MAGNETIC MOMENT OF CHARMED BARYON

Emi KOU (LAL)
for charm g-2 collaboration
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France-Ukraine workshop, 26-28 October 2018 at LAL

MAGNETIC MOMENT OF ELEMENTARY PARTICLES

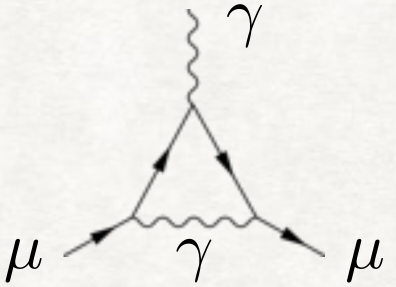
LEPTON, PROTON AND QUARK

- The spin 1/2 particle such as leptons (electron, muon…) have a magnetic moment of the form

$g_{electron}=2.00231930436182 \pm (2.6\times10^{-13})$

$$\mu = g\frac{|e|Q}{2m}$$

where Q and m are the charge and mass of the particle.



- The g factor is 2 at the classic level while it is slightly modified by the quantum effect. This correction is called anomalous magnetic moment and defined as a=g-2/2.

- There is a longstanding question of muon anomalous magnetic moment: the experiment is 3.6 sigma away from experiment (hint of new physics?)

$a_\mu^{exp.}=116592091(54)(33) \times 10^{-11}$.

$a_\mu^{the.}=116591803(1)(42)(26) \times 10^{-11}$

3.6σ effect!

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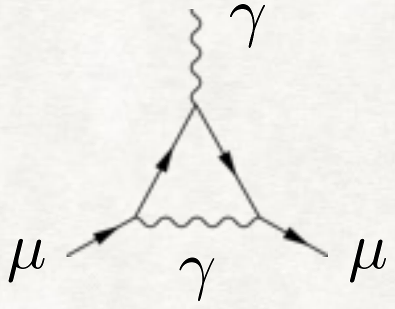
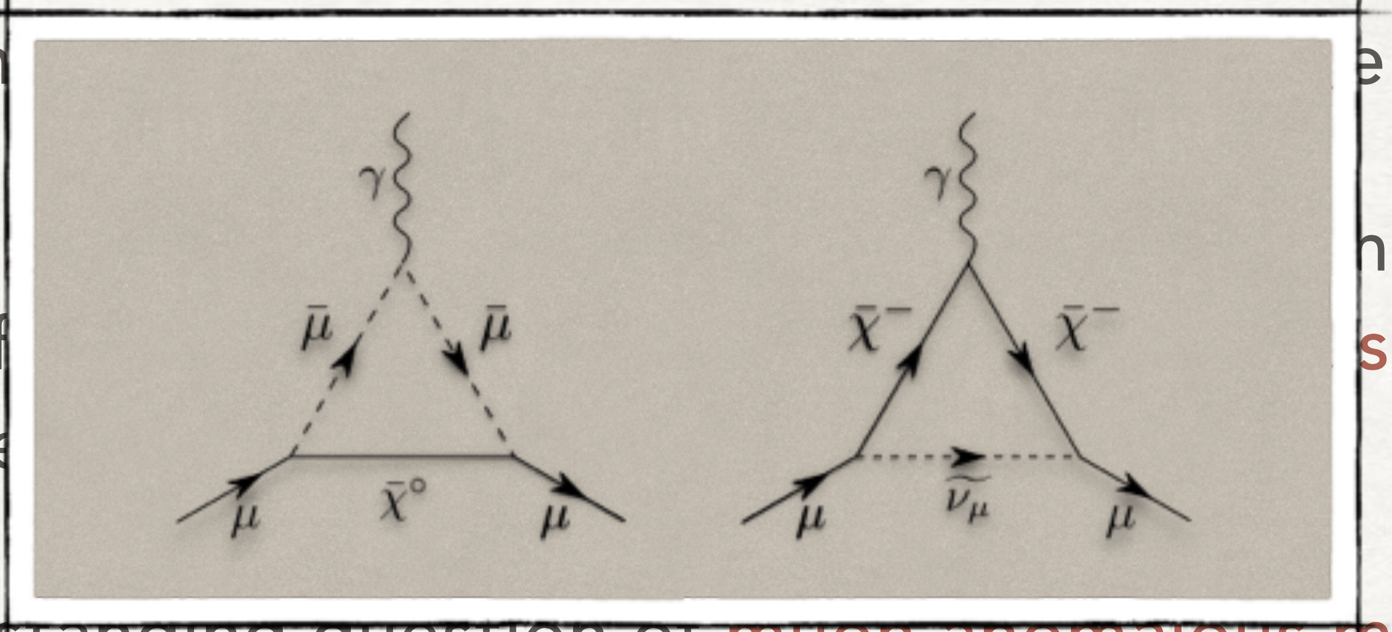


where Q and m

e.



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3.6σ effect!

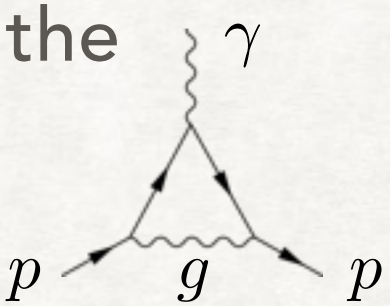
MAGNETIC MOMENT OF ELEMENTARY PARTICLES

LEPTON, PROTON AND QUARK

- The proton magnetic moment is also measured very precisely. But how do we interpret this result?

g_{proton}=5.585694702(17)

- If we consider the proton to be a fundamental particle, the magnetic moment can be written as



$$\mu = g_P \frac{|e|}{2m_P}$$

- g>>2 can be understood by a large strong interaction effect?
- The proton is not a fundamental particle. So this may not be the solution…

μ_M=|e|/2M_P is called the nuclear magneton

PROTON MAGNETIC MOMENT IN QUARK MODEL

- In quark model, magnetic moment of proton is a sum of the magnetic moment of the constituent quark (up-up-down) with fully symmetric spin configuration.

