$D^0 – \overline{D}^0$ Mixing Measurement at LHCb

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Outline

- Introduction
- Charm mixing and analysis strategies
- Trigger and data selection
- Toy simulation studies on the fit of mixing parameters
- Summary

Introduction

- Recent history of D^0 mixing meaurements

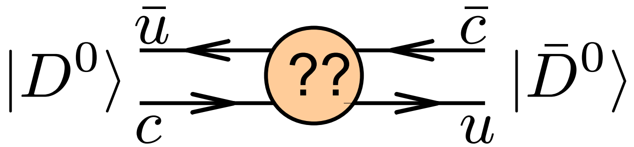
  Beginning of 2007 the Belle and *BABAR* Collaborations presented evidence for $D^0 - \bar{D}^0$ Mixing, CDF II presented evidence end of 2007

  A combination of all mixing measurements provides a ~10 σ effect

- Neutral meson mixing has been already observed in the *K* (1956), *B* (1987) and B_s (2006) systems
- Why is D^0 mixing interesting ?
  - Processes with down type quarks are involved in the mixing loop
  - Within the Standard Model mixing and CP violation in the charm sector are expected to be small
  - Depending on the measured values of the parameters it could indicate new physics
- Discuss prospects to measure D^0 mixing in the decay $D^0 \to K\pi$ at LHCb

Mixing Formalism

Neutral D^0 mesons are created as flavor eigenstates of the strong interaction. They can mix through weak interactions.



- The time evolution is obtained by

$$i\frac{\partial}{\partial t}\begin{pmatrix} D^0(t) \\ \bar{D}^0(t) \end{pmatrix} = (M - \frac{i}{2}\Gamma)\begin{pmatrix} D^0(t) \\ \bar{D}^0(t) \end{pmatrix}$$

- The physical eigenstates are D_1 and D_2:

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

$$|D_{1,2}(t)\rangle = e^{-i(M_{1,2}-i\Gamma_{1,2}/2)t}|D_{1,2}(t=0)\rangle$$

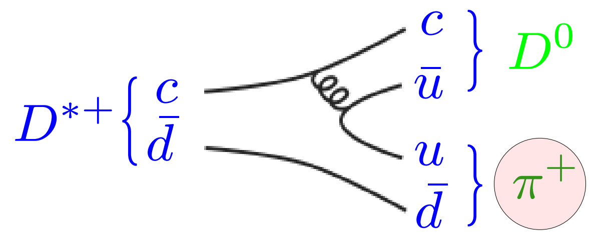
D_1 : CP even
D_2 : CP odd

- Define mass and lifetime differences of D_1 and D_2:

$$x = \frac{\Delta M}{\Gamma} = \frac{M_1 - M_2}{\Gamma} \qquad y = \frac{\Delta\Gamma}{2\Gamma} = \frac{\Gamma_1 - \Gamma_2}{2\Gamma}$$

$$\Gamma = \frac{\Gamma_1 + \Gamma_2}{2}$$

Mixing in $D^0 \to K\pi$ - Flavor Tagging



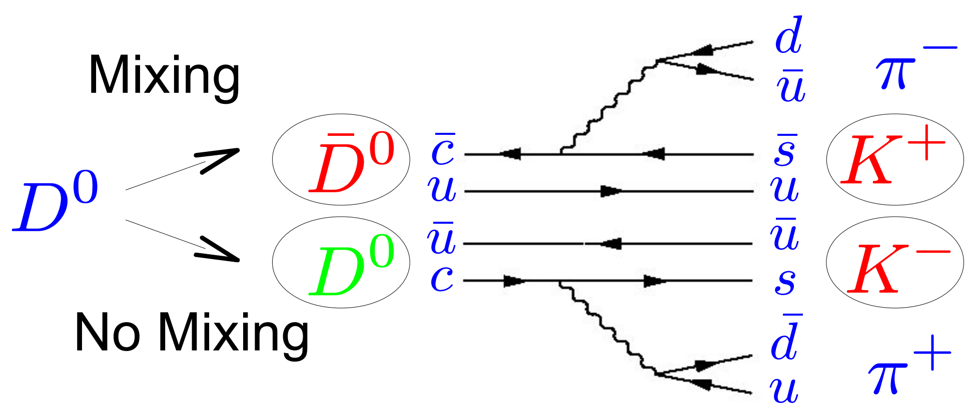
- Flavor tagging at production time
  - Standard technique in charm physics: use

    $$Q = m(D^0\pi^+) - m(D^0) - m(\pi^+) \approx 6 MeV$$

    - Narrow peak in $\Delta m = m(D^0\pi^+) - m(D^0)$ due to a small Q
    - The charge of the low energy π determines the flavor of the D^0

- Flavor at decay time
  - Use final state particle properties to tag the D^0 flavor at the decay time

$D^0 \to K\pi$:

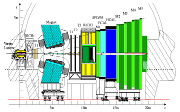


Wrong Sign Decay (WS)

D^0 Mixing

Right Sign Decay (RS)

no D^0 Mixing

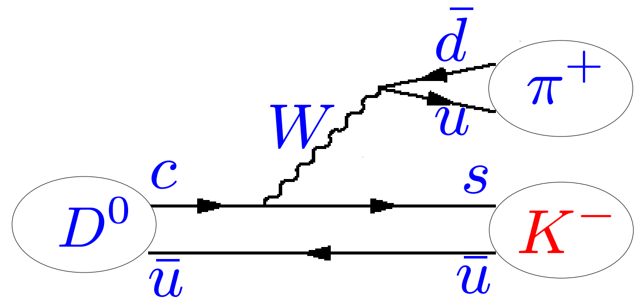


Decays Classes $D^0 \to K\pi$

The flavor tagging at decay time does not uniquely identify Mixing in hadronic D^0 decays

Cabibbo favored (CF) decay

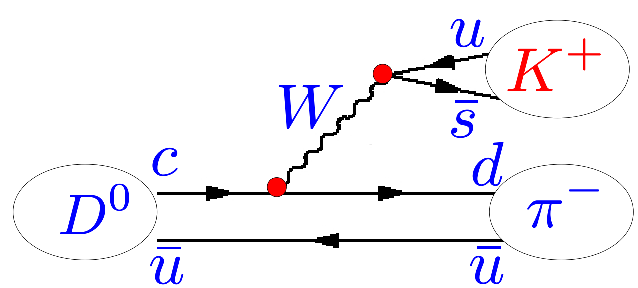
$R \approx 1$



RS decays

Doubly Cabibbo suppressed (DCS) decay

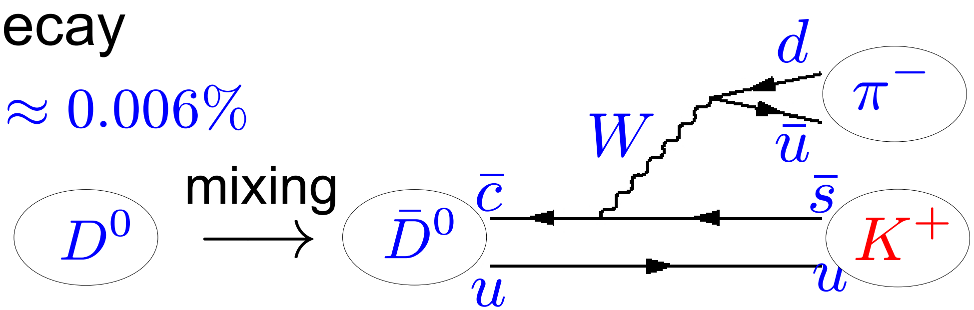
$R_D \approx 0.3\%$



WS decays

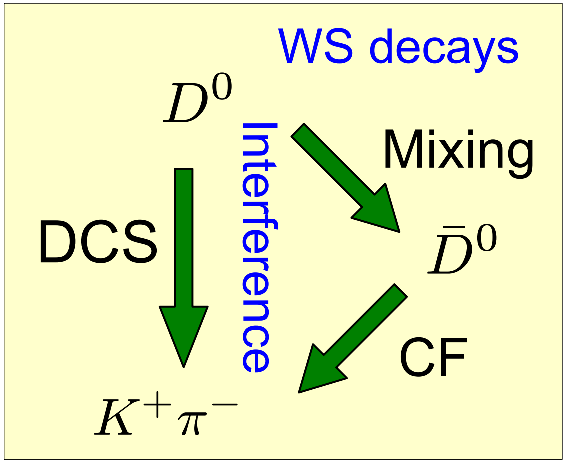
Mixed CF decay

$R_M \approx 0.006\%$



Interference between DCS and mixed CF decay

Time Evolution in $D^0 \rightarrow K\pi$ Decays



- Discriminate DCS and mixing by their proper time evolution
  - DCS: exponential time distribution
  - mixed decays occur with a time structure

