MAGNETIC DIPOLE MOMENTS OF HEAVY BARYONS AND QUARKS

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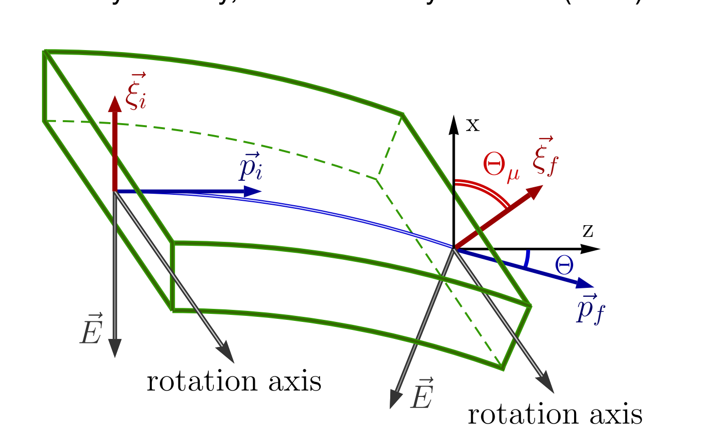
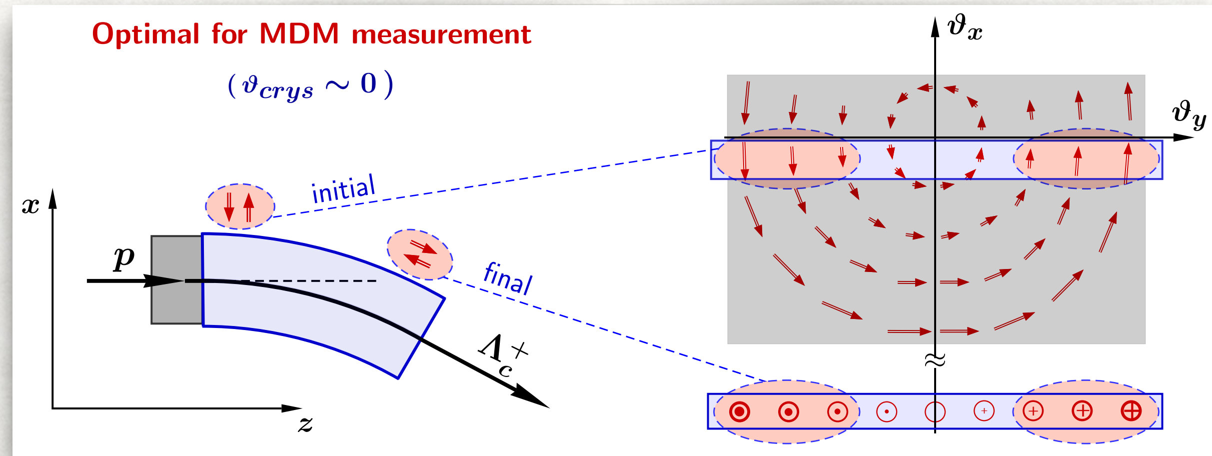
Introduction

A new experiment is proposed to measure the MDM of charmed baryon.
Short life time is compensated by the strong magnetic field created by bent crystal.

Fomine et al, JHEP 08 ('17) 120
Aiola Phys.Rev.D 103 (2021) 7

V.G. Baryshevsky, Sov. Tech. Phys. Lett. 5 (1979) 73.





The difference between the initial and final polarisations of c baryon gives information of the g-factor

V.L. Lyuboshits, Sov. J. Nucl. Phys. 31 (1980) 509 [inSPIRE].

$$\Theta_\mu \equiv \angle(\xi_i \xi_f) = (1 + \gamma a)\,\Theta \qquad a = \frac{g-2}{2}, \qquad \Theta = \frac{L}{R}$$

A.S. Fomin et al. Eur. Phys. J. C ('20) 80:358

Sensitivity to the Λ_c MDM is estimated to be $\Delta g \approx 0.35(0.14)$ for LHCB (IR3) after 10 years of experiment, assuming the initial Λ_c polarisation to be 0.26 (0.22).

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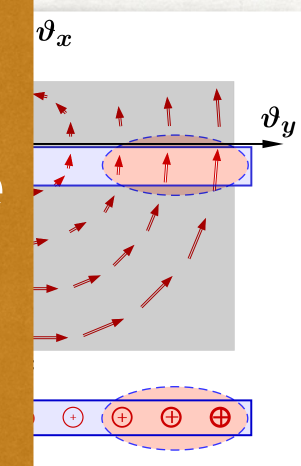

In relation to this new proposal, we will briefly review the current status of

- ✓ The prediction of the Λ_c MDM
- ✓ The polarisation measurement of Λ_c at LHC

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SPIRE].

$\Theta = \frac{L}{R}$

A.S. Fomin et al. Eur. Phys. J. C ('20) 80:358

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MAGNETIC MOMENT OF Λ_C AND CHARM QUARK

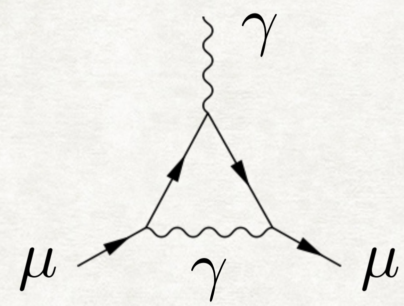
MAGNETIC MOMENT OF ELEMENTARY PARTICLES

LEPTON

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

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

$g_{electron}$=2.00231930436182 ± (2.6×10^{-13})



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) × 10^{-11} .

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

3.6 σ effect!