$$\mathbf{M} = \sum_q \mathbf{M}_q \qquad \mathbf{M}_q = \mu \frac{e_q}{e} \sigma_q$$

μ=|e|/2M$_q$

where q is the constituent quark and **σ** is the spin operator

$$\begin{aligned}\Psi^{\text{proton}}_{\text{spin+flavor}} = \big[& 2\,u\uparrow u\uparrow d\downarrow \; - u\downarrow u\uparrow d\uparrow \; - u\uparrow u\downarrow d\uparrow \\ & + 2\,u\uparrow d\downarrow u\uparrow \; - u\downarrow d\uparrow u\uparrow \; - u\uparrow d\uparrow u\downarrow \\ & + 2\,d\downarrow u\uparrow u\uparrow \; - d\uparrow u\downarrow u\uparrow \; - d\uparrow u\uparrow u\downarrow \big]/\sqrt{18}\,,\end{aligned}$$

- Then the magnetic moment of proton is computed as

$$\begin{aligned}\mu_p &= \langle \phi_P | \mathbf{M}_u + \mathbf{M}_u + \mathbf{M}_d | \phi_P \rangle \\ &= \frac{1}{18}(4 \times 3(2e_u - e_d) + 6 \times e_d)\mu \\ &= \mu = \frac{|e|}{2m_q}\end{aligned}$$

Similar to the previous result but now, the denominator is not proton mass but quark mass!

Using the constituent quark mass m$_q$=1/3 m$_P$, we find g$_P$=1.86!

PROTON MAGNETIC MOMENT IN QUARK MODEL

- g_P is now close to 2 but this result depends on the quark mass.
- In addition, since it is known that the large portion of the proton spin is actually carried by the gluons, gluon contributions to the magnetic moment has to be considered.
- On the other hand, the quark model can predict the relation of proton and neutron/Lambda magnetic moment without quark mass dependence

$$\mu_N = -\frac{2}{3}\mu_p, \qquad \mu_\Lambda = -\frac{1}{3}\mu_p$$

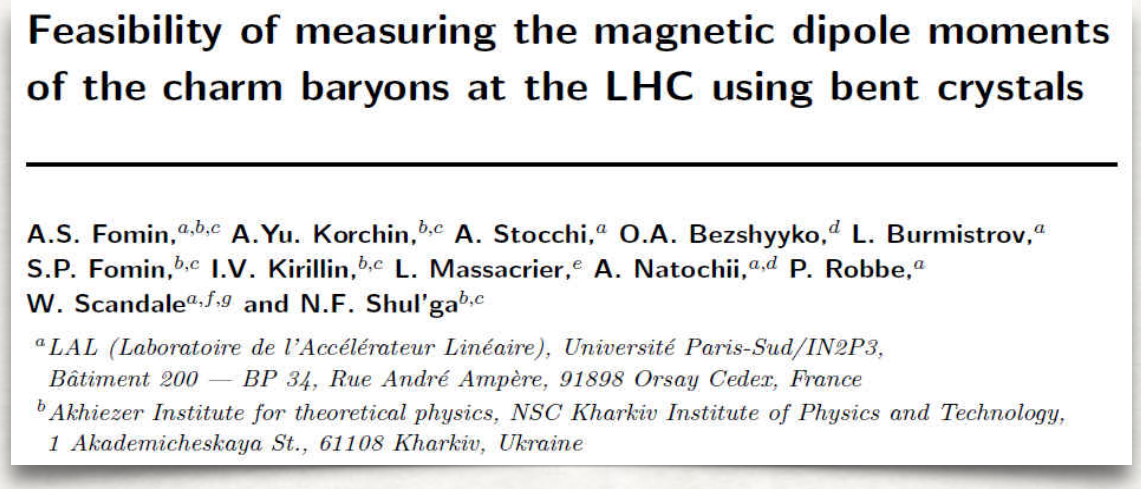
  which is satisfied well by the experiment.

$g_{proton} = 5.585694702(17)$
$g_{neutron} = -3.82608545(90)$
$g_{lambda} = -1.226(8)$

- In any case, the proton magnetic moment is an input for various theoretical computations, it is important to measure it very precisely.

CHARMED BARYON MAGNETIC MOMENT

- An experimental proposal to measure charmed baryon magnetic moment by using precession induced by the VERY strong magnetic field generated by bent crystal (1000T).



Feasibility of measuring the magnetic dipole moments of the charm baryons at the LHC using bent crystals

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- It will be the first measurement of the magnetic moment of the charmed baryon.

- Different from light baryon, spin is known to be carried mostly by the heavy quark (charm quark) —> direct connection to the charm quark (anomalous) magnetic moment.

- LHCb are producing many new results on charmed baryon (e.g. discovery of doubly charged charmed baryon!) and charmed baryon spectroscopy is becoming very interesting.

BARYON SPECTROSCOPY
LIGHT BARYONS

- Let us start with the light baryons. SU(3) symmetry for 3 quark states

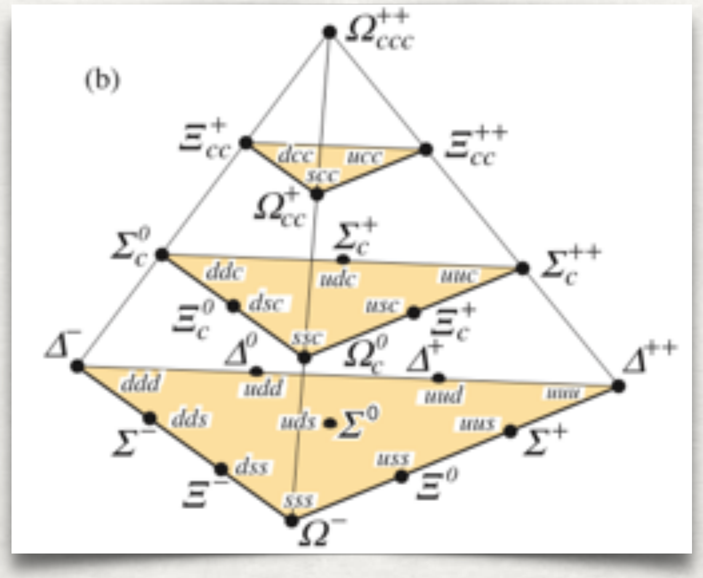
$$3 \otimes 3 \otimes 3 = 10_s \oplus 8_s \oplus 8_a \oplus 1_a$$

where s and a corresponds to symmetric and anti-symmetric of flavour, e.g.

