First Row CKM Unitarity Tests and the MSSM

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Motivation

Low energy observables provide a route for constraining new physics. First row CKM unitarity tests are a possible avenue.

We are computing MSSM corrections to the CKM matrix element V_{ud}, as measured from beta decay. This determines the benchmark of precision for CKM unitarity tests to constrain the MSSM.

First Row CKM Unitarity

CKM unitarity in the Standard Model demands that
$|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 1.$

Physics beyond the Standard Model can lead to actual or apparent violations of this relation.

An actual violation can occur when there is an extra generation.

An apparent violation occurs when the measured values of CKM matrix elements are not the true values. Standard Model assumptions go into matrix element measurements.

Measuring V_{ud}

The matrix element V_{ud} is determined from the Fermi constant G_V^{β} for beta decay. The measured value of V_{ud} is

$$V_{ud}^{(\mathrm{measured})} = \frac{G_V^{\beta}}{G_{\mu}(1 + \Delta r_{\beta}^{(SM)} - \Delta r_{\mu}^{(SM)})}$$

The weak coupling is measured from G_{μ}: the Fermi constant for muon decay. The quantities $\Delta r_{\beta}^{(SM)}$ and $\Delta r_{\mu}^{(SM)}$ are Standard Model corrections to G_V^{β} and G_{μ}. These are not the true values, if new physics contributes to $\Delta r_{\beta}^{(V)}$ and Δr_{μ}.

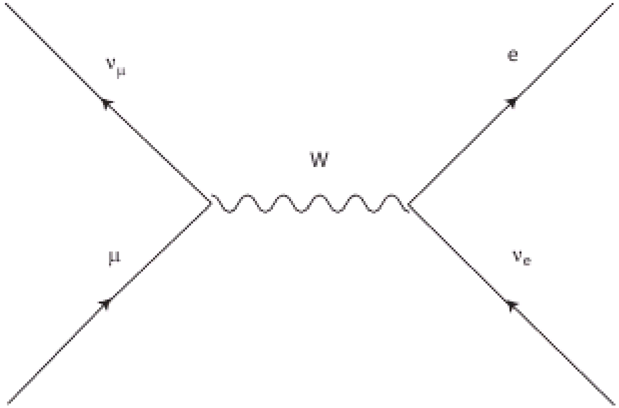
Hence, the measured value of V_{ud} may not be the actual value. Apparent violations of CKM unitarity can occur.

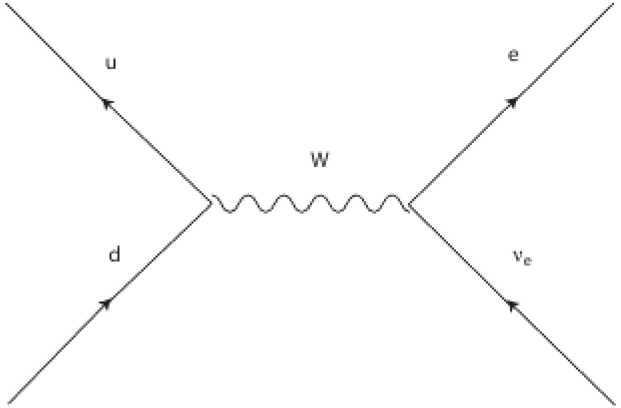
MSSM Corrections to the Fermi Constant

The MSSM might lead to an apparent violation of first-row CKM unitarity. We computed MSSM corrections to $\Delta r_\beta^{(V)} - \Delta r_\mu$, in order to constrain the parameter space of the theory.

We assumed R-parity and minimal flavor violation, and calculated corrections at one-loop order.

