Four-body D mixing at LHCb

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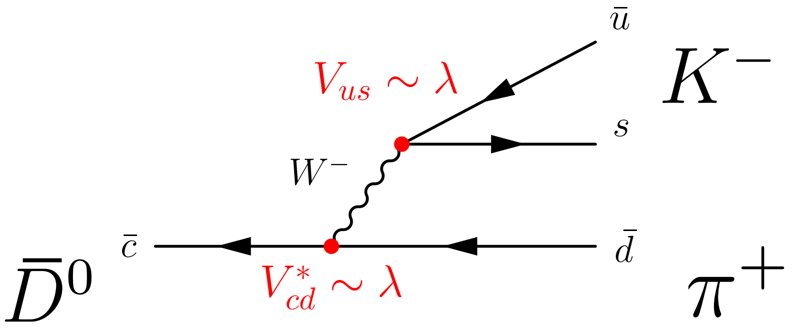
D decays to $K\pi$

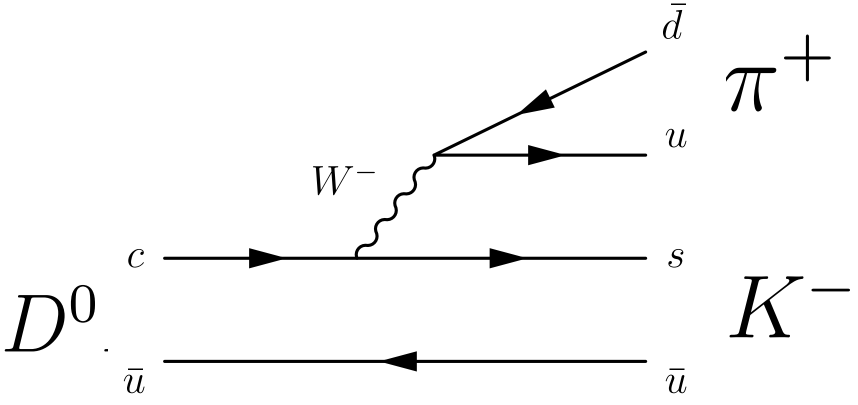
- D meson decays to the $K\pi$ final state can proceed directly or via mixing

$$\begin{tikzcd} D^0 \arrow[rr, "\text{DCS}"] \arrow[dr, "\text{mix}"'] & & K^+\pi^- \\ & \bar{D}^0 \arrow[ur, "\text{CF}"'] & \end{tikzcd}$$

- For doubly Cabibbo-supressed (DCS) decays these two processes can be comparable



DCS



CF

Mixing formalism

- Mass eigenstates in terms of flavour eigenstates (no CP violation)

$$|D_{1,2}\rangle = |D^0\rangle \pm |\overline{D}^0\rangle$$

- Time evolution of mass eigenstates

$$|D_{1,2}\,(t)\rangle = e^{-iM_{1,2}-\frac{1}{2}\Gamma_{1,2}t}\,|D_{1,2}\,(t=0)\rangle$$

- Define mixing parameters

$$x \equiv \frac{M_2 - M_1}{\left(\Gamma_1 + \Gamma_2\right)/2} \quad \text{and} \quad y \equiv \frac{\Gamma_2 - \Gamma_1}{\Gamma_1 + \Gamma_2}$$

Two-body mixing

- For Kπ, time dependent DCS/CF ratio is:

$$r\left(t\right) = r_D + \sqrt{r_D}y'tΓ + \frac{x'^2 + y'^2}{4}\left(tΓ\right)^2$$

DCS decays

interference

mixing

- *x* and *y* are rotated by strong phase difference between DCS and CF decays

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

strong phase difference between DCS and CF

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

Four-body mixing

- For *Kπππ*, decay usually occurs via intermediate resonances
- Time dependent DCS/CF ratio is now:

$$r\left(t\right) = r_D + \boxed{R_{K3\pi}}\sqrt{r_D}\,y'''t\Gamma + \frac{x'''^2 + y'''^2}{4}\left(t\Gamma\right)^2$$

- Coherence factor appears in 1st order *t* term
  - between 0 and 1
  - gives a measure of the coherence of intermediate resonances
  - low if decay proceeds via many destructively interfering resonances

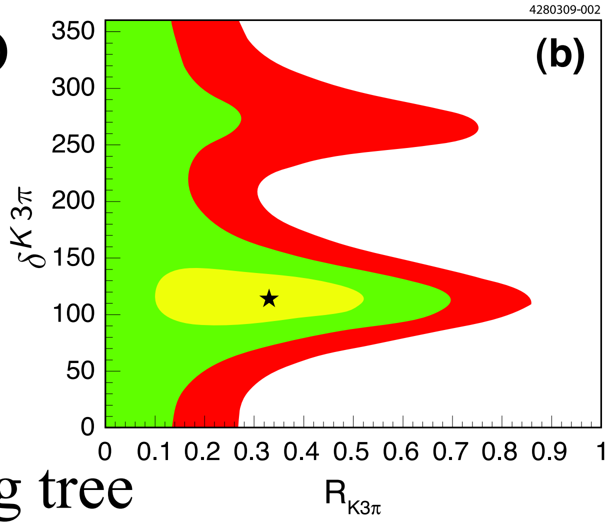
$$x''' \equiv x\cos\delta_{K3\pi} + y\sin\boxed{\delta_{K3\pi}}$$

