Masses and Electricmagnetic Form Factors of Doubly Charmed Baryons

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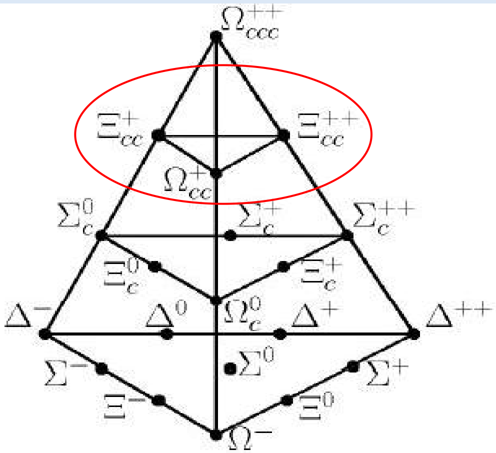
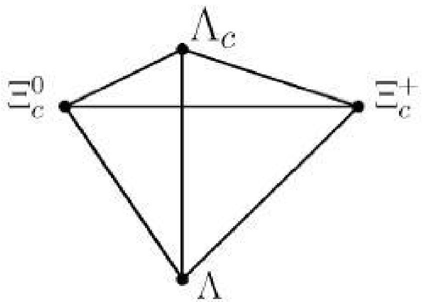
Outline

- Experiments
- CHPT
- Masses
- Form Factors
- Summary

Experiments





$$\Xi_{cc}^{++} = ccu, \Xi_{cc}^{+} = ccd, \Omega_{cc}^{+} = ccs$$

SELEX Collaboration

$$\Lambda_c^+ K^- \pi^+ : \ \Xi_{cc}^+(3443) \quad \Xi_{cc}^+(3520)$$

$$pD^+K^- / \Xi_c^+\pi^+\pi^- : \ \Xi_{cc}^+(3520)$$

$$\Lambda_c^+ K^- \pi^+ \pi^+ : \ \Xi_{cc}^{++}(3460) \quad \Xi_{cc}^{++}(3541) \quad \Xi_{cc}^{++}(3780)$$

not suported by other experiments

LHCb Collaboration

$$\Xi_{cc}^{++} \to \Lambda_c^+ K^- \pi^+ \pi^+$$

$$\mathrm{M} = 3621.40 \pm 0.72(stat) \pm 0.27(syst) \pm 0.14(\Lambda_c^+)\ \mathrm{MeV}$$

$$\tau = 0.256^{+0.024}_{-0.022}(stat) \pm 0.014(syst)\ \mathrm{ps}$$

$$\Xi_{cc}^{++} \to \Xi_c^+ \pi^+$$

$$\mathrm{M} = 3620.6 \pm 1.5(stat) \pm 0.4(syst) \pm 0.3(\Xi_c^+)\ \mathrm{MeV}$$

PRL 119(2017)112001 PRL 121(2018)052002 PRL 121(2018)162002

CHPT

- **QCD** → **Strong interaction**

Asymptotic Freedom

(high energy)

Quark Confinement

(low energy)

Chiral Symmetry

The corresponding phenomenon locates at **low energy** region: **Non-perturbative, quark confinement**

Chiral perturbation theory

Hadronic degree of freedom (meson and baryon)

effective theory of strong interactions at distances ~Mpi^{-1}

Lagrangian

- **Chiral symmetry** -> the light quark
- strong interactions ->**parity, charge conjugation**

$$\mathcal{L}^{(1)} = \bar{\psi}(i\not{D} - m + \frac{g_A}{2}\gamma^\mu\gamma_5 u_\mu)\psi,$$

$$\mathcal{L}^{(2)} = c_1\bar{\psi}\langle\chi_+\rangle\psi - \left\{\frac{c_2}{8m^2}\bar{\psi}\langle u_\mu u_\nu\rangle\{D^\mu, D^\nu\}\psi + h.c.\right\}$$
$$- \left\{\frac{c_3}{8m^2}\bar{\psi}\{u_\mu, u_\nu\}\{D^\mu, D^\nu\}\psi + h.c.\right\} + \frac{c_4}{2}\bar{\psi}\langle u^2\rangle\psi$$
$$+ \frac{c_5}{2}\bar{\psi}u^2\psi + \frac{ic_6}{4}\bar{\psi}\sigma^{\mu\nu}[u_\mu, u_\nu]\psi + c_7\bar{\psi}\hat{\chi}_+\psi$$
$$+ \frac{c_8}{8m}\bar{\psi}\sigma^{\mu\nu}\hat{f}^+_{\mu\nu}\psi + \frac{c_9}{8m}\bar{\psi}\sigma^{\mu\nu}\langle f^+_{\mu\nu}\rangle\psi$$

