Review of Tevatron results on charm mixing and CP violation

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Charm 2013, 1 September 2013

Measurement of ΔA_{CP} between $D^0 \rightarrow KK$ and $D^0 \rightarrow \pi\pi$ (9.7 fb^{-1})

Phys. Rev. Lett. 109, 111801 (2012)

CDF - CP Violation in Charm

- Previous results
  - CDF 2011: use displaced track triggers to obtain huge data samples PRD85, 012009 (2012)

$$A_{CP}\left(D^0 \to K^+K^-\right) = (-0.24 \pm 0.22 \pm 0.10)\,\%$$

$$A_{CP}\left(D^0 \to \pi^+\pi^-\right) = (+0.22 \pm 0.24 \pm 0.11)\,\%$$

  - LHCb 2012: 3.5σ deviation from SM PRL 108, 111602 (2012)

$$\Delta A_{CP} = A_{CP}(D^0 \to K^+K^-) - A_{CP}(D^0 \to \pi^+\pi^-)$$

maximally sensitive to NP.

Experimentally convenient:

instrumental asymmetries cancel.

$$\Delta A_{CP} = (-0.82 \pm 0.21 \pm 0.11)\,\%$$

ΔA_{CP} in $D^0 \to K^+K^-$ and $D^0 \to \pi^+\pi^-$

Phys. Rev. Lett. 109, 111801 (2012)

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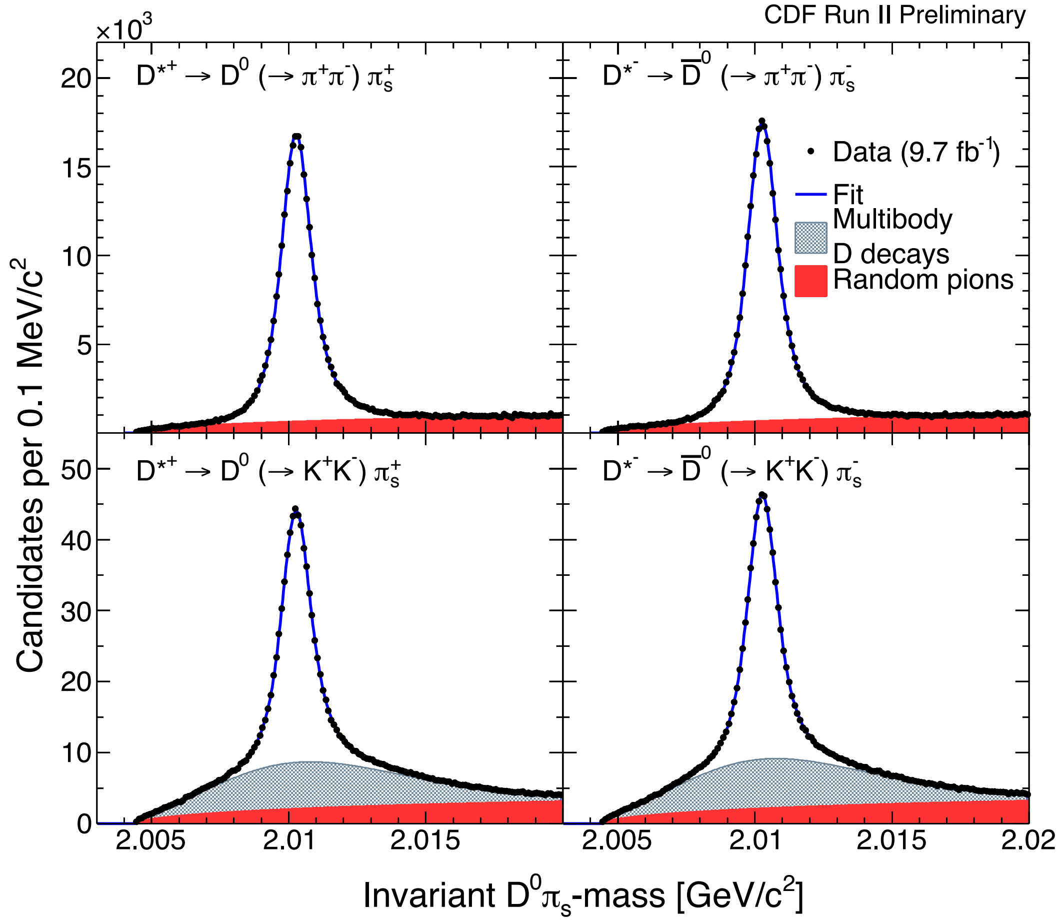
$$\Delta A_{CP} = A^*_{raw}(K^+K^-) - A^*_{raw}(\pi^+\pi^-)$$

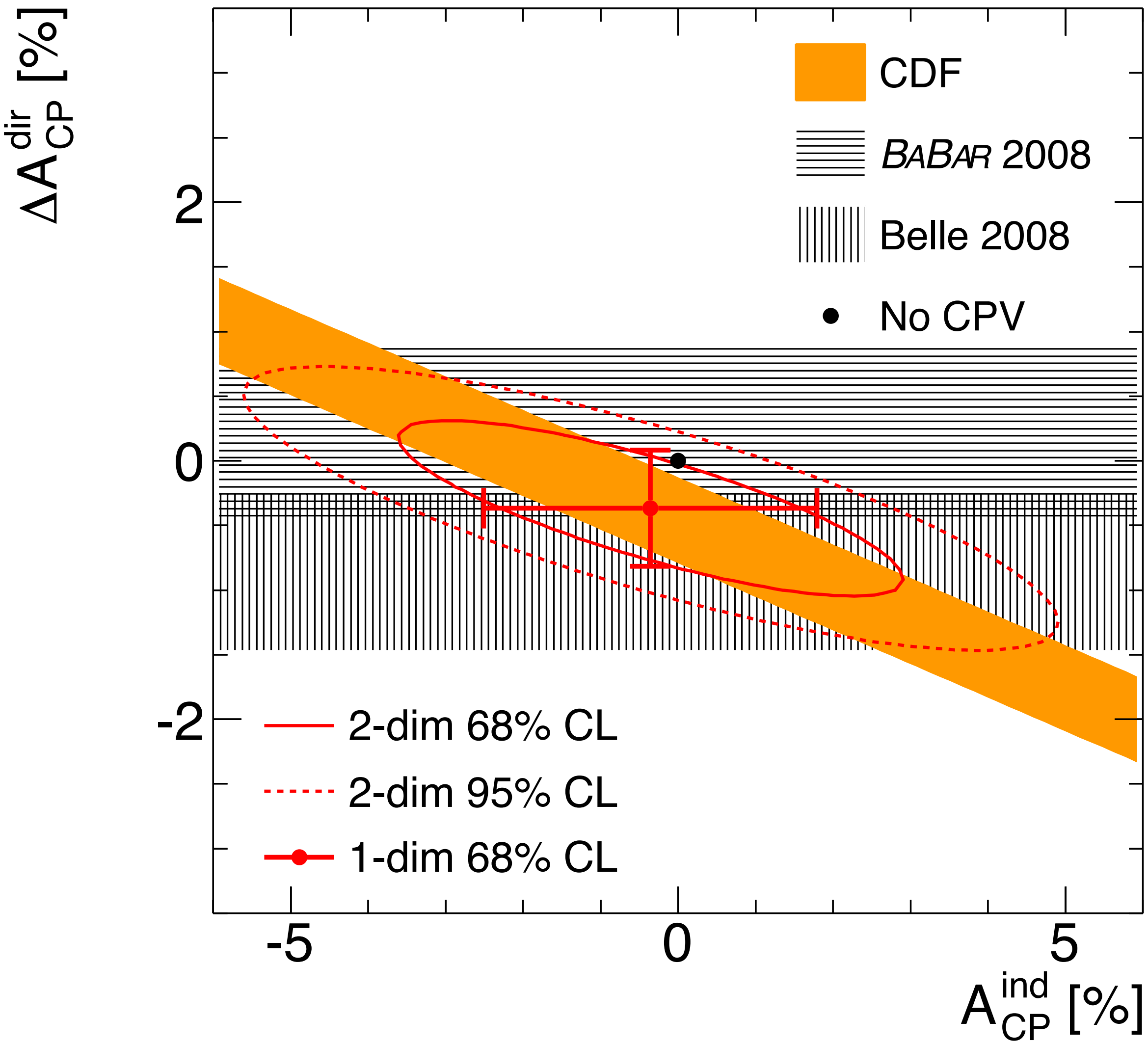
- Optimised data selection for ΔA_{CP} doubling the signal
- loosened selection (removing IP requirement)
- Use $D^{*+} \to D^0 \pi^+$ and c.c. decays, where the charge of the π tags the D^0 production flavour.