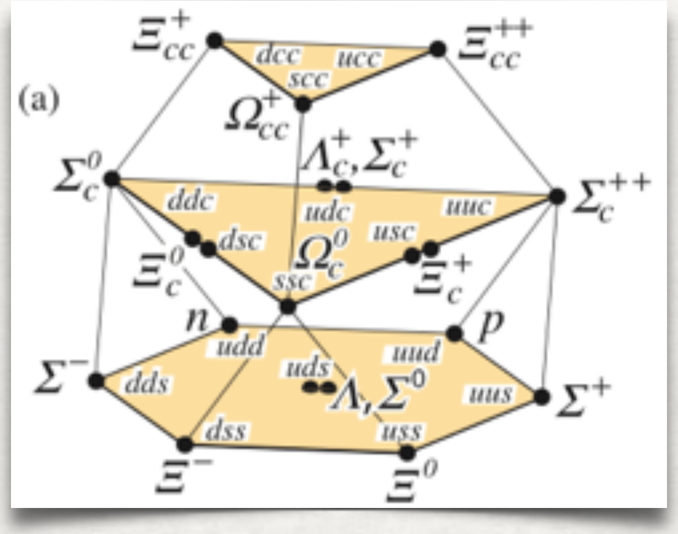
$$Symmetric: \qquad uuu, ddd, \frac{1}{\sqrt{2}}\left[ud + du\right]u, \frac{1}{\sqrt{2}}\left[us + su\right]u \cdots$$

$$Anti - Symmetric: \qquad \frac{1}{\sqrt{2}}\left[ud - du\right]u, \frac{1}{\sqrt{2}}\left[us - su\right]u \cdots$$

- This results in 10 spin 3/2 baryons and 8 spin 1/2 baryons



J=3/2
totally-symmetric
decuplet



J=1/2
mixed-symmetry
octet

BARYON SPECTROSCOPY

LIGHT BARYONS

- Let us start with the light baryons. SU(3) symmetry for 3 quark states

$$3 \otimes 3 \otimes 3 = 10_s \oplus 8_s \oplus 8_a \oplus 1_a$$

whe

e.g.

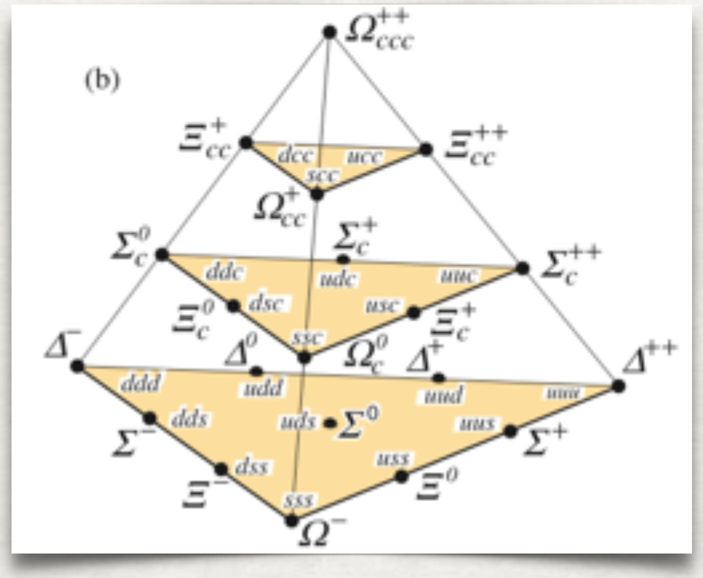
NOTE ON OCTET STATES:

8s and 8a states are mixed.

The qqq′ sates (like proton=uud), multiplying with the spin symmetry, they turn out to have exactly the same wave function.

For Λ and Σ^0 (uds states), the wave function is different: Λ is anti-symmetric and Σ^0 is symmetric.

- This



J=3/2
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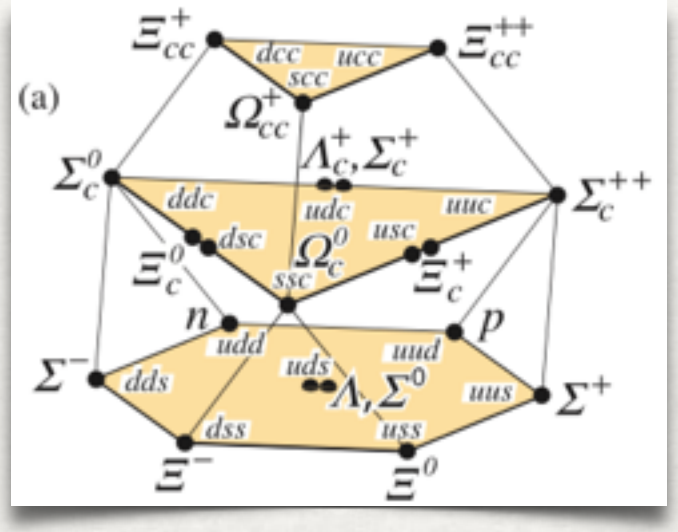