$$\mathcal{L}^{(3)} = \left\{\frac{i}{2m}d_1\bar{\psi}[D^\mu, \hat{f}^+_{\mu\nu}]D^\nu\psi + h.c.\right\} + \left\{\frac{2i}{m}d_2\bar{\psi}[D^\mu, \langle f^+_{\mu\nu}\rangle]D^\nu\psi + h.c.\right\} + \ldots$$

...

$$\mathcal{L}_2 = \frac{F_0^2}{4}\mathrm{Tr}[D_\mu U(D^\mu U)^\dagger] + \frac{F_0^2}{4}\mathrm{Tr}(\chi U^\dagger + U\chi^\dagger)$$

$$\mathcal{L}_4 = L_1\left\{\mathrm{Tr}[D_\mu U(D^\mu U)^\dagger]\right\}^2 + L_2\mathrm{Tr}\left[D_\mu U(D_\nu U)^\dagger\right]\mathrm{Tr}\left[D^\mu U(D^\nu U)^\dagger\right]$$

...

· Power counting

Infinit terms of the constructed Lagrangian, infinit free paremeters
we need to assess the importance of a certain diagram

Weinberg's scheme: (for Goldstone mesons)

$$\left|\vec{q}\right| \sim \left|p\right| \sim \left|M_{Goldstone}\right| \sim Q \ll \Lambda_0$$

- **The amplitude of Feynman diagram can be expanded by powers of momentum and masses of Goldstone mesons (π, K and η)**

- **the Lagrangian can be classes by different order. derivative -> momentum, terms containing meson mass.**

$$D = 4N_L - 2I_M + \sum_{n=1}^{\infty} 2nN_{2n}^M$$

extending to both mesons and baryons

$$D = 4N_L - 2I_M - I_B + \sum_{n=1}^{\infty} 2nN_{2n}^M + \sum_{n=1}^{\infty} nN_n^B.$$

- **The nonzero mass of the baryon in chiral limit breaks the power counting.**

✓ Extended-on-mass-shell (**EOMS**)

✓ Heavy-Baryon chiral perturbation theory (HB**CHPT**)

✓ Infrared BChPT

✓ Extended-on-mass-shell (**EOMS**)

➡ Ultraviolet (UV) divergence: Dimensional regularisation, MS-1 subtraction
➡ PCB terms: polynomials, removed by redefinition of LECs in Effective Lagrangian

✓ Scale independent
✓ Correct power counting (respectively faster convergence)
✓ keep original analyticity and all assumed symmetries

From De-Liang Yao's talk

Masses

Quark model

Roncaglia, Lichtenberg, Predazzi, Phys. Rev. D52,1722(1995)

Ebert, Faustov, Galkin, Martynenko, Saleev, Z. Phys. C76, 111(1997)

B. Silvestre-Brac, Prog.Part. Nucl. Phys. 36, 263(1996)

Tong, Ding, Guo, Jin, Li, Shen, Zhang, Phys. Rev. D62, 054024(2000)

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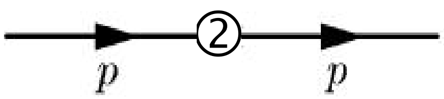
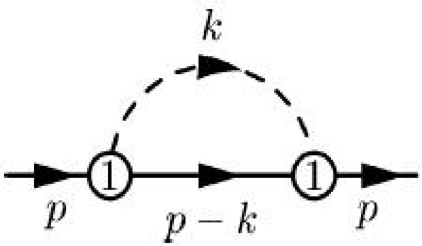
Lattice QCD

Lewis, Mathur, Woloshyn, Phys. Rev. D64, 094509(2001)
Heechang Na, Steven Gottlieb, PoS LATTICE 2008, 119(2008)
Liu, Lin, Orginos, Walker-Loud, Phys. Rev. D81, 094505(2010)
PACS-CS Collaboration, PoS LATTICE 2012, 139(2012)
Alexandrou, Carbonell, Christaras, Drach, Gravina, Papinutto, PRD86, 114501(2012)

