Electroweak Penguin decays at Belle

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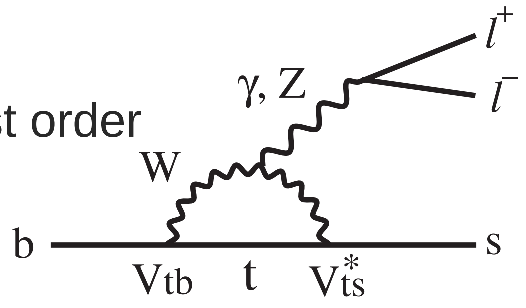
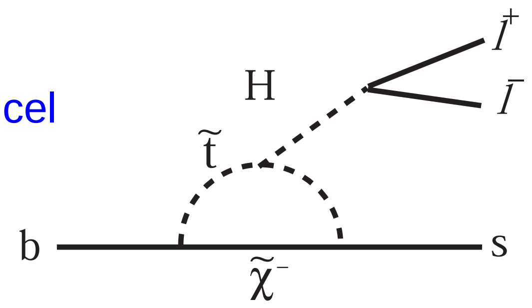
KEK

Flavor Changing Neutral Current Decays

- Flavor Changing Neutral Current decays, $b \rightarrow s\gamma$, $b \rightarrow sll$
  - Forbidden at tree level
  - induced through Penguin or Box diagrams at lowest order
  - sensitive to heavy particles (SUSY, heavy Higgs)
- Observables
  - Decay Width (Branching Fraction)
    - Inclusive decay, theoretically clean, experimentally hard.
    - Exclusive decays, large uncertainty due to form factor
      - →test of QCD in B decays
  - Ratio of Decay Width
    - Some theoretical and experimental uncertainties cancel
    - Good probe also for exclusive decays!
      - CP Asymmetry
      - Isospin Asymmetry
      - Up-Down Asymmetry
      - BF ratio of electron mode to muon mode
      - Forward-Backward Asymmetry



Penguin diagram in the SM



Beyond the SM diagram

OPE and Wilson Coefficient

- Effective Hamiltonian is expressed in term of Operator Product Expansion.

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

  - $O_{1,2}$: current current operator
  - $O_{3\text{-}6}$: QCD penguin operator
  - $O_{7,8}$: electro- and chromo-magnetic operator
  - $O_{9,10}$: semileptonic operator
  - C_i : Wilson coefficient
- Wilson coefficient is a strength of corresponding short distance operator.
- Precise measurement of Wilson coefficients is one of the goals for B physics.
- For $b \to s\gamma$ and $b \to ll$ case, only O_7, O_9 and O_{10} appear in the Hamiltonian.

$$\begin{aligned}
\mathcal{O}_1 &= (\bar{s}_\alpha \gamma_\mu L c_\beta)(\bar{c}_\beta \gamma^\mu L b_\alpha), \\
\mathcal{O}_2 &= (\bar{s}_\alpha \gamma_\mu L c_\alpha)(\bar{c}_\beta \gamma^\mu L b_\beta), \\
\mathcal{O}_3 &= (\bar{s}_\alpha \gamma_\mu L b_\alpha) \sum_{q=u,d,s,c,b} (\bar{q}_\beta \gamma^\mu L q_\beta), \\
\mathcal{O}_4 &= (\bar{s}_\alpha \gamma_\mu L c_\beta) \sum_{q=u,d,s,c,b} (\bar{q}_\beta \gamma^\mu L q_\alpha), \\
\mathcal{O}_5 &= (\bar{s}_\alpha \gamma_\mu L b_\alpha) \sum_{q=u,d,s,c,b} (\bar{q}_\beta \gamma^\mu R q_\beta), \\
\mathcal{O}_6 &= (\bar{s}_\alpha \gamma_\mu L c_\beta) \sum_{q=u,d,s,c,b} (\bar{q}_\beta \gamma^\mu R q_\alpha), \\
\mathcal{O}_7 &= \frac{e}{16\pi^2} \bar{s}_\alpha \sigma_{\mu\nu} (m_s L + m_b R) b_\alpha F^{\mu\nu}, \\
\mathcal{O}_8 &= \frac{g}{16\pi^2} \bar{s}_\alpha \sigma_{\mu\nu} (m_s L + m_b R) T^a_{\alpha\beta} b_\beta G^{a\mu\nu}, \\
\mathcal{O}_9 &= \frac{e^2}{16\pi} \bar{s}_\alpha \gamma^\mu L b_\alpha \bar{\ell} \gamma_\mu \ell, \\
\mathcal{O}_{10} &= \frac{e^2}{16\pi} \bar{s}_\alpha \gamma^\mu L b_\alpha \bar{\ell} \gamma_\mu \gamma_5 \ell,
\end{aligned}$$

New Physics changes the Wilson Coefficients

$b \to s\gamma$ and $b \to sll$ decays

Decay widths for $b \to s\gamma$ and $b \to sll$ can be described with Wilson coefficients.

- $$\Gamma(b \to s\gamma) = \frac{G_F^2 \alpha_{em} m_b^5 |V_{ts}^* V_{tb}|^2}{32\pi^3} |C_7^{\text{eff}}|^2$$ → Absolute value of C_7^{eff} can be measured.

- $$\frac{d\Gamma(b \to s\ell^+\ell^-)}{d\hat{s}} = \left(\frac{\alpha_{em}}{4\pi}\right)^2 \frac{G_F^2 m_b^5 |V_{ts}^* V_{tb}|^2}{48\pi^3} (1-\hat{s})^2$$
$$\times \left[(1+2\hat{s})\left(|C_9^{\text{eff}}|^2 + |C_{10}^{\text{eff}}|^2\right) + 4\left(1+\frac{2}{\hat{s}}\right)|C_7^{\text{eff}}|^2 + 12\,\mathrm{Re}\left(C_7^{\text{eff}} C_9^{\text{eff}*}\right)\right]$$

$$\frac{d}{d\hat{s}}(\Gamma_F^{K*} - \Gamma_B^{K*}) = \frac{G_F^2 \alpha^2 m_B^5}{2^8 \pi^5} |V_{ts}^* V_{tb}|^2\, \hat{s}\hat{u}(\hat{s})^2$$
$$\times \left[\mathrm{Re}(C_9{}^{\text{eff}}) C_{10} V A_1 + \frac{\hat{m}_b}{\hat{s}} C_7{}^{\text{eff}} C_{10} (V T_2 (1 - \hat{m}_{K^*}) + A_1 T_1 (1 + \hat{m}_{K^*}))\right].$$

Interference terms

→ Relative signs can be also determined from interference terms!!

