Measurements of $\bar{B} \to D^{(*)}\tau^-\bar{\nu}_\tau$ Decays and Implications for Charged Higgs Bosons

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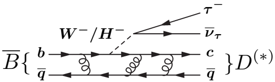

Florian Bernlochner

on behalf of the BaBar collaboration

University of Victoria, Canada

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Flavor physics and physics beyond the Standard Model (SM):

* Precision measurements in Flavor sector

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  Constrain new physics $\mathcal{O}(500\text{GeV} - 1\,TeV)$
* Directs where direct search are promising.

SM Semileptonic decays: Weak $b \to c$ transition moderated by a (virtual) W boson:

* $\mathcal{H}_{\text{eff}}^{\text{SM}} = \frac{4G_F V_{cb}}{\sqrt{2}} \left[(\bar{c}\gamma_\mu P_L b)\,(\bar{\tau}\gamma^\mu P_L \nu_\tau) \right]$

  P_L = projection operators, h.c. term dropped

BSM Contributions: 2 Higgs Doublet Model (2HDM) type II or III

an extension of the Higgs mechanism necessary e.g. for SUSY

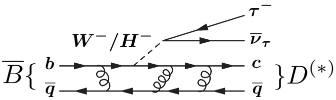
* $\mathcal{H}_{\text{eff}}^{\text{SM}} + \frac{4G_F V_{cb}}{\sqrt{2}} \left[S_L\,(\bar{c}P_L b)\,(\bar{\tau}P_L \nu_\tau) + S_R\,(\bar{c}P_R b)\,(\bar{\tau}P_L \nu_\tau) \right]$

in type II $S_L = 0$; in type III:$S_L \neq 0$

Beyond SM decay:

→ Charged Higgs mediator modifies decay rate

→ Function of $\tan\beta / m_{H^\pm}$



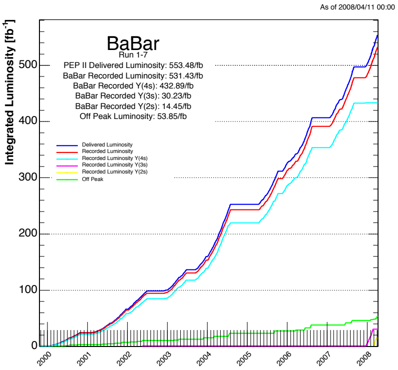
Motivation

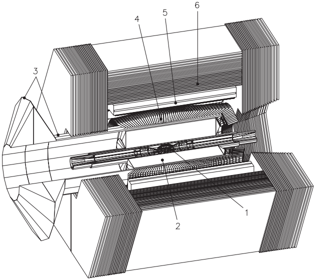
Use rate and final state kinematic to constrain parameter space of these models.

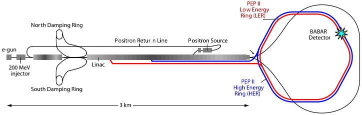
BaBar was a multipurpose experiment operated at the **Pep-II** ***B*-Factory**

colliding $e^+ e^-$ at the energy of the $\Upsilon(4S)$ resonance at $\sqrt{s} = 10.58$ GeV with the focus

CP violation, τ physics, ISR, b and c quark decays







(1) Silicon vertex tracker; (2) Drift chamber; (3) Cherenkov light detector; (4) Electromagnetic calorimeter; (5) superconducting coil; (6) Flux return & Muon detection

Recorded 432/fb or about 471 million $\Upsilon(4S) \to B\bar{B}$ decays

all of them are used in this analysis.

Reconstruct $\bar{B} \to D^{(*)}\tau^- \bar{\nu}_\tau$ with $\tau^- \to \ell^- \bar{\nu}_\ell$

To reconstruct the *missing momentum* of the neutrino: try to fully reconstruct the 2nd B

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* $\Upsilon(4S) \to B\bar{B}$ decays are tagged by **hadronic decays** of one of the B mesons
* **Semi-exclusive** algorithm; constructing many 2nd B candidates per event

→ Select best candiate with lowest $\mathbf{E}_{\text{extra}}$

$\mathbf{E}_{\text{extra}}$ = energy sum of all photons not associated with $B\bar{B}$ pair; minimal threshold 50 MeV.

