SLAC-WP-088

Indirect Charged Higgs Constraints from *BABAR*

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SLAC National Accelerator Laboratory, Menlo Park, CA 94025

Indirect constraints

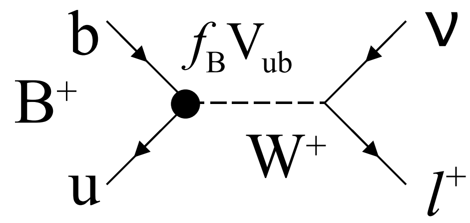
Indirect charged Higgs limits obtained from B decay measurements:

- Comparatively large coupling to charge Higgs due to mass of b quark

Large-tanβ region accessible via tree level processes:

- Leptonic decays of heavy pseudoscalar mesons:

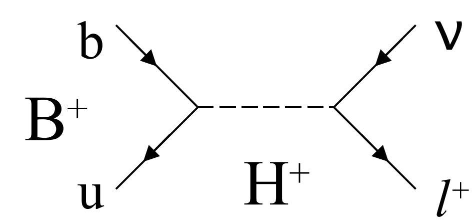
$$\mathcal{B}r(B^+ \to \ell^+ \nu_\ell) = \frac{G_f^2}{8\pi} |V_{ub}|^2 f_B^2 m_B m_\ell^2 \tau_B \left(1 - \frac{m_\ell^2}{m_B^2}\right)^2$$



  - Charged Higgs (2HDM) modifies SM Br by a multiplicative factor which is independent of lepton flavor:

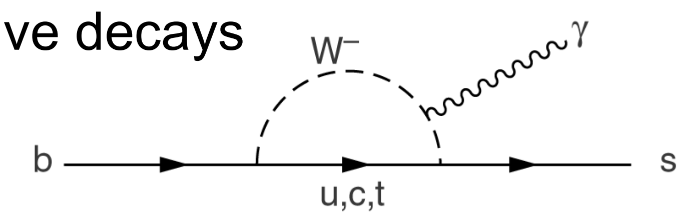
$$r_{H+} = [\ 1 - \tan^2\beta\ (m^2_B/m^2_{H+})\ ]^2$$

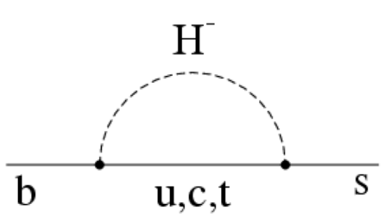
W.S.Hou Phys. Rev. D48, 2342 (1993)



FCNC SM processes can have sizable new physics contributions:

- Radiative decays

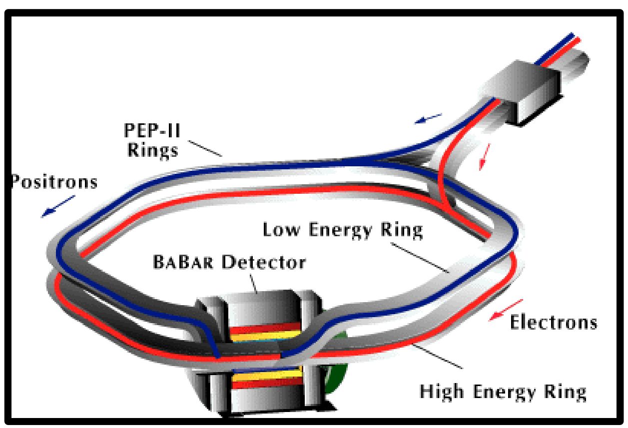


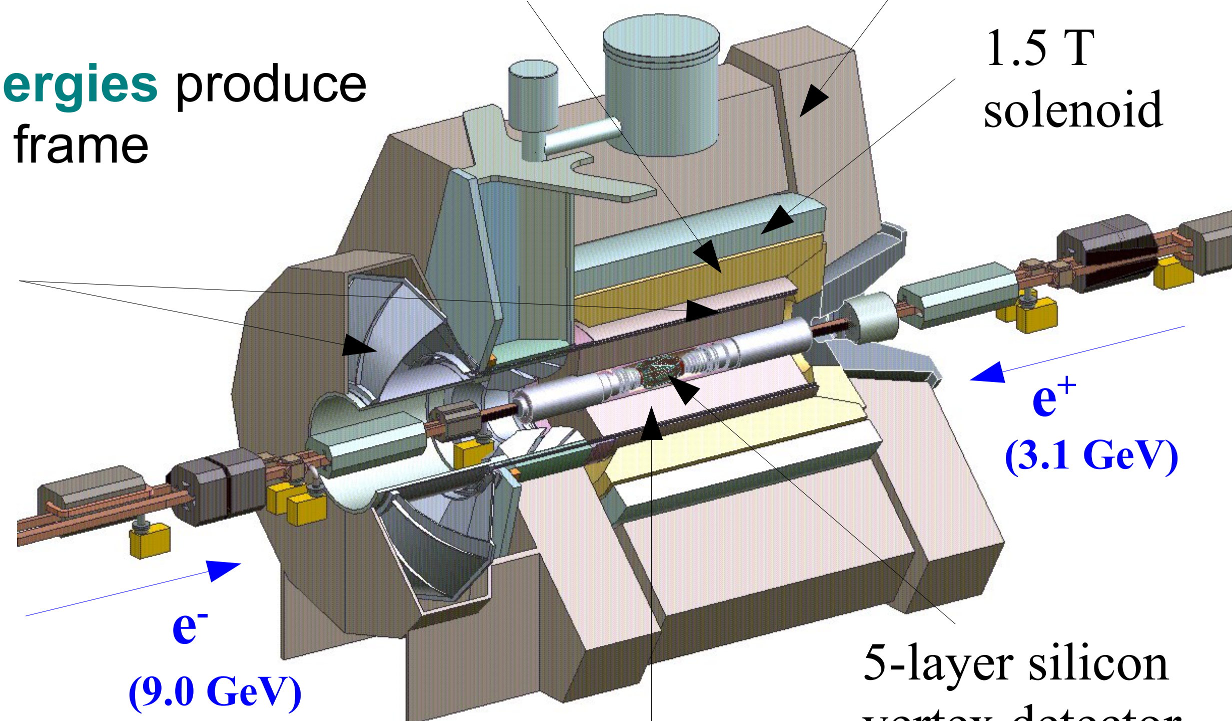


The *BaBar* detector

B factory operations at SLAC from 1999 until beginning of 2008

- Centre of mass energy of 10.58 GeV for **Υ(4S) → BB**
- **Asymmetric beam energies** produce boost of $\beta\gamma$=0.56 in lab frame



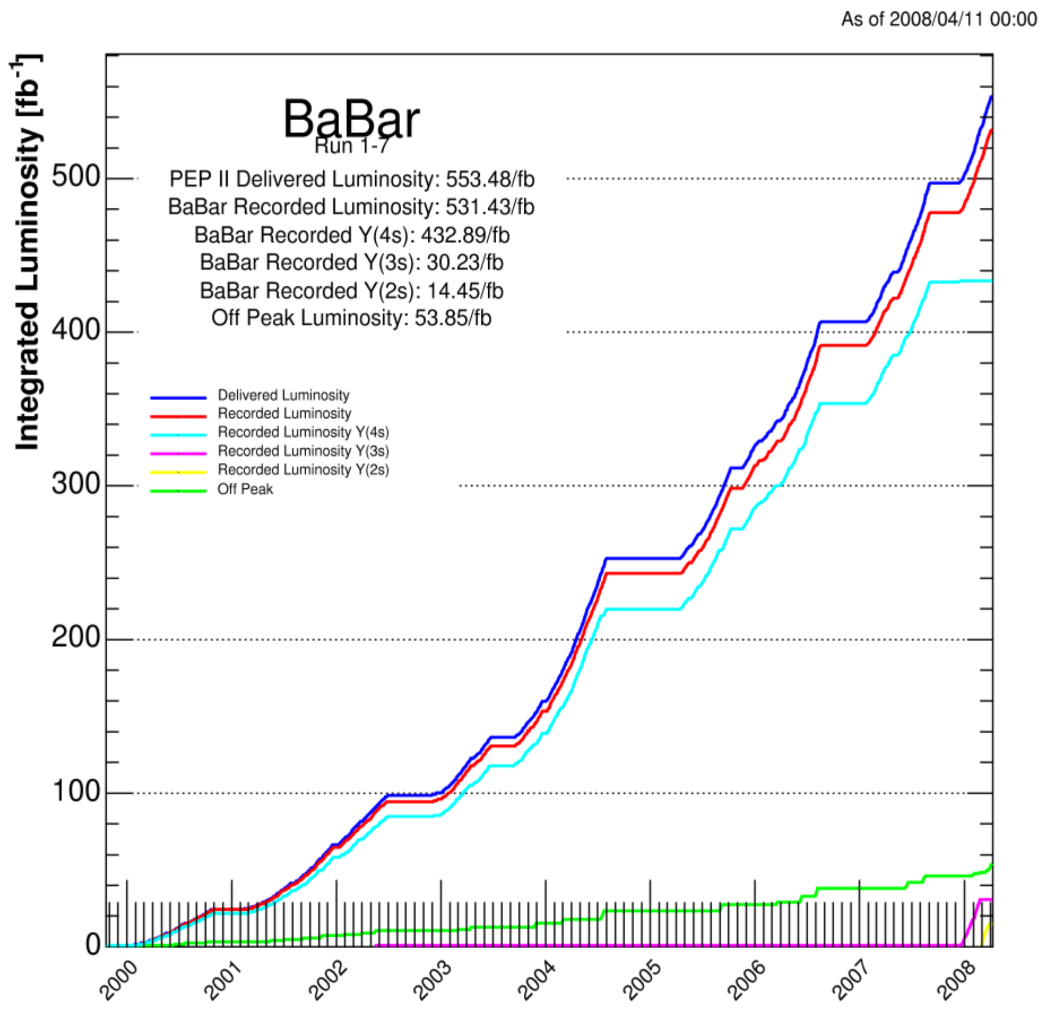


$\sigma_{p_T}/p_T = (0.13 \cdot p_T /[\mathrm{GeV}/c] + 0.45)\%$

BaBar/PEP-II Operations

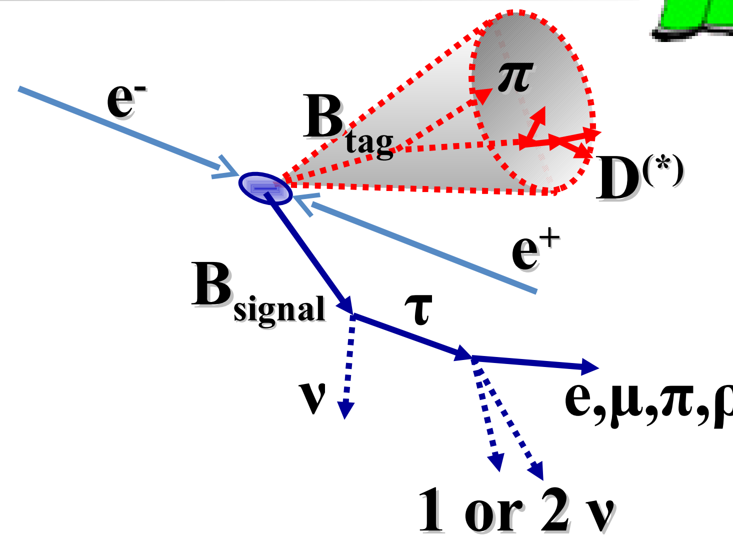
Final BABAR Υ(4S) "onpeak" data sample of ~0.5×10^9 BB pairs, corresponding to an integrated luminosity of 430 fb^{-1}

- also substantial samples of continuum tau- and charm-pair events
- also ~45 fb^{-1} of Υ "narrow resonance" data (surprise!)...



