$\overline{B} \to D^{(*)}\tau\overline{\nu}_\tau$ decays with hadronic and **semileptonic** tagging at Belle

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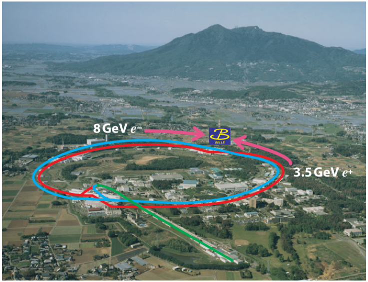
Outline

- **Review of Belle's 2015 result of $\bar{B} \to D^{(*)}\tau^-\bar{\nu}_\tau$ with hadronic tagging, and the current world average.**
- **Introduce Belle's new measurement of $\bar{B}^0 \to D^{*+}\tau^-\bar{\nu}_\tau$ with the semileptonic tagging method and compatibility with New Physics models.**

The Belle Experiment

The KEKB accelerator

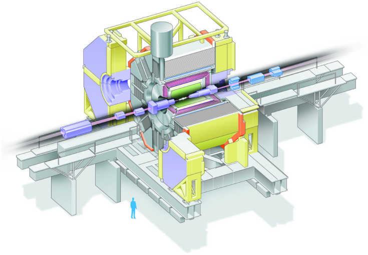
- Asymmetric e^+e^- collider
- Mainly operates at the $\Upsilon(4S)$ resonance

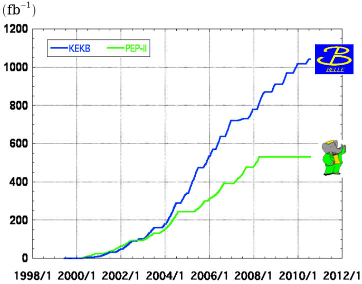


Final data sample

- $711 fb^{-1}$ $\Upsilon(4S)$ resonance
- $121 fb^{-1}$ $\Upsilon(5S)$ resonance

The Belle detector

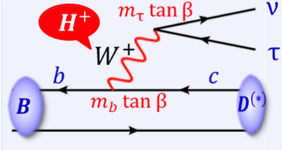




Semitauonic B decays of type $b \to c\tau\nu_\tau$ are sensitive probes to search for New Physics. NP could change $\mathcal{B}$ and τ polarization. Effect could be different for D and D^*.

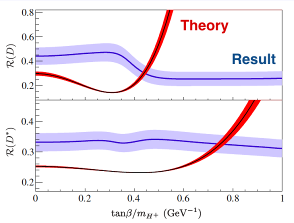
2HDM of type II

- A charged Higgs of spin 0 couples to the τ.
- Could enhance or decrease the ratios $\mathcal{R}(D^{(*)}) = \frac{\mathcal{B}(\overline{B}\to D^{(*)}\tau\nu)}{\mathcal{B}(\overline{B}\to D^{(*)}\ell\nu)}$ depending on $\tan^2\beta/m^2_{H^\pm}$.



BaBar 2013: The combination of $\mathcal{R}(D)$ and $\mathcal{R}(D^*)$ excludes the type II 2HDM charged Higgs boson at 99.8% confidence level for any value of $\tan\beta/m_{H^\pm}$.

Phys. Rev. D **78** 072012 (2013)



Measure the ratios:

$$\mathcal{R}(D^{(*)}) = \frac{\mathcal{B}(\overline{B} \to D^{(*)}\tau\nu)}{\mathcal{B}(\overline{B} \to D^{(*)}\ell\nu)} = \frac{\text{signal}}{\text{normalization}} \quad (\ell = e, \mu)$$

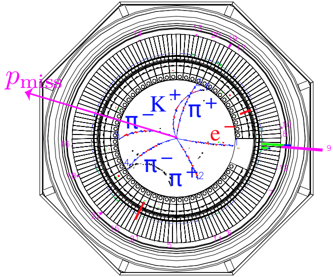
τ reconstructed only using leptonic decays, $\tau \to \ell\nu_\tau\nu_\ell$:

