B_d Mixing with Same Side Tagging Algorithm @ DØ

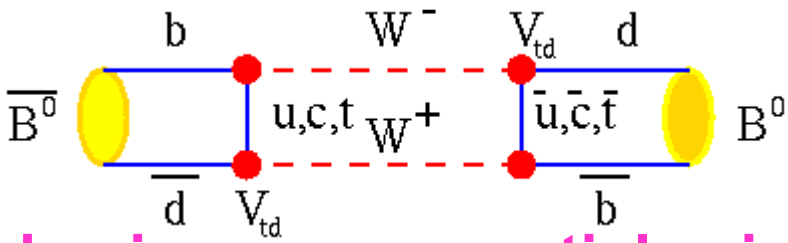
S.Burdin (Fermilab)
for DØ

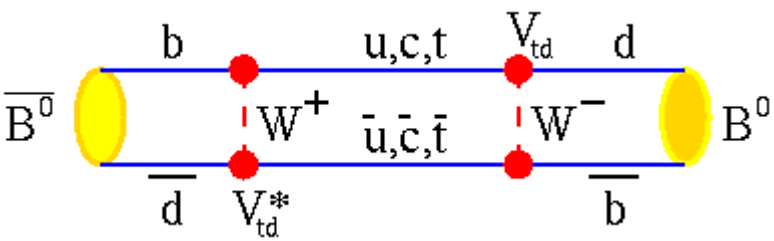
Chicago Flavor
8/13/2004

- Introduction
- Data Sample
- Different tagging algorithms
- Same Side Tagging algorithm
- Asymmetry
- Fitting procedure
- Sample composition
- $c\bar{c}$ contamination
- D** contribution
- Results

$B^0/\overline{B}^0$ mixing

SM:





new physics → new particles in the box

small contribution to Δm_d, can be large to Δm_s (see hep-ph/0405294, hep-ph/0404001, …)

B_d oscillation frequency:

$$\Delta m_d = \frac{G_F^2}{6\pi^2} m_B m_t^2 F\left(\frac{m_t^2}{m_W^2}\right) \eta_{QCD} B_{B_d} f_{B_d}^2 |V_{tb}^* V_{td}|^2$$

cancellation

If we measure Δm_s and Δm_d then:

$$\frac{\Delta m_s}{\Delta m_d} = \frac{m_{B_s^0}}{m_{B_d^0}} \frac{B_{B_s^0} f_{B_s^0}^2}{B_{B_d^0} f_{B_d^0}^2} \frac{|V_{ts}|^2}{|V_{td}|^2}$$

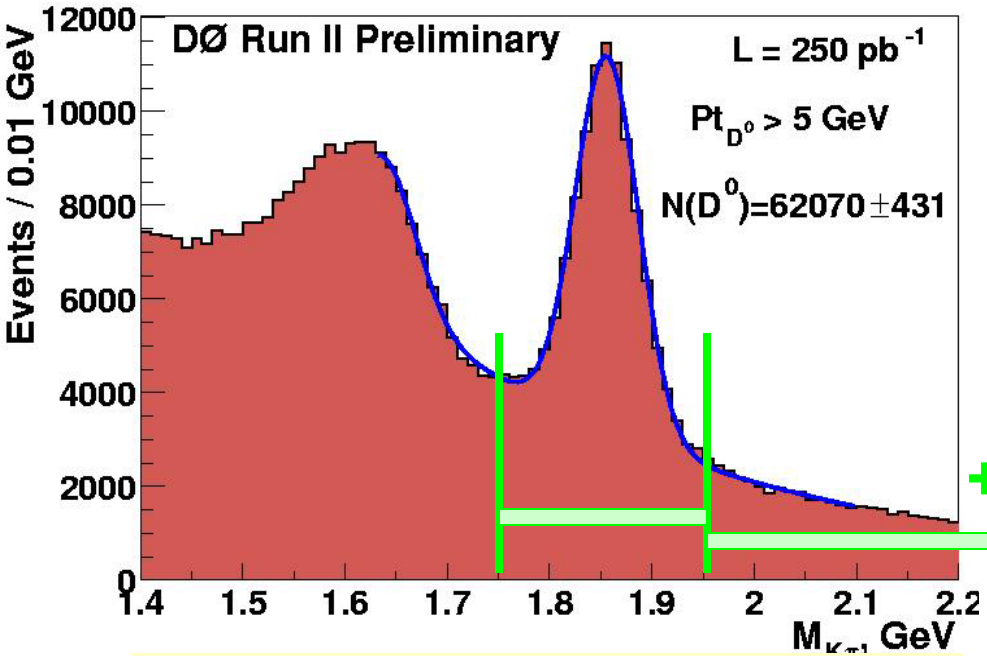
- **Why we measure B_d mixing?**
  - **We are not competitive with B-factories (now)**
    - ✓ Last Δm_d results from BELLE/BaBar have error ~1.5% !!!
  - **B_d mixing measurements are essential for initial flavor tagging algorithm tuning and certification**
    - ✓ will be used for B_s mixing and CP violation measurements

Semileptonic Data Samples

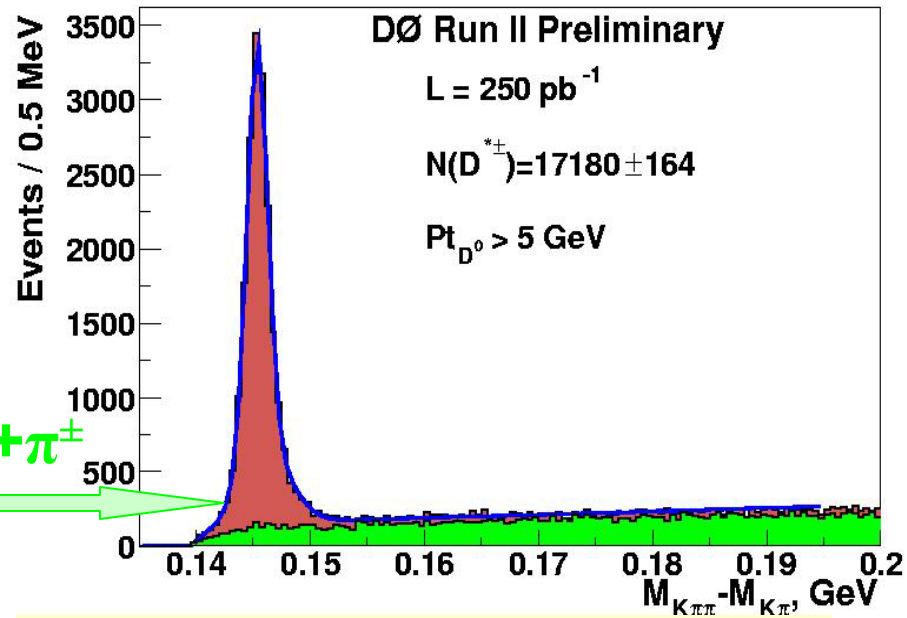
- Looking for $B \rightarrow \mu^- \nu D^0 X$, $D^0 \rightarrow K^- \pi^+$
  - Charge conjugate always implied
- Select D^0 candidates
- Search for a pion track which gives D^* invariant mass in combination with D^0: $D^{*+} \rightarrow D^0 \pi^+$
- Divide the $\mu D^0 X$ candidates into 2 sub samples:
  - D^* was found: D^* sample
  - No D^*'s were found: D^0 sample

Semileptonic B_d sample

- In the data sample corresponding to $L=250pb^{-1}$
  - 109k inclusive $B \rightarrow \mu \nu D^0$ candidates but after cut $Pt_{D0}>5GeV$ (needed to remove dependence of D* reconstruction efficiency on lifetime and to be consistent with lifetime ratio analysis)
    - ✓ 62k inclusive $B \rightarrow \mu \nu D^0$ candidates
    - ✓ 17k $B \rightarrow \mu \nu D^*$ candidates



$+\pi^{\pm}$



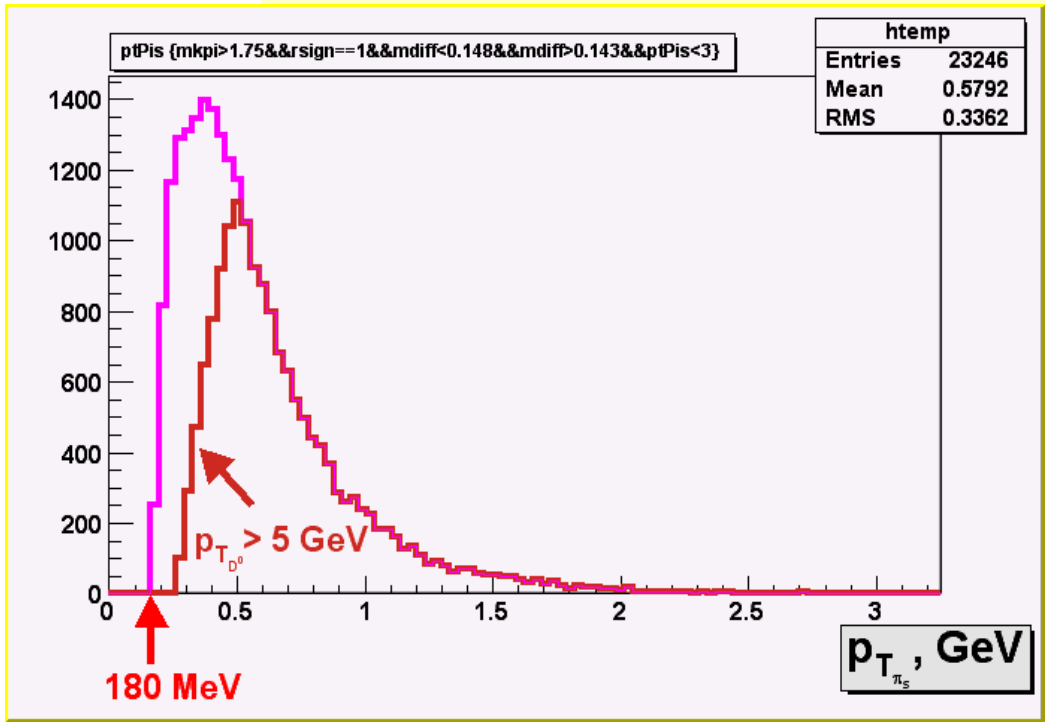
Dominated by B^+ decays

Dominated by B^0 decays

D* Selections

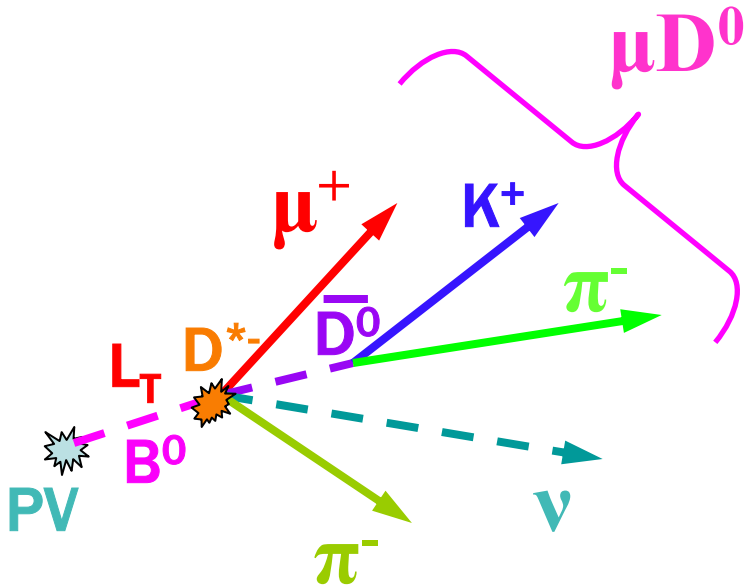
- Reconstruct slow pion from D* without biasing lifetime
  - ✓Only requirement on slow pion is to give correct $m(D^*)-m(D^0)$ value
  - ✓If slow pion is not reconstructed then the event goes to D^0 sample
    - ❖ Taken into account in the sample composition
  - ✓Slow pion is
    - ❖ NOT used for calculation of VPDL
    - ❖ NOT used in B-vertex
    - ❖ NOT used in K-factors
  - ✓Therefore μD^0 and μD^* samples are completely consistent
    - ❖Reduces systematics

p_T spectrum of soft pion candidate in $D^* \rightarrow D^0 \pi$



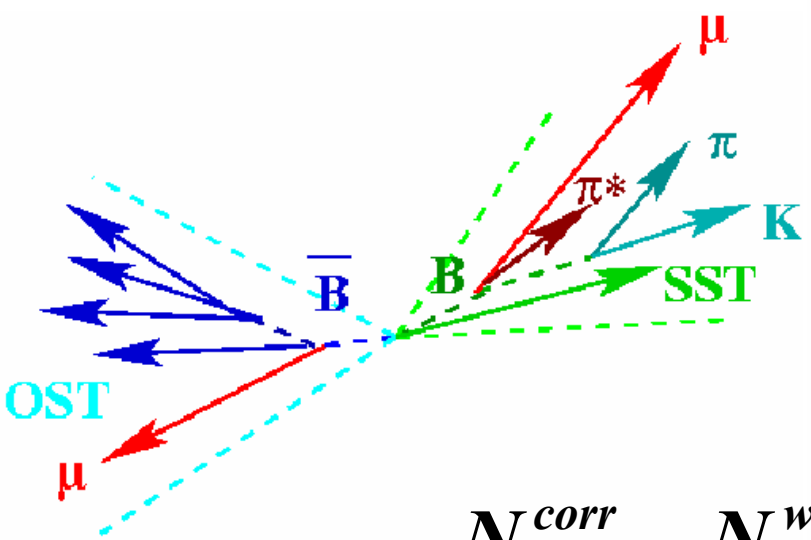
Visible Proper Decay Length

- Determine distance between μD^0 vertex and primary vertex in transverse plane: L_T
- Determine transverse momentum of μD^0 system: $P_T(\mu D^0)$
- Calculate Visible Proper Decay Length:
  - $VPDL = L_T/P_T(\mu D^0) \cdot M_B$



