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Prospects for discovering new physics in charm sector through low-energy scattering processes $e^- p \to e^-(\mu^-)\Lambda_c$

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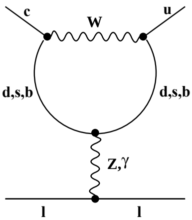
Outline

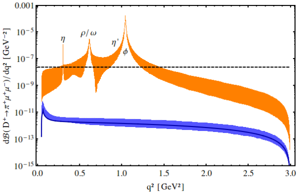
1. Motivation
2. Theoretical framework
3. Fixed-target scattering
4. Lepton flavor conserving scattering process: $e^- p \to e^- \Lambda_c$
5. Lepton flavor violating scattering process: $e^- p \to \mu^- \Lambda_c$
6. Summary

Why FCNC in charm sector

- In the SM, Flavor-changing-neutral -current (FCNC) transitions do not exist at tree level
- FCNC transitions in charm sector are strongly GIM-suppressed , ideal ground for NP searches
- FCNC processes in charm sector
  - Decay
    - semileptonic decays, e.g., $D^+ \to \pi^+\mu^+\mu^-$
      S. Boer and G. Hiller, 1510.00311
    - leptonic decays, e.g., $D^0 \to \mu^+\mu^-$
      S. Fajfer et al., 1510.00965
  - High-energy collider, e.g., $pp(q\bar{q}) \to \ell^+\ell^-$
    J. Fuentes-Martin et al., 2003.12421
  - Low-energy scattering processes (NEW)



FCNC in charm sector

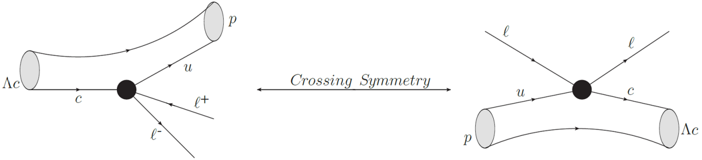


Resonance problem

S. Boer et al., 1510.00311

Why low-energy scattering in charm sector

- Low-energy scattering processes



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

- In theory:
  - free from the SM long-distance pollution, due to different kinematics
  - Lepton flavor conserving (LFC) $e^-p \to e^-\Lambda_c$ and lepton flavor violating (LFV) $e^-p \to \mu^-\Lambda_c$, can be detected with one experimental setup
- In experiment:
  - electron beam and proton target have been used in the APEX and Qweak experiments at JLab for hunting sub-GeV dark vector bosons

APEX Collaboration, S. Abrahamyan et al., 1108.2750
Qweak Collaboration, T. Allison et al., 1409.7100

Effective Lagrangian

The general effective Lagrangian responsible for the process $\ell u \to \ell^{(\prime)} c$ is given by

$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{eff}}^{\text{SM}} + \mathcal{L}_{\text{eff}}^{\text{NP}}$$

$$\begin{aligned}\mathcal{L}_{\text{eff}}^{\text{NP}} = \sum_{i,j,m,n} \Big\{ & [g_V^{LL}]^{ij,mn} (\bar{\ell}_L^i \gamma_\mu \ell_L^j)(\bar{q}_L^m \gamma^\mu q_L^n) + [g_V^{LR}]^{ij,mn} (\bar{\ell}_L^i \gamma_\mu \ell_L^j)(\bar{q}_R^m \gamma^\mu q_R^n) \\ & + [g_V^{RL}]^{ij,mn} (\bar{\ell}_R^i \gamma_\mu \ell_R^j)(\bar{q}_L^m \gamma^\mu q_L^n) + [g_V^{RR}]^{ij,mn} (\bar{\ell}_R^i \gamma_\mu \ell_R^j)(\bar{q}_R^m \gamma^\mu q_R^n) \\ & + [g_T^{L}]^{ij,mn} (\bar{\ell}_R^i \sigma^{\mu\nu} \ell_L^j)(\bar{q}_R^m \sigma_{\mu\nu} q_L^n) + [g_T^{R}]^{ij,mn} (\bar{\ell}_L^i \sigma^{\mu\nu} \ell_R^j)(\bar{q}_L^m \sigma_{\mu\nu} q_R^n) \\ & + [g_S^{L}]^{ij,mn} (\bar{\ell}_R^i \ell_L^j)(\bar{q}_R^m q_L^n) + [g_S^{R}]^{ij,mn} (\bar{\ell}_L^i \ell_R^j)(\bar{q}_L^m q_R^n) \Big\}\end{aligned}$$

Leptoquark model

- Why LQ?

