Λ_c^+ POLARIZATION MEASUREMENT TROUGH $\Lambda_c^+ \to p\, K^- \pi^+$ DECAY IN pp AND FIXED-TARGET DATA AT LHCb

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Motivations

Goal: measure Λ_c^+ polarization

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EPJC 77 (2017) 828

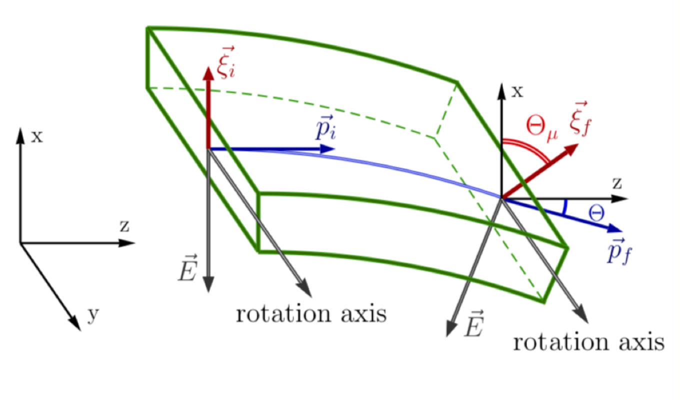
- **Why:** Proposal for MDM and EDM measurement of charm baryons at LHCb. The combined measurements of MDMs of Ξ_c^+ and Λ_c^+ can help understand the g-factor of the charm quark

  → Need the polarization in fixed-target collision as input of MDM measurements.

- Fixed-target pNe sample collected at LHCb in 2017 is too small so we perform a preliminary analysis in the pp collision system to fix the amplitude model and fit the amplitude parameters.

- Previous amplitude analysis: amplitude fit of $\boldsymbol{\Lambda_c^+ \to p\, K^- \pi^+}$ with 946 events (FermiLab) but in LHCb we have >100 times more events

- Final step: apply the model obtained in pp to the fixed-target sample and measure the polarization



Example of Λ_c^+ precession in a crystal

LHCb detector and position of the crystals

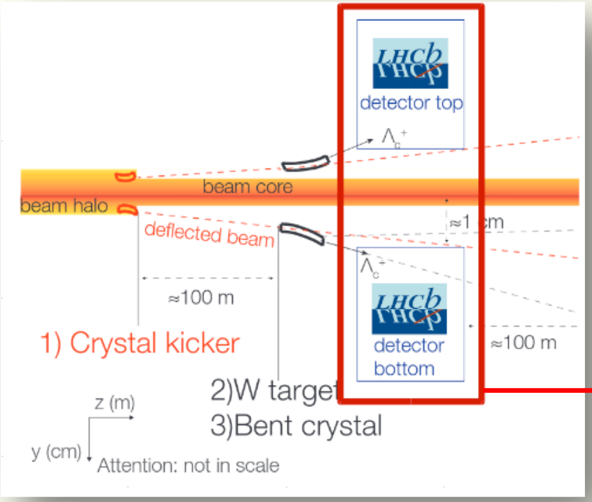
LHCb detector: is a single-arm forward spectrometer, designed for the study of beauty and charm hadrons.

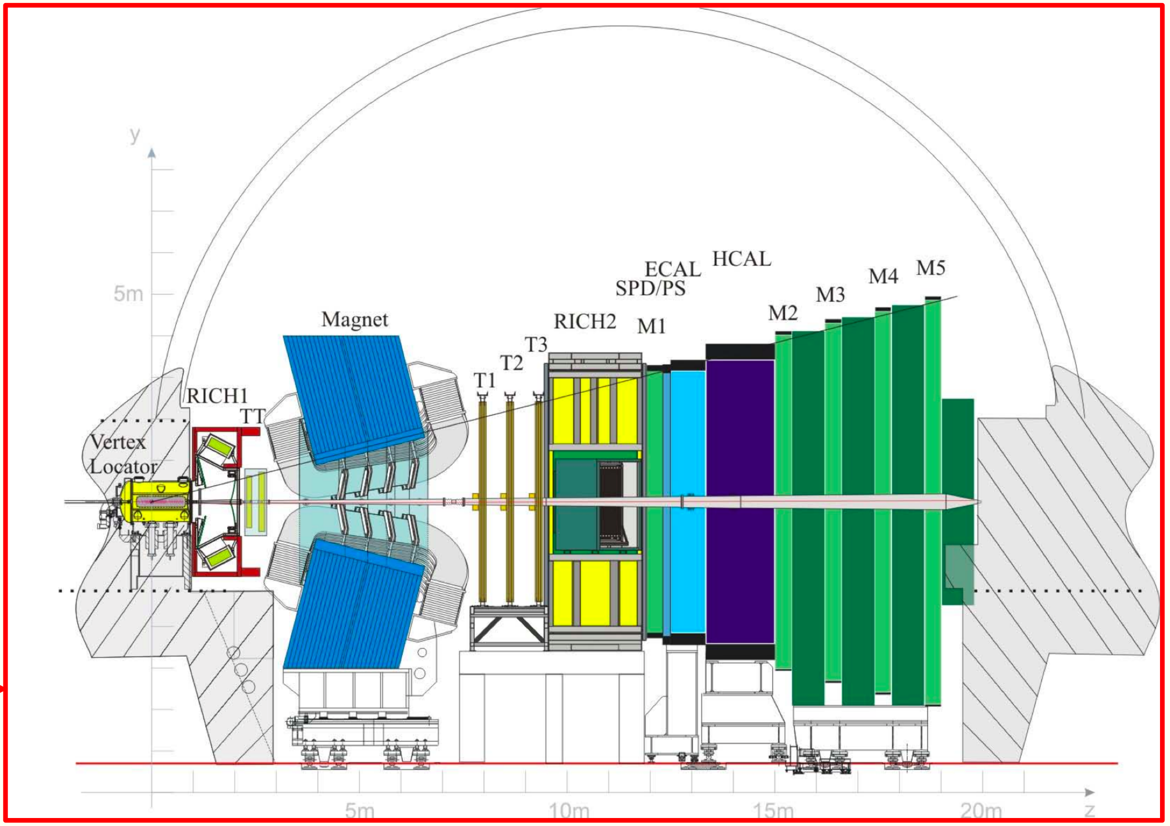
[IJMPA 30 (2015) 1530022]
[JINST 3 (2008) S08005]

- Typical momentum resolution ~0.5%
- Typical K/π separation ~95% for 5% misID.
- reconstruct vertices decay time resolution: 45 fs and IP resolution: 20 μm
- Acceptance $2 < \eta < 5$
- SMOG system for fixed target mode

The crystal kickers and analysers:

placed upstream of LHCb (which is used to analyse the decay products.)

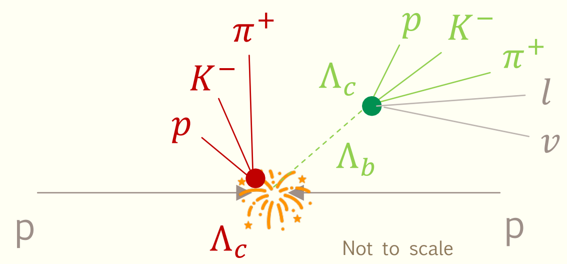




Λ_c^+ polarization

Is Λ_c^+ expected to be polarized?

It depends on the production mode.



- Weak production: from $\Lambda_b \to \Lambda_c l v$ then Λ_c can acquire a polarization.
- Strong production (prompt): **parity conservation** holds, if there is a polarization it expected to be perpendicular to the production plane.
  Although due to gluon emission during the production at LHC energy we expect the polarization to be lost.

Decay studied:

Λ_c^+ 3-body resonant decay $\Lambda_c^+ \to p\, K^- \pi^+$
It has a very rich structure, it passes by 3 different intermediate kind of resonances and this is the key to measure polarization

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

How can we measure Λ_c^+ polarization:

But why do we need different chains?

