Charm Physics at LHCb

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On behalf of LHCb Collaboration

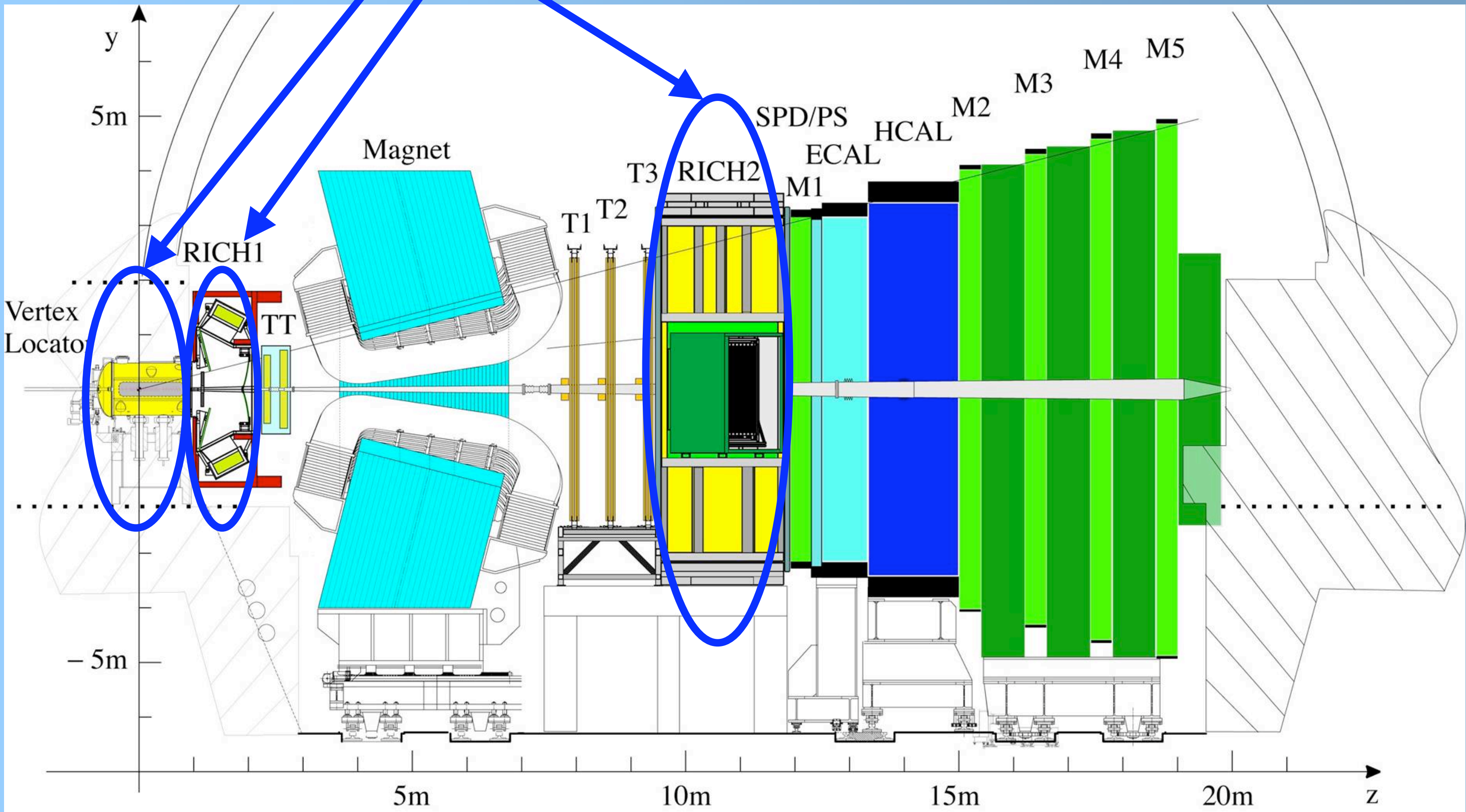
Prepared for the CERN Theory Institute
"Flavour as a Window to New Physics at LHC"

Outline

- LHCb and its charm physics trigger;
- CP violation searches in D decays at LHCb;
- Charm mixing measurements at LHCb;
- Summary.

LHCb

VELO and RICH-es are the most important detectors for charm analysis.



LHCb

- Very high statistics;
- Outstanding vertexing and proper time resolution ~ 45 fs for secondary D^0;
- Good tracking and momentum resolution ~ 6 MeV at D^0 mass.

VELO

LHCb

- Very high statistics;
- Outstanding vertexing and proper time resolution ~ 45 fs for secondary D^0;
- Good tracking and momentum resolution ~ 6 MeV at D^0 mass;
- Excellent K-π discrimination.

RICH 2

LHCb trigger overview

40 MHz

Pile-up system
Calorimeters
Muon system

Level 0 – Hardware
Favours bb events over prompt charm;
int/crossings

[redacted] > [redacted]
[redacted]$^{\gamma,\pi}$ > [redacted]
[redacted]$^{\mu,\mu\mu}$ > [redacted]

1 MHz

Full detector Information (partial reco)

HLT- Event filter farm
Confirm L0
optional add IP cut
parallel μ, e,h,γ alley
Inclusive/exclusive selections

2kHz

200 Hz Exclusive B modes
300 Hz D* → D^0(hh)π
600 Hz 2μ J/ψ,
b → J/ψ X
900 Hz 1 μ inclusive for b data mining

LHCb sources of charm

B decays ($B \to D^{(*)}X$):

+ Favoured by LHCb triggers;

+ Potentially less background;

- New techniques need to be developed – no published measurements.

Prompt production in primary interaction:

+ Triggered less efficiently but prolific production;

- Potentially larger backgrounds – random π_s for D* ;

+ CDF has proved measurements possible in hadronic environment.

Estimated $D^* \rightarrow D^0(hh)\pi$ yields, events to tape @ 2 fb^{-1} from b-hadrons:

$D^0 \rightarrow K^- \pi^+$ 50 x 10^6 ; $D^0 \rightarrow K^- K^+$ 5 x 10^6;

$D^0 \rightarrow K^+ \pi^-$ 0.2 x 10^6; $D^0 \rightarrow \pi^- \pi^+$ 2 x 10^6.