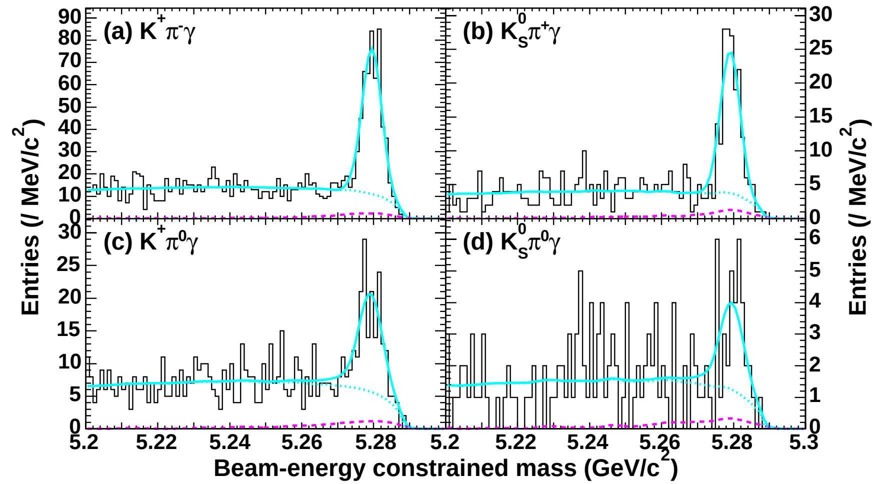
C_7^{eff}, C_9^{eff} and C_{10}^{eff} can be extracted from $B(b \to s\gamma)$, $B(b \to sl^+l^-)$ and $A_{FB}(b \to sl^+l^-)$!

(sometimes we do not use C_i but A_i which is leading coefficient)

In the SM $A_7 = -0.330,\ A_9 = 4.069,\ A_{10} = -4.213$ at $\mu = 2.5\text{GeV}$

Branching Fraction of B→K*γ

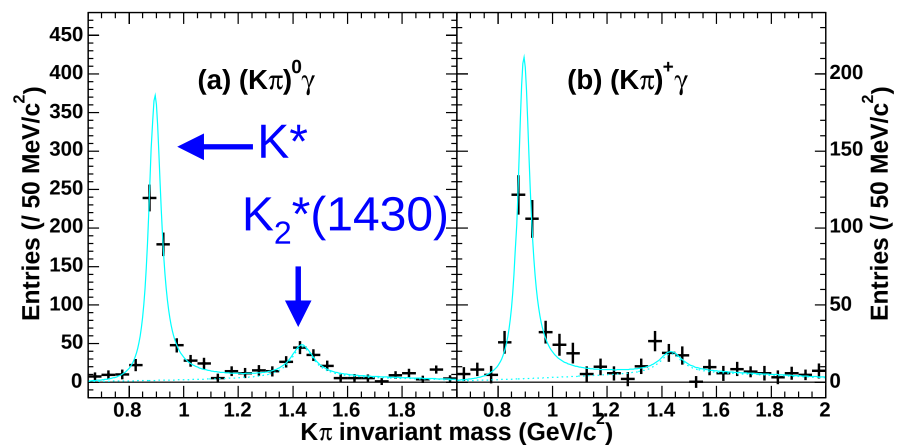
- b→sγ was observed at CLEO in K*γ
- K* is reconstructed from 4 modes
  - $K^+\pi^-$, $K_s\pi^0$, $K^+\pi^0$, $K_s\pi^+$
  - $|M_{K*} - M_{K\pi}| < 75\text{MeV}$



$$B(B^0 \to K^{*0}\gamma) = (40.9 \pm 2.1 \pm 1.9) \cdot 10^{-6}$$

$$B(B^+ \to K^{*+}\gamma) = (44.0 \pm 3.3 \pm 2.4) \cdot 10^{-6}$$

- Better than 10% accurary!
- Theoretical preduction
  - QCD fact. $(70 \pm 25) \cdot 10^{-6}$
  - LEET $(68 \pm 23) \cdot 10^{-6}$
  - pQCD $(35 \pm 10) \cdot 10^{-6}$
  - Lattice $(35 \pm 16) \cdot 10^{-6}$



Theoretical uncertainties are large

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Asymmetry in $B \to K^*\gamma$

- Isospin Asymmetry Δ_{0+} is sensitive to sign of Wilson coefficients C_6/C_7

$$\Delta_{0+} = \frac{\tau_{B^+}/\tau_{B^0}\, \mathrm{B}(B^0 \to K^{0*}\gamma) - \mathrm{B}(B^+ \to K^{+*}\gamma)}{\tau_{B^+}/\tau_{B^0}\, \mathrm{B}(B^0 \to K^{0*}\gamma) + \mathrm{B}(B^+ \to K^{+*}\gamma)}$$

A.Kagan and M.Neubert, PLB 539, 227 (2002)

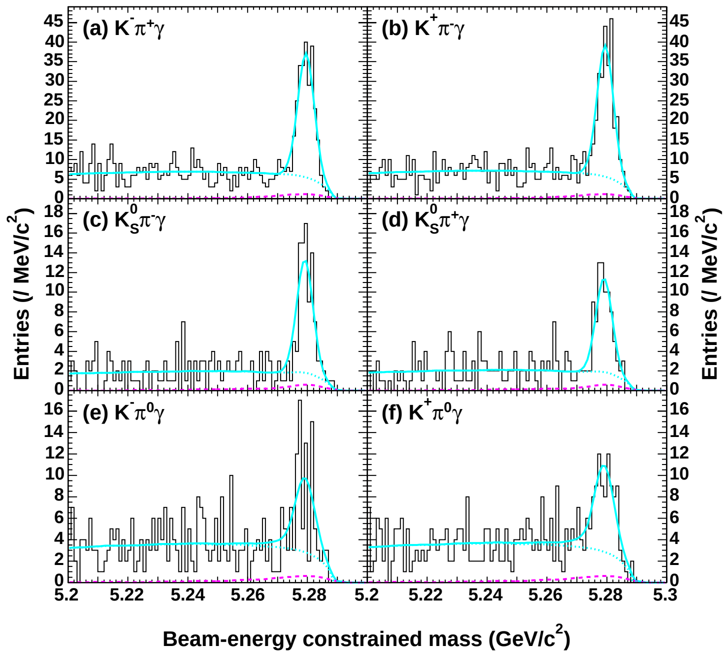
- Δ_{0+} = +5~10% and $C_6/C_7 > 0$ in the SM
- If $C_6/C_7 < 0$, $\Delta_{0+} < 0$.

$$\Delta_{0+} = (+3.4 \pm 4.4(\mathrm{stat}) \pm 2.6(\mathrm{syst}) \pm 2.5(f_{+-}/f_{00}))\%$$

- Direct CPV is less than 1% in the SM
- 5% CPV is allowed in new physics

$$A_{CP} = (-0.1 \pm 4.4 \pm 0.8)\%$$

$\overline{B}^0$ B^0



Time dependent CPV in $B \to K_s \pi^0 \gamma$

- Not only the $K^{*0}\gamma$, but any $K_s\pi^0\gamma$ can be used for TCPV measurement.