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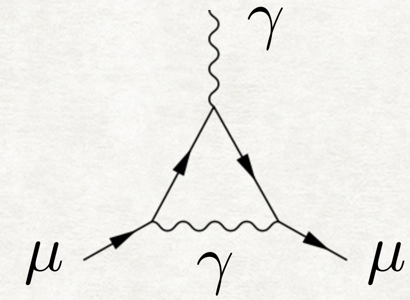
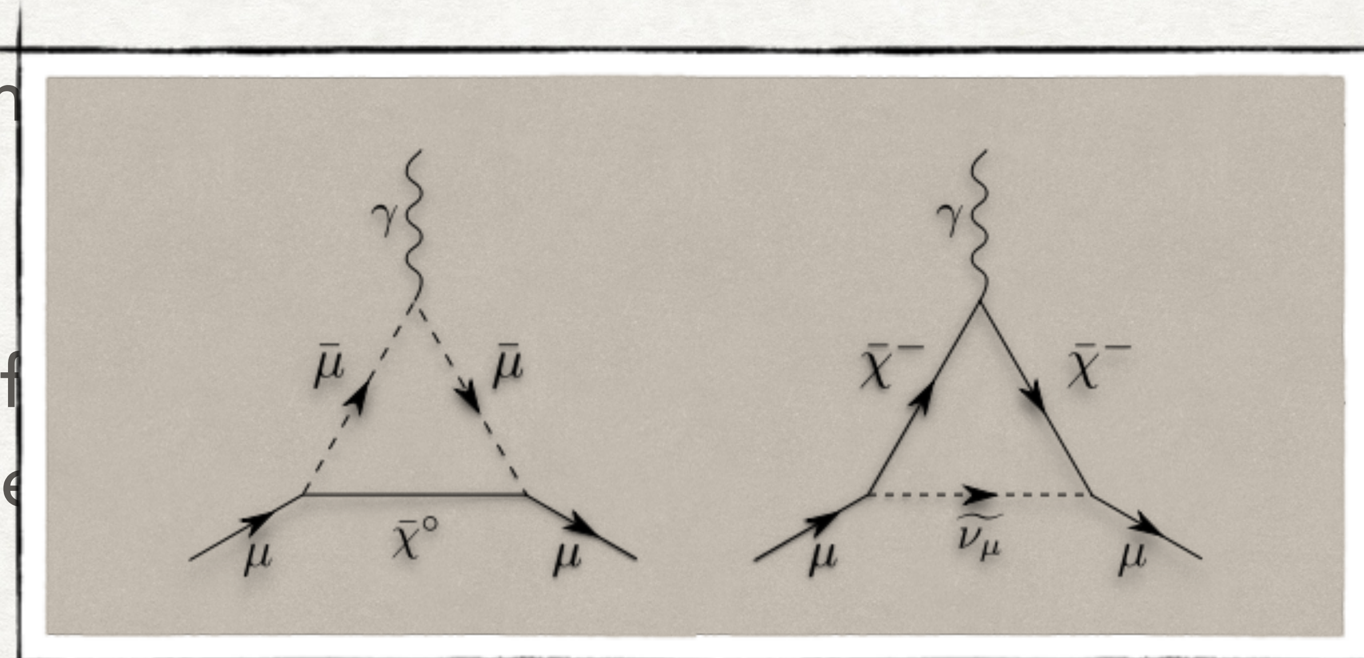


where Q and m ... e.



- The g factor is ... modified by the quantum ef... s magnetic moment and de...

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MAGNETIC MOMENT OF “ELEMENTARY” PARTICLES

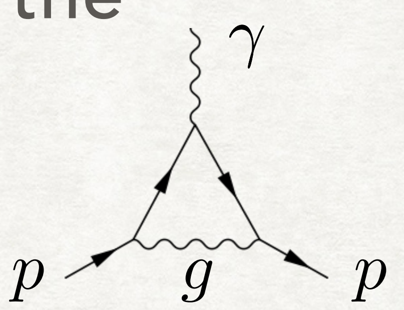
PROTON

- 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

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



- g>>2 indicates that the proton is NOT a fundamental particle.

MAGNETIC MOMENT OF ELEMENTARY PARTICLES

QUARK

- 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.

$$\mu_q = \frac{g_q}{2}\frac{|e|Q_q}{2m_q}$$

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

- Then the magnetic moment of proton is computed as

$$\mu_P = \frac{1}{3}(4\mu_u - \mu_d)$$

- In the isospin limit μ_d=-1/2μ_u, we find

$$\mu_P = \frac{3}{2}\mu_u = \frac{g_u}{2}\frac{|e|}{2m_u}$$

This shows that the quark g factor value depends strongly on the quark mass we assume!

MAGNETIC MOMENT OF Λc AND CHARM QUARK

- We compute the Λc (udc, spin anti-symmetric state) magnetic moment in the quark model:

$$\mu_{\Lambda_c} = \mu_c = \frac{g_c}{2}\frac{Q_c|e|}{2m_c}$$

No contribution from light quarks

- Heavy quark chiral Perturbation Theory: the fact that the light degree of freedom is spineless configuration leads to a negligible higher order correction.

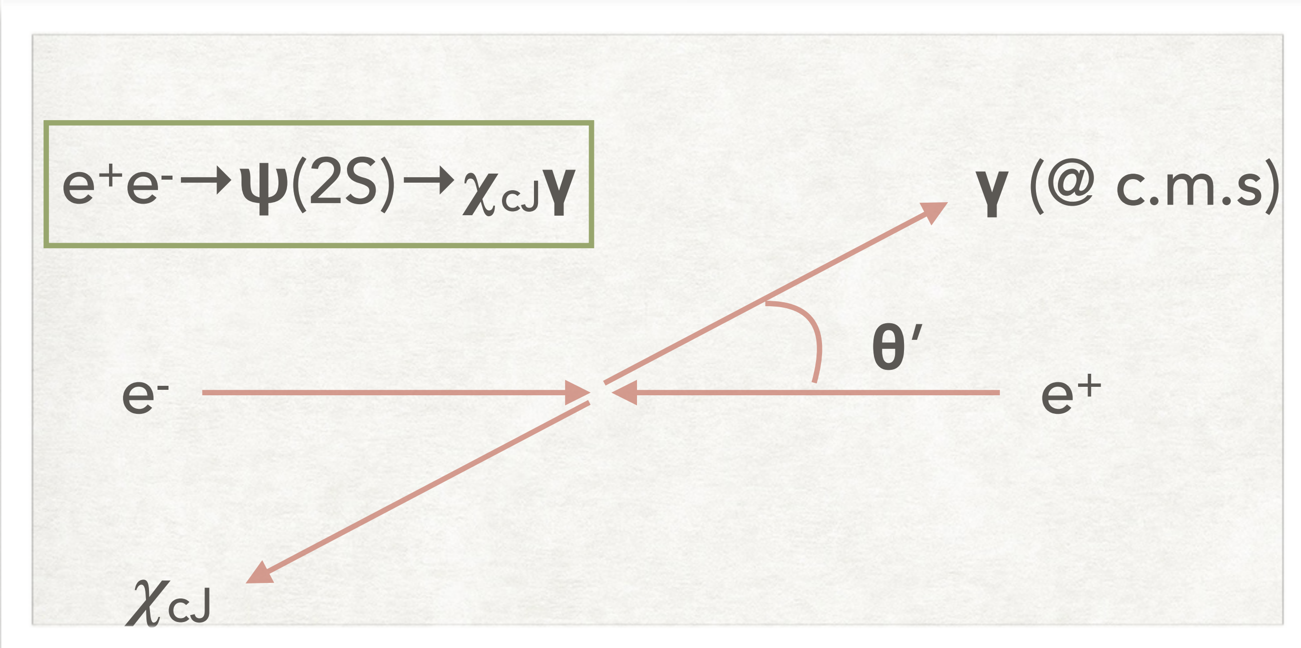
- Various theoretical estimates of Λc magnetic moment can be summarised as