$$y''' \equiv y\cos\delta_{K3\pi} - x\sin\delta_{K3\pi}$$

AVERAGE strong phase difference between DCS and CF

Current results

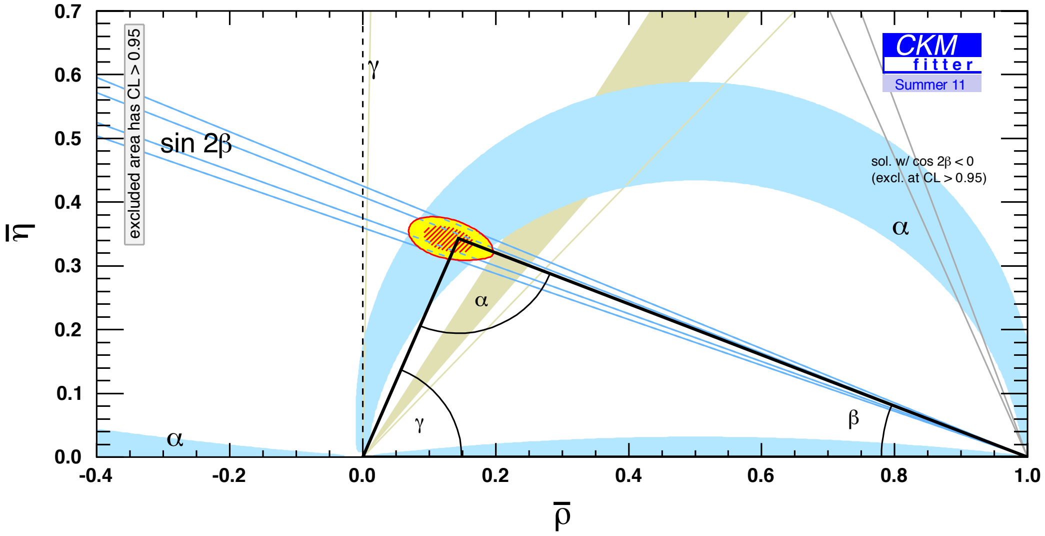
- Best measurements of *K*3π parameters from CLEO



$K^- \pi^- 2\pi^+$ coherence factor $R_{K3\pi} = 0.36^{+0.24}_{-0.30}$

$K^- \pi^- 2\pi^+$ average relative strong phase $\delta^{K3\pi} = (118^{+60}_{-50})^\circ$

- We can significantly improve these
- Vital inputs for measuring CPV weak phase γ using tree level *B*➔*DK* decays



Ratio extraction

$$\frac{N_{\bar{D}^0\to K^+\pi^+\pi^-\pi^-}}{N_{\bar{D}^0\to K^-\pi^+\pi^+\pi^-}} = \frac{1}{r}\,d$$

r = DCS/CF

$$\frac{N_{D^0\to K^-\pi^+\pi^+\pi^-}}{N_{D^0\to K^+\pi^+\pi^-\pi^-}} = \frac{1}{r}\,\frac{1}{d}$$

$$\frac{N_{\bar{D}^0\to K^+\pi^+\pi^-\pi^-}}{N_{\bar{D}^0\to K^-\pi^+\pi^+\pi^-}} \times \frac{N_{D^0\to K^-\pi^+\pi^+\pi^-}}{N_{D^0\to K^+\pi^+\pi^-\pi^-}} = \frac{1}{r^2}$$

- Where d is detection asymmetry $(K^+\pi^-)/(K^-\pi^+)$
- ALL* production and detection asymmetries cancel!

*We assume the same selection efficiency for DCS and favoured (assign systematic based on potential Dalitz plot differences)

