Rare Decays

Logarithmically enhanced corrections in $\bar{B} \to X_s \ell^+ \ell^-$

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in collaboration with

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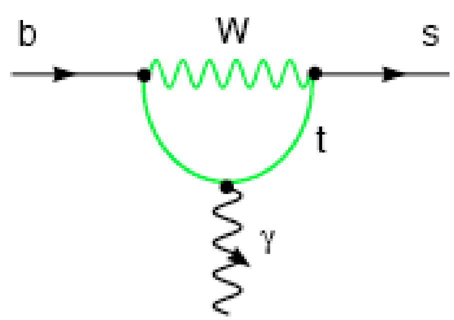
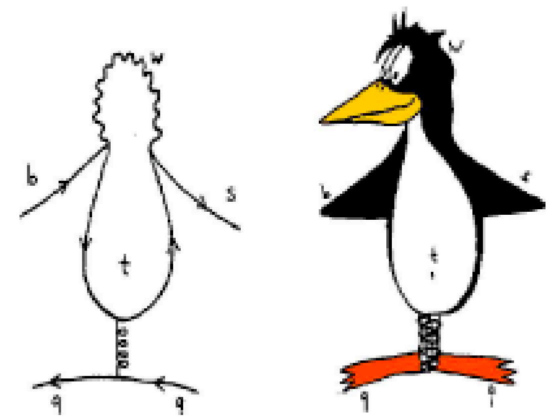
Indirect exploration of higher scales via flavour observables

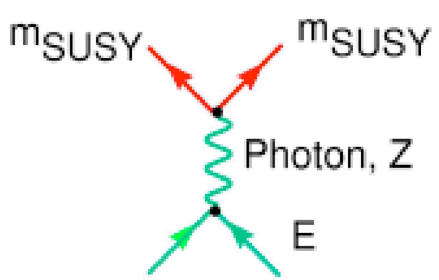
- Flavour changing neutral current processes like $b \to s\,\gamma$ or $b \to s\,\ell^+\ell^-$ directly probe the SM at the one-loop level.



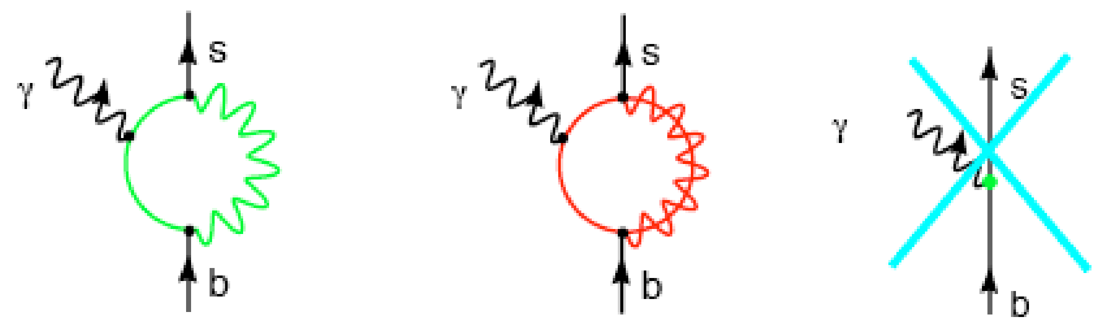


- Indirect search strategy for new degrees of freedom beyond the SM

Direct:



Indirect:

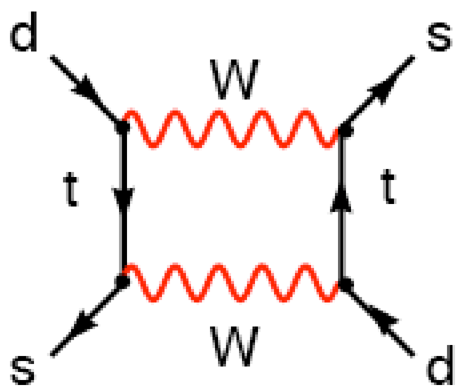


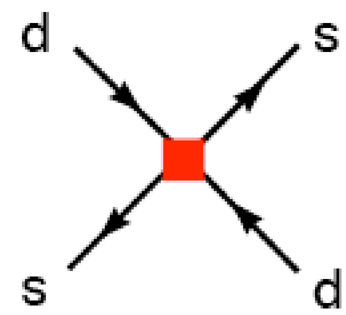
- Immense potential for synergy and complementarity between collider and flavour physics within the search for new physics

Flavour problem or how do FCNCs hide?

$$\mathcal{L} = \mathcal{L}_{Gauge} + \mathcal{L}_{Higgs} + \sum_i \frac{c_i^{New}}{\Lambda_{\mathrm{NP}}} \mathcal{O}_i^{(5)} + \ldots$$

- SM as effective theory valid up to cut-off scale Λ_{NP}
- $K^0 - \bar{K}^0$-mixing $\mathcal{O}^6 = (\bar{s}\, d)^2$: $c^{SM}/M_W^2 \times (\bar{s}\, d)^2 + c^{New}/\Lambda^2 \times (\bar{s}\, d)^2 \Rightarrow \Lambda_{\mathrm{NP}} > 100\,\mathrm{TeV}$

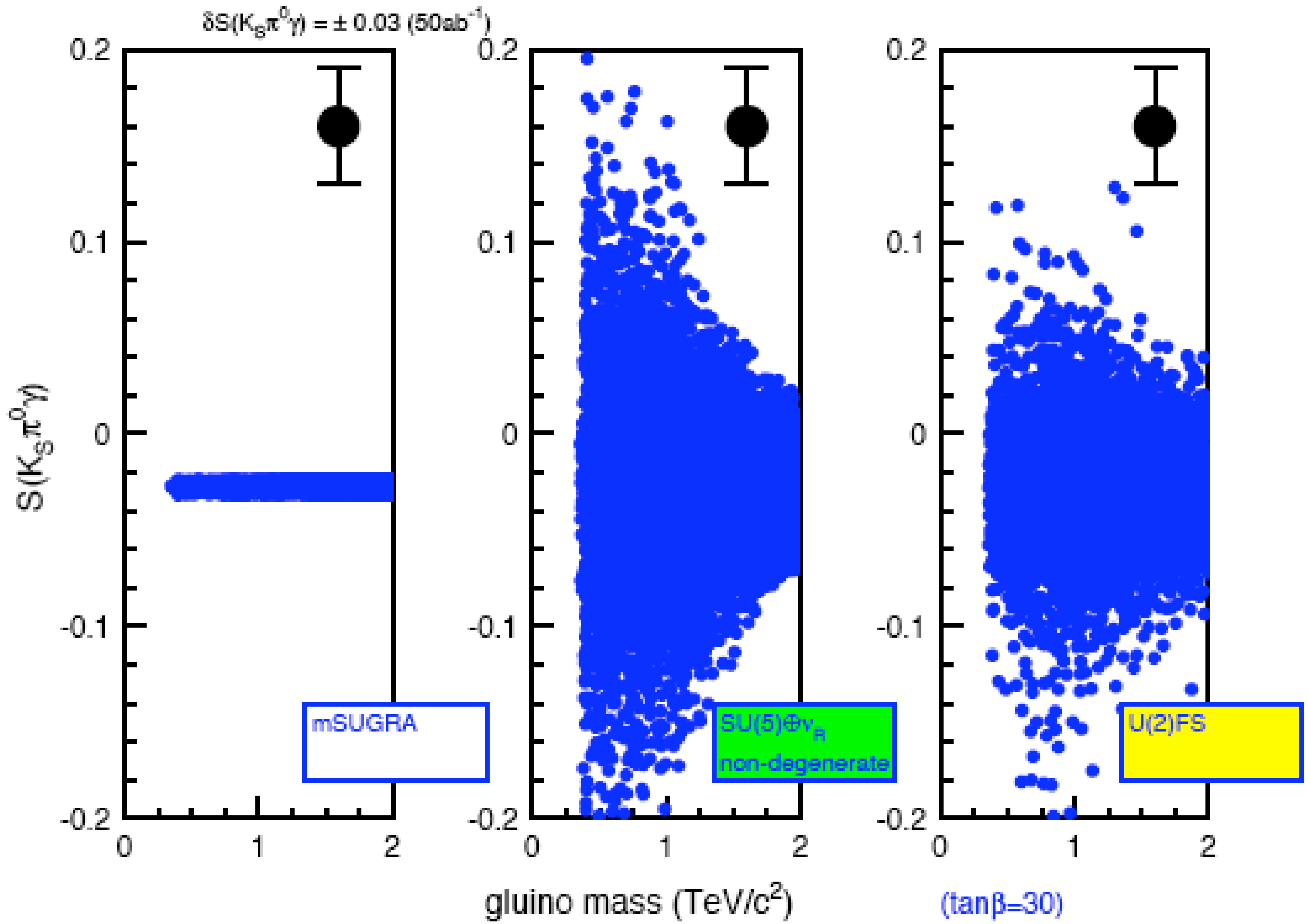




- Natural stabilisation of Higgs boson mass (hierarchy problem) $\Rightarrow \Lambda_{\mathrm{NP}} \leq 1\mathrm{TeV}$
  (i.e. supersymmetry, little Higgs, extra dimensions)
- In addition: EW precision data $\leftrightarrow$ little hierarchy problem $\Rightarrow \Lambda_{\mathrm{NP}} \sim 3 - 10\mathrm{TeV}$

