Hadronic Moments in Semileptonic *B* Decays

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(For the CDF II Collaboration)

Motivation (I)

Most precise determination of V_{cb} comes from Γ_{sl} ("inclusive" determination):

$$\Gamma_{sl}(b \to c\ell^- \bar{\nu}) = \boxed{\frac{BR(b \to c\ell^- \bar{\nu}_\ell)}{\tau_b}} = |V_{cb}|^2 \times \boxed{F_{theory}}$$

Υ(4S), LEP/SLD, CDF measurements. Experimental $\Delta\|V_{cb}\|\sim 1\%$	Theory with pert. and non-pert. corrections. $\Delta\|V_{cb}\|\sim 2.5\%$

F_{theory} evaluated using OPE in HQET: expansion in α_s and $1/m_B$ powers:

$O(1/m_B)$ $\to$ 1 parameter: Λ (Bauer et al., PRD 67 (2003) 071301)

$O(1/m_B^2)$ $\to$ 2 more parameters: λ_1, λ_2

$O(1/m_B^3)$ $\to$ 6 more parameters: $\rho_1, \rho_2, T_{1\text{-}4}$

$$\Gamma_{sl} = \frac{G_F^2 |V_{cb}|^2}{192\pi^3} m_B^5 c_1 \left\{ 1 - c_2 \frac{\alpha_s}{\pi} + \frac{c_3}{m_B} \Lambda \left(1 - c_4 \frac{\alpha_s}{\pi}\right) + \frac{c_5}{m_B^2} (\Lambda^2 + c_6 \lambda_1 + c_7 \lambda_2) + O\left(\frac{1}{m_B^3}\right) + O\left(\frac{\alpha_s^2}{\pi}\right) \cdots \right\}$$

Motivation (II)

Many inclusive observables can be written using the same expansion (same non-perturbative parameters) – the spectral moments:

- Photonic moments: Photon energy in $b \rightarrow s\gamma$ (CLEO)
- Leptonic moments: $B \rightarrow X_c l\nu$, lepton E in B rest frame (CLEO, DELPHI, BABAR)
- Hadronic moments: $B \rightarrow X_c l\nu$, recoil mass $M^2(X_c)$ (CLEO, DELPHI, BABAR, CDFII)

$$M_1 = \int_{s_H^{min}}^{s_H^{max}} ds_H \left(s_H - m_D^2\right) \frac{1}{\Gamma_{sl}} \frac{d\Gamma_{sl}}{ds_H} = \boxed{\langle s_H \rangle} - m_D^2 , \qquad \boxed{s_H \equiv M_{X_c}^2}$$

$$M_2 = \int_{s_H^{min}}^{s_H^{max}} ds_H \left(s_H - \langle s_H \rangle\right)^2 \frac{1}{\Gamma_{sl}} \frac{d\Gamma_{sl}}{ds_H} = \left\langle \left(s_H - m_D^2\right)^2 \right\rangle - M_1^2$$

Constrain unknown non-pert. parameters to reduce $|V_{cb}|$ uncertainty.

With enough measurements: test of underlying assumptions (duality…).

What are the X_c?

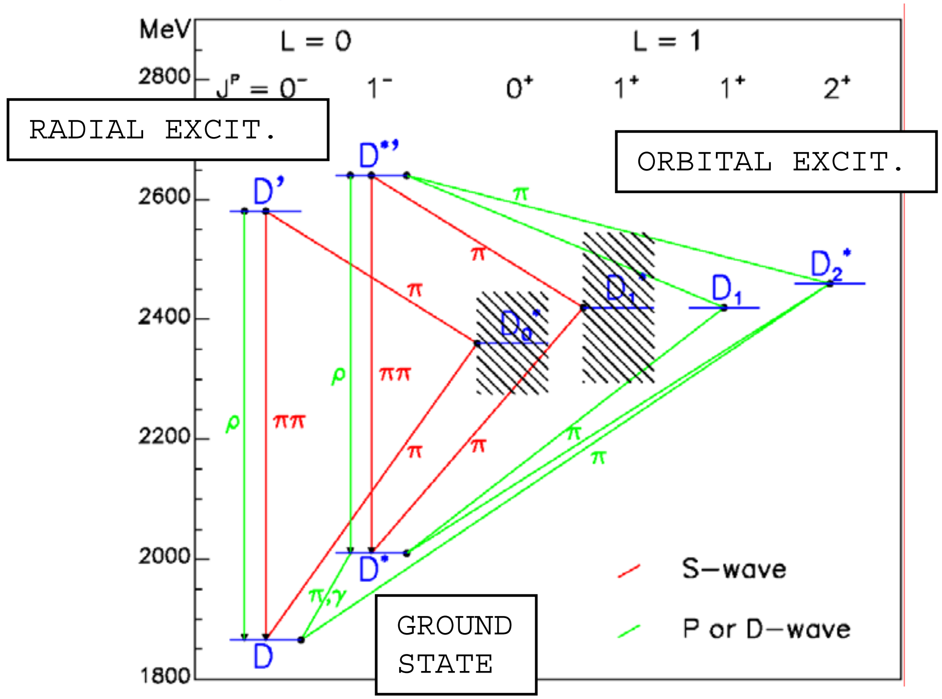
Semi-leptonic widths (PDG 03):

	BR (%)
$B^+ \rightarrow X_c\, l\, \nu$	10.89 ± 0.26
$B^+ \rightarrow D^*\, l\, \nu$	6.00 ± 0.24
$B^+ \rightarrow D\, l\, \nu$	2.23 ± 0.15

($b/B^+/B^0$ combination, $b \rightarrow u$ subtracted)

➔ ~25% of semileptonic width poorly accounted for

Higher mass states: D^{**}



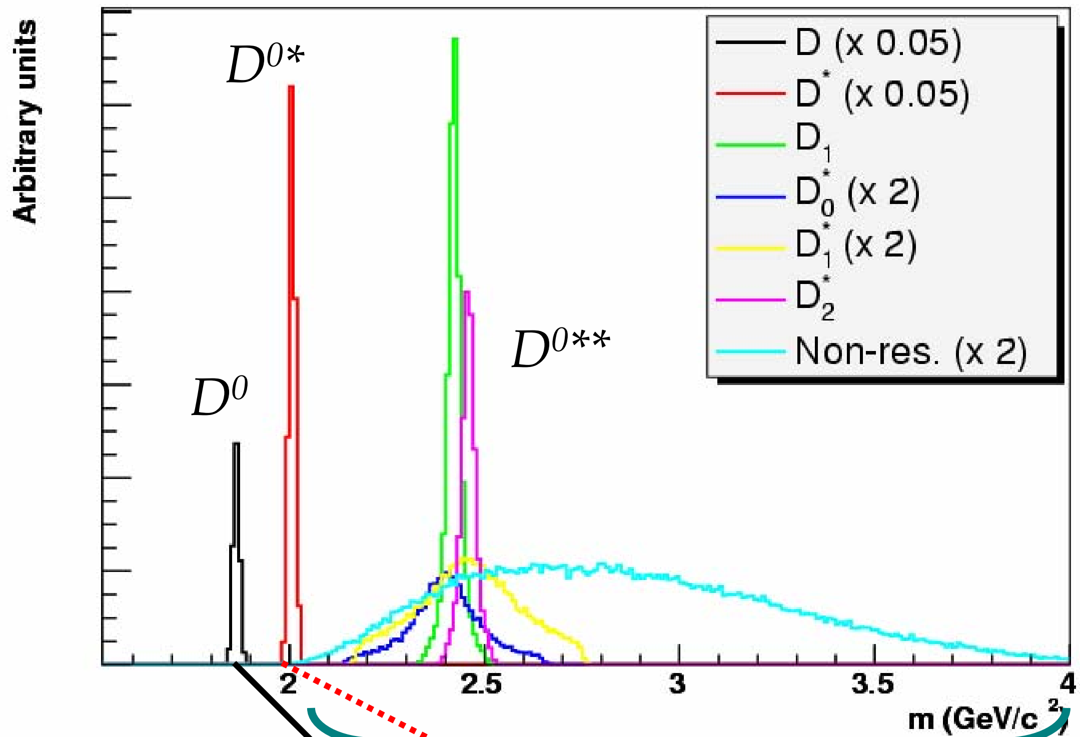
Possible $D' \rightarrow D^{(*)}\pi\pi$ contributions neglected:

- No experimental evidence so far
- DELPHI limit: $\begin{cases} BR(b \rightarrow D^+\pi^+\pi^-\ell^-\nu) < 0.18\% \text{ @ } 90\%\ CL \\ BR(b \rightarrow D^{*+}\pi^+\pi^-\ell^-\nu) < 0.17\% \text{ @ } 90\%\ CL \end{cases}$

We assume no D′ contribution in our measurement

Analysis Strategy

Typical mass spectrum $M(X^0_c)$ (Monte Carlo):



