ΔA_{CP} in $\Lambda_c \to ph^+h^-$ at LHCb

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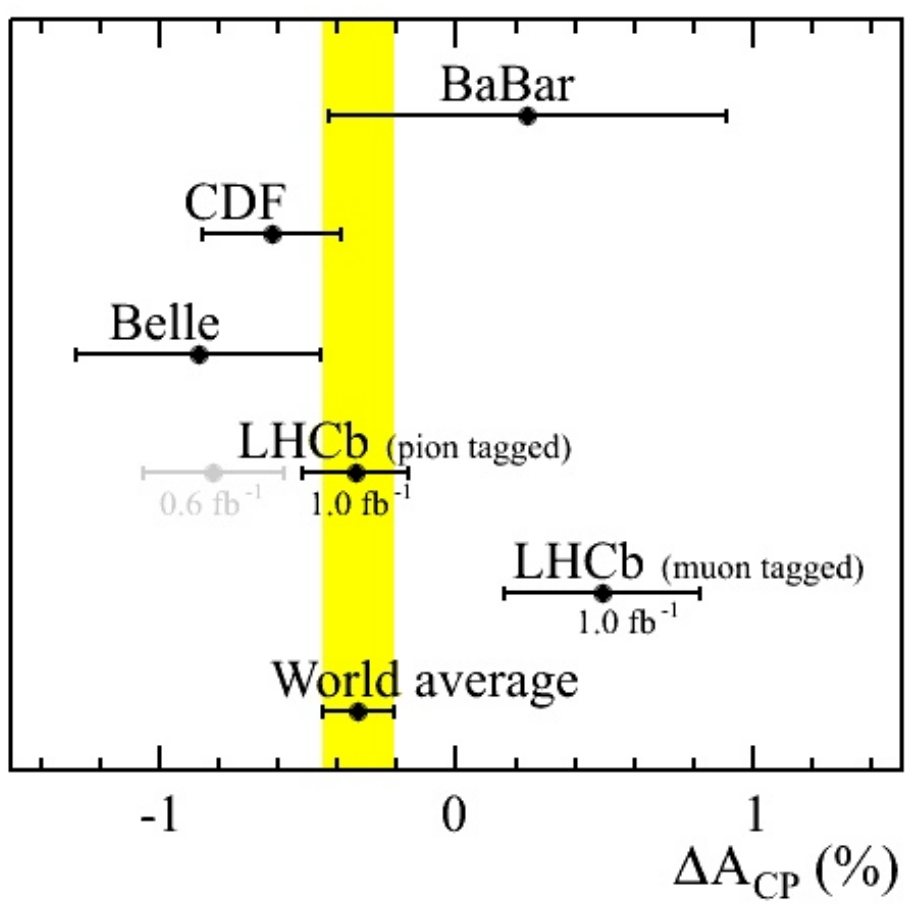
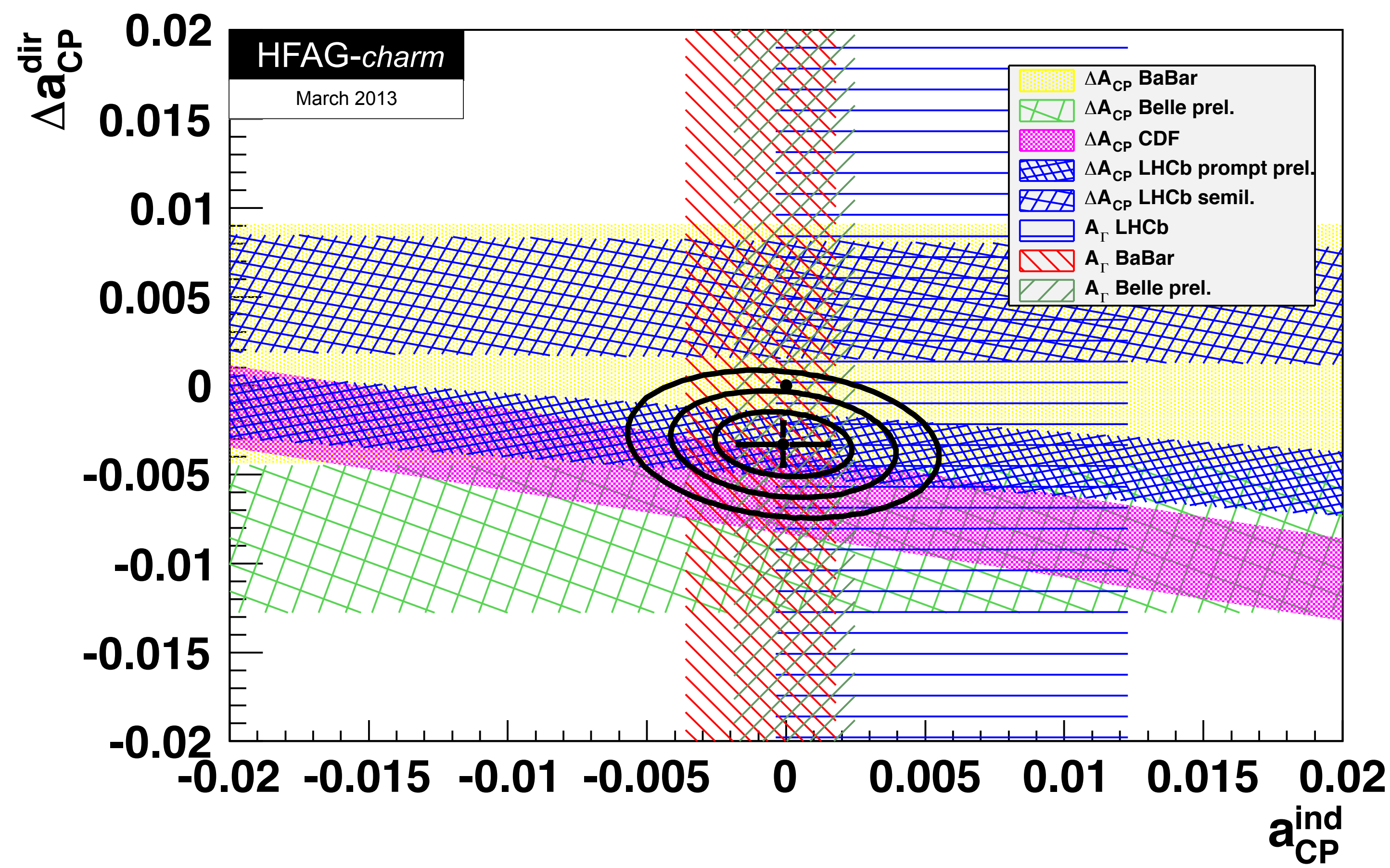
Contents