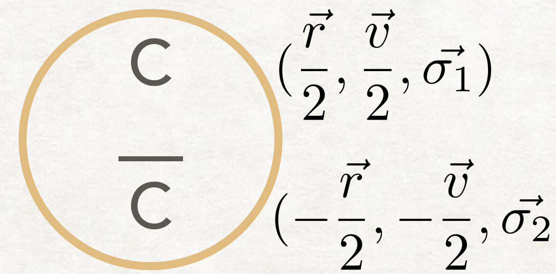
$$\frac{\mu(\Lambda_c^+)}{\mu_N} = 0.37\text{–}0.42,$$

$\mu_N = |e|/2M_P$ is called the nuclear magneton

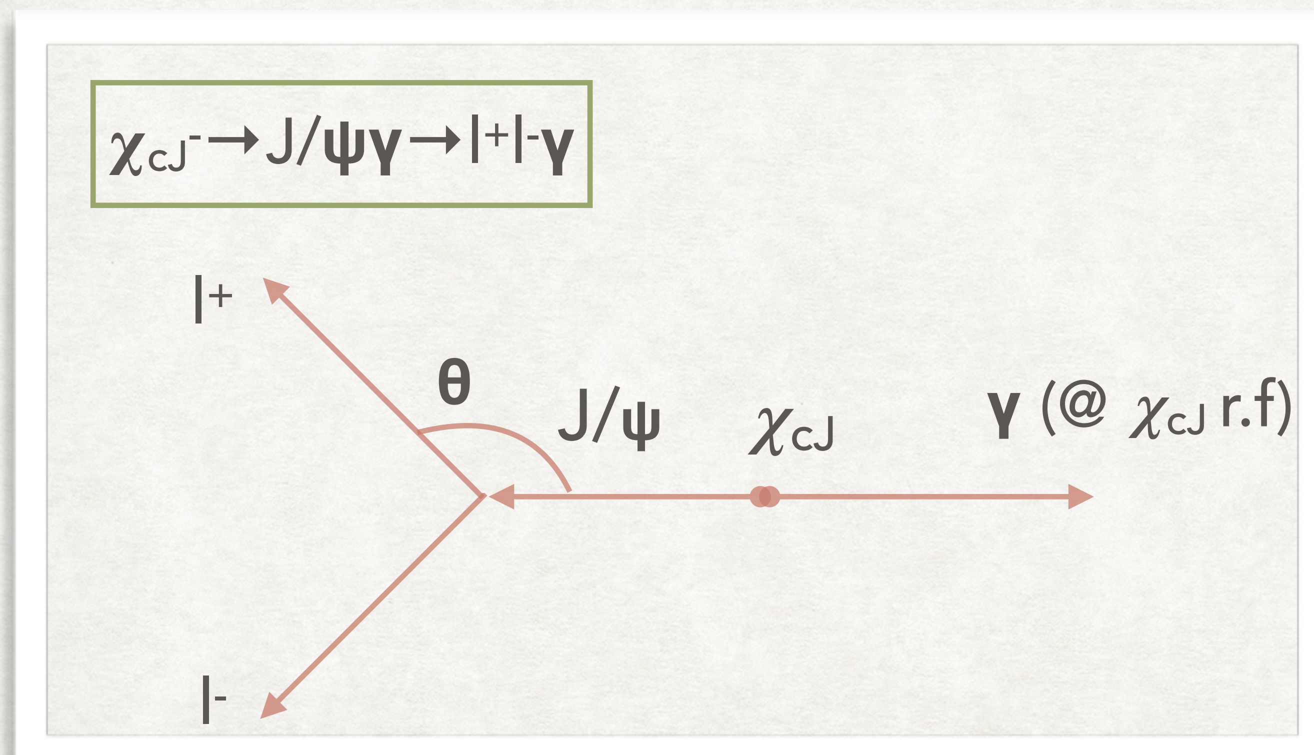
PREDICTING Λ_C MAGNETIC MOMENT WITH BESIII RESULT

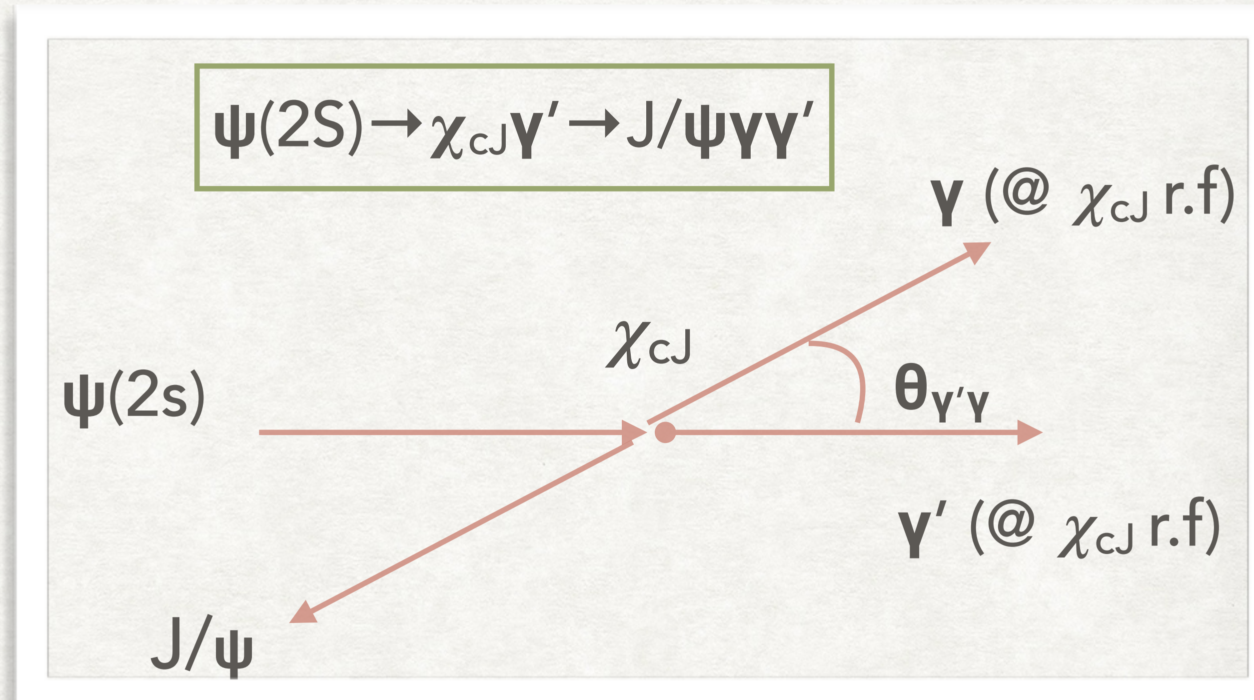
Karl et al PR D13 '76





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}	$a^2_2 = -0.120 \pm 0.013 \pm 0.004$, $b^2_2 = 0.017 \pm 0.008 \pm 0.002$
	$a^2_3 = -0.013 \pm 0.009 \pm 0.004$, $b^2_3 = -0.014 \pm 0.007 \pm 0.004$
	$\rho^2_{a_2b_2} = -0.605$, $\rho^2_{a_2a_3} = 0.733$, $\rho^2_{a_2b_3} = -0.095$
	$\rho^2_{a_3b_2} = -0.422$, $\rho^2_{b_2b_3} = 0.384$, $\rho^2_{a_3b_3} = -0.024$

