Experimental Status of $B \rightarrow D^{**}(D^{(*)}n\pi)\ell\nu$ Decays

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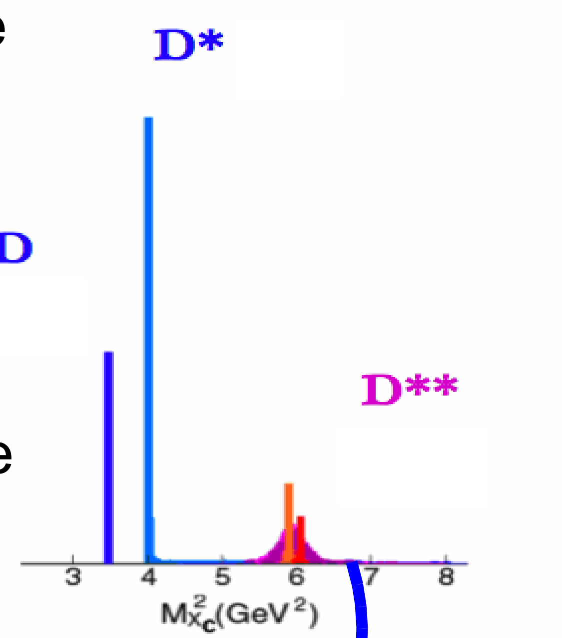
The X_c System in $B \to X_c \ell\nu$ Decays

$BR(B \to X_c l\, \nu) \sim 10.5\%$

- In addition to the "well" measured $D^{(*)}$ states, there are the D** states, orbital excitations of the D-mesons
- Heavy Quark Symmetry predicts 4 D** states, 2 narrow and 2 broad, all observed in hadronic decays
- The naïve assumption X_c=D+D*+D** is contradicted by the experiments that show a 10-15% difference between direct measurements of the inclusive $X_c \ell\nu$ rate and the sum of the D/D*/D**$\ell\nu$ rates



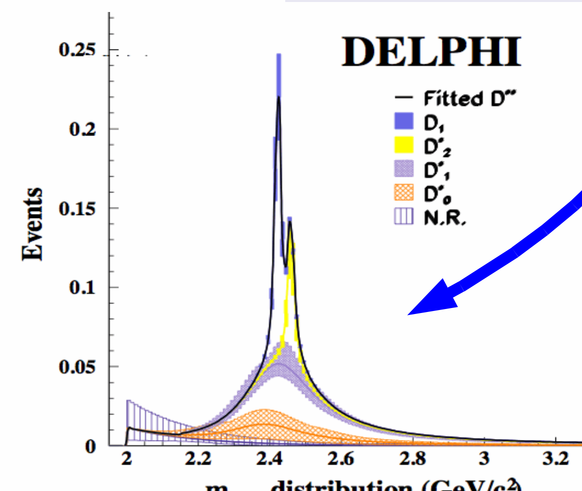
??????

$B(D^{**}\ell\nu) = 1.6\%$

$B(D\ell\nu) \sim 2.3\%$

$B(D^*\ell\nu) \sim 5.4\%$

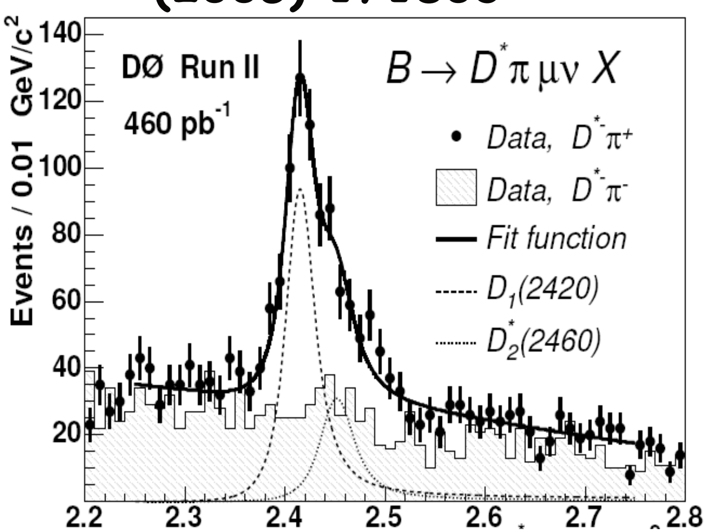
$B(X_c \ell\nu) \sim 10.5\%$



Spectroscopy of excited D mesons

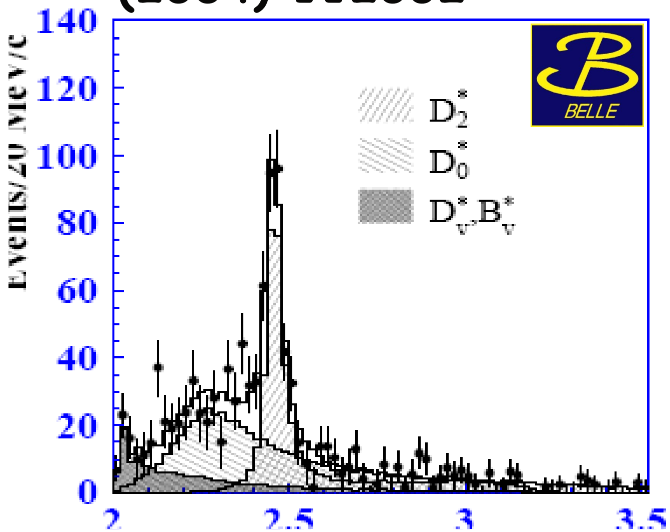
- Use D** as nickname for states $D^{(*)}(n\pi)$ with n>0 including:
  - Narrow resonances D_1, D_2^*
  - Broad resonances D_0^*, D_1'
  - Non-resonant?
- Need help from hadronic $B \rightarrow D^{**}\pi$ to characterize D** broad states

Abazov et al, PRL 95 (2005) 171803

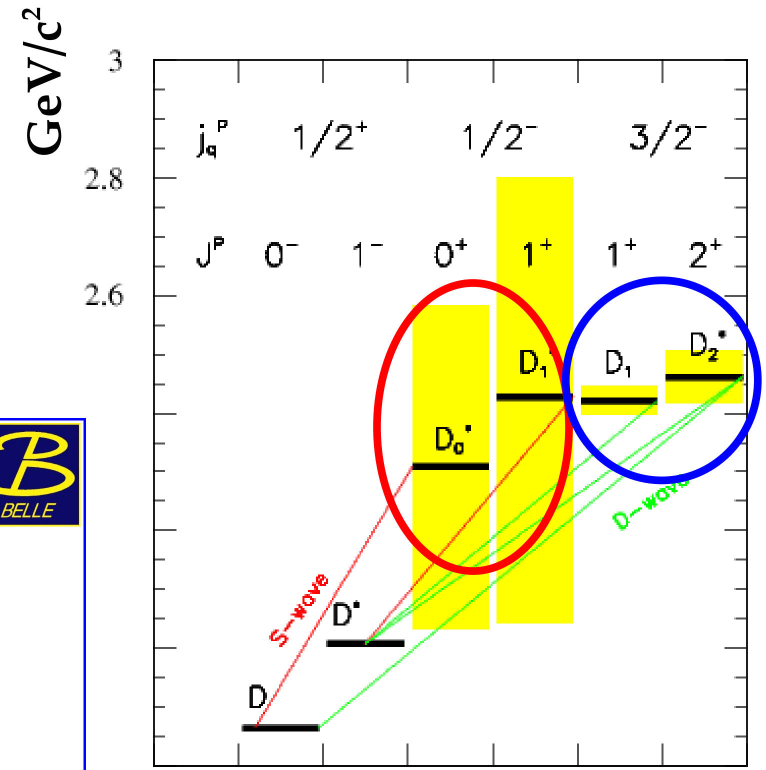


D*π Invariant Mass [GeV/c²]