Possible New Physics at the TeV scale has to have a very non-generic flavour structure

Example: Supersymmetry Dynamics of flavour ↔ Mechanism of SUSY breaking



Discrimination between various SUSY-breaking mechanism via flavour observables

Okada et al. (see archiv:0710.3799[hep-ph])

Status of the inclusive mode $\bar{B} \to X_s\gamma$

- Perturbative QCD corrections are dominant and lead to large logarithms
  $\alpha_s(M_W) Log(m_b^2 / M_W^2)$ → resummation of Logs necessary:

LL	Leading Logs	$G_F (\alpha_s Log)^N$	$N = 0, 1, 2, ...$
NLL	Next-to-leading Logs	$G_F \alpha_s (\alpha_s Log)^N$	
NNLL	Next-to-next-to-leading Logs	$G_F \alpha_s^2 (\alpha_s Log)^N$	

- Previous NLL prediction Hurth,Lunghi,Porod,hep-ph/0312260

$$\mathcal{B}(\bar{B} \to X_s\gamma) \times 10^4|_{E_\gamma > 1.6 GeV} = (3.61 \ {}^{+0.24}_{-0.40}\Big|_{m_c/m_b} \pm 0.02_{\rm CKM} \pm 0.25_{\rm param} \pm 0.15_{\rm scale})$$

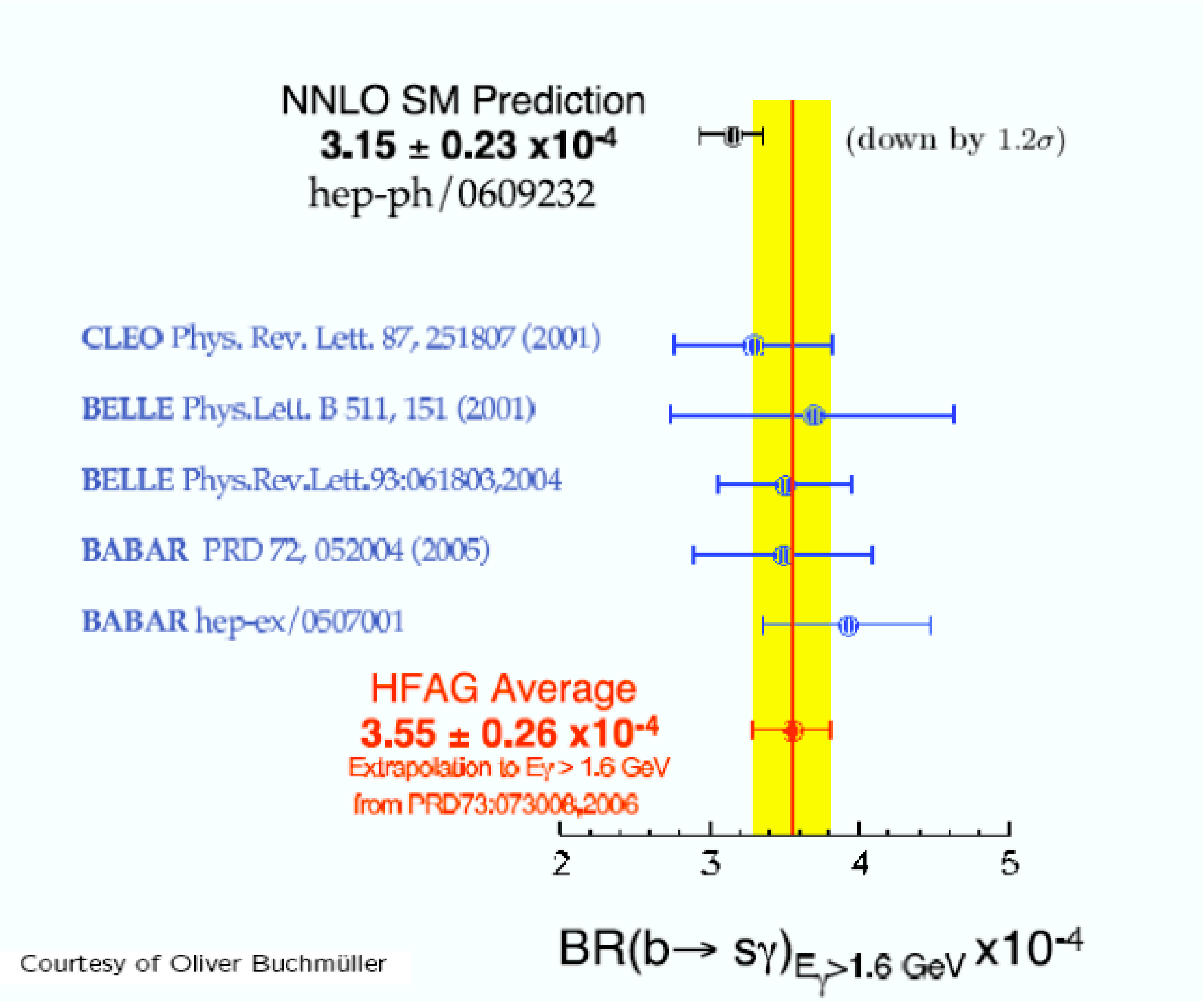
  First NNLL prediction of $\bar{B} \to X_s\gamma$ Misiak (spokesperson) et al.,hep-ph/0609232

$$\mathcal{B}(\bar{B} \to X_s\gamma) \times 10^4|_{E_\gamma > 1.6 GeV} = (3.17 \pm 0.23)$$

  Experimental world average HFAG

$$\mathcal{B}(\bar{B} \to X_s\gamma) \times 10^4|_{E_\gamma > 1.6 GeV} = (3.55 \ {}^{+0.09}_{-0.10}\Big|_{syst} \pm 0.24_{\rm stat} \pm 0.03_{\rm shape,dgamma})$$

- Also in beyond-the-SM scenarios NLL calculations exist: $C_i^{SM}(M_W) + C_i^{New}(M_W)$
  NLL analysis in MFV-supersymmetry Degrassi,Gambino,Slavich, hep-ph/0601135
  NLL in general supersymmetry (uMSSM) Greub,Hurth,Steinhauser, work in progress


NNLO SM Prediction
3.15 ± 0.23 x10-4
hep-ph/0609232
(down by 1.2σ)
CLEO Phys. Rev. Lett. 87, 251807 (2001)
BELLE Phys.Lett. B 511, 151 (2001)
BELLE Phys.Rev.Lett.93:061803,2004
BABAR PRD 72, 052004 (2005)
BABAR hep-ex/0507001
HFAG Average
3.55 ± 0.26 x10-4
Extrapolation to Eγ > 1.6 GeV
from PRD73:073008,2006
2
3
4
5
BR(b→ sγ)Eγ>1.6 GeV x10-4
Courtesy of Oliver Buchmüller

- Nonperturbative corrections $\Lambda^2/m_{b,c}^2$ to $\Gamma(\bar{B} \to X_s\gamma)$ are well under control
- However: Estimation of power corrections of $O(\alpha_s \Lambda/mb)$ should be improved:
  Largest uncertainty (5%) in our new NNLL prediction (see Lee et al)
- Further uncertainties: parametric (3%), higher-order (3%), mc-interpolation (3%)

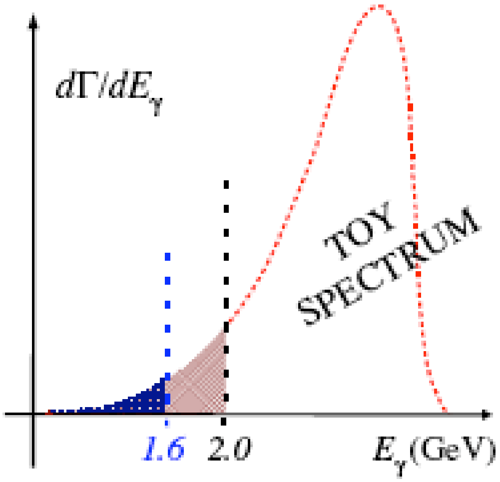
$$BR(\bar{B} \to X_s\gamma)_{E_\gamma > 1.6\,\mathrm{GeV}} = BR(\bar{B} \to X_c e\bar{\nu})^{\mathrm{exp}} \left[\frac{\Gamma(b \to s\gamma)}{\Gamma(b \to ce\bar{\nu})}\right]_{\mathrm{LO\,EW}} f\left(\frac{\alpha_s(M_W)}{\alpha_s(m_b)}\right) \times$$

$$\times \left\{1 + \underbrace{\mathcal{O}(\alpha_s)}_{\mathrm{NLO}} + \underbrace{\mathcal{O}(\alpha_s^2)}_{\mathrm{NNLO}} + \mathcal{O}(\alpha_{\mathrm{em}}) + \mathcal{O}\left(\frac{\Lambda^2}{m_b^2}\right) + \mathcal{O}\left(\frac{\Lambda^2}{m_c^2}\right) + \mathcal{O}\left(\frac{\alpha_s\Lambda}{m_b}\right)\right\}$$

~25% ~7% ~4% ~1% ~3% ~5%

- Additional sensitivities to nonperturbative physics
  due to necessary cuts in the photon energy spectrum
  to suppress the $B\bar{B}$ background:

  Shape function methods and multi-scale SCET analysis
  $\Rightarrow$ Additional theoretical uncertainties



More details: Additional sensitivities to nonperturbative physics

- s-quark propagator in the correlator of OPE:

$$S_s(k) = \frac{\not{k} + i\not{D}}{k^2 + 2ik\cdot D - \not{D}\not{D} + i\varepsilon} \; .$$

  - far away from singular kinematical points:
  $k \sim m_b$, $k^2 \sim m_b^2 \;\Rightarrow\; k^2 \sim m_b^2 \gg k\cdot D \sim m_b\Lambda \gg \not{D}\not{D} \sim \Lambda^2$

  Expansion $S_s(k) = \not{k}/k^2 + \mathcal{O}(\Lambda/m_b)$ valid !

