ELECTROMAGNETIC STRUCTURE OF CHARMED BARYONS — EXTENDED TO SPIN-3/2

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OUTLINE

- Motivation
- Electromagnetic (EM) form factors
  - Parameterisation
  - Lattice Formulation
- Simulation Details
- Results
- Summary

MOTIVATION

- Probe the hadron structure
  - size, charge radius, magnetic moment
  - Effect of heavy quarks

    kuc, G. Erkol, M. Oka, A. Ozpineci, T.T. Takahashi PLB 719

    - Previous works: heavy quark shrinks the mesons & baryons

    kuc, G. Erkol, B. Isildak, M. Oka, T.T. Takahashi JHEP05(2014) 125

  - ***Effect of spin structure?***

$\mathcal{EM\ FORM\ FACTORS}$

spin-$1/2$ Continuation of JHEP05(2014) 125

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

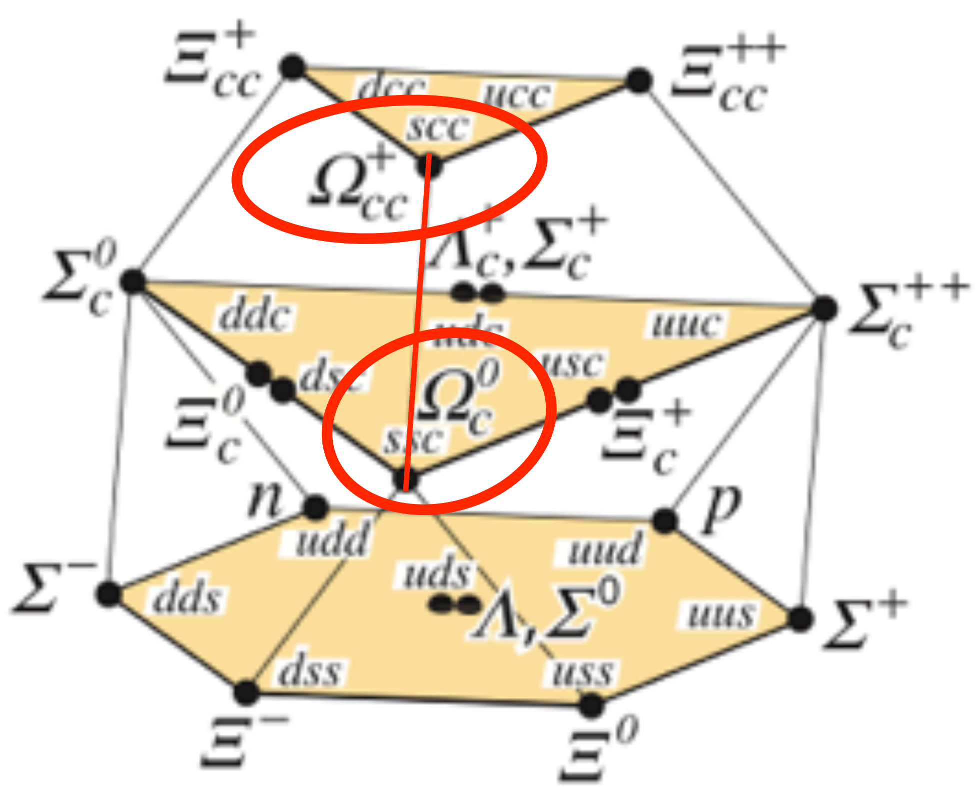
Sachs FFs

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

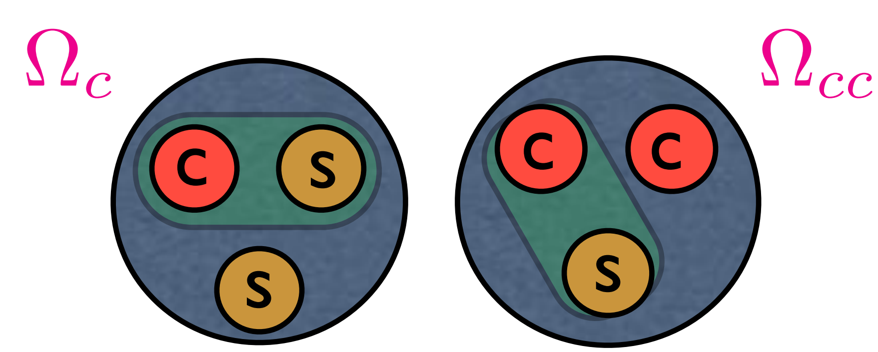
$$G_{M,\mathcal{B}}(q^2) = F_{1,\mathcal{B}}(q^2) + F_{2,\mathcal{B}}(q^2)$$

$$\langle r_E^2\rangle = -6\frac{d}{dQ^2}G_{E0}(Q^2)|_{Q^2=0}$$

$$\mu_B = G_{M1}(0)\frac{m_N}{m_B}\mu_N$$



$$\eta_{\Omega_c}(x) = \epsilon^{ijk}[s^{Ti}(x)C\gamma_5 c^j(x)]s^k(x)$$
$$\eta_{\Omega_{cc}}(x) = \epsilon^{ijk}[c^{Ti}(x)C\gamma_5 s^j(x)]c^k(x)$$



EM FORM FACTORS

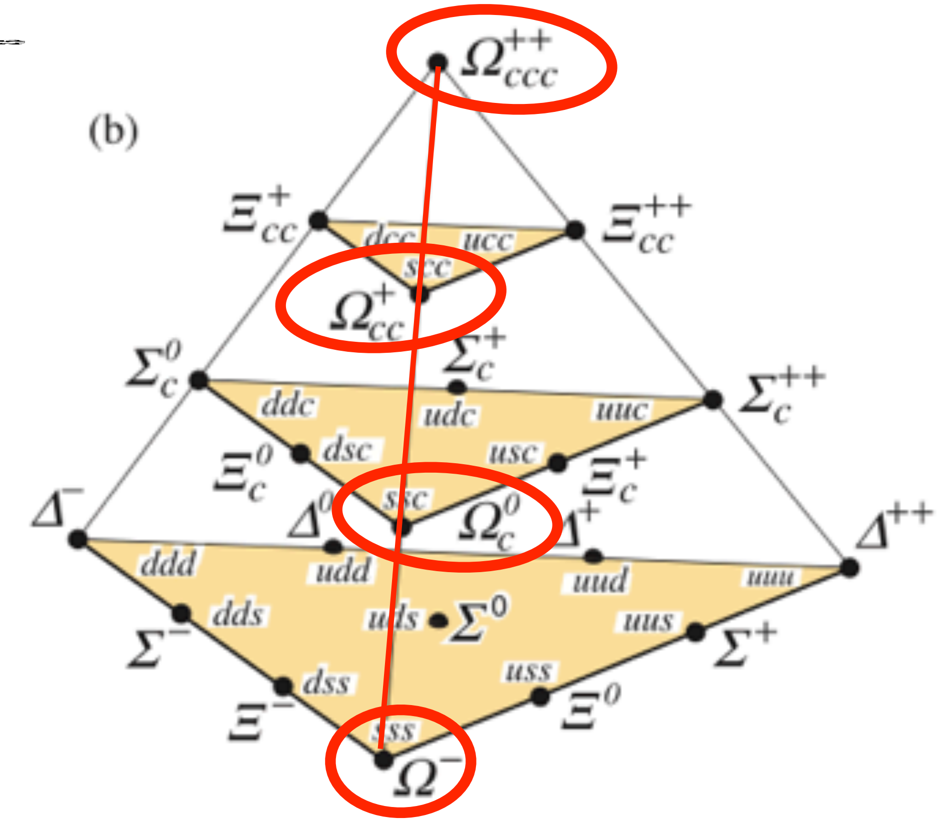
spin-3/2

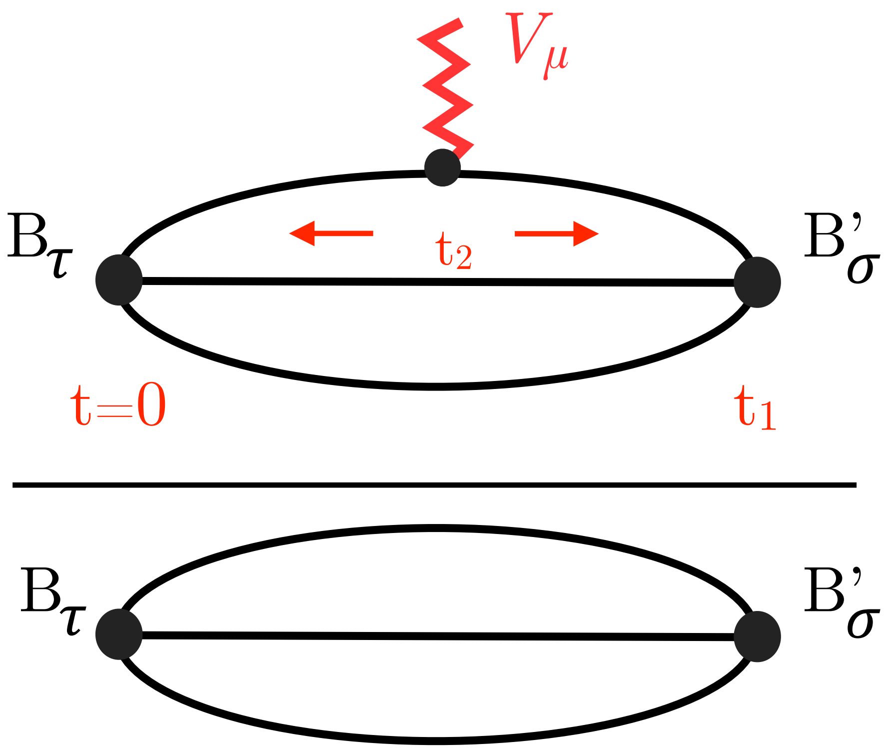
$$\langle \mathcal{B}_\sigma(p',s')|j_\mu|\mathcal{B}_\tau(p,s)\rangle = \sqrt{\frac{M_{\mathcal{B}}^2}{E\,E'}}\,\bar{u}_\sigma(p',s')\mathcal{O}^{\sigma\mu\tau}u_\tau(p,s)$$

$$\mathcal{O}^{\sigma\mu\tau} = -g^{\sigma\tau}\left\{a_1\gamma^\mu + \frac{a_2}{2M_{\mathcal{B}}}P^\mu\right\} - \frac{q^\sigma q^\tau}{(2M_{\mathcal{B}})^2}\left\{c_1\gamma^\mu + \frac{c_2}{2M_{\mathcal{B}}}P^\mu\right\}$$

as drived in S. Nozawa and D. Leinweber, PRD42, 3567(1990) P = p' + p

for Lattice formulation: PRD80 054505(2009) q = p' - p





τ=σ=1,2,3

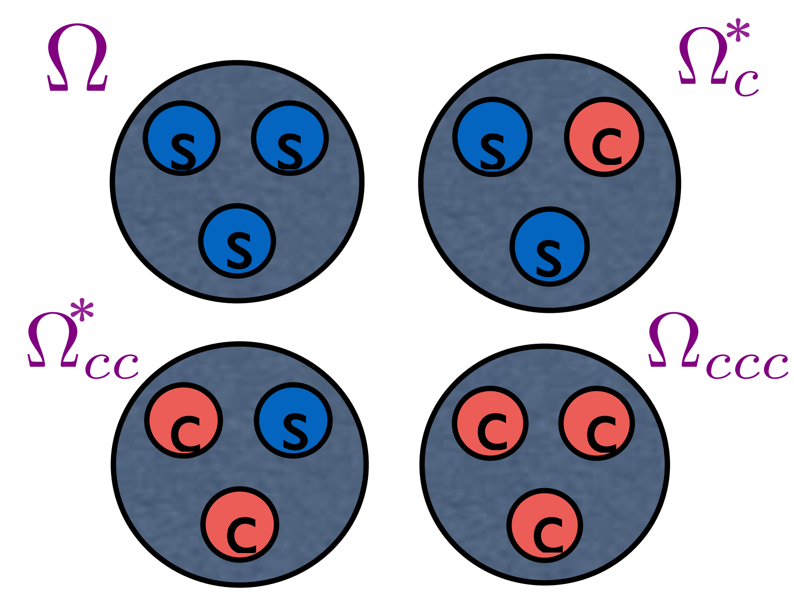
$$V_\mu = \sum_q e_q \bar{q}\gamma_\mu q$$

μ=0 -> E0 and E2 FF
electric charge, electric quadrupole

μ=1,2,3 -> M1 FF
magnetic dipole

same as the Δ interpolating field

$$\eta_\mu(x) = \frac{1}{\sqrt{3}}\epsilon^{ijk}\{2[q_1^{Ti}(x)C\gamma_\mu q_2^j(x)]q_3^k(x) + [q_1^{Ti}(x)C\gamma_\mu q_3^j(x)]q_2^k(x)\}$$



SIMULATION DETAILS

PACS-CS 2+1 flavor Clover Phys. Rev. D79 (034503)

$N_s^3 \times N_t$	κ_{ud}	m_π [MeV]	κ_s	a, a^{-1}	L [fm]	$t_s = 12a$	# confs	# meas.
$32^3 \times 64$	0.13781	156	0.1364	0.0907 fm	2.9	1.09 fm	200	200 (spin-1/2)
				2.176 GeV				300 (spin-3/2)

Clover action for all valance quarks

$\kappa_s = 0.13640$

$m_{\Omega^-} = 1.790(17)\,\text{GeV}$

PRD79 034503 (2009) $m_{\Omega^-} = 1.772(7)\,\text{GeV}$

PDG (2014) $m_{\Omega^-}^{exp} = 1.673(29)\,\text{GeV}$

$\kappa_c = 0.1246$ JHEP05(2014) 125

tuned to 1S $M_{\eta\text{-}J/\psi}$, $M_{D\text{-}D^*}$, $M_{D_s\text{-}D_s{}^*}$

