Electromagnetic form factor of single charm baryons in lattice QCD

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Research Status

* Ever since the discovery of the J/ψ particle in 1974, charm physics has become an important research field of hadron physics.

* Recently, BESIII has completed the first measurement of the electromagnetic form factors of Λ_c^+ Phys.Rev.Lett. 131 (2023) 19, 191901

* Given the scarcity of experimental data on the magnetic moments of charmed baryons, the electromagnetic form factors provide the testing hypotheses for distinct models of hadronic structure.

Lattice QCD K.U. Can et al JHEP 05(2014) 125

* Chiral extrapolation performed solely on one lattice QCD ensemble.

* A wide range of physical implications remains to be explored.

Method

The vector current insertion matrix element is required.

* $V_\mu = \frac{2}{3}\bar{c}\gamma_\mu c + e_q \bar{q}\gamma_\mu q$

* $\langle \mathcal{B}(p',s')|V_\mu|\mathcal{B}(p,s)\rangle = \bar{\mu}(p',s')[\gamma_\mu F_{1,\mathcal{B}}(q^2) + i\frac{\sigma_{\mu\upsilon}q^\upsilon}{2m_\mathcal{B}}F_{2,\mathcal{B}}(q^2)]\mu(p,s)$

* $G_{E,\mathcal{B}}(q^2) = F_{1,\mathcal{B}}(q^2) + \frac{q^2}{4m_\mathcal{B}^2}F_{2,\mathcal{B}}(q^2) \qquad G_{M,\mathcal{B}}(q^2) = F_{1,\mathcal{B}}(q^2) + F_{2,\mathcal{B}}(q^2)$

where q denotes the flavor of the light quarks u, d, and strange quarks s, for Σ_c^{++}, Σ_c^0 and Ω_c^0 and e_q represents their charge ($2/3$ or $-1/3$).

$$\langle \mathcal{B}(p',s')|V_\mu|\mathcal{B}(p,s)\rangle = \tfrac{2}{3}\langle \mathcal{B}(p',s')|\bar{c}\gamma_\mu c|\mathcal{B}(p,s)\rangle + 2e_q\langle \mathcal{B}(p',s')|\bar{q}\gamma_\mu q|\mathcal{B}(p,s)\rangle$$

Method

The definitions of the two-point and three-point correlation functions are as follows:

* $G(q, t_f) = \sum_{x_f} e^{-ix_f \cdot q} \Gamma_0^{\beta\alpha} \langle \chi_\alpha(t_f, x_f) \bar{\chi}_\beta(0,0) \rangle$

* $G^\mu(\Gamma_\upsilon, q, t) = \sum_{x, x_f} e^{ix \cdot q} \Gamma_\upsilon^{\beta\alpha} \langle \chi_\alpha(t_f, x_f) V_\mu(t, x) \bar{\chi}_\beta(0,0) \rangle$

where $\Gamma_0 = \frac{1+\gamma_4}{2}$, $\Gamma_i = i\Gamma_0\gamma_5\gamma_k$.

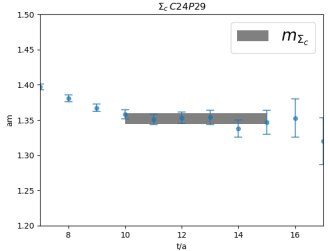
Selection of operators for single-charm baryons $\chi = \epsilon_{abc} q_{\alpha,a} (q^T_{\beta,b} (C\gamma_5) c_{\gamma,c})$

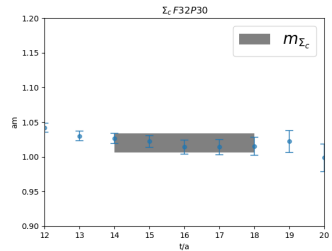
Here a、b、c are color indices、α、β、γ are spinor indices, and the charge conjugation matrix is defined as $C = \gamma_4\gamma_2$.

