$B \to \tau\nu$ AND RELATED RESULTS

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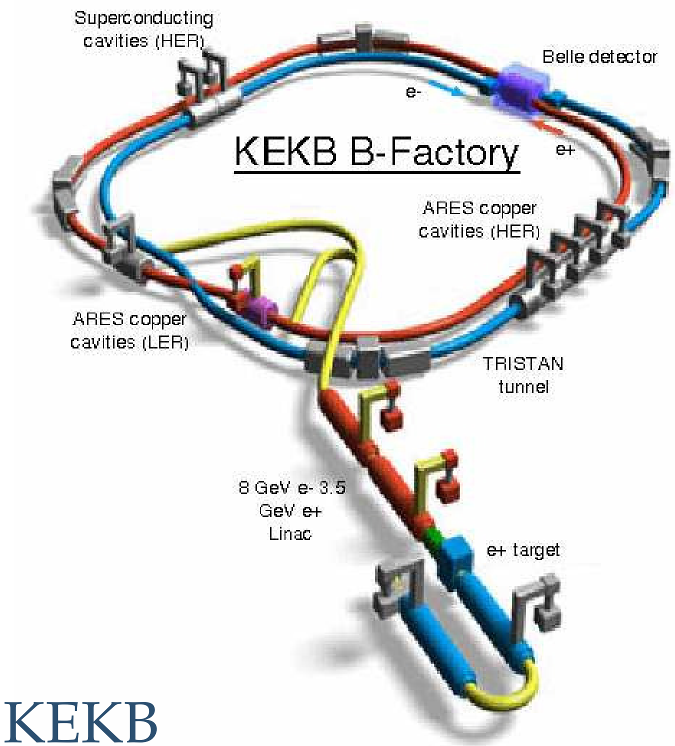
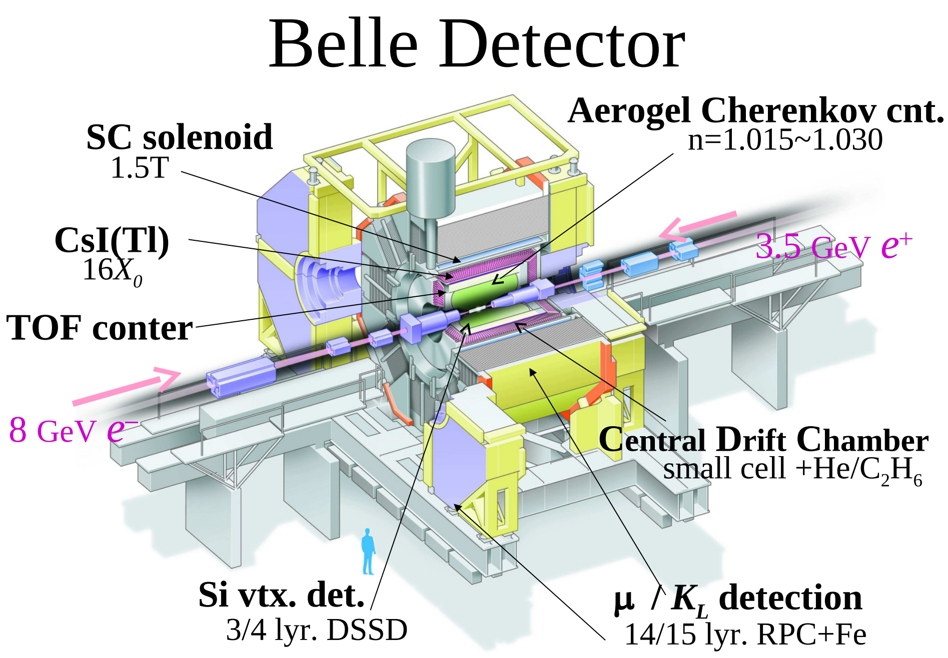
on behalf of the Belle collaboration

QFTHEP'2013, St. Peterburg, Russia, June 28, 2013

Belle experiment

$$c\bar{c}, q\bar{q}, \ell\ell \leftarrow e^+e^- \rightarrow \Upsilon(4S) \rightarrow B\bar{B}$$

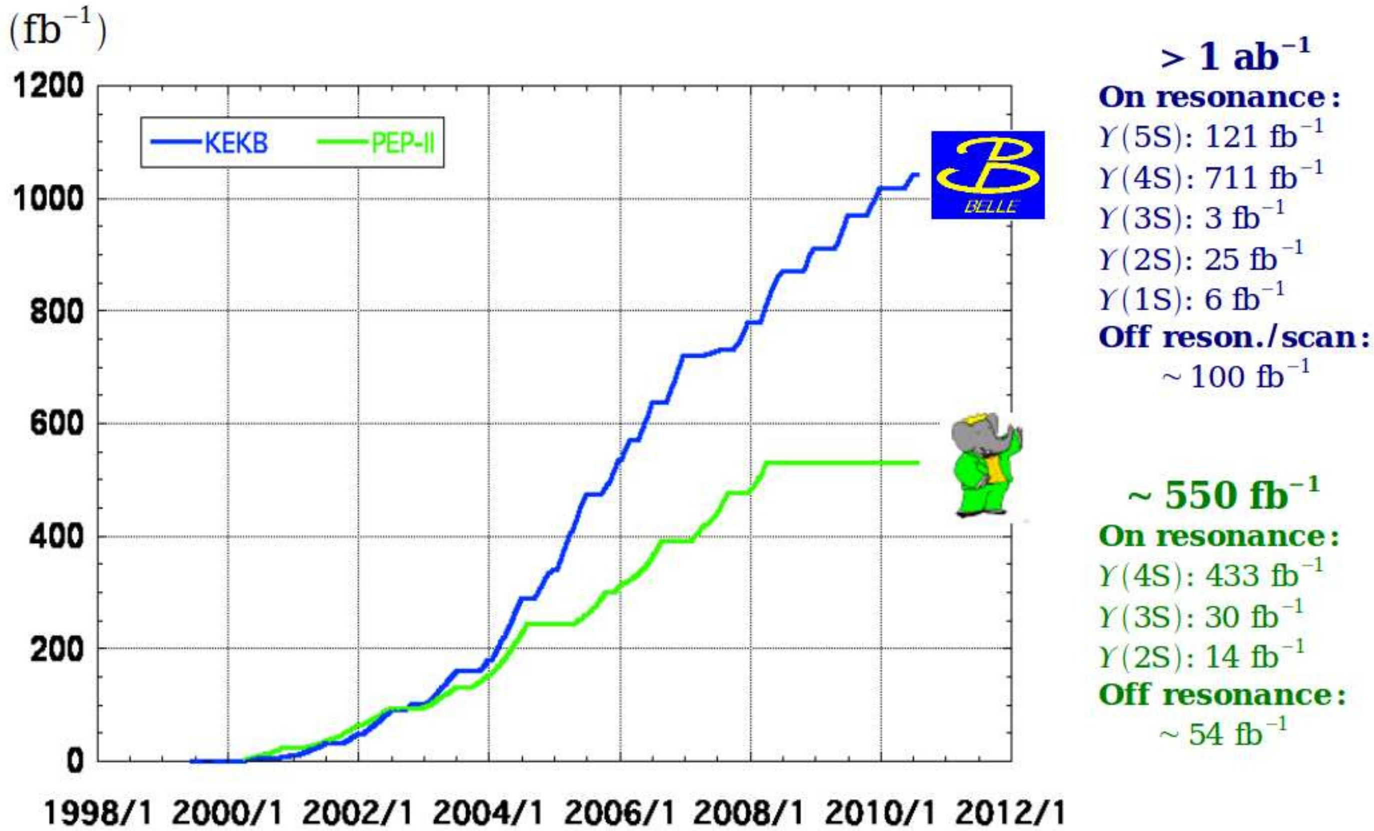




- KEKB
  - Asymmetric-energy e^+e^- collider: $3.5\text{GeV} \times 8\text{GeV}$
  - Record luminosity $L = 2.1 \times 10^{34} cm^{-2} s^{-1}$
- Belle
  - Designed for CP violation study in B decays
  - Suitable for many other studies: charm, τ etc.

