$B \to D^{**}l\nu$ – puzzle 1/2 vs 3/2

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- Questions about excited D meson states
- $B \to D^{**}l\nu$ and lattice QCD
- $B_{(s)} \to D^{**}_{(s)}\pi$: a more favorable situation?

Questions about excited D meson states

Processes involving excited states occur often in experiments. However it is difficult to deal with them $\Longrightarrow$ potential loss of information that could be precious in the seek of New Physics.

What is the composition of the hadronic final state X_c in $B \to X_c l\nu$?

$$J = \frac{1}{2} \oplus j_l$$

		Mass (MeV)	Width (MeV)	j_l^P	J^P
S: $D^{(*)}$	$D^{\pm}$	1869±0.5	-	$\frac{1}{2}^-$	0^-
	$D^{*\pm}$	2010±0.4	96±25		1^-
P: D^{**}	D_0^*	2352± 50	261 ± 50	$\frac{1}{2}^+$	0^+
	D_1^*	2427± 26 ± 25	$384^{+107}_{-75} \pm 74$		1^+
	D_1	2421.8 ± 1.3	$20.8^{+3.3}_{-2.8}$	$\frac{3}{2}^+$	1^+
	D_2^*	2461.1± 1.6	32± 4		2^+

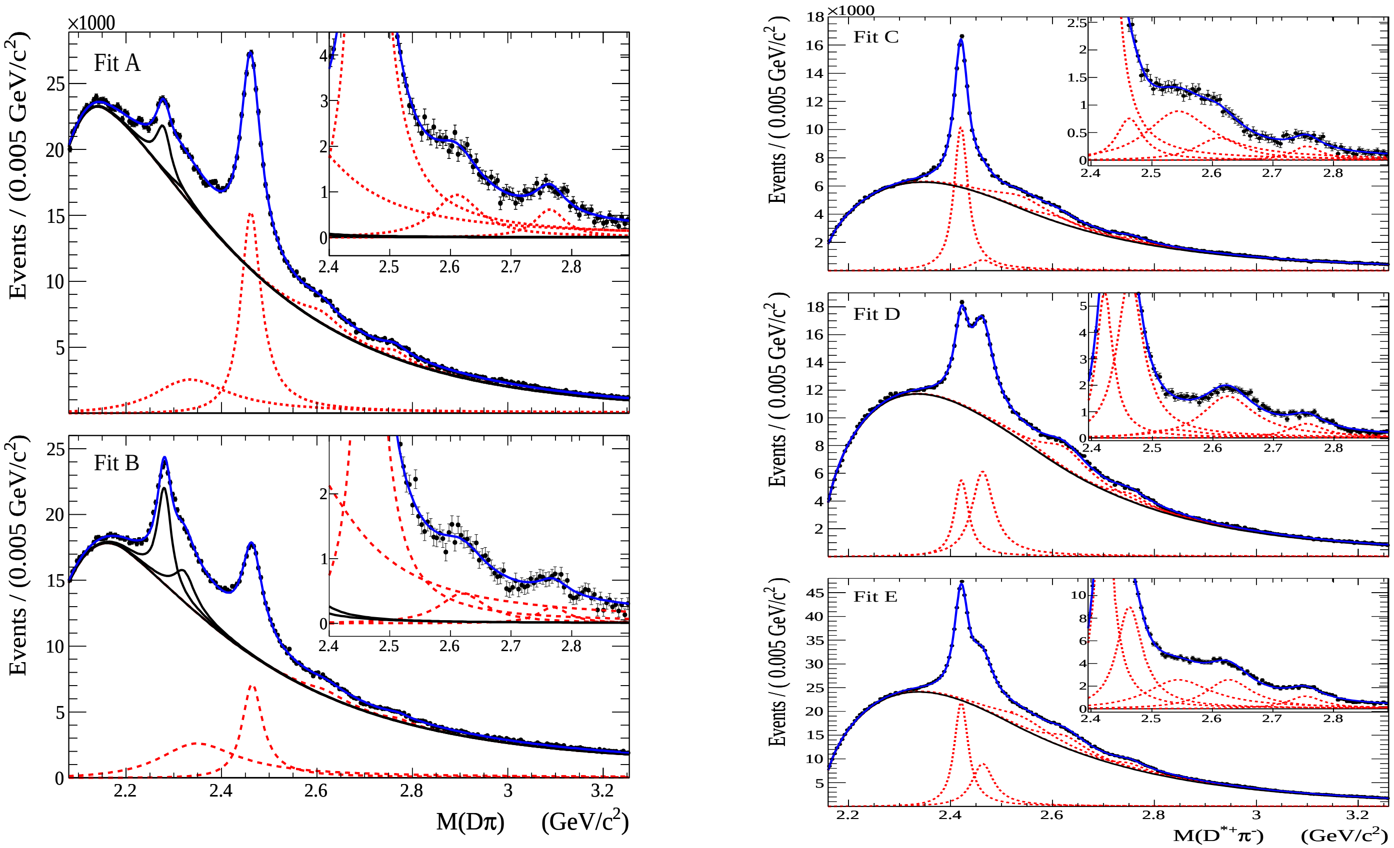
$D^{**} \to D^{(*)}\pi$ is the main decay channel: parity and orbital momentum conservation $\Longrightarrow$ the decay occurs with the pion in a S wave or in a D wave

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

Recently the BaBar Collaboration claimed to have isolated a couple of excited D states

[BaBar Collaboration, ’11]



$D\pi$ distribution: a clear peak is observed for $D_2^*(2460)$, “enhancements” are seen and correspond to $D^*(2600)$ and $D^*(2760)$

$D^*\pi$ distribution: a peak is visible for $D_1(2420$ and 2 structures are observed, interpreted as $D(2550) \equiv D'$ (somehow confirmed by LHCb in 2013) and $D(2750)$

