XSUSY
A multipurpose program for calculations in SUSY models with non-minimal flavour violation

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Outline

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Constrained minimal flavour violation (= *usual MSSM*)

[Ciuchini, Degrassi, Gambino, Giudice (1998)]

- Squared sfermion mass matrices:

$$M^2_{\tilde{F}} = \begin{pmatrix} M^2_{LL,1} & 0 & 0 & m_1\, m_{LR,1} & 0 & 0 \\ 0 & M^2_{LL,2} & 0 & 0 & m_2\, m_{LR,2} & 0 \\ 0 & 0 & M^2_{LL,3} & 0 & 0 & m_3\, m_{LR,3} \\ m_1\, m_{RL,1} & 0 & 0 & M^2_{RR,1} & 0 & 0 \\ 0 & m_2\, m_{RL,2} & 0 & 0 & M^2_{RR,2} & 0 \\ 0 & 0 & m_3\, m_{RL,3} & 0 & 0 & M^2_{RR,3} \end{pmatrix}$$

  * All flavour-violating elements of $M^2_{\tilde{F}}$ are zero.
  * Sfermion mixing: $(\tilde{f}_L,\, \tilde{f}_R) \Rightarrow (\tilde{f}_1,\, \tilde{f}_2)$ with flavour conservation.
  * Small first- and second-generation fermion masses: $m_1, m_2 \longrightarrow 0$.
  * Three flavour-conserving mixing angles, $\theta_{\tilde{t}}$, $\theta_{\tilde{b}}$ and $\theta_{\tilde{\tau}}$.

- Flavour violation in the squark sector
  * Flavour violation is governed by the CKM matrix, within the interactions.
  * e.g. chargino-squark up-quark bottom vertex proportional to V_{ub}.

Non-minimal flavour violation

[Gabbiani, Gabrielli, Masiero, Silvestrini (1996)]

- The squared squark mass matrices are

$$M^2_{\tilde{Q}} = \begin{pmatrix} M^2_{LL,1} & \Delta^{12}_{LL} & \Delta^{13}_{LL} & m_1\, m_{LR,1} & \Delta^{12}_{LR} & \Delta^{13}_{LR} \\ \Delta^{21}_{LL} & M^2_{LL,2} & \Delta^{23}_{LL} & \Delta^{21}_{RL} & m_2\, m_{LR,2} & \Delta^{23}_{LR} \\ \Delta^{31}_{LL} & \Delta^{32}_{LL} & M^2_{LL,3} & \Delta^{31}_{RL} & \Delta^{32}_{RL} & m_3\, m_{LR,3} \\ m_1\, m_{RL,1} & \Delta^{12}_{RL} & \Delta^{13}_{RL} & M^2_{RR,1} & \Delta^{12}_{RR} & \Delta^{13}_{RR} \\ \Delta^{21}_{LR} & m_2\, m_{RL,2} & \Delta^{23}_{RL} & \Delta^{21}_{RR} & M^2_{RR,2} & \Delta^{23}_{RR} \\ \Delta^{31}_{LR} & \Delta^{32}_{LR} & m_3\, m_{RL,3} & \Delta^{31}_{RR} & \Delta^{32}_{RR} & M^2_{RR,3} \end{pmatrix}.$$

  * The off-diagonal elements are 24 new free parameters, parameterized by

$$\Delta^{qq'}_{ij} = \lambda^{qq'}_{ij}\, M_{ii,q} M_{jj,q'}.$$

  * Diagonalization through 6×6 rotation matrices R^u and R^d.

- Physical eigenstates given by

$$(\tilde{u}_1, \tilde{u}_2, \tilde{u}_3, \tilde{u}_4, \tilde{u}_5, \tilde{u}_6)^T = R^u (\tilde{u}_L, \tilde{c}_L, \tilde{t}_L, \tilde{u}_R, \tilde{c}_R, \tilde{t}_R)^T,$$
$$(\tilde{d}_1, \tilde{d}_2, \tilde{d}_3, \tilde{d}_4, \tilde{d}_5, \tilde{d}_6)^T = R^d (\tilde{d}_L, \tilde{s}_L, \tilde{b}_L, \tilde{d}_R, \tilde{s}_R, \tilde{b}_R)^T.$$

Constraints on non-minimal flavour violation

- FCNC: upper limits on λ's.
  - * Neutral kaon sector (Δm_K, ε, ε'/ε)
  - * B-meson oscillations,
  - * D-meson oscillations (Δm_D),
  - * Rare decays (BR($b \to s\gamma$), BR($\mu \to e\gamma$), BR($\tau \to e\gamma$), BR($\tau \to \mu\gamma$)),
  - * Electric dipole moments (d_n and d_e).