CP Violation in Charm

- Large interest in charm sector CP violation (CPV), mostly D^0 decays, all mesons
  - Mixing, direct in ΔA_{CP} and indirect in A_Γ
- Significant deviations from SM could mean new physics
- Good agreement with SM constrain other models



Values for ΔACP in D^0 to h^+h^- decays

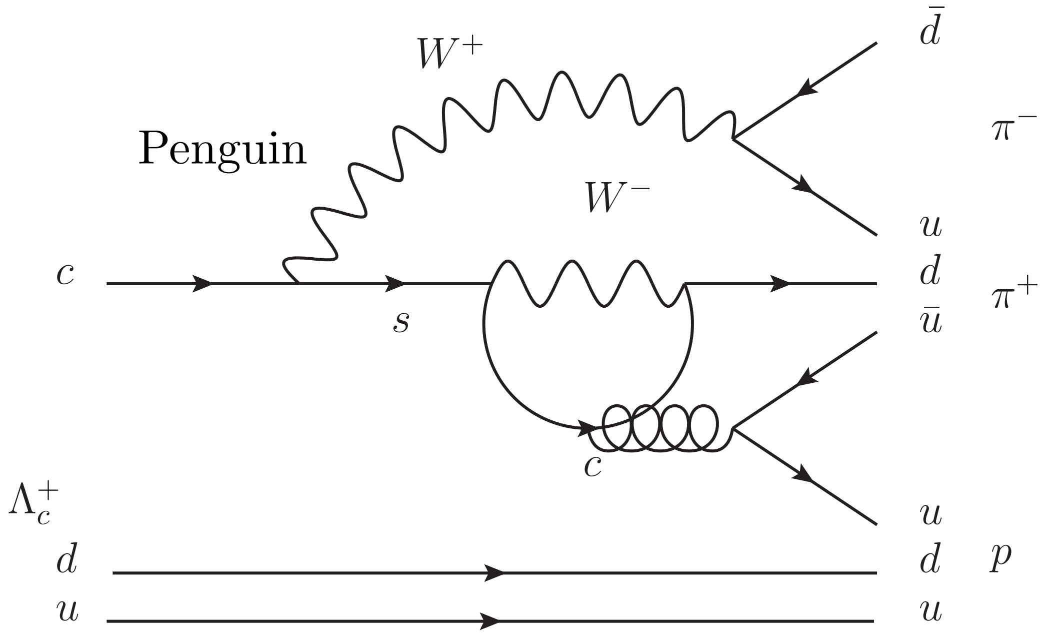


Filled circle represents no CPV (0, 0), bands represent $\pm 1\sigma$ intervals
Cross is best fit, ellipses are 68%, 95%, 99.7% CL regions