A fit gives $m(D') = 2539(8)$ MeV and $\Gamma(D') = 130(18)$ MeV

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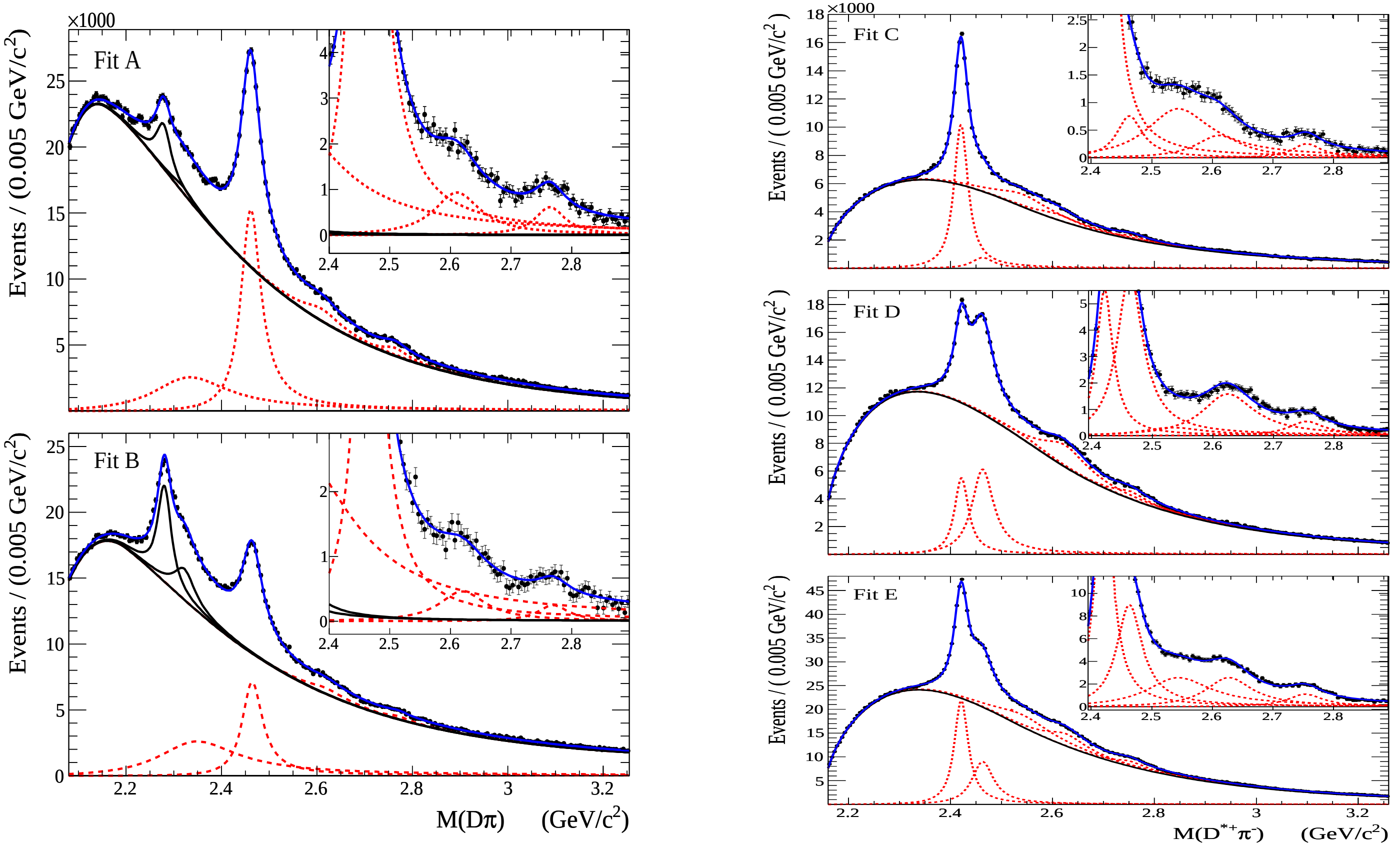


Is this interpretation correct? Popular quark models obtain roughly the same mass (2580 MeV) but a much smaller width (70 MeV) [F. Close and E. Swanson, '05; Z. Sun *et al*, '10]

☹ Radial excitations are very sensitive to the position of the nodes of wave functions, that depend strongly on the model.

$$\mathcal{B}(B_d \to X_c l\nu) = (10.09 \pm 0.22)\%$$
$$\mathcal{B}(B_d \to [\text{non} - D^{(*)}]l\nu) = 2.86 \pm 0.25)\%$$
$$\mathcal{B}(B_d \to D^{**}_{\text{narrow}} l\nu) = (0.87 \pm 0.06)\%$$
$$\mathcal{B}(B_d \to D^{(*)}\pi l\nu) = (1.43 \pm 0.08)\%$$
$$\mathcal{B}(B_d \to [D\pi]_{\text{broad}} l\nu) = (0.42 \pm 0.06)\%$$
$$\mathcal{B}(B_d \to [D^*\pi]_{\text{broad}} l\nu) = (0.33 \pm 0.07)\%$$

We are concerned by 25% of the total branching ratio $B \to X_c l\nu$

1/3 of the remaining component comes from the narrow D^{**}

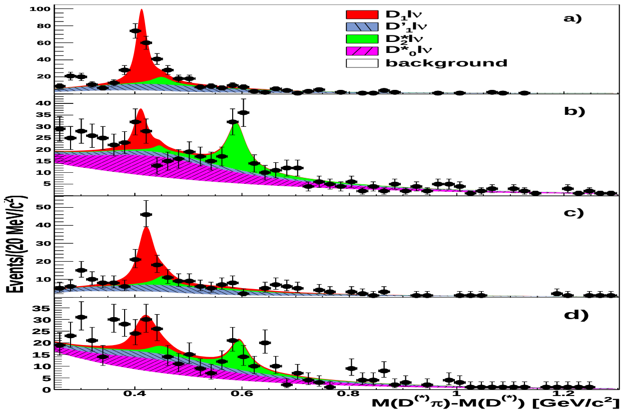
[BaBar, '08]

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

b) $D^+\pi^-$

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

d) $D^0\pi^+$



[F. Bernlochner *et al*, '12]:
Assume a large $\mathcal{B}(B \to D' l\nu)$:
$\Gamma(D' \to D_{1/2}\pi) \gg \Gamma(D' \to D_{3/2}\pi)$

$\Longrightarrow$ Excess of $B \to D_{1/2}(\pi)l\nu$ events with respect to $B \to D_{3/2}(\pi)l\nu$

Is this potentially large $B \to D' l\nu$ width might explain the "1/2 vs. 3/2 puzzle"?

$[\Gamma(B \to D_{1/2} l\nu) \simeq \Gamma(B \to D_{3/2} l\nu)]^{\text{exp}}$ while $[\Gamma(B \to D_{1/2} l\nu) \ll \Gamma(B \to D_{3/2} l\nu)]^{\text{th}}$

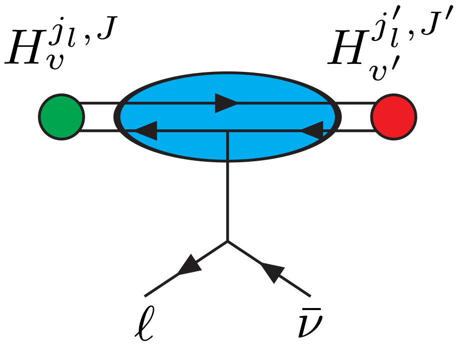
[V. Morénas *et al*, '01; N. Uraltsev, '04]: $\frac{d\Gamma^{B \to D_{1/2}}}{d\Gamma^{B \to D_{3/2}}} = \frac{2}{(w+1)^2}\left(\frac{\tau_{1/2}(w)}{\tau_{3/2}(w)}\right)^2$

$B_d \to D^{**} e\nu$	$\mathcal{B}_{\text{exp}}/\mathcal{B}_{\text{th}}$
D_2^*	0.5
D_1	1
D_1^*	[0, 5]
D_0^*	6 ± 1

Experimental issue: identification of the D_0^*, disagreement in $\mathcal{B}(B \to D_1^* l\nu)$ between Belle (no events) and BaBar (claim of a signal)
Theoretical issue: predictions made essentially in the infinite mass limit, including lattice QCD calculations of Isgur-Wise functions $\tau_{1/2}$ and $\tau_{3/2}$

$B \to D^{**} l\nu$ and lattice QCD

Infinite mass limit



With the *trace formalism* the transitions $H_v^{j_l,J} \to H_{v'}^{j_l',J'}$ are expressed in terms of universal form factors: the Isgur-Wise functions $\Xi(w \equiv v \cdot v')$.