J=1/2
mixed-symmetry
octet

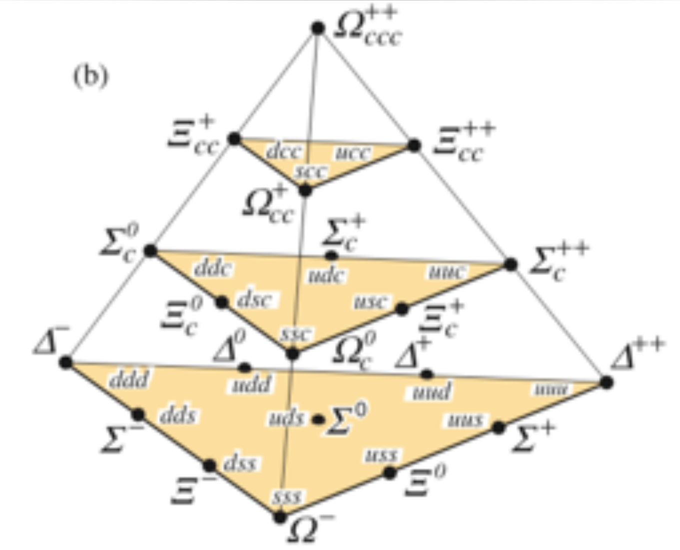
BARYON SPECTROSCOPY

CHARMED BARYONS

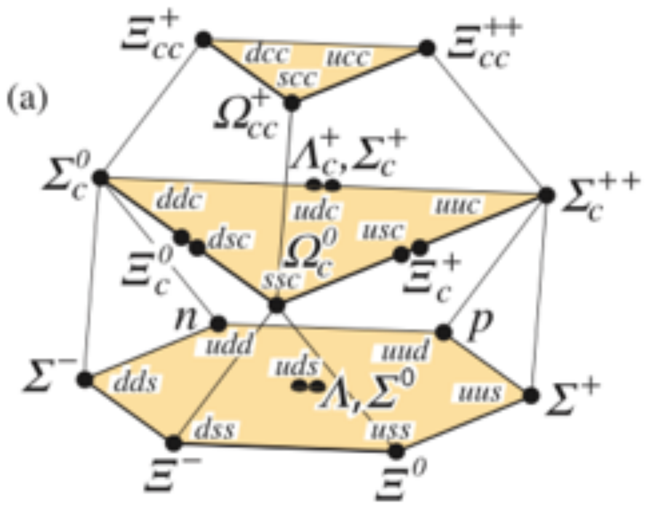
- Let us now include charm quark. SU(4) symmetry for 3 quark states

$$4 \otimes 4 \otimes 4 = 20_s \oplus 20_s \oplus 20_a \oplus 4_a$$

- Considering charmed baryons, this results in 6 spin 3/2 baryons and 9 spin 1/2 baryons.
- Different from the light baryons, not only **Λ**c (udc) and **Σ**c^0 (udc), but also Ξc$^+$ (udc) and Ξc^0 (dsc) are no longer degenerated.
- The new names are NOT given to these particles but to distinguish them, it is sometimes called ($\Xi_{c1,}$ Ξ_{c2}) or ($\Xi_{c,}$ Ξ_{c}').



