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Rare Λ_c decays

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HFCPV2024

2024.10.27 @衡阳

FCNC process in baryon sector

- $b \to s\ell\ell$:

$$Br(\Lambda_b \to \Lambda\mu^+\mu^-) = (1.73 \pm 0.42 \pm 0.55) \times 10^{-6}$$

CDF, 2011

$$Br(\Lambda_b \to \Lambda\mu^+\mu^-) = (0.96 \pm 0.16 \pm 0.13 \pm 0.21) \times 10^{-6}$$

LHCb, 2013

- $s \to d\ell\ell$:

$$Br(\Xi^0 \to \Lambda e^+e^-) = (7.6 \pm 0.4 \pm 0.4 \pm 0.2) \times 10^{-6}$$

NA48, 2007

$$Br(\Sigma^+ \to p\mu^+\mu^-) = (2.2^{+1.8}_{-1.3}) \times 10^{-8}$$

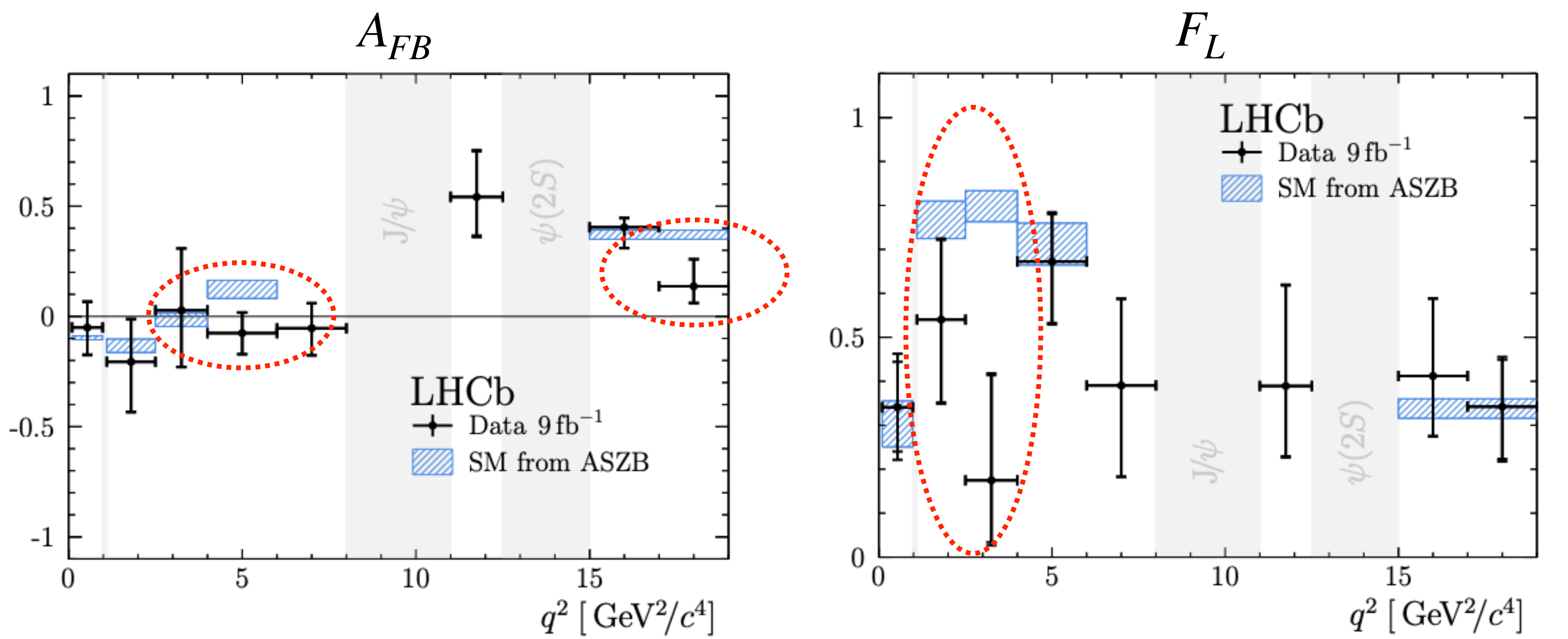
LHCb, 2018

$$c \to u\ell\ell$$

- Stronger GIM suppression
- Resonance contributions

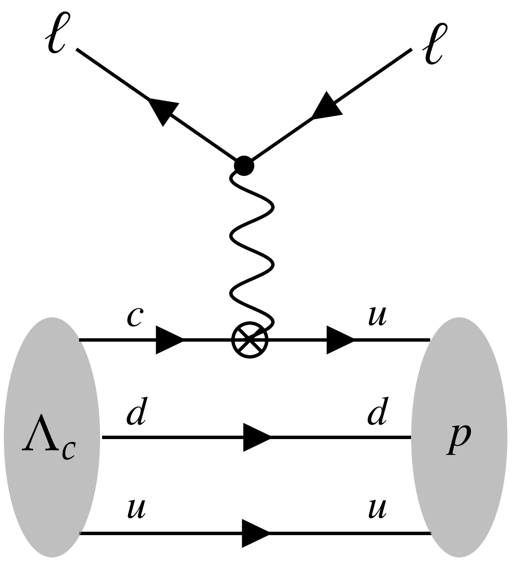
Deviations from standard model in B decays

$B^+ \to K^{*+}\mu^+\mu^-$ LHCb, 2021



- Require careful scrutiny of experimental data and SM predictions.
- Need examination in $c \to u\ell\ell$.

Theoretical perspective for $\Lambda_c \to p\ell\ell$



$$H_{eff} = \frac{G_F\,\alpha}{2\sqrt{2}\pi}\Big\{C_9[\bar{u}\gamma^\mu(1-\gamma_5)c][\bar{\ell}\gamma_\mu\ell] + C_{10}[\bar{u}\gamma^\mu(1-\gamma_5)c][\bar{\ell}\gamma_\mu\gamma_5\ell]$$

$$-C_7\frac{2m_c}{q^2}[\bar{u}i\sigma_{\mu\nu}q^\nu(1+\gamma_5)c][\bar{\ell}\gamma_\mu\ell]\Big\}\ ,$$

hadronic part:

- $c \to u$ transition: $\bar{u}\,\gamma_\mu(1-\gamma_5)\,c,\ \ \bar{u}\,i\sigma_{\mu\nu}q^\mu(1+\gamma_5)\,c$
- parametrized in terms of form factors

$$\langle p\,|\,J_\mu^{h,V-A}\,|\,\Lambda_c\rangle = \bar{u}_2\Big[\gamma_\mu(f_1 - g_1\gamma_5) + i\sigma_{\mu\nu}\frac{q^\nu}{M_{\Lambda_c}}(f_2 - g_2\gamma_5) + \frac{q_\mu}{M_{\Lambda_c}}(f_3 - g_3\gamma_5)\Big]u_1$$

$$\langle p\,|\,J_\mu^{h,Tensor}\,|\,\Lambda_c\rangle = \bar{u}_2\Big[\frac{\gamma^\mu q^2 - q^\mu \not{q}}{M_{\Lambda_c}}(f_1^T + g_1^T\gamma_5) - i\sigma_{\mu\nu}q^\nu(f_2^T + g_2^T\gamma_5)\Big]u_1$$

Form factors in QCD sum rules

SUM RULES AND THE PION FORM FACTOR IN QCD

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Laboratory of Theoretical Physics, JINR, Dubna, USSR

Received 12 May 1982

MESON WIDTHS AND FORM FACTORS AT INTERMEDIATE MOMENTUM TRANSFER IN NON-PERTURBATIVE QCD

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ITEP, Moscow, 117259, USSR

Received 14 September 1982

light and heavy hadrons. The applications include the pion electromagnetic form factor,[100] radiative charmonium decays such as $J/\psi \to \eta_c\gamma$,[101] D and B semileptonic and flavor-changing neutral current (FCNC) transitions [102–107] and, more recently, the radiative decays $\phi \to (\eta, \eta')\gamma$.[108]

