Charm mixing and CP violation in LHCb

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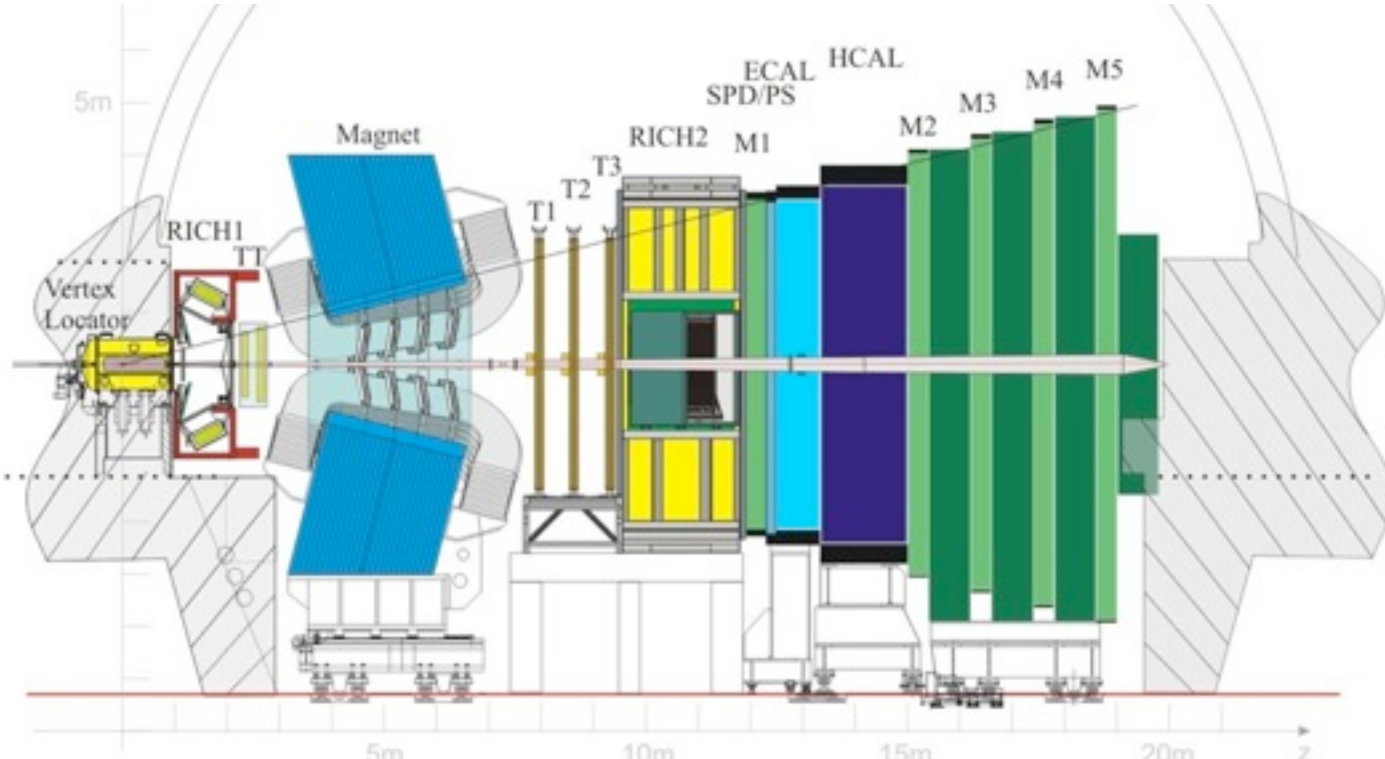
On behalf of the LHCb collaboration

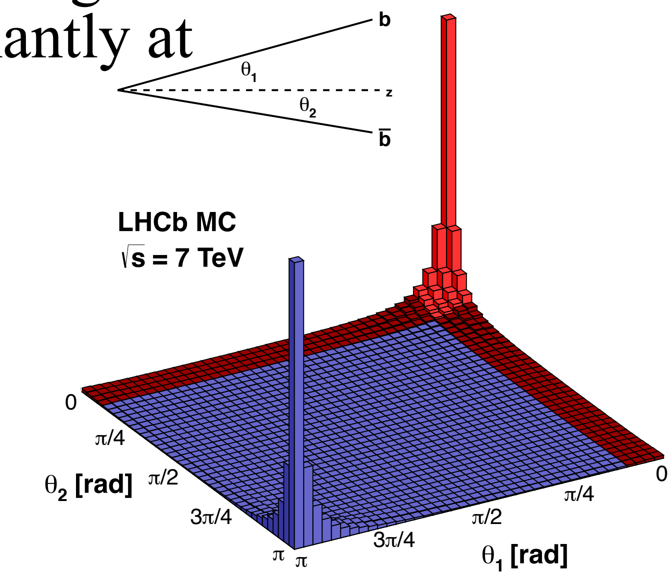
LHCb detector



- Forward spectrometer with unique pseudorapidity coverage $2 < \eta < 5$
- Two RICH detectors vital for K-π separation
- Silicon Vertex Locator allows precise reconstruction of primary and secondary vertices
- Excellent momentum resolution
- 1.0 fb^{-1} of 7TeV data recorded in 2011, 2 fb^{-1} of 8TeV data recorded in 2012

Charm at LHCb

- Optimised for heavy flavour physics, taking advantage of highly correlated $b\bar{b}$ and $c\bar{c}$ trajectories, predominantly at low angles to the beam line.



- Copious b quark production

$$\sigma(pp \to b\bar{b}X) = (284 \pm 20 \pm 49)\ \mu\mathrm{b} \quad [1]$$

- ~20x larger c quark production

$$\sigma(c\bar{c})_{4\pi} = 6100 \pm 934\,\mu\mathrm{b} \quad [2]$$

$$\sigma(c\bar{c})_{p_\mathrm{T}<8\,\mathrm{GeV}/c,\,2.0<y<4.5} = 1419 \pm 12\,(\mathrm{stat}) \pm 116\,(\mathrm{syst}) \pm 65\,(\mathrm{frag})\ \mu\mathrm{b} \quad [3]$$

- Produce ~10^{12} c quark pairs per fb^{-1} within acceptance.

