# Polarisation determination with $\Lambda_c \to pK\pi$ decay towards MDM measurement


*Collaboration with F. Callet, A. Korchin, V. Kovalchuk, A. Lukianchuk, R. Ovsiannikov*

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# Outline

- Introduction: $\Lambda c$ MDM measurement
- Model dependent amplitude analysis of $\Lambda c \to pK\pi$ decay
  - ✓ LHCb analysis
  - ✓ Our work in progress
- Model independent amplitude analysis of $\Lambda c \to pK\pi$ decay
  - ✓ Example of model independent analysis: BPGGSZ method
  - ✓ Idea of using the e+e- $\to \Lambda c\ \Lambda c$(bar) data???
  - ✓ Example: full angular analysis of e+e- $\to \Lambda\ \Lambda$(bar)

# Introduction

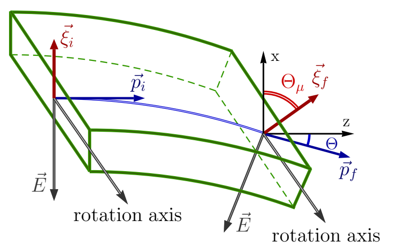
# Introduction

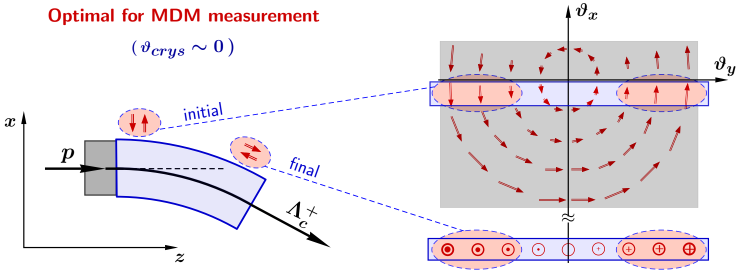
<u>A new experiment is proposed to measure the MDM of charmed baryon.</u>

<u>Short life time is compensated by the strong magnetic field created by bent crystal.</u>

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

# Issue of measuring the $\Lambda_c$ polarisation

- The angular distribution of the $\mathbf{\Lambda_c}$ decay carries information of polarisation however, it can not trivial to separate it form the so-called asymmetry parameter **α**.

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

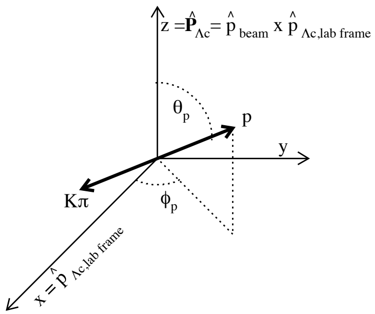
hadronic parameter ($\alpha$)

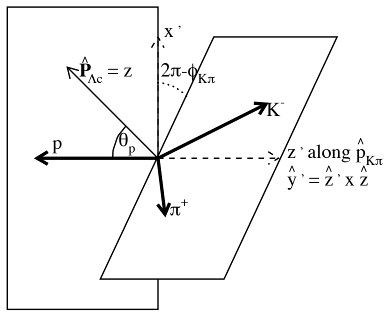
polarisation ($\xi_k$)

# Polarisation measurement in Λc→pKπ decay

<u>Λc→(K*p, Δ⁺⁺K,Λπ…)→pKπ decay</u>

- It was first studied by the Fermilab E791 experiment.
- E791: amplitude analysis including 3 resonances, using the helicity amplitude method.
- This study was extended by including many more resonances by LHCb (see next)
- We propose an optimal observable for sensitivity study (but only 3 resonance, see next)
- A possible model independent study using the BESIII data???



# Model dependent amplitude analysis of $\Lambda_c \to pK\pi$ decay

# LHCb amplitude analysis

*LHCb, arXiv:2208.03262*

400k event (30% of full sample)

