$B \to l\,\nu$ ($l = \tau, \mu, e$)
Belle results and outlook for Belle II

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7th Workshop on the CKM Unitary Triangle
Cincinnati, Ohio USA
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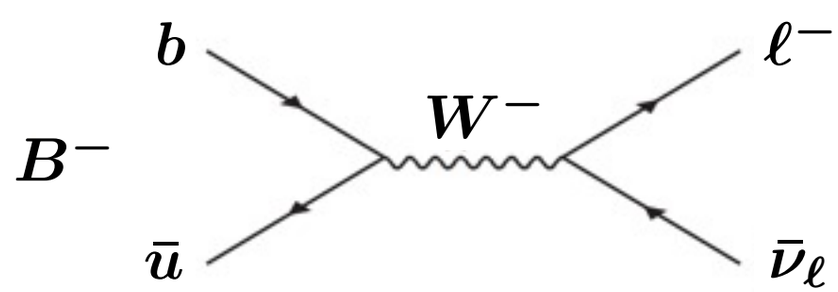
B→lν in Standard Model

- In the SM, annihilation process mediated by $W^{\pm}$.



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

$$\mathcal{B}(\ell = \tau) > \mathcal{B}(\ell = \mu) > \mathcal{B}(\ell = e)$$

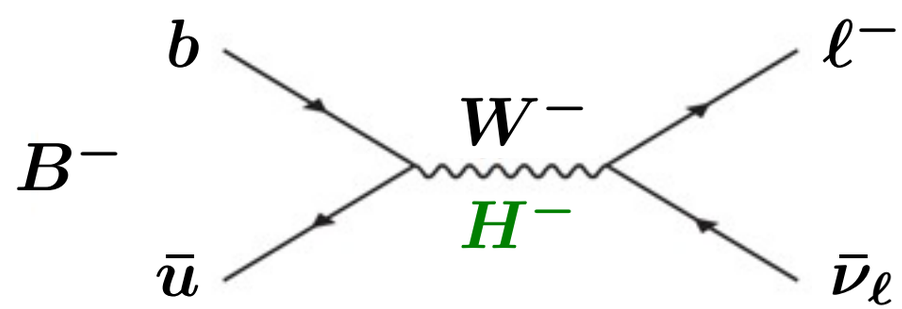
$$\mathcal{O}(10^{-4}) \qquad \mathcal{O}(10^{-7}) \qquad \mathcal{O}(10^{-11})$$

- f_B: B meson decay constant. *Can be calculated from Lattice QCD.*
- V_{ub}: CKM matrix element. *Can be measured from b→ulν decays.*

Both can also be obtained from a CKM global fit.

Possible effect of $H^{\pm}$ for $B \to l\nu$

- $B \to l\nu$ could be affected by charged Higgs.



- Example of modifications:

$$\mathcal{B}(B^- \to \ell^- \bar{\nu}_\ell) = \mathcal{B}(B^- \to \ell^- \bar{\nu}_\ell)_{\rm SM} \times r_H$$

where common r_H is considered for $l = e, \mu$, and τ.

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

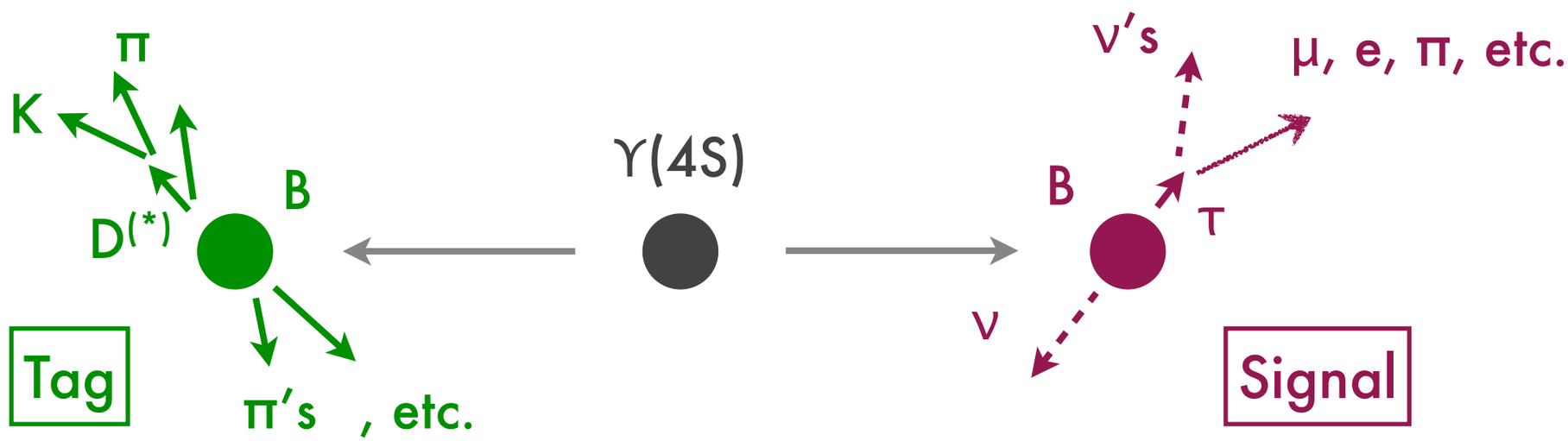
W. S. Hou, Phys. Rev. D 48, 2342 (1993), type II of two Higgs doublet model (2HDM).

$$r_H = \left(1 - \frac{\tan^2\beta}{1+\tilde{\epsilon}_0 \tan\beta} \, \frac{m_B^2}{m_H^2}\right)^2$$

A. G. Akeroyd and S. Recksiegel, J. Phys. G 29, 2311 (2003), higher order correction in SUSY models.

Methods for analyzing $B \to \tau\nu$

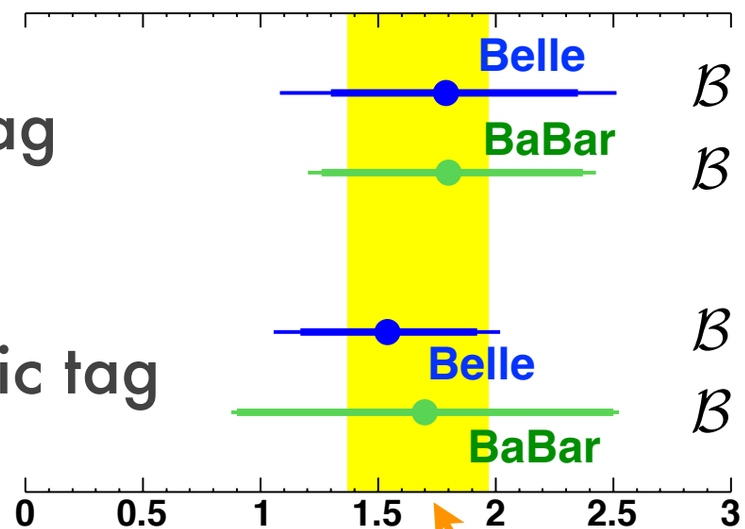
Exploit that a B meson pair is generated by $e^+e^- \to \Upsilon(4S) \to BB$ for "seeing" multiple neutrinos.



Two independent tags are used.

- Hadronic tag: tag B in hadronic decays $B \to D^{(*)}\pi$, etc.
- Semileptonic tag: tag B in semileptonic decays $B \to D^{(*)}l\nu$. (l = e or μ)

Summary for B→τν in early 2012



Hadronic tag

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

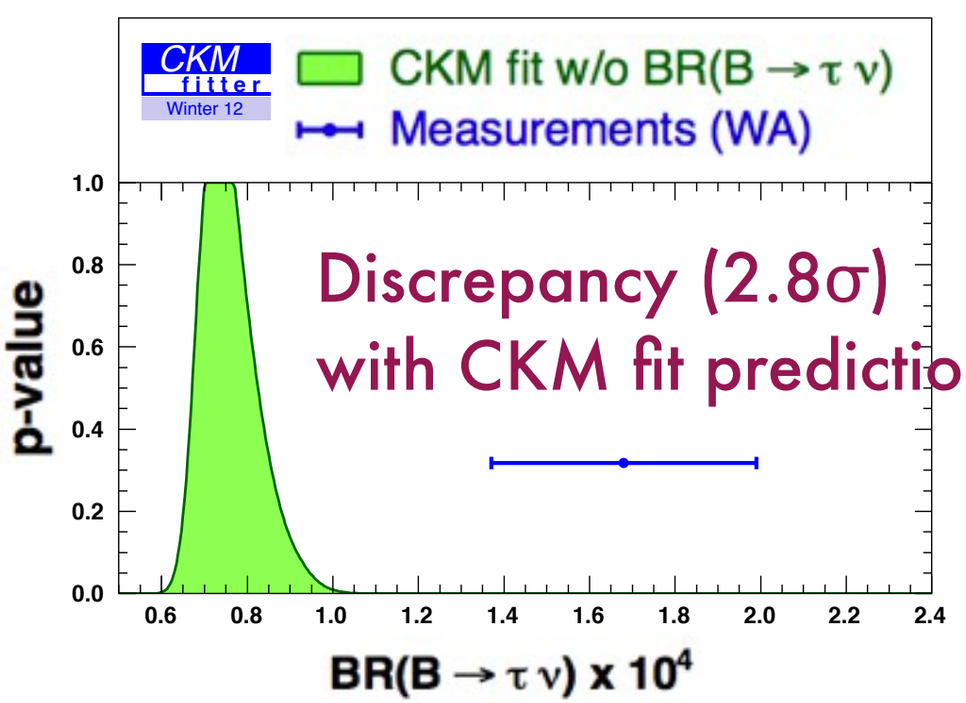
$$\mathcal{B} = [1.80^{+0.57}_{-0.54}(\text{stat}) \pm 0.26(\text{syst})] \times 10^{-4}$$

Semileptonic tag

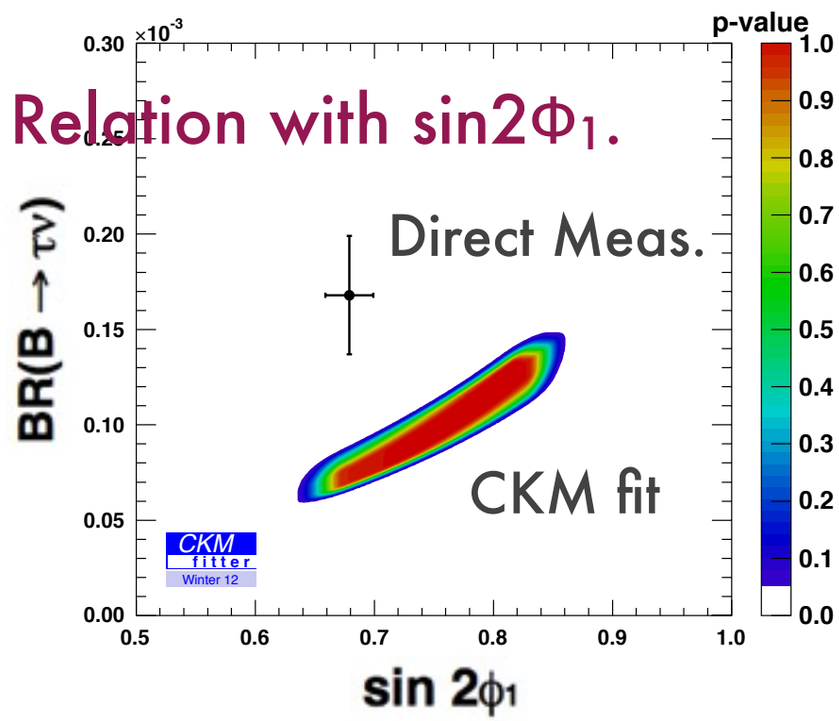
$$\mathcal{B} = [1.54^{+0.38}_{-0.37}(\text{stat})^{+0.29}_{-0.31}(\text{syst})] \times 10^{-4}$$