Abe et al, PRD 69 (2004) 112002



Dπ Invariant Mass [GeV/c²]

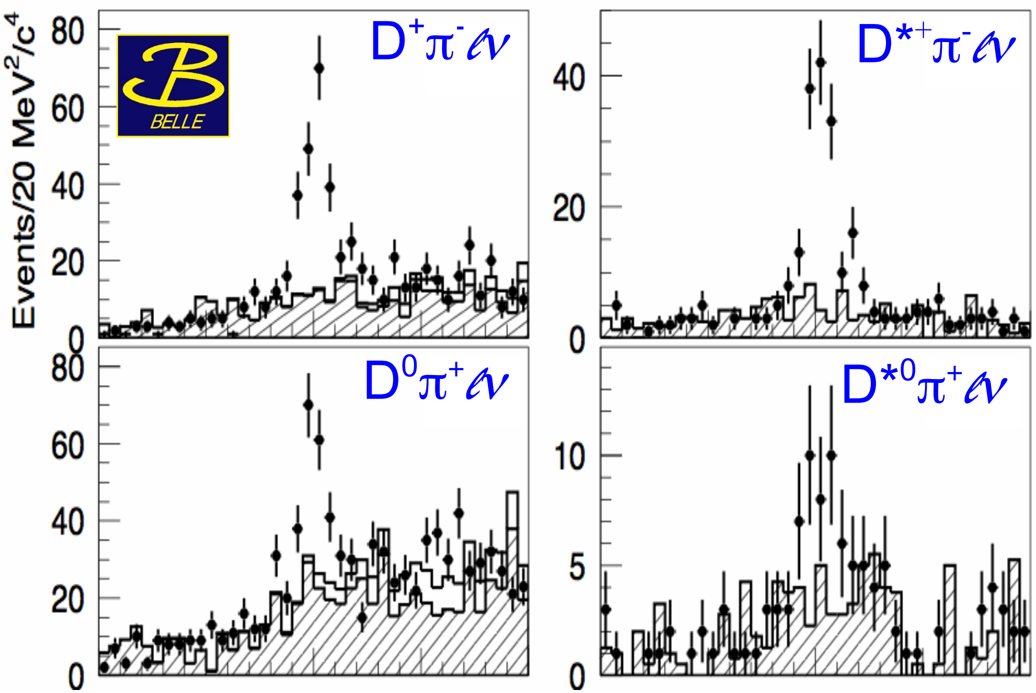


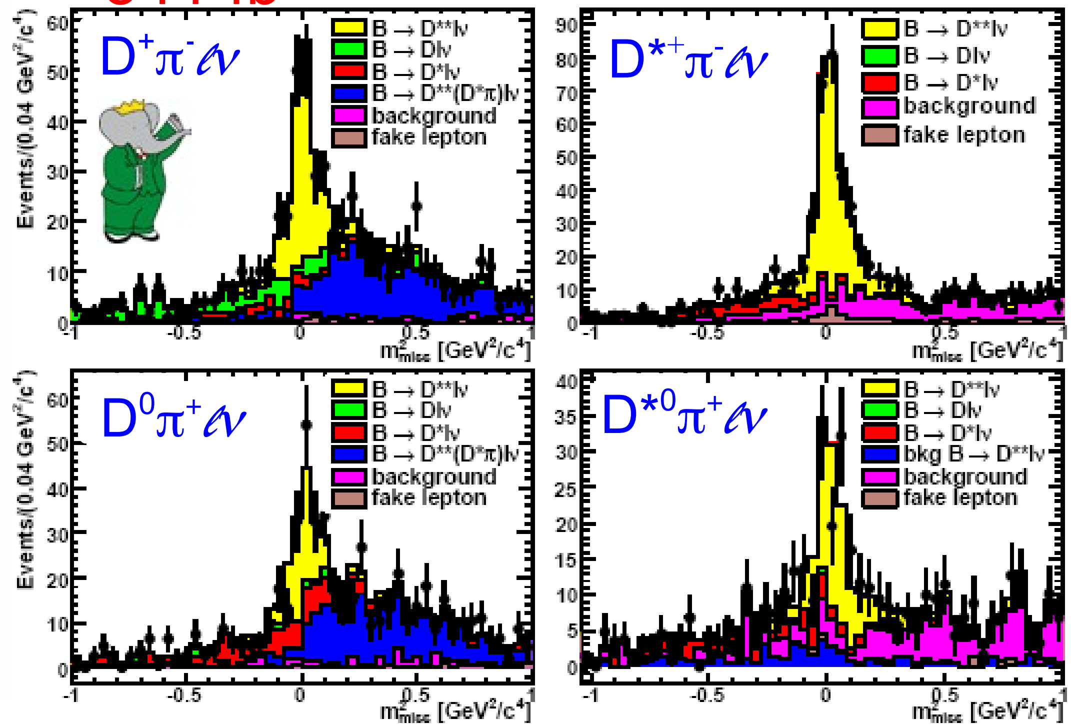
Charm States

$B \rightarrow D^{(*)}\pi\ell\nu$ Branching Fractions

605 fb^{-1} PRD 77: 091503 (2008)

341 fb^{-1} PRL 100: 151802 (2008)





- Clean samples of $B \rightarrow D^{(*)}\pi\ell\nu$ events in both BaBar and Belle analysis, similar techniques and excellent agreement in the measurement of branching fractions

HFAG 2009

$$\mathcal{B}(B^- \rightarrow D^{(*)+}\pi\ell^-\bar{\nu}_\ell) = (1.55 \pm 0.10)\%$$

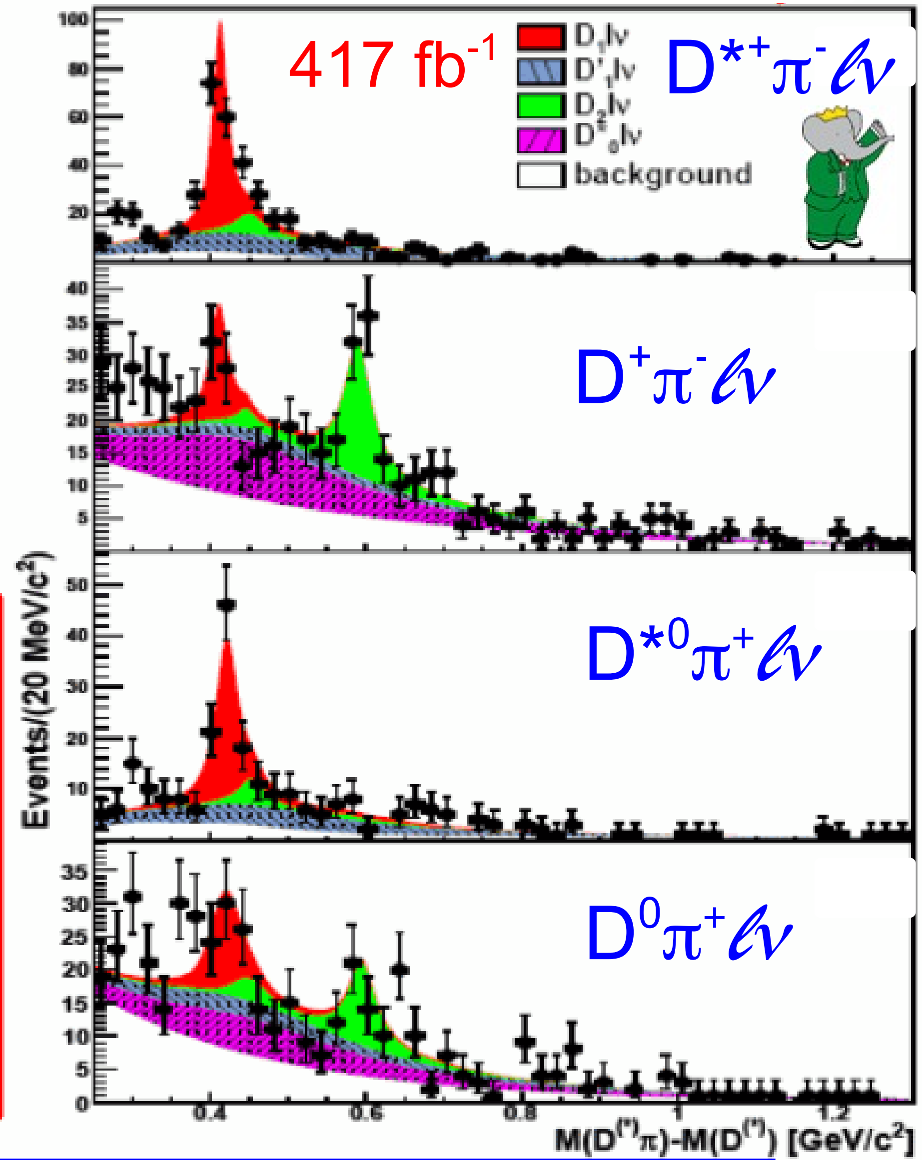
$$\mathcal{B}(\bar{B}^0 \rightarrow D^{(*)0}\pi\ell^-\bar{\nu}_\ell) = (1.38 \pm 0.14)\%$$

