DCPV/Rare

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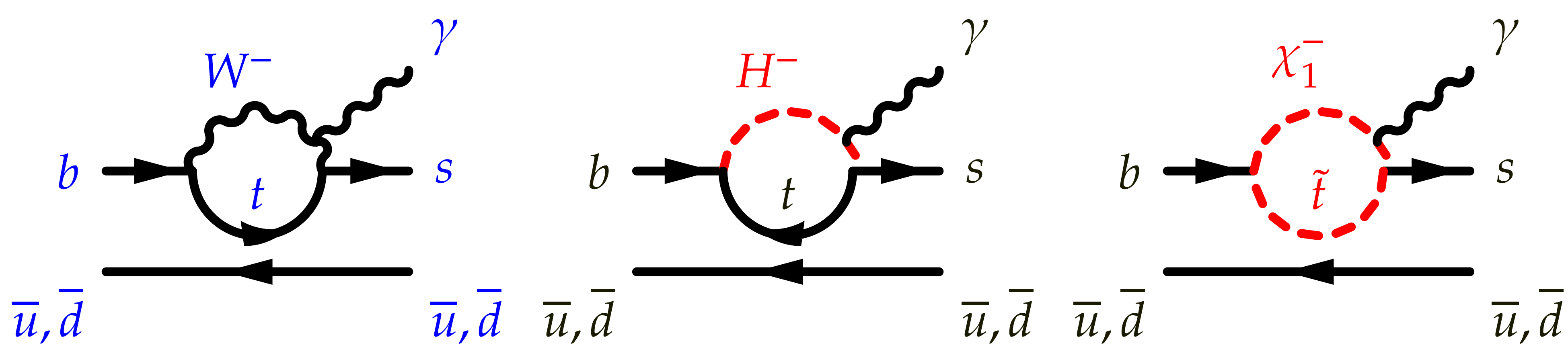
(historically the physics subgroup that covers charmless, electroweak, and other rare decays and their direct CPV has been called the "DCPV/Rare" group in Belle.)

Contents

- Inclusive and exclusive $b \to s\gamma$
- Inclusive and exclusive $b \to d\gamma$
- Inclusive and exclusive $b \to s\ell^+\ell^-$
- Hadronic rare decays — $K\pi$ puzzle

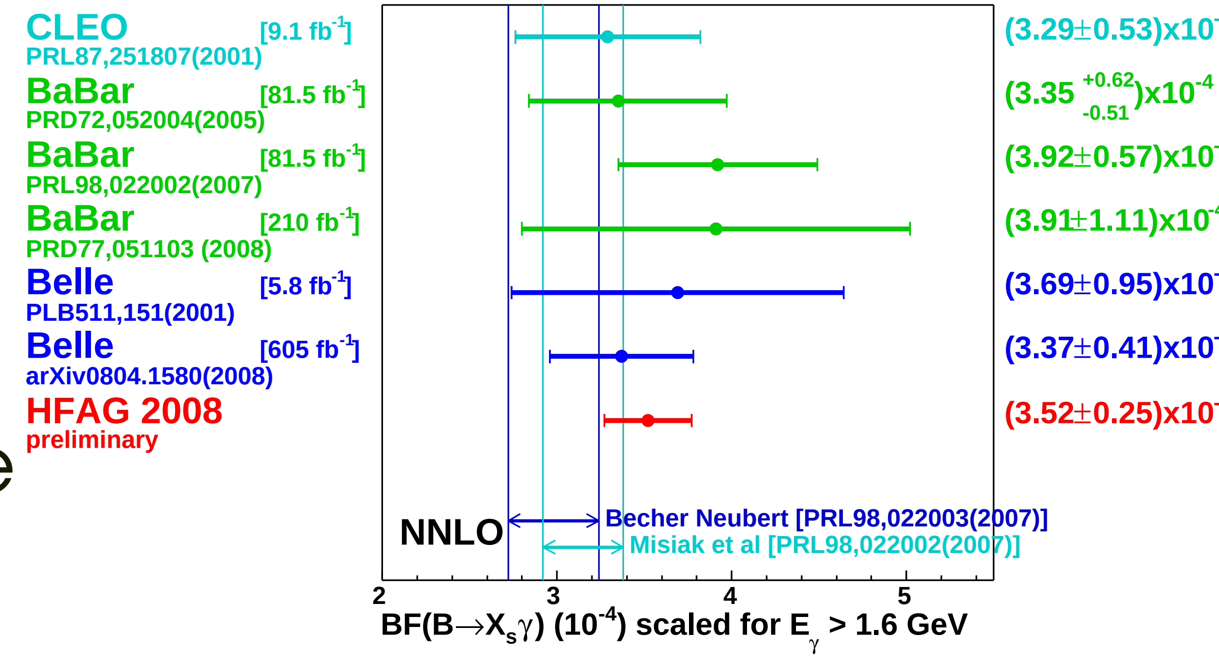
$b \to s\gamma$

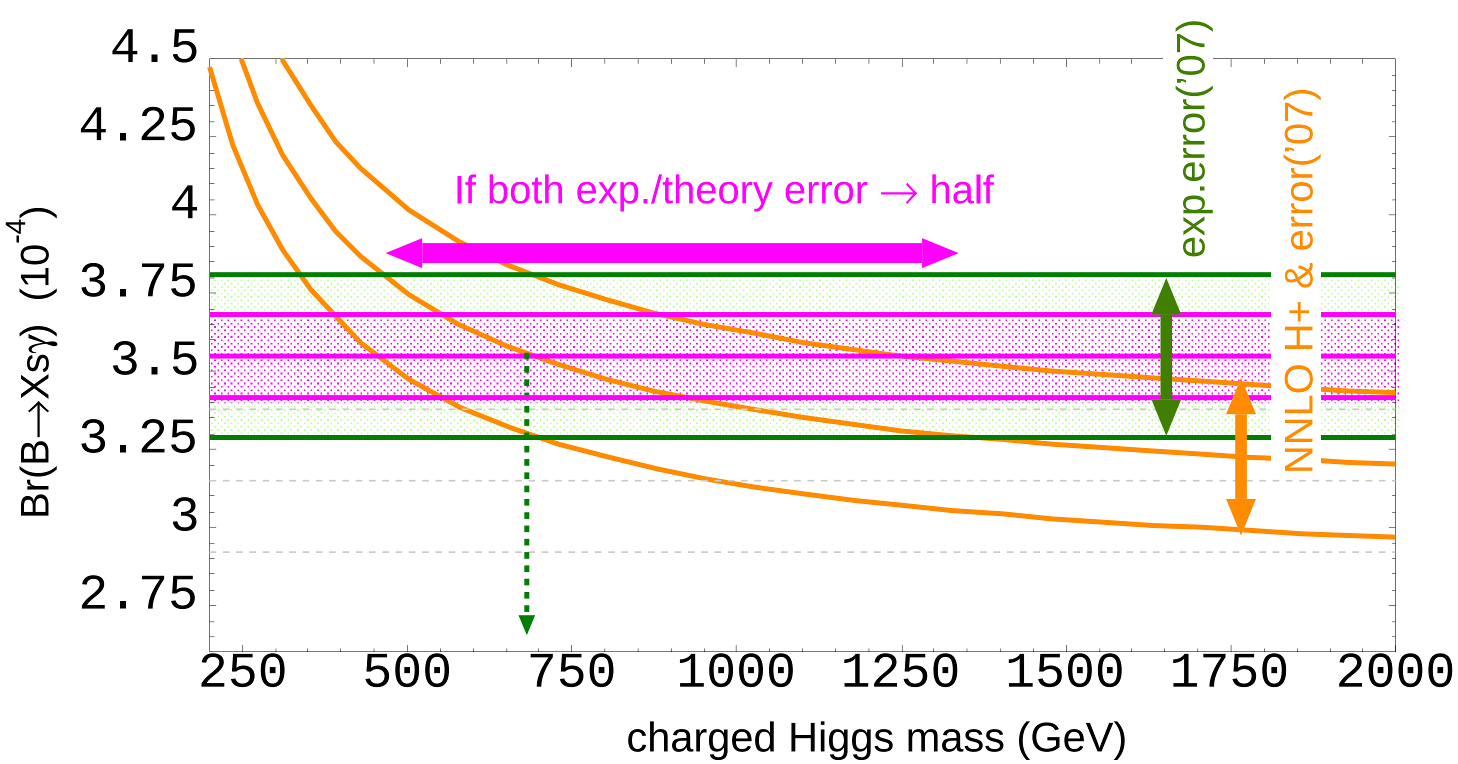
- Rich program
  - Fully inclusive BF and moment measurements
  - Direct CP asymmetry
  - Isospin asymmetry (exclusive/inclusive)
  - Time-dependent CP asymmetry (exclusive)
  - More observable sensitive to the photon helicity
- Sensitive to new physics
  - Reliable theory calculations are available to compare



$B \to X_s\gamma$ branching fraction

- Now: in agreement with theory within $\sim 1\sigma$
- Strong constraints on most of new physics models
- Not so easy to reduce the theory error (already NNLO)



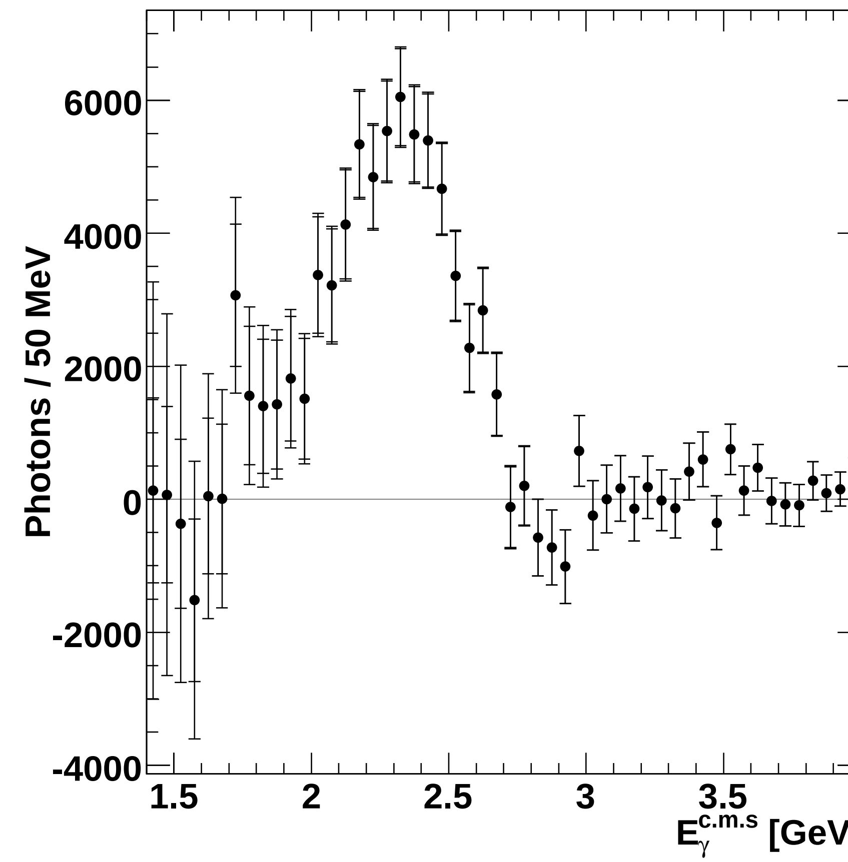


Charged Higgs

- Already in the range not easy even at LHC
- Chance to set limit if errors are reduced
- Light H^+ at LHC ➡ evidence for destructing NP amplitude

