Amplitude analysis and polarisation measurement of the Λ_c^+ baryon in $pK^-\pi^+$ final state for electromagnetic dipole moment experiment

Daniele Marangotto

Supervisor: Prof. Nicola Neri
Coordinator: Prof. Matteo Paris

Reviewers:
Dr. Alessandro Pilloni
Prof. Tomasz Skwarnicki

Commission:
Prof. Vincenzo Guidi
Prof. Fernando Martinez Vidal
Prof. Guy Wilkinson

Università degli studi di Milano & INFN Milano

... tutto era così sbagliato
che bisognava cominciare a sbagliare in un altro modo.

Piero Chiara, *Il Piatto Piange*

...it was all so wrong
that it was necessary to start to mistake otherwise

Thesis outline

- **Part I**: Short-lived particles electromagnetic dipole moment experiment proposal
- **Part II**: Amplitude analysis of the $\Lambda_c^+ \to pK^-\pi^+$ decay at LHCb
- **Part III**: Λ_c^+ polarisation measurement in p-Ne collisions at $\sqrt{s} = 68.6\,\mathrm{GeV}$ at LHCb

Part I:
Short-lived particles electromagnetic dipole moment experiment proposal

Electromagnetic dipole moments

- Magnetic (MDM) and electric (EDM) dipole moments are electromagnetic properties proportional to the particle spin

$$\hat{\boldsymbol{\mu}} = g\frac{\mu_B}{\hbar}\hat{\mathbf{S}} \qquad\qquad \hat{\boldsymbol{\delta}} = d\frac{\mu_B}{\hbar}\hat{\mathbf{S}}$$

- Elementary particles $g = 2 +$ QFT loop corrections
- Composite particles $g \neq 2$ depending on their structure

→ Probe for baryon structure

Low-energy QCD physics

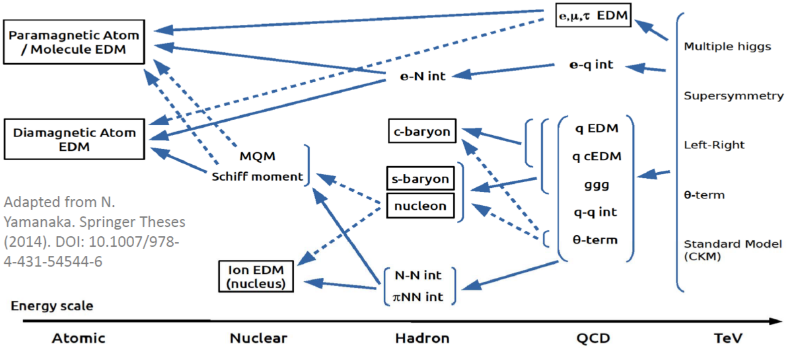
- EDM violates time-reversal and parity symmetries
- No flavour-diagonal *CP*-violation sources in the SM

→ Probe for new physics

No SM background

EDM as probe of new physics

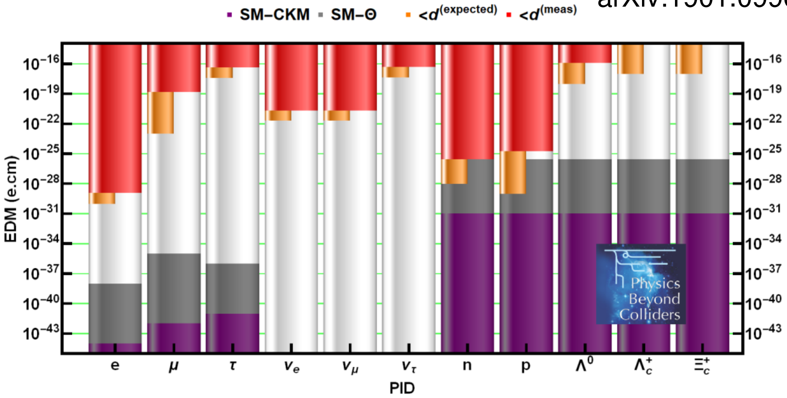
- SM EDMs practically zero, but enhanced in many beyond the SM (BSM) physics scenarios
- Different BSM models predict EDM for different systems
- Extensive EDM searches to disentangle BSM contributions



Adapted from N. Yamanaka. Springer Theses (2014). DOI: 10.1007/978-4-431-54544-6

EDM measurements

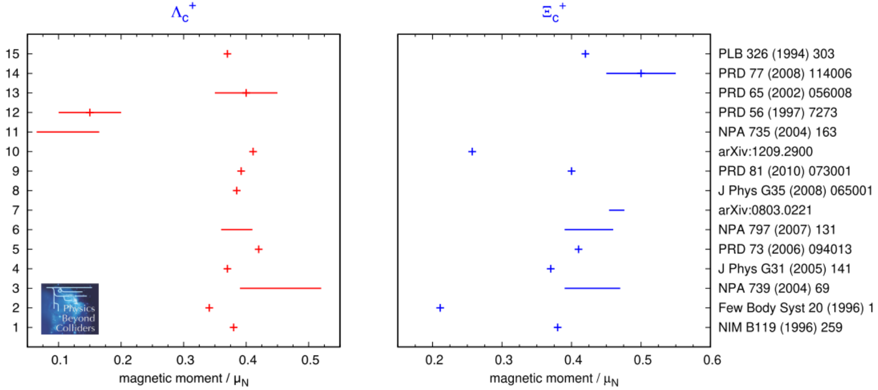
arXiv:1901.09966



- EDMs probed in different systems: leptons, nucleons, nuclei, atoms, and Λ baryon
- Heavy baryon and τ lepton EDMs never measured so far; only indirect limits from other measurements available

MDM as probe for baryon structure

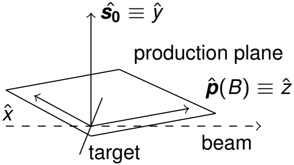
arXiv:1901.04482

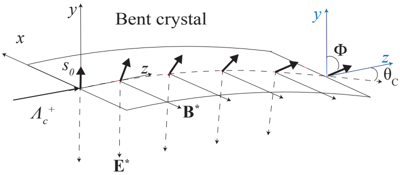


- No heavy baryon MDM measurement performed to date, precise measurement can discriminate among different theoretical models

Experiment concept

- Source of polarised heavy baryons
  - Selected from *p*-nucleus collisions, with polarisation orthogonal to the *p*-*B* production plane for parity symmetry in strong interactions





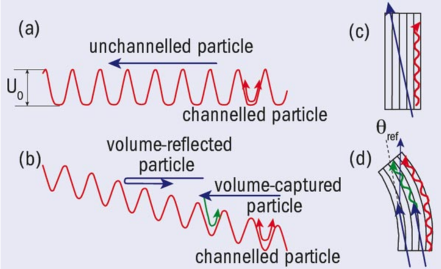
- Intense EM field enough to induce significant spin precession before the baryon decay

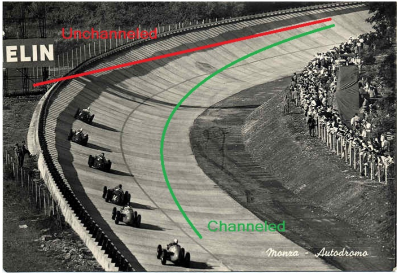
→ Exploit the interatomic electric field $\boldsymbol{E} \approx 10^{11} eV/m$ of a bent crystal

- Derived spin evolution equations in which EDM effects are treated as small corrections to the MDM induced precession

Particle channeling in bent crystals

- Positive particles can be trapped between crystal atomic planes, acting as potential barriers
- In bent crystals channeled particles are deflected following planar or axial channels
- The electric field deflecting the particle produce spin precession



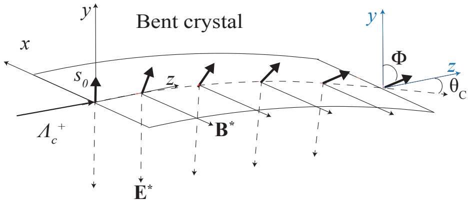


Heavy baryon spin precession

- Spin after channeling along the crystal with deflection angle θ_C

$$\mathbf{s} = s_0 \left(\frac{d}{g-2}(1-\cos\Phi), \cos\Phi, \sin\Phi \right)$$

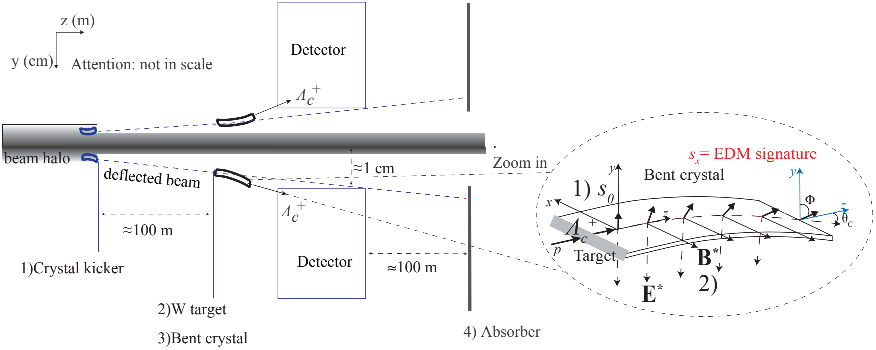
$$\Phi \approx \frac{g-2}{2}\gamma\theta_C$$



- Main MDM precession in the bending plane, the EDM producing an orthogonal spin component otherwise not present
- Spin precession proportional to $\gamma\theta_C$: need high momentum baryons and high crystal bending angle
- Measurement of the heavy baryon polarisation after channeling reconstructing the decay angular distribution

Heavy baryon DM experiment layout

- First bent crystal to extract protons from the LHC beam halo
- Directed on a target attached to a second bent crystal for spin precession
- Heavy baryons deflected into LHCb experiment acceptance
- Non-interacting protons follow the beampipe to be absorbed after LHCb



Sensitivity to dipole moments

- Sensitivity estimated for Λ_c^+ baryon and LHCb upgraded for Run 3
- Assumed flux of 10^7 p/s
- Bent crystal of 10 cm length, 10 mrad bending, 5mm target
- Polarisation measured using $\Lambda_c^+ \to \Delta^{++} K^-$ decay
- Precision dominated by statistics: limited by channeling probability and reconstruction efficiency

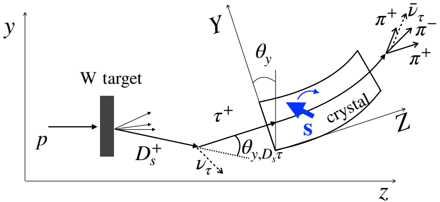
- Dedicated run ($\approx$ 1 month) allows proof-of-principle test
- Synergetic data-taking with *pp* collision program ($\approx$ 2 years) would allow the first measurement of Λ_c^+ DMs down to precisions of

$$\sigma_g \approx 4\%, \qquad \sigma_\delta \approx 1.8 \times 10^{-16} e\,\mathrm{cm}$$