- Flexible trigger with ~ 1/3 trigger bandwidth allocated to prompt charm decays.

[1] Phys. Lett. B694: 209-216, 2010
[2] LHCb-CONF-2010-013
[3] arXiv:1302.2864, accepted by Nucl. Phys. B

Charm mixing

Charm mixing

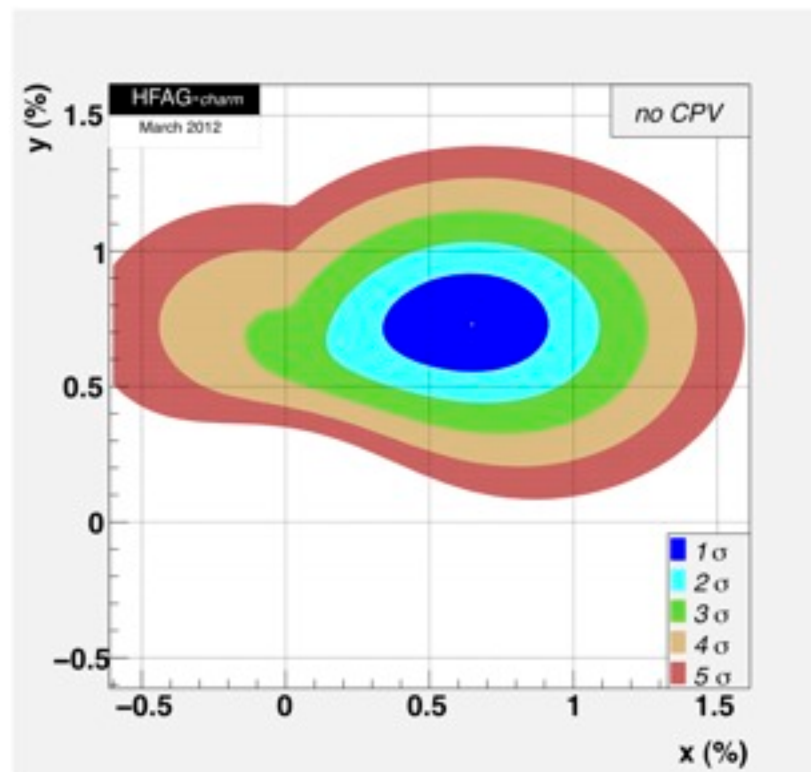
- Two D mass eigenstates can be written in terms of flavour eigenstates

$$|D_{1,2}\rangle = p|D^0\rangle \pm q|\overline{D}^0\rangle \qquad |p|^2 + |q|^2 = 1$$

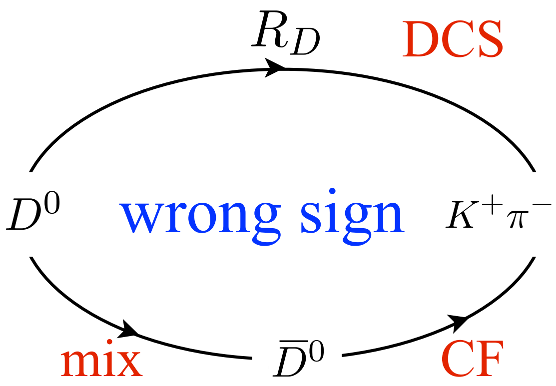
- CPV if q/p differs from 1
- Define dimensionless mixing parameters

$$x \equiv \frac{M_2 - M_1}{(\Gamma_1 + \Gamma_2)/2} \quad \text{and} \quad y \equiv \frac{\Gamma_2 - \Gamma_1}{\Gamma_1 + \Gamma_2}$$

- Before LHCb: mixing well established but no <u>single</u> 5σ observation.



Time dependent WS/RS ratio



- $D^0 \to K^+\pi^-$ ("wrong sign") decays can occur via two routes.
- $D^0 \to K^-\pi^+$ ("right sign") decays completely dominated by CF amplitude.
- Time dependent WS/RS ratio given by

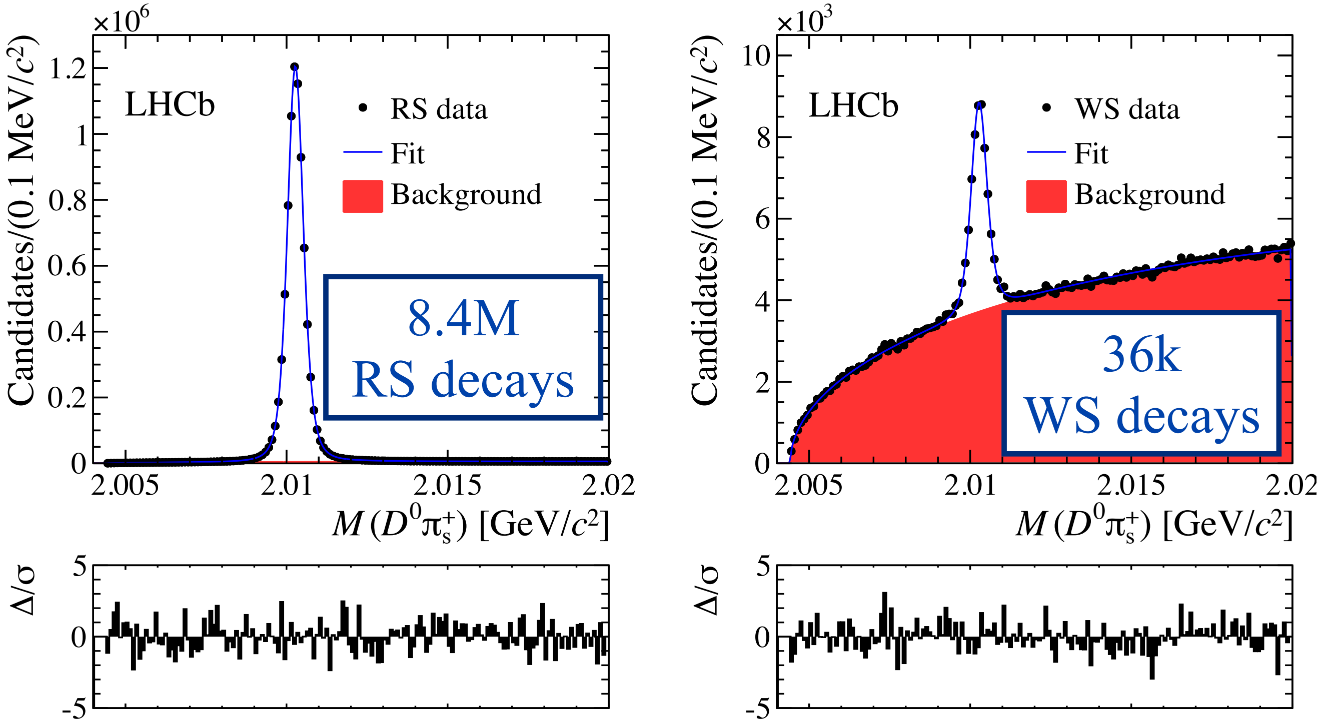
$$R(t) \approx R_D + \sqrt{R_D}\, y' \,\frac{t}{\tau} + \frac{x'^2 + y'^2}{4} \left(\frac{t}{\tau}\right)^2$$

