Robust statements and open problems in $B \longrightarrow$ excited D mesons

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15 years of discussion about $B \to D^{**}$: Why is it so important?

- System of $L = 1$ excitations D^{**}; two doublets ($\vec{j} = \vec{\ell} + \vec{s}_q$)

$$j^P = \left(\frac{1}{2}\right)^+ \; [0^+, 1^+_{1/2}] \text{ broad} \qquad j^P = \left(\frac{3}{2}\right)^+ \; [1^+_{3/2}, 2^+] \text{ narrow}$$

- $B \to D^{**}(0^+, 1^+_{1/2})\ell\nu$ – **exceptional case** where a huge discrepancy is found between theory and experiment. *One order of magnitude!!!*

- Theoretical statements formulated by quark models in 1997 have been maintained since and confirmed in other approaches.

- Continuous experimental effort has not resolved the discrepancy noted a long time ago, in the pioneering work of DELPHI. Currently,

$$\text{Theory}_{m_Q \to \infty} : \frac{BR_{SL}(1/2)}{BR_{SL}(3/2)} \simeq \frac{1}{10} \qquad \text{Exp.} : \frac{BR_{SL}(1/2)_{0^+}}{BR_{SL}(3/2)} \simeq 1$$

N.B. Belle observe $BR_{SL}(1^+_{1/2}) \ll BR_{SL}(0^+)$ – contradicts heavy quark symmetry

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- $m_Q \to \infty$ is a useful simplification
- Lattice QCD confirmed the previous quark model results
- Corrections $\propto 1/m_Q^n$ could not explain discrepancy between theory and experiment

Leibovich et al. 1997

Theoretical results: an explanation

$$\text{Theory}_{m_Q \to \infty} : \frac{BR_{SL}(1/2)}{BR_{SL}(3/2)} \simeq \frac{1}{10} \qquad \text{Exp.} : \frac{BR_{SL}(1/2)_{0^+}}{BR_{SL}(3/2)} \simeq 1$$

- spatial wave functions of $(1/2)^+$ and $(3/2)^+$ states are almost identical
- corresponding amplitudes, conventionally called $\tau_{1/2}(w)$ and $\tau_{3/2}(w)$, enter in

$$R = \frac{d\Gamma_{1/2}}{d\Gamma_{3/2}} = \frac{2}{(w+1)^2} \left(\frac{\tau_{1/2}(w)}{\tau_{3/2}(w)} \right)^2$$

- $R \ll 1$ because
  - the kinematical factor $\frac{2}{(w+1)^2} < 1$
  - $|\tau_{1/2}(w)|^2 \ll |\tau_{3/2}(w)|^2$
- $|\tau_{1/2}(w)|^2 \ll |\tau_{3/2}(w)|^2$ is well understood in relativistic quark models à la Bakamjian-Thomas and suggested by Uraltsev SR

Uraltsev, 2001

N.B *in non relativistic limit* $\tau_{1/2}(w) = \tau_{3/2}(w)$

Relativistic quark model à la Bakamjian-Thomas (BT) with Godfrey-Isgur w.f.

■ Covariance and Isgur-Wise scaling in the heavy quark limit
■ IW functions $\xi^{(n)}(w), \tau_{1/2}^{(n)}(w), \tau_{3/2}^{(n)}(w)$ automatically satisfy Bjorken, Uraltsev SR,... (explicit laboratory of the OPE)

◎ Fixed number of constituents; not a field theory.
But : *exact representations of the Poincaré group*.

◎ Complete separation between global variables ($\vec{P}$, $\vec{R}$, $\vec{S}$) and internal relative variables. Both types of variables commute

◎ Rest frame Hamiltonian (Mass Operator) depends on relative coordinates. W.f. at rest are eigenstates of the mass operator

◎ Unitary transformation: w.f. at rest → *Lorentz boost* (LB) ⟶ w.f. in motion; LB is independent on interaction and contains Wigner rotations

◎ Mass operator taken from the Godfrey-Isgur model (the best model for observed spectroscopy)

