SusyBSG: a fortran code for $\mathrm{BR}\,[B \to X_s\,\gamma]$ in the MSSM with Minimal Flavor Violation

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CERN & LAPTH Annecy

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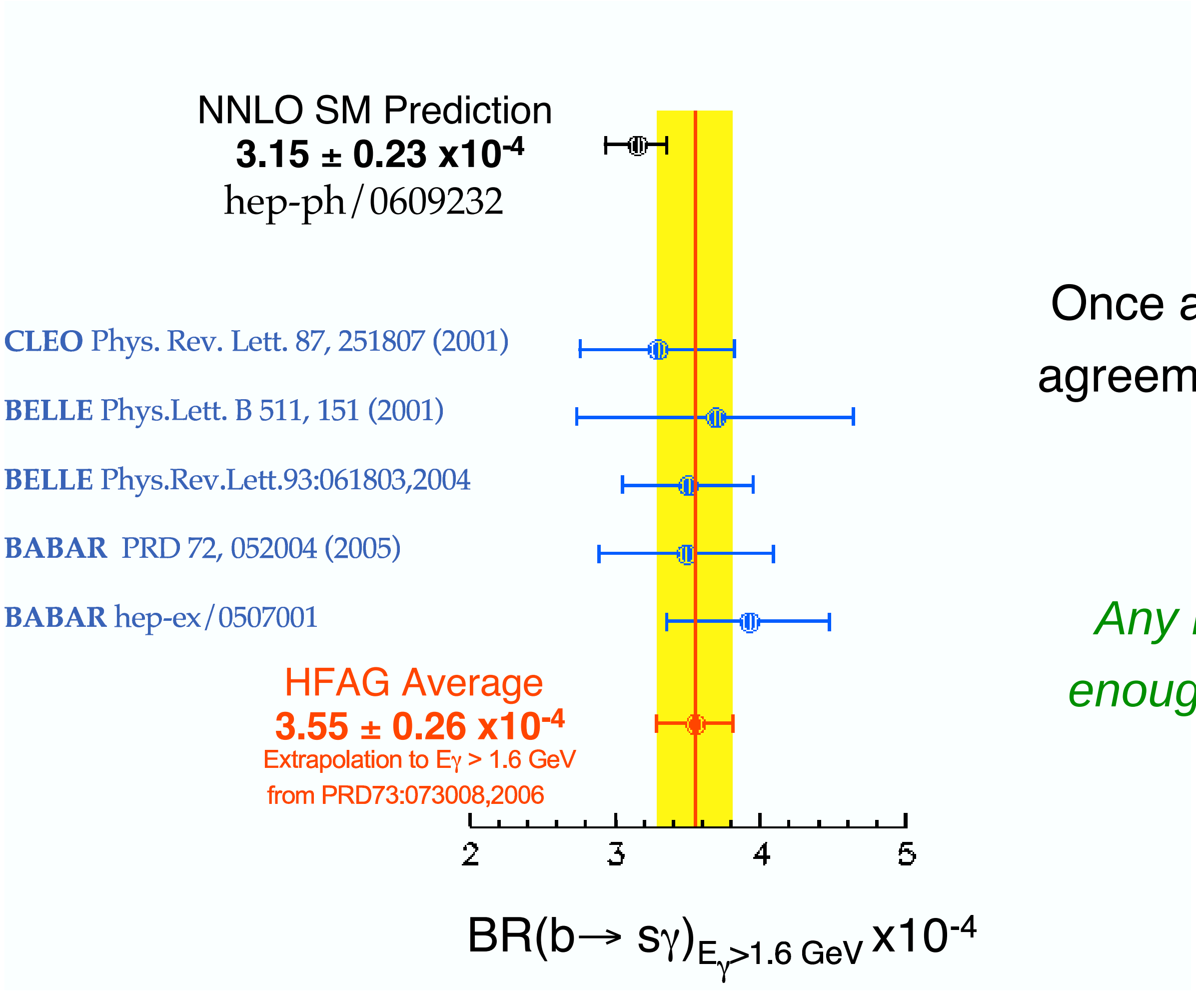
Based on: *G. Degrassi, P. Gambino and P. S., PLB 635 (2006) 335 and arXiv:0712.3265*

Radiative B decays

$B \to X_s\,\gamma$ is a (not-so) rare FCNC decay, well measured at CLEO, BABAR and BELLE

The SM prediction for BR($B \to X_s\,\gamma$) includes most of the NNLO QCD contributions

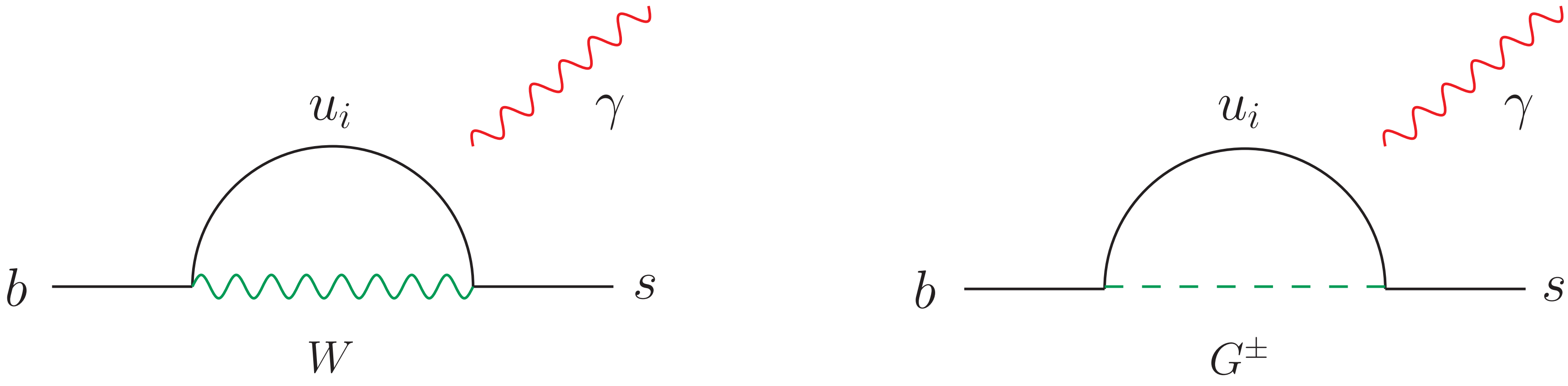


Once again, the SM prediction is in fair agreement with the experimental results

Any NP contribution must be small enough not to upset the agreement!!!

SM contributions to $B \to X_s \gamma$

In the SM the LO contributions to the $b \; \to \; s\,\gamma$ amplitude arise at one loop



The chiral transition $b_R \to s_L$ is suppressed by a quark-mass insertion

Working out masses and couplings: $\mathcal{A} \; \propto \; G_F \, m_b \sum_i m^2_{u^i} \, V^*_{is} \, V_{ib}$

An effective-theory approach is necessary to resum large logarithmic corrections

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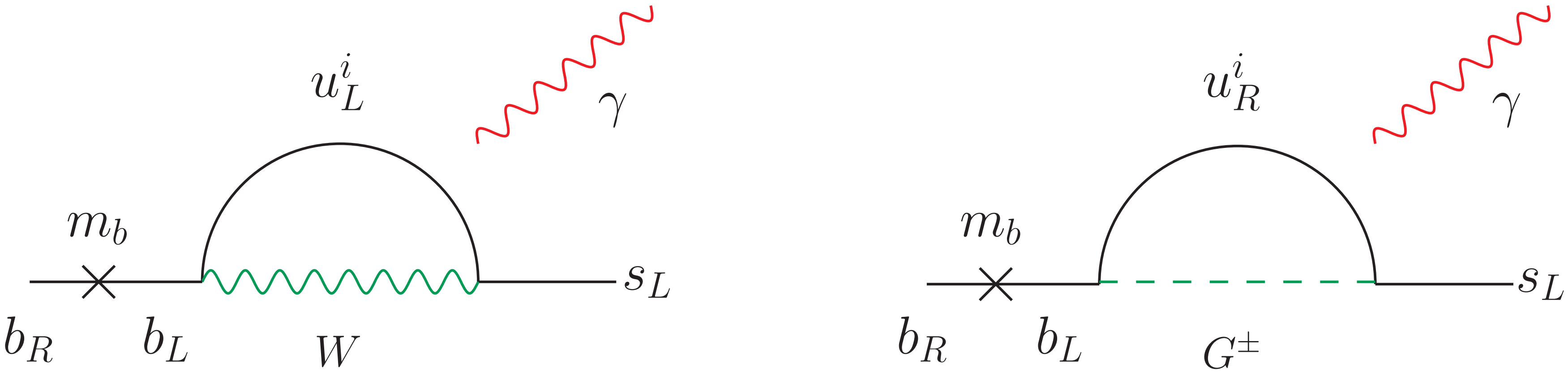

