"Amplitude for polarisation measurement, future BSM searches"

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International Workshop on Partial Wave Analyses and Advanced Tools for Hadron Spectroscopy

"On behalf of the LHCb collaboration"

Focus of the talk

1. The amplitude description
2. Production polarization
3. New physics searches

Amplitude for polarisation measurement

- Polarisation: spin projection on a given axis.
- Technique to measure it, example of 2-body decays:

  → 2 main elements: asymmetry parameter and polarization vector

$$\frac{1}{N}\frac{d\Gamma}{d\cos\theta} \propto \frac{1}{2}\left(1 + \boldsymbol{\alpha}\,\boldsymbol{P}\cos\theta\right)$$

θ : angle baryon momentum and baryon spin
P is the magnitude of the polarization vector

1. The decay asymmetry parameter α :is independent of the production mechanism.
2. The polarization **P** **instead depends on the production mechanism**.

Asymmetry parameter

- Asymmetry parameter α : is a property of the decay studied.
- It depends on the final/initial state spins and on the interactions involved

$$\alpha = \frac{2Re(A^*_{PV} A_{PC})}{|A_{PV}|^2 + |A_{PC}|^2}$$

A_{PV} = parity violating
A_{PC} = parity conserving

- The larger is $\boldsymbol{\alpha}$ the larger is the sensitivity on the polarization
- If parity is conserved, $\boldsymbol{\alpha = 0}$ → **loss of sensitivity**. Need a weak decay.
- Both, PV and PC amplitude needed
- However if $P = 0$, α can still be measured

Amplitude

- 3-body case: subsequent decays $A \rightarrow B(\rightarrow D + E) + C$

Isobar decomposition: factorize the amplitude in dynamic part and angular part:

$$\mathscr{A}(\vec{\Omega}) = \sum_i \psi_{r_i}(\vec{\Omega})\Delta_{r_i}(m_{r_i})$$

Most of the resonances described using relativistic Breit Wigner lineshape, but not always..

Helicity formalism [M. Jacob and G.C. Wick Annals Phys. 7, 404 (1959)]

- Nowadays huge datasets to perform very detailed analysis →the formalism need to evolve
- Two-body formula sill holds:

$$\frac{1}{N}\frac{d\Gamma}{d\cos\theta_i} \propto \frac{1}{2}(1 + \boldsymbol{\alpha_i}\, \boldsymbol{P} \cos\theta_i)$$

- Different angles depending on the chain
- Intermediate resonant states interfere between different chains

- Caveat: spin matching is not trivial!

Spin projection axis

- Example for $\Lambda_c^+ \to p \;\; K^- \pi^+$:

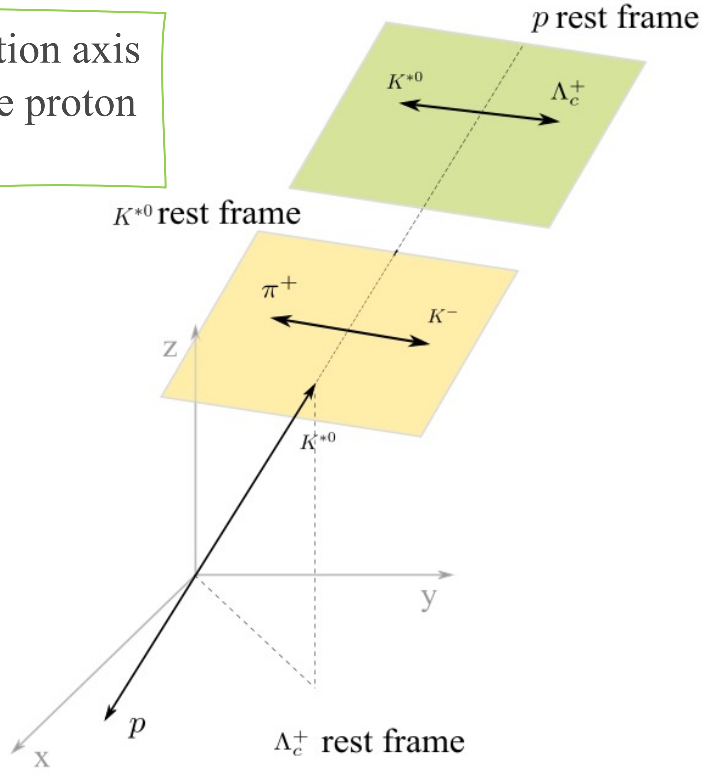
$$\Lambda_c^+ \to p \;\; K^- \pi^+ \;\; \Rightarrow$$

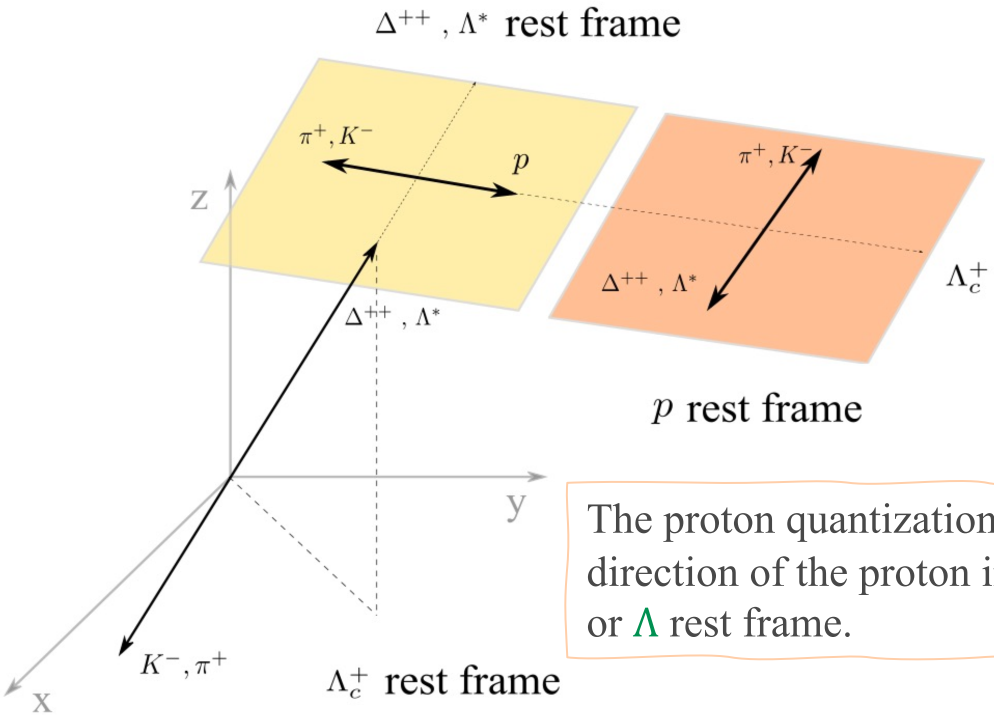
1. $\Lambda_c^+ \to (K^* \to K^- \pi^+)\, p$
2. $\Lambda_c^+ \to (\Delta^{++} \to p\pi^+)\, K^-$
3. $\Lambda_c^+ \to (\Lambda \to pK^-)\, \pi^+$

$$\frac{1}{N}\frac{d\Gamma}{d\cos\theta_i} \propto \frac{1}{2}(1 + \boldsymbol{\alpha_i}\, \boldsymbol{P} \cos\theta_i)$$

- The proton helicity frame is reached through a *different sequence of rotations and boosts*:

The proton quantization axis is the direction of the proton in the Λ_c^+ rest frame





The proton quantization axis is the direction of the proton in the Δ^{++} or Λ rest frame.