Extracting anomalous magnetic moment

$$1+\kappa = -\frac{4m_c}{E_{\gamma_2}[\chi_{c1}\to\gamma_2 J/\psi]}a^1_2 = \frac{g_c}{2}$$
$$=1.140 \pm 0.051 \pm 0.053 \pm 0.229,$$

error from charm mass mc=1.5±0.3 GeV

Thus, the Λ_c magnetic moment is determined very precisely

$$\frac{\mu_{\Lambda_c}}{\mu_N} = 0.48 \pm 0.04$$

Slightly higher than the theory predictions. This sets our precision goal ~10%

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

Corrections to the relation
Savage et al PLB326 ('94)
Banuls et al PRD61 ('00)

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

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

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

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

NEW ANGULAR OBSERVABLES FOR MEASURING THE Λ_C POLARISATION

Issue of measuring the Λ_c polarisation

- The angular distribution of the Λ_c decay carries information of polarisation however, it can not trivial to separate it form the so-called asymmetry parameter **α**.

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

weak parameter (α) polarisation (ξ_k)

Polarisation measurement in weak-weak decay

- **Λc→Λπ→pππ decay**

$$
\begin{aligned}
\frac{dN}{d\cos\theta} &= 4m_\Lambda^2 N_1 N_2 (1 + \alpha_1\alpha_2\cos\theta - \xi(\alpha_1 - \alpha_2\cos\theta)) \\
&= 4m_\Lambda^2 N_1 N_2 (1 - \xi\alpha_1 + \alpha_2(\alpha_1 + \xi)\cos\theta)
\end{aligned}
$$

$$
\begin{aligned}
N_1 &= (E_{\Lambda_c} + m_{\Lambda_c})|A|^2 + (E_{\Lambda_c} - m_{\Lambda_c})|B|^2 \\
N_2 &= (E_p + m_p)|a|^2 + (E_p - m_p)|b|^2 \\
\alpha_1 &= \frac{2\mathrm{Re}(AB^*)|\vec{p}_{\Lambda_c}|}{N_1} \\
\alpha_2 &= \frac{2\mathrm{Re}(ab^*)|\vec{p}_p|}{N_2}
\end{aligned}
$$

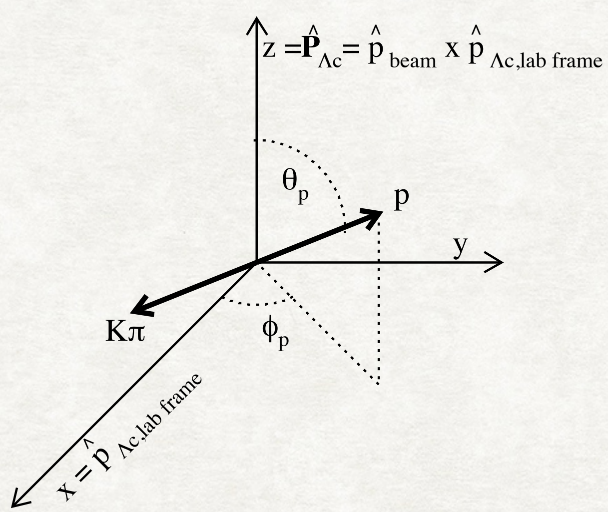
A,B: form factor for Λc→Λπdecay
a,b: form factor for Λ→pπdecay
parity violating

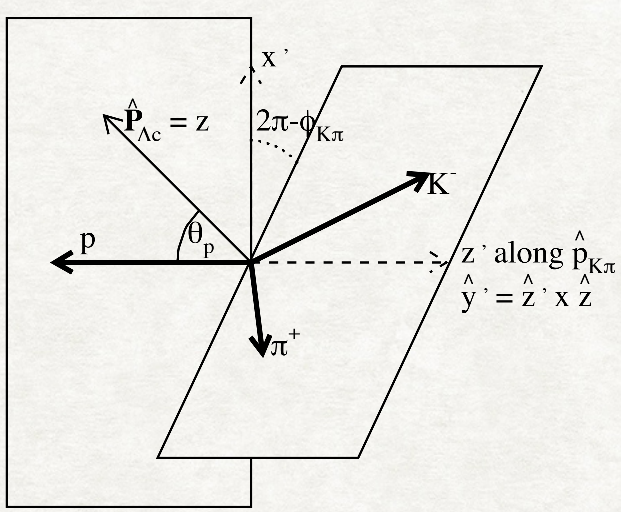
- In this case where the first and the second decays are weak decays (both include parity violation), the angular dependence together with the information of α_2=0.642±0.013 allows to determine ξ and α_1 separately.
- Problem: the decay rate is very small.

Polarisation measurement in weak-strong decay

$\Lambda c \rightarrow (K^{*}p,\ \Delta^{++}K, \Lambda\pi) \rightarrow pK\pi$ decay

- It was first studied by the Fermilab E791 experiment.
- E791: amplitude analysis including 3 resonances, using the helicity amplitude method.
- Successfully measured the polarisation!
- This study was extended by including many more resonances by LHCb (see talks tomorrow)