This work $m_{\Omega_c^*} - m_{\Omega_c} = 54 \pm 17\,\text{MeV}$

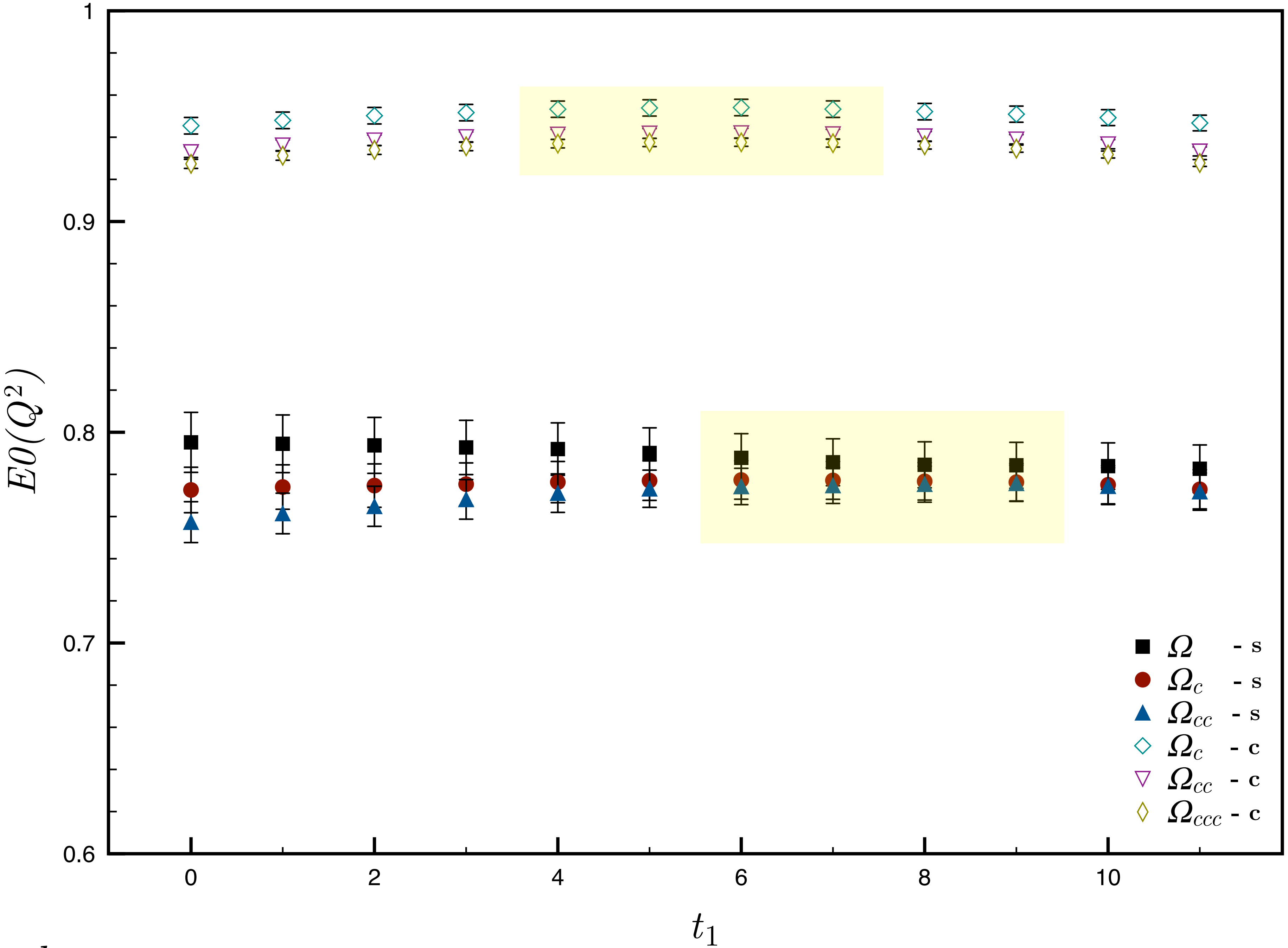
Belle Collab. PLB 672 (2009) $m_{\Omega_c^*} - m_{\Omega_c} = 70.7 \pm 0.9^{+0.1}_{-0.9}\,\text{MeV}$

1. Lowest momenta, |q|=2π/L
2. *Point-split (conserved) vector current:* renormalisation not necessary
3. *Shell source - Wall sink pairs*
   I. Wall sinks: no need for sequential inversions
4. *Connected diagrams only*
5. $\langle \mathcal{O} \rangle = N_s e_s \langle \mathcal{O}_s \rangle + N_c e_c \langle \mathcal{O}_c \rangle$
6. *Single-elimination Jackknife analysis*

RESULTS

$m_\pi \sim 156$ MeV
$\mathbf{q}^2 = 0.183$ GeV^2

E0 Form Factor
normalised to unit charge



c Ω_c^* Ω_{cc}^* Ω_{ccc}

s Ω Ω_c^* Ω_{cc}^*

$$\langle r_E^2 \rangle = -6 \frac{d}{dQ^2} G_{E0}(Q^2)|_{Q^2=0}$$

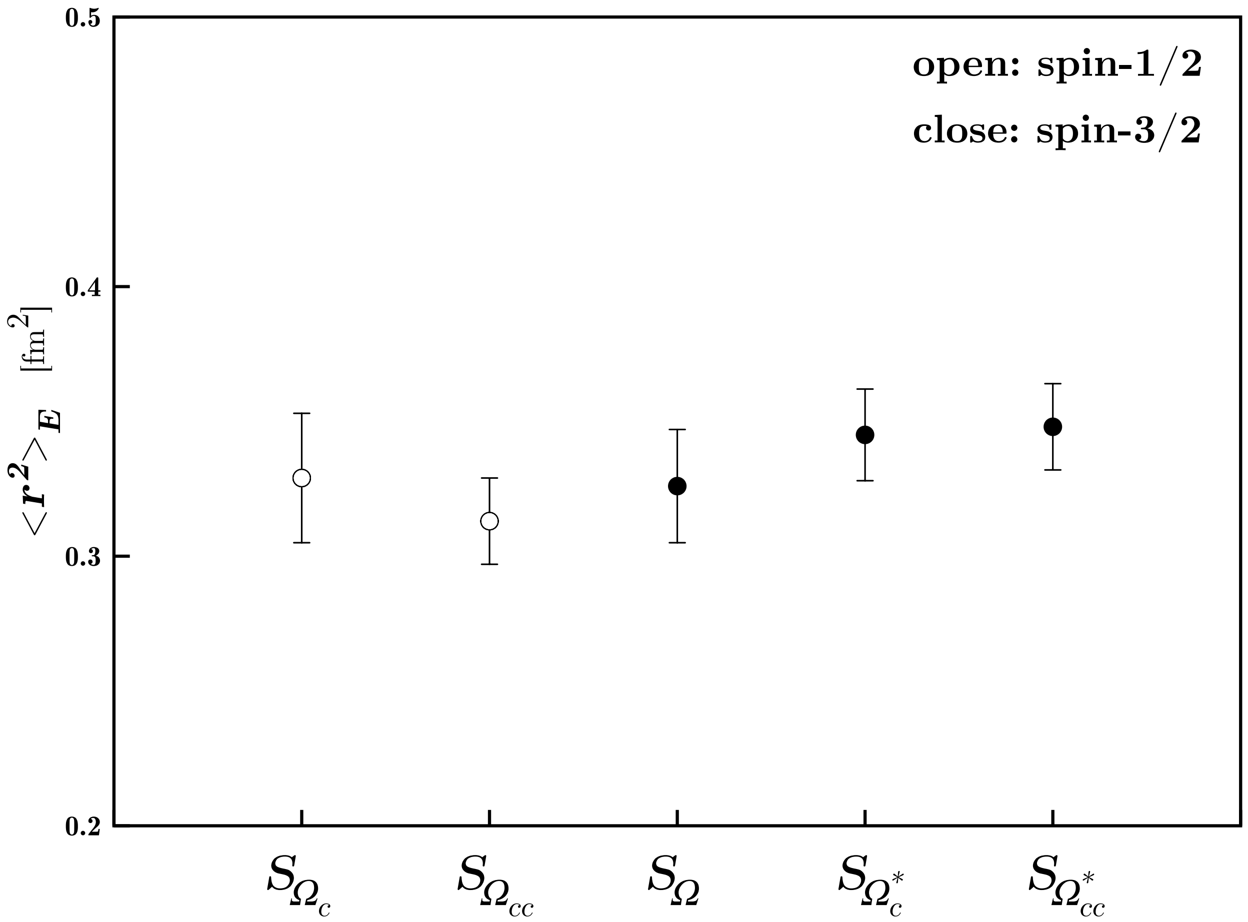
$$G_{E0}(Q^2) = \frac{G_{E0}(0)}{(1+Q^2/\Lambda^2)^2}$$

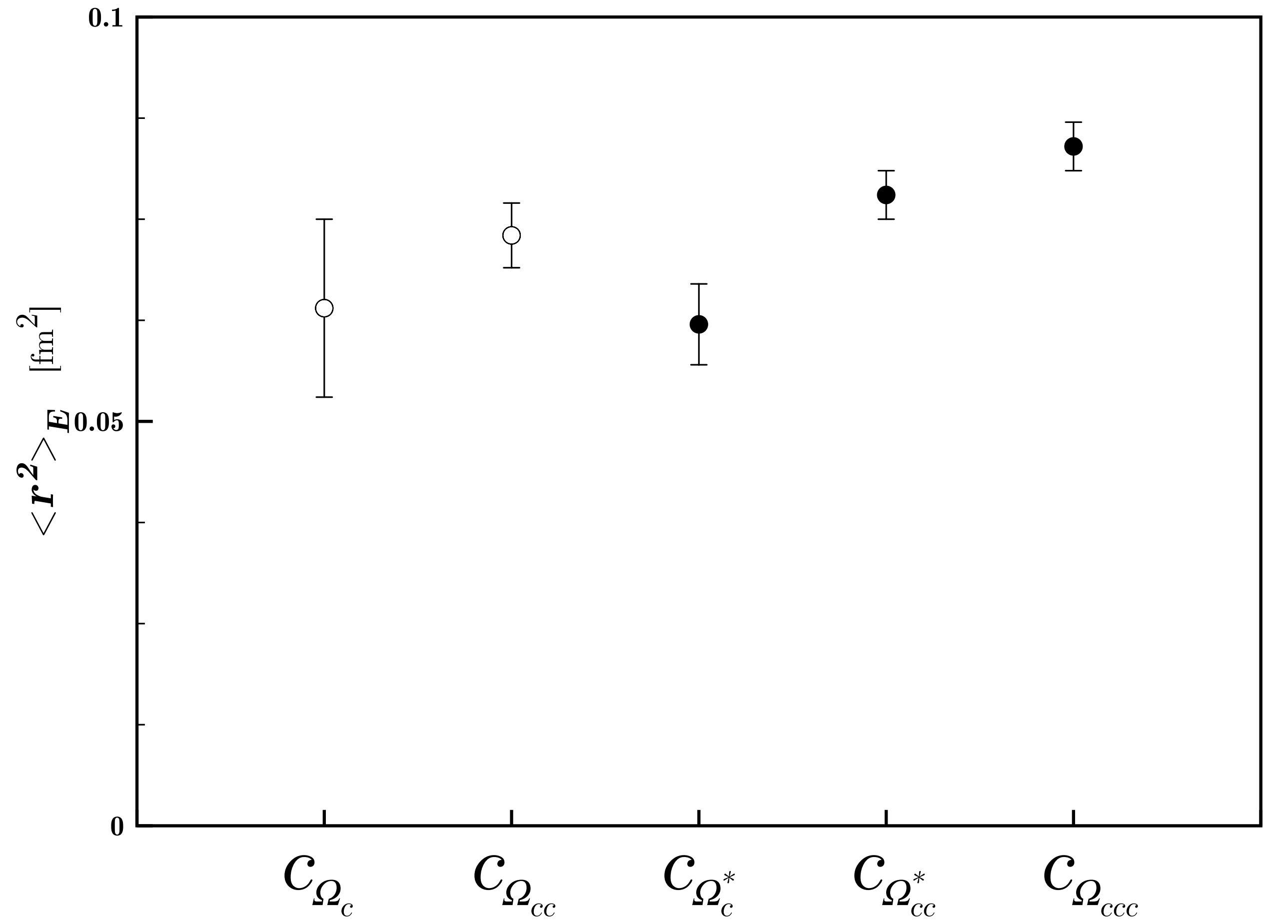
$$\frac{\langle r_E^2 \rangle}{G_{E0}(0)} = \frac{12}{Q^2_{min}} \left(\sqrt{\frac{G_{E0}(0)}{G_{E0}(Q^2_{min})}} - 1 \right)$$

RESULTS

single quark contribution
normalised to unit charge

Electric charge radii
(Quark sectors)



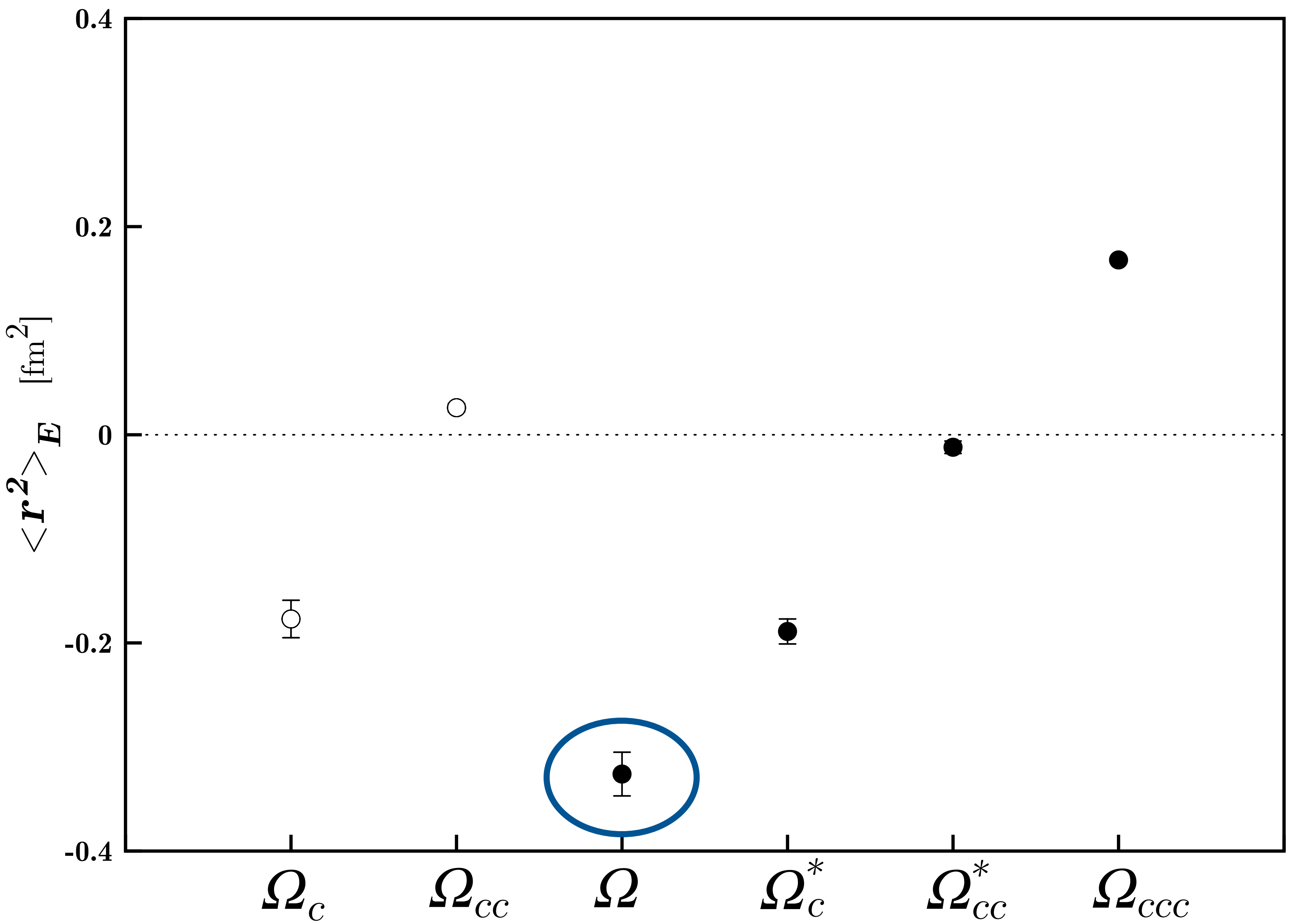


- Strange quark charge radii insensitive to baryon composition
- Charm has a tendency to increase with the c-quark number

RESULTS

$\langle \mathcal{O} \rangle = N_s e_s \langle \mathcal{O}_s \rangle + N_c e_c \langle \mathcal{O}_c \rangle$