- Current world average consistent with no CPV at 2% CL

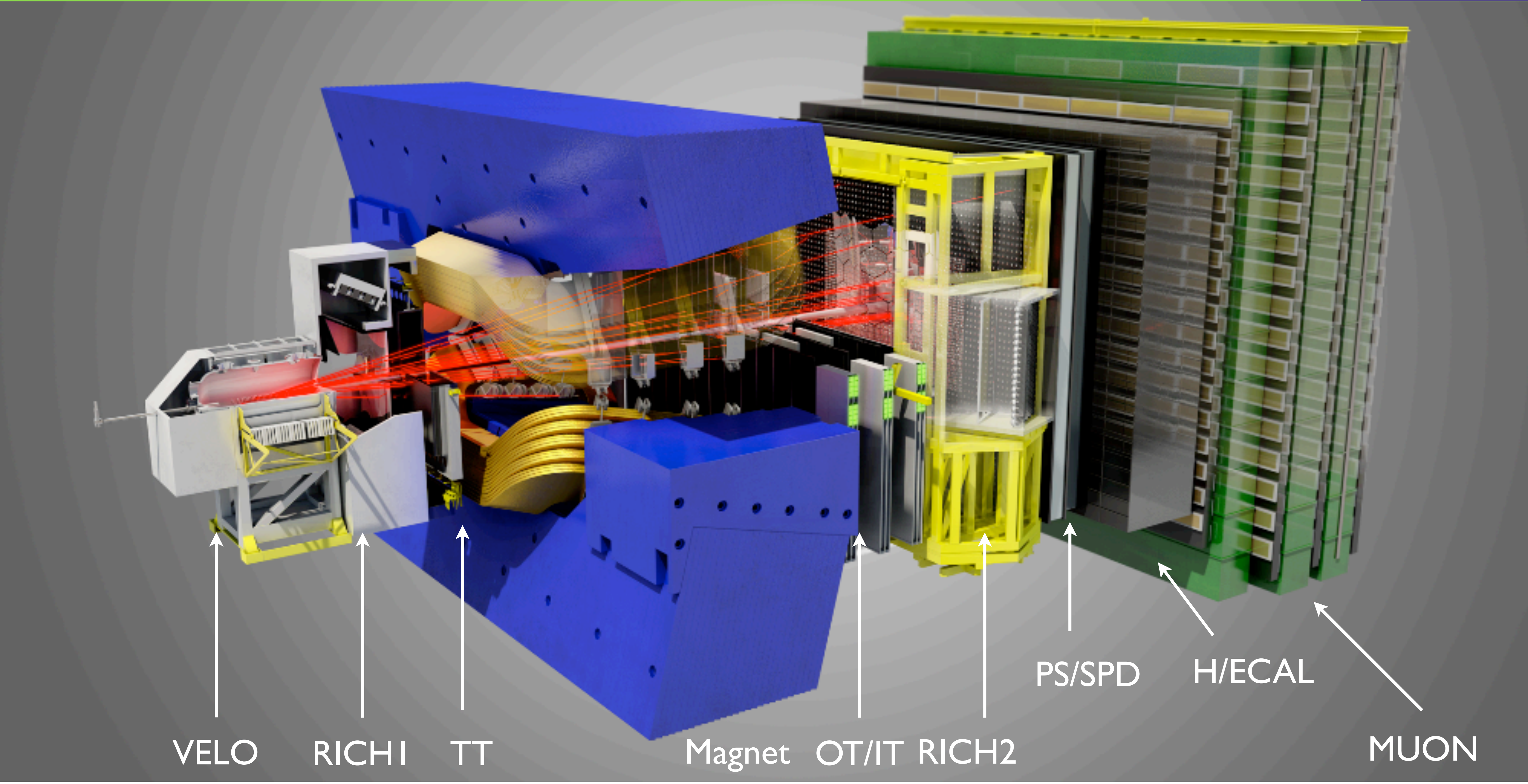
Origins of CPV

- Weak phase from CKM matrix can lead to interference in Feynman diagrams and non-zero cancellation of matrix elements, i.e. CPV
- A singly Cabibbo-suppressed (SCS) vertex provides a possible source of CP violation this way:



- SM still doesn't predict our existence, must be undiscovered CPV somewhere
- Charm CPV predictions very small; $O(1\%)$ effect could be new physics

The LHCb Detector



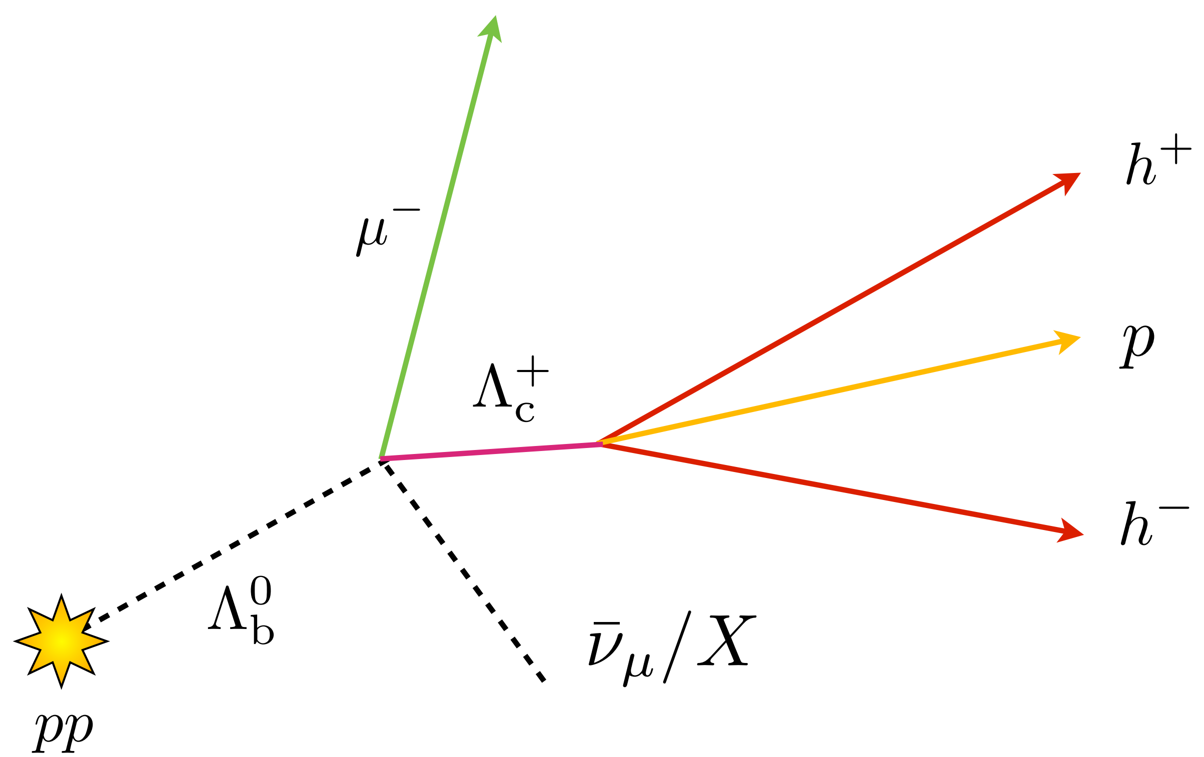
- Forward spectrometer designed for precision beauty and charm physics
- 853 members from 63 institutes in 17 counties
- Excellent vertex resolution and particle identification
- Triggering reduces LHC rate of 40 MHz to 3 kHz for storage
- Largest charm yields in the world

