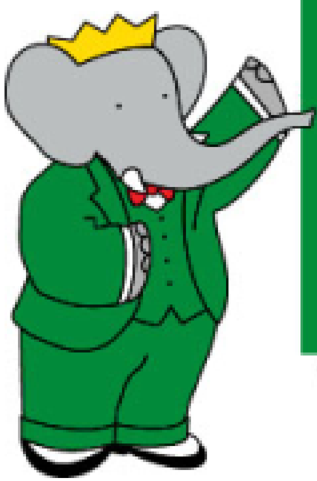
Semileptonic Decays at BABAR™



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Semileptonic Decays at BaBar

- $|V_{ub}|$ from $B\to X_u l\nu$ decays
- Isospin violation in $B\to X_u l\nu$ decays
- $B^-\to D^{*0}e\nu$
- $B\to D/D^*/D^{**}l\nu$
- $B\to D^{(*)}\tau\nu$
- Conclusions

See also Kerstin Tackmann's talk on Friday morning for more about $|V_{cb}|$ and SL decays (and a whole lot more)

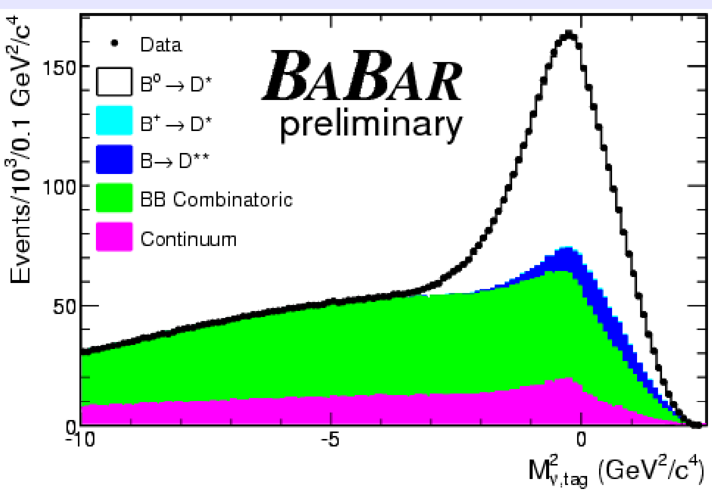
Experimental Techniques

B-factory operation: $e^+e^- \to \Upsilon(4S) \to B^+B^-$ or $B^0\overline{B}^0$ (~50% each)

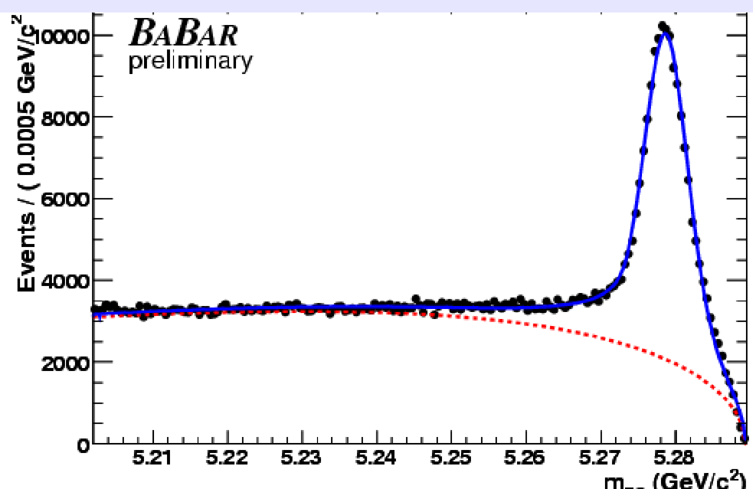
Untagged analysis: Reconstruct $X+l$ from one $B \to Xl\nu$ decay

"Tagged" analyses provide kinematic constraints, BG suppression for the other B

- $B^0 \to D^{*-} l\nu$ **partial reco**
  - e or μ, π_s from $D^{*-} \to D^0\pi_s$
  - Calculate $M^2_{\nu,tag}$ assuming D^0 was produced parallel to π_s



- $B_{tag} \to D^{(*)}Y^{\pm}$ **Full reconstruction**
  - $Y^{\pm} \in \pi^{\pm}, \pi^0, K^{\pm}, K_S$
  - over 1000 modes, ε = 0.3 – 0.5%
  - Determines momentum, charge and flavor of the other B



Inclusive $B \to X_u l\nu$ Measurement

- Precision measurement of $|V_{ub}|$ is one of the main goals of the *B*-factory program
  - Along with β, $|V_{ub}|$ helps to determine the apex of the unitarity triangle
- Can measure $|V_{ub}|$ by studying exclusive modes $B \to \pi l\nu$, $\rho l\nu$, etc..., or the inclusive mode $B \to X_u l\nu$
  - Challenging because background from $B \to X_c l\nu$ is ~50x larger
  - Need to select regions of phase space where charm BG is suppressed

$$\Gamma(B \to X_u \ell \nu) = \frac{G_F^2 |V_{ub}|^2 m_b^5}{192\pi^3}\left[1 + \mathcal{O}(\alpha_s) + \mathcal{O}(1/m_b^2) + \ldots\right]$$

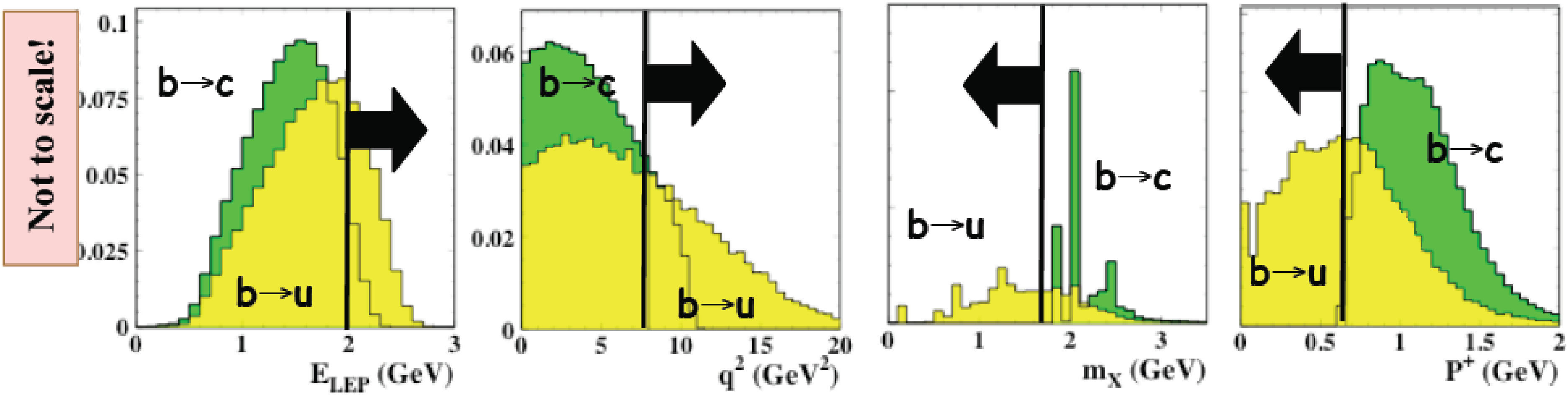
OPE calculation ~5% uncertainty

Need *b*-quark mass to extract $|V_{ub}|$
More details in K. Tackmann's talk

$B \to X_u l\nu$ Signal Reconstruction

- Reconstruct B_{tag} + lepton
- Assign all remaining particles in event to the X_u system