If we only have one intermediate resonances the information is lost.
Take for instance Δ^{++} chain, the angular distribution looks like:

Equations by Emi Kou

$$d\Gamma(\xi) \propto [a_0 - b_0 \xi \cos\theta - b_1 \xi \sin\theta \cos\phi] \longrightarrow \left[\begin{array}{lll} a_0 & : & |A|^2, |B|^2 \\ b_0 & : & \xi Re(AB^*) \\ b_1 & : & \xi Re(AB^*) \end{array} \right.$$

polarization

We can't mesure the phase of the amplitude (since we take the modulus squared), hence **we cannot measure the polarization** but only the product $\xi |A||B| \cos\delta_{AB}$

If we have interferences between different chains, we can measure the phases of the couplings (δ_{AB}, δ_{CD} etc..) or a combination of them and eventually get to measure the polarization!

$$a_0 \longrightarrow |A|, |B|, |C|, |D|, \; |A||D| \cos\delta_{AD}, |A||D| \sin\delta_{AD}, \; |B||C| \cos\delta_{BC}, |B||C| \sin\delta_{BC} \tag{59}$$

$$\begin{aligned} b_0 \longrightarrow \; & \xi |A||B| \cos\delta_{AB}, \xi |A||B| \sin\delta_{AB}, \; \xi |C||D| \cos\delta_{CD}, \xi |C||D| \sin\delta_{CD}, \\ & \xi |A||C| \cos\delta_{AC}, \xi |A||C| \sin\delta_{AC}, \; \xi |B||D| \cos\delta_{BD}, \xi |B||D| \sin\delta_{BD} \end{aligned} \tag{60}$$

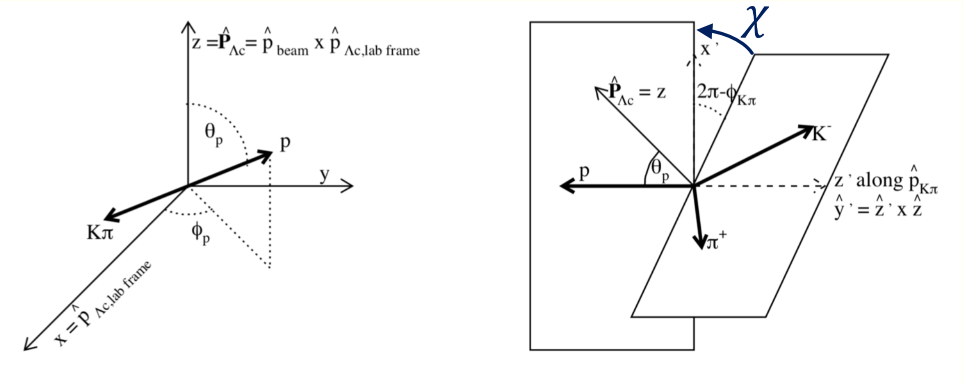
A Dalitz plot analysis is needed to disantangle the resonance's contributions

Amplitude formalism for $\Lambda_c^+ \to p\, K^-\pi^+$: angles and frames

- In the Λ_c^+ restframe: intial state characterized by the spin projection $m = \pm\frac{1}{2}$ along the spin quantization axis z
- Prompt production: polarization expected perpendicular to the production plane (parity conservation in strong production)
- We define $\Re$ **the polarization frame** as follow:

$$\hat{z} = \hat{p}_{beam} \times \hat{p}^{lab}_{\Lambda_c^+} \qquad \hat{x} = \hat{p}^{lab}_{\Lambda_c^+} \qquad \hat{y} = \hat{z} \times \hat{x}$$

- Angles:
  - θ_p , ϕ_p : proton polar and azimuthal angle
  - χ : angle between the planes formed by the proton direction and the z axis and K and π directions



- $\Lambda_c^+ \to p\, K^-\pi^+$ 3-body decay proceding via intermediate resonances:

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

- Angles of the resonances in $\Re$:

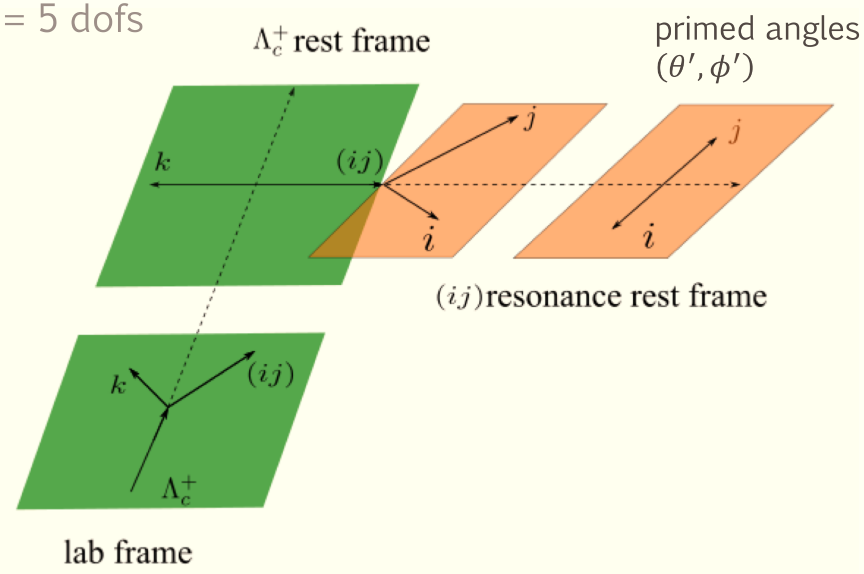
$$\theta_{K^{*0}},\ \phi_{K^{*0}},\ \theta_{\Delta},\ \phi_{\Delta},\ \theta_{\Lambda^*}\ \phi_{\Lambda^*}$$

$$\theta_R = \mathrm{Atan2}\left(\vec{p}_R^{\,\mathrm{lab}} \cdot \hat{y}, \vec{p}_R^{\,\mathrm{lab}} \cdot \hat{x}\right)$$

$$\phi_R = \mathrm{Atan2}\left(\sqrt{(\vec{p}_R^{\,\mathrm{lab}} \cdot \hat{x})^2 + (\vec{p}_R^{\,\mathrm{lab}} \cdot \hat{y})^2}, \vec{p}_R^{\,\mathrm{lab}} \cdot \hat{z}\right)$$

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

The kinematics of Λ_c^+ 3-body decay can be described by 5 variables :
(4 momenta of 3 particles (12 dofs) – energy momentum conservation - 3 masses = 5 dofs



- θ_p polar angle of the proton @Λ_c^+
- ϕ_p: azimuthal angle of the proton @Λ_c^+
- χ : angle between the planes formed by the proton direction and the z axis and K and π directions
- $m_{p\pi}^2 = (P_p + P_\pi)^2$
- $m_{pK}^2 = (P_p + P_K)^2$

Why: in the Λ_c^+ rest frame, p, K, π are in the same plane, angles between them are determined by $m_{p\pi}^2$ and m_{pK}^2. The orientation of the plane is given by 3 Euler angles θ_p , ϕ_p and χ describing a rotation from the $\Re$ frame to a $\Re''$ frame where the z'' axis = proton direction and p, K, π lie in the (x'', z'') plane.

The helicity formalism

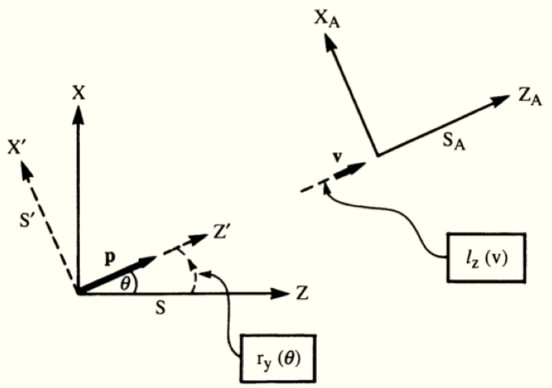
The helicity operator is defined as: $\Lambda = \dfrac{\vec{J}\cdot\vec{p}}{||\vec{p}||} = (\vec{L}+\vec{S})\cdot\hat{\mathbf{p}} = \vec{S}\cdot\hat{\mathbf{p}}$

One can build a basis of simultaneous eigenstates of $\vec{J}^2, J_z, \vec{S}^2$ and Λ the **helicity basis**.