  - endpoint region of photon energy spectrum in $\bar{B} \to X_s\gamma$:
  $k \sim m_b$ but $k^2 \sim m_b\Lambda \;\Rightarrow\; k^2 \sim m_b\Lambda \approx k\cdot D \sim m_b\Lambda \gg \not{D}\not{D} \sim \Lambda^2$

  Expansion in Λ/m_b still possible, but $k\cdot D/k^2$ is $\mathcal{O}(1)$, partial resummation of these effects to all-orders in a nonperturbative shape-function necessary !
  Neubert,Mannel; Bigi et al.

- General folklore: With $E_\gamma^0 \leq 1.9 GeV$ local OPE of the rate is valid again.

- But: Becher,Neubert,hep-ph/06100067
A low cut around $1.8 GeV$ might not guarantee that a theoretical description in terms of a local OPE is sufficient because of the sensitivity to the scale $\Delta = m_b - 2E_\gamma^0$.

  - Multiscale OPE with three short-distance scales m_b, $\sqrt{m_b \Delta}$ and Δ needed to connect the shape function and the local OPE region.
  - Using SCET, effects at the 3%-level found not by power corrections Λ_{QCD}/Δ, but by perturbative ones
  - $BR(\bar{B} \to X_s\gamma)_{E_\gamma > 1.6\,\text{GeV}} = 2.98 \pm 0.26$

- Nevertheless: Misiak, 2.workshop on Flavour Dynamics, Albufeira, 3.-10.11.2007
For $E_\gamma^0 = 1.6 GeV$ or lower, the cutoff-enhanced perturbative corrections undergo a dramatic cancellation with the so-called power-suppressed terms. Consequently, both types of terms must be treated with the same precision. Until this is done, the fixed-order results should be considered more reliable.

$$\text{const.} + \log(\Delta/m_b) + \log^2(\Delta/m_b) + \ldots$$

versus

$$(\Delta/m_b) + (\Delta/mb)^2 + (\Delta/m_b)\log(\Delta/m_b) + \ldots$$

$\mathcal{O}(\alpha_s)\surd$; $\mathcal{O}(\alpha_s^2)\surd$; but not terms of $\mathcal{O}(\alpha_s^3)$

Currently known contributions $\mathcal{B}(\bar{B} \to X_s\gamma)$ that have not been included in the estimate $\underset{(\pm 7.3\%)}{(3.15 \pm 0.23)} \times 10^{-4}$ in hep-ph/0609232:

- New/old large-β_0 bremsstrahlung effects
  [Ligeti, Luke, Manohar, Wise, 1999] $\Rightarrow$ $+2.0\%$ in the BR
  [Ferroglia, Haish, 2007, to be published]
- Four-loop mixing into the $b \to sg$ operator Q_8
  [Czakon, Haisch, MM, hep-ph/0612329] $\Rightarrow$ -0.3% in the BR
- Charm mass effects in loops on gluon lines in K_{77}
  [Asatrian, Ewerth, Gabrielyan, Greub, hep-ph/0611123] $\Rightarrow$ $+0.3\%$ in the BR
  [Czarnecki, Pak, to be published]
- Charm and bottom mass effects in loops on gluon lines in the three-loop $b \to s\gamma$ matrix elements of Q_1 and Q_2
  [Boughezal, Czakon, Schutzmeier, arXiv:0707.3090] $\Rightarrow$ $+1.1\%$ in the BR
- Non-perturbative $\mathcal{O}\left(\alpha_s \frac{\Lambda}{m_b}\right)$ effects in the term $\sim C_7 C_8$
  [Lee, Neubert, Paz, hep-ph/0609224] $\Rightarrow$ -1.5% in the BR

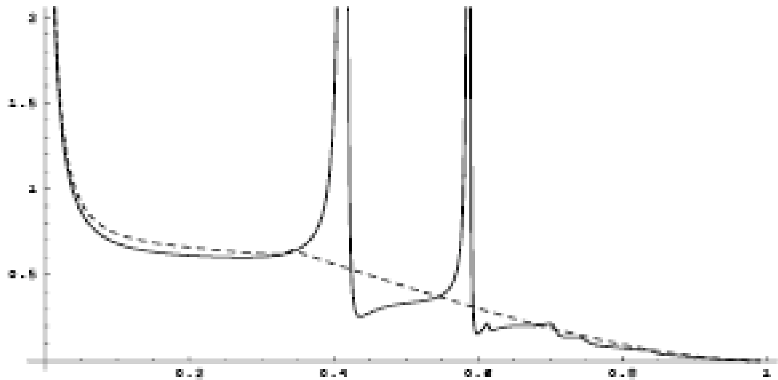
Total: $+1.6\%$ in the BR

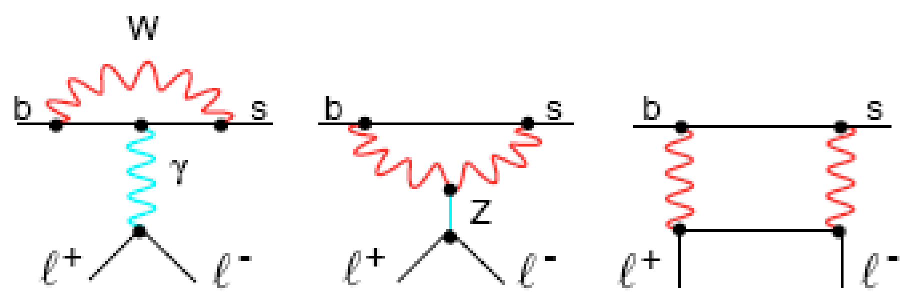
Courtesy of Mikolaj Misiak

Status of the inclusive mode $\bar{B} \to X_s \ell^+ \ell^-$

- On-shell-$c\bar{c}$-resonances $\Rightarrow$ cuts in dilepton mass spectrum necessary :
  $1\text{GeV}^2 < q^2 < 6\text{GeV}^2$ and $14.4\text{GeV}^2 < q^2$ $\Rightarrow$ perturbative contributions dominant

$\frac{d}{d\hat{s}} BR(\bar{B} \to X_s l^+ l^-) \times 10^{-5}$





$\hat{s} = q^2/m_b^2$

- NNLL prediction of $\bar{B} \to X_s \ell^+ \ell^-$: dilepton mass spectrum
  Asatryan,Asatrian,Greub,Walker, hep-ph/0204341;
  Ghinculov,Hurth,Isidori,Yao hep-ph/0312128:

$$BR(\bar{B} \to X_s \ell^+ \ell^-)_{Cut:\ q^2 \in [1GeV^2, 6GeV^2]} = (1.63 \pm 0.20) \times 10^{-6}$$

$$BR(\bar{B} \to X_s l^+ l^-)_{Cut:\ q^2 > 14.4 GeV^2} = (4.04 \pm 0.78) \times 10^{-7}$$

NNLL QCD corrections $q^2 \in [1GeV^2, 6GeV^2]$

central value: -14%, perturbative error: $13\% \to 6.5\%$

- Further refinements:
  - Completing NNLL QCD corrections:
    Mixing into $\mathcal{O}_9$ (+1%), NNLL matrixelement of $\mathcal{O}_9$ (−4%)
  - NLL QED two-loop corrections to Wilson coefficients
    −1.5% shift for $\alpha_{em}(\mu = m_b)$, −8.5% for $\alpha_{em}(\mu = m_W)$
    Bobeth,Gambino,Gorbahn,Haisch, hep-ph/0312090
  - QED two-loop corrections to matrix elements in the low-q^2 region
    +2% effect in the low-q^2 region for muons
    Huber,Lunghi,Misiak,Wyler, hep-ph/0512066

- NNLL prediction of $\bar{B} \to X_s \ell^+ \ell^-$: forward-backward-asymmetry (FBA)
  Asatrian, Bieri, Greub, Hovhannisyan, hep-ph/0209006;
  Ghinculov,Hurth,Isidori,Yao, hep-ph/0208088, hep-ph/0312128:

$$A_{\rm FB} \equiv \frac{1}{\Gamma_{semilep}} \left(\int_0^1 d(\cos\theta) \frac{d^2\Gamma}{dq^2 d\cos\theta} - \int_{-1}^0 d(\cos\theta) \frac{d^2\Gamma}{dq^2 d\cos\theta} \right)$$

(θ angle between ℓ^+ and B momenta in dilepton CMS)

$$A_{FB}(q_0^2) = 0 \quad \text{for} \quad q_0^2 \sim C_7/C_9 \quad q_0^2 = (3.90 \pm 0.25) GeV^2$$

$$A_{\rm FB} \approx \left\{ -6\,{\rm Re}\left(\tilde{C}^{eff}_{7,FB} \tilde{C}^{*\,eff}_{10,FB}\right) - 3\hat{s}\,{\rm Re}\left(\tilde{C}^{eff}_{9,FB} \tilde{C}^{*\,eff}_{10,FB}\right) + A^{brems}_{FB} \right\}$$

