

# Search for CP violation in the charm sector at LHCb

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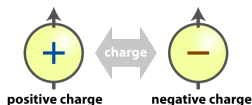


# CP violation

- CP violation has been observed in weak interactions
- CP violation exists in the Standard Model (SM) but it is too small to explain a matter-dominated universe
- New Physics (NP) processes could fill this gap of the SM

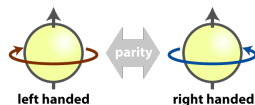
## Charge conjugation symmetry C

$$q \rightarrow -q$$



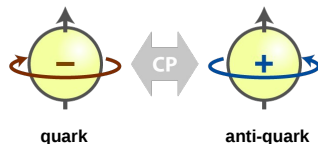
## Parity symmetry P

$$\vec{x} \rightarrow -\vec{x}$$



## CP symmetry

$$(q, \vec{x}) \rightarrow (-q, -\vec{x})$$

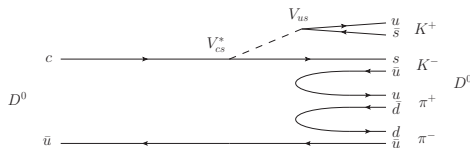


- CP violation in charm decays is a very good probe for NP beyond the SM
  - CP violation in charm decays is expected to be very small in SM  $\mathcal{O}(10^{-4} - 10^{-3})$ 
    - see [PRD 51 \(1995\) 3478](#)
  - NP could enhance this CP violation up to  $\mathcal{O}(10^{-2})$ 
    - see [PRD 75 \(2007\) 036008](#)
  - Effects from both direct (decay) and indirect (mixing) CP violation can be searched for

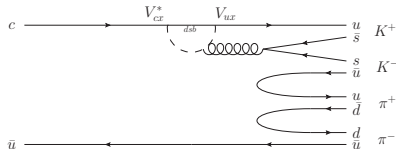
# CP violation in $D^0 \rightarrow K^+ K^- \pi^+ \pi^-$ decays

- $D^0 \rightarrow K^+ K^- \pi^+ \pi^-$  is a good probe for the search of CP violation in charm decays
  - It is singly Cabibbo suppressed with two competing diagrams

## Tree

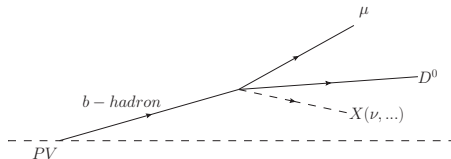


## Loop

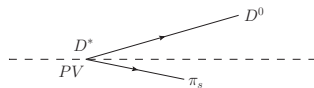


- Many competing amplitudes could enhance local CP violation effects
- It has two tagging channels with large statistics

## Semileptonic (180k)



## Prompt (250k)



# Previous results on $D^0 \rightarrow K^+ K^- \pi^+ \pi^-$

FOCUS (PLB 610 (2005) 225) and CLEO (PRD 85 (2012) 122002) did an amplitude analysis with  $\sim 1300$  and  $\sim 3000$  signal events respectively

- The sensitivity achieved is **5% – 30%** per amplitude and no CP violation has been found

BaBar (PRD 81 (2010) 111103) and LHCb (JHEP 10 (2014) 005) did an integrated measurement of the CP violation

→ Best result has been achieved by LHCb with :

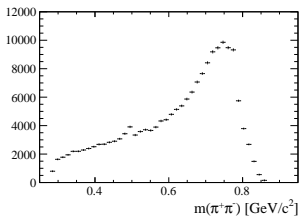
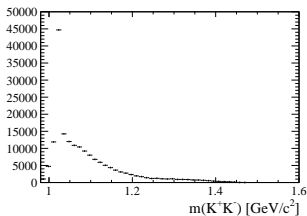
$A_{CP} = (1.8 \pm 2.9(\text{stat}) \pm 0.4(\text{syst})) \times 10^{-3}$ , ie. compatible with no CP violation.