- EDM value comparable to current indirect limits, at $10^{-17} - 10^{-15}$ *e cm* level

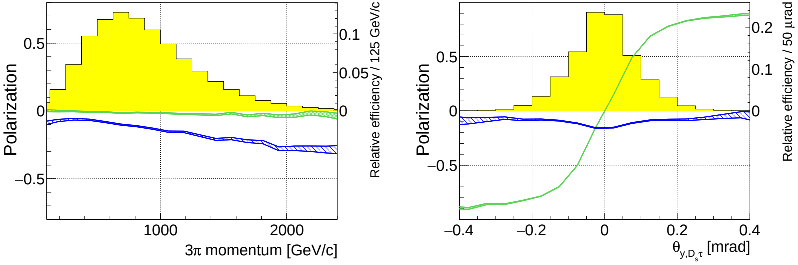
Extension to τ DM measurement

- τ lepton looks like a charm baryon, can apply the same experiment concept
- Complicated by undetectable neutrinos in production and decay
- Developed new techniques:
  - Initial polarisation of τ leptons from crystal channeling kinematic requirements
  - Polarisation extraction via multivariate classifiers including partial reconstruction effects



Initial τ polarisation

- Main τ source in *pN* collisions from $D_s^+ \to \tau^+\nu_\tau$ decays
  - But meson decays are isotropic
- Order 10% longitudinal polarisation selected from narrow acceptance of channeling
- Up to full transverse polarisation if $D_s^+ - \tau$ angle could be controlled, by additional crystal or special tracking detectors



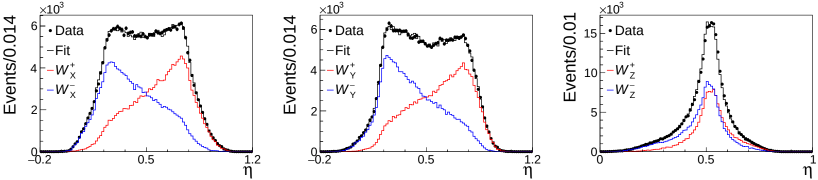
Novel method for τ polarisation measurement

- Polarisation extraction technique used at LEP (Phys. Lett. B306 411) not applicable because of unknown τ energy
- Explored novel technique with amplitudes replaced by multivariate classifiers including partial reconstruction effects
- Trained three classifiers discriminating between full positive and negative polarisations, for each axis, on simulated $\tau^+ \to \pi^+\pi^-\pi^+\bar{\nu}_\tau$ decays
  - $\tau^+ \to \pi^+\pi^-\pi^+\bar{\nu}_\tau$ features good BF, a single missing neutrino and reconstructible hadron decay vertex
  - Discrimination based on reconstructed decay distributions
- Turned polarisation measurement into discrimination problem

Novel method for τ^+ polarisation measurement

- Polarisation component s_i extracted fitting the classifier distributions with templates representing the response distributions $\mathcal{W}_i^{\pm}(\eta)$ for ± 1 polarisation

$$\mathcal{W}_i(\eta) = \frac{1+s_i}{2}\mathcal{W}_i^+(\eta) + \frac{1-s_i}{2}\mathcal{W}_i^-(\eta)$$
$$= \frac{\mathcal{W}_i^+(\eta)+\mathcal{W}_i^-(\eta)}{2} + s_i\frac{\mathcal{W}_i^+(\eta)-\mathcal{W}_i^-(\eta)}{2}.$$



Sensitivity to τ dipole moments

- Sensitivity estimated for a dedicated fixed-target experiment at the LHC
- Assumed bent crystal of 8 cm length, 16 mrad bending, 25mm target
- $g-2$ SM prediction testable with order 10^{17} protons-on-target
- Search for τ EDM at $10^{-17} e\,\mathrm{cm}$ precision with same dataset

Part I Conclusions

- Proposal for short-lived particles dipole moments measurement using bent crystals at the LHC
  - Generalised spin-precession equations to EDM case
  - Developed new methods for τ lepton
  - Performed sensitivity studies
- Interesting measurement for charm baryons already feasible using LHCb detector
- Need dedicated experiment for valuable measurement of beauty baryon and τ dipole moments

Part II:
Amplitude analysis of the $\Lambda_c^+ \to pK^-\pi^+$ decay at LHCb

Physics with amplitude analysis

- Study of the decay structure
  - Resonance composition, characterisation and interference
- Polarisation measurements
  - Essential information for heavy baryons dipole moment measurement
- Parity-violation studies
  - P-violation determines correlation between polarisation and decay kinematics

$$\frac{dN}{d\Omega^*} \propto 1 + \alpha_f \, \mathbf{s} \cdot \hat{\mathbf{k}},$$

- *CP*-violation searches with enhanced sensitivity
  - Decay structure allow to search and localise *CP*-violation sources

Amplitude analyses of $\Lambda_c^+ \to pK^-\pi^+$ decay

- Λ_c^+ is the most abundant charm baryon
  - Best precision on charm quark dipole moments
- $\Lambda_c^+ \to pK^-\pi^+$ main decay channel, $\mathcal{B} \approx 6\%$, allowing polarisation measurement with maximum statistics
  - Two-body decays have lower $\mathcal{B} \lessapprox 1\%$ and involve long-living strange particles
- Previous amplitude analysis on ≈ 1000 events performed by E791 experiment (Phys. Lett. B471 (2000) 449) not useful
- Order one million events recorded by LHCb from semileptonic production $\Lambda_b^0 \to \Lambda_c^+\mu^-X$

Helicity amplitudes

- Decay model written in terms of helicity amplitudes: two-body decay amplitudes for specific initial and final-state helicities (spin projections along their momentum)
- Structure:
  - Complex coupling: encodes the decay dynamics, to be determined from fit
  - Angular dependence: fixed from angular momentum conservation, expressed in terms of Wigner D-matrices
  - Invariant mass dependence: parametrisation of the A particle width

$$\mathcal{A}^{A\to BC}_{\lambda_B,\lambda_C} = \mathcal{H}^{A\to BC}_{\lambda_B,\lambda_C} \times D^{J_A}_{m_A,\lambda_B-\lambda_C}(\phi_B,\theta_B,0)^* \times \mathcal{R}(m^2_{BC})$$

Amplitude model for $\Lambda_c^+ \to pK^-\pi^+$ decay

- Amplitudes built for each intermediate resonance R
  $\Lambda_c^+ \to R\{p, K^-, \pi^+\}$, $R \to \{K^-\pi^+, p\pi^+, pK^-\}$
  multiplying two-body helicity amplitudes, e.g.

$$\mathcal{A}^{[R]}_{m_{\Lambda_c^+},\lambda_R,\lambda_p}(\Omega) = \mathcal{A}^{\Lambda_c^+ \to R\pi^+}_{\lambda_R,0}\, \mathcal{A}^{R \to pK^-}_{\lambda_p,0}$$

- Total helicity amplitudes for definite initial and final particles helicities obtained summing over all intermediate resonance helicity states

$$\mathcal{A}_{m_{\Lambda_c^+},\lambda_p}(\Omega) = \sum_{i=1}^{N_R} \sum_{\lambda_{R_i}=-J_{R_i}}^{J_{R_i}} \mathcal{A}^{[R_i]}_{m_{\Lambda_c^+},\lambda_{R_i},\lambda_p}(\Omega)$$

Proton spin rotation

- Definition of proton helicity frame depends on the particular decay chain considered (i.e. the proton momentum in the resonance rest frame)
- Amplitudes can be summed only if the proton spin is referred to a single frame, of arbitrary choice
- Additional rotation to be applied to the helicity amplitudes: given reference proton spin states $|1/2, m_p\rangle$ amplitudes written in terms of $|1/2, \lambda_p\rangle$ states are transformed as

$$\mathcal{A}^{[R_i]}_{m_{\Lambda_c^+},\lambda_{R_i},m_p}(\Omega) = \sum_{\lambda_p} D^{1/2}_{\lambda_p,m_p}(\alpha,\beta,\gamma)^* \mathcal{A}^{[R_i]}_{m_{\Lambda_c^+},\lambda_{R_i},\lambda'_p}(\Omega)$$

with α, β, γ the Euler angles describing the rotation acting on the proton spin states

Polarised decay rate

- Generic Λ_c^+ particle polarisation in a given coordinate frame described by the density matrix

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

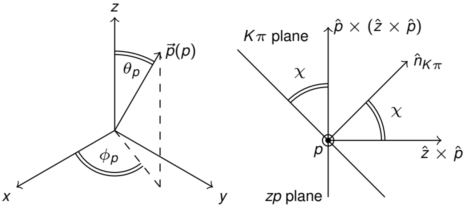
- Decay probability distribution obtained summing modulo squared helicity amplitudes over initial Λ_c^+ polarisation and unmeasured final particles helicities

$$\begin{aligned} p(\Omega, \boldsymbol{P}) \propto \sum_{m_p=\pm 1/2} \Big[& (1+P_z)|\mathcal{A}_{1/2,m_p}(\Omega)|^2 + (1-P_z)|\mathcal{A}_{-1/2,m_p}(\Omega)|^2 \\ & + (P_x - iP_y)\mathcal{A}^*_{1/2,m_p}(\Omega)\mathcal{A}_{-1/2,m_p}(\Omega) \\ & + (P_x + iP_y)\mathcal{A}_{1/2,m_p}(\Omega)\mathcal{A}^*_{-1/2,m_p}(\Omega)\Big] \end{aligned}$$

Baryon 3-body decay kinematics description

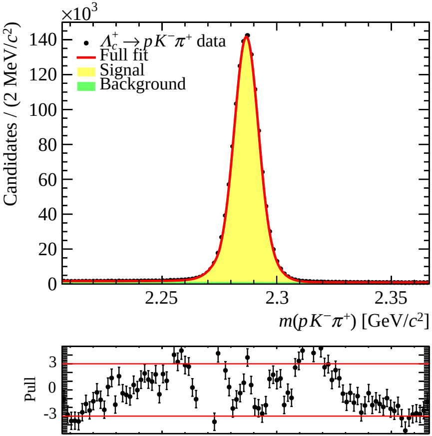
- Three-body decays described by 5 degrees of freedom: 2 two-body "Dalitz" invariant masses + 3 decay plane orientation angles
- For polarised baryons spherical symmetry is broken: decay plane orientation angles must be included in the amplitude analysis

