$B \to D$ exclusive

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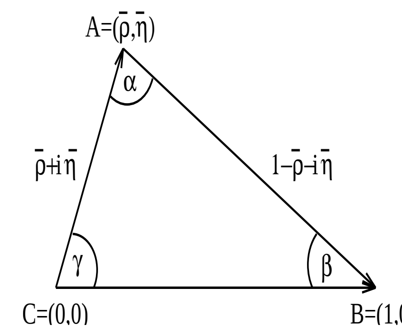
SuperB Workshop, 17^{th} February 2009

- Generalities
- Decay into S states
- Decay into P states: "1/2 vs. 3/2" puzzle
- Outlook

Generalities

$$\underbrace{\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix}}_{\text{weak int.}} = V_{\rm CKM} \underbrace{\begin{pmatrix} d \\ s \\ b \end{pmatrix}}_{\text{strong int.}} \qquad V_{\rm CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}.$$



Without constraint: $\delta V_{ij} < 5\%$, $\delta V_{ij} > 5\%$, $\delta V_{cb} \sim 1.5\%$

$$|\epsilon_K| = \bar\eta A^2 \hat{B}_K [1.11(5) A^2 (1-\bar\rho) + 0.31(5)], \quad V_{cb} \sim \lambda^2 A$$

$$\delta\epsilon_K < 1\%, \quad \delta\hat{B}_K \sim 7\%, \quad \delta\bar\eta(V_{cb}) \sim 6\%$$

$$|V_{cb}|(\bar{B} \to D^* l \bar\nu) = (38.6 \pm 0.9_{\rm exp} \pm 1.0_{\rm theo}) \times 10^{-3}$$ [PDG, '08]

$$|V_{cb}|({\rm incl.}) = (41.6 \pm 0.7) \times 10^{-3}$$ [PDG, '08]

It is important to well figure out the QCD nonperturbative dynamics which enters in all processes involving bound quarks $\Longrightarrow$ their SM contribution can be more easily distinguished from the contribution coming from a new physics.

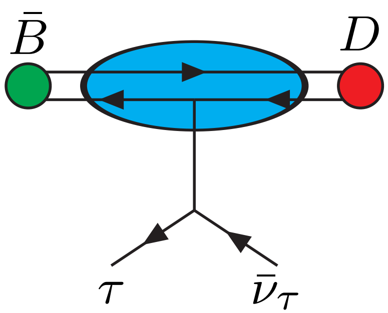
		Mass (MeV)	Width (MeV)	J^P	j_l^P
S: $D^{(*)}$	$D^{\pm}$	1869$\pm$0.5	-	0^-	$\frac{1}{2}^-$
	$D^{*\pm}$	2010$\pm$0.2	96$\pm$25	1^-	
P: D^{**}	D_0^*	2352$\pm$ 50	261 $\pm$ 50	0^+	$\frac{1}{2}^+$
	D_1^*	2427$\pm$ 26 $\pm$ 25	$384^{+107}_{-75} \pm 74$	1^+	
	D_1	2422.3 $\pm$ 1.3	20.4 $\pm$ 1.7	1^+	$\frac{3}{2}^+$
	D_2^*	2461.1$\pm$ 1.6	43$\pm$ 4	2^+	

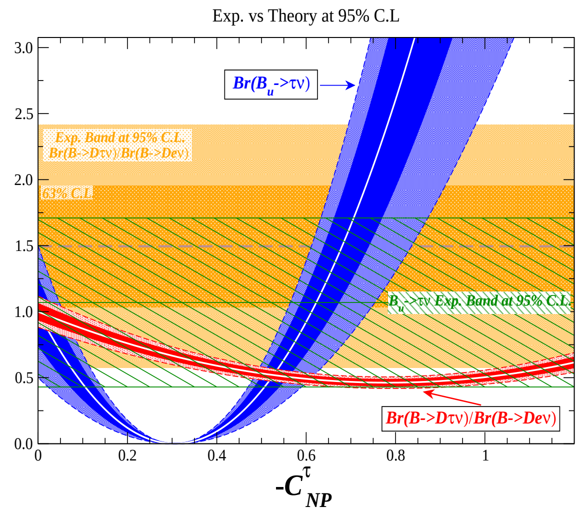
$D^{**} \to D^{(*)}\pi$ is the main decay channel: parity and orbital momentum conservation $\Longrightarrow$ the decay occurs with the pion in a S wave or in a D wave

