Supersymmetry at the LHC

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Based on the work done with Peter Skands [arXiv:1109.5852] and Biswarup Mukhopadhyaya [*in preparation*]

Part I: Implementation of SUSY in Pythia 8

Part II: Interpretation of ATLAS SUSY limits for third-generation squarks

Part I: Implementation of SUSY in Pythia 8

SUSY in Pythia 8

Read in new masses and couplings
- Can read in files SUSY Les Houches v2 (SLHA2) format
- Completely flavour general couplings [Bozzi et. al. 2007]

$$\begin{pmatrix} \tilde{u}_1 \\ \tilde{u}_2 \\ \tilde{u}_3 \\ \tilde{u}_4 \\ \tilde{u}_5 \\ \tilde{u}_6 \end{pmatrix} = R^u \begin{pmatrix} \tilde{u}_L \\ \tilde{c}_L \\ \tilde{t}_L \\ \tilde{u}_R \\ \tilde{c}_R \\ \tilde{t}_R \end{pmatrix} ; \begin{pmatrix} \tilde{d}_1 \\ \tilde{d}_2 \\ \tilde{d}_3 \\ \tilde{d}_4 \\ \tilde{d}_5 \\ \tilde{d}_6 \end{pmatrix} = R^d \begin{pmatrix} \tilde{d}_L \\ \tilde{s}_L \\ \tilde{b}_L \\ \tilde{d}_R \\ \tilde{s}_R \\ \tilde{b}_R \end{pmatrix}$$

SUSY in Pythia 8

Allows processes with
- CP violation
- Flavour violation
- R-parity violation

Calculates all decay widths for 2-body decays of squarks, sleptons, gluino, neutralinos and charginos.

Cross sections
- Pair production of all strongly charged superparticles
- Pair production of Neutralinos and Charginos

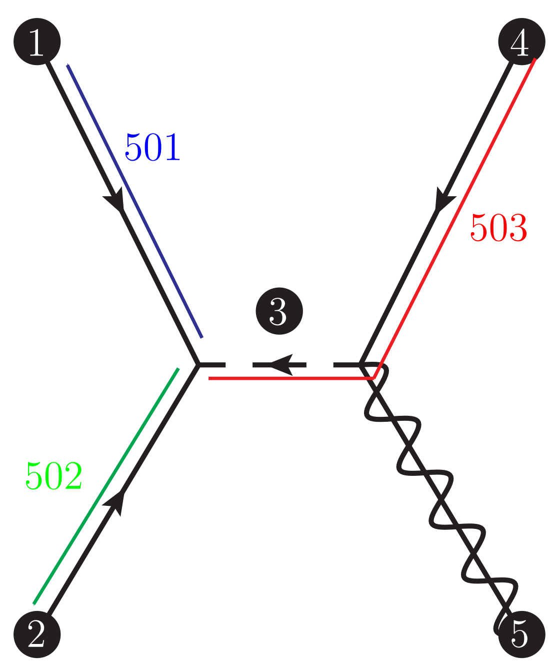
Production processes

Chargino and neutralino production	qqbar2chi0chi0, qqbar2chi+-chi0, qqbar2chi+chi-.
Gaugino squark production	qg2chi0squark, qg2chi+-squark.
Gluino production	gg2gluinogluino, qqbar2gluinogluino.
Squark-gluino production	qg2squarkgluino
Squark-pair production	gg2squarkantisquark, qqbar2squarkantisquark ★ qq2squarksquark ★
RPV resonant squark production	qq2antisquark

R-parity violating production

Three types of RPV couplings: LLE, LQD, UDD

$(\lambda_{ijk}, \lambda'_{ijk}$ and $\lambda''_{ijk})$



$q_i q_j \to \tilde{q}_k^*$ via λ''_{ijk}

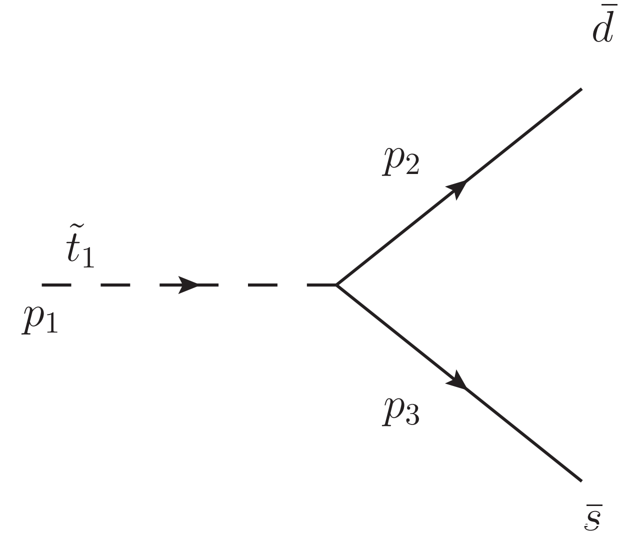
$$\sigma_{\tilde{u}_i^*} \quad = \quad \frac{2\pi}{3m_i^2} \sum_{jk} \sum_{i'} |\lambda''_{i'jk} (R^u)_{ii'}|^2$$

Sparticle Decays

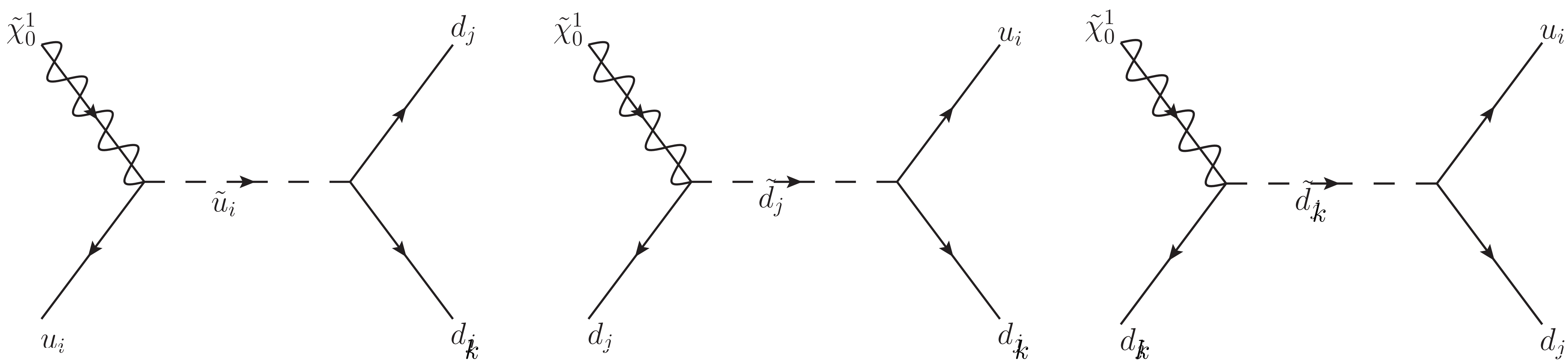
- $\tilde{g} \to \tilde{q}_i q_j$
- $\tilde{\chi}_i^0 \to \tilde{q}_i q_j,\ \tilde{l}_i l_j\ \tilde{\chi}_j^0 Z,\ \tilde{\chi}_j^+ W^-, \tilde{\chi}_j^0 H_k, \tilde{\chi}_j^+ H^-$
- $\tilde{\chi}_i^+ \to \tilde{q}_i q_j,\ \tilde{l}_i l_j\ \tilde{\chi}_j^+ Z,\ \tilde{\chi}_j^0 W^+, \tilde{\chi}_j^+ H_k, \tilde{\chi}_j^0 H^+$
- $\tilde{q}_i \to q_j \tilde{\chi}_k^0,\ q_j \tilde{\chi}_k^+,\ \tilde{q}_j Z,\ \tilde{q}_j W^+, \tilde{q}_j H_k, \tilde{q}'_j H^+$

