ \rightarrow \Lambda^*_0 (\rightarrow pK^-)\pi$
  2. $\Lambda_c^+ \rightarrow \Delta^{++} (\rightarrow p\pi^-)K^-$
  3. $\Lambda_c^+ \rightarrow K^*_0 (\rightarrow K^-\pi^+)p$

- Different decay chains interfere(!)
  
  One still can write for longitudinal polarization:

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

  But:

  - Different $\cos \beta$ for every chain
  - Various chains influence each other, changing $\alpha$-s.
The Dalitz-Plot decomposition

Reformulation of the helicity approach

General expression of the decay amplitude:

\[ p_0, \Lambda \rightarrow M_\{\lambda\} \rightarrow p_1, \lambda_1, p_2, \lambda_2, p_3, \lambda_3 \]

\[ \left\{ \begin{array}{c} \sigma_3 \\ \sigma_1 \end{array} \right\} = \sum_{\nu} D_{\Lambda\nu}^J*(\alpha, \beta, \gamma) \times O_\{\lambda\}^{\nu}(m_{12}^2, m_{23}^2) \]

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 \( m_{23}^2 \)
- \( O_\{\lambda\}^{\nu} \) is hadronic dynamic function (to be measured once).

Impacted range of analyses

- Pentaquark analysis, \( \Lambda_b/\Lambda_c \) polarionation measurements, Baryonic decay chains, . . .
$\Lambda_c^+ \rightarrow pK^-\pi^+$ decay amplitude

\[ M^\Lambda_\lambda = \sum_\nu D^{1/2}\nu_\lambda^\Lambda (\alpha, \beta, \gamma) O^\nu_\lambda (m^2_{K\pi}, m^2_{p\pi}), \]

Decay matrix elements: coupling $\times$ d $\times$ coupling

\[ H(\Lambda_c \rightarrow RP) d(\cos) H(R \rightarrow PP): \]

\[ O^{(K^*0)}_\lambda = H^{(K^*0)}_{\nu + \lambda, \lambda} d^{1/2}_{\nu,0} (\theta_{23}) H_{0,0} BW(m^2_{K\pi}), \]

\[ O^{(\Delta^{**})}_\lambda = H^{(\Delta^{**})}_{\nu,0} d^{1/2}_{\nu,\lambda} (\theta_{31}) H_{0,\lambda} BW(m^2_{p\pi}), \]

\[ O^{(\Lambda^*)}_\lambda = H^{(\Lambda^*)}_{\nu,0} d^{1/2}_{\nu,\lambda} (\theta_{12}) H_{\lambda,0} BW(m^2_{pK}); \]

Spin alignment is taken care when adding chains:

\[ O^\nu_\lambda (m^2_{K\pi}, m^2_{p\pi}) = O^{(1)}_\lambda + \sum_{\nu',\lambda'} d^{1/2}_{\nu,\nu'} (\hat{\theta}_{2(1)}) O^{(2)}_{\lambda',\nu'} d^{1/2}_{\nu',\lambda} (\zeta^1_{2(1)}) + \sum_{\nu',\lambda'} d^{1/2}_{\nu,\nu'} (\hat{\theta}_{3(1)}) O^{(3)}_{\lambda',\nu'} d^{1/2}_{\nu',\lambda} (\zeta^1_{3(1)}) \]

- for every decay chain $\alpha$ can be calculate from $H^{(\text{chain})}$
- Influence between channels, analysing power should be constructed from whole matrix element

\[ \alpha_1(m^2_{K\pi}, m^2_{p\pi}) = \frac{l^{1/2}_{\nu} - l^{-1/2}_{\nu}}{l^{1/2}_{\nu} + l^{-1/2}_{\nu}}, \quad l_{\nu} = \sum_\lambda |O^\nu_\lambda (m^2_{K\pi}, m^2_{p\pi})|^2 \]
Analysing power in three-body decay (toy model)

\[ \alpha_{1}^{(2d)}(m_{K\pi}^{2}, m_{p\pi}^{2}) = \frac{l_{1/2} - l_{-1/2}}{l_{1/2} + l_{-1/2}}, \quad \alpha_{1}^{(1d)}(m_{K\pi}^{2}) = \frac{\int l_{1/2} dm_{p\pi}^{2} - \int l_{-1/2} dm_{p\pi}^{2}}{\int l_{1/2} dm_{p\pi}^{2} + \int l_{-1/2} dm_{p\pi}^{2}}. \]
Can we determine $\alpha$ just from Dalitz Plot?

Recap of the methods to measure $\alpha$:

- 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:

\[
\begin{pmatrix}
100 & 14 + 5i & -0.8i \\
14 - 5i & 100 & 0.7 + 2i \\
0.8i & 0.7 - 2i & 100 \\
100 & -10 - 10i & 0.2 + 0.2i \\
-10 + 10i & 100 & -5 - 2i \\
0.2 - 0.2i & -5 + 2i & 100
\end{pmatrix}
\]

- 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 distinguish the sectors

How difficult is it?

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Very difficult!

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 distinguished 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:

- $\alpha$ becomes a function of the dalitz-plot variables ($m_{12}^2, m_{23}^2$)
- Interference of the PC and PV vanish at every point on Dalitz
- 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. $\Lambda_c^+ \rightarrow \Lambda^0 (\rightarrow p\pi)\pi^+$
- Polarized initial state: $\Lambda_b^0 \rightarrow \Lambda_c^+ (l^- \bar{\nu})$, or $\Lambda_b \rightarrow \Lambda_c \pi$
- Large interference on the Dalitz plot (no ambiguities are not guaranteed)