$$\mathcal{B} = [1.7 \pm 0.8(\text{stat}) \pm 0.2(\text{syst})] \times 10^{-4}$$

WA (HFAG): $\mathcal{B}$ = (1.67 ± 0.30) x 10^{-4}

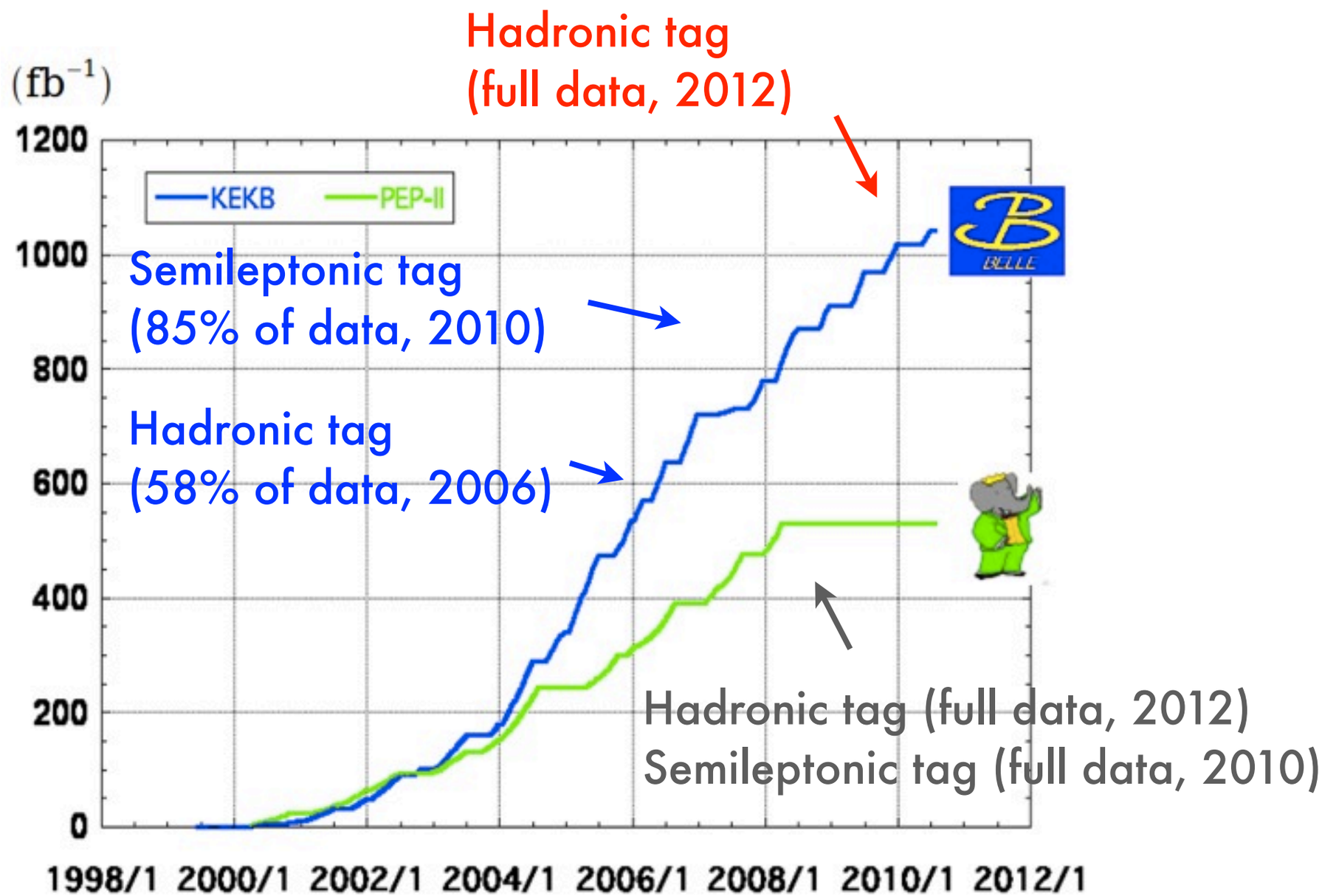


Discrepancy (2.8σ) with CKM fit prediction.



Relation with sin2Φ₁.

Data samples used for B→τν

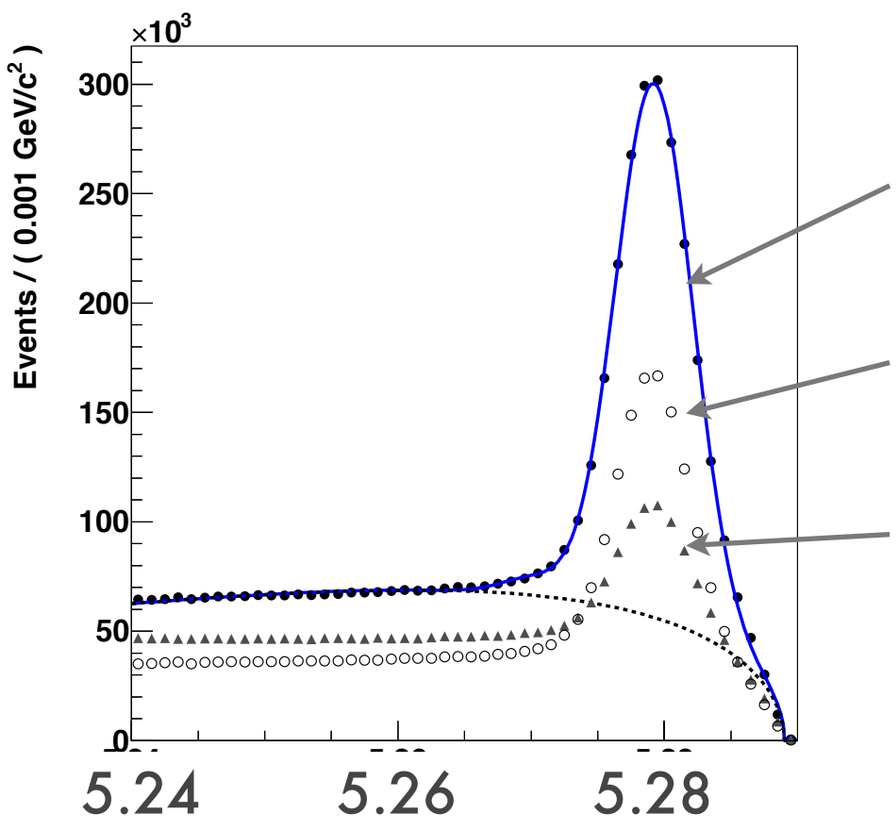


We focus on latest results obtained from Belle.

B→τν by hadronic tag, increased tagged events

NIMA 654, 432 (2011)

- Improved hadronic tag:
  - Add decay modes (B→Dπππ, etc.) which have several final-state particles.
  - Use NeuroBayes package for a better separation with backgrounds.



Beam-energy-constrained B mass [GeV/c²]

New tag on full data (reprocessed)

New tag on previous data

Classical tag on previous data

× 1.8 (data increase)

× 1.7 (tag improvement)

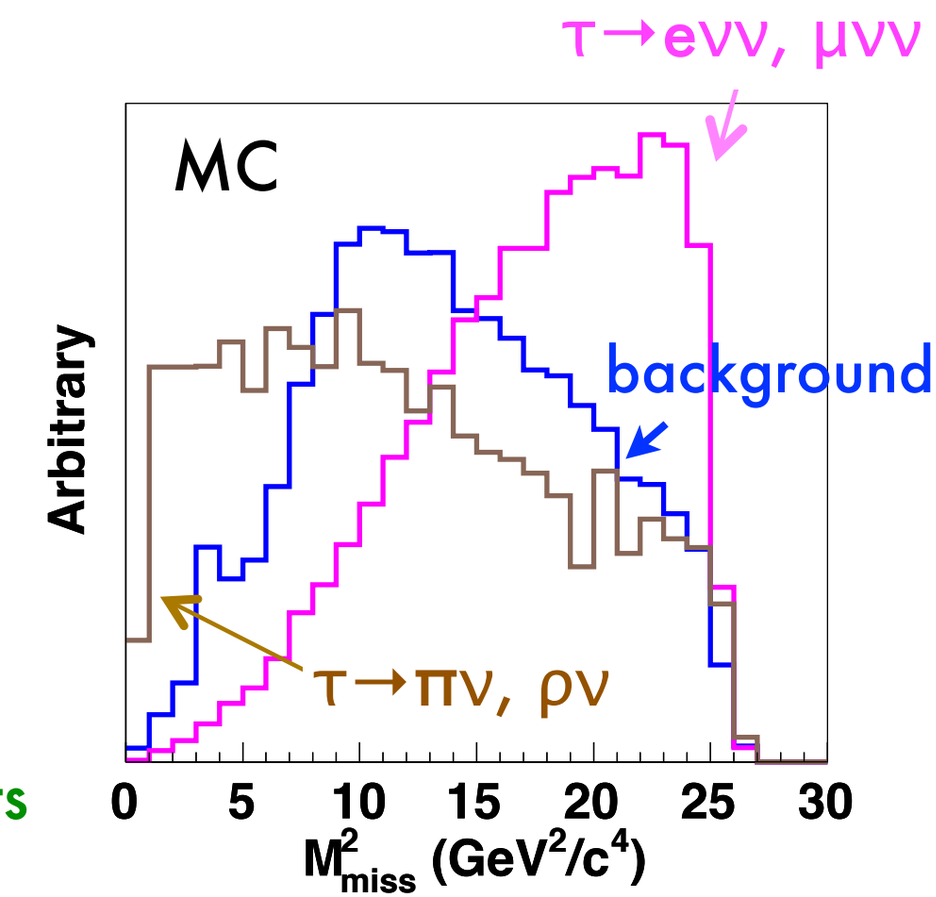
Purity also improved.

3.0 times larger tagged events in total

(Efficiency slightly larger if signal side is B→τν.)

$B \to \tau\nu$ by hadronic tag, method of signal extraction

- Use $\tau \to e\nu\nu$, $\mu\nu\nu$, $\pi\nu$, and $\rho\nu$.
- Events including $X^{\pm}$, π^0, K_L (new) rejected.
- Signal extraction based on two variables.
  - E_{ECL}: remaining energy in electromagnetic calorimeter.
  - M_{miss}^2: missing mass squared (new, removing tight momentum requirements for e, μ, π, and ρ).

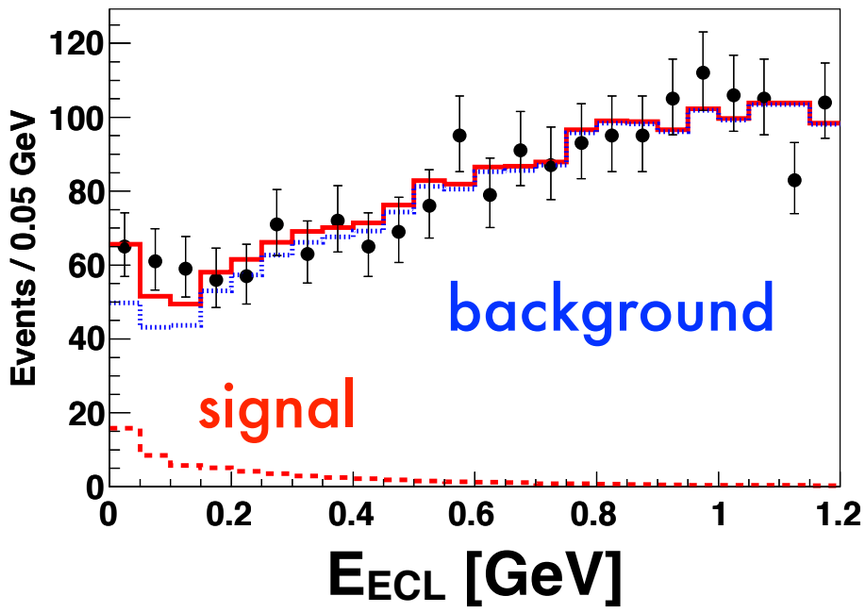


- Sensitivity for $B \to \tau\nu$ improved by a factor of about 25% (5% by including K_L veto, 20% by the new signal extraction method).
- Result less sensitive to the backgrounds which peak at E_{ECL} = 0 GeV.

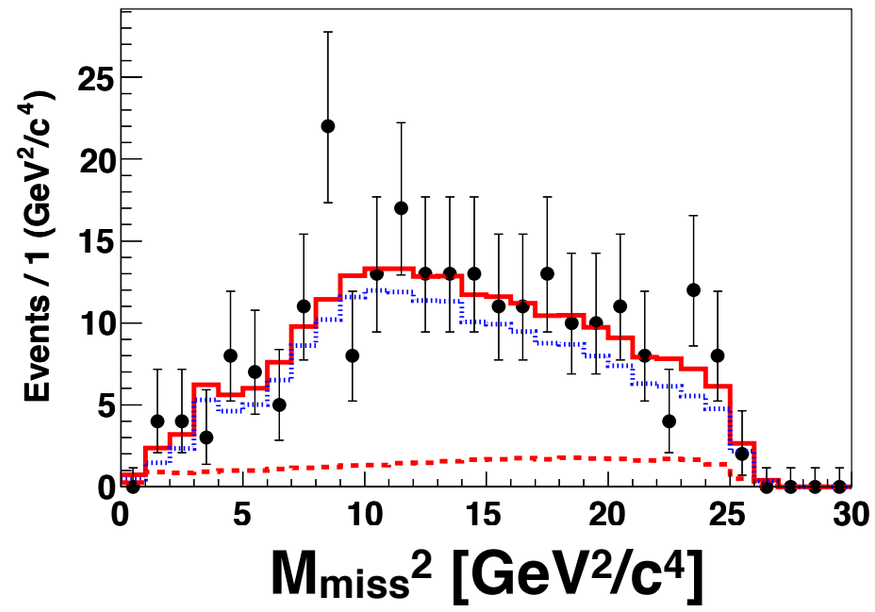
$B \to \tau\nu$ by hadronic tag, signal extraction

Simultaneous fit to different τ decay samples.
Figures shown for the sum of different τ decays.

ICHEP 2012 preliminary, arXiv:1208.4678



(Projection for all M_{miss}^2 region.)