LQ models can explain B anomalies, such as $R(D^{(*)})$ and $R(K^{(*)})$

I. Doršner et al., 1603.09443; A. Crivellin and F. Saturnino, 1905.08297

Scalar LQ	SM Rep.	Vector LQ	SM Rep.
$S_1 Q_L L_L$, $S_1 u_R e_R$	$(\bar{3},1,1/3)$	$V_{2\mu} u_R \gamma^\mu L_L$	$(\bar{3},2,-1/6)$
$\tilde{R}_2 \bar{d}_R L_L$	$(3,2,1/6)$	$V_{2\mu} d_R \gamma^\mu L_L$, $V_{2\mu} Q_L \gamma^\mu e_R$	$(\bar{3},2,5/6)$
$S_3 Q_L L_L$	$(\bar{3},3,1/3)$	$U_{1\mu} \bar{Q}_L \gamma^\mu L_L$, $U_{1\mu} \bar{d}_R \gamma^\mu e_R$	$(3,1,2/3)$
$\tilde{S}_1 d_R e_R$	$(\bar{3},1,4/3)$	$U_{3\mu} \bar{Q}_L \gamma^\mu L_L$	$(3,3,2/3)$
$R_2 \bar{u}_R L_L$, $R_2 \bar{Q}_L e_R$	$(3,2,7/6)$	$\tilde{U}_{1\mu} \bar{u}_R \gamma^\mu e_R$	$(3,1,5/3)$

→ mediate proton decays at tree level, $\tau(p \to \pi^0 e^+) > 1.6 \times 10^{33}$ years

P. Nath, P. F. Perez, hep-ph/0601023

→ cannot mediate $e^- p \to e^- \Lambda_c$ at tree level

- Interactions of $R_2, U_3, \tilde{U}_1$ with the SM fermions in the mass eigenstates:

$$\mathcal{L}_{R_2} \supset R_2^{\frac{5}{3}} \left[(\lambda_2^S)_{ij} \bar{u}_R^i e_L^j + (\lambda_2'^S)_{ij} \bar{u}_L^i e_R^j \right] + \text{H.c.}$$

$$\mathcal{L}_{U_3} \supset U_{3\mu}^{\frac{5}{3}} (\lambda_3^V)_{ij} \bar{u}_L^i \gamma^\mu e_L^j + \text{H.c.}$$

$$\mathcal{L}_{\tilde{U}_1} \supset \tilde{U}_{1\mu}^{\frac{5}{3}} (\lambda_{\tilde{1}}^V)_{ij} \bar{u}_R^i \gamma^\mu e_R^j + \text{H.c.}$$

Wilson Coefficients

- $\mu = M = 1$ TeV CMS Collaboration, A. M. Sirunyan et al., 1809.05558

	g_V^{LL}	g_V^{LR}	g_V^{RL}	g_V^{RR}	g_T^{L}	g_T^{R}	g_S^{L}	g_S^{R}
R_2	✗	✓	✓	✗	✓	✓	✓	✓
U_3	✓	✗	✗	✗	✗	✗	✗	✗
$\tilde{U}_1$	✗	✓	✗	✗	✗	✗	✗	✗

$$g_S^{L,R} = 4\ g_T^{L,R} (R_2 \text{ model})$$

- $\mu = 2$ GeV

$$g_S^{L,R}(2\text{ GeV}) \approx 2.0\ g_S^{L,R}(1\text{ TeV}) - 0.5\ g_T^{L,R}(1\text{ TeV})$$

$$g_T^{L,R}(2\text{ GeV}) \approx 0.8\ g_T^{L,R}(1\text{ TeV}) \quad g_V^{\alpha}(2\text{ GeV}) \approx g_V^{\alpha}(1\text{ TeV})$$

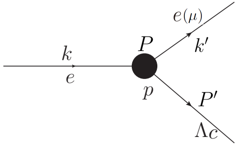
$$\Longrightarrow \quad g_S^{L,R}(2\text{ GeV}) \approx 9.4\ g_T^{L,R}(2\text{ GeV})\ (R_2 \text{ model})$$

Cross section and kinematics

- The event rate of fixed-target scattering experiments dN/dt is defined as

$$dN/dt = \mathcal{L}\sigma = \phi\rho_T L\sigma$$

- $e^-(k) + p(P) \to e^-(\mu^-)(k') + \Lambda_c(P')$



$$\sigma = \frac{1}{64\pi m_p^2 E^2}\int_{q^2_{\rm min}}^{q^2_{\rm max}} dq^2\overline{|\mathcal{M}|}^2$$

$$\mathcal{M} = \sum g_{\alpha\beta}\langle k'|j_\alpha|k\rangle\boxed{\langle P', s'|J_\beta|P, s\rangle}$$