D^0 and D^{*0} well-known
➔ measure only f^{**}
➔ only shape needed

1) Measure $f^{**}(s_H)$
2) Correct for background, acceptances, bias
➔ moments of D^{**}
3) Add D and D^* ➔ M_1, M_2
4) Extract Λ, λ_1

$$s_H \equiv M^2_{X_c}$$

$$\frac{1}{\Gamma_{sl}}\frac{d\Gamma_{sl}}{ds_H} = \frac{\Gamma_0}{\Gamma_{sl}}\delta(s_H - m^2_{D^0}) + \frac{\Gamma_*}{\Gamma_{sl}}\delta(s_H - m^2_{D^{*0}}) + \left(1 - \frac{\Gamma_0}{\Gamma_{sl}} - \frac{\Gamma_*}{\Gamma_{sl}}\right)\cdot f^{**}(s_H)$$

Channels

Must reconstruct all channels to get all the D^{**} states.
➔ However CDF has limited capability for neutrals

- $\bar{B}^0 \rightarrow D^{**+} l^- \nu$ always leads to neutral particles ➔ ignore it
- $B^- \rightarrow D^{**0} l^- \nu$ doable, use isospin for missing channels:
  - D^{**0}

(i) $\rightarrow D^+\pi^-$ OK

(ii) $\rightarrow D^0\pi^0$ Not reconstructed: ½ rate of $D^+\pi^-$ (i)

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

(iii) $D^{*+} \rightarrow D^0\pi^+$ OK

(iv) $D^{*+} \rightarrow D^+\pi^0$ Not reco'd: feed-down to $D^+\pi^-$ (iii)

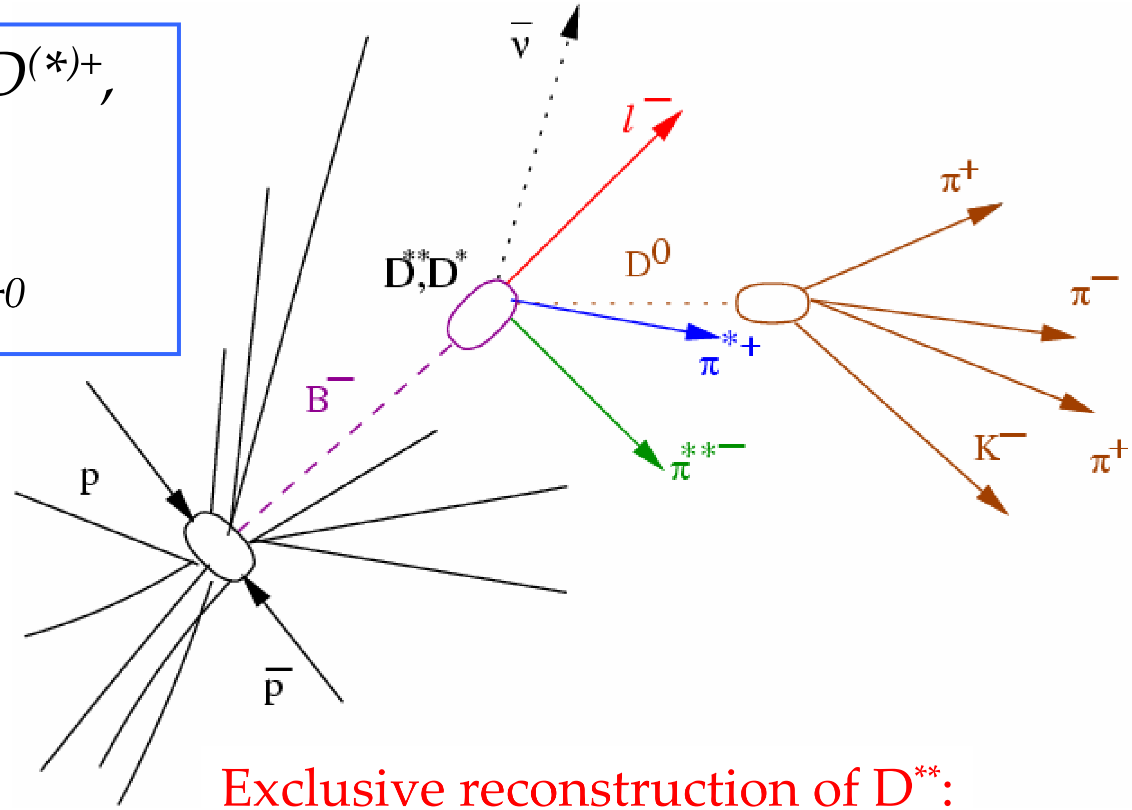
(v) $\rightarrow D^{*0}\pi^0$ Not reconstructed: ½ rate of $D^{*+}\pi^-$ (iii) & (iv)

Event Topology

Reconstruct l+$D^{(*)+}$,

Add π^{**} track

$\rightarrow$get l+D^{**0}



Exclusive reconstruction of D^{**}:

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

$\hookrightarrow$ $\boxed{K^- \pi^+ \pi^+}$ (BR=9.1%)

$\boxed{D^+}$

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

$\hookrightarrow$ $D^0 \pi^{*+}$ (BR=67.7%)

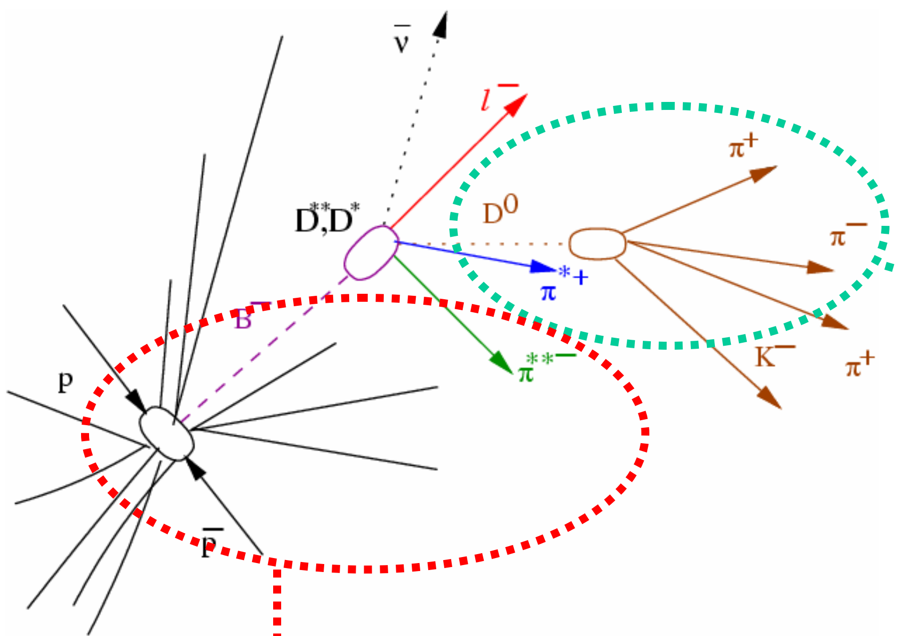
$\hookrightarrow$ $K^- \pi^+$ (BR=3.8%)

$\hookrightarrow$ $K^- \pi^+ \pi^- \pi^+$ (BR=7.5%)

$\hookrightarrow$ $K^- \pi^+ \pi^0$ (BR=13.1%)

$\boxed{D^{*+}}$

Backgrounds



<u>Physics background:</u>

$B \rightarrow D^{(*)+} D_s^-$, $D_{(s)} \rightarrow X l \nu$

➔ MC, subtracted

<u>Combinatorial background</u>

under the D$^{(*)}$ peaks:

➔ sideband subtraction

<u>Prompt pions faking π**:</u>

- fragmentation
- underlying event

➔separate B and primary vertices

(also remove prompt charm)

➔ use impact parameters to discriminate

➔ model: wrong-sign $\pi^{**+} \ell^-$ combinations

<u>Feed-down in signal:</u>

$D^{**0} \rightarrow D^{*+}[\rightarrow D^+ \pi^0] \pi^-$

irreducible background to

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

➔subtracted using data:

➔shape from $D^0\pi^-$ in

$D^{**0} \rightarrow D^{*+}[\rightarrow D^0 \pi^+] \pi^-$

➔rate:

½ (isospin) x *eff.* x *BR*

Lepton-$D^{(*)+}$ Reconstruction

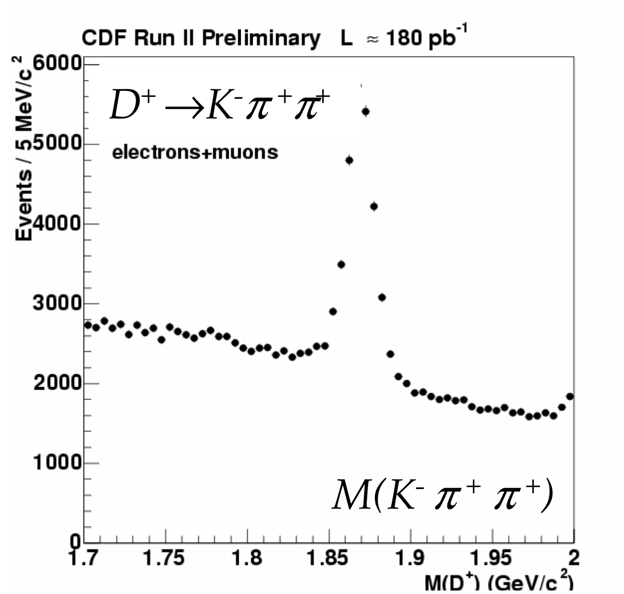
Data Sample:
- e/μ + displaced track
- ~ 180 pb^{-1}

