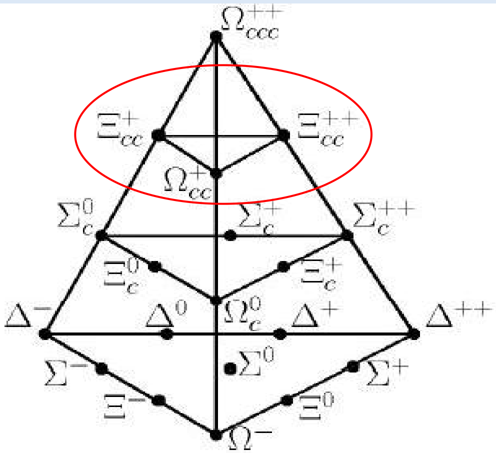
Masses and Electricmagnetic Form Factors of Doubly Charmed Baryons

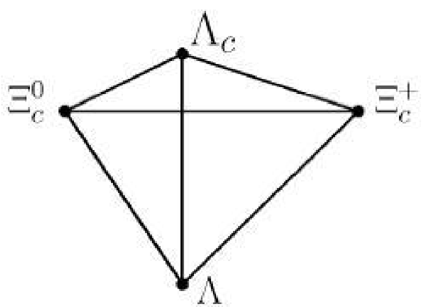
Zhi-Feng Sun

Outline

- Experiments
- CHPT
- Masses
- Form Factors
- Summary

Experiments





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

SELEX Collaboration

Ξ_{cc}^{+} (3443) Ξ_{cc}^{+} (3520) Ξ_{cc}^{++} (3460)
Ξ_{cc}^{++} (3541) Ξ_{cc}^{++} (3780)

not suported by other experiments

LHCb Collaboration

Ξ_{cc}^{++} MASS

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	COMMENT
3621.2 ±0.7 OUR AVERAGE					
3620.6 ±1.5 ±0.4 ±0.3	91	[1] AAIJ	18BA	LHCB	pp at 13 TeV
3621.40±0.72±0.27±0.14	313	[2] AAIJ	17BC	LHCB	pp at 13 TeV

[1] The third error in AAIJ 18BA value is from the uncertainty of the Ξ_c^+ mass.
[2] The third error in AAIJ 17BC value is from the uncertainty of the Λ_c^+ mass. The width of the signal is 6.6 ± 0.8 MeV, consistent with the experimental resolution.

$3621.55 \pm 0.23\,(\text{stat}) \pm 0.30\,(\text{syst})\ \text{MeV}/c^2$ JHEP 02 (2020) 049

Ξ_{cc}^{++} MEAN LIFE

VALUE (10^{-15} s)	EVTS	DOCUMENT ID		TECN	COMMENT
$256^{+24}_{-22}\pm 14$	304	AAIJ	18G	LHCB	pp at 13 TeV

Ξ_{cc}^{++} DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	$\Lambda_c^+ K^- \pi^+ \pi^+$	seen
Γ_2	$\Xi_c^+ \pi^+$, $\Xi_c^+ \to p K^- \pi^+$	seen
Γ_3	$D^+ p K^- \pi^+$	

CHPT

- **QCD** → **Strong interaction**

Asymptotic Freedom
(high energy)

Quark Confinement
(low energy)

Chiral Symmetry

Chiral perturbation theory

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

Hadronic degree of freedom (meson and baryon)

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

Lagrangian

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

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

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

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

…

$$L_2 = F_0^2 Tr\left[u_\mu u^\mu + \frac{\chi_+}{4}\right]$$

$$L_4 = a_1\{Tr[u_\mu u^\mu]\}^2 + a_2 Tr[u_\mu u_\nu]Tr[u^\mu u^\nu]$$

…

$$\psi = \begin{pmatrix} \Xi_{cc}^{++} \\ \Xi_{cc}^{+} \\ \Omega_{cc}^{+} \end{pmatrix} \qquad \phi = \begin{pmatrix} \pi^0 + \frac{1}{\sqrt{3}}\eta & \sqrt{2}\pi^+ & \sqrt{2}K^+ \\ \sqrt{2}\pi^- & -\pi^0 + \frac{1}{\sqrt{3}}\eta & \sqrt{2}K^0 \\ \sqrt{2}K^- & \sqrt{2}\bar{K}^0 & -\frac{2}{\sqrt{3}}\eta \end{pmatrix}$$

$$u = e^{i\phi/(2F_0)}$$

$$u_\mu = i\left[u^+(\partial_\mu - ir_\mu)u + u(\partial_\mu - il_\mu)u^+\right]$$

- **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)

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

- **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)**

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

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)

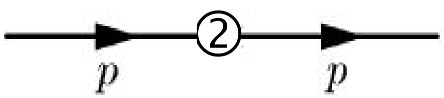
...