$$A^*_{raw}(\pi\pi) - A^*_{raw}(K\pi) + A_{raw}(K\pi)$$
$$-[A^*_{raw}(KK) - A^*_{raw}(K\pi) + A_{raw}(K\pi)]$$



- Cross check with data binned in different η, phi regions

ΔA_{CP} Measurement

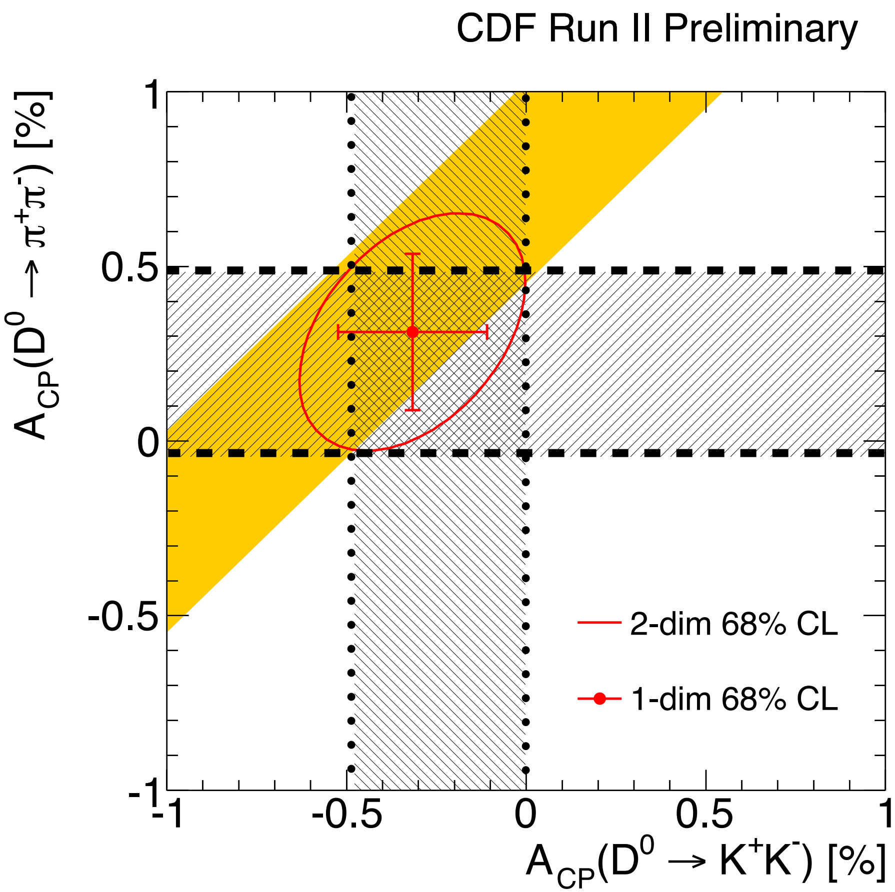


$$\Delta A_{CP} = (-0.62 \pm 0.21 \pm 0.10)\%$$

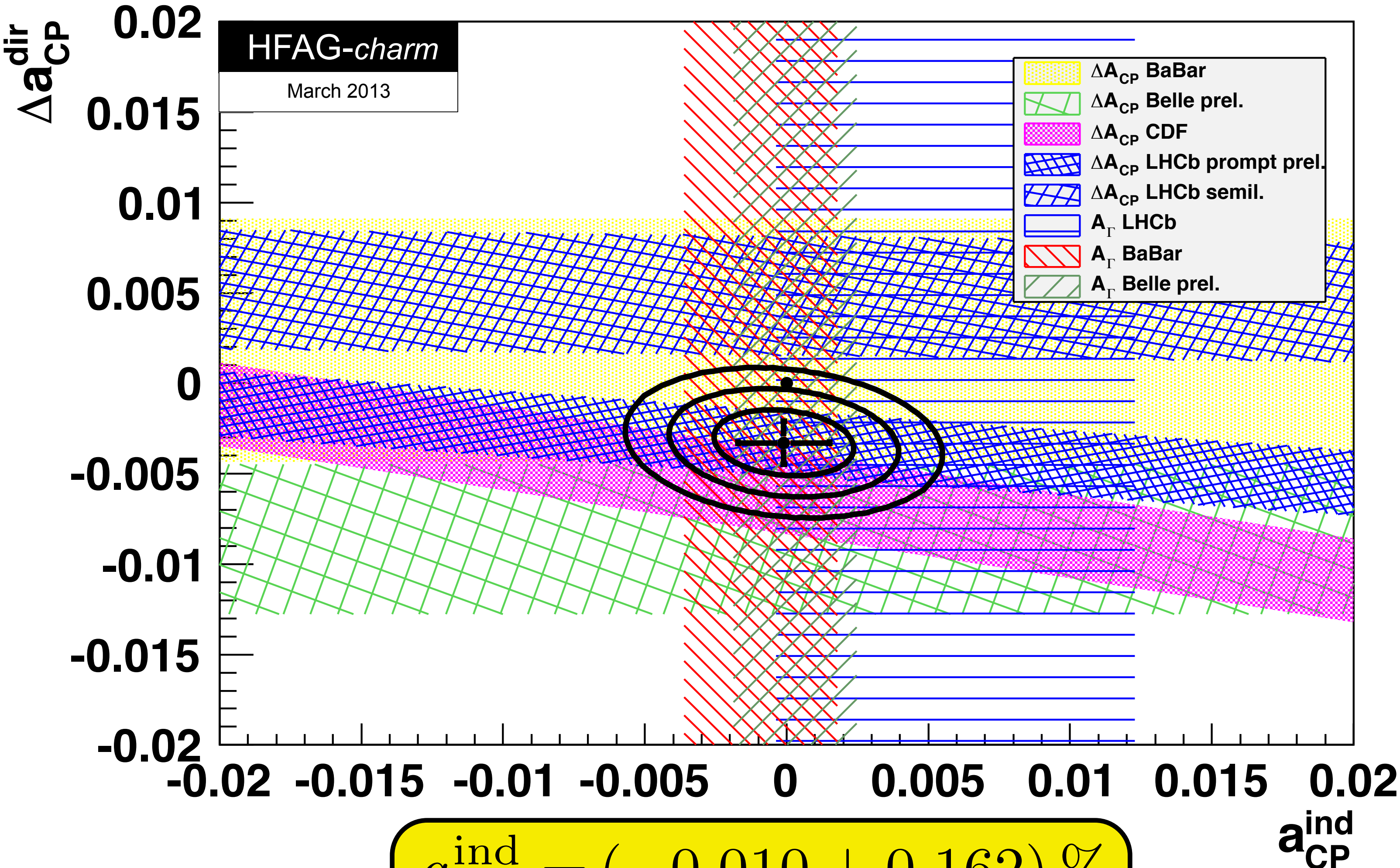
Combine Two Measurements

$$A_{CP}\left(D^0 \to \pi^+\pi^-\right) = (+0.31 \pm 0.22)\,\%$$
$$A_{CP}\left(D^0 \to K^+K^-\right) = (-0.32 \pm 0.21)\,\%$$