Integrated luminosity

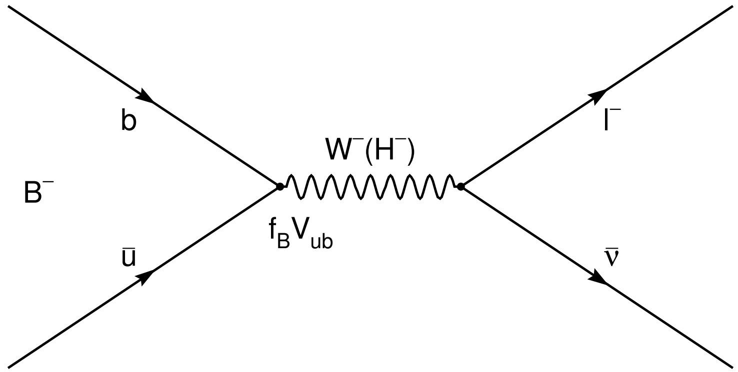
- Data was taken in 1999 – 2010
- World largest accumulated luminosity $> 1ab^{-1}$
- $711 fb^{-1}$ on $\Upsilon(4S)$ resonance correspond to 772×10^6 $B\bar{B}$ pairs



Standard Model and New Physics

- The Standard Model describes known processes very well;
- However, there are indications, that the Standard Model is not complete:
  - neutrino oscillations, baryon asymmetry, dark matter;
  - too many parameters, hierarchy problem;
- There should be something beyond the Standard Model — New Physics.
- New Physics effects are expected to be small, therefore the best way to look is to study rare decays.

New Physics and $B \to \ell\nu$



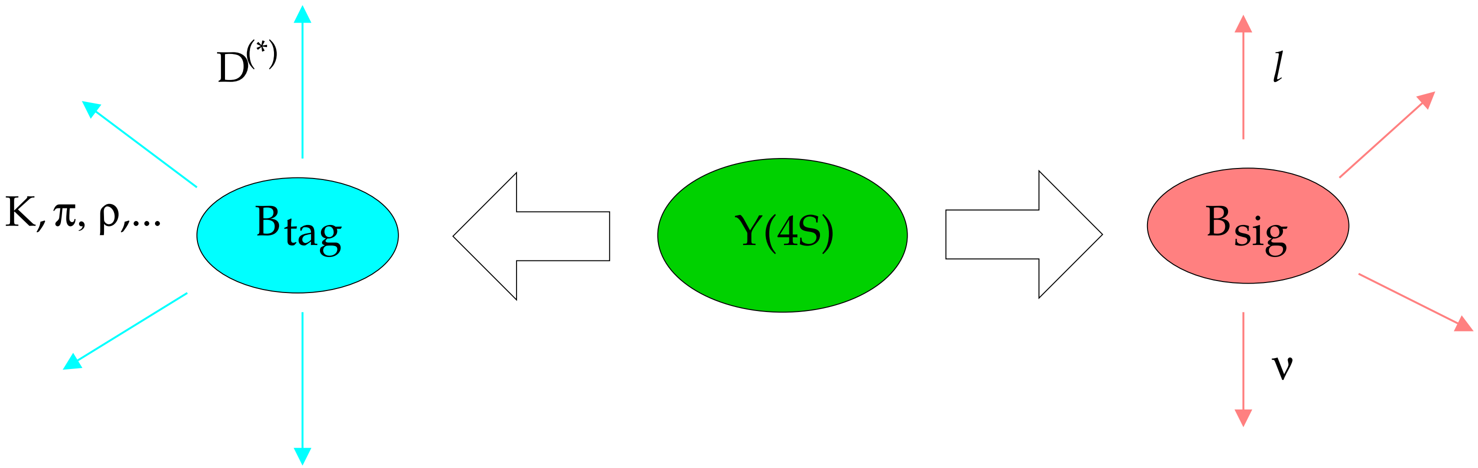
$$\mathcal{B}(B^- \to \ell^- \bar{\nu}_\ell) = \frac{G_F^2 m_B m_\ell^2}{8\pi}(1 - \frac{m_\ell^2}{m_B^2})^2 f_B^2 |V_{ub}|^2 \tau_B$$

- Leptonic B decays are clean since there are no hadronic uncertainties.
- Leptonic decays are helicity-suppressed:
  $\mathcal{B}(B^- \to e^- \bar{\nu}_e) \ll \mathcal{B}(B^- \to \mu^- \bar{\nu}_\mu) \ll \mathcal{B}(B^- \to \tau^- \bar{\nu}_\tau)$.
- Good place to look for New Physics, *e.g.* charged Higgs exchange:
  $\mathcal{B}_{NP}(B^- \to \ell^- \bar{\nu}_\ell) = \mathcal{B}_{SM}(B^- \to \ell^- \bar{\nu}_\ell) \times r_H$,
  where r_H depends on the Higgs model, but not on the mode.
  In Type II 2HDM (W. S. Hou, PRD 48, 2342 (1993)) $r_H = (1 - \frac{m_B^2}{m_H^2} \tan^2 \beta)^2$.

Full reconstruction tagging

- At B factory events are clearly separated;
- $\Upsilon(4S)$ decays into two B mesons;
- All particles (but neutrinos) are detected;
- Initial energy is known.

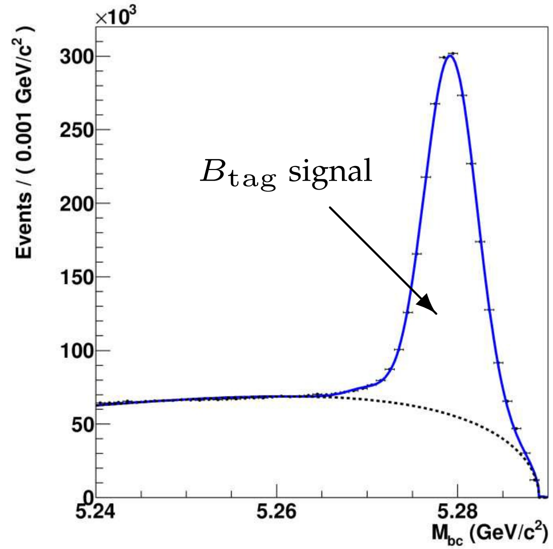
We can resonstruct one B meson in hadronic or semileptonic mode ($B_{\rm tag}$), reconstruct some particles from the other B meson ($B_{\rm sig}$), and restrict unreconstructed part from the information about the whole event.



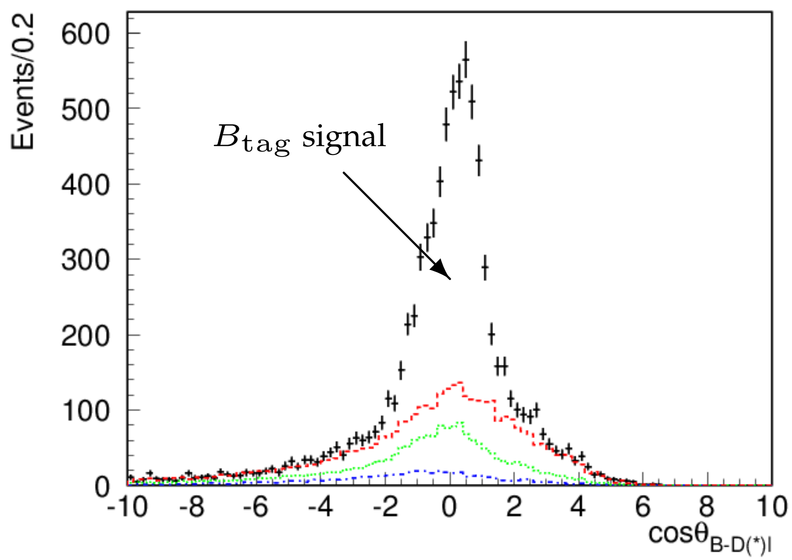
Full reconstruction types

- Hadronic tagging
  - Exclusive tagging:
    - $B_{\rm tag}$ is reconstructed as $D^{(*)}X$ combination;
    - $B_{\rm sig}$ is reconstructed;
  - Inclusive tagging:
    - $B_{\rm sig}$ is reconstructed;
    - The rest of the event is combined into $B_{\rm tag}$ and checked if it is consistent with B meson hypothesis;
  - Efficiency $\sim 0.2\%$;
- Semileptonic tagging
  - B meson is reconstructed as $D^{(*)}\ell$;
  - Efficiency $\sim 0.7\%$, but more background;

$$\Delta E = E_B - E_{beam}, M_{bc} = \sqrt{E_{beam}^2 - p_B^2}$$



$$\cos\theta_{B,D\ell} = \frac{2E_{beam}E_{D\ell} - m_B^2 - M_{D\ell}^2}{2P_B P_{D\ell}}$$



Existing experimental results

- Belle

Hadronic tagging, 449M $\mathcal{B} = [1.79^{+0.56}_{-0.49}{}^{+0.46}_{-0.51}] \times 10^{-4}$

Semileptonic tagging, 657M $\mathcal{B} = [1.54^{+0.38}_{-0.37}{}^{+0.29}_{-0.31}] \times 10^{-4}$