Analysis

- 3 Λ_c decays: SCS pKK and $p\pi\pi$ for CP measurement, Cabibbo-favoured $pK^-\pi^+$ as control mode

$$\Lambda_b^0 \to \Lambda_c^+ \mu^- X, \quad \Lambda_c^+ \to p h^+ h^-, \quad h \in [K, \pi]$$

- Measure relative branching fractions of the SCS modes to CF
- Pros and cons compared to D^0 analyses
  - ✓ Double tagging, no lifetime dependance (no indirect CPV)
  - × 5D phase space, due to spin, adds complexity
- Full 2011 & 2012 dataset (3 fb^{-1})



ΔA_{CP}

- Given no CP violation, the difference of branching fractions between matter and antimatter modes would be zero, measure of the deviation is A_{CP}

$$A_{CP}^{\Lambda_c}(h) = \frac{\Gamma(\Lambda_c^+ \to p h^+ h^-) - \Gamma(\Lambda_c^- \to \bar{p} h^+ h^-)}{\Gamma(\Lambda_c^+ \to p h^+ h^-) + \Gamma(\Lambda_c^- \to \bar{p} h^+ h^-)}$$

- What's measured is the matter and antimatter yields, tagged by the proton/muon charge; but contaminated by 'background' asymmetries

$$\begin{aligned} A_{\mathrm{Raw}}^{\Lambda_c}(h) &= \frac{N(\Lambda_c^+ \to p h^+ h^-) - N(\Lambda_c^- \to \bar{p} h^+ h^-)}{N(\Lambda_c^+ \to p h^+ h^-) + N(\Lambda_c^- \to \bar{p} h^+ h^-)} \\ &= A_{CP}^{\Lambda_c}(h) + A_{P}^{\Lambda_b}(h) + A_{D}^{p}(h) + A_{D}^{\mu}(h) + \mathcal{O}(A^3) \end{aligned}$$

- Tricky to measure A_P and A_D, but if these background asymmetries are mode-independent can take the difference to leave pure physics

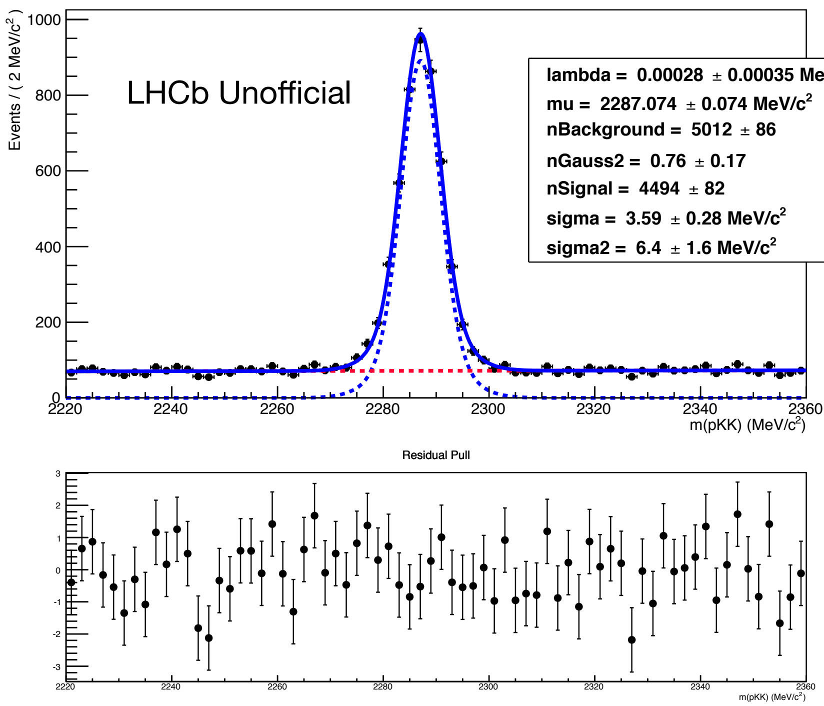
$$\Delta A_{CP}^{\Lambda_c} = A_{\mathrm{Raw}}^{\Lambda_c}(K) - A_{\mathrm{Raw}}^{\Lambda_c}(\pi) \approx A_{CP}^{\Lambda_c}(K) - A_{CP}^{\Lambda_c}(\pi)$$

