Charm Physics at LHCb

Patrick Spradlin

University of Oxford Particle Physics

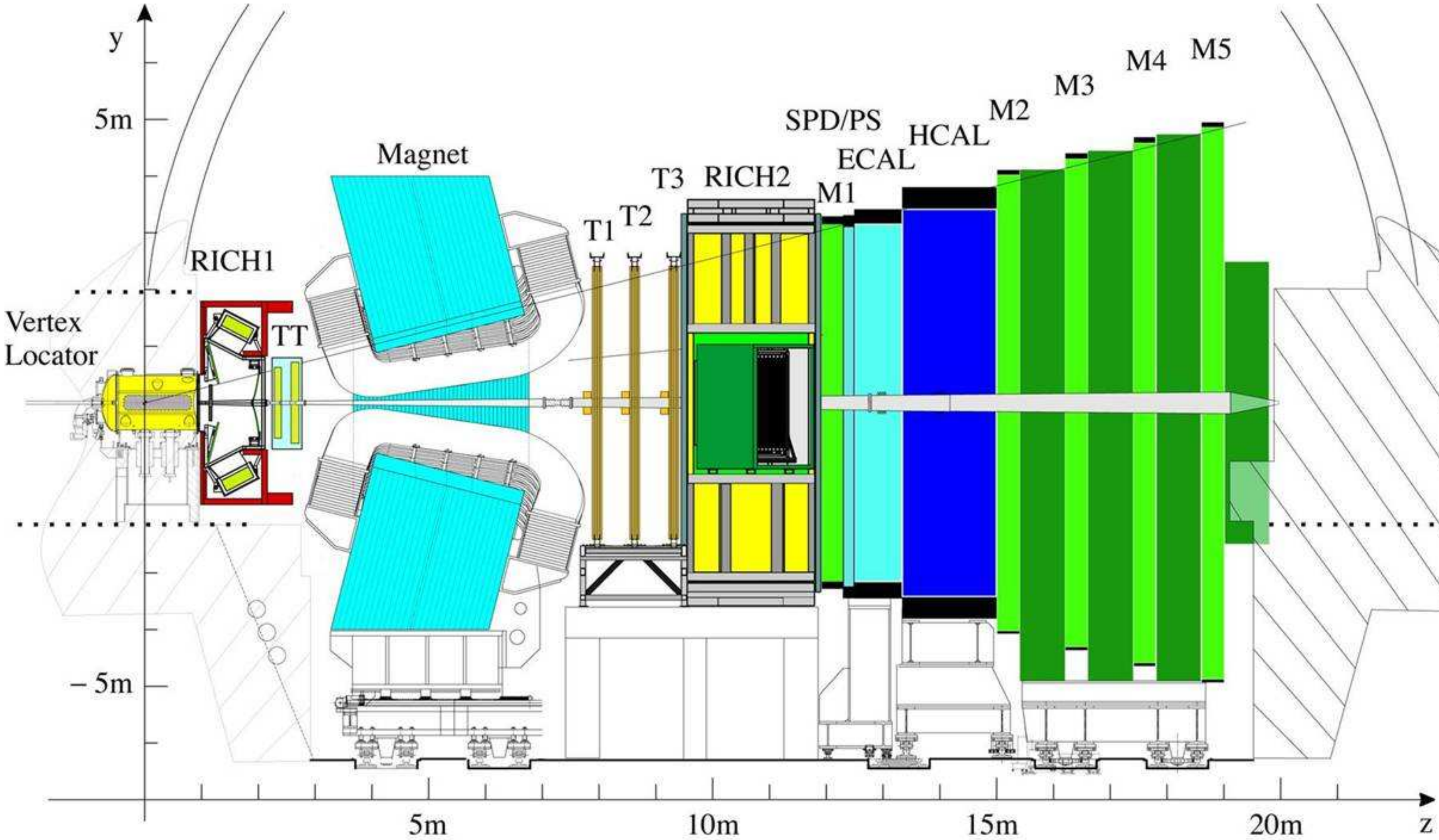
On behalf of the LHCb collaboration

Outline

- LHCb and its charm physics trigger
- Charm Physics
  - Mixing Searches
  - Direct CPV
  - Rare decay $D^0 \to \mu\mu$

  } Unobserved phenomena
- Summary

The LHCb detector



VELO and RICH are essential for charm physics

LHCb D^* trigger

- L0 hardware trigger — high p_t particles
- HLT software trigger
  - 2 kHz output rate

    200 Hz Exclusive B specific final states

    300 Hz $D^* \to \pi D^0(hh)$

    600 Hz Di-muon $J/\psi, b \to J/\psi X$

    900 Hz Single muon trigger for b data mining
- Estimated yields; events to tape in $2\ \mathrm{fb}^{-1}$ from b hadrons

$D^0 \to K^- \pi^+$	50×10^6	$D^0 \to K^- K^+$	5×10^6
$D^0 \to \pi^- K^+$	0.2×10^6	$D^0 \to \pi^- \pi^+$	2×10^6

