# B decays with neutrinos

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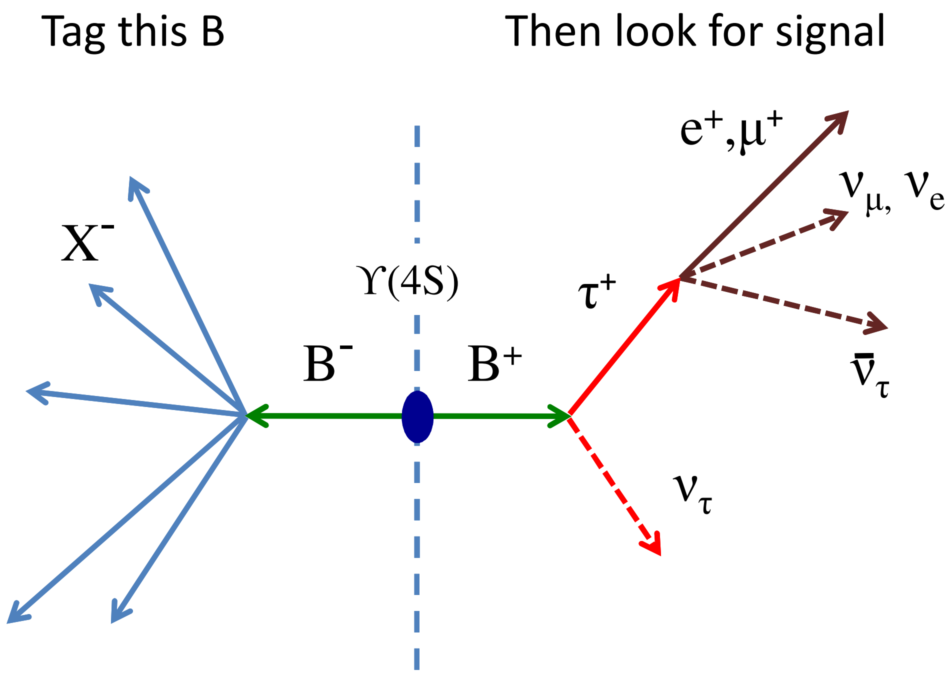
# Outline

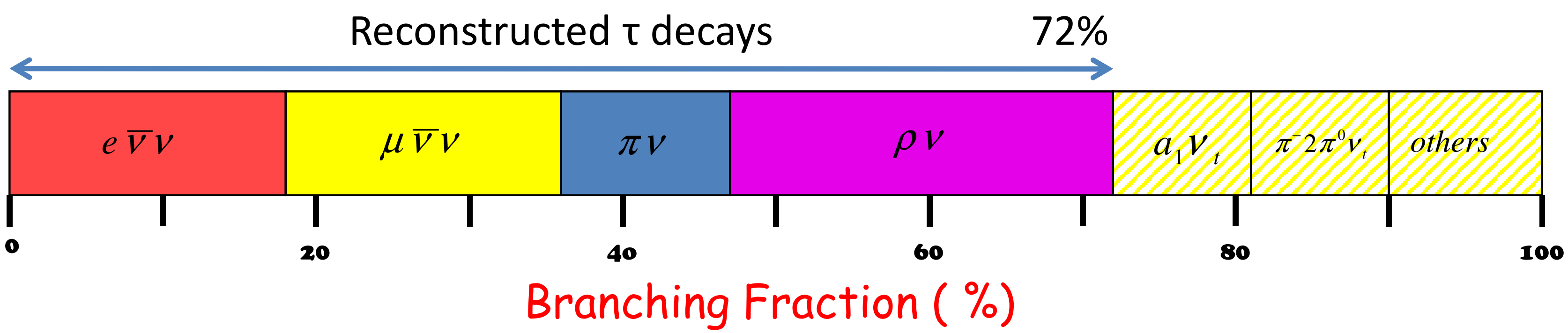
- Description of the tagging method
- Leptonic B decays
  - Experimental status
  - Implications on NP models (Charged Higgs search)
  - Extrapolation of Super Flavour Factories sensitivity
- $b \to s \nu \nu$ decays
  - Experimental status
  - Implication on NP models
  - Extrapolation of Super Flavour Factories sensitivity

# Tagging method

# Tagging method

- Weak signal signature
  - Decay with missing momentum (many neutrinos in the final state)
  - Lack of kinematics constraints in final state
- background rejection improved identifying the companion B
- Look for signal in the rest of the event
  - Expect to find nothing more than visible signal decay products and no extra activity in the calorimeter

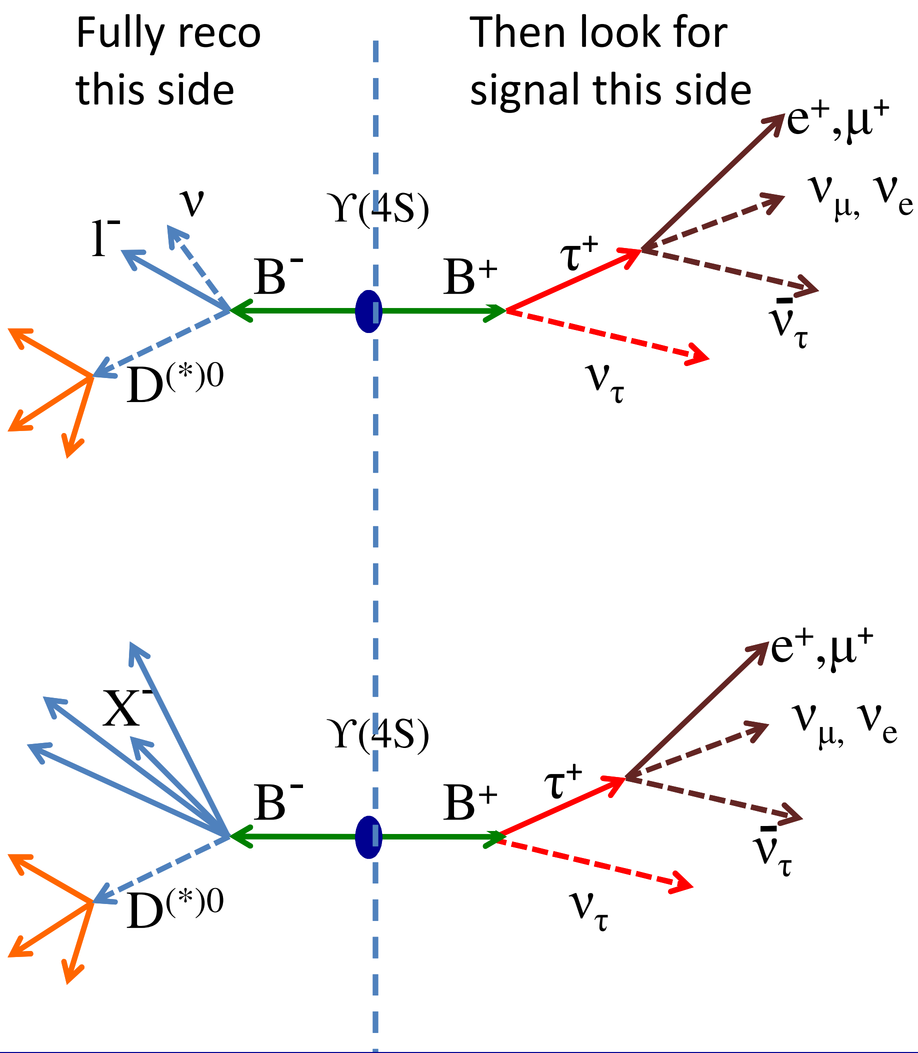


# Fully reconstructed hadronic and semileptonic modes

- Semileptonic B decays
  - $B \to D^* l \nu$
  - PRO: Higher efficiency $\varepsilon_{tag} \sim 1.5\%$
    CON: more backgrounds, B momentum unmeasured

- Hadronic B decays with charm
  $B^+ \to D^{(*)0} X^+$ or $B^0 \to D^{(*)+} X^-$
  - X is a charged system of hadrons among ($\pi$,K,$\pi^0$,$K_s$) up to 5 charged particles and 2 neutrals
  - PRO: cleaner events,
    B momentum reconstructed
    CON: smaller efficiency $\varepsilon_{tag} \sim 0.15\%$



# Fully reconstructed hadronic and semileptonic modes

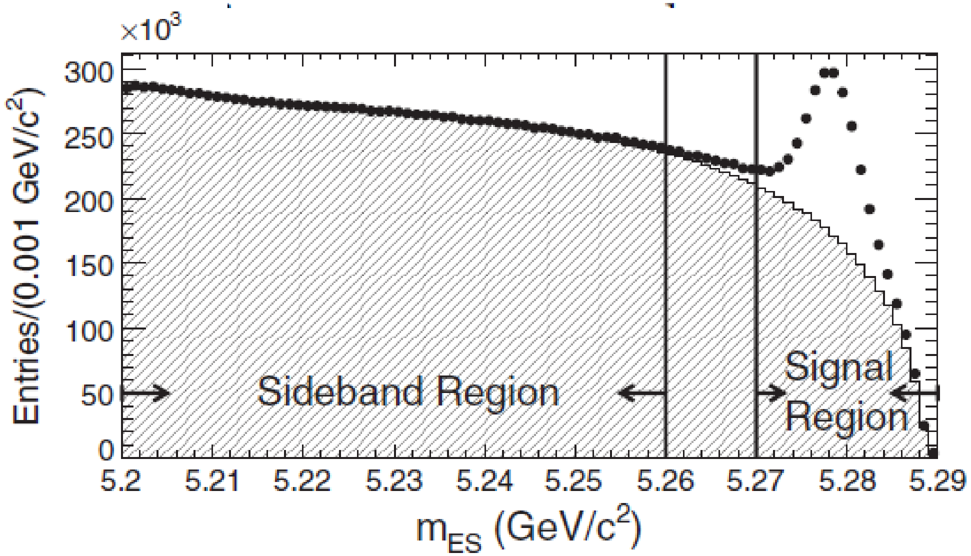
**Hadronic tags:**

Full reconstruction of the B decay chain.

Requirements on the quality of the tag are analysis dependent

Separate the mis-reconstructed tags from correct (peaking) tags in data

$$m_{ES} = \sqrt{s/4 - p_B^2}$$

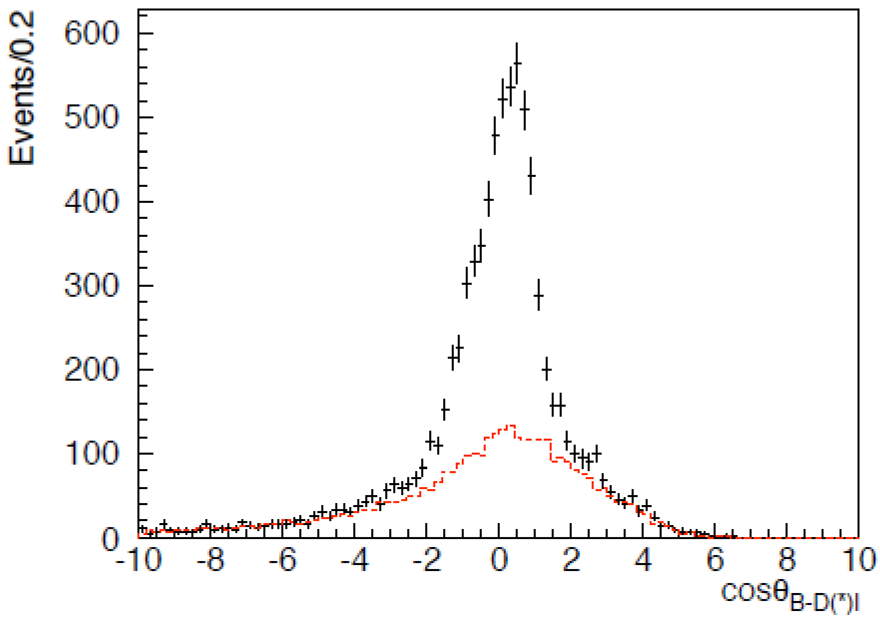



**Semileptonic tags:**

Recontruct the D-l pair (Y)

Kinematics and known B meson energy determine the angle between B and Y.

$$\cos\theta_{B,Y} = \frac{2E_B E_Y - m_B^2 - m_Y^2}{2|\vec{p}_B||\vec{p}_Y|}$$

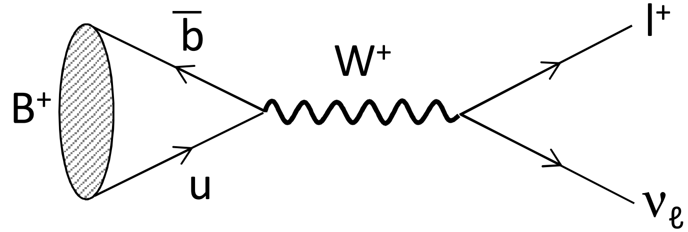


# Leptonic B decays

# Leptonic B decays

- $B \rightarrow l\nu$ very clean theoretically. The only uncertainty in the B decay constant $f_B$