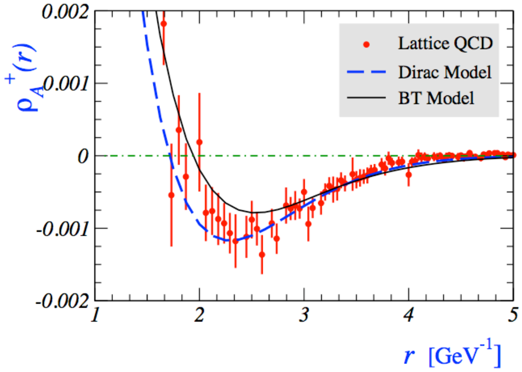
⇒ BT APPROACH DOES NOT INTRODUCE ANY EXTRA PARAMETER

Illustration of validity of the BT approach

- Using Godfrey-Isgur w.f., the BT approach reproduces remarkably well the lattice QCD results for radial distribution of various current densities in the $m_Q \to \infty$ limit

- Example of the density $\rho_A(r)$: $\langle B_1|\bar{u}\vec{\gamma}\gamma_5 d|B_0^*\rangle = \int_0^\infty \rho_A(r) d\vec{r}$

B_1, B_0^* being $(1/2)^+$-states



Orsay Group, 2011

Explanation why $\tau_{1/2}(w) \ll \tau_{3/2}(w)$ in BT approach

$$\tau_{3/2}(1) - \tau_{1/2}(1) = \frac{1}{2}\int_0^\infty dp\ p^2\ \phi_1(p)\frac{p}{p_0+m}\phi_0(p)$$

$w = 1$ corresponds to $q^2_{\rm max} = (m_B - m_{D^{**}})^2$, i.e. zero-recoil

- $\phi_{L=0,1}(p)$ are the (*positive*) radial wave functions; no nodes
- for simplicity $\phi_1(p)$ is same for all four states
- $\frac{p}{p_0+m}$ comes from the Wigner rotation of the light quark, which acts differently on $(1/2)^+$ and $(3/2)^+$ states — Morenas et al. 1997
- $\tau_{3/2}(1) - \tau_{1/2}(1)$ is *positive* and *large* for relativistic internal quark velocities, $\mathcal{O}(v/c)$

N.B. *in the non-relativistic limit,* $\tau_{3/2}(1) - \tau_{1/2}(1) = 0$

Results for IW functions in the BT model

Morenas et al. 1997

- Elastic IW function $\overline{B} \to D^{(*)}$ $\quad \xi(w) = \left(\frac{2}{w+1}\right)^{2\rho^2} \quad \rho^2 = 1.02$

- Inelastic IW functions $\overline{B} \to D^{**}$

$$\tau_{1/2}(w) = \tau_{1/2}(1)\left(\frac{2}{w+1}\right)^{2\sigma^2_{1/2}} \qquad \tau_{1/2}(1) = 0.22 \qquad \sigma^2_{1/2} = 0.83$$

$$\tau_{3/2}(w) = \tau_{3/2}(1)\left(\frac{2}{w+1}\right)^{2\sigma^2_{3/2}} \qquad \tau_{3/2}(1) = 0.54 \qquad \sigma^2_{3/2} = 1.50$$

Lattice QCD, static

$\tau(1)$'s calculable through operators with derivatives, at $v = (1,0,0,0)$:

$$\langle 0^+|\bar{h}_v \gamma^i \gamma_5 D^j h_v|0^-\rangle \propto \tau_{1/2}(1)$$
$$\langle 2^+|\bar{h}_v (\gamma D)^{\{ij\}} \gamma_5 h_v|0^-\rangle \propto \tau_{3/2}(1)$$

- *Quenched QCD* $m_q \sim m_s$, static b and c

Becirevic et al. (2005), Blossier et al. (2005)

$$\tau_{1/2}(1) \sim 0.3 - 0.4 \qquad \tau_{3/2}(1) \sim 0.5 - 0.6$$

- *Unquenched QCD* $m_s/6 \lesssim m_q \lesssim m_s$, static b and c

Blossier et al. (2009)

$$\tau_{1/2}(1) = 0.29 \pm 0.03 \qquad \tau_{3/2}(1) = 0.52 \pm 0.03$$

✓ Results agree with BT [$\tau_{1/2}(1) = 0.22$, $\tau_{3/2}(1) = 0.54$]
× Desired: inclusion of the propagating c quark and $w \neq 1$

[expansion in $1/m_c$ unreliable]

Phenomenology of the BT model: 1) semileptonic rates

Disregarding $1/m_Q$ effects, there follow predictions for SL decays. Small numbers are herefrom marked in red (1/10 with respect to dominant BR)