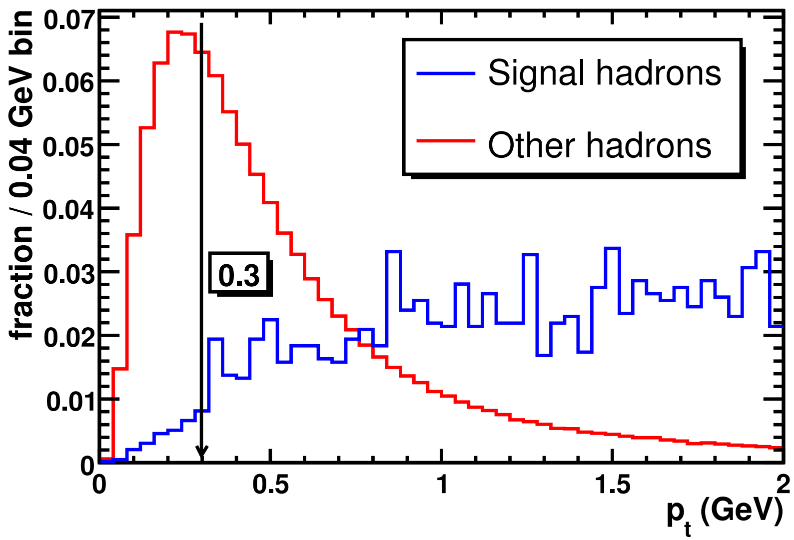
- Similar number of prompt D^* are expected

10^8 potentially usable $D^* \to \pi D^0(hh)$ events per $2\ \mathrm{fb}^{-1}$

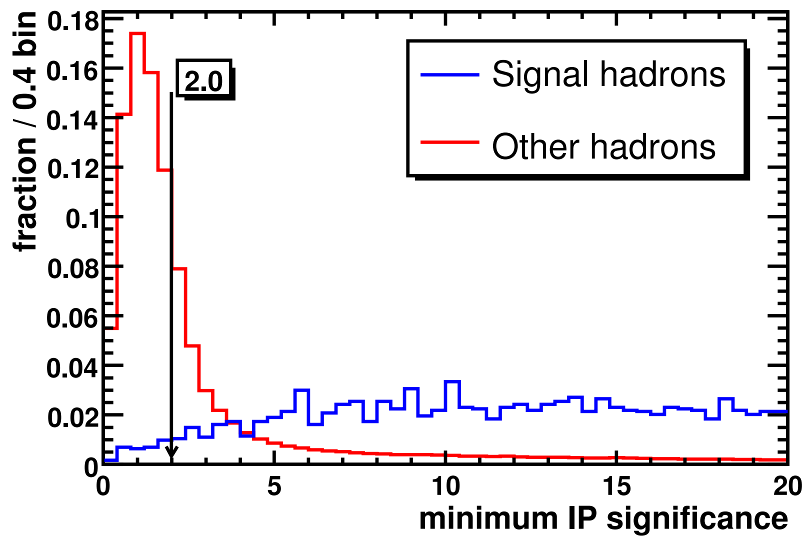
$D^* \to \pi D^0(hh)$ trigger stream

- Trigger selection favors D^*s coming from b hadrons
- Loose cuts on:
  - Final state hadrons p_t and min IP significance
  - D^0 mass and Δm, the D^*-D^0 mass difference

Track p_t



Track min IP significance



Charm physics at LHCb

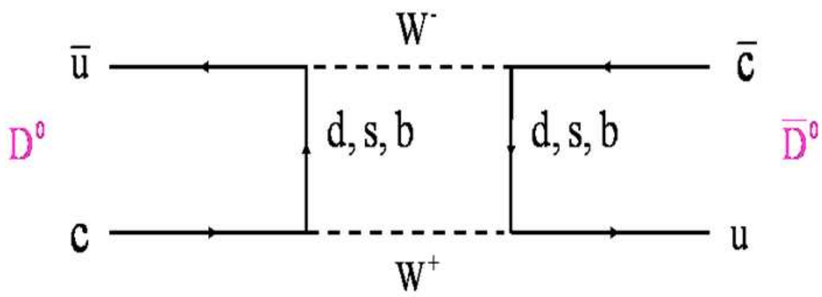
- Initial focus on $D^0 \to h^- h^+$ decays
- Lifetime difference of CP eigenstates
  - CP-even Singly-Cabibbo Suppressed (SCS): $D^0 \to K^- K^+$ or $\pi^- \pi^+$
  - Non-CP eigenstate Right Sign (RS): $D^0 \to K^- \pi^+$.
- Time-dependent mixing
  - Wrong Sign (WS) decay $D^0 \to \pi^- K^+$.
- Direct CP violation
  - SCS $D^0 \to K^- K^+ (\pi^- \pi^+)$
- Other interesting studies
  - Search for $D \to \mu^- \mu^+$
  - Investigation of $D^0 \to 4h$ modes
  - Many other measurements for which LHCb potential is yet unexamined