(Projection for $E_{ECL} < 0.2$ GeV)

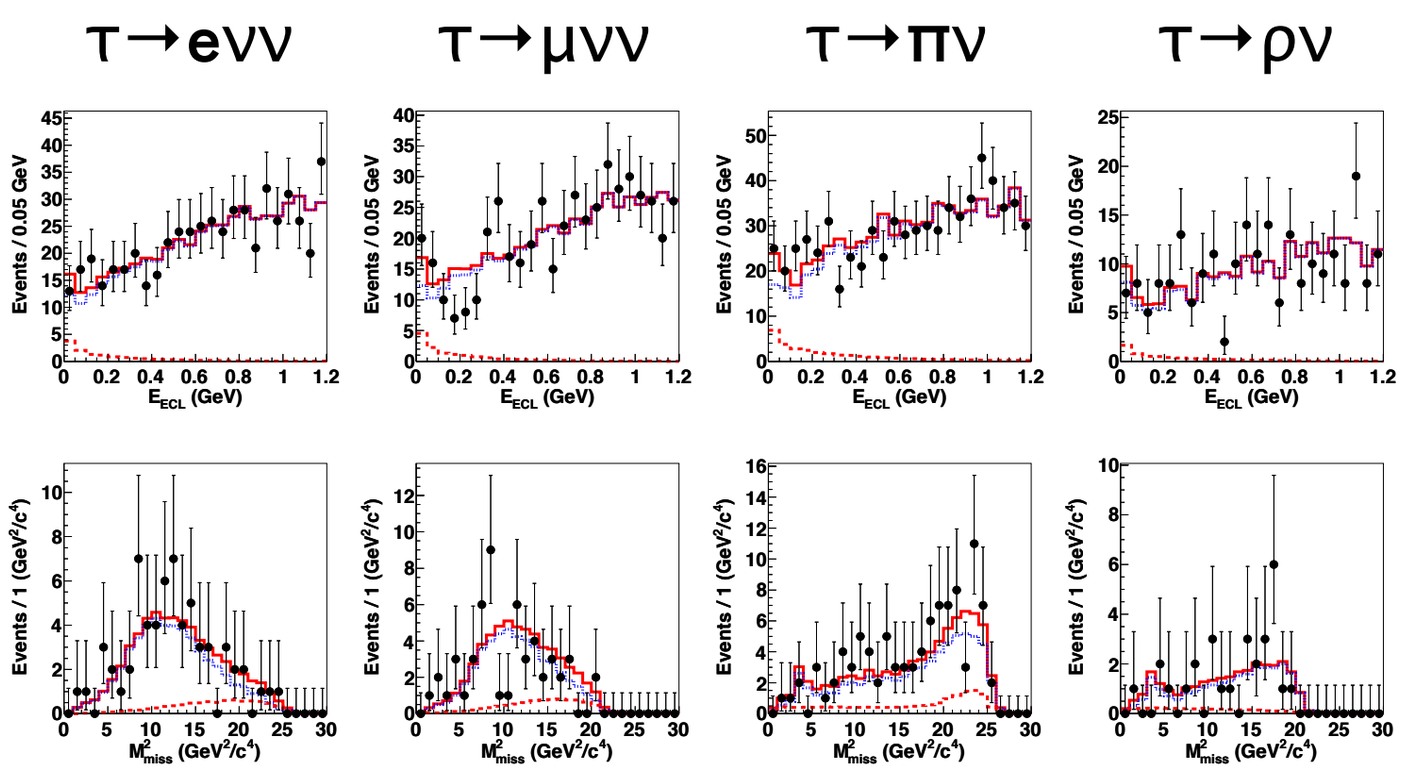
- Signal yield: $62\ ^{+23}_{-22}$ (stat) ± 6 (syst).
- $B(B \to \tau\nu) = [0.72\ ^{+0.27}_{-0.25}$ (stat) ± 0.11 (syst)$] \times 10^{-4}$.

Significance: 3.0σ (including syst)

Systematic error due to background PDFs, tag efficiency, K_L veto efficiency, ...

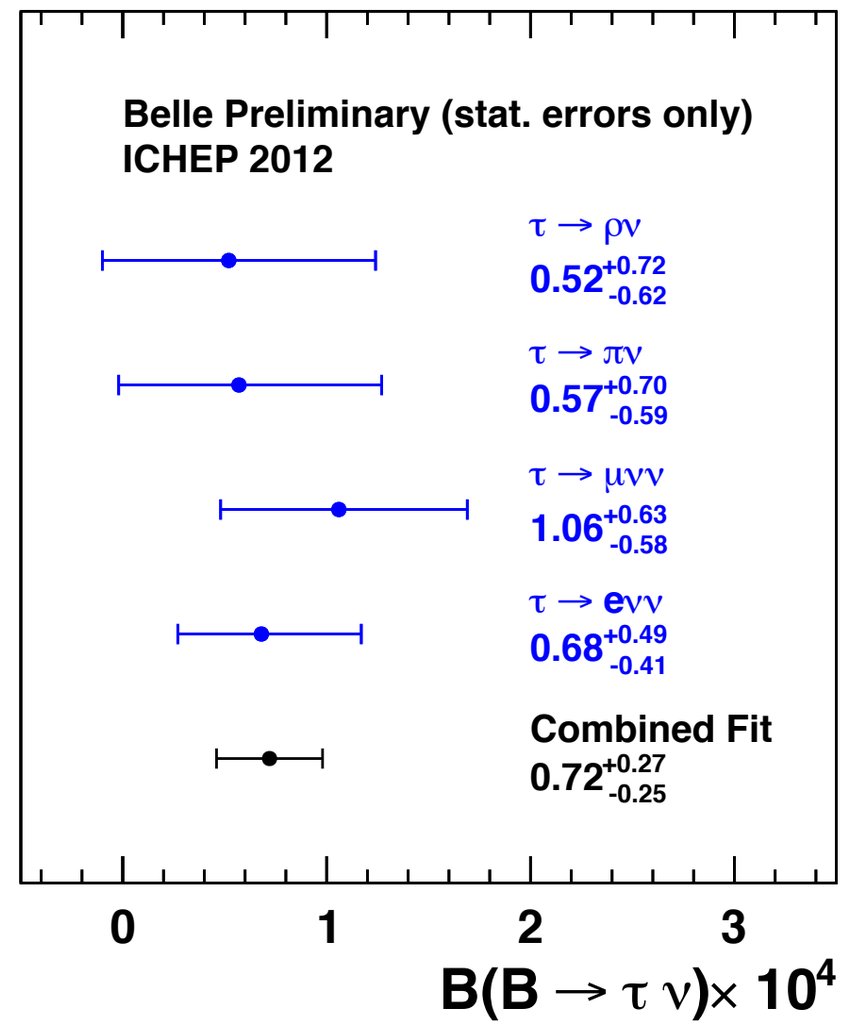
B→τν by hadronic tag, mode independence

As a check, we fit by floating the yields for different τ modes.



Take τ→eνν, μνν, ρν cross-feeds in τ→πν candidates as signal.

Mode	Number of signal	Efficiency
$e^-\overline{\nu}_e\nu_\tau$	$15.5^{+11.2}_{-9.4}$	2.98×10^{-4}
$\mu^-\overline{\nu}_\mu\nu_\tau$	$25.6^{+15.1}_{-13.8}$	3.12×10^{-4}
$\pi^-\nu_\tau$	$7.8^{+9.5}_{-7.9}$	1.76×10^{-4}
$\rho^-\nu_\tau$	$13.6^{+18.7}_{-16.1}$	3.37×10^{-4}



Consistent results.

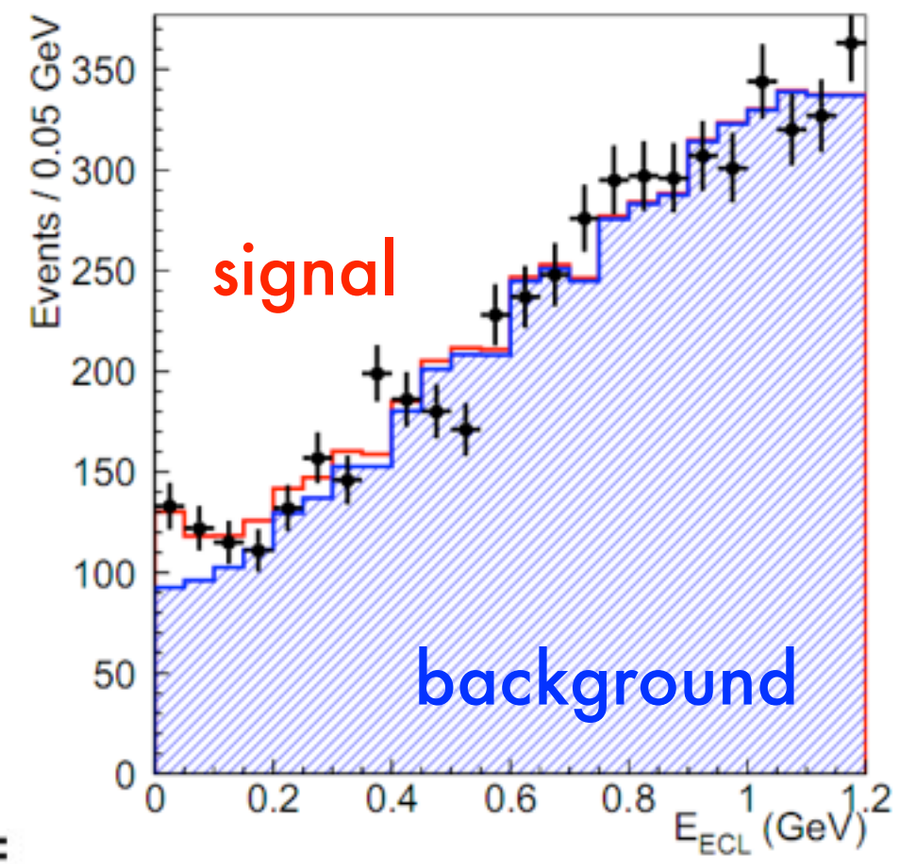
Rare unobserved BG decays (e.g. B→μνγ) would show up in individual signal modes.

B→τν by semileptonic tag

- Using 657 M BB (85% of full data).
- Evidence of signal (3.6σ).

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

Syst. from BG PDF, tag efficiency, etc.

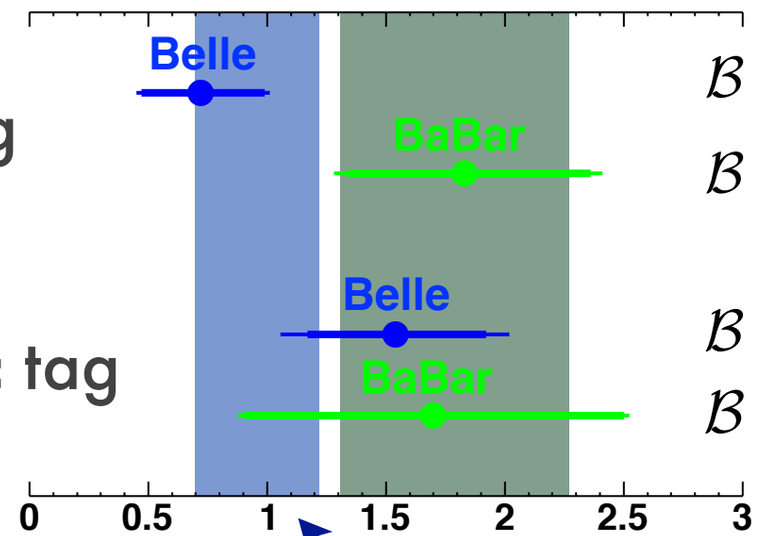


Fitted by histogram PDFs.

Decay mode	Signal yield	ε, 10^{-4}	$\mathcal{B}$, 10^{-4}
$\tau^- \to e^- \bar{\nu}_e \nu_\tau$	73^{+23}_{-22}	5.9	$1.90^{+0.59+0.33}_{-0.57-0.35}$
$\tau^- \to \mu^- \bar{\nu}_\mu \nu_\tau$	12^{+18}_{-17}	3.7	$0.50^{+0.76+0.18}_{-0.72-0.21}$
$\tau^- \to \pi^- \nu_\tau$	55^{+21}_{-20}	4.7	$1.80^{+0.69+0.36}_{-0.66-0.37}$
Combined	143^{+36}_{-35}	14.3	$1.54^{+0.38+0.29}_{-0.37-0.31}$

PRD 82, 071101(R) (2010)

Summary for B→τν (latest)



Hadronic tag

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

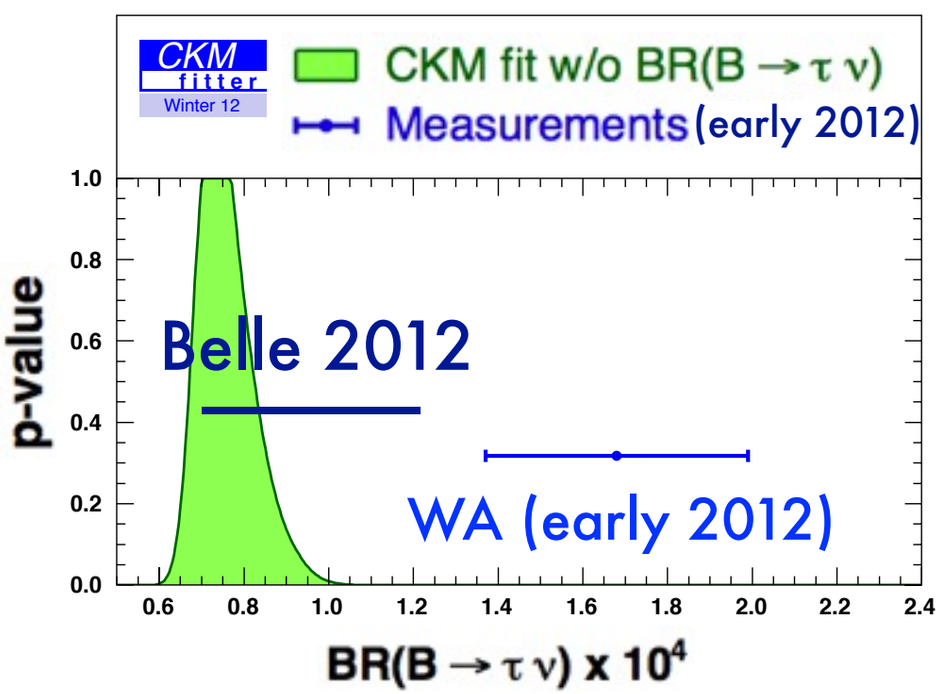
$$\mathcal{B} = [1.83^{+0.53}_{-0.49}(\text{stat}) \pm 0.24(\text{syst})] \times 10^{-4}$$

