Leptonic and Semileptonic Decays at Belle

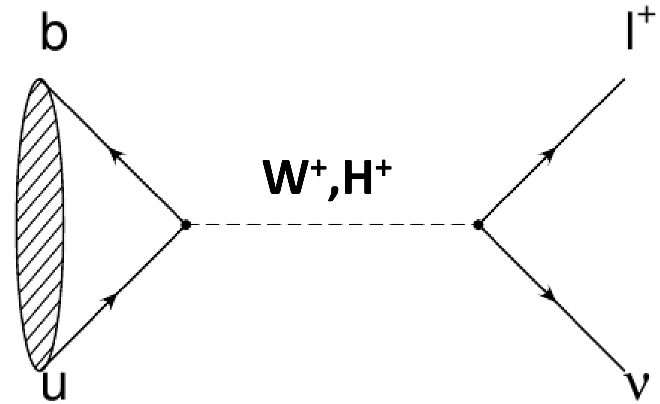
BELLE

Kurtis Nishimura
(on behalf of the Belle Collaboration)

August 16, 2013

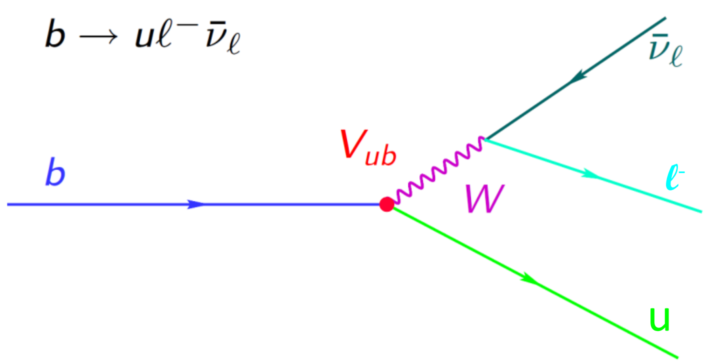
2013 DPF UC SANTA CRUZ

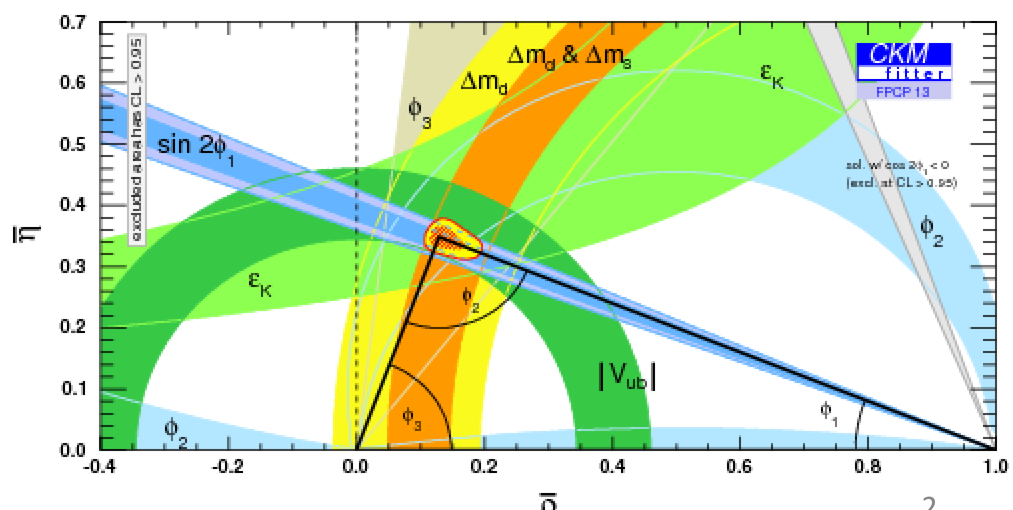
Leptonic and Semileptonic Decays



- Rare decays, e.g.:
  - $B \rightarrow \tau \nu$
  - $B \rightarrow D^{(*)} \tau \nu$

  allow precision tests of Standard Model.
  - Deviations from SM predictions would suggest new physics.
- Other modes provide relatively clean access to CKM elements $|V_{ub}|$ and $|V_{cb}|$ via tree-level transitions.
  - For example, $b \rightarrow u \ell \nu$ / $B \rightarrow X_u \ell \nu$

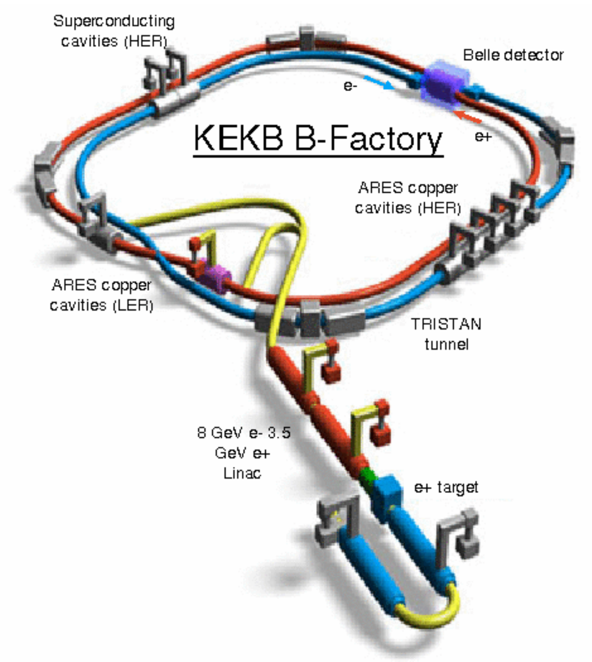


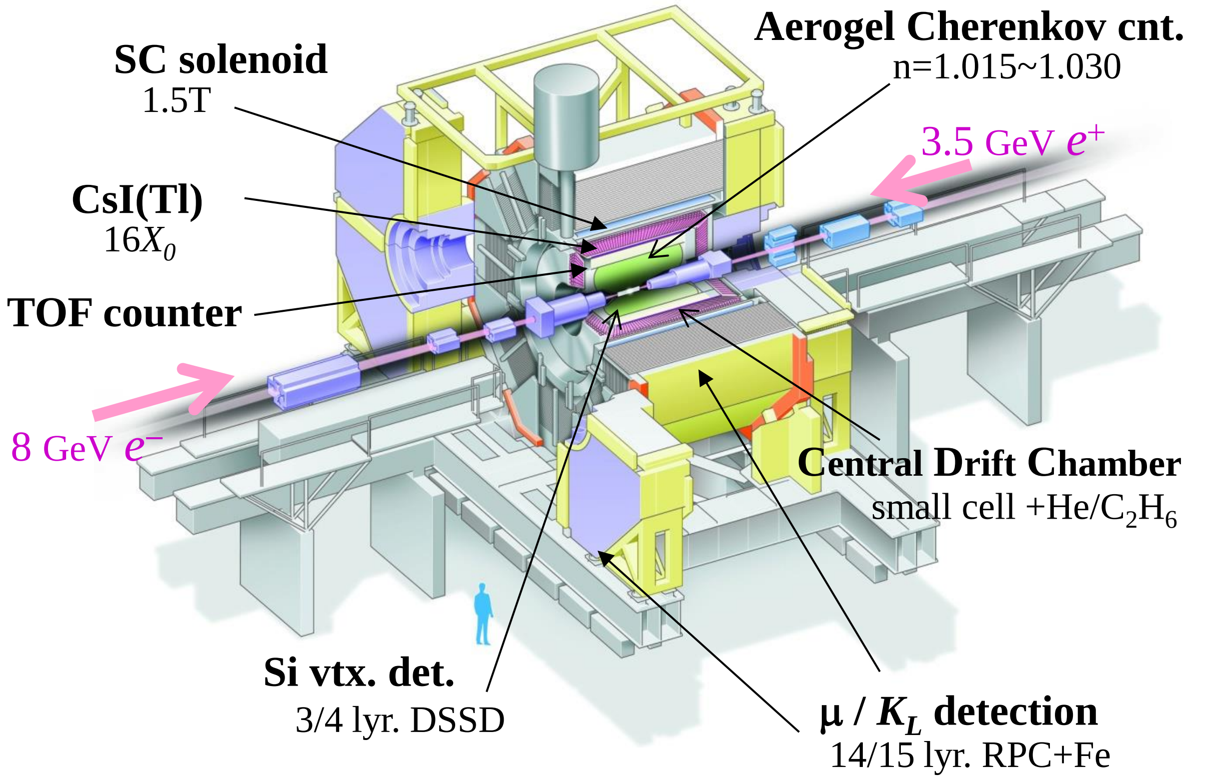


Dataset with the Belle Detector

- Data collected with Belle detector at KEKB asymmetric e^+e^- collider: **3.5 GeV x 8 GeV**
- Total of 711 fb^{-1} of data collected at $\Upsilon(4S)$.

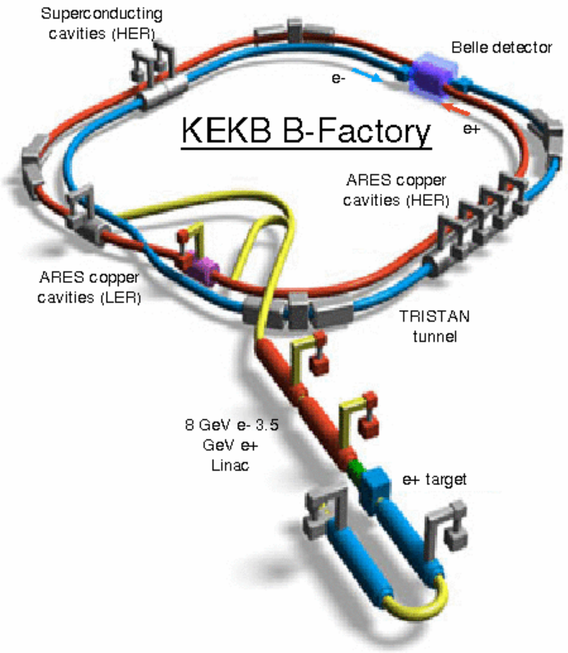
➔ 772 M $B\bar{B}$ pairs!