Update with electromagnetic corrections for dilepton mass spectrum and FBA including the high-q^2 region Huber,Hurth,Lunghi

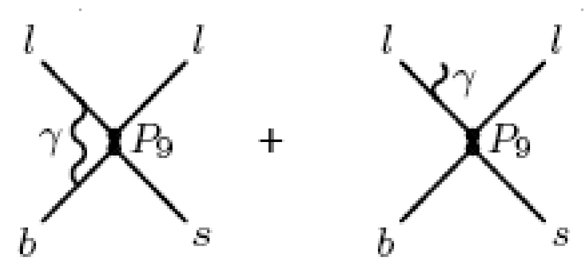
Electromagnetic corrections

- Focus on corrections to the Wilson coefficients which are enhanced by a large logarithm $\alpha_{em} Log(m_W/m_b)$

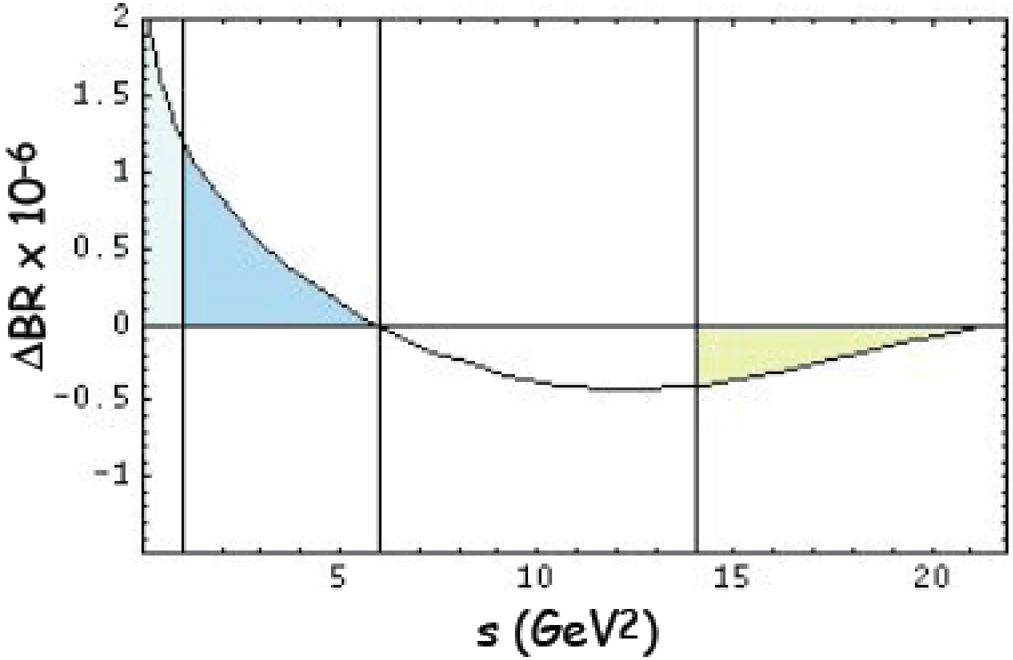
- Corrections to matrix elements lead to large collinear logarithm $Log(m_b/m_\ell)$ which survive intregration if a restricted part of the dilepton mass spectrum is considered
  - $+2\%$ effect in the low-q^2 region for muons, for the electrons the effect depends on the experimental cut parameters:

    Presence of this logarithm depends on the experimental set-up due to finite detector resolution for collinear photons. This is not a problem for muons, but for electrons in the present Babar and Belle set-up a cone of opening angle θ_c is used inside which collinear γ's are included in the reconstructed four-momentum:

    $$q^2 = (p_+ + p_- + p_\gamma)^2 \qquad m_\ell^2 \le (p_\ell + p_\gamma)^2 \le \Lambda^2 \simeq 2E_\ell^2(1-\cos\theta_c) \qquad \Lambda \sim \mathcal{O}(m_\mu)$$



– Note that the coefficient of this logarithm vanishes when integrated over the whole spectrum



⇒ Relative effect of this logarithm in the high-q^2 region much larger

Forward-backward-asymmetry

- Each of the brackets gets fully expanded in all couplings, but no overall expansion

$$[\frac{A_{FB}^{bs\ell\ell}(q^2)}{\Gamma_u}] \,/\, [\frac{\Gamma^{bs\ell\ell}(q^2)}{\Gamma_u}]\,; \quad m_{b,\mathrm{pole}} \leftrightarrow m_{b,\overline{\mathrm{MS}}} \leftrightarrow m_{b,\mathrm{1S}}$$

  Large m_b scheme ambiguity of 10% of the Zero of FBA diminished.

- Residual μ-dependence also for the Zero of the AFB a good estimate of the perturbative error

Our perturbative expansion almost reach the formal N^3LO QCD accuracy

$$\begin{aligned}\mathcal{A} \;=\; & \kappa\left[\mathcal{A}_{LO} + \alpha_s\,\mathcal{A}_{NLO} + \alpha_s^2\,\mathcal{A}_{NNLO} + \mathcal{O}(\alpha_s^3)\right] \\ & +\kappa^2\left[\mathcal{A}_{LO}^{em} + \alpha_s\,\mathcal{A}_{NLO}^{em} + \alpha_s^2\,\mathcal{A}_{NNLO}^{em} + \mathcal{O}(\alpha_s^3)\right] + \mathcal{O}(\kappa^3)\end{aligned}$$

with $\mathcal{A}_{LO} \sim \alpha_s\;\mathcal{A}_{NLO}$ and $\mathcal{A}_{LO}^{em} \sim \alpha_s\;\mathcal{A}_{NLO}^{em}$ $\qquad \kappa = \alpha_{\rm em}/\alpha_s$

$$\begin{aligned}\mathcal{A}^2 \;=\; & \kappa^2\Big[\mathcal{A}_{LO}^2 + \alpha_s\,2\mathcal{A}_{LO}\mathcal{A}_{NLO} + \alpha_s^2\,(\mathcal{A}_{NLO}^2 + 2\mathcal{A}_{LO}\mathcal{A}_{NNLO}) \\ & \quad +\alpha_s^3\,2(\mathcal{A}_{NLO}\mathcal{A}_{NNLO} + \ldots) + \mathcal{O}(\alpha_s^4))\Big] \\ + \; & \kappa^3\Big[2\mathcal{A}_{LO}\mathcal{A}_{LO}^{em} + \alpha_s\,2(\mathcal{A}_{NLO}\mathcal{A}_{LO}^{em} + \mathcal{A}_{LO}\mathcal{A}_{NLO}^{em}) \\ & \quad +\alpha_s^2\,2(\mathcal{A}_{NLO}\mathcal{A}_{NLO}^{em} + \mathcal{A}_{NNLO}\mathcal{A}_{LO}^{em} + \mathcal{A}_{LO}\mathcal{A}_{NNLO}^{em}) \\ & \quad +\alpha_s^3\,2(\mathcal{A}_{NLO}\mathcal{A}_{NNLO}^{em} + \mathcal{A}_{NNLO}\mathcal{A}_{NLO}^{em} + \ldots) + \mathcal{O}(\alpha_s^4)\Big] \\ + \; & \mathcal{O}(\kappa^4)\,.\end{aligned}$$

$\mathcal{A}_{LO}\mathcal{A}_{NNNLO}$ and $\mathcal{A}_{LO}^{em}\mathcal{A}_{NNNLO}$ unknown, but can safely be neglected

due to $\mathcal{A}_{LO} \sim \alpha_s\mathcal{A}_{NLO}$, $\mathcal{A}_{LO}^{em} \sim \alpha_s\mathcal{A}_{NLO}^{em}$ $\qquad \alpha_s\mathcal{A}_{NNNLO} \ll \mathcal{A}_{NNLO}$

- Again additional subtleties $\Rightarrow$ additional uncertainties
  - Locally: breakdown of OPE in Λ_{QCD}/m_b in the high-s (q^2) endpoint
    Partonic contribution vanishes in the limit $s \to 1$, while the $1/m_b^2$ corrections in $R(s)$ tend towards a nonzero value.

