The non-minimal flavour-violating MSSM: Constraints and Phenomenology

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Outline

1. Introduction to Supersymmetry and flavour violation
2. Constraints on the MSSM
3. Benchmark points for the mSUGRA model
4. Flavour violation in GMSB scenarios
5. Production of superpartners at the LHC
6. Conclusion and Perspectives

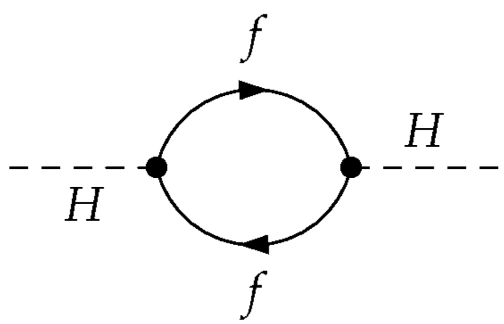
Introduction: SUSY and Flavour Violation

Motivations for physics beyond the Standard Model

Particle physics: Standard Model rather "low-energy" limit of a more fundamental theory

☑ "Hierarchy problem"

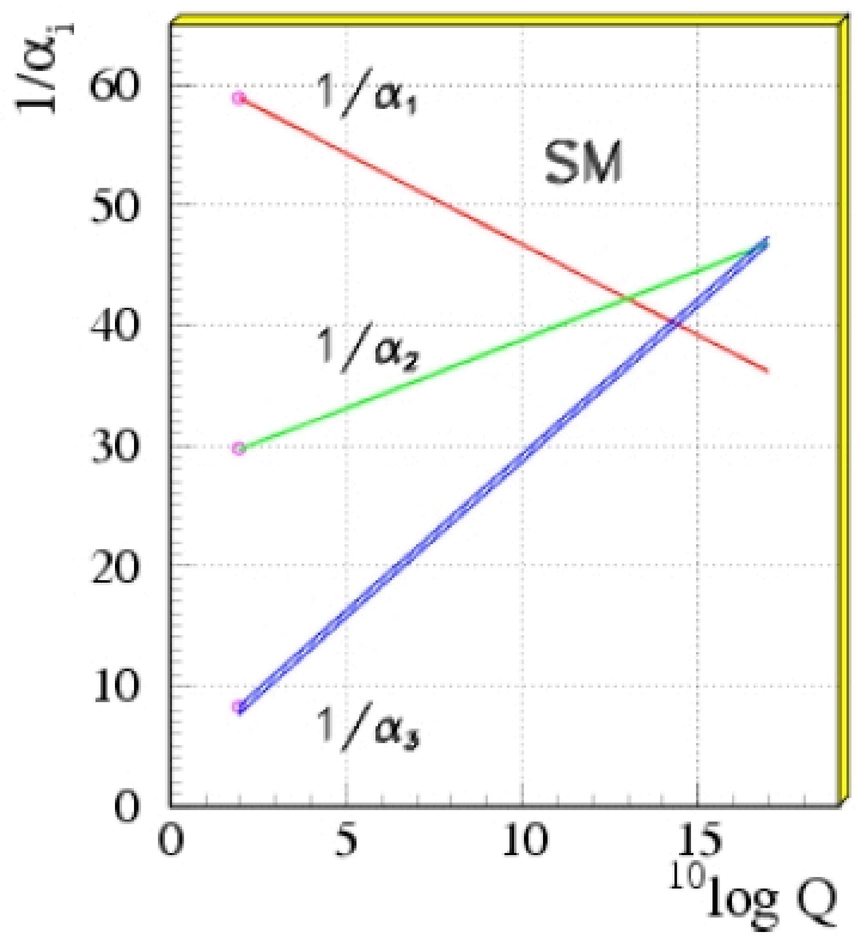
Higgs mass receives quadratically divergent fermionic loop corrections [Witten 1981, Kaul 1982]



$$\Delta m_H^2 = \frac{|\lambda_f|^2}{16\pi^2}\left[-2\ \Lambda_{\rm UV}^2 + 6m_f^2 \log\frac{\Lambda_{\rm UV}}{m_f} + \dots\right]$$

☑ Gauge coupling unification

Running coupling constants should meet in single point if corresponding interactions unify



☑ Gravity

Cannot be ignored at energies near the Planck scale

☑ "Aesthetic" reasons

Number of parameters in Standard Model, ...

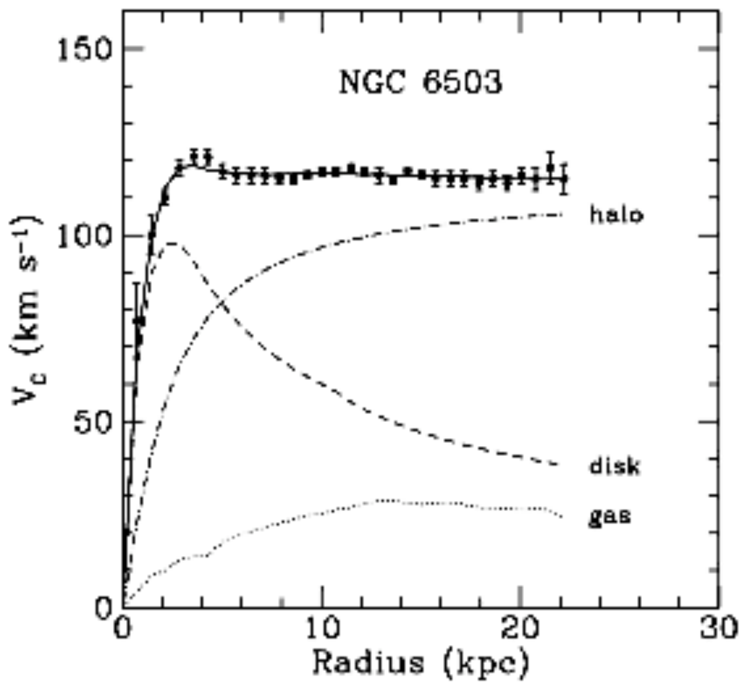
Motivations for physics beyond the Standard Model

Cosmology: Standard Model does not include candidate for cold dark matter

First observational hints

Velocity dispersion and rotation curves

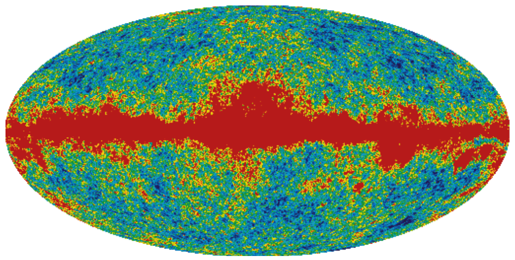
[Zwicky 1933, Rubin *et al.* 1970]



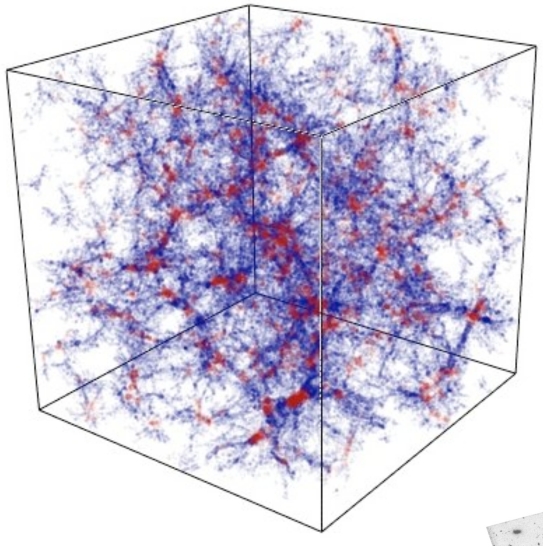
CMB anisotropies

Cosmological parameters from WMAP mission

[Komatsu *et al.* (WMAP) 2008]



$$\Omega_{\rm tot} = 1.005 \pm 0.034$$
$$\Omega_{\rm CDM} = 0.223 \pm 0.013$$



Structure formation

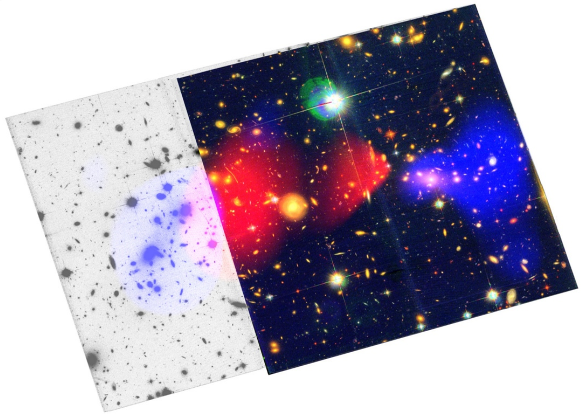
Cold dark matter needed to explain large structures

[Blumenthal *et al.* 1984]

First direct observation

Observation of "Bullet Cluster" proofs existence of dark matter

[Clowe *et al.* 2006]



Supersymmetry and the MSSM

Supersymmetry relates bosons and fermions

$$\mathcal{Q}\,|b\rangle = |f\rangle \qquad \mathcal{Q}\,|f\rangle = |b\rangle$$

Minimal supersymmetric theory including the Standard Model particles

SM Particles		Spin		Spin		Superpartners
Quarks	$(u_L \;\; d_L)$	$1/2$	Q	0	$(\tilde{u}_L \;\; \tilde{d}_L)$	Squarks
	$u_R^\dagger$	$1/2$	$\bar{u}$	0	$\tilde{u}_R^*$	
	$d_R^\dagger$	$1/2$	$\bar{d}$	0	$\tilde{d}_R^*$	
Leptons	$(\nu \;\; e_L)$	$1/2$	L	0	$(\tilde{\nu} \;\; \tilde{e}_L)$	Sleptons
	$e_R^\dagger$	$1/2$	$\bar{e}$	0	$\tilde{e}_R^*$	
Higgs	$(H_u^+ \;\; H_u^0)$	0	H_u	$1/2$	$(\tilde{H}_u^+ \;\; \tilde{H}_u^0)$	Higgsinos
	$(H_d^0 \;\; H_d^-)$	0	H_d	$1/2$	$(\tilde{H}_d^0 \;\; \tilde{H}_d^-)$	
Gluon	g	1		$1/2$	$\tilde{g}$	Gluino
W bosons	$W^0, W^\pm$	1		$1/2$	$\tilde{W}^0, \tilde{W}^\pm$	Winos
B boson	B^0	1		$1/2$	$\tilde{B}^0$	Bino
Graviton	G	2		$3/2$	$\tilde{G}$	Gravitino

Supersymmetry Breaking

No superpartners observed so far: Supersymmetry broken at the electroweak scale

Supersymmetry breaking occurs at scale $\langle F \rangle$ in some "hidden" sector and is mediated to the "observable" sector through a shared interaction

"Soft" Supersymmetry breaking terms are included in the Lagrangian at the electroweak scale

$$\begin{aligned}
\mathcal{L}_{\text{soft}} \quad = \quad & -\frac{1}{2}\Big(M_1 \tilde{B}\tilde{B} + M_2 \tilde{W}\tilde{W} + M_3 \tilde{g}\tilde{g} + \text{h.c.}\Big) \\
& -\Big(\tilde{Q}^\dagger \mathbf{m_Q^2} \tilde{Q} + \tilde{\bar{u}} \mathbf{m_{\bar{u}}^2} \tilde{\bar{u}}^\dagger + \tilde{\bar{d}} \mathbf{m_{\bar{d}}^2} \tilde{\bar{d}}^\dagger + \tilde{L}^\dagger \mathbf{m_L^2} \tilde{L} + \tilde{\bar{e}} \mathbf{m_{\bar{e}}^2} \tilde{\bar{e}}^\dagger\Big) \\
& -\Big(m_{H_u}^2 H_u^* H_u + m_{H_d}^2 H_d^* H_d + b\big(H_u H_d + \text{h.c.}\big)\Big) \\
& -\Big(\tilde{\bar{u}} \mathbf{a_u} \tilde{Q} H_u - \tilde{\bar{d}} \mathbf{a_d} \tilde{Q} H_d - \tilde{\bar{e}} \mathbf{a_e} \tilde{L} H_e + \text{h.c.}\Big)
\end{aligned}$$

124 *a priori* free parameters at the electroweak scale,
often restricted to a few universal parameters at the grand unification scale

Minimal Supergravity (mSUGRA)

Supersymmetry breaking mediated to observable sector through gravity

Observable sector
(MSSM particles)

Hidden sector
(SUSY breaking)