- Can combine the ΔA_{CP} result with the $A_{CP}(\pi\pi)$ and $A_{CP}(KK)$ result
  - remove events from the ΔA_{CP} analysis that were used in the other analysis, to create a independent sample
  - roughly 15% improvement on uncertainty from the earlier ACP($\pi\pi$) and ACP(KK) result



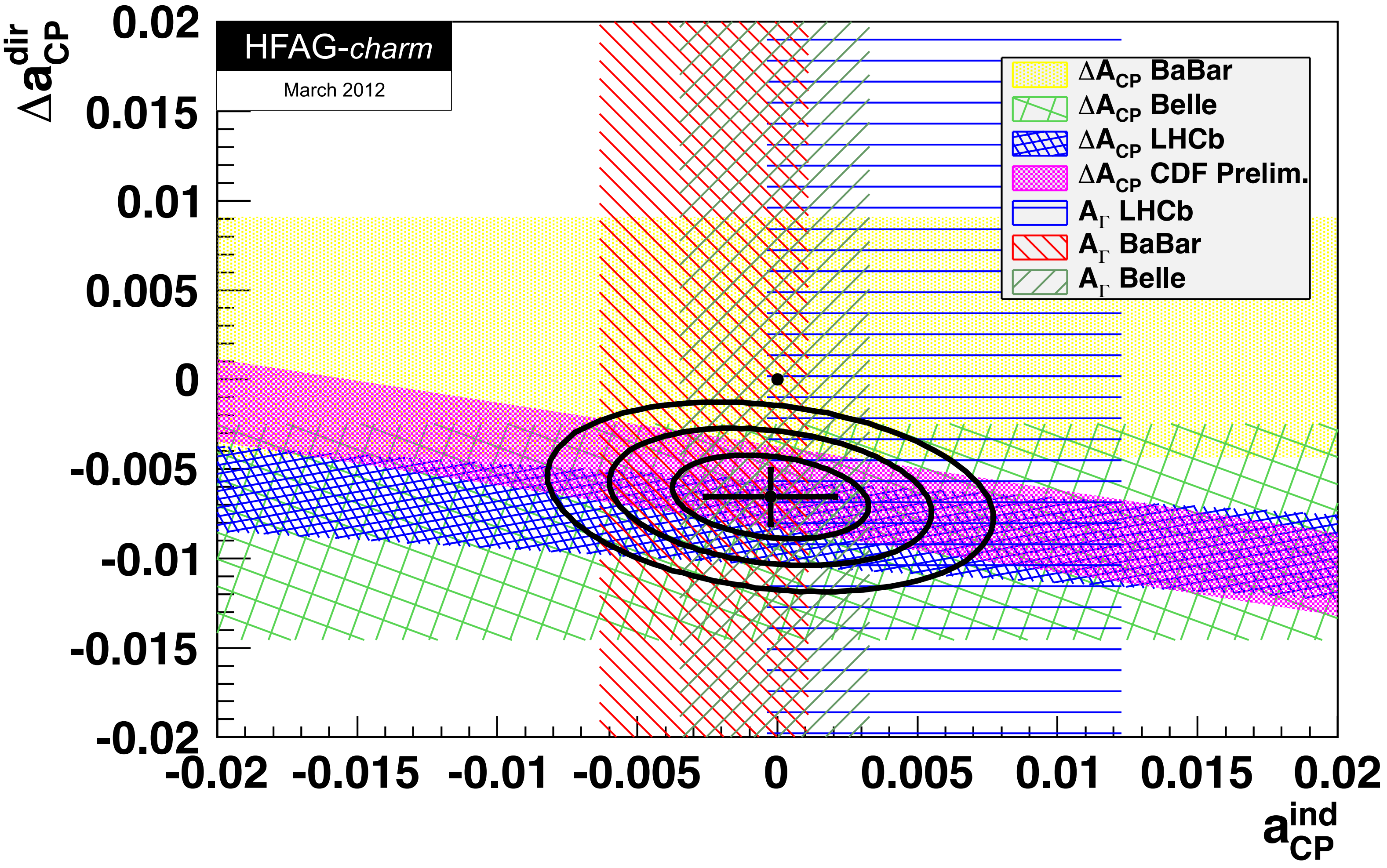
HFAG Average



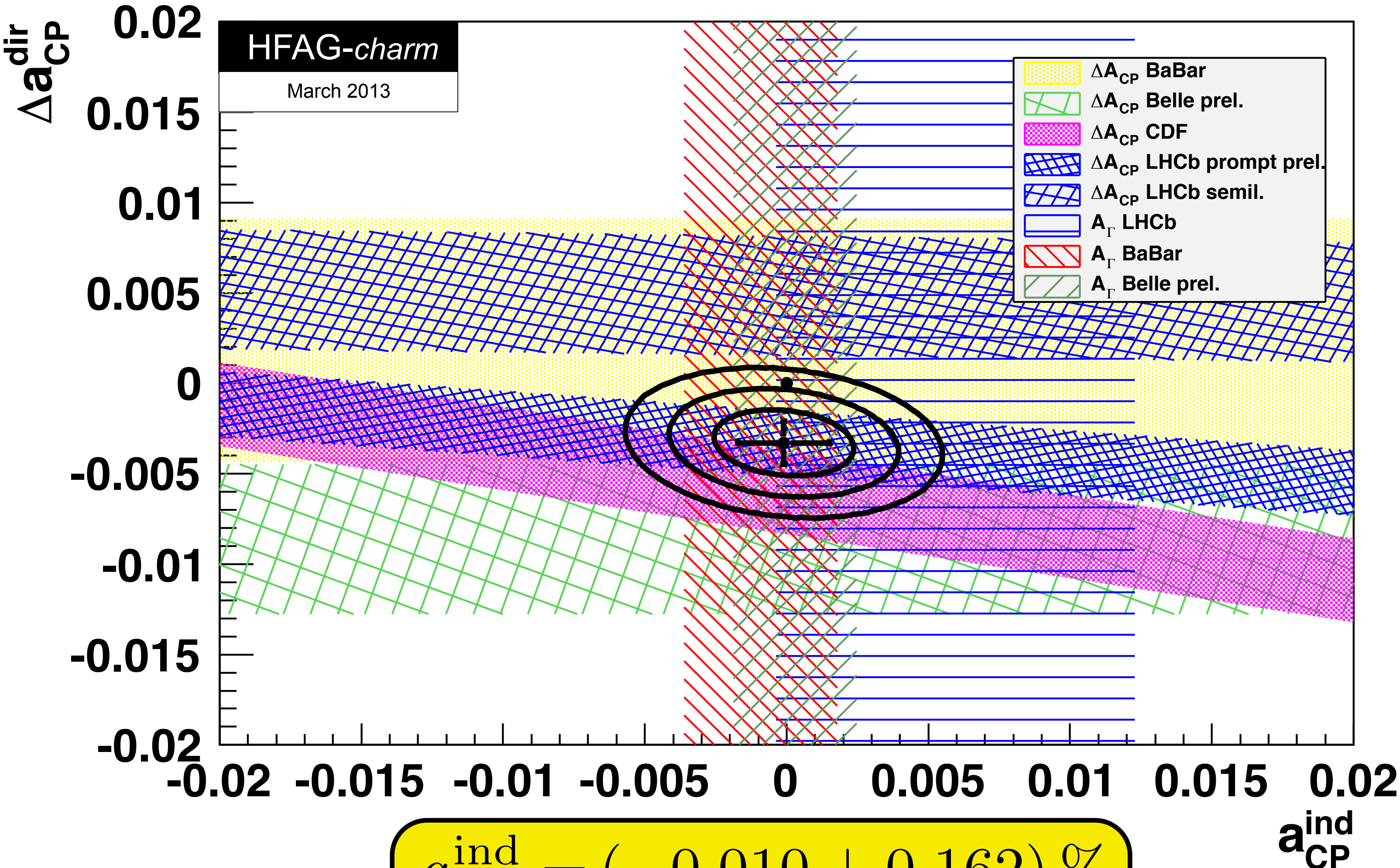
$$a_{CP}^{ind} = (-0.010 \pm 0.162)\,\%$$