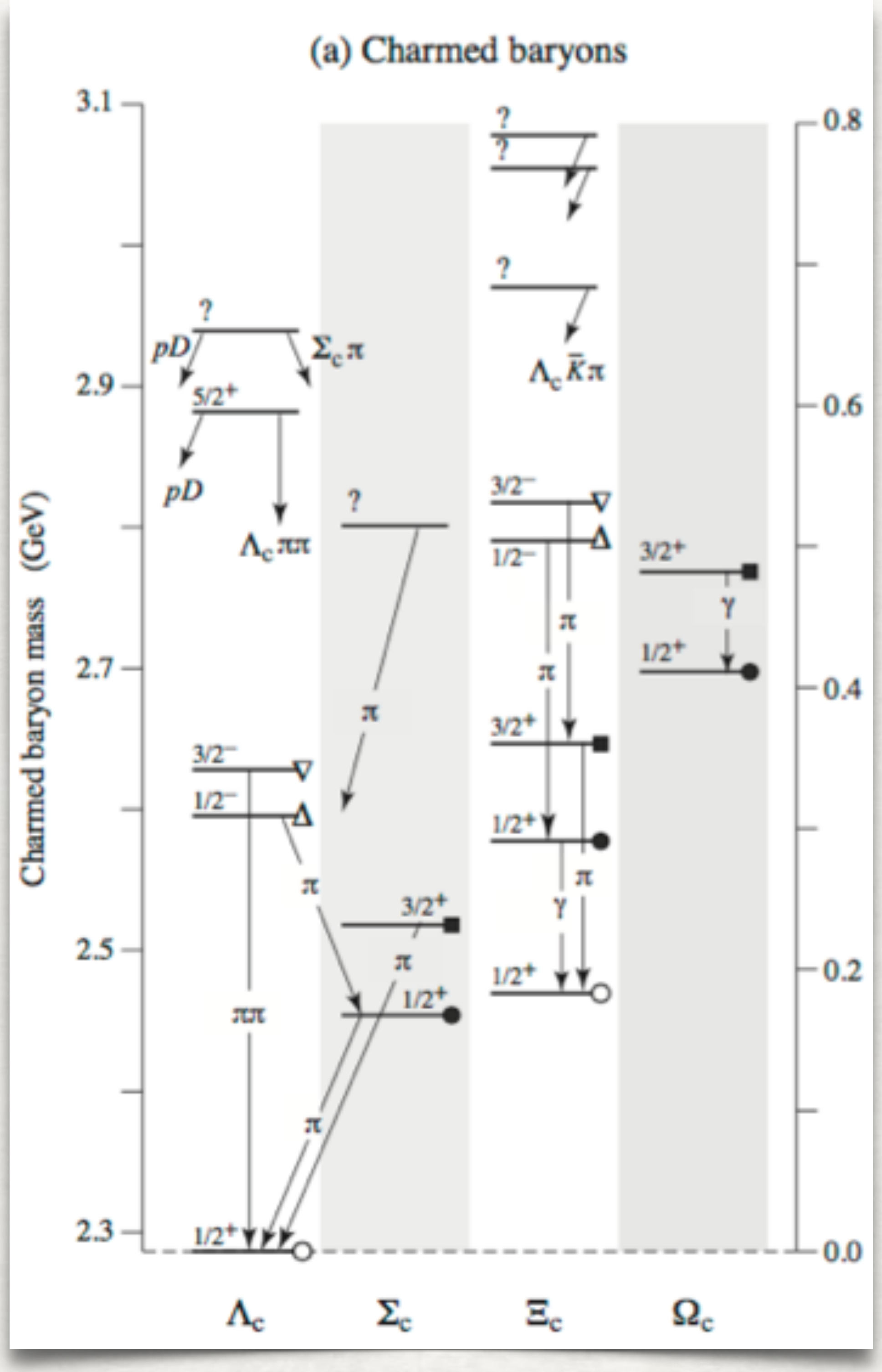
J=3/2
totally-symmetric
decuplet



J=1/2
mixed-symmetry
octet

QUESTION OF TWO ΞC STATES

Ξ_{C1}^{+}, Ξ_{C2}^{+}???



At heavy quark limit :

○: the anti-symmetric 1/2 (Λc,Ξ_{c1}^{+},Ξ_{c1}^{0})

●: the symmetric 1/2 (Σc^{0},Ξ_{c2}^{+},Ξ_{c2}^{0})

■: the symmetric 3/2 (Σc^{0*},Ξ_{c}^{+*},Ξ_{c}^{0*})

But this has never been confirmed…
The observed state can be a mixture of Ξ_{c1} and Ξ_{c2}. How can we distinguish?

We show below that

magnetic moment, which measures directly the quark spin-configuration, is the most powerful tool to distinguish different charmed baryon states!

Λc MAGNETIC MOMENT

- We compute the Λc (udc, spin anti-symmetric state) magnetic moment in the quark model. The result turns out that Λc magnetic moment is equal to the charm quark magnetic moment.

$$\begin{aligned}\mu_{\Lambda_c} &= \langle \phi_{\Lambda_c} | \mathbf{M}_u + \mathbf{M}_d + \mathbf{M}_c | \phi_{\Lambda_c} \rangle \\ &= \mu_c\end{aligned}$$

- Using the definition

$$\mu_{\Lambda_c} \left(= \frac{g_{\Lambda_c}}{2} \frac{|e|Q_c}{2m_P} \right) = \mu_c \left(= \frac{g_c}{2} \frac{|e|Q_c}{2m_c} \right)$$

the measurement of $g_{\Lambda c}/2$ can be translated to the charm quark magnetic moment $g_c/2$

$$\frac{g_{\Lambda_c}}{2} = \frac{m_{\Lambda_c}}{m_c} \frac{g_c}{2}$$

- If the measured $g_{\Lambda c}/2$ is far from $m_{\Lambda c}/m_c$~1.3-1.9 (m_c=1.2-1.8GeV) then, that is an indication of large anomalous magnetic moment of charm quark.
- However, the quantitative statement is model-dependent.

OTHER CHARMED BARYON MAGNETIC MOMENT

- Spin anti-symmetric state

$$\mu_{\Xi_c^{0,+}} = \mu_c$$

~0.39N.M.

which is the same as Λc magnetic moment

- Spin symmetric state

$$\mu_{\Sigma_c^+} = -\frac{1}{3}\mu_c + \frac{2}{3}\mu_u + \frac{2}{3}\mu_d, \quad \mu_{\Sigma_c^0} = -\frac{1}{3}\mu_c + \frac{4}{3}\mu_d$$

~0.54N.M.

~−1.46N.M.

@SU(3) limit

$\mu_{\Sigma c}=\mu_{\Xi c'}$

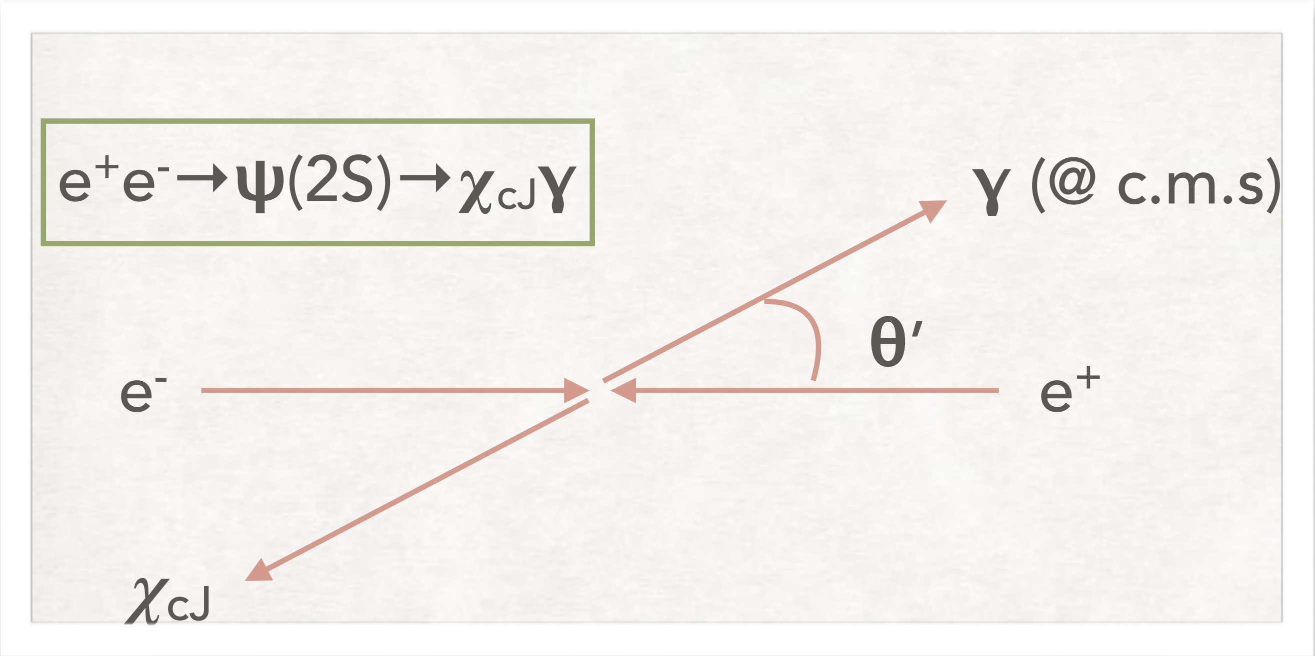
$$\mu_{\Xi_c^{\prime +}} = -\frac{1}{3}\mu_c + \frac{2}{3}\mu_u + \frac{2}{3}\mu_s, \quad \mu_{\Xi_c^{\prime 0}} = -\frac{1}{3}\mu_c + \frac{2}{3}\mu_d + \frac{2}{3}\mu_s$$