Analysis technique

Inclusive final states, or those containing (one or more) neutrinos may lack kinematic constraints which can be exploited for background suppression



- Reconstruct the decay of the non-signal "tag" B^- in $\Upsilon(4S) \to B^+B^-$ in one of a large number of exclusive decay modes

  ⇛ attribute all other particles to the decay of the "signal" B^+ candidate

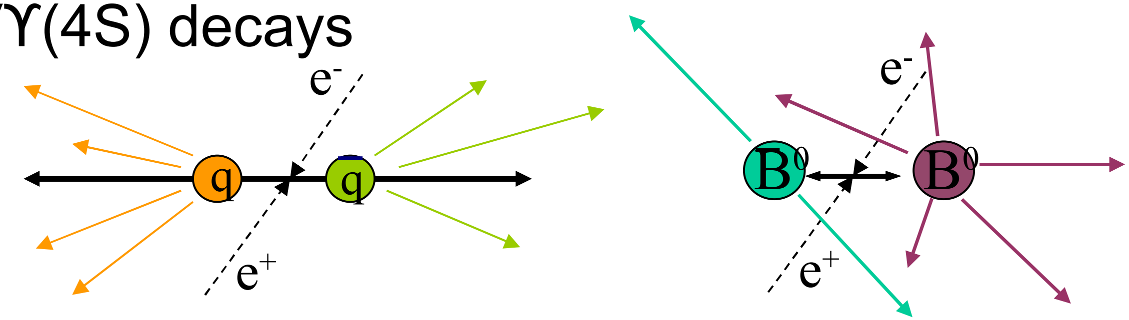
$$m_{ES} \equiv \sqrt{E^{*2}_{\rm beam} - p^{*2}_B}$$
$$\Delta E^* \equiv E^*_B - E^*_{\rm beam}$$

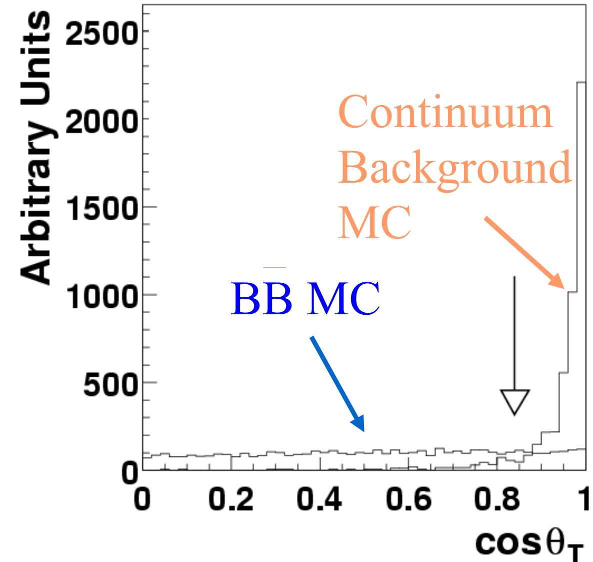
- $B^- \to D^{(*)0} X^-$ Hadronic tags
  - yield ~2700/fb^{-1}
- $B^- \to D^0 l^- \nu X^0$ Semileptonic tags
  - yield ~6000/fb^{-1}
  - similar method but lower yield for neutral B tags...

$B^- \to D^{(*)0} X^-$
- $\to K^- \pi^+$
- $\to K^- \pi^+ \pi^0$
- $\to K^- \pi^+ \pi^- \pi^+$
- $\to K^0_s \pi^+ \pi^-$

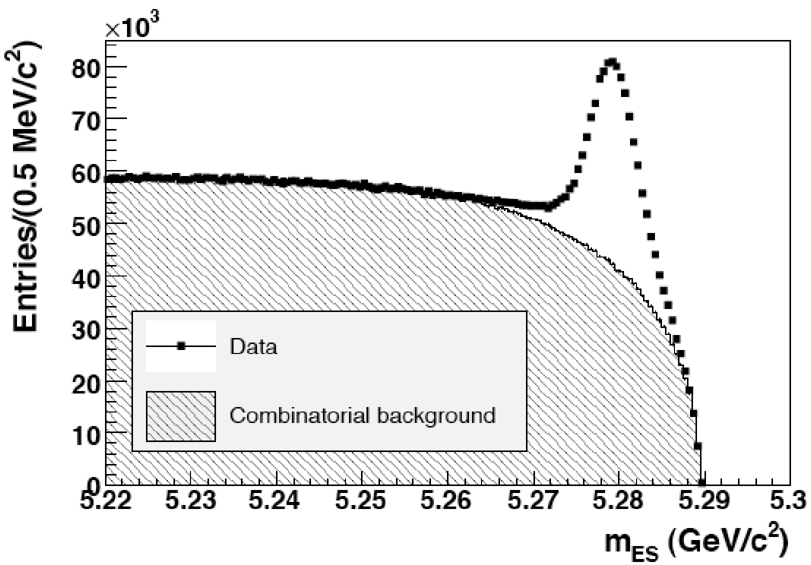
Event selection

- Suppress continuum backgrounds by exploiting differences in event “shapes” resulting from low momentum of B mesons from ϒ(4S) decays





- Calibrate tag yield and continuum background contributions directly from data



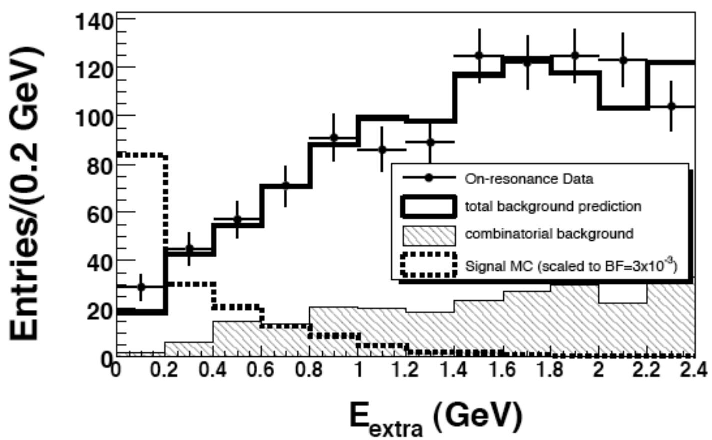
- Signal candidate is defined from all remaining tracks/clusters in the event after excluding “tag B” daughters

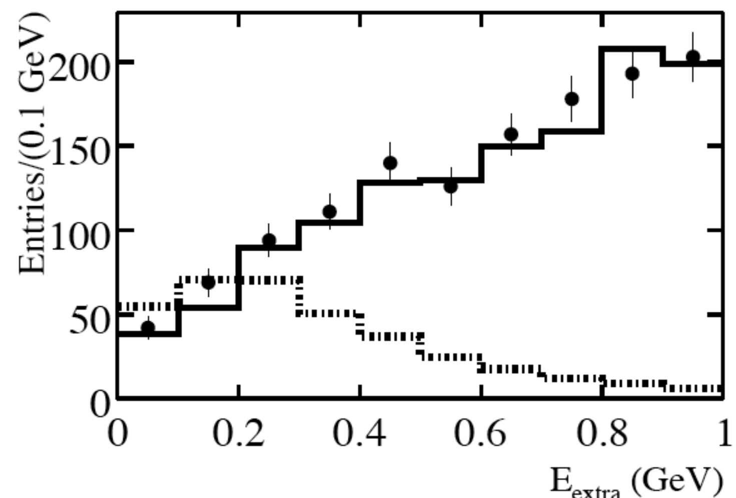
$B^+ \to \tau^+ \nu$

Phys. Rev. D76, 052002 (2007)
Phys. Rev. D77, 011107 (2008)

Experimentally challenging due to presence of multiple neutrinos:

- Search for 1-prong τ decays: $\tau \to e\nu\nu$, $\tau \to \mu\nu\nu$, $\tau \to \pi\nu$ and $\tau \to \pi\pi^0\nu$
- "Topological" signal candidate selection, then require residual calorimeter energy to be consistent with "noise"





BABAR searches based on 383 x 10^6 B meson pairs

$$\mathcal{B}(B^+ \to \tau^+\nu) = (0.9 \pm 0.6(\text{stat.}) \pm 0.1(\text{syst.})) \times 10^{-4} \quad \text{(SL tag)}$$

$$\mathcal{B}(B^+ \to \tau^+\nu) = (1.8^{+0.9}_{-0.8} \pm 0.4 \pm 0.2) \times 10^{-4} \quad \text{(Had tag)}$$

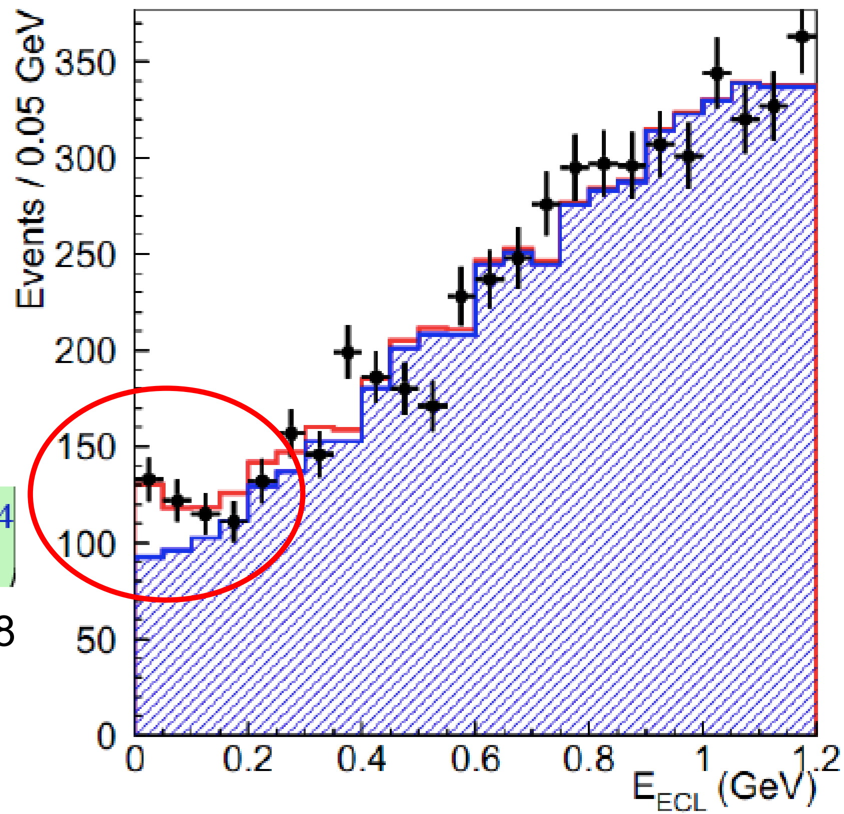
Combined result: (2.6σ significance)

$$\mathcal{B}(B^+ \to \tau^+\nu) = (1.2 \pm 0.4_{\text{stat.}} \pm 0.3_{\text{bkg.}} \pm 0.2_{\text{syst.}}) \times 10^{-4}.$$