Similar number of prompt D* are expected to pass the trigger and to be reconstructed.

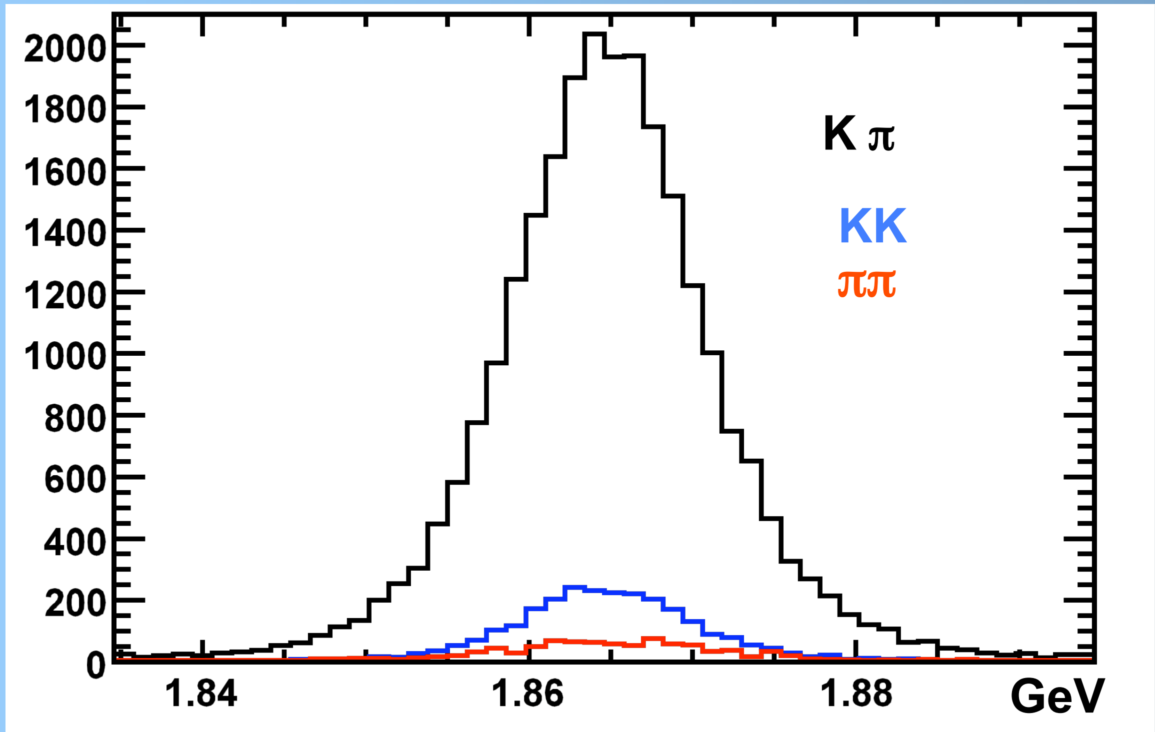
10^8 potentially usable $D^* \rightarrow D^0(hh)\pi$ events per 2 fb^{-1} are available for:

- ***Charm Physics studies***
- ***RICH calibration***

The LHCb numbers in the following slides are obtained using exclusively the D* from the b-hadrons.

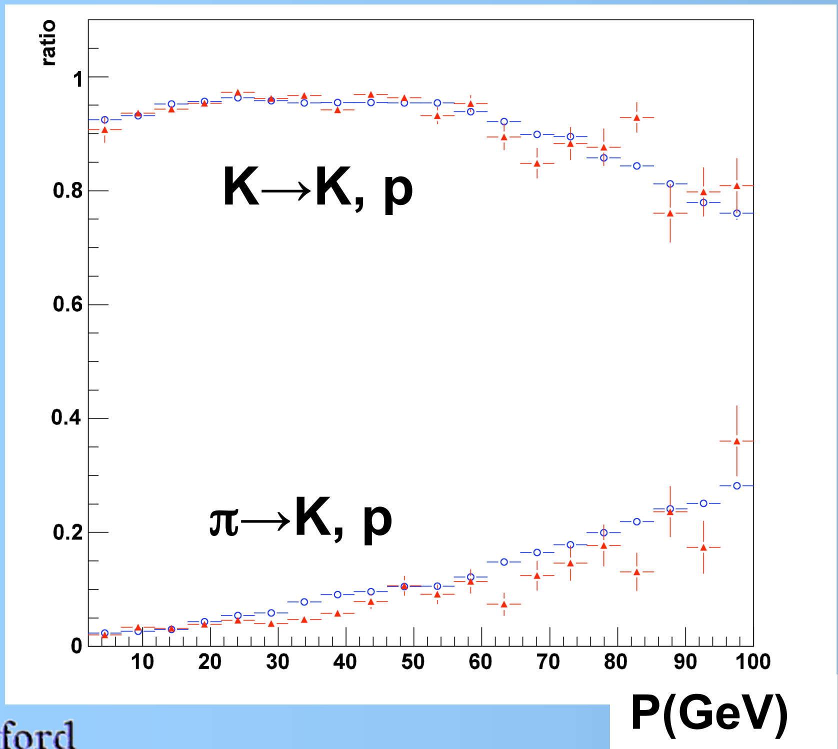
$D^* \rightarrow D^0(hh)\pi$ trigger stream

- Loose cuts on hadrons p_t, min IP sign, D^0 mass and (D^*-D^0) mass. Present values favour the D^* coming from b hadrons.
- RICH information not used in the trigger
- HLT assumes $K\pi$, π K, KK, $\pi\pi$, masses in turn.