Spin projection axis

Spin axis matching methods: $\Lambda_c^+ \to p \; K^- \pi^+$

1. Add a rotation to each chain [soon in my thesis]

$$\mathcal{A}_{m,\lambda_p}(\Omega) = \mathcal{A}^{K^*}_{m,\lambda_p}(\Omega_{K^*}) + \sum_{\lambda'_p} \mathcal{A}^{\Lambda^*}_{m,\lambda'_p}(\Omega_{\Lambda^*})\, D(\alpha_1, \beta_{\Lambda^*}, \phi'_{K^-}) + \sum_{\lambda'_p} \mathcal{A}^{\Delta^{++}}_{m,\lambda'_p}(\Omega_{\Delta^{++}})\, D(\alpha_2, \beta_{\Delta^*}, \phi'_{K^-})$$

$$\alpha_1 = \begin{cases} 2\pi & \text{if } |\phi_p - \phi_\pi| > \pi \\ 0 & \text{else} \end{cases} \qquad \alpha_2 = \begin{cases} 2\pi & \text{if } |\phi_p - \phi_K| > \pi \\ 0 & \text{else} \end{cases}$$

The Wigner rotation contains an extra **"2π factor"** to compensate for the fact that a 2π rotation does not leave the system invariant. This is due to the two-to-one homomorphism SU(2)→ SO(3)

Spin projection axis

Spin axis matching methods:

1. Add a rotation to each chain [soon in my thesis]

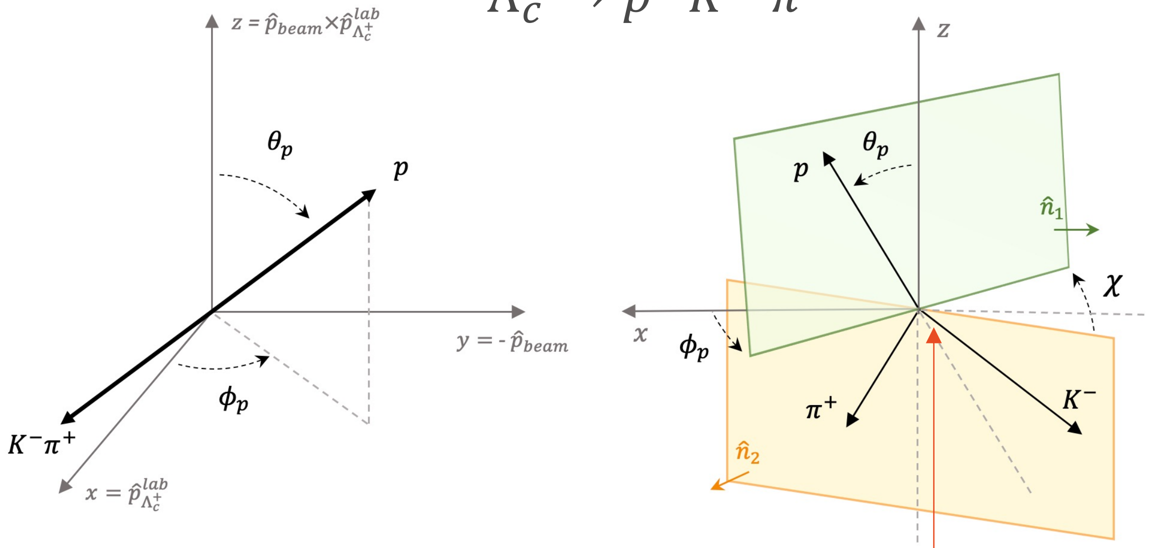
2. Factorize [MM et al.(JPAC), arXiv:1910.04566]

$$M_\lambda^\Lambda = \sum_\nu D_{\Lambda,\nu}^{1/2*}(\phi_1,\theta_1,\phi_{23})\,O_\lambda^\nu(\{\sigma\})$$

Plane orientation : containing polarization effects

Dalitz plot function : depends only on pair of invariant masses

$\Lambda_c^+ \to p\ \ K^-\ \pi^+$



Polarization responsible for the relative orientation of these two planes

3. Match the spin using canonical spin states (see Daniele Marangotto talk): [Adv.High Energy Phys. 2020 (2020), 6674595]

Spin projection axis

- Need: **Wigner rotation** to align the proton projection axis.

$$\mathcal{A}_{m,\lambda_p}(\Omega) = \mathcal{A}^{K^*}_{m,\lambda_p}(\Omega_{K^*}) + \sum_{\lambda'_p} \mathcal{A}^{\Lambda^*}_{m,\lambda'_p}(\Omega_{\Lambda^*})\, D(\alpha_1, \beta_{\Lambda^*}, \phi'_{K^-}) + \sum_{\lambda'_p} \mathcal{A}^{\Delta^{++}}_{m,\lambda'_p}(\Omega_{\Delta^{++}})\, D(\alpha_2, \beta_{\Delta^*}, \phi'_{K^-})$$

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- The wigner rotation contains a **"2π factor"** to compensate for the fact that a 2π rotation leave not the system invariant. This is due to the two-to-one homomorphism SU(2)→ SO(3)

Benchmark tests

Tests used to check the amplitude formalism and asses the necessity of the wigner rotations and 2π factor

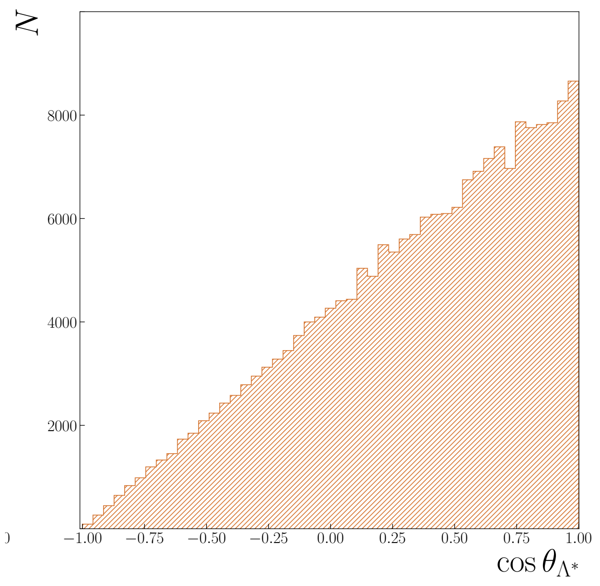
1. Linearity: if only one chain is included, the angular distribution MUST BE linear:

   Example for the Λ^* chain:

$$\frac{d\Gamma}{d\cos\theta} \sim \frac{4}{3}\left(1 + P_{\Lambda_c}\alpha_{\Lambda_c}^{\Lambda^*}\cos\theta_{\Lambda^*}\right)$$

where

$$\alpha_{\Lambda_c}^{\Lambda^*} = \frac{|H_{1/2,0}^{\Lambda_c^+\to\Lambda^*\pi^+}|^2 - |H_{-1/2,0}^{\Lambda_c^+\to\Lambda^*\pi^+}|^2}{|H_{1/2,0}^{\Lambda_c^+\to\Lambda^*\pi^+}|^2 + |H_{-1/2,0}^{\Lambda_c^+\to\Lambda^*\pi^+}|^2}:$$