## Goals of the analysis :

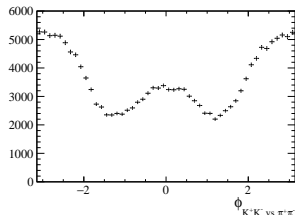
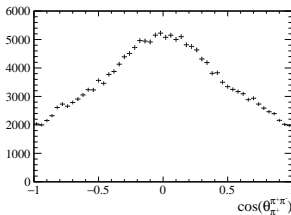
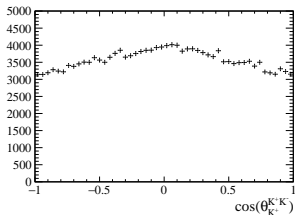
- Do a complete amplitude analysis
  - Use Run 1 data ( $\sim 200000$ ) with possible addition of Run 2
  - Achieve sensitivity  $< 1\%$  on all amplitudes
- could lead to first observation of CP violation in charm

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

- $D^0 \rightarrow K^+ K^- \pi^+ \pi^-$  is a four-body decay
- It is described by a 5D phase space
- The following 5 variables (Cabibbo-Maksimowicz variables) describe the phase space :



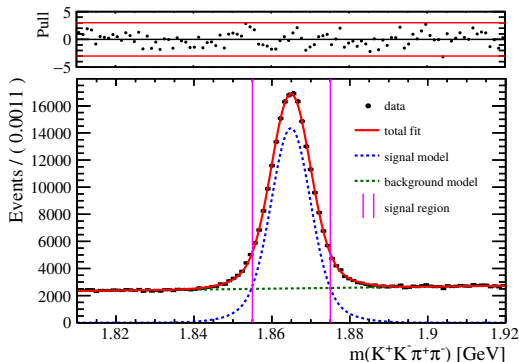
Full Run 1 data  
signal distribution



- Create a Boosted Decision Tree (BDT)
- Selected 15 most discriminating variables
  - Only topological variables, no particle identification (PID)
- Signal is 2012 MC sample, MU + MD, 180k events
- Background is 2012 data sidebands, MU + MD, 180k events
- Signal and background samples are split in two for Training and Testing
- Significance is optimised on data for the BDT and the PID variables

# Mass distribution

Resulting mass distribution with optimised cuts (full Run I)



● Parameters of the distribution inside  $\pm 2\sigma$  signal region :

- $N_{\text{sig}} = 161103 \pm 551$
- $N_{\text{bkg}} = 46277 \pm 122$
- purity = 78%
- significance = 354

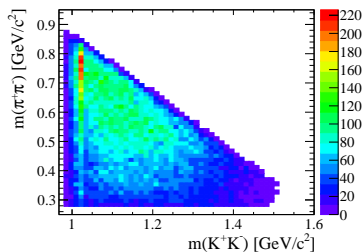


# Study of the background

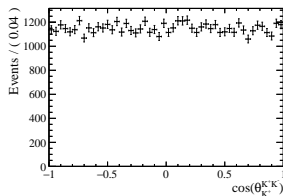
- The purity of the selected data is  $\sim 80\%$
- The remaining  $\sim 20\%$  need to be handled carefully
- Different strategies have been studied
  - background subtraction with the sPlot technique
  - background description with empirical 5D pdf
  - background parametrisation
- All have their advantages and drawbacks

# Background description

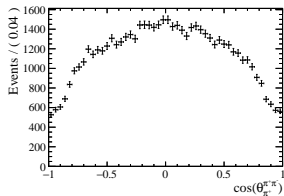
- Empirical description of the data sidebands with histograms
- Used 4 histograms to build the pdf
  - $2D \times 1D \times 1D \times 1D$
  - $(m_{KK}, m_{\pi\pi}) \times \cos(\theta_K) \times \cos(\theta_\pi) \times \phi$



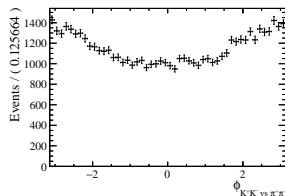
×



×



×



# Fitting the signal

A fitter has been developed in order to interact directly with the well-known minimizer *Minuit*. The main component is the construction of the likelihood that will be minimized :

$$\mathcal{L} = -2 \cdot \ln \left( \prod_{data} \mathcal{L}(\mathbf{x}_i) \right)$$
$$\mathcal{L}(\mathbf{x}_i) = \frac{\left| \sum_{amp} c_j \cdot A_j(\mathbf{x}_i) \right|^2}{\int_{MC} \left| \sum_{amp} c_j \cdot A_j(\mathbf{p}) \right|^2 d\mathbf{p}}$$

where :

