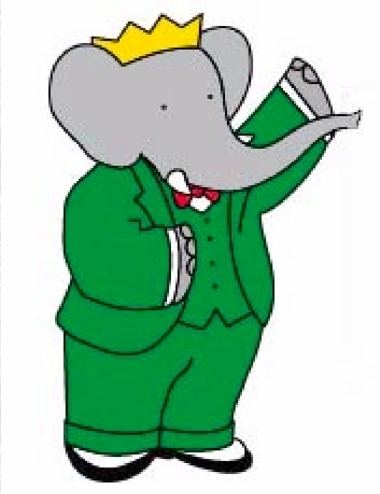
# $B^+ \to \tau^+\nu$ and $B \to K^{(*)}\nu\bar{\nu}$ at BaBar and SuperB



SuperB

Dana Lindemann
On Behalf of the BaBar Collaboration

CKM Workshop
October 2, 2012

SLAC
NATIONAL ACCELERATOR LABORATORY

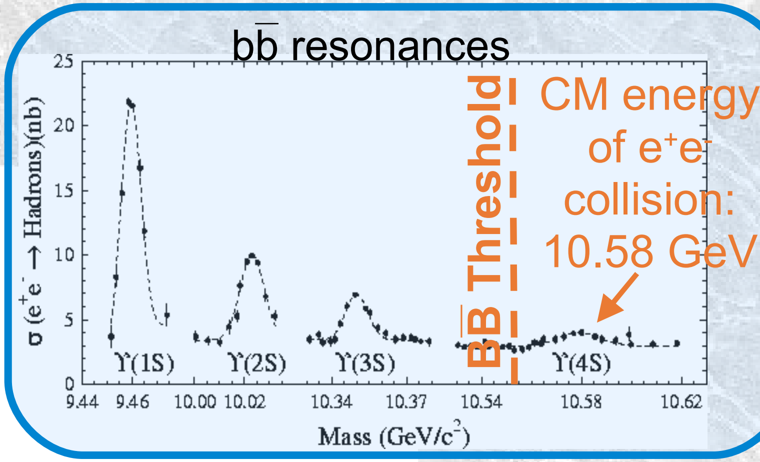
# Outline

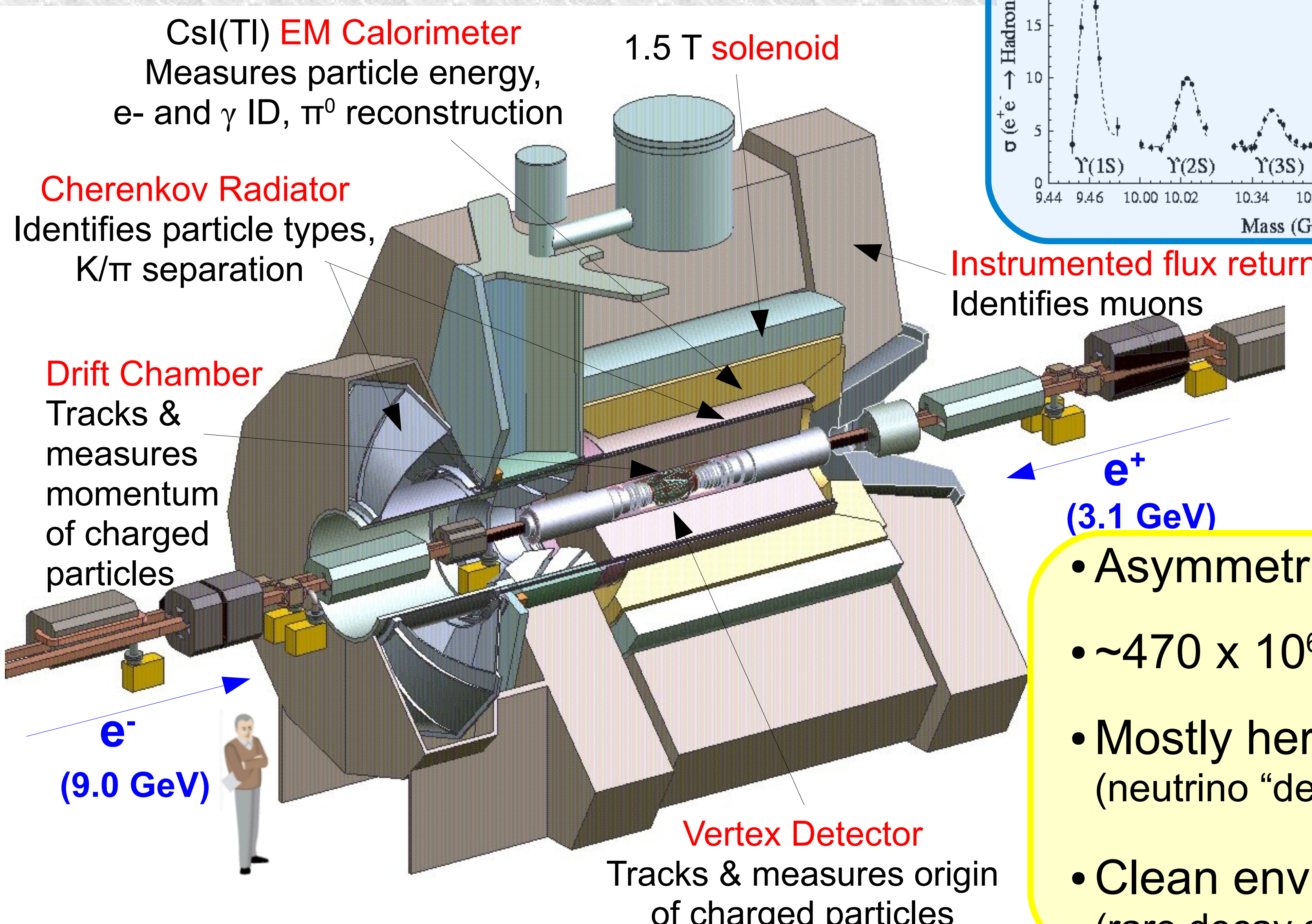
- Introduction
  - BaBar, SuperB, Hadronic Tag Reconstruction
- Updates on BaBar searches and prospects at SuperB for:
  - $B^+ \rightarrow \tau^+ \nu$ [arXiv: 1207.0698, Submitted to PRD]
  - $B \rightarrow K^{(*)} \nu \bar{\nu}$ ← **Preliminary New Results**

*Charge conjugate modes implied throughout talk*

# The BaBar Experiment

$e^+e^- \rightarrow \Upsilon(4S) \rightarrow B^+B^-, B^0\overline{B}^0$



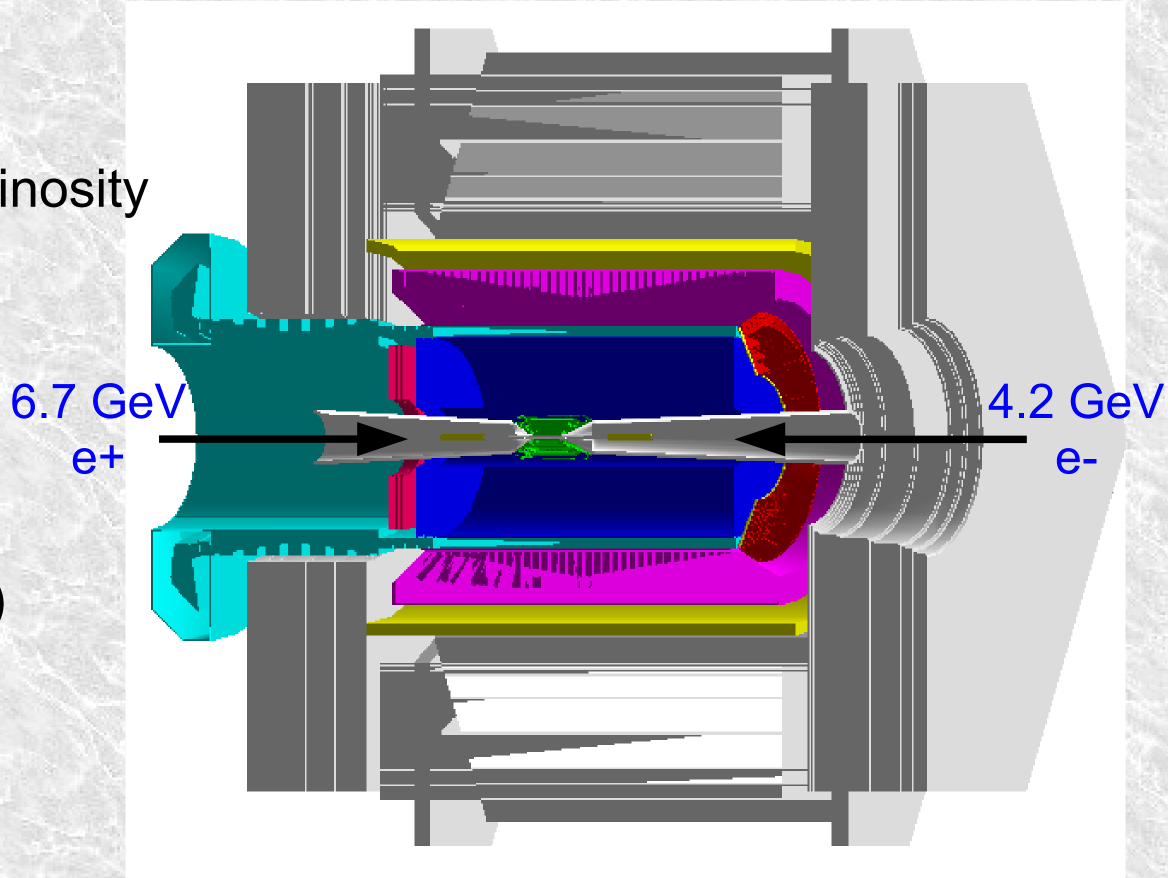




- Asymmetric Collider
- ~470 x $10^6$ $B\overline{B}$ (429 $fb^{-1}$)
- Mostly hermetic detector
  (neutrino "detection" via $p_{miss}$)
- Clean environment
  (rare decay searches)

# The SuperB Experiment

- Goal: 75 $ab^{-1}$ at $\Upsilon(4S)$ over 5 years
- $\mathscr{L} = 10^{36}$ $cm^{-2}s^{-1}$ (x100 luminosity of BaBar)
- Flexible running energies (charm threshold to $\Upsilon(6S)$)
- 80% polarized electrons

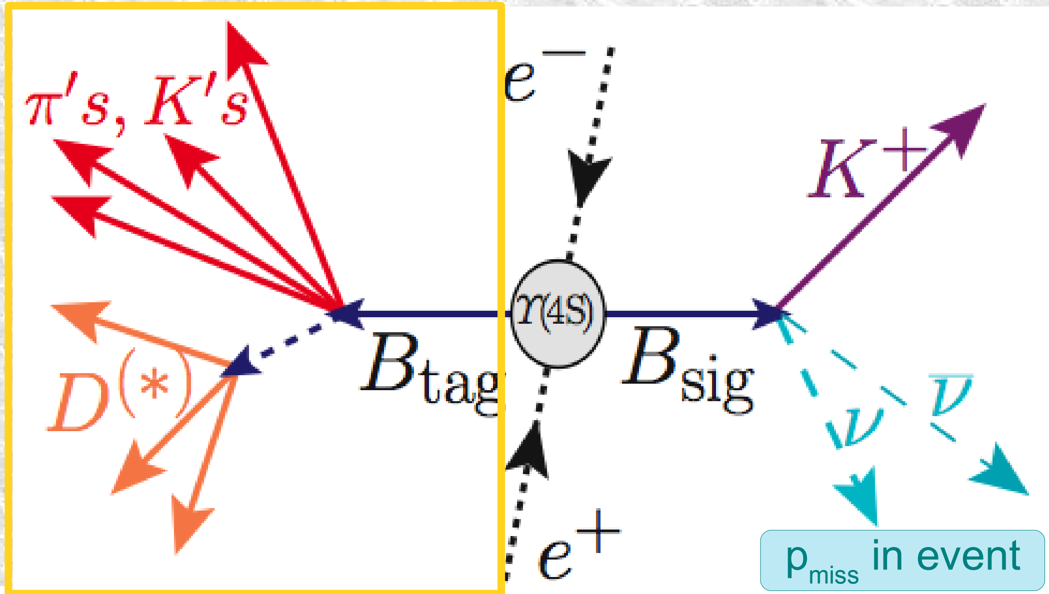
- New collider design
  Smaller emittance → higher luminosity
- Detector concept based on
  reuse of BaBar components
  (also PEP-II components)
- Will be at Cabibbo Lab
  on Tor Vergata campus (Italy)



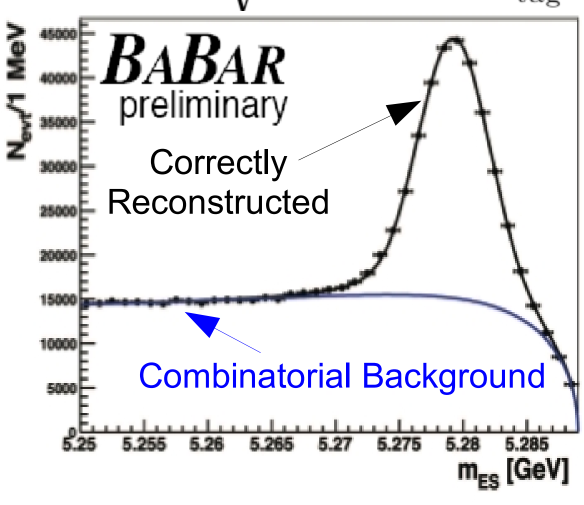
# Hadronic Tag Reconstruction

- Distinguish signal decay and $E_{miss}$ by exploiting $\Upsilon(4S) \rightarrow B\overline{B}$ production

1 Fully reconstruct $B_{tag}$ in hadronic modes



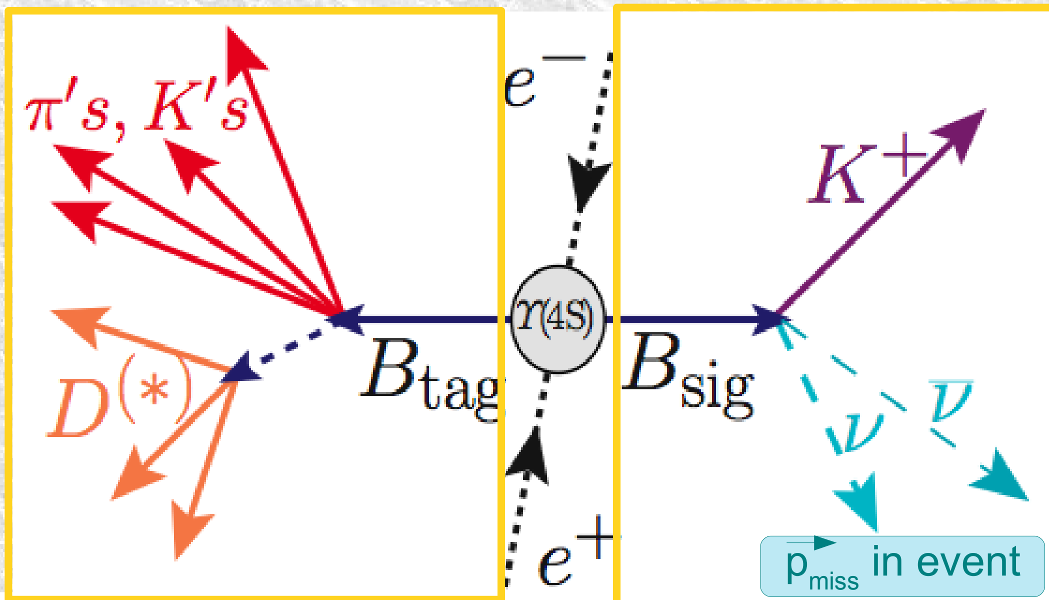

$$m_{ES} \equiv \sqrt{E^2_{\mathrm{beam}} - \vec{p}^{\,2}_{\mathrm{B_{tag}}}}$$



# Hadronic Tag Reconstruction

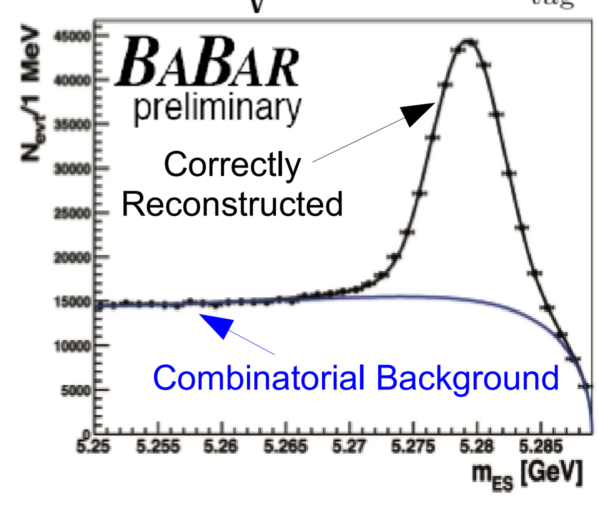
- Distinguish signal decay and $E_{miss}$ by exploiting $\Upsilon(4S)\rightarrow B\overline{B}$ production