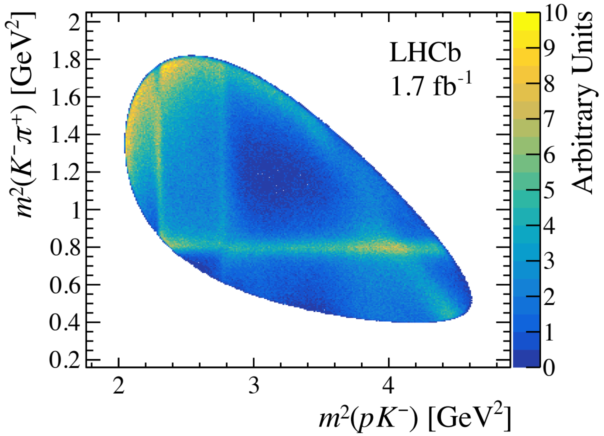
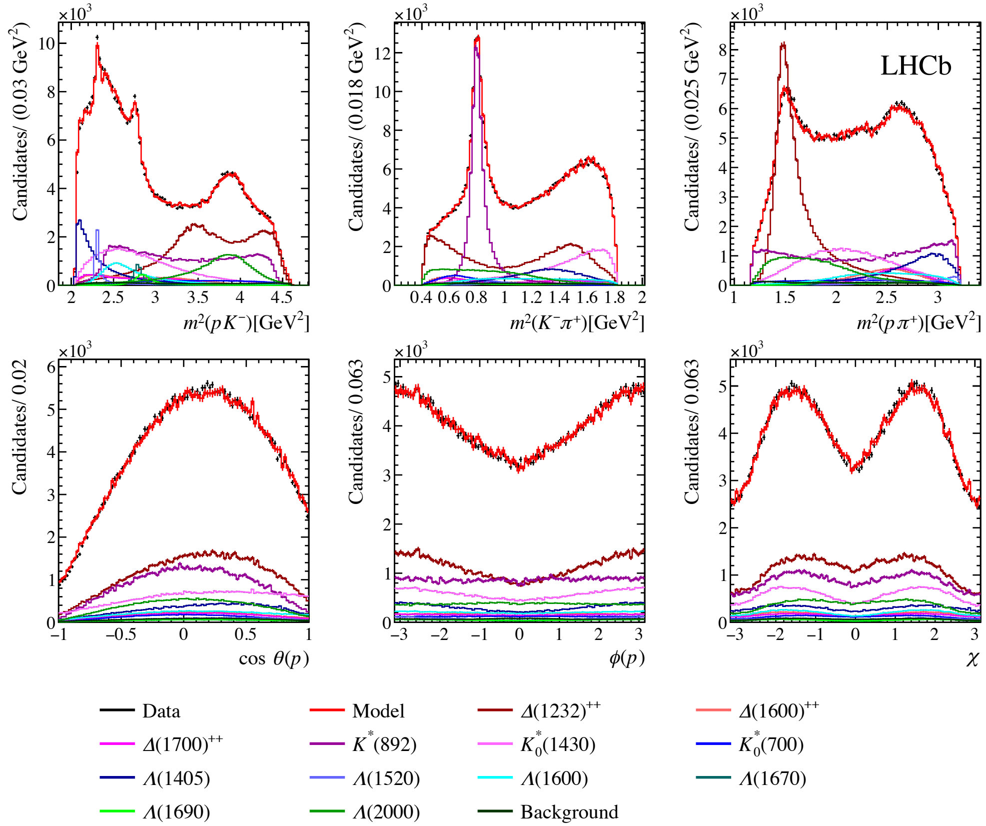



Figure 2: Dalitz plot for the total sample of $\Lambda_c^+ \to pK^-\pi^+$ candidates.

| Resonance | $J^P$ | Mass (MeV) | Width (MeV) |
|---|---|---|---|
| $\Lambda(1405)$ | $1/2^-$ | 1405.1 | 50.5 |
| $\Lambda(1520)$ | $3/2^-$ | 1515 − 1523 | 10 − 20 |
| $\Lambda(1600)$ | $1/2^+$ | 1630 | 250 |
| $\Lambda(1670)$ | $1/2^-$ | 1670 | 30 |
| $\Lambda(1690)$ | $3/2^-$ | 1690 | 70 |
| $\Lambda(2000)$ | $1/2^-$ | 1900 − 2100 | 20 − 400 |
| $\Delta(1232)^{++}$ | $3/2^+$ | 1232 | 117 |
| $\Delta(1600)^{++}$ | $3/2^+$ | 1640 | 300 |
| $\Delta(1700)^{++}$ | $3/2^-$ | 1690 | 380 |
| $K_0^*(700)$ | $0^+$ | 824 | 478 |
| $K^*(892)$ | $1^-$ | 895.5 | 47.3 |
| $K_0^*(1430)$ | $0^+$ | 1375 | 190 |




Model dependent amplitude analysis of LHCb

# LHCb amplitude analysis

*LHCb, arXiv:2208.03262*

$$\frac{d\Gamma}{d\cos\theta_R} \propto \frac{1}{2}\left(1 + \alpha P \cos\theta_R\right), \qquad \alpha = \frac{|\mathcal{H}_{1/2,0}|^2 - |\mathcal{H}_{-1/2,0}|^2}{|\mathcal{H}_{1/2,0}|^2 + |\mathcal{H}_{-1/2,0}|^2}.$$

Table 7: Measured polarization components. The first uncertainty is statistical, the second is the amplitude model choice systematic contribution and the third is the combination of the other systematic uncertainties.