Parameters at the low scale are obtained from universal parameters at the high scale through renormalization group running

$$\begin{aligned} M_3 = M_2 = M_1 &= m_{1/2} \\ \mathbf{m^2_Q} = \mathbf{m^2_{\bar{u}}} = \mathbf{m^2_{\bar{d}}} = \mathbf{m^2_L} = \mathbf{m^2_{\bar{e}}} &= m_0^2 \mathbf{1} \\ m^2_{H_u} = m^2_{H_d} &= m_0^2 \\ \mathbf{a}_i &= A_0 \mathbf{y}_i \qquad \text{for } i = u, d, e \end{aligned}$$

Five universal parameters at the SUSY breaking scale: $m_0, \; m_{1/2}, \; A_0, \; \tan\beta, \; \mathrm{sgn}(\mu)$

Flavour dependent gravitational interaction gives rise to important flavour violating terms in the Lagrangian at low energy (FCNC), in contradiction to current measurements

→ "flavour problem" in Supersymmetry

Gauge-Mediated Supersymmetry Breaking (GMSB)

Supersymmetry breaking mediated to observable sector through gauge interactions

[Giudice & Rattazzi 1999]

Observable sector (MSSM particles)	Messenger sector (messengers fields)	Hidden sector (SUSY breaking)

Important FCNC naturally suppressed, since gauge interactions are "flavour-blind"

Masses of MSSM particles stem from messenger loops

$$M_i = \frac{\alpha_i}{4\pi} \Lambda \, g(x) \, \left(N_5 + 3N_{10}\right) \qquad x = \frac{\Lambda}{M_{\rm mes}}$$

$$m^2_{\tilde{j}} = 2 \sum_{i=1}^{3} \frac{\alpha_i^2}{16\pi^2} \Lambda^2 \, f(x) \, \left(N_5 + 3N_{10}\right) C_{ij}$$

Five parameters at the SUSY breaking scale:

$$\Lambda = \frac{\langle F_S \rangle}{\langle S \rangle}, \;\; M_{\rm mes}, \;\; N_{\rm mes}, \;\; \tan\beta, \;\; {\rm sgn}(\mu)$$

No physical solutions to the RGE if $\Lambda > M_{\rm mes}$

Higgs and Gaugino Sectors

Cancellation of chiral anomalies requires two complex Higgs doublets

→ five physical Higgs bosons after electroweak symmetry breaking: $h^0, \; H^0, \; A^0, \; H^+, \; H^-$

All parameters of the Higgs sector are related to the key parameters tanβ and m_A

$$
\begin{aligned}
m^2_{h^0,H^0} &= \frac{1}{2}\left(m_A^2 + m_Z^2 \mp \sqrt{\left(m_A^2 + m_Z^2\right)^2 - 4 m_A^2 m_Z^2 \cos 2\beta} \right) \\
m_A^2 &= \frac{2b}{\sin 2\beta} \\
m^2_{H^\pm} &= m_A^2 + m_W^2
\end{aligned}
$$

After breaking of *SU(2)xU(1)*, the neutral higgsinos and gauginos mix, giving rise to four neutralinos

$$
\begin{aligned}
\tilde{\chi}^0_i &= \mathcal{N}_{i1}\tilde{B}^0 + \mathcal{N}_{i2}\tilde{W}^0 + \mathcal{N}_{i3}\tilde{H}^0_d + \mathcal{N}_{i4}\tilde{H}^0_u \\
\mathrm{diag}(m_{\tilde{\chi}^0_1}, m_{\tilde{\chi}^0_2}, m_{\tilde{\chi}^0_3}, m_{\tilde{\chi}^0_4}) &= \mathcal{N}^* \mathcal{M}_{\tilde{\chi}^0} \mathcal{N}^{-1}
\end{aligned}
$$

In the same way, the charged higgsinos and $W^\pm$ mix, resulting in the charginos $\widetilde{\chi}^\pm_{1,2}$

Being the only fermionic octet, the gluino cannot mix with other particles

Sfermion Sector and Flavour Violation

Squared sfermion mass matrices at the electroweak scale

$$M^2_{\tilde{q}} = \left(\begin{array}{ccc|ccc} M^2_{L_1} & \Delta^{12}_{\rm LL} & \Delta^{13}_{\rm LL} & m_1 X_1 & \Delta^{12}_{\rm LR} & \Delta^{13}_{\rm LR} \\ \Delta^{12*}_{\rm LL} & M^2_{L_2} & \Delta^{23}_{\rm LL} & \Delta^{12*}_{\rm RL} & m_2 X_2 & \Delta^{23}_{\rm LR} \\ \Delta^{13*}_{\rm LL} & \Delta^{23*}_{\rm LL} & M^2_{L_3} & \Delta^{13*}_{\rm RL} & \Delta^{23*}_{\rm RL} & m_3 X_3 \\ \hline m_1 X_1^* & \Delta^{12}_{\rm RL} & \Delta^{13}_{\rm RL} & M^2_{R_1} & \Delta^{12}_{RR} & \Delta^{13}_{RR} \\ \Delta^{12*}_{\rm LR} & m_2 X_2^* & \Delta^{23}_{\rm RL} & \Delta^{12*}_{RR} & M^2_{R_2} & \Delta^{23}_{RR} \\ \Delta^{13*}_{\rm LR} & \Delta^{23*}_{\rm LR} & m_3 X_3^* & \Delta^{13*}_{RR} & \Delta^{23*}_{RR} & M^2_{R_3} \end{array}\right)$$

In the minimal model, flavour violation arises through rotation of gauge eigenstates into physical mass eigenstates and different renormalizations of quarks and squarks

Minimal flavour violation (MFV): $\Delta^{qq'}_{ij}$ deduced from CKM-matrix

Constrained minimal flavour violation (cMFV): only diagonal entries, $\Delta^{qq'}_{ij} = 0$

Neglect helicity mixing for 1st and 2nd generations and introduce mixing angles for 3rd generation

$$\begin{aligned} \mathrm{diag}(m^2_{\tilde{f}_1}, m^2_{\tilde{f}_2}) &= \mathcal{R}^{\tilde{f}} \mathcal{M}_{\tilde{f}} \mathcal{R}^{\tilde{f}\dagger} \\ (\tilde{f}_1, \tilde{f}_2)^T &= \mathcal{R}^{\tilde{f}} (\tilde{f}_L, \tilde{f}_R)^T \end{aligned} \qquad \mathcal{R}^{\tilde{f}} = \begin{pmatrix} \cos\theta_{\tilde{f}} & \sin\theta_{\tilde{f}} \\ -\sin\theta_{\tilde{f}} & \cos\theta_{\tilde{f}} \end{pmatrix}$$

Non-Minimal Flavour Violation in the Squark Sector

New sources of flavour violation can appear when embedding SUSY in larger structures

[Gabbiani & Masiero 1989]

Flavour violating entries no longer deduced from the CKM-matrix alone

Convenient parametrization for non-minimal flavour violation (NMFV): 24 free parameters $\Delta_{ij}^{qq'}$

Normalization to diagonal entries

$$\boxed{\Delta_{ij}^{qq'} = \lambda_{ij}^{qq'} M_i M_j}$$

Non-minimal flavour violation governed by 24 *a priori* free parameters $\lambda_{ij}^{qq'}$ [Gabbiani *et al.* 1996]

Flavour mixing between 2nd and 3rd generations least constrained [Gabbiani *et al.* 1996, Ciuchini *et al.* 2007]

In gravity-mediation scenarios: $\Delta_{\rm LL} \gg \Delta_{\rm LR,RL} \gg \Delta_{\rm RR}$ [Gabbiani & Masiero 1989]

In gauge-mediation scenarios: $\Delta_{\rm LL,RR} \gg \Delta_{\rm LR,RL}$ due to small A-terms [Dittmaier *et al.* 2007]

Diagonalization of the mass matrices involves two 6x6 rotation matrices

$$\begin{aligned} \mathrm{diag}\left(m_{\tilde{q}_1}^2, m_{\tilde{q}_2}^2, m_{\tilde{q}_3}^2, m_{\tilde{q}_4}^2, m_{\tilde{q}_5}^2, m_{\tilde{q}_6}^2\right) &= \mathcal{R}^{\tilde{q}} \mathcal{M}_{\tilde{q}}^2 \mathcal{R}^{\tilde{q}\dagger} \\ \left(\tilde{q}_1, \tilde{q}_2, \tilde{q}_3, \tilde{q}_4, \tilde{q}_5, \tilde{q}_6\right)^T &= \mathcal{R}^{\tilde{q}} \left(\tilde{q}_{1L}, \tilde{q}_{2L}, \tilde{q}_{3L}, \tilde{q}_{1R}, \tilde{q}_{2R}, \tilde{q}_{3R}\right)^T \end{aligned}$$

All relevant couplings have to be generalized to take into account the 6x6 matrices $\mathcal{R}^{\tilde{u}}$ and $\mathcal{R}^{\tilde{d}}$

R-Parity and Dark Matter

Additional symmetry in the MSSM in order to avoid possible proton decay

$$\tau_p \gtrsim 10^{29}\ \mathrm{yr} \simeq 10^{19} a_0$$

Definition of R-parity related to baryon and lepton numbers

$$\boxed{P_R = (-1)^{3(B-L)+2s}} = \begin{cases} +1 & \text{for Standard Model particles} \\ -1 & \text{for their superpartners} \end{cases}$$

R-parity conservation has important phenomenological implications

Only vertices involving an even number of superpartners allowed

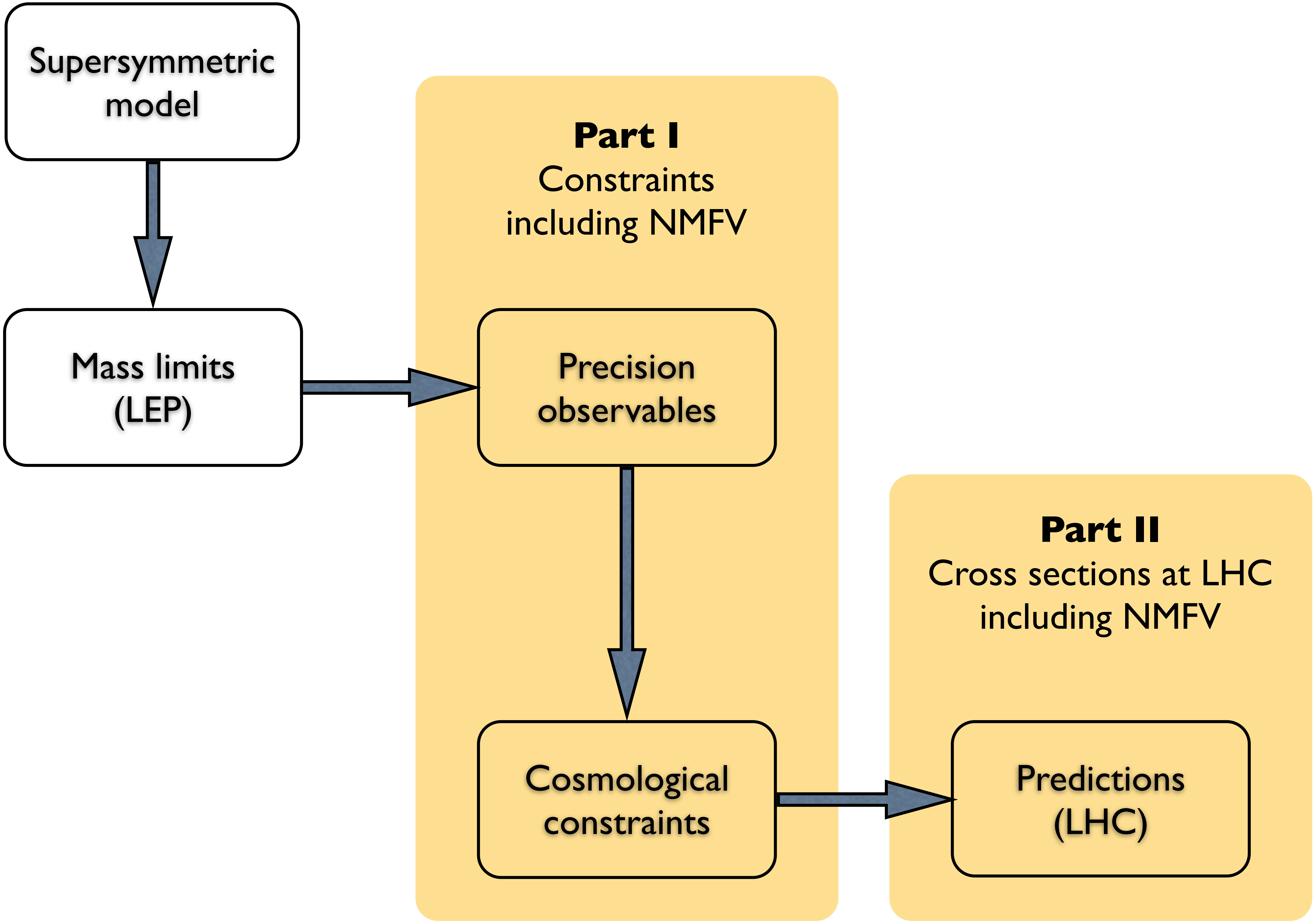
→ supersymmetric particles always produced in pairs

