BSM at Belle: $B \to K^* \ell^+ \ell^-$ and search for leptonic $B$ decays

Stefano Villa, April 24, 2006

based on (i.e. same as) the talk given at
Les Rencontres de Physique de la Vallée d’Aoste,
La Thuile, Italy, March 10, 2006

NEW: updated with Belle result on $B \to \tau \nu_\tau$
Summary

• $B$ physics at Belle
• The $B \to K^* \ell^+ \ell^-$ channel
  → forward-backward asymmetry
  → measurement of Wilson coefficients
• $B \to \ell \nu_{\ell}$ searches
• $B \to \ell^+ \ell^-$ searches
• Future prospects
• Conclusions

Notation:
• $B^0 \equiv B^0_d$
• Charge-conjugate modes always included
B physics at Belle

**B production**

$BB$ pairs produced at KEKB in $e^+e^-$ (3.5 GeV on 8 GeV) collisions at the $\gamma(4S)$ resonance. Collected so far more than 500 fb$^{-1}$

**Charged tracks reconstruction/ID:**
- electron ID: loss in CDC, shower shape in ECL and response of ACC; eff $\geq$ 90%, $\pi$-misID rate $\approx$ 0.1%
- muon ID: based on ECL and KLM; eff $\geq$ 90%, $\pi$-misID rate $\approx$ 1%
- $K^\pm$ selected using ACC, TOF and CDC; eff $\geq$ 90% and $\pi$-misID rate $\approx$ 6%
- Other charged tracks identified as $\pi^\pm$

**B signal selection:**

Typically based on event shape variables with signal window defined using

\[ M_{bc} = \sqrt{E_{beam}^2 - p_B^2} \ (\approx m_B) \]

and \[ \Delta E = E_B - E_{beam} \ (\approx 0) \]
$B \rightarrow K^{*} \ell^{+} \ell^{-}$
$B \to K^{*} \ell^+ \ell^-$: a window on BSM physics

**SM:**
- $b \to s \ell^+ \ell^-$: FCNC process, forbidden at tree level
- at lowest order via electromagnetic penguin or box diagrams

Lepton pair yields useful observables for testing the theory:
- forward-backward asymmetry ($A_{FB}$)
- invariant mass ($q^2$)

**BSM:**
Sensitive to new physics via insertion of heavy particles in the internal lines.
$B \rightarrow K^* \ell^+ \ell^-$: Wilson coefficients

New Physics at the one loop level can be described in terms of an effective Hamiltonian:

$$\mathcal{H}_{\text{eff}} = -\frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \sum_{i=1}^{10} C_i(\mu) O_i(\mu)$$

- $C_i(\mu)$ Wilson coefficients: effective strength of short distance interactions
- To leading order, only $O_7$, $O_9$ and $O_{10}$ contribute to $b \rightarrow s \ell^+ \ell^-$
- $C_i$ computed perturbatively up to NNLO: $C_i = A_i + \text{higher order terms}$
- The $B \rightarrow K^* \ell^+ \ell^-$ amplitude depends on $A_7$, $A_9$ and $A_{10}$ under the assumption that higher order terms behave like in the SM.