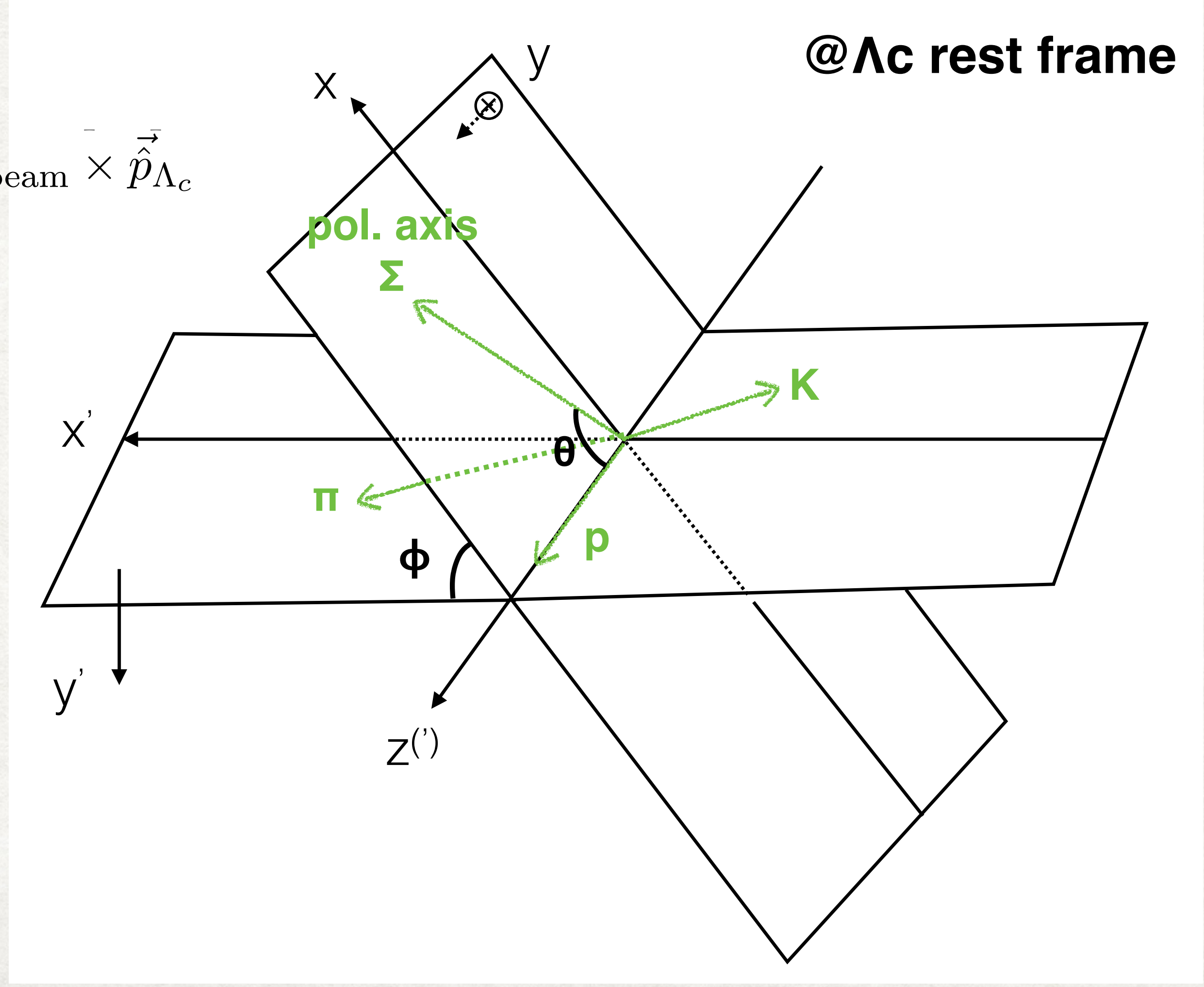
Strong-Weak decay in another frame…

E.K. A. Korchin, V. Kovalchuk, A. Lukianchuk

Λc→(K*p, Δ++K,Λπ)→pKπ decay

- Choice of frame : common for 3 resonances
- Amplitude computation by Feynman diagram
- Only intermediate 3 resonances (3/2+, 3/2-, 1-), to start

$\vec{\Sigma} = \vec{p}_{\rm beam} \times \vec{p}_{\Lambda_c}$



We use Λc rest frame with

- x′-y′-z′: the pKπ decay plane
- x-z: p-Σ plane
- z(′): proton direction

Different from the helicity amplitude, the angular dependence is clearer, which allows us to perform a more advanced sensitivity study!

Strong-Weak decay in another frame...

E.K. A. Korchin, V. Kovalchuk, A. Lukianchuk

- Our final result can be written as :

$$\frac{d\Gamma}{ds_{12}d_{13}d\cos\theta d\phi} = a(s_{12},s_{13}) + \xi\Big(\underbrace{b_0(s_{12},s_{13})\cos\theta + b_1(s_{12},s_{13})\sin\theta\cos\phi + b_2(s_{12},s_{13})\sin\theta\sin\phi}_{\equiv b(s_{12},s_{13},\cos\theta,\phi)}\Big)$$

a, b_0, b_1, b_2 are written by the form factors, A, B, C, D, E_i, F_i and the Breit-Wigner of each resonance.

A ($\not{\mathscr{P}}$), B($\mathscr{P}$)
C ($\mathscr{P}$), D($\not{\mathscr{P}}$)
$E_{1,2}$ ($\mathscr{P}$), $F_{1,2}$($\not{\mathscr{P}}$)

a : Dalitz distribution (parity even)
b_0 : Equivalent to **a** (parity odd)
b_2 : triple product (CP or T odd ?)

- a contains $|A|^2$, $|B|^2$, ... $|F_i|^2$ and interferences, BC, AD, $BE_{1,2}$, $AF_{1,2}$....
- b_0 contains interferences, AB, CD, $E_{1,2}F_{1,2}$, AC, BD, $AE_{1,2}$, $BF_{1,2}$....
- b_2 contains imaginary part

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We perform the simultaneous fit of form factor (A, B…F_i) and polarisation ξ using 4 dimensional kinematics (s_{12}, s_{13}, θ ϕ).

A ($\not{\mathscr{P}}$), B($\mathscr{P}$)
C ($\mathscr{P}$), D($\not{\mathscr{P}}$)
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The sensitivity study: proof of concept

E.K. F. Callet

Step 1) Obtain an example MC data from LHCb (with only 3 resonances)
Step 2) Construct our model (i.e. fitting our form factors using the MC Dalitz plot)
Step 3) Perform the simultaneous fit using events generated using our model

We use the “omega” method (c.f. Gampola, tau polarisation measurement, ILC top spin measurement…).