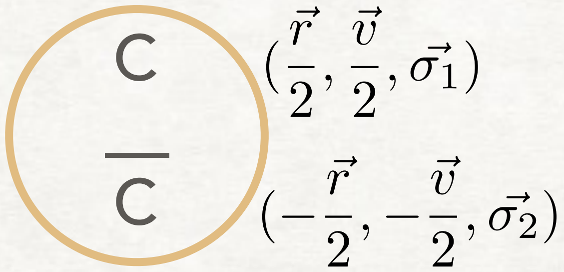
If heavy quark limit is correct and Ξc (Ξc′) state is purely anti-symmetric (symmetric) state, we would observe

$\mu_{\Lambda c}=\mu_{\Xi c}{}^{0} \gg \mu_{\Xi c}{}^{0\prime}$

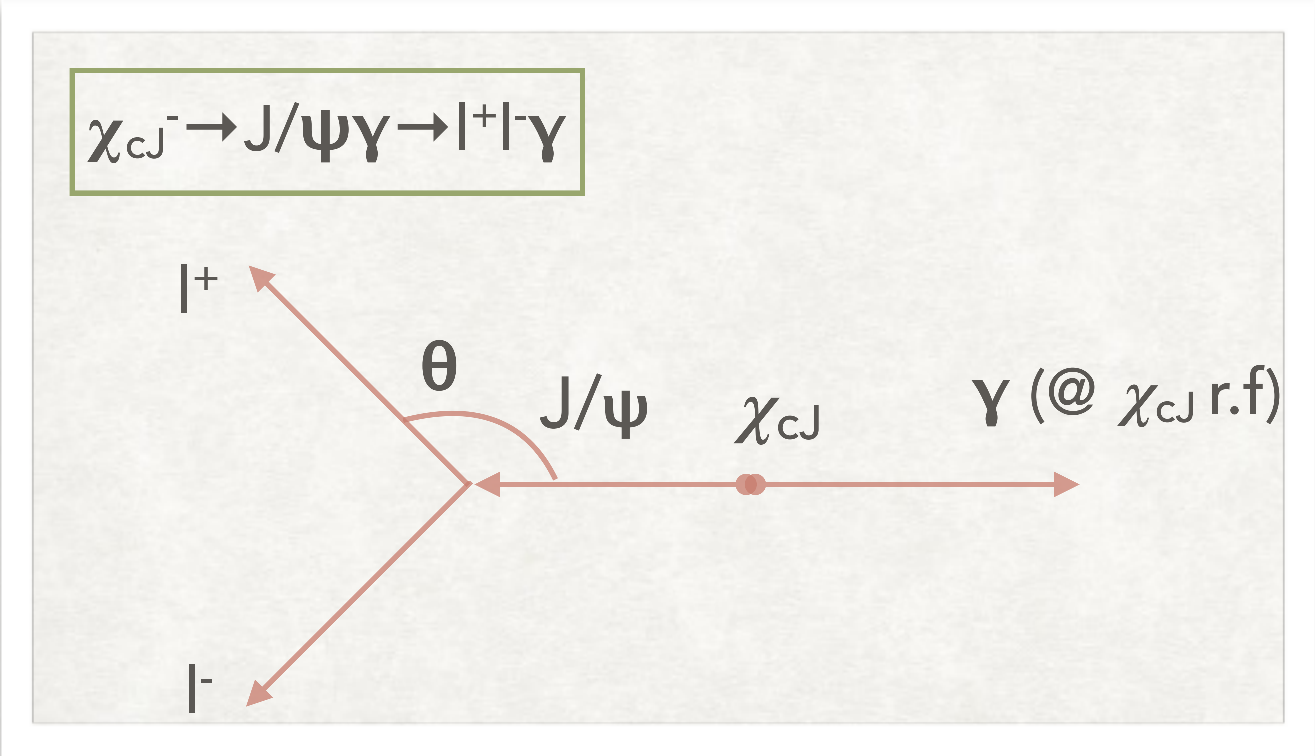
PREDICTING Λ_C MAGNETIC MOMENT WITH BESIII RESULT

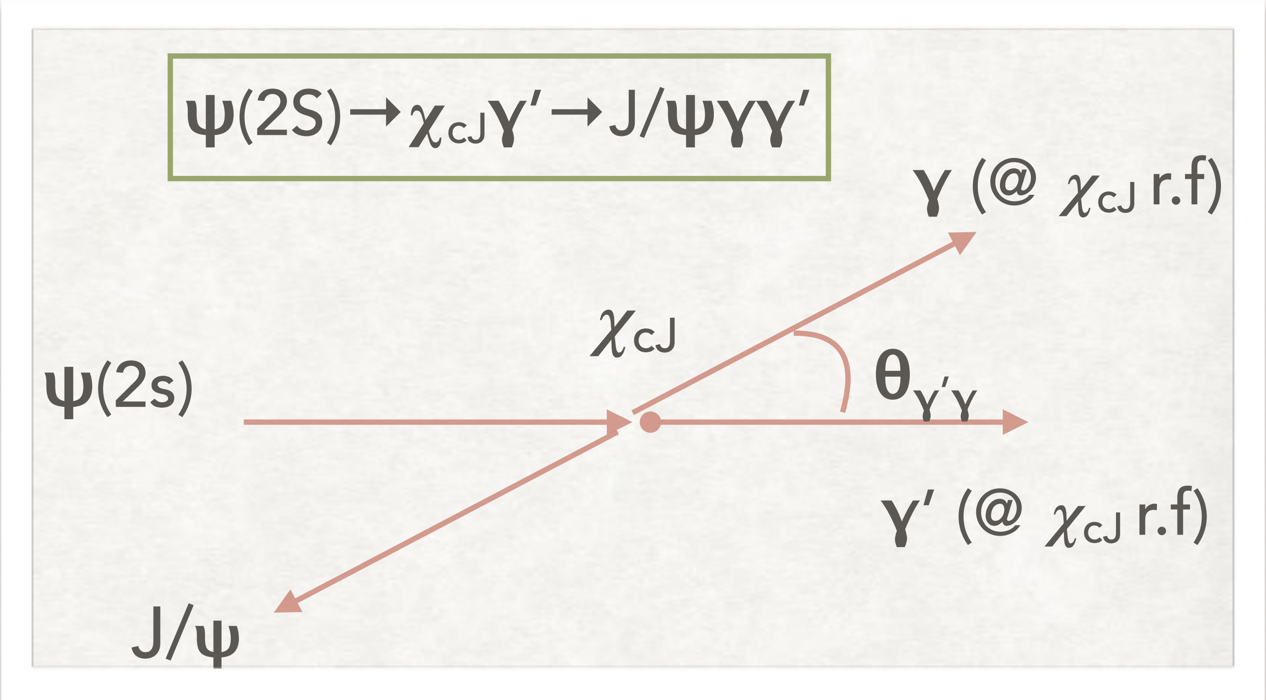
Karl et al PR D13 '76





The charm quark magnetic moment can be determined by the charmonium radiative decays





5 angles to disentangle different contributions

$(\theta, \phi, \theta', \phi', \theta_{\gamma'\gamma})$

which is in BESIII/CLEO paper

$(\theta_3, \phi_3, \theta_1, \phi_1, \theta_2)$

PREDICTING Λ_C MAGNETIC MOMENT WITH BESIII RESULT

arXiv: 1701.01197 (also see CLEO 0910.0046)