Decays via UDD

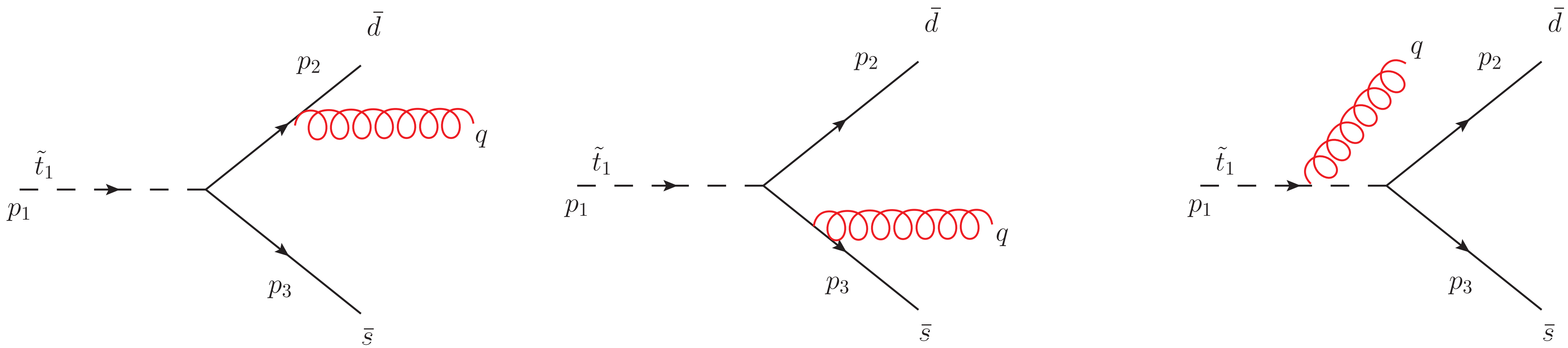
Squark decays: $\tilde{q}_i \to \bar{q}_j \bar{q}_k$



Neutralino Decays: $\tilde{\chi}_i^0 \to u_i d_j d_k$



Showering in the presence of baryon-number violation

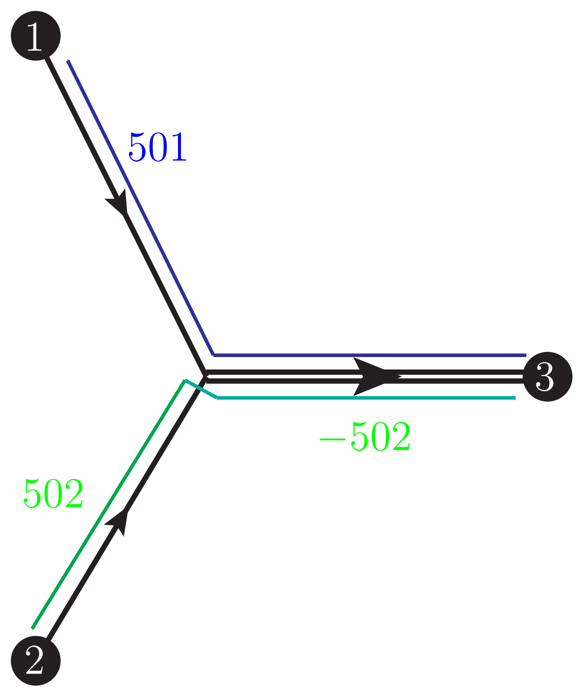


$$\frac{|M_1|^2}{|M_0|^2} = 4\pi\alpha_s C_F \left[\frac{1}{(N_c-1)}\left(\frac{2s_{23}}{s_{2q}s_{3q}} + \frac{2s_{12}}{s_{1q}s_{2q}} + \frac{2s_{13}}{s_{1q}s_{3q}}\right) + \frac{s_{2q}}{ss_{3q}} + \frac{s_{3q}}{ss_{2q}}\right]$$

$$+ \text{ finite terms}$$

Case of $\tilde{\chi}_i^0 \to u_i d_j d_k$ is similar, with three half-strength dipoles between the quarks

Other exotic colour structures: Sextets



Needs two color indices

We use a negative anti-colour index to denote the extra colour

Implementing completely new BSM models

Method 1: Use QNUMBERS and read in LHEF events

```
SLHA:file = fileName

BLOCK QNUMBERS 8765432 # yup yupbar
      1     2  # 3 times electric charge
      2     2  # number of spin states (2S+1)
      3     3  # colour rep (1: singlet, 3: triplet, 6: sextet, 8: octet)
      4     1  # Particle/Antiparticle distinction (0=own anti)


 BLOCK MASS
 #     ID code  pole mass in GeV
       8765432   600.0  # m(yup)
```

Use LHEF format to pass events to Pythia8

Method 2: Use Pythia's semi-internal process machinery

Write the process as an inherited class of Pythia's `SigmaProcess`

Use the SLHA file to pass any user-defined blocks. This can be used to pass couplings etc. for a new model which can be accessed from within the process using

```
bool slhaPtr->getEntry(string blockName, double& val);
bool slhaPtr->getEntry(string blockName, int indx, double& val);
bool slhaPtr->getEntry(string blockName, int indx, int jndx, double& val);
bool slhaPtr->getEntry(string blockName, int indx, int jndx, int kndx, double& val);
```

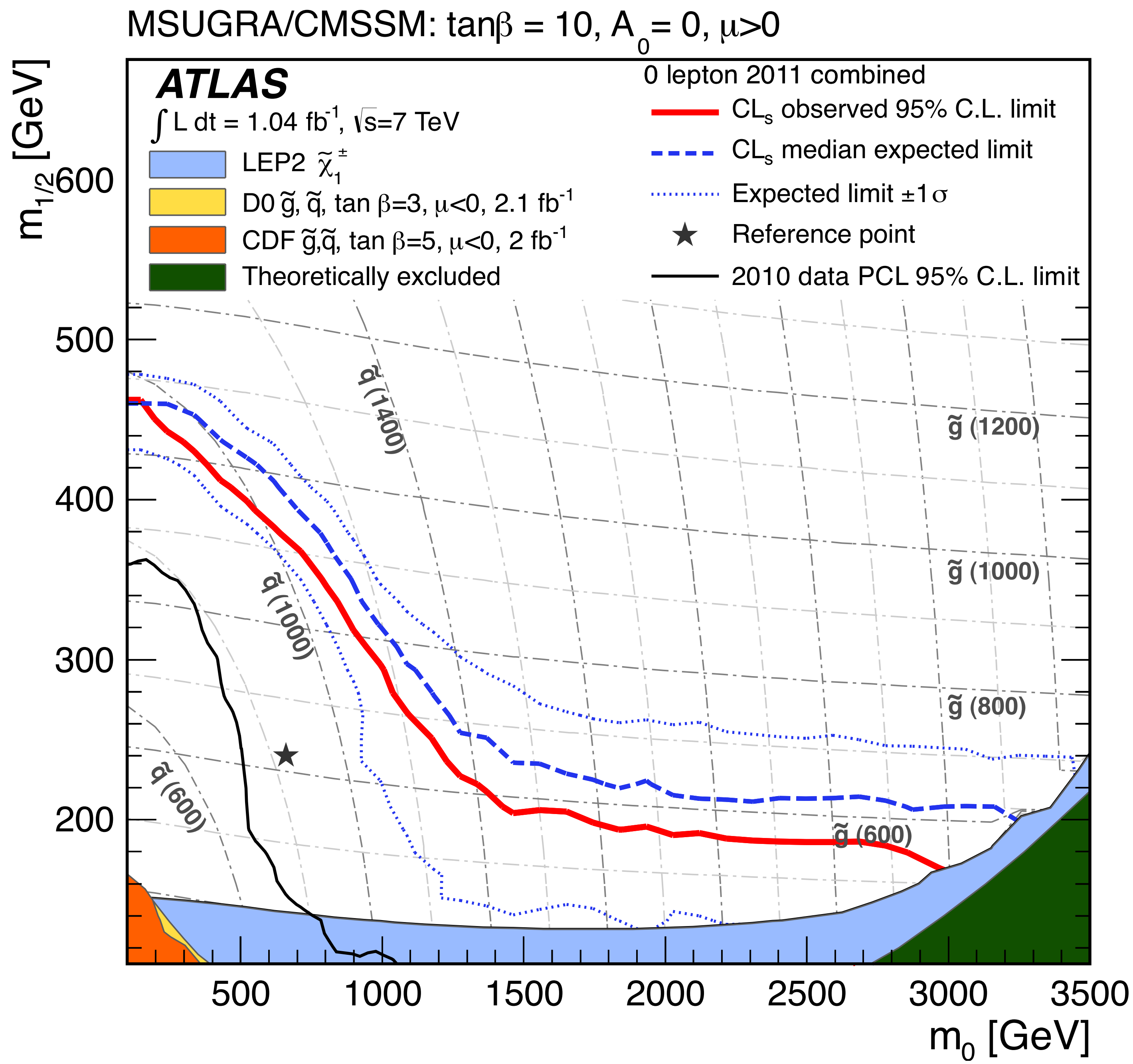
SUSY in Pythia8 is ready to be tested in the field!