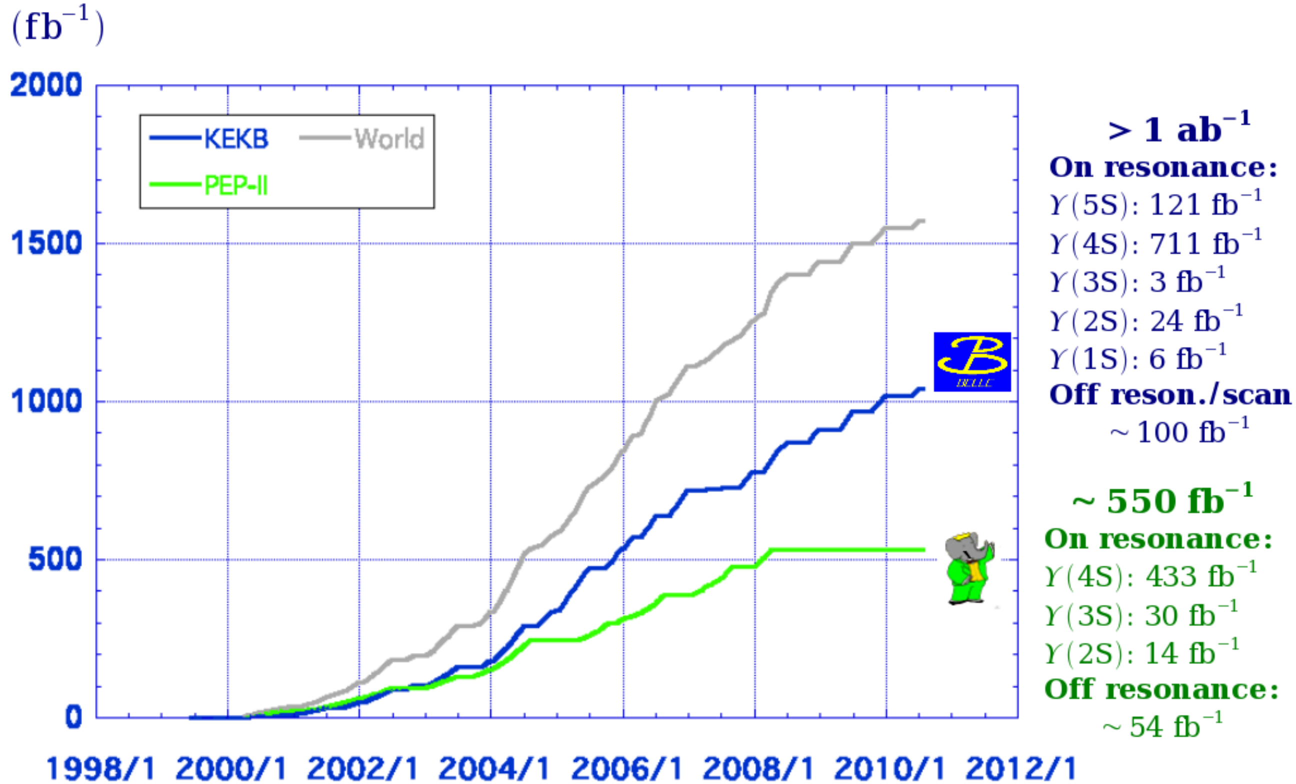




Dataset with the Belle Detector

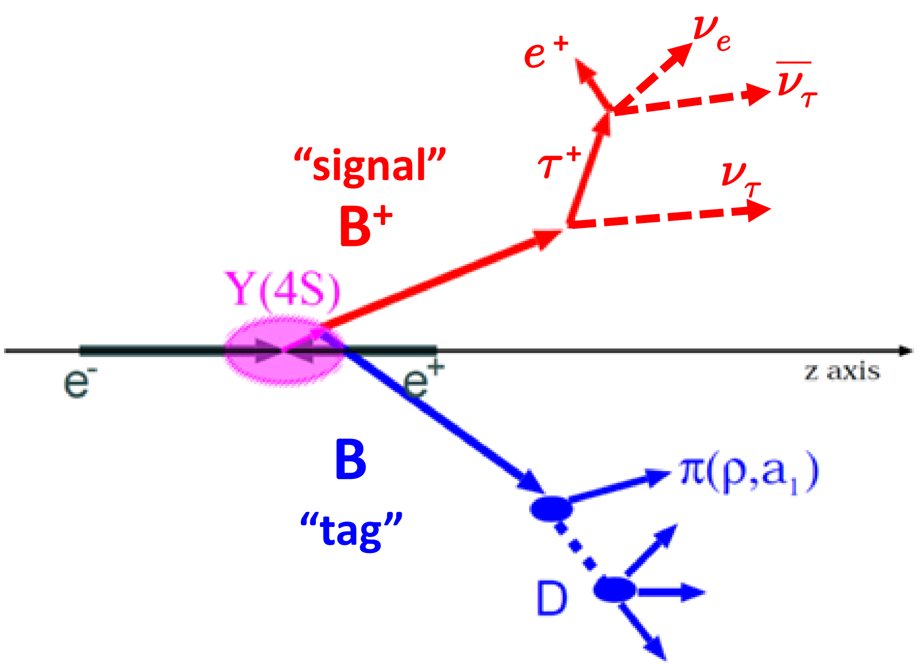
- Data collected with Belle detector at KEKB asymmetric e^+e^- collider: **3.5 GeV x 8 GeV**
- Total of 711 fb^{-1} of data collected at $\Upsilon(4S)$.
  - ➔ 772 M $B\bar{B}$ pairs!



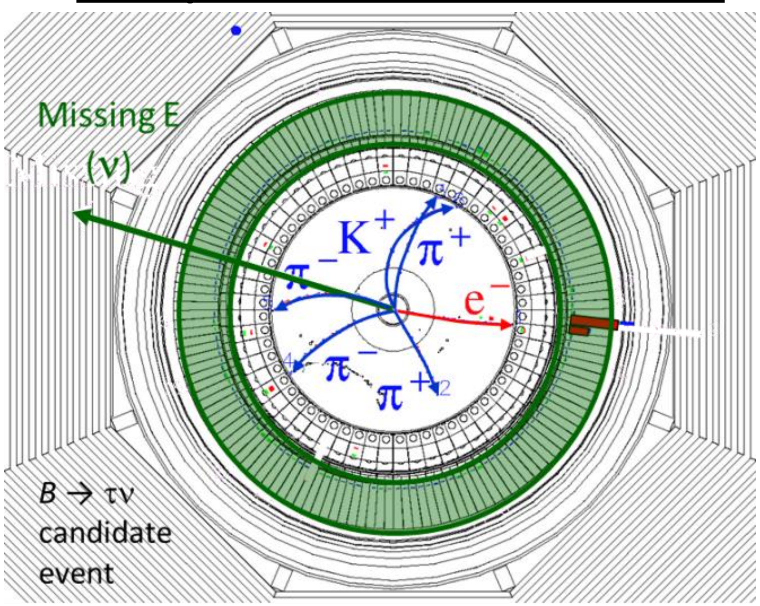


Missing Energy Decays at B Factories

- All decays mentioned include missing energy, one or more neutrinos.
- Measurements difficult at hadron collider, well suited to B factories.
- At B factories, process is:
  - Clean event topology: $e^+e^- \to \Upsilon(4S) \to B\bar{B}$
  - Other (**tag**) B in the event can be fully or partially reconstructed.
  - Excess energy and missing mass can be studied for (**signal**) B.