**SM VALUES:** $A_7 = -0.330$, $A_9 = 4.069$, $A_{10} = -4.213$

Operators in $\mathcal{H}_{\text{eff}}$

\[ O_1 = \langle \bar{s}_\alpha \gamma_\mu L \bar{c}_\beta \rangle \langle \bar{c}_\beta \gamma^\mu L b_\alpha \rangle, \]
\[ O_2 = \langle \bar{s}_\alpha \gamma_\mu L c_\alpha \rangle \langle \bar{c}_\beta \gamma^\mu L b_\beta \rangle, \]
\[ O_3 = \langle \bar{s}_\alpha \gamma_\mu L b_\alpha \rangle \sum_{q=u,d,s,c,b} \langle \bar{q}_\beta \gamma^\mu L q_\beta \rangle, \]
\[ O_4 = \langle \bar{s}_\alpha \gamma_\mu L c_\beta \rangle \sum_{q=u,d,s,c,b} \langle \bar{q}_\beta \gamma^\mu L q_\alpha \rangle, \]
\[ O_5 = \langle \bar{s}_\alpha \gamma_\mu L b_\alpha \rangle \sum_{q=u,d,s,c,b} \langle \bar{q}_\beta \gamma^\mu R q_\beta \rangle, \]
\[ O_6 = \langle \bar{s}_\alpha \gamma_\mu L c_\beta \rangle \sum_{q=u,d,s,c,b} \langle \bar{q}_\beta \gamma^\mu R q_\alpha \rangle, \]
\[ O_7 = \frac{e}{16\pi^2} \langle \bar{s}_\alpha \sigma_{\mu\nu} (m_s L + m_b R) b_\alpha \rangle F_{\mu\nu}, \]
\[ O_8 = \frac{g}{16\pi^2} \langle \bar{s}_\alpha \sigma_{\mu\nu} (m_s L + m_b R) T_{\alpha\beta}^a b_\beta \rangle G^{a\mu\nu}, \]
\[ O_9 = \frac{e^2}{16\pi} \langle \bar{s}_\alpha \gamma^\mu L b_\alpha \bar{\ell} \gamma_{\mu} \ell \rangle, \]
\[ O_{10} = \frac{e^2}{16\pi} \langle \bar{s}_\alpha \gamma^\mu L b_\alpha \bar{\ell} \gamma_{\mu} \gamma_5 \ell \rangle, \]

- Electromagnetic operator
- Semileptonic vector
- Semileptonic axial-vector
Constraints on Wilson coefficients

The absolute value of $C_7$ is constrained by $B \to X_s \gamma$; constraints on $C_9$ and $C_{10}$ (donut-shape) are derived from the $B \to X_s \ell^+\ell^-$ branching fractions.

To determine sign of $C_7$ and to measure $C_9$ and $C_{10}$ need to look at the differential distributions in $B \to K^* \ell^+\ell^-$. 

Allowed region at 90% CL, based on NNLO and experimental bounds on $B \to X_s \gamma$ and $B \to X_s \ell^+\ell^-$ Br's; $A_7 < 0$


SUSY Extended-MFV

SM:
Forward-backward asymmetry in $K^*\ell^+\ell^-$

\[ A_{FB}(q^2) = \frac{\Gamma(q^2, \cos \theta_{B\ell^-} > 0) - \Gamma(q^2, \cos \theta_{B\ell^-} < 0)}{\Gamma(q^2, \cos \theta_{B\ell^-} > 0) + \Gamma(q^2, \cos \theta_{B\ell^-} < 0)} \]

- $\theta_{B\ell^-}$ ($\equiv \theta$): angle between $B$ and $\ell^-$ in the dilepton rest frame
- $A_{FB}$ is a function of $q^2$ of the dilepton system
- $A_{FB}$ non-zero due to interference of vector ($C_7, C_9$) and axial vector ($C_{10}$) couplings

More generally, one can extract the coefficients by fitting the double-differential decay width:

\[ d^2\Gamma / dq^2 \ d \cos \theta \]
**B → K*ℓ⁺ℓ⁻ selection**

- Dataset: 357 fb⁻¹ = 386M BB pairs
- Modes: $K^{*+} \rightarrow K^+ \pi^0$, $K_S \pi^+$; $K^{*0} \rightarrow K^+ \pi^-$
- lepton = $e, \mu$
- Charmonium ($J/\psi$, $\psi(2S)$) veto
- Dominant background: BB with both B's decaying semileptonically: suppressed using $E_{\text{miss}}$ and $\cos \theta_B$
- $B \rightarrow K \ell^+ \ell^-$ used as “null test”: $A_{FB} \approx 0$ in SM, small BSM


**Signal yield:** $N_{\text{sig}} = 114 \pm 13$

Consistent with Belle measurement (140fb⁻¹):

$\text{Br}(B \rightarrow K^* \ell^+ \ell^-) = (11.5^{+2.6}_{-2.4} \pm 0.8 \pm 0.2) \times 10^{-7}$

Extraction of $A_{FB}$ and Wilson coeffs.

- Extract the ratio of Wilson coefficients $A_9 / A_7$, $A_{10} / A_7$ ($A_7 = A_7^{SM} = -0.330$) from an unbinned maximum likelihood fit on events in the signal window with a pdf including $g(q^2, \theta) = d^2 I / dq^2 \ d \cos \theta$.