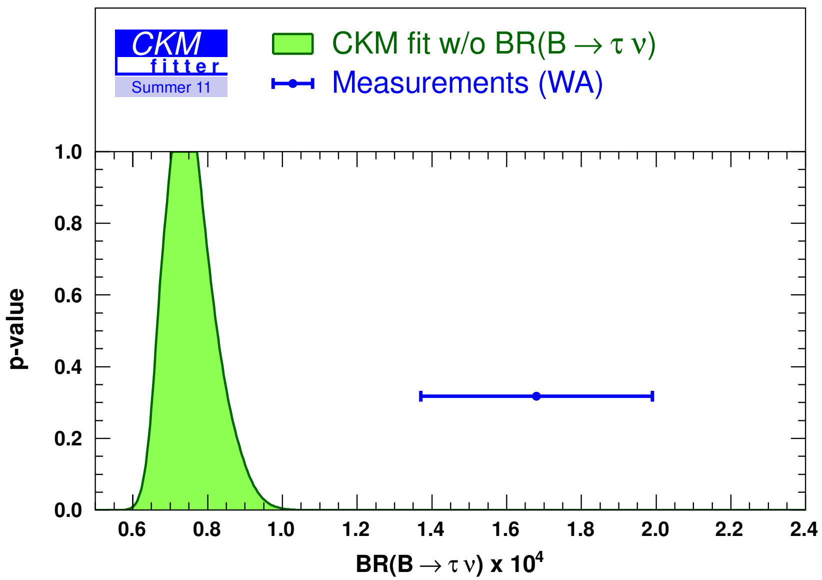
- BaBar

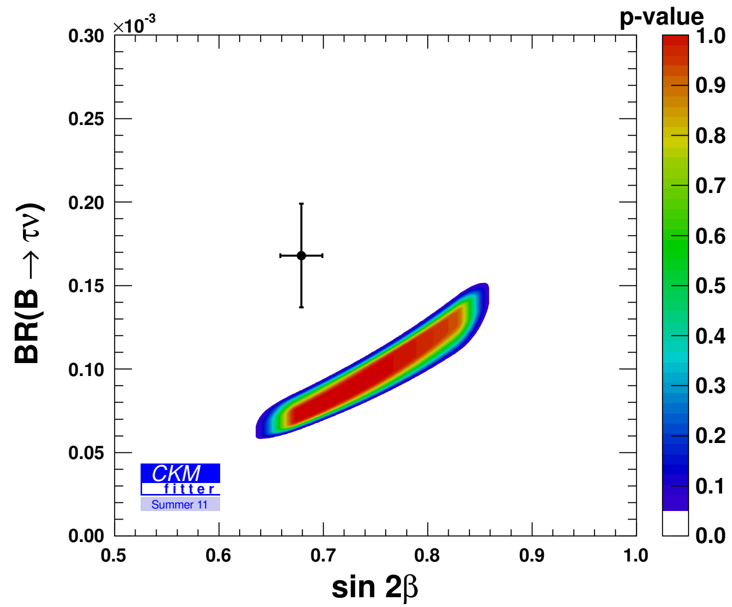
Hadronic tagging, 468M $\mathcal{B} = [1.80^{+0.57}_{-0.54} \pm 0.24] \times 10^{-4}$

Semileptonic tagging, 459M $\mathcal{B} = [1.7 \pm 0.8 \pm 0.2] \times 10^{-4}$

2.8σ deviation

"Tension" in CKM global fit?





Improvement in hadronic tagging

Analysis of $B \to \tau\nu_\tau$ with hadronic tag was already made by Belle at smaller data sample (PRL 97, 251802 (2006)).
What is new in this analysis?

- All data reprocessed; better efficiency of low p_T tracks and neutrals reconstruction;
- Increased data sample 449M $\Rightarrow$ 772M (factor of 1.7);
- Improved hadronic tagging efficiency due to new algorythm (factor of 2.2); NIM A654, 432 (2011)
- Improved signal efficiency due to less restricive requirements (factor of 1.8);
- 2D fit (residual calorimeter energy E_{ECL} vs missing mass M_{miss}) instead of 1D fit (residual energy only);
- Background rejection with reconstructed K_L.

Analysis procedure

772M $B\bar{B}$

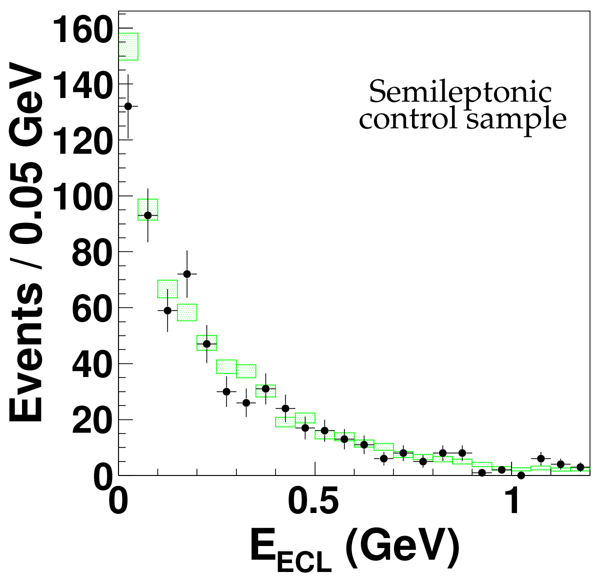
PRL 110, 131801 (2013)

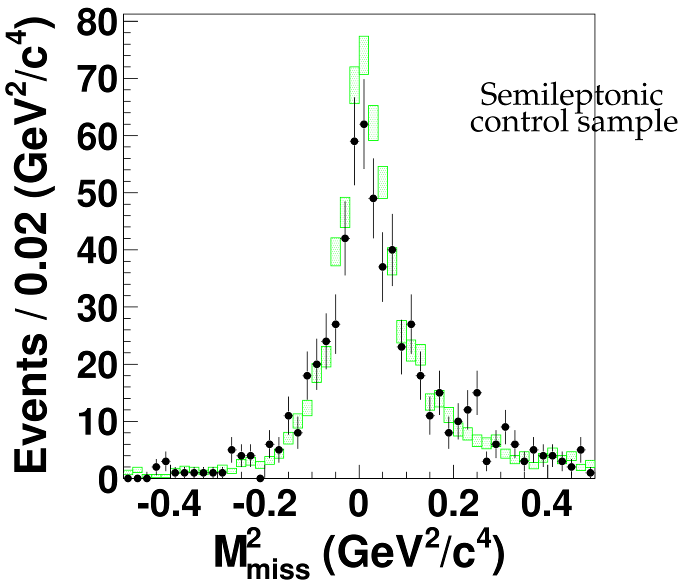
- τ^- is identified in the $e^-\bar{\nu}_e\nu_\tau$, $\mu^-\bar{\nu}_\mu\nu_\tau$, $\pi^-\nu_\tau$, and $\pi^-\pi^0\nu_\tau$ decay channels;
- No tracks, π^0, K_L left in the event after $B_{\rm tag}$, $B_{\rm sig}$ reconstruction;
  - ✦ K_L efficiency checked in $D^0 \to \phi K_S$, $\phi \to K_L K_S$ vs $\phi \to K^+K^-$;
- Backgrounds were simulated by MC;
- E_{ECL}, M^2_{miss} distributions were validated in number of samples: sidebands, B^0 sample, $B^-_{\rm sig} \to D^{*0}\ell^-\bar{\nu}_\ell$.