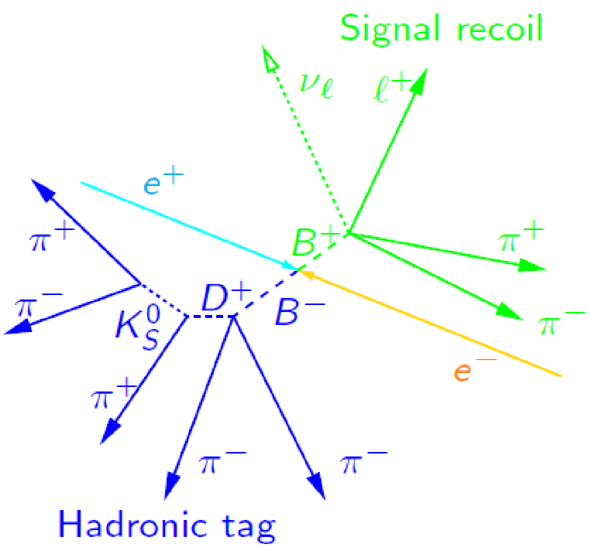


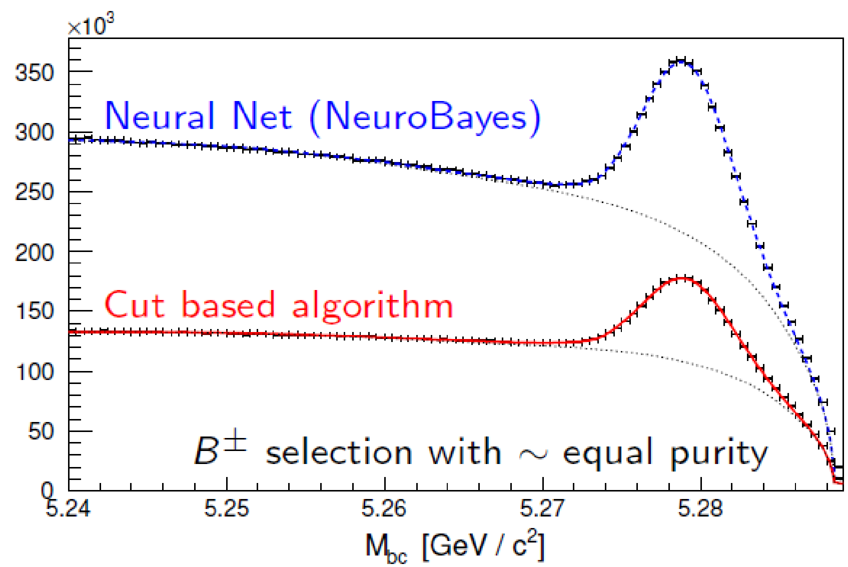
Example Belle B → $\tau\nu$ candidate



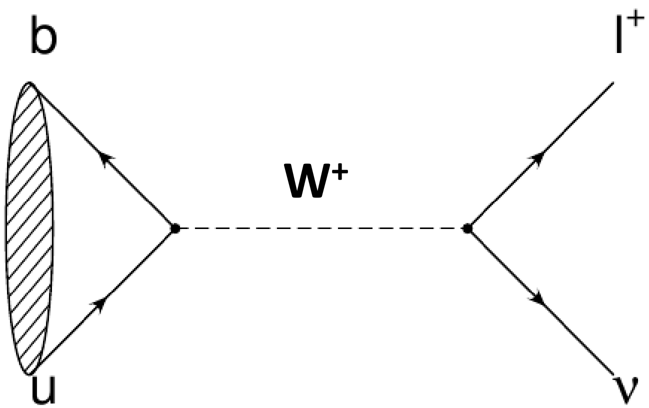
Belle Tagging Improvements

- Recent improvements to Belle hadronic tagging: **NIM A654, 432 (2011)**
  - Based on NeuroBayes package.
  - Reconstructs tag-side *B* meson in >1100 exclusive hadronic decay modes.
  - Calibrated with charm semileptonic decays.
  - Gives ~2x more efficiency than previous cut-based tagging method.





Leptonic Decays $B \to \ell \nu$



<u>SM Predictions</u>:

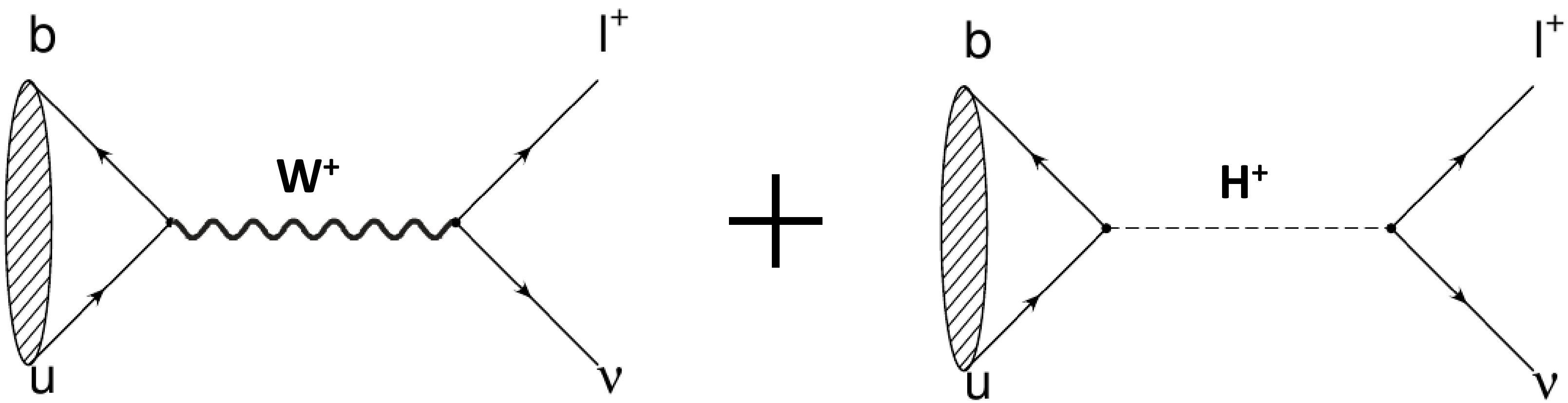
$$\mathcal{B}(B \to e\nu) \sim 10^{-11}$$
$$\mathcal{B}(B \to \mu\nu) \sim 10^{-7}$$
$$\mathcal{B}(B \to \tau\nu) \sim 10^{-4}$$

- In Standard Model, these processes occur via annihilation into W, rate given by:

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

*Note rates sensitive to $|V_{ub}|$. Other semileptonic *B* decays provide access to this observable. More later…

New Physics in $B \to \ell\, \nu$



- Interference from charged Higgs can modify SM branching fraction by factor r_H.

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

e.g., Type II Two Higgs Doublet Model (Type II 2HDM)
W.S. Hou PRD 48, 2342 (1993).

$$\times \quad r_H = \left(1 - \frac{m_B^2}{m_H^2}\tan^2\beta\right)^2$$

$B \to \tau\nu$ (pre-ICHEP 2012)

- Based on:

Hadronic tags (449M BB):

$$\mathcal{B} = (1.79^{+0.56+0.46}_{-0.49-0.51}) \times 10^{-4}$$

Semileptonic tags (449M BB):

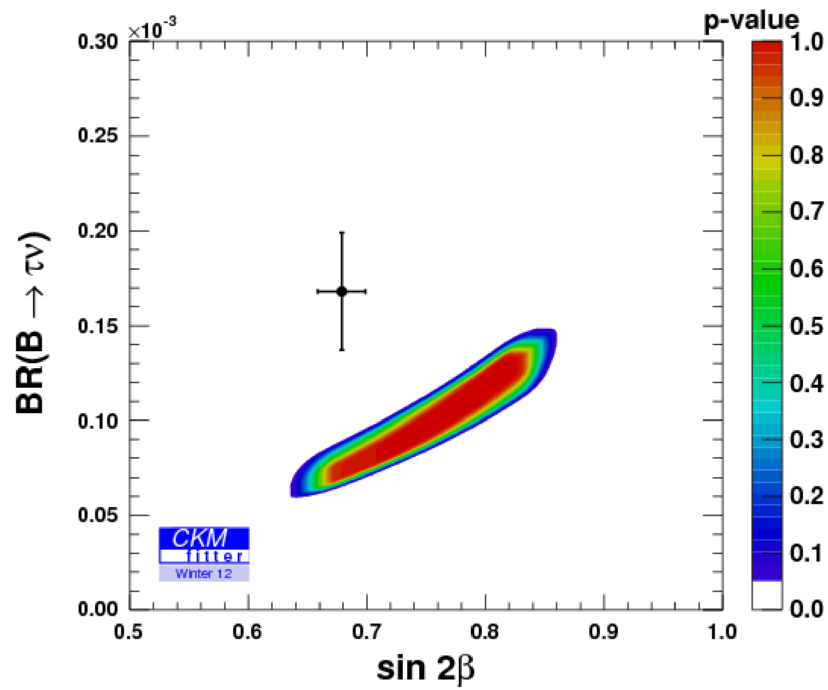
$$\mathcal{B} = (1.54^{+0.38+0.29}_{-0.37-0.31}) \times 10^{-4}$$

Hadronic tags (468M BB):

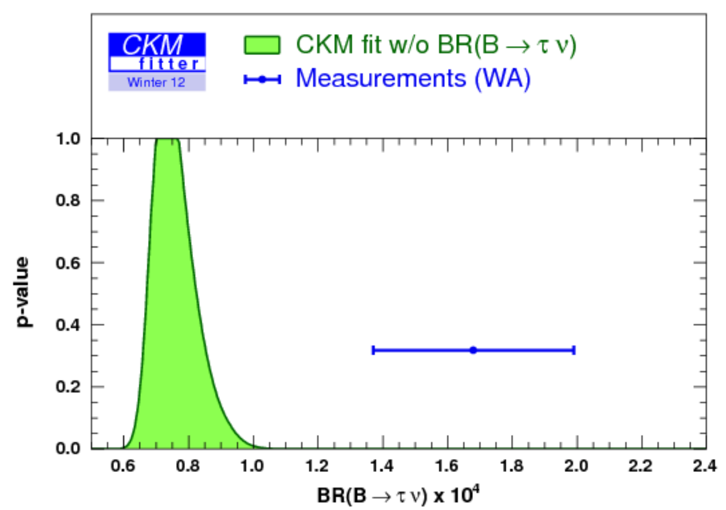
$$\mathcal{B} = (1.80^{+0.57}_{-0.54} \pm 0.24) \times 10^{-4}$$

Semileptonic tags (459M BB):

$$\mathcal{B} = (1.7 \pm 0.8 \pm 0.2) \times 10^{-4}$$

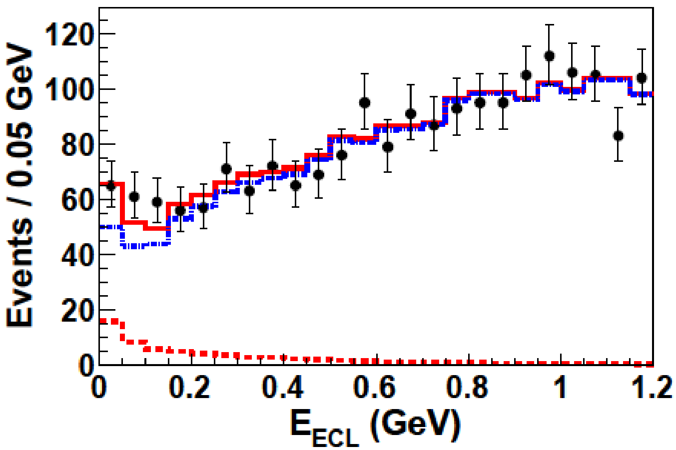


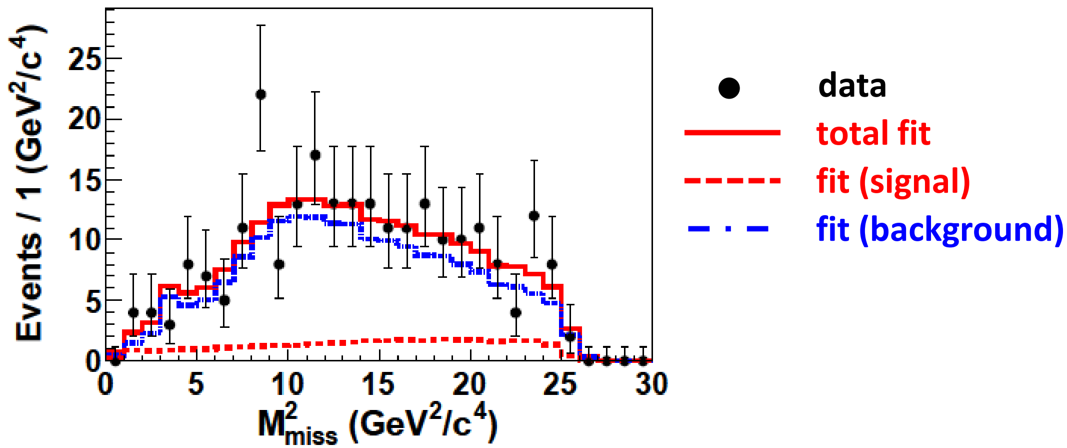
- Some tension in CKM fit between sin($2\phi_1$), BF($B \to \tau\nu$):
  - ~2.8 σ disagreement.