Electric charge radii



open: spin-1/2

close: spin-3/2

$$< r_E^2 >_{\Omega^-} = -0.326(21)\,\mathrm{fm}^2$$

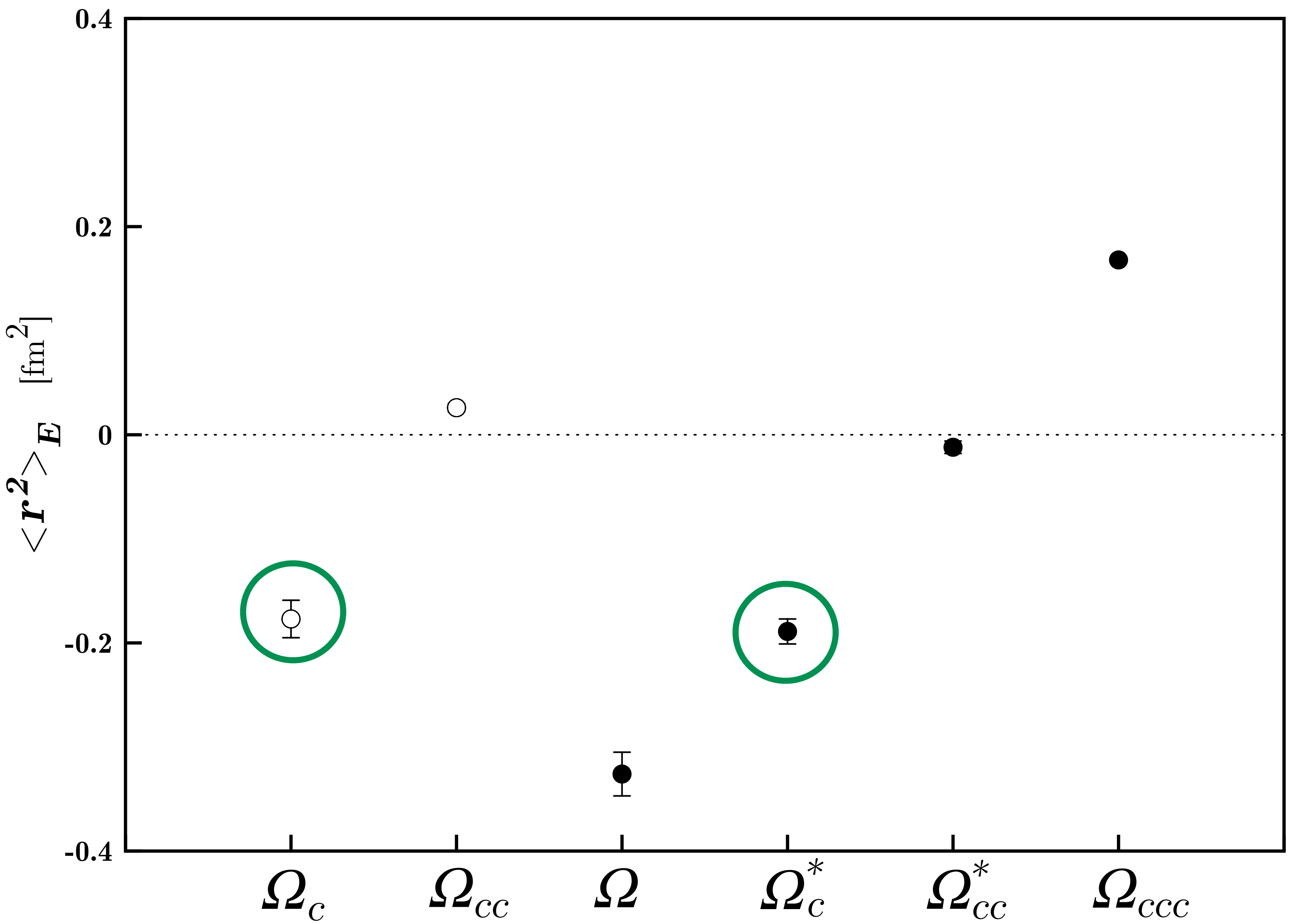
$$\langle r_E^2 \rangle_{\Omega^-} = -0.307(15)\,\mathrm{fm}^2$$ Adelaide group PRD80, 054505(2009)

$$\langle r_E^2 \rangle_{\Omega^-} = 0.321(16)\,\mathrm{fm}^2$$ PRD82, 034504(2010) Alexandrou et.al

RESULTS

$\langle \mathcal{O} \rangle = N_s e_s \langle \mathcal{O}_s \rangle + N_c e_c \langle \mathcal{O}_c \rangle$

Electric charge radii



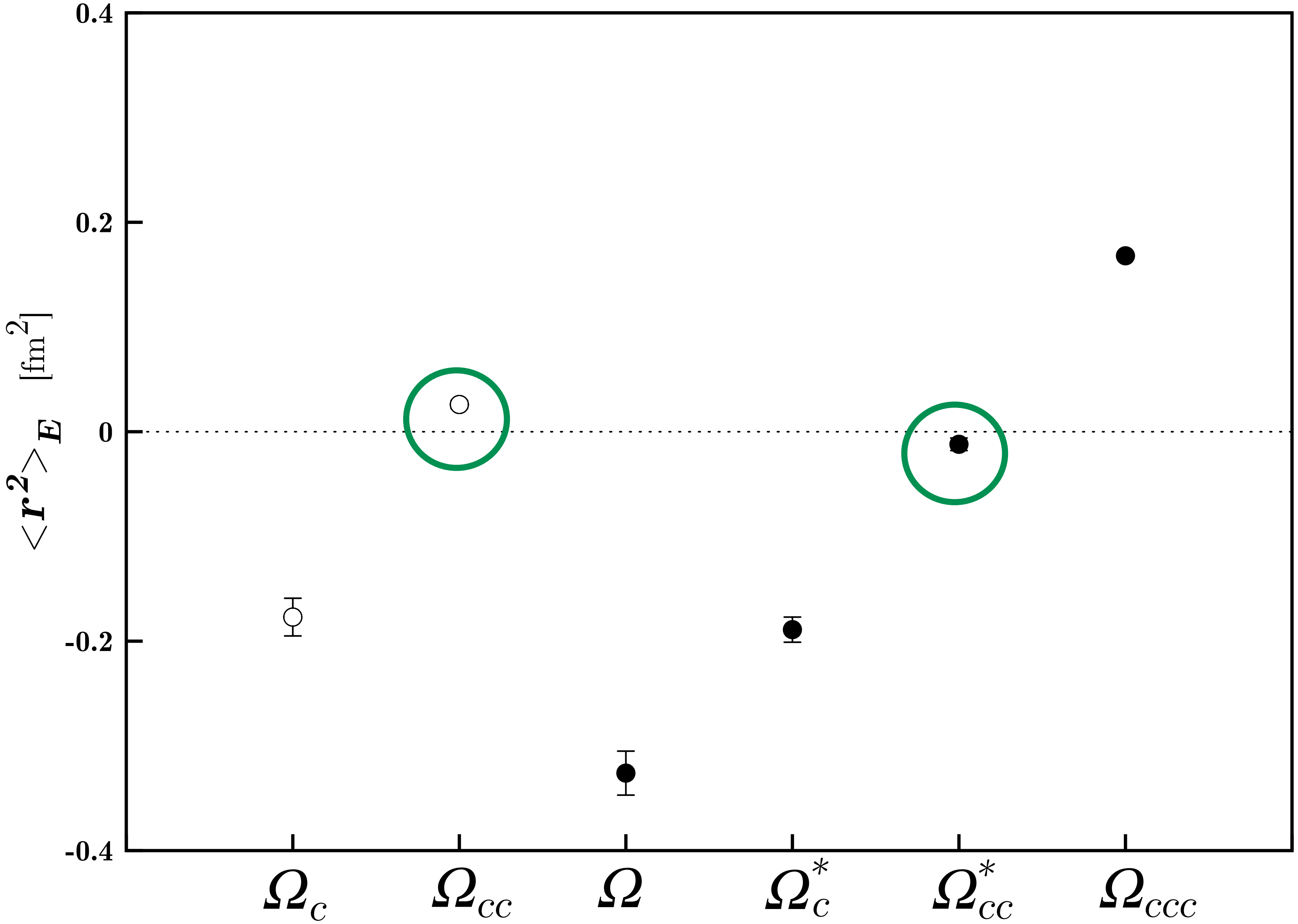
open: spin-1/2
close: spin-3/2

- Ω_c and $\Omega^*{}_c$ have similar charge radius

RESULTS

$\langle \mathcal{O} \rangle = N_s e_s \langle \mathcal{O}_s \rangle + N_c e_c \langle \mathcal{O}_c \rangle$

Electric charge radii



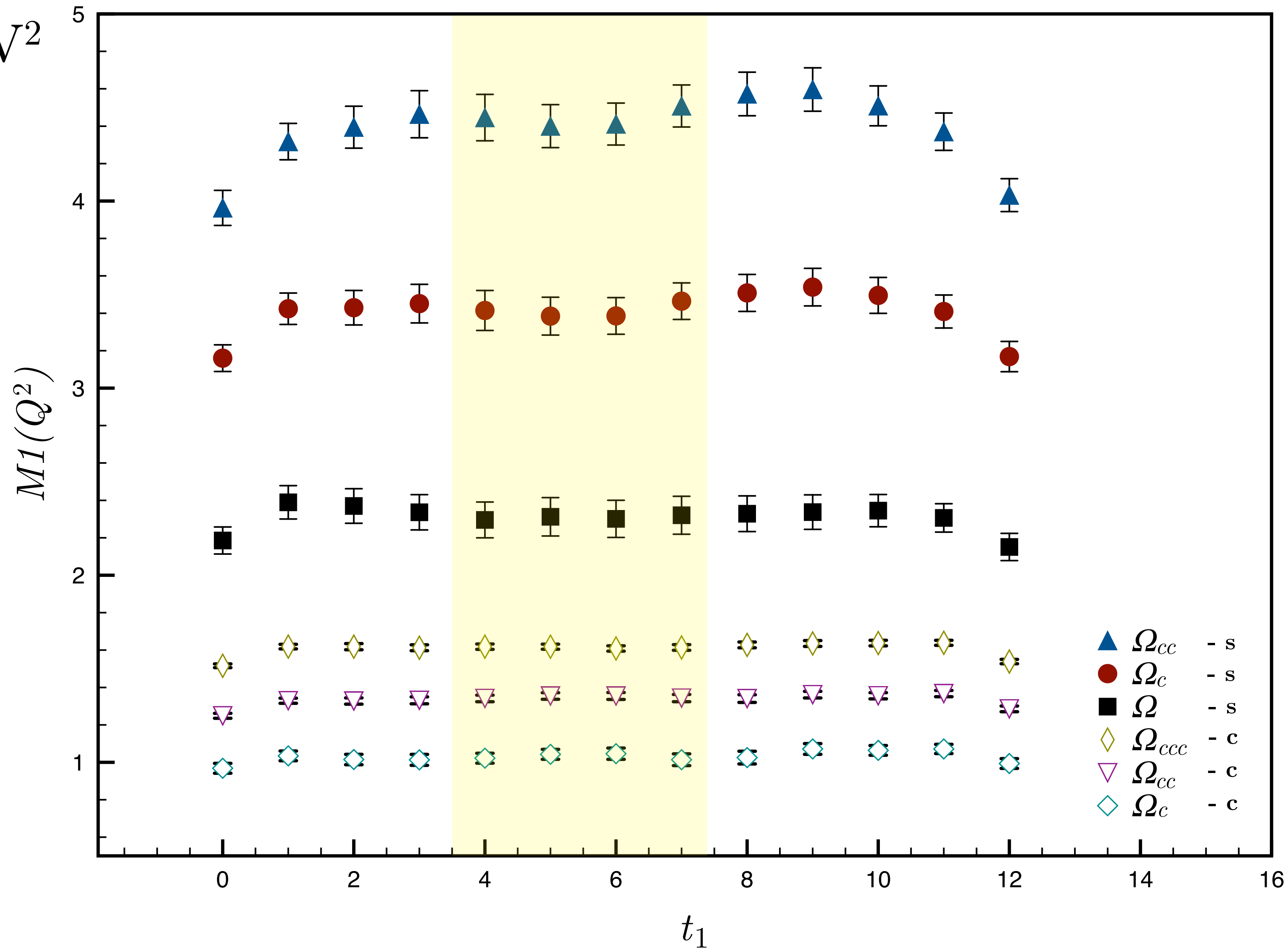
open: spin-1/2
close: spin-3/2

- Ω_{cc} and Ω^*_{cc} charge radii differ due to non-trivial cancellations between quark sectors