1 Fully reconstruct $B_{tag}$ in hadronic modes

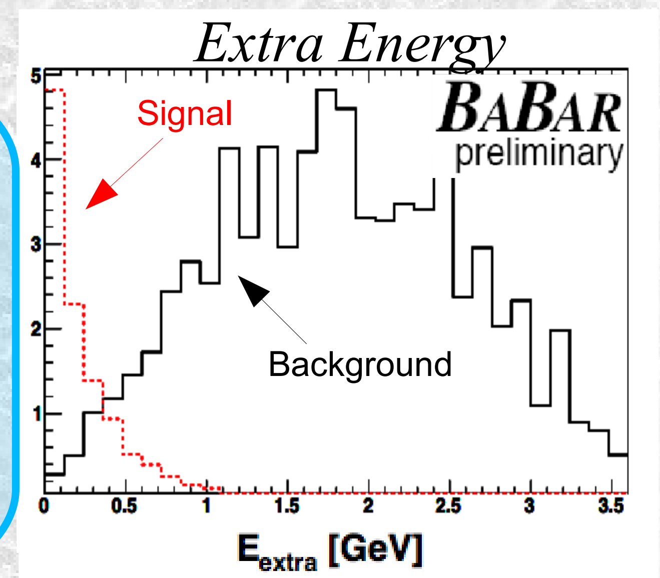



2 Look for signal decay in rest of the event

$$m_{ES} \equiv \sqrt{E^2_{\mathrm{beam}} - \vec{p}^{\,2}_{\mathrm{B_{tag}}}}$$




- Clean B samples with suppressed backgrounds
- $B_{sig}$ 4-vector is determined, improving resolution on signal kinematics and $\vec{p}_{miss}$
- Low reconstruction efficiency



# Search for $B^+ \rightarrow \tau^+ \nu$

# $B^+ \to l^+ \nu$: Theoretical Motivation

Provides clean predictions of SM parameters without hadronic (QCD) final-state uncertainties

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

Helicity suppression

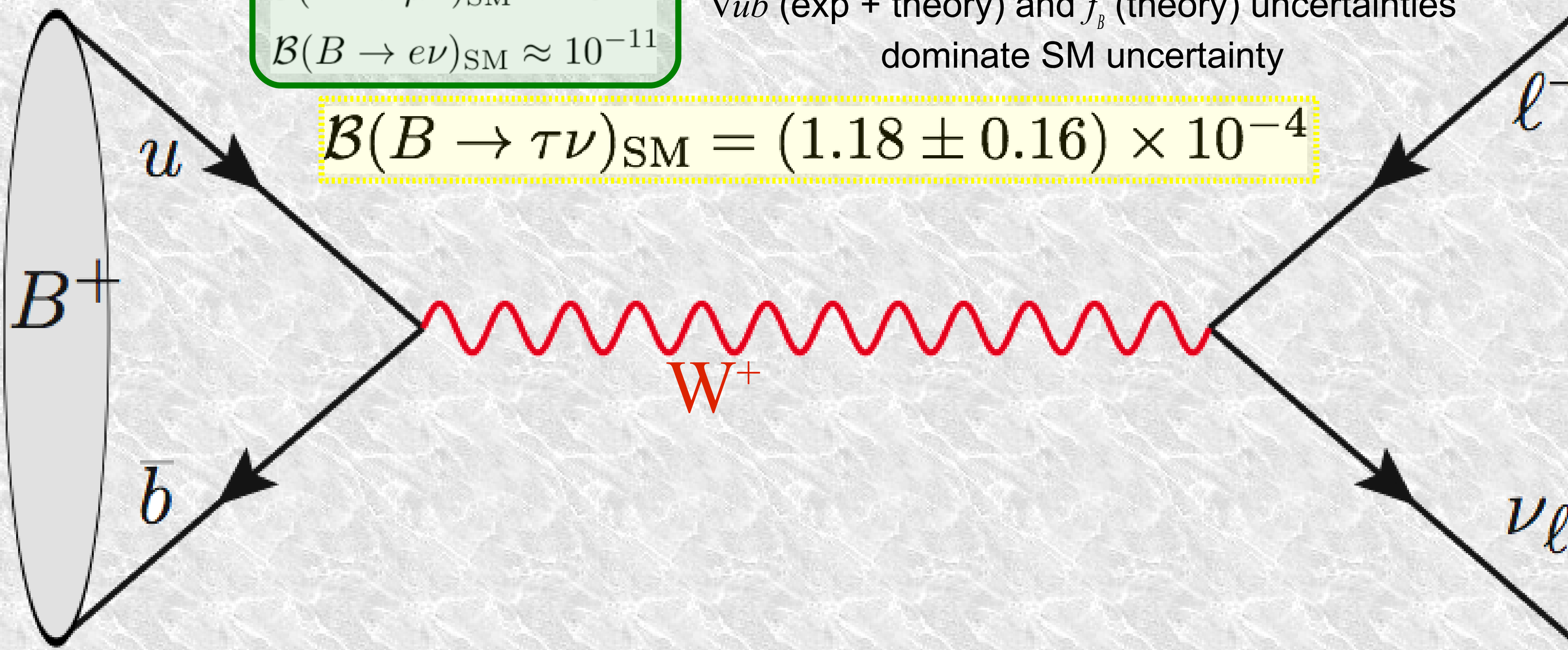
$$\mathcal{B}(B \to \mu\nu)_{\rm SM} \approx 10^{-7}$$

$$\mathcal{B}(B \to e\nu)_{\rm SM} \approx 10^{-11}$$

*Experimental sensitivity to $f_B|V_{ub}|$*

$V_{ub}$ (exp + theory) and $f_B$ (theory) uncertainties dominate SM uncertainty

$$\mathcal{B}(B \to \tau\nu)_{\rm SM} = (1.18 \pm 0.16) \times 10^{-4}$$



# $B^+ \to l^+ \nu$: Theoretical Motivation

Provides clean predictions of SM parameters without hadronic (QCD) final-state uncertainties

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

Helicity suppression

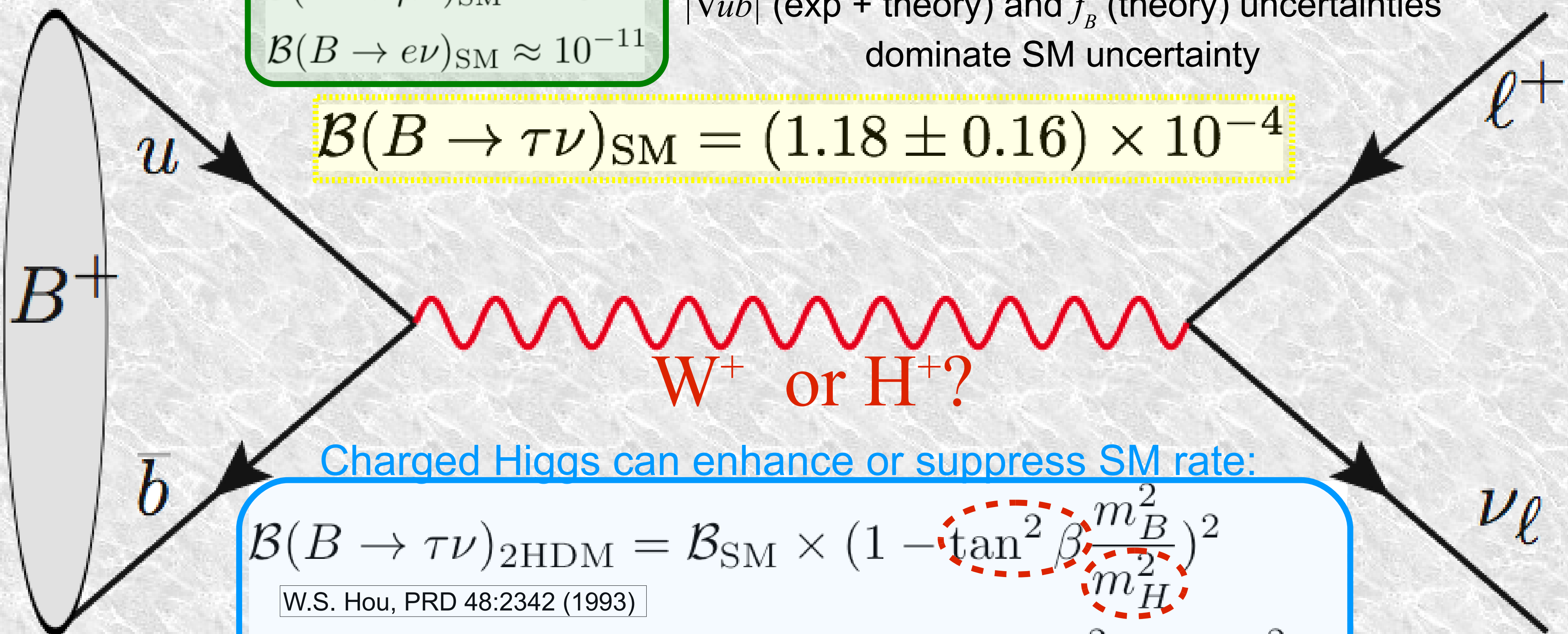
$$\mathcal{B}(B \to \mu\nu)_{\rm SM} \approx 10^{-7}$$

$$\mathcal{B}(B \to e\nu)_{\rm SM} \approx 10^{-11}$$

Experimental sensitivity to $f_B|Vub|$

$|Vub|$ (exp + theory) and $f_B$ (theory) uncertainties dominate SM uncertainty

$$\mathcal{B}(B \to \tau\nu)_{\rm SM} = (1.18 \pm 0.16) \times 10^{-4}$$




Charged Higgs can enhance or suppress SM rate:

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

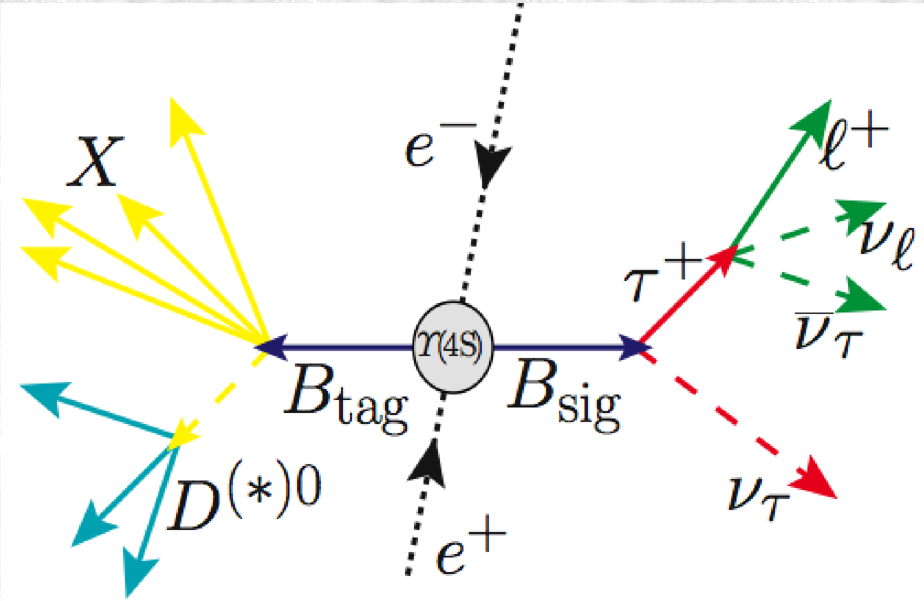
W.S. Hou, PRD 48:2342 (1993)

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

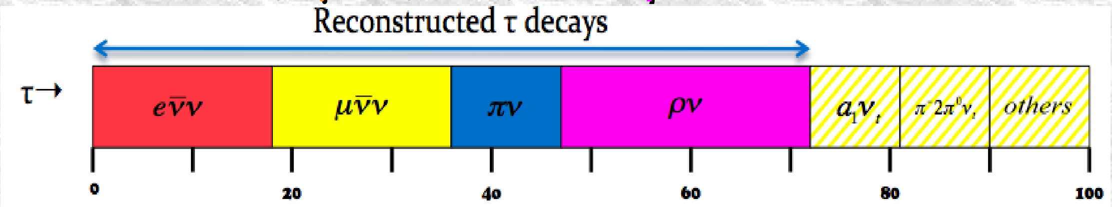
Akeroyd and Recksiegel, J. Phys G29:2311 (2003)

# $B^+ \to \tau^+ \nu$ with Hadronic Tags

arXiv:1207.0698
Submitted to PRD



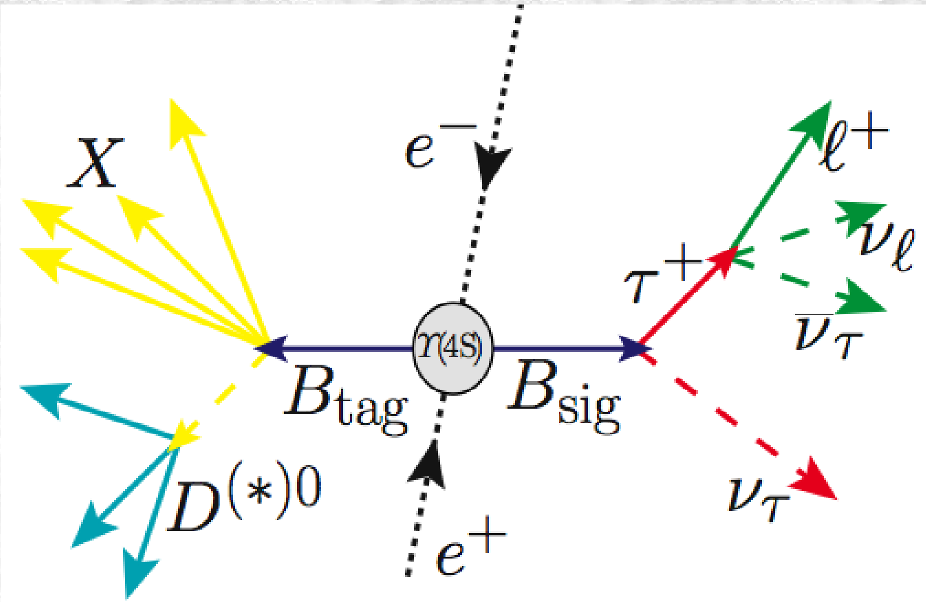

- Reconstruct 1-prong $\tau$ decay modes:
  $e\nu\bar{\nu}$, $\mu\nu\bar{\nu}$, $\pi\nu$, and $\rho\nu \to \pi^+\pi^0\nu$



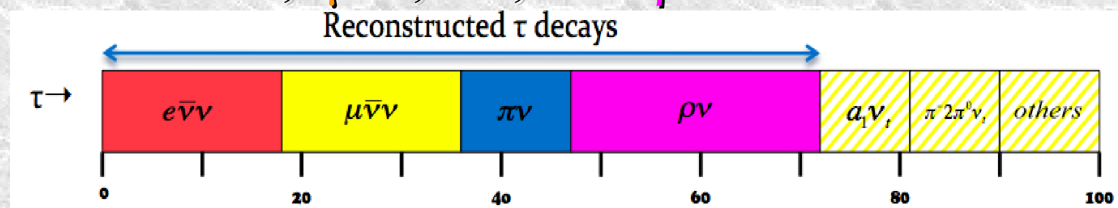

- Exactly 1 track
- Suppress continuum bkg using 2 event-shape variables (R2, $\cos\theta_{Thrust}$)
- 2-variable LHR for $\pi\nu$ ($p^*_\pi$ and $\cos\theta_{miss}$)
- 4-variable LHR for $\rho\nu$ ($\cos\theta_{miss}$, $m_{\pi 0}$, $m_{\pi\pi 0}$, $p^*_\rho$)

arXiv:1207.0698
Submitted to PRD

# $B^+ \to \tau^+ \nu$ with Hadronic Tags



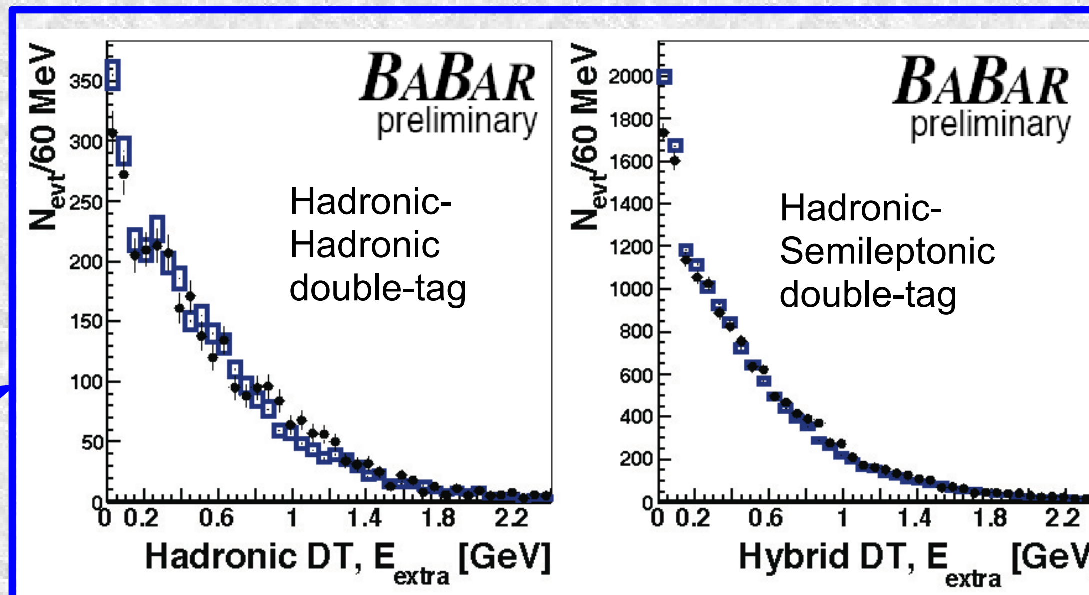

- Reconstruct 1-prong $\tau$ decay modes:
  $e\nu\bar{\nu}$, $\mu\nu\bar{\nu}$, $\pi\nu$, and $\rho\nu \to \pi^+\pi^0\nu$