→ lightest supersymmetric particle (LSP) cannot decay and must be stable

Dark matter candidate ("WIMP") must be massive, stable, neutral in electric charge and colour

→ Two candidates within the MSSM: Lightest neutralino (mSUGRA)
Gravitino (GMSB)

Phenomenological Strategy



Constraints and Benchmark Points

Electroweak Precision and Low-Energy Observables

Decay b→sγ

Squarks enter calculation already at the one-loop level, sensitive to flavour violation
Strongly constrained by precision measurements at BaBar, Belle, and CLEO

$$\mathrm{BR}(b \to s\gamma) \;=\; \big(3.55 \pm 0.26\big) \cdot 10^{-4}$$

[Barbiero *et al.* (HFAG) 2006]

Theoretical accuracy: two-loop QCD / one-loop SUSY-QCD [Hahn *et al.* 2005, Kagan *et al.* 1998]

Electroweak ρ-parameter

Relates self-energies of W and Z bosons at zero external momentum
Sensitive to squark mass splitting and thus also to squark flavour violation

$$\Delta\rho \;=\; \frac{\Sigma_Z(0)}{m_Z^2} - \frac{\Sigma_W(0)}{m_W^2} \;=\; \big(1.02 \pm 0.86\big) \cdot 10^{-3}$$

[Yao *et al.* (PDG) 2007]

Theoretical accuracy: two-loop cMFV / one-loop NMFV [Heinemeyer *et al.* 2004]

Anomalous magnetic moment of the muon

Two-loop squark contribution suppressed with respect to one-loop slepton diagrams

$$\Delta a_\mu \;=\; a_\mu^{\rm exp} - a_\mu^{\rm SM} \;=\; \big(29.2 \pm 8.6\big) \cdot 10^{-10}$$

[Yao *et al.* (PDG) 2007]

Theoretical accuracy: two-loop level [Heinemeyer *et al.* 2004]
SUSY one-loop contribution favours positive values of μ [Moroi 1996]

Cosmological Constraints

Dark matter relic density required to agree with WMAP+SN+BAO data

$$0.1097 \leq \Omega_{\mathrm{CDM}} h^2 \leq 0.1165$$

[Hinshaw *et al.* (WMAP) 2008]

Further constraints for gravitino dark matter

Nature of dark matter related to gravitino mass

"hot"	"warm"	"cold"
$m_{\tilde{G}} \lesssim 1$ keV	$1 \text{ keV} \lesssim m_{\tilde{G}} \lesssim 100$ keV	$m_{\tilde{G}} \gtrsim 100$ keV

$m_{\tilde{G}}$

Gravitino relic density receives contributions from thermal production and NLSP decay

[Bolz *et al.* 2001]

$$\Omega^{\mathrm{th}}_{\tilde{G}} h^2 \sim \frac{T_{\mathrm{R}}}{m_{\tilde{G}}} m^2_{\tilde{g}} \qquad\qquad \Omega^{\mathrm{non-th}}_{\tilde{G}} h^2 = \frac{m_{\tilde{G}}}{m_{\mathrm{NLSP}}} \Omega^{\mathrm{th}}_{\mathrm{NLSP}} h^2$$

NLSP lifetime has to preserve abundances of light elements in the Universe [Pradler & Steffen 2007]

$$\tau_{\mathrm{NLSP}} \sim \frac{m^2_{\tilde{G}}}{m^5_{\mathrm{NLSP}}} \lesssim 2 \cdot 10^3 \text{ s}$$

Leptogenesis may explain the cosmic baryon asymmetry, but favours high reheating temperatures

[Buchmüller *et al.* 2007]

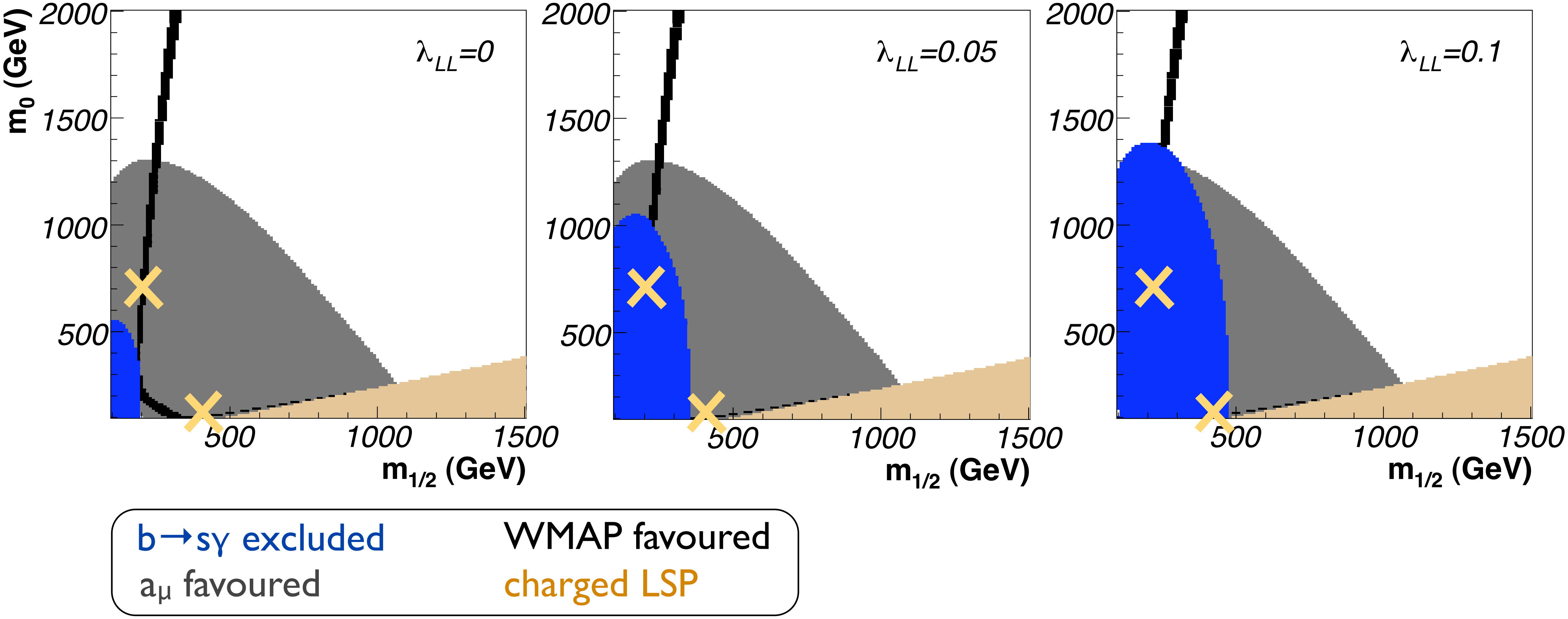
$$T_{\mathrm{R}} \gtrsim 10^9 \text{ GeV}$$

Scans of the mSUGRA Parameter Space

Impose constraints at 2σ on m_0-$m_{1/2}$ plane for fixed tanβ, A_0, and sgn(μ)

Renormalization group running: SPheno 2.2.3 [Porod 2004]
Physical mass spectrum and constraints: FeynHiggs 2.5.1 [Heinemeyer *et al.* 2000]
Neutralino relic density: DarkSUSY 4.1 (NMFV-adapted)

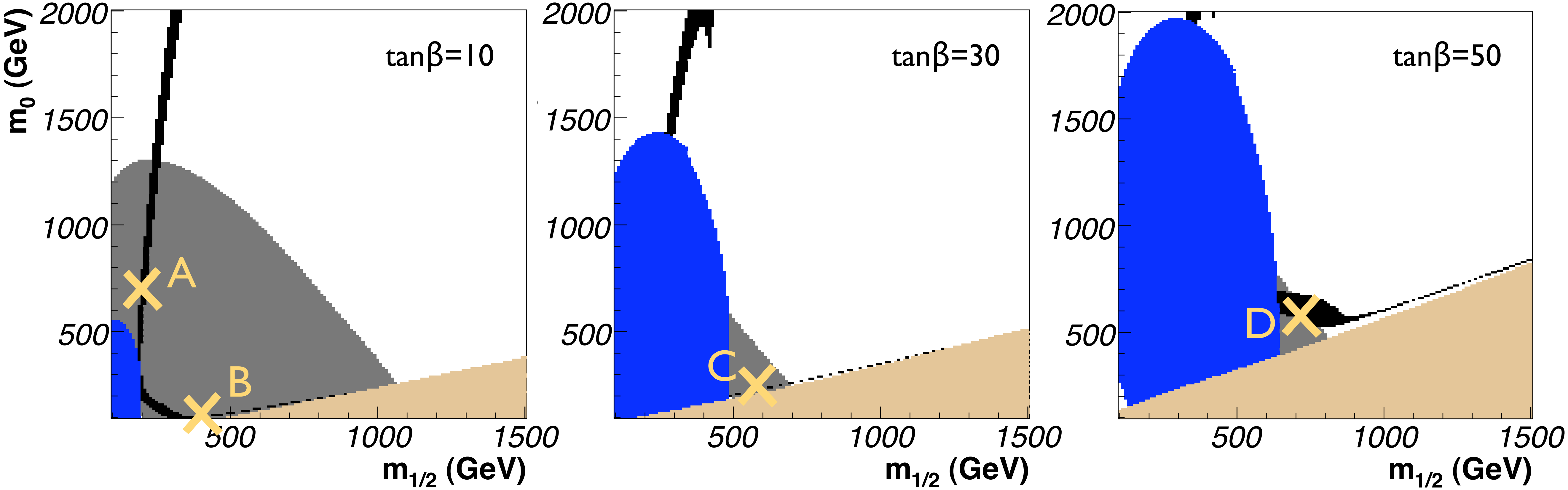
Example: tanβ=10, A_0=0, μ>0, λ_{LL}=0...0.1



Benchmark Points for mSUGRA

Define four "collider-friendly" benchmark points allowing for flavour violation

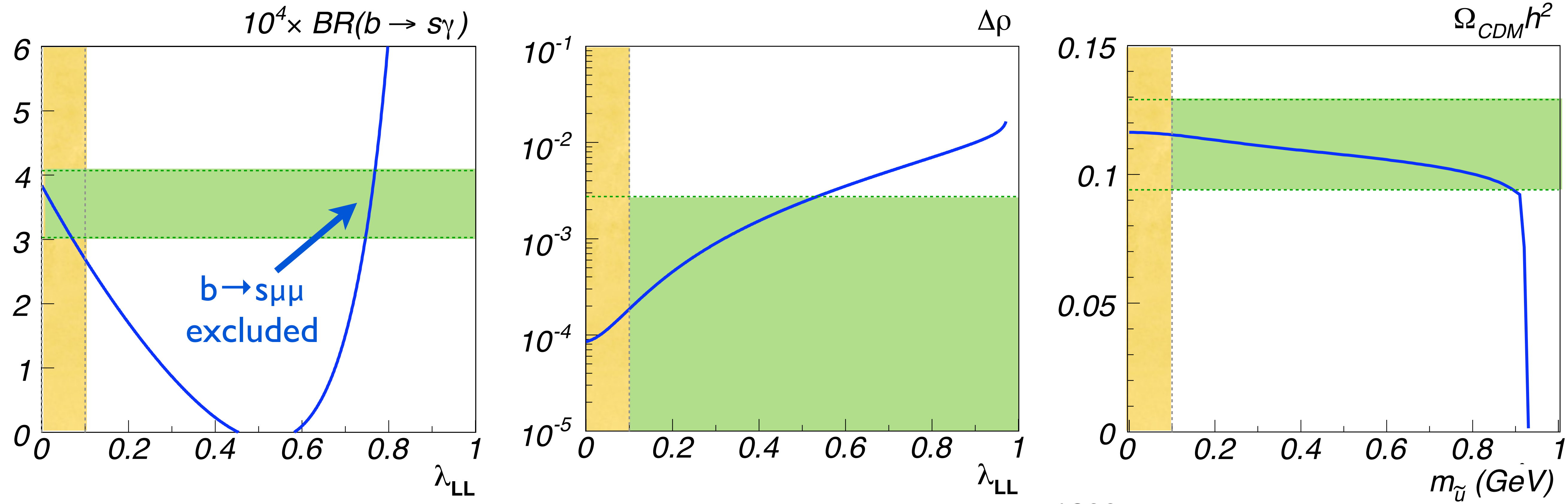
	m_0 (GeV)	$m_{1/2}$ (GeV)	A_0	$\tan\beta$	sgn(μ)	SPS
A	700	200	0	10	+	2
B	100	400	0	10	+	3
C	230	590	0	30	+	1b
D	600	700	0	50	+	4