Hadronic reconstruction efficiency: ϵ_{tag} challenging to derive reliably

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* Can be avoided with ratio of two branching fractions:
  $\epsilon_{\text{tag}}^{\text{decay 1}} / \epsilon_{\text{tag}}^{\text{decay 2}} = 1$
  when decays have the same final state topology

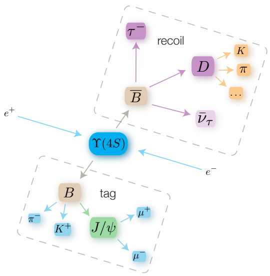

Illustration of hadronic 'tag' and 'recoil' B

Measurement Goal

$$R(D^*) = \frac{\mathcal{B}(\bar{B}\to D^{(*)}\tau\bar{\nu}_\tau)}{\mathcal{B}(\bar{B}\to D^{(*)}\ell\bar{\nu}_\ell)}$$

Benefits: Dependency on $|V_{cb}|$ drop out, QCD form factor uncertainties correlated, ϵ_{tag} drops out.

After initial selection $\bar{B} \rightarrow D^{(*)}(\tau/\ell)\,\bar{\nu}$ account only for 2% of the total events

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Kinematic cut on $q^2 = (p_B - p_{D^*})^2$ rejects most semileptonic background $q^2_{\text{min}} = m^2_\ell$

Boosted Decision Tree to separate semileptonic decays with $q^2 > 4\,\text{GeV}^2$ from other background

* Trained with **8** variables on simulated signal and background

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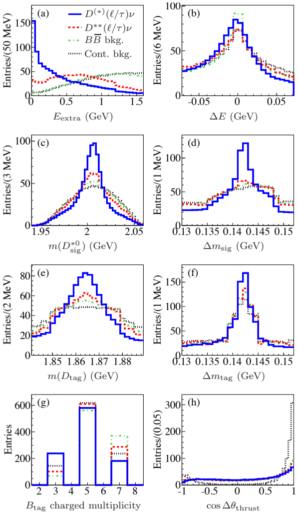
After BDT selection $\bar{B} \rightarrow D^{(*)}(\tau/\ell)\,\bar{\nu}$ purity increases to 39%



8 input variables of the BDT

Signal and Background separation: unbinned extended maximum likelihood fit in 2D

- **Lepton 3-momentum in B meson rest frame**: $|p^*_\ell|$

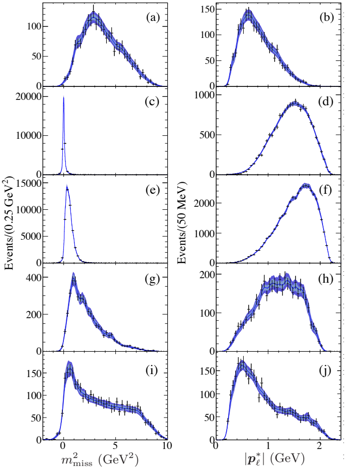
  $B \to D^{(*)}\tau\bar{\nu}_\tau$ signal: Lepton from $\tau \to \ell\,\bar{\nu}_\ell$ decay

- **Missing mass squared**: $m^2_{\mathrm{miss}} = m^2_\nu = (p_{B^{\mathrm{tag}}} - p_{D^{(*)}} - p_\ell)^2$

Signal & Background PDFs:

2D Gaussian kernel estimators with appropriate smoothing from simulated signal and background decays

Statistical uncertainty on shape introduced as nuisance parameter in fit.



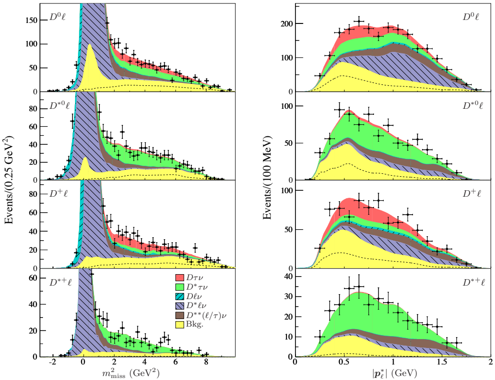
(a,b) $D^0\tau\nu$; (c,d) $D^0\ell\nu$; (e,f) $D^{*0}\ell\nu$; (g,h) $D^{**}(\ell/\tau)\nu$ and (i,j) other $B\bar{B}$ background

iii.d Fit result for 4 final states: $D^0\,\ell$, $D^{*0}\,\ell$, $D^+\,\ell$, $D^{*+}\,\ell$