$B \to X_s\gamma$ branching fraction

Precise photon energy spectrum is crucial for both the branching fraction and moments



- Now: E_γ down to 1.7 GeV
  $\Leftrightarrow$ theories are based at 1.6 GeV
  3–4 times more data needed
- Now: $\sim 1\sigma$ for lowest bin
  10 times more data needed
  to make it $\sim 3\sigma$
- Limited by off-resonance statistics
- More methods (cross checks)
  - Tag: lepton-tag, $D^*\ell\nu$-tag, full-reconstruction tag (better S/N $\Leftrightarrow$ at a cost of statistics)
  - Sum-of-exclusive (good $\sigma(E_\gamma)$ $\Leftrightarrow$ non-uniform ϵ)
  - Converted photon (good $\sigma(E_\gamma)$ $\Leftrightarrow$ small ϵ)

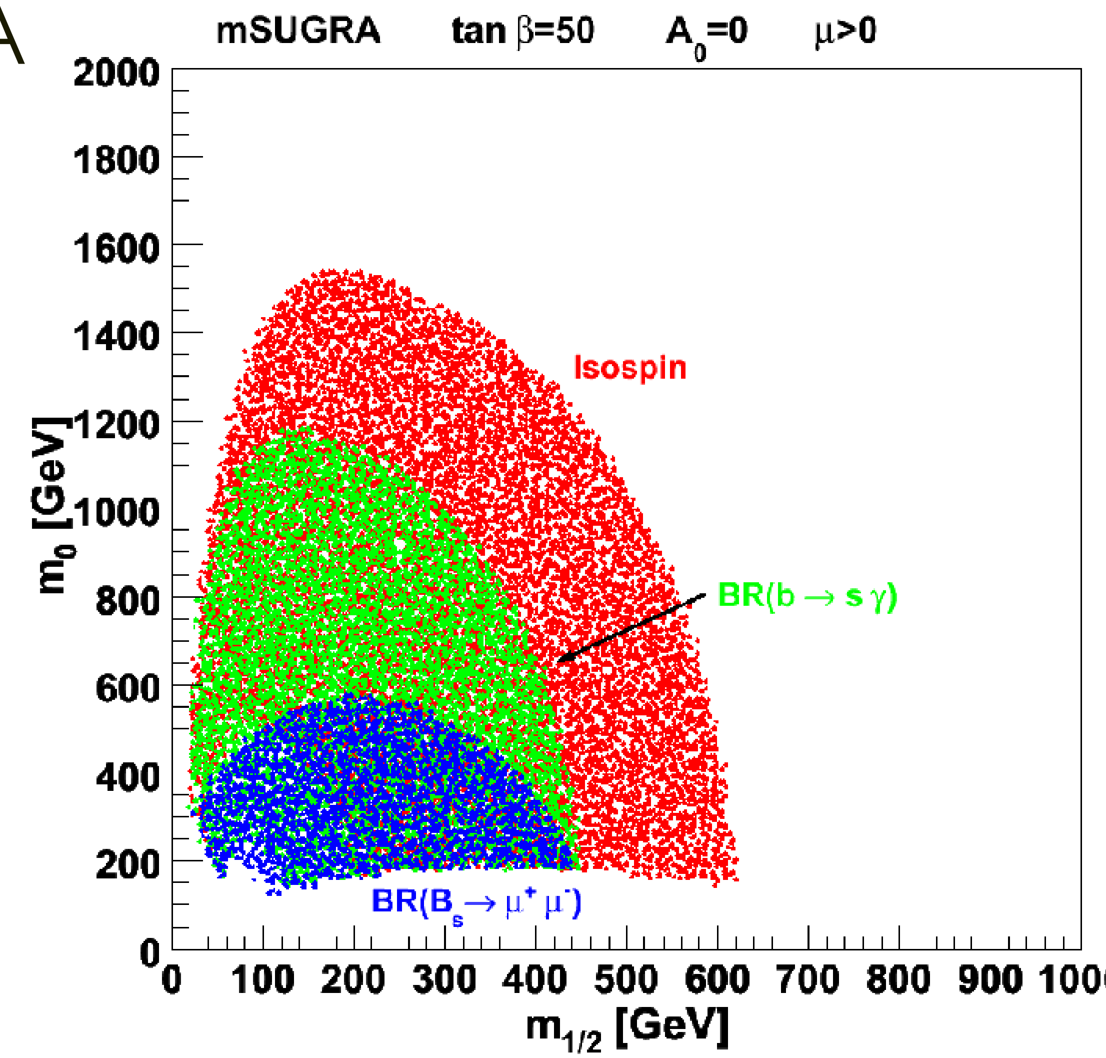
Direct CPV in $b \to s\gamma$

- Sum of exclusive modes (self tag modes)
  - Sensitivity estimated in LoI
    $\delta A_{CP} = \pm 0.009(\text{stat}) \pm 0.006(\text{syst})$ (5 ab^{-1})
    $\delta A_{CP} = \pm 0.003(\text{stat}) \pm 0.002(\text{syst}) \pm 0.003(\text{syst})$ (50 ab^{-1})
    based on previous Belle analysis with 140 fb^{-1}
  - SM prediction
    $A_{CP}(\text{SM}) = +0.0042 + 0.0017 - 0.0012(\text{theo})$
    50 ab^{-1} is not enough to measure the SM A_{CP}
- Fully inclusive (lepton tag asymmetry)
  - Cannot distinguish between $b \to s\gamma$ and $b \to d\gamma$
  - Statistical error ~ 0.06 for 0.6 ab^{-1}
    $\Rightarrow \sim 0.02$ for 5 ab^{-1} / ~ 0.006 for 50 ab^{-1} (stat only)
  - Cancelation between $b \to s\gamma$ and $b \to d\gamma$ in the SM

Really precision measurement

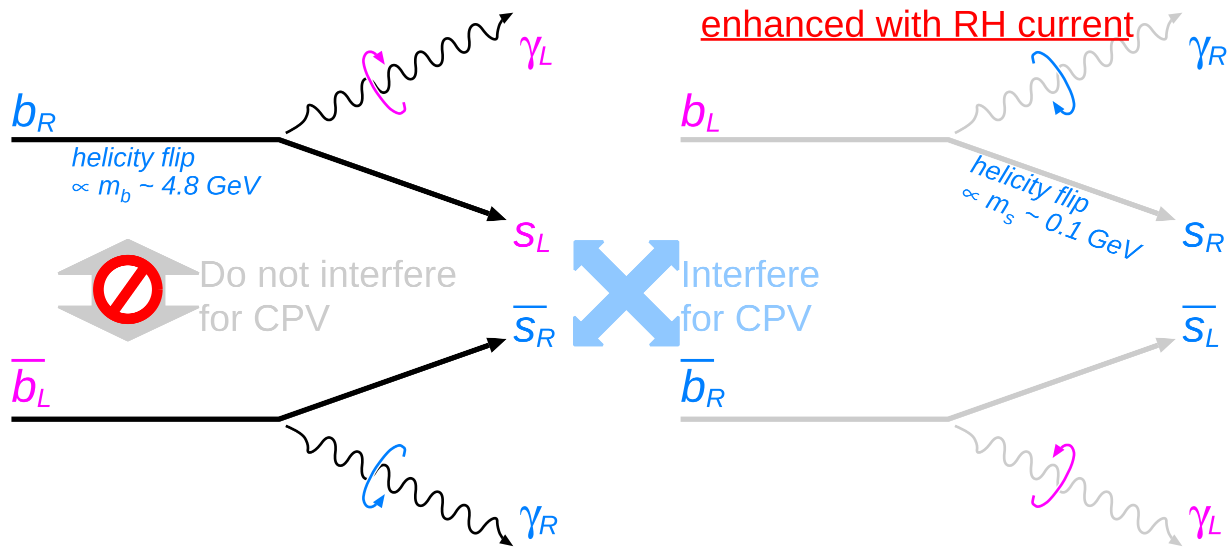
Isospin asymmetry in $b \to s\gamma$

- Constraints e.g. on mSUGRA $m_{1/2}$–m_0 space (Mahmoudi 2007)



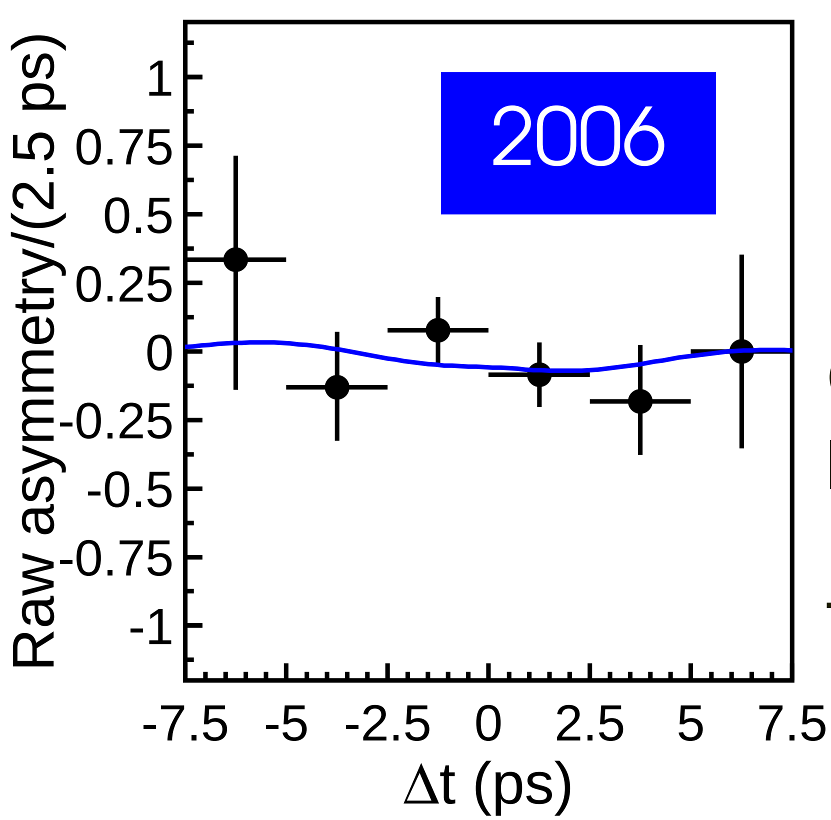
- Exclusive $B \to K^*\gamma$
  - Precise measurement is possible, provided that K^0_S and π^0 efficiency systematic errors are nailed down
- Inclusive $B \to X_s\gamma$
  - By-product of sum-of-exclusive $B \to X_s\gamma$ analysis
  - By-product of full-reconstruction tag $B \to X_s\gamma$ analysis

