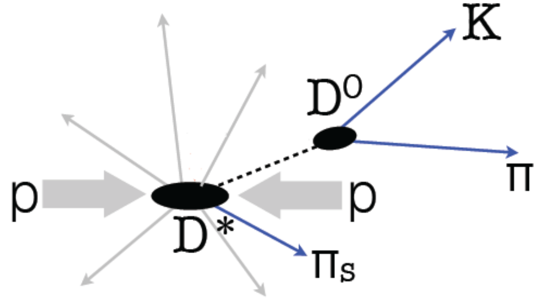

CP Violation Measurements in Wrong-Sign $D^0 \to K\pi$ Decays

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Outline

- Motivation & formalism for measuring D-$\overline{D}$ mixing & CPV
- Experimental status
- LHCb 3fb^{-1} observations
  - Published in Phys. Rev. Lett. 111, 251801 (2013)
- Interpretation of the LHCb results

Formalism in neutral meson mixing

- Schrödinger equation describing the time evolution:

$$i\frac{\partial}{\partial t}\begin{pmatrix}|P^0(t)\rangle \\ |\overline{P}^0(t)\rangle\end{pmatrix} = \left[\begin{pmatrix}M_{11} & M_{12} \\ M_{12}^* & M_{22}\end{pmatrix} - \frac{i}{2}\begin{pmatrix}\Gamma_{11} & \Gamma_{12} \\ \Gamma_{12}^* & \Gamma_{22}\end{pmatrix}\right]\begin{pmatrix}|P^0(t)\rangle \\ |\overline{P}^0(t)\rangle\end{pmatrix}$$

- Mass eigenstates can be different from their flavor eigenstates: *CPT* invariance => $M_{11} = M_{22}$, $\Gamma_{11} = \Gamma_{22}$

$$|P_{L,H}\rangle = p|P^0\rangle \pm q|\overline{P}^0\rangle \quad \text{where} \quad \frac{q}{p} = \sqrt{\frac{M_{12}^* - \frac{i}{2}\Gamma_{12}^*}{M_{12} - \frac{i}{2}\Gamma_{12}}}$$

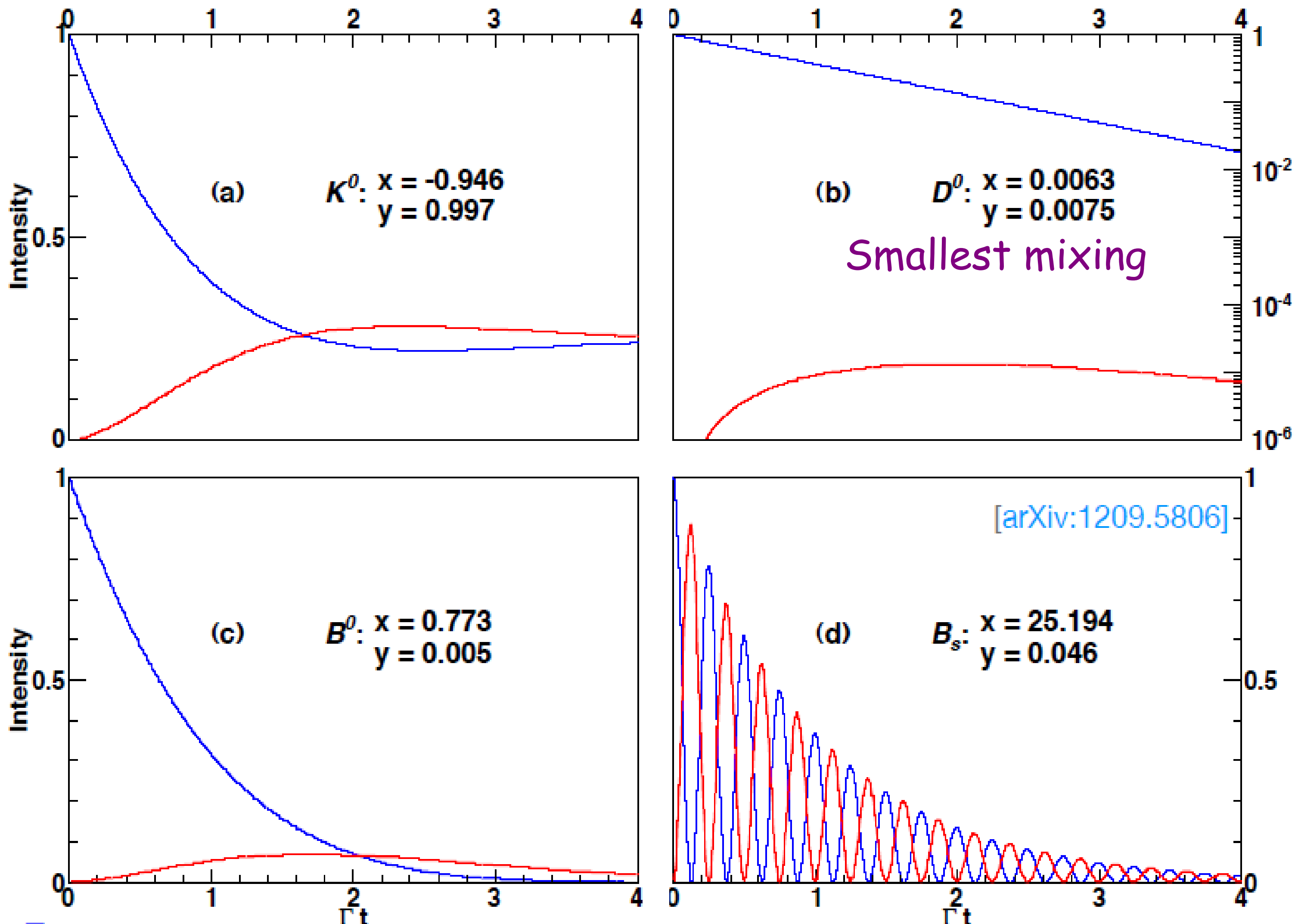
$$x = \frac{\Delta m}{\Gamma} = \frac{m_H - m_L}{(\Gamma_H + \Gamma_L)/2}, \quad y = \frac{\Delta\Gamma}{2\Gamma} = \frac{\Gamma_H - \Gamma_L}{\Gamma_H + \Gamma_L}$$

- If *CP* is conserved, q and p are real, *i.e.* |q/p| = 1 and φ = arg(q/p) = 0

Mixing of neutral mesons: phenomenology

Blue line:
given a P^0, at t=0, the probability of finding a P^0 at t

Red Line:
given a P^0, at t=0, the probability of finding a $\overline{P}^0$ at t

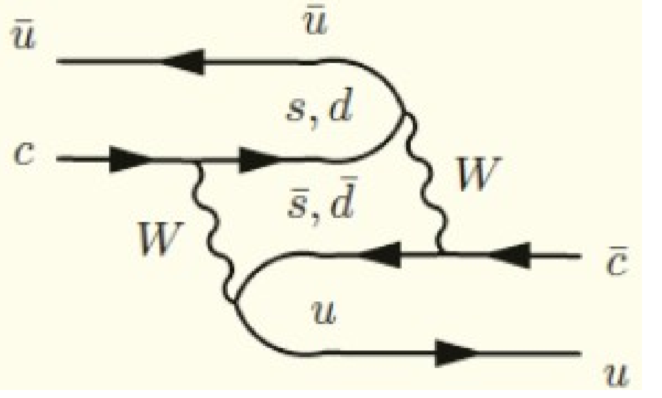


$$|\langle P^0(0)|P^0(t)\rangle|^2 \propto e^{-\Gamma t}\left[\cosh(y\Gamma t) + \cos(x\Gamma t)\right]$$

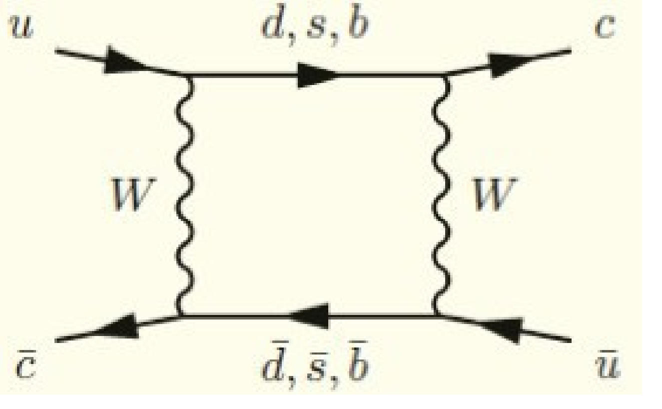
$$|\langle P^0(0)|\overline{P}^0(t)\rangle|^2 \propto e^{-\Gamma t}\left[\cosh(y\Gamma t) - \cos(x\Gamma t)\right]$$

Motivation in measuring charm mixing & CPV

- $D^0 - \overline{D}^0$ oscillation is slow (x, y ~ 1%), and goes through two different mechanisms:
  - Long distance contribution is dominant but hard to predict
  - Short distance contribution is CKM + GIM suppressed. NP might manifest in the loop
    - FCNC processes with up-type quark, complementary to those with down quarks (K or B mesons, already studied with observed CPV)
- Observation of enhanced CPV (>> 1%) in the charm sector would be a clear indication of new physics



Long-distance contribution



Short-distance contribution

CKM suppression: *b*

GIM suppression: *d, s*

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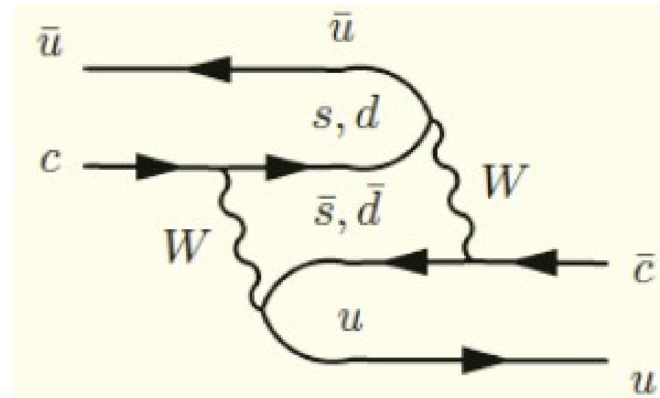
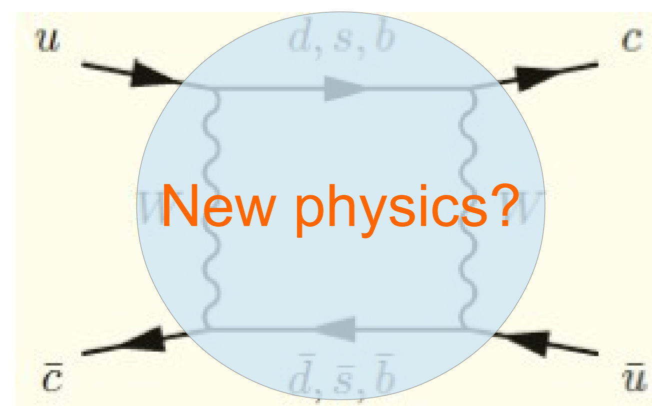


Long-distance contribution

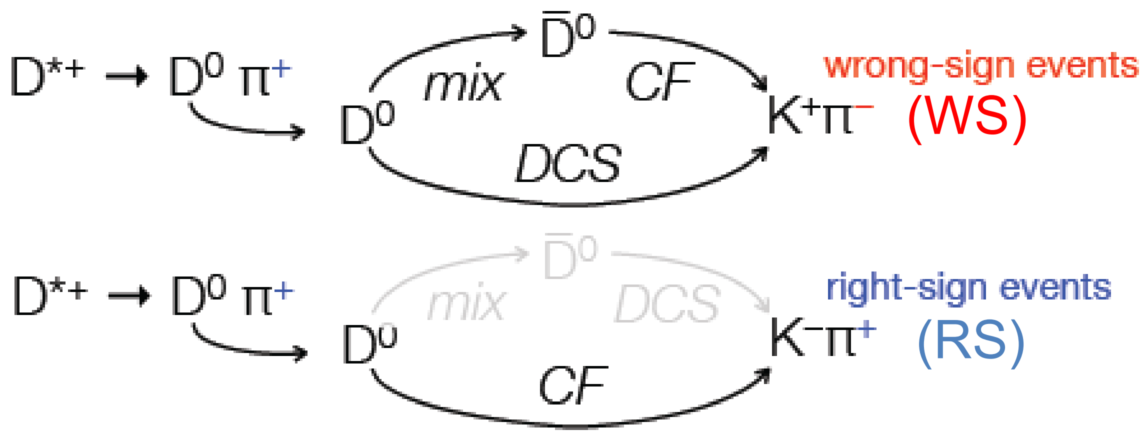


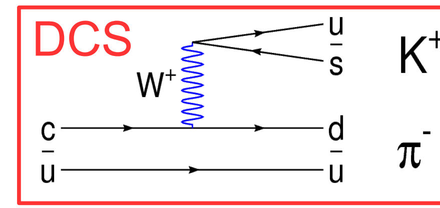
Short-distance contribution
NP might manifest in the loop