| Component | Value (%) |
|---|---|
| $P_x$ (*lab*) | $60.32 \pm 0.68 \pm 0.98 \pm 0.21$ |
| $P_y$ (*lab*) | $-0.41 \pm 0.61 \pm 0.16 \pm 0.07$ |
| $P_z$ (*lab*) | $-24.7 \pm 0.6 \pm 0.3 \pm 1.1$ |
| $P_x$ ($\tilde{B}$) | $21.65 \pm 0.68 \pm 0.36 \pm 0.15$ |
| $P_y$ ($\tilde{B}$) | $1.08 \pm 0.61 \pm 0.09 \pm 0.08$ |
| $P_z$ ($\tilde{B}$) | $-66.5 \pm 0.6 \pm 1.1 \pm 0.1$ |

Polarisation measurements

# Our ongoing work…

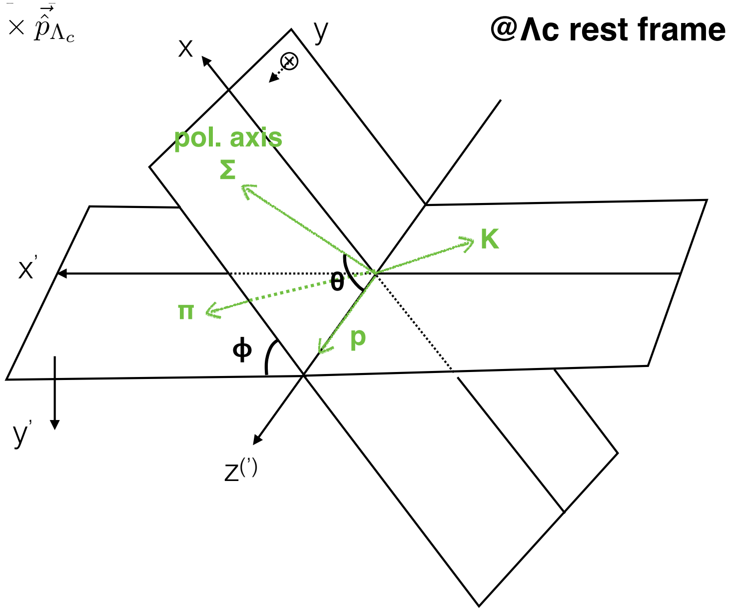
*F. Callet, E.K. A. Korchin, V. Kovalchuk, A. Lukianchuk*

*From last year's WS*

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

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

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




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!**

# Our ongoing work…

*F. Callet, E.K. A. Korchin, V. Kovalchuk, A. Lukianchuk*

*From last year's WS*

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

**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 ?)

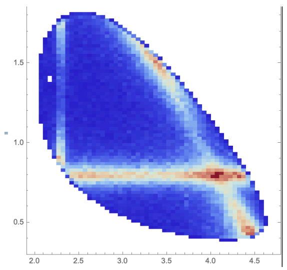
- a contains $|A|^2$, $|B|^2$, … $|F_i|^2$ and interferences, BC, AD, $BE_{1,2}$, $AF_{1,2}$….
- $b_0$ contains interferences, AB, CD, $E_{1,2}F_{1,2}$, AC, BD, $AE_{1,2}$, $BF_{1,2}$….
- $b_2$ contains imaginary part

# The sensitivity study: proof of concept

From last year's WS

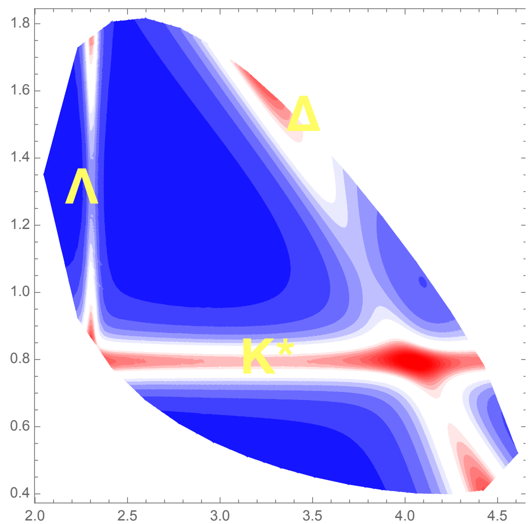
Step 1) Obtain an example MC data from LHCb (with only 3 resonances)
Step 2) Construct our model (i.e. fitting our form factors using the MC Dalitz plot)
Step 3) Perform the simultaneous fit using events generated using our model

