Radiative B Decays in the SM and the MSSM

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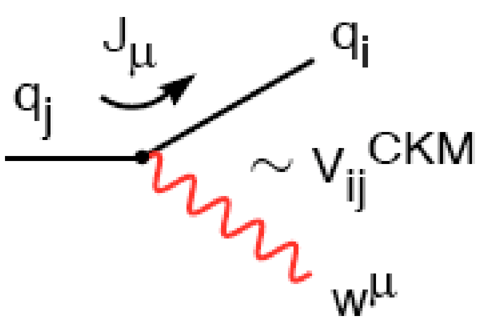
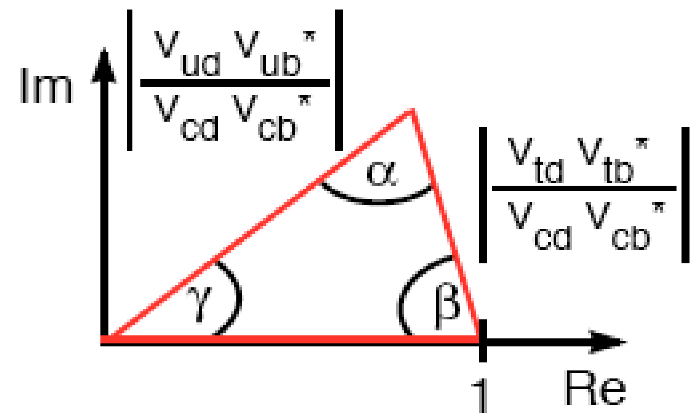
Prologue

Flavour in the SM

CKM mechanism of flavour mixing and CP violation: V_{CKM}, J_{CKM}





$$Im[V_{ij}\,V_{kl}\,V_{il}^*\,V_{kj}^*] = J_{\mathrm{CKM}} \sum_{m,n=1}^{3} \epsilon_{ikm}\,\epsilon_{jln}$$

$$J_{\mathrm{CKM}} \sim \mathcal{O}(10^{-5})$$

$$V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0$$

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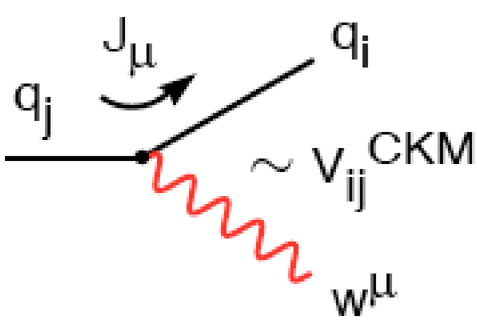

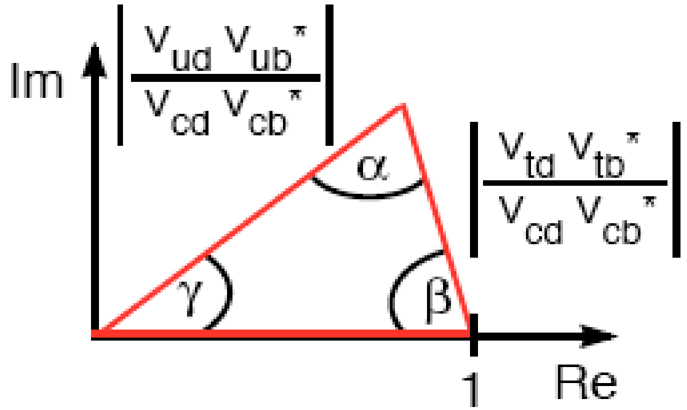

$$Im[V_{ij}V_{kl}V_{il}^*V_{kj}^*] = J_{\text{CKM}} \sum_{m,n=1}^{3} \epsilon_{ikm}\epsilon_{jln} \qquad J_{\text{CKM}} \sim \mathcal{O}(10^{-5})$$

All present measurements (BaBar, Belle, CLEO, CDF, D0,....)
of rare decays ($\Delta F = 1$),
of mixing phenomena ($\Delta F = 2$) and
of all CP violating observables at tree and loop level
are consistent with the CKM theory.

Impressing success of SM and CKM theory !!

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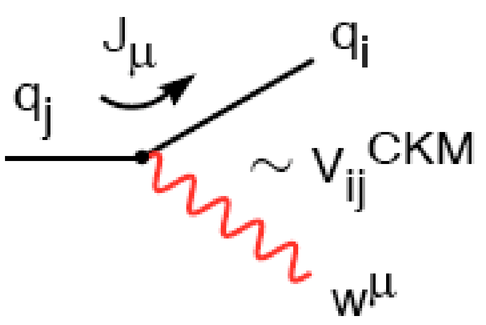
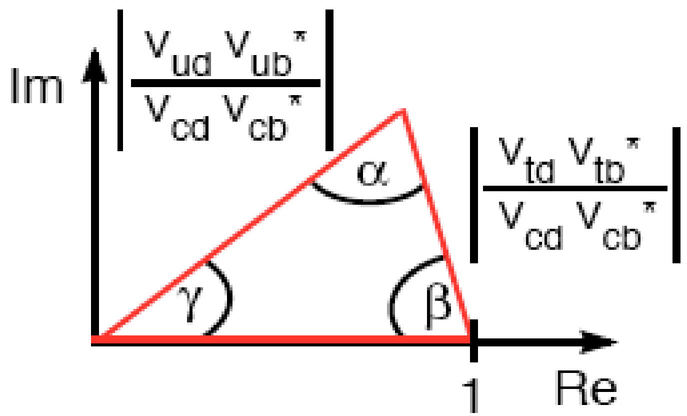
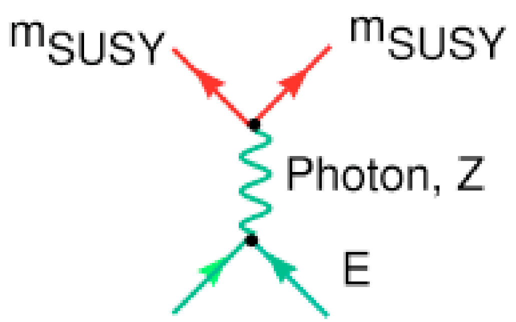
Flavour in the SM

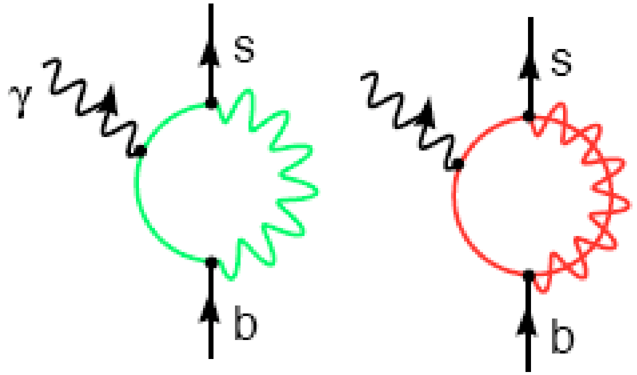
CKM mechanism of flavour mixing and CP violation: V_{CKM}, J_{CKM}





This success is somehow unexpected !!

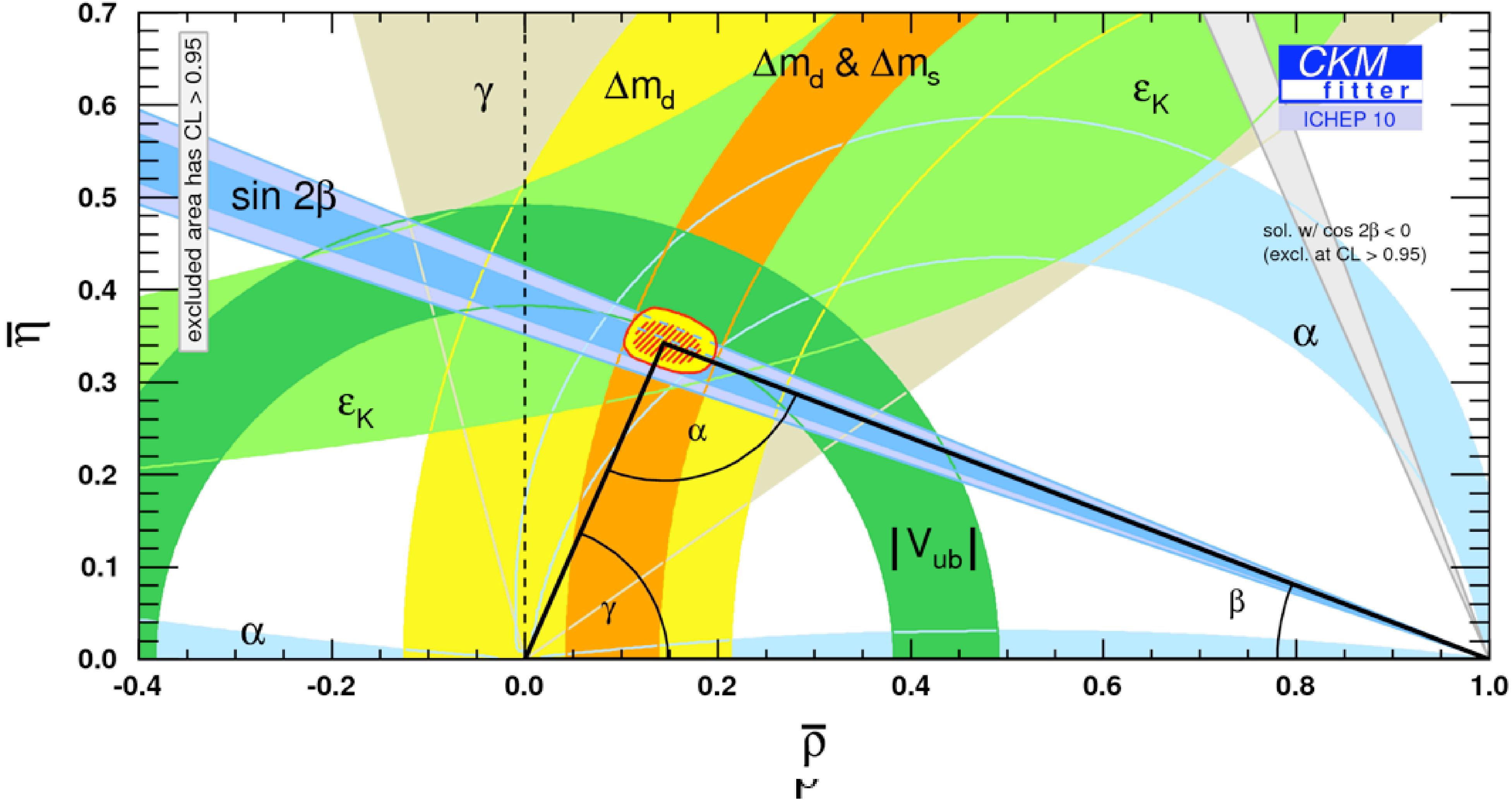




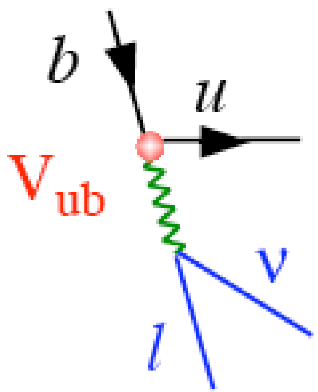
Flavour-changing-neutral-currents as loop-induced processes are highly-sensitive probes for possible new degrees of freedom

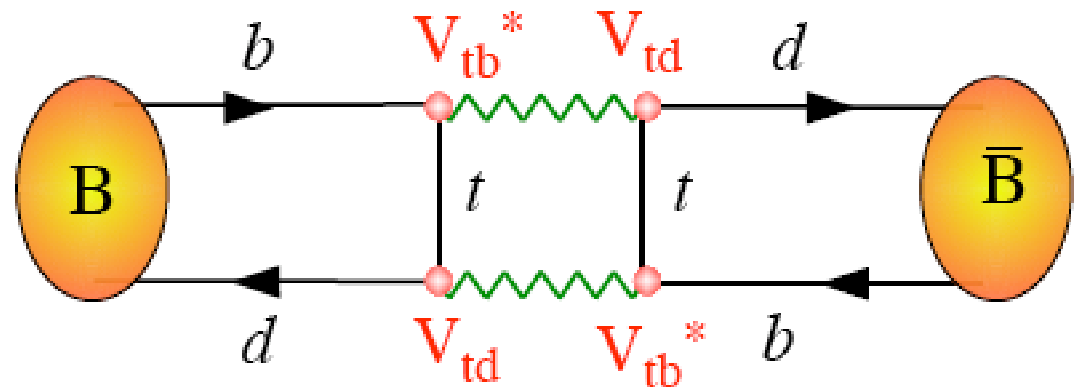
Impressing success of SM and CKM theory !!

Global fit, consistency check of the CKM theory.