Work done with Peter Skands [arXiv:1109.5852]

Part II: Interpretation of ATLAS SUSY limits for third-generation squarks

ATLAS limits with 1fb^{-1} (jets+MET) and 0.833 fb^{-1} (bjets+MET)

Channel	$\sigma \times acc$ (fb)
2 jets + MET	24
3 jets + MET	30
4 jets + MET (M_{eff} =1 TeV)	32
1 btag + $M_{eff} > 500$ (3JA)	288
1 btag + $M_{eff} > 700$ (3JB)	61
2 btag + $M_{eff} > 500$ (3JC)	78
2 btag + $M_{eff} > 700$ (3JD)	17



Why separate limits for third generation squarks?

– Motivation for TeV-scale SUSY: hierarchy problem i.e. $\tilde{t}_1$ mass should be ~ 500 GeV or less.

– Strongest limits currently from jets+MET signals which are tailored to detect squarks of first two generations

– The limits on third generation squarks are indirect.

– We are already on the brink of un-naturalness if we use limits from jets+MET searches.

Breaking free (somewhat) from the cMSSM

$$m_0, m_{1/2}, A_0, \tan\beta, sign(\mu)$$

↓

$$m_q, m_u, m_d, m_{q3}, m_{tR}, m_{bR}$$

$$M_1, M_2, M_3$$

$$A_t, A_b, A_\tau$$

$$m_\ell, m_E, m_{\ell 3}, m_{\tau R}$$

$$\mu, \tan\beta, m_A$$

Direct limits on third generation squarks

Consider the case where the first two generations of squarks and all sleptons are heavy enough that they cannot be probed at the 7 TeV run of the LHC.

Only third generation squarks are accessible.

$$m_q, m_u, m_d, m_\ell, m_e, m_{\ell 3}, m_{\tau R} \sim 2 \text{ TeV}$$

We also retain the cMSSM gaugino mass pattern

$$M_1 : M_2 : M_3 \simeq 1 : 2 : 6$$

(hence the "somewhat" breaking free)

For parametrising the third generation, consider the stop mass matrix

$$\begin{pmatrix} M_{\tilde{t}_1} & 0 \\ 0 & M_{\tilde{t}_2} \end{pmatrix} = \mathcal{R} \begin{pmatrix} m_{q3} & m_t X_t \\ m_t X_t & m_{tR} \end{pmatrix} \mathcal{R}^{-1} \; ; \; \mathcal{R} = \begin{pmatrix} \cos\theta_{\tilde{t}} & \sin\theta_{\tilde{t}} \\ -\sin\theta_{\tilde{t}} & \cos\theta_{\tilde{t}} \end{pmatrix}$$

$$X_t = A_t - \mu \cot\beta$$

For fixed values of μ and $\tan\beta$, the independent parameters are m_{q3}, m_{tR}, A_t

Equivalently, we can invert the equation to have

$$M_{\tilde{t}_1}, M_{\tilde{t}_2}, \sin\theta_{\tilde{t}}$$

as the parameters of the scan

Of course, one has to be careful while applying the same inversion to the sbottom sector because it shares the parameter m_{q3}

Case A: $\tilde{t}_1$ lighter than other third generation squarks (closest to the cMSSM case)

$$\tilde{t}_1 \sim \tilde{t}_R (\sin\theta_{\tilde{t}} = 0.99)$$

Step 1: Choose $M_{\tilde{t}_1}$

Step 2: Set $M_{\tilde{t}_2} = M_{\tilde{t}_1} + 500 \text{ GeV}$

Step 3: Calculate m_{q3}, m_{tR}, A_t

Step 4: Set $m_{bR} = m_{q3} (\sin\theta_{\tilde{b}} = 0.707)$

We can now scan over a $M_{\tilde{t}_1} - M_2$ plane for fixed values of $\mu, \tan\beta, m_A$

What does Case A probe?

Dominant production processes: $\tilde{g}\tilde{g}, \tilde{t}_1\tilde{t}_1^*$

$$M_2 > 150 \text{ GeV} \Rightarrow M_{\tilde{g}} > 450 \text{ GeV}$$
$$\Rightarrow \tilde{g} \to t\bar{t}\tilde{\chi}_i^0$$

$$M_{\tilde{t}_1} < M_{\tilde{\chi}_1^0} \Rightarrow \text{Stop LSP!}$$
$$M_{\tilde{\chi}_1^0} < M_{\tilde{t}_1} < M_{\tilde{\chi}_1^0} + M_t \Rightarrow \tilde{t}_1 \to c\tilde{\chi}_1^0$$
$$M_{\tilde{t}_1} > M_{\tilde{\chi}_1^0} + M_t \Rightarrow \tilde{t}_1 \to t\tilde{\chi}_1^0$$
$$M_{\tilde{t}_1} > M_{\tilde{\chi}_1^+} + M_b \Rightarrow \tilde{t}_1 \to b\tilde{\chi}_1^+$$

Simulation of Signal

– Generate spectrum using SUSPect

– Use Pythia 6.4 for signal, Prospino for NLO normalisation

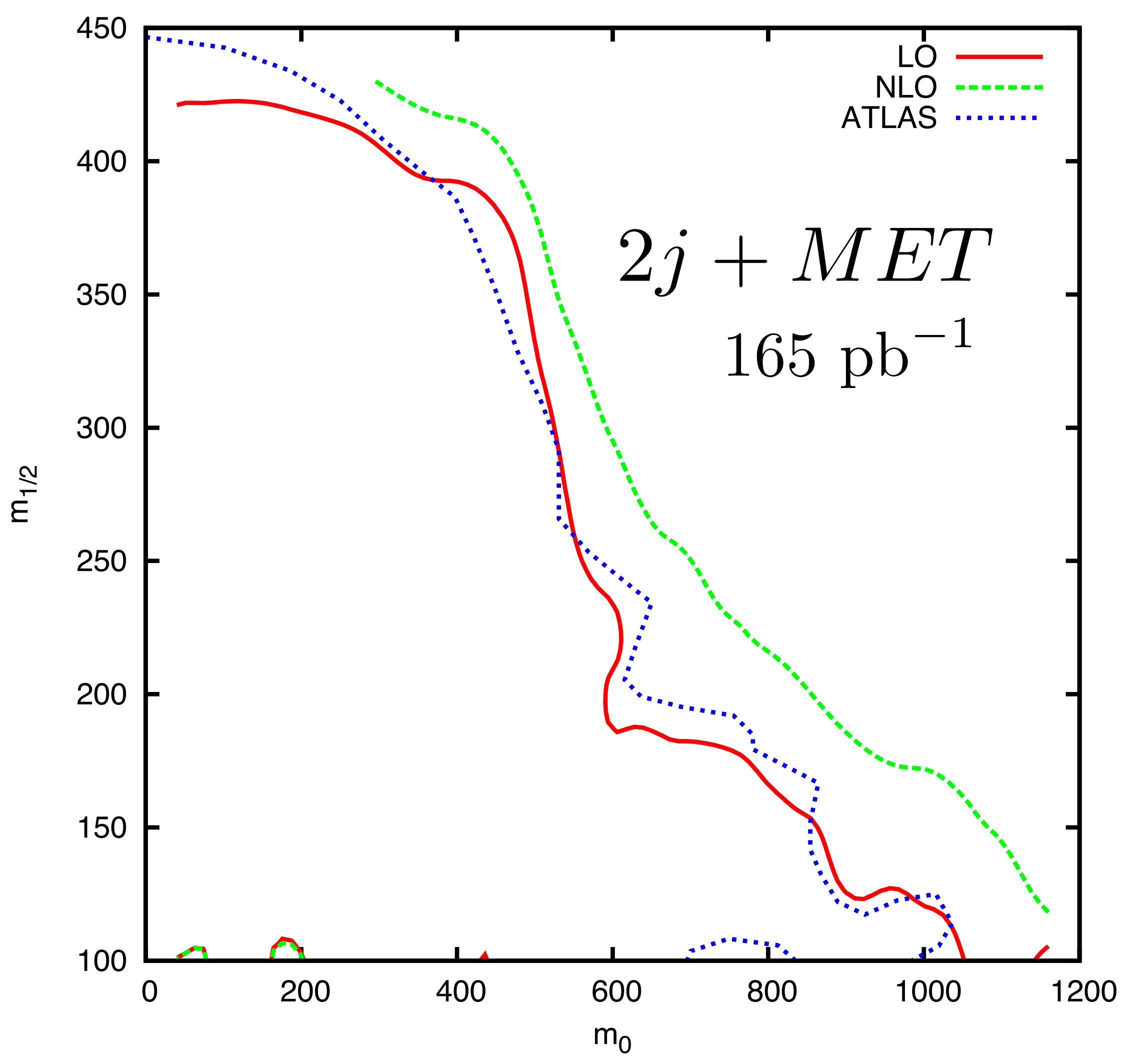
– Anti-kt algorithm for forming jets (FastJet)