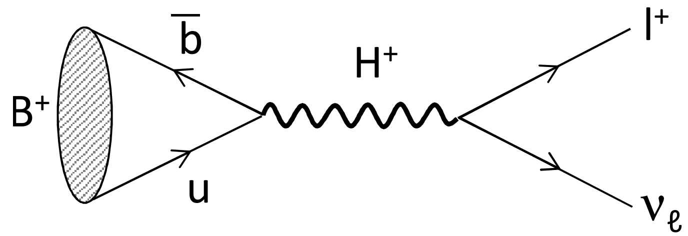
$$\mathcal{B}(B \to l\nu) = \frac{G_F^2 m_B}{8\pi} m_l^2 (1 - \frac{m_l^2}{m_B^2})^2 f_B^2 |V_{ub}|^2 \tau_B$$




- Interesting probe of physics beyond the SM, since also a charged Higgs can mediate the decay

$$\mathcal{B}(B \to l\nu)_{2HDM} = \mathcal{B}(B \to l\nu)_{SM} \times (1 - tan^2\beta \frac{m_B^2}{m_H^2})^2$$

$$\mathcal{B}(B \to l\nu)_{SUSY} = \mathcal{B}(B \to l\nu)_{SM} \times (1 - \frac{tan^2\beta}{1 + \epsilon_0 tan\beta} \frac{m_B^2}{m_H^2})^2$$




- $B \rightarrow \tau\nu$ used in global UT fits. $B \rightarrow \mu\nu$ out of reach of current B-factories
- Current measurements already exclude regions of $M_H$ – tan β plane

# Tipical signal selection and fit strategy

- Exploit kinematics and topology of in the signal side
  - Single charged tracks passing particle identification criteria
  - Requirement on CMS momentum for 1 prong modes
  - More constraints for $\tau \to \pi\pi^0\nu$

- Most discriminating variable residual energy in the calorimeter ($E_{extra}$)
  - Defined as the total energy of clusters passing a minimum energy requirement
  - Used in a maximum likelihood fit to determine the branching fraction

- $E_{extra}$ distribution validated with the use of double-tagged events

- Simultaneous fit of the BF to $E_{extra}$

$$\mathcal{L}_k = e^{-(n_{s,k}+n_{b,k})} \prod_{i=1}^{N_k} \left\{ n_{s,k}\mathcal{P}_k^s(E_{i,k}) + n_{b,k}\mathcal{P}_k^b(E_{i,k}) \right\}$$

$$n_{s,k} = N_{B\overline{B}} \times \epsilon_k \times BF$$

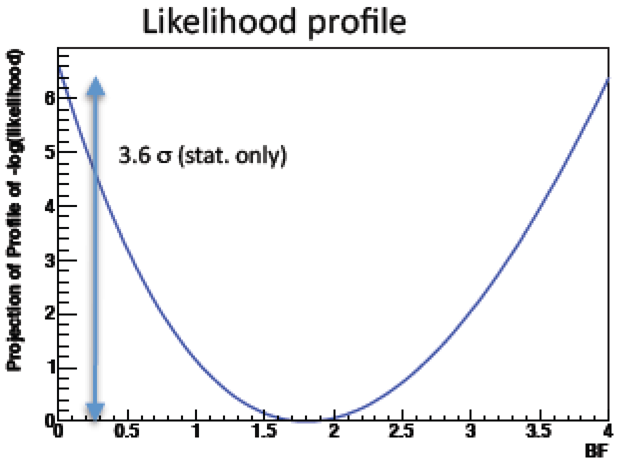
# Branching ratio with hadronic tags from BaBar

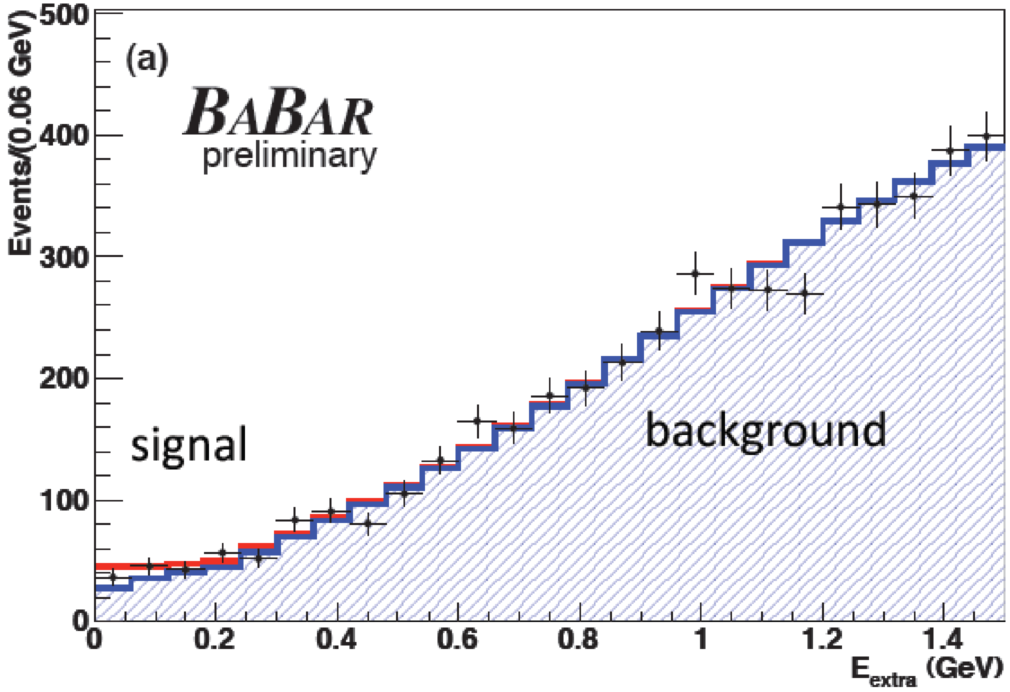
- Combinatorial background estimated from data, $B^+$ background shape from MC
- Fit to $E_{extra}$ distribution show an excess of events consistent with null hypothesis at 3.3 σ only

arXiv:1008.0104[hep-ex]
468 M B pairs

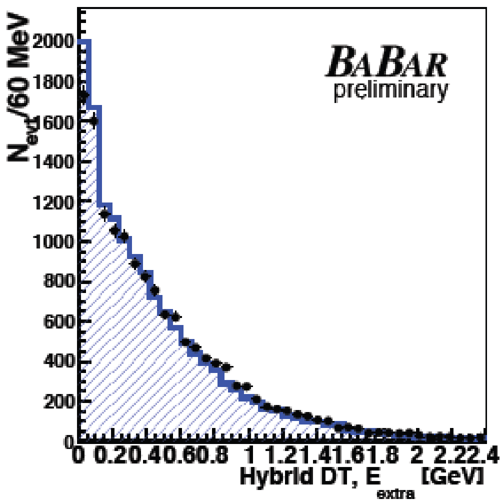
PRELIMINARY

$$\mathcal{B}(B \to \tau\nu) = (1.80^{+0.57}_{-0.54} \pm 0.26) \times 10^{-4}$$




MC modelling of signal $E_{extra}$ PDF checked with double tags



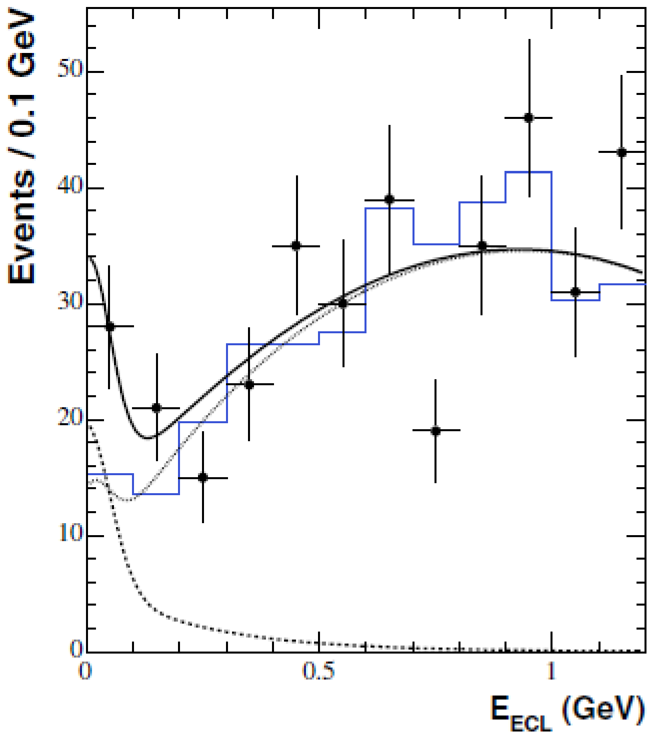
# Branching ratio with hadronic tags from Belle

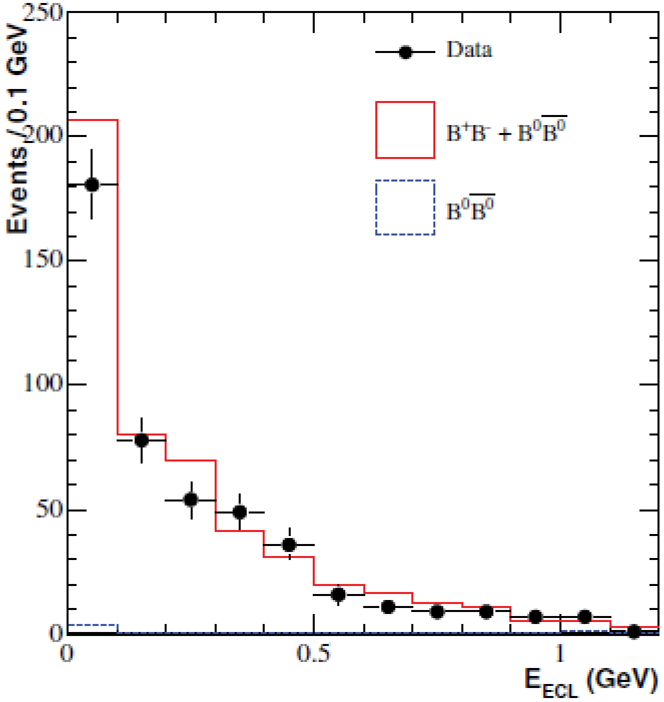
- Combinatorial background estimated from data
- Polynomial PDF for background, plus a peaking background form MC. Gaussian PDF for signal
- Excess of events excludes null hypothesis at 3.3 σ

Phys. Rev. Lett. 97, 251802 (2006)
449 M B pairs

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

MC modelling of $E_{extra}$ checked with double tags



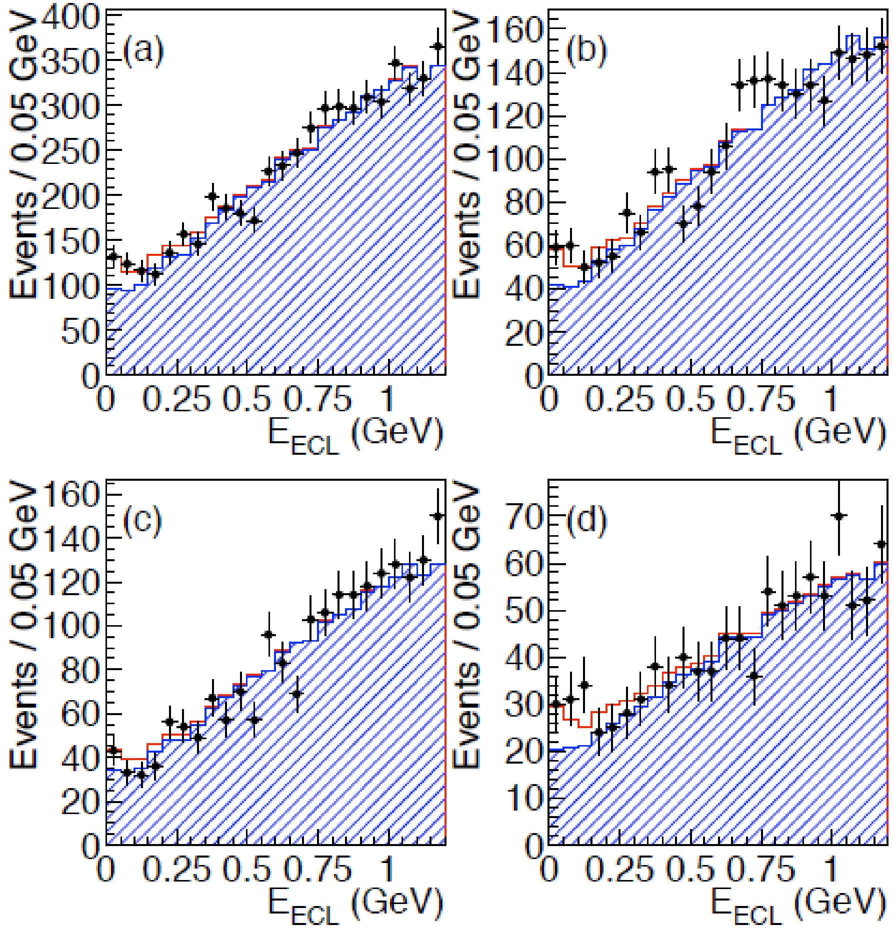



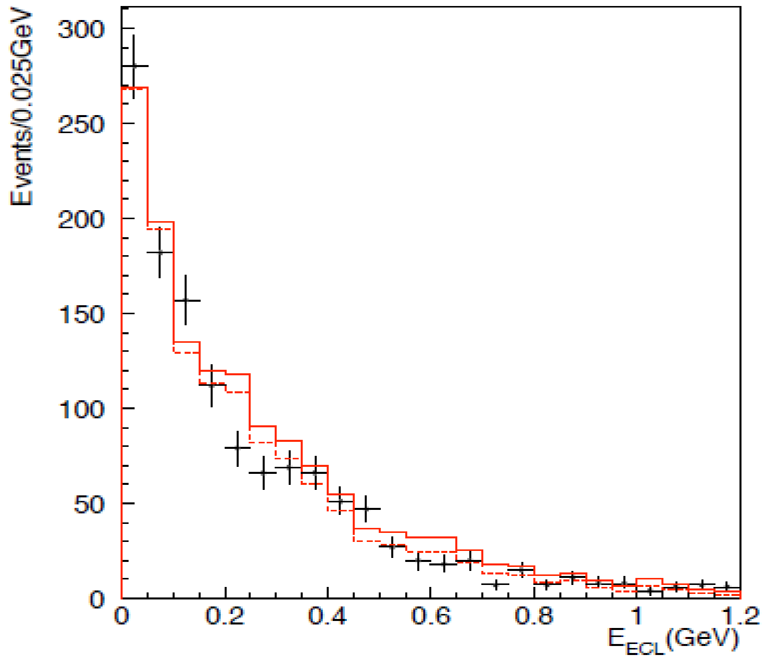
# Branching ratio with semileptonic tags from Belle

