Phenomenology of SUSY Breaking

by

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Talk outline

- Current constraints on SUSY breaking
- Flavour violation
- R-parity violation
- LHC constraints on SUSY breaking

Global SUSY Fits

Q: Why perform global fits to SUSY using DM+indirect data?

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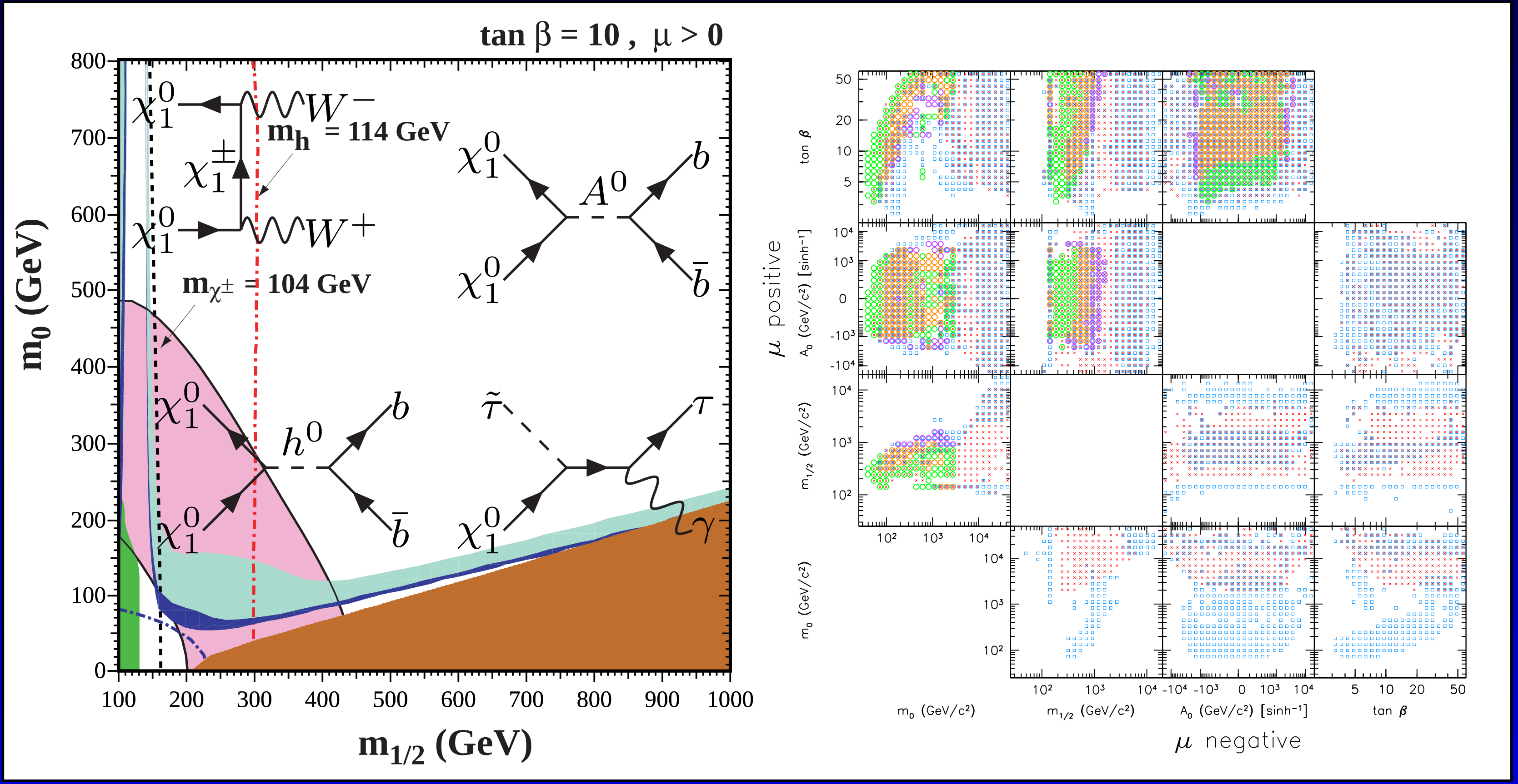
Constraints on SUSY Models

CMSSM well-studied in literature: eg Ellis, Olive *et al* PLB565 (2003) 176; Roszkowski *et al* JHEP 0108 (2001) 024; Baltz, Gondolo, JHEP 0410 (2004) 052;…



Implementation

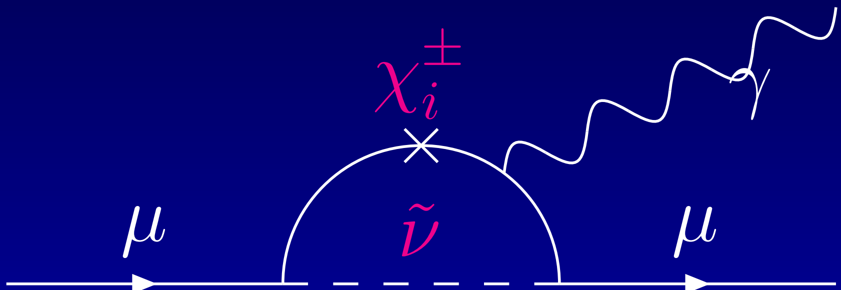
25 pMSSM input parameters are: $M_{1,2,3}$, $A_{t,b,\tau,\mu}$, $m_{H_{1,2}}$, $\tan\beta$, $m_{\tilde{d}_{R,L}} = m_{\tilde{s}_{R,L}}$, $m_{\tilde{u}_{R,L}} = m_{\tilde{c}_{R,L}}$, $m_{\tilde{e}_{R,L}} = m_{\tilde{\mu}_{R,L}}$, $m_{\tilde{t},\tilde{b},\tilde{\tau}_{R,L}}$ m_t, $m_b(m_b)$ $\alpha_s(M_Z)^{\overline{MS}}$, $\alpha^{-1}(M_Z)^{\overline{MS}}$, M_Z. We use

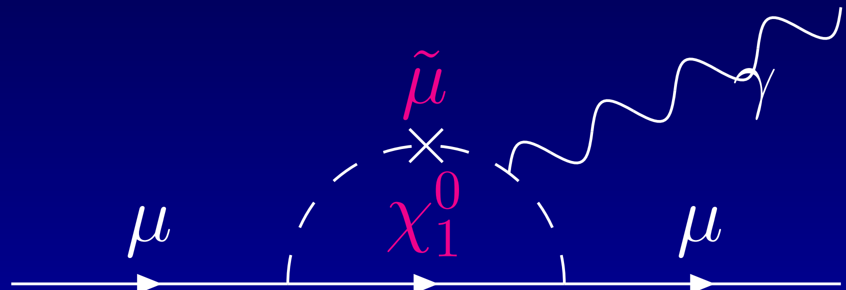
- *95% C.L. direct search constraints*
- $\Omega_{DM}h^2 = 0.1143 \pm 0.02$ Boudjema *et al*
- $\delta(g-2)_\mu/2 = (29.5 \pm 8.8) \times 10^{-10}$ Stöckinger *et al*
- $B-$physics observables including $BR[b \rightarrow s\gamma]_{E_\gamma > 1.6 \text{ GeV}} = (3.52 \pm 0.38) \times 10^{-4}$
- Electroweak data W Hollik, A Weber *et al*

$$2 \ln \mathcal{L} = -\sum_i \chi_i^2 + c = \sum_i \frac{(p_i - e_i)^2}{\sigma_i^2} + c$$

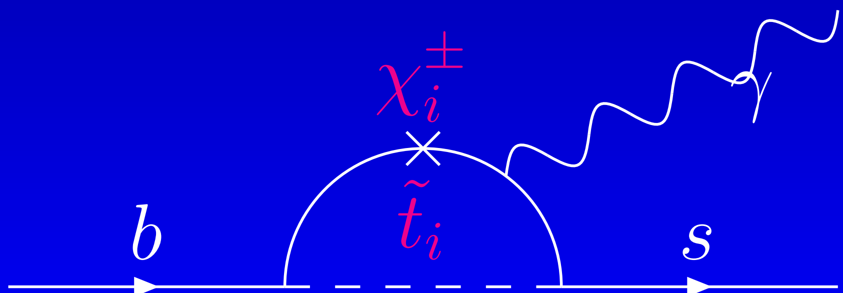
Additional observables

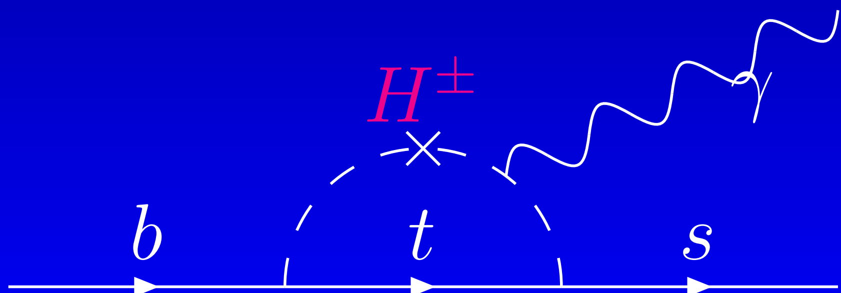
$$\delta \frac{(g-2)_\mu}{2} \sim 13 \times 10^{-10} \left(\frac{100 \text{ GeV}}{M_{SUSY}} \right)^2 \tan\beta$$





$$BR[b \to s\gamma] \propto \tan\beta (M_W/M_{SUSY})^2$$





Application of Bayes'

$\mathcal{L} \equiv p(\underline{d}|\underline{m}, H)$ is pdf of reproducing data $\underline{d}$ assuming pMSSM hypothesis H and model parameters $\underline{m}$

$$p(\underline{m}|\underline{d}, H) = p(\underline{d}|\underline{m}, H)\frac{p(\underline{m}, H)}{p(\underline{d}, H)}$$

$p(\underline{m}|\underline{d}, H)$ is called the posterior pdf. We will compare $p(\underline{m}, H) = c$ with a *different* prior.

$$p(m_0, M_{1/2}|\underline{d}, H) = \int d\underline{o}\, p(m_0, M_{1/2}, \underline{o}|\underline{d}, H)$$

Likelihood and Posterior

Q: What's the chance of observing someone to be pregnant, given that they are female?