- Several event categories:
  - signal + “cross feeds” from misreconstructed $B \rightarrow K^{(*)} \ell^+ \ell^-$ or other $b \rightarrow s \ell \ell$
  - 4 background sources – dominated by dilepton (80%)

$A_{FB}$ simply obtained by integration:

$$A_{FB}(q^2) = \frac{\int_{-1}^{1} \text{sgn}(\cos \theta) g(q^2, \theta) \ d \cos \theta}{\int_{-1}^{1} g(q^2, \theta) \ d \cos \theta}$$

Null test: extract $A_{FB}$ for $B \rightarrow K \ell^+ \ell^-$

$A_{FB}^{bkg-sub}(B \rightarrow K^{+} \ell \ell) = 0.09 \pm 0.14\text{ (stat.)}$

consistent with 0!
Fit results hep-ex/0603018 submitted to PRL

\[ A_7 = -0.330; \quad A_{FB} > 0 \text{ at } 3.4\sigma \]

\[ A_{bkg-sub}^{B\rightarrow K^*\ell\ell}(B) = 0.56 \pm 0.13 \text{ (stat.)} \]

Both \( A_7A_{10} \) and \( A_9A_{10} \) signs flipped excluded!

\[ \frac{A_9}{A_7} = -15.3 \pm 3.4 \]

\[ \frac{A_{10}}{A_7} = 10.3 \pm 5.2 \quad (A_7^{SM}) \]

\[ -1401 < \frac{A_9A_{10}}{A_7^2} < -26.4 \quad (95\% \text{ CL, any } A_7) \]

SM:

\[ \frac{A_9}{A_7} = -12.3, \]

\[ \frac{A_{10}}{A_7} = 12.8. \]
Positive $A_7$ solution

Best fit for positive $A_7$ (non-SM like):

$$A_9/A_7 = -16.3^{+3.7}_{-5.7} \pm 1.4,$$
$$A_{10}/A_7 = 11.1^{+6.0}_{-3.9} \pm 2.4,$$

SM:

$$A_9/A_7 = -12.3,$$
$$A_{10}/A_7 = 12.8.$$
LEPTONIC $B$ DECAYS
\[ B^- \rightarrow \ell^- \bar{\nu}_\ell \]

**SM:**

\[
\mathcal{B}(B^- \rightarrow \ell^- \bar{\nu}) = \frac{G_F^2 m_B m^2_\ell}{8\pi} \left(1 - \frac{m^2_\ell}{m^2_B}\right)^2 f^2_B |V_{ub}|^2 \tau_B
\]

**B lifetime**

- \[ \text{Br}(B \rightarrow \tau \nu_\tau) \approx 1 \times 10^{-4} \]
- Other leptons suppressed \( \sim (m_\ell)^2 \):
  - by 1/225 for \( B \rightarrow \mu \nu_\mu \), \( 10^{-7} \) for \( B \rightarrow e \nu_e \)

**Direct Measurement of decay constant \( f_B \)!

**BSM:**

- MSSM (charged Higgs): can explore the \((M_H, \tan \beta)\) plane.
- Pati-Salam models: can set limit on the mass of LQ

Possible enhancements of BF in
$B^- \rightarrow e^- \overline{\nu}_e$ and $B^- \rightarrow \mu^- \overline{\nu}_\mu$

- One highly energetic lepton
- Charmonium veto
- Large missing $E$ and $p$
- Signal window defined on $\Delta E$ and $M_{bc}$ of the companion $B$
- Cut on lepton momentum in $B$ rest frame

**Belle results** at 90% CL

$\text{Br}(B \rightarrow \mu \nu_\mu) < 2.0 \times 10^{-6}$ hep-ex/0408132, 140 fb$^{-1}$

$\text{Br}(B \rightarrow e \nu_e) < 5.4 \times 10^{-6}$ Belle-conf-0247, 60 fb$^{-1}$

update coming soon!
$B^- \rightarrow \tau^- \bar{\nu}_\tau$ NEW: submitted to PRL, hep-ex/0604018

- Reconstruct the companion $B$ in exclusive $D^{(*)0}h^+$ and $D^{(*)0}D^{(*)+}_s$ channels to get a pure (55%) $B^+B^-$ sample ($6.8 \times 10^5$ evts)
- Reconstruct signal from remaining particles in the event
- Final selection based on remaining energy in ECL: $E_{ECL} \approx 0$ for signal