P. Colangelo et al., *QCD sum rules, a modern perspective*(2000)

★ *FCNC transition*

HCS&YHG, 1999

★ *Semileptonic decay*

DYB&HCS&HMQ&LC, 1996

HCS&QCF&YHG, 1998

WZG, 2014

SYJ&WW&ZZX, 2020

XZP&ZZX, 2021

★ *Strong decay*

LDK&CW&CHX, 2023

WZG, 2016, 2024

Dias&LX&Nielsen, 2013

WBD&QCF, 2021

Three-point correlation function

$$\Pi_\mu(q_1^2, q_2^2, q^2) = i^2 \int d^4x\, d^4y\, e^{i(-q_1 x + q_2 y)} < 0 | T\{j_p(y) j_\mu(0) j_{\Lambda_c}^\dagger(x)\} | 0 >$$

$j_{\Lambda_c(p)}$: interpolating current that couple to the hadronic states

✦ $j_{\Lambda_c} = \epsilon_{ijk}\left(u_i^T C\gamma_5 d_j\right) c_k\,, \quad j_p = \epsilon_{ijk}\left(u_i^T C\gamma_5 d_j\right) u_k$

j_μ: weak transition current

✦ $j_\mu = \bar{u}\gamma_\mu(1-\gamma_5)c\,,\ \bar{u} i\sigma_{\mu\nu} q^\nu (1+\gamma_5)c$

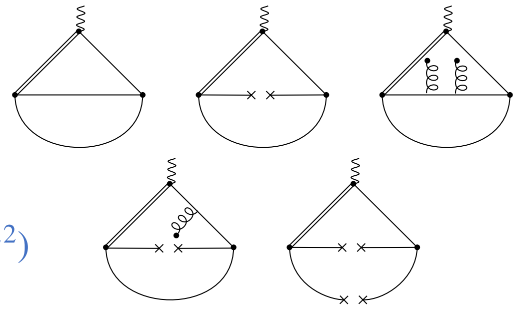
dispersion relations

$$\Pi_\mu(q_1^2, q_2^2, q^2) = \int ds_1 \int ds_2 \frac{\rho_\mu(s_1, s_2, q^2)}{(s_1 - q_1^2)(s_2 - q_2^2)}$$

Two representations

Quark level

$$\Pi_\mu^{\rm QCD}(q_1^2, q_2^2, q^2) = \int_{s_1^{\rm min}}^{\infty} ds_1 \int_{s_2^{\rm min}}^{\infty} ds_2 \frac{\rho_\mu^{\rm QCD}(s_1, s_2, q^2)}{(s_1 - q_1^2)(s_2 - q_2^2)}$$



$$\rho_\mu^{\rm QCD}(s_1, s_2, q^2) = \rho_\mu^{\rm pert}(s_1, s_2, q^2) + \rho_\mu^{\langle\bar{q}q\rangle}(s_1, s_2, q^2) + \rho_\mu^{\langle g_s^2 G^2\rangle}(s_1, s_2, q^2)$$
$$+\rho_\mu^{\langle g_s\bar{q}\sigma\cdot Gq\rangle}(s_1, s_2, q^2) + \rho_\mu^{\langle\bar{q}q\rangle^2}(s_1, s_2, q^2)$$

Quark-hadron duality $\Pi_\mu^{\rm phe} \simeq \Pi_\mu^{\rm QCD}$

Hadron level

$$\Pi_\mu^{\rm phe}(q_1^2, q_2^2, q^2) = \frac{\lambda_p(\not{q}_2 + M_p)\left[\gamma_\mu(f_1 - g_1\gamma_5) + \frac{i\sigma_{\mu\nu}q^\nu}{M_{\Lambda_c}}(f_2 - g_2\gamma_5) + \frac{q_\mu}{M_{\Lambda_c}}(f_3 - g_3\gamma_5)\right]\lambda_{\Lambda_c}(\not{q}_1 + M_{\Lambda_c})}{(q_1^2 - M_{\Lambda_c}^2)(q_2^2 - M_p^2)}$$
$$+\frac{\lambda_p(\not{q}_2 + M_p)\left[\frac{\gamma^\mu q^2 - q^\mu \not{q}}{M_{\Lambda_c}}(f_1^T + g_1^T\gamma_5) - i\sigma_{\mu\nu}q^\nu(f_2^T + g_2^T\gamma_5)\right]\lambda_{\Lambda_c}(\not{q}_1 + M_{\Lambda_c})}{(q_1^2 - M_{\Lambda_c}^2)(q_2^2 - M_p^2)}$$

