$B \to D^{**}\, \ell\, \bar{\nu}_\ell$: An experimental overview

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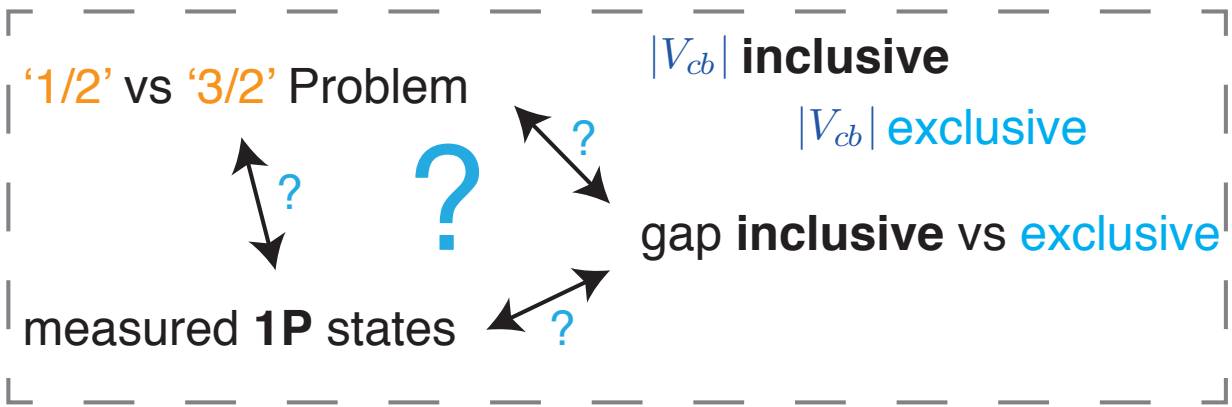
Waypoints:

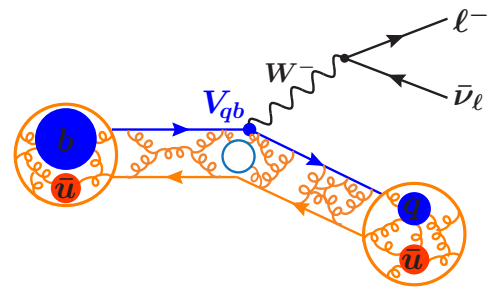
* Introduction What modes are covered by our $B \to D^{**}\, \ell\, \bar{\nu}_\ell$ measurements
* Recap of essential experimental methods: **Tagging and $m^2_{\mathbf{miss}}$**
* Relevant measurements:
  - Tagged $B \to D^{(*)}\, \pi\, \ell\bar{\nu}_\ell$ measurements: arXiv:0712.3503v1 & arXiv:0711.3252
  - Tagged $B \to D^{**}_{\hookrightarrow D^{(*)}\pi}\, \ell\bar{\nu}_\ell$ measurements: arXiv:0808.0528v1 & arXiv:0711.3252
  - Tagged $B \to D^{(*)}\, X\, \ell\bar{\nu}_\ell$ measurements: Preliminary *Belle*
  - World averages from HFAG arXiv:1207.1158v1
    * Tensions between broad state measurements
    * Experimental limits on non-resonant GR-type decays
    * Semi-inclusive $B \to D^{(*)}\, X\, \ell\bar{\nu}_\ell$ v exclusive $B \to D^{**}_{\hookrightarrow D^{(*)}\pi}\, \ell\bar{\nu}_\ell$
    * Putting everything together: 'Gap' inclusive v exclusive
* ? Neglected channels: $D^{**} \to D^{(*)}\pi\pi$ & $D^{**} \to D^{(*)}\eta$
* Summary and my conclusions

i. Introduction



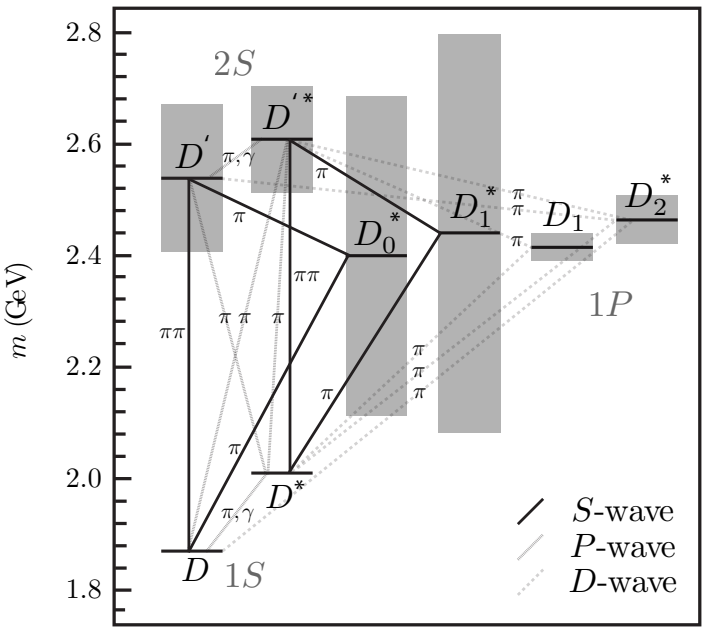
$\Leftrightarrow$ What modes are covered by our $B \to D^{**}\,\ell\,\bar{\nu}_\ell$ measurements?

* Three kinds of measurements:
  - $\to$ Semi-inclusive measurements of $D^{**} \to D^{(*)}\pi$
  - $\to$ Exclusive measurements of $m_{D^{(*)}\pi}$ with resonances which are assigned to $1P$
  - $\to$ Semi-inclusive measurements of $D^{**} \to D^{(*)}X$ and sum over all resonances



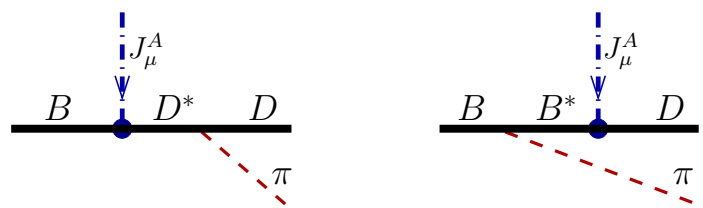
Leading order Weak $b \to q$ diagram

i Expected Quark Model $(c\bar{q})$ states:



Notation used in talk:

* $D^{**}(1P)$, $D^{**}(2S)$, $D^{**}(1D)$, ...
* Continuum/Non-resonant decays $\mathcal{B}^{\mathrm{NR}}(B \to D^{(*)}\,\pi\,\ell\,\bar{\nu}_\ell)$



Diagrams contributing to continuum $B \to D\pi$

ii Continuum (or non-resonant) contributions see e.g. [JHEP 1210 (2012) 169]

* Exclusive branching fractions assigned to $B \to D^{**}_{\hookrightarrow D^{(*)}\pi}(1P)\,\ell\bar{\nu}_\ell$

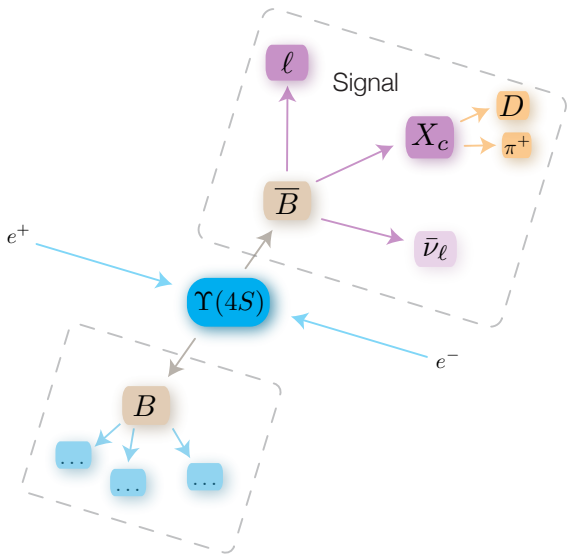
ii. Experimental methods

* **Tagging** at the B Factories:

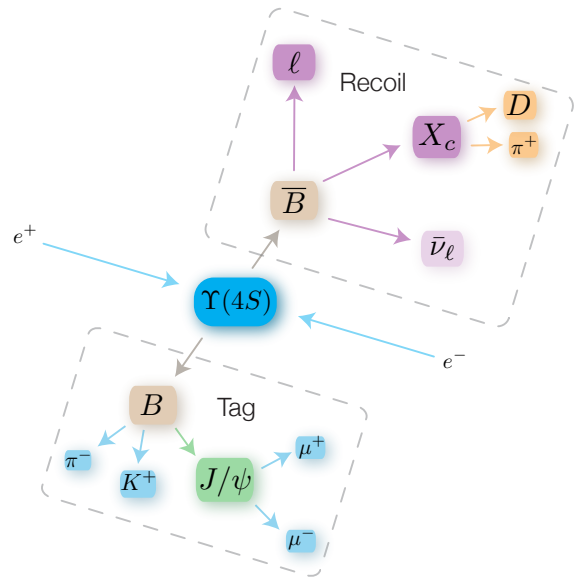
Hadronic B tagging: Reconstruct one B meson and look at rest of the event

→ Expect only particles from signal

Untagged



Tagged



Signal side characteristics:

→ Decay with missing momentum due to neutrino in final state:

$$\mathbf{m}^2_{\text{miss}} = \left(p_{\Upsilon(4S)} - p_{B\text{tag}} - p_{D^{**}} - p_\ell\right)^2 \quad \widehat{=} \quad m^2_\nu$$

* For true $B \to D^{**}\,\ell\,\bar{\nu}_\ell$ decays this should peak at 0; for sl with a true D missing particles tend to push distribution to positive values, randomly assigned to either positive or negative values.

* Two dominant sources of background: **combinatorial** B and **continuum**

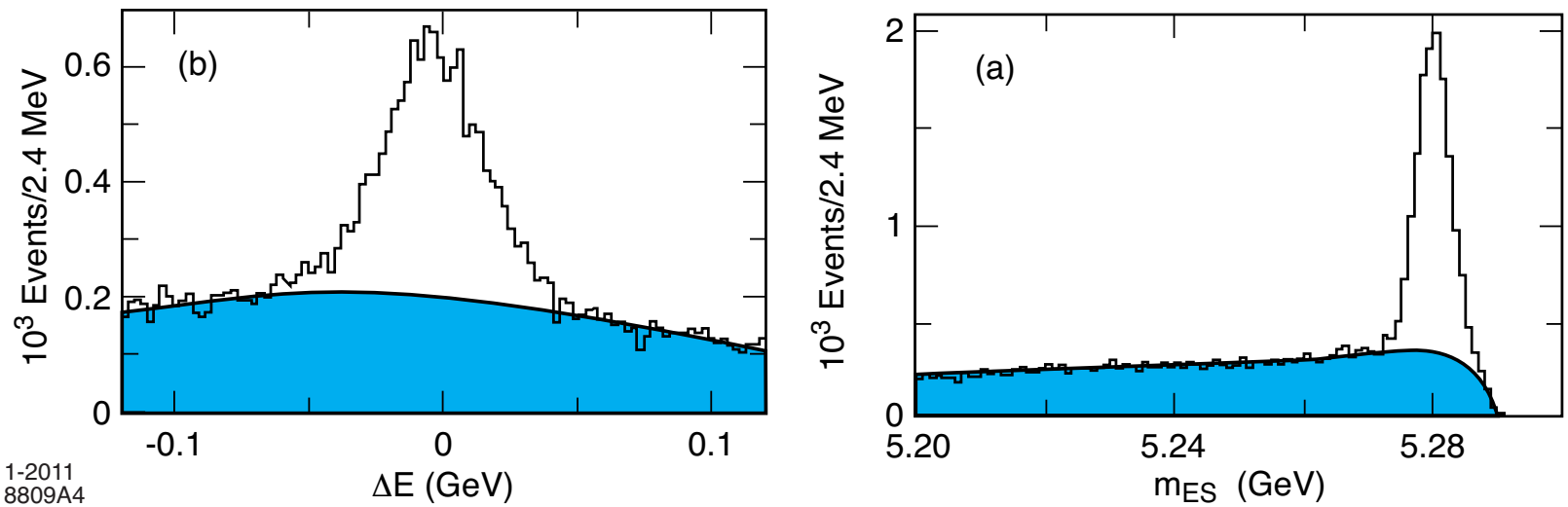
  → B meson Production at B Factories through well defined initial state: $e^+e^- \to \Upsilon(4S) \to b\bar{b}$
  ⇔ charge and momentum correlation of final states completely determined.

* Energy difference $\mathbf{\Delta}E$ and beam constrained mass $\mathbf{m}_{bc/ES}$:

$$\mathbf{\Delta}E = E_{B^{\text{tag}}} - E_{\text{beam}} \qquad \mathbf{m}_{bc/ES} = \sqrt{E^2_{\text{beam}} - \mathbf{p}^2_{\mathbf{B}^{\text{tag}}}}$$

$E_{\text{beam}} = \sqrt{s}/2 \backsim 5.29 GeV$

Correctly reconstructed B^{tag} should have $\Delta E \approx 0$ and $m_{bc/ES} \approx m_B$



Blue combinatorial and continuum background; white hadronic B decays (both simulated)

iii.a Semi-inclusive $B \to D^{(*)}\,\pi\,\ell\bar{\nu}_\ell$

Semi-inclusive $B \to D^{(*)}\,\pi\,\ell\bar{\nu}_\ell$ measurements: *BABAR*

Phys.Rev.Lett. 100 (2008) 151802; arXiv:0712.3503v1

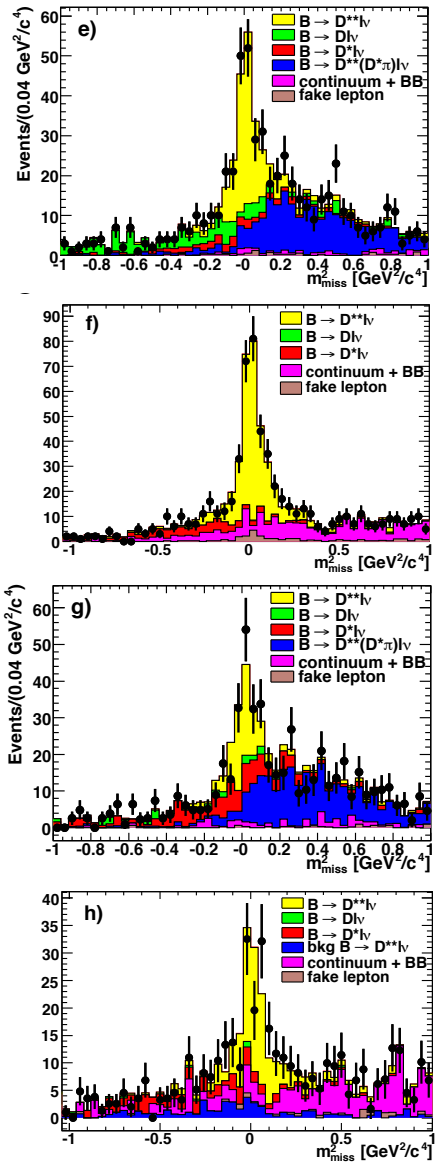
* **Tagged measurement:** 80% of *BABAR* dataset (341.1/fb)
  * Hadronic tag: $B^{\rm tag} \to DY$ with "$K\&\pi \in Y$"
    $\approx \mathcal{O}(1000)$ decay modes
  - $5.27\text{GeV}/c^2 < \mathbf{m}_{ES} < 5.29\text{GeV}/c^2$ & $B^{\rm tag}$ w. smallest $\mathbf{\Delta}E$
  * Signal/recoil side: lepton with $p_l^* \geq 0.6\,\text{GeV}/c$;
    reconstruct D and D^* candidates from K and π

    Further requirements:
    $m_{D\pi} - m_D > 0.18\ \text{GeV}/c^2$ to veto $B \to D^*\,\ell\,\bar{\nu}_\ell$ events.
    Total energy not assigned to $B^{\rm tag}$ or signal side less than 1 GeV.