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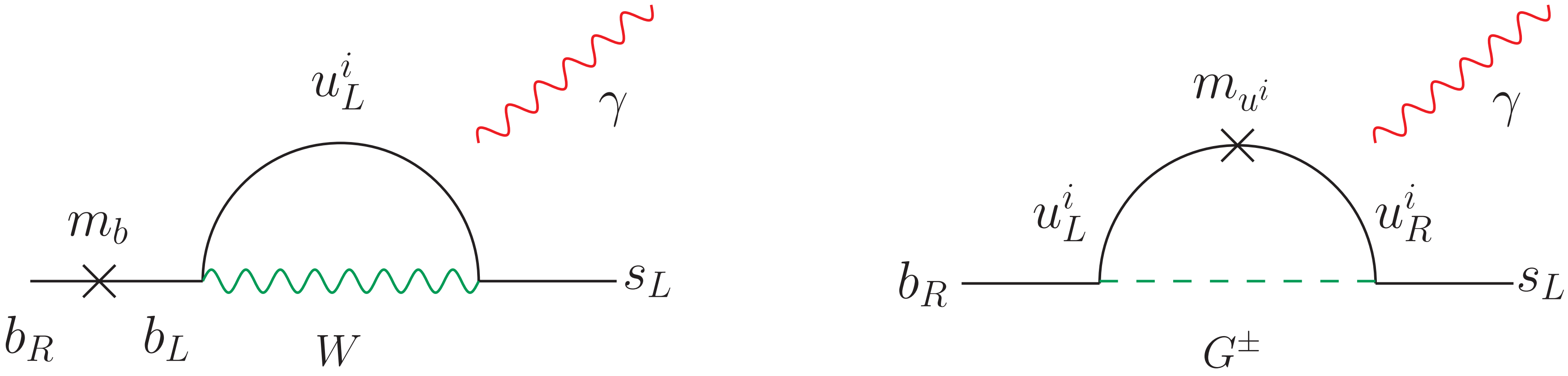

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An effective-theory approach is necessary to resum large logarithmic corrections

Integrating out the heavy particles, the operators relevant to the $b \;\rightarrow\; s$ transition are

$$\mathcal{H}_{\rm eff} \;=\; -\,\frac{4\,G_\mu}{\sqrt{2}}\,V_{ts}^* V_{tb}\,\sum_i C_i(\mu_W)\,Q_i(\mu_W)$$

$$Q_{1,2} \;=\; (\bar s\,\Gamma_i\,c)\,(\bar c\,\Gamma_i\,b)\,, \qquad\qquad Q_{3,4,5,6} \;=\; (\bar s\,\Gamma_i\,b)\,(\bar q\,\Gamma_i\,q)$$

$$Q_7 \;=\; \frac{e}{16\pi^2}\,m_b\,\bar s_L\,\sigma^{\mu\nu}\,b_R\,F_{\mu\nu}\,, \qquad\qquad Q_8 \;=\; \frac{g_s}{16\pi^2}\,m_b\,\bar s_L\,\sigma^{\mu\nu}\,T^a\,b_R\,G_{\mu\nu}$$

- Compute the matching conditions for the Wilson coefficients C_i at the scale μ_W
- Evolve the Wilson Coefficients down to the scale μ_b characteristic of B physics
- Compute $\mathrm{BR}\,[B \rightarrow X_s\,\gamma]$ in terms of the coefficients at the B-physics scale

The presence of New Physics affects only the matching of the Wilson coefficients

$$C_i(\mu_W) \;=\; C_i^{\rm SM}(\mu_W) \;+\; C_i^{\rm NP}(\mu_W) \qquad\qquad (i = 1\ldots 8)$$

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In general the Minimal Supersymmetric Standard Model (MSSM) predicts:

- *New Particles in the loops:* extended Higgs sector, gauginos, higgsinos, squarks
- *New Sources of Flavor Violation:* in the flavor structure of the soft squark masses

$$\mathcal{M}_{\tilde{d}}^2 = \begin{pmatrix} \hat{m}_Q^2 + m_d^2 + D_{d_L} & v_1 \hat{T}_D - \mu^* m_d \tan\beta \\ v_1 \hat{T}_D - \mu\, m_d \tan\beta & \hat{m}_D^2 + m_d^2 + D_{d_R} \end{pmatrix}$$

The good agreement between SM predictions and experimental results for FCNC processes puts stringent constraints on the flavor structure of the soft mass terms

In the Minimal Flavor Violation (MFV) scenario we assume that the soft masses are flavor-diagonal in the basis were the Yukawa matrices are diagonal, so that *the only source of flavor violation is the CKM matrix (as in the SM)*

$$\mathcal{L}^{MFV} \supset V_{ij}^{CKM} \left(W_\mu^+ \, \bar{u}^i \gamma^\mu P_L \, d^j + W_\mu^+ \, \tilde{u}_L^{i*} \, \partial^\mu \, \tilde{d}_L^j + \tilde{u}_L^{i*} \, \overline{w^-} \, P_L \, d^j + \ldots \right)$$

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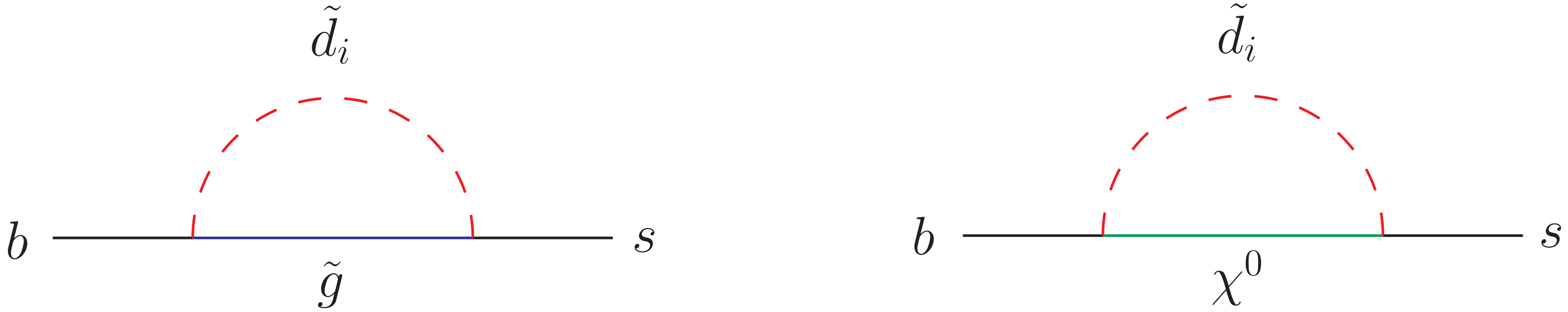
One-loop MSSM contributions to $B \to X_s \gamma$

Contributions from charged-current vertices (controlled by the CKM matrix in MFV)

Additional contributions from neutral-current vertices (only beyond MFV)



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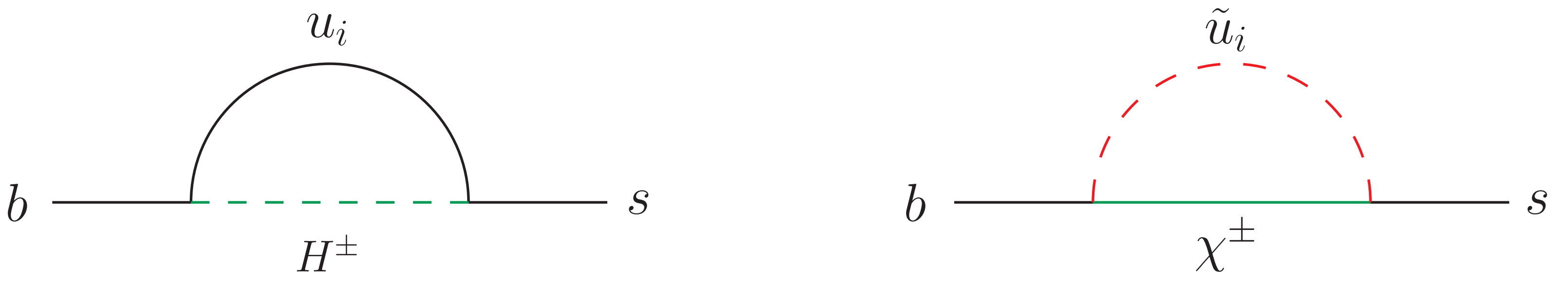

