Symposium on Prospects in the Physics of Discrete Symmetries IOP Publishing
Journal of Physics: Conference Series **335** (2011) 012032 doi:10.1088/1742-6596/335/1/012032

Semileptonic and Leptonic decays in the BABAR experiment

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Abstract. We describe recent measurements of B and charm semileptonic and leptonic decay branching fractions and the determination of CKM matrix elements.

1. Introduction

The study of semileptonic decays of charm and bottom mesons provides a good testing ground for QCD models. In the following we will summarize new and very competitive results from the BABAR collaboration for semileptonic decays both on the charm and bottom sectors.
In the charm sector the analysis $D^+ \to K^-\pi^+e^+\nu_e$ high statistics analysis provides very competitive results for several physical parameters that can be compared with theoretical predictions and calculations.
In the bottom sector, three analyses are presented which study $B \to X_u l^+\nu_l$ charmless decays of B mesons. The main goal of these analyses is the most accurate determination of the CKM matrix element $|V_{ub}|$. These analysis fall in two different reconstruction approaches whether the final hadronic state is inclusive or exclusive.
Finally a B leptonic decay analysis, $B^+ \to \tau^+\nu_\tau$, is also presented and provides a competitive measurement of the branching ratio for this decay. This last analysis can be used both as a probe for new physics and is also very sensitive to the CKM element $|V_{ub}|$.

2. $D^+ \to K^-\pi^+e^+\nu_e$[1]

A detailed study of the $D^+ \to K^-\pi^+e^+\nu_e$ is of interest for three main reasons :

- It allows measurements of the different $K\pi$ resonant and non-resonant amplitudes that contribute to this decay. In this respect, we have measured the S-wave contribution and searched for radially excited P-wave and D-wave components. Accurate measurements of the various contributions can serve as useful guidelines to B-meson semileptonic decays where there are still missing exclusive final states with mass higher than the D^* mass.
- High statistics in this decay allows accurate measurements of the properties of the $K^{*0}(892)$ meson. Both resonance parameters and hadronic transition form factors can be precisely measured. The latter can be compared with hadronic model expectations and Lattice QCD computations.

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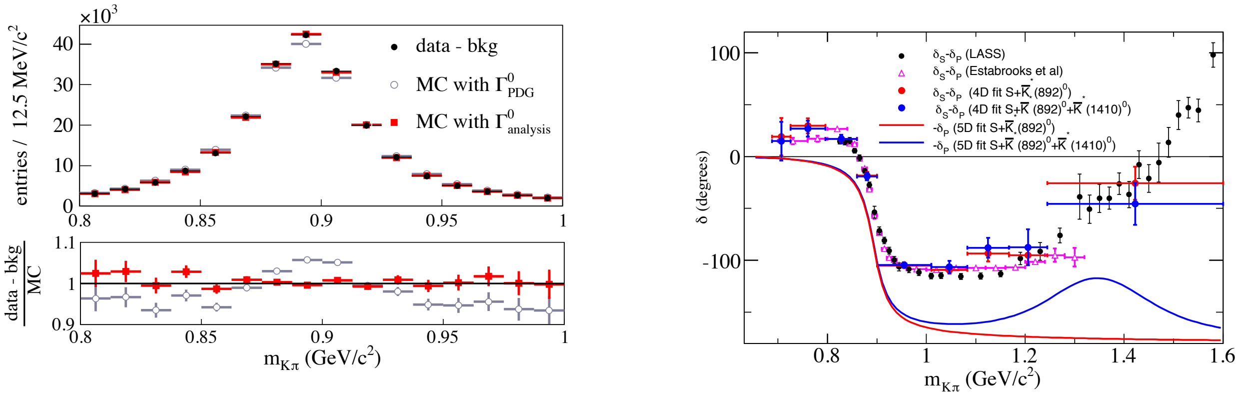