Most surprising is the consistency between the tree-level and loop-induced observables



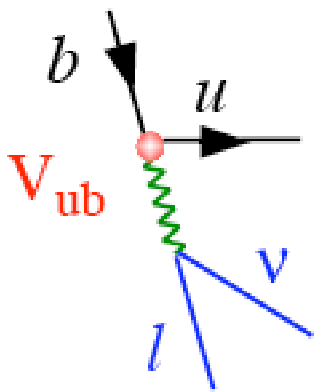


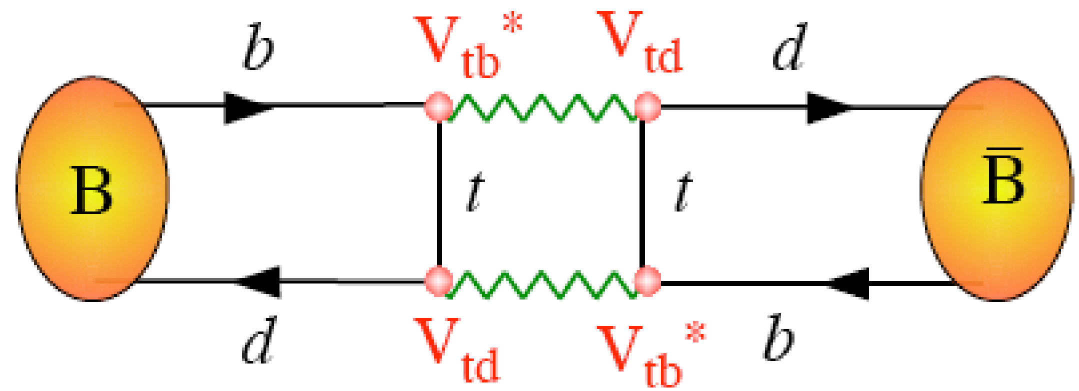
Semileptonic tree-decays versus Neutral-meson mixing $\Delta F = 2$

SM-dominated

Potentially more sensitive to New Physics

Most surprising is the consistency between the tree-level and loop-induced observables





Semileptonic tree-decays versus Neutral-meson mixing $\Delta F = 2$

SM-dominated

Potentially more sensitive to New Physics

There is much more data not shown in the unitarity fits which confirms the SM pedictions of flavour mixing like rare decays $(\Delta F = 1)$

However,...

- CKM mechanism is the dominating effect for CP violation and flavour mixing in the quark sector;

  but there is still room for sizable new effects and new flavour structures (the flavour sector has only be tested at the 10% level in many cases).

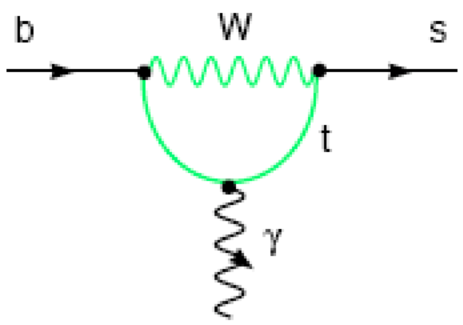
- The SM does not describe the flavour phenomena in the lepton sector.

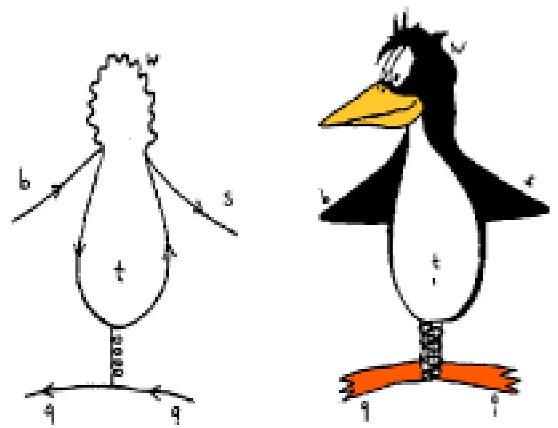
- No guiding principle in the flavour sector:

  CKM mechanism (3 Yukawa SM couplings) provides a phenomenological descripton of quark flavour processes, but leaves significant hierarchy of quark masses and mixing parameters unexplained.

Independent approach to new physics

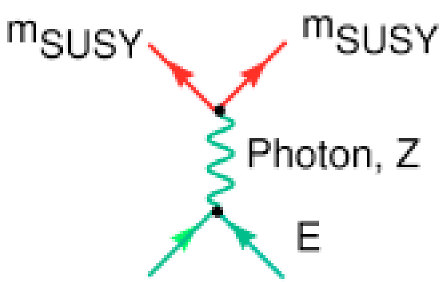
- Flavour changing neutral current processes like $b \to s\,\gamma$ or $b \to s\,\ell^+\ell^-$ directly probe the SM at the one-loop level.



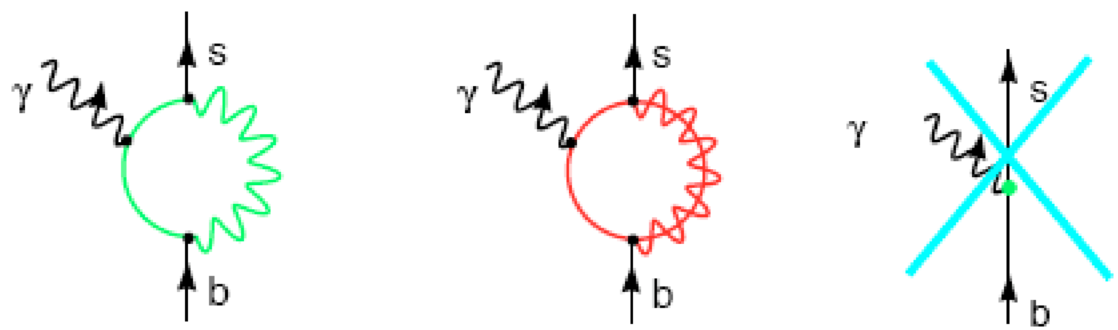


- Indirect search strategy for new degrees of freedom beyond the SM

Direct:



Indirect:



- High sensitivity for 'New Physics' ($\leftrightarrow$ electroweak precision data, 10% $\leftrightarrow$ 0.1%)

- Large potential for synergy and complementarity between collider (high-p_T) and flavour physics within the search for new physics

Flavour problem of New Physics 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}

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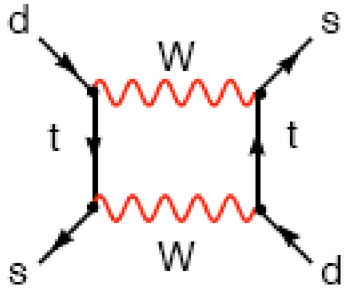
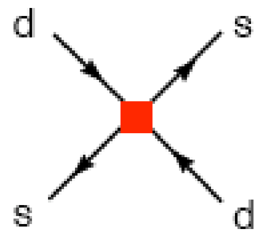
- SM as effective theory valid up to cut-off scale $\Lambda_{\rm NP}$
- Typical example: $K^0 - \bar{K}^0$-mixing $\mathcal{O}^6 = (\bar{s}\,d)^2$:





$$c^{SM}/M_W^2 \times (\bar{s}\,d)^2 + c^{New}/\Lambda_{\rm NP}^2 \times (\bar{s}\,d)^2 \qquad \Rightarrow \qquad \Lambda_{\rm NP} > 10^4\,\text{TeV}$$

(tree-level, generic new physics)

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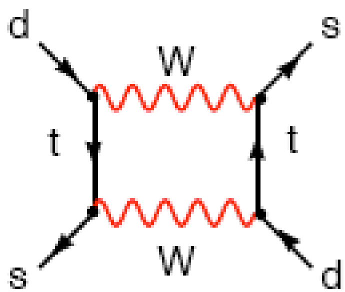

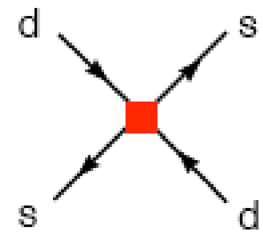

$c^{SM}/M_W^2 \times (\bar{s}\, d)^2 + c^{New}/\Lambda_{\mathrm{NP}}^2 \times (\bar{s}\, d)^2$ $\Rightarrow$ $\Lambda_{\mathrm{NP}} > 10^4\,\mathrm{TeV}$

(tree-level, generic new physics)

- Natural stabilisation of Higgs boson mass (hierarchy problem)

(i.e. supersymmetry, little Higgs, extra dimensions) $\Rightarrow$ $\Lambda_{\mathrm{NP}} \leq 1\mathrm{TeV}$

- 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

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

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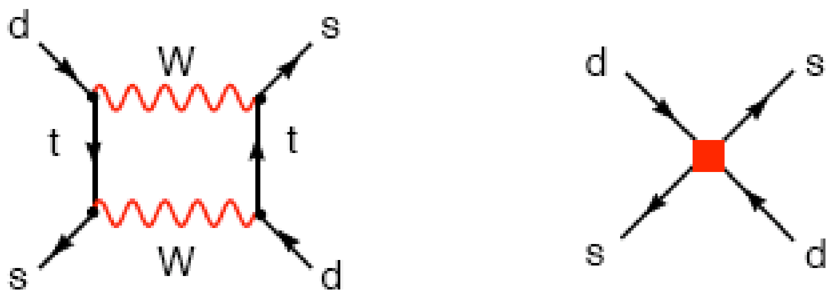

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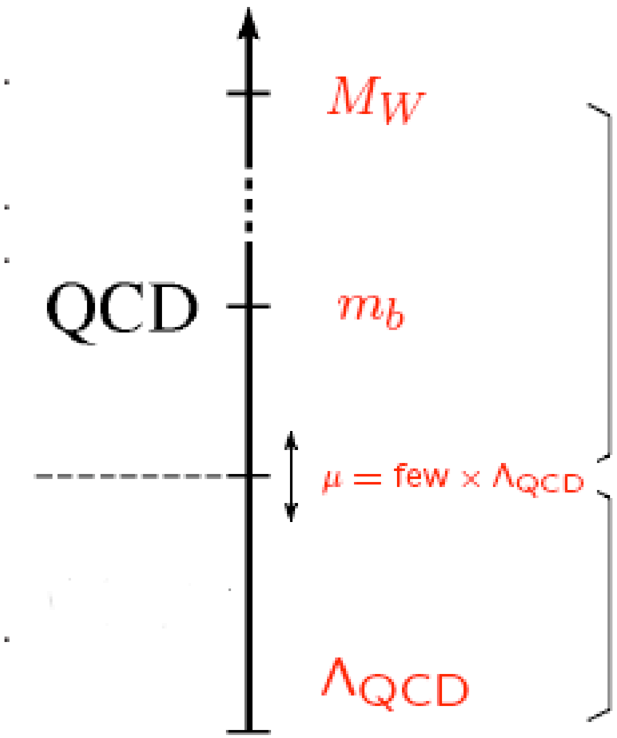
Ambiguity of new physics scale from flavour data

$$(\, C^i_{\mathrm{SM}}/M_W + C^i_{\mathrm{NP}}/\Lambda_{\mathrm{NP}}\,) \times \mathcal{O}_i$$



QCD effects in B decays

short-distance physics
perturbative

long-distance physics
nonperturbative

Factorization theorems: separating long- and short-distance physics

- Electroweak effective Hamiltonian: $H_{eff} = -\frac{4G_F}{\sqrt{2}} \sum C_i(\mu, M_{heavy})\ \mathcal{O}_i(\mu)$

- $\mu^2 \approx M_{New}^2 >> M_W^2$: 'new physics' effects: $C_i^{SM}(M_W) + C_i^{New}(M_W)$

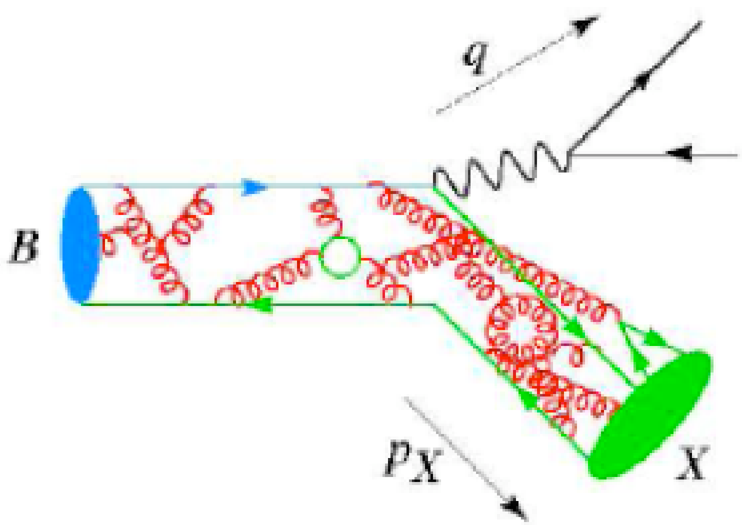
How to compute the hadronic matrix elements $\mathcal{O}_i(\mu = m_b)$?