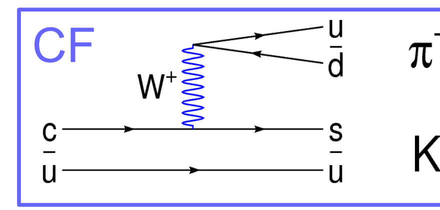
Charm mixing with $D^0 \to K\pi$

- Two-body decays with only tree-level contribution

D^0 flavor is tagged by the "soft" pion from D*







- Assuming x, y << 1 and no CPV, we have the time-dependent WS/RS ratio:

$$R(t) = \frac{N_{WS}(t)}{N_{RS}(t)} = R_D + \sqrt{R_D}\, y' t + \frac{x'^2 + y'^2}{4} t^2$$

δ: strong phase between DCS and CF amplitudes

$$x' = x \cos\delta + y \sin\delta$$
$$y' = y \cos\delta - x \sin\delta$$

R_D → Ratio of DCS to CF decay rates

$\sqrt{R_D}\, y' t$ → Interference of DCS and mixed decays

$\frac{x'^2 + y'^2}{4} t^2$ → Mixing parameters

Measurements on R_D, x'^2, and y'

CPV in charm mixing

- Allowing for CPV, the WS-to-RS ratios are expressed separately for D^0 and $\overline{D}^0$:
  - $$R^+(t) = R_D^+ + \sqrt{R_D^+}\, y'^+ t + \frac{(x'^+)^2 + (y'^+)^2}{4} t^2,$$
    $$R^-(t) = R_D^- + \sqrt{R_D^-}\, y'^- t + \frac{(x'^-)^2 + (y'^-)^2}{4} t^2.$$

Mixing measurements on $R_D^\pm$, $x'^{2\pm}$, and $y'^\pm$ in $D^{*\pm}$, and look for the differences

$$x'^\pm = \left(\frac{1 \pm A_M}{1 \mp A_M}\right)^{1/4} (x' \cos\phi \pm y' \sin\phi)$$

$$y'^\pm = \left(\frac{1 \pm A_M}{1 \mp A_M}\right)^{1/4} (y' \cos\phi \mp x' \sin\phi)$$

$$A_D = \frac{R_D^+ - R_D^-}{R_D^+ + R_D^-}$$

CPV in WS decay amplitude (**Direct CPV**)

$$A_M = \frac{|q/p|^2 - |p/q|^2}{|q/p|^2 + |p/q|^2}, \qquad \phi = \arg\left(\frac{q}{p}\right),$$

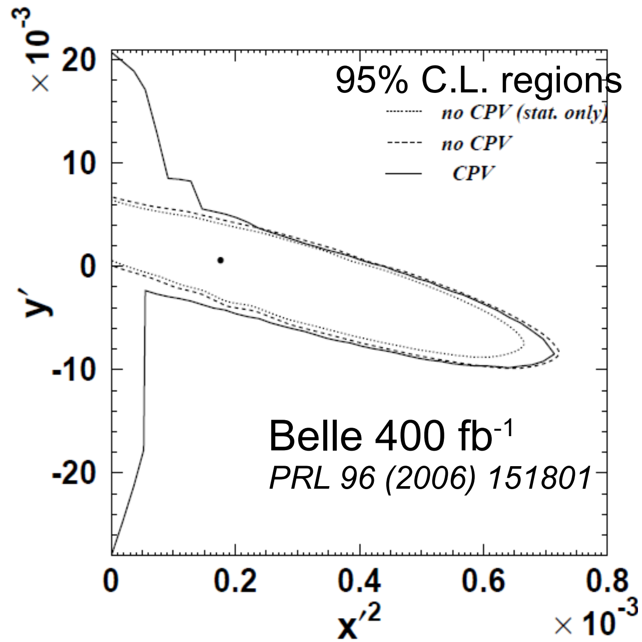
CPV in mixing / interference between mixing and decay

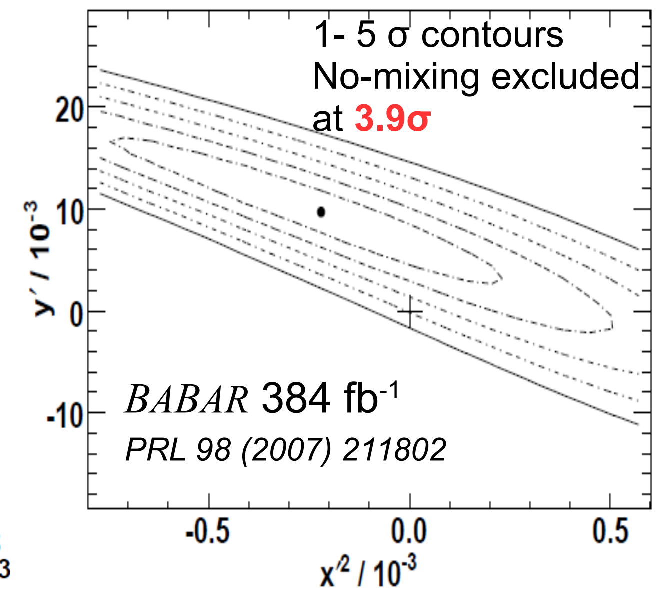
Common methods in charm mixing/CPV measurements

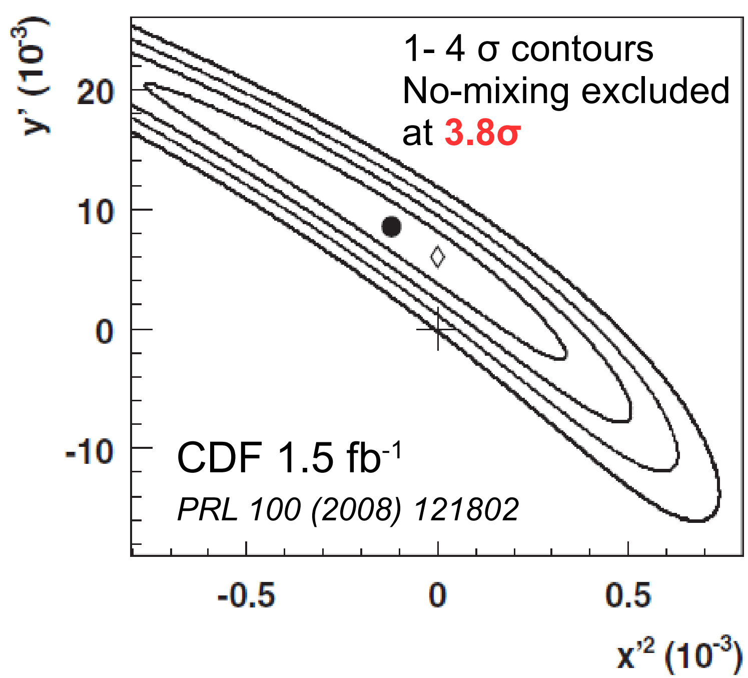
- Divide RS and WS events into a number of bins of D^0 decay time
- In each time bin, the RS and WS signal yields are collected from fits to get the WS-to-RS ratio
  - The WS signal shapes are fixed to the RS ones
- Fit the WS/RS ratio vs. D decay time to extract charm mixing parameters
- Correction to account for (secondary) D* from B decays with mis-assigned decay time
- Search for CPV: separate mixing measurements for D / $\overline{D}$

History of experimental observations

- 2006: “Improved constraints” from Belle
- 2007: Evidence for D^0-$\overline{D}^0$ mixing from BABAR
- 2008: Evidence for D^0-$\overline{D}^0$ mixing from CDF
- Observation (> 5σ) only when all the above results are combined

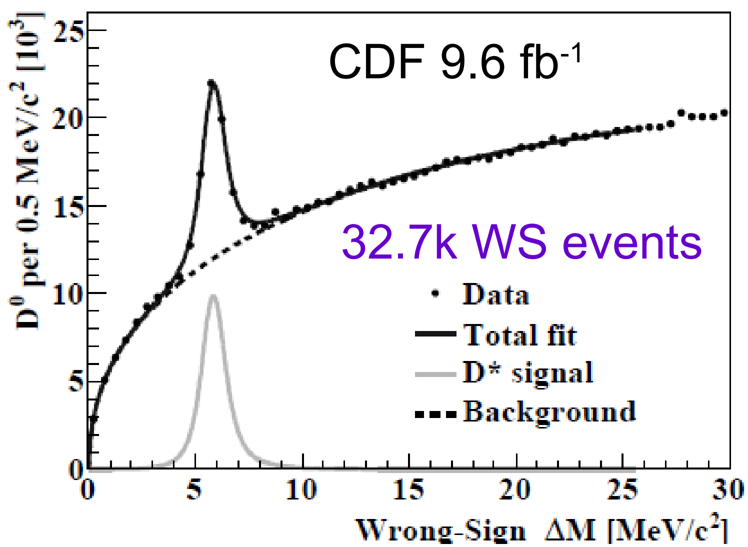




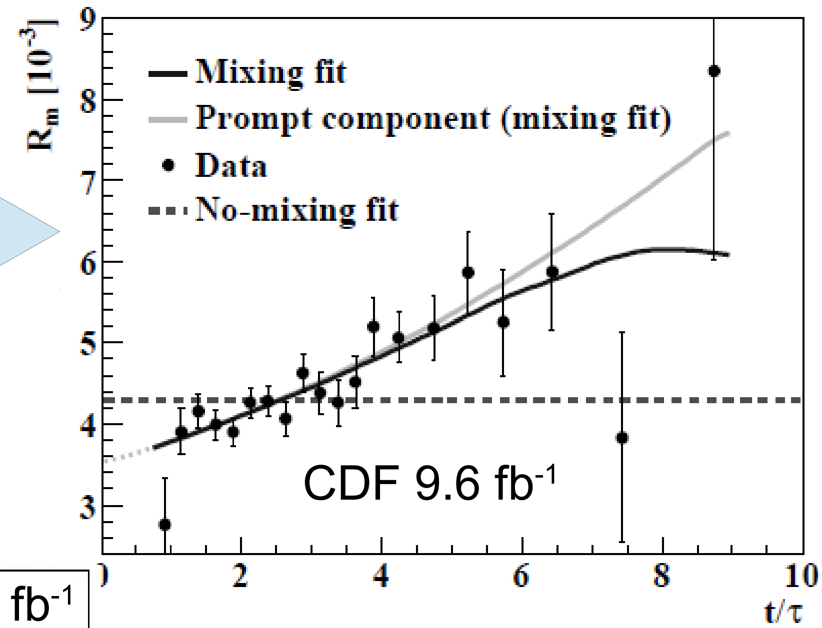


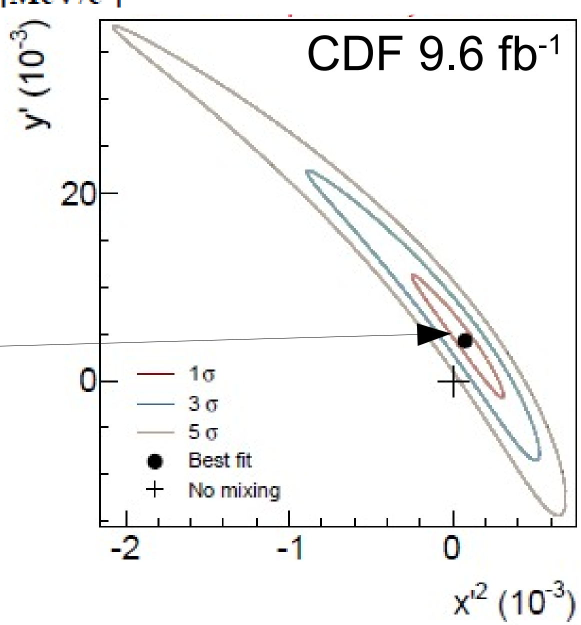
D^0 mixing @ CDF in 2013

Extraction of WS signals from the fit to the mass difference of $M(K^+\pi^-\pi^+) - M(K^+\pi^-) - M(\pi^+)$