$B \rightarrow D^{**}\ell\nu$ (BaBar)

ArXiv:0808.0528 [hep-ex], PRL 101,261802(2008)

- Reconstruct $B \rightarrow D^{(*)}\pi^{\pm}l\nu$ in events tagged by hadronic B
- Simultaneous fit to $M(D^{(*)}\pi)-M(D^{(*)})$, including cross-feed
- Background yield constrained from fit to m_{ES}, shape checked on wrong-sign data combinations
- Large rate for broad states!!

Decay Mode	$\mathcal{B}(\bar{B} \rightarrow D^{**}\ell^-\bar{\nu}_\ell) \times \mathcal{B}(D^{**} \rightarrow D^{(*)}\pi)$ %
$B^- \rightarrow D_1^0\ell^-\bar{\nu}_\ell$	$0.29 \pm 0.03 \pm 0.03$
$B^- \rightarrow D_2^{*0}\ell^-\bar{\nu}_\ell$	$0.22 \pm 0.03 \pm 0.04$
$B^- \rightarrow D_1^{\prime 0}\ell^-\bar{\nu}_\ell$	$0.27 \pm 0.04 \pm 0.05$
$B^- \rightarrow D_0^{*0}\ell^-\bar{\nu}_\ell$	$0.26 \pm 0.05 \pm 0.04$
$\bar{B}^0 \rightarrow D_1^+\ell^-\bar{\nu}_\ell$	$0.27 \pm 0.04 \pm 0.03$
$\bar{B}^0 \rightarrow D_2^{*+}\ell^-\bar{\nu}_\ell$	$0.10 \pm 0.04 \pm 0.03$
$\bar{B}^0 \rightarrow D_1^{\prime +}\ell^-\bar{\nu}_\ell$	$0.31 \pm 0.07 \pm 0.05$
$\bar{B}^0 \rightarrow D_0^{*+}\ell^-\bar{\nu}_\ell$	$0.44 \pm 0.08 \pm 0.06$



$B \to D^{**}\ell\nu$ (Belle)

605 fb^{-1}

ArXiv:0711.3252 [hep-ex], PR D77,091503(2008)

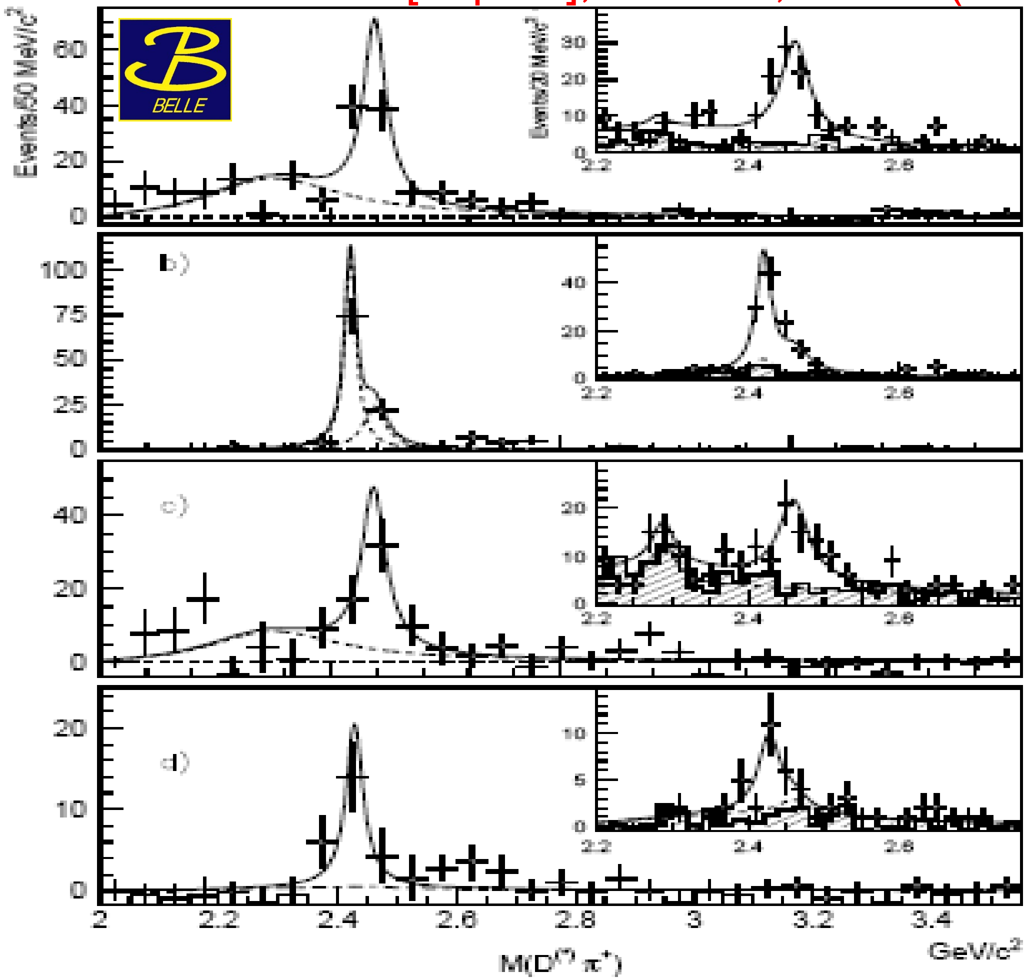
$$\mathcal{B}(\text{mode}) \equiv \mathcal{B}(B \to D^{**}\ell\nu) \times \mathcal{B}(D^{**} \to D^{(*)}\pi^+)$$

$D\pi$ invariant mass study

Mode	Yield	$\mathcal{B}$, %	Signif.
$B^+ \to \bar{D}_0^{*0}\ell^+\nu$	102 ± 19	$0.24 \pm 0.04 \pm 0.06$	5.4
$B^+ \to \bar{D}_2^{*0}\ell^+\nu$	94 ± 13	$0.22 \pm 0.03 \pm 0.04$	8.0
$B^0 \to D_0^{*-}\ell^+\nu$	61 ± 22	$0.20 \pm 0.07 \pm 0.05$	2.6
$B^0 \to D_2^{*-}\ell^+\nu$	68 ± 13	$0.22 \pm 0.04 \pm 0.04$	5.5

$D^*\pi$ invariant mass study

Mode	Yield	$\mathcal{B}$, %	Signif.
$B^+ \to \bar{D}_1'^0\ell^+\nu$	-5 ± 11	< 0.07 @ 90% C.L.	
$B^+ \to \bar{D}_1^0\ell^+\nu$	81 ± 13	$0.42 \pm 0.07 \pm 0.07$	6.7
$B^+ \to \bar{D}_2^{*0}\ell^+\nu$	35 ± 11	$0.18 \pm 0.06 \pm 0.03$	3.2
$B^0 \to D_1'^-\ell^+\nu$	4 ± 8	< 0.5 @ 90% C.L.	
$B^0 \to D_1^-\ell^+\nu$	20 ± 7	$0.54 \pm 0.19 \pm 0.09$	2.9
$B^0 \to D_2^{*-}\ell^+\nu$	1 ± 6	< 0.3 @ 90% C.L.	