assuming no CPV, i.e. q/p =1

- Measure number of WS/RS decays in different decay time bins: deviation from horizontal line is clear indication of oscillations.
- Initial flavour is "tagged" using the strong decay $D^{*+} \to D^0\pi^+$.

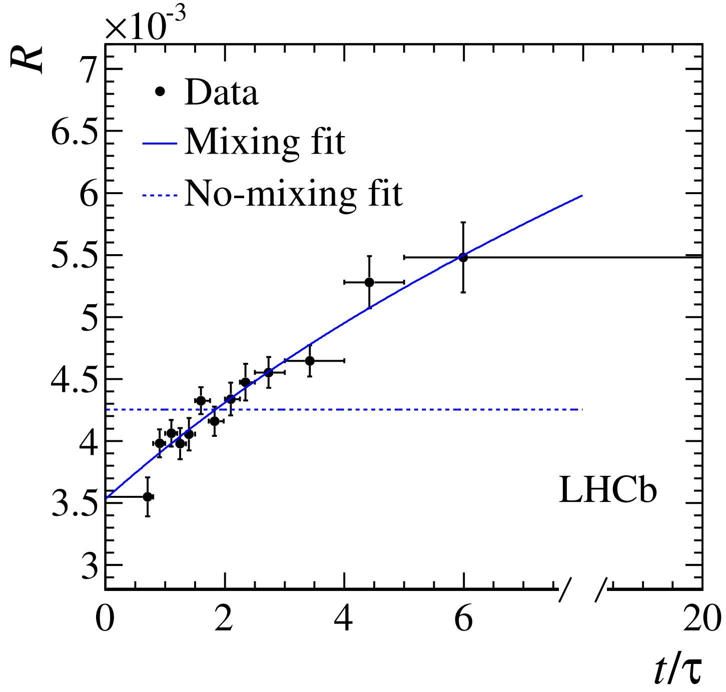
Event yields

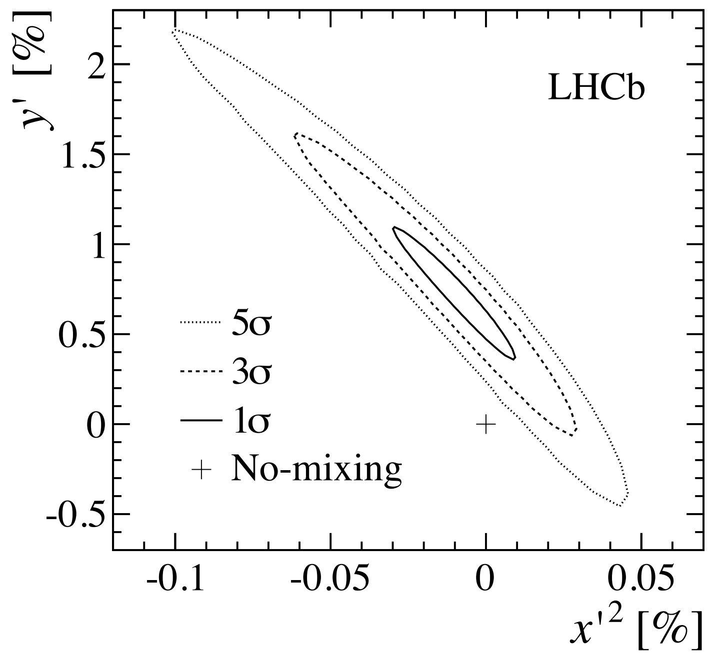
arXiv:1211.1230v1 accepted by PRL



- Above: fit to reconstructed D^* mass with 1.0 fb^{-1} over entire lifetime range.
- Analysis performed by fitting data in 13 bins of D^0 measured lifetime

Results





Fit type (χ^2/ndf)	Parameter	Fit result (10^{-3})
Mixing (9.5/10)	R_D	3.52 ± 0.15
	y'	7.2 ± 2.4
	x'^2	-0.09 ± 0.13
No mixing (98.1/12)	R_D	4.25 ± 0.04

~10% of the uncertainty is due to systematic effects

- No-mixing hypothesis excluded by 9.1σ
- World's first single >5σ measurement with 1 fb^{-1}