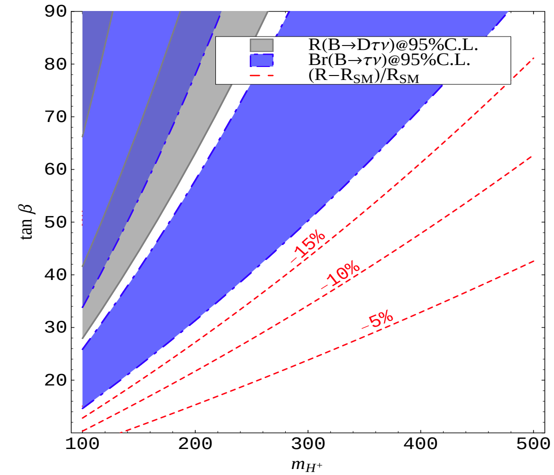
$D_{0,1}^* \to D^{(*)}\pi$: S wave $\quad D_2^* \to D^{(*)}\pi$: D wave

$D_1 \to D^*\pi$: S and D wave are *a priori* allowed; however the S wave is forbidden by Heavy Quark Symmetry

Decay to S states







$$\frac{d\Gamma}{dw}(\bar{B} \to D\ell\bar{\nu}_\ell = \frac{G_F^2 |V_{cb}|^2 m_B^5}{192\pi^3} K_V(w) G(w)^2 \left(1 - \frac{m_\ell^2}{m_B^2}\left|1 + \frac{t(w)}{(m_b - m_c)m_\ell} C^\ell_{NP}\right|^2 K_s(w) \Delta_S(w)^2\right)$$

$$w = \frac{p_B \cdot p_D}{m_B m_D} \qquad t(w) = m_B^2 + m_D^2 - 2w m_B m_D$$

$$\mathcal{B}(\bar{B} \to D\tau\bar{\nu}_\tau) > 50 \times \mathcal{B}(\bar{B} \to \tau\bar{\nu}_\tau) \qquad \delta[\Delta(w)]^{\text{quenched}} \sim 2\%$$

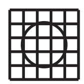
[G. M. de Divitiis, R. Petronzio, N. Tantalo, ’07] [U. Nierste, S. Trine, S. Westhoff, ’08] [J. Kamenik, F. Mescia, ’08]

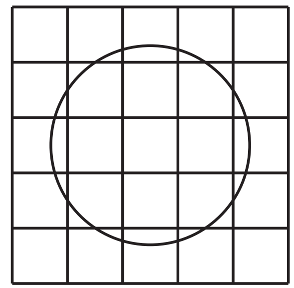
The computation on the lattice of quantities involving heavy quarks is not straightforward because of cut-off effects: $am_b \gtrsim 1$. It is cared by considering effective theories (HQET, NRQCD) which integrate out $\mathcal{O}(m_b)$ degrees of freedom.

Other technique used to measure G and Δ_s: the Step Scaling Functions integrate out the various degrees of freedom between m_b and $\Lambda_{\rm QCD}$ by doing the calculation in different physical volumes and taking for each of them the continuum limit:

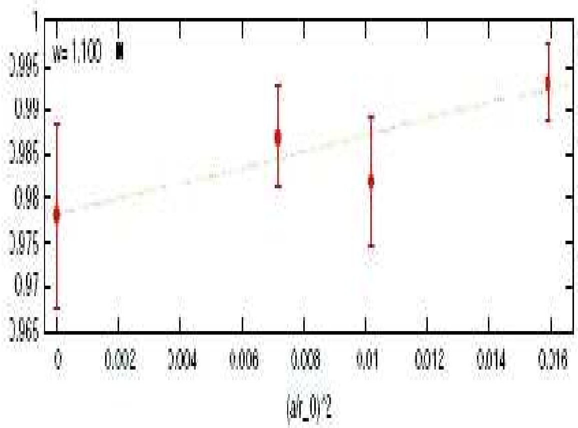
$$A = \underbrace{\sigma_1(L)}_{a\to 0} \times \underbrace{\sigma_2(2L)}_{a\to 0} \times \cdots \times \underbrace{\sigma_n(nL)}_{a\to 0}$$