- $c_j$  : are the complex fit parameters
- $A_j$  : are the amplitudes described by the multiplication of a Blatt-Weisskopf factor, a Breit-Wigner lineshape and a spin factor
- $\mathbf{x}_i$  : are the data events
- $\mathbf{p}$  : are the MC events

# Amplitude model

- A new amplitude model will be developed
- Starting point is CLEO model
  - 11 amplitudes
  - [PRD 85 \(2012\) 122002](#)

$$D^0 \rightarrow \phi(1020)^0(\rightarrow K^+, K^-), \rho(770)^0(\rightarrow \pi^+, \pi^-)$$

$$D^0 \rightarrow \phi(1020)^0(\rightarrow K^+, K^-), \rho(770)^0(\rightarrow \pi^+, \pi^-) \text{ (D wave)}$$

$$D^0 \rightarrow \phi(1020)^0(\rightarrow K^+, K^-), \text{NonRes}(\pi^+, \pi^-)_S$$

$$D^0 \rightarrow K^*(892)^0(\rightarrow K^+, \pi^-), \overline{K^*(892)^0}(\rightarrow K^-, \pi^+)$$

$$D^0 \rightarrow K_1(1270)^+(\rightarrow \overline{K^*(892)^0}(\rightarrow K^+, \pi^-), \pi^+), K^-$$

$$D^0 \rightarrow K_1(1270)^-(\rightarrow \overline{K^*(892)^0}(\rightarrow K^-, \pi^+), \pi^-), K^+$$

$$D^0 \rightarrow K_1(1270)^+(\rightarrow \rho(770)^0(\rightarrow \pi^+, \pi^-), K^+), K^-$$

$$D^0 \rightarrow K_1(1270)^-(\rightarrow \rho(770)^0(\rightarrow \pi^-, \pi^+), K^-), K^+$$

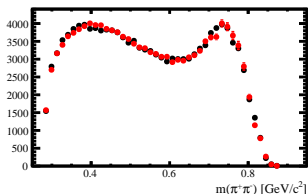
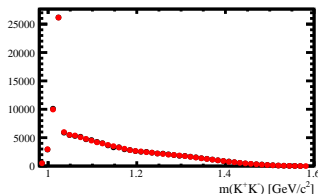
$$D^0 \rightarrow K^*(1410)^+(\rightarrow \overline{K^*(892)^0}(\rightarrow K^+, \pi^-), \pi^+), K^-$$

$$D^0 \rightarrow K^*(1410)^-(\rightarrow \overline{K^*(892)^0}(\rightarrow K^-, \pi^+), \pi^-), K^+$$

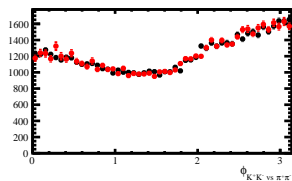
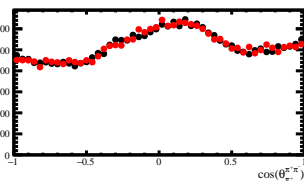
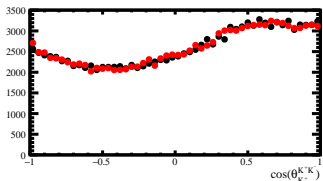
$$D^0 \rightarrow \text{NonRes}(K^-, \pi^+)_P, \text{NonRes}(K^+, \pi^-)_S$$

# Pseudo-experiment

- Fitting procedure has been tested on pseudo-experiments
- Good agreement between generated and fitted sample
- Test done for signal model



