Experimental prospects for CPV measurements in baryons, and T- and P-odd symmetries

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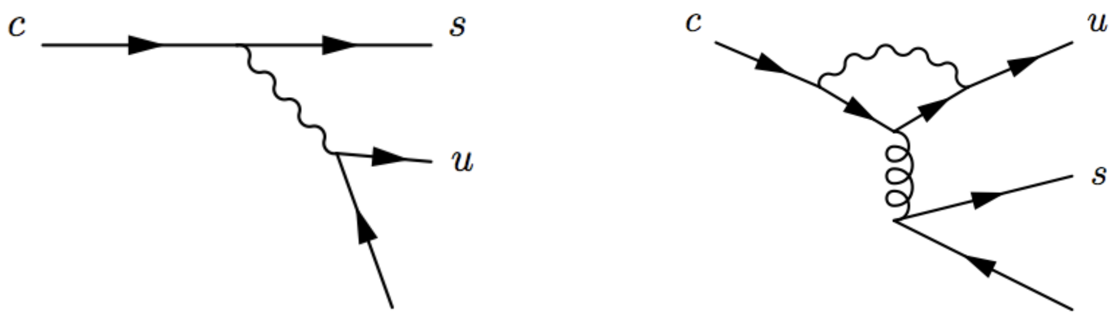
Towards the Ultimante Precision in Flavour Physics
University of Warwick, 16.04.2018

Outline

- Decays of Interest
- Current Experimental Status
- Future Challenges
- Outlook

Decays of Interest for this Talk



(a) *Tree diagram.* (b) *Penguin diagram.*

$\Lambda_c^+ \rightarrow p h^+ h^-$

$\Lambda_c^+ \rightarrow \Lambda^0 K^- \pi^+ \pi^-$

$\Lambda_c^+ \rightarrow p K^0_S K^- \pi^+$

$D^0 \rightarrow h^+ h^- \pi^+ \pi^-$

$D^0 \rightarrow K^0_S \pi^+ \pi^- \pi^0$

baryon decays

T- and P-odd moments

ΔA_{CP} in Λ_c^+ baryons

LHCb-PAPER-2017-044
Accepted by JHEP

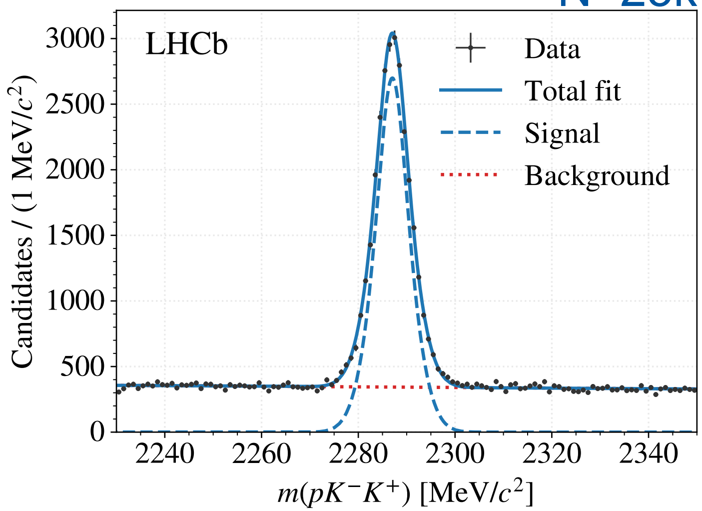
Measurement

- Comparison of raw asymmetries between $\Lambda_c^+ \to pK^+K^-$ and $\Lambda_c^+ \to p\pi^+\pi^-$ decays

$$\Delta A_{CP} = A_{CP}^{\mathrm{raw}}(\Lambda_c^+ \to pK^+K^-) - A_{CP}^{\mathrm{raw}}(\Lambda_c^+ \to p\pi^+\pi^-)$$

- First ever measurement by LHCb using 3 fb^{-1} data from $\Lambda_b^0 \to \Lambda_c^+ \mu^-$ decays
- ΔA_{CP} Cancels proton and muon reconstruction asymmetry and Λ_b^0 production asymmetry
- Not enough…