- Signal and normalization are identified by the same particles in the final state.
- Leads to cancellation of dependence on form factors, the CKM matrix element $|V_{cb}|$, and on various sources of uncertainty in the ratios $\mathcal{R}(D^{(*)})$.
- Also allows for precise SM predictions with uncertainties 2% (6%) for $\mathcal{R}(D)$ ($\mathcal{R}(D^*)$). Phys. Rev. D **78**, 014003 (2008), Phys. Rev. D **85**, 094025 (2012)

Experimentally challenging: Neutrinos in the final state prohibit direct signal-side reconstruction

$\Rightarrow$ ***Must fully reconstruct $e^+e^- \to \Upsilon(4S) \to B_{tag}B_{sig}$ events***

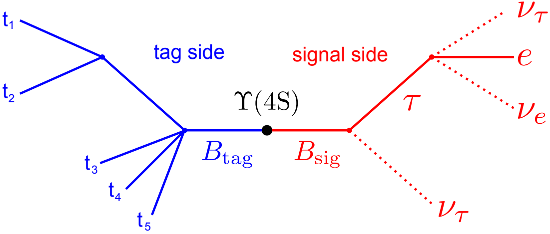
Typical B factory event



$B^+_{tag} \to \bar{D}^0\pi^+\pi^+\pi^-$
$\hookrightarrow K^+\pi^-$

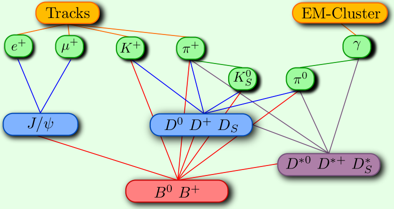
$B^-_{sig} \to \tau^-\bar{\nu}_\tau$
$\hookrightarrow e^-\bar{\nu}_e\nu_\tau$

Tag- and signal-side of the full reconstruction

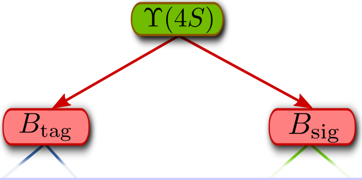


- Hierarchical reconstruction of the B_{tag} using NeuroBayes[1].
- Check if the remaining particles in the detector are consistent with the signal signature.

[1] Nucl. Instrum. Meth. A654: 432 (2011)



Which tag-side reconstruction?



Tagging techniques

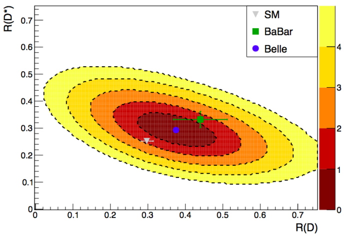
Purity $\longrightarrow$

$\longleftarrow$ Efficiency

Inclusive	Semileptonic	Hadronic
$B \to$ anything	$B \to D^{(*)}\ell\nu_\ell$	$B \to$ hadrons
$\epsilon \approx \mathcal{O}(2\%)$	$\epsilon \approx \mathcal{O}(0.2\%)$	$\epsilon \approx \mathcal{O}(0.1\%)$
Very large statistics; Also very large background	Mid-range reconstruction efficiency; Less information about B_{tag} due to neutrino	Cleaner sample Knowledge of $p(B_{\text{sig}})$; Lower tagging efficiency