D* → D^0(hh)π trigger stream

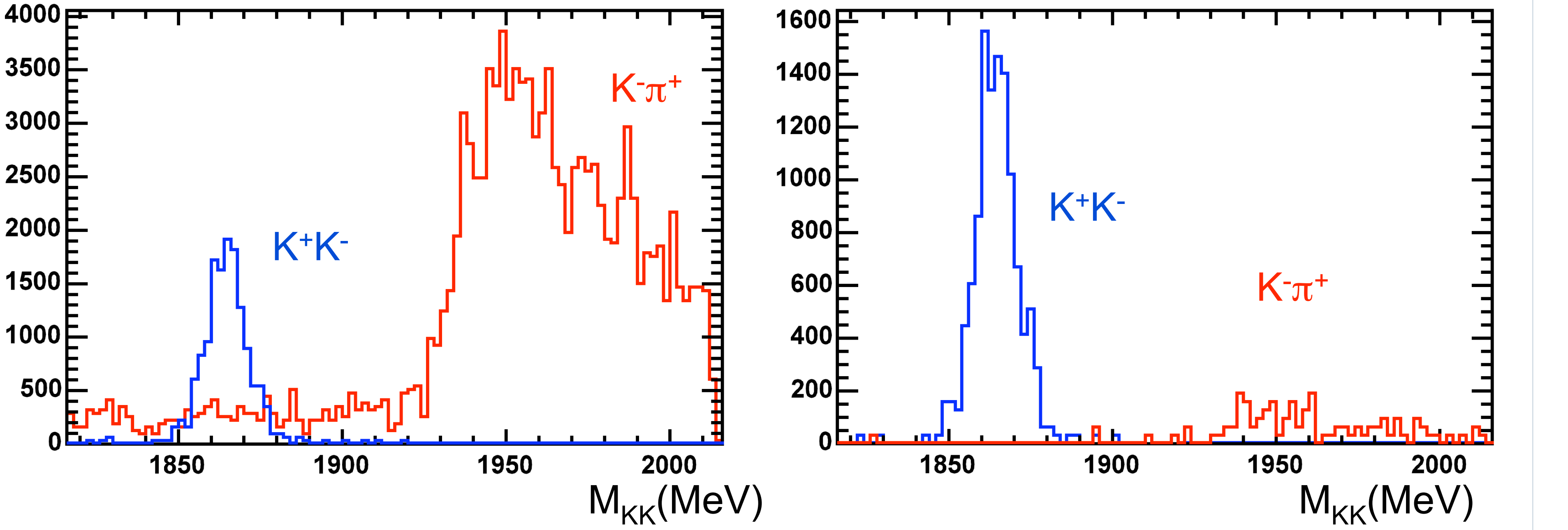
- Loose cuts on hadrons p_t, min IP sign, D^0 mass and (D^*-D^0) mass. Present values favour the D^* coming from b hadrons.
- HLT assumes Kπ, π K, KK, ππ, masses in turn.
- RICH information not used in the trigger → unbiased sample for MC - independent RICH calibration.



All kaons and pions identified using MC truth (pt >1GeV)

Kaons and pions from the MC independent calibration sample (pt >1GeV)

RICH information and various D^0 decay modes



PID RICH information very important to select clean samples of different D^0 decay modes.

CP violation searches in the charm sector at LHCb

The Standard Model (SM) predicts any CP violation (CPV) in charm decays to be very small. Observable CPV at the level 1% would be an unambigous sign of new physics (NP).

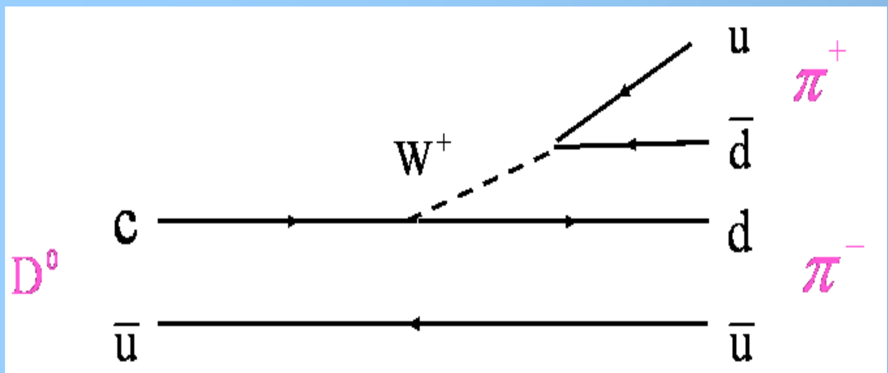
- Time integrated and time dependent CPV searches in as many charm channels as possible;
- Two body $K\pi$, K^-K^+, $\pi^-\pi^+$ modes; ⇦ **Main focus of this talk**
- Three body charged and neutral decays:
  - Amplitude analyses;
  - $D^0 \rightarrow K_s \pi^+ \pi^-$, $K_s K^+ K^-$, $K_s K \pi$, $D^+ \rightarrow K^+ K^- \pi^+$, $K \pi \pi$;
- Four body decays:
  - Quantities odd under T;
  - Amplitude analyses;
  - $D^0 \rightarrow K^+ K^- \pi^+ \pi^-$, $K \pi \pi \pi$.

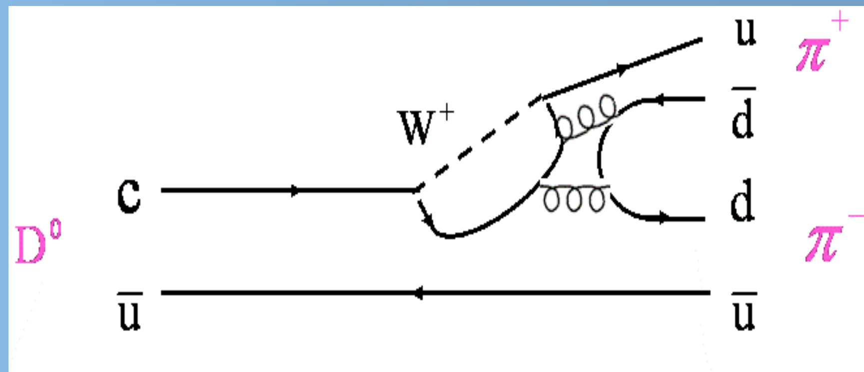
CPV in $D^0 \rightarrow K^+ K^-$ $(\pi^+ \pi^-)$

Occurs when the absolute value of the D decay amplitude to a final state is not equal to the CP conjugate amplitude.

$$\text{[redacted]} = \frac{\Gamma\,\text{[redacted]} \rightarrow \text{[redacted]}\,\pi\pi\,\text{[redacted]} - \Gamma\,\text{[redacted]} \rightarrow \text{[redacted]}\,\pi\pi\,\text{[redacted]}}{\Gamma\,\text{[redacted]} \rightarrow \text{[redacted]}\,\pi\pi\,\text{[redacted]} + \Gamma\,\text{[redacted]} \rightarrow \text{[redacted]}\,\pi\pi\,\text{[redacted]}}$$

D^0, [redacted] tagged using the slow pion sign





Singly Cabibbo Supressed (SCS) decay, easy to modify its topology to get a penguin.