1. B-meson produced at primary vertex
2. After passing L_T in transverse plane it decays to $D^{*-/0}\mu X$
   - D^{*-} decays immediately to $D^0\pi$
3. D^0 decays to $K\pi$ after passing some distance

Initial State Tagging

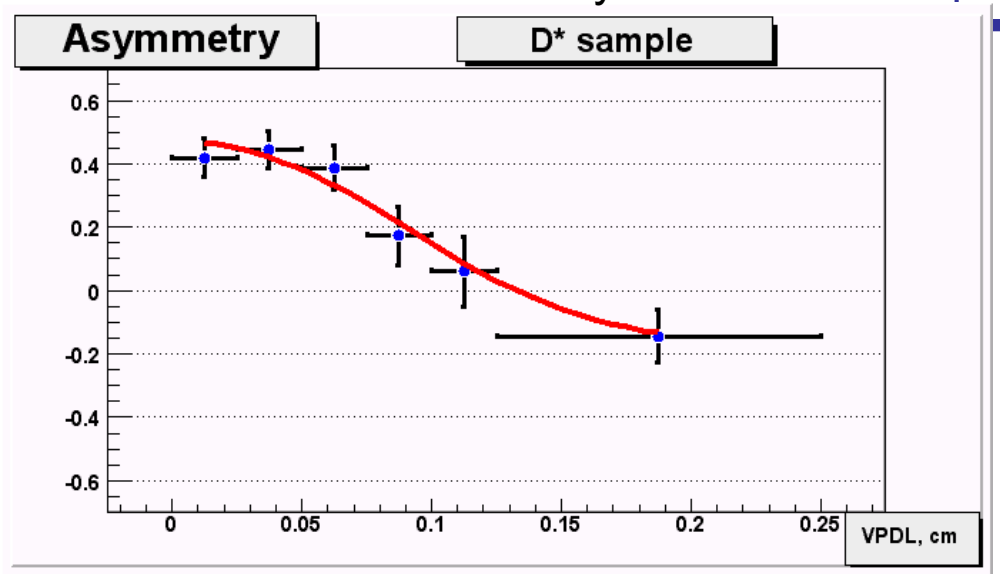


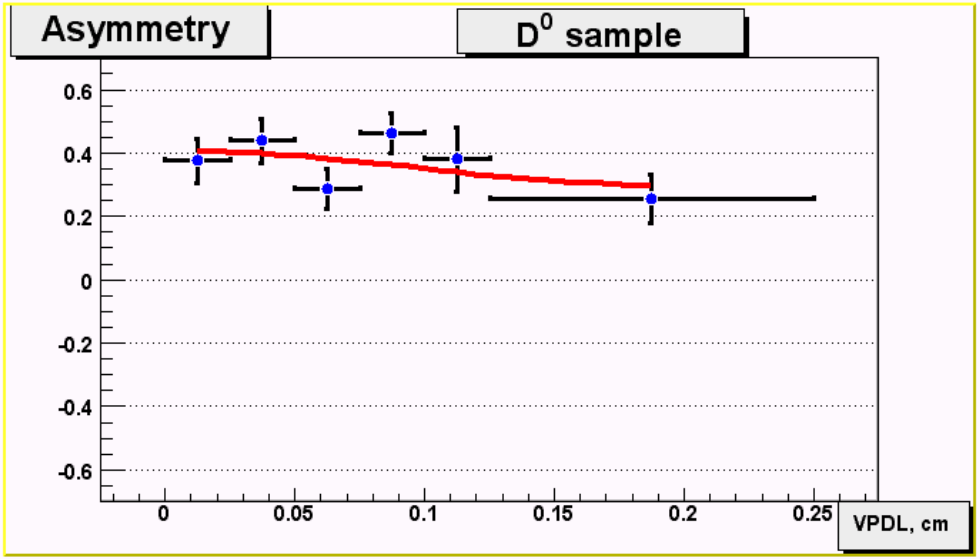
$$\text{Dilution} = \frac{N^{corr} - N^{wr}}{N^{corr} + N^{wr}}$$

- ✓ B flavor tagging methods:
  - Opposite Side Lepton Tag
    - High Dilution: D=0.5
    - Low Efficiency: ε=0.05
  - Jet Charge Tag
    - Moderate Dilution: D=0.1-0.3
    - Moderate Efficiency: ε=0.5
  - Same Side Tag
    - Low Dilution: D=0.1-0.2
    - High Efficiency: ε=0.7-0.8
- ✓ Significance of mixing measurement: $S \propto \varepsilon D^2$
- ✓ The methods can be combined

B_d mixing @ DØ

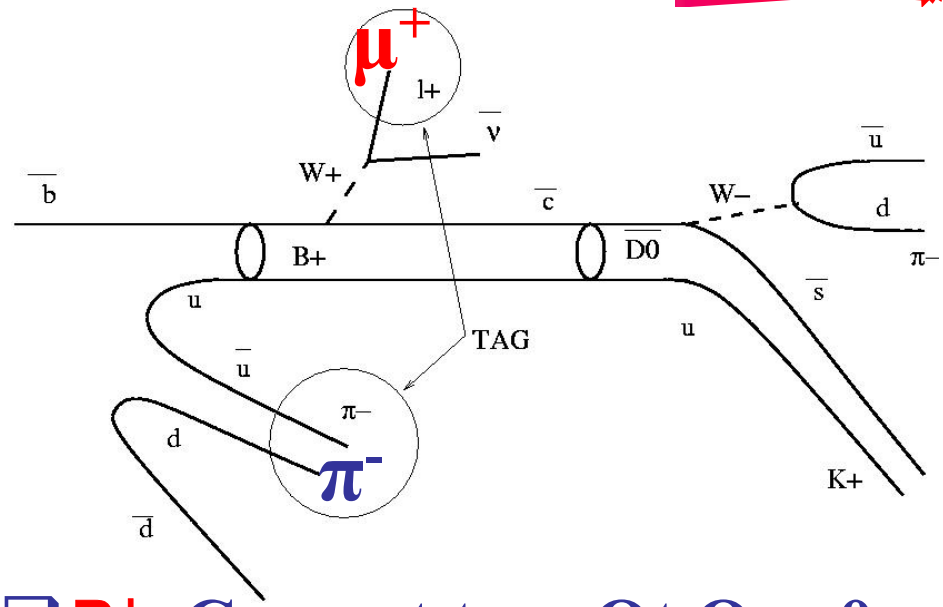
DØ RunII Preliminary

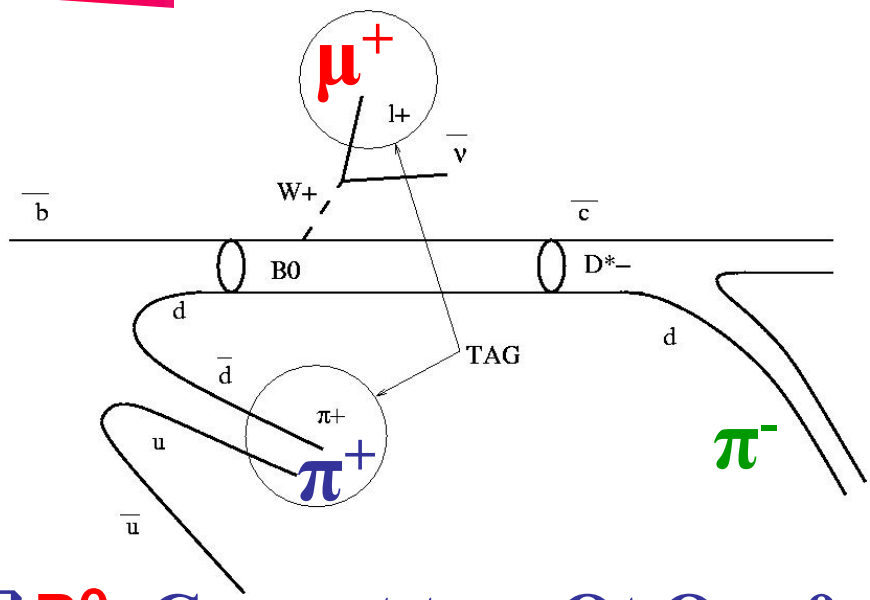




- Using the semileptonic B sample the B_d oscillations were already measured with the Opposite Side Muon tagging algorithm:
  - $\Delta m_d = 0.506 \pm 0.055$ (stat.) $\pm$ 0.049 (syst.) ps^{-1}
  - Main systematic error comes from the mass peak fitting procedure. Can be improved significantly.

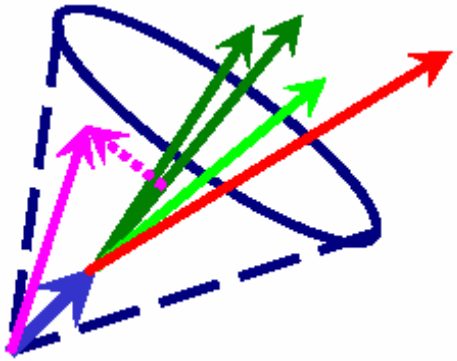
B_d mixing with Same Side Tagging





- B^+: Correct tag: $Q_t \cdot Q_\mu < 0$
- B^0: Correct tag: $Q_t \cdot Q_\mu > 0$

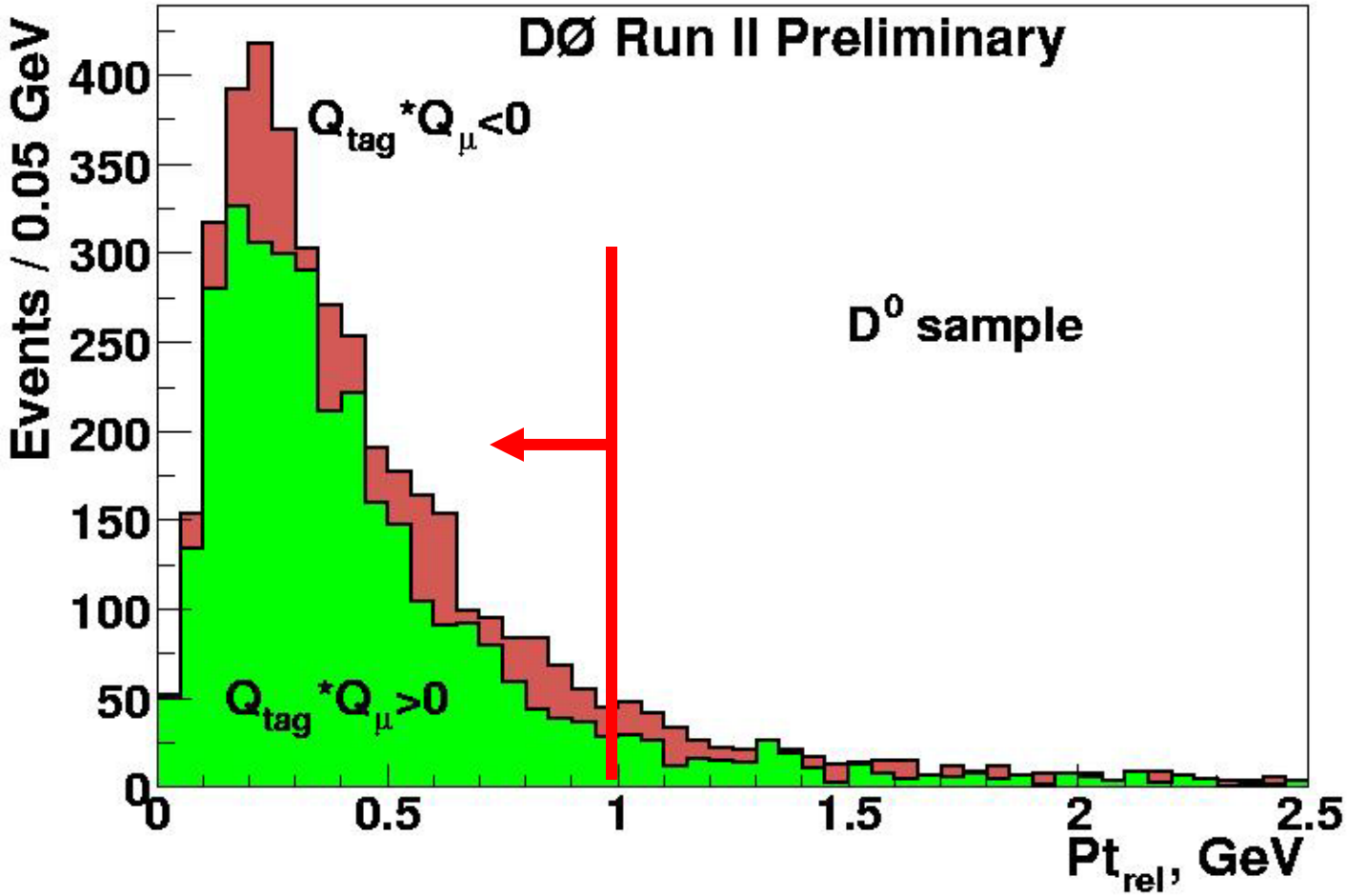
Tagging track:



Lowest Pt_{rel} track wrt B-meson in $\Delta R<0.7$ cone around B

- ✓Used by CDF in Run I
- ✓Other algorithms checked so far have similar or worse performance

Pt_{rel} distribution for tagging track

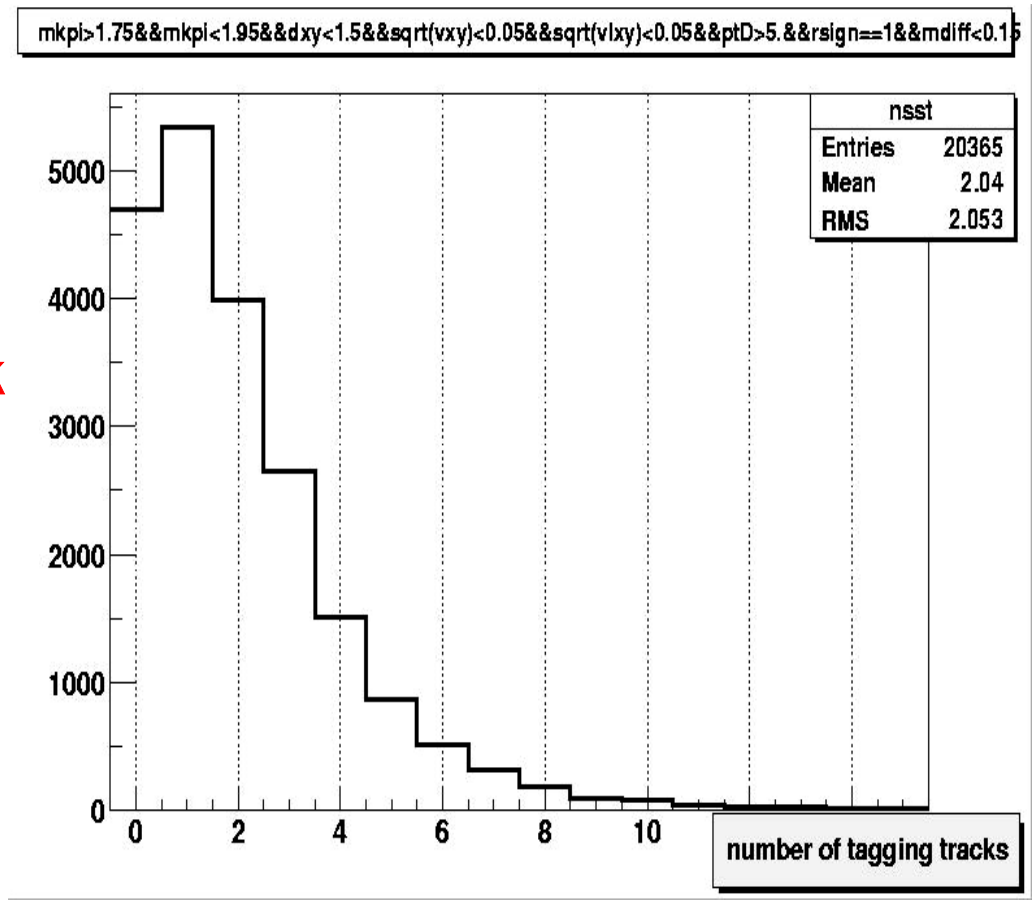


- Tracks with Pt_{rel} < 1GeV used for tagging

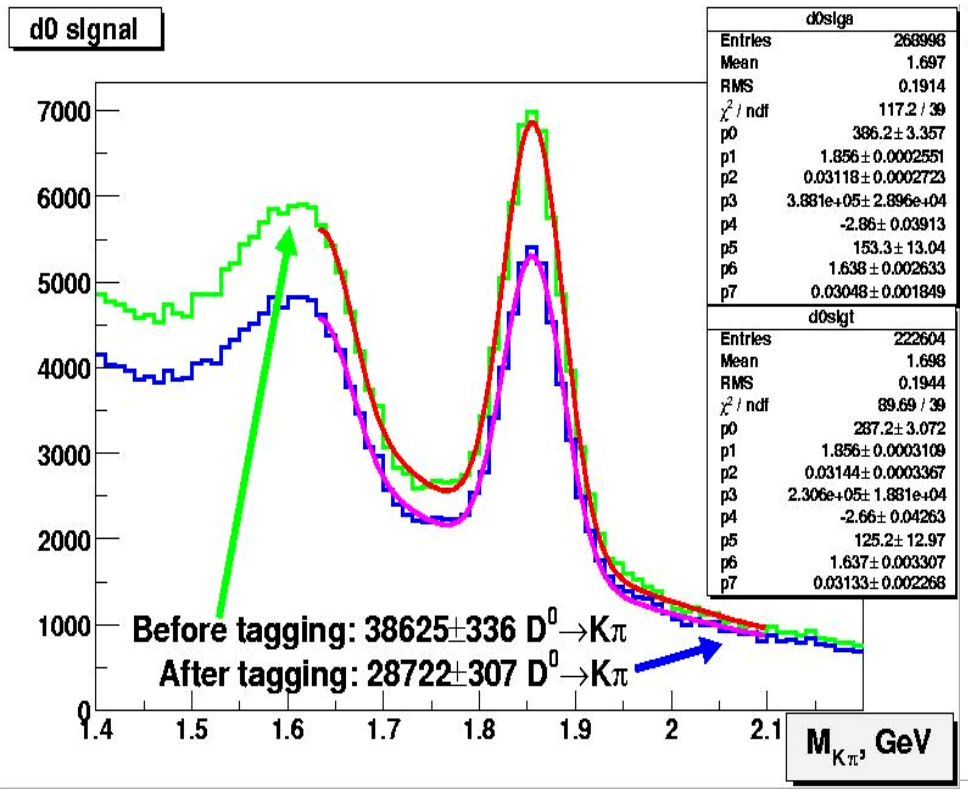
Additional Cuts on Tagging Track

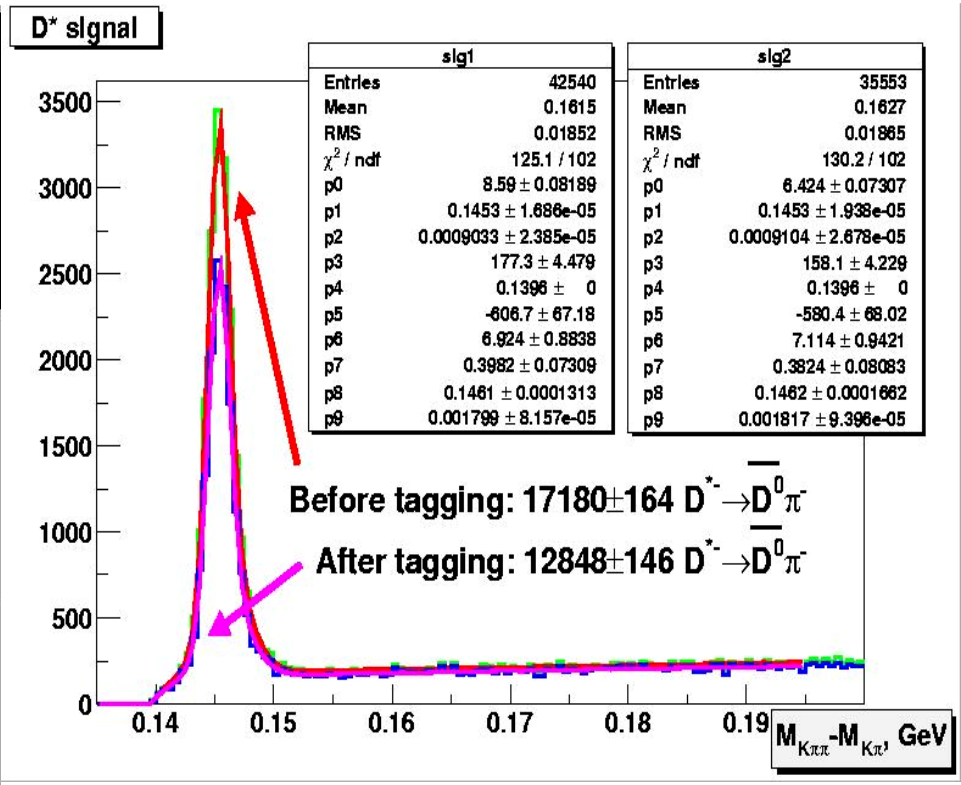
- Signal in the Silicon Micro Tracker
- Signal in the Central Fiber Tracker
- Not associated with muon
- Transverse momentum: $Pt_{tag} > 0.5GeV$
- Total energy of tagging track and μD^0: $E_{\mu D^0 \pi} > 12GeV$
- Invariant mass of μD^0-π system: $M_{\mu D^0 \pi} < 5.5GeV$
- No IP cut on the tagging track
  - Reduced bias
- μD^0 sample was used to optimize cuts

Number of tagging tracks per μD^* candidate



Tagging Efficiency





μD^0 sample:

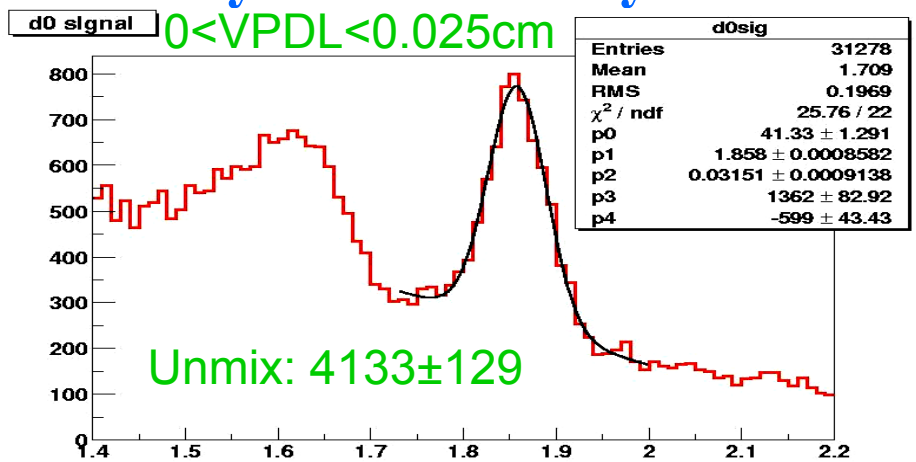
- $\varepsilon_{tag} = 0.744 \pm 0.004$

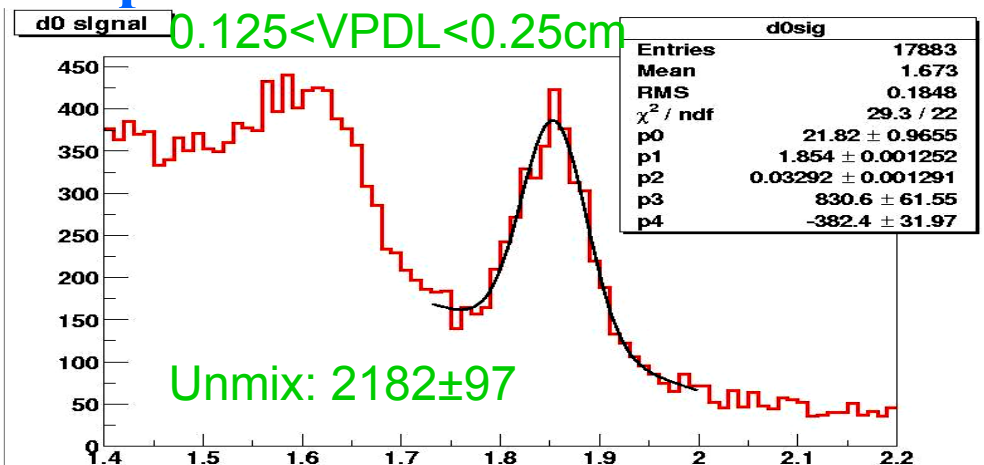
μD^* sample:

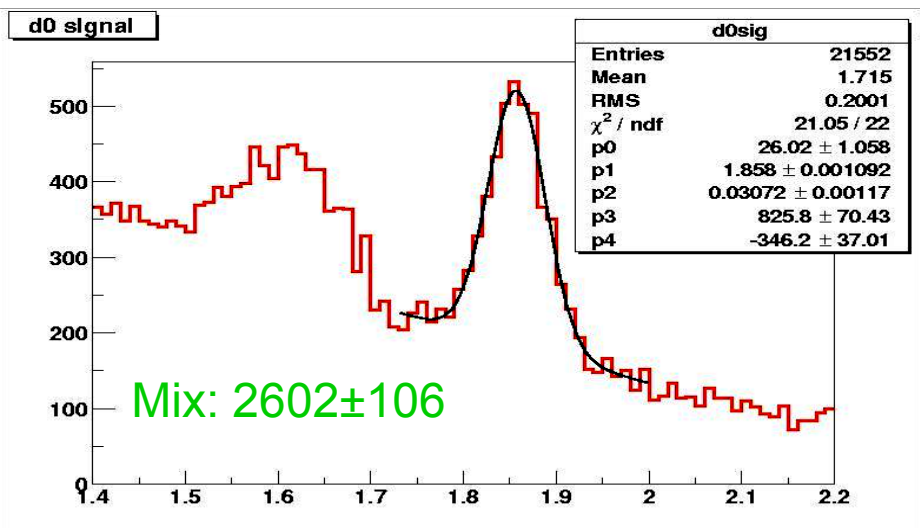
- $\varepsilon_{tag} = 0.748 \pm 0.004$

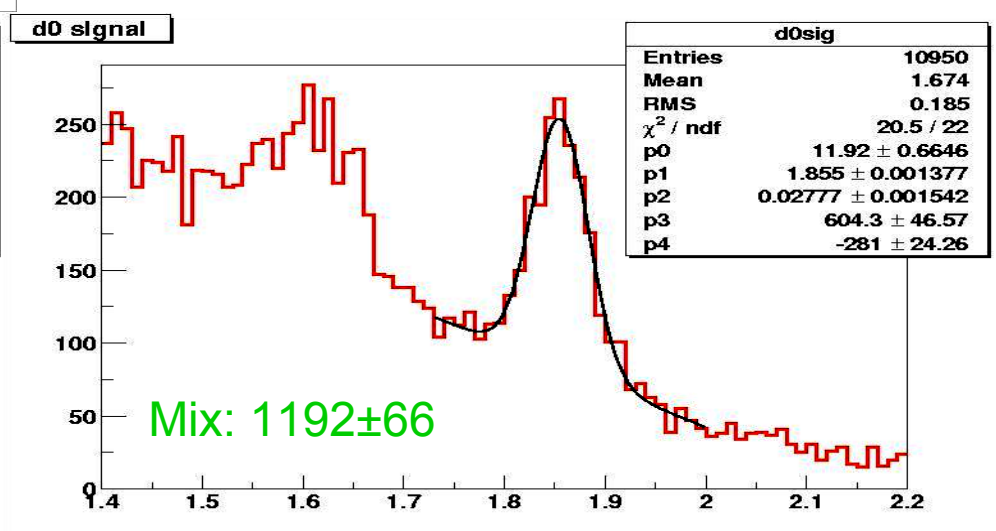
Fitting mass spectra: μD^0 sample

- **1 Gaussian + Linear Background**
  - Systematic study: fit to the left peak with ½ of Gaussian



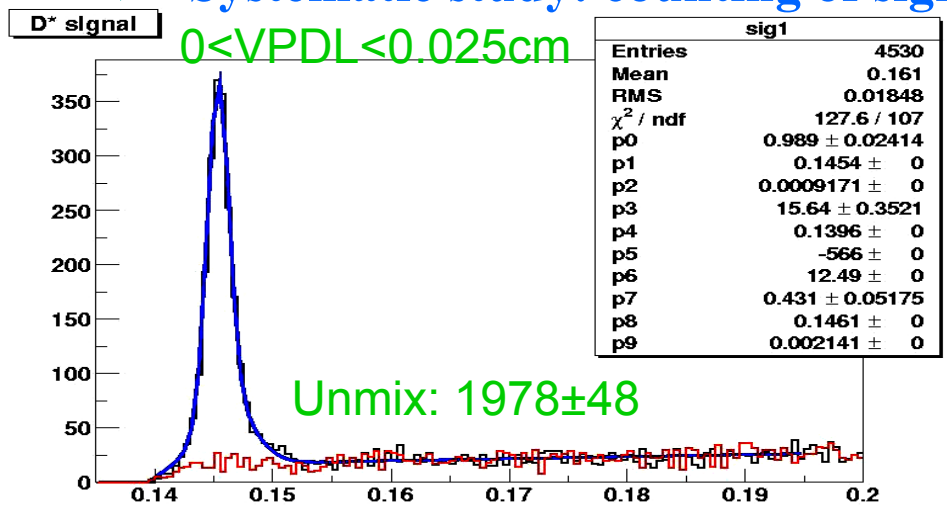


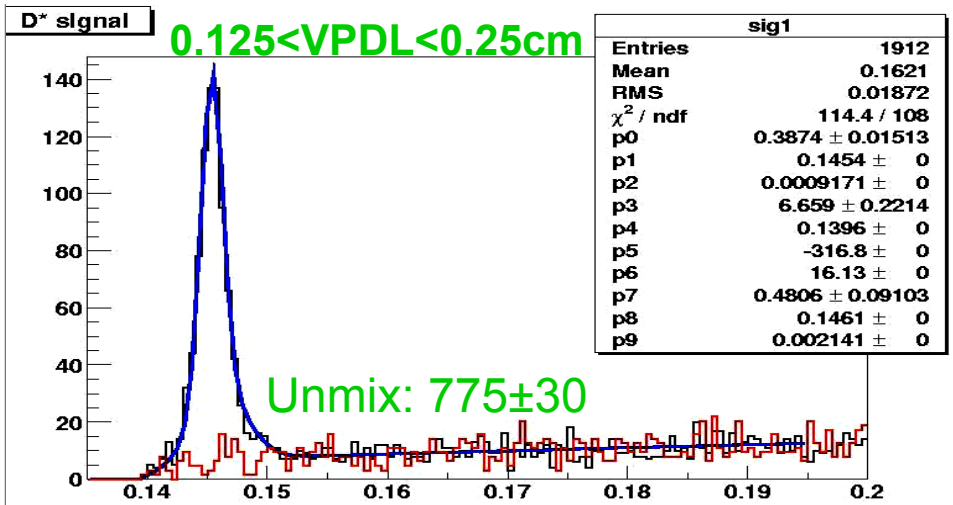


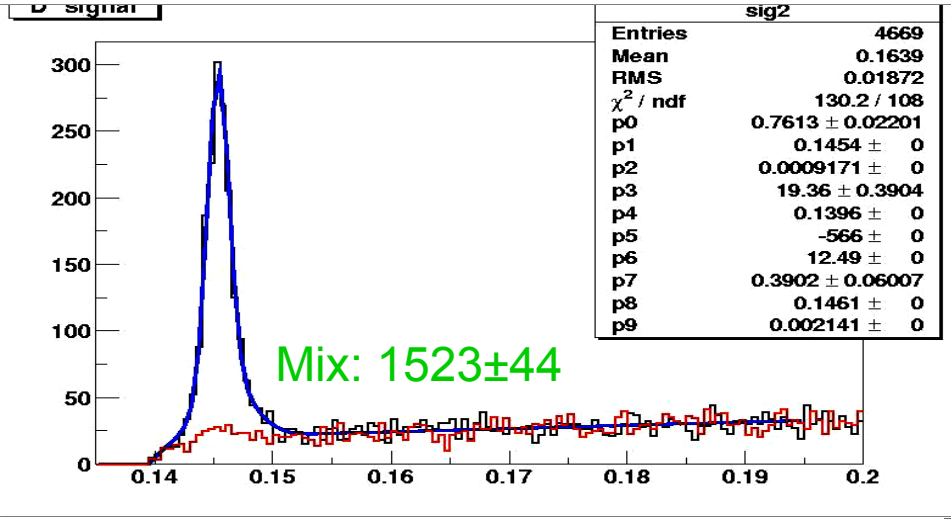


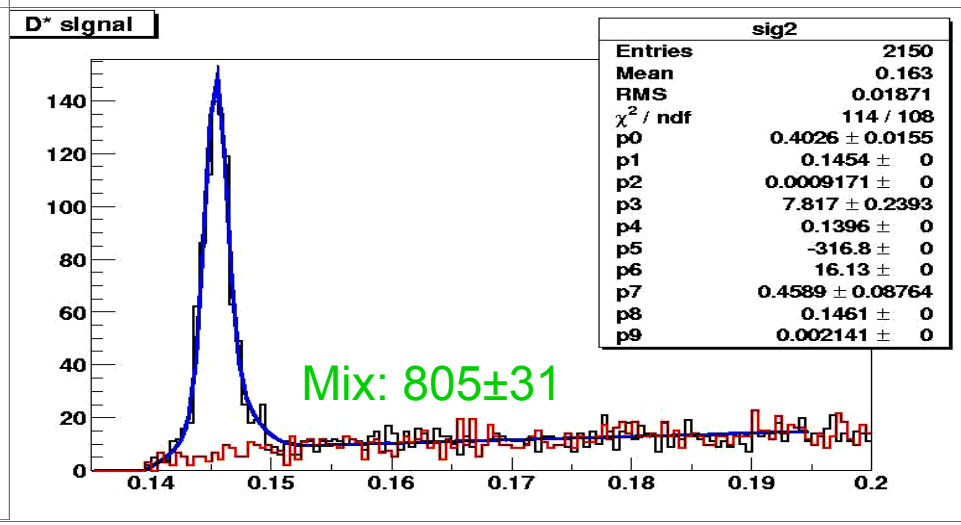
Fitting mass spectra: μD^* sample

- 2 Gaussians + Background (a · (1 – exp) + linear)
  - Systematic study: counting of signal events in the mass window