Likelihood

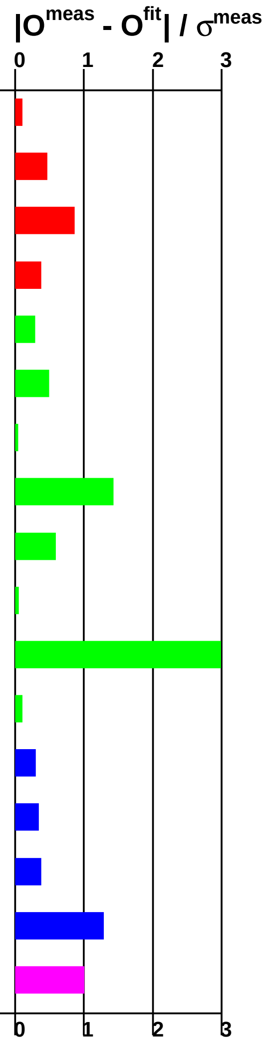
p(pregnant | female, human) = 0.01

Posterior

p(female | pregnant, human) = 1.00

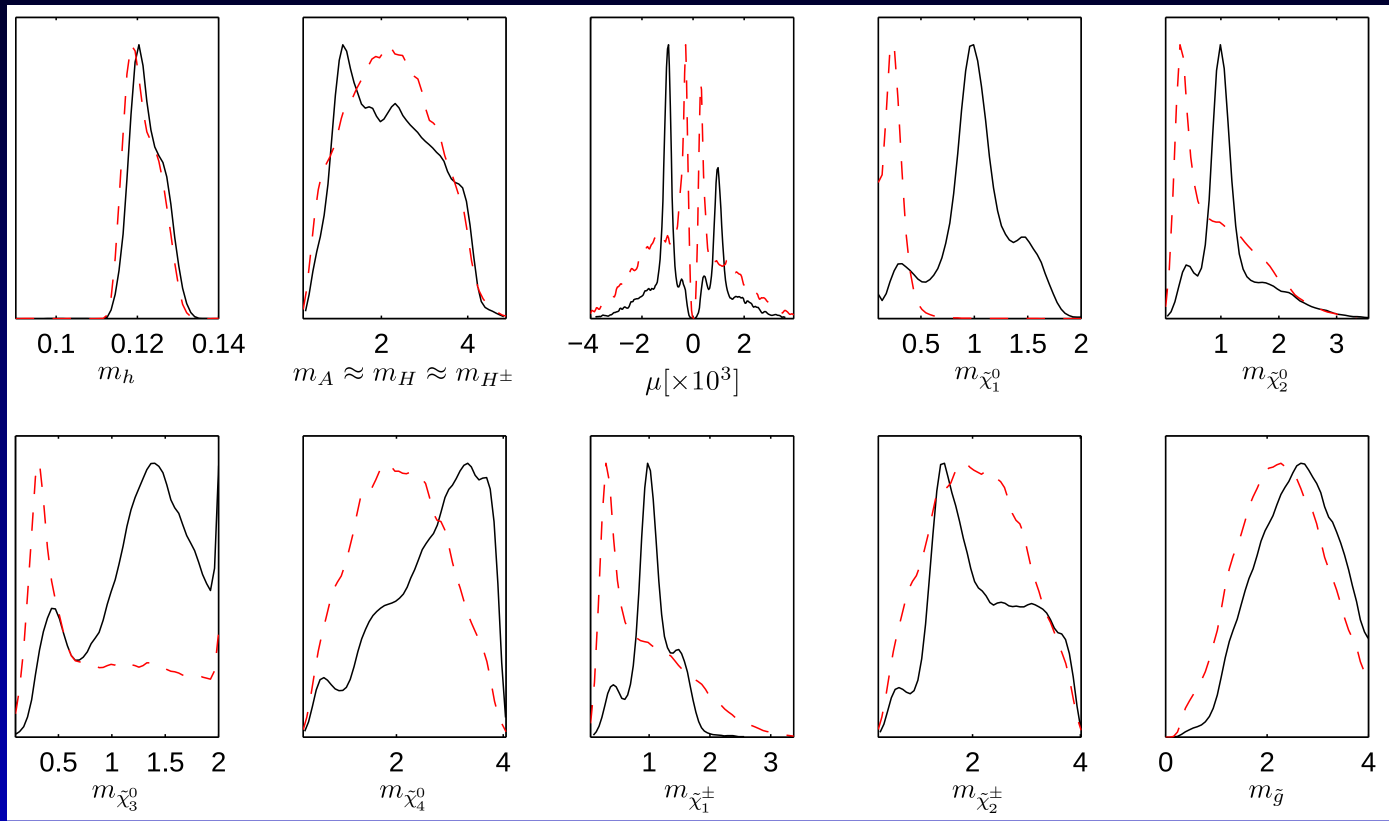
Best-Fit Point

Observable	Measurement	Fit(Log)
m_W [GeV]	80.399 ± 0.025	80.402
Γ_Z [GeV]	2.4952 ± 0.0025	2.4964
$\sin^2 \theta^{eff}_{lep}$	0.2324 ± 0.0012	0.2314
$\delta(g-2)_\mu \times 10^{10}$	30.20 ± 9.02	26.74
R^0_l	20.767 ± 0.025	20.760
R_b	0.21629 ± 0.00066	0.21962
R_c	0.1721 ± 0.0030	0.1723
A_e	0.1513 ± 0.0021	0.1483
A_b	0.923 ± 0.020	0.935
A_c	0.670 ± 0.027	0.685
A^b_{FB}	0.0992 ± 0.0016	0.1040
A^c_{FB}	0.071 ± 0.035	0.074
$BR(B \to X_s \gamma) \times 10^4$	3.55 ± 0.42	3.42
$R_{BR(B_u \to \tau \nu)}$	1.11 ± 0.32	1.00
$R_{\Delta M_{B_s}}$	1.15 ± 0.40	1.00
Δ_{0-}	0.0375 ± 0.0289	0.0748
$\Omega_{CDM} h^2$	0.11 ± 0.02	0.13



AbdusSalam, BCA, Quevedo, Feroz, Hobson, `arXiv:0904.2548`

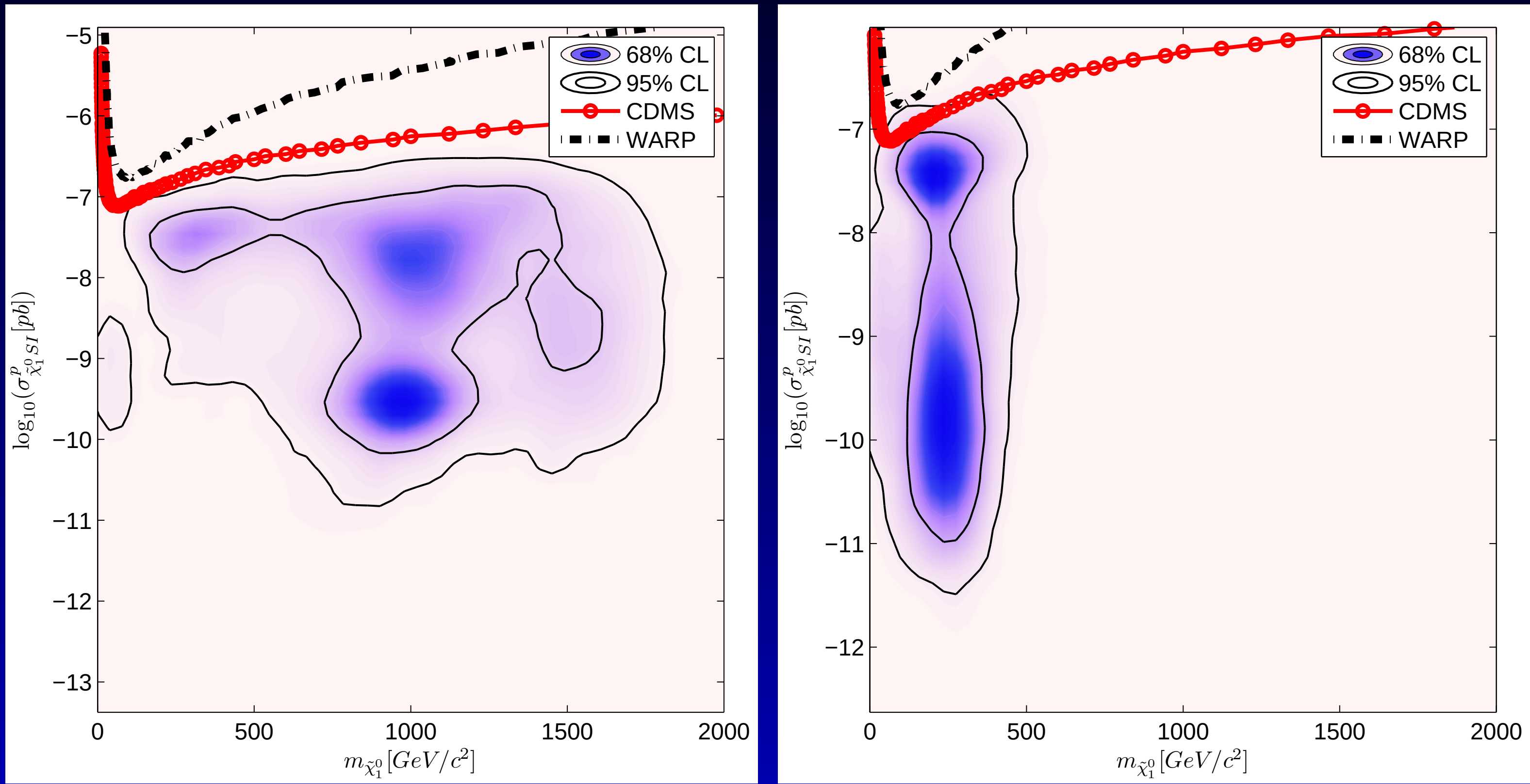
Spectrum



Obtained with `MultiNest`[a] algorithm in 16 CPU years. Prior dependence is *useful*: which predictions are robust?

[a] Feroz, Hobson `arxiv:0704.3704`

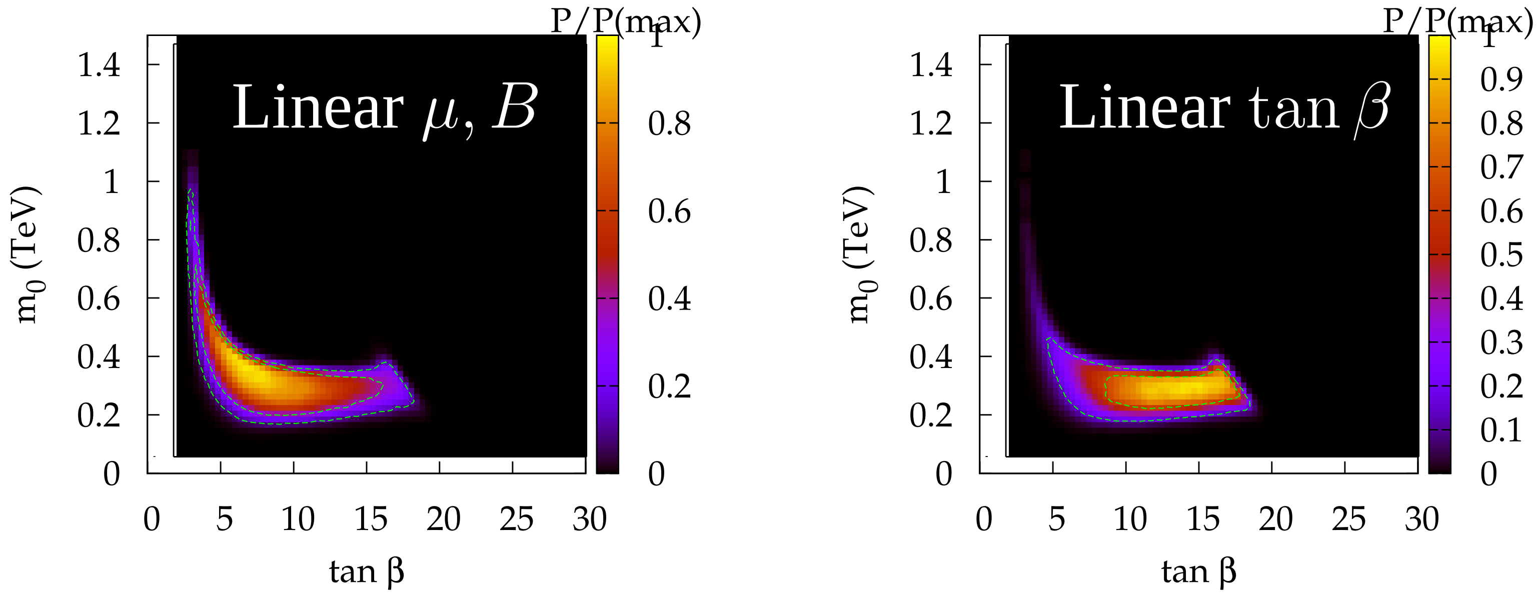
Dark matter detection



DM properties look too prior dependent to say anything concrete

Large Volume String Models

BCA, Dolan, JHEP08 (2008) 015, `arXiv:0806.1184`



$$M_{1/2} = -A_0 = m_0/\sqrt{3}$$

$$M_X = 10^{11}\ \text{GeV}$$

Two constraints almost enough

Model Comparison

Calculate the *Bayesian evidence* of each model

$$\mathcal{Z}_i = \int p(\underline{d}|\underline{m}, H_i)\, p(\underline{m}|H_i)\, d\underline{m}$$

$$\frac{p(H_1|\underline{d})}{p(H_0|\underline{d})} = \frac{p(\underline{d}|H_1)p(H_1)}{p(\underline{d}|H_0)p(H_0)} = \frac{\mathcal{Z}_1}{\mathcal{Z}_0}\frac{p(H_1)}{p(H_0)},$$

$p_i/p^{lin}_{\rm mSUGRA}$	asymmetric[a] $\mathcal{L}_{\rm DM}$		
Model/Prior	linear	log	flat μ, B
mSUGRA	1	3	4
mAMSB	164	403	148
LVS	18	20	22

[a] AbdusSalam, BCA, Dolan, Feroz, Hobson, to appear

Any Questions?

Flavour Violating SUSY

In the MSSM, we additionally have soft mass terms like

$$V_2 = \tilde{Q}^*_{iLa}\,(m^2_{\tilde{Q}})_{ij}\,\tilde{Q}^a_{jL} + \tilde{u}_{iR}\,(m^2_{\tilde{u}})_{ij}\,\tilde{u}^*_{jR} + \tilde{d}_{iR}\,(m^2_{\tilde{d}})_{ij}\,\tilde{d}^*_{jR}.$$

SUSY flavour problem: *Nearly all of this parameter space is ruled out by flavour constraints*.
There is clearly a need for some organising principle from symmetry and/or additional dynamics.
There are many approaches to the flavour problem in SUSY breaking (eg mSUGRA, GMSB, $\tilde{g}$MSB, MRSSM[a] etc)

[a] Kribs, Poppitz, Weiner, `arXiv:0712.2039`

Anomaly Mediated SUSY Breaking

Loop suppressed soft masses[a]

$$M_\alpha = m_{3/2}\beta_{g_\alpha}/g_\alpha,$$
$$(m^2)^i{}_j = \frac{1}{2}m_{3/2}^2\mu\frac{d}{d\mu}\gamma^i{}_j,$$
$$\gamma^i_j = \frac{1}{2}Y^{ikl}Y_{jkl} - 2\sum_\alpha g_\alpha^2[C(R_\alpha)]^i{}_j.$$

- Always present for a hidden sector
- Dominant in brane set-up:

$$\mathcal{L} = \mathcal{L}_{vis} + \mathcal{L}_{hid}$$

- SUSY Flavour problem ameliorated

SUSY Breaking Terms

Scale invariant expressions[a] in terms of SUSY couplings and gravitino mass $m_{3/2}$.

$$M_i = \beta_i \frac{g_i^2}{16\pi^2} m_{3/2}, \ \beta_i = (33/5, 1, -3)$$

$$m^2_{\tilde{u}_R, \tilde{c}_R} = \frac{m^2_{3/2}}{(16\pi^2)^2} \left(-\frac{88}{25} g_1^4 + 8 g_3^4 \right)$$

$$m^2_{\tilde{e}_R} = -\frac{198}{25} \frac{m^2_{3/2} g_1^4}{(16\pi^2)^2}$$

$\mathcal{Q}$: What makes the slepton mass squared values positive?