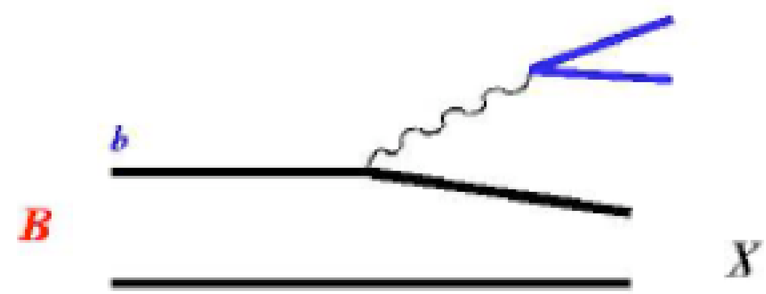
Inclusive modes $B \to X_s\gamma$ or $B \to X_s\ell^+\ell^-$

- Heavy mass expansion for inclusive modes:

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

No linear term Λ_{QCD}/m_b (perturbative contributions dominant)





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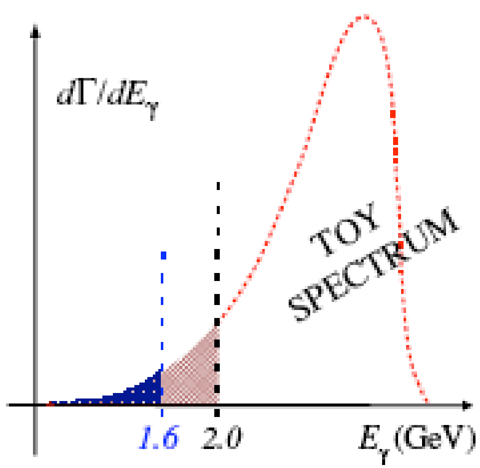
– More sensitivities to nonperturbative physics due to kinematical cuts: shape functions; multiscale OPE (SCET) with $\Delta = m_b - 2E_\gamma^0$

Becher,Neubert,hep-ph/0610067



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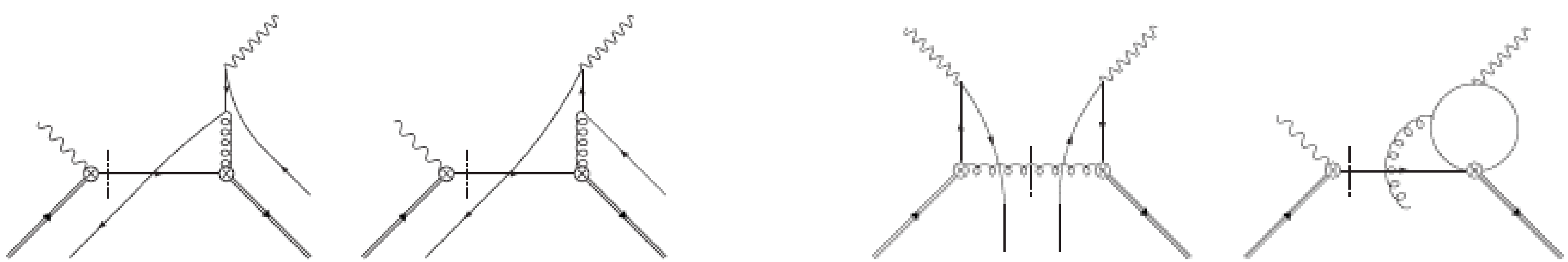
– If one goes beyond the leading operator ($\mathcal{O}_7$, $\mathcal{O}_9$):

  breakdown of local expansion

  naive estimate of non-local matrix elements leads to 5% uncertainty.

  Benzke,Lee,Neubert,Paz,arXiv:1003.5012



see talk of Michael Benzke

Exclusive modes $B \to K^*\gamma$ or $B \to K^*\ell^+\ell^-$

Naive approach:

Parametrize the hadronic matrix elements in terms of form factors

How to compute the hadronic matrix elements $\mathcal{O}(m_b)$?

Exclusive modes $B \to K^*\gamma$ or $B \to K^*\ell^+\ell^-$

QCD-improved factorization: BBNS 1999

$$\mathcal{T}_a^{(i)} = C_a^{(i)} \xi_a + \phi_B \otimes T_a^{(i)} \otimes \phi_{a,K^*} + O(\Lambda/m_b)$$

Existence of 'non-factorizable' strong interaction effects which do *not* correspond to form factors

Exclusive modes $B \to K^* \gamma$ or $B \to K^* \ell^+ \ell^-$

QCD-improved factorization: BBNS 1999

$$\mathcal{T}_a^{(i)} = C_a^{(i)} \xi_a + \phi_B \otimes T_a^{(i)} \otimes \phi_{a,K^*} + O(\Lambda/m_b)$$

– Separation of perturbative hard kernels from process-independent nonperturbative functions like form factors

– Relations between formfactors in large-energy limit

– Limitation: insufficient information on power-suppressed Λ/m_b terms (breakdown of factorization: 'endpoint divergences')

Phenomenologically highly relevant issue

general strategy of LHCb to look at ratios of exclusive modes

Egede,Hurth,Matias,Ramon,Reece
arXiv:0807.2589

There is much more data not shown in the unitarity fits which confirms the SM pedictions of flavour mixing like rare decays

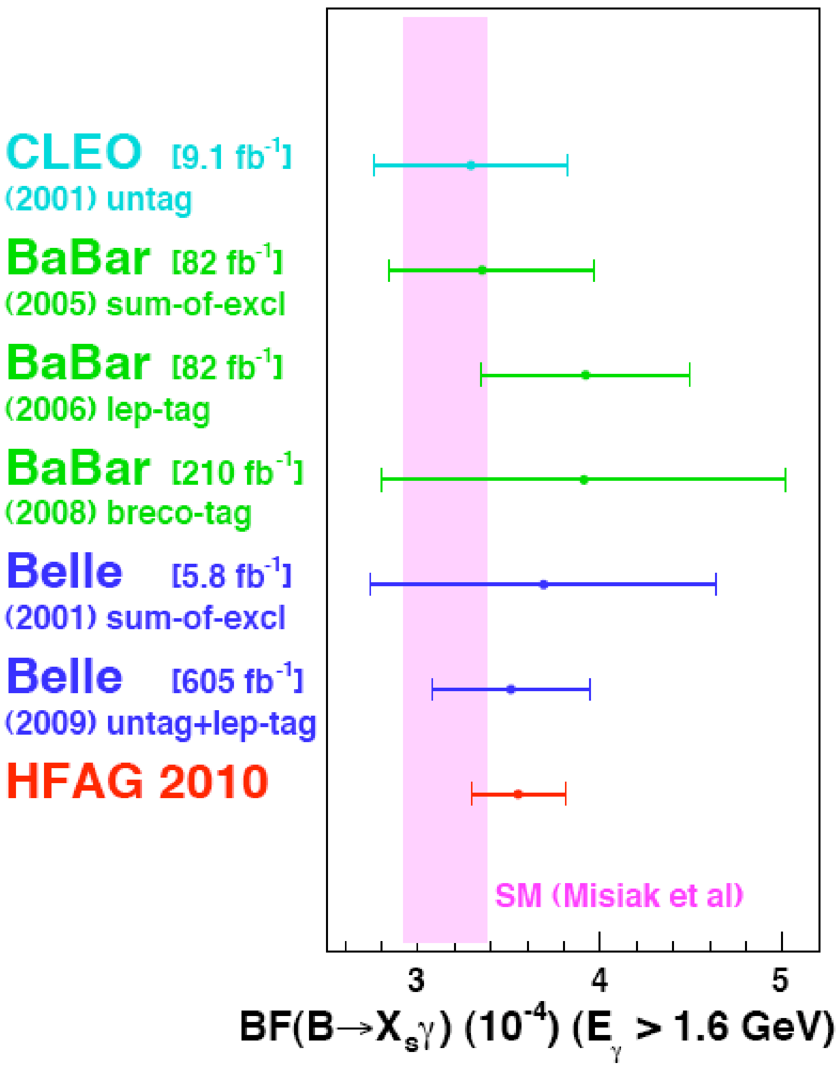
Status of the inclusive mode $\bar{B} \to X_s\gamma$

HFAG: $\mathcal{B}(B \to X_s\gamma) = (3.55 \pm 0.24) \times 10^{-4}$ (for $E_\gamma > 1.6$ GeV)

vs

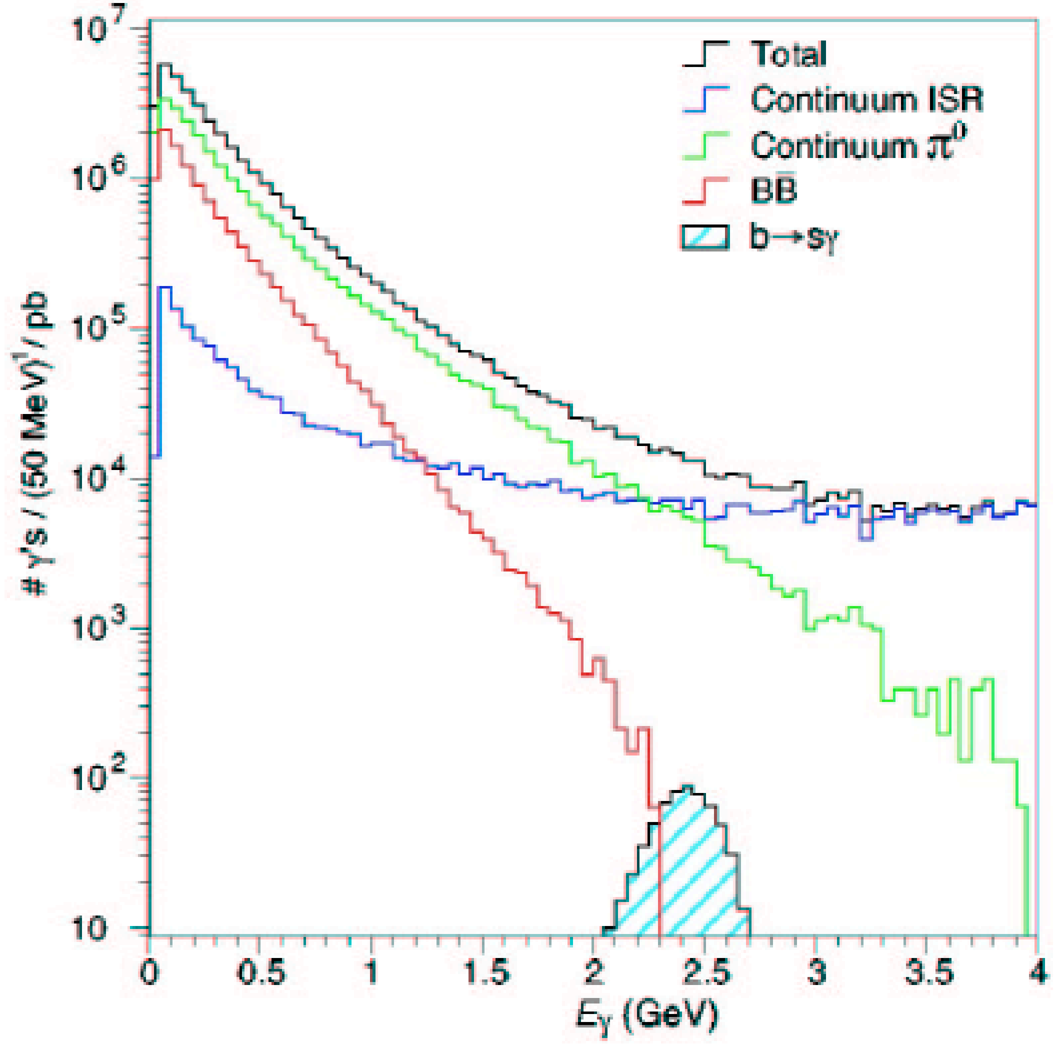
SM: $\mathcal{B}(B \to X_s\gamma) = (3.15 \pm 0.23) \times 10^{-4}$ (for $E_\gamma > 1.6$ GeV) PRL98,022003(2007)

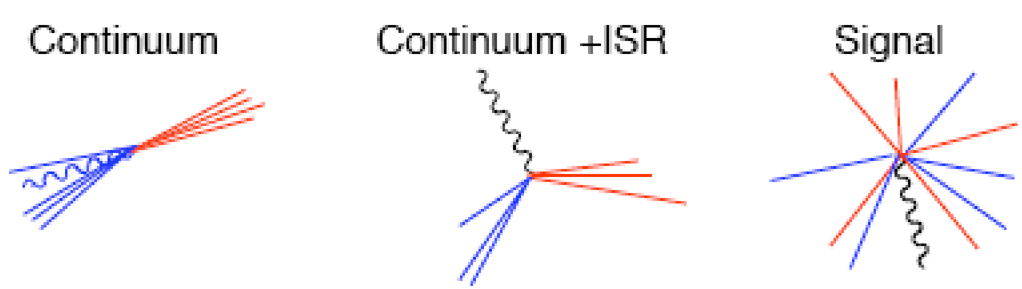
NNLO calculation by M.Misiak et al.



Courtesy of Mikihiko Nakao

CLEO (similiar for BABAR and BELLE)





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

- Perturbative QCD corrections are dominant and lead to large logarithms

$\alpha_s(M_W) Log(m_b^2 / M_W^2) \to$ resummation of Logs necessary:

LL	Leading logs	$G_F\,(\alpha_s\,Log\,)^N$	$N = 0, 1, 2, \ldots.$
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 $\bar{B} \to X_s\gamma$: Hurth,Lunghi,Porod, hep-ph/0312260

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

Largest uncertainty due to the charm mass scheme ambiguity !
$\Rightarrow$ NNLL QCD calculation needed for uncertainty $\ll 10\%$!