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

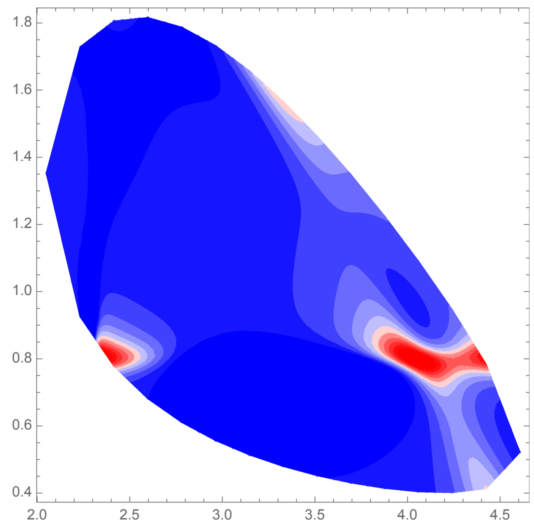


**P1: p**
**P2: K**
**P3: pi**

**a coefficient on m12-m23 Dalitz plane**




**$b_0$ coefficient on m12-m23 Dalitz plane**

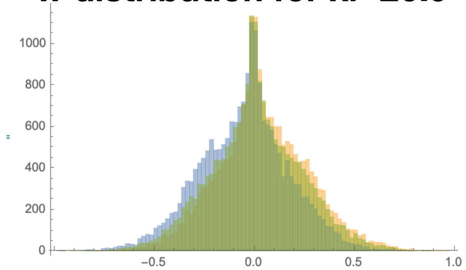


# The sensitivity study: proof of concept

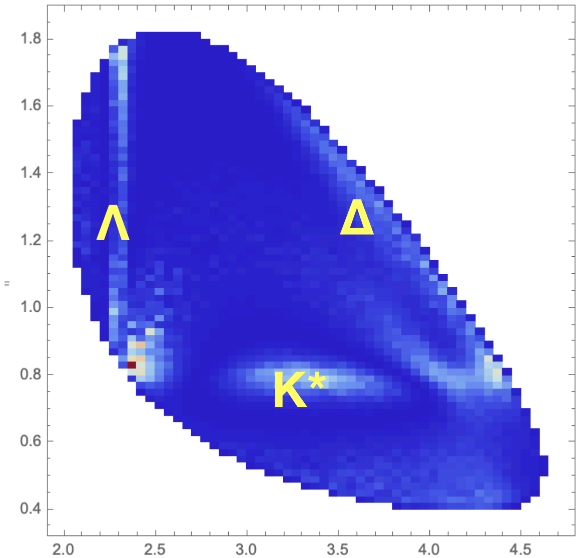
*F. Callet, E.K. A. Korchin, V. Kovalchuk, A. Lukianchuk*

From last year's WS

## w distribution for xi=±0.9




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




```
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
```

| | 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 |

Fit result for ξ (for ξ=0.9)

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**

# Recent LHCb polarimetry paper

*LHCb, arXiv:2301.07010*

Similar result is obtained recently by LHCb (using the LHCb model of arXiv:2208.03262)

$$|\mathcal{M}(\phi,\theta,\chi,\kappa)|^2 = I_0(\kappa)\left(1+\sum_{i,j} P_i R_{ij}(\phi,\theta,\chi)\alpha_j(\kappa)\right),$$

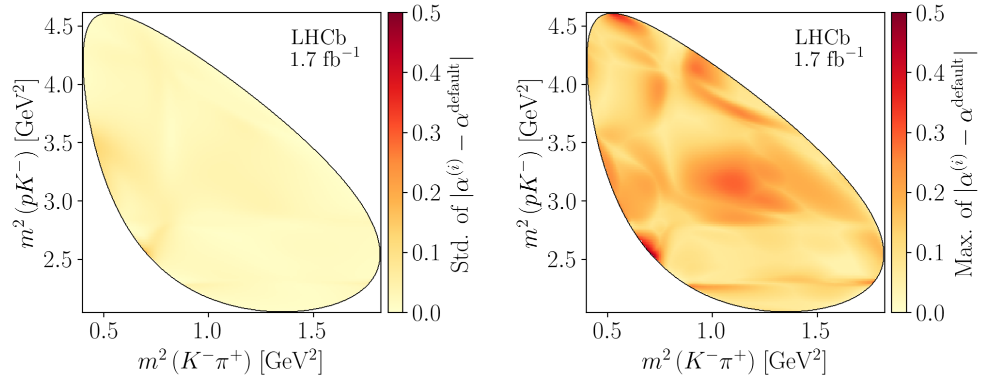



Figure 4: Uncertainties on the length of the aligned polarimeter vector for each phase-space point. The left panel shows combined statistical and systematic uncertainties, and the right panel shows the model uncertainties.