- Exactly 1 track
- Suppress continuum bkg using 2 event-shape variables (R2, $\cos\theta_{Thrust}$)
- 2-variable LHR for $\pi\nu$ ($p^*_\pi$ and $\cos\theta_{miss}$)
- 4-variable LHR for $\rho\nu$ ($\cos\theta_{miss}$, $m_{\pi 0}$, $m_{\pi\pi 0}$, $p^*_\rho$)

**Most discriminating variable: $E_{extra}$**

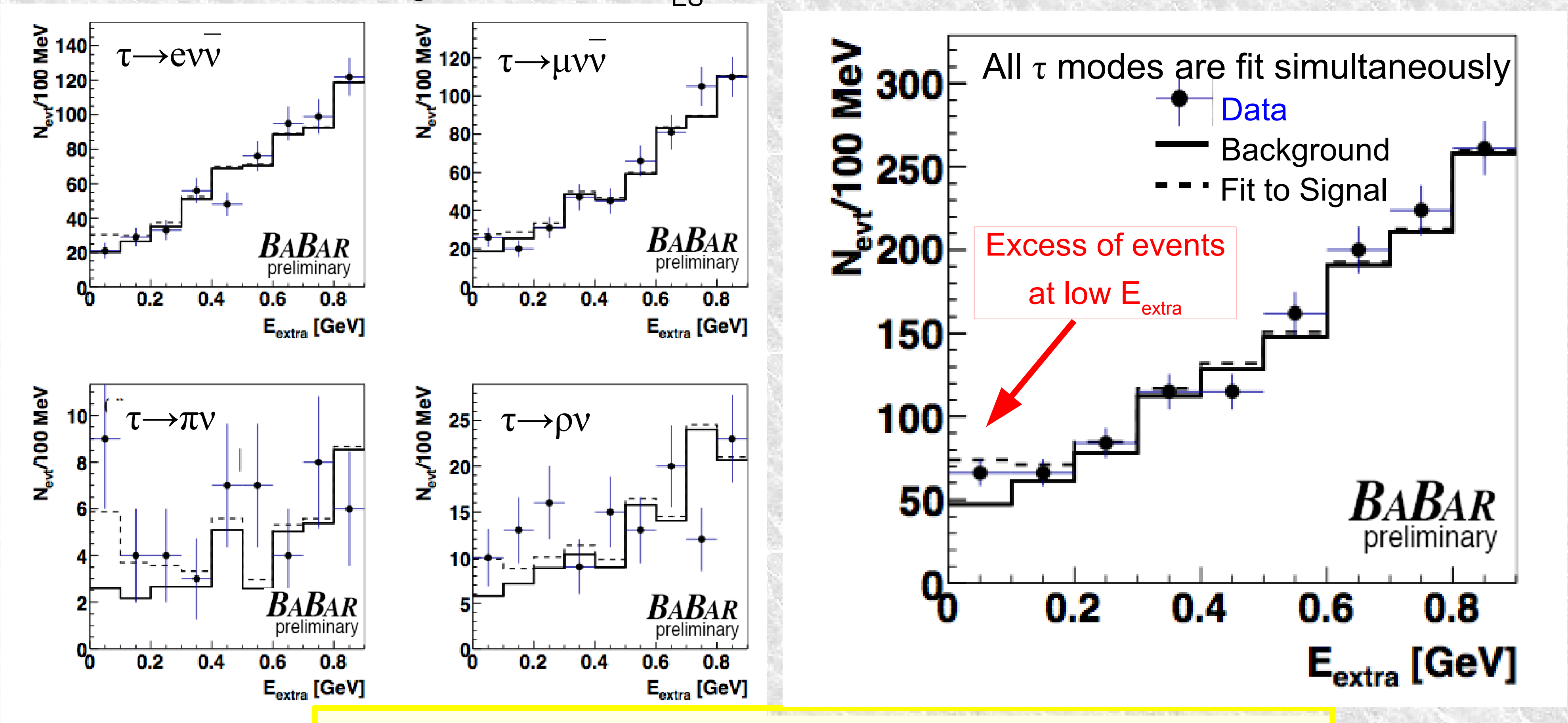
- Sum of all remaining energy in calorimeter should be zero
- Misreconstructions, split-offs, & beam bkgs produce excess
- Validate $E_{extra}$ with data using double-tagged samples



arXiv:1207.0698
Submitted to PRD

# $B^+ \to \tau^+ \nu$: Results

- Extract BF using unbinned maximum likelihood fit to $E_{extra}$
- Signal and peaking bkg PDFs from MC corrected for data/MC ratio using $m_{ES}$
  Combinatorial bkg PDF from $m_{ES}$ sidebands in data




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

Exclusion of null hypothesis at 3.8 σ (incl. syst.)

# $B^+ \to \tau^+ \nu$ Results within Context

| Previous Branching Fractions ($\times 10^{-4}$) | | |
|---|---|---|
| BaBar Hadronic | (2008) | $1.8\ ^{+0.9}_{-0.8} \pm 0.4 \pm 0.2$ |
| BaBar SL | (2010) | $1.7 \pm 0.8 \pm 0.2$ |
| Belle Hadronic | (2006) | $1.79\ ^{+0.56}_{-0.49}\ ^{+0.46}_{-0.51}$ |
| Belle SL | (2010) | $1.54\ ^{+0.38}_{-0.37}\ ^{+0.29}_{-0.31}$ |
| Belle Hadronic | (2012) | $0.72\ ^{+0.27}_{-0.25} \pm 0.11$ |
| **BaBar Hadronic** | **(2012)** | $1.83^{+0.53}_{-0.49} \pm 0.24$ |

**BaBar combined** $\mathcal{B}(B \to \tau\nu) = (1.79 \pm 0.48) \times 10^{-4}$

$f_B$ = (189±4) MeV [(HPQCD) arXiv:1202.4914]

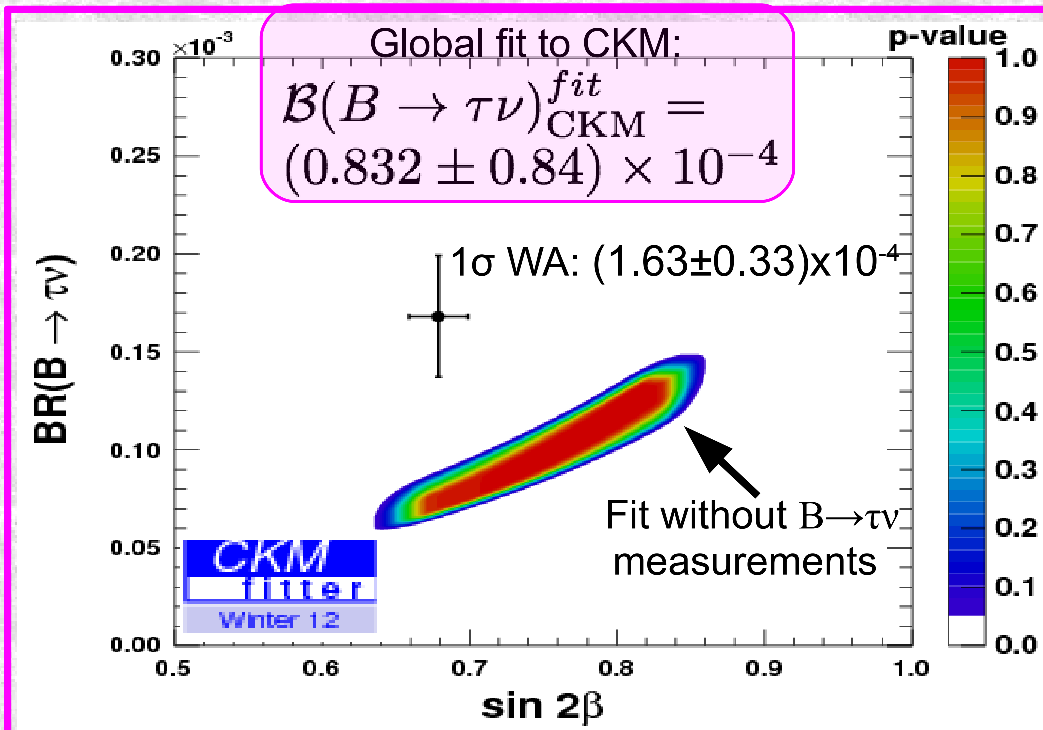
Inclusive BaBar |Vub| [arXiv:1112.0702]

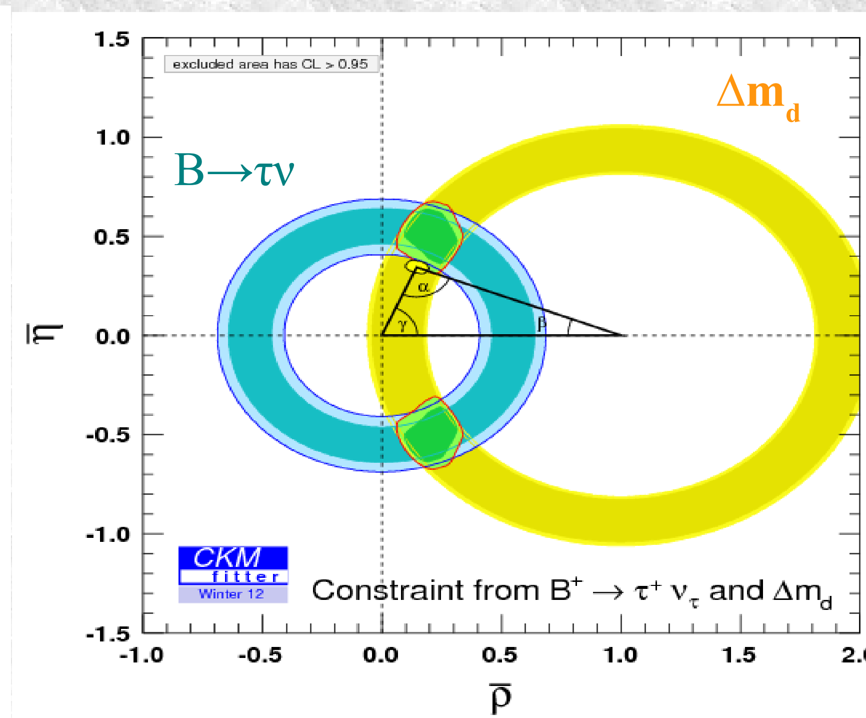
$$\mathcal{B}_{SM} = (1.18 \pm 0.16) \times 10^{-4}$$

Exclusive BaBar |Vub| [PoS(EPS-HEP2011)155 (2011)]

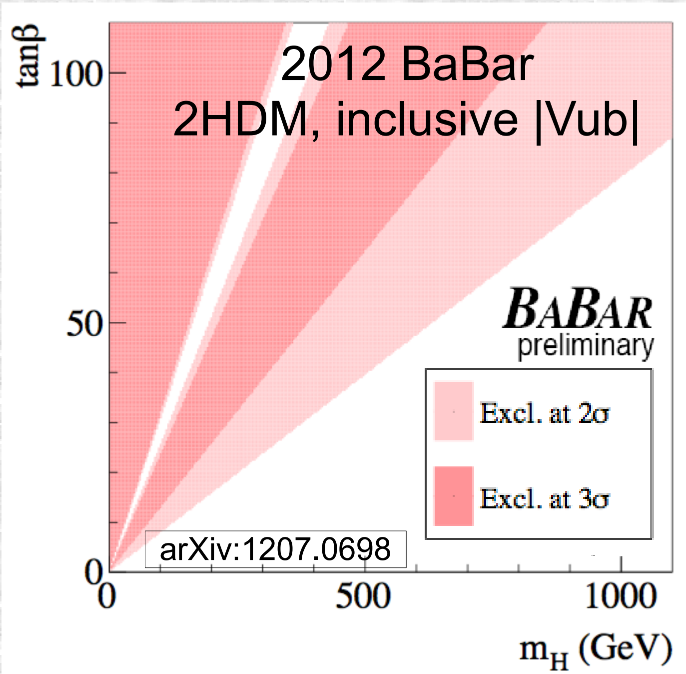
$$\mathcal{B}_{SM} = (0.62 \pm 0.12) \times 10^{-4}$$

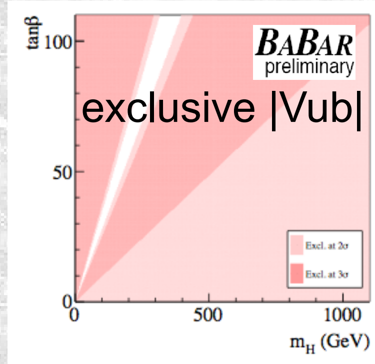
**Measurement is 1.6σ larger than SM prediction**

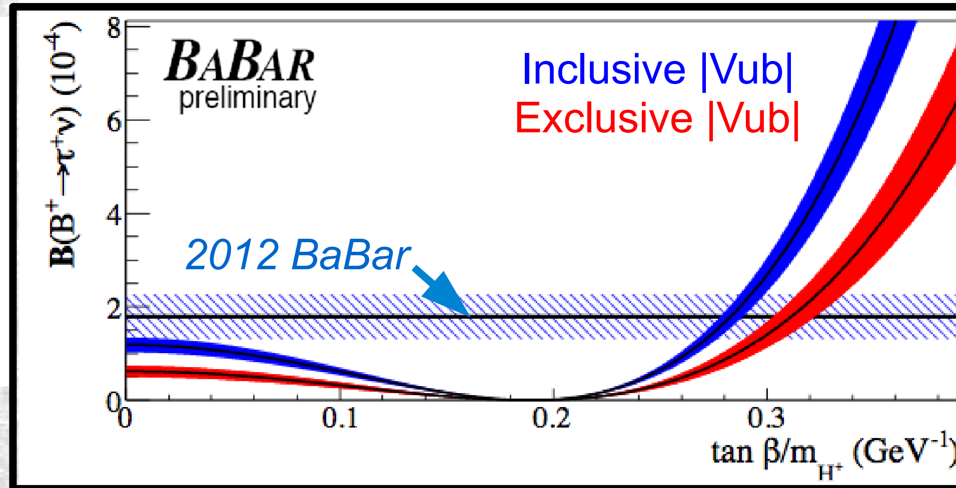


# $B^+ \to \tau^+ \nu$ at BaBar



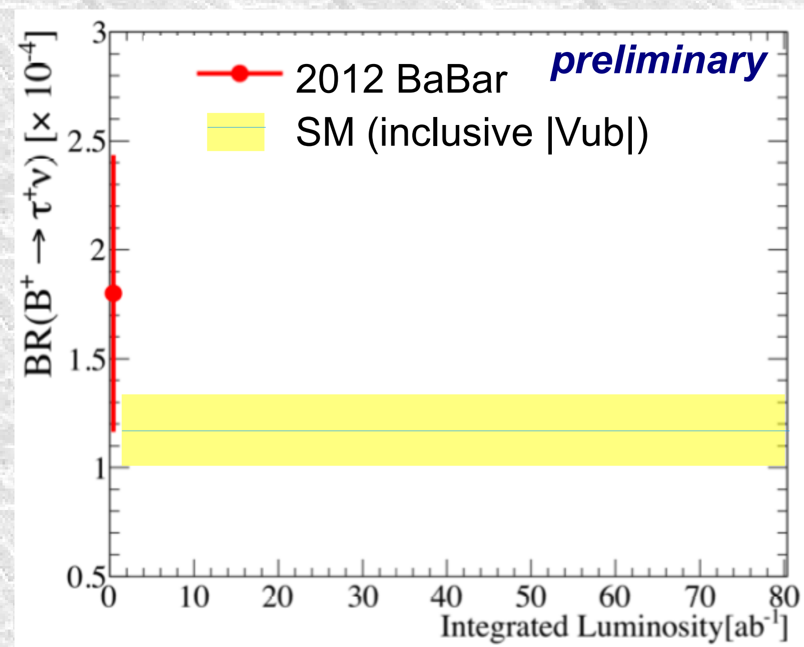

Exclusion

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

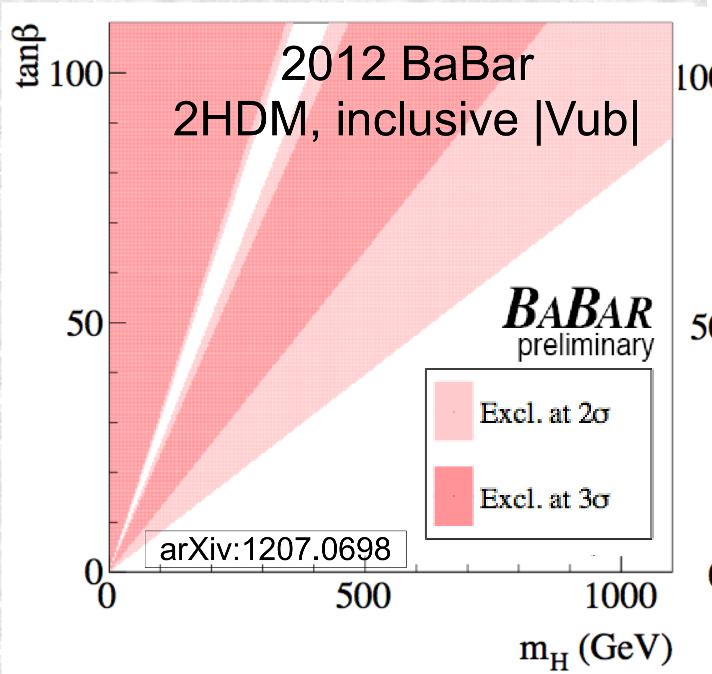
Current world $B \to \tau\nu$ precision:

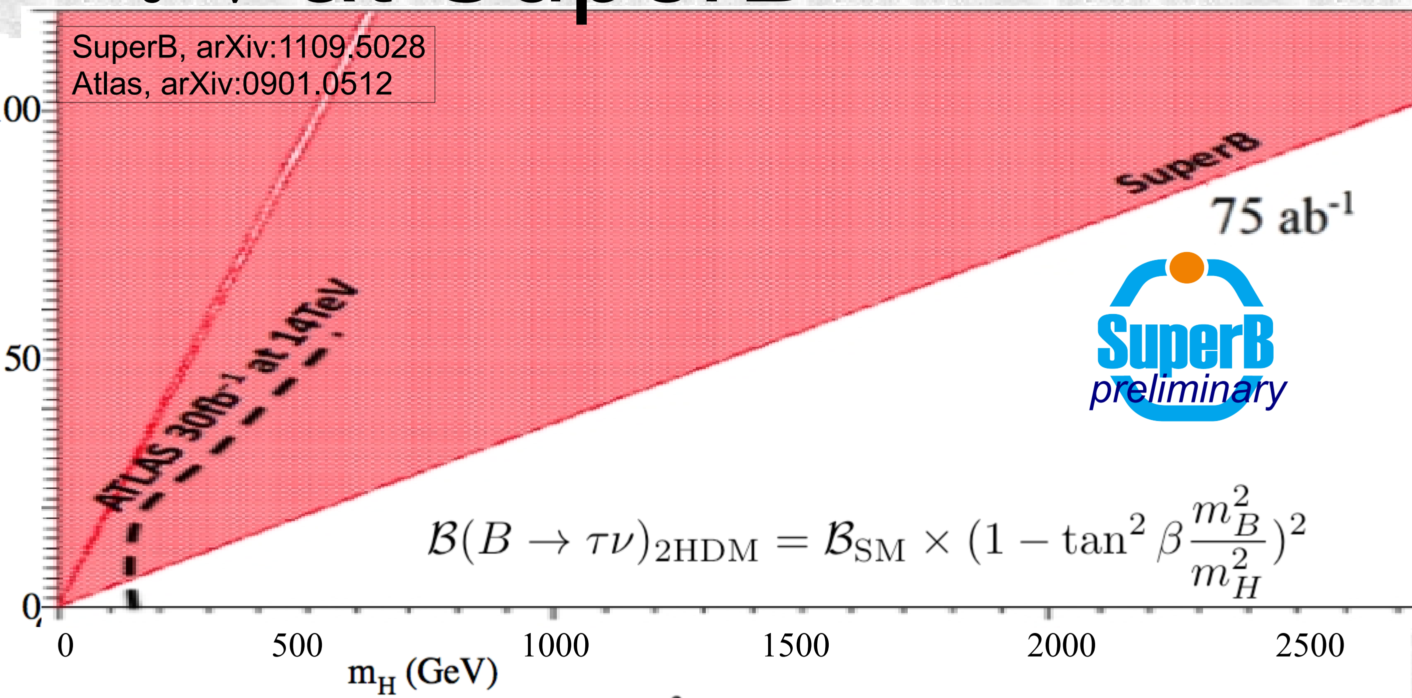
$$(\frac{\delta\mathcal{B}}{\mathcal{B}})_{1.1ab^{-1}} \approx 20\%$$

- $\delta_{syst}$ dominated by statistical origin that scales with luminosity
- Other systematics may be irreducible



# $B^+ \to \tau^+ \nu$ at SuperB




Current world $B \to \tau\nu$ precision:

$$\left(\frac{\delta\mathcal{B}}{\mathcal{B}}\right)_{1.1ab^{-1}} \approx 20\%$$

SuperB $B \to \tau\nu$ precision:

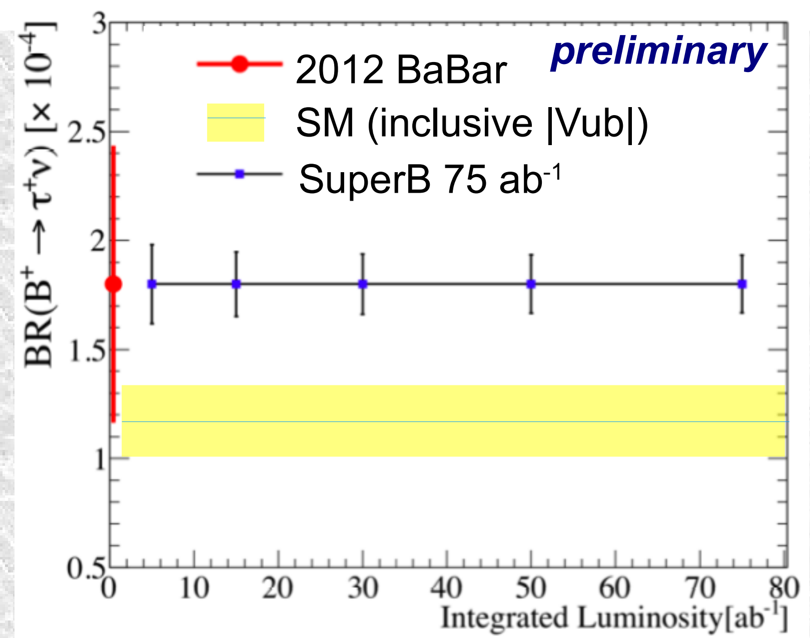
$$\left(\frac{\delta\mathcal{B}}{\mathcal{B}}\right)_{75ab^{-1}} \approx 3-4\%$$

*(limited by exp. systematics)*

SuperB $B \to \mu\nu$ precision (currently unobserved):

$$\left(\frac{\delta\mathcal{B}}{\mathcal{B}}\right)_{75ab^{-1}} \approx 5-6\%$$

BF($B \to \mu\nu$)/BF($B \to \tau\nu$) ratio independent of $f_B$|Vub|

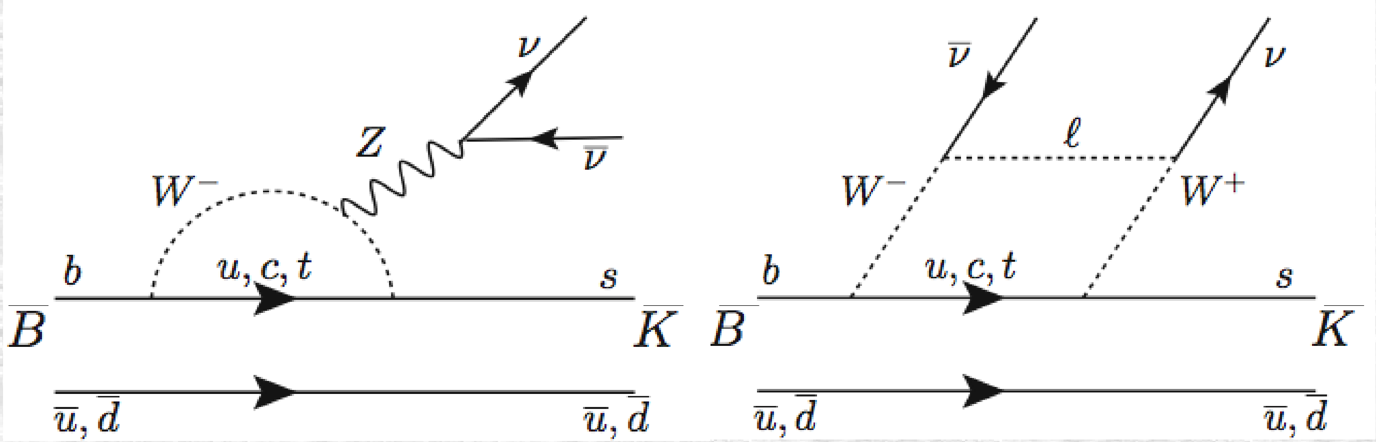



Based on simulation studies by E. Manoni

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

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

Flavor-Changing Neutral Current processes are not allowed at tree-level in SM

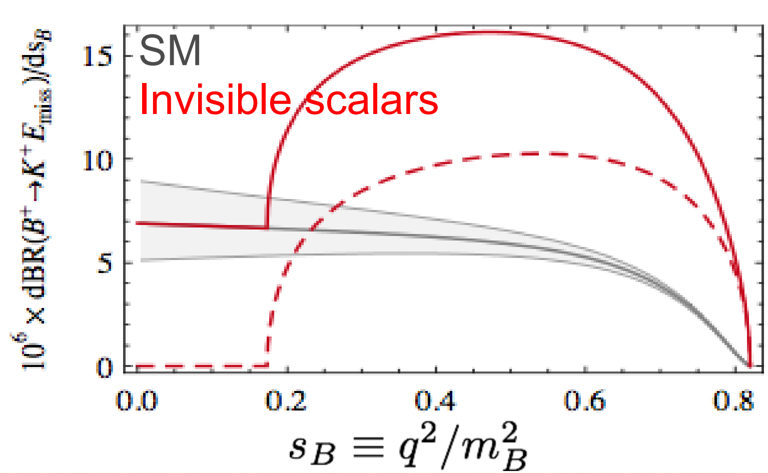


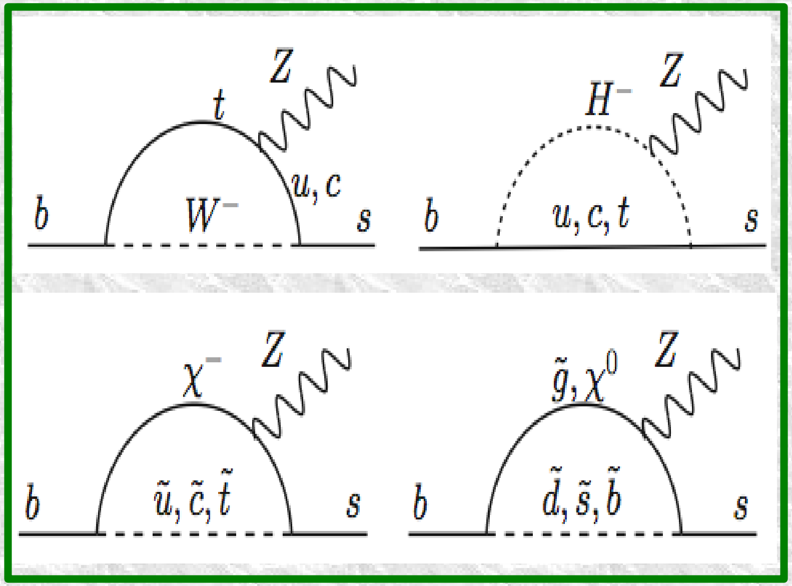

$$\mathcal{B}(B \to K\ \nu\overline{\nu})_{\rm SM} \sim 4 \times 10^{-6}$$
$$\mathcal{B}(B \to K^*\nu\overline{\nu})_{\rm SM} \sim 6 - 13 \times 10^{-6}$$

Branching Fractions can be enhanced at same order as SM:

- Non-standard Z or Z' couplings
- New Physics entering in loops
- New Physics with $K^{(*)}$+invisible signature

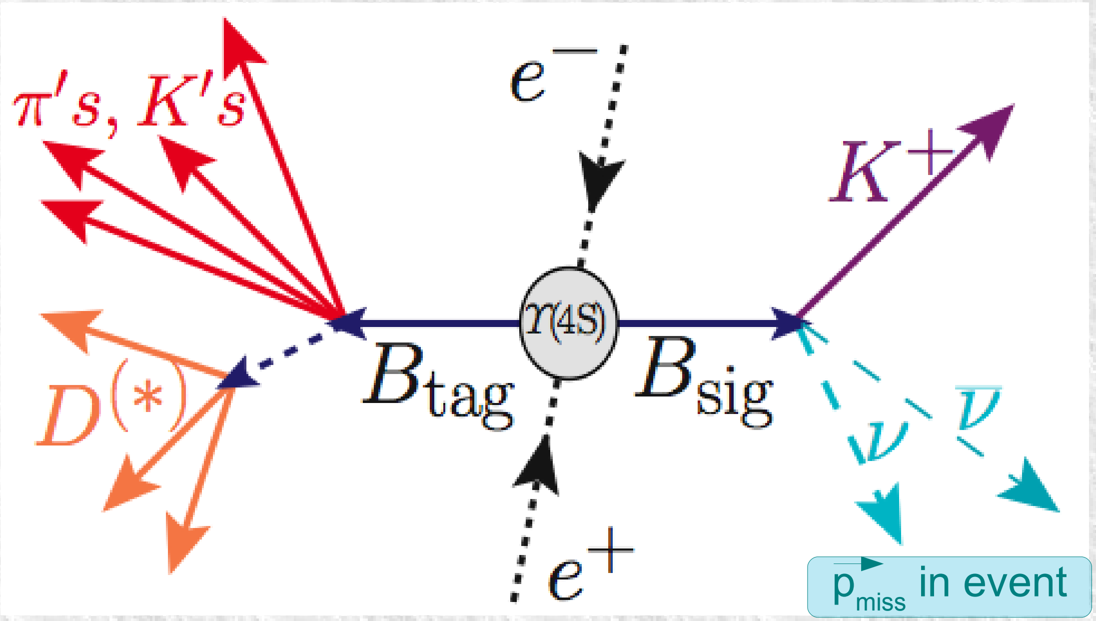
Can also enhance kinematic spectrum!




Altmannshofer, Buras, Straub, Wick
JHEP 0904:022 (2009)

# $B \to K^{(*)} \nu\bar{\nu}$: with Hadronic Tag




- Reconstruct 6 signal channels in rest-of-event:
  - $B \to K^{+} \nu\bar{\nu}$
  - $B \to K_s^{0} \nu\bar{\nu}$
  - $B \to [K^{*+} \to K^{+}\pi^{0}]\, \nu\bar{\nu}$
  - $B \to [K^{*+} \to K_s^{0}\pi^{+}]\, \nu\bar{\nu}$
  - $B \to [K^{*0} \to K^{+}\pi^{-}]\, \nu\bar{\nu}$
  - $B \to [K^{*0} \to K_s^{0}\pi^{0}]\, \nu\bar{\nu}$

- No additional tracks
- Restrict to low values of $E_{extra}$
- Suppress continuum bkg using LHR of 6 event-shape variables
- Define kinematic variable: $s_B = q^2/m_B^2$ (normalized invariant mass of neutrino pair)

# $B \rightarrow K^{(*)} \nu\bar{\nu}$: Results

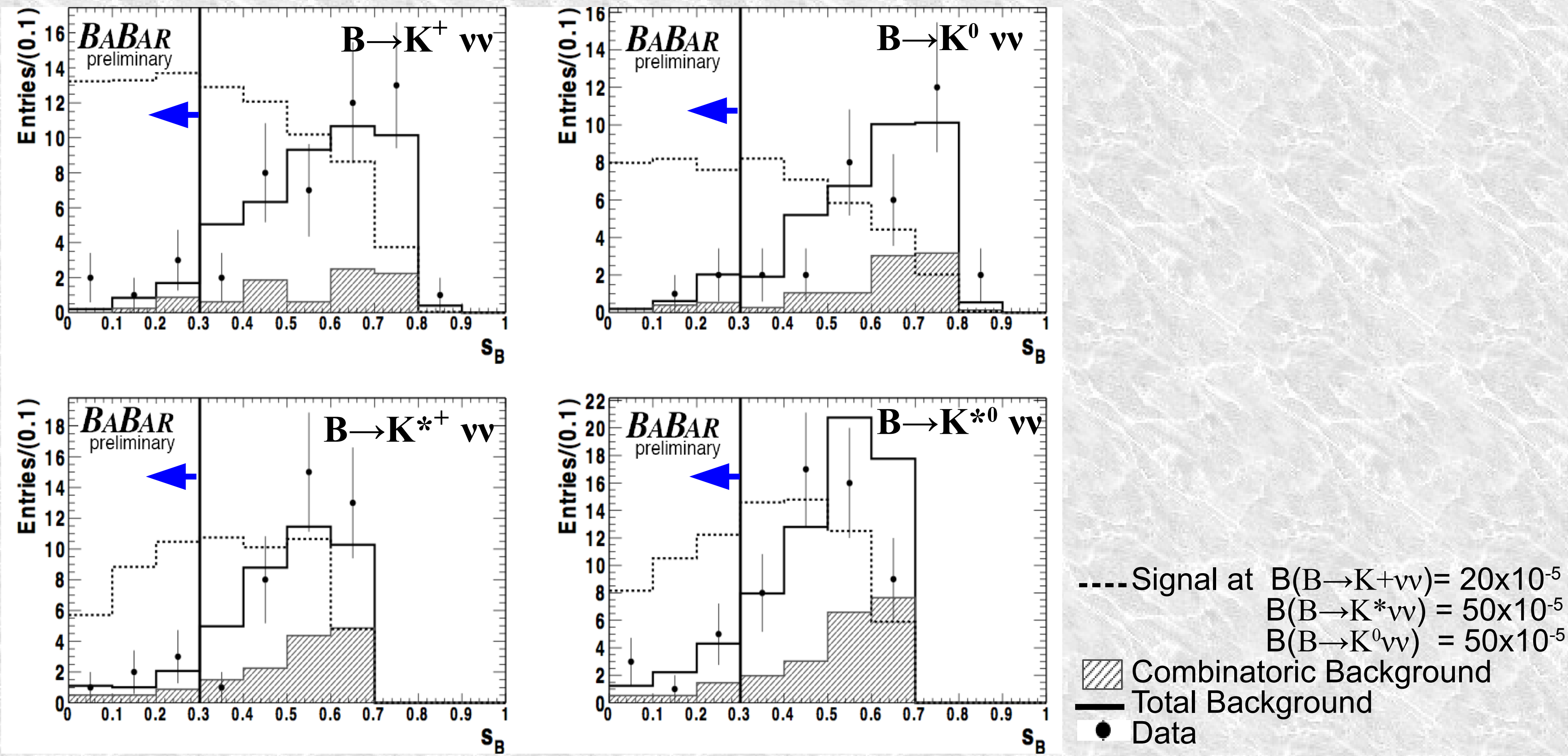
Branching-fraction upper limits at 90% CL within the low $s_B = q^2/m_B^2$ region

| $B \rightarrow K^+ \nu\bar{\nu}$ | $B \rightarrow K^0 \nu\bar{\nu}$ | $B \rightarrow K^{*+} \nu\bar{\nu}$ | $K^{*0} \nu\bar{\nu}$ |
|---|---|---|---|
| (>0.4, < 3.7) | < 8.1 | < 11.6 | < 9.3 |
| (>0.2, < 3.2) | | < 7.9 | |