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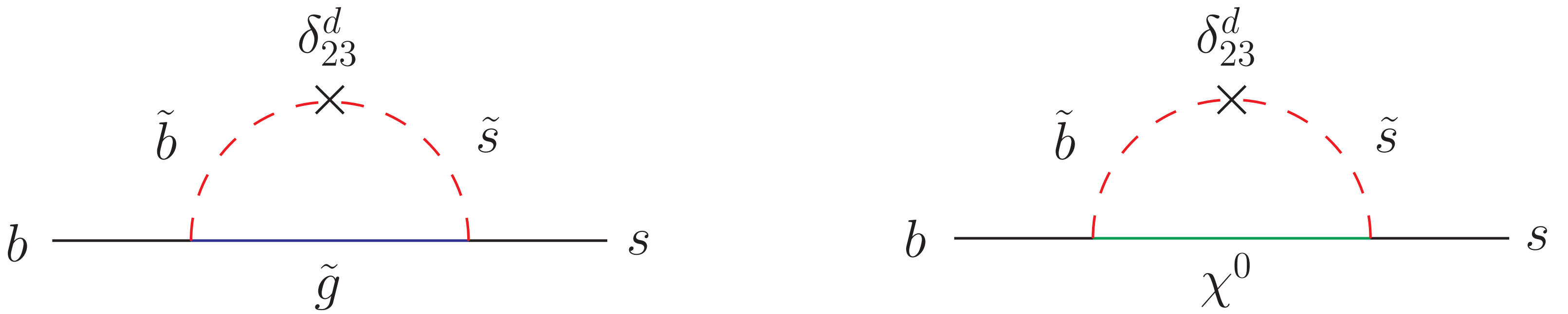

Effective Lagrangian approach at large $\tan\beta$

The two Higgs fields of the MSSM give mass to up-type and down-type quarks, respectively

$$m_t = h_t\, v_2\ , \qquad m_b = h_b\, v_1 \qquad\qquad v_i = \langle H_i^0 \rangle$$

the MSSM Yukawa couplings are rescaled w.r.t. their SM counterparts

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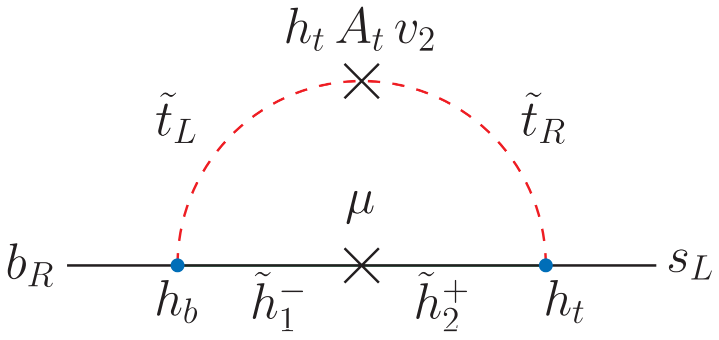
In particular, $\dfrac{h_b}{h_t} = \dfrac{m_b}{m_t}\tan\beta$, thus $h_b \simeq h_t$ for $\tan\beta \sim 40-50$

At large $\tan\beta$ diagrams involving a bottom Yukawa coupling are not necessarily suppressed by m_b, unless they also contain at least one insertion of v_1

For example, there are unsuppressed diagrams that involve charginos:



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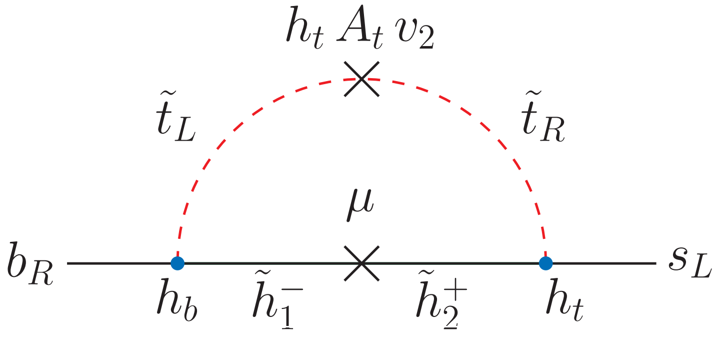

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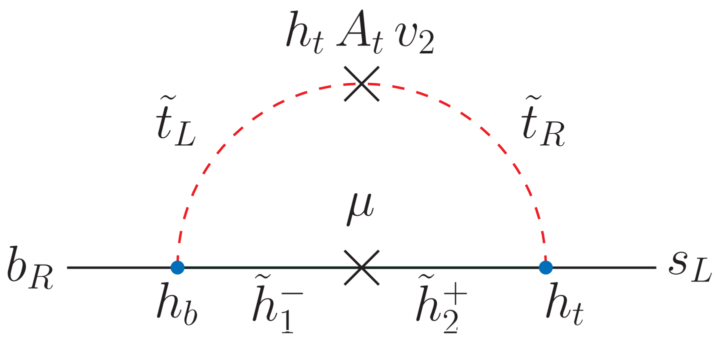
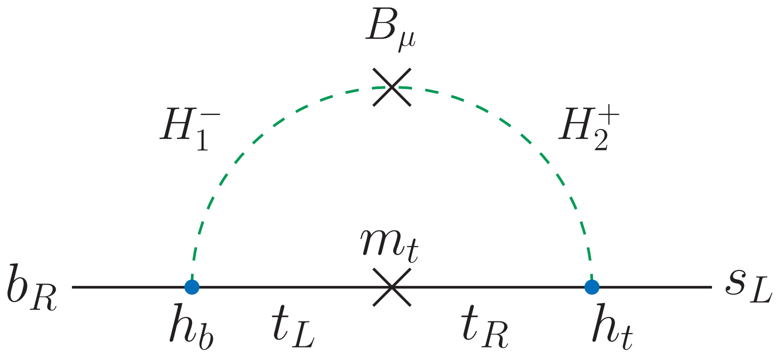
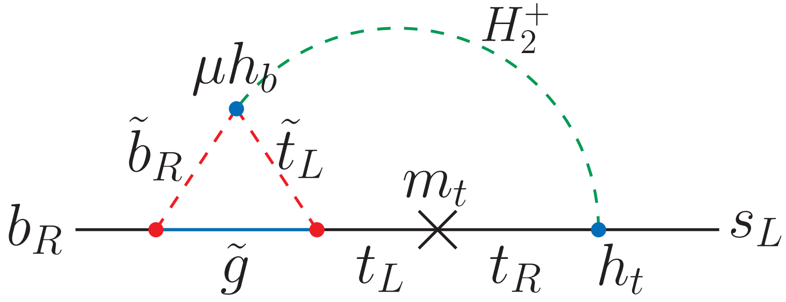


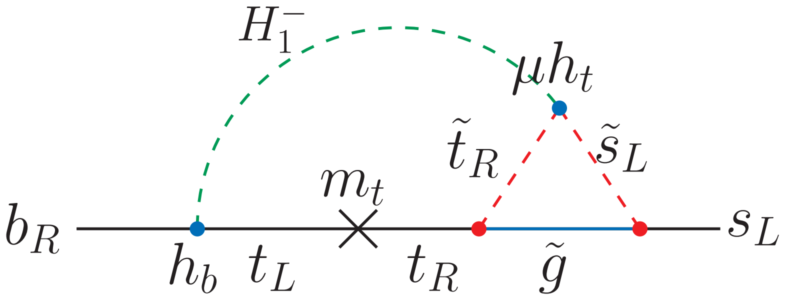
One-loop corrections to the charged-Higgs-quark vertices induce $\tan\beta$-enhanced contributions to the $b_R \to s_L$ transition at two loops



$B_\mu \propto v_1 v_2$, so the one-loop Higgs contribution has the usual m_b suppression

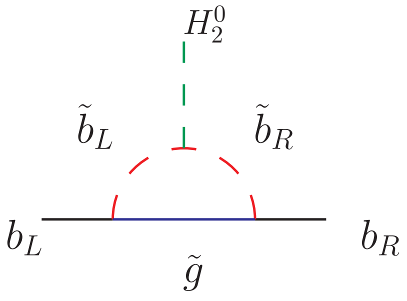
Inserting a gluino-squark loop in the Higgs-quark vertices allows us to bypass B_μ