- Euler rotation angles ϕ_p, θ_p, χ from polarisation frame to decay plane



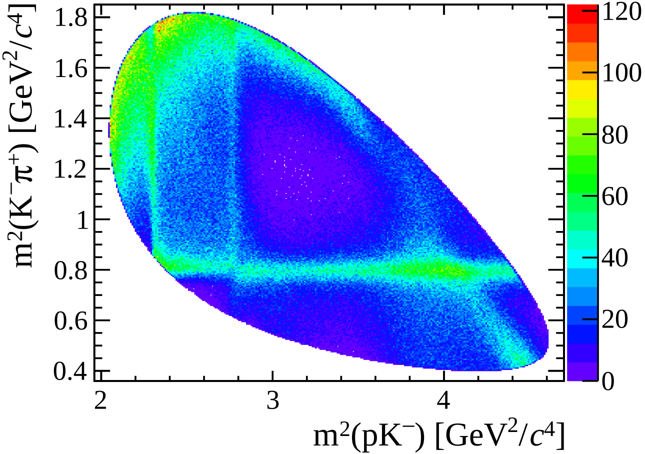
$\Lambda_c^+ \to pK^-\pi^+$ decays from semileptonic production

- Considered $\Lambda_c^+ \to pK^-\pi^+$ decays from Λ_b^0 semileptonic decays
  - $\Lambda_c^+\mu^-$ vertices displaced from pp collision vertex
- Very pure selection exploiting LHCb particle identification
  - $\sim$ 1 million of $\Lambda_c^+ \to pK^-\pi^+$ candidates from 2016 dataset only
  - Negligible background contribution $\approx 1.7\%$



$\Lambda_c^+ \to pK^-\pi^+$ Dalitz plot

- Efficiency-uncorrected Dalitz plot for $\Lambda_c^+ \to pK^-\pi^+$ decays



Model building

- Included resonance contributions from PDG information
- Resonance lineshapes parametrised by default with relativistic Breit-Wigner lineshapes
  - $\Lambda^*(1405)$ parametrised with a sub-threshold relativistic Breit-Wigner (featuring a different mass-dependent width to parametrise *pK* channel opening)
  - Spin-zero K^* contributions included using LASS parametrisation (Nucl. Phys. B296 (1988) 493)
- Set masses and widths fixed or floating following PDG uncertainties
- Chosen two models with same resonance content but different fit parameters

Reduced model

Resonance	J^P	BW mass (MeV)	BW width (MeV)
$\Lambda^*(1405)$	$1/2^-$	1405.1	50.5
$\Lambda^*(1520)$	$3/2^-$	1515 – 1523	10 – 20
$\Lambda^*(1600)$	$1/2^+$	1600	150
$\Lambda^*(1670)$	$1/2^-$	1670	25
$\Lambda^*(1690)$	$3/2^-$	1690	60
$\Lambda^*(2000)$	$1/2^-$	1900 – 2100	20 – 400
$\Delta^{++*}(1232)$	$3/2^+$	1232	120
$\Delta^{++*}(1620)$	$1/2^-$	1620	130
Non-resonant	0^+		
$K^*(892)$	1^-	891.76	47.3
$K^*(1410)$	1^-	1421	236
$K_0^*(1430)$	0^+	1425	270

Extended model

Resonance	J^P	BW mass (MeV)	BW width (MeV)
$\Lambda^*(1405)$	$1/2^-$	1405.1	50.5
$\Lambda^*(1520)$	$3/2^-$	$1515 - 1523$	$10 - 20$
$\Lambda^*(1600)$	$1/2^+$	$1550 - 1700$	$50 - 300$
$\Lambda^*(1670)$	$1/2^-$	1670	$25 - 50$
$\Lambda^*(1690)$	$3/2^-$	1690	60
$\Lambda^*(2000)$	$1/2^-$	$1900 - 2100$	$20 - 400$
$\Delta^{++*}(1232)$	$3/2^+$	$1200 - 1300$	$110 - 150$
$\Delta^{++*}(1620)$	$1/2^-$	$1590 - 1630$	$110 - 150$
Non-resonant	0^+		
$K^*(892)$	1^-	891.76	47.3
$K^*(1410)$	1^-	1421	236
$K_0^*(1430)$	0^+	$1375 - 1475$	$190 - 350$

Maximum likelihood fit

- Model parameters (polarisation, couplings, resonance parameters) determined from data by minimising the negative log-likelihood

$$-\log \mathcal{L}(\omega) = -\sum_{i=1}^{N} \log p_{tot}(\Omega_i|\omega),$$

$$p_{tot}(\Omega_i|\omega) = \frac{p(\Omega_i|\omega)\epsilon(\Omega_i)}{I(\omega)}$$

- Efficiency parametrisation not needed since background is negligible: folded in model normalisation computed using simulated events

$$-\log \mathcal{L}(\omega) = -\sum_{i=1}^{N} \log p(\Omega_i|\omega) + N \log I(\omega) + const.$$

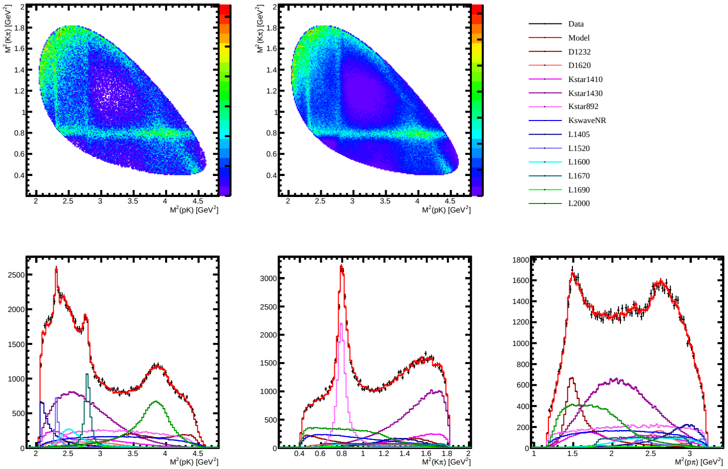
General strategy for amplitude fits

- Performed on 100k $\Lambda_c^+ \to pK^-\pi^+$ candidates, with 450k MC events for integration/efficiency folding
- Performed 10 times with randomised starting values for floating parameters, best result chosen according to best log-likelihood
- Started with Dalitz plot fits, integrating over decay orientation angles
- Same strategy for full phase space fits

Dalitz plot fits

- 3+1 fits performed:
  - Reduced model
  - Extended model
  - Reduced model on alternative data sample
- Good fit quality, similar in all cases
  - Reduced model without $\Lambda^*(2000)$ contribution
- Bad fit quality in $m^2_{pK^-} \in 3.8 - 4.0\,\mathrm{GeV}^2$

Dalitz fit, reduced model



Dalitz fits fit fractions

Resonance	FF reduced	FF extended	FF reduced alternative sample
Non resonant	0.109282	0.182511	0.109799
$K^*(892)$	0.151852	0.143938	0.178592
$K^*(1410)$	0.076787	0.097761	0.179808
$K^*(1430)$	0.287793	0.415955	0.205860
$\Lambda^*(1405)$	0.054438	0.052562	0.062724
$\Lambda^*(1520)$	0.022108	0.017247	0.015797
$\Lambda^*(1600)$	0.046379	0.024183	0.030307
$\Lambda^*(1670)$	0.048842	0.054381	0.033665
$\Lambda^*(1690)$	0.009556	0.004960	0.016908
$\Lambda^*(2000)$	0.162436	0.156100	0.180881
$\Delta^{*++}(1232)$	0.093962	0.098731	0.091483
$\Delta^{*++}(1620)$	0.035749	0.055507	0.042587
Sum	1.099183	1.303839	1.148411

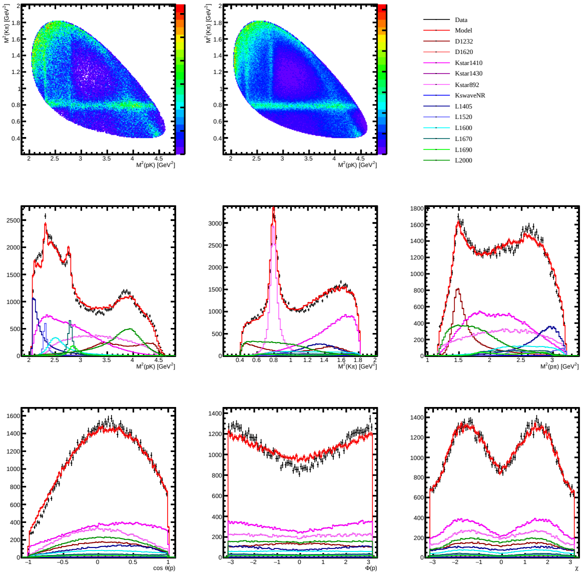
Dalitz fit results

- No basic difference between reduced and extended models
- $\Lambda^*(2000)$ contribution needed to obtain a good fit of the $m^2_{pK^-}$ invariant mass in the 2 GeV region
  - Statistical significance of 32.5σ from Wilks' theorem, demonstrating the presence of Λ^* resonances contribution in the region $m^2_{pK^-} \in 3.8 - 4.0\,\mathrm{GeV}^2$
  - Contribution can be parametrised by a spin 1/2 state with a mass around 1.97 GeV and a width around 140 MeV
- Fit fractions values have big fluctuations among different fits for overlapping resonances
- Also the sum of the fit fractions differs from fit to fit: interference effects poorly constrained

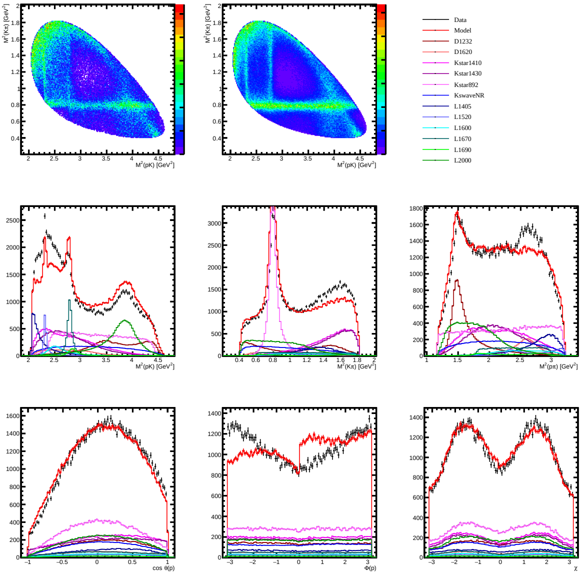
Full phase space fits

- Two fits performed:
  - Reduced model
  - Reduced model fixed to Dalitz fit results, polarisation only fit
- Poor fit quality for the first
- Evident unphysical effects in the second

