Results on Searches for New Physics at B Factories

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Introduction

With the high statistics of the B-factories (BABAR: 531 fb\(^{-1}\), Belle: 899 fb\(^{-1}\)) it has become possible to explore rare decays with branching fractions of \(10^{-4}-10^{-7}\) in the \(b\bar{b}\) system.

Rare decays involve suppression mechanisms in the Standard Model, e.g.: higher order processes (penguin loops, box diagrams), CKM suppression, helicity suppression (W-annihilation).

Rare decays are very sensitive to new physics contributions as higher-order processes with new particles may contribute interfering constructively or destructively with the Standard Model.

\(\Rightarrow\) thus, rare decays are very suitable to search for new physics providing a complementary approach to direct searches at the LHC.

E.g., Measurements of \(B \rightarrow X_s \gamma\) have set stringent constraints on the SUSY parameter space.

\[ \begin{array}{c}
\text{Standard Model} \\
\begin{array}{ccc}
W & \rightarrow & \nu \\
 & \rightarrow & W^+ \rightarrow t
\end{array}
\end{array} \quad \begin{array}{c}
\text{New Physics} \\
\begin{array}{ccc}
H^- & \rightarrow & b, u, c, t, s \\
\chi^- & \rightarrow & \tilde{u}, \tilde{c}, \tilde{t}, s \\
\tilde{g}, \chi^0 & \rightarrow & b, d, \tilde{s}, \tilde{b}, s
\end{array}
\end{array} \]
Measurement of $\beta(B \rightarrow \tau \nu)$
B→τν Introduction

- B⁺→τ⁺ντ is a weak annihilation process (helicity suppressed)

- The SM branching fraction is proportional to $f_B$ and $|V_{ub}|$
  \[
  \mathcal{B}_{SM}(B \rightarrow \tau\nu) = \frac{G_F^2}{8\pi} m_B m_\tau \left( 1 - \frac{m_\tau^2}{m_B^2} \right)^2 f_B^2 |V_{ub}|^2 \tau_B
  \]

- $f_B$ is determined in unquenched lattice calculations

- For $V_{ub}=(3.93±0.36)\times10^{-3}$ (PDG 08) calculate
  \[
  \mathcal{B}_{SM}(B \rightarrow \tau\nu) = (1.04 \pm 0.19 V_{ub} \pm 0.12 f_B) \times 10^{-4}
  \]

- Extra contribution may come from a charged Higgs boson, modifying the branching fraction

\[
\mathcal{B}(B \rightarrow \tau\nu) = \mathcal{B}_{SM}(B \rightarrow \tau\nu) \times r_H
\]

\[
r_H = \left( 1 - \frac{m_B^2}{m_{H^+}^2} \tan^2 \beta \right)^2
\]

- W. S. Hou, PR D 48, 2342 (1993)
- C. Bernard et al., hep-lat/0902.1895 (2009)
**B→τν Analysis Strategy (BABAR)**

- We reconstruct ("tag") one B meson in semileptonic \( B^- \rightarrow D^0 \nu X^- \) decays \( \varepsilon_{\text{tag}} \sim 1.5\% \)
- In the recoil, we look for signal \( \tau \rightarrow e\nu\nu, \mu\nu\nu, \pi\nu, \rho\nu \)
- Sample: 467 million \( \bar{B}B \) events
- Use kinematic constraints and event shape information to select signal
- Study extra neutral energy in event, \( E_{\text{extra}} \), i.e. the energy of all photons in the EM calorimeter that do not belong to the signal nor the reconstructed tag
  ➞ for correctly reconstructed tags this is the summed noise in the calorimeter

Total selection efficiency \( \varepsilon = (1.18 \pm 0.1) \times 10^{-3} \)

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B→τν Results

- Use double tag B→D(∗)0ℓν̅_ℓ vs B^+→D(∗)0ℓ^+ν_ℓ to check data/MC agreement
  → sample of 3.4×10^6 events

- Compare E_{extra} distributions in data & MC
  they have same shape, but MC is too high,
  → apply correction to ε_{tag} (-11 %)

- Use E_{Extra} sidebands (>0.6 GeV) to extract background in signal region

- Observe 89±44 events in total sample

- Combine results with previous analysis that used hadronic tags
  PRD77, 011107 (2008)

\[ B(B \rightarrow \tau \nu) = (1.8 \pm 0.6_{\text{stat}} \pm 0.1_{\text{sys}}) \times 10^{-4} \]