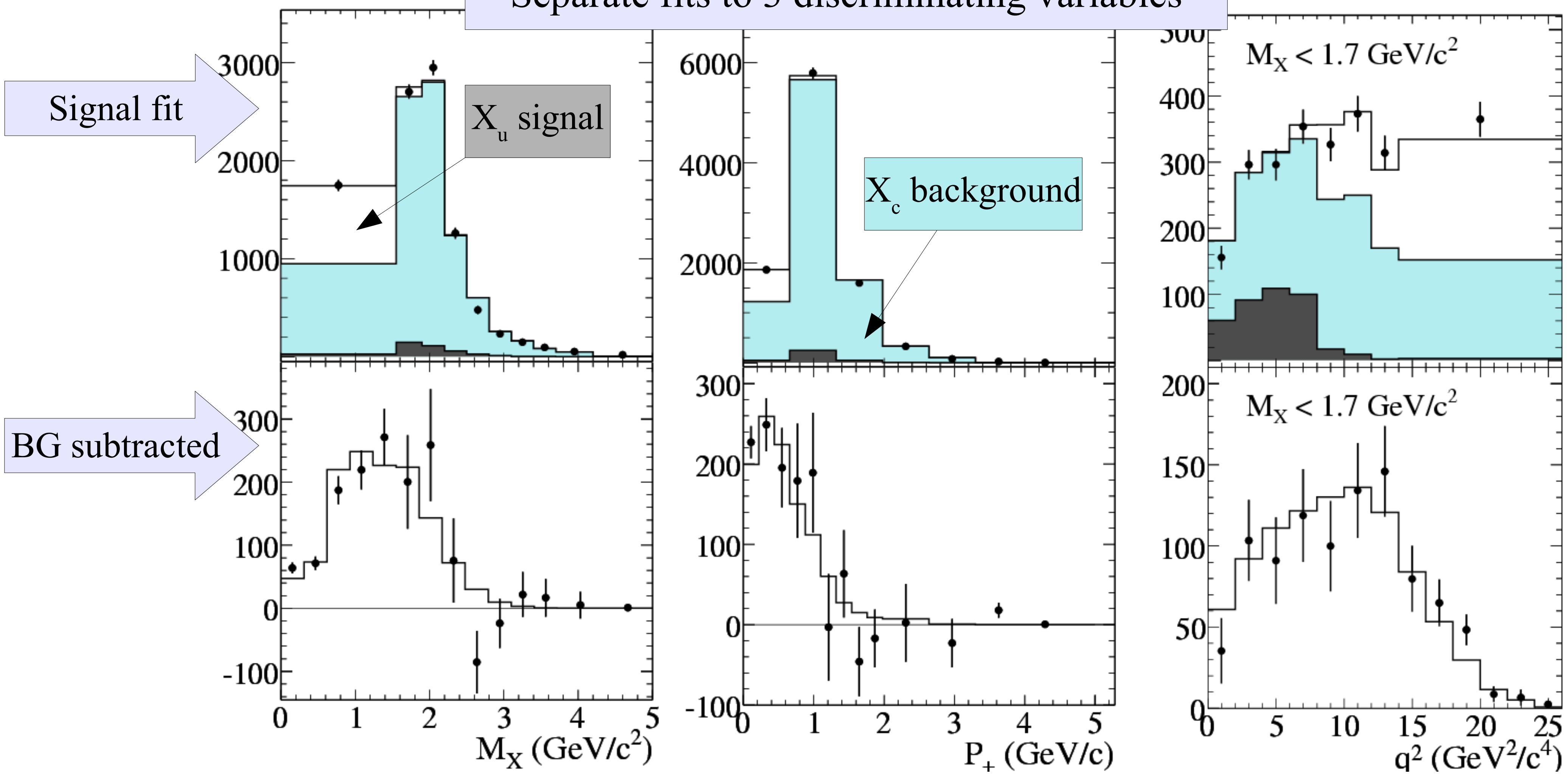
Use kinematics to distinguish X_u signal from X_c background ($m_c >> m_u$)



- E_{LEP} = lepton energy
- q^2 = momentum transfer squared = $(p_B - p_X)^2 = (p_l + p_\nu)^2$
- m_X = mass of the hadronic system
- P+ = $E_X - |p_X|$ = light-cone component of X momentum

$B \to X_u l\nu$ Signal Fits

Separate fits to 3 discriminating variables



Branching Fractions and $|V_{ub}|$

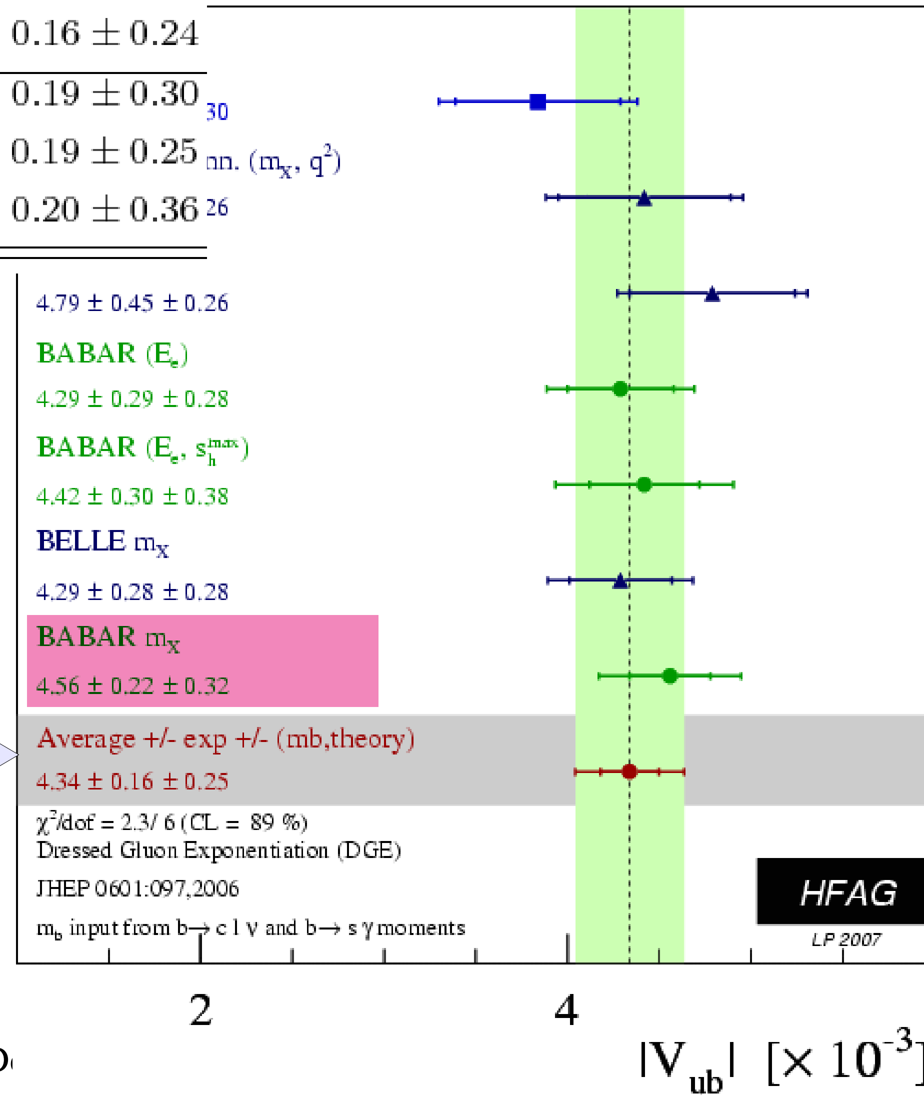
	$\Delta\mathcal{B}(\overline{B} \to X_u \ell \bar{\nu})$ (10^{-3})	$\lvert V_{ub}\rvert$ (10^{-3})
$M_X < 1.55$ GeV/c^2	$1.18 \pm 0.09 \pm 0.07 \pm 0.01$	$4.27 \pm 0.16 \pm 0.13 \pm 0.30$
		$4.56 \pm 0.17 \pm 0.14 \pm 0.32$
$P_+ < 0.66$ GeV/c^2	$0.95 \pm 0.10 \pm 0.08 \pm 0.01$	$3.88 \pm 0.19 \pm 0.16 \pm 0.28$
		$3.99 \pm 0.20 \pm 0.16 \pm 0.24$
$M_X < 1.7$ GeV/c^2, $q^2 > 8.0$ GeV$^2/c^4$	$0.76 \pm 0.08 \pm 0.07 \pm 0.02$	$4.48 \pm 0.22 \pm 0.19 \pm 0.30$
		$4.53 \pm 0.22 \pm 0.19 \pm 0.25$
		$4.81 \pm 0.23 \pm 0.20 \pm 0.36$