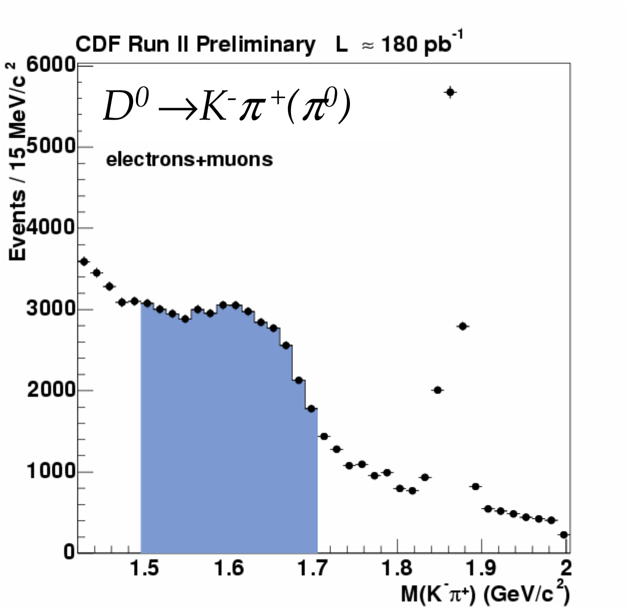
(→ Sep. 2003)

Track Selection:
- e/μ: $p_T > 4$ GeV
- other: $p_T > 0.4$ GeV

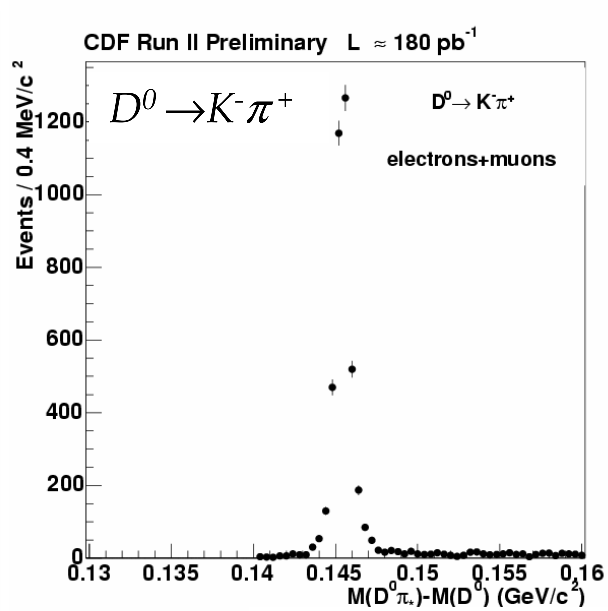
Lepton + $D^{(*)+}$:
- D vertex:
  - 3D
- l+D(+π^*) vertex ("B"):
  - 3D
  - $L_{XY}(B) > 500$ μm
  - $M(B) < 5.3$ GeV

Total: ~ 28000 events

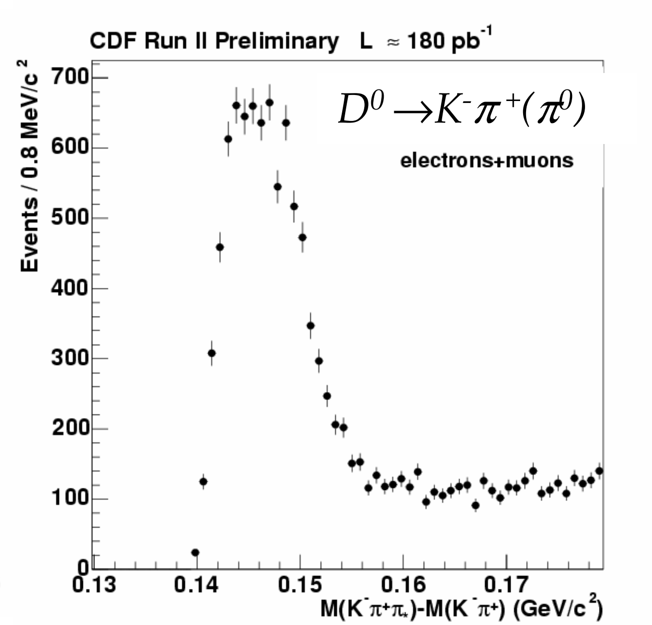




28 Aug 2004 $M(K^- \pi^+)$



DPF2004 $M(D^0 \pi^+)$ -$M(D^0)$

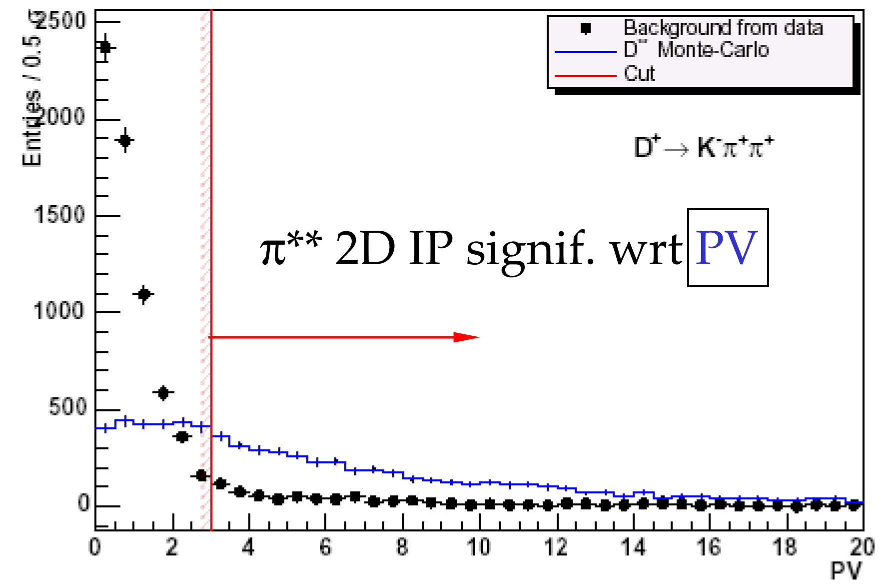


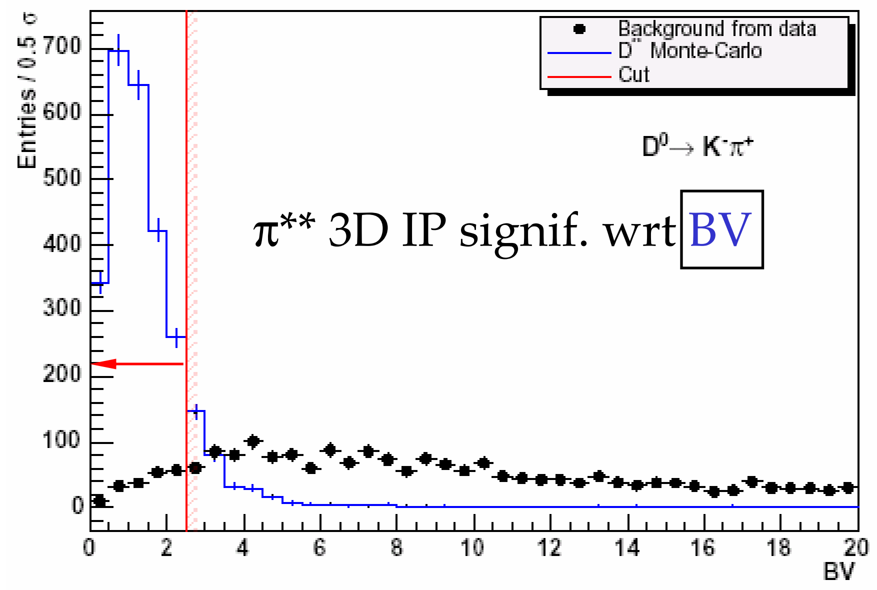
$M(D^0 \pi^+)$ -$M(D^0)$

π^{**} Selection

Based on topology:

- impact parameter significances w.r.t. primary, B and D vertices





Cuts are optimized using MC and background data:

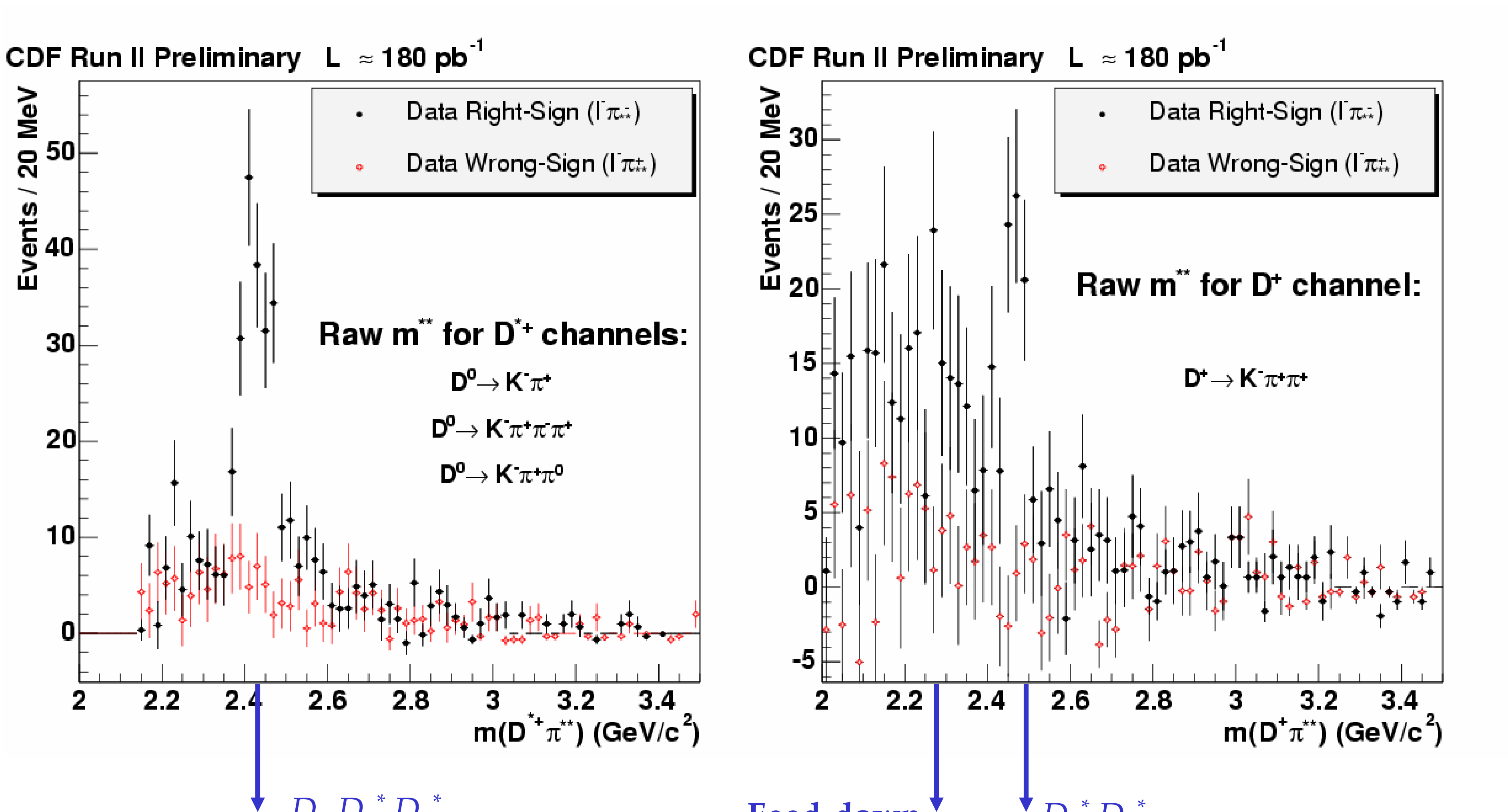
- $p_T > 0.4$ GeV
- $\Delta R < 1.0$
- $|d_0^{PV}/\sigma| > 3.0$
- $|d_0^{BV}/\sigma| < 2.5$

Additional cuts only for D^+:

$|d_0^{DV}/\sigma| > 0.8$

$L_{xy}^{B\rightarrow D} > 500\mu m$

Raw m^{**} Distribution



D_1, D_1^*, D_2^*

Feed-down

D_2^*, D_0^*

Efficiency Corrections

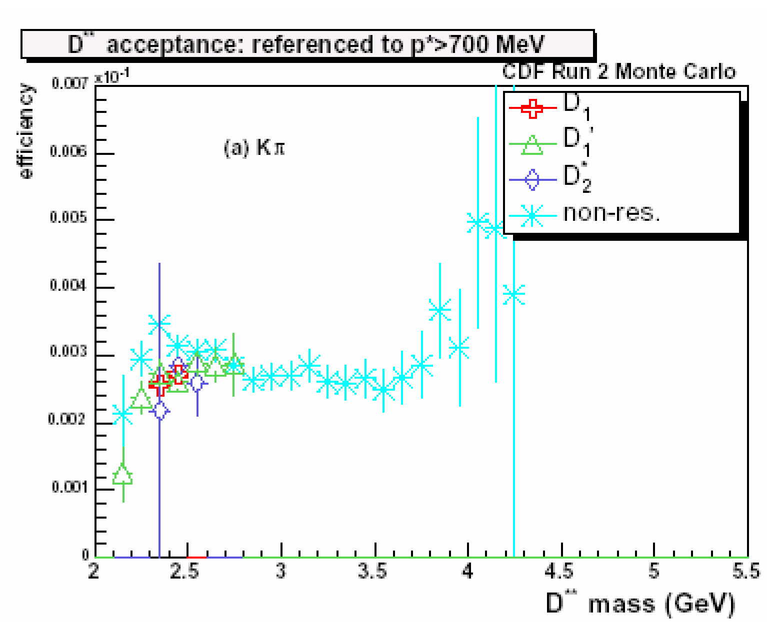
1) Correct the raw mass for any dependence of ε_{reco} on M(D**):

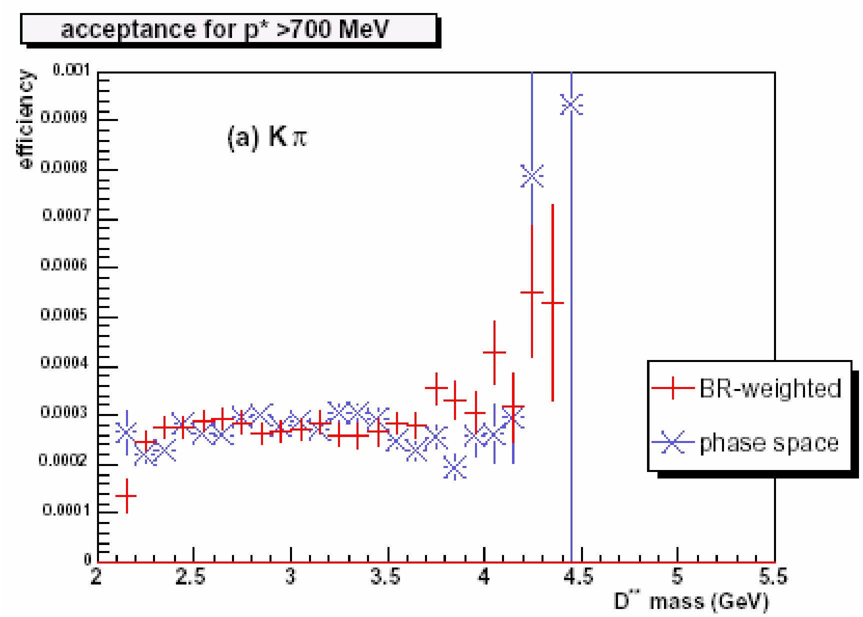
- Possible dependence on the D** species (spin).
- Monte Carlo for all D** (Goity-Roberts for non-resonant), cross-checked with pure phase space decays.

2) "Cut" on lepton energy in *B* rest frame:

- Theoretical predictions are given for well-defined p_l^* cuts.
- We cannot measure p_l^*, but we can correct our measurement to a given cut:

$\rightarrow p_l^* > 700$ MeV/c.