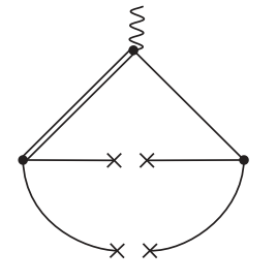
$$\sum_H |H\rangle\langle H| = 1$$

Restrictions

➡ Operator product expansion: convergence

$\Pi \sim C_1 O_1 + C_2 O_2 + C_3 O_3 + \ldots\ldots C_m O_m$

Contributions from highest order should be small



➡ Pole dominance: ground-state hadrons

Borel transform

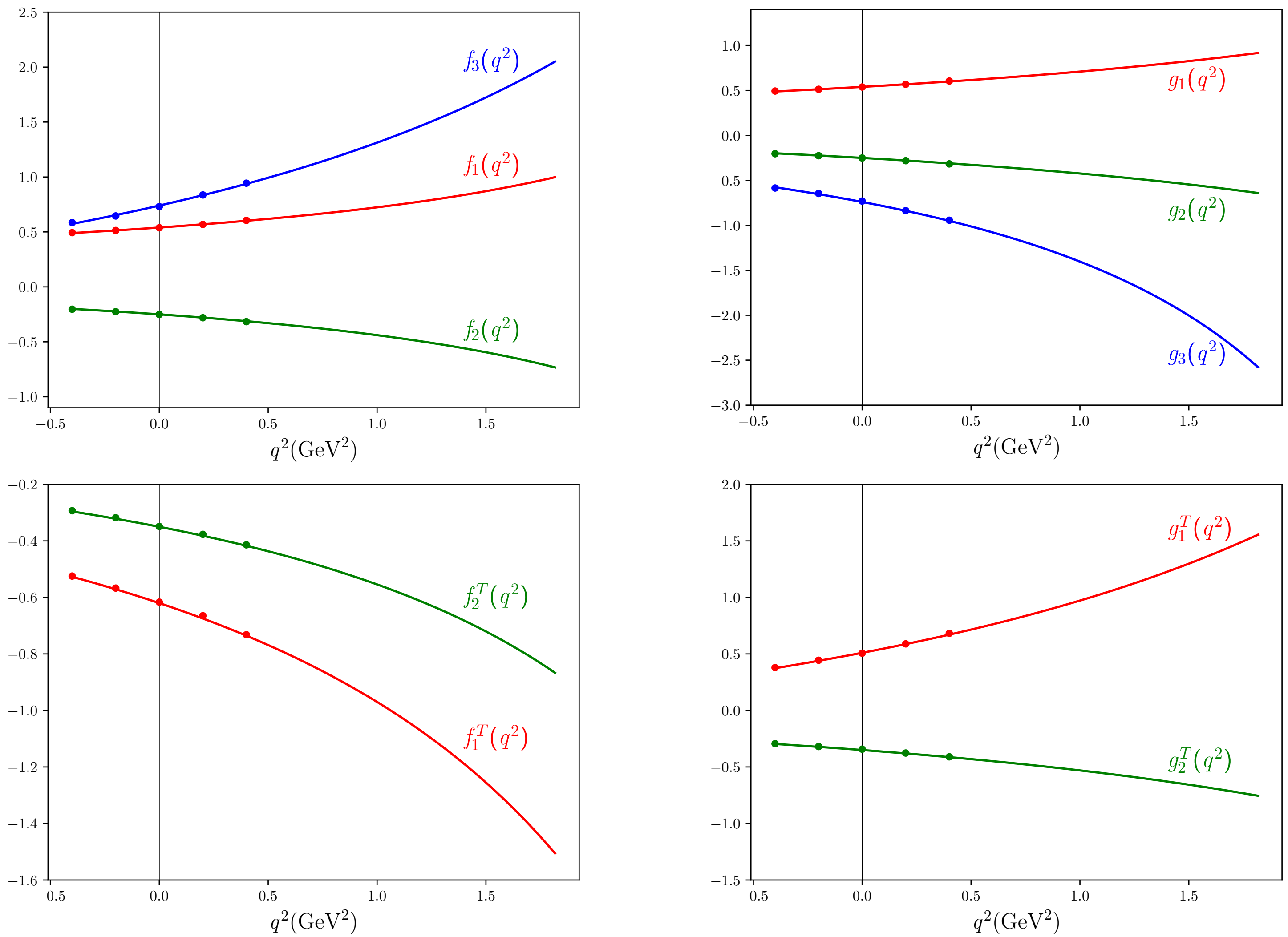
$$\mathscr{B}[g(Q^2)] \equiv g(M_B^2) = \lim_{\substack{Q^2, n \to \infty \\ n/Q^2 = 1/M_B^2}} \frac{(-1)^n (Q^2)^{n+1}}{n!} \left(\frac{\partial}{\partial Q^2} \right)^n g(Q^2)$$