Belle Updates to B $\rightarrow \tau\nu$

- Belle improved measurement using hadronic tags: **PRL 110 131801 (2013)**
  - Uses full Belle data sample 449 M ➔ 772 M BB pairs.
  - Reprocessed Belle data with higher efficiency for low p_T tracks and neutrals.
  - Improved hadronic tagging efficiency due to NeuroBayes neural network algorithm (see slide 6).
  - 2D signal extraction in excess calorimeter energy (E_{ECL} and M^2_{miss}):





Sub-mode	N_{sig}	ϵ (10^{-4})	$\mathcal{B}$ (10^{-4})
$\tau^- \to e^-\bar{\nu}_e\nu_\tau$	16^{+11}_{-9}	3.0	$0.68^{+0.49}_{-0.41}$
$\tau^- \to \mu^-\bar{\nu}_\mu\nu_\tau$	26^{+15}_{-14}	3.1	$1.06^{+0.63}_{-0.58}$
$\tau^- \to \pi^-\nu_\tau$	8^{+10}_{-8}	1.8	$0.57^{+0.70}_{-0.59}$
$\tau^- \to \pi^-\pi^0\nu_\tau$	14^{+19}_{-16}	3.4	$0.52^{+0.72}_{-0.62}$
Combined	62^{+23}_{-22}	11.2	$0.72^{+0.27}_{-0.25}$

$$\mathcal{B}(B^- \to \tau^-\bar{\nu}_\tau) = [0.72^{+0.27}_{-0.25}(\text{stat}) \pm 0.11(\text{syst})] \times 10^{-4}$$

Significance: 3.0 σ.

$B \to \tau\nu$ (pre-ICHEP 2012)

- Results pre-ICHEP 2012:

Hadronic tags (449M $B\bar{B}$):

$$\mathcal{B} = (1.79^{+0.56}_{-0.49}{}^{+0.46}_{-0.51}) \times 10^{-4}$$

Semileptonic tags (449M $B\bar{B}$):

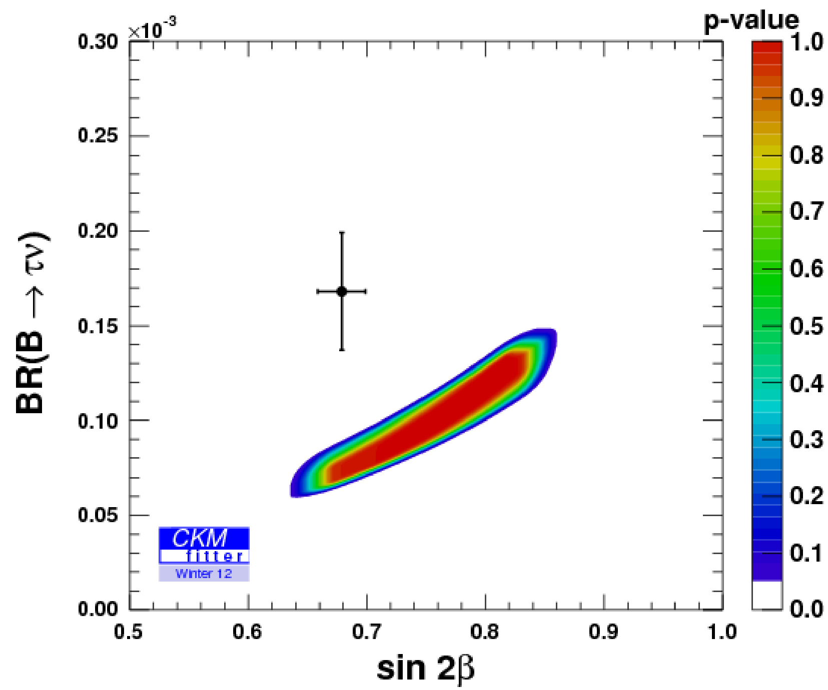
$$\mathcal{B} = (1.54^{+0.38}_{-0.37}{}^{+0.29}_{-0.31}) \times 10^{-4}$$

Hadronic tags (468M $B\bar{B}$):

$$\mathcal{B} = (1.80^{+0.57}_{-0.54} \pm 0.24) \times 10^{-4}$$

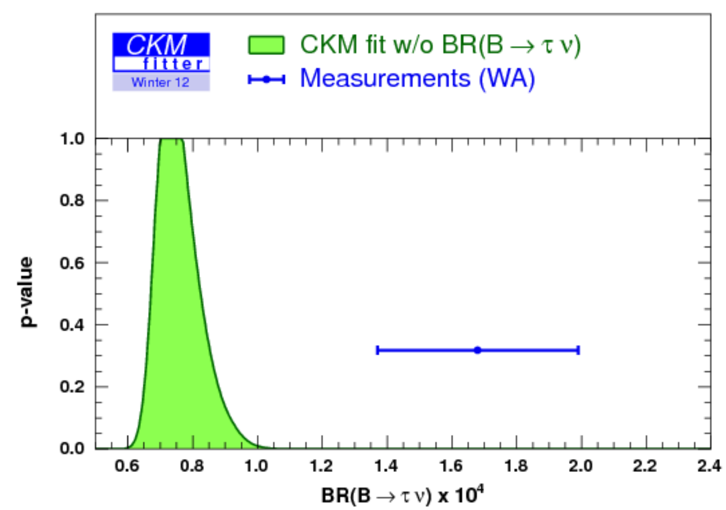
Semileptonic tags (459M $B\bar{B}$):

$$\mathcal{B} = (1.7 \pm 0.8 \pm 0.2) \times 10^{-4}$$



HFAG World Average (August 2012):

$$\mathcal{B} = (1.66 \pm 0.33) \times 10^{-4}$$



B $\rightarrow \tau\, \nu$ (post-ICHEP 2012)

- **Updated at ICHEP 2012**

Hadronic tags (772M B$\bar{\text{B}}$):

$$\mathcal{B} = (0.72^{+0.27}_{-0.25} \pm 0.11) \times 10^{-4}$$

Semileptonic tags (449M B$\bar{\text{B}}$):

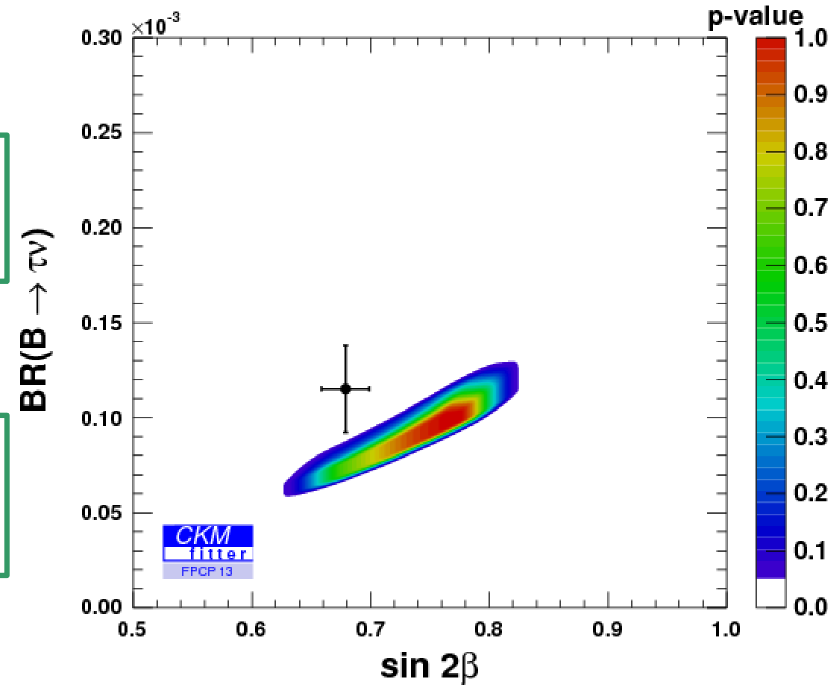
$$\mathcal{B} = (1.54^{+0.38}_{-0.37}{}^{+0.29}_{-0.31}) \times 10^{-4}$$

Hadronic tags (468M B$\bar{\text{B}}$):

$$\mathcal{B} = (1.83^{+0.53}_{-0.49} \pm 0.24) \times 10^{-4}$$

Semileptonic tags (459M B$\bar{\text{B}}$):

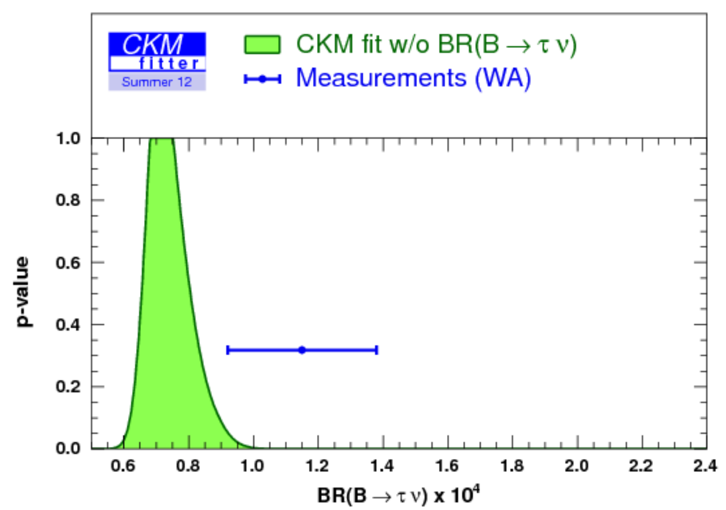
$$\mathcal{B} = (1.7 \pm 0.8 \pm 0.2) \times 10^{-4}$$



HFAG World Average (August 2012):

$$\mathcal{B} = (1.14 \pm 0.22) \times 10^{-4}$$

- Tension in global fit significantly eased.
  - ➔Now reduced to ~1.6 σ.