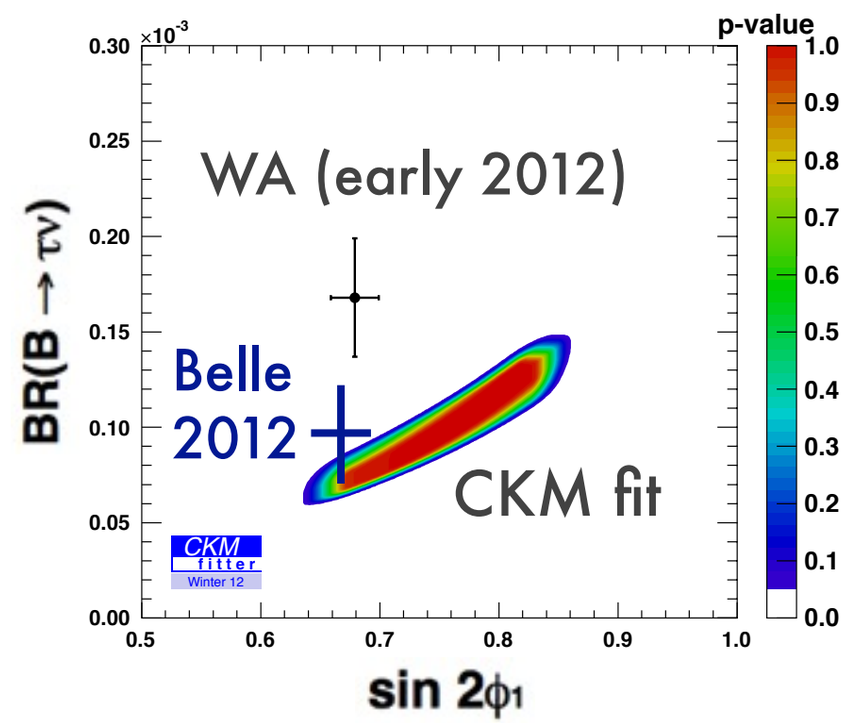
Semileptonic tag

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

$$\mathcal{B} = [1.7 \pm 0.8(\text{stat}) \pm 0.2(\text{syst})] \times 10^{-4}$$

Belle combined: $\mathcal{B}$ = (0.96 ± 0.26) x 10^{-4}



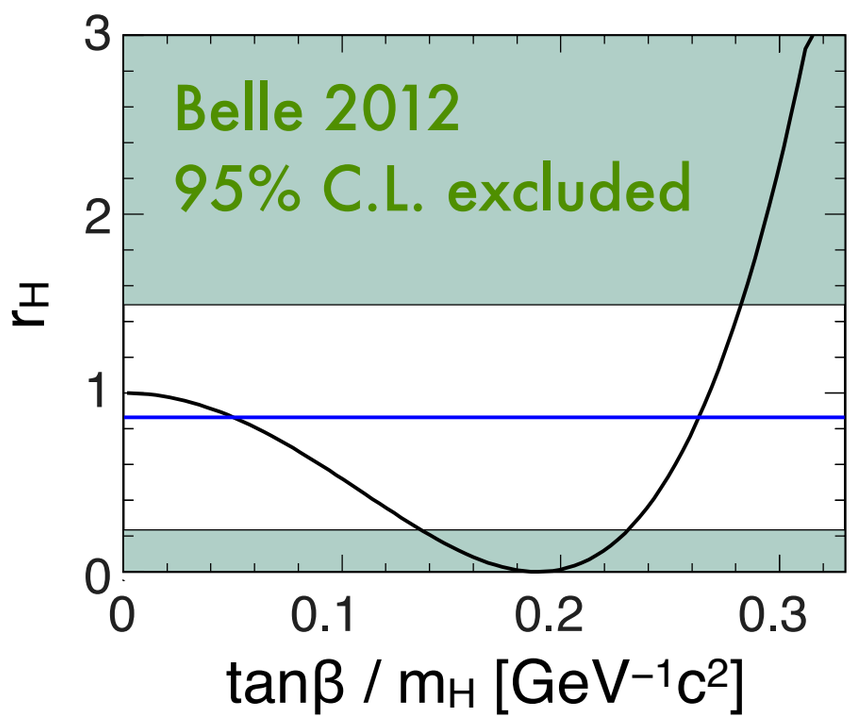


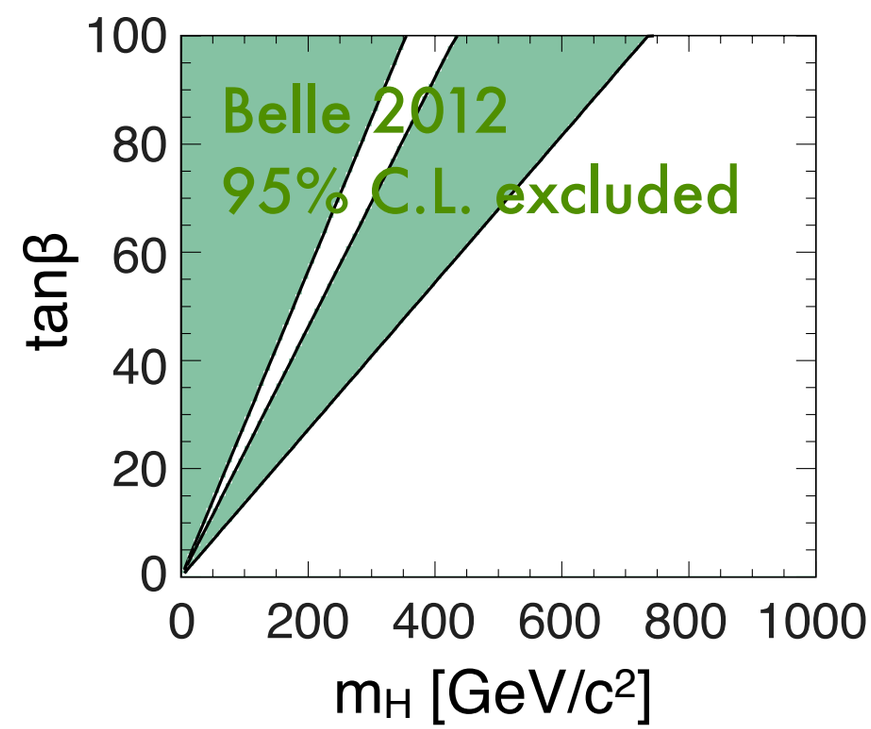
Consistent with CKM fit prediction.

Constraint on charged Higgs

- Assume Type II of two Higgs doublet model.

$$\mathcal{B}(B \to \tau\nu) = \mathcal{B}(B \to \tau\nu)_{\rm SM} \times r_H \qquad r_H = \left(1 - \frac{m_B^2}{m_H^2}\tan^2\beta\right)^2$$





Note: exclusion region strongly depends on the central values of f_B and $|V_{ub}|$.
In this calculation, we use f_B = 191±9 MeV (HPQCD, PRD86, 034506)
and $|V_{ub}| = (4.15\pm0.49)\times10^{-3}$ (PDG2012, inclusive + exclusive $b\to u l\nu$ decays).

B→μν/eν by hadronic tag

ICHEP 2012 preliminary

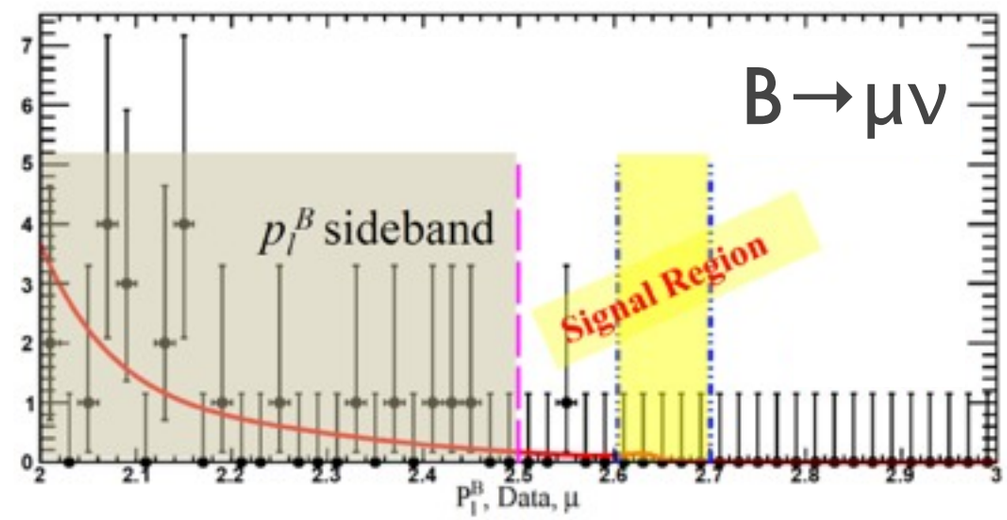
- Use 711 fb^{-1} (full data).
- Hadronic tag as done for B→τν.
- Signal extraction by momentum of μ/e in B rest frame: p_l^B.
- Requirement is applied for E_{ECL}.

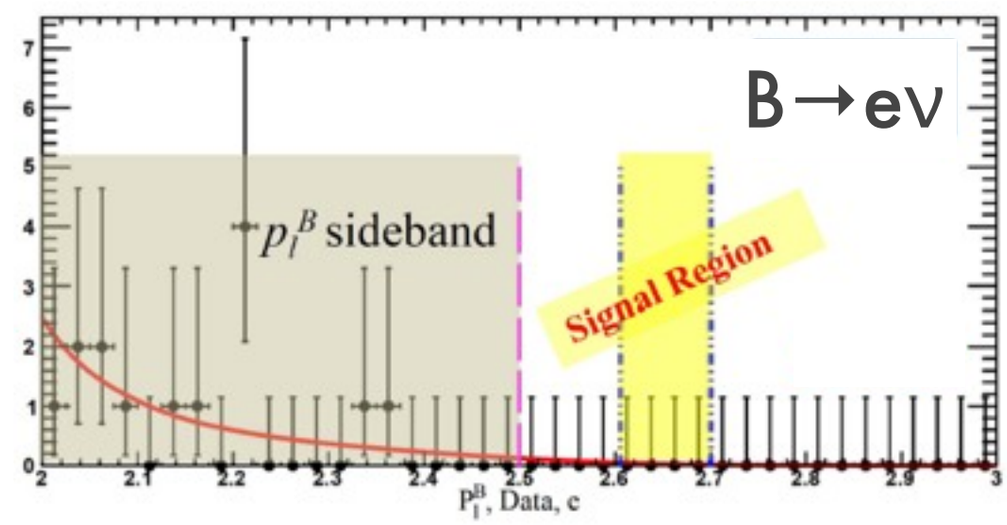
$$\mathcal{B}(B^- \to \mu^- \bar{\nu}_\mu) < 2.5 \times 10^{-6}$$

$$\mathcal{B}(B^- \to e^- \bar{\nu}_e) < 3.5 \times 10^{-6}$$

(90% C.L.)

Errors dominated by statistical uncertainties.





BG yield obtained by sideband fit.
UL estimated by Feldman-Cousins method.

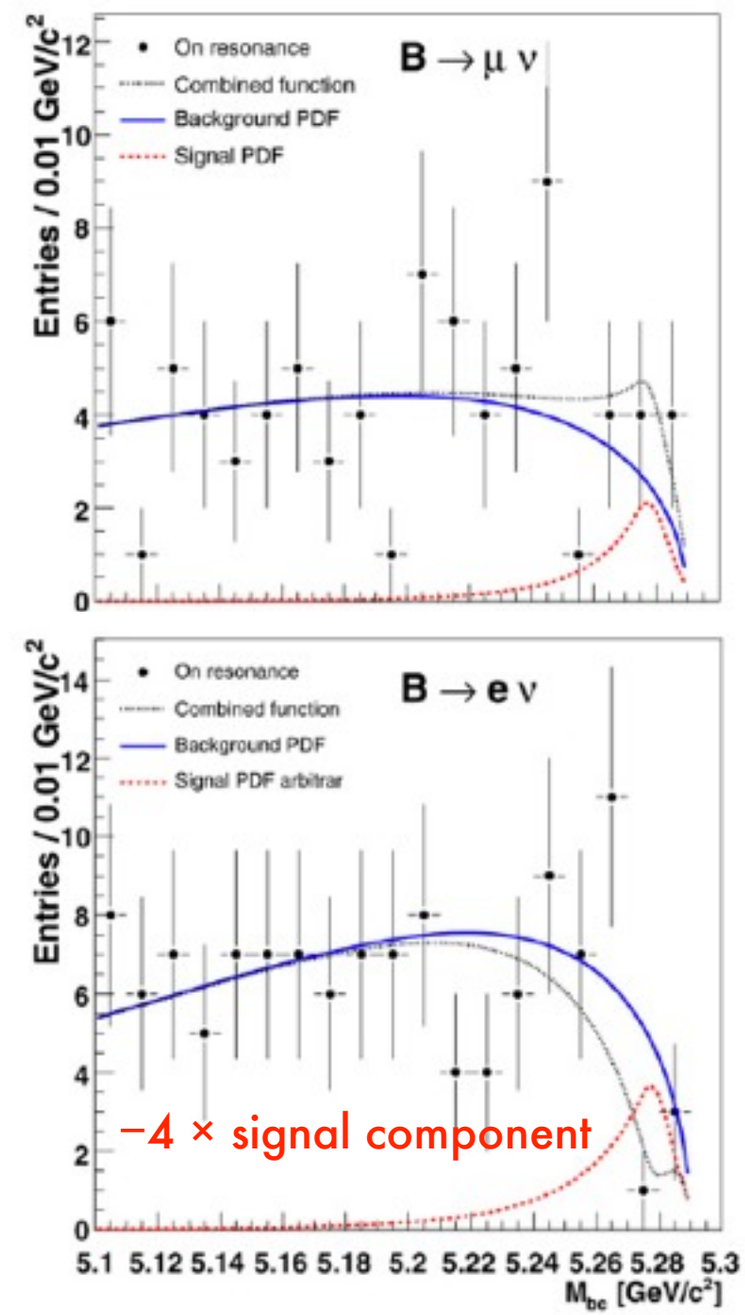
B→μν/eν by inclusive tag

PLB 647, 67 (2007)