Decomposition in the LS-basis

$$\begin{cases} h_{\frac{1}{2},0}^{\Lambda_c^+\to\Lambda^*\pi^+} = -\sqrt{\frac{1}{2}}\left(h_{\mathrm{PC}}^{\Lambda^*} + h_{\mathrm{PV}}^{\Lambda^*}\right) \\ h_{-\frac{1}{2},0}^{\Lambda_c^+\to\Lambda^*\pi^+} = -\sqrt{\frac{1}{2}}\left(h_{\mathrm{PC}}^{\Lambda^*} - h_{\mathrm{PV}}^{\Lambda^*}\right) \end{cases}$$

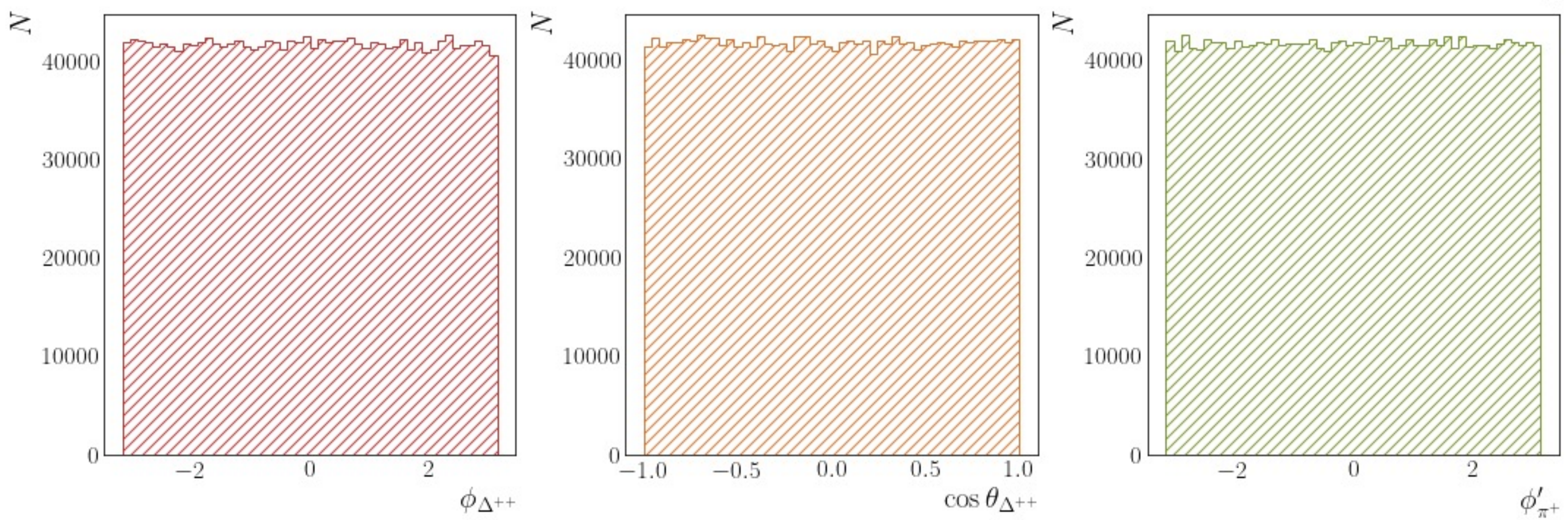
$$\alpha_{\Lambda_c}^{\Lambda^*} = -2\frac{\mathrm{Re}\left\{h_{PC}^{\Lambda^*}h_{PV}^{\Lambda^**}\right\}}{|h_{PC}^{\Lambda^*}|^2 + |h_{PV}^{\Lambda^*}|^2}$$

Non zero assymmetry parameter → need both parity violating(PV) and parity conserving (PC) amplitudes

Benchmark tests

1. If $P = 0$, the angular dependance drops
2. If parity conservation enforced for the Λ_c^+ decay, $\alpha_{\Lambda_c^+} = 0$