Fit to the WS/RS ratios with different mixing hypotheses



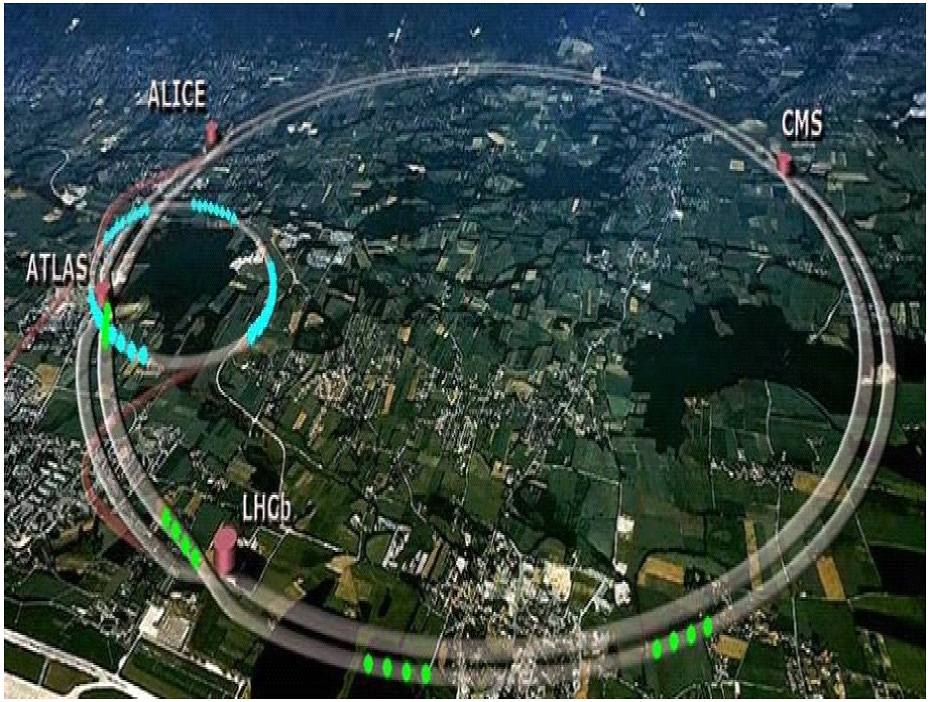


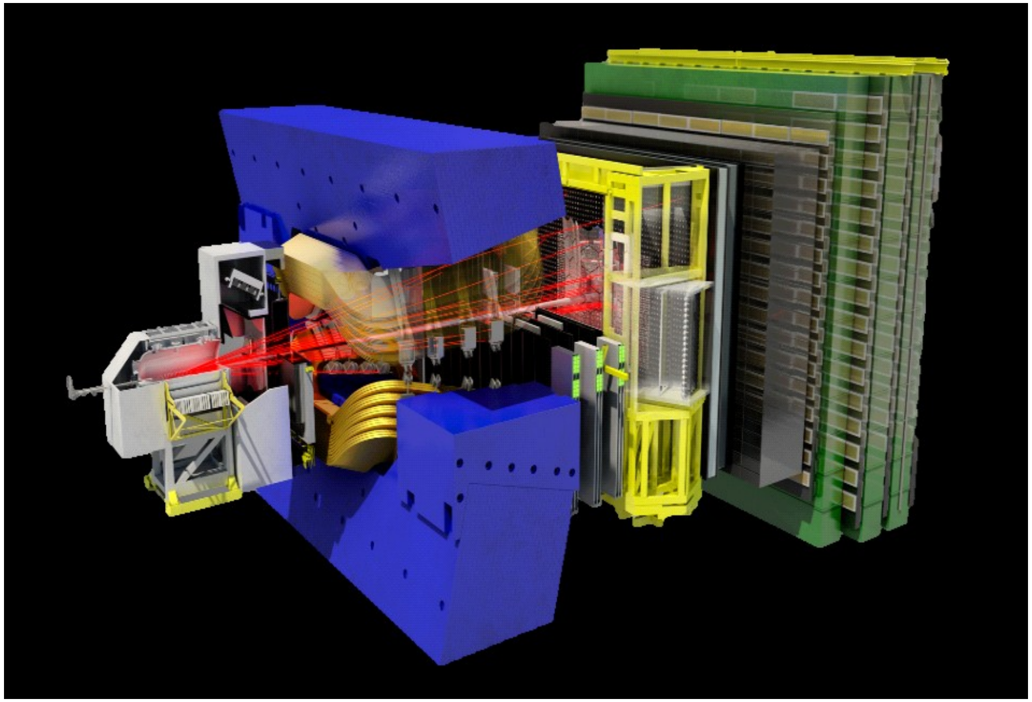
No-mixing hypothesis excluded at 6.1σ

The **second** D^0-$\overline{D}^0$ mixing observation from a single experiment after LHCb in 2012 (*PRL 110, 101802 (2013)*)

PRL 111, 231802 (2013)

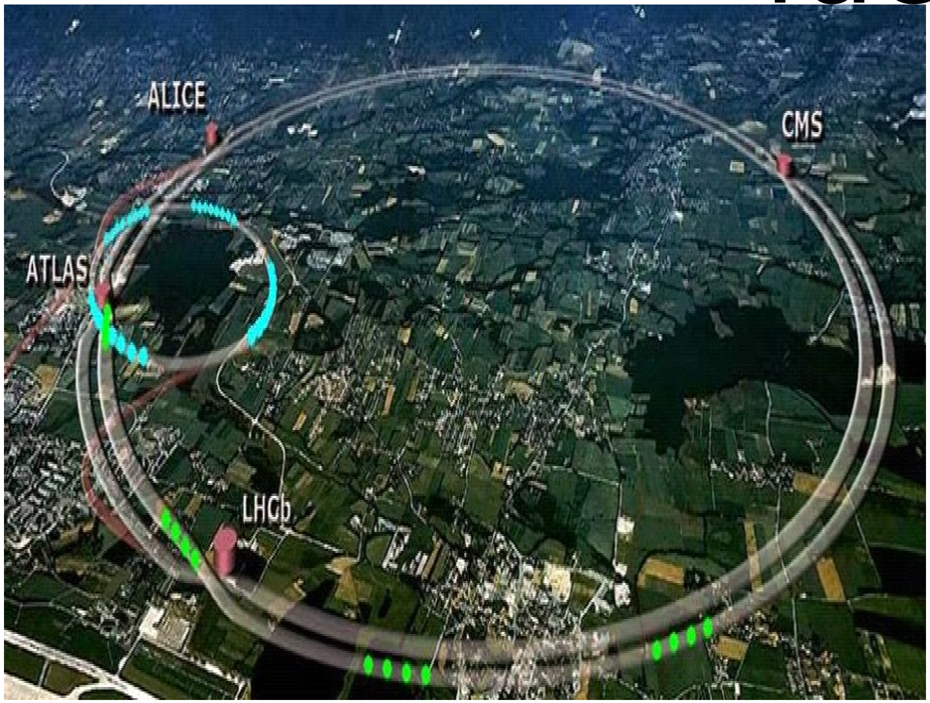
LHCb experiment

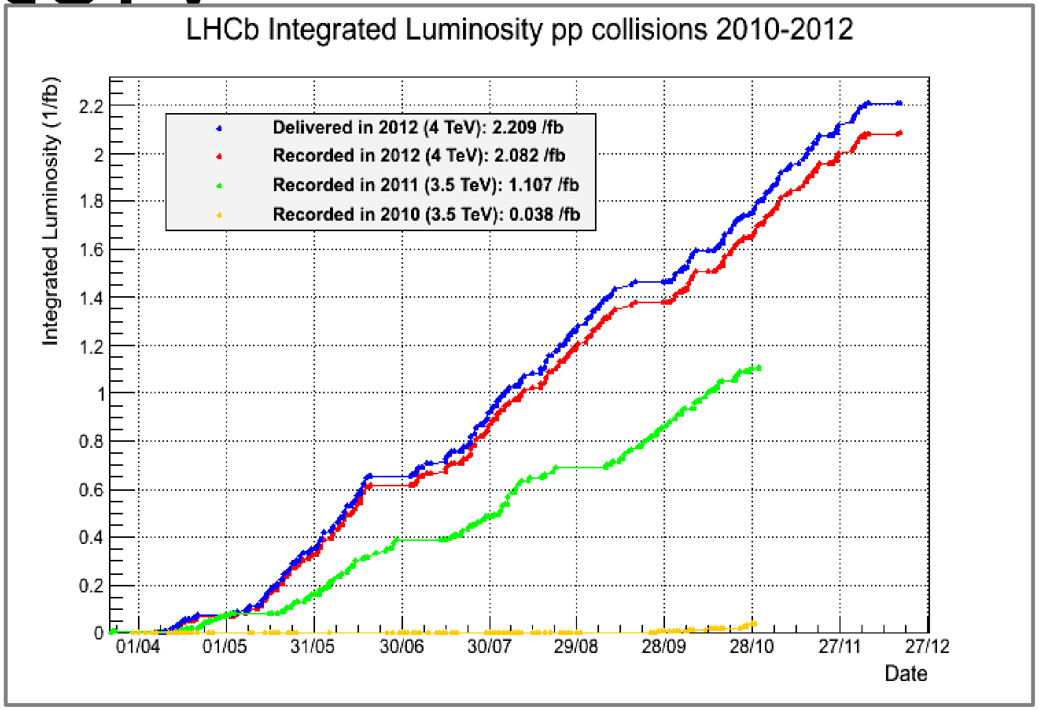




- Single-arm forward spectrometer covering the pseudo-rapidity range $2 < \eta < 5$
- Detection of particles containing *b* or *c* quarks

LHCb experiment as a charm factory





- 20x larger charm cross-section than beauty:

$\sigma(pp \to b\bar{b}X) = 75 \pm 14\ \mu b$ [PLB694:209-216]

$\sigma(pp \to c\bar{c}X) = 1419 \pm 134\ \mu b$ [arXiv:1302.2864]

→ at 7 TeV in the LHCb acceptance

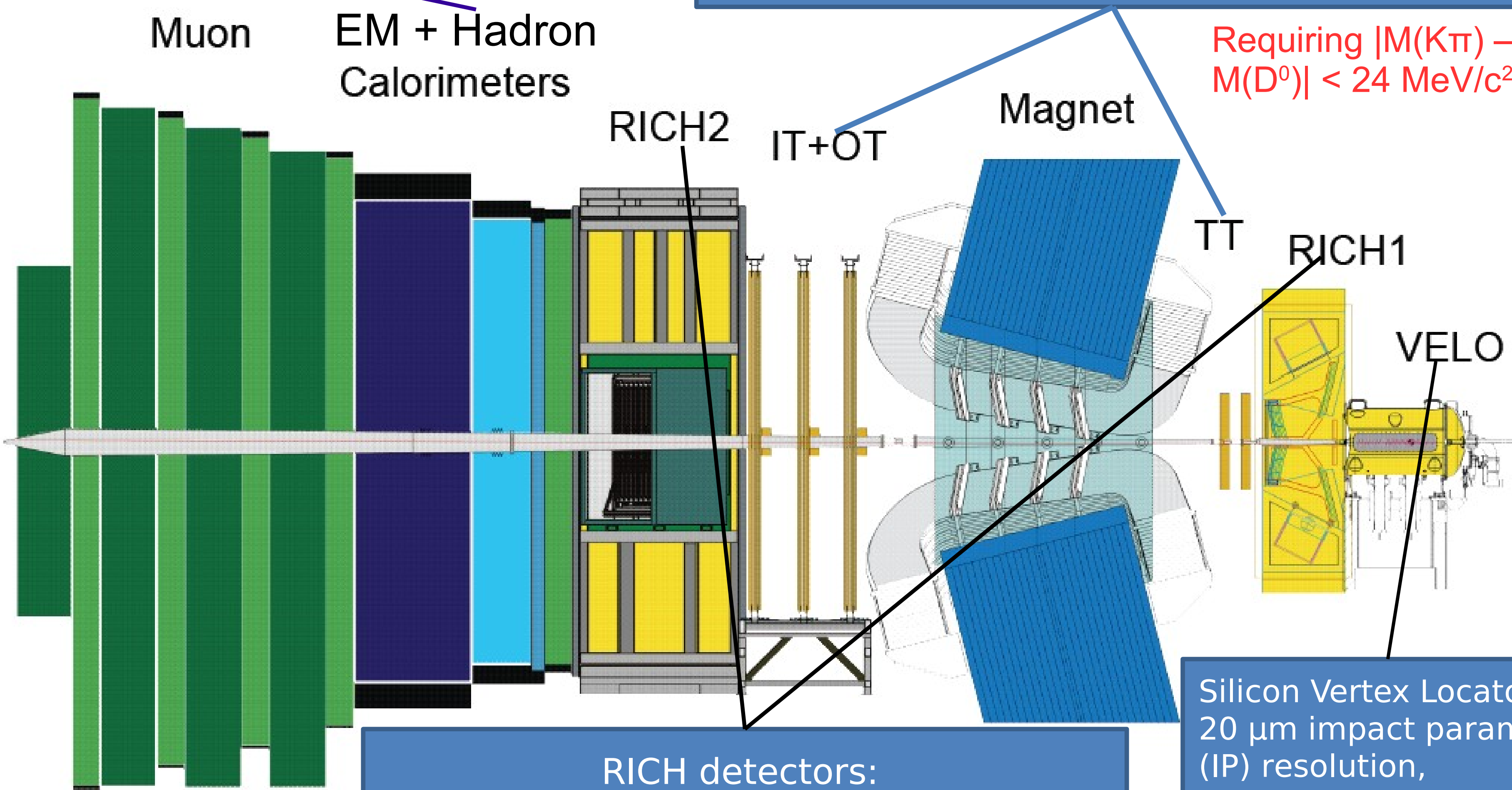
The world's largest charm samples!

LHCb detector

Hardware trigger system for hadrons: based on large E_T depositions in the hadron Cal.

