Observation of charm mixing at CDF

Paolo Maestro
University of Siena and INFN

On behalf of the CDF collaboration

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Flavour mixing in the charm sector

- 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

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

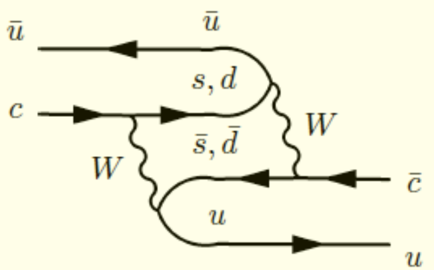
$$y = \frac{\Gamma_1 - \Gamma_2}{2\Gamma_D} = \frac{\Gamma_1 - \Gamma_2}{\Gamma_1 + \Gamma_2}$$

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

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

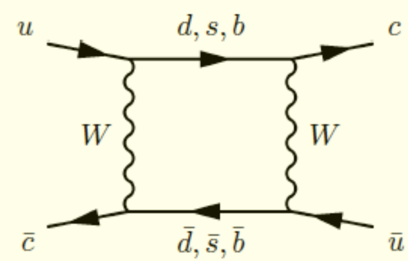
- D^0 mixing may occur through:

• **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.

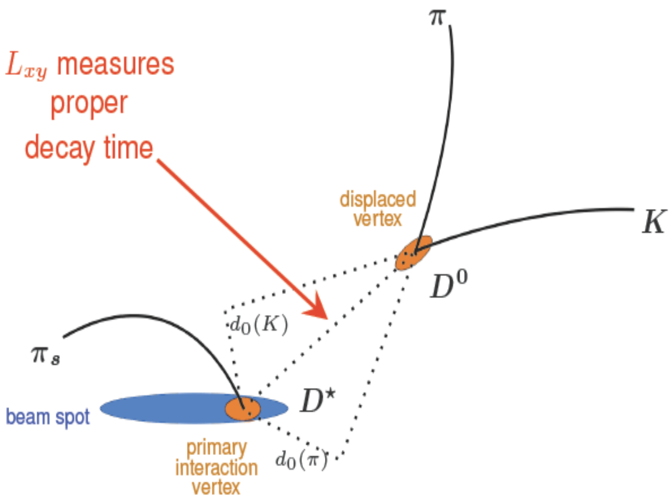
- Measurements of x and y are at the upper limit of SM ➔ **Powerful probe for NP**

D^0- $\overline{D}^0$ mixing

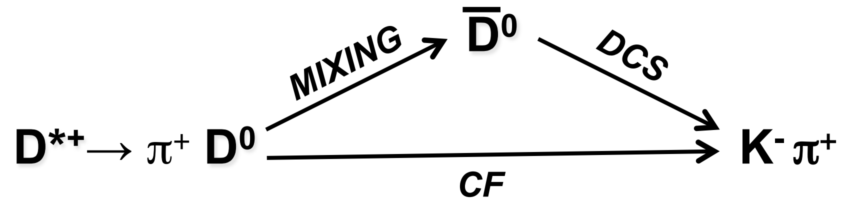
$1.5\ fb^{-1}$ **Evidence** *PRL 100, 121802 (2008)*

$9.6\ fb^{-1}$ **Observation** **BRAND NEW!**

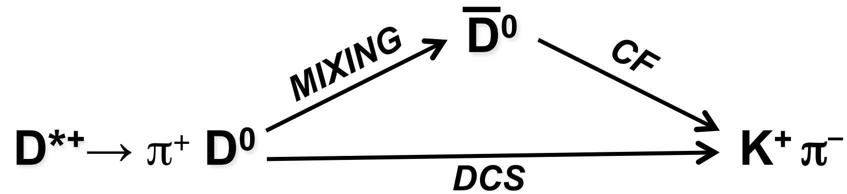
Charm mixing in $D^0 \to K^+\pi^-$



D^0 is tagged by $D^{*+} \to D^0 \pi_s^+$ decay



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



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

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

Mixing rate

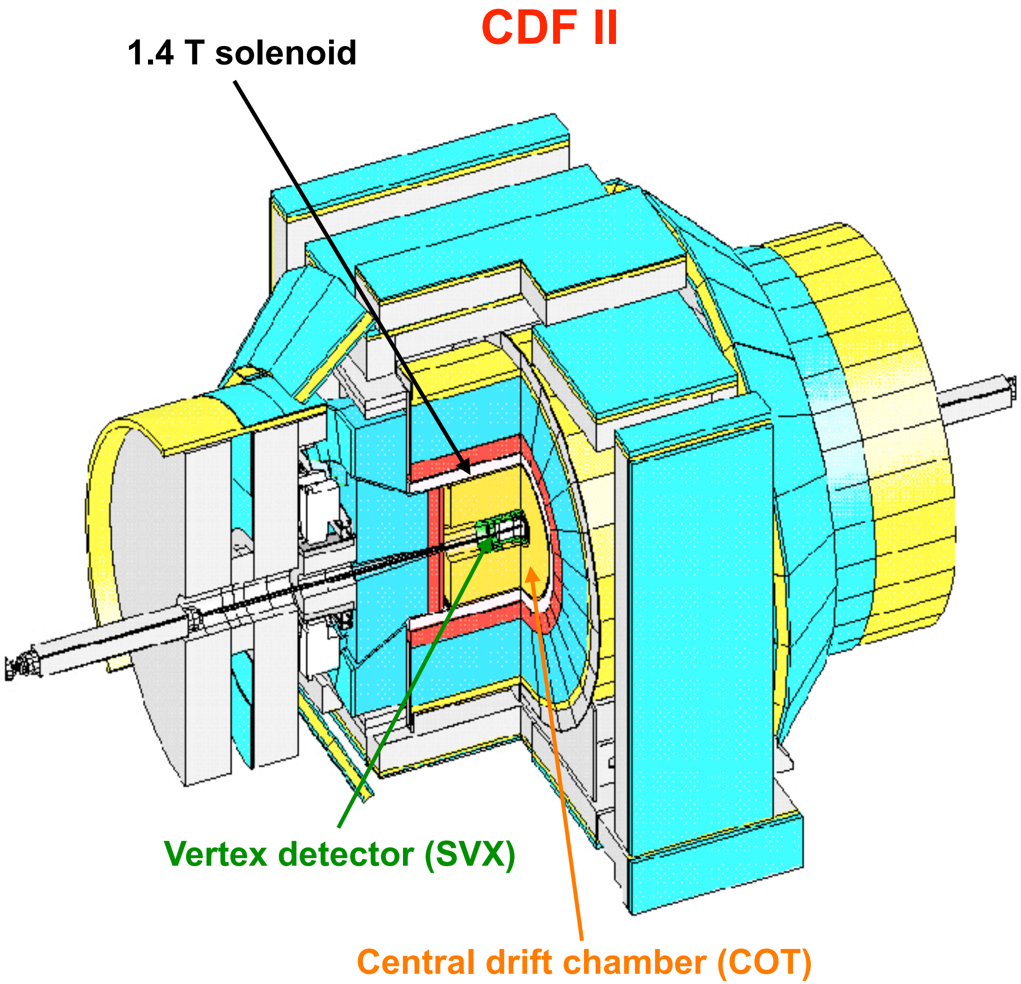
$$R(t) = R_D + \sqrt{R_D}\, y' t + \frac{x'^2 + y'^2}{4} t^2$$

DCS to CF ratio

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

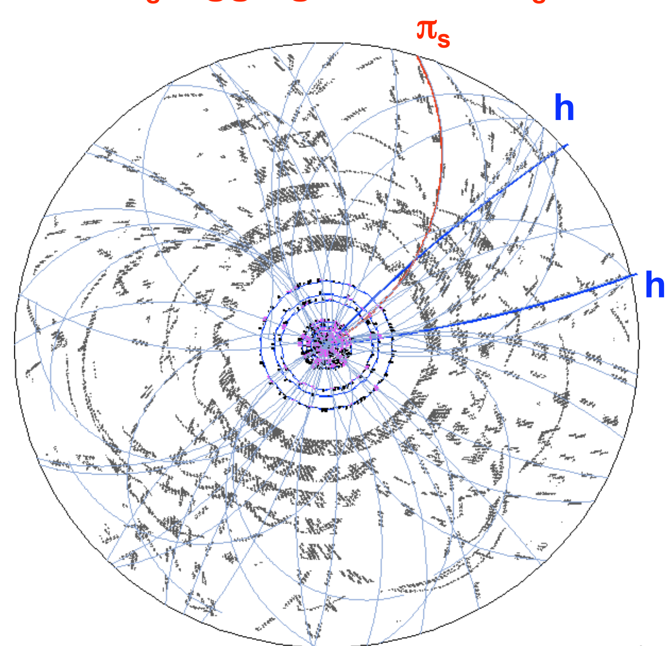
$\delta_{K\pi}$: strong phase difference between CF and DCS amplitudes