* **Events analyzed in fit to $\mathbf{m}^2_{\rm miss} = m^2_\nu$:** (PDFs from MC)
  → e) $B^- \to D^+\pi^-\,\ell\,\bar{\nu}_\ell$
  f) $B^- \to D^{*\,+}\pi^-\,\ell\,\bar{\nu}_\ell$
  g) $\bar{B}^0 \to D^0\pi^+\,\ell\,\bar{\nu}_\ell$
  h) $\bar{B}^0 \to D^{*\,0}\pi^-\,\ell\,\bar{\nu}_\ell$
  → Yellow: Signal
  Green/Red: Background from $B \to D^{(*)}\,\ell\,\bar{\nu}_\ell$
  Blue: Down feed from $B \to D^*\,\pi\,\ell\,\bar{\nu}_\ell$
  Magenta: continuum

* **Signal BF extracted with normalization channel**
  ($B \to X\,\ell\,\bar{\nu}_\ell$, to cancel tagging systematics)

[%]	
$B^+ \to D^-\pi^+\,\ell^+\,\nu_\ell$	$0.42 \pm 0.06 \pm 0.03$
$B^+ \to D^{*\,-}\pi^+\,\ell^+\,\nu_\ell$	$0.59 \pm 0.05 \pm 0.04$
$B^0 \to \bar{D}^0\pi^-\,\ell^+\,\nu_\ell$	$0.43 \pm 0.08 \pm 0.03$
$B^0 \to \bar{D}^{*\,0}\pi^-\,\ell^+\,\nu_\ell$	$0.48 \pm 0.08 \pm 0.04$



Semi-inclusive $B \to D^{(*)}\,\pi\,\ell\bar{\nu}_\ell$ measurements: *Belle*

Phys.Rev. D77 (2008) 091503; arXiv:0711.3252

* **Tagged measurement:** 85% of *Belle* dataset (605/fb)
  * Hadronic tag: $B^{\text{tag}} \to DY$ with "$\pi \in Y$"
  - $\mathbf{m}_{ES} > 5.27\text{GeV}/c^2$ and $|\mathbf{\Delta}E| < 40$ MeV
  * Signal/recoil side: lepton with $p_l^* \geq 1.0\,\text{GeV}/c$; reconstruct D and D^* candidates from K and π

* **Events analyzed in fit to $\mathbf{m}^2_{\text{miss}} = m^2_\nu$:**

  Continuum and $B\bar{B}$ Background subtracted from data using ΔE and $m_{D^{(*)}}$ sidebands. Down feed from simulation.

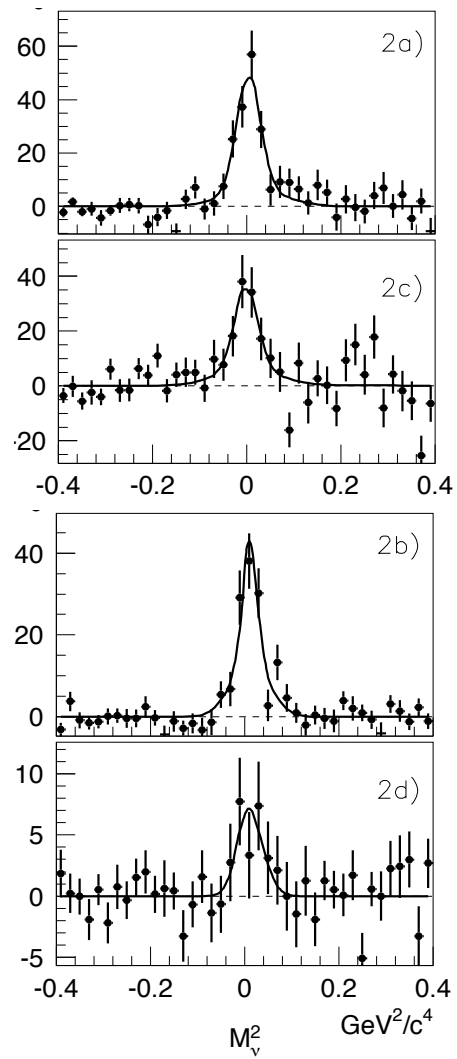
  → 2a) $B^- \to D^+\pi^-\,\ell\,\bar{\nu}_\ell$
  2c) $\bar{B}^0 \to D^0\pi^+\,\ell\,\bar{\nu}_\ell$
  2b) $B^- \to D^{*\,+}\pi^-\,\ell\,\bar{\nu}_\ell$
  2d) $\bar{B}^0 \to D^{*\,0}\pi^-\,\ell\,\bar{\nu}_\ell$

  → Fit function: relativistic Breit-Wigner.

* **Signal BF extracted with normalization channel**

  ($B \to D\,\ell\,\bar{\nu}_\ell$, to cancel tagging systematics)

[%]	
$B^+ \to D^-\pi^+\,\ell^+\,\nu_\ell$	$0.40 \pm 0.04 \pm 0.06$
$B^+ \to D^{*\,-}\pi^+\,\ell^+\,\nu_\ell$	$0.65 \pm 0.08 \pm 0.09$
$B^0 \to \bar{D}^0\pi^-\,\ell^+\,\nu_\ell$	$0.42 \pm 0.07 \pm 0.06$
$B^0 \to \bar{D}^{*\,0}\pi^-\,\ell^+\,\nu_\ell$	$0.56 \pm 0.21 \pm 0.08$



arXiv:1207.1158v1

* *BABAR* and *Belle* are in good agreement:

[%]	*BABAR*
$B^+ \to D^- \pi^+ \ell^+ \nu_\ell$	$0.42 \pm 0.06 \pm 0.03$
$B^+ \to D^{*-} \pi^+ \ell^+ \nu_\ell$	$0.59 \pm 0.05 \pm 0.04$
$B^0 \to \bar{D}^0 \pi^- \ell^+ \nu_\ell$	$0.43 \pm 0.08 \pm 0.03$
$B^0 \to \bar{D}^{*0} \pi^- \ell^+ \nu_\ell$	$0.48 \pm 0.08 \pm 0.04$

[%]	*Belle*
$B^+ \to D^- \pi^+ \ell^+ \nu_\ell$	$0.40 \pm 0.04 \pm 0.06$
$B^+ \to D^{*-} \pi^+ \ell^+ \nu_\ell$	$0.65 \pm 0.08 \pm 0.09$
$B^0 \to \bar{D}^0 \pi^- \ell^+ \nu_\ell$	$0.42 \pm 0.07 \pm 0.06$
$B^0 \to \bar{D}^{*0} \pi^- \ell^+ \nu_\ell$	$0.56 \pm 0.21 \pm 0.08$

* HFAG averages for Branching Fractions:

(Private average $\widehat{=}$ isospin average of both modes with $\tau_{+0} = 1.079 \pm 0.007$)

[%]	HFAG	Private average
$B^+ \to D^- \pi^+ \ell^+ \nu_\ell$	0.42 ± 0.05	0.44 ± 0.05
$B^+ \to D^{*-} \pi^+ \ell^+ \nu_\ell$	0.61 ± 0.05	0.58 ± 0.06
$B^+ \to D\pi \ell^+ \nu_\ell$	0.63 ± 0.08	0.66 ± 0.08
$B^+ \to D^*\pi \ell^+ \nu_\ell$	0.92 ± 0.08	0.87 ± 0.09
$B^+ \to D^{(*)}\pi \ell^+ \nu_\ell$	1.55 ± 0.11	$\mathbf{1.53 \pm 0.12}$

[%]	HFAG	Private average
$\bar{B}^0 \to D^0 \pi^+ \ell^- \bar{\nu}_\ell$	0.43 ± 0.06	0.41 ± 0.05
$\bar{B}^0 \to D^{*0} \pi^+ \ell^- \bar{\nu}_\ell$	0.49 ± 0.08	0.54 ± 0.06
$\bar{B}^0 \to D \pi \ell^- \bar{\nu}_\ell$	0.65 ± 0.09	0.61 ± 0.09
$\bar{B}^0 \to D^* \pi \ell^- \bar{\nu}_\ell$	0.74 ± 0.12	0.80 ± 0.09
$\bar{B}^0 \to D^{(*)} \pi \ell^- \bar{\nu}_\ell$	1.38 ± 0.15	$\mathbf{1.42 \pm 0.12}$

