The Electroweak Sector of the pMSSM in the Light of LHC - 8 TeV and Other Data

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Based on [JHEP 1407 (2014) 019, arXiv 1404.4841] with Utpal Chattopadhyay, Arghya Choudhury, Amitava Datta, Sujoy Poddar

August 23, 2014
Experimental status:

- Higgs boson found, but no SUSY signal yet.
- DM detection experiments becoming more and more sensitive.

MSSM can be broadly divided into two sectors: strong and electroweak → In 'unprejudiced' MSSM scenarios they are independent.

- Strong sector sparticles ⇒ produced with large cross-sections, thus receiving stringent bounds.
- EW sparticles ⇒ modest production cross-section : direct mass bounds rather weak.

In this work we try to constrain the EW sector with the direct results from the LHC as well as a few indirect constraints like those coming from experiments on dark matter searches and muon (g-2).
MSSM Superpotential:
\[ W_{\text{MSSM}} = \bar{u} Y_u Q H_u - \bar{d} Y_d Q H_d - \bar{e} Y_e L H_d + \mu H_u H_d \]

Soft breaking terms:
\[ \mathcal{L}_{\text{soft}}^{\text{MSSM}} = -\frac{1}{2} \left( M_3 \tilde{g} \tilde{g} + M_2 \tilde{W} \tilde{W} + M_1 \tilde{B} \tilde{B} + \text{c.c.} \right) \\
- \left( \tilde{u} a_u \tilde{Q} H_u - \tilde{d} a_d \tilde{Q} H_d - \tilde{e} a_e \tilde{L} H_d + \text{c.c.} \right) \\
- \tilde{Q}^\dagger m_Q^2 \tilde{Q} - L^\dagger m_L^2 \tilde{L} - \tilde{u} m_u^2 \tilde{u}^\dagger - \tilde{d} m_d^2 \tilde{d}^\dagger - \tilde{e} m_e^2 \tilde{e}^\dagger \\
- m_{H_u}^2 H_u^* H_u - m_{H_d}^2 H_d^* H_d - (b H_u H_d + \text{c.c.}) \]
Linear superposition of gauge eigenstates:
→ neutralino: \((\tilde{B}, \tilde{W}^3, H^0_u, H^0_d)\).
→ chargino: \((\tilde{W}^\pm, H^\pm_{u/d})\).

Degree of mixing determined by:
→ U(1) and SU(2) gaugino masses \(M_1\) and \(M_2\)
→ Higgs mass parameter \(\mu\)
→ \(\tan\beta\): the ratio of Higgs vevs.

R-parity conserving scenario → LSP is a good candidate for DM. We consider lightest neutralino to be the LSP.

Neutralinos can be bino, wino or higgsino dominated depending on the values of \(M_1, M_2\) and \(\mu\).

Chargino can be wino or higgsino-like.
The neutralino mass matrix:

$$M_N = \begin{pmatrix}
M_1 & 0 & -M_Z c \beta s W & M_Z s \beta s W \\
0 & M_2 & -M_Z s \beta c W & M_Z c \beta c W \\
-M_Z c \beta s W & M_Z c \beta c W & 0 & -M_Z s \beta c W \\
M_Z s \beta s W & -M_Z s \beta c W & -M_Z s \beta c W & -\mu \\
\end{pmatrix}$$

Chargino mass matrix:

$$M_C = \begin{pmatrix}
M_2 & \sqrt{2} M_W \cos \beta \\
\sqrt{2} M_W \sin \beta & \mu \\
\end{pmatrix}$$
For $M_1 < M_2 << \mu \Rightarrow$ bino-like $\tilde{\chi}_1^0$ and wino-like $\tilde{\chi}_1^\pm / \tilde{\chi}_2^0$.

For $M_2 < M_1 << \mu$, $\tilde{\chi}_1^0$ would be wino (neutral), $\tilde{\chi}_1^\pm$ wino (charged) and $\tilde{\chi}_2^0$ bino-like.

For $M_2 \simeq M_1$, $\tilde{\chi}_1^0 / \tilde{\chi}_2^0$ would be wino-bino admixture.