Data sample



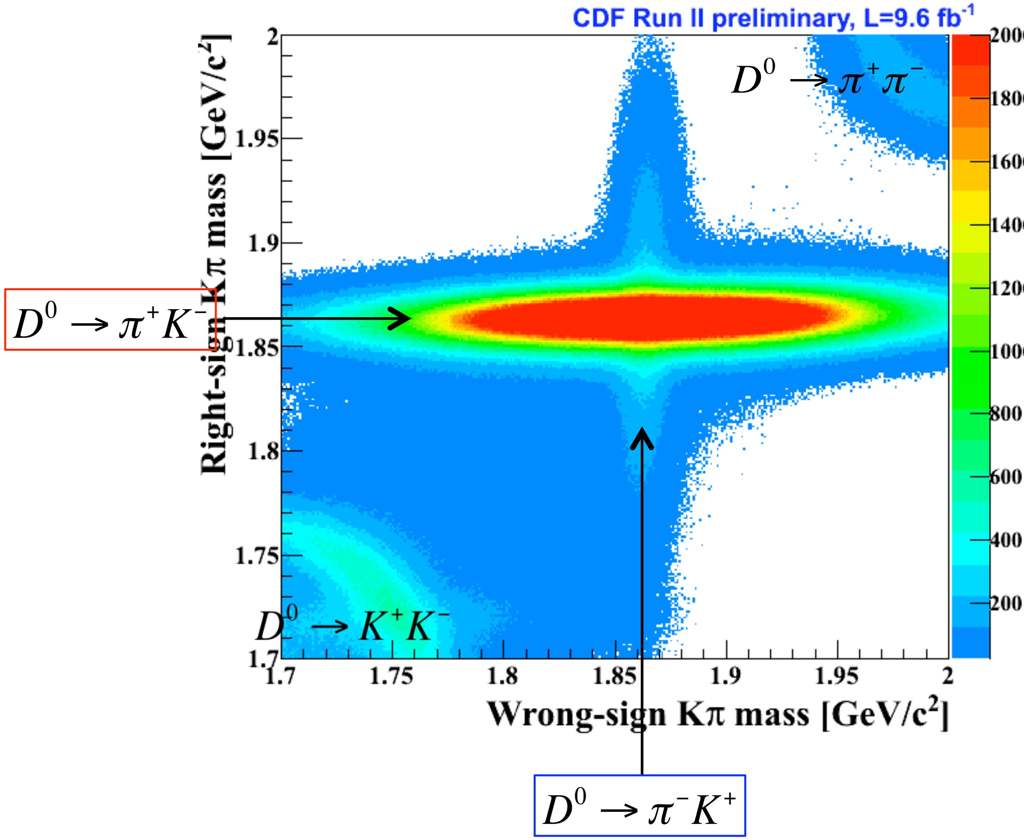
- **Data collected from Feb. 2002 to Sep. 2011 9.6 fb^{-1} @ $\sqrt{s}$ =1.96 TeV**
- **Hadronic trigger: two opposite charge particle tracks in COT+SVX from a displaced vertex**
- **Excellent p_T and mass resolution**

  $s_{pT}/p_T = 0.07\%\ p_T$
- **Impact parameter resolution ~30 μm**
- **Particle ID (from dE/dx)**
- **"Soft" π_s tagging: $D^* \rightarrow D^0 \pi_s \rightarrow hh' \pi_s$**



RS and WS signal extraction

- Tracks are considered with both Kπ and πK interpretations. RS or WS depends on D* tag
- The mis-assigned interpretation has a Kπ distribution 10× wider than a correctly reconstructed D^0.

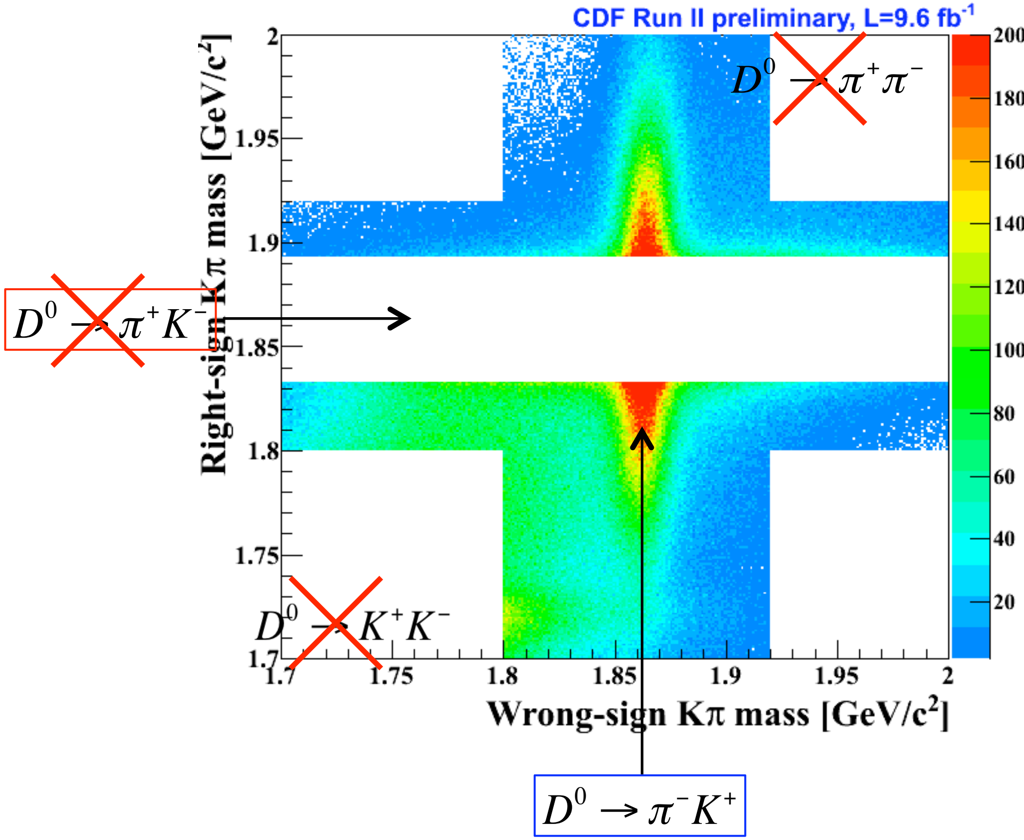


RS and WS signal extraction

- Tracks are considered with both Kπ and πK interpretations. RS or WS depends on D* tag
- The mis-assigned interpretation has a Kπ distribution 10× wider than a correctly reconstructed D^0.
- Limit mass range to 1.8<m(Kπ)<1.92 GeV/c^2 excludes almost all $D^0 \to KK, \pi\pi$
- **Opposite-assigned-mass (OAM) cut**:
  RS D^0 candidates with

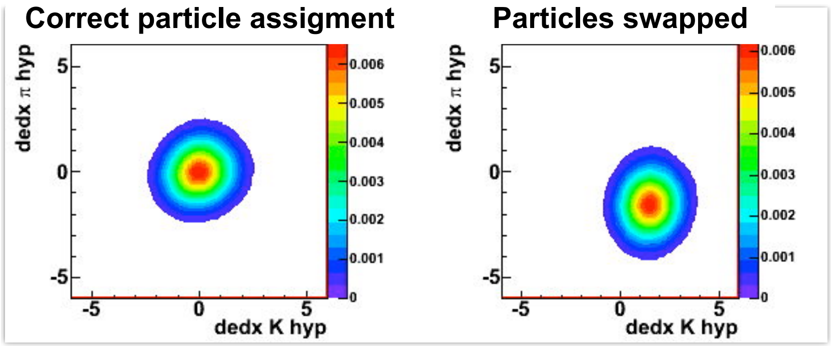
  $$|m(K^- \pi^+) - m(D^0)| < 20 \text{ MeV}/c^2$$

  are removed from WS sample.
- Exclude WS from RS sample with a similar OAM cut.
- OAM cut keeps 78% of signal, 3.6% mis-assigned.



RS and WS signal extraction

- Compare two-track PID probability (from dE/dx) for RS and WS assignments, and retain the most probable hypothesis.
- PID: 85% efficiency,15% mis-assigned (w/o OAM)