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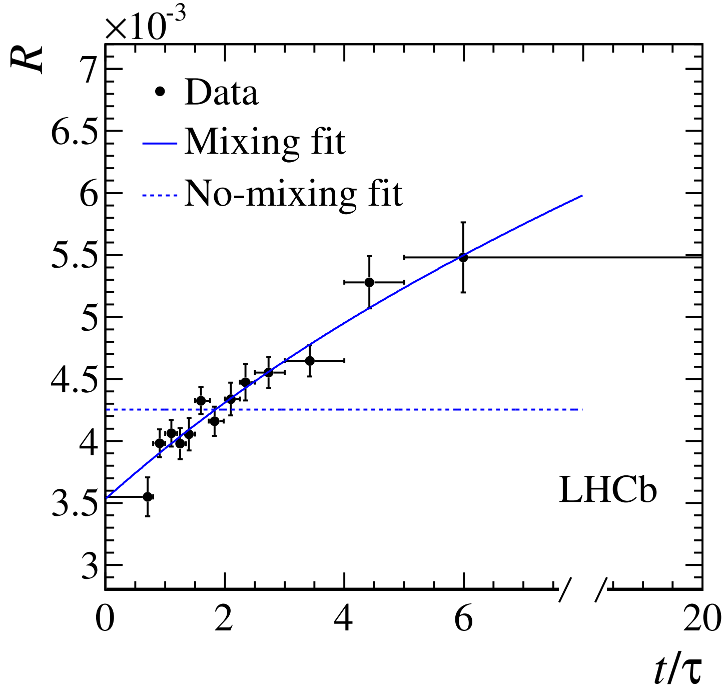
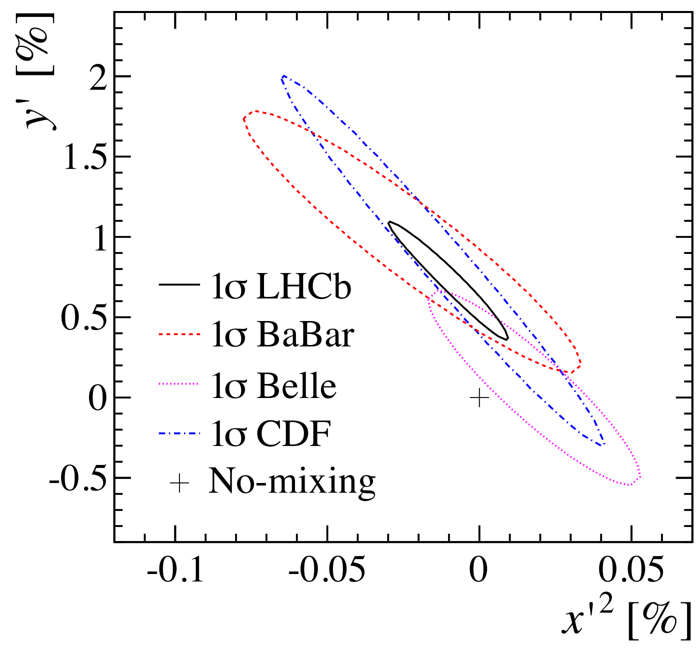
Results





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CP violation

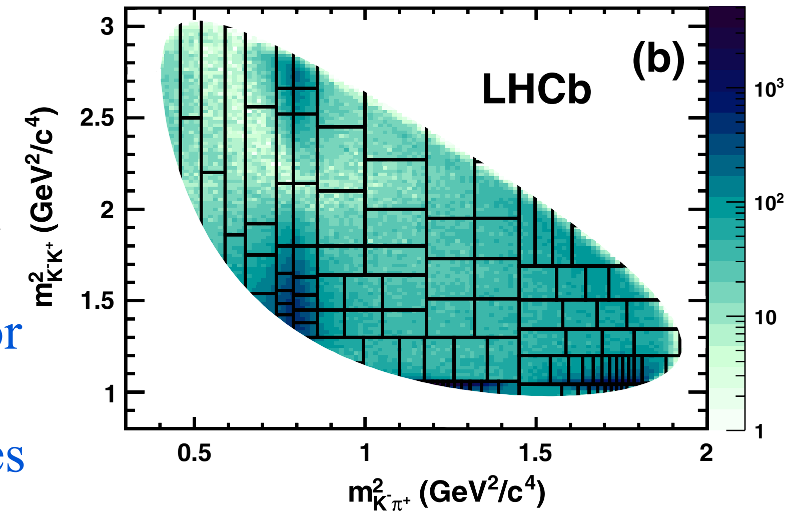
Search for CPV across the Dalitz plot

- Using the SCS decay $D^+ \to K^- K^+ \pi^+$, search for local CP asymmetries by comparing D^+ and D^- Dalitz plots ("Miranda" method).

- Define local CP asymmetry variable, for each Dalitz bin i

$$\mathcal{S}^{\,i}_{CP} = \frac{N^i(D^+) - \alpha N^i(D^-)}{\sqrt{N^i(D^+) + \alpha^2 N^i(D^-)}}, \qquad \alpha = \frac{N_{\rm tot}(D^+)}{N_{\rm tot}(D^-)},$$

accounts for global asymmetries



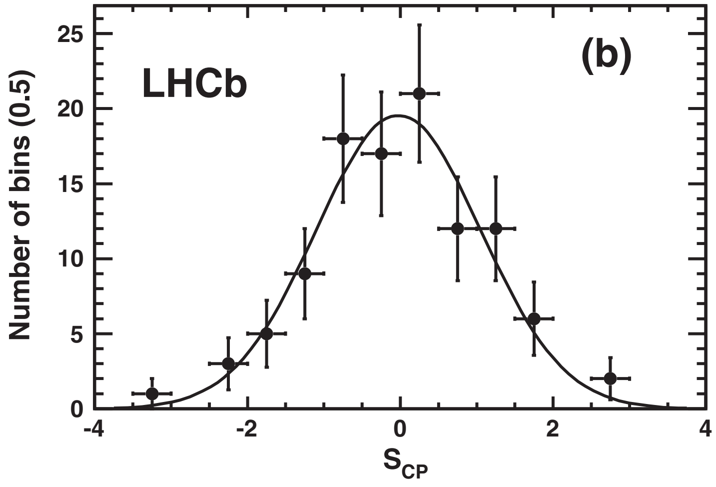
- Expect Gaussian distribution with μ=0, σ=1 for no CPV.

- Use high statistics CF control mode to test for detector asymmetries.

- Calculate p-value from $\chi^2 = \sum_i (S^i_{CP})^2$

- Several binning schemes tested (right: 106 bins, p-value of 10.6%), all consistent with no CPV.

- 35 pb^{-1} used, ~300k signal decays.



