Status of $R(D^{(*)})$ measurement with semileptonic tagging at *BABAR*

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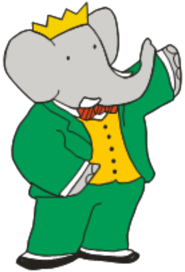
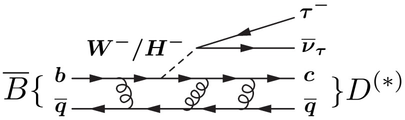


Motivation for $R(D^{(*)})$ measurements



Signal mode

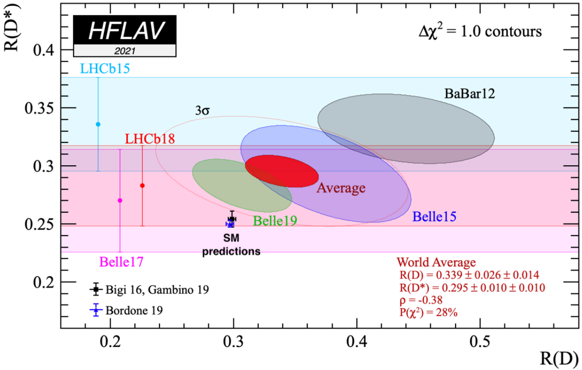
$$R\left(D^{(*)}\right) = \frac{\mathcal{B}\left(B \to D^{(*)}\,\tau\nu_\tau\right)}{\mathcal{B}\left(B \to D^{(*)}\,l\,\nu_l\right)}$$

Normalization mode

- Semileptonic decays of B mesons mediated by W bosons.
- Decays involving electrons or muons are less sensitive to beyond standard model (BSM) contribution, while decays involving higher-mass τ lepton are sensitive to additional amplitudes.
- Development of heavy quark effective theory (HQET) and precise measurements of $B \to D^{(*)} l\nu$:

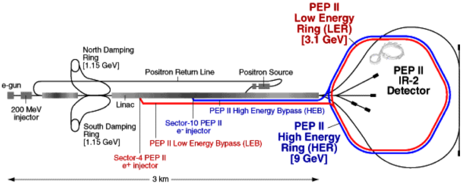
$$R(D)_{\mathsf{SM}} = 0.299 \pm 0.003, R(D^*)_{\mathsf{SM}} = 0.254 \pm 0.005$$

Previous measurements



Experiment	$R(D)$	$R(D^*)$	Method
BaBar 2012	$0.440 \pm 0.058 \pm 0.042$	$0.322 \pm 0.024 \pm 0.018$	hadronic tag, $\tau \to l\nu\nu$
Belle 2015	$0.375 \pm 0.064 \pm 0.026$	$0.293 \pm 0.038 \pm 0.015$	hadronic tag, $\tau \to l\nu\nu$
LHCb 2015	-	$0.336 \pm 0.027 \pm 0.030$	$\tau \to \mu\nu\nu$
Belle 2017	-	$0.270 \pm 0.035 \pm 0.027$	hadronic tag
LHCb 2018	-	$0.283 \pm 0.019 \pm 0.029$	$\tau \to 3\pi\nu$
Belle 2019	$0.307 \pm 0.037 \pm 0.016$	$0.283 \pm 0.018 \pm 0.014$	semileptonic tag

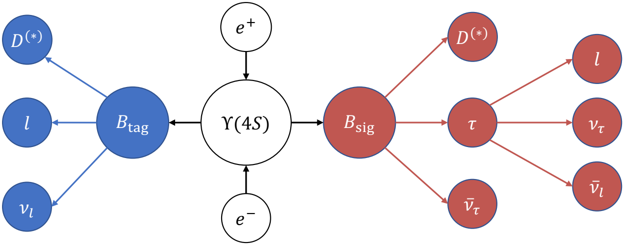
BABAR experiment



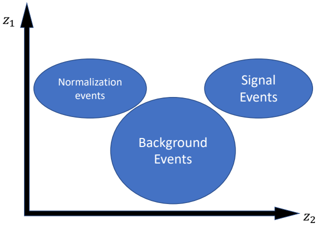
- Asymmetric e^+e^- collider operating at center-of-mass energy of 10.58 GeV.
- Total integrated luminosity of 514 fb^{-1} was collected (1999-2008), mostly at the $\Upsilon(4S)$ resonance, but also at the $\Upsilon(3S)$ and $\Upsilon(2S)$ peaks, as well as off-resonance.