For $M_1 > M_2 > \mu$, $\tilde{\chi}_1^0$, $\tilde{\chi}_2^0$ and $\tilde{\chi}_1^\pm$ are all higgsino-like and almost mass-degenerate.
LHC searches

- ATLAS searches are restricted for simplified models → where all sparticles except those relevant for the signal are taken to be decoupled.

- When all strong sector sparticles are heavy (∝ TeV), direct production of chargino-neutralinos may be the dominant SUSY process.

- \( \tilde{\chi}_1^\pm \) and \( \tilde{\chi}_2^0 \) are taken to be mass-degenerate and purely wino.

- Lightest neutralino is assumed to be predominantly bino.

- All three generations of sleptons and sneutrinos are assumed mass degenerate.
pair production leading to 3l final states

Decay via sleptons

Decay via gauge bosons
LHC searches: $3l + \mathcal{E}_T$ channel

Searches for final states with 3 leptons and missing $E_t$ are categorized as follows:

**Decay via sleptons**

- Decay modes: $\tilde{\chi}_1^\pm \rightarrow \tilde{l}_L^\pm \nu$ and $\tilde{\chi}_1^\mp \rightarrow \nu \tilde{l}_L^\mp$.
  
  $\Rightarrow \tilde{\chi}_2^0 \rightarrow \tilde{\nu} \nu$ and $\tilde{\chi}_2^0 \rightarrow \tilde{l}_L^\pm \nu \tilde{l}_L^\mp$.

- Sneutrinos and sleptons are assumed to be mass degenerate with their masses lying midway between $\tilde{\chi}_1^\pm$ and $\tilde{\chi}_1^0$.

**Decay via gauge bosons**

- There can be decays via gauge bosons when sleptons are heavier than $\tilde{\chi}_1^\pm / \tilde{\chi}_2^0$.

- ATLAS searches assume 100 % BR for the decay modes: $\tilde{\chi}_1^\pm \rightarrow \mathcal{W}^\pm \tilde{\chi}_1^0$ and $\tilde{\chi}_2^0 \rightarrow \mathcal{Z} \tilde{\chi}_1^0$.

- BR for the decay mode $\tilde{\chi}_2^0 \rightarrow h \tilde{\chi}_1^0$ is taken to be zero.
Our analysis

- Strong sector beyond LHC reach \( \Rightarrow \) all squark masses and CP-odd, heavy Higgs masses are taken to be decoupled.

- \( \tilde{\chi}_1^0 \) taken to be bino-dominated and \( \tilde{\chi}_2^0/\tilde{\chi}_1^\pm \) wino-dominated.

- Right and left slepton masses are placed in different relative positions in between \( M_1 \) and \( M_2 \).

- For models where sleptons are taken to be heavier than \( \tilde{\chi}_1^\pm \), we take \( m_{\tilde{\ell}} = M_2 + 200 \text{ GeV} \).

- Sneutrino mass is calculated according to pMSSM mass relations:
  \[
  m_{\tilde{\nu}}^2 = m_{\tilde{\ell}}^2 + \frac{1}{2} m_Z^2 \cos 2\beta
  \]

- We use PYTHIA [version 6.4] for event generation using the selection criteria of ATLAS collaboration at the generator level. [Ref. ATLAS-CONF-2013-035]
We try to constrain pMSSM parameter space with the help of following indirect constraints:

- WMAP/PLANCK relic density.
- Muon (g-2).
- Spin independent direct detection data from XENON/LUX.

We also study indirect detection prospects of dark matter.
Indirect constraints: muon (g-2)

- One of the most precisely determined quantities of particle Physics.
- Largest established discrepancy from SM (more than $3\sigma$): $a_{\mu}^{\text{exp}} - a_{\mu}^{\text{SM}} = (29.3 \pm 8) \times 10^{-10}$
- Important probe for new physics.
- SM contributions: QED, weak, hadronic vacuum polarization, hadronic light by light scattering.
- Significant theoretical uncertainty in calculating hadronic contribution.
SUSY contributions to muon \((g-2)\)