$\times 10^{-5}$

BABAR preliminary

Most stringent reported limits using hadronic reconstruction



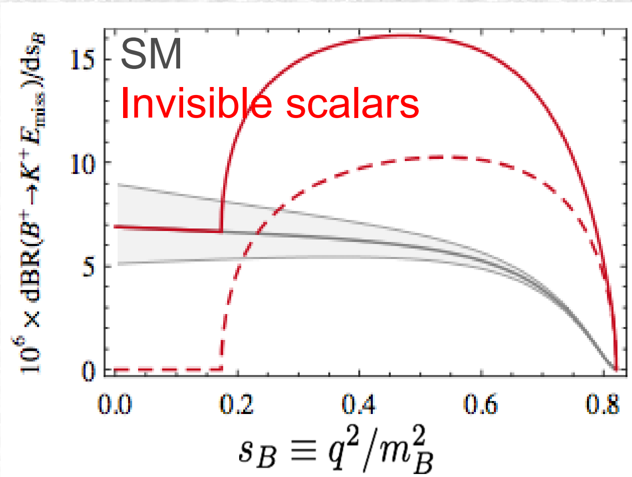
# $B \to K^{(*)}\nu\nu$ Partial Branching Fractions

- Partial branching fractions in bins of $s_B = 0.1$

BF in bin • ε fraction

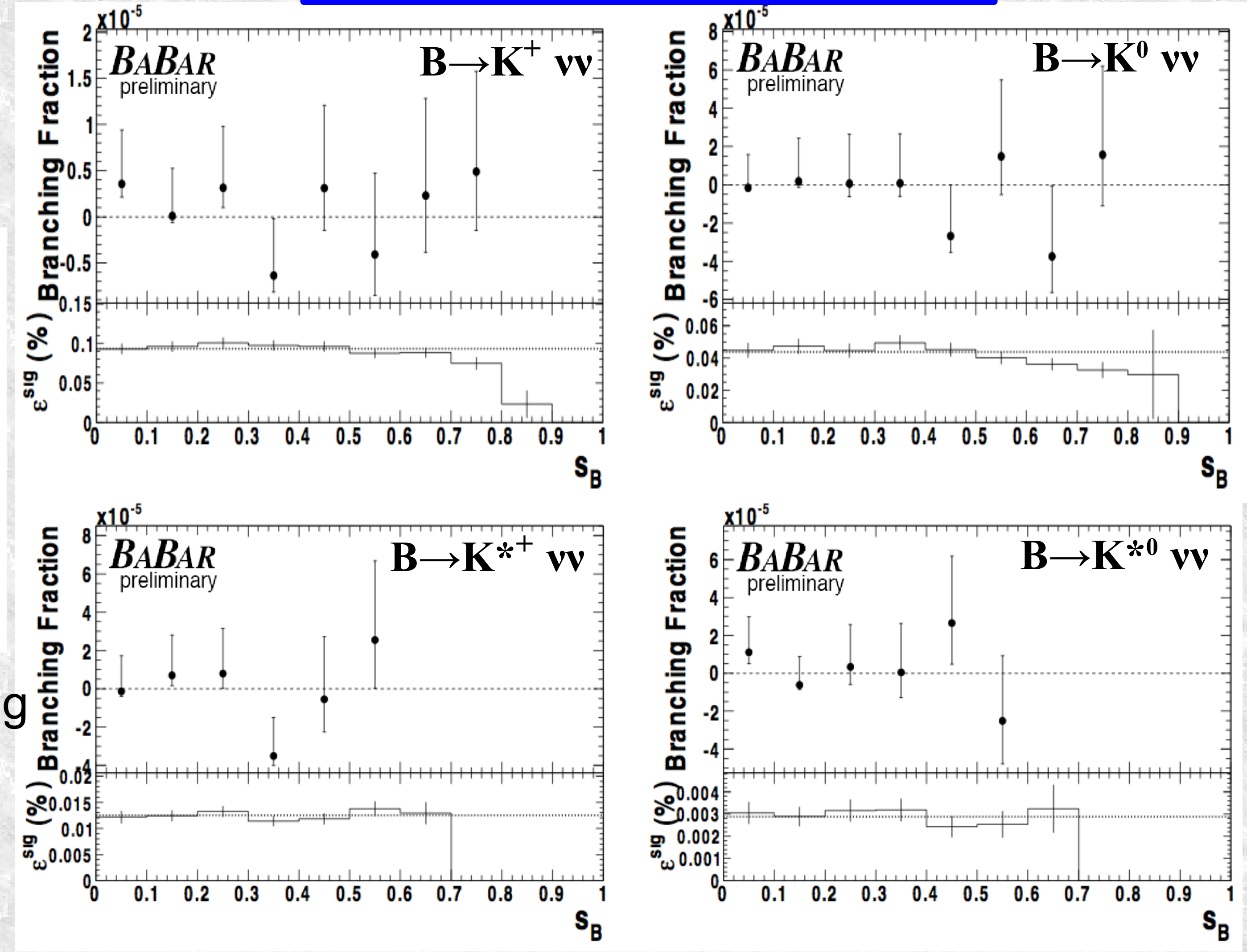
$$\Delta\mathcal{B} = \frac{N^{obs}_{bin} - N^{bkg}_{bin}}{N_B\,\epsilon^{sig}_{bin}} \cdot \frac{\epsilon^{sig}_{bin}}{\epsilon^{sig}_{full}}$$

- Provides model-independent sensitivity to New Physics models




- Upper limits on branching fractions of several NP models at $O(10^{-5})$

*See backup slide for usage example*



# $B \to K^{(*)}\nu\nu$: New Physics Constraints

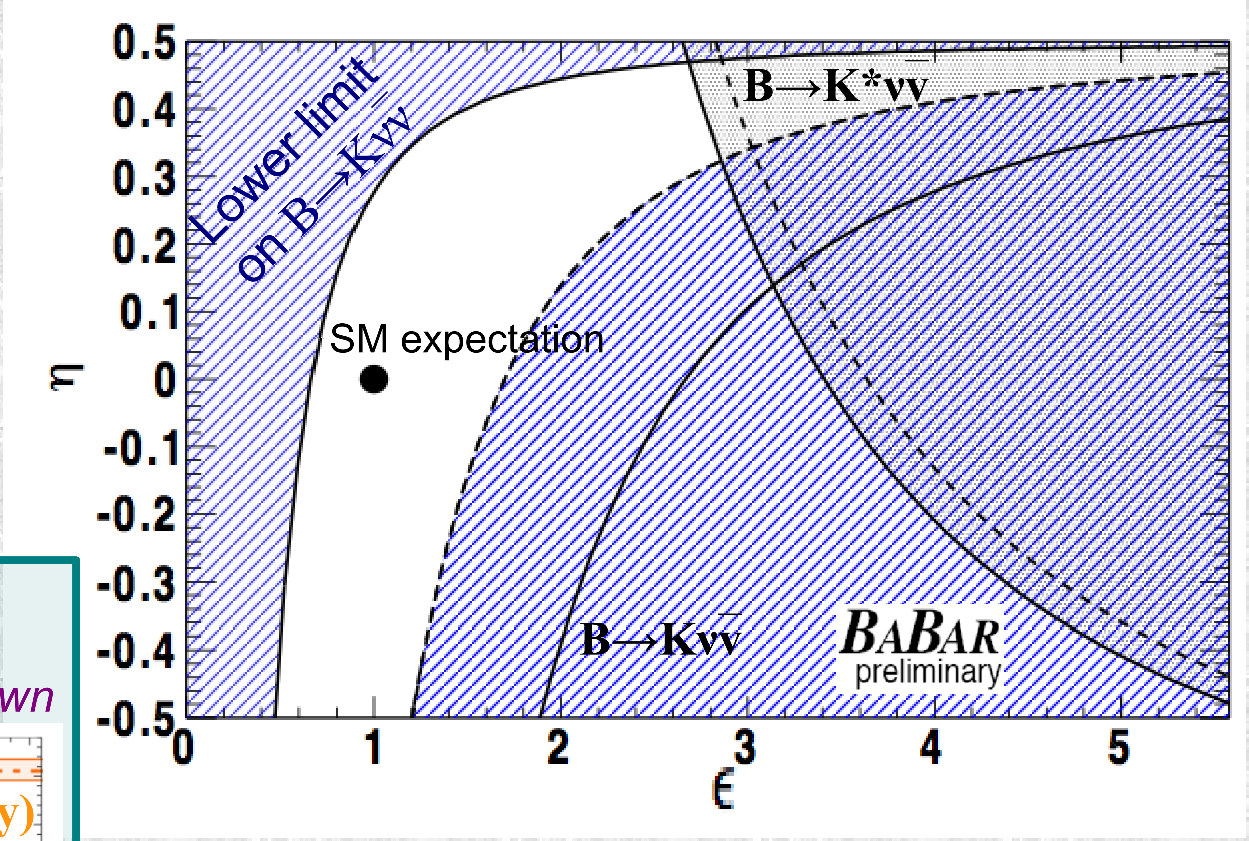
**Wilson Coefficients describing $qq \to \nu\nu$**

$$\epsilon = \frac{\sqrt{|C_L^\nu|^2 + |C_R^\nu|^2}}{|C_{L,\mathrm{SM}}^\nu|}$$

$$\eta = \frac{-\mathrm{Re}(C_L^\nu C_R^{\nu *})}{|C_L^\nu|^2 + |C_R^\nu|^2}$$

$C_R^\nu = 0$ in SM

Altmannshofer, Buras, Straub, Wick
JHEP 0904:022 (2009)



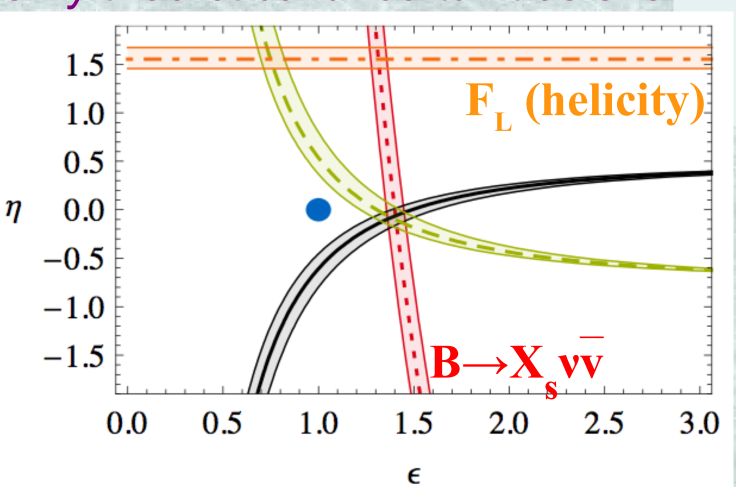

— 2012 analysis constraints
- - - Most stringent previous constraints (SL-tag):

$B+ \to K+\nu\bar{\nu} < 1.3 \times 10^{-5}$ BaBar PRD 78:072007 (2008)

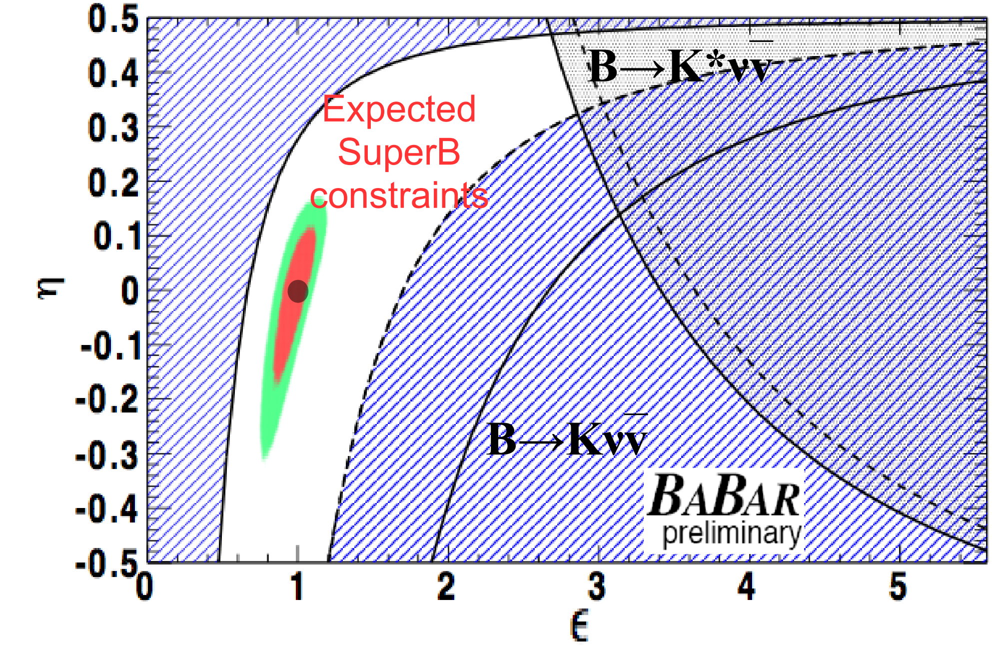
$B+ \to K^*+\nu\bar{\nu} < 9.0 \times 10^{-5}$ BaBar PRD 82:112002 (2010)