CPV in $D^0 \rightarrow K^+ K^-$ ($\pi^+ \pi^-$)

In SM $A_{CP} \leq 10^{-3}$ for SCS decays. Possible NP enhancements to 1% from, e.g., penguin diagram

	A_{cp}(%)	N (K^+K^-)	N ($\pi^+ \pi^-$)	Data set
BaBar	0.26 ± 0.36 ± 0.08	69696	30679	384 fb^{-1}
Belle	0.01 ± 0.30 ± 0.15	111000	49000	540 fb^{-1}
HFAG	0.123 ± 0.248			
LHCb	~ 0.04 % order (stat)	8 x 10^6	3 x 10^6	10 fb^{-1}

Belle and BaBar calculate the asymmetries using $\tau(K^+K^-)$ rather than $\Gamma(K^+K^-)$.

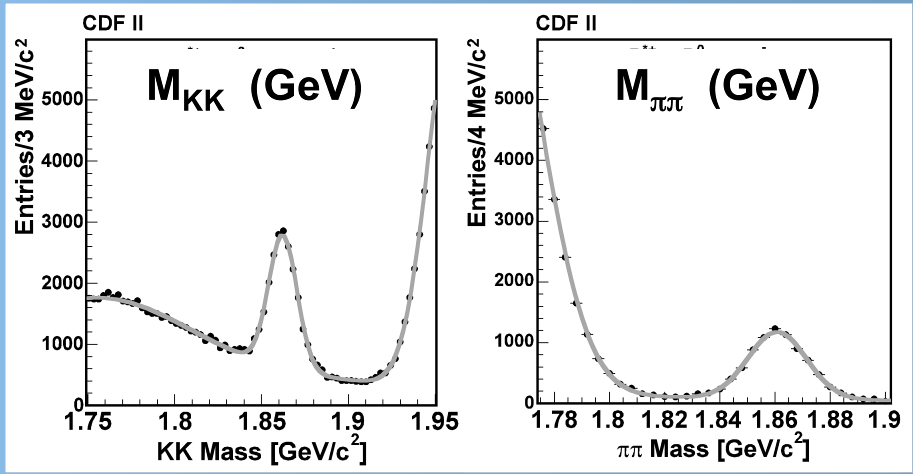
CDF direct CPV search in K^+K^-,$\pi\pi$

Phys.Rev.Lett.94:122001, 2005

$A_{cp}(K^+K^-)(\%) = 2.0 \pm 1.2 \pm 0.6$

$A_{cp}(\pi^+\pi^-)(\%) = 1.0 \pm 1.3 \pm 0.6$

N (K^+K^-) =16200 for 123 pb^{-1}.



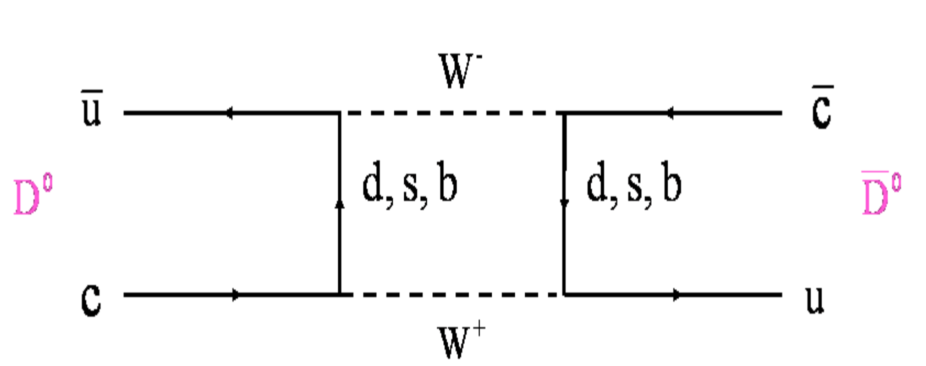
■■ – $\overline{■■}$ mixing

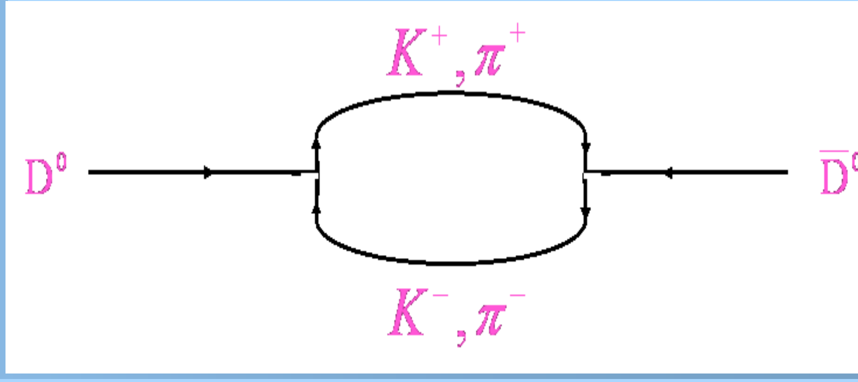
$$■ = \frac{■■_{■} - ■■_{■}}{\Gamma} \qquad ■ = \frac{\Gamma_{■} - \Gamma_{■}}{■\Gamma}$$

Indexes associated to the mass eigenstates , Γ av. width.

- sensitive to new particles in the box diagram loop;
- contributions from all the energy scales, sensitive to NP.

- mixing through physical decay states (long range) ;
- expected to be dominated by SM contributions.