Estimate of the reduction of the scheme dependence at NNLL: $12.4\% \to 5.1\%$
Asatrian,Hovhannisyan,Poghosyan,Greub,Hurth, hep-ph/0505068

NNLL QCD calculation - 'global effort'

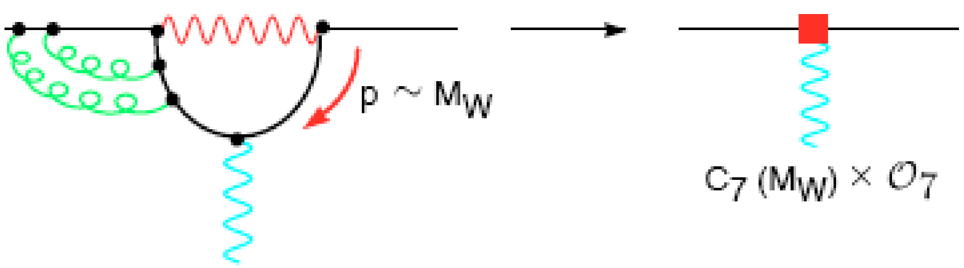
- Consistent calculation of perturbative QCD corrections:

  I) Initial conditions: $C_i(\mu \simeq M_W)$
  II) RGE: $\mu \frac{d}{d\mu} C_i(\mu) = \gamma_{ij} C_j(\mu) \Rightarrow \; C_i(\mu \simeq m_b)$
  III) matrix elements : $\prec \mathcal{O}_i(\mu \simeq m_b) \succ$

I) Initial conditions $C_i(\mu \simeq M_W)$
NLL calculation: (Adel, Yao, 1993) (Greub, Hurth, 1997)

* sensitivity for 'new physics'
* no large logs (fixed-point perturbation theory is sufficient)

Steinhauser, Misiak, hep-ph/0401041:
Three-loop matching conditions

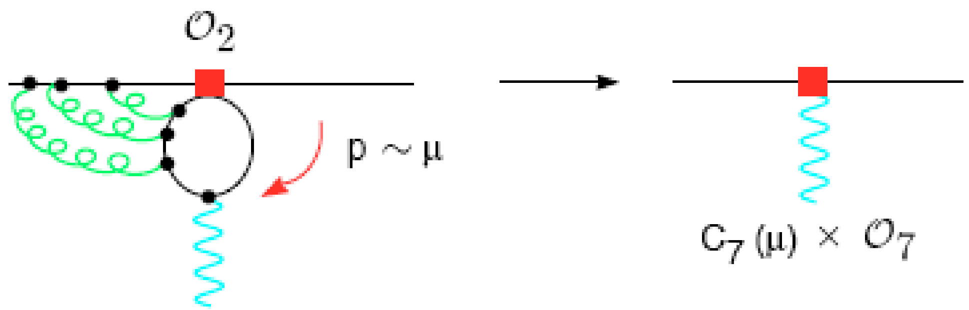


II) Coefficients γ_{ij} in $\mu\frac{d}{d\mu}C_i(\mu) = \gamma_{ij}C_j(\mu)$ $\Rightarrow$ $C_i(\mu \simeq m_b)$

NLL: (Chetyrkin, Misiak, Münz, 1996) (Gambino, Gorbahn, Haisch, 2003)

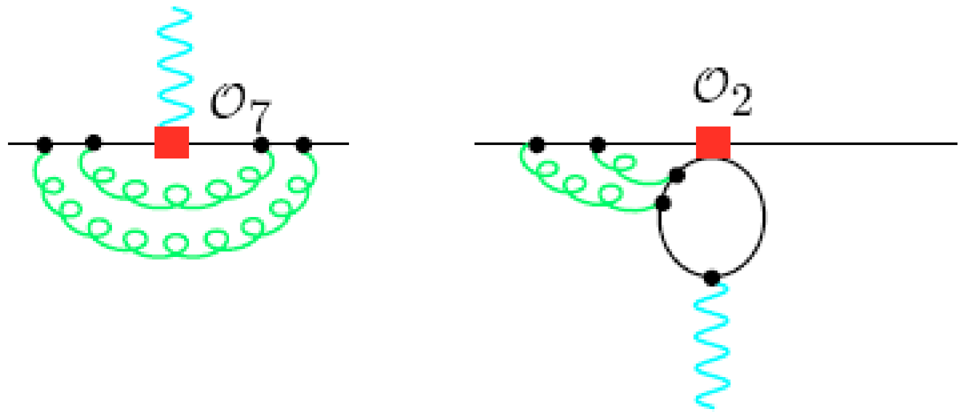
QCD-mixing of operators: 'new physics' information in $C_7(M_W)$ gets covered up

Gorbahn, Haisch, hep-ph/0411071:
Three-loop mixing among the four-quark operators $\mathcal{O}_i$, $i = 1..6$
Gorbahn, Haisch, Misiak, hep-ph/0504194:
Three-loop mixing among the dipole operators $\mathcal{O}_7$ and $\mathcal{O}_8$
Czakon, Haisch, Misiak, hep/ph0612329
Four-loop mixing of the four-quark into the dipole operators



III) Matrix elements: $\prec O_{7,8}(\mu \simeq m_b) \succ$ $\prec O_2(\mu \simeq m_b) \succ$
NLL: (Greub, Hurth, Wyler, 1996) (Buras et al., 2001)

* perturbative contributions are dominant
* $\Gamma(B \to X) \sim Im \prec B|H_{eff}H_{eff}|B \succ$



Blokland,Czarnecki,Misiak,Slusarczyk,Tkachov, hep-ph/0506055;
Asatrian,Ewerth,Greub,Hurth, hep-ph/0605009:
Two-loop matrix elements of the dipole operator
Melnikov, Mitov, hep-ph/0505097;
Asatrian,Ewerth,Ferroglia,Gambino,Greub, hep-ph/0607316:
Perturbative corrections to the photon spectrum due to $\mathcal{O}_7$
Bieri,Greub,Steinhauser, hep-ph/0302051:
Three-loop matrix elements of $\mathcal{O}_2$, fermionic contributions of order $\alpha_s^2 n_f$
Steinhauser,Misiak, hep-ph/0609241:
Three-loop matrix elements of $\mathcal{O}_2$
Interpolation between the formal $m_c >> m_b/2$ limit and the $\alpha_s^2 n_f$ approximation,
this part is the main origin of charm dependence $\Rightarrow$ space for improvements

First NNLL prediction of $\bar{B} \to X_s\gamma$ hep-ph/0609232

$$BR(\bar{B} \to X_s\gamma) \times 10^4|_{E_\gamma > 1.6 GeV} = (3.17 \pm 0.23) \quad \text{Misiak et al.}$$

- Nonperturbative corrections $\Lambda^2/m_{b,c}^2$ to $\Gamma(\bar{B} \to X_s\gamma)$ are well below 10%.
  Falk et al., Ali et al., Buchalla et al., ...
- However: Estimation of power corrections Benzke,Lee,Neubert,Paz,arXiv:1003.5012
  Largest uncertainty (5%) in new NNLL prediction
- Further uncertainties: parametric (3%), higher-order (3%), mc-interpolation (3%)

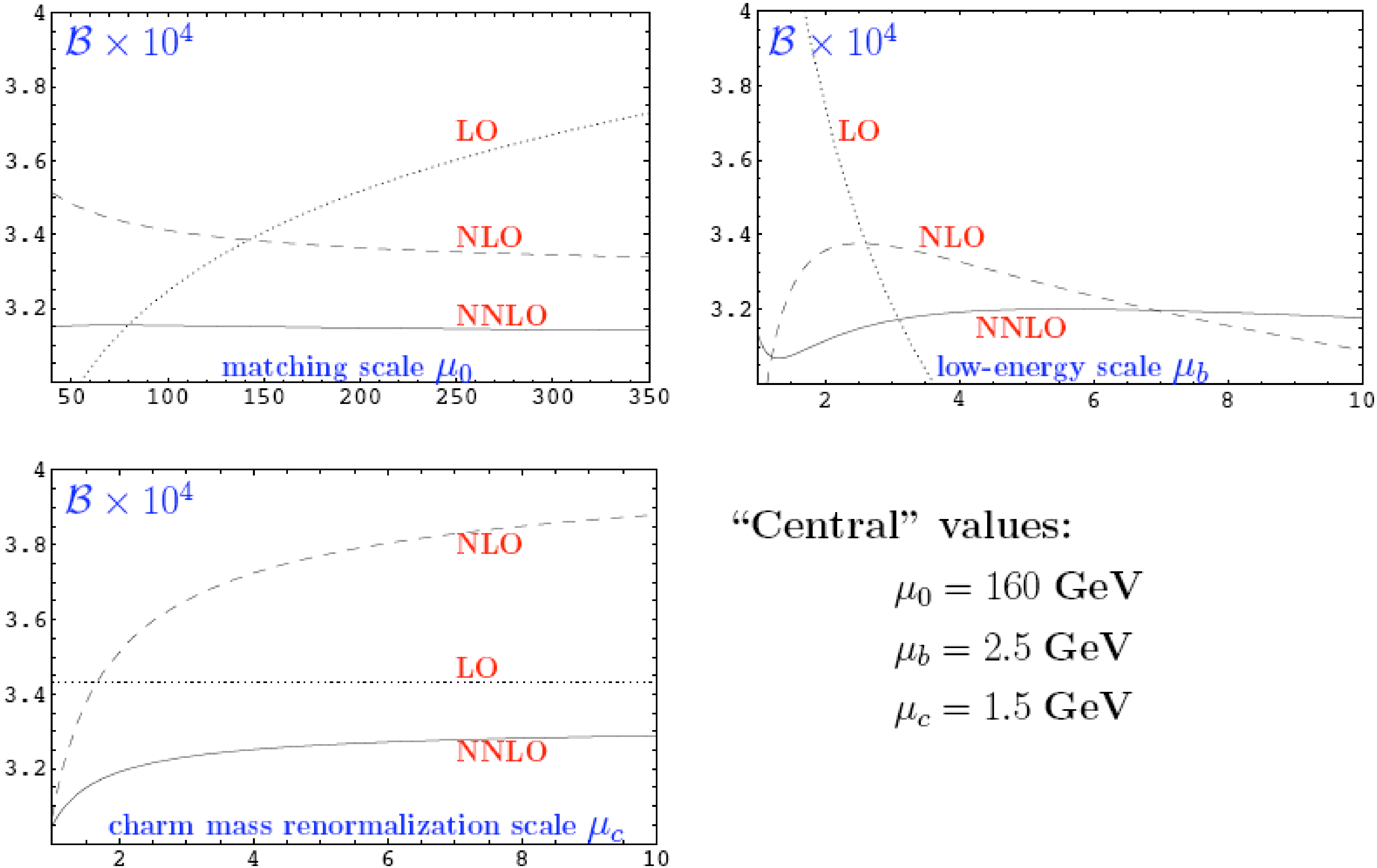
$$BR(\bar{B} \to X_s\gamma)_{E_\gamma > 1.6\,\text{GeV}} = BR(\bar{B} \to X_c e\bar{\nu})^{\text{exp}} \left[\frac{\Gamma(b \to s\gamma)}{\Gamma(b \to ce\bar{\nu})}\right]_{\text{LO EW}} f\left(\frac{\alpha_s(M_W)}{\alpha_s(m_b)}\right) \times$$

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

$\sim$25% $\sim$7% $\sim$4% $\sim$1% $\sim$3% $\sim$5%

- Experimental world average HFAG

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



"Central" values:

$$\mu_0 = 160 \text{ GeV}$$

$$\mu_b = 2.5 \text{ GeV}$$

$$\mu_c = 1.5 \text{ GeV}$$

Open issues

- The semileptonic phase factor:

$$\mathrm{BR}_\gamma(E_0) \equiv \mathrm{BR}[B \to X_s\gamma]_{E_\gamma > E_0} = \frac{\mathrm{BR}_{c\ell\nu}}{C}\left(\frac{\Gamma[B \to X_s\gamma]_{E_\gamma > E_0}}{|V_{cb}/V_{ub}|^2\,\Gamma[B \to X_u e\bar{\nu}]}\right)$$

$$C = \left|\frac{V_{ub}}{V_{cb}}\right|^2 \frac{\Gamma[\bar{B}\to X_c e\bar{\nu}]}{\Gamma[\bar{B}\to X_u e\bar{\nu}]} = \begin{cases} 0.582 \pm 0.016, \\ 0.546^{+0.023}_{-0.033}, \end{cases}$$

1S scheme has to be updated!
Trott et al.,hep-ph/0408002
kinetic scheme
Gambino,Giordano,arXiv:0805.0271

Enhancement of BR_γ in kinematic scheme

+4.8%!? $\frac{\delta}{\delta m_c} Pert(E_0) \prec 0,\ \bar{m}_c(\bar{m}_c)_{1S} \prec \bar{m}_c(\bar{m}_c)_{kinetic}$