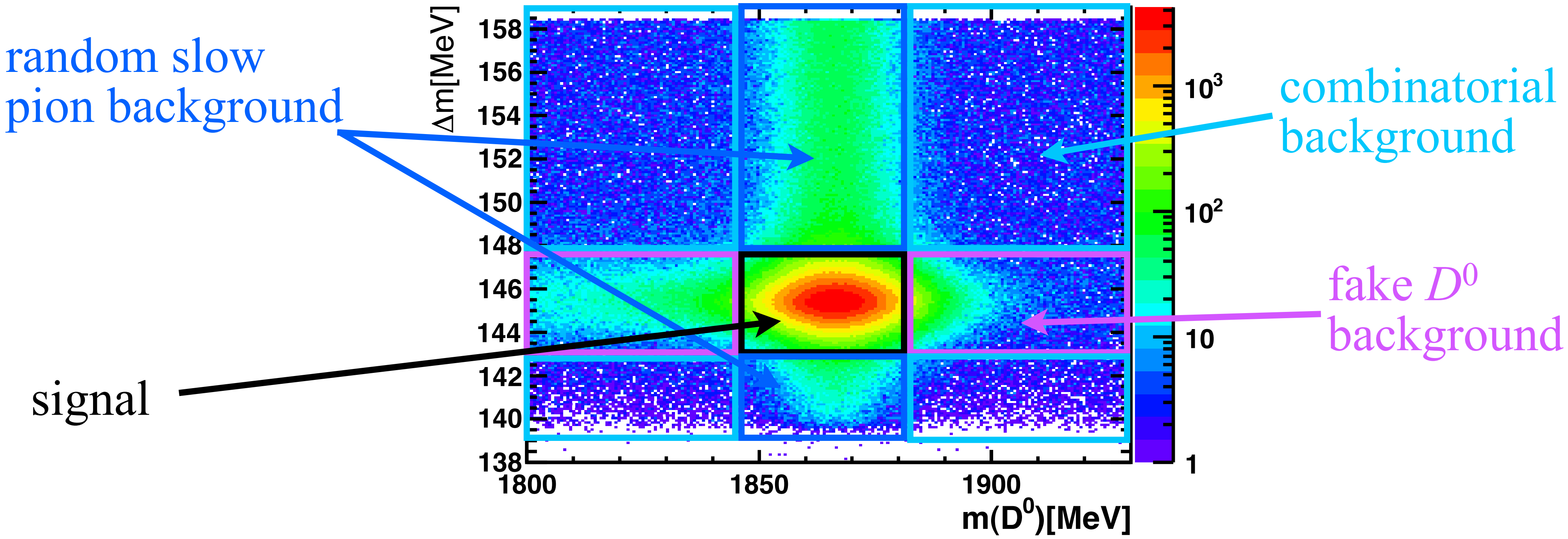
Flavour tagging

- We take our D^0s from strong decays $D^{*+} \rightarrow D^0\pi^+$ (and the charge conjugate)

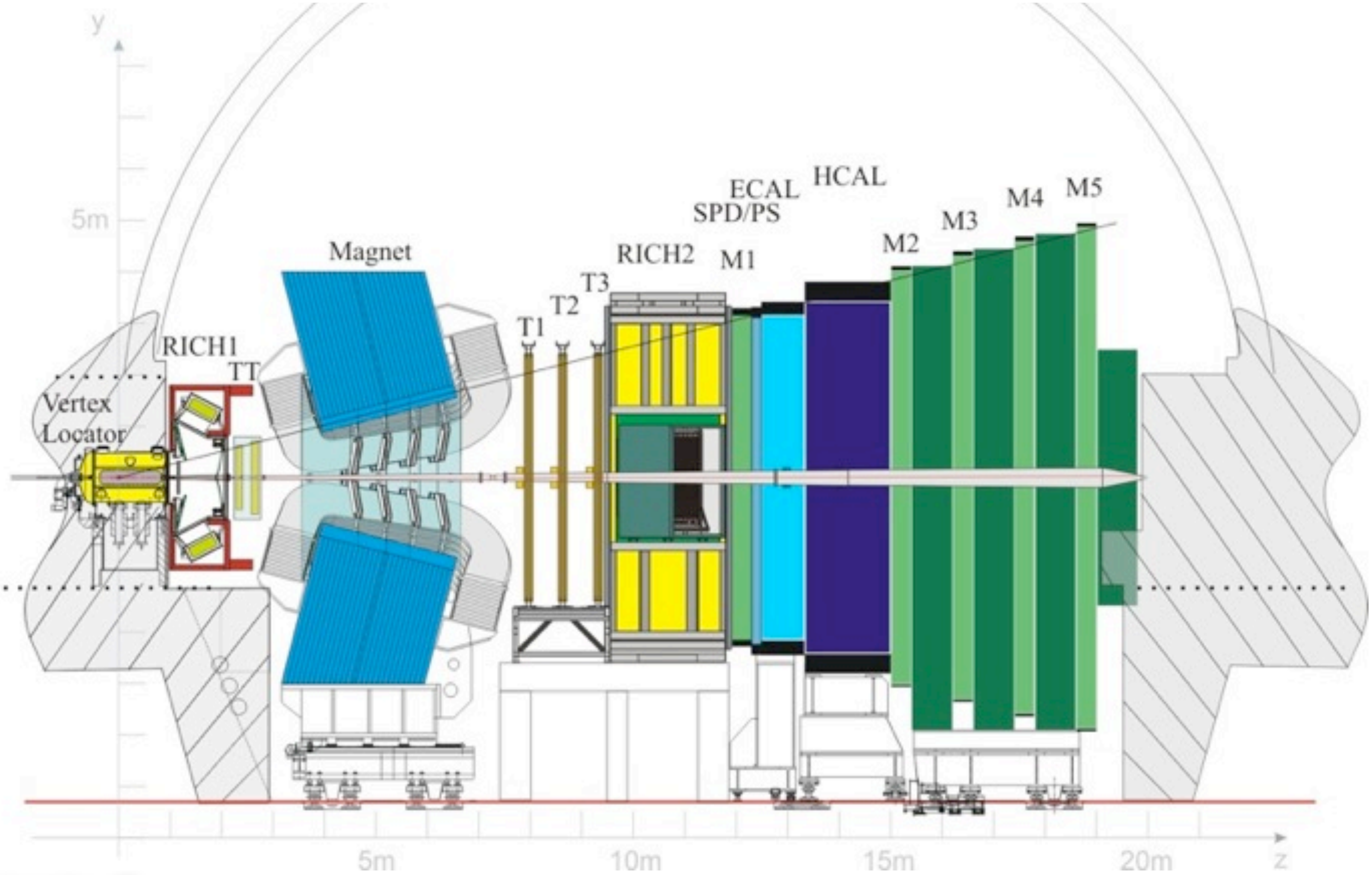
  then we know the flavour of the D

  since the π is low energy, we call it a “slow pion”