[a] Gherghetta, Giudice and Wells, `hep-ph/9904378`

Solving Tachyonic Sleptons

- Bulk singlet contributions m_0: mAMSB
- Non-decoupling effects:
  - Katz, Shadmi, Shirman
  - Pomarol, Rattazzi
- Extra D-terms from additional U(1): Jack, Jones
- Extra (heavy) leptons: Chacko *et al*
- R_p Violation: BCA, Dedes

Here, we shall consider the squark mixings, and therefore only the models which leave the squarks' AMSB terms untouched (in some cases, approximately and in some exactly).

Flavoured AMSB

Previous literature only considers (33) entries to Yukawas. We include flavour corrections, e.g.

$$\frac{(16\pi^2)^2 (m^2_{\tilde{Q}})^T}{m^2_{3/2}} = \left(-\frac{11}{50} g_1^4 - \frac{3}{2} g_2^4 + 8 g_3^4 \right) .\mathbf{1} +$$

$$(Y_U Y_U^\dagger) \left(3 \mathrm{Tr}(Y_U Y_U^\dagger) - \frac{13}{15} g_1^2 - 3 g_2^2 - \frac{16}{3} g_3^2 \right) +$$

$$(Y_D Y_D^\dagger) \left(3 \mathrm{Tr}(Y_D Y_D^\dagger) + \mathrm{Tr}(Y_E Y_E^\dagger) - \frac{7}{15} g_1^2 - 3 g_2^2 - \frac{16}{3} g_3^2 \right)$$

$$+ Y_U Y_U^\dagger Y_D Y_D^\dagger + Y_D Y_D^\dagger Y_U Y_U^\dagger + 3 (Y_U Y_U^\dagger)^2 + 3 (Y_D Y_D^\dagger)^2.$$

NB *Extremely predictive*. We'll use this to predict squark mixing

Dominant Third Family Approximation

$$\begin{aligned}
\left(m^2_{\tilde{U}_L}\right)_{ij} &= \frac{m^2_{3/2}}{(16\pi^2)^2}\left[\delta_{ij}\left(-\frac{11}{50}g_1^4 - \frac{3}{2}g_2^4 + 8g_3^4\right)\right. \\
&+ \delta_{i3}\delta_{j3}\lambda_t^2(\hat{\beta}_{\lambda_t} - \lambda_b^2) \\
&+ V_{ib}V^*_{jb}\lambda_b^2(\hat{\beta}_{\lambda_b} - \lambda_t^2) \\
&+ \left.\lambda_t^2\lambda_b^2(\delta_{i3}V^*_{jb}V_{tb} + \delta_{j3}V_{ib}V^*_{tb})\right], \\
\hat{\beta}_{\lambda_t} &= 6\lambda_t^2 + \lambda_b^2 - \left(\frac{13}{15}g_1^2 + 3g_2^2 + \frac{16}{3}g_3^2\right), \\
\hat{\beta}_{\lambda_b} &= 6\lambda_b^2 + \lambda_\tau^2 + \lambda_t^2 - \left(\frac{7}{15}g_1^2 + 3g_2^2 + \frac{16}{3}g_3^2\right).
\end{aligned}$$

in the super-CKM basis. $\beta_i < 0$. NB *at low* $\tan\beta, \hat{\beta}_{\lambda_t}, \lambda_b \to 0$: *AMSB is flavour conserving.*

$$(\delta^u_{ij})_{LL} \equiv m^2_{\tilde{u}_{Lij}} / \sqrt{m^2_{\tilde{u}_{Lii}} + m^2_{\tilde{u}_{Ljj}}}$$

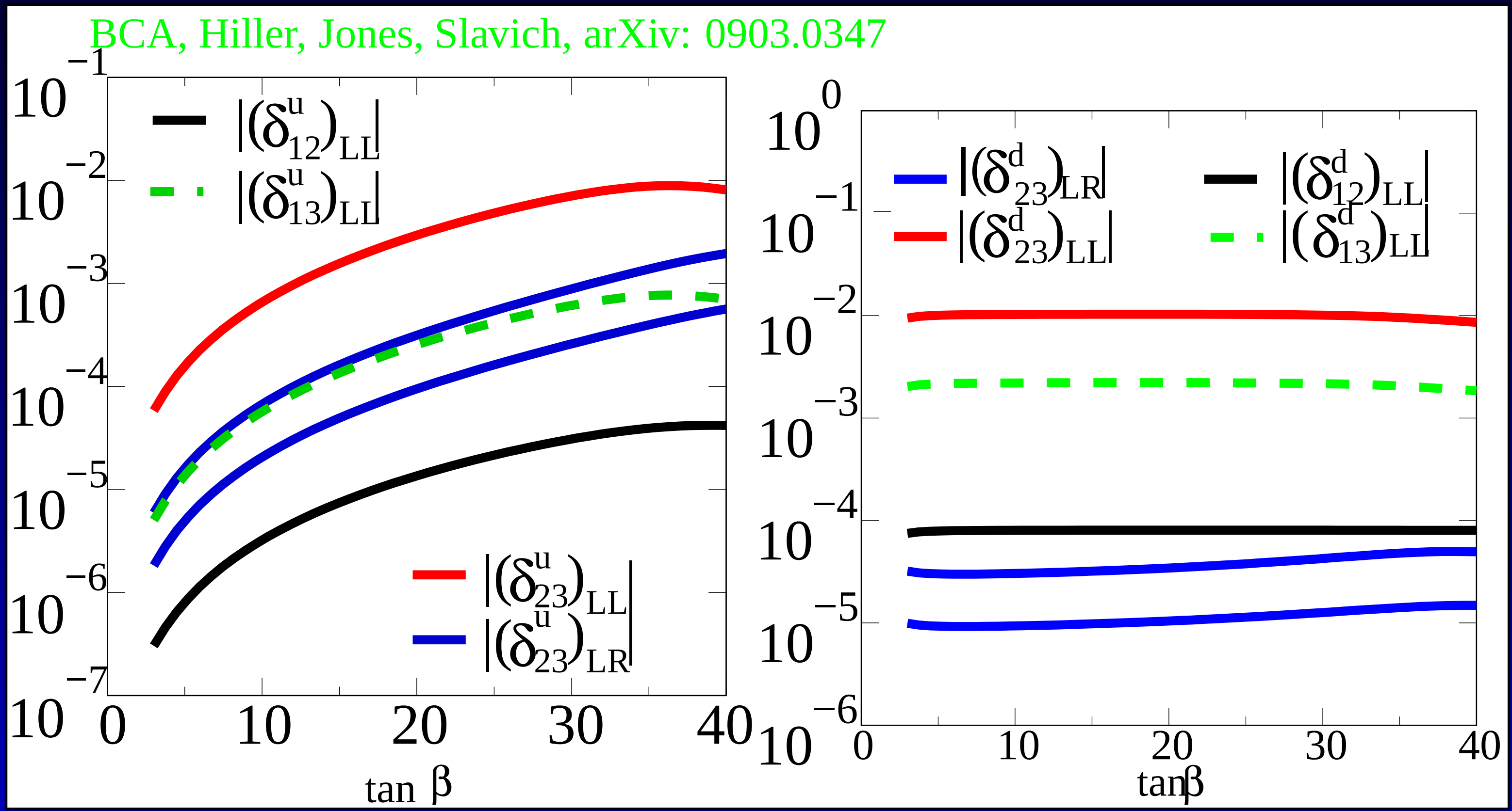


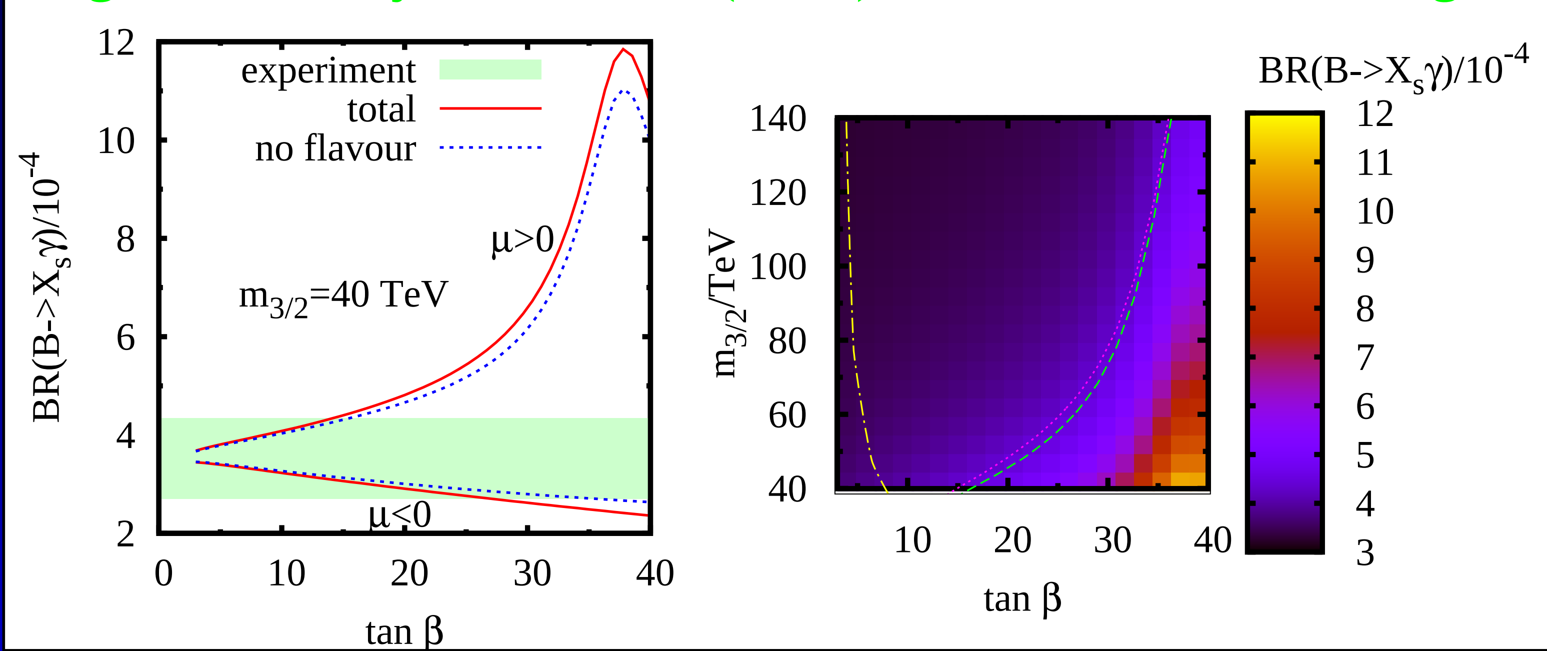
Figure 1: Largest flavour violating parameters for $m_{3/2} = 40 - 140$ TeV. Note that δ^d_{23} can affect $b \to s$.

$BR(B \to X_s \gamma)$

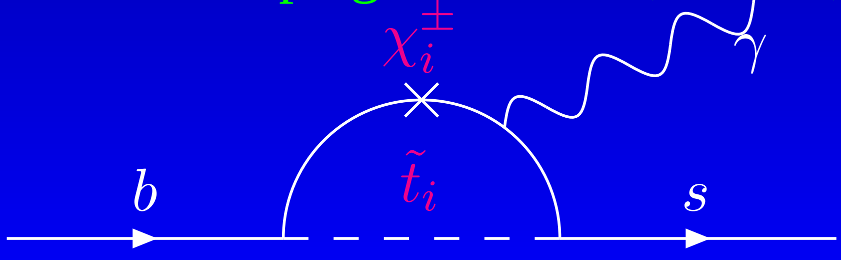
$m_{3/2} = 40$ TeV. SOFTSUSY3.0 and SusyBSG1.2.