Tracking system:
$\Delta p/p$ = 0.4-0.6% @ 5-100 GeV/c, corresponding to ~8 MeV/c^2 mass resolution for $D \to K\pi$

Requiring $|M(K\pi) - M(D^0)| < 24$ MeV/c^2



RICH detectors:
Good K/π separation for p < 100 GeV/c with mis-ID rate at a few percent

Silicon Vertex Locator:
20 μm impact parameter (IP) resolution, corresponding to ~0.1τ decay-time resolution for $D \to K\pi$

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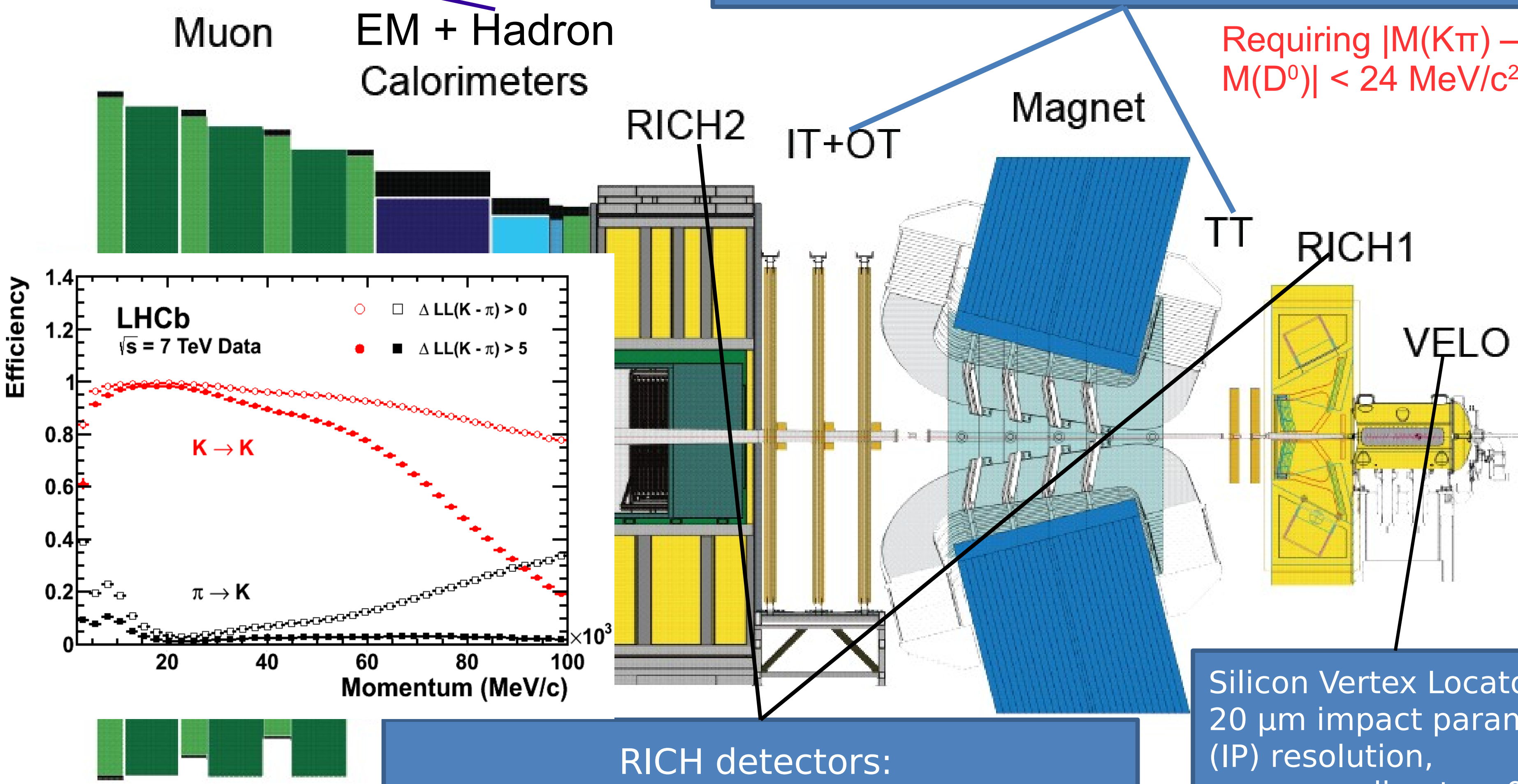

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LHCb trigger on hadronic charm decays

LHC rate ~ 15 MHz — $c\bar{c}$ fraction ~ 10%

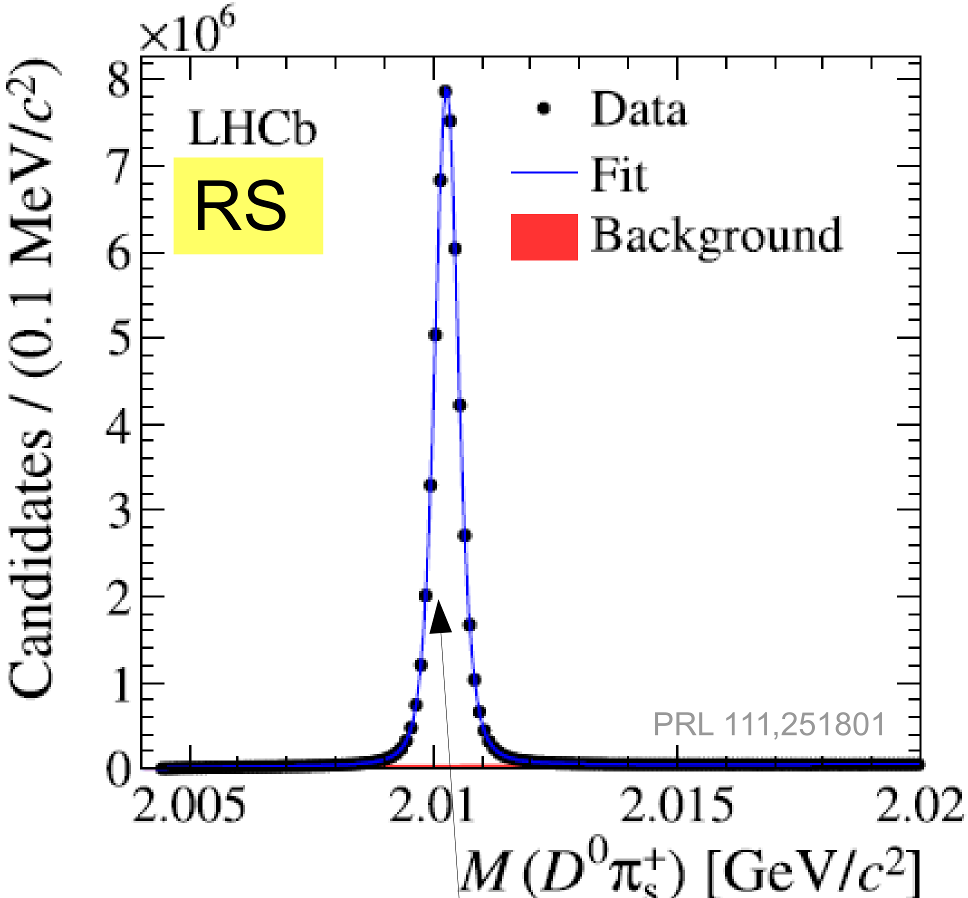
Hardware E_T trigger ~ 1 MHz — $c\bar{c}$ fraction ~ 50%

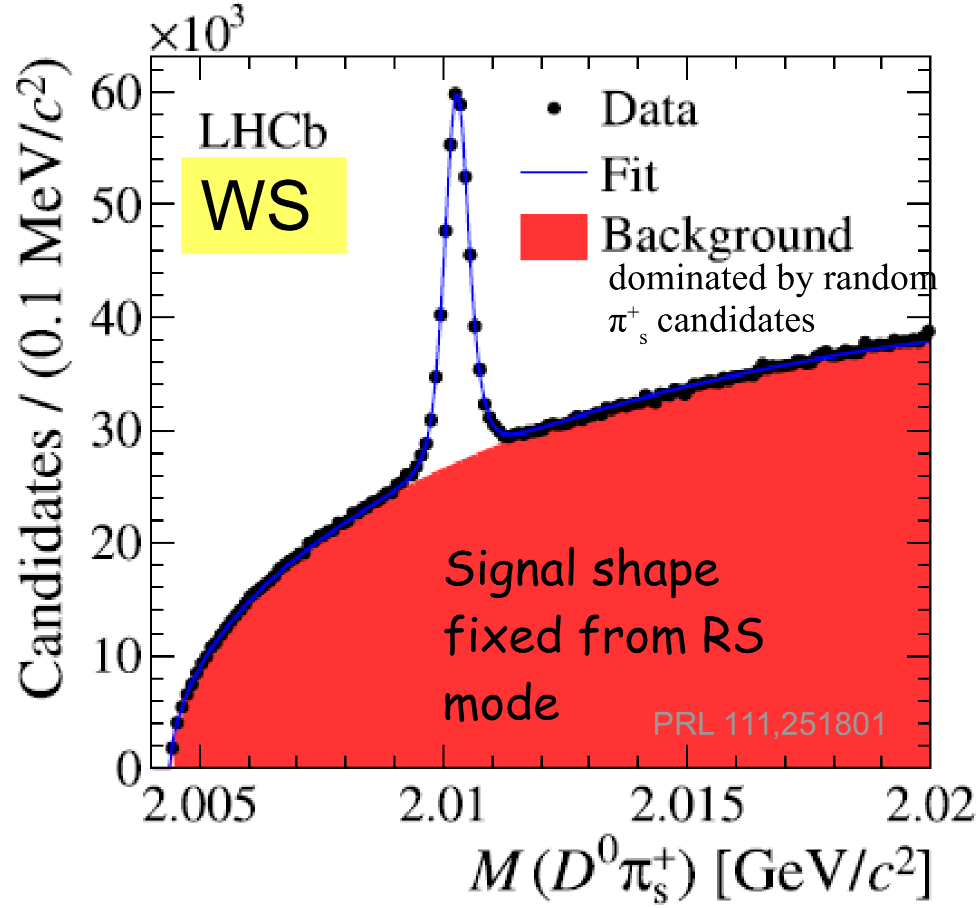
- Two stages: hardware L0 and software HLT
- High charm rate requires exclusive reconstruction in trigger

High pT, IP track ~ 80 kHz — efficiency ~ 50%

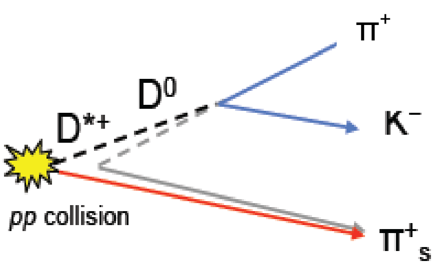
Exclusive D→hh/3h/4h ~ 2 kHz — efficiency ~ 50-90%

Fits to extract WS/RS signals





Computed with known D^0 and π^+ masses

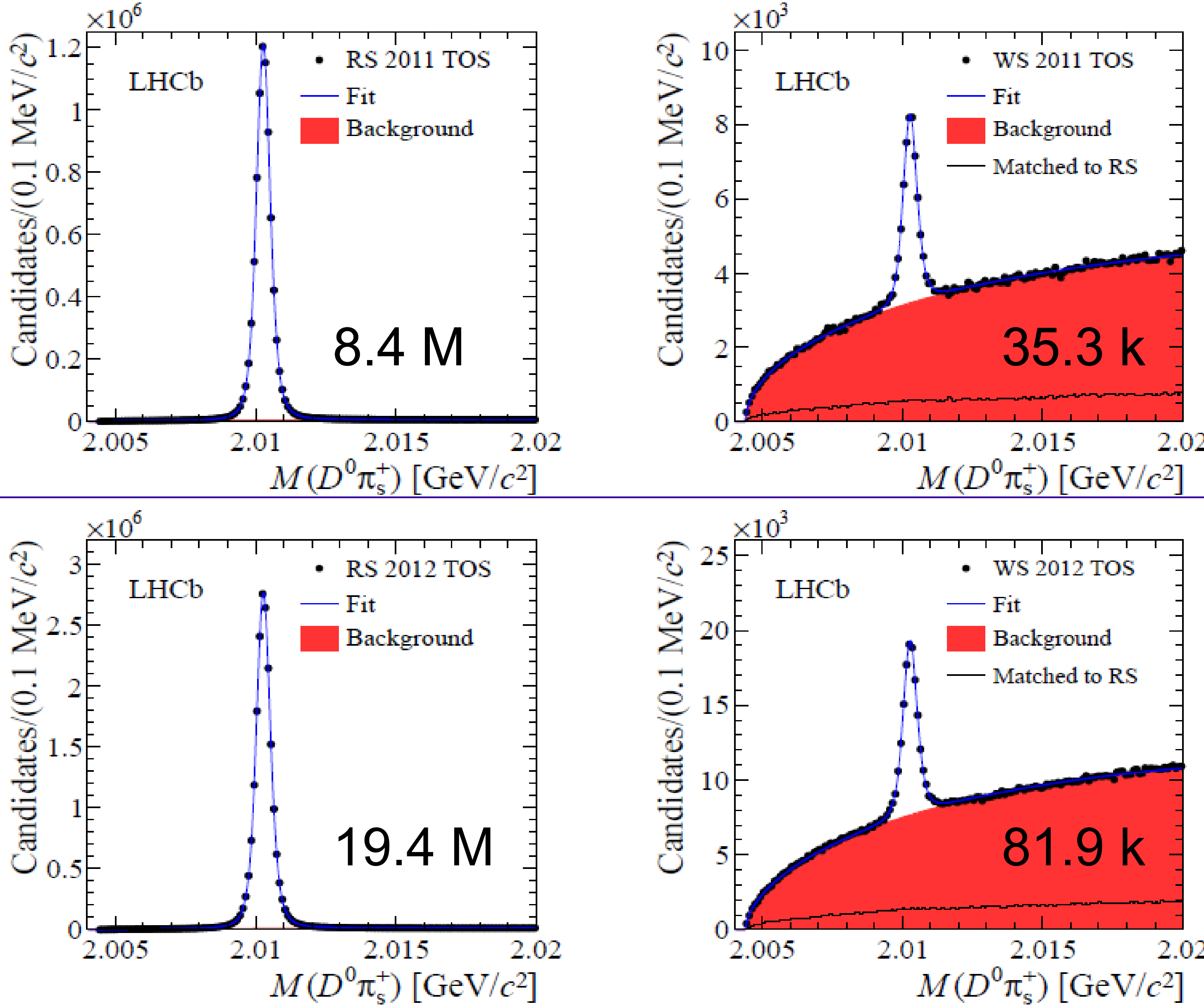


Mass resolution at ~ 0.3 MeV/c^2 due to D^* vertex being well constrained to measured PV position

Time-integrated fits to 3fb^{-1} 2011+2012 data. In total ~54 M RS candidates and ~0.23 M WS candidates are collected.