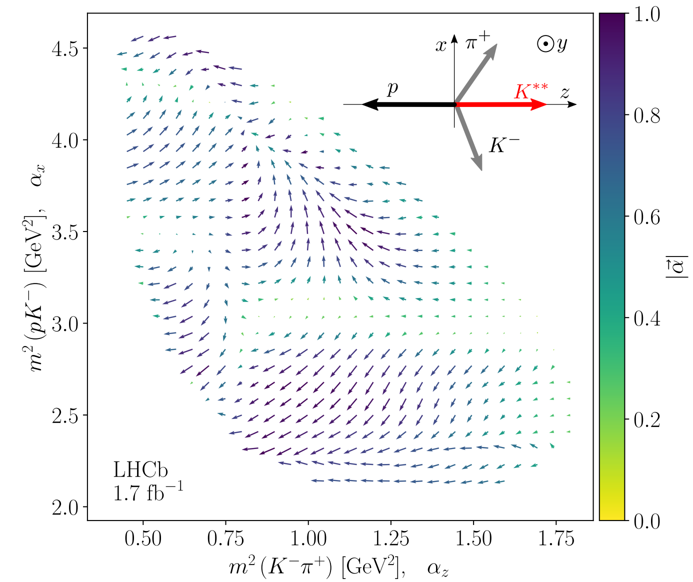



Figure 2: Aligned polarimeter vector field in Dalitz-plot coordinates. The $z$ and $x$ components of the $\alpha$ vector are shown by the horizontal and vertical projections of the arrow, respectively. The colour indicates the length of the polarimeter vector. The sketch in the top right corner shows the decay-plane orientation. The momentum arrows for the pion and the kaon are shown in gray, since their orientation depends on the kinematic variables, $m^2(K^-\pi^+)$ and $m^2(pK^-)$.

# Model independent amplitude analysis of $\Lambda_c \to pK\pi$ decay

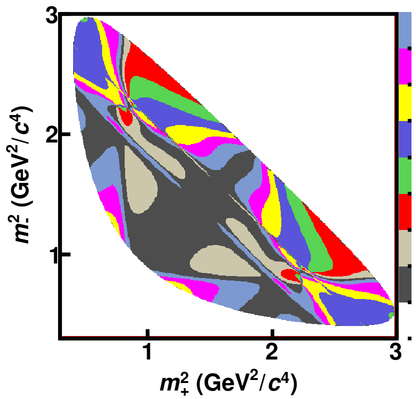
# Example of Model independent analysis

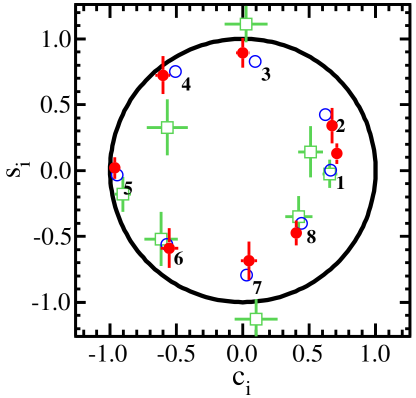
Determining the CKM phase ϕ3 (γ) using external input (model independent) of strong phase

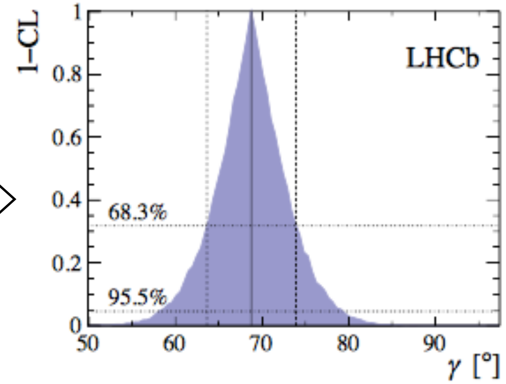
*hep-ex/0303187*
*Giri, Grossman Soffer, Zupan*
*hep-ph/0510246*
*Bondar, Poluektov*

$$c(s_{12}, s_{13}) = A_D(s_{12}, s_{13})A_D(s_{13}, s_{12})\cos[\delta_D(s_{12}, s_{13}) - \delta_D(s_{13}, s_{12})]$$
$$s(s_{12}, s_{13}) = A_D(s_{12}, s_{13})A_D(s_{13}, s_{12})\sin[\delta_D(s_{12}, s_{13}) - \delta_D(s_{13}, s_{12})]$$

*arXiv:2010.08483*

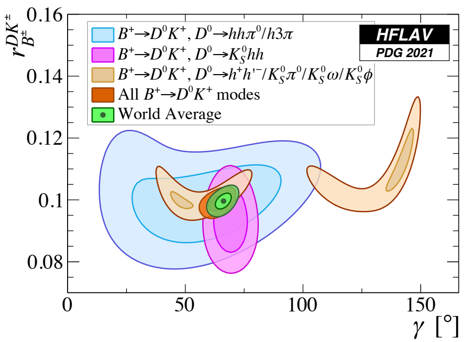


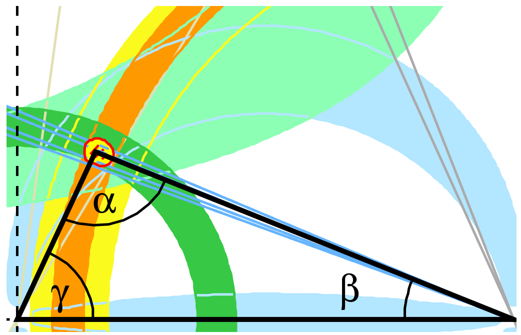




Strong phase from BESIII *arXiv:2003.00091*

LHCb γ measurement




$$\gamma = (68.7^{+5.2}_{-5.1})^\circ,$$
$$r_B^{DK^\pm} = 0.0904^{+0.0077}_{-0.0075},$$
$$\delta_B^{DK^\pm} = (118.3^{+5.5}_{-5.6})^\circ,$$
$$r_B^{D\pi^\pm} = 0.0050 \pm 0.0017,$$
$$\delta_B^{D\pi^\pm} = (291^{+24}_{-26})^\circ.$$



