Charmed baryons:
CP violation and rare decays

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Weakly decaying charmed baryons

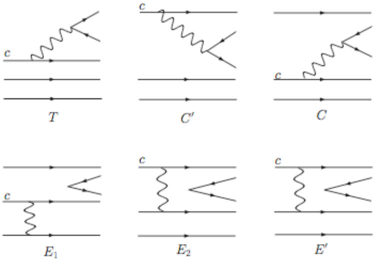
- $J^P = 1/2^+$: $SU(3)_{fl}$ $\bar{3}$-plet: $SU(3)_{fl}$ 6-tet:

Λ_c $[cud]$		.....
Ξ_c^0 $[cds]$	Ξ_c^+ $[cus]$	Ω_c^0 $[css]$

- all other charmed baryons decay strongly or e.m.
- LHCb: at 1 fb^{-1} "expect 4 M $\Lambda_c \to pK\pi$ events" ($BR \sim 5\%$)
- $\sim$ number of events for $\Xi_c^{+,0}$?,
- antibaryons (for direct CP violation)
  production ratio $(pp \to \bar{\Lambda}_c + ...)/(pp \to \Lambda_c + ...)$ at LHCb?
  $\bar{\Lambda}/\Lambda \sim$ "smaller in data than predicted in simulation" [1107.0882]
- SCS modes ($c \to u$ transitions, NP-sensitive)
  e.g, $\Lambda_c \to p\pi^+\pi^-$, $BR \sim 0.35\%$, ($(V_{cd}/V_{cs})^2 \sim 0.05$))

Dynamics of hadronic Λ_c decays

- quark diagrams ($SU(3)_{fl}$, isospin, U-spin selection rules)
- hadronic matrix elements not accessible in QCD/ eff. theories: charm too light for QCDF/SCET, final state pions too energetic for ChPT



- no factorization (internal W- exchanges $\oplus$ hadronization $\oplus$ FSI)
- $\Lambda_c \to p\phi$, factorizable SCS mode ($BR \sim 8 \times 10^{-3}$) naive factorization fails $\Rightarrow$ large FSI
- on the theory side: constituent quark models with baryon wave functions, pole diagram approximations ,... ["BESS-3 physics book" [0809.169]]

Direct CPV asymmetry

(no major differences with D-decays)

- SCS modes are more promising than CF 's
- "Richness" of strong interactions $\Rightarrow$ large FSI phases, good for direct CPV,
- in SM the CKM phase effect is tiny ($O(\lambda^4) \sim 3 \times 10^{-3}$)
- direct asymmetry in $\Lambda_c \to f$ (two-body, quasi-two body)

$$A^{CP}(\Lambda_c \to f) = \frac{\Gamma(\Lambda_c \to f^+) - \Gamma(\bar{\Lambda}_c \to f^-)}{\Gamma(\Lambda_c \to f^+) + \Gamma(\bar{\Lambda}_c \to f^-)} \sim |r| Sin(\Delta_S) Sin(\Theta)$$

Δ_S (Θ) - difference between strong (CPV) phases of the SM and NP contribuitons to the decay amplitude,
$|r|$ the ratio of magnitudes

- even if $A^{CP}(\Lambda_c \to f) \neq 0$, very difficult to quantify the NP
- no special reasons to expect enhancement/suppression in $A^{CP}(\Lambda_c \to f)/SM$ vs $A^{CP}(D \to f')/SM$

Dalitz-plot analysis

- worked out for three-body D-decays
  [I.Bigi et al,. 0905.4223]
- CPV bin-asymmetries, use of resonance phases
- possibilities to use $\Lambda_c \to p\pi^+\pi^-$ and $\bar{\Lambda}_c \to \bar{p}\pi^-\pi^+$
  for a Dalitz-plot analysis
  (a) baryon resonances in the two $p\pi$ channels:
  $\Lambda_c \to p\pi^+\pi^- \to \Delta^{++}\pi^-$
  $\Lambda_c \to p\pi^+\pi^- \to \Delta^0\pi^+$
  $\oplus$ excited $\Delta' s$ and N'

  (b) meson resonances in 2π channel:
  $\Lambda_c \to p\pi^+\pi^- \to p\rho \;\; (pf_0, p\sigma, ...)$
- baryon resonances are well established (PDG)
- additional angular measurements
  $\to$ polarization of baryons

Triple correlations

- demand many-body meson decays, in case of polarized baryons accessible in two-body decays
- the idea: (for a pedagogical explanation see I.Bigi, A.Sanda, "CP-violation")
  $A(\Lambda_c \to BP) = \bar{u}_B(A_s e^{i\delta_S} + A_P e^{i\delta_P}\gamma_5)u_{\Lambda_c}$

  rest frame of polarized Λ_c, the decay width contains a term:
  $|A(\Lambda_c \to BP)|^2 = ... + Im[e^{i(\delta_S - \delta_P)}(A_S A_P^*)]\vec{p}_B \cdot (\vec{s}_B \times \vec{s}_{\Lambda_c})$

  CPV can induce a complex relative phase between A_S and A_P, in principle measurable if $(\delta_S - \delta_P)$ is precisely known, FSI not needed if forming asymmetry (adding !) the same term for $\bar{\Lambda}_c$
- effect proportional to $Cos[\delta_S - \delta_P]$
- recently investigated in detail for $\Lambda_c \to BP$, $\Lambda_c \to BV$ in
  X. -W. Kang, H. -B. Li, G. -R. Lu, A. Datta, [arXiv:1003.5494 [hep-ph]].