Figure 1. (color online) Left plot: Comparison between measured and fitted $K\pi$ mass distributions in the $\overline{K}^*(892)^0$ region. Results of a fit in which the width of the $\overline{K}^*(892)^0$ meson is fixed to 50.3 MeV/c^2 [2] are also given. Right plot :Difference between the $I = 1/2$ S- and P-wave phase versus the $K\pi$ mass. Measurements are similar whether or not the $\overline{K}^*(1410)^0$ is included in the P-wave parameterization. Results are compared with measurements from $K\pi$ scattering. The red and blue lines give the phase variation with a minus sign $(-\delta_P)$ for the $\overline{K}^*(892)^0$ and $\overline{K}^*(892)^0 + \overline{K}^*(1410)^0$, respectively. The difference between these curves and the measured points corresponds to the S-wave contribution.

- Variation of the $K\pi S$ -wave phase versus the $K\pi$ mass can be determined, and compared with other experimental determinations.

Semileptonic decays into a final state with four particles depend on five variables : $q^2, m_{K\pi}$ and three angles ($\cos\theta_K, \cos\theta_e$ and χ)[1]. This allows to separate the different signal components according to angular momentum (S,P,D waves) and gives sensitivity to the interference between these states.
This analysis provides for the first time a full 5D phase space analysis of this decay.
Having reconstructed the charged $K^-\pi^+e^+$ system, the neutrino energy (and D direction) are finally estimated by taking into account the remaining particles in the event. This method provides a high efficiency and results in a non negligible amount of background.
The simulation of signal and background events is improved thanks to extensive studies on the fragmentation of charm mesons using special control samples and comparing data to MC simulation. The background sources ($B\bar{B}$ and $c\bar{c}$) are suppressed using multivariate discriminant variables which separate signal from background based on the topology of the decay ($B\bar{B}$) and the properties of the spectator system ($c\bar{c}$).

The main results are presented in Table 1 and Figure 1. In particular this analysis provides: 1) the most precise results for the hadronic form factor parameters of the $\overline{K}^{*0}$ component, assuming a single pole dominance model and these results serve as reference for LQCD, 2) very precise determinations of the resonance parameters of the $\overline{K}^{*0}$ component, 3) agreement with corresponding S-wave phase measurements done in K^-p interactions producing $K^-\pi^+$ at small transfer. This is a confirmation of these results and illustrates the importance of final state interactions when this phase is obtained from three body Dalitz plot analyses of D-meson hadronic decays and 4) precise determinations of the different branching ratios and very low

[1] For a precise definition of the angles, the reader is refered to [1]

Table 1. Comparison between these measurements and present world average results. Values for $\mathcal{B}(D^+ \to \overline{K}^*(1410)^0/\overline{K}_2^*(1430)^0 e^+\nu_e)$ are corrected for their respective branching fractions into $K^-\pi^+$.

Measured quantity	This analysis	World average [2]
$m_{K^*(892)^0}(\mathrm{MeV}/c^2)$	$895.4 \pm 0.2 \pm 0.2$	896.00 ± 0.25
$\Gamma^0_{K^*(892)^0}(\mathrm{MeV}/c^2)$	$46.5 \pm 0.3 \pm 0.2$	50.3 ± 0.6
$r_{BW}(\mathrm{GeV}/c)^{-1}$	$2.1 \pm 0.5 \pm 0.5$	2.72 ± 0.55
r_V	$1.463 \pm 0.017 \pm 0.031$	1.62 ± 0.08
r_2	$0.801 \pm 0.020 \pm 0.020$	0.83 ± 0.05
$m_A(\mathrm{GeV}/c^2)$	$2.63 \pm 0.10 \pm 0.13$	no result
$\mathcal{B}(D^+ \to K^-\pi^+e^+\nu_e)(\%)$	$4.04 \pm 0.03 \pm 0.04 \pm 0.09$	4.1 ± 0.6
$\mathcal{B}(D^+ \to K^-\pi^+e^+\nu_e)_{\overline{K}^*(892)^0}(\%)$	$3.80 \pm 0.04 \pm 0.05 \pm 0.09$	3.66 ± 0.21
$\mathcal{B}(D^+ \to K^-\pi^+e^+\nu_e)_{S-wave}(\%)$	$0.234 \pm 0.007 \pm 0.007 \pm 0.005$	0.21 ± 0.05
$\mathcal{B}(D^+ \to \overline{K}^*(1410)^0e^+\nu_e)(\%)$	$0.30 \pm 0.12 \pm 0.18 \pm 0.06$ (< 0.6 at 90% C.L.)	
$\mathcal{B}(D^+ \to \overline{K}_2^*(1430)^0e^+\nu_e)(\%)$	$0.023 \pm 0.011 \pm 0.011 \pm 0.001$ (< 0.05 at 90% C.L.)	