- Clean selection to prevent asymmetries from other processes

2011 Selection

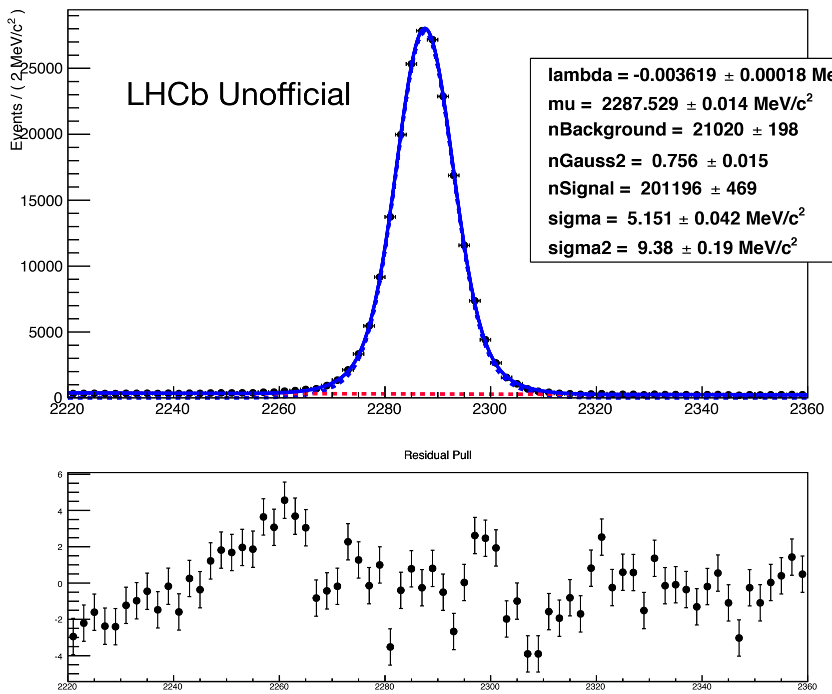
- Per-mode selections consist of a multivariate algorithm (boosted decision tree) and tight particle identification (PID) requirements
- Kinematics vetoes imposed, in p and η, to improve PID performance
- Misidentifications checked, e.g. $D_s \to KKK$, by testing wrong mass hypothesis, no peaking backgrounds found

pKK (SCS)



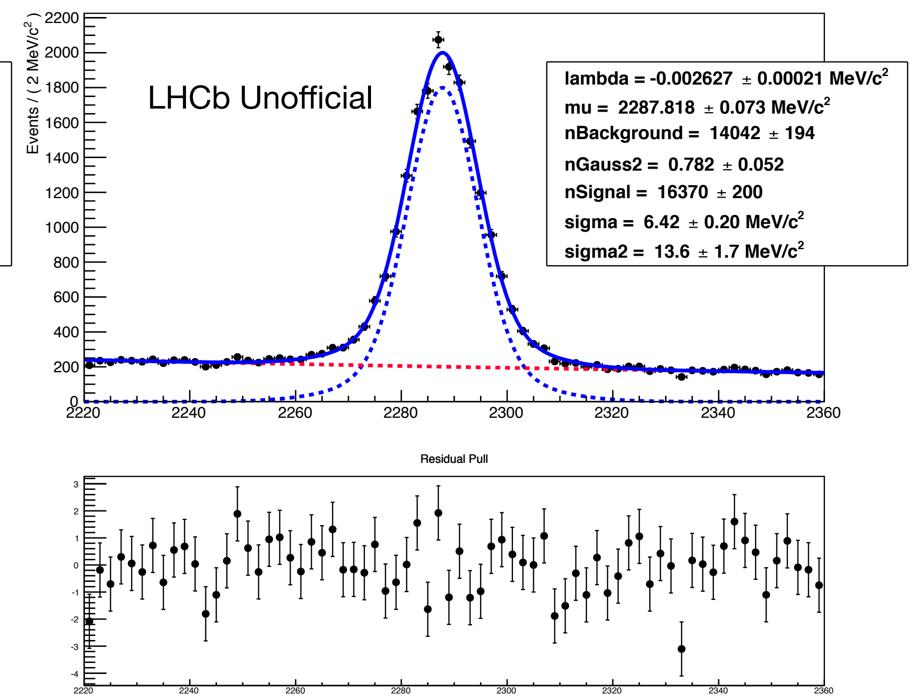
Signal yield: *4494 ± 82*

$pK^-\pi^+$ (CF)



Signal yield: *201196 ± 469*

$p\pi\pi$ (SCS)



Signal yield: *16370 ± 194*

- Raw yields extracted from unbinned fits to Λ_c mass; double Gaussian signal, exponential background
- Efficiencies must be calculated to know the production yield

2011 Selection - Efficiencies

- Efficiencies compensate for detector and selection imperfections
  - We don't detect every produced signal decay
  - Cuts reduce background at the cost of signal
- True production yields calculable with efficiencies

Detector	**Selection**
Acceptance	Stripping
Reconstruction	Kinematic vetoes
Tracking	MVA
	PID
	Trigger

$$N_{\text{Raw}} = N_{\text{Produced}} \times \epsilon_{\text{Selection}} \epsilon_{\text{Detector}}$$

- MVA, PID, tracking, and veto efficiencies from data
- Stripping, trigger, reconstruction, and acceptance from full LHCb simulation

		ε Selection (%)	ε Detector (%)
pK^+K^-	Magnet Up	3.752 ± 0.278	4.120 ± 0.017
	Magnet Down	3.305 ± 0.179	3.305 ± 0.017
$p\pi^+\pi^-$	Magnet Up	2.663 ± 0.083	3.651 ± 0.015
	Magnet Down	2.631 ± 0.066	3.650 ± 0.015

2011 Selection - Relative Branching Fractions

- Measured pKK and $p\pi\pi$ branching fractions, relative to CF $pK^-\pi^+$

LHCb Unofficial	$B(ph^+h^-)/B(pK^-\pi^+)$ ($\times$ 10^{-2})		
	Magnet Up	**Magnet Down**	**PDG**
pK^+K^-	1.406 ± 0.114	1.552 ± 0.094	1.5 ± 0.8
$p\pi^+\pi^-$	8.162 ± 0.311	8.093 ± 0.256	7.0 ± 0.4

- Errors are purely statistical, and include statistical errors in the efficiencies
- Fit, PID, and trigger systematics are being assessed