- Signal D^* decays are characterised by a narrow peak in the D^*-D^0 mass distribution (“delta mass”)
- Use the 2D D^0 mass vs delta mass plane to find events which are both D^* and D^0 signal decays

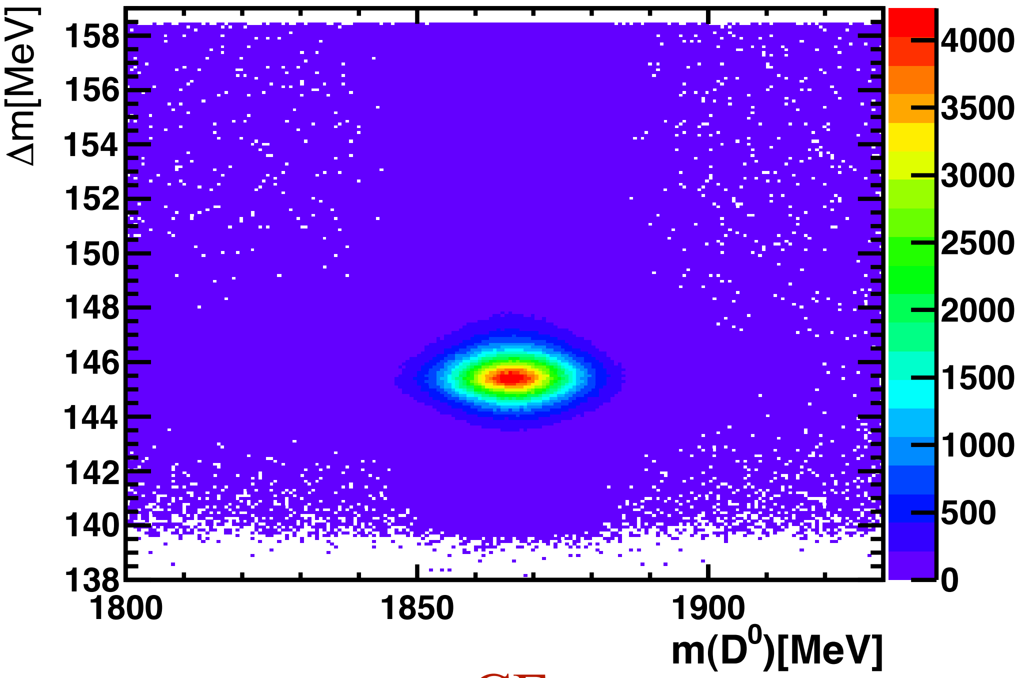


LHCb detector

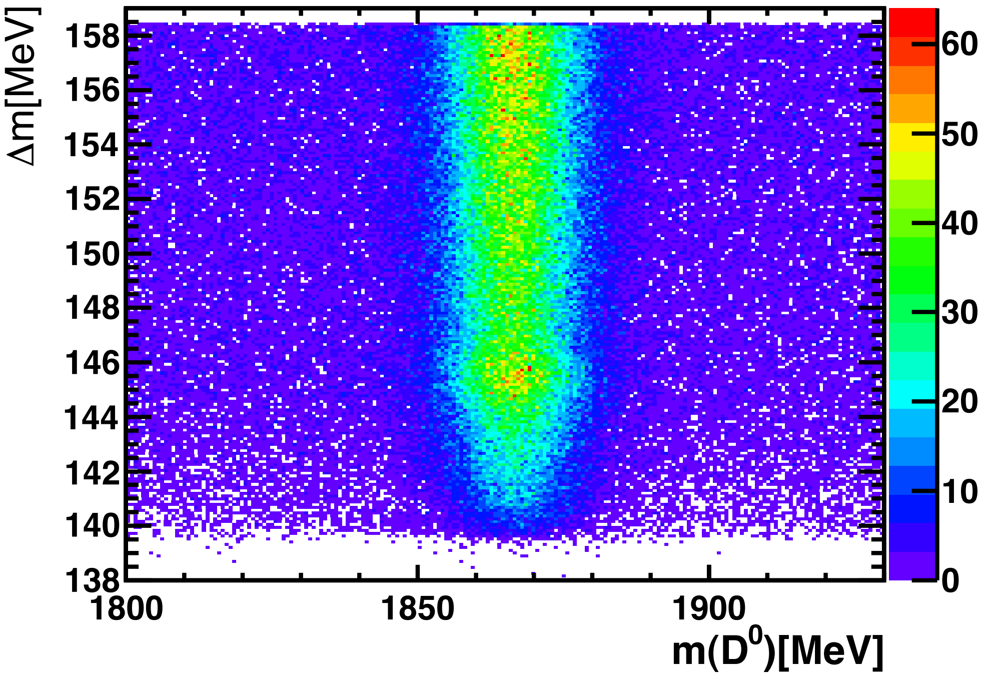


2011 data

- ~1fb^{-1} shown below
- Majority of events in DCS sample are CF D^0 decays combined with a random background slow pion