Muon and Beta Decay

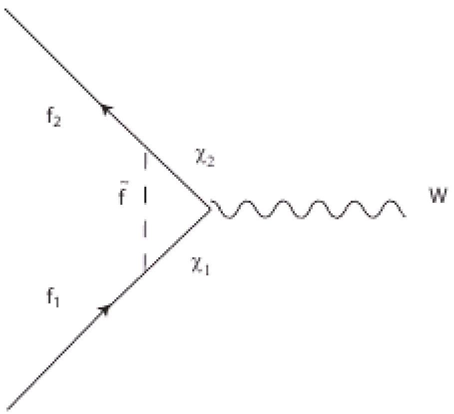


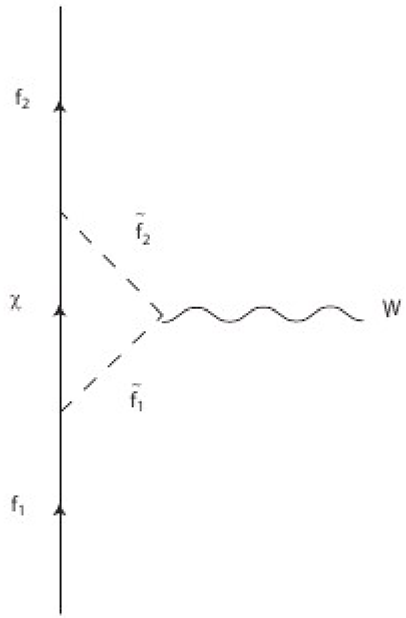


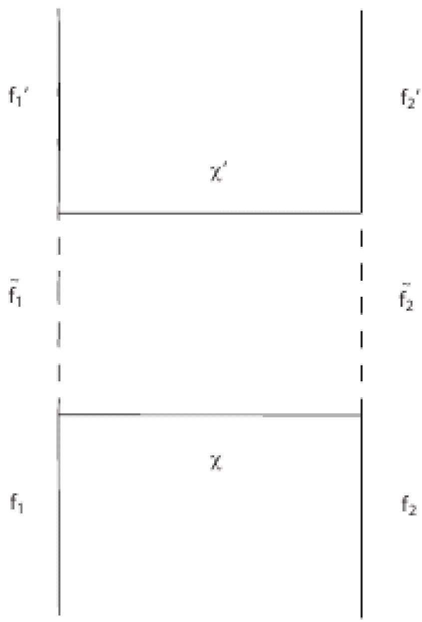
Superpartner loops enter external leg, vertex and box graphs.

Vacuum polarization diagrams cancel in $\Delta r_\beta^{(V)} - \Delta r_\mu$. Regulator dependence cancels as well.