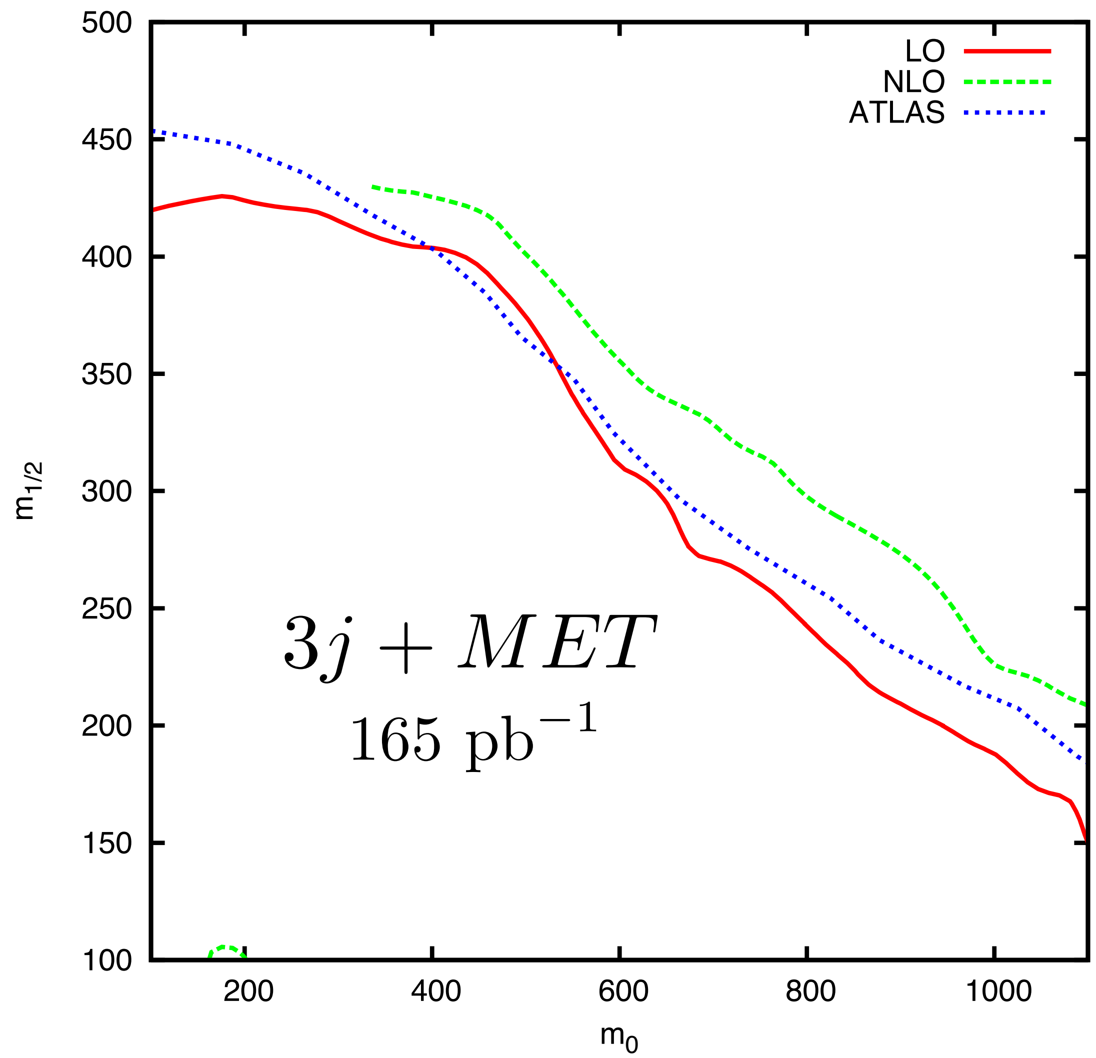
– Smear momenta of all objects

– Apply cuts as mentioned in the paper
(jets+MET: [ATLAS-CONF-2011-086; arXiv:1109.6572];
bjets+MET: ATLAS-CONF-2011-098)

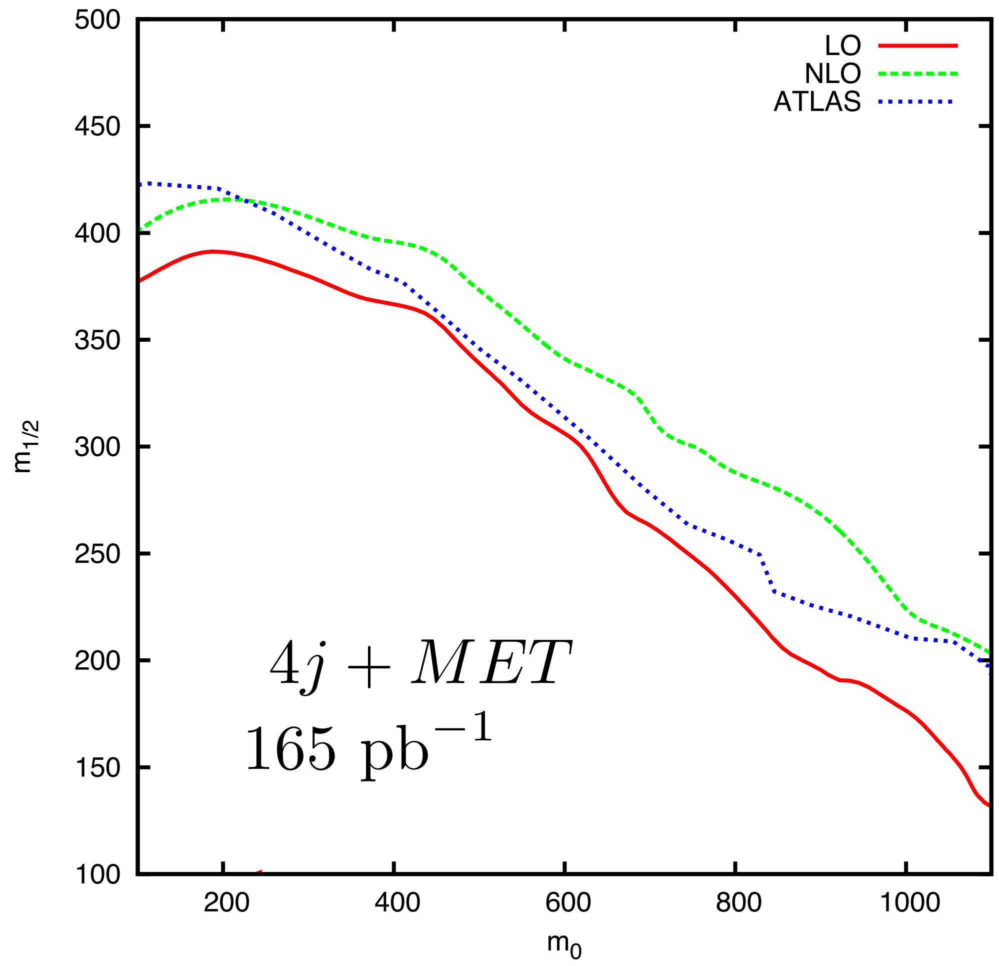
Ask how well do we reproduce ATLAS's exclusion curve?