- Multiscale OPE: Becher,Neubert,hep-ph/0610067

Misiak et al.	BR_γ(1GeV)	BR_γ(1.6GeV)
hep-ph/0609232 'fixed order'	3.27 10^{-4}	(3.15±0.23) 10^{-4}
hep-ph/0610067 multisc. OPE	3.27 10^{-4} (adapted from above)	(2.98±0.26) 10^{-4}

without
-1.5% of $\mathcal{O}(\alpha_s\Lambda/m_b)$
3.05 10^{-4}

Ongoing discussion on cut-effects   Misiak arXiv:0808.3134 [hep-ph]

- 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
  - $BR(\bar{B} \to X_s \gamma)_{E_\gamma > 1.6\,\mathrm{GeV}} = 2.98 \pm 0.26$

- 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 $\mathcal{O}(\alpha_s^3)$

CP asymmetries in $b \to s\gamma$

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

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

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

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

Should be resolved! $\Delta S = 0.02 - 0.03$ (Super B sensitivity)
see JHEP 0802 (2008) 110, arXiv:0710.3799

- **Direct CP asymmetries in $b \to s/d\gamma$**

$$\alpha_{CP}(b \to s/d\,\gamma) = \frac{\Gamma(\bar{B} \to X_{s/d}\gamma) - \Gamma(B \to X_{\bar{s}/\bar{d}}\gamma)}{\Gamma(\bar{B} \to X_{s/d}\gamma) + \Gamma(B \to X_{\bar{s}/\bar{d}}\gamma)} \simeq$$

$$\alpha_{CP}(b \to s\gamma) \approx 0.5\%, \qquad \alpha_{CP}(b \to d\gamma) \approx -12\%$$

Smallness of $\alpha_{CP}(b \to s\gamma)$ results from three factors:

α_s (strong phase), λ^2 (CKM), m_c^2/m_b^2 (GIM)

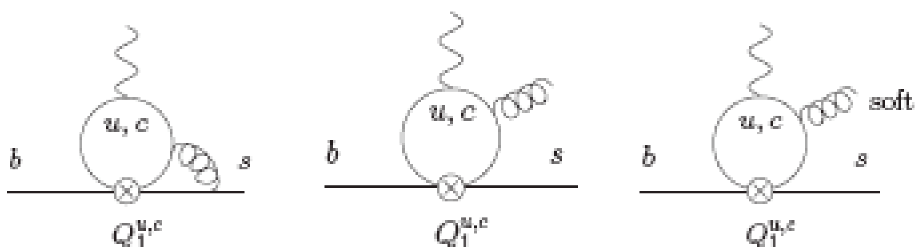
- NLL prediction Hurth,Lunghi,Porod, hep-ph/0312260

$$\alpha_{CP}(b \to s\gamma) = \left(0.44\ {}^{+0.15}_{-0.10}\Big|_{m_c/m_b} \pm 0.03_{\mathrm{CKM}}\ {}^{+0.19}_{-0.09}\Big|_{\mathrm{scale}}\right) \times 10^{-2}$$

- However: Long-distance dominance Benzke,Lee,Neubert,Paz arXiv:1012.31.67

$$-0.6 \times 10^{-2} < \alpha_{CP}(b \to s\gamma) < +2.8 \times 10^{-2}$$

Resolved photon contribution:



no α_s-suppression

see talk of Michael Benzke

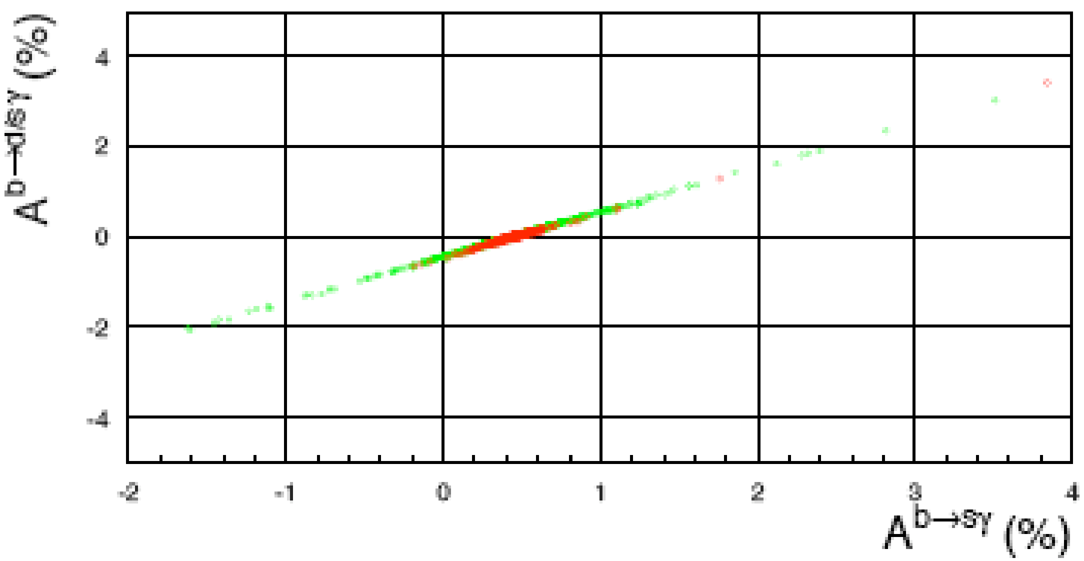
- Untagged direct CP asymmetries in $b \to s/d$ transitions

  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

Resolved contributions cancel at order Λ/m_b



MFV with (flavourblind) phases

More details

$$\Delta\Gamma_{CP}(B \to X_{s+d}\gamma) = \Gamma(\bar{B} \to X_{s+d}\gamma) - \Gamma(B \to X_{\bar{s}+\bar{d}}\gamma)$$

KM mechanism CKM unitarity

$$\Rightarrow \; J = \mathrm{Im}(\lambda_u^{(s)}\lambda_c^{(s)*}) = (-1)\; \mathrm{Im}(\lambda_u^{(d)}\lambda_c^{(d)*})$$

$+$ U spin symmetry of matrix elements $d \leftrightarrow s$:

$$\Delta\Gamma_{CP}(B \to X_{s+d}\gamma) = b_{inc}\Delta_{inc}$$

b_{exc}: 'relative U-spin-breaking'; Δ_{exc}: 'typical size' of CP violating rate difference

$|b_{inc}| \sim m_s^2/m_b^2 \sim 5 \cdot 10^{-4}$ (also in $1/m_b^2$ and in $1/m_c^2$ corrections)

(Resolved contributions cancel at order Λ/m_b)

$$|\Delta\mathcal{B}_{CP}(B \to X_{s+d}\gamma)| \sim 1 \cdot 10^{-9} \approx 0$$

Very clean test, whether new CP phases are active or not

Flavour problem in supersymmetric models

- In the general MSSM too many contributions to flavour violation
  - CKM-induced contributions from H^+, χ^+ exchanges (quark mixing)
  - flavour mixing in the sfermion mass matrix

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- Possible solutions:
  - Decoupling: Sfermion mass scale high
    (i.e. split supersymmetry)
  - Super-GIM: Sfermion masses almost degenerate
    (i.e. gauge-mediated supersymmetry breaking)
  - Alignment: Sfermion mixing suppressed

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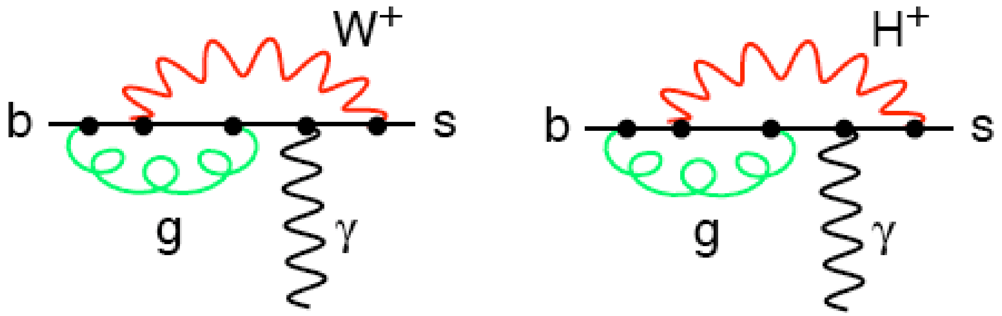
- Dynamics of flavour $\leftrightarrow$ mechanism of SUSY breaking
  ($BR(b \to s\gamma) = 0$ in exact supersymmetry)

Parameter bounds $\quad \bar{B} \to X_s \gamma$

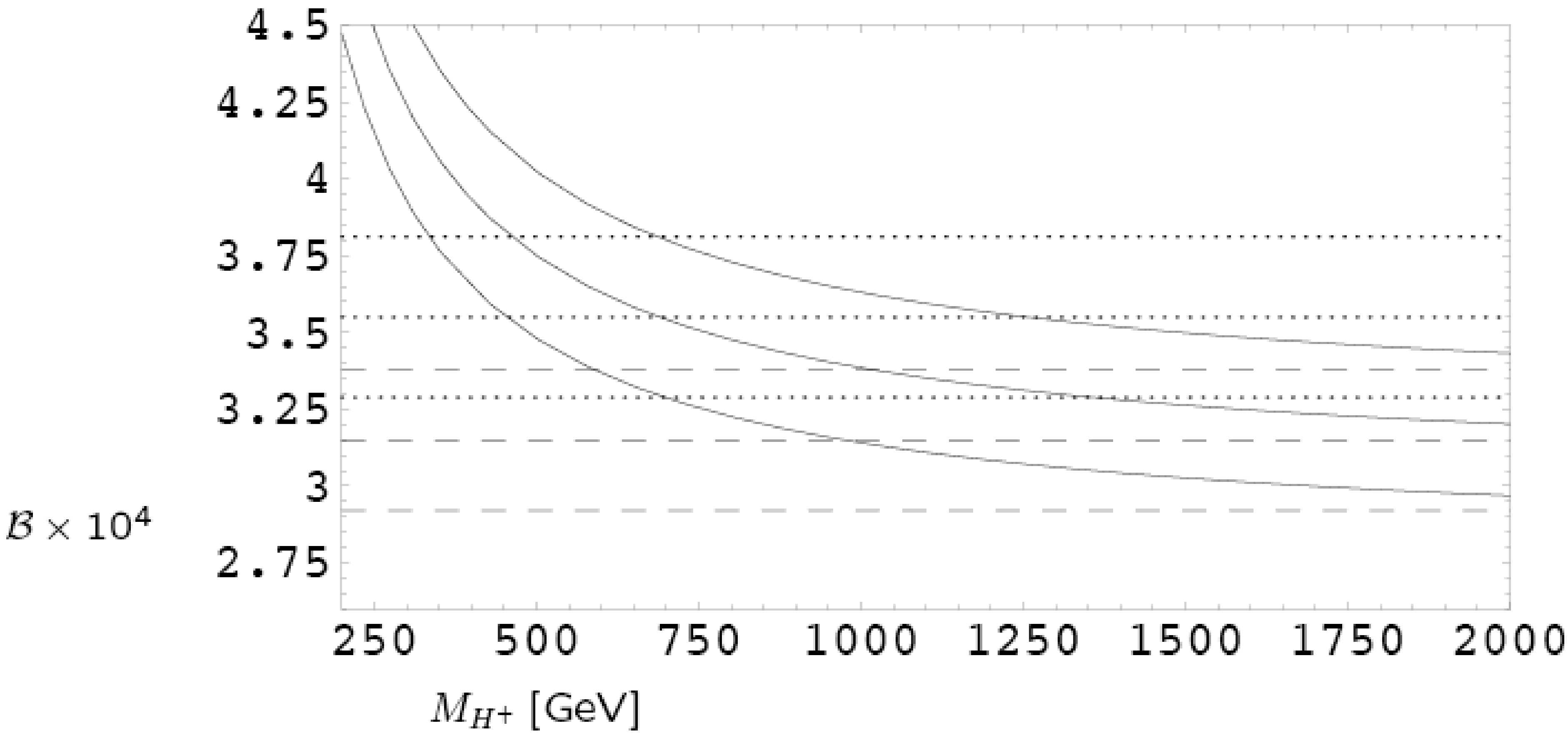


$$C_{NLL}(M_W) = C_{NLL}{}^{SM}(M_W) + C_{NLL}{}^{NEW}(M_W)$$

Charged Higgs contribution always adds to the SM one !