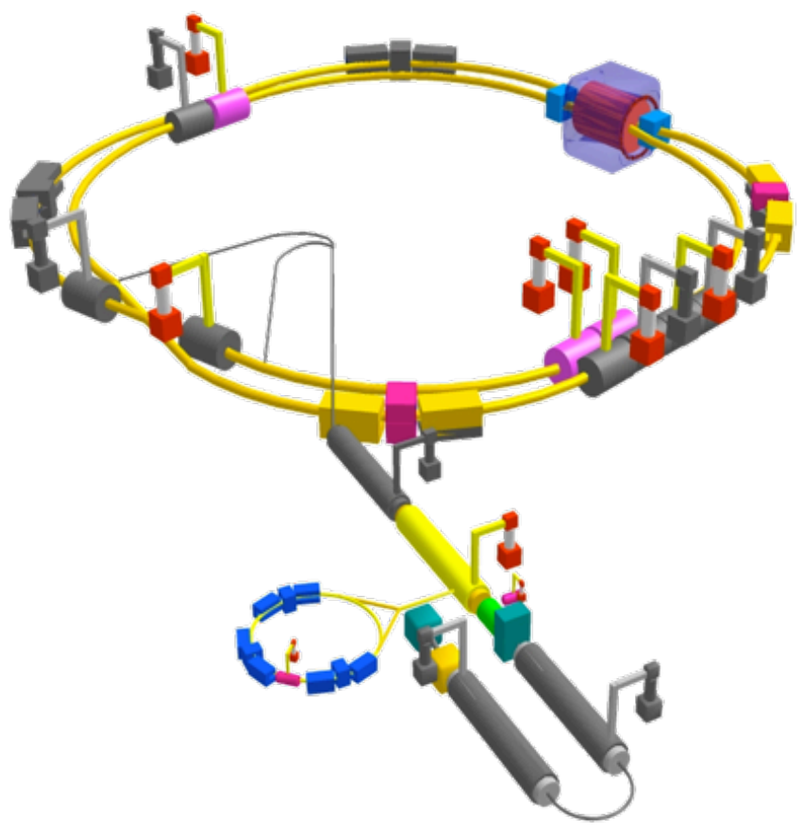
- Use 253 fb^{-1} (36% of data).
- First reconstruct signal μ/e.
  - Requirement on momentum of μ/e.
- Then reconstruct the other B meson using all the remaining particles.
  - Signal extraction by fitting beam-energy-constrained mass M_{bc}.

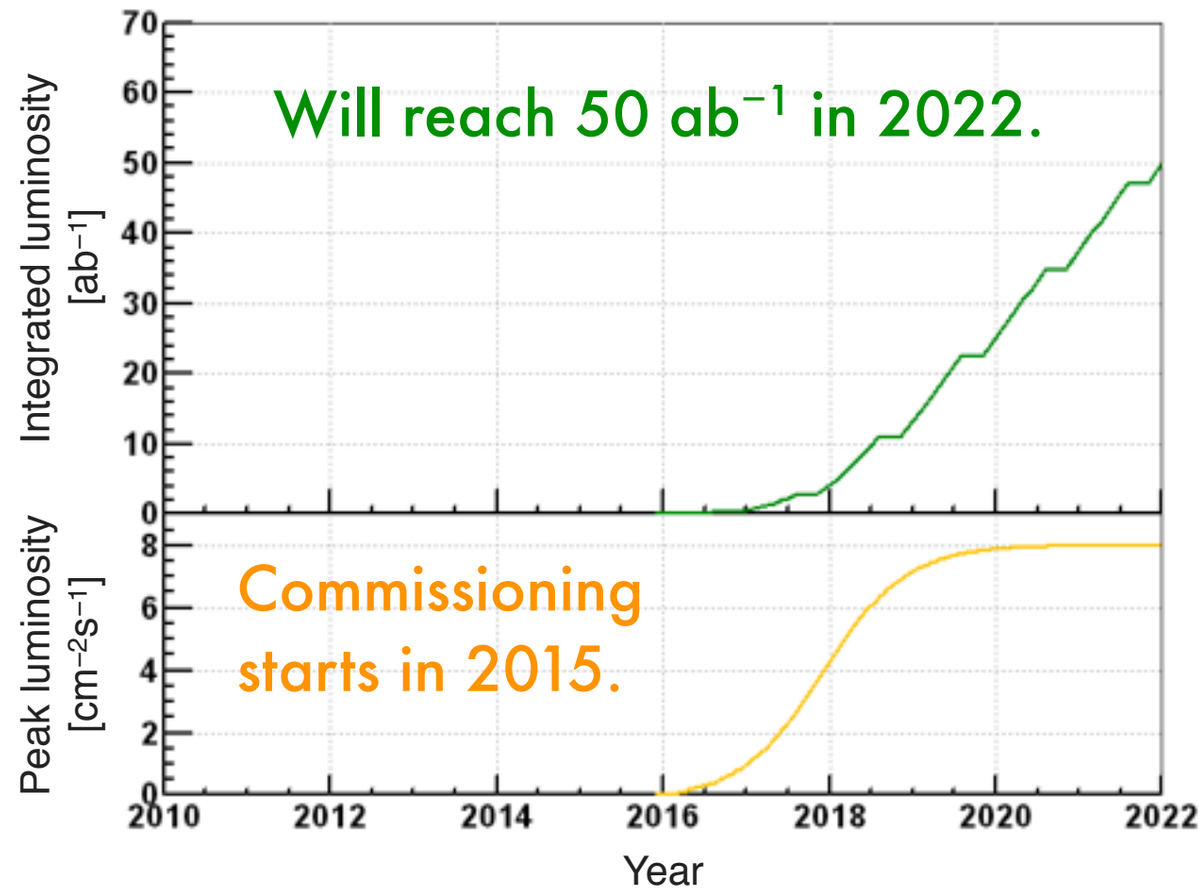
$$\mathcal{B}(B^- \to \mu^- \bar{\nu}_\mu) < 1.7 \times 10^{-6}$$
$$\mathcal{B}(B^- \to e^- \bar{\nu}_e) < 9.8 \times 10^{-7}$$
(90% C.L.)

Errors dominated by statistical uncertainties.



SuperKEKB collider

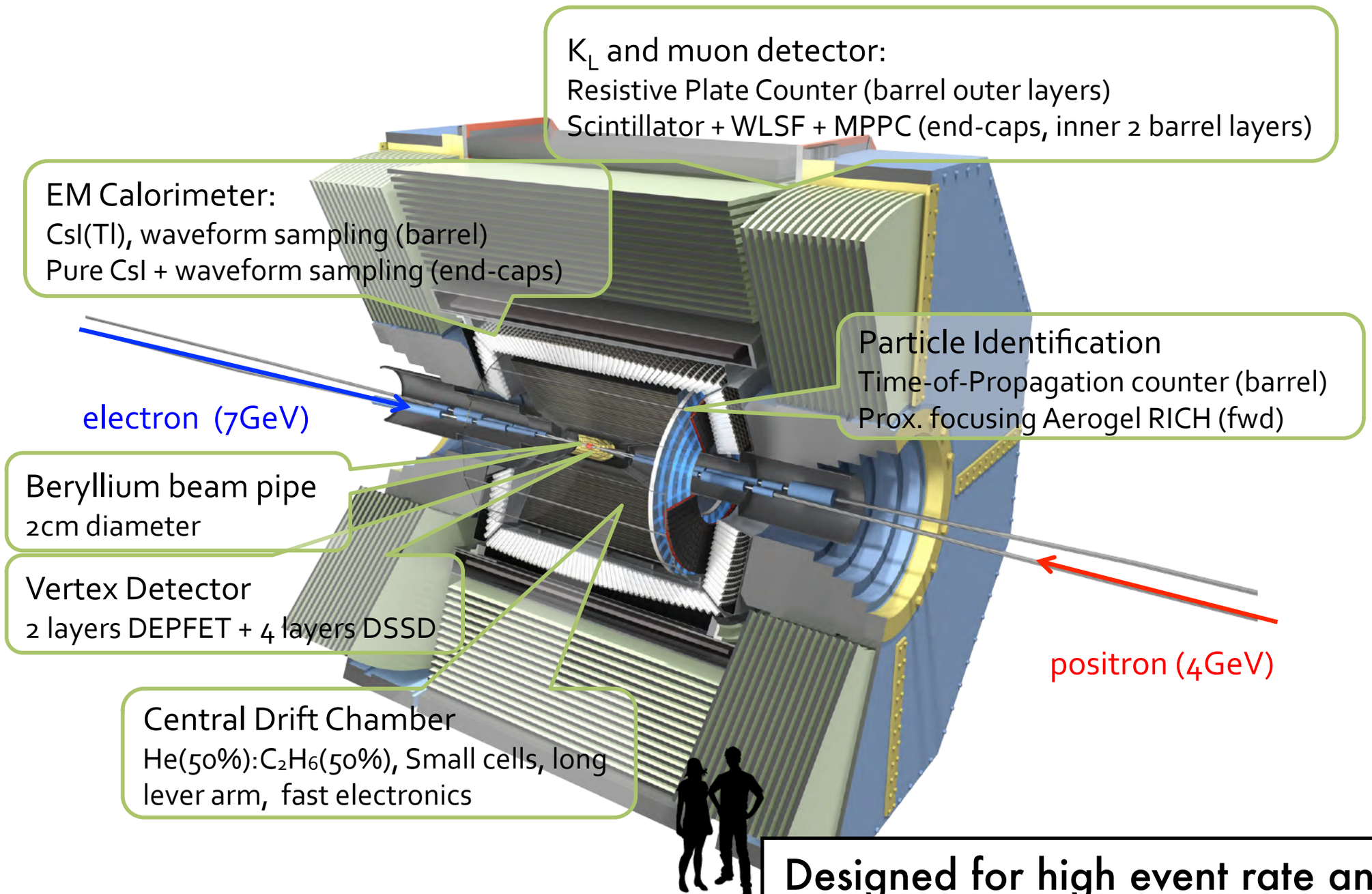




- Design luminosity: 8×10^{35} cm^{-2}s^{-1} (×40 of KEKB).
  - Achieved by small beam sizes (×20) and high currents (×2).
- Target of integrated luminosity: 50 ab^{-1} (×50 of KEKB).

Belle II detector

TDR at arXiv:1011.0352



Designed for high event rate and beam BG.
Improved vertex resolution and particle ID.

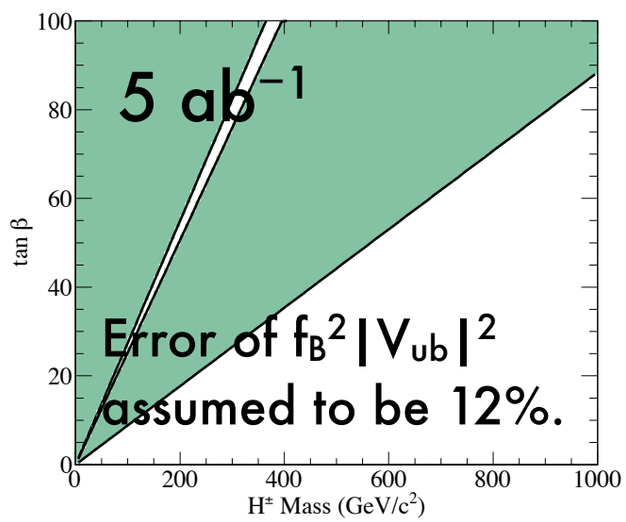
Considerations for $B \to l\nu$ at Belle II

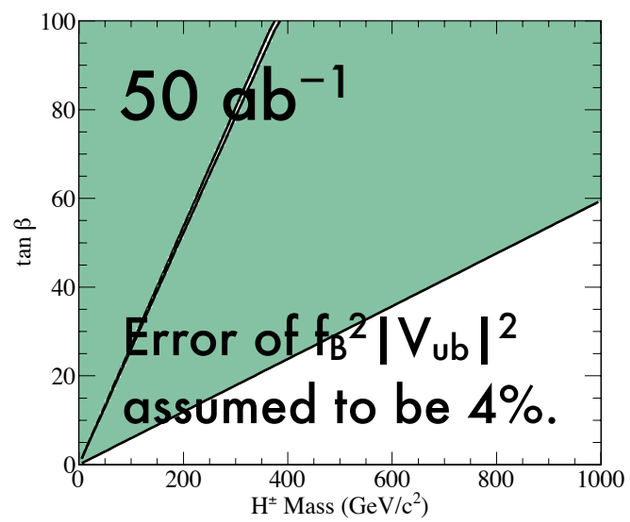
- Data increased (×50).
  - Both statistical and systematic errors reduce.
    (Main systematic uncertainties estimated by data.)
- Particle ID improved (mis-ID rate for $K^{\pm}/\pi^{\pm}$ of % level).
  - Background due to mis-ID decreases.
    (Many $K^{\pm}/\pi^{\pm}$ used in tag-side reconstruction.)
- Beam background increased (×10–20).
  - Signal has larger tail in E_{ECL} distribution,
    while BG has also larger E_{ECL} value.