- The experimental parameters for the low-energy scattering experiments

APEX electron beam[1],[2]		Liquid hydrogen target[3]		Luminosity
Energy(GeV)	Current (μA)	Length (cm)	Density (g/cm^3)	(s^{-1}cm^{-2})
3	150	40	71.3×10^{-3}	1.6×10^{39}

[1] APEX Collaboration, S. Abrahamyan et al., 1108.2750;
[2] R. Essig et al., 1001.2557;
[3] Qweak Collaboration, T. Allison et al., 1409.7100

Model independent results of LFC scatter process

- Model independent results $(G_F^2 \alpha_e^2/\pi^2)$

Processes	$\lvert g_V^{LL,RR} \rvert^2$	$\lvert g_V^{LR,RL} \rvert^2$	$\lvert g_S^{L,R} \rvert^2$	$\lvert g_T^{L,R} \rvert^2$
$D^0 \to e^- e^+$ [1]	\	\	0.062	\
$D^+ \to \pi^+ e^- e^+$ [2]	14	14	6.3	13
$pp(q\bar{q}) \to e^- e^+$ [3]	3.6	3.6	22	0.57
$e^- p \to e^- \Lambda_c$	0.035	0.083	0.17	0.0056

[1] LHCb Collaboration, R. Aaij et al., 1512.00322;
[2] BaBar Collaboration, J. Lees et al., 1107.4465;
[3]A. Angelescu et al., 2002.05684

- Low-energy scattering process can provide more competitive constraints and build a further complementary relation with the D-meson leptonic decays
- Constraints on $g_V^{LL,RR}$ and $g_V^{LR,RL}$ are different compared with other processes

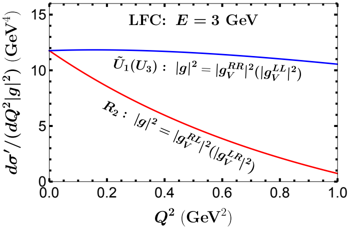
Results in LQ models

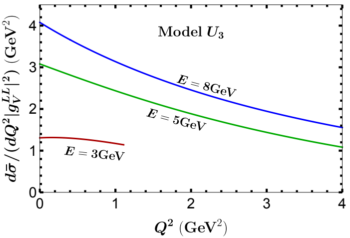
- Event rate forecast in units of number per year in LQ models

Models	g_V^{LL}	g_V^{RR}	$g_V^{LR,RL}$	$g_S^{L,R}$
R_2	\	\	43	0.25
U_3	103	\	\	\
$\tilde{U}_1$	\	\	\	\

  - promising event rates can be expected for the scattering process
  - the vector LQ models are expected to generate more events than the scalar one

The differential cross section





- $\sigma' = (256\pi m_p^2 E^2)\sigma$
- distinguish the survived scalar and vector LQs in future low-energy scattering experiments, e.g., $d\Gamma(D^+ \to \pi^+ e^+ e^-)/d\sigma(e^- p \to e^- \Lambda_c)$ in $Q^2 \in [0.04, 0.9]$ GeV^2

- $\bar{\sigma} = (256\pi m_p^2)\sigma$
- $d\bar{\sigma}$ falls gradually, but still not as dramatically as in the R_2 model
- high beam energy clearly favors high event rate

Model independent results of LFV scatter process

- Model independent results $(G_F^2 \alpha_e^2/\pi^2)$

Processes	$\lvert g_V^{LL,RR} \rvert^2$	$\lvert g_V^{LR,RL} \rvert^2$	$\lvert g_S^{L,R} \rvert^2$	$\lvert g_T^{L,R} \rvert^2$
$D^0 \to e^- \mu^+$ [1]	\	\	0.010	\
$D^+ \to \pi^+ e^- \mu^+$ [2]	40	40	19	34
$pp(q\bar{q}) \to e^- \mu^+$ [3]	1.2	1.2	5.8	0.19
$e^- p \to \mu^- \Lambda_c$	0.039	0.091	0.18	0.0063

[1] LHCb Collaboration, R. Aaij et al., 1512.00322;
[2] BaBar Collaboration, J. Lees et al., 1107.4465;
[3]A. Angelescu et al., 2002.05684

- Low-energy scattering process can provide more competitive constraints and build a further complementary relation with the D-meson leptonic decays
- Constraints on $g_V^{LL,RR}$ and $g_V^{LR,RL}$ are different compared with other processes