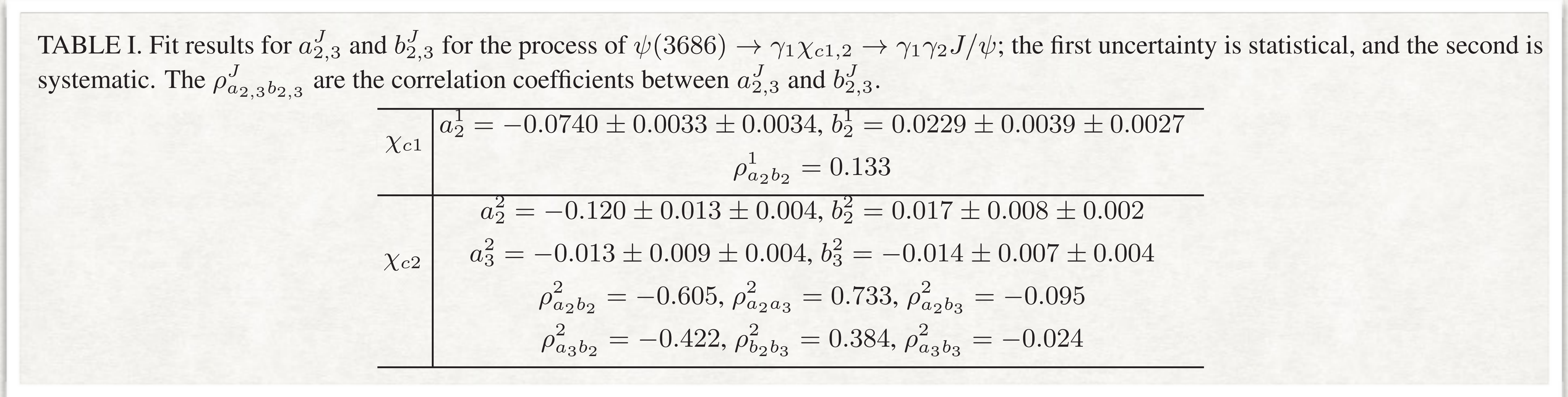


TABLE I. Fit results for $a^J_{2,3}$ and $b^J_{2,3}$ for the process of $\psi(3686) \to \gamma_1\chi_{c1,2} \to \gamma_1\gamma_2 J/\psi$; the first uncertainty is statistical, and the second is systematic. The $\rho^J_{a_{2,3}b_{2,3}}$ are the correlation coefficients between $a^J_{2,3}$ and $b^J_{2,3}$.

χ_{c1}	$a^1_2 = -0.0740 \pm 0.0033 \pm 0.0034,\ b^1_2 = 0.0229 \pm 0.0039 \pm 0.0027$ $\rho^1_{a_2b_2} = 0.133$
χ_{c2}	$a^2_2 = -0.120 \pm 0.013 \pm 0.004,\ b^2_2 = 0.017 \pm 0.008 \pm 0.002$ $a^2_3 = -0.013 \pm 0.009 \pm 0.004,\ b^2_3 = -0.014 \pm 0.007 \pm 0.004$ $\rho^2_{a_2b_2} = -0.605,\ \rho^2_{a_2a_3} = 0.733,\ \rho^2_{a_2b_3} = -0.095$ $\rho^2_{a_3b_2} = -0.422,\ \rho^2_{b_2b_3} = 0.384,\ \rho^2_{a_3b_3} = -0.024$