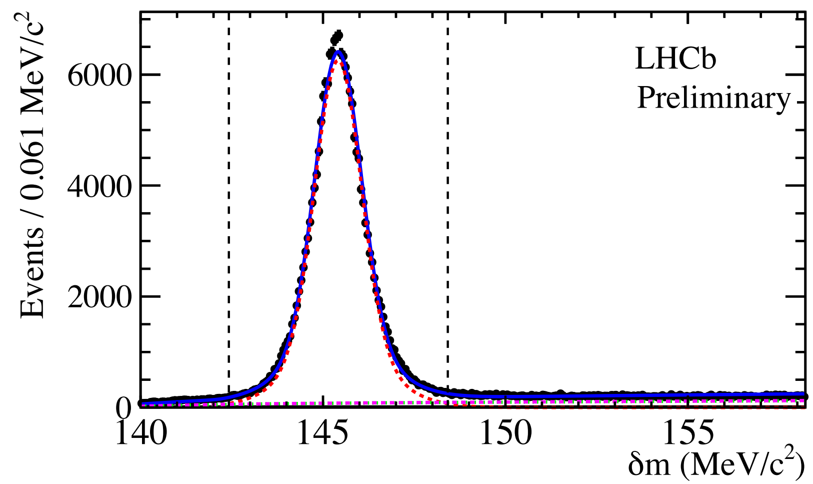
Phys Rev D84, 112008

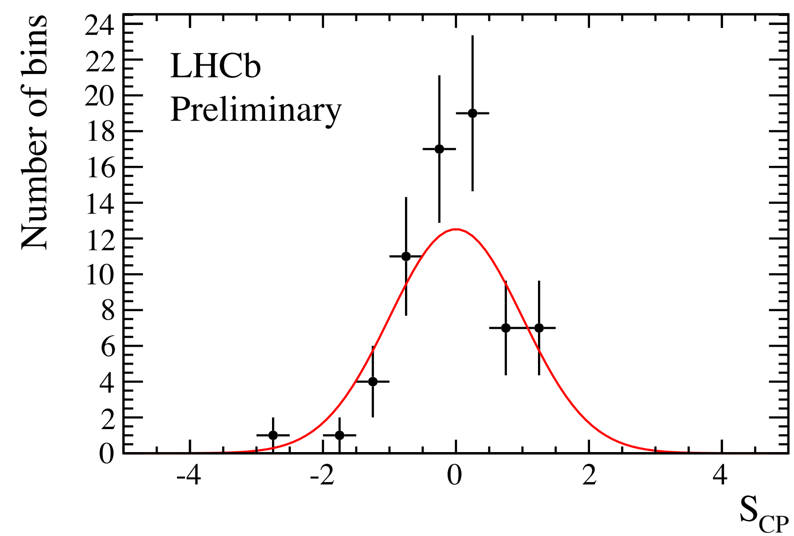
Miranda method with $D^0 \to \pi^+\pi^-\pi^+\pi^-$

- The same method is applied to D^* tagged $D^0 \to \pi^+\pi^-\pi^+\pi^-$ decays using 1.0 fb^{-1}.
- 180k signal candidates, high purity

  particularly impressive for a SCS five pion final state where the majority of background is low momentum pions

- Dalitz space is now FIVE dimensional.
- Measure S_{CP} in each of the 5D bins and calculate χ^2.
- All binning schemes consistent with no CPV.
- Right: 66 bins, p-value = 99.8%, Gaussian with μ=0, σ=1 plotted for illustration only.



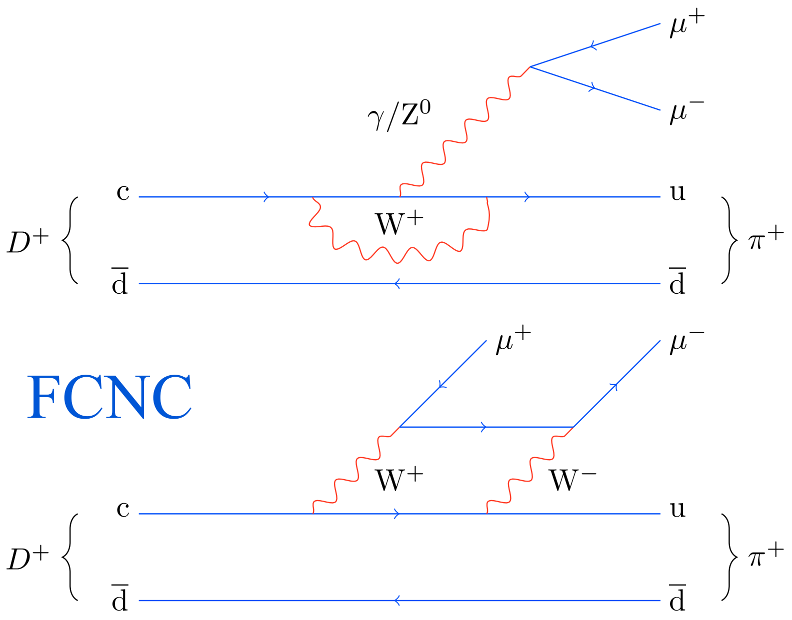


LHCb-CONF-2012-019

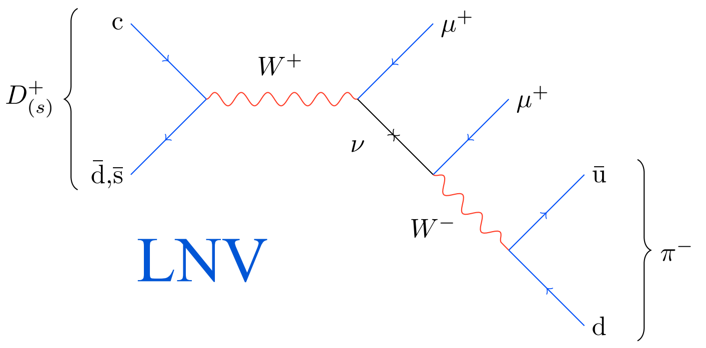
Rare decays

Rare decays and LNV

- FCNC heavily suppressed by GIM mechanism in charm decays.
- In SM $c \to u\mu^+\mu^-$ transitions predicted with branching fraction of ~1-3x10^{-9}.
- Probe for new physics.