limits to high mass contributions.

3. $B^0 \to \pi^- l^+\nu_l, B^+ \to \eta^{(')} l^+\nu_l$ and $B^{0/+} \to \pi^{-/0} l^+\nu_l, B^{0/+} \to \rho^{-/0} l^+\nu_l$

B meson semileptonic exclusive decays are excellent channels for the determination of $|V_{ub}|$ since they provide the best trade-off between statistics and theoretical knowledge of the decay.
The precise determination of $|V_{ub}|$ constrains the description of the Standard Model in the flavour sector. These channels allow also to test the QCD predictions for the form factors.
In the following, two analyses of B decays into semileptonic exclusive modes are presented, both extract $|V_{ub}|$ and test several theoretical models and calculations for the hadronic form factors variation with q^2 (the lepton system mass squared) :

- $\pi - \rho$ analysis[3], which studies four decay modes : $B^{0/+} \to \pi^{-/0} l^+\nu_l, B^{0/+} \to \rho^{-/0} l^+\nu_l$
- $\pi - \eta$ analysis[4], which studies three decay modes : $B^0 \to \pi^- l^+\nu_l, B^+ \to \eta^{(')} l^+\nu_l$

The $\pi - \rho$ analysis also extracts $|V_{ub}|$ by combining their results on$\Delta\ \mathcal{B}/\Delta q^2$ with the results from the FNAL/MILC collaboration.
The measurement of the missing energy and momentum of the whole event are used to reconstruct the neutrino. This is done without explicitely reconstructing the other B meson, resulting in a high signal sample. The main source of background comes from $B \to X_c l^+\nu_l$ decays which are much more frequent than $B \to X_u l^+\nu_l$ decays ($|V_{cb}|^2/|V_{ub}|^2 \approx 50$). The signal is extracted by performing maximum-likelihood fits using the variables m_{ES} (the energy-substituted mass), ΔE and over each of the q^2 bins.

The fitted distributions of$\Delta\ \mathcal{B}/\Delta q^2$ are presented in Figure 2. One finds that the best agreement with data is found for the theoretical prediction coming from HPQCD. However, theory predictions are valid in restricted regions of phase space and their extrapolation on the entire phase space brings large uncertainties. Both analyses find good agreement in$\Delta\ \mathcal{B}/\Delta q^2$ for the common mode $B^0 \to \pi^- l^+\nu_l$.
A summary of the results on V_{ub} for the two analyses is given in Table 2 using different theoretical models for parameterisation of the form factors. The expression that allows one to get