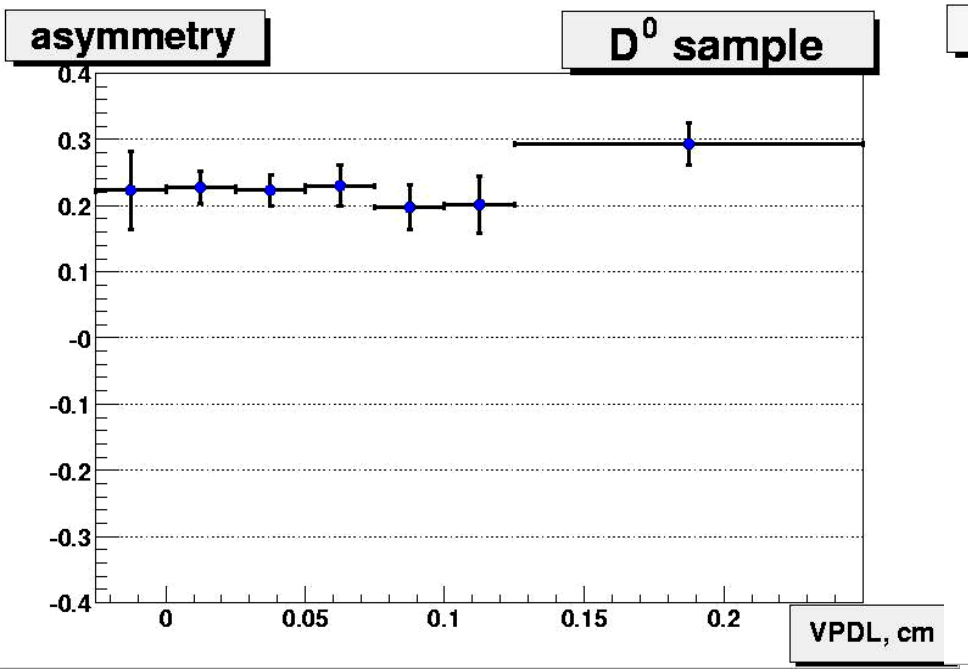


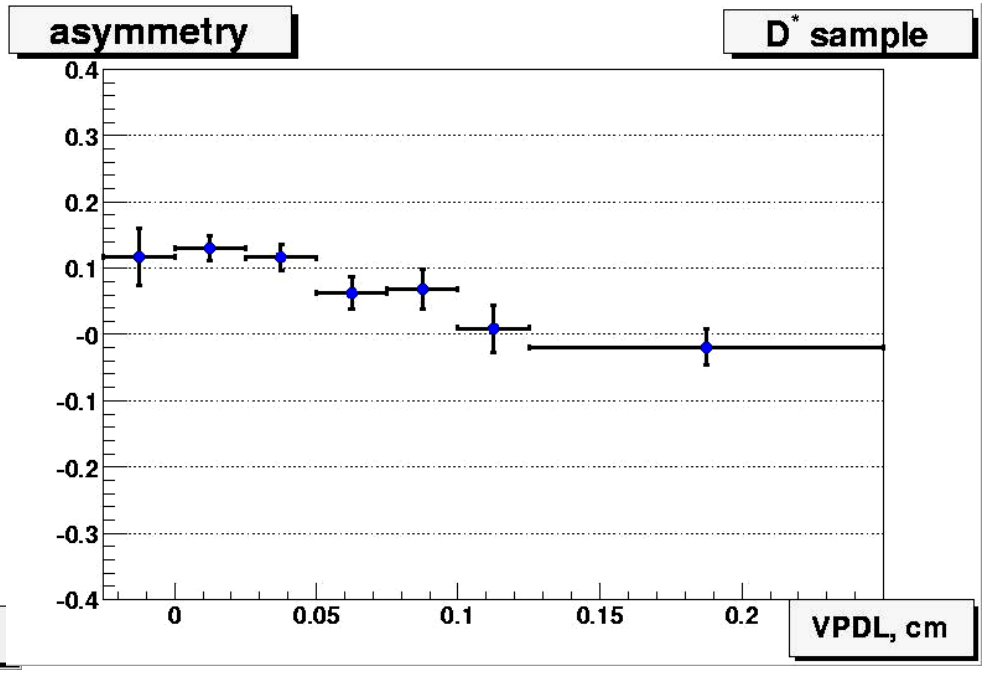




Asymmetry

$$A = \frac{N_{unmix} - N_{mix}}{N_{unmix} + N_{mix}}$$

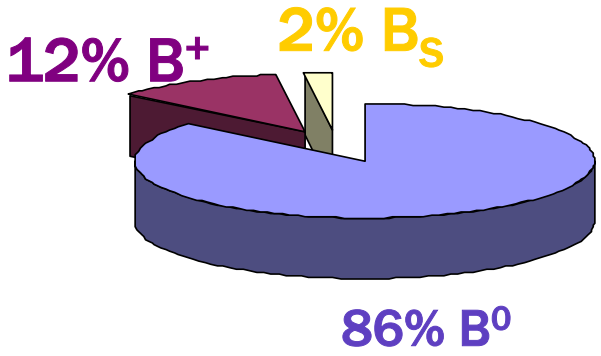




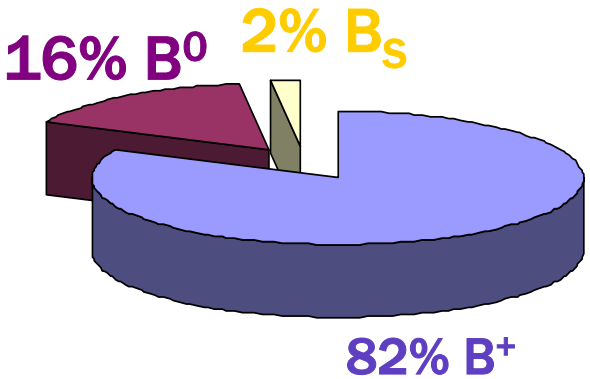
Sample Composition

- **μD^* sample**

1. $B_d^0 \to \mu^+ \nu D^{*-}$;
2. $B_d^0 \to \mu^+ \nu D^{**-} \to \mu^+ \nu D^{*-} X$;
3. $B^+ \to \mu^+ \nu \bar{D}^{**0} \to \mu^+ \nu D^{*-} \pi^{**+}$



- **μD^0 sample**



4. $B^+ \to \mu^+ \nu \bar{D}^0$;
5. $B^+ \to \mu^+ \nu \bar{D}^{*0} \to \mu^+ \nu \bar{D}^0$;
6. $B^+ \to \mu^+ \nu \bar{D}^{**0} \to \mu^+ \nu \bar{D}^0 X$;
7. $B^+ \to \mu^+ \nu \bar{D}^{**0} \to \mu^+ \nu \bar{D}^{*0} X \to \mu^+ \nu \bar{D}^0 X$;
8. $B_d^0 \to \mu^+ \nu D^{**-} \to \mu^+ \nu \bar{D}^0 \pi^{**-}$;
9. $B_d^0 \to \mu^+ \nu D^{**-} \to \mu^+ \nu \bar{D}^{*0} \pi^{**-} \to \mu^+ \nu \bar{D}^0 \pi^{**-} X$;
10. $B_d^0 \to \mu^+ \nu D^{*-}$ (with lost π_*);
11. $B_d^0 \to \mu^+ \nu D^{**-} \to \mu^+ \nu D^{*-} X$ (with lost π_*).

B_s was taken into account later and included into the systematic uncertainty

Expected number of events in the μD* sample

- $B_d^0 \to \mu^+\nu D^{*-}$ and $B_d^0 \to \mu^+\nu D^{**-} \to \mu^+\nu D^{*-}X$:

$$n^c_{j=1,2}(x) = \frac{K}{c\tau_{B^0}} \exp(-\frac{Kx}{c\tau_{B^0}}) \cdot 0.5 \cdot (1 + (2\eta_0 - 1)\cos(\Delta m \cdot Kx/c))$$

$$n^w_{j=1,2}(x) = \frac{K}{c\tau_{B^0}} \exp(-\frac{Kx}{c\tau_{B^0}}) \cdot 0.5 \cdot (1 - (2\eta_0 - 1)\cos(\Delta m \cdot Kx/c))$$

- $B^+ \to \mu^+\nu \bar{D}^{**0} \to \mu^+\nu D^{*-}\pi^{**+}X$.

π^{**} term: $n^c_{j=3**}(x) = P^{**} \cdot \frac{K}{c\tau_{B^+}} \exp(-\frac{Kx}{c\tau_{B^+}})$

$$n^c_{j=3}(x) = \frac{K}{c\tau_{B^+}} \exp(-\frac{Kx}{c\tau_{B^+}}) \cdot (1 - \eta_+)$$

$$n^w_{j=3}(x) = \frac{K}{c\tau_{B^+}} \exp(-\frac{Kx}{c\tau_{B^+}}) \cdot \eta_+$$

K – factor:

$$K = P_T^{\mu D^0} / P_T^B$$

***x* – Visible Proper Decay Length**

$\eta = N_{correct\ tag} / N_{tot\ tag}$

***P^{**}* – Probability to take π^{**} as a tag**

Expected number of events in the μD^0 sample

The first four processes:

$$n^c_{j=4-7}(x) = \frac{K}{c\tau_{B^+}} \exp(-\frac{Kx}{c\tau_{B^+}}) \cdot \eta_+$$

$$n^w_{j=4-7}(x) = \frac{K}{c\tau_{B^+}} \exp(-\frac{Kx}{c\tau_{B^+}}) \cdot (1-\eta_+)$$

- The processes $B^0_d \to \mu^+\nu D^{**-} \to \mu^+\nu\bar{D}^0\pi^{**-}$ and $B^0_d \to \mu^+\nu D^{**-} \to \mu^+\nu\bar{D}^{*0}\pi^{**-} \to \mu^+\nu\bar{D}^0\pi^{**-}X$

π^{**} term: $n^c_{j=8**,9**}(x) = P^{**} \cdot \frac{K}{c\tau_{B^0}} \exp(-\frac{Kx}{c\tau_{B^0}})$

$$n^c_{j=8,9}(x) = \frac{K}{c\tau_{B^0}} \exp(-\frac{Kx}{c\tau_{B^0}}) \cdot 0.5 \cdot (1-(2\eta_0-1)\cos(\Delta m \cdot Kx/c))$$

$$n^w_{j=8,9}(x) = \frac{K}{c\tau_{B^0}} \exp(-\frac{Kx}{c\tau_{B^0}}) \cdot 0.5 \cdot (1+(2\eta_0-1)\cos(\Delta m \cdot Kx/c))$$

- The processes $B^0_d \to \mu^+\nu D^{*-}$ and $B^0_d \to \mu^+\nu D^{**-} \to \mu^+\nu D^{*-}X$ (both with lost π_*) :

$$n^c_{j=10,11}(x) = \frac{K}{c\tau_{B^0}} \exp(-\frac{Kx}{c\tau_{B^0}}) \cdot 0.5 \cdot (1-(2\eta_0-1)\cos(\Delta m \cdot Kx/c))$$

$$n^w_{j=10,11}(x) = \frac{K}{c\tau_{B^0}} \exp(-\frac{Kx}{c\tau_{B^0}}) \cdot 0.5 \cdot (1+(2\eta_0-1)\cos(\Delta m \cdot Kx/c))$$

Fitting to the asymmetry

Transition to the measured VPDL, x^M, is achieved by integration over K-factors and resolution functions:

$$N_j^{c,\ w}(x^M) = \int dx\ Res_j(x - x^M) \cdot Eff_j(x) \int dK\ D_j(K) \cdot \theta(x) \cdot n_j^{c,\ w}(x, K).$$

The expected number of events with "correct, wrong" tags in the i-th bin of VPDL is equal to

$$N_i^{e;c,w} = \int_i dx^M \sum_j (Br_j \cdot N_j^{c,w}(x^M))$$

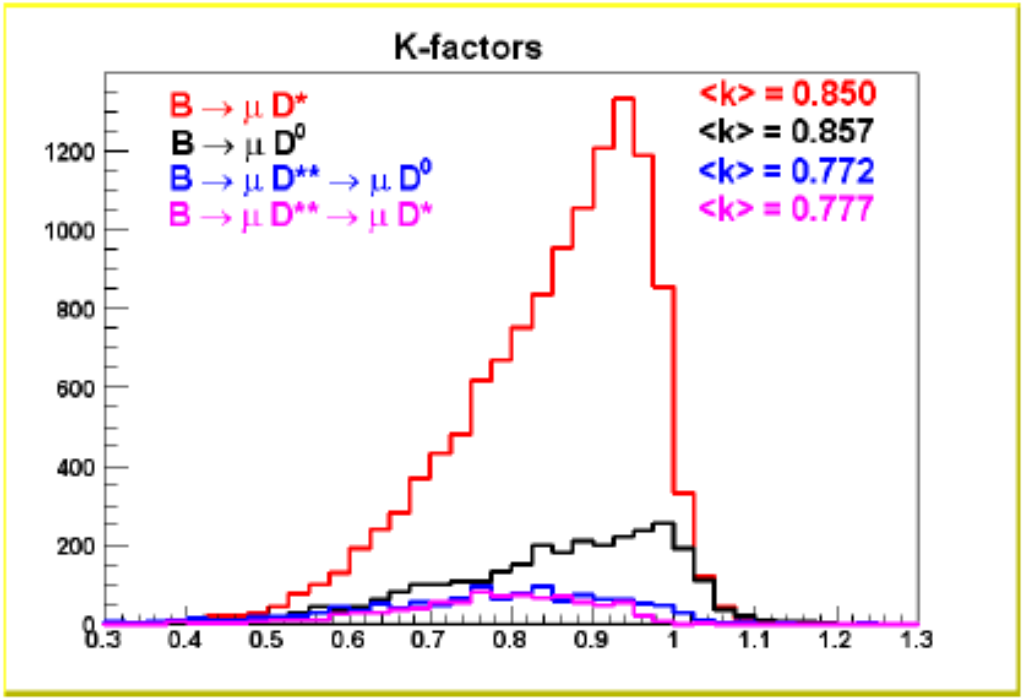
The fit values of Δm, η_0 and η_+ were determined from the minimization of a $\chi^2(\Delta m, \eta_0, \eta_+)$ defined as:

$$\chi^2(\Delta m, \eta) = \sum_i \frac{(A_i - A_i^e(\Delta m, \eta_0, \eta_+))^2}{\sigma^2(A_i)}$$

The variables Δm, η_0, η_+ were the only free parameters of the fit.