  [Gabbiani, Gabrielli, Masiero, Silvestrini (1996)]

  [Ciuchini, Masiero, Paradisi, Silvestrini, Vempati, Vives (2007)]

  [Bozzi, BF, Herrmann, Klasen (2007)]

- Cosmological constraints: upper limits on λ's
  - * Color singlet and electrically neutral LSP $\Rightarrow$ dark matter candidate.
    [Ellis *et al.* (1984)]
  - * Dark matter relic density
    (WMAP, SDSS, SNLS, and Baryon Acoustic Oscillations data)
    [Hamann, Hannestad, Sloth, Wong (2007)]

Tools needed for a complete NMFV study

- Inputs
  - SM parameters.
  - Reduced number of SUSY parameters at GUT scale.
  - NMFV parameters at low-energy scale.
- Outputs:
  - Are NMFV SUSY models experimentally viable?
    $\Rightarrow$ Analysis of the allowed parameter space.
  - What is the flavour content of the physical particles?
    $\Rightarrow$ Analysis of the flavour structure in the squark sector.
  - Are hadron colliders sensible to NMFV?
    $\Rightarrow$ Dependence of the production cross sections on flavour violation.
    $\Rightarrow$ Dependence of the decay widths on flavour violation.

Existing and missing tools

- From GUT scale to EW scale
  - Solution to the renormalization group equations.
  - `SPheno` 2.2.3 [Porod (2003)], `SuSpect` 2.34 [Djouadi, Kneur, Moultaka (2007)],... (only constrained Minimal Flavour Violation (cMFV) scenarios.)
- Introduction of NMFV at low energy:
  - Generalized squark mass matrices, SUSY spectrum and mixing matrices.
  - `FeynHiggs` 2.5.1. [Heinemeyer, Hollik, Weiglein (2000)].
- Constraints:
  - Low energy and EW constraints in cMFV: `FeynHiggs`, `SPheno`, `SuSpect`.
  - Low energy and EW constraints in NMFV: `FeynHiggs`.
  - Dark matter relic density in cMFV: `DarkSUSY` 4.1 [Gondolo *et al.* (2004)],...
- Missing pieces:
  - Dark matter relic density in NMFV.
  - Production cross sections.
  - Decays widths.