Isospin splitting of doubly heavy baryons

Brodsky, Guo, Hanhart, Meißner, PLB698:251-255, 2011





Doubly heavy baryon mass under **EOMS** renormalization

$$m_a \doteq m - 2c_1(2m_K^2 + m_\pi^2) - 2c_7\left[\chi_{aa} - \frac{1}{3}(2m_K^2 + m_\pi^2)\right]$$

$$+ \sum_{b=1}^{3}\sum_{\lambda=\pi,K,\eta}(-)C_{ab}^{\lambda}\frac{g_A^2}{4F_\lambda^2}2mM_\lambda^2\frac{1}{(4\pi)^2}\left[\frac{M_\lambda^2}{2m^2}\ln\frac{M_\lambda^2}{m^2}\right.$$

$$\left.+\frac{M_\lambda\sqrt{4m^2 - M_\lambda^2}}{m^2}\arccos\frac{M_\lambda}{2m}\right]$$

保持数幂律！

Power counting breaking terms:

$$\delta m_a = -\sum_{b=1}^{3}\sum_{\lambda=\pi,K,\eta}C_{ab}^{\lambda}\frac{g_A^2}{32\pi^2F_\lambda^2}mM_\lambda^2$$

The estimation of the axial vector charge $\boldsymbol{g_A}$

Heavy diquark symmetry

J. Hu and T. Mehen, PRD 73. 054003

$$\mathcal{L} = \mathrm{Tr}[T_a^\dagger (iD_0)_{ba} T_b] - g\mathrm{Tr}[T_a^\dagger T_b \vec{\sigma} \cdot \vec{A}_{ba}] + \cdots$$

$$T_{a,i\beta} = \sqrt{2}\left(\Xi^*_{a,i\beta} + \frac{1}{\sqrt{3}} \Xi_{a,\gamma} \sigma^i_{\gamma\beta}\right)$$

$$\mathcal{L}^{(1)} = \bar{\psi}(i\not{D} - m + \frac{g_A}{2}\gamma^\mu \gamma_5 u_\mu)\psi$$