Thanks to heavy quark and spin symmetries, their number is small:

– $\xi(w)$ parameterizes the elastic transition $H_v^{\frac{1}{2}^-} \to H_{v'}^{\frac{1}{2}^-}$: $\xi(1) = 1$

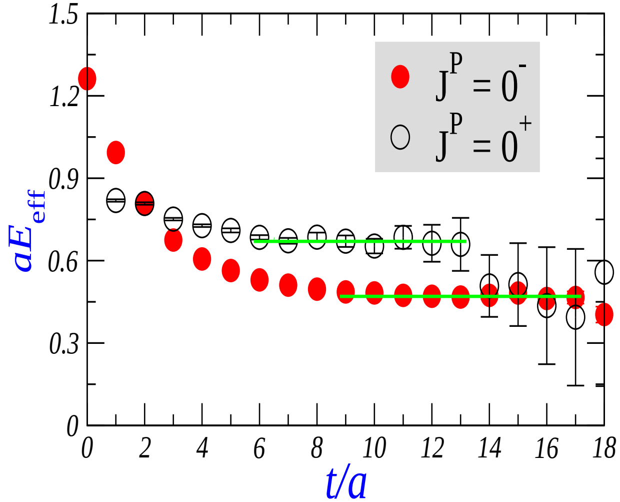
– $\langle H_{v'}^{0^+} | \bar{h}_{v'} \gamma^\mu \gamma^5 h_v | H_v^{0^-} \rangle \equiv \tau_{\frac{1}{2}}(\mu, w)(v - v')^\mu$

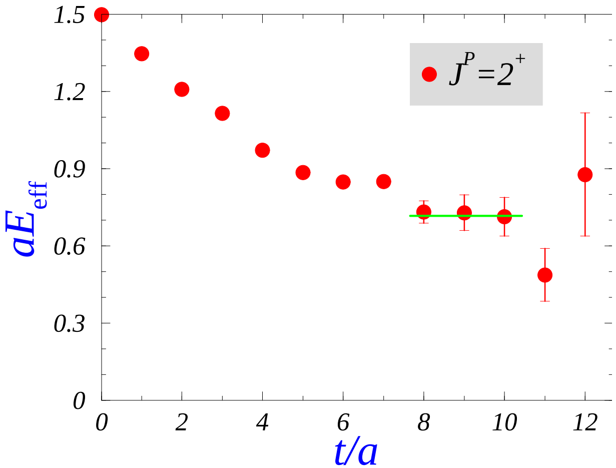
– $\langle H_{v'}^{2^+} | \bar{h}_{v'} \gamma^\mu \gamma^5 h_v | H_v^{0^-} \rangle \equiv \sqrt{3}\, \tau_{\frac{3}{2}}(\mu, w)[(w+1)\epsilon^{*\mu\alpha} v_\alpha - \epsilon^*_{\alpha\beta} v^\alpha v^\beta v'^\mu]$

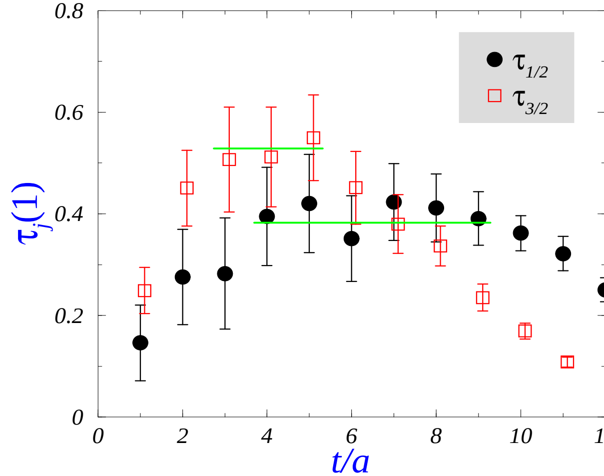
$\tau_{\frac{1}{2}}$ and $\tau_{\frac{3}{2}}$ are not normalised at zero recoil; however, $\tau_{\frac{1}{2},\frac{3}{2}}(\mu, 1) \equiv \tau_{\frac{1}{2},\frac{3}{2}}(1)$

Quenched lattice QCD [D. Bećirević *et al*, '04]:

Wilson-Clover & Eichten-Hill/HYP1 #=600 $\mathrm{N_f} = 0$ $a = 0.1$ fm $L \sim 1.6$ fm $m_q \gtrsim m_s$