Benchmark points are valid in the vicinity of cMFV ($\lambda_{LL} \approx 0 \ldots 0.1$)

Phenomenology of Point B

Study constraints and mass eigenvalues as function of flavour violation parameter λ_{LL}



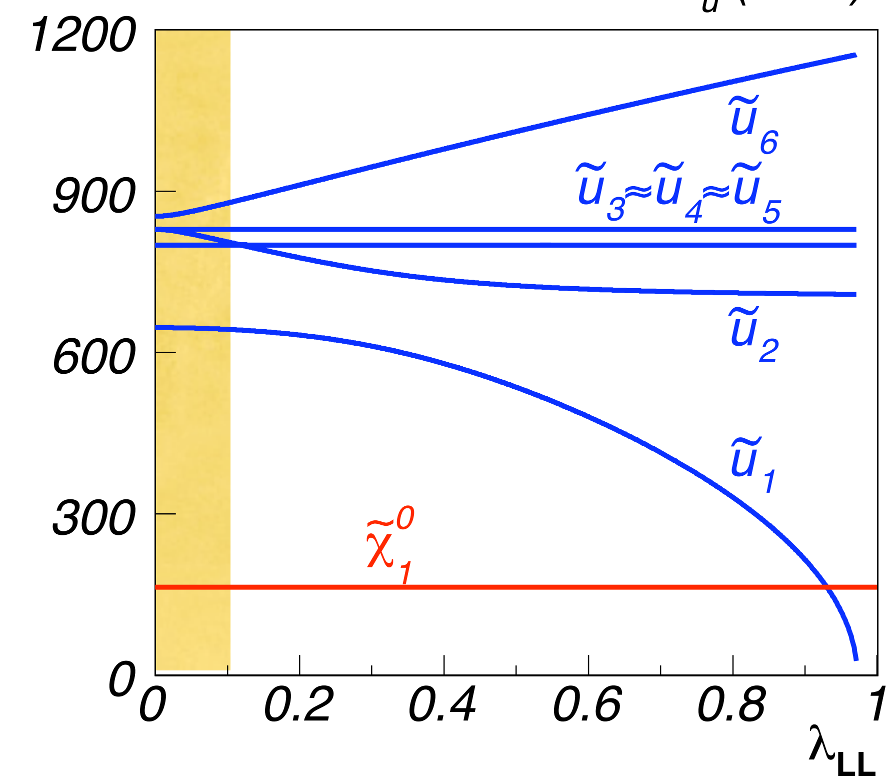
a_μ independent of λ_{LL} (not shown)

Allowed range for λ_{LL} from b→sγ: $\lambda_{LL} \lesssim 0.1$

Experimental errors of $\Delta\rho$ allow for large interval

Important splitting of mass eigenvalues for large λ_{LL}

Small mass difference between $\tilde{\chi}_1$ and $\tilde{u}_1$ at large λ_{LL}
→ $\Omega_{CDM}h^2$ falls due to important coannihilations and light squark propagated annihilation processes



Scans of the Minimal GMSB Parameter Space

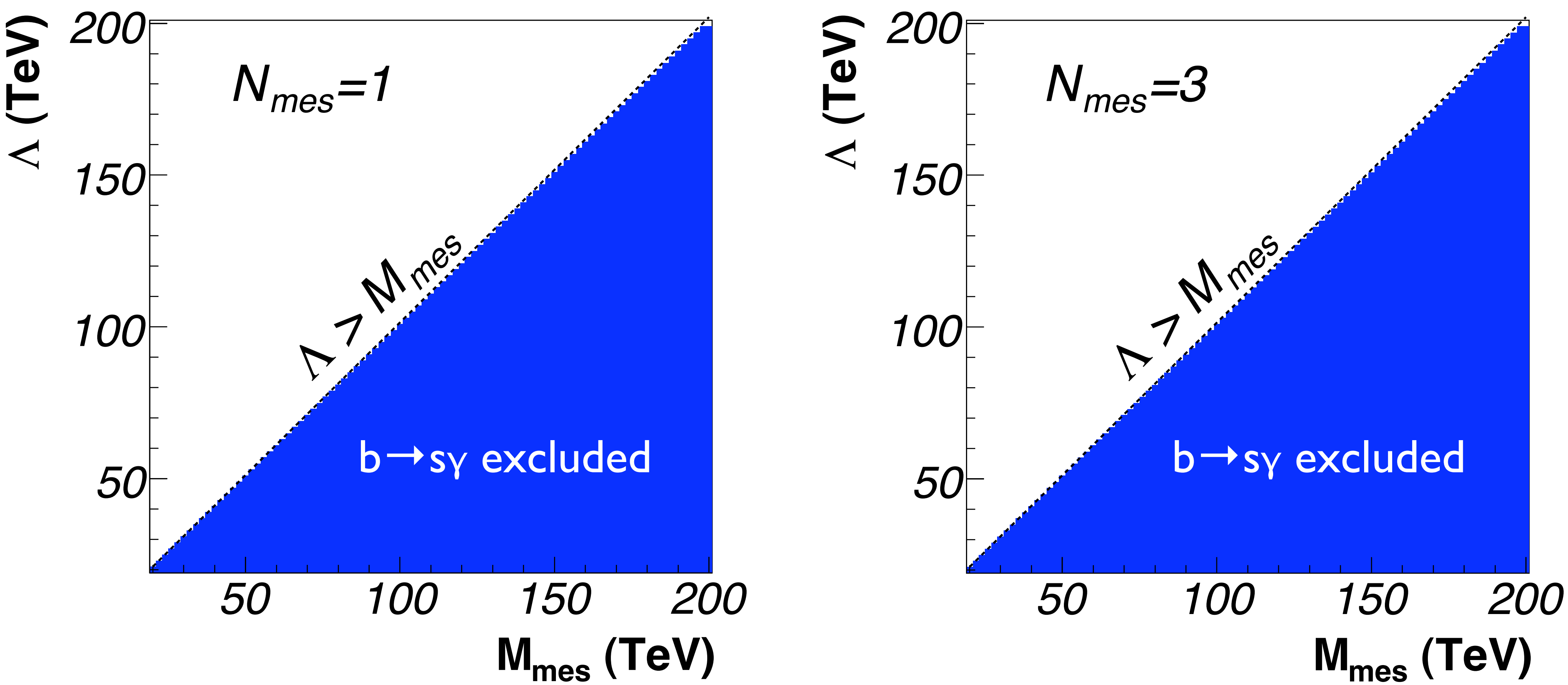
Impose constraints at 2σ on Λ-M_{mes} plane for fixed $\tan\beta$, N_{mes}, and sgn(μ)

Renormalization group running: SPheno 2.2.3 [Porod 2004]

Physical mass spectrum and constraints: FeynHiggs 2.6.4 [Heinemeyer *et al.* 2000]

Remember: Flavour violation naturally suppressed in minimal GMSB models

Example: $\tan\beta$=15



"Collider-friendly" regions excluded by $b\to s\gamma$ constraint for all $\tan\beta$ and N_{mes}

Flavour Violation in GMSB Models

Several possibilities reintroduce flavour violation in GMSB models

[Giudice & Rattazzi 1999, Tobe *et al.* 2004, Dubovsky & Gorbunov 1999]

We consider mixing between messenger and matter fields

→ two possible scenarios depending on nature of messengers [Dubovsky & Gorbunov 1999]

☑ Fundamental messengers (5 and $\overline{5}$ representations of *SU(5)*)

Carry quantum numbers of left-handed leptons and right-handed quarks

→ induce flavour violation in the sector of right-handed sleptons and left-handed squarks

$$\lambda_{\rm LL} > 0 \qquad \lambda_{\rm RR} = 0$$

☑ Antisymmetric messengers (10 and $\overline{10}$ representations of *SU(5)*)

Carry quantum numbers of right-handed leptons and left-handed quarks

→ flavour violation in the sector of left-handed sleptons and left- & right-handed squarks

$$\lambda_{\rm LL} = \lambda_{\rm RR} > 0$$

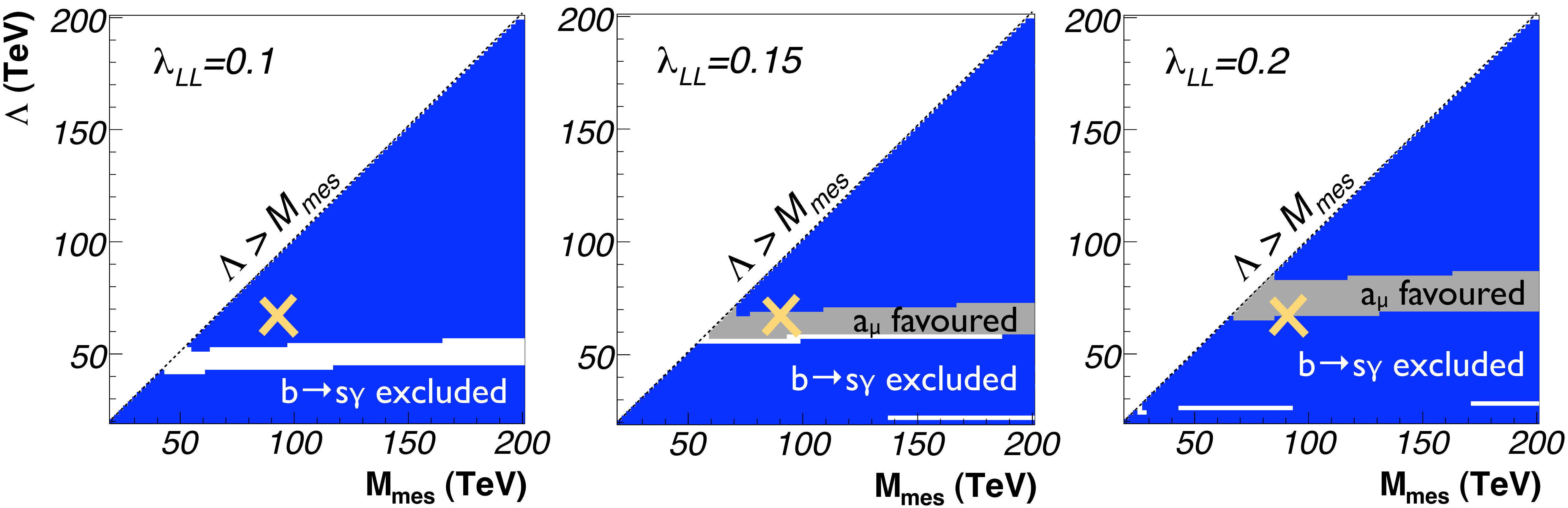
For *SU(2)* gauge invariance and simplicity: $\lambda^{sb}_{\rm LL} = \lambda^{sb}_{\rm RR} = \lambda^{ct}_{\rm LL} = \lambda^{ct}_{\rm RR}$

In gauge-mediated scenarios: $\Delta_{\rm LL,RR} \gg \Delta_{\rm RL,LR}$ due to small A-terms [Dittmaier *et al.* 2007]

Scans of the Minimal GMSB Parameter Space

Re-scan parameter space and impose constraints at 2σ

Example: N_{mes}=1, tanβ=15, μ>0, λ_{RR}=0



Flavour mixing between 2nd and 3rd generation squarks opens allowed and favoured windows in the GMSB parameter space

No significant differences between the two implementations of flavour violation

Benchmark Points for GMSB

Define six "collider-friendly" benchmark points allowing for flavour violation

	Λ	M_{mes}	N_{mes}	$\tan\beta$	$\mathrm{sgn}(\mu)$	λ_{LL}	NLSP	SPS
E	65 TeV	90 TeV	1	15	+	[0.14, 0.20]	$\tilde{\chi}^0_1$	8
F	30 TeV	80 TeV	3	15	+	[0.12, 0.18]	$\tilde{\tau}_1$	7
G	100 TeV	110 TeV	1	30	+	[0.14, 0.20]	$\tilde{\tau}_1$	–
H	45 TeV	100 TeV	3	30	+	[0.12, 0.18]	$\tilde{\tau}_1$	–
I	130 TeV	140 TeV	1	50	+	[0.14, 0.20]	$\tilde{\tau}_1$	–
J	60 TeV	100 TeV	3	50	+	[0.14, 0.20]	$\tilde{\tau}_1$	–