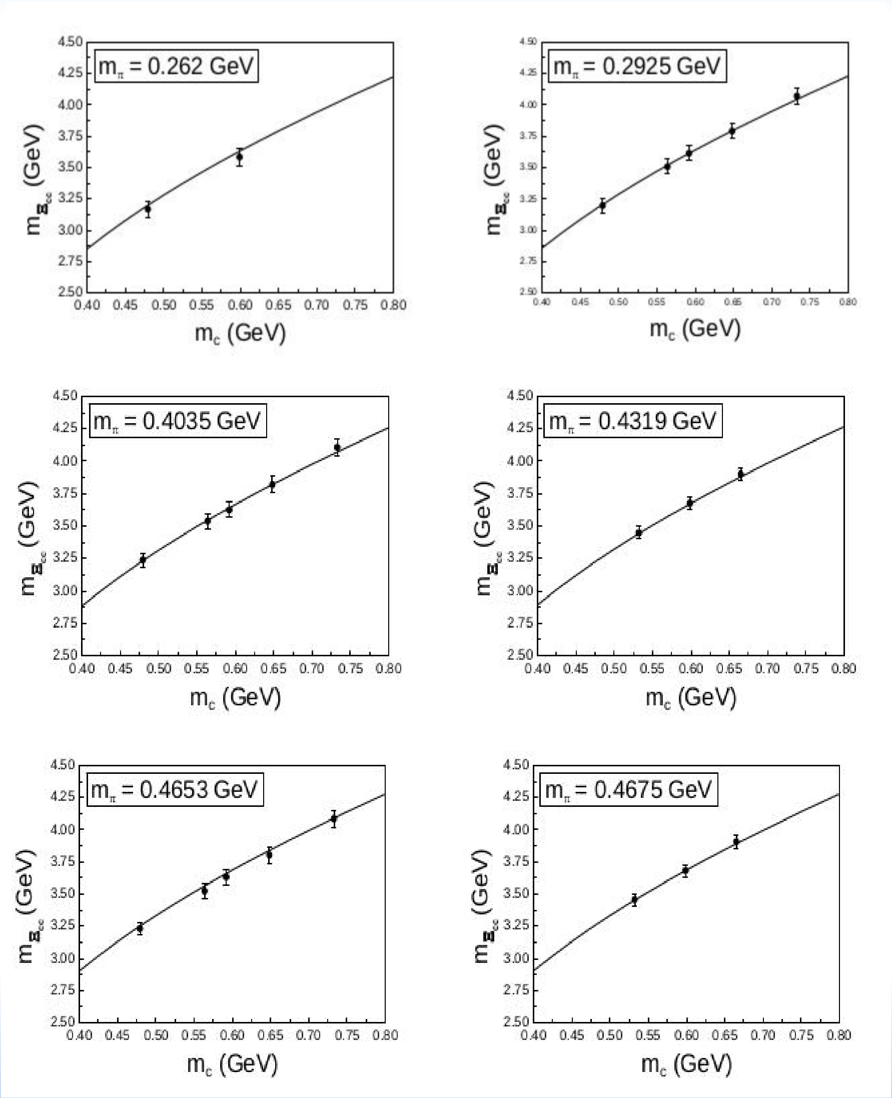
$$g_A = -g/3 = -0.2$$

c_1, c_7 and m still unknown

The heavy quark expansion

$$m = \tilde{m}_0 + 2m_c + \alpha/m_c + O(1/m_c^2)$$

Fitting the lattice data



C. Alexandrou et al., PRD 86, 114501

m_c^{phy}	$m_{\Xi_{cc}^{++/+}}$	$m_{\Omega_{cc}^{+}}$	$\chi^2_{d.o.f}$
0.598 ± 0.066	3.608 ± 0.218	3.663 ± 0.223	
0.591 ± 0.028	3.585 ± 0.166	3.640 ± 0.173	0.22
0.598 ± 0.070	3.608 ± 0.225	3.663 ± 0.230	

夸克模型: $M(\Xi_{cc}) = 3.48 \sim 3.74\text{GeV}$

$M(\Omega_{cc}) = 3.59 \sim 3.86\text{GeV}$

格点QCD: $M(\Xi_{cc}) = 3.51 \sim 3.67\text{GeV}$

$M(\Omega_{cc}) = 3.68 \sim 3.76\text{GeV}$

LHCb: $M(\Xi_{cc}^{++}) = 3621.40 \pm 0.72\,(\text{stat}) \pm 0.27\,(\text{syst}) \pm 0.14\,(\Lambda_c^+)\ \text{MeV}$

$M = 3620.6 \pm 1.5(stat) \pm 0.4(syst) \pm 0.3(\Xi_c^+)\ \text{MeV}$

Doubly heavy baryon mass under **EOMS** renormalization

$$m_a \doteq m - 2c_1(2m_K^2 + m_\pi^2) - 2c_7\left[\chi_{aa} - \frac{1}{3}(2m_K^2 + m_\pi^2)\right]$$

$$+ \sum_{b=1}^{3}\sum_{\lambda=\pi,K,\eta}(-)C_{ab}^{\lambda}\frac{g_A^2}{4F_\lambda^2}2mM_\lambda^2\frac{1}{(4\pi)^2}\left[\frac{M_\lambda^2}{2m^2}\ln\frac{M_\lambda^2}{m^2}\right.$$

$$\left. + \frac{M_\lambda\sqrt{4m^2 - M_\lambda^2}}{m^2}\arccos\frac{M_\lambda}{2m}\right]$$

Expand by powers of M_λ

$$m_a = m - 2c_1(2m_K^2 + m_\pi^2) - 2c_7\left[\chi_{aa} - \frac{1}{3}(2m_K^2 + m_\pi^2)\right] - \sum_{b=1}^{3}\sum_{\lambda=\pi,K,\eta}C_{ab}^{\lambda}\frac{g_A^2}{32\pi^2F_\lambda^2}m\left[\frac{\pi M_\lambda^3}{m} + \cdots\right]$$