N=25k



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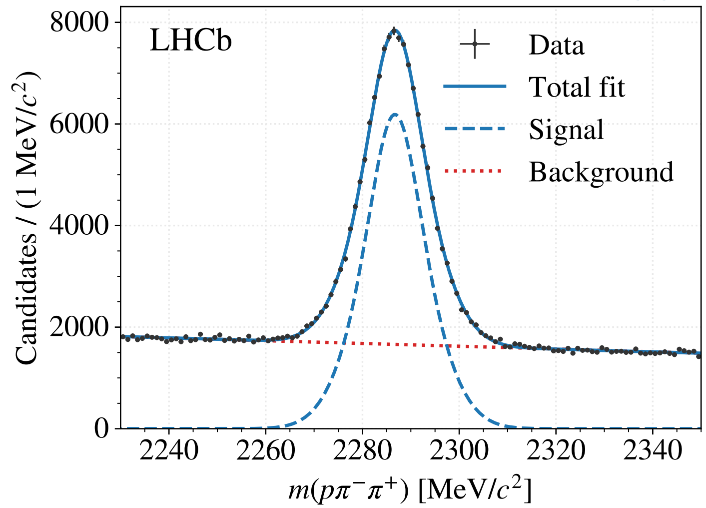

ΔA_{CP} in Λ_c^+ baryons - Phase Space Difference

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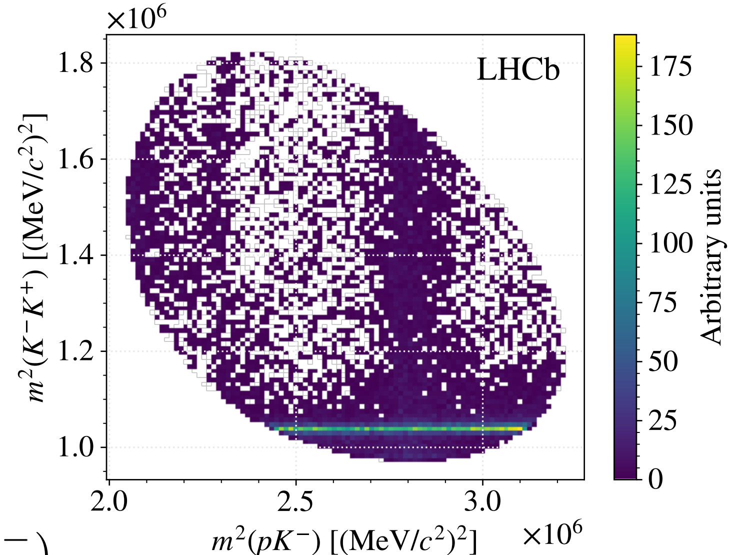
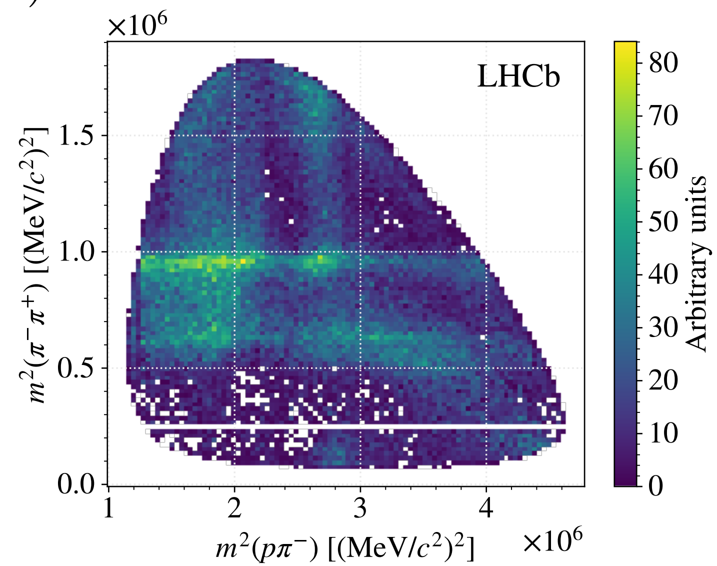
Phase Space

- **Decays described by a 5D phase space**
- **Projections on the Dalitz plot look very different already**
- **This could generate unwanted asymmetries due to detector reconstruction and selection differences in regions of phase space**
- **Corrected with reweighing and simulation**

$$\Delta A_{CP}^{\mathrm{wgt}} = A_{CP}(\Lambda_c^+ \to pK^+K^-) - A_{CP}^{\mathrm{wgt}}(\Lambda_c^+ \to p\pi^+\pi^-)$$
$$= (0.30 \pm 0.91 \pm 0.61)\%$$