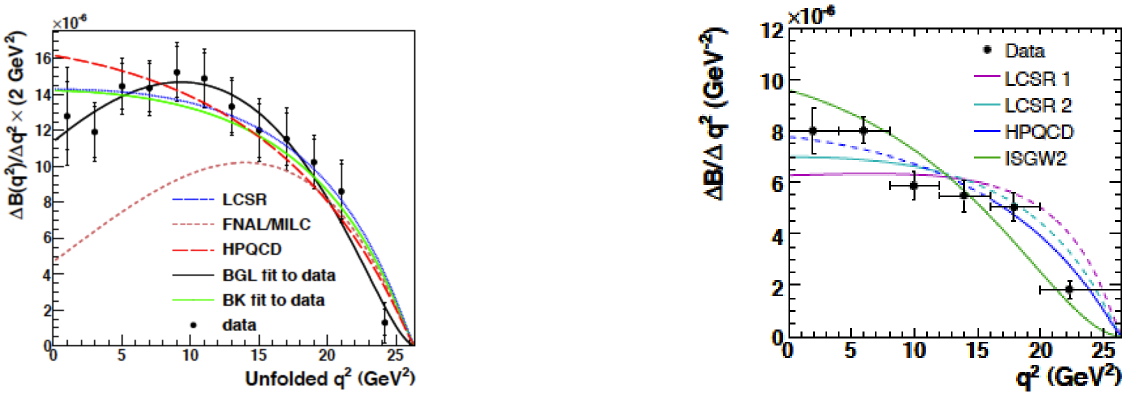

Figure 2. Fitted distributions of$\Delta\ \mathcal{B}/\Delta q^2$.

Table 2. Results found in $|V_{ub}|$ for both analyses, using different theoretical calculations. Units for $|V_{ub}|$ are (10^{-3})

$q^2\ (GeV^2)$	$\lvert V_{ub}\rvert(\pi-\rho)$	$\lvert V_{ub}\rvert(\pi-\eta)$
$HPQCD\ > 16$	$3.21 \pm 0.17^{+0.55}_{-0.36}$	$3.24 \pm 0.13 \pm 0.16^{+0.57}_{-0.37}$
$FNAL\ > 16$		$3.14 \pm 0.12 \pm 0.16^{+0.35}_{-0.29}$
$LCSR\ < 12$	$3.78 \pm 0.13^{+0.55}_{-0.40}$	$3.70 \pm 0.07 \pm 0.09^{+0.54}_{-0.39}$

$|V_{ub}|$ from$\Delta\ \mathcal{B}/\Delta q^2$ is given in Equation 2.

The analysis $\pi-\rho$ makes a combined fit to LQCD and BABAR data. The fit is based on the z-expansion[1] (BGL) and takes advantage of the q^2 variation over the whole q^2 spectrum from the BABAR measurements and the shape plus normalization from LQCD. The determination of the q^2 shape is dominated by the BABAR data.
This procedure allows to reduce the theory error by a factor 2 (8.5% while traditional method gives $^{+17\%}_{-11\%}$). The value extracted for $|V_{ub}| = (2.95 \pm 0.31) \times 10^{-3}$.

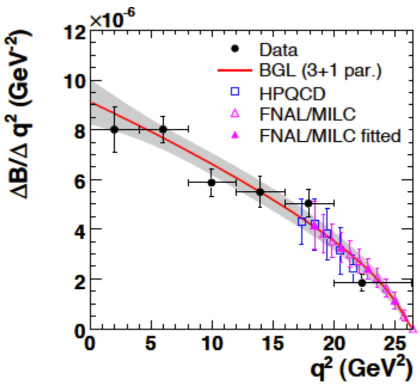

Figure 3. (color online) Simultaneous fits of the BGL parameterization to data (solid points with vertical error bars representing the total experimental uncertainties) and to four of the twelve points of the FNAL/MILC lattice prediction (magenta, closed triangles).The LQCD results are rescaled to the data according to the $|V_{ub}|$ value obtained in the fit. The shaded band illustrates the uncertainty of the fitted function. For comparison, the HPQCD (blue, open squares) lattice results are also shown.