RESULTS

M1 Form Factor

$m_\pi \sim 156$ MeV
$\mathbf{q}^2 = 0.183$ GeV^2



Ω^*_{cc}

s Ω^*_c

Ω

Ω_{ccc}

c Ω^*_{cc}

Ω^*_c

Assume E0 and M1 scales similarly for low Q^2

m_N : physical mass of nucleon
m_B : lattice mass of the baryon

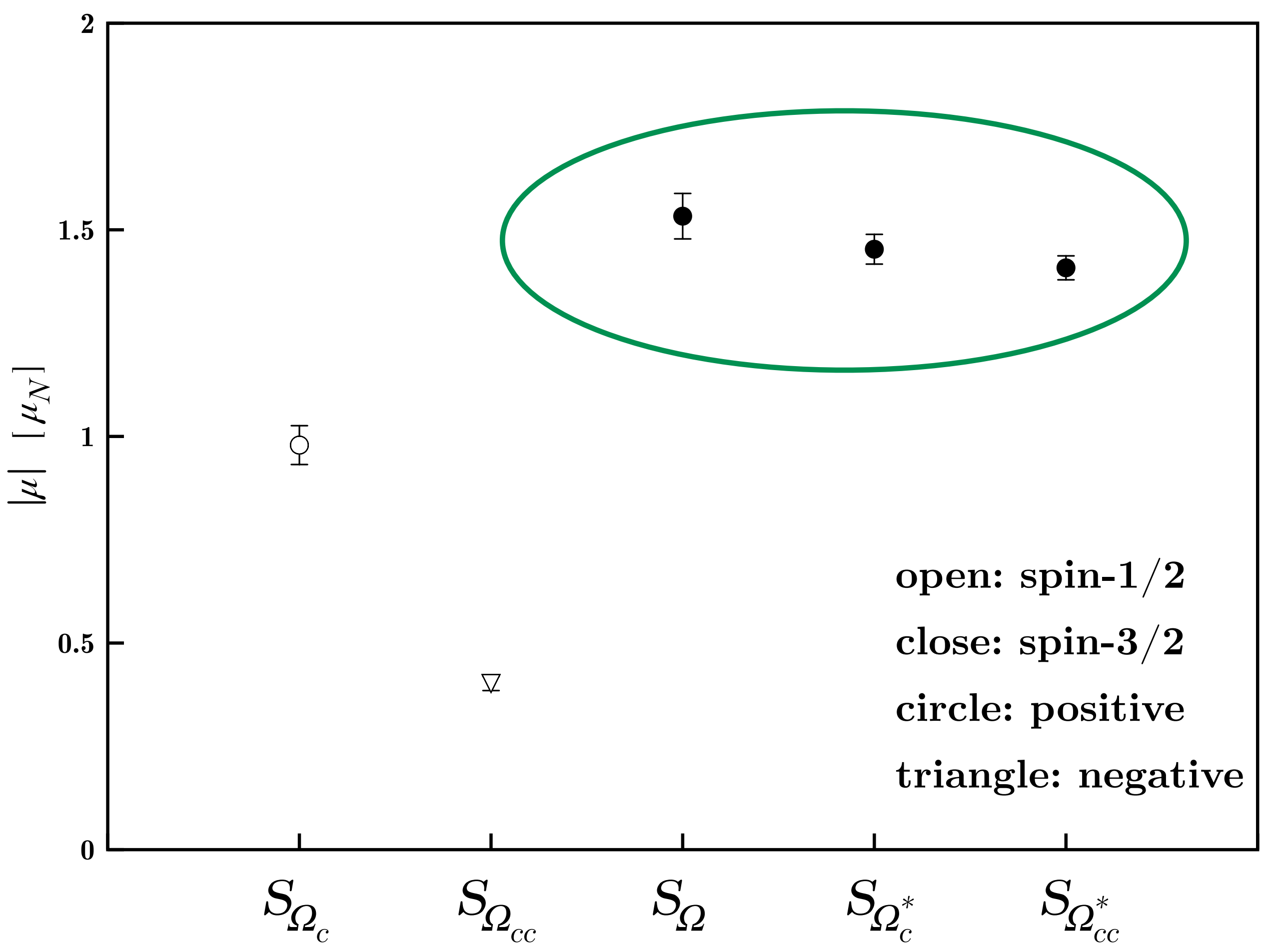
Estimate　　Extract

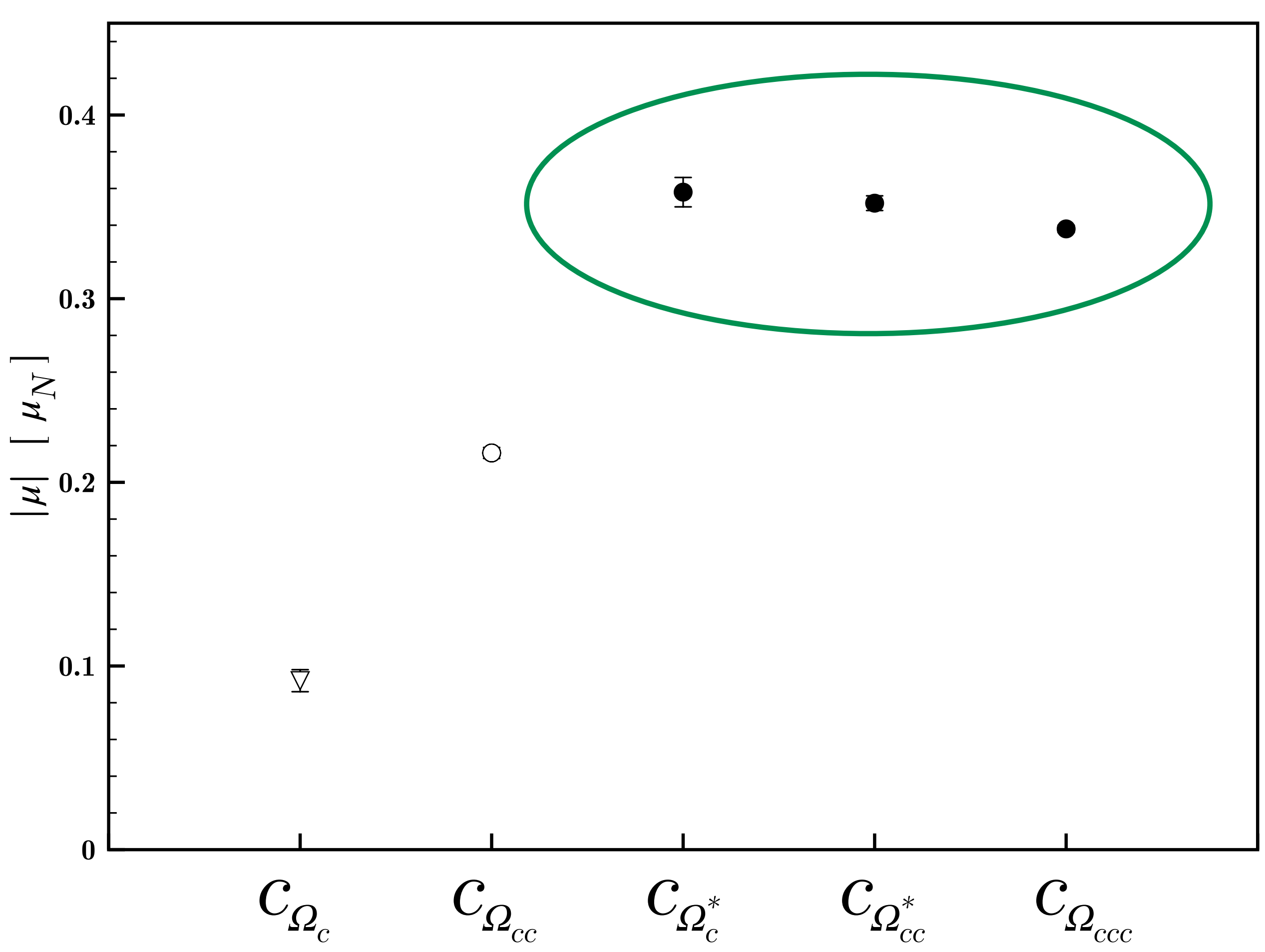
$$G^{s,c}_{M1}(0) = G^{s,c}_{M1}(Q^2_{min})\frac{G^{s,c}_E(0)}{G^{s,c}_E(Q^2_{min})} \longrightarrow \mu_B = G_{M1}(0)\frac{m_N}{m_B}\mu_N$$

RESULTS

single quark contribution normalised to unit charge

Magnetic moments (Quark sectors)





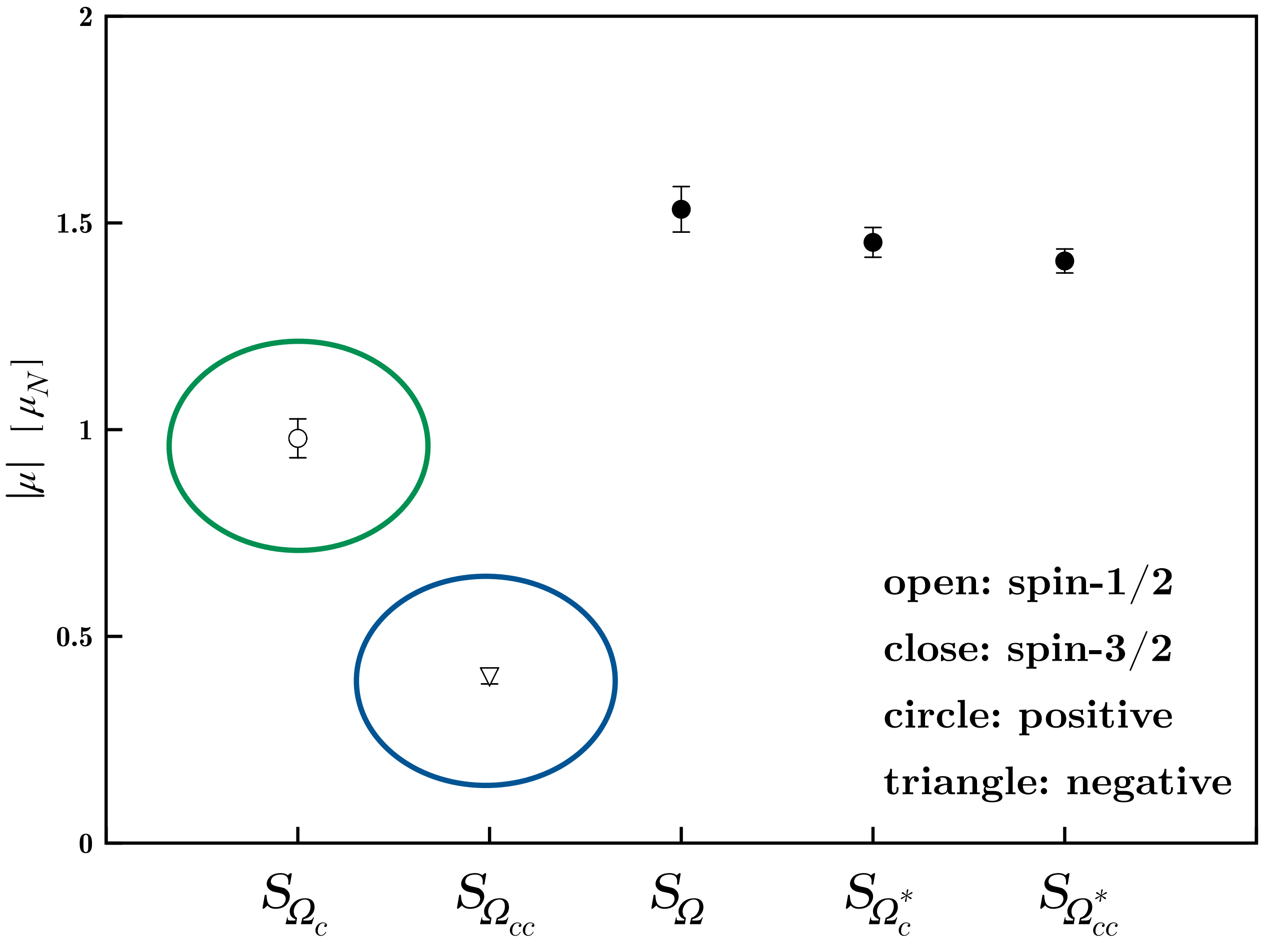
- Quark sector contributions are similar amongst spin-3/2

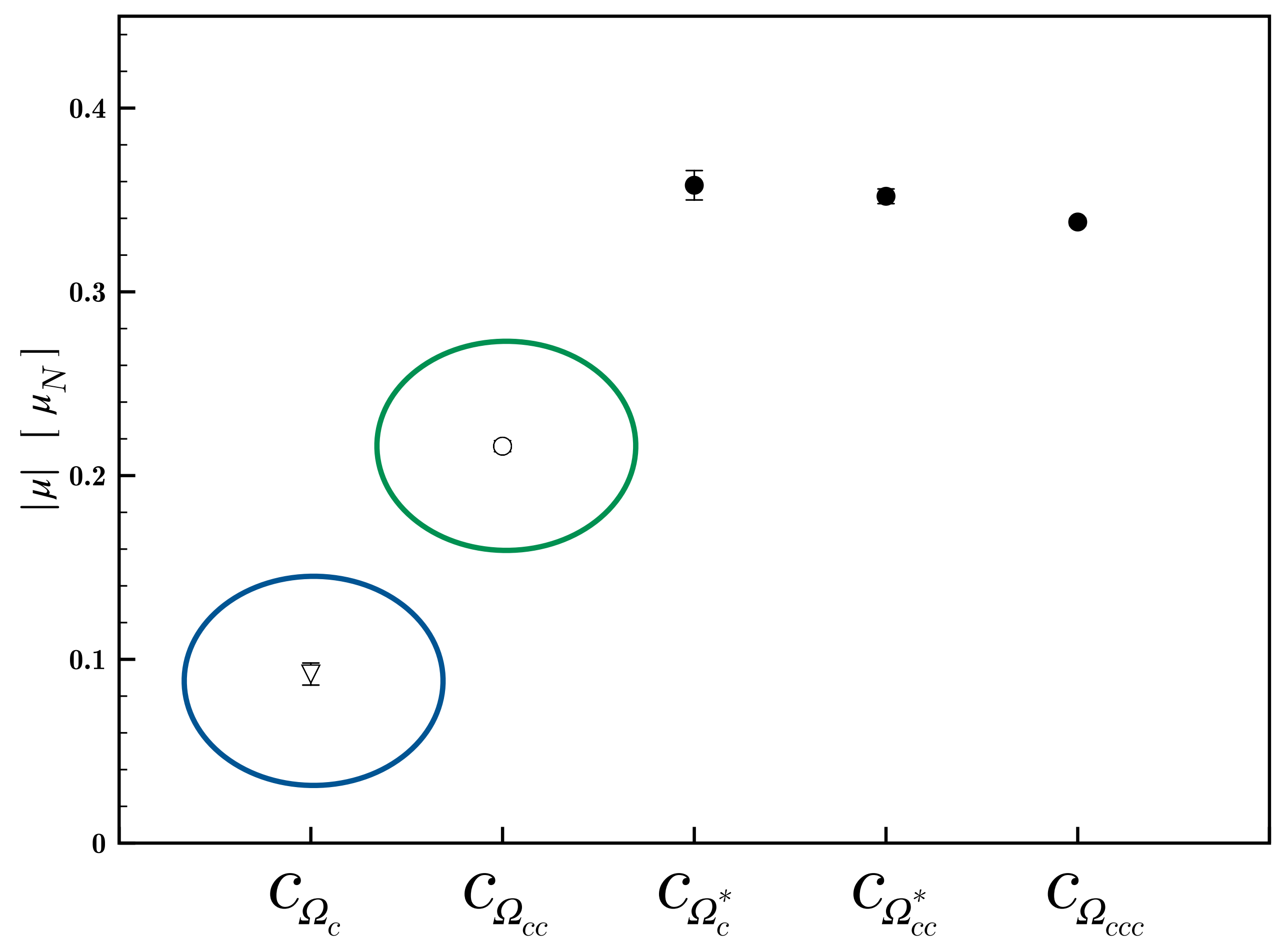
  (expected from a quark model approach)

RESULTS

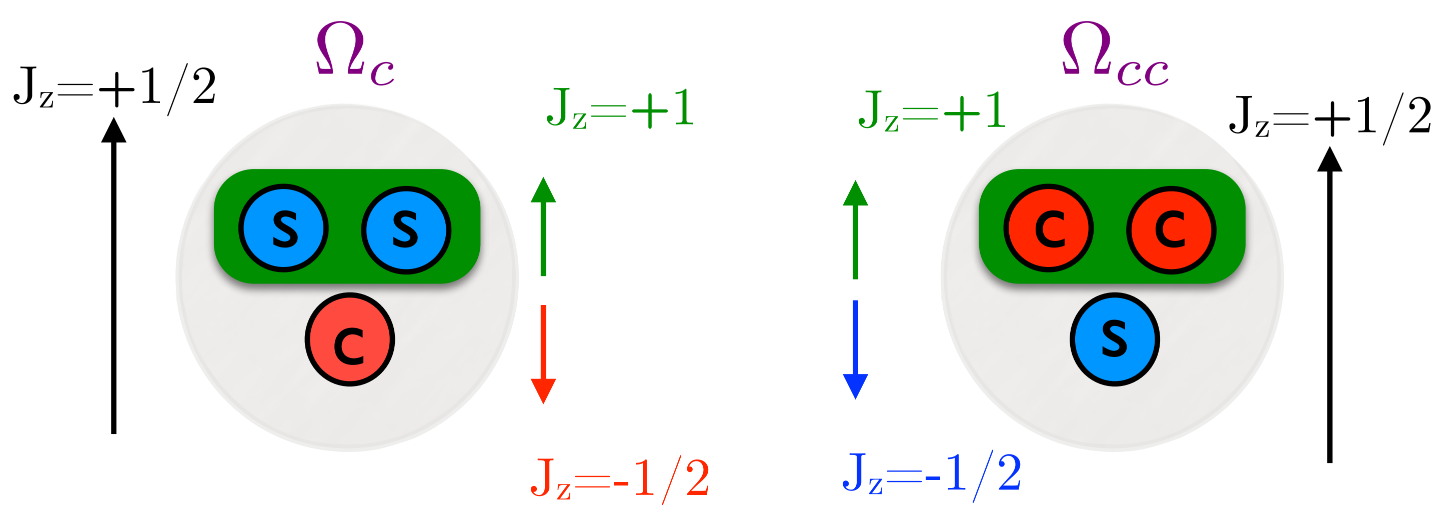
single quark contribution normalised to unit charge