Time-dep. CPV in $B \to K_S^0 \pi^0 \gamma$



- CPV suppressed by $(m_s/2m_b)$
- Right-handed BSM amplitude relaxes this suppression

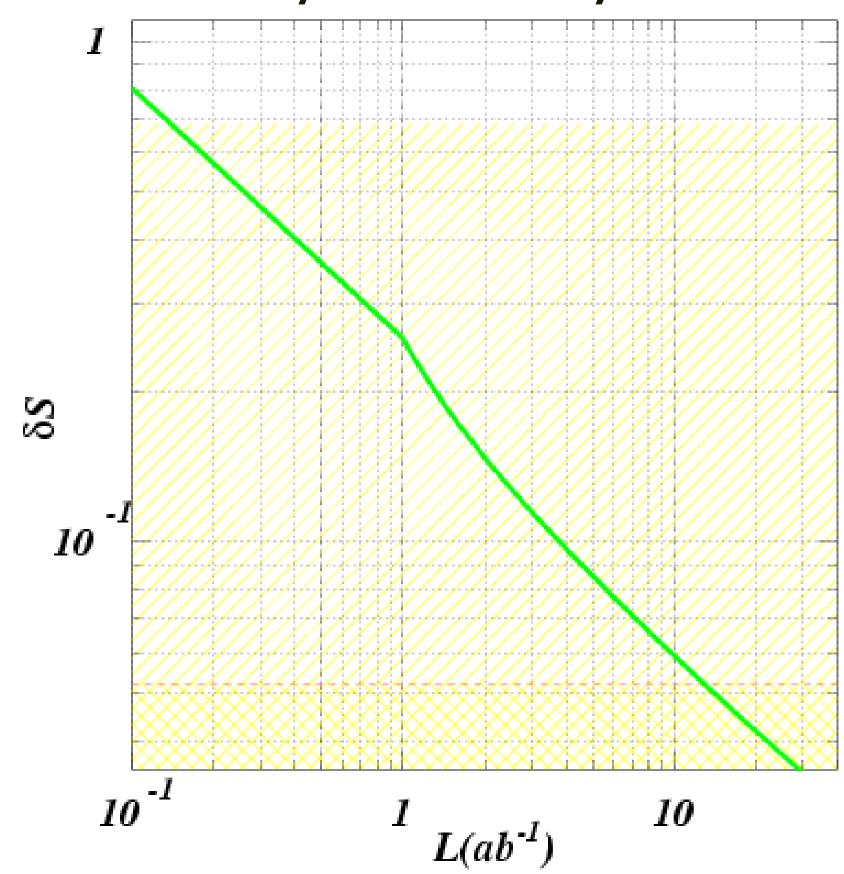
Now: $\mathcal{S} = -0.10 \pm 0.31 \pm 0.07$ (consistent with null asymmetry)



$\delta\mathcal{S} \sim 0.06$ at 10 ab^{-1}

(improvement due to larger SVD radius)

theory error ~ 0.04

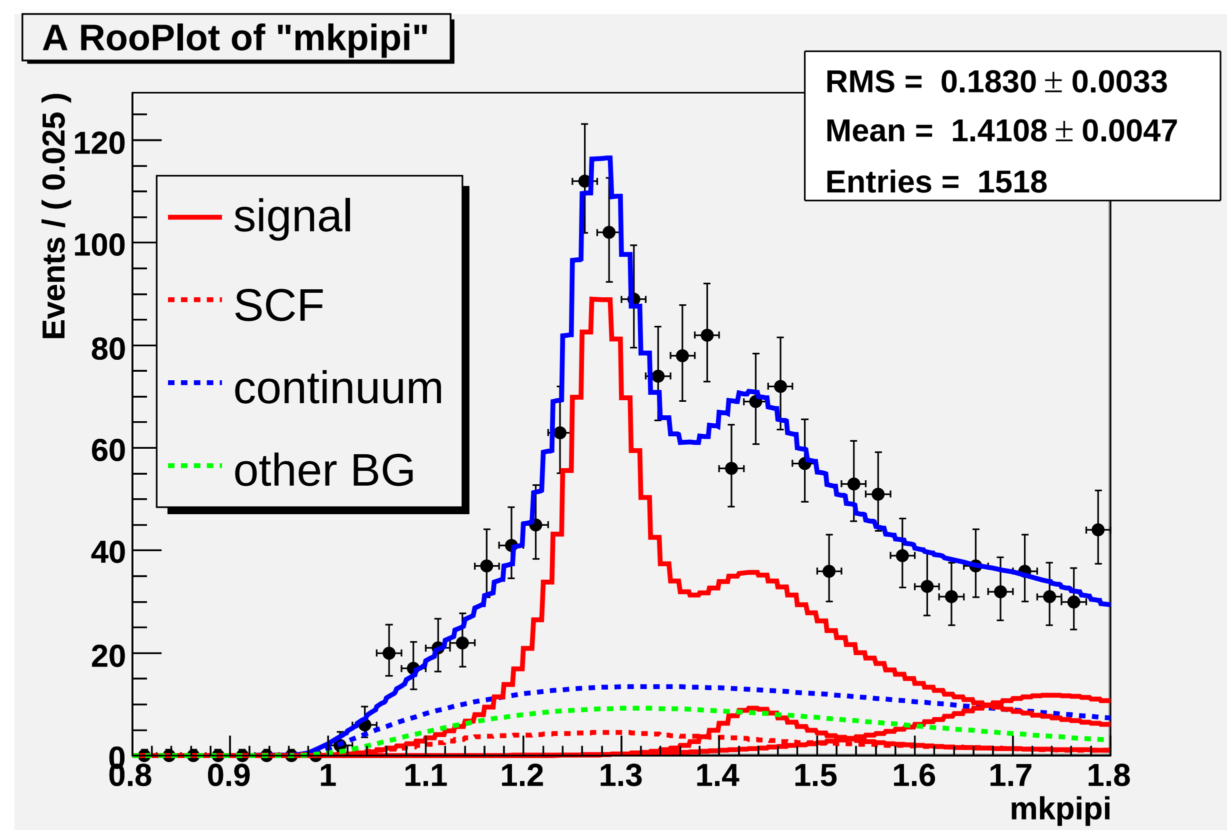


More time-dependent CPV in $b \to s\gamma$

- Competition with LHCb — $B_s \to \phi\gamma$
  - $\mathcal{S}$ is already pretty suppressed ($\sin\phi_s$ is small)
  - Coefficient (A^{Δ}) to $\sinh(\Gamma_s/2)$ is sensitive — $\propto \cos\phi_s$
  - $\sigma(A^{\Delta}) \sim 0.22$ with 2 fb^{-1} at LHCb (V. Belyaev, CKM2008)
- More modes
  - $B \to K^0_S \rho^0 \gamma$ — similar $\delta\mathcal{S}$ as $K^*\gamma$
  - $B \to K^0_S \phi\gamma$, $B \to K^0_S \eta\gamma, \ldots$
- No good theory for three-body radiative decays…

More methods for right-handed current searches

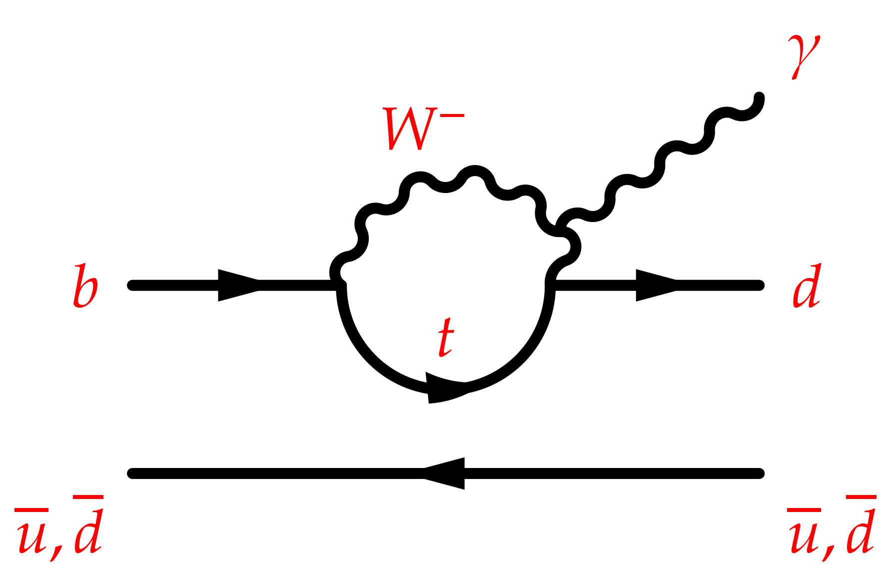
- Photon polarization using photon conversion
  - Oscillation in ϕ — very hard to measure ϕ when opening angle is small
  - Almost no sensitivity even with 50 ab^{-1}
- Photon polarization through triple product asymmetry
  - $B^0 \to K_1(1400)\pi \to K^+\pi^-\pi^0$ gives $A_{SM} = 0.34 \pm 0.05$ (Gronau *et al.*2002)
  - K_1 amplitude can be disentangled
  - NP signal is the dilution in A — hard to distinguish from many other dilution factors

