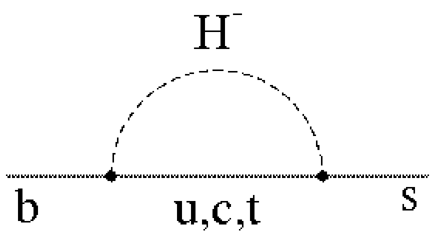
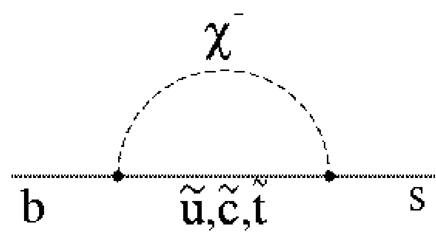
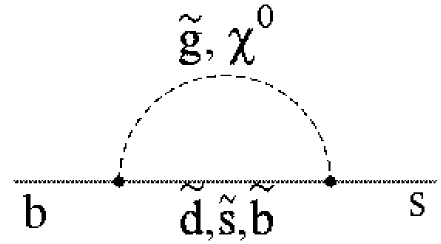
Radiative Penguin Decays

B **decay signatures for New Physics**
in $b \to s(d)\gamma$ **and** $b \to s(d)\ell^+\ell^-$







Steve Playfer
University of Edinburgh
on behalf of the
BaBar and Belle collaborations

Flavianet Workshop, Kazimierz, Poland 24/7/09

Outline of Talk

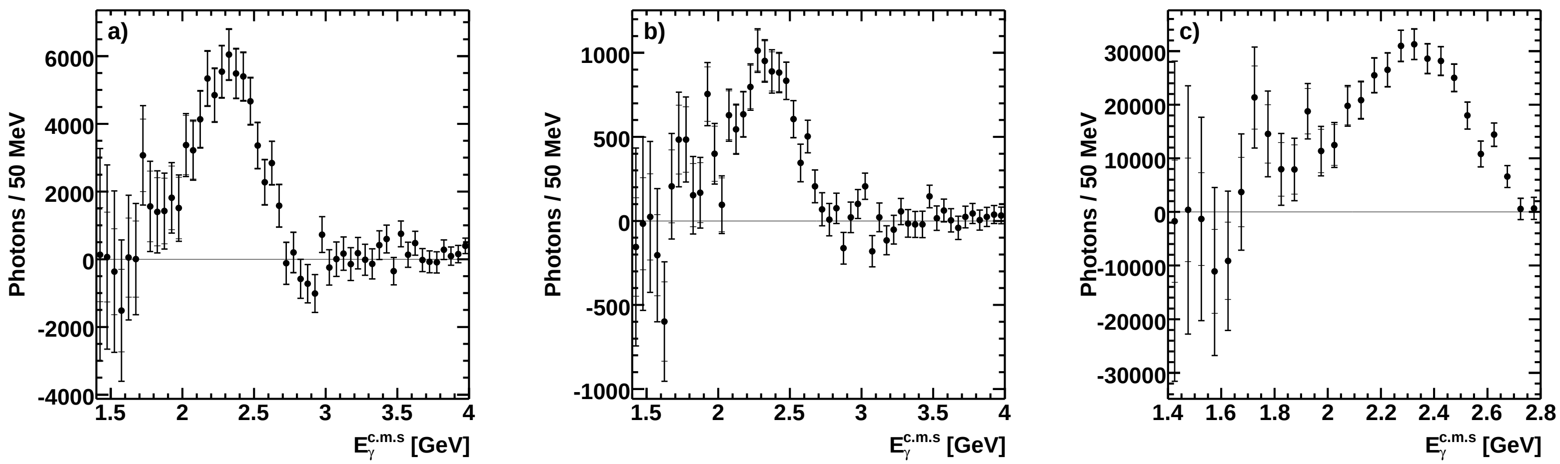
- Inclusive $b \to s\gamma$ branching fraction & spectral shape
- Measurements of $b \to d\gamma$ and extraction of $|Vtd|/|Vts|$
- Direct and time-dependent CP asymmetries
- Exclusive $B \to K^{(*)}\ell^+\ell^-$ branching fractions & asymmetries
- Angular distributions in $B \to K^*\ell^+\ell^-$
- Inclusive $b \to s\ell^+\ell^-$ & exclusive $B \to \pi\ell^+\ell^-$

Focus on comparison of experimental & theoretical uncertainties

- As they are now after the B factories
- Prospects with LHCb & Super B factories

Belle: Fully Inclusive $b \to s\gamma$

657M $B\bar{B}$ pairs, arXiv:0907.1384 (hep-ex)



Untagged (left), lepton-tagged (centre), combined (right)

Combined plot is spectrum corrected for efficiency and resolution

Energy threshold $E_\gamma > 1.7$ GeV

$$BF(b \to s\gamma) = (3.45 \pm 0.15 \pm 0.40) \times 10^{-4}$$

Large off-resonance data subtraction (68/fb)

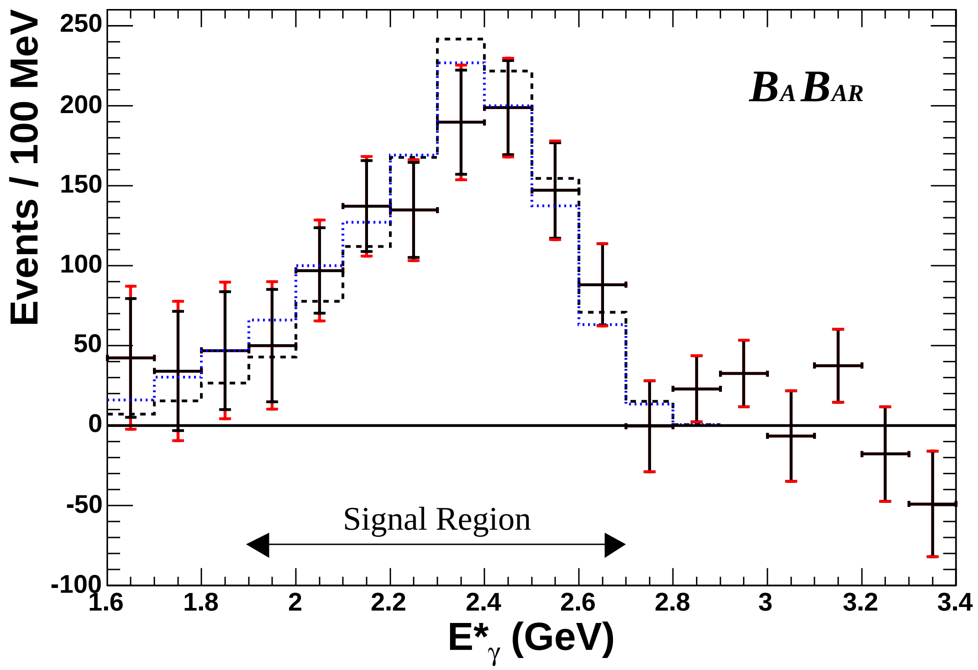
Large B background subtraction, π^0 *and* η *checked with data*

Fully Inclusive Results & Errors

E_γ threshold in GeV	> 1.7	> 1.8	> 1.9	> 2.0
$BF(b \to s\gamma) \times 10^{-4}$	3.45	3.36	3.21	3.02
Statistical error	4.4%	3.9%	3.4%	3.3%
Systematic error	11.6%	7.4%	5.0%	3.6%

- Statistical error is dominated by off-resonance subtraction.
- The largest experimental systematic errors are from continuum subtraction, selection efficiency and B background.
- B background systematic increases rapidly at low E_γ. Lepton-tag does not reduce this error at all.
- Smallest total error is 5% for threshold 2.0 GeV!

BaBar: Lepton-tagged Inclusive $b \to s\gamma$



PRL 97, 171803 (2006)

Only 89M $B\bar{B}$ pairs (out of 465M total)

lepton-tag from other B suppresses continuum

B backgrounds from MC *checked with data*

E^*_γ event spectrum (as shown) is not corrected for efficiency or calorimeter resolution. Curves are KN, BBU model fits.

Extrapolation from $E_\gamma > 1.9$ GeV to > 1.6 GeV by HFAG:

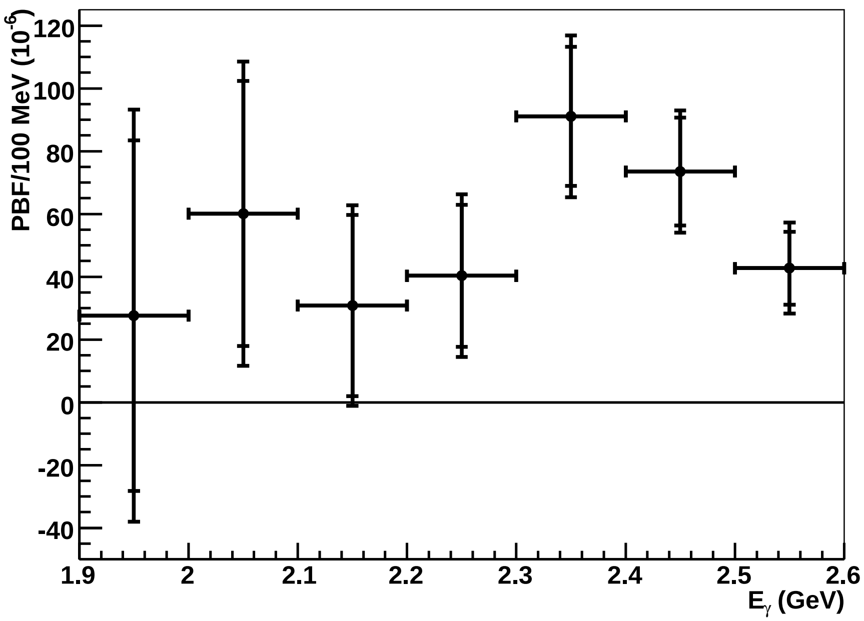
$$BF(b \to s\gamma) = (3.92 \pm 0.31 \pm 0.36 \pm 0.31) \times 10^{-4}$$

Lepton-tagged Results & Errors

E_γ threshold in GeV	> 1.9	> 2.0	> 2.1	> 2.2
$BF(b \to s\gamma) \times 10^{-4}$	3.67	3.41	2.97	2.42
Statistical error	7.9%	7.9%	8.1%	8.7%
Systematic error	9.3%	8.5%	8.4%	6.7%
Model error	7.9%	6.7%	5.7%	5.4%

- Statistical error is determined by lepton-tag efficiency.
- The largest experimental systematic errors are from B background subtraction and lepton-tag efficiency.
- Model error enters through efficiency dependence.
  Parameters: $m_b = 4.60 \pm 0.15$ GeV, $\mu_\pi^2 = 0.45 \pm 0.20$ GeV^2.
- Total error is $\approx 14\%$ for thresholds 1.9, 2.0 GeV.
  Can be reduced to $\approx 7\%$ with full data sample? ($\times 5$ statistics)

BaBar: B-tagged Inclusive $b \to s\gamma$



PRD-RC 77, 051103 (2008)

232M $B\bar{B}$ pairs

(out of 465M total)

reconstruct hadronic decays of other B to suppress continuum and most B backgrounds

Peaking $B \to X\pi^0(\eta)$ backgrounds from MC

Extrapolation from $E_\gamma > 1.9$ GeV to > 1.6 GeV:

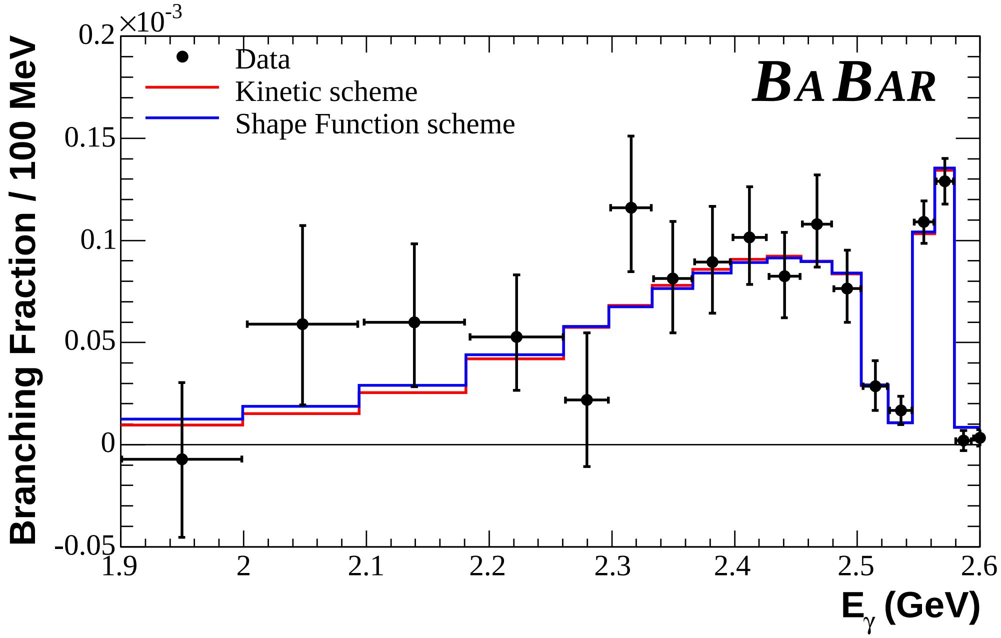
$$BF(b \to s\gamma) = (3.91 \pm 0.91 \pm 0.64) \times 10^{-4}$$