This expression is the same as that under heavy-baryon CHPT

Form Factors

- 核子的形状因子 → 内部结构
- 本世纪初，SELEX实验对 Σ^- 重子的电荷半径，研究了它的电磁结构
- 我们在理论上研究双重味重子的形状因子

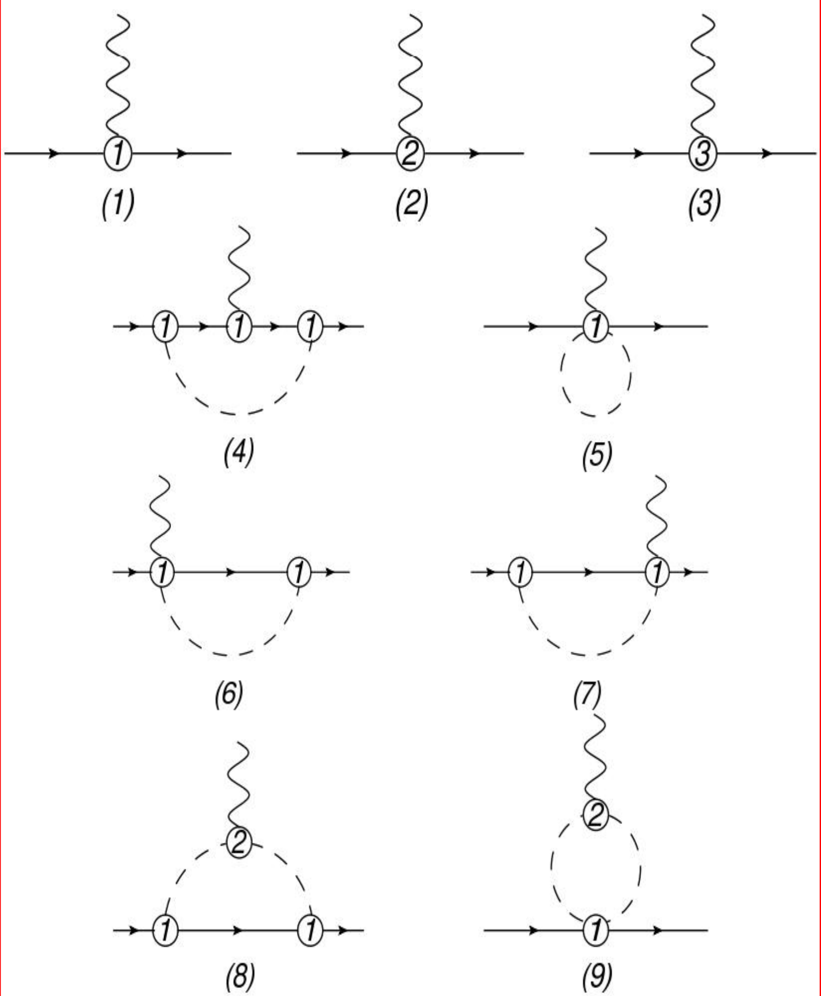
Spatial charge and moment densities:

$$e_1(r) = \int \frac{d^3\mathbf{q}}{(2\pi)^3} F_1(-\mathbf{q}^2) e^{-i\mathbf{q}\cdot\mathbf{r}}$$

$$e_2(r) = \int \frac{d^3\mathbf{q}}{(2\pi)^3} F_2(-\mathbf{q}^2) e^{-i\mathbf{q}\cdot\mathbf{r}}.$$

H. S. Li, L. Meng, Z. W. Liu, S. L. Zhu, PRD96,076011(2017)

M. Z. Liu, Y. Xiao, L. S. Geng, PRD98 (2018) 014040



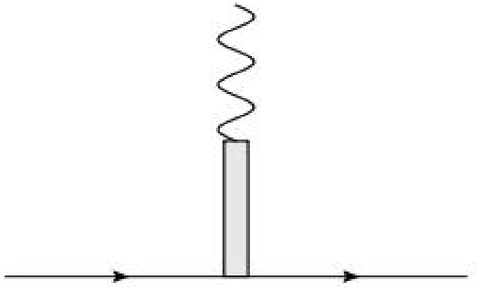
$$\langle B(p_f)|J^{\mu}(0)|B(p_i)\rangle = \bar{u}(p_f)\left[\gamma^{\mu}F_1^B(q^2) + \frac{i\sigma^{\mu\nu}q_{\nu}}{2m_B}F_2^B(q^2)\right]u(p_i)$$