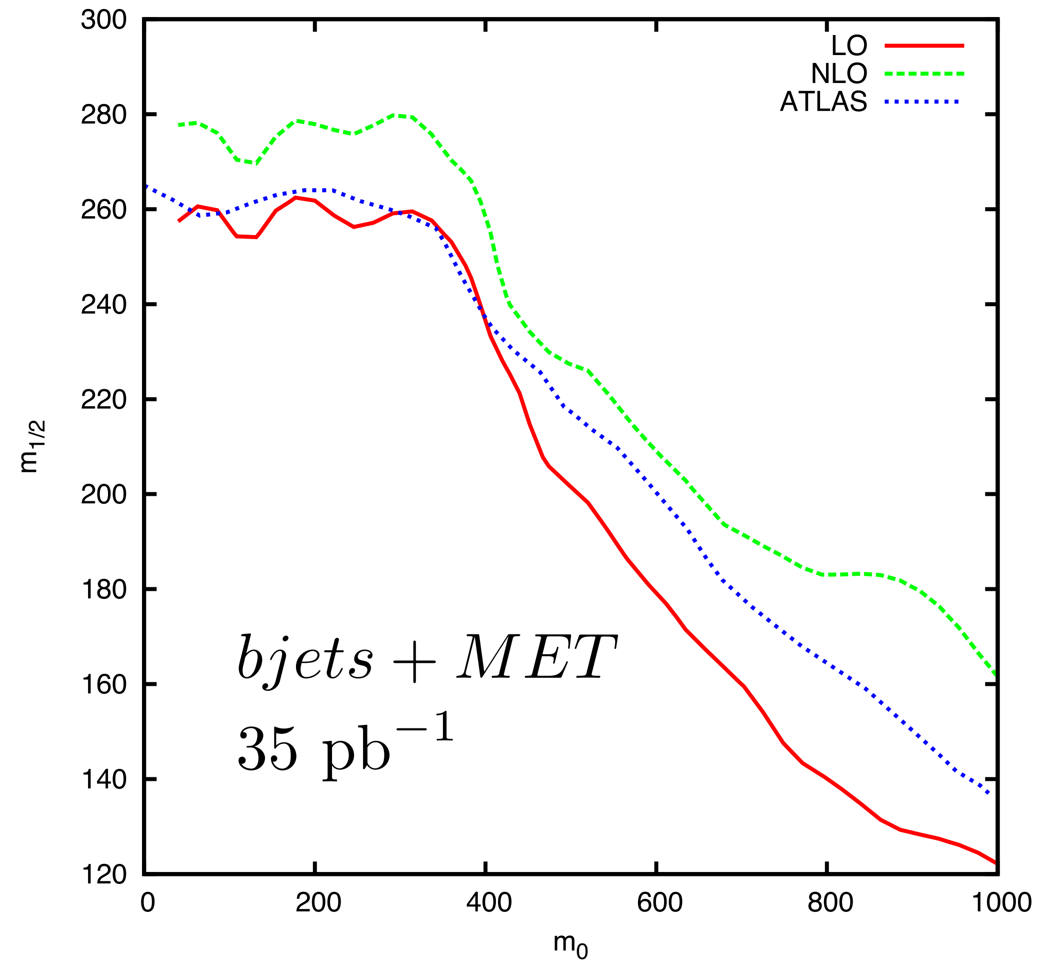
Comparison to ATLAS contours





Comparison to ATLAS contours





LO (and NLO) contours agree within 20% in all cases!

Signal x Acceptance used for contours

Channel	$\sigma \times acc$ (fb)
2 jets + MET	24
3 jets + MET	30
4 jets + MET (M_{eff} =1 TeV)	32
1 btag + $M_{eff} > 500$ (3JA)	288
1 btag + $M_{eff} > 700$ (3JB)	61
2 btag + $M_{eff} > 500$ (3JC)	78
2 btag + $M_{eff} > 700$ (3JD)	17

Case A: $\tilde{t}_1$ lighter than other third generation squarks (closest to the cMSSM case)

$$\tilde{t}_1 \sim \tilde{t}_R (\sin\theta_{\tilde{t}} = 0.99)$$

Step 1: Choose $M_{\tilde{t}_1}$

Step 2: Set $M_{\tilde{t}_2} = M_{\tilde{t}_1} + 500 \text{ GeV}$

Step 3: Calculate m_{q3}, m_{tR}, A_t

Step 4: Set $m_{bR} = m_{q3} (\sin\theta_{\tilde{b}} = 0.707)$

Case B: $\tilde{t}_1 \sim \tilde{t}_L; M_{\tilde{t}_1} \sim M_{\tilde{b}_1}$

$$\sin\theta_{\tilde{t}} = \sin\theta_{\tilde{b}} = 0.1$$

Step 1: Choose $M_{\tilde{t}_1}$

Step 2: Set $M_{\tilde{t}_2} = M_{\tilde{t}_1} + 500\ \mathrm{GeV}$

Step 3: Calculate m_{q3}, m_{tR}, A_t

Step 4: Set $m_{bR} = m_{tR}$

Degenerate $\tilde{t}_1, \tilde{b}_1; \tilde{t}_2, \tilde{b}_2$

This case is interesting because of the enhanced squark couplings to the wino-like neutralino.

Case C: $\tilde{b}_1 \sim \tilde{b}_R; M_{\tilde{t}_1} = M_{\tilde{t}_2} = M_{\tilde{b}_2}$

This case is never realised in cMSSM-type high scale models but is closest to the model considered in the paper