- Complementary LHCb analysis allows us to validate our selection (ongoing)
  - Prompt Λ_c, different PID criteria and MVA inputs
- PDG values for these poorly known; 50% errors. LHCb can do much better!
- Other measurements differ greatly; worth getting this right

CLEO II[1] $(3.9 \pm 0.9 \pm 0.7) \times 10^{-2}$, Belle[2] $(1.4 \pm 0.2 \pm 0.2) \times 10^{-2}$

Back to ΔA_{CP}

- With production yields now known, ΔA_{CP} should be simple: separate the decays by proton/muon charge and do some arithmetic

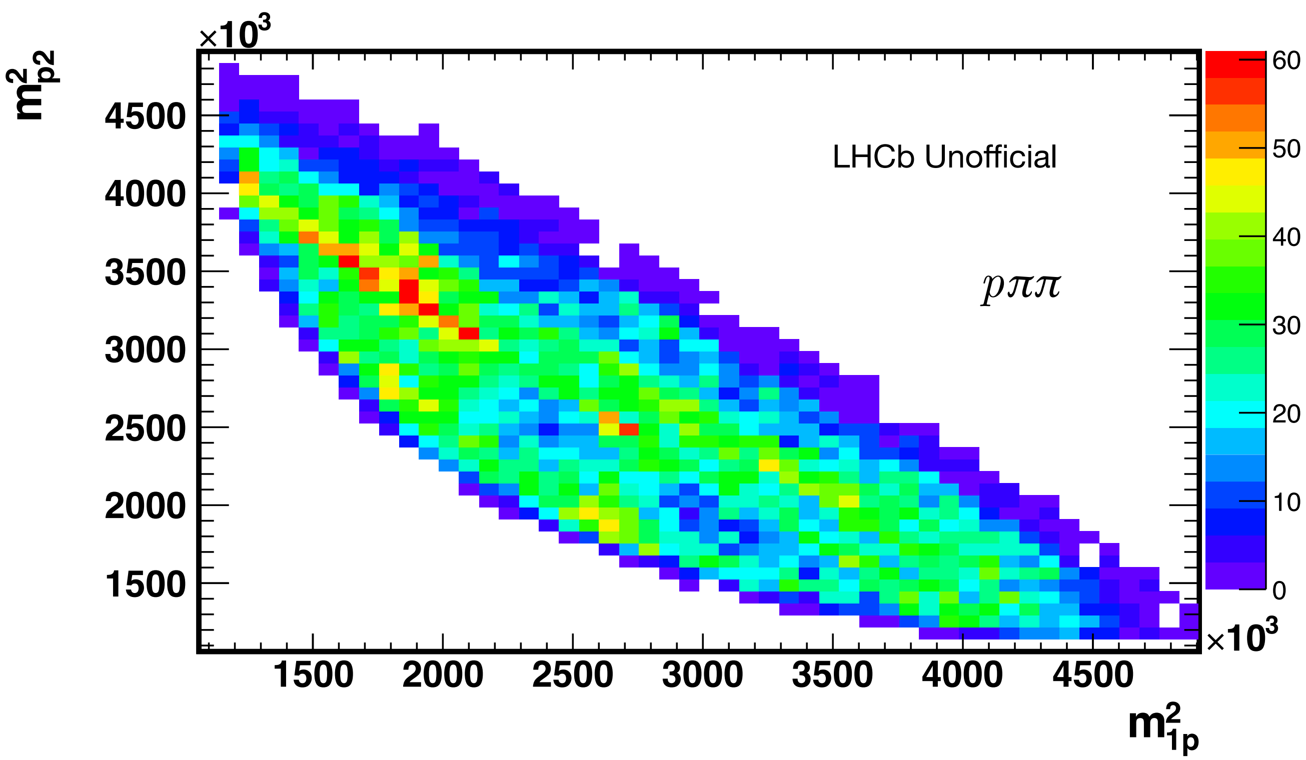
$$A_{\mathrm{Raw}}^{\Lambda_c}(h) = \frac{N(\Lambda_c^+ \to p h^+ h^-) - N(\Lambda_c^- \to \bar{p} h^+ h^-)}{N(\Lambda_c^+ \to p h^+ h^-) + N(\Lambda_c^- \to \bar{p} h^+ h^-)}, \quad \Delta A_{CP} = A_{\mathrm{Raw}}^{\Lambda_c}(K) - A_{\mathrm{Raw}}^{\Lambda_c}(\pi)$$