New Physics scenario with invisible scalar contributions

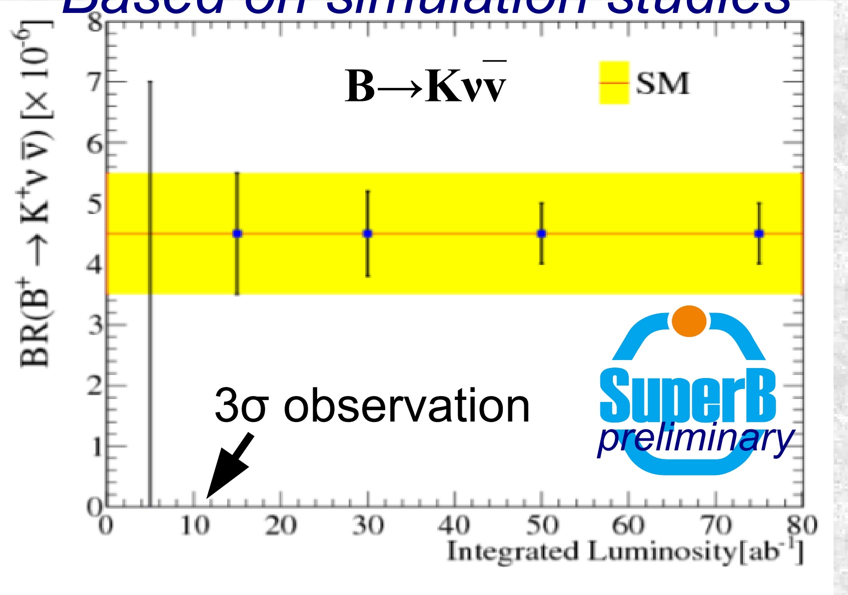
*Only theoretical uncertainties shown*

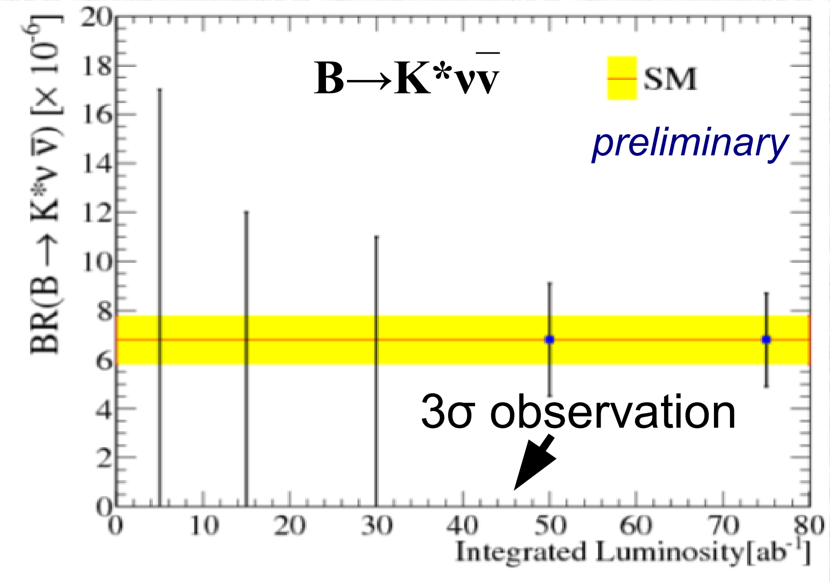


# B→K(*)νν at SuperB



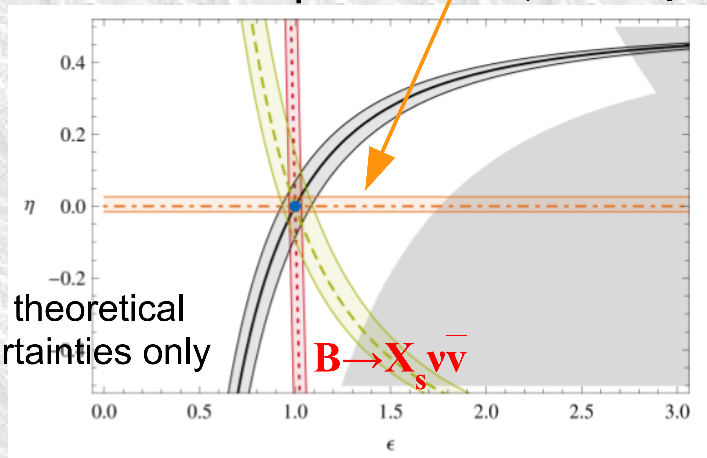

*Based on simulation studies*




arXiv:1008.1541

- Predict 15-20% precision on BF at 75 $ab^{-1}$
- Expect to measure $F_L$ (polarization fraction) of **B→K*νν** to ~50% precision (currently unmeasured)

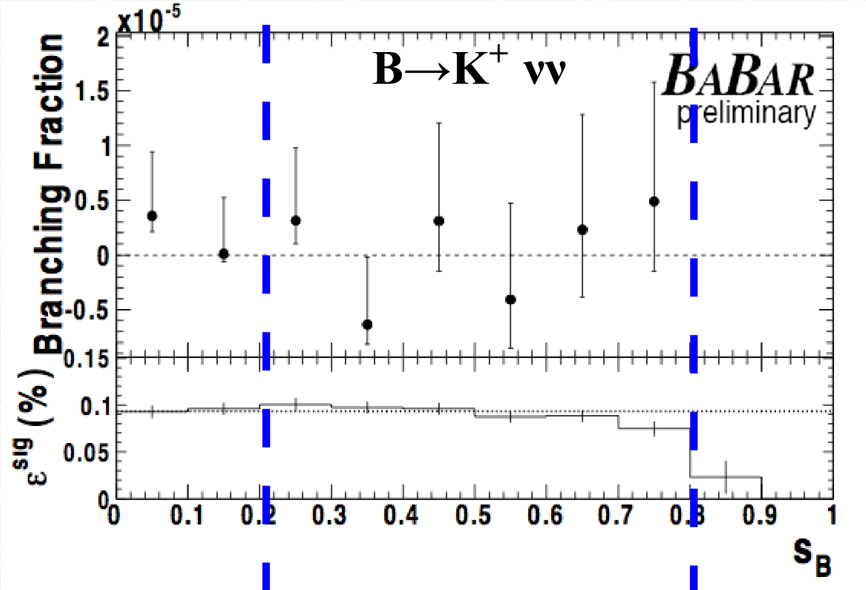


# Conclusions

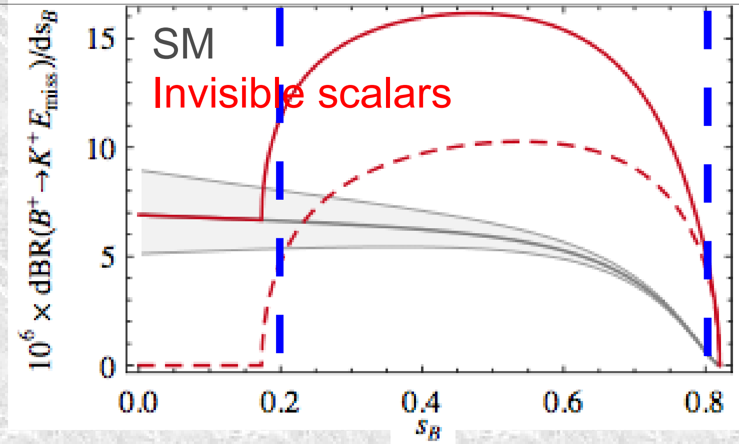
- Using hadronic-tag reconstruction, BaBar recently measured:
- $B \to \tau\nu$ branching fraction: $(1.83^{+0.53}_{-0.49} \pm 0.24) \times 10^{-4}$
  - Consistent with previous BaBar measurements
  - High compared with SM expectations
  - SuperB expects to measure $B \to \mu\nu$ and $B \to \tau\nu$ at 3-6% precision
- $B \to K^{(*)}\nu\bar{\nu}$ branching fraction upper limits
  - Consistent with SM but process unobserved
  - Tighter constraints and partial branching fraction: offer improved sensitivity to New Physics
  - SuperB expects to observe and measure at 15-20% precision, assuming SM rates

# Extra Slides

# $B \to K^{(*)} \nu\bar{\nu}$ Partial BF Example




Altmannshofer, Buras, Straub, Wick, JHEP 0904:022 (2009)




BF in bin • ϵ fraction

$$\Delta\mathcal{B} = \frac{N^{\rm obs}_{\rm bin} - N^{\rm bkg}_{\rm bin}}{N_B\,\epsilon^{\rm sig}_{\rm bin}} \cdot \frac{\epsilon^{\rm sig}_{\rm bin}}{\epsilon^{\rm sig}_{\rm full}}$$

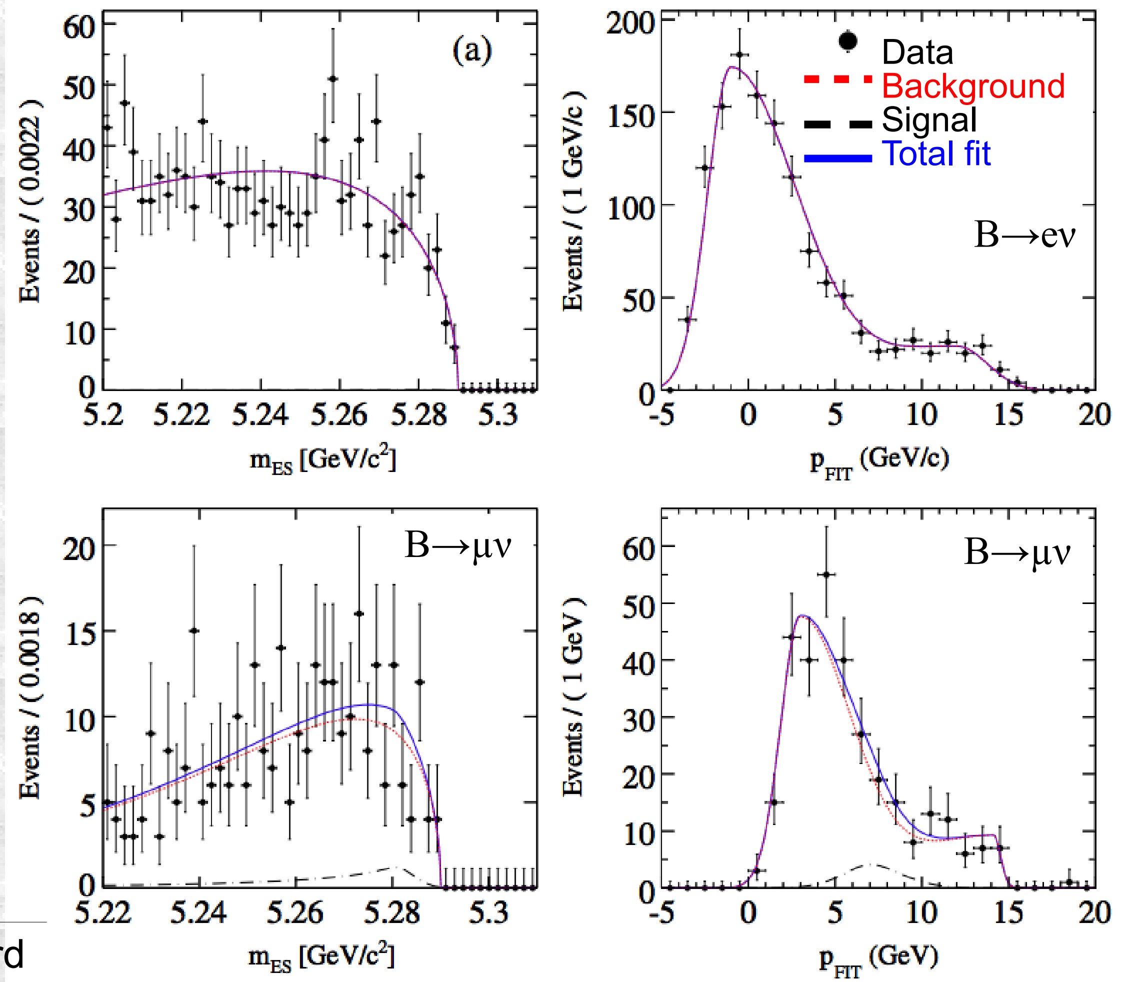
- ϵ fraction ~85% in bins 0.2-0.8 for this invisible scalar model
- Divide "sum" of bins by ϵ fraction: $(0.35^{+3.1}_{-1.5}) \times 10^{-5}$
- Corresponds to Upper Limit at 90% CL of $\sim 4.2 \times 10^{-5}$ for this model

PRD 79:091101 (2009)

# B→ℓν Inclusive Analysis

**Helicity suppressed but clean decay with monoenergetic lepton (2.64 GeV/*c*)**

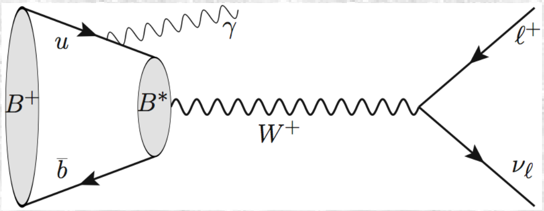
- Assign high momentum lepton (particle ID) and missing energy as signal decay
- Reject events with more leptons.
- Assign $B_{tag}$ as rest of event with requirements on its $\Delta E$ and $p_T$
- Suppress background using Fisher discriminant of kinematic and event-shape variables.
- Extract yield from 2D fit to $m_{ES}$ and $p_{FIT} = a_0 + a_1 p_\ell^{CM} + a_2 p_\ell^{B\_rest}$
- No signal decays were observed.




| 90% CL | BaBar Inclusive | Belle<br>Phys Lett B 647, 67 (2007) | Standard Model |
|---|---|---|---|
| B→eν | $< 1.9\times10^{-6}$ | $< 0.98\times10^{-6}$ | $\sim1\times10^{-11}$ |
| B→μν | $< 1.0\times10^{-6}$ | $< 1.7\times10^{-6}$ | $\sim5\times10^{-7}$ |

PRD 80:111105 (2009)

# B→ℓνγ with Hadronic Tag




$$\mathcal{B}(B \to \ell\nu\gamma) \approx \frac{\alpha_{em} G_F^2}{288\pi^2} |V_{ub}|^2 f_B^2 m_B^5 \tau_B \left( \frac{Q_u}{\lambda_B} + \frac{Q_b}{m_b} \right)^2$$

Korchemsky, Pirjol, & Yan, PRD 61 114510 (2000).

1st inverse moment of B wave function, present in B→π transitions, theoretically uncertain

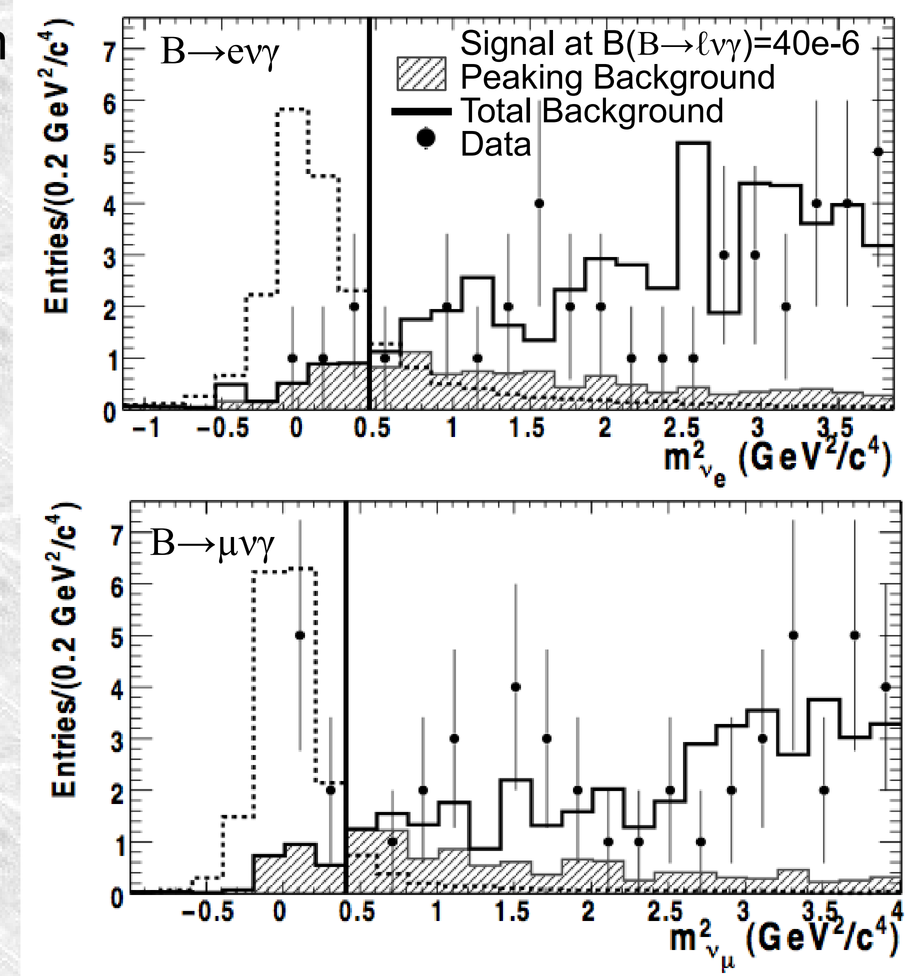
- Reconstruct $B_{tag}$ and suppress continuum using event-shape variables
- Require 1 track, choose highest energy photon, apply $\pi^0$ vetos, restrict ν-ℓ angle
- Restrict neutrino mass $m^2_\nu = |p_B - p_\ell - p_\gamma|^2$
- No requirements on lepton/photon kinematics provides first measurement independent of B→γ form-factor models

$$\mathcal{B}(B \to \ell\nu\gamma) = (6.5^{+7.6+2.8}_{-4.7-0.8}) \times 10^{-6} \text{ at } 2.1\sigma$$

| B→eνγ | B→μνγ | B→ℓνγ | SM |
|---|---|---|---|
| < 17x10$^{-6}$ | < 26x10$^{-6}$ | < 15.6x10$^{-6}$ | 10$^{-6}$ |

Most stringent reported limits (90% CL) to date

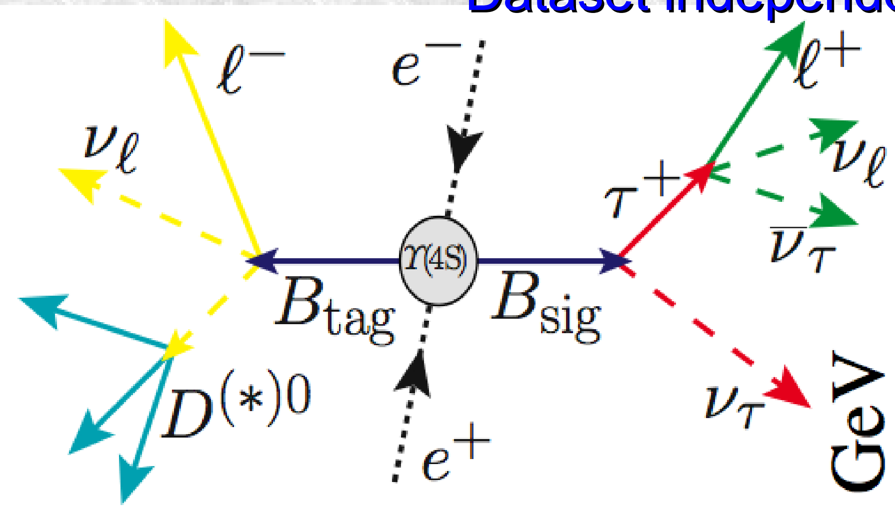
- Also provides model-dependent results by restricting γ-ν and γ-ℓ angles