Stringent bounds on new-physics models

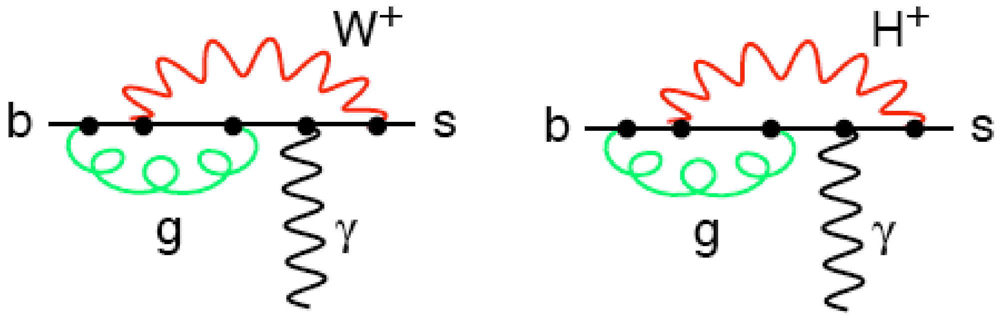
Example: Two-Higgs-Doublet Model-II at $\tan\beta = 2$: $\Rightarrow$ $M_{H+} \succ$ 295GeV at 95%CL

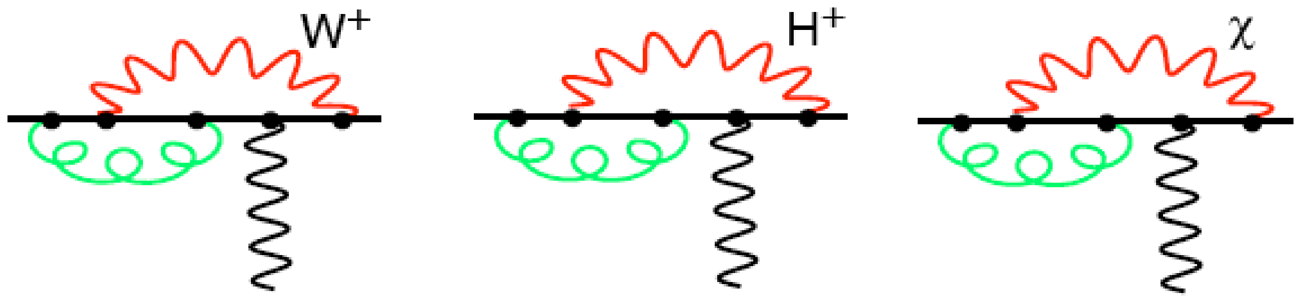


$\mathcal{B}(\bar{B} \to X_s\gamma)$ as a function of the charged Higgs boson mass (solid line)
Experiment/SM Theory, central values with 1σ bounds (dotted/dashed)

Misiak et al.

$\bar{B} \to X_s\gamma$





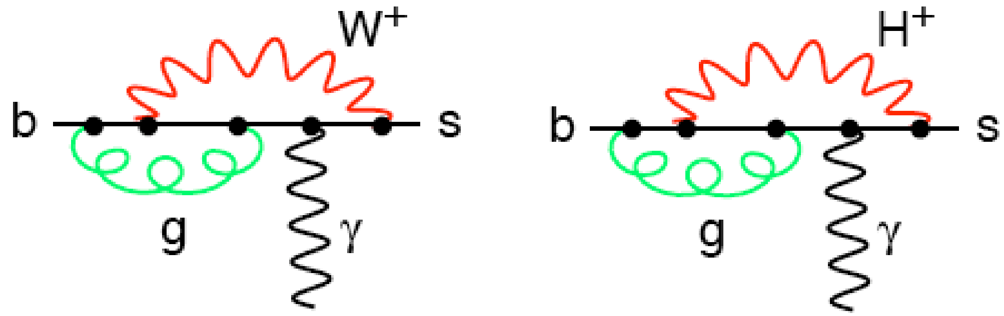
$$C_{NLL}(M_W) = C_{NLL}{}^{SM}(M_W) + C_{NLL}{}^{H^+}(M_W) + C_{NLL}{}^{\chi}(M_W)$$

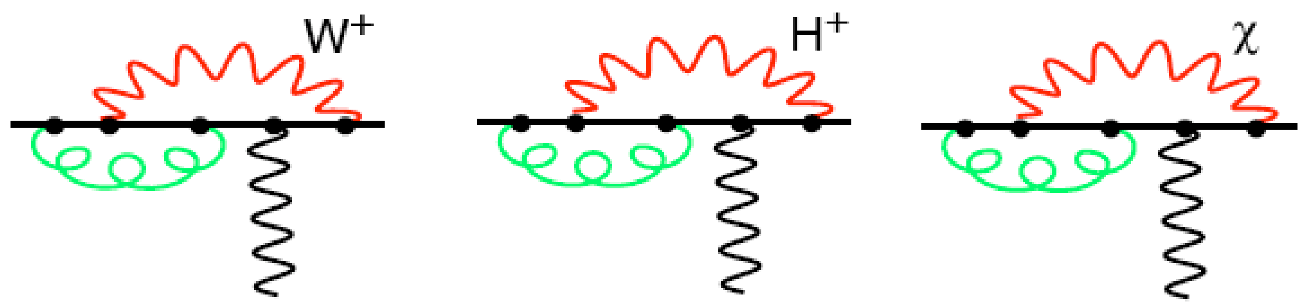
Within supersymmetry possible cancellation with chargino contribution.

Note: There are generically new contributions via squark mixing !

Parameter bounds model-dependent

$\bar{B} \to X_s\gamma$





$$C_{NLL}(M_W) = C_{NLL}{}^{SM}(M_W) + C_{NLL}{}^{H^+}(M_W) + C_{NLL}{}^{\chi}(M_W)$$

Also in beyond-the-SM scenarios NLL calculations existing:

NLL analysis in MFV-Supersymmetry

Degrassi,Gambino,Slavich, hep-ph/0602198

NLL in general supersymmetry (uMSSM)

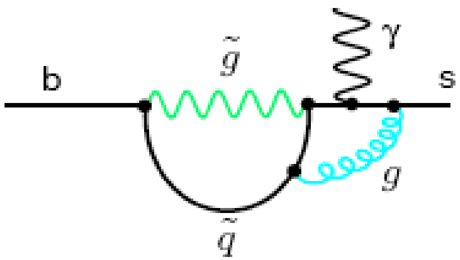
New sources of flavour violation via squark mixing

Complete NLL

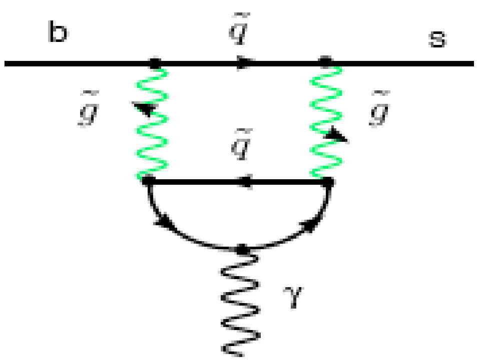
$W\, g \quad H^+\, g \quad \chi^+\, g \quad \chi^0\, g \quad \tilde{g}\, g$ Bobeth,Misiak,Urban hep-ph/9904413

$W\, \tilde{g} \quad H^+\, \tilde{g} \quad \chi^+\, \tilde{g} \quad \chi^0\, \tilde{g} \quad \tilde{g}\, \tilde{g}$

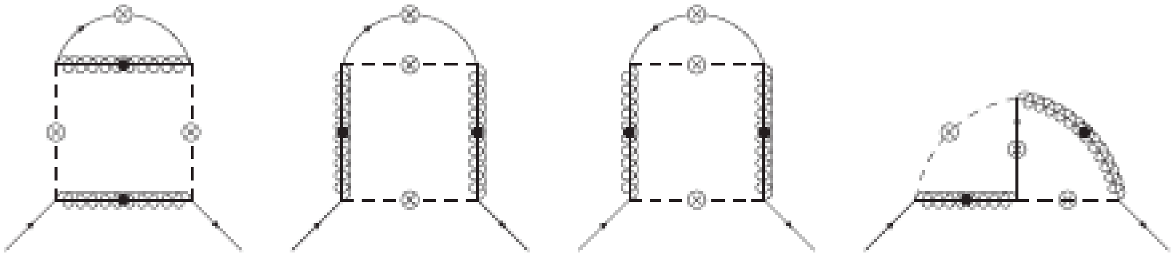
Gluonic Parts ($\tilde{g}\, g$)



Two-Gluino Parts ($\tilde{g}\, \tilde{g}$)

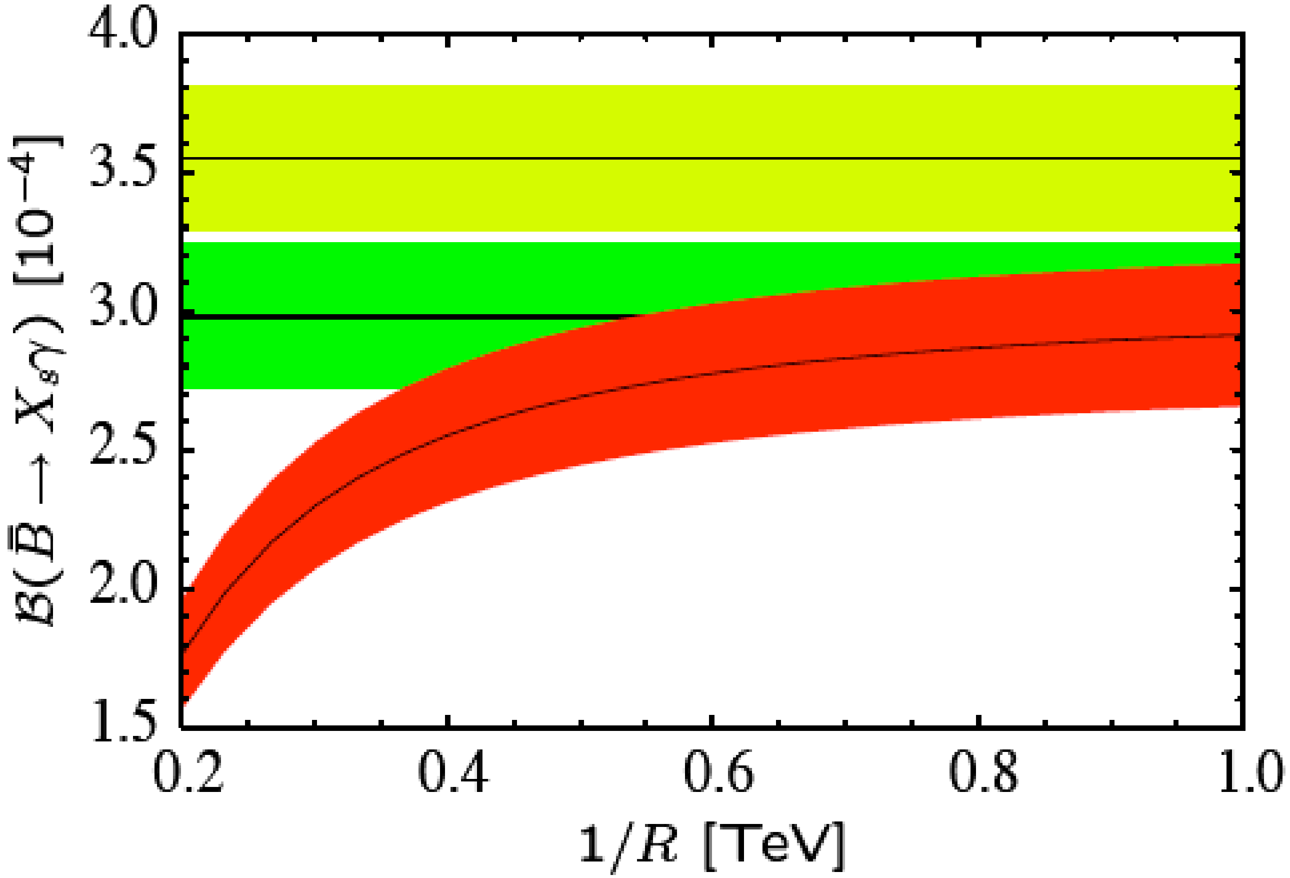


Greub,Hurth,Pilipp,Schupbach,Steinhauser arXiv:1105.1330 [hep-ph]