Full phase space fit, reduced model



Full phase space fit, fixed reduced model



Tests

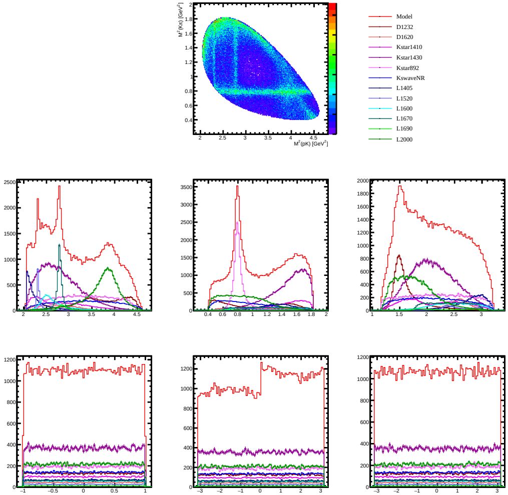
- Tests performed on the decay model, checking properties of the decay rate following from rotational invariance, valid irrespective of the decay model

- Decay rate is isotropic in decay orientation angles for zero polarisation
  - Failed for proton azimuthal angle ϕ_p distribution
  - Anisotropy only present when resonances associated to different decay channels interfere

- Invariant mass distributions are independent of the polarisation
  - Almost OK

Isotropy test

- Generated phase-space distributions according to amplitude model for zero polarisation
- Anisotropy in ϕ_p distribution only
- Distributions associated to single resonances fractions are uniform, indicating the anisotropy comes from interference effects

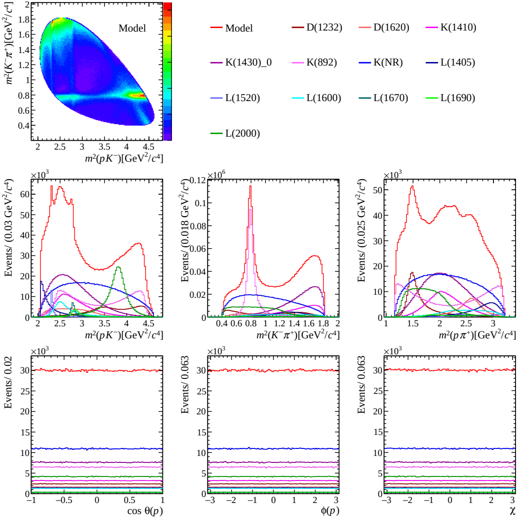


Possible solution of the problem

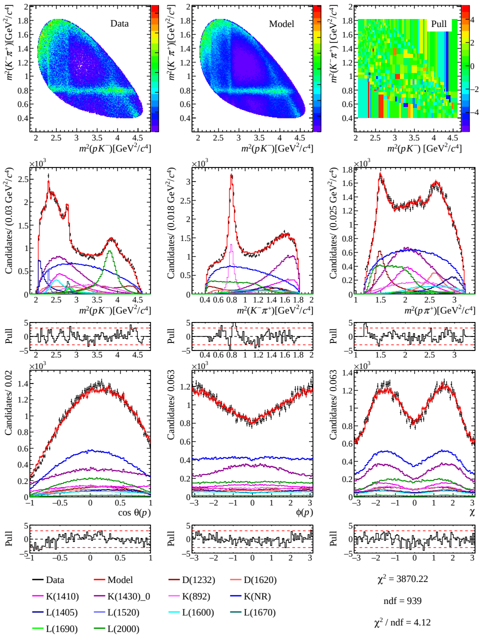
- During review, found an issue in the matching of proton spin states in helicity amplitudes, documented in arXiv:1911.10025
- Related to spin state phases introduced in the helicity transformation sequence
  - Basic quantum-mechanics property of spin states under rotations apparently neglected in the literature up to now
  - Compatible with the observed unphysical interference effects
- Corrected amplitude model seems to fully solve the problem
  - Pass isotropy and invariant mass distribution tests
  - New full phase space fit shows no significant discrepancies anymore
- Proposed solution still to be accepted

Isotropy test after fix

- Generated phase-space distributions according to amplitude model for zero polarisation
- Model precisely isotropic in orientation angles
- Tested on 3 million events

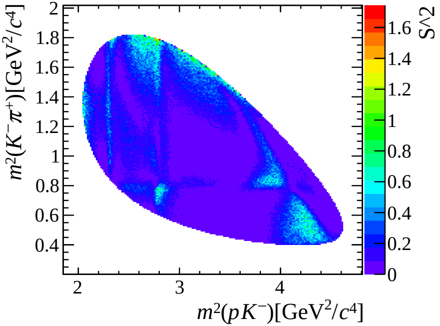


- Full phase space fit with reduced model
- No significant discrepancies anymore



Sensitivity to polarisation study

- Computed average event Fisher information for the reduced model from Dalitz fits
  - S = 0.378105
  - Effective α = 0.654896
- Similar to that assumed for $\Lambda_c^+ \to \Delta^{++}K^-$ decays in the Λ_c^+ dipole moments sensitivity study
- Can increase the useful $\Lambda_c^+ \to pK^-\pi^+$ decay statistics to measure the Λ_c^+ dipole moments by a factor six



Part II Conclusions

- Amplitude model for full phase space fit of $\Lambda_c^+ \to pK^-\pi^+$ decays with extraction of the polarisation vector developed in the helicity formalism
- Selected $\approx$ 1M $\Lambda_c^+ \to pK^-\pi^+$ decays from semileptonic production with negligible background
- Dalitz plot fits well describe invariant mass distributions
  - Observed unexpected Λ^* contributions
  - Fit fractions for overlapping resonances not well determined
- Full phase space fits showed a problem related to the implementation of the amplitude model
  - Carefully studied and possibly solved
- Sensitivity to polarisation evaluated

Part III:

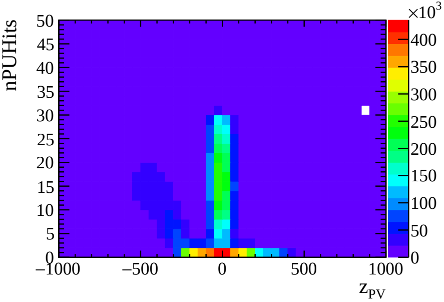
Λ_c^+ polarisation measurement in p-Ne collisions at $\sqrt{s} = 68.6\,\mathrm{GeV}$ at LHCb

Motivation

- Polarisation measurements are interesting probes for QCD spin physics
  - According to HQET, most of c-quark polarisation retained by the charm baryon, in contrast to light baryons
  - This measurement can shed light on the heavy quark polarisation production processes
- Measurements at lower energy suggest a trend of increasing polarisation with p_{T}
- Fixed-target SMOG p-Ne $\Lambda_c^+ \to pK^-\pi^+$ sample allows to probe Λ_c^+ polarisation at unprecedented center-of-mass energy $\sqrt{s_{NN}} = 68.6\,\mathrm{GeV}$
- Sensitivity on dipole moments depends crucially on the polarisation degree

SMOG events selection

- SMOG p-Ne $\Lambda_c^+ \to pK^-\pi^+$ 2017 sample recorded simultaneously with *pp* collisions at $\sqrt{s} = 5\,\mathrm{TeV}$
- Three event types:
  - SMOG events inside VELO
  - SMOG events upstream VELO
  - ghost charge *pp* collision events



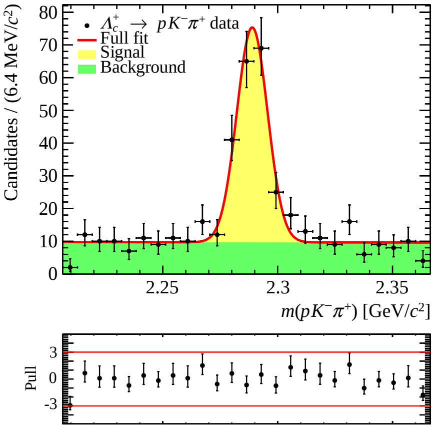
- SMOG events selected thanks to different topology, exploiting vertex position, backward tracks and VELO pile-up modules

SMOG $\Lambda_c^+ \to pK^-\pi^+$ events election

- Two selection strategies considered
  - Simple cut-based approach
  - BDT-based approach using topological information only, with training on more abundant $D^+ \to K^-\pi^+\pi^+$ events
- Similar performances, but the second can be further improved better tuning the training sample and adding PID information
- A few hundreds $\Lambda_c^+ \to pK^-\pi^+$ candidates can be selected with enough purity for the polarisation measurement

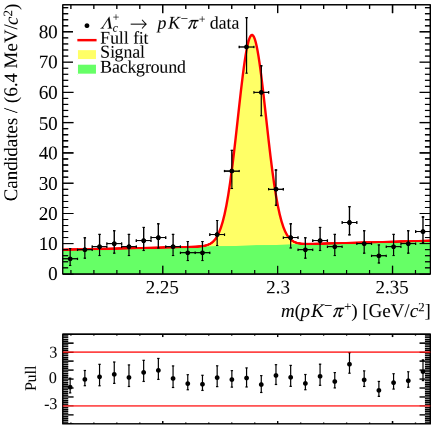
Cut-based selection for SMOG $\Lambda_c^+ \to pK^-\pi^+$

- Using topological, PID and trigger information
- Signal & background yields
  - $S = 153 \pm 15$, $B = 197 \pm 16$, width ≈ 6.6 MeV
  - $\approx 19\%$ bkg fraction in ± 15 GeV signal region
  - Significance $S/\sqrt{S+B} = 11.1$



BDT-based selection for SMOG $\Lambda_c^+ \to pK^-\pi^+$

- Applied BDT cut suggested from $D^+ \to K^-\pi^+\pi^+$ optimisation
- Signal & background yields
  - $S = 156 \pm 15$, $B = 221 \pm 17$, width 6.1 ± 0.5 MeV
  - $\approx 21\%$ bkg fraction in ± 15 GeV signal region
  - Significance $S/\sqrt{S+B} = 11.1$
- Similar power as cut-based selection but without PID and trigger cuts



Strategy for polarisation measurement

- Maximum precision on polarisation achieved with amplitude model of $\Lambda_c^+ \to pK^-\pi^+$ decay
- Polarisation on SMOG $\Lambda_c^+ \to pK^-\pi^+$ events extracted fixing all other parameters from *pp* collision data results
- Polarisation orthogonal to Λ_c^+-beam plane for parity symmetry

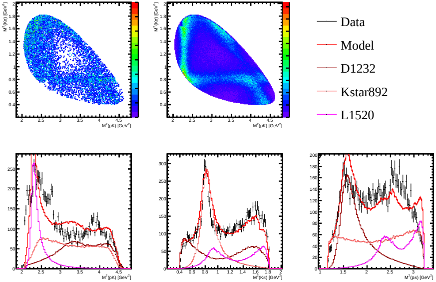
- Two possible fits:

- Fit only for orthogonal component, 1 parameter, minimum uncertainty
- Fit for polarisation vector, 3 parameters, for cross-checking

Amplitude models for toy studies

- Two amplitude models considered:
- **Nominal**: reduced model from Dalitz fit
- **Alternative**: effective 3-resonance model with parameters fit from 10k $\Lambda_c^+ \to pK^-\pi^+$ candidates of LHCb *pp* collisions data