B-tagged Results & Errors

E_γ threshold in GeV	> 1.9	> 2.0	> 2.1	> 2.2
$BF(b \to s\gamma) \times 10^{-4}$	3.66	3.39	2.78	2.48
Statistical error	23.2%	18.8%	17.1%	15.3%
Systematic error	13.1%	10.0%	8.8%	8.2%
Model error	3.1%	3.2%	3.5%	3.7%

- Statistical error dominates because of B-tag efficiency.
- The largest experimental systematic errors are from fits, B background subtraction and B-tag efficiency.
- Model error enters through efficiency dependence. Parameters: $m_b = 4.60 \pm 0.10$ GeV, $\mu_\pi^2 = 0.45 \pm 0.10$ GeV^2.
- Total error is $20 - 25\%$ for thresholds 1.9, 2.0 GeV. Will be best method at a Super B factory? ($\times$100 statistics)

BaBar: Sum of Exclusive $b \to s\gamma$



PRD 72, 052004 (2005)

89M $B\bar{B}$ pairs

(out of 465M total)

Reconstruct $B \to X_s\gamma$

X_s is $K + n\pi$ $(n \leq 4)$

$B \to X_s\pi^0$ from MC

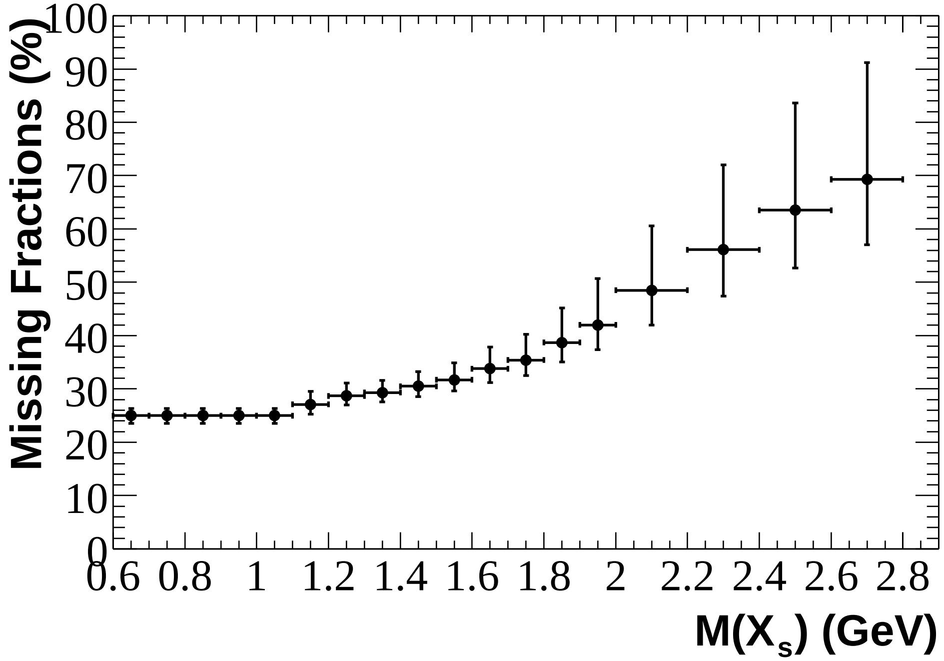
Model X_s fragmentation and missing final states

For the BBU (kinetic) and BLNP (shape function) fits the integral over $E_\gamma > 2.5$ GeV is replaced with a $K^*(892)$ resonance.

Extrapolation from $E_\gamma > 1.9$ GeV to > 1.6 GeV:

$$BF(b \to s\gamma) = (3.49 \pm 0.20^{+0.59}_{-0.46}) \times 10^{-4}$$

X_s Fragmentation & Missing Fractions



- Fragmentation of X_s is modelled by JETSET.
  Adjusted to match observed distribution of final states.
- Flat 25% is from missing K_L states by isospin symmetry.
- Missing high-multiplicity final states give large errors at low E_γ/high $M(X_s)$. These will be hard to reduce!

Sum of Exclusive Results & Errors

E_γ threshold in GeV	> 1.9	> 2.0	> 2.09	> 2.18
$BF(b \to s\gamma) \times 10^{-4}$	3.27	3.31	3.03	2.77
Statistical error	5.5%	3.9%	3.3%	2.9%
Fragmentation error	5.9%	5.5%	5.3%	5.2%
Missing fractions	$^{+13.8\%}_{-7.6\%}$	$^{+10.2\%}_{-5.3\%}$	$^{+7.0\%}_{-3.1\%}$	$^{+4.8\%}_{-2.9\%}$
Other Systematics	7.5%	7.3%	7.3%	7.2%

- Statistical errors are already smaller than systematic errors.
- Missing fractions error dominates at low E_γ.
  Other systematics from efficiency and backgrounds.
- Total error is $13 - 15\%$ for thresholds 1.9, 2.0 GeV.
  With more data understand missing fractions better.
  Can reduce total error to $< 10\%$? ($\times 5$ statistics)

B factory average Branching Fractions

E_γ threshold	> 1.7	> 1.8	> 1.9	> 2.0
Belle inclusive	3.45 ± 0.43	3.36 ± 0.28	3.21 ± 0.19	3.02 ± 0.15
BaBar l-tagged			3.67 ± 0.53	3.41 ± 0.46
BaBar B-tagged			3.66 ± 0.98	3.39 ± 0.73
BaBar Σ exclusive			3.27 ± 0.50	3.31 ± 0.42
B factory average	3.45 ± 0.43	3.36 ± 0.28	3.35 ± 0.20	3.18 ± 0.13
HFAG extrapolation	0.985(4)	0.967(6)	0.936(12)	0.894(20)
$E_\gamma > 1.6$ GeV	3.50 ± 0.44	3.47 ± 0.29	3.58 ± 0.22	3.56 ± 0.16

experimental errors are quadratic sums of statistical and systematic errors

Most accurate experimental result by extrapolating from $E_\gamma > 2.0$ GeV

$BF(b \to s\gamma) = (3.56 \pm 0.16) \times 10^{-4}$ for $E_\gamma > 1.6$ GeV

Theory predictions (NNLO) for $E_\gamma > 1.6$ GeV:

$BF(b \to s\gamma) = (3.15 \pm 0.23) \times 10^{-4}$ Misiak & Steinhauser hep-ph/0609241

$BF(b \to s\gamma) = (2.98 \pm 0.26) \times 10^{-4}$ Becker & Neubert hep-ph/0610067

$BF(b \to s\gamma) = (3.28 \pm 0.25) \times 10^{-4}$ Gambino & Giordano arXiv:0805.0271

Spectral Moments

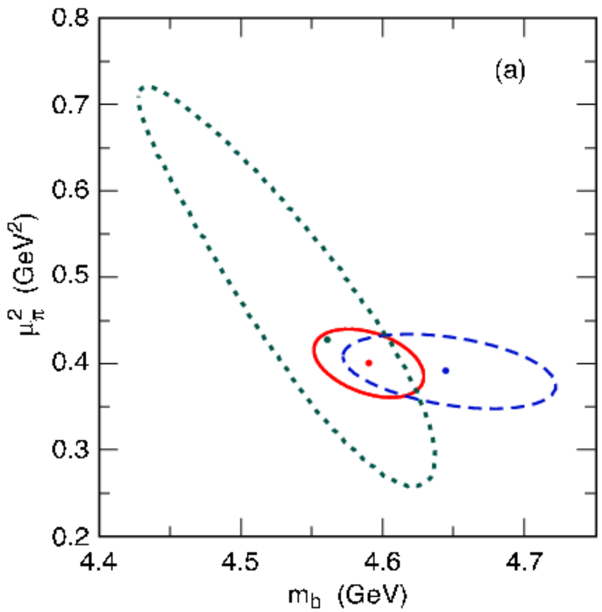
First Moments $< E_\gamma >$ in GeV $\times 10^3$

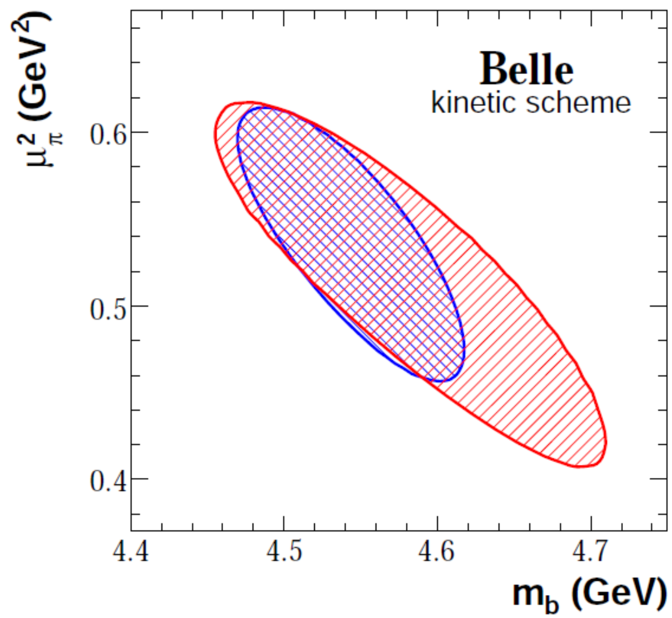
E_γ threshold	> 1.7	> 1.8	> 1.9	> 2.0	> 2.1
Belle inclusive	2282 ± 53	2294 ± 30	2311 ± 18	2334 ± 11	2350 ± 14
BaBar l-tagged			2288 ± 33	2316 ± 22	2355 ± 19
BaBar B-tagged			2289 ± 64	2315 ± 41	2371 ± 27
BaBar Σ exclusive			2321 ± 47	2314 ± 31	2357 ± 21
B factory average	2282 ± 53	2294 ± 30	2304 ± 16	2324 ± 10	2357 ± 10

Second Moments $< E_\gamma^2 - < E_\gamma >^2 >$ in GeV$^2 \times 10^4$

E_γ threshold	> 1.7	> 1.8	> 1.9	> 2.0	> 2.1
Belle inclusive	428 ± 207	370 ± 86	302 ± 36	230 ± 21	170 ± 22
BaBar l-tagged			328 ± 60	266 ± 34	191 ± 25
BaBar B-tagged			334 ± 139	265 ± 62	142 ± 39
BaBar Σ exclusive			253 ± 107	273 ± 40	183 ± 25
B factory average	428 ± 207	370 ± 86	305 ± 32	253 ± 17	174 ± 13

Fits to Spectral Shape (BBU kinetic scheme)





$b \to s\gamma + b \to c\ell\nu$ moments

Only $b \to c\ell\nu$ moments

Only $b \to s\gamma$ moments

$m_b = 4.590 \pm 0.039$ GeV

$\mu_\pi^2 = 0.401 \pm 0.040$ GeV^2

Buchmüller & Flächer hep-ph/0507253

$b \to s\gamma + b \to c\ell\nu$ moments

Only $b \to c\ell\nu$ moments

$m_b = 4.543 \pm 0.075$ GeV

$\mu_\pi^2 = 0.539 \pm 0.079$ GeV^2

C.Schwanda et al, arXiv:0803.2158 (hep-ex)

Neither of these fits includes latest Belle results!

BaBar: Sum of Exclusive $b \to d\gamma$

383M $B\bar{B}$ pairs, arXiv:0807.4975, PRL 102, 161803 (2009)

Measure the ratio of $B \to X_d\gamma/B \to X_s\gamma$ by comparing modes with $\pi^\pm/K^\pm$. $M(X) < 1.8$ GeV corresponds to $E_\gamma > 2.3$ GeV.