$$A_{CP} = \frac{\Gamma\left(\overline{B^0}(t) \to K_S^0 \pi_0 \gamma\right) - \Gamma\left(B^0(t) \to K_S^0 \pi^0 \gamma\right)}{\Gamma\left(\overline{B^0}(t) \to K_S^0 \pi_0 \gamma\right) + \Gamma\left(B^0(t) \to K_S^0 \pi^0 \gamma\right)} = S \sin \Delta m \Delta t + A \cos \Delta m \Delta t$$

Atwood, Gershon, Hazumi, Soni
PRD71 (2005) 076003

- In the SM, S<0.1, A<0.01.
- Right handed currents induce large value of S
  - S corresponds to fraction of C_{7R} to C_{7L}
- $M_{K s \pi 0}$ < 1.8GeV

First Measurement

$$S(K_S^0 \pi^0 \gamma) = -0.58 {}^{+0.46}_{-0.38} (stat) \pm 0.11 (syst)$$

$$A(K_S^0 \pi^0 \gamma) = +0.03 \pm 0.34 (stat) \pm 0.11 (syst)$$

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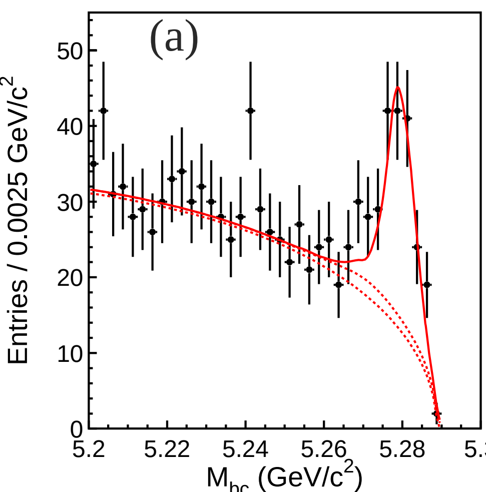
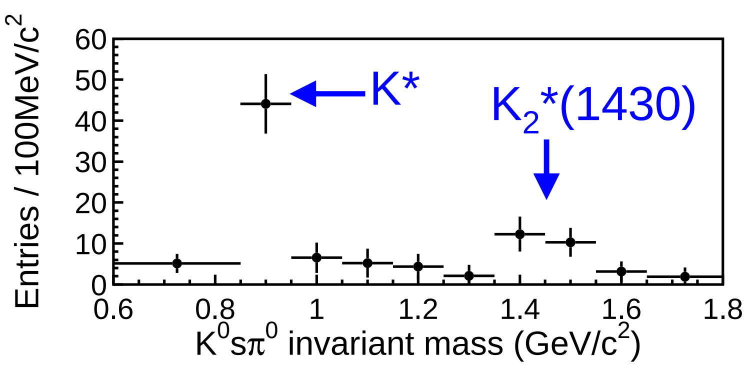
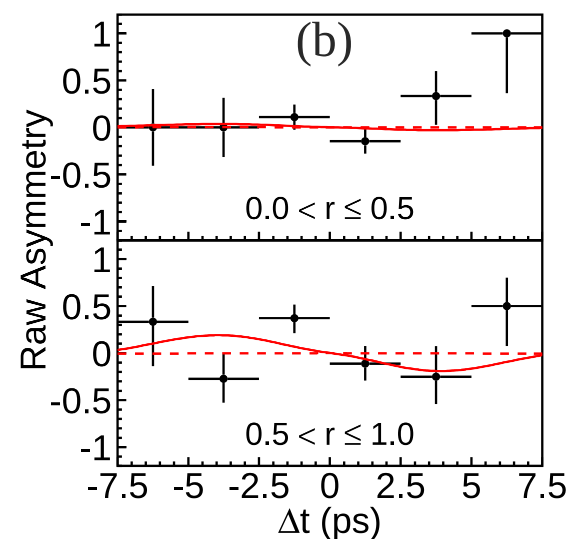






Observation of B→Kηγ

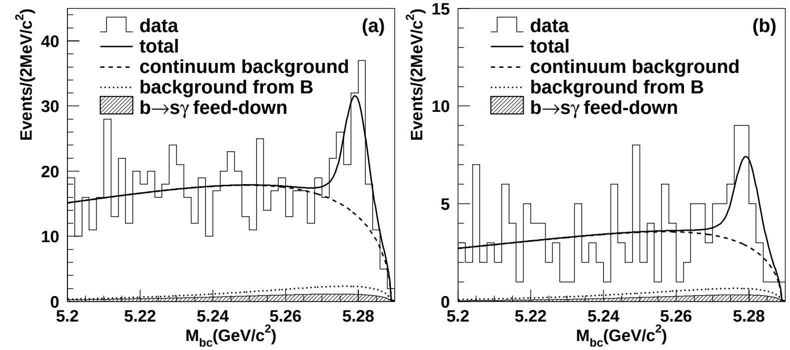
First Observation

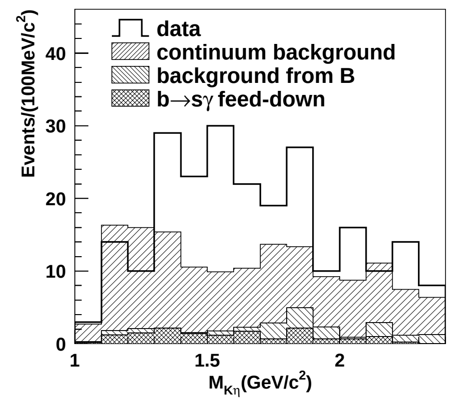
- $K_s\eta\gamma$ can be used for time dep. CPV measurement to search for right handed currents.
- $B \rightarrow K^+\eta\gamma$, $K_s\eta\gamma$
  - η is reconstructed from $\gamma\gamma$ and $\pi\pi\pi^0$
  - $M_{K\eta} < 2.4\text{GeV}$

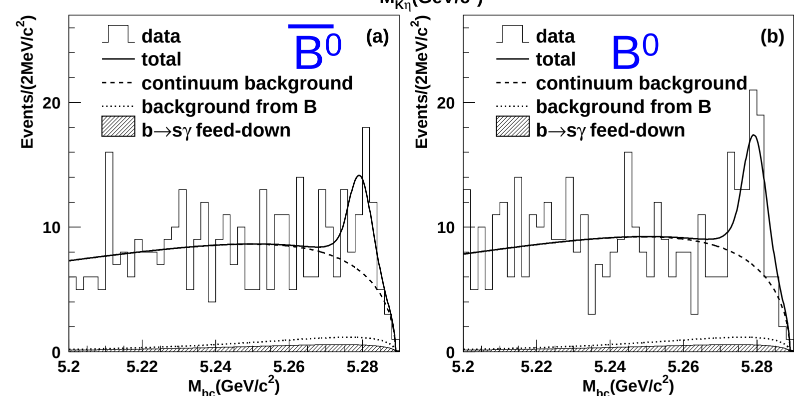
$$\mathrm{B}(B^+ \rightarrow K^+\eta\gamma) = \left(8.4 \pm 1.5\,^{+1.2}_{-0.9}\right) \cdot 10^{-6}$$

$$\mathrm{B}(B^0 \rightarrow K_S^0\eta\gamma) = \left(8.4\,^{+3.1}_{-2.7}\,^{+1.9}_{-1.6}\right) \cdot 10^{-6}$$

$$A_{CP}(B^+ \rightarrow K^+\eta\gamma) = 16 \pm 9 \pm 6\%$$







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Observation of B→$K_1(1270)\gamma$