$$A_{CP}^{dir} = (-0.329 \pm 0.121)\,\%$$

HFAG Average



HFAG Average



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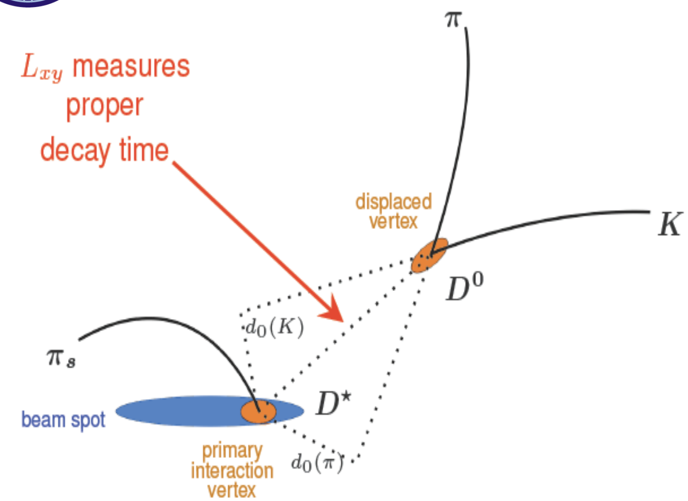
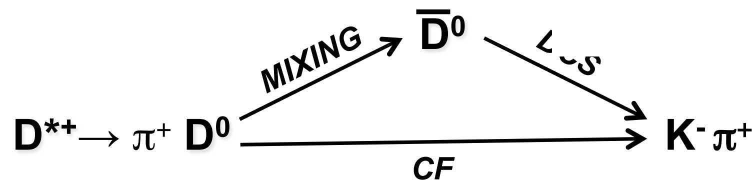
$D^0 \rightarrow K\pi$ Mixing (9.7 fb^{-1})

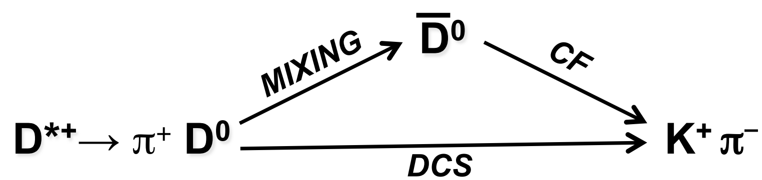
CDF Public Note 10990

D^0 Mixing





Right-sign (RS) decay (π with the same charge)



Wrong-sign (WS) decay (π with opposite charge)

- Measure the ratio R(t) of WS $D^{*+} \rightarrow D^0 \pi_s^+ \rightarrow K^+\pi^-\pi_s^+$ to RS $D^{*+} \rightarrow D^0 \pi_s^+ \rightarrow K^-\pi^+\pi_s^+$ decay rates can be approximated (assuming |x|,|y|<<1 and no CPV) by:

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

Mixing Rate

DCS to CF Ratio

$$x = \frac{m_1 - m_2}{\Gamma_D} = 2\frac{m_1 - m_2}{\Gamma_1 + \Gamma_2}$$

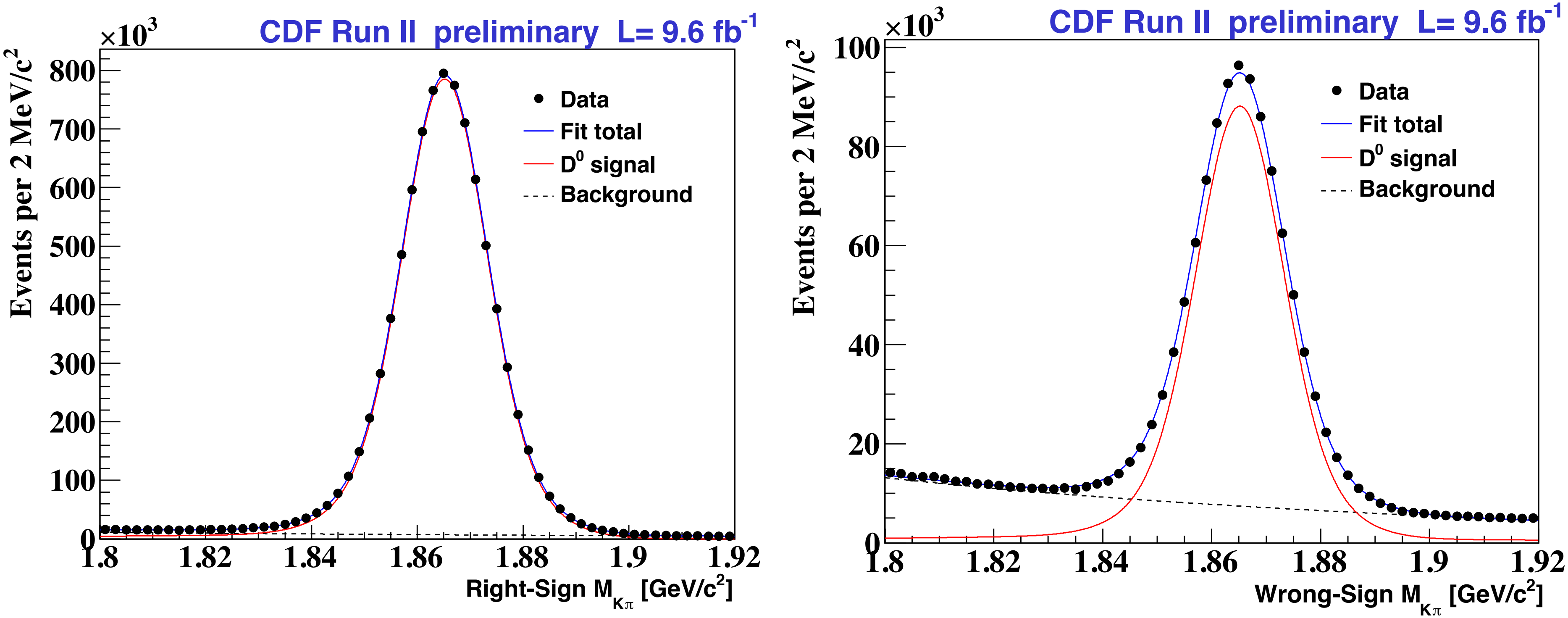
$$y = \frac{\Gamma_1 - \Gamma_2}{2\Gamma_D} = \frac{\Gamma_1 - \Gamma_2}{\Gamma_1 + \Gamma_2}$$