Collaboration is still active more than 10 years after data taking ended!

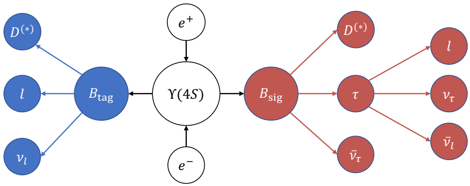
Analysis strategy



- Measure $R(D^{(*)})$ using semileptonic tagging and leptonic τ decays.
- Combined measurements of $R(D^0)$ and $R(D^+)$ with isospin average.
- 2-dimensional maximum likelihood fit on data for signal extraction.
- The yields of signal and normalization modes are extracted simultaneously, aiming to eliminate some sources of systematic uncertainties.



Reconstruction

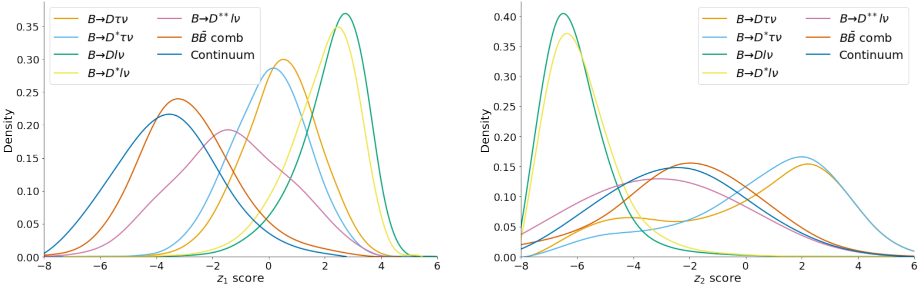


- Charged tracks are identified using loose PID. Photons are only considered with energy larger than 30 MeV.
- Criteria on reconstructed $m(D)$ and $\Delta M = m(D^*) - m(D)$ based on resolution for each $D^{(*)}$ mode.
- To identify B_{tag}, we require $\cos\theta^{tag}_{B-D^{(*)}l} \in [-2, 1]$.

$$\cos\theta^{tag}_{B-D^{(*)}l} = \frac{2E_{beam}E_{D^{(*)}l} - m_B^2 - m_{D^{(*)}l}^2}{2|\mathbf{p}_B| \cdot |\mathbf{p}_{D^{(*)}l}|}$$

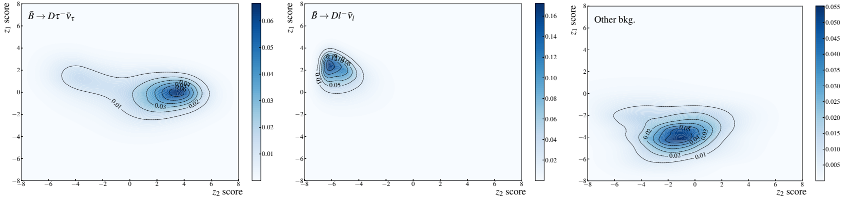
- Search for $D^{(*)}l$ from the remaining tracks and neutral clusters: $D^+l, D^0l, D^{*+}l, D^{*0}l$.
- No extra charged tracks, K_S^0 or π^0 particles.

Multivariate analysis for signal separation



- z_1 aims to distinguish signal and normalization events from all types of backgrounds.
- z_2 aims to distinguish between signal and normalization events.
- Both classifiers are boosted decision tree (BDT) models.

Signal modeling



- Adaptive kernel density estimation is applied to learn the PDFs for each event type densities.
- Dual-tree algorithm with GPU acceleration for speed-up [A. Gray and A. Moore, 2003].

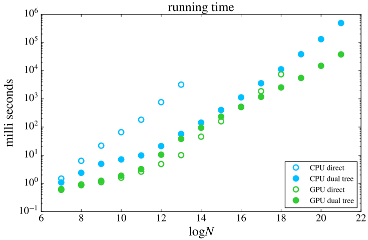


Figure: Benchmark performance for various implementations, as a function of sample size (N) $(\log = \log_2)$.