Why the helicity basis? There are some useful property of the helicity operator:

- invariance under rotations
- invariance under boosts along $\hat{p}$

Clever choice to project the total angular momentum→ a frame where the particle momentum is aligned to the z-axis and the particle is at rest i.e. **the helicity frame**. In this frame the spin projection s_z and the helicity λ coincide.



@ S : A is described by $|\boldsymbol{p};\lambda\rangle$
@ S_A : A is at rest with spin component $s_Z = \lambda$

Transformation between this 2 frames:

boost + rotation → $h(\boldsymbol{p}) = r(\phi,\theta,0)l_z(v)$ and $S = h^{-1}(\boldsymbol{p})S_A$

For the particle state this translate to: $|\boldsymbol{p};\lambda\rangle = U[h(\boldsymbol{p})]\big|p_0; s, s_z = \lambda\rangle$

The helicity formalism

a → 1(→ 3 + 4) + 2

$$A_{angular}(a \to f) = \sum_{\lambda_1} D^{s_1^*}_{\lambda_1,\lambda_3-\lambda_4}(\phi_3,\theta_3,0) D^{J^*}_{M,\lambda_1-\lambda_2}(\phi_1,\theta_1,0) B_{\lambda_3,\lambda_4} A_{\lambda_1,\lambda_2}$$

$J = \Lambda_c^+$ spin, λ_i = particles helicities

Angles: θ_1, ϕ_1 = measured in restframe of a (Λ_c^+)
θ_3, ϕ_3 = measured in restframe of 1 (resonance R)

D. Richman, An experimenters guide to the helicity formalism

- $B_{\lambda_3,\lambda_4}, A_{\lambda_1,\lambda_2}$ = helicity couplings (parameters to fit)
- $D^{j}_{m',m}(\phi,\theta,0)$ = wigner functions
- When the intermediate decay it's strong (Λ's and Δ's) parity conservation reduce the number of parameters (A_i, B_i) :

$$\langle \lambda_1,\lambda_2 | U | a\rangle = \langle \lambda_1,\lambda_2 | \Pi U \Pi | a \rangle = \eta_1\eta_2\eta_a(-i)^{s_1+s_2-J} \times \langle -\lambda_1,-\lambda_2 | U | a\rangle$$

- Multiply the angular part by the relativistic Breit-Wigner: $A_{res}(a \to f) = B_r(m_r) A_{angular}(a \to f)$
- Amplitude of each chain:

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

$$A_{K^*}(m,\lambda_p) = B_{K^*}(m_{K\pi}) \sum_{\lambda_{K^*}} D^{s_{K^*}*}_{\lambda_{K^*},0}(\phi'_K,\theta'_K,0)\, D^{\frac{1}{2}*}_{m,\lambda_{K^*}-\lambda_p}(\phi_{K^*},\theta_{K^*},0)\, b_{\lambda_p}\, a_{\lambda_{K^*}}$$

$$A_{\Delta}(m,\lambda_p) = B_{\Delta}(m_{p\pi}) \sum_{\lambda_{\Delta}} D^{s_{\Delta}*}_{\lambda_{\Delta},-\lambda_p}(\phi'_\pi,\theta'_\pi,0)\, D^{\frac{1}{2}*}_{m,\lambda_{\Delta}}(\phi_{\Delta},\theta_{\Delta},0)\, d_{\lambda_p}\, c_{\lambda_{\Delta}}$$

$$A_{\Lambda^*}(m,\lambda_p) = B_{\Lambda^*}(m_{pK}) \sum_{\lambda_{\Lambda^*}} D^{s_{\Lambda}*}_{\lambda_{\Lambda^*},\lambda_p}(\phi'_p,\theta'_p,0)\, D^{\frac{1}{2}*}_{m,\lambda_{\Lambda^*}}(\phi_{\Lambda^*},\theta_{\Lambda^*},0)\, f_{\lambda_p}\, e_{\lambda_{\Lambda^*}}$$

m	λ_p
$\frac{1}{2}$	$\frac{1}{2}$
$\frac{1}{2}$	$-\frac{1}{2}$
$-\frac{1}{2}$	$\frac{1}{2}$
$-\frac{1}{2}$	$-\frac{1}{2}$

	J^P
Λ_c^+	$\frac{1}{2}^-$
p	$\frac{1}{2}^-$
K	0^-
π^+	0^-

$\Lambda_c^+ \to p\, K^- \pi^+$ non resonant

$\Lambda_c^+ \to (K^* \to K^- \pi^+)\, p$ K^* chain

$\Lambda_c^+ \to (\Delta^{++} \to p\pi^+)\, K^-$ Δ chain

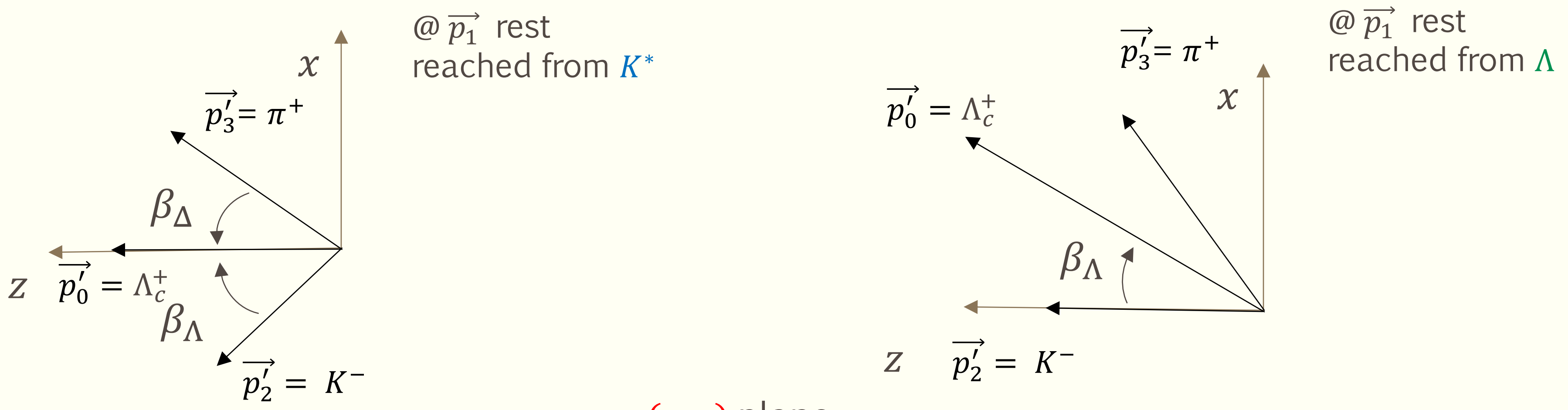
$\Lambda_c^+ \to (\Lambda \to pK^-)\, \pi^+$ Λ chain

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

What happen 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).

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



(x, z) plane

$\boxed{\text{2 non collinear boost give rise to a Wigner rotation}}$

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

$$\mathcal{A}_{m,\lambda_p} = \sum_s \sum_{\lambda_{K^{*0}}} B_s(M_{K\pi}) \times D^{s*}_{\lambda_{K^{*0}},0}(\phi'_K, \theta'_K, 0)\, D^{\frac{1}{2}*}_{m,\lambda_{K^{*0}}-\lambda_p}(\phi_{K^{*0}}, \theta_{K^{*0}}, 0)\, ba_{\lambda_{K^{*0}},\lambda_p}$$

$$+\sum_s \sum_{\lambda'_p,\lambda_{\Delta^{++}}} B_s(M_{p\pi}) \times D_{\lambda'_p,\lambda_p}(\alpha_2, \beta_{\Delta^{++}}, \phi'_K) D^{s*}_{\lambda_{\Delta^{++}},-\lambda'_p}(\phi'_\pi, \theta'_\pi, 0)\, D^{\frac{1}{2}*}_{m,\lambda_{\Delta^{++}}}(\phi_{\Delta^{++}}, \theta_{\Delta^{++}}, 0)\, d_{\lambda'_p} c_{\lambda_{\Delta^{++}}}$$

$$+\sum_s \sum_{\lambda'_p,\lambda_{\Lambda^*}} B_s(M_{pK}) \times D_{\lambda'_p,\lambda_p}(\alpha_1, \beta_{\Lambda^*}, \phi'_K) D^{s*}_{\lambda_{\Lambda^*},\lambda'_p}(\phi'_p, \theta'_p, 0)\, D^{\frac{1}{2}*}_{m,\lambda_{\Lambda^*}}(\phi_{\Lambda^*}, \theta_{\Lambda^*}, 0)\, f_{\lambda'_p} e_{\lambda_{\Lambda^*}}$$

$$\alpha_1 = 2\pi \text{ if } \phi_p - \phi_K > -\pi$$
$$\alpha_1 = -2\pi \text{ if } \phi_p - \phi_K > \pi$$
$$\alpha_1 = 0 \text{ else}$$

$$\alpha_2 = 2\pi \text{ if } \phi_p - \phi_\pi > -\pi$$
$$\alpha_2 = -2\pi \text{ if } \phi_p - \phi_\pi > \pi$$
$$\alpha_2 = 0 \text{ else}$$