- Suppress the OPE and continuum states contributions
- Minimal dependence of M_B^2

Form factors

z-series parametrization: $f_i(q^2) = \dfrac{f_i(0)}{1 - q^2/(m_{\rm pole})^2}\{1 + a_1(z(q^2, t_0) - z(0,t_0))\}$

χ^2 fitting method



Decay observables via helicity amplitude

$$\frac{d\Gamma(\Lambda_c \to p\ell\ell)}{dq^2} = \frac{\alpha^2\, G_F^2\, q^2\, \sqrt{Q_+Q_-}}{(2\pi)^5\, 48\, M_{\Lambda_c}^3} \sqrt{1 - \frac{4m_\ell^2}{q^2}} H_{tot}\,,$$

$$A_{FB}^{\ell}(q^2) = -\frac{3}{4}\frac{\sqrt{1-\frac{4m_l^2}{q^2}}H_P^{12}}{H_{tot}}\,,$$

$$F_L(q^2) = \frac{\frac{1}{2}\left(1-\frac{4m_l^2}{q^2}\right)(H_L^{11}+H_L^{22}) + \frac{m_l^2}{q^2}(H_U^{11}+H_L^{11}+H_S^{22})}{H_{tot}}\,,$$

$$H_{tot} = \frac{1}{2}(H_U^{11}+H_U^{22}+H_L^{11}+H_L^{22})\left(1-\frac{4m_\ell^2}{q^2}\right) + \frac{3m_\ell^2}{q^2}(H_U^{11}+H_L^{11}+H_S^{22})\,,$$

$$H_U^{mm'} = \mathrm{Re}(H^m_{\frac{1}{2},1}H^{\dagger m'}_{\frac{1}{2},1}) + \mathrm{Re}(H^m_{-\frac{1}{2},-1}H^{\dagger m'}_{-\frac{1}{2},-1})\,, \qquad H_L^{mm'} = \mathrm{Re}(H^m_{\frac{1}{2},0}H^{\dagger m'}_{\frac{1}{2},0}) + \mathrm{Re}(H^m_{-\frac{1}{2},0}H^{\dagger m'}_{-\frac{1}{2},0})\,,$$

$$H_S^{mm'} = \mathrm{Re}(H^m_{\frac{1}{2},t}H^{\dagger m'}_{\frac{1}{2},t}) + \mathrm{Re}(H^m_{-\frac{1}{2},t}H^{\dagger m'}_{-\frac{1}{2},t})\,, \qquad H_P^{mm'} = \mathrm{Re}(H^m_{\frac{1}{2},1}H^{\dagger m'}_{\frac{1}{2},1}) - \mathrm{Re}(H^m_{-\frac{1}{2},-1}H^{\dagger m'}_{-\frac{1}{2},-1})\,.$$

Decay observables via helicity amplitude

$$H^{Vm}_{\frac{1}{2},0} = \sqrt{\frac{Q_-}{q^2}}\left(M_+ F^{Vm}_1 + \frac{q^2}{M_{\Lambda_c}} F^{Vm}_2\right) , \qquad H^{Am}_{\frac{1}{2},0} = \sqrt{\frac{Q_+}{q^2}}\left(M_- F^{Am}_1 - \frac{q^2}{M_{\Lambda_c}} F^{Am}_2\right) ,$$