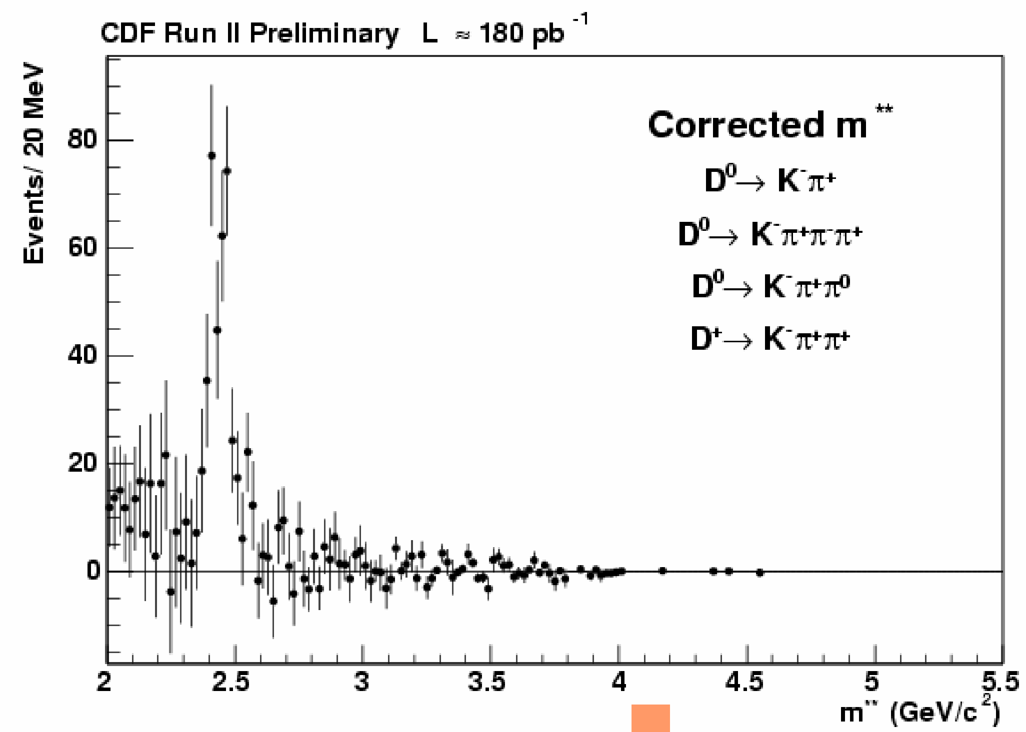


Corrected Mass and D** Moments

Procedure:

- Unbinned procedure using weighted events.
  - Assign negative weights to background samples.
  - Propagate efficiency corrections to weights.
  - Take care of the D^+ / D^{*+} relative normalization.
- Compute mean and sigma of distribution.

Results:



No Fit !

$$m_1 = \langle m_{D^{**}}^2 \rangle = (5.83 \pm 0.16_{stat})\,GeV^2$$

$$m_2 = \langle (m_{D^{**}}^2 - m_1)^2 \rangle = (1.30 \pm 0.69_{stat})\,GeV^4$$

Final Results

D^{**} part

$$m_1 \equiv \left\langle m_{D^{**}}^2 \right\rangle = (5.83 \pm 0.16_{\rm stat} \pm 0.08_{\rm exp})\ {\rm GeV}^2$$
$$m_2 \equiv \left\langle \left(m_{D^{**}}^2 - \left\langle m_{D^{**}}^2 \right\rangle\right)^2 \right\rangle = (1.30 \pm 0.69_{\rm stat} \pm 0.20_{\rm exp})\ {\rm GeV}^4$$
$$\rho_{m_1,m_2} = 0.61$$

plus PDG info

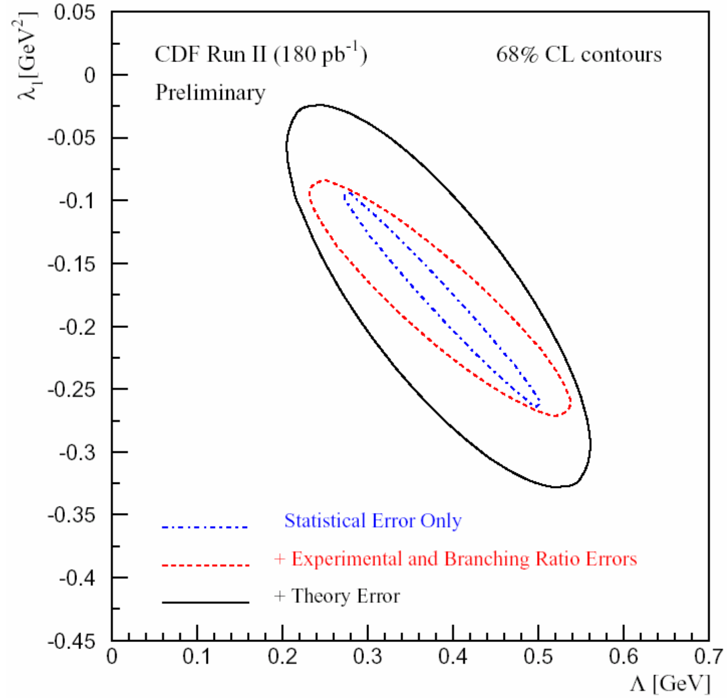
$$M_1 \equiv \langle s_H \rangle - m_D^2 = (0.459 \pm 0.037_{\rm stat} \pm 0.019_{\rm exp} \pm 0.062_{\rm BR})\ {\rm GeV}^2$$
$$M_2 \equiv \left\langle (s_H - \langle s_H \rangle)^2 \right\rangle = (1.04 \pm 0.25_{\rm stat} \pm 0.07_{\rm exp} \pm 0.10_{\rm BR})\ {\rm GeV}^4$$
$$\rho_{M_1,M_2} = 0.69$$

Pole mass scheme

$$\Lambda = (0.390 \pm 0.075_{\rm stat} \pm 0.026_{\rm exp} \pm 0.064_{\rm BR} \pm 0.058_{\rm theo})\ {\rm GeV}$$
$$\lambda_1 = (-0.182 \pm 0.055_{\rm stat} \pm 0.016_{\rm exp} \pm 0.022_{\rm BR} \pm 0.077_{\rm theo})\ {\rm GeV}^2$$

1S mass scheme

$$m_b(1S) = (4.661 \pm 0.076_{\rm stat} \pm 0.026_{\rm exp} \pm 0.064_{\rm BR} \pm 0.089_{\rm theo})\ {\rm GeV}$$
$$\lambda_1 = (-0.276 \pm 0.047_{\rm stat} \pm 0.016_{\rm exp} \pm 0.022_{\rm BR} \pm 0.094_{\rm theo})\ {\rm GeV}^2$$



Systematic Errors

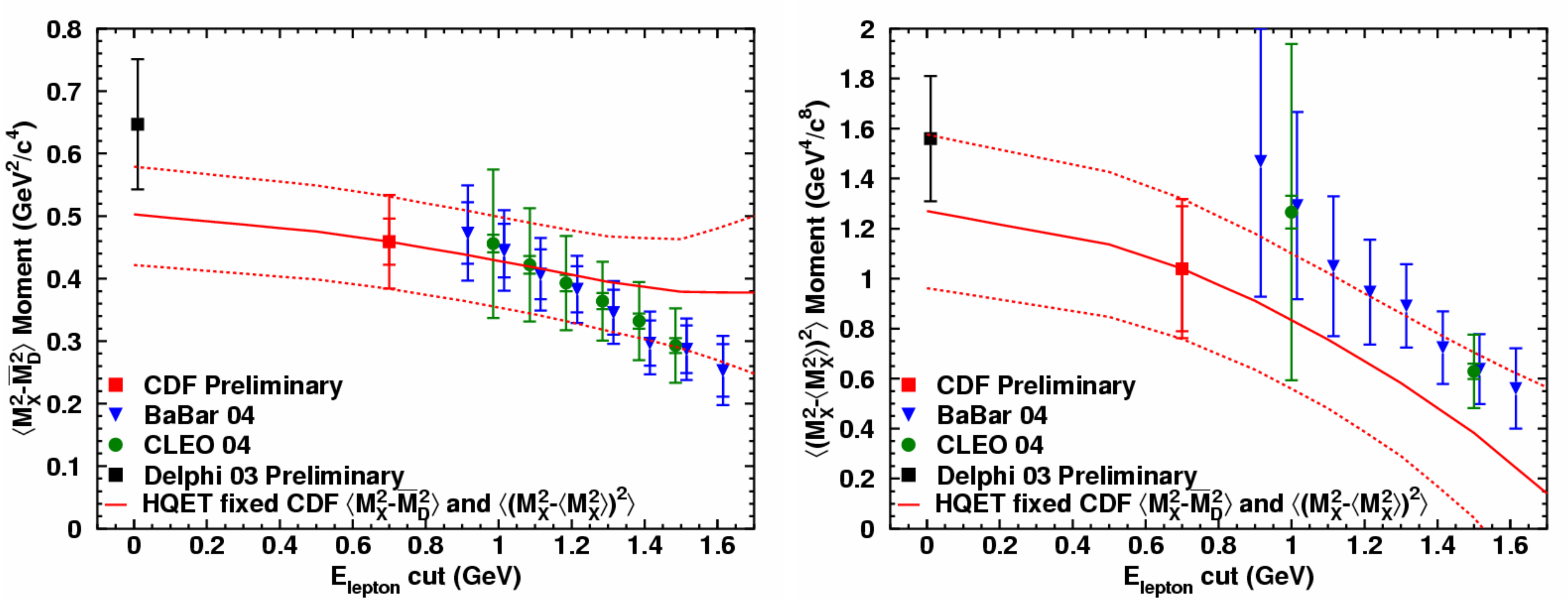
	Δm_1 (GeV^2)	Δm_2 (GeV^4)	ΔM_1 (GeV^2)	ΔM_2 (GeV^4)	$\Delta\Lambda$ (GeV)	$\Delta\lambda_1$ (GeV^2)
Stat.	0.16	0.69	0.037	0.25	0.075	0.055
Syst.	0.08	0.20	0.065	0.12	0.090	0.082
Mass resolution	0.02	0.13	0.005	0.04	0.012	0.009
Eff. Corr. (data)	0.03	0.13	0.006	0.05	0.014	0.011
Eff. Corr. (MC)	0.06	0.05	0.016	0.03	0.017	0.006
Bkgd. (scale)	0.01	0.03	0.002	0.01	0.003	0.002
Physics bkgd.	0.01	0.02	0.002	0.01	0.004	0.002
D^+ / D^{*+} BR	0.01	0.02	0.002	0.01	0.004	0.002
D^+ / D^{*+} Eff.	0.02	0.03	0.004	0.01	0.005	0.002
Semileptonic BRs			0.062	0.10	0.064	0.022
ρ_1					0.041	0.069
T_i					0.032	0.031
α_s					0.018	0.007
m_b, m_c					0.001	0.008
Choice of p_l^* cut					0.019	0.009