- The relativistic Breit-Wigner (BW=1 for the non resonant)

$F_L(q)$: Blatt-Weisskopf strong coupling factors

$$B_r(m_r) = (-2|p_c||p_a|)^L \frac{F_{\Lambda_c} F_r}{m_0^2 - m_r^2 - i m_0 \Gamma_r}$$

$$\Gamma_r = \Gamma_0 (\frac{q}{q_0})^{2L+1} \frac{m_0}{m_r} \frac{F_r^2(q)}{F_r^2(q_0)}$$

Amplitude formalism: energy part and polarization

- Spin density matrix for spin ½ baryons: due to parity conservation→ keep only P_z

$$\rho = \frac{1}{2}\left(1 + \boldsymbol{P}_{\boldsymbol{\Lambda_c}} \cdot \vec{\sigma_i}\right) = \begin{pmatrix} \frac{1+P_z}{2} & P_x + i\,P_y \\ P_x - i\,P_y & \frac{1-P_z}{2} \end{pmatrix}$$

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

- Total amplitude with polarization $P_{\Lambda_c^+}$ along z:

Coherent sum over resonances

Angular part

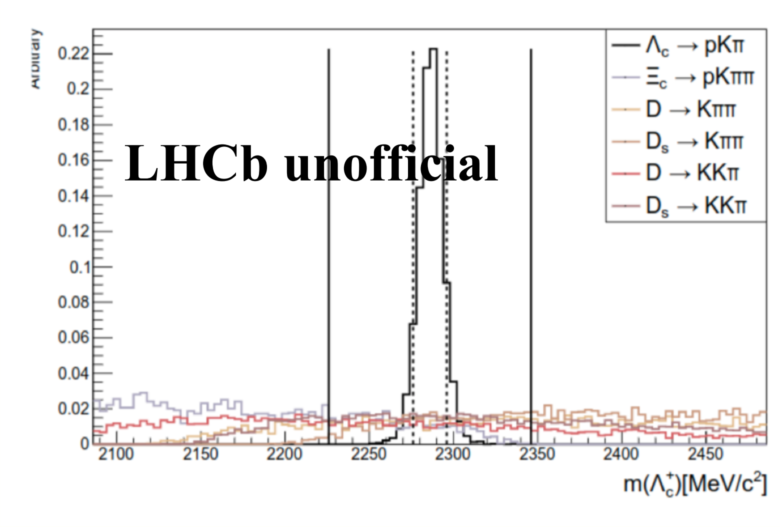
$a \rightarrow r(\rightarrow 3 + 4) + 2$

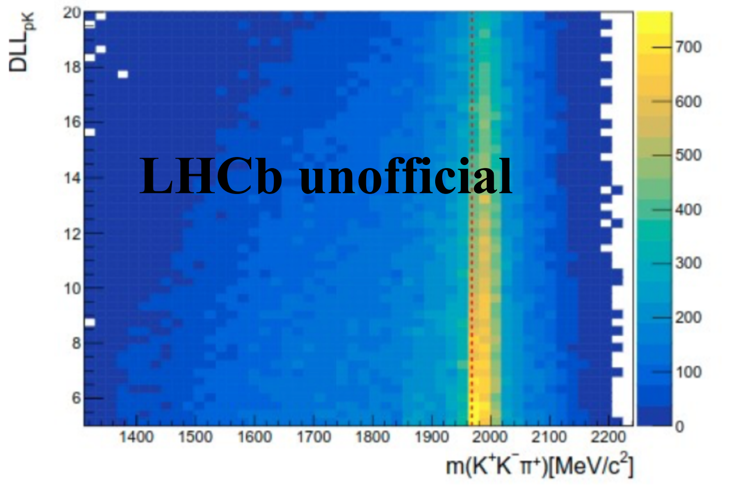
$$d\Gamma \sim S(\vec{x}) = \frac{(1 + \mathbf{P}_{\Lambda_c})}{2}\left(|\sum_r B_r(m_r)\alpha_{r,\frac{1}{2},\frac{1}{2}}|^2 + |\sum_r B_r(m_r)\alpha_{r,\frac{1}{2},-\frac{1}{2}}|^2\right)$$
$$+ \frac{(1 - \mathbf{P}_{\Lambda_c})}{2}\left(|\sum_r B_r(m_r)\alpha_{r,-\frac{1}{2},\frac{1}{2}}|^2 + |\sum_r B_r(m_r)\alpha_{r,-\frac{1}{2},-\frac{1}{2}}|^2\right)$$

The DATA sample

Fit on full data sample (*pp* 2016 after selections, with less than 1% background) and MC Sim09e.

- First designed general-purpose cuts to remove combinatorial background (table on the right).
- IP: impact parameter → related to a given particle coming from a secondary vertex.
- ProbNN: neural-network particle identification variable.
- Lots of possible misidentified backgrounds but mostly flat in the invariant-mass window
- Still so abundant they clearly show in data





Any track
$9 < \chi^2_{\rm IP}(h) < 200$
$\mathrm{GhostProb(h)} < 0.4$
$p_T(h) > 500\,\mathrm{MeV}/c$
$3 < p(h) < 150\,\mathrm{GeV}/c$
$ProbNNh(h) > 0.4$
Proton only
$p_T(p) > 1000\,\mathrm{MeV}/c$
$10 < p(p) < 100\,\mathrm{GeV}/c$
Λ_c^+ cuts
$\tau(\Lambda_c^+) < 0.0015\,\mathrm{ns}$
$\chi^2_{\rm flydist.}(\Lambda_c^+) > 40$
$\chi^2/\mathrm{ndf(endvertex)} < 5$
$\mathrm{DIRA}(\Lambda_c^+) > 0.99995$