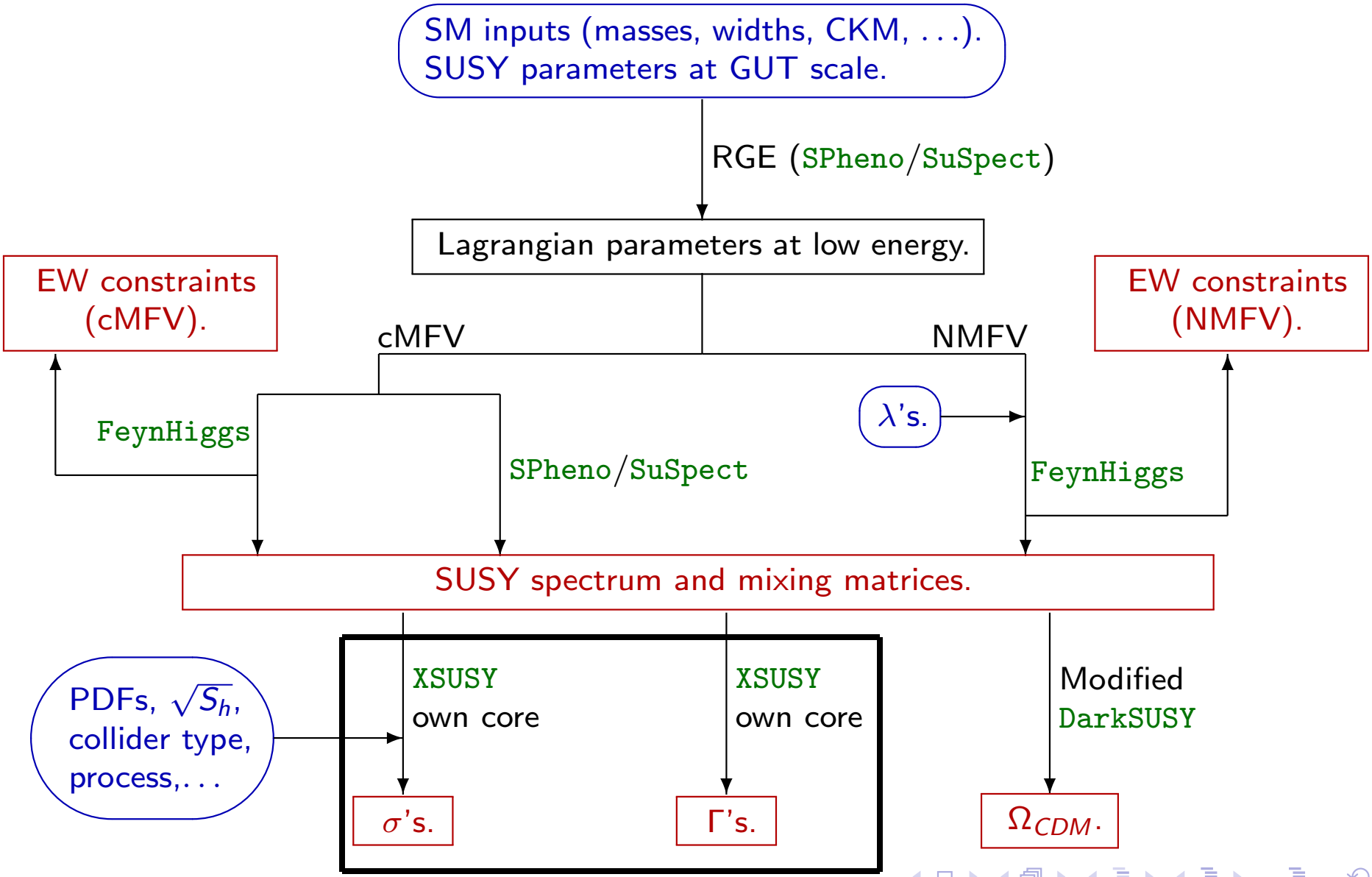
Outline

The XSUSY approach

Current version: `XSUSY` 1.8.0 [BF, *in preparation*]

- Evolution from the GUT scale to the EW scale in cMFV:
  - `SPheno` or `SuSpect`.
- SUSY spectrum and mixing matrices:
  - `FeynHiggs` (NMFV).
  - `FeynHiggs`, `SPheno` or `SuSpect` (cMFV).
- Low-energy and electroweak constraints:
  - `FeynHiggs` (NMFV and cMFV).
- Dark matter relic density (NMFV and cMFV):
  - Modified `DarkSUSY`.
- Production cross sections and decay widths:
  - Own XSUSY core (NMFV and cMFV).

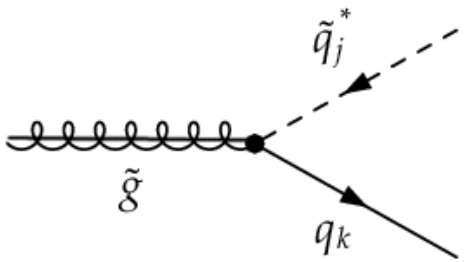
Scheme of the program



NMFV couplings

- Flavour violating couplings:
  - * $\tilde{q} - q - \tilde{\chi}$,
  - * $\tilde{q} - q - \tilde{g}$,
  - * $\tilde{q} - \tilde{q} - \phi$,
  - * $\tilde{q} - \tilde{q} - V$

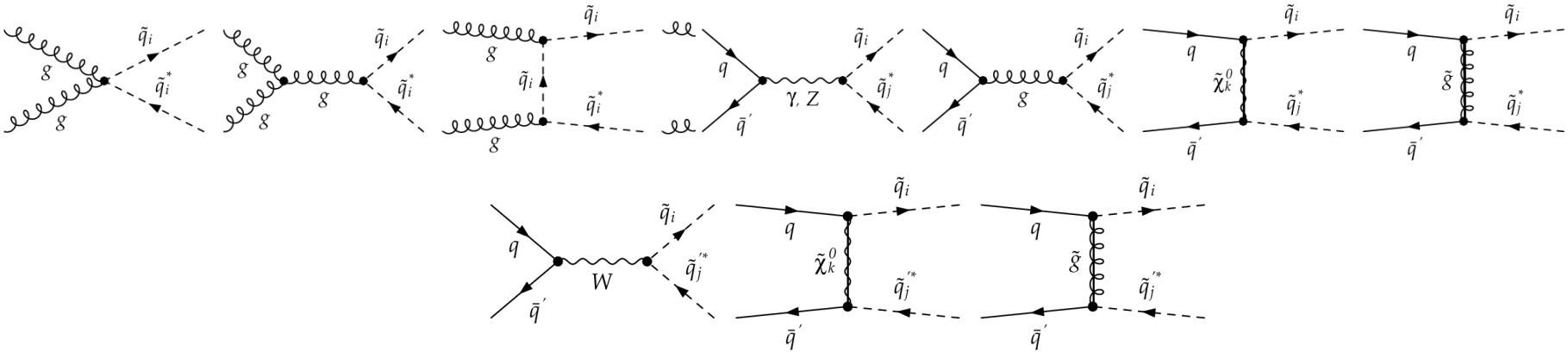
  .
- Example: squark-quark-gluino coupling