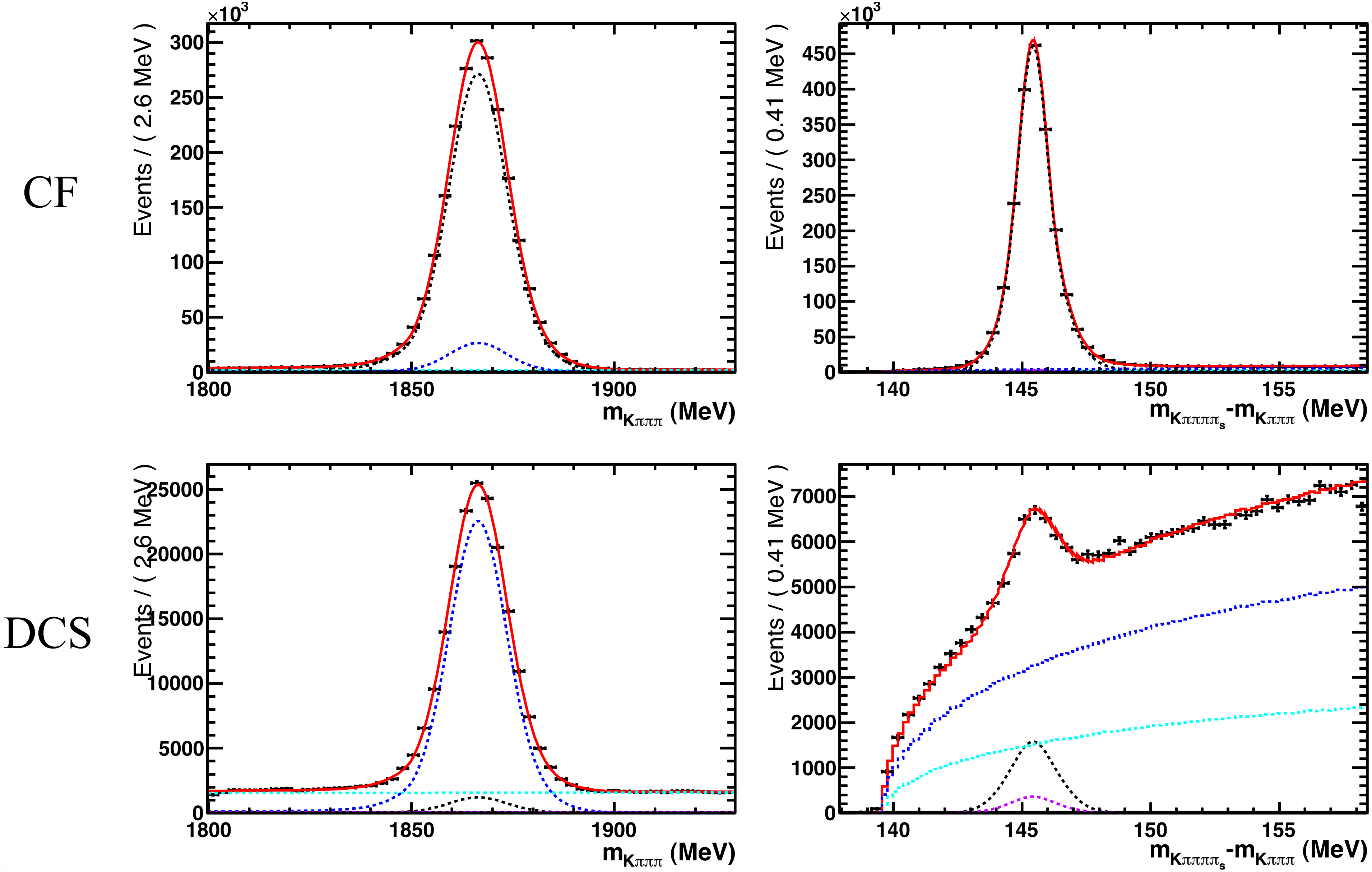


CF



DCS

Fit projections

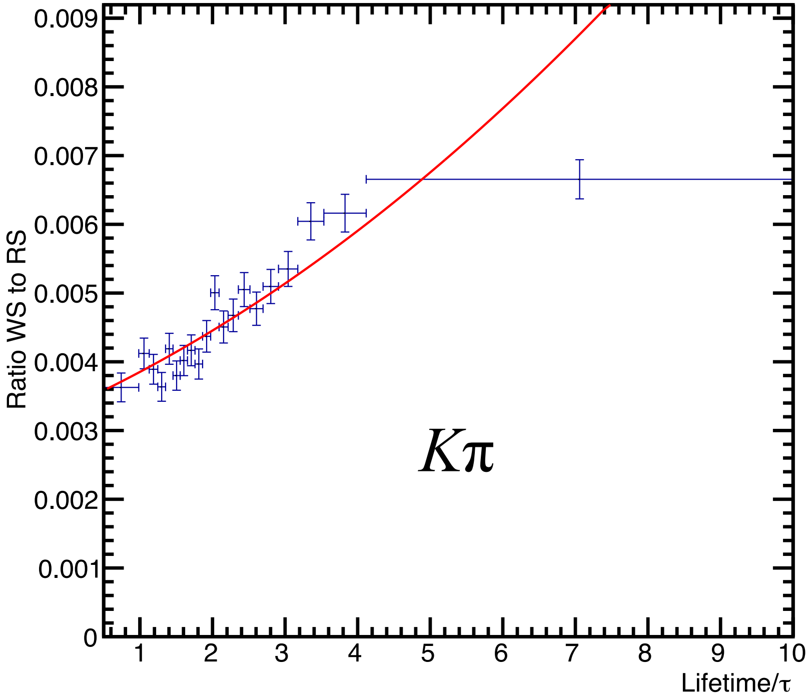


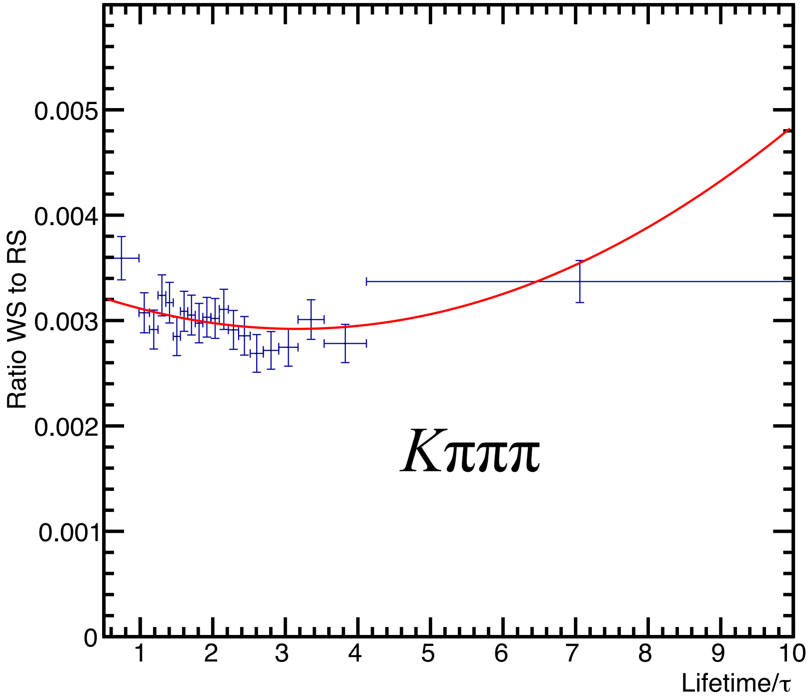
Lifetime binning

- Fit yields in D^0 lifetime bins to extract parameters
- Use toy study to maximise our sensitivity by optimising our lifetime binning
- Note that the size of the coherence factor determines our sensitivity to the interference term

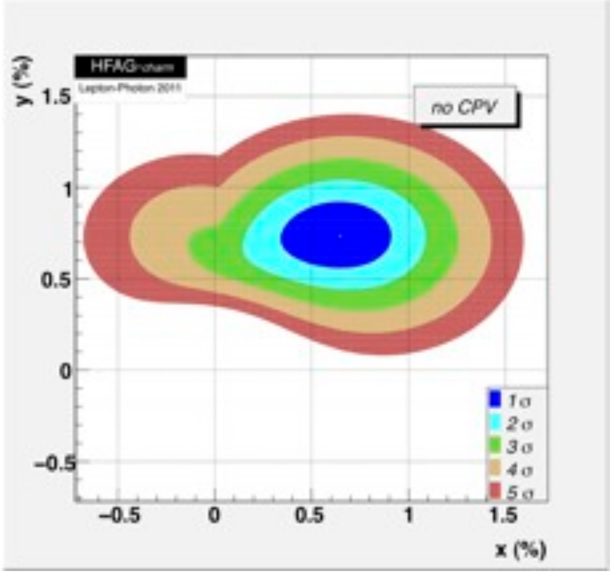
$$r\left(t\right) = r_D + \sqrt{r_D}y' t\Gamma + \frac{x'^2 + y'^2}{4}\left(t\Gamma\right)^2$$

$$r\left(t\right) = r_D + R_{K3\pi}\sqrt{r_D}y''' t\Gamma + \frac{x'''^2 + y'''^2}{4}\left(t\Gamma\right)^2$$





Summary and plans



- *D* mixing mixing already well established (although no single 5σ measurement)

- Use our huge DCS sample to measure DCS/CF ratio in lifetime bins

  sample size will more than double by end of 2012

- We plan to significantly improve coherence factor and average strong phase difference measurements

  vital input for CKM angle γ

- Plan to be ready for summer conferences

Back up

Slow π asymmetry

$$\frac{N_{D^0\to K^-\pi^+\pi^+\pi^-}}{N_{\bar{D}^0\to K^-\pi^+\pi^+\pi^-}} = \frac{1}{r}\,p$$

$$\frac{N_{D^0\to K^+\pi^+\pi^-\pi^-}}{N_{\bar{D}^0\to K^+\pi^+\pi^-\pi^-}} = r\,p$$

$$\frac{N_{D^0\to K^-\pi^+\pi^+\pi^-}}{N_{\bar{D}^0\to K^-\pi^+\pi^+\pi^-}} \Bigg/ \frac{N_{D^0\to K^+\pi^+\pi^-\pi^-}}{N_{\bar{D}^0\to K^+\pi^+\pi^-\pi^-}} = \frac{1}{r^2}$$