$B^+ \to \tau^+ \nu$ (Belle)

Belle reported a new preliminary result at ICHEP08 based on SL tag reconstruction (657M B meson pairs):

- Clear excess visible in signal region of "Extra energy" variable



$$\mathcal{B}(B \to \tau\nu) = [1.65^{+0.38}_{-0.37}(stat)^{+0.35}_{-0.37}(syst)] \times 10^{-4}$$

Presentation by K. Hara , ICHEP08

- Previous Belle hadronic tag result (statistically independent sample):

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

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

⇒ Consistent results, but high compared with SM expectation

Interpretation

Assuming SM is given by CKMfitter expectation:

$$\mathcal{B}(B \to \tau\upsilon)_{SM} = (0.93^{+0.12}_{-0.11}) \times 10^{-4}$$

- Alternate prescription would be to use f_B from lattice, V_{ub} from experimental world average:

$|V_{ub}| = (4.39 \pm 0.54) \times 10^{-3}$, $f_B = 0.189 \pm 0.027$ GeV

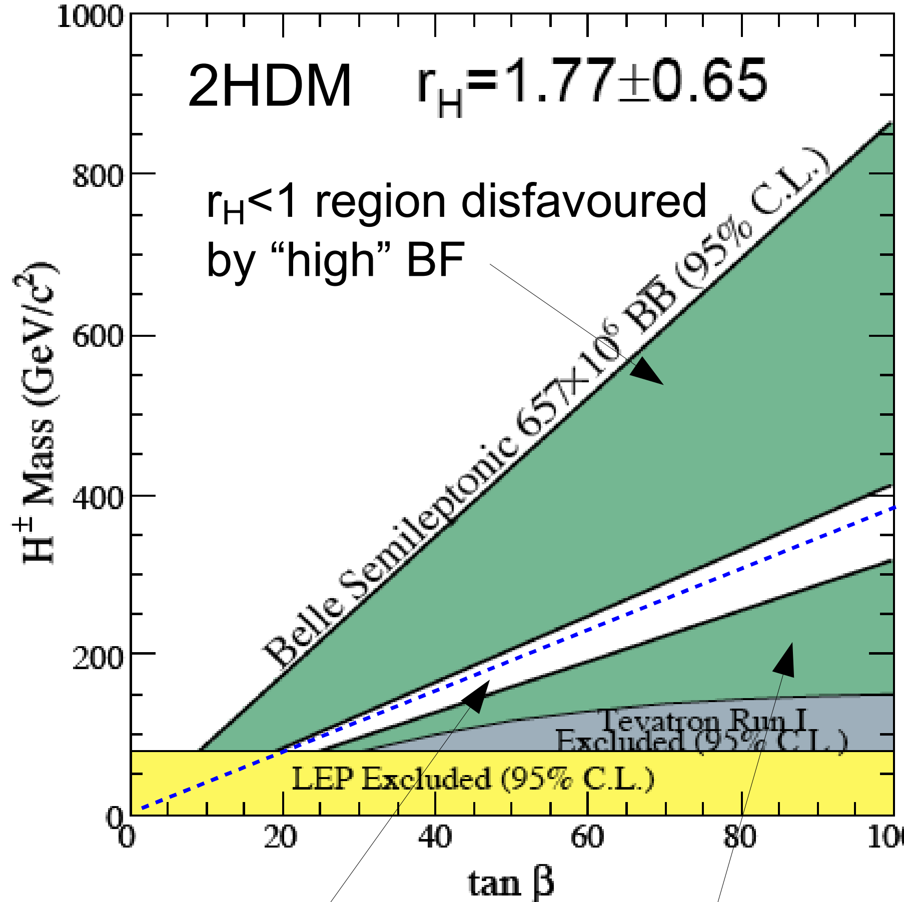
$B(B\to\tau\nu)_{SM} = (1.2 \pm 0.4) \times 10^{-4}$,

Naïve combination of BABAR and Belle results yields

$$\mathbf{B(B\to\tau\nu) = (1.51 \pm 0.33) \times 10^{-4}}$$

...very close to 5σ from zero

- $r_H \sim 1.6$



Plot from K. Hara , ICHEP08

"Pathological" case where Higgs contribution is exactly double the SM contribution

Large - r_H region (ruled out by BF upper limits)

Consistency with SM

Specific bound also depends on the scenario – e.g. MSSM

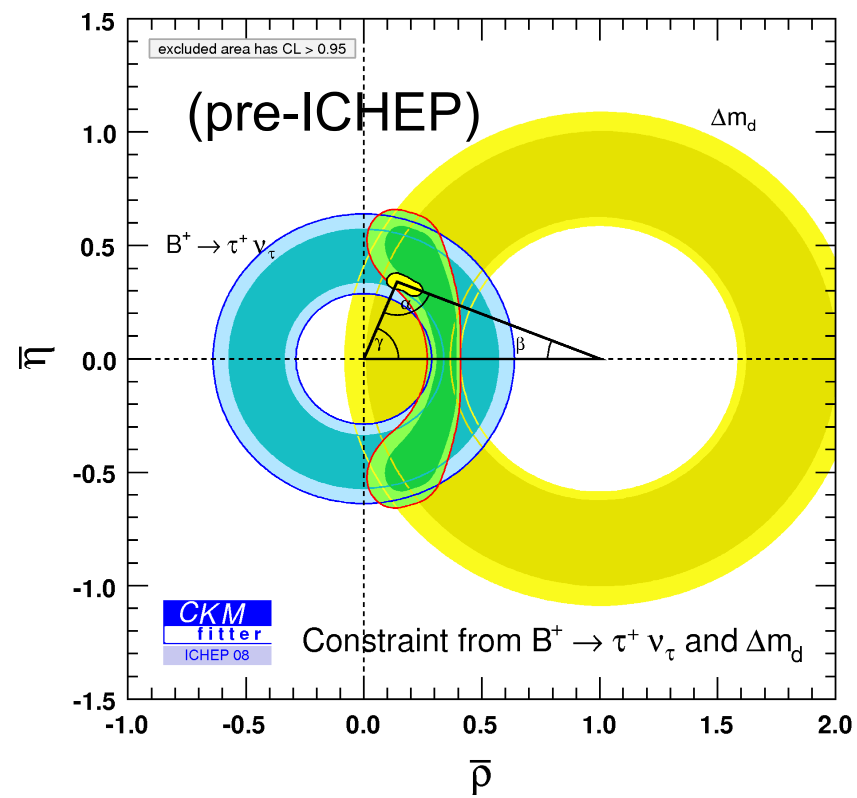
- EFT approach in MFV: (G. Isidori, arXiv:0710.5377)

$$r_H \overset{\text{SUSY}}{=} \left[1 - \left(\frac{m_B^2}{m_{H^\pm}^2}\right)\frac{\tan^2\beta}{(1+\epsilon_0\tan\beta)}\right]^2$$

with $\varepsilon_0 \tan\beta \sim O(1)$ for large $\tan\beta$

A better way to think of this is that the combination of $B\to\tau\nu$ with other flavor observables can be used to verify the overall consistency of the CKM picture

- If $B\to\tau\nu$ is incompatible, then evidence of NP, but interpretation is (obviously) model dependent
- Tension in the overall CKM determination at the level of about ~1.5σ



Beyond Tree Level...

Tree-level charged Higgs (Type-II 2HDM or MSSM) contribution has the same effect on all leptonic modes:

$$B(B^+ \to l^+ \nu)^{2HDM} = B(B^+ \to l^+ \nu)^{SM} \times \left[1 - \tan^2\beta \, (m^2_B / m^2_{H+}) \right]^2$$

- "Universality" preserved at tree level
- Equal sensitivity in all modes!

At one-loop level, potentially large **Lepton Flavour Violation (LFV)** effects entering from e.g. SUSY in grand unification scenarios:

i.e. $\mathbf{B}^+ \to l^+ \nu_{l'}$ where $l' \neq l$ via effective $l H^+ \nu$ coupling

Observable effects in ratios, $R_b^{l/\tau}$, of B leptonic branching ratios:

$$\left(R_B^{\ell/\tau}\right)^{\rm MSSM}_{\rm LFV} = \left(R_B^{\ell/\tau}\right)^{\rm SM} \left[1 + \frac{1}{R_{B\tau\nu}} \left(\frac{m_B^4}{M_{H\pm}^4}\right) \left(\frac{m_\tau^2}{m_\ell^2}\right) |\Delta_R^{\tau\ell}|^2 \frac{\tan^6\beta}{(1+\epsilon_0 \tan\beta)^2}\right]$$

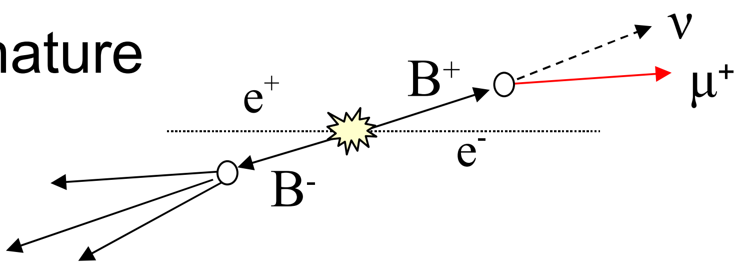
- Uncertainties from V_{ub} and f_B cancel in ratio of modes!