Magnetic moments (Quark sectors)





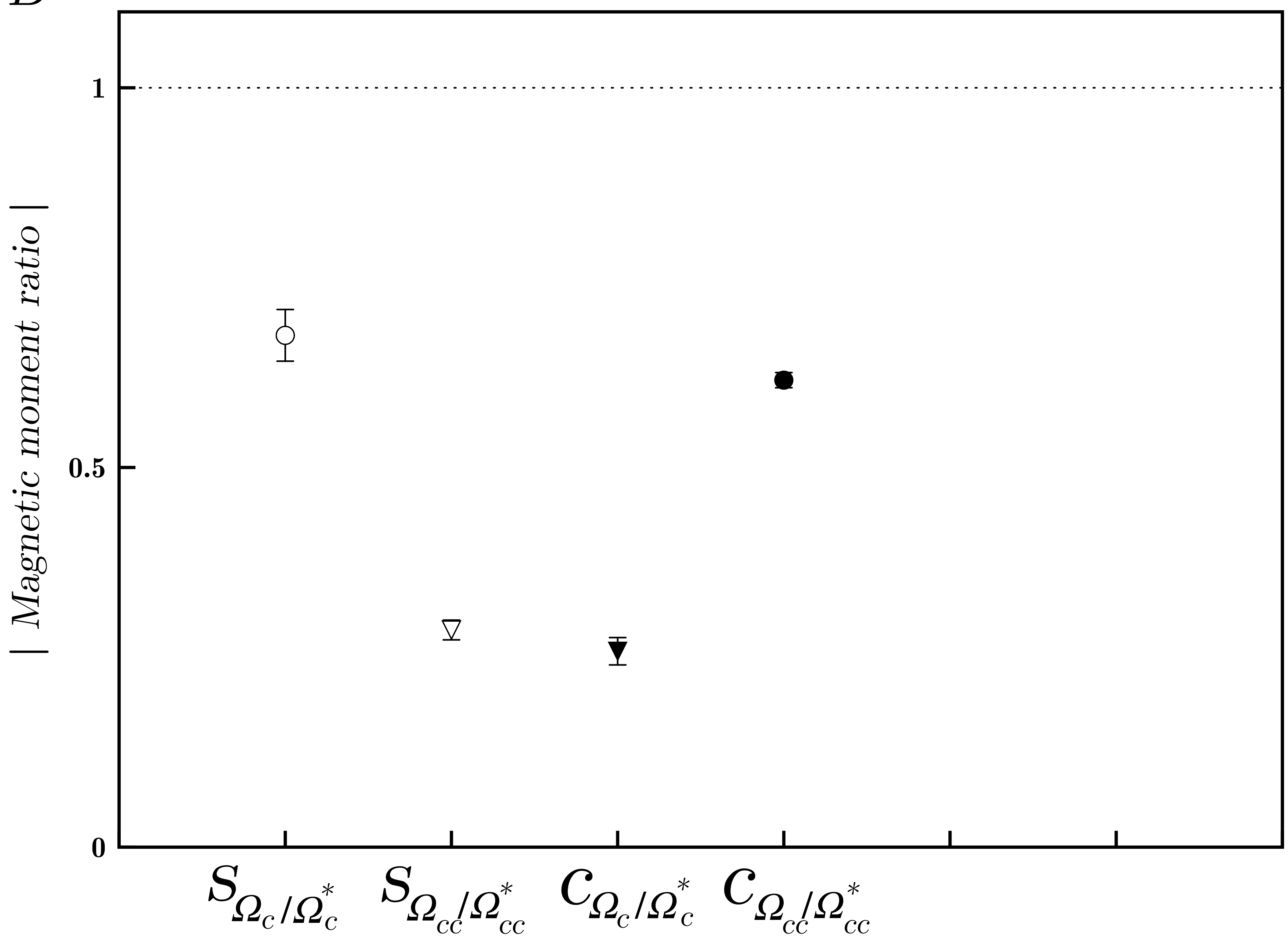
- Sign change due to spin-flip
- $\mu_q^{[qq]} > \mu_q^{[q]}$



RESULTS

Magnetic moments

μ^q_B/μ^q_{B*}

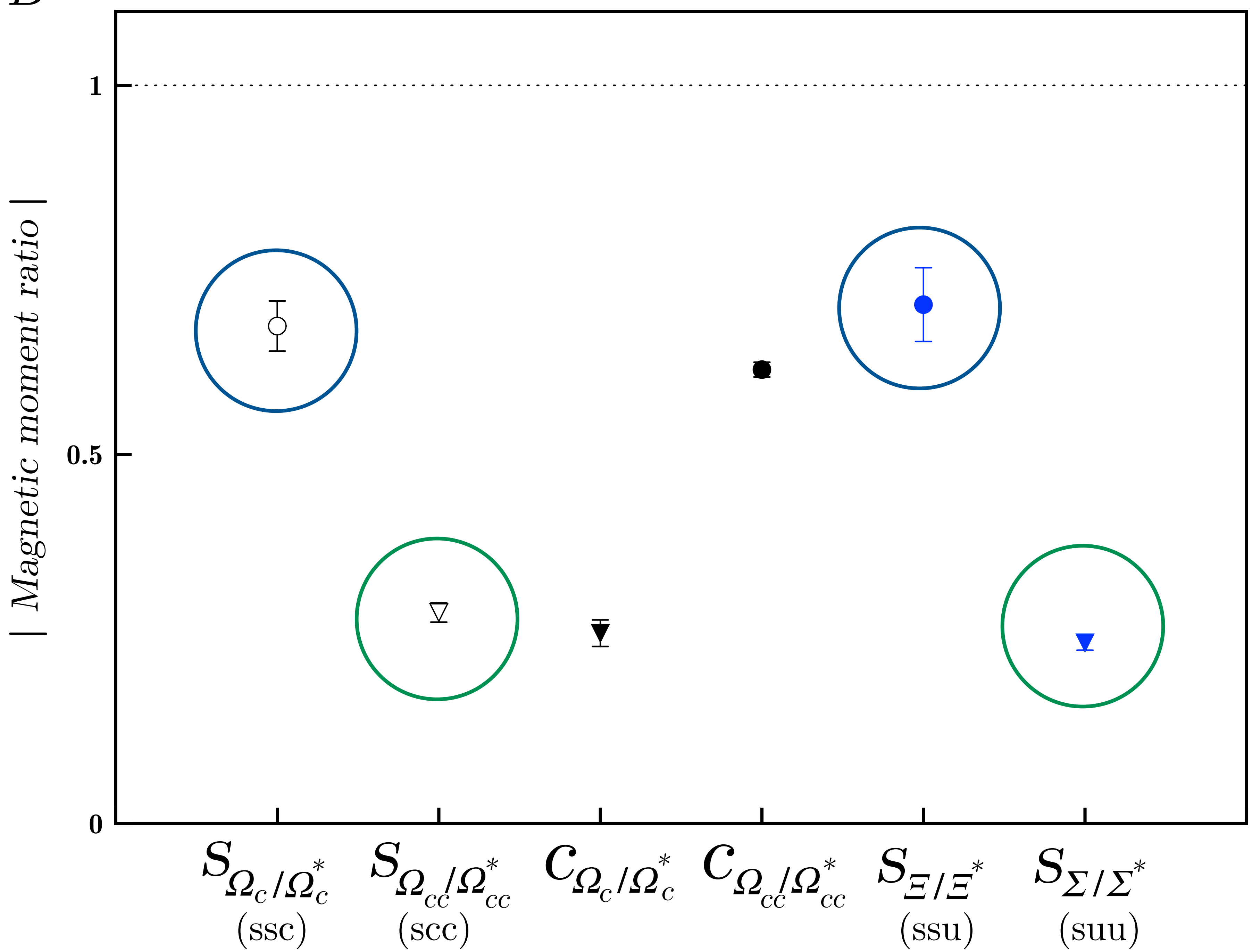


- Contributions within spin-3/2 systems are larger

RESULTS

μ^q_B / μ^q_{B*}

Magnetic moments



Adelaide group

$m_\pi \sim 300$ MeV (quenched)

PRD74, 093005 (2006)

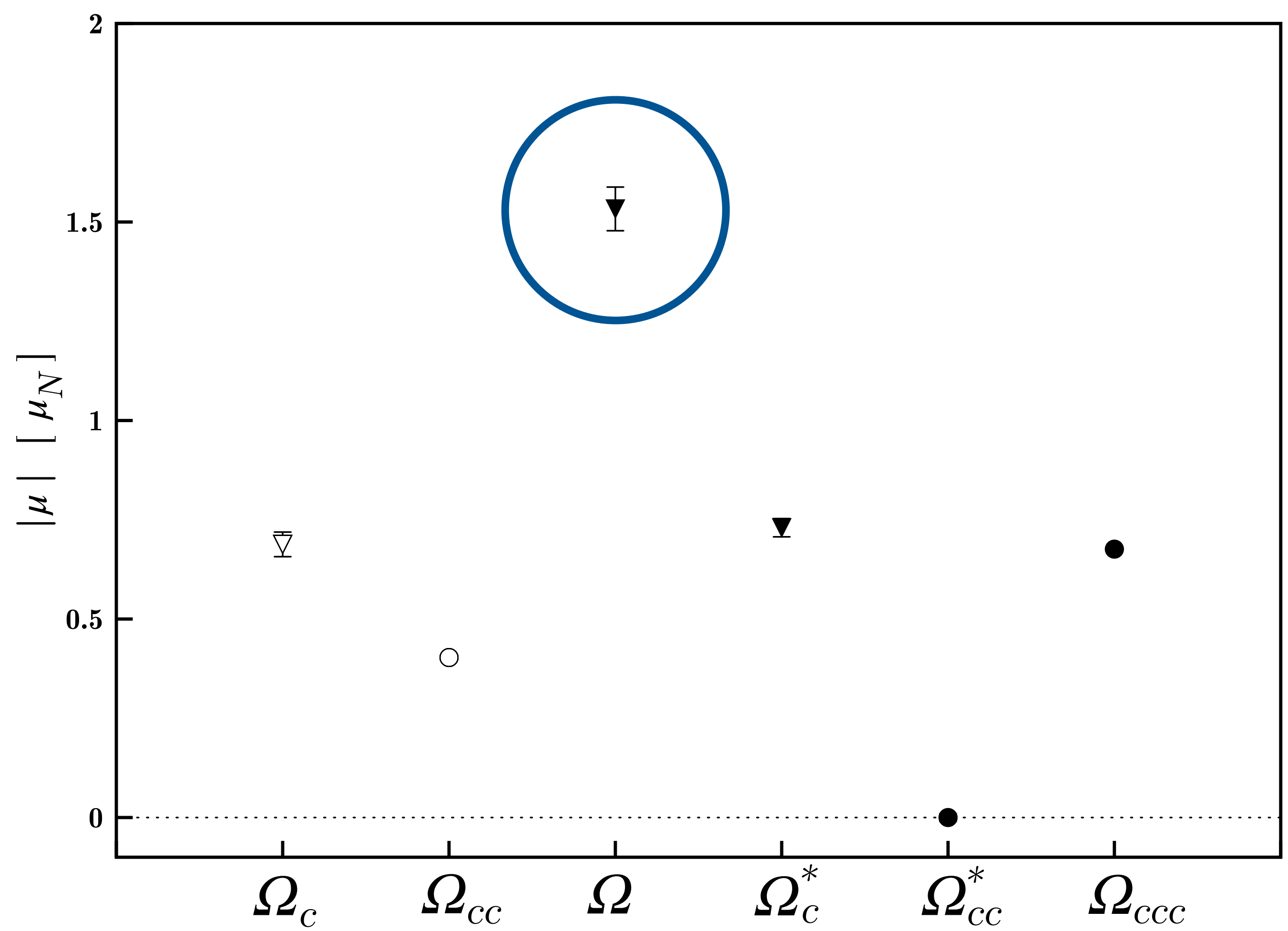
PRD80, 054505 (2009)

- u -> c , s contribution is insensitive
- uu -> cc , effect of uu component is bigger

RESULTS

$\langle \mathcal{O} \rangle = N_s e_s \langle \mathcal{O}_s \rangle + N_c e_c \langle \mathcal{O}_c \rangle$

Magnetic moments



open: spin-1/2

close: spin-3/2

circle: positive

triangle: negative

$$\mu_{\Omega^-} = -1.533(55)\,\mu_N$$

$m_{\Omega^-} = 1.790(17)\ \mathrm{GeV}^2$ this work

$m_{\Omega^-} = 1.772(7)\ \mathrm{GeV}^2$ PACS-CS, PRD79 034503 (2009)

$m_{\Omega^-}^{exp} = 1.673(29)\ \mathrm{GeV}^2$ PDG (2014)

$\mu_{\Omega^-}^{exp} = -2.02(5)\,\mu_N$ PDG, Chin.Phys.C38 090001 (2014)

$\mu_{\Omega^-} = -1.697(65)\,\mu_N$ PRD80, 054505 (2009)

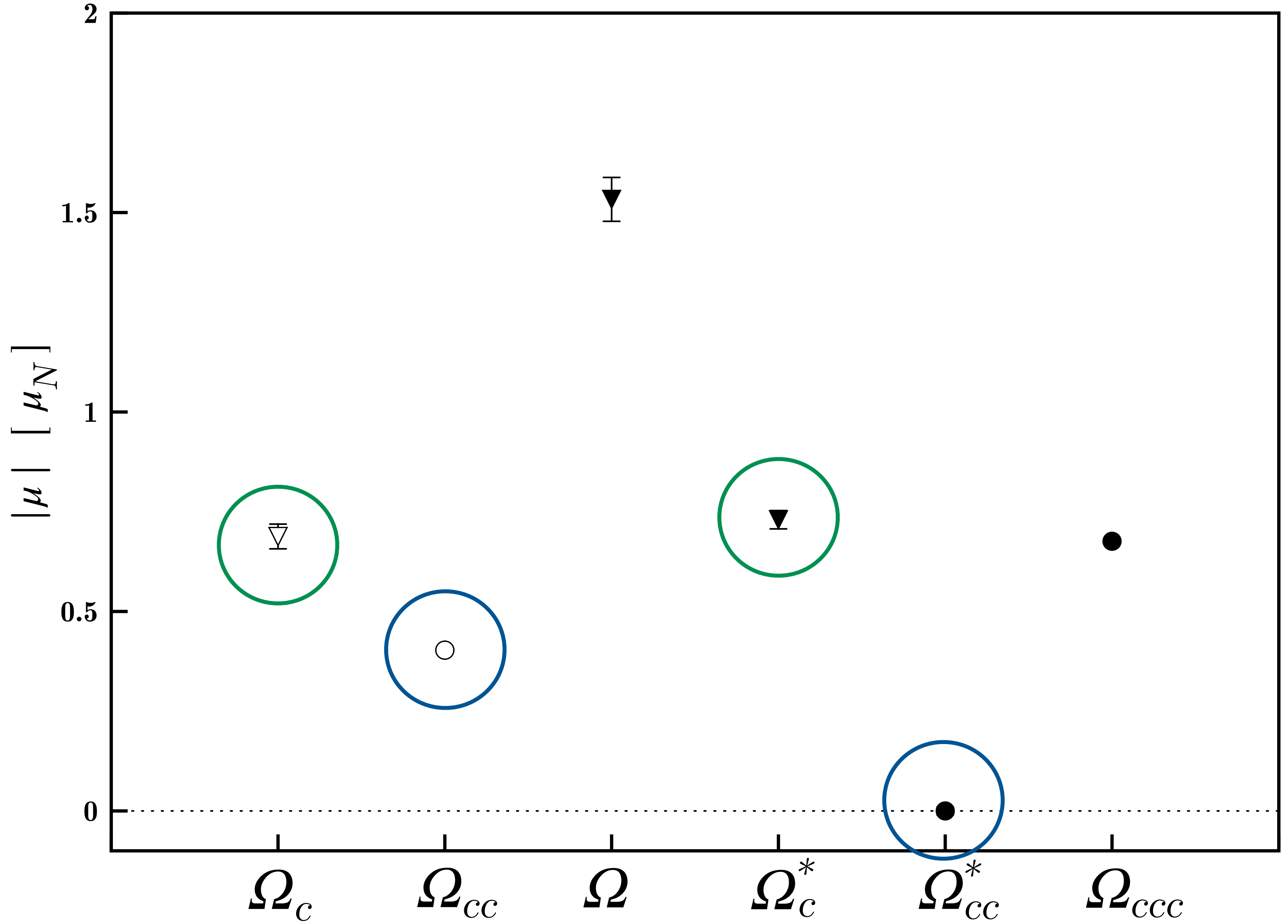
$\mu_{\Omega^-} = -1.875(399)\,\mu_N$ PRD82, 034504 (2010)