$M(X)$	$\mathcal{B}(b \to d\gamma) \times 10^{-6}$	$\mathcal{B}(b \to s\gamma)$	$\mathcal{B}(b \to d\gamma)/\mathcal{B}(b \to s\gamma)$
$0.6 - 1.0$	$1.2 \pm 0.5 \pm 0.1$	$47 \pm 1 \pm 3$	$0.026 \pm 0.011 \pm 0.002$
$1.0 - 1.8$	$6.0 \pm 2.6 \pm 2.3$	$168 \pm 14 \pm 33$	$0.036 \pm 0.015 \pm 0.009$
$0.6 - 1.8$	$7.1 \pm 2.7 \pm 2.3$	$215 \pm 14 \pm 33$	$0.033 \pm 0.013 \pm 0.009$

Systematics from backgrounds and X_d/X_s fragmentation

$$|V_{td}/V_{ts}| = 0.177 \pm 0.043(\text{exp.}) \pm 0.001(\text{theo.})$$

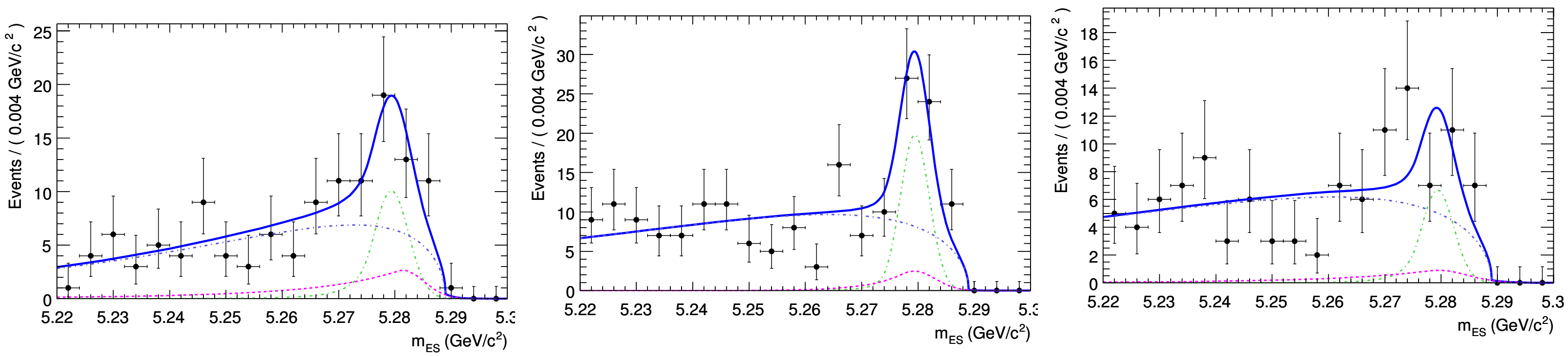
Small theory error is based on a fully inclusive ratio:

A. Ali, H. Asatrian & C. Greub, PLB 429, 87 (1998)

Best method for V_{td}/V_{ts} at a Super B factory? ($\times$100 statistics)

BaBar: Exclusive $B \to \rho(\omega)\gamma$

465M $B\bar{B}$ pairs, arXiv:0808.1379, PRD 78, 112001 (2008)



$BF(B^{\pm} \to \rho^{\pm}\gamma) =$ $(1.20 \pm 0.40 \pm 0.20) \times 10^{-6}$

$BF(B^{0} \to \rho^{0}\gamma) =$ $(0.97 \pm 0.23 \pm 0.06) \times 10^{-6}$

$BF(B^{0} \to \omega\gamma) =$ $(0.50 \pm 0.25 \pm 0.09) \times 10^{-6}$

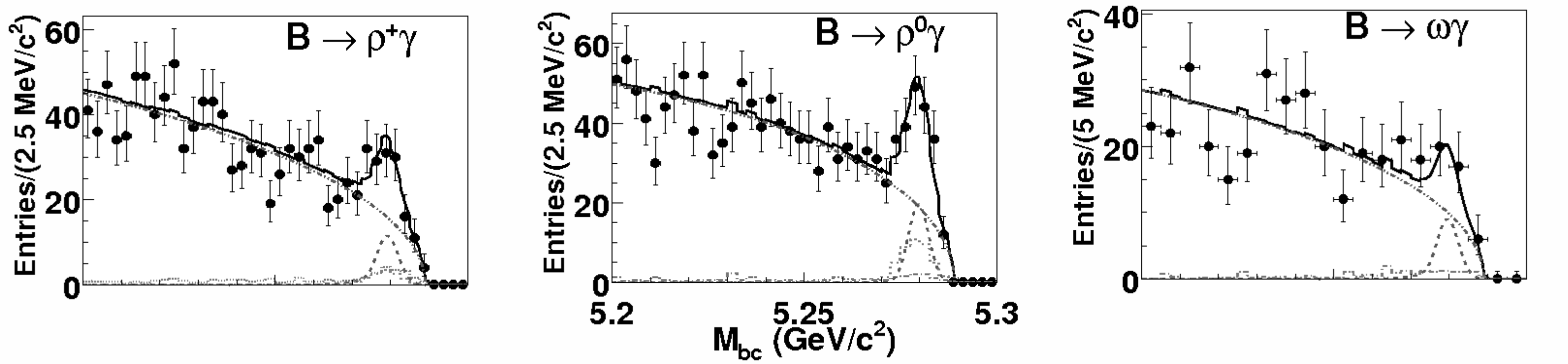
Isospin averages:

$$BF(B \to \rho\gamma) = (1.73 \pm 0.33 \pm 0.17) \times 10^{-6}$$

$$BF(B \to \rho(\omega)\gamma) = (1.63 \pm 0.29 \pm 0.16) \times 10^{-6}$$

Belle: Exclusive $B \to \rho(\omega)\gamma$

657M $B\bar{B}$ pairs, arXiv:0804.4770, PRL 101, 111801 (2008)



$BF(B^{\pm} \to \rho^{\pm}\gamma) =$ $(0.87 \pm 0.28 \pm 0.09) \times 10^{-6}$

$BF(B^{0} \to \rho^{0}\gamma) =$ $(0.78 \pm 0.17 \pm 0.10) \times 10^{-6}$

$BF(B^{0} \to \omega\gamma) =$ $(0.40 \pm 0.18 \pm 0.13) \times 10^{-6}$

Isospin averages:

$$BF(B \to \rho\gamma) = (1.21 \pm 0.23 \pm 0.12) \times 10^{-6}$$

$$BF(B \to \rho(\omega)\gamma) = (1.14 \pm 0.20 \pm 0.11) \times 10^{-6}$$

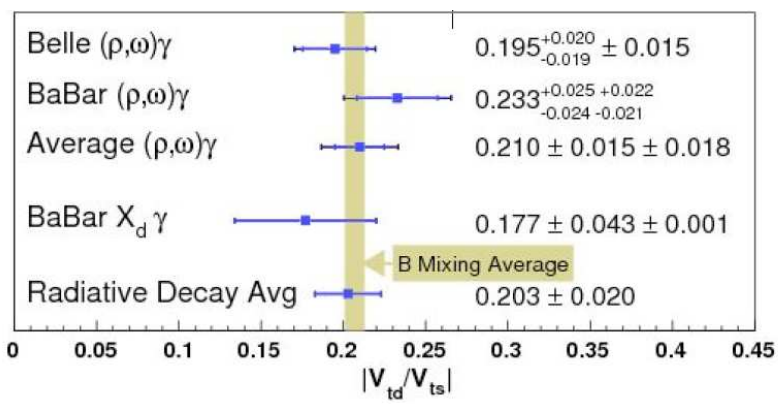
Extraction of $|V_{td}|/|V_{ts}|$ from $B \to \rho\gamma$

$$\frac{BF(B \to \rho\gamma)}{BF(B \to K^*\gamma)} = S_\rho \left|\frac{V_{td}}{V_{ts}}\right|^2 \left(\frac{1 - m_\rho^2/m_B^2}{1 - m_{K*}^2/m_B^2}\right) \zeta^2 \left[1 + \Delta R\right]$$

Isospin factor $S_\rho = 1, 0.5, \approx 0.5$ for ρ^+, ρ^0, ω

ζ is ratio of $(B \to \rho)/(B \to K^*)$ form factors

$\Delta R = 0.031 \pm 0.005$ corrects for annihilation diagrams (mainly ρ^+)



P. Ball, G.W. Jones & R. Zwicky, PRD75:054004 (2007)

Isospin Asymmetries in $B \to K^*\gamma$, $\rho\gamma$

Inconsistent definitions in the literature!

$$\Delta_{0+}(K^*) = \frac{\Gamma(B^0 \to K^{*0}\gamma) - \Gamma(B^+ \to K^{*+}\gamma)}{\Gamma(B^0 \to K^{*0}\gamma) + \Gamma(B^+ \to K^{*+}\gamma)} \qquad \Delta_{0+}(\rho) = \frac{\Gamma(B^+ \to \rho^+\gamma) - 2\Gamma(B^0 \to \rho^0\gamma)}{2\Gamma(B^0 \to \rho^0\gamma)}$$

Standard Model:

$$\Delta_{0+}(K^*) = +(2.6 \pm 0.8)\% \qquad \Delta_{0+}(\rho) = -(5 \pm 5)\%$$

Y.Y. Keum, M. Matsumori, A.I. Sanda, Phys.Rev.D72:014013,(2005)

C.D. Lu, M. Matsumori, A.I. Sanda, M.Z. Zhang, Phys.Rev.D72:094005,2005

BaBar results:

$$\Delta_{0+}(K^*\gamma) = +(6.6 \pm 2.1 \pm 2.2)\% \qquad \Delta_{0+}(\rho\gamma) = -(43 \pm 24 \pm 10)\%$$

arXiv:0906.2177, submitted to PRL (2009)   arXiv:0808.1379, PRD 78, 112001 (2008)

Belle results:

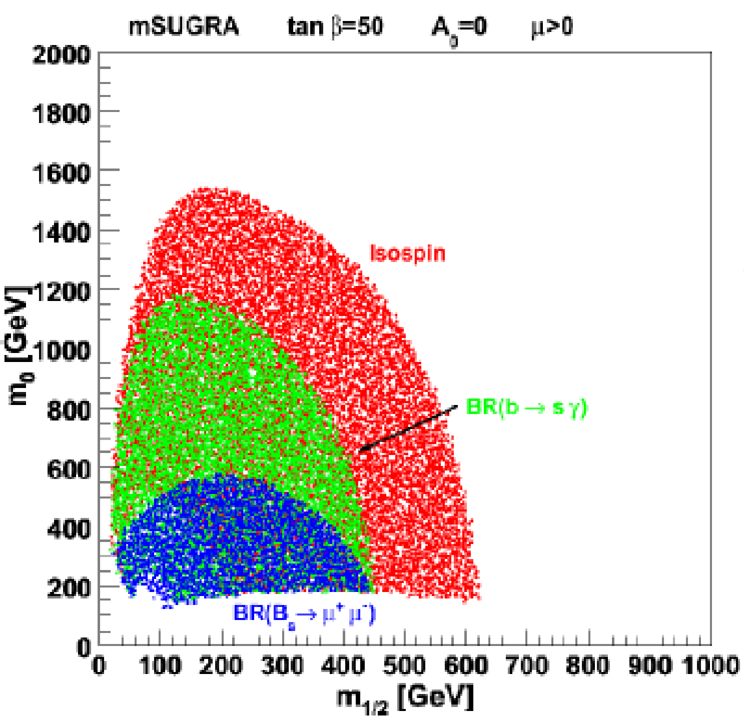
$$\Delta_{0+}(K^*\gamma) = +(1.2 \pm 4.4 \pm 2.6)\% \qquad \Delta_{0+}(\rho\gamma) = -(48 \pm 20 \pm 8)\%$$

hep-ex/0402042, PRD 69, 112001 (2004)   arXiv:0804.4770, PRL 101, 111801 (2008)

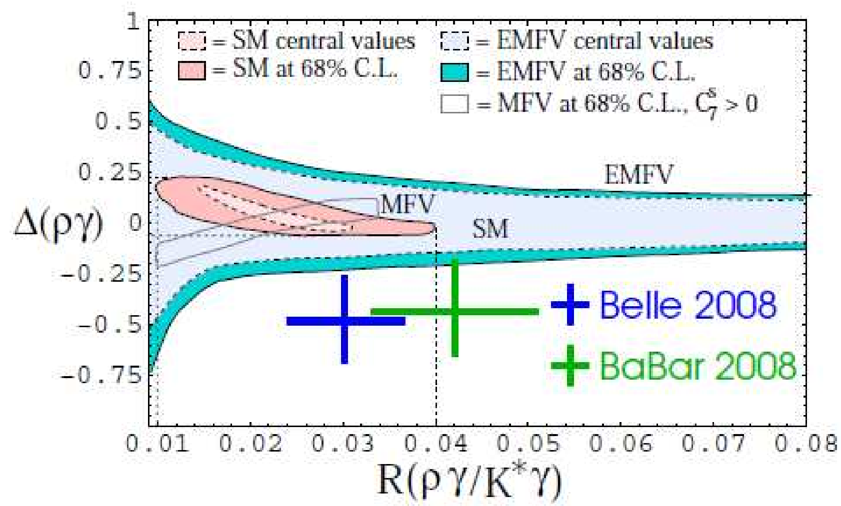
Isospin Asymmetries and New Physics

Isospin asymmetries need contributions from exchange and annihilation diagrams which involve the spectator quark.