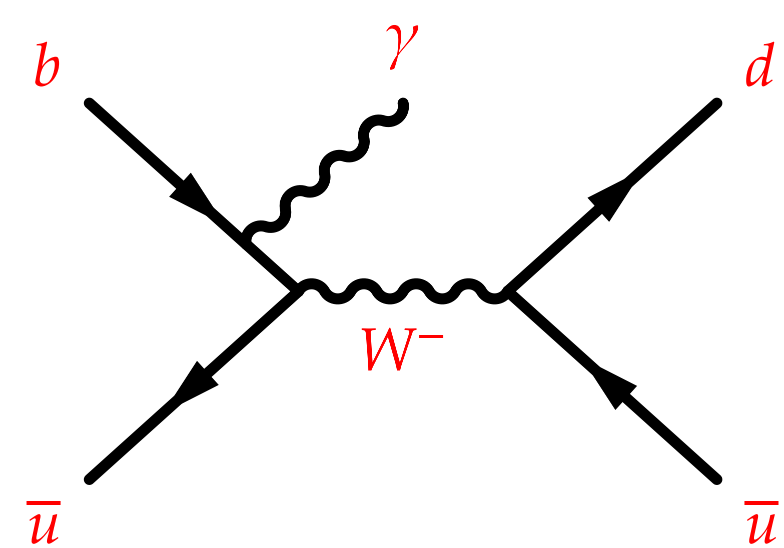


($K_1(1400)$ is visible but small)

$b \to d\gamma$

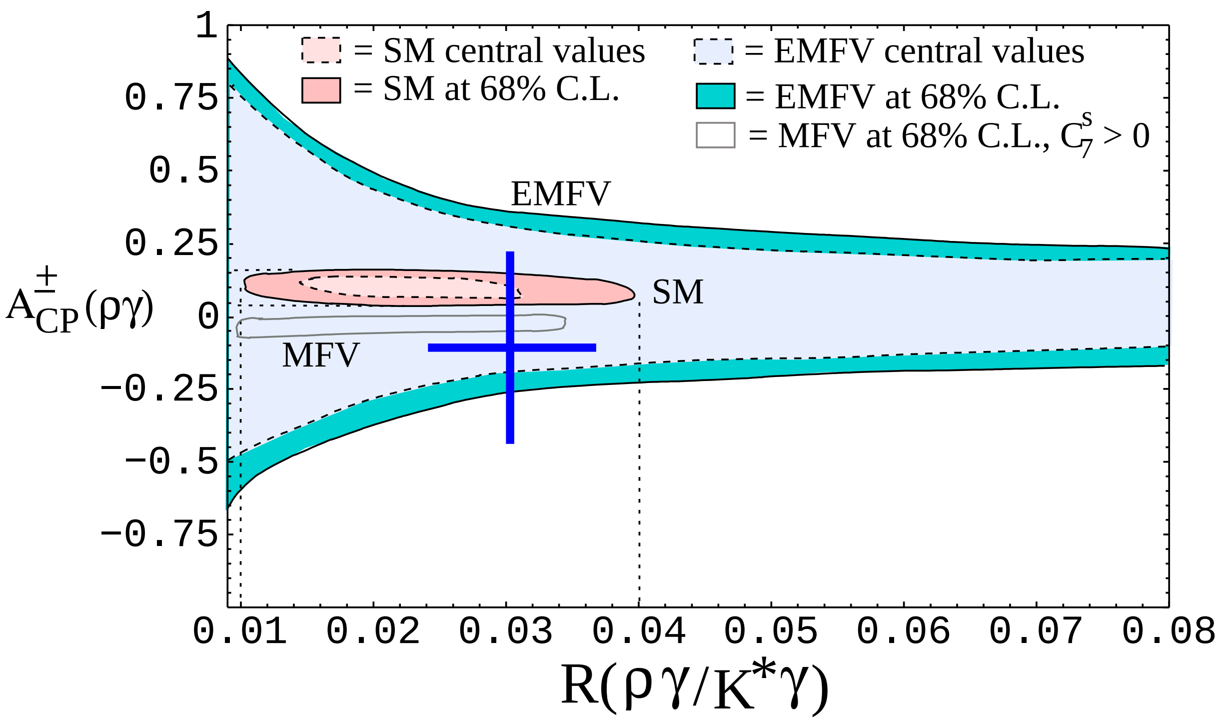
- Similarity to $b \to s\gamma$ in SM, potential difference in NP
  (No reason that NP contribution follows the V_{td}/V_{ts} ratio)
  - Exclusive modes: $B \to \rho\gamma$ and $B \to \omega\gamma$
  - Inclusive analysis as sum-of-exclusives
- Large contribution of annihilation diagram
  - Direct CPV and isospin asymmetry could be large and good observables

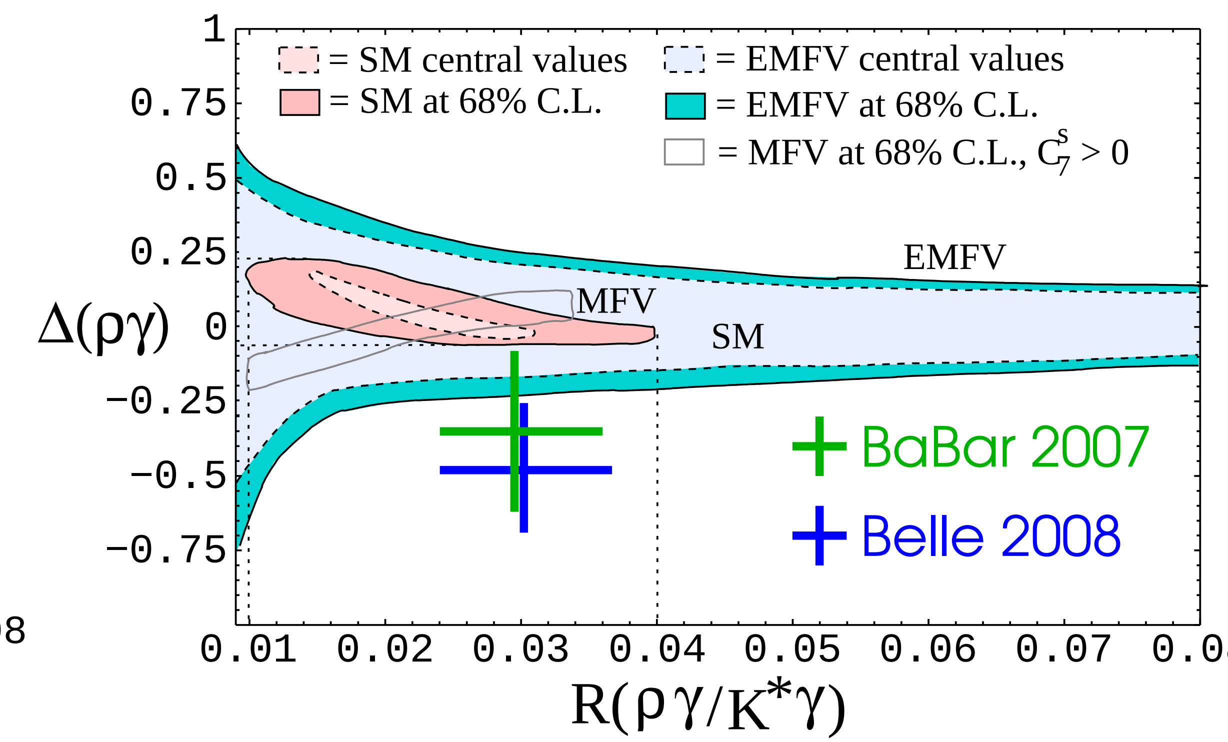




$B \to \rho\gamma$

- Charge averaged branching fraction will not have a big impact on $|V_{td}/V_{ts}|$ anymore (large theory error on form factor)
- Direct and isospin asymmetry will be interesting observables (Ali-Lunghi 2002)





(Belle 2008)

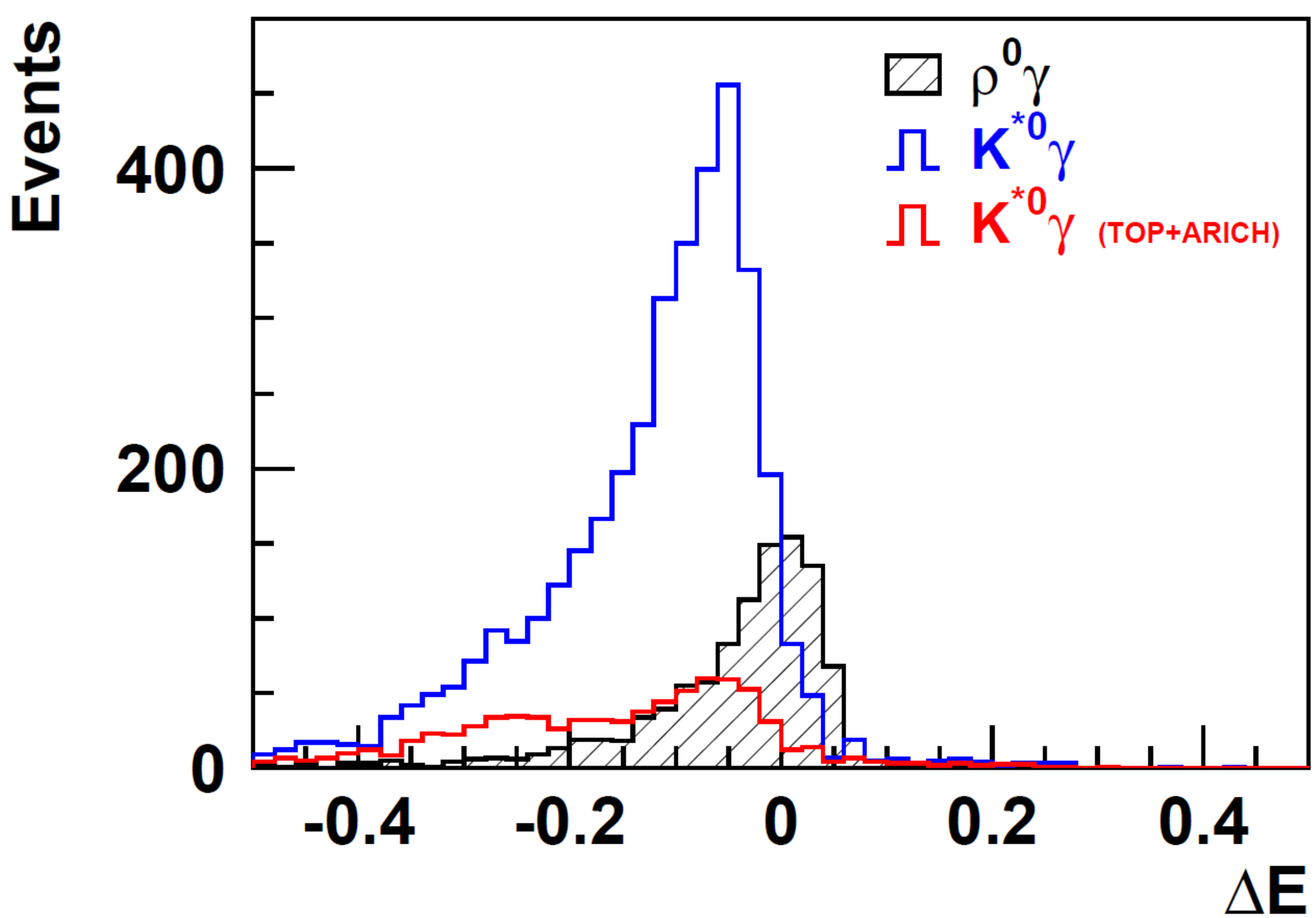
$$R(\rho\gamma/K^*\gamma) = 0.0302\,^{+0.0060}_{-0.0055}\,^{+0.0026}_{-0.0028}$$