- Hadronic tag analysis from Belle
- Similar technique to BaBar, independent fits for different final states
- Confirm signals for narrow D_1 and D_2, sees only broad D_0^*, no D_1'

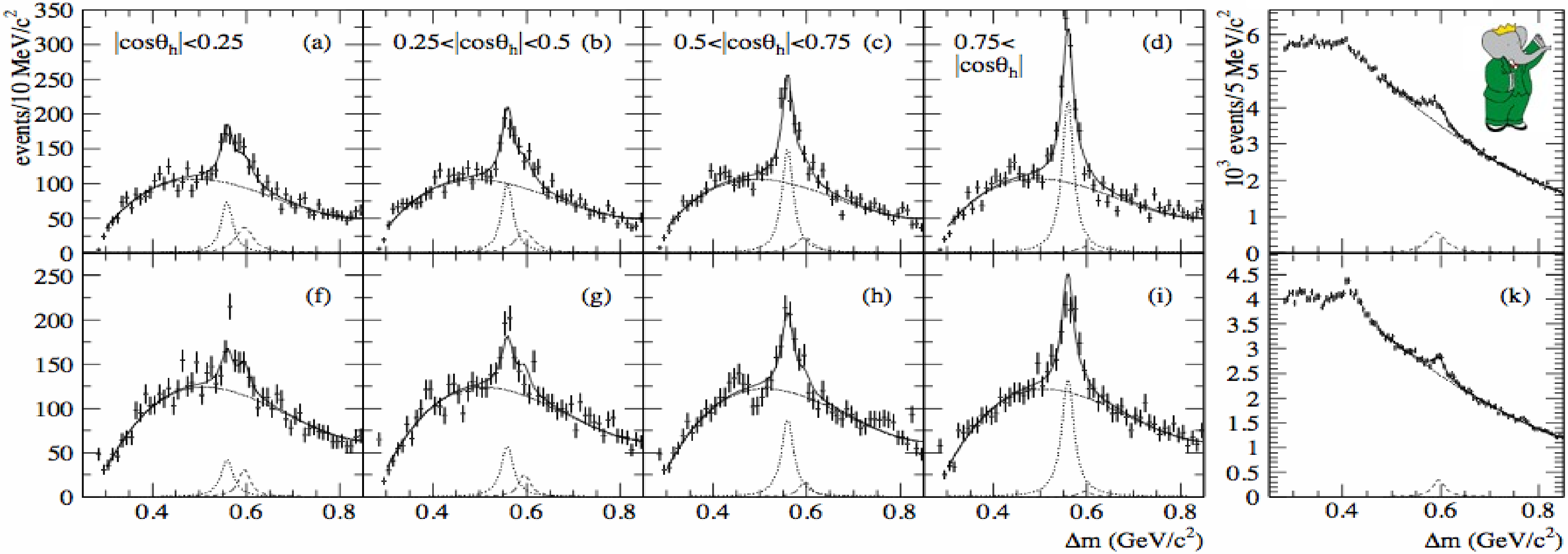
Comparison BaBar-Belle

Decay Mode	Yield	$\mathcal{B}(\bar{B} \to D^{**}\ell^-\bar{\nu}_\ell) \times \mathrm{B}(D^{**} \to D^{(*)}\pi)$ %(BELLE)	BABAR Yield	BABAR Branching Fraction
$D\pi$ invariant mass fit				
$B^- \to D_0^{*0}\ell^-\bar{\nu}_\ell$	102 ± 19	$0.24 \pm 0.04 \pm 0.06$	137 ± 26	$0.26 \pm 0.05 \pm 0.04$
$B^- \to D_2^0\ell^-\bar{\nu}_\ell$	94 ± 13	$0.22 \pm 0.03 \pm 0.04$	97 ± 16	$0.15 \pm 0.02 \pm 0.01$
$\bar{B}^0 \to D_0^{*+}\ell^-\bar{\nu}_\ell$	61 ± 22	$0.20 \pm 0.07 \pm 0.05$	142 ± 26	$0.44 \pm 0.08 \pm 0.07$
$\bar{B}^0 \to D_2^+\ell^-\bar{\nu}_\ell$	68 ± 13	$0.22 \pm 0.04 \pm 0.04$	29 ± 13	$0.07 \pm 0.03 \pm 0.01$
$D^*\pi$ invariant mass fit				
$B^- \to D_1^{\prime 0}\ell^-\bar{\nu}_\ell$	-5 ± 11	< 0.07 @ 90CL	142 ± 21	$0.27 \pm 0.04 \pm 0.05$
$B^- \to D_1^0\ell^-\bar{\nu}_\ell$	81 ± 13	$0.42 \pm 0.07 \pm 0.07$	165 ± 18	$0.29 \pm 0.03 \pm 0.03$
$B^- \to D_2^0\ell^-\bar{\nu}_\ell$	35 ± 11	$0.18 \pm 0.06 \pm 0.03$	40 ± 7	$0.07 \pm 0.01 \pm 0.006$
$\bar{B}^0 \to D_1^{\prime +}\ell^-\bar{\nu}_\ell$	4 ± 8	< 0.5 @ 90CL	86 ± 18	$0.31 \pm 0.07 \pm 0.05$
$\bar{B}^0 \to D_1^+\ell^-\bar{\nu}_\ell$	20 ± 7	$0.54 \pm 0.19 \pm 0.09$	88 ± 14	$0.27 \pm 0.05 \pm 0.03$
$\bar{B}^0 \to D_2^+\ell^-\bar{\nu}_\ell$	1 ± 6	< 0.3 @ 90CL	12 ± 5	$0.03 \pm 0.01 \pm 0.006$

- Result for the D_0^* broad state consistent between BaBar and BELLE
- BaBar observes the D_1', not present in the BELLE data
- Narrow D** results consistent with preliminary untagged BaBar results and D0 measurement (PRL 95, 171803 (2005)).