[1] A summary of this expansion may be found in [3]

4. $B \to X_u l^+ \nu_l$ with hadronic tags[5]

The main purpose of this analysis is to determine the channel's branching ratio and from this extract to $|V_{ub}|$.
However, and since there is a huge background from $b \to c$ decays, this type of analysis relies traditionally on hard cuts in the phase space to minimize the background. Therefore one measures partial branching ratios (PBR) and this fact entails that there is a dependence on the theoretical description of these PBR's to extract $|V_{ub}|$. Therefore such studies are done by applying independently various cuts on different phase space regions so to check the consistency of the theoretical description.
With the ever more greater knowledge about B semileptonic decays, the understanding of the background of this channel becomes solid and that permits this analysis to use only mild cuts of the phase space. They are $M_X < 1.55$ GeV/c^2, $M_X < 1.70$ GeV/c^2, $P_+ < 0.66$ GeV/c, $M_X < 1.70$ GeV/c^2 *and* $q^2 > 8$ GeV^2/c^2, $p_l^* > 1.0$ GeV/c, $p_l^* > 1.3$ GeV/c, where M_X stands for the X_u system mass, $P_+ = E_X - P_X$, q^2 the leptonic system mass squared and P_l^* the lepton momentum.
This analysis is an update of an earlier one and uses the entire BABAR $\Upsilon(4S)$ dataset. The event is reconstructed by fully measuring one B meson into hadronic decay modes (this is commonly known as hadronic tag method and this B meson is the B_{reco}). The B_{reco} decays into states DY, where D stands for $D^{(*)0\pm}$ and Y is a system of π and Kaons. The variablesΔ $E = E_B - \sqrt{s}/2$ and $m_{ES} = \sqrt{s/4 - p_B^2}$ are used to distinguish events where B_{reco} is well reconstructed from combinatorial background. Furthermore, the amount of combinatorial background is extracted by using an Argus function in the m_{ES} variable.
The remaining particles in the event, not included in B_{reco}, are associated to the X_u candidate system. A lepton of the correct charge tags the semileptonic events.
These events fall into two categories according to whether they pass or not a veto on kaons and D^* candidates. Events that pass the veto are signal enriched and are used in the fit to extract the PBR while the others are signal depleted and this sample is used to cross-check the agreement between data and Monte Carlo.
The PBR is obtained from the observed number of signal events in the kinematic regions considered, normalized to the total number of semileptonic decays, by using Equation 1,

$$\Delta R = \frac{\Delta\mathcal{B}(B \to X_u l^+ \nu_l)}{\mathcal{B}(B \to X l^+ \nu_l)} = \frac{N_u^{true}}{N_{sl}^{true}} \tag{1}$$

where N_u^{true} corresponds to the actual number of signal events, corrected for reconstrucion efficiency and particle identification, and N_{sl}^{true} stands for the total number of B semileptonic decays, also efficiency corrected, determined in a fit to the m_{ES} distribution at the level of the semileptonic tagging of the event.
To extract afterwards the PBF one uses the world average value $\mathcal{B}(B \to X l^+ \nu_l) = (10.75 \pm 0.15)\%$. The result found for the most inclusive fits is given in Table 3 and agreement is found with the Belle analysis.

Table 3. Partial Branching Ratios for most inclusive analyses

Variable, cutΔ	$\mathcal{B}(B \to X_u l^+ \nu_l)_{BABAR} \times 10^{-3}$	$\Delta\mathcal{B}(B \to X_u l^+ \nu_l)_{Belle} \times 10^{-3}$[6]
$p_l^*,\ p_l^* > 1.0\ GeV/c$	$1.80 \pm 0.13_{stat.} \pm 0.15_{syst.}$	-
$(M_X, q^2),\ p_l^* > 1.0\ GeV/c$	$1.76 \pm 0.16_{stat.} \pm 0.18_{syst}$	$1.96 \pm 0.17_{stat.} \pm 0.16_{syst.}$

The extraction of $|V_{ub}|$ is made using Equation 2

$$|V_{ub}| = \sqrt{\frac{\Delta\mathcal{B}(B \to X_u l^+ \nu_l)}{\tau_B \Delta\Gamma_{theory}}} \quad (2)$$

where $\Delta\Gamma_{theory}$ is the theoretical $B \to X_u l^+ \nu_l$ width according to the applied cut in phase space. This width depends on the theoretical model used and several models are checked. An estimate of $|V_{ub}|$ using the most inclusive analysis gives $(4.31 \pm 0.35) \times 10^{-3}$ where the signal model systematics are the biggest source of uncertainty.