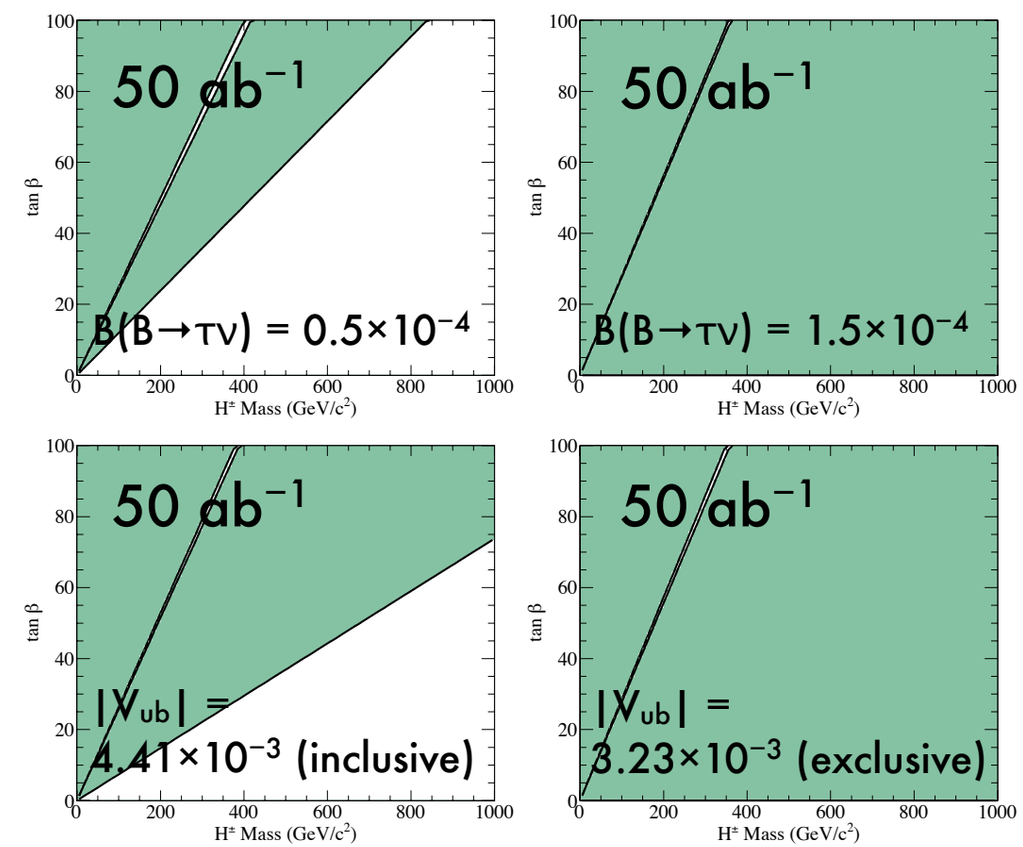
Prospects for Belle II (√ luminosity assumption)

$B \to \tau\nu$

- Expected sensitivity: a few % at 50 ab^{-1}.
- For type II of 2HDM, we show expected exclusion region at 95% C.L.:







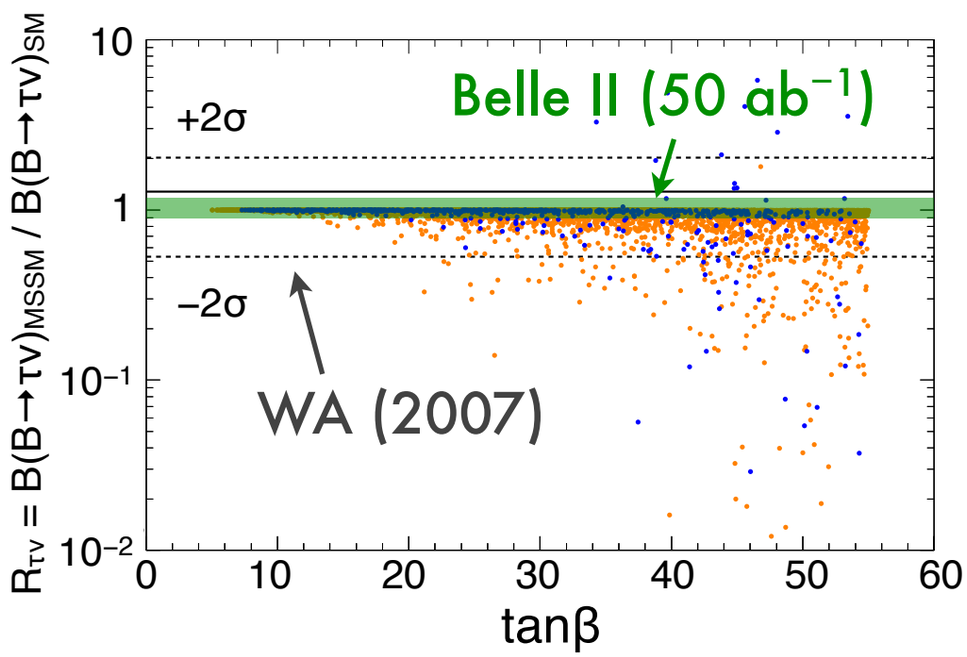
- Central values of $B(B\to\tau\nu) = 1\times10^{-4}$, $f_B = 190$ MeV, and $|V_{ub}| = 4.15\times10^{-3}$ are assumed.
- Relative error of $f_B^2|V_{ub}|^2$ assumed to be comparable to the one of measured $B(B\to\tau\nu)$.

Strong dependence on central values of $B(B\to\tau\nu)$ and $|V_{ub}|$.

Prospects for Belle II (√ luminosity assumption)

$B \to \tau\nu$

- Assuming 2-parameter nonuniversal Higgs model, we expect



H. Baer, V. Barger, and A. Mustafayev, PRD85, 075010

$\mu>0$, m_h = 125±1 GeV, m_t = 173.3 GeV

blue: m_0 < 5 TeV, orange: m_0 < 20 TeV

$B \to \mu\nu$, $e\nu$

- 5σ observation expected for $B(B\to\mu\nu)_{SM}$ at ~10 ab^{-1}.
- $\mathcal{O}(10^{-8})$ sensitivity at 50 ab^{-1}.

Interesting to compare with $B\to\tau\nu$.

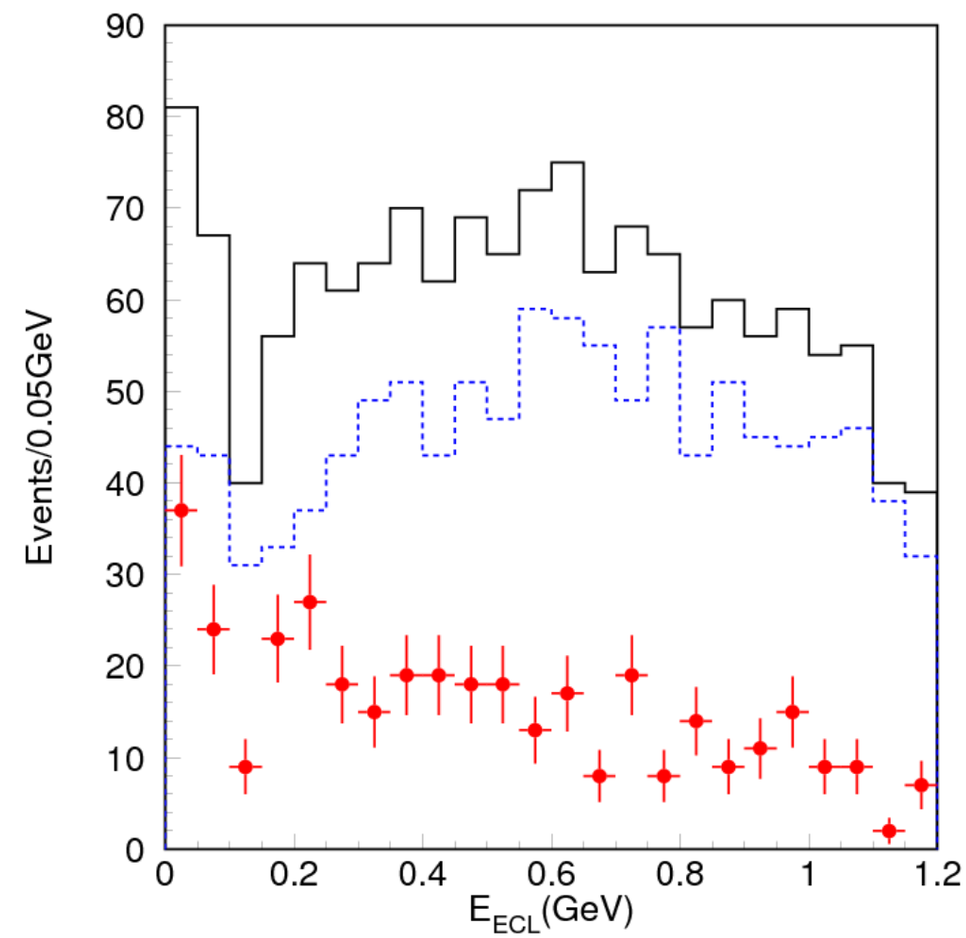
Summary

- $B \to l\nu$ ($l = \tau, \mu, e$) is a good probe for constraining new-physics models.
- Update on hadronic tag from Belle in summer 2012.
- All results are consistent with SM within the errors.
- Constraint on charged Higgs (Type II of 2HDM) discussed.
- Strong relation with f_B and $|V_{ub}|$.
- One of the main topics at Belle II.
  - Sensitivity % level for $B \to \tau\nu$ and better than SM expectation for $B \to \mu\nu$.

Backup slides

K_L veto

- Background rejection using K_L is introduced.
- Effective to reduce peaking backgrounds.
- Improves the statistical significance by about 5%.



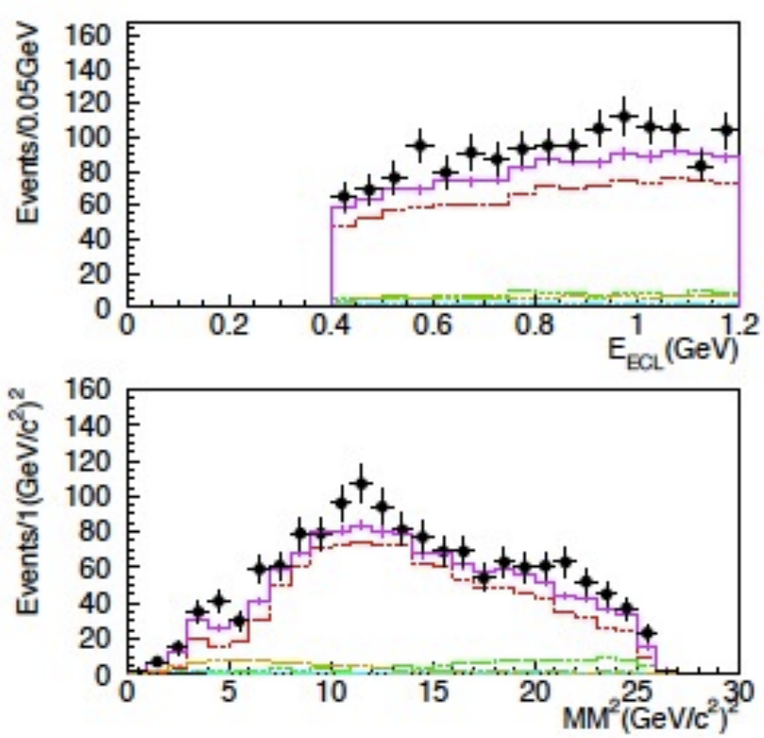
B^0-tagged total
without reconstructed K_L
with reconstructed K_L

K_L veto

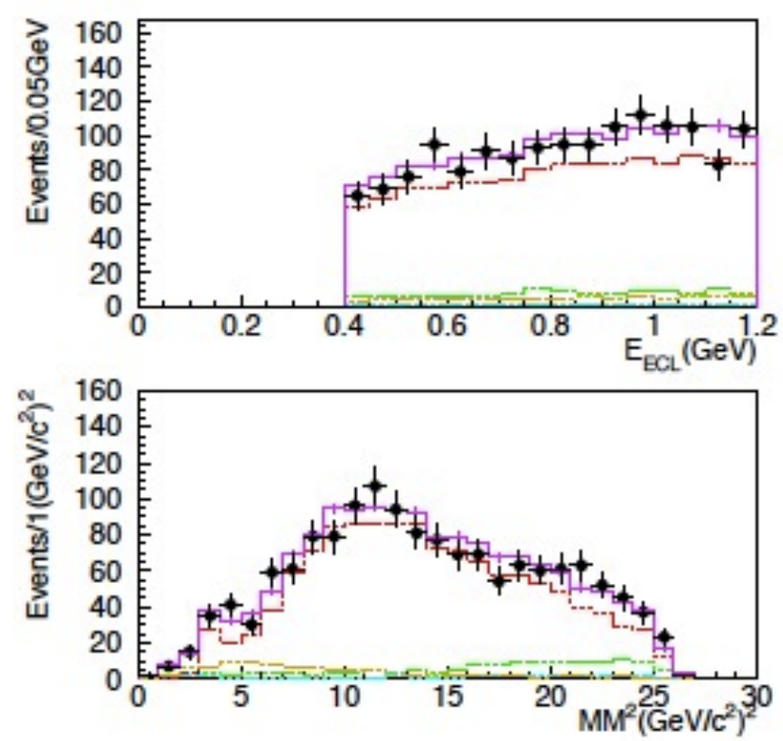
- Efficiency difference in data and MC calibrated by $D^0 \to \Phi K_S$, $\Phi \to K_S K_L$ (normalized by $\Phi \to K^+K^-$).
- Validity checked using $B^0 \to D^{*-}\pi^+$, $D^{*-} \to D\pi^-$, $D \to K_L\pi^0$.