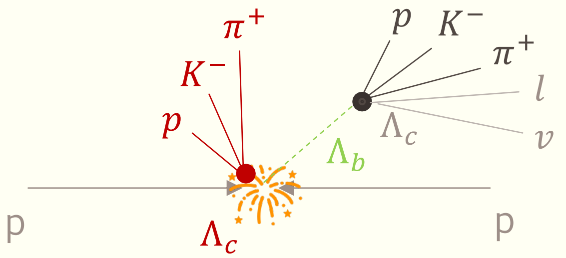
The DATA sample

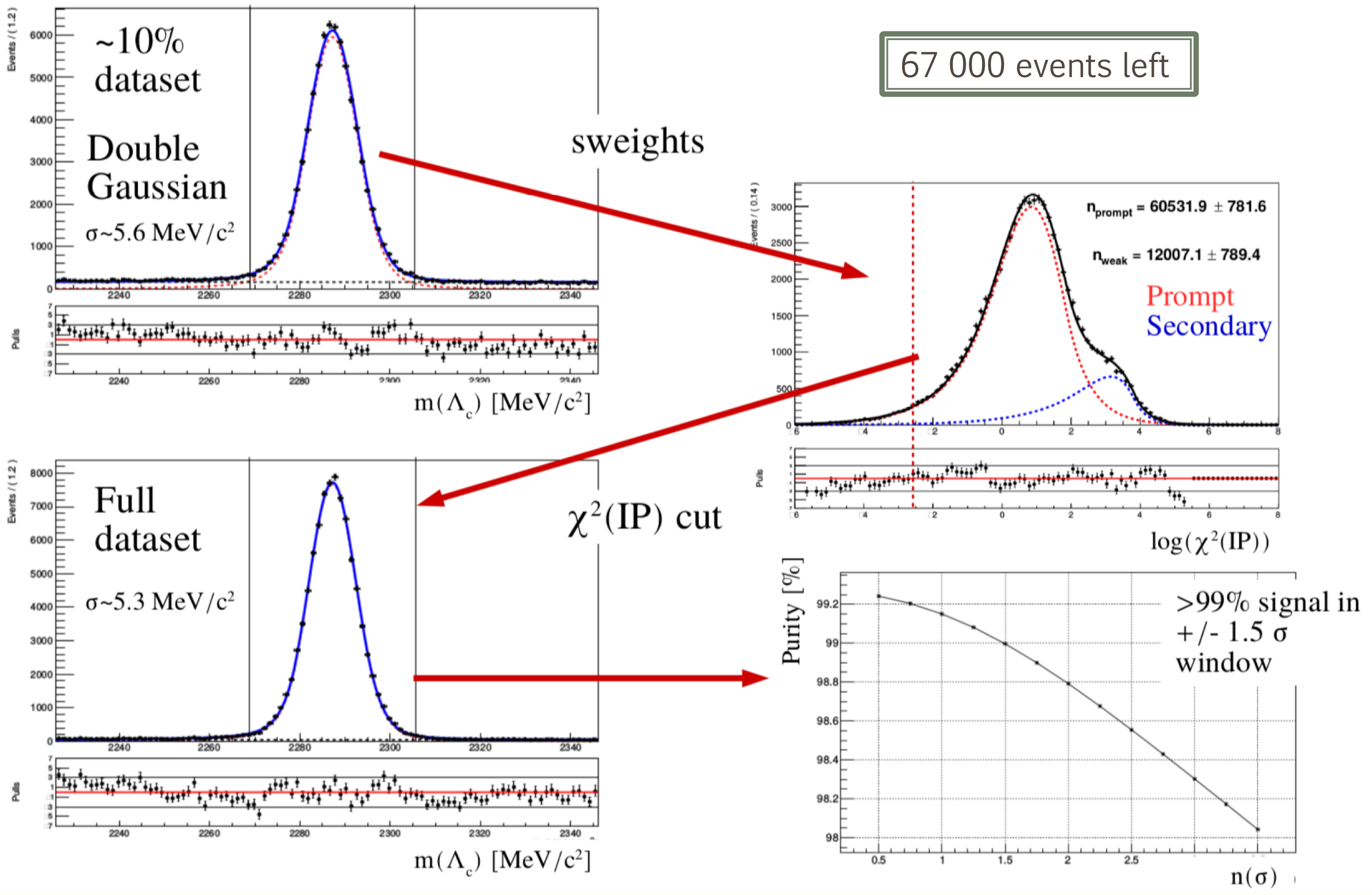
Strategy to remove secondaries:

Use $\chi^2(IP)$ variable to separate prompt form secondaries

IP = Impact parameter, i.e. the transverse distance of closest approach between a particle trajectory and primary proton-proton interaction vertex

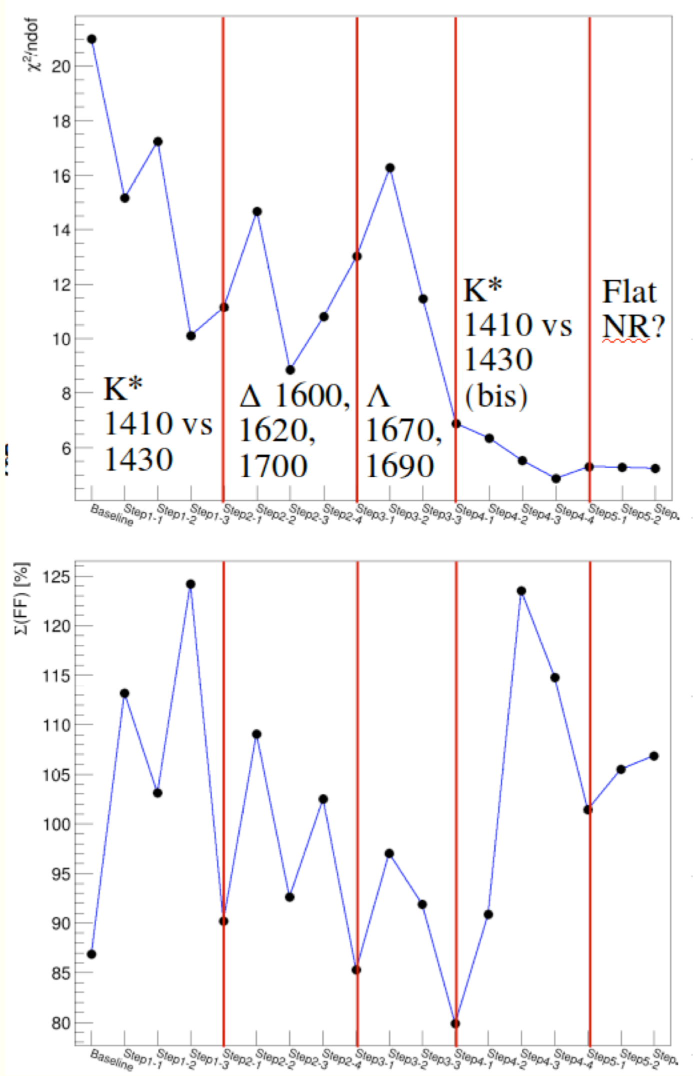
$\boldsymbol{\chi^2(IP)}$ = quality of the vertex fit when adding the track or not





Tensor Flow based fitter

- TensorFlow is a library created by Google, able to run on CPU and GPU architecture.
  - Code creates operation graphs that are built at compile time.
  - Created for machine learning, but suited to highly complex fits → ported to TensorFlowAnalysis by few LHCb physicists.
- Implementation using local option files allows to change model easily.
- We are currently building the model iteratively, monitoring at each change the variation in χ^2/ndof and of the sum of fit fractions.
  - The latter helps understanding how much interference is in the model.
- Work in progress, in parallel with the RooFit-based fitter.



RooFit fitter

- Base class RooAbsPdf is the abstract interface for all PDF
- Write the likelihood

$$\boxed{-\ln L(\vec{w}) = \sum_i \ln \frac{|M(\vec{x}_i|\vec{w})|^2}{I(\vec{w})} = \sum_i \ln |M(\vec{x}_i|\vec{w})|^2 - \ln I(\vec{w})}$$

MC sample for normalization:Contains the phase space and the efficiency

Over data sample: PDF containing the **helicity amplitude**

- Efficiency folding, no need to parametrize a 5 dimensional efficiency

- Computing the normalization at each minimization step is too long, split the likelihood in two parallel process and use Multiple Process (MP) in RooFit → declare two PDFs and combine them:
  - one for the signal (running on data sample) ~ $\ln|M(\vec{x}_i|\vec{w})|^2$
  - one for the normalization (running on MC sample) ~ $\ln I(\vec{w})$

- The minimization is done using Migrad and then Hesse.
- For now Minos error are too computational expensive so it is not used.

Code optimisation

How did we optimize such a computational expensive fit?

1. Separate the likelihood in 2 part to compute the normalization and the signal PDF in parallel and fold the efficiency

2. Avoid calculating same number at each minimization step: the Wigner functions can be computed once at the beginning and then it can be stocked in memory.

3. For N events, instead of calling N times **evaluate()** call once **evaluateBatch()** and optimize using the properties of our likelihood (store constant terms).