Extraction of $|V_{ub}|$ depends on theoretical framework

383M BB pairs

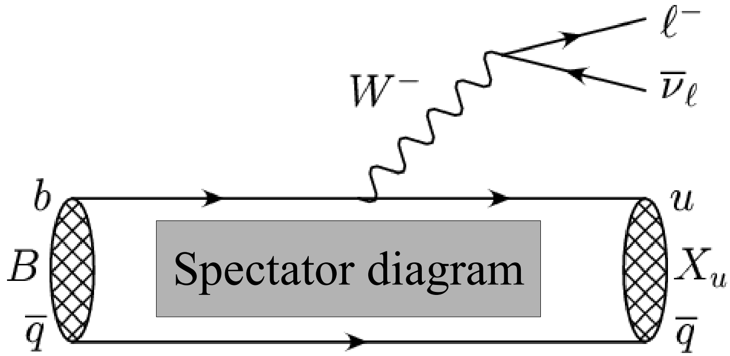
Dominant systematic errors due to MC statistics and reconstruction efficiency

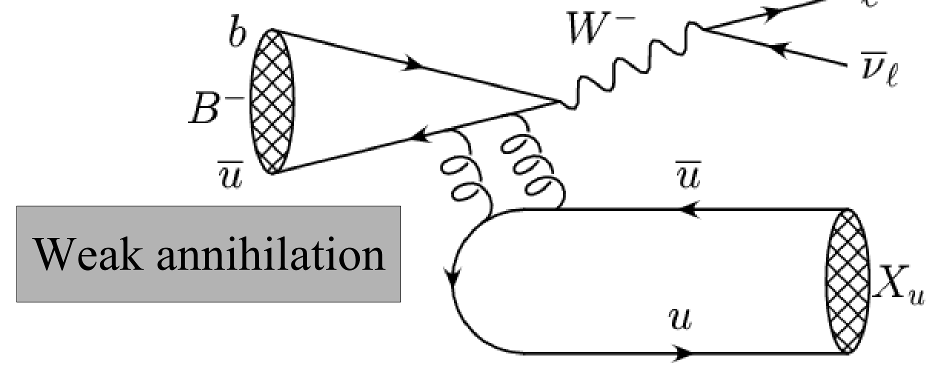
HFAG comparison of $|V_{ub}|$ in DGE framework



arXiv:0708.3702 [hep-ex] submitted to PRL

Isospin Violation in $B \to X_u l\nu$





- Weak annihilation only occurs for charged B decays
  - Expected to be ~few % of the total $B \to X_u l\nu$ rate
    - Up to 30% in some regions of phase space

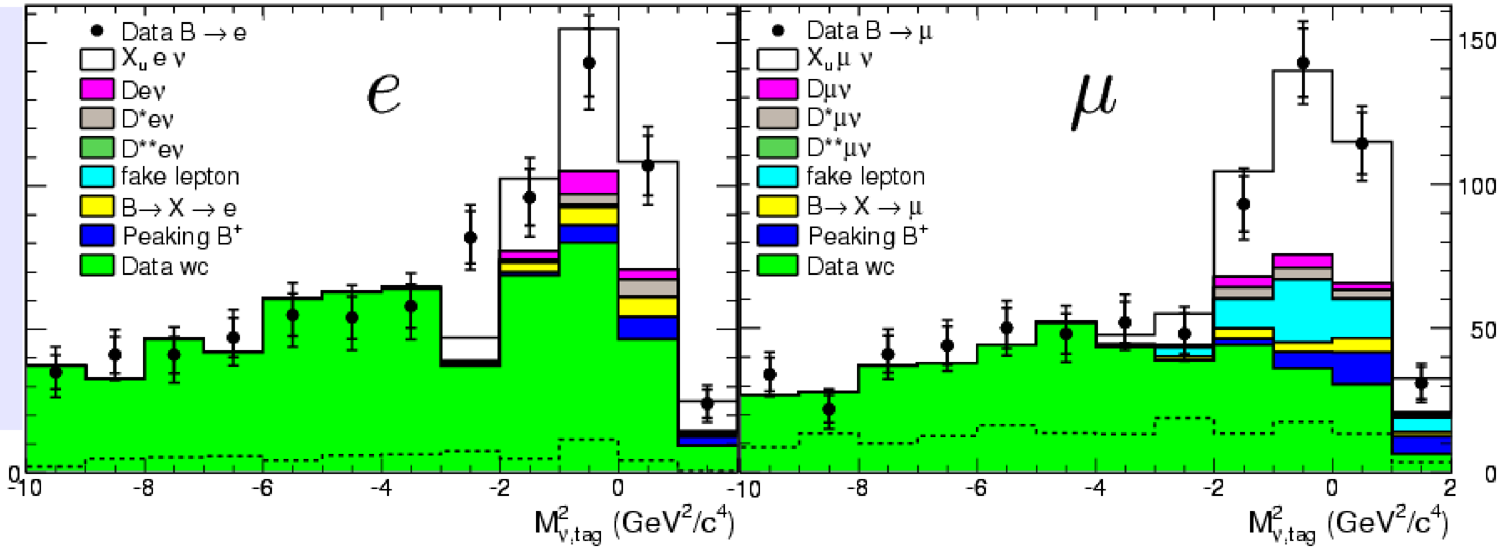
see, i.e., Leibovich, Ligeti, and Wise, PL**B539** 242.

- Tag $B^0\overline{B}^0$ events by partially reconstructing one B meson as $B^0 \to D^{*-} l\nu$
- Compare B^0 results to untagged (mix of B^+B^-, $B^0\overline{B}^0$) to look for isospin breaking

Isospin Violation Results

Fit $M^2_{\nu,tag}$ to determine signal yield

- 3 overlapping momentum intervals



ΔP_ℓ	$\Delta\mathcal{B}(B)\cdot 10^4$	$\Delta\mathcal{B}(B^0)\cdot 10^4$	$R^{+/0}$
$2.2-2.6\,\mathrm{GeV}/c$	$2.31\pm0.10\pm0.18$	$2.62\pm0.33\pm0.16$	$0.71\pm0.22\pm0.16$
$2.3-2.6\,\mathrm{GeV}/c$	$1.46\pm0.06\pm0.10$	$1.30\pm0.21\pm0.07$	$1.18\pm0.35\pm0.17$
$2.4-2.6\,\mathrm{GeV}/c$	$0.75\pm0.04\pm0.06$	$0.76\pm0.15\pm0.05$	$0.91\pm0.37\pm0.18$

arXiv:0708.1753 [hep-ex]

Untagged BaBar measurement
PR **D73** 012006 (2006)

$$\frac{|\Gamma_{WA}|}{\Gamma_u} < \frac{3.8\ \%}{f_{WA}(2.3-2.6)}, \quad \text{at 90\% C.L.}$$