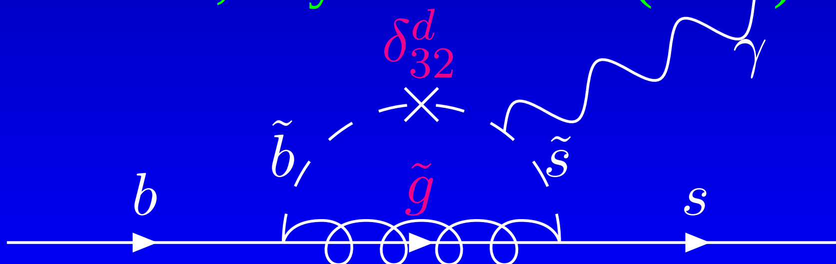
$BR^{exp} = (3.52 \pm 0.23 \pm 0.09) \times 10^{-4}$,

See Feng, Moroi, Phys. Rev. D61 (2000) 095004 for flavour diagonal AMSB



Includes 2-loop eg Borzumati, Greub, Yamada, Phys. Rev. D69 (2004) 055005





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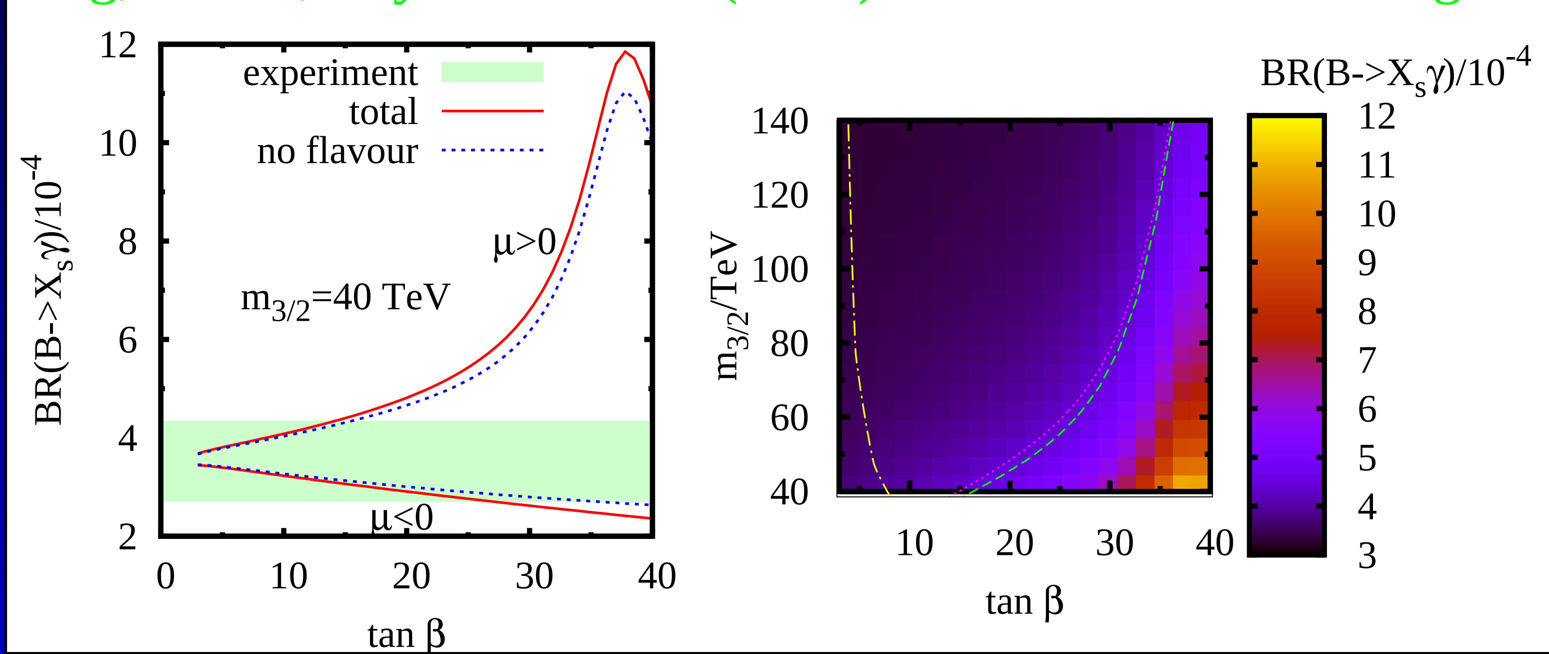
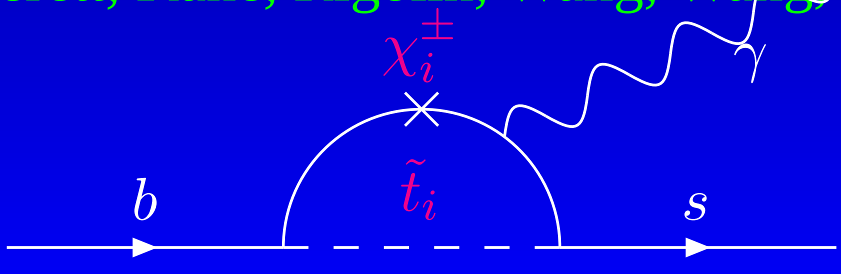
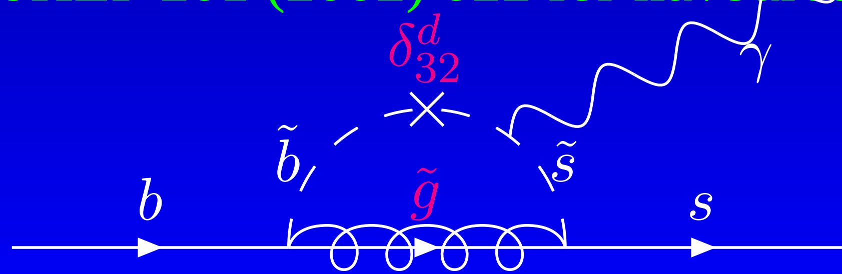


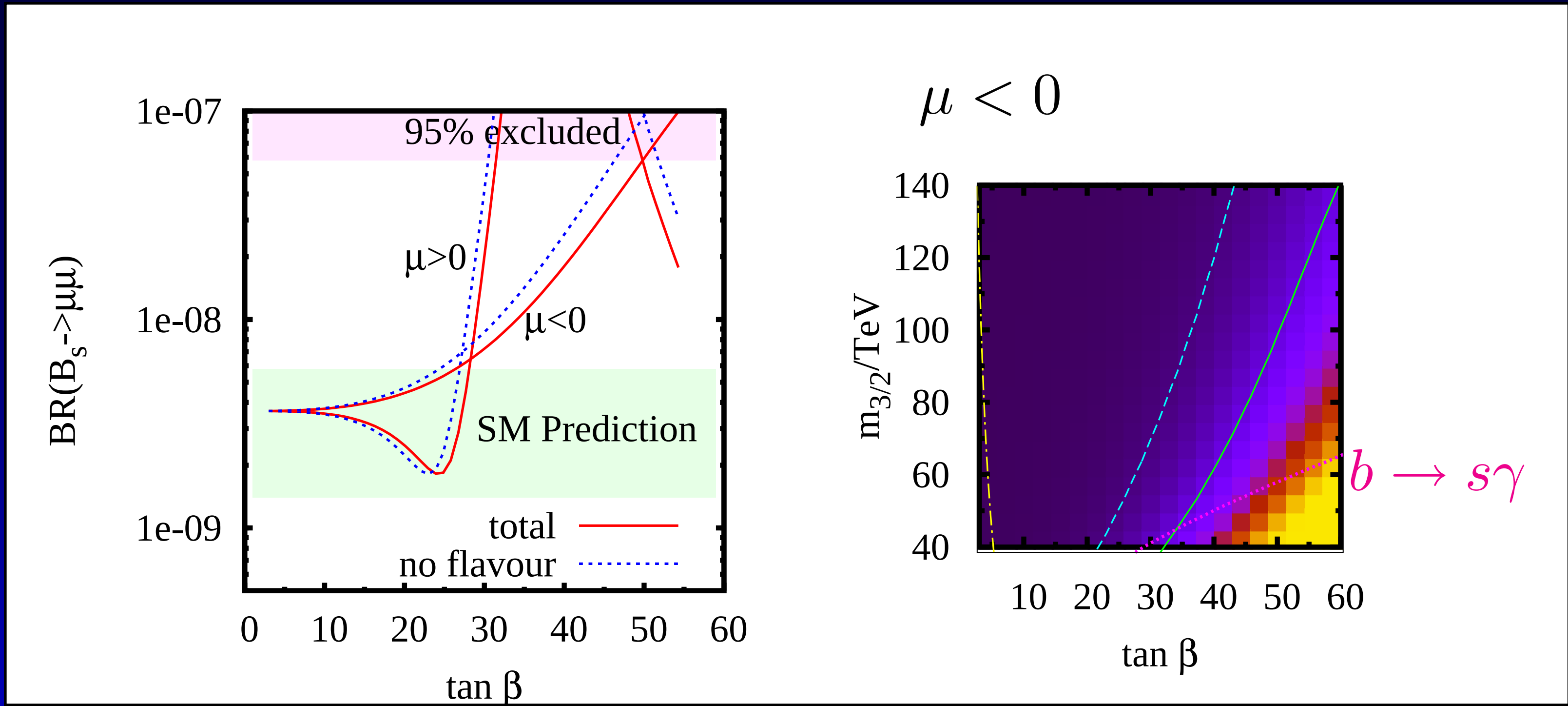
Everett, Kane, Rigolin, Wang, Wang, JHEP 201 (2002) 022 for flavoured MSSM

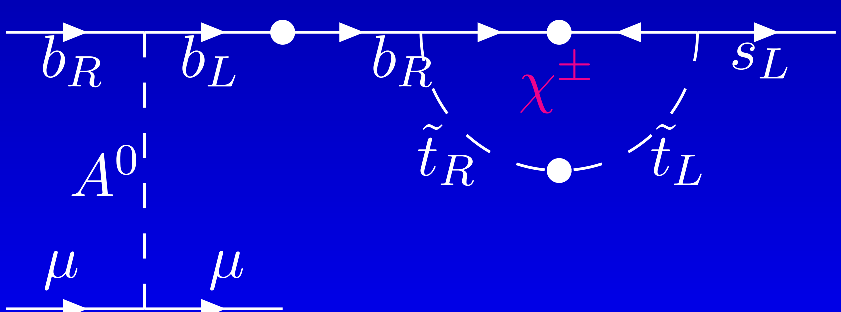


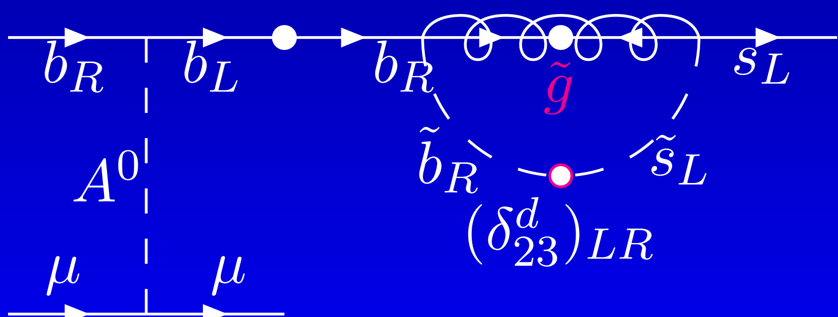


$BR(B_s \to \mu^+\mu^-)$: LHCb

SOFTSUSY3.0. $BR^{exp} < 58 \times 10^{-9}$,



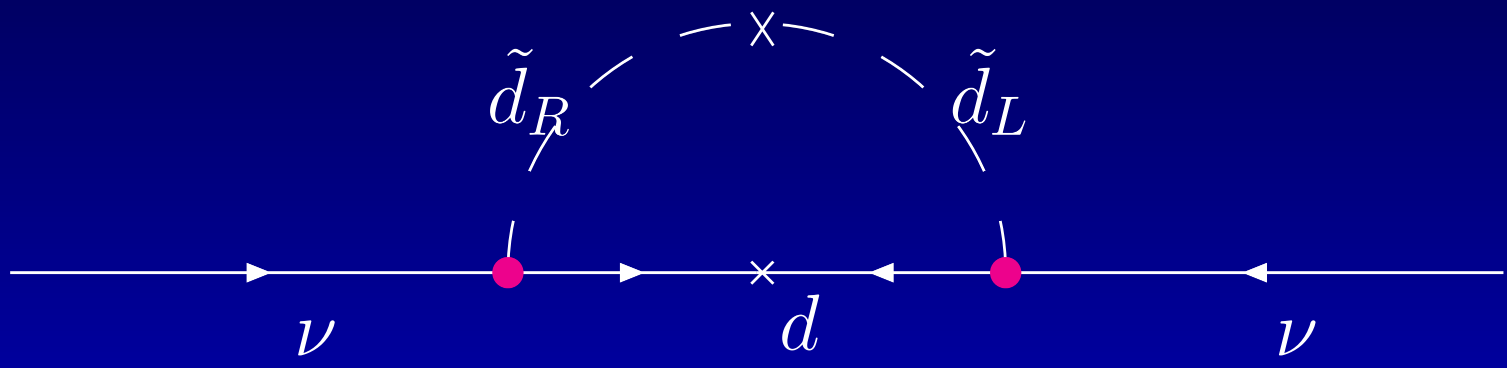




Any Questions?