The isospin factor applied to $B^+ \to \bar{D}^{(*)-} \pi^+ \ell^+ \nu_\ell$ or $\bar{B}^0 \to D^{(*)0} \pi^+ \ell^- \bar{\nu}_\ell$ is $\frac{3}{2}$. For isospin average assumed a 100% correlation on the uncertainties between isospin conjugated channels.

iii.b Exclusive $B \to D^{**}_{\hookrightarrow D^{(*)}\pi}\, \ell\bar{\nu}_\ell$

Exclusive $B \to D^{**}_{\hookrightarrow D^{(*)}\pi}\,\ell\bar{\nu}_\ell$ measurements: *BABAR*

Phys.Rev.Lett. 101 (2008) 261802; arXiv:0808.0528v1

* **Tagged measurement:** 97% of *BABAR* dataset (417/fb)
  * Hadronic tag: $B^{tag} \to DY$ with "$K\&\pi \in Y$"
    $\approx \mathcal{O}(1000)$ decay modes
  - $5.27\text{GeV}/c^2 < \mathbf{m}_{ES} < 5.29\text{GeV}/c^2$ & B^{tag} w. highest Purity
  * Signal/recoil side: lepton with $p^*_l \geq 0.6\,\text{GeV}/c$;
    reconstruct D and D^* candidates from K and π

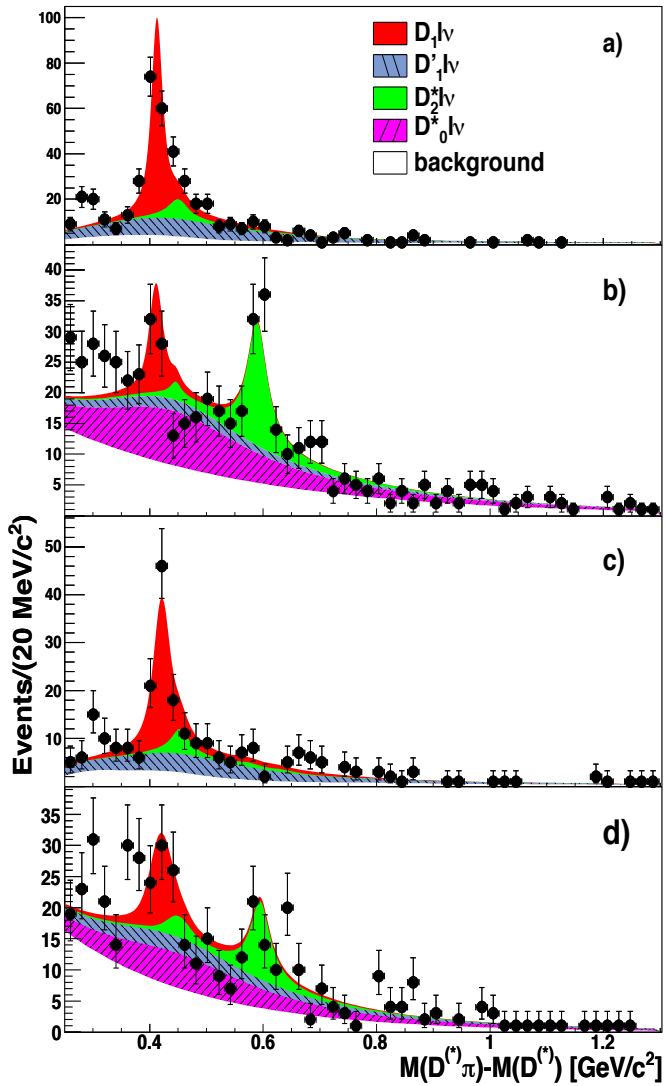
    Further requirements:
    $m_{D\pi} - m_D > 0.18\ \text{GeV}/c^2$ to veto $B \to D^*\,\ell\,\bar{\nu}_\ell$ events.

* **Analyze $m_{D^{(*)}\pi} - m_{D^{(*)}}$ in windows of $\mathbf{m}^2_{\text{miss}}$**
  - Variable cut on $|\mathbf{m}^2_{\text{miss}}|$; relative broad window for $D\pi$
  - Signal (Breit-Wigner * Gaussian), resolution from MC.
  - Bkg PDFs (KEYS or Exponential * Gaussian) from MC.
  - $D^*\pi \to D\pi$ down feed fixed and from MC.
  → a) $B^- \to D^{*+}\pi^-\,\ell\,\bar{\nu}_\ell$ b) $B^- \to D^+\pi^-\,\ell\,\bar{\nu}_\ell$
    c) $\bar{B}^0 \to D^{*0}\pi^+\,\ell\,\bar{\nu}_\ell$ d) $\bar{B}^0 \to D^0\pi^-\,\ell\,\bar{\nu}_\ell$

  → Red: $B \to D_1\,\ell\,\bar{\nu}_\ell$ Green: $B \to D_2\,\ell\,\bar{\nu}_\ell$
    Purble: $B \to D'_1\,\ell\,\bar{\nu}_\ell$ Magenta: $B \to D_0\,\ell\,\bar{\nu}_\ell$

* **Fit results:** isospin scaled HFAG numbers; $f_{D_2} = 1.56 \pm 0.16$

[%]	$D^{**} \to D^{(*)}\pi$
$B^+ \to \bar{D}^0_1\,\ell^+\,\nu_\ell$	$0.42 \pm 0.05 \pm 0.05$
$B^+ \to \bar{D}^{*0}_2\,\ell^+\,\nu_\ell$	$0.26 \pm 0.03 \pm 0.06$
$B^+ \to \bar{D}'^0_1\,\ell^+\,\nu_\ell$	$0.41 \pm 0.06 \pm 0.06$
$B^+ \to \bar{D}^0_0\,\ell^+\,\nu_\ell$	$0.48 \pm 0.06 \pm 0.08$



Exclusive $B \to D^{**}_{\hookrightarrow D^{(*)}\pi}\, \ell\bar{\nu}_\ell$ measurements: *Belle*

Phys.Rev. D77 (2008) 091503; arXiv:0711.3252

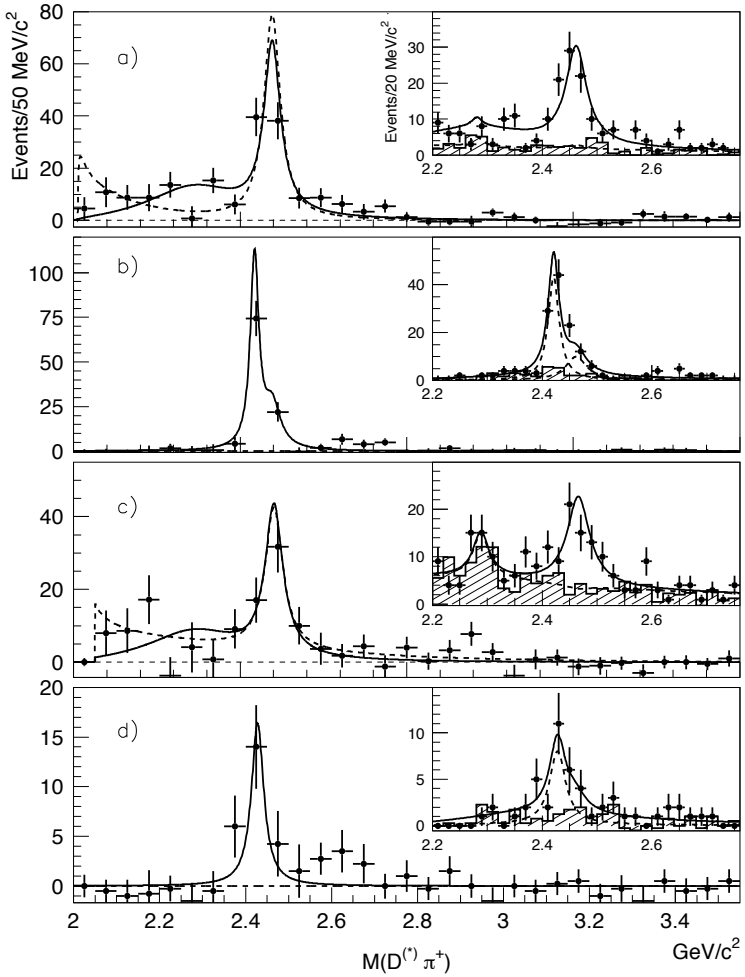
* **Tagged measurement:** 85% of *Belle* dataset (605/fb)
  * Hadronic tag: $B^{tag} \to DY$ with "$\pi \in Y$"
  - $\mathbf{m}_{ES} > 5.27\text{GeV}/c^2$ and $|\mathbf{\Delta}E| < 40$ MeV
  * Signal/recoil side: lepton with $p^*_l \geq 1.0\,\text{GeV}/c$; reconstruct D and D^* candidates from K and π