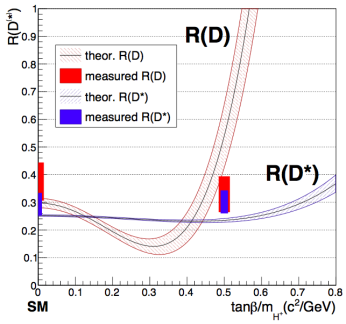
Phys. Rev. D 92, 072014

$$R(D) = 0.375 \pm 0.064 \pm 0.026$$
$$R(D^*) = 0.293 \pm 0.038 \pm 0.015$$



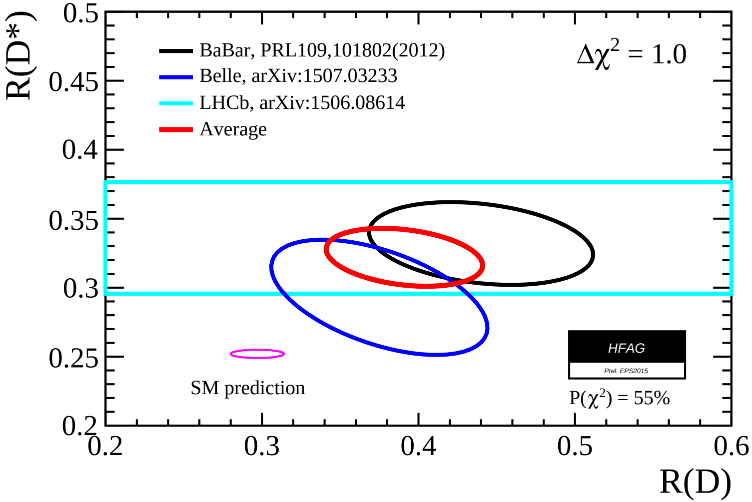
Belle result lies between the SM prediction (1.4σ away) and BaBar's hadronic tag result (1.8σ away) Phys. Rev. D 88, 072012 (2013)

Fit is repeated with PDF generated for type II 2HDM with $\tan\beta/m_H = 0.5$ GeV^{-1}



Compatible with type II 2HDM around $\tan\beta/m_H = 0.5$ GeV^{-1}

Including LHCb $\mathcal{R}(D^*)$ measurement



3.9σ combined deviation (including correlations) from the SM

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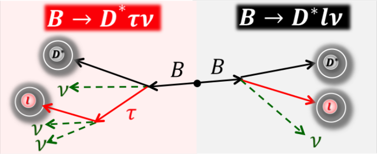
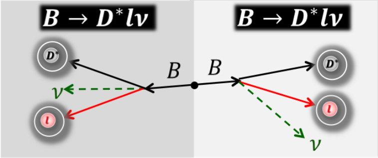
Semitauonic signal-side decay and semileptonic tag-side.



Numerator in $\mathcal{R}(D^*)$

Normalization events are double semileptonic decays.



Denominator in $\mathcal{R}(D^*)$

D^* reconstruction:

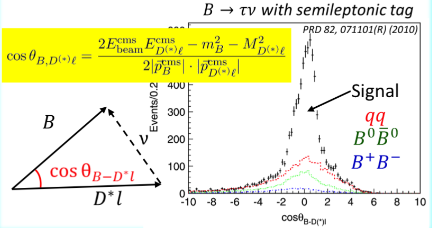
- $D^{*+} \to D^0\pi^+, D^+\pi^0$ ($\sim 100\%$)

  D^0: 10 modes ($\sim 37\%$)

  D^+: 5 modes ($\sim 22\%$)

Tag semileptonic B-decay: Combine D^{*+} and oppositely-charged lepton candidates and calculate the cosine of the angle between the B momentum and the D^*l in the $\Upsilon(4S)$ frame.

$\Rightarrow$



✓ **tag candidates: $\cos\theta_{B-D^*\ell} \in [-1, 1]$**

Image credits: Y. Sato (Nagoya)

Separate correctly reconstructed signal and normalization events using NeuroBayes NN with the following variables:

- Missing mass squared: $M^2_{\text{miss}} = \sqrt{(2E_{\text{beam}} - \sum_i E_i)^2 - |\sum_i \vec{p}_i|^2}$
- Visible energy: $E_{\text{vis}} = \sum_i E_i$, where $(\vec{p}_i, E_i)$ is the reconstructed four-momentum at the $\Upsilon(4S)$ rest frame of particles used in the reconstruction.
- $\cos\theta_{B\text{-}D^*\ell}$

$\Rightarrow$ *Trained on MC samples of signal and normalization.*

Dominant backgrounds:

- Fake (falsely reco'd) D^*.
- $B \to D^{**} l \nu_l$, with $D^{**} \to D^{(*)}$
- $B \to X_c D^*$, with $X_c \to$ decaying semileptonically.