Check done also for $B \to \tau\nu$ BG in E_{ECL} sideband data.

w/ K_L veto, w/o K_L veto efficiency correction

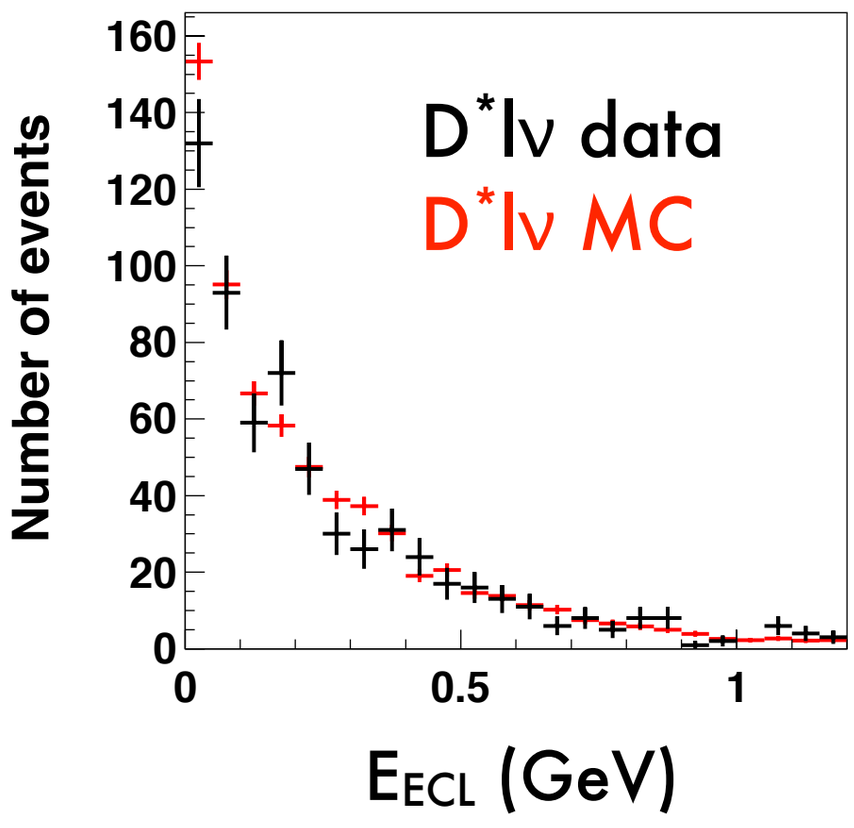


w/ K_L veto, w/ K_L veto efficiency correction

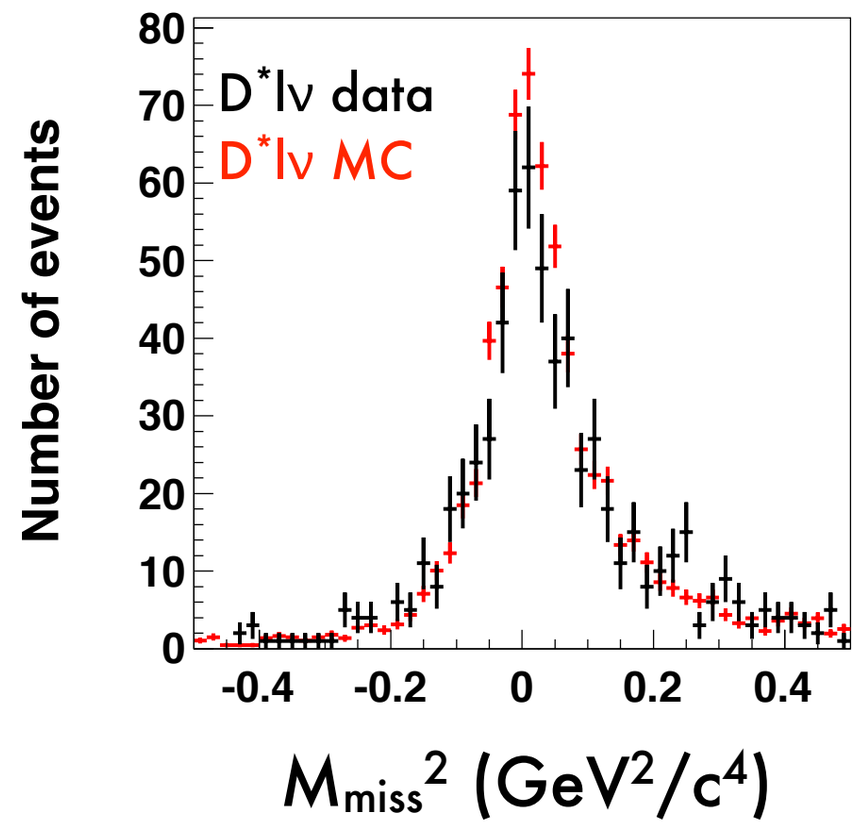


Signal PDFs for E_{ECL} and M_{miss}^2

Signal PDF for E_{ECL} is checked using $D^*l\nu$ control sample.

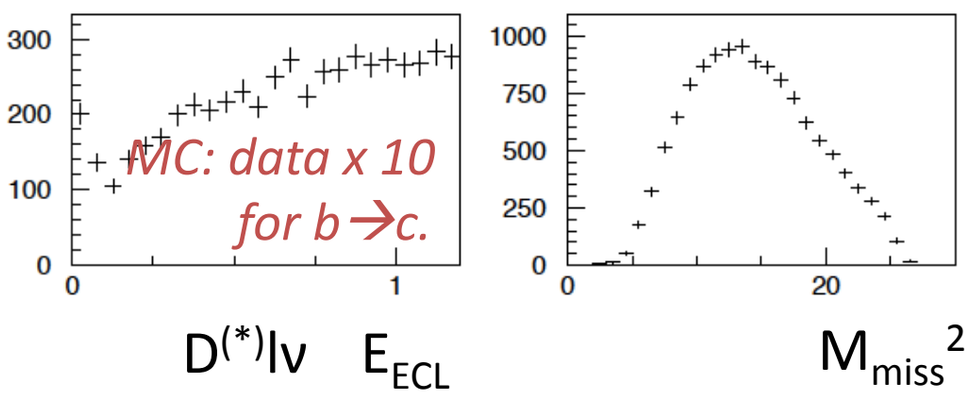


Signal PDF for M_{miss}^2 is affected by momentum resolutions.
Since M_{miss}^2 for $B \to \tau\nu$ has wide distribution, do not apply correction.

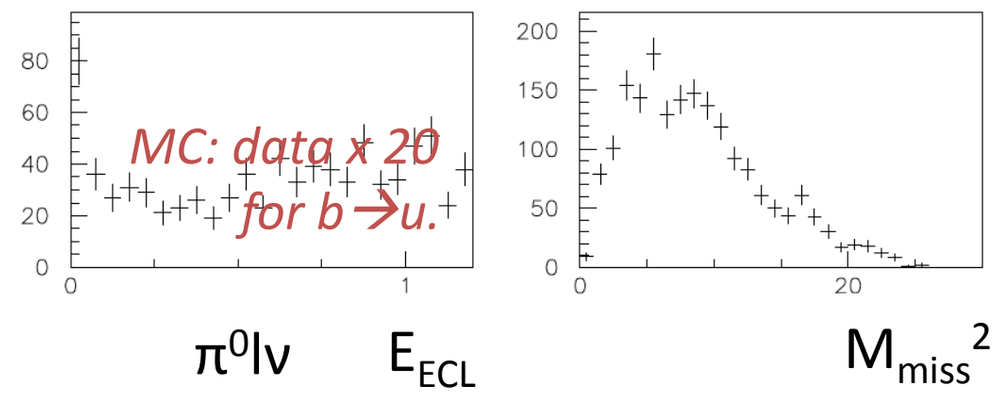


Peaking backgrounds

- At least one of E_{ECL} and M_{miss}^2 distributions have difference from signal. Result is less sensitive to peaking backgrounds.
- If BR is known, error of BR and MC statistics in Syst.

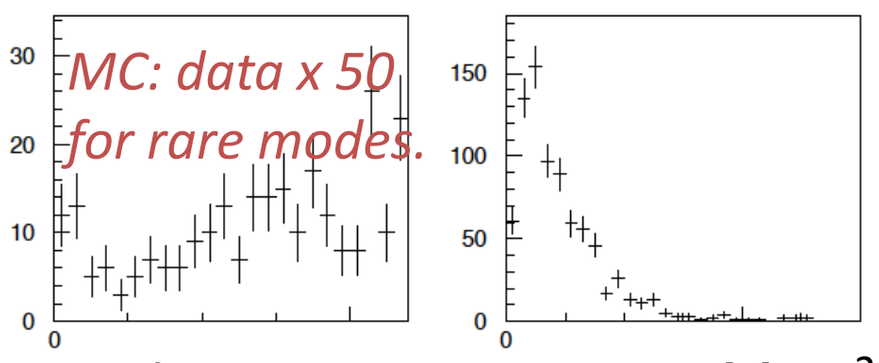


$D^{(*)}l\nu$ E_{ECL} M_{miss}^2

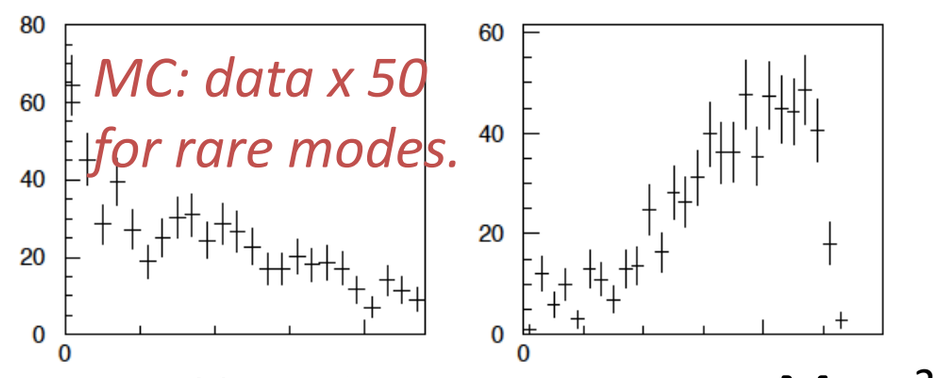


$\pi^0 l\nu$ E_{ECL} M_{miss}^2

- If BR is not known, assume SM value in the nominal fit. SM value ±50% and MC statistics in Syst.



$l\nu\gamma$ E_{ECL} M_{miss}^2



$X_s\nu\nu$ E_{ECL} M_{miss}^2

Systematic uncertainties

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

Source	$\mathcal{B}$ syst. error (%)
Signal PDF	4.2
Background PDF	8.8
Peaking background	3.8
B_{tag} efficiency	7.1
Particle identification	1.0
π^0 efficiency	0.5
Tracking efficiency	0.3
τ branching fraction	0.6
MC efficiency statistics	0.4
K_L^0 efficiency	7.3
$N_{B^+B^-}$	1.3
Total	14.7

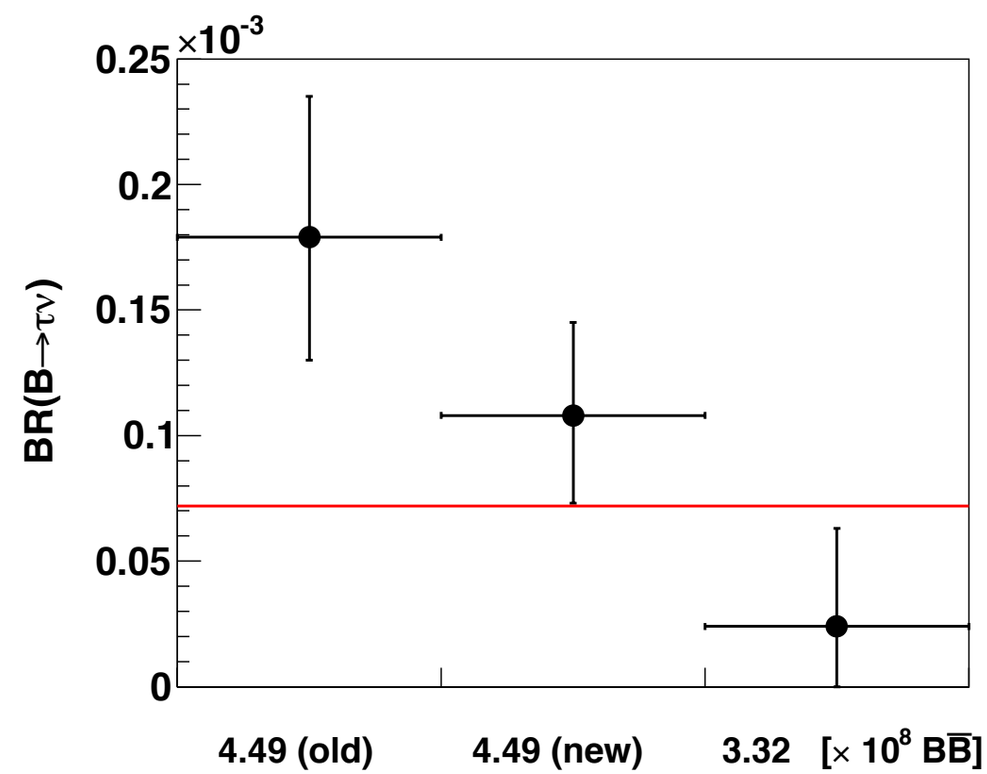
- Uncertainties due to background PDFs are estimated by varying the background yields by BR and MC-statistics errors.
- Uncertainties due to tag efficiency and K_L veto are estimated by using a clean control sample $B \to D^* l \nu$.