$$H^{Vm}_{\frac{1}{2},1} = \sqrt{2Q_-}\left(F^{Vm}_1 + \frac{M_+}{M_{\Lambda_c}} F^{Vm}_2\right) , \qquad H^{Am}_{\frac{1}{2},1} = \sqrt{2Q_+}\left(F^{Am}_1 - \frac{M_-}{M_{\Lambda_c}} F^{Am}_2\right) ,$$

$$H^{Vm}_{\frac{1}{2},t} = \sqrt{\frac{Q_+}{q^2}}\left(M_- F^{Vm}_1 + \frac{q^2}{M_{\Lambda_c}} F^{Vm}_3\right) , \qquad H^{Am}_{\frac{1}{2},t} = \sqrt{\frac{Q_-}{q^2}}\left(M_+ F^{Am}_1 - \frac{q^2}{M_{\Lambda_c}} F^{Am}_3\right) .$$

$$F^{V1}_1 = C^{\mathrm{eff}}_9 f_1 - \frac{2m_c}{M_{\Lambda_c}} C^{\mathrm{eff}}_7 f^T_1 , \qquad F^{A1}_1 = C^{\mathrm{eff}}_9 g_1 + \frac{2m_c}{M_{\Lambda_c}} C^{\mathrm{eff}}_7 g^T_1 ,$$

$$F^{V1}_2 = C^{\mathrm{eff}}_9 f_2 - \frac{2m_c M_{\Lambda_c}}{q^2} C^{\mathrm{eff}}_7 f^T_2 , \qquad F^{A1}_2 = C^{\mathrm{eff}}_9 g_2 + \frac{2m_c M_{\Lambda_c}}{q^2} C^{\mathrm{eff}}_7 g^T_2 ,$$

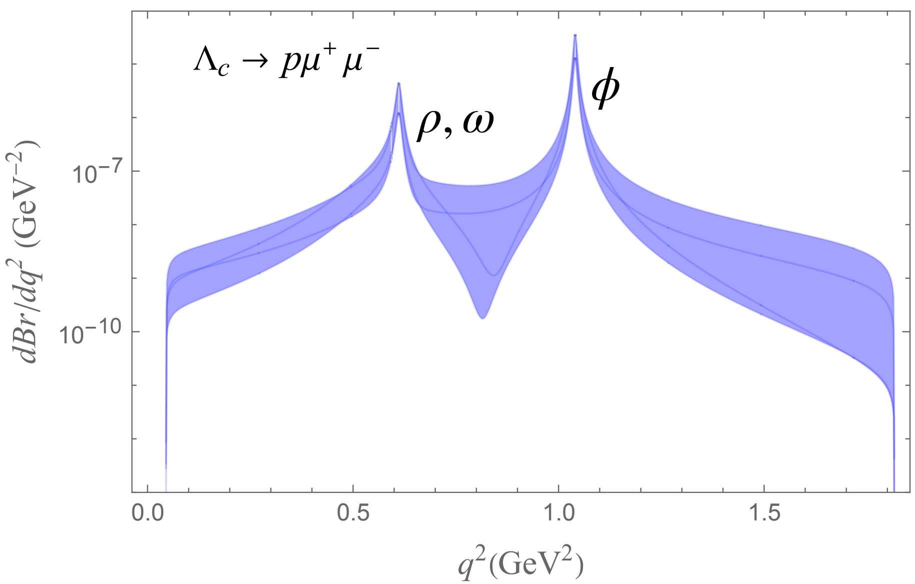
$$F^{V1}_3 = C^{\mathrm{eff}}_9 f_3 + \frac{2m_c M_-}{q^2} C^{\mathrm{eff}}_7 f^T_1 , \qquad F^{A1}_3 = C^{\mathrm{eff}}_9 g_3 + \frac{2m_c M_+}{q^2} C^{\mathrm{eff}}_7 g^T_1 ,$$

$$F^{V2}_i = C_{10} f_i , \qquad F^{A2}_i = C_{10} g_i .$$

Branching fractions

- Resonance contributions: $\Lambda_c \to pM(M \to \ell\ell),\ M = \rho, \omega, \phi$
- Breit-Wigner structure:

$$\star\, C_9^{\mathrm{R}}(q^2) = a_\omega e^{i\delta_\omega}\left(\frac{1}{q^2 - M_\omega^2 + iM_\omega\Gamma_\omega} - \frac{3}{q^2 - M_\rho^2 + iM_\rho\Gamma_\rho}\right) + \frac{a_\phi e^{i\delta_\phi}}{q^2 - M_\phi^2 + iM_\phi\Gamma_\phi}$$