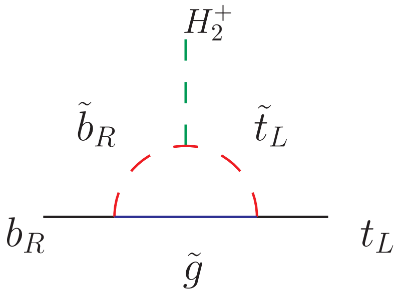


For heavy superpartners the leading NLO terms can be computed with an effective Lagrangian. Integrating out the SUSY particles leaves us with effective Higgs-quark-quark vertices:

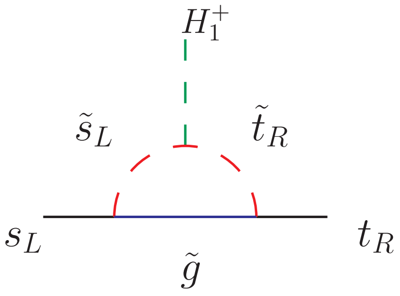
$$\begin{aligned}\mathcal{L} \quad \supset \quad & \frac{g}{\sqrt{2}M_W} G^+ \left\{ m_t\, V_{ts} \bar{t}_R s_L - m_b\, V_{tb} \frac{1+\epsilon'_b(t)\tan\beta}{1+\epsilon_b \tan\beta} \bar{t}_L b_R \right\} \\ + \quad & \frac{g}{\sqrt{2}M_W} H^+ \left\{ V_{ts} \frac{m_t\,[1-\epsilon'_t(s)\tan\beta]}{\tan\beta} \bar{t}_R s_L + V_{tb} \frac{m_b \tan\beta}{1+\epsilon_b\tan\beta} \bar{t}_L b_R \right\} + \text{h.c.}\end{aligned}$$



ϵ_b



$\epsilon'_b(t)$



$\epsilon'_t(s)$

Computing the one-loop diagrams with these effective Higgs-quark-quark vertices we get

$$\begin{aligned}\delta\, C_{7,8}^{(G^\pm)}(\text{leading}\tan\beta) &= \frac{[\epsilon_b - \epsilon'_b(t)]\tan\beta}{1+\epsilon_b\tan\beta} F_{7,8}(m_t^2/m_W^2) \\ \delta\, C_{7,8}^{(H^\pm)}(\text{leading}\tan\beta) &= -\frac{[\epsilon'_t(s)+\epsilon_b]\tan\beta}{1+\epsilon_b\tan\beta} F_{7,8}(m_t^2/m_H^2)\end{aligned}$$

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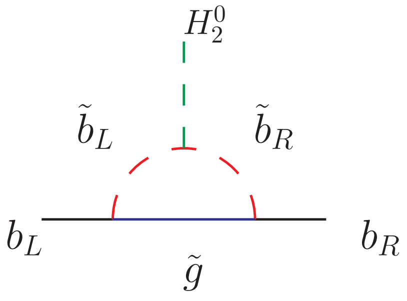
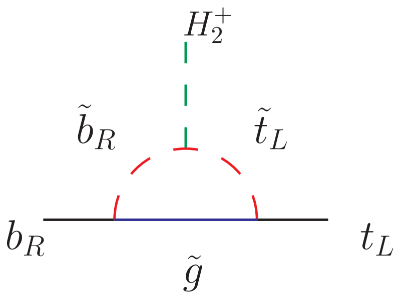
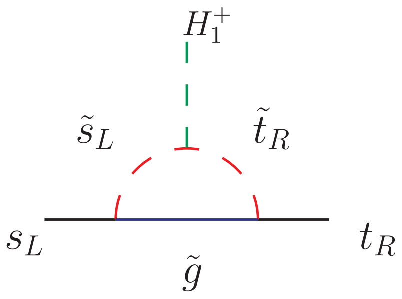


ϵ_b



$\epsilon_b'(t)$



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Beyond the effective Lagrangian approach

If the superparticles are not much heavier than the weak scale the effective Lagrangian approach may provide a poor approximation to the complete result

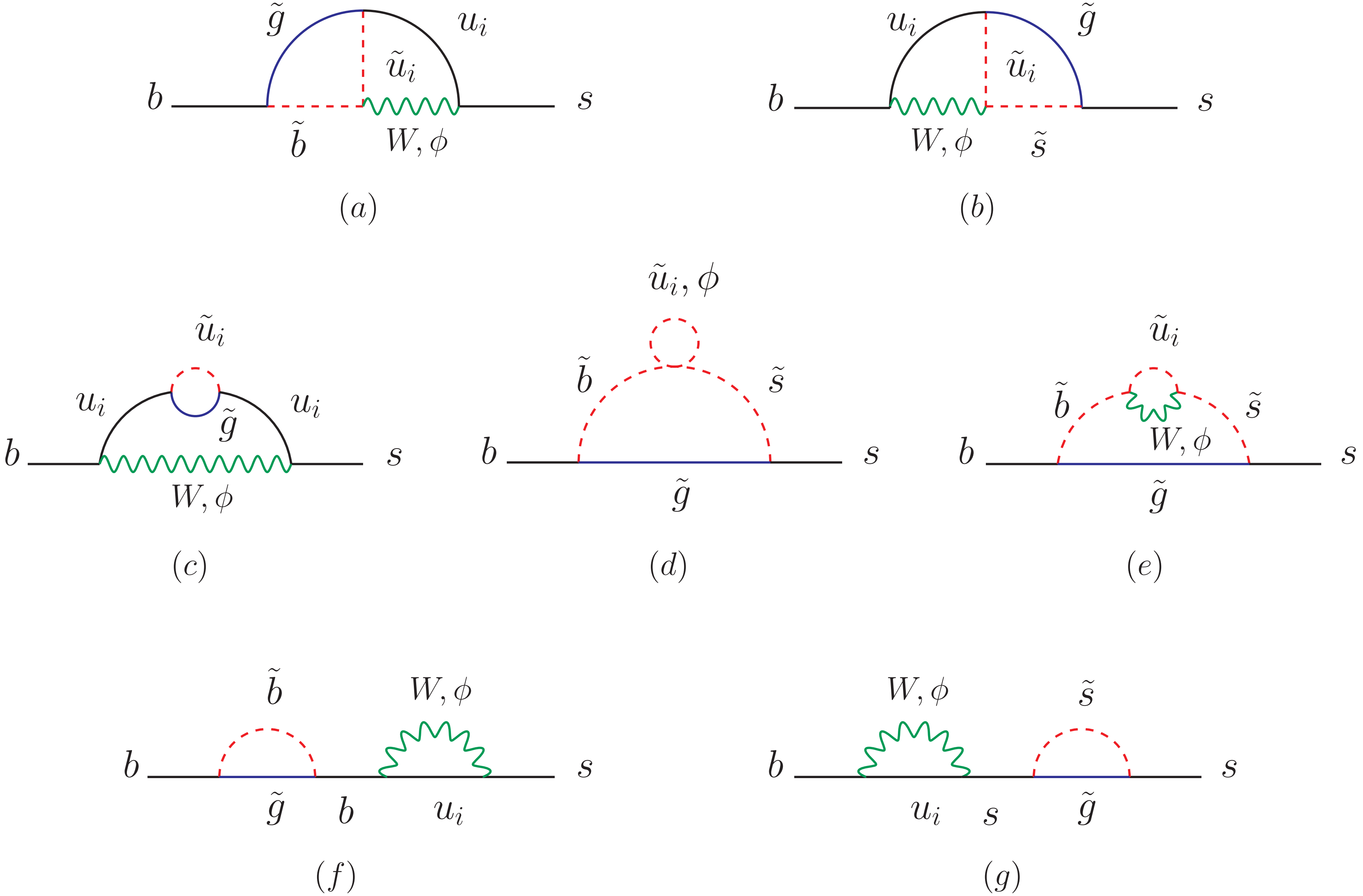
Also, the two-loop chargino contributions to $\mathrm{BR}(B \to X_s\,\gamma)$ include $\tan\beta$-enhanced terms that would be missed in the effective Lagrangian approach

→ A complete NLO calculation is in order

The two-loop contributions involving gluons were computed long ago in the limit of heavy gluinos *[Ciuchini, Degrassi, Gambino & Giudice (1998); Bobeth, Misiak & Urban (1999)]*

More recently we computed the two-loop contributions involving gluinos in the MFV scenario *[Degrassi, Gambino & P.S., PLB 635, 335 (2006)]*