$$A_{CP}(\rho^+\gamma) = -0.11 \pm 0.32 \pm 0.09$$

$$\Delta(\rho\gamma) = -0.48\,^{+0.21}_{-0.19}\,^{+0.08}_{-0.09}$$

$B \to \rho\gamma$ with SuperBelle

- $B \to \rho\gamma$ is one of the highlights with a big improvement
  - Equivalent to +83% gain in luminosity in statistics
    (TOP + ARICH + dE/dx, depending on options)
  - Huge $B \to K^{*}\gamma$ background becomes sub-dominant, hopefully reduces systematic error



$\delta\Delta(\rho\gamma)$ (stat only)

$\sim$ 5% at 5 ab^{-1}

$\sim$ 2% at 50 ab^{-1}

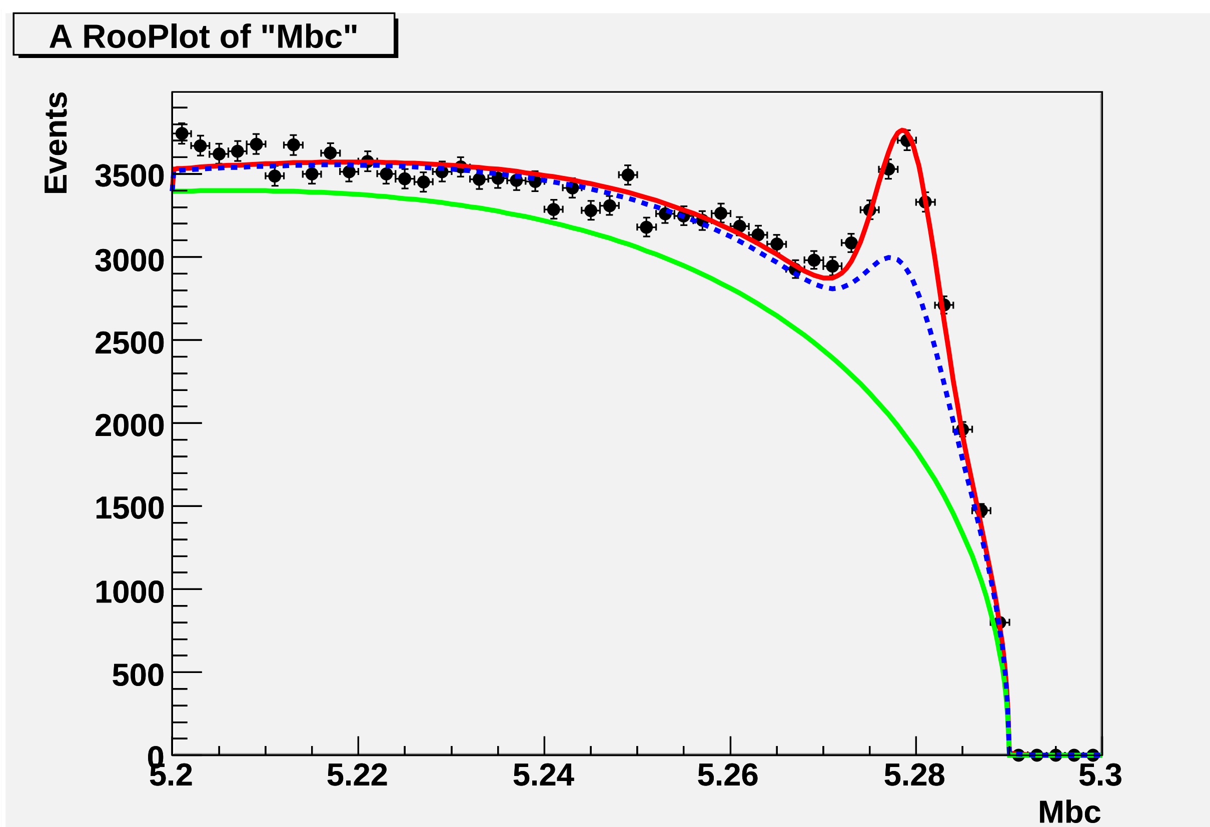
$\delta A_{CP}(\rho^{+}\gamma)$ (stat only)

$\sim$ 8% at 5 ab^{-1}

$\sim$ 3% at 50 ab^{-1}

$B \to X_d\gamma$

- Sum-of-exclusive mode is possible to reconstruct partial set of inclusive $b \to d\gamma$ (BaBar has already done this)
- BaBar doesn't provide better $|V_{td}/V_{ts}|$ yet, understanding the missing modes and $B \to X_s\gamma$ background are crucial
- Need a Belle analysis to learn how to proceed at SuperBelle



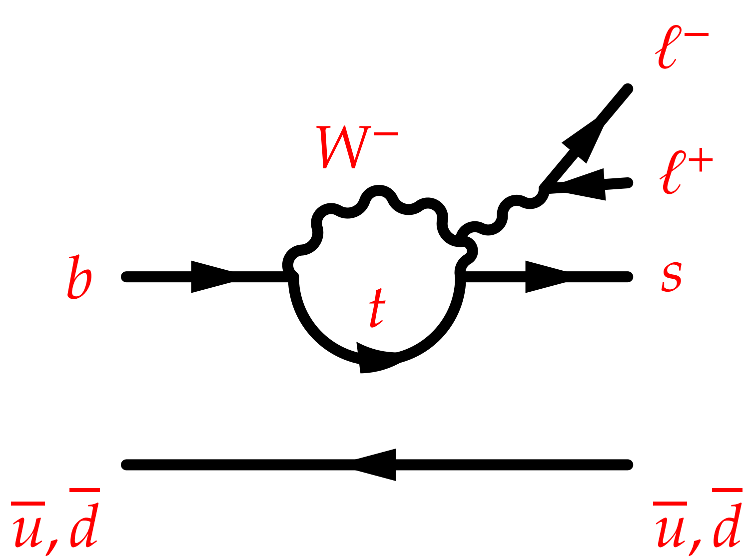
With 5 ab^{-1}, no problem in seeing the signal

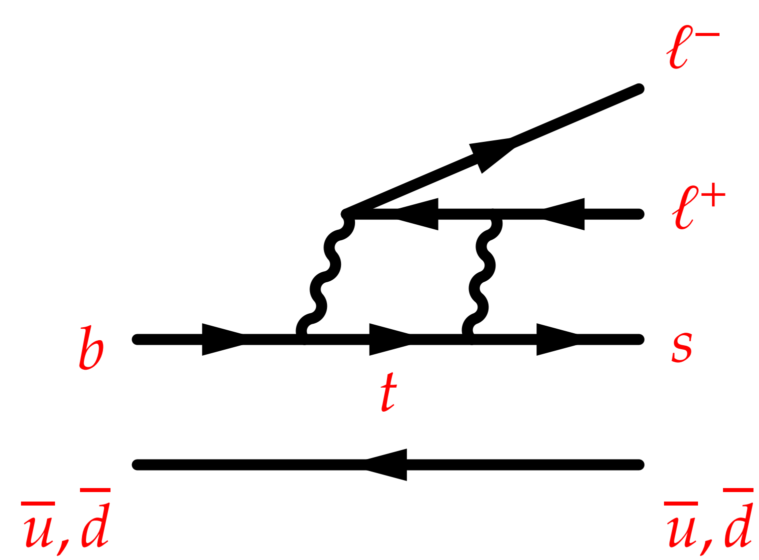
$b \to s\ell^+\ell^-$

- Three types of operators = amplitudes = interactions parametrized by Wilson coefficients C_7, C_9 and C_{10}

$$\frac{d\Gamma(b \to s\ell^+\ell^-)}{d\hat{s}} = \left(\frac{\alpha_{\rm em}}{4\pi}\right)^2 \frac{G_F^2 m_b^5 \left|V_{ts}^* V_{tb}\right|^2}{48\pi^3}(1-\hat{s})^2$$
$$\times\left[(1+2\hat{s})\left(|C_9|^2+|C_{10}|^2\right)+4\left(1+\frac{2}{\hat{s}}\right)|C_7|^2+12{\rm Re}\,(C_7C_9)\right]+\text{corr.}$$