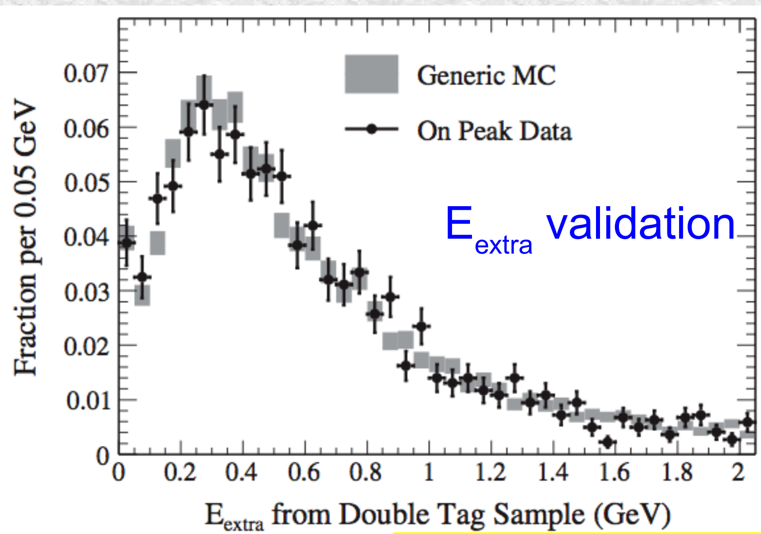
PRD81:051101 (2010)
459 x10^6 B$\overline{B}$

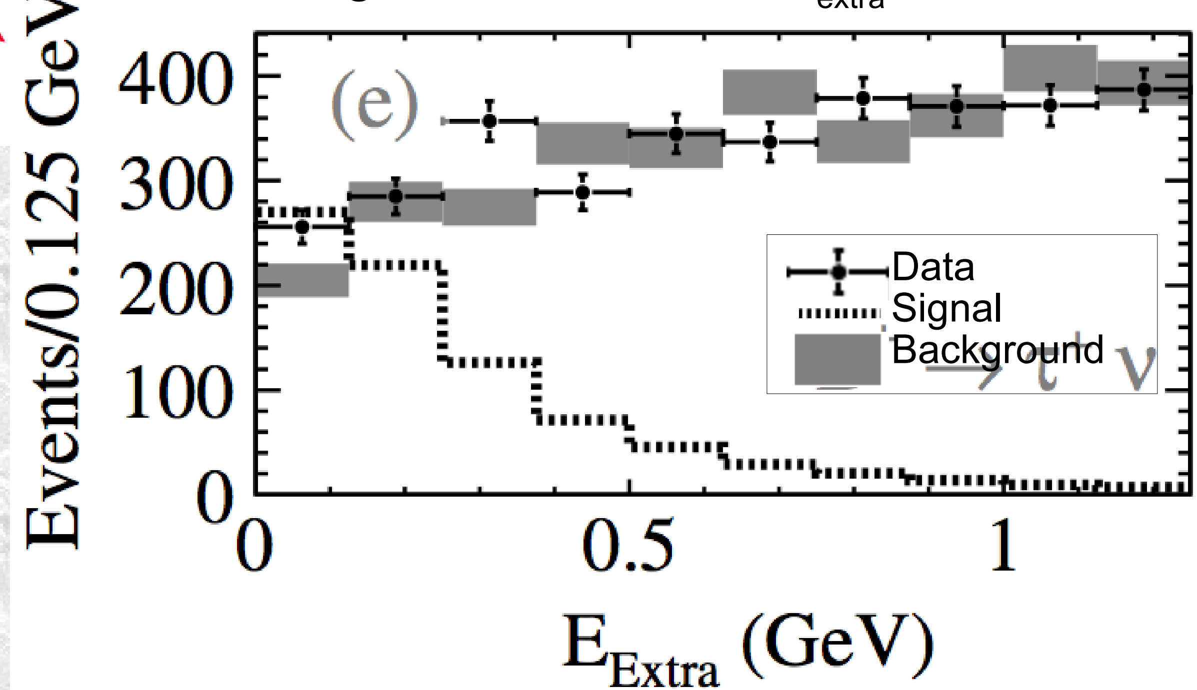
# $B \to \tau\nu$ Semi-Leptonic Tag

**Dataset independent from hadronic analysis!**




- Reconstruct same 4 $\tau$ modes
- Applies signal, continuum and $B\overline{B}$ bkg LHR of many variables in MC
- Background prediction calibrated using data/MC ratio in $E_{extra}$ sideband



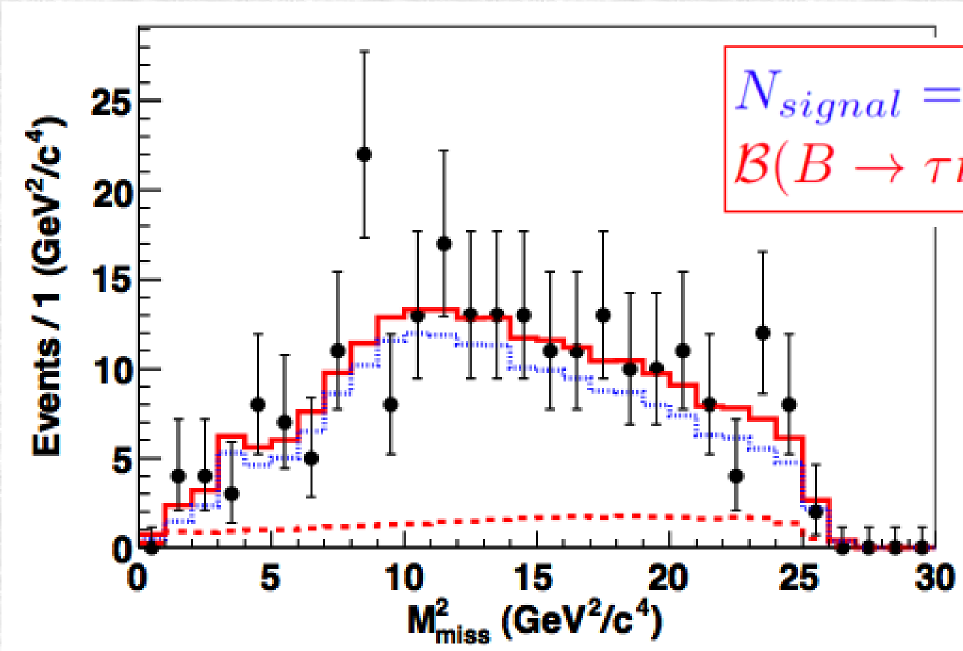




$$\mathcal{B}(B \to \tau\nu) = (1.7 \pm 0.8 \pm 0.2) \times 10^{-4}$$

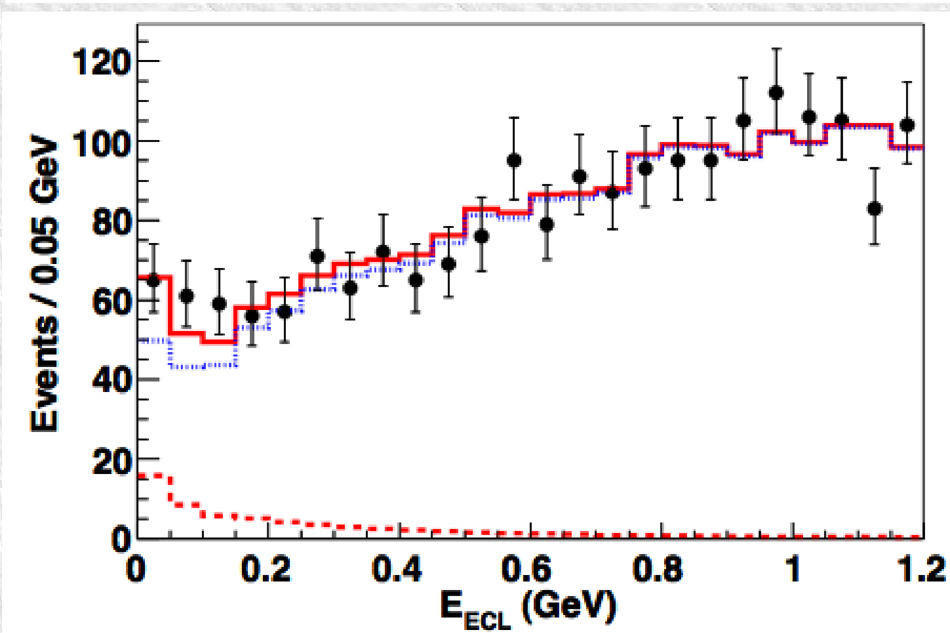
Exclusion of null hypothesis at 2.3 σ

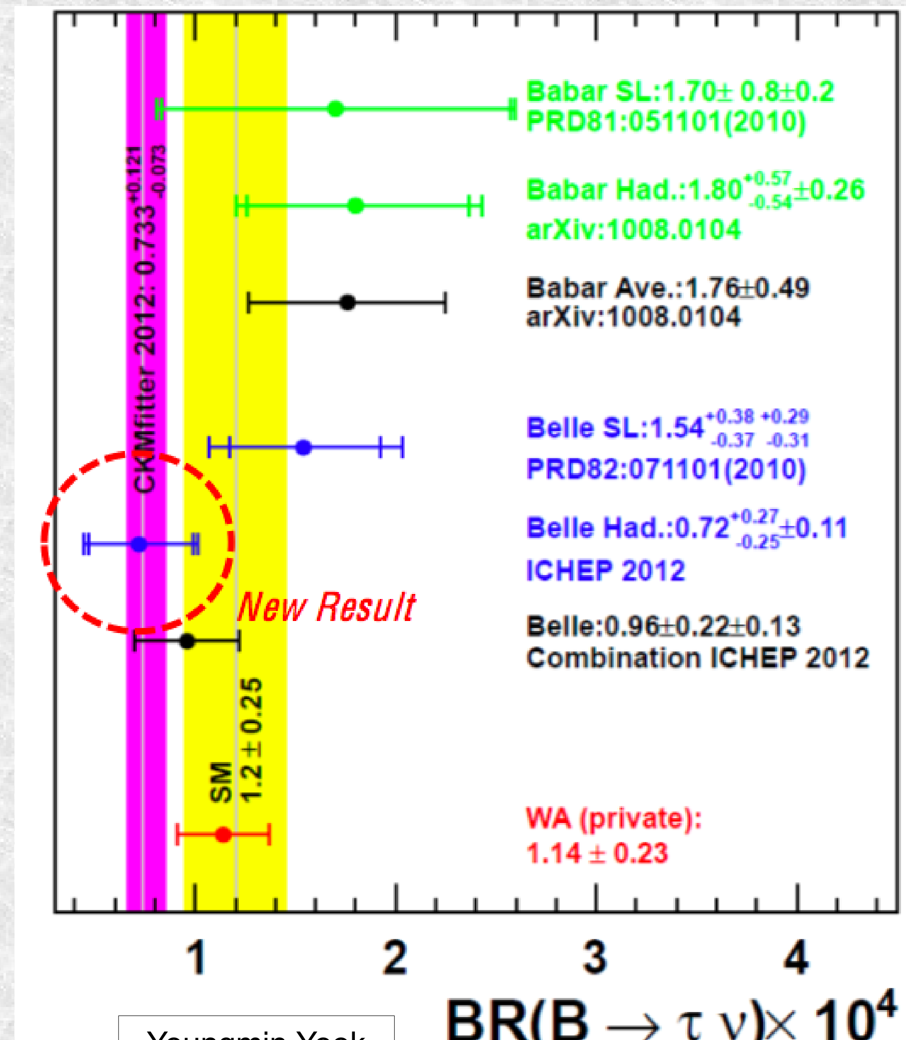
arXiv 1208.4678 (2012)

# Belle B→τν Hadronic Tag




$$N_{signal} = 62.3^{+23.1}_{-21.7}$$
$$\mathcal{B}(B \to \tau\nu) = (0.72^{+0.27}_{-0.25}(\text{stat.}) \pm 0.11(\text{syst.})) \times 10^{-4}$$