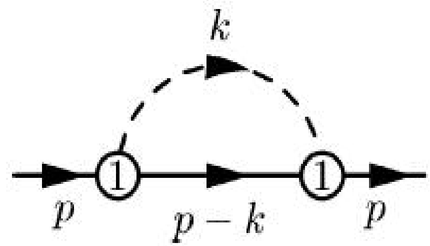
Lattice QCD

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)

Effective field theory

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





Doubly heavy baryon mass under **EOMS** renormalization

$$m_B = m - 2c_1\left(2M_K^2 + M_\pi^2\right) - 2c_7\left[\chi_{BB} - \frac{1}{3}\left(2M_K^2 + M_\pi^2\right)\right]$$
$$+ \sum_{b=1}^{3}\sum_{\lambda=\pi,K,\eta}(-)C_{ab}^{\lambda}\frac{g_A^2}{4F_\lambda^2}2m\frac{1}{(4\pi)^2}\left[\frac{M_\lambda^4}{2m^2}\ln\frac{M_\lambda^2}{m^2}\right.$$
$$\left.+\frac{M_\lambda^3\sqrt{4m^2 - M_\lambda^2}}{m^2}\arccos\frac{M_\lambda}{2m}\right]$$

保持数幂律！

Power counting breaking terms:

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

The estimation of the axial vector charge g_A

Heavy diquark symmetry

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

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

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

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

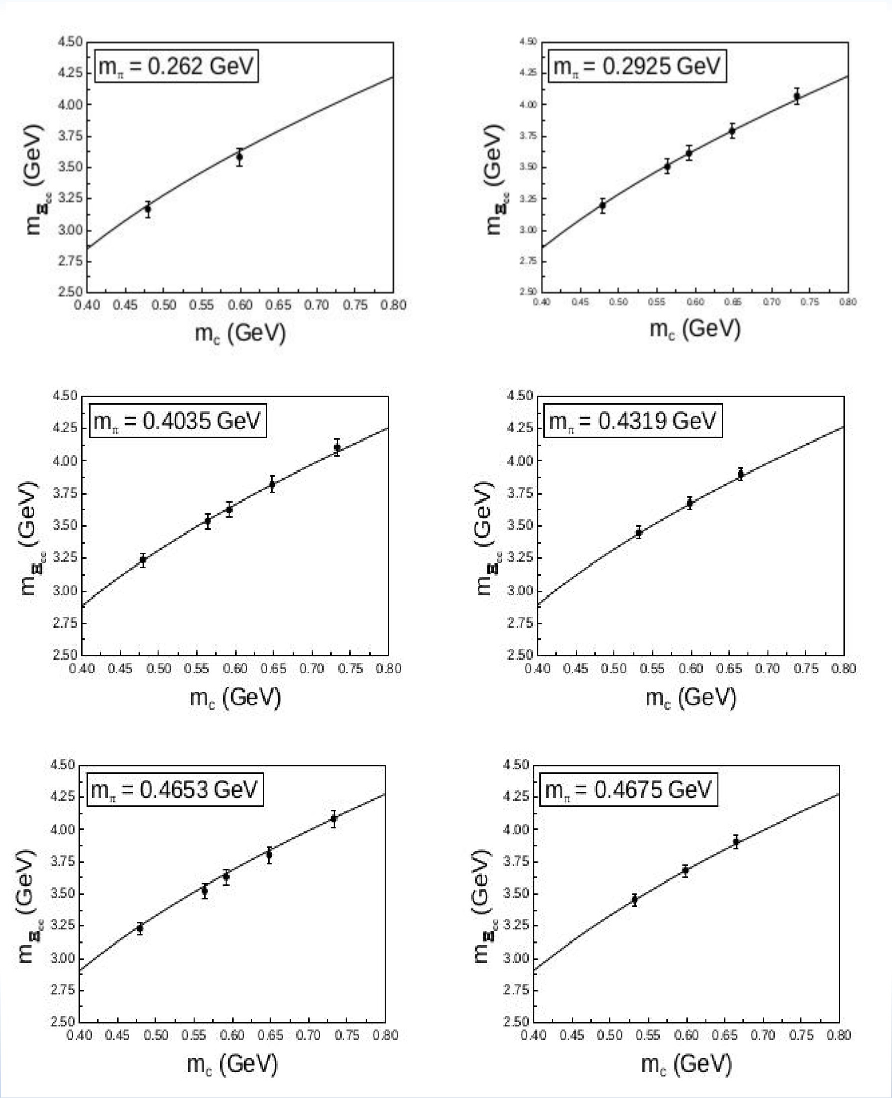
$$g_A = -g/3 = -0.2$$

c_1, c_7 and m still unknown

The bare mass of the baryon

$$m = \tilde{m}_0 + 2m_c + \alpha/m_c$$

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	

LHCb : $\mathbf{M} = 3621.55 \pm 0.23\,(\text{stat}) \pm 0.30\,(\text{syst})\ \text{MeV}/c^2$