Lattice Set up

Ensemble	C32P23	C24P29	F32P21	F32P30	H48P32
a(fm)	0.10530(18)	0.10530(18)	0.07746(18)	0.07746(18)	0.05187(26)
$a\mu_l$	-0.2790	-0.2770	-0.2320	-0.2295	-0.1850
$a\mu_s$	-0.2400	-0.2400	-0.2050	-0.2050	-0.1700
$a\mu_c$	0.4500	0.4479	0.2110	0.2079	0.0581
$L^3 \times T$	$32^3 \times 64$	$24^3 \times 72$	$32^3 \times 64$	$32^3 \times 96$	$48^3 \times 144$
m_π(MeV)	228.0(1.2)	292.7(1.2)	210.9(2.2)	303.4(0.9)	317.2(0.9)
$N_{cfg} \times N_{src}$	400×3	476×3	194×3	206×3	176×12

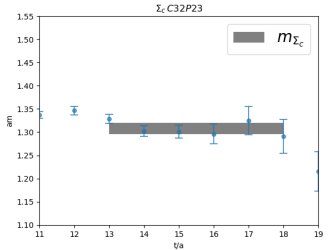
2-point function fitting for Σ_c

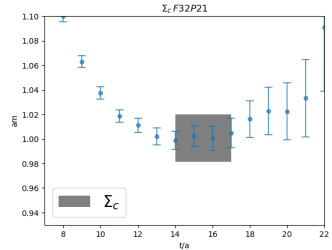


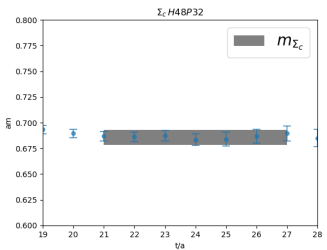


Fitting method:
$m = A_1 e^{-E_1 t}$

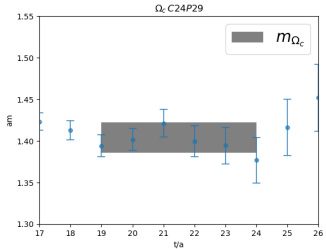
Fitting interval: Select at least four time slices before the noise-dominated area, and make $t_{min} \pm 2$and $t_{max} \pm 1$to consider the systematic error

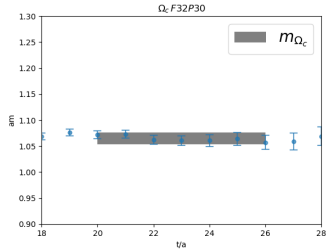


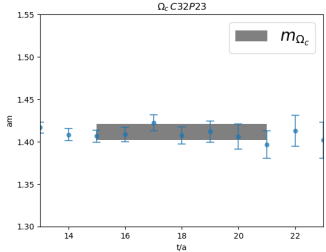


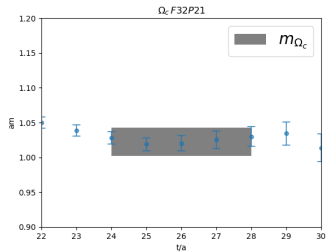


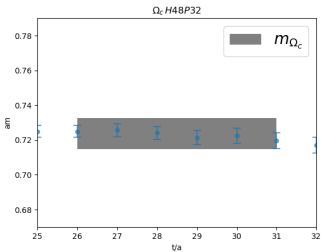
2-point function fitting for Ω_c











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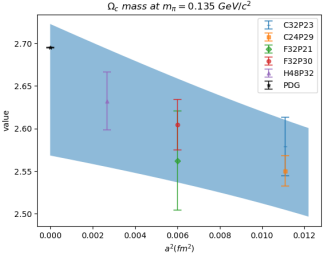
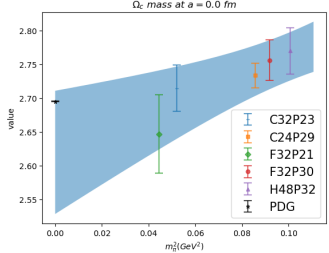
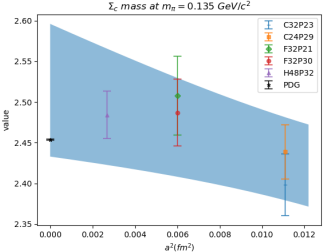
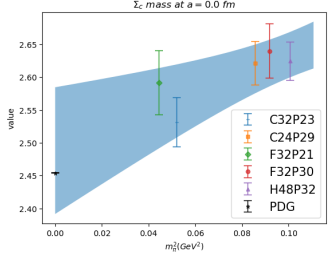
2-point function fitting