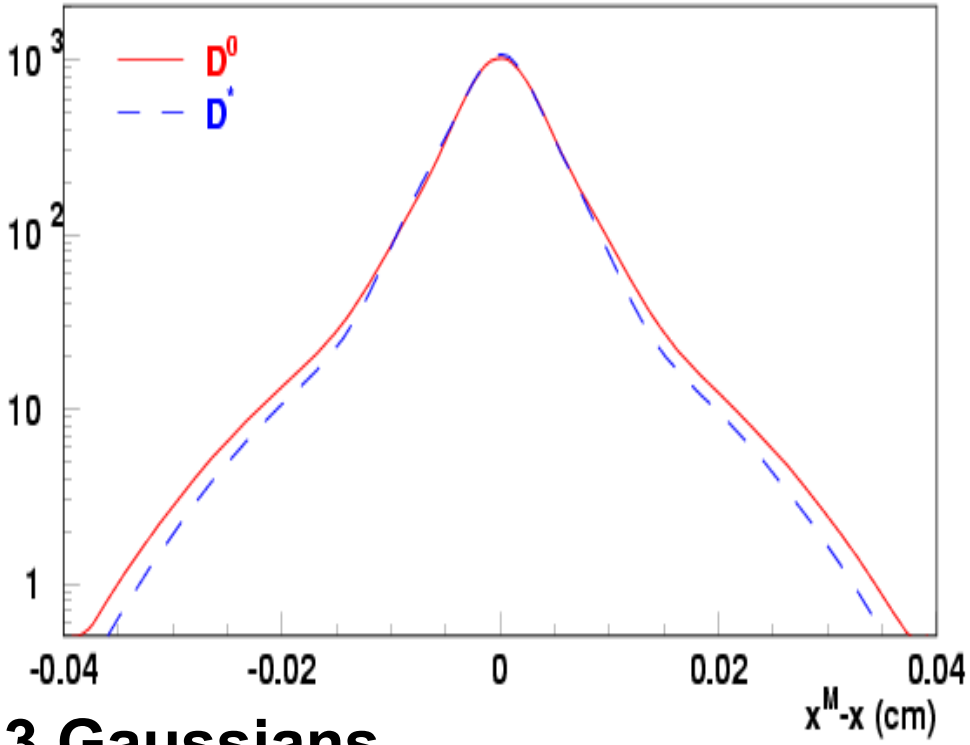
K-factors

- K-factors take into account not reconstructed particles
- Production $B \to D^* \mu \nu X$ dominates both for D^* and D^0 samples
- K-factors are computed as: $K = P_T(\mu D^0) / P_T(B)$, even for D^{*-} sample
  - K-factors are the same for $B^0 \to D^{*-} \mu \nu X$ and $B^+ \to D^{*0} \mu \nu X$ decays
    - ✓ Reduced systematics
- 4 groups of K-factors
  - $B \to D^* \mu$
    - ✓ $B^0 \to D^{*-} \mu \nu$
    - ✓ $B^+ \to D^{*0} \mu \nu$
  - $B \to D^0 \mu$
    - ✓ $B^+ \to D^0 \mu \nu$
  - $B \to D^{**} \mu \to D^0 \mu$
    - ✓ No D^{*-} reconstructed
  - $B \to D^{**} \mu \to D^{*-} \mu$



VPDL Resolution

- Determined from MC
  - Described by 3 Gaussians
- Ratio fitting procedure assumes resolution is the same for D^0 and D*
  - We do not use slow pion for B-vertex
- Resolution and tails of resolution were varied in wide range to study systematics due to resolution effects
- Not so important for B_d studies



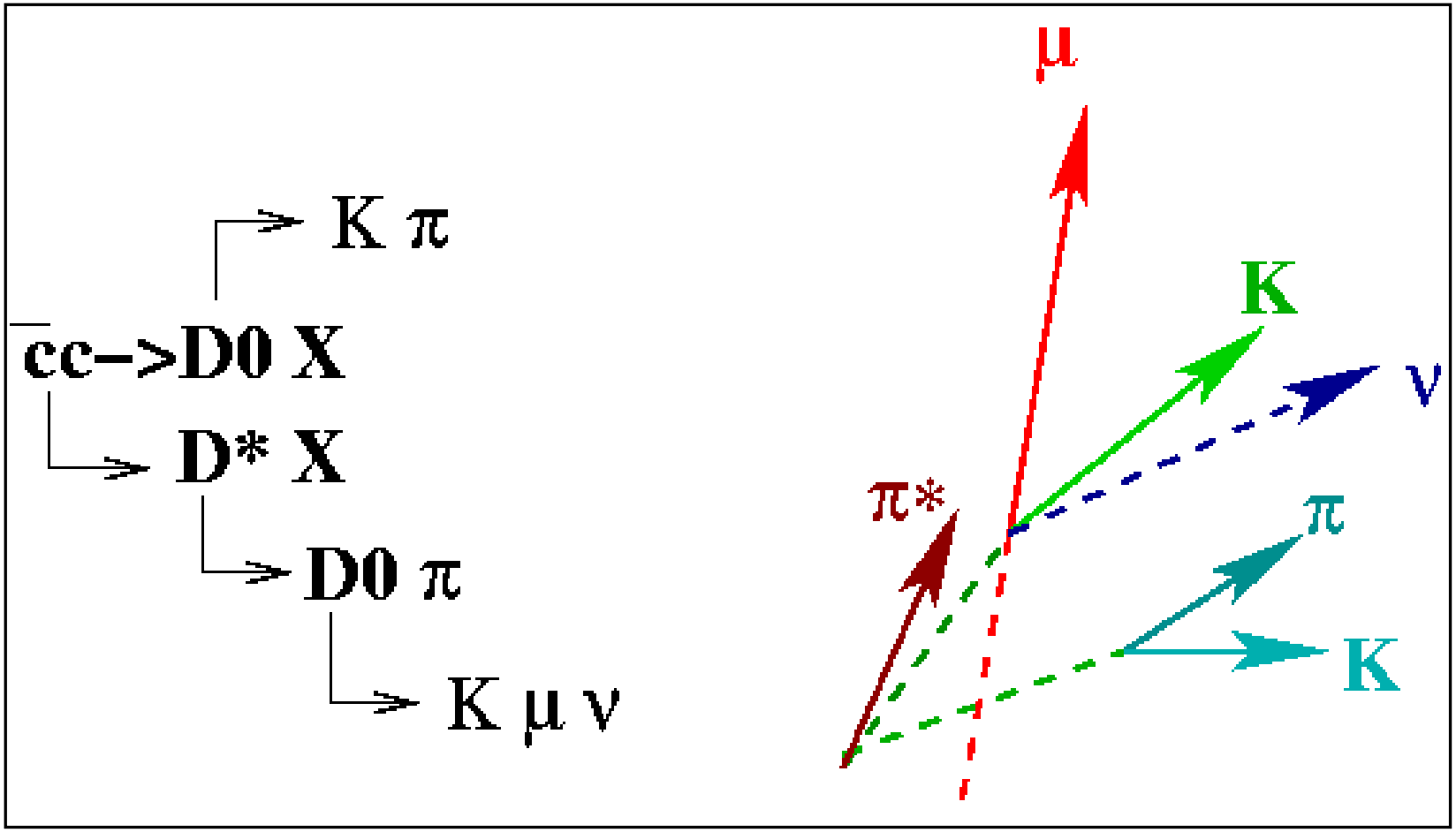
3 Gaussians

- σ_1= 22.2 μm – 28%
- σ_2= 47.3 μm – 57%
- σ_3= 131 μm – 15%

$c\bar{c}$ contamination

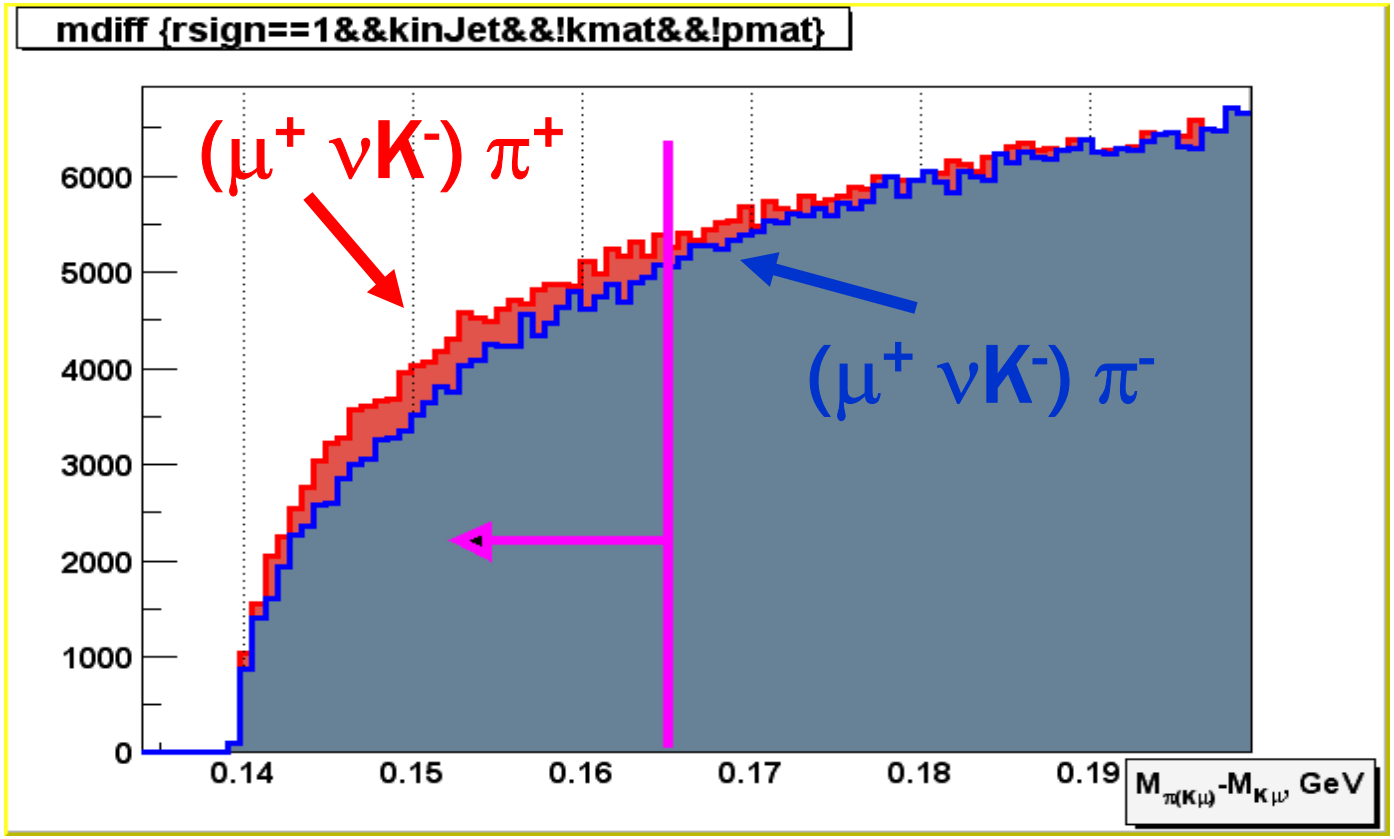
- $c\bar{c}$ can produce $\mu^- D^0$: $\bar{c} \to \mu^- X$ and $c \to D^0 X$;
- $c\bar{c}$ sources, which give μ^- and D^0 in the same jet:
  - gluon splitting: $g \to c\bar{c}$;
  - final state gluon radiation in $q\bar{q} \to c\bar{c}g$ ($gg \to c\bar{c}g$) can bring both c-quarks in the same jet;
- Similarly, $\mu^- D^0$ can be produced in gluon splitting $g \to b\bar{b}$, and $qq \to b\bar{b}\, g$, when $b \to \mu^- X$ and $\bar{b}$:
  - oscillates and decays to D^0;
  - decays to $D^0\bar{D}X$;

Estimate $C\ \overline{C}$ from D^0D^* events



$D^{*+} \to D^0\pi^+$; $D^0 \to \mu^+ \nu K^-$ +additional $D^0 \to K\pi$

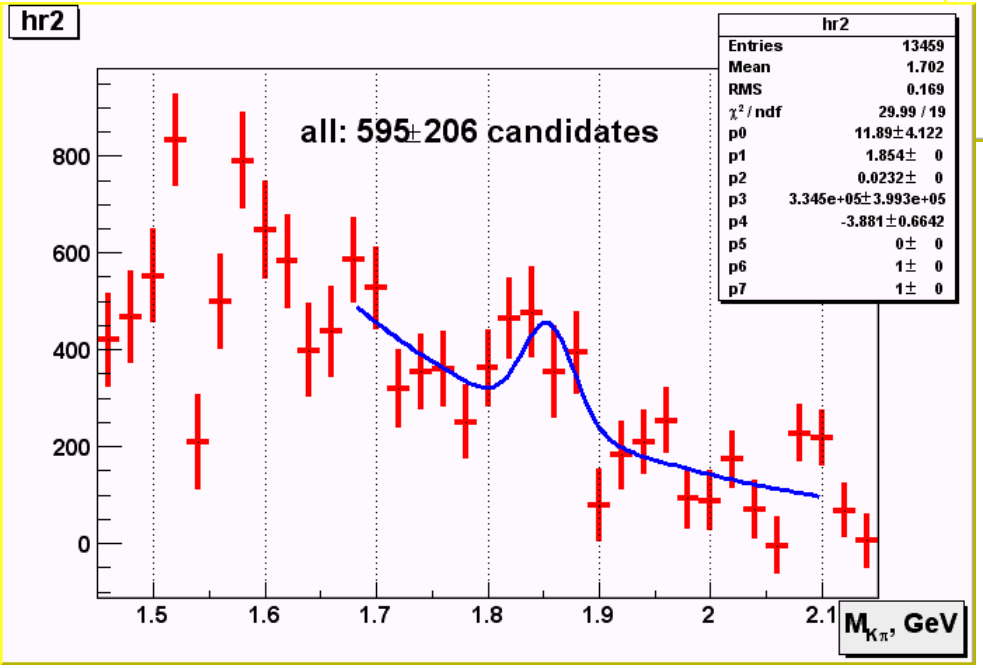
- We also see the presence of $D^{*+} \to (\mu^+ \nu K^-)\ \pi^+$ in our (μD^0) sample;
- Histograms show "right" and "wrong sign" $(\mu^+ \nu K^-)\ \pi$ combinations;
- Excess in "right sign" can be attributed to $D^{*+} \to (\mu^+ \nu K^-)\ \pi^+$