$B \to D^{**}\ell\nu$ (Narrow States,BaBar)

ArXiv:0808.0333 [hep-ex], PRL 103,051803(2009)



Fit D*π-D invariant mass distributions in 4 helicity bins, maximize D_1-D_2 separation, also measure $\mathcal{B}(D_1 \to D\pi)/\mathcal{B}(D_1 \to D^*\pi)$ and D_1 polarization

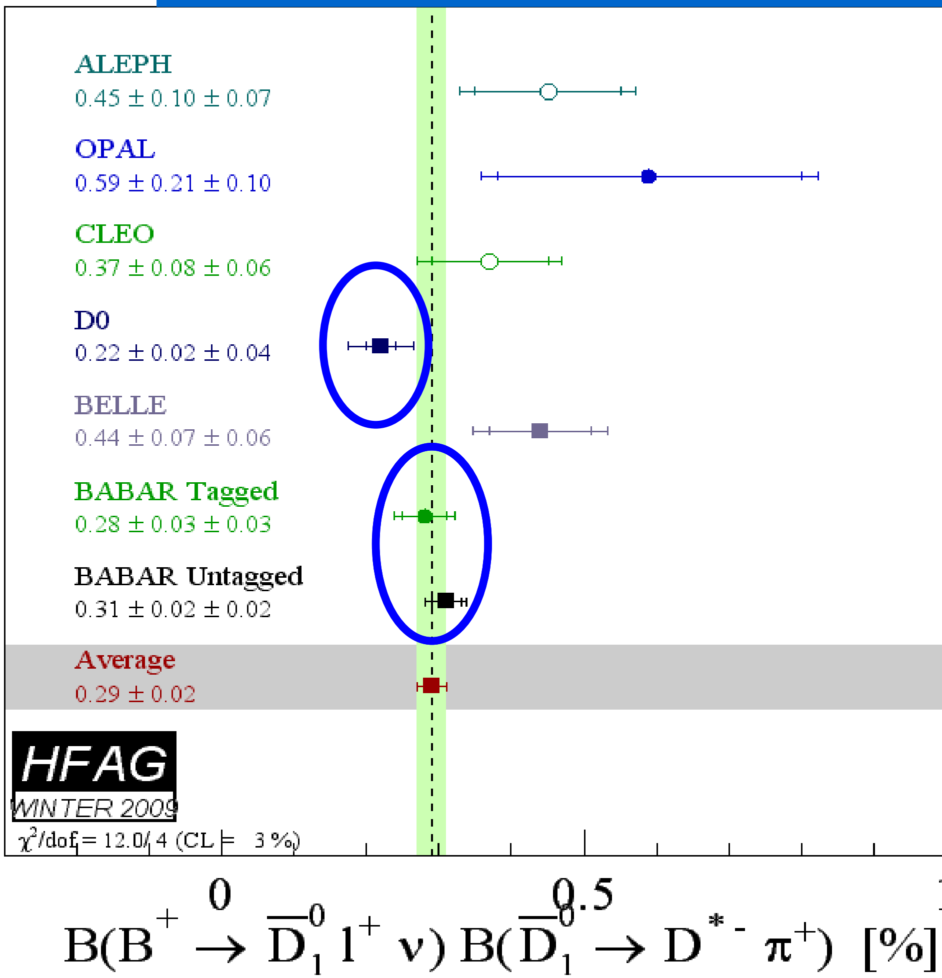
$$\mathcal{B}(B^+ \to D_1^0 \ell^+ \nu_\ell) \times \mathcal{B}(D_1^0 \to D^{*+}\pi^-) = (2.97 \pm 0.17_{\rm stat} \pm 0.17_{\rm syst}) \times 10^{-3},$$

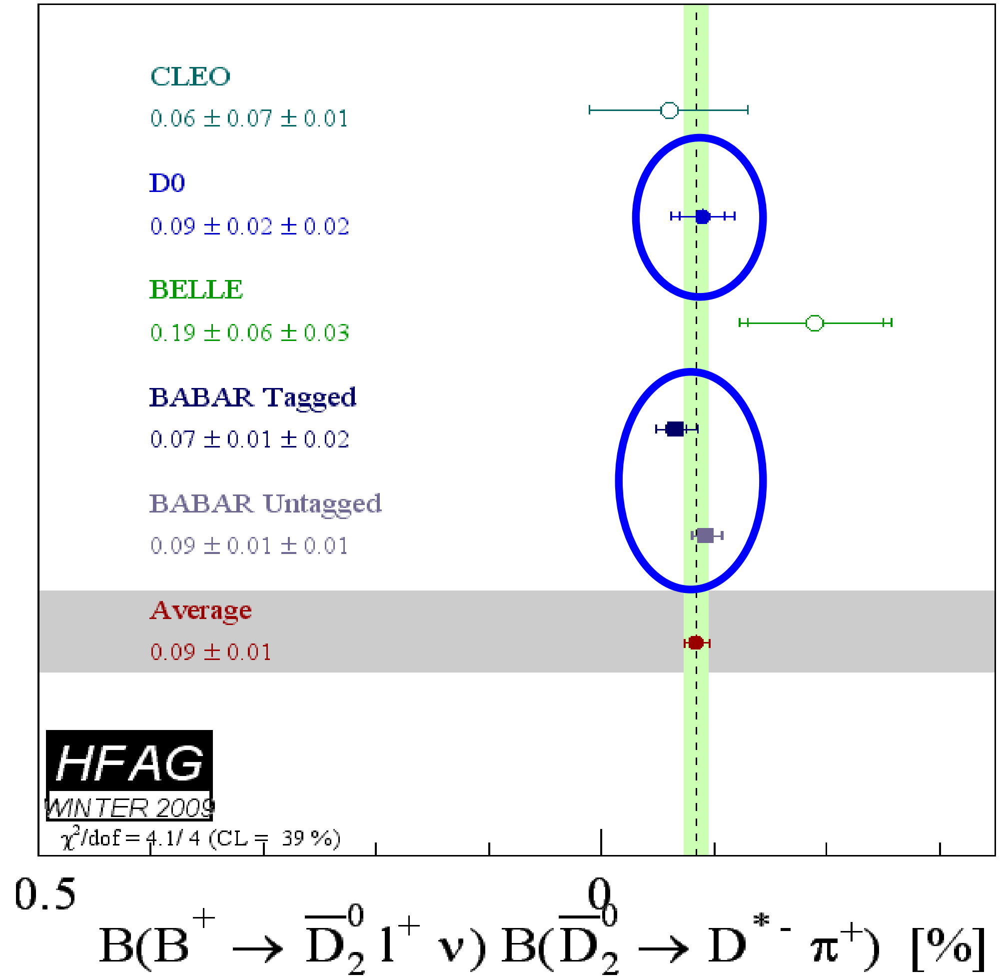
$$\mathcal{B}(B^+ \to D_2^{*0} \ell^+ \nu_\ell) \times \mathcal{B}(D_2^{*0} \to D^{(*)+}\pi^-) = (2.29 \pm 0.23_{\rm stat} \pm 0.21_{\rm syst}) \times 10^{-3},$$

$$\mathcal{B}(B^0 \to D_1^- \ell^+ \nu_\ell) \times \mathcal{B}(D_1^- \to D^{*0}\pi^-) = (2.78 \pm 0.24_{\rm stat} \pm 0.25_{\rm syst}) \times 10^{-3},$$

$$\mathcal{B}(B^0 \to D_2^{*-} \ell^+ \nu_\ell) \times \mathcal{B}(D_2^{*-} \to D^{(*)0}\pi^-) = (1.77 \pm 0.26_{\rm stat} \pm 0.11_{\rm syst}) \times 10^{-3}.$$