Significance: 3.2σ
Belle Analysis

- Use 657 million BB events with semileptonic D(*)0lv tags, Belle observes a 3.8σ significant excess in the extra neutral energy distribution of

\[ N_{\text{sig}} = 154^{+36}_{-35} \text{(stat)}^{+20}_{-22} \text{(sys)} \]

- Branching fraction is

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

- As cross check use double semileptonic tags

- This agrees with their previous 3.5σ result in 449 million BB events using hadronic tags

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

PRL 97, 251802 (2006)

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Constraints in the \( m_H - \tan \beta \) Plane

- Naïve average of BABAR and Belle results yields

\[
\mathcal{B}(B \to \tau \nu) = (1.73 \pm 0.35) \times 10^{-4}
\]

- Significance: 4.6 \( \sigma \)

- For SM prediction yield

\[
r_H = 1.67 \pm 0.34_{\text{exp}} \pm 0.36_{f_B \cdot \nu_{ud}}
\]

- Including \( B \to X_s \gamma \), \( K \to \mu \nu \), dark matter & \( 2 \Delta a = g_\mu - g_\mu^{SM} \) we exclude large regions of \( m_H - \tan \beta \) plane

\( 0.079 < \Omega_{CDM} h^2 < 0.119 \) at 2\( \sigma \)

Isidori: hep-ph/0710.5377, 0801.3039
The $K\pi$ Puzzle
Amplitudes in $B\to K\pi$ Decays

- $B\to K\pi$ decays are dominated by gluonic penguin diagrams
  - $B^0\to K^+\pi^-$
  - $B^+\to K^+\pi^0$

- In addition electroweak penguin diagrams contribute
  - $\lambda = 0.22$
  - $\gamma$ is weak phase

Amplitudes:

$$A_{+-} = P'_{tc} - (P'_{uc} + T')e^{i\gamma} - \frac{2}{3} \frac{P_c}{c_{EW}}$$

$$\sqrt{2}A_{+0} = P'_{tc} - (P'_{uc} + T' + C')e^{i\gamma} - P'_{EW} - \frac{2}{3} \frac{P_c}{c_{EW}}$$

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Comparison of $B \rightarrow K\pi$ Decays & Direct CP

Since these two amplitudes differ at $\mathcal{O}(\lambda^2)\sim 5\%$ each we expect observables to be similar in size at $\mathcal{O}(0.1)$

E.g., ratio of measured branching fractions

$$\frac{B(B^0 \rightarrow K^+\pi^-)}{2 \times B(B^+ \rightarrow K^+\pi^0)} \frac{\tau_+}{\tau_0} = 0.81 \pm 0.05$$

For the corresponding decays with a $K^0$, $B^0 \rightarrow K^0\pi^0$ and $B^+ \rightarrow K^0\pi^+$ similar diagrams contribute yielding amplitudes

$$\sqrt{2} A_{00} = -P_{tc} + (P_{uc} - C')e^{i\nu} - P_{EW} - \frac{1}{3} P_{c}$$

$$A_{0+} = -P_{tc} + P_{uc} e^{i\nu} - \frac{1}{3} P_{c}$$

Here, ratio of branching fractions yields

$$\frac{B(B^0 \rightarrow K^0\pi^0)}{2 \times B(B^+ \rightarrow K^+\pi^0)} \frac{\tau_+}{\tau_0} = 0.91 \pm 0.07$$

For $\bar{B}$ decays, weak phases change sign in amplitudes $\bar{A}$

Direct CP asymmetry is defined by

$$A_{CP} = \frac{\bar{A}^2 - A^2}{\bar{A}^2 + A^2} \propto \sum_{i,j} A_i A_j \sin(\delta_i - \delta_j) \sin(\phi_i - \phi_j)$$

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Results on $\mathcal{A}_{CP}$ in $B^0 \rightarrow K^+\pi^-$ and $B^0 \rightarrow K^+\pi^0$