Source	Uncertainty [%]
Fit signal model	0.20
Fit background model	—
Residual asymmetries	0.10
Limited simulated sample size	0.57
Prompt Λ_c^+	—
Total	0.61





P- and T-odd Observables

Phys. Rev. D92 (2015) 076013

Sensitivity

- **Probe CPV in the interference between spin states of the decay amplitudes**
- **Complementarity with typical CP asymmetry measurements**
  More sensitive in regions with small variations of strong phases

Experimental Technique

- **Measure asymmetries on D and $\bar{D}$ decays separately and combine**

$$A_{\hat{T}} = \frac{\Gamma(D \to f, \Phi > 0) - \Gamma(D \to f, \Phi < 0)}{\Gamma(D \to f, \Phi > 0) + \Gamma(D \to f, \Phi < 0)} \qquad \overline{A}_{\hat{T}} = \frac{\Gamma(\overline{D} \to \overline{f}, -\overline{\Phi} > 0) - \Gamma(\overline{D} \to \overline{f}, -\overline{\Phi} < 0)}{\Gamma(\overline{D} \to \overline{f}, -\overline{\Phi} > 0) + \Gamma(\overline{D} \to \overline{f}, -\overline{\Phi} < 0)}$$

$$a_{CP}^{\hat{T}-\mathrm{odd}} = \frac{1}{2}\left(A_{\hat{T}} - \overline{A}_{\hat{T}}\right)$$

- **Initially explored with C_T (triple product)**

$$C_T = \vec{p}_a \cdot \vec{p}_b \times \vec{p}_c$$

- **Potential improvements from the generalisation of the triple product Φ_{lmn}**

$$\Phi_{lmn} = P_l(\cos\theta_a)P_m(\cos\theta_b)\sin(n\phi)$$

More in previous talk by Gauthier

Example: T-odd Observables in $\Lambda_b^0 \to p\pi^-\pi^+\pi^-$

Triple Product Observable

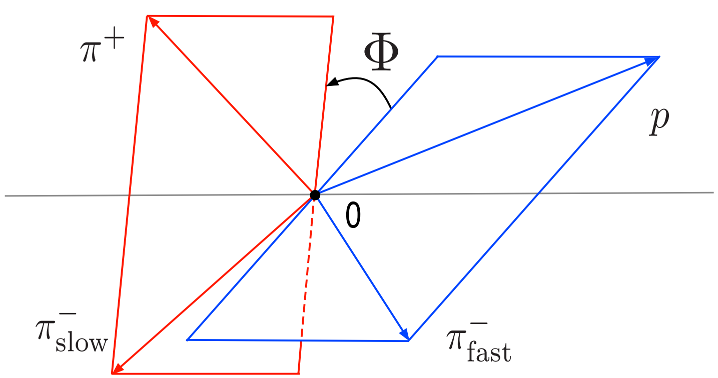
$$C_{\hat{T}} = \vec{p}_p \cdot \vec{p}_{\pi^-_{\text{fast}}} \times \vec{p}_{\pi^+}$$