M.Gronau et al. PRL88 051802 (2002)

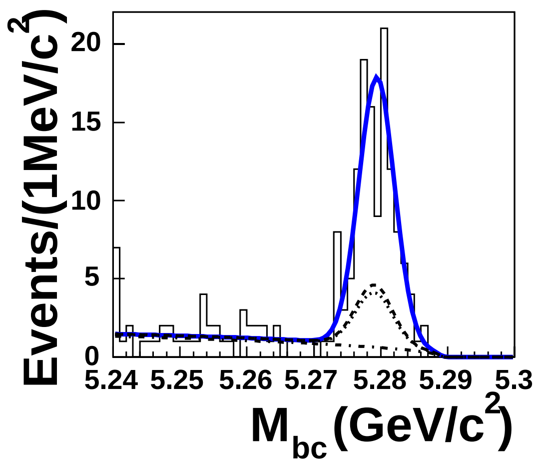
- B→$K\pi\pi^0\gamma$ final state via $K_1\gamma$ can be used for up-down Asymmetry to search for right handed currents.
  - $K_1(1270)$ is reconstructed from $K^+\pi^+\pi^-$ and $K_s\pi^+\pi^-$.
  - 0.6< $M_{\pi\pi}$ < 0.9GeV (ρ mass region) to enhance $K_1(1270)$
  - Resonance components are extracted by fitting to the hadronic mass distribution.

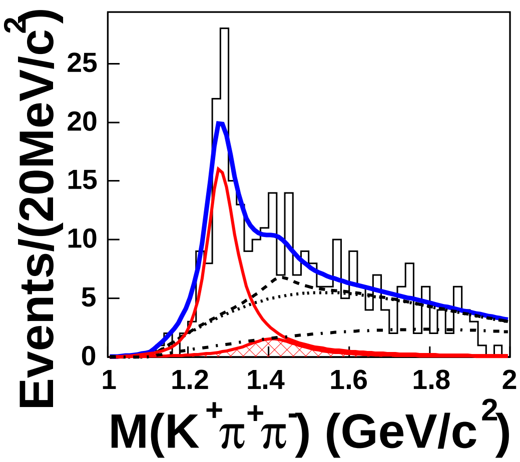
$$\mathrm{B}(B^+ \to K_1(1270)^+\gamma) = (4.3 \pm 0.9 \pm 0.9)\cdot 10^{-5}$$

First Observation

$$\mathrm{B}(B^0 \to K_1(1270)^0\gamma) < 5.8\cdot 10^{-5}$$

$$\mathrm{B}(B^+ \to K_1(1400)^+\gamma) < 1.5\cdot 10^{-5}$$





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Observation of B→ p$\bar{\Lambda}\gamma$

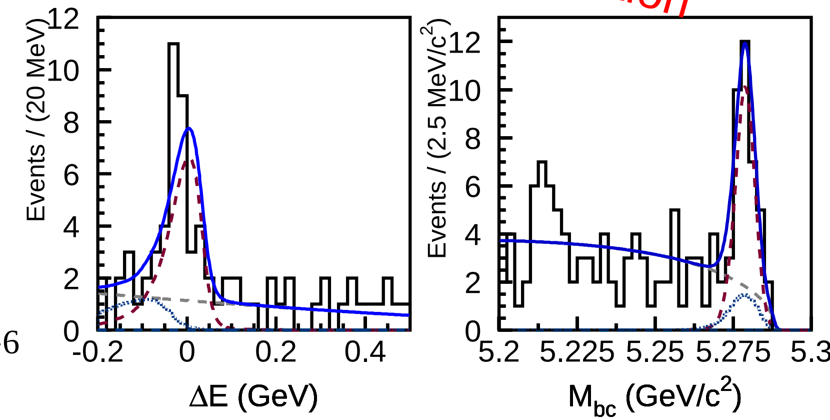
- Baryon production via weak decay of meson
- Near threshold enhancement of di-baryon system is observed in B→p$\bar{\Lambda}\pi$ (b→s process)

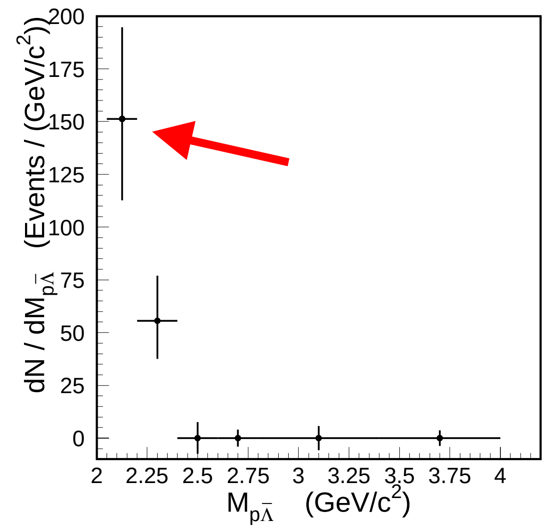
$$\mathrm{B}(B^{+} \to p\bar{\Lambda}\gamma) = \left(2.16^{+0.58}_{-0.53} \pm 0.20\right) \cdot 10^{-6}$$

Theoretical prediction ~10^{-6}

- Near threshold enhancement also observed
  - Fragmentation?

First Observation





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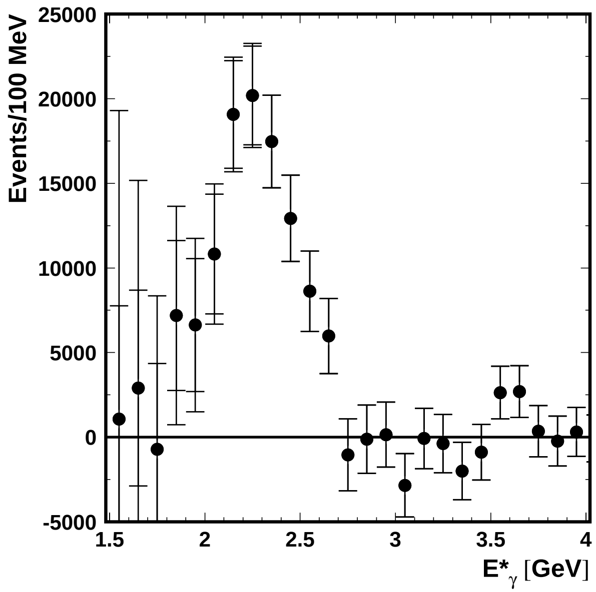
Inclusive $B \to X_s\gamma$