G. Isidori and P. Paradisi hep-ph/0605012
A. Masiero, P. Paradisi and R. Petronzio hep-ph/0511289

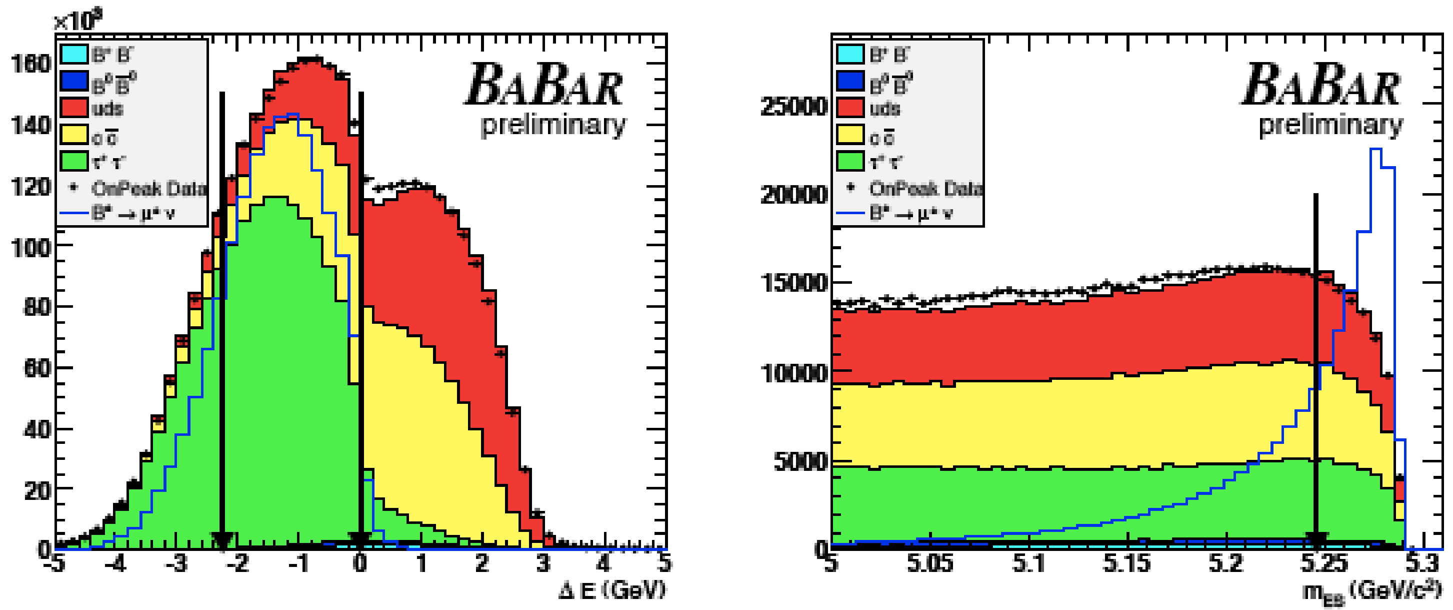
"Inclusive" $B^+ \to \mu^+ \nu$

Two body $B^+ \to \mu^+ \nu$ final state with a high momentum muon yields a distinctive signature

- Search can be performed either with* or without tag reconstruction



* Phys.Rev.D77:091104,2008.

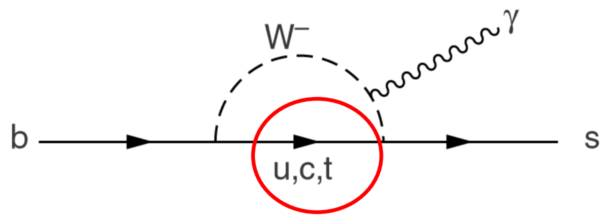


$B(B^+ \to \mu^+ \nu) < 1.3 \times 10^{-6}$
arXiv:0807.4187v1 [hep-ex]

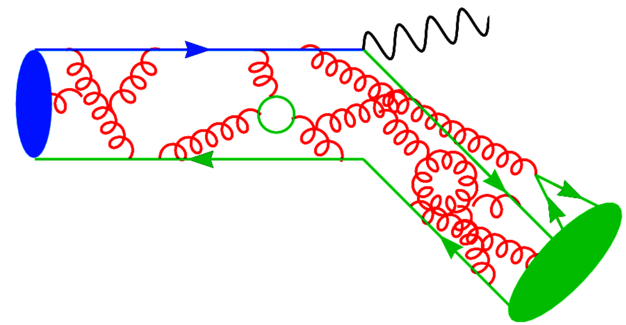
Current experimental limits only about a factor of two from the SM! $B(B^+ \to \mu^+ \nu)_{SM} \sim 5 \times 10^{-7}$

Inclusive $B \to X_s \gamma$

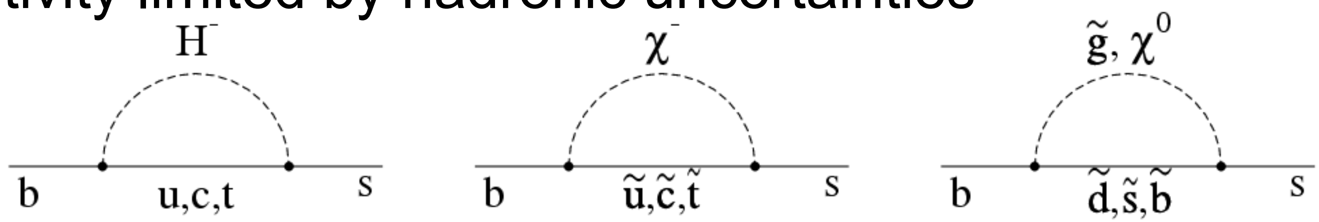
FCNC process in SM:



SM dominated by t-quark contribution



NP could enter at one loop level, same as SM contribution, but sensitivity limited by hadronic uncertainties



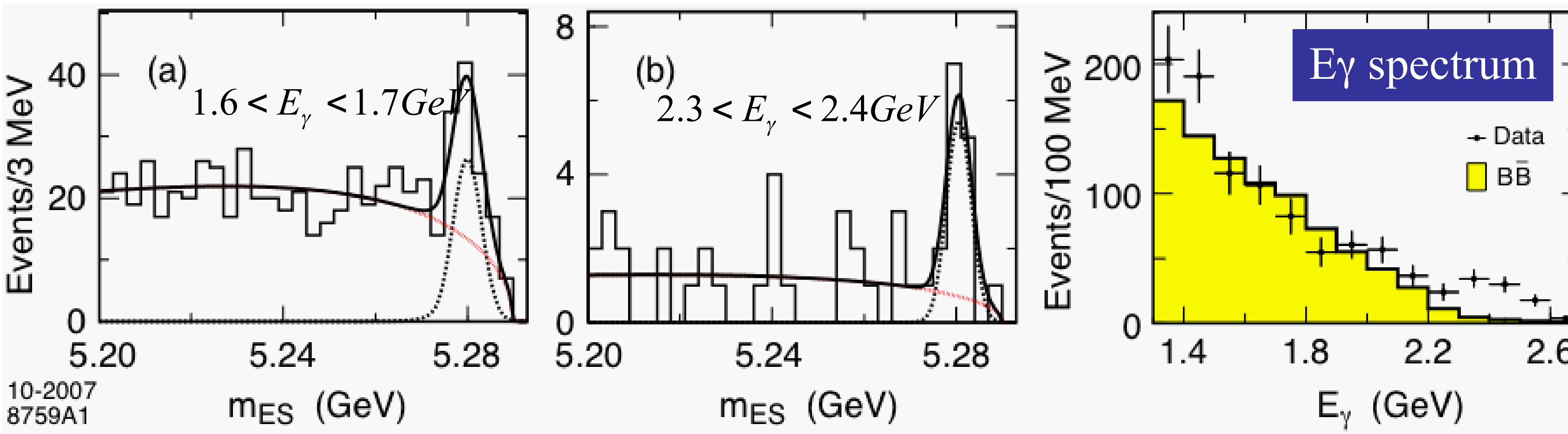
- Inclusive calculation more reliable (assuming quark – hadron duality), but more difficult experimentally

Recent NNLO QCD correction substantially reduces the main theoretical uncertainties on inclusive $b \to s\gamma$ calculation

- "Robust" experimental determination with <10% precision

Inclusive $B \rightarrow X_s \gamma$ (with tag reco)

Recent BABAR measurement utilizing hadronic tag reconstruction (based on 210 fb^{-1} i.e. about half of full data statistics)



$$B(B \rightarrow X_s\gamma, E_\gamma > 1.9GeV) = 3.66 \pm 0.85(stat) \pm 0.60(sys) \times 10^{-4}$$

Also obtain moments of photon energy distribution: PRD 77:051103 2008

$$\langle E_\gamma \rangle (E_\gamma > 1.9GeV) = 2.289 \pm 0.058 \pm 0.027 GeV$$

$$\langle (E_\gamma - \langle E_\gamma \rangle)^2 \rangle = 0.0334 \pm 0.0124 \pm 0.0062 GeV^2$$

- determine heavy quark parameters as inputs for CKM element determinations

- Technique currently limited by data statistics (low efficiency due to tag selection), but would be method of choice for a "Super B factory"

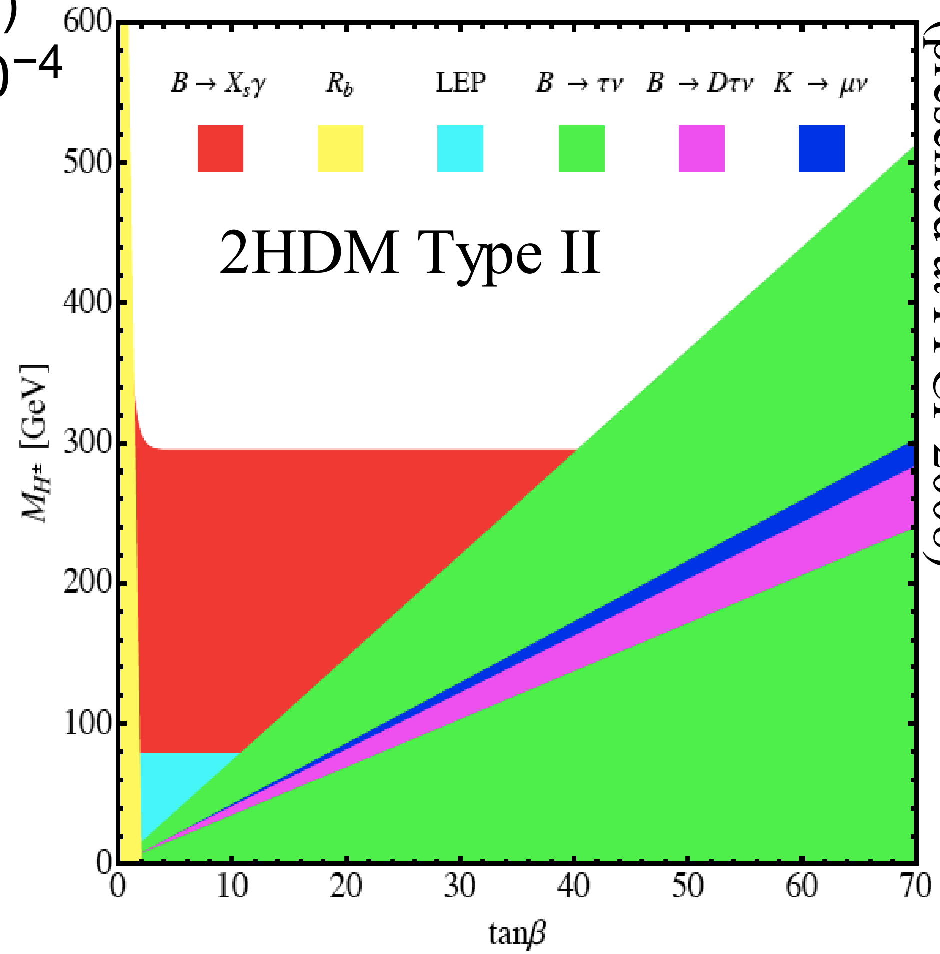
$B \to X_s \gamma$

HFAG experimental average (April 2008)
$B(B \to X_s\gamma) = (3.52 \pm 0.23 \pm 0.09) \times 10^{-4}$

Improved theoretical prediction*
for inclusive branching fraction:

$B(B \to X_s\gamma) = (3.0 - 3.5) \times 10^{-4}$
for E > 1.6 GeV with uncertainties that vary from 7% to 14%