(l = e or μ)

Comparison with the previous hadronic-tag result

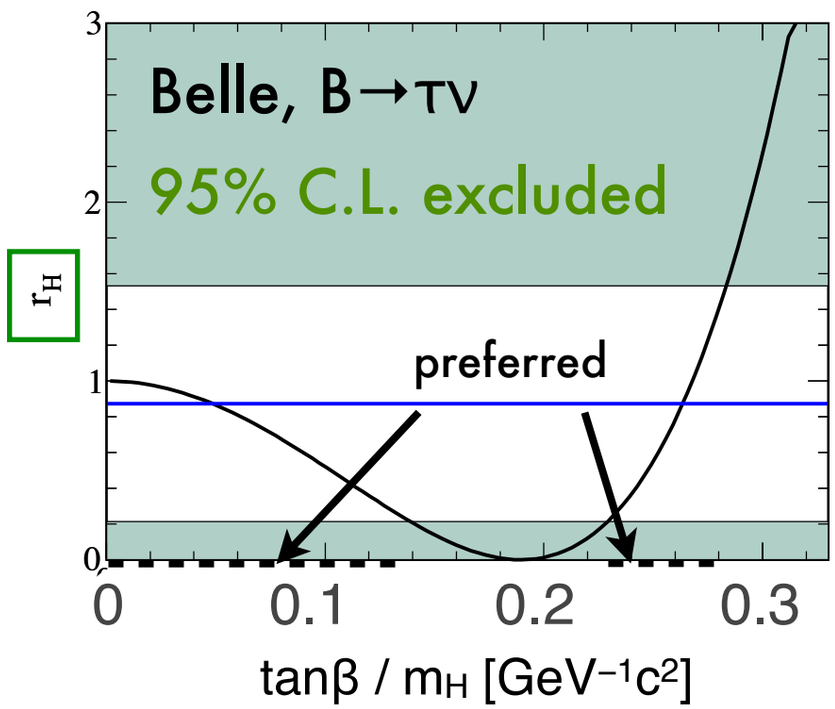
	PRL 97 (2006)	This analysis	
Tag	Hadronic tag	Hadronic tag (new)	
Number of $B\overline{B}$ events ($\times 10^8$)	4.49	4.49	3.22
Efficiency ($\times 10^{-4}$)	3.0	11.2	11.2
Signal yield	$24.1^{+7.6}_{-6.6}$	$54.1^{+18.8}_{-17.4}$	$8.6^{+14.0}_{-12.4}$
$\mathcal{B}(B^- \to \tau^- \overline{\nu}_\tau)$ ($\times 10^{-4}$)	$1.79^{+0.56}_{-0.49}$	$1.08^{+0.37}_{-0.35}$	$0.24^{+0.39}_{-0.34}$

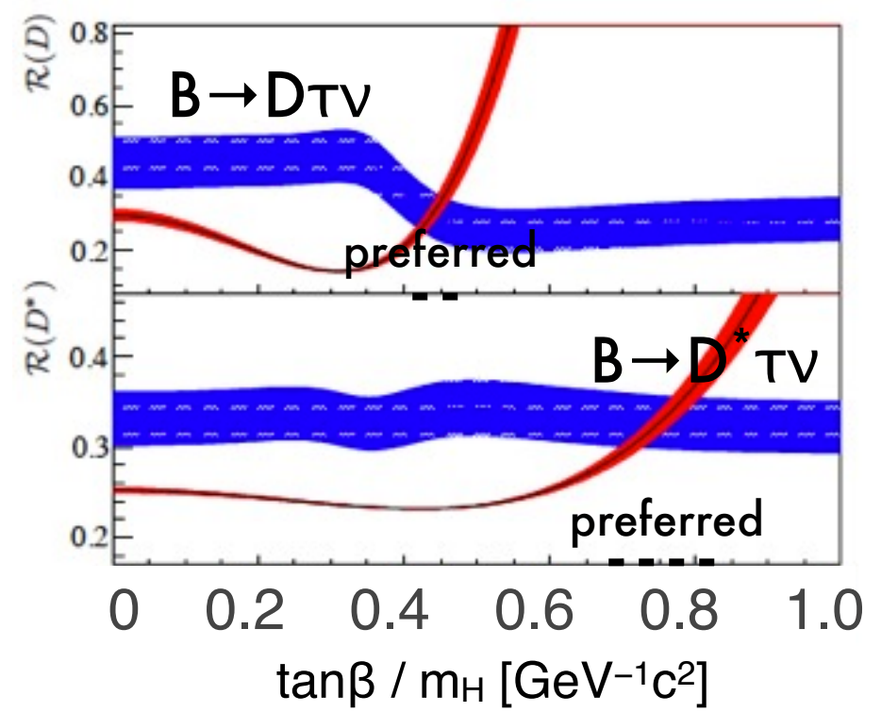
- New analysis is based on improved tag, loose event selection, and reprocessed data.
- Most of the data after the selection are independent from old analysis.
- Assuming that all events in old analysis are included in new analysis, the remaining data sample in $N_{BB} = 4.49 \times 10^8$ provides BR ~ $(0.6 \pm 0.4) \times 10^{-4}$ (1.9σ from old result).



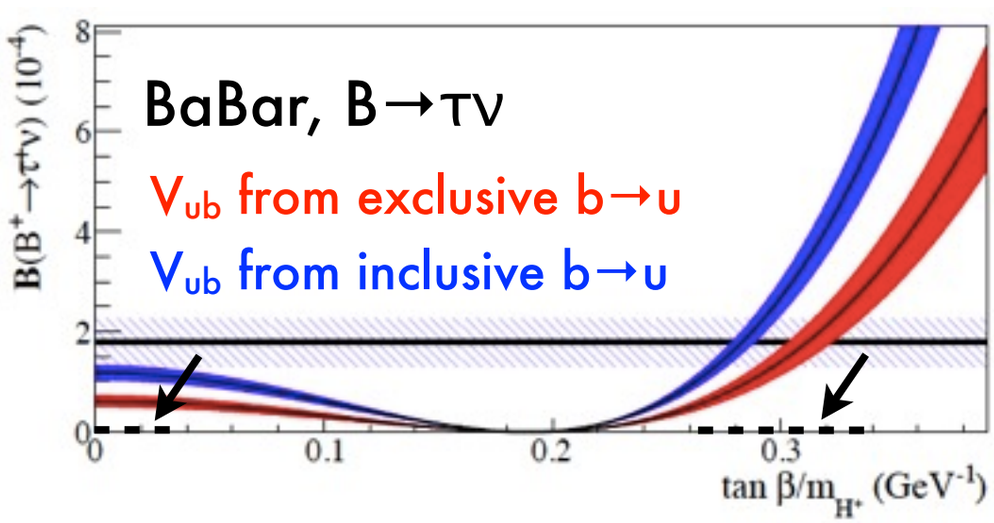
Comparison with $B \to D^{(*)}\tau\nu$

Compare constraints on $\tan\beta/m_H$ assuming Type II.





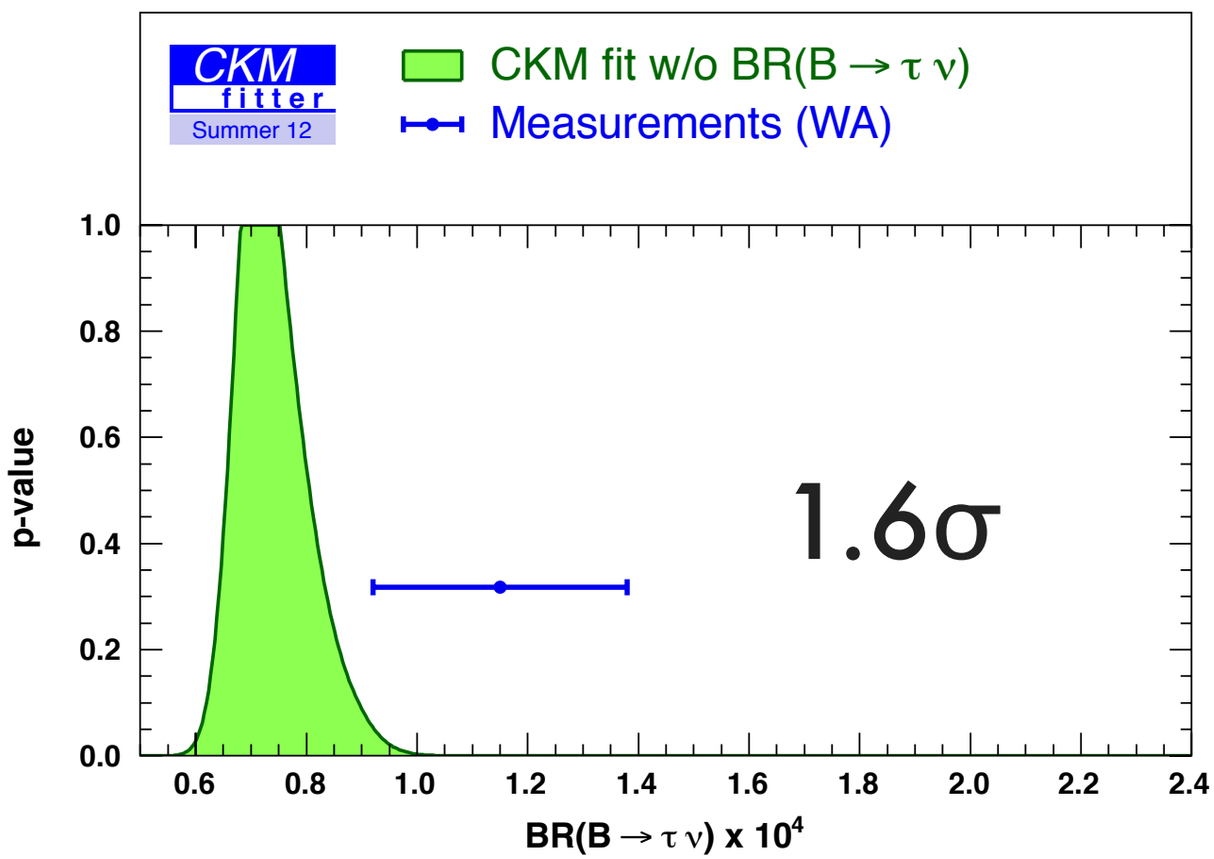
BaBar, arXiv:1205.5442

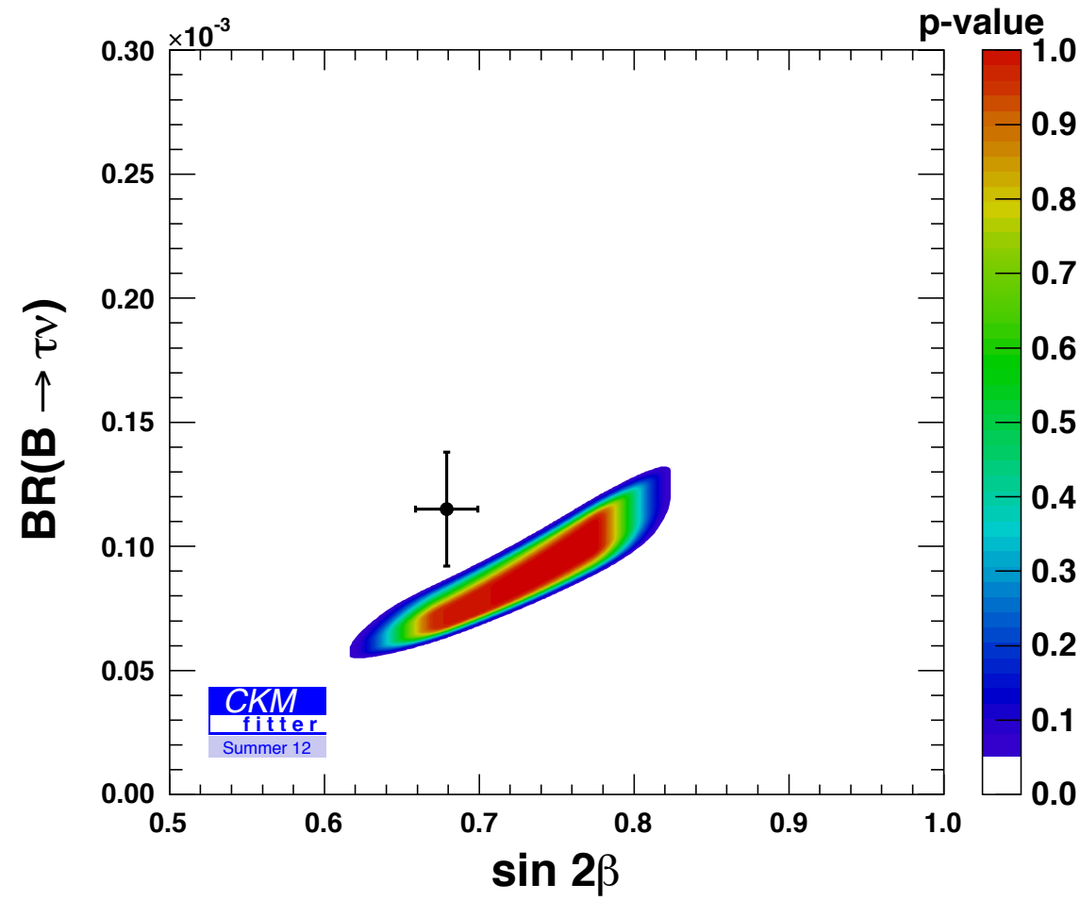


$B \to \tau\nu$, $D\tau\nu$, and $D^*\tau\nu$ prefer different regions of $\tan\beta/m_H$.

Type II disfavored...?
Need further studies.

Comparison with CKM fit (ICHEP2012)





NUHM2

H. Baer, V. Barger, and A. Mustafayev, PRD85, 075010