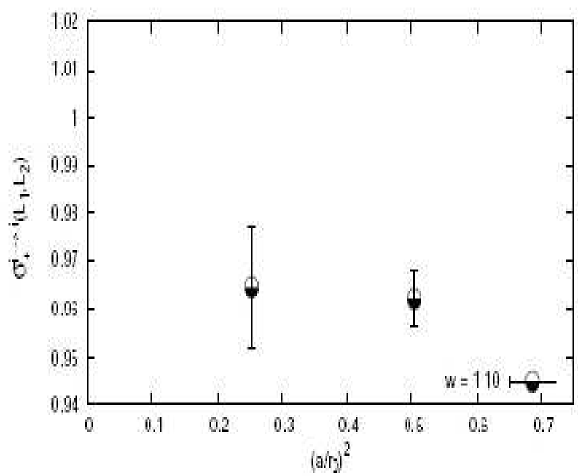
L $\quad$ $4L$

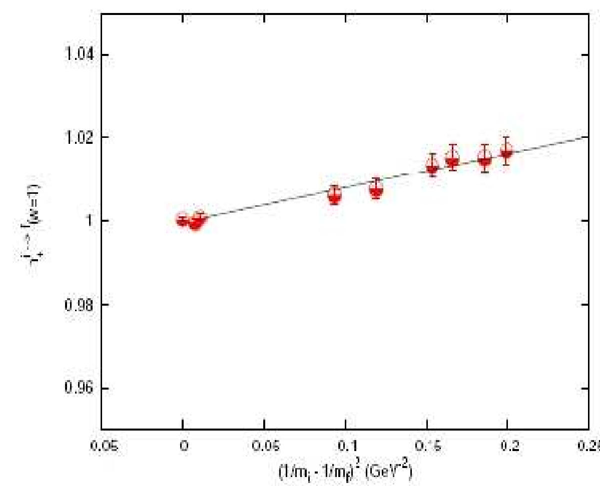




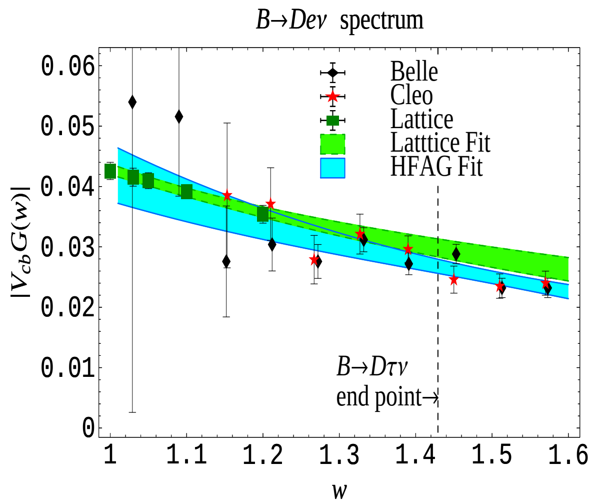
$\Lambda_{\rm Compt} \sim 1/m_Q$ $\quad$ $\Gamma_{\rm bind} \sim 1/\Lambda_{\rm QCD}$

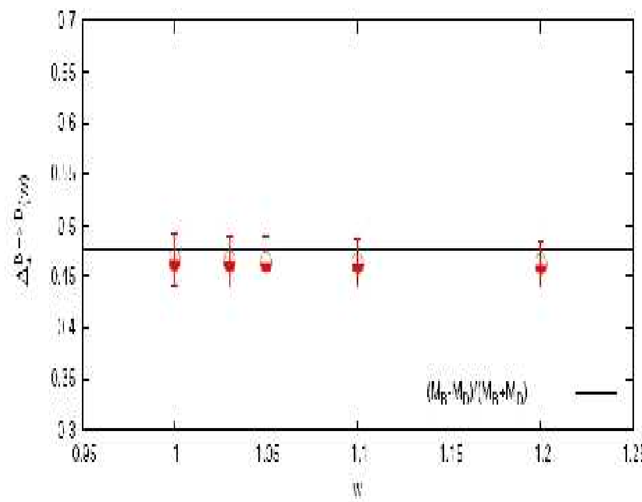






Lattice data on G cover a kinematical region hardly reachable by the experiment.