    Theoretically: s-quark propagator in the correlator of OPE:

$$S_s(k) = \frac{\not k + i \not D}{k^2 + 2ik \cdot D - \not D \not D + i\varepsilon} \; .$$

    Endpoint region of the q^2 spectrum in $\bar{B} \to X_s l^+ l^-$ different from endpoint region of the photon spectrum of $\bar{B} \to X_s \gamma$:
    $q^2 \approx m_b^2 \approx M_B^2 \;\Rightarrow k \sim \Lambda, \quad k^2 \sim \Lambda^2$ $\Rightarrow$ complete breakdown of OPE
    no partial all-orders resummation possible, shape-function irrelevant
    Buchalla,Isidori

    Practically: for integrated high-s (q^2) spectrum one finds an effective expansion ($s_{\text{min}} \approx 0.6$): Ghinculov,Hurth,Isidori,Yao hep-ph/0312128

$$\int_{s_{\text{min}}}^{1} ds \; R(s) = \left[1 - \frac{1.6\lambda_2}{m_b^2(1-\sqrt{s_{\text{min}}})^2} + \frac{1.8\rho_1 + 1.7 f_1}{m_b^3(1-\sqrt{s_{\text{min}}})^3} \right] \times \int_{s_{\text{min}}}^{1} ds \;\; R(s)|_{m_b \to \infty}$$

Recent proposal: normalization to semileptonic $B \to X_u \ell\nu$ decay rate with the same cut reduces the impact of $1/m_b$ corrections in the high-q^2 region significantly. Ligeti,Tackmann,hep-ph/0707.1694

– Hadronic invariant-mass cut is imposed in order to eliminate the background like $b \to c\,(\to s e^+ \nu) e^- \bar{\nu} = b \to s e^+ e^- +$ missing energy

* Babar,Belle: $m_X < 1.8\,\text{or}\,2.0 GeV$
* high-q^2 region not affected by this cut
* kinematics: X_s is jetlike and $m_X^2 \leq m_b \Lambda_{QCD}$ $\Rightarrow$ shape function region
* SCET analysis: universality of jet and shape functions found:

  the 10-30% reduction of the dilepton mass spectrum can be accurately computed using the $\bar{B} \to X_s \gamma$ shape function
  (5% additional uncertainty due to subleading shape functions)
  Lee,Stewart, hep-ph/0511334;
  Lee,Ligeti,Stewart,Tackmann, hep-ph/0512191

Numerical results Huber, Hurth, Lunghi preliminary

- Zero of the forward-backward asymmetry q_0^2:

$$q^2_{0,\mu\mu} = \left[3.543 \pm 0.075_{\text{scale}} \pm 0.003_{m_t} \pm 0.03_{m_c,C} \pm 0.05_{m_b} \pm 0.074_{\alpha_s(M_Z)}\right] \text{GeV}^2 \,,$$

$$q^2_{0,ee} = \left[3.421 \pm 0.07_{\text{scale}} \pm 0.003_{m_t} \pm 0.03_{m_c} \pm 0.046_{m_b} \pm 0.07_{\alpha_s(M_Z)}\right] \text{GeV}^2 \,.$$

- Integrated FBA for different bins:

$$\bar{A}_{ee[1,3.5]} = (-8.20 \pm 0.90)\,\% \,, \qquad \bar{A}_{\mu\mu[1,3.5]} = (-9.17 \pm 0.90)\,\%$$

$$\bar{A}_{ee[3.5,6]} = (7.61 \pm 0.61)\,\% \,, \qquad \bar{A}_{\mu\mu[3.5,6]} = (7.12 \pm 0.64)\,\%$$

$$\bar{A}_{ee[1,6]} = (-1.27 \pm 0.78)\,\% \,, \qquad \bar{A}_{\mu\mu[1,6]} = (-1.93 \pm 0.81)\,\%$$

- Branching ratio for $q^2 > 14.4 GeV$ (high-q^2 region):

$$BR(\bar{B} \to X_s ee) = (2.15 \pm 0.56) \cdot 10^{-7}$$

$$BR(\bar{B} \to X_s \mu\mu) = (2.47 \pm 0.58) \cdot 10^{-7}$$

Experiment:

$$BR(\bar{B} \to X_s ll) = (4.18 \pm 1.17_{stat.}\, {}^{+0.61}_{-0.68}{}_{sys.}) \cdot 10^{-7}$$ Belle

$$BR(\bar{B} \to X_s ll) = (5 \pm 2.5_{stat.}\, {}^{+0.8}_{-0.7}{}_{sys.}) \cdot 10^{-7}$$ Babar

- Branching ratio for $1GeV < q^2 < 6GeV$ (low-q^2 region):
  not updated, from hep-ph/0512066

$$BR(\bar{B} \to X_s ee) = (1.64 \pm 0.08_{scale} \pm 0.06_{m_t} \pm 0.015_{m_b} \pm 0.025_{C,m_c} \pm 0.02_{\alpha_s(M_Z)} \pm 0.015_{CKM} \pm 0.026_{\mathrm{BR}_{sl}}) \cdot 10^{-6}$$

$$BR(\bar{B} \to X_s \mu\mu) = (1.59 \pm 0.08_{scale} \pm 0.06_{m_t} \pm 0.015_{m_b} \pm 0.024_{C,m_c} \pm 0.02_{\alpha_s(M_Z)} \pm 0.015_{CKM} \pm 0.026_{\mathrm{BR}_{sl}}) \cdot 10^{-6}$$

Experiment:

$$BR(\bar{B} \to X_s ll) = (1.493 \pm 0.504_{stat.} {}^{+0.411}_{-0.321}{}_{sys.}) \cdot 10^{-6}$$ Belle

$$BR(\bar{B} \to X_s ll) = (1.8 \pm 0.7_{stat.} \pm 0.5_{sys.}) \cdot 10^{-6}$$ Babar

- Model-independent analysis of $b \to s\ell^+\ell^-$ and $b \to s\gamma$:

  * Global fit to the Wilson coefficients C_7, C_9, C_{10}
  $\Rightarrow$ Determines magnitude + sign of these coefficients

  * In MFV the sign of C_7 is already fixed by $b \to s\ell^+\ell^-$ data

- Experimental issues in $b \to s\ell^+\ell^-$:

  * End of Babar and Belle (1/ab) 15% accuracy possible
  * LHCb: only semi-inclusive analysis possible without the π_0 modes

- For new physics search measurements of kinematical distributions are needed (high statistics necessary !):

  SuperB factories versus SuperLHCb Achille's talk

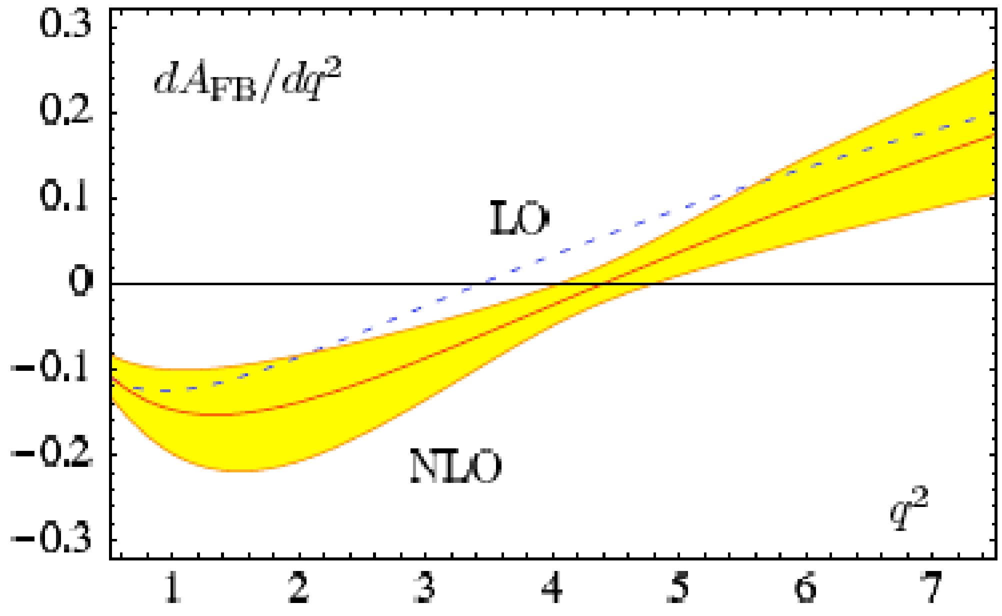
  Measurement of inclusive modes restricted to e^+e^- machines.
  (S)LHC experiments: Focus on theoretically clean exclusive modes necessary.

- Third independent combination of Wilson coefficents in $\bar{B} \to X_s\ell^+\ell^-$ $(z = cos\theta)$ Lee et al.

$$\frac{d^2\Gamma}{dq^2\,dz} = 3/8\,\left[(1+z^2)\,H_T(q^2)\,+\,2\,z\,H_A(q^2) + 2\,(1-z^2)\,H_L(q^2)\right]$$

$$\frac{d\Gamma}{dq^2} = H_T(q^2)\,+H_L(q^2)\,, \qquad \frac{dA_{\rm FB}}{dq^2} = 3/4\,H_A(q^2)$$

Focus on ratios of exclusive modes like FBA in $B \to K^* \ell^+ \ell^-$



- At LO the zero depends on the short-distance Wilson coefficients only because the formfactor dependence cancels out:

$$q_0^2 = q_0^2(C_7, C_9), \quad q_0^2 = (3.4 + 0.6 - 0.5) GeV^2 \quad \text{(LO)}$$

- NLO contribution calculated within QCD factorization approach leads to a large shift: Beneke,Feldmann,Seidel,hep-ph/0412400

$$q_0^2 = (4.39 + 0.38 - 0.35) GeV^2 \quad \text{(NLO)}$$

- Issue of power corrections $(1/m_b)$!