Step 1: Choose $M_{\tilde{b}_1}$

Step 2: Set $M_{\tilde{b}_2} = M_{\tilde{b}_1} + 500 \text{ GeV}$

Step 3: Calculate m_{q3}, m_{bR}, A_b

Step 4: Set $m_{tR} = m_{q3}; \sin\theta_{\tilde{t}} = 0.707$

Gluino decays via: $\tilde{g} \to b\bar{b}\tilde{\chi}_1^0$

Sbottom decays via: $\tilde{b}_1 \to b\tilde{\chi}_1^0$

Case D: All third generation squarks nearly degenerate

$$\sin\theta_{\tilde{t}} = \sin\theta_{\tilde{b}} = 0.707$$

Step 1: Choose $M_{\tilde{t}_1}$

Step 2: Set $M_{\tilde{t}_1} = M_{\tilde{t}_2}$

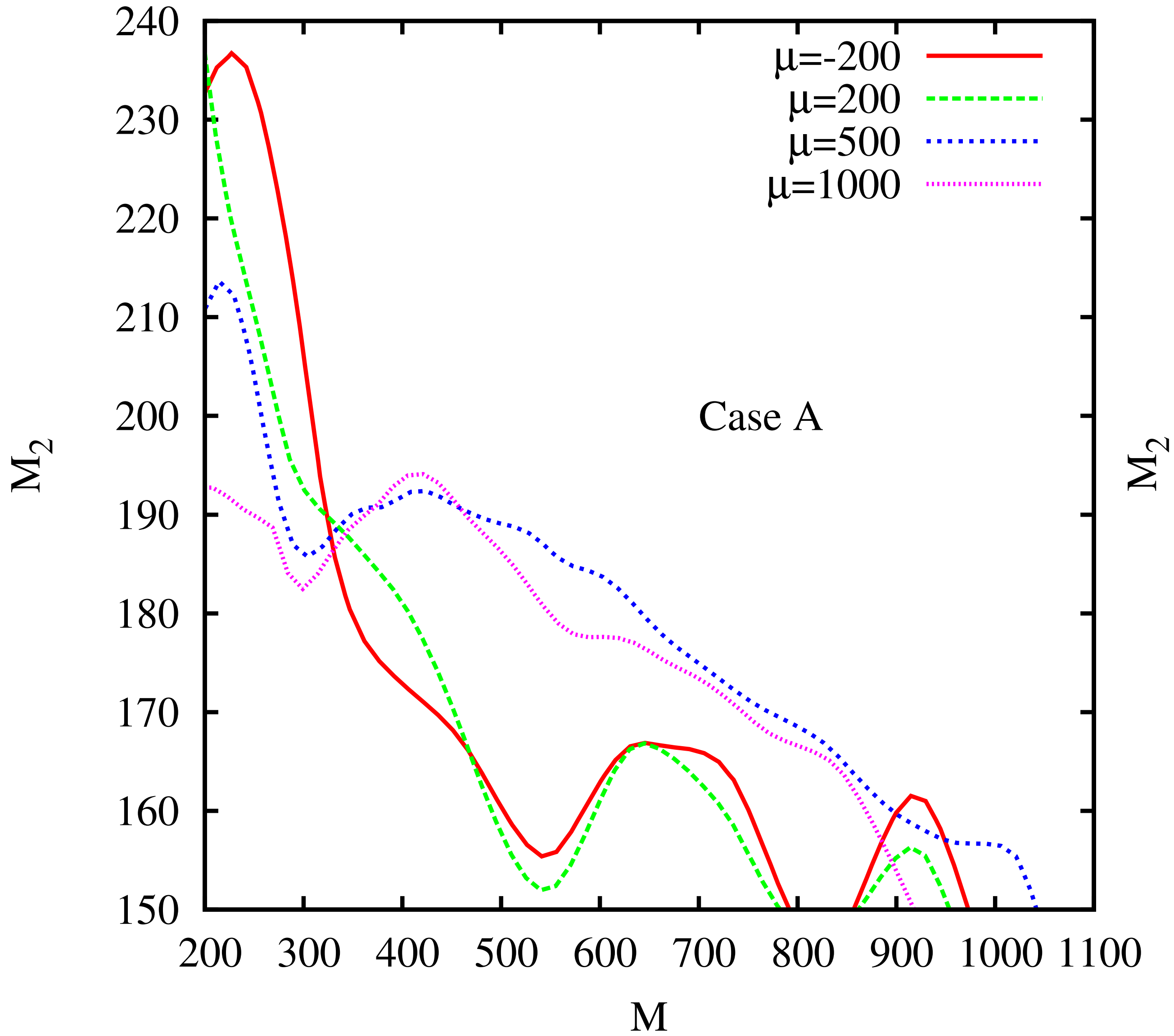
Step 3: Calculate m_{q3}, m_{tR}, A_t

Step 4: Set $m_{bR} = m_{tR}$

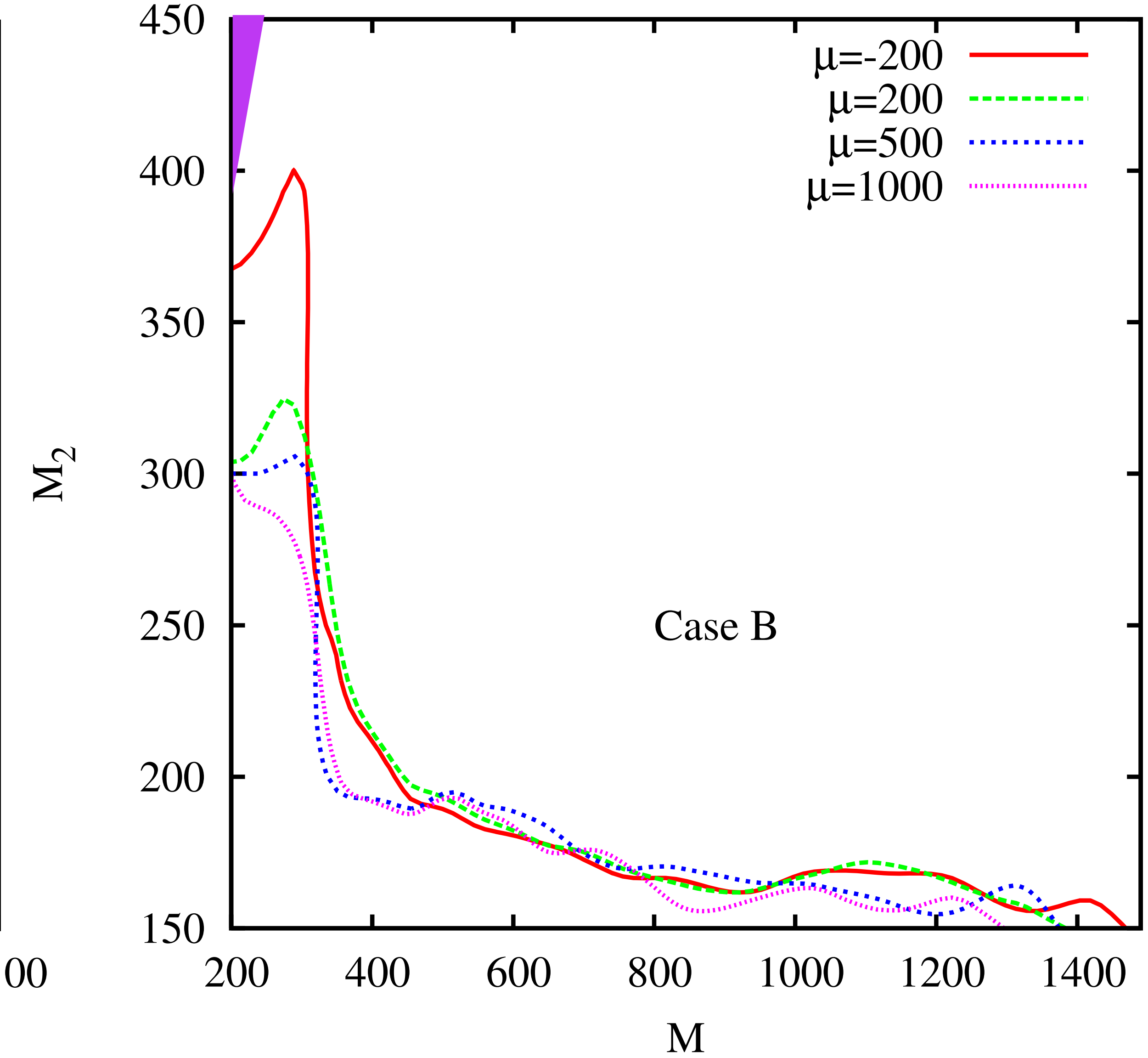
We scan over the following parameters

Parameter	Scan range
$M_{\tilde{t}_1}$	100 - 2000 GeV
M_2	150 - 600 GeV
$\tan\beta$	5, 10, 40
μ	-200, 200, 500, 1000 GeV

Effect of μ

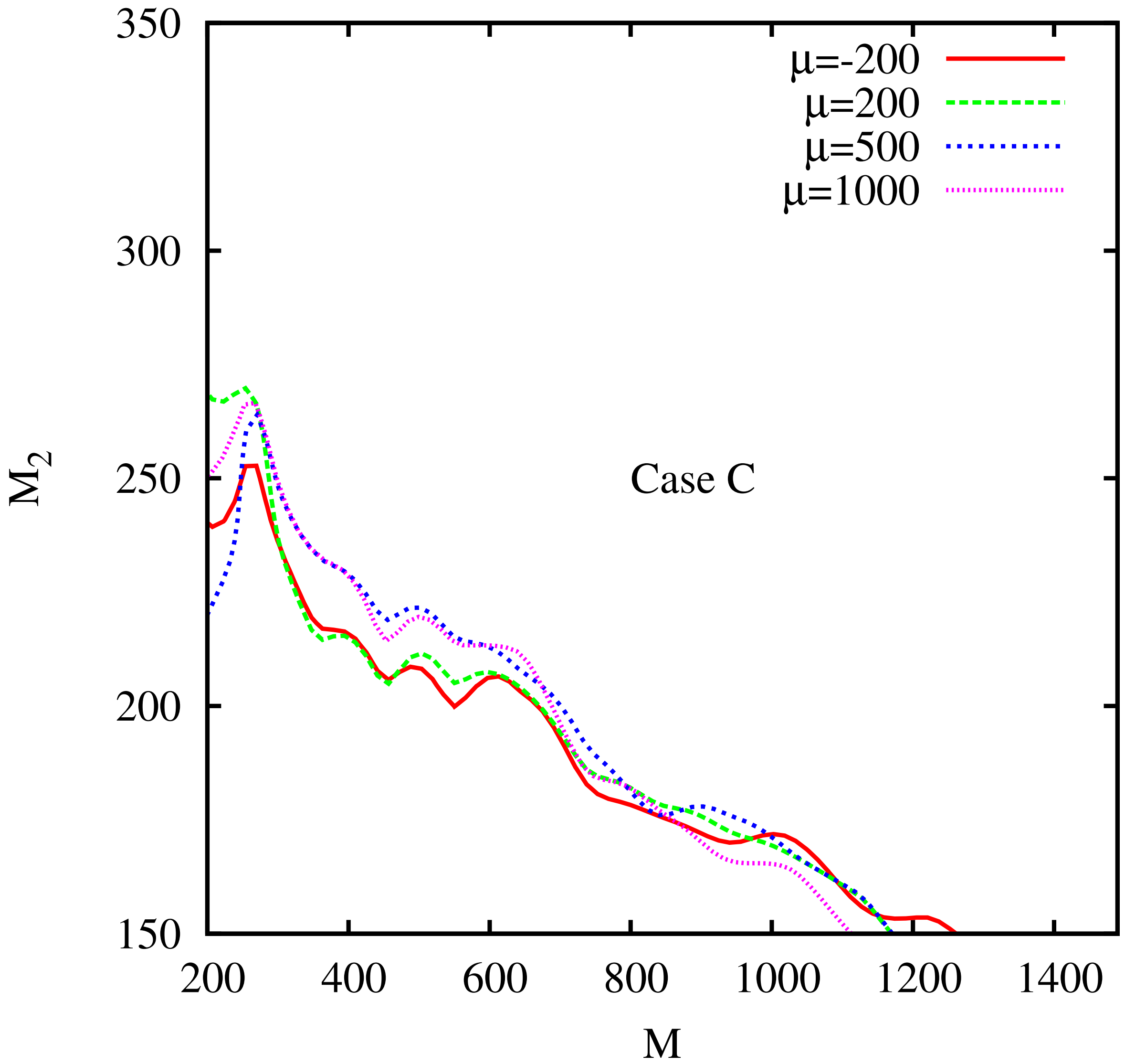


240
230
220
210
200
190
180
170
160
150
200 300 400 500 600 700 800 900 1000 1100
M
M2
μ=-200
μ=200
μ=500
μ=1000
Case A