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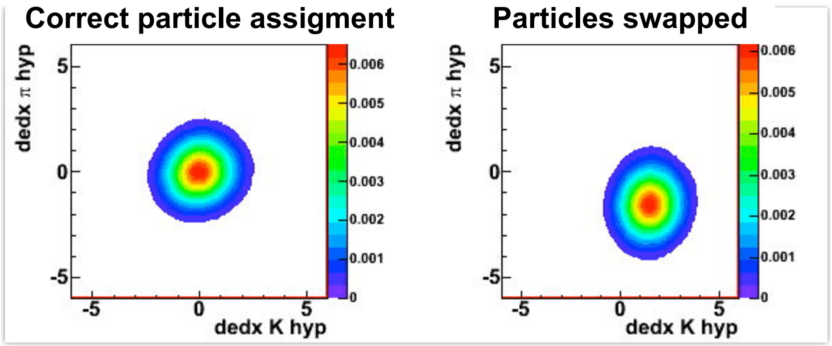
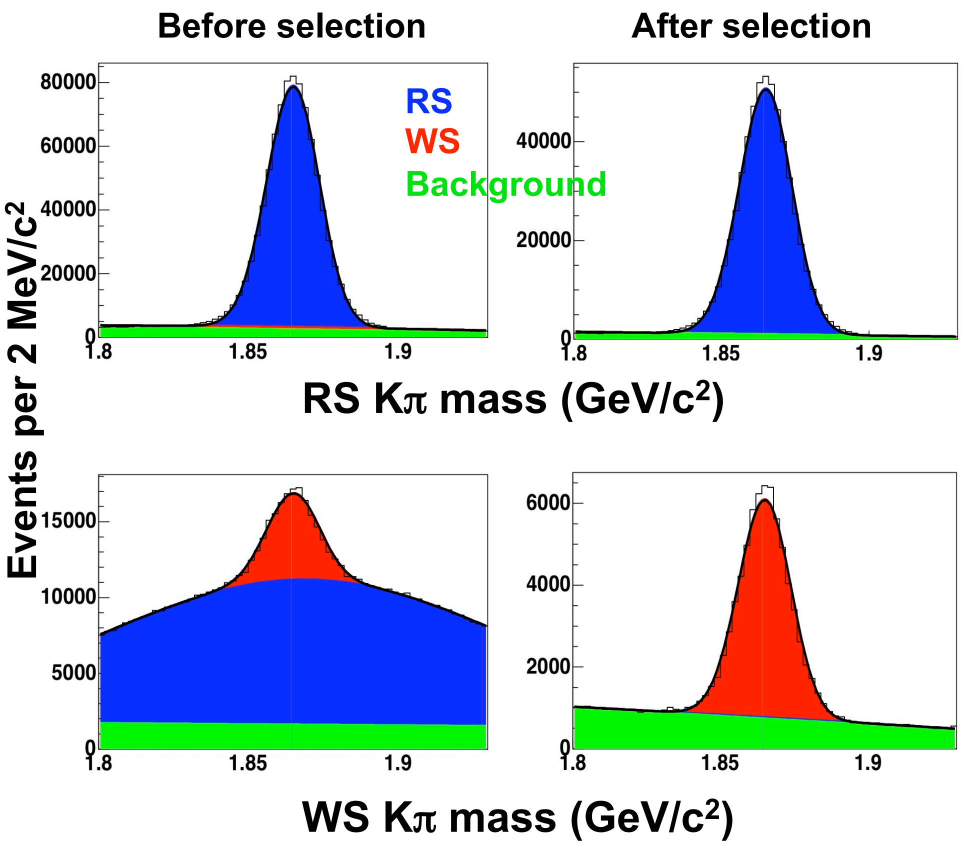




- OAM and PID cuts greatly clean up the mis-assigned background.

Analysis Strategy

Step 0: divide RS and WS candidates in 20 decay-time and

60 bins of $\Delta m = M(K\pi\pi) - M(K\pi) - M(\pi)$

➔ 2400 RS and WS $K\pi$ mass distributions.

Step 1: fit RS and WS $K\pi$ mass distributions to get the D^0 yields

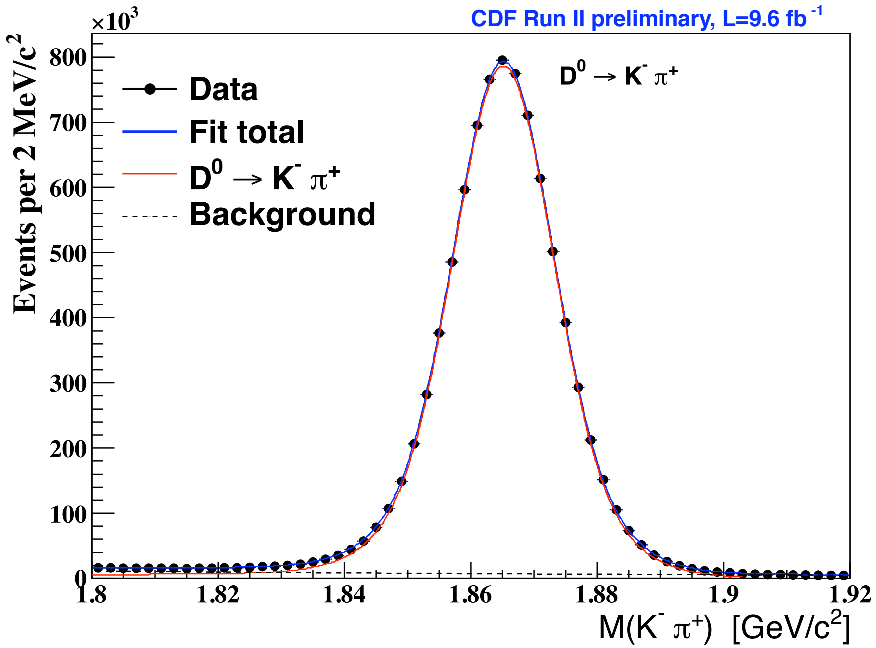
Step 2: fit Δm distributions to get D^* yields

Step 3: measure the WS/RS ratio vs. proper decay time

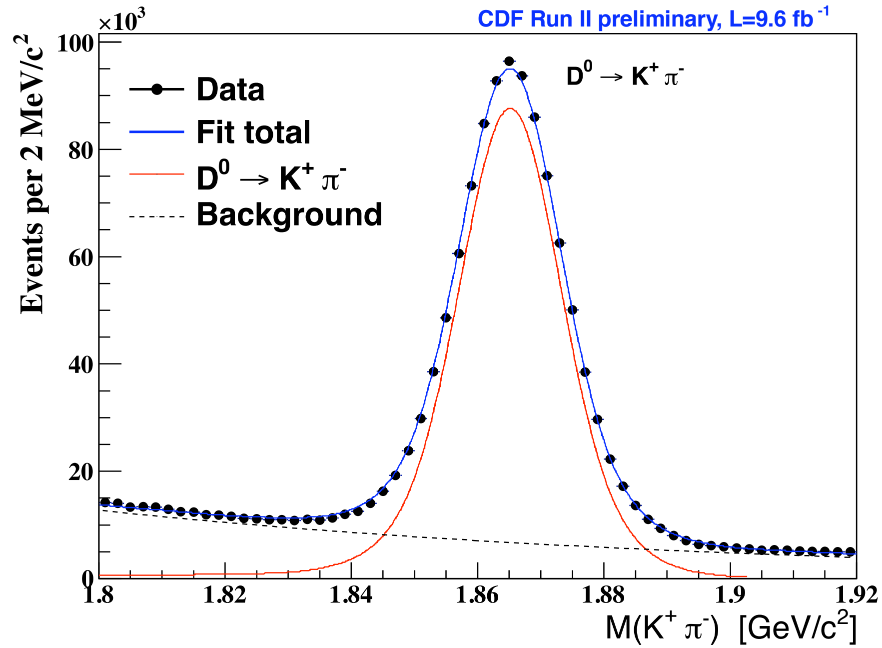
Step 4: fit the WS/RS ratio to estimate the charm mixing parameters

Step 1: Kπ fits

- For each of the 1200 RS (WS) bins, a binned maximum likelihood fit to the M(Kπ) distribution is performed to get the RS (WS) D^0 signal yield.



RS (time-integrated Δm-summed)

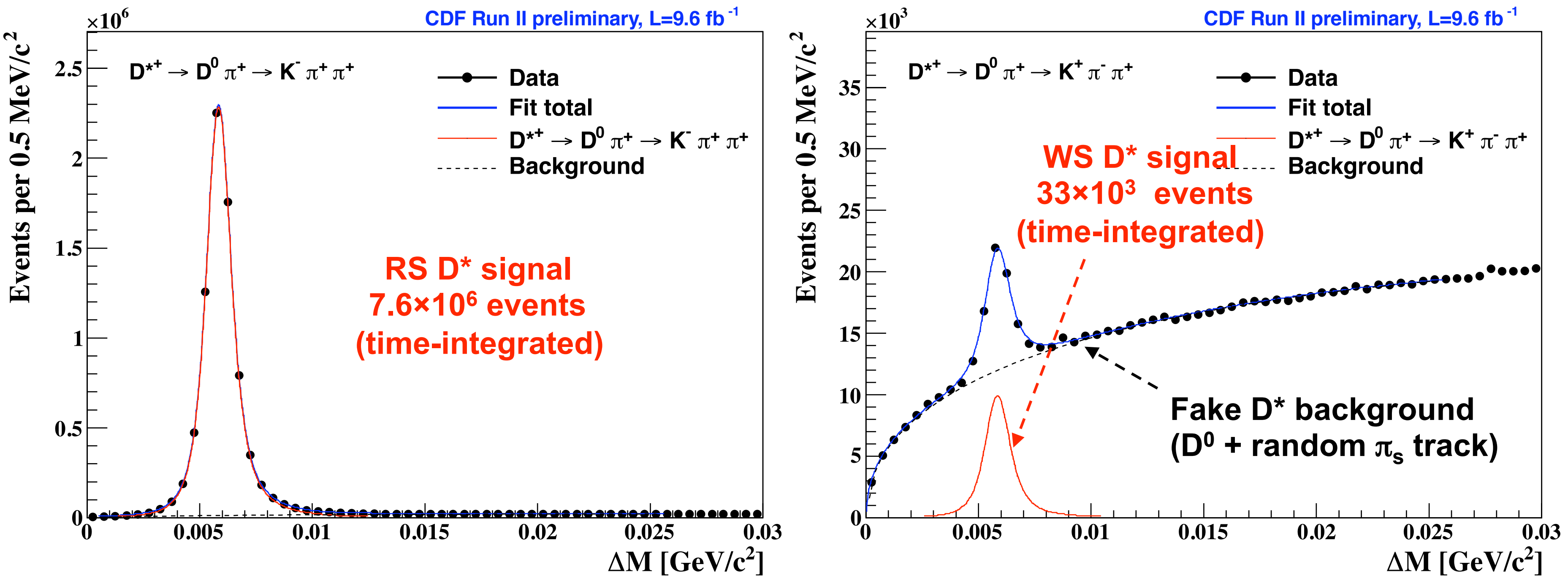


WS (time-integrated Δm-summed)