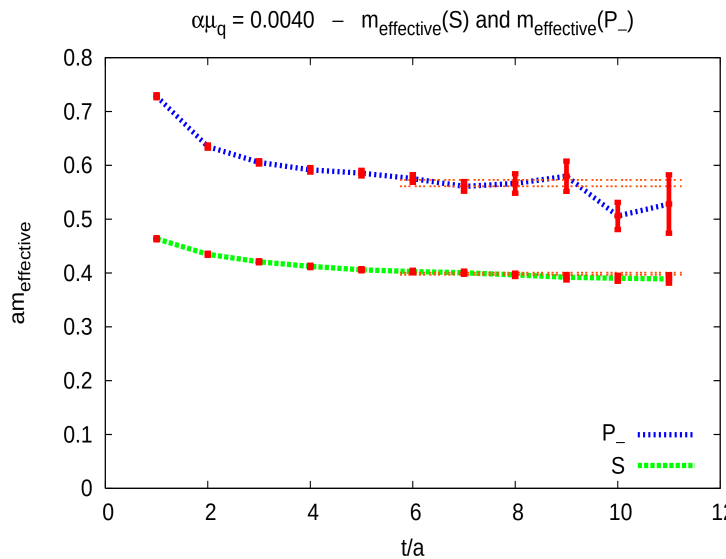


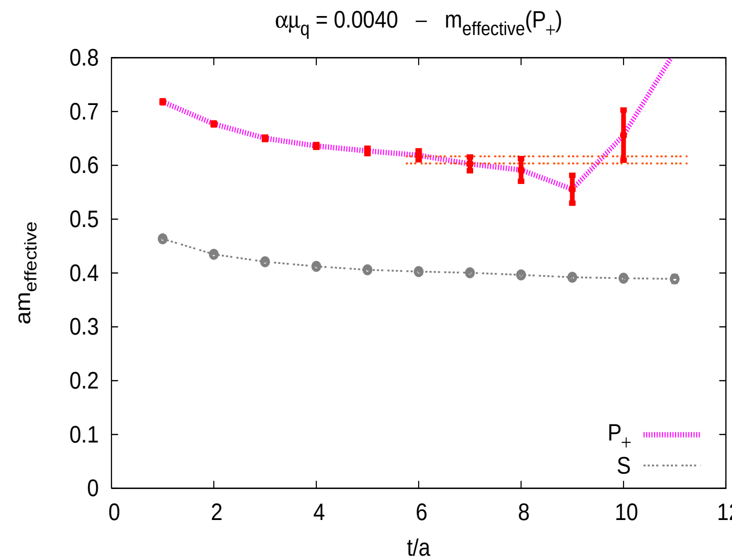


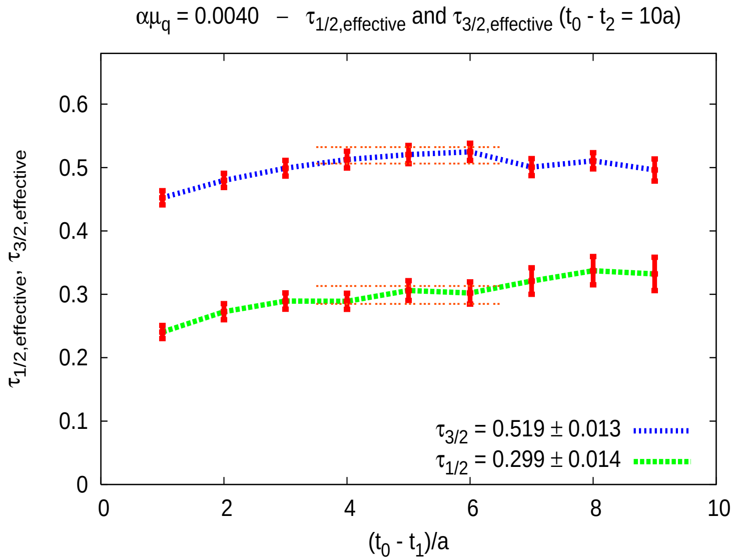
Short plateaus of the 2^+ state effective mass and of $\tau_{\frac{1}{2},\frac{3}{2}}(1)$; however, $\tau_{\frac{1}{2}} \lesssim \tau_{\frac{3}{2}}$.

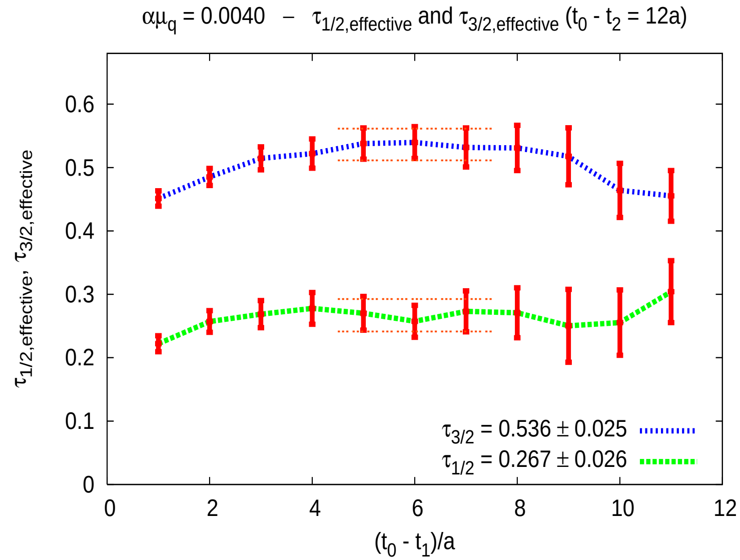
$\mathrm{N_f} = 2$ lattice QCD [B. B. *et al*, '10]

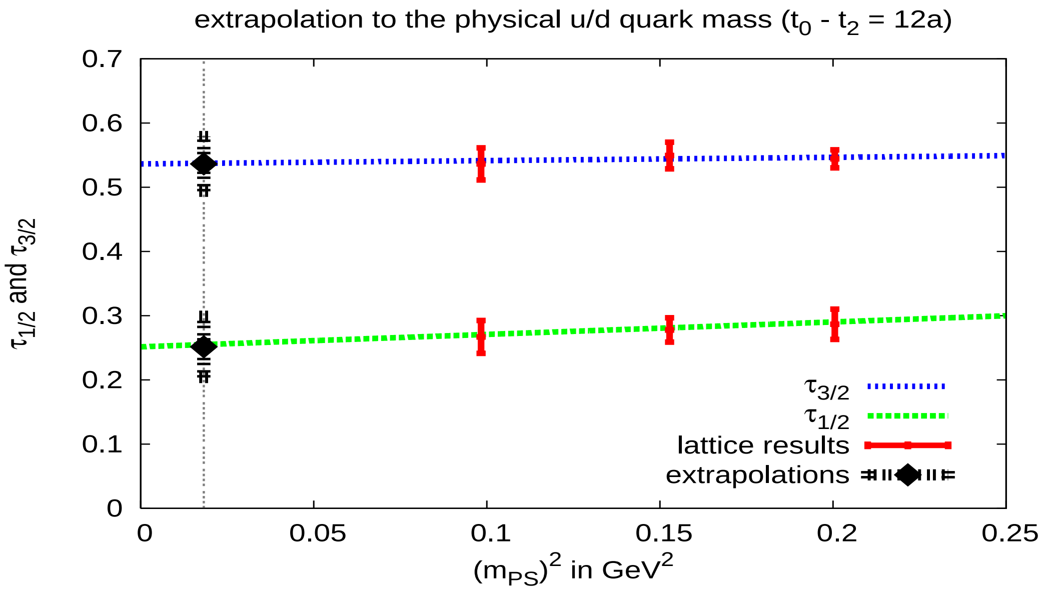
ETMC ensembles with $a \sim 0.085$ fm, $L \sim 2.1$ fm and $\mathrm{m}_\pi \in$ [300 - 450] MeV.











Once again $\tau_{\frac{1}{2}}(1)$ seems significantly smaller than $\tau_{\frac{3}{2}}(1)$: lattice results point in the same direction as quark models [A. Le Yaouanc *et al*, ’96; D. Ebert *et al*, ’00] and OPE based sum rules [A. Le Yaouanc *et al*, ’00; N. Uraltsev, ’01].

Towards realistic b and c quark masses [M. Atoui *et al*, work in progress]

With $V_\mu = \bar{c}\gamma_\mu b$ and $A_\mu = \bar{c}\gamma_\mu\gamma^5 b$:

$$\langle D_0^*|A^\mu|B\rangle = \tilde{u}^+\,(p_B+p_D)^\mu + \tilde{u}^-\,(p_B-p_D)^\mu$$

$$\langle D_2^*(\epsilon^{(\lambda)})|V^\mu|B\rangle = i\tilde{h}\,\epsilon^{\mu\nu\rho\sigma}\epsilon^{(\lambda)*}_{\nu\alpha}p_B^\alpha(p_B+p_D)_\rho(p_B-p_D)_\sigma$$

$$\langle D_2^*(\epsilon^{(\lambda)})|A^\mu|B\rangle = \tilde{k}\,\epsilon^{(\lambda)\,\mu\nu\,*}p_{B\,\nu} + \epsilon^{(\lambda)\,*}_{\alpha\beta}p_B^\alpha p_B^\beta[\tilde{b}^+\,(p_B+p_D)^\mu + \tilde{b}^-\,(p_B-p_D)^\nu]$$

With the kinematical configuration $\vec{p}_D=\vec{0}$, $\vec{p}_B=(\theta,\theta,\theta)$, defining the tensors of polarisation accordingly, the leading form factors contributing to the widths are

$$\tilde{k} = -\frac{\sqrt{6}}{\theta}\mathcal{F}_A^{(0)\,1} = -\frac{\sqrt{6}}{\theta}\mathcal{F}_A^{(0)\,2} = \frac{\sqrt{6}}{2\theta}\mathcal{F}_A^{(0)\,3}$$