Observables

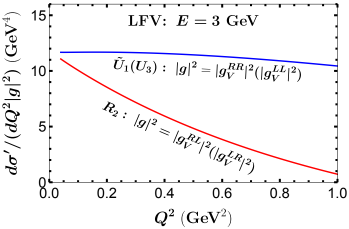
- Event rate forecast in LFV case

Models	g_V^{LL}	g_V^{RR}	$g_V^{LR,RL}$	$g_S^{L,R}$
R_2	\	\	13	0.039
U_3	31	\	\	\
$\tilde{U}_1$	\	31	\	\

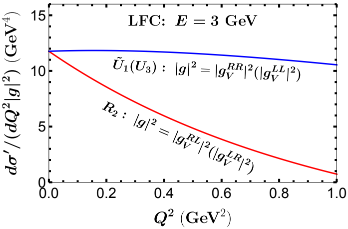
- Event rate forecast in LFC case

Models	g_V^{LL}	g_V^{RR}	$g_V^{LR,RL}$	$g_S^{L,R}$
R_2	\	\	43	0.25
U_3	103	\	\	\
$\tilde{U}_1$	\	\	\	\

- Differential cross section in the LFV case



- Differential cross section in the LFC case

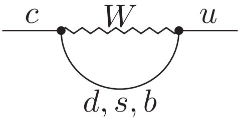


Summary

- Search for LQ contributions to the FCNC in charm sector through $e^- p \to e^- \Lambda_c$ and $e^- p \to \mu^- \Lambda_c$
- Low-energy scattering experiments can provide more competitive constraints compared with charm decays and high-p_T invariant mass tails of dilepton, and build a further complementary relation with the D-meson leptonic decays
- Promising event rates can be expected for both LFC and LFV scattering experiments in the LQ models
- Providing a potential path to distinguish the survived scalar and vector LQs in future experiments
- Since most of our analyses are based on the general effective Lagrangian, our results can be directly applied to other NP models

Thanks for your attention !

- GIM-suppression

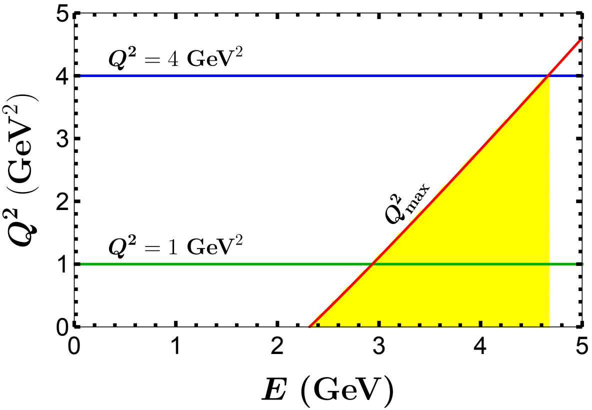


$$\mathcal{A}(c \to u) = V_{cs}^* V_{us} \left(f(m_s^2/m_W^2) - f(m_d^2/m_W^2) \right) + V_{cb}^* V_{ub} \left(f(m_b^2/m_W^2) - f(m_d^2/m_W^2) \right)$$

- $\mathcal{L}_{\text{eff}} = \sum g_{\alpha\beta} j_\alpha J_\beta$

$$\begin{aligned} j_S^{R,L} &= \bar{\ell} P_{R,L} \ell, & J_S^{R,L} &= \bar{q} P_{R,L} q, \\ (j_V^{R,L})^\mu &= \bar{\ell} \gamma^\mu P_{R,L} \ell, & (J_V^{R,L})^\mu &= \bar{q} \gamma^\mu P_{R,L} q, \\ (j_T^{R,L})^{\mu\nu} &= \bar{\ell} \sigma^{\mu\nu} P_{R,L} \ell, & (J_T^{R,L})^{\mu\nu} &= \bar{q} \sigma^{\mu\nu} P_{R,L} q. \end{aligned}$$

$$\mathcal{M} = \sum g_{\alpha\beta} \langle k' | j_\alpha | k \rangle \langle P', s' | J_\beta | P, s \rangle,$$



- $Q^2_{\rm max} = -\frac{2E(M^2_{\Lambda_c} - m_p^2 - 2m_p E)}{m_p + 2E}$
- $\mathcal{L}_{\rm eff}(\mu = 2\,\text{GeV}) \Longrightarrow Q^2 < 4\,\text{GeV}^2$
- consider a benchmark scenario with $Q^2_{\rm max} \leq 1\,\text{GeV}^2$ and $E \leq 3\,\text{GeV}$