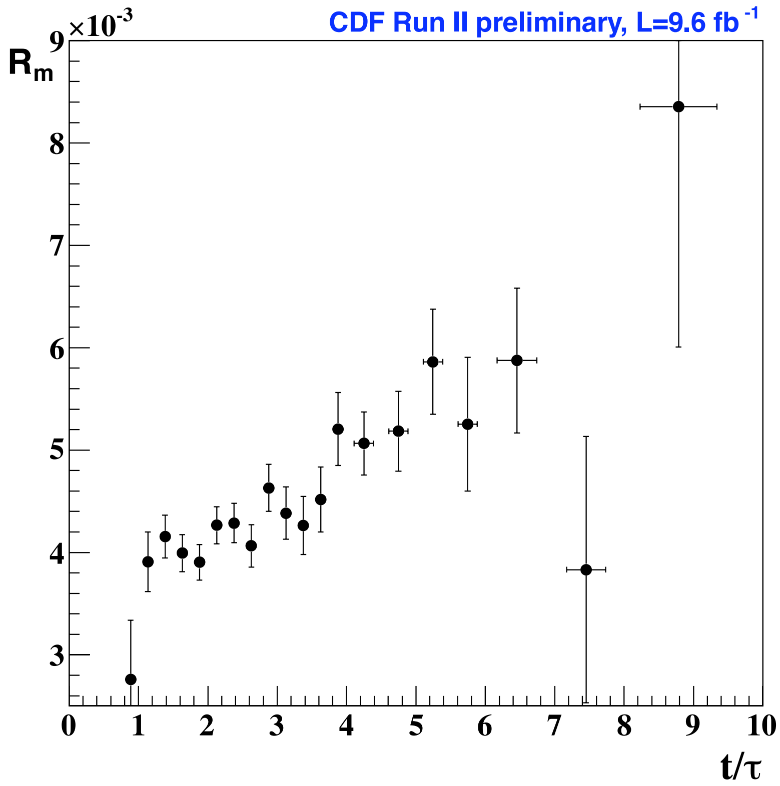
- The signal shape is modeled by double-Gaussian with low-mass tail, background by an exponential.
- For WS, misidentified RS background is included.
- Signal shape parameters are fixed in each bin to RS time-integrated values.

Step 2: Δm fits

- The D* signal for each time bin is determined from 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 an artificial random combination of a well-reconstructed D^0 from each event combined with π_s from other events.
  - WS signal shape is fixed to RS signal shape.

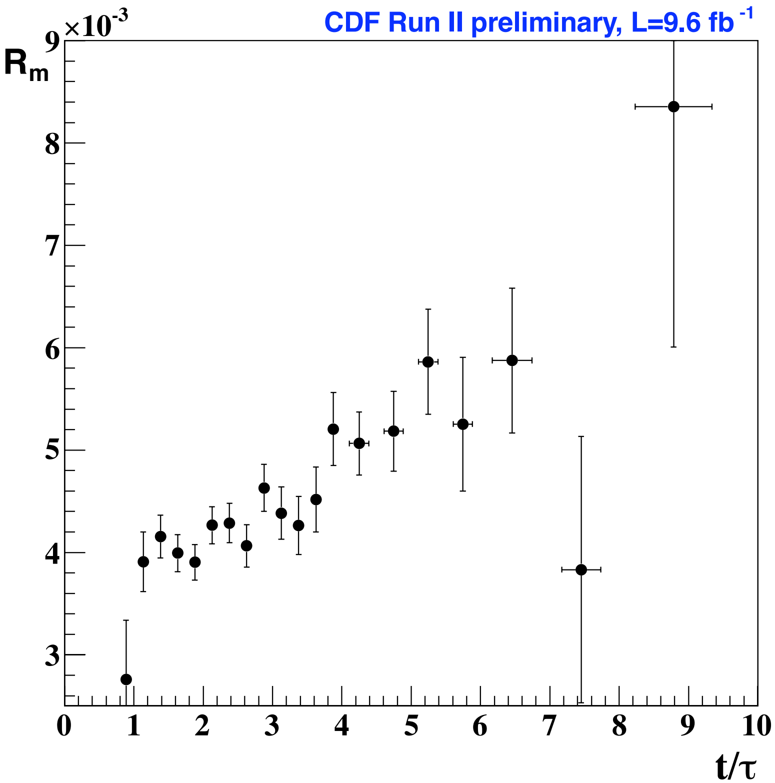


Step 3: WS/RS ratio vs. decay time



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

Step 3: WS/RS ratio vs. decay time



- 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

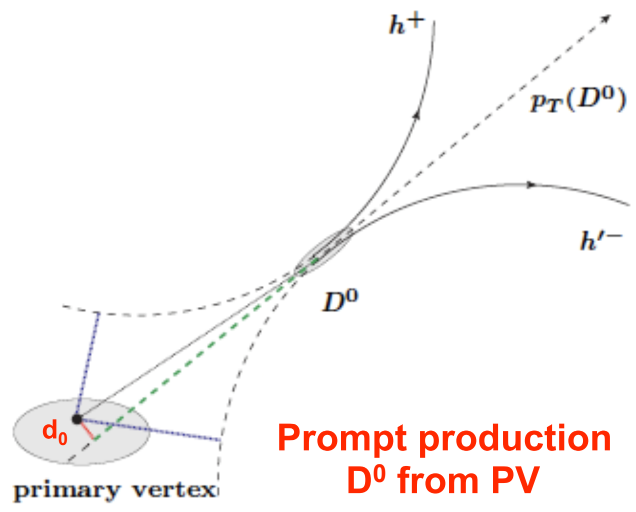
$$R_m(t) = \frac{N^{WS}(t) + N_B^{WS}(t)}{N^{RS}(t) + N_B^{RS}(t)}$$

which modifies the time dependence of the observed WS/RS ratio (R_m) w.r.t.

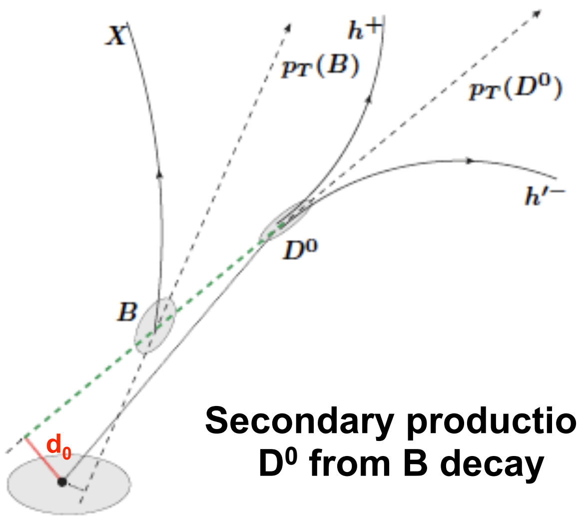
$$R(t) = \frac{N^{WS}(t)}{N^{RS}(t)}$$

- Contribution from B hadron decays is included in the WS/RS ratio fit.

D* from B decays



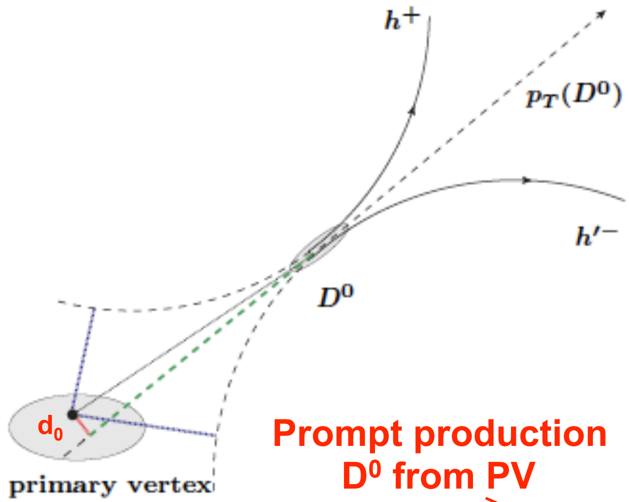
Prompt production
D^0 from PV



Secondary production
D^0 from B decay

- 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.