2D fit

- Extract signals from each of four subsets $D^+l, D^0l, D^{*+}l, D^{0*}l$ **independently**.
- For each subset, the distribution is combination of signal, normalization, feed-up (feed-down), $B \to D^{**}l\nu$, $B\bar{B}$ combinatorial and continuum events.
- Maximum likelihood fit is applied on each subset. **All the yields are free** parameters (Y_js) during the 2D fit.

$$\max_{\mathbf{Y}} \mathcal{L} = \Pi_{i=1}^{n}(\textstyle\sum_{j=1}^{C} Y_j \cdot f(z_{1j}, z_{2j})) \\ s.t. \sum_{j=1}^{C} Y_j = N \tag{1}$$

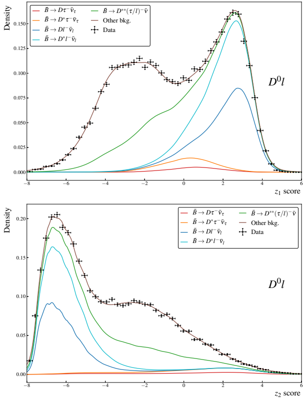


Figure: Example of 2D fit on D^0l subset.

Systematic uncertainties (preliminary)

Source	$\Delta R(D)$ (%)	$\Delta R(D^*)$ (%)
$B \to Dl\nu$ form factor	0.48	0.30
$B \to D^*l\nu$ form factor	0.96	0.58
$B \to D^{**}l\nu$ form factor	0.35	0.20
$\mathcal{B}(B \to D^{(*)}l\nu)$	0.47	0.32
$\mathcal{B}(b \to c\bar{c})$	0.49	0.25
$\mathcal{B}(B \to D^{**}l\nu)$	2.94	2.53
$\mathcal{B}(D)$	0.87	0.91
PDF shapes MC statistics	4.12	4.37
$B\bar{B}$ Background calibration	2.60	0.94
$\mathcal{B}(\Upsilon(4S))$	0.29	0.33
PID efficiency	0.29	0.40
Soft π^0 efficiency	0.84	1.24
$\mathcal{B}(\tau \to l^-\bar{\nu}_l\nu_\tau)$	0.16	0.16
Systematic Total	5.98	5.31
Statistical Uncertainty	19.6	9.9
Total	20.68	11.23

Table: Summary of uncertainties evaluated on MC.

- The overall uncertainties are still dominated by statistics.
- Statistical uncertainties can be reduced if including cross-feed matrix constraints.

Conclusion

- Another precise measurement of $R(D^{(*)})$ from *BABAR* after a decade.
- *BABAR*'s first $R(D^{(*)})$ measurement using semileptonic B-tagging method and leptonic τ decays.
- Proposed a new measurement method, more data-driven, fewer assumptions from MC.
- Hopefully, a comparable measurement on $R(D^{(*)})$ will be delivered soon.

Thanks for your attention!

Event types definition for the measurement

Event type		Description
Signal event	signal D	One B decays to $D^{(*)}l\nu$, the other B decays to $D\tau\nu$, $\tau \to$ leptons
	signal D^*	One B decays to $D^{(*)}l\nu$, the other B decays to $D^*\tau\nu$, $\tau \to$ leptons
Normalization event	norm D	One B decays to $D^{(*)}l\nu$, the other B decays to $Dl\nu$
	norm D^*	Both B decay to $D^*l\nu$
D^{**} event		At least one B decays to $D^{**}(l/\tau)\nu$, where D^{**} includes $1P$ states D_0^*, D_1, D_1', D_2^*, $2S$ states, and non-resonant states.
combinatorial $B\bar{B}$ event		Any $B\bar{B}$ events that are not signal and not normalization and not D^{**}.
Continuum event		non-$B\bar{B}$ events produced in the detector

Table: Definition of event types in the B-factory system.

Probability modeling setup for the measurement

Denote

$$P := \mathcal{B}(B \to D\tau\nu), P^* := \mathcal{B}(B \to D^*\tau\nu)$$
$$Q := \mathcal{B}(B \to Dl\nu), Q^* := \mathcal{B}(B \to D^*l\nu) \tag{2}$$

Therefore, $R(D) = \frac{P}{Q}$ and $R(D^*) = \frac{P^*}{Q^*}$. The expected number of signal (normalization) events generated in the detector would be

$$N(\text{signal } D) = 2N \cdot (2Q + 2Q^*) \cdot P \cdot \mathcal{B}(\tau \to leptons)$$
$$N(\text{signal } D^*) = 2N \cdot (2Q + 2Q^*) \cdot P^* \cdot \mathcal{B}(\tau \to leptons)$$
$$N(\text{norm } D) = 4N \cdot (Q^2 + 2QQ^*) \tag{3}$$
$$N(\text{norm } D^*) = 4N \cdot Q^{*2}$$