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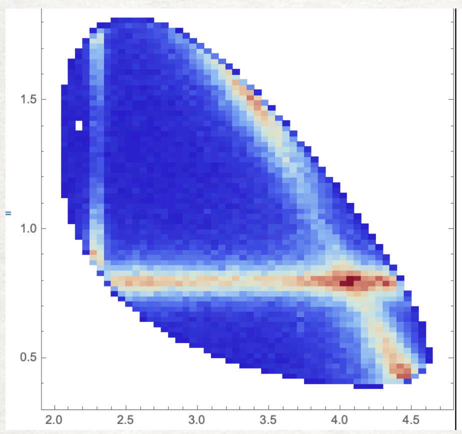
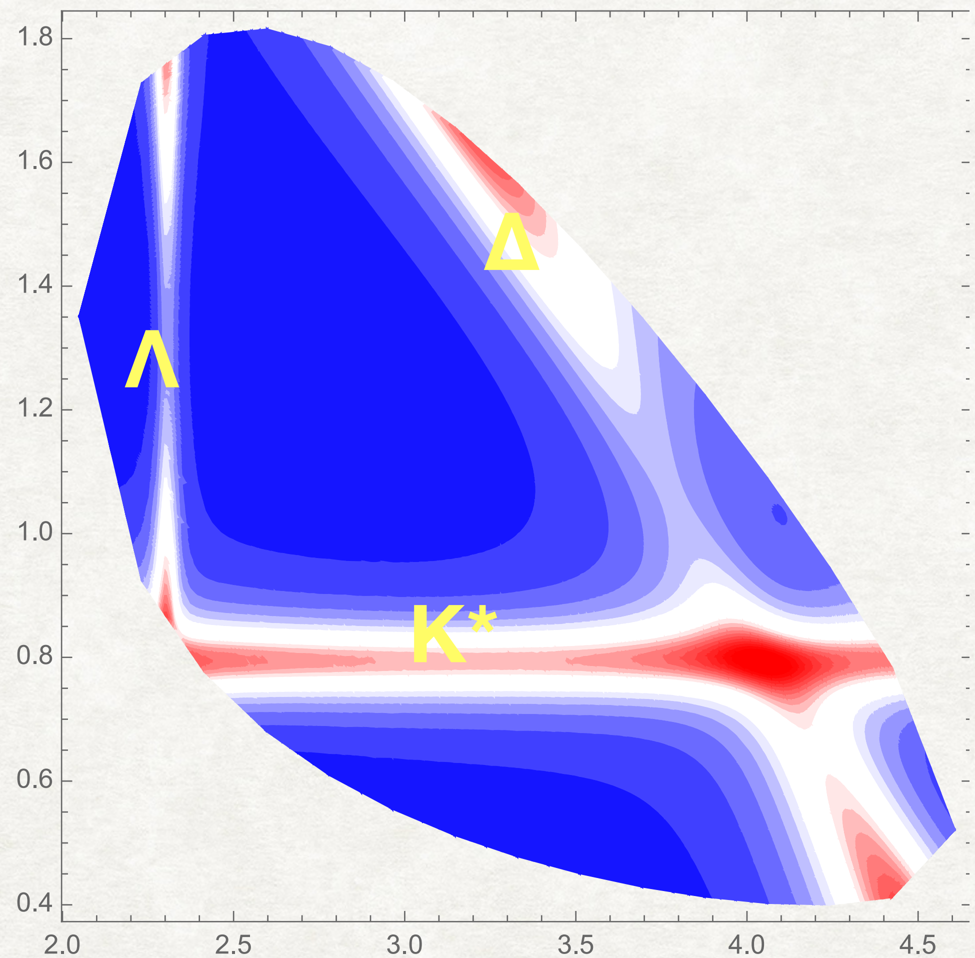
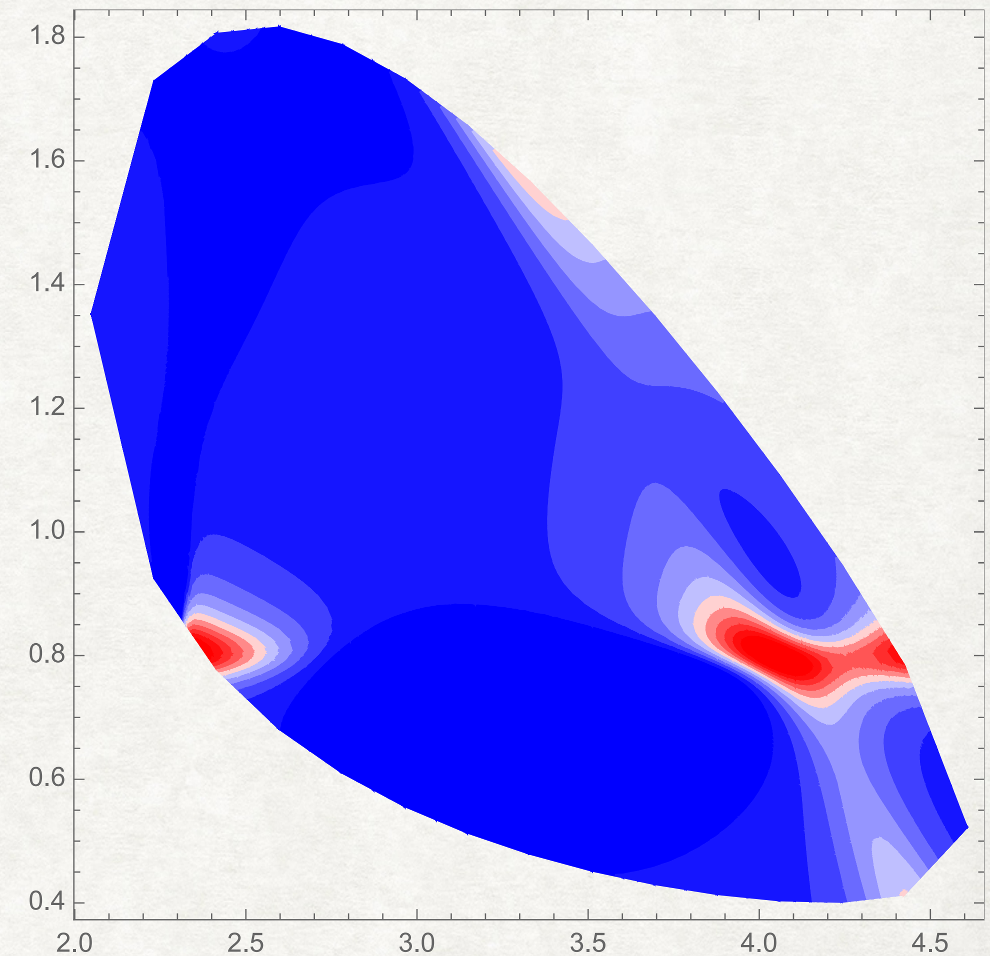