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

$$x \equiv \frac{m_2 - m_1}{\Gamma} \qquad y \equiv \frac{\Gamma_2 - \Gamma_1}{2\Gamma}$$

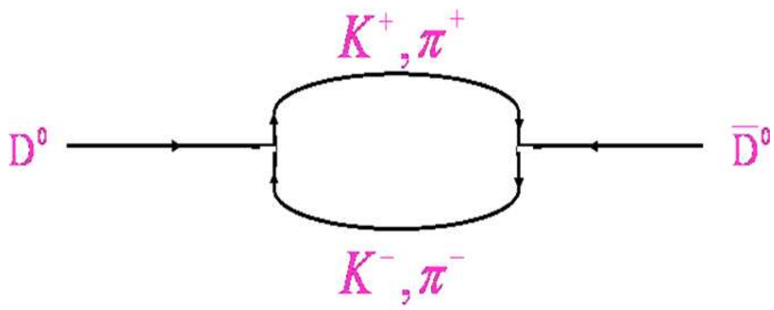
Indices associated with the mass eigenstates. Γ is the average width

Short-range mixing



- Contributions from all energy scales
- sensitive to new physics

Long-range mixing



- Rescattering through physical D decay states
- Dominated by SM

SM predictions highly uncertain

$x, y \lesssim 10^{-2}$

Lifetime ratio

Compare lifetimes of the non-eigenstate RS decay $D^0 \to K^-\pi^+$ and CP even decays $D^0 \to K^-K^+(\pi^-\pi^+)$

$$y_{\mathrm{CP}} \equiv \frac{\tau(D^0 \to K^-\pi^+)}{\tau(D^0 \to (K^+K^-, \pi^+\pi^-)} - 1 = y\cos\phi - x\sin\phi\left[\frac{R_m^2 - 1}{2}\right]$$

$R_m = \frac{1}{2}(x^2 + y^2)$; y and y_{CP} differ by CP violating phase ϕ

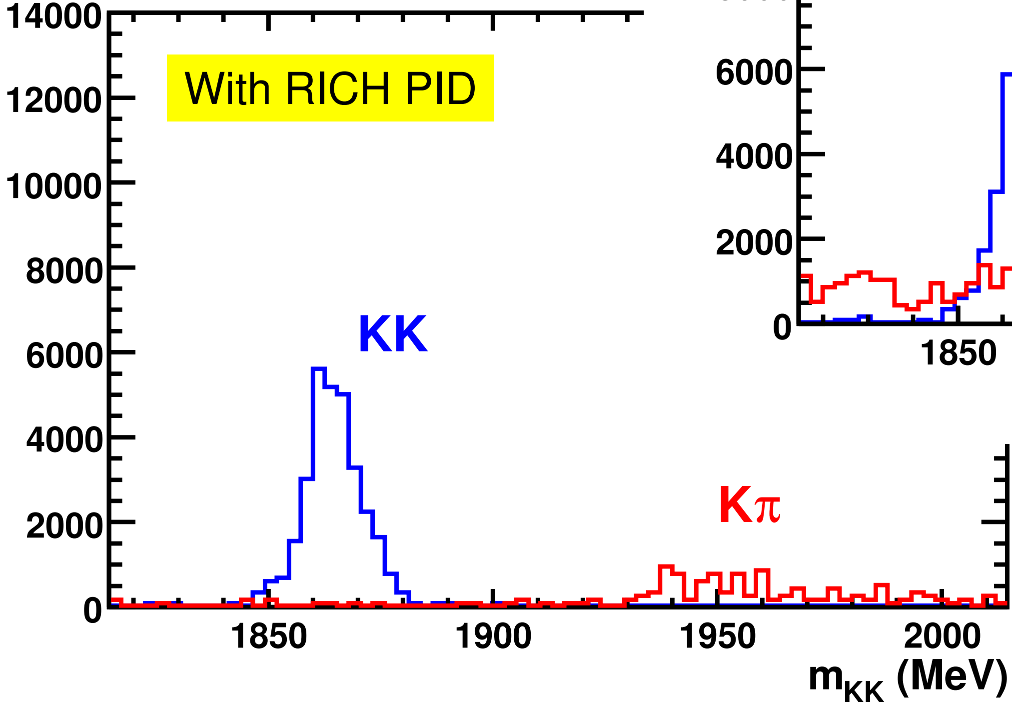
See, e.g., D. Asner, D^0–$\overline{D^0}$ Mixing, J.Phys.G33:1,2006 (PDG 2006)