$B \to \tau\nu$ (post-ICHEP 2012)

- **Updated at ICHEP 2012**

Hadronic tags (772M $B\bar{B}$):

$$\mathcal{B} = (0.72^{+0.27}_{-0.25} \pm 0.11) \times 10^{-4}$$

Semileptonic tags (449M $B\bar{B}$):

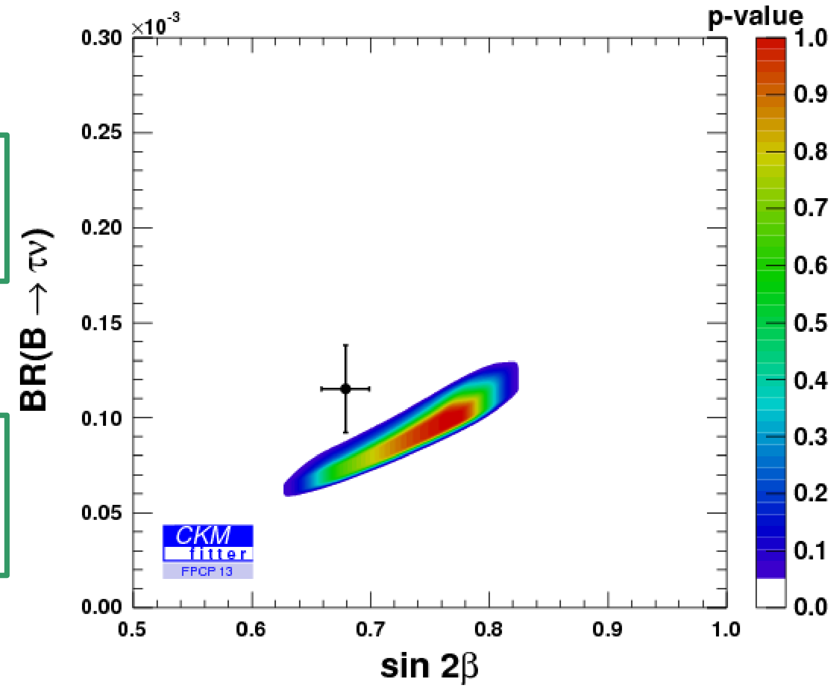
$$\mathcal{B} = (1.54^{+0.38}_{-0.37}{}^{+0.29}_{-0.31}) \times 10^{-4}$$

Hadronic tags (468M $B\bar{B}$):

$$\mathcal{B} = (1.83^{+0.53}_{-0.49} \pm 0.24) \times 10^{-4}$$

Semileptonic tags (459M $B\bar{B}$):

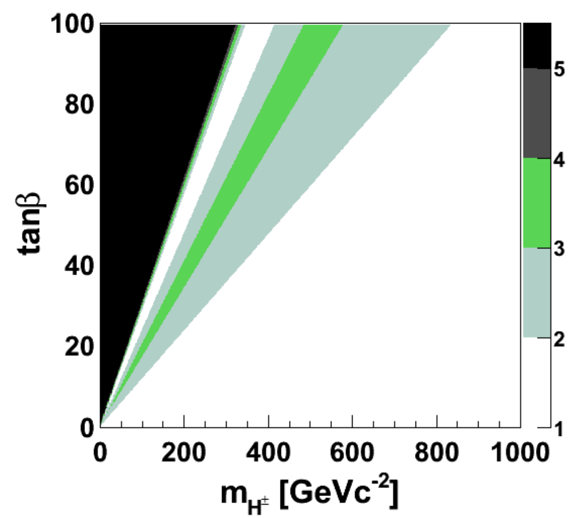
$$\mathcal{B} = (1.7 \pm 0.8 \pm 0.2) \times 10^{-4}$$



<u>HFAG World Average (August 2012)</u>:

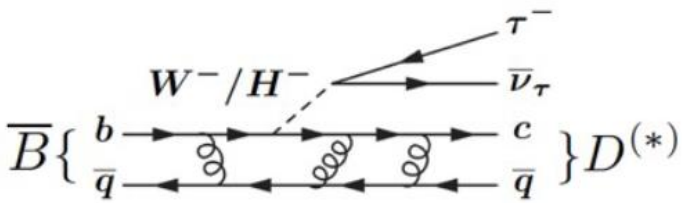
$$\mathcal{B} = (1.14 \pm 0.22) \times 10^{-4}$$

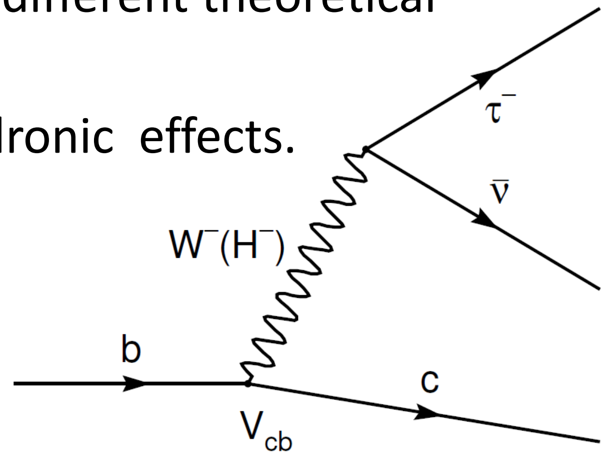
- Tension in global fit significantly eased.
  - ➔Now reduced to ~1.6 σ.
- Sets very powerful constraints on tanβ, m_H parameter space.
  - •Note that constraints depend on f_B, $|V_{ub}|$.



Charged Higgs and B → D$^{(*)}$ $\tau\,\nu$

- Also sensitive to charged Higgs.
  - Complementary: larger branching fractions, different theoretical systematics.
  - But with significant uncertainties due to hadronic effects.





  - Uncertainties related to |V_{cb}| and hadronic effects cancel in ratios:

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

  - Standard model expectations:

$$\mathcal{R}(D) \sim 0.3 \qquad \mathcal{R}(D^*) \sim 0.25$$

$B \to D^{(*)} \tau \nu$ from BaBar

- BaBar recently measured R(D$^{(*)}$):

  PRL 109, 101802 (2012)

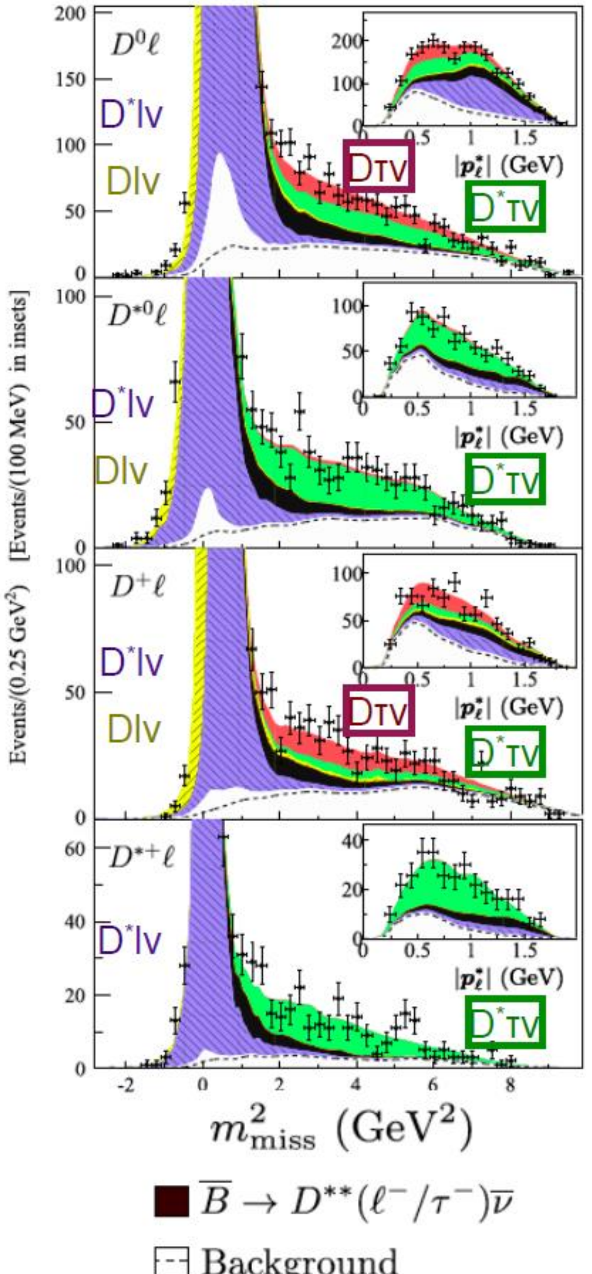
  arXiv:1303.0571

  – Boosted decision tree analysis.
  – 471 M BB pairs.
  – Hadronic tagging significantly improved over previous analysis.
  – Results:

$$\mathcal{R}(D) = 0.440 \pm 0.058 \pm 0.042$$
$$\mathcal{R}(D^*) = 0.332 \pm 0.024 \pm 0.018$$