Separated from signal and normalization using the ***sum of energies of neutral clusters not associated with reco'd particles:*** E_{ECL}

2D fit to NN and E_{ECL} to extract signal and normalization

Component	Yield	Shape
Signal	Float	1D X 1D
Normalization	Float	2D
Fake $D^{(*)}$	Fix	2D
$B \to D^{**} l\nu$	Float	2D
Other	Fix	2D

Determination of $\mathcal{R}(D^*)$

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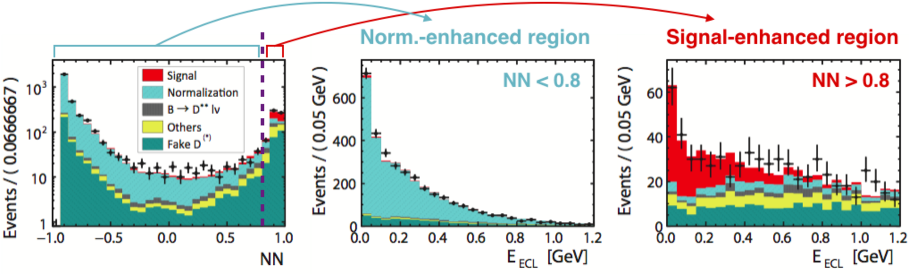
2D fit to NN and E_{ECL}:

Preliminary



$$\mathcal{R}(D^*) = \frac{1}{\mathcal{B}(\tau^- \to l^- \bar{\nu}_l \nu_\tau)} \cdot \frac{\varepsilon_{\text{norm}}}{\varepsilon_{\text{sig}}} \cdot \frac{N_{\text{sig}}}{N_{\text{norm}}}$$

$\varepsilon_{\text{norm}}/\varepsilon_{\text{sig}} = 1.289 \pm 0.015$ (from MC simulation)

$$\mathcal{R}(D^*) = 0.302 \pm 0.030(\text{stat}) \pm 0.011(\text{syst}) \quad (13.8\sigma)$$

	$\mathcal{R}(D^*)$ [%]		
Sources	$\ell^{\text{sig}} = e, \mu$	$\ell^{\text{sig}} = e$	$\ell^{\text{sig}} = \mu$
MC statistics for PDF shape	2.2%	2.5%	3.9%
PDF shape of the normalization	$^{+1.1}_{-0.0}$%	$^{+2.1}_{-0.0}$%	$^{+2.8}_{-0.0}$%
PDF shape of $B \to D^{**}\ell\nu_\ell$	$^{+1.0}_{-1.7}$%	$^{+0.7}_{-1.3}$%	$^{+2.2}_{-3.3}$%
PDF shape and yields of fake $D^{(*)}$	1.4%	1.6%	1.6%
PDF shape and yields of $B \to X_c D^*$	1.1%	1.2%	1.1%
Reconstruction efficiency ratio $\varepsilon_{\text{norm}}/\varepsilon_{\text{sig}}$	1.2%	1.5%	1.9%
Modeling of semileptonic decay	0.2%	0.2%	0.3%
$\mathcal{B}(\tau^- \to \ell^- \bar{\nu}_\ell \nu_\tau)$	0.2%	0.2%	0.2%
Total systematic uncertainties	$^{+3.4}_{-3.5}$%	$^{+4.1}_{-3.7}$%	$^{+5.9}_{-5.8}$%

- Dominant uncertainty arises from the limited size of the MC samples for the PDF shapes. $\Rightarrow$ *Evaluated with Toy MC studies.*
- Large error due to poorly known $\mathcal{B}(B \to D^{**} l \nu_l)$ and of the D^{**} decay. $\Rightarrow$ *Varied within their uncertainties.*