Dirac FF   Pauli FF

Power counting breaking terms:

$$\Delta F_2^4 = C_4\frac{g_A^2 m^2}{16\pi^2 F^2}, \qquad \Delta F_2^8 = C_8\frac{g_A^2 m^2}{32\pi^2 F^2}$$

rescattering effects → $\rho/\omega/\phi$ resonances



$$\mathcal{L}_\gamma = -\frac{1}{2\sqrt{2}}\frac{F_V}{M_V}\langle V_{\mu\nu} f^{+\mu\nu}\rangle$$

$$\mathcal{L}_{VBB} = (\bar{\Xi}^{++}_{QQ}, \bar{\Xi}^{+}_{QQ})\left(g_v^{\Xi_{QQ}}\gamma^\mu + g_t^{\Xi_{QQ}}\frac{\sigma^{\mu\nu}\partial_\nu}{2m_B}\right)\begin{pmatrix} \frac{1}{\sqrt{2}}\rho^0 + \frac{1}{\sqrt{2}}\omega & \rho^+ \\ \rho^- & -\frac{1}{\sqrt{2}}\rho^0 + \frac{1}{\sqrt{2}}\omega \end{pmatrix}_\mu \begin{pmatrix} \Xi^{++}_{QQ} \\ \Xi^{+}_{QQ} \end{pmatrix}$$
$$+\bar{\Omega}^{+}_{QQ}\left(g_v^{\Omega_{QQ}}\gamma^\mu + g_t^{\Omega_{QQ}}\frac{\sigma^{\mu\nu}\partial_\nu}{2m_B}\right)\phi_\mu\Omega^{+}_{QQ}.$$

$$F_1^{VB} = -C_{VB}\frac{F_V}{M_V}\frac{g_v^B q^2}{q^2 - M_V^2 + i\epsilon}$$
$$F_2^{VB} = C_{VB}\frac{F_V}{M_V}\frac{g_t^B q^2}{q^2 - M_V^2 + i\epsilon}.$$

Sachs Form Factor

$$G_E^B(q^2) = F_1^B(q^2) + \frac{q^2}{4m_B^2} F_2^B(q^2) \Longrightarrow G_E^B(0) \Rightarrow charge$$

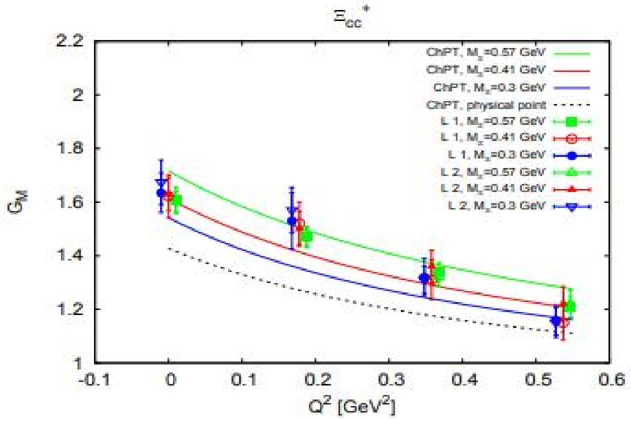
$$G_M^B(q^2) = F_1^B(q^2) + F_2^B(q^2). \Longrightarrow \mu_B = G_M(0)\frac{e}{2m_B}$$

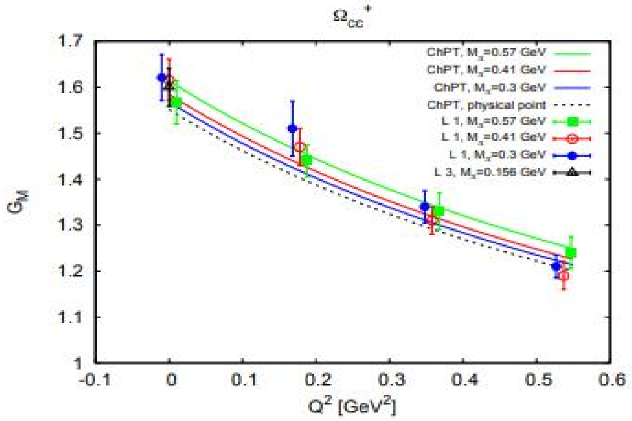
electric and magnetic radii

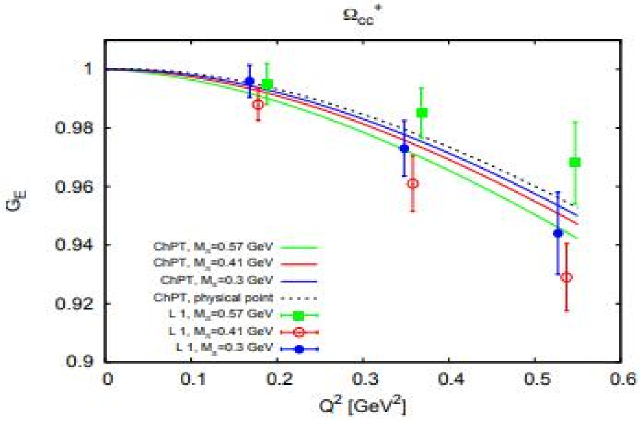
$$\langle r_{E,M}^2 \rangle_B = \frac{6}{G_{E,M}^B(0)} \frac{dG_{E,M}^B(q^2)}{dq^2}\bigg|_{q^2=0}$$