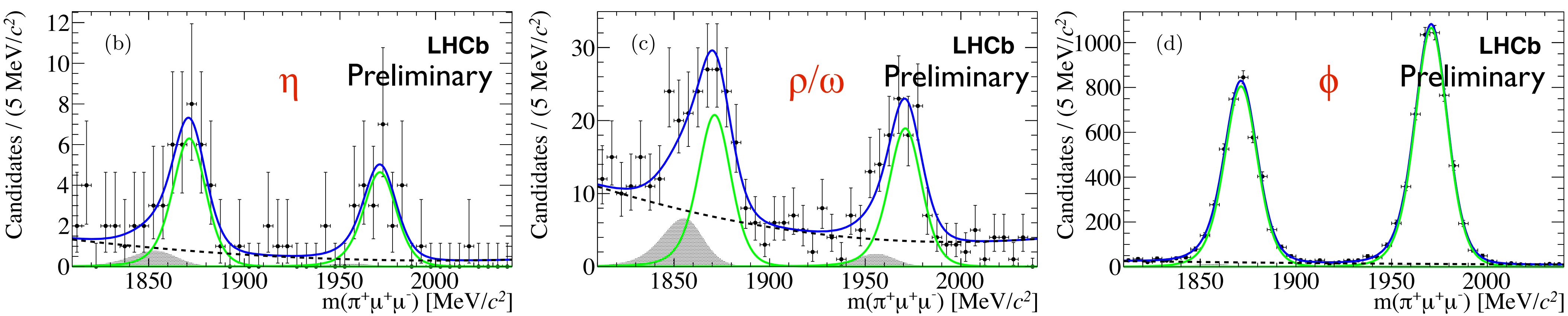
- LNV processes forbidden in SM
- Can occur if mediated by Majorana neutrino.



FCNC - $D^+_{(s)} \rightarrow \pi^+\mu^+\mu^-$

new

- Search for FCNC using $D^+_{(s)} \rightarrow \pi+\mu+\mu^-$ decays in 1.0 fb^{-1}.
- Search performed in different bins of $q^2=m(\mu,\mu)$ to isolate search windows from μμ resonances (η, ρ, ω, φ).
- φ resonance used for normalisation.
- Grey component is misidentified $D^+_{(s)} \rightarrow \pi+\pi+\pi^-$.
- Green component is signal.



LHCb-PAPER-2012-051

FCNC - $D^+_{(s)} \to \pi^+\mu^+\mu^-$

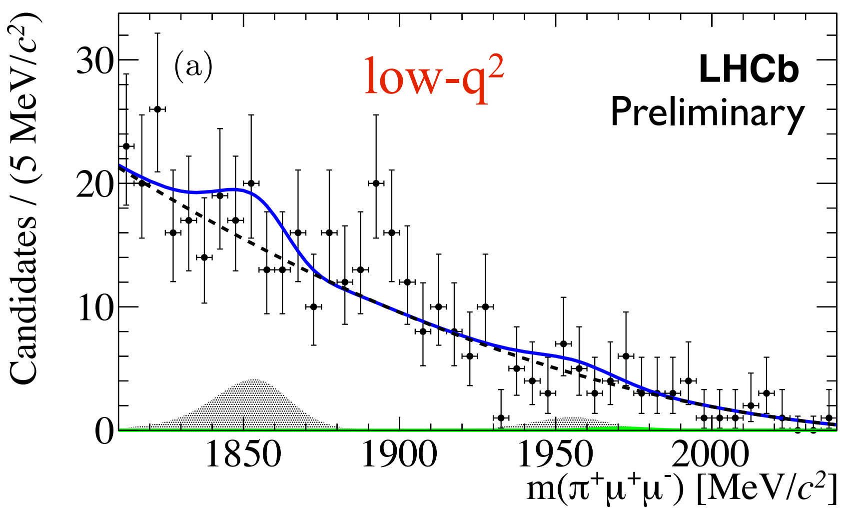
new

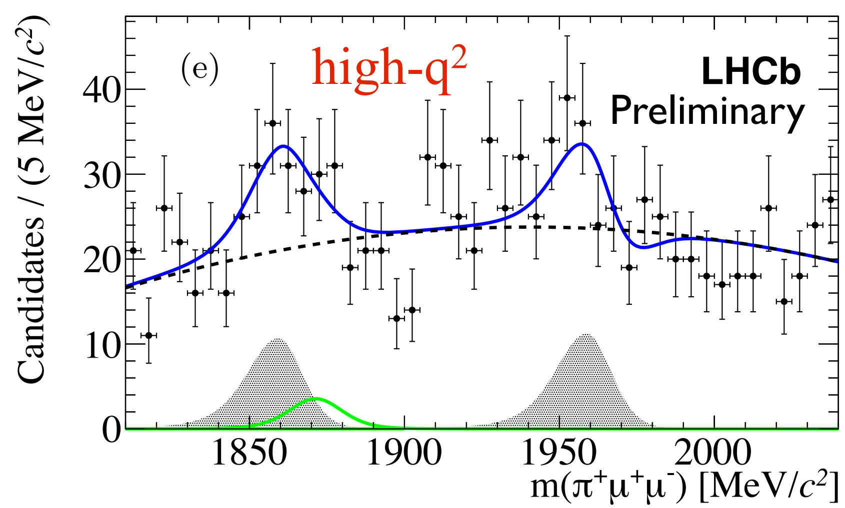
- Low and high q^2 regions used to search for FCNC decays.
- Both consistent with no signal, use to place limits:

$$\mathcal{B}(D^+ \to \pi^+\mu^+\mu^-) < 8.3 \times 10^{-8} \text{ at } 95\% \text{ C.L.}$$
$$\mathcal{B}(D_s^+ \to \pi^+\mu^+\mu^-) < 47.7 \times 10^{-8} \text{ at } 95\% \text{ C.L.}$$

Preliminary

- ~50-100 times better than limits previously published by D0 and Babar (Phys. Rev. Lett. 100 (2008) 101801, Phys. Rev. D84 (2011) 072006).