- Contribution from chargino-sneutrino and neutralino-smuon loop diagrams.
- Contributions proportional to \(\tan \beta \rightarrow\) can explain the anomaly.
- In the mSUGRA chargino-sneutrino loop dominates.
- In presence of light left-right sleptons neutralino-smuon loop can give significant contribution in pMSSM.
SUSY contributions to muon \((g-2)\)

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SUSY contributions to muon $\mu(g-2)$

$$\Delta a_\mu(\tilde{W}, \tilde{H}, \tilde{\nu}_\mu) \simeq 15 \times 10^{-9} \left( \frac{\tan \beta}{10} \right) \left( \frac{(100 \text{ GeV})^2}{M_{2\mu}} \right) \left( \frac{f_C}{1/2} \right),$$

$$\Delta a_\mu(\tilde{W}, \tilde{H}, \tilde{\nu}_L) \simeq -2.5 \times 10^{-9} \left( \frac{\tan \beta}{10} \right) \left( \frac{(100 \text{ GeV})^2}{M_{2\mu}} \right) \left( \frac{f_N}{1/6} \right),$$

$$\Delta a_\mu(\tilde{B}, \tilde{H}, \tilde{\nu}_L) \simeq 0.76 \times 10^{-9} \left( \frac{\tan \beta}{10} \right) \left( \frac{(100 \text{ GeV})^2}{M_{1\mu}} \right) \left( \frac{f_N}{1/6} \right),$$

$$\Delta a_\mu(\tilde{B}, \tilde{H}, \tilde{\nu}_R) \simeq -1.5 \times 10^{-9} \left( \frac{\tan \beta}{10} \right) \left( \frac{(100 \text{ GeV})^2}{M_{1\mu}} \right) \left( \frac{f_N}{1/6} \right),$$

$$\Delta a_\mu(\tilde{\nu}_L, \tilde{\nu}_R, \tilde{B}) \simeq 1.5 \times 10^{-9} \left( \frac{\tan \beta}{10} \right) \left( \frac{(100 \text{ GeV})^2}{m_{\tilde{\nu}_L}^2 m_{\tilde{\nu}_R}^2 / M_{1\mu}} \right) \left( \frac{f_N}{1/6} \right).$$

[Ref. arXiv 1303.4256 by Endo, Hamaguchi, Iwamoto, Yoshinaga]
DM relic density constraint

- Some annihilation channels that could give right relic density:

- There can be coannihilations with sparticles of slightly heavier masses:
DM direct detection

- Relies on elastic scattering of LSP off nuclei in a detector: nuclear recoil energy is measured.

- Interactions can be spin-dependent/independent.

\[
\mathcal{L}_{SI} = \lambda_N \bar{\psi}_N \psi_N \bar{\psi}_N \psi_N \\
\mathcal{L}_{SD} = \xi_N \bar{\psi}_N \gamma_5 \gamma_\mu \psi_N \bar{\psi}_N \gamma_5 \gamma^\mu \psi_N
\]

- Cross-section for scattering:
\[
\sigma_{SI}^0 = \frac{4\mu_\chi^2}{\pi} (\lambda_p Z + \lambda_n (A - Z))^2,
\]
where \(\mu_\chi\) is the WIMP-nucleus reduced mass.

\[
\sigma_{SD}^0 \propto \Lambda^2 J(J + 1), \text{ with } \Lambda \propto \frac{1}{J}
\]

- Taking \(\lambda_p \simeq \lambda_n\) there is strong enhancement for large nuclei →
\[
\sigma_{SI}^0 \propto A^2.
\]

- SI interaction usually dominates SD ones for heavier nuclei.
DM direct detection

Calculation of WIMP - nucleus interaction is a three-step process.

- WIMP-quark/gluon interaction : depends on particle physics inputs.