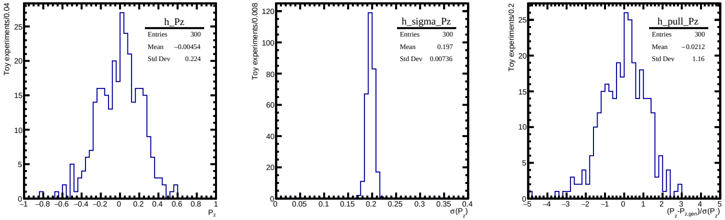
- Crude approximation of the phase space distributions



Toy studies for polarisation measurement

- Polarisation extraction studied by means of toy experiments
- Fit stability for low statistics tested generating from and fitting the nominal model for floating P_z or polarisation vector
  - Considered samples of 200 generated $\Lambda_c^+ \to pK^-\pi^+$ events including a 20% flat background, as worst-case scenario
- Systematic uncertainty associated to fit model choice studied fitting pseudoexperiments generated from the nominal model with the alternative one
  - Considered samples of 1000 events with no background, as best-case scenario
- Toy samples generated for zero polarisation

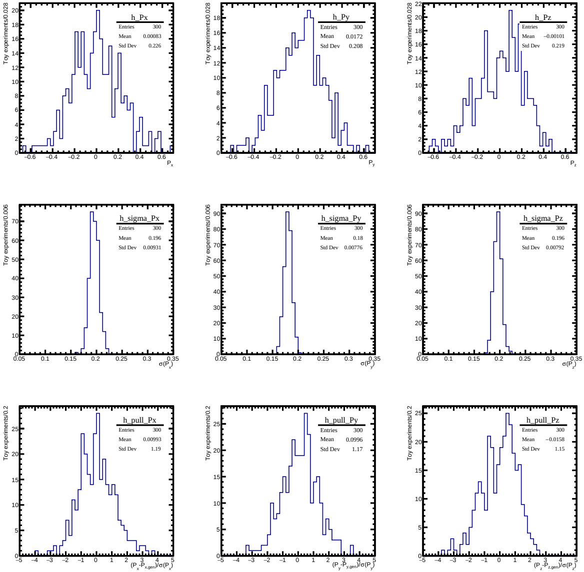
P_z extraction on 200 events, nominal model



- Fairly regular polarisation distribution
- Effective statistical uncertainty ≈ 0.22 comparable to analytical one ≈ 0.2
- Negligible bias on the mean polarisation value

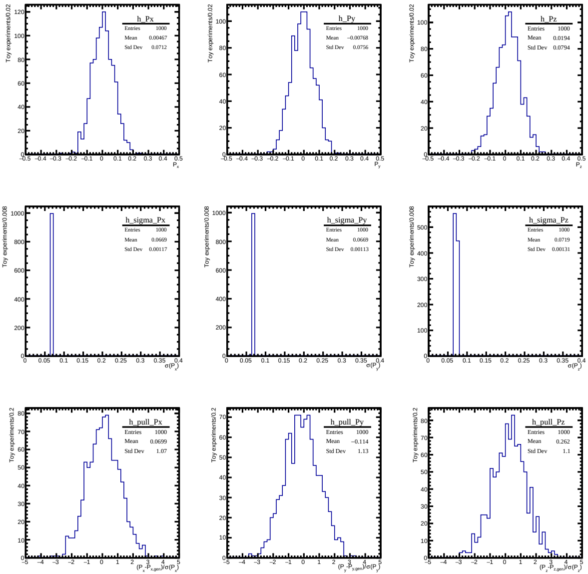
P extraction on 200 events, nominal model fit

- Analogous behaviour as before
  - Polarisation vector extraction works
- With improved selection one can expect statistical uncertainties < 0.2



P extraction on 1000 events, alternative model

- Bias $\leq$ 0.02 smaller than statistical uncertainties $\approx$ 0.07, even with alternative model very different from nominal one
- Systematic uncertainty associated to fit model subdominant w.r.t. statistical uncertainty



Part III Conclusions

- Demonstrated feasibility of Λ_c^+ polarisation measurement in p-Ne collisions at LHCb
- A few hundreds $\Lambda_c^+ \to pK^-\pi^+$ candidates can be selected
- Fit for polarisation extraction based on amplitude models derived from *pp* collision data works even at very low statistics
  - Expected statistical uncertainty < 0.2
- Systematic uncertainty associated to fit model subdominant w.r.t. statistical uncertainty, expected to be < 0.02

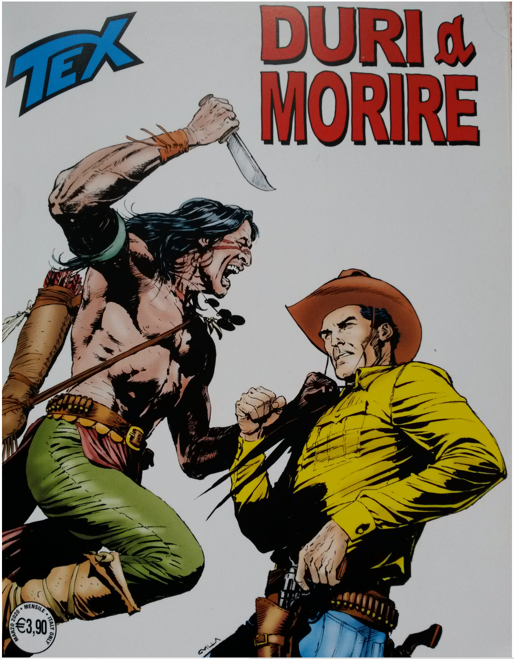
- Much greater precision expected with new p-Gas collision samples in Run 3, thanks to new SMOG2 system

THE END

(NOT QUITE THE END)

'Cause nothing can stop research...

Researchers fighting the coronavirus...

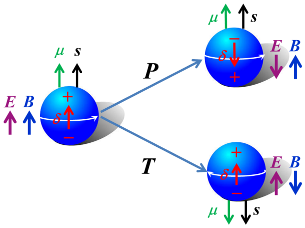


Backup Slides

Electric dipole moment (EDM)

- Classical definition $\boldsymbol{\delta} = \int \mathbf{r}\rho(\mathbf{r})d^3r$
- Quantum systems: $\boldsymbol{\delta}$ must be proportional to $\boldsymbol{s}$, the only vector describing the particle

$$\boldsymbol{\delta} = d\frac{\mu_B}{\hbar}\boldsymbol{s}$$

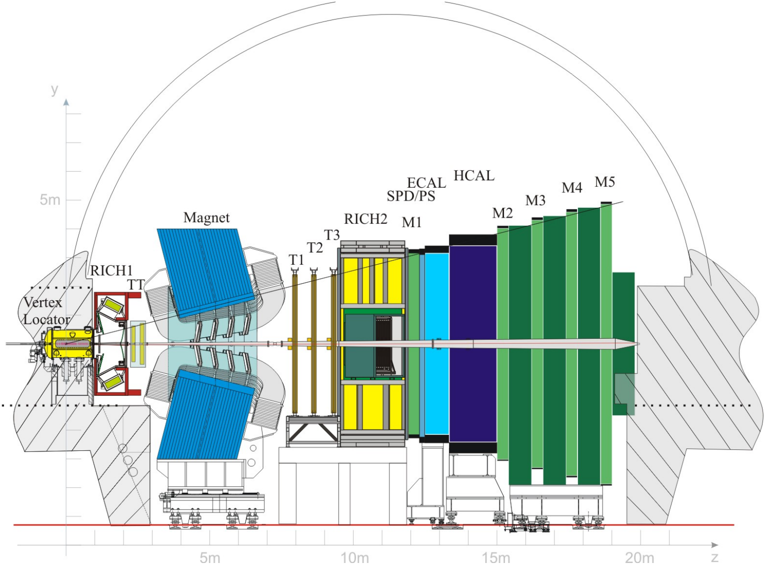


- Parity: $\mathcal{P}\boldsymbol{\delta} = -\boldsymbol{\delta}$ but $\mathcal{P}\boldsymbol{s} = +\boldsymbol{s}$
- Time reversal: $\mathcal{T}\boldsymbol{\delta} = +\boldsymbol{\delta}$ but $\mathcal{T}\boldsymbol{s} = -\boldsymbol{s}$
- Spin - EM field interaction:

$$\mathcal{H} = -\boldsymbol{\delta} \cdot \mathrm{E} - \boldsymbol{\mu} \cdot \mathbf{B}$$

- An EDM violates $\mathcal{P}$ and $\mathcal{T}$, thus *CP* symmetry for CPT theorem
- The EDM, together with the magnetic dipole moment $\boldsymbol{\mu} = g\frac{\mu_B}{\hbar}\mathbf{s}$, drives the particle spin precession in electromagnetic (EM) fields

LHCb detector (Run 1-2)



Novel method for τ^+ polarisation measurement

- Relation between τ^+ polarisation and decay distribution depends critically on the orientation of the 3π system in the τ^+ rest frame
  - Approximate τ^+ momentum estimated taking the mean expected value in bins of the 3π momentum magnitude and angle formed with the τ^+ decay direction
  - Rest frame obtained assuming τ^+ flight direction from D_s^+ production vertex to 3π vertex
- Other variables employed:
  - 2- and 3-pion invariant masses
  - Pion decay plane Euler orientation angles w.r.t. 3π helicity frame reached from the approximate τ^+ rest frame

Partial reconstruction effect

- Precision loss due to partial reconstruction estimated computing the statistical separation between classifier distributions, inversely proportional to the polarisation uncertainty

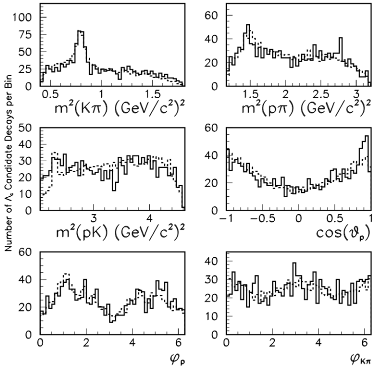
$$S_i^2 = \frac{1}{N\sigma_i^2} = \left\langle \left(\frac{\mathcal{W}_i^+(\eta) - \mathcal{W}_i^-(\eta)}{\mathcal{W}_i^+(\eta) + \mathcal{W}_i^-(\eta)} \right)^2 \right\rangle ,$$

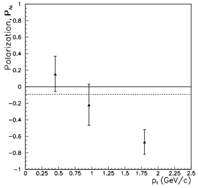
- Ideal case: $S_i = 0.58$ (Phys. Lett. B306 411)
- Measured: $S_x \approx S_y \approx 0.42$ and $S_z \approx 0.23$
  - Factor ≈ 1.4 precision loss for x, y polarisation and ≈ 2.5 for z component