→ angular distributions should be flat

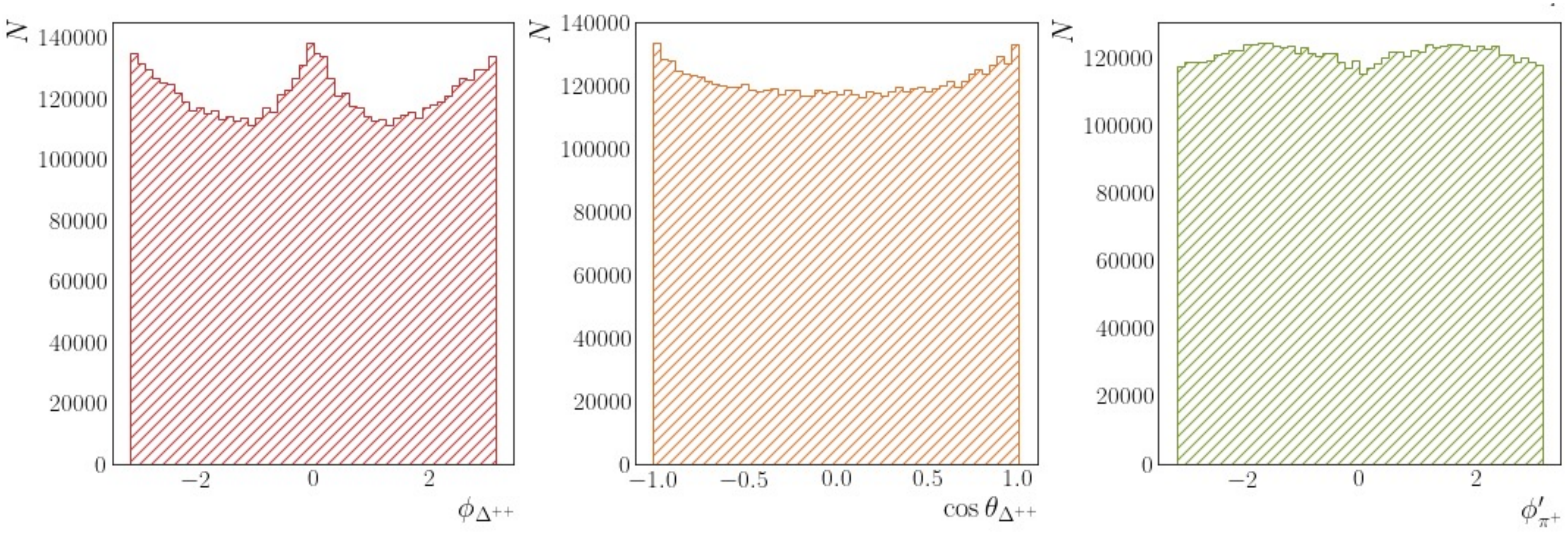


Example : Δ^{++} chain angles

Benchmark tests

Test used to assess the need of the azimuthal part of the Wigner rotation,

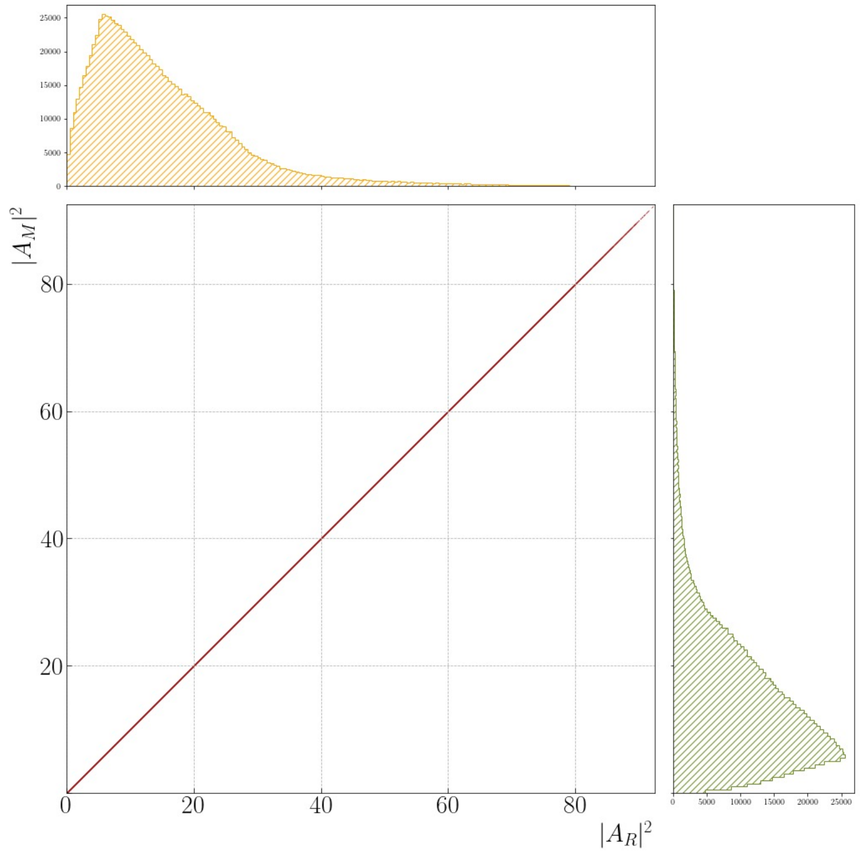
Without Wigner rotation and 2π condition the angular distributions **are not flat**



Example : Δ^{++} chain angles, without incuding the 2π condition

Additional test: comparison with DPD formalism

- This formalism and the Dalitz plot decomposition proposed in MM et al.(JPAC), arXiv:1910.04566 have been compared numerically and proven to be equivalent.
- Also compatible with the covariant formalism



Amplitude analysis: the model choice

Polarization included via spin density matrix, for spin ½ :

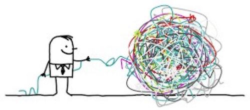
$$\rho = \frac{1}{2}\left(\mathcal{I} + \vec{P}\cdot\vec{\sigma}\right) = \frac{1}{2}\begin{pmatrix} 1+P_z & P_x - iP_y \\ P_x + iP_y & 1-P_z \end{pmatrix}$$

$$\Gamma = \rho_{\frac{1}{2},\frac{1}{2}}\left(|\mathcal{A}_{\frac{1}{2},\frac{1}{2}}|^2 + |\mathcal{A}_{\frac{1}{2},-\frac{1}{2}}|^2\right) + \rho_{-\frac{1}{2},\frac{1}{2}}\left(\mathcal{A}_{-\frac{1}{2},\frac{1}{2}}\mathcal{A}^*_{\frac{1}{2},\frac{1}{2}} + \mathcal{A}_{-\frac{1}{2},-\frac{1}{2}}\mathcal{A}^*_{\frac{1}{2},-\frac{1}{2}}\right) + \rho_{\frac{1}{2},-\frac{1}{2}}\left(\mathcal{A}_{\frac{1}{2},\frac{1}{2}}\mathcal{A}^*_{-\frac{1}{2},\frac{1}{2}} + \mathcal{A}_{\frac{1}{2},-\frac{1}{2}}\mathcal{A}^*_{-\frac{1}{2},-\frac{1}{2}}\right) + \rho_{-\frac{1}{2},-\frac{1}{2}}\left(|\mathcal{A}_{-\frac{1}{2},\frac{1}{2}}|^2 + |\mathcal{A}_{-\frac{1}{2},-\frac{1}{2}}|^2\right)$$

- The choice of the **model** give the **largest systematic** on the polarization measurement
- Need to assess which resonances contributes to the amplitude, by eye it is impossible to decide
- The choice of the model give the largest systematique on the polarization measurement
- Need to assess which resonances contributes to the amplitude, by eye it is impossible to decide
- Look at 2D χ^2/ndf , fit fractions

			Status as seen in —		
Particle	J^P	Overall status	$N\overline{K}$	$\Sigma\pi$	Other channels
$\Lambda(1116)$	$1/2^+$	****			$N\pi$ (weak decay)
$\Lambda(1380)$	$1/2^-$	**	**	**	
$\Lambda(1405)$	$1/2^-$	****	****	****	
$\Lambda(1520)$	$3/2^-$	****	****	****	$\Lambda\pi\pi, \Lambda\gamma$
$\Lambda(1600)$	$1/2^+$	****	***	****	$\Lambda\pi\pi, \Sigma(1385)\pi$
$\Lambda(1670)$	$1/2^-$	****	****	****	$\Lambda\eta$
$\Lambda(1690)$	$3/2^-$	****	****	***	$\Lambda\pi\pi, \Sigma(1385)\pi$
$\Lambda(1710)$	$1/2^+$	*	*	*	
$\Lambda(1800)$	$1/2^-$	***	***	**	$\Lambda\pi\pi, \Sigma(1385)\pi, N\overline{K}^*$
$\Lambda(1810)$	$1/2^+$	***	**	**	$N\overline{K}^*_2$
$\Lambda(1820)$	$5/2^+$	****	****	****	$\Sigma(1385)\pi$
$\Lambda(1830)$	$5/2^-$	****	****	****	$\Sigma(1385)\pi$
$\Lambda(1890)$	$3/2^+$	****	****	**	$\Sigma(1385)\pi, N\overline{K}^*$
$\Lambda(2000)$	$1/2^-$	*	*	*	
$\Lambda(2050)$	$3/2^-$	*	*	*	
$\Lambda(2070)$	$3/2^+$	*	*	*	
$\Lambda(2080)$	$5/2^-$	*	*	*	
$\Lambda(2085)$	$7/2^+$	**	**	*	
$\Lambda(2100)$	$7/2^-$	****	****	**	$N\overline{K}^*$
$\Lambda(2110)$	$5/2^+$	***	**	**	$N\overline{K}^*$
$\Lambda(2325)$	$3/2^-$	*	*		
$\Lambda(2350)$	$9/2^+$	***	***	*	
$\Lambda(2585)$		*	*		

PDG 2020



Focus of the talk

1. The amplitude description
2. **Production polarization**
3. New physics searches

Production polarization: experimental status

First measurements in 90's for strange baryons: strange baryons produced using unpolarized beams found polarized