Two-loop diagrams with gluino and Higgs or W boson

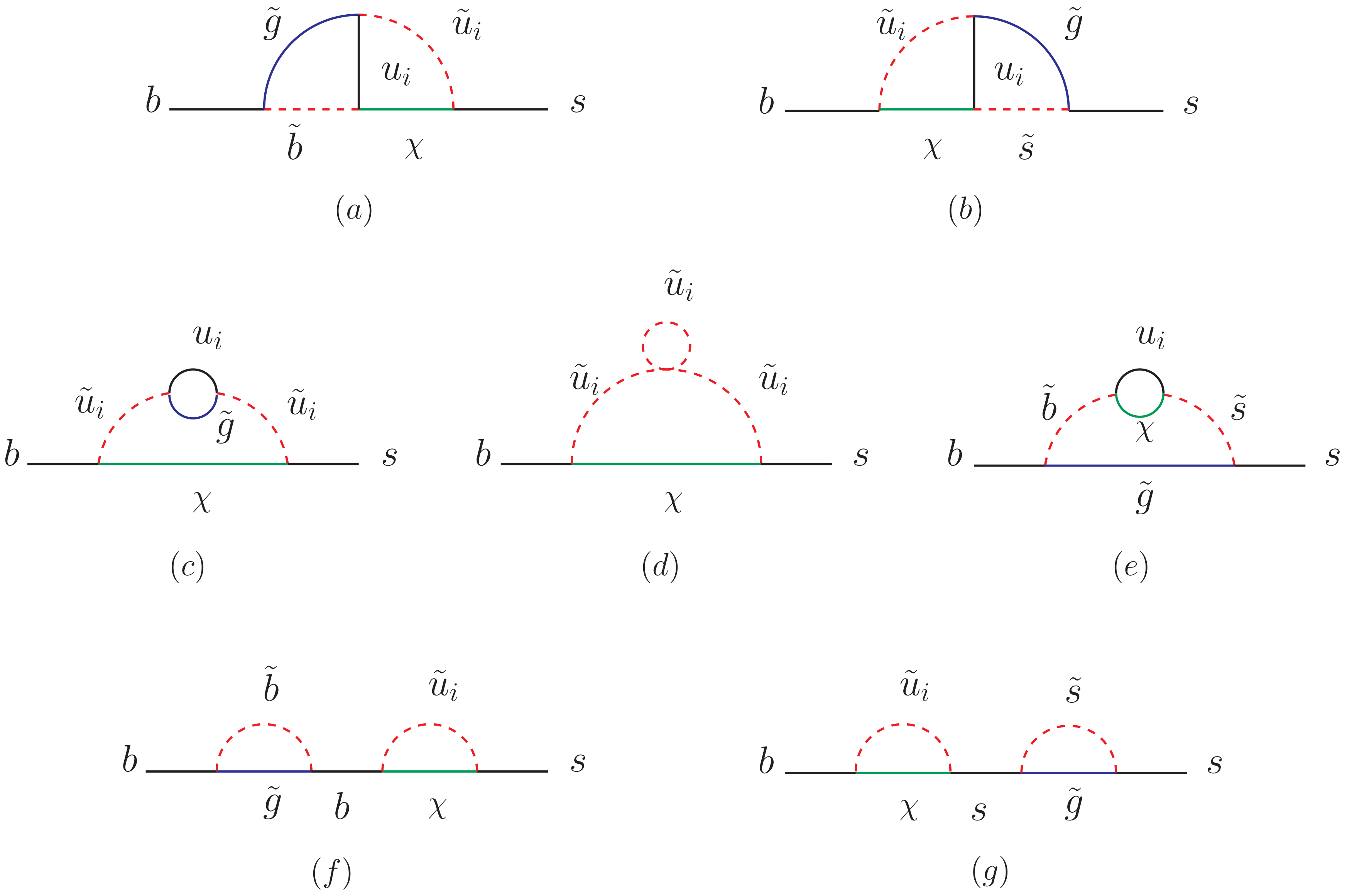


(a) (b)

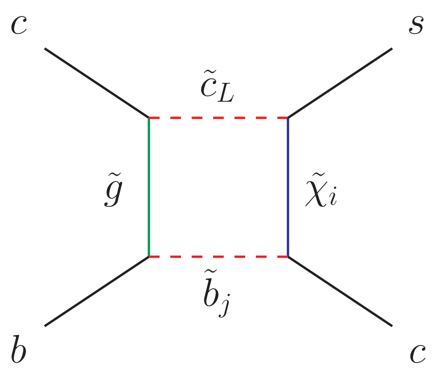
(c) (d) (e)

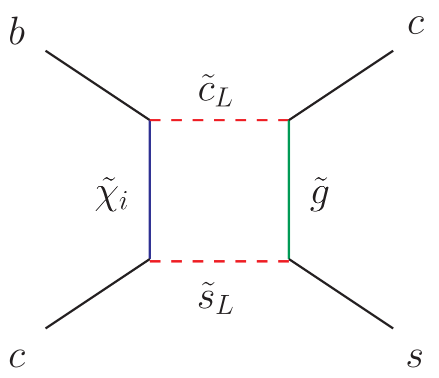
(f) (g)

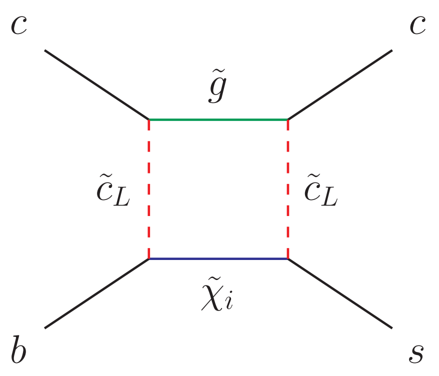
Two-loop diagrams with gluino and chargino

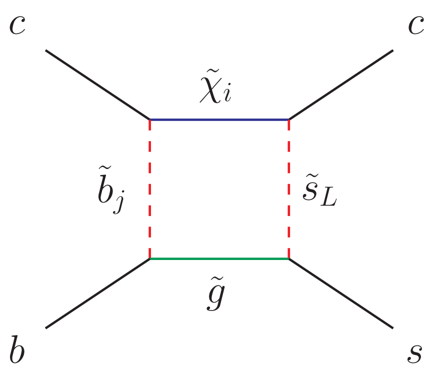


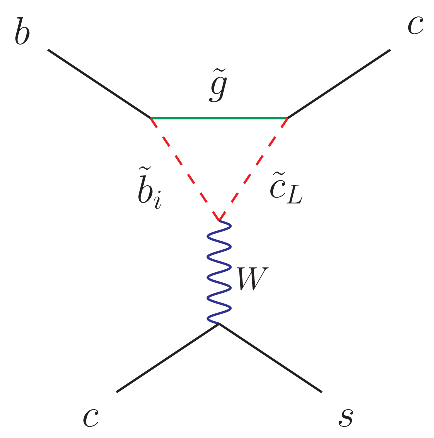
One-loop contributions to the four-fermion operators

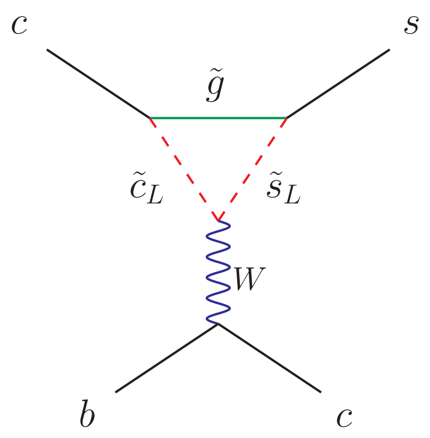












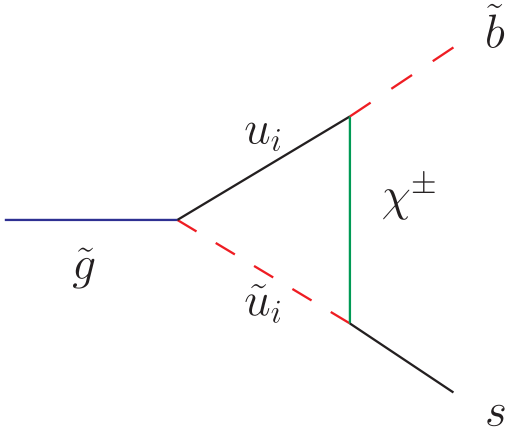
Outline of the NLO calculation

We followed the same procedure as in the earlier computation of gluon corrections:

- write down all the two-loop $b \to s\,\gamma$ amplitudes
- extract the contributions to $Q_{7,8}$ using a suitable projector
- expand the diagrams in powers of the external momenta, neglecting all terms suppressed by m_b/m_W or m_b/m_{susy}
- work out the resulting two-loop vacuum integrals

A complication: the MFV condition is affected by radiative corrections!!!