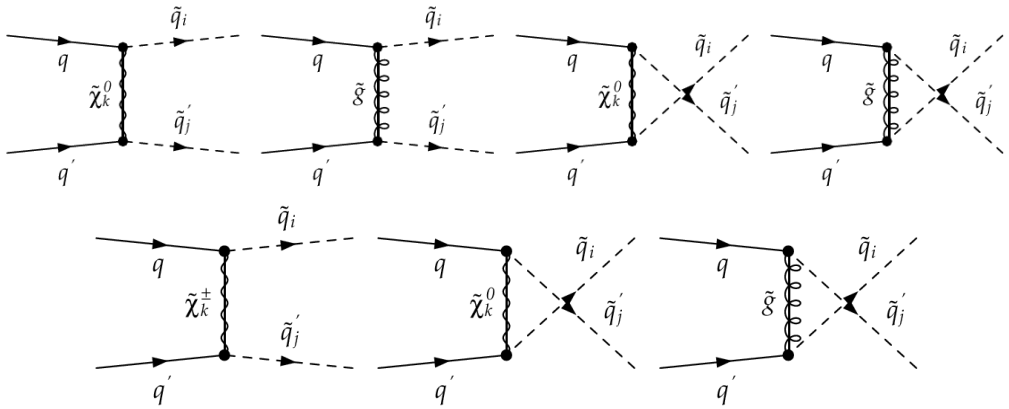
* MSSM: non zero coupling
  - $\Leftrightarrow$ same squark and quark flavour,
  - $\Leftrightarrow$ proportional to $\cos\theta_{\tilde{q}}$, $\sin\theta_{\tilde{q}}$.
* NMFV SUSY:
  - $\Leftrightarrow$ any squark and quark flavour,
  - $\Leftrightarrow$ proportional to R^q_{jk}, $R^q_{j(k+3)}$.

Cross sections (1)

- Squark-antisquark pair production: neutral and charged currents

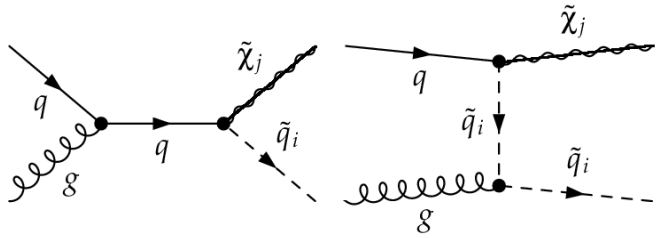


- Squark-squark pair production: same and different isospins

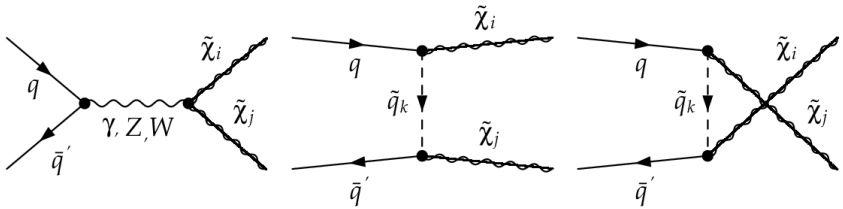


Cross sections (2)