* **Analyze** $m_{D^{(*)}\pi} - m_{D^{(*)}}$ **in windows of** $\mathbf{m}^2_{\text{miss}}$
  - Cut on $|\mathbf{m}^2_{\text{miss}}| < 0.1\ \text{GeV}^2/c^4$
  - Continuum and $B\bar{B}$ Bkg subtracted data using sidebands.
  - Signal (Breit-Wigner; NR shape from MC)
  - $D^*\pi \to D\pi$ down feed fixed and from MC.

  a) $B^- \to D^+\pi^-\,\ell\,\bar{\nu}_\ell$ b) $B^- \to D^{*+}\pi^-\,\ell\,\bar{\nu}_\ell$
  c) $\bar{B}^0 \to D^0\pi^+\,\ell\,\bar{\nu}_\ell$ d) $\bar{B}^0 \to D^{*0}\pi^-\,\ell\,\bar{\nu}_\ell$

* **Fit results:** Isospin averaged modes; values HFAG rescaled

[%]	$D^{**} \to D^{(*)}\pi$
$B^+ \to \bar{D}^0_1\,\ell^+\,\nu_\ell$	$0.67 \pm 0.10 \pm 0.09$
$B^+ \to \bar{D}^{*0}_2\,\ell^+\,\nu_\ell$	$0.72 \pm 0.03 \pm 0.06$
$B^+ \to \bar{D}'^0_1\,\ell^+\,\nu_\ell$	$-0.05 \pm 0.09 \pm 0.11$
$B^+ \to \bar{D}^0_0\,\ell^+\,\nu_\ell$	$0.37 \pm 0.05 \pm 0.09$



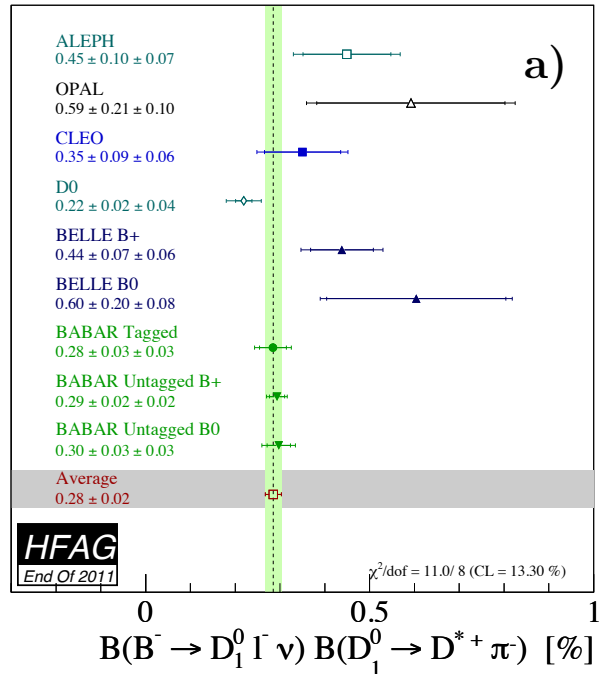
arXiv:1207.1158v1

* HFAG Summary of D_1 Branching Fractions:

(isospin averaged)

[%]	HFAG
$B^+ \to \bar{D}_1^0\, \ell^+\, \nu_\ell$ $\hookrightarrow D^{*-}\pi^+$	0.285 ± 0.018
$B^+ \to \bar{D}_1^0\, \ell^+\, \nu_\ell$ $\hookrightarrow D^*\pi$	0.428 ± 0.027

The isospin factor applied to $B^+ \to \bar{D}_1^0\, \ell^+\, \nu_\ell$ with two-body fragmentations is $\frac{3}{2}$.



* Hadronic 3-Body modes: $\mathcal{B}(B \to D_1\pi) \times \mathcal{B}(D_1 \to D\pi\pi)$ Phys.Rev. D84 (2011) 092001

Estimate $B^+ \to \bar{D}_1^0{}_{\hookrightarrow D^{(*)}\pi\pi}\, \ell^+\, \nu_\ell$ via naive scaling:

$$R_{D_1} = \frac{\mathcal{B}(B^+ \to D_1^0\pi^+) \times \mathcal{B}(D_1^0 \to D\pi\pi)}{\mathcal{B}(B^+ \to D_1^0\pi^+) \times \mathcal{B}(D_1^0 \to D^*\pi)} = 0.67 \pm 0.18$$

Assumes no isospin breaking effects

[%]	Private
$B^+ \to \bar{D}_1^0\, \ell^+\, \nu_\ell$ $\hookrightarrow D^*\pi$	0.428 ± 0.027
$B^+ \to \bar{D}_1^0\, \ell^+\, \nu_\ell$ $\hookrightarrow D\pi\pi$	0.287 ± 0.081
$B^+ \to \bar{D}_1^0\, \ell^+\, \nu_\ell$ $\hookrightarrow D^{(*)}\pi(\pi)$	$\mathbf{0.715 \pm 0.091}$

HFAG averages and summary $B \to D^{**}_{\hookrightarrow D^{(*)}\pi}\, \ell\bar{\nu}_\ell$: Narrow states D_2

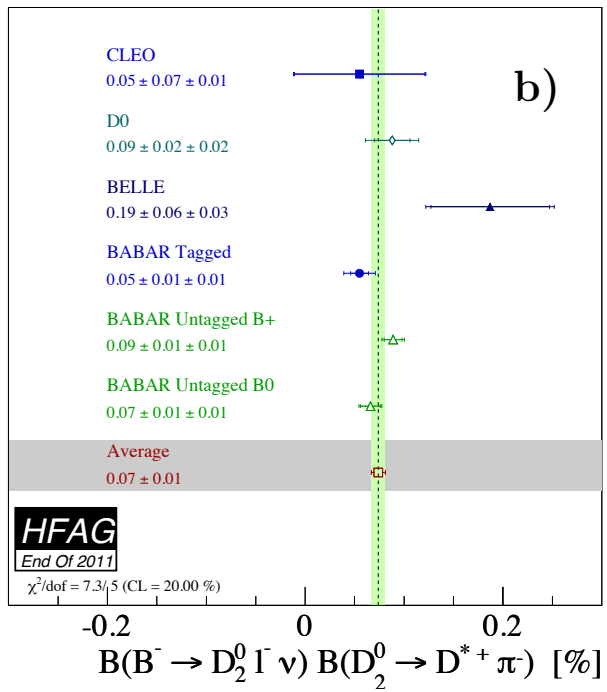
arXiv:1207.1158v1

* HFAG Summary of D_2 Branching Fractions:

(isospin averaged)

[%]	HFAG
$B^+ \to \bar{D}^0_2\, \ell^+\, \nu_\ell$ $\hookrightarrow D^{*+}\pi^-$	0.074 ± 0.007
$B^+ \to \bar{D}^0_2\, \ell^+\, \nu_\ell$ $\hookrightarrow D^{(*)+}\pi^-$	0.189 ± 0.035
$B^+ \to \bar{D}^0_2\, \ell^+\, \nu_\ell$ $\hookrightarrow D^{(*)}\pi$	0.284 ± 0.050

The isospin factors applied to $B^+ \to \bar{D}^0_2\, \ell^+\, \nu_\ell$ or $B^0 \to \bar{D}^+_2\, \ell^-\, \bar{\nu}_\ell$ with two-body fragmentations is $\frac{3}{2}$. HFAG combined the $D_2 \to D\pi$ channel with $f_{D_2} = 2.2 \pm 0.5$. I've applied a scaling using the PDG value for the resulting HFAG number of $f_{D_2} = 1.56 \pm 0.16$ to obtain the $D^{(*)}\pi$ branching fraction.