Benchmark points not valid for (constrained) minimal flavour violation

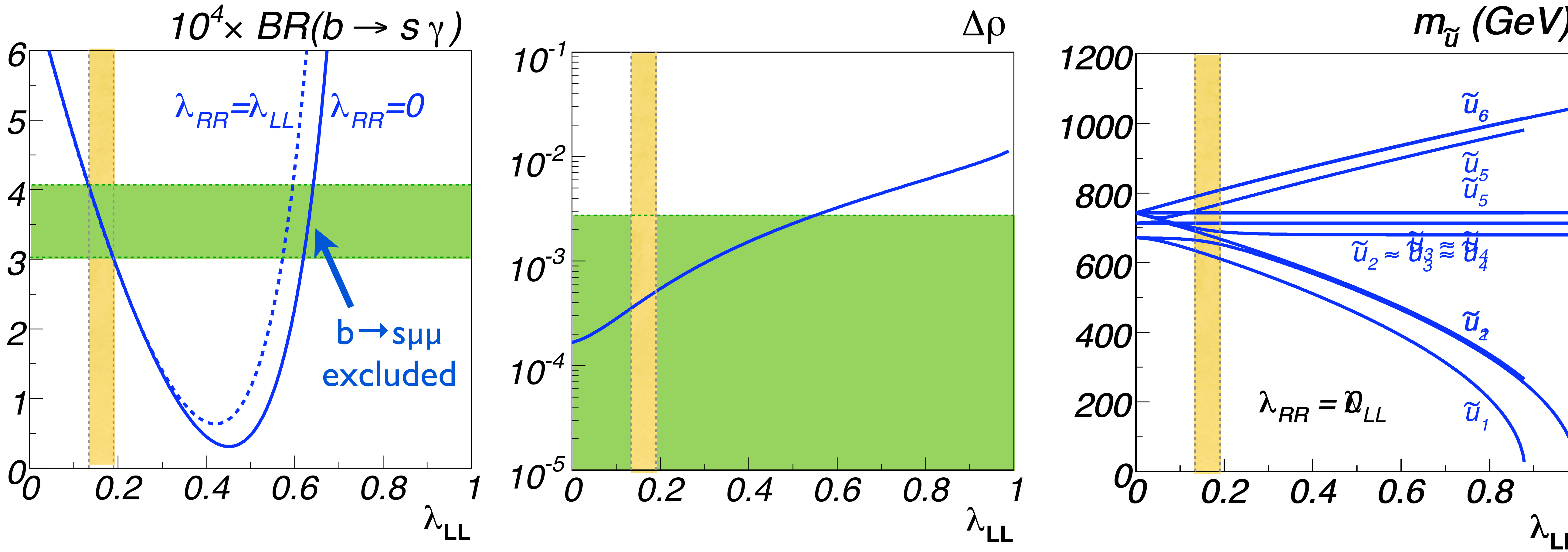
→ indicate valid range for flavour violation parameter λ_{LL}

Scenarios differ in nature of NLSP and number of particles that are close in mass

Flavour violation through mixing with either fundamental or antisymmetric messengers

Phenomenology of Point E

Study constraints and mass eigenvalues as function of flavour violation parameter λ_{LL}



Allowed range for flavour violation parameter determined from $b \to s\gamma$

$$0.14 \leq \lambda_{\rm LL} \leq 0.20$$

Main difference between the two flavour violation scenarios in the splitting of mass eigenvalues

"Avoided crossings" of mass eigenvalues with corresponding changes in flavour contents

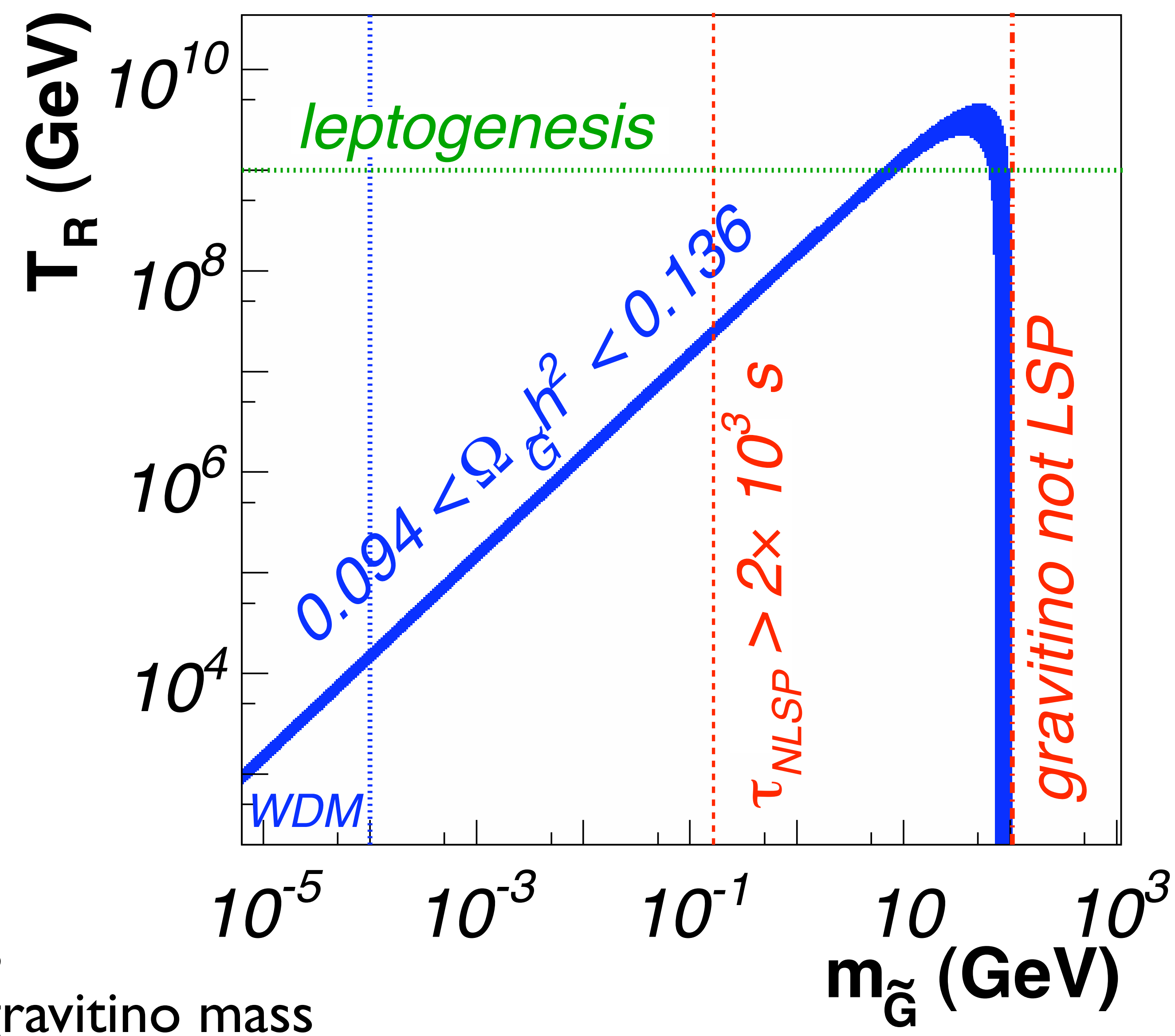
Cosmological Constraints in GMSB

Gravitino mass has to lead to cosmologically viable configuration

Constraints involve given masses of gluino and NLSP
Determine allowed regions in the $m_{\tilde{G}} - T_R$ plane

Example: Point E

$$\begin{aligned} m_{\tilde{\chi}_1^0} &= 95.4 \text{ GeV} \\ \Omega_{\tilde{\chi}} h^2 &= 0.1275 \\ m_{\tilde{g}} &= 534.2 \text{ GeV} \end{aligned}$$



All constraints cannot be fulfilled together

Allow for lower reheating temperatures
and set gravitino mass

$$m_{\tilde{G}} \sim 10^{-1} \text{ GeV}$$

Similar situation for the other benchmark points,
leading to the same order of magnitude for the gravitino mass

Supersymmetric Particle Production at the LHC

Cross Section Calculation

QCD factorization theorem: Convolution of partonic cross section with parton densities

$$\sigma \;=\; \underbrace{\int_{t_-}^{t_+} \mathrm{d}t}_{\text{Phase space}} \; \underbrace{\int_{4m^2/s}^{1} \mathrm{d}\tau \int_{-1/2\ln\tau}^{1/2\ln\tau} \mathrm{d}y}_{\text{Convolution}} \; \underbrace{f_{a/A}(x_a, M_a^2)\; f_{b/B}(x_b, M_b^2)}_{\text{Parton density functions (PDF)}} \; \boxed{\frac{\mathrm{d}\hat{\sigma}}{\mathrm{d}t}}$$

$$x_{a,b} = \sqrt{\tau}e^{\pm y}$$

Unpolarized cross sections obtained by averaging over initial state spins

$$\boxed{\mathrm{d}\hat{\sigma} \;=\; \frac{1}{4}\Big[\mathrm{d}\hat{\sigma}_{1,1} + \mathrm{d}\hat{\sigma}_{1,-1} + \mathrm{d}\hat{\sigma}_{-1,1} + \mathrm{d}\hat{\sigma}_{-1,-1}\Big]}$$

Analytical expressions for helicity-depending partonic production cross sections in non-minimal flavour violating Supersymmetry [Bozzi, Fuks, Herrmann, Klasen 2007; Fuks, Herrmann, Klasen 2008]

Numerical examples of squark and gaugino production cross sections for benchmark scenario H

- → "light" quark masses neglected with respect to $\sqrt{s} = 14$ TeV
- → leading order CTEQ6 global parton density fit
- → running strong and weak coupling constants
- → set scales to average final state mass $\mu_R = M_a = M_b = \dfrac{m_1 + m_2}{2}$

Partonic Cross Sections

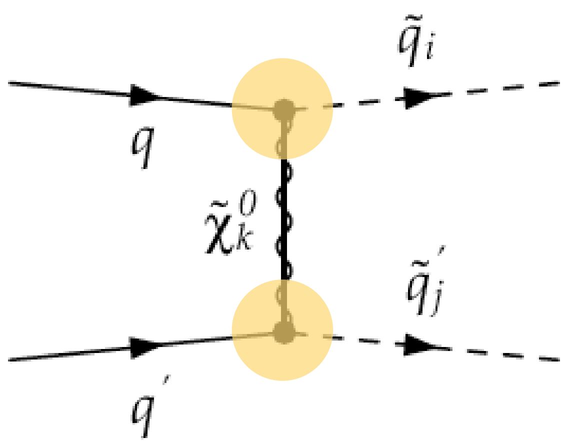
Express cross sections in terms of generalized couplings to include flavour violation

Example: Squark pair production through t-channel neutralino exchange

$$\frac{\mathrm{d}\hat{\sigma}_{h_a h_b}}{\mathrm{d}t} = (1-h_a)(1-h_a)\sum_{k,l=1}^{4}\frac{[\mathcal{NT}]^{kl}_{11}}{t_{\tilde{\chi}^0_k}t_{\tilde{\chi}^0_l}} + (1+h_a)(1+h_a)\sum_{k,l=1}^{4}\frac{[\mathcal{NT}]^{kl}_{22}}{t_{\tilde{\chi}^0_k}t_{\tilde{\chi}^0_l}}$$
$$+(1-h_a)(1+h_a)\sum_{k,l=1}^{4}\frac{[\mathcal{NT}]^{kl}_{12}}{t_{\tilde{\chi}^0_k}t_{\tilde{\chi}^0_l}} + (1+h_a)(1-h_a)\sum_{k,l=1}^{4}\frac{[\mathcal{NT}]^{kl}_{21}}{t_{\tilde{\chi}^0_k}t_{\tilde{\chi}^0_l}}$$

Form factors include coupling constants and Dirac traces

$$[\mathcal{NT}]^{kl}_{mn} = \frac{\pi\,\alpha^2}{\sin^4\theta_W\ \cos^4\theta_W\ s^2}\,\mathcal{C}^{n*}_{\tilde{q}_j q' \tilde{\chi}^0_k}\,\mathcal{C}^{m*}_{\tilde{q}_i q \tilde{\chi}^0_k}\,\mathcal{C}^{n}_{\tilde{q}_j q' \tilde{\chi}^0_l}\,\mathcal{C}^{m}_{\tilde{q}_i q \tilde{\chi}^0_l}$$
$$\times\left[\left(u\,t - m^2_{\tilde{q}_i}\,m^2_{\tilde{q}_j}\right)(1-\delta_{mn}) + m_{\tilde{\chi}^0_k}\,m_{\tilde{\chi}^0_l}\,s\,\delta_{mn}\right]$$