Gluino contribution dominant due to strong coupling

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

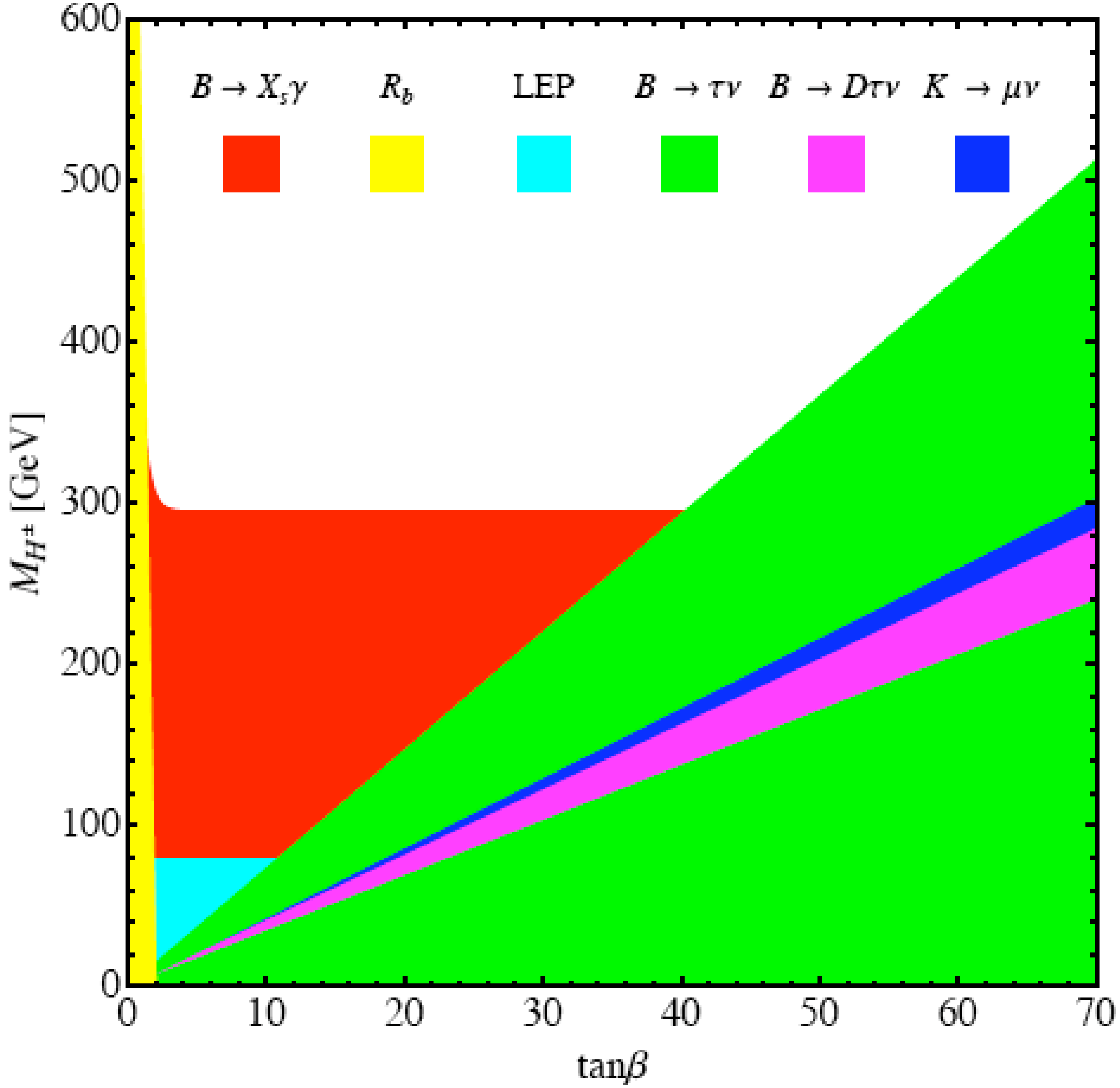


Red: LO-UED, Green: SM Theory, Yellow: Experiment By far best bound !

Haisch et al

Parameter bounds in THDMs

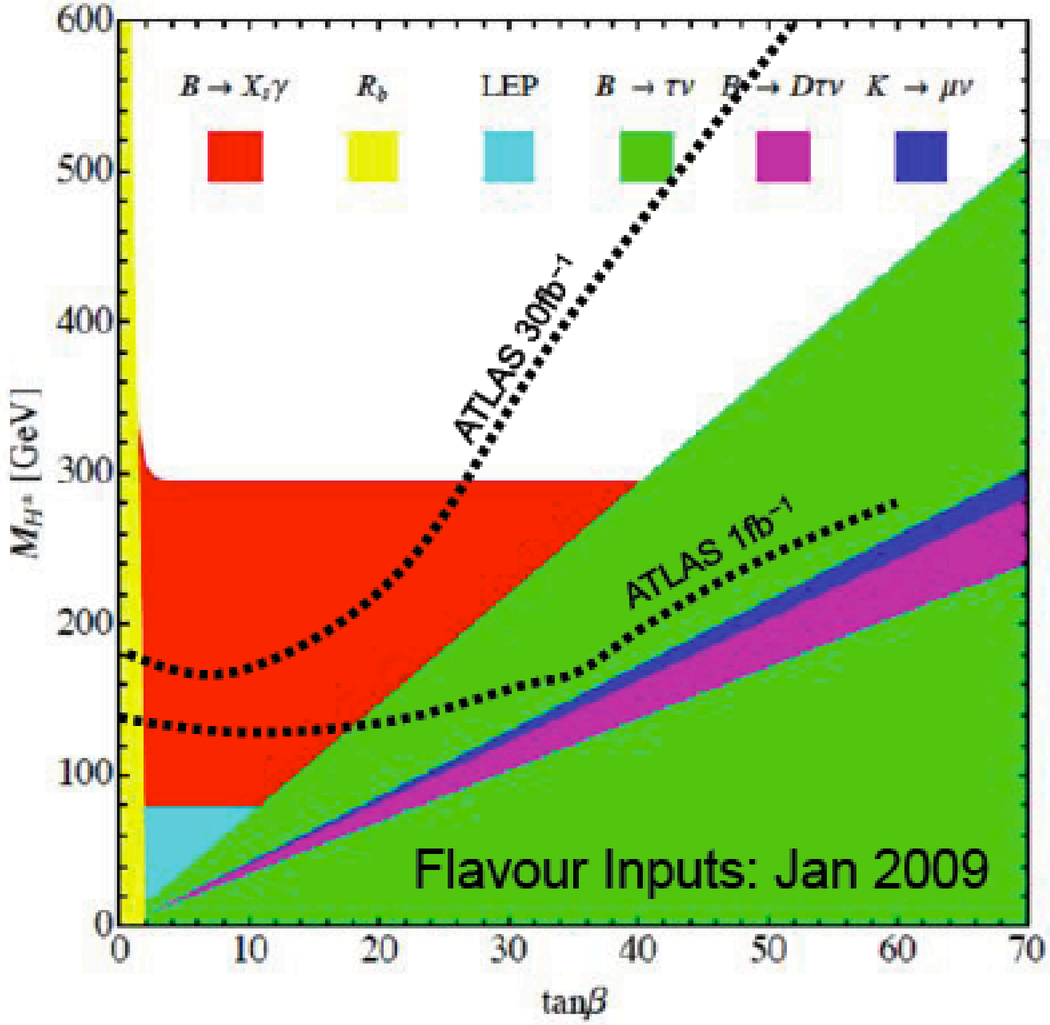
Haisch,arXiv:0805.2141



See also Deschamps et al.(CKMfitter), arXiv:0907.5135. Mahmoudi, Stal, arXiv:0907.1791. Erikson, Mahmoudi, Stal, arXiv:0808.3551.

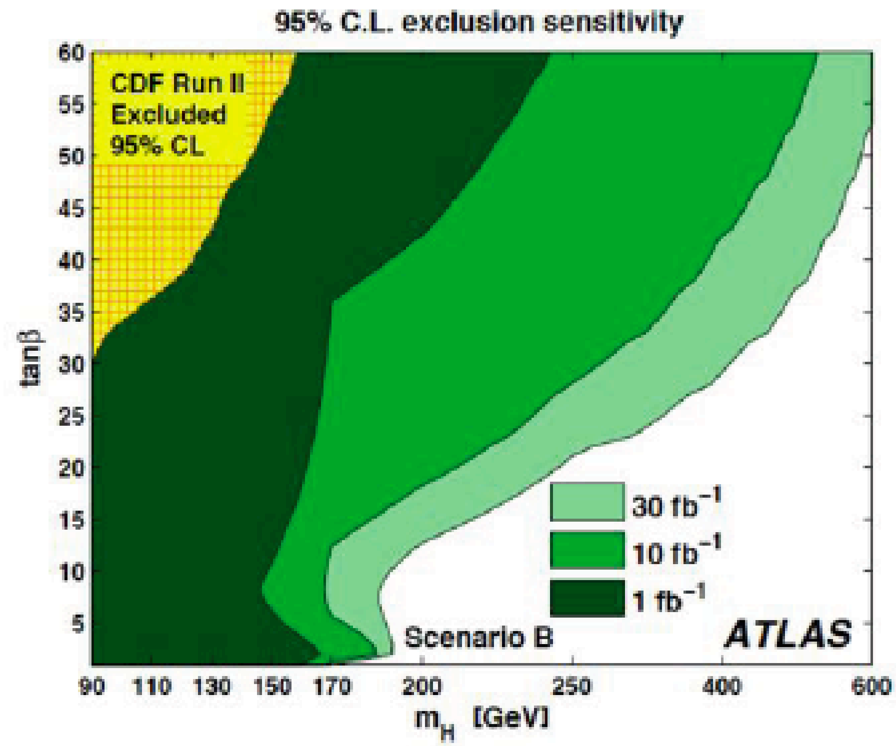
LHC versus Flavour constraints

Combined Higgs search constraint from ATLAS: arXiv:0901.1502



U. Haisch 0805.2141
2HDM

Converted constraints expected from ATLAS onto the plot by hand.



Courtesy of Adrian Bevan

LHC versus Flavour constraints

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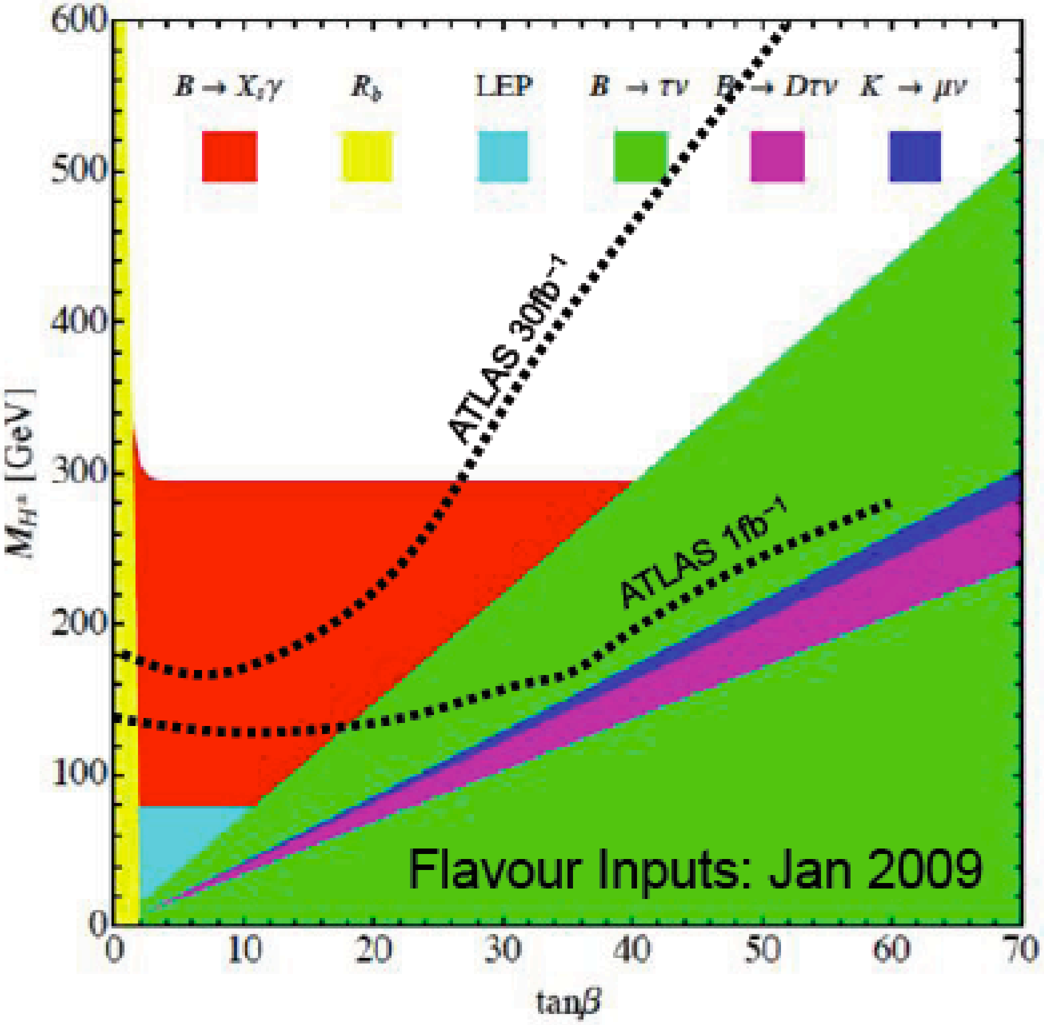
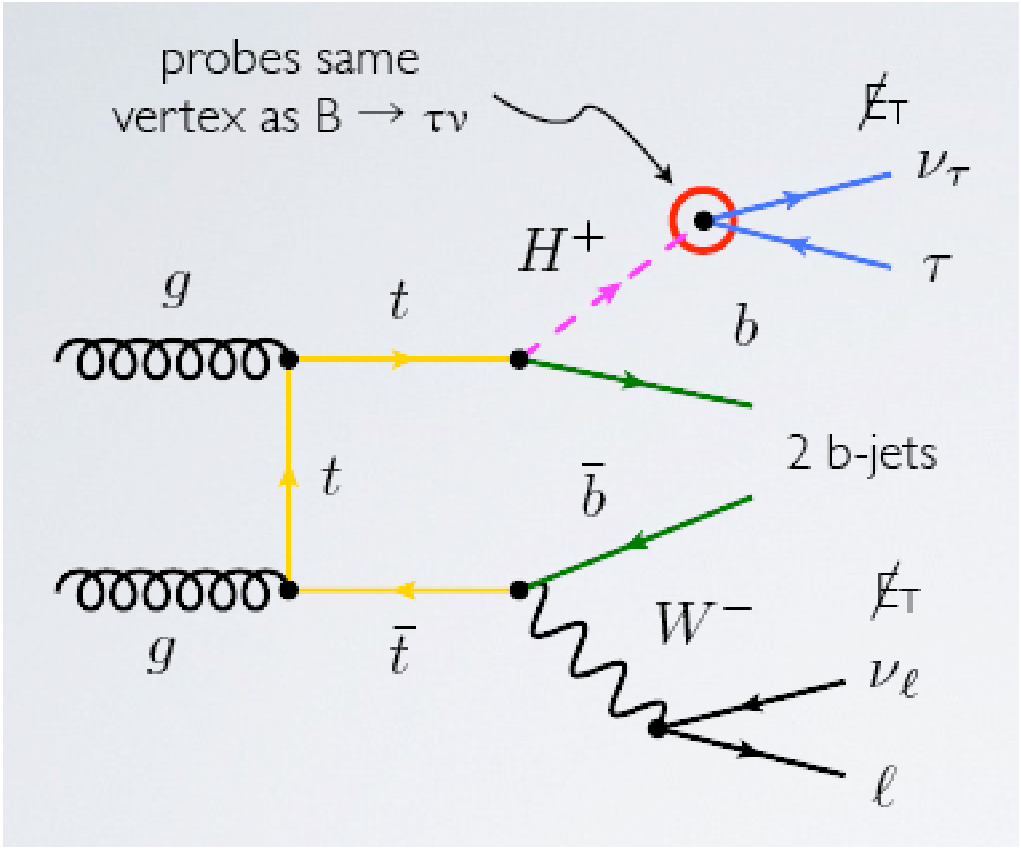