Given the estimated number of generated signal events $\hat{N}(\text{signal } D)$ and $\hat{N}(\text{signal } D^*)$ and normalization events $\hat{N}(\text{norm } D)$ and $\hat{N}(\text{norm } D^*)$, the estimated $P^{(*)}$ and $Q^{(*)}$ can be solved from Equation (3):

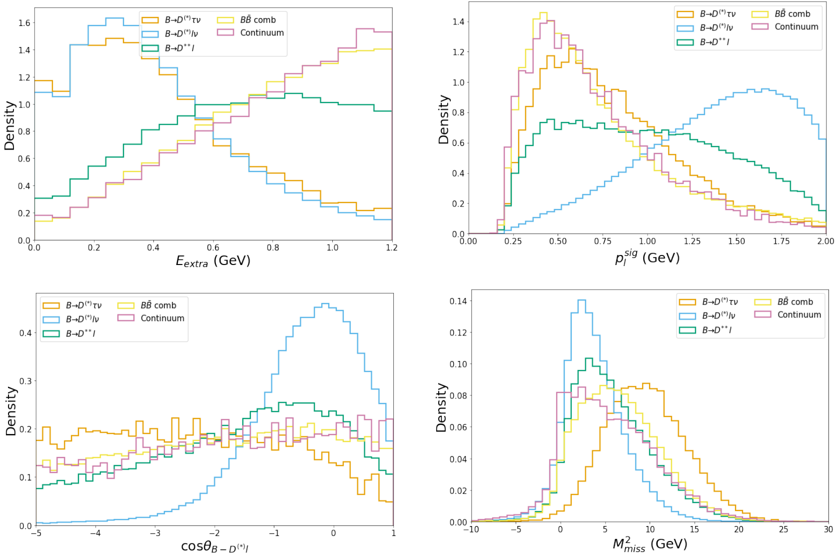
$$\hat{P} = \frac{\hat{N}(\text{signal } D)}{2\sqrt{N} \cdot \mathcal{B}(\tau \to leptons) \cdot \sqrt{\hat{N}(\text{norm } D) + \hat{N}(\text{norm } D^*)}}$$

$$\hat{P^*} = \frac{\hat{N}(\text{signal } D^*)}{2\sqrt{N} \cdot \mathcal{B}(\tau \to leptons) \cdot \sqrt{\hat{N}(\text{norm } D) + \hat{N}(\text{norm } D^*)}} \tag{4}$$

$$\hat{Q} = \frac{\sqrt{\hat{N}(\text{norm } D) + \hat{N}(\text{norm } D^*)} - \sqrt{\hat{N}(\text{norm } D^*)}}{2\sqrt{N}}$$

$$\hat{Q^*} = \sqrt{\frac{\hat{N}(\text{norm } D^*)}{4N}}$$

Distribution of selected variables



Maximum likelihood estimation details

For the $D^{+}l$ subset, the distribution is combination of signal, signal feed-down, normalization, normalization feed-down, $B \to D^{**}l\nu$, $B\bar{B}$ combinatorial and continuum events:

$$\begin{aligned} f(z_1, z_2) = & N_{B\to D\tau\nu} f_{B\to D\tau\nu}(z_1, z_2) + N_{B\to D^*\tau\nu} f_{B\to D^*\tau\nu}(z_1, z_2) \\ & + N_{B\to Dl\nu} f_{B\to Dl\nu}(z_1, z_2) + N_{B\to D^*l\nu} f_{B\to D^*l\nu}(z_1, z_2) \\ & + N_{B\to D^{**}l\nu} f_{B\to D^{**}l\nu}(z_1, z_2) + N_{\text{Other Bkgs}} f_{\text{Other Bkgs}}(z_1, z_2) \end{aligned} \tag{5}$$

Detailed systematic of $\mathcal{B}(B \to D^{**} l\nu)$

Generally, D^{**} is defined as any excited charmed meson states that is not in the 1S ground state. The following possibilities are considered in this analysis:

- Resonant $D^{**}(1P)$ state: include the four lightest orbitally excited charmed meson states $D_0^*(2400), D_1^{'}(2430), D_1(2420), D_2^*(2460)$.
- Resonant $D^{**}(2S)$ state: radially-excited modes.
- Non-resonant $B \to D^{**}(l/\tau)\nu$ where $D^{**} \to D^{(*)}\pi$