$$f = c_0 + c_1 a^2 + c_2 (m_\pi^2 - m_{\pi,phys}^2)$$

Ω_c	**Mass(GeV)**
extrapolation	2.642(77)
PDG	2.6953(4)

Σ_c	**Mass(GeV)**
extrapolation	2.514(82)
PDG	2.45375(14)

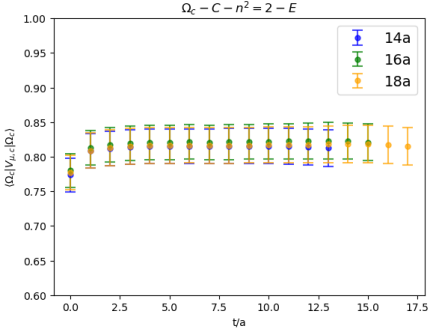
3-point function fitting

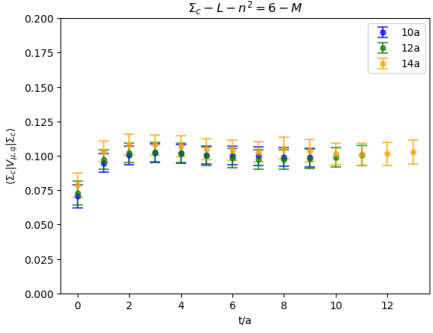
$$G^{\mu}(\Gamma_{\upsilon}, q, t) = \sum_{m,n} \langle \Omega | \hat{\chi} | m \rangle \langle m | (\vec{p}_f | V_{\mu} | n \rangle \langle n | \hat{\chi}^{\dagger}(\vec{p}_i) | \Omega \rangle e^{-E_m(t_f - t)} e^{-E_n t}$$

$$G(p_i, t) = \sum_n |\langle n | \hat{\chi}_i^{(\dagger)}(p_i) | \Omega \rangle e^{-E_n t} \text{、} \quad G(p_f, t) = \sum_{n(m)} |\langle m | \hat{\chi}_f^{(\dagger)}(p_f) | \Omega \rangle e^{-E_m t}$$

We believe that 2pt and 3pt share parameters and amplitudes, and conduct joint fitting on them

$$G^4(\Gamma_4, q, t) \propto G_E(q^2) \text{ and } G^i(\Gamma_j, q, t) \propto G_M(q^2)$$





Form factor fitting

Phenomenological formulas

$$G_{E,M} = \frac{G_{E,M}(0)}{(1+Q^2/\Lambda^2_{E,M})^2} = \frac{G_{E,M}(0)}{1+Q^2/\Lambda^2_{E,M}} = G_{E,M}(0)e^{Q^2/2\Lambda^2_{E,M}}$$

There are dipole、monpole and gaussian form individually

Establish a connection with physical observability

$\langle r^2_{E,M}\rangle = \frac{n}{\Lambda^2_{E,M}}$、 $\langle r^2_{E,M}\rangle = \frac{6}{G_{E,M}(0)}\frac{d}{dq^2}G_{E,M}(q^2)|_{q^2=0}$、

$\mu_{\mathcal{B}} = G_M(0)(\frac{e}{2m}) = G_M(0)(\frac{m_N}{m_B})\mu_N$

Here, n=6 for monpole, n=12 for dipole, m_N is the nucleon mass and $m_{\mathcal{B}}$ is the corresponding charmed baryon mass calculated on each ensemble.