D* from B decays



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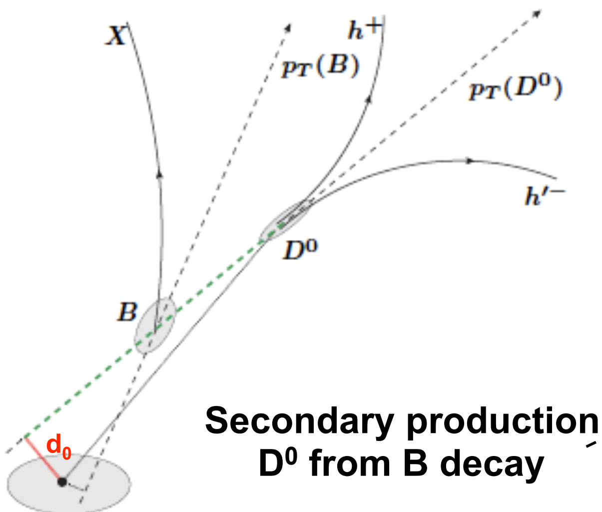
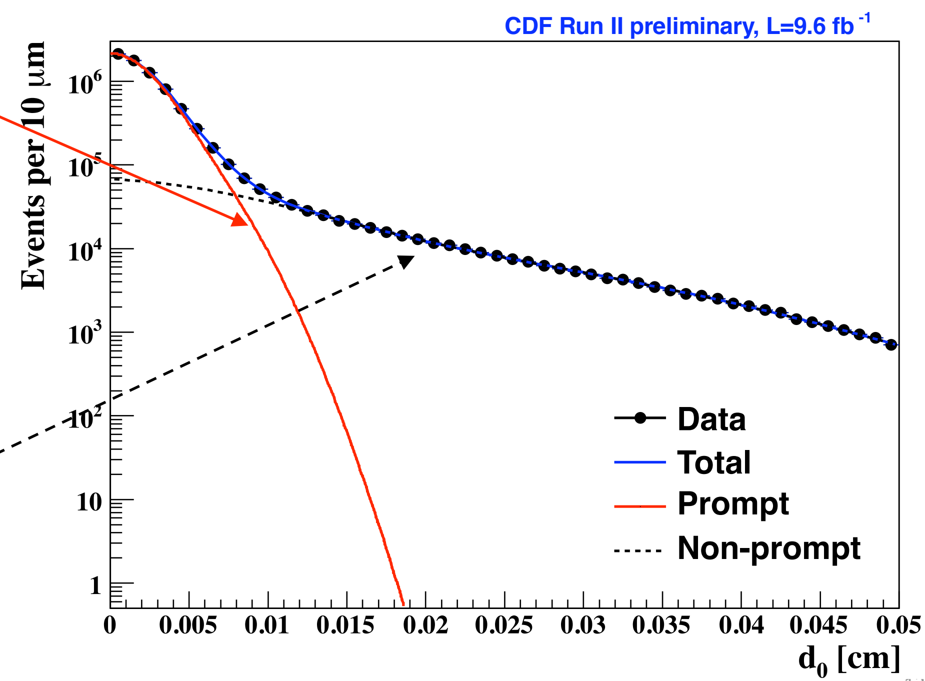
D^0 from PV



Secondary production
D^0 from B decay

- 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 $B \rightarrow D^* X \rightarrow D^0$ have a broader impact parameter (d_0) distribution than D^0 (prompt) originating from D* produced at the collision point.
- Apply $d_0(D^0) < 60$ μm cut to reduce non-prompt.



Step 4: WS/RS fit

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

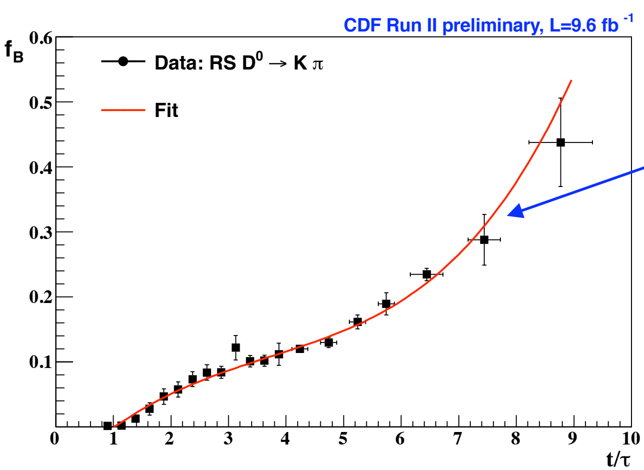
$$\chi^2 = \sum_{i=1}^{20} \left[\frac{r_i - R_m(t_i)}{\sigma_i} \right]^2 + C_{f_B}(\mathbf{p}) + C_{R_B}(\mathbf{h})$$

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

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



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

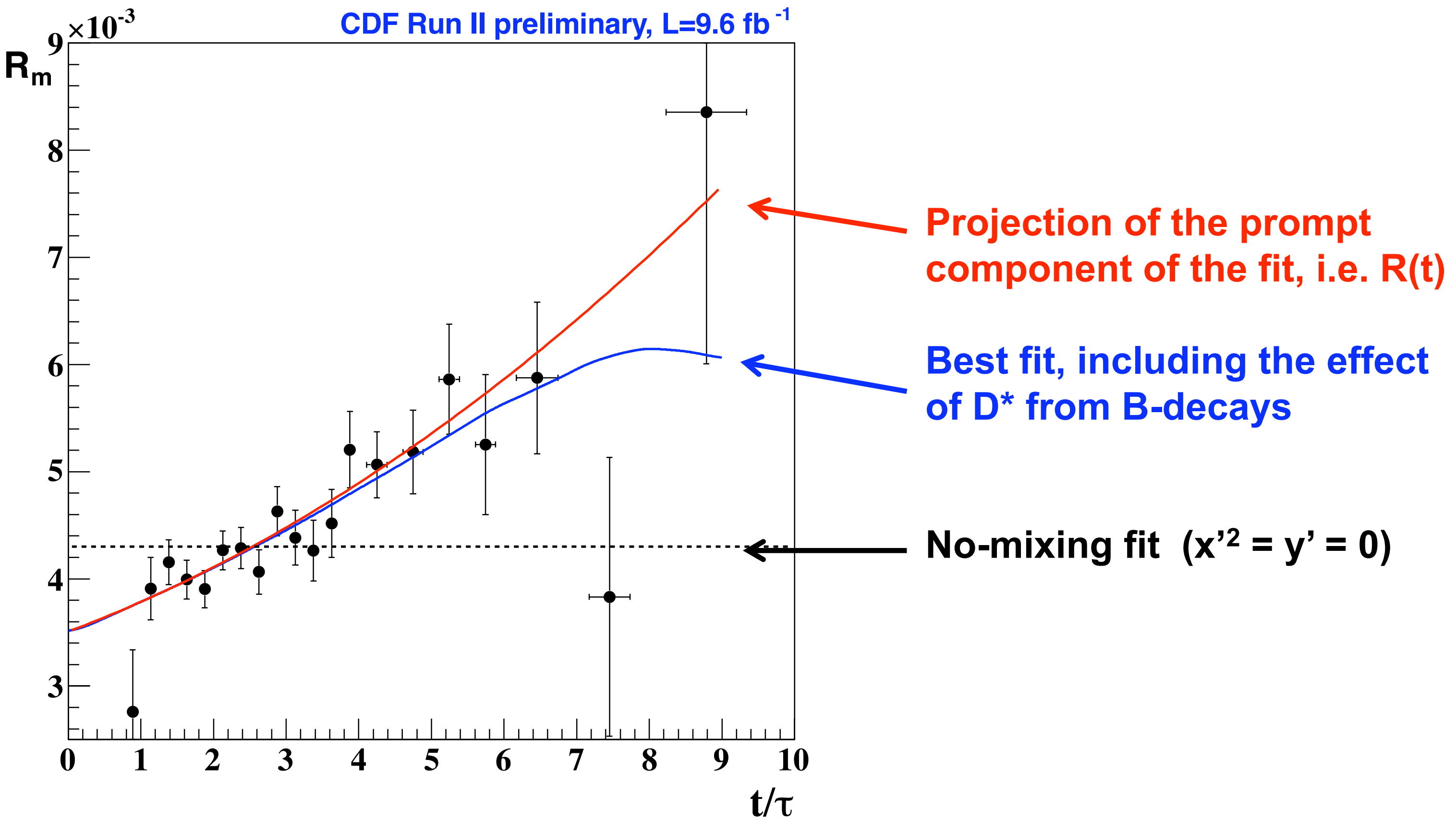
Fraction of RS D* from B decays measured from data (fit d_0 distributions in each time-bin)