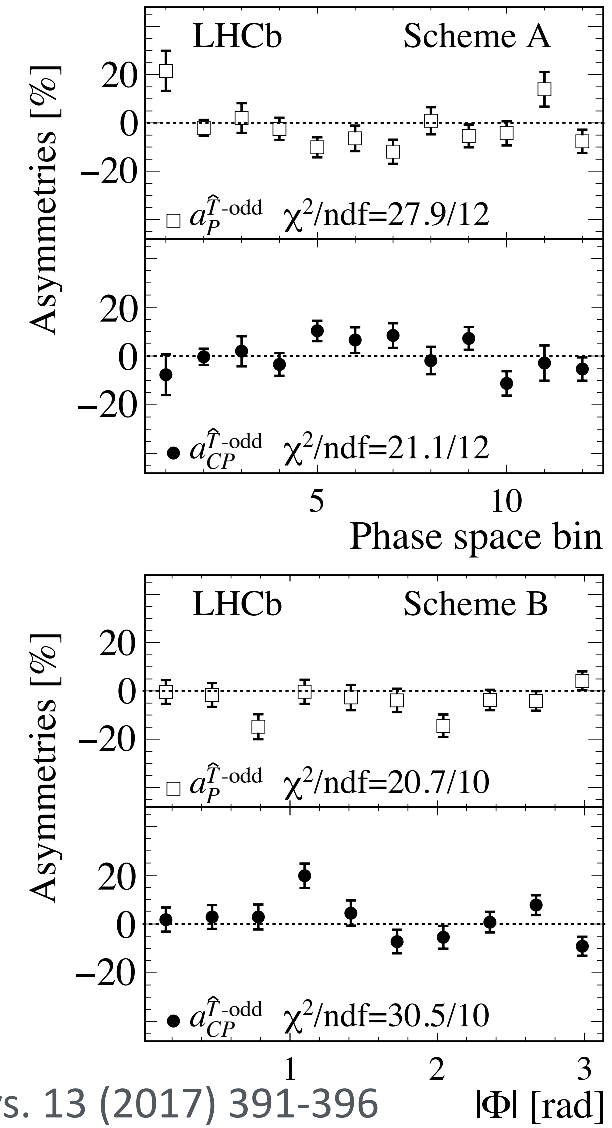
Measurements

- a_{CP} and a_P
- Integrated

$$a_{CP}^{\hat{T}-\text{odd}} = (1.15 \pm 1.45_{\text{stat}} \pm 0.32_{\text{syst}})\%$$

- 2 binning schemes - combined p-value=9.8×10^{-4} (3.4σ)
  A: 12 regions of phase space
  B: 10 regions of Φ





Nature Phys. 13 (2017) 391-396

T-odd Observables in Charm

Advantages

- **Multibody decays are specially suited for the study of T-odd observables**
- **Large branching fractions**
- **Rich and dense amplitude structure in the phase space**
- **Small systematics: asymmetry measured as a difference between asymmetries each calculated on the same decay mode**
  - Charge-reconstruction asymmetries are null by construction
  - Independent of production asymmetries

Status

- **So far studied in $D^0 \rightarrow K^+K^-\pi^+\pi^-$, $D^0 \rightarrow K^0_S\pi^+\pi^-\pi^0$ (C_T) and $D^0 \rightarrow \pi^+\pi^-\pi^+\pi^-$ (Energy Test)**