They give additional sensitivity to new physics



F. Mahmoudi, arXiv:0710.3791 (2007)

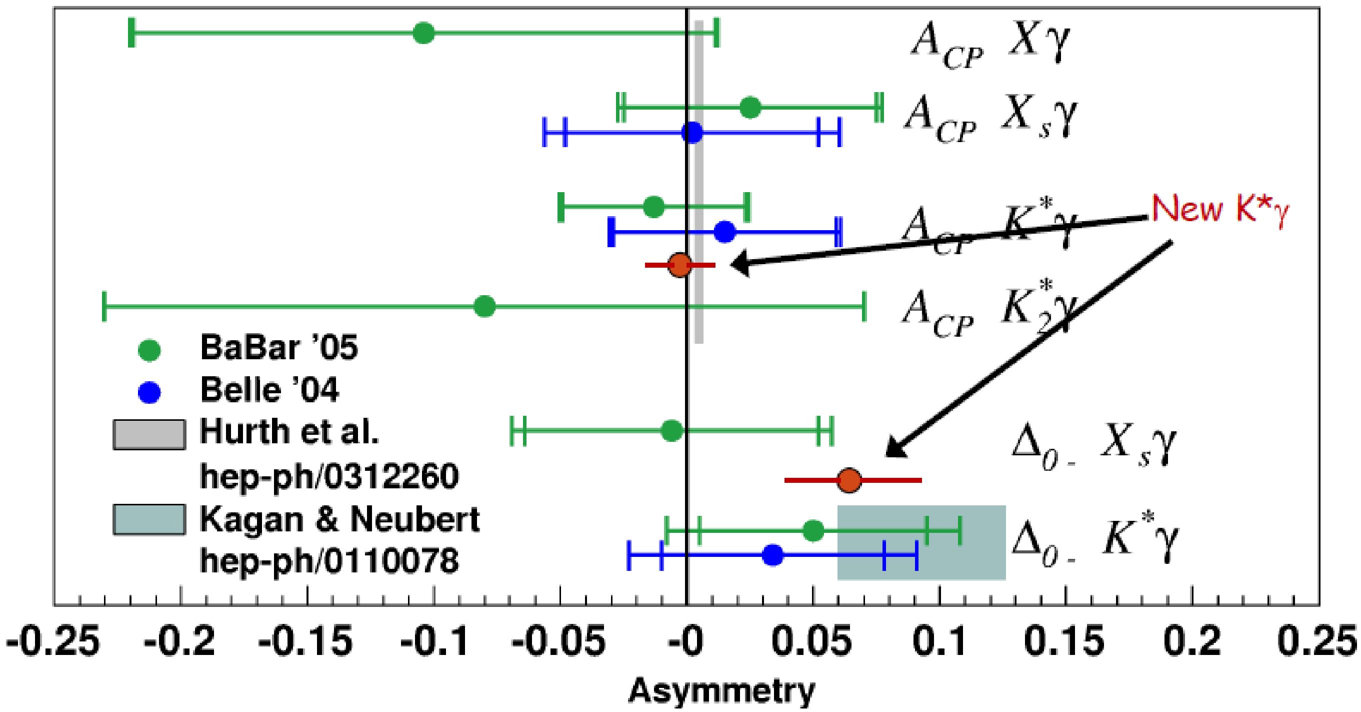


A. Ali & E. Lunghi, hep-ph/0206242 (2002)

Room for New Physics in $B \to \rho\gamma$*?*

Direct CP Asymmetries in $B \to X_s\gamma$

These are very small (<1%) in the Standard Model



$A_{CP}(X\gamma)$ measured in lepton and B-tagged $b \to (s+d)\gamma$

$A_{CP}(X_s\gamma)$ measured in sum of exclusive $b \to s\gamma$

New BaBar results on $B \to K^*\gamma$ are still statistics limited

Time-Dependent CP Asymmetry in $B \to K_s \pi^0 \gamma$

Interference with mixing between dominant decay helicities

$$b \to s\gamma_L \quad \text{or} \quad \bar{b} \to \bar{s}\gamma_R$$

and suppressed decay helicities:

$$b \to s\gamma_R \quad \text{or} \quad \bar{b} \to \bar{s}\gamma_L$$

Naively gives time-dependent sine term:

$$S = 2\frac{m_s}{m_b}\sin 2\beta = 0.027$$

Detailed calculations including gluonic corrections:

- $S = 0.035 \pm 0.017$ M. Matsumori & A.I. Sanda, Phys.Rev.D73:114072,(2006)
- $S = 0.022 \pm 0.015$ P.Ball & R. Zwicky, Phys.Lett.B642:478,(2006)

Sensitive to helicity-changing new physics contributions

BaBar Time-Dependent CP: $B \to K^*(K_s\pi^0)\gamma$

B vertex is determined by extrapolating from K_s decay to beam axis

339 signal events

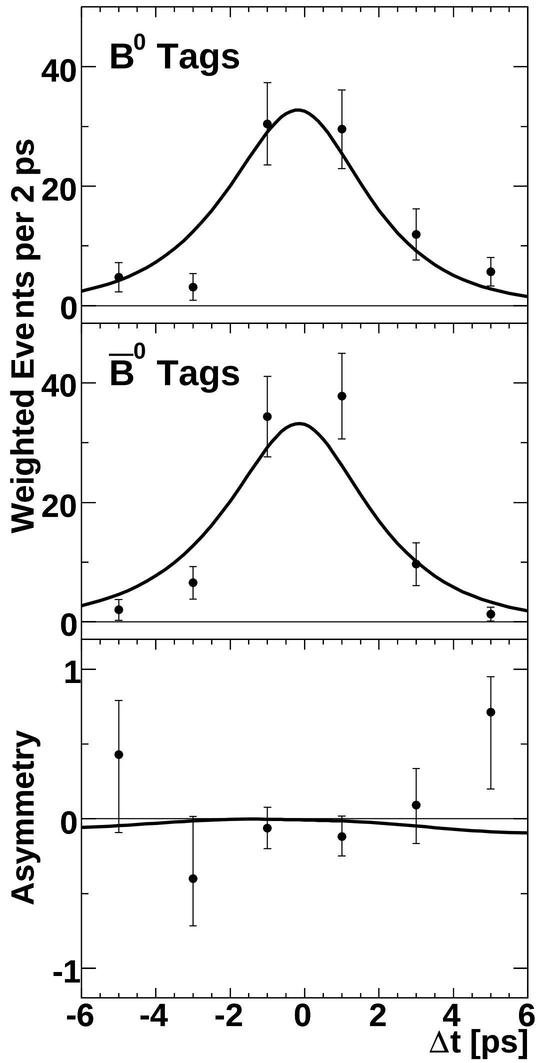
$M(K_s\pi^0) = 0.8 - 1.0$ GeV

$S = -0.03 \pm 0.29 \pm 0.03$

$C = -0.14 \pm 0.16 \pm 0.03$

467M $B\bar{B}$

Phys.Rev.D78:071102,(2008)



Belle Time-Dependent CP: $B \to K_s \pi^0 \gamma$

B vertex is determined by extrapolating from K_s decay to beam axis

177 signal events

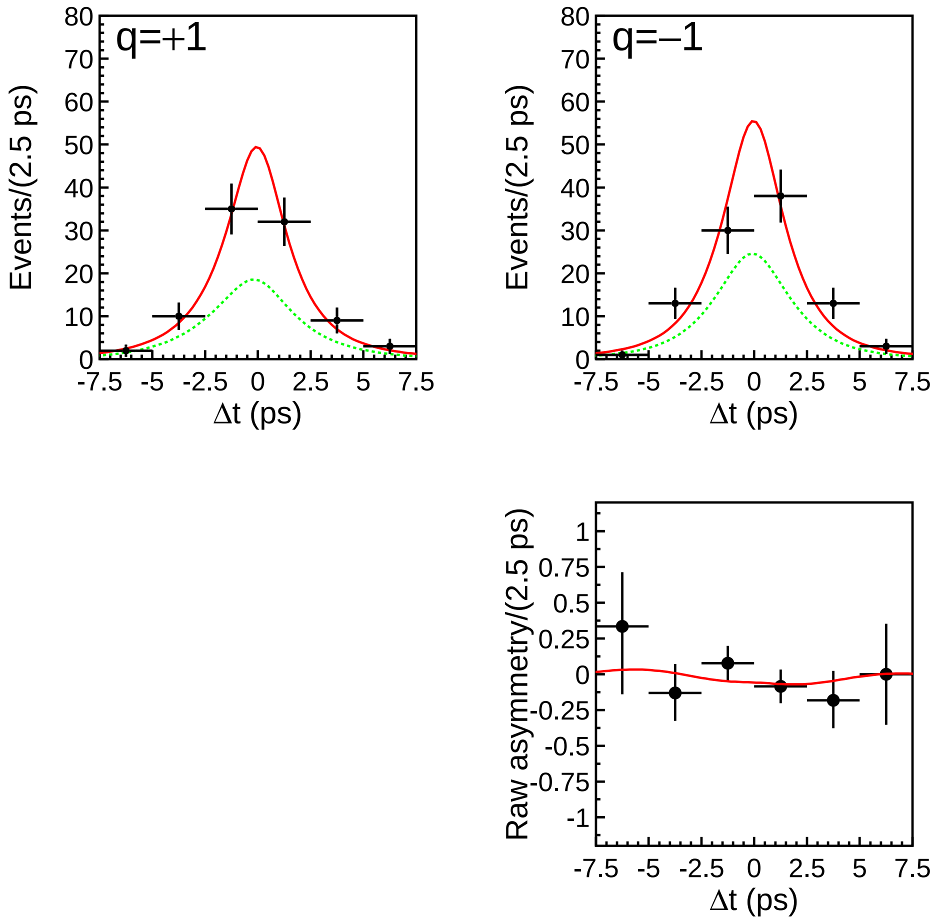
$M(K_s\pi^0) = 0.6 - 1.8$ GeV

$S = -0.10 \pm 0.31 \pm 0.07$

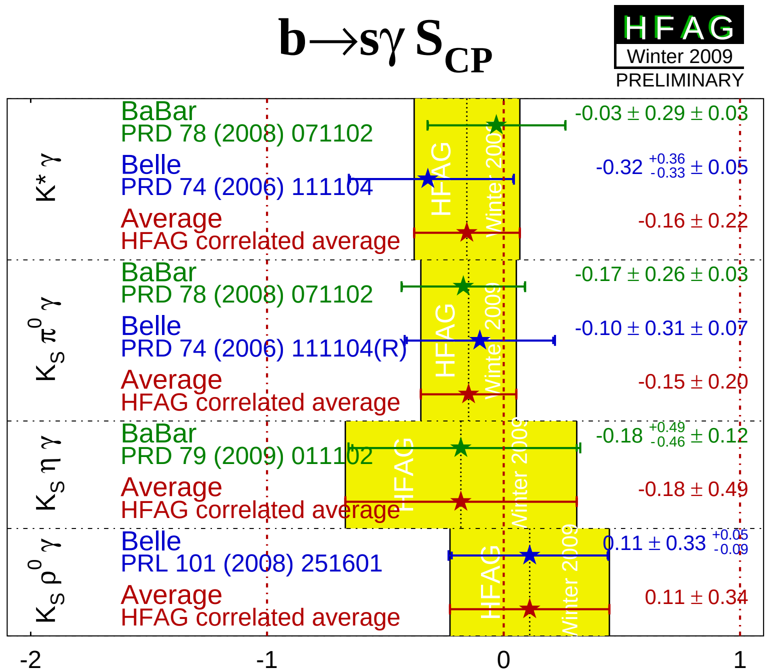
$C = -0.20 \pm 0.20 \pm 0.06$

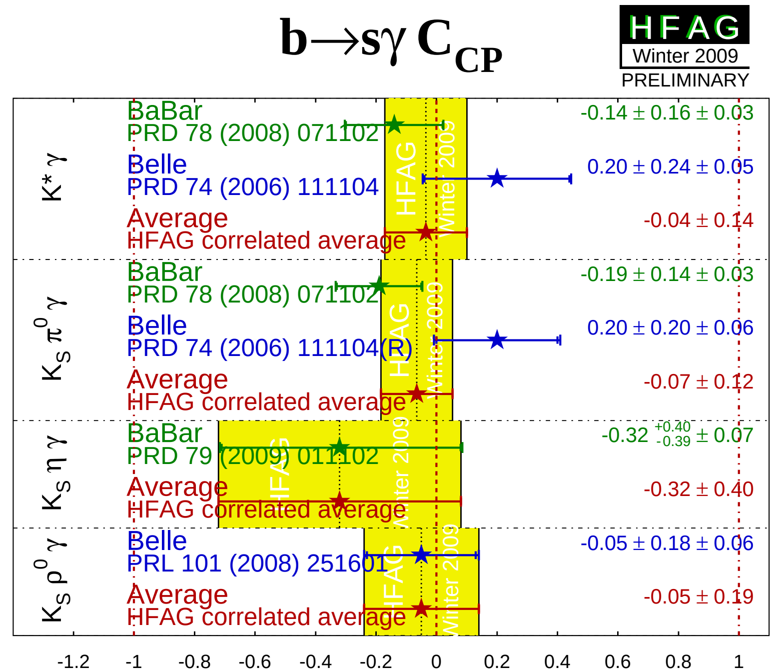
535M $B\bar{B}$

Phys.Rev.D74:111104,(2006)