- Excluding null hypothesis at 3.6 σ

Phys. Rev. D 82,071101(R) (2010)
657 M B pairs

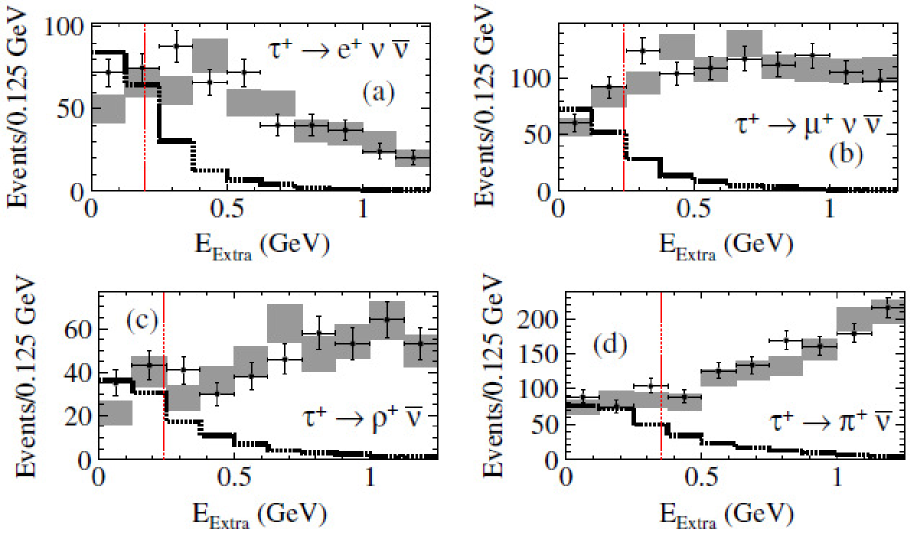
$$\mathcal{B}(B \to \tau\nu) = (1.54^{+0.38}_{-0.37}(\text{stat.})^{+0.29}_{-0.31}) \times 10^{-4}$$




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

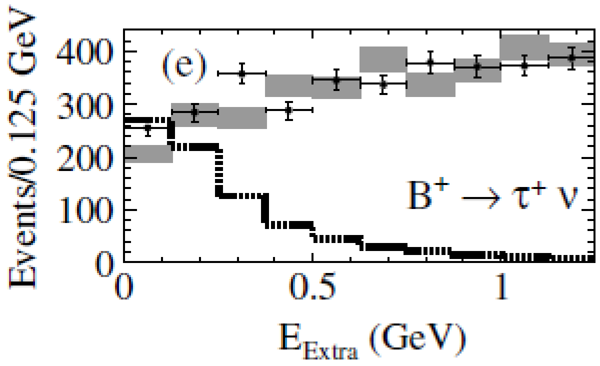
# Branching ratio with semileptonic tags from BaBar




Phys. Rev. D 81,051101(R) (2010)

459 M B pairs

Excludes null hypothesis at 2.3 σ




| Mode | $\mathcal{N}_{bg}^{data}$ | $N_{obs}$ | Branching fraction ($\times 10^{-4}$) |
|---|---|---|---|
| $\tau^+ \to e^+ \nu_e \bar{\nu}_\tau$ | $81 \pm 12$ | 121 | $(3.6 \pm 1.4)$ |
| $\tau^+ \to \mu^+ \nu_\mu \bar{\nu}_\tau$ | $135 \pm 13$ | 148 | $(1.3^{+1.8}_{-1.6})$ |
| $\tau^+ \to \rho^+ \bar{\nu}_\tau$ | $59 \pm 9$ | 71 | $(2.1^{+2.0}_{-1.8})$ |
| $\tau^+ \to \pi^+ \bar{\nu}_\tau$ | $234 \pm 19$ | 243 | $(0.6^{+1.4}_{-1.2})$ |
| $B^+ \to \tau^+ \nu_\tau$ | $509 \pm 30$ | 583 | $(1.7 \pm 0.8 \pm 0.2)$ |
| $B^+ \to \mu^+ \nu_\mu$ | $13 \pm 8$ | 12 | $<0.11$ (90% C.L.) |
| $B^+ \to e^+ \nu_e$ | $24 \pm 11$ | 17 | $<0.08$ (90% C.L.) |

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

# Branching fractions summary

BABAR Hadronic tags

$$\mathcal{B}(B \to \tau\nu) = (1.80^{+0.57}_{-0.54} \pm 0.26) \times 10^{-4}$$

arXiv:1008.0104[hep-ex]

BABAR Semi-leptonic tags

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

Phys. Rev. D 81, 051101(R) (2010)

BABAR combined

$$\mathcal{B}(B \to \tau\nu) = (1.76 \pm 0.49) \times 10^{-4}$$

BELLE Hadronic tags

$$\mathcal{B}(B \to \tau\nu) = (1.79^{+0.56}_{-0.49}(\mathrm{stat.})^{+0.46}_{-0.51}) \times 10^{-4}$$

Phys. Rev. Lett. 97, 251802 (2006)

BELLE Semi-leptonic tags

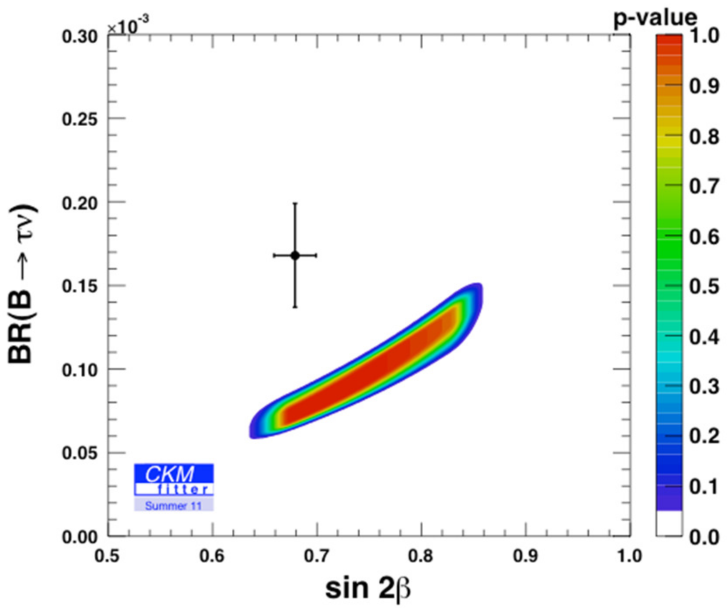
$$\mathcal{B}(B \to \tau\nu) = (1.54^{+0.38}_{-0.37}(\mathrm{stat.})^{+0.29}_{-0.31}) \times 10^{-4}$$

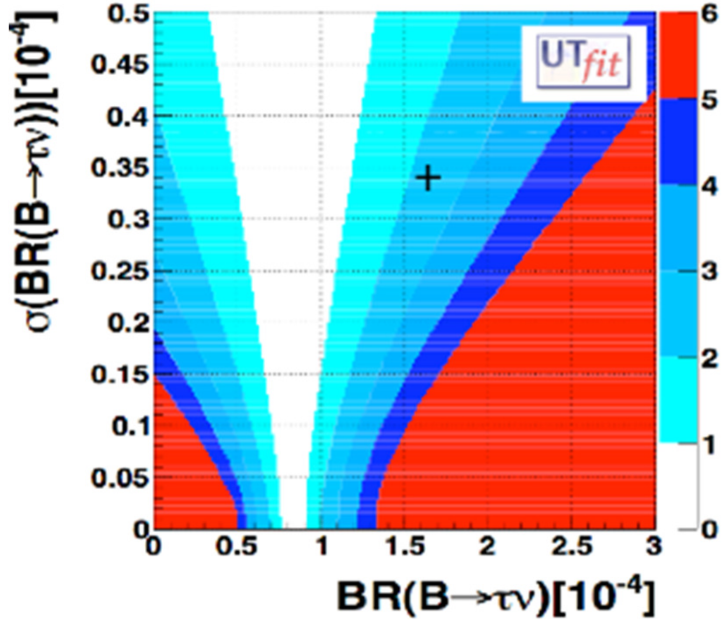
Phys. Rev. D 82, 071101(R) (2010)

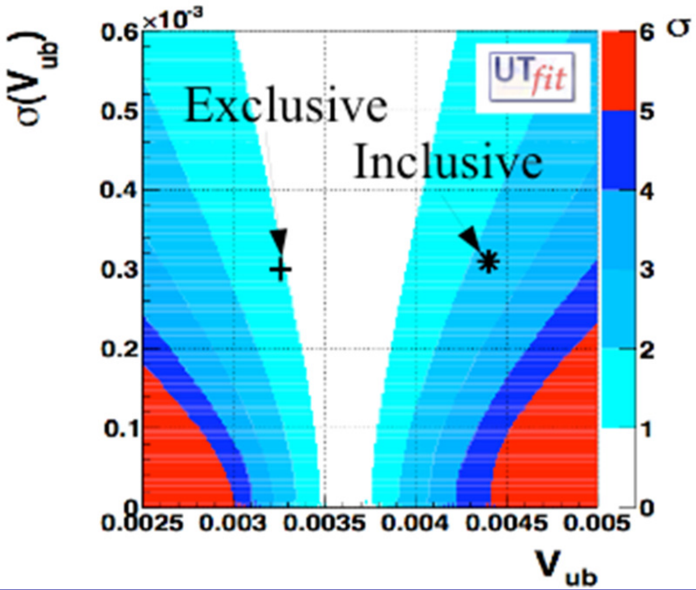
HFAG average: $\mathcal{B}(B \to \tau\nu) = (1.64 \pm 0.34) \times 10^{-4}$