- Time evolution of the WS decay rate

assume CP conservation and $|x| \ll 1 \; ; \; |y| \ll 1$

$$T_{WS}(t) \propto e^{-\Gamma t} \left(\underbrace{R_D}_{\text{DCS}} + \underbrace{\sqrt{R_D}\, y' \,\Gamma t}_{\text{Interference}} + \underbrace{\frac{x'^2 + y'^2}{4} (\Gamma t)^2}_{\text{Mixing}} \right)$$

DCS   Interference   Mixing

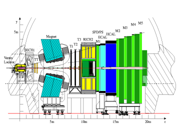
$$\int_t = \frac{x'^2 + y'^2}{2} = R_M$$

- Strong phase $\delta_{K\pi}$

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

$$y'^2 + x'^2 = x^2 + y^2$$

$\delta_{K\pi}$ is the strong phase between CF and DCS amplitudes ($D^0 \rightarrow K\pi$)



Analysis Strategy

BABAR approach

- Determine signal and background PDF's by unbinned max. likelihood fit
- Unbinned maximum likelihood fit of the wrong sign D^0 decay time distribution

BABAR (384 fb^{-1})
PRL 98, 211802 (2007)

Use the fit results of RS decay time and the resolution function

no mixing fit: R_D

$$\frac{\Gamma_{WS}(t)}{e^{-\Gamma t}} = R_D + y'\sqrt{R_D}\Gamma t + \frac{x'^2 + y'^2}{4}(\Gamma t)^2$$

mixing fit: the full expression

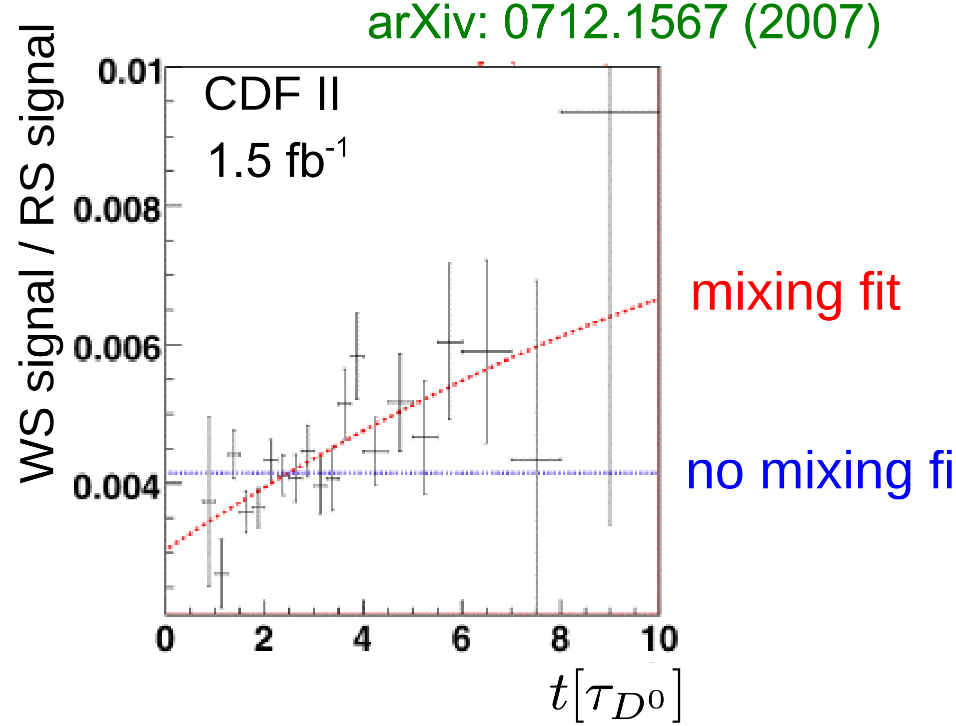
CDF approach

- Measure the Number of WS and RS D^0 decays in bins of the decay time

$$N_{RS}^{tot} = (3.044 \pm 0.0023) \cdot 10^6$$
$$N_{WS}^{tot} = (12.7 \pm 0.3) \cdot 10^3$$

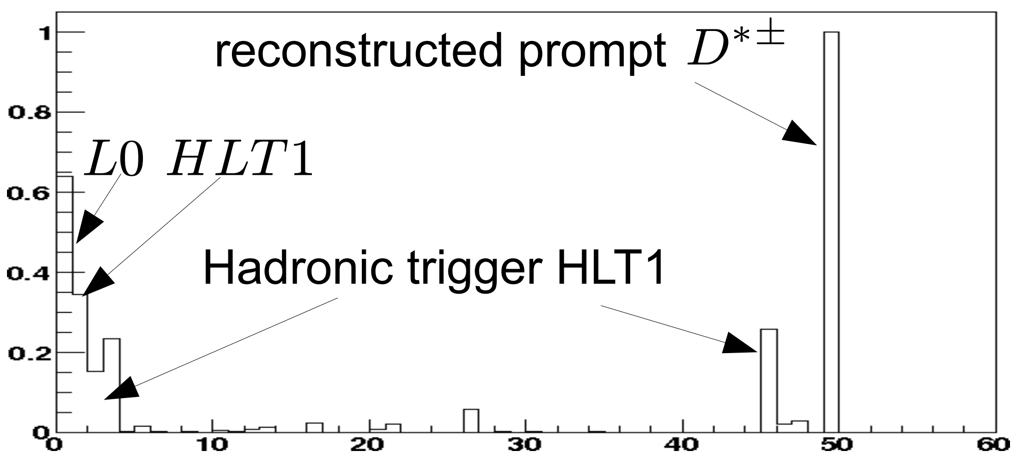
- Fit the $N_{WS}^{tot}/N_{RS}^{tot}$ vs the D^0 decay time

arXiv: 0712.1567 (2007)



MC Data Sample

- Data samples
  - $D^{*+} \to \pi^+(D^0 \to \{K^+\pi^-, K^-\pi^+\}) + cc$
    $1 \cdot 10^7$ signal events $\equiv \int \mathcal{L} \approx 0.33\, pb^{-1}$
  - $3.6 \cdot 10^6$ L0 triggered min. bias events
- Trigger mainly via hadron lines



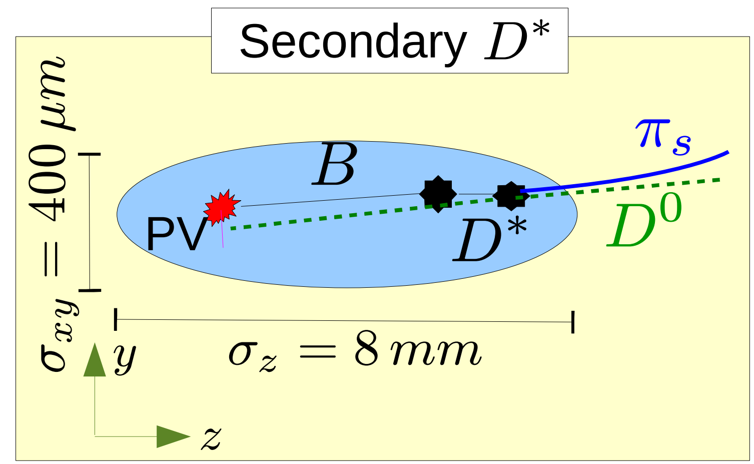
65 % L0 triggered

35 % L0 ∩ HLT1 triggered

- Selection $D^0 \to K\pi$ via $D^* \to \pi D^0 \to \pi K \pi$
  - Perform a preselection based on m, p, p_t of the D^*, D^0 and the daughter hadrons.
  - Final selection is based on
    - ✗ particle id of K, π
    - ✗ track and vertex fit quality
    - ✗ track distance and significance of π_s to the primary vertex and of K, π to the D^0 vertex
    - ✗ D^0 flight length significance
    - ✗ pointing to primary vertex