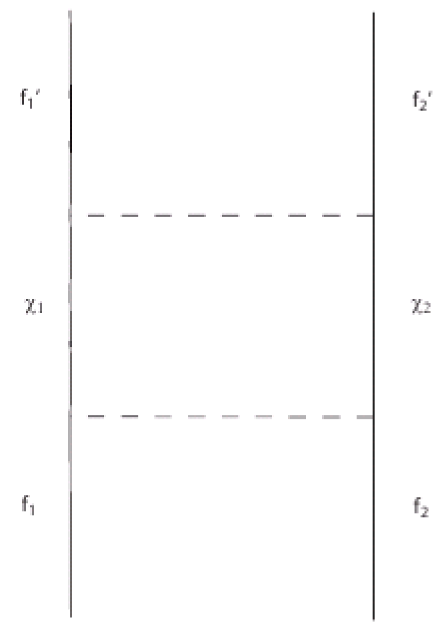
Example Graphs







f1′
f2′
χ′
f̃1
f̃2
χ
f1
f2



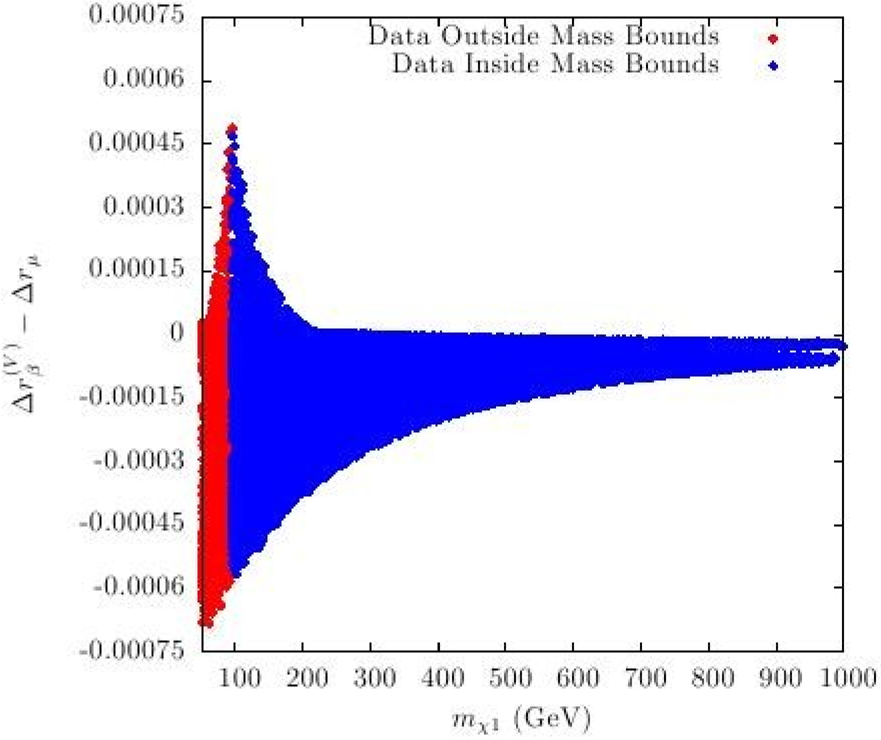
f1′
f2′
χ1
χ2
f1
f2

Our Setup

- We wrote a code to scan over the parameter space of the MSSM.
- For every point of parameter space in the scan, our code diagonalizes gauginos and Higgsinos into charginos and neutralinos, and diagonalizes slepton and squark masses.
- Our code computes MSSM corrections to $\Delta r_\beta^{(V)}$ and Δr_μ from all one-loop diagrams, in the chargino-neutralino basis.
- Our code outputs plots of $\Delta r_\beta^{(V)} - \Delta r_\mu$, as functions of the parameters in the scan. These plots represent MSSM corrections to the Fermi constant, which would show up as apparent violations of first row CKM unitarity.

Results

- The correction $\Delta r^{(V)}_{\beta} - \Delta r_{\mu}$ is on the order of 10^{-4}. This is of a similar size as the current uncertainty in V_{ud} measurements.
- Corrections are maximized when there is a large difference between first generation squark and second generation slepton masses. (Either $\Delta r^{(V)}_{\beta}$ or Δr_{μ} is suppressed in the difference, $\Delta r^{(V)}_{\beta} - \Delta r_{\mu}$.)
- Vertex and external leg contributions tend to cancel with box graph contributions. Corrections are maximized when one is suppressed, but not the other.
- Corrections depend weakly on M_1 and tan β.



50 GeV < M_1, $|M_2|$, $|\mu|$ < 1000 GeV, M_3 = 10 TeV, tan β = 1.

Slepton masses = 110 GeV, squark masses = 10 TeV, left-right sfermion mass mixings vanish.

Constraints are on superpartner masses. Oblique parameter constraints have not yet been incorporated. However, they are not expected to be significantly more limiting than mass constraints.

Hadronic Uncertainties

$\Delta r_\beta^{(SM)} - \Delta r_\mu^{(SM)} = (2.361 \pm 0.038)\times 10^{-2}$ [Phys. Rev. C **79**, 05550 (2009); arXiv:0812.1202].

The uncertainty is dominated by hadronic effects, and is of a similar size as SUSY corrections.

Calculations of the hadronic contributions have undergone remarkable progress in recent years. Marciano and Sirlin recently developed a new technique which reduced hadronic uncertainties by a factor of 2 [Phys. Rev. Lett. **96**, 032002 (2006); arXiv:hep-ph/0510099]

Further reductions in hadronic uncertainties might allow beta decay corrections to constrain the MSSM.