- Full inclusive $b \to \gamma$
- Photon with E>1.8GeV
- Veto photons from π^0 and η
- Subtract continuum with off-resonance data
- Moment analysis to extract HQET parameter



$<E_\gamma> = 2.289 \pm 0.026 \pm 0.035$ GeV

$<E_\gamma^2> - <E_\gamma>^2 = 0.0311 \pm 0.0073 \pm 0.0063$ GeV

→HQET parameter $\bar{\Lambda} = 0.66^{+0.08}_{-0.05}\,\mathrm{GeV/c^2}$

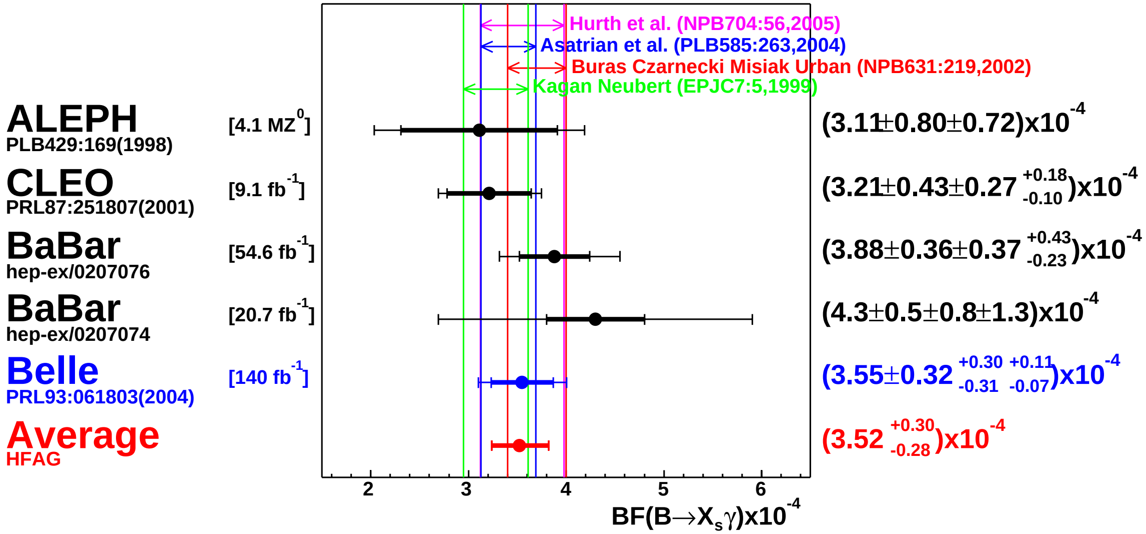
used to extract V_{cb} and V_{ub}

140/fb data

BF of Inclusive $B \to X_s \gamma$

- Subtract $b \to d\gamma$ assuming $B(b \to d\gamma)/B(b \to s\gamma) = 3.8 \pm 0.6\%$

$$B(B \to X_s \gamma) = (3.59 \pm 0.32(stat)\,{}^{+0.30}_{-0.31}(syst)\,{}^{+0.11}_{-0.07}(theo)) \cdot 10^{-4}$$

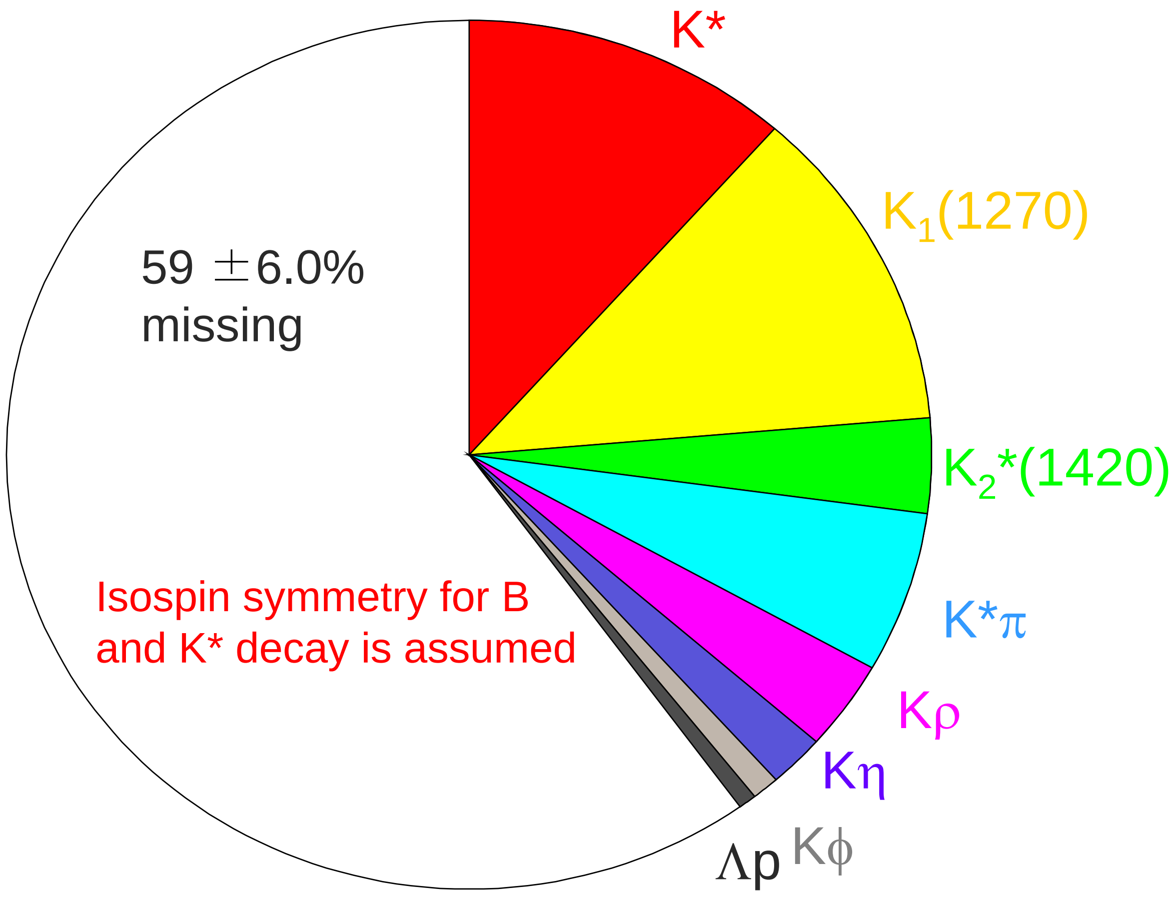


- Measured BF is consistent with theoretical predictions.
  - M_{H+} >200GeV 95%CL (M.Neubert CKM2005)
- Limit on Wilson coefficient A_7
  - $-0.36 < A_7 < -0.17$ or $0.21 < A_7 < 0.42$
  - In the SM $A_7 = -0.33$ at $\mu = 2.5$GeV