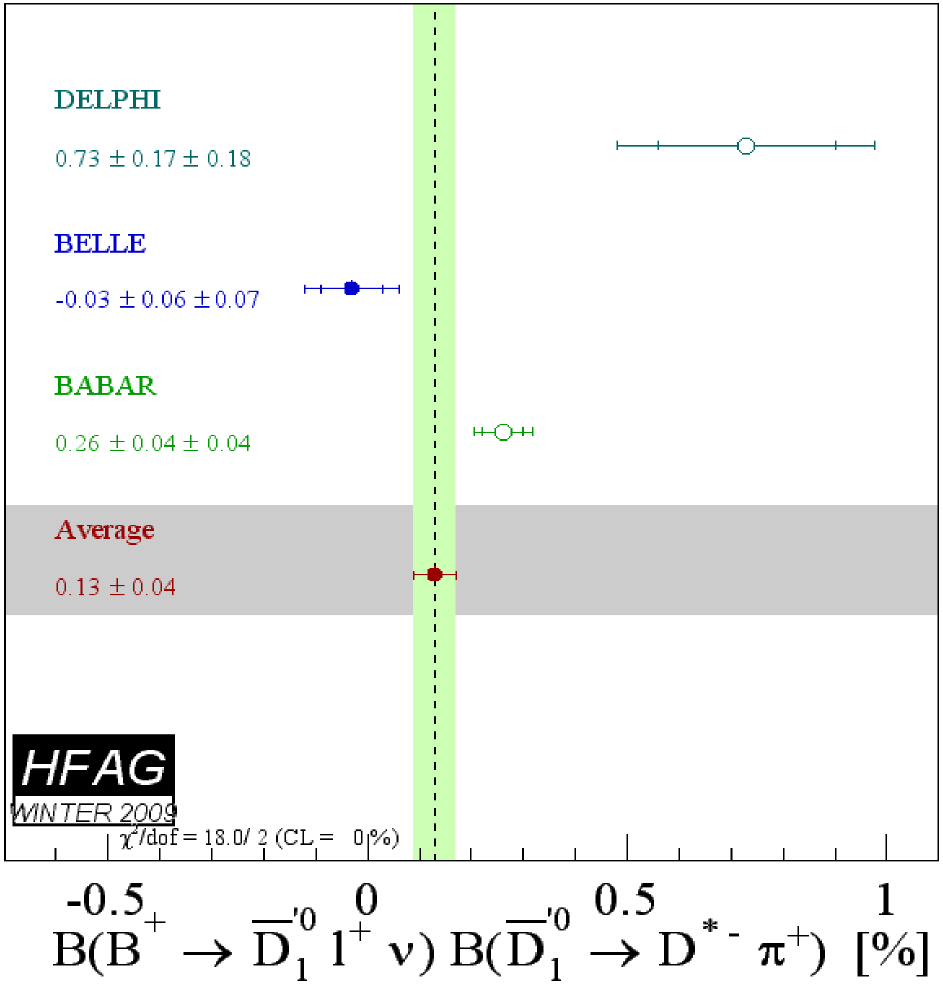
Consistency: the big Picture

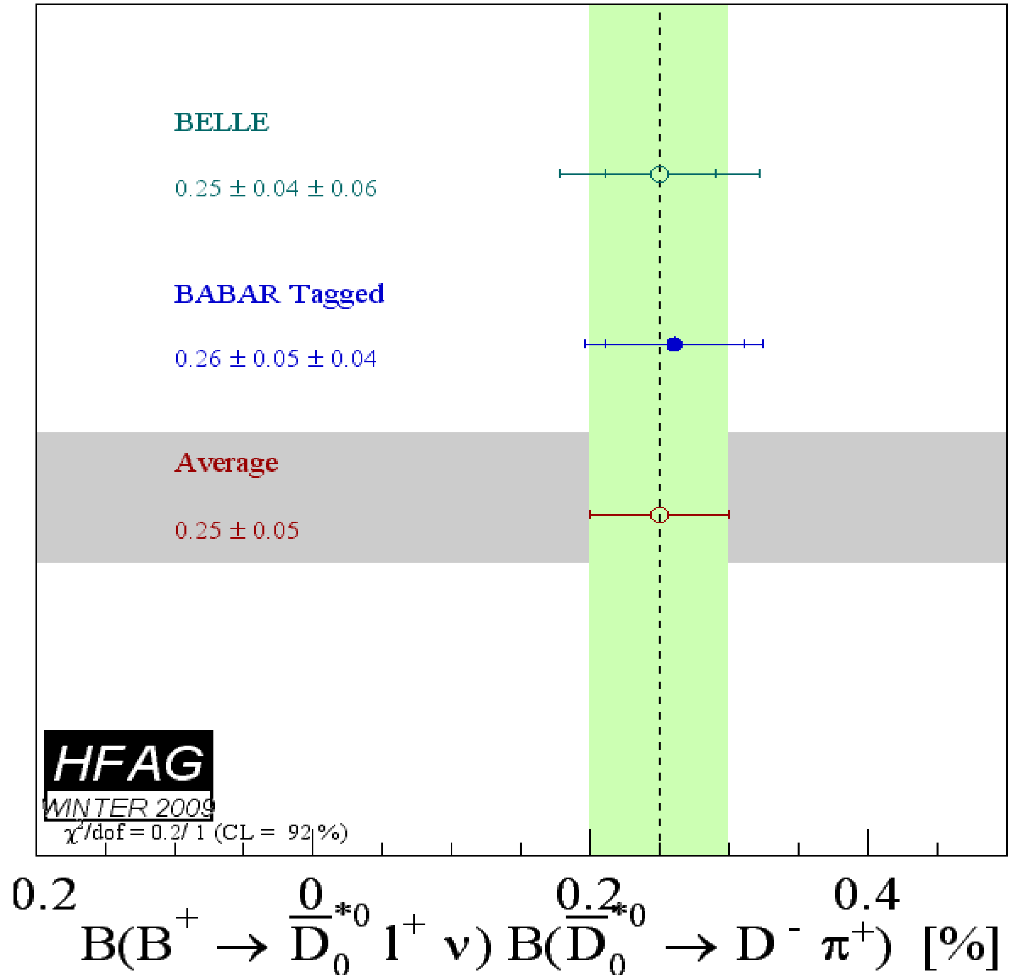




- Excellent agreement of the most precise measurements, in particular the tagged and untagged Babar analysis

Consistency: the big Picture





- Situation more complicated for the broad states.....

Comments

- BaBar and Belle measure $\mathcal{B}(B \to D^{(*)}\pi\ell\nu) \sim 1.5\%$
- About 0.6% of this rate is due to the narrow D_1 and D_2 states
- What is the rest?
- BaBar measures about 0.9% for the broad states (an old measurement from Delphi is in agreement with the BaBar findings),
- Belle agrees for the D_0^*, while it sets a very stringent upper limit for the D_1'
- We are left with 2 puzzles:
  The broad rate is in contrast with theoretical predictions (3/2 vs 1/2 puzzle, see also Bigi's talk)
  What is the difference between the inclusive rate and the Σ Excl$(D/D^*/D^{(*)}\pi\ell\nu)$?