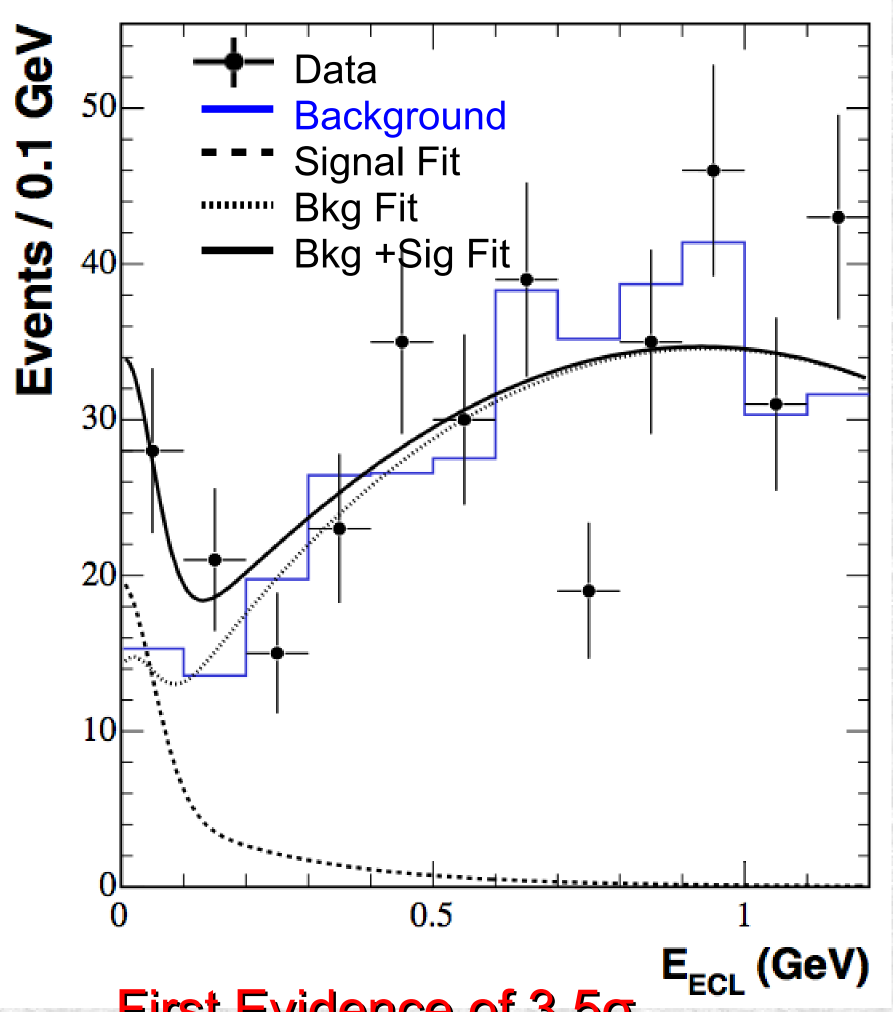



Youngmin Yook
ICHEP 2012

PRL 97 251802 (2006)
449 x$10^6$ $B\bar{B}$

# Belle $B \to \tau\nu$ Hadronic 2006



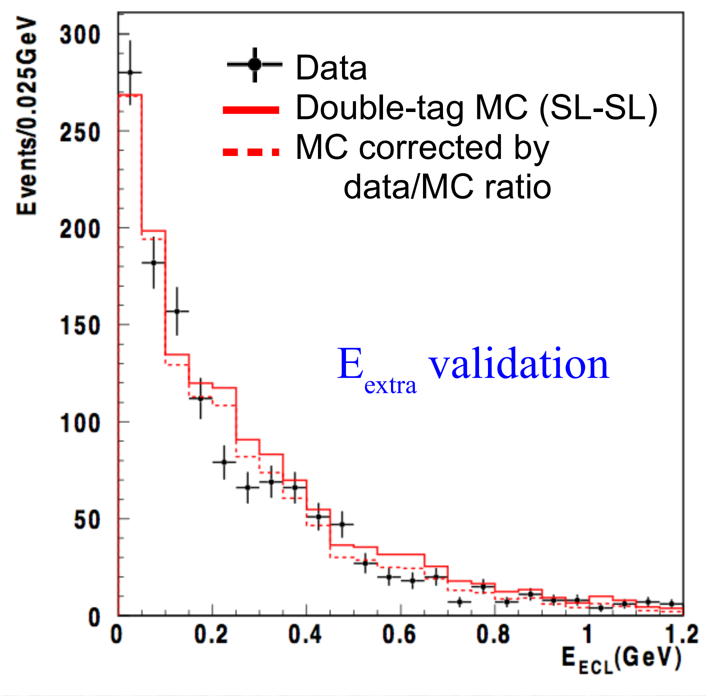

First Evidence of 3.5σ

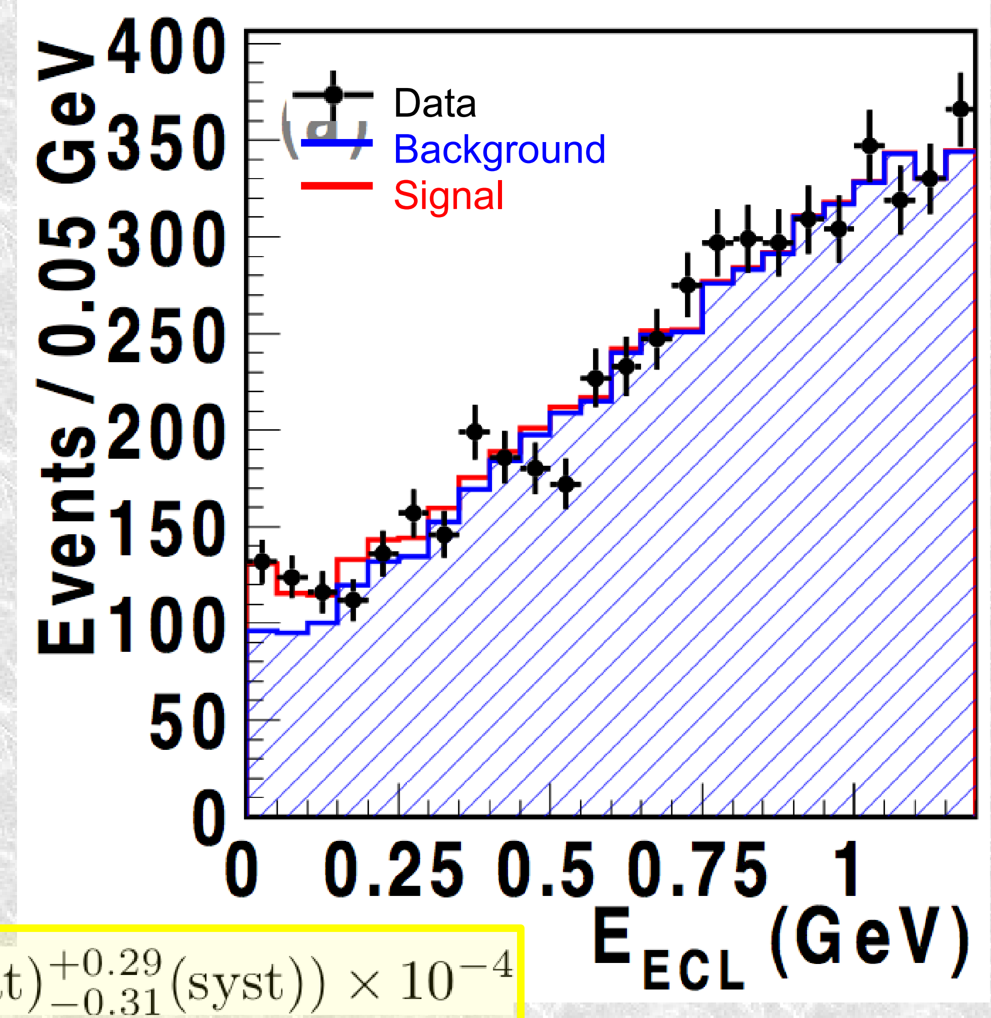
$$\mathcal{B}(B \to \tau\nu) = (1.79^{+0.56}_{-0.49}(\text{stat})^{+0.46}_{-0.51}(\text{syst})) \times 10^{-4}$$

arXiv:1006.4201 (2010)
657 x$10^6$ $B\bar{B}$

# Belle $B \to \tau\nu$ Semi-Leptonic Tag

- Reconstruct $e\nu\bar{\nu}$, $\mu\nu\bar{\nu}$, and $\pi\nu$ (50% of $\tau$ modes)
- Requirements on $\tau$ momentum and $\cos\theta_{B,D\ell}$
- MC corrected for data/MC ratio using double-tagged $E_{extra}$
- Signal and bkg PDFs from MC. Continuum MC corrected using off-resonance data




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

Exclusion of null hypothesis at 3.6 σ

# Channel Details

BaBar preliminary

| Variable | $e^+$ | $\mu^+$ | $\pi^+$ | $\rho^+$ |
|---|---|---|---|---|
| $\mathcal{P}$ | $> 10\%$ | | | |
| Cluster energy (MeV) | $> 60$ | | | |
| $\mathcal{R}2$ | $< 0.57$ | $< 0.56$ | $< 0.56$ | $< 0.51$ |
| $\lvert\cos\theta_{TB}\rvert$ | $< 0.95$ | $< 0.90$ | $< 0.65$ | $< 0.8$ |
| $L_P$ | | | $> 0.30$ | $> 0.45$ |

| Decay Mode | $\epsilon_k(\times10^{-4})$ | Signal yield | $\mathcal{B}(\times10^{-4})$ |
|---|---|---|---|
| $\tau^+ \to e^+\nu\bar{\nu}$ | $2.47 \pm 0.14$ | $4.1 \pm 9.1$ | $0.35^{+0.84}_{-0.73}$ |
| $\tau^+ \to \mu^+\nu\bar{\nu}$ | $2.45 \pm 0.14$ | $12.9 \pm 9.7$ | $1.12^{+0.90}_{-0.78}$ |
| $\tau^+ \to \pi^+\nu$ | $0.98 \pm 0.14$ | $17.1 \pm 6.2$ | $3.69^{+1.42}_{-1.22}$ |
| $\tau^+ \to \rho^+\nu$ | $1.35 \pm 0.11$ | $24.0 \pm 10.0$ | $3.78^{+1.65}_{-1.45}$ |
| combined | | $62.1 \pm 17.3$ | $1.83^{+0.53}_{-0.49}$ |

| | $B^+ \to K^+\nu\bar{\nu}$ | $B^0 \to K^0\nu\bar{\nu}$ |
|---|---|---|
| $N_i^{\rm comb}$ | $1.1 \pm 0.4 \pm 0.0$ | $0.9 \pm 0.4 \pm 0.1$ |
| $N_i^{\rm peak}$ | $1.8 \pm 0.4 \pm 0.1$ | $2.0 \pm 0.5 \pm 0.2$ |
| $N_i^{\rm bkg}$ | $2.9 \pm 0.6 \pm 0.1$ | $2.9 \pm 0.6 \pm 0.2$ |
| $\varepsilon_i^{\rm sig}$ $(\times10^{-5})$ | $43.8 \pm 0.7 \pm 3.0$ | $10.3 \pm 0.2 \pm 1.2$ |
| $N_i^{\rm obs}$ | 6 | 3 |
| Limits | $(> 0.4, < 3.7) \times 10^{-5}$ | $< 8.1 \times 10^{-5}$ |
| $\mathcal{B}_i$ | $(1.5^{+1.7+0.4}_{-0.8-0.2}) \times 10^{-5}$ | $(0.14^{+6.0+1.7}_{-1.9-0.9}) \times 10^{-5}$ |
| Combined Limits | $(> 0.2, < 3.2) \times 10^{-5}$ | |
| $\mathcal{B}(B \to K\nu\bar{\nu})$ | $(1.4^{+1.4+0.3}_{-0.9-0.2}) \times 10^{-5}$ | |

| | $B^+ \to [K^+\pi^0]\nu\bar{\nu}$ | $B^+ \to [K^0_S\pi^+]\nu\bar{\nu}$ | $B^0 \to [K^+\pi^-]\nu\bar{\nu}$ | $B^0 \to [K^0_S\pi^0]\nu\bar{\nu}$ |
|---|---|---|---|---|
| $N_i^{\rm comb}$ | $0.8 \pm 0.3 \pm 0.0$ | $1.1 \pm 0.4 \pm 0.0$ | $2.0 \pm 0.5 \pm 0.1$ | $0.5 \pm 0.3 \pm 0.0$ |
| $N_i^{\rm peak}$ | $1.3 \pm 0.4 \pm 0.1$ | $1.2 \pm 0.4 \pm 0.1$ | $5.0 \pm 0.8 \pm 0.5$ | $0.2 \pm 0.2 \pm 0.0$ |
| $N_i^{\rm bkg}$ | $2.0 \pm 0.5 \pm 0.1$ | $2.3 \pm 0.5 \pm 0.1$ | $7.0 \pm 0.9 \pm 0.5$ | $0.7 \pm 0.3 \pm 0.0$ |
| $\varepsilon_i^{\rm sig}$ $(\times10^{-5})$ | $6.0 \pm 0.2 \pm 0.5$ | $4.9 \pm 0.2 \pm 0.4$ | $12.2 \pm 0.3 \pm 1.4$ | $1.2 \pm 0.1 \pm 0.1$ |
| $N_i^{\rm obs}$ | 3 | 3 | 7 | 2 |
| Limits | $< 17.0 \times 10^{-5}$ | $< 19.4 \times 10^{-5}$ | $< 8.9 \times 10^{-5}$ | $< 86 \times 10^{-5}$ |
| $\mathcal{B}_i$ | $(3.5^{+10.4+2.5}_{-3.2-1.2}) \times 10^{-5}$ | $(3.0^{+12.5+3.1}_{-3.9-1.5}) \times 10^{-5}$ | $(0.08^{+6.6+2.3}_{-3.1-1.5}) \times 10^{-5}$ | $(23^{+47+15}_{-11-4}) \times 10^{-5}$ |
| Combined Limits | $< 11.6 \times 10^{-5}$ | | $< 9.3 \times 10^{-5}$ | |
| $\mathcal{B}(B^{+/0} \to K^{*+/0}\nu\bar{\nu})$ | $(3.3^{+6.2+1.7}_{-3.6-1.3}) \times 10^{-5}$ | | $(2.0^{+5.2+2.0}_{-4.3-1.7}) \times 10^{-5}$ | |
| Combined Limits | $< 7.9 \times 10^{-5}$ | | | |
| $\mathcal{B}(B \to K^*\nu\bar{\nu})$ | $(2.7^{+3.8+1.2}_{-2.9-1.0}) \times 10^{-5}$ | | | |

# Systematics

BABAR preliminary

| Source of systematics | $\mathcal{B}$ uncertainty (%) |
|---|---|
| Additive | |
| Background PDF | 10 |
| Signal PDF | 2.6 |
| Multiplicative | |
| Tag-$B$ efficiency | 5.0 |
| $B$ counting | 1.1 |
| Electron identification | 2.6 |
| Muon identification | 4.7 |
| Kaon identification | 0.4 |
| Tracking | 0.5 |
| MC statistics | 0.6 |
| Total | 13 |

| Source | $K^+$ | $[K^+\pi^0]$ | $[K^0_S\pi^+]$ | $K^0_S$ | $[K^+\pi^-]$ | $[K^0_S\pi^0]$ |
|---|---|---|---|---|---|---|
| $\varepsilon_i^{\rm sig}$ normalization | 3.5 | 3.5 | 3.5 | 8.9 | 8.9 | 8.9 |
| $N_i^{\rm bkg}$ normalization | 2.3 | 2.3 | 2.3 | 6.0 | 6.0 | 6.0 |
| $N_i^{\rm peak}$ $\mathcal{B}$s | 2.8 | 2.8 | 2.8 | 2.8 | 2.8 | 2.8 |
| $K^0_S$ reconstruction | – | – | 1.4 | 1.4 | – | 1.4 |
| $K^*$ reconstruction | – | 2.8 | 2.8 | – | 2.8 | 2.8 |
| $\pi^0$ reconstruction | – | 3.0 | – | – | – | 3.0 |
| $E_{\rm extra}$ shape | 4.5 | 6.0 | 6.5 | 6.0 | 6.0 | 6.5 |
| $s_B$ resolution | 3.6 | 3.6 | 3.6 | 3.6 | 3.6 | 3.6 |
| Total $N_i^{\rm peak}$ syst. | 6.8 | 8.9 | 8.8 | 9.7 | 10.0 | 10.9 |
| Total $N_i^{\rm comb}$ syst. | 2.3 | 2.3 | 2.3 | 6.0 | 6.0 | 6.0 |
| Total $\varepsilon_i^{\rm sig}$ syst. | 6.7 | 8.8 | 8.8 | 11.4 | 11.7 | 12.4 |

# Future Reach of SuperB and LHCb

Experiment: Red = No Result, Yellow = Moderate Precision, Green = Precise, Blue = Very Precise

Theory: Yellow = Moderately Clean, Green = Clean, Needs Lattice, Blue = Clean

| Observable/mode | Current (now) | LHCb (2017) | SuperB (2021) | LHCb upgrade (2030?) | theory | |
|---|---|---|---|---|---|---|
| **$\tau$ Decays** | | | | | | |
| $\tau \to \mu\gamma$ | yellow | yellow | green | yellow | green | Benefit from polarized e- beam |
| $\tau \to e\gamma$ | yellow | yellow | green | yellow | green | |
| **$B_{u,d}$ Decays** | | | | | | |
| $B \to \tau\nu, \mu\nu$ | yellow | red | blue | red | blue | Very precise with improved detector |
| $B \to K^{(*)+}\nu\bar{\nu}$ | red | red | green | red | green | Statistically limited |
| $S$ in $B \to K^0_S\pi^0\gamma$ | yellow | red | green | red | yellow | Right handed currents |
| $S$ in other penguin modes | yellow | yellow | green | blue | yellow | SuperB measures more modes |
| $A_{CP}(B \to X_s\gamma)$ | blue | yellow | green | yellow | green | Systematic error is main challenge |
| $BR(B \to X_s\gamma)$ | blue | yellow | green | yellow | yellow | Control systematic error with data |
| $BR(B \to X_s\ell\ell)$ | yellow | red | green | red | green | |
| $BR(B \to K^{(*)}\ell\ell)$ | yellow | blue | green | green | yellow | SuperB measures e mode well, LHCb does μ |
| **$B_s$ Decays** | | | | | | |
| $B_s \to \mu\mu$ | red | blue | red | green | green | |
| $\beta_s$ from $B_s \to J/\psi\phi$ | red | blue | red | green | green | |
| $B_s \to \gamma\gamma$ | red | red | blue | red | green | |
| $a_{sl}$ | red | red | green | red | green | |
| **$D$ Decays** | | | | | | |
| mixing parameters | yellow | blue | green | green | green | |
| CPV | red | blue | green | green | green | Clean NP search |
| **Precision EW** | | | | | | |
| $\sin^2\theta_W$ at $\Upsilon(4S)$ | red | red | green | red | green | Theoretically clean |
| $\sin^2\theta_W$ at Z-pole | red | blue | red | green | yellow | B fragmentation limits interpretation |

# Previous Measurements

| Observable | BaBar | Belle |
|---|---|---|
| $BR(B^+ \to \tau^+ \nu_\tau)$ (SL) | $(1.7 \pm 0.8 \pm 0.2) \times 10^{-4}$ [11] | $(1.54^{+0.38+0.29}_{-0.37-0.31} \times 10^{-4}$ [12] |
| $BR(B^+ \to \tau^+ \nu_\tau)$ (HD) | $(1.8^{+0.57}_{-0.54} \pm 0.26) \times 10^{-4}$ [13] | $(1.79^{+0.56+0.46}_{-0.49-0.51}) \times 10^{-4}$ [14] |
| $BR(B^+ \to e^+ \nu_e)$ (SL) | $< 0.8 \times 10^{-5}$ [11] | — |
| $BR(B^+ \to e^+ \nu_e)$ (HD) | $< 1.9 \times 10^{-6}$ [15] | $< 0.98 \times 10^{-6}$ [16] |
| $BR(B^+ \to \mu^+ \nu_\mu)$ (SL) | $< 1.1 \times 10^{-5}$ [11] | — |
| $BR(B^+ \to \mu^+ \nu_\mu)$ (HD) | $< 1.0 \times 10^{-6}$ [15] | $< 1.70 \times 10^{-6}$ [16] |

| Collaboration | Year | $N_{B\bar{B}}$ pairs $(\times 10^6)$ | Tag | $\mathcal{B}(B \to K^+ \nu\bar{\nu})$ $(\times 10^{-5})$ | $\mathcal{B}(B \to K^0_S \nu\bar{\nu})$ $(\times 10^{-5})$ | $\mathcal{B}(B \to K^{*+} \nu\bar{\nu})$ $(\times 10^{-5})$ | $\mathcal{B}(B \to K^{*0} \nu\bar{\nu})$ $(\times 10^{-5})$ |
|---|---|---|---|---|---|---|---|
| BABAR [23] | 2005 | 89 | SL | $< 7$ | – | – | – |
| BABAR [23] | 2005 | 89 | Had | $< 6.7$ | – | – | – |
| Belle [24] | 2007 | 535 | Had | $< 1.4$ | $< 16$ | $< 14$ | $< 34$ |
| BABAR [25] | 2008 | 454 | SL | – | – | $< 9$ | $< 18$ |
| BABAR [25] | 2008 | 454 | Had | – | – | $< 21$ | $< 11$ |
| BABAR [26] | 2010 | 459 | SL | $< 1.3$ | $< 5.6$ | – | – |

$$BR(B \to K^* \nu\bar{\nu}) = 6.8 \times 10^{-6} (1 + 1.31\,\eta)\epsilon^2 ,$$

$$BR(B \to K \nu\bar{\nu}) = 4.5 \times 10^{-6} (1 - 2\,\eta)\epsilon^2 ,$$

$$BR(B \to X_s \nu\bar{\nu}) = 2.7 \times 10^{-5} (1 + 0.09\,\eta)\epsilon^2 ,$$

$$\langle F_L \rangle = 0.54 \frac{(1 + 2\,\eta)}{(1 + 1.31\,\eta)} .$$

Altmannshofer, Buras, Straub, Wick, JHEP 0904:022 (2009)

# More Exclusion Plots

B→D(*)τν