Cross Checks

- Kurylov and Ramsey-Musolf computed SUSY corrections to the Fermi constant in certain limits [Phys. Rev. Lett. **88**, 071804 (2002); hep-ph/0109222]. Our code reproduces their results in these limits.

- Ramsey-Musolf, Su and Tulin performed a scan over the parameter space of the MSSM, to compute SUSY corrections to $\Gamma(\pi^+ \rightarrow e^+\nu_e)/\Gamma(\pi^+ \rightarrow \mu^+\nu_\mu)$ [Phys. Rev. D **76**, 095017 (2007); arXiv:0705.0028]. The computation is similar to that of beta decay. We modified our code, to compute this ratio. Our results are in agreement.

- We checked that our code works as expected in the limit of no spontaneous symmetry breaking.

Conclusions

Low-energy precision tests provide new probes to physics beyond the Standard Model. Beta decay is an exciting avenue. New physics corrections to the Fermi constant for beta decay would manifest as apparent violations of CKM unitarity. Nuclear physics effects do not limit the usefulness of beta decay, because current conservation constrains form factors.

We scanned over the parameter space of the MSSM, and computed SUSY corrections to the Fermi constant for beta decay.

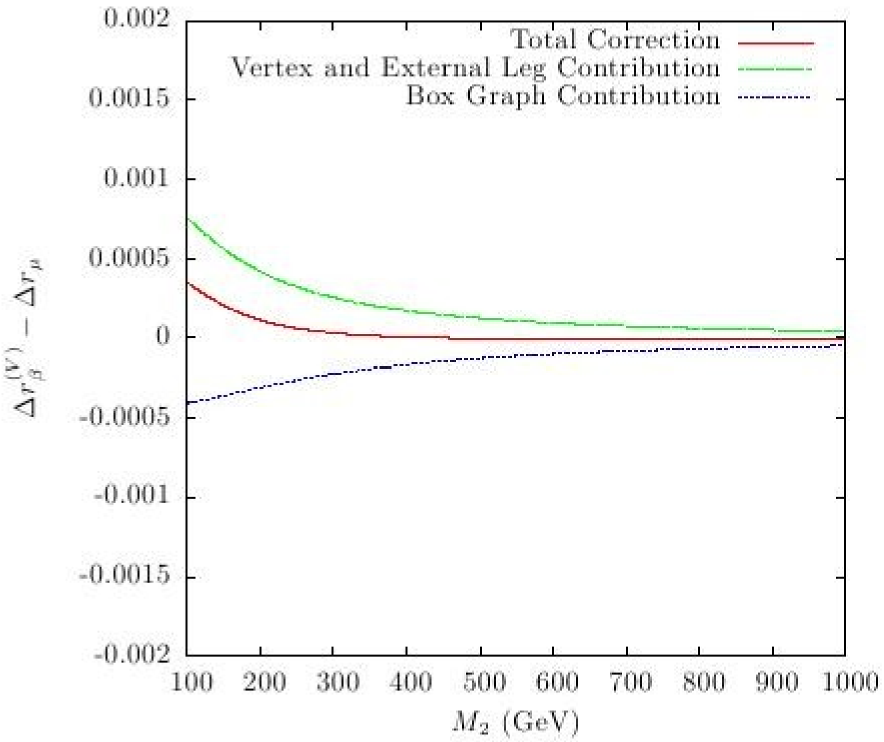
Our scans reproduce other results in the literature and agree with expected limiting cases.

The current uncertainty in $\Delta r_\beta^{(SM)} - \Delta r_\mu^{(SM)}$ is 3.8×10^{-4}, and is dominated by hadronic effects. Remarkable calculational progress is being made, with the hadronic uncertainty recently being reduced by a factor of 2.