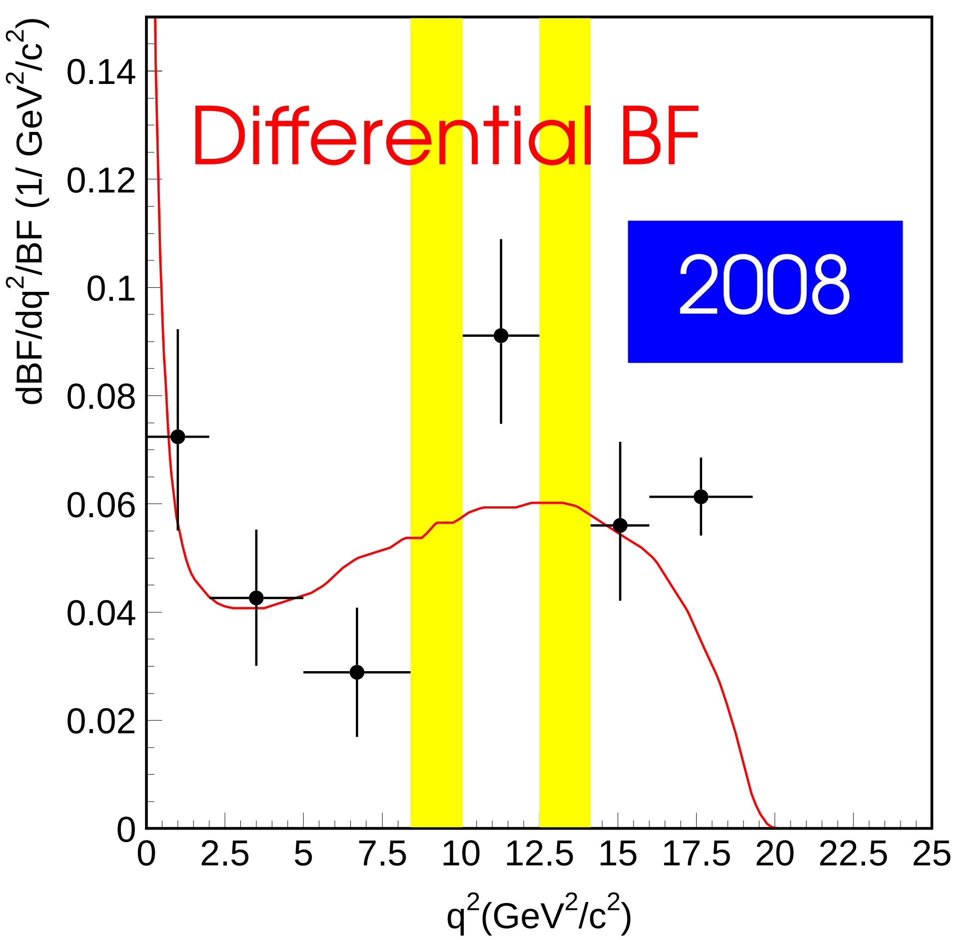
- Wilson coefficients are precisely calculated in the SM
- $|C_7|$ is constrained from $B \to X_s\gamma$, $s = q^2$ dependence to dientangle C_9, C_{10} and relative signs

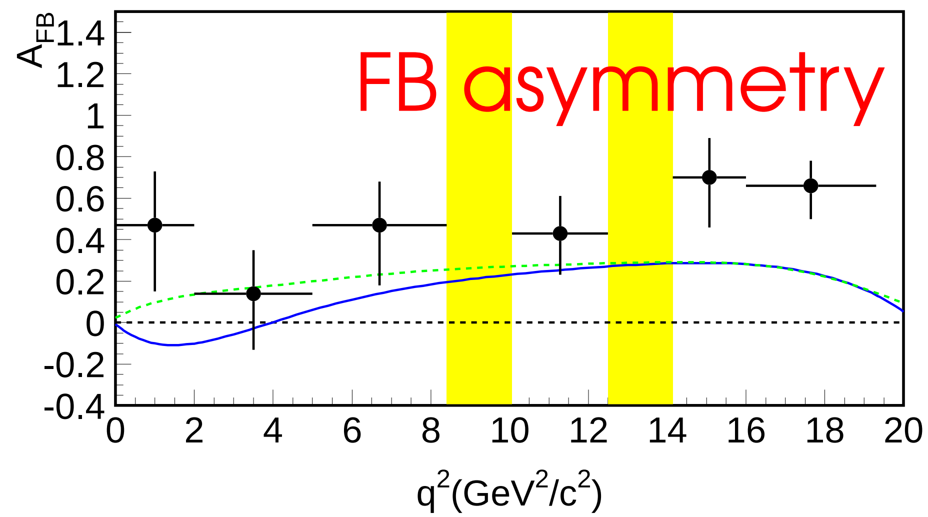


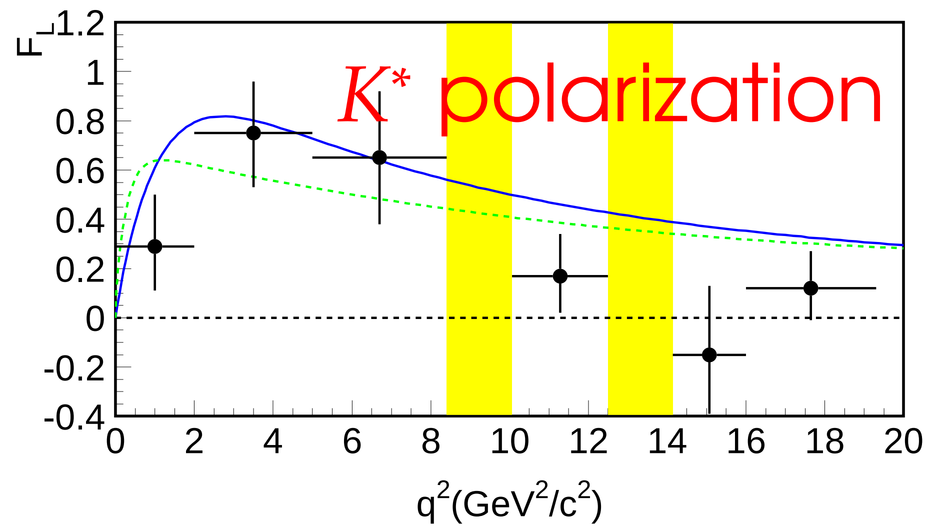


$B \to K^* \ell^+ \ell^-$

- Exclusive mode is easy to reconstruct (also at LHCb)
  $K^* J/\psi$ and $K^* \psi'$ are excluded (excellent control sample)
- BF is not sensitive to new physics due to theory uncertainty
- Many other observables that are sensitive to new physics, especially as functions of $q^2 = m^2(\ell^+\ell^-)$



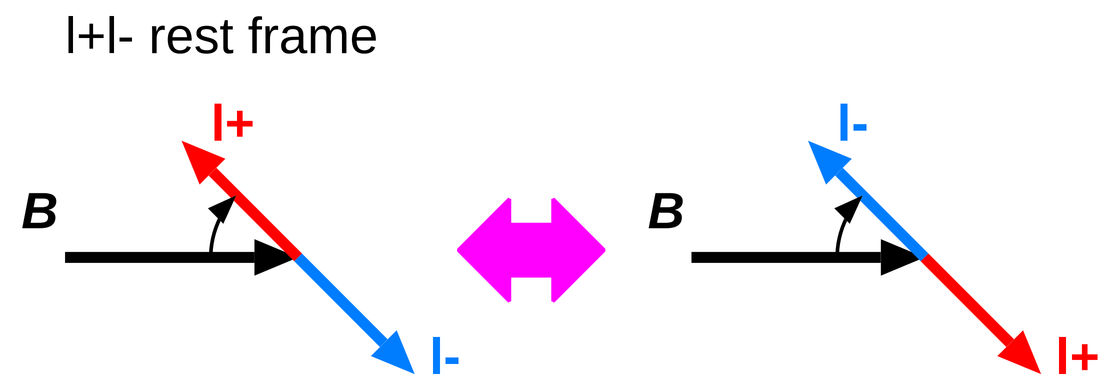


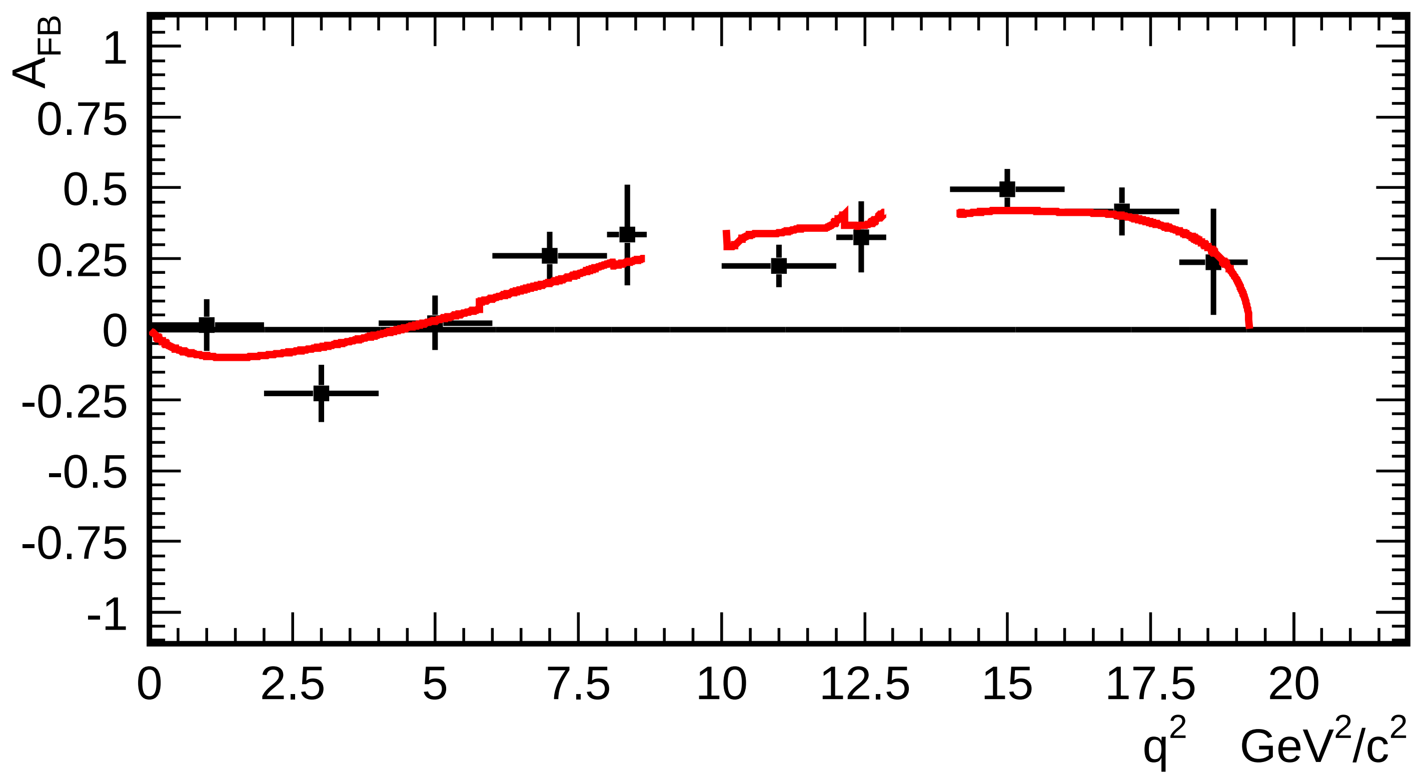


Do we see deviation from theory?