electric radii for neutral baryons

$$\langle r_E^2 \rangle_B = 6\frac{dG_E^B(q^2)}{dq^2}\bigg|_{q^2=0}$$







Phys. Lett. B 726, 703 (2013)

JHEP 1405, 125 (2014)

Phys. Rev. D 92,114515 (2015)

Contributions to μB for the double-charm baryons

	Tree	Loops HB	Loop HB [μ_N]	Loop EOMS [μ_N]	μ [μ_N]	Ref. [31]
Ξ_{cc}^{++}	$2 + \frac{2}{3}c_8 + 4c_9$	$-\frac{g_A^2}{8\pi}\left[\frac{M_\pi m_{\Xi_{cc}}}{F_\pi^2} + \frac{M_K m_{\Omega_{cc}}}{F_K^2}\right]$	-2.09g_A^2	$-1.21g_A^2$	—	—
Ξ_{cc}^{+}	$1 - \frac{1}{3}c_8 + 4c_9$	$\frac{g_A^2 m_{\Xi_{cc}}}{8\pi}\frac{M_\pi}{F_\pi^2}$	$0.60g_A^2$	$0.80g_A^2$	**0.37(2)**	0.425(29)
Ω_{cc}^{+}	$1 - \frac{1}{3}c_8 + 4c_9$	$\frac{g_A^2 m_{\Xi_{cc}}}{8\pi}\frac{M_K}{F_K^2}$	$1.46g_A^2$	$1.59g_A^2$	**0.40(3)**	0.413(24)

TABLE V. Tree-level contributions to the double charm F_1 and F_2 from the chiral Lagrangian (χPT) and vector-meson diagrams (VM).

	χPT F_1	VM F_1	χPT F_2	VM F_2
Ξ_{cc}^{++}	$2-\frac{4d_1}{3}t-8d_2t$	$-\sum_{V=\rho,\omega,\phi} C_{VB}\frac{F_V t}{M_V}\frac{g_v^{\Xi_{cc}}}{t-M_V^2}$	$\frac{2}{3}c_8+4c_9+\frac{4d_1}{3}t+8d_2t$	$\sum_{V=\rho,\omega,\phi} C_{VB}\frac{F_V t}{M_V}\frac{g_t^{\Xi_{cc}}}{t-M_V^2}$
Ξ_{cc}^{+}	$1+\frac{2d_1}{3}t-8d_2t$	$-\sum_{V=\rho,\omega,\phi} C_{VB}\frac{F_V t}{M_V}\frac{g_v^{\Xi_{cc}}}{t-M_V^2}$	$-\frac{1}{3}c_8+4c_9-\frac{2d_1}{3}t+8d_2t$	$\sum_{V=\rho,\omega,\phi} C_{VB}\frac{F_V t}{M_V}\frac{g_t^{\Xi_{cc}}}{t-M_V^2}$
Ω_{cc}^{+}	$1+\frac{2d_1}{3}t-8d_2t$	$-\sum_{V=\rho,\omega,\phi} C_{VB}\frac{F_V t}{M_V}\frac{g_v^{\Omega_{cc}}}{t-M_V^2}$	$-\frac{1}{3}c_8+4c_9-\frac{2d_1}{3}t+8d_2t$	$\sum_{V=\rho,\omega,\phi} C_{VB}\frac{F_V t}{M_V}\frac{g_t^{\Omega_{cc}}}{t-M_V^2}$

Summary

- The mass corrections and the form factors of doubly heavy baryons are calculated in the frame of EOMS scheme.
- The EOMS scheme keep the power counting. And we compare the difference of the results in HBCHPT and EOMS scheme.
- We fit the Lattice data and predict the masses and the magnetic moments of doubly charmed baryons. Our results are consistent with other theoretical calculations and the LHCb measurement.

Thank you!