- From WIMP-quark to WIMP - nucleon : nuclear matrix elements are required.

\[
< N| m_q \bar{\psi} \psi| N > = f_q^N M_N.
\]

\[
\lambda^N = \sum_{q=1,6} f_q^N \lambda_q^N
\]

- From WIMP-nuclear to WIMP-nucleon : Nuclear form factors are introduced.
Sources of uncertainty

- **Nuclear matrix elements**: Pion-nucleon sigma term $\sigma_{\pi N} = m_l < p|\bar{u}u + \bar{d}d|p >$ with $m_l = \frac{m_u + m_d}{2}$.
- Strangeness content of nucleon $\sigma_s = m_s < p|\bar{s}s|p >$

- Local DM density, local DM velocity.
- DM density profile and velocity distribution.
SUSY diagrams for SI and SD scattering

Diagrams contributing to SI interaction

Diagrams contributing to SD interaction

- We would focus on SI interaction: Since squarks are heavy in our case, Higgs exchange diagrams dominate.
Signals from pair annihilation of LSP’s in astrophysically dense regions like galactic core, dwarf galaxies etc.

Photons can come from final state radiation, decays and hadronization of the product of final state particles etc.

p-wave processes are velocity suppressed since $\frac{v}{c} \sim 10^{-3}$ in present universe.

s-wave processes are helicity suppressed.

As we take highly bino-dominated LSP $\Rightarrow$ small annihilation cross-section.
Models analyzed

We study following models keeping slepton masses in different relative positions wrt chargino and neutralino:

\[ M_\tilde{l} = xM_1 + (1 - x)M_2 \text{ with } 0 < x < 1. \]  

1. **Light Gaugino and Left Slepton (LGLS) Scenario** : Left slepton mass is kept midway between chargino and neutralino by taking \( M_{\tilde{l}_L} = 0.5M_1 + 0.5M_2 \). Right sleptons are taken to be heavy.

2. **Tilted-LGLS scenario** : Left slepton mass is placed more towards chargino or neutralino \( \Rightarrow x = 0.25/0.75 \) respectively. Right sleptons are taken to be heavy.

3. **Light Gaugino and Left and Right Slepton (LGLRS) Scenario** : Left and right sleptons are mass-degenerate. Slepton mass is kept midway between chargino and neutralino.

4. **Tilted-LGLRS scenario** : Left and right slepton masses are placed more towards chargino or neutralino \( \Rightarrow x = 0.25/0.75 \) respectively.
We also study:

- **Light Gaugino and Right Slepton (LGRS) scenario**: Left sleptons are taken to be heavier than chargino. Right slepton mass lies midway between chargino and neutralino.

- **Light Gaugino and Heavy Slepton (LGHS) scenario**: Both left and right sleptons are taken to be heavier than chargino.

- Light Left Slepton (**LLS**) scenario and Light Left and Right Slepton (**LLRS**) scenario in the light of slepton pair production leading to $2l + \not{E}_T$ final states.
LGLS scenario: $x = 0.5$

- L sleptons of all three generations have masses midway between $M_1$ & $M_2$. R sleptons are taken to be heavy.

- In the left plot we reproduce ATLAS result by our simulation $\rightarrow$ small difference due to:
  - $\rightarrow$ D-term contribution in sneutrino masses.
  - $\rightarrow$ No detector simulation.

- Chargino-sneutrino loop contribution to muon (g-2) dominates.

- Relic density satisfying mechanism: sneutrino coannihilation for the upper branch. $Z/h$ resonance for the lower branch.
For high $\tan\beta$ muon (g-2) satisfied regions shift towards right: significant amount of parameter space left allowed by combined constraints.

- No effect of increasing $\tan\beta$ on collider sector.
- Higgs-resonance region disappears for high $\tan\beta$ at larger $m_{\tilde{\chi}_1^\pm}$ → higgsino component becomes too small.
- h/Z resonance region is disfavored under combined constraints.
Tilted-LGLS scenario: $x = 0.25$

- Left sleptons are shifted more towards chargino. Right sleptons are heavy.

- The leptons arising from decays of $\tilde{\chi}_1^\pm/\tilde{\chi}_2^0$ would be softer. This reduces the trilepton efficiency and relaxes the LHC constraints.
L and R sleptons are mass-degenerate with masses midway between $M_1$ & $M_2$.

Since $\tilde{\chi}_1^\pm$ and $\tilde{\chi}_2^0$ are wino-dominated they decay mainly via left sleptons. Thus the inclusion of right sleptons has almost no effect on collider limit.