Motivation for $\not{R}_p$

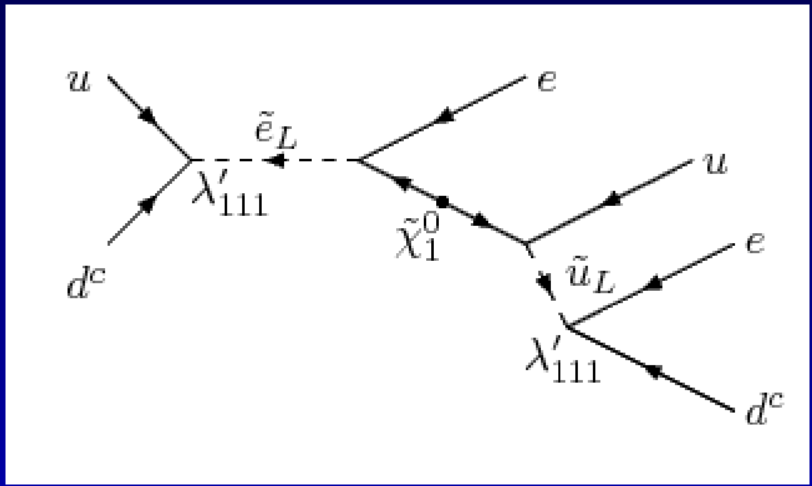
- It has additional search possibilities.
- Neutrino masses and mixings testable at LHC

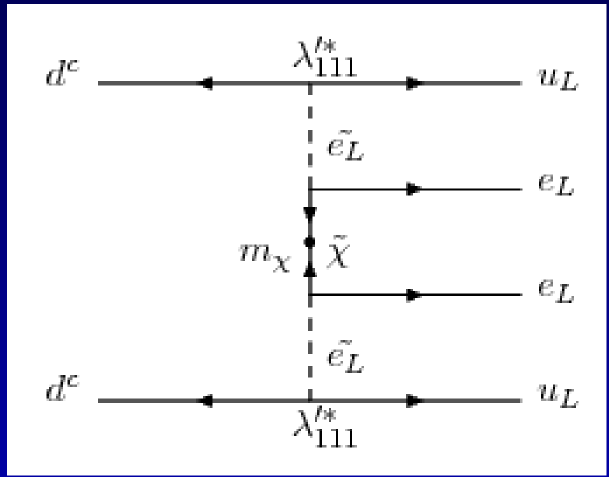


$$(m_\nu)_{11} = \frac{3}{32\pi^2} m_d {\lambda'_{111}}^2 \sin 2\theta_d \ln \frac{m^2_{\tilde{d}_L}}{m^2_{\tilde{d}_R}}$$

LHC Single Selectron Production

Like-sign dielectrons and two hard jets connects with neutrinoless double beta decay:





$$\sigma(pp \to \tilde{l}) \propto \frac{|\lambda'_{111}|^2}{m^3_{\tilde{e}_L}} \qquad [T^{0\nu\beta\beta}_{1/2}(\mathbf{Ge})]^{-1} \propto \frac{|\lambda'_{111}|^4}{M^{10}_{susy}}$$

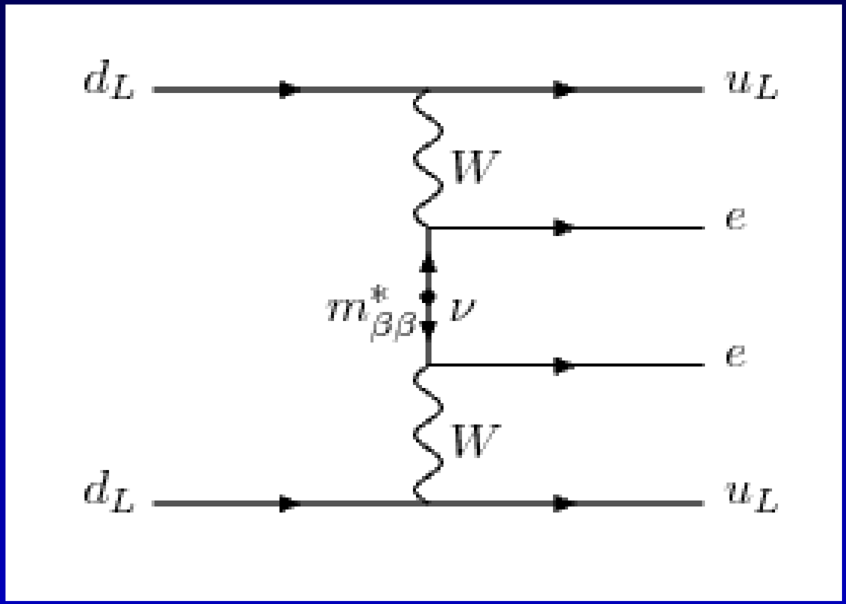
So, there is an interesting interplay between the two[a]

[a] BCA, Kom, Päs, arXiv:0902.4697

Neutrinoless Double Beta Decay

Heidelberg-Moscow limit:

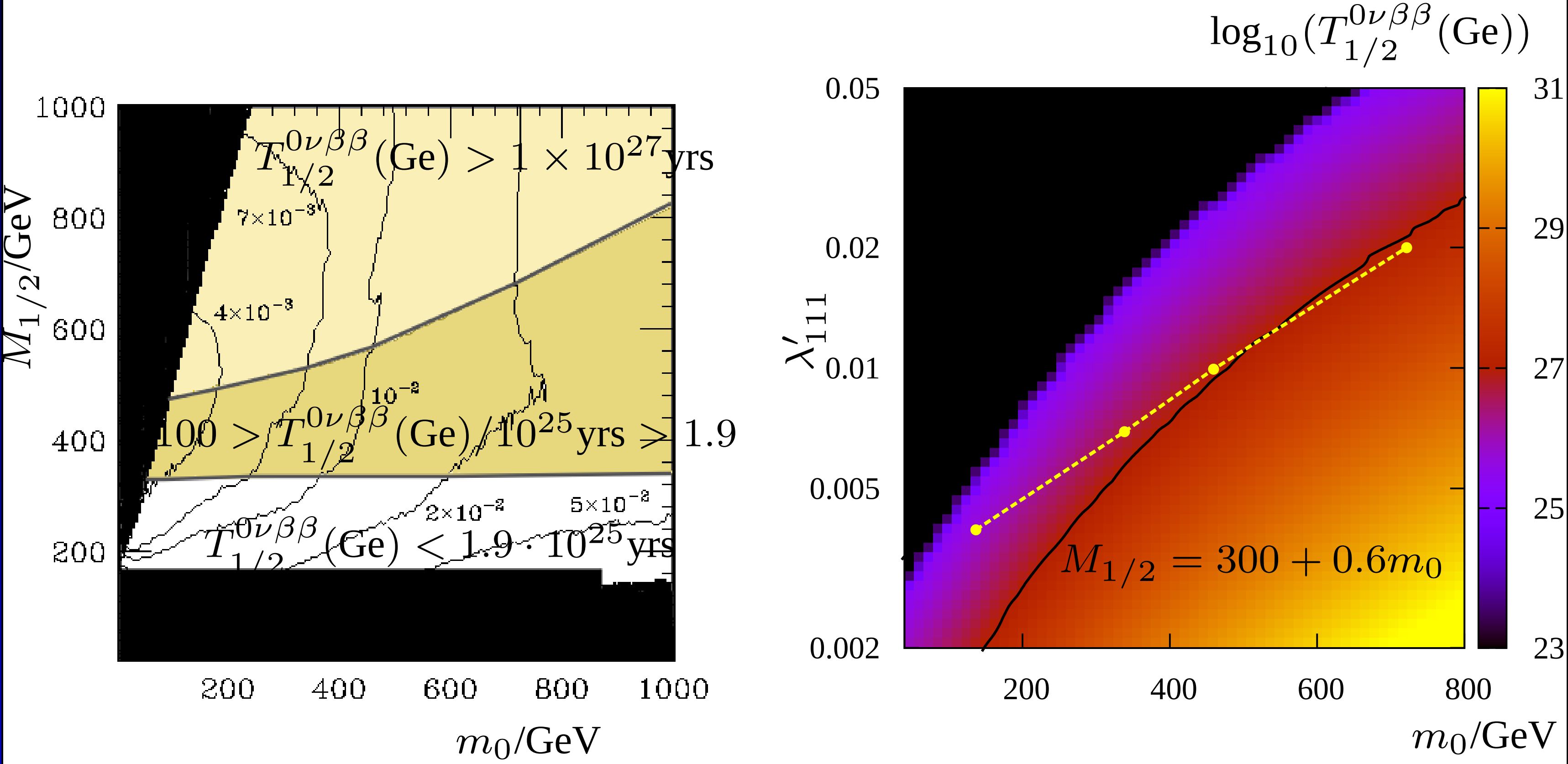
$$T_{1/2}^{0\nu\beta\beta}(\mathrm{Ge}) \geq 1.9 \cdot 10^{25}\mathrm{yrs} \Rightarrow m_\nu < 0.46\mathrm{eV}.$$



Next round of experiments are going to improve the $T_{1/2}^{0\nu\beta\beta}(Ge)$ bound by a couple of orders of magnitude

Neutrinoless-LHC Interplay

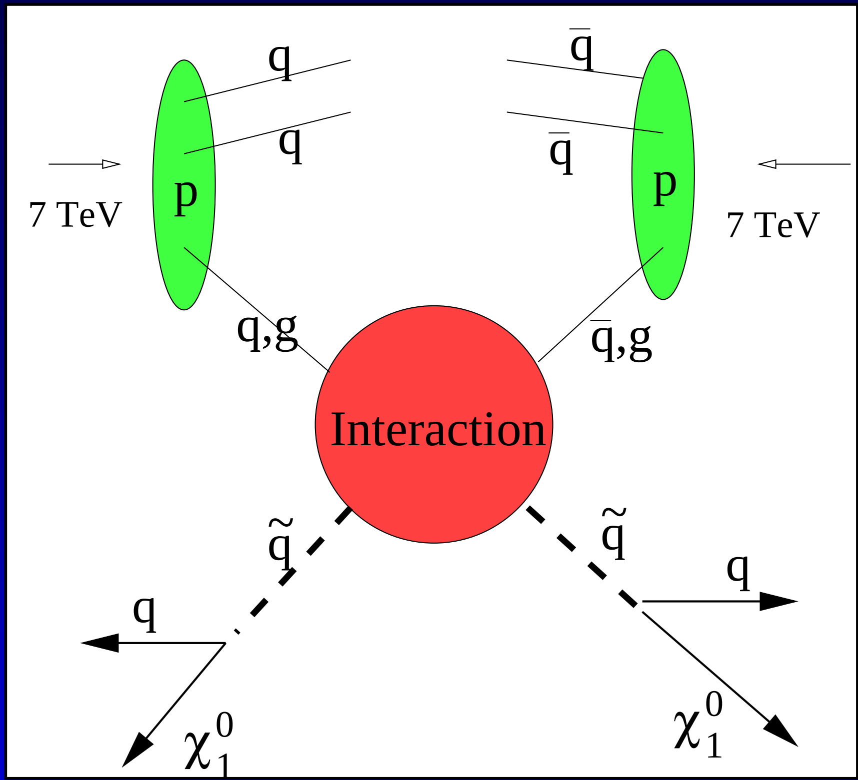
Used Dreiner, Richardson, Seymour, PRD63 (2001) 055008 for reach 10 fb^{-1}, $\tan\beta = 10$, 5σ discovery of $\tilde{e}$



Any Questions?

Collider Sparticle Production

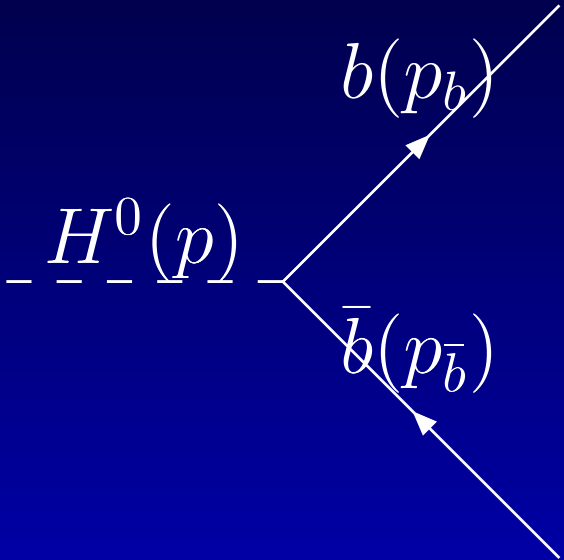
Strong sparticle production and decay to dark matter particles.