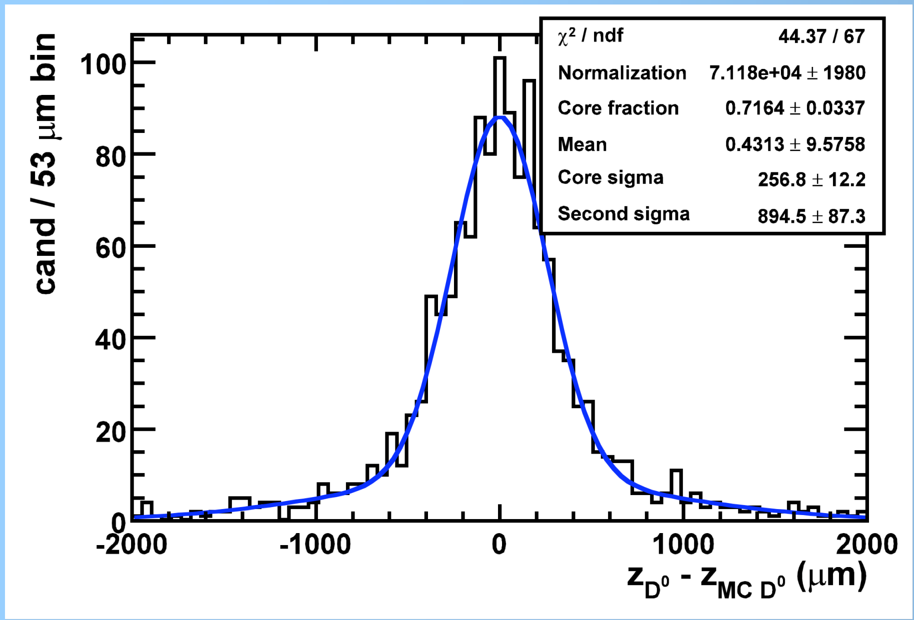
■■, $\overline{■■}$ tagged unambiguously at production using the slow π sign.

Charm mixing studies at LHCb

- **Precise mixing measurements:**
  - **Measure CPV in mixing – dominant mixing process.**
- **WS $D^0 \rightarrow \pi^- K^+$ mixing analysis:**
  - **BaBar 3.9 σ evidence, confirmed by CDF 3.8 σ evidence;**
  - **Require measurement of strong phase δ by CLEO/BES-III to relate the Cabibbo Favoured (CF) amplitude to the Double Cabibbo Suppressed one (DCS).**
- **CP Eigenstate Lifetime Difference measurement**
  - **Comparing the CP even SCS $D^0 \rightarrow K^+ K^-$ ($\pi^+ \pi^-$) with non-eigenstate Right Sign (RS) $D^0 \rightarrow K^- \pi^+$.**
  - **Belle 3.2 σ evidence, confirmed by BaBar 3 σ evidence.**
- **Amplitude analysis of $D^0 \rightarrow K_s \pi^+ \pi^-$:**
  - **Powerful technique demonstrated by CLEO and Belle.**
- **Mixing measurements in $D^0 \rightarrow 4h$.**

D^0 production and decay vertices

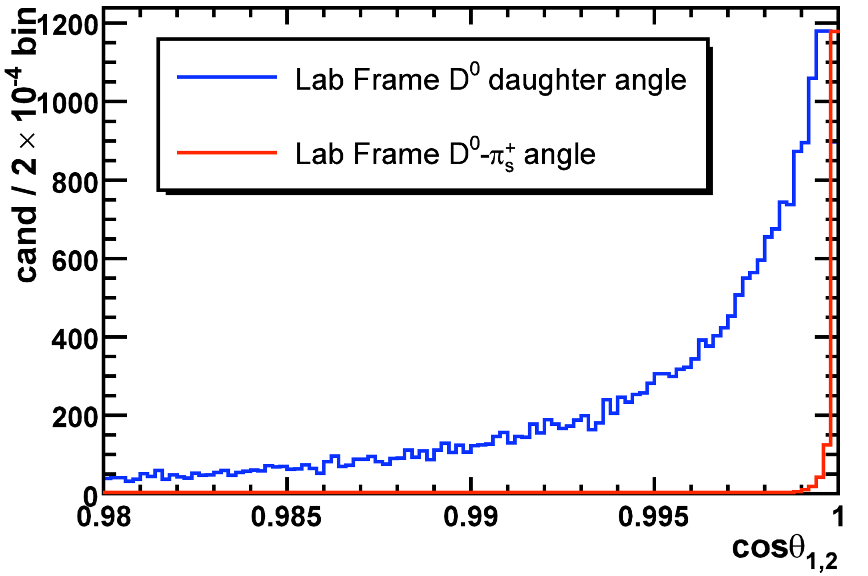
- D^0 lifetime measurement necessary input for mixing studies;
- Need good resolution for both the production and the decay vertex.



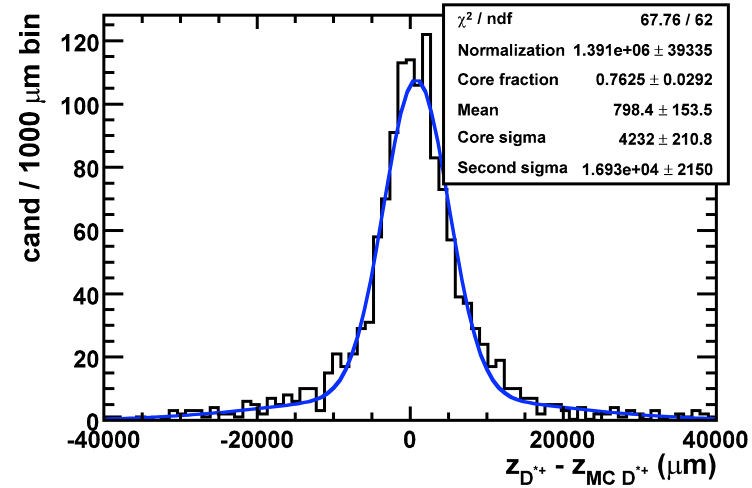
D^0 lifetime $\tau = 0.4101 \pm 0.0015$ ps
D^0 flight distance 60 GeV
$\beta\gamma c\tau \approx 4$ mm