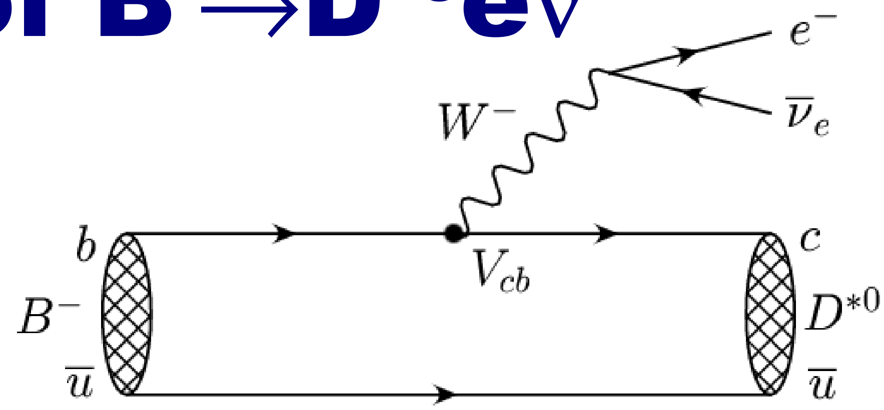
Compatible with CLEO result $(\Gamma_{WA}/\Gamma_u)<7.4\%$
PRL **96** 121801

Measurement of $B^- \to D^{*0} e \nu$

$$\frac{d\Gamma}{dw}(B \to D^* \ell \nu) = \frac{G_F^2 |V_{cb}|^2}{48\pi^3} \mathcal{F}^2(w) \mathcal{G}(w)$$

Form factor

Phase space



$$w \equiv \frac{m_B^2 + m_{D^*}^2 - q^2}{2 m_B m_{D^*}}$$

- $B \to D^* l \nu$ has been extensively studied, but discrepancies still exist:
  - CLEO's BF for $D^{*0} l \nu$ much larger than that of $D^{*+} l \nu$ (including factor τ^+/τ^0)
  - Form factor slope ρ^2 is not quite consistent
- Goal: measure BF, $d\Gamma/dw$, $|V_{cb}|$ in the D^{*0} channel
  - Main experimental systematic error (low-momentum π^0 efficiency) is distinct from D^{*+} analysis
  - Independent measurement will help to resolve these discrepancies

$B^- \to D^{*0} e\nu$ – Signal Fit

- Binned maximum likelihood fit to:

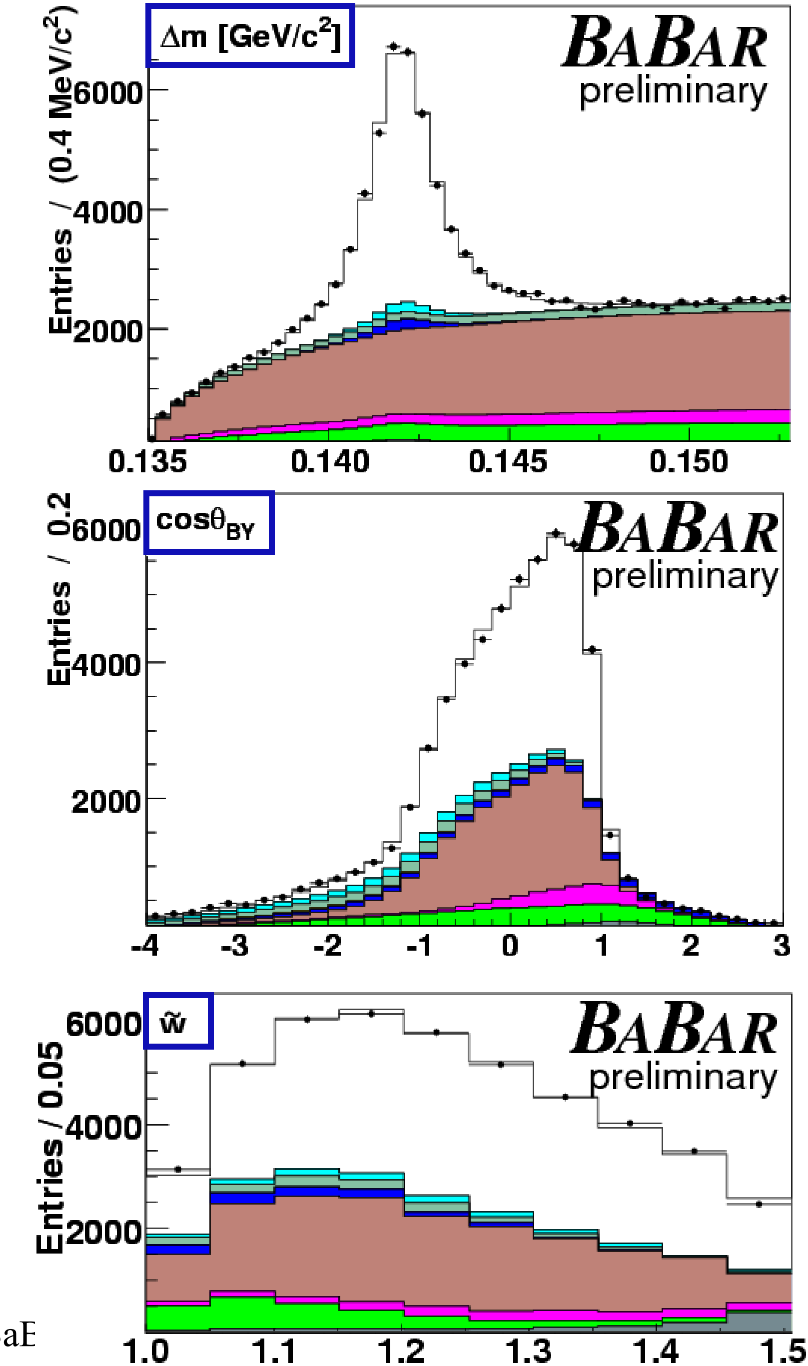
$$\Delta m \equiv m(D^{*0}) - m(D^0)$$

$$\cos\theta_{BY} \equiv \frac{2E_B E_Y - m_B^2 - m_Y^2}{2p_B p_Y}$$

$$\widetilde{w} \approx w \equiv \frac{m_B^2 + m_{D^*}^2 - q^2}{2m_B m_{D^*}}$$

$Y \equiv D^{*0} l$

226M BB pairs
Fit 23500±330 signal events



- Signal
- D^{**} (Δm-peaking)
- D^{**} (Δm-flat)
- Correlated
- Uncorrelated
- Signal like
- $D^0 e\nu$
- Combinatorial D^{*0}
- $c\bar{c}$ events

$B^- \to D^{*0} e\nu$ – Results

arXiv:0707.2655 [hep-ex]