$L=0$ $\quad BR(\overline{B}\to D\ell\overline{\nu})=1.95\cdot 10^{-2}, \quad BR(\overline{B}\to D^{*}\ell\overline{\nu})=5.90\cdot 10^{-2}$

$L=1$ $\quad BR(\overline{B}\to D_0^{1/2}\ell\overline{\nu})=0.6\cdot 10^{-3}, \quad BR(\overline{B}\to D_1^{1/2}\ell\overline{\nu})=0.7\cdot 10^{-3}$

$\quad BR(\overline{B}\to D_1^{3/2}\ell\overline{\nu})=0.45\cdot 10^{-2}, \quad BR(\overline{B}\to D_2^{3/2}\ell\overline{\nu})=0.7\cdot 10^{-2}$

- Ground state: BR and $\xi(w)$ agree very well with experiment
- $L=1$ states: strong disagreement with experiment for $j=1/2$ states

N.B.: In **non-leptonic decays**, assuming factorisation, theory and experiment agree also for $L=1$ states!! (see below)

$m_Q \to \infty$ approximation

- Limit $m_Q \to \infty$ is useful

A number of advantageous properties: heavy quark symmetry (HQS), Sum Rules, *covariance* of matrix elements in the BT approach...
"Economical" (=cheap) for the lattice [Wilson lines for heavy quarks]

- $1/m_Q$ corrections seem moderate in BR

especially when one sums over the members of a j-doublet;
cannot explain discrepancies of one order of magnitude claimed in semileptonic decays.

$1/m_Q$ corrections are not large for $B \to D^{(*)}$ [lattice QCD and models]
$1/m_Q$ corrections for $B \to D^{**}$: model calculation (BT) in progress (covariance lost!)
$1/m_Q$ corrections for $B \to D^{**}$: lattice calculation in progress (c.f. talk by Morenas)

Semileptonic data: Experiment versus Theory

Decay mode	BELLE	BABAR	BT model
$BR_{SL}(\overline{B} \to D_0^{1/2})$	$(0.36 \pm 0.09)\ 10^{-2}$	$(0.42 \pm 0.09)\ 10^{-2}$	$0.6 \cdot 10^{-3}$
$BR_{SL}(\overline{B} \to D_1^{1/2})$	$< 1.05 \cdot 10^{-3}$	$(0.40 \pm 0.06)\ 10^{-2}$	$0.7 \cdot 10^{-3}$
$BR_{SL}(\overline{B} \to D_1^{3/2})$	$(0.93 \pm 0.22)\ 10^{-2}$	$(0.64 \pm 0.15)\ 10^{-2}$	$0.45 \cdot 10^{-2}$
$BR_{SL}(\overline{B} \to D_2^{3/2})$	$(0.54 \pm 0.12)\ 10^{-2}$	$(0.39 \pm 0.1)\ 10^{-2}$	$0.7 \cdot 10^{-2}$

BR from charged B; 2^+ from $D\pi$ channel

- Experiments disagree on $BR_{SL}(\overline{B} \to D^{**})$ [c.f. $BR_{SL}(\overline{B} \to D_1^{1/2})$]

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- $j = 3/2$ in agreement with theory when both modes are summed

Reversed hierarchy of separate modes is due to $1/m_Q$-corrections   Leibovich et al. 1997

- $j = 1/2$ **completely at odds with theory**

  BaBar problem $\longrightarrow |\tau_{1/2}|^2 \simeq |\tau_{3/2}|^2$ Vs. theory $|\tau_{1/2}|^2 \ll |\tau_{3/2}|^2$

  Belle problem $\longrightarrow$ in conflict with HQS in $j = 1/2$

$\Rightarrow$ **"1/2 semileptonic puzzle"**

Since the pioneering work of DELPHI, the puzzle remains as puzzling as ever.

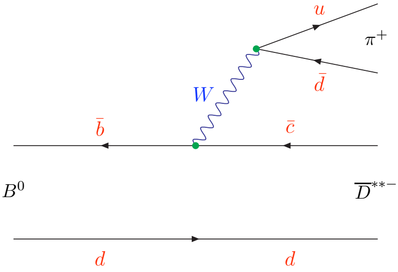
Phenomenology: 2) Importance of non-leptonic decays to elucidate the problem