1. 1976: 300 GeV protons on Be target FERMILAB-PUB-76-157-E : **polarization up to 28%**
2. 1978: 400 GeV proton beam on Be target FERMILAB-PUB-78-145-E: polarization up to 24% and most importantly. $\bar{\Lambda}^0$ **polarisztion found to be zero**

	Baryon	System	Beam energy [GeV]	Result	p_T range [GeV/c]
1976	Λ^0	pBe	300	18%	1.5
		pBe	400	24%	2.1
		pC and pW	920	~ 0	~ 0.8
		pN	450	up to 0.29%	0.86
1978	$\bar{\Lambda}^0$	pBe	400	0	up to 1.2
		p-X	400	0	up to 2.4
	Ω^-	pBe	800	~ 0	[0.5, 1.3]
1993	Σ^+	pCu	800	16%	1.0
	Ξ^0	pCu and pBe	400	$\sim 20\%$	1.6
	Ξ^+	pBe	800	up to 0.09%	0.76
1990	Ξ^-	pBe	400	up to 10%	1.21
		pCu	400	up to 0.07%	0.63
		pBe	800	up to 0.1%	>0.8

Features that seem to emerge:

- Increasing polarization with p_T, with a plateau at high p_T which depends on the energy
- A (not well-defined) target dependence
- Different polarization between hyperon and anti-hyperon.

J.Lach FNAL/C-92/378; CONF-9209299-1):

- Explain origin of polarization:

  Λ need a strange quark from the sea

  Strange quark polarized (for some p_T)

  →Predicting unpolarized anti-baryons. However, a non-zero polarization was measured later on for Ξ^- PhysRevD.33.3172 .

Mechanism at the origin of baryons polarization not understood, need new measurements

And new theoretical inputs

Production polarization

Production mechanism:

1. Strong interactions: $pp \rightarrow Baryons + X$

   Polarization matrix (for spin ½ baryons) :

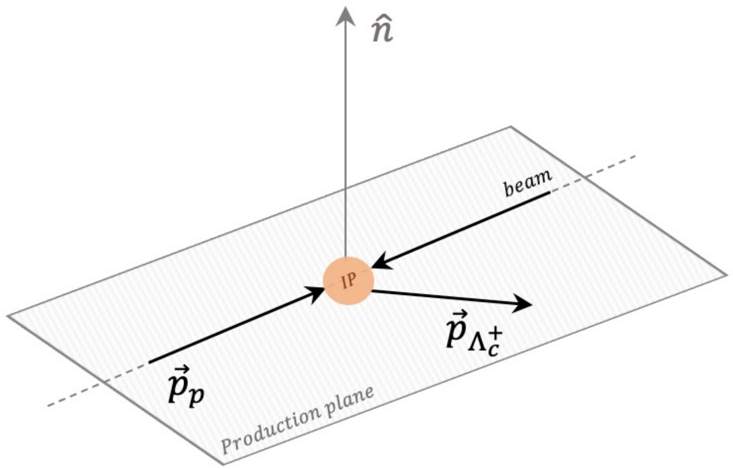
$$\rho = \frac{1}{2}\left(\mathcal{I} + \vec{P}\cdot\vec{\sigma}\right) = \frac{1}{2}\begin{pmatrix} 1+P_z & P_x - iP_y \\ P_x + iP_y & 1-P_z \end{pmatrix}$$

Parity conservation implies: $\rho_{\lambda,\lambda'} = \rho_{-\lambda,-\lambda'}$

i.e. $P_x = P_y = 0$

The polarization matrix is diagonal

- Polarization perpendicular to the production plane for strong production (along $\hat{n}$)



Polarization of beauty baryons: Λ_b^0 at LHCb

- Measurement of beauty baryon polarization: using $\boldsymbol{\Lambda_b^0 \to J/\psi\Lambda}$ at 7,8 and 13 TeV with the LHCb detector.
  Result: **P is compatible with zero**

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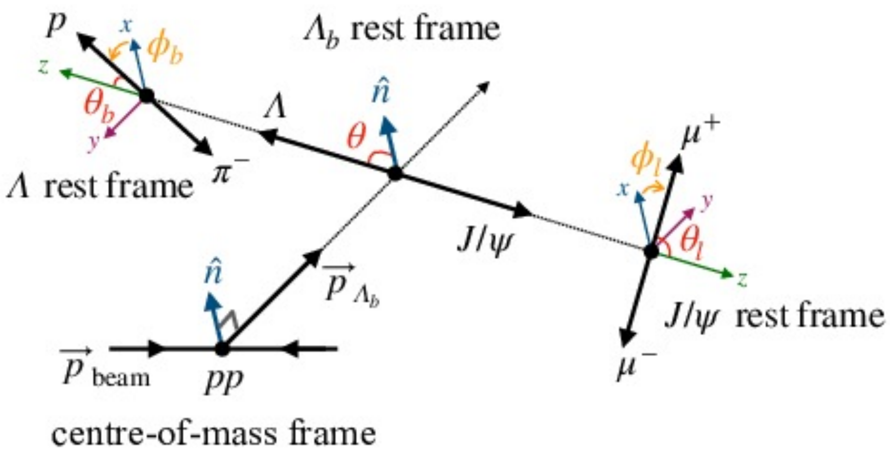
LHCB-PAPER-2012-057

- Kinematics of $\Lambda_b^0 \to J/\psi(\to \mu^+\mu^-)\Lambda$: 5 decay angles, one unit vector

$\hat{n} = \vec{p}_{beam} \times \vec{p}_{\Lambda_b} / |\vec{p}_{beam} \times \vec{p}_{\Lambda_b}|$ in pp c.o.m. frame



- Angular distribution

$$\frac{d^5\Gamma}{d\vec{\Omega}} = \frac{3}{32\pi^2} \sum_i J_i(a_+, a_-, b_+, b_-, \alpha_\Lambda, P_b) f_i(\vec{\Omega})$$

Angular term → polarisation accessible via J_{11} and J_{34}

Angular functions

$\frac{1}{4}P_b(2\lvert a_+\rvert^2 - 2\lvert a_-\rvert^2 + \lvert b_+\rvert^2 - \lvert b_-\rvert^2)$	$\sin^2\theta_l \cos\theta$
$\frac{1}{2}P_b\alpha_\Lambda \mathrm{Im}(b_+^* b_-)$	$\sin^2\theta_l \sin\theta_b \sin(2\phi_l + \phi_b) \sin\theta$