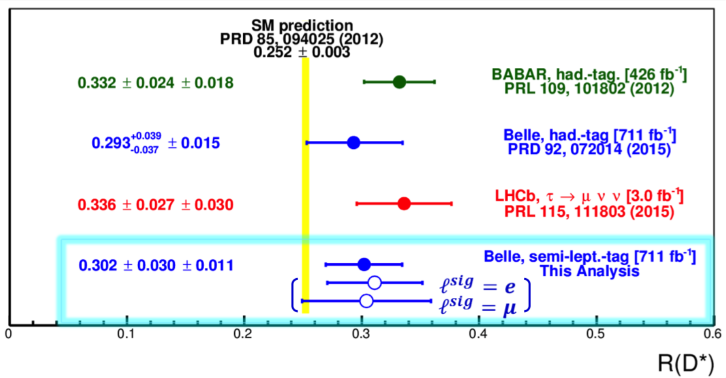
Consistent results for individual samples (separated @ B_{sig})

$$\mathcal{R}(D^*) = 0.311 \pm 0.038 \pm 0.013 \;\; (\ell^{\text{sig}} = e)$$

$$\mathcal{R}(D^*) = 0.304 \pm 0.051 \pm 0.018 \;\; (\ell^{\text{sig}} = \mu)$$

Comparison with other measurements

Preliminary



Central value close to Belle hadronic tag result.

Precision improvement over Belle hadronic tag and LHCb results.

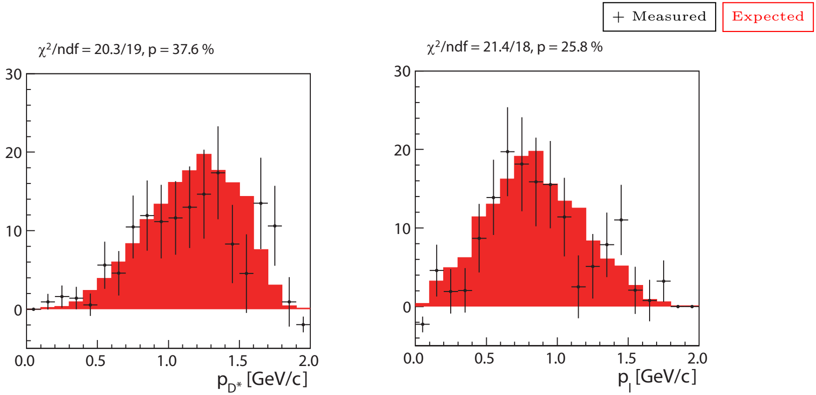
Compatibility test at SM

Kinematic variables:

Preliminary

- The momentum transfer $q^2 \equiv (p_B - p_{D^{(*)}})^2$ cannot be calculated with a semileptonic tag due to a neutrino on the tag side (employed in the hadronic analyses).

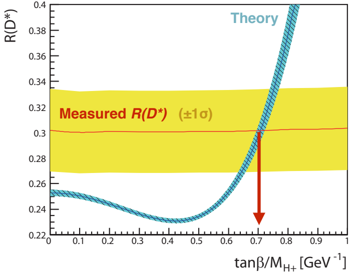
$\Rightarrow$ *Use the background-subtracted momenta of D^* and lepton in the CM frame in the signal region: $NN > 0.8$ and $E_{ECL} < 0.5$*

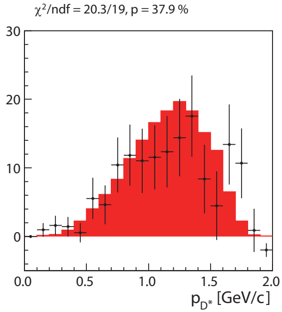


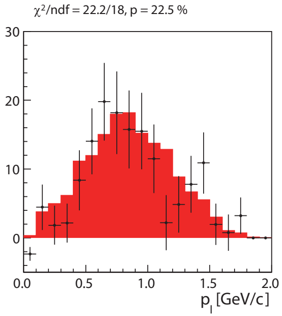
$\mathcal{R}(D^*)$ in 2HDM type-II

Compatibility test: Preliminary

1) Construct a PDF for signal events for a *scan* of $\tan\beta/m_{H^\pm} \in [0,1]\text{GeV}^{-1}$.
2) Find that the measured value of $\mathcal{R}(D^*)$ matches the theoretical prediction at $\frac{\tan\beta}{m_{H^\pm}} \approx 0.7\ \text{GeV}^{-1}$.
3) *P-values of p_{D^*} and p_l similar to SM case.*