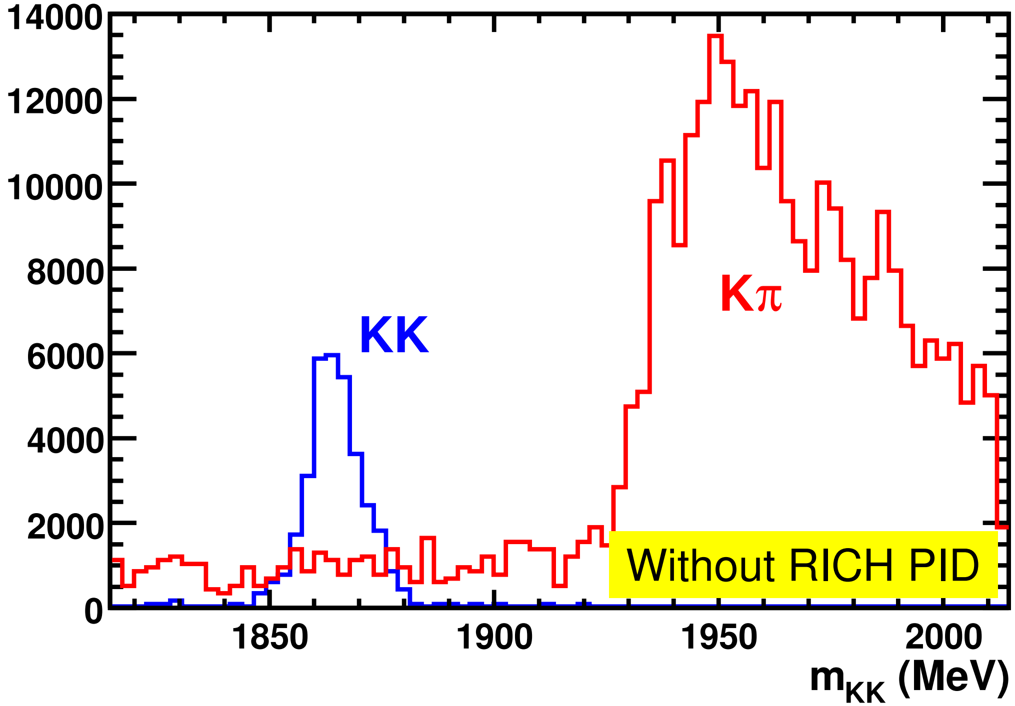
	$y_{\mathrm{CP}}\,(\%)$	$N(K^-K^+)$	Data set
Belle	$1.2 \pm 0.7 \pm 0.4$	36480	$158\,\mathrm{fb}^{-1}$
BaBar	$1.5 \pm 0.8 \pm 0.5$	26084	$91\,\mathrm{fb}^{-1}$
CLEO	$-1.2 \pm 2.5 \pm 1.4$	2463	$9\,\mathrm{fb}^{-1}$
FOCUS	$3.4 \pm 1.4 \pm 0.7$	10331	
E791	$0.8 \pm 2.9 \pm 1.0$	3200	

LHCb: $\approx 5 \times 10^6$ potentially useful tagged $D^0 \to K^-K^+$ from b events per $2\,\mathrm{fb}^{-1}$