Main Systematics

- Semileptonic branching ratios when combining D^{**} with D and D^*
- Efficiency corrections from data
  - Use data-corrected efficiency. vs. pure MC efficiency
- Efficiency corrections from D^{**} Monte-Carlo
  - D^{**} states + NR Goity-Roberts vs. pure phase-space
- Mass resolution:
  - Dominated by satellite: ± 60 MeV
- Prompt background scale
  - Charge correlations WS / RS: ± 4%
- Other: D^+/D^* normalization, physics background, p_l^* cut, theory…

Comparison with Previous Measurements

Red bands represent HQET predictions using CDF measurement as input.



NB: measurements of two moments highly correlated

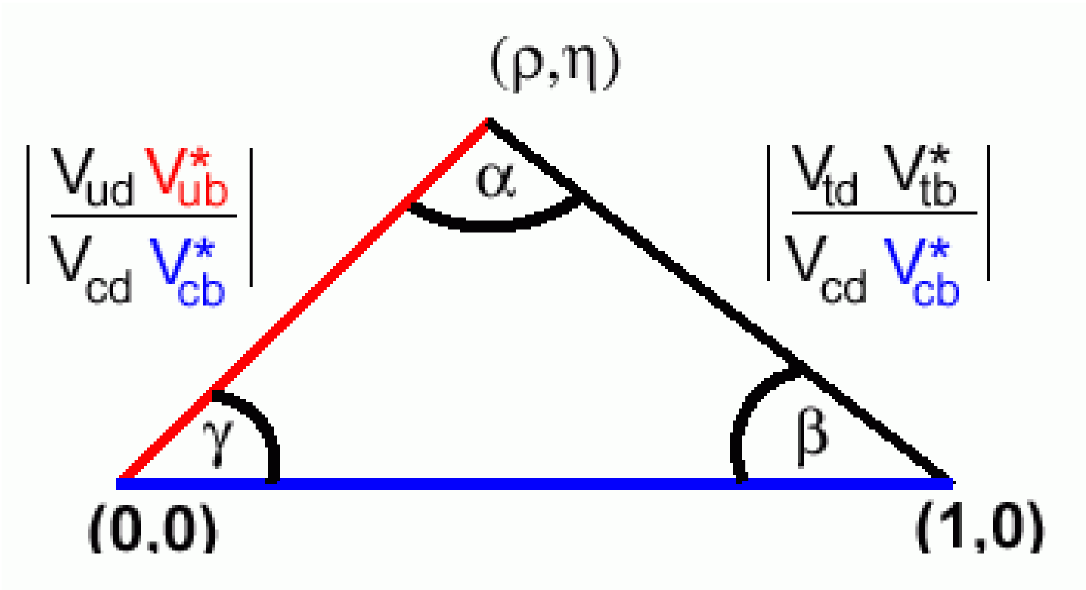
Pole mass scheme

Summary

- First measurement of hadronic moments in semileptonic B decays performed at a hadron collider.
- Good HQET agreement with previous determinations.
- Competitive with other experiments. Little model dependency. No assumptions on shape or rate of D** components.
- Increased statistics and improved tracking will lead to substantially more precise results in the near future.

BACKUP SLIDES

CKM and V_{cb}



$|V_{cb}| = A\lambda^2$

(defines the scale of UT)

V_{cb} measurements

$|V_{cb}|$ from exclusive B decays

- Large statistics on $B_d^0 \rightarrow D^{(*)}\ell^- \nu$ available and new measurements are coming
- Present precision (5%) is systematics limited:

  Experiments: D** states, D's BR

  Theory: form factor extrapolation, corrections to F(1)=1

can be reduced in the future

$$\boxed{|V_{cb}|^{excl} = (42.1 \pm 1.1_{exp} \pm 1.9_{theo}) \times 10^{-3}}$$

(PDG 2002, V_{cb} review)

$|V_{cb}|$ from inclusive B decays

- Experiment: large statistics on $BR(B \rightarrow X_c \ell^- \nu)$ and t_B and small systematics

$$\boxed{|V_{cb}|^{incl} = (40.4 \pm 0.5_{exp} \pm 0.5_{\Lambda,\lambda} \pm 0.8_{theo}) \times 10^{-3}}$$

(PDG 2002, V_{cb} review)

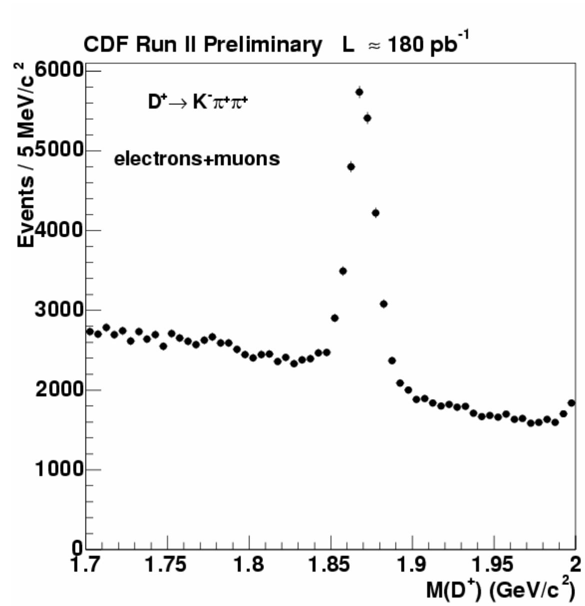
Lepton + D Reconstruction

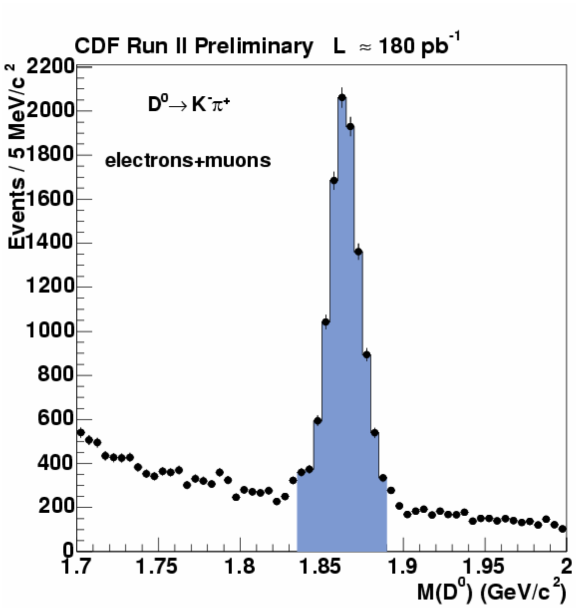
Data Sample:
- e/μ + displaced track
- ~ 180 pb^{-1}

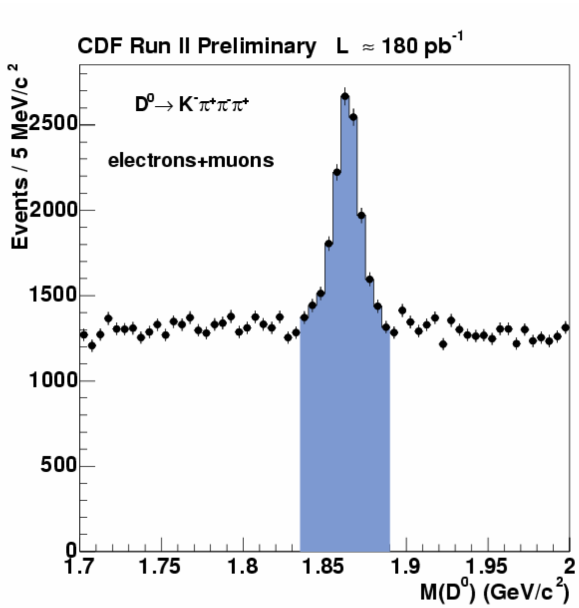
($\rightarrow$ Sep 2003)