Summary of Time-Dependent CP Measurements





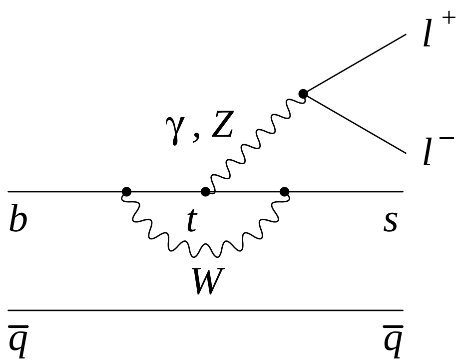
Belle $B \to \rho^0\gamma$: $S = -0.83 \pm 0.65 \pm 0.18$, $C = +0.44 \pm 0.49 \pm 0.14$

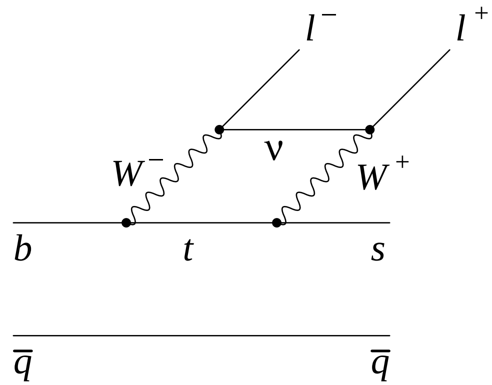
All measurements are statistics limited

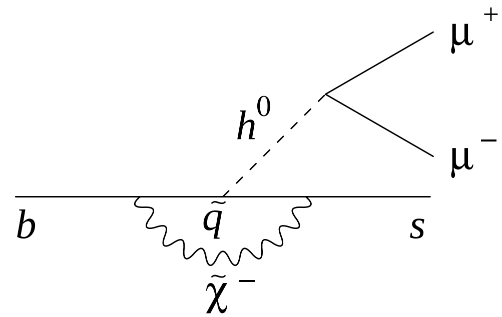
Can reach SM predictions at Super B factory

or using $B_s \to \phi\gamma$ at LHCb F. Muheim, Y. Xie, R. Zwicky, Phys.Lett.B664, 174 (2008)

The rare decays $b \to s\ell^+\ell^-$

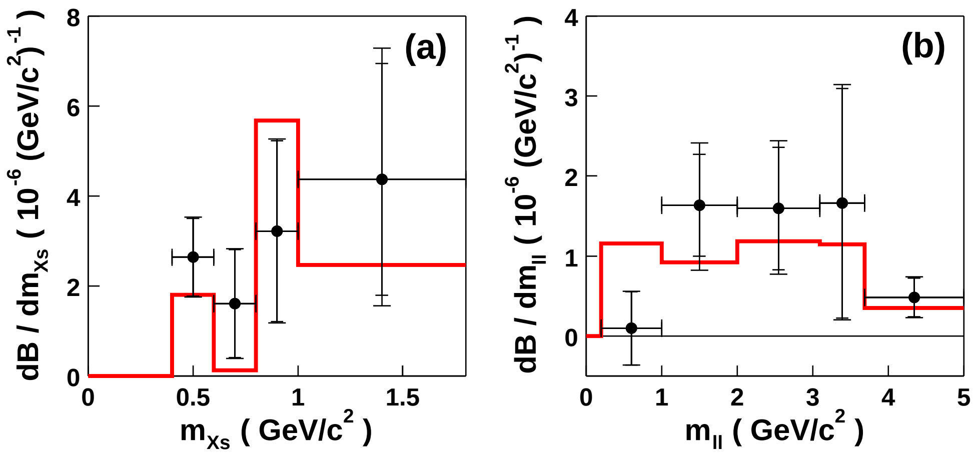






- Effective Wilson coefficients C_7, C_9 and C_{10} describe electromagnetic, electroweak vector and axial-vector couplings.
- C_7 dominates at low dilepton mass-squared q^2.
  $|C_7| = 0.3$ is known from $b \to s\gamma$.
- Need to veto charmonium resonance regions (J/ψ and ψ').
  Used as control samples for data analysis.
- C_9 and C_{10} dominate at high q^2 (left-handed V-A).
- Sensitivity to New Physics from rates and interference effects.

Inclusive $b \to s\ell^+\ell^-$ (Sum of Exclusives)



BaBar:

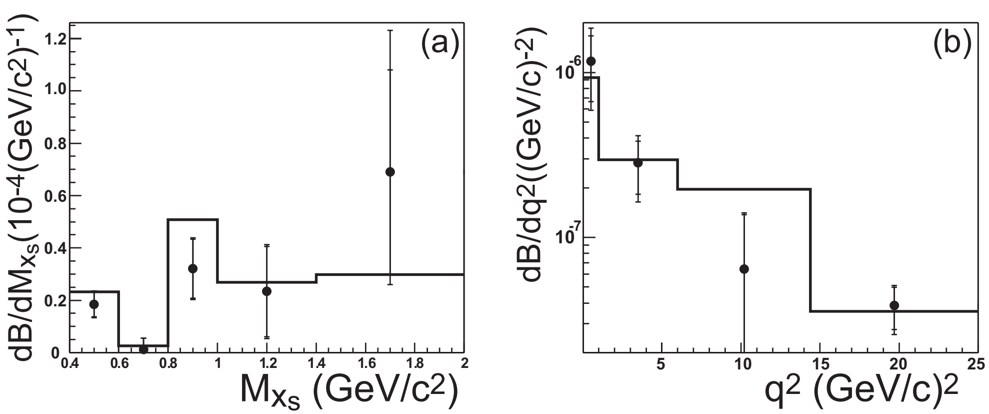
PRL 93, 081802 (2004)

89M $B\bar{B}$ pairs

Reconstruct $B \to X_s\ell^+\ell^-$

X_s is $K + n\pi$ $(n \leq 2)$

$\ell = e$ or μ



Belle:

PRD 72, 092005 (2005)

152M $B\bar{B}$ pairs

Reconstruct $B \to X_s\ell^+\ell^-$

X_s is $K + n\pi$ $(n \leq 4)$

$\ell = e$ or μ

Summary of Inclusive $b \to s\ell^+\ell^-$

Remove photon pole $m_{\ell\ell} > 0.2$ GeV so that $\mu^+\mu^- = e^+e^-$

BaBar:

$BF(b \to s\ell^+\ell^-) = (5.6 \pm 1.5(stat) \pm 0.6(syst) \pm 1.6(model)) \times 10^{-6}$

Belle:

$BF(b \to s\ell^+\ell^-) = (4.1 \pm 0.8(stat) \pm 0.8(syst)) \times 10^{-6}$

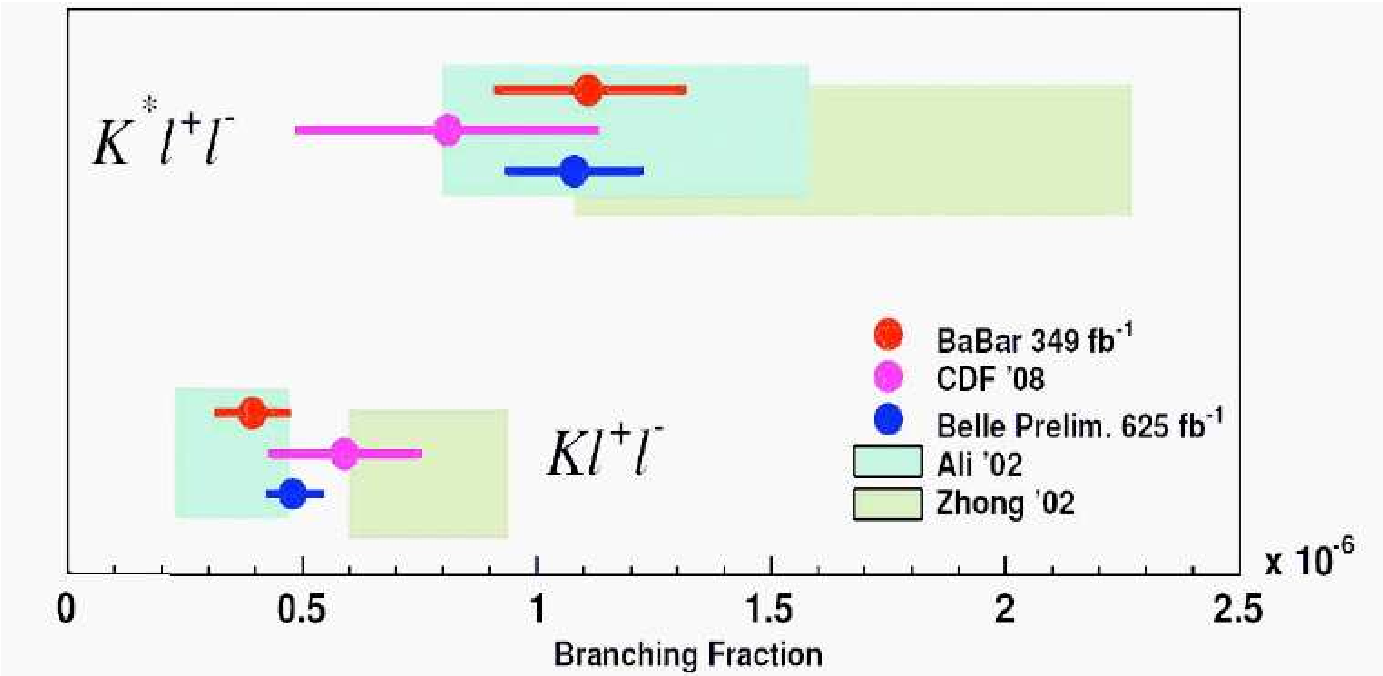
World average: $BF(b \to s\ell^+\ell^-) = (4.5 \pm 1.0) \times 10^{-6}$

Standard Model: $BF(b \to s\ell^+\ell^-) = (4.4 \pm 0.7) \times 10^{-6}$
$C_7 = -C_7^{SM}$: $BF(b \to s\ell^+\ell^-) = (8.8 \pm 1.0) \times 10^{-6}$
Favours SM sign for C_7 P. Gambino, U. Haisch, M. Misiak, PRL 94, 061803 (2005)

Experimental errors can be halved with current data samples.

B-tagged fully inclusive analysis is possible at Super B factory.