Magnetic properties

$\mu_{\Omega_c^0}$, **All results are presented in units of nuclear magnetons**

	C24P29	C32P23	F32P21	F32P30	H48P32
dipole	-0.939(30)	-0.970(25)	-0.888(28)	-0.820(19)	-0.806(20)
monpole	-1.060(47)	-1.040(34)	-1.000(42)	-1.040(34)	-0.880(28)
gaussian	-0.857(22)	-0.917(20)	$\chi^2/dof = 1.7$	$\chi^2/dof = 1.9$	$\chi^2/dof = 2.5$

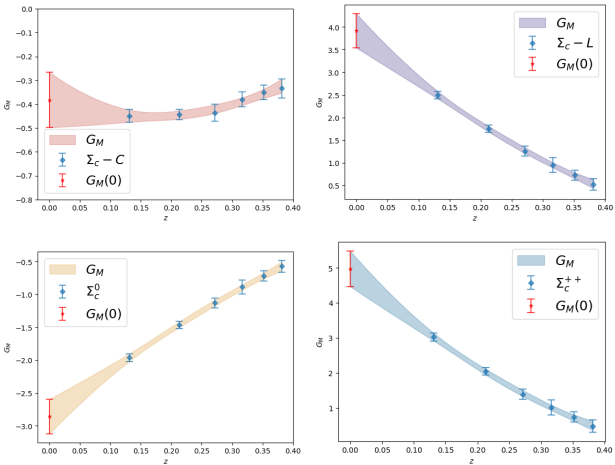
$\mu_{\Sigma_c^0}$, **All results are presented in units of nuclear magnetons**

	C24P29	C32P23	F32P21	F32P30	H48P32
dipole	-1.057(60)	-1.113(47)	-0.916(37)	-0.861(24)	-0.829(16)
monpole	-1.26(12)	-1.212(66)	-1.050(57)	-0.950(36)	-0.904(23)
gaussian	-0.939(42)	-1.045(35)	-0.834(28)	-0.798(18)	$\chi^2/dof = 3.3$

$\mu_{\Sigma_c^{++}}$, **All results are presented in units of nuclear magnetons**

	C24P29	C32P23	F32P21	F32P30	H48P32
dipole	2.03(19)	2.03(11)	1.71(10)	1.487(68)	1.410(37)
monpole	$\chi^2/dof = 1.5$	2.40(20)	$\chi^2/dof = 1.9$	$\chi^2/dof = 2.6$	$\chi^2/dof = 2.5$
gaussian	1.641(98)	1.828(82)	1.415(58)	1.283(43)	$\chi^2/dof = 1.7$

Magnetic properties of Σ_c



Analysis method:
Z-expansion method

Theoretical formula:
$t_{\text{cut}} = 4m_\pi^2,\ t_0 = 0$

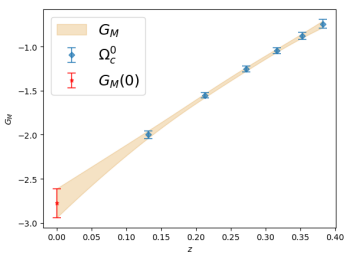
$$z(t, t_{\text{cut}}, t_0) = \frac{\sqrt{t_{\text{cut}} - t} - \sqrt{t_{\text{cut}} - t_0}}{\sqrt{t_{\text{cut}} - t} + \sqrt{t_{\text{cut}} - t_0}}$$

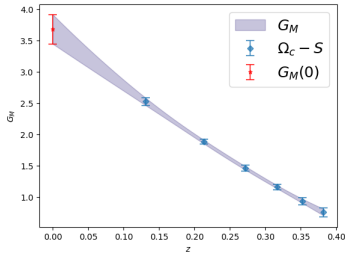
$$G_{E,M}(q^2) = \sum_{i=0}^{2} a_i z(q^2)^i$$