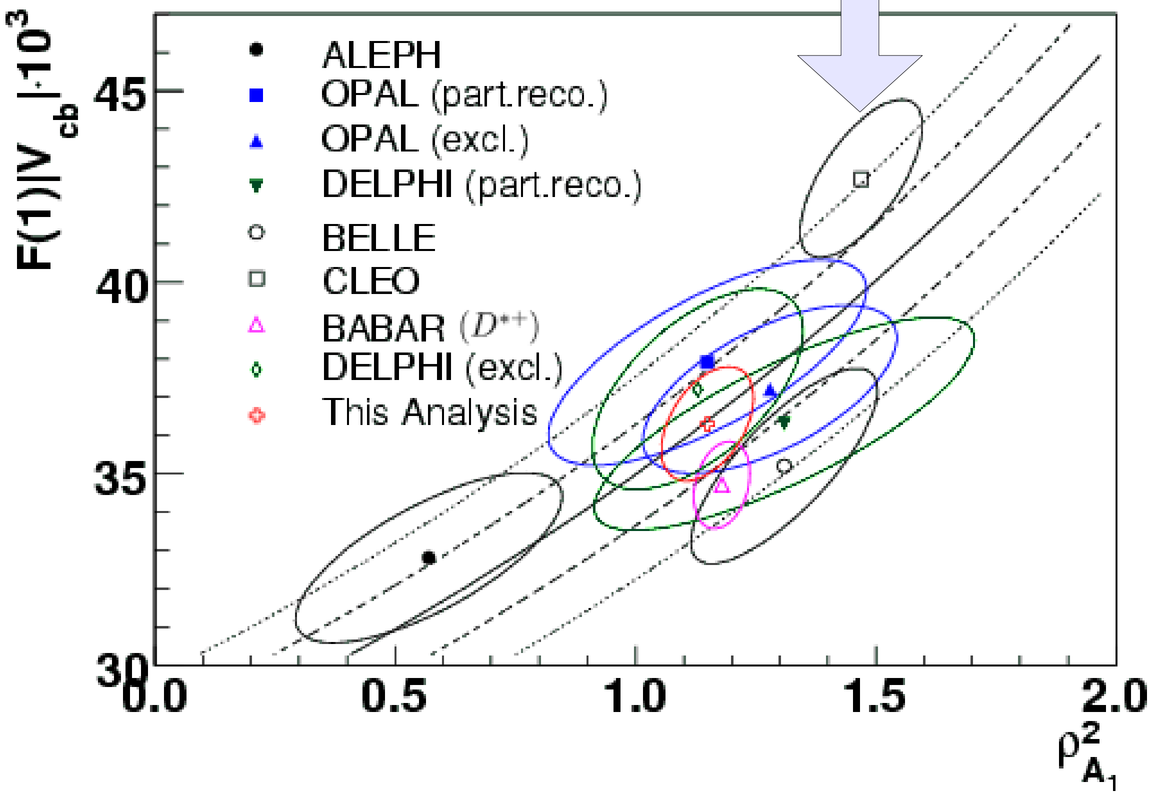
Take $F(1)$ from theory to get $|V_{cb}|$

$$\mathcal{F}(1) \cdot |V_{cb}| = (36.3 \pm 0.6 \ \pm 1.4) \times 10^{-3}$$

$$\rho^2_{A_1} = 1.15 \ \pm 0.06 \pm 0.08$$

$$\mathcal{B}(B^- \to D^{*0} e^- \overline{\nu}_e) = (5.71 \pm 0.08 \pm 0.41)\%$$

Only one previous D^{*0} result



- Main systematic uncertainties
  - π^0 efficiency
  - BF ($D^{*0} \to D^0\pi^0$)
  - Form factor ratios R1, R2