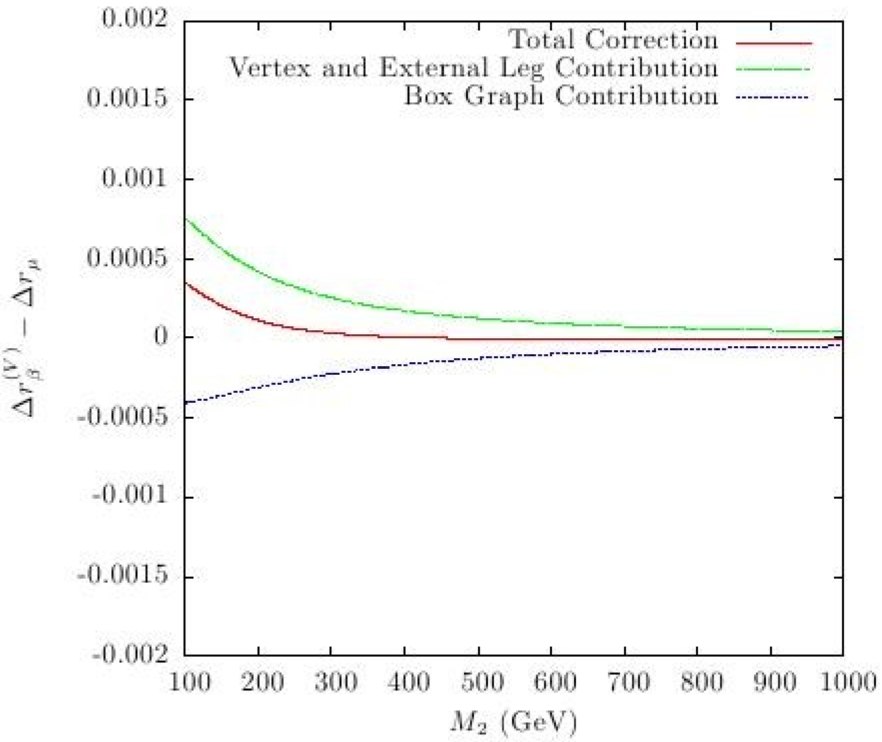
Loop corrections to beta decay are at the 10^{-4} level: the threshold for constraining the MSSM.

Addendum

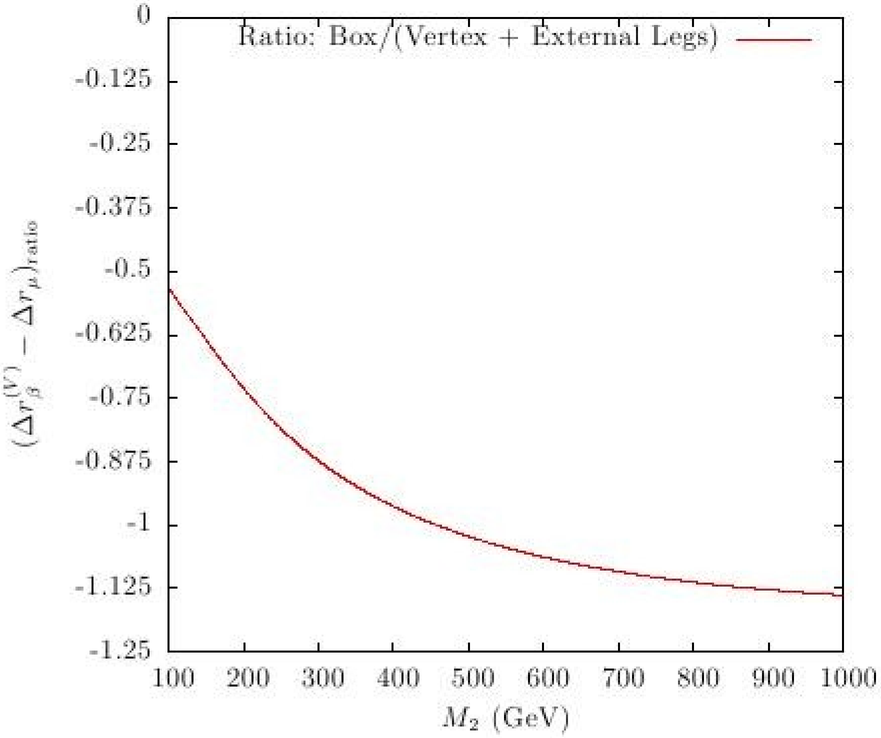
Yes, we have more plots. . . .