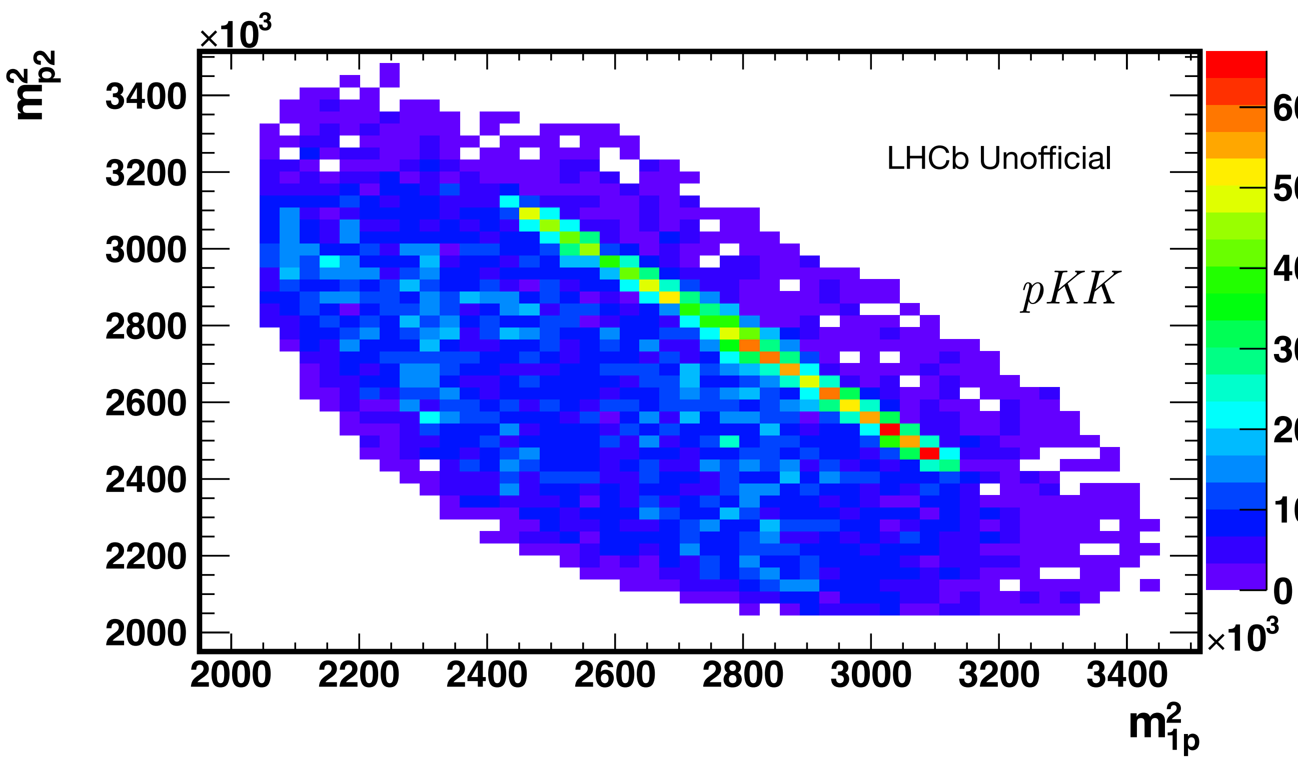
- This rests on the assumption that the background asymmetries are mode independent...

$$A_P^{\Lambda_b}(K) = A_P^{\Lambda_b}(\pi), \quad A_D^p(K) = A_D^p(\pi), \quad A_D^\mu(K) = A_D^\mu(\pi)$$

- ... but
  - In general, A_D^p will depend on proton kinematics
  - Proton kinematics will differ between pKK and $p\pi\pi$, as h^+h^- q^2 values are different, so cancellation is not exact

- Difficulties arise from rich resonance structure and large phase space (5D)
  - Relative phases of CPV across the space may cancel when averaged
  - Baryonic ΔA_{CP} difficult to predict, and hard to interpret experimentally
    - If there is CPV, where is it? What's producing it?
  - Crossing resonances may cause inexact $K^{\pm}$ detection asymmetry cancellation
    - Difficult to control $\rightarrow$ large systematic