4. Parallelization

5. Run on GPU's: looking forward for Dorothea and Anton GdR lectures !

Results: example of fit

- Two resonances with different Breit-Wigner in green (see backup for details)
- In red 3 resonances measured by E791

$\Lambda(1405)$	sub-threshold Breit-Wigner
$K^*(1430)$	LASS parametrization

Λ^* resonances

Particle	J^P	Overall status	Status as seen in — $N\overline{K}$	$\Lambda\pi$	$\Sigma\pi$	Other channels
$\Lambda(1116)$	1/2+	****		F		$N\pi$(weakly)
$\Lambda(1405)$	1/2−	****	****	o	****	
$\Lambda(1520)$	3/2−	****	****	r	****	$\Lambda\pi\pi, \Lambda\gamma$
$\Lambda(1600)$	1/2+	***	***	b	**	
$\Lambda(1670)$	1/2−	****	****	i	****	$\Lambda\eta$
$\Lambda(1690)$	3/2−	****	****	d	****	$\Lambda\pi\pi, \Sigma\pi\pi$
$\Lambda(1800)$	1/2−	***	***	d	**	$N\overline{K}^*, \Sigma(1385)\pi$
$\Lambda(1810)$	1/2+	***	***	e	**	$N\overline{K}^*$
$\Lambda(1820)$	5/2+	****	****	n	****	$\Sigma(1385)\pi$
$\Lambda(1830)$	5/2−	****	***	F	****	$\Sigma(1385)\pi$
$\Lambda(1890)$	3/2+	****	****	o	**	$N\overline{K}^*, \Sigma(1385)\pi$
$\Lambda(2000)$		*		r	*	$\Lambda\omega, N\overline{K}^*$

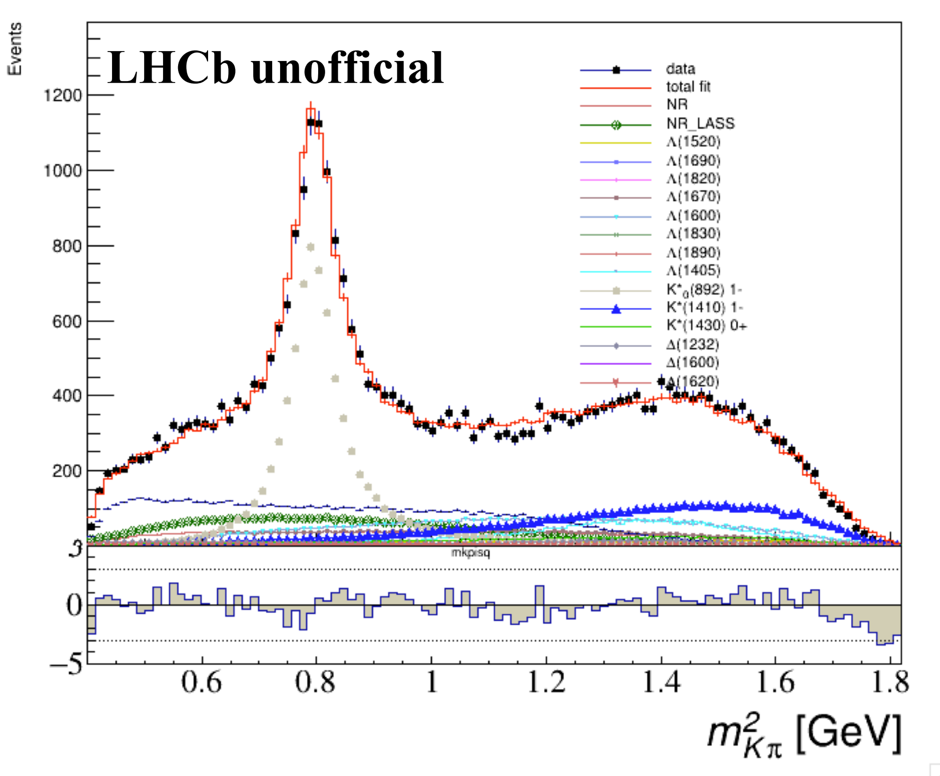
Δ resonances

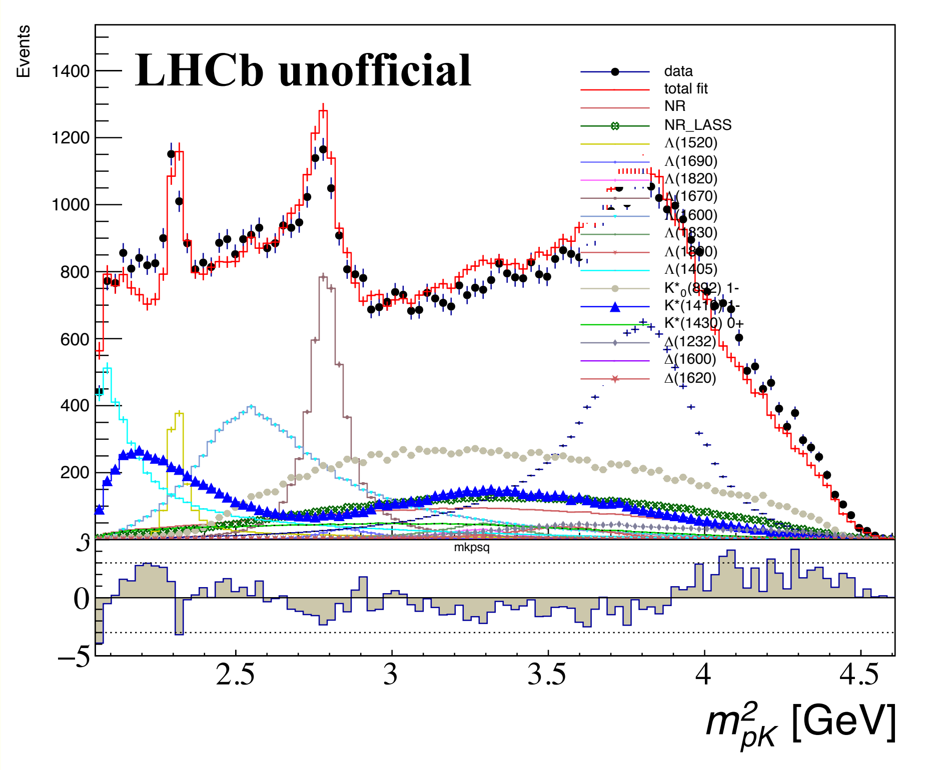
Particle	J^P	overall	$N\gamma$	$N\pi$	$\Delta\pi$	ΣK	$N\rho$	$\Delta\eta$
$\Delta(1232)$	$3/2^+$	****	****	****				
$\Delta(1600)$	$3/2^+$	****	****	***	****			
$\Delta(1620)$	$1/2^-$	****	****	****	****			
$\Delta(1700)$	$3/2^-$	****	****	****	****	*	*	

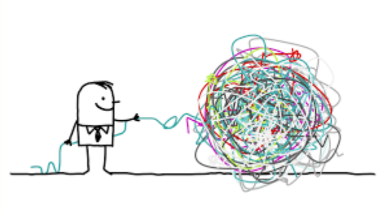
K* resonances

$n^{2s+1}\ell_J$	J^{PC}	I = 1 $u\bar{d}, \bar{u}d, \frac{1}{\sqrt{2}}(d\bar{d}-u\bar{u})$	I = $\frac{1}{2}$ $u\bar{s}, d\bar{s}; \bar{d}s, \bar{u}s$
1^1S_0	0^{-+}	π	K
1^3S_1	1^{--}	$\rho(770)$	$K^*(892)$
1^1P_1	1^{+-}	$b_1(1235)$	$K_{1B}{}^\dagger$
1^3P_0	0^{++}	$a_0(1450)$	$K_0^*(1430)$
1^3P_1	1^{++}	$a_1(1260)$	$K_{1A}{}^\dagger$
1^3P_2	2^{++}	$a_2(1320)$	$K_2^*(1430)$
1^1D_2	2^{-+}	$\pi_2(1670)$	$K_2(1770)^\dagger$
1^3D_1	1^{--}	$\rho(1700)$	$K^*(1680)^\ddagger$
1^3D_2	2^{--}		$K_2(1820)^\dagger$
1^3D_3	3^{--}	$\rho_3(1690)$	$K_3^*(1780)$
1^3F_4	4^{++}	$a_4(1970)$	$K_4^*(2045)$
1^3G_5	5^{--}	$\rho_5(2350)$	$K_5^*(2380)$
2^1S_0	0^{-+}	$\pi(1300)$	$K(1460)$
2^3S_1	1^{--}	$\rho(1450)$	$K^*(1410)^\ddagger$
2^3P_1	1^{++}	$a_1(1640)$	
2^3P_2	2^{++}	$a_2(1700)$	$K_2^*(1980)$