E791 amplitude analysis

Phys. Lett. B471 (2000) 449

- E791 500 GeV π-Pt fixed-target experiment at FNAL
- 946 ± 38 $\Lambda_c^+ \to pK^-\pi^+$ decays
- Trend of increasing negative polarisation with increasing p_T
- Problems (beyond statistics):
  - Amplitude model not correct (no proton spin rotation)
  - No separation between $\Lambda_c^+/\overline{\Lambda}_c^-$ events, may have different polarisation





Polarisation frame definition

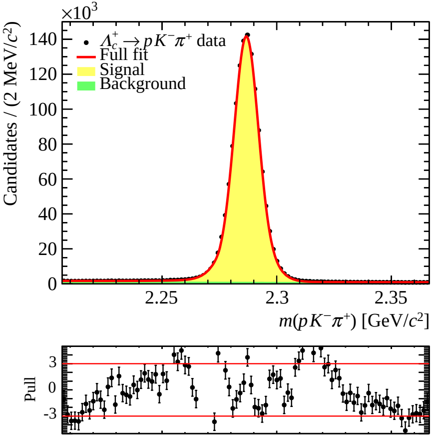
- Chosen Λ_c^+ helicity rest frame reached from the laboratory frame

$$
\begin{aligned}
\hat{\boldsymbol{z}}_{\Lambda_c^+} &= \hat{\boldsymbol{p}}(\Lambda_c^+) \\
\hat{\boldsymbol{x}}_{\Lambda_c^+} &= \frac{\boldsymbol{p}(\mu^-) - [\boldsymbol{p}(\mu^-) \cdot \hat{\boldsymbol{p}}(\Lambda_c^+)]\, \hat{\boldsymbol{p}}(\Lambda_c^+)}{\left|\boldsymbol{p}(\mu^-) - \left[\boldsymbol{p}(\mu^-) \cdot \hat{\boldsymbol{p}}(\Lambda_c^+)\right] \hat{\boldsymbol{p}}(\Lambda_c^+)\right|} \\
&= \frac{\boldsymbol{p}(\Lambda_c^+) \times \boldsymbol{p}(\mu^-)}{\left|\boldsymbol{p}(\Lambda_c^+) \times \boldsymbol{p}(\mu^-)\right|} \times \hat{\boldsymbol{p}}(\Lambda_c^+) \\
\hat{\boldsymbol{y}}_{\Lambda_c^+} &= \hat{\boldsymbol{z}}_{\Lambda_c^+} \times \hat{\boldsymbol{x}}_{\Lambda_c^+} \\
&= \frac{\boldsymbol{p}(\Lambda_c^+) \times \boldsymbol{p}(\mu^-)}{\left|\boldsymbol{p}(\Lambda_c^+) \times \boldsymbol{p}(\mu^-)\right|}
\end{aligned} \tag{1}
$$

with momenta expressed in the laboratory frame

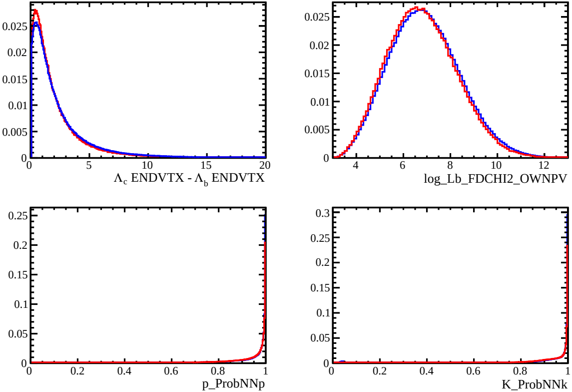
Selection

- Λ_c^+ vertex z position - Λ_b^0 vertex z position $< 6\ \mathrm{mm}$
- $\log(\mathrm{FD}\chi^2)(\Lambda_b^0) > 6.5$
- $\mathrm{ProbNN}(p \to p) > 0.95$
- $\mathrm{ProbNN}(p \to K^-) > 0.7$



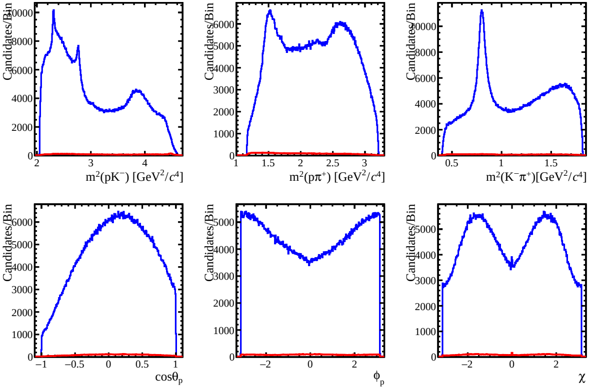
- Selected 1.27 millions of 2016 $\Lambda_c^+ \to pK^-\pi^+$ candidates
- Combinatorial background in $|m(pK^-\pi^+) - m(\Lambda_c^+)_{\mathrm{PDG}}| < 15\,\mathrm{MeV}$ signal region equal to 1.7% of the candidates

Data/MC comparison



- Simulation (blue) well reproduces the selection distribution after PID correction

Background contribution



- Background contribution (red) separated using sPlot technique
- Neglected in the amplitude fit

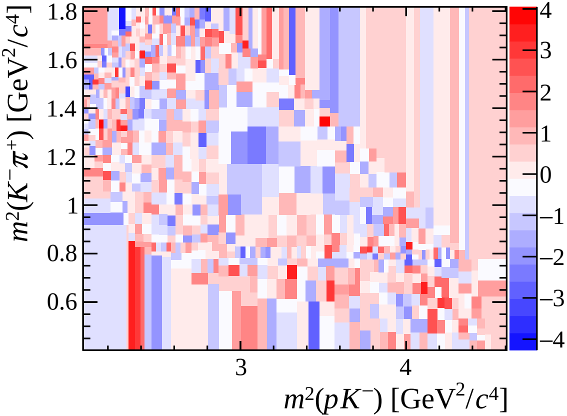
PDG Λ^* resonances

Resonance	J^P	BW mass (MeV)	BW width (MeV)	Existence
$\Lambda^*(1405)$	$1/2^-$	$1405.1^{+1.3}_{-1.0}$	50.5 ± 2.0	certain
$\Lambda^*(1520)$	$3/2^-$	1519.5 ± 1.0	15.6 ± 1.0	certain
$\Lambda^*(1600)$	$1/2^+$	$1560 - 1700$	$50 - 250$	very likely
$\Lambda^*(1670)$	$1/2^-$	$1660 - 1680$	$25 - 50$	certain
$\Lambda^*(1690)$	$3/2^-$	$1685 - 1695$	$50 - 70$	certain
$\Lambda^*(1710)$	$1/2^+$	1713 ± 13	180 ± 40	poor
$\Lambda^*(1800)$	$1/2^-$	$1720 - 1850$	$200 - 400$	very likely
$\Lambda^*(1810)$	$1/2^+$	$1750 - 1850$	$50 - 250$	very likely
$\Lambda^*(1820)$	$5/2^+$	$1815 - 1825$	$70 - 90$	certain
$\Lambda^*(1830)$	$5/2^-$	$1810 - 1830$	$60 - 110$	certain
$\Lambda^*(1890)$	$3/2^+$	$1850 - 1910$	$60 - 200$	certain
$\Lambda^*(2000)$		≈ 2000		poor
$\Lambda^*(2020)$	$7/2^+$	≈ 2020		poor
$\Lambda^*(2050)$	$3/2^-$	2056 ± 22	493 ± 60	poor
$\Lambda^*(2100)$	$7/2^-$	$2090 - 2110$	$100 - 250$	certain
$\Lambda^*(2110)$	$5/2^+$	$2090 - 2140$	$150 - 250$	very likely

PDG Δ^{++*} and K^* resonances

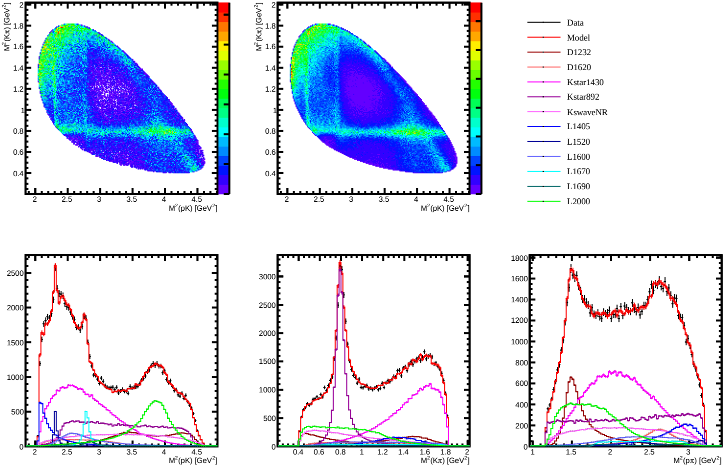
Resonance	J^P	BW mass (MeV)	BW width (MeV)	Existence
$\Delta^{++*}(1232)$	$3/2^+$	$1230 - 1234$	$114 - 120$	certain
$\Delta^{++*}(1600)$	$3/2^+$	$1500 - 1640$	$200 - 300$	certain
$\Delta^{++*}(1620)$	$1/2^-$	$1590 - 1630$	$110 - 150$	certain
$\Delta^{++*}(1700)$	$3/2^-$	$1690 - 1730$	$220 - 380$	certain
$K_0^*(700)$	0^+	824 ± 30	478 ± 50	certain
$K^*(892)$	1^-	891.76 ± 0.25	50.3 ± 0.8	certain
$K^*(1410)$	1^-	1421 ± 9	236 ± 18	certain
$K_0^*(1430)$	0^+	1425 ± 50	270 ± 80	certain

Dalitz fit, reduced model, residuals

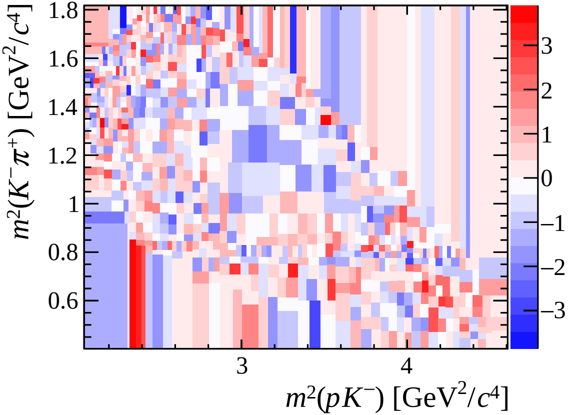


- χ^2/ndf = 1436.37/939 = 1.53
- Data overestimated at Dalitz plot center, underestimated where $\Lambda^*(1520)$ and $K^*(892)$ resonances meet