E_{ECL} and M^2_{miss} for $B^-_{\rm sig} \to D^{*0}\ell^-\bar{\nu}_\ell$

Dots with error bars — data

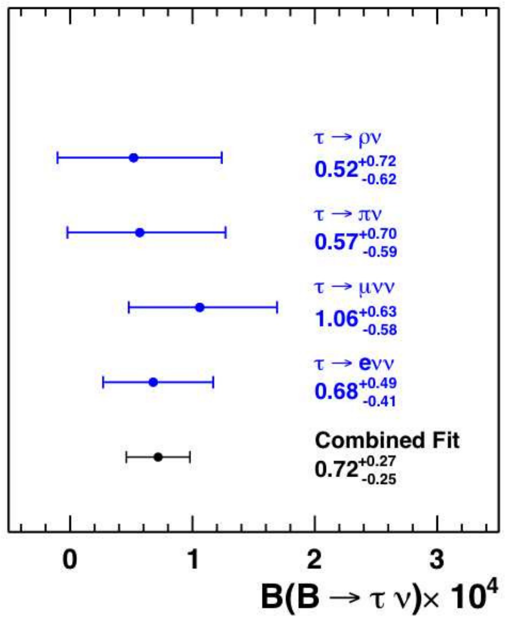
Rectangles — normalized MC

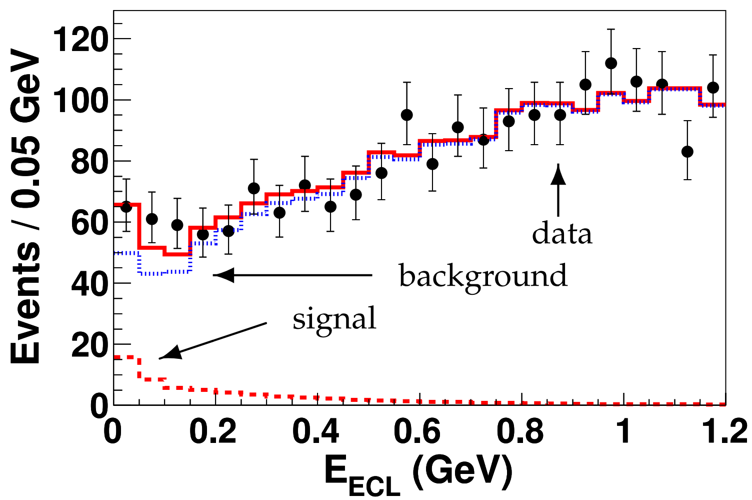


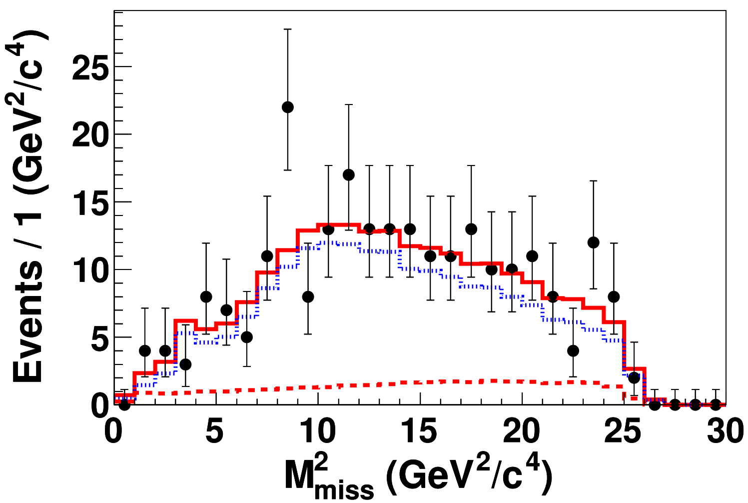


New $B \to \tau\nu_\tau$ study results

- Simultaneous fit to different τ decay modes.
- Signal yield $N = 62^{+23}_{-22} \pm 6$
- $\mathcal{B}(B^- \to \tau^- \bar{\nu}_\tau) = [0.72^{+0.27}_{-0.25} \pm 0.11] \times 10^{-4}$
- Significance = 3.0σ including systematic error
- Results for individual decay modes are consistent.
- Result at the data sample used earlier is consistent with the previous result.

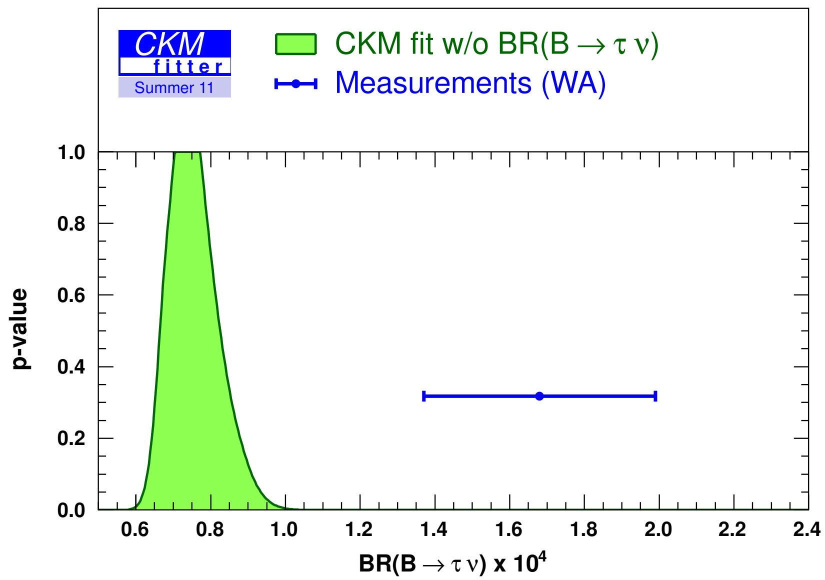


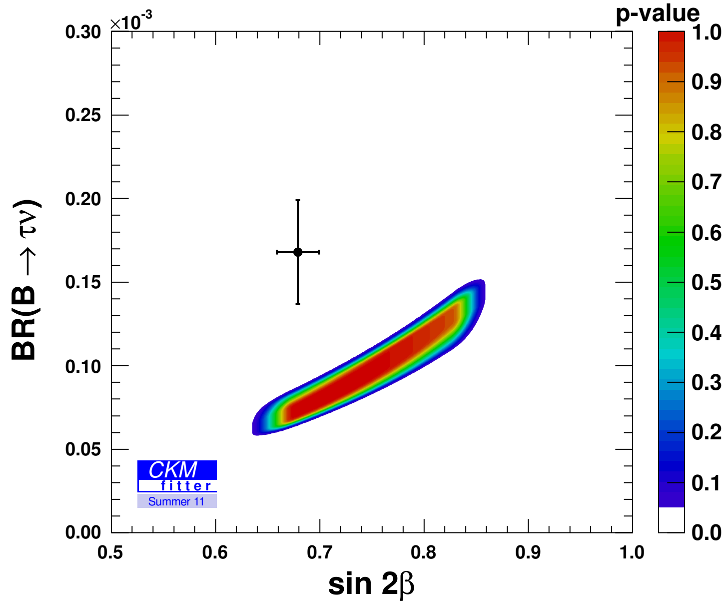




Comparison of the $B \to \tau\nu_\tau$ results

Latest Belle result	$\mathcal{B}(B^- \to \tau^-\bar{\nu}_\tau) = [0.72^{+0.27}_{-0.25} \pm 0.11] \times 10^{-4}$
Latest Belle average	$\mathcal{B}(B^- \to \tau^-\bar{\nu}_\tau) = [0.96 \pm 0.26] \times 10^{-4}$
Measured world average	$\mathcal{B}(B^- \to \tau^-\bar{\nu}_\tau) = [1.15 \pm 0.23] \times 10^{-4}$
CKM global fit	$\mathcal{B}(B^- \to \tau^-\bar{\nu}_\tau) = [0.73^{+0.12}_{-0.07}] \times 10^{-4}$





Comparison of the $B \to \tau\nu_\tau$ results

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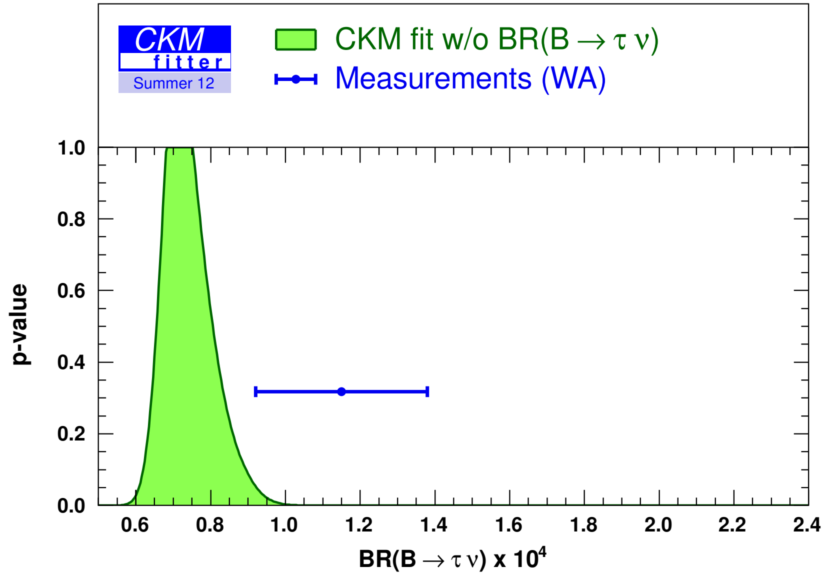
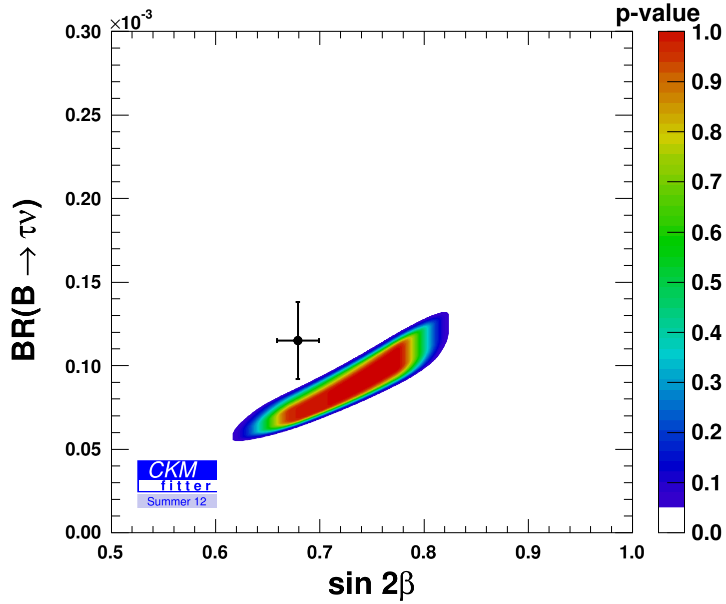