Fit results:

isospin uncon. fit

2D projections



Results for $\mathcal{R}(D^{(*)})$:

Decay	$N_{\rm sig}$	$N_{\rm norm}$	$\varepsilon_{\rm sig}/\varepsilon_{\rm norm}$	$\mathcal{R}(D^{(*)})$	$\mathcal{B}(B\to D^{(*)}\tau\nu)$ (%)	$\Sigma_{\rm stat}$	$\Sigma_{\rm tot}$
$B^-\to D^0\tau^-\overline{\nu}_\tau$	314 ± 60	1995 ± 55	0.367 ± 0.011	0.429 ± 0.082 ± 0.052	0.99 ± 0.19 ± 0.12 ± 0.04	5.5	4.7
$B^-\to D^{*0}\tau^-\overline{\nu}_\tau$	639 ± 62	8766 ± 104	0.227 ± 0.004	0.322 ± 0.032 ± 0.022	1.71 ± 0.17 ± 0.11 ± 0.06	11.3	9.4
$\overline{B}^0\to D^+\tau^-\overline{\nu}_\tau$	177 ± 31	986 ± 35	0.384 ± 0.014	0.469 ± 0.084 ± 0.053	1.01 ± 0.18 ± 0.11 ± 0.04	6.1	5.2
$\overline{B}^0\to D^{*+}\tau^-\overline{\nu}_\tau$	245 ± 27	3186 ± 61	0.217 ± 0.005	0.355 ± 0.039 ± 0.021	1.74 ± 0.19 ± 0.10 ± 0.06	11.6	10.4
$\overline{B}\to D\tau^-\overline{\nu}_\tau$	489 ± 63	2981 ± 65	0.372 ± 0.010	0.440 ± 0.058 ± 0.042	1.02 ± 0.13 ± 0.10 ± 0.04	8.4	6.8
$\overline{B}\to D^*\tau^-\overline{\nu}_\tau$	888 ± 63	11953 ± 122	0.224 ± 0.004	0.332 ± 0.024 ± 0.018	1.76 ± 0.13 ± 0.10 ± 0.06	16.4	13.2

Full set of systematic uncertainties is evaluated:

Source of uncertainty	Fractional uncertainty (%) $\mathcal{R}(D^0)$	$\mathcal{R}(D^{*0})$	$\mathcal{R}(D^+)$	$\mathcal{R}(D^{*+})$	$\mathcal{R}(D)$	$\mathcal{R}(D^*)$	Correlation D^0/D^{*0}	D^+/D^{*+}	D/D^*
Additive uncertainties									
PDFs									
MC statistics	6.5	2.9	5.7	2.7	4.4	2.0	−0.70	−0.34	−0.56
$\overline{B} \to D^{(*)}(\tau^-/\ell^-)\overline{\nu}$ FFs	0.3	0.2	0.2	0.1	0.2	0.2	−0.52	−0.13	−0.35
$D^{**} \to D^{(*)}(\pi^0/\pi^\pm)$	0.7	0.5	0.7	0.5	0.7	0.5	0.22	0.40	0.53
$\mathcal{B}(\overline{B} \to D^{**}\ell^-\overline{\nu}_\ell)$	1.0	0.4	1.0	0.4	0.8	0.3	−0.63	−0.68	−0.58
$\mathcal{B}(\overline{B} \to D^{**}\tau^-\overline{\nu}_\tau)$	1.2	2.0	2.1	1.6	1.8	1.7	1.00	1.00	1.00
$D^{**} \to D^{(*)}\pi\pi$	2.1	2.6	2.1	2.6	2.1	2.6	0.22	0.40	0.53
Cross-feed constraints									
MC statistics	2.6	0.9	2.1	0.9	2.4	1.5	0.02	−0.02	−0.16
$f_{D^{**}}$	6.2	2.6	5.3	1.8	5.0	2.0	0.22	0.40	0.53
Feed-up/feed-down	1.9	0.5	1.6	0.2	1.3	0.4	0.29	0.51	0.47
Isospin constraints	–	–	–	–	1.2	0.3	–	–	−0.60
Fixed backgrounds									
MC statistics	4.3	2.3	4.3	1.8	3.1	1.5	−0.48	−0.05	−0.30
Efficiency corrections	4.8	3.0	4.5	2.3	3.9	2.3	−0.53	0.20	−0.28
Multiplicative uncertainties									
MC statistics	2.3	1.4	3.0	2.2	1.8	1.2	0.00	0.00	0.00
$\overline{B} \to D^{(*)}(\tau^-/\ell^-)\overline{\nu}$ FFs	1.6	0.4	1.6	0.3	1.6	0.4	0.00	0.00	0.00
Lepton PID	0.9	0.9	0.9	0.8	0.9	0.9	1.00	1.00	1.00
$\pi^0/\pi^\pm$ from $D^* \to D\pi$	0.1	0.1	0.0	0.0	0.1	0.1	1.00	1.00	1.00
Detection/Reconstruction	0.7	0.7	0.7	0.7	0.7	0.7	1.00	1.00	1.00
$\mathcal{B}(\tau^- \to \ell^-\bar{\nu}_\ell\nu_\tau)$	0.2	0.2	0.2	0.2	0.2	0.2	1.00	1.00	1.00
Total syst. uncertainty	12.2	6.7	11.4	6.0	9.6	5.6	−0.21	0.10	0.05
Total stat. uncertainty	19.2	9.8	18.0	11.0	13.1	7.1	−0.59	−0.23	−0.45
Total uncertainty	22.8	11.9	21.3	12.5	16.2	9.0	−0.48	−0.15	−0.27

Compatibility of the result with the SM:

	$\mathcal{R}(D)$	$\mathcal{R}(D^*)$
This Analysis	0.440 ± 0.072	0.332 ± 0.030
Standard Model Prediction	0.297 ± 0.017	0.252 ± 0.003

SM prediction uses the latest world averages for the QCD form factors from HFAG.

→ **Excess** of 2σ & 2.7σ in $\mathcal{R}(D)$ & $\mathcal{R}(D^*)$

Experimental values are correlated:
Can make a stronger statement

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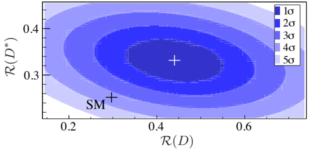
In the 2D plane of $\mathcal{R}(D)$-$\mathcal{R}(D^*)$ the observed combination of both has a $\chi^2 = 14.6$

→ **SM** probability is 6.9×10^{-4}
(or SM expectation 3.4σ away)



2D correlation plot for $\mathcal{R}(D)$ & $\mathcal{R}(D^*)$

$$\chi^2 = (\Delta, \Delta^*) \begin{pmatrix} \sigma^2_{\rm exp} + \sigma^2_{\rm th} & \rho\,\sigma_{\rm exp}\,\sigma^*_{\rm exp} \\ \rho\,\sigma_{\rm exp}\,\sigma^*_{\rm exp} & \sigma^{*2}_{\rm exp} + \sigma^{*2}_{\rm th} \end{pmatrix}^{-1} \begin{pmatrix} \Delta \\ \Delta^* \end{pmatrix},$$

χ^2 definition; theory uncertainties are assumed uncorrelated.

The compatibility of the result with a charged Higgs Boson 2HDM type II can also be tested

Presence of **additional scalar mediator** for weak decay changes **decay rate and lepton momentum** of $\bar{B} \to D^{(*)}\,\tau\,\bar{\nu}_\tau$

↓

Signal PDF shape and efficiency change.

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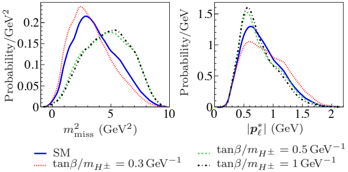
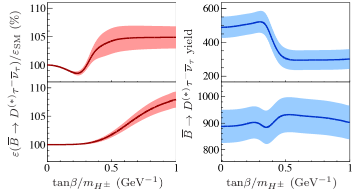
Can redetermine $\mathcal{R}(D^{(*)})$ for various points of $\tan\beta/m_{H^\pm}$ what scans the coupling and mass of a 2HDM type II charged Higgs boson.