$$x' = x\cos\delta_{K\pi} + y\sin\delta_{K\pi}$$

$$y' = y\cos\delta_{K\pi} - x\sin\delta_{K\pi}$$

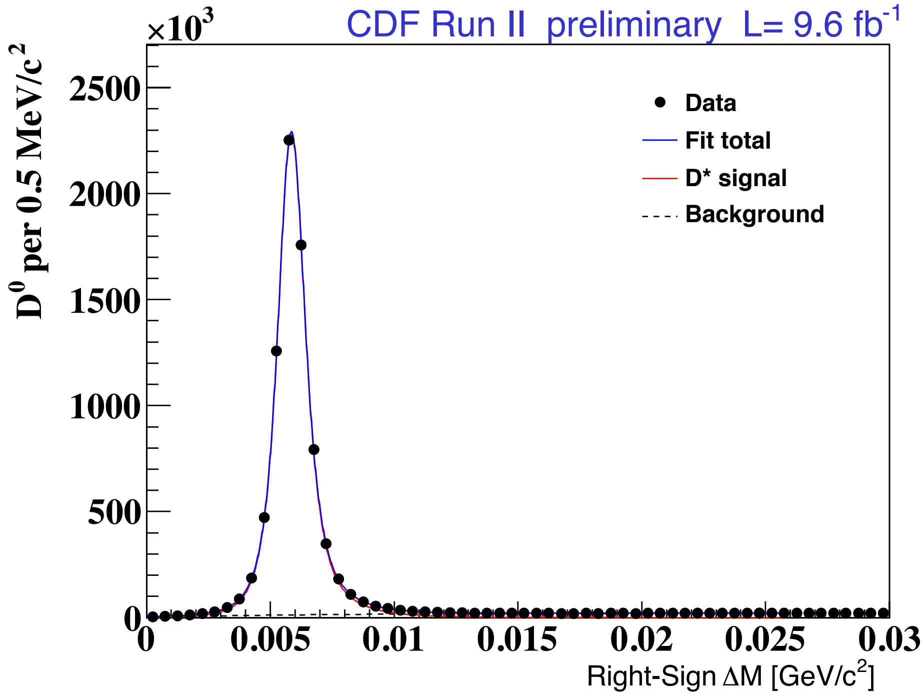
$\delta_{K\pi}$: strong phase difference between CF and DCS amplitudes

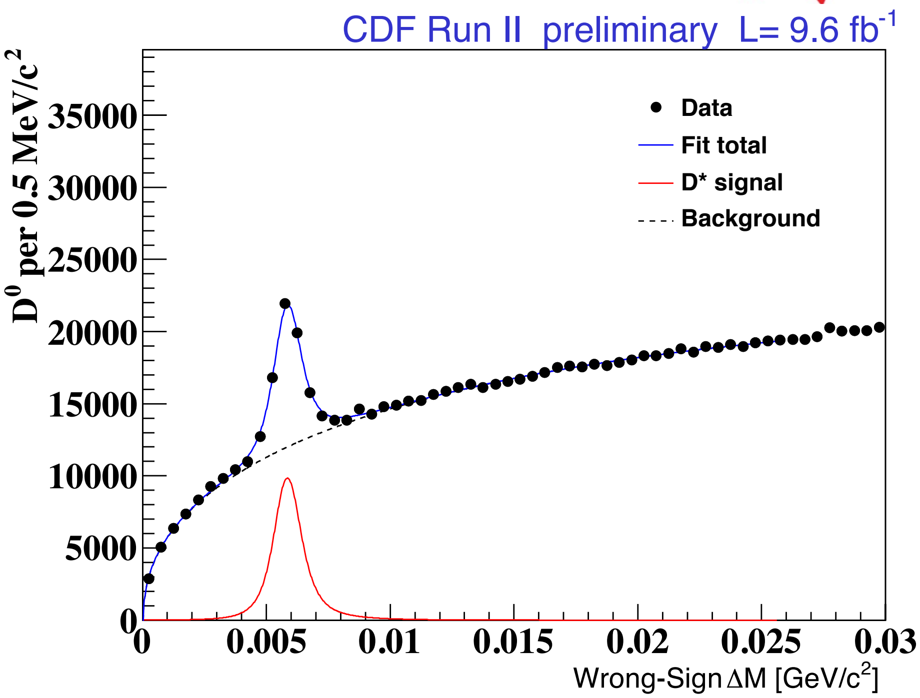
D0 → $K^{\mp}\pi^{\pm}$ Signal



- The signal shape is modeled by double-Gaussian with low-mass tail, background by an exponential.
- For WS, misidentified RS background is included.
- Signal shape parameters are fixed in each bin to RS time-integrated values.