Other examples: $\leftrightarrow$ $B_d \to \rho \ell^+ \ell^-$ or $B_s \to \Phi \ell^+ \ell^-$ $\leftrightarrow$ $B_s \to K^* \ell^+ \ell^-$ $\quad [b \to s] \leftrightarrow [b \to d]$

Transversity amplitudes in $B \to K^* \ell^+ \ell^-$ very sensitive probe for right-handed current
$\to$ Quim's talk

Hadronic matrix elements known from experiment

Example: $K^+ \to \pi^+ \nu\bar{\nu}$

- BNL–E787/E949: three events 3/2004 !

$$BR(K^+ \to \pi^+ \nu\bar{\nu}) = \left(1.47 \, {}^{+\,1.3}_{-\,0.9}\right) \times 10^{-10}$$

- Present SM theory (in future error below 5% possible) Buras et al..

$$BR(K^+ \to \pi^+ \nu\bar{\nu})_{\mathrm{SM}} = (0.790 \pm 0.067) \times 10^{-10} \; .$$

What makes the neutrino modes $K \to \pi\nu\bar{\nu}$ so attractive?

- leading hadronic matrix element is known from K_{l3} decays: $< \pi \,|\, (\bar{s}d)_{V-A} \,|\, K >$
- amplitude dominated by short-distance due to quadratic GIM: $A^q \sim m_q^2 V_{qs} V_{qd}$

Neutrino modes as theoretically clean as inclusive B decays !

$\Rightarrow$ highly sensitive probe for degrees of freedom at higher scales

Main motivation: we need theoreticallly clean $s \to d$ transitions in order to test the main consequence of the MFV scenario:

usual CKM relations between $[b \to s] \leftrightarrow [b \to d] \leftrightarrow [s \to d]$ transitions

Crucial problem: Separation of new physics effects and hadronic uncertainties!

Focus on theoretically clean observables is mandatory

Three strategies:

- focus on inclusive modes: operator product expansion (OPE)

  $$\Gamma(\bar{B} \to X_s\gamma) \stackrel{m_b\to\infty}{\longrightarrow} \Gamma(b \to X_s^{parton}\gamma)\,, \quad \Delta^{nonpert.} \sim \Lambda_{QCD}^2/m_b^2$$

  No linear term Λ_{QCD}/m_b (perturbatively calculable contribution dominant)

  In general restricted to e^+e^- machines

- focus on ratios of exclusive modes like asymmetries
  (hadronic uncertainties partially cancel out)

  General strategy followed at LHCb

- focus on specific decays like $K \to \pi\nu\bar{\nu}$
  (hadronic matrix elements known from experiment)

Possible future scenarios:

A couple of years after the start of the LHC, may be

1. many new degrees of freedom discovered at ATLAS and CMS, and new FCNCs at flavour experiments

2. many new particles discovered at ATLAS and CMS, but no new FCNCs at flavour experiments
   $\Rightarrow$ important input to understand the New Physics

3. No new particles discovered at ATLAS and CMS (except one Higgs), but new FCNCs at flavour experiments
   $\Rightarrow$ tells us something about the mass scale to aim at (modulo flavour problem)

4. ....

5. ....

Note: With flavour observables we measure c_i^{New}/Λ_{NP} :

c_i^{New} may be constrained by symmetry, may depend on different interactions

5 meetings between 11/2005 and 3/2007, Yellow Report to appear

see http://mlm.home.cern.ch/mlm/FlavLHC.html

Goals of the workshop

- to outline and document a programme for flavour physics for the next decade,
- to discuss new experimental proposals in flavour physics,
- to address the complementarity and synergy between the LHC and the flavour factories in our search for new physics.

Follow-up workshop:

Working Group on the Interplay Between Collider and Flavour Physics

The working group addresses the complementarity and synergy between the LHC and the flavour factories within the new physics search. New collaborations on this topic were triggered by the two recent CERN workshop series Flavour in the Era of the LHC and CP Studies and Non–Standard Higgs Physics at the border line of collider and flavour physics and experiment and theory. This follow–up working group wants to provide a continuous framework for such collaborations and trigger new research work in this direction. Regular meetings at CERN (well–connected by VRVS) are planned in the near future.

https://twiki.cern.ch/twiki/bin/view/Main/ColliderAndFlavour

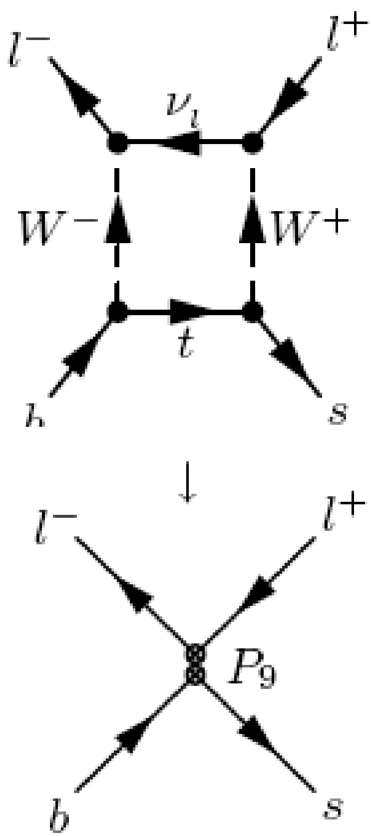
Kick-off meeting 3.-4.December 2007 at CERN

http://indico.cern.ch/conferenceDisplay.py?confId=22180

Extra

Effective Lagrangean

$$\mathscr{L}_{eff} = \mathscr{L}_{QCD\times QED}(u,..,b,e,\mu,\tau) + \frac{4G_F}{\sqrt{2}}\, V_{ts}^* V_{tb} \cdot \left[\sum_{i=1}^{10} C_i\, P_i + \underbrace{\sum_{i=3}^{6} C_{iQ}\, P_{iQ} + C_b\, P_b}_{for\ QED\ corrections} \right]$$



C_i: Wilson Coefficients

scale dependent effective couplings, process independent

$C_i(\mu_W)$ obtained by matching on full theory

$C_i(\mu_b)$ obtained by solving perturbatively

the RGE $\quad \mu \frac{d}{d\mu} \vec{C}(\mu) = \hat{\gamma}^T(\mu)\, \vec{C}(\mu)$

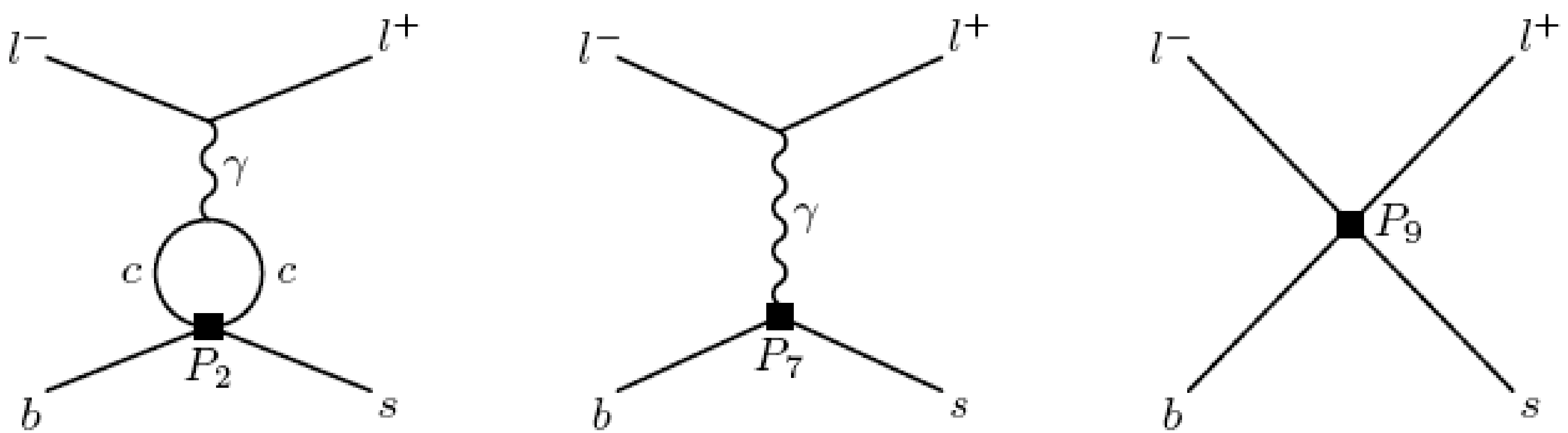
$\vec{C}(\mu_b) = \hat{R}\, \vec{C}(\mu_W)$