- Associated gaugino-squark production



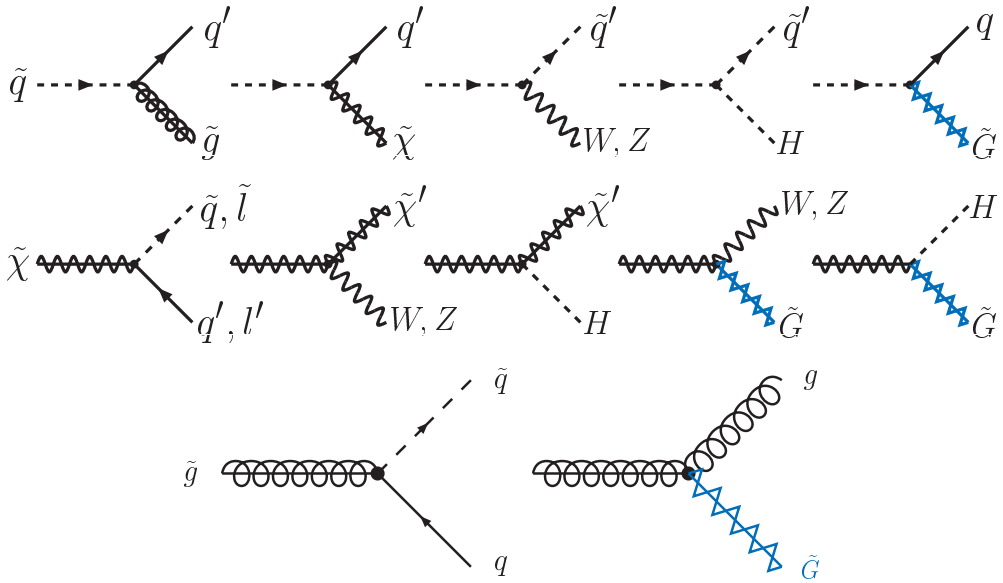
- Gaugino pair production



* All LO QCD and EW diagrams.
* Compact expressions for cross sections $\Rightarrow$ form factors.

2-body decay widths

- Squark, gaugino and gluino decays:



* Gravitino, Higgses and (s)leptons included.

Outline

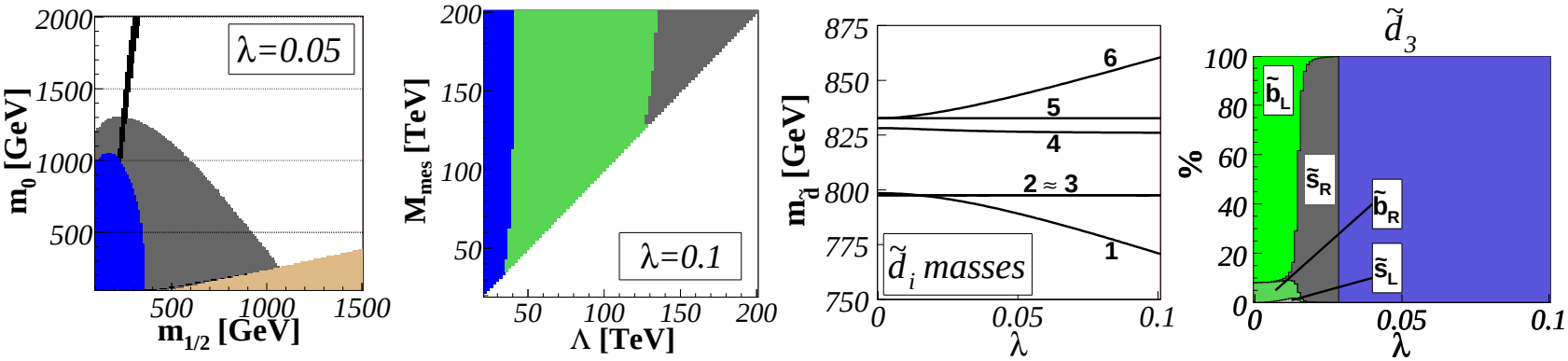
Simplified NMFV scenario

- The squared squark mass matrices are approximated

$$M^2_{\tilde{Q}} = \begin{pmatrix} M^2_{LL,1} & 0 & 0 & m_1\, m_{LR,1} & 0 & 0 \\ 0 & M^2_{LL,2} & \lambda M_{LL,2} M_{LL,3} & 0 & m_2\, m_{LR,2} & 0 \\ 0 & \lambda M_{LL,2} M_{LL,3} & M^2_{LL,3} & 0 & 0 & m_3\, m_{LR,3} \\ m_1\, m_{RL,1} & 0 & 0 & M^2_{RR,1} & 0 & 0 \\ 0 & m_2\, m_{RL,2} & 0 & 0 & M^2_{RR,2} & 0 \\ 0 & 0 & m_3\, m_{RL,3} & 0 & 0 & M^2_{RR,3} \end{pmatrix} .$$

- One single parameter λ both for up-type and down-type sectors.
- Complete phenomenological study:
  see Björn Herrmann's talk in *Colliders* session.