Neutralino-smuon loop contribution to muon (g-2) is dominant.

$\tilde{\tau}_1$ is the NLSP. Stau coannihilation, Z/h resonance mechanisms in action.

For higher tan$\beta$ Higgs resonance region disappears.
Left sleptons are shifted more towards $\tilde{\chi}_1^\pm$. L-R sleptons are mass degenerate.

The leptons arising from $\tilde{\chi}_1^\pm/\tilde{\chi}_2^0$ decays would be softer. This reduces the trilepton efficiency and relaxes the LHC constraints.

For higher $\tan\beta$, in addition there is large mixing $\Rightarrow$ stau lighter than selectron. This further reduces the efficiency.
LGHS scenario

- L and R sleptons are assumed mass degenerate and heavier than $\tilde{\chi}_1^\pm / \tilde{\chi}_2^0$.

- Neutralino-smuon loop contribution to muon (g-2) is dominant.
- WMAP satisfying mechanisms: Higgs/ Z resonance for the lower branch, $\tilde{\chi}_1^\pm / \tilde{\chi}_2^0$ coannihilations for the upper branch.
- 100 % BR assumed for the decay $\tilde{\chi}_2^0 \rightarrow Z \tilde{\chi}_1^0$. But spoiler mode $\tilde{\chi}_2^0 \rightarrow h \tilde{\chi}_1^0$ can open for some parts where $m_{\tilde{\chi}_2^0} > m_h + m_{\tilde{\chi}_1^0}$.
- Higgs resonance region can not be excluded beyond doubt.
LGLS scenarios: heavy tan$\beta$ cases still allowed and to be probed by future XENON1T experiment.

LGLRS scenarios: LGLRS ($x = 0.5$ and 0.25) low tan$\beta$ cases are marginally allowed by LUX.

LGLRS scenarios: LGLRS ($x = 0.5$) high tan$\beta$ case to be probed by XENON1T. LGLRS ($x = 0.25$) high tan$\beta$ case allowed even by XENON1T.
Black points allowed by combined constraints: still allowed by LUX.
What if gluino is within LHC reach?

- Gluino is the strong sparticle with the largest cross-section at LHC.
- We try to see the effect of taking one strong sector sparticle within LHC reach on the EW sector.
- For the LGLS and LGLRS models gluino will decay to $\tilde{\chi}_1^\pm / \tilde{\chi}_2^0$ which will decay further to leptons making leptonic signals stronger.
- For the LGHS scenario gluino decays via $\tilde{g} \rightarrow q\bar{q}\tilde{\chi}_1^0$ making 0-lepton signal strongest.

Thus, it is possible to distinguish among different EW scenarios by looking at the gluino decays in the $n$ leptons $+$ jets $+ \not{E}_T$ channels with $n = 0, 1, 2$. 
| BP  | $m_{\tilde{\chi}^0_1}$ (GeV) | $m_{\tilde{\chi}_1^\pm}$ (GeV) | $m_{\tilde{\chi}^0_2}$ (GeV) | $M_{\tilde{\nu}_L}^{D_{e,\mu}}$ (GeV) | $M_{\tilde{\nu}_R}^{D_{e,\mu}}$ (GeV) | $\bar{\tau}_1$ (GeV) | $M_{\tilde{\nu}}^D$ (GeV) | $\Omega_{\tilde{\chi}} h^2$ | $\sigma_{SI}$ (pb) $\times 10^{-10}$ | $a_{\mu}^{SUSY}$ (pb) $\times 10^{-9}$ |
|-----|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| BP1 | 232             | 266             | 267             | 255             | 2000            | 255             | 243             | 0.116           | 5.7             | 2.9             |
| BP2 | 240             | 298             | 299             | 263             | 2000            | 263             | 251             | 0.127           | 2.8             | 2.5             |
| BP3 | 220             | 248             | 249             | 246             | 2000            | 245             | 233             | 0.109           | 8.1             | 3.4             |
| BP4 | 61              | 695             | 695             | 374             | 374             | 355             | 366             | 0.137           | 1.9             | 0.3             |
| BP5 | 350             | 491             | 491             | 420             | 420             | 354             | 413             | 0.098           | 0.7             | 1.3             |
| BP6 | 187             | 287             | 286             | 263             | 263             | 197             | 251             | 0.125           | 1.6             | 3.6             |
| BP7 | 171             | 196             | 196             | 397             | 397             | 371             | 390             | 0.127           | 16.2            | 3.1             |

**Table:** The sparticle spectra corresponding to different benchmark points (BPs) allowed by combined constraints.
Direct LHC bounds on EW sector sparticles are rather weak.