+ fit  
+ simulated events



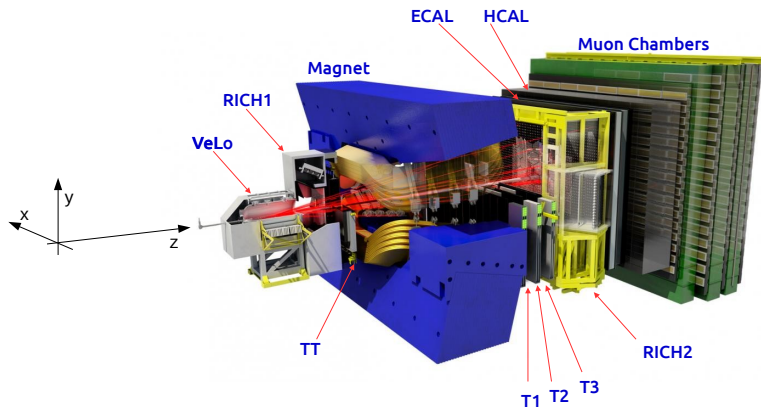
# Conclusion

- The first part of the analysis is to fit the data with an amplitude model
- The background will be fitted by an empirical pdf
- Various signal models will be tested
- Systematics uncertainties will be studied
- Once the best model and all uncertainties are determined, the data will be split between the  $D^0$  and  $\bar{D}^0$  in order to search for CP violation
- Any hint of CP violation of  $\mathcal{O}(10^{-2})$  or above would be a clear sign for NP

# Backup Slides

# The LHCb detector

- One of the four main experiments of the LHC
- Forward arm spectrometer
- Main goals of LHCb
  - Search for New Physics (NP) beyond the Standard Model (SM)
  - Study  $b$ - and  $c$ -hadrons
  - Study for CP violation, i.e. understand the differences between matter and anti-matter





- Stripping requirements
  - Stripping 20, semileptonic.dst
  - Stripping line : b2D0MuX2K2PiB2DMuNuXLine
- Trigger requirements (L0 && HLT1 && HLT2)
  - L0 : D0\_L0HadronDecision\_TOS || Mu\_L0MuonDecision\_TOS
  - HLT1 : B\_Hlt1TrackAllL0Decision\_TOS  
|| Mu\_Hlt1TrackAllMuonDecision\_TOS
  - HLT2 : Mu\_Hlt2SingleMuonDecision\_TOS  
|| B\_Hlt2TopoMu2BodyBBDTDecision\_TOS  
|| B\_Hlt2TopoMu3BodyBBDTDecision\_TOS  
|| B\_Hlt2TopoMu4BodyBBDTDecision\_TOS

# Stripping selection requirements

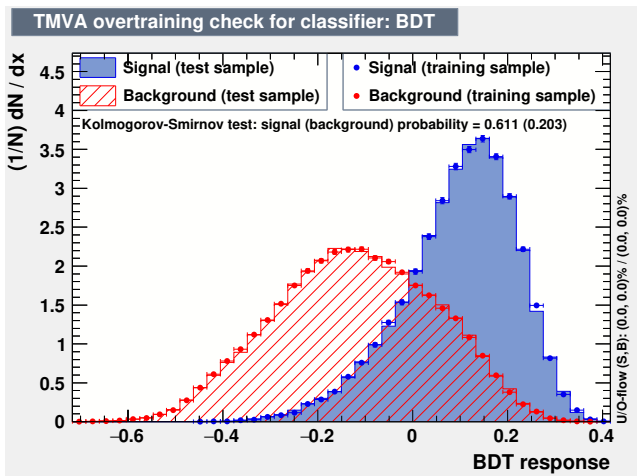
Table 44: Stripping selection requirements.