$\mu_{\Omega^-} = -1.93(8)\,\mu_N$ PRD79, 051502 (2009) background field method

RESULTS

$\langle \mathcal{O} \rangle = N_s e_s \langle \mathcal{O}_s \rangle + N_c e_c \langle \mathcal{O}_c \rangle$

Magnetic moments



open: spin-1/2
close: spin-3/2
circle: positive
triangle: negative

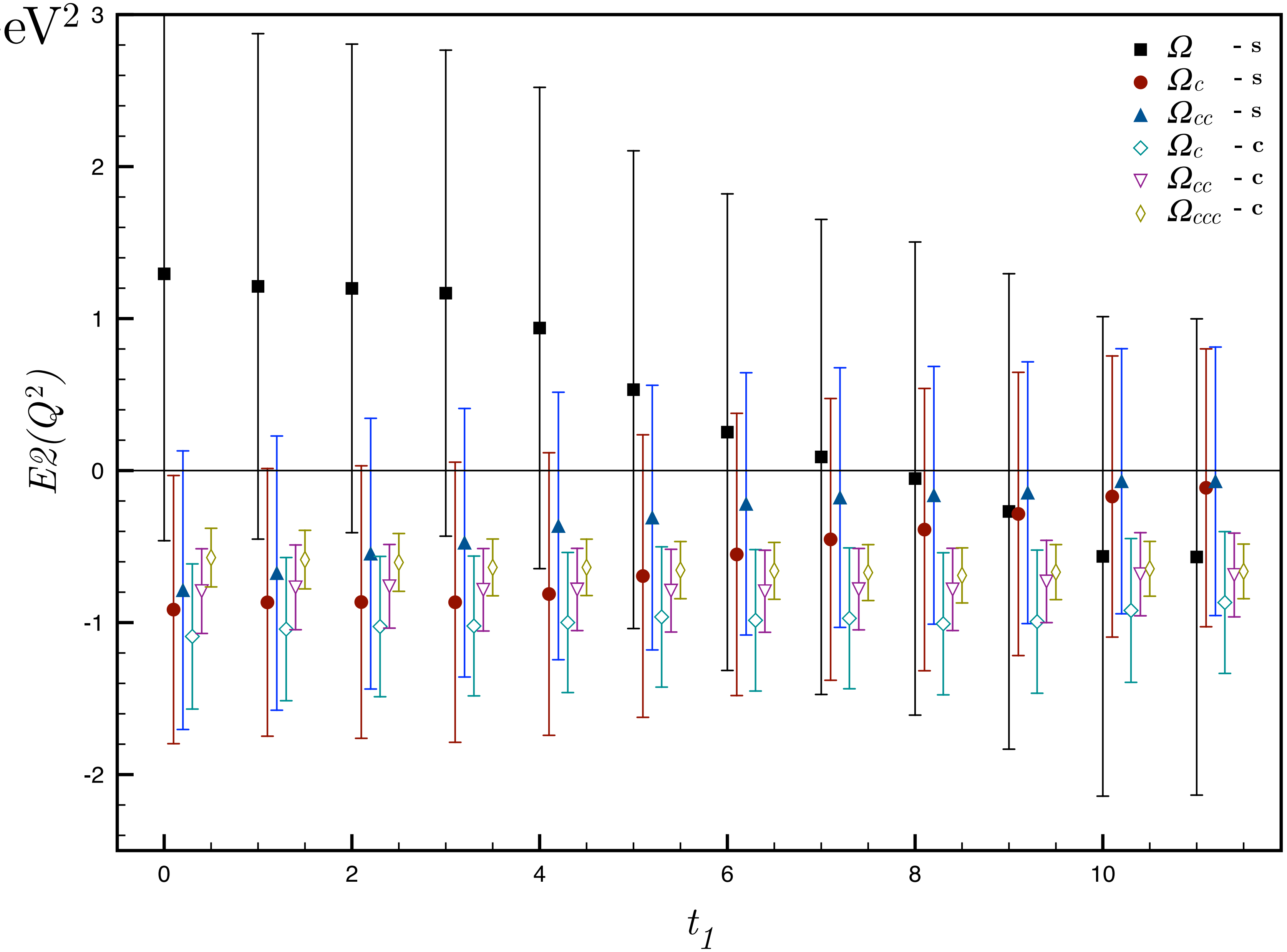
- Ω_c and Ω^*_c have similar magnetic moments in magnitude
- Ω^*_{cc} has a vanishing mag. moment unlike Ω_{cc}

RESULTS

E2 Form Factor

E2 moment

$m_\pi \sim 156$ MeV
$\mathbf{q}^2 = 0.183\ \mathrm{GeV}^2$



Ω

s Ω^*_{cc}

Ω^*_c

Ω_{ccc}

c Ω^*_{cc}

Ω^*_c

$$\mathcal{G}_{E2}(0) = M_B^2 \int d^3r \bar{\psi}(r)(3z^2 - r^2)\psi(r)$$

shape of the electric charge distribution

	$E_2(Q^2)_s$	$E_2(Q^2)_c$	$E_2(Q^2)$
	$[e/m^2]$	$[e/m^2]$	$[e/m^2]$
Ω^*_{cc}	-0.091(277)	-0.255(87)	-0.310(128)
Ω_{ccc}	—	-0.136(38)	-0.273(76)

oblate

- Ω^*_{cc} and Ω_{ccc} have oblate electric charge distributions

SUMMARY

- **Charge radii:**
  - $\langle r_E^2 \rangle_s$ is insensitive to the composition of the baryon
  - $\langle r_E^2 \rangle_c$ slightly increases with the increasing number of c-quarks
- **Magnetic moments:**
  - $\mu_s^{3/2} > \mu_s^{1/2}, \quad \mu_c^{3/2} > \mu_c^{1/2}$
  - u -> c , s-quark contribution is insensitive,
  - uu -> cc , effect of *uu* component is bigger
  - Ω_c and Ω^*_c have similar mag. moments in magnitude
  - Ω^*_{cc} has a vanishing mag. moment unlike Ω_{cc}
- **E2 moments:**
  - Ω^{*+}_{cc} and Ω^{++}_{ccc} have oblate electric charge distributions

ACKNOWLEDGEMENTS

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THANK YOU

BACKUP SLIDES

EM FORM FACTORS

Lattice Formulation

$$\langle C^{\mathcal{B}}(t;\mathbf{p};\Gamma_4)\rangle = \sum_{\mathbf{x}} e^{-i\mathbf{p}\cdot\mathbf{x}}\Gamma_4^{\alpha\alpha'}\langle \text{vac}|T[\eta_{\mathcal{B}}^{\alpha}(x)\bar{\eta}_{\mathcal{B}}^{\alpha'}(0)]|\text{vac}\rangle$$

$$\langle C^{\mathcal{B}\mathcal{V}_\mu\mathcal{B}'}(t_2,t_1;\mathbf{p}',\mathbf{p};\Gamma)\rangle = -i\sum_{\mathbf{x_2},\mathbf{x_1}} e^{-i\mathbf{p}\cdot\mathbf{x_2}}e^{i\mathbf{q}\cdot\mathbf{x_1}}\Gamma^{\alpha\alpha'}\langle \text{vac}|T[\eta_{\mathcal{B}}^{\alpha}(x_2)V_\mu(x_1)\bar{\eta}_{\mathcal{B}'}^{\alpha'}(0)]|\text{vac}\rangle$$

$$R(t_2,t_1;\mathbf{p}',\mathbf{p};\Gamma;\mu) = \frac{\langle C^{\mathcal{B}\mathcal{V}_\mu\mathcal{B}'}(t_2,t_1;\mathbf{p}',\mathbf{p};\Gamma)\rangle}{\langle C^{\mathcal{B}\mathcal{B}}(t_2;\mathbf{p}';\Gamma_4)\rangle}$$
$$\times\left[\frac{\langle C^{\mathcal{B}\mathcal{B}}(t_2-t_1;\mathbf{p};\Gamma_4)\rangle\langle C^{\mathcal{B}\mathcal{B}}(t_1;\mathbf{p}';\Gamma_4)\rangle\langle C^{\mathcal{B}\mathcal{B}}(t_2;\mathbf{p}';\Gamma_4)\rangle}{\langle C^{\mathcal{B}\mathcal{B}}(t_2-t_1;\mathbf{p}';\Gamma_4)\rangle\langle C^{\mathcal{B}\mathcal{B}}(t_1;\mathbf{p};\Gamma_4)\rangle\langle C^{\mathcal{B}\mathcal{B}}(t_2;\mathbf{p};\Gamma_4)\rangle}\right]^{1/2}$$

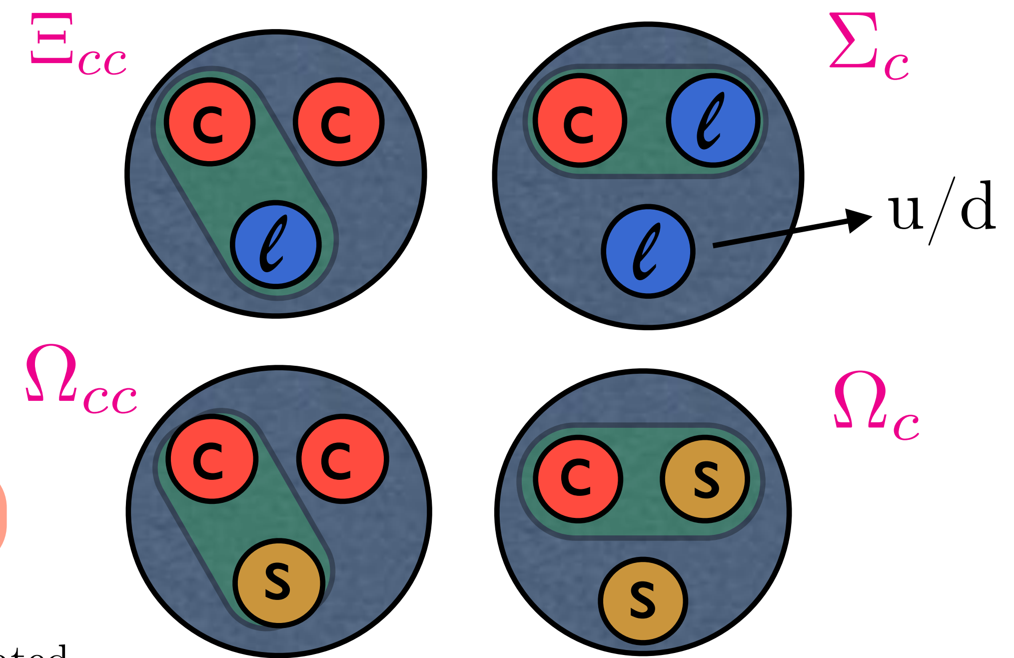
$$\eta_{\Xi_{cc}}(x) = \epsilon^{ijk}[c^{Ti}(x)C\gamma_5\ell^j(x)]c^k(x)$$
$$\eta_{\Sigma_c}(x) = \epsilon^{ijk}[\ell^{Ti}(x)C\gamma_5c^j(x)]\ell^k(x)$$
$$\eta_{\Omega_{cc}}(x) = \epsilon^{ijk}[c^{Ti}(x)C\gamma_5s^j(x)]c^k(x)$$
$$\eta_{\Omega_c}(x) = \epsilon^{ijk}[s^{Ti}(x)C\gamma_5c^j(x)]s^k(x)$$

$$R(t_2,t_1;\mathbf{p}',\mathbf{p};\Gamma;\mu) \xrightarrow[t_2-t_1\gg a]{t_1\gg a} \Pi(\mathbf{p}',\mathbf{p};\Gamma;\mu)$$

$$\Pi(\mathbf{0},-\mathbf{q};\Gamma_4;\mu=4) = \left[\frac{(E_{\mathcal{B}}+m_{\mathcal{B}})}{2E_{\mathcal{B}}}\right]^{1/2} G_{E,\mathcal{B}}(q^2)$$

$$\Pi(\mathbf{0},-\mathbf{q};\Gamma_j;\mu=i) = \left[\frac{1}{2E_{\mathcal{B}}(E_{\mathcal{B}}+m_{\mathcal{B}})}\right]^{1/2} \epsilon_{ijk}q_k G_{M,\mathcal{B}}(q^2)$$

G(0) should be extrapolated from higher momenta



EM FORM FACTORS

spin-3/2

$$\langle \mathcal{B}_\sigma(p', s')|j_\mu|\mathcal{B}_\tau(p,s)\rangle = \sqrt{\frac{M_{\mathcal{B}}^2}{E\,E'}}\bar{u}_\sigma(p',s')\mathcal{O}^{\sigma\mu\tau}u_\tau(p,s)$$

$$\mathcal{O}^{\sigma\mu\tau} = -g^{\sigma\tau}\left\{a_1\gamma^\mu + \frac{a_2}{2M_{\mathcal{B}}}P^\mu\right\} - \frac{q^\sigma q^\tau}{(2M_{\mathcal{B}})^2}\left\{c_1\gamma^\mu + \frac{c_2}{2M_{\mathcal{B}}}P^\mu\right\}$$

P = p' + p

q = p' - p

as drived in S. Nozawa and D. Leinweber, Phys.Rev. D42, 3567(1990)

Electric charge

$$G_{E0}(q^2) = (1+\frac{2}{3}\tau)\{a_1 + (1+\tau)a_2\} - \frac{1}{3}\tau(1+\tau)\{c_1 + (1+\tau)c_2\}\,,$$

Magnetic dipole

$$G_{M1}(q^2) = (1+\frac{4}{3}\tau)a_1 - \frac{2}{3}\tau(1+\tau)c_1,$$

Electric quadrupole

$$G_{E2}(q^2) = \{a_1 + (1+\tau)a_2\} - \frac{1}{2}(1+\tau)\{c_1 + (1+\tau)c_2\}\,,$$

$\tau = -q^2/(2M_B)^2$

EM FORM FACTORS

spin-3/2

Adelaide group: PRD80, 054505 (2009)