U. Haisch 0805.2141

2HDM



Courtesy of Uli Haisch

Epilogue Future Opportunities

- LHCb (5 years) $10fb^{-1}$: allows for wide range of analyses,

  highlights: B_s mixing phase, angle γ, $B \to K^*\mu\mu$, $B_s \to \mu\mu$,$B_s \to \phi\phi$

  then possibility for upgrade to $100fb^{-1}$

- Dedicated kaon experiments J-PARC E14 and CERN P-326/NA62:

  rare kaon decays $K_L^0 \to \pi^0\nu\bar{\nu}$ and $K^+ \to \pi^+\nu\bar{\nu}$

- Two proposals for a Super-B factory:

  BELLE II at KEK and SuperB in Frascati ($75ab^{-1}$)

  Super-B is a Super Flavour factory: besides precise B measurements, CP violation in charm, lepton flavour violating modes $\tau \to \mu\gamma$,...

  Both projects have multi-year funding !

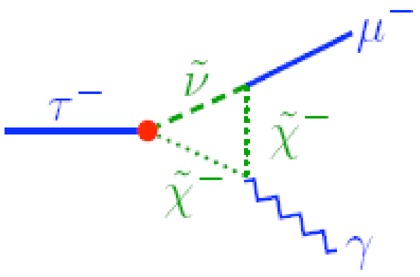
Opportunities at a Super Flavour Factory

see JHEP 0802 (2008) 110, arXiv:0710.3799

Measurement of lepton flavour violation

$\tau \to \mu\gamma$ and $\to 3\mu$

$$\mathrm{BR}(l_j^- \to l_i^- \gamma)|_{\mathrm{SM}_R} \approx (m_\nu/M_W)^2 \sim \mathcal{O}(10^{-54})$$



Process	Expected 90%CL upper limited	4σ Discovery Reach
$\mathcal{B}(\tau \to \mu\gamma)$	2×10^{-9}	5×10^{-9}
$\mathcal{B}(\tau \to \mu\mu\mu)$	2×10^{-10}	8.8×10^{-10}

Use modes to distinguish SUSY vs LHT

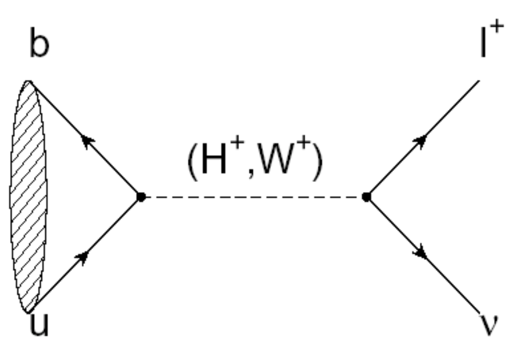
Blanke et al.

ratio	LHT	MSSM (dipole)	MSSM (Higgs)
$\frac{\mathcal{B}(\tau^- \to e^- e^+ e^-)}{\mathcal{B}(\tau \to e\gamma)}$	$0.4 \ldots 2.3$	$\sim 1 \cdot 10^{-2}$	$\sim 1 \cdot 10^{-2}$
$\frac{\mathcal{B}(\tau^- \to \mu^- \mu^+ \mu^-)}{\mathcal{B}(\tau \to \mu\gamma)}$	$0.4 \ldots 2.3$	$\sim 2 \cdot 10^{-3}$	$0.06 \ldots 0.1$
$\frac{\mathcal{B}(\tau^- \to e^- \mu^+ \mu^-)}{\mathcal{B}(\tau \to e\gamma)}$	$0.3 \ldots 1.6$	$\sim 2 \cdot 10^{-3}$	$0.02 \ldots 0.04$
$\frac{\mathcal{B}(\tau^- \to \mu^- e^+ e^-)}{\mathcal{B}(\tau \to \mu\gamma)}$	$0.3 \ldots 1.6$	$\sim 1 \cdot 10^{-2}$	$\sim 1 \cdot 10^{-2}$
$\frac{\mathcal{B}(\tau^- \to e^- e^+ e^-)}{\mathcal{B}(\tau^- \to e^- \mu^+ \mu^-)}$	$1.3 \ldots 1.7$	~ 5	$0.3 \ldots 0.5$
$\frac{\mathcal{B}(\tau^- \to \mu^- \mu^+ \mu^-)}{\mathcal{B}(\tau^- \to \mu^- e^+ e^-)}$	$1.2 \ldots 1.6$	~ 0.2	$5 \ldots 10$

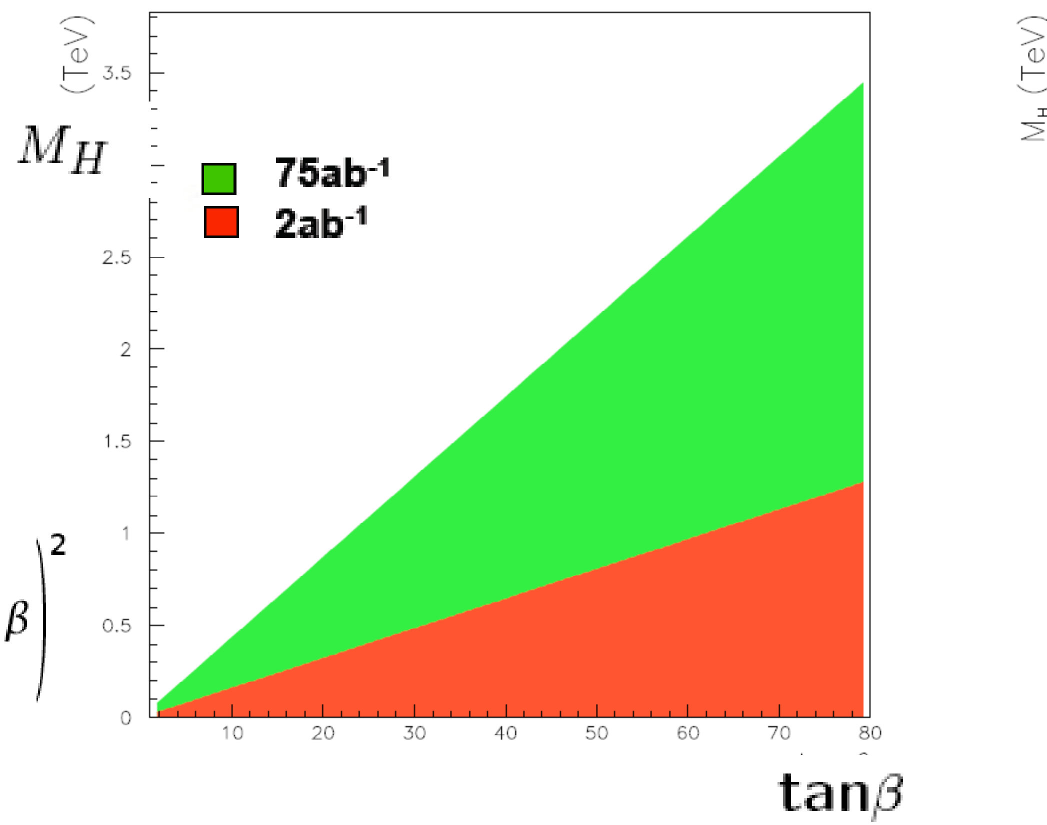
Superflavour factory: measurement of clean modes

$B \to \tau\nu$: B factories 20% Super B factories 4%

2HDM-II



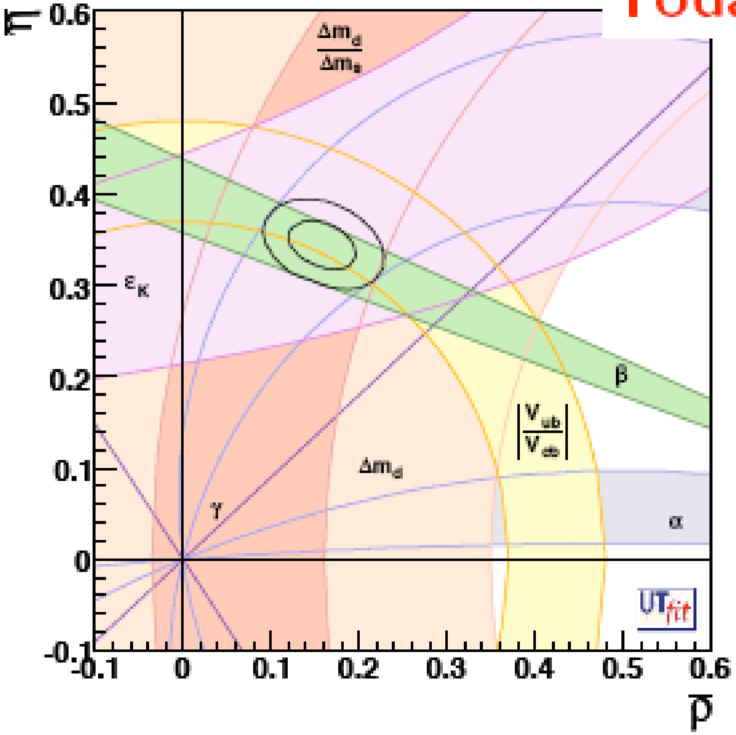
$$\mathrm{BR}(B \to \tau\nu) = \mathrm{BR}_{\mathrm{SM}}(B \to \tau\nu)\left(1 - \frac{m_B^2}{M_H^2}\tan^2\beta\right)^2$$



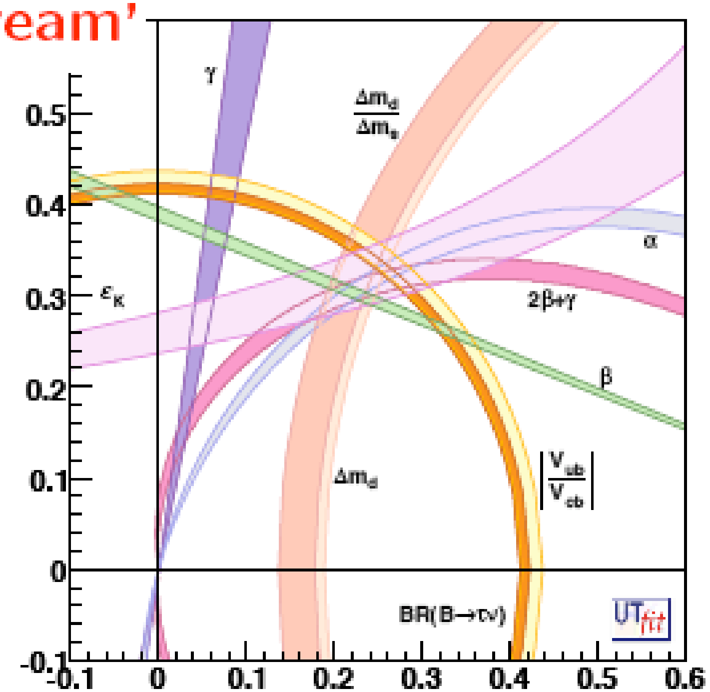
(Assuming SM branching fraction is measured)

Superflavour factory: CKM theory gets tested at 1%

Today



'the dream'



'the nightmare'