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

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

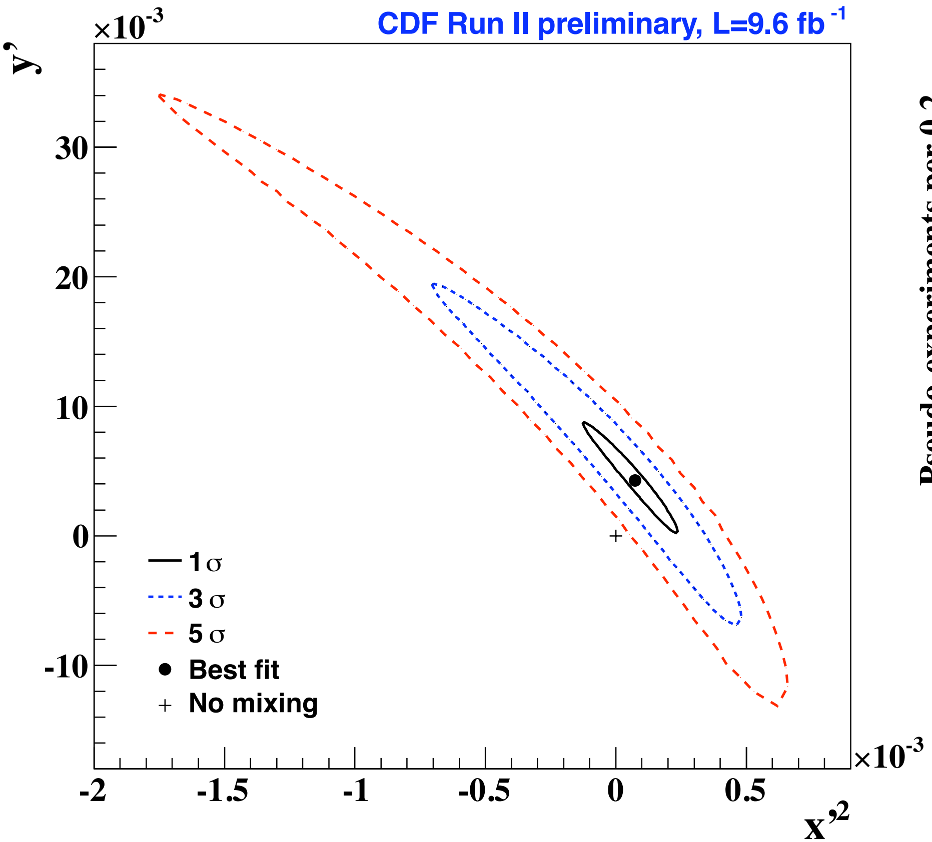
Improved the technique pioneered by LHCb, PRL 110 (2013) 101802

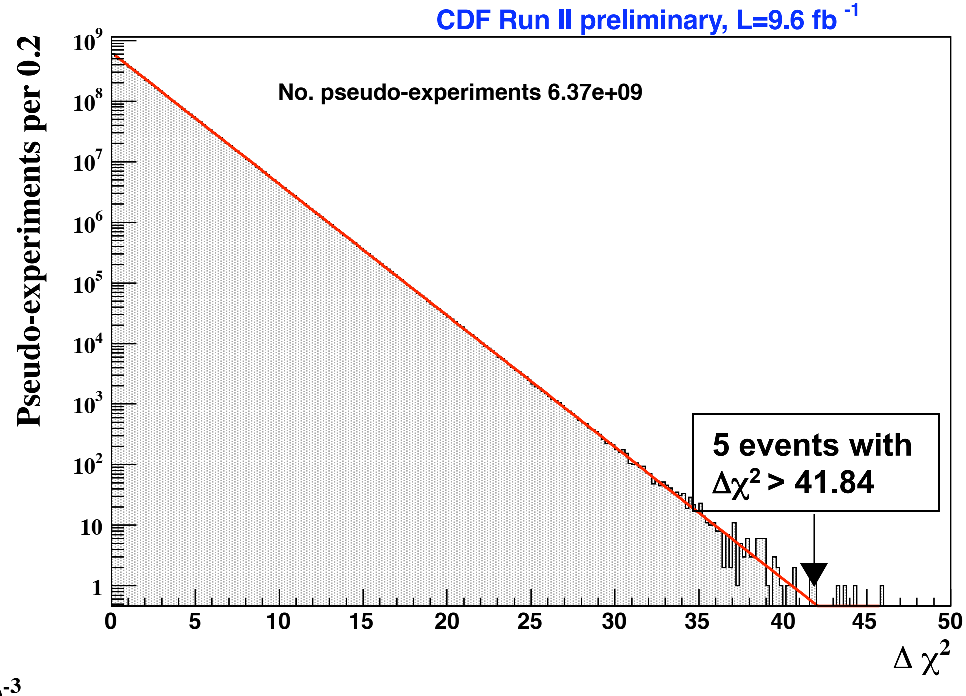
Result



Fit type	χ^2/ndf	Parameter	Fitted values $\times10^{-3}$	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			

Mixing significance





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

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

Other systematics and checks

- Additional sources of systematical uncertainties include:
  - Detector charged track asymmetries
  - Uncertainties in signal shapes in $K\pi$ and Δm fits
  - Background due to $D^+ \rightarrow K^- \pi^+ \pi^+$ and partially reconstructed charm decays
  - Uncertainties in the shape of non-prompt component in d_0 fits which affect f_B estimate
  - MC decay time distributions of non-prompt D^0

  All these were found to be negligible compared to the mixing parameter errors.

- Mass distributions were simulated for different sets of mixing parameters.

  For each set, the entire analysis procedure is performed.

  The distribution of fitted parameters turned out to have mean values equal to the input values within statistical accuracy.

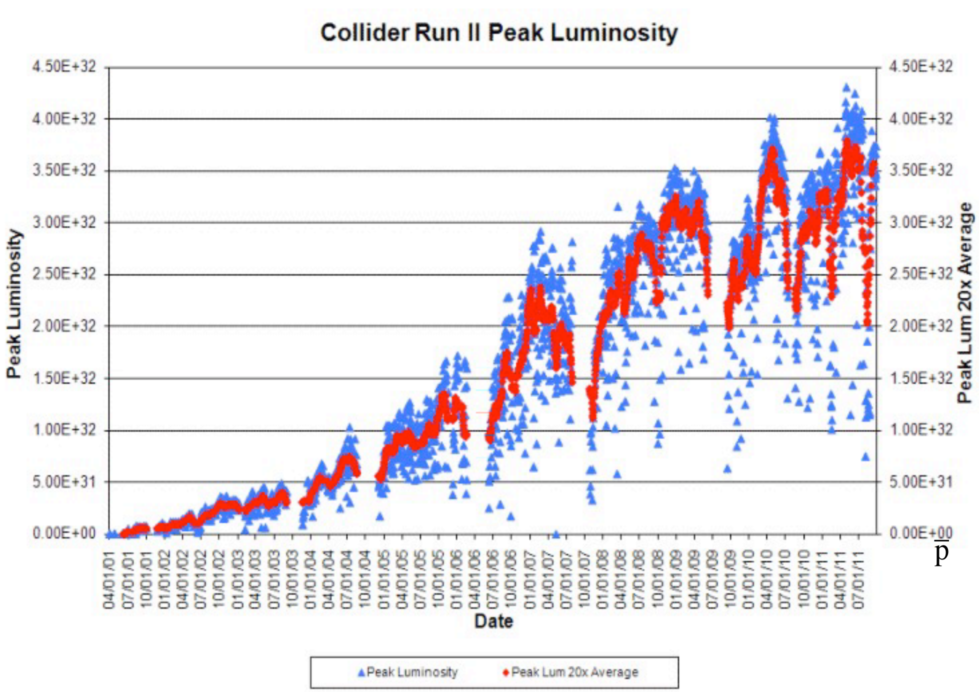
Conclusions

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

Experiment	R_D $\times 10^{-3}$	y' $\times 10^{-3}$	x'^2 $\times 10^{-3}$	No-mixing exclusion significance
Belle Phys. Rev. Lett. 96 (2006) 151801	**3.64±0.17**	$0.6^{+0.4}_{-3.9}$	$0.18^{+0.21}_{-0.23}$	**2.0**
Babar Phys. Rev. Lett. 98 (2007) 211802	**3.03±0.19**	**9.7±5.4**	**-0.22±0.37**	**3.9**
CDF (2007) Phys. Rev. Lett. 100 (2008) 121802	**3.04±0.55**	**8.5±7.6**	**-0.12±0.35**	**3.8**
LHCb Phys. Rev. Lett. 110 (2013) 101802	**3.52±0.15**	**7.2±2.4**	**-0.09±0.13**	**9.1**
CDF (2013)	**3.51±0.35**	**4.3±4.3**	**0.08±0.18**	**6.1**