Data Selection Results

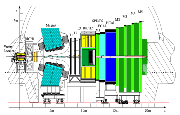
	signal		minbias
	RS	WS	RS
signal	8325(8617)	48(52)	9(9)
background	483(650)	25(199)	2(2)
secondary D*	318(327)	1(1)	1(1)
ghosts	131(168)	3(19)	0(0)
double mis-id	0(0)	5(15)	0(0)
random SlowPi	16(127)	12(151)	1(1)
D^0 combinatoric	0(0)	0(0)	0(0)



Secondary D^* background: 3.5%

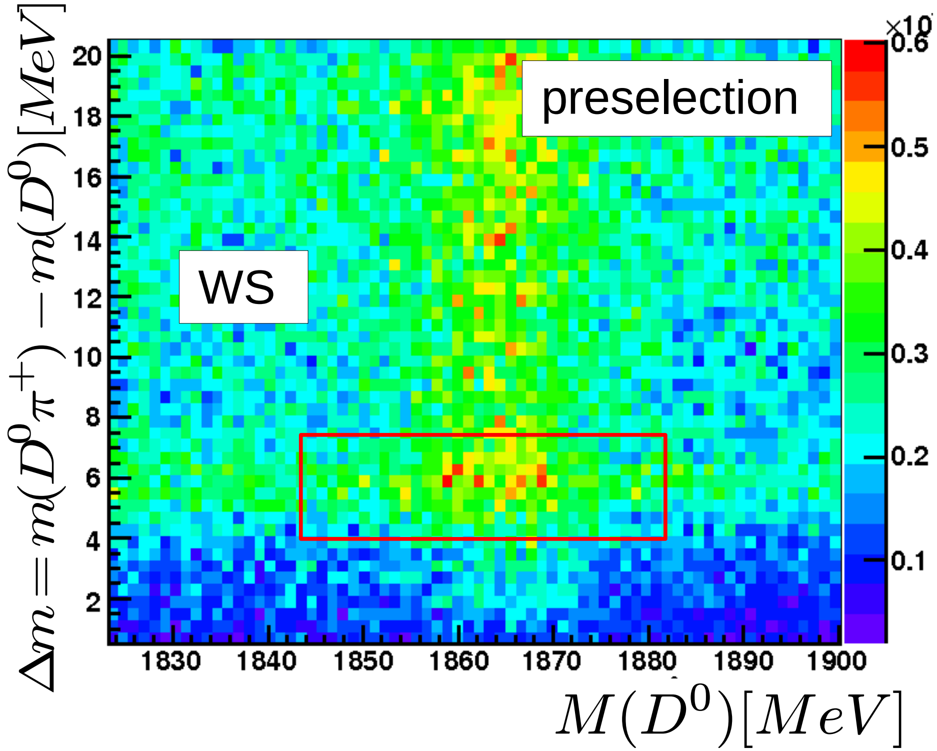
produces D^0 which seem to have large decay length

- Selection efficiency on HLT1 triggered events: $\epsilon_{sel} = 0.10$
- Expected RS (WS) events $\int \mathcal{L} \approx 50\,pb^{-1} \equiv 1.3 \cdot 10^6 \quad (4.5 \cdot 10^3)$



WS and RS Data

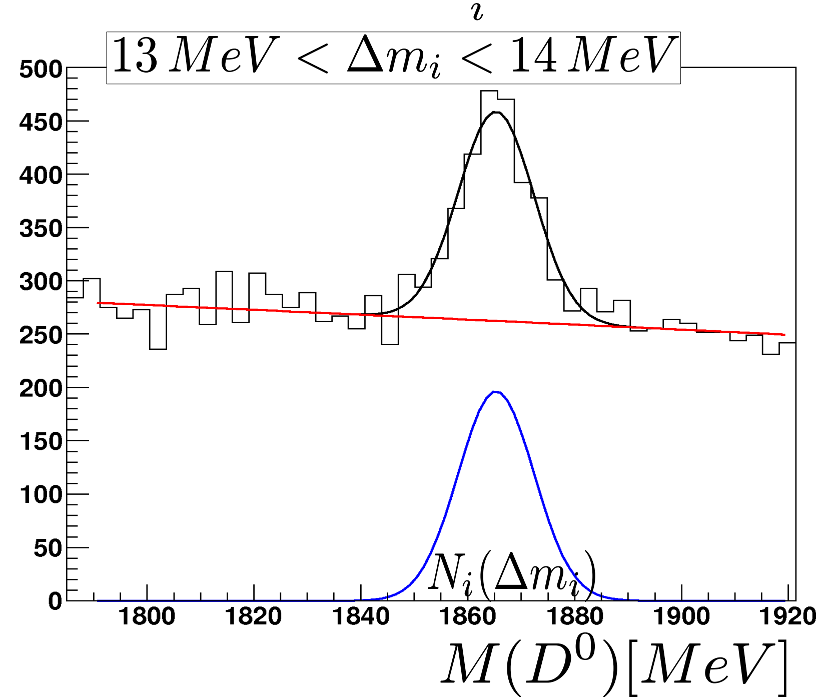
➢ Events in the $\Delta m, M(D^0)$ plane



- background contributions
  - random slow π
  - mis id π or K
  - combinatoric

➢ Extract N_{RS} and N_{WS}

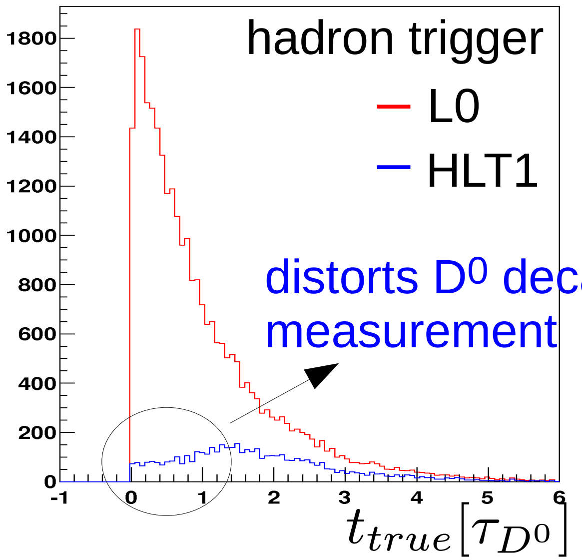
- Split data in $\Delta t_j(D^0)$
- Obtain for each bin Δm_i the number of signal events $N_i(\Delta m_i)$ in a fit to the D^0 mass distribution
- $N_{RS/WS}(\Delta t_j) = \sum_i N_i(\Delta m_i)$