RICH and $D^0 \to K^- K^+$

RICH PID information eliminates cross-feed backgrounds

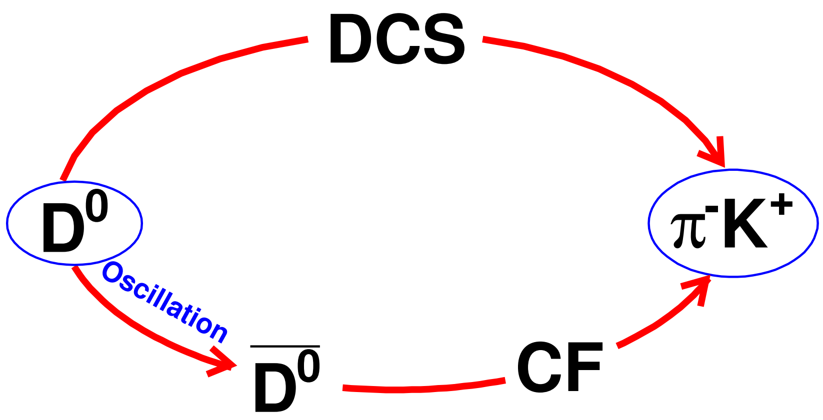




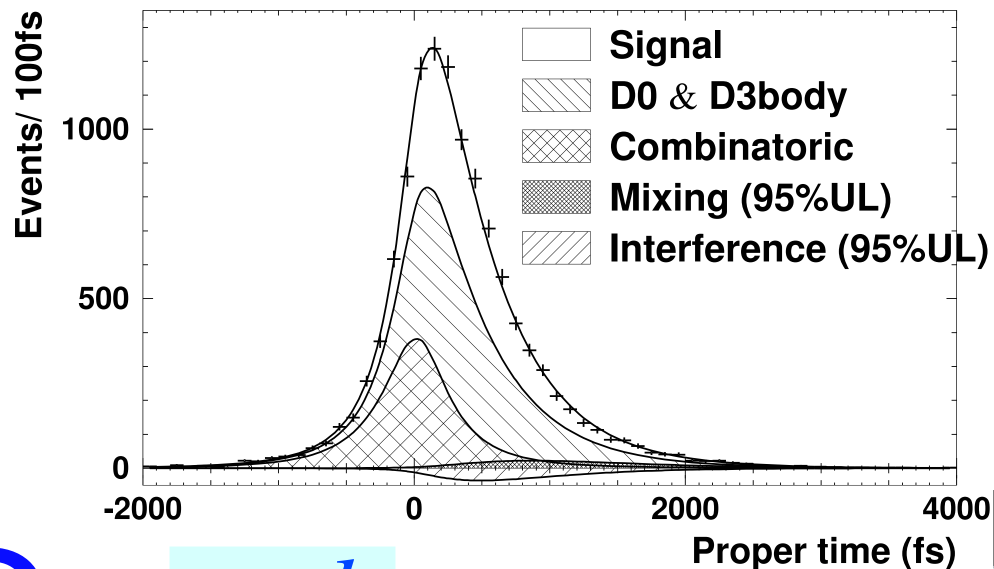
Oscillation search with WS $K\pi$

Two paths from D^0 to $\pi^- K^+$

- Direct Doubly Cabibbo Suppressed (DCS) decay
- Oscillation to $\overline{D^0}$ followed by a Cabibbo Favored (CF) decay



$$\Gamma(t; D^0 \to \pi^- K^+) \propto e^{-\Gamma t}\left[R_D + \sqrt{R_D}y'\Gamma t + \frac{1}{4}(y'^2 + x'^2)(\Gamma t)^2\right]$$



R_D: ratio of DCS to CF decay rates

(x', y') related to (x, y) by a strong phase

Small effect $\Rightarrow$ Requires large statistics

Belle, Phys.Rev.Lett.96:151801,2006

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Oscillation search with WS $K\pi$

	Data set	$N(\pi^- K^+)$	$x'^2 (\times 10^{-3})$	$y' (\times 10^{-3})$
Belle	$400\,\text{fb}^{-1}$	4024	< 0.72	$-9.9 < y' < 6.8$
BaBar	$57.1\,\text{fb}^{-1}$	430	< 2.0	$-27 < y' < 22$
CLEO	$9\,\text{fb}^{-1}$	45	< 0.78	$-52 < y' < 2$
FOCUS			< 8.3	$-72 < y' < 41$

Wrong sign branching fraction measurement at CDF demonstrates that WS analyses can be successful at hadron colliders

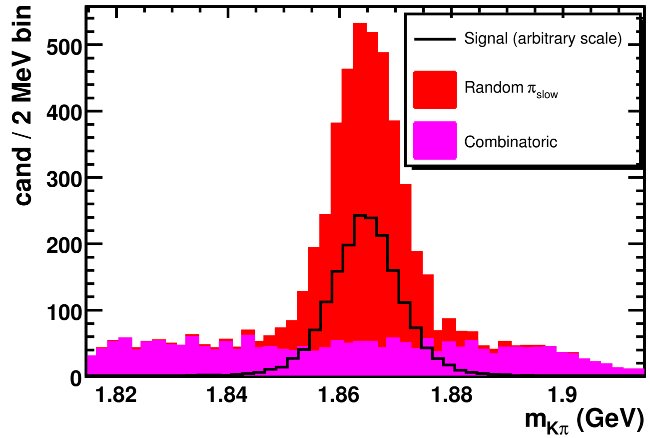
2004 ± 104 observed wrong sign events ($0.35\,\text{fb}^{-1}$)

LHCb: $\approx 0.2 \times 10^6$ potentially useful tagged $D^0 \to \pi^- K^+$ from b events per $2\,\text{fb}^{-1}$