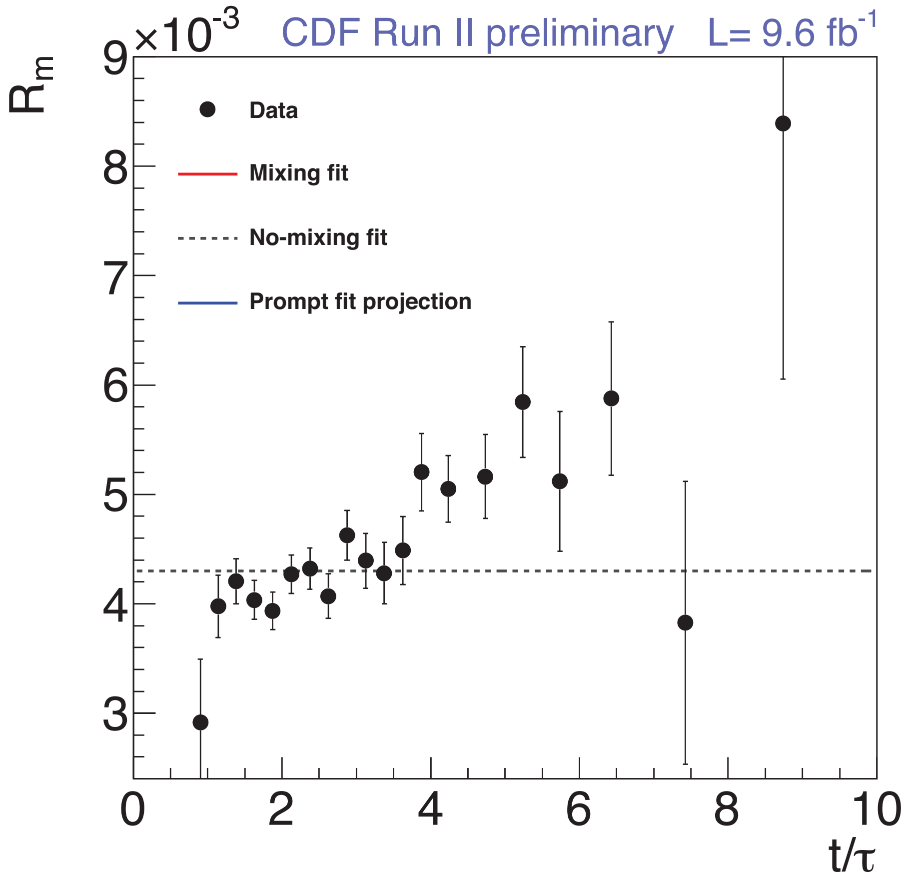
D^* Signal





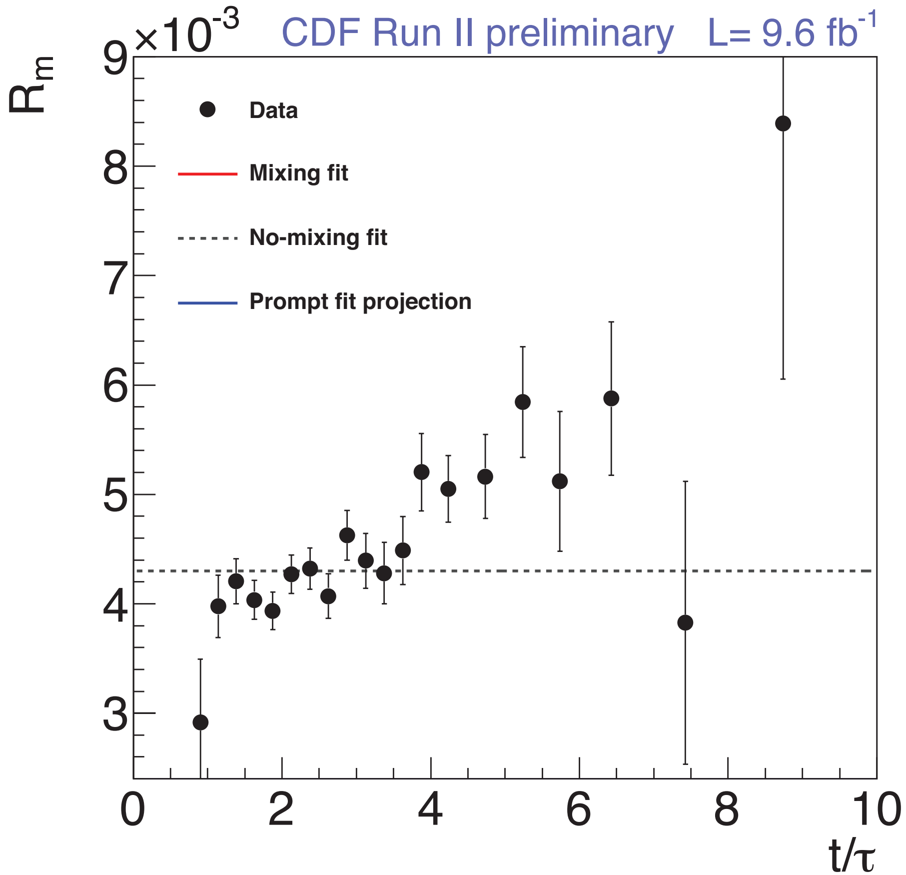
- The D* signal for each time bin is found with a χ^2 fit of the D^0 signal yield versus Δm.
- The signal shape is modeled by double-Gaussian and an asymmetric tail function.
- Background is modeled by an empirical shape form extracted from data by forming a random combination of a D0 from each event combined with πs
- WS signal shape is fixed to RS signal shape.

Results



- Calculate the WS/RS ratio from measured D^* yields in each decay time bin.

Results



- Calculate the WS/RS ratio from measured D^* yields in each decay time bin.
- But measured yields include the contribution of D* mesons from b-hadron decays

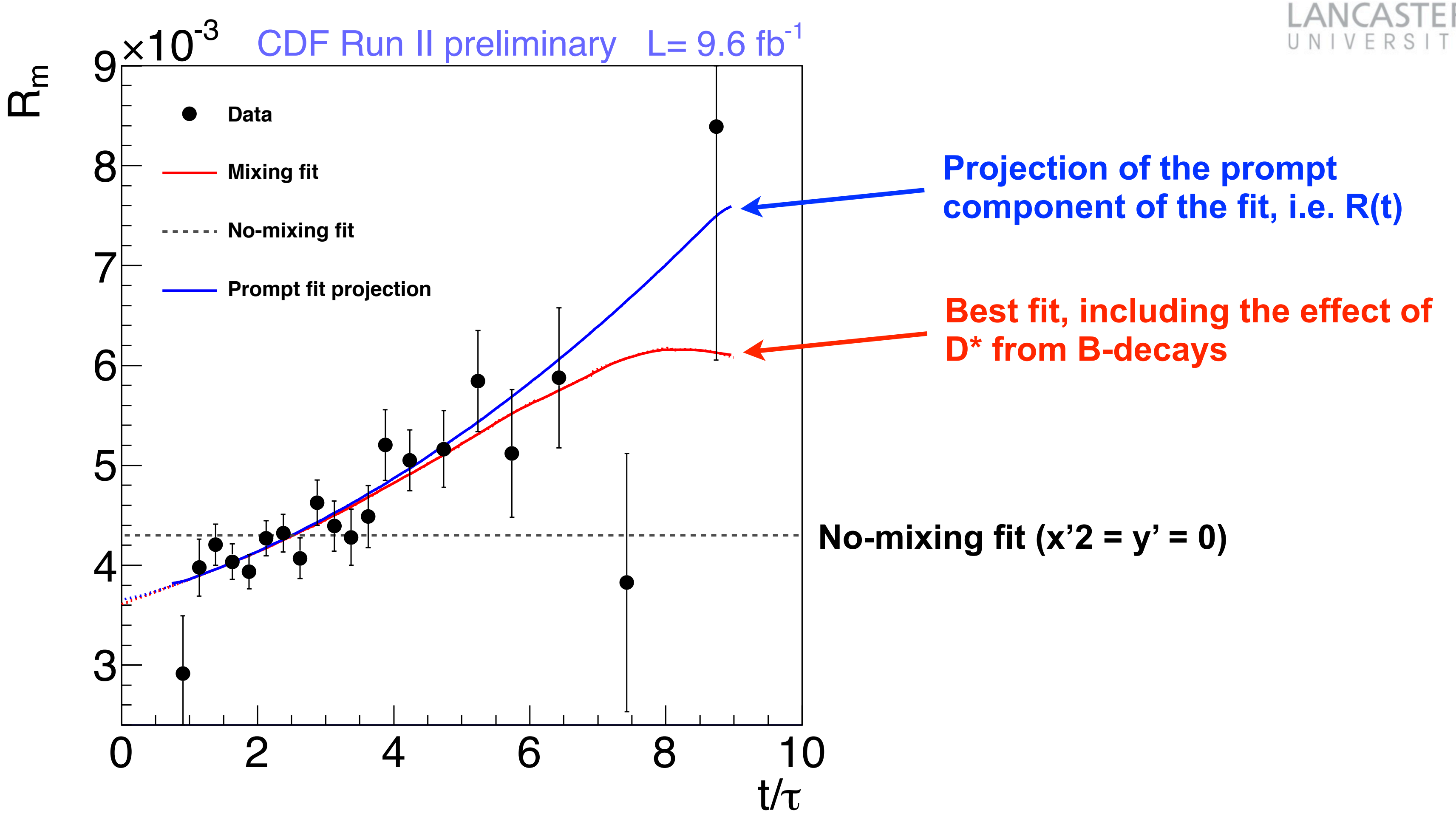
$$R_m(t) = \frac{N^{WS}(t) + N_B^{WS}(t)}{N^{RS}(t) + N_B^{RS}(t)}$$