G.Hiller and F.Krueger

PRD 69 (2004) 074020

Exclusive $B \rightarrow X_s\gamma$ / Inclusive $b \rightarrow s$



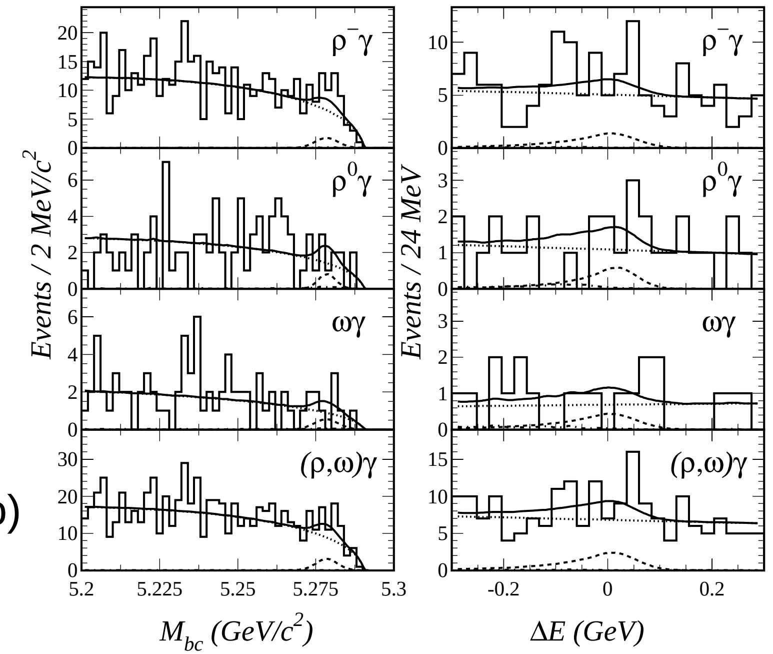
- 40% of $b \rightarrow s\gamma$ are measured exclusively.
- Next step : $B^0 \rightarrow K^0 S^0 \gamma$ for TCPV analysis.
  - $K\eta'$, Kf_0, Ka_0…..

Search for B→ργ ωγ

- b→dγ process has not been observed
- Simultaneous fit to $B^- \to \rho^- \gamma$, $B^0 \to \rho^0 \gamma$ and $B^0 \to \omega\gamma$
- From isospin relations:

$$B(B^- \to \rho^- \gamma) = 2\,(\tau(B^-)/\tau(B^0)) \cdot B(B^0 \to \rho^0 \gamma)$$
$$= 2\,(\tau(B^-)/\tau(B^0))\;\; B(B^0 \to \omega\gamma)$$

$$B(B \to (\rho,\omega)\gamma) = B(B \to \rho^- \gamma) < 1.4 \cdot 10^{-6}$$



SM predictions:

$B(B^- \to \rho^- \gamma) = (0.90 \pm 0.34) \cdot 10^{-6}$ (Ali-Parkhomenko)
$B(B^- \to \rho^- \gamma) = (1.50 \pm 0.50) \cdot 10^{-6}$ (Bosch-Buchalla)

Just above the SM prediction!!

- constrain $|V_{td}/V_{ts}|$

$$\frac{B(B \to (\rho,\omega)\gamma)}{B(B \to K^*\gamma)} = \left|\frac{V_{td}}{V_{ts}}\right|^2 \frac{(1 - m^2_{(\rho,\omega)}/m_B^2)^3}{(1 - m^2_{K^2}/m_B^2)^3} \varsigma^2 (1 + \Delta R)$$

ΔR : form factor ratio

ζ : SU(3) breaking effect

$$\left|\frac{V_{td}}{V_{ts}}\right| < 0.22$$

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Inclusive $B \rightarrow X_s ll$

- Semi-inclusive technique
- Electron or muon pair
  - $M_{ll} > 0.2\text{GeV}$
  - Charmonium veto
- Xs is reconstructed from K^+ or K_s + 0-4π (at most one π^0 is allowed)
  - $M_{Xs} < 2.0$ GeV

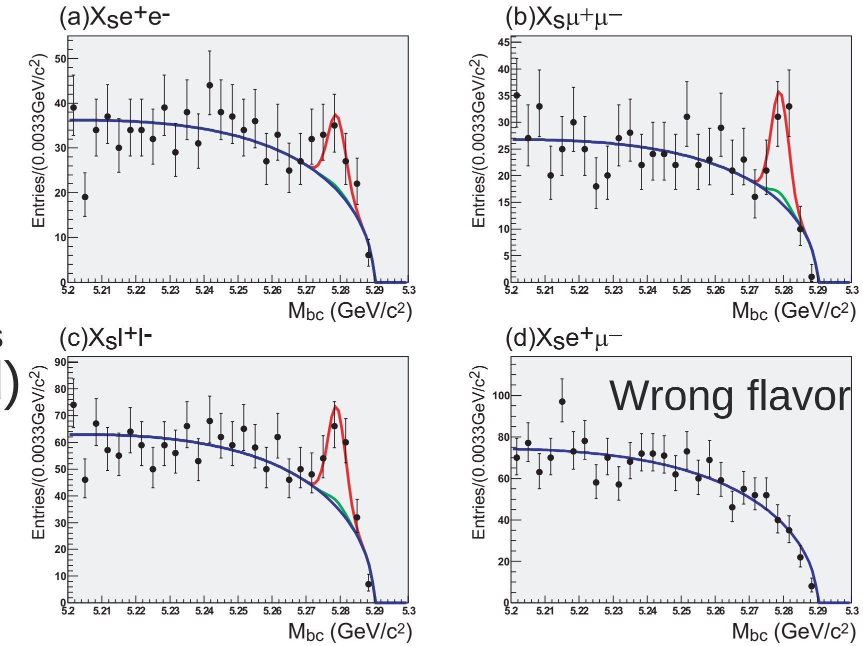
$$B(B \rightarrow X_s \ell^+ \ell^-) = \left(4.11 \pm 0.83^{+0.85}_{-0.81}\right) \cdot 10^{-6}$$

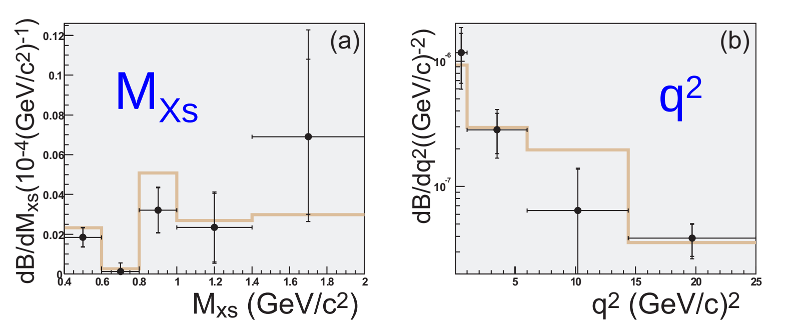
$$B(B \rightarrow X_s \mu^+ \mu^-) = \left(4.13 \pm 1.05^{+0.85}_{-0.81}\right) \cdot 10^{-6}$$

$$B(B \rightarrow X_s e^+ e^-) = \left(4.04 \pm 1.30^{+0.87}_{-0.83}\right) \cdot 10^{-6}$$