Doubly heavy baryon mass under **EOMS** renormalization

$$m_B = m - 2c_1\left(2M_K^2 + M_\pi^2\right) - 2c_7\left[\chi_{BB} - \frac{1}{3}\left(2M_K^2 + M_\pi^2\right)\right]$$
$$+\sum_{b=1}^{3}\sum_{\lambda=\pi,K,\eta}(-)C_{ab}^{\lambda}\frac{g_A^2}{4F_\lambda^2}2mM_\lambda^2\frac{1}{(4\pi)^2}\left[\frac{M_\lambda^2}{2m^2}\ln\frac{M_\lambda^2}{m^2}\right.$$
$$\left.+\frac{M_\lambda\sqrt{4m^2-M_\lambda^2}}{m^2}\arccos\frac{M_\lambda}{2m}\right]$$

Expand by powers of M_λ

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

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

Phys. Rev. D 91 (2015) 094030

Form Factors

- 核子的形状因子 ⟶ 内部结构
- 本世纪初，SELEX实验测量了 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

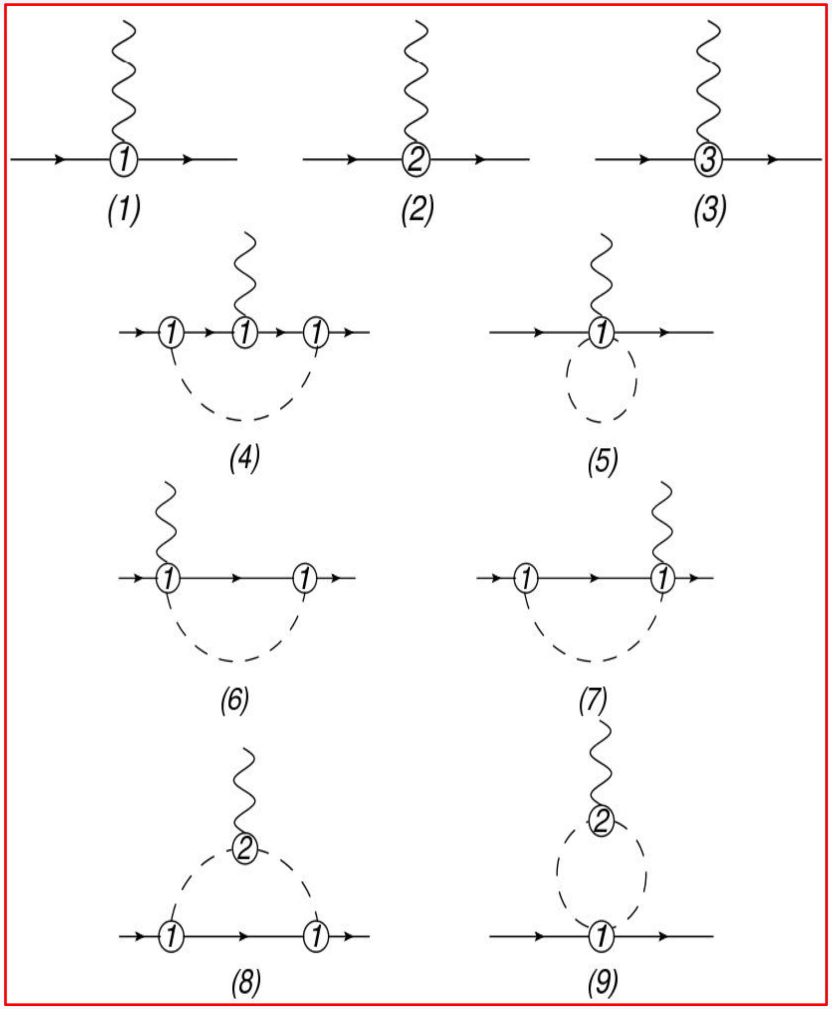
Spatial charge and moment densities:

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

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

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



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

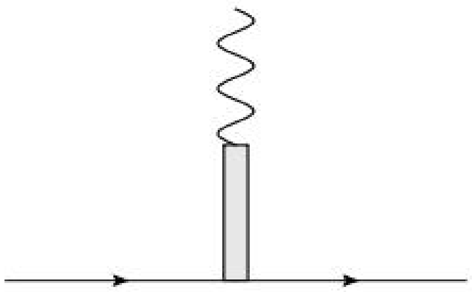
Dirac FF

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

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

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

electric and magnetic radii

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

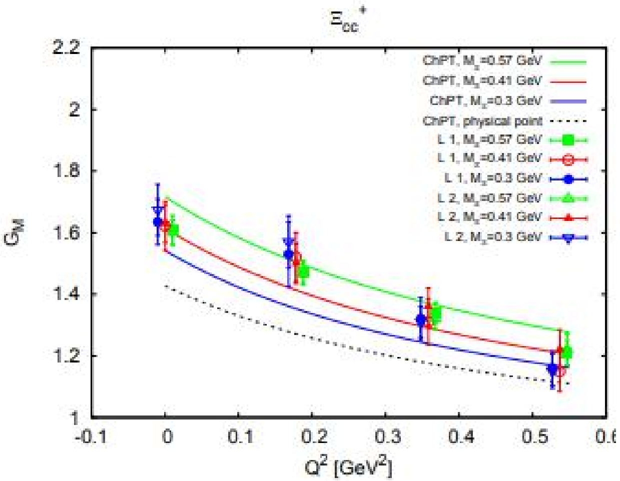
electric radii for neutral baryons

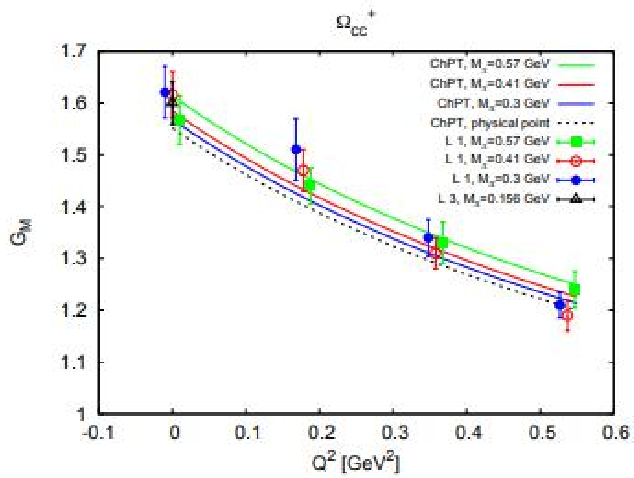
$$\langle r_E^2 \rangle_B = 6\frac{dG_E^B(q^2)}{dq^2}\bigg|_{q^2=0}$$

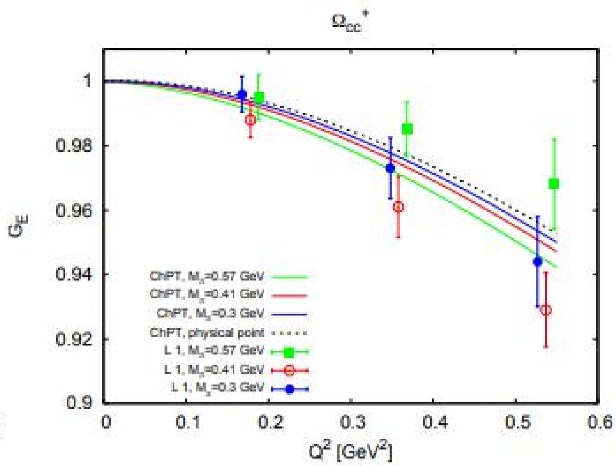
Fitting the lattice data

Phys. Lett. B 726, 703 (2013) JHEP 1405, 125 (2014)

Phys. Rev. D 92,114515 (2015)







$$c_{89} = -\frac{1}{3}c_8 + 4c_9 = 0.32(2) \qquad d_{12} = -\frac{1}{3}d_1 + 4d_2 = -0.12(11) \qquad g_v^{\Omega_{cc}} = -3.7 \pm 3.9$$

$$g_{vt}^{\Xi_{cc}} = g_v^{\Xi_{cc}} - g_t^{\Xi_{cc}} = -10.4(7) \qquad g_t^{\Omega_{cc}} = -18.9 \pm 4.2$$

$$\chi^2_{d.o.f} = 2.1$$

Contributions to μ_B for the double-charm baryons

JHEP 1405, 125 (2014)

	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)

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!