Time-integrated fits

TOS: events that meet the hardware trigger requirement

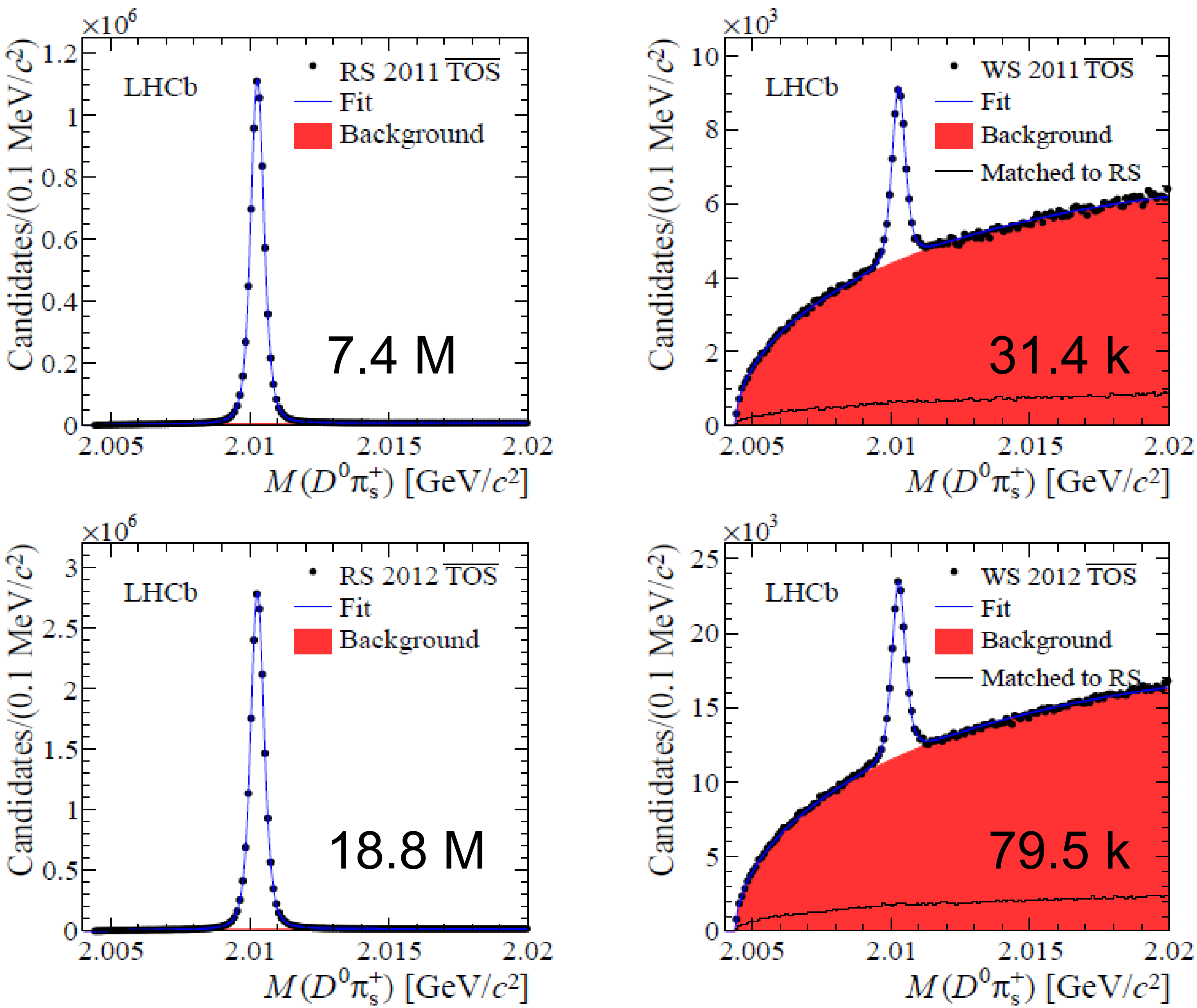


$1fb^{-1}$ collected @ 7 GeV, used in 2011 mixing analysis

$2fb^{-1}$ collected @ 8 GeV

Time-integrated fits

$\overline{\text{TOS}}$: events being the complement of TOS



$1 fb^{-1}$ collected @ 7 GeV

$2 fb^{-1}$ collected @ 8 GeV

Charge asymmetry in Kπ detection

- In the WS/RS ratio separated by D* charge:

$$\frac{N^{\pm}_{WS}}{N^{\pm}_{RS}} = \frac{N(D^{*\pm} \to [K^{\pm}\pi^{\mp}]_D \pi^{\pm}_s)}{N(D^{*\pm} \to [K^{\mp}\pi^{\pm}]_D \pi^{\pm}_s)} = R^{\pm} \frac{\epsilon(K^{\pm}\pi^{\mp})}{\epsilon(K^{\mp}\pi^{\pm})}$$

  – D* production and soft pion instrumental asymmetries cancel out in the ratio

- Still needed to consider: the non-zero detection asymmetry $A_{k\pi}$:

$$A_{K\pi} = \frac{\epsilon(K^+\pi^-) - \epsilon(K^-\pi^+)}{\epsilon(K^+\pi^-) + \epsilon(K^-\pi^+)}$$

  – The efficiency ratio $\varepsilon_r^+ = 1/\varepsilon_r^- = \varepsilon(K^+\pi^-)/\varepsilon(K^-\pi^+)$ is obtained from dedicated control samples:

$$\frac{\epsilon(K^+\pi^-)}{\epsilon(K^-\pi^+)} = \frac{N(D^- \to K^+\pi^-\pi^-)}{N(D^+ \to K^-\pi^+\pi^+)} \times \frac{N(D^+ \to K^0_s\pi^+)}{N(D^- \to K^0_s\pi^-)}$$

  – $A_{k\pi}$ is found to be at ~1% with 0.2% precision and independent of decay time

Charge asymmetry in Kπ detection

- In the WS/RS ratio separ

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  – D* production and sof cancel out in the ratio

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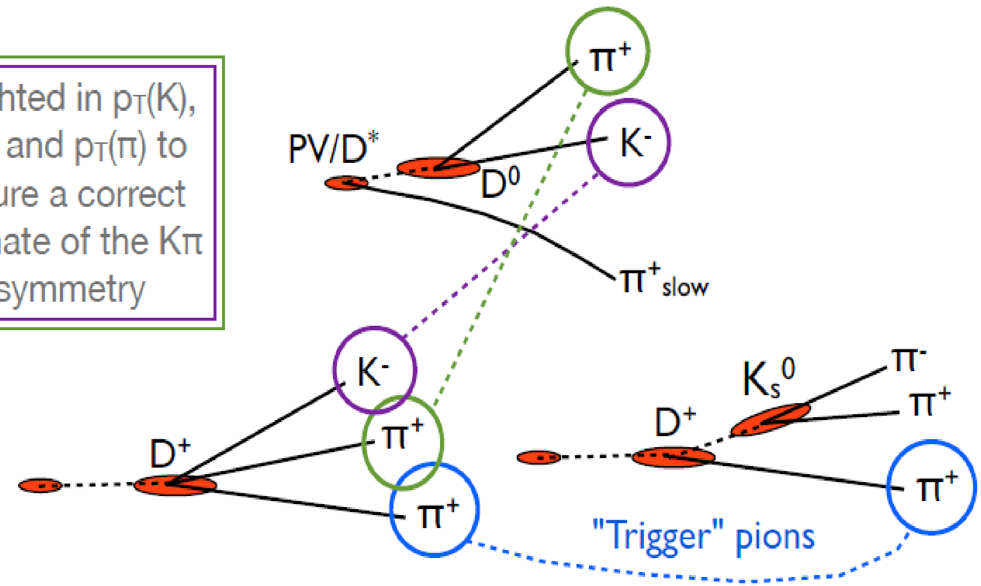
weighted in $p_T(K)$, $\eta(K)$ and $p_T(\pi)$ to ensure a correct estimate of the Kπ asymmetry



- Still needed to consider: $A_{K\pi}$:

$$A_{K\pi} = \frac{\epsilon(K^+\pi^-) - \epsilon(K^-\pi}{\epsilon(K^+\pi^-) + \epsilon(K^-\pi}$$

  – The efficiency ratio ε_r obtained from dedicat

2

weighted in $p_T(\pi_{trig})$, $p_T(D^+)$ and $\eta(D^+)$ to match the (now reweighted) $D^+ \to K^-\pi^+\pi^+$ sample, in order properly cancel any production asymmetry and any instrumental asymmetry associated with the trigger pion

$$\frac{\epsilon(K^+\pi^-)}{\epsilon(K^-\pi^+)} = \frac{N(D^- \to K^+\pi^-\pi^-)}{N(D^+ \to K^-\pi^+\pi^+)} \times \frac{N(D^+ \to K^0_s\pi^+)}{N(D^- \to K^0_s\pi^-)}$$

  – $A_{K\pi}$ is found to be at ~1% with 0.2% precision and independent of decay time

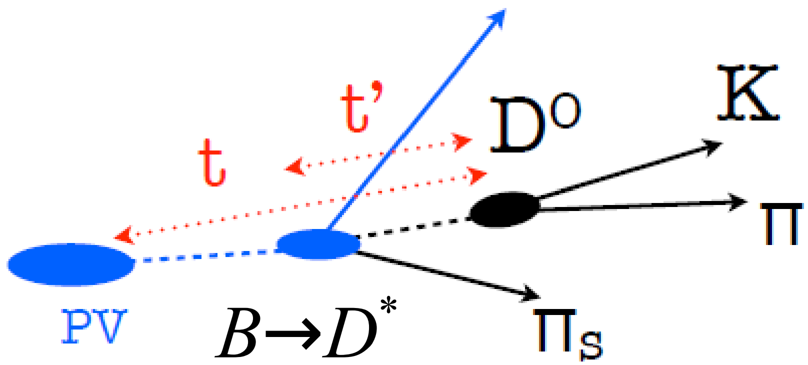
Background from secondary D decays

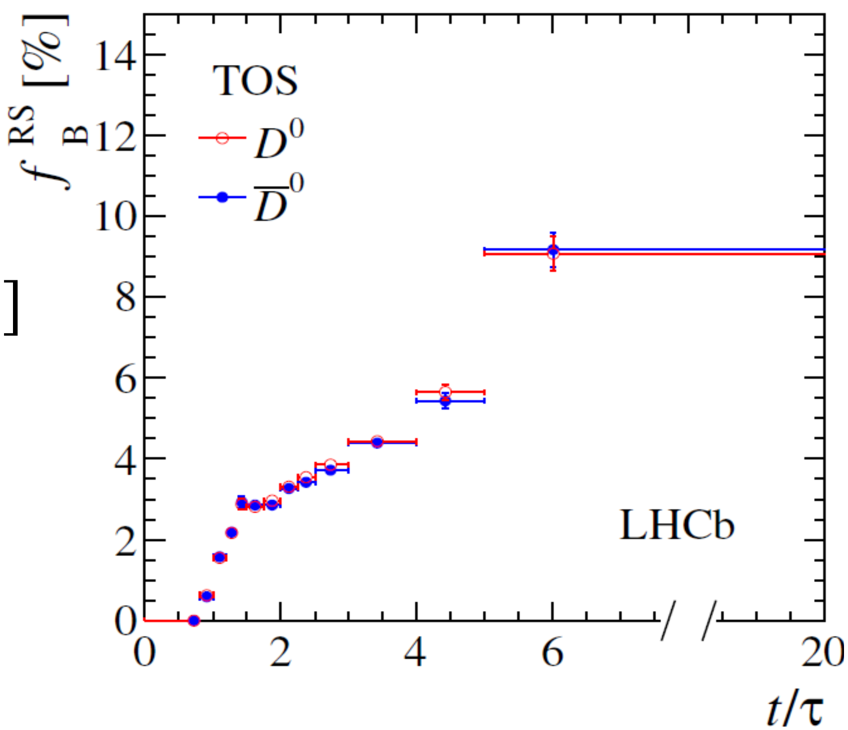
- D^0-s from B decays are assigned with wrong decay-time
- Suppressed with requirement on χ^2(IP)
- The fraction of this secondary component $f_B^{RS}(t)$ can induce bias $\Delta_B(t)$ in time-dependent WS/RS ratio. The bias is bounded by:

$$0 \leq \Delta_B(t) \leq f_B^{RS}(t)[1 - R_D / R(t)],$$

with observed ratio $R^m(t) = R(t)[1 - \Delta_B(t)]$

- Due to small level of contamination, we can simply assume the maximum bias
- No charge asymmetry observed, contamination assumed to be symmetric in the fit