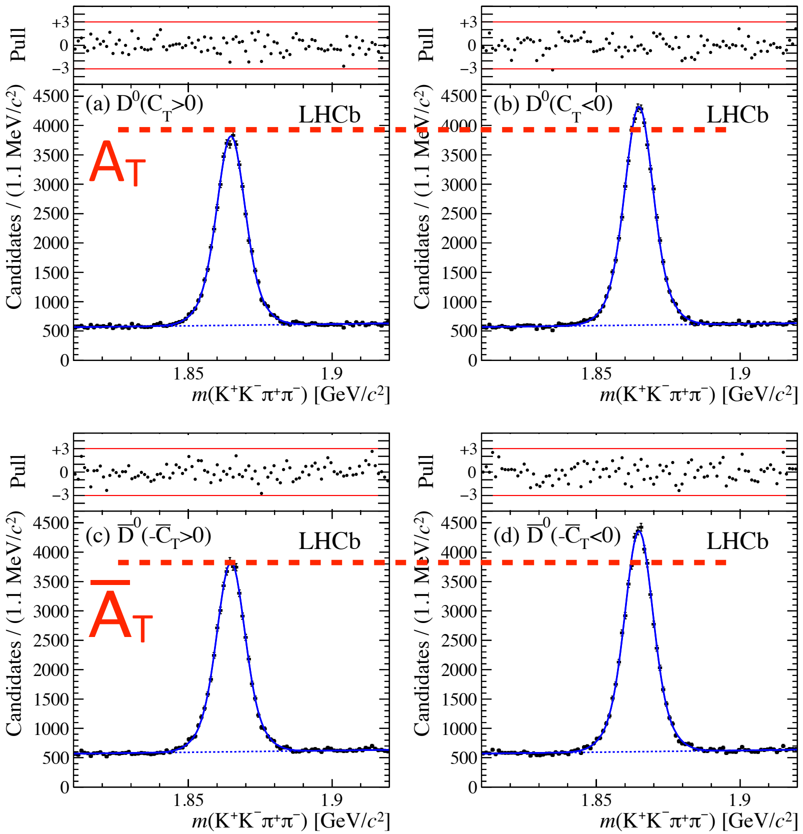
Covered in Chris' talk

Triple Product Asymmetries in $D^0 \to K^+K^-\pi^+\pi^-$

Established Measurement

- **Pioneering work by FOCUS**
- **Optimisation in BaBar**
- **Further improvements in LHCb**
  - $D^0 \to K^+K^-\pi^+\pi^-$ from semileptonic B decays, tagged from muon charge $B \to D^0\mu^-X$, $D^0 \to K^+K^-\pi^+\pi^-$
  - 3 fb^{-1} data recorded in 2011+2012
  - Largest systematic uncertainty from prompt decays background and flavour misidentification
  - Studied asymmetry variation in the phase space

$B \to D^0\mu^-X$, $D^0 \to K^+K^-\pi^+\pi^-$



Integrated Analysis

$$A_{\hat{T}} = (-71.8 \pm 4.1_{\mathrm{stat}} \pm 1.3_{\mathrm{syst}}) \times 10^{-3}$$

$$\overline{A}_{\hat{T}} = (-75.5 \pm 4.1_{\mathrm{stat}} \pm 1.2_{\mathrm{syst}}) \times 10^{-3}$$

$$a_{CP}^{\hat{T}-\mathrm{odd}} = (1.8 \pm 2.9_{\mathrm{stat}} \pm 0.4_{\mathrm{syst}}) \times 10^{-3}$$

3fb^{-1}: N_{ev}~170k

JHEP10(2014)005

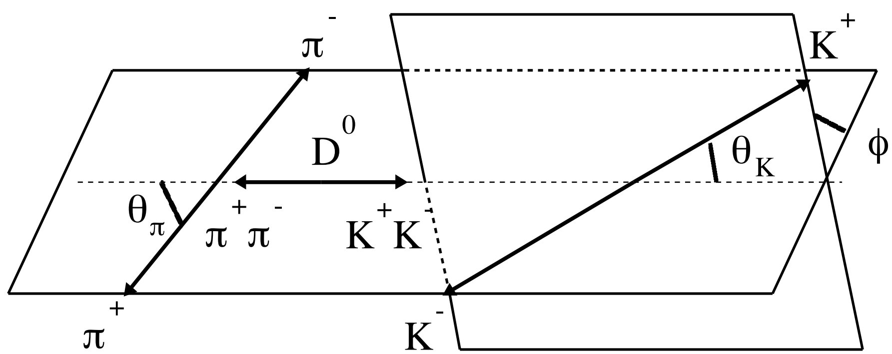
Triple Product Asymmetries in $D^0 \to K^+K^-\pi^+\pi^-$