Polarization of beauty baryons: Λ_b^0 at LHCb

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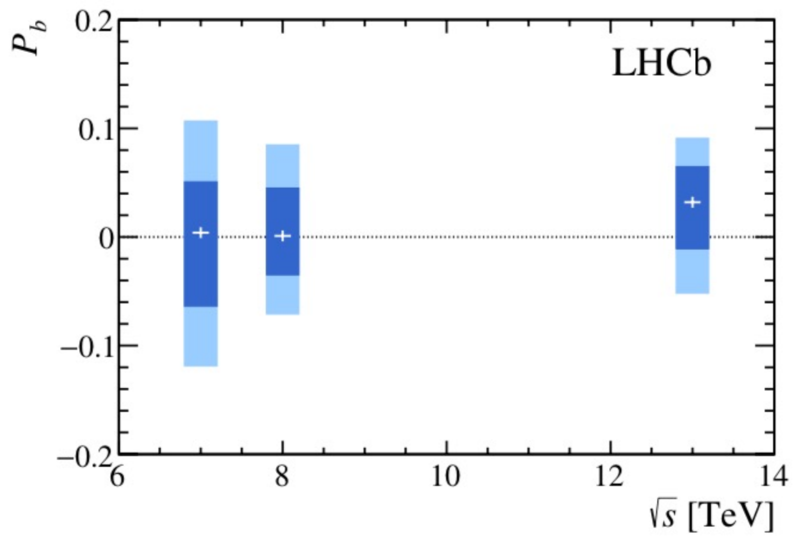
Observable	MPV	Interval
$\|a_+\|$	0.129	$[\ 0.033,\ 0.163]$
$\|a_-\|$	1.021	$[\ 0.998,\ 1.041]$
$\|b_-\|$	0.145	$[\ 0.060,\ 0.188]$
$\arg(a_+)$ [rad]	-2.523	$[-\pi, -1.131]$ or $[2.117, \pi]$
$\arg(a_-)$ [rad]	1.122	$[-2.633, -1.759]$ or $[0.101, 2.224]$
$\arg(b_-)$ [rad]	1.788	$[-\pi, -2.275]$ or $[0.232, \pi]$
P_b (7 TeV)	-0.004	$[-0.064,\ 0.051]$
P_b (8 TeV)	0.001	$[-0.035,\ 0.045]$
P_b (13 TeV)	0.032	$[-0.011,\ 0.065]$
α_b	-0.022	$[-0.048,\ 0.005]$

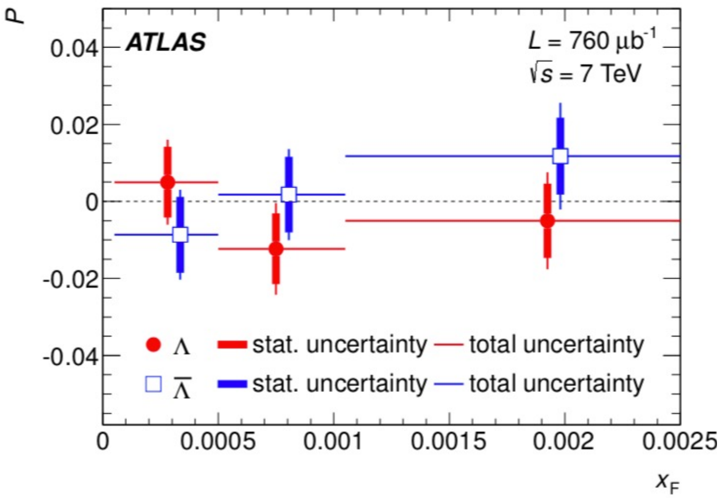


1. The Λ_b^0 production polarisation is consistent with zero, with 68% credibility level intervals of [−0.06,0.05], [−0.04,0.05] and [−0.01,0.07] at $\sqrt{s}$ of 7, 8 and 13TeV
2. $\alpha_b = -0.022$, 68% interval $[-0.048, 0.005]$
3. Measurement uses the new BES III value for α_Λ

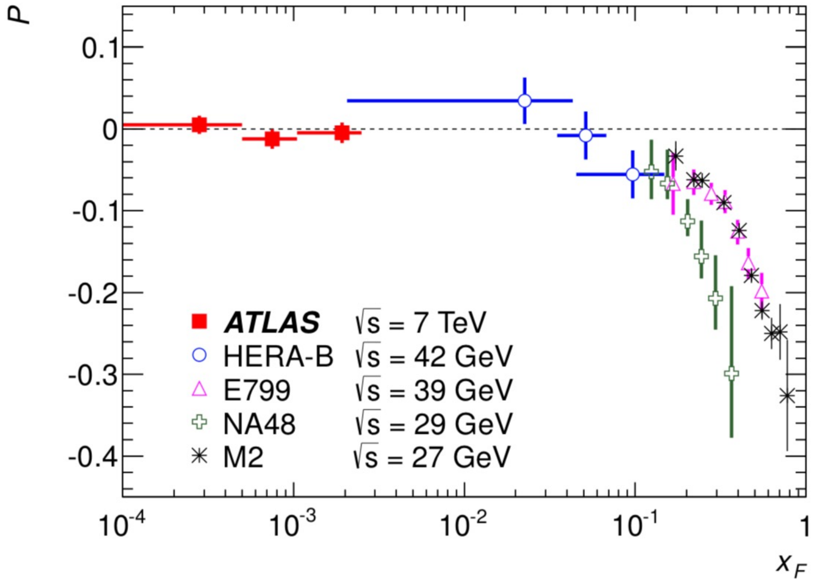
Hyperon polarisation, ATLAS

- 2014 by ATLAS Phys. Rev. D 91, 032004 (2015)

$$x_F = \frac{P_z}{P_{beam}}$$



- In the absence of any new polarization producing mechanism that would manifest itself at low x_F and high center-of-mass energies, the measured polarization is expected to be consistent with zero



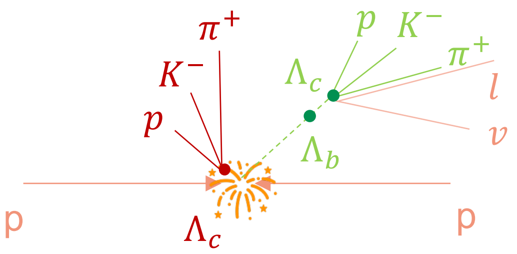
Sample	$\bar{x}_F$ [10^{-4}]	$\bar{p}_T$ [GeV]	Polarization Λ	Polarization $\bar{\Lambda}$
Full fiducial volume	10.0	1.91	$-0.010 \pm 0.005 \pm 0.004$	$0.002 \pm 0.006 \pm 0.004$
$x_F \in (0.5, 5) \times 10^{-4}$	2.8	1.83	$0.005 \pm 0.009 \pm 0.006$	$-0.009 \pm 0.010 \pm 0.006$
$x_F \in (5, 10.5) \times 10^{-4}$	7.5	1.85	$-0.012 \pm 0.009 \pm 0.008$	$0.002 \pm 0.010 \pm 0.007$
$x_F \in (10.5, 100) \times 10^{-4}$	19.3	2.12	$-0.005 \pm 0.010 \pm 0.008$	$0.012 \pm 0.010 \pm 0.010$
$p_T \in (0.8, 1.3)$ GeV	7.5	1.07	$-0.008 \pm 0.012 \pm 0.011$	$-0.004 \pm 0.013 \pm 0.013$
$p_T \in (1.3, 2.03)$ GeV	9.3	1.64	$-0.019 \pm 0.009 \pm 0.007$	$-0.003 \pm 0.010 \pm 0.007$
$p_T \in (2.03, 15)$ GeV	12.6	2.84	$-0.005 \pm 0.008 \pm 0.005$	$0.009 \pm 0.009 \pm 0.004$

- Good extrapolation from beam-line experiment

Production polarization

Production mechanism:

2. Weak interactions: for instance $pp \to \Lambda_b(\to B\ l\nu) + X$.
   W-boson involved



- Different projection axis
- The known V-A current is involved
- Prediction from HQET available [PRD49, 2363 (1994)]:

  - $\alpha_{\Lambda_b \to \Lambda_c^+ (l \to \nu\ l^-)} = -0.77(HQET)$
  - $\alpha_{\Lambda_b \to \Lambda_c^+ (l \to \nu\ l^-)} = -0.81(FQD)$

Polarized production expected

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3. **New physics searches**

Magnetic dipole moments (MDM)

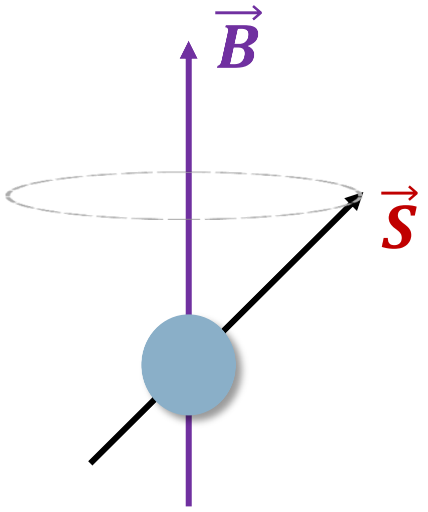
The measurement of Λ_c^+ polarization at LHCb is a necessary input for a long-term project aiming at measuring the magnetic dipole moment of charmed baryons

MDM is a fundamental property of particles with spin:

$$\vec{\mu} = \frac{g}{2}\frac{q}{m}\vec{S}$$ where g is the gyromagnetic factor

- For elementary particles, classical prediction $g = 2$. Quantum corrections can modify this values.
- If g ≠ 2 indication of a composite structure (→New Physics)

- Measured using **spin precession** in a magnetic field.
- Method successfully used for *leptons MDM* :
  1. Muon, g-2 expriment→4.2 σ tension with the SM Phys. Rev. Lett. 126, 141801
  2. Tau: short lifetime (87 μm), no direct measurements



Spin precession

Magnetic dipole moments (MDM)

(a) Science. 358 (6366): 1081–1084.
(b) Phys. Rev. D. 86 (1): 010001.

Baryons MDM:

- Proton and neutron measured, results in agreement with quark model prediction: $\boldsymbol{\mu_n = -\frac{2}{3}\mu_p}$
- Short lived baryons is harder → requires a strong magnetic field to precess before the decay

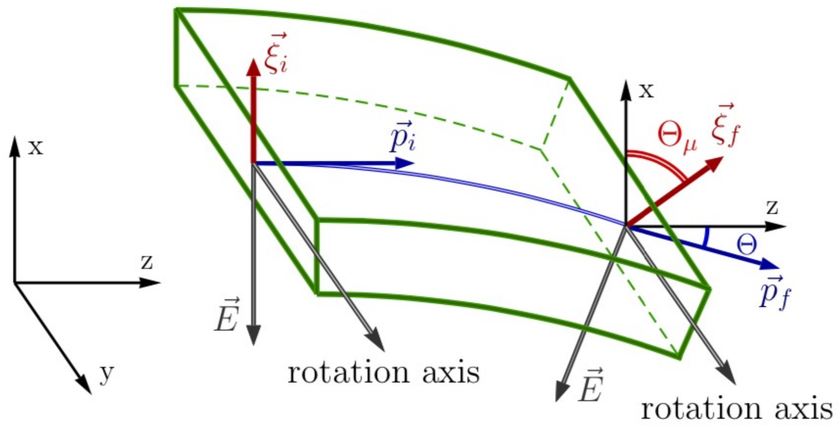
→ need for a new technique

MDM measurement using bent crystals:

- Conventional methods: maximum 45 T
- Use strong effective magnetic field produced beween crystal planes.
- Done in 1990 for Σ^+ and promising for charmed baryons FERMILAB-THESIS-1992-40

	$c\tau$
Σ^+	2.4 cm
Λ_c^+	**60 μm**

LHCb-INT-2017-011
JHEP 08 (2017)
EPJC-C (80) (2019)
EPJC 77 (2017)
JHEP 1708:120 (2017)
EPJC 77 (2017) 828
EPJ.C 80 (2020) 10, 929
arxiv:2010:11902



Λ_c^+ precession in a crystal

$$\Theta_\mu \approx \gamma\left(\frac{g}{2} - 1\right)\Theta$$

Need initial ($\overrightarrow{\xi_i}$) and final ($\overrightarrow{\xi_f}$) $\boldsymbol{\Lambda_c^+}$ polarization

Magnetic dipole moments (MDM): baryons

	$c\tau$	**Comments**	g **– factor – exp.**
p		Quark model description	$+5.585\ 694\ 702\ (17)$
n		$\mu_n = -\frac{2}{3}\mu_p$ satisfied	$-3.826\ 085\ 45\ (90)$
Σ^+	2.4 cm	Measured using bent crystals	$+6.1\ (12)_{stat}\ (10)_{syst}$
Λ_c^+	**60 μm**	**Not measured**	

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Prediction for $\boldsymbol{\Lambda_c^+}$ MDM: suffers from uncertanty on the charm quark mass

- Quark model: $\mu_{\Lambda_c^+} = \mu_c$
- Inserting the constituent quark mass: $\mu_{\Lambda_c^+} = 0.37\,\frac{g_c}{2}\,\mu_N$
- All predictions: $[0.34 - 0.43]\mu_N$

$$\mu_{\Lambda_c^+} = \langle \Lambda_c^+; \frac{1}{2}, +\frac{1}{2} | (\vec{\mu}_1 + \vec{\mu}_2 + \vec{\mu}_3) \cdot \vec{S}_z | \Lambda_c^+; \frac{1}{2}, +\frac{1}{2} \rangle$$

- Prediction using *radiative charmonium decays* (using BES III experimental data) without any charm quark mass uncertainty

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$$\frac{g_c}{2m_c} = 0.76 \pm 0.05\,\mathrm{GeV}^{-1}$$

$$\mu_{\Lambda_c} = \mu_c = \frac{g_c}{2m_c}\frac{2}{3}m_p\,\mu_N = (0.48 \pm 0.03)\,\mu_N$$

Conclusions

1. Amplitude analysis can be cumbersome and very model/person dependent (reproducibility can be an issue)
2. Baryon's polarisation has been studied starting from the first puzzling results on hyperon polarisation
3. Polarisation used to discriminate within different theoretical predictions
4. Since the 90's progress have been made:
   →new precise measurements requiring more sophisticated models
5. Recent and (close) future experiments can perform precise measurements on baryons (and not only) polarisation and asymmetry parameters with complex multi-dimensional analyses
6. Physics beyond the standard model: MDM

More measurements in the future

1. ee colliders: Belle II
2. pp colliders: LHC upgraded experiments
3. Fixed-target samples at LHCb, SMOG2
4. Study other baryons polarisation: $\Xi_c, \Omega_b, \Sigma_b, \Sigma_c, \ldots$

Back Up

Helicity formalism : amplitude for $\Lambda_c^+ \to p\, K^- \pi^+$

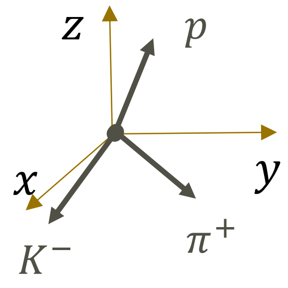
What happens when we sum up different chains? We pass through different paths.