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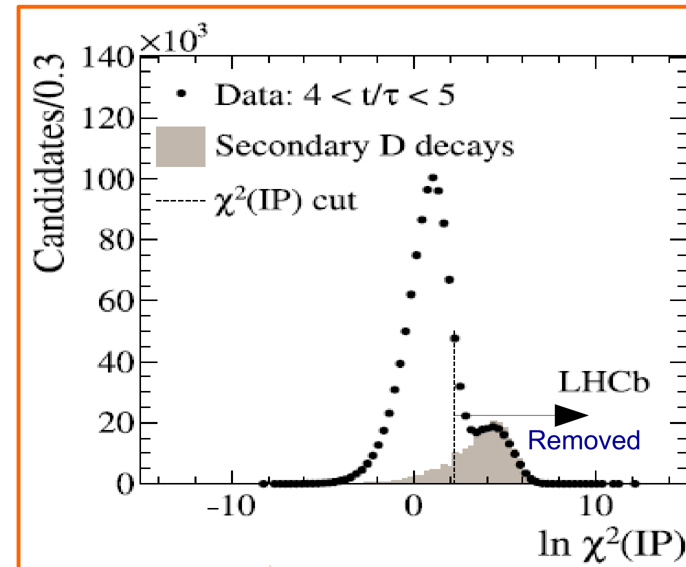
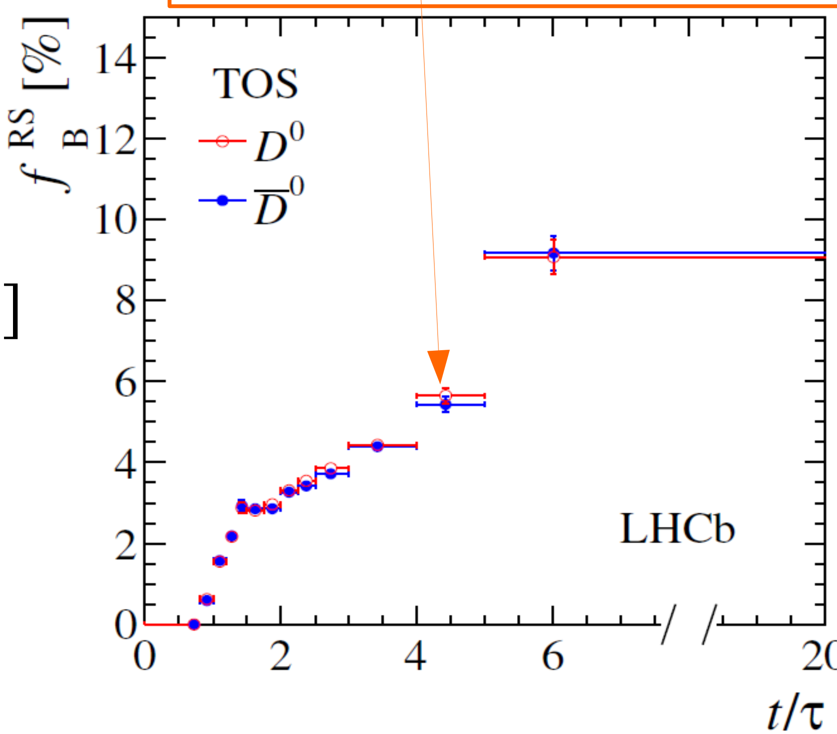
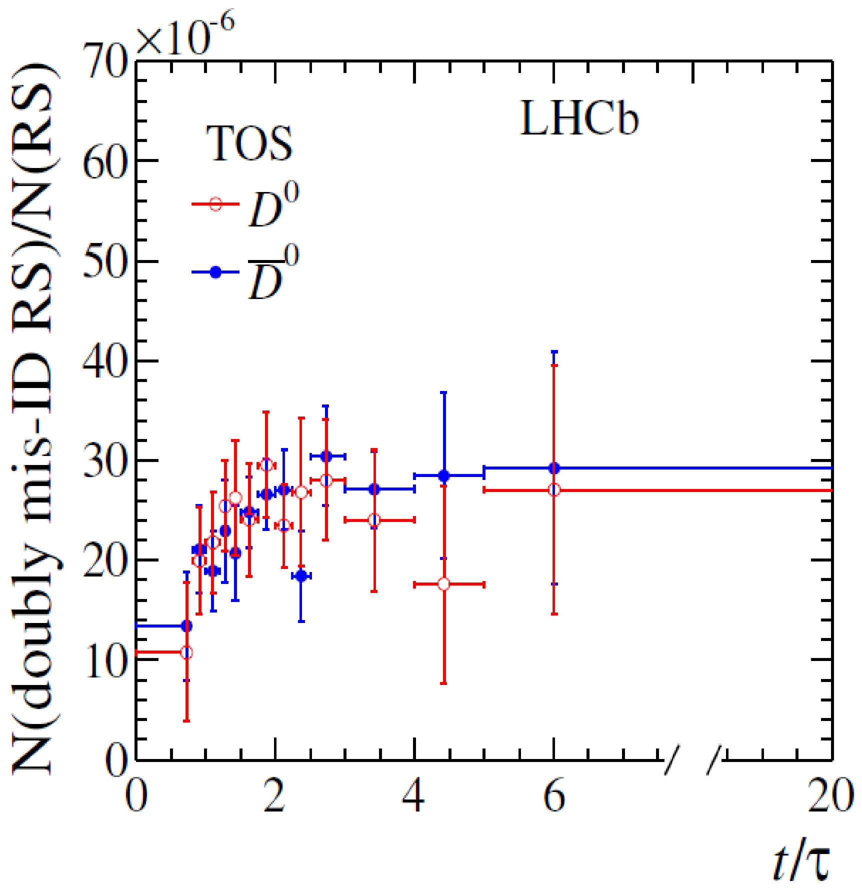




Peaking background

- RS events with both K and π being mis-IDed as each other will be indistinguishable with real WS signals in $m(D_0\pi_s)$ fits, and cause bias in the WS/RS ratio
- The overall effect is well below 1% of WS signals due to tight requirements on PID and M(Kπ) window
- No charge asymmetry observed, contamination assumed to be symmetric in the fit

$$R^m(t) = R(t) + \frac{N^{RS}(\text{double mis-ID})}{N^{RS}}$$



Time-dependent fit configuration

- The mixing parameters are determined by minimizing:

Predicted ratios corrected for the peaking and secondary backgrounds

$$\chi^2 = \sum_i \left[\left(\frac{r_i^+ - \epsilon_r^+ R_{i,\,\mathrm{pred}}^+}{\sigma_i^+} \right)^2 + \left(\frac{r_i^- - \epsilon_r^- R_{i,\,\mathrm{pred}}^-}{\sigma_i^-} \right)^2 \right] + \chi_\epsilon^2 + \chi_B^2 + \chi_p^2$$

Sum over 13 time bins for separately for 2011 and 2012 data, and for TOS and TOS samples

$$\chi_\epsilon^2 = \left(\frac{a_{K\pi} - A_{K\pi}}{\sigma_{A_{K\pi}}} \right)^2$$

Constraint for detection asymmetry

$$\chi_p^2 = \sum_j \left(\frac{p_j - P_j}{\sigma_{P_j}} \right)^2$$

Constraint for peaking background:
Mainly candidates with K,π from D^0 both being mis-IDed, suppresed by tight PID requirements

$$\chi_B^2 = \sum_l \left(\frac{b_l - B_l}{\sigma_{B_l}} \right)^2$$

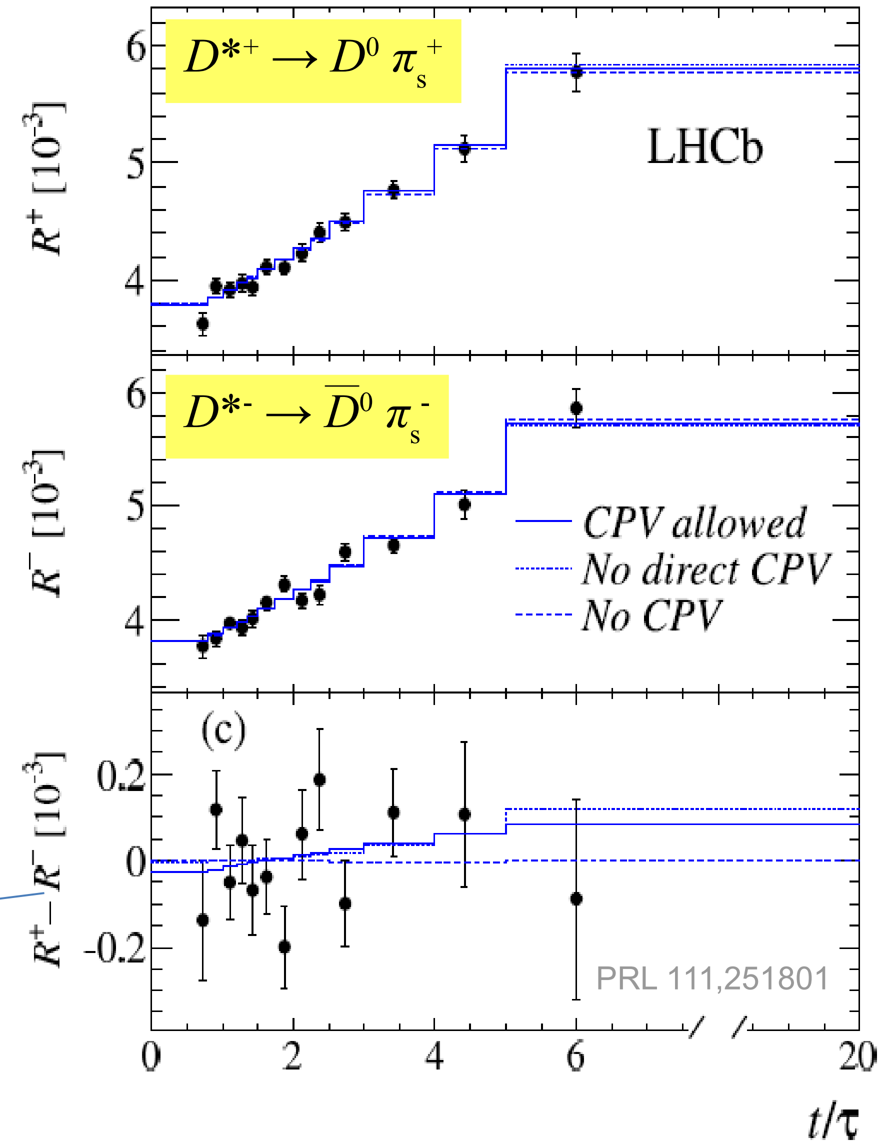
Constraint for secondary background

Systematic effects are accounted for in the final fits

WS/RS yield ratio fits

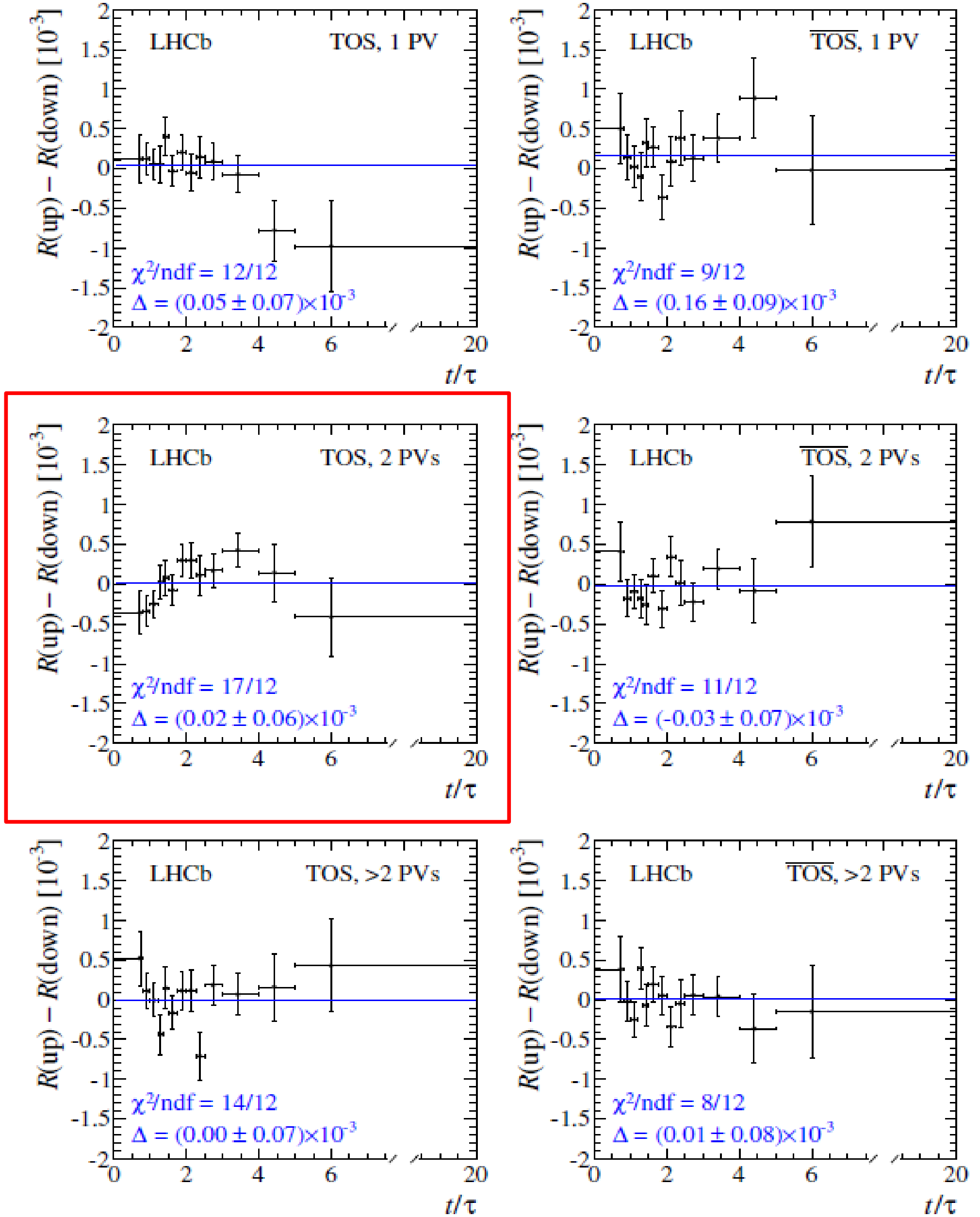
- Fits to the $3fb^{-1}$ data for 3 different hypotheses on the CP symmetry