"Tension" in CKM global fit is reduced (1.6σ).

$B \to \ell\nu$ with hadronic tagging

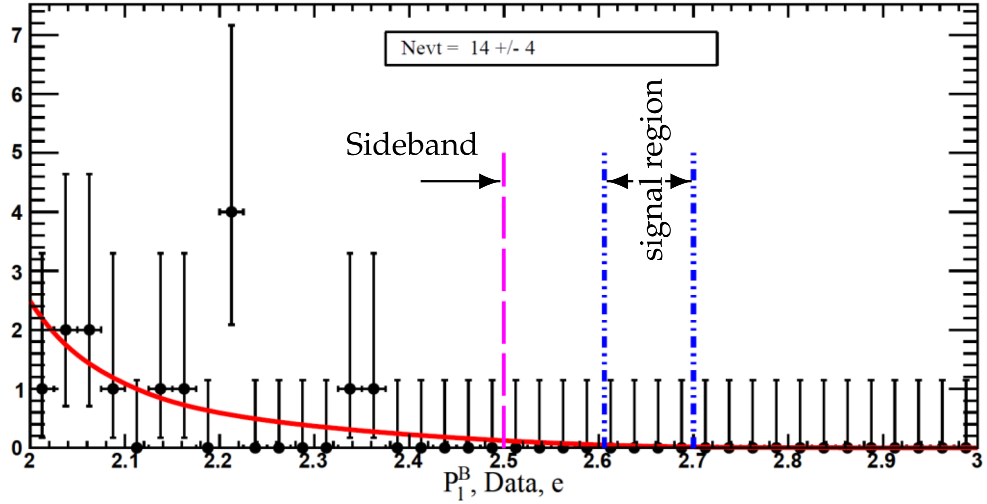
772M $B\bar{B}$

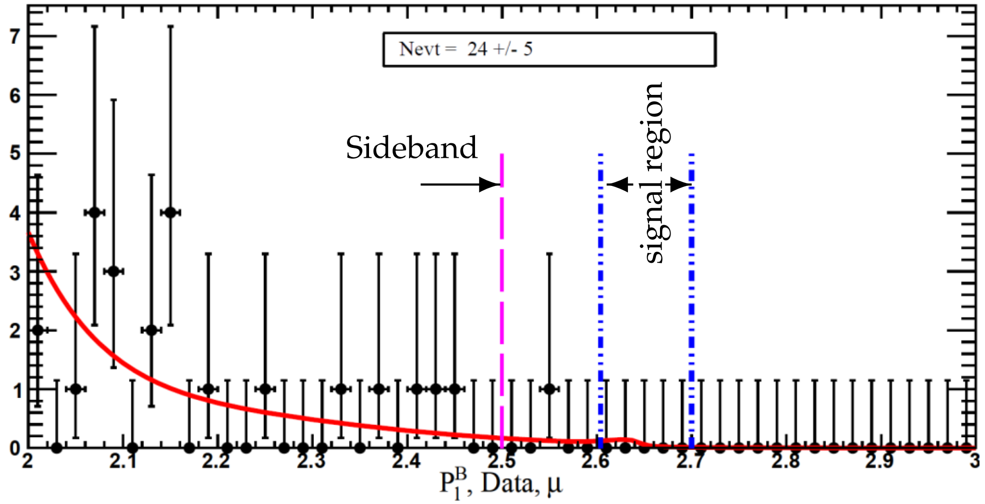
ICHEP2012

- SM expectation:
  $\mathcal{B}(B \to e\nu_e) \sim 1 \times 10^{-11}$
  $\mathcal{B}(B \to \mu\nu_\mu) \sim 5 \times 10^{-7}$

- Exclusive hadronic tagging
- Zero events observed
- $\mathcal{B}(B \to e\nu_e) < 3.5 \times 10^{-6}$
  $\mathcal{B}(B \to \mu\nu_\mu) < 2.5 \times 10^{-6}$

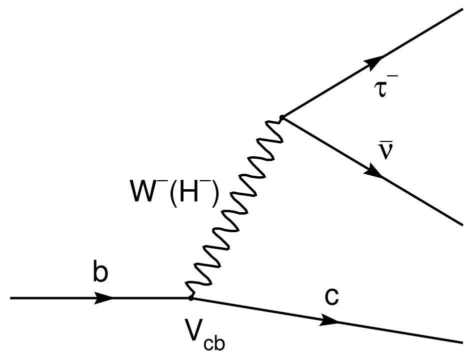
- Inclusive tag with 277M $B\bar{B}$
  (PLB 647, 67 (2007))
  $\mathcal{B}(B \to e\nu_e) < 1.7 \times 10^{-6}$
  $\mathcal{B}(B \to \mu\nu_\mu) < 0.98 \times 10^{-6}$





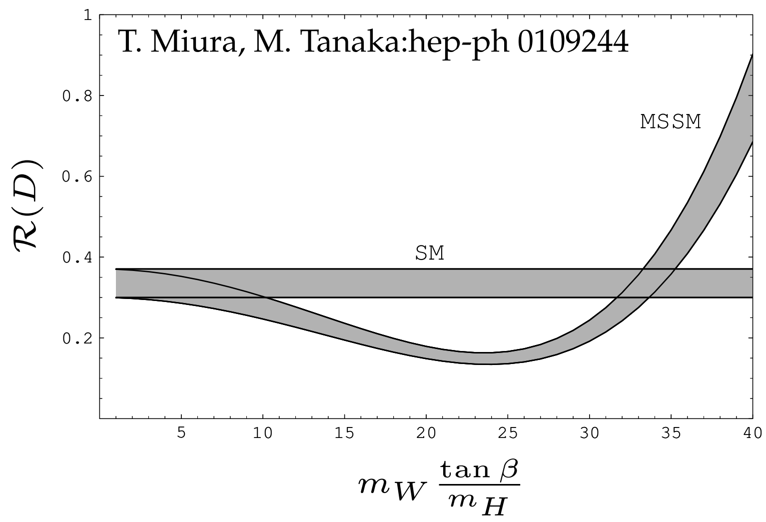
$B \to \bar{D}^{(*)}\tau\nu_\tau$ study

Semileptonic $B \to \bar{D}^{(*)}\tau\nu_\tau$ decays
are sensitive to charged Higgs and
are complementary to leptonic $B \to \tau\nu$ decay.