Exclusive $B \to K^{(*)}\ell^+\ell^-$ Branching Fractions

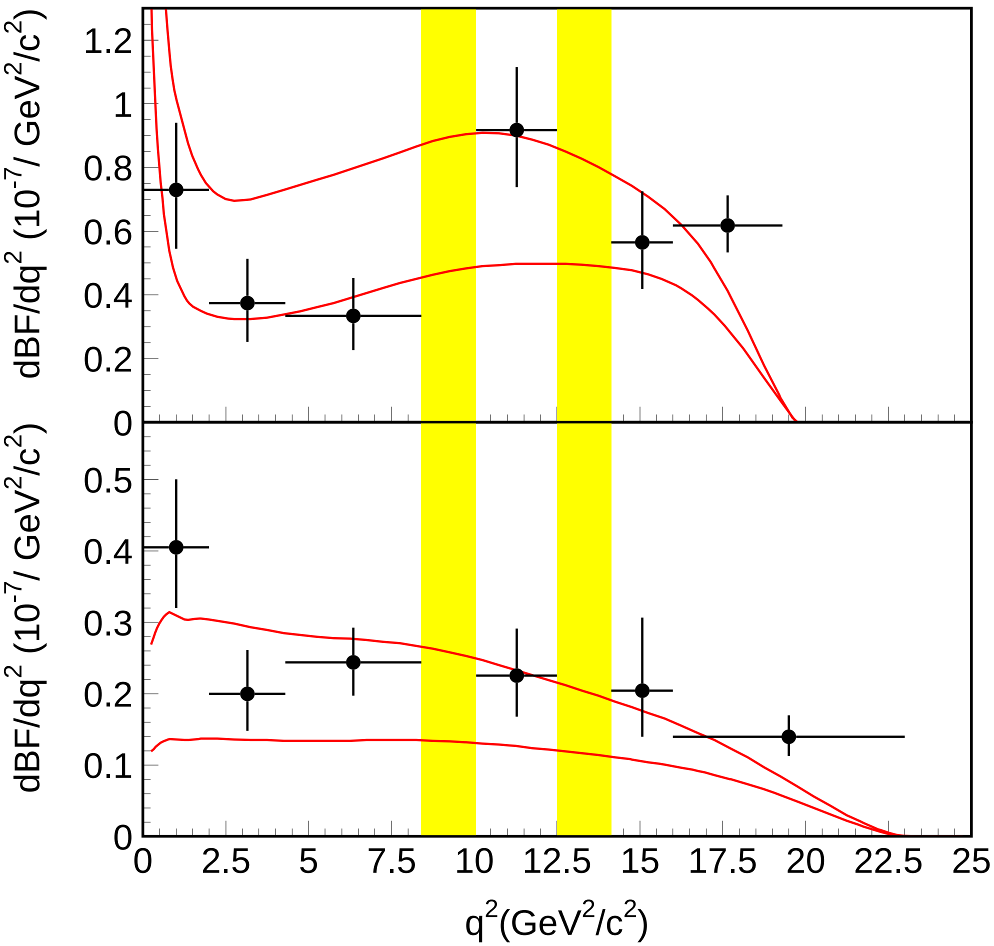


BaBar 349/fb arXiv:0807.4119, PRL 102, 091803 (2009)

Belle 625/fb arXiv:0904.0770 (2009), submitted to PRL

Large theoretical uncertainties from $B \to K^{(*)}$ form factors

$B \to K^{(*)}\ell^+\ell^-$ Partial Branching Fractions



$K^*\ell^+\ell^-$

Shaded regions show charmonium vetos

$K\ell^+\ell^-$

lines show spread of SM predictions (range of form factors)

Belle 625/fb arXiv:0904.0770 (2009), submitted to PRL

$B \to K^{(*)}\ell^+\ell^-$ Direct CP Violation

Standard Model prediction is a few percent at most

$$A_{CP} \equiv \frac{\mathcal{B}(\overline{B} \to \overline{K}^{(*)}\ell\ell) - \mathcal{B}(B \to K^{(*)}\ell\ell)}{\mathcal{B}(\overline{B} \to \overline{K}^{(*)}\ell\ell) + \mathcal{B}(B \to K^{(*)}\ell\ell)}$$

BaBar & Belle see no evidence for Direct CP violation

Mode	BaBar	Belle	Average
$K^+\ell^+\ell^-$	$-0.18 \pm 0.18 \pm 0.01$	$+0.04 \pm 0.10 \pm 0.02$	-0.04 ± 0.09
$K^*\ell^+\ell^-$	$+0.01 \pm 0.16 \pm 0.01$	$-0.10 \pm 0.10 \pm 0.01$	-0.06 ± 0.09

LHCb & Super B improve $\times 10$ (still statistics limited)

$B \to K^{(*)}\ell^+\ell^-$ Lepton Flavour Asymmetry

Standard Model prediction is one for $K\ell^+\ell^-$ to within a few 10^{-4}.
For $K^*\ell^+\ell^-$ it is 0.75 including the photon pole region for e^+e^-.

$$R \equiv \frac{\mathcal{B}(K^{(*)}\mu^+\mu^-)}{\mathcal{B}(K^{(*)}e^+e^-)}$$

BaBar & Belle measurements (including photon pole for $K^*\ell^+\ell^-$)

Mode	BaBar	Belle	Average
$K\ell^+\ell^-$	$0.96 \pm 0.39 \pm 0.05$	$1.03 \pm 0.19 \pm 0.06$	1.01 ± 0.19
$K^*\ell^+\ell^-$	$1.10 \pm 0.37 \pm 0.07$	$0.83 \pm 0.17 \pm 0.05$	0.92 ± 0.17

Sensitive to non-SM Higgs scalar contribution

$B \to K^{(*)}\ell^+\ell^-$ Isospin Asymmetry

Standard Model prediction is at most a few percent.
Largest at the photon pole (see $K^*\gamma$), and $< 1\%$ elsewhere.

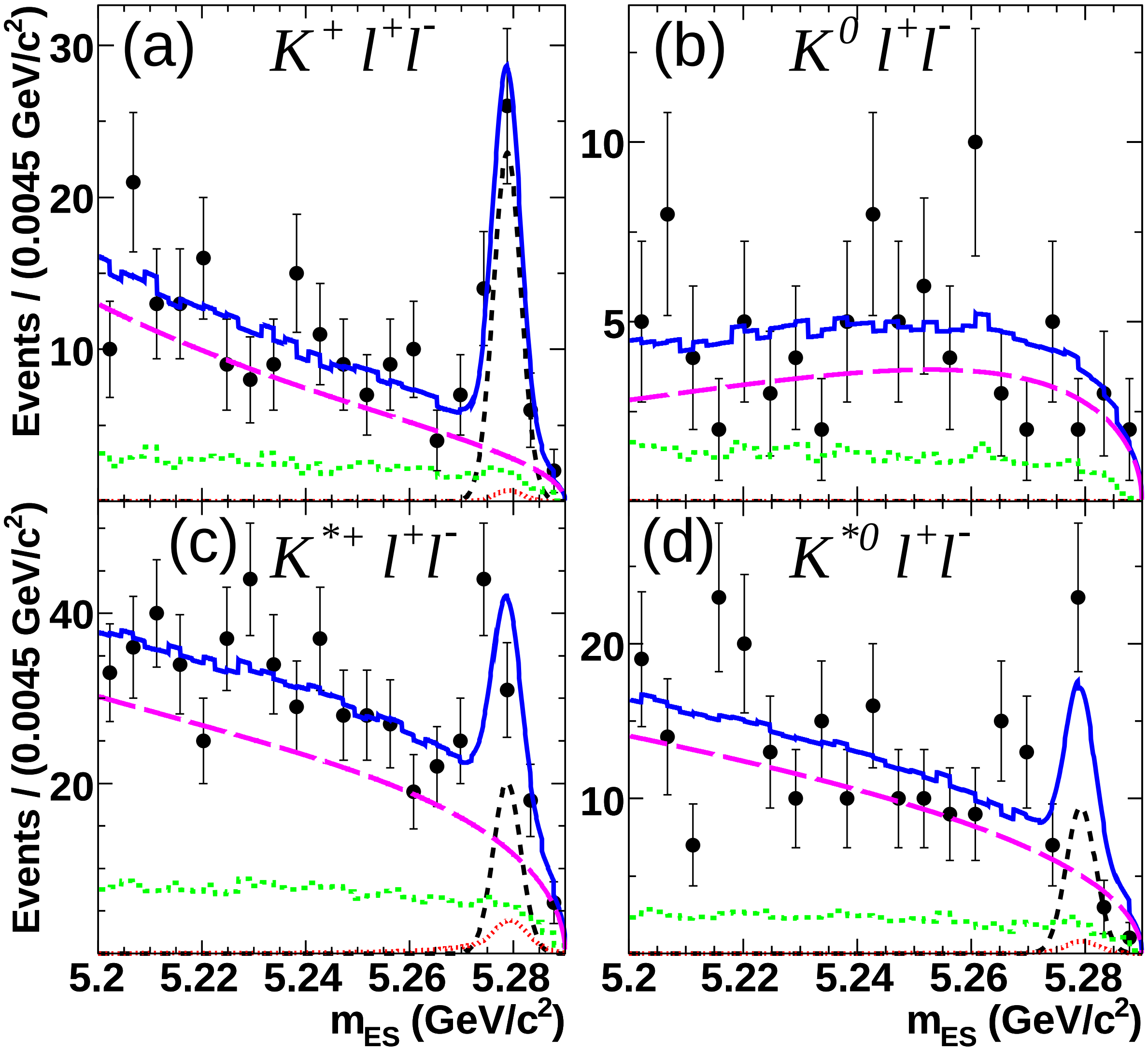
$$A_I \equiv \frac{\mathcal{B}(B^0 \to K^{(*)0}\ell^+\ell^-) - r\mathcal{B}(B^\pm \to K^{(*)\pm}\ell^+\ell^-)}{\mathcal{B}(B^0 \to K^{(*)0}\ell^+\ell^-) + r\mathcal{B}(B^\pm \to K^{(*)\pm}\ell^+\ell^-)}$$

where $r = \tau_0/\tau_+ = 1/(1.07 \pm 0.01)$ is the B lifetime ratio

BaBar measures significant asymmetries at low q^2 ($> 3\sigma$)!
Belle does not disagree with this (averages still $> 3\sigma$ from zero)

Mode	q^2	BaBar	Belle	Average
$K\ell^+\ell^-$	low	$-1.43^{+0.56}_{-0.85} \pm 0.05$	$-0.31 \pm 0.16 \pm 0.05$	-0.53 ± 0.18
	high	$+0.28 \pm 0.27 \pm 0.03$	$-0.11 \pm 0.19 \pm 0.05$	$+0.06 \pm 0.16$
$K^*\ell^+\ell^-$	low	$-0.56 \pm 0.16 \pm 0.03$	$-0.29 \pm 0.16 \pm 0.03$	-0.42 ± 0.11
	high	$+0.18 \pm 0.32 \pm 0.04$	$+0.03 \pm 0.14 \pm 0.05$	$+0.08 \pm 0.14$

low q^2 region is $< J/\psi$, high q^2 region is $> J/\psi$ (excluding ψ')



BaBar data at low q^2

Expected

$\approx 14\ K^0\ell^+\ell^-$

$\approx 36\ K^+\ell^+\ell^-$

Expected

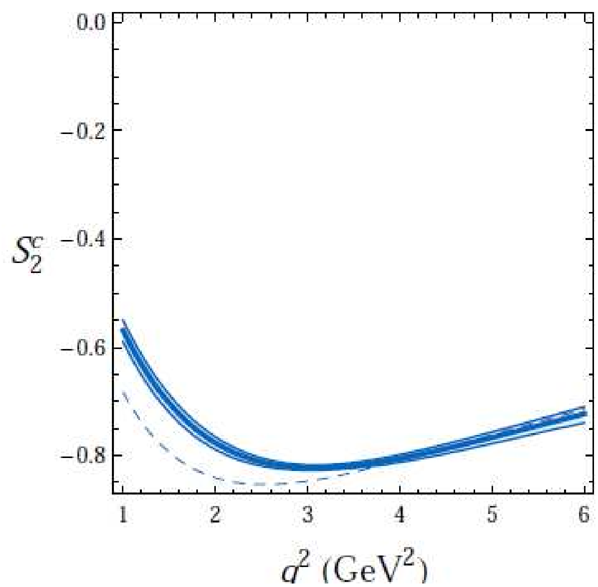
$\approx 31\ K^{*0}\ell^+\ell^-$

$\approx 25\ K^{*+}\ell^+\ell^-$

Angular Distributions

K^* longitudinal polarization
F_L from angle θ_K between K
and B in K^* rest frame

$\frac{3}{2} F_L \cos^2\theta_K + \frac{3}{4}(1 - F_L)(1 - \cos^2\theta_K)$

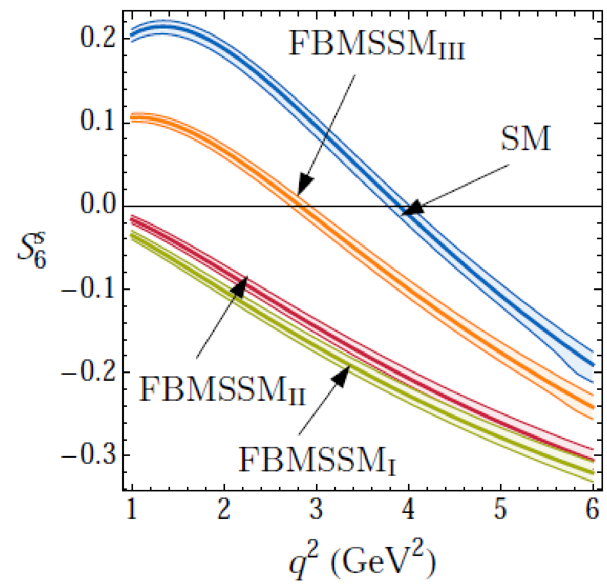


$F_L = -S_2^c \to 0$ as $q^2 \to 0$

$F_L \to 0.3$ at large q^2

Forward-backward asymmetry
A_{FB} from angle θ_ℓ between $\ell^+(\ell^-)$
and $B(\bar{B})$ in $\ell^+\ell^-$ rest frame