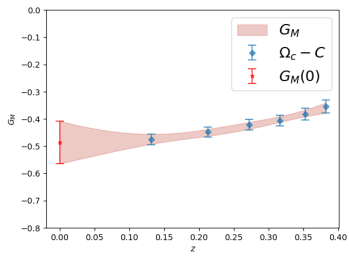
Extrapolation:

$$f = c_0 + c_1 a^2 + c_2 (m_\pi^2 - m_{\pi,phys}^2)$$

Magnetic properties of Ω_c







Magnetic properties

Σ_c, All results are presented in units of nuclear magnetons

	μ_c	μ_l	$\mu_{\Sigma_c^0}$	$\mu_{\Sigma_c^{++}}$
C24P29	-0.141(43)	1.45(14)	-1.058(97)	1.84(19)
C32P23	-0.178(47)	1.66(14)	-1.23(10)	2.09(19)
F32P21	-0.144(60)	1.40(14)	-1.03(10)	1.77(19)
F32P30	-0.181(17)	1.167(76)	-0.899(52)	1.43(10)
H48P32	-0.183(30)	1.162(41)	-0.902(35)	1.429(59)

Ω_c, In units of nuclear magnetons

	μ_c	μ_s	$\mu_{\Omega_c^0}$
C24P29	-0.173(28)	1.104(83)	-0.984(58)
C32P23	-0.187(27)	1.320(90)	-1.005(63)
F32P21	-0.170(25)	1.31(13)	-0.984(87)
F32P30	-0.179(16)	1.129(48)	-0.872(34)
H48P32	-0.181(25)	1.123(55)	-0.869(40)

Magnetic properties

Σ_c (nuclear magnetons)

	μ_c	μ_l	$\mu_{\Sigma_c^0}$	$\mu_{\Sigma_c^{++}}$
extrapolation	-0.175(99)	1.58(21)	-1.13(16)	2.06(26)
K.U. Can	-0.099(21)	2.369(362)	-0.852(33)	1.569(253)

Ω_c (nuclear magnetons)

	μ_c	μ_s	$\mu_{\Omega_c^0}$
extrapolation	-0.171(51)	1.48(18)	-0.99(13)
K.U. Can	-0.099(14)	1.710(150)	-0.608(45)

Relevant discussions:

$f_{lin} = a_1 m_\pi^2 + b_1$、 $f_{quad} = a_2 m_\pi^4 + b_2 m_\pi^2 + c_2$

No evidence supports the quadratic fit over the linear one; only linear fit results are presented here.

Our calculations similarly demonstrate the dominant contribution from light quarks.

Magnetic properties

	$\mu_{\Omega_c^0}(\mu_N)$	$\mu_{\Sigma_c^0}(\mu_N)$	$\mu_{\Sigma_c^{++}}(\mu_N)$
This work	-0.99(13)	-1.13(16)	2.06(26)
K.U. Can	-0.608(45)	-0.852(33)	1.159(253)
[1]	-0.905	-1.234	2.095
[2]	-0.85(5)	-1.24(5)	2.15(10)
[3]	-0.949	-	-
[4]	-0.85	-1.04	1.76
[5]	-0.90	-1.60	2.20
[6]	-0.90	-1.60	2.20
[7]	-0.69	-0.97	1.50
[8]	-0.9	-1.5	2.4
[9]	-	-1.6(2)	2.1(3)

Our results show closer agreement with a range of phenomenological estimates, differing from earlier lattice studies that reported systematically lower values.