To reduce experimental and theoretical
uncertainties we use ratio

$$\mathcal{R}(D) \equiv \frac{\mathcal{B}(B \to \bar{D}\tau\nu_\tau)}{\mathcal{B}(B \to \bar{D}\ell\nu_\ell)}$$



SM expected values:
$\mathcal{B}(B \to \bar{D}\tau\nu_\tau) \sim 0.7\%$
$\mathcal{B}(B \to \bar{D}^*\tau\nu_\tau) \sim 1.4\%$

$B^0 \to D^{*-}\tau^+\nu_\tau$ with inclusive tagging

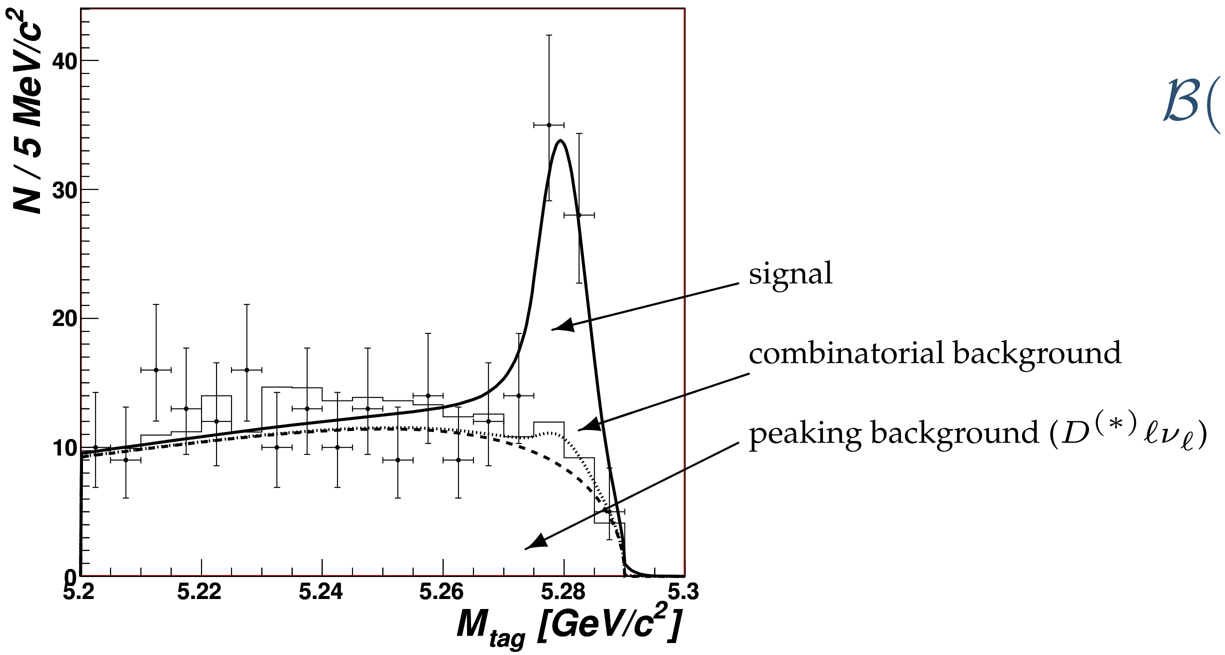
535M $B\bar{B}$

PRL 99, 191807 (2007)

Inclusive tagging is a variant of "full reconstruction" tagging:

- $B_{\rm sig}$ is reconstructed as $D^{*-}\tau^+$;
- The rest of the event is checked to be consistent with B hypothesis.

The first observation of exclusive B decay due to $b \to c\tau\nu_\tau$ transition.



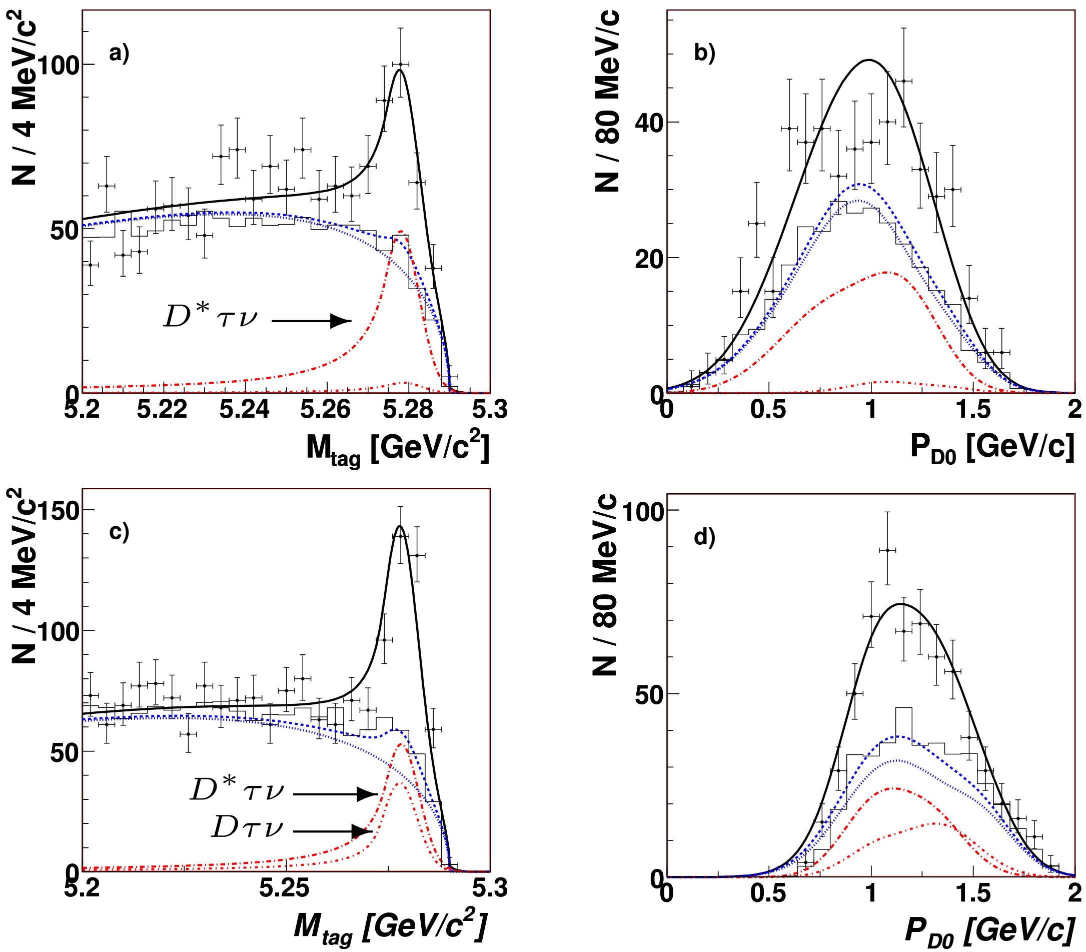
$$\mathcal{B}(B^0 \to D^{*-}\tau^+\nu_\tau) = (2.02^{+0.40}_{-0.37} \pm 0.37)\%,$$
5.2σ significance

$B^+ \to \bar{D}^{(*)0}\tau^+\nu_\tau$ with inclusive tagging

657M $B\bar{B}$

PRD 82, 072005(2010)

- Simultaneous extraction of D and D^* yields;
- 2D fit to $M_{\rm tag}$ and P_D.



$$\mathcal{B}(B^+ \to \bar{D}^{*0}\tau^+\nu_\tau) = (2.12^{+0.28}_{-0.27} \pm 0.29)\%,$$
8.1σ significance

$$\mathcal{B}(B^+ \to \bar{D}^{0}\tau^+\nu_\tau) = (0.77 \pm 0.22 \pm 0.12)\%,$$
3.5σ significance

a), b) $D^{*0}\tau\nu_\tau$

c), d) $D^0\tau\nu_\tau$

$B^0 \to D^{(*)-}\tau^+\nu_\tau$ with exclusive tagging

657M $B\bar{B}$

arXiv:0910.4301

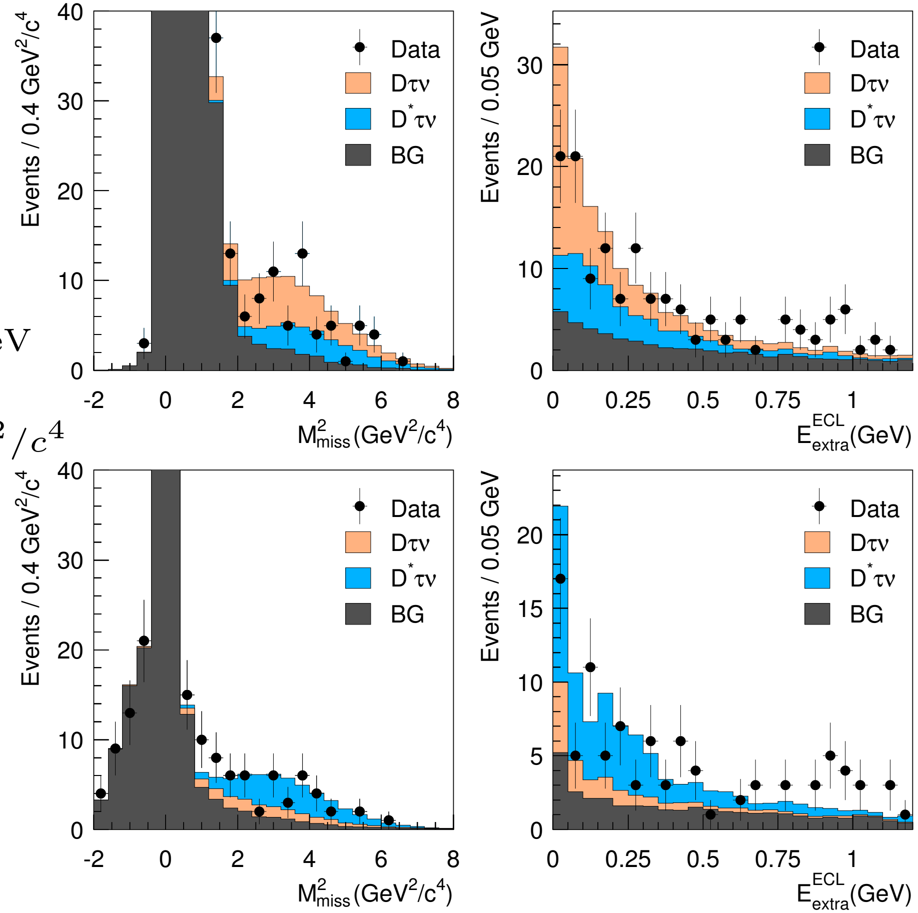
- Exclusive hadronic tagging method;
- Simultaneous extraction of D and D^* yields;
- 2D fit to M^2_{miss} and E_{ECL}.