- puzzling situation in semileptonic decays
  $\Rightarrow$ non-leptonic B-decays might help ✓ Jugeau et al 2005
- $BR(B \to D^{**}\pi)$ have been measured by BaBar and Belle ✓
- $BR(B \to D^{**}\pi)$ are much lower than $BR(B \to D^{**}\ell\nu)$ $\times$
  detection efficiency is however much better ✓
  $\Leftrightarrow$ much more observed $B \to D^{**}\pi$ events ✓

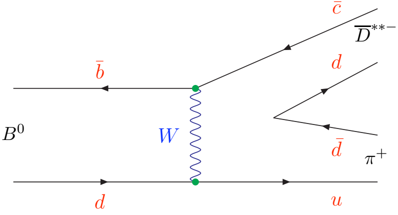
Several Thousands of observed $B \to D^{**}\pi$ events
Vs. Several Hundreds of $BR(B \to D^{**}\ell\nu)$ events

- BR's predictable within the factorization approximation Neubert 1998

Class I non-leptonic decays



Class I (a)

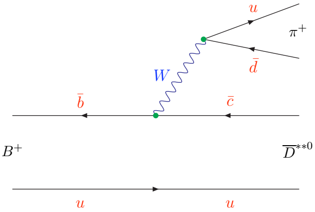


Class I (b)

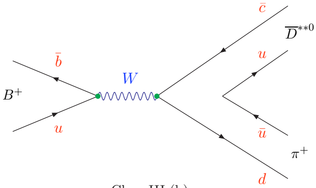
Pion emission: "$B \to D^{**}$" $\times$ f_π

B Annihilation

Class III non-leptonic decays



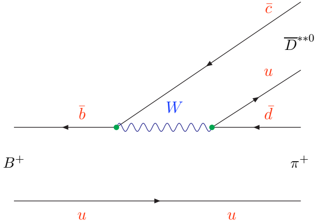
Class III (a)



Class III (b)

Pion emission: "$B \to D^{**}$" $\times$ f_π

B Annihilation



Class III (c)

D^{**} emission: "$B \to \pi$" $\times f_{D^{**}}$

Nonleptonic data

Decay channel	Class I decays (π emission)	Class III ($\pi + D^{**}$ emission)
$\overline{D}_0\pi^+$	$(1.0 \pm 0.5) \times 10^{-4}$	$(0.96 \pm 0.27) \times 10^{-3}$
$\overline{D}_1^{1/2}\pi^+$	$< 1 \times 10^{-4}$	$(0.75 \pm 0.17) \times 10^{-3}$
$\overline{D}_1^{3/2}\pi^+$	$(0.82^{+0.25}_{-0.17}) \times 10^{-3}$	$(1.51 \pm 0.34) \times 10^{-3}$
$\overline{D}_2\pi^+$	$(0.49 \pm 0.07) \times 10^{-3}$	$(0.82 \pm 0.11) \times 10^{-3}$

- All entries are of order 10^{-3} except the red ones that are $\mathcal{O}(10^{-4})$
- A striking difference in Class I:

  $\sim 10^{-4}$ for $j = 1/2$ and $\sim 10^{-3}$ for $j = 3/2$ (a factor $1/10$)

  In Class III all j are of the same order $\sim 10^{-3}$ [Why is that so?!!]

Class I decays: Theory/Experiment

▶ Using the factorisation and the form factors computed at $q^2 \simeq 0$ with BT model ($m_Q \to \infty$) one obtains

$$\overline{B} \to D_0^{1/2}\pi : \quad 1.3 \cdot 10^{-4} \qquad \overline{B} \to D_1^{1/2}\pi : \quad 1.1 \cdot 10^{-4}$$

$$\overline{B} \to D_1^{3/2}\pi : \quad 1.3 \cdot 10^{-3} \qquad \overline{B} \to D_2^{3/2}\pi : \quad 1.1 \cdot 10^{-3}$$

$$\Longrightarrow \frac{\text{“}j = 1/2\text{”}}{\text{“}j = 3/2\text{”}} = \frac{1}{10} \text{ in agreement with experiment } [\mathcal{O}(1/10)]$$

Striking agreement between experiment and theory!

N.B. Observed difference between $B(\overline{B} \to D_1^{3/2}\pi)$ and $B(\overline{B} \to D_2^{3/2}\pi)$ is due to $1/m_Q$ corrections.