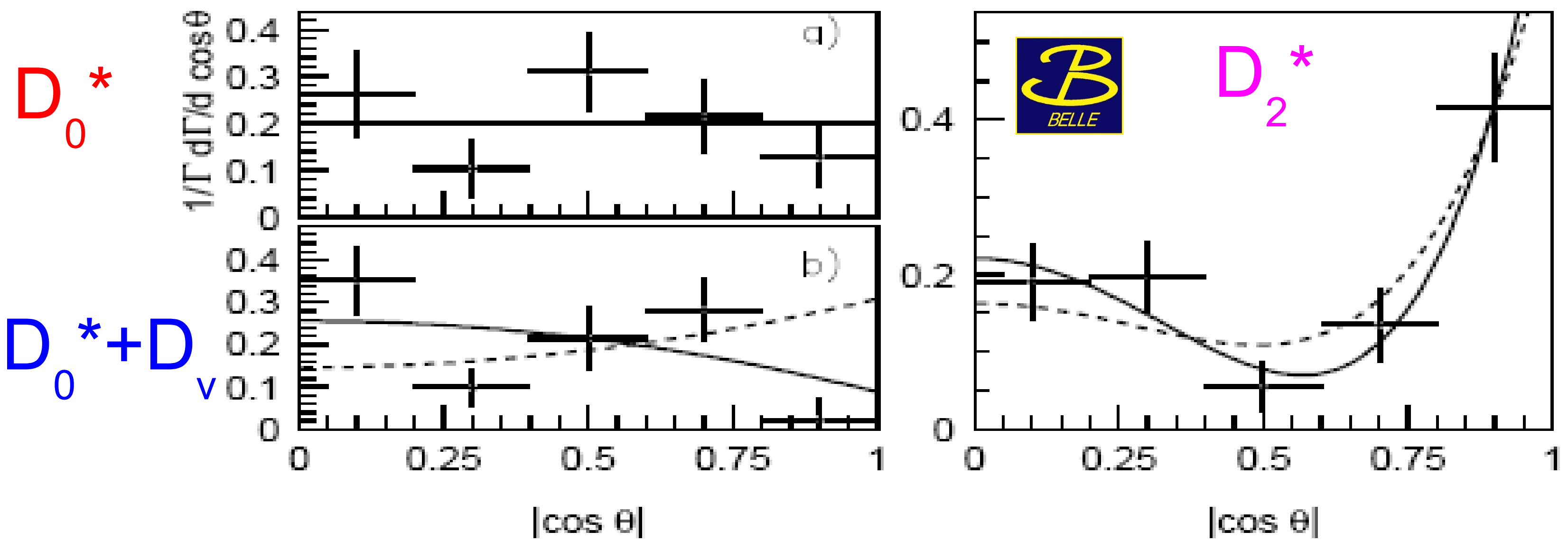
On the 3/2 vs 1/2 puzzle

- Both Babar and Belle include the possibility for a non-resonant $D^{(*)}$ component, finding a rate consistent with zero
- A study of the helicity distribution can be used to confirm/not if the fitted "broad" component is consistent with the expected quantum numbers

Belle only reports the helicity study for the $D_2(D\pi)$ and $D_0^*(D\pi)$ channels

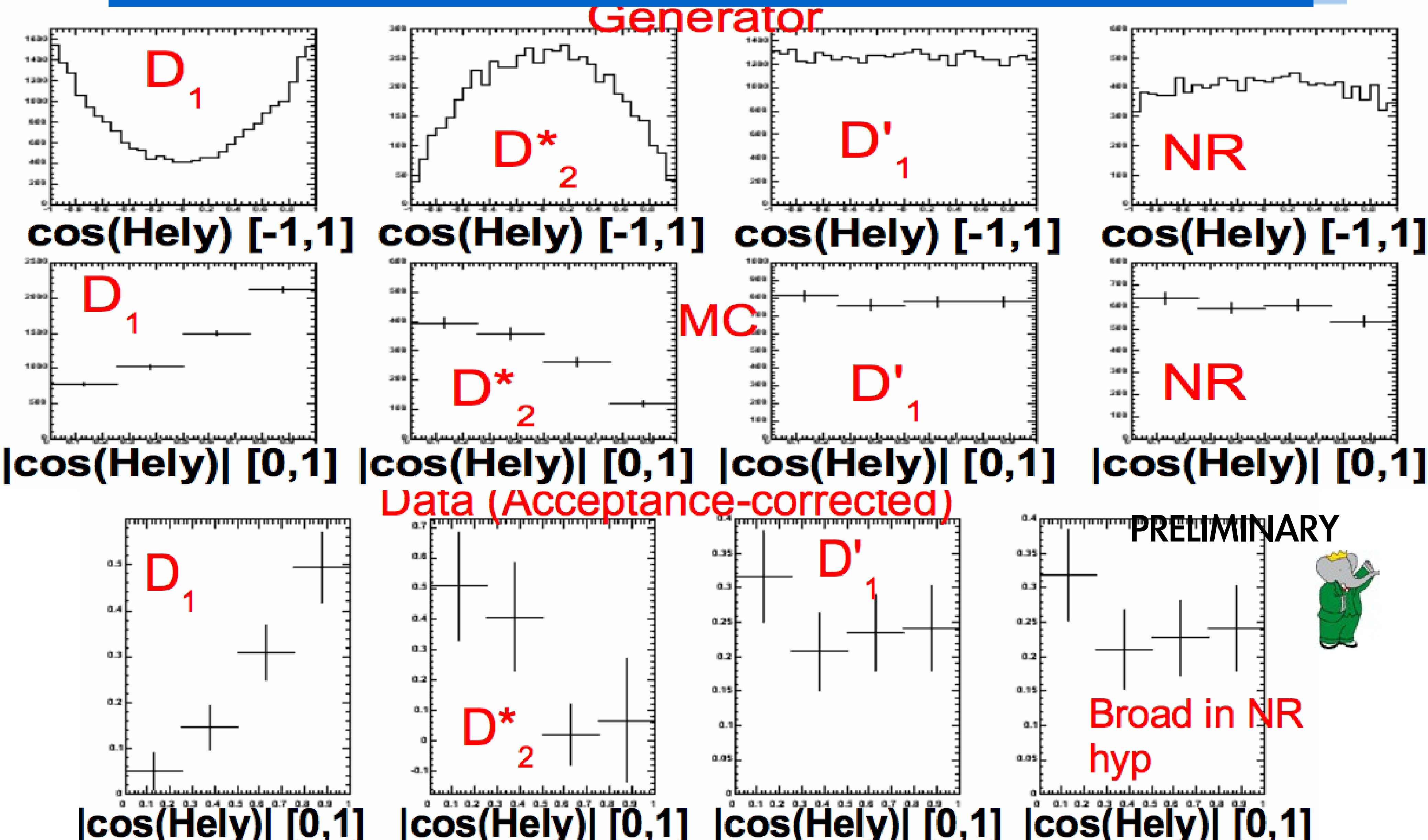
- Fit of the invariant mass in helicity bins; fit |**hely**| with theoretical shapes for tensor and scalar states