$B^0 \to D\tau\nu$

M^2_{miss} : $E_{ECL} < 0.2\text{GeV}$

E_{ECL} : $M^2_{miss} > 2.0\text{GeV}^2/c^4$

$B^0 \to D^*\tau\nu$



$$\mathcal{B}(B^0 \to D^-\tau^+\nu_\tau) = (1.01^{+0.46}_{-0.41}\,{}^{+0.13}_{-0.11} \pm 0.10)\%,$$

2.6σ significance

$$\mathcal{B}(B^0 \to D^{*-}\tau^+\nu_\tau) = (2.56^{+0.75}_{-0.66}\,{}^{+0.31}_{-0.22} \pm 0.10)\%$$

4.7σ significance

$$\mathcal{R}(D^0) = 0.70^{+0.19}_{-0.18}\,{}^{+0.11}_{-0.09}$$
$$\mathcal{R}(D^{*0}) = 0.47^{+0.11}_{-0.10}\,{}^{+0.06}_{-0.07}$$

$B^+ \to \bar{D}^{(*)0}\tau^+\nu_\tau$ with exclusive tagging

657M $B\bar{B}$

arXiv:0910.4301

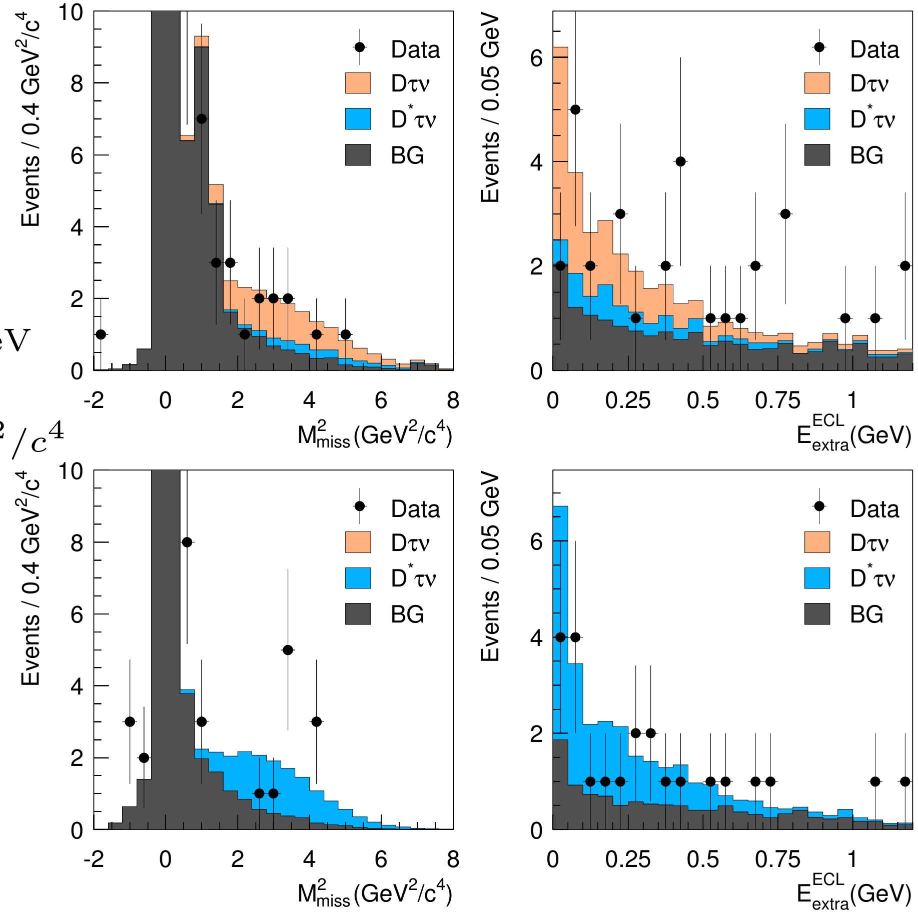
- Exclusive hadronic tagging method;
- Simultaneous extraction of D and D^* yields;
- 2D fit to M^2_{miss} and E_{ECL}.

$B^+ \to \bar{D}\tau\nu$

M^2_{miss} : $E_{ECL} < 0.2\text{GeV}$

E_{ECL} : $M^2_{miss} > 2.0\text{GeV}^2/c^4$

$B^+ \to \bar{D}^*\tau\nu$



$$\mathcal{B}(B^+ \to \bar{D}^0\tau^+\nu_\tau) = (1.51^{+0.41}_{-0.39}{}^{+0.24}_{-0.19} \pm 0.15)\%,$$
3.8σ significance

$$\mathcal{B}(B^+ \to \bar{D}^{*0}\tau^+\nu_\tau) = (3.04^{+0.69}_{-0.66}{}^{+0.40}_{-0.47} \pm 0.22)\%,$$
3.9σ significance

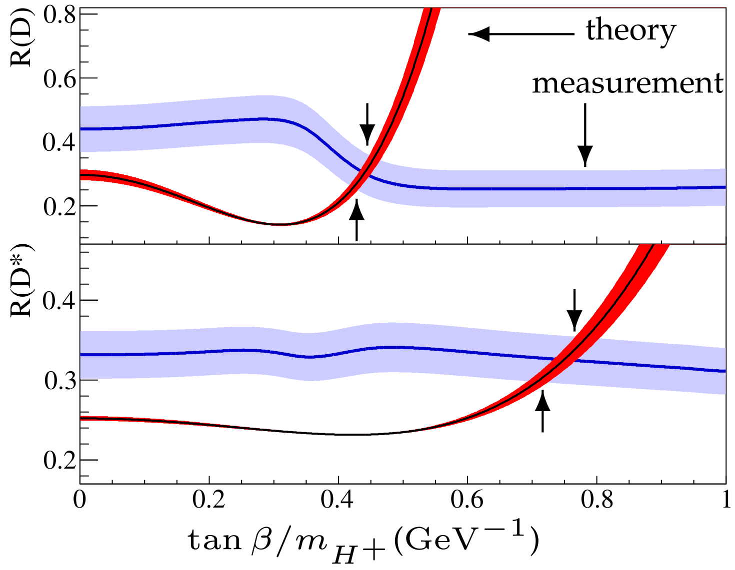
$$\mathcal{R}(D^-) = 0.48^{+0.22}_{-0.19}{}^{+0.06}_{-0.05}$$
$$\mathcal{R}(D^{*-}) = 0.48^{+0.14}_{-0.12}{}^{+0.06}_{-0.04}$$

Constraint for 2HDM type II

- Combining results from $B \to \tau\nu_\tau$ and $B \to \bar{D}^{(*)}\tau\nu_\tau$ we can constrain charged Higgs model 2HDM type II.
- On all figures prefered regions are different.
- 2HDM type II is excluded?