$\frac{3}{4} F_L (1 - \cos^2\theta_\ell) + \frac{3}{8}(1 - F_L)(1 + \cos^2\theta_\ell)$
$+ A_{FB} \cos\theta_\ell$



q^2

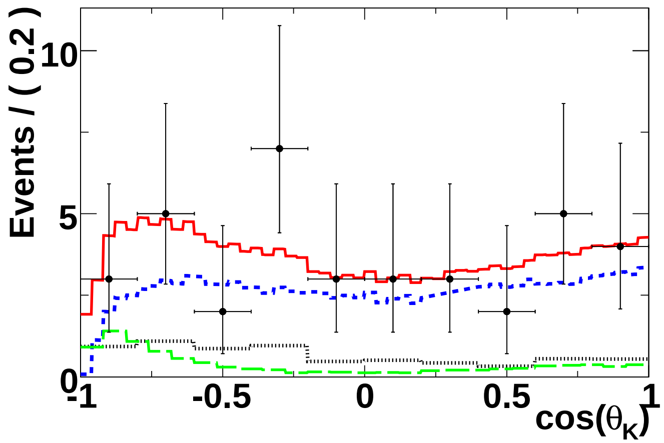
$A_{FB} = -S_6^s \to 0$ as $q^2 \to 0$

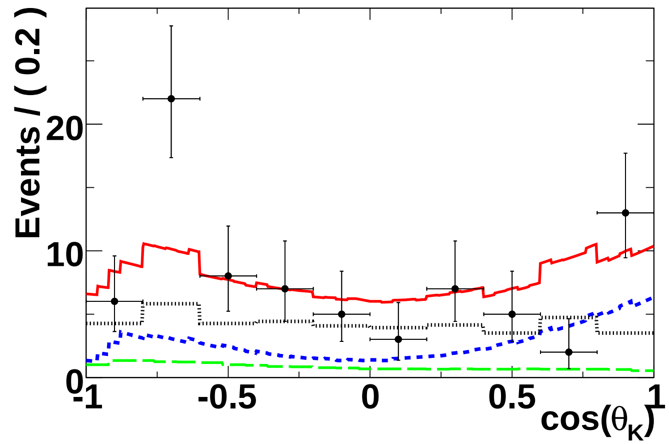
$A_{FB} \to +0.4$ at large q^2

Error bands from form factors

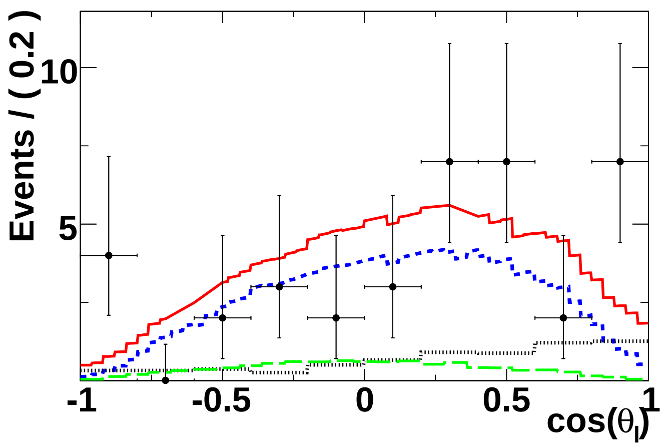
Altmannshofer, Ball, Bharucha, Buras, Straub & Wick, arXiv:0811.1214

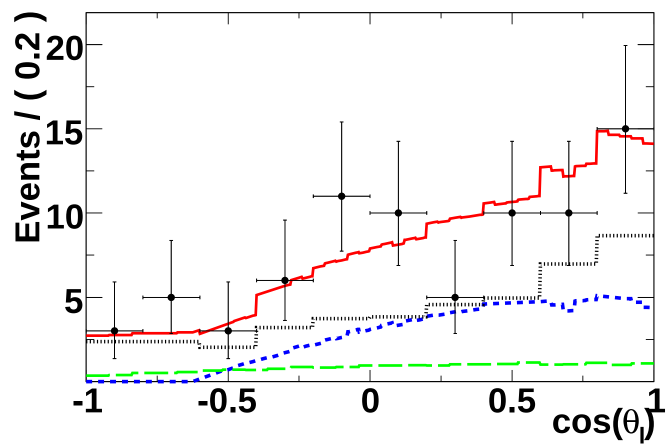
BaBar $K^*\ell^+\ell^-$ Angular Fits





F_L





A_{FB}

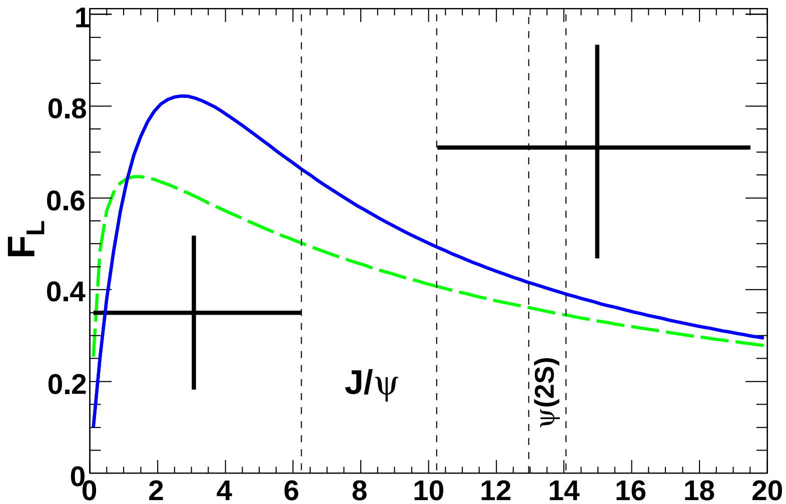
Low $q^2 < 6.25\mathrm{GeV}^2/c^4$

High $q^2 > 10.24\mathrm{GeV}^2/c^4$

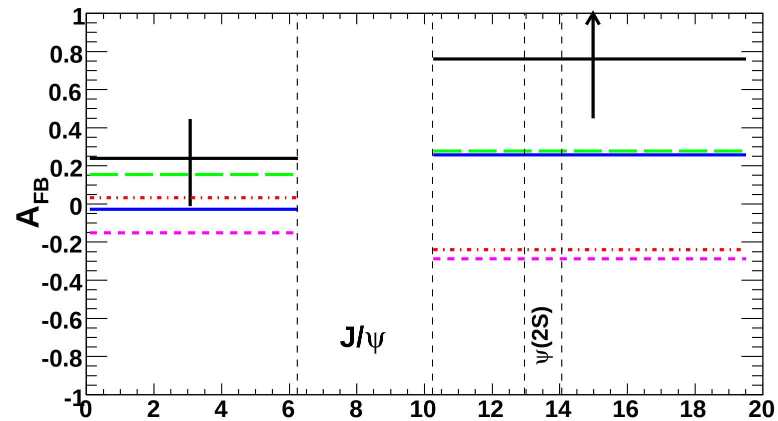
dash: signal   dot-dash: background   long dash: peaking bgd

BaBar Angular Analysis of $K^*\ell^+\ell^-$

K^* longitudinal polarization



Forward-backward asymmetry



solid: Standard Model (SM)

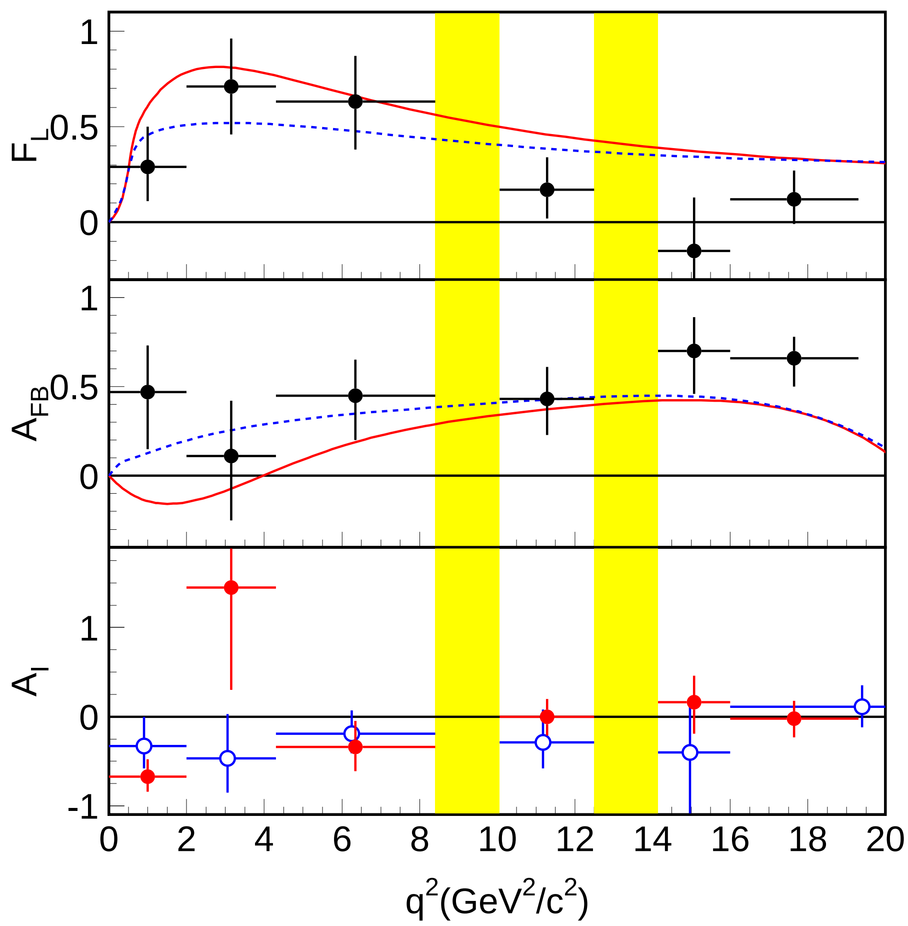
dash: $C_7 = -C_7^{SM}$

short dash: $C_9 C_{10} = -C_9 C_{10}^{SM}$

dot dash: $C_7 C_{10} = -C_7 C_{10}^{SM}$

q^2	F_L	A_{FB}
low	$0.35 \pm 0.16 \pm 0.04$	$+0.24^{+0.18}_{-0.23} \pm 0.06$
high	$0.71^{+0.20}_{-0.22} \pm 0.05$	$+0.76^{+0.52}_{-0.32} \pm 0.07$

Belle Angular Analysis of $K^*\ell^+\ell^-$



K^* polarization

SM prediction

$C_7 = -C_7^{SM}$

Di-lepton asymmetry

Isospin asymmetry

$K\ell^+\ell^-$

$K^*\ell^+\ell^-$

Belle 625/fb arXiv:0904.0770 (2009), submitted to PRL

Perspectives on Angular Distributions

- B factories don't have enough statistics for precision measurements ($\mathcal{O}(100)$ signal events in each experiment).
- Theoretical uncertainties are smaller than experimental errors, particularly at low q^2 and for A_{FB} zero-crossing point.
- Photon pole region can be used to analyse L/R helicity.
- Low q^2 results from BaBar and Belle have positive A_{FB}
  World averages $F_L = 0.47 \pm 0.12$, $A_{FB} = +0.33 \pm 0.13$
  No evidence for a zero crossing point yet.
  Results prefer $C_7 = -C_7^{SM}$?
- High q^2 results consistent with left-handed electroweak (V-A).
  World averages $F_L = 0.22 \pm 0.09$, $A_{FB} = +0.62 \pm 0.10$
- LHCb (and Super B) are likely to have a big impact.

Combined Angular and CP Asymmetries

Complete angular distribution for $B \to K^* \ell^+ \ell^-$
(ϕ is the angle between the K^* and dilepton decay planes)

$$J_1^s \sin^2\theta_K + J_1^c \cos^2\theta_K + J_2^s \sin^2\theta_K \cos 2\theta_\ell + J_2^c \cos^2\theta_K \cos 2\theta_\ell$$

$$+J_3 \sin^2\theta_K \sin^2\theta_\ell \cos 2\phi + J_4 \sin 2\theta_K \sin 2\theta_\ell \cos\phi$$

$$+J_5 \sin 2\theta_K \sin\theta_\ell \cos\phi + J_6 \sin^2\theta_K \cos\theta_\ell + J_7 \sin 2\theta_K \sin\theta_\ell \sin\phi$$

$$+J_8 \sin 2\theta_K \sin 2\theta_\ell \sin\phi + J_9 \sin^2\theta_K \sin^2\theta_\ell \sin 2\phi$$

Forward-backward asymmetry $J_6 = A_{FB}$ is just one of many angular observables

Can eventually measure CP asymmetries of angular coefficients.