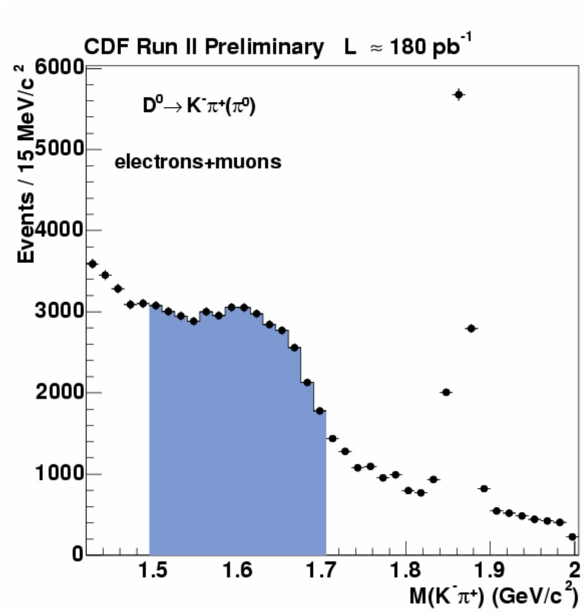
Track Selection:
- e/μ: $p_T > 4$ GeV
- other: $p_T > 0.4$ GeV

Lepton + $D^{(*)+}$:
- D vertex:
  - 3D
- l+D(+π^*) vertex ("B"):
  - 3D
  - $L_{XY}(B) > 500$ µm
  - $M(B) < 5.3$ GeV



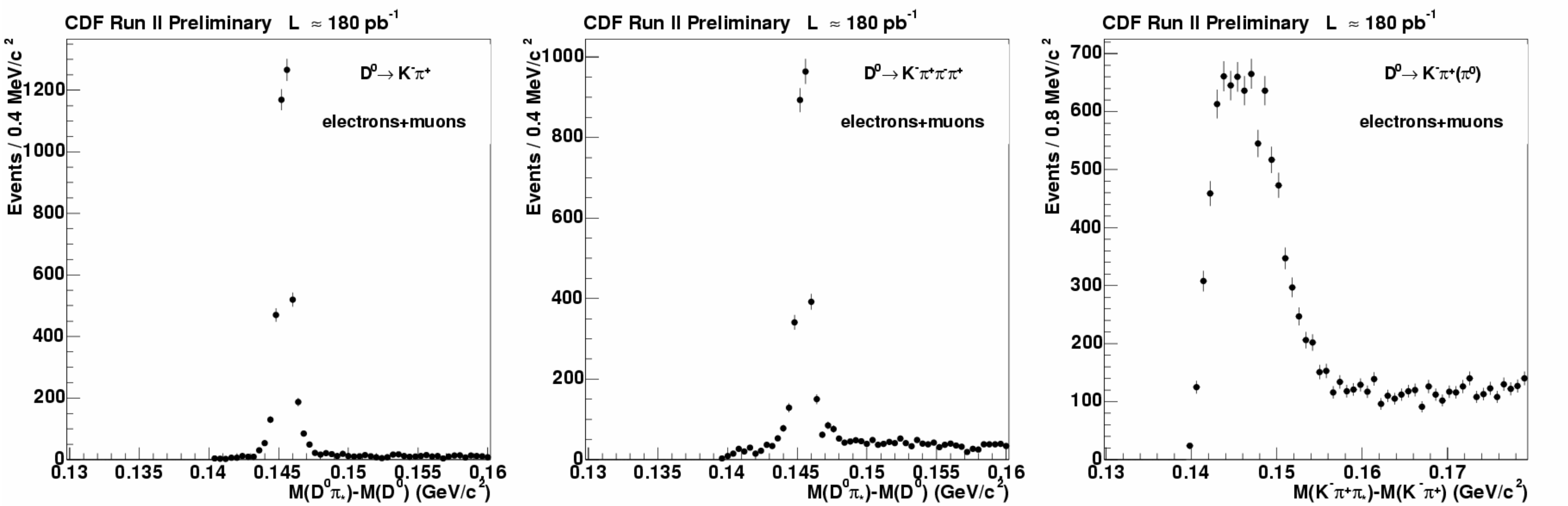






D*+ Reconstruction and Yields

D*+ channels: $\Delta m^* \equiv M(D^0\pi^*) - M(D^0)$



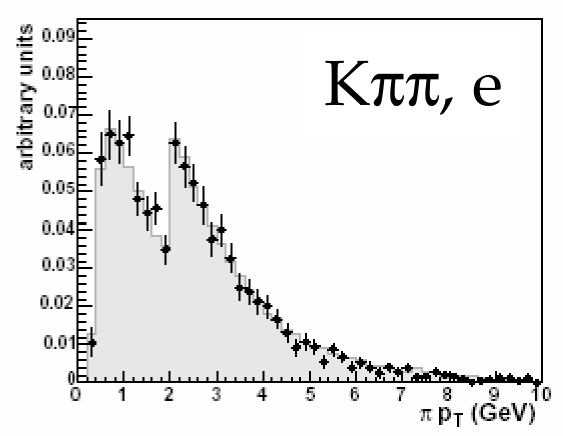
D(*)+ l- (+cc) yields:

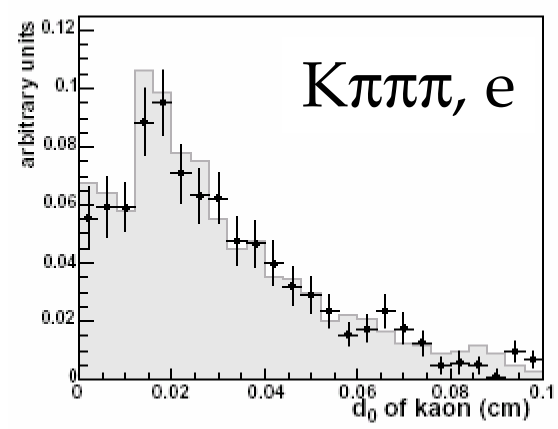
	D^{*+} channels			D^+ channel
	$K^-\pi^+$	$K^-\pi^+\pi^-\pi^+$	$K^-\pi^+\pi^0$	$K^-\pi^+\pi^+$
		$D^{(*)+}l^-$ yields		
Electrons	1723 ± 42	1299 ± 38	3037 ± 66	6859 ± 122
Muons	2168 ± 47	1695 ± 43	3611 ± 72	8204 ± 136
Combined	3890 ± 63	2994 ± 57	6638 ± 98	14416 ± 202

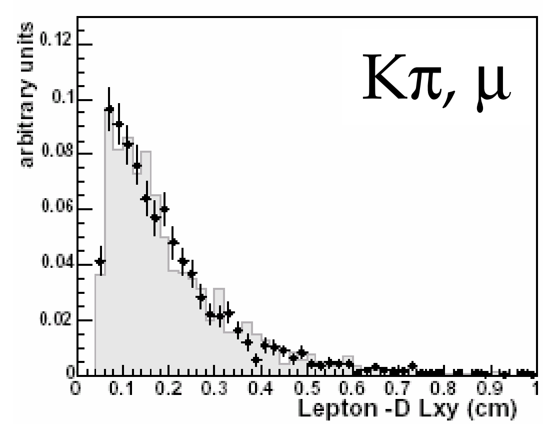
~ 28000 events

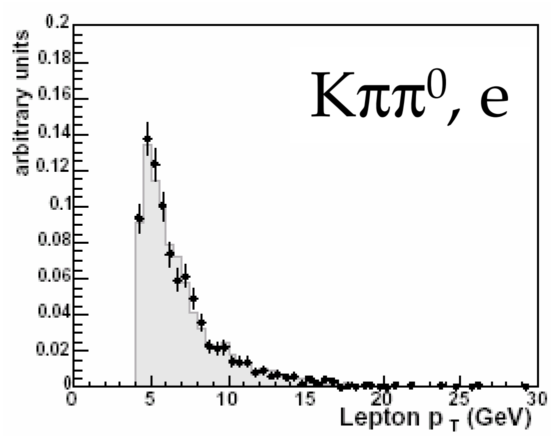
Monte-Carlo Validation (I)

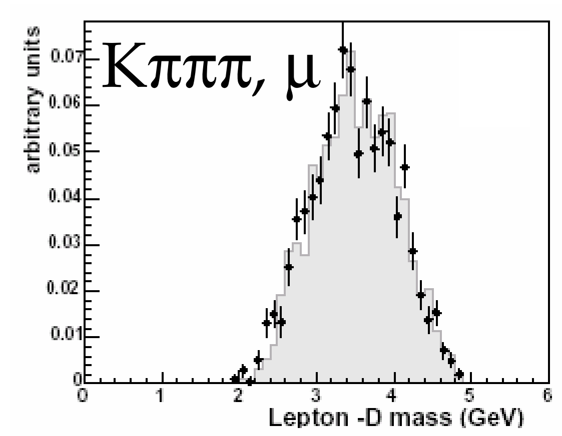
MC vs. semileptonic sample:

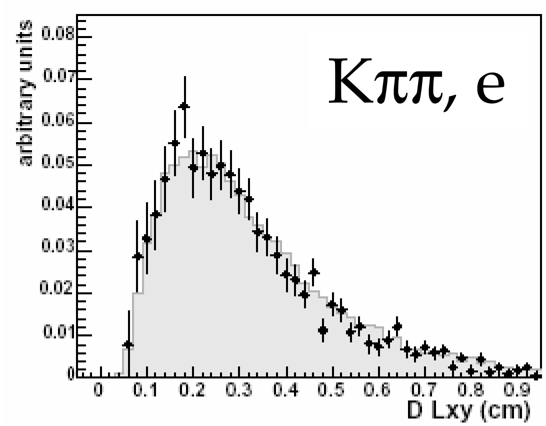












Matching χ^2 probability for those plots:

67%	74%	23%
43%	69%	87%

Monte-Carlo Validation (II)

Relative yield prediction K3π/Kπ: (cross-check)

$$R_{K3\pi/K\pi} \equiv \frac{N(D^{*+}l\bar{\nu}X, D^{*+} \to D^0\pi^+, D^0 \to K^-\pi^+\pi^-\pi^+)}{N(D^{*+}l\bar{\nu}X, D^{*+} \to D^0\pi^+, D^0 \to K^-\pi^+)}.$$

$R_{data} = 0.77\pm0.02$
$R_{pred} = 0.80\pm0.04$
$R_{pred}/R_{data} = 1.04\pm0.06$

➔ efficiency for adding tracks understood

Relative yield prediction K2π/Kπ: (needed for D^+/D^* normalization)

$$R_{D^+/K\pi} \equiv \frac{N(B \to D^+l\bar{\nu}X, D^+ \to K^-\pi^+\pi^+)}{N(B \to D^{*+}l\bar{\nu}X, D^{*+} \to D^0\pi^+, D^0 \to K^-\pi^+)},$$

Two methods (a,b) to derive this BR

+ PDG BR + MC efficiency ratios

a) Based on inclusive $b \to D^{(*)+}l\nu$

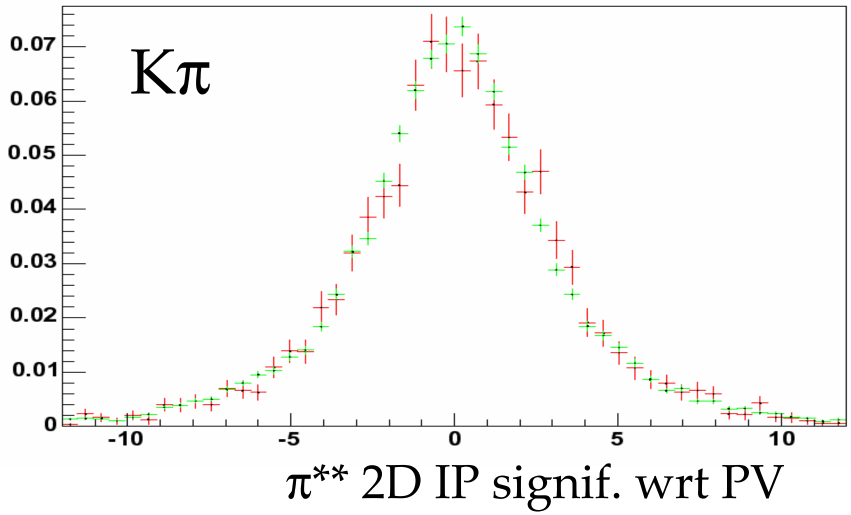
b) Based on exclusive $B \to D^{(*)+}l\nu$, $D^{**}l\nu$

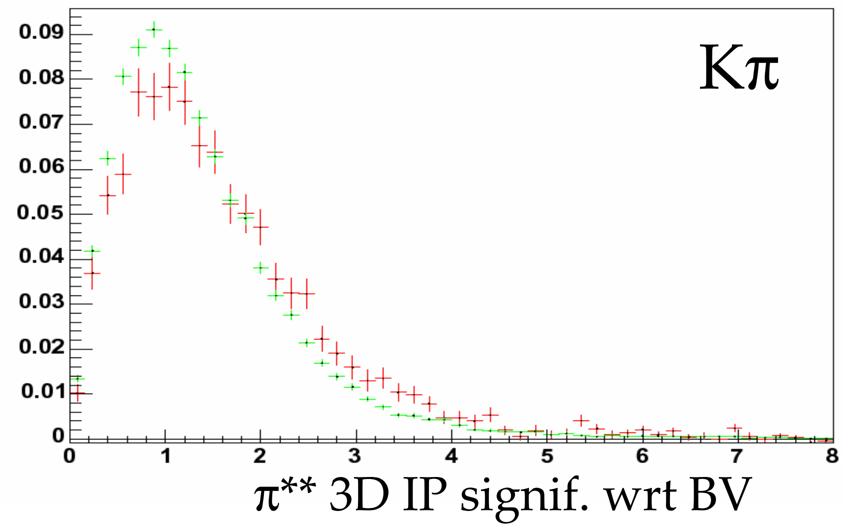
R_{data}	R_{pred}	R_{pred}/R_{data}
3.71±0.08	3.31±0.58	0.89±0.16
3.71±0.08	3.23±0.29	0.87±0.08

➔ uncertainties in Br (incl.) and D** spectroscopy (excl.) compromise prediction
➔ 1. – 0.87 = 13% used as systematics

Impact Parameters in MC

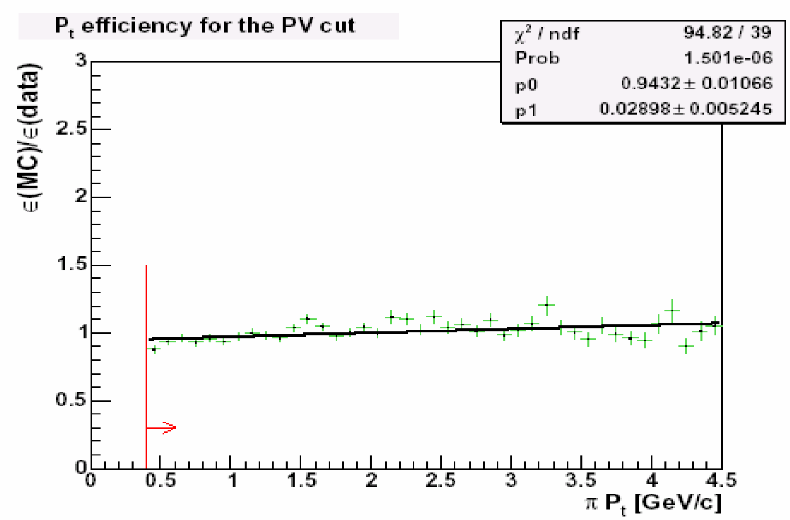
Comparison data/MC for IP: (worst case)





Residual corrections:

- derived from data:
  - π^*
  - non-SVT D daughters ($p_T > 1.5$ GeV)
- corrections from double ratios
  - in p_T
  - in m**



Background Subtraction

- Use mass side-bands to subtract combinatorial background.
- Use $D^{*+}[\rightarrow D^0 \pi^+]\pi^-$ to subtract feed-down from $D^{*+}[\rightarrow D^+ \pi^0]\pi^-$ to $D^+ \pi^-$.
- Use wrong-sign $\pi^{**+} l^-$ combinations to subtract prompt background to π^{**}.
  - Possible charge asymmetry of prompt background studied with fully reconstructed B's: 4% contribution at most.
- Possible $D' \rightarrow D^{(*)}\pi\pi$ contributions neglected:
  - No experimental evidence so far.
  - DELPHI limit:

$$\begin{cases} BR\left(b \rightarrow D^+\pi^+\pi^-\ell^-\nu\right) < 0.18\% \text{ @ } 90\% \text{ CL} \\ BR\left(b \rightarrow D^{*+}\pi^+\pi^-\ell^-\nu\right) < 0.17\% \text{ @ } 90\% \text{ CL} \end{cases}$$

We assume no D′ contribution in our sample

Combination with D^0, D^{*0}

$$\frac{1}{\Gamma_{sl}}\frac{d\Gamma_{sl}}{ds_H} = \frac{\Gamma_0}{\Gamma_{sl}}\cdot\delta(s_H - m^2_{D^0}) + \frac{\Gamma_*}{\Gamma_{sl}}\cdot\delta(s_H - m^2_{D^{*0}}) + \left(1 - \frac{\Gamma_0}{\Gamma_{sl}} - \frac{\Gamma_*}{\Gamma_{sl}}\right)\cdot f^{**}(s_H)$$

Take $M(D^0)$, $M(D^{*0})$, Γ_{sl}, Γ_0, Γ_* from PDG 2003 :

- Γ_{sl}, Γ_0, Γ_* are obtained combining BR's for B^-, B^0 and admixture, assuming the widths are identical (not the BR's themselves), and using

$$f_- / f_0 = 1.04 \pm 0.08$$

$$\tau(B^-) / \tau(B^0) = 1.085 \pm 0.017$$

- Results:

$$BR(B^+ \to X^0_c\, l^+\, \nu_l) = 0.1089 \pm 0.0026$$

$$BR(B^+ \to D^0\, l^+\, \nu_l) = 0.0223 \pm 0.0015$$

$$BR(B^+ \to D^{*0}\, l^+\, \nu_l) = 0.0600 \pm 0.0024$$