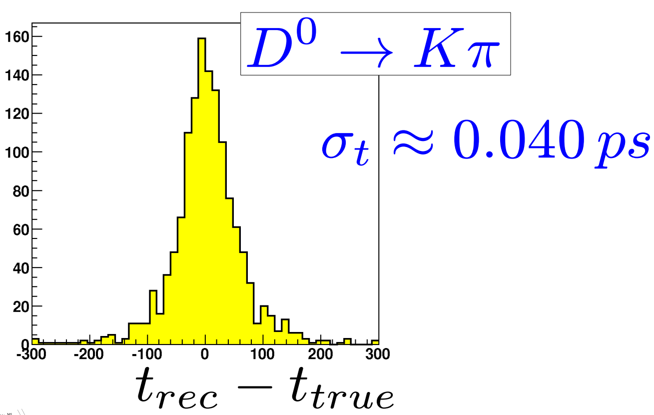
D^0 Lifetime and Mass

- D^0 lifetime in trigger

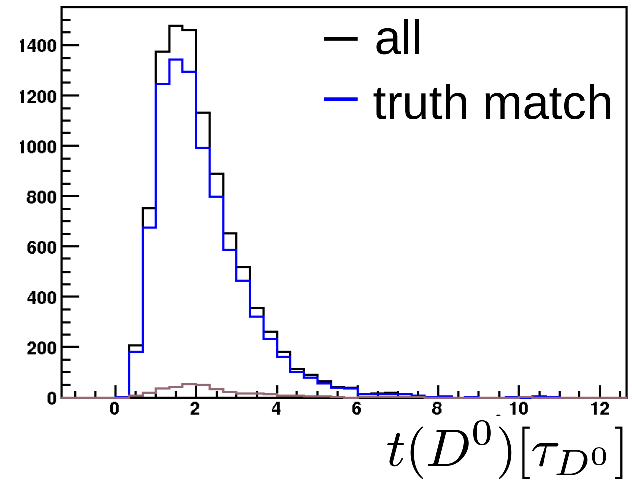
reconstructible prompt $D^{*\pm}$



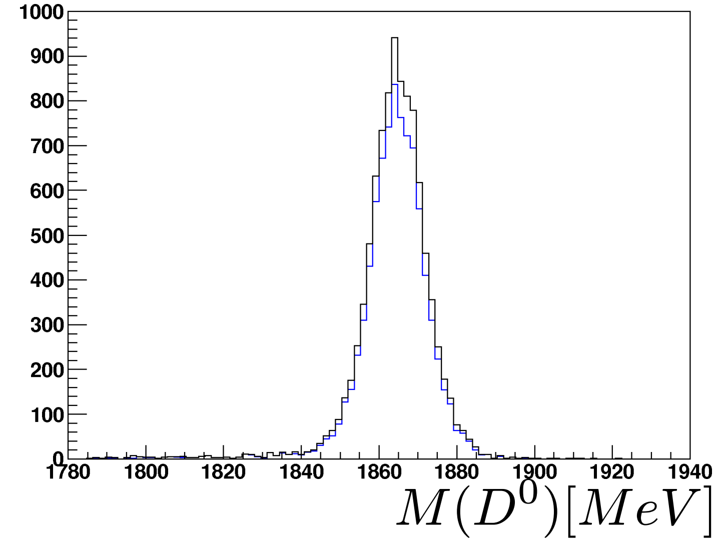
- Time resolution



- D^0 lifetime after selection



- D^0 mass after selection

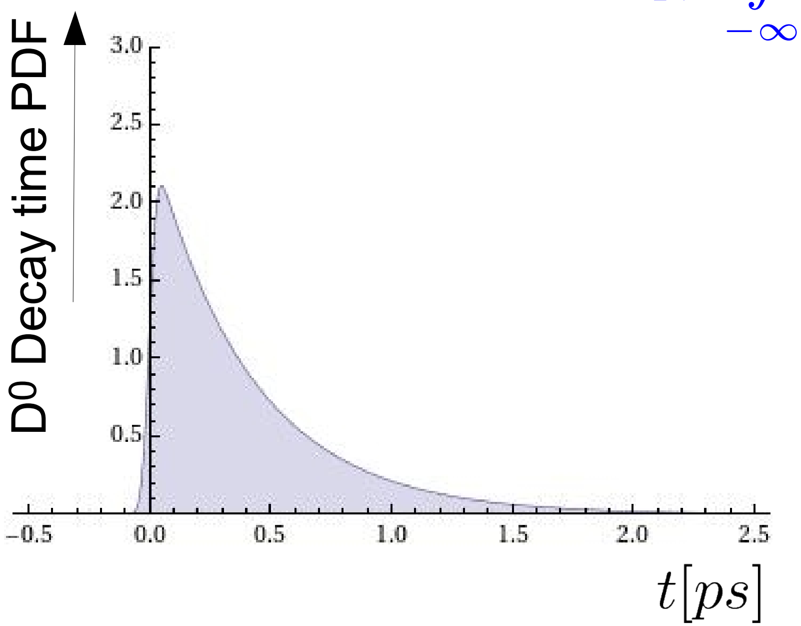


Toy MC Simulation

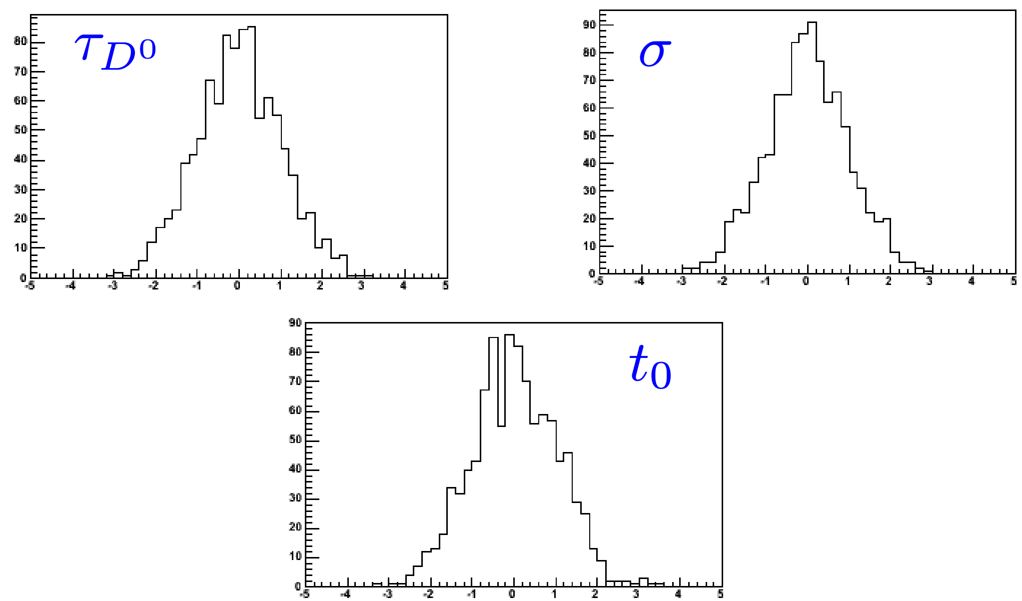
Develop Toy Monte Carlo Simulations to understand mixing parameter extraction, fitting strategies and statistical significance of the results.

- Determine D^0 decay time and time resolution in RS events using an unbinned maximum likelihood fit to the lifetime measurement.

$$PDF(t;\tau,t_0,\sigma) = \frac{\theta(t)}{N} \int_{-\infty}^{+\infty} e^{t'/\tau} e^{-\frac{(t_0-t'-t)^2}{2\sigma^2}} dt'$$

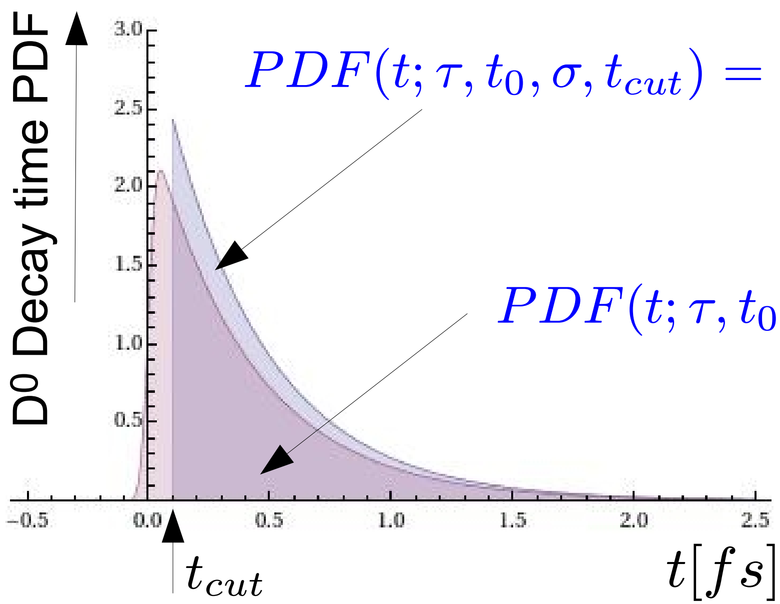


Pull Distributions: 1000 toy sets, 10^6 events



Toy Simulations – RS Decays

- Cut in the D^0 lifetime distributions



$$PDF(t;\tau,t_0,\sigma,t_{cut}) = \frac{\theta(t)}{N(t_{cut})}\int_{t_{cut}}^{+\infty} e^{t'/\tau} e^{-\frac{(t_0-t'-t)^2}{2\sigma^2}} dt'$$