Dalitz fit, extended model

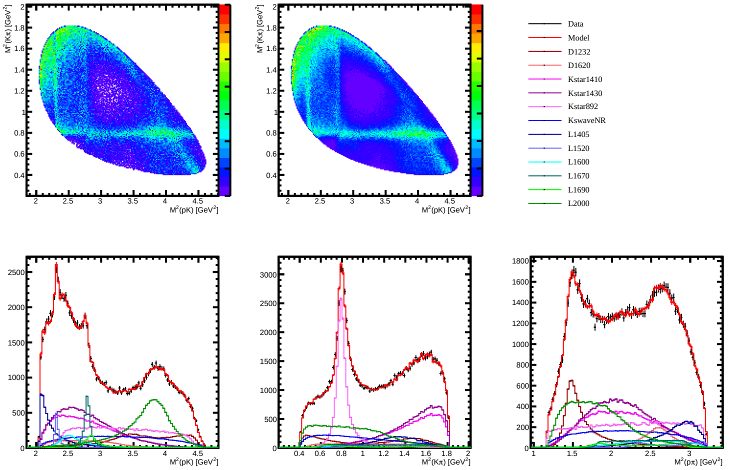


Dalitz fit, extended model, residuals

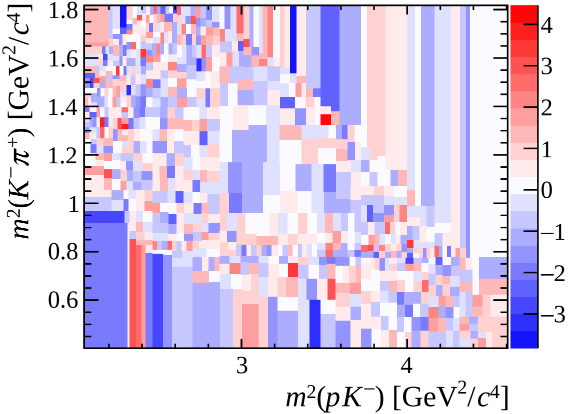


- χ^2/ndf = 1418.05/928 = 1.53
- Same pattern as for reduced model

Dalitz fit, reduced model, alt. sample

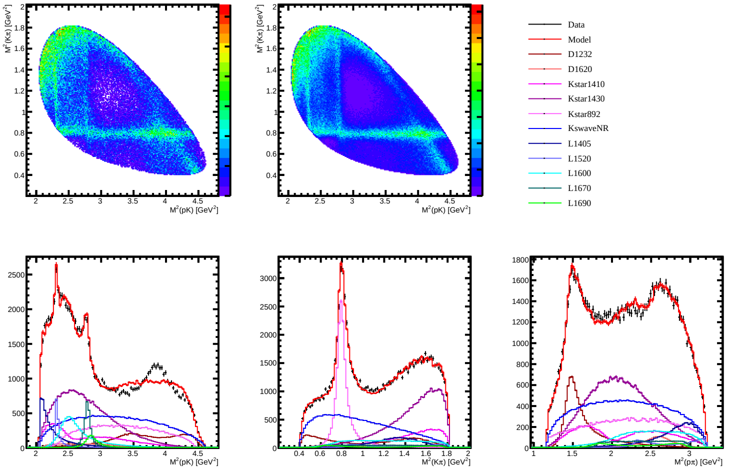


Dalitz fit, extended model, alt. sample, residuals



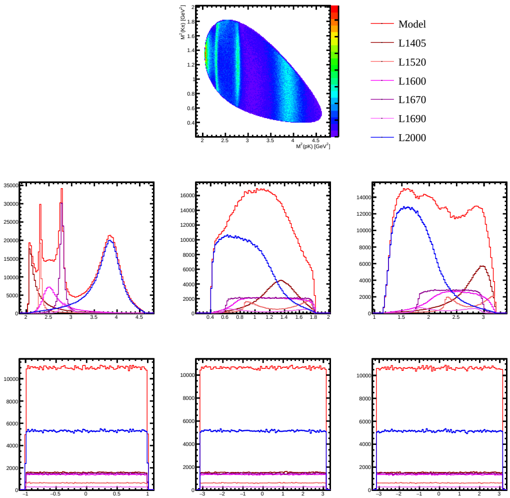
- χ^2/ndf = 1393.59/939 = 1.48
- Roughly same pattern as before

Dalitz fit, reduced model, no $\Lambda^*(2000)$



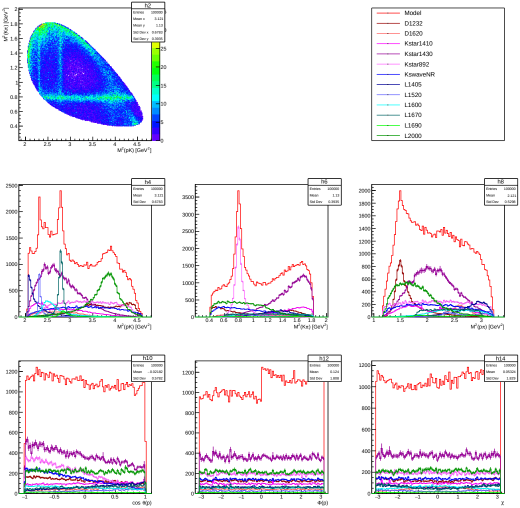
Model (an)isotropy, Λ^* resonances only

- Generated phase-space distributions according to amplitude model for zero polarisation with Λ^* resonances only
- Model isotropic as should be



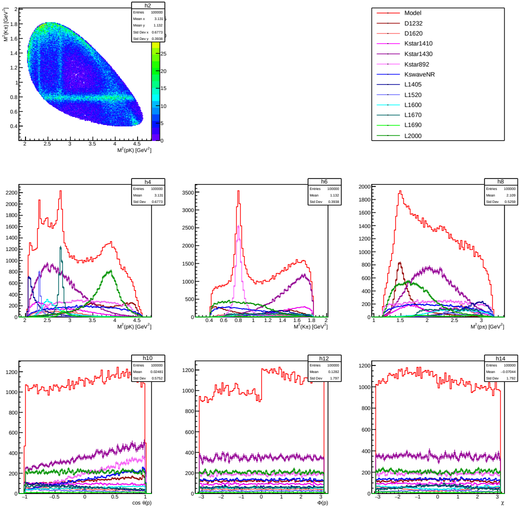
Mass distributions vs polarisation

- Generated phase-space distributions according to Dalitz fit reduced model results with full polarisation, here $P_z = 1$
- Basically same invariant mass distributions for zero and full polarisations, checked separately for the three components
- Note the interference pattern different from single resonance fractions



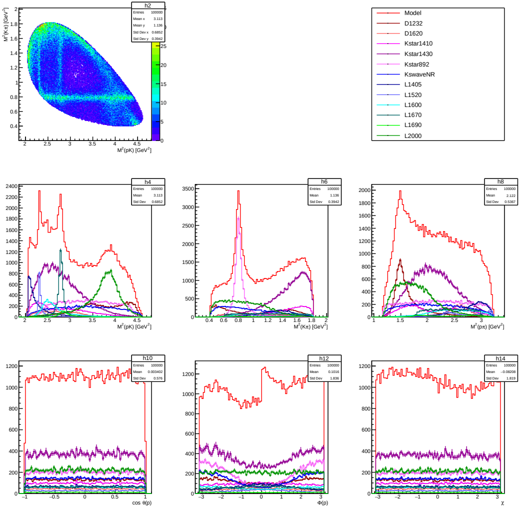
Mass distributions vs polarisation

- Generated phase-space distributions according to Dalitz fit reduced model results with full polarisation, here $P_z = -1$



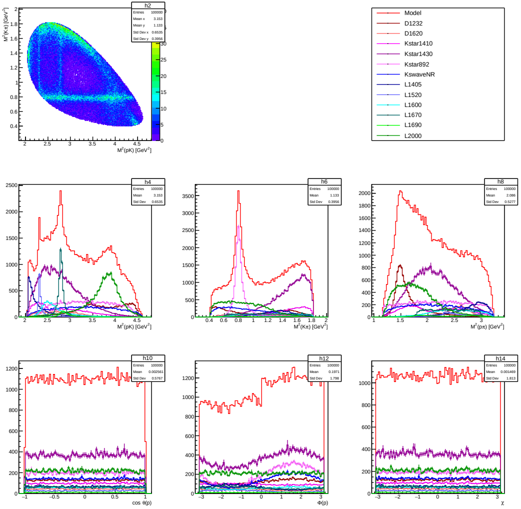
Mass distributions vs polarisation

- Generated phase-space distributions according to Dalitz fit reduced model results with full polarisation, here $P_x = -1$



Mass distributions vs polarisation

- Generated phase-space distributions according to Dalitz fit reduced model results with full polarisation, here $P_y = 1$



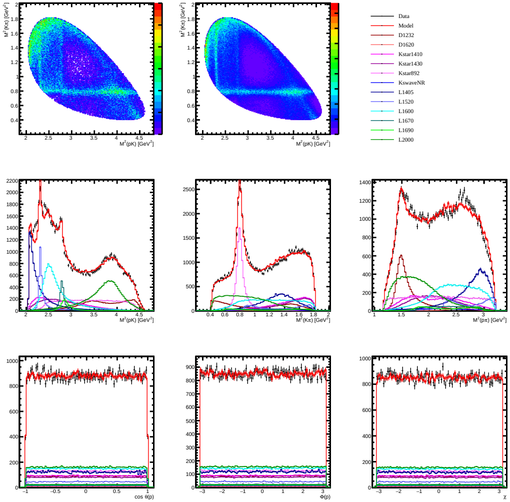
Phase space fit to generated events, no efficiency

- Full phase space amplitude fit using reduced model to 80’000 generated events
- Invariant mass distributions generated according to Dalitz fit
- Uniformly generated angular distributions corresponding to zero polarisation
- No detector effects included

Phase space fit to generated events, no efficiency

- Fit able to select an amplitude model with uniform angular distributions at the price of creating discrepancies in the invariant masses
- Extracted polarisation close to zero

$$P_x = -0.005 \pm 0.007$$
$$P_y = -0.033 \pm 0.008$$
$$P_z = -0.014 \pm 0.003$$



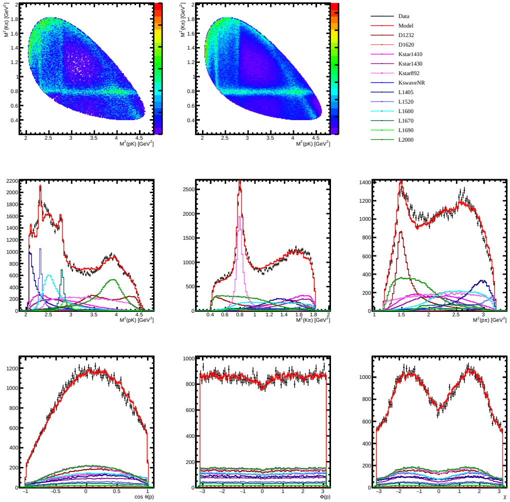
Phase space fit to generated events, with efficiency