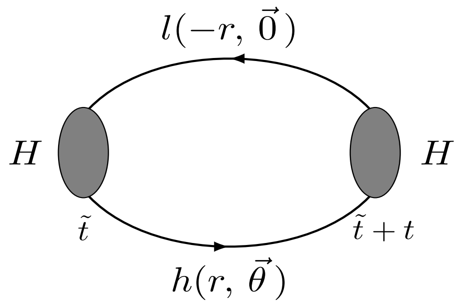
$$\tilde{k} = \frac{1}{\theta}\left[\mathcal{F}_A^{(+2)\,1}+\mathcal{F}_A^{(-2)\,1}\right] = -\frac{1}{\theta}\left[\mathcal{F}_A^{(+2)\,2}+\mathcal{F}_A^{(-2)\,2}\right]$$

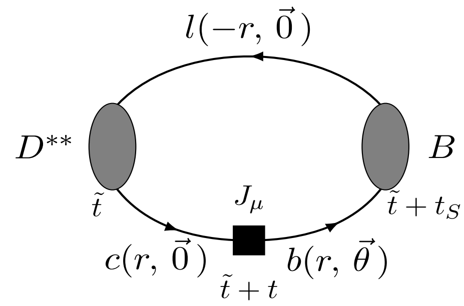
$$\tilde{u}^+ \quad = \quad -\frac{1}{2\,m_{D_0^*}}\left[\frac{E_B-m_{D_0^*}}{3\theta}(\mathcal{F}_A^1+\mathcal{F}_A^2+\mathcal{F}_A^3)-\mathcal{F}_A^0\right] \qquad (1)$$

$\mathcal{F}_A^{(\lambda)\,\mu} \equiv \langle D_2^*(\epsilon^{(\lambda)})|A^\mu|B\rangle \qquad \mathcal{F}_A^\mu \equiv \langle D_0^*|A^\mu|B\rangle$

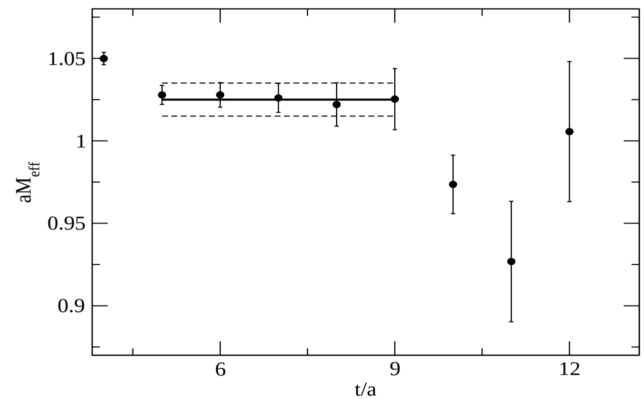
Preliminary study performed using $N_f = 2$ ETMC ensembles:
real c quark, "light" b quarks $\longrightarrow$ extrapolation to m_b, 2 (finally, 3) lattice spacings to remove cut-off effects

Twisted boundary conditions required to give a momentum to the B meson in 2-pt and 3-pt correlators



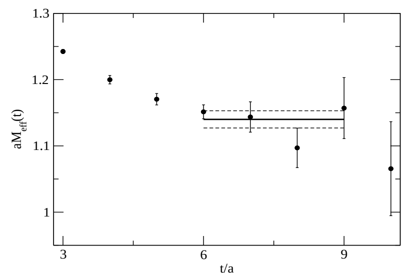


$a \sim 0.085$ fm, $m_\pi \sim 420$ MeV

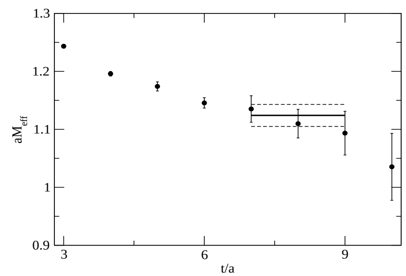


Isolating the signal for D_0^* is difficult because of the mixing with D state due to a breaking parity cut-off effect: solving a generalized eigenvalue problem helps

E



T2



Isolating the signal for D_2^* is difficult because of the noise, despite averaging over different interpolating fields belonging to the same representation (E or T2) of the O_h cubic group

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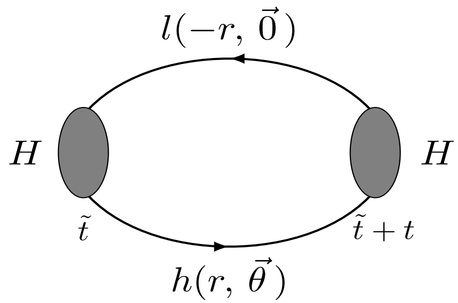
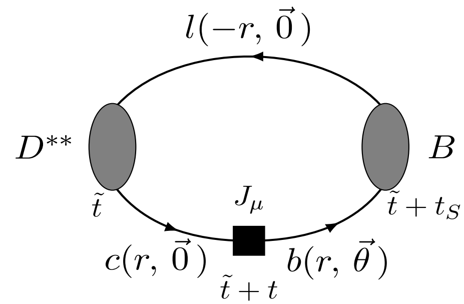
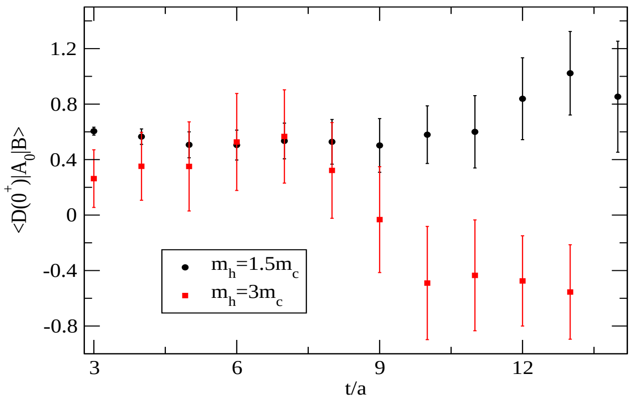




Isolating at zero recoil the signal for $\mathcal{F}_A^0$ seems possible but it deteriotates if the b quark mass gets closer to m_b.