- **new** $\mathcal{A}_{CP}(K^+\pi^-) = -0.107 \pm 0.016^{+0.006}_{-0.016}$

- **World average** (BABAR, Belle, CDF, CLEO)
  $\mathcal{A}_{CP}(K^+\pi^-) = -0.098^{+0.012}_{-0.011}$ $\Rightarrow 8.1 \sigma$

- For $B^+ \rightarrow K^+\pi^0$ modes, world average is
  (BABAR, Belle, CLEO)
  $\mathcal{A}_{CP}(K^+\pi^0) = 0.050 \pm 0.025$ $\Rightarrow 2.0 \sigma$

- CP asymmetries in $B^0$ & $B^+$ decays differ
  $\Rightarrow 5.3 \sigma$ significance

- What causes this effect, since theory expect $\Delta \mathcal{A}_{K\pi} \sim 0$?
  - Enhancement of large $C$ with large strong phase to $T$
    $\Rightarrow$ strong interaction effect?
  - enhancement of large $P_{EW}$
    $\Rightarrow$ new physics?

Chang et al 2004
Li, Mishima, Sanda 2005
Yoshikawa 2003, Mishima-Yoshikawa 2004
Results on $A_{\text{CP}}$ in $B^+ \rightarrow K^0\pi^+$ & $B^0 \rightarrow K^0\pi^0$

- For complete picture we need to include CP asymmetries with $K^0$ decays

- The BABAR/Belle WA for $K^0\pi^+$ is consistent with zero

\[ A_{\text{CP}}(K^0\pi^+) = 0.009 \pm 0.025 \]

- For $K^0\pi^0$ both BABAR and Belle have updated results

- BABAR observes $556 \pm 32$ $K^0_S\pi^0$ signal events (467 million $B\overline{B}$) measuring

\[ A_{\text{CP}}(K^0\pi^0) = -0.13 \pm 0.13 \pm 0.03 \]

- Belle see $657 \pm 37$ $K^0_S\pi^0$ & $285 \pm 77$ $K^0_L\pi^0$ events (657 million $B\overline{B}$) yielding

\[ A_{\text{CP}}(K^0\pi^0) = 0.14 \pm 0.13 \pm 0.06 \]
Model-independent Analysis in $B \to K\pi$ Modes

- The CP asymmetries in the four $K\pi$ modes are related via SM sum rule

\[
A_{\text{CP}}(K^+\pi^-) + A_{\text{CP}}(K^0\pi^-) \frac{B(K^0\pi^-)}{B(K^+\pi^-)} \frac{\tau_0}{\tau_+} = A_{\text{CP}}(K^+\pi^0) \frac{2B(K^+\pi^0)}{B(K^+\pi^-)} \frac{\tau_0}{\tau_+} + A_{\text{CP}}(K^0\pi^0) \frac{2B(K^0\pi^0)}{B(K^+\pi^-)}
\]


- Sum rules predicts $A_{\text{CP}}(K^0\pi^0) = -0.151 \pm 0.043$

- Present world average is $A_{\text{CP}}(K^0\pi^0) = 0.01 \pm 0.10$

- Due to large errors deviation is $\sim 1.4\sigma$

- Need high statistic to settle issue experimentally

- Need SuperB factory since hadron colliders cannot measure $K^0\pi^0$ mode

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Search for Neutral Light Higgs in $\gamma$ Decays
Search for a Light Neutral Higgs

In the simplest extension of the MSSM (NMSSM) a CP-odd Higgs singlet $A_s$ is introduced that mixes with the MSSM CP-odd state $A_{MSSM}$

$$A^0 = \sin \theta_A A_s + \cos \theta_A A_{MSSM}$$

LEP results impose lower bound of $|\cos \theta_A| \geq 0.04$ at $\tan \beta = 10$

Coupling in $A^0 \rightarrow \tau^+\tau^-$ is $\propto \cos \theta \tan \beta$

$A^0$ may be produced in radiative $\gamma$ decays with $B(\gamma \rightarrow \gamma A^0) \sim \mathcal{O}(10^{-4})$

Use $(121.8 \pm 1.2) \times 10^6 \gamma(3S)$ decays to look for $\gamma(3S) \rightarrow \gamma A^0, A^0 \rightarrow \mu^+\mu^-$

$A^0 \rightarrow$ invisible

Gunion et al, PRD76,051105 (2007)
Analysis Strategy for $A^0 \rightarrow \mu^+\mu^-$