Example of fit: masses

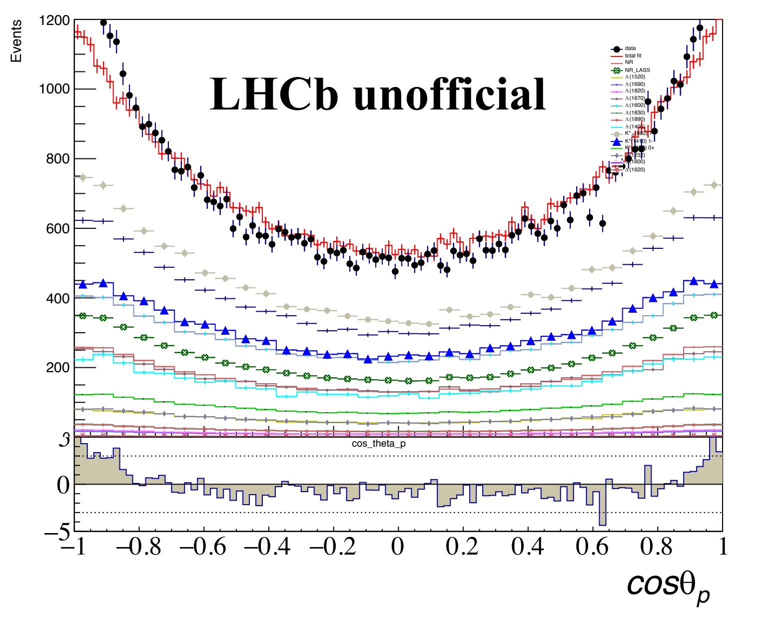


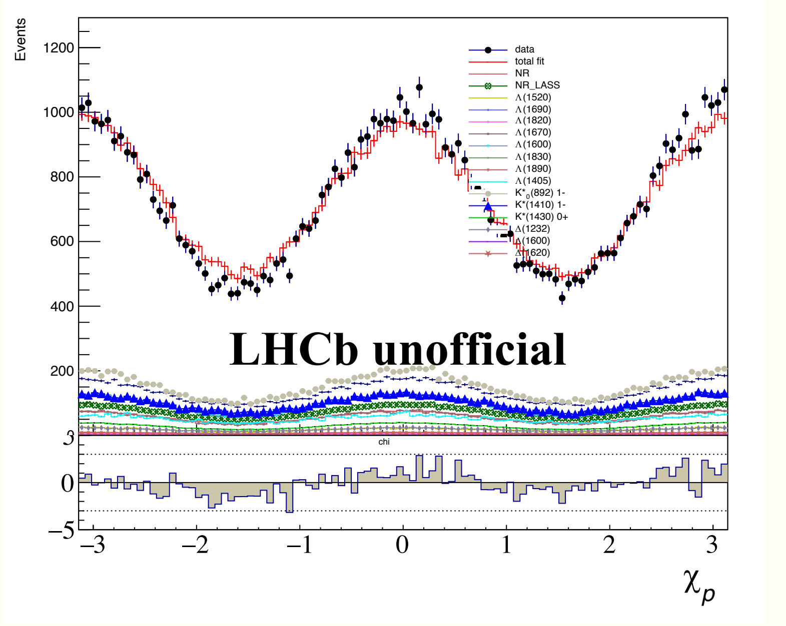


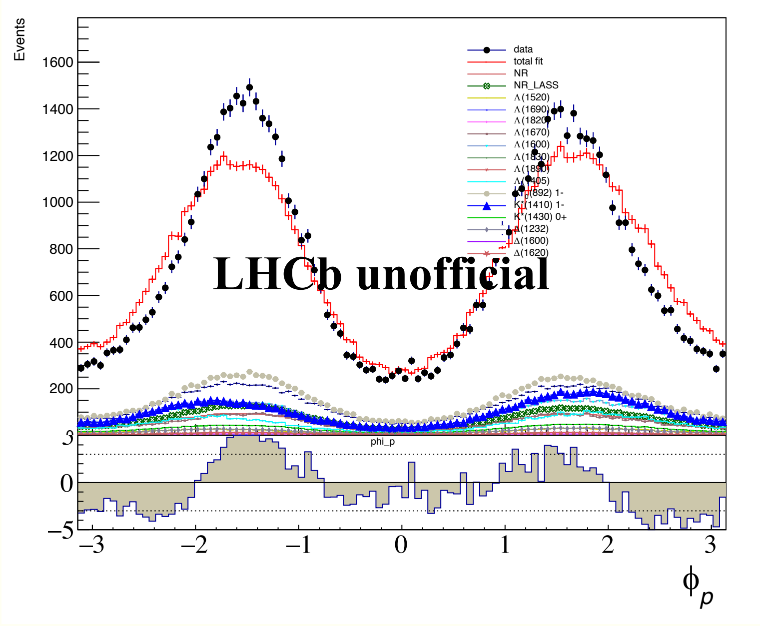


That's why I said that a Dalitz plot analysis is needed to disentangle the resonance's contributions, it's a jungle!

Example of PRELIMINARY fit: masses







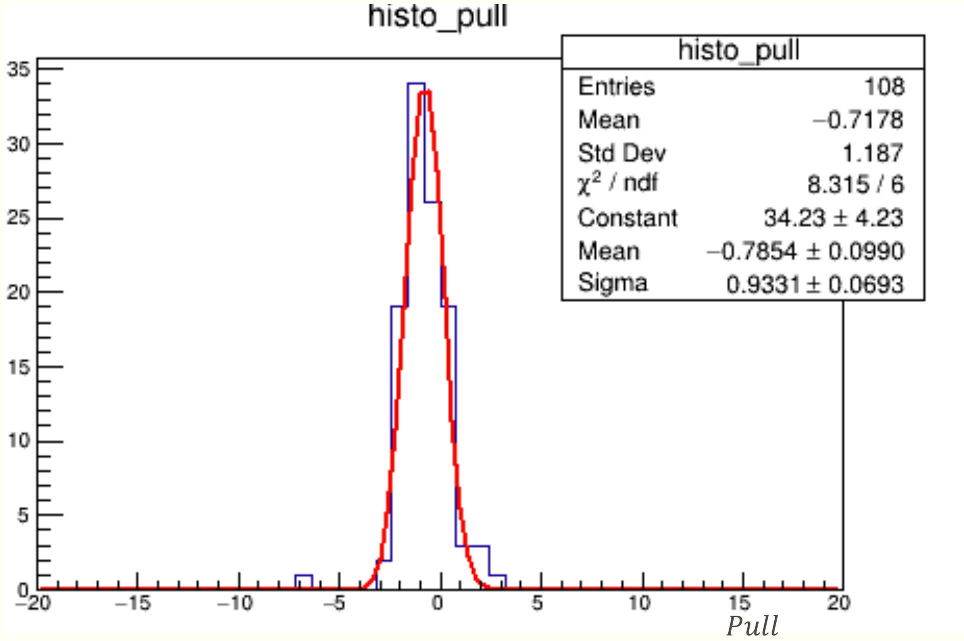
- Here the discrepancies are due to a bad understanding of the efficiency.
- New MC sample available
- Neural Network to parametrize efficiency under study

Pulls tests

Procedure for e.g helicity coupling E:

1. Pick a random parameter
   (from gaussian distribution) : E^{gen}
2. Generate with E^{gen} keeping other parameters fixed
   (~20 000 events)
3. Apply efficiency (from array)
4. Fit the generation:
   return E^{fit} and associated $error$
5. Compute the pull:

$$Pull = \left(\frac{E^{gen} - E^{fit}}{erorr}\right)$$



- Result for model icluding previous resonances + Λ ~1800
  The errors are computed correctly.
  Biais: shift in the mean (account for it in the systematics)

- With only 3 resonances it gets better :
  mean=-0.40 ± 0.15 and sigma =1.04 ± 0.132

- Disclamer: this has to be done again since an old version of the formalism was used!