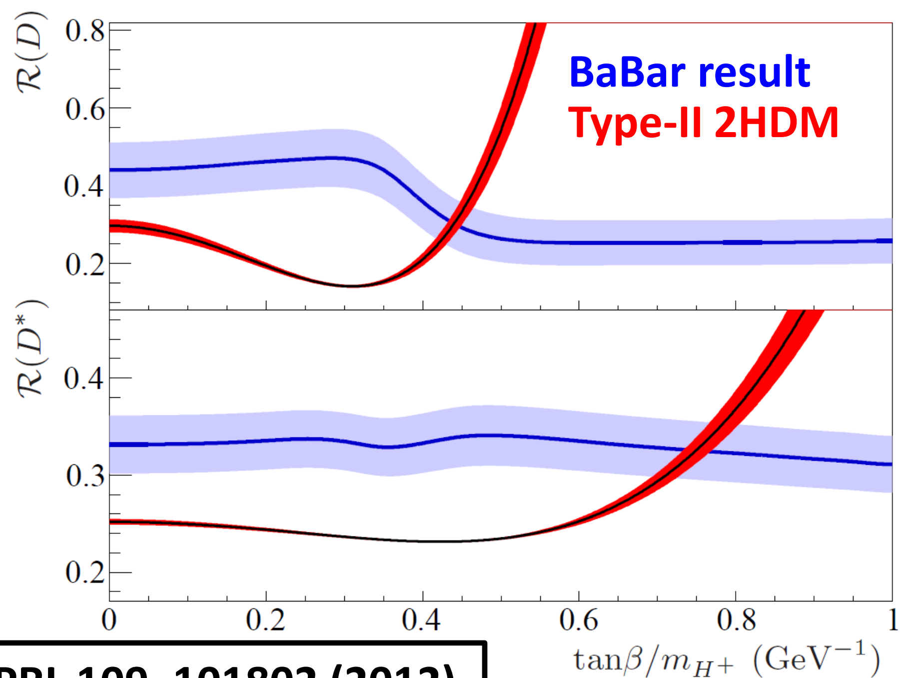
  – Standard Model expectations:

$$\mathcal{R}(D) \sim 0.3$$
$$\mathcal{R}(D^*) \sim 0.25$$

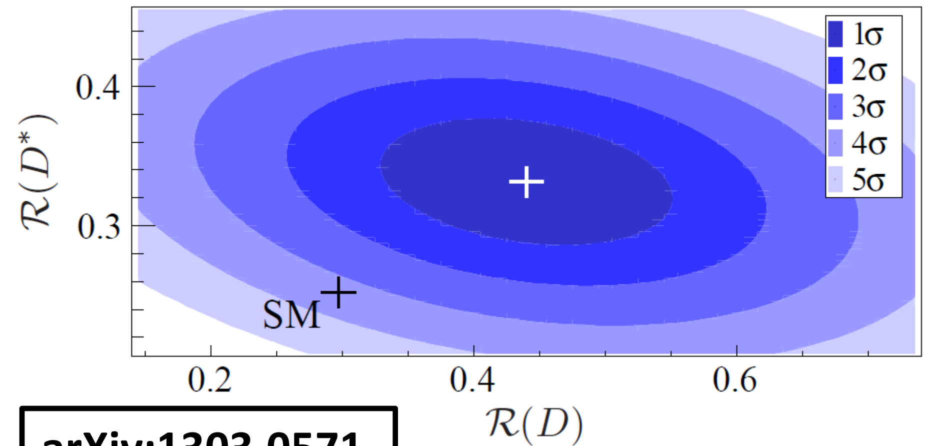


BaBar $B \to D^{(*)} \tau \nu$ Interpretations

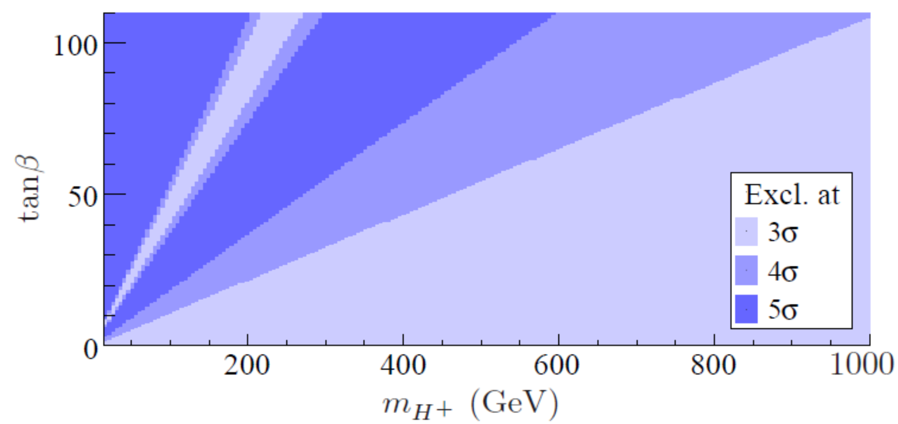
- Recent BaBar $R(D^{(*)})$ values inconsistent with SM at ~3.4 σ level.
- But same results exclude Type-II 2HDM at 99.8% confidence level for all values of $\tan\beta$, m_H.
  - Other models could still be viable.



PRL 109, 101802 (2012)



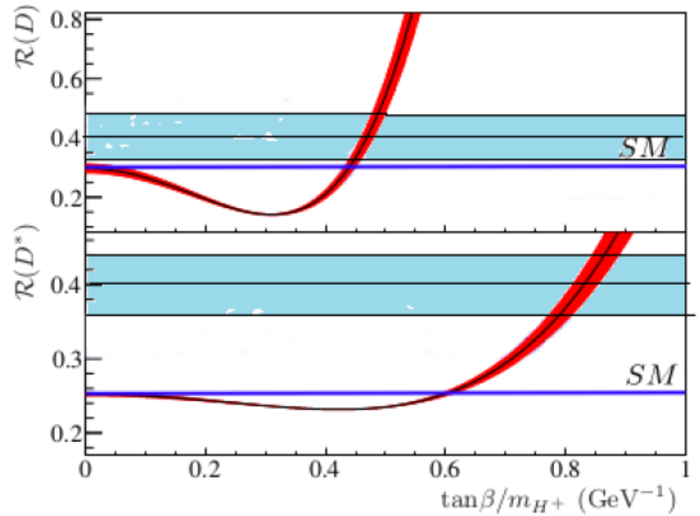
arXiv:1303.0571

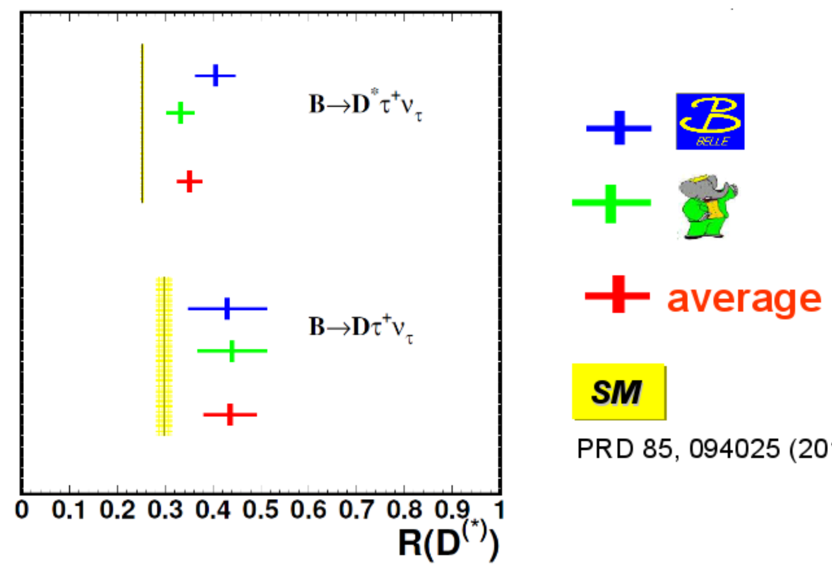


Belle Results on $B \to D^{(*)} \tau \nu$

- Previous Belle measurements:
  - **Inclusive tagging:**
    - (First observation) $B^0 \to D^{*-} \tau^+ \nu$ **[PRL99, 191807 (2007)]**
    - $B^0 \to D^{(*)0} \tau^+ \nu$ **[PRD82, 072005 (2010)]**
  - **Exclusive tagging:**
    - $B^0 \to D^{(*)-} \tau^+ \nu$
      $B^+ \to D^{(*)0} \tau^+ \nu$ **[arXiv:0910.4301]**
- Belle deviations from SM:
  - Unofficial averages of prior Belle results:
    - (See A. Bozek, FPCP)
  - R(D): 3.0 σ
  - R(D*): 1.4 σ
  - Combined D/D*: 3.3 σ
- BaBar deviations from SM:
  - R(D): 2.0 σ
  - R(D*): 2.7 σ
  - Combined D/D*: 3.4 σ
- **Combined for Belle / BaBar: 4.8 σ**

R(D$^{(*)}$) analysis for final Belle data set underway, coming soon!

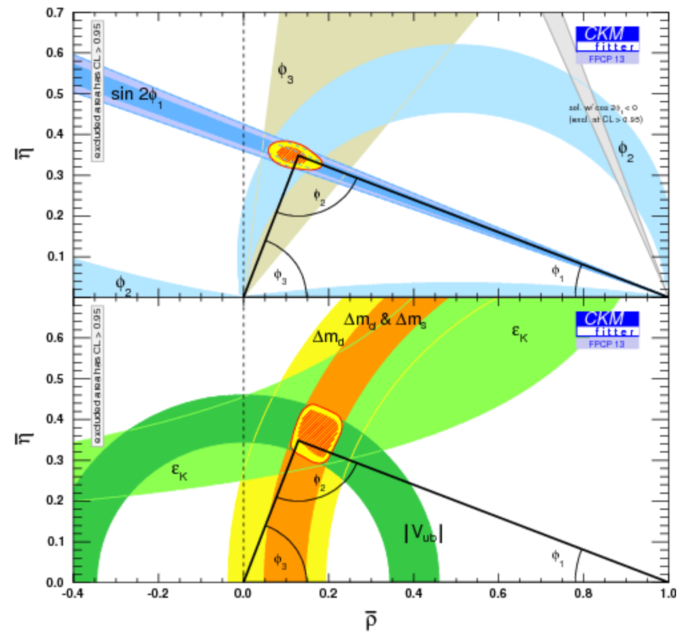




PRD 85, 094025 (2012)

Exclusive Semileptonic Decays

- $|V_{ub}|$ is a valuable input for predictions of other processes (e.g., $B \to \tau\,\nu$).
- Precision on $|V_{ub}|$ is poor (e.g., relative to $\sin 2\phi_1$ and $|V_{cb}|$).
- Some tension exists in inclusive vs. exclusive determinations of $|V_{ub}|$.
  - Important to clarify for further consistency checks.