①

$$\langle G^{\mathcal{B}\mathcal{B}}_{\sigma\tau}(t;\mathbf{p};\Gamma_4)\rangle = \sum_{\mathbf{x}} e^{-i\mathbf{p}\cdot\mathbf{x}}\Gamma_4^{\alpha\alpha'} \times \langle \mathrm{vac}|T[\eta^\alpha_\sigma(x)\bar{\eta}^{\alpha'}_\tau(0)]|\mathrm{vac}\rangle$$

$$\langle G^{\mathcal{B}j^\mu\mathcal{B}}_{\sigma\tau}(t_2,t_1;\mathbf{p}',\mathbf{p};\mathbf{\Gamma})\rangle = -i\sum_{\mathbf{x_2},\mathbf{x_1}} e^{-i\mathbf{p}\cdot\mathbf{x_2}}e^{i\mathbf{q}\cdot\mathbf{x_1}} \times\mathbf{\Gamma}^{\alpha\alpha'}\langle \mathrm{vac}|T[\eta^\alpha_\sigma(x_2)j_\mu(x_1)\bar{\eta}^{\alpha'}_\tau(0)]|\mathrm{vac}\rangle$$

②

$$R_\sigma{}^\mu{}_\tau(t_2,t_1;\mathbf{p}',\mathbf{p};\mathbf{\Gamma}) = \left[\frac{\langle G^{\mathcal{B}j^\mu\mathcal{B}}_{\sigma\tau}(t_2,t_1;\mathbf{p}',\mathbf{p};\mathbf{\Gamma})\rangle\langle G^{\mathcal{B}j^\mu\mathcal{B}}_{\sigma\tau}(t_2,t_1;\mathbf{p},-\mathbf{p}';\mathbf{\Gamma})\rangle}{\langle G^{\mathcal{B}\mathcal{B}}_{\sigma\tau}(t_2;\mathbf{p}';\Gamma_4)\rangle\langle G^{\mathcal{B}\mathcal{B}}_{\sigma\tau}(t_2;-\mathbf{p};\Gamma_4)\rangle}\right]^{1/2}$$

$$\xrightarrow[t_2-t_1\gg a]{t_1\gg a} \left(\frac{E_p+M_\mathcal{B}}{2E_p}\right)^{1/2}\left(\frac{E_{p'}+M_\mathcal{B}}{2E_{p'}}\right)^{1/2} \times \Pi_\sigma{}^\mu{}_\tau(\mathbf{p}',\mathbf{p};\mathbf{\Gamma})$$

③

$$G_{E0}(q^2) = \frac{1}{3}\left(\Pi_1{}^4{}_1(\mathbf{q}_i,0;\Gamma_4)+\Pi_2{}^4{}_2(\mathbf{q}_i,0;\Gamma_4) +\Pi_3{}^4{}_3(\mathbf{q}_i,0;\Gamma_4)\right),$$

$$G_{M1}(q^2) = -\frac{3}{5}\frac{E+M}{|\mathbf{q}_1|^2}\left(\Pi_1{}^3{}_1(\mathbf{q}_1,0;\Gamma_2) +\Pi_2{}^3{}_2(\mathbf{q}_1,0;\Gamma_2)+\Pi_3{}^3{}_3(\mathbf{q}_1,0;\Gamma_2)\right),$$

can't extract $q^2=0$ directly

$$G_{E2}(q^2) = 2\frac{M(E+M)}{|\mathbf{q}_i|^2}\left(\Pi_1{}^4{}_1(\mathbf{q}_i,0;\Gamma_4) +\Pi_2{}^4{}_2(\mathbf{q}_i,0;\Gamma_4)-2\Pi_3{}^4{}_3(\mathbf{q}_i,0;\Gamma_4)\right),$$

[21] PRD87 094512 (2013)
[14] PRD79 034503 (2009) PRD90 074501 (2014) PRD86 094504 (2012)

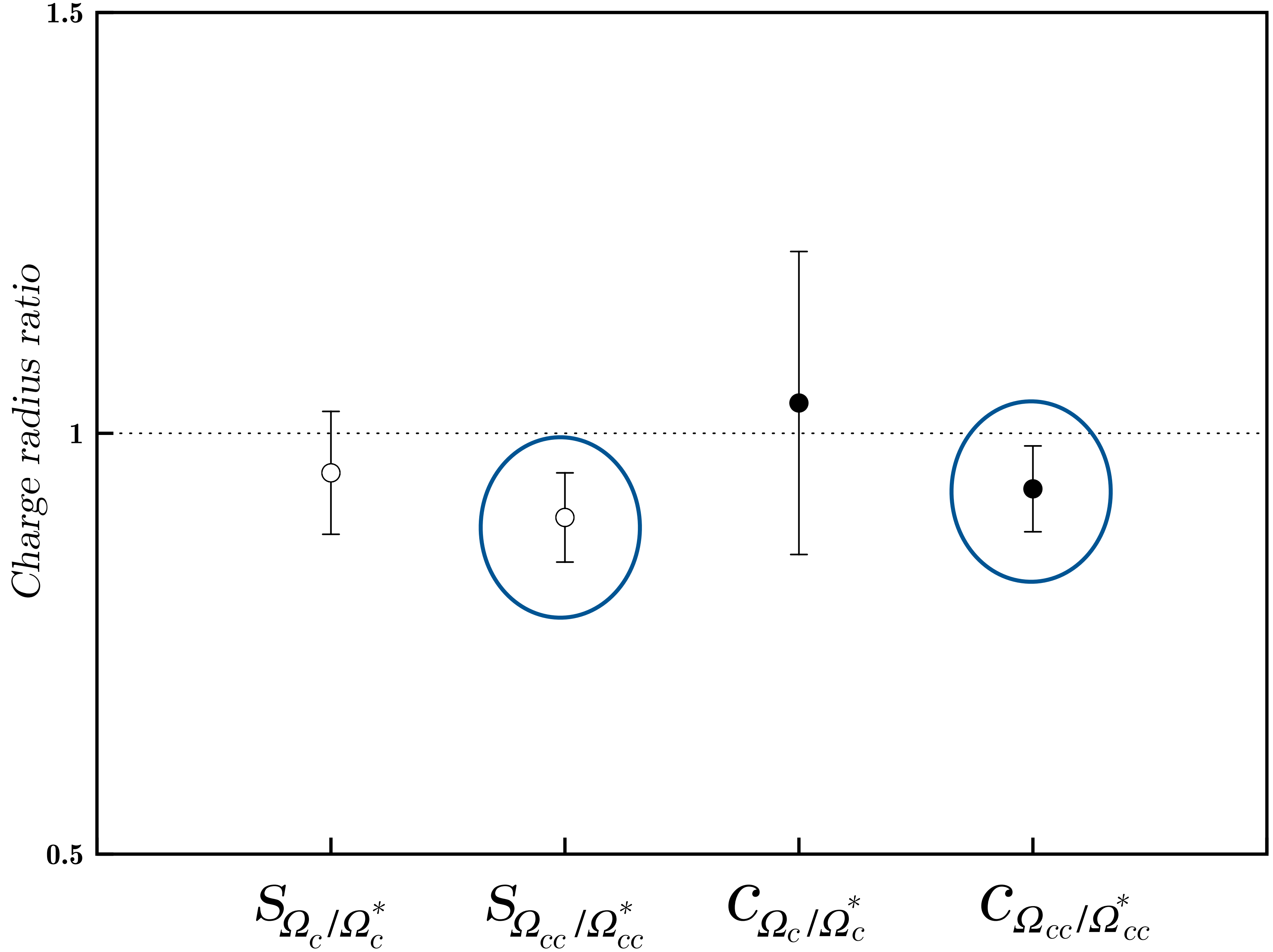
	J^P	This work	PACS-CS [21]	ETMC [13]	Briceno *et al.* [23]	Exp. [22]
		[GeV]	[GeV]	[GeV]	[GeV]	[GeV]
Ω_c	$\frac{1}{2}^+$	2.783(13)	2.673(17)	2.629(22)	2.681(48)	2.695(2)
Ω_{cc}	$\frac{1}{2}^+$	3.747(10)	3.704(21)	3.654(18)	3.679(62)	—
Ω	$\frac{3}{2}^+$	1.790(17)	1.772(7) [14]	1.672(18)	—	1.673(29)
Ω_c^*	$\frac{3}{2}^+$	2.837(18)	2.738(17)	2.709(26)	2.764(49)	2.766(2)
Ω_{cc}^*	$\frac{3}{2}^+$	3.819(10)	3.779(23)	3.724(21)	3.765(65)	—
Ω_{ccc}	$\frac{3}{2}^+$	4.769(6)	4.789(27)	4.733(18)	4.761(79)	—

$$m_{\Omega_c^*} - m_{\Omega_c} = 54 \pm 17\,\mathrm{MeV}$$ This work

$$m_{\Omega_c^*} - m_{\Omega_c} = 70.7 \pm 0.9^{+0.1}_{-0.9}\,\mathrm{MeV}$$ Belle Collab. PLB 672 (2009)

RESULTS

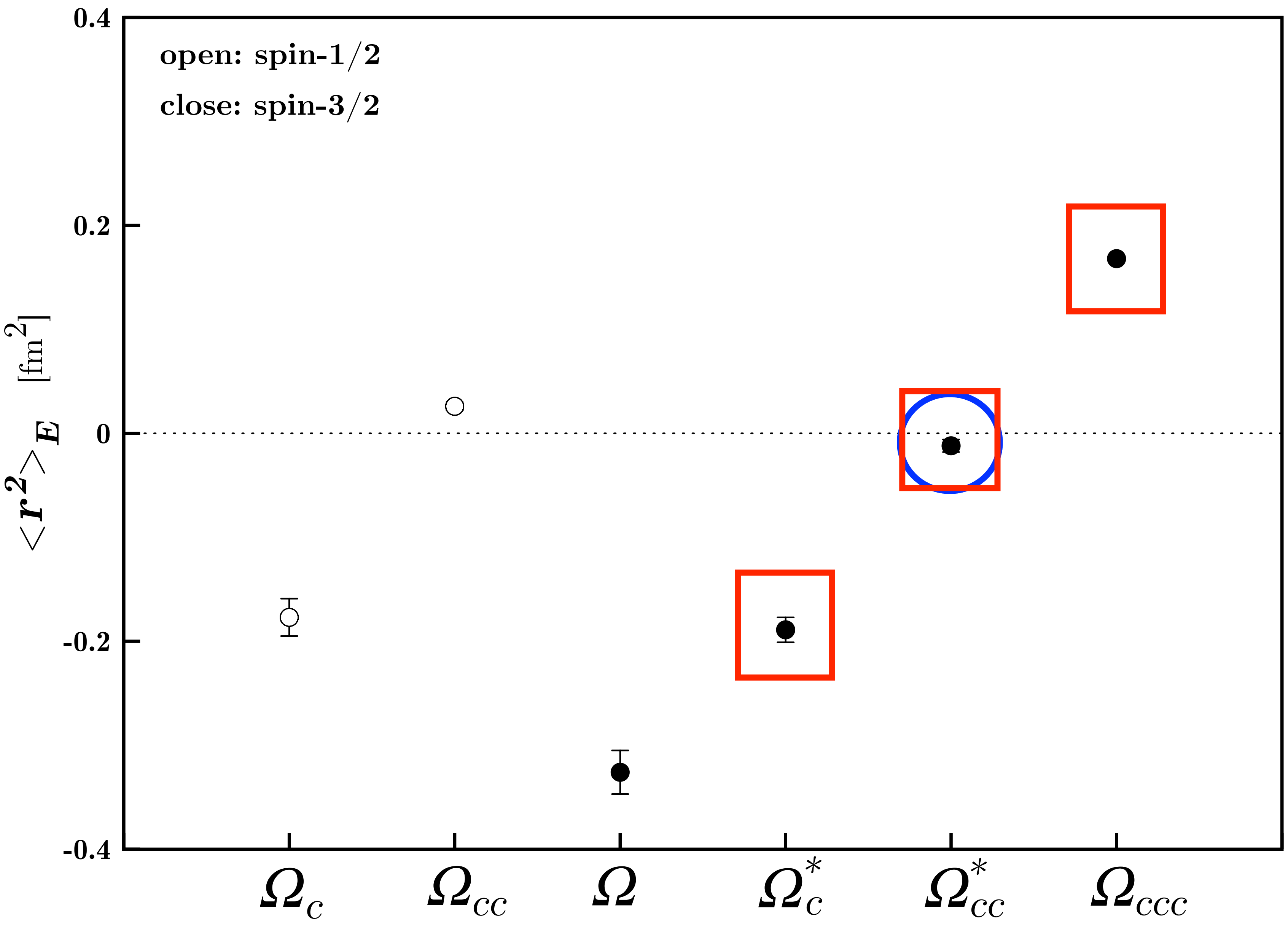
$\langle r_E^2 \rangle_B^q / \langle r_E^2 \rangle_{B^*}^q$



- Quark charge radii increase in doubly charmed spin-$3/2$

RESULTS

Electric charge radii
(QM relation)



$$\langle \mathcal{O} \rangle = N_s e_s \langle \mathcal{O}_s \rangle + N_c e_c \langle \mathcal{O}_c \rangle$$

$$\langle r_E^2 \rangle^s_{\Omega_c^*} = \langle r_E^2 \rangle^s_{\Omega_{cc}^*} = R_s^2$$

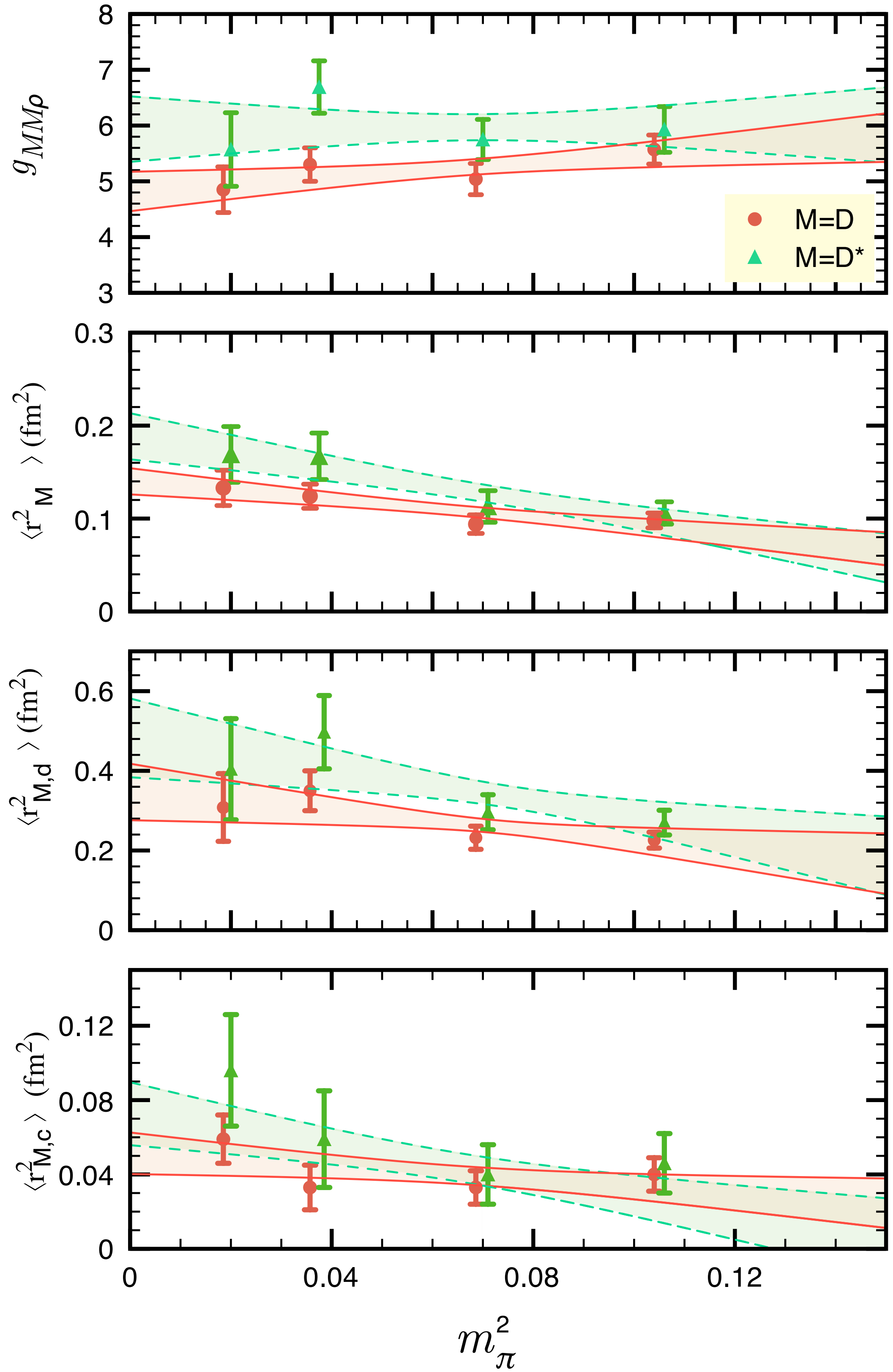
$$\langle r_E^2 \rangle^c_{\Omega_c^*} = \langle r_E^2 \rangle^c_{\Omega_{cc}^*} = \langle r_E^2 \rangle^c_{\Omega_{ccc}} = R_c^2$$

$$\left(\langle r_E^2 \rangle_{\Omega_c^*} + \langle r_E^2 \rangle_{\Omega_{ccc}} \right) / 2 = \langle r_E^2 \rangle_{\Omega_{cc}^*}$$