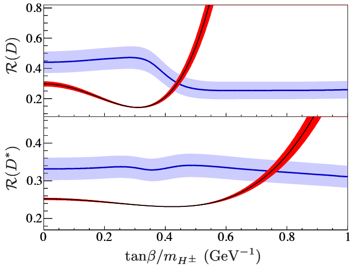
Change in missing mass squared and lepton momentum for various $\tan\beta/m_{H^\pm}$ points and SM.



Efficiency and predicted yields for $\bar{B} \to D^{(*)}\,\tau\,\bar{\nu}_\tau$

Compatibility with 2HDM type II:

$\tan\beta/m_{H^\pm}$	$\tan\beta/m_{H^\pm}$
$0.44 \pm 0.02\ \mathrm{GeV}^{-1}$	$0.75 \pm 0.04\ \mathrm{GeV}^{-1}$



Comparison of result (blue) with the predicted values for $\mathcal{R}(D^{(*)})$ in the 2HDM type II model.

Observed values for $\mathcal{R}(D)$ & $\mathcal{R}(D^*)$ impose strong limits on 2HDM type II parameter space.

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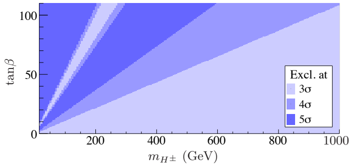
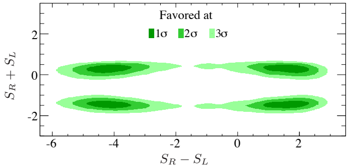
The full $\tan\beta - m_{H^\pm}$ parameter space is excluded by 3σ; certain areas up to 5σ.



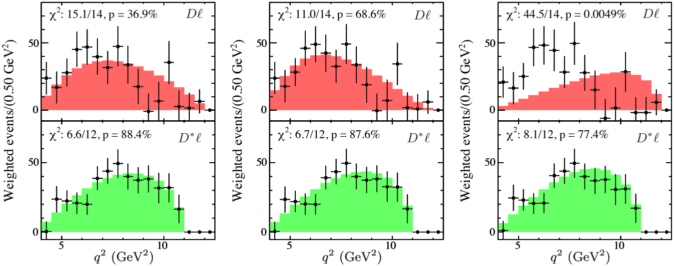
Exclusion plot for $\tan\beta/m_{H^\pm}$ parameter space

Compatibility with 2HDM type III:

Type III Model has one degree of freedom more to accommodate the observed difference:



The $q^2 = \left(p_B - p_D^{(*)}\right)^2$ spectrum can be used to further test the compatibilities of the type III configurations:

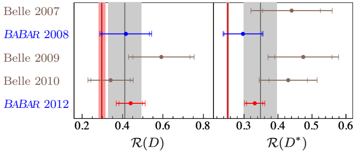


efficiency corrected q^2 spectra for (left) SM, (center) $S_L + S_R \backsim 0.4$, (right) $S_L + S_R \backsim -1.5$; uncertainties are statistical + systematics.

Based on the observed q^2 spectrum the solution with $S_L + S_R \backsim -1.5$ can be excluded with 2.9 σ.

Measurement of the ratio of $\bar{B} \rightarrow D^{(*)}\,\tau^-\,\bar{\nu}_\tau$ and $\bar{B} \rightarrow D^{(*)}\,\ell\,\bar{\nu}_\ell$ using the full *BABAR* dataset.

Observe tension of 3.4 σ in the measured ratio of $\bar{B} \rightarrow D^{(*)}\,\tau^-\,\bar{\nu}_\tau$ and $\bar{B} \rightarrow D^{(*)}\,\ell\,\bar{\nu}_\ell$ decays and the SM expectation. The result is compatible with earlier measurements and the previous world average:



Measured ratio excludes together with $B \rightarrow X_s\gamma$ the full 2HDM type II parameter space.

Measured ratio can be accommodated by certain configurations of type III models, i.e. $|S_R + S_L| < 1.4$