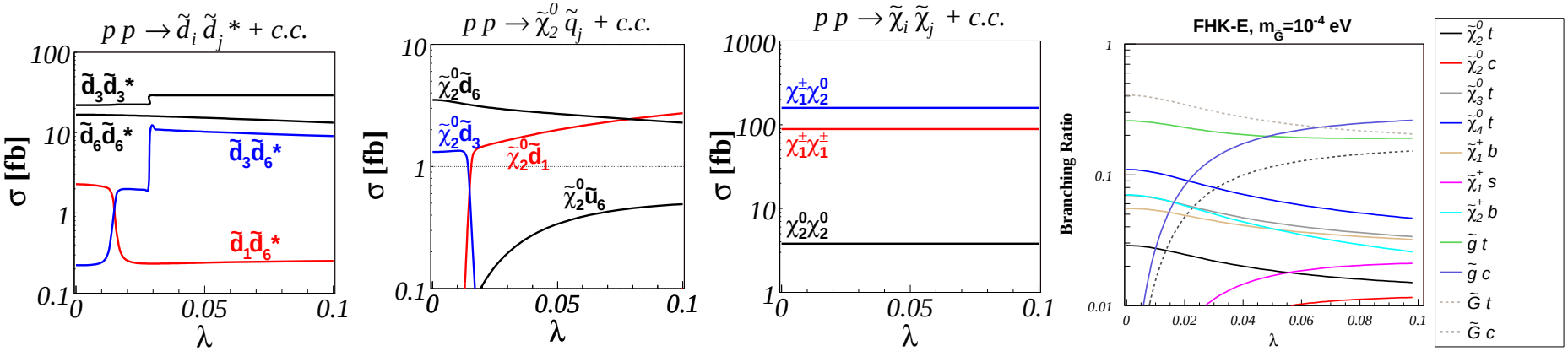
Parameter space and flavour structure



[Bozzi, BF, Herrmann, Klasen (2007); BF, Herrmann, Klasen (*in prep.*)]

- mSUGRA parameter space scan (first plot: $\tan\beta = 10, \mu > 0, A_0 = 0$ GeV).
  $\Rightarrow$ EW: a_μ-favoured (grey) and $b \to s\gamma$-excluded (blue) regions.
  $\Rightarrow$ Cosmo: regions with a charged LSP (beige), favoured by Ω_{CDM} (black).
- GMSB parameter space scan (second plot: $\tan\beta = 15, \mu > 0, N_{\rm mes} = 3$).
  $\Rightarrow$ EW: a_μ-favoured (green) and $b \to s\gamma$-excluded (blue) regions.
- Flavour structure analysis (third and fourth figures).
  $\Rightarrow$ Mass dependence on NMFV.
  $\Rightarrow$ Avoided crossings.
  $\Rightarrow$ Dependence of the flavour content on NMFV.

Production cross sections and decay widths



[Bozzi, BF, Herrmann, Klasen (2007); BF, Herrmann, Klasen (*in prep.*)]

- Production cross sections (3 first figures, BFHK-B benchmark point).
  ⇒ Avoided crossings in the flavour structure ⇔ sharp transitions (flips) in σ.
  ⇒ Smooth dependence in the flavour structure ⇔ smooth variations of σ.
  ⇒ Reduced dependence on λ due to summation over the mass eigenstates.
- Decay widths (fourth figure, FHK-E benchmark point).
  ⇒ Dominant channels depend on NMFV.

Outline

Summary and outlook

- `XSUSY` is a multipurpose program to study NMFV SUSY models.
  - Interface with `DarkSUSY`, `FeynHiggs`, `SPheno` and `SuSpect`.
  - mSUGRA, GMSB and AMSB scenarios implemented.
  - Allows for a detailed analysis of the NMFV parameter space.
  - Allows for a detailed analysis of the squark sector flavour structure.
  - LO cross sections for (most of) all sparticle pair-production processes.
  - All SUSY particles two-body decays at LO.
- Current status (version 1.8.0):
  - Writing of the manual: $\sim$ 10% done.
  - Public version of the code: $\sim$80% done.
  - Finalized public version: $\sim$ March 2008.
- To do list:
  - Three-body decays.
  - Remaining cross sections.
  - Next-to-leading order
  - Full experimental study
    (heavy-flavour tagging efficiencies, detector resolutions, background,...)
    $\Rightarrow$ Complete understanding of flavour violating effects.
    $\Rightarrow$ Sensitivity of colliders to NMFV.