a coefficient on m12-m23 Dalitz plane



b_0 coefficient on m12-m23 Dalitz plane



P1: p
P2: K
P3: pi

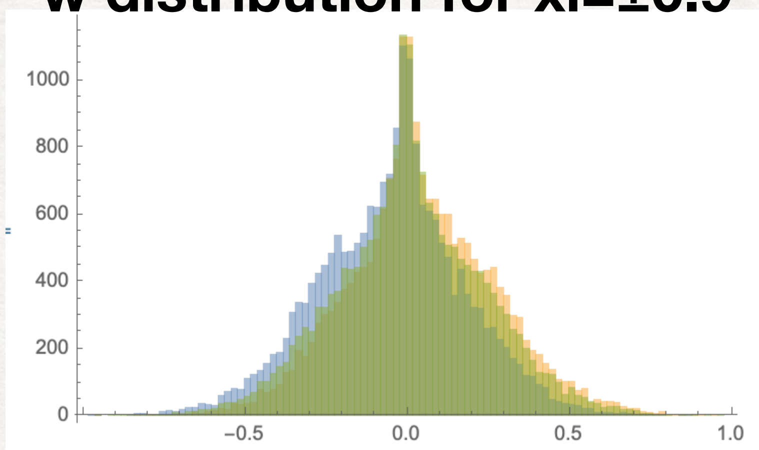
The sensitivity study: proof of concept

E.K. F. Callet

Preliminary result of fit

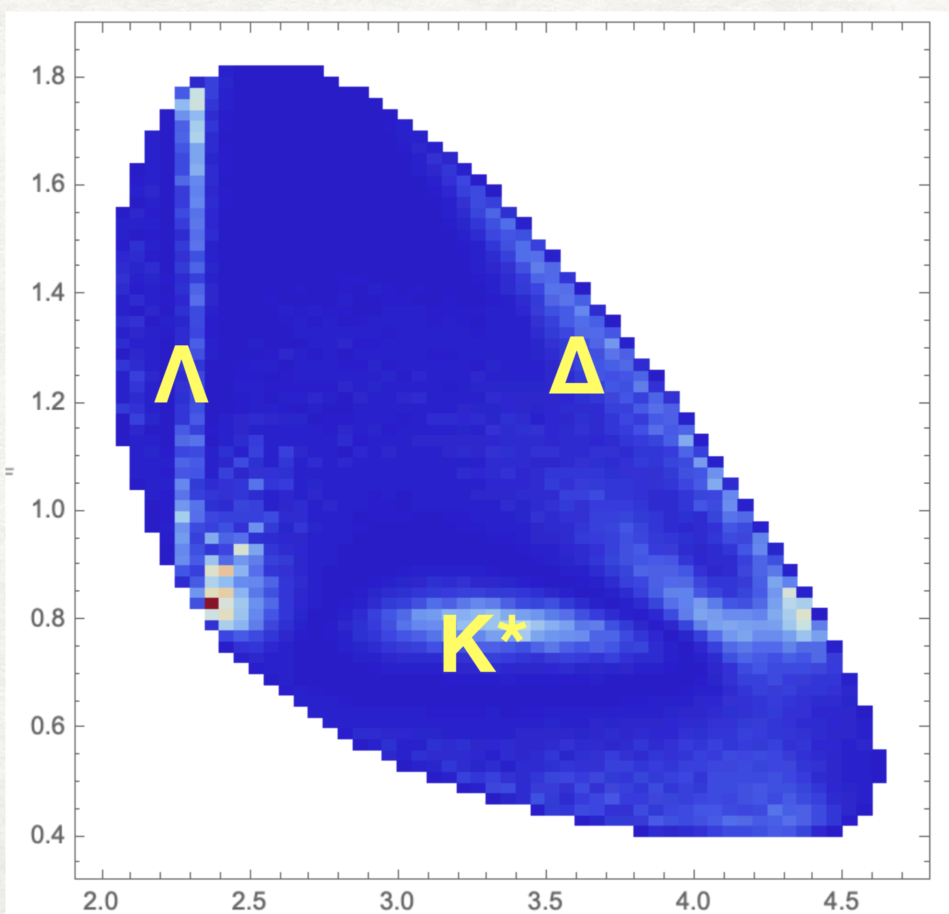
```
Param :
A,B,C,D,A1,A2,B1,B2
-0.762658,1.14336,4.65073,1.25921,-0.278177,0.0303613,0.257899,-0.480634
```

w distribution for xi=±0.9



	A	B	C	D	A1	A2	B	B2
A	1	0.221319	0.423237	-0.518167	0.435468	-0.435138	0.259507	-0.0576802
B	0.221319	1	0.437175	-0.25942	-0.25835	0.150533	0.213008	-0.0084081
C	0.423237	0.437175	1	-0.642163	-0.013463	0.0186317	0.0825147	0.1264
D	-0.518167	-0.25942	-0.642163	1	-0.150709	0.0912629	-0.11742	-0.212142
A1	0.435468	-0.25835	-0.013463	-0.150709	1	-0.957669	0.227852	-0.0970739
A2	-0.435138	0.150533	0.0186317	0.0912629	-0.957669	1	-0.27546	0.309624
B1	0.259507	0.213008	0.0825147	-0.11742	0.227852	-0.27546	1	-0.302171
B2	-0.0576802	-0.0084081	0.1264	-0.212142	-0.0970739	0.309624	-0.302171	1

w^2 weighted Dalitz plot on m12-m23 with xi=0.9



<u>Fit result for ξ (for ξ=0.9)</u>

ξ=0.890±0.009 (for 200k event)

ξ=0.882±0.028 (for 20k event)

The w^2 distribution is approximately 1/sigma_xi^2 distribution (sigma_xi =error on xi), i.e. the plot shows the region of high sensitivity

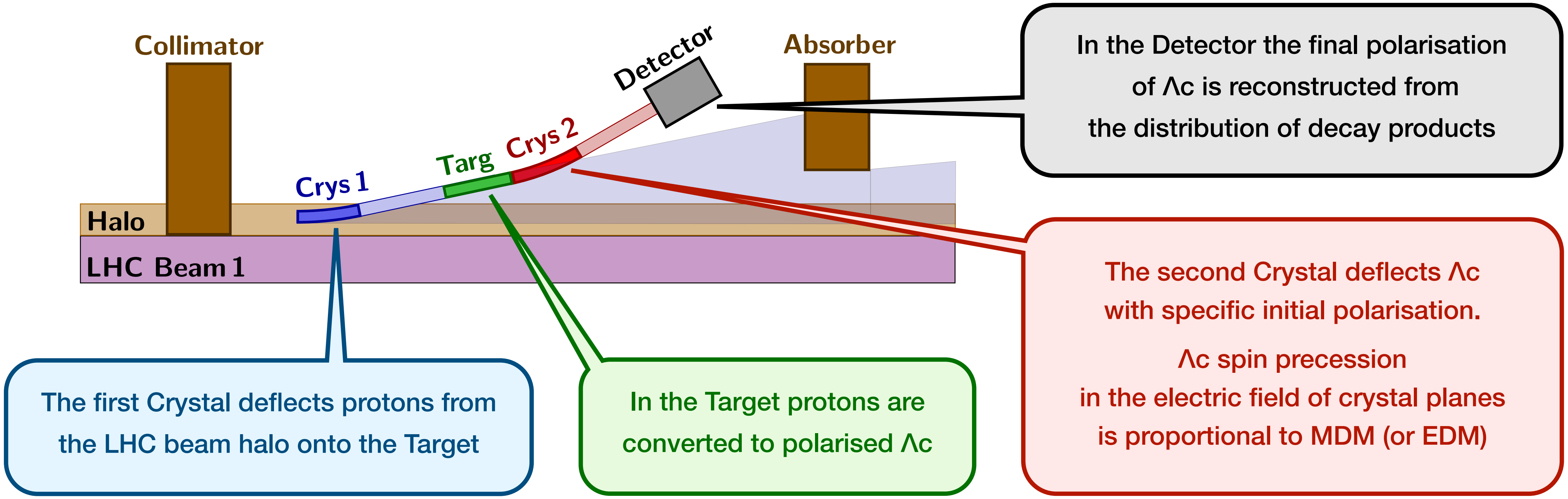
Conclusions

- The charm magnetic moment determination with bent-crystal requires a measurement of the Λ_c polarisation. Last few years, there have been impressive progresses on the Λ_c polarisation measurement at LHCb.
- Charmonium radiative decay can indirectly provide an estimate $\mu_{\Lambda_c} \approx 0.48 \pm 0.04$ n.m., which is slightly higher than the theoretical predictions (~0.37-0.42 n.m.).
- The MDM measurement requires the simultaneous determination of the Λ_c polarisation and the "asymmetry parameter (i.e. form factors)".
- We propose a new framework to perform the sensitivity study. Our preliminary result shows that the polarisation can be measured at 3 (1)% precision for 20k (200k) $\Lambda_c \to pK\pi$ events. The next step is to include more resonances.