Full angular analysis may be possible at LHCb

Bobeth, Hiller & Piranishvili, arXiv:0805.2525

Altmannshofer, Ball, Bharucha, Buras, Straub & Wick, arXiv:0811.1214

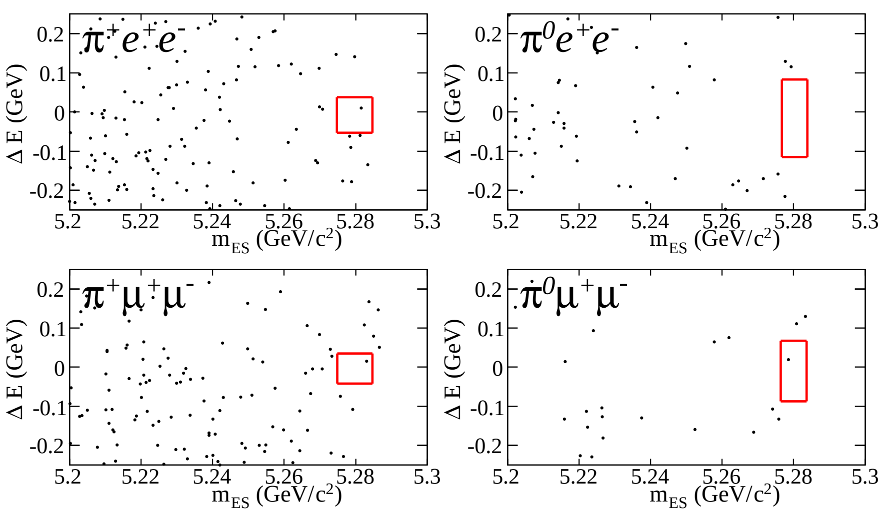
Upper limits on $B \to \pi\ell^+\ell^-$

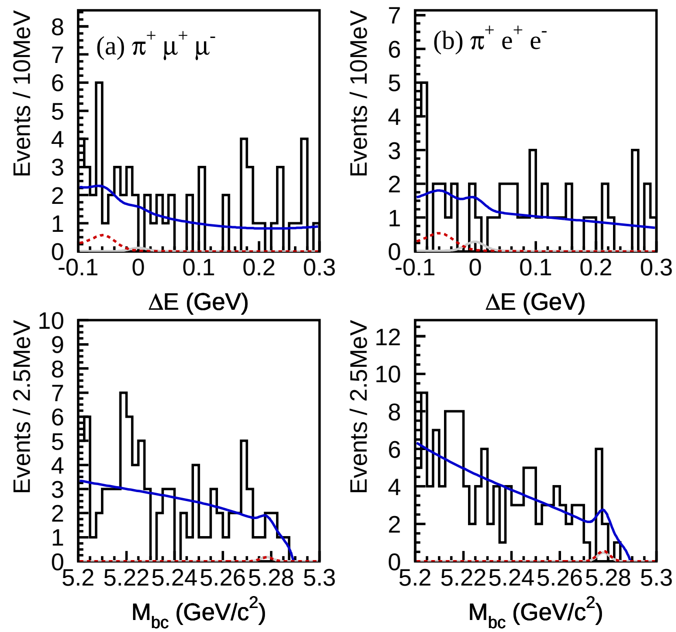
SM prediction: $BF(B \to \pi\ell^+\ell^-) = (3.3 \pm 1.0) \times 10^{-8}$

T.M. Aliev & M. Savci, PRD 60, 014005 (1999)

Belle 657M $B\bar{B}$,
PRD78, 011101 (2008)

BaBar 230M $B\bar{B}$,
PRL 99, 051801 (2007)





$BF(B \to \pi\ell^+\ell^-) < 9.1 \times 10^{-8}$
(90% C.L.)

$BF(B \to \pi\ell^+\ell^-) < 6.2 \times 10^{-8}$
(90% C.L.)

Almost no background. Should see at LHCb and SuperB.

Summary & Conclusions

- $BF(b \to s\gamma) = (3.56 \pm 0.16) \times 10^{-4}$ extrapolated from $E_\gamma > 2.0$
  Larger experimental errors for lower thresholds.
  Is theoretical extrapolation under control?
- $B \to \rho\gamma$ and $b \to d\gamma$ consistent with $|V_{td}/V_{ts}|$ from mixing.
- Isospin and Direct CP asymmetries sensitive to New Physics.
- Time-dependent CP violation $S(K_s\pi^0\gamma)$ is statistics limited.
- Inclusive $BF(b \to s\ell^+\ell^-) = (4.5 \pm 1.0) \times 10^{-6}$ prefers C_7^{SM}.
  Can still improve by factor of two at B factories.
- $B \to K^{(*)}\ell^+\ell^-$ rates and asymmetries agree with SM.
  Apart from isospin asymmetries at low q^2!
- Angular analysis of $K^*\ell^+\ell^-$ is statistics limited.
  A_{FB} positive and no evidence for zero-crossing?

- Apart from $BF(b \to s\gamma)$ all measurements are still statistics limited.
- Theoretical errors on asymmetries and angular distributions are small.
- There is a lot of work left for LHCb and a Super B factory.

BACKUP SLIDES

Fully Inclusive $b \to s\gamma$ Analysis Details

1. Select isolated high energy photons (veto π^0 and η).
2. Use event shape variables to suppress continuum background. Subtract remaining continuum background using 68/fb of off-resonance data.
3. Subtract background from other B decays: π^0 (58%), η (20%), e (7%), $\bar{n}$ (3%), other (12%). Monte Carlo adjusted to match data control samples for $\pi^0(\eta)$. Otherwise vary by $\pm 20\%$.
4. Unfold calorimeter resolution to give E^*_γ in Υ(4S) frame.
5. Correct for variation in photon efficiency as function of E^*_γ.
6. Subtract $(4.0 \pm 0.3)\%$ contribution from $b \to d\gamma$.

Lepton-tagged $b \to s\gamma$ Analysis Details

1. Select isolated high energy photons (veto π^0 and η).
   Use event shape variables to suppress continuum background.
2. Tag with $e(\mu)$ with $p > 1.25(1.50)$ GeV from semileptonic decay of other B. Efficiency for signal events is 5%.
   Suppresses continuum (but not B) background by 7×10^{-4}.
3. Subtract photons from other B decays:
   π^0 (64%), η (17%), e (4%), $\bar{n}$ (8%), other (7%).
   Monte Carlo adjusted to match data control samples.
4. Correct for variation in photon efficiency as function of E^*_γ.
5. Subtract $(4.0 \pm 1.6)\%$ contribution from $b \to d\gamma$.
6. Adjust results by unfolding calorimeter resolution and boosting from Υ(4S) to B rest frame.

B-tagged $b \to s\gamma$ Analysis Details

1. Select isolated high energy photons (veto π^0 and η).
2. Tag by reconstructing hadronic decays of other B. Efficiency for signal events is 0.3%. BRECO-tag gives charge, flavour and momentum of B. E_γ is measured in B rest frame.
3. Fit to beam-constrained mass m_{ES} of hadronic B tags removes continuum and most B backgrounds.
4. Subtract photons from peaking B backgrounds (π^0, η). Monte Carlo adjusted to match data control samples.
5. Correct for variation in photon efficiency as function of E_γ, and for calorimeter energy resolution.
6. Subtract $(4.0 \pm 0.4)\%$ contribution from $b \to d\gamma$.

Sum of Exclusive $b \to s\gamma$ Analysis Details

1. Reconstruct exclusive B decays to a strange X_s system and an isolated high energy photon (veto π^0 and η).
   The X_s is $K^{\pm}$ or K_S (or 3K) plus up to $4\pi/\eta$ (at most $1\pi^0$ or η).
2. From $M(X_s)$ measure E_γ in B rest frame with resolution of a few MeV. No dependence on calorimeter energy resolution.
3. Fit to m_{ES} removes continuum and most B backgrounds.
4. Subtract photons from peaking B backgrounds (π^0, η).
   Monte Carlo adjusted to match data control samples.
5. Correct for variation in efficiency as function of E_γ. Need to understand fragmentation of X_s and missing final states.
6. No $b \to d\gamma$ subtraction is required.

Charmonium Samples

$B^0 \to J/\psi K^{*0}, J/\psi \to e^+e^-$

$B \to J/\psi K^*$ and $\psi' K^*$

have Branching Fractions $\approx 10^{-3}$

Removed by $2.5 < m_{\ell\ell} < 3.2\text{GeV}/c^2$

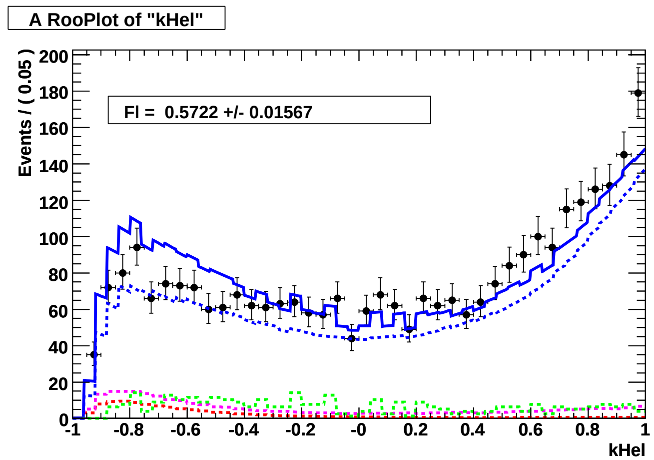
and $3.6 < m_{\ell\ell} < 3.75\text{GeV}/c^2$

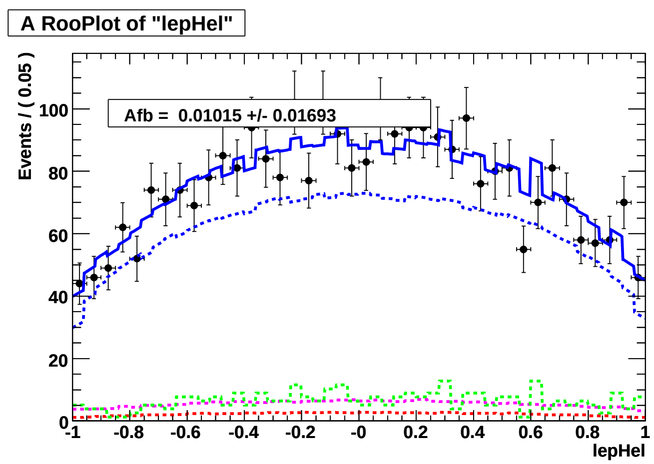
Used to check analysis:

Mode	F_L	A_{FB}
$K^+\pi^0\mu^+\mu^-$	0.54 ± 0.03	-0.04 ± 0.05
$K_S^0\pi^+\mu^+\mu^-$	0.55 ± 0.02	$+0.00 \pm 0.05$
$K^+\pi^-\mu^+\mu^-$	0.56 ± 0.02	-0.02 ± 0.02
$K^+\pi^0 e^+e^-$	0.54 ± 0.03	$+0.02 \pm 0.03$
$K_S^0\pi^+ e^+e^-$	0.55 ± 0.02	-0.02 ± 0.04
$K^+\pi^- e^+e^-$	0.56 ± 0.02	$+0.01 \pm 0.02$

K^* polarization $F_L = 0.56 \pm 0.01$

Forward-backward asymmetry $A_{FB} = 0$





Sources and Treatment of $K(*)\ell\ell$ Backgrounds

A $5.20 < m_{ES} < 5.27$ sideband region is used to determine the background angular distributions.

In order of importance the backgrounds to $K^*\ell^+\ell^-$ are:

- Combinatorial from $B \rightarrow \bar{D}^{(*)}\ell^+\nu_\ell$, $\bar{B} \rightarrow D^{(*)}\ell^-\bar{\nu}_\ell$
- Correlated from $B \rightarrow \bar{D}^{(*)}\ell^+\nu_\ell$, $\bar{D}^{(*)} \rightarrow K^{(*)}\ell^-\bar{\nu}_\ell$
- Continuum from $c \rightarrow s\ell^+\nu_\ell$, $\bar{c} \rightarrow \bar{s}\ell^-\bar{\nu}_\ell$
- Peaking backgrounds from mis-reconstructed signal, charmonium leakage and low mass e^+e^- pairs.
- Hadrons (h) that fake muons. These are corrected for using reconstructed $K^*h^\pm\mu^\mp$ sample weighted by the muon fake rate.

$K^*e^\pm\mu^\mp$ samples check average of $K^*e^+e^-$, $K^*\mu^+\mu^-$ backgrounds.