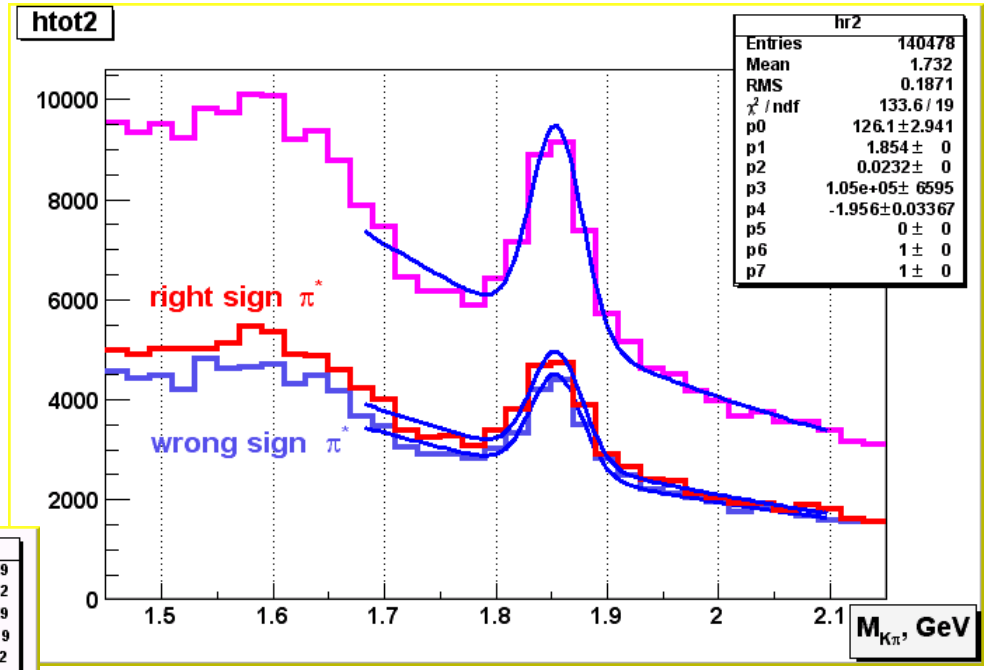


Number of $C\,\overline{C}$ in μD^0 sample

$D^0 \rightarrow K\,\pi$ peak for events with selected D*'s (ΔM<0.165 GeV)

595 candidates





- Difference between right and wrong sign π^*

$c\bar{c}$ rate from D^*D^0 events

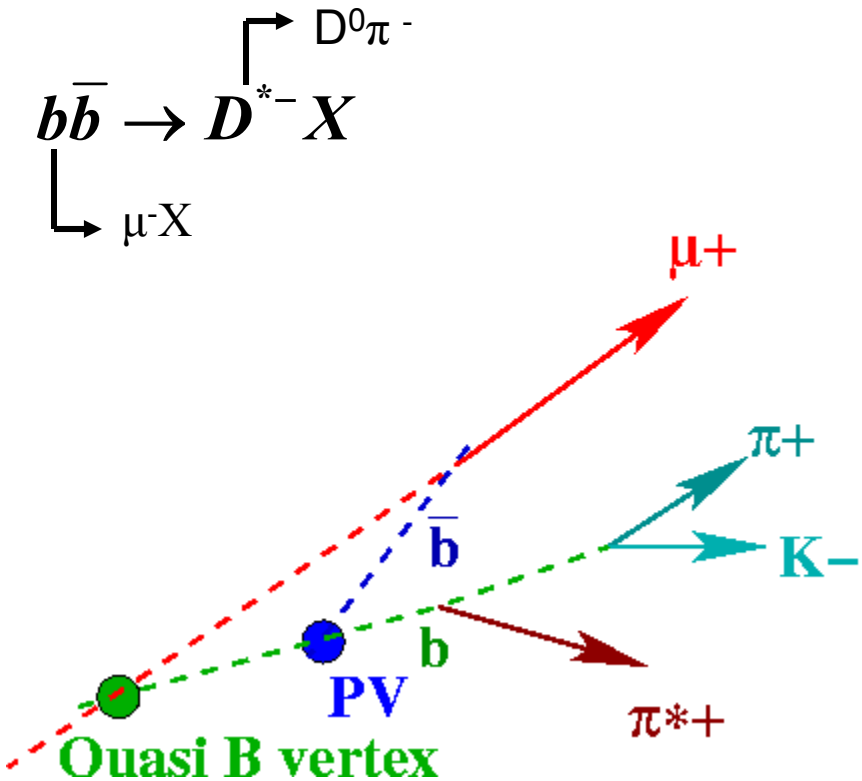
- Using the estimated number (595±206) of D^*D^0 events and taking into account all branching fractions, we can estimate the fraction of $c\bar{c}$ events in $\mu^- D^0$ sample:

$$12 \pm 4\%$$

- This number assumes efficiency to reconstruct $D^{*+} \rightarrow (\mu^+ \nu K^-) \pi^+$ events is ~50% (excluding muon efficiency);
- Main part of D^*D^0 events has very small decay length of (μ^+ - D^0) quasi-vertex:

N(VPDL<0.025 cm) = 555±112 events

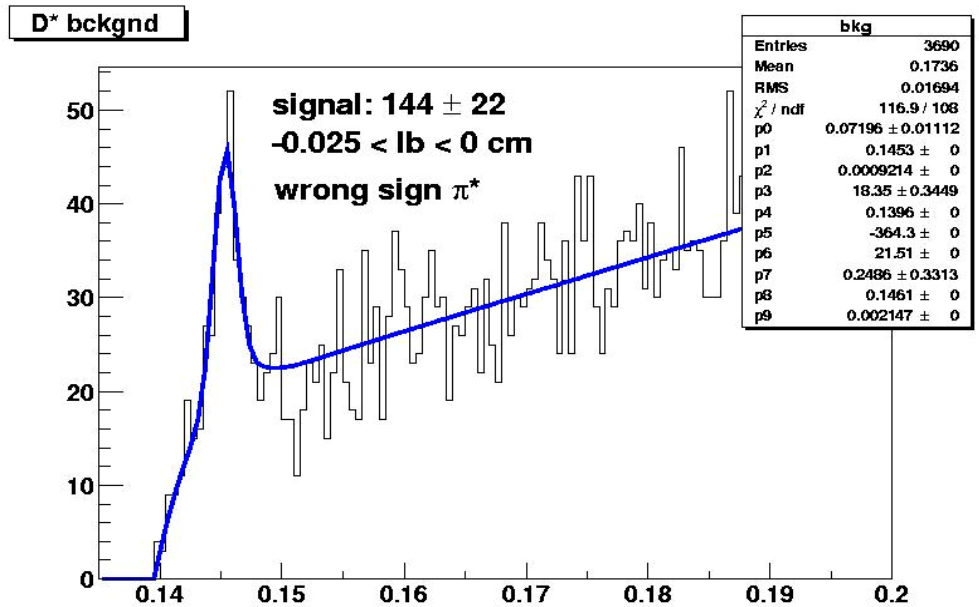
Decay length distribution from μ^+-D^* events

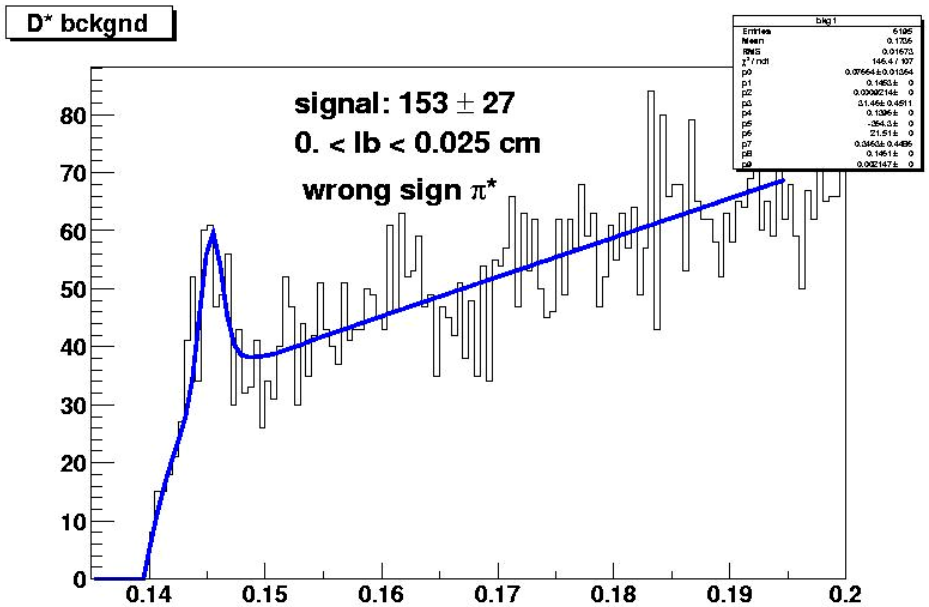


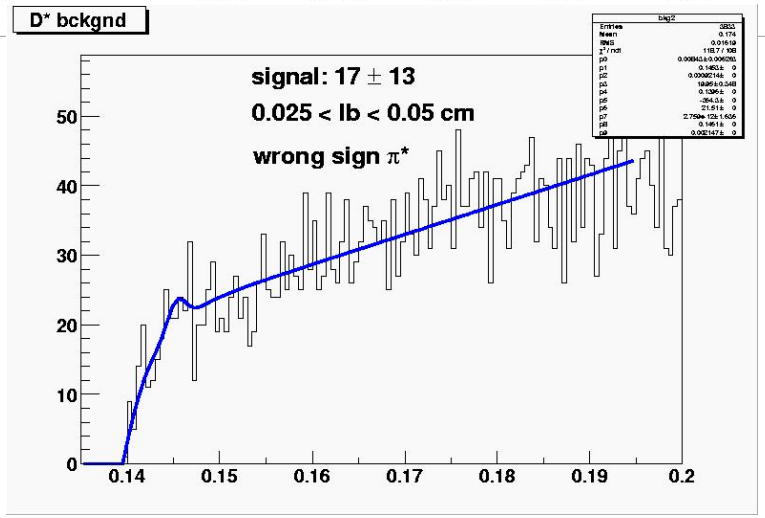
- μ and D^0 in $c\bar{c}$ ($b\bar{b}$) events are not correlated;
- Since both quarks come from the primary vertex, μ and D^0 should produce the effective vertex near the primary vertex with small effective decay length;
- Large fraction should have negative decay length;
- For ($c\bar{c}$) events, decay length of quasi-vertex should be even less than for ($b\bar{b}$) events (D^0 comes from primary vertex);

Distributions of $b\bar{b}$ in different VPDL bins

- Visible contribution only in negative and first positive bins (as expected)