Efficiency corrected differences between the WS/RS ratios of $D^{*\pm}$

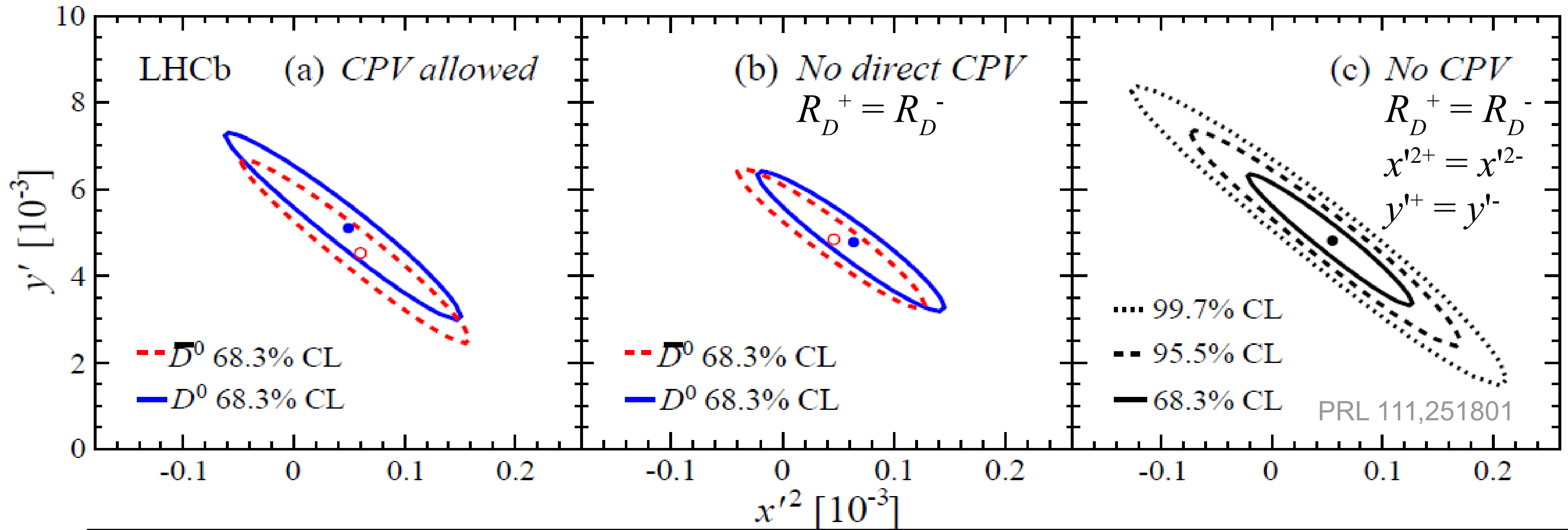


Systematics

- Data are divided into independent subsets to check for difference in time-dependence of WS-to-RS ratios
  - The χ^2 values in the $\overline{\text{TOS}}$ sample, suggest a systematically better consistency than those in the TOS sample
  - The statistical uncertainty of each of the WS-to-RS ratios in the TOS samples is increased by a factor of $\sqrt{17/12}$



LHCb results



LHCb

Uncertainties are statistical and systematic combined

Direct and indirect CP violation			no direct CP violation			no CP violation		
R_D	$[10^{-3}]$	3.568 ± 0.066	R_D	$[10^{-3}]$	3.568 ± 0.066	R_D	$[10^{-3}]$	3.568 ± 0.066
A_D	$[10^{-2}]$	-0.7 ± 1.9	y'^+	$[10^{-3}]$	4.78 ± 1.07	y'	$[10^{-3}]$	4.81 ± 1.00
y'^+	$[10^{-3}]$	5.1 ± 1.4	x'^{2+}	$[10^{-5}]$	6.4 ± 5.5	x'^2	$[10^{-5}]$	5.5 ± 4.9
x'^{2+}	$[10^{-5}]$	4.9 ± 7.0	y'^-	$[10^{-3}]$	4.83 ± 1.07	χ^2/ndf		$86.41/101$
y'^-	$[10^{-3}]$	4.5 ± 1.4	x'^{2-}	$[10^{-5}]$	4.6 ± 5.5			
x'^{2-}	$[10^{-5}]$	6.0 ± 6.8	χ^2/ndf		$85.99/99$			
χ^2/ndf		$85.87/98$						

$$A_D = \frac{R_D^+ - R_D^-}{R_D^+ + R_D^-}$$

Results are consistent with *CP* conservation

From Phys.Rev.Lett. 111 (2013) 251801

Table 1: Results of fits to the data for different hypotheses on the *CP* symmetry. The reported uncertainties are statistical and systematic, respectively.

Direct and indirect *CP* violation		
R_D^+	$[10^{-3}]$	$3.545 \pm 0.082 \pm 0.048$
y'^+	$[10^{-3}]$	$5.1 \pm 1.2 \pm 0.7$
x'^{2+}	$[10^{-5}]$	$4.9 \pm 6.0 \pm 3.6$
R_D^-	$[10^{-3}]$	$3.591 \pm 0.081 \pm 0.048$
y'^-	$[10^{-3}]$	$4.5 \pm 1.2 \pm 0.7$
x'^{2-}	$[10^{-5}]$	$6.0 \pm 5.8 \pm 3.6$
χ^2/ndf		85.9/98
No direct *CP* violation		
R_D	$[10^{-3}]$	$3.568 \pm 0.058 \pm 0.033$
y'^+	$[10^{-3}]$	$4.8 \pm 0.9 \pm 0.6$
x'^{2+}	$[10^{-5}]$	$6.4 \pm 4.7 \pm 3.0$
y'^-	$[10^{-3}]$	$4.8 \pm 0.9 \pm 0.6$
x'^{2-}	$[10^{-5}]$	$4.6 \pm 4.6 \pm 3.0$
χ^2/ndf		86.0/99
No *CP* violation		
R_D	$[10^{-3}]$	$3.568 \pm 0.058 \pm 0.033$
y'	$[10^{-3}]$	$4.8 \pm 0.8 \pm 0.5$
x'^2	$[10^{-5}]$	$5.5 \pm 4.2 \pm 2.6$
χ^2/ndf		86.4/101

From Phys.Rev.Lett. 111 (2013) 251801

Table 2: Detailed fit results. Reported uncertainties and correlation coefficients include both statistical and systematic sources.

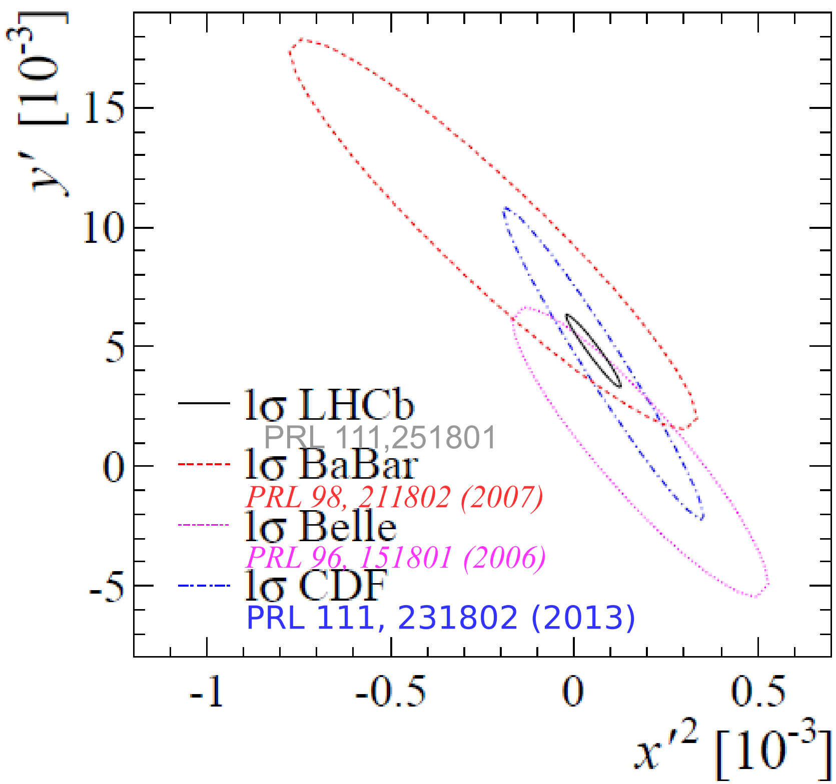
Direct and indirect CP violation							
Results		Correlations					
Parameter	Fit value	R_D^+	y'^+	x'^{2+}	R_D^-	y'^-	x'^{2-}
R_D^+ $[10^{-3}]$	3.545 ± 0.095	1.000	−0.942	0.862	−0.016	−0.007	0.006
y'^+ $[10^{-3}]$	5.1 ± 1.4		1.000	−0.968	−0.007	0.007	−0.007
x'^{2+} $[10^{-5}]$	4.9 ± 7.0			1.000	0.005	−0.007	0.008
R_D^- $[10^{-3}]$	3.591 ± 0.094				1.000	−0.941	0.858
y'^- $[10^{-3}]$	4.5 ± 1.4					1.000	−0.966
x'^{2-} $[10^{-5}]$	6.0 ± 7.0						1.000

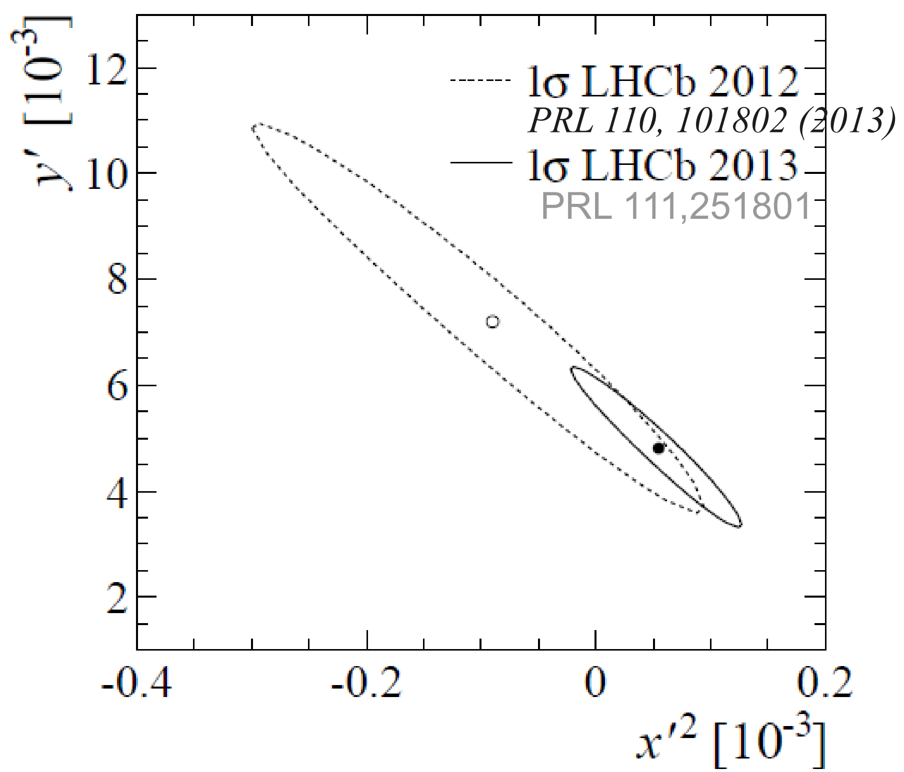
No direct CP violation						
Results		Correlations				
Parameter	Fit value	R_D	y'^+	x'^{2+}	y'^-	x'^{2-}
R_D $[10^{-3}]$	3.568 ± 0.066	1.000	−0.894	0.770	−0.895	0.772
y'^+ $[10^{-3}]$	4.8 ± 1.1		1.000	−0.949	0.765	−0.662
x'^{2+} $[10^{-5}]$	6.4 ± 5.5			1.000	−0.662	0.574
y'^- $[10^{-3}]$	4.8 ± 1.1				1.000	−0.950
x'^{2-} $[10^{-5}]$	4.6 ± 5.5					1.000