Backup

PROPOSED EXPERIMENT

- L. Burmistrov et al., CERN-SPSC-2016-030, CERN, Geneva Switzerland, **June 2016** [SPSC-EOI-012].
- A. Stocchi, W. Scandale, talks at Physics Beyond Collider Workshop, CERN, Geneva Switzerland, **6–7 September 2016**.



MAGNETIC MOMENT OF ELEMENTARY PARTICLES

QUARK

- 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.

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

$\mu = |e|/2M_q$

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

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

- Then the magnetic moment of proton is computed as

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

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 $g_P = 1.86$!

PREDICTING Λc 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

error from charm mass mc=1.5±0.3 GeV

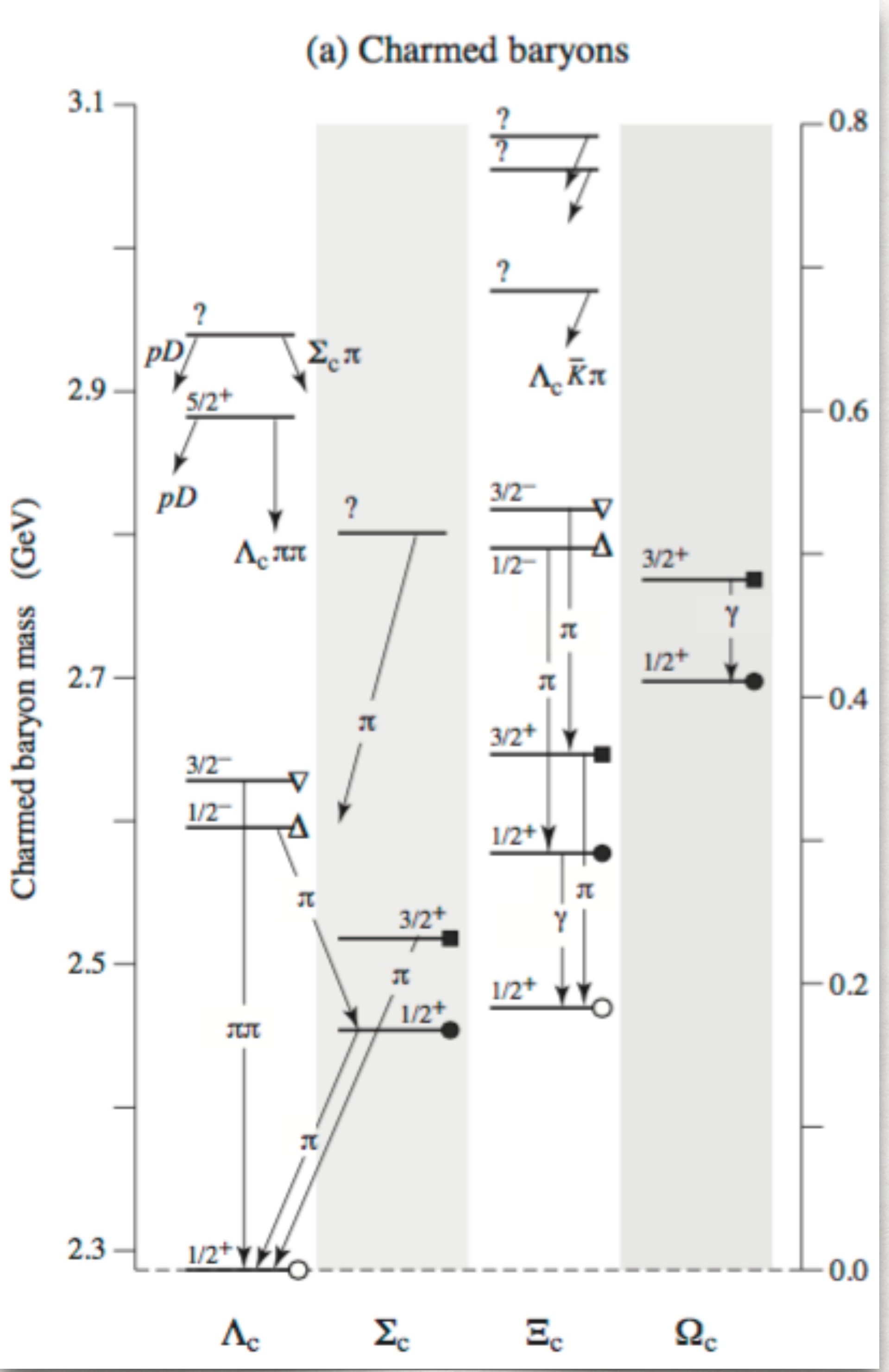
Extracting anomalous magnetic moment

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

$$= 1.140 \pm 0.051 \pm 0.053 \pm 0.229, \qquad = \frac{g_c}{2}$$

QUESTION OF TWO Ξ_C 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!

Project to include more resonances

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- In the previous work, we had only 3 resonances:

  Λ′ (3/2-)Δ++(3/2+),K*(1-)

- Now, we try to include following resonances (Model 6):

  ***Λ**$^{1/2-}$(1405)*, ***Λ**$^{3/2-}$(1520)*, **Λ**$^{1/2+}$(1600), **Λ**$^{1/2-}$(1670), ***Λ**$^{1/2+???}$(2000)*

  Δ$^{3/2+}$(1232), Δ$^{3/2+}$(1600), *Δ$^{1/2-}$(1620)*, Δ$^{3/2-}$(1700)

  κ^{0+}(700), *K*$^{1-}$(892)*, K*0^{0+}(1430)

- We name these particles as 1~n and then, the parity even and odd form factors are named as A_i and B_i (i=1~(n+1)*).

- So on total (n+1)x2 (or (n+1)x4 if they are imaginary) parameters to fit.

- a0 (parity even) : function of A_ixA_j and B_ixB_j (i,j=1~n+1). This means we need 20, 58, 242,1454 decompositions for n=3, 4, 5, 6 resonances.

** K* has 4 form factors*