Forward-backward asymmetry

- $\delta C_9 \sim 11\%$, $\delta C_{10} \sim 13\%$ at 5 ab^{-1}
  $\delta C_9 \sim 4\%$, $\delta C_{10} \sim 4\%$ at 50 ab^{-1}
  (with some SM based assumptions)

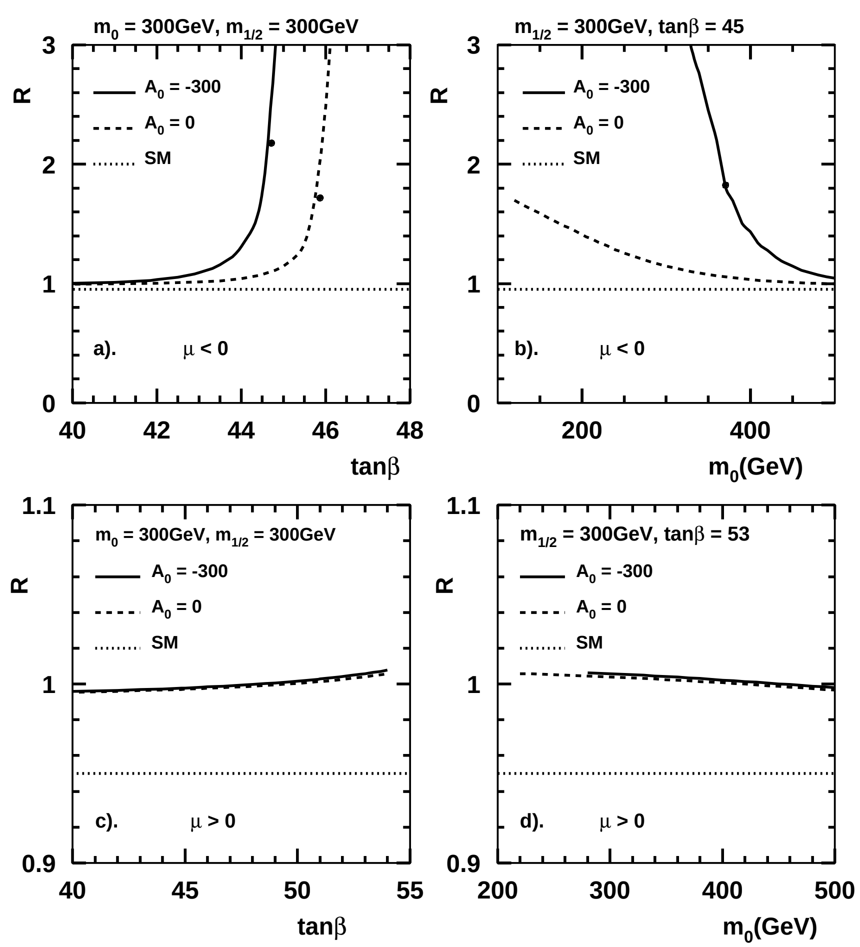




- LHCb will have much bigger statistics for $B \to K^{*0}\mu^+\mu^-$, and good efficiency for small q^2 (How about systematic error?)

$B \to K^{(*)} e^+ e^-$

- Ratio $R_{K^{(*)}} = \mathcal{B}(B \to K^{(*)} \mu^+ \mu^-)/\mathcal{B}(B \to K^{(*)} e^+ e^-)$ is sensitive e.g. to mSUGRA Higgs, a large enhancement at large $\tan\beta \sim 45$
- In the SM, $R_K = 1$ and $R_{K^*} = 0.75$ (due to photon pole at $q^2 = 0$)
- Belle results
  $R_K = 1.03 \pm 0.21$, $R_{K^*} = 0.83 \pm 0.18$ (Belle 2008)
  are in very good agreement with SM

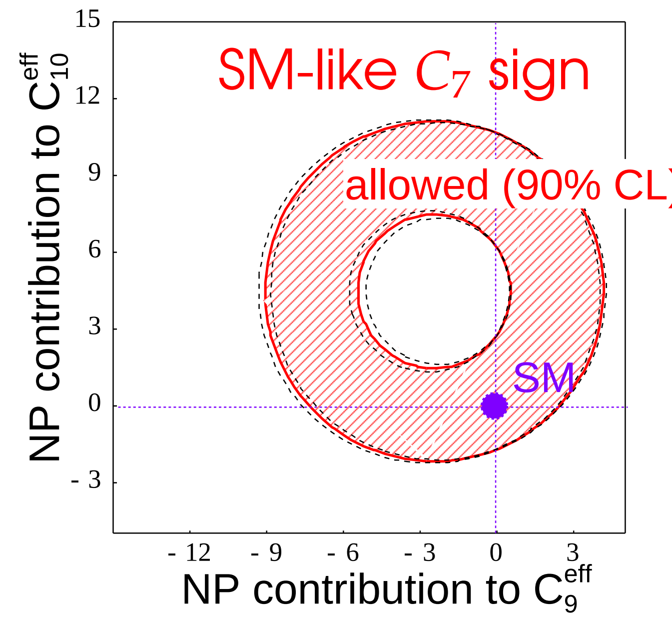


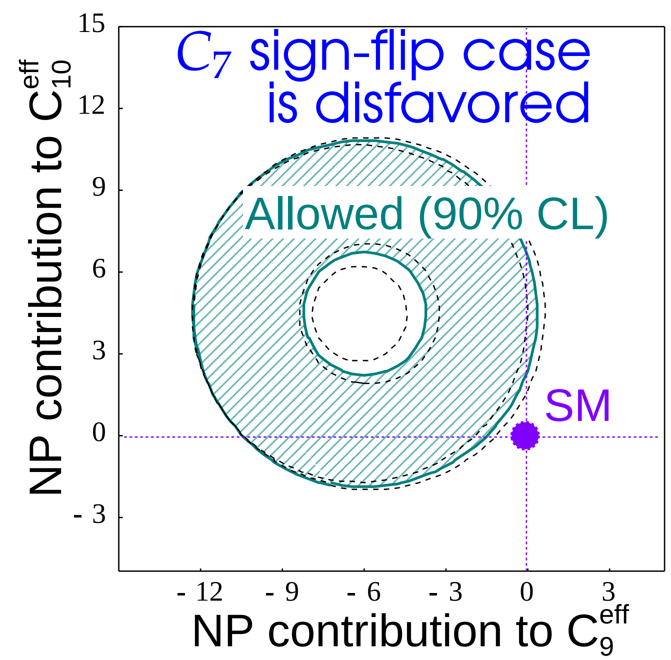
Now: $\sim 20\%$ error
$\Rightarrow \sim 7\%$ at 5 ab^{-1}, $\sim 2\%$ at 50 ab^{-1}

(Wang-Atwood 2003)

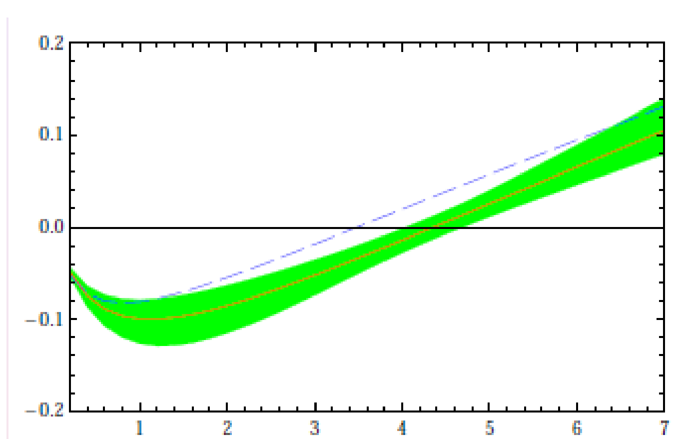
$B \to X_s \ell^+ \ell^-$

- Semi-inclusive analysis
  $\mathcal{B}(B \to X_s \ell^+ \ell^-) = (4.5 \pm 1.0) \times 10^{-6}$
  (Belle+BaBar)
- Already systematic error dominated, mostly due to unknown missing modes
- Sensitive to C_9 and C_{10}
- Forward-backward asymmetry better NP probe than $A_{FB}(B \to K^* \ell^+ \ell^-)$

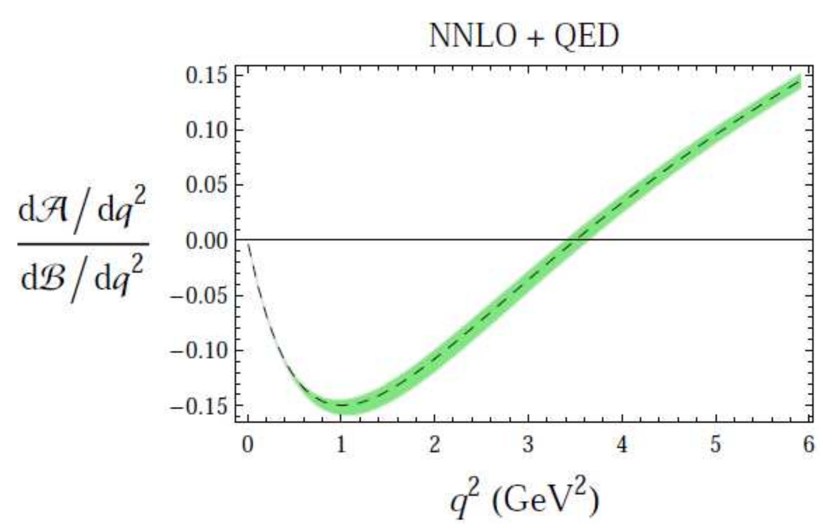




$B \to K^* \ell^+ \ell^-$
(Feldmann CKM2008)