Class III decays: Theory/Experiment

- Great difference between class III and class I experimental results
  - $j = \frac{3}{2}$ rates are similar in size [class I & class III are $\mathcal{O}(10^{-3})$]
  - $j = \frac{1}{2}$ rates differ in size ["class III" $\gg$ "class I"]
    Class III $j = 1/2$ is as large as $j = 3/2$ [$\mathcal{O}(10^{-3})$]

- Easily explained: In class III, there is an extra D^{**}-emission diagram which is suppressed for $j = 3/2$, but not for $j = 1/2$ (HQS).
  $\Longrightarrow$ the hierarchy of class I [$BR_{NL}(1/2) \ll BR_{NL}(3/2)$] completely disappear in class III.

Surprisingly, in contrast to the semileptonic data
there is a complete theoretical understanding of the NL ones.

Conclusions and Proposal

- Theoretical predictions at $m_Q \to \infty$ seem robust; $1/m_Q$ corrections could not change the order of magnitude of the decay rates
- Non-leptonic data confirm the theoretical expectations
- Main problem: semileptonic decays and concerns only $B \to D_{1/2}$ decays; Decay to narrow $B \to D_{3/2}$ are OK
- Semileptonic decays $B \to D_{1/2}$: experimental results are incompatible among themselves and with theory
  - *Several experimental data are at odds with dynamical QCD predictions*
  - *One even violates the HQS within the multiplet*
- Radial excitations cannot change the predicted rates into $D_{1/2}$

Conclusions and Proposal (contd.)

- Possible origin of the problem: misinterpretation of broad resonances ($\Gamma \simeq 300$ MeV) due to difficulties in the empirical separation of the resonance from the continuum, especially with the lack of the partial wave analysis
  - *No safe theory of continuum; Similar difficulties are well known for baryons for which the experimental conditions are much more favorable*
- Problem of dealing with broad resonances is also present in non-leptonic modes but it is less serious because there are much more observed events than in the SL decays
- To test the above explanation in an optimal situation one can study the transitions $B_s \to D_{s0}$, where D_{s0} is $j = 1/2$-state but it is narrow!

TRANSPARENTS DE RESERVE

Inelastic transitions $D^{(*)}\left(\frac{1}{2}^-\right) \to D^{**}\left(\frac{1}{2}^+\right)$: theoretical constraints

Sum rules from QCD in the heavy quark limit $(\epsilon_n = m_{D^{(n)}} - m_D)$

$$\sum_n |\tau_{3/2}^{(n)}(1)|^2 - \sum_m |\tau_{1/2}^{(m)}(1)|^2 = \frac{1}{4}$$

$$2\sum_n \epsilon_n^2 |\tau_{3/2}^{(n)}(1)|^2 + \sum_m \epsilon_m^2 |\tau_{1/2}^{(m)}(1)|^2 = \frac{1}{3}\mu_\pi^2$$

$$2\sum_n \epsilon_n^2 |\tau_{3/2}^{(n)}(1)|^2 - 2\sum_m \epsilon_m^2 |\tau_{1/2}^{(m)}(1)|^2 = \frac{1}{3}\mu_G^2$$

$$B^* - B \text{ splitting} \quad \to \quad \mu_G^2(1\ \text{GeV}) = (0.35 \pm 0.03)\ \text{GeV}^2$$

$$\text{Inclusive moments} \quad \overline{B} \to X_c \ell \overline{\nu} \quad \to \quad \mu_\pi^2(1\ \text{GeV}) = (0.40 \pm 0.04)\ \text{GeV}^2$$

$$\mu_\pi^2 - \mu_G^2 = 9\sum_m \epsilon_m^2 |\tau_{1/2}^{(m)}(1)|^2 \quad \to \quad \underline{\epsilon_0^2 |\tau_{1/2}^{(0)}(1)|^2 \leq \frac{1}{9}[\mu_\pi^2 - \mu_G^2]}$$

Naturally one expects

$$\epsilon_{1/2}(1) \sim (300 - 500)\ \text{MeV} \qquad \left|\tau_{1/2}^{(0)}(1)\right| \lesssim 0.15 - 0.25$$

The question of radial excitations

Two new states observed at BABAR (2010) in $D^{(*)}\pi$ can be interpreted as a doublet $\frac{1}{2}^-$ of radial excitation $n = 1$:
D'(0^-)(2.54) ($\Gamma = 130 MeV$) D'*(1^-)(2.61) ($\Gamma = 90 MeV$)

For the elastic IW function $\xi_{(n=0)}(1) = 1$
In the inelastic case $\overline{B} \to D^{(n=1)}\ell\overline{\nu}$ $\xi_{(n=0\to n=1)}(1) = 0$
$\to$ then there is of course a well known suppression of $BR(\overline{B} \to D^{(n=1)}\ell\overline{\nu})$ in the heavy quark limit
But in addition,in the BT model, one finds a **much smaller value** of $\xi_{(n=0\to n=1)}$ than Galkin et al. . This conclusion is not spoiled with finite masses. The first radial excitation contribution is negligible. (Proposal). Also found with other w.f., although less pronounced.