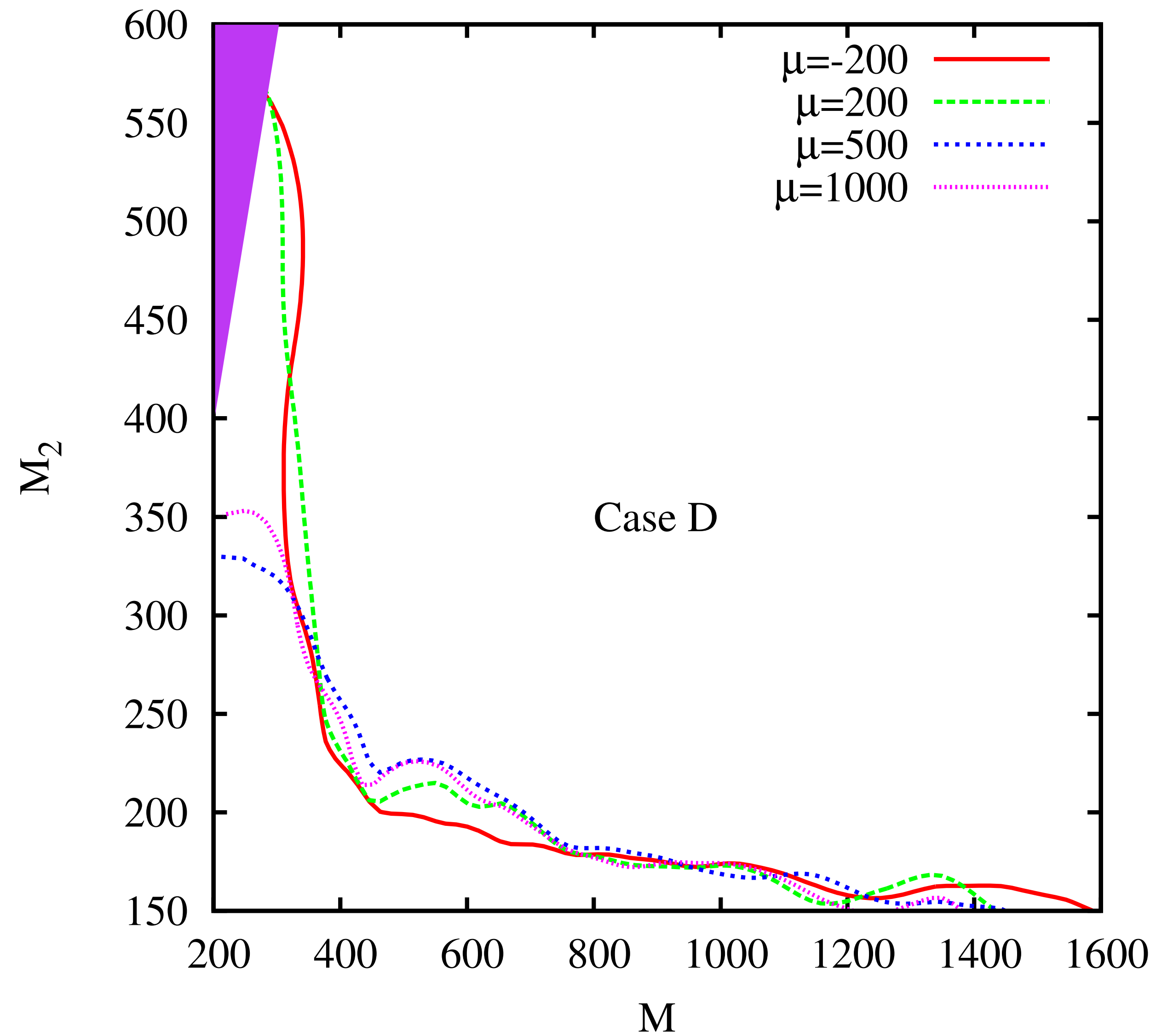


450
400
350
300
250
200
150
200 400 600 800 1000 1200 1400
M
M2
μ=-200
μ=200
μ=500
μ=1000
Case B

Effect of μ



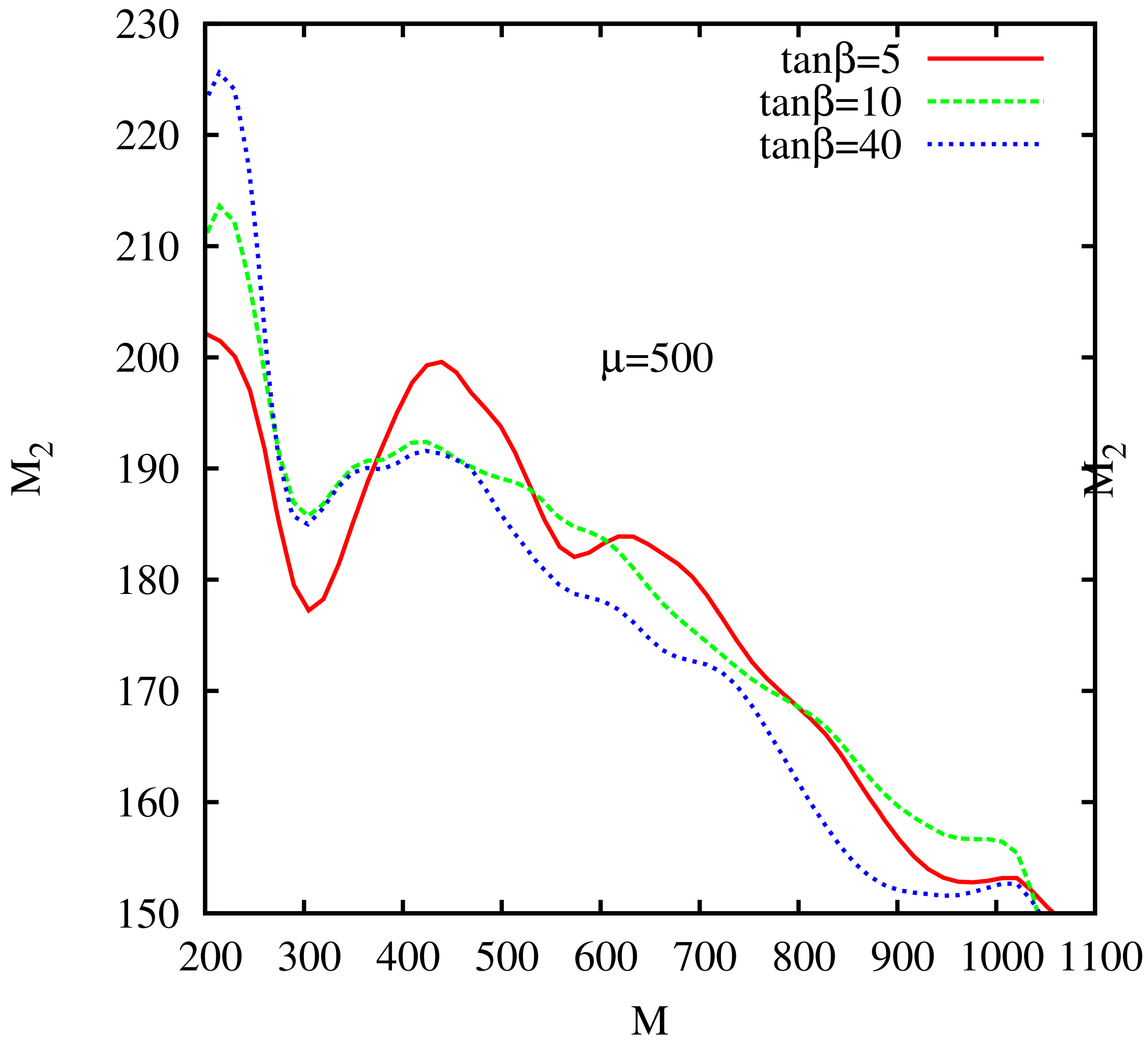
μ=-200
μ=200
μ=500
μ=1000
Case C
M2
M
350
300
250
200
150
200
400
600
800
1000
1200
1400