Effective Operators

$$P_1 = (\bar{s}_L \gamma_\mu T^a c_L)(\bar{c}_L \gamma^\mu T^a b_L), \quad P_4 = (\bar{s}_L \gamma_\mu T^a b_L) \sum_q (\bar{q}\gamma^\mu T^a q),$$
$$P_2 = (\bar{s}_L \gamma_\mu c_L)(\bar{c}_L \gamma^\mu b_L), \quad P_5 = (\bar{s}_L \gamma_\mu \gamma_\nu \gamma_\sigma b_L) \sum_q (\bar{q}\gamma^\mu \gamma^\nu \gamma^\sigma q),$$
$$P_3 = (\bar{s}_L \gamma_\mu b_L) \sum_q (\bar{q}\gamma^\mu q), \quad P_6 = (\bar{s}_L \gamma_\mu \gamma_\nu \gamma_\sigma T^a b_L) \sum_q (\bar{q}\gamma^\mu \gamma^\nu \gamma^\sigma T^a q),$$

$$P_7 = \frac{e}{16\pi^2} m_b (\bar{s}_L \sigma^{\mu\nu} b_R) F_{\mu\nu}, \quad P_9 = (\bar{s}_L \gamma_\mu b_L) \sum_l (\bar{l}\gamma^\mu l),$$
$$P_8 = \frac{g}{16\pi^2} m_b (\bar{s}_L \sigma^{\mu\nu} T^a b_R) G^a_{\mu\nu}, \quad P_{10} = (\bar{s}_L \gamma_\mu b_L) \sum_l (\bar{l}\gamma^\mu \gamma_5 l),$$

$$P_{3Q} = (\bar{s}_L \gamma_\mu b_L) \sum_q Q_q (\bar{q}\gamma^\mu q),$$
$$P_{4Q} = (\bar{s}_L \gamma_\mu T^a b_L) \sum_q Q_q (\bar{q}\gamma^\mu T^a q),$$
$$P_{5Q} = (\bar{s}_L \gamma_\mu \gamma_\nu \gamma_\sigma b_L) \sum_q Q_q (\bar{q}\gamma^\mu \gamma^\nu \gamma^\sigma q),$$
$$P_{6Q} = (\bar{s}_L \gamma_\mu \gamma_\nu \gamma_\sigma T^a b_L) \sum_q Q_q (\bar{q}\gamma^\mu \gamma^\nu \gamma^\sigma T^a q),$$
$$P_b = \frac{1}{12}\left[(\bar{s}_L \gamma_\mu \gamma_\nu \gamma_\sigma b_L)(\bar{b}\gamma^\mu \gamma^\nu \gamma^\sigma b) - 4(\bar{s}_L \gamma_\mu b_L)(\bar{b}\gamma^\mu b)\right]$$



Input parameters

$\alpha_s(M_z) = 0.1182 \pm 0.0027$	$m_e = 0.51099892$ MeV
$\alpha_e(M_z) = 1/127.918$	$m_\mu = 105.658369$ MeV
$s_W^2 \equiv \sin^2\theta_W = 0.2312$	$m_\tau = 1.77699$ GeV
$\|V_{ts}^* V_{tb}/V_{cb}\|^2 = 0.967 \pm 0.009$	$m_c(m_c) = (1.224 \pm 0.017 \pm 0.054)$ GeV
$BR(B \to X_c e \bar{\nu})_{\rm exp} = 0.1061 \pm 0.0017$	$m_b^{1S} = (4.68 \pm 0.03)$ GeV
$M_Z = 91.1876$ GeV	$m_{t,\rm pole} = (172.7 \pm 2.9)$ GeV
$M_W = 80.426$ GeV	$m_B = 5.2794$ GeV
$\lambda_2 \simeq \frac{1}{4}\left(m_{B^*}^2 - m_B^2\right) \simeq 0.12\ {\rm GeV}^2$	$C = 0.58 \pm 0.01$
$\lambda_1 = -0.27 \pm 0.04\ {\rm GeV}^2$	$\rho_1 = 0.06 \pm 0.06{\rm GeV}^3, \quad f_1 = 0$

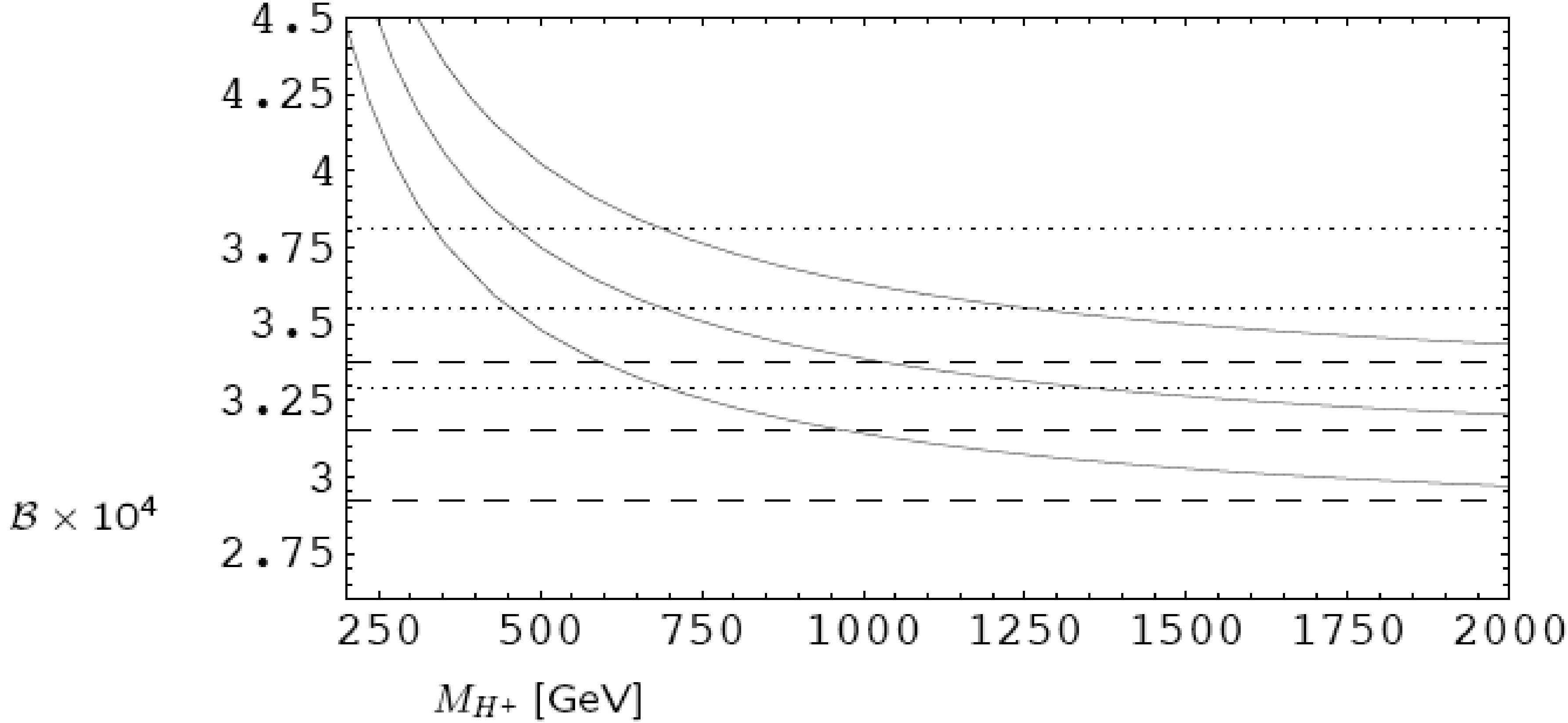
Numerical values for $\widetilde{\alpha}_s(\mu_b)$ and $\kappa(\mu_b)$ with $\mu_b = 5$ GeV

$$\widetilde{\alpha}_s(\mu_b) = 0.0170$$
$$\kappa(\mu_b) = 0.0354$$

Extra Extra

Stringent bounds on new-physics models

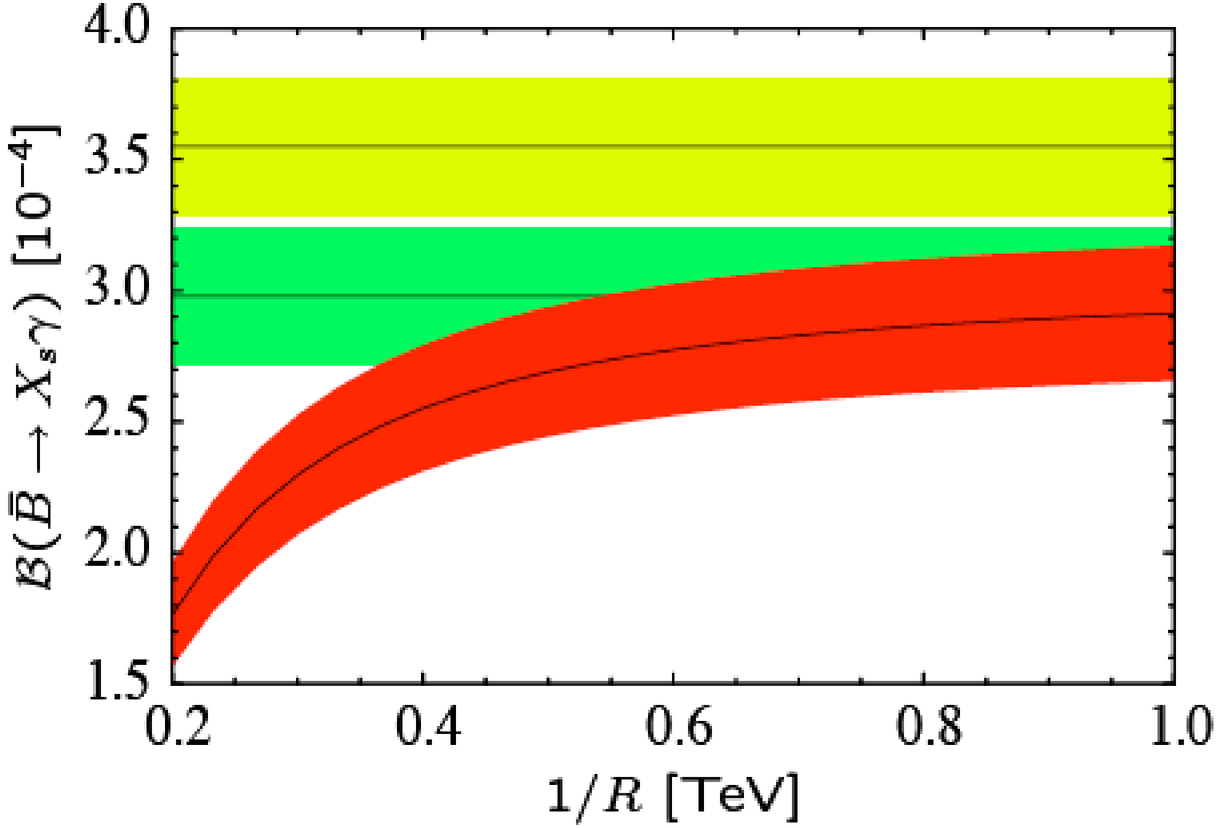
Example: Two-Higgs-Doublet Model-II at $\tan\beta = 2$: $\Rightarrow$ $M_{H^+} \succ 295$GeV at 95%CL



$\mathcal{B}(\bar{B} \to X_s\gamma)$ as a function of the charged Higgs boson mass (solid line)
Experiment/SM Theory, central values with 1σ bounds (dotted/dashed)

Misiak et al., hep-ph/0612231

Example: Bound on minimal universal extra dimensions $\Rightarrow 1/R \succ 600\text{GeV at } 95\%\text{CL}$



Red: LO-UED, Green: SM Theory, Yellow: Experiment By far best bound !