* Hadronic 3-Body modes: seem negligible cf. Phys.Rev.Lett. 94 (2005) 221805

HFAG averages and summary $B \to D^{**}_{\hookrightarrow D^{(*)}\pi}\, \ell\bar{\nu}_\ell$: broad states

arXiv:1207.1158v1

* How much space is there for broad or continuum states?

[%]	HFAG
$B^+ \to \bar{D}_2^0\, \ell^+\, \nu_\ell$	
$\hookrightarrow D\pi$	0.12 ± 0.02
$B^+ \to D^{**}(1P)_{\text{narrow}}\, \ell^+\, \nu_\ell$	
$\hookrightarrow D\pi$	$\mathbf{0.12 \pm 0.02}$

Semi-inclusive

[%]	Private average
$B^+ \to D\pi\, \ell^+\, \nu_\ell$	0.66 ± 0.08

[%]	HFAG
$B^+ \to \bar{D}_1^0\, \ell^+\, \nu_\ell$	
$\hookrightarrow D^*\pi$	0.43 ± 0.03
$B^+ \to \bar{D}_2^0\, \ell^+\, \nu_\ell$	
$\hookrightarrow D^*\pi$	0.07 ± 0.01
$B^+ \to D^{**}(1P)_{\text{narrow}}\, \ell^+\, \nu_\ell$	
$\hookrightarrow D^*\pi$	$\mathbf{0.50 \pm 0.03}$

Semi-inclusive:

[%]	Private average
$B^+ \to D^*\pi\, \ell^+\, \nu_\ell$	0.87 ± 0.09

$\to$

$$\mathcal{B}(B^+ \to D\pi\, \ell^+\, \nu_\ell) - \mathcal{B}(B^+ \to D^{**}(1P)_{\text{narrow}\hookrightarrow D\pi}\, \ell^+\, \nu_\ell) = (0.54 \pm 0.08)\,\%$$

$$\mathcal{B}(B^+ \to D^*\pi\, \ell^+\, \nu_\ell) - \mathcal{B}(B^+ \to D^{**}(1P)_{\text{narrow}\hookrightarrow D^*\pi}\, \ell^+\, \nu_\ell) = (0.37 \pm 0.10)\,\%$$

HFAG averages and summary $B \to D^{**}_{\hookrightarrow D^{(*)}\pi}\, \ell\bar{\nu}_\ell$: Broad states D_0

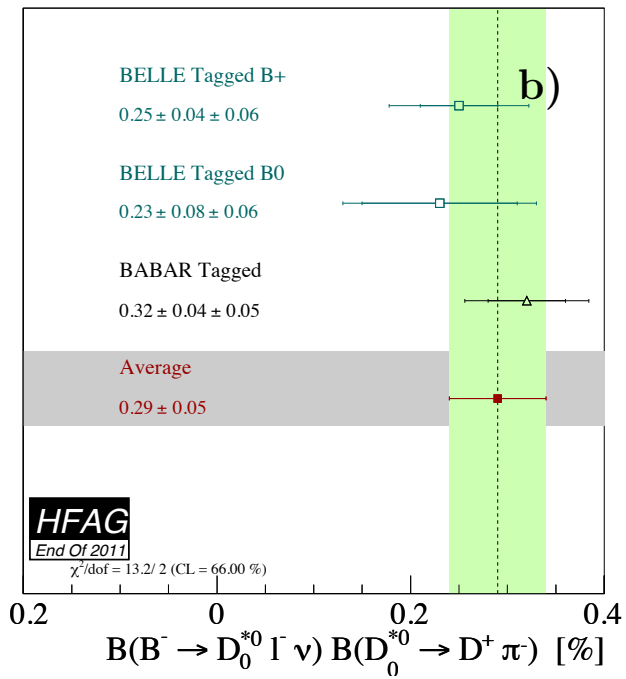
arXiv:1207.1158v1

* HFAG Summary of D_0 Branching Fractions:

(isospin averaged)

[%]	HFAG
$B^+ \to \bar{D}^0_0\, \ell^+\, \nu_\ell$ $\hookrightarrow D^-\pi^+$	0.29 ± 0.05
$B^+ \to \bar{D}^0_0\, \ell^+\, \nu_\ell$ $\hookrightarrow D\pi$	0.44 ± 0.08

The isospin factor applied to $B^+ \to \bar{D}^0_1\, \ell^+\, \nu_\ell$ or $B^0 \to \bar{D}^+_1\, \ell^-\, \bar{\nu}_\ell$ with two-body fragmentations is $\frac{3}{2}$.f



⇒ Tricky measurement but consistent picture (?) : **P-Value** of combination 66%

HFAG averages and summary $B \to D^{**}_{\hookrightarrow D^{(*)}\pi}\, \ell\bar{\nu}_\ell$: Broad states D_1'

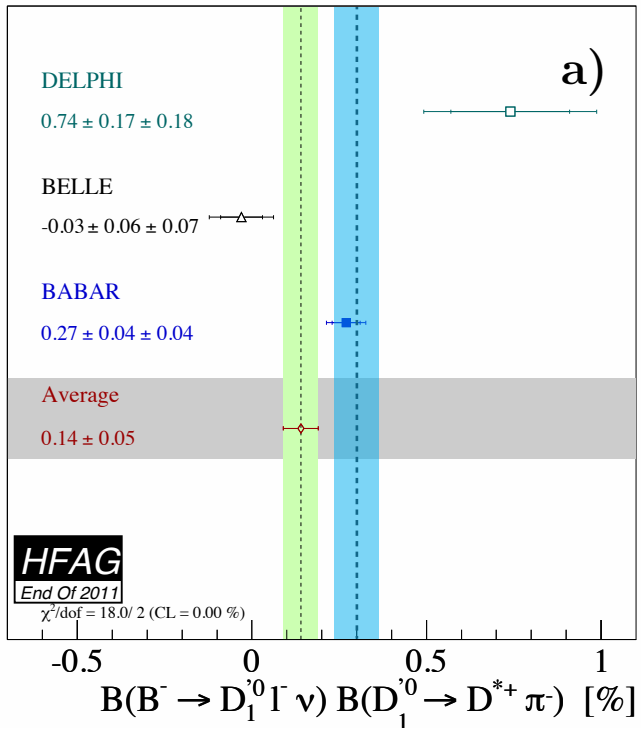
arXiv:1207.1158v1

* HFAG Summary of D_1' Branching Fractions:

(isospin averaged)

[%]	HFAG
$B^+ \to \bar{D}_1'^0\, \ell^+\, \nu_\ell$ $\hookrightarrow D^{*-}\pi^+$	0.13 ± 0.04
$B^+ \to \bar{D}_1'^0\, \ell^+\, \nu_\ell$ $\hookrightarrow D^*\pi$	0.20 ± 0.06

The isospin factor applied to $B^+ \to \bar{D}_1^0\, \ell^+\, \nu_\ell$ or $B^0 \to \bar{D}_1^+\, \ell^-\, \bar{\nu}_\ell$ with two-body fragmentations is $\frac{3}{2}$.