- Where p is production AND detection asymmetry π^+/π^-
- All efficiencies cancel again (gives exactly the same result)

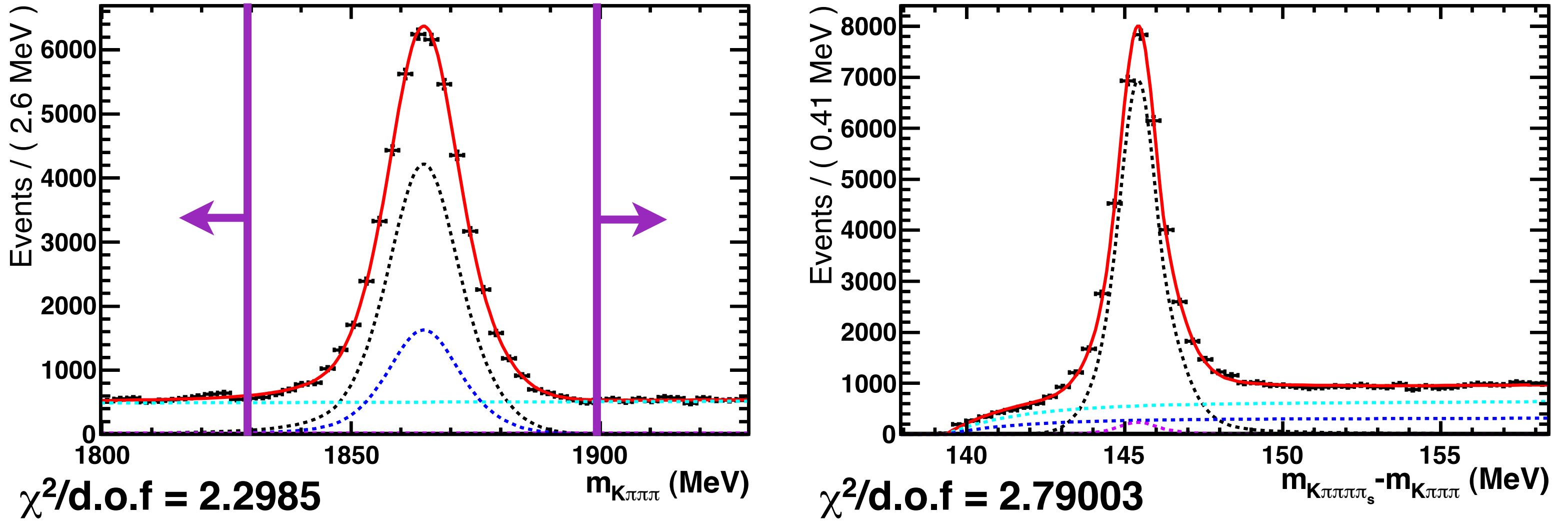
Cut optimisation

- Use D^0 mass sidebands from 2010 data as background sample and Monte Carlo signal events to tune selection cuts
- Perform 2D fit to obtain signal/background ratio

use to scale signal and background in optimisation

scale signal to DCS branching fraction

2D fit projections



Additional criteria

- Tighten PID cuts for all daughters
- Require events to have been triggered by the *D*➔hhhh trigger

  significantly improves S/B
- For DCS we expect large contribution from doubly misidentified CF decays (*K*↔π)

  veto any candidates which lie within ±30 MeV of PDG D^0 mass after swapping mass hypotheses of *K*,π
- Keep only one candidate per event

  best D^0 vertex chi^2 (or D^* vertex chi^2 if the same D^0)
- Then separate CF and DCS decays...