Any (light enough) dark matter candidate that couples to hadrons can be produced at the LHC

SUSY Kinematics: a Reminder

Take a particle decaying into 2 particles, eg $H^0 \to b\bar{b}$.
We define the invariant mass of the $b\bar{b}$ pair such that:



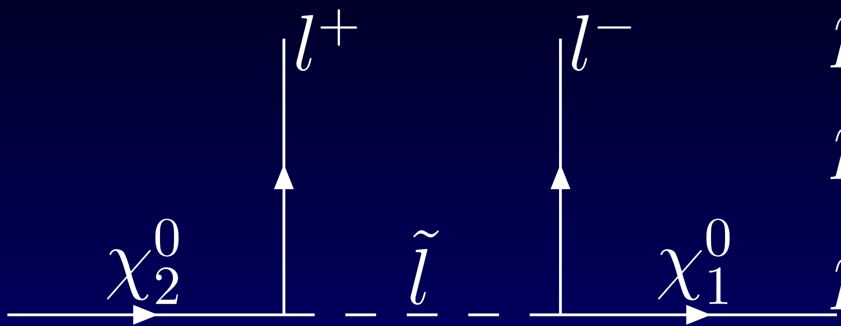
$$p^\mu = (\sqrt{m_H^2 + p^2}, \underline{p}) = p_b^\mu + p_{\bar{b}}^\mu$$

$$\Rightarrow p^2 = m_H^2 = (p_b + p_{\bar{b}})^2$$

Is *invariant* in boosted frames

Question: What happens to invariant mass in SUSY cascade decays, where we miss the final particle?

Cascade Decay



$$p^\mu_{\tilde{l}} = (m_{\tilde{l}}, \underline{0})$$
$$p^\mu_{l^\pm} = (|\underline{p}_{l\pm}|, \underline{p}_{l\pm})$$
$$p^\mu_{\chi^0_{1,2}} = \left(\sqrt{{m_{\chi^0_{1,2}}}^2 + |\underline{p}_{\chi^0_{1,2}}|^2}, \underline{p}_{\chi^0_{1,2}}\right)$$

The invariant mass of the l^+l^- pair is

$$m^2_{ll} = (p_{l^+} + p_{l^-})^\mu (p_{l^+} + p_{l^-})_\mu = p^2_{l^+} + p^2_{l^-} + 2 p_{l^+} \cdot p_{l^-}$$
$$= 2|\underline{p}_{l+}||\underline{p}_{l-}|(1 - \cos\theta) \leq 4|\underline{p}_{l+}||\underline{p}_{l-}|.$$

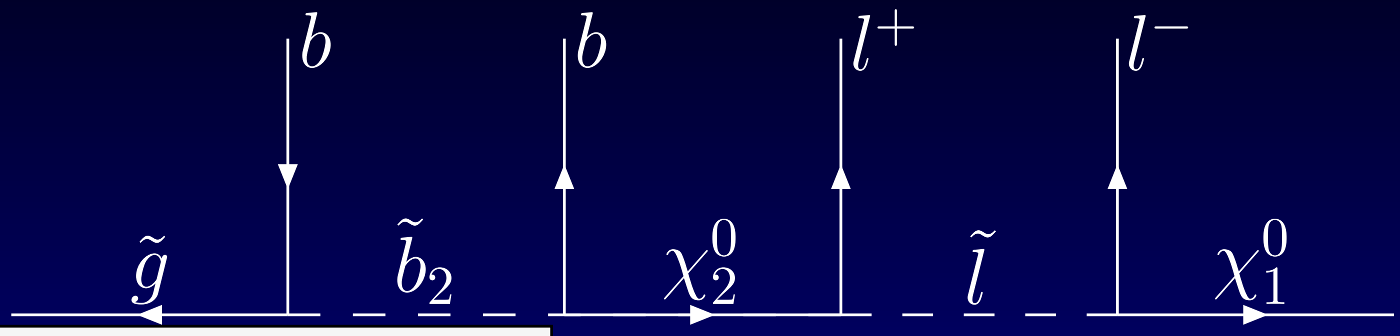
Momentum conservation:

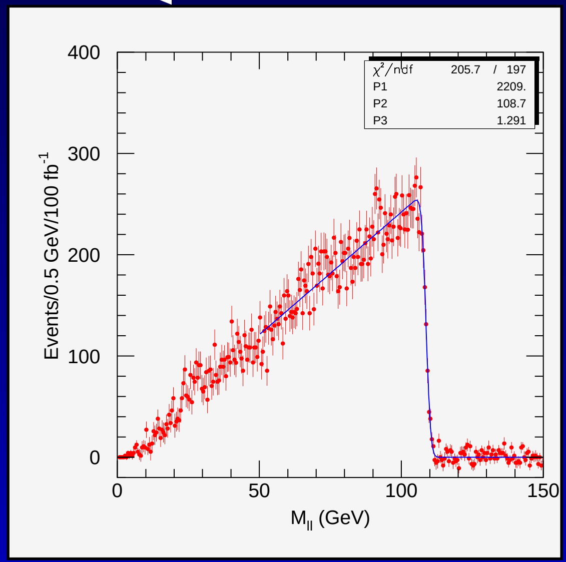
$$\Rightarrow \underline{p}_{\chi^0_2} + \underline{p}_{l+} = \underline{0}, \qquad \underline{p}_{l-} + \underline{p}_{\chi^0_1} = \underline{0}.$$

Energy conservation: $\sqrt{{m_{\chi^0_2}}^2 + |\underline{p}_{l+}|^2} = m_{\tilde{l}} + |\underline{p}_{l+}|$,

$$\Rightarrow |\underline{p}_{l+}| = \frac{m^2_{\chi^0_2} - m^2_{\tilde{l}}}{2 m_{\tilde{l}}}. \text{ Similarly } |\underline{p}_{l-}| = \frac{m^2_{\tilde{l}} - m^2_{\chi^0_1}}{2 m_{\tilde{l}}}.$$

LHC SUSY Measurements





$$m_{ll}^2 = \frac{(m^2_{\chi_2^0} - m^2_{\tilde{l}})(m^2_{\tilde{l}} - m^2_{\chi_1^0})}{m^2_{\tilde{l}}}$$

Q: Can we measure enough of these to pin SUSY[a] down?

[a] BCA, Lester, Parker, Webber, JHEP 0009 (2000) 004

Selectron-Smuon Splitting

In GUT-scale models,

$$\Delta m^2(M_Z) = \Delta m^2(M_X) + \frac{8m_\mu^2}{16\pi^2 v^2}\Big[m^2_{\tilde{\mu}_R}(M_X) + m^2_{\tilde{\mu}_L}(M_X) + m^2_{H_1}(M_X) + A^2_\mu(M_X)\Big]\tan^2\beta \ln\left(\frac{M_X}{M_Z}\right).$$

In AMSB, we have

$$\frac{(16\pi^2)^2(m^2_{\tilde{e}_R})}{m^2_{3/2}} = \left(-\frac{198}{25}g_1^4\right).\mathbf{1} + 6(Y_E^\dagger Y_E)^2 + (Y_E^\dagger Y_E)\left(\mathrm{Tr}(2Y_E Y_E^\dagger + 6Y_D Y_D^\dagger) - \frac{18}{5}g_1^2 - 6g_2^2\right)$$

Selectron-smuon mass splitting

In AMSB,

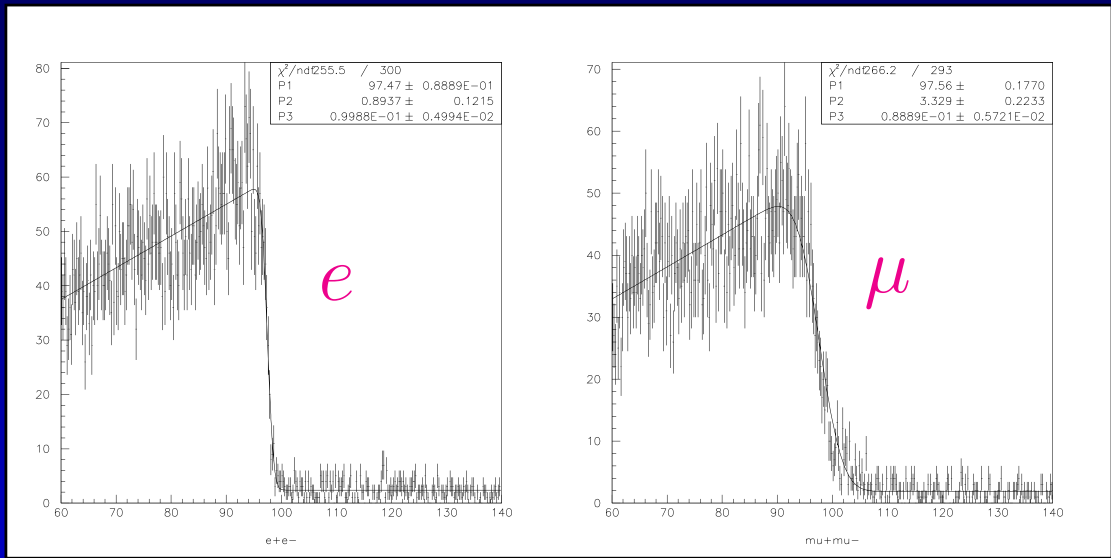
$$\frac{\Delta m^2}{m_{3/2}^2} = \frac{2m_\mu^2 \tan^4\beta}{(16\pi^2)^2 v^2}\left[\frac{12m_b^2 + 4m_\tau^2}{v^2} - \frac{1}{\tan^2\beta}\left(\frac{18}{5}g_1^2 + 6g_2^2\right)\right]$$

Dilepton edge at $m_{ll}^2(\text{max}) = \frac{(m^2_{\chi_2^0} - m^2_{\tilde{l}})(m^2_{\tilde{l}} - m^2_{\chi_1^0})}{m^2_{\tilde{l}}}$

$$\Rightarrow \frac{\Delta m_{ll}}{m_{ll}} = \frac{\Delta m_{\tilde{l}}}{m_{\tilde{l}}}\left(\frac{m^2_{\chi_1^0} m^2_{\chi_2^0} - m^4_{\tilde{l}}}{(m^2_{\chi_2^0} - m^2_{\tilde{l}})(m^2_{\tilde{l}} - m^2_{\chi_1^0})}\right),$$

Experimental Precision

SUGRA point 5: $m_0 = 100$ GeV, $m_{1/2} = 300$ GeV, $A_0 = 300$ GeV, $\tan\beta = 2.1$. Total SUSY cross-section from `HERWIG6.510` is 24 pb. Pass through `AcerDet` minimal rough detector sim,



16 fb^{-1}. Require 2 OSSF isolated leptons with $p_T > 10$ GeV, missing $E_T > 100$ GeV. Perform $\log L$ fit to Gaussian-smeared Δ and number of events.

Background Subtraction

We can still subtract[a] SM backgrounds like those from $t\bar{t}$ or W^+W^- by (eg)

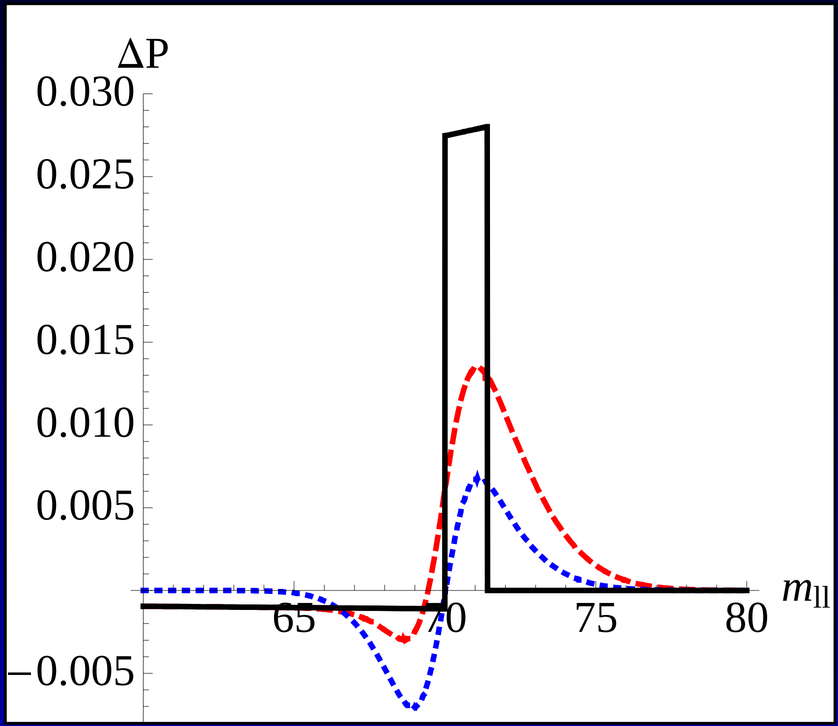
$$N_{e^+e^-} - \frac{1}{2}\left(N_{e^+\mu^-} + N_{e^-\mu^+}\right),$$

but we'll have to know the efficiencies of es and μs well.