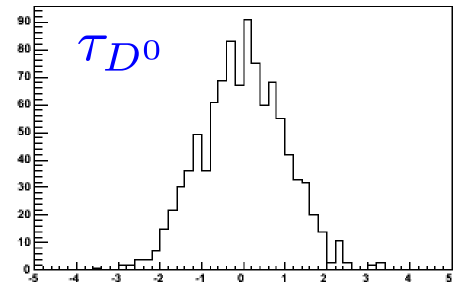
$$PDF(t;\tau,t_0,\sigma) = \frac{\theta(t)}{N}\int_{-\infty}^{+\infty} e^{t'/\tau} e^{-\frac{(t_0-t'-t)^2}{2\sigma^2}} dt'$$

$t_{cut} = 0.5 \cdot \tau_{D^0}$

Applying t_{cut} the fit does not allow to determine t_0, σ

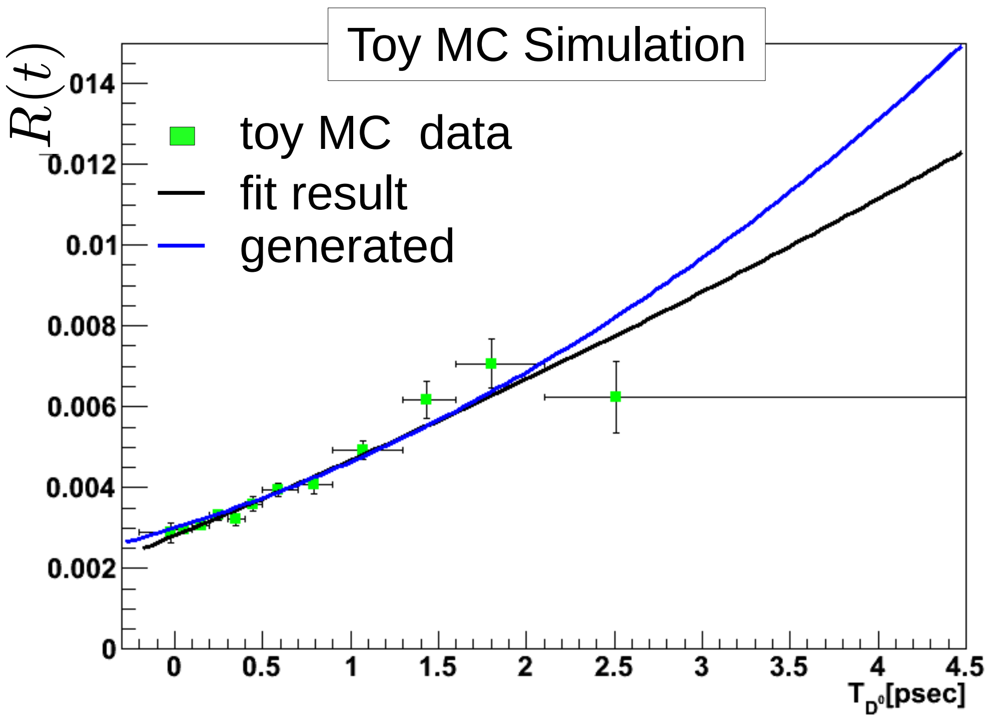
Still measure D^0 decay time

Pull Distribution: 1000 toy simulations, 10^6 events:



Mixing Parameter Determination

- Measure the number of WS and RS $D^0 \to K\pi$ decays in bins of of the decay time t and determine $R(t) = N_{WS}/N_{RS}\,(t)$



- Simulate decay time distributions of of WS and RS decays

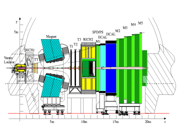
$\sigma_t = 0.040\,ps \qquad \tau_{D^0} = 0.41\,ps$

$x = 0.01 \quad y = 0.01 \quad R_D = 0.003$

- Obtain N_{RS} and N_{WS} for a given binning in the decay time
- Fit $R = N_{WS}/N_{RS}$ as function of the average decay time in each bin

$$\to \sqrt{R_D},\, y',\, x'^2$$

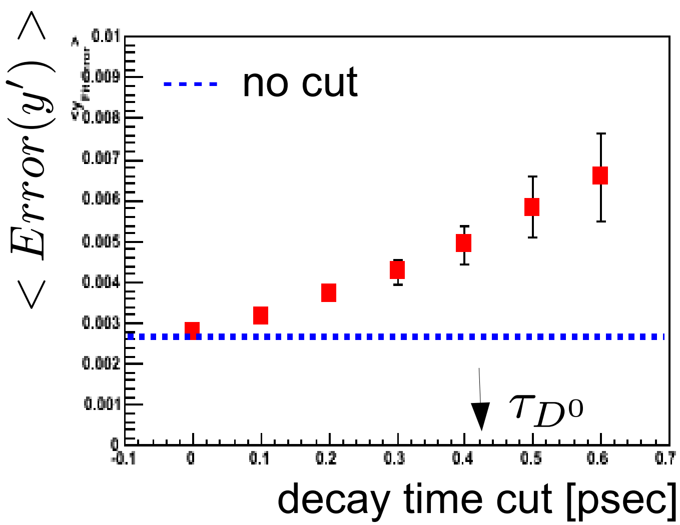
$$R(t) = R_D + y'\sqrt{R_D}\frac{t}{\tau_{D^0}} + \frac{x'^2 + y'^2}{4}\left(\frac{t}{\tau_{D^0}}\right)^2$$

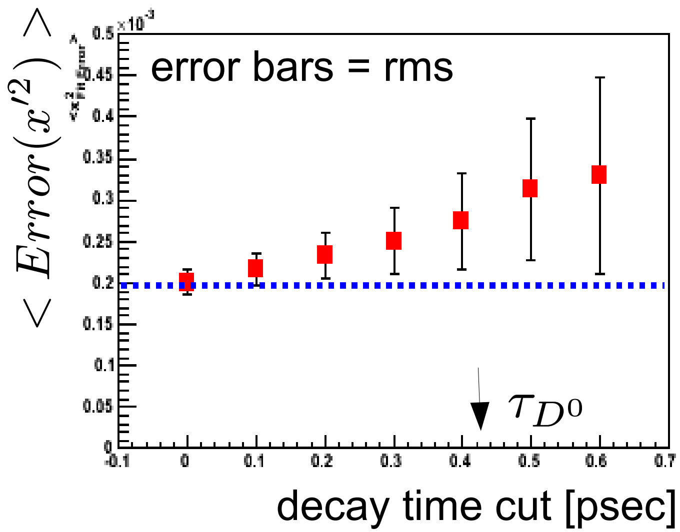


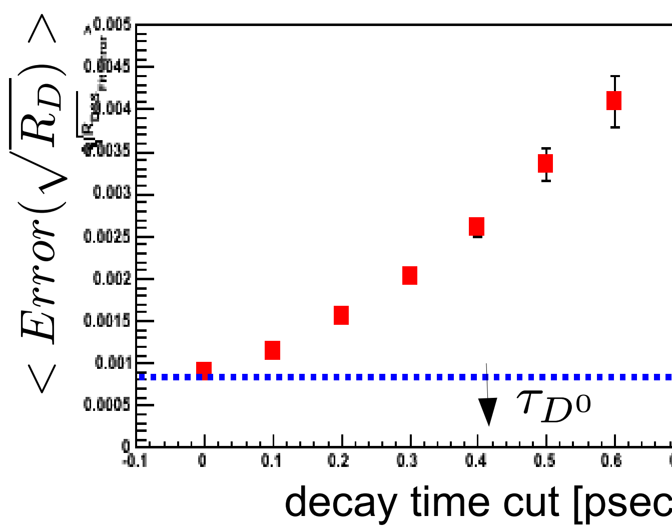
Fit Results - Decay Time Acceptance

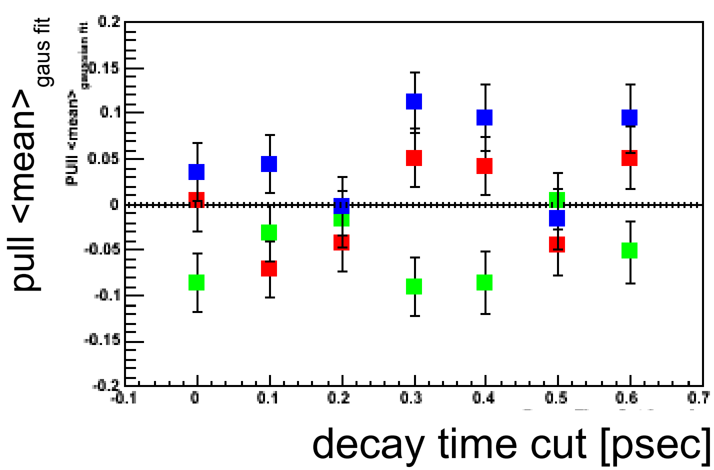
- Systematic errors due to cuts in the decay time distribution