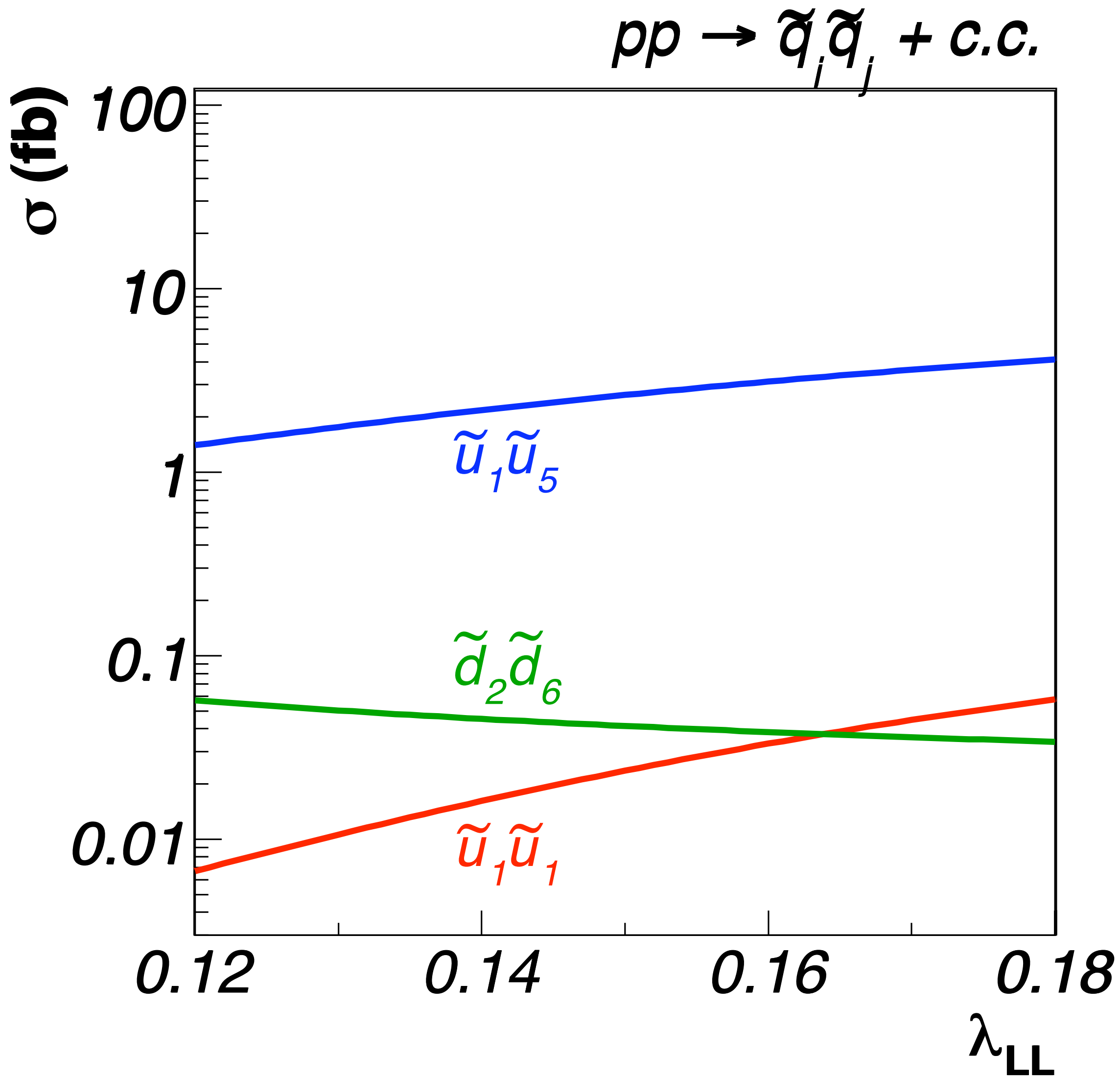


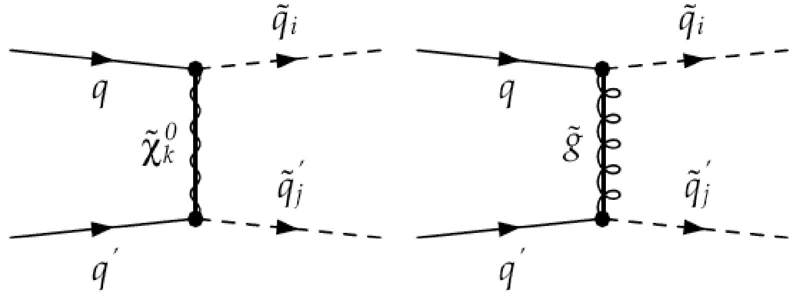
Generic notation for left- and right-handed couplings: $\{\mathcal{C}^1_{abc},\mathcal{C}^2_{abc}\} = \{L_{abc}, R_{abc}\}$

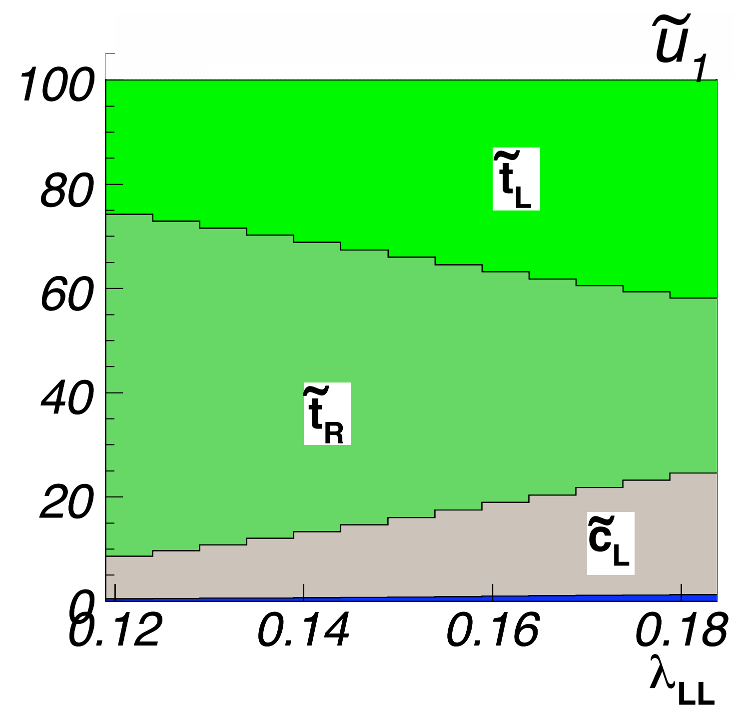
Agreement with previous results in constrained minimal flavour violation [Bozzi, Fuks, Klasen 2005]

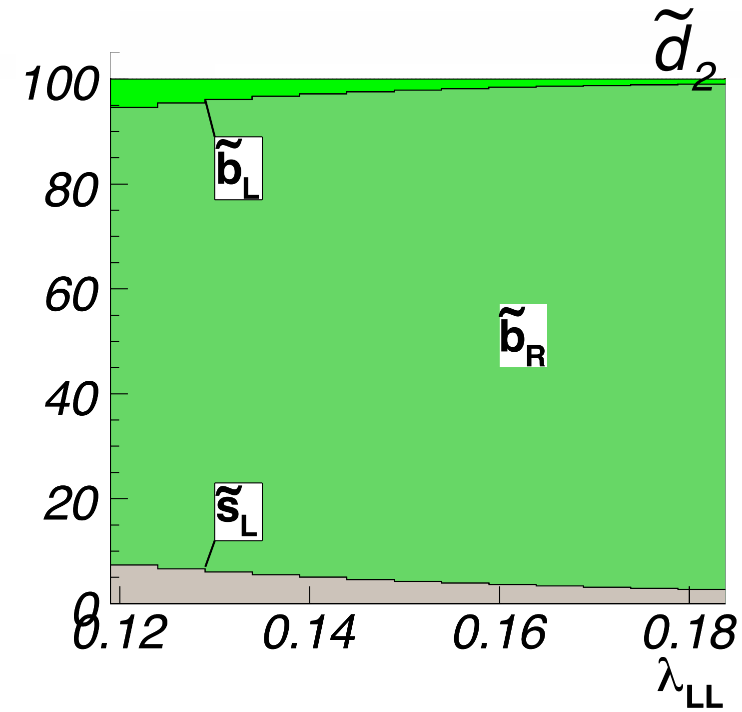
Squark Pair Production

Cross sections sensitive to flavour violation due to $q\tilde{q}\tilde{g}$- and $q\tilde{q}\tilde{\chi}$-vertices







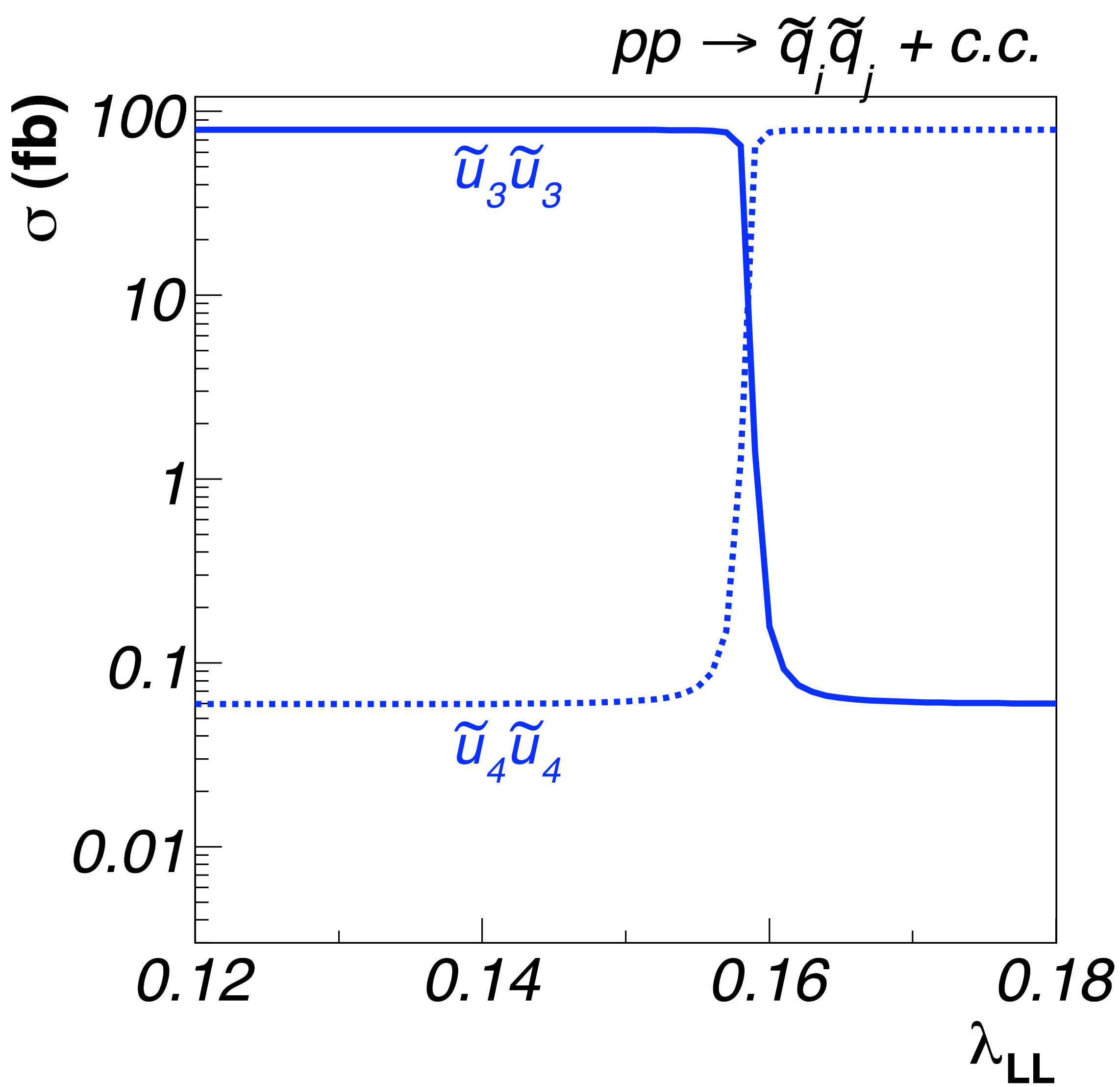


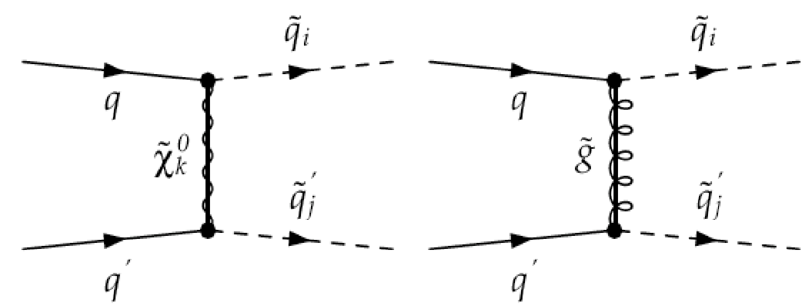
$\tilde{u}_1\tilde{u}_5$ and $\tilde{u}_1\tilde{u}_1$ production cross sections increase with light flavour content in $\tilde{u}_1$