Haisch,Weiler,hep-ph/0703064

Note: Flavour non-universal boundary terms arise radiatively.

- Mixing-induced CP asymmetries in $b \to s\gamma$ transitions
  - General folklore: within the SM are small, $O(m_s/m_b)$

$$\mathcal{O}_{7L} \equiv \frac{e}{16\pi^2} m_b\, \bar{s}\sigma_{\mu\nu} P_R\, b F^{\mu\nu} \quad \mathcal{O}_{7R} \equiv \frac{e}{16\pi^2} m_{s/d}\, \bar{s}\sigma_{\mu\nu} P_L\, b F^{\mu\nu} \; .$$

Mainly: $\bar{B} \to X_s\gamma_L$ and $B \to X_s\gamma_R$ $\Rightarrow$ almost no interference in the SM

  - But: within the inclusive case the assumption of a two-body decay is made, the argument does not apply to $b \to s\gamma gluon$

    Corrections of order $O(\alpha_s)$, mainly due operator $\mathcal{O}_2$ $\Rightarrow \Gamma_{22}^{\text{brems}}/\Gamma_0 \sim 0.025$
    $\Rightarrow$ 11% right-handed contamination
    Grinstein,Grossman,Ligeti,Pirjol, hep-ph/0412019

  - QCD sum rule estimate of the time-dependent CP asymmetry in $B^0 \to K^{*0}\gamma$ including long-distance contributions due to soft-gluon emission from quark loops versus dimensional estimate of the nonlocal SCET operator series:
    Ball,Zwicky,hep-ph/0609037 $\leftrightarrow$ Grinstein,Pirjol,hep-ph/0510104

$$S = -0.022 \pm 0.015^{+0}_{-0.01}, \; S^{sgluon} = -0.005 \pm 0.01 \leftrightarrow |S^{sgluon}| \approx 0.06$$

Note: Expansion parameter is Λ_{QCD}/Q where Q is the kinetic energy of the hadronic part. There is no contribution at leading order. Therefore, the effect is expected to be larger for larger invariant hadronic mass, thus, the K^* mode has to have the smallest effect, below the 'average' 10%

Experiment: $S = -0.28 \pm 0.26$

- Untagged direct CP asymmetries in $b \to s/d$ transitions

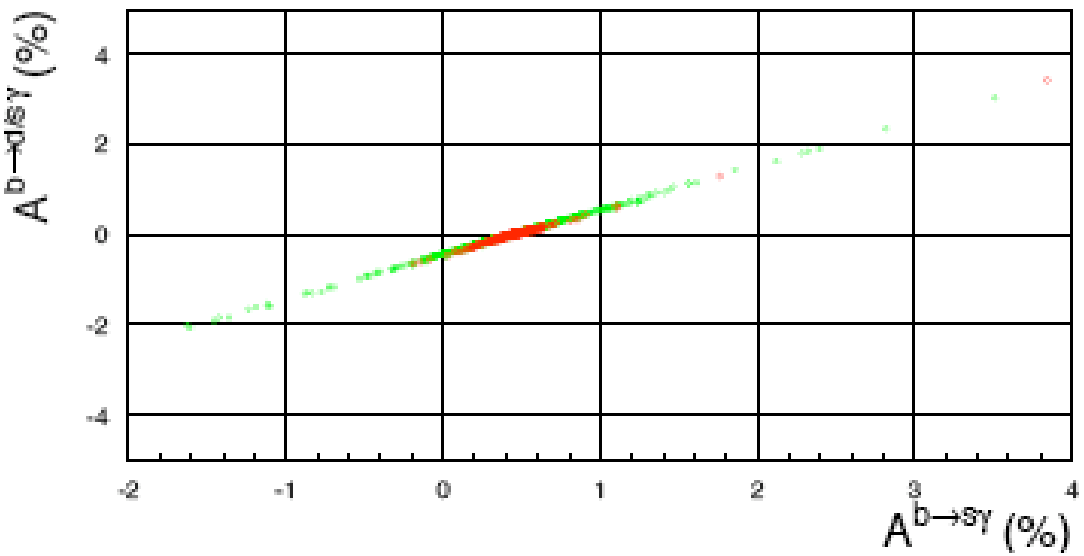
KM mechanism CKM unitarity + U spin symmetry of matrix elements $d \leftrightarrow s$:

$$|\Delta BR_{CP}(B \to X_s\gamma) + \Delta BR_{CP}(B \to X_d\gamma)| \sim 1 \cdot 10^{-9} \approx 0$$

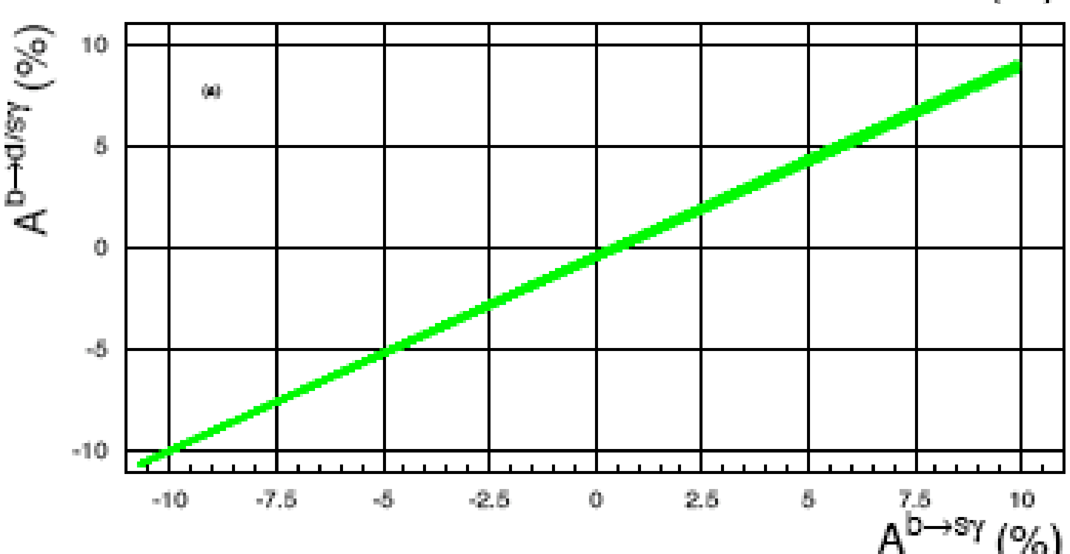
Clean test, whether new CP phases are active or not

Hurth,Mannel,hep-ph/0109041; Hurth,Lunghi,Porod,hep-ph/0312260

Experiment: (Super-) B-factories ±3% (±0.3%) precision possible



MFV with (flavourblind) phases



Model-independent analysis C_7^s;

Addendum: Many more opportunities

- opportunity at LHC: $B_{s/d} \to \mu\mu$ Babu,Kolda
  - helicity suppression in the SM: $A_{SM} \sim m_\mu / m_b$
  - hadronic matrix element simple (f_B lattice calculations)
  - order-of-magnitude enhancements possible in multi-Higgs models even without new flavour structures: $A_{H^0,A^0} \sim tan^3\beta$
- angular distribution and transversity amplitudes in $B \to K^*\mu\mu$ and $B_s \to \Phi\mu\mu$ Melikhov,Nikitin,Simula; Kim,Kim,Lü; Krüger et al.; Krüger,Matias
- CP averaged isospin asymmetry $B^0 \to K^{*0}\mu^+\mu^-$ versus $B^\pm \to K^{*\pm}\mu^+\mu^-$ Feldmann,Matias
- $b \to se^+e^-$ versus $b \to s\mu^+\mu^-$ inclusive/exclusive Hiller
- CP violation in $B_d \to K^*\gamma$ and in $B_s \to \Phi\gamma$
- $B \to \rho\gamma$ / $B \to K^*\gamma$
- $B \to (D, D^*, X_c)\tau\nu$
- $B \to \tau\nu$, $B \to \mu\nu$
- $b \to s\nu\bar{\nu}$, $B \to K\nu\bar{\nu}$
-