Use muons/electrons from Z^0 pole to calibrate energies/efficiencies by extrapolation: for SPS1a,3,5,9 $m_{ll} = 80, 118, 99, 122, 343$ GeV. Best guess $\Delta E/E = 0.1\%$

[a] See Goto, Kawagoe, Nojiri, Phys. Rev. D70 (2004) 075016 for BRs/charge asymmetries sensitive to $\tilde{\mu}_L - \tilde{\mu}_R$ mixing

Difference in mass distributions



$\Delta m/m = 2\%$ and (black) no energy resolution

Red: Energy resolution

Blue: $\Delta m/m = 0$ with energy resolution

Thus we could be fooled by the difference.

Best to fit both $\tilde{e}$, $\tilde{\mu}$ endpoints separately.[a]

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[a] BCA, Conlon, Lester, Phys. Rev. D77 (2008) 076006, `arXiv:0801.366`

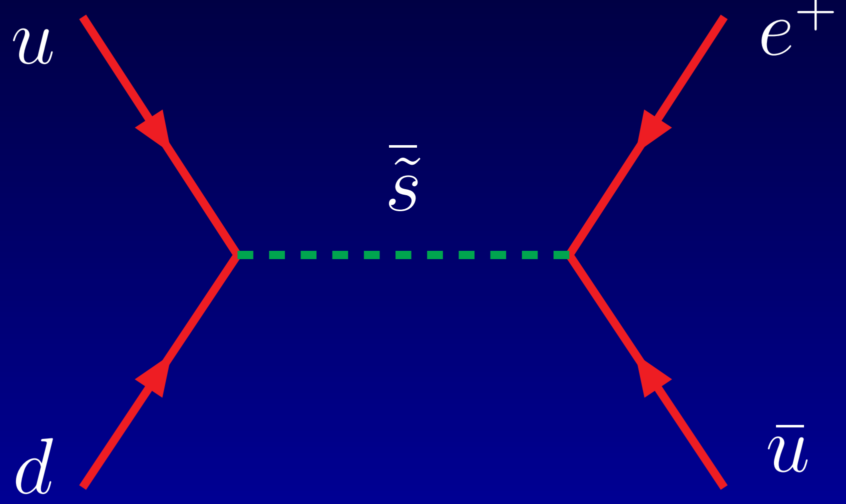
Summary

- Current indirect data are weak and only constrain models with a couple of extra parameters: LHC will change this situation
- Want predictivity in flavour sector eg AMSB. LHCb data going to provide $BR(B_s \rightarrow \mu^+\mu^-)$ for instance.
- SLHA2 compliant flavour tools developed in process `SOFTSUSY3.0`[a]:, `SUSYBSG1.3`[b]
- Does your model violate R_p? It could lead to interesting *detection possibilities*.
- Constrained models' useful predictions are *those that can be easily measured* - bear in mind

[a] BCA, arXiv:0903.1805

Proton decay

$R\!\!\!/_p$ terms are lepton number L, or baryon number B violating.



$$\Gamma(p \rightarrow e^+\pi^0) \approx \frac{\lambda'^2_{11k}\lambda''^2_{11k}}{16\pi^2\tilde{m}^4_{d_k}} M^5_{proton}.$$

$$\tau(p \rightarrow \nu K^+) > 7 \cdot 10^{32}\, yr \Rightarrow \lambda'_{11k} \cdot \lambda''_{11k} \lesssim 10^{-27} \left(\frac{\tilde{m}_{d_k}}{100 \text{ GeV}}\right)^2.$$

Alternatives to R_p

All of the following stabilise the proton:

- Matter Parity $M_p = (-1)^{3B+L}$.
  Does exactly the same job as R_p.
- Baryon Parity $B_p = (-1)^{3B}$.
  Allows $\not{R}_p$ terms $\lambda_{ijk} L_i L_j \bar{E}_k + \lambda'_{ijk} L_i Q_j \bar{D}_k$.
- Lepton Parity $L_p = (-1)^{L}$.
  Allows $\not{R}_p$ terms $\lambda''_{ijk} \bar{U}_i \bar{D}_j \bar{D}_k$.

The second two alternatives allow for increased SUSY detection possibilities.

Minimal Flavour Violation

In BSM models, MFV says that, essentially

> SM Yukawa couplings contain *all* of the flavour violation in the model.

SM has a global $U(3)_Q \times U(3)_L \times U(3)_e \times U(3)_d \times U(3)_u$ flavour symmetry where Q, L, e_R, u_R, d_R all transform as a fundamental representation under a $U(3)$ and singlets under the rest, since terms like

$$\mathcal{L}_{kin} = \bar{Q}_i i \not{D} Q_i + \bar{L}_i i \not{D} L_i + \bar{e}_{Ri} i \not{D} e_{Ri} + \ldots$$

are *invariant*.

MFV and Yukawa Couplings

Even Yukawa couplings like

$$\mathcal{L}_{yuk} = \bar{Q}_i H (Y_U)_{ij} u_{Rj}$$

are invariant if we impose that, under $U(3)^5$

$$(Y_U)_{ij} \to U_Q (Y_U)_{ij} U_u^\dagger.$$

transforms as a spurion field[a].

These models are in general safer than non-MFV models from being ruled out by flavour constraints.

[a] D'Ambrosio, Giudice, Isidori, Strumia, Nucl. Phys. B645 (2002) 155

SUSY

which look like they break the symmetry. Suppose we can write, for some SUSY breaking scheme, e.g.

$$(m^2_{\tilde{u}})_{ij} = z_1^u \delta_{ij} + z_2^u (Y_U^\dagger Y_U) + z_3^u\, Y_U^\dagger Y_D Y_D^\dagger Y_U + z_4^u (Y_U^\dagger Y_U)^2 + \ldots$$

then MFV is preserved in the term

$$\tilde{u}_{iR}\,(m^2_{\tilde{u}})_{ij}\,\tilde{u}^*_{jR}.$$

In fact, such an expansion spans all possible[a] $(m^2_{\tilde{u}})_{ij}$ unless

$$\frac{z_{i>1}}{z_1} \leq \mathcal{O}(1) \Rightarrow \text{AMSB}$$

[a] Colangelo, Nikolidakis, Smith, Eur. Phys. J. C59 (2009) 75

MSSM is MFV?

By use of Cayley-Hamilton identities[a]

$$0 = M^3 - [M]M^2 + \frac{1}{2}M([M]^2 - [M^2]) - |M|$$
$$|M| = \frac{1}{3}[M^3] - \frac{1}{2}[M][M^2] + \frac{1}{6}[M]^3,$$

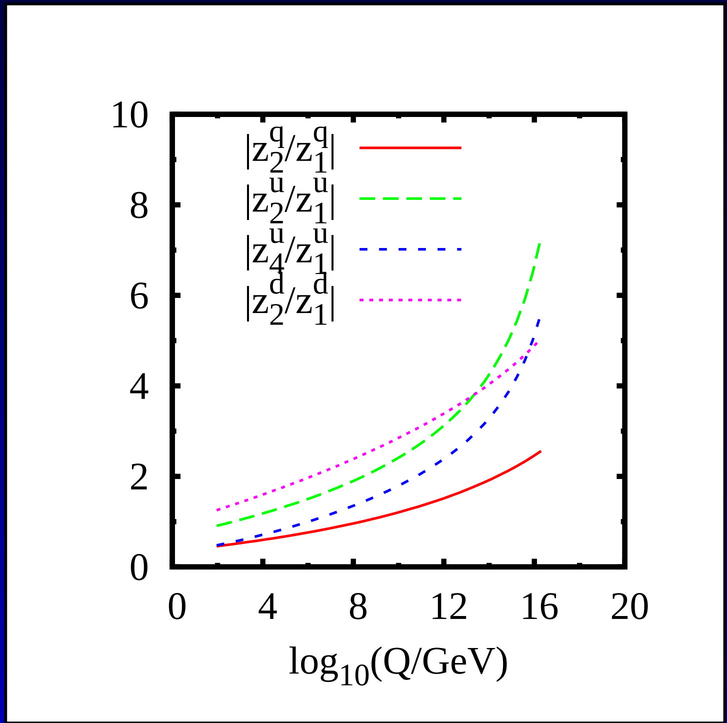
it can be shown that the MFV expansion terminates after 18 terms *for an arbitrary hermitian matrix*. Thus, the MSSM *always* respects $U(3)^5$! To make the definition of MFV meaningful, we add

$$\frac{z_{i>1}}{z_1} \leq \mathcal{O}(1) \Rightarrow \text{AMSB}$$

[a] Colangelo, Nikolidakis, Smith, Eur. Phys. J. C59 (2009) 75

MFV Decomposition

$\tan\beta = 10$



$$z_1^u = m_{3/2}^2(-\frac{88}{25}g_1^4 + 8g_3^4)/(16\pi^2)$$

$$z_4^u = 6m_{3/2}^2/(16\pi^2)$$

Nowhere flavour blind

MSUGRA/GMSB have small $z_{i>1}$

AMSB is MFV

We'll predict δs, eg:

$$(\delta_{ij}^q)_{LL} = m_{\tilde{q}_{ij}}^2 / \sqrt{m_{\tilde{q}_{Lii}}^2 m_{\tilde{q}_{Ljj}}^2}. \quad (1)$$

Volume Effects

Can't rely on a good χ^2 in non-Gaussian situation

QIRFP of λ_t

Neglecting electroweak gauge couplings, solve RGEs to obtain in IRQFP limit $\lambda_t(M_X) \rightarrow \infty$

$$\frac{\lambda_t^2(m_t)}{g_3^2(m_t)} = \frac{7}{18}\left(1 - \left(\frac{g_3^2(M_X)}{g_3^2(m_t)}\right)^{\frac{7}{9}}\right)^{-1}.$$

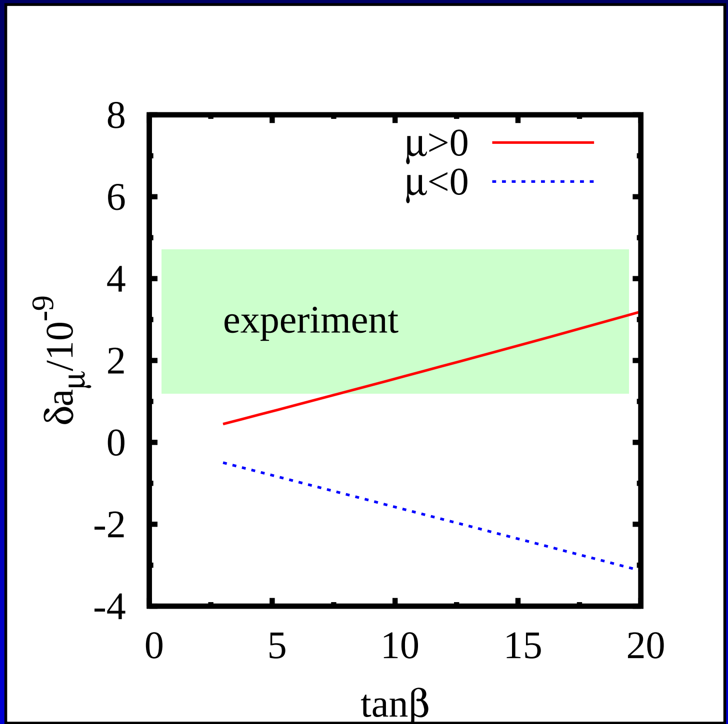
Putting in the electroweak corrections and $M_X = M_{GUT}$,

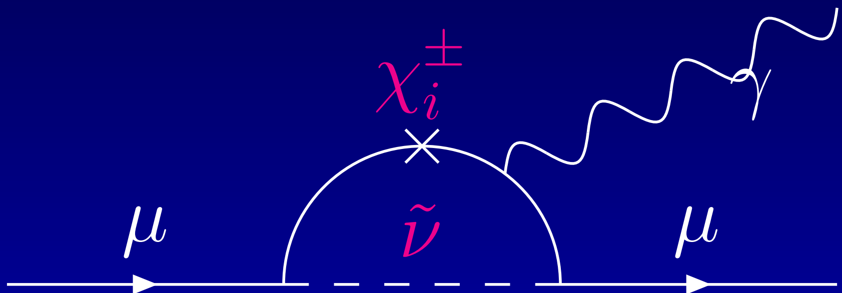
$$\lambda_t(m_t) = 1.1$$

whereas $\hat{\beta}_t$ vanishes for $\lambda_t = 1.2$: flavour violation at low $\tan\beta$ has an additional suppression.