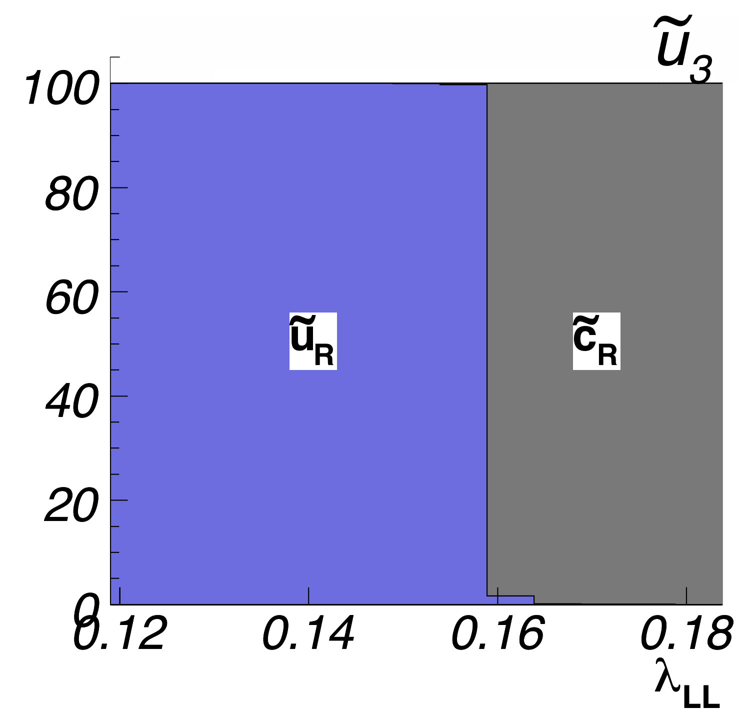
$\tilde{d}_2\tilde{d}_6$ production cross section decreases with light flavour content in $\tilde{d}_2$

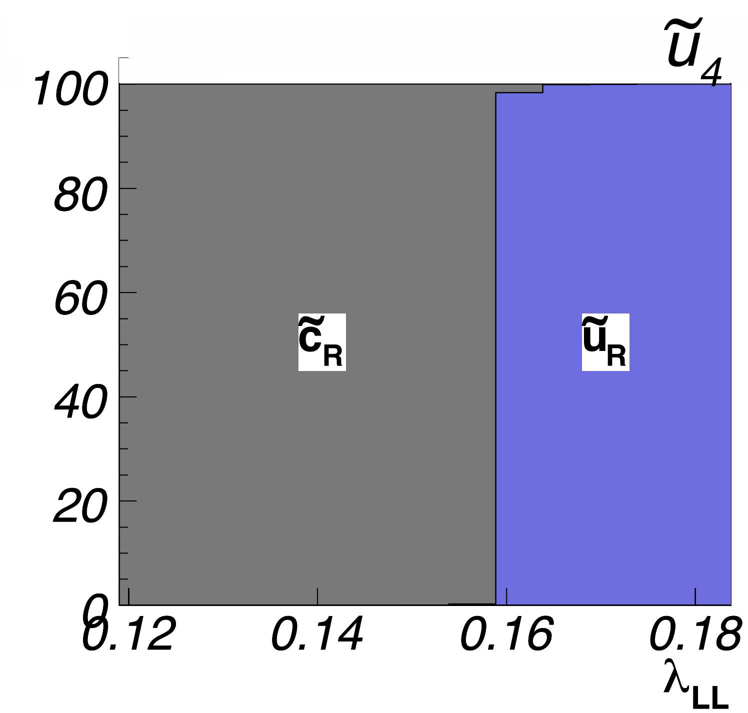
Squark Pair Production

Cross sections sensitive to flavour violation due to $q\tilde{q}\tilde{g}$- and $q\tilde{q}\tilde{\chi}$-vertices









Flavour exchanges between $\tilde{u}_3$ and $\tilde{u}_4$ related to "avoided crossings" of mass eigenvalues

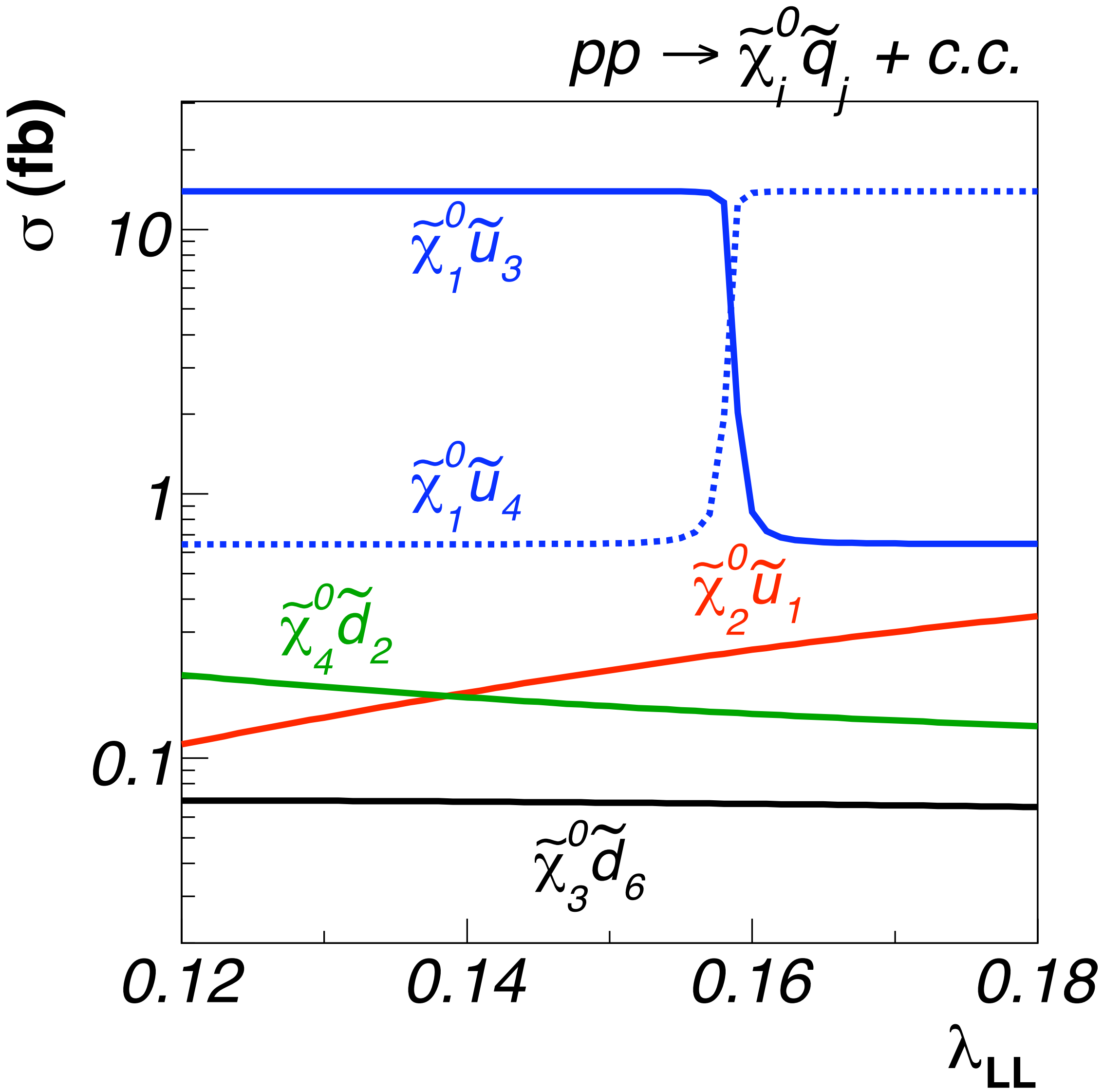
➞ flavour exchanges lead to sharp transitions in particular production channels

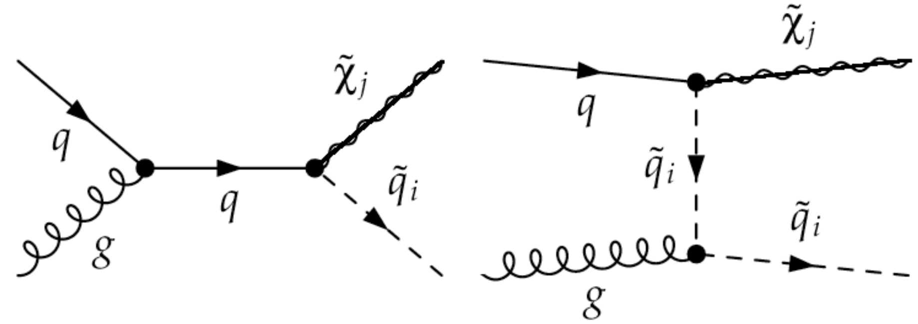
Resonance-like behaviour of $\tilde{u}_3\tilde{u}_4$ production cross section due to smooth flavour exchange

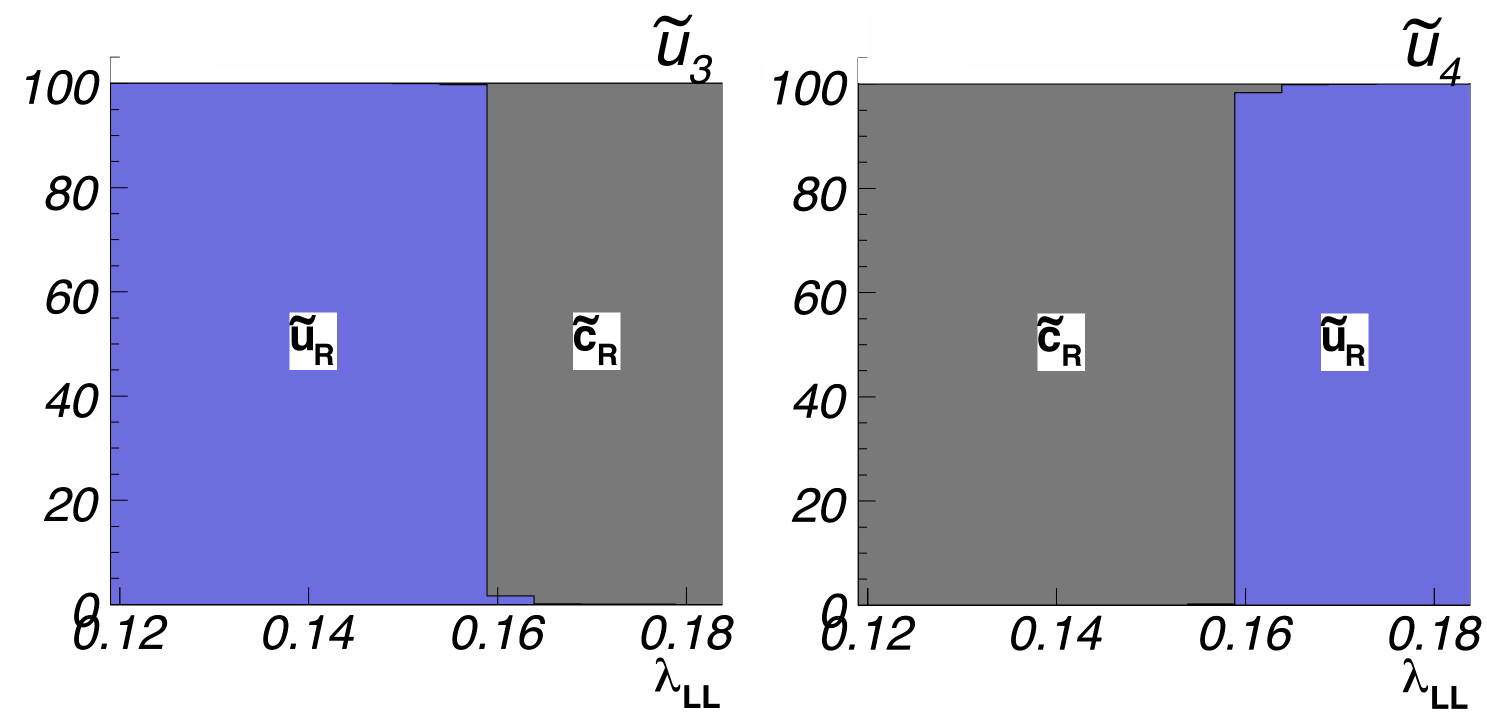
➞ both squark mass eigenstates receive significant up-quark contributions

Squark-Neutralino Associated Production

Cross sections sensitive to flavour violation due to $q\tilde{q}\tilde{\chi}$-vertices







$\tilde{u}_1$ production cross section increases with "light" flavour content in $\tilde{u}_1$