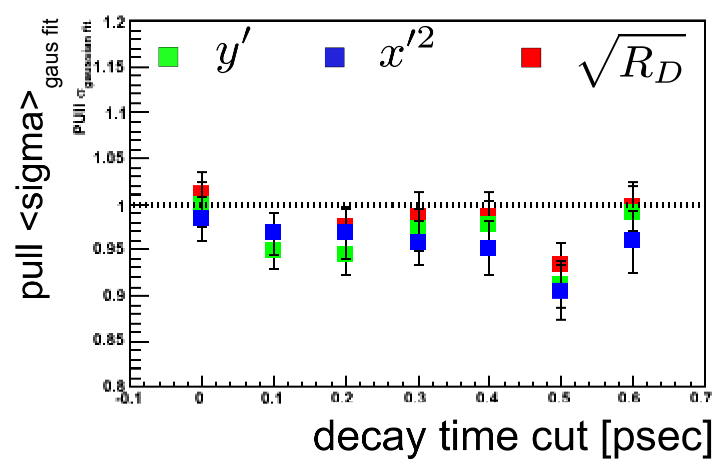
Generate 1000 toy sets / point (10^6 events each) for different cuts in decay time

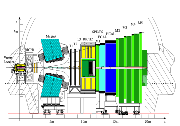












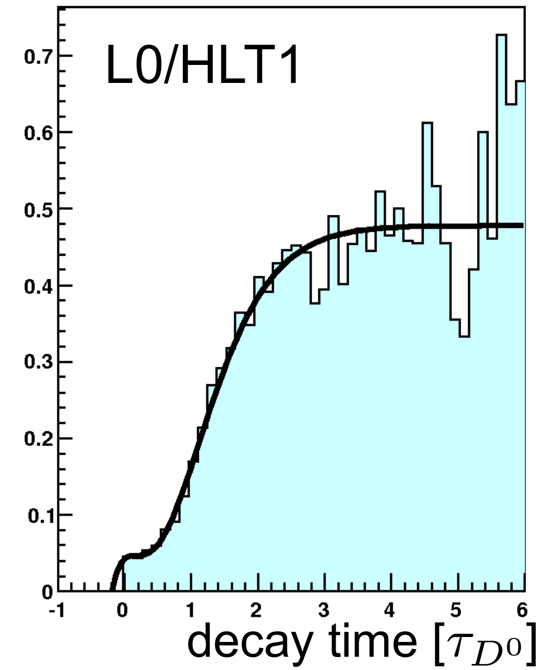
Fit Results - Decay Time Acceptance

➢ Decay time acceptance from the trigger

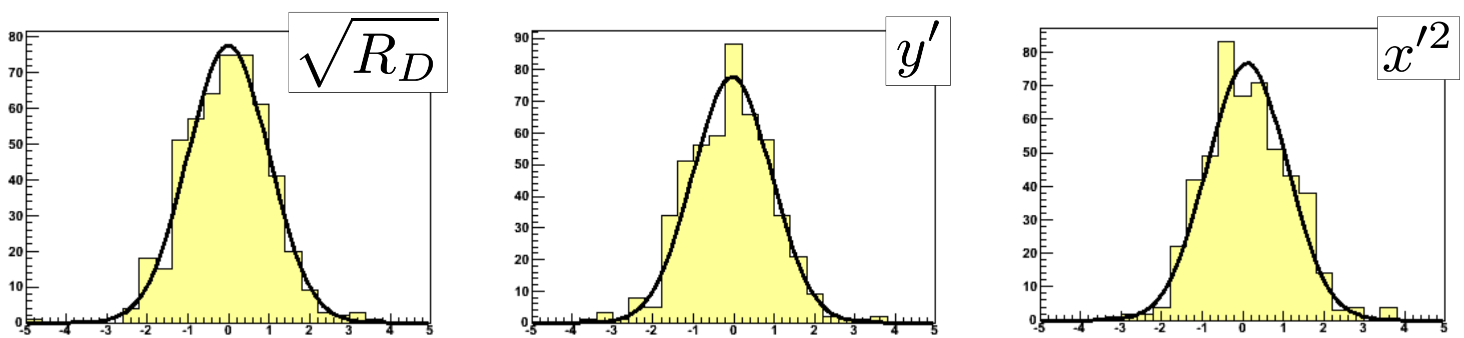
Using triggered prompt $D^{*\pm}$ decays the HLT1 acceptance is derived and included in the toy simulation.
Decay time resolution: $\sigma_t = 0.040\ ps$

- Errors of the mixing parameters are similar to the no cut case

- Mean and width of the pull distributions of the mixing parameters show that the fit is unbiased