HFAG does not use the 2006 Belle hadronic tag result

# Tensions in the Global Fit

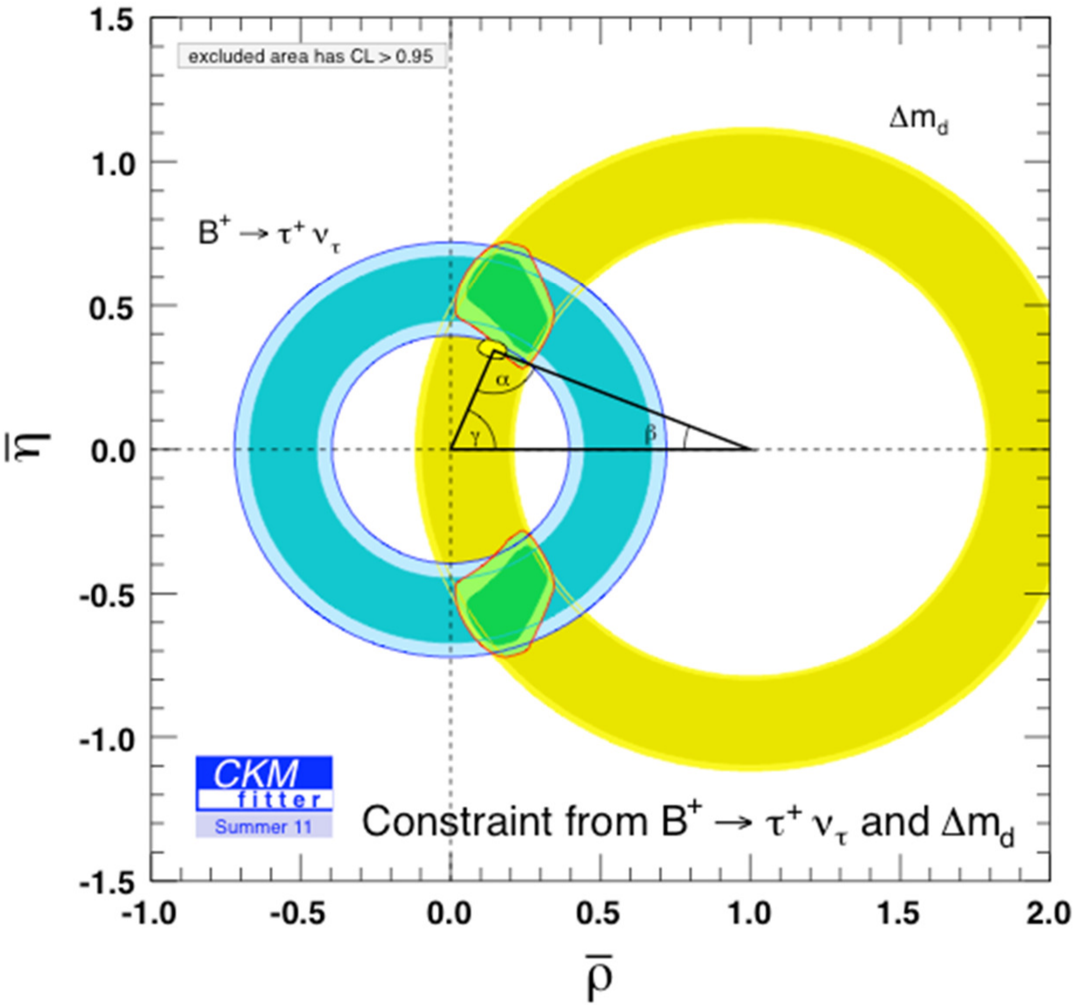


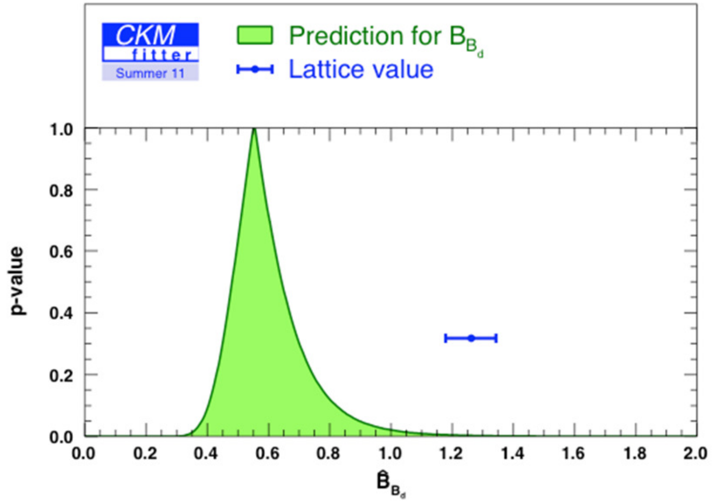




- Despite the striking overall consistency of the UT constraints some measurements show “tensions”
- Statistical fluctuations, unknown systematic uncertainties or hints of New Physics around the corner?

# Combining $B \to \tau\nu$ and $\Delta m_d$




Extract $B_{Bd}$ experimental value from the ratio of $B \to \tau\nu$ and $\Delta m_d$

# B →eν, μν untagged analysis

- Monochromatic e or μ in B rest frame
- NO tag reconstruction but exploit kinematics and and topology of the rest of the event
- No significant signal seen

Phys. Rev. D 79,091101 (2009)
Phys. Lett. B 647 (2007) 67

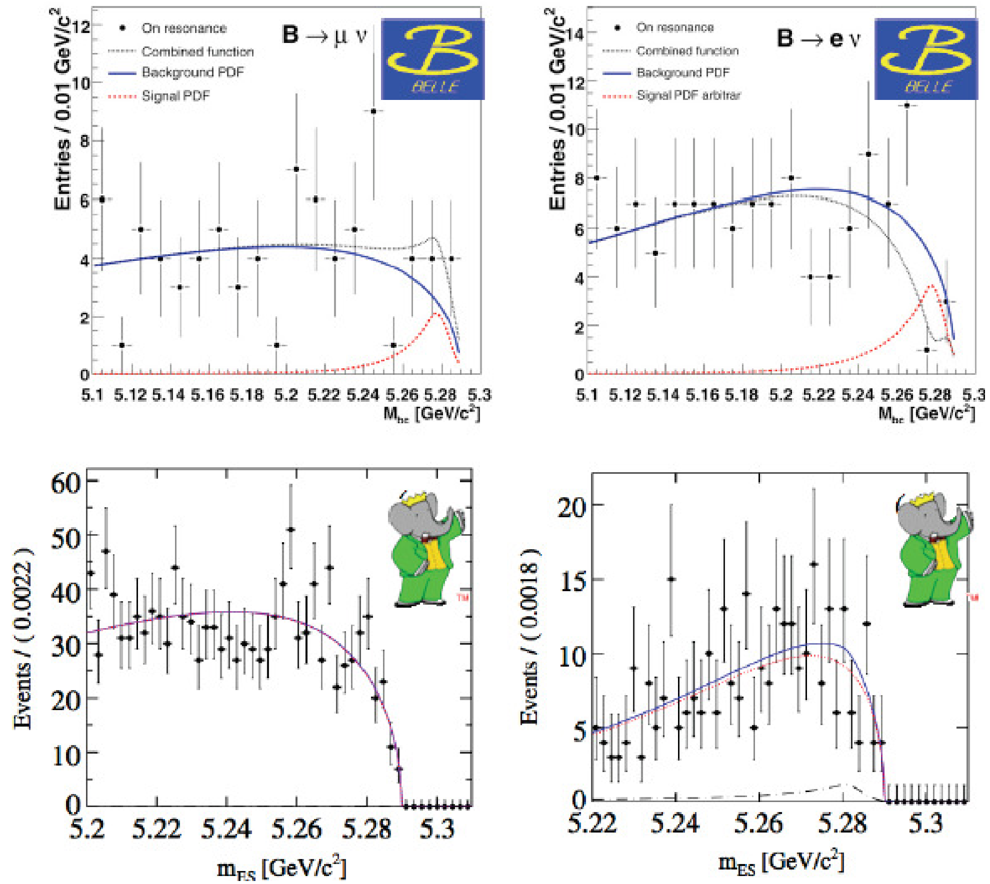
90% C.L. limits:

BF( B → eν ) < 1.9 × $10^{-6}$ BABAR
BF( B → eν ) < 0.98 × $10^{-6}$ BELLE

BF( B → μν ) < 1.0 × $10^{-6}$ BABAR
BF( B → μν ) < 1.7 × $10^{-6}$ BELLE

B (r.o.e.) mass

B →eν    B →μν



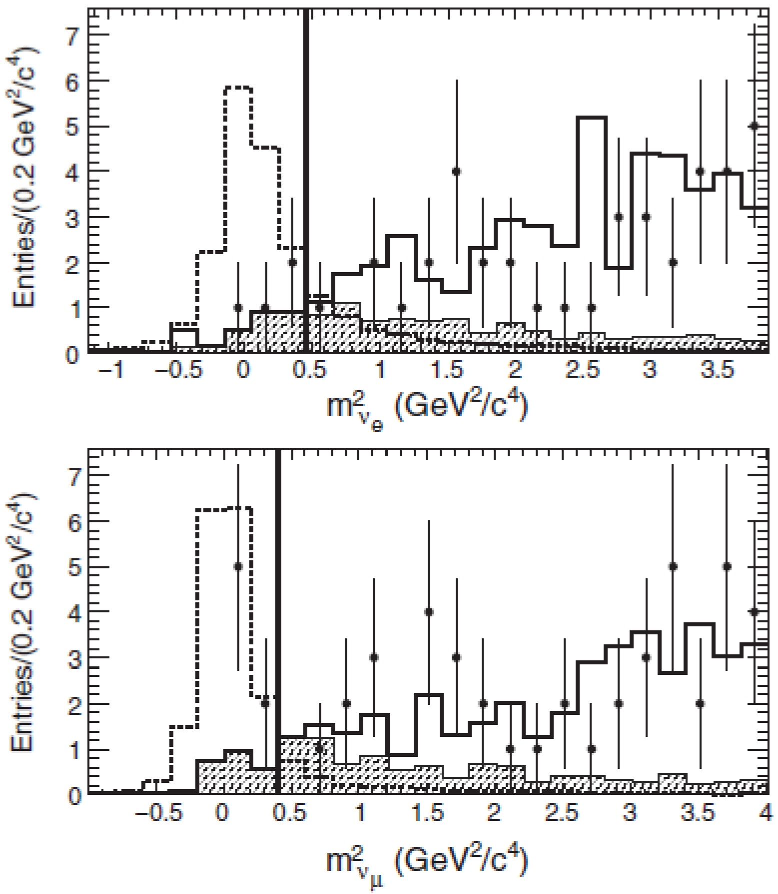
# B → lνγ with hadronic tags from BaBar

- Small excess for muon channel consistent with a 2.1 σ background fluctuation

| | B→eνγ | B→μνγ |
|---|---|---|
| Expected bkg | 2.7 ± 0.3 ±0.4 | 3.4 ± 0.7 ±0.7 |
| Observed events | 4 | 7 |
| Signal efficiency | (7.8 ± 0.1 ±0.3) % | (8.1 ± 0.1 ±0.3)% |
| FC confidence limit | $<17 \times 10^{-6}$ | $<26 \times 10^{-6}$ |
| | $<15 \times 10^{-6}$ | |

Phys. Rev. D 80, 111105 (2009)

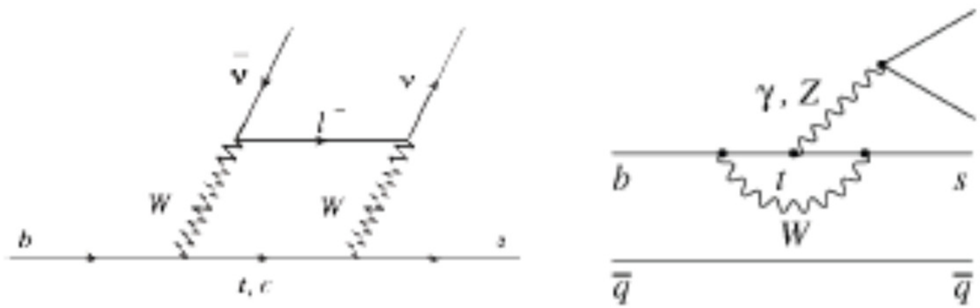
Missing mass



# $B \to K^{(*)}\nu\nu$

# Physics Motivation

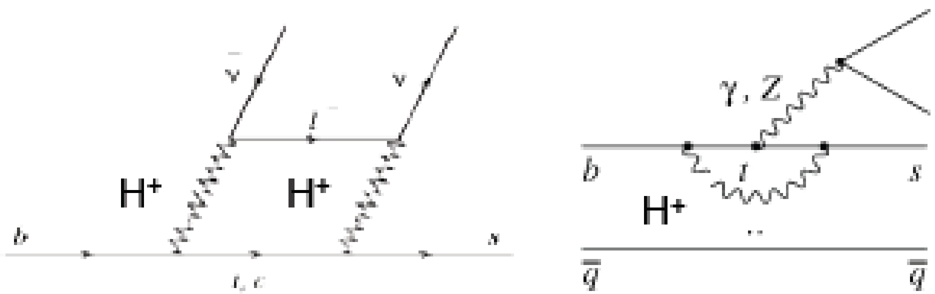
- FCNC b → s transition in the SM by W box or Z penguin




- Small SM branching fraction

BF( $B^+ \to K^+ \nu \nu$ ) ~ $4 \times 10^{-6}$

- 2ν final state make it theoretically cleaner than other b → s modes




- Many new physics models may enhance the BF.