Theoretical preduction by Ali et al.

$$B(B \rightarrow X_s \ell^+ \ell^-) = \left(4.2 \pm 0.70\right) \cdot 10^{-6}$$





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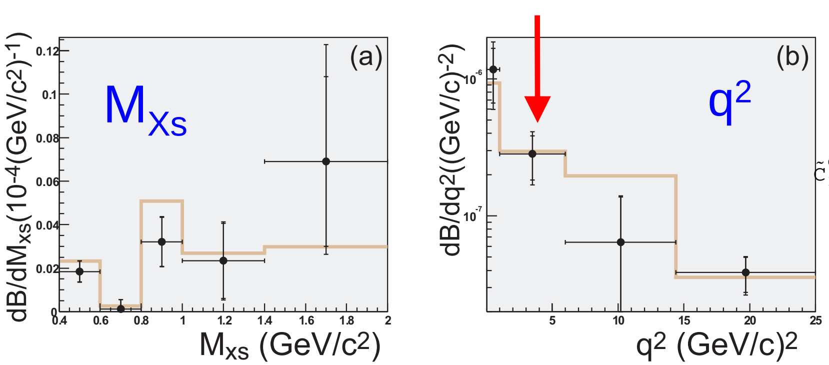
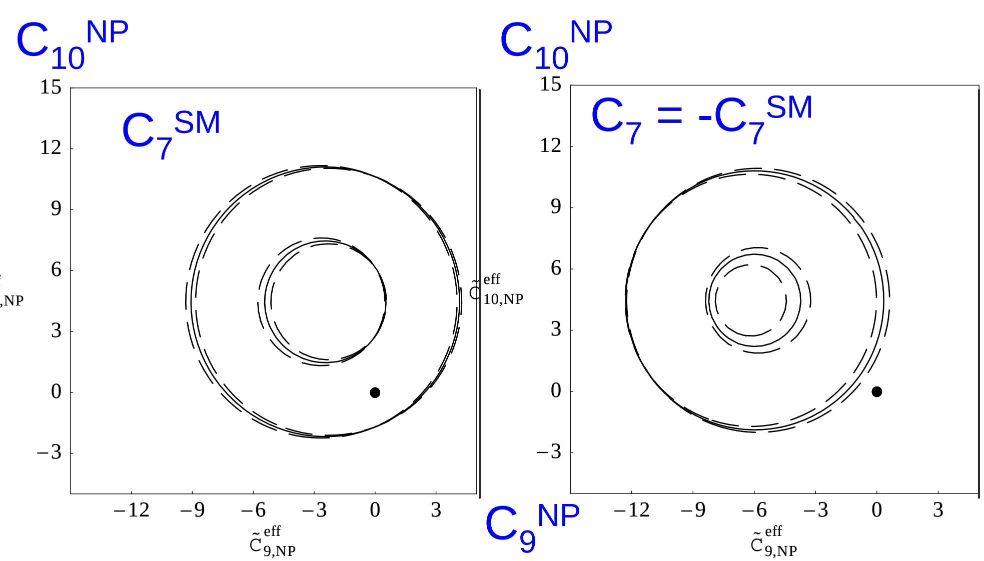
Limit on Wilson Coefficients

P.Gambino, U.Haisch and M.Misiak PRL 94 061803 (2005)

- Clean prediction of BF of $B(B \rightarrow X_s ll)$ for $1<q^2<6GeV^2$ is available.
  - Combine Belle and Babar results
  - Sign of C_7 flipped case with SM C_9 and C_{10} value is unlikely.

BF	Belle	Babar	WA	SM	$C_7 = -C_7^{SM}$
$q^2>(2m_\mu)^2$	4.11 ± 1.1	5.6 ± 2.0	4.5 ± 1.0	4.4 ± 0.7	8.8 ± 0.7
$1<q^2<6GeV^2$	1.5 ± 0.6	1.8 ± 0.9	1.60 ± 0.5	1.57 ± 0.16	3.30 ± 0.25





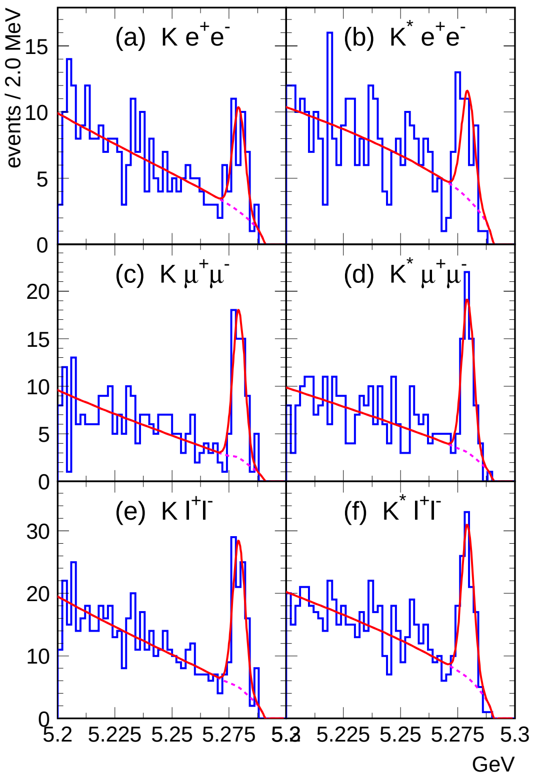
Branching Fraction of B→K$^{(*)}$ ll

- K^+, K_s or $K^*(K^+\pi^-, K_s\pi^+, K^+\pi^0)$ + e^+e^- or $\mu^+\mu^-$
  - $M_{ll}>0.14$GeV

$$\mathcal{B}(B \to K\ell^+\ell^-) = (5.50^{+0.75}_{-0.70} \pm 0.27 \pm 0.02) \times 10^{-7}$$
$$\mathcal{B}(B \to K^*\ell^+\ell^-) = (16.5^{+2.3}_{-2.2} \pm 0.9 \pm 0.4) \times 10^{-7}$$

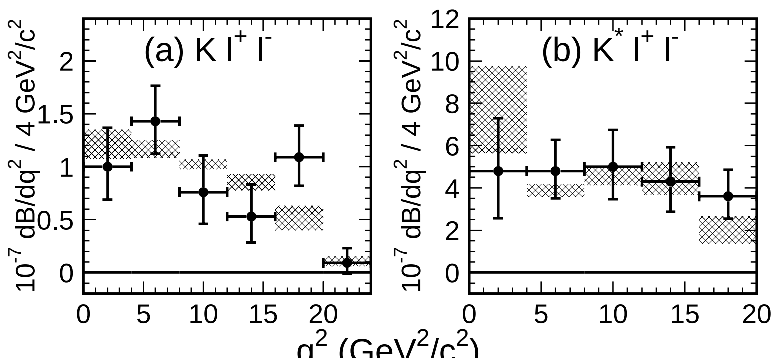
Prediction by Ali et al.