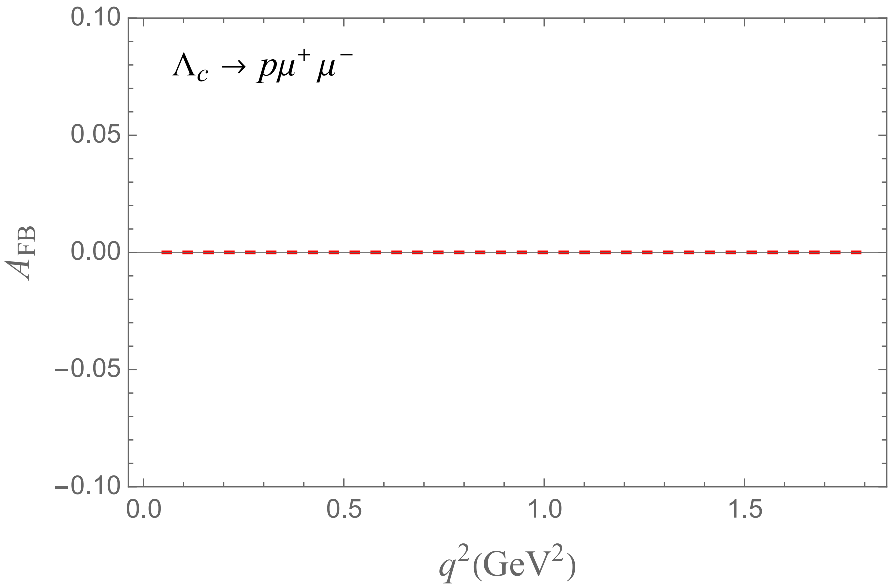


- $\mathrm{d}Br/\mathrm{d}q^2 \equiv \tau_{\Lambda_c}\mathrm{d}\Gamma/\mathrm{d}q^2$
- $Br(\Lambda_c \to p\mu^+\mu^-) = (4.9 \pm 1.4) \times 10^{-7}$
- LQCD: $Br(\Lambda_c \to p\mu^+\mu^-) = (3.7 \pm 1.3) \times 10^{-7}$