Binned Analysis

- **Bins of phase-space**

  No significant deviation from 0 observed

  CP conservation tested with $P(\chi^2)=74\%$

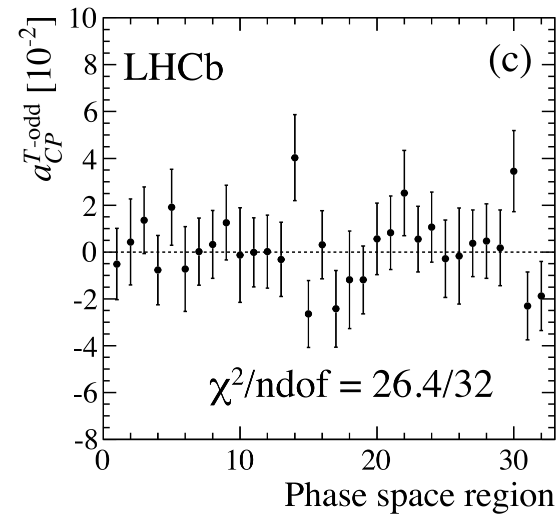


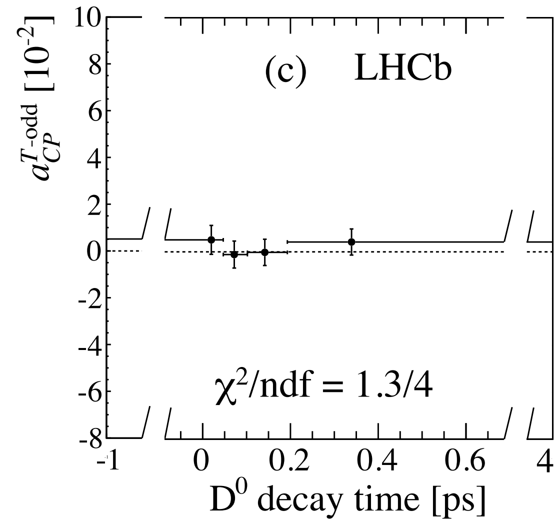
- **Bins of proper time**

  No significant deviation from 0 observed

  CP conservation tested with $P(\chi^2)=83\%$

JHEP10(2014)005





Triple Product Asymmetries in $D^0 \rightarrow K^0_S \pi^+ \pi^- \pi^0$

Phys. Rev. D 95, 091101 (2017)

Self-Conjugate CF Final State

- Precise Tests of CP symmetry with no charge reconstruction asymmetry effects
- Global measurement (N_{ev}~750k)

$$a_{CP}^{T-\text{odd}} = (-0.28 \pm 1.38^{+0.23}_{-0.76}) \times 10^{-3}$$

- Detailed analysis in relevant regions of phase-space shows no CPV
- Systematics
  - signal and background models
  - efficiency vs. C_T
  - C_T resolution
  - fit bias
- Belle-II sensitivity ($50 ab^{-1}$)
  - integrated: 0.2%
  - single amplitude: 0.7%

Bin	Resonance	Invariant mass requirement (GeV/c^2)	$A_T(\times 10^{-2})$	$a_{CP}^{T\text{-odd}}(\times 10^{-3})$
1	$K^0_S\omega$	$0.762 < M_{\pi^+\pi^-\pi^0} < 0.802$	$3.6 \pm 0.5 \pm 0.5$	$-1.7 \pm 3.2 \pm 0.7$
2	$K^0_S\eta$	$M_{\pi^+\pi^-\pi^0} < 0.590$	$0.2 \pm 1.3 \pm 0.4$	$4.6 \pm 9.5 \pm 0.2$
3	$K^{*-}\rho^+$	$0.790 < M_{K^0_S\pi^-} < 0.994$ $0.610 < M_{\pi^+\pi^0} < 0.960$	$6.9 \pm 0.3\ ^{+0.6}_{-0.5}$	$0.0 \pm 2.0^{+1.6}_{-1.4}$
4	$K^{*+}\rho^-$	$0.790 < M_{K^0_S\pi^+} < 0.994$ $0.610 < M_{\pi^-\pi^0} < 0.960$	$22.0 \pm 0.6 \pm 0.6$	$1.2 \pm 4.4^{+0.3}_{-0.4}$
5	$K^{*-}\pi^+\pi^0$	$0.790 < M_{K^0_S\pi^-} < 0.994$	$25.5 \pm 0.7 \pm 0.5$	$-7.1 \pm 5.2^{+1.2}_{-1.3}$
6	$K^{*+}\pi^-\pi^0$	$0.790 < M_{K^0_S\pi^+} < 0.994$	$24.5 \pm 1.0\ ^{+0.7}_{-0.6}$	$-3.9 \pm 7.3^{+2.4}_{-1.2}$
7	$K^{*0}\pi^+\pi^-$	$0.790 < M_{K^0_S\pi^0} < 0.994$	$19.7 \pm 0.8\ ^{+0.4}_{-0.5}$	$0.0 \pm 5.6^{+1.1}_{-0.9}$
8	$K^0_S\rho^+\pi^-$	$0.610 < M_{\pi^+\pi^0} < 0.960$	$13.2 \pm 0.9 \pm 0.4$	$7.6 \pm 6.1^{+0.2}_{-0.0}$
9	Remainder	–	$20.5 \pm 1.0\ ^{+0.5}_{-0.6}$	$1.8 \pm 7.4^{+2.1}_{-5.3}$

$$C_T = \vec{p}_{K^0_S} \cdot \vec{p}_{\pi^+} \times \vec{p}_{\pi^-}$$

Prospects for $D^0 \to h^+h^-\pi^+\pi^-$

Analysis Technique

- **Extend to Φ_{lmn}**
- **Study $h^+h^-,\pi^+\pi^-$ and $h^+\pi^-,h^-\pi^+$ configuration to build angles**
- **Explore phase-space binning such as regions with rapidly changing strong phase can be separated**
  i.e.: split resonances in the middle