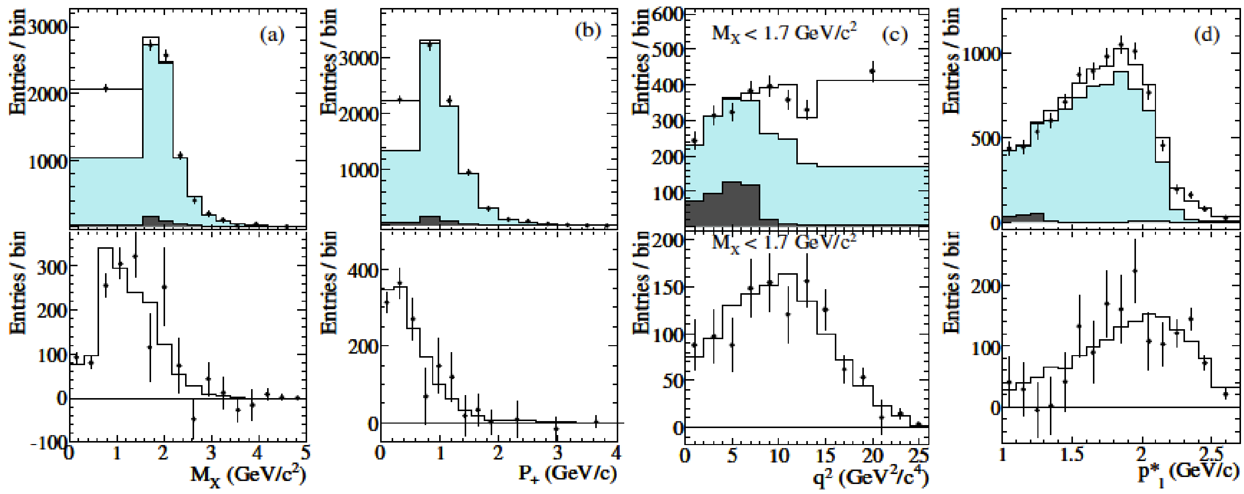

Figure 4. (color online) Upper row (data points): measured M_X (a), P_+ (b), q^2 with $M_X < 1.7GeV/c^2$ (c) and p_l^*(d) spectra. Results from the fit of three MC contributions are shown as histograms : : $B \to X_u l \nu_l$ decays generated inside (no shading) and outside (dark shading) the selected kinematic region, and $B \to X_c l \nu_l$ and other background (light shading). Lower row: corresponding spectra for $B \to X_u l \nu_l$ after $B \to X_c l \nu_l$ and other background subtraction; they have been rebinned in order to show the shape of the kinematic variables. Background-subtracted distributions are not efficiency corrected.

Furthermore, the charged and neutral B-meson decay modes are also studied separately and a search for weak-annihilation effects (isospin breaking effects) is done. It consists of measuring differences in the decay widths. This analysis finds no appreciable differences to the widths and subsequently limits are imposed to the fraction of weak-annihilation effects ($-0.13 < \gamma_{WA}/\Gamma < 0.09$ at $90\%CL$).

5. $B^+ \to \tau^+ \nu_\tau$ with hadronic tags[7]

This decay is, assuming only SM contributions, at tree level, sensitive to the decay constant of the B meson (f_B) and to $|V_{ub}|$. It is an helicity suppressed channel. Its branching ratio expression is given in Equation 3 and the expected value is $(1.2 \pm 0.2) \times 10^{-4}$, using [2] for the input parameters.

$$\mathcal{B}(B^+ \to \tau^+ \nu_\tau) = f_B^2 |V_{ub}|^2 \frac{G_F^2 m_B m_\tau^2}{8\pi} [1 - \frac{m_\tau^2}{m_B^2}]^2 \tau_{B^+} \quad (3)$$

This channel is also sensitive to *possible* extensions of the SM such as two-Higgs doublet models and minimal supersymmetry where the interaction would be mediated by a charged Higgs boson.