# $B \to h \nu\nu$ experimental measurements

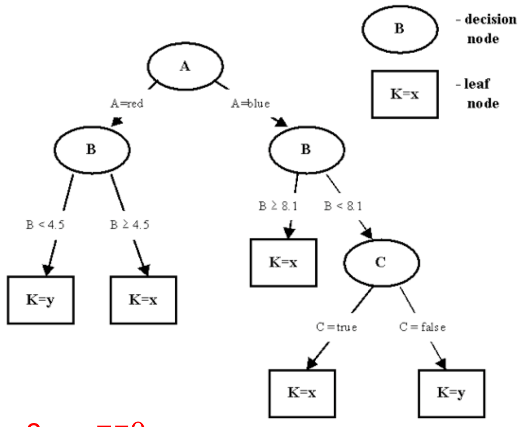
| Mode | BaBar Had tag | BaBar SL tag | Belle Had tag | Belle SL tag |
|---|---|---|---|---|
| $K^+ \nu \nu$ | ✓ | ✓ | ✓ | |
| $K_S \nu \nu$ | | ✓ | ✓ | |
| $K^{*+} \nu \nu$ | ✓ | ✓ | ✓ | |
| $K^{*0} \nu \nu$ | ✓ | ✓ | ✓ | |
| $\pi^+ \nu \nu$ | | | ✓ | |
| $\pi^0 \nu \nu$ | | | ✓ | |
| $\rho^+ \nu \nu$ | | | ✓ | |
| $\rho^0 \nu \nu$ | | | ✓ | |
| $\phi \nu \nu$ | | | ✓ | |

- Babar uses both tags – Belle hadronic tags only
- Belle searched also for other non-kaonic modes

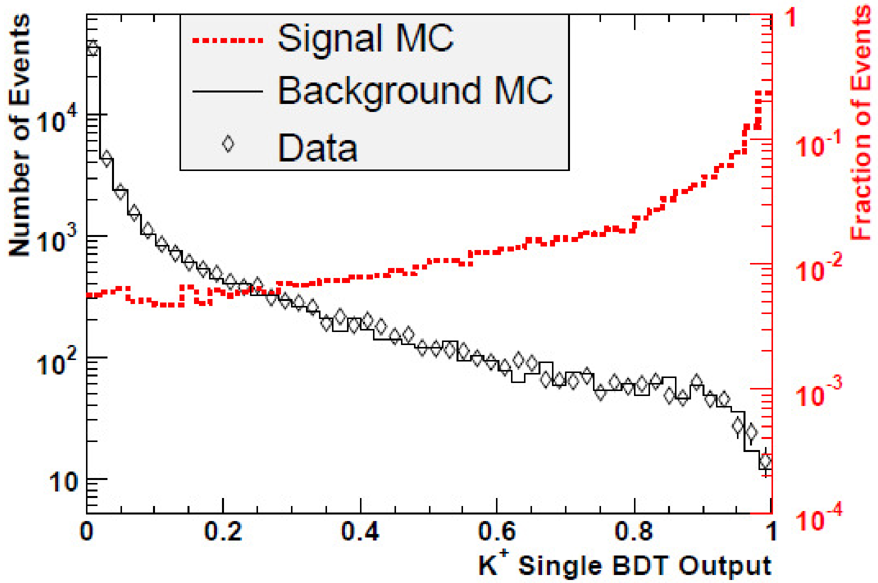
# $B^+ \to K^+ \nu \nu$ and $B^0 \to K_S \nu \nu$ with SL tags from BaBar

Phys. Rev. D 82, 112002 (2010)
459 M B pairs

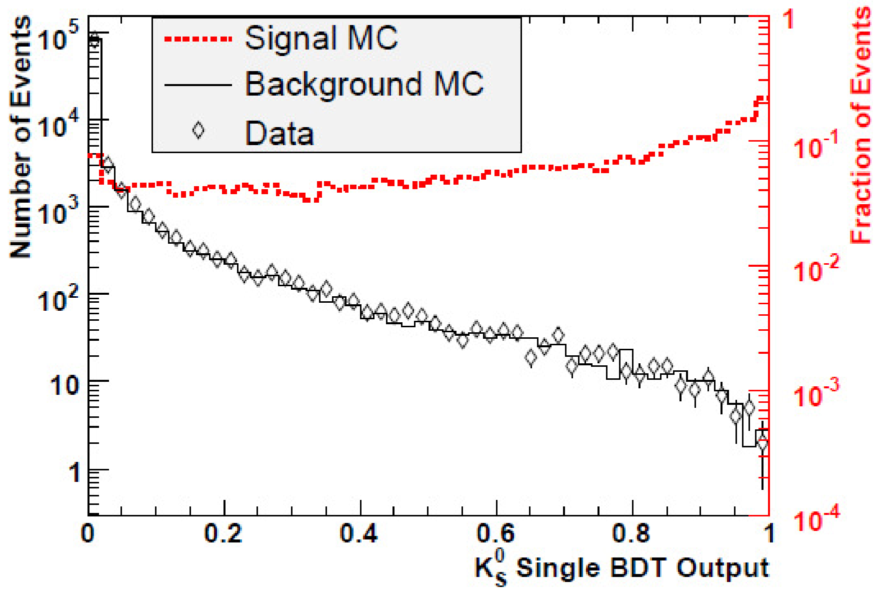
- Multivariate analysis using bagged decision trees
- Trained on MC simulated signal and background events
- 26 ($K^+$) and 38($K_S$) variables exploiting missing energy, event shape, kinematics and quality of the tag reconstruction




$B^+ \to K^+ \nu \nu$




$B^0 \to K^0 \nu \nu$

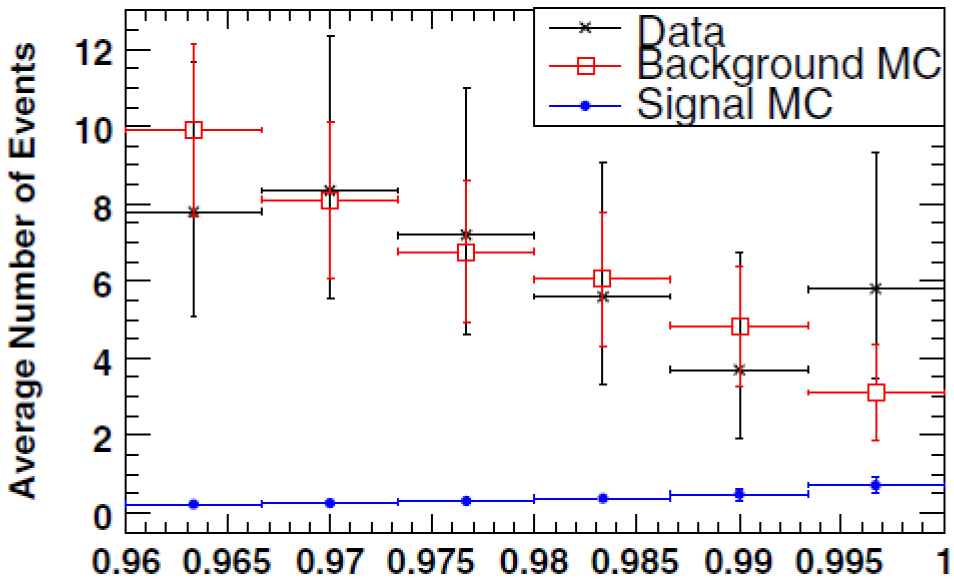


# $B^+ \to K^+ \nu\nu$ and $B^0 \to K_S \nu\nu$ with SL tags from BaBar

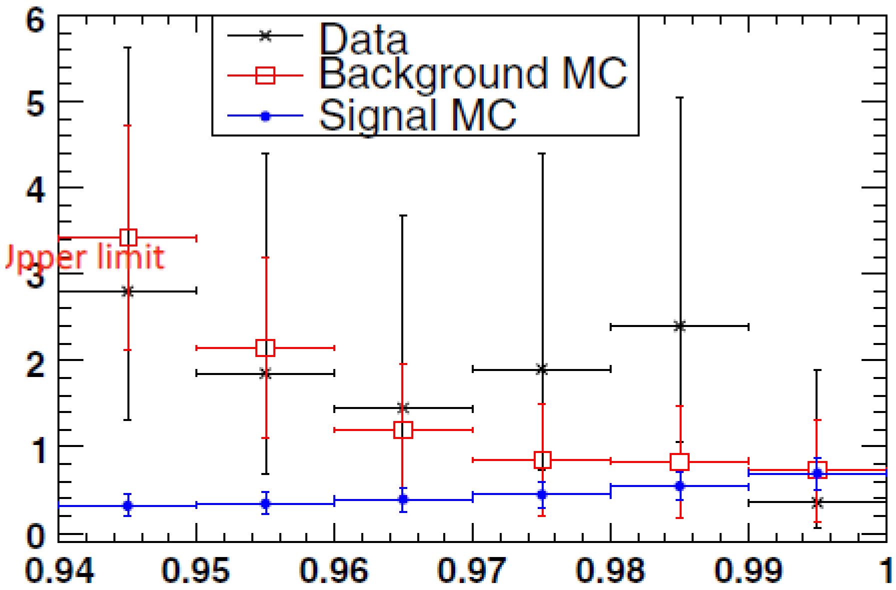
- Signal not significant, upper limits set to
  $B(B^+ \to K^+ \nu\nu) < 16 \times 10^{-6}$
  $B(B^0 \to K^0 \nu\nu) < 56 \times 10^{-6}$

Zoom in the signal region

$B^+ \to K^+ \nu\nu$




$B^0 \to K^0 \nu\nu$

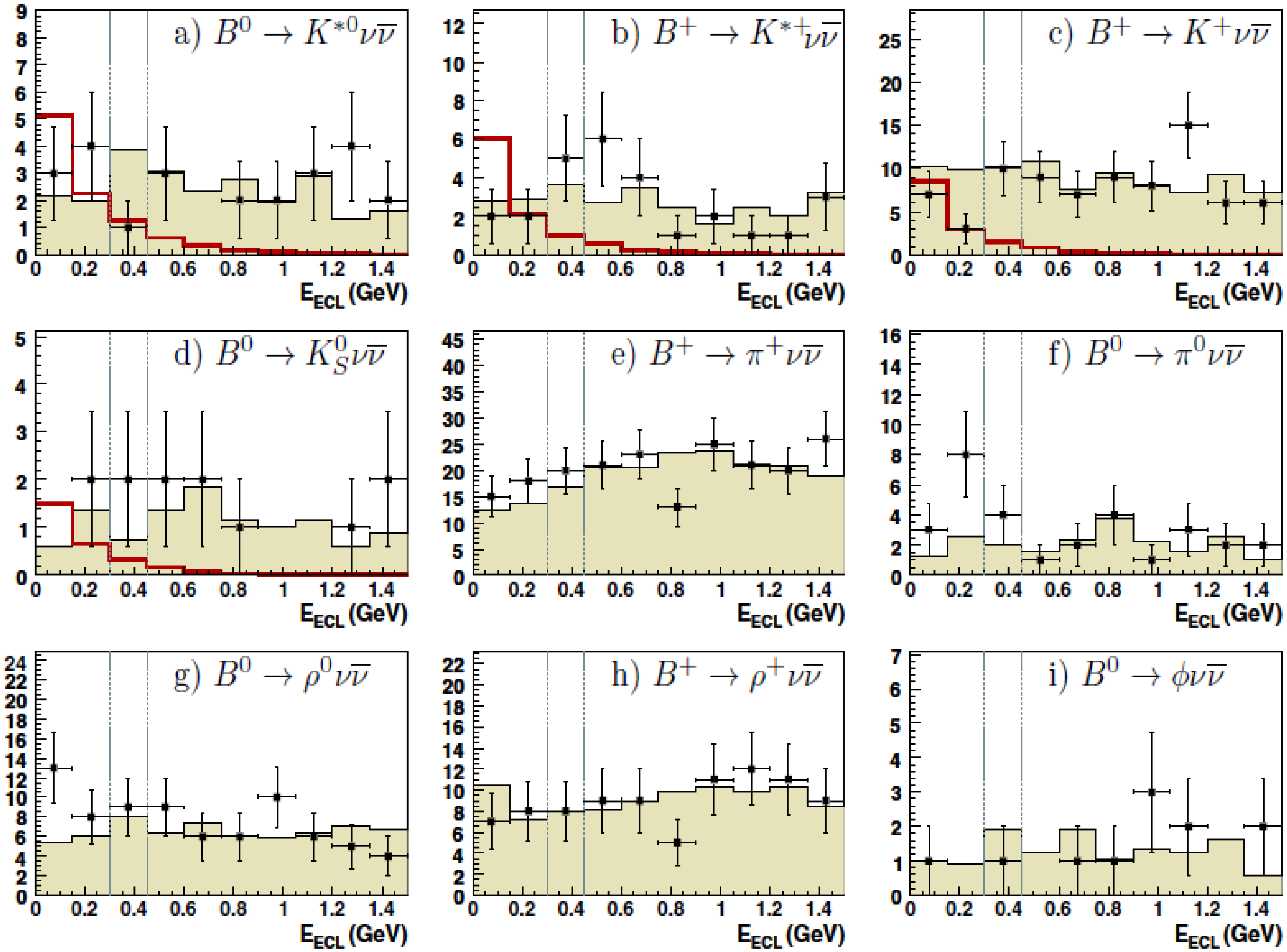


# $B \to h^{(*)} \nu \nu$ with hadronic tags from Belle

Phys. Rev. Lett. 99, 221802 (2007)
535 M B pairs

- Reconstruction of many final states in the rest of the event
  - $K^+$, $\pi^+$, $K^{*+}(K\pi)$, $K^{*0}(K\pi)$, $K_S(\pi^+\pi^-)$, $\rho^+$, $\rho^0$, $\phi$ (KK)
- Selection requirements on kinematics and veto of extra charged particles or $\pi^0$.
- Extra energy in the calorimeter defines the signal region
  - Signal region is residual calorimeter energy $E_{extra}$ < 300 MeV
  - Sideband region 450 MeV < $E_{extra}$ < 1.5 GeV
- Cut and count analysis
  - Background yield measured on the sideband and scaled using MC

# Belle B → h(*) ν ν




No evidence of signal:

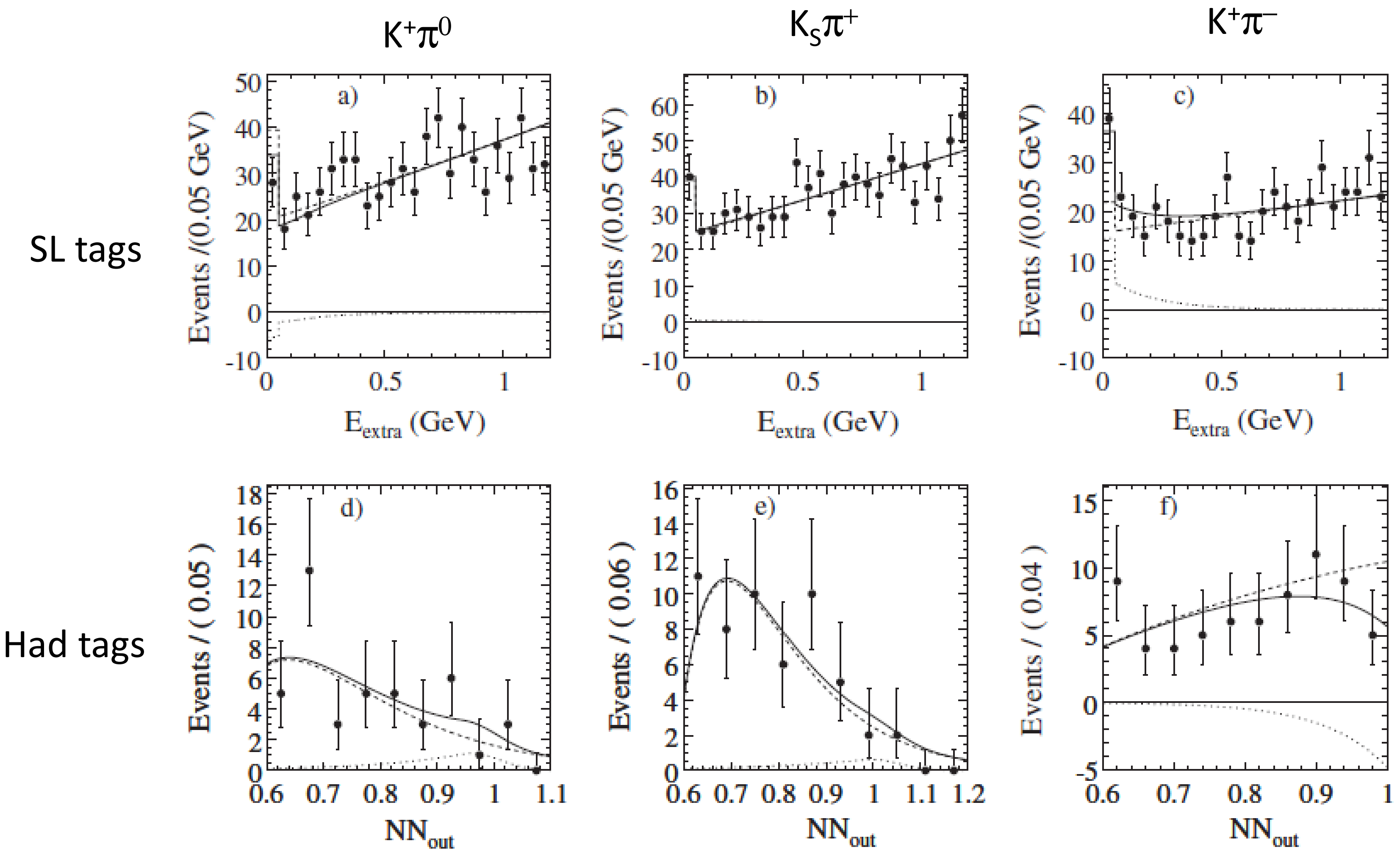
| | |
|---|---|
| B( B → $K^+$ ν ν ) | < 14 × $10^{-6}$ |
| B( B → $K^{*+}$ ν ν ) | < 140 × $10^{-6}$ |
| B( B → $K^{*0}$ ν ν ) | < 340 × $10^{-6}$ |

# $B \to K^{(*)} \nu \nu$ with hadronic and semileptonic tags BaBar

Phys. Rev. D 78, 072007 (2008)
454 M B pairs

- Final state $K^{*+}$ ( $K^+\pi^0$, $K_s\pi^+$) and $K^{*0}(K\pi)$
- Signal selection based on event shape, tag reconstruction quality, missing momentum
- Hadronic tag analysis combines the variables in a Neural net

- Signal yield extracted by a maximum likelihood fit to
  - Residual energy in the calorimeter (SL tag analysis)
  - NN distribution (hadronic tags)

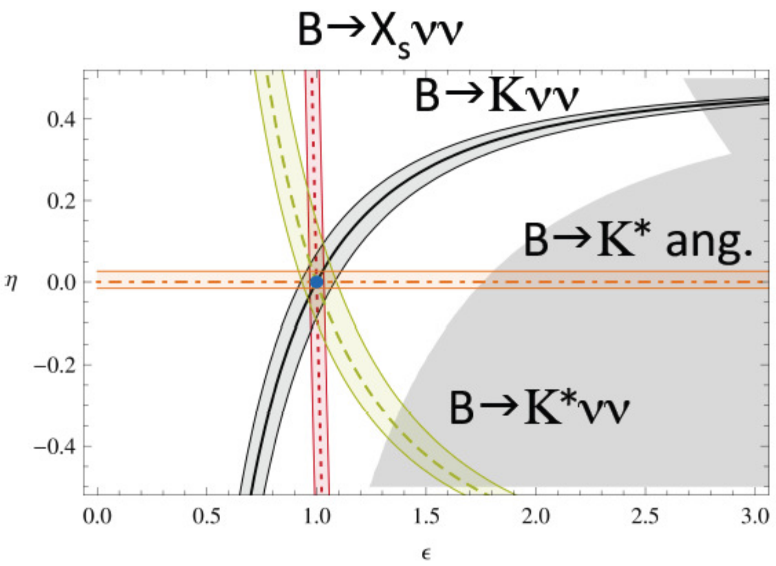



$B(B^+ \rightarrow K^{*+} \nu) < 80 \times 10^{-6}$ $B(B^0 \rightarrow K^{*0} \nu) < 120 \times 10^{-6}$

# Model independent NP Constraints

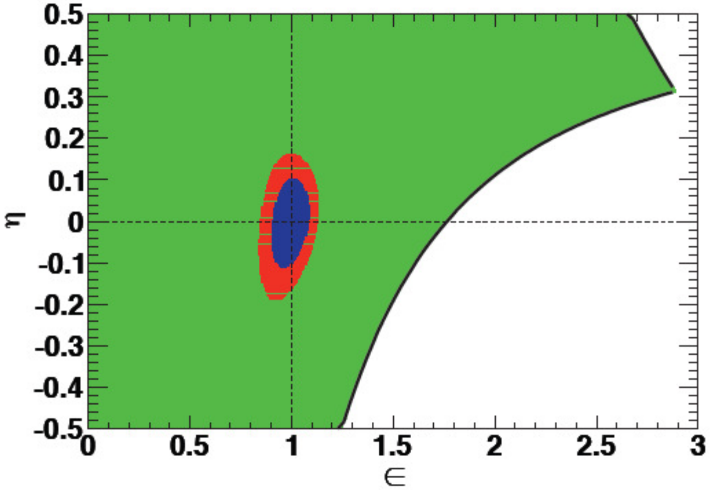
- Model independent NP constraints by measurements of branching fraction and K* polarization   Altmannshofer, Buras et al. JHEP 04, 022 (2009

$$\epsilon = \frac{\sqrt{|C_L^\nu|^2 + |C_R^\nu|^2}}{|(C_L^\nu)^{\rm SM}|}\,, \qquad \eta = \frac{-\mathrm{Re}\,(C_L^\nu C_R^{\nu *})}{|C_L^\nu|^2 + |C_R^\nu|^2}$$




SuperB 75 ab-1

arXiv:0901.0512



# Conclusions – Leptonic decays

- Leptonic B decays allow NP searches reasonably clean from theoretical complications
- $B \rightarrow \tau\nu$ BF is $O(10^{-4})$: not rare but experimentally challenging. As today, we still lack a single publication with a $5\sigma$ observation.
- To overcome the weak decay signature fruitful tagging methods have been exploited
- 4 statistically independent measurements provide a combined result with 20% accuracy. Consistent but not perfectly fitting within SM
  - Statistical fluctuation, overlooked systematics or new physics?
- $B \rightarrow \mu\nu$ still below the sensitivity of current B-factories
- Future B-factories will measure both the $B \rightarrow \tau\nu$ and $B \rightarrow \mu\nu$ branching fractions precisely (much better than 5%)

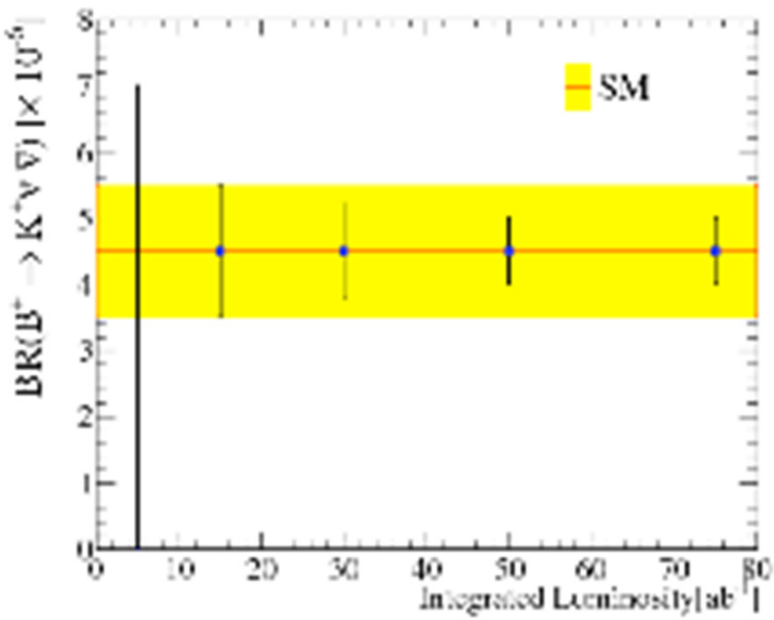
# Conclusions - B → $K^{(*)}\nu\nu$

- FCNC b → s transitions are rare in the SM and new physics may enter enhancing the branching fraction
- Among them the B → $K^{(*)}\nu\nu$ are the cleanest theoretically
- Experimentally they are as challenging as B → $\tau\nu$
- At current B-factories we didn't see any significant signal.
  The $B^+ \to K^+\nu\nu$ search being the most sensitive at 4x SM prediction
- At future B factories we expect to observe a SM signal with the full dataset
- Moreover with the hadronic tagging will be possible to perform angular analysis of B $\to K^*\nu\nu$ decays
- Combining several observables NP contributions may be constrained (a la UT fits)

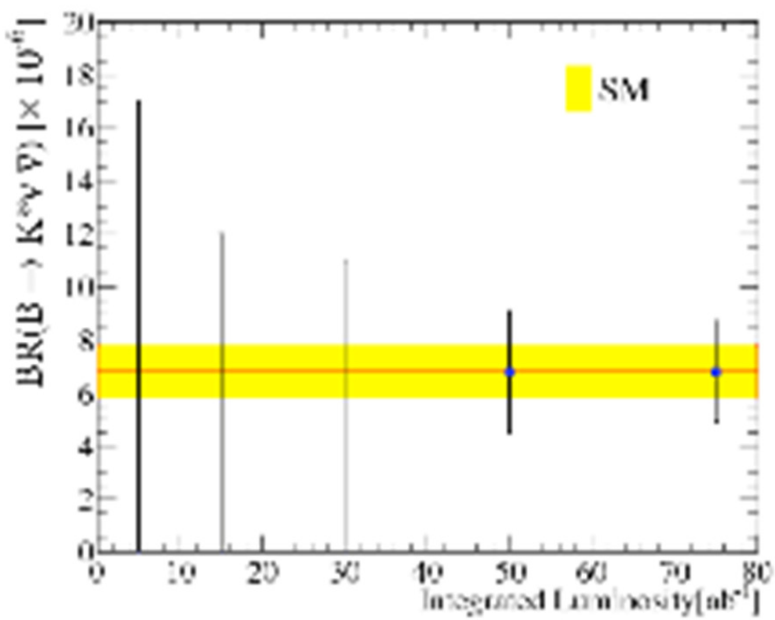
# Backup

- Benefits of lower boost and dectector improvements:
  - educated guesses by Belle-II point to 30-35% precision
    - Extrapolating performances of $B\rightarrow\tau\nu$ and assuming 70% improvements in reconstruction due to detector improvements
  - fast simulation studies by SuperB point to 15-20% precision

$B^+ \rightarrow K^+ \nu$



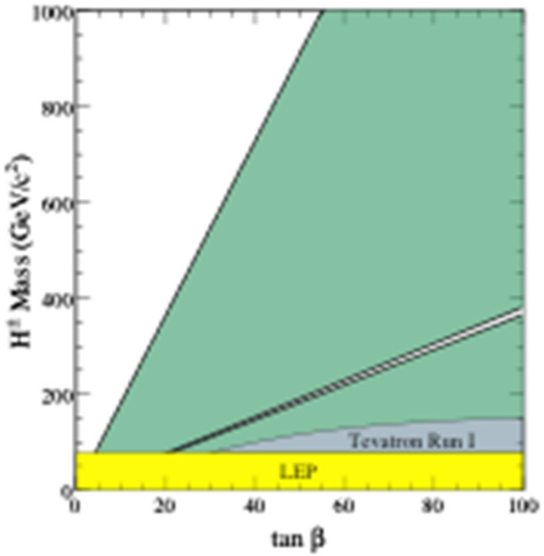

$B^+ \rightarrow K^{*+} \nu$



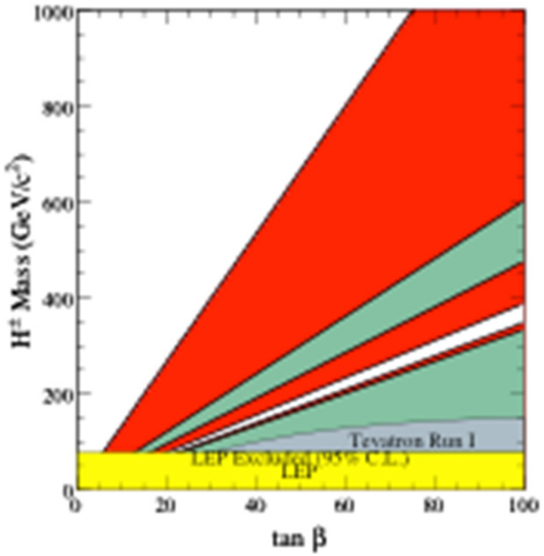
# Belle II extrapolations

- From Belle-II collaboration Physics Report (arXiv:1002.5012)
- Scale both the statistical and systematical uncertainty  by luminosity
- Resulting in a 4% total uncertainty with the full dataset of 50 $ab^{-1}$