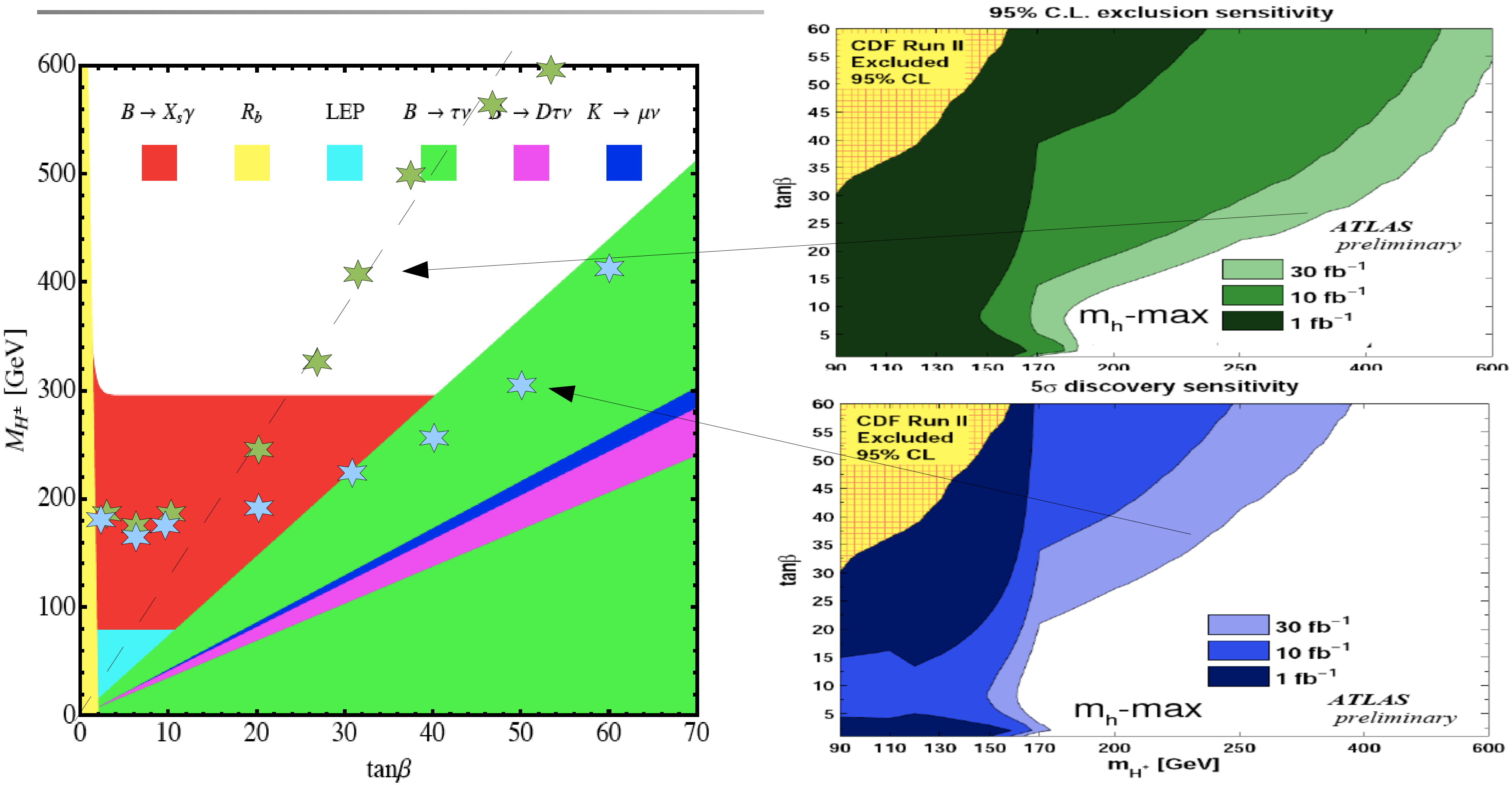
- SM prediction is ~1σ below current experimental average (previously good agreement with NLO predictions)



U. Haisch arXiv:0805.2141 [hep-ph] (presented at FPCP 2008)

* M. Misiak et al., Phys. Rev. Lett. 98, 022002 (2007).
T. Becher andM. Neubert, Phys. Lett. B637, 251 (2006).
J. R. Andersen and E. Gardi, JHEP 01, 029 (2007).

LHC vs Flavour Constraints



ATLAS 30fb^{-1} sensitivity mapped onto current flavour bounds

- comparable to bound from B(B→τν) if measured with ~15% precision (assuming SM rate)

Summary

Recent B Factory rare decay results significantly constrain m_H – $\tan\beta$ plane for type II 2HDM

- $B\to\tau\nu$ almost 5σ signal and currently about 1.5σ from SM
- $B\to\mu\nu$ limits approaching SM expectation; will potentially impose a substantial constraint in the future

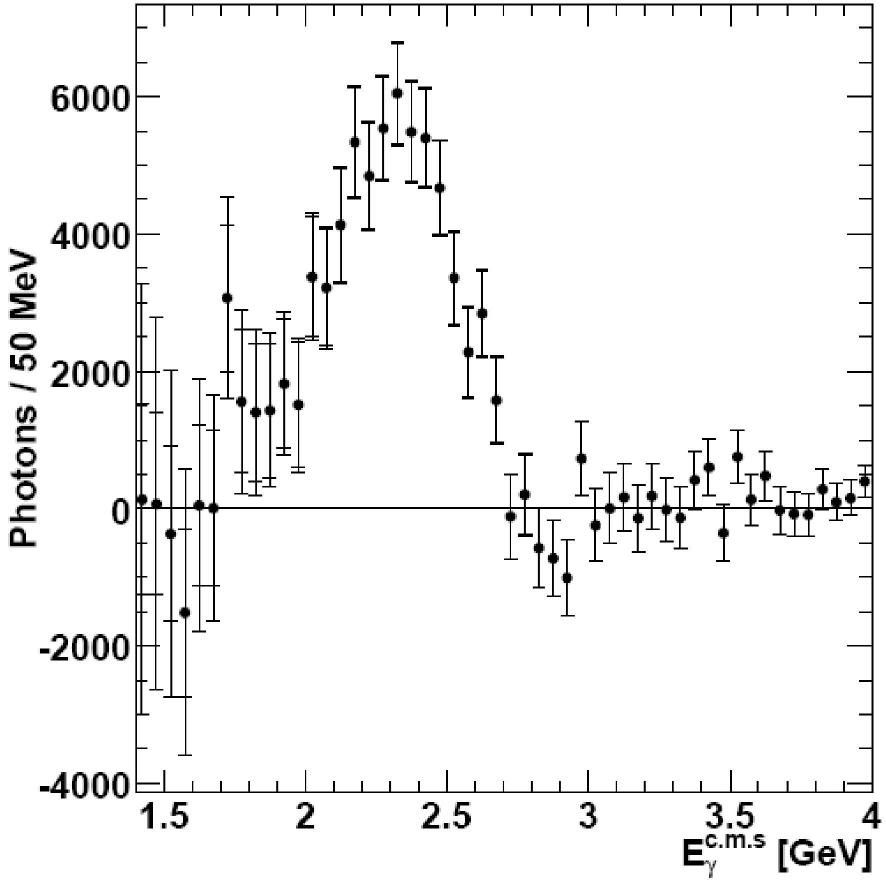
Experimentally robust determination of inclusive $b\to s\gamma$ branching fraction slightly high compared with recent theory predictions

- “Weaker” m_H constraint than previously (or favours charged Higgs...)

Backup Slides

Belle inclusive B → Xs γ

For Eγ >1.7 GeV:



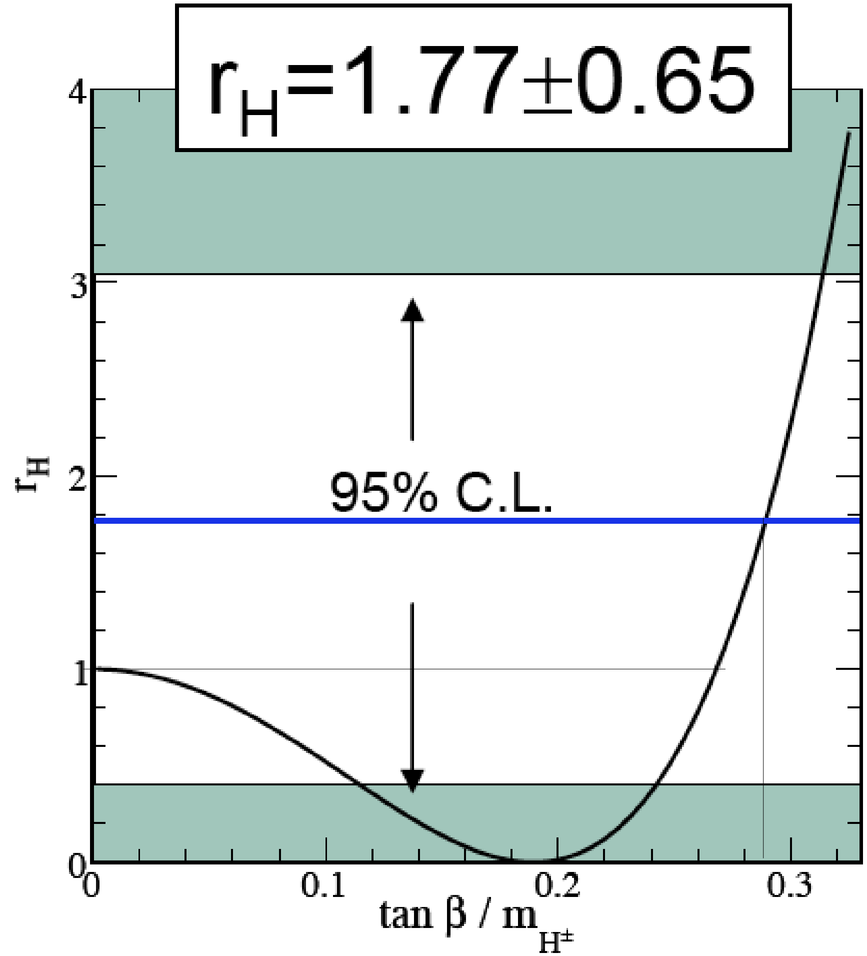
$$\mathcal{B}(B \to X_s\gamma) = (3.31 \pm 0.19 \pm 0.37 \pm 0.01) \times 10^{-4}$$
(stat.) (syst.) (boost.)