- Look for events with energetic photon ($E > 0.5$ GeV) recoiling against 2 tracks with $\Delta Q = 0$
- In CM $\mu\mu$ & $\gamma$ back-to-back
- Perform kinematic $\gamma(3S)$ fit
- Perform 1-d fit to reduced mass $m_R = \sqrt{m_{\mu\mu}^2 - 4m_\mu^2}$
  motivated by continuum background from $e^+e^- \rightarrow \gamma\mu^+\mu^-$
  which is smooth near $m_R \sim 0$
Dimuon Mass Scan

- Scan region $2m_\mu < m_{A0} < 9.3$ GeV
- Perform maximum likelihood fit in 300 MeV $m_R$ bins
- Suppress $\rho^0$ background require 2 identified $\mu$'s for $m_{\mu\mu} < 1.05$ GeV

PDF is gotten from fit to signal MC

Signal PDF

Background PDF

PDF is gotten from fit to 78.5 fb$^{-1}$ data at $\gamma(4S)$
Upper Limits on $A^0 \rightarrow \mu^+\mu^-$

- We see no signal in the entire mass region (0.21 - 9.3 GeV) and set branching fraction upper limits at 90% CL.

Most significant structure (3σ incl systematics) is seen at 4.94 GeV with $\mathcal{B}(4.94 \rightarrow \mu^+\mu^-) = (1.9\pm0.6\pm0.1) \times 10^{-6}$.

Second most significant structure (2.9σ incl systematics) is seen at 0.426 GeV with $\mathcal{B}(0.426 \rightarrow \mu^+\mu^-) = (3.1\pm1.1\pm0.3) \times 10^{-6}$.

arXiv: hep-ex/0902.2176
Search for Invisible $A^0$

- The $A^0$ may decay into invisible particles, e.g. LSP pair

- Fit for missing mass in events with a high-energy photon consistent with the mass hypothesis $0 < m_{A^0} < 7.8$ GeV

- No significant signal is seen anywhere
  - set branching fraction upper limits @ 90%CL

arXiv:hep-ex/0808.0017
Comparison of $B$ upper Limits with NMSSM

- Look at 4 separate mass regions & plot highest limit

$A^0 \rightarrow \mu \mu$

$A^0 \rightarrow \text{invisible}$

Exclude mass regions <7.5 (2mτ) GeV in $\mu^+\mu^-$ (invisible) final states

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Conclusion and Outlook

Present results on $B^+ \rightarrow \tau^+ \nu_\tau$ are higher than the SM predictions providing stringent constraints in the $m_H$-$\tan \beta$ plane ($m_H>300$ GeV)

$r_H = 1.67 \pm 0.34_{\text{exp}} \pm 0.36_{f_B,V_{ub}}$

A significant CP asymmetry is observed in $B^0 \rightarrow K^+ \pi^-$ ($8.1 \sigma$) but not in $B^+ \rightarrow K^+ \pi^0$

$A_{CP}(K^+\pi^-) = -0.098^{+0.012}_{-0.011}$

solution of $K\pi$ puzzle requires a precise measurement of $A_{CP}(K^0\pi^0)$

this will tell us if new physics contributions are necessary or not

A light Higgs in $\gamma$ decays is ruled out at $<4 \times 10^{-6}$ ($<2 \times 10^{-5}$) in the $\mu^+\mu^-$ (invisible) final state in the 0.2-9.3 GeV mass region

rules out masses $<7.5$ GeV ($<2m_\tau$) in $\mu^+\mu^-$ (invisible) final state in NMSSM

For a considerable improvement of these measurements a SuperB factory is needed
**Comparison: B Upper Limits vs Axion Model**

Other model predicts axion-like state, \( a \), in \( 0.36 < m_a < 0.8 \) GeV mass range with \( a \rightarrow \mu^+\mu^- \), \( B(\gamma \rightarrow \gamma a) \sim 10^{-5} - 10^{-6} \).

- **Axion Model BF Range**
  - **High UL**
  - **Upper Limit**

**Graphs:**
- **BR(\( \gamma \rightarrow A^0 \))**
  - **A^0 \rightarrow \mu \mu**
  - **A^0 \rightarrow \text{invisible}**

**Normura, Thaler**
hep-ph/0810.5397

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