$a \sim 0.085$ fm, $m_\pi \sim 420$ MeV



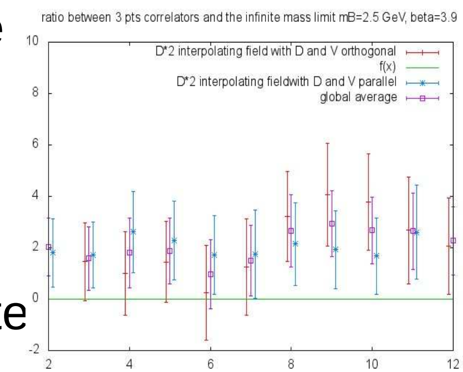
At zero recoil $\mathcal{F}_A^{(\lambda)\,\mu} = 0$; need to inject large momenta, where the data are also noisy

Normalizing $\tilde{k}$ by the $m_h \to \infty$ limit term

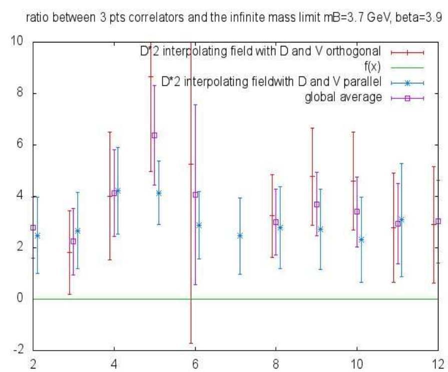
$\tilde{k}_\infty = \sqrt{3}\sqrt{r_{D_2^*}}(w+1)\tau_{3/2}(w)$, $r_{D_2^*} = \dfrac{m_{D_2^*}}{m_B}$,

results are encouraging at $w_{\max}$, though quite larger than 1

$m_h = 1.5 m_c$



$m_h = 3 m_c$

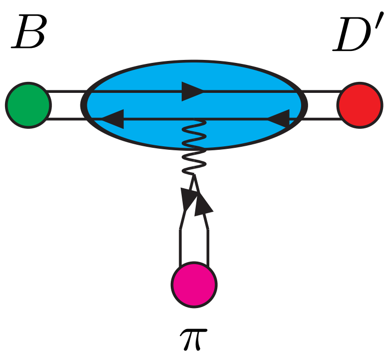


$B_{(s)} \to D_{(s)}\pi$: a more favorable situation?

$B_d \to D^{**}\pi$	$\mathcal{B}_{\rm exp}/\mathcal{B}_{\rm th}$
D_2^*	$\sim$ 0.5
D_1	[0.5, 1]
D_1^*	no result
D_0^*	[0.2, 2.6]

Experimental disagreement in $\mathcal{B}(B_d \to D_0^*\pi)$ between Belle and BaBar, not so conclusive however
Theoretical predictions based on factorisation approximation that works well for Class I decay
Globally, much better agreement between theory and experiment for $B_d \to D_0^*\pi$ than for $B_d \to D_0^* l\nu$

Largeness of $\mathcal{B}(B \to D' l\nu)$ checked on $B \to D'\pi$

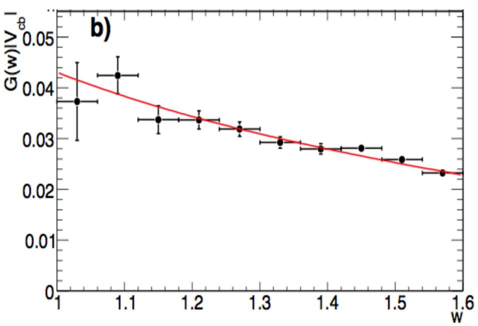


Class I: factorisation approximation

$$\frac{\mathcal{B}(\bar{B}^0 \to D'^+\pi^-)}{\mathcal{B}(\bar{B}^0 \to D^+\pi^-)} = \left(\frac{m_B^2 - m_{D'}^2}{m_B^2 - m_D^2}\right)^2 \left[\frac{\lambda(m_B, m_{D'}, m_\pi)}{\lambda(m_B, m_D, m_\pi)}\right]^{1/2} \left|\frac{f_+^{B\to D'}(0)}{f_+^{B\to D}(0)}\right|^2$$

$$\lambda(x,y,z) = [x^2 - (y+z)^2][x^2 - (y-z)^2] \quad f_+^{B\to D^{(\prime)}}(m_\pi^2) \sim f_+^{B\to D^{(\prime)}}(0)$$

[BaBar Collaboration, '10]



$V_{cb} f_+^{B\to D}(0) = 0.02642(8)$ and $|V_{cb}| = 0.0411(16)$:
$f_+^{B\to D}(0) = 0.64(2)$

$m_{D'} = 2.54$ GeV: $\frac{\mathcal{B}(\bar{B}^0 \to D'^+\pi^-)}{\mathcal{B}(\bar{B}^0 \to D^+\pi^-)} = (1.65 \pm 0.13) \times \left|f_+^{B\to D'}(0)\right|^2$

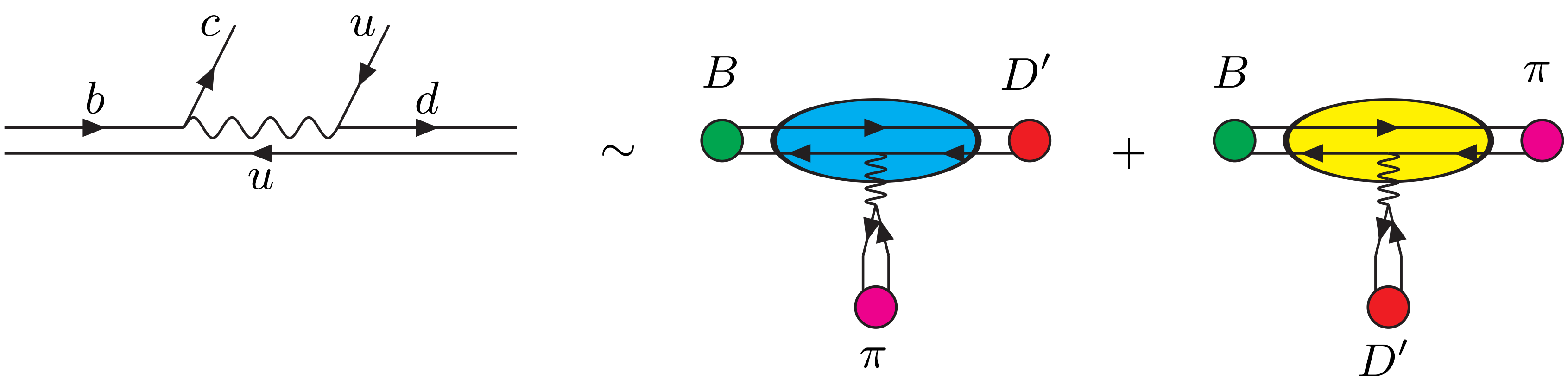
$\mathcal{B}(\bar{B}^0 \to D^+\pi^-) = 0.268(13)\%$: $\mathcal{B}(\bar{B}^0 \to D'^+\pi^-) = \left|f_+^{B\to D'}(0)\right|^2 \times (4.7 \pm 0.4) \times 10^{-3}$

Theoretical estimates of $f_+^{B\to D'}(0)$ are in the range $[0.1,\, 0.4]$

[F. Bernlochner *et al*, '12; D. Ebert *et al*, '99; N. Faustov and V. Galkin, *'12*; Z. Wang *et al*, '12]

$\mathcal{B}(\bar{B}^0 \to D'^+\pi^-)^{\rm th} \sim 10^{-4}$: it can be measured with the B factories samples and at LHCb.