D^0 decay vertex resolution 0.257 mm

D^0 production and decay vertices



D^0 and π_s almost colinear



Poor resolution of the D^0 production vertex
= 4.232 mm to be
compared to 4 mm

Proper time resolution = 0.465 ps to be
compared to 0.410 ps

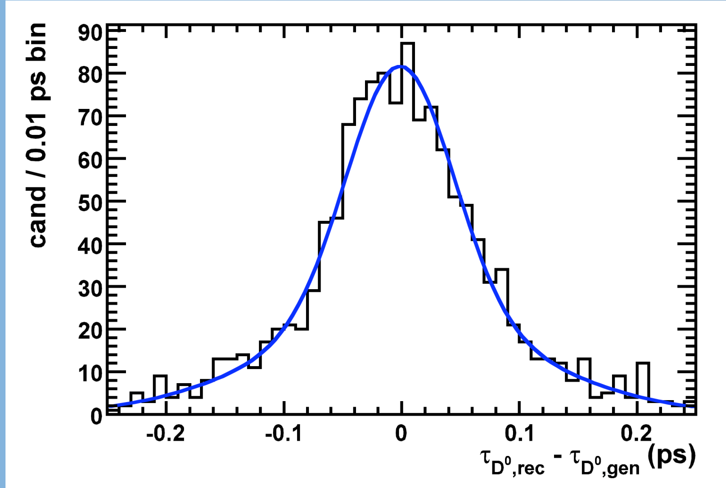
For p_{D0}= 60 GeV

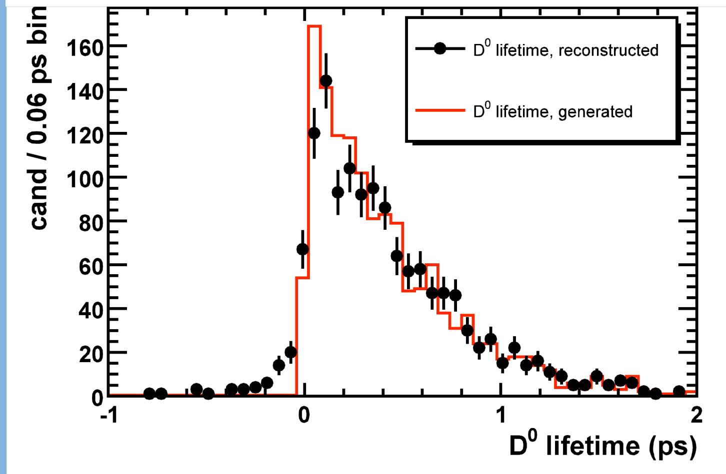
Birth vertex improvement

- Use additional tracks at the production vertex;
- 76% of D* from B's have at least one charged sister;
- 63% have reconstructed sister tracks that pass some basic criteria;
- Use one additional track to partially reconstruct parent B_{parent}.

	D^0	D*	B_{parent}
x	21.6	187	18.1
y	16.9	144	18.4
z	**257**	**4232**	**237**

Vertex resolutions (μm)



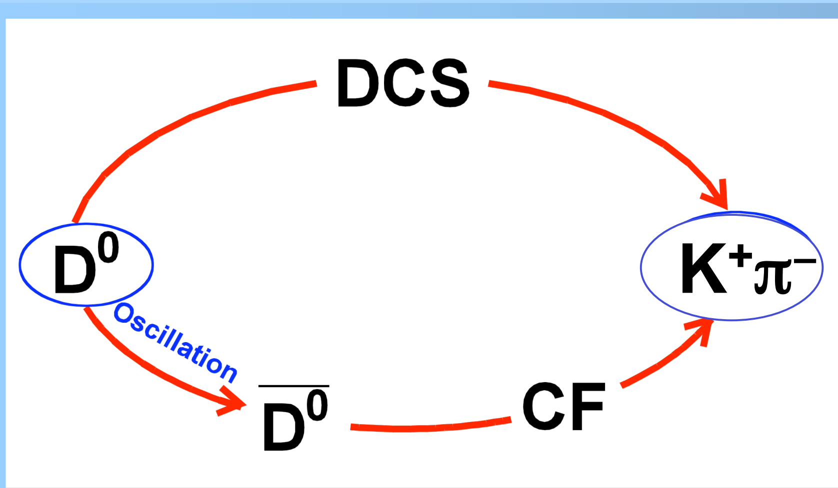


Proper time resolution = 0.045 ps (bef. 0.465 ps); New technique → factor of 10 improvement.

Oscillation Search with WS Kπ

D^0 can arrive to a WS hadronic final state ($K^+\pi^-$) via:

- DCS decay $D^0 \rightarrow K^+\pi^-$
- Oscillating to [illegible] + CF decay [illegible] → [illegible]



3 contributions

$$\Gamma_{WS} \propto exp(-t)[R_D + \sqrt{R_D}\, y' t + 1/4(x'^2 + y'^2)t^2]$$

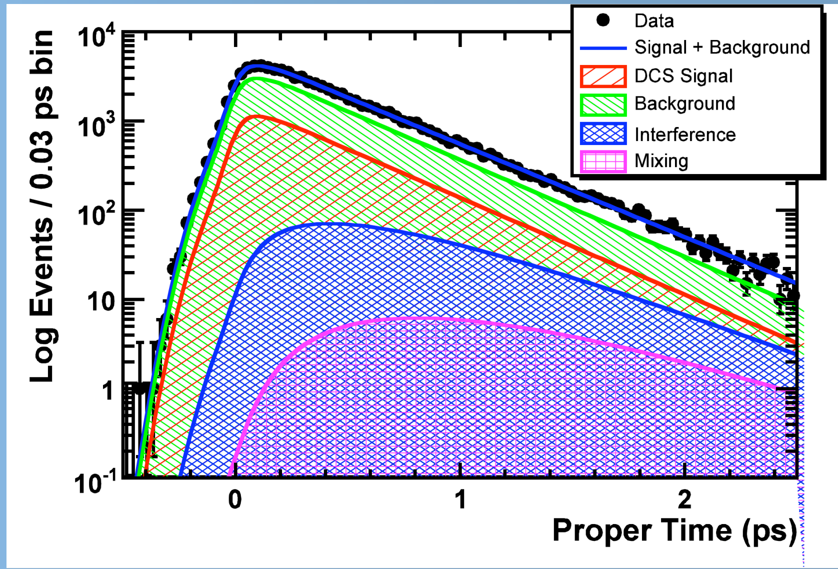
Strong phase difference between CF and DCS amplitudes [illegible] → [illegible]

R_D is the ratio of DCS decay rate to the CF decay rate.