Flavor-changing gluino vertices induce poles that need to be cancelled by suitable counterterms



Squark flavor mixing itself must be renormalized:

if the squark masses are flavor-diagonal at $\mu_{\rm MFV}$, they will not be so at a different scale

If the MFV hypothesis is valid at a scale much larger than the superparticle masses (e.g. in mSUGRA) we need to resum large logarithmic corrections:

- start from flavor-diagonal squark masses at the high scale $\mu_{\rm MFV}$
- evolve the quark and squark mass matrices down to the low scale $\mu_{\rm SUSY}$ (this induces a misalignment between quarks and squarks)
- diagonalize the squark mass matrices at the low scale
- compute the Wilson coeffs at LO including the effect of squark flavor mixing
- add NLO contributions computed with the MFV assumption and $\mu_{\rm MFV} = \mu_{\rm SUSY}$

So doing, we absorb the large logarithms at LO in the one-loop neutral current diagrams, and use MFV as an approximation for the two-loop results

NOTE: we can use some public code (SoftSusy, SPheno) *to perform the RG evolution*

Two numerical examples

We assume that the squark soft SUSY-breaking masses and trilinear interactions are expressed in the $\overline{\mathrm{DR}}$ renormalization scheme at a scale $\mu_{\mathrm{SUSY}} = \mu_{\mathrm{MFV}} = 500\ \mathrm{GeV}$

We consider two sets of representative choices for the MSSM input parameters:

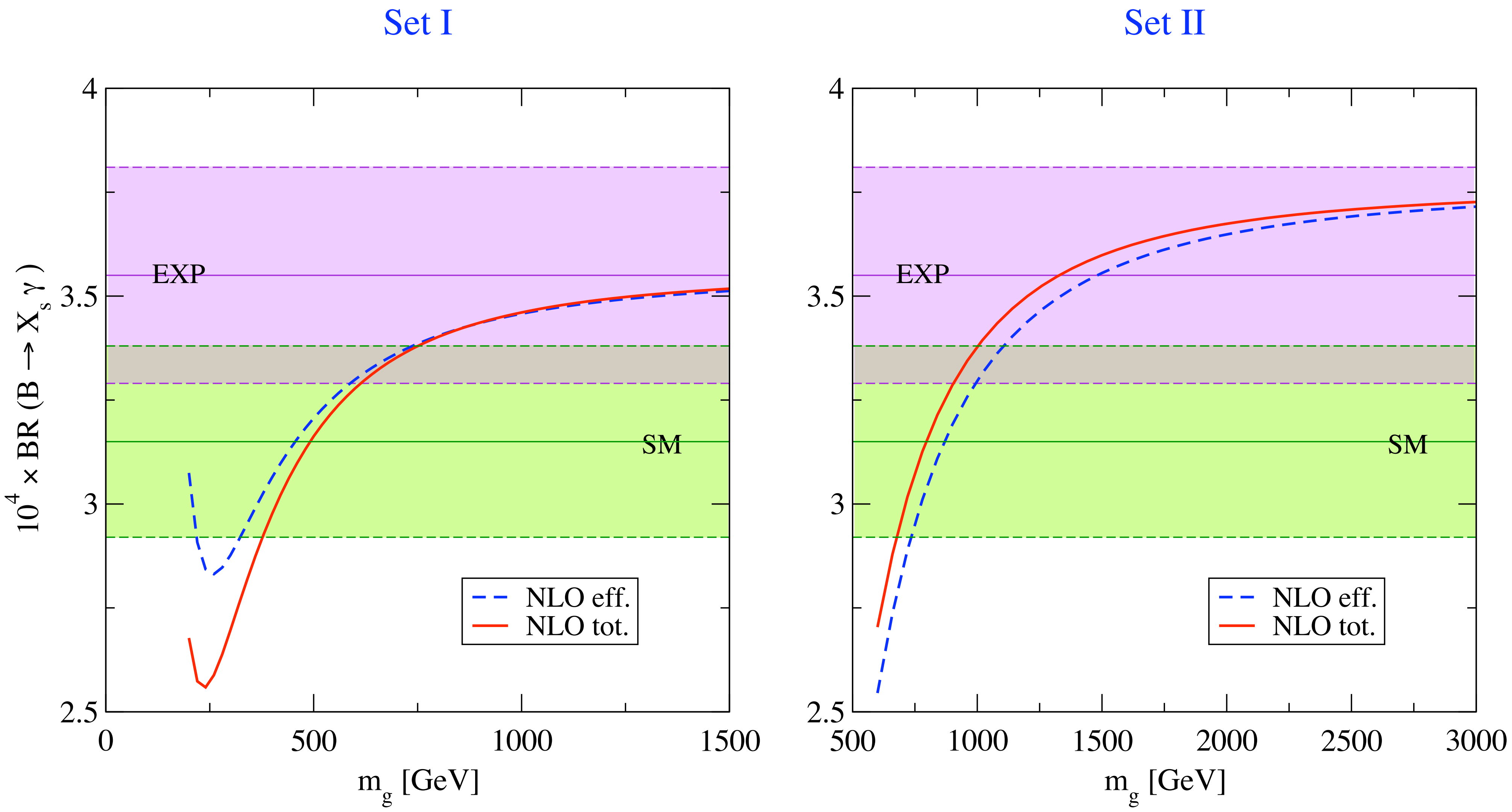
(I)
$$m_Q = 230\ \mathrm{GeV},\quad m_T = 210\ \mathrm{GeV},\quad m_B = 260\ \mathrm{GeV},\quad A_t = -70\ \mathrm{GeV},\quad A_b = 0,$$
$$m_{H^\pm} = 350\ \mathrm{GeV},\quad m_{\tilde{g}} = M_2 = 200\ \mathrm{GeV},\quad \mu = 250\ \mathrm{GeV},\quad \tan\beta = 30$$

(II)
$$m_Q = 480\ \mathrm{GeV},\quad m_T = 390\ \mathrm{GeV},\quad m_B = 510\ \mathrm{GeV},\quad A_t = -560\ \mathrm{GeV},\quad A_b = -960\ \mathrm{GeV},$$
$$m_{H^\pm} = 430\ \mathrm{GeV},\quad m_{\tilde{g}} = 600\ \mathrm{GeV},\quad M_2 = 190\ \mathrm{GeV},\quad \mu = 390\ \mathrm{GeV},\quad \tan\beta = 10$$

(*SPS1a'* benchmark point: $m_{1/2} = 250\ \mathrm{GeV},\ m_0 = 70\ \mathrm{GeV},\ A_0 = -300\ \mathrm{GeV}$)

We compare our full NLO results with the results of the effective Lagrangian approach

To study the decoupling behavior for heavy superparticles, we rescale all the SUSY masses by a common increasing factor *(but we keep m_H fixed)*


Set I
Set II
$10^4 \times BR(B \to X_s \gamma)$
EXP
SM
NLO eff.
NLO tot.
4
3.5
3
2.5
0
500
1000
1500
2000
2500
3000
m_g [GeV]