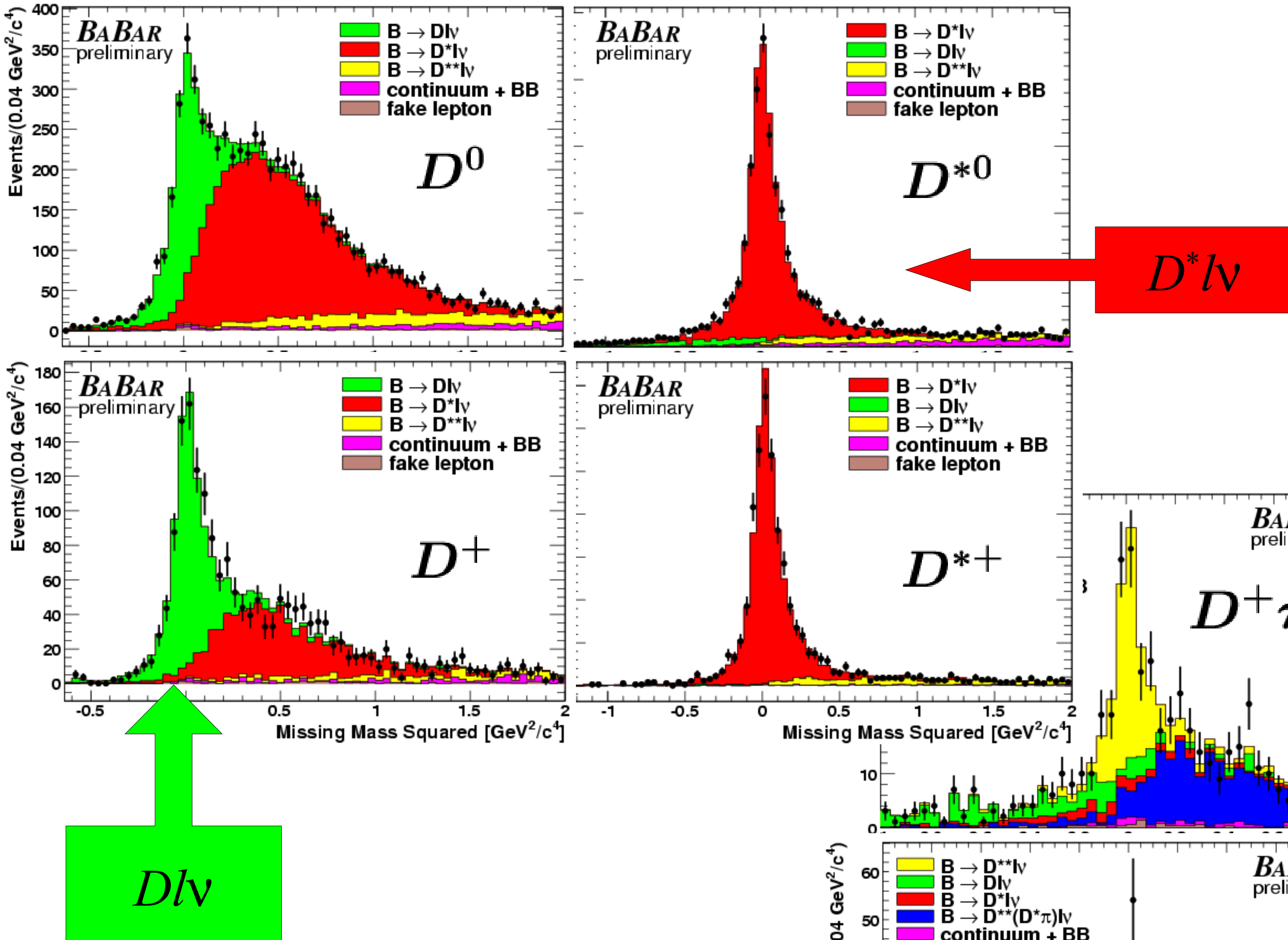
$B \to D/D^*/D^{**} l\nu$

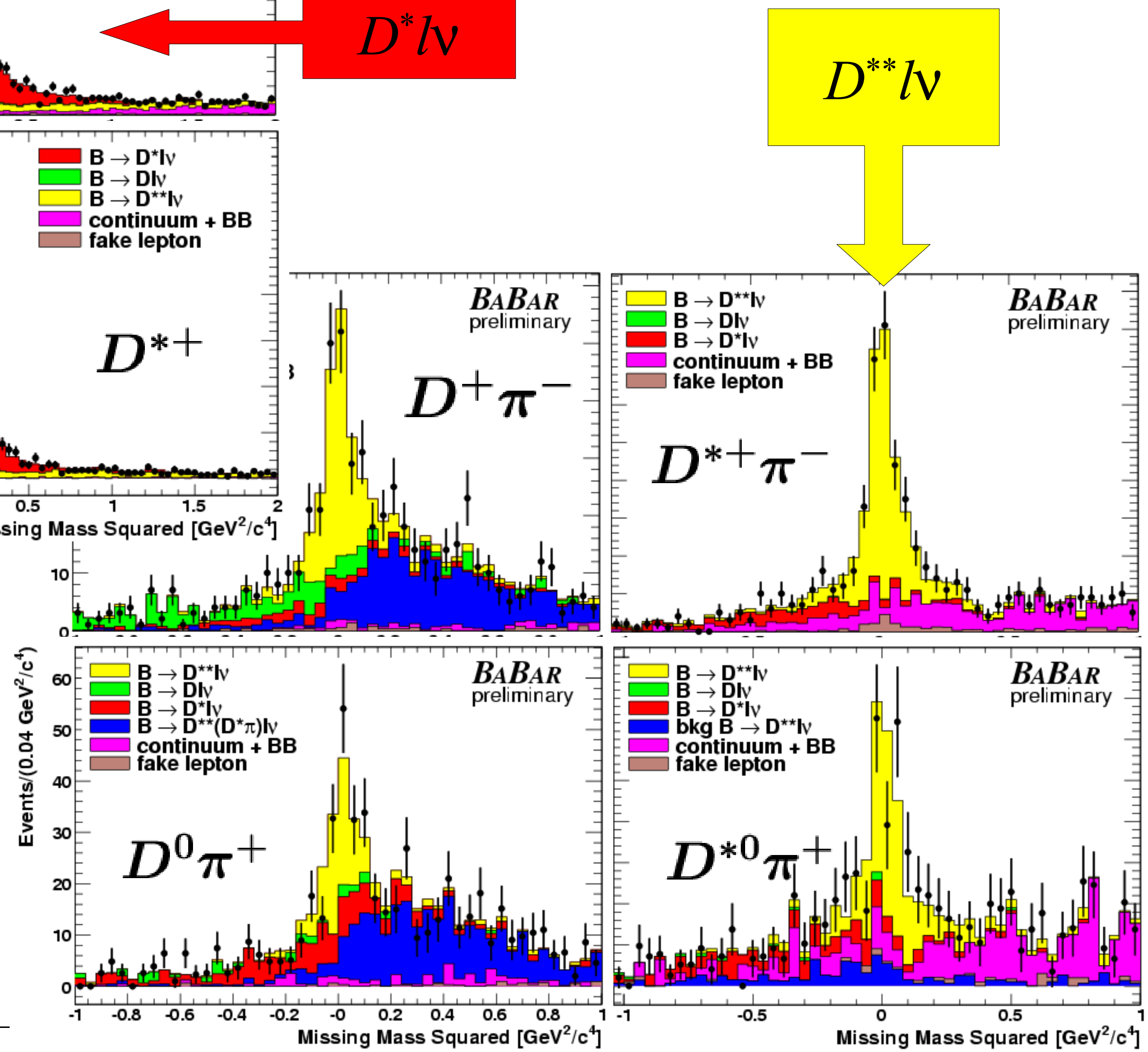
- Try to understand the composition of exclusive states in $B \to X_c l\nu$
  - Further help to resolve D^{*0}/D^{*+} isospin puzzle
  - Understand role of D^{**} decays in saturating inclusive semileptonic rate

- Experimental approach
  - Fully reconstruct B_{tag}
  - Reconstruct lepton (e or μ) in the recoil
  - Reconstruct D^0, D^+, D^{*0}, D^{*+}, as well as $D^{(*)}\pi^{\pm}$ in the recoil
  - Extract signals by fitting m^2_{miss}

$$m_{miss}^2 = (p(\Upsilon(4S)) - p(B_{tag}) - p(D^{(*)}(\pi)) - p(\ell))^2$$

B→D/D*/D**lν Signal Fits





$B \to D/D^*/D^{**} l\nu$ Results

arXiv:0708.1738 [hep-ex]

$$\mathcal{B}(B^- \to D^0 \ell^- \bar{\nu}_\ell) = (2.33 \pm 0.09_{stat.} \pm 0.09_{syst.})\%$$
$$\mathcal{B}(B^- \to D^{*0} \ell^- \bar{\nu}_\ell) = (5.83 \pm 0.15_{stat.} \pm 0.30_{syst.})\%$$
$$\mathcal{B}(\overline{B^0} \to D^+ \ell^- \bar{\nu}_\ell) = (2.21 \pm 0.11_{stat.} \pm 0.12_{syst.})\%$$
$$\mathcal{B}(\overline{B^0} \to D^{*+} \ell^- \bar{\nu}_\ell) = (5.49 \pm 0.16_{stat.} \pm 0.25_{syst.})\%$$
$$\mathcal{B}(B^- \to D^+ \pi^- \ell^- \bar{\nu}_\ell) = (0.42 \pm 0.06_{stat.} \pm 0.03_{syst.})\%$$
$$\mathcal{B}(B^- \to D^{*+} \pi^- \ell^- \bar{\nu}_\ell) = (0.59 \pm 0.05_{stat.} \pm 0.04_{syst.})\%$$
$$\mathcal{B}(\overline{B^0} \to D^0 \pi^+ \ell^- \bar{\nu}_\ell) = (0.43 \pm 0.08_{stat.} \pm 0.03_{syst.})\%$$
$$\mathcal{B}(\overline{B^0} \to D^{*0} \pi^+ \ell^- \bar{\nu}_\ell) = (0.48 \pm 0.08_{stat.} \pm 0.04_{syst.})\%$$

378M BB pairs

$D^{*0} l\nu$ BF consistent with untagged result (5.71±0.08±0.41)%

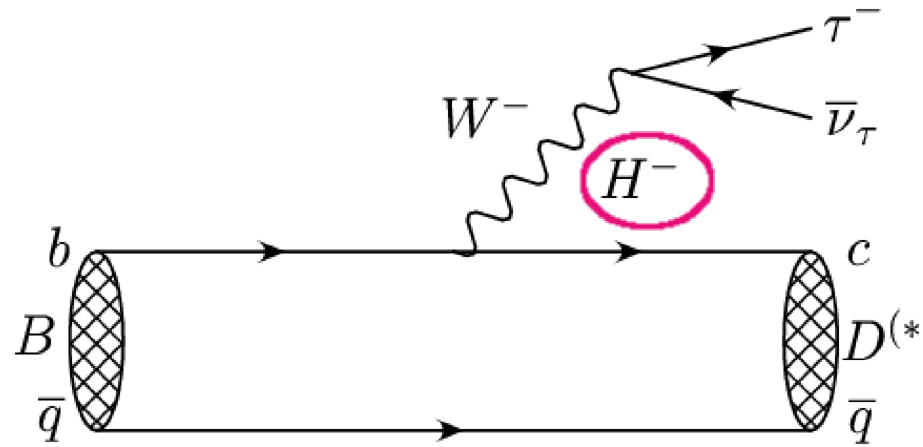
All results compatible with isospin symmetry

Most precise individual branching fraction measurements

Dominant systematic errors due to $D^{(*)}$ BFs, B_{tag} selection, and charged-track reconstruction

Measurement of $B \to D^{(*)}\tau\nu$

- Large τ mass gives sensitivity to new physics at tree level
  - Charged Higgs boson