Dataset: $414 \text{ fb}^{-1}$
To validate the $E_{ECL}$ cut, use control sample of double tagged events: $B_{\text{sig}}$ substituted by $B \to D^{*0}\ell\nu$

FIT RESULT:

- signal
- background
- total
$B^- \rightarrow \tau^- \bar{\nu}_\tau$ : results

\[
\begin{array}{cccccc}
N_{\text{obs}} & N_s & N_b & B(10^{-4}) & \Sigma \\
\hline
\mu^- \bar{\nu}_\mu \nu_\tau & 13 & 5.4^{+3.2}_{-2.2} & 9.1^{+0.2}_{-0.1} & 1.01^{+0.59}_{-0.41} & 2.3\sigma \\
e^- \bar{\nu}_e \nu_\tau & 12 & 3.9^{+3.5}_{-2.5} & 9.2^{+0.2}_{-0.1} & 0.79^{+0.71}_{-0.49} & 1.5\sigma \\
\pi^- \nu_\tau & 9 & 3.4^{+2.6}_{-1.6} & 4.0^{+0.2}_{-0.1} & 0.96^{+0.74}_{-0.46} & 1.9\sigma \\
\pi^- \pi^0 \nu_\tau & 11 & 6.2^{+3.9}_{-2.7} & 4.2^{+0.3}_{-0.1} & 1.23^{+0.77}_{-0.53} & 2.6\sigma \\
\pi^- \pi^+ \pi^- \nu_\tau & 9 & 3.1^{+3.1}_{-2.6} & 3.7^{+0.3}_{-0.2} & 2.99^{+3.01}_{-2.49} & 1.2\sigma \\
\hline
\text{Combined} & 54 & 21.2^{+6.7}_{-5.7} & 30.2^{+0.5}_{-0.4} & 1.06^{+0.34}_{-0.28} & 4.2\sigma \\
\end{array}
\]

**BELLE result**

$\text{Br}(B \rightarrow \tau \nu_\tau) = (1.06^{+0.34}_{-0.28} \text{ (stat)} ^{+0.18}_{-0.16} \text{ (syst)}) \times 10^{-4}$

$f_B = 0.176^{+0.028}_{-0.023} \text{ (stat)} ^{+0.020}_{-0.019} \text{ (syst)} \text{ GeV}$

obtained using $|V_{ub}| = (4.39 \pm 0.33) \times 10^{-3}$ (HFAG)

**SM:**

$\text{Br}(B \rightarrow \tau \nu_\tau) = (1.59 \pm 0.40) \times 10^{-4}$

$f_B = 0.216 \pm 0.022 \text{ GeV} \text{ (from lattice QCD)}$

First evidence of a purely leptonic $B$ decay

First direct determination of $f_B$
$B^+ \rightarrow \tau^- \bar{\nu}_{\tau}$: constraints on BSM

Constraint on Charged Higgs (two Higgs doublet model, type II)

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

$$r_H = (1 - \frac{m_B^2}{m^2_{H}} \tan^2 \beta)^2 \rightarrow r_H = 0.67^{+0.29}_{-0.26}$$

$$\mathcal{B}(B \rightarrow \tau \nu) = (1.06^{+0.34}_{-0.28} \text{(stat)} + 0.18 \text{(syst)}) \times 10^{-4}$$

SM: $\mathcal{B}(B \rightarrow \tau \nu) = (1.59 \pm 0.40) \times 10^{-4}$

\[ B^0 \rightarrow \ell^+ \ell^- \]

**SM:**
- Box or annihilation diagram
- \( \text{Br}(B^0 \rightarrow \mu^+ \mu^-) = (1.0 \pm 0.1) \times 10^{-10} \)
- \( \text{Br}(B^0 \rightarrow e^+ e^-) = (2.3 \pm 0.3) \times 10^{-15} \)
- \( \text{Br}(B^0 \rightarrow \mu^+ e^-) \approx 0 \) (neutrino osc.)
- Helicity suppressed \( \sim (m_\ell)^2 \)