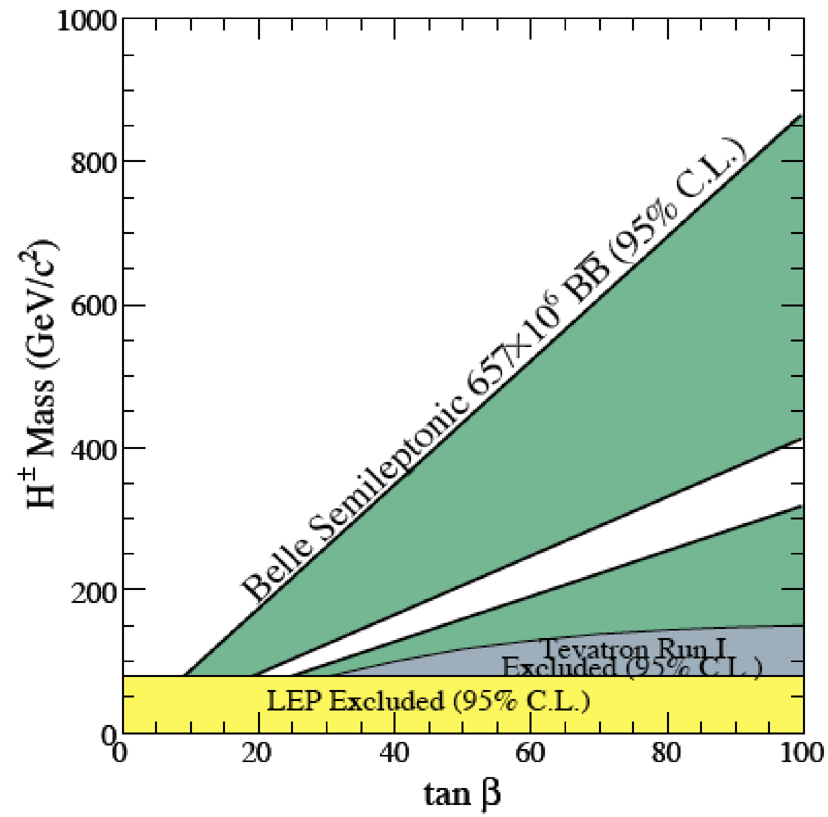
$$\langle E_\gamma \rangle = 2.281 \pm 0.032 \pm 0.053 \pm 0.002\,\text{GeV}$$

$$\langle E_\gamma^2 \rangle - \langle E_\gamma \rangle^2 = 0.0396 \pm 0.0156 \pm 0.0214 \pm 0.0012\,\text{GeV}^2$$

arXiv: 0804.1580

Belle $B^+ \to \tau^+ \nu$ interpretation

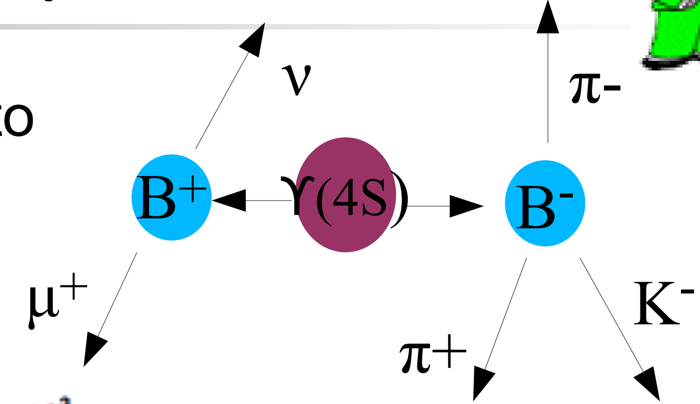


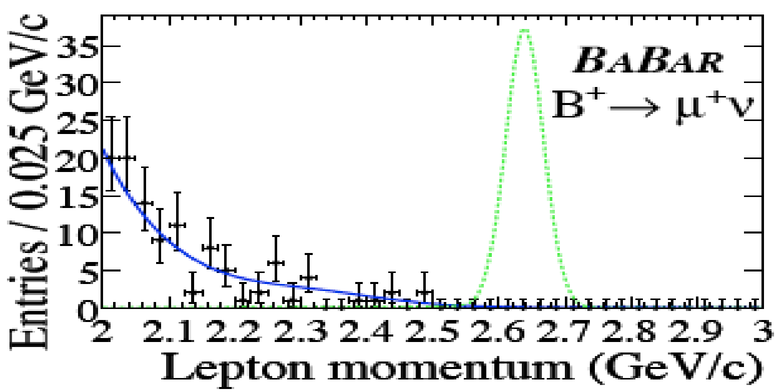


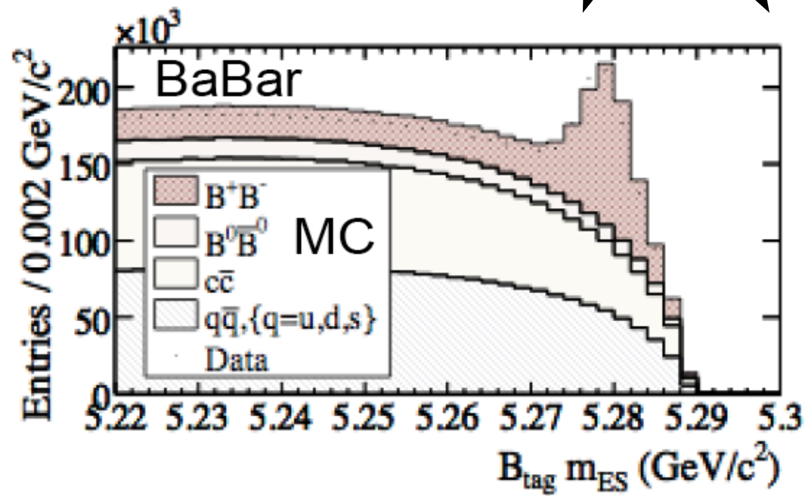
From ICHEP08 presentation by
Koji Hara (Nagoya University)

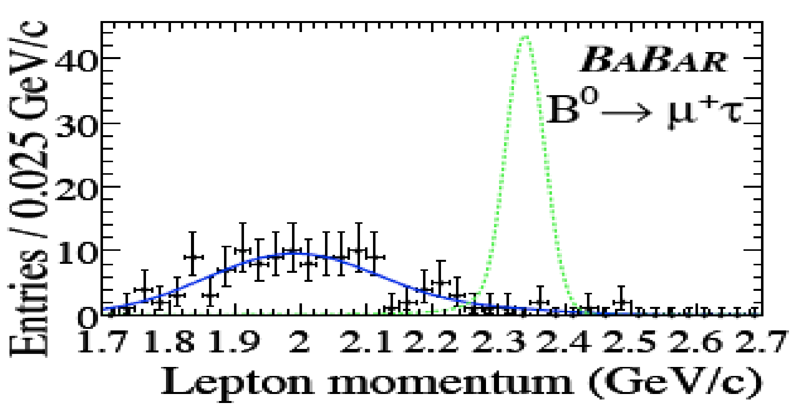
Tagged $B^+ \rightarrow l^+\nu$ (l = e, μ) and LFV

- Use hadronic tag reconstruction method to search for leptonic and lepton flavor violating B decay modes
  - Two-body decays yield clean signature in signal B rest frame







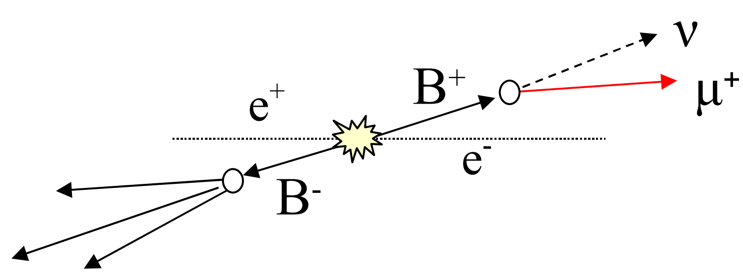


Mode	Data Sample	90% CL limit
$B^+ \rightarrow \mu^+\nu$		5.6×10^{-6}
$B^+ \rightarrow e^+\nu$	378 M	5.2×10^{-6}
$B^0 \rightarrow \mu^+\tau^-$		2.2×10^{-5}
$B^0 \rightarrow e^+\tau^-$		2.8×10^{-5}

PRD-RC 77, 091104 (2008)

Inclusive $B^+ \to l^+\nu$ ($l = e, \mu$)

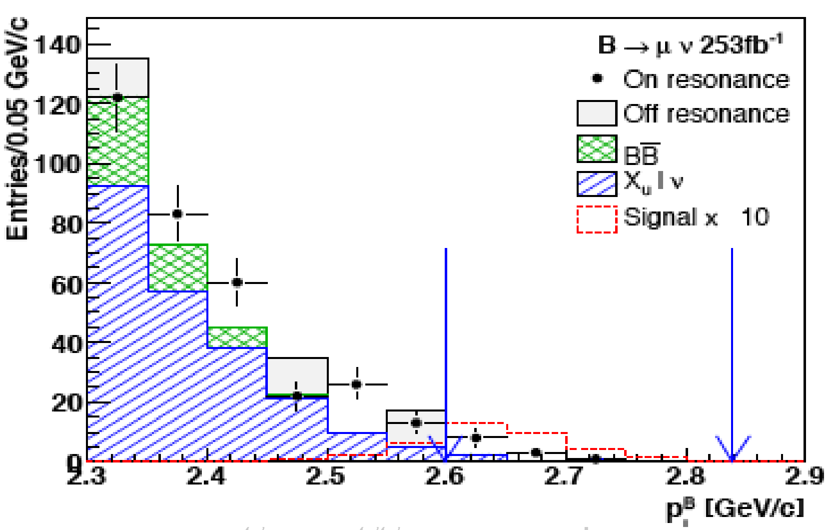
- Efficiencies much higher than exclusive method, but also higher backgrounds: ϵ_μ=(2.18 ± 0.06)% ϵ_e=(2.39 ± 0.06)%
- Extract signal from fit to M_{bc} distribution in region: 5.1< M_{bc} < 5.29; -0.8 (-1.0) < ΔE <0.4 GeV for μ(e)

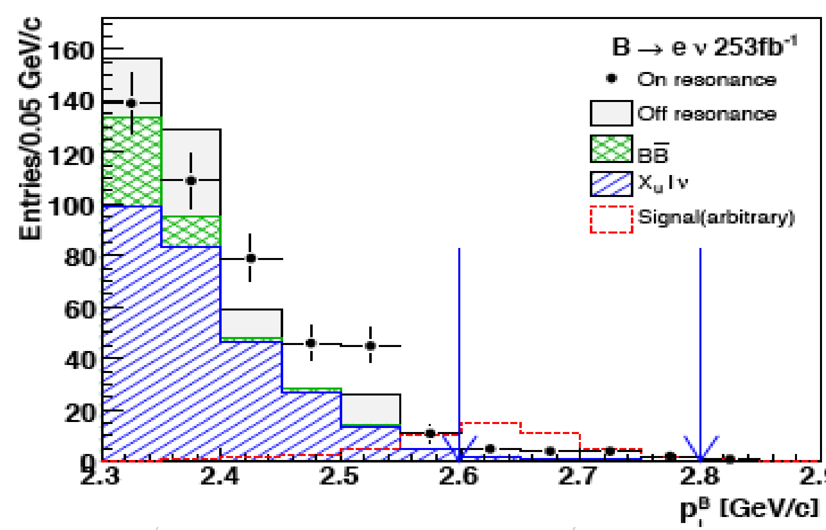


Phys.Lett.B647:67-73,2007.