Contribution to wrong π* sign combination

$$b\bar{b} \rightarrow D^{*-}X$$

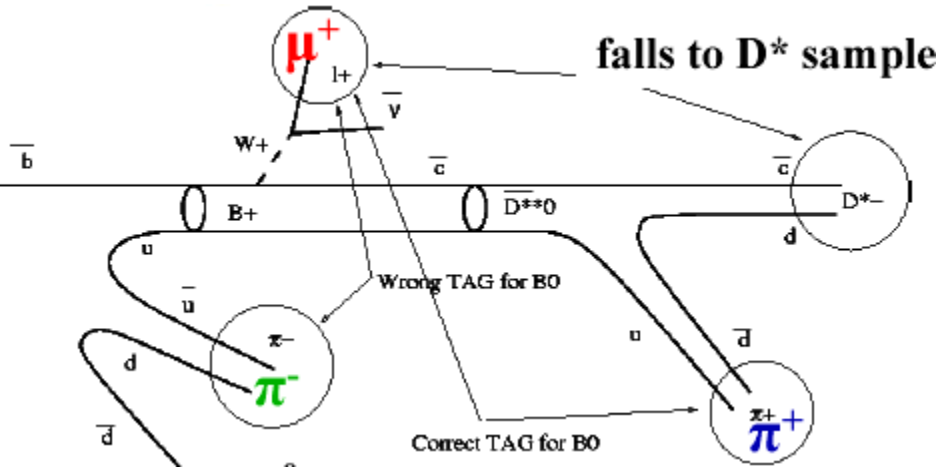
$D^{*-} \rightarrow D^0\pi^-$

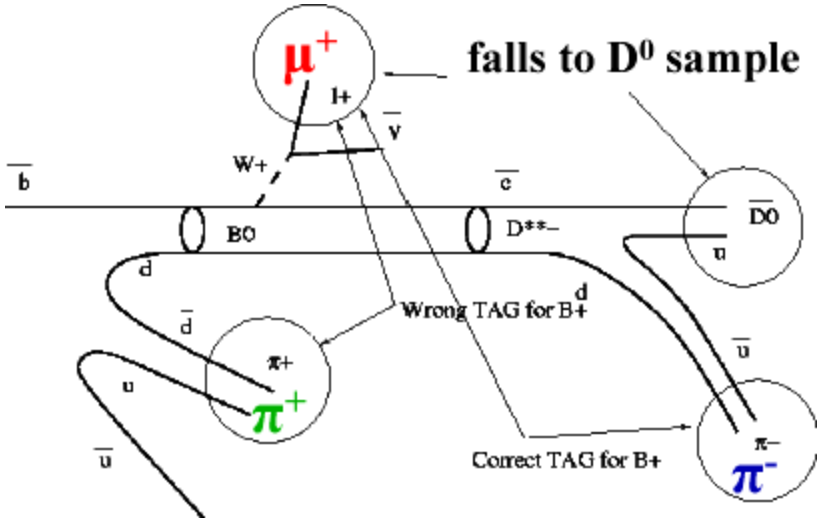
$b\bar{b} \rightarrow \mu^- X$

Conclusion for $c\bar{c}$ contamination

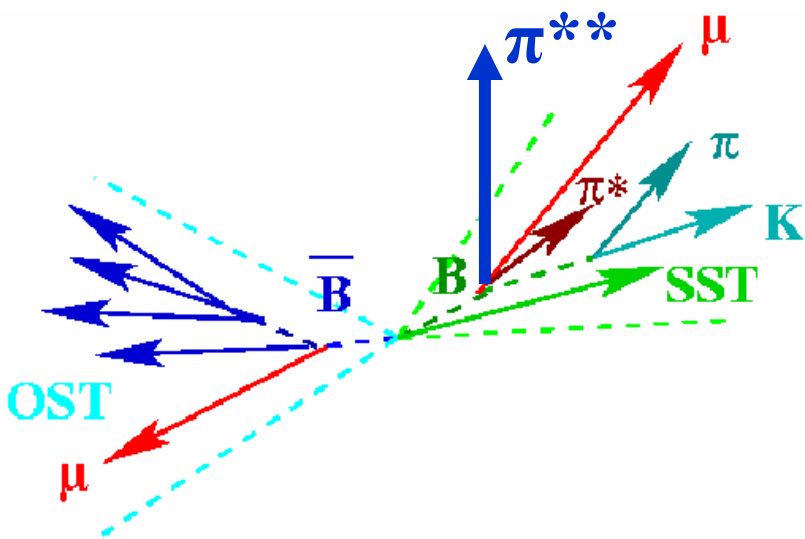
- Different methods were used to estimate the $c\bar{c}$ contamination in the μD^0 sample
- All of them give qualitatively similar result, confirming each other
- As a result the value 10 ± 7 % was obtained
- In this analysis the $c\bar{c}$ contamination was taken into account in systematic errors by omitting the negative and first positive bins in the asymmetry fit

D^{**} contribution

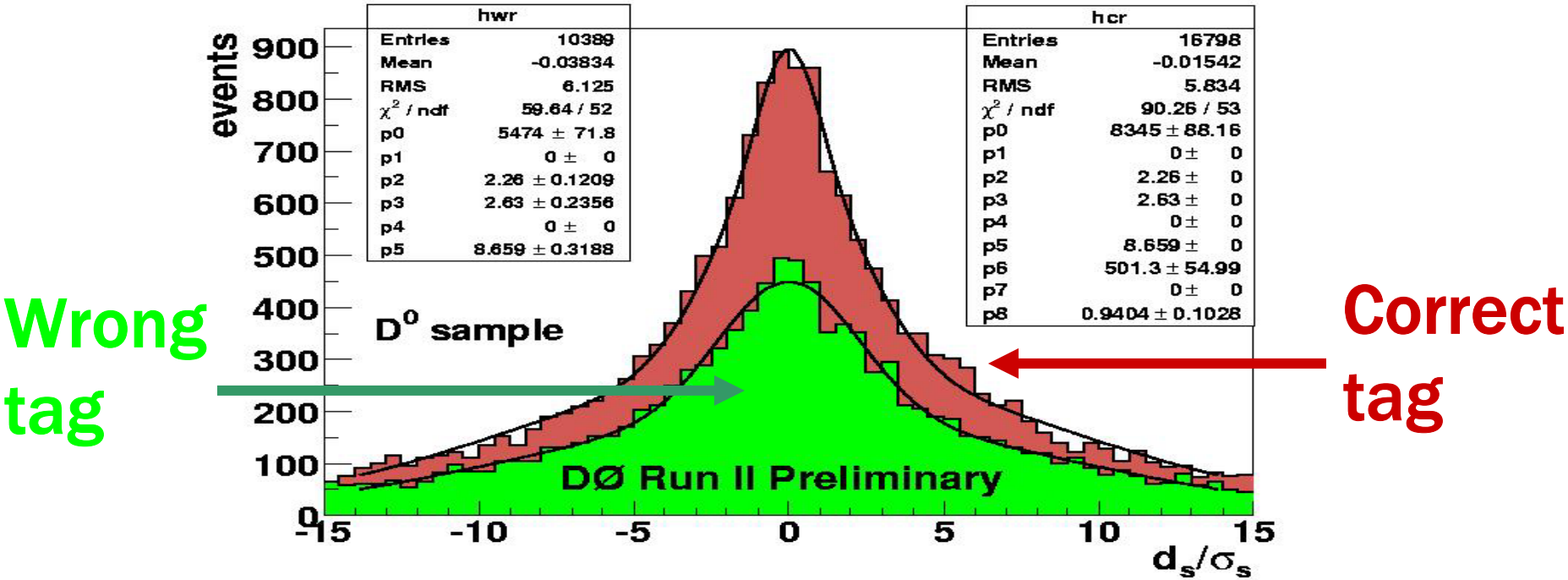




- **Difficulties arise due to D^{**} contribution**
  - Charged pion from D^{**} can be taken as a tag
- **Estimated from D^{**} topological analysis**
  - Use impact parameter of pion from $D^{**} \rightarrow D^{*}\pi$
  - Used by CDF in RunI for cross check



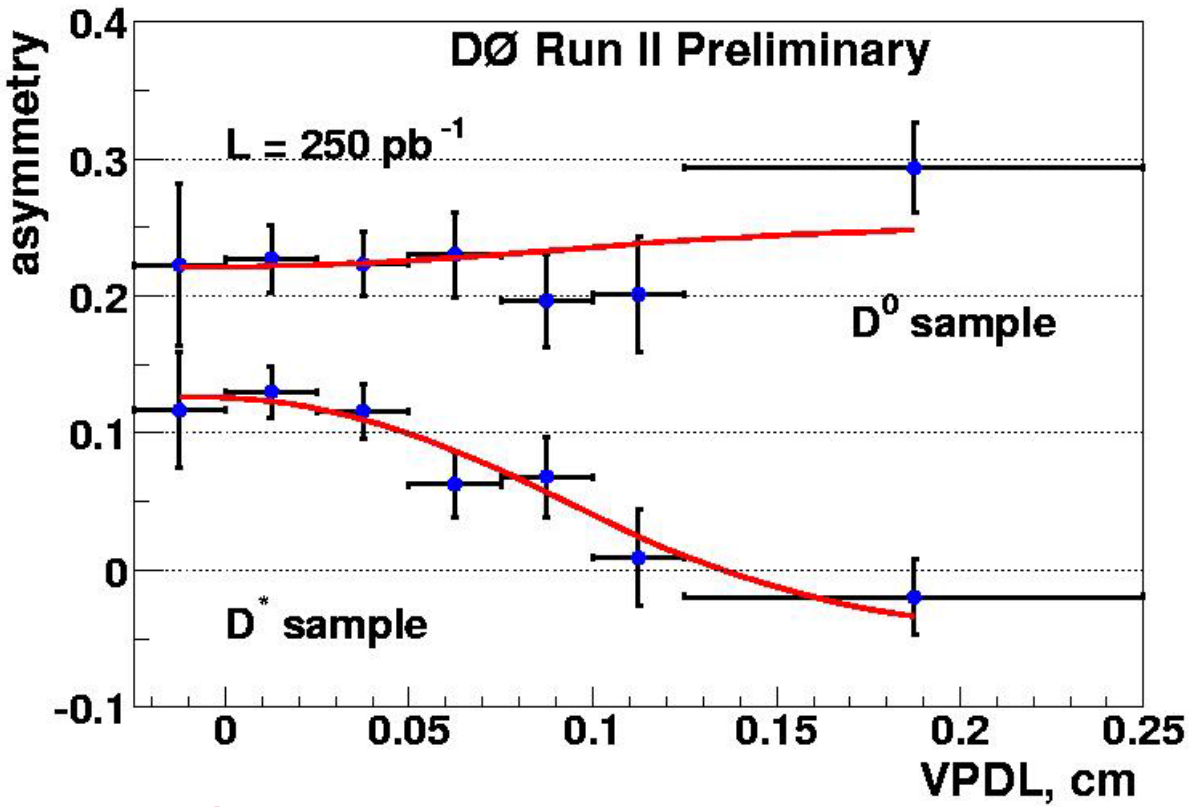
Impact parameter significance of tagging track with respect to B-vertex



- **From these distributions:**
  - Fraction of events where π^{**} was taken as a tag in μD^0 sample: $R^{**} = 4.7 \pm 0.6$ %
  - Using sample composition can determine the probability to take π^{**} as a tag: $P^{**} = 25.5$ %
  - Contribution from $D^{**} \rightarrow D^0\pi^+\pi^-$ is visible (taken into account as systematic uncertainty of R^{**})
- **No IP cuts → P^{**} does not depend on the Visible Proper Decay Length**

B_d mixing result with SST

- Oscillataion frequency: $\Delta m = 0.488 \pm 0.066$ (stat) ± 0.044 (syst)



- Purity ($\eta = N_{corr}/(N_{corr}+N_{wrong})$) for B_d:

$\eta_o = 0.558 \pm 0.007$ (stat) ± 0.008 (syst)

- Purity for $B_\pm$: $\eta_\pm = 0.622 \pm 0.008$ (stat) ± 0.012 (syst)

Systematic errors for Bd mixing with SST

	variation	Δm change	η_0 change	η_+ change
$Br(B^0 \to D^{*-}\mu^+\nu)$	$5.53 \pm 0.23\%$	0.003 ps^{-1}	0.001	0.001
$Br(B^\pm \to D^*\pi\mu\nu X)$	$1.07 \pm 0.25\%$	0.017 ps^{-1}	0.001	0.001
$\Delta\tau/\tau$	0.086 ± 0.017	0.001 ps^{-1}	0.001	0.001
resolution	SF: 1 — 2	0.005 ps^{-1}	0.001	0.000
alignment (from OST)	$10\mu m$	0.007 ps^{-1}	0.004	0.004
k-factor (from OST)	average value $\pm$ 2%	0.009 ps^{-1}	0.000	0.000
MC efficiency for slow pion	set to 100%	0.001 ps^{-1}	0.001	0.010
D^{**} contribution	$R_0^{**} = 4.7 \pm 0.6\%$	0.035 ps^{-1}	0.004	0.004
MC efficiency for D**	set C_Y to 1 (see [1])	0.008 ps^{-1}	0.001	0.001
B_S contribution	added B_S modes	0.008 ps^{-1}	0.003	0.002
$c\bar{c}$	see text	0.001 ps^{-1}	0.002	0.001
D^0 fitting procedure	see text	0.005 ps^{-1}	0.001	0.003
D^* fitting procedure	see text	0.007 ps^{-1}	0.002	0.000
binning in D^0 sample	from 80 to 160	0.003 ps^{-1}	0.000	0.000
binning in D^* sample	from 130 to 200	0.001 ps^{-1}	0.000	0.000
Total systematic error		0.044 ps^{-1}	0.008	0.012

Conclusions

- The B_d mixing parameter was measured using semileptonic data sample with
  - ✓ Opposite Muon Tagging algorithm
    - ✓ $\Delta m_d = 0.506 \pm 0.055$ (stat.) $\pm$ 0.049 (syst.) ps^{-1}
    - ✓ $D = 0.460 \pm 0.042$ (stat.) $\pm$ 0.016 (syst.)
  - ✓ Same Side Tagging algorithm
    - ✓ $\Delta m_d = 0.488 \pm 0.066$ (stat.) $\pm$ 0.046 (syst.) ps^{-1}
    - ✓ $D_0 = 0.116 \pm 0.014$ (stat.) $\pm$ 0.016 (syst.)
    - ✓ $D_\pm = 0.244 \pm 0.016$ (stat.) $\pm$ 0.024 (syst.)
- Work on combining of these tagging algorithms is in progress