Channels useful for direct CPV

- two- and three-body (quasi-two body) hadronic decays of Λ_c and other weakly decaying charmed baryons
- CF modes: $\Lambda_c \to p\bar{K}^0, \Lambda\pi^+$,..
  $\Lambda_c \to pK^-\pi^+$,... ($BR \sim 1 - 5\%$),
- NP not expected, still useful to understand the dynamics of hadronic weak decays
  (amplitude relations, hierarchy of quark diags, resonances)
- SCS modes $\Lambda_c \to \Lambda K^+$,...
  $\Lambda_c \to p\pi^+\pi^-, pK^+K^-, \Sigma^+K^+\pi^-$ ($BR \simeq 10^{-3}$)
- direct CP asymmetries and Dalitz plots studies, similar to D decays, triple correlations may turn out more interesting for charmed baryons
- task for phenomenology: models with resonances and relative phases to be developed and MC-ed

Rare decays in charm sector

- $c \to u$ transitions, e.g., $D \to \pi \ell^+ \ell^-$

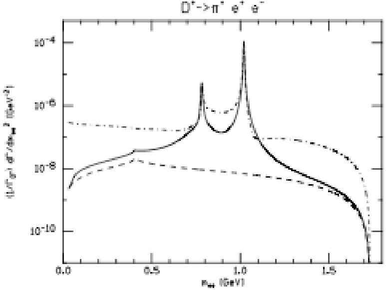


Figure 27.3: Predicted dilepton mass distributions for $D^+ \to \pi^+ e^+ e^-$. The dashed (solid) line is the short-distance (total) SM contribution. The dot-dashed line is the R-parity violating SUSY contribution.

[from Burdman,Golovich,Hewett,Pakvasa PRD(2002)]

- at small q^2 NP contribution predicted larger than SM
(in SM dominated by long-distance contributions:
$D \to \pi V$, $V \to \ell^+ \ell^-$)

$\Lambda_c \to p\ell^+\ell^-$

- in SM dominated by long-distance contributions, modelled by $\Lambda_c \to pV$, $V \to \ell^+\ell^-$ $(V = \rho, \omega, \phi)$
  (plus excited V' resonances)
- short-distance contributions due to NP , $\bar{u}c\bar{\ell}\ell$ operators , factorized with $\Lambda_c \to p$ form factors
- need a reliable model of LD contributions
  (dispersion relation in $q^2 = (p_\ell^+ + p_\ell^-)^2$)
  in $B \to K^{(*)}\ell^+\ell^-$ applied in [AK, Th.Mannel,A.Pivovarov, YM.Wang, (2010)
- input: data on $\Lambda_c \to pV$ amplitudes
  from hadronic Λ_c decays
- need accurate $\Lambda_c \to p$ form factors

$\Lambda_c \to p, \Lambda$ form factors

- definition of the form factors

$$\langle p(P)|\bar{u}\,\gamma_\mu\, c|\Lambda_c(P+q)\rangle = \bar{u}_p(P)\Big\{ f_1(q^2)\,\gamma_\mu + i\,\frac{f_2(q^2)}{m_{\Lambda_c}}\,\sigma_{\mu\nu}q^\nu + \frac{f_3(q^2)}{m_{\Lambda_c}}\,q_\mu \Big\} u_{\Lambda_c}(P+q)\,,$$

($\oplus$ 3 axial-vector form factors , $\gamma_\mu \to \gamma_\mu\gamma_5 \Rightarrow g_{1,2,3}(q^2)$)

- $\Lambda_c \to \Lambda$, related via $SU(3)_{fl}$ to $\Lambda_c \to p$,
  accessible in semileptonic $\Lambda_c \to \Lambda \ell \nu_\ell$
- needed for modelling factorizable approximation for hadronic decays, e.g. $\Lambda_c \to p\phi$
- no lattice QCD calculations of these form factors yet so far
  spectroscopy of charmed baryons on the lattice
- alternative method: QCD light-cone sum rules
  successful for $D \to \pi, K$ form factors
  recently used to calculate the $\Lambda_c \to p$ form factors

LCSR calculation $\Lambda_c \to p$ form factors

[AK, Ch.Klein, Th. Mannel, Y.-M. Wang, (2011)]

- method: employing light-cone DA's of nucleon
  [V.Braun, A.Lenz et al....]
- byproduct of $\Lambda_b \to p$ form factor calculation,
  finite heavy quark mass
- still large uncertainties, also from the choice of interpolating current for the charmed baryon, no radiative corrections,...
- $\Lambda_c \to p\ell^+\ell^-$ can be investigated in more details

interpol. current for Λ_c	axial	pseudoscalar
$f_1(0)$	$0.46^{+0.15}_{-0.11}$	$0.59^{+0.15}_{-0.16}$
$f_2(0)$	$-0.32^{+0.08}_{-0.07}$	$-0.43^{+0.13}_{-0.12}$
$g_1(0)$	$0.49^{+0.14}_{-0.11}$	$0.55^{+0.14}_{-0.15}$
$g_2(0)$	$-0.20^{+0.09}_{-0.06}$	$-0.16^{+0.08}_{-0.05}$

Conclusion

- Charmed baryon weak decays offer additional possibilities to study CPV and $c \to u$ FCNC at LHCb

- spin structure of decay amplitudes via angular distributions $\Rightarrow$ additional techniques/observables/asymmetries

- theory/phenomenology not sufficiently developed, deserve dedicated efforts