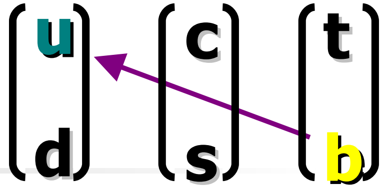
hep-ex/0611045

$B(B^+ \to \mu^+\nu) < 1.7 \times 10^{-6}$
$B(B^+ \to e^+\nu) < 0.98 \times 10^{-6}$

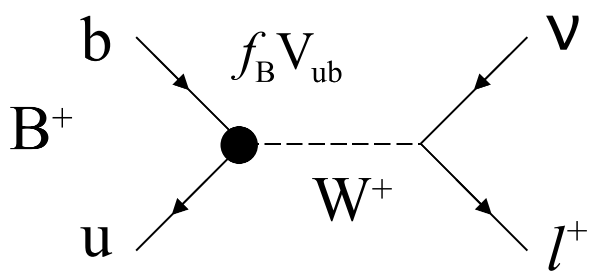




Leptonic B decays



- Leptonic B decays are helicity-suppressed EW tree processes in the SM:



Standard Model Rates

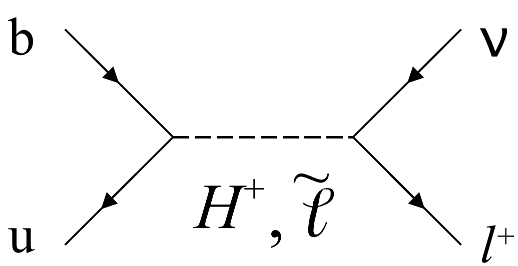
$B(B^+ \to \tau^+\nu) \sim 1\text{x}10^{-4}$

$B(B^+ \to \mu^+\nu) \sim 4\text{x}10^{-7}$

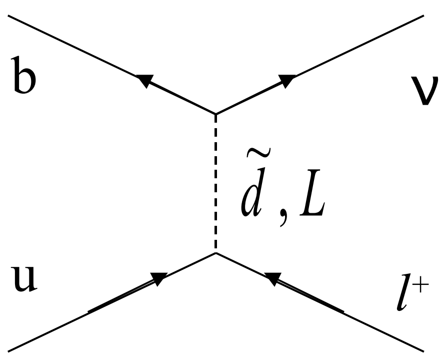
$B(B^+ \to e^+\nu) \sim 10^{-12}$

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

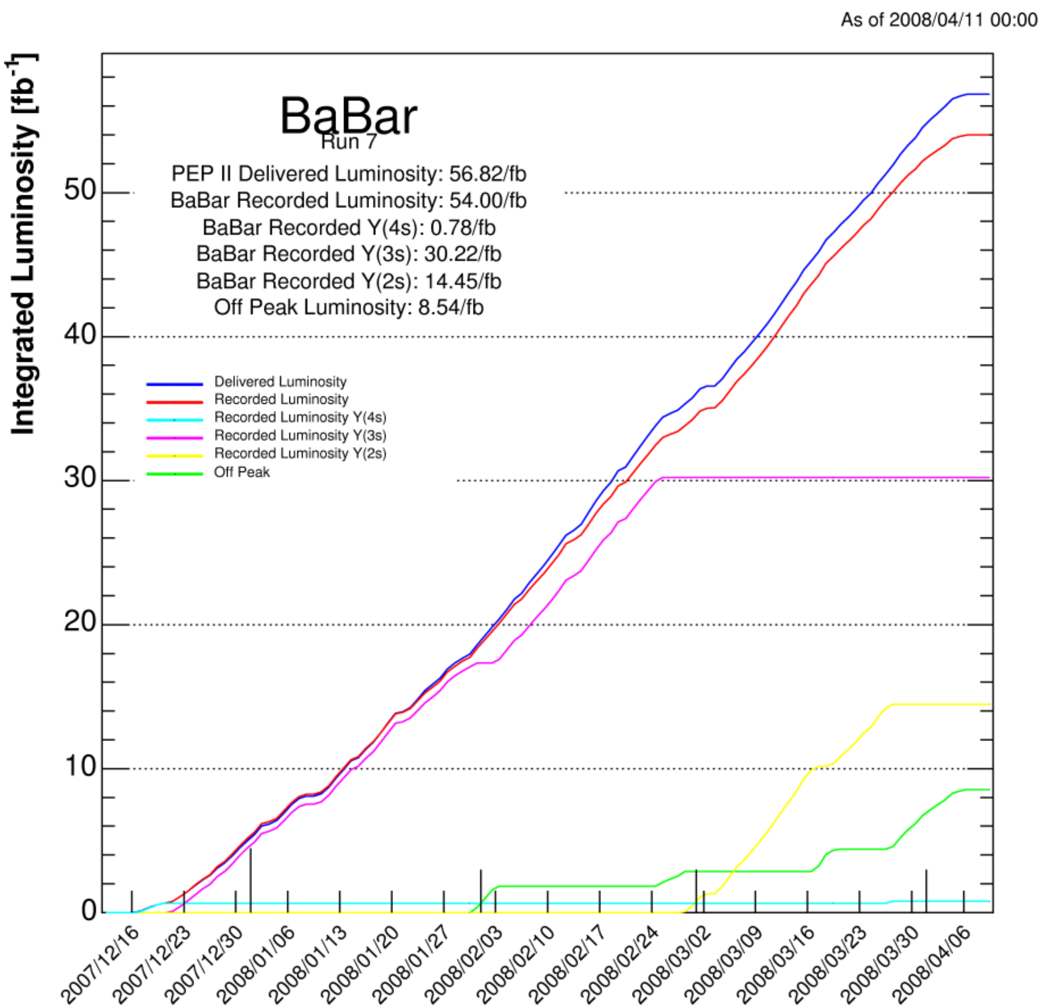
- New physics contributions can arise from diagrams with internal lines containing non-SM particles:



- Charged Higgs, R-parity violating SUSY scalar sparticles, Pati-Salam leptoquarks...



Run 7



- Data taken between December 16, 2007 and April 7, 2008
- 30.2 fb^{-1} at ϒ(3S)
- 14.5 fb^{-1} at ϒ(2S)
- ~5 fb^{-1} above ϒ(4S) scan
- Several ϒ(3S) analyses and above ϒ(4S) scan targeting ICHEP 2008

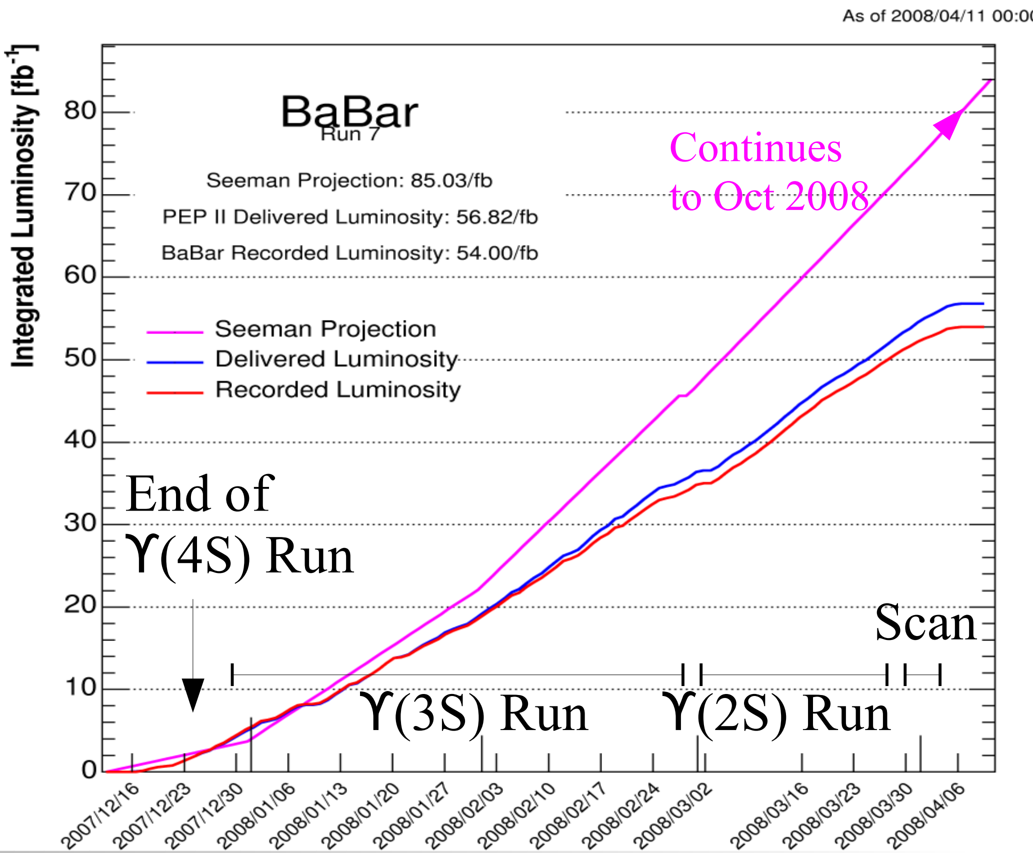
Interesting times...

Run plan for Run 7 approved until Oct 2008 with luminosity target of ~2x10^{34} with anticipation of an additional ~50% new data

- substantial upgrades to accelerator during 3-month shutdown in fall 2007
- BABAR IFR (barrel muon system) upgrade completed prior to 2007 run

Dec 21st – Congressional budget cuts (targetted at ILC) result in termination of BABAR run effective Jan 1st 2008

- BABAR successfully argues that physics case for ϒ(3S) & ϒ(2S) justifies a 3-month extension of the run
- PEP-II/BABAR retool accelerator, detector and trigger system within a 3-day period over the holiday break