The program SusyBSG

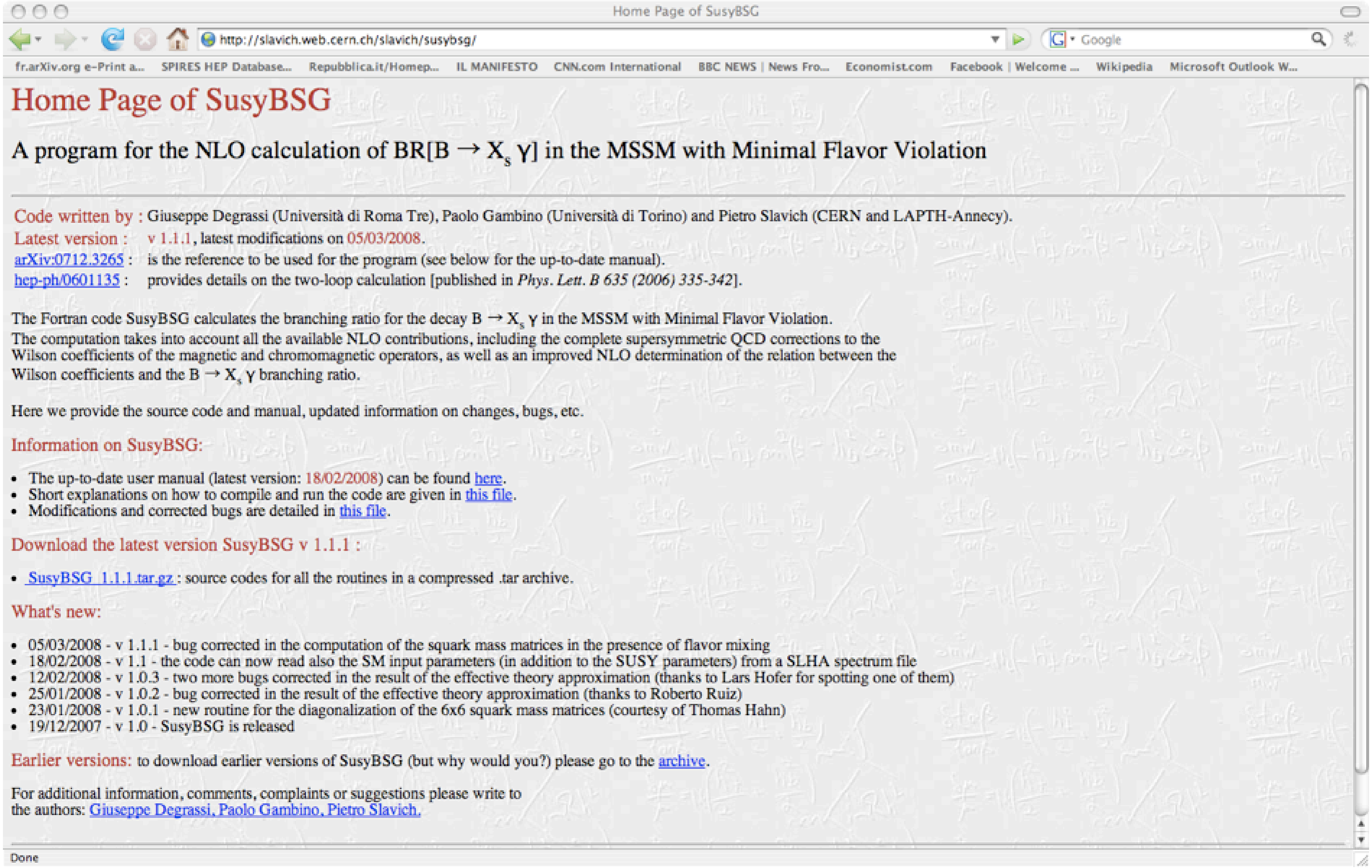
A public fortran code for the NLO calculation of $\mathrm{BR}(B \to X_s\, \gamma)$ in the MSSM with MFV

G. Degrassi, P. Gambino and P.S., arXiv:0712.3265

- The program includes our full two-loop-QCD calculation of the matching conditions
- The result of the effective-Lagrangian approximation is provided for comparison
- The program also allows to take into account at LO the effect of squark flavor mixing
- The relation between Wilson coefficients and branching ratio is computed at NLO following *P. Gambino and M. Misiak, Nucl. Phys. B611 (2001) 338* but the free scales are adjusted so as to reproduce the NNLO result in the SM

SusyBSG can be downloaded from http://cern.ch/slavich/susybsg/

The program SusyBSG



Home Page of SusyBSG

A program for the NLO calculation of BR[B → X_s γ] in the MSSM with Minimal Flavor Violation

---

Code written by : Giuseppe Degrassi (Università di Roma Tre), Paolo Gambino (Università di Torino) and Pietro Slavich (CERN and LAPTH-Annecy).
Latest version : v 1.1.1, latest modifications on 05/03/2008.
arXiv:0712.3265 : is the reference to be used for the program (see below for the up-to-date manual).
hep-ph/0601135 : provides details on the two-loop calculation [published in *Phys. Lett. B 635 (2006) 335-342*].

The Fortran code SusyBSG calculates the branching ratio for the decay B → X_s γ in the MSSM with Minimal Flavor Violation.
The computation takes into account all the available NLO contributions, including the complete supersymmetric QCD corrections to the Wilson coefficients of the magnetic and chromomagnetic operators, as well as an improved NLO determination of the relation between the Wilson coefficients and the B → X_s γ branching ratio.

Here we provide the source code and manual, updated information on changes, bugs, etc.

Information on SusyBSG:

- The up-to-date user manual (latest version: 18/02/2008) can be found here.
- Short explanations on how to compile and run the code are given in this file.
- Modifications and corrected bugs are detailed in this file.

Download the latest version SusyBSG v 1.1.1 :

- SusyBSG_1.1.1.tar.gz : source codes for all the routines in a compressed .tar archive.

What's new:

- 05/03/2008 - v 1.1.1 - bug corrected in the computation of the squark mass matrices in the presence of flavor mixing
- 18/02/2008 - v 1.1 - the code can now read also the SM input parameters (in addition to the SUSY parameters) from a SLHA spectrum file
- 12/02/2008 - v 1.0.3 - two more bugs corrected in the result of the effective theory approximation (thanks to Lars Hofer for spotting one of them)
- 25/01/2008 - v 1.0.2 - bug corrected in the result of the effective theory approximation (thanks to Roberto Ruiz)
- 23/01/2008 - v 1.0.1 - new routine for the diagonalization of the 6x6 squark mass matrices (courtesy of Thomas Hahn)
- 19/12/2007 - v 1.0 - SusyBSG is released

Earlier versions: to download earlier versions of SusyBSG (but why would you?) please go to the archive.

For additional information, comments, complaints or suggestions please write to
the authors: Giuseppe Degrassi, Paolo Gambino, Pietro Slavich.

The program SusyBSG

A public fortran code for the NLO calculation of $\mathrm{BR}(B \to X_s\, \gamma)$ in the MSSM with MFV

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SusyBSG can be downloaded from http://cern.ch/slavich/susybsg/

SusyBSG is structured in two subroutines:

WilsonCoeff computes the weak-scale matching conditions for the Wilson Coefficients

```
        call  WilsonCoeff( imod, scheme, mu0, mususy, mumfv,
     $        msq3, mstr, msbr, msql, At, Ab, mHp, mg, M2, mu, tanb,
     $        ciSM, c7SM, c8SM, ciNP, c7NP, c8NP, prob, eqmass)
```

getBR computes the branching ratio for $B \to X_s \gamma$ at NLO in QCD

```
        call  getBR( muw, mut, mub, muc, E0, ciNP, c7NP, c8NP, BR)
```

The SM and B-physics input parameters must be provided in common blocks

```
common/SMINPUTS/ mz, mw, mtpole, mbmb, hsm, asmz, azinv
common/BRINPUTS/ a0inv, mcmc, rbs, hlam, ccsl, bsl, lambda, A, rhobar, etabar
```

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```
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     $        ciSM, c7SM, c8SM, c
```

imod: choice of the model
- 0 - SM
- 1 - THDM
- 2 - MSSM - effective Lagrangian
- 3 - MSSM - full NLO
- 4 - MSSM - full NLO + LO FV

getBR computes the branching ratio fo

```
      call  getBR( muw, mut, mub, muc,
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     $        ciSM, c7SM, c8SM, ciNP
```

scheme(1): squark masses
scheme(2): MFV condition

.true. = OS, .false. = $\overline{\text{DR}}$

getBR computes the branching ratio for $B \to X_s$

```
      call  getBR( muw, mut, mub, muc, E0, ciNP, c7NP, c8NP, BR)
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SusyBSG is structured in two subroutines:

WilsonCoeff computes the weak-scale matching conditions for the Wilson Coefficients

call WilsonCoeff(imod, scheme, μ_0 , $\mu_{\rm SUSY}$, $\mu_{\rm MFV}$
\$ msq3, mstr, msbr, msql, At, Ab, mHp, mg, M2, mu, tanb,
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call WilsonCoeff(imod, scheme, mu0, mususy, mumfv,

$$m_{Q_3}\,,\quad m_T\,,\quad m_B\,,\quad m_Q\,,\quad A_t\,,\quad A_b\,,\quad m_{H^\pm}\,,\quad m_{\tilde g}\,,\quad M_2\,,\quad \mu\,,\quad \tan\beta$$

`$        ciSM, c7SM, c8SM, ciNP, c7NP, c8NP, prob, eqmass)`

getBR computes the branching ratio for $B \to X_s\,\gamma$ at NLO in QCD

call getBR(muw, mut, mub, muc, E0, ciNP, c7NP, c8NP, BR)

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WilsonCoeff computes the weak-scale matching conditions for the Wilson Coefficients

call WilsonCoeff(imod, scheme, mu0, mususy, mumfv,
$ msq3, mstr, msbr, msql, At, Ab, mHp, mg, M2, mu, tanb,
$ $C_i^{\rm SM}(\mu_0)\,, \quad C_i^{\rm NP}(\mu_0) \qquad (i=1\ldots8)$ prob, eqmass)

getBR computes the branching ratio for $B \to X_s\,\gamma$ at NLO in QCD

call getBR(muw, mut, mub, muc, E0, ciNP, c7NP, c8NP, BR)