(According to Galkin et al. quark model : $BR(\overline{B} \to D'^{(*)}\ell\overline{\nu}) \sim 0.4\%$, finite mass effects small : 30%)

BELLE (2007)

Notation $BR(\overline{B} \to D^{**})_{part} = BR(\overline{B} \to D^{**}\ell\nu) \times \mathrm{BR}(\mathrm{D}^{**} \to D^{(*)}\pi^+)$

$D\pi$ modes

$BR(B^- \to D_0^{1/2\,0})_{part} = (0.24 \pm 0.06)\%$ $BR(\overline{B}_d \to D_0^{1/2\,+})_{part} = (0.20 \pm 0.08)\%$

$BR(B^- \to D_2^{3/2\,0})_{part} = (0.22 \pm 0.05)\%$ $BR(\overline{B}_d \to D_2^{3/2\,+})_{part} = (0.22 \pm 0.05)\%$

$D^*\pi$ modes

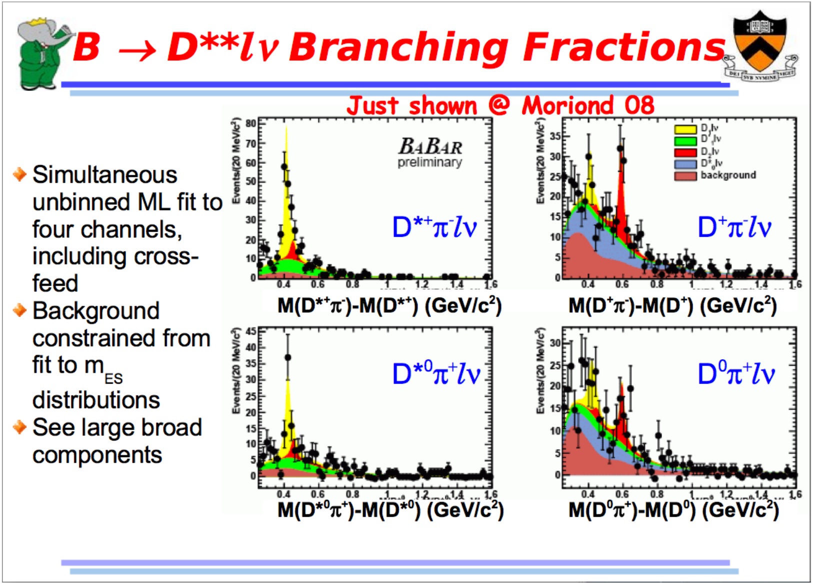
$BR(B^- \to D_1^{1/2\,0})_{part} <$ 0.07 (90% C.L.) $BR(\overline{B}_d \to D_1^{1/2\,+})_{part} < 0.5$ (90% C.L.)

$BR(B^- \to D_1^{3/2\,0})_{part} = (0.42 \pm 0.10)\%$ $BR(\overline{B}_d \to D_1^{3/2\,+})_{part} = (0.54 \pm 0.21)\%$

$BR(B^- \to D_2^{3/2\,0})_{part} = (0.18 \pm 0.07)\%$ $BR(\overline{B}_d \to D_2^{3/2\,+})_{part} < 0.3$ (90% C.L.)

$\Rightarrow$ N.B. strong violation of HQS in $j = 1/2$

BABAR (2008)


B → D**lν Branching Fractions
Just shown @ Moriond 08
Simultaneous unbinned ML fit to four channels, including cross-feed
Background constrained from fit to m_ES distributions
See large broad components
BABAR preliminary
D*+π-lν
D+π-lν
D*0π+lν
D0π+lν
background
Events/(20 MeV/c²)
M(D*+π-)-M(D*+) (GeV/c²)
M(D+π-)-M(D+) (GeV/c²)
M(D*0π+)-M(D*0) (GeV/c²)
M(D0π+)-M(D0) (GeV/c²)