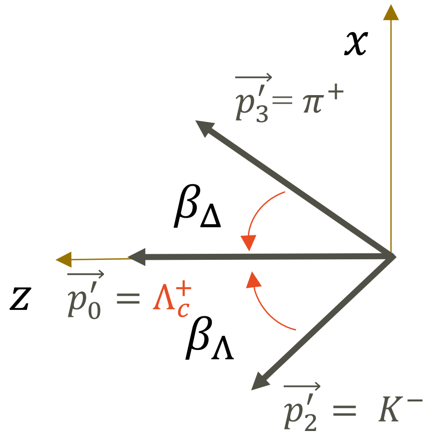
We need to sum over the final state helicities (only proton is non zero), but the definition of the helicity changes depending on the path used to reach the helicity frame (of the proton).

$\Lambda_c^+ \to p\, K^- \pi^+$	non resonant
$\Lambda_c^+ \to (K^* \to K^- \pi^+)\, p$	K^* chain
$\Lambda_c^+ \to (\Delta^{++} \to p \pi^+)\, K^-$	Δ chain
$\Lambda_c^+ \to (\Lambda \to p K^-)\, \pi^+$	Λ chain

From $\Lambda_c^+ \to \mathit{Res\ helicity\ frame}$ then from $\mathit{Res} \to \mathit{proton\ helicity\ frame}$

$@\Lambda_c^+$

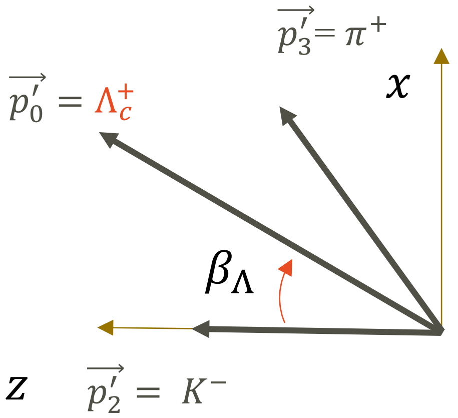




$@\ \vec{p_1}$ rest
reached from K^*

boost from $\vec{p_{\Lambda_c^+}} = 0$
along $\vec{p_1}$ $\parallel z$ ➔
$\vec{p'_{\Lambda_c^+}}$ $\parallel -z$

(x, z) plane



$@\ \vec{p_1}$ rest
reached from Λ

boost from $\vec{p_0}$ along
Λ^*
➔ $\vec{p_2'}$ $\parallel -z$

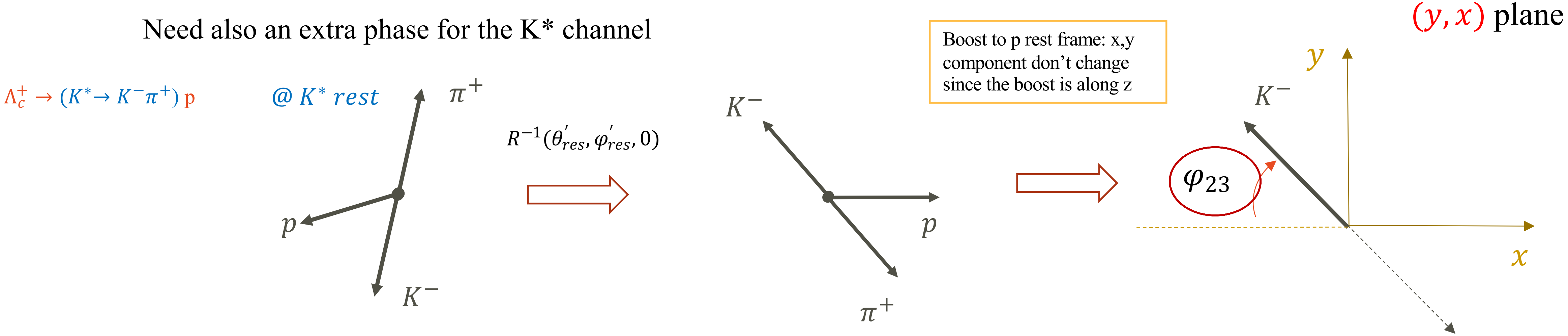
Boost along z direction:

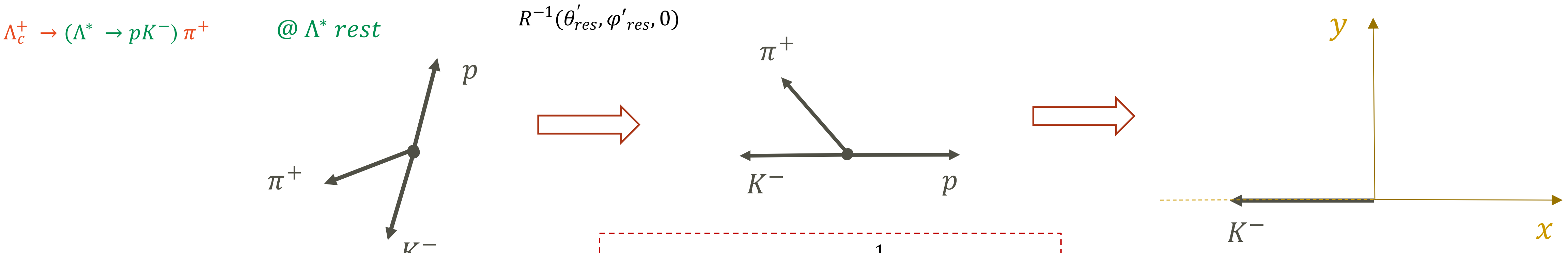
$$t' = \gamma\left(t - \frac{v}{c^2} z\right)$$
$$x' = x$$
$$y' = y$$
$$z' = \gamma\,(z - vt)$$

2 non collinear boost give rise to a Wigner rotation:
need to rotate around y axis of beta angles

Helicity formalism : Wigner rotation, azimuthal part

Need also an extra phase for the K* channel





$$D^{s*}_{\lambda_\Lambda,\lambda_p}(\phi', \theta', 0) * D^{\frac{1}{2}*}_{m,\lambda_\Lambda}(\phi, \theta, 0)$$

MDM predictions

nb.	$\mu_{\Lambda_c^+}[\mu_N]$	Approach	Ref.
1	0.15 ± 0.05	QCD spectral sum rule	[94]
2	0.24 ± 0.02	NNLO in the HHCPT	[95]
5	$0.33 - 0.34$	Interquark potential and Fadeev formalism	[96]
3	0.34	Independent quark model, power-law potential	[97]
4	$0.369 - 0.385$	Hyper central Coulomb plus power potential	[98]
5	$0.36 - 0.41$	5q components contributions	[99]
6	0.37	Chiral perturbation theory	[100]
7	0.38	Soliton model and chiral perturbation theory	[101]
8	0.392	SU(4) chiral constituent quark model	[102]
9	0.40 ± 0.05	Light cone QCD sum rules	[103]
10	0.411	Bag model reexamined	[104]
11	0.42 ± 0.01	Relativistic three-quark model	[105]
12	0.48 ± 0.03	Radiative charmonium decays	[3]
13	0.52	Dirac point-form dynamics	[106]

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