In this framework one can constrain the model's parameter space.
This analysis uses the so-called hadronic tags to reconstruct one of the B mesons while the signal decay mode is searched on the recoil of this fully reconstructed meson. This analysis is an update of an older BABAR analysis, using the entire BABAR $\Upsilon(4S)$ dataset.
One B meson is reconstructed in hadronic modes of type $(D^{(*)0}X^-, J/\psi X^-)$ where X^- is a system of light quark mesons (π, K) with total charge -1. Reconstructed events fall in two major categories, those where the former B meson is well reconstructed (peaking events) and those not well reconstructed (combinatorial). The variable $m_{ES} = \sqrt{s/4 - p_B^2}$ is used to evaluate the amount of combinatorial events under the peaking events distribution, a typical procedure in this type of analyses. Furthermore the actual suppression of combinatorial background is done using a likelihood ratio taking variables constructed from the kinematics of the tag B candidate. In the peaking events, one distinguishes between events actually coming from the signal decay channel and the background, using an unbinned maximum likelihood. It is found that the most important discriminating input variable is E_{extra}, the sum of the energies of the neutral clusters not associated with the tag B or with the signal. There is a minimum of 60 MeV for the energy requirement of these clusters for them to be taken into account. One uses this variable to define the probability density functions for the signal and background. Essentially, signal events tend to peak at low E_{extra} while background, with more neutral clusters in average, appear for higher values of this variable.

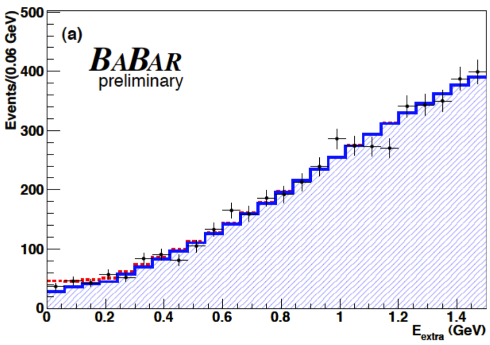

Figure 5. (color online) E_{extra} in data (dots with error bars) with all selection requirements applied and fit results overlaid. The hatched histogram is the background, the red dashed component is the signal.

The τ signal is reconstructed in 4 decay modes : $\tau \to (e\bar{\nu}_e\nu_\tau, \mu\bar{\nu}_\mu\nu_\tau, \pi\nu_\tau, \rho\nu_\tau)$. The four decay modes are fitted in parallel to extract the branching ratio of the signal decay channel. Both the signal and background PDF are taken from MC simulation. The signal PDF shape is corrected by using specially selected control samples, where both B mesons are reconstructed hadronically. This is done in data and MC. Differences in the shapes of the E_{extra} distributions between data and MC are taken as correction to the signal PDF. The resulting distributions after the fit are presented in Figure 5
This analysis finds that $\mathcal{B}(B^+ \to \tau^+\nu_\tau) = (1.80^{+0.57}_{-0.54}) \times 10^{-4}$, which corresponds to a statistical significance of 3.6 sigmas.
The dominant source of systematic originates from the background PDF due to the finite statistics of the simulation. The final error budget leads to an overall significance of this decay of 3.3 sigmas.
Combining this result with another BABAR analysis, done with semileptonic tags, leads to a branching ratio of $(1.76 \pm 0.49) \times 10^{-4}$, well in agreement with the $(1.2 \pm 0.2) \times 10^{-4}$ of the SM expectations.

6. Summary
We have presented new results for B and charm semileptonic and leptonic decays from the BABAR collaboration.

7. Acknowledgements
The author thanks the BABAR collaboration for the invitation, the DISCRETE conference organizers , and DESY for the travel arrangements.

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