95% excl. 50$ab^{-1}$



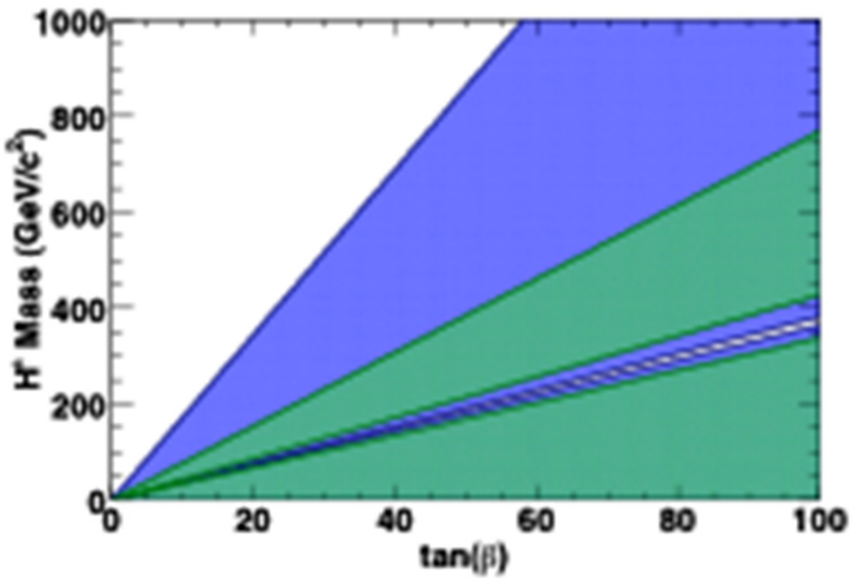

5σ observation regions

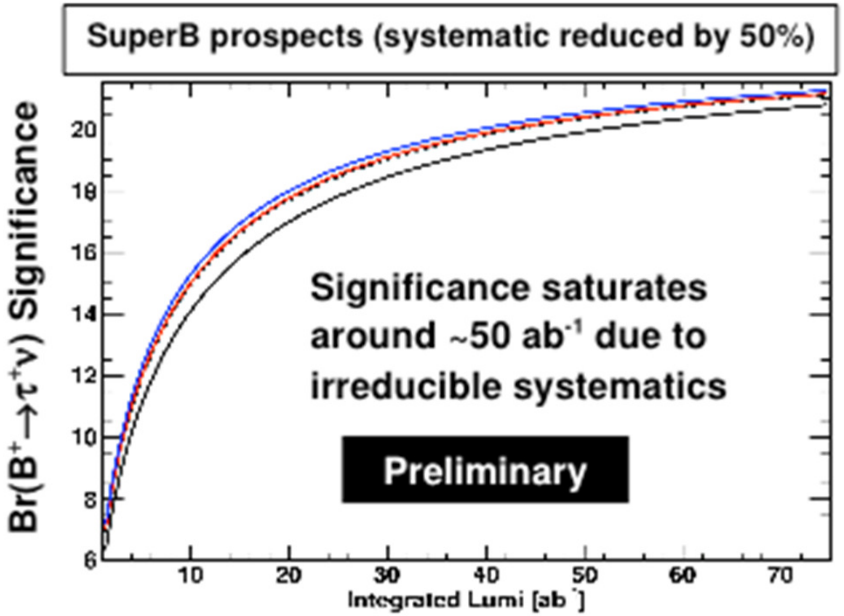


# SuperB extrapolations

- The measurements will rapidly become systematically limited
- Expect a final precision of 4% (systematic dominated) well before 75ab$^{-1}$
- Caveat: 4% is half of the current systematic uncertainty
  - We assess most of systematics from data so it may be conservative

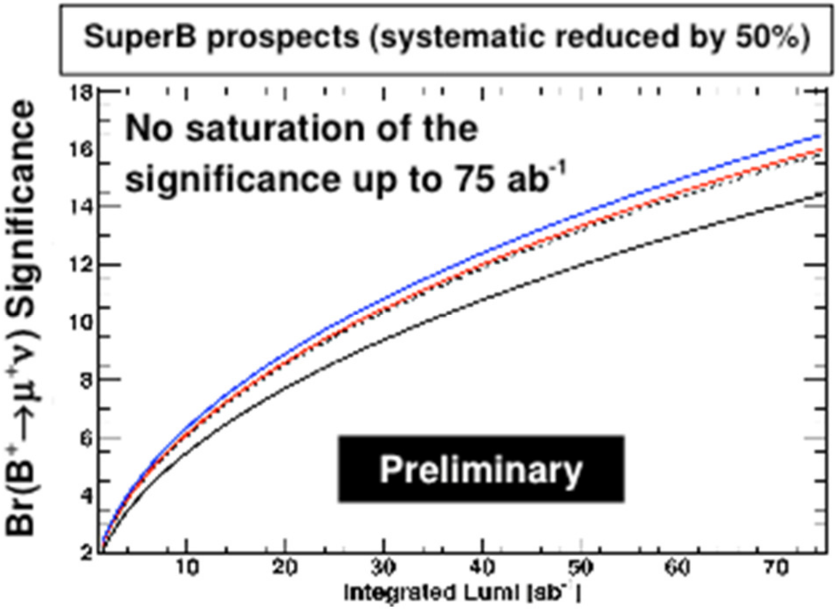
From Alejandro Perez @ HQL 2010

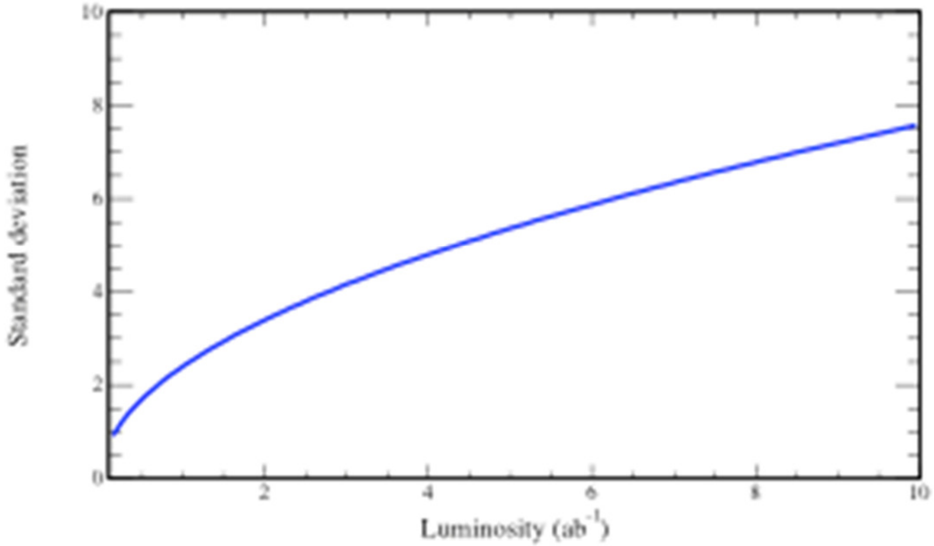


# Prospects of B→μν in SuperB and Belle-II

- Scaling the statistical uncertainty of the untagged method with luminosity
- Assuming a moderate improvement in systematic uncertainty
- Both collaborations assume that an hadronic tagging will perform better

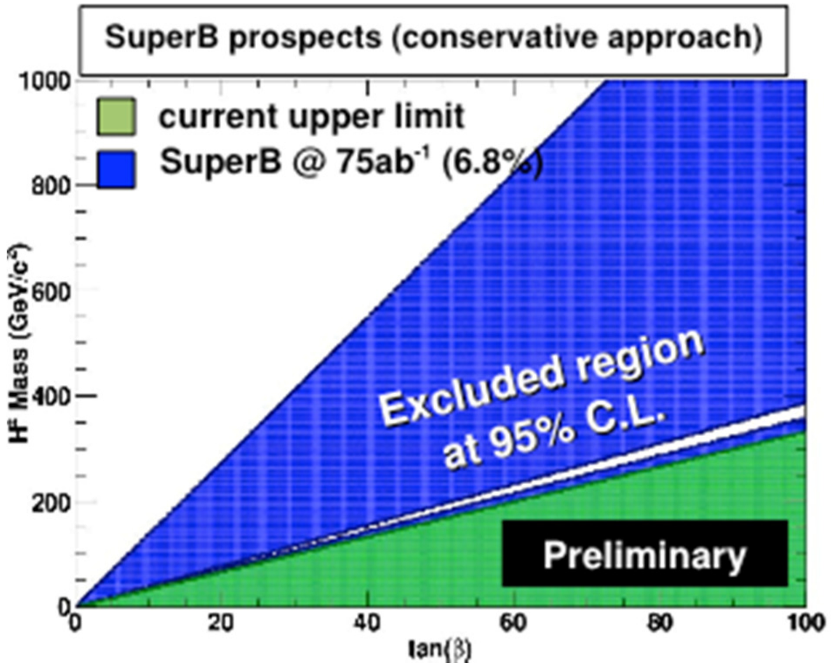


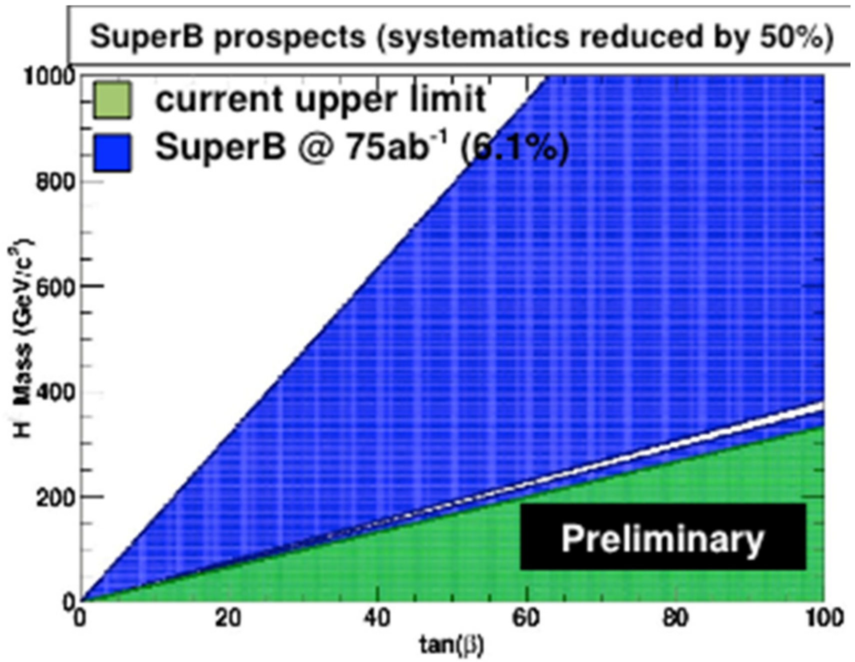




Both SuperB and Belle-II extrapolate a 5σ observation within SM before $10ab^{-1}$
Scaling to 75 $ab^{-1}$ expect SuperB to measure BF(B→μν ) at 4%
Scaling to 50 $ab^{-1}$ expect Belle-II to measure BF(B→μν ) at 6%