Factorised amplitude of the Class III decay normalised by the Class I decay



$$A^{III}_{\rm fact} = -i\frac{G_F}{\sqrt{2}} V_{cb}V^*_{ud}\left[a_1 f_\pi [m_B^2 - m_{D'}^2] f^{B\to D'}(m_\pi^2) + a_2 f_{D'} [m_B^2 - m_\pi^2] f^{B\to\pi}(m_{D'}^2)\right]$$

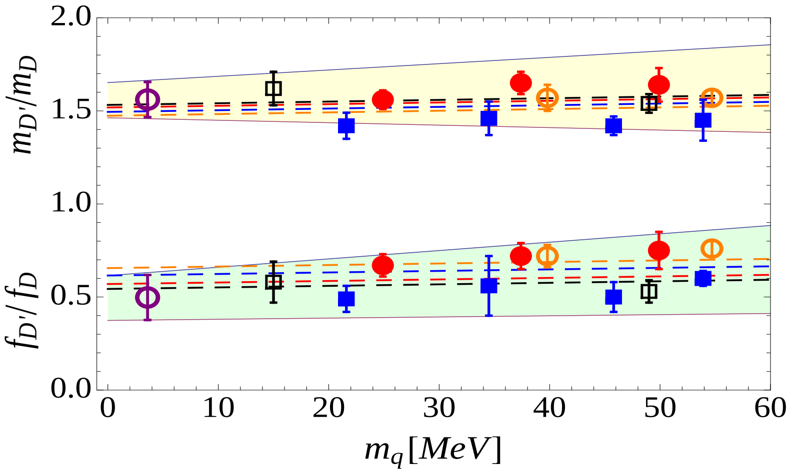
$$\frac{\mathcal{B}(B^-\to D'^0\pi^-)}{\mathcal{B}(\bar{B}^0\to D'^+\pi^-)} = \frac{\tau_{B^-}}{\tau_{\bar{B}^0}}\left[1 + \frac{a_2}{a_1}\times\frac{m_B^2 - m_\pi^2}{m_B^2 - m_{D'}^2}\times\frac{f_0^{B\to\pi}(m_{D'}^2)}{f_+^{B\to D'}(0)}\,\frac{f_{D'}}{f_D}\,\frac{f_D}{f_\pi}\right]^2$$

a_2/a_1 determined from $\frac{\mathcal{B}(B^-\to D^0\pi^-)}{\mathcal{B}(\bar{B}^0\to D^+\pi^-)}$, known experimentally

$f_{D'}/f_D$ and f_D/f_π extracted from lattice QCD simulations

Combined fit of ETMC data at different a and $m_{\rm sea}$ [D. Becirevic *et al*, '13]:

$$\mathcal{F}^{\rm latt.} = A_{\mathcal{F}}\left[1 + B_{\mathcal{F}} m_q + C_{\mathcal{F}}\left(\frac{a}{a_{\beta=3.9}}\right)^2\right] \qquad a_{\beta=3.9} = 0.085 \text{ fm}$$



$$\frac{m_{D'_s}}{m_{D_s}} = 1.53(7) \qquad \frac{f_{D'_s}}{f_{D_s}} = 0.59(11)$$

$$\frac{m_{D'}}{m_D} = 1.55(9) \qquad \frac{f_{D'}}{f_D} = 0.57(16)$$

$$(m_{D'}/m_D)^{\rm exp} = 1.36$$

Lattice inputs: $m_{D'}/m_D = 1.55(9) \quad f_{D'}/f_D = 0.57(16) \quad f_D/f_\pi = 1.56(3)(2)$

Phenomenological inputs: $a_2/a_1 = 0.368 \quad \tau_{\bar{B}^0}/\tau_{B^-} = 1.079(7) \quad f_+^{B\to D}(0) = 0.64(2)$

$f_0^{B\to\pi}(m_D^2) = 0.29(4)$

$$\frac{\mathcal{B}(B^- \to D'^0\pi^-)}{\mathcal{B}(\bar{B}^0 \to D'^+\pi^-)} = \frac{\tau_{B^-}}{\tau_{\bar{B}^0}}\left[1 + \frac{0.14(4)}{f_+^{B\to D'}(0)}\right]^2$$

$$\frac{\mathcal{B}(\bar{B}^0 \to D'^+\pi^-)}{\mathcal{B}(\bar{B}^0 \to D^+\pi^-)} = (1.24 \pm 0.21) \times |f_+^{B\to D'}(0)|^2$$

$$\left.\frac{\mathcal{B}(\bar{B}^0 \to D'^+\pi^-)}{\mathcal{B}(\bar{B}^0 \to D^+\pi^-)}\right|_{(m_{D'}/m_D)^{\rm exp}} = (1.65 \pm 0.13) \times \left|f_+^{B\to D'}(0)\right|^2$$

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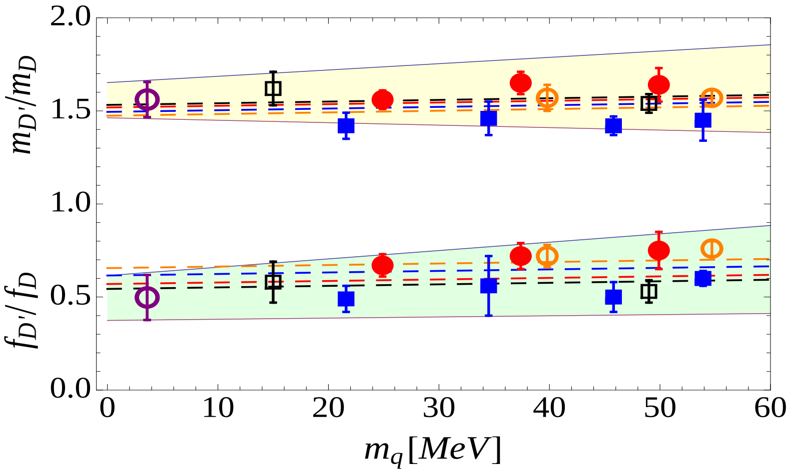

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$$(m_{D'}/m_D)^{\rm exp} = 1.36$$

Lattice inputs: $m_{D'}/m_D = 1.55(9)$ $\quad f_{D'}/f_D = 0.57(16)$ $\quad f_D/f_\pi = 1.56(3)(2)$

Phenomenological inputs: $a_2/a_1 = 0.368$ $\quad \tau_{\bar{B}^0}/\tau_{B^-} = 1.079(7)$ $\quad f_+^{B\to D}(0) = 0.64(2)$
$f_0^{B\to\pi}(m_D^2) = 0.29(4)$