Direct	Relation
-0.012(6)	-0.011(8) fm^2

RESULTS

κ_{ud} (137-)	70	54	27	00	
stat.	70	50	50	45	samples



m_π ~ 300 410 570 700 MeV

D and D electric charge radius extrapolations*

$\kappa_{val}^{u,d}$	$g_{DD\rho}$	$\langle r^2_D \rangle$ (fm^2)	$\langle r^2_{D,d} \rangle$ (fm^2)	$\langle r^2_{D,c} \rangle$ (fm^2)
0.13700	5.57(27)	0.098(8)	0.226(20)	0.040(9)
0.13727	5.03(28)	0.094(10)	0.232(29)	0.033(9)
0.13754	5.30(30)	0.124(13)	0.350(50)	0.033(12)
0.13770	4.85(41)	0.133(19)	0.308(85)	0.059(13)
Lin. Fit	4.84(34)	0.138(13)	0.342(67)	0.051(11)
Quad. Fit	4.90(56)	0.152(26)	0.320(118)	0.074(16)

$\kappa_{val}^{u,d}$	$g_{D^*D^*\rho}$	$\langle r^2_{D^*} \rangle$ (fm^2)	$\langle r^2_{D^*,d} \rangle$ (fm^2)	$\langle r^2_{D^*,c} \rangle$ (fm^2)
0.13700	5.93(41)	0.106(12)	0.270(31)	0.035(13)
0.13727	5.75(36)	0.113(17)	0.296(44)	0.036(14)
0.13754	6.69(47)	0.167(25)	0.497(92)	0.044(21)
0.13770	5.57(66)	0.169(30)	0.404(127)	0.075(26)
Lin. Fit	5.94(56)	0.185(24)	0.475(94)	0.071(16)
Quad. Fit	5.42(94)	0.192(43)	0.406(156)	0.096(29)

$<r^2>_D = 0.138$ fm^2 , $<r^2>_{D,d} = 0.342$ fm^2 , $<r^2>_{D,c} = 0.051$ fm^2

$<r^2>_{D^*} = 0.185$ fm^2 , $<r^2>_{D^*,d} = 0.475$ fm^2 , $<r^2>_{D^*,c} = 0.071$ fm^2

$<r^2>_\pi = 0.452$ fm^2

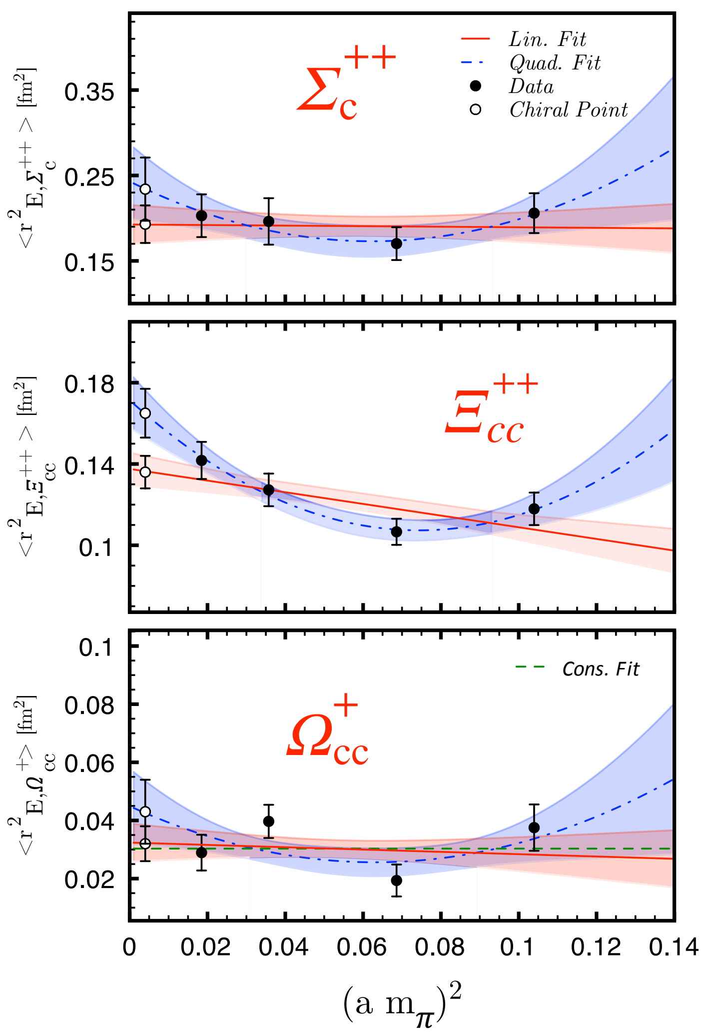
kuc, G. Erkol, M. Oka, A. Ozpineci, T. T. Takahashi, Phys.Lett. B719 (2013) 103-109

κ_{ud}(137-)	70	54	27	00
stat. (Σ_c, Ξ_{cc})	170	150	100	100
stat. (Ω_c, Ω_{cc})	130	100	100	100

RESULTS

Charmed, strange baryon extrapolations

$<r^2_E>$

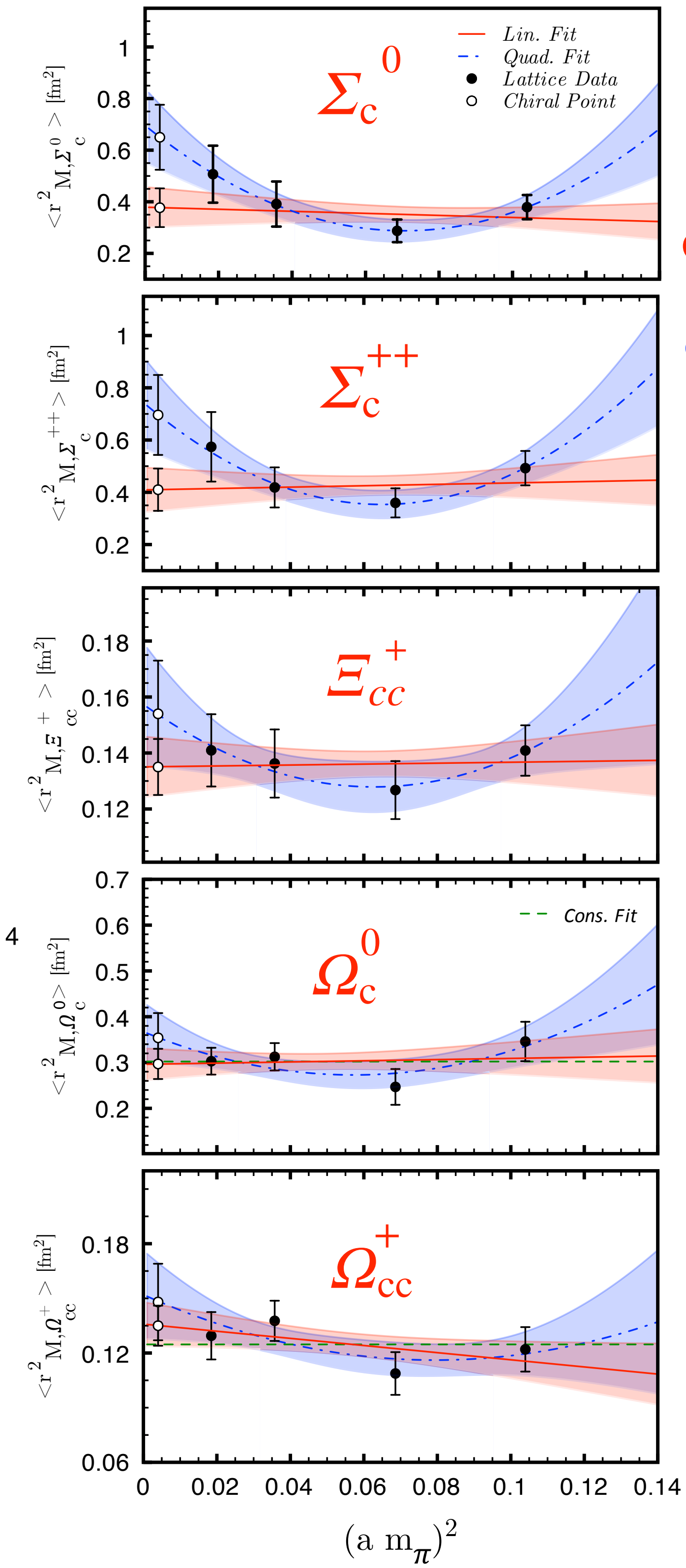


m_π ~ 300 410 570 700MeV

Fit Form	Quad. Fit
uuc $\langle r^2_{E,\Sigma_c^{++}} \rangle$	0.234(37)
ucc $\langle r^2_{E,\Xi_{cc}^{++}} \rangle$	0.165(12)
scc $\langle r^2_{E,\Omega_{cc}^{+}} \rangle$	0.043(11)
dcc $<r^2_{E,\Xi_{cc}^{+}}> = 0.042(9)$	

*$<r^2_{E,p}> = 0.770\ fm^2$

$<r^2_M>$

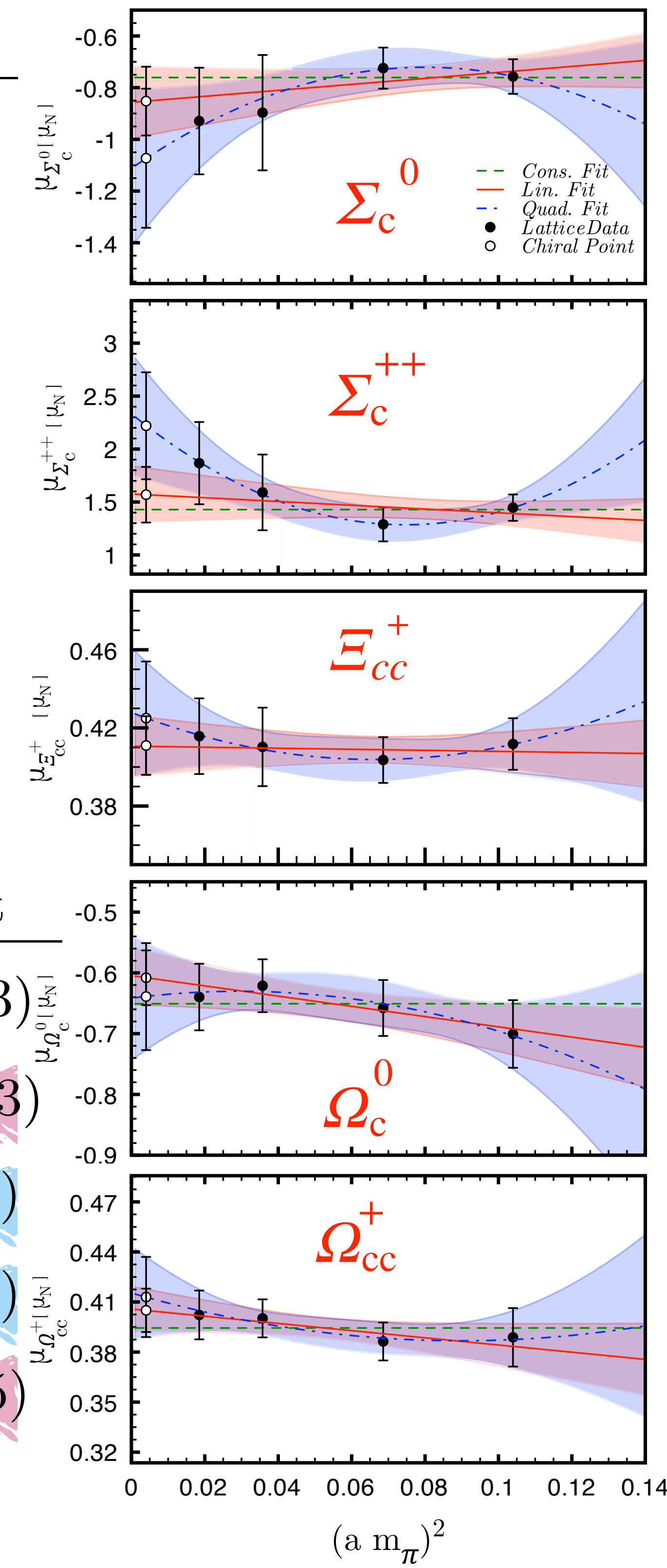


Fit Form	Quad. Fit
uuc $\langle r^2_{M,\Sigma_c^{++}} \rangle$	0.696(153)
ddc $\langle r^2_{M,\Sigma_c^{0}} \rangle$	0.650(126)
dcc $\langle r^2_{M,\Xi_{cc}^{+}} \rangle$	0.154(19)
scc $\langle r^2_{M,\Omega_{cc}^{+}} \rangle$	0.148(21)
ssc $\langle r^2_{M,\Omega_c^{0}} \rangle$	0.354(54)

*$<r^2_{M,p}> = 0.604\ fm^2$

$<r^2_{M,n}> = 0.862\ fm^2$

μ



Fit Form	Lin. Fit
uuc $\mu_{\Sigma_c^{++}}$	1.569(253)
ddc $\mu_{\Sigma_c^{0}}$	-0.852(133)
dcc $\mu_{\Xi_{cc}^{+}}$	0.411(15)
scc $\mu_{\Omega_{cc}^{+}}$	0.405(13)
ssc $\mu_{\Omega_c^{0}}$	-0.608(45)

*$\mu_p = 2.793\ \mu_N$

$\mu_n = -1.913\ \mu_N$

* PDG values

kuc, G. Erkol, B. Isildak, M. Oka, T.T. Takahashi, JHEP05(2014)125