Oscillation Search with WS Kπ

Toy MC study

- Investigate sensitivity to [illegible]′[illegible] and [illegible]′
  1D fit to proper time;
- 10 fb^{-1} simulated signal events/toy;
- Exponential background
  [illegible] − [illegible] τ [illegible]
- Acceptance and resolution effects included.



3 contributions

$$\Gamma_{WS} \propto exp(-t)[R_D + \sqrt{R_D}\, y't + 1/4(x'^2 + y'^2)t^2]$$

For more information CERN-LHCb-2007-049

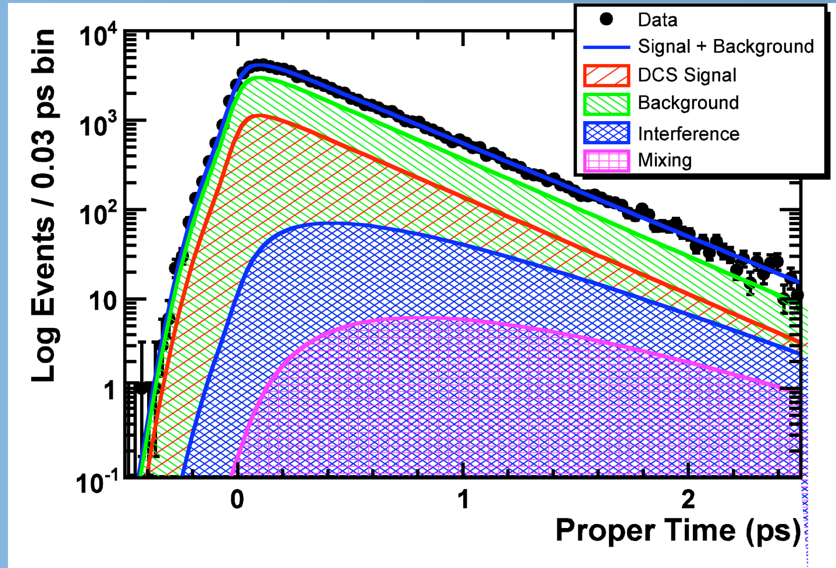
Oscillation Search with WS Kπ

Toy MC study

- Investigate sensitivity to [illegible] and [illegible]

1D fit to proper time;

- 10 fb^{-1} simulated signal events/toy;
- Exponential background: [illegible] ;
- Acceptance and resolution effects included.



	Data set	N(K⁺π⁻)	$x'^2 \times 10^{-3}$	$y' \times 10^{-3}$
Belle	400 fb^{-1}	4024	$0.18\,^{+0.21}_{-0.23}$	$0.6\,^{+4}_{-3.9}$
BaBar	384 fb^{-1}	4030	- 0.22 ± 0.30 ± 0.21	9.7 ± 4.4 ± 3.1
CDF	1.5 fb^{-1}	12700	-0.12 ± 0.35	8.5±7.6
B factories	2 ab^{-1}		[illegible] ± 0.15	y' ± 2.5
LHCb	10 fb^{-1}		[illegible] ± 0.064(stat)	[illegible] ± 0.87 (stat)

Lifetime ratio

Lifetime splitting, y_{CP} can be measured by comparing the non-eigenstate decay $D^0 \to K^- \pi^+$ to CP even decay $D^0 \to K^+ K^-$ $(\pi^+ \pi^-)$.

$$y_{CP} = \frac{\tau(D^0 \to K^-\pi^+)}{\tau(D^0 \to K^+K^-, \pi^+\pi^-)} - 1 = y\cos\Phi - x\sin\Phi\left[\frac{R_m^2 - 1}{2}\right]$$

$$R_m = \frac{1}{2}\left(x^2 + y^2\right)$$

y and y_{cp} differ by CP violating phase Φ

Lifetime ratio Toy MC study

- 10 fb^{-1} simulated signal events/toy;
- Exponential background:

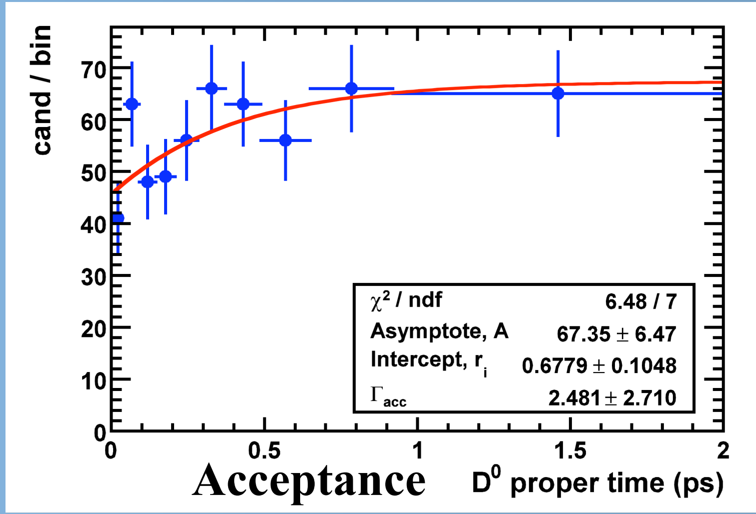
  [illegible] ;
- Acceptance and resolution effects included.

	N (K^+K^-)	Data set	y_{CP}(%)
BaBar*	69696	384 fb^{-1}	1.03 ± 0.33± 0.19
Belle*	111000	540 fb^{-1}	1.31 ± 0.32 ± 0.25
HFAG average*			1.132 ± 0.266

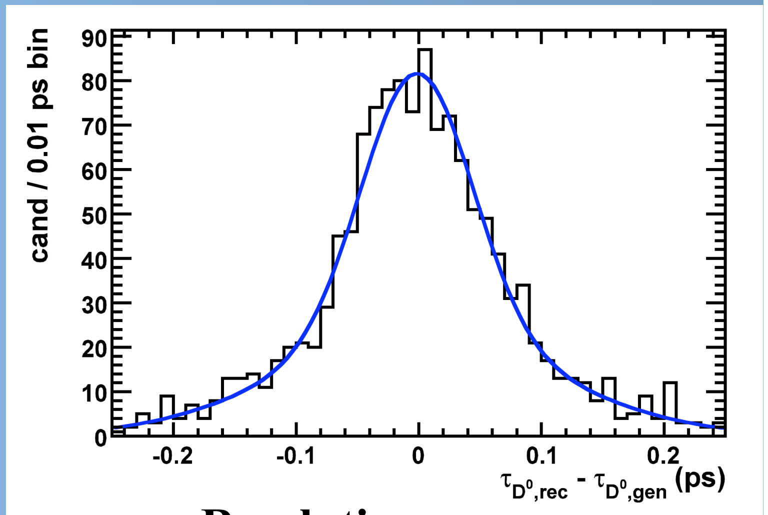
B factories**		2 ab^{-1}	y_{cp}± 0.3
LHCb**	8 x 10^6	10 fb^{-1}	y_{cp}± 0.05 (stat)

* both KK and ππ pairs were used.