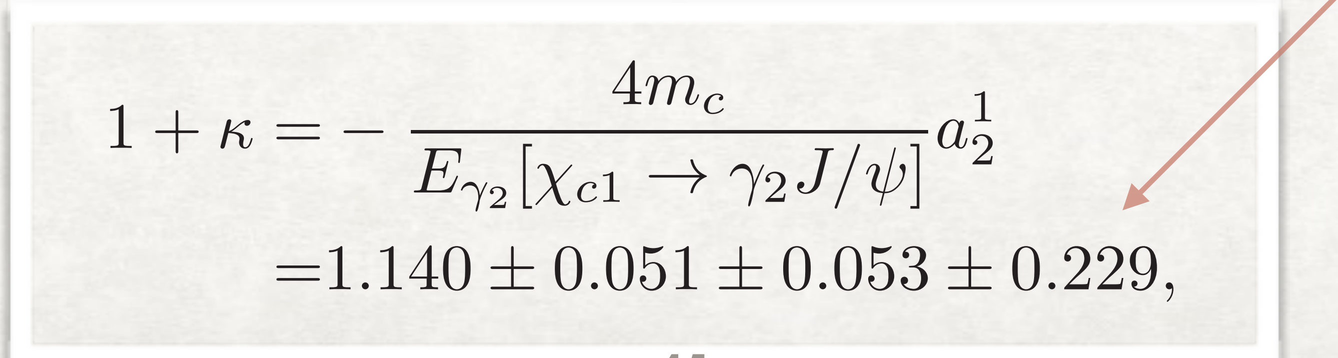
theory

$b^1_2/b^2_2 = 1.35 \pm 0.72,$ ←1.00±0.015

$a^1_2/a^2_2 = 0.617 \pm 0.083.$ ←0.676±0.071

Extracting anomalous magnetic moment

error from charm mass
mc=1.5±0.3 GeV



$$1 + \kappa = -\frac{4m_c}{E_{\gamma_2}[\chi_{c1} \to \gamma_2 J/\psi]} a^1_2$$
$$= 1.140 \pm 0.051 \pm 0.053 \pm 0.229,$$

PREDICTING Λc MAGNETIC MOMENT

- Using the BES III data, we can predict magnetic moment of Λc

$$\boxed{\frac{g_{\Lambda_c}}{2} = 1.75 \pm 0.13 \longrightarrow \mu_{\Lambda_c} = 0.48 \pm 0.04 (n.m.)}$$

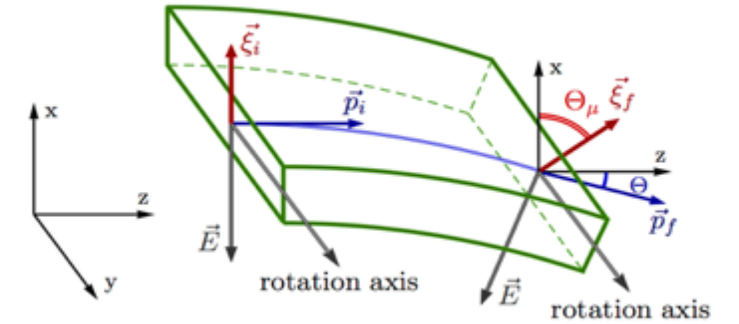
without charm mass ambiguity.

This value should be compared with theoretical predictions (where charm quark mass is often obtained from other observable)

$$\frac{\mu(\Lambda_c^+)}{\mu_N} = 0.37\text{–}0.42,$$

which implies a slightly higher charm anomalous magnetic moment (g_c>2?).

Towards μ$_{\Lambda c}$ measurement



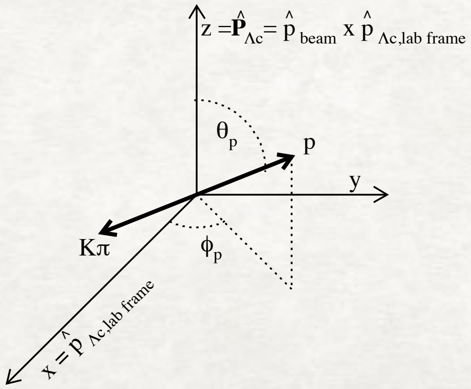
- The magnetic moment is determined by measuring the Λ$_c$ polarisation passing through the bent crystal.
- Thus, Λ$_c$ polarisation has to be measured.
- The angular distribution of the Λ$_c$ decay carries information of polarisation however, it can not be separated so-called asymmetry parameter **α**.
- We need to measure this parameter at LHCb in advance.

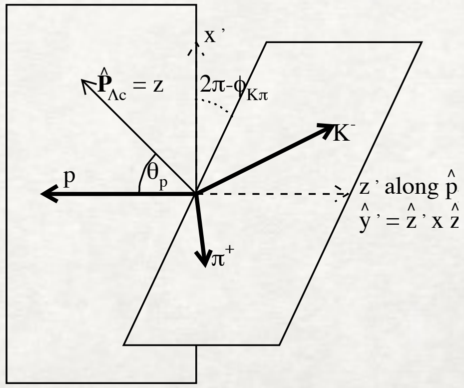
$$\frac{1}{N}\frac{dN}{d\cos\vartheta_k} = \frac{1}{2}\left(1+\alpha\,\boxed{\xi_k}\cos\vartheta_k\right)\Big|_{k=x,y,z}$$

weak parameter polarisation

INTERNSHIP PROJECTS
MAKSYM LIUL

- Theoretical computation of the Λc→Kpπ decays





CONCLUSIONS

- Charm quark magnetic moment has never been measured directly.
- A new idea to measure the magnetic moment of charmed baryon $\mu_{\Lambda c}$, using the bent-crystal is proposed (a hight precision expected). $\mu_{\Lambda c}$ can be translated to the magnetic moment of charm quark, $\mu_{c.}$
- We showed that the measurement of various charmed baryon, such as Ξ_c can provide important information on the charmed baryon spectroscopy.
- Charmonium radiative decay can indirectly provide the charm quark magnetic moment. Using BESIII result, we made an estimate on $\mu_{\Lambda c}$. We found that the obtained value of $\mu_{\Lambda c}$ is slightly higher than the theory predictions.
- We are currently working on LHCb measurement of polarisation and weak parameter of Λ_c, which is a crucial factor for $\mu_{\Lambda c}$ determination.