Anomalous mag. moment of μ

$U(1)'$ solution to tachyonic sleptons[a]. $m_{3/2} = 40$ TeV, $\mu > 0$, have a solution to $\delta a_\mu = (29.5 \pm 8.8) \times 10^{-10}$, $BR(B_s \to X_S \gamma)$ for $8 < \tan\beta < 14$:





$$a_\mu \propto \frac{\tan\beta}{M^2_{SUSY}}$$

Depends on slepton fix

[a] Hodgson, Jack, Jones, JHEP 0710 (2007) 070, arXiv:0709.2854

Constraints

$\mathcal{L}_{MSSM}$ strongly constrained by absence of new physics contributions to FCNCs, eg $BR(\mu \to e\gamma) < 1.2 \times 10^{-11}$ by MEGA. Constrains off-diagonal propagator mixing between selectron and smuon flavour eigenstates to

$$\frac{m^2_{\tilde{L}_{12}}}{m^2_{\tilde{L}_{11}} + m^2_{\tilde{L}_{22}}} \lesssim 6 \times 10^{-4}. \quad (2)$$

RR constraints similar over most of parameter space, but there are possible cancellations.

Unconstraints

However, these constraints do *not* constrain selectron-smuon mass splitting

$$\Delta m^2 \equiv m^2_{\tilde{\mu}_R} - m^2_{\tilde{e}_R} \quad (3)$$

in the absence of lepton flavour violation (LFV).
Some other work on SUSY LFV at LHC:

Agashe, Graesser hep-ph/9904422; Hinchliffe, Paige hep-ph/0010086; Hisano, Kitano, Nojiri hep-ph/0202129; Carvallo, Ellis, Gomez, Lola, Romao hep-ph/0206148; Bartl, Hidaka, Hohenwarter-Sodek, Kernreiter, Majerotto, Porod 0510074; Grossman, Nir, Thaler, Volansky, Zupan 0706.1845; Feng, Lester, Nir, Shadmi 0712.0674

Enhancement Factor

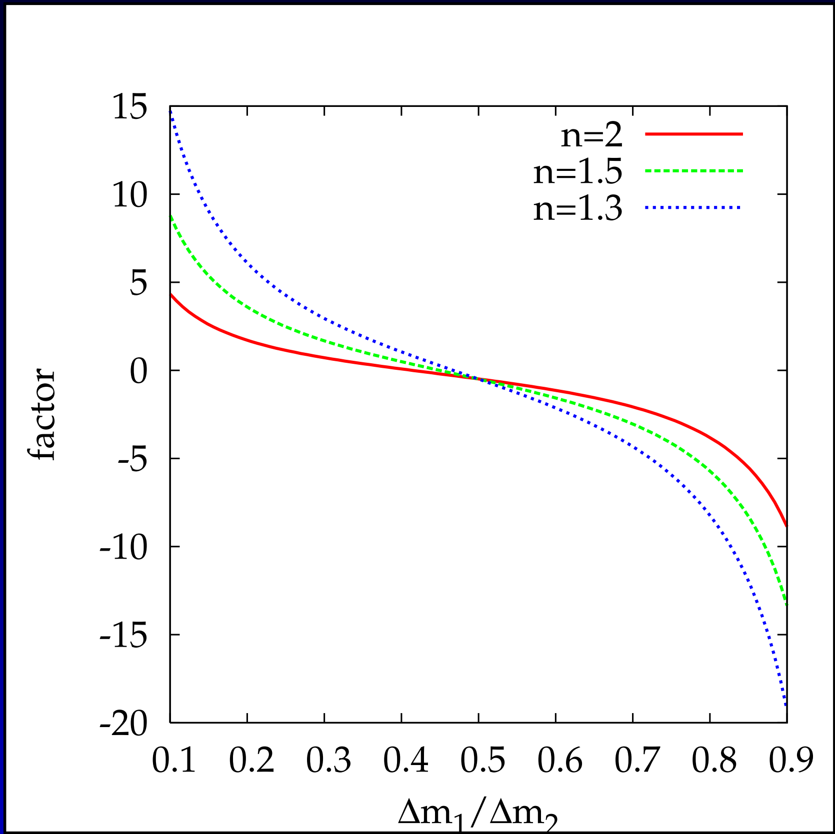


Figure 2: $(\Delta m_{ll}/m_{ll})/(\Delta m_{\tilde{l}}/m_{\tilde{l}})$ as a function of $\Delta m_1/\Delta m_2 \equiv (m_{\tilde{l}} - m_{\chi_1^0})/(m_{\chi_2^0} - m_{\chi_1^0})$ for three different values of $n \equiv m_{\chi_2^0}/m_{\chi_1^0}$.

Luminosity Dependence

Integrated Luminosity (fb^{-1})	Events below 100 GeV	Electron Endpoint (GeV)	Muon Endpoint (GeV)
16.0	22145	97.47 ± 0.09	97.56 ± 0.18
8.0	11131	97.41 ± 0.13	97.83 ± 0.23
4.0	5520	97.54 ± 0.19	97.63 ± 0.35
2.0	2707	97.52 ± 0.28	97.56 ± 0.50

Fractional fit error $\Sigma = \sqrt{(0.002\sqrt{22145/N})^2 + 0.001^2}$ defined by $\Delta E/E$ and largest endpoint error.

Splitting Discovery

Define splitting discovery significance

$$S_1 = \left| \frac{\Delta m_{ll}}{m_{ll}} \right| \div \Sigma$$

In mSUGRA, $S_1(\text{max}) = 0.5$. If trigger and reconstruction efficiencies could be controlled, one could also use

$$S_2 = \frac{N_{ee} - N_{\mu\mu}}{\sqrt{N}}. \quad (4)$$

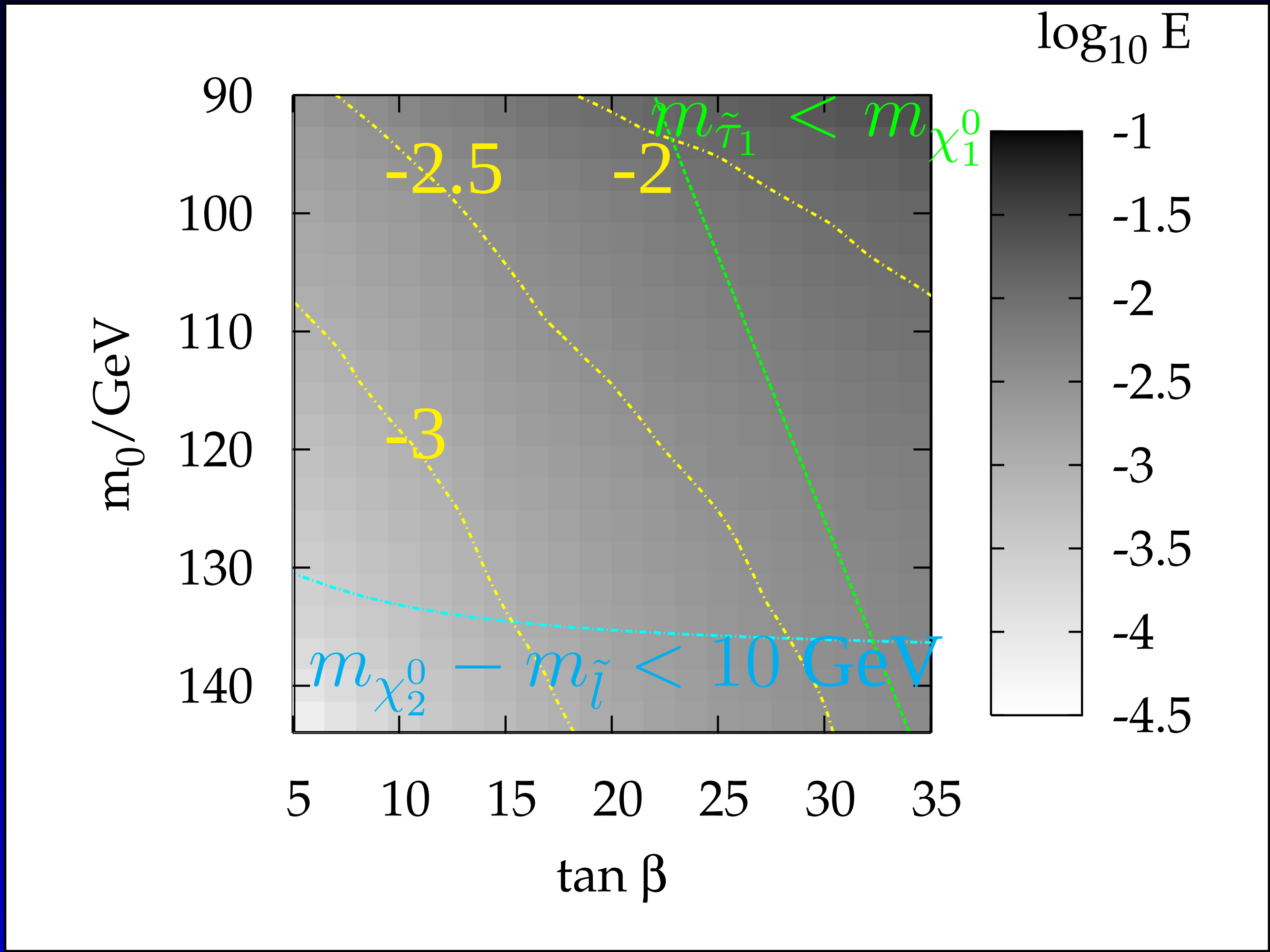
(we won't)

mSUGRA Degeneracy

In fact, mSUGRA splittings at large $\tan\beta$ can often be several $\%$. But at large $\tan\beta$, $\tilde{\tau}_R$ is light and dominates decay modes with $BR(\chi_2^0 \to \tilde{l}_R l) \ll 1$, $BR(\chi_2^0 \to \tilde{\tau}_1 \tau) \approx 1$.

If we depart from mSUGRA by making $\tilde{\tau}$s heavy, one might easily discriminate from smuon-selectron universality: $m_0 = 148$ GeV, $m_{1/2} = 250$ GeV, $A_0 = -600$ GeV, $\tan\beta = 40$ but $m_{\tilde{\tau}_{L.R}} = 950$ GeV: $\Delta m_{\tilde{l}}/m_{\tilde{l}} = 2.3 \times 10^{-3}$ and $\Delta m_{ll}/m_{ll} = 1.5\%$ whereas $\Sigma = 0.27\%$, allowing an $(S_1 > 5)$-sigma discovery.

1σ Sensitivity to $\tilde{e}$-$\tilde{\mu}$ Universality



$\mathcal{L} = 30$ fb^{-1} SPS1a. E $\equiv \left. \frac{\Delta m_{\tilde{l}}}{m_{\tilde{l}}} \right|_{S_1=1}$.

Extra Broken $U(1)$

Q	$\bar{U}$	$\bar{D}$	H_1	H_2	$\bar{\nu}$
$-\frac{1}{3}L$	$-e-\frac{2}{3}L$	$e+\frac{4}{3}L$	$-e-L$	$e+L$	$-2L-e$

$$m^2_{\tilde{Q}} \rightarrow m^2_{\tilde{Q}} - \xi \frac{L}{3}.\mathbf{1},\ m^2_{\tilde{u}} \rightarrow m^2_{\tilde{u}} - \xi\left(e+\frac{2}{3}L\right).\mathbf{1},$$

$$m^2_{\tilde{d}} \rightarrow m^2_{\tilde{d}} + \xi\left(e+\frac{4}{3}L\right).\mathbf{1}$$

a

[a] Hodgson, Jack, Jones, JHEP 0710 (2007) 070, arXiv:0709.2854

Lepton number violation

Need to get all six slepton masses positive, while respecting bounds on couplings: $W = \lambda_{ijk} L_i L_j E_k$

$$\lambda_{mni} \not\mapsto \lambda_{mnj} \quad , \quad \lambda_{imn} \not\mapsto \lambda_{jmn} \qquad i \neq j,$$

$$\lambda_{123} \lesssim 0.49 \times \frac{m_{\tilde{\tau}_R}}{1 \text{ TeV}}$$

$$\lambda_{132} \lesssim 0.62 \times \frac{m_{\tilde{\mu}_R}}{1 \text{ TeV}}$$

$$\lambda_{231} \lesssim 0.70 \times \frac{m_{\tilde{e}_R}}{1 \text{ TeV}},$$

Search through min number of operators, and get BCA, Dedes, JHEP 06 (2000) 017, hep-ph/0003222

$$(m_E^2)_2^2 = \frac{M_{3/2}^2}{(16\pi^2)^2} \left[\lambda_{231}^2 (4\lambda_{231}^2 + \lambda_{123}^2 + \lambda_{132}^2) - \frac{198}{25} g_1^4 \right]$$