# Can we do the same?

## Determining the polarisaion using external input (model independent)?

*E.K. A. Korchin, R. Ovsiannikov*

### Using $\Lambda_c^+ \to pK^-\pi^+$ as a spin polarimeter*

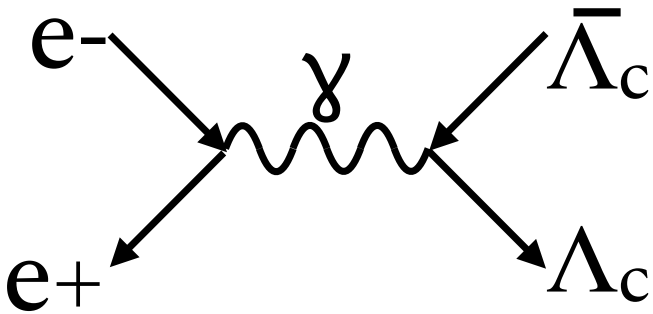
Dai-Hui Wei(魏代会)[1] Yong-Xu Yang(杨永栩)[1] Rong-Gang Ping(平荣刚)[2,3†]

[1]School of Physical Science and Technology, Guangxi Normal University, Guilin 541004, China
[2]Institute of High Energy Physics, Chinese Academy of Sciences, Beijing 100049, China
[3]University of Chinese Academy of Science, Beijing 100049, China

**Abstract:** Polarization transfer measurement plays an important role in the search for new physics processes in charmed baryon decays. The measurement of the $\Lambda_c^+ \to pK^-\pi^+$ decay is suggested as a spin polarimeter. A general description of the decay is developed using Euler angles, and the polarization parameters are derived. Its relationship with parity violation is found using the phenomenological amplitude model. A Monte-Carlo simulation is performed, and the results show that charmed baryon polarization is well determined using a set of Monte-Carlo events with selected asymmetry parameters. The experimental measurement of these asymmetry parameters is suggested.

**Keywords:** $\Lambda_c$, baryon, polarization

**DOI:** 10.1088/1674-1137/ac5e93



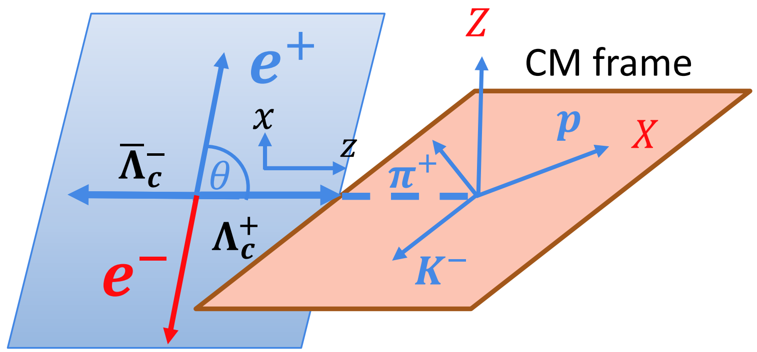




**Fig. 2.** (color online) Definition of the $\Lambda_c^+$ helicity system for its production from the $e^+e^- \to \Lambda_c^+\bar{\Lambda}_c^-, \Lambda_c^+ \to pK^-\pi^+$ process.

Spin correlation of $\Lambda_c$ and $\Lambda_c$bar can disentangle the polarisation information?!

# Investigating Spin-correlation of ΛΛbar

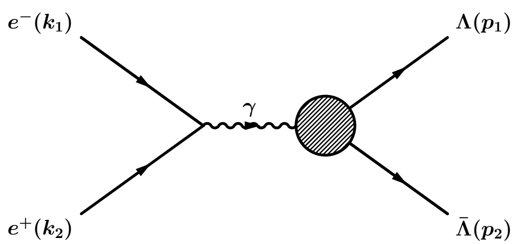
## Similar example: full angular analysis of e+e- —> ΛΛbar

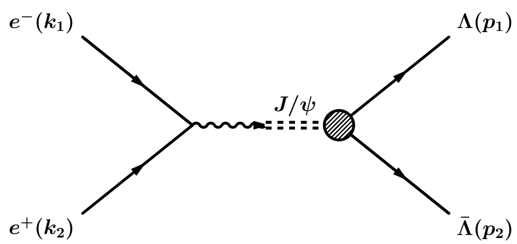
**Polarization and Entanglement in Baryon-Antibaryon Pair Production in Electron-Positron Annihilation**

arXiv:1808.08917
BESIII

(Dated: August 28, 2018)