**BSM:**
- Enhancement of BF\( (B^0 \rightarrow \mu^+ \mu^-, e^+ e^-) \) in high \( \tan \beta \) MSSM (2 orders of magnitude) and SUSY
- \( B^0 \rightarrow \mu^\pm e^\mp \) allowed in Pati-Salam (leptoquark) and SUSY models

**BELLE results**
- 90% CL limits based on 78 fb\(^{-1}\)
  - \( \text{Br}(B \rightarrow \mu^+ \mu^-) < 1.6 \times 10^{-7} \)
  - \( \text{Br}(B \rightarrow e^+ e^-) < 1.9 \times 10^{-7} \)
  - \( \text{Br}(B \rightarrow \mu^\pm e^\mp) < 1.7 \times 10^{-7} \)

Limit on the Pati-Salam LQ mass:
\[ M_{LQ} > 46 \text{ TeV}/c^2 \] at 90% CL
Super Belle: expected performance

Goal: \( \mathcal{L} = 5 \times 10^{35} \text{cm}^{-2} \text{s}^{-1}; \) in 1 year \( \int \mathcal{L} = 5 \text{ ab}^{-1} \)

expected performance on \( B \rightarrow K^* \ell^+ \ell^- \)
with 1 year of data taking \( \) no syst. errors included

\[ L = 5 \times 10^{35} \text{cm}^{-2} \text{s}^{-1}; \]

\[ \text{in 1 year } \int L = 5 \text{ ab}^{-1} \]

from \( A_{FB}(K^* \ell^+ \ell^-) \)

\[ \Delta A_9 / A_9 \sim 11\% \]
\[ \Delta A_{10} / A_{10} \sim 13\% \]

zero of \( A_{FB}(q^2) \) is very sensitive to BSM effects. Will be able to measure it.

A. Ishikawa at Lake Louise 2006
Conclusions

• Belle performed the **first measurement of Wilson Coefficients in** $B \to K^{*} \ell^{+} \ell^{-}$:
  - Integrated forward-backward asymmetry significantly $> 0$
  - First determination of sign of $A_9 A_{10}$
  - Results compatible with SM prediction and ruling out many BSM scenarios

• $B$ leptonic decays set constraints on BSM parameter space
  - $M_H - \tan \beta$ in MSSM
  - $M_{LQ}$ in Pati-Salam models
  - **First evidence of $B \to \tau \nu \tau$!**

• Still a lot to come from Belle and hopefully Super Belle!

but something else happened since la Thuile...
NEW! Cecilia was born!

\[ m_C = 3650 \text{ g} \]
\[ L_C = 53 \text{ cm} \]
\[ t^0 = \text{Apr. 7, 22:26} \]
BACKUP SLIDES
Details of the fit

The Probability Density Function:

\[ P(M_{bc}, q^2, \cos \theta; A_9/A_7, A_{10}/A_7) \]

\[ = \frac{1}{N_{\text{sig}}} f_{\text{sig}} \epsilon_{\text{sig}}(q^2, \cos \theta) g(q^2, \cos \theta) \]

\[ + \frac{1}{N_{\text{CF}}} f_{\text{CF}} \epsilon_{\text{CF}}(q^2, \cos \theta) g(q^2, \cos \theta) \]

\[ + \frac{1}{N_{\text{IF}}} f_{\text{IF}} \epsilon_{\text{IF}}(q^2, \cos \theta) g(q^2, -\cos \theta) \]

\[ + (1 - f_{\text{sig}} - f_{\text{CF}} - f_{\text{IF}} - f_{K^*h h} - f_{\psi X_s}) \times \]

\[ \left\{ (f_{K^*\ell h} \mathcal{P}_{K^*\ell h}(q^2, \cos \theta) + (1 - f_{K^*\ell h}) \mathcal{P}_{\text{dil}}(q^2, \cos \theta) \right\} \]

\[ + f_{K^*h h} \mathcal{P}_{K^*h h}(q^2, \cos \theta) + f_{\psi X_s} \mathcal{P}_{\psi X_s}(q^2, \cos \theta). \]

\( \epsilon \): efficiency functions, estimated from data and MC

\( f \): event by event signal and background probability, from \( M_{bc} \) fit
Systematic uncertainties

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<th>source</th>
<th>negative $A_7$ solution</th>
<th>positive $A_7$ solution</th>
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<td>$A_9/A_7$</td>
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<td>$A_7$</td>
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