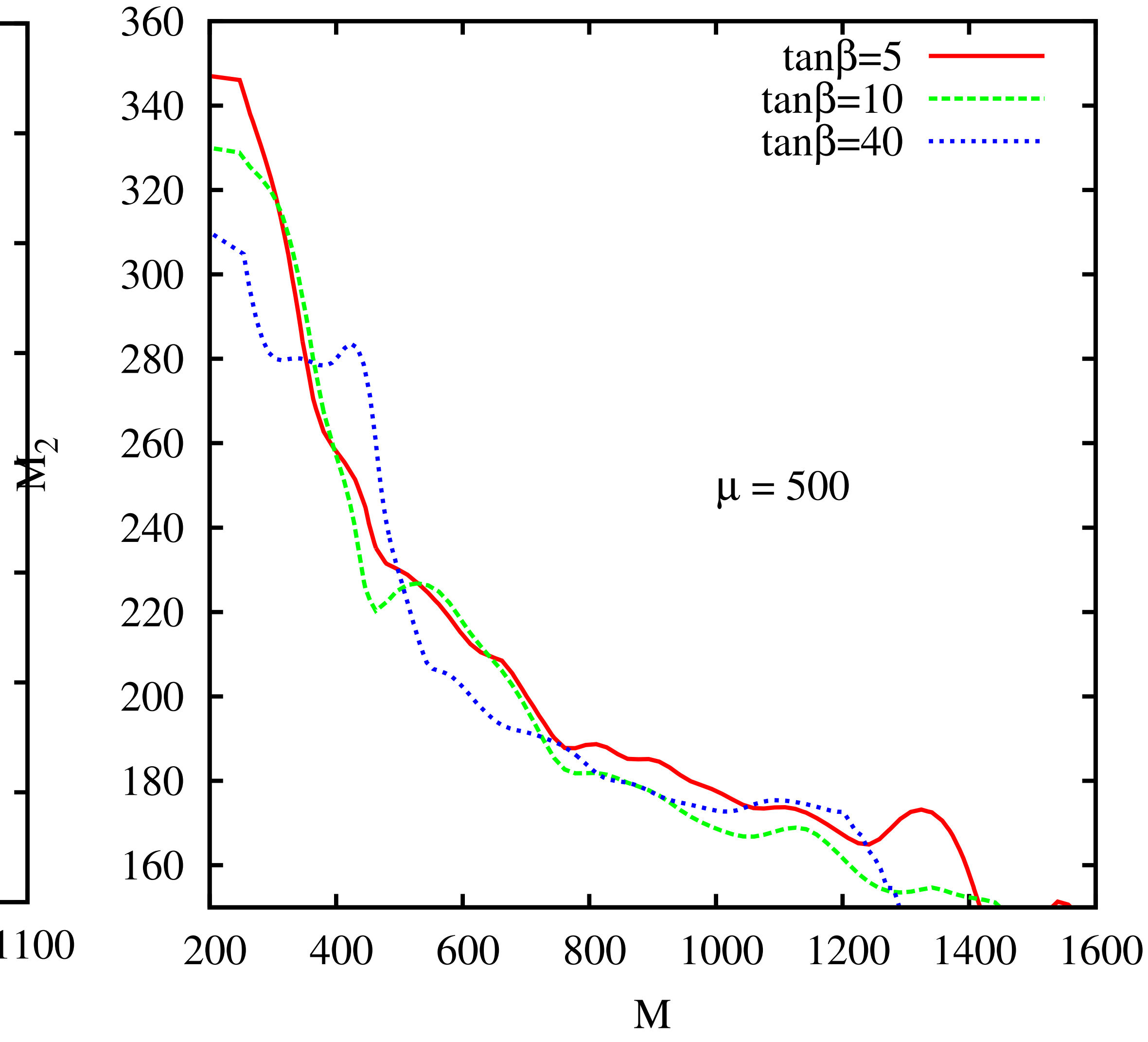
μ=-200
μ=200
μ=500
μ=1000
Case D
M2
M
600
550
500
450
400
350
300
250
200
150
200
400
600
800
1000
1200
1400
1600

Effect of tan β

Case A



Case D



High-Scale Non-Universality

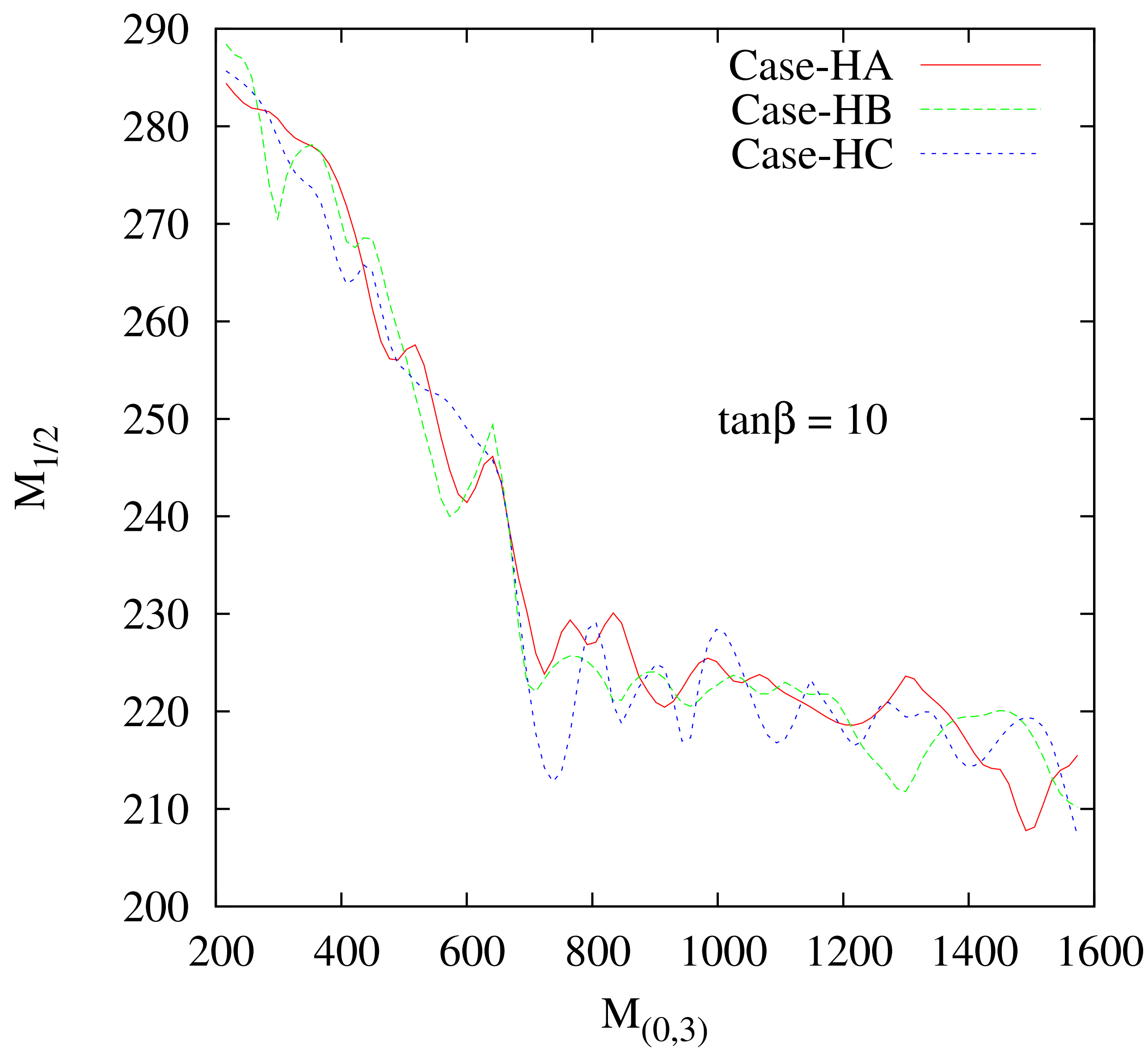
We now address the question of what happens if sleptons are also possibly light

Two scales in the scalar sector: $M_{\rm heavy}, M_{\rm light}$

We still want the first two generations of squarks to be heavy

Case HA: All sleptons heavy
Case HB: First two generations of sleptons heavy
Case HC: All sleptons light

High-Scale Non-Universality



Conclusions

If one considers the limit on gluino mass to be 600 (700) GeV, that translates to a limit of

$M_{\tilde{t}_1} > 300 - 350$ (300) GeV (Case A)

$M_{\tilde{t}_1, \tilde{b}_1} > 340 - 450$ (300 – 400)GeV (Case B)

$M_{\tilde{b}_1} > 750$ (350 – 450) GeV (Case C)

$M_{\tilde{t}_i, \tilde{b}_i} > 450 - 700$ (400 – 500) GeV (Case D)