Pull Distributions: 500 toy simulations, 10^6 events

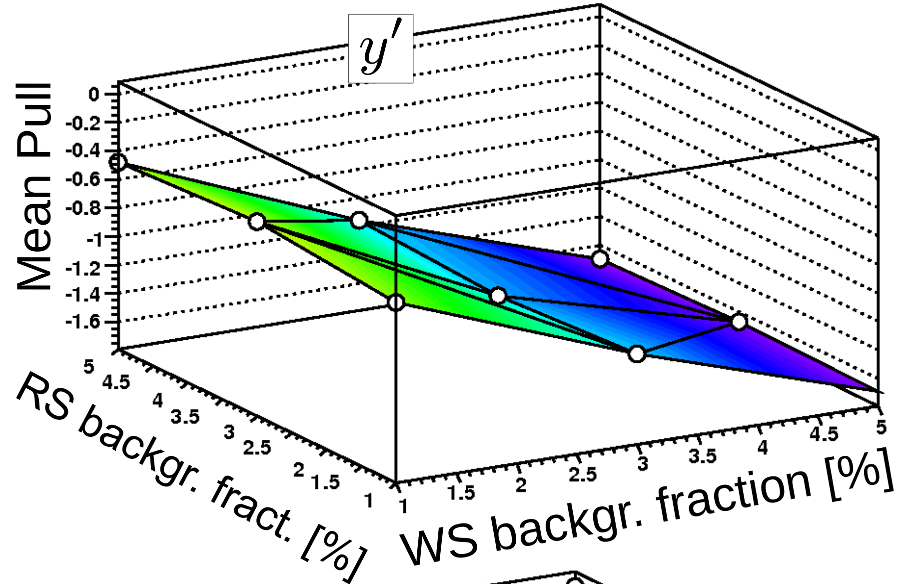


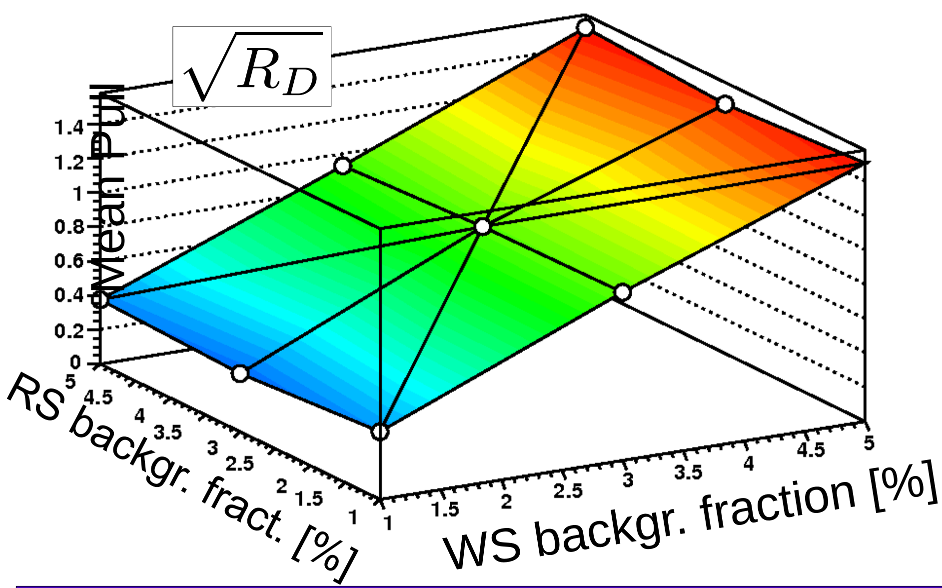
Fit Results - Background Dependence

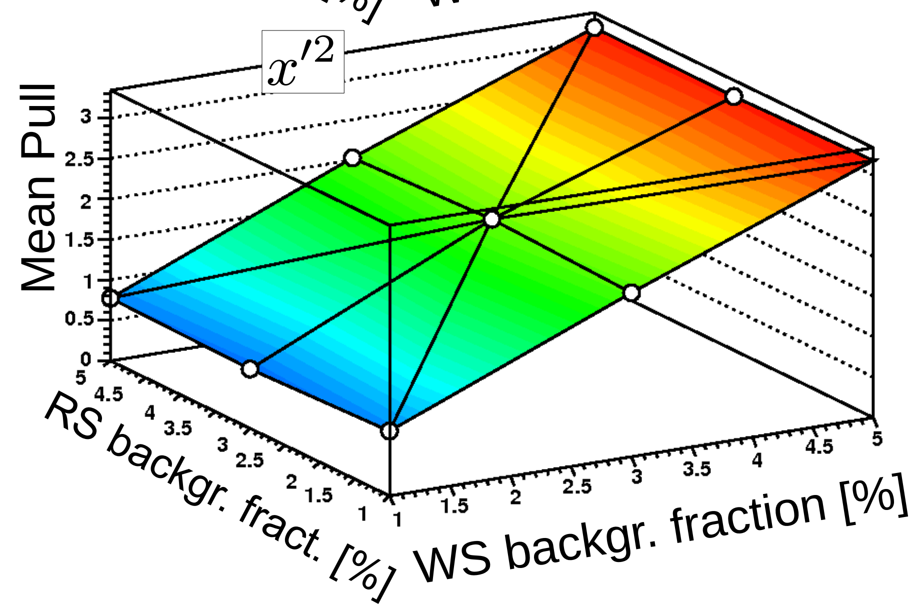
- Systematic errors due to $B \to D^*$

  $D^{*\pm}$ from B decays are background to the WS and RS decay time distributions. Simulate exponential decay time distr. from B decays.

  - Errors and width of the pull distr. of the mixing parameters are unchanged
  - Systematic changes of the mixing parameters on the 3 sigma level



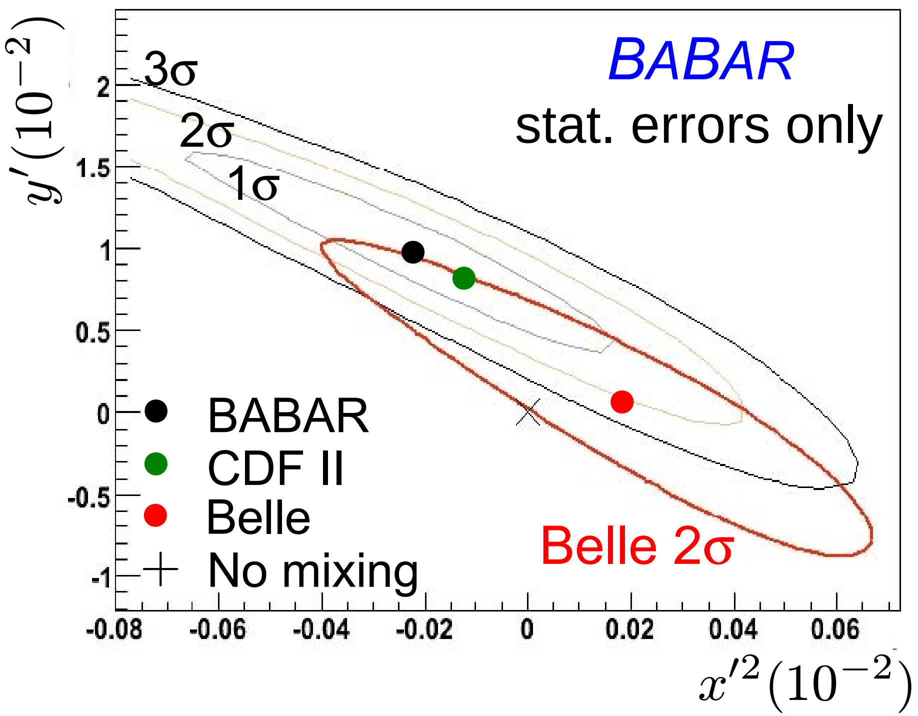




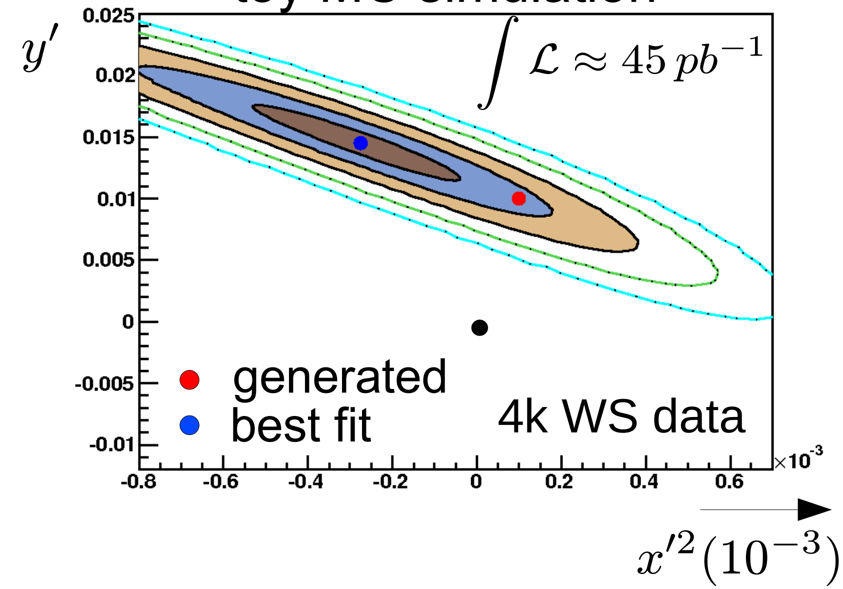
Prospects at LHCb

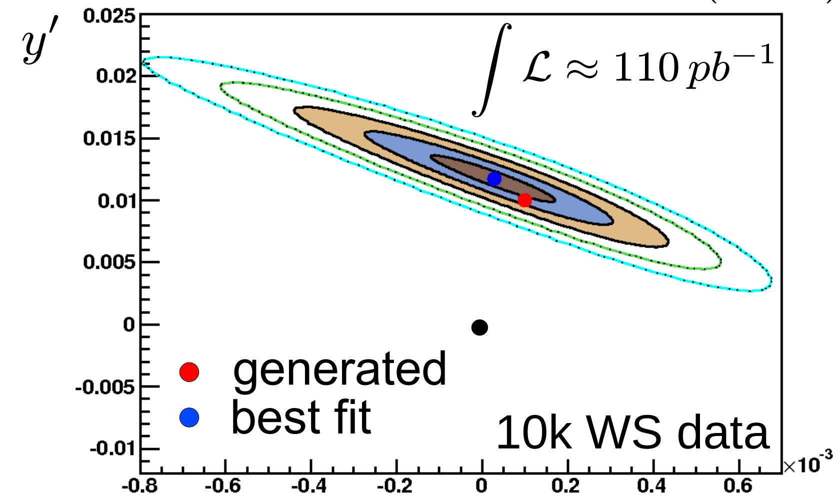
➢ Compare $D^0 \to K\pi$ results

recent measurements



toy MC simulation





Summary

- 50 pb^{-1} of LHCb data yields the amount of $D^0 \to K\pi$ events used in the *BABAR* D^0 mixing analysis
- We select $D^0 \to K\pi$ events in HLT1 triggered data with 10 % selection efficiency
- Using toy MC we test a scheme to extract decay time and mixing parameters in fits to RS and WS $D^0 \to K\pi$ decay time distributions