Conclusions

- Essential part of a long-term program to directly measure charm-quark g factor
- After many discussion about the spin matching method for defferent decay chains the formalism is now understood
- Two fitters have been implemented: TensorFlow based and RooFit based
- Model building technique: studying a robust method to add resonances and check the fit performances with the two fitters
- Randomize the initial values and perform several fits in order to avoid local minima
- Finalize the polarization measurement in pp 2016 sample to measure the polarization in the pNe sample

Thank you

… BACKUP

Fit implementation: efficiency folding

- Signal PDF:

Amplitude

Efficiency

$$Sig(\vec{x},\Omega|\vec{w}) = \frac{|M(\vec{x}|\vec{w})|^2 \varepsilon(\vec{x})}{N(\vec{w})}$$

Normalization

$$N(\vec{w}) = \iint |M(\vec{x}|\vec{w})|^2 \varepsilon(\vec{x}) d\,\vec{x} = \mathrm{C} * \mathrm{I}(\vec{w})$$

$$\mathrm{I}(\vec{w}) = \frac{\sum_j |M(\vec{x}_j|\vec{w})|^2}{N_{tot}^{MC}}$$

PHSP MC including efficiency effects

$\vec{x} = (m_{kp}^2, m_{p\pi}^2, \cos\theta_p\,, \phi_p, \chi)$ 5 variables

$\vec{w}$ = fitting parameters

- The likelihood (without background parametrization for now)

$$-\ln L(\vec{w}) = -\sum_i \ln Sig(\vec{x_i}|\vec{w})$$

$$= \sum_i \ln \frac{|M(\vec{x}_i|\vec{w})|^2 \varepsilon(\vec{x})}{N(\vec{w})} = \sum_i \ln \frac{|M(\vec{x}_i|\vec{w})|^2}{I(\vec{w})} \cancel{- \sum_i \ln(\frac{\varepsilon(\vec{x})}{C})}$$

Constant term, doesn't depend on the fit parameters $\vec{w}$

LASS parametrization

$$S = \underbrace{B * \sin(\delta_B + \varphi_B) * e^{-i(\delta_B+\varphi_B)}}_{\text{background i.e. non-resonant contribution}} + \underbrace{R * e^{i\varphi_R} * e^{2i(\delta_B+\varphi_B)} * \sin(\delta_R) * e^{-i\delta_R}}_{\text{Resonant contribution}}$$

B, φ_B, R and φ_R are constants, the phases δ_B and δ_R depend on $k\pi$ mass.

The mass dependence of δ_B is described by means of an effective range parametrization :

$$\cot(\delta_B) = \frac{1}{aq} + \frac{1}{2} rq$$

Where:
a = scattering length
r = effective range
q = $\sqrt{(s - [m_K + m_\pi]^2) * (s - [m_K - m_\pi]^2) / (4 * s)}$ with $\sqrt{s}$= mass of the $k\pi$ system = M ,

The mass dependence of δ_R is described by means of a Breit-Wigner parametrization of the form:

$$\cot(\delta_R) = \frac{M_R^2 - s}{M_R * G(M)}$$

where M_R = resonance mass
$G(M)$= energy-dependent total width = $GR * [q/M] * [M_R/q_R]$ where $q_R = q(M = M_R)$ for an S-wave BW.

$\Lambda(1405)$

For resonances outside the kinematic region, modify the Relativistic Breit-Wigner introducing an effective mass term replacing the mass of the resonance.

Only the tail of the RBW function enters the Dalitz plot

$$m_{min} = m_p + m_K < m_{pK} < M - m_\pi = m^{max}$$

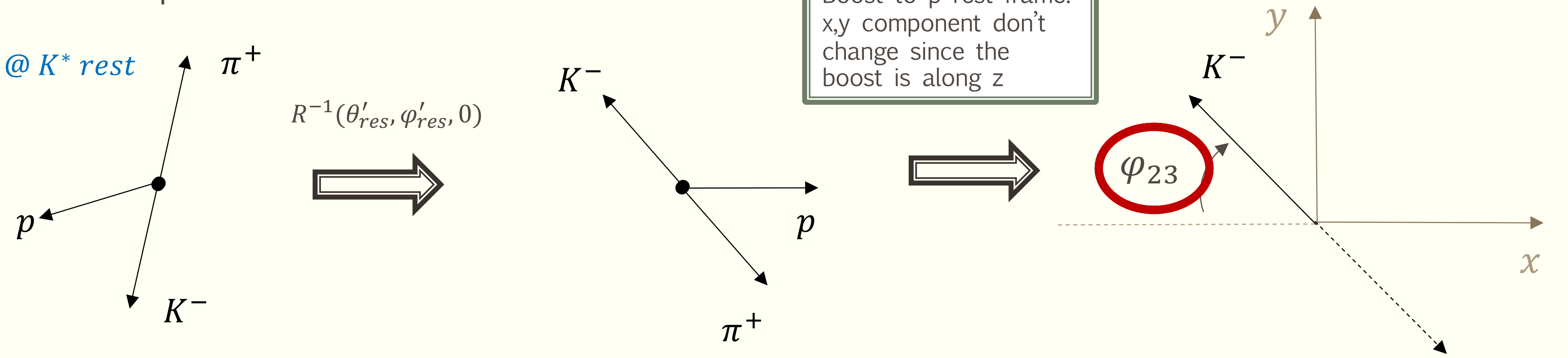
$$m_0^{\mathrm{eff}}(m_0) = m^{\mathrm{min}} + \frac{1}{2}(m^{\mathrm{max}} - m^{\mathrm{min}})\left[1 + \tanh\left(\frac{m_0 - \frac{m^{\mathrm{min}}+m^{\mathrm{max}}}{2}}{m^{\mathrm{max}} - m^{\mathrm{min}}}\right)\right]$$

Helicity formalism : azimuthal Wigner rotation

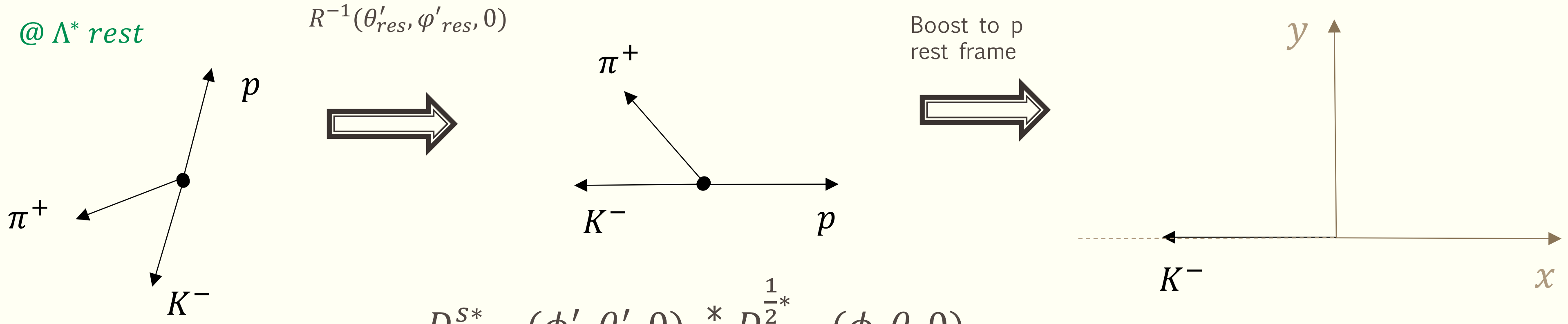
Need also an extra phase for the K* channel

(y,x) plane

$\Lambda_c^+ \rightarrow (K^* \rightarrow K^-\pi^+)\, p$



$\Lambda_c^+ \rightarrow (\Lambda^* \rightarrow pK^-)\, \pi^+$



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