The function $\Delta^{B\to D}$ can be measured experimentally from $\frac{d\Gamma^{B\to D\tau\nu_\tau}}{d\Gamma^{B\to D(e,\mu)\nu_{e,\mu}}}$.

Lepton-flavour universality checks on the extraction of V_{cb}.

$$\frac{d\Gamma}{dw}(\bar{B} \to D^* \ell \bar{\nu}_\ell) = \frac{G_F^2}{4\pi^2} |V_{cb}|^2 m_{D^*}^3 (m_B - m_{D^*})^2 \sqrt{w^2 - 1} G'(w) |\mathcal{F}_{B \to D^*}(w)|^2$$

$G'(1) = 1$ $\quad \mathcal{F}_{B \to D^*}(1)$ depends on the single form factor $h_{A_1}(1)$:

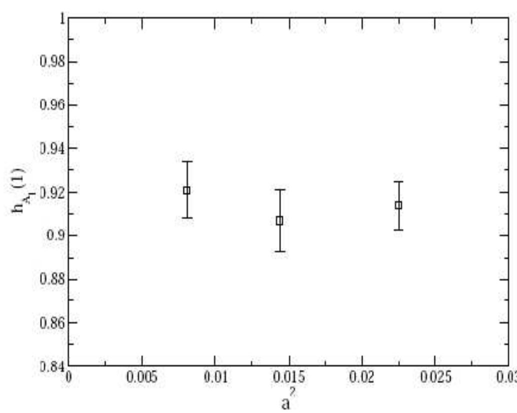
$$\langle D^*(v, \epsilon') | A^\mu | \overline{B}(v) \rangle = \sqrt{2 m_B 2 m_{D^*}}\ \bar{\epsilon}'^\mu\, h_{A_1}(1)$$

Heavy Quark Symmetry: $h_{A_1}(1) = \eta_A \left[1 - \frac{\ell_v}{(2m_c)^2} + \frac{2\ell_A}{2m_c 2m_b} - \frac{\ell_P}{(2m_b)^2} \right]$

The "double ratio" technique has been used by FNAL/MILC [C. Bernard et al, '08]:

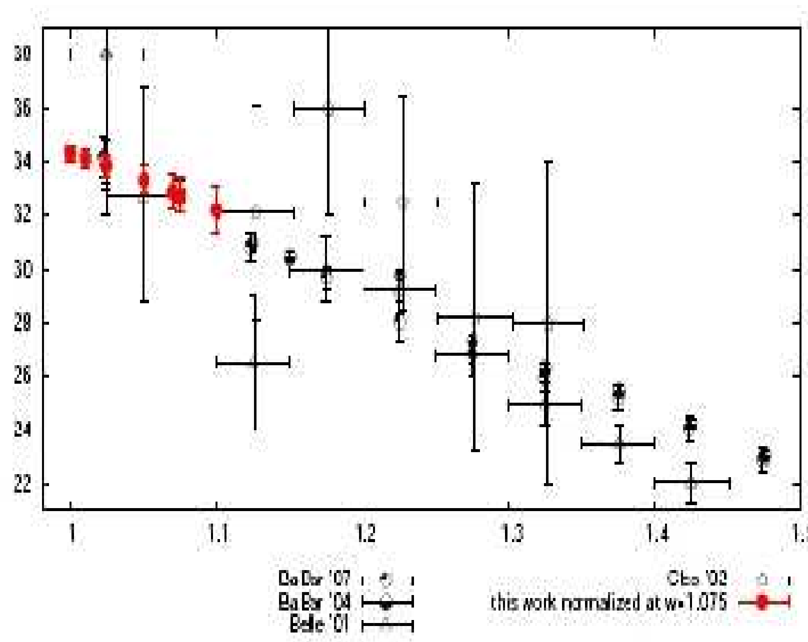
$$\frac{\langle D^* | \bar{c}\gamma_j\gamma_5 b | \overline{B} \rangle \langle \overline{B} | \bar{b}\gamma_i\gamma_5 c | D^* \rangle}{\langle D^* | \bar{c}\gamma_0 c | D^* \rangle \langle \overline{B} | \bar{b}\gamma_4 b | \overline{B} \rangle} = h_{A_1}(1)$$