# Muon mode extrapolation on 2HDM

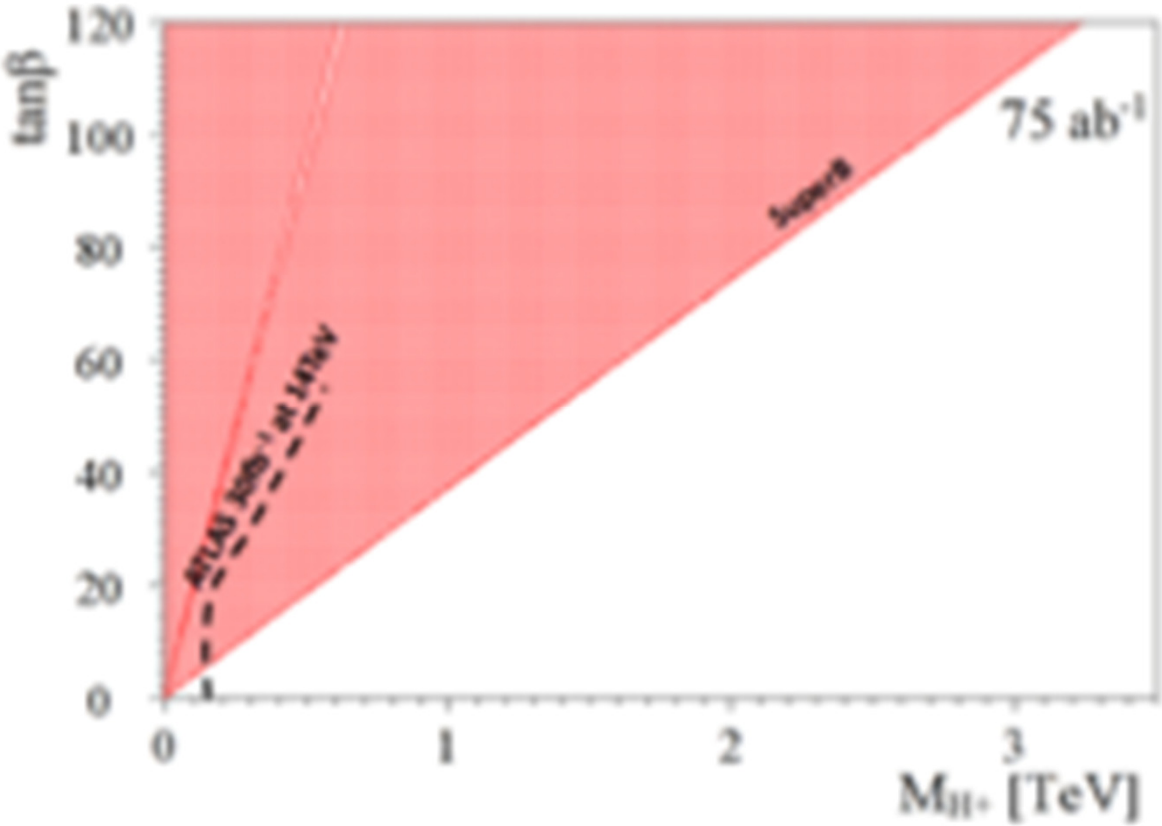
From Alejandro Perez @ HQL 2010



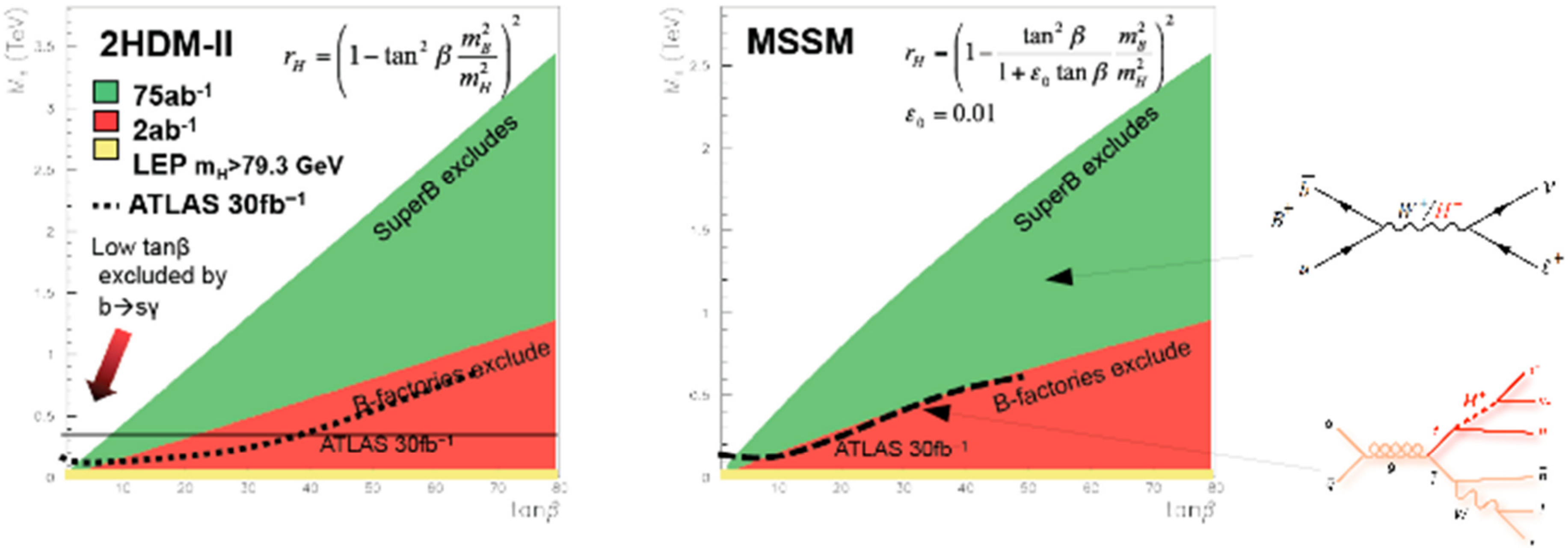
# SuperB B→τν + B→μν

- 75 ab-1 SuperB  expected exclusion region on 2HDM parameters from “the impact of SuperB on flavour Physics” arXiv:0901.0512
- ATLAS constraint from arXiv:0901.0512



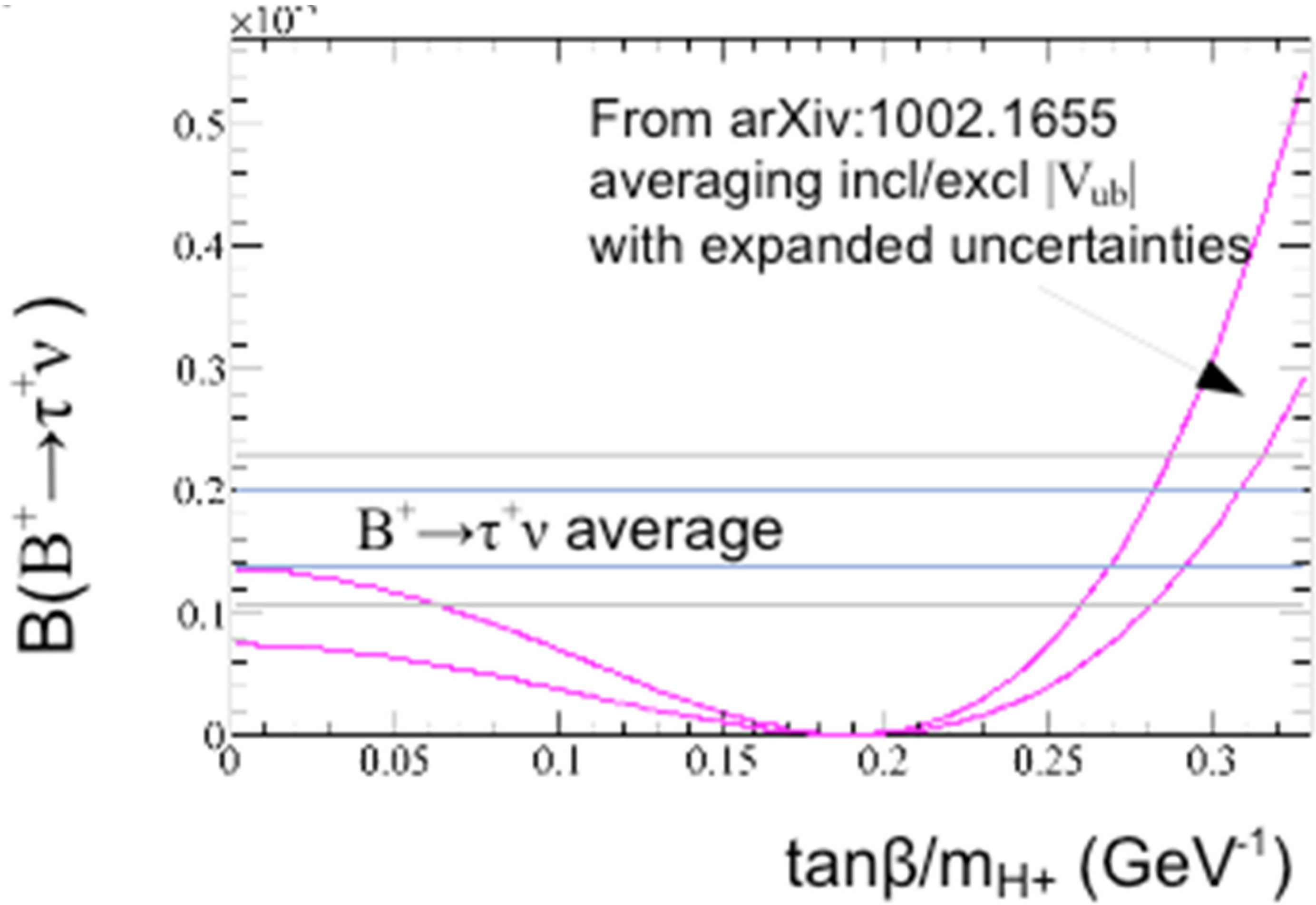
- From S.Robertson @ Miami workshop

- Potential enhancement or suppression of branching fraction by $H^+$




- Precision measurements of both $B^+ \to \tau^+ \nu$ and $B^+ \to \mu^+ \nu$ feasible at SuperB (presumably $B \to D^{(*)} \tau\nu$ also, but not yet studied)

# $B \to \tau\nu$ exclusion plot



# BABAR $B^+ \to K^+ \tau^+ \tau^-$

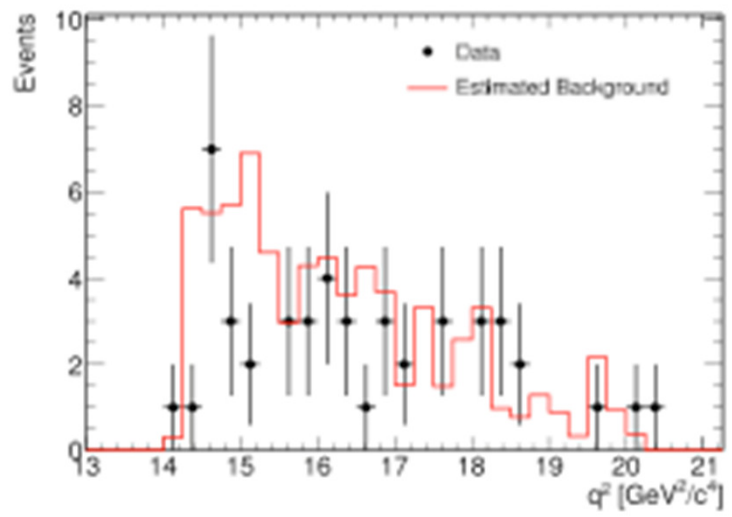
460 M B pairs

- Hadronic tag
- 1 prong $\tau$ decays, exactly three tracks, particle ID
- Requirements on $q^2$, track momentum, event shape, missing momentum, residual energy in calorimeter

- Expected background events: 65 ± 7
- Observed events: 47
- Signal efficiency $4.4 \times 10^{-4}$

- No excess of events seen
- 90% CL upper limit set to BF < $3.3\ 10^{-3}$

Momentum transfer to lepton pair $q^2$



# Belle $B \to h^{(*)} \nu \nu$

- No evidence of signal in any mode
- Assessed 90% U.L. with Feldman-Cousins prescriptions

| Mode | $N_{obs}$ | $N_{side}$ | $N_b$ | $\epsilon(\times 10^{-5})$ | U.L. |
|---|---|---|---|---|---|
| $K^{*0}\nu\bar{\nu}$ | 7 | 16 | $4.2 \pm 1.4$ | $5.1 \pm 0.3$ | $<3.4 \times 10^{-4}$ |
| $K^{*+}\nu\bar{\nu}$ | 4 | 18 | $5.6 \pm 1.8$ | $5.8 \pm 0.7$ | $<1.4 \times 10^{-4}$ |
| $\to K_S^0\pi^+$ | 1 | 7 | $2.3 \pm 1.2$ | $2.8 \pm 0.3$ | |
| $\to K^+\pi^0$ | 3 | 11 | $3.3 \pm 1.4$ | $3.0 \pm 0.4$ | |
| $K^+\nu\bar{\nu}$ | 10 | 60 | $20.0 \pm 4.0$ | $26.7 \pm 2.9$ | $<1.4 \times 10^{-5}$ |
| $K^0\nu\bar{\nu}$ | 2 | 8 | $2.0 \pm 0.9$ | $5.0 \pm 0.3$ | $<1.6 \times 10^{-4}$ |
| $\pi^+\nu\bar{\nu}$ | 33 | 149 | $25.9 \pm 3.9$ | $24.2 \pm 2.6$ | $<1.7 \times 10^{-4}$ |
| $\pi^0\nu\bar{\nu}$ | 11 | 15 | $3.8 \pm 1.3$ | $12.8 \pm 0.8$ | $<2.2 \times 10^{-4}$ |
| $\rho^0\nu\bar{\nu}$ | 21 | 46 | $11.5 \pm 2.3$ | $8.4 \pm 0.5$ | $<4.4 \times 10^{-4}$ |
| $\rho^+\nu\bar{\nu}$ | 15 | 66 | $17.8 \pm 3.2$ | $8.5 \pm 1.1$ | $<1.5 \times 10^{-4}$ |
| $\phi\nu\bar{\nu}$ | 1 | 9 | $1.9 \pm 0.9$ | $9.6 \pm 1.4$ | $<5.8 \times 10^{-5}$ |