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LNV - $D^+_{(s)} \to \pi^- \mu^+ \mu^+$

new

- Search performed in different bins of m(π, μ) to increase sensitivity (also 1.0 fb^{-1}):

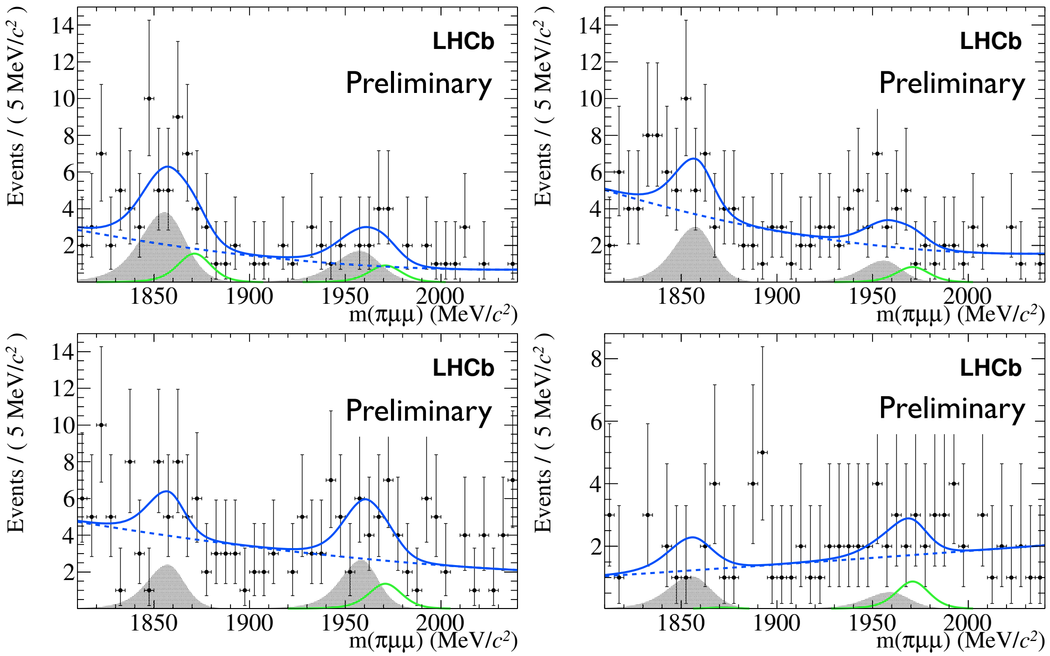
  $250 < m(\pi, \mu) < 1140$ MeV/c^2
  $1140 < m(\pi, \mu) < 1340$ MeV/c^2
  $1340 < m(\pi, \mu) < 1540$ MeV/c^2
  $1540 < m(\pi, \mu) < 2000$ MeV/c^2

- No evidence of LNV decays

$$\mathcal{B}(D^+ \to \pi^- \mu^+ \mu^+) < 2.5 \times 10^{-8} \text{ at } 95\% \text{ C.L.}$$
$$\mathcal{B}(D_s^+ \to \pi^- \mu^+ \mu^+) < 14.1 \times 10^{-8} \text{ at } 95\% \text{ C.L.}$$

Preliminary

- Limits are 100 times lower than previous best measurement by Babar (Phys.Rev. D84 (2011) 072006).



LHCb-PAPER-2012-051

Summary

- LHCb has recorded vast samples of charm decays.
- First single observation of neutral charm meson oscillations with 1.0 fb^{-1}.
- Searches for local CPV in three and four-body SCS charm decays are consistent with no CPV.
- No evidence of FCNC in charm decays, still above SM predictions.
- Still to come:
- CPV in mixing with WS $D^0 \to K^+\pi^-$ decays
- mixing with $D^0 \to K_S h^+ h^-$ and $D^0 \to K^+\pi^-\pi^+\pi^-$
- T-odd moments with $D^0 \to K^+K^-\pi^+\pi^-$
- much more...

Backup slides

ΔA_{CP}

- Measured asymmetry for D* tagged decays to final state f given by

$$A_{\mathrm{raw}}(f) \equiv \frac{N(D^{*+} \to D^0(f)\pi_s^+) \, - \, N(D^{*-} \to \bar{D}^0(f)\pi_s^-)}{N(D^{*+} \to D^0(f)\pi_s^+) \, + \, N(D^{*-} \to \bar{D}^0(f)\pi_s^-)}$$

- Can be written as four components

final state detection asymmetry

production asymmetry

$$A_{\mathrm{raw}}(f) = \boxed{A_{CP}(f)} + \boxed{A_{\mathrm{D}}(f)} + \boxed{A_{\mathrm{D}}(\pi_{\mathrm{s}}^+)} + \boxed{A_{\mathrm{P}}(D^{*+})}$$

CP asymmetry (what we're after)

slow pion detection asymmetry

- $A_D(f) = 0$ for self-conjugate final states K^+K^-, $\pi^+\pi^-$

- $A_D(\pi_s)$ and $A_p(D^{*+})$ are independent of the final state, therefore measure

$$\Delta A_{CP} = A_{\mathrm{raw}}(K^-K^+) \, - \, A_{\mathrm{raw}}(\pi^-\pi^+)$$

$$\Delta A_{CP} = [-0.82 \pm 0.21(\mathrm{stat.}) \pm 0.11(\mathrm{syst.})]\% \quad (3.5\sigma \text{ significance})$$