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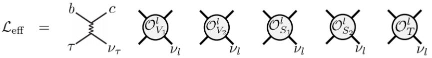
- **Bosons** which couple to a **lepton-quark** pair.
- **Carry color & electric charge, baryon &lepton #.**
- **Unified** description of **leptons and quarks**.

$$-\mathcal{L}_{\rm eff} = 2\sqrt{2}G_F V_{cb} \sum_{l=e,\mu,\tau} \left[(\delta_{l\tau} + C^l_{V_1})\mathcal{O}^l_{V_1} + C^l_{V_2}\mathcal{O}^l_{V_2} + C^l_{S_1}\mathcal{O}^l_{S_1} + C^l_{S_2}\mathcal{O}^l_{S_2} + C^l_T\mathcal{O}^l_T\right]$$



Assignment of Quantum Numbers

	S_1	S_3	V_2	R_2	U_1	U_3
spin	0	0	1	0	1	1
$F = 3B + L$	−2	−2	−2	0	0	0
$SU(3)_c$	3^*	3^*	3^*	3	3	3
$SU(2)_L$	1	3	2	2	1	3
$U(1)_{Y=Q-T_3}$	1/3	1/3	5/6	7/6	2/3	2/3

Six LQ Models

		$\mathcal{O}^l_{V_1}$	$\mathcal{O}^l_{V_2}$	$\mathcal{O}^l_{S_1}$	$\mathcal{O}^l_{S_2}$	$\mathcal{O}^l_T$
Scalar	S_1	● (red)			● (blue)	− ● (blue) /4
Scalar	S_3	● (red)				
Scalar	R_2				● (red)	● (red) /4
Vector	V_2^μ			● (red)		
Vector	U_1^μ	● (red)		● (blue)		
Vector	U_3^μ	● (red)				

6 LQ models in $b \to c\tau\nu_\tau$ decays

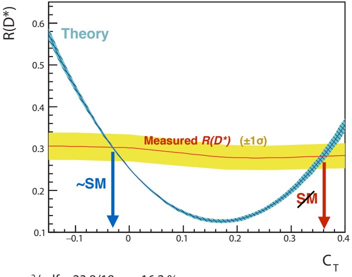
- $B \to D^{(*)}\tau\nu$ is sensitive to the **tensor operator**.
- **R_2-type** LQ model good candidate for compatibility test.
- Relative Wilson coeffs. $C_{S_2} = +7.8\ C_T$ at the b mass scale, assuming $M_{LQ} = O(1)$ TeV.

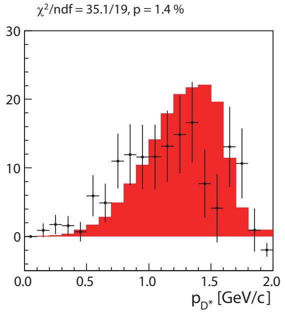
References: PRD **87**, 034028 (2013); PRD **88**, 094012 (2013). Image credits: Y. Sakaki (KEK)

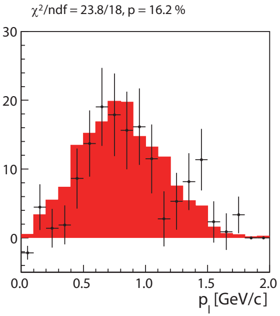
Compatibility test: Preliminary

- Two favored regions found:
  SM-like @ $C_T = -0.03$
  Non-SM-like @ $C_T = +0.36$
  (shown below)

$\Rightarrow$ *Large disagreement in D^* momentum distribution*







Summary

- **$\bar{B} \to D^{(*)}\tau^- \bar{\nu}_\tau$ results with hadronic tag compatible with type II 2HDM around $\tan\beta/m_H = 0.5$ GeV^{-1}.**

- **First result of $\bar{B}^0 \to D^{*+}\tau^- \bar{\nu}_\tau$ with the semileptonic tagging method shown today.**
    - **Central value** close to Belle hadronic tag result. **Precision** improvement over Belle hadronic tag and LHCb results.
    - Compatible with the SM and type-II 2HDM around $\tan\beta/m_H = 0.7$ GeV^{-1}.
    - R_2 type leptoquark model with $C_T = +0.36$ is disfavored.
    - To be submitted to PRD this month.