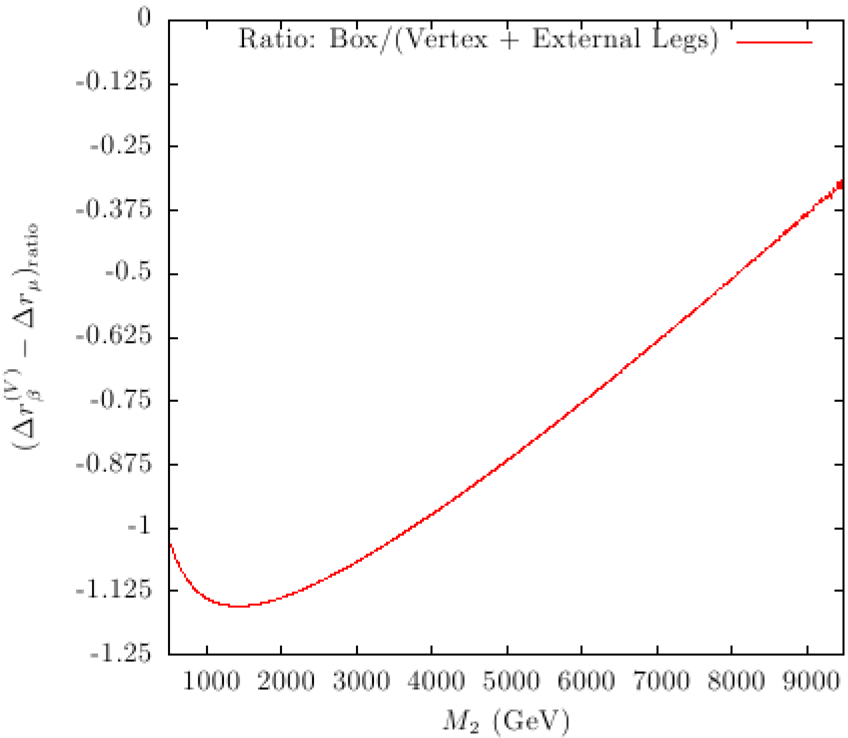
$M_1 = \mu = 50$ GeV, $M_3 = 10$ TeV, tan $\beta = 1$. Slepton masses = 110 GeV, squark masses = 10 TeV, left-right sfermion mass mixings vanish.



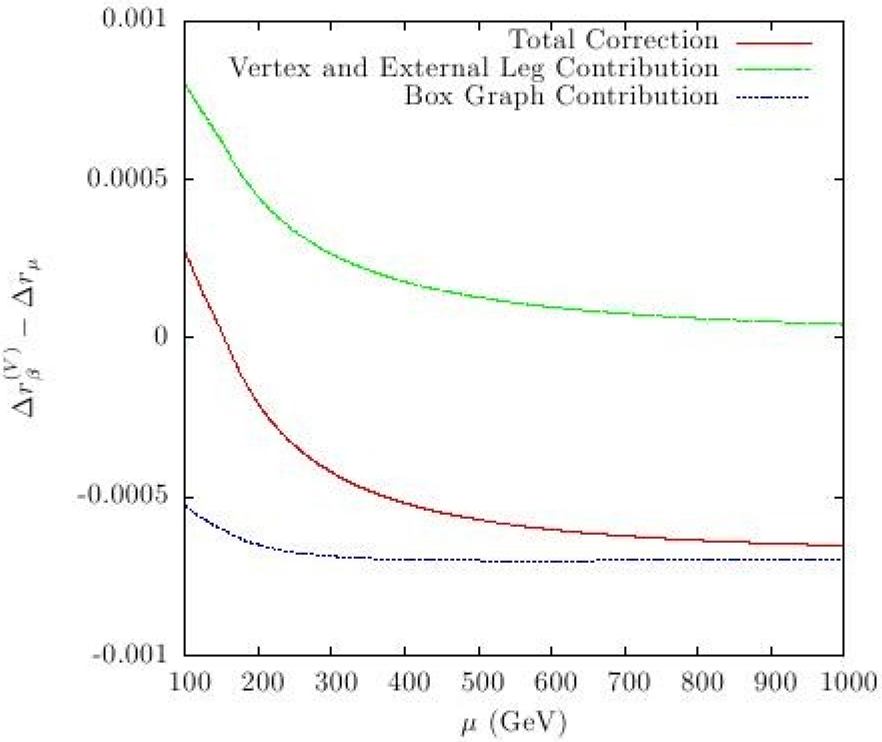
Vertex and external leg corrections tend to cancel with box graph corrections.