$$\mathcal{B}(B \to K\ell^+\ell^-) = (3.5 \pm 1.2) \times 10^{-7}$$
$$\mathcal{B}(B \to K^*\ell^+\ell^-) = (11.9 \pm 3.9) \times 10^{-7}$$



- A ratio of BF of K$^{(*)}\mu\mu$ to K$^{(*)}$ee is sensitive to neutral heavy Higgs in 2HDM with large tanβ. In the SM, the ratio is 1.00 and ~0.75 for Kll and K*ll

$$\mathcal{R}_K = \frac{\mathcal{B}(B\to K\mu\mu)}{\mathcal{B}(B\to Kee)} = 1.38^{+0.39+0.06}_{-0.41-0.07}$$
$$\mathcal{R}_{K^*} = \frac{\mathcal{B}(B\to K^*\mu\mu)}{\mathcal{B}(B\to K^*ee)} = 0.98^{+0.30}_{-0.31} \pm 0.08$$



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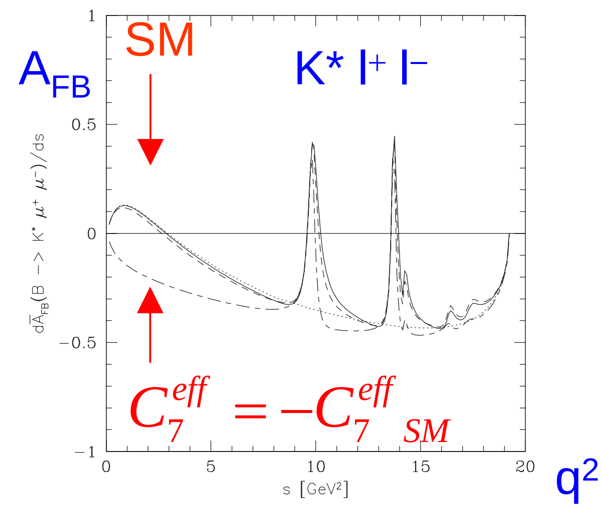
G.Hiller and F.Krueger PRD 69 (2004) 074020

Y. Wang and D. Atwood PRD68 (2003) 094016

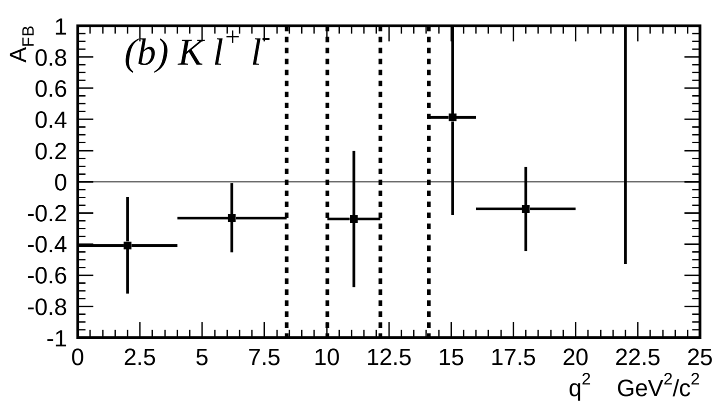
First look at A_{FB} in K*ll

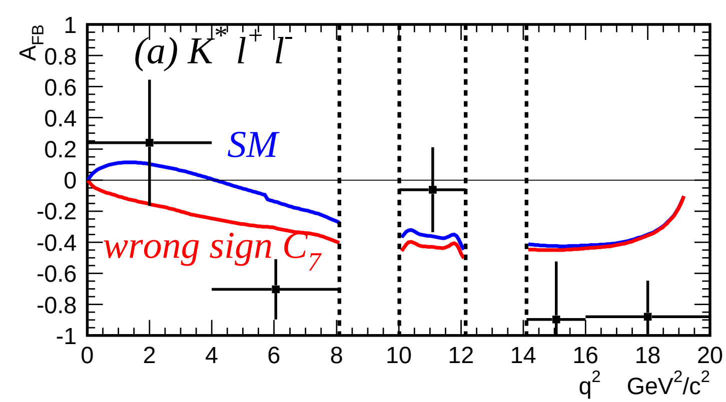
- Sign of $C_7 C_{10}$ can be determined from Forward-Backward Asymmetry in K*ll.
- Raw A_{FB} in each q^2 region is extracted from M_{bc} fit.
- Kll has no asymmetry, so it is a good control sample.
- Curves show theoretical distributions including experimental efficiency effect (not fitted lines!).
- Both curves are in agreement with data, so far.



Ali et al. Phys.Rev. D61 (2000) 074024

$$\frac{d}{d\hat{s}}(\Gamma_F - \Gamma_B) = \frac{G_F^2 \alpha^2 m_B^5}{2^8 \pi^5} |V_{ts}^* V_{tb}|^2 \hat{s}\hat{u}(\hat{s})^2 \times \left[\mathrm{Re}(C_9{}^{\mathrm{eff}}) C_{10} V A_1 + \frac{\hat{m}_b}{\hat{s}} C_7{}^{\mathrm{eff}} C_{10} (V T_2 (1 - \hat{m}_{K^*}) + A_1 T_1 (1 + \hat{m}_{K^*})) \right] .$$





Summary

- Many results for BF are consistent with the SM
  - Precision of BF($b \rightarrow s\gamma$) is 15% level.
    - Negative A_7 solution is consistent with the SM A_7 value
  - Upper limit on B($B \rightarrow (\rho,\omega)\gamma$) is just above the predictions
    - Constrain $|V_{td}/V_{ts}|$
  - Improved measurement of inclusive $B \rightarrow Xsll$ decay
    - Sign of C_7 flipped case with SM C_9 and C_{10} values is unlikely
    - stringent limits on C_9 and C_{10}
- Many measurements of Ratio
  - Precisions of Δ_{0+} ($B \rightarrow K^*\gamma$) are 5% level
    - Towards sign of (C_6/C_7).
  - Time dep. CPV in $B \rightarrow K_s\pi^0\gamma$ is measured for the first time
    - Search for right handed component in C_7
  - First look at Forward-Backward Asymmetry in $B \rightarrow K^*ll$
    - Will be used for measurement of A_9 and A_{10}
- New results will be presented at Lepton Photon 05.
- Stay tuned

Backup Slides

A_{FB} at Super Belle

- 1 year running at $5\text{x}10^{35}$/nb/sec
- → 5/ab integrated luminosity, 10 billion B mesons!!
  - We have accumulated ~0.46/ab, about x10
- $\Delta A_9/A_9$~11%, $\Delta A_{10}/A_{10}$~13%
  - A_7 fixed to SM value
  - systematic error is not included