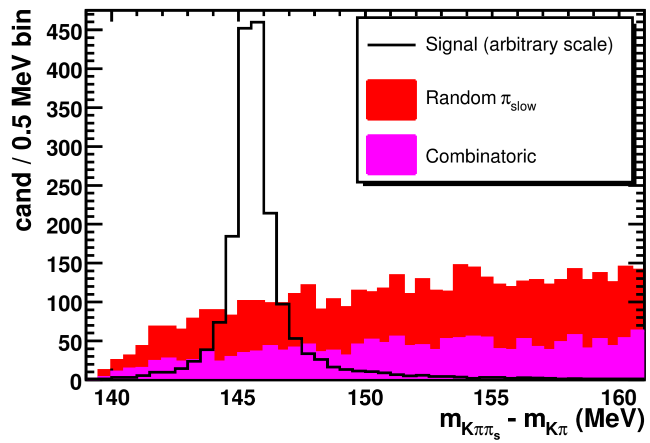
WS $\pi^- K^+$ time-dependent mixing

- WS selection most challenging
  - $\mathcal{B}(\pi^- K^+) = (1.43 \pm 0.04) \times 10^{-4}$
  - $\mathcal{B}(\pi^- K^+)/\mathcal{B}(K^- \pi^+) = 3.76 \times 10^{-3}$
- D^0, $\overline{D^0}$ tagged using slow pion sign
- Background peaking in $m_{K\pi}$
  - Right sign decays mistagged by combination with a random pion
  - Further suppression a topic of current work
- Background peaking in Δm
  - Double misidentification of right sign decay products
  - Effectively eliminated by RICH PID
- Preliminary Monte Carlo lifetime fitting and sensitivity studies are underway

D^0 mass ($m_{K\pi}$)



D^*-D^0 mass difference (Δm)



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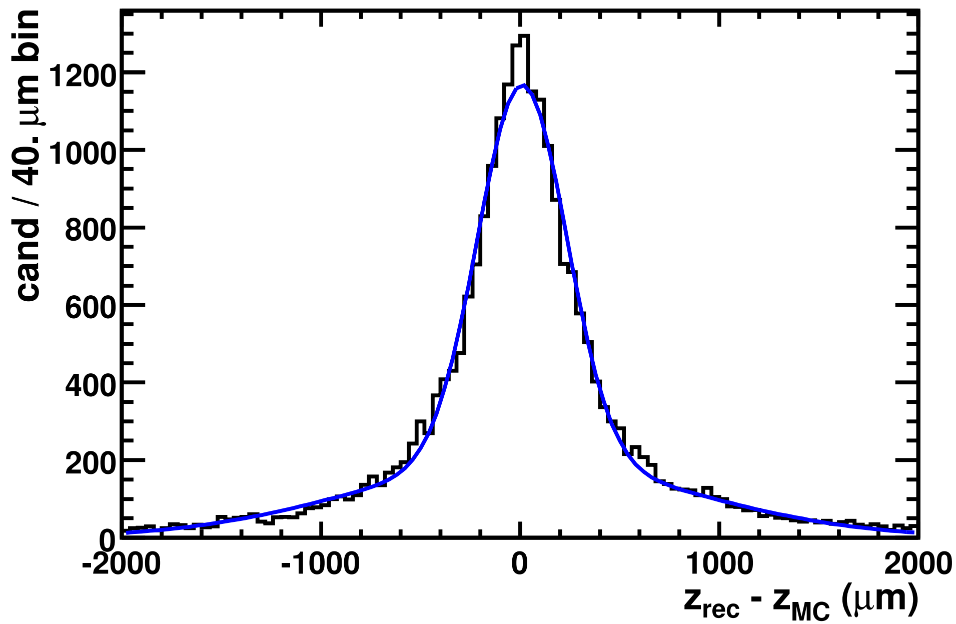
D^0 production and decay vertices

Time-dependent measurements require good resolution of both the production and the decay vertices

D^0 lifetime $\tau = 0.4101 \pm 0.0015\,\mathrm{ps}$
D^0 flight distance at $60\,\mathrm{GeV}$ $\beta\gamma c\tau \approx 4\,\mathrm{mm}$

D^0 resolution in z



D^0 decay vertex resolution
$0.225\,\mathrm{mm}$

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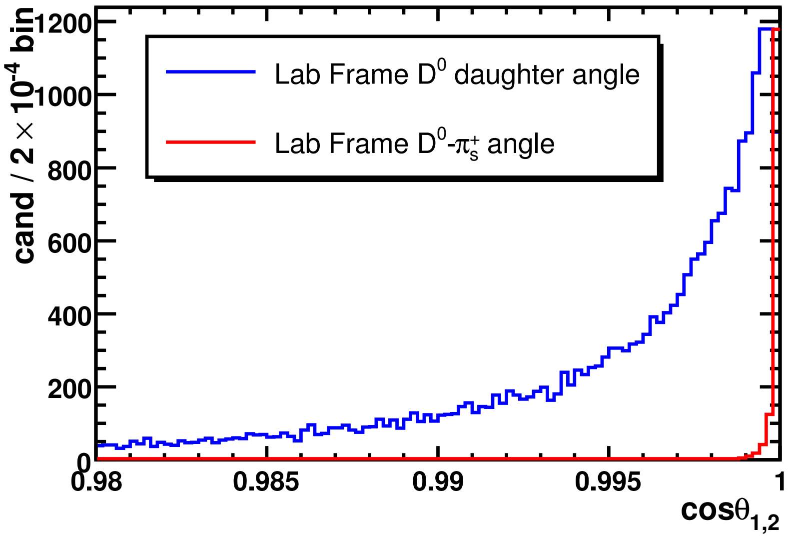
D^0 production and decay vertices