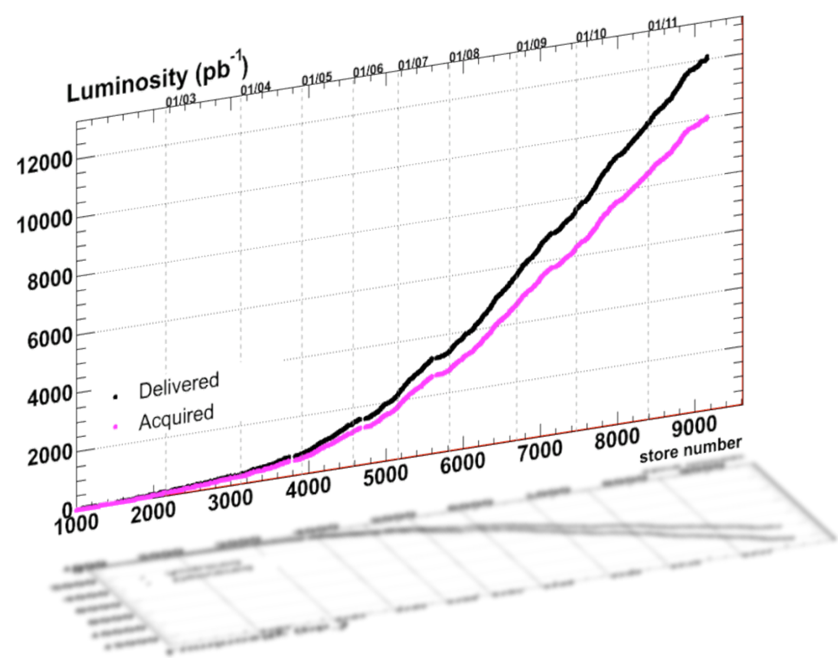
BACKUP SLIDES

Tevatron



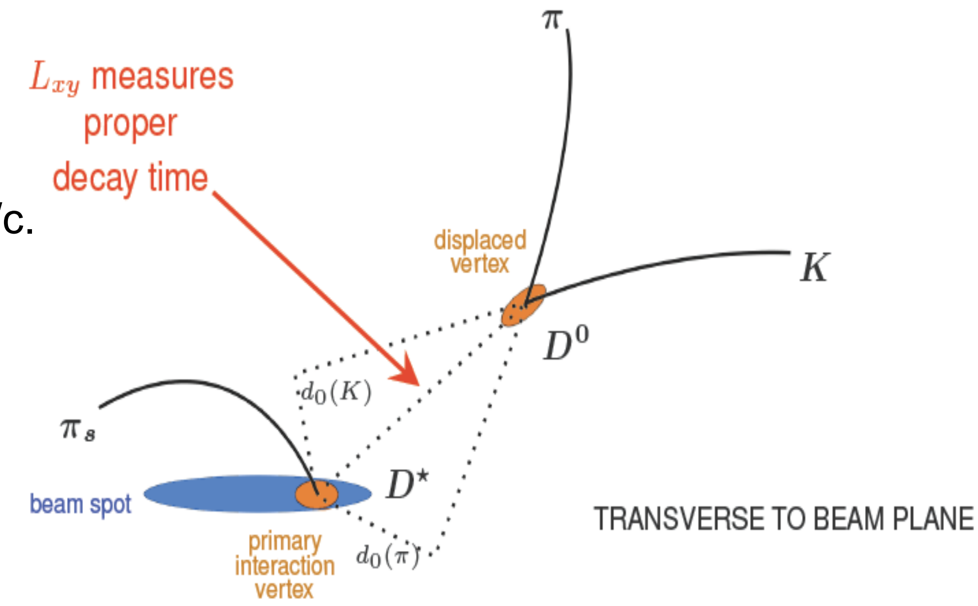
- Tevatron ended running on October 2011, after 30 years of operation.
- Peak luminosity increased almost until the very end, with typical values of **3.5×10^{32} cm^{-2} s^{-1}**

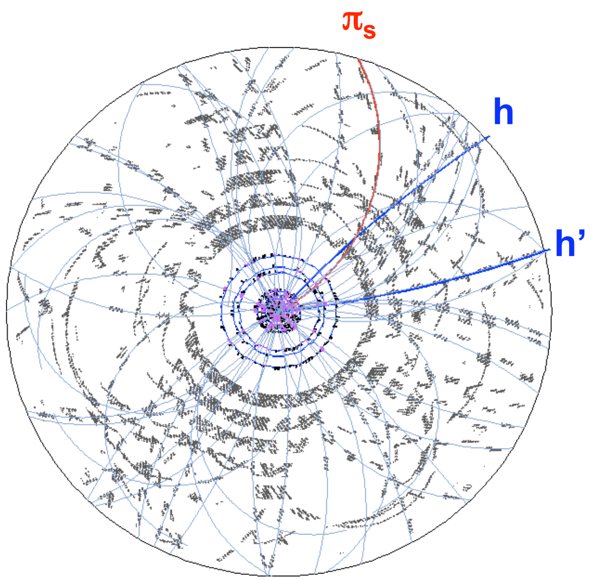
- **p anti-p collisions at $\sqrt{s}$=1.96 TeV**
- **>50 pb^{-1} collected per week**
- **Delivered 12 fb^{-1} and recorded ~10 fb^{-1}**



$D^0 \rightarrow hh'$ decay reconstruction

- Data collected by **Two-track trigger (TTT)** designed to select heavy flavour decays.
- **TTT requires two opposite charge tracks from a displaced vertex** with $\Sigma p_T > 5.5$ GeV/c. Each track is required to have:
  - $p_T > 2$ GeV/c
  - $0.1 < d_0 < 1$ mm
  - $L_{xy} > 200\ \mu m$
  - $2° < \Delta\phi < 90°$
  - $|\eta| < 1.2$
  - $|\Delta z_0| < 5$ cm
- Selection criteria for $D^0 \rightarrow hh'$ candidate
  - $d_0(D^0) < 60\ \mu m$
  - $L_{xy}/\sigma_{xy} > 4$
- **A "soft" track is added to form a $D^* \rightarrow D^0 \pi_s$ candidate.** π_s is required to have:
  - $0.4 < p_T < 2$ GeV/c
  - $d_0 < 600\ \mu m$
  - $|z| < 1.5$ cm





Step 0: Time and Δm bins

- RS and WS D^0 candidates are divided in:

  - 20 bins of t/τ

    Range 0.75-10.0

    Bin of increasing size from 0.25 to 2

$$t = \frac{M_{D^0} L_{xy}}{p_T}$$ **Proper decay time**

$$M_{D^0} = 1.8648 \ \text{GeV/c}^2 \ \text{(PDG)}$$

$$\tau = 410.1 \ \text{fs} \ \text{(PDG)}$$ **Mean D^0 lifetime**

  - 60 bins of mass difference $\Delta m = M(K\pi\pi) - M(K\pi) - M(\pi)$

    Range 0-30 MeV/c^2

    Bin size 0.5 MeV/c^2

- 1200 $K\pi$ mass distributions for RS (WS), one for each (t/τ , Δm) bin

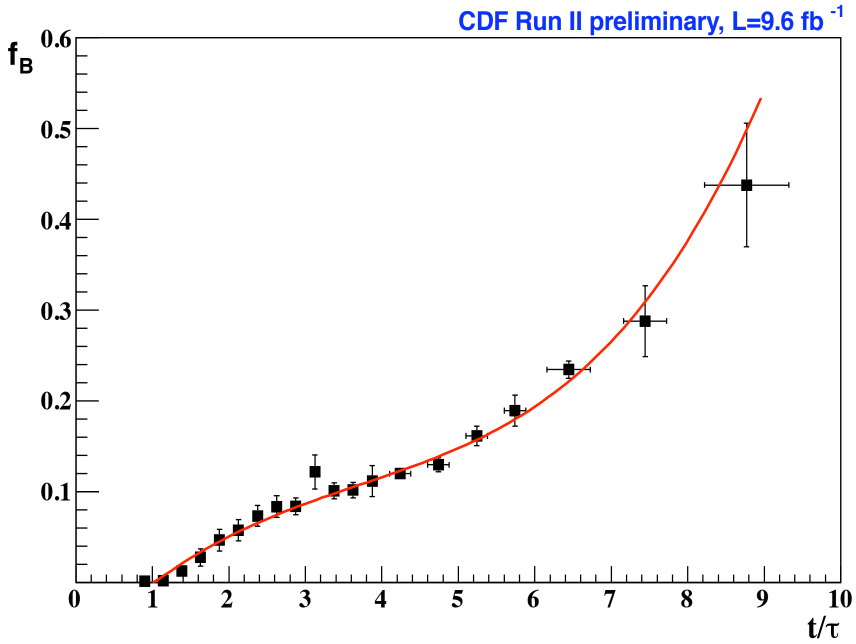
$f_B^{RS}(t)$ measurement

- For each time bin, the prompt P and non-prompt P_B component of the RS signal are determined by fitting the d_0 distribution.

- These fits are used to determine $f_B^{RS}(t)$ the fraction of D* (with d_0 < 60 μm) that come from B-decays

$$f_B = \frac{N_B^{RS}}{N^{RS} + N_B^{RS}} = \frac{\int_0^{60\,\mu m} P_B(d_0)\, \mathrm{d}(d_0)}{\int_0^{60\,\mu m} P(d_0)\, \mathrm{d}(d_0) + \int_0^{60\,\mu m} P_B(d_0)\, \mathrm{d}(d_0)}$$