- which modifies the quantity we are after:

$$R(t) = \frac{N^{WS}(t)}{N^{RS}(t)}$$

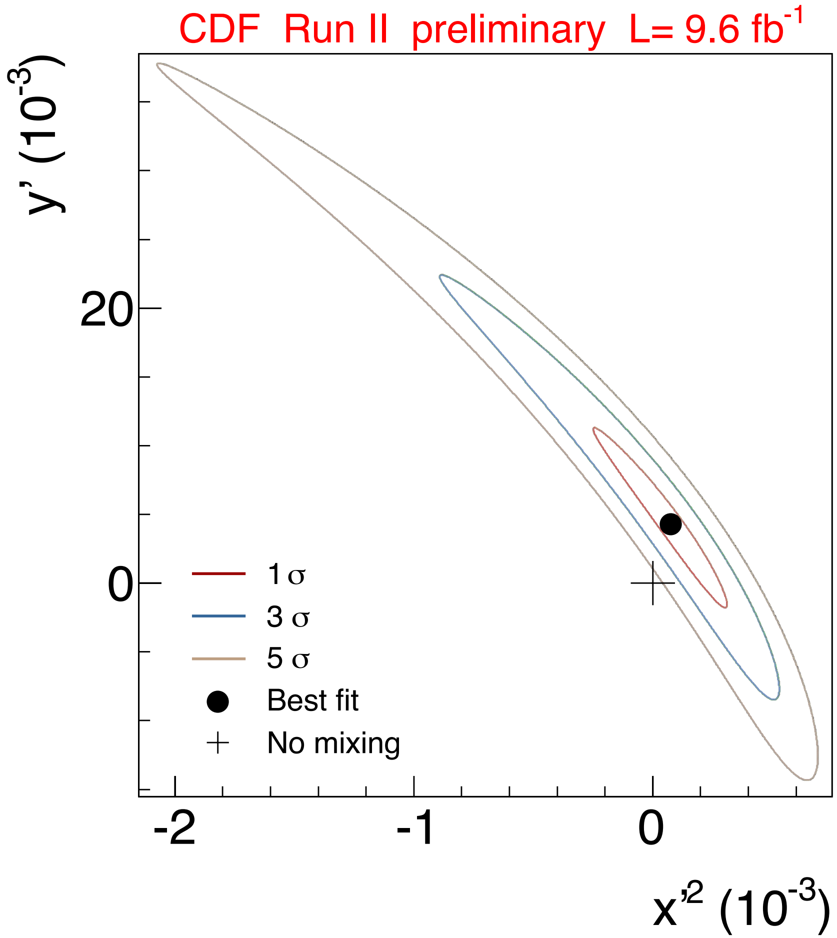
- Contribution from B-decays has to be corrected.

Results



Fit type	χ^2/ndf	Parameter	Fitted values $\times 10^{-3}$	Correlation coefficient R_D	y'	x'^2
Mixing	16.91/17	R_D	3.51 ± 0.35	1	-0.967	0.900
		y'	4.3 ± 4.3		1	-0.975
		x'^2	0.08 ± 0.18			1
No-mixing	58.75/19	R_B	4.30 ± 0.06			

Significance



Bayesian probability contours in x'^2-y' parameter space.

- p-value test: no-mixing hypothesis ($x'^2=y'=0$) is excluded with a probability of **6.1 Gaussian standard deviations**.

Comparison of Results

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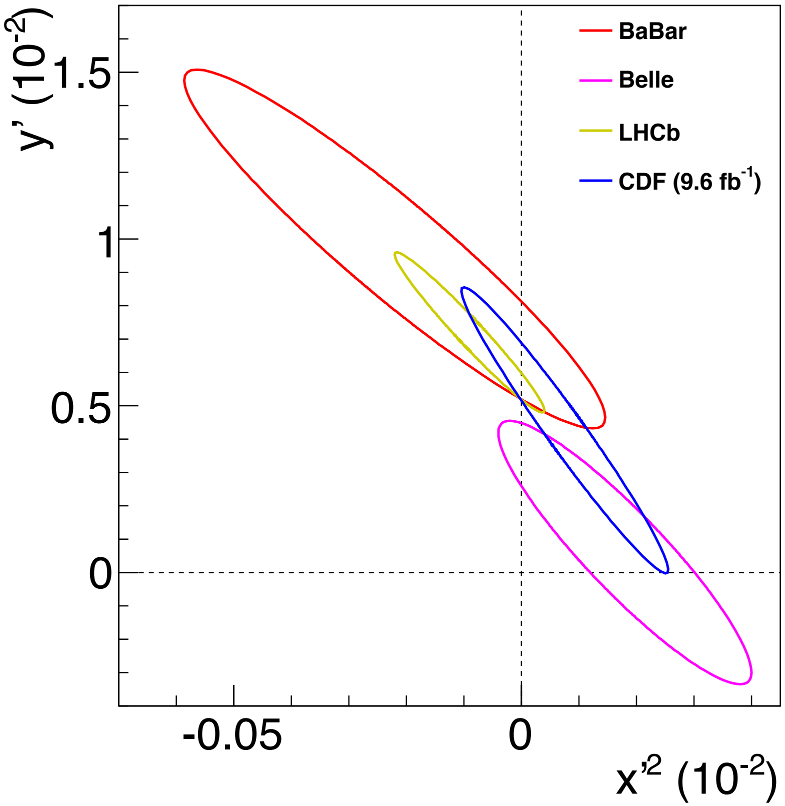


	RD (×10^{-3})	y' (×10^{-3})	x'^{2} (×10^{-3})	Sig.
Belle PRL 96 151801 (2006)	3.64±0.17	$0.6^{+0.4}_{-3.9}$	$0.18^{+0.21}$	2.0
BaBar PRL 98 211802 (2007)	3.03±0.19	9.7±5.4	-0.22±0.37	3.9
LHCb PRL 110 101802 (2012)	3.52±0.15	7.2±2.4	-0.09±0.13	9.1
CDF This result (2013)	3.51±0.35	4.3±4.3	0.08±0.18	6.1

CDF confirms the LHCb observation of charm mixing.
No-mixing hypothesis is excluded at 6.1σ level.

Backup Slides

- Neutral mesons can oscillate between matter and anti-matter. **Mass eigenstates ≠ flavor eigenstates**

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

Mixing parameters

$$x = \frac{m_1 - m_2}{\Gamma_D} = 2\frac{m_1 - m_2}{\Gamma_1 + \Gamma_2}$$

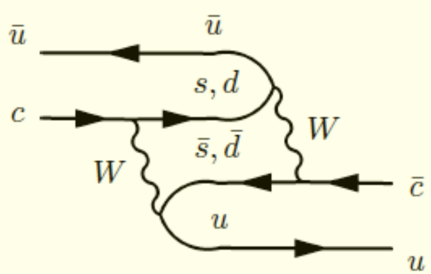
$$y = \frac{\Gamma_1 - \Gamma_2}{2\Gamma_D} = \frac{\Gamma_1 - \Gamma_2}{\Gamma_1 + \Gamma_2}$$

- Experimental evidence by Belle (2006), Babar and CDF (2007). First observation by LHCb (2012)