Quark model

[1] Binesh Mohan, et al PhysRevD.106.113007

[2] Ghil-Seok Yang, et al, j.physletb.2018.04.042

[3] Sinem Küçükyılmaz, et al, arXiv:2504.10630

[4] Amand Faessler, et al, PhysRevD.73.094013

[5] Neetika Sharma, et al, PhysRevD.81.073001

Bag model

[6] Vytautas Simonis arXiv:1803.01809

Chiral perturbation

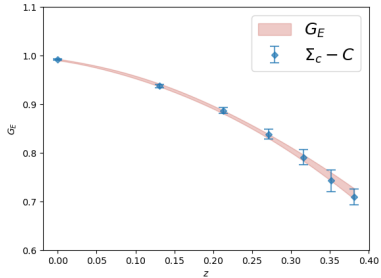
[7] G-J Wang, et al PhysRevD.98.054026

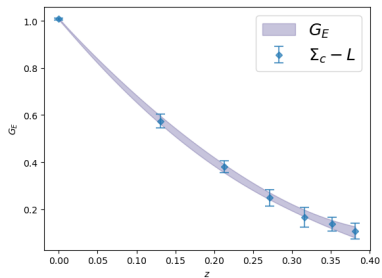
QCD sum rules

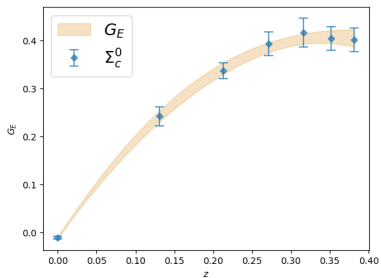
[8] Shi-Lin Zhu, et al, PhysRevD.56.7273

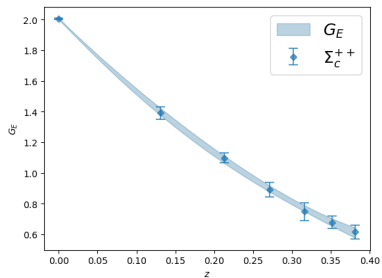
[9] T.M. Aliev, et al, PhysRevD.91.116008

Electrical properties of Σ_c

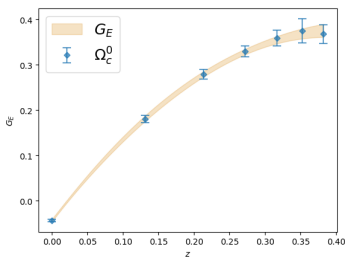


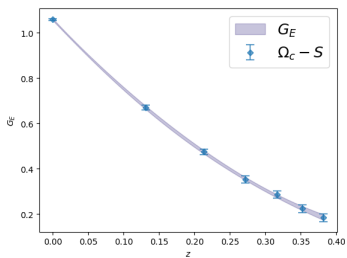


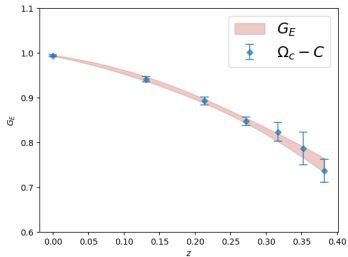




Electrical properties of Ω_c







Electrical properties

electric charge radii, All results are presented in units of fm^2

	Σ_c			Ω_c	
Ensemble	$r^2_{E,c}$	$r^2_{E,l}$	$r^2_{E,\Sigma_c^{++}}$	$r^2_{E,c}$	$r^2_{E,s}$
C24P29	0.0398(76)	0.633(36)	0.435(25)	0.046(12)	0.500(15)
C32P23	0.0323(86)	0.739(73)	0.503(49)	0.030(12)	0.484(28)
F32P21	0.0157(65)	0.718(30)	0.479(21)	0.0081(62)	0.488(21)
F32P30	0.0370(48)	0.513(17)	0.353(11)	0.0395(40)	0.3988(96)
H48P32	0.0425(33)	0.439(15)	0.3075(98)	0.0460(37)	0.3490(95)
extrapolation	0.001(13)	0.736(61)	0.485(43)	-0.016(14)	0.421(38)
K.U. Can	0.032(18)	0.347(49)	0.192(22)	0.064(10)	0.330(32)

The significant discrepancy observed for the light quark is attributed to the choice of the fitting scheme. 0.458(10) for F32P30 and 0.706(31) for C32P23

We can notice $r^2_{E,l}/r^2_{E,s} = 1.75(21)$

Summary

Conclusion

* We have systematically computed the electromagnetic form factors of Σ_c^0, Σ_c^{++}, and Ω_c^0 using five gauge ensembles.

* We observed significant model dependence when fitting the form factors and consequently adopted the mainstream z-expansion method for the fitting procedure.

* We note that $r^2_{E,l}/r^2_{E,s} = 1.75(21)$, and our calculated magnetic moments are in closer agreement with phenomenological estimates.

Thank You!