- The time dependence of f_B^{RS} is parametrized by a 4-degree polynomial

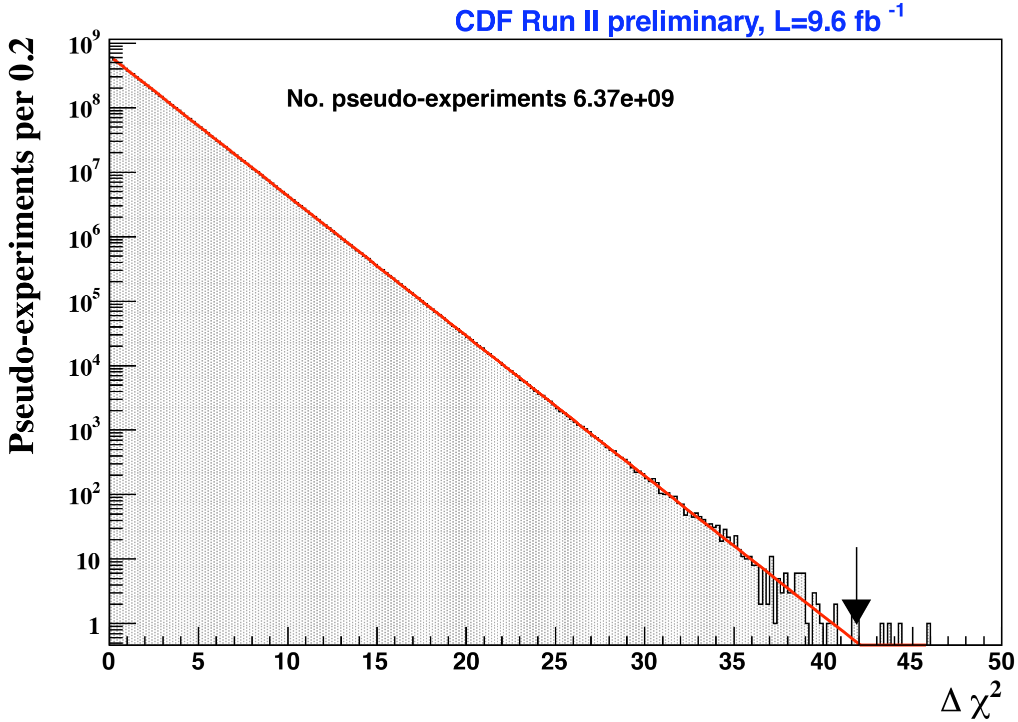


p-value test

- Toy MC: 6.37×10^9 pseudo-experiments.
- In each experiment, the WS/RS decay rate ratio vs. time is simulated assuming no-mixing.
- In each time bin, the WS/RS ratio is extracted according to a gaussian distribution with mean $R_D=4.3\times10^{-3}$ (from the constant fit to data) and sigma equals to the error bar from the data.
- Distribution of the χ^2 difference between the mixing and no-mixing fits for all the experiments.
- 5 experiments gives a $\Delta\chi^2 > 41.86$ as in the fit to data. The probability is

$$\left(7.9^{+5.4}_{-3.4}\right)\times10^{-10}$$

which corresponds to a significance of $$\left(6.15^{+0.09}_{-0.08}\right)\sigma$$



Bias in WS/RS due to non-prompt contamination

Let's indicate with N^x (N_B^x) the number of prompt (non-prompt) $x = WS$ or RS decays reconstructed at a given proper time t (in unit of D^0 lifetimes). When the non-prompt component is not subtracted, then the measured WS/RS ratio, $\mathscr{R}_m$, at a given decay time t, is:

$$\mathscr{R}_m = \frac{N^{WS} + N_B^{WS}}{N^{RS} + N_B^{RS}} = \frac{N_B^{RS}}{N^{RS} + N_B^{RS}} \left(\frac{N^{RS}}{N^{RS}} \frac{N^{WS}}{N_B^{RS}} + \frac{N_B^{WS}}{N_B^{RS}} \right) = \frac{N_B^{RS}}{N^{RS} + N_B^{RS}} \left(\frac{N^{WS}}{N^{RS}} \frac{N^{RS}}{N_B^{RS}} + \frac{N_B^{WS}}{N_B^{RS}} \right) \tag{1}$$

We define

$$\mathrm{f}_B^{RS} = \frac{N_B^{RS}}{N^{RS} + N_B^{RS}} \qquad \mathscr{R} = \frac{N^{WS}}{N^{RS}} \qquad \mathscr{R}_B = \frac{N_B^{WS}}{N_B^{RS}} \qquad \Delta_B = \mathrm{f}_B^{RS} \left(1 - \frac{\mathscr{R}_B}{\mathscr{R}} \right)$$

where f_B^{RS} is the fraction of secondary decays in the RS sample; $\mathscr{R}$ and $\mathscr{R}_B$ are the ratio of prompt D^0's and non-prompt D^0's from B meson decays, respectively; Δ_B is a time dependent bias due to secondary contamination. One can rewrite Eq. 1 as

$$\mathscr{R}_m = \mathrm{f}_B^{RS} \left(\mathscr{R} \frac{N^{RS}}{N_B^{RS}} + \mathscr{R}_B \right) =$$

$$= \mathrm{f}_B^{RS} \mathscr{R} \frac{N^{RS}}{N_B^{RS}} + \mathrm{f}_B^{RS} \mathscr{R}_B = \left(1 - \mathrm{f}_B^{RS}\right) \mathscr{R} + \mathrm{f}_B^{RS} \mathscr{R}_B$$

$$\mathscr{R}_m = \mathscr{R} \left[1 + \mathrm{f}_B^{RS} \left(\frac{\mathscr{R}_B}{\mathscr{R}} - 1 \right) \right] = \mathscr{R} \left[1 - \Delta_B \right] \tag{2}$$

Bias in WS/RS due to non-prompt contamination (cont.)

Reminding that $\mathscr{R}(t)$ is a monotonic increasing function of t and that for non-prompt decays the reconstructed proper time, t, overestimates the true proper time of the D^0 meson, t' (being $t \approx t_B + t' \geq t'$, where t_B is the B meson decay time), one has:

$$\mathscr{R}(0) \leq \mathscr{R}_B(t) = \mathscr{R}(t') \leq \mathscr{R}(t) \quad \Longrightarrow \quad \frac{\mathscr{R}(0)}{\mathscr{R}(t)} \leq \frac{\mathscr{R}_B(t)}{\mathscr{R}(t)} \leq 1 \quad \forall t \tag{3}$$

It follows that the bias in the evaluation of $\mathscr{R}(t)$ when neglecting the non-prompt contribution in the WS/RS ratio, $\Delta_B(t)$, is bounded from the upper side:

$$0 \leq \Delta_B(t) \leq \mathrm{f}_B^{RS}\left(1 - \frac{\mathscr{R}(0)}{\mathscr{R}(t)}\right) \tag{4}$$

Maximum bias

- **The maximum bias can be calculated by estimating (from data) the fraction f_B of secondary decays in the RS sample as a function of time.**
- **To calculate the actual bias, we also need to know the non-prompt WS/RS ratio ($R_B(t)$ in eq. 2). This can be estimated from MC. We named it MC bias in the next slides.**

Modified χ^2 function for WS/RS fit

$$\chi^2 = \sum_{i=1}^{20}\left[\frac{r_i - R(t_i)\left(1-\Delta_B(t_i)\right)}{\sigma_i}\right]^2 + \sum_{k=0}^{4}\sum_{l=0}^{4}\left(p_k-\theta_k\right) V_{kl}^{-1}\left(p_l-\theta_l\right) + \sum_{i=1}^{20}\sum_{\substack{j=1,\\ j\neq \text{empty}}}^{100}\left(\frac{h_{ij}-\tilde{h}_{ij}}{\Delta h_{ij}}\right)^2$$

$$\chi^2 = \sum_{i=1}^{20}\left[\frac{r_i - R(t_i)\left(1-f_B(t_i)\left(1-\frac{R_B(t_i)}{R(t_i)}\right)\right)}{\sigma_i}\right]^2 + \sum_{k=0}^{4}\sum_{l=0}^{4}\left(p_k-\theta_k\right) V_{kl}^{-1}\left(p_l-\theta_l\right) + \sum_{i=1}^{20}\sum_{\substack{j=1,\\ j\neq \text{empty}}}^{100}\left(\frac{h_{ij}-\tilde{h}_{ij}}{\Delta h_{ij}}\right)^2$$

$$\chi^2 = \sum_{i=1}^{20}\left[\frac{r_i - R(t_i) + R(t_i)f_B(t_i) - R_B(t_i)f_B(t_i)}{\sigma_i}\right]^2 + \sum_{k=0}^{4}\sum_{l=0}^{4}\left(p_k-\theta_k\right) V_{kl}^{-1}\left(p_l-\theta_l\right) + \sum_{i=1}^{20}\sum_{\substack{j=1,\\ j\neq \text{empty}}}^{100}\left(\frac{h_{ij}-\tilde{h}_{ij}}{\Delta h_{ij}}\right)^2$$

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

Mixing function

$$R_B(t_i) = \frac{\sum_{j=1}^{M}\tilde{h}_{ij}R\left(t'_j\right)}{\sum_{j=1}^{M}\tilde{h}_{ij}}$$

We can estimate R_B (i.e. non-prompt WS/RS ratio) in each time-bin *i* (we are using for data) from MC.

For each time-bin i, we use the MC histogram h_{ij} of the non-prompt D^0 decay time t' (to B-vertex), binned in M bins (j=1,..,M=100).

$\tilde{h}_{ij}$ are nuisance parameters, gaussian constrained to the counts h_{ij} of the MC histograms, with statistical error Δh_{ij}. We have 907 parameters corresponding to non empty h_{ij} bins.

Modified χ^2 function for WS/RS fit (cont.)

- r_i are the 20 measured WS/RS points with error σ_i
- p_k (k=0, …, 4) are 5 parameters used to model the time dependence of the secondary fraction f_B.
- V_{kl} is the covariance matrix of the parameters p_k
- θ_κ are nuisance parameters, gaussian constrained to the values (p_k) from sec. fraction f_B vs. time fit