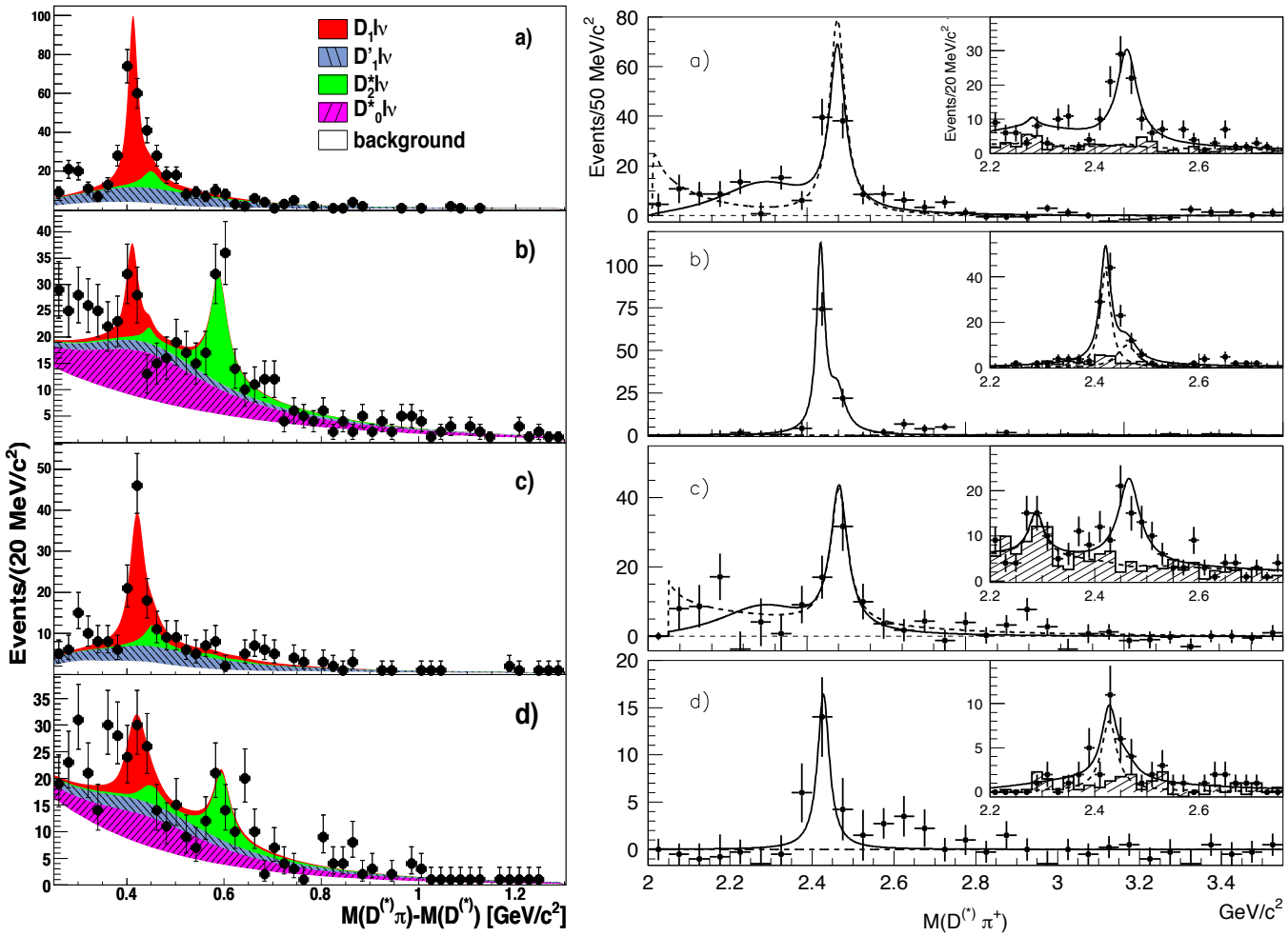


⇒ Not very consistent picture: Combination results in $\chi^2/ndf = 18/2$.

* How to deal with this?
  - i Blue line $\widehat{=}$ average without *Belle* ...
  - ii Maybe this just reflects our poor understanding ...

arXiv:1207.1158v1

* Both measurements included continuum; both got yields compatible with zero



→ Both measurements use very different setup: *BABAR* trusts simulation and uses cross feed to gain sensitivity; *Belle* tries to use sidebands and makes strict cuts on $m^2_{\mathbf{miss}}$.

HFAG averages and summary $B \to D^{**}_{\hookrightarrow D^{(*)}\pi}\, \ell\bar{\nu}_\ell$: continuum states

arXiv:1207.1158v1

* How much space is there for continuum states? Using the HFAG averages

[%]	HFAG
$B^+ \to \bar{D}_2^0\, \ell^+\, \nu_\ell$	
$\hookrightarrow D\pi$	0.12 ± 0.02
$B^+ \to \bar{D}_0^0\, \ell^+\, \nu_\ell$	
$\hookrightarrow D\pi$	0.44 ± 0.08
$B^+ \to D^{**}(1P)\, \ell^+\, \nu_\ell$	
$\hookrightarrow D\pi$	$\mathbf{0.56 \pm 0.08}$

Semi-inclusive

[%]	Private average
$B^+ \to D\pi\, \ell^+\, \nu_\ell$	0.66 ± 0.08

[%]	HFAG
$B^+ \to \bar{D}_1^0\, \ell^+\, \nu_\ell$	
$\hookrightarrow D^*\pi$	0.43 ± 0.03
$B^+ \to \bar{D}_2^0\, \ell^+\, \nu_\ell$	
$\hookrightarrow D^*\pi$	0.07 ± 0.01
$B^+ \to \bar{D}_1^{\prime 0}\, \ell^+\, \nu_\ell$	
$\hookrightarrow D^*\pi$	0.20 ± 0.06
$B^+ \to D^{**}(1P)\, \ell^+\, \nu_\ell$	
$\hookrightarrow D^*\pi$	$\mathbf{0.70 \pm 0.07}$

Semi-inclusive:

[%]	Private average
$B^+ \to D^*\pi\, \ell^+\, \nu_\ell$	0.87 ± 0.09

→ Continuum $B^+ \to D\pi\, \ell^+\, \nu_\ell$ & $B^+ \to D^*\pi\, \ell^+\, \nu_\ell$

$$\mathcal{B}(B^+ \to D\pi\, \ell^+\, \nu_\ell) - \mathcal{B}(B^+ \to D^{**}(1P)_{\hookrightarrow D\pi}\, \ell^+\, \nu_\ell) = (0.10 \pm 0.11)\,\%$$
$$\mathcal{B}(B^+ \to D^*\pi\, \ell^+\, \nu_\ell) - \mathcal{B}(B^+ \to D^{**}(1P)_{\hookrightarrow D^*\pi}\, \ell^+\, \nu_\ell) = (0.17 \pm 0.11)\,\%$$

iii.c Exclusive $B \to D^{(*)}/D^{**}_{\hookrightarrow D^{(*)}\pi}\,\ell\bar{\nu}_\ell$

v

Inclusive $B \to X_c\,\ell\,\bar{\nu}_\ell$

Private averages; arXiv:1207.1158v1

* Summary: Optimistic & non-controversial

[%]	HFAG
$B^+ \to \bar{D}^0\, \ell^+\, \nu_\ell$	**2.30 ± 0.10**
$B^+ \to \bar{D}^{*\,0}\, \ell^+\, \nu_\ell$	**5.34 ± 0.12**
$B^+ \to \bar{D}_0^0\, \ell^+\, \nu_\ell$	
$\hookrightarrow D\pi$	0.44 ± 0.08
$B^+ \to \bar{D}_1'^0\, \ell^+\, \nu_\ell$	
$\hookrightarrow D^*\pi$	0.20 ± 0.06
$B^+ \to \bar{D}_1^0\, \ell^+\, \nu_\ell$	
$\hookrightarrow D^*\pi$	0.43 ± 0.03
$B^+ \to \bar{D}_2^0\, \ell^+\, \nu_\ell$	
$\hookrightarrow D^{(*)}\pi$	0.28 ± 0.05
$B^+ \to D^{**}(1P)\, \ell^+\, \nu_\ell$	
$\hookrightarrow D^{(*)}\pi$	**1.35 ± 0.12**
$B^+ \to \bar{D}_1^0\, \ell^+\, \nu_\ell$	
$\hookrightarrow D\pi\pi$	**0.29 ± 0.08**
NR $B^+ \to \bar{D}\,\pi\, \ell^+\, \nu_\ell$	**0.10 ± 0.11**
NR $B^+ \to \bar{D}^*\,\pi\, \ell^+\, \nu_\ell$	**0.17 ± 0.11**
$\sum$	**9.55 ± 0.26**
Incl. $B^+ \to X_c\, \ell\, \nu$	10.91 ± 0.14
'Gap' Incl. vs excl.	1.36 ± 0.30

[%]	HFAG
$B^+ \to \bar{D}^0\, \ell^+\, \nu_\ell$	**2.30 ± 0.10**
$B^+ \to \bar{D}^{*\,0}\, \ell^+\, \nu_\ell$	**5.34 ± 0.12**
$B^+ \to D^{(*)}\pi\, \ell^+\, \nu_\ell$	**1.53 ± 0.12**
$\sum$	**9.17 ± 0.20**
Incl. $B^+ \to X_c\, \ell\, \nu$	10.91 ± 0.14
'Gap' Incl. vs excl.	1.74 ± 0.24

⇒ Significant Gap between inclusive v exclusive of 1.36 - 1.74 % (4.5 - 7.3 σ)

iv. Neglected channels?