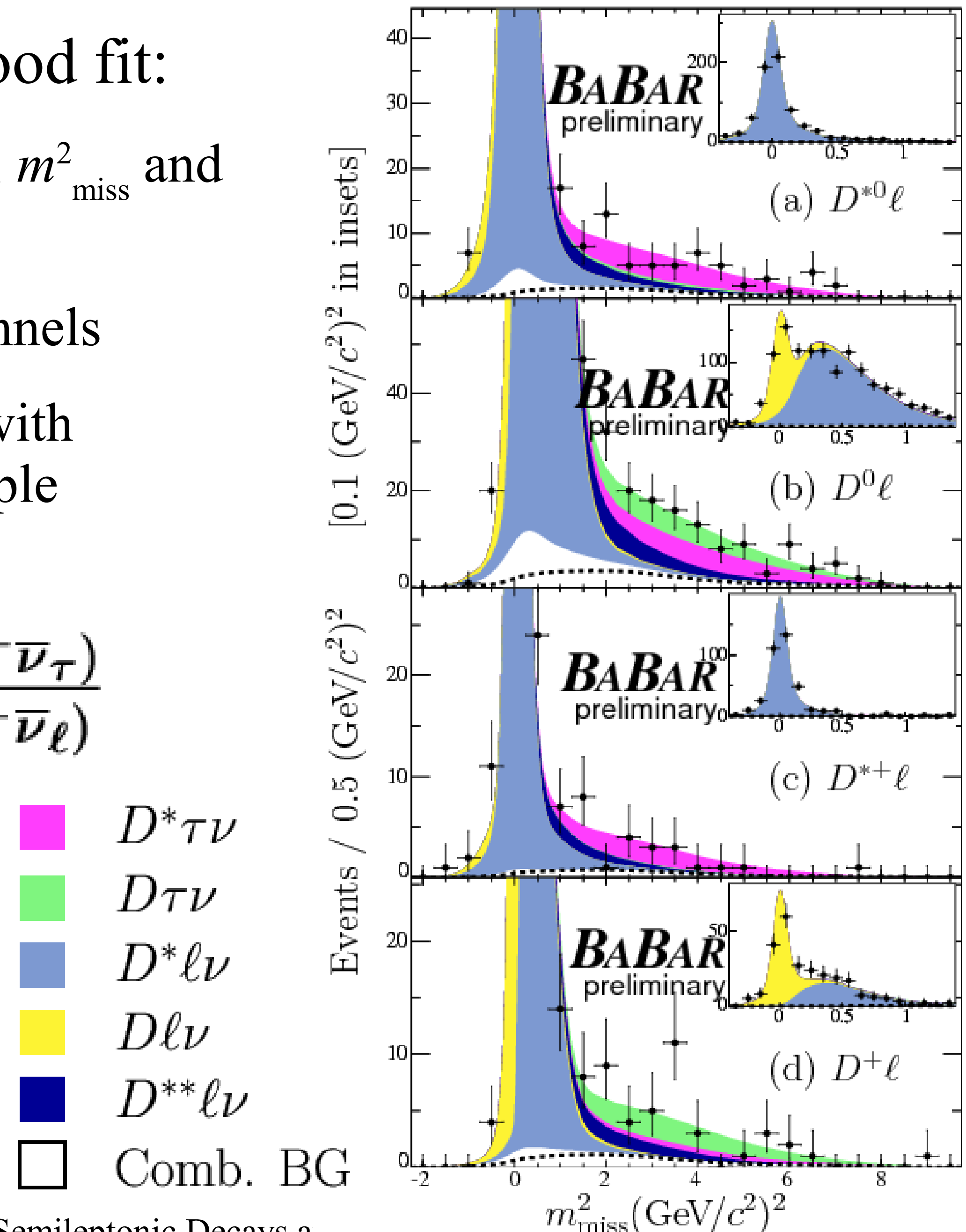
- Very challenging: $\tau \to e\nu\nu$, $\mu\nu\nu$ decay produces additional ν's
- Simultaneous measurement of $D^0\tau\nu$, $D^{*0}\tau\nu$, $D^+\tau\nu$, $D^{*+}\tau\nu$
  - B_{tag}, D/D^* + lepton in recoil
  - Look for events with **large** m^2_{miss} – signal events have 3ν
  - Use m^2_{miss}~0 region to normalize signals

$B \to D^{(*)}\tau\nu$ – Signal Fit

- Unbinned maximum likelihood fit:
  - Two discriminating variables, m^2_{miss} and lepton momentum
  - Simultaneous fit to 4 $D^{(*)}$ channels
  - Constrain $D^{**}l\nu$ background with independent data control sample
- Measure $$R \equiv \frac{\mathcal{B}(B \to D^{(*)}\tau^- \overline{\nu}_\tau)}{\mathcal{B}(B \to D^{(*)}\ell^- \overline{\nu}_\ell)}$$

232M BB pairs

Fit 66.9±18.9 $D\tau\nu$ signal
101.4±19.1 $D^*\tau\nu$ signal



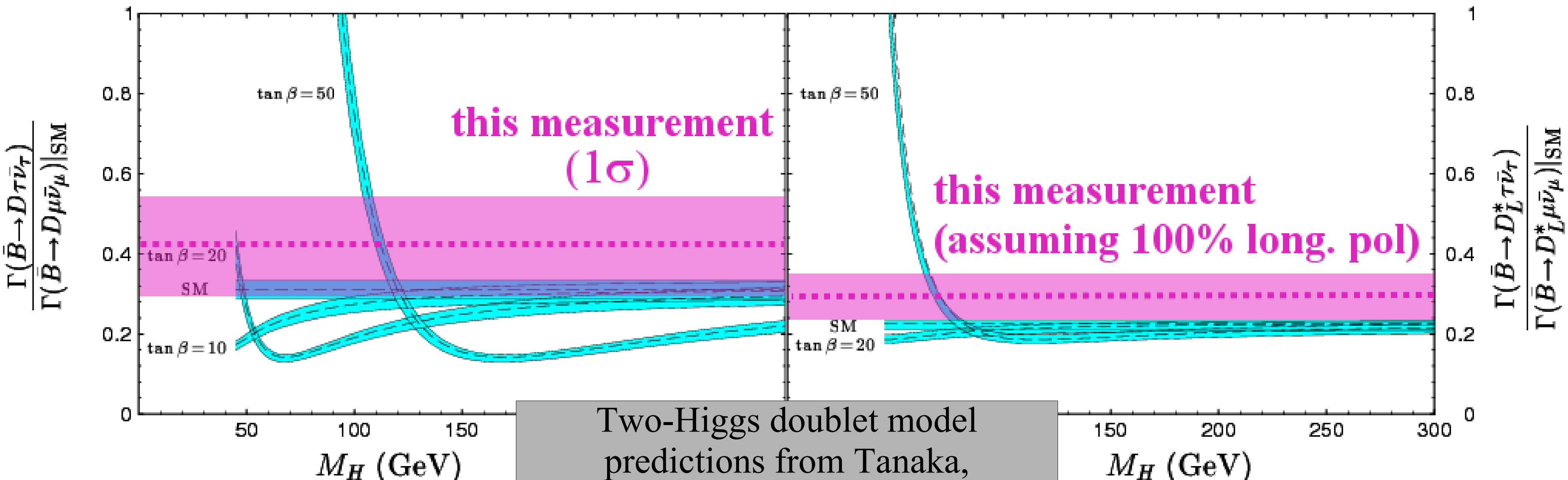
$B \rightarrow D^{(*)}\tau\nu$ – Results

arXiv:0709.1698 [hep-ex] submitted to PRL

Mode	$\mathcal{R}$ [%]	$\mathcal{B}$ [%]	
$B \rightarrow D\tau^-\overline{\nu}_\tau$	41.6±11.7±5.2	$0.86 \pm 0.24 \pm 0.11 \pm 0.06$	3.6σ
$B \rightarrow D^*\tau^-\overline{\nu}_\tau$	29.7± 5.6±1.8	$1.62 \pm 0.31 \pm 0.10 \pm 0.05$	6.2σ