Datasets

- **$D^0 \to \pi^+\pi^-\pi^+\pi^-$ could also be studied**
  Use momentum to separate pions
  About x2 more signal

LHCb Upgrade(s)

In red the published results
black are extrapolations

Decay Mode	Run1 (3/fb)	Run1+Run2 (9/fb)	Upgrade (50/fb)	UpgradeII (300/fb)
$D^0 \to K^+K^-\pi^+\pi^-$	0.17M 2.9×10^{-3}	4.7M 5.4×10^{-4}	26M 2.4×10^{-4}	156M 1.0×10^{-4}
$D^0 \to \pi^+\pi^-\pi^+\pi^-$	1.0M 1.2×10^{-3}	13.5M 3.3×10^{-4}	150M 1.0×10^{-4}	900M 4.0×10^{-5}

big gain from improved trigger selection in Run2

Upgrade extrapolations assume same efficiency as LHCb

Prospects for Λ_c^+ baryons

ΔA_{CP} Towards the LHCb Upgrade

- **A sensitivity of 0.5×10^{-4} can be reached by the end of Run5 (300/fb)**
- **Nevertheless there are two considerations on the analysis technique**
  1) It may mask effects of same-sign CP violation
  2) It strongly relies on simulation to correct for phase-space difference effects

P- and T-odd Asymmetries

- **Other channels can be used to study P- and T-odd asymmetries in charm baryons**
  $\Lambda_c^+ \to \Lambda^0 K^- \pi^+ \pi^-$
  $\Lambda_c^+ \to p K^0_S K^+ \pi^-$
  $\Lambda_c^+ \to p h^+ h^-$
- **Similar approaches as those used for Λ_b^0 analysis**
- **Efficiency may be reduced from reconstruction of long-lived particles (K^0_S, Λ^0)**

Challenges

Unprecedented Running Conditions

- **So far extrapolation based on the ideal scenario of LHCb upgrade performance similar to LHCb**

Detector Challenges

- **Vertexing**
  Charm physics requires accurate detection of primary vertices to study lifetime
- **Reconstruction efficiency**
  - Momentum Acceptance ➡ Multi-body decays characterised by low-momentum particles, these are not hard to reconstruct and to use in your triggers <u>provided you have enough computing power</u>
  - Tracking Efficiency ➡ a 5% tracking inefficiency = ~20% inefficiency on a 4-body channel
- **Homogeneous phase-space**
  Related to the above, you don't want unexpected detector-related asymmetries bias your phase-space
- **Charged-tracks reconstruction asymmetry**
  Getting it to the sub-permille level is a non-negligible task, even using large control samples from data

Computing Challenges

Huge Datasets

- **Data Collection**
  - We want to be as efficient as possible, but the we cannot store everything
  - Especially in Charm, there may be the need of choosing a trade-off between efficiency and stored information ➡ Experience from Run2 and Upgrade will be fundamental
- **Data Processing**
  Should be parallelised through the Grid as much as possible, but resources aren't infinite
- **Simulation**
  - Size of simulated samples is the major systematic uncertainty in some LHCb analysis
  - We demonstrated that we can do a lot without simulation, but for multi body decays it is fundamental to understand the reconstruction efficiency
  - The success of the Upgrade program for Charm will also depend on how faster the simulation will become

Conclusions

Outlook

- **Study of charmed baryon decays just started at LHCb**
  New techniques will surely come up to face the challenges of this so far unexplored area
- **P- and T-odd observables will maintain their potential**
  These variables are in principle independent from charged particles reconstruction asymmetries and production asymmetries ➡ <u>very low systematic uncertainties</u> (expected to scale with statistics as evaluated on control samples)

No free meal

- **The unprecedented conditions of the LHCb Upgrade and especially Upgrade-II will create challenges that will require a strenuous effort to be overcome**
- **Nevertheless, a few years ago it seemed impossible to run a B physics experiment at a hadron collider…**

Spares

Triple Product Asymmetries in $D^0 \to K^0_S \pi^+ \pi^- \pi^0$

Phys. Rev. D 95, 091101 (2017)