No CP violation				
Results		Correlations		
Parameter	Fit value	R_D	y'	x'^2
R_D $[10^{-3}]$	3.568 ± 0.066	1.000	−0.953	0.869
y' $[10^{-3}]$	4.8 ± 1.0		1.000	−0.967
x'^2 $[10^{-5}]$	5.5 ± 4.9			1.000

Comparison of mixing results

- The current LHCb results are consistent with other results, and provide an update to the previous ones with $1fb^{-1}$ 2011 data





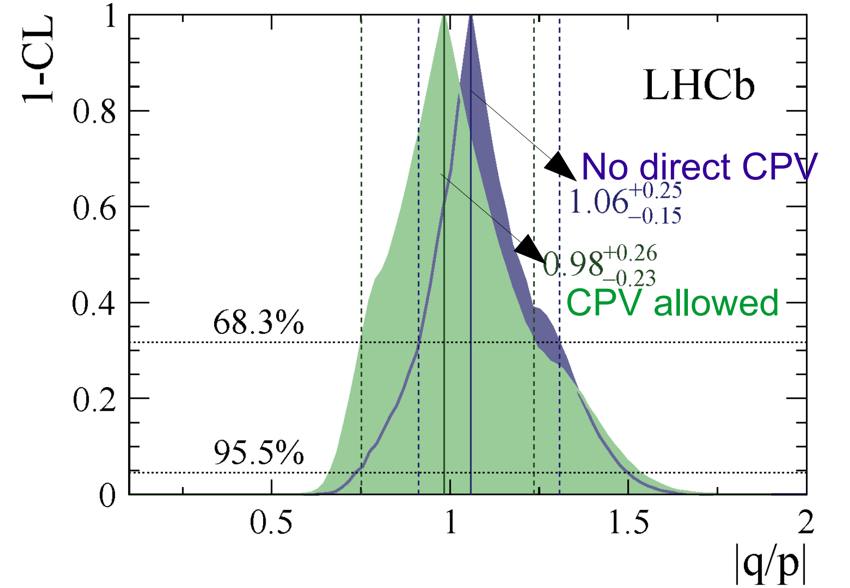
Interpretation of the LHCb results

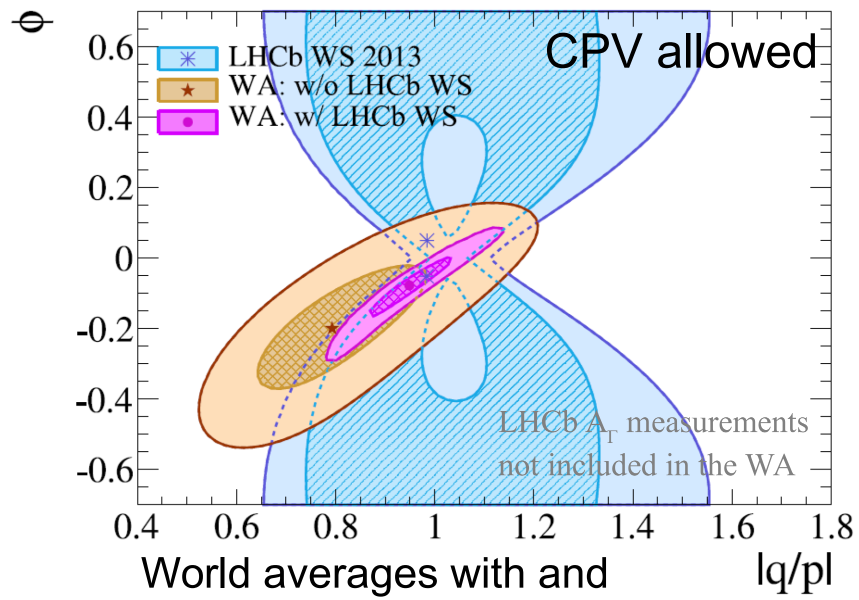
- Using only the LHCb results, and with the constraints of:

$$x'^{\pm} = (|q/p|)^{\pm 1}\,(x'\cos\phi \pm y'\sin\phi)$$
$$y'^{\pm} = (|q/p|)^{\pm 1}\,(y'\cos\phi \mp x'\sin\phi)$$

$$\phi = \arg\left(\frac{q}{p}\right)$$

- The 68.3% C.L. constraints
  - $0.75 < |q/p| < 1.24$ for all CPV allowed
  - $0.91 < |q/p| < 1.31$ for the case without direct CPV
- The LHCb results contribute in the global fits for $D^0 - \overline{D}^0$ mixing

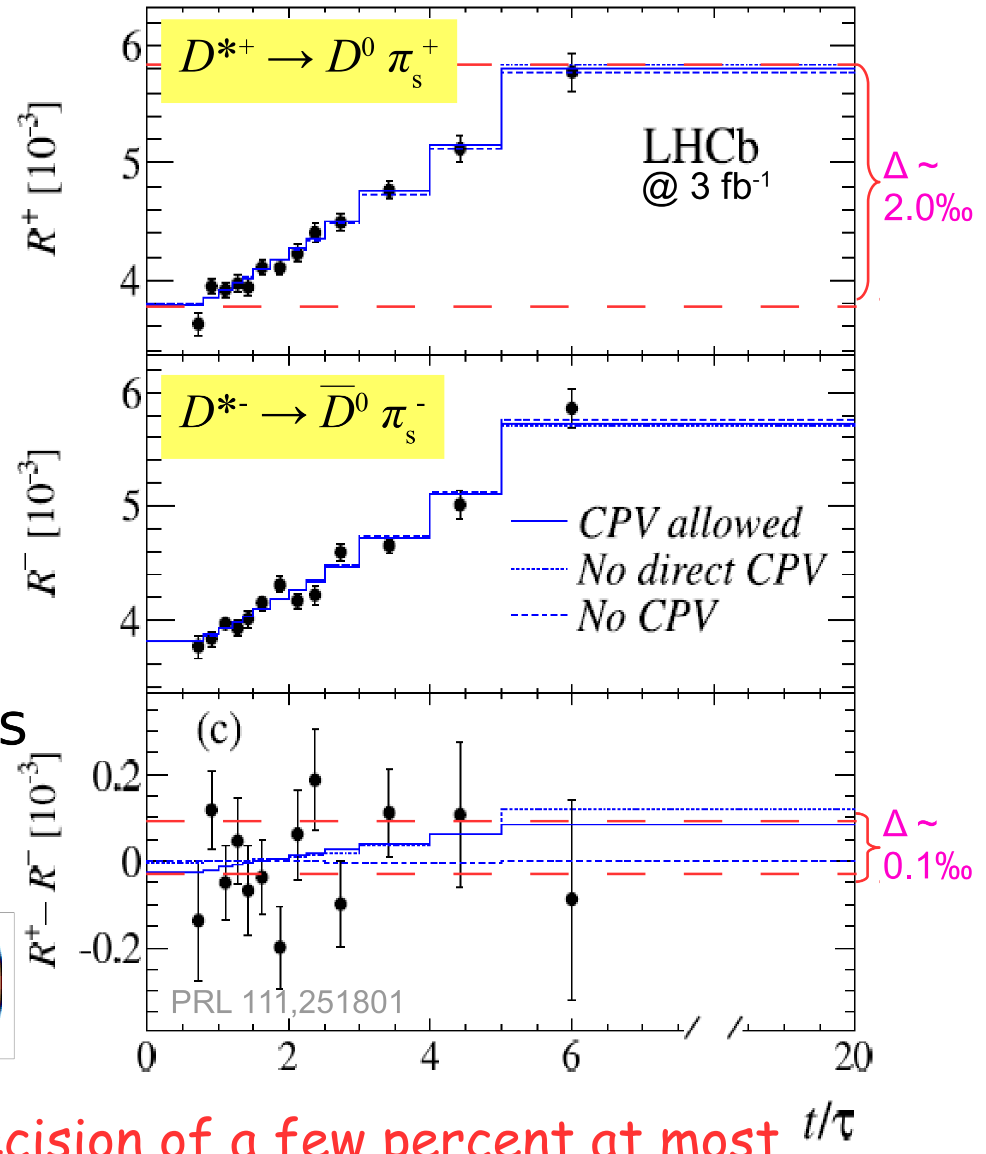




World averages with and without the LHCb results

WS/RS ratio versus D^0 decay time

- In the case of no DCPV, and x', y' ,φ being very close to 0
  - The slope of the ratios and differences in the ratios are proportional to y', and (|q/p|-|p/q|) y', respectively
  - Within six decay-times:
    - The ratios vary within ~2x10^{-3}
    - The differences of the ratios vary within ~0.1x10^{-3}



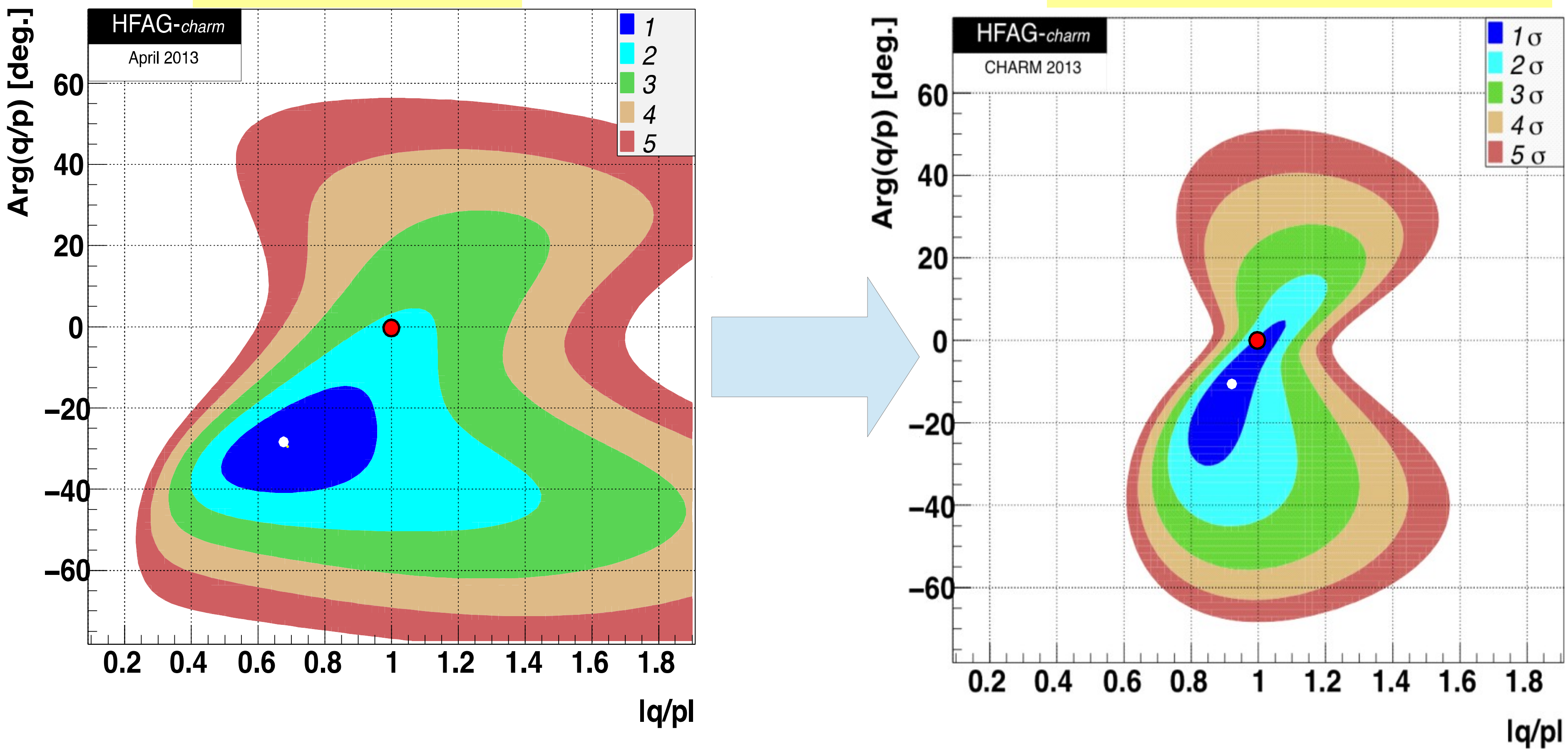
In the limit of ||q/p|-1| << 0: $\phi = \tan^{-1}\left(\frac{1-|q/p|^2}{1+|q/p|^2}\frac{x}{y}\right)$

A. L. Kagan, M. D. Sokoloff, PRD 80, 076008 (2009)

|q/p| can be constrained with the precision of a few percent at most

Global Fit for D^0 - $\overline{D}^0$ Mixing (allowing for CP violation)

April, 2013 | September, 2013



Much improved constraints on |q/p| and φ after the inclusion of the most recent LHCb D mixing/CPV results and CDF D mixing results, as well as the LHCb A_Γ results (*PRL 112 (2014) 041801*)

Summary

- The WS mixing and CPV results from hadron colliders are presented with unprecedented level of precision
- We now have the observation of D^0-$\overline{D}^0$ oscillations from one single experiment
- Neither direct CPV or CPV in mixing is observed, being consistent with SM
- The LHCb CPV results are capable of playing an important role in constraining $|q/p|$

Thanks!