- Measured with 0.6 fb^{-1}

UPDATE IMMINENT

Phys. Rev. Lett. 108 (2012) 111602

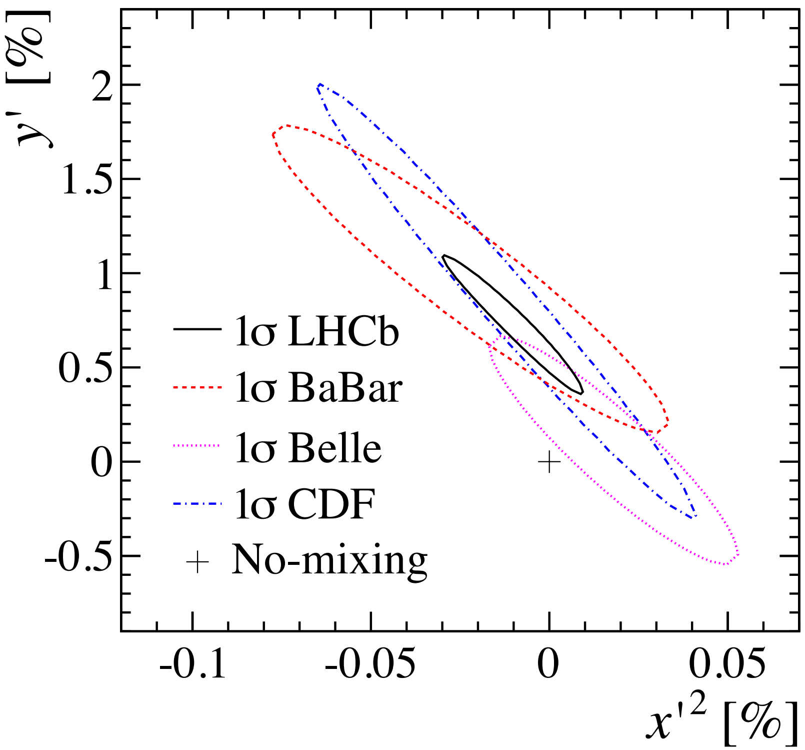
Systematic biases for mixing

- Two major sources of potential bias: secondary D decays (D from B), and peaking background from doubly misidentified D^0 daughters (RS decay faking a WS decay).

- Majority of secondary decays (D from B decays) removed by strict impact parameter requirements.
- Remaining fraction is estimated by fitting $\log(IP\chi^2)$, used to correct the measured WS/RS ratio

- Double mis-IDs do not peak in D^0 invariant mass: can evaluate the number using sidebands.
- Majority are removed before fit to D^* mass by tight mass window cut, RICH particle ID requirements, and vetoing candidates which lie within D^0 mass window when their daughter mass hypotheses are swapped

Mixing

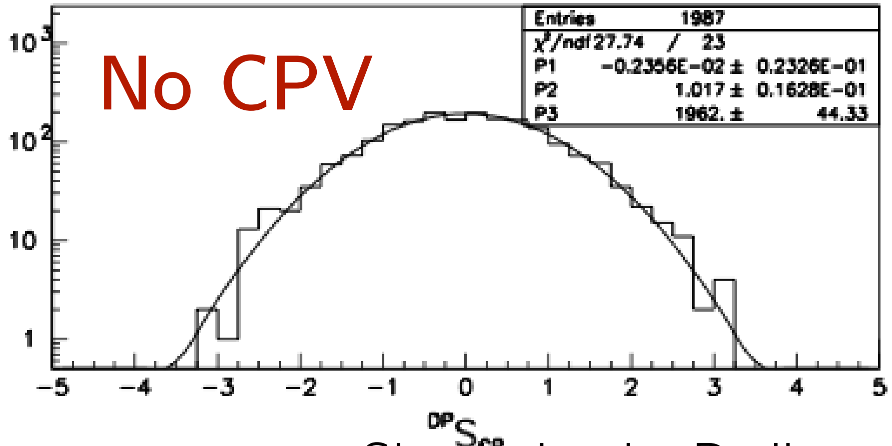


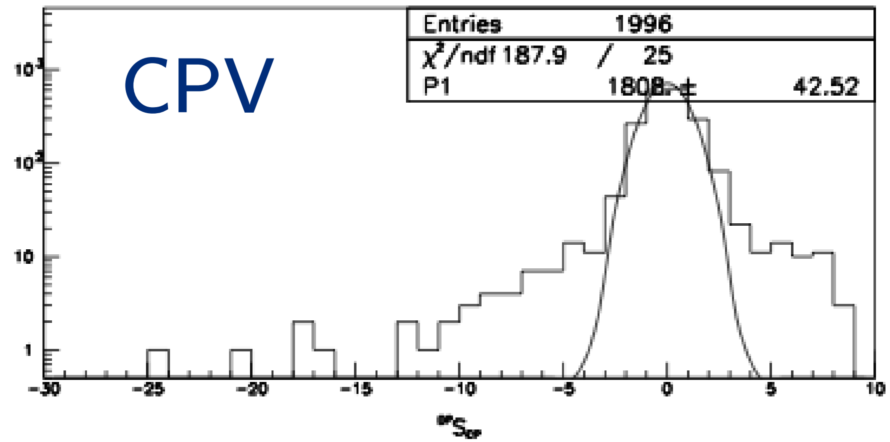
Experiment	R_D (%)	y' (%)	x'^2 (%)
LHCb 2011	0.352 ± 0.015	0.72 ± 0.24	-0.009 ± 0.013
BaBar	0.303 ± 0.019	0.97 ± 0.54	-0.022 ± 0.037
Belle	0.364 ± 0.017	$0.06^{+0.40}_{-0.39}$	$0.018^{+0.021}_{-0.023}$
CDF	0.304 ± 0.055	0.85 ± 0.76	-0.012 ± 0.035

FCNC yields

Bin	Lower $m(\mu^+\mu^-)$ limit	Upper $m(\mu^+\mu^-)$ limit	D^+ yield	D_s^+ yield
low-$m(\mu^+\mu^-)$	250 MeV/c^2	525 MeV/c^2	-3 ± 11	1 ± 6
η	525 MeV/c^2	565 MeV/c^2	29 ± 7	22 ± 5
ρ/ω	565 MeV/c^2	850 MeV/c^2	96 ± 15	87 ± 12
ϕ	850 MeV/c^2	1250 MeV/c^2	2745 ± 67	3855 ± 86
ϕ	850 MeV/c^2	1250 MeV/c^2	3683 ± 90	4857 ± 90
high-$m(\mu^+\mu^-)$	1250 MeV/c^2	2000 MeV/c^2	16 ± 16	-17 ± 16

CPV in Dalitz plot





Simulation by Bediaga et al, Phys.Rev.D80:096006,2009