- Charm mixing is much slower than B and K mixing $x,y \leq 10^{-3}$

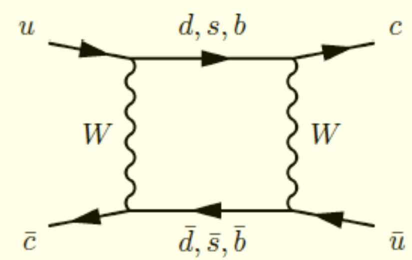
- D^0 mixing may occur through:

- **long-range intermediate states**



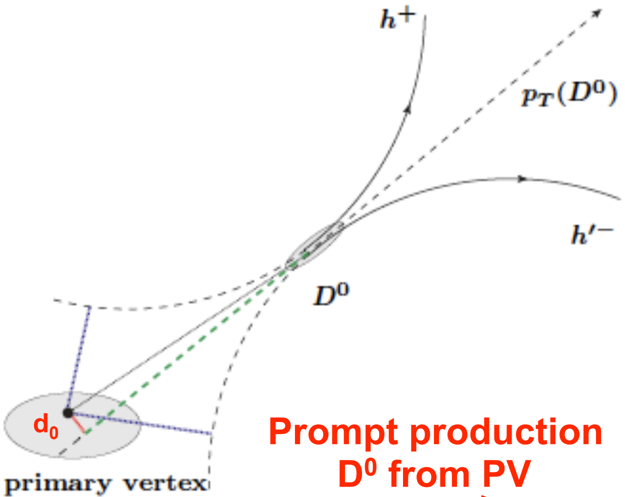
Dominant but large theoretical uncertainties.

- **short-range ("box", "penguin") diagrams**



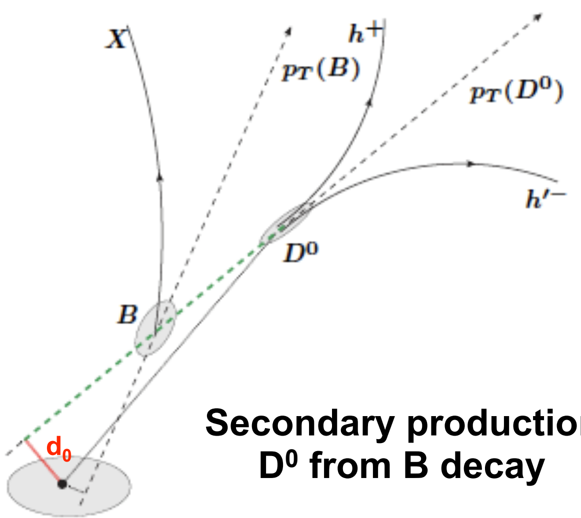
Highly GIM and CKM suppressed in SM.
Possible enhancement in many NP theories.

- Measurements of x and y are at the upper limit of SM ➔ **Powerful probe for NP**

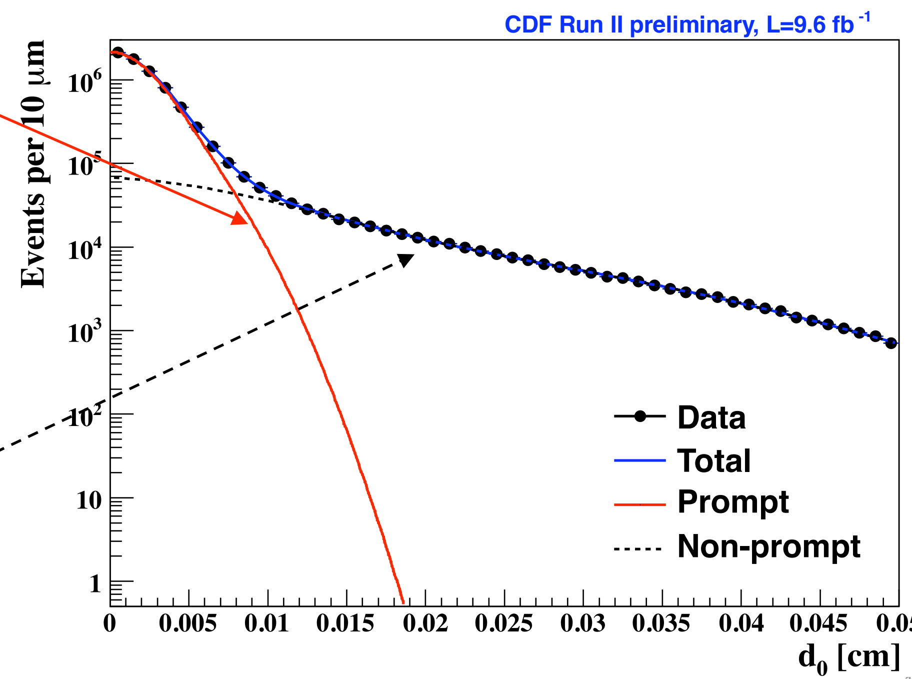


Prompt production
D^0 from PV

- D^0 produced from B decays have wrong proper decay time, since it is calculated w.r.t. the primary vertex and not from the B decay point.
- Due to the decay length of B hadrons, the D^0 (non-prompt) from the decay chain $B \to D^* X \to D^0$ have a broader impact parameter (d_0) distribution than D^0 (prompt) originating from D^* produced at the collision point.
- Apply $d_0(D^0) < 60\ \mu m$ cut to reduce non-prompt.



Secondary production
D^0 from B decay



The fraction R(t) is determined from a χ^2 fit to the data for R_m

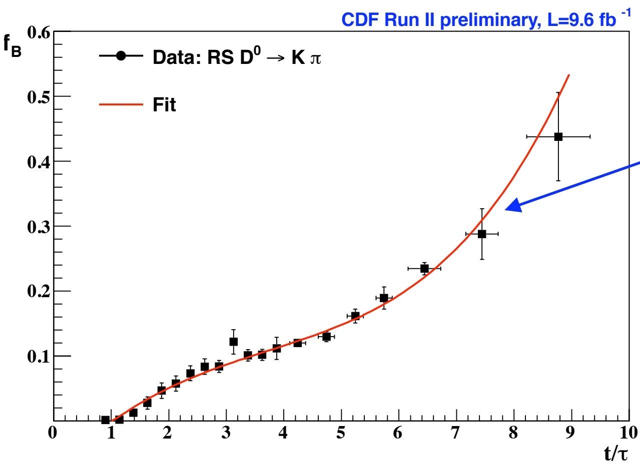
$$\chi^2 = \sum_{i=1}^{20}\left[\frac{r_i - R_m(t_i)}{\sigma_i}\right]^2 + C_{f_B}(\mathbf{p}) + C_{R_B}(\mathbf{h})$$

20 measured WS/RS points r_i with error σ_i

Gaussian constraint on f_B parameters (p)

Gaussian constraint on MC decay time distributions (h) of D* from B

$$R_m(t) = \frac{N^{WS}(t) + N_B^{WS}(t)}{N^{RS}(t) + N_B^{RS}(t)} = R(t)\left[1 + f_B^{RS}(t)\left(\frac{R_B(t)}{R(t)} - 1\right)\right]$$



$$f_B^{RS}(t) = \frac{N_B^{RS}(t)}{N^{RS}(t) + N_B^{RS}(t)}$$

Fraction of RS D* from B decays measured from data (fit d_0 distributions in each time-bin)

$$R_B(t) = \frac{N_B^{WS}(t)}{N_B^{RS}(t)}$$

WS/RS ratio of non-prompt D^0
Calculated by weighting R(t) with the decay-time distribution of secondary D^0 from MC

Improved the technique pioneered by LHCb, PRL 110 (2013) 101802