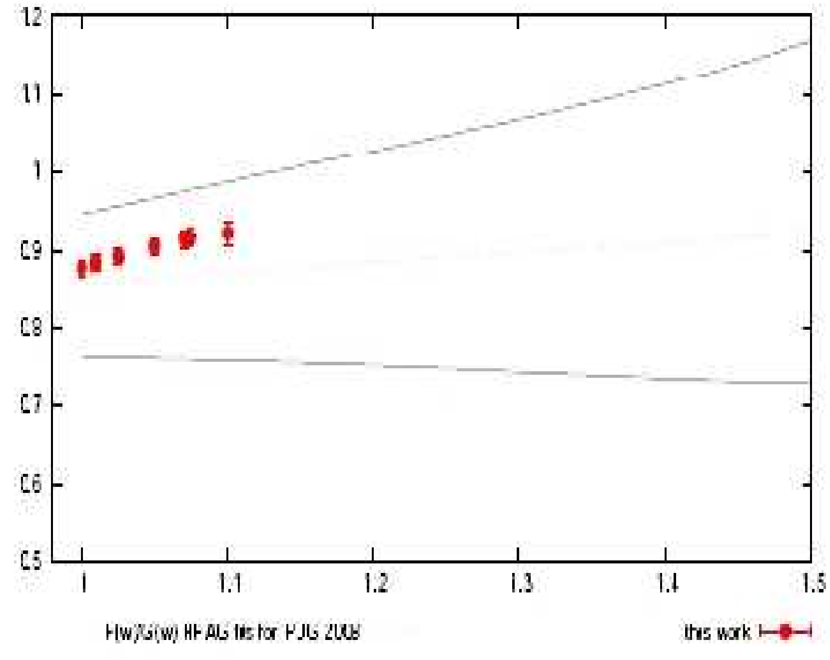
Discretisation errors are reduced by tuning the parameters entering in the heavy quark action.



$$h_{A_1}^{\mathrm{N_f}=2+1}(1) = 0.921(13)(20)$$

The Step Scaling method has been also used to measure the form factor $\mathcal{F}_{B\to D^*}$ at non zero recoil [G.M. de Divitiis et al, '08].





$$\mathcal{F}^{\mathrm{N_f}=0}_{B\to D^*}(1) = 0.917(8)(5)$$

At maximal recoil LCSR have obtained results for $B \to D^{(*)} l\nu$ form factors in reasonable agreement with experimental data [S. Faller et al, '08]:

$\mathcal{G}(w_{\max}) = 0.61 \pm 0.11 \pm (0.10)_{f_B} \pm (0.07)_{f_D}$

$h_{A_1}(w_{\max}) = 0.65 \pm 0.12 \pm (0.11)_{f_B} \pm (0.07)_{f_{D^*}}$

Decay to P states: "1/2 vs. 3/2" puzzle

Corroborated features

Theory: – OPE and HQE $\Longrightarrow$ Bjorken, Uraltsev, Voloshin and moments sum rules
– Quark models that are covariant in the $m_Q \to \infty$ limit
example: models *à la* Bakamijan-Thomas
– Lattice QCD

Experiment: B factories, LEP, Tevatron

States	% of $\Gamma(\bar{B} \to X_c l \bar{\nu})$
D, D^*	75 %
$D(3/2)$	$\sim$ 10 %

[Babar, '07]
[HFAG, '07]
[ALEPH, '97]
[DELPHI, '06]
[D0, '05]
[V. Morénas *et al*, '97] BT models

D, D^* and $D(3/2)$ do not saturate the total width; $\sim$ 15 % is composed of an unknown part D_X.

$B^* - B$ splitting: $\mu_G^2(1\,\mathrm{GeV}) = 0.35(3)\,\mathrm{GeV}^2$

$\mu_\pi^2(\mu) > \mu_G^2(\mu)$

$\mu_\pi^2(1\,\mathrm{GeV})|_{\mathrm{ref}} = 0.45\,\mathrm{GeV}^2$

[O. Buchmüller, H, Flächer, '05]
[Belle, '06]
[Babar, '07]
[I. Bigi *et al*, '95] OPE

OPE treatment is successful for subclasses of inclusive transitions.