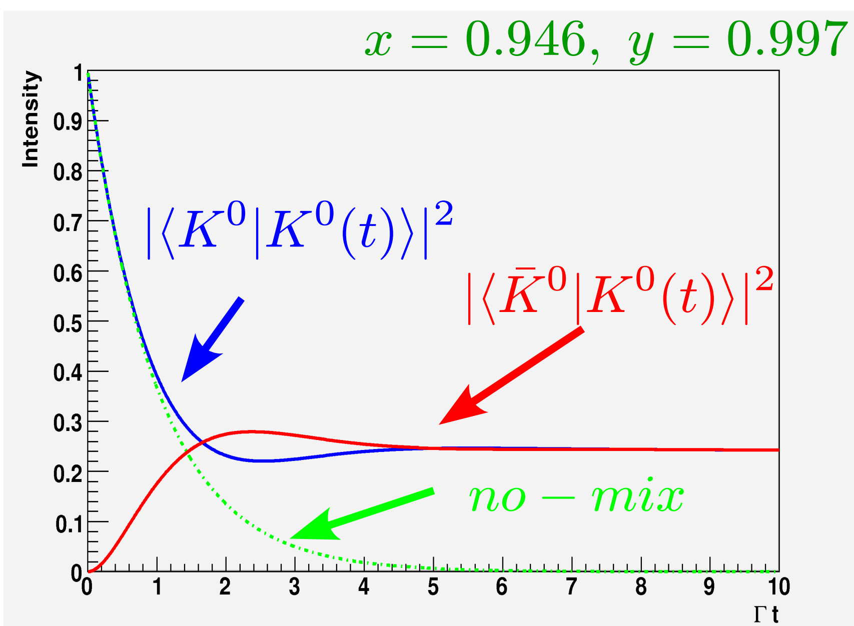
Back up Slides

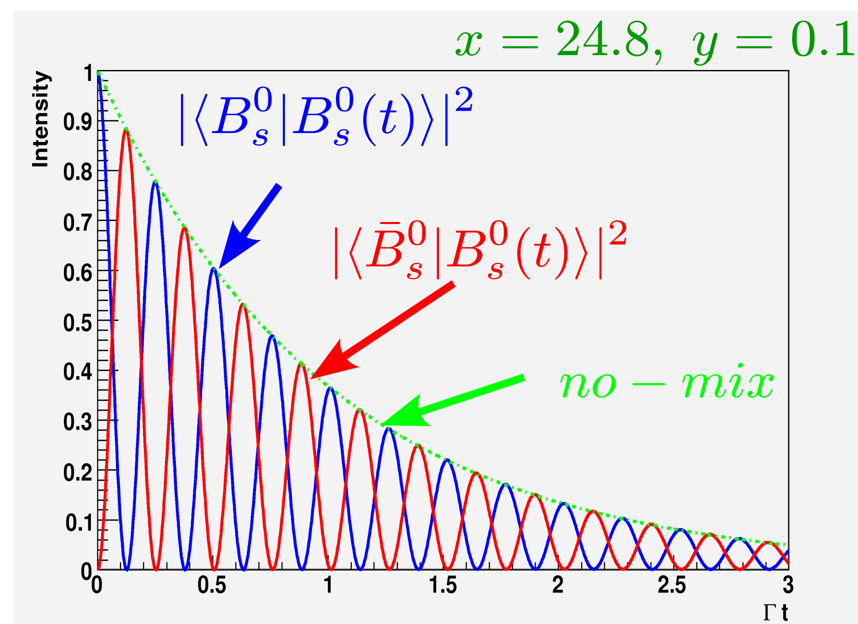
Time Evolution and Mixing

Mixing will occur if either x or y is non – zero. The time evolution of the probability to find a D^0($\bar{D}^0$) after a time t is:

$$I(D^0 \to D^0; t) \; : \; |\langle D^0 | D^0(t) \rangle|^2 = \frac{e^{-\Gamma t}}{2}[cosh(y\Gamma t) + cos(x\Gamma t)]$$

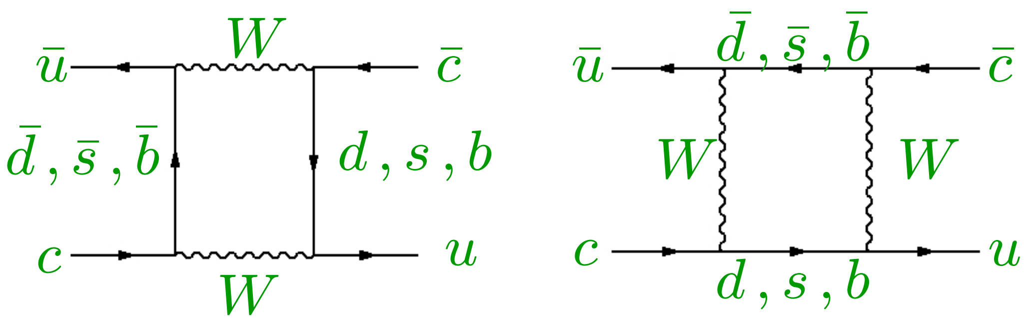
$$I(D^0 \to \bar{D}^0; t) \; : \; |\langle \bar{D}^0 | D^0(t) \rangle|^2 = \frac{e^{-\Gamma t}}{2}[cosh(y\Gamma t) - cos(x\Gamma t)]|\frac{p}{q}|^2$$





Charm Mixing Processes

- The box diagram contributions to charm mixing in the Standard Model are expected to be very small
  - ❖ d-type quarks enter the mixing loop



  - ❖ Suppression by
    - GIM mechanism (d,s)

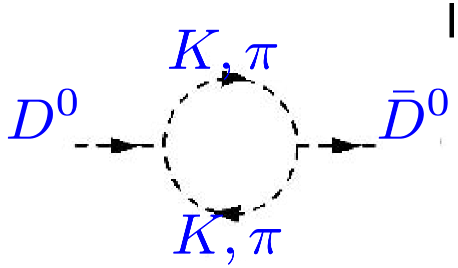
$$x \sim \frac{m_s^2 - m_d^2}{m_c^2}$$

    - CKM matrix (b)

  - ❖ Lowest order short distance calculation: $x_{box} \approxeq O(10^{-5})$ $y_{box} \approxeq O(10^{-7})$
  - ❖ x and y enhancement due to higher orders in OPE: $x \sim y \approxeq O(10^{-3})$

- Long distance contributions dominate

Numerical predictions lack in precision



$$x \approxeq O(10^{-2})$$

$$y \approxeq O(10^{-2})$$

- New Physics
  - ❖ E.Golowich et al.: arXiv:0705.3650
    Which new physics model can yield sizeable values for x and y
  - ❖ CP violation in charm is small in SM
    Measurement of CPV: New Physics

Selection Details

$PreSelection$

$M(D^0) = M_{PDG} \pm 80\,MeV$
$M(D^*) = M_{PDG} \pm 80\,MeV$
$\Delta M \; < \; 20.5\,MeV$
$p(D^0) > 10\,GeV$
$p_t(D^0) > 2\,GeV$
$p_t(D^*) > 2\,GeV$
$p(h) > 5\,GeV$
$p_t(h) > 500\,MeV$

$$\Delta M = M(D^0\pi) - M(D^*)$$

$Signal\,Region$

$M(D^0) = M_{PDG} \pm 25\,MeV$
$4\,MeV < \; \Delta M \; < 7.5\,MeV$
$IP(D^0) < 0.05\,mm$

$D^0 \& hh$

$DLL(\pi) < 0 \; DLL(k) > 8$
$\chi^2/Ndof(track\,hh) < 2$
$doca < 0.08$
$cos(\xi) < -0.92$
$p_t(D^0) > 5\,GeV$
$p(D^0) > 40\,GeV$
$dira > 0.99997$
$fDistanceSig > 4$
$\chi^2/Ndof(D^0 vtx) < 5$

$D^* \& \pi_{slow}$

$DLL(\pi_s) < -2.5$
$IP(\pi_s) < 0.15\,mm$
$p_t(\pi_s) > 350\,MeV$
$\chi^2/nDoF(track\,\pi_s) < 2$
$IP(D^*) < 0.035\,mm$
$\chi^2/Ndof(D^* vtx) < 5$