The SM and B-physics input parameters must be provided in common blocks

common/SMINPUTS/ mz, mw, mtpole, mbmb, hsm, asmz, azinv
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getBR computes the branching ratio for $B \rightarrow X_s\,\gamma$ at NLO in QCD

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     $          ciSM, c7SM, c8SM, ciNP, c7NP, c8NP, prob, eqmass)
```

prob, eqmass(12):
flags for accidentally
similar masses

getBR computes the branching ratio for $B \to X_s \gamma$ at NLO in QC

```
      call  getBR( muw, mut, mub, muc, E0, ciNP, c7NP, c8NP, BR)
```

The SM and B-physics input parameters must be provided in common blocks

```
common/SMINPUTS/ mz, mw, mtpole, mbmb, hsm, asmz, azinv
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```

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```

getBR computes the branching ratio for $B \to X_s \gamma$ at NLO in QCD

call getBR(μ_W , μ_t , μ_b , μ_c E0, ciNP, c7NP, c8NP, BR)

The SM and B-physics input parameters must be provided in common blocks

```
common/SMINPUTS/ mz, mw, mtpole, mbmb, hsm, asmz, azinv
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```
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```

$E_\gamma > E_0$

The SM and B-physics input parameters must be provided in common blocks

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     $       ciSM, c7SM, c8SM, ciNP, c7NP, c8NP, prob, eqmass)
```

getBR computes the branching ratio for $B \to X_s\,\gamma$ at NLO in QCD

call getBR(muw, mut, mub, muc, E0, ciNP, c7NP, c8NP, $\mathrm{BR}\,[B \to X_s\,\gamma]$

The SM and B-physics input parameters must be provided in common blocks

```
common/SMINPUTS/ mz, mw, mtpole, mbmb, hsm, asmz, azinv
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```
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The SM and B-physics input parameters must be provided in common blocks

common/SMINPUTS/ $m_Z\,,\; m_W\,,\; m_t\,,\; m_b(m_b)\,,\; m_h\,,\; \alpha_s(m_Z)\,,\; \alpha(m_Z)^{-1}$

common/BRINPUTS/ a0inv, mcmc, rbs, hlam, ccsi, bsi, lambda, A, rhobar, etabar

The SM and MSSM input parameters can also be read from a SLHA/SLHA2 spectrum file

SusyBSG is structured in two subroutines:

WilsonCoeff computes the weak-scale matching conditions for the Wilson Coefficients

```
      call  WilsonCoeff( imod, scheme, mu0, mususy, mumfv,
     $        msq3, mstr, msbr, msql, At, Ab, mHp, mg, M2, mu, tanb,
     $        ciSM, c7SM, c8SM, ciNP, c7NP, c8NP, prob, eqmass)
```

getBR computes the branching ratio for $B \to X_s \gamma$ at NLO in QCD

```
      call  getBR( muw, mut, mub, muc, E0, ciNP, c7NP, c8NP, BR)
```

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```
common/SMINPUTS/ mz, mw, mtpole, mbmb, hsm, asmz, azinv
common/BRINPUTS/ a0inv, mcmc, rbs, hlam, ccsl, bsl, lambda, A, rhobar, etabar
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common/BR $\alpha(m_0)^{-1}\,,\ m_c(m_c)\,,\ m_s/m_b\,,\ \lambda_2\,,\ C\,,\ \mathrm{BR}[b \to X_c\, e\nu]\,,\ \lambda\,,\ A\,,\ \bar\rho\,,\ \bar\eta$

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Summary

- SM prediction and exp. measurement of $\mathrm{BR}(B \to X_s\,\gamma)$ agree very well, putting severe constraints on the flavor structure of any New Physics model
- In the MSSM large contributions to $\mathrm{BR}(B \to X_s\,\gamma)$ can arise even with MFV
- To achieve a theoretical accuracy even remotely comparable to that of the experimental results we must compute the SUSY-QCD contributions at NLO
- The program SusyBSG provides the most complete NLO calculation (so far) of $\mathrm{BR}(B \to X_s\,\gamma)$ in the MSSM with Minimal Flavor Violation

Thank you!!!

Spare parts: renormalization of flavor mixing

Start from the gluino-quark-squark Lagrangian in the super-CKM basis

$$\mathcal{L} \;\supset\; -\,g_s\,T^a\,\sqrt{2}\,\Big(\bar{\tilde{g}}^a\,b_L\,\tilde{b}_L^* - \bar{\tilde{g}}^a\,b_R\,\tilde{b}_R^* + \bar{\tilde{g}}^a\,s_L\,\tilde{s}_L^*\Big) + \text{h.c.}$$

The mixing matrices for quarks and squarks have to be renormalized

$$\begin{pmatrix} \tilde{d}_1 \\ \tilde{d}_2 \\ \tilde{d}_3 \end{pmatrix} = (U^r + \delta U) \begin{pmatrix} \tilde{b}_L \\ \tilde{b}_R \\ \tilde{s}_L \end{pmatrix} \qquad \begin{pmatrix} d_{1\,L} \\ d_{2\,L} \end{pmatrix} = (u^{L\,r} + \delta u^L) \begin{pmatrix} b_L \\ s_L \end{pmatrix}$$

The MFV condition is imposed at the level of the renormalized matrices

$$U^r = \begin{pmatrix} B & 0 \\ 0 & 1 \end{pmatrix} = \begin{pmatrix} \cos\theta_{\tilde{b}} & \sin\theta_{\tilde{b}} & 0 \\ -\sin\theta_{\tilde{b}} & \cos\theta_{\tilde{b}} & 0 \\ 0 & 0 & 1 \end{pmatrix} \qquad u^{L\,r} = \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix}$$

But the counterterm matrices are not flavor diagonal!!!

The mixing counterterms induce flavor-changing gluino interactions that we insert in the one-loop gluino diagrams to cancel the poles in the two-loop diagrams

$$\mathcal{L} \supset -g_s\, T^a \sqrt{2} \left[(\delta U^\dagger_{3i} + B^\dagger_{1i}\, \delta u^L_{21})\, \overline{s_L}\, g^a\, \tilde{b}_i \right.$$
$$\left. +(\delta U_{31} - \delta u^L_{21})\, \bar{g}^a\, b_L\, \tilde{s}^*_L - \delta U_{32}\, \bar{g}^a\, b_R\, \tilde{s}^*_L \right] + \text{h.c.}$$

The counterterms are required to cancel the poles in the antihermitian part of the WFR

$$\delta u^L_{21} = -\frac{1}{2} \left[\Sigma^L_{sb}(0) + 2\, \Sigma^S_{sb}(0) \right] \;, \qquad \delta U_{ik} = \frac{1}{2}\, \Sigma_{j\neq i}\, \frac{\Pi_{ij}(m_j^2) + \Pi^*_{ji}(m_i^2)}{m_i^2 - m_j^2}\, U_{jk}$$

The interpretation of MFV depends on what we do with the finite parts of the self-energies:

- drop: MFV is imposed on the running Lagrangian parameters at a scale $\mu_{\rm MFV}$
- keep: MFV is imposed “on shell” (whatever that means ;-)

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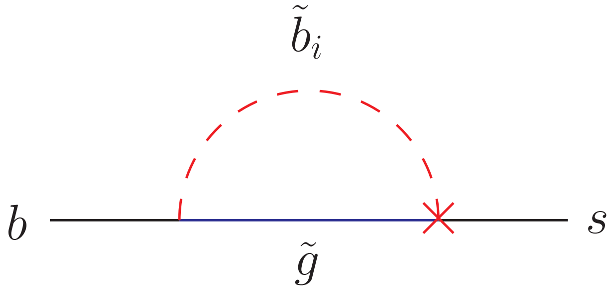

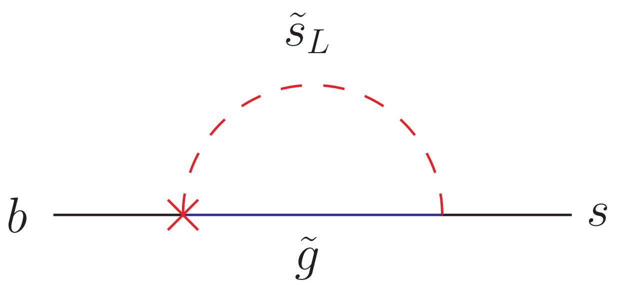

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