Generalisation of the IW function $\xi(w)$

$\Gamma(\bar{B} \to D^{(n)}_{1/2[3/2]} l\bar{\nu}) \propto |\tau^{(n)}_{1/2[3/2]}(w_n)|^2$

$\sum_n \left[\tau^{(n)}_{3/2}(1)\right]^2 - \sum_n \left[\tau^{(n)}_{1/2}(1)\right]^2 = \frac{1}{4}$

$\tau^0_{3/2}(1) > \tau^0_{1/2}(1)$

$\tau^0_{1/2}(1) \in [0.20, 0.40]$, $\tau^0_{3/2}(1) \in [0.55, 0.70]$

Suppression of $D(1/2)$ with respect to $D(3/2)$ due to kinematics

Factorisation in the Class I $\bar{B} \to D^{**}\pi$: from analyses at B factories it is expected that $\tau^0_{3/2} > \tau^0_{1/2}$ as well

[V. Morénas *et al*, '97] BT models

[A. K. Leibovich *et al*, '98]

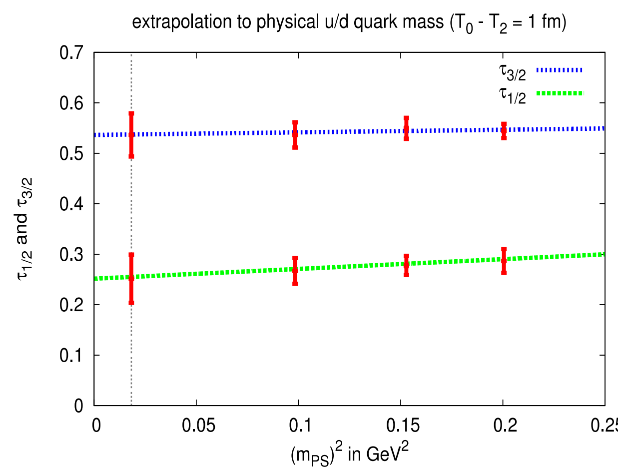
[D. Ebert *et al*, '98] Relativistic model

[P. Colangelo *et al*, '98] Sum rules *à la* SVZ

[N. Uraltsev, '01] Uraltsev sum rule

[D. Bećirević *et al*, '05] Lattice

[B. B. *et al*, '09, preliminary] Lattice



[Belle, '04]

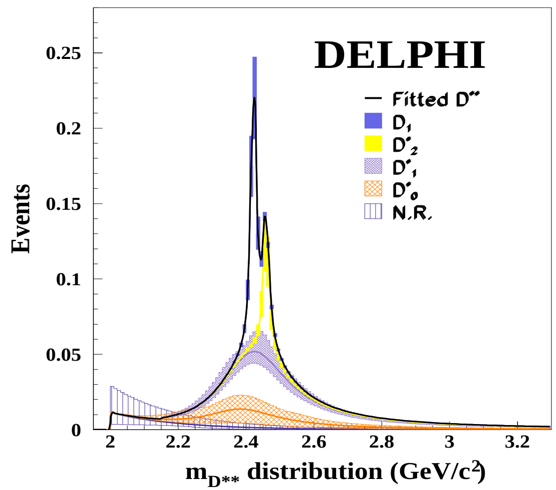
[Babar, '06]

$D(3/2)$ is expected to dominate $D(1/2)$ in $\bar{B} \to X_c l\bar{\nu}$.