- Matrix element of $B \to X_u\, l\, \nu$:

$$\mathcal{M}(B \to X_u \ell \bar{\nu}_\ell) = \frac{G_F}{\sqrt{2}} V_{ub} L^\mu H_\mu, \;\; L^\mu = \bar{u}_\ell \gamma^\mu (1-\gamma^5) v_\nu$$

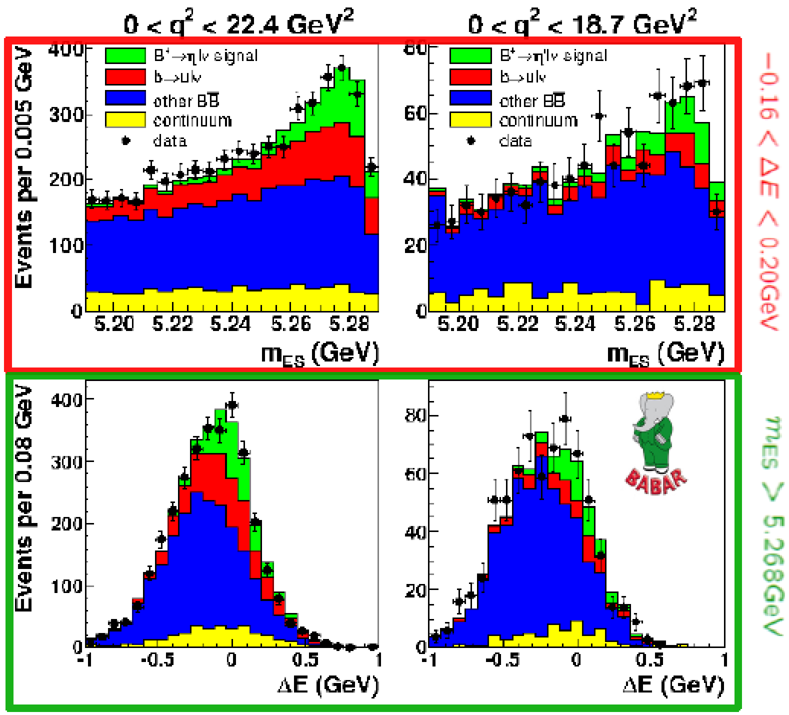
- For example, decay rate for π mode has form:

$$\frac{\mathrm{d}\Gamma(B \to \pi \ell \bar{\nu}_\ell)}{\mathrm{d}q^2} = \frac{G_F^2 p_\pi^3}{24\pi^3} |V_{ub}|^2 |f_+(q^2)|^2$$

- Measurements allow clean extraction of $|V_{ub}|$.
  - For π mode, Bourrely, Caprini, Lellouch (BCL) parameterization can be used to determine **$f_+(q^2)$** in a model-independent way. **PRD 79, 013008 (2009)**

$B \to \eta \ell \nu$ and $B \to \eta' \ell \nu$

[hep-ex] 1208.1253

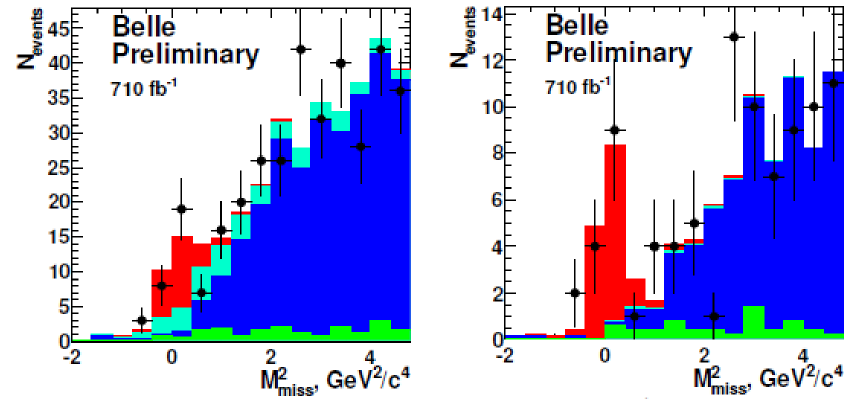


Babar Loose Untagged

$B \to \eta \ell \nu$
$N_S = 867 \pm 101$
$\mathcal{B} = 0.38 \pm 0.05 \pm 0.04$

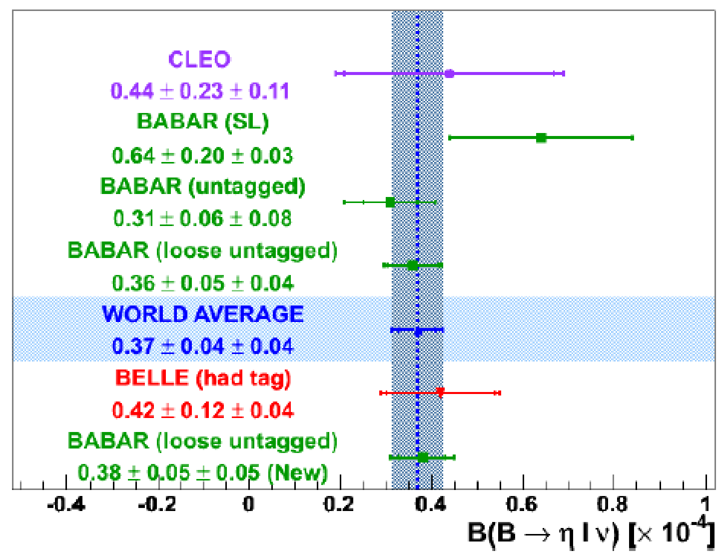
$B \to \eta' \ell \nu$
$N_S = 141 \pm 49$
$\mathcal{B} = 0.24 \pm 0.08 \pm 0.03$

Belle Hadronic Tag

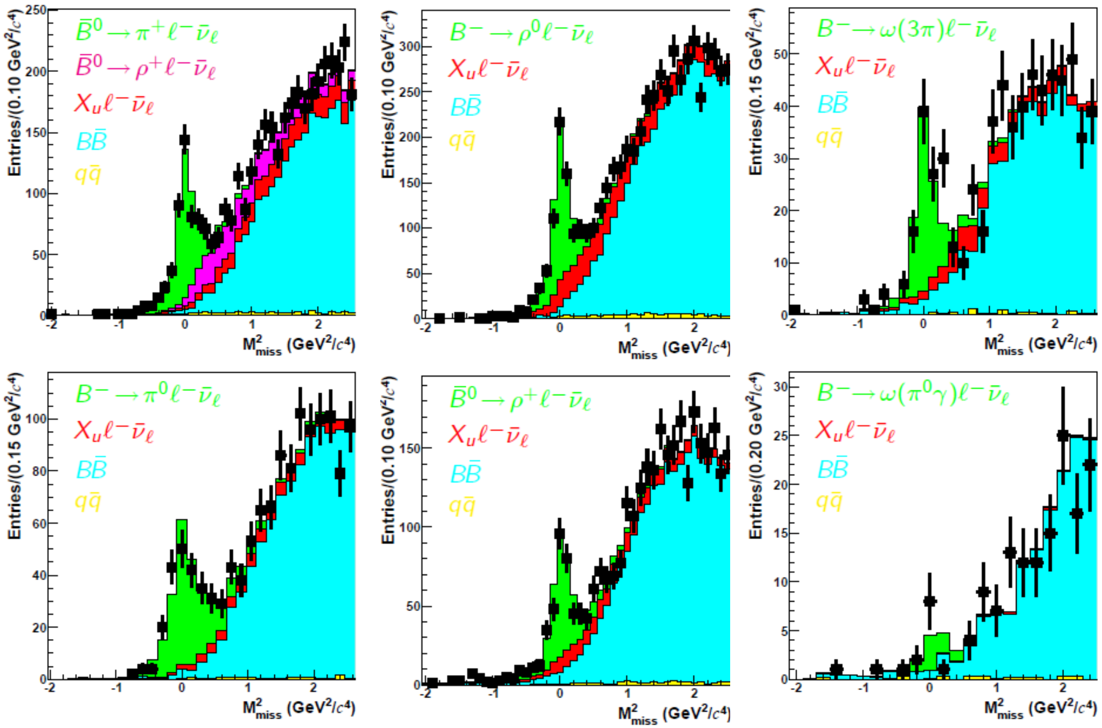


$B \to \eta \ell \nu$
$N_S = 39 \pm 11$
$\mathcal{B} = 0.42 \pm 0.12 \pm 0.05$

$B \to \eta' \ell \nu$
$N_S = 6.1 \pm 4.7$
$\mathcal{B} < 0.57$ at 90% CL



B → (π,ρ,ω) ℓ ν at Belle



X_u	N^{fit}	$\mathcal{B}$ (x10⁴)
π^0	232.2 ± 22.6	$0.80 \pm 0.08 \pm 0.04$
π^+	462.6 ± 27.7	$1.49 \pm 0.09 \pm 0.07$
ρ^0	621.7 ± 35.0	$1.83 \pm 0.10 \pm 0.10$
ρ^+	343.3 ± 28.3	$3.22 \pm 0.27 \pm 0.24$
$\omega(3\pi)$	96.7 ± 14.5	$1.07 \pm 0.16 \pm 0.07$
$\omega(\pi^0\gamma)$	9.0 ± 4.0	$1.06 \pm 0.47 \pm 0.07$
ω(average)		$1.07 \pm 0.15 \pm 0.07$