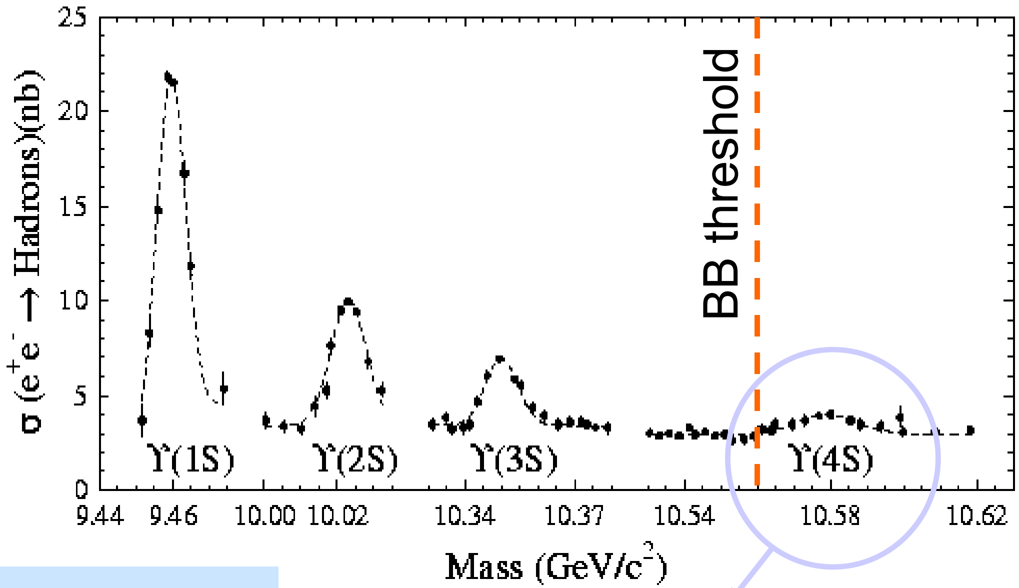


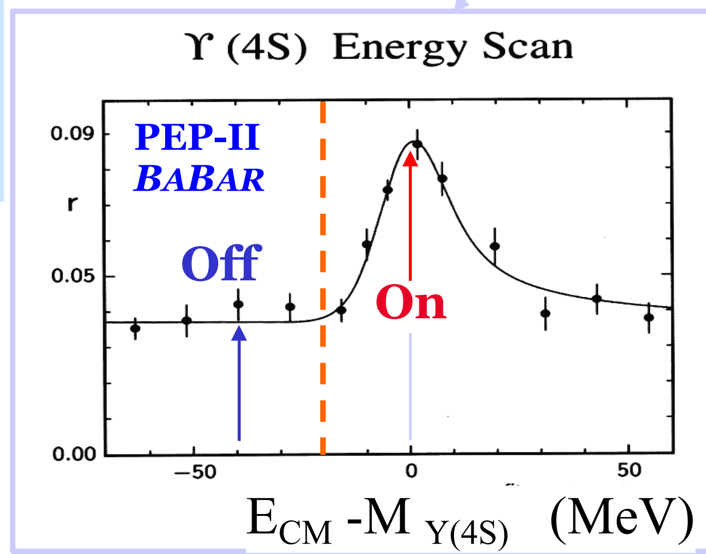
Υ(4S)

The Υ(4S) is a $b\bar{b}$ resonance which lies just above the mass threshold for production of $B\bar{B}$ meson pairs.

- Cross section of ~1.1nb

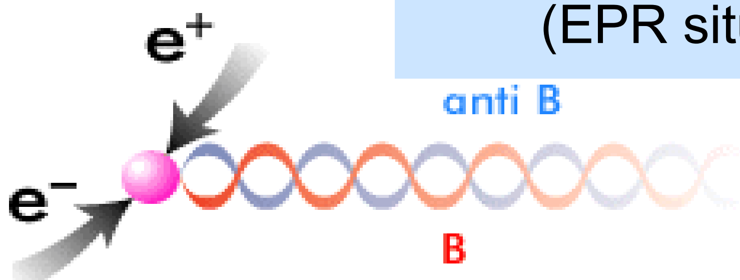
  ~1.1 million $B\bar{B}$ pairs per fb^{-1}





$B^0\bar{B}^0$ pair is produced in a coherent L=1 state

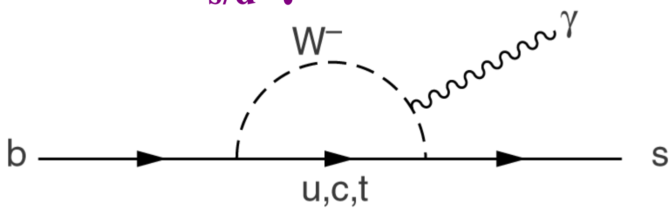
The two B mesons evolve in phase until one decays (EPR situation)



⇒ Enables studies of time-dependence of decays of "flavour-tagged" neutral B mesons

Electroweak FCNCs

$B \rightarrow X_{s/d}\, \gamma$

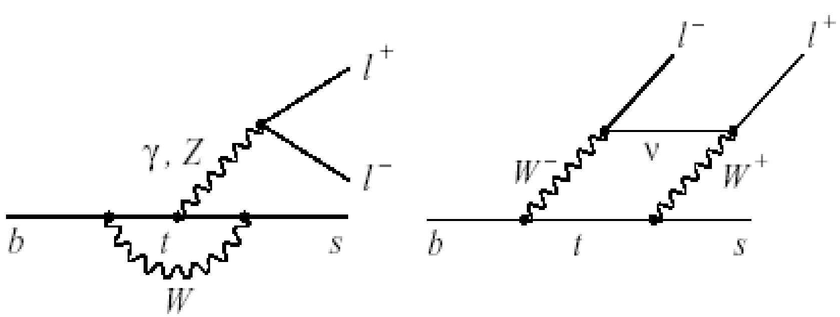


C_7 (Photon penguin) only

Observables: branching fractions E_γ (or m_{had}) spectrum, A_{CP}

New physics could result in a distinctive pattern of deviations in observables across a variety of related FCNC modes

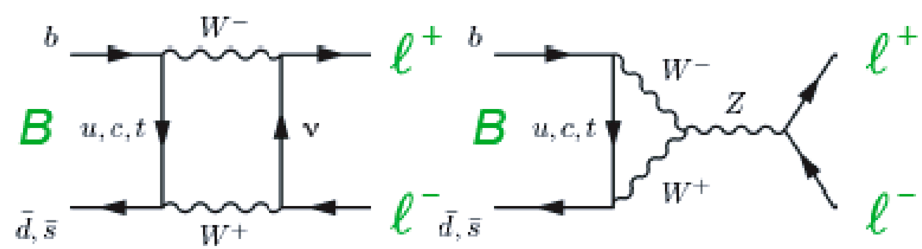
$B \rightarrow X_{s/d}\, l^+ l^-$



C_7 ,C_9 (Vector EW) and C_{10}

Observables: (partial) branching fractions, dilepton A_{FB}, A_{CP}

$B^0_{s/d} \rightarrow l^+ l^-$

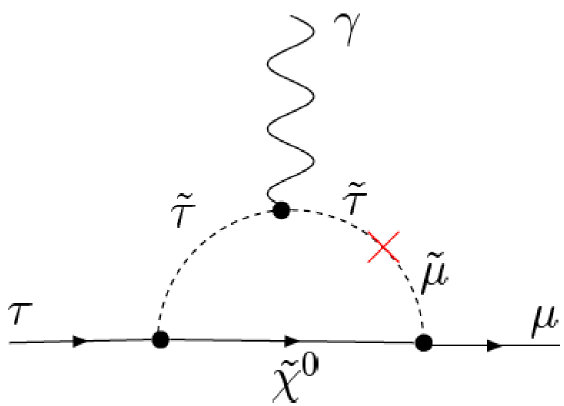


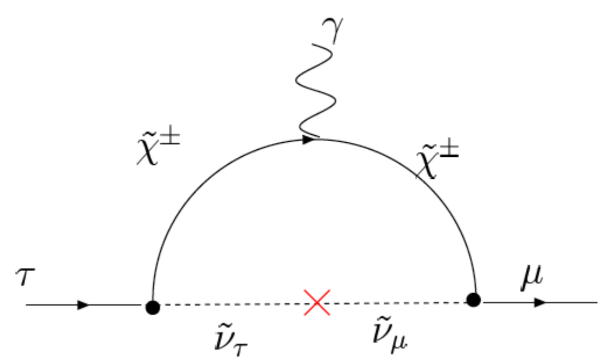
C_{10} (Axial vector EW) only

Observables: branching fractions

Lepton Flavour Violation

- In Standard Model, lepton flavour conservation is not associated with any underlying symmetry principle
  - LFV generally permitted in New Physics models containing more than one Higgs doublet
    - In SUSY seesaw models, flavour changing insertions arise from Yukawa couplings in the slepton mass RGEs:

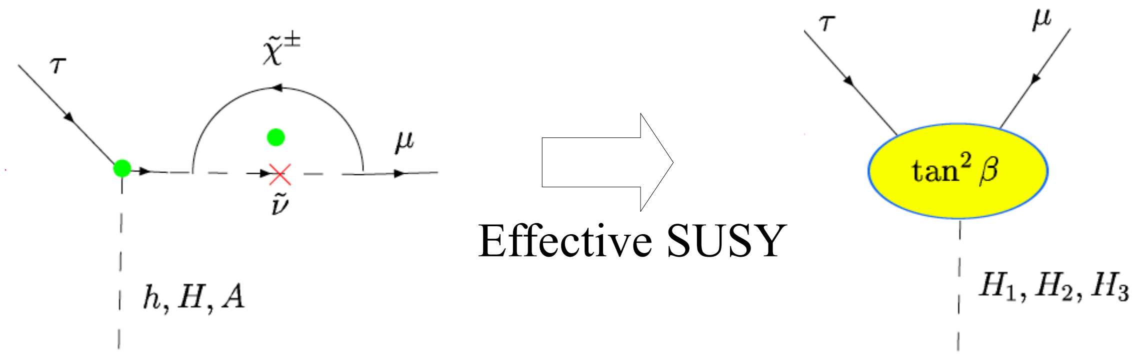




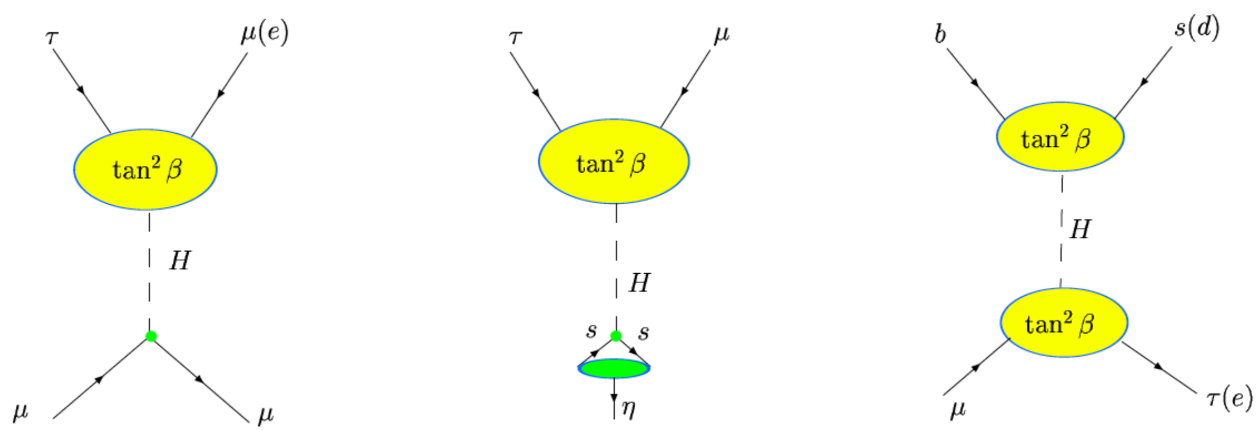
- ⇒ New Physics effects in $\tau \rightarrow l\,\gamma$ (l = e,μ) can saturate experimental bounds in natural and well-motivated models
    - MSSM with heavy right-handed neutrinos and seesaw mechanism: Br~10^{-7}
    - heavy Dirac neutrinos, RPV SUSY models, flavour changing Z' models...

Higgs mediated LFV

- Higgs mediated LFV present in MSSM at loop level given that there is a source of LFV among sleptons:



  - Predicts LFV effects in a variety of τ and B decay modes (with preference for 3rd generation couplings):



From A. Dedes, Super B Factory proceedings: hep-ph/0503261

Analysis Technique illustrated with updated *B → K*(892)γ*