** only KK pairs

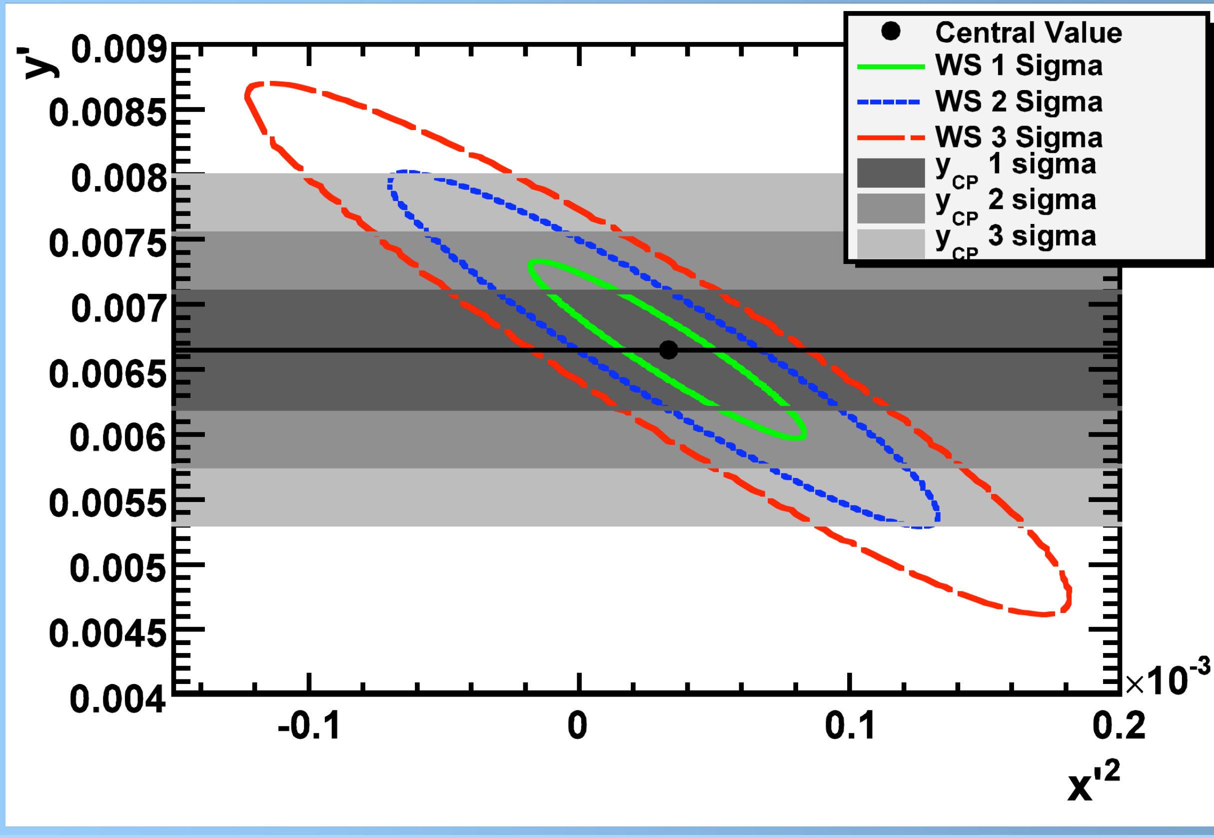


Acceptance



Resolution

Summary of LHCb at 10 fb^{-1}



Sensitivities (10 fb^{-1}) from the WS study and the y_{CP} study.
Contours correspond to 1, 2, and 3 confidence levels from the WS study.
Horizontal bands correspond to 1, 2, and 3 confidence levels from the y_{CP} study.

Summary

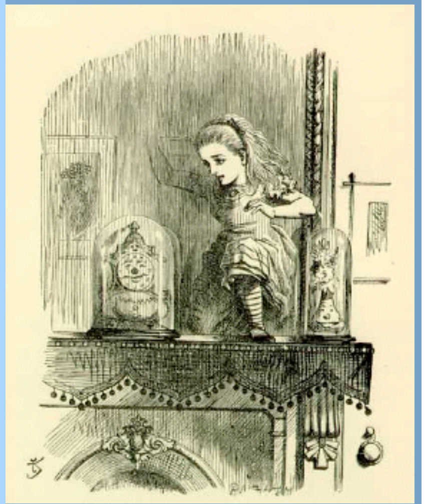
- The LHCb experiment has an exciting potential for charm physics studies.
- A dedicated D* trigger will provide 10^8 flavour tagged $D^0 \to hh$ per 2 fb^{-1}, giving unprecedented sensitivity in searches for D^0 mixing and CP violation.
- Multihadron D decay studies are also envisaged:

  $D^0 \to K_s \pi^+ \pi^-$, $K_s K^+ K^-$, $K_s K \pi$, $D^+ \to K^+ K^- \pi^+$, $K \pi \pi$,

  $D^0 \to K^+ K^- \pi^+ \pi^-$, $K \pi \pi \pi$.

We have only begun to tap the potential of our charming experiment.

The looking-glass world Alice entered would indeed be a very different place. Not only will the books be written from right to left, but you must walk in the opposite direction to reach your goals and the White Queen, first bandages her finger, then begins to bleed, then screams, and finally pricks her finger. Also, as Alice suggested to her kitten, looking-glass milk would almost certainly not be good to drink.



LHCb Holding a mirror to physics

LHCb Holding a mirror to physics