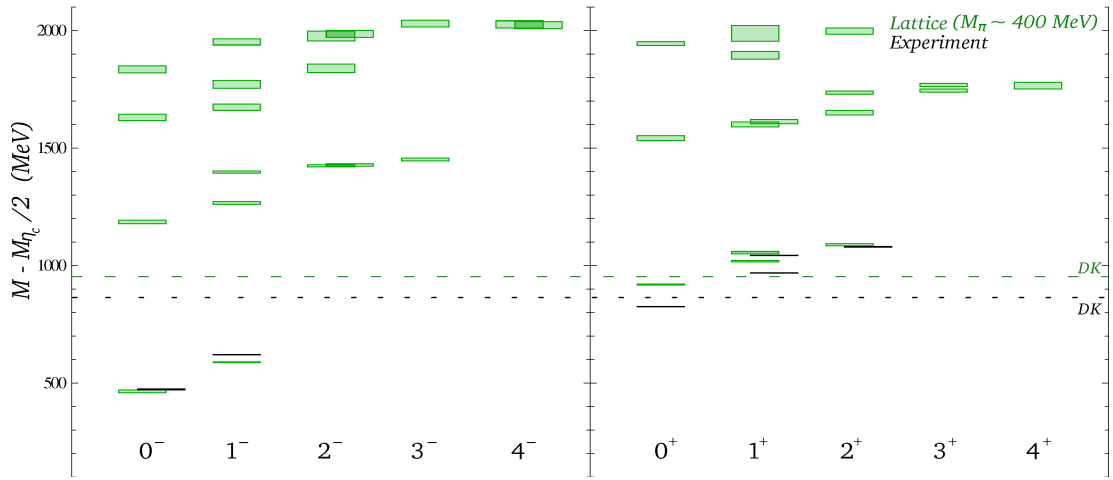
Fixing $f_+^{B\to D'}(0) = 0.4$ and taking $(m_{D'}/m_D)^{\rm exp}$ we have also:

$$\frac{\mathcal{B}(\bar{B}^0 \to D'^+\pi^-)}{\mathcal{B}(\bar{B}^0 \to D_2^{*+}\pi^-)} = 1.6(3) \qquad \frac{\mathcal{B}(B^- \to D'^0\pi^-)}{\mathcal{B}(B^- \to D_2^{*0}\pi^-)} = 1.4(3)$$

If $f_+^{B\to D'}$ is large, as claimed by many authors, the measurement of $\mathcal{B}(B \to D'\pi)$ should be as feasible as $\mathcal{B}(B \to D_2^*\pi)$

$B_s \to D_s^{**}\pi$

[M. Peardon *et al*, ’13]



$D^*_{s\,0}(2317)$ and $D^*_{s\,1}(2460)$ stand below DK and D^*K thresholds: they are narrow state.

☺ No experimental issue from the broadness!

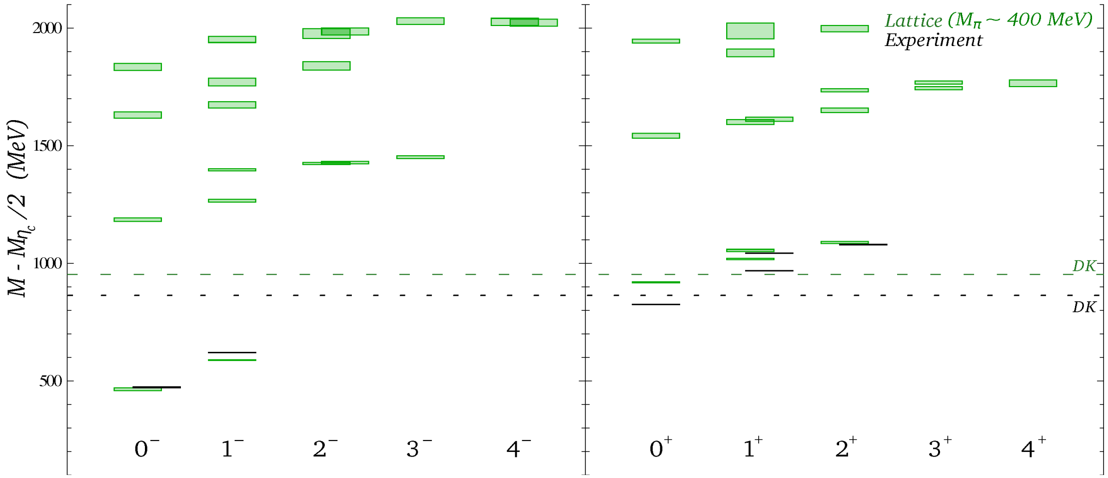
It has been proposed to study hadronic decays $B_s \to D^{*+}_{s0}(2317)\pi^-$ and $B_s \to D^{*+}_{s1}(2460)\pi^-$ [D. Becirevic *et al*, ’12].

Only upper limits on $\mathcal{B}(D^{*+}_{s0} \to \ldots)$ are available, $\mathcal{B}(D^{*+}_{s0} \to D^+_s\gamma,\ D^{*+}_{s0} \to D^{*+}_s\gamma\gamma) < 0.2\%$. $\mathcal{B}(D^{*+}_{s0} \to D^+_s\pi^0) = (97 \pm 3)\%$ taken in phenomenological analyses.

$$\mathcal{B}(D^{*+}_{s1} \to D^{*+}_s\pi^0) = (48 \pm 11)\%$$
$$\mathcal{B}(D^{*+}_{s1} \to D^+_s\gamma) = (18 \pm 4)\%$$
$$\mathcal{B}(D^{*+}_{s1} \to D^+_s\pi^+\pi^-) = (4.3 \pm 1.3)\%$$
$$\mathcal{B}(D^{*+}_{s1} \to D^{*+}_{s0}\gamma) = (3.7^{+5.0}_{-2.4})\%$$

$$B_s \to D_s^{**}\pi$$

[M. Peardon *et al*, '13]



$D_{s0}^*(2317)$ and $D_{s1}^*(2460)$ stand below DK and D^*K thresholds: they are narrow states.

☺ No experimental issue from the broadness!

It has been proposed to study the hadronic decays $B_s \to D_{s0}^{*+}(2317)\pi^-$ and $B_s \to D_{s1}^{*+}(2460)\pi^-$ [D. Becirevic *et al*, '12].

At LHCb: measurement of the cascade $B_s \to D_{s0}^{*-}\pi^+$, $D_{s0}^{*-} \to D_s^-\pi^0$, $D_s^- \to K^+K^-\pi^-$; the 4-momentum of the non detected π^0 is extracted from the B_s flight direction and the known m_{B_s} and m_{π^0}. The narrow peak in the $D_{s0}^-\pi^0$ mass distribution can be observed, depending on the accuracy of tracking capabilities.

Neglecting SU(3) breaking effects, with $\mathcal{B}(B_s \to D_s^+\pi^-) = (2.95 \pm 0.28) \times 10^{-3}$ and $\mathcal{B}(B_s \to D_{s0}^{*-}\pi^+) = (1 \pm 0.5)10^{-4}$, the number of expected events with 1 fb^{-1} of integrated luminosity is $N(B_s \to D_{s0}^{*-}\pi^+) = 600 \times (1 \pm 0.5) \times \mathcal{B}(D_{s0}^{*-} \to D_s^-\pi^0) \times \epsilon_{\pi^0}$: ~ 100.

Outlook

- Excited meson states are massively produced in experiments. To exploit fruitfully the numerous data at Super Belle and LHCb, theorists do have to put an important effort in confronting their models predictions with measurements, by proposing to experimenters unambiguous observables to look at.

- The case of D^{**} mesons is illuminating: understanding their physics and tracking the contradiction between theory and experiment in semiletponic $B \to D^{**}_{\rm broad}$ decays will help to control systematics on V_{cb}.

- Non leptonic decays are promising, especially the Class I decay $B_s \to D^{*+}_{s0} \pi^-$: D^{*+}_{s0} is a narrow state, easy to see at LHCb. Lattice inputs enter the calculation to compare with theory, a long-term work is going on to extract the relevant form factor at realistic c and b quark masses.