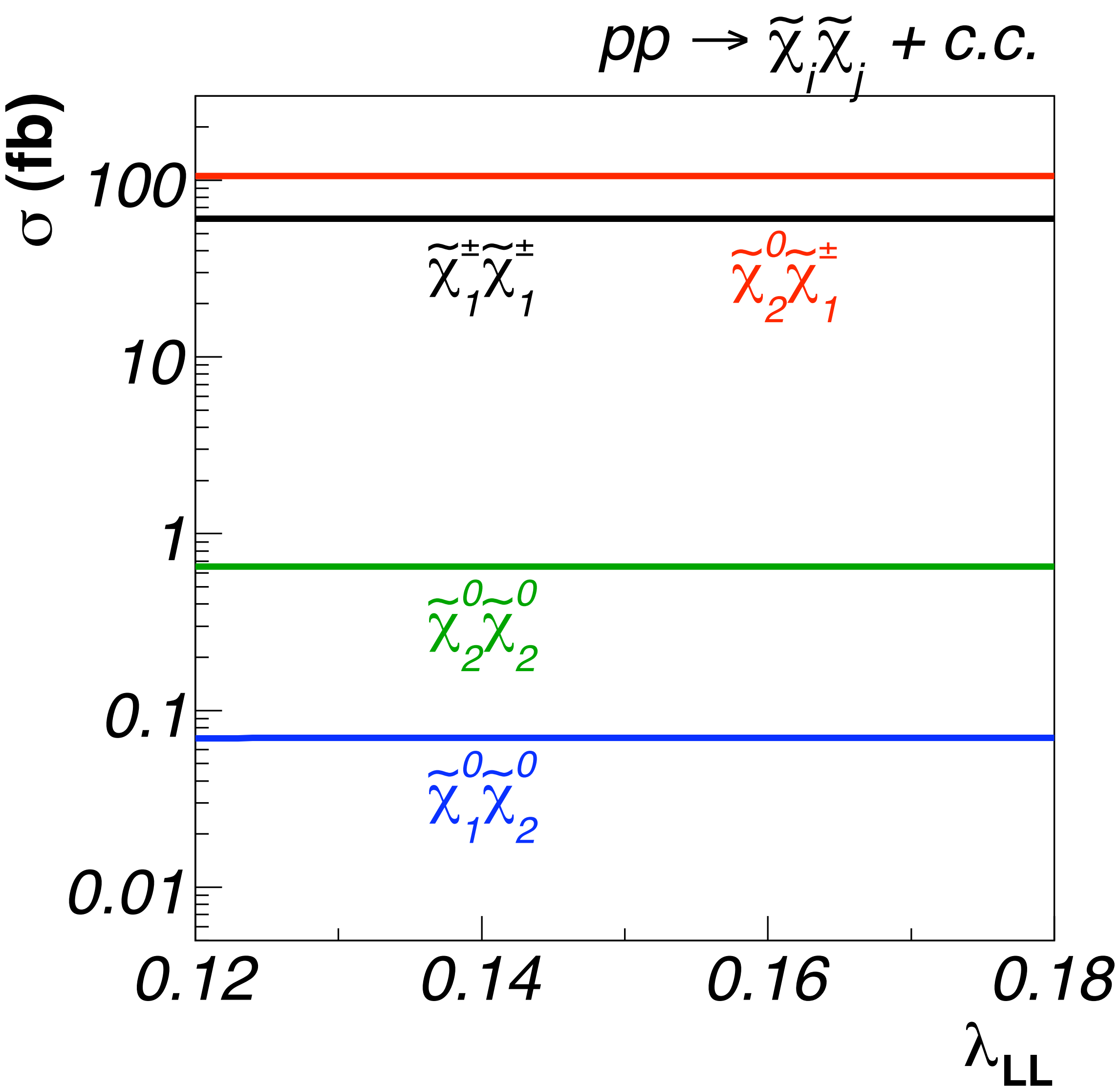
$\tilde{d}_2$ production cross section decreases with "light" flavour content in $\tilde{d}_2$

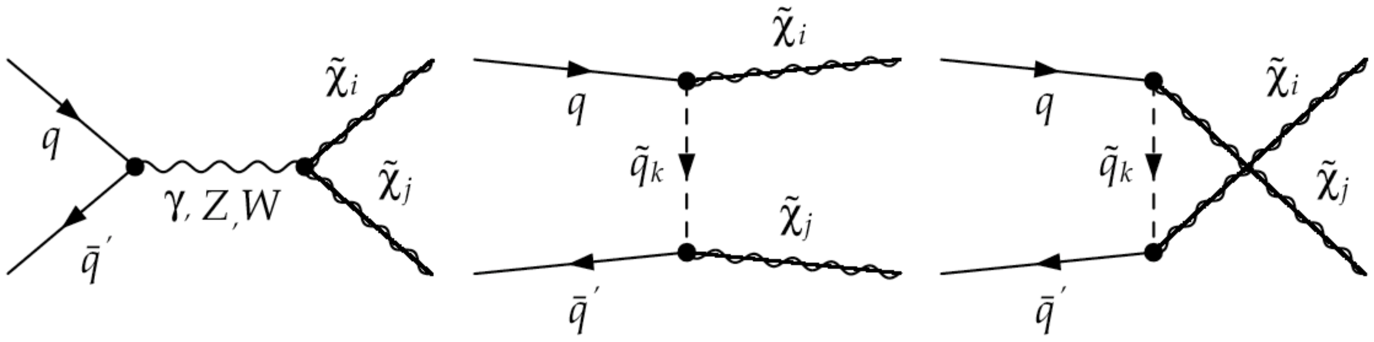
Flavour exchanges between $\tilde{u}_3$ and $\tilde{u}_4$ related to "avoided crossings" of mass eigenvalues

→ flavour exchanges lead to sharp transitions in particular production channels

Gaugino Pair Production

Flavour violation involved through $q\tilde{q}\tilde{\chi}$-vertices





Numerically important due to relatively light gauginos

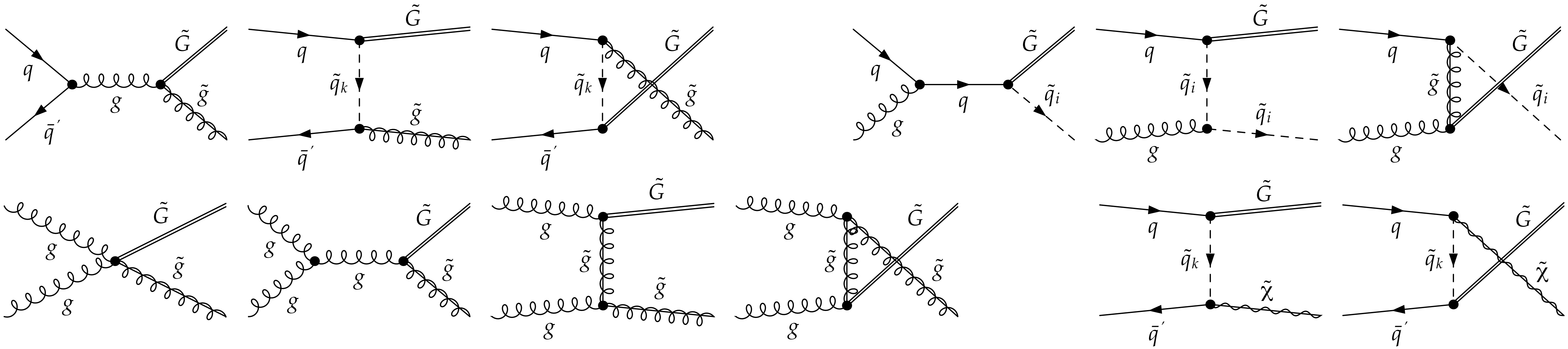
Cross section independent of flavour violation

Squarks only appear in t- or u-channel propagators

→ sum over all physical squark states

Gravitino Production

Light gravitino production interesting at current hadron colliders, in particular in GMSB scenarios



Flavour violation effects arise through vertices involving quarks and squarks

Cross sections proportional to inverse gravitino mass squared [Fayet 1986]

$$\mathcal{V}_{q\tilde{q}\tilde{G}} = \pm\, i \frac{m_{\tilde{q}}^2 - m_q^2}{\sqrt{6} M_{\rm P} m_{\tilde{G}}} P_{R,L} \qquad \mathcal{V}_{g\tilde{g}\tilde{G}} = i \frac{m_{\tilde{g}}}{2\sqrt{6} M_{\rm P} m_{\tilde{G}}} \left[\not{p}, \gamma^\mu \right]$$

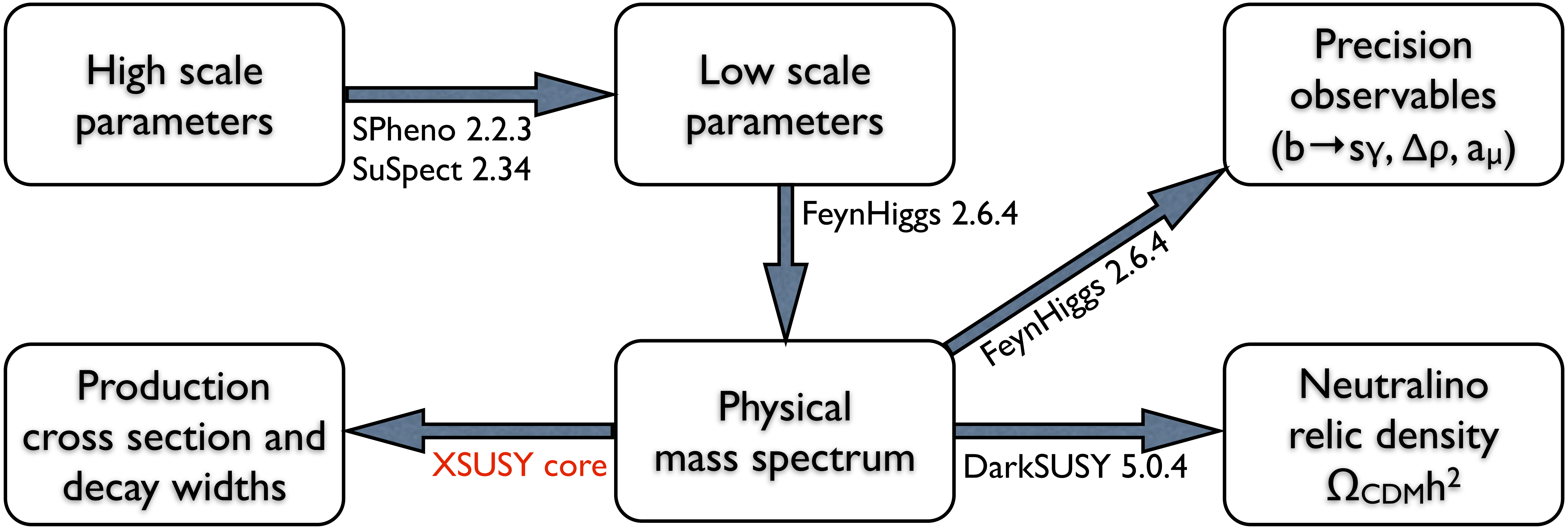
Only light gravitinos (i.e. hot dark matter) allow for sizeable cross sections

→ production invisible for $m_{\tilde{G}} \sim 10^{-1}$ GeV in our benchmark scenarios

Conclusion and Perspectives

XSUSY - A Multipurpose Code for the NMFV-MSSM

Implementation of constraints, cross sections, and decay widths in a flexible computer code



Compatible with SUSY Les Houches Accord 2 (SLHA2)

Possibility of scanning over the parameter space (e.g. mSUGRA, GMSB, AMSB)

Ongoing work: Implementation of gluino production cross sections

Completion of the manual

Last consistency and functionality checks

Hopefully to be released before summer 2009....

[Fuks & Herrmann *(to be published)*]

Conclusion and Perspectives

Supersymmetry is attractive extension of Standard Model of particle physics

→ "hierarchy problem", gauge coupling unification, dark matter candidates

→ important flavour-changing neutral currents may arise in GUT theories

Constraining the supersymmetric parameter space is essential

→ Extensive analysis of electroweak, low-energy, and cosmological constraints

→ Benchmark points for mSUGRA and GMSB scenarios with NMFV

→ Dependence of observables on flavour violation

Predictions for production cross sections at the LHC

→ Flavour mixing leads to interesting phenomenology at hadron colliders

Outlook I: Extension of presented analysis

→ Include further scenarios (AMSB, ...) [Fuks, Herrmann, Klasen *(in preparation)*]

→ Define renormalization scheme and perform calculation at next-to-leading order [Fuks, Herrmann, Klasen, Kovarik *(in preparation)*]

Outlook II: Full Monte-Carlo study for squark and gluino production with NMFV

→ determine experimental signatures at hadron colliders

→ propose possible strategies for LHC [Herrmann & Porod *(in preparation)*]