- Full phase space amplitude fit using reduced model to 80’000 generated events
- Events generated as before but throwing events from the flat phase space simulated sample
- This way detector efficiency effects are included

Phase space fit to generated events, with efficiency

- Similar results as without efficiency
- Extracted polarisation less close to zero than before

$$P_x = -0.059 \pm 0.005$$
$$P_y = -0.014 \pm 0.005$$
$$P_z = 0.066 \pm 0.005$$



Sensitivity to polarisation study

- Average event Fisher information also computed for single resonance contribution
  - (preliminary) measurement of decay asymmetry parameters

Resonance	α
$\Delta^{*++}(1232)$	0.326167
$\Delta^{*++}(1620)$	0.838581
$K^*(1410)$	0.534397
$K_0^*(1430)$	0.334020
$K^*(892)$	0.804092
$K^*(NR)$	0.719274
$\Lambda^*(1405)$	0.662372
$\Lambda^*(1520)$	0.691277
$\Lambda^*(1600)$	0.492067
$\Lambda^*(1670)$	0.565408
$\Lambda^*(1690)$	0.407455
$\Lambda^*(2000)$	0.065092

Experimental status

- No polarisation measurements of the Λ_c^+ baryon at SMOG center-of-mass energies
- NA32 experiment at SPS (Phys. Lett. B286 (1992) 175) in 230 GeV π^- on Cu target collisions, 121 $\Lambda_c^+ \to pK^-\pi^+$ events
  - Indication of negative Λ_c^+ polarization for $p_{\mathrm{T}} > 1.1\,\mathrm{GeV}$
- E791 experiment at FNAL (Phys. Lett. B471 (2000) 449) in 500 GeV π^- on Pt-diamond target, 1000 $\Lambda_c^+ \to pK^-\pi^+$ events
  - Trend of increasing negative polarisation with increasing p_{T}

Global Event Selection for SMOG events

- Conservative Global Event Selection applied to remove *pp* collisions

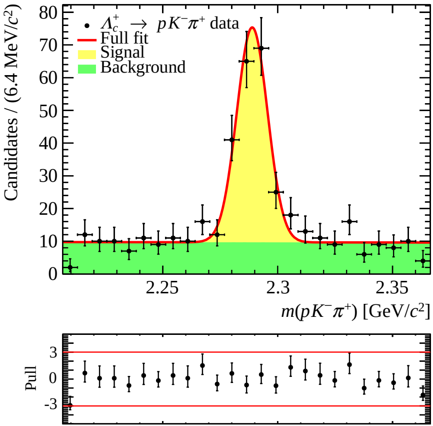
z_{PV} region (mm)	`nPUHits`	`nBackTracks`
$-200 < z_{PV} < -100$	< 5	< 5
$-100 < z_{PV} < 100$	$= 0$	$= 0$
$100 < z_{PV} < 200$	< 5	< 5

Preliminary cut-based selection for $\Lambda_c^+ \to pK^-\pi^+$

- Signal cut-based selection, “hand-made” optimisation, aiming at high signal purity
- TOS on `Hlt1SMOGpKPi` and `Hlt2SMOGLc2KPPi` trigger lines
- $PID_p(p) > 15$
- $PID_K(K) > 15$
- $PID_K(\pi) < -30$
- $ENDVTX\chi^2/nDOF(\Lambda_c^+) < 6$ (good Λ_c^+ decay vertex)
- $IP\_OWNPV\chi^2/nDOF(\Lambda_c^+) < 2$ (Λ_c^+ production compatible with PV)
- $\arccos(DIRA\_OWNPV(\Lambda_c^+)) < 0.015$ (Λ_c^+ momentum compatible with flight direction)
- $\tau(\Lambda_c^+) > 0.5$ ps (remove prompt background)

Preliminary cut-based selection for $\Lambda_c^+ \to pK^-\pi^+$

- Signal & background yields
  - $S = 153 \pm 15$, $B = 197 \pm 16$, width ≈ 6.6 MeV
  - $\approx 19\%$ bkg fraction in ± 15 GeV signal region
  - Significance $S/\sqrt{S+B} = 11.1$

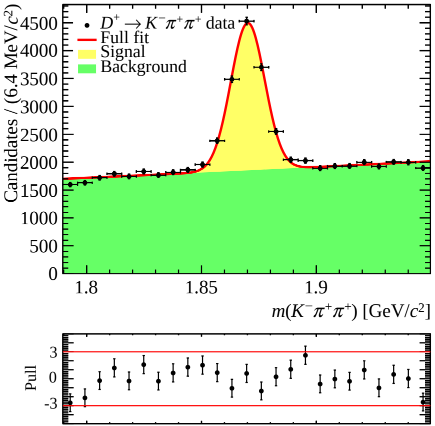


Preliminary BDT selection strategy

- Idea: use the $D^+ \to K^-\pi^+\pi^+$ p-Ne sample, with higher statistics and similar 3-body decay topology (but $\tau(D^+) \approx 5\tau(\Lambda_c^+)$), to train a BDT using topological variables
  - Apply a loose preselection to produce a pure enough $D^+ \to K^-\pi^+\pi^+$ sample to apply sWeighting
  - Train a BDT separating S/B distributions
  - Apply an analogous loose preselection to $\Lambda_c^+ \to pK^-\pi^+$
  - Optimise BDT cut maximising significance in signal region ($\pm 15 MeV$ from PDG Λ_c^+ mass) according to $\Lambda_c^+ \to pK^-\pi^+$ preselected data fit
- PID cuts to be studied separately (calibration samples?)
- Trigger requirements removed having 1/3 signal efficiency only

$D^+ \to K^-\pi^+\pi^+$ preselection

- Preselection cuts:
  - $PID_K(K) > 0$
  - $PID_K(\pi) < -70$
  - $\tau(D^+) > 0.3$ ps
  - $\arccos(DIRA\_OWNPV(D^+)) < 0.03$
  - $IP\_OWNPV\chi^2/nDOF(D^+) < 4$
- Signal & background yields
  - $S = 7652 \pm 155$,
    $B = 46347 \pm 250$,
    width 7.39 ± 0.16 MeV
  - ≈ 8690 bkg events in ± 15 MeV signal region

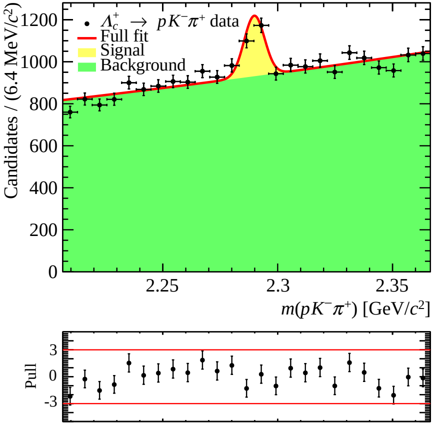


$D^+ \to K^-\pi^+\pi^+$ BDT

- Trained a BDT on sWeighted $D^+ \to K^-\pi^+\pi^+$ data with the following variables
  - $\tau(D^+)$ (against prompt background)
  - $ENDVTX\chi^2/nDOF(D^+)$ (good Λ_c^+ decay vertex)
  - $\arccos(DIRA\_OWNPV(D^+))$ (Λ_c^+ momentum compatible with flight direction)
  - $IP\_OWNPV\chi^2/nDOF(D^+)$ (Λ_c^+ direction compatible with PV)
  - $log(IP\_OWNPV\chi^2/nDOF(h))$ (hadron tracks compatible with PV)
  - $log(OWNPV\chi^2(D^+))$ (good PV)

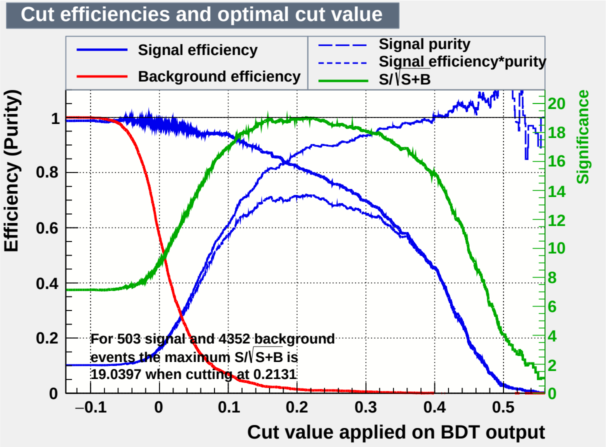
$\Lambda_c^+ \to pK^-\pi^+$ preselection

- Preselection cuts:
  - $PID_K(K) > 0$
  - $PID_K(\pi) < -70$
  - $\tau(D^+) > 0.3$ ps (remove prompt background)
  - $\arccos(DIRA\_OWNPV(\Lambda_c^+)) < 0.03$ (Λ_c^+ momentum compatible with flight direction)
  - $IP\_OWNPV\chi^2/nDOF(\Lambda_c^+) < 4$ (Λ_c^+ production compatible with PV)
- Signal & background yields
  - $S = 503 \pm 72$, $B = 23213 \pm 167$
  - ≈ 4352 bkg events in ± 15 MeV



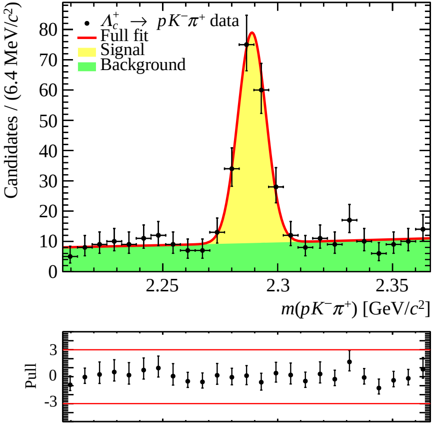
D^+ BDT cut optimisation

- Suggested BDT>0.2131, but large plateau near maximum



$\Lambda_c^+ \to pK^-\pi^+$ yield, D^+ optimisation

- Applied suggested BDT cut
- Signal & background yields
  - $S = 156 \pm 15$, $B = 221 \pm 17$, width 6.1 ± 0.5 MeV
  - $\approx 21\%$ bkg fraction in ± 15 GeV signal region
  - Significance $S/\sqrt{S+B} = 11.1$
  - Much lower significance (signal efficiency) than expected from $D^+ \to K^-\pi^+\pi^+$
- Similar power as cut-based selection but without PID and trigger cuts



$\Lambda_c^+ \to pK^-\pi^+$ yield, looser BDT cut

- Tried looser BDT cut: preselection + BDT>0.07
- Signal & background yields
  - $S = 356 \pm 24$, $B = 1104 \pm 37$, width 5.3 ± 0.4 MeV
  - $\approx 37\%$ bkg fraction in ± 15 GeV signal region
  - Significance $S/\sqrt{S+B} = 15.0$