Main systematic errors from PDF parameterization, combinatoric BG model

D^{*}-τν consistent with Belle result
Other modes studied for the first time



Two-Higgs doublet model predictions from Tanaka, Z. Phys **C67** 321

Summary

- $|V_{ub}|$ from $B \to X_u l\nu$ decays
  - Tests of the CKM mechanism for CP violation
  - Current precision on $|V_{ub}|$ ~8% (previous BaBar measurement was ~13%)
  - Limit on WA contribution will allow greater precision in $|V_{ub}|$ extraction
- $B^- \to D^{*0} e\nu$ and $B \to D/D^*/D^{**} l\nu$
  - New precise measurements of $|V_{cb}|$, ρ^2, and BFs help resolve discrepancies
  - Working towards understanding all of the contributions to the inclusive rate
- $B \to D^{(*)}\tau\nu$
  - First evidence for $D\tau\nu$ and observation of $D^*\tau\nu$
  - Study of τ modes can provide limits on $H^\pm$

FINE

Backup: Systematic Errors

$|V_{ub}|$

	Detector	Shape function	$\mathcal{B}(\overline{B} \to X_u \ell \bar{\nu})$ $X_u = \pi, \rho, \ldots$	Gluon splitting	$\mathcal{B}(\overline{B} \to X_c \ell \bar{\nu})$	$B \to D^* \ell^- \bar{\nu}$ form factors	$\mathcal{B}(D)$	m_{ES} fit	Monte Carlo statistics	Total
M_X	1.92	0.90	2.08	1.62	0.87	0.21	0.44	3.71	3.22	6.07
P_+	3.88	1.31	2.22	1.47	2.80	0.39	0.73	3.98	4.62	8.38
M_X, q^2	3.83	2.43	2.71	1.02	1.17	0.55	0.79	5.17	4.29	8.81

Isospin

ΔP_ℓ lepton momentum range	2.2-2.6	2.3-2.6	2.4-2.6
Statistical	12.6	16.1	19.3
Systematics	6.1	5.	6.4
Monte Carlo statistics	2.8	3.4	5.0
Peaking B^+	2.5	1.1	1.2
N_B^0	1.3	1.3	1.3
B movement	0.4	1.0	1.5
Event Selection	1.0	1.1	1.9
PID	1.3	1.5	1.4
Radiation	1.1	1.2	1.3
$J/\psi, \psi'$ bkg	0.5	0.2	0.2
Fake lepton	2.3	2.9	1.7
$B \to D \ell \nu$	1.9	0.0	0.0
$B \to D^* \ell \nu$	2.4	0.5	0.0
$B \to D^{**} \ell \nu$	0.1	0.0	0.0
X_u composition	0.7	0.4	0.4
$s\bar{s}$ pair production	1.2	0.5	0.3

$D^{*0} e \nu$

	$\Delta V/V$	$\Delta \rho^2/\rho^2$	$\Delta \mathcal{B}/\mathcal{B}$
tracking efficiency (ϵ_{tr})	1.2	-	2.4
p_T dependence of ϵ_{tr}	0.3	0.5	0.2
particle ID efficiency	0.9	2.0	1.6
extrapolated π^0 efficiency (ϵ_{π^0})	1.8	-	3.6
p_{π^0} dependence of ϵ_{π^0}	1.0	3.5	0.4
Δm shape of D^{**} background	0.1	0.1	0.2
shape parameters	1.0	2.5	0.6
number of $B\overline{B}$ events	0.6	-	1.1
off-peak luminosity	0.1	0.4	<0.1
total internal	**2.8**	**4.8**	**4.8**
$R_1(1)$ and $R_2(1)$	0.1	4.7	0.3
$\mathcal{B}(\Upsilon(4S) \to B^+ B^-)$	0.8	-	1.6
$\mathcal{B}(D^{*0} \to D^0 \pi^0)$	2.3	-	4.7
$\mathcal{B}(D^0 \to K^- \pi^+)$	0.9	-	1.8
B^- life time	0.3	-	-
D^{**} decay fractions	0.3	0.7	0.3
number of D^{*0} in $c\bar{c}$ events	0.2	0.7	<0.1
total external	**2.6**	**4.8**	**5.3**
total	**3.9**	**6.8**	**7.2**

Backup: Systematic Errors

	Systematic uncertainty on $\Gamma(\overline{B} \to D^{(*)}\ell^-\overline{\nu}_\ell)/\Gamma(\overline{B} \to X\ell^-\overline{\nu}_\ell)$			
	$B^- \to D^0\ell^-\overline{\nu}_\ell$	$B^- \to D^{*0}\ell^-\overline{\nu}_\ell$	$\overline{B^0} \to D^+\ell^-\overline{\nu}_\ell$	$\overline{B^0} \to D^{*+}\ell^-\overline{\nu}_\ell$
Tracking efficiency	1.4	1.2	1.4	1.5
Neutral reconstruction	0.7	1.9	0.5	1.1
lepton ID	0.5	0.4	0.5	0.6
Soft particle efficiency	-	1.3	-	1.2
Monte Carlo corrections				
Conversion and Dalitz decay background	0.04	0.07	0.06	0.05
Cascade $\overline{B} \to X \to \ell^-$ decay background	0.6	0.6	1.0	1.0
$\overline{B^0} - B^-$ cross-feed	0.2	0.3	0.2	0.3
Form factors	0.4	0.8	0.4	0.8
$D^{(*)}$ branching fractions	2.3	3.5	4.1	2.7
$\overline{B} \to X\ell^-\overline{\nu}_\ell$ branching fraction	1.9	1.9	1.9	1.9
B_{tag} selection	0.9	1.7	1.8	1.3
Fit technique				
$\overline{B} \to X\ell^-\overline{\nu}_\ell$ yield	0.5	0.5	0.9	0.9
$\overline{B} \to D^{(*)}\ell^-\overline{\nu}_\ell$ yield	0.6	0.4	1.2	0.4
Total systematic error	3.7	5.2	5.4	4.5

	Systematic uncertainty on $\Gamma(\overline{B} \to D^{(*)}\pi\ell^-\overline{\nu}_\ell)/\Gamma(\overline{B} \to X\ell^-\overline{\nu}_\ell)$			
	$B^- \to D^+\pi^-\ell^-\overline{\nu}_\ell$	$B^- \to D^{*+}\pi^-\ell^-\overline{\nu}_\ell$	$\overline{B^0} \to D^0\pi^+\ell^-\overline{\nu}_\ell$	$\overline{B^0} \to D^{*0}\pi^+\ell^-\overline{\nu}_\ell$
Tracking efficiency	1.8	2.7	1.5	1.7
Neutral reconstruction	1.7	1.8	1.1	1.8
lepton ID	2.3	3.0	2.6	1.8
Soft particle efficiency	-	1.2	-	1.3
Monte Carlo corrections				
Conversion and Dalitz decay background	0.15	0.4	0.05	0.2
Cascade $\overline{B} \to X \to \ell^-$ decay background	0.6	0.6	1.0	1.0
$\overline{B^0} - B^-$ cross-feed	0.2	0.3	0.2	0.3
Form factors	0.4	0.8	0.4	0.8
$D^{(*)}$ branching fractions	4.2	2.9	2.5	4.4
$\overline{B} \to X\ell^-\overline{\nu}_\ell$ branching fraction	1.9	1.9	1.9	1.9
B_{tag} selection	5.0	4.3	4.0	5.6
Fit technique				
$\overline{B} \to X\ell^-\overline{\nu}_\ell$ yield	0.5	0.5	0.9	0.9
$\overline{B} \to D^{(*)}\pi\ell^-\overline{\nu}_\ell$ yield	1.2	0.9	1.8	1.5
Total systematic error	7.7	7.3	6.4	8.4

Backup: $D^{(*)}\tau\nu$ Signal Fit

Fit projections to lepton momentum spectrum at low m^2_{miss} (left) and high m^2_{miss} (right)