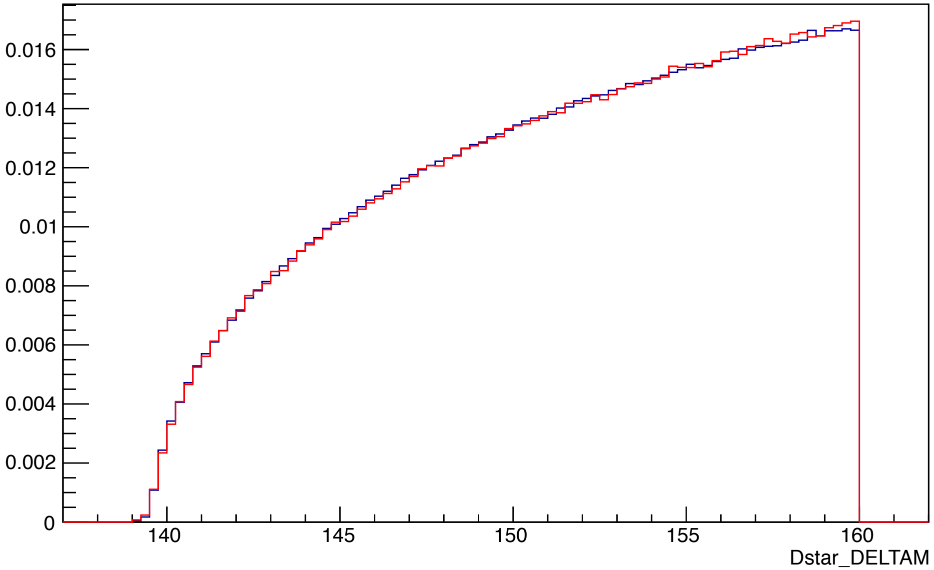
Fitting

- Perform a 2D unbinned maximum likelihood fit to the mass vs delta mass plane
- Signal in mass and delta mass described by the sum of a Gaussian and a Crystal Ball function (fix for DCS after fit to CF)
- Background in D^0 mass parameterised with a 1st order polynomial
- Delta mass background is modelled using data

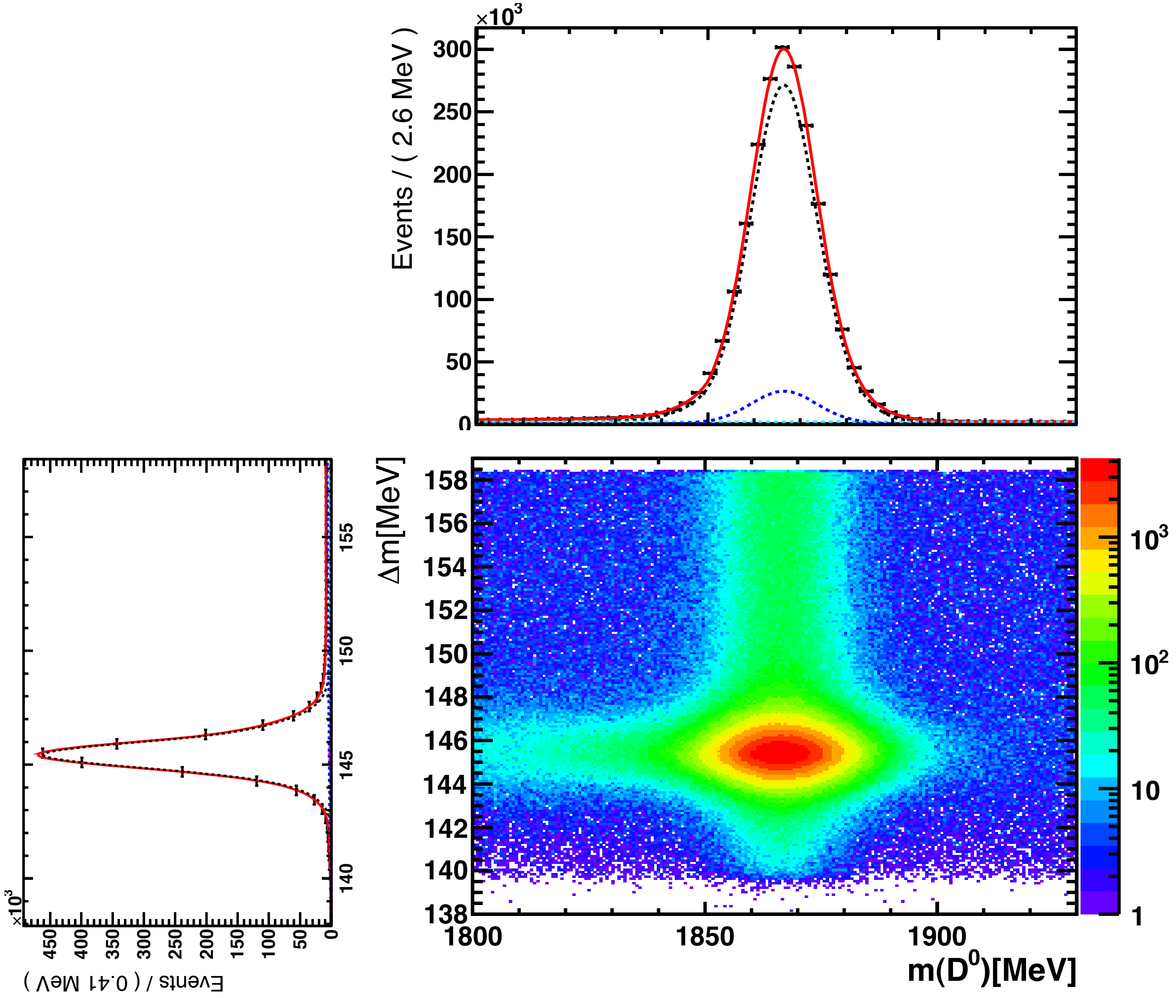
take D^0 4-vector from one event

combine with slow pion 4-vector from another event

use the same shape for both CF and DCS



2011 data CF


×10^3
Events / (2.6 MeV)
300
250
200
150
100
50
0
Δm[MeV]
158
156
154
152
150
148
146
144
142
140
138
1800
1850
1900
m(D^0)[MeV]
10^3
10^2
10
1
Events / (0.41 MeV)
×10^3
450
400
350
300
250
200
150
100
50
0
140
145
150
155