Using a sample of $1.31 \times 10^9$ $J/\psi$ events collected with the BESIII detector, we report the first observation of spin polarization of $\Lambda$ and $\bar{\Lambda}$ hyperons from the coherent production in the $J/\psi \to \Lambda\bar{\Lambda}$ decay. We measure the phase between the hadronic form factors to be $\Delta\Phi = (42.4 \pm 0.6 \pm 0.5)^\circ$. The decay parameters for $\Lambda \to p\pi^-$ ($\alpha_-$), $\bar{\Lambda} \to \bar{p}\pi^+$ ($\alpha_+$) and $\bar{\Lambda} \to \bar{n}\pi^0$ ($\bar{\alpha}_0$) are measured to be $\alpha_- = 0.750 \pm 0.009 \pm 0.004$, $\alpha_+ = -0.758 \pm 0.010 \pm 0.007$ and $\bar{\alpha}_0 = -0.692 \pm 0.016 \pm 0.006$, respectively. The obtained value of $\alpha_-$ is higher by $(17 \pm 3)\%$ than the current world average. In addition, the $CP$ asymmetry $A_{CP} = (\alpha_- + \alpha_+)/(\alpha_- - \alpha_+)$ of $-0.006 \pm 0.012 \pm 0.007$ is extracted with substantially improved precision. The ratio $\bar{\alpha}_0/\alpha_+ = 0.913 \pm 0.028 \pm 0.012$ is also measured.




arXiv:1702.07288

TABLE I. Summary of the results: the $J/\psi \to \Lambda\bar{\Lambda}$ angular distribution parameter $\alpha_\psi$, the phase $\Delta\Phi$, the asymmetry parameters for the $\Lambda \to p\pi^-$ ($\alpha_-$), $\bar{\Lambda} \to \bar{p}\pi^+$ ($\alpha_+$) and $\bar{\Lambda} \to \bar{n}\pi^0$ ($\bar{\alpha}_0$) decays, the $CP$ asymmetry $A_{CP}$, and the ratio $\bar{\alpha}_0/\alpha_+$. The first uncertainty is statistical, and the second one is systematic.

| Parameters | This work | Previous results |
|---|---|---|
| $\alpha_\psi$ | $0.461 \pm 0.006 \pm 0.007$ | $0.469 \pm 0.027$ [25] |
| $\Delta\Phi$ | $(42.4 \pm 0.6 \pm 0.5)^\circ$ | – |
| $\alpha_-$ | $0.750 \pm 0.009 \pm 0.004$ | $0.642 \pm 0.013$ [27] |
| $\alpha_+$ | $-0.758 \pm 0.010 \pm 0.007$ | $-0.71 \pm 0.08$ [27] |
| $\bar{\alpha}_0$ | $-0.692 \pm 0.016 \pm 0.006$ | – |
| $A_{CP}$ | $-0.006 \pm 0.012 \pm 0.007$ | $0.006 \pm 0.021$ [27] |
| $\bar{\alpha}_0/\alpha_+$ | $0.913 \pm 0.028 \pm 0.012$ | – |

For Λ, a detailed parameter measurement (including the Electric/Magnetic form factor) has been done using the full angular analysis

# Investigating Spin-correlation of ΛΛbar

Similar example: full angular analysis of e+e- —> ΛΛbar

**Probing hyperon electric dipole moments with a full angular analysis**

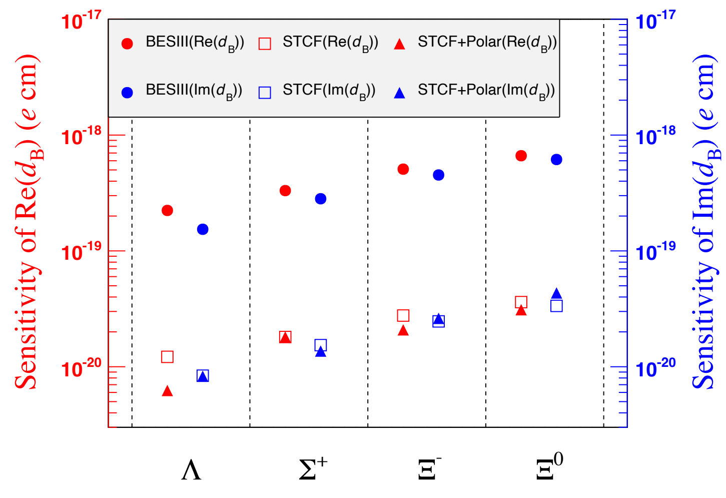
Jinlin Fu[1,*] Hai-Bo Li[1,2], Jian-Peng Wang[3,4,†] Fu-Sheng Yu[3,4,5], and Jianyu Zhang[1‡]

arXiv:2307.04364

$$\mathcal{A}^\mu = \bar{u}(k_1)\left[\gamma^\mu F_V + \frac{i}{2m_\Lambda}\sigma^{\mu\nu}q_\nu H_\sigma + \gamma^\mu\gamma_5 F_A + \sigma^{\mu\nu}q_\nu\gamma_5 H_T\right]v(k_2),$$