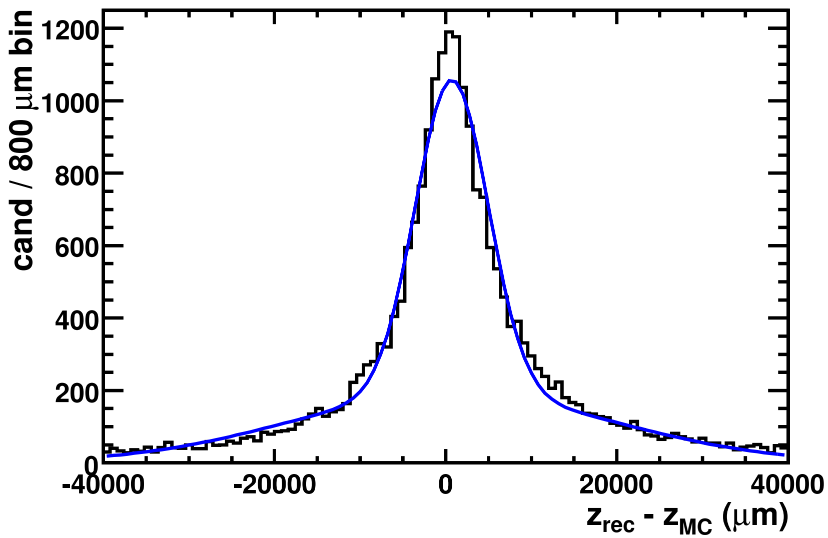
Lab frame decay angles



Very little energy released in D^* decay
$\Rightarrow$ D^0 and π_{slow} almost colinear

- Poor resolution of the D^0 production vertex $= 4.270\,\mathrm{mm}$
  (Recall $\beta\gamma c\tau(60\,\mathrm{MeV}) \approx 4\,\mathrm{mm}$)
- Proper time τ resolution $= 0.591\,\mathrm{ps}$
  (Recall $\tau = 0.410\,\mathrm{ps}$)

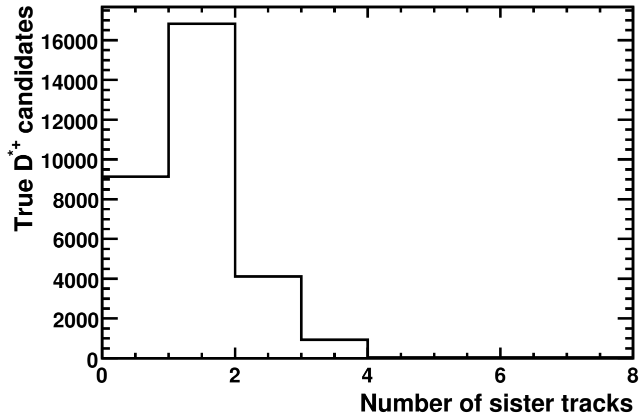
D^* resolution in z



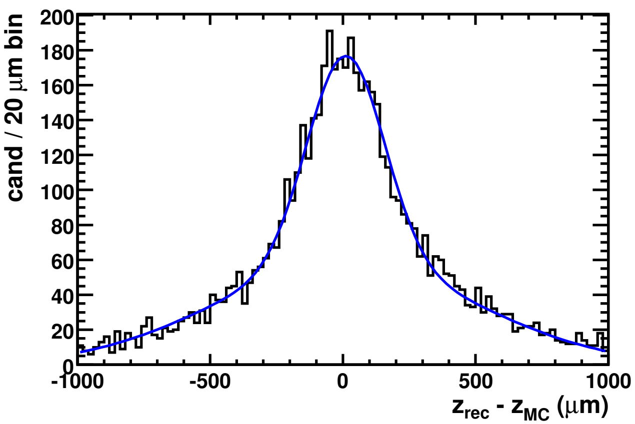
D^0 production vertex

- Use additional tracks at production vertex
  1. Use prompt D^{*+} from PV
     - MC not yet available
  2. Partially reconstruct parent B
     - Preliminary work shows promise
- 70% of D^{*+} from B's have at least one charged sister
- 45% have sister tracks which are reconstructed and pass some basic criteria

Sister multiplicity



B_{parent} resolution



Decay vertex resolutions

	D^0	D^{*+}	B_{parent}
x	$22.8\ \mu m$	$250.\ \mu m$	$17.\ \mu m$
y	$19.1\ \mu m$	$160.\ \mu m$	$15.\ \mu m$
z	$225.\ \mu m$	$4270.\ \mu m$	$137.\ \mu m$