* Easiest explanation: we are missing some modes
* Obvious candidates: $B \to D^{(*)}\,\pi\,\pi\,\ell\bar{\nu}_\ell$ & $B \to D^{(*)}\,\eta\,\ell\bar{\nu}_\ell$
* Origin? A bit unclear 3-body decays from the $1P$ states studied hadronically, all but D_1 very small

→ List of prospective blameworthy sources:

  * Continuum ?
  * Beyond $1P$? $2S$ or $1D$?
  * Something else?

* *BABAR* & *Belle* tell us, it's not $B^+ \to D_s^{(*)}\,K^+\,\ell\,\nu_\ell$ PDG Live from this morning

$$\mathcal{B}(B^+ \to D_s^{(*)}\,K^+\,\ell\,\nu_\ell) = (0.061 \pm 0.012)\,\%$$

* Lesson from fully inclusive $B \to X\,\ell\,\bar{\nu}_\ell$ lepton spectrum:
  → Missing component has a hard lepton spectrum.
  → Continuum type models (e.g. Goity-Roberts type models, cf. Phys. Rev. D 51, 3459) tend to not accommodate this

iv. Semi-inclusive $B \to D^{(*)} X \ell \bar{\nu}_\ell$

* From Christian Oswald's talk from ICHEP12:

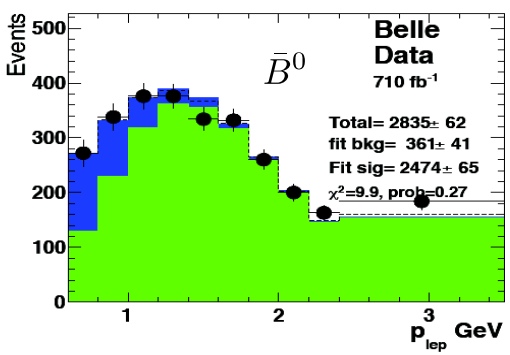
Semi-inclusive $B \to D^{(*)} X \ell \nu$

Full hadronic reconstruction of tag B with neural network

Reconstruction of signal:

$$\left.\begin{array}{l} D^0 \to K^-\pi^+(\pi^+\pi^-) \\ D^- \to K^-\pi^-\pi^+ \\ D^{*0} \to D^0\pi^0_{\rm slow} \\ D^{*+} \to D^0\pi^+_{\rm slow} \end{array}\right\} \text{x 2 B flavours = 8 different modes}$$

Secondary+fake lepton bkg subtracted from a χ^2 fit to the lepton momentum

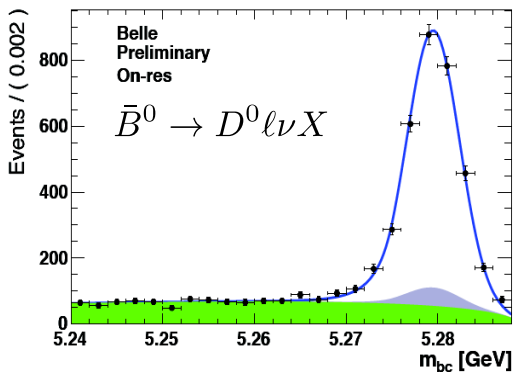


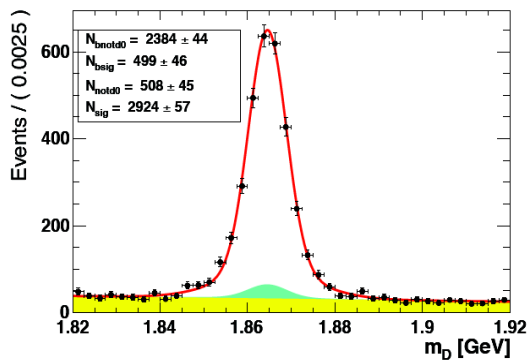
$772 \times 10^6\ B\bar{B}$

2D unbinned fit in $m_{\rm bc}$ and

m_D (D modes)

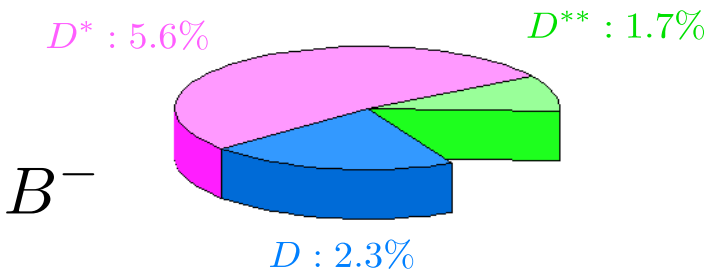
$\Delta m = m_{D^*} - m_D$ (D^* modes)

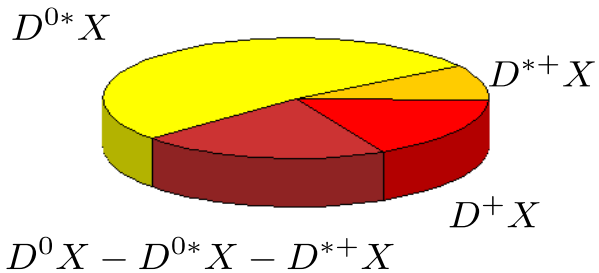




- **Inclusive vs. Exclusive puzzle:**
  - Full semilept. width described by semi-inclusive modes:

$$B^0: \quad \mathcal{B}(D^0X + D^+X)/\mathcal{B}(X) = 1.027 \pm 0.018_{\text{stat.}} \pm 0.012_{\mathcal{B}(\text{D})} \pm 0.040_{\text{sys}}$$
$$B^-: \quad \mathcal{B}(D^0X + D^+X)/\mathcal{B}(X) = 1.010 \pm 0.015_{\text{stat.}} \pm 0.011_{\mathcal{B}(\text{D})} \pm 0.040_{\text{sys}}$$





⇒ Inclusive rate well described by semi-inclusive measurement.

* Looking forward to learn from *Belle* what X is.

v. Summary

My take:

* Narrow states leave a relative consistent picture
* Situation with broad states:
  * Discussion dominated by two measurements, both use slightly different approaches:
  i *BABAR* relies more on MC, makes use of cross feed to gain sensitivity
  ii *Belle* uses more data driven background estimates, but has a reduced sensitivity

→ Need more experimental input: $j_{1/2}$ v $j_{3/2}$ dominated by two measurements!

→ Continuum (e.g. Goity-Roberts type models, cf. Phys. Rev. D 51, 3459) produces $m_{D^*\pi}$ mass spectrum not compatible with observation.

* Situation with 'Gap':
  * Missing modes most compelling explanation
  → $B \to D^{(*)}\,\pi\,\pi\,\ell\bar{\nu}_\ell$ & $B \to D^{(*)}\,\eta\,\ell\bar{\nu}_\ell$
  → Semileptonic modes: need more tagged measurements from the B-Factories

* These decay modes are of course also present in the hadronic modes:
  → Interesting opportunity for LHCb to help the B-Factories.

Outlook from *BABAR* :

* Plan to look at $B \to D^{(*)}\,\pi\,\pi\,\ell\bar{\nu}_\ell$ & $B \to D^{(*)}\,\eta\,\ell\bar{\nu}_\ell$

Outlook from *Belle*:

* Plan to look at X cf. slide 27 , maybe more ?