Other constraints

- Processes involving the CKM and PMNS matrices
  - the flavor structure of λ is unknown
  - without additional assumptions
- Measurements of $D^0 - \bar{D}^0$ mass and lifetime difference
  - set constraints on Re$[(\lambda^{u\ell}(\lambda^{c\ell})^*)^2]$
  - constraint from the measurement of $D^0 - \bar{D}^0$ mass difference is much less severe in comparison with that from meson decays
  - the measurement of $D^0 - \bar{D}^0$ lifetime difference sets no constraints on the Wilson coefficients for 1 TeV LQs
- Measurement of anomalous magnetic moments and electric dipole moments (EDM)
  - no constraints can be set on $|\lambda|$ for 1 TeV vector LQs
  - Re$[(\lambda_2^S)_{ce}(\lambda_2^{\prime S})^*_{ce}] \in [0.00, 0.01]$
  - Im$[(\lambda_2^S)_{ce}(\lambda_2^{\prime S})^*_{ce}] \lesssim 2 \times 10^{-11}$
- Corrections to $Z \to ff$
  - $\lambda \lesssim \frac{M}{Tev}$, yielding no constraint
- Measurements of $\mu \to e$ conversion in nuclei
  - $|g_V|^{e\mu,uu} < 2.4 \times 10^{-7} G_F$

- Electron beam

  Favor an electron beam with an intensity up to 150 μA and beam energy ranging from 1.1 - 4.5 GeV in the APEX experiment at Jefferson Laboratory (JLab)

- The proton target
  - Select a liquid hydrogen target due to its higher number density
  - Cooling system

$$H = L\rho dE/dL \quad P = HI$$

where H is the energy stored in the target, dE/dL represents the mean rate of electron energy loss in units of MeV g^{-1} cm^2, ρ and L denote the respective density and length of the target and P is the cooling power

In the physical limits $(a = 0; m_\pi = m_{\pi,phys})$, the form factor takes the form

$$f(q^2) = \frac{1}{1 - q^2/(m_{pole}^f)^2} \sum_{n=0}^{n_{max}} a_n^f [z(q^2)]^n$$

where the expansion variable is defined as

$$z(q^2) = \frac{\sqrt{t_+ - q^2} - \sqrt{t_+ - t_0}}{\sqrt{t_+ - q^2} + \sqrt{t_+ - t_0}} \quad t_+ = (m_D + m_\pi)^2$$

$$t_+ = (m_D + m_\pi)^2 \quad t_0 = (m_{\Lambda_c} - m_N)^2$$

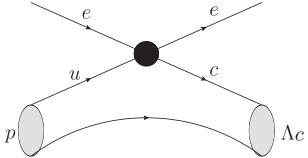
To fit the parameters a_n^f in L_{QCD}, form factor must modified by incorporating lattice information. Two independent fits are performed: a "normal" fit and a "higher-order" (HO) fit The form factor function for normal fit is given by

$$f(q^2) = \frac{1}{1 - (a^2 q^2)/(a m_D + a\Delta^f)^2} [a_0^f (1 + c_0^f \frac{m_\pi^2 - m_{\pi,phys}^2}{\Lambda_\chi^2}) + a_1^f z(q^2) + a_2^f [z(q^2)]^2] \times [1 + b^f a^2 |\mathbf{p}^{'}|^2 + d^f a^2 \Lambda_{had}^2]$$

(Stefan Meinel,arxiv:1712.05783)

Form factor parametrization

- $\mathcal{M} = \sum g_{\alpha\beta} \langle k' | j_\alpha | k \rangle \langle P', s' | J_\beta | P, s \rangle$



- Use form factors to parametrize the hadronic contributions as in charm decays

$$\langle p(P,s)|\bar{u}\gamma^\mu c|\Lambda_c(P',s')\rangle = \bar{u}_p(P,s)\Big[f_0(q^2)(m_{\Lambda_c} - m_p)\frac{q^\mu}{q^2} + f_+(q^2)\frac{m_{\Lambda_c}+m_p}{s_+}\Big(P'^\mu + P^\mu - (m_{\Lambda_c}^2 - m_p^2)\frac{q^\mu}{q^2}\Big) + f_\perp(q^2)\Big(\gamma^\mu - \frac{2m_N}{s_+}P'^\mu - \frac{2m_{\Lambda_c}}{s_+}P^\mu\Big)\Big]u_{\Lambda_c}(P',s')$$

- Analyticity of the form factor parametrization in the complex q^2-plane

C. Bourrely et al., 0807.2722; S. Meinel, 1712.05783