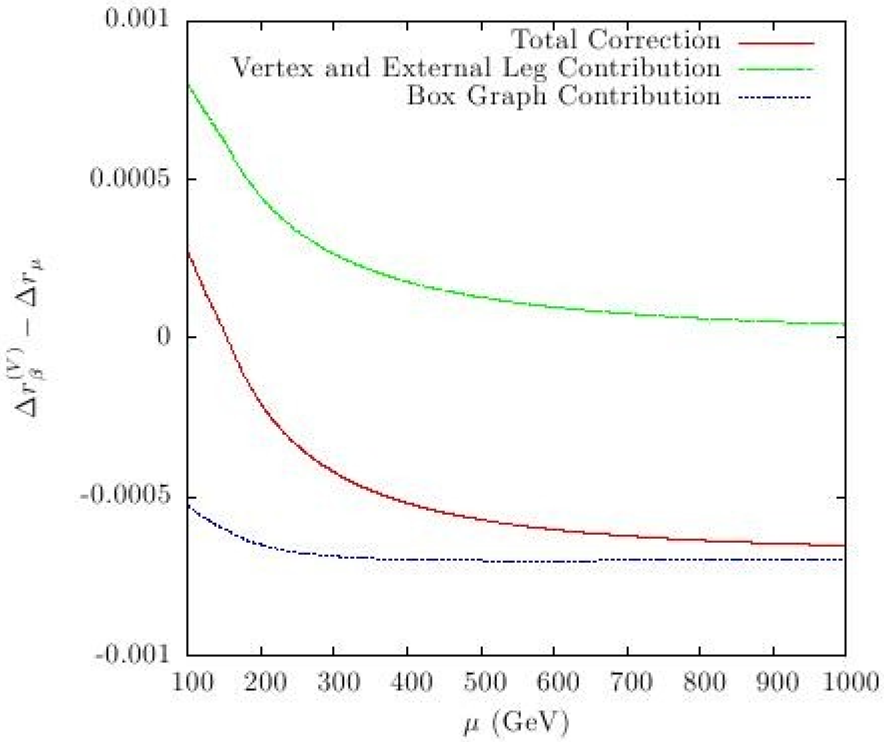
The Ratio of the Box Graph Contribution to the Vertex and External Leg Contribution



The rough cancellation between box graphs and vertex and external line graphs breaks down. It appears to be a coincidence.



$M_1 = M_2 = 50$ GeV, $M_3 = 10$ TeV, tan $\beta = 1$. Slepton masses = 110 GeV, squark masses = 10 TeV, left-right sfermion mass mixings vanish.



In the limit of large μ, vertex and external line corrections approach zero. Box graph corrections dominate, and the total correction is maximized.

When μ is much greater than m_Z and m_W, electroweak symmetry breaking has a minimal effect on chargino and neutralino masses and mixings. In the limit of electroweak symmetry, vertex and external leg contributions cancel exactly in $\Delta r_\beta^{(V)} - \Delta r_\mu$. Therefore, this contribution tends to zero.

The box graph contribution is nonzero, regardless of whether electroweak symmetry is broken. It dominates when μ is large.