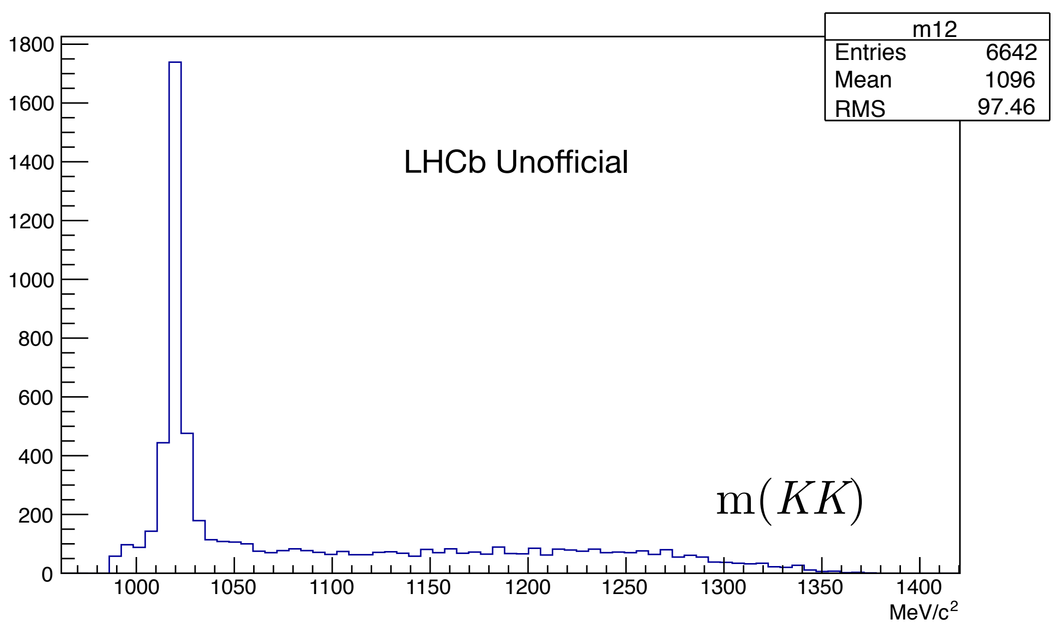


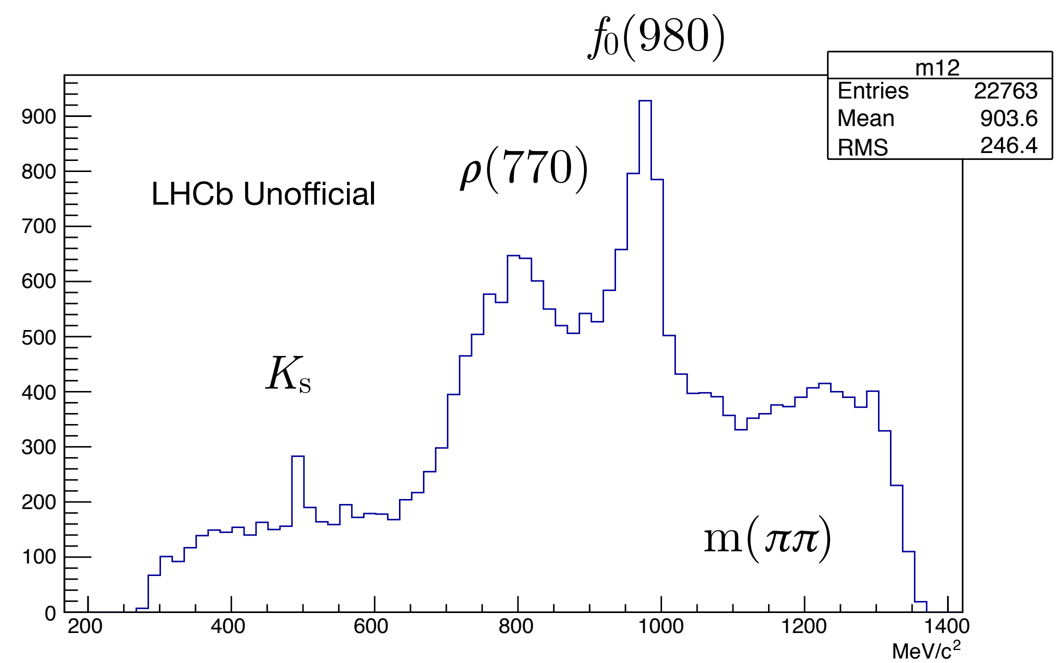
Dalitz plots of Λ_c daughters: ph^- vs. ph^+

We can use these resonances to our advantage!

Using Λ_c Resonances

- A neater analysis could use two-body Λ_c resonances: $p\phi$ ($\rightarrow KK$), pK_s ($\rightarrow \pi\pi$)
  - Measure A_{CP} in $p\phi$, using CF pK_s as a control mode
  - Two-body decays are easier to predict theoretically
  - Any measured CPV is easily attributable to its source
  - KK from ϕ is very strong and narrow, so very little signal is sacrificed, and restricted $K^{\pm}$ momentum makes the detection asymmetry easier to handle





- Proton asymmetries still an issue, but manageable
- Also investigating $pf_0(980)$ ($\rightarrow \pi\pi$): similar proton kinematics to $p\phi$

Conclusions

- LHCb is carrying out precision charm measurements

- We have performed a selection on the Cabibbo-favoured $pK^{-}\pi^{+}$ and the Cabibbo-suppressed pKK and $p\pi\pi$ modes
- The detector and selection efficiencies have been evaluated, allowing us to conduct relative branching fraction measurements
- The selection and BF measurements will soon be updated with the full 3 fb^{-1} dataset

- We are now looking forward to be among the first to test for CP violation in charmed baryon decays
- Moving on to study $p\phi$, $pf_0(980)$, and pK_{s} resonances,
- Future measurement of $p/\bar{p}$ detection asymmetry directly; would greatly aide future analyses at LHCb

Backup

References

1. CLEO II pKK BF (1995): http://arxiv.org/abs/hep-ex/9508005
2. Belle pKK BF (2001): http://arxiv.org/abs/hep-ex/0111032

Deriving A_{Raw}

- One production and two detection asymmetries defined as

$$A_P^{\Lambda_b^0} = \frac{\mathcal{P}(\Lambda_b^0) - \mathcal{P}(\bar{\Lambda}_b^0)}{\mathcal{P}(\Lambda_b^0) + \mathcal{P}(\bar{\Lambda}_b^0)},$$

$$A_D^p = \frac{\epsilon(p) - \epsilon(\bar{p})}{\epsilon(p) + \epsilon(\bar{p})},$$

$$A_D^\mu = \frac{\epsilon(\mu^-) - \epsilon(\mu^+)}{\epsilon(\mu^-) + \epsilon(\mu^+)}.$$

- The product of these with the true number of events is the measured number

$$N_{\text{Raw}}(\Lambda_c^+) = \mathcal{P}(\Lambda_b^0)\epsilon(p)\epsilon(\mu^-)N_{\text{True}}(\Lambda_c^+)$$

- Substitute the following for each asymmetry in N_{Raw}, then N_{Raw} in to A_{Raw}

$$A = \frac{f - \bar{f}}{f + \bar{f}}, \quad f = \frac{1}{2}(f + \bar{f})(1 + A), \quad \bar{f} = \frac{1}{2}(f + \bar{f})(1 - A)$$

Selection Details

- BDT input variables chosen to maximise signal/background discrimination
  - Muon and Λ_c daughter p_T
  - Muon and Λ_c daughter track fit quality
  - Lowest impact parameter of the Λ_c daughters
  - Distance of closest approach of daughters to Λ_c vertex
  - Λ_b vertex, impact parameter, and flight distance quality
- PID cuts optimised to maximise signal significance, then tuned for signal purity
- Kinematic vetoes imposed to eliminate tracks with poor PID performance