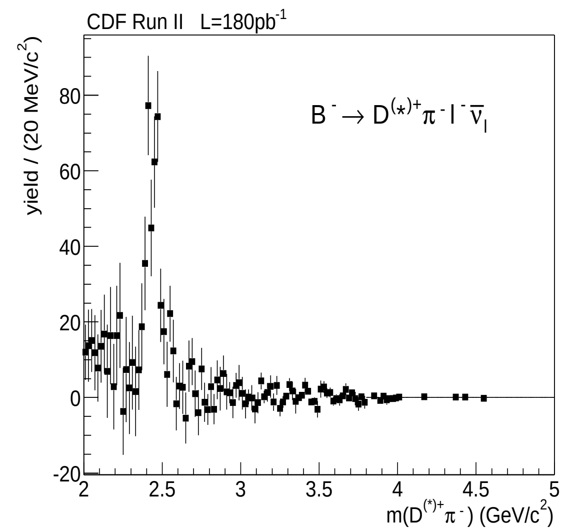
Issues

DELPHI found a larger component of broad states than of the narrow states.
Interpretation as D_0^* and D_1^*?? $\Longrightarrow$ Clear conflict with theory, '1/2' vs. '3/2' puzzle
[V. Morénas et al, '01], [N. Uraltsev, '04]

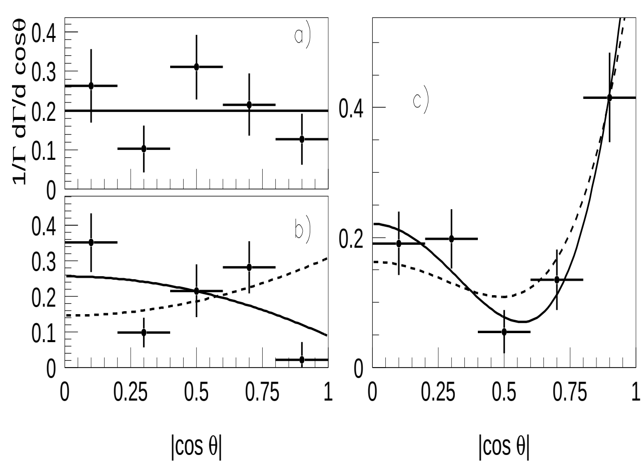
[DELPHI, '06]



[CDF, '05]



Belle analysis:
a) D_0^* b) D_v^* c) D_2^*

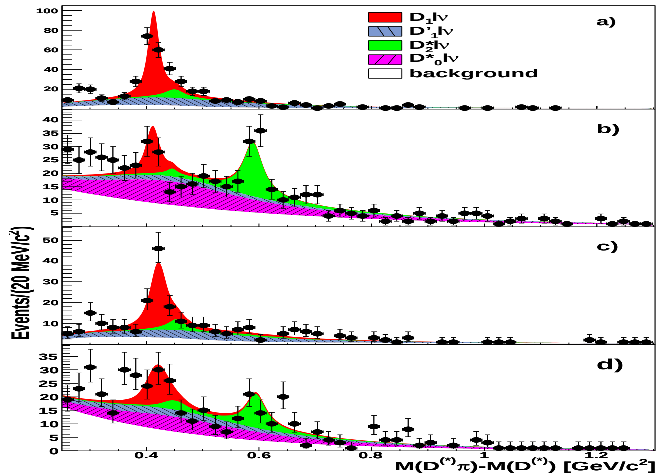


Belle has reported a suppression of $B \to D_1^* l\nu$
Difficult to define an Isgur-Wise function from such data

Babar analysis:

a) $D^{*+}\pi^-$ b) $D^+\pi^-$

c) $D^{*0}\pi^+$ d) $D^0\pi^+$



Babar has observed a huge component of broad states

Up to now the experimental verdict about $\bar{B} \to [D/D^*\pi]_{\rm broad} l \bar{\nu}$ is not clear.

No obvious theoretical candidates for those broad states if the mass distribution is centered below 2.5 GeV.

[I. Bigi et al, '07]

Outlook

- The experimental measurement of $B \to D\tau\nu_\tau$ is essential to perform the lepton-flavour universality check on the extraction of V_{cb}.
- Nice improvement of lattice calculations of the heavy-heavy form factors at non zero recoil have been done recently, especially in regions of the phase space where the experimental uncertainty is large.
- B decay into P states is still controversial: the "1/2 vs. 3/2" puzzle is not solved yet.
- On the experimental side, a large integrated luminosity might help to better figure out the broad structure observed in the $D^{(*)}\pi$ spectrum around 2.5 GeV.
- On the theoretical side, taking account of $1/m_Q$ corrections is crucial, either in the analytical treatement of QCD (OPE, quark models) or in its numerical one (lattice).