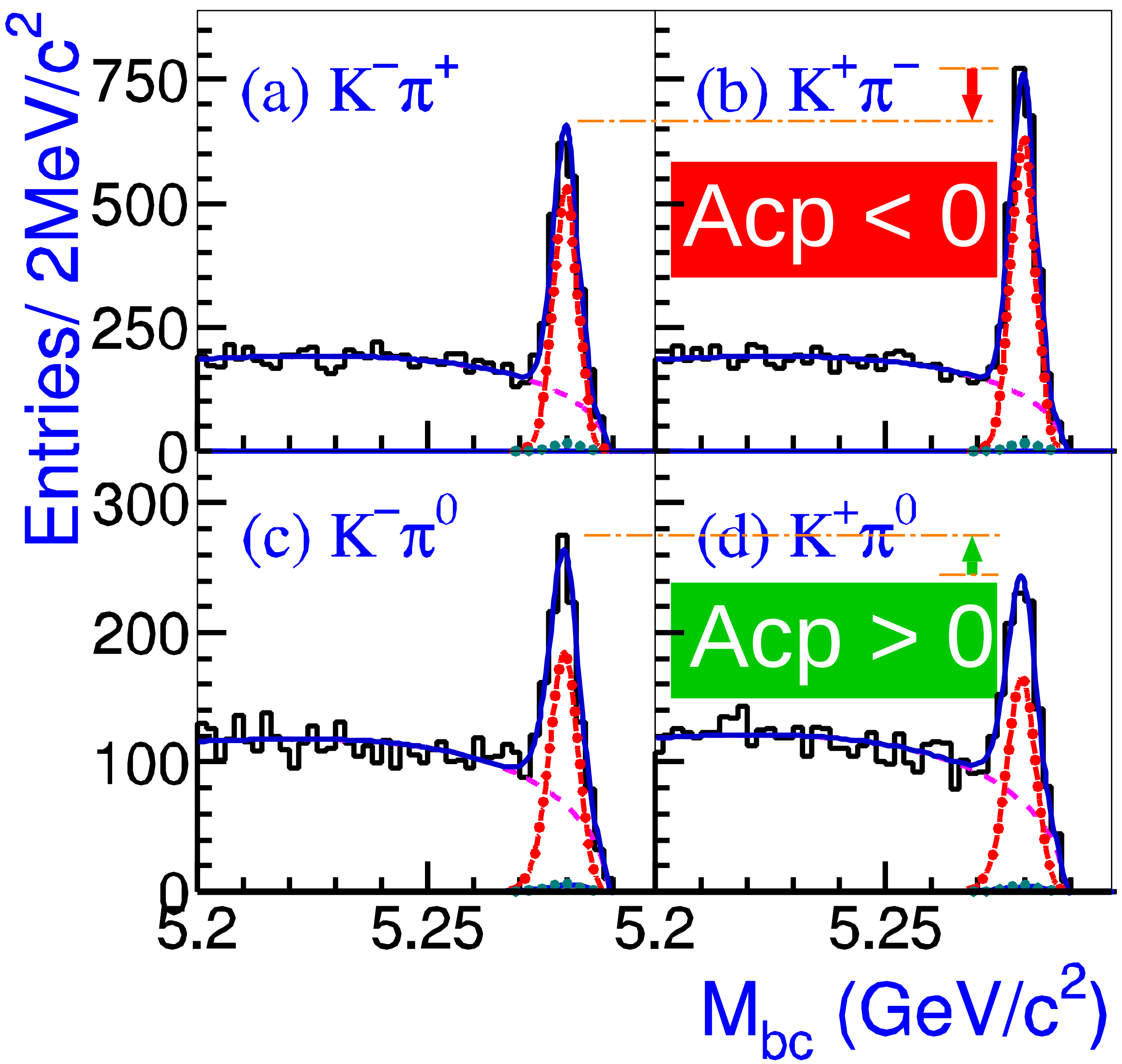
$B \to X_s \ell^+ \ell^-$
(Huber et al 2008)



$B \to K\pi$

- One of the first charmless hadronic decay modes:
  $\mathcal{B} \sim O(10^{-5})$
- Very simple event topology — easy to reconstruct
  Four charge combinations $K^+\pi^-$, $K^+\pi^0$, $K^0_S\pi^+$, $K^0_S\pi^0$
- Sensitive to $b \to s$ and $b \to u$ transitions and phase ϕ_3
- Many theory framework to calculate branching fractions and CP asymmetries (QCDF, pQCD, SCET)
  - Absolute branching fractions were not well predicted
  - A_{CP} were not well predicted ($K\pi$ puzzle)
  - Various ratios and relations are believed to hold (old $K\pi$ puzzle — resolved by new data)

Direct CPV in $K\pi$



- $B \to K^+\pi^-$ and $B \to K^+\pi^0$ have common $b \to s$ penguin and $b \to u$ tree to generate direct CPV
- Differences in sub-leading diagrams: EW penguin and color suppressed tree
- At least within factorization-based theories, no large difference is expected

$$A_{CP}(K^+\pi^-) = -0.094 \pm 0.018 \pm 0.008$$
$$A_{CP}(K^+\pi^0) = +0.07 \pm 0.03 \pm 0.01$$ (Belle 2008)

Opposite sign in $B^0 \to K\pi$ and $B^+ \to K\pi$
— $K\pi$ puzzle as long as no theory reliably predicts this difference

Sum rule

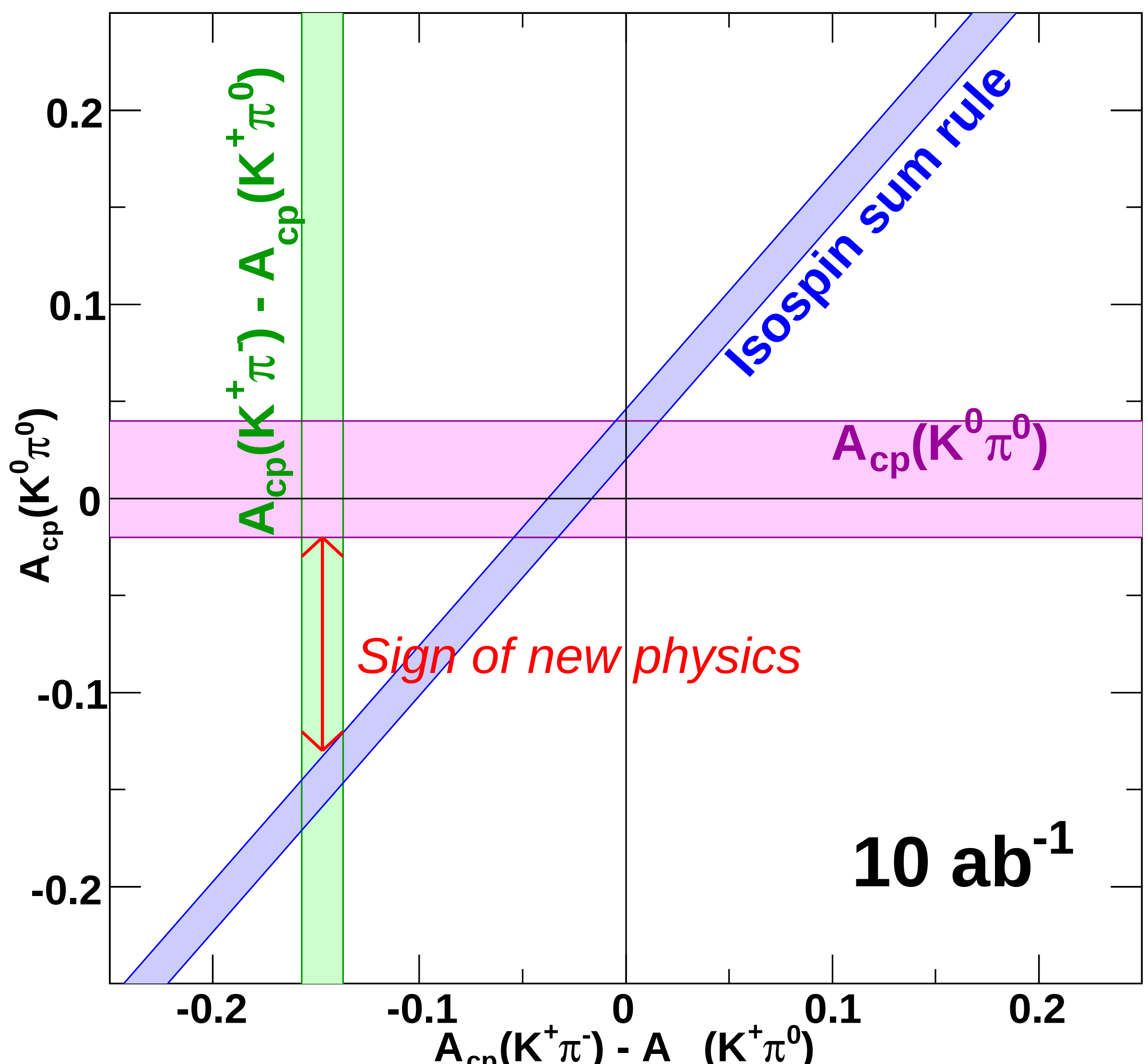
(Gronau 2005)

$$A_{CP} \times \Gamma(K^+\pi^-) + A_{CP} \times \Gamma(K^0\pi^+) = 2A_{CP} \times \Gamma(K^+\pi^0) + 2A_{CP} \times \Gamma(K^0\pi^0)$$

$$A_{CP}(K^0\pi^0)_{\text{sumrule}} = -0.146 \pm 0.041 \Leftrightarrow A_{CP}(K^0\pi^0)_{\text{measured}} = +0.01 \pm 0.10$$

- $A_{CP}(K^0\pi^0)$ is statistical error dominated, a large integrated luminosity brings down the error
- All the other measurements are (will be) systematic error dominated

Assumption: systematic error could be halved with 10 ab^{-1}



Belle vs SuperBelle

Gear change: $O(1)$ deviation search ➡ $O(5\%)$ deviation search

- Many of the rare decays at $O(10^{-5})$–$O(10^{-6})$, have been suitable for discovery at Belle ($b \to s$, $b \to u$ and $b \to d$)
- However, Belle's luminosity is not sufficient for precision measurements
  - Only SuperBelle allows us precision (i.e., meaningful) measurements
  - Need equally qualified theory, useful decay modes are limited
- Finding a few of yet-to-be-discovered rare decays would not be so interesting

List of more modes

- $B \to \pi \ell^+ \ell^-$ and $B \to \rho \ell^+ \ell^-$
- $B \to K^{(*)} \nu \bar{\nu}$
- $B \to \gamma\gamma$
- $B \to \phi\phi$
- $B^+ \to K^+ K^+ \pi^-$ (doubly strange)
- $B \to$ charmless 3-body decays (Dalitz analysis)
- $B \to$ charmless vector-vector final states
- $B \to$ charmless modes with η and η'
- Lepton flavor violating modes such as $B \to X e \mu$
- ....

Problem: we do not have a good theory guideline for hadronic decay modes

Summary and Comments

- More emphasis on inclusive (and sum-of-exclusive) analysis
  - Many potential measurements to probe NP
  - More data improves our understanding of backgrounds
- Need to spend more time on systematic errors
  - There have been too many modes to work on and had not really time to concentrate on systematic errors
- More off-resonance data would be preferable
  - 10% has been the limiting factor for $b \to s\gamma$, and too small for any other continuum background studies
    How about 20%? (i.e., ON : OFF = 4 : 1)
  - Better control on B background if one can fix the shape and size of continuum in a sum-of-exclusive analysis
- PID and pixel detector
  - Need to develop analysis to exploit their performance, e.g. in continuum background suppression