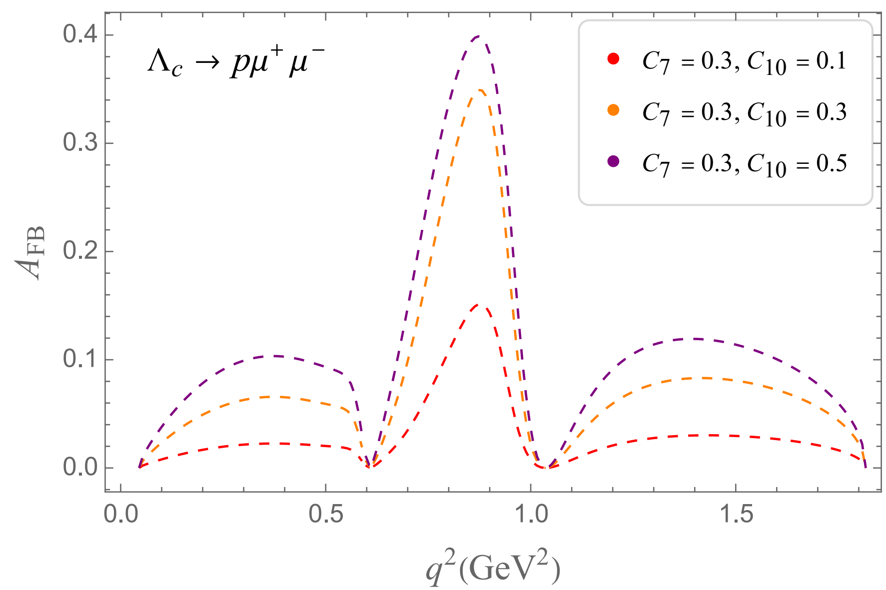
  S.Meinel, 2018

Lepton forward-backward asymmetry A_{FB}

Standard model



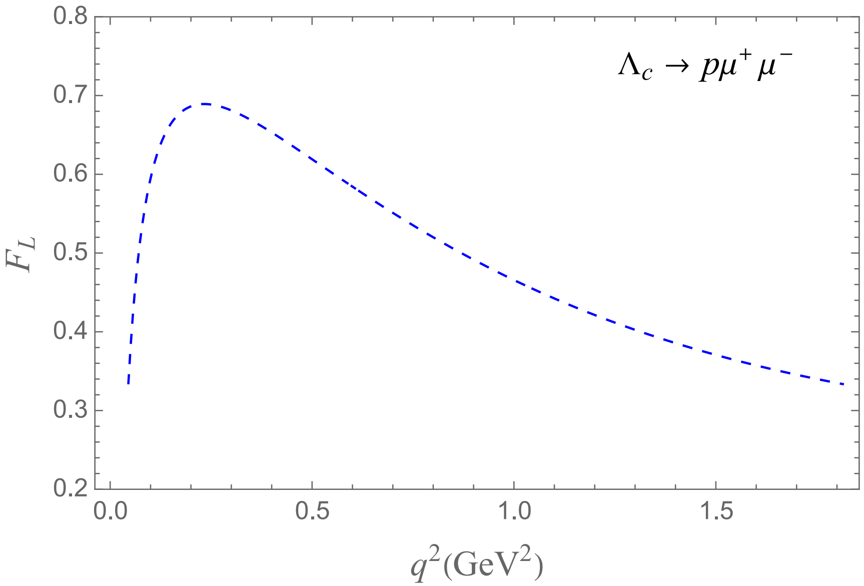
New physics



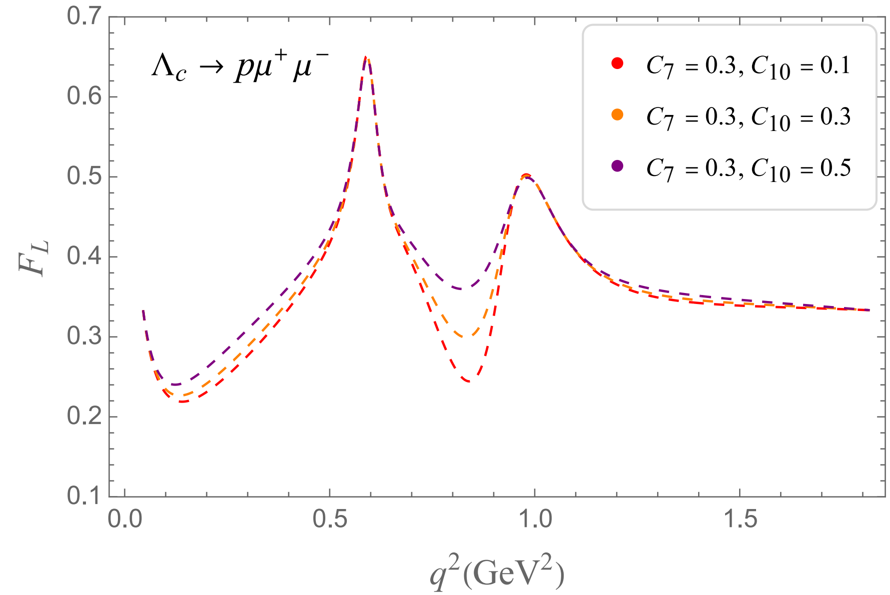
- $A_{FB} \sim C_{10}$ is zero within SM, since C_{10} is predicted to be zero.
- Clean signal: any measurement deviation from zero will indicate potential new physics effects.

Longitudinal polarization F_L

Standard model



New physics



no resonance contributions

resonance contributions

Summary

- We derive the form factors of rare $\Lambda_c \to p\ell\ell$ decay mode in the frame work of QCD sum rules.
- We predicted the branching fractions and angular observables based on the obtained form factors.
- We analyze the potential new physics effects through angular observables.
- Potential improvements: inverse method

See Zhao zhenxing&Xiong aosheng's talk

Thanks