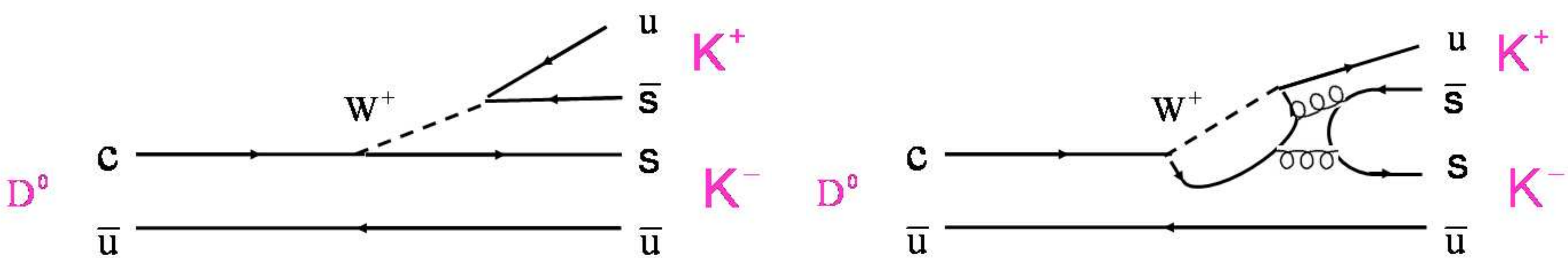
Improved proper time resolution $= 0.059$ ps

Direct CPV in $D^0 \to K^-K^+(\pi^-\pi^+)$

Occurs when the absolute value of the D decay amplitude to a final state is not equal to the CP conjugate amplitude

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

D^0, $\overline{D^0}$ tagged using the slow pion sign



SCS decays, interfering amplitudes

Direct CPV in $D^0 \to K^-K^+(\pi^-\pi^+)$

In SM, $A_{\mathrm{CP}} \lesssim 10^{-3}$ for SCS decays.

Possible NP enhancements to 1%.

	$A_{\mathrm{CP}}(K^-K^+)(\%)$	$A_{\mathrm{CP}}(\pi^-\pi^+)(\%)$	$N(K^-K^+)$	Data set
CDF	$2.0 \pm 1.2 \pm 0.6$	$1.0 \pm 1.3 \pm 0.6$	16220	$123\,\mathrm{pb}^{-1}$
Belle	$-0.2 \pm 0.6 \pm 0.3$		36480	$158\,\mathrm{fb}^{-1}$
BaBar	$-1.3 \pm 0.8 \pm 0.2$	$0.3 \pm 1.1 \pm 0.2$	26084	$91\,\mathrm{fb}^{-1}$
CLEO	$0.0 \pm 2.2 \pm 0.8$	$1.9 \pm 3.2 \pm 0.8$	3023	$9\,\mathrm{fb}^{-1}$
FOCUS	$-0.1 \pm 2.2 \pm 1.5$	$4.8 \pm 3.9 \pm 2.5$	3330	
E791	$-1.0 \pm 4.9 \pm 1.2$	$-4.9 \pm 7.8 \pm 3.0$	609	

LHCb: $\approx 5 \times 10^6$ potentially useful tagged $D^0 \to K^-K^+$ from b events per $2\,\mathrm{fb}^{-1}$

Statistical precision $\mathcal{O}(10^{-3})$

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More charm physics!

Rare decay $D^0 \to \mu\mu$

- Strongly suppressed in SM: $\lesssim 10^{-12}$
- Enhancement in some SUSY models

  Up to 10^{-6}
- Current best branching fraction limit from BaBar
  $\mathcal{B}(D^0 \to \mu\mu) < 1.3 \times 10^{-6}$ $(122\,\mathrm{fb}^{-1})$

LHCb $\mathcal{B}(D^0 \to \mu\mu) < 5 \times 10^{-8}$

Oscillation search: WS $K\pi\pi\pi$

- A possible $D^{*+} \to \pi^+ D^0(4h)$ trigger in the HLT is under study
- Large branching fraction

  $\mathcal{B}(K\pi\pi\pi) \sim 2\mathcal{B}(K\pi)$
- Additional channel for mixing searches

  Complementary to $\pi^- K^+$
- Added value for γ measurements
  - γ from 4-body Dalitz analyses of $B^+ \to K^+ D(4h)$
  - Sample allows calibration of $D^0 \to 4h$ decay models

LHCb: $\approx 25 \times 10^6$ potentially useful tagged $D^0 \to K\pi\pi\pi$ from b events per $2\,\mathrm{fb}^{-1}$

Summary

- The LHCb experiment has an exciting potential for charm physics studies
- A dedicated D^* trigger will provide 10^8 flavor tagged $D^0 \to hh$ per $2\,\mathrm{fb}^{-1}$
- Working to improve background suppression
- Unprecedented sensitivity in searches for:
  - D^0 mixing
  - CP violation
  - $D^0 \to \mu^- \mu^+$

We have only begun to tap LHCb's potential for charm physics

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