Candidate	Variable	2K2Pi	K3Pi
<i>K</i>	track $\chi^2/n_{\text{dof}}$	< 3	
	$p$	> 2 GeV/c	
	$p_T$	> 300 MeV/c	
	$\chi^2(\text{IP})$	> 9	
	PIDK	> 4	> 8
	Prob(ghost)	< 0.5	
$\pi$	track $\chi^2/n_{\text{dof}}$	< 3	
	$p$	> 2 GeV/c	
	$p_T$	> 300 MeV/c	
	$\chi^2(\text{IP})$	> 9	
	PIDK	< 10	
	Prob(ghost)	< 0.5	
$\mu$	track $\chi^2/n_{\text{dof}}$	< 3	
	$p$	> 2 GeV/c	
	$p_T$	> 1.2 GeV/c	
	$\chi^2(\text{IP})$	> 9	
	PIDmu	> 0	
	Prob(ghost)	< 0.5	
$D^0$	mass	$\epsilon[1.8, 1.925]$ GeV/ $c^2$	
	$\sum \text{daughters } p_T^i$	> 1.8 GeV/c	
	$\chi^2(\text{Vtx})/n_{\text{dof}}$	< 6	
	cos(DIRA)	> 0.99	
<i>B</i>	$M(p_{D^0} + p_{\mu})$	< 6.2 GeV/ $c^2$	
	mass	$\epsilon[2.5, 6.0]$ GeV/ $c^2$	
	$\chi^2(\text{Vtx})/n_{\text{dof}}$	< 6	
	cos(DIRA)	> 0.999	

# BDT variables

- $B$   $p_T$  corrected mass
- $B \log(\chi_{IP}^2)$
- $B$  mass
- $B \log(\min \Delta\chi^2 \text{ 1 track})$
- $B \chi_{\text{vtx}}^2$
- $D^0 \log(\min \Delta\chi^2 \text{ M 1 track})$
- $D^0 \log(\min \Delta\chi^2 \text{ 2 tracks})$
- $D^0 p_{T,\text{asym}}$
- $D^0 \log(\text{DLS})$
- $D^0 \log(\tau)$
- $D^0 \log(\min \Delta\chi^2 \text{ 1 track})$
- $D^0 p$
- $D^0 p_T$
- $D^0 \log(\chi_{IP}^2)$
- $\mu \log(\chi_{IP}^2)$

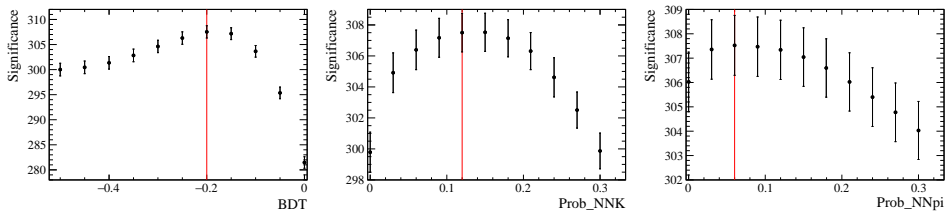
# BDT response



# Selection optimisation

- Optimisation is done on data
  - Optimisation is done on the BDT, Prob\_NNK on kaons and Prob\_NNpi on pions
  - Significance ( $S/\sqrt{S+B}$ ) in  $\pm 2\sigma$  signal region is used as FoM
  - The 3 sets of cuts are applied simultaneously
  - Explore a volume of BDT  $\in [-0.5, 0]$ , Prob\_NNK and Prob\_NNpi  $\in [0, 0.3]$  (2000 fits)
- ⇒ Cuts chosen: BDT  $> -0.2$ , Prob\_NNK  $> 0.12$  and Prob\_NNpi  $> 0.06$

2012 plots:



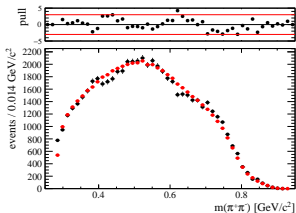
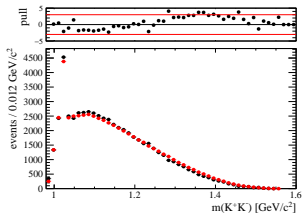
- Similar behaviour is observed for 2011 data sample

# Expected systematics

- The method chosen will be insensitive to :
  - $D^0 - \overline{D^0}$  production asymmetry
  - $D^0$  flavour-tagging asymmetry
  - $K^+ K^- (\pi^+ \pi^-)$  reconstruction asymmetry (to first order)
- It will have to be studied where the main systematics come from :
  - the model
  - the background description
  - the efficiency determination

# Fit of the sidebands

- The 2012 sidebands have been fitted
- Integration MC sample : 1 M phase space events



$\phi\pi\pi$   
 $\rho KK$   
 $K^*K\pi$   
 $\overline{K^*}K\pi$   
 $KK\pi\pi$