PRD **88**, 032005 (2013) [arXiv:1306.2781]

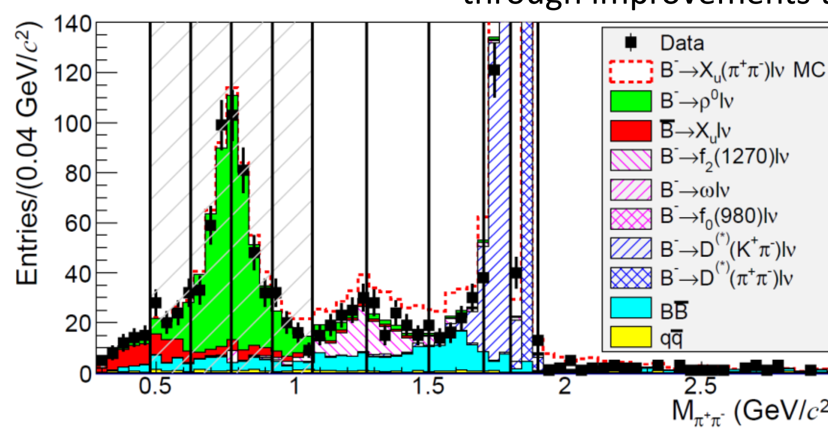
- π and ρ measurements allow tests of isospin symmetry:

$$2 \times \frac{\mathcal{B}(B^- \to \pi^0 \ell^- \bar{\nu}_\ell)}{\mathcal{B}(\bar{B}^0 \to \pi^+ \ell^- \bar{\nu}_\ell)} \frac{\tau_{B^0}}{\tau_{B^+}} = 1.00 \pm 0.13_{\text{tot}}$$

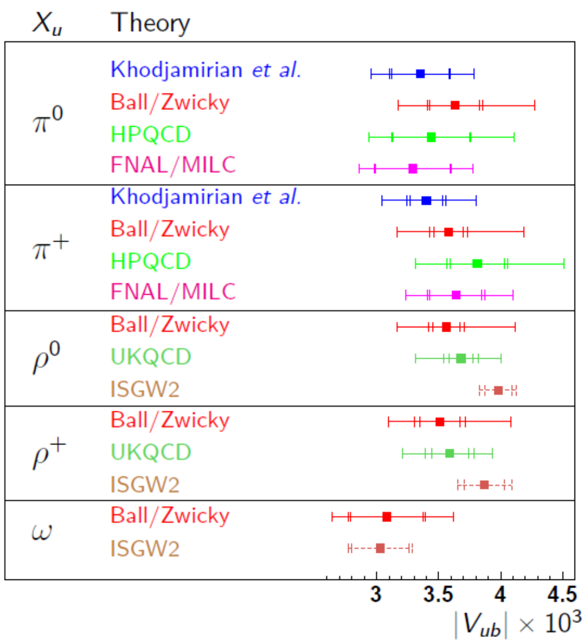
$$2 \times \frac{\mathcal{B}(B^- \to \rho^0 \ell^- \bar{\nu}_\ell)}{\mathcal{B}(\bar{B}^0 \to \rho^+ \ell^- \bar{\nu}_\ell)} \frac{\tau_{B^0}}{\tau_{B^+}} = 1.06 \times (1 \pm 0.13_{\text{tot}})$$

  - Both consistent with 1, SM expectations.
- B → ρ **ℓ ν**:
  - Deficit of nonresonant $\pi\pi$ predicted by PYTHIA.
  - ~3x higher f_2 contribution than ISWG2

➔ Potentially impacts inclusive $|V_{ub}|$ through improvements to MC.



Impacts on $|V_{ub}|$



Khodjamirian *et al.*
PRD **83**, 094031 (2011)

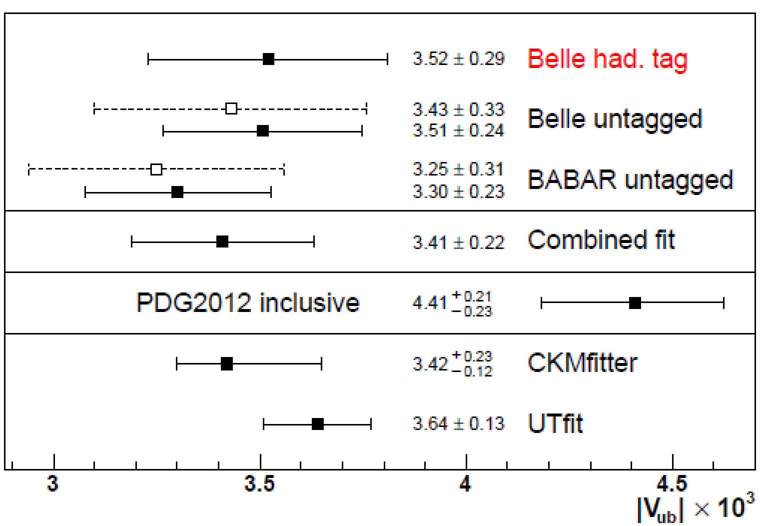
Ball/Zwicky
PRD **71**, 014015 (2005)
PRD **71**, 014029 (2005)

HPQCD
PRD **73**, 074502 (2006)

FNAL/MILC
PRD **79**, 054507 (2009)

UKQCD
PLB **416**, 392 (1998)

ISGW2
PRD **52**, 2783 (1995)
Theory error is not available.



- These results can be used to estimate $|V_{ub}|$ based on various theoretical predictions of form factor.
- Experimental uncertainty typically ~2-3 times less than theoretical uncertainty.
- $|V_{ub}|$ can be studied in a model-independent way using $B \to \pi \ell \nu$ decays and BCL form factor parameterization.
  - Simultaneous fit to available $B \to \pi \ell \nu$ data and LCSR/LQCD form factor prediction.

LCSR	JHEP **1205**, 092 (2012) [arXiv:1203.1359]
LQCD	PRD **79**, 054507 (2009) [arXiv:0811.3640]
Belle had. tag	PRD **88**, 032005 (2013) [arXiv:1306.2781]
Belle	PRD **83**, 071101(R) (2011) [arXiv:1012.0090]
BaBar	PRD **86**, 092004 (2012) [arXiv:1208.1253]

Summary

- Belle results for $B \to \tau \nu$ with improved hadronic tags:
  - Tension in CKM fit is now reduced to < 2 σ level.
- $B \to D^{(*)}\tau \nu$ appears to be a promising place for new physics searches.
  - Recent BaBar results disfavor SM predictions, but also largely exclude type II 2HDM.
  - Measurements from Belle with final data sample coming soon.

- Other Belle semileptonic measurements:
  - $\mathbf{B \to \rho \ell \nu}$: improved precision over world average by factor of 2.
  - $\mathbf{B \to \pi \ell \nu}$, $\mathbf{B \to \omega \ell \nu}$:new measurements consistent with previous results.
  - New values of $|V_{ub}|$ extracted, exclusive/inclusive measurements of $|V_{ub}|$ still in tension at ~3σ level.

- Stay tuned for new results!

Next level of precision searches for new physics in these modes and others will be conducted at Belle II / SuperKEKB.

(See Sven Vahsen's talk from earlier today.)

$B \to D^{(*)}\tau\nu$ results

Analysis	$\mathcal{B}$ [%]	R	significance
	$B^+ \to \bar{D}^{*0}\tau^+\nu_\tau$		
Belle incl.	$2.12^{+0.28}_{-0.27} \pm 0.29$	$0.372^{+0.049}_{-0.047} \pm 0.057$(*)	
Belle excl.	$2.68\ ^{+0.63}_{-0.57}\ ^{+0.34}_{-0.40} \pm 0.09$(*)	$0.47\ ^{+0.11}_{-0.10}\ ^{+0.06}_{-0.07}$	
Belle average	$2.24 \pm 0.29 \pm 0.15$	$0.393 \pm 0.051 \pm 0.027$	
BABAR	$1.71 \pm 0.17 \pm 0.13$	$0.322 \pm 0.032 \pm 0.022$	
WA	-	0.344 ± 0.036	
	$B^0 \to D^{*-}\tau^+\nu_\tau$		
Belle incl.	$2.02^{+0.40}_{-0.37} \pm 0.37$	$0.408^{+0.081}_{-0.075} \pm 0.077$(*)	
Belle- excl.	$2.38\ ^{+0.69}_{-0.59}\ ^{+0.30}_{-0.20} \pm 0.05$(*)	$0.48\ ^{+0.14}_{-0.12}\ ^{+0.06}_{-0.04}$	
Belle average	$2.24 \pm 0.29 \pm 0.15$	$0.393 \pm 0.051 \pm 0.027$	
BABAR	$1.74 \pm 0.19 \pm 0.12$	$0.355 \pm 0.039 \pm 0.021$	
WA	-	0.372 ± 0.039	
	$B^+ \to \bar{D}^0\tau^+\nu_\tau$		
Belle incl.	$0.77 \pm 0.22 \pm 0.12$	$0.341^{+0.097}_{-0.097} \pm 0.063$(*)	
Belle excl.	$1.58\ ^{+0.43}_{-0.41}\ ^{+0.25}_{-0.20} \pm 0.08$(*)	$0.70\ ^{+0.19}_{-0.18}\ ^{+0.11}_{-0.09}$	
Belle average	$0.95 \pm 0.21 \pm 0.08$	$0.420 \pm 0.091 \pm 0.034$	
BABAR	$0.99 \pm 0.19 \pm 0.13$	$0.429 \pm 0.082 \pm 0.052$	
WA	-	0.425 ± 0.069	
	$B^0 \to D^-\tau^+\nu_\tau$		
Belle excl.	$1.04\ ^{+0.48}_{-0.41}\ ^{+0.13}_{-0.11} \pm 0.06$	$0.48\ ^{+0.22}_{-0.19}\ ^{+0.06}_{-0.05}$(*)	
BABAR	$1.01 \pm 0.18 \pm 0.12$(*)	$0.469 \pm 0.084 \pm 0.053$	
WA	-	0.471 ± 0.090	