Confirm predictions for these two states

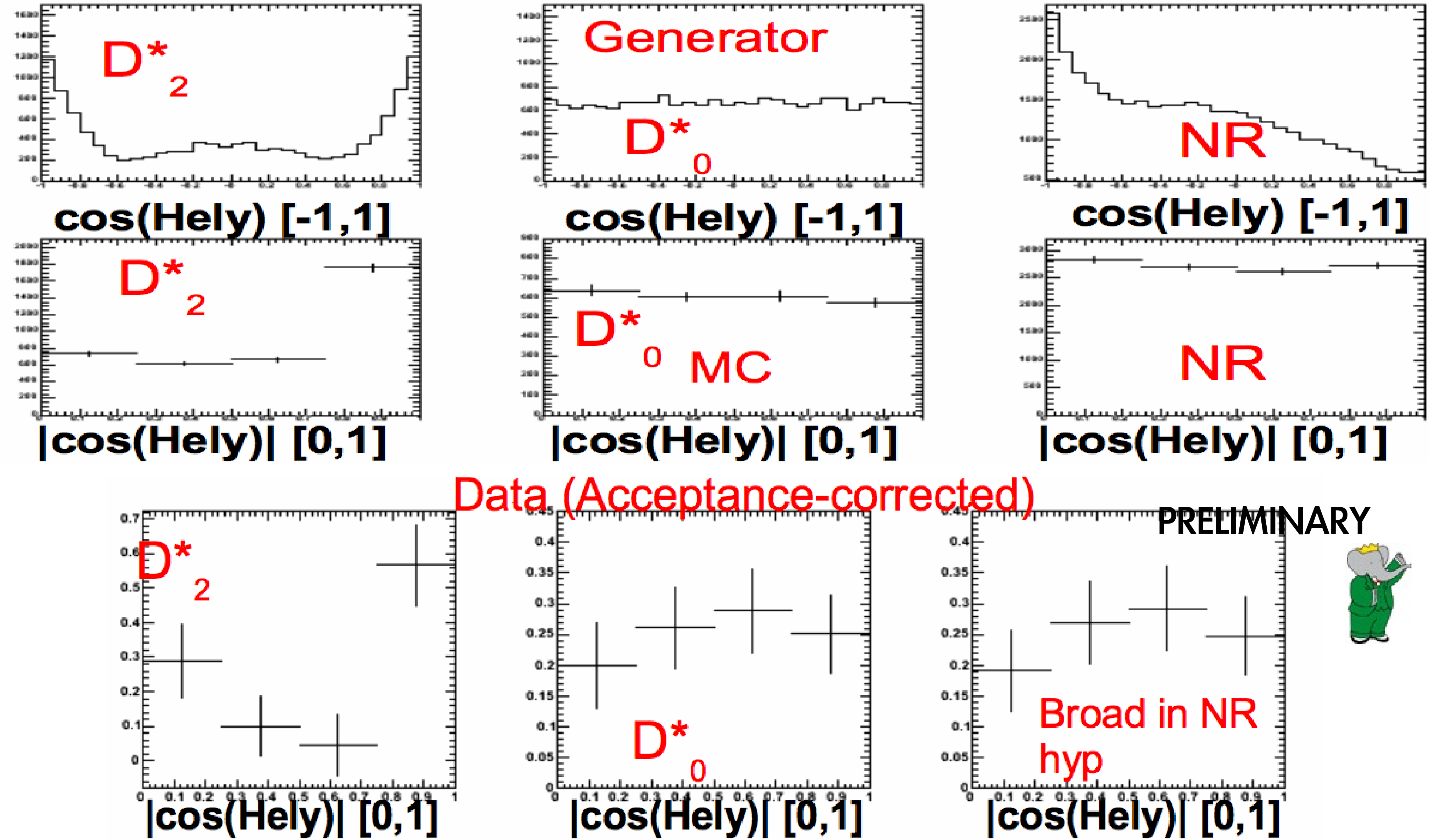


Theory – dashed line
D_v -- virtual D^* produced off-shell

On the 3/2 vs 1/2 puzzle



On the 3/2 vs 1/2 puzzle

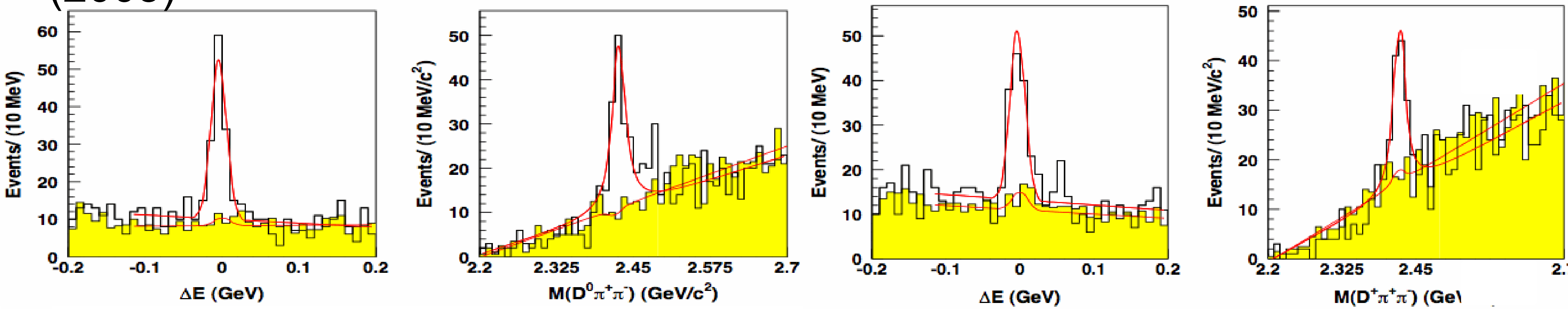


On the 3/2 vs 1/2 puzzle

- The helicity distributions can help in confirm the nature of the measured “broad” states, but current statistics is a problem
- It was also suggested (I. Bigi) that the measured broad states are radial excitations (p-wave)
- Also in this case, an helicity study could help, but statistics may be a limiting factor also for the full dataset/final measurement from BaBar and Belle

On the Incl-Σ Excl puzzle

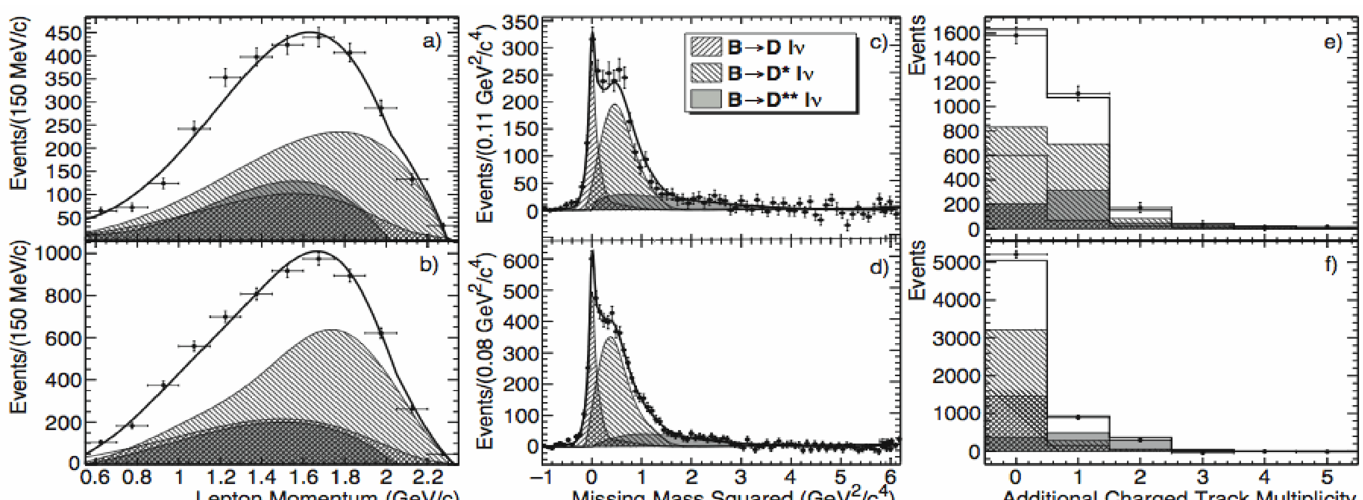
- The most likely candidate to fill the inclusive rate is $B \to D^{(*)} n\pi \ell\nu$,with n>1:
- We have already evidence for $D^{**} \to D\pi\pi$ decays, Belle PRL 94, 221805 (2005)



- BaBar measured the relative branching fraction

$\mathcal{B}(B \to D^{(*}(n\pi)\ell\nu)/$

$\mathcal{B}(B \to DX\ell\nu)$=0.197 ± 0.013 ± 0.013 ± 0.012, PR D76, 051101 (2007)



On the Incl-Σ Excl puzzle

- How likely is that we will observe $B \to D^{(*)}\pi\pi\ell\nu$ decays?
- The hadronic tag is the most obvious choice
- Challenging however, high multiplicity on the SL side affects hadronic tag selection/purity
- If we assume a rate of 0.2% for $B \to D_{1,2}\ell\nu$, $D_{1,2} \to D^{(*)}\pi\pi$, we should see a few tens of events in 1 ab^{-1} of Belle data
- BaBar has a new hadronic tag algorithm, expect about >100% improvement in signal yield w.r.t. previous BaBar tagged analysis
- Manpower however is clearly an issue at this point in the experiments

Conclusions

- Comparing with a few years ago, our knowledge of B semileptonic decays to orbitally excited D mesons has grown a lot
- However, puzzles remain:
  Large rate for the broad components
  Large difference between the BaBar and Belle results
  Role of $D \rightarrow D^{(*)}\pi\pi$ decays
- Measurements are still statistically limited!
  Room for improvement
- Is it worth?
  Yes, systematic uncertainty in $|V_{cb}|$ and $|V_{ub}|$ is directly affected by our knowledge of D** states

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