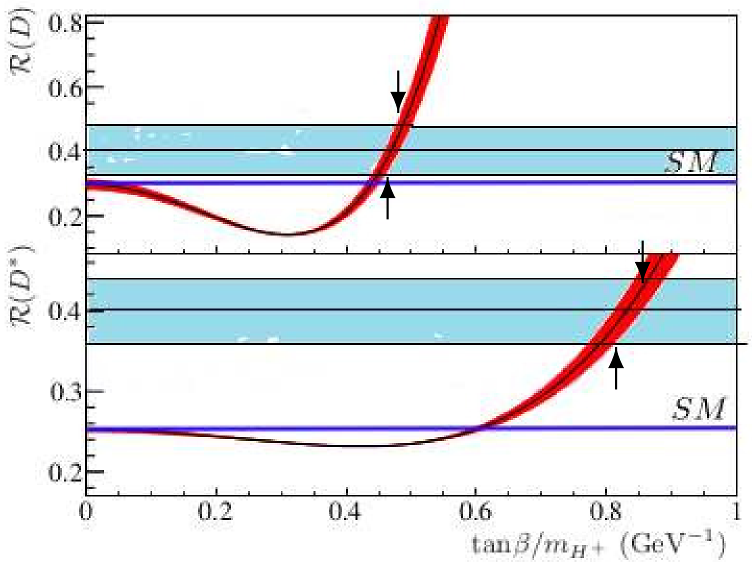
BaBar

$B \to \bar{D}^{*()}\tau\nu_\tau$



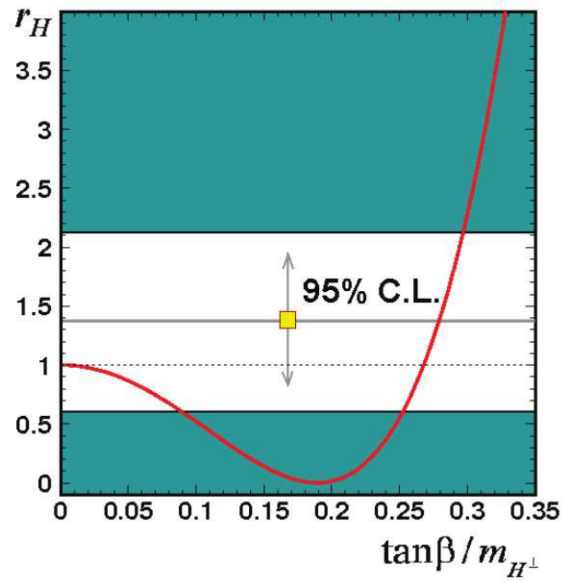
Belle

$B \to \bar{D}^{*()}\tau\nu_\tau$



Belle

$B \to \tau\nu_\tau$



$B \to \bar{D}^{(*)}\tau\nu_\tau$ and SM

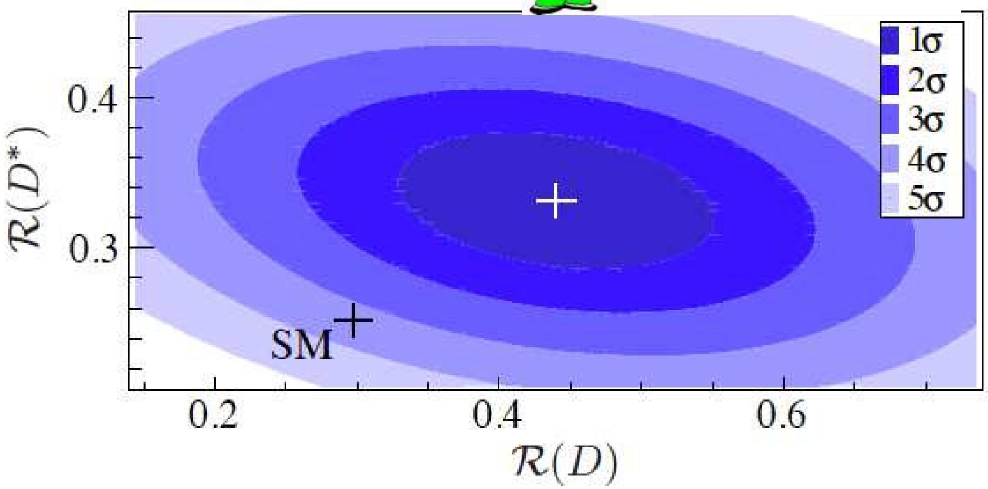
PRD 85, 094025 (2012)

SM	Belle	Deviation
$\mathcal{R}(D) = 0.297 \pm 0.017$	$\mathcal{R}(D) = 0.430 \pm 0.091$	1.4σ
$\mathcal{R}(D^*) = 0.252 \pm 0.003$	$\mathcal{R}(D^*) = 0.405 \pm 0.047$	3.0σ
	Combined	3.3σ

PRL 109, 101802 (2012)

BaBar	Deviation
$\mathcal{R}(D) = 0.440 \pm 0.058 \pm 0.042$	2.0σ
$\mathcal{R}(D^*) = 0.332 \pm 0.024 \pm 0.018$	2.7σ
Combined	3.4σ

Belle & BaBar	Deviation
$\mathcal{R}(D)$	2.4σ
$\mathcal{R}(D^*)$	3.8σ
Combined	4.8σ



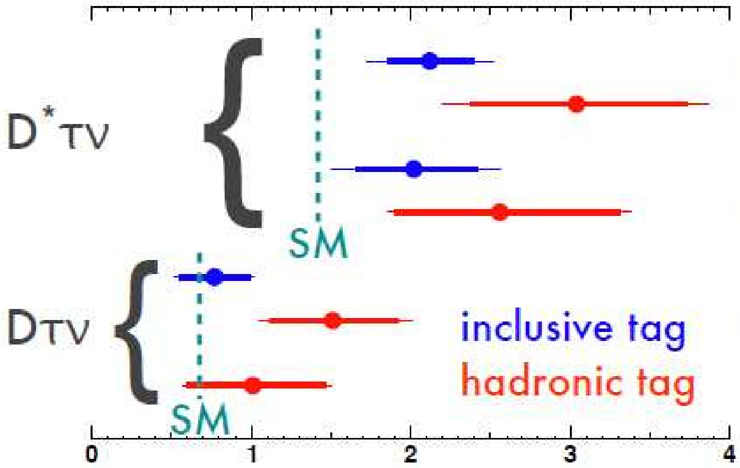
Summary

- $B \to \tau\nu_\tau$ decay was studied at Belle with different tagging. Results are consistent with each other and BaBar result;
- Recent result is much closer to SM prediction, "tension" in CKM global fit is reduced;
- Results for $B \to \bar{D}^{(*)}\tau\nu_\tau$ are consistent between tagging types and experiments;
- 2HDM type II seems to be excluded by combination of $B \to \tau\nu_\tau$ and $B \to \bar{D}\tau\nu_\tau$ results;
- Results for $\mathcal{R}(D^{(*)})$ are different from SM at 4.8σ for combination of Belle and BaBar results.

Stay tuned for updated results and upcoming Belle II results.

Thank you!

Comparison of the $B \to \bar{D}^{(*)}\tau\nu_\tau$ results



$\mathcal{B}(D^{*0}\tau^-\bar{\nu}_\tau) = [2.12^{+0.28}_{-0.27}(\mathrm{stat}) \pm 0.29(\mathrm{syst})]\%$

$\mathcal{B}(D^{*0}\tau^-\bar{\nu}_\tau) = [3.04^{+0.69}_{-0.66}(\mathrm{stat})^{+0.40}_{-0.47}(\mathrm{syst}) \pm 0.22(\mathrm{norm})]\%$

$\mathcal{B}(D^{*+}\tau^-\bar{\nu}_\tau) = [2.02^{+0.40}_{-0.37}(\mathrm{stat}) \pm 0.37(\mathrm{syst})]\%$

$\mathcal{B}(D^{*+}\tau^-\bar{\nu}_\tau) = [2.56^{+0.75}_{-0.66}(\mathrm{stat})^{+0.31}_{-0.22}(\mathrm{syst}) \pm 0.10(\mathrm{norm})]\%$

$\mathcal{B}(D^{0}\tau^-\bar{\nu}_\tau) = [0.77 \pm 0.22(\mathrm{stat}) \pm 0.12(\mathrm{syst})]\%$

$\mathcal{B}(D^{0}\tau^-\bar{\nu}_\tau) = [1.51^{+0.41}_{-0.39}(\mathrm{stat})^{+0.24}_{-0.19}(\mathrm{syst}) \pm 0.15(\mathrm{norm})]\%$

$\mathcal{B}(D^{+}\tau^-\bar{\nu}_\tau) = [1.01^{+0.46}_{-0.41}(\mathrm{stat})^{+0.13}_{-0.11}(\mathrm{syst}) \pm 0.10(\mathrm{norm})]\%$

- Good agreement between different tagging;
- Good agreement with BaBar:
  $\mathcal{B}(B \to \bar{D}^{*}\tau\nu_\tau) = [1.76 \pm 0.13 \pm 0.12]\%$
  $\mathcal{B}(B \to \bar{D}\tau\nu_\tau) = [1.02 \pm 0.13 \pm 0.11]\%$;
- All results are slightly larger than SM predictions.