TABLE I. Estimated yields of pseudoexperiments based on the statistics from BESIII and STCF experiments, where $B_{tag}$ represents the branching ratio of cascade decay, $\epsilon_{tag}$ represents the expected detection efficiency, and $N^{evt}_{tag}$ represents the number of expected events after reconstruction.

| Decay channel | $J/\psi \to \Lambda\bar{\Lambda}$ | $J/\psi \to \Sigma^+\bar{\Sigma}^-$ | $J/\psi \to \Xi^-\bar{\Xi}^+$ | $J/\psi \to \Xi^0\bar{\Xi}^0$ |
|---|---|---|---|---|
| $B_{tag}/(\times 10^{-4})$ [31] | 7.77 | 2.78 | 3.98 | 4.65 |
| $\epsilon_{tag}/\%$ [24, 28, 32, 33] | 40 | 25 | 15 | 7 |
| $N^{evt}_{tag}/(\times 10^5)$(BESIII) | 31.3 | 7.0 | 6.0 | 3.3 |
| $N^{evt}_{tag}/(\times 10^8)$(STCF) [13] | 10.6 | 2.4 | 2.0 | 1.1 |




(a) Sensitivity for $Re(d_B)$ and $Im(d_B)$

A more recent sensitive study including EDM measurement of Λ, for BESIII and SuperTauCharmFactory

# Towards $\Lambda_c\Lambda_c$bar

## Cross-section measurements of +e- —> ΛcΛcbar are done by BESIII

**Measurement of the Energy-Dependent Electromagnetic Form Factors of a Charmed Baryon**

*arXiv:2307.07316*
*BESIII*

(Dated: July 17, 2023)

We study the process $e^+e^- \to \Lambda_c^+\bar{\Lambda}_c^-$ at twelve center-of-mass energies from 4.6119 to 4.9509 GeV using data samples collected by the BESIII detector at the BEPCII collider. The Born cross sections and effective form factors ($|G_{\rm eff}|$) are determined with unprecedented precision after combining the single and double-tag methods based on the decay process $\Lambda_c^+ \to pK^-\pi^+$. Flat cross sections around 4.63 GeV are obtained and no indication of the resonant structure $Y(4630)$, as reported by Belle, is found. In addition, no oscillatory behavior is discerned in the $|G_{\rm eff}|$ energy-dependence of $\Lambda_c^+$, in contrast to what is seen for the proton and neutron cases. Analyzing the cross section together with the polar-angle distribution of the $\Lambda_c^+$ baryon at each energy point, the moduli of electric and magnetic form factors ($|G_E|$ and $|G_M|$) are extracted and separated. For the first time, the energy-dependence of the form factor ratio $|G_E/G_M|$ is observed, which can be well described by

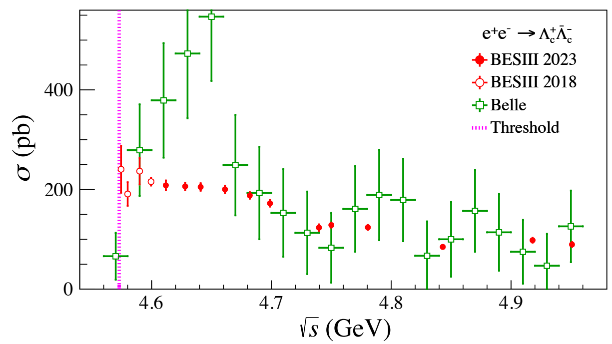



FIG. 2. Comparison of the cross sections of the $e^+e^- \to \Lambda_c^+\bar{\Lambda}_c^-$ process, where the red dots denote the results of this study and the green open squares indicate those of Belle [26]. The results of the previous BESIII measurement [32] are also updated and shown as red open dots.

$$\sigma_{B\bar{B}}(s) = \frac{4\pi\alpha^2 C\beta}{3s}|G_M(s)|^2\left(1 + \frac{2m_B^2c^4}{s}\left|\frac{G_E(s)}{G_M(s)}\right|^2\right).$$

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A large sample of BESIII on $\Lambda_c$ production available...

# Conclusions

- The $\Lambda_c$ MDM measurement requires the $\Lambda_c$ polarisation determination.
- LHCb has performed a full amplitude analysis including a large number of intermediate resonances.
- To obtain a higher precision in polarisation measurement, the model dependence of the amplitude analysis must be reduced.
- I introduced the idea of the model independent analysis using the e+e- data, that can potentially remove the model uncertainties.