It is possible to constrain pMSSM parameter space with the help of indirect constraints along with direct collider limits.

WMAP relic density data, muon (g-2) constraint and DM direct detection experiments can be very significant.

Some DM mechanisms like sneutrino coannihilation which are disfavored in mSUGRA type of scenarios are still allowed in PMSSM. h/Z resonance mechanisms, bulk annihilation are in tension even in pMSSM under combined constraints.

Different EW scenarios can be distinguished if gluino remains within LHC reach.
Thank You
ATLAS latest $3l + E_{t\text{miss}}$ [Ref: arXiv 1402.7029]
Uncertainties

- Calculation of WIMP-nucleus interaction is a three-step process:
  1. Calculation of WIMP interaction with quark (both valence and sea)/gluons.
  2. Translation of microscopic interaction to nucleon interaction: evaluation of matrix elements of quark and gluon operators in a nucleon state → \( <N|m_q \bar{\Psi} \Psi|N> \) \( f_q^N M_N \).
     → This is interpreted as the quark/gluon contribution to the mass of the nucleon.
     → Pion-nucleon sigma term \( \sigma_{\pi N} \) and strange quark content \( \sigma_s \) required.
     \[ \sigma_{\pi N} = m_l < p | \bar{u} u + \bar{d} d | p > \quad \text{with} \quad m_l = \frac{m_u + m_d}{2}. \]
     \[ \sigma_{\pi N} = m_s < p | \bar{s} s | p > \]
     → evaluated using chiral perturbation theory and lattice QCD calculations: largest source of uncertainty.
  3. From nuclear to nucleon nucleon.

- Velocity distribution of WIMPs wrt to the rest frame of the detector.
- Local value of DM velocity.
- Local DM density.
gluonic loops for SI interaction
SI interaction

\[ f_p = \sum_f f^H_q \langle p|q\bar{q}|p \rangle \]

\[ = \sum_{q=u,d,s} \frac{f^H_q}{m_q} m_p f^{T_q(p)} + \frac{2}{27} f_{T_G} \sum_{q=c,b,t} \frac{f^H_q}{m_q} m_p. \]

(2)

where \( f_{T_G} = 1 - \sum_{u,d,s} f^{T_q(p)} \). The second term comes from coupling of heavy quarks to gluons through trace anomalies. The effective coupling between the neutralino and nucleon through the Higgs exchange, \( f^H_q \), is given by

\[ f^H_q = m_q \frac{g_2^2}{4m_W} \left( \frac{C_{h\tilde{\chi}^0\tilde{\chi}^0} C_{hqq}}{m_{h^0}^2} + \frac{C_{H\tilde{\chi}^0\tilde{\chi}^0} C_{Hqq}}{m_{H^0}^2} \right), \]

(3)

[Ref. Hisano et al. arXiv:0912.4701]
Here we show the qualitative behavior of $h^0(H^0) - \tilde{\chi}^0 - \tilde{\chi}^0$ coupling in the limit case of $m_{H^0} = m_A$, where $m_A$ stands for the mass of CP-odd Higgs boson. For the Bino-like $\tilde{\chi}^0$ ($M_1 \ll M_2, \mu$), the diagonalizing matrix of neutralino is calculated perturbatively, and $C_{h\tilde{\chi}\tilde{\chi}}$ and $C_{H\tilde{\chi}\tilde{\chi}}$ are approximated as follows

$$C_{h\tilde{\chi}\tilde{\chi}} \simeq \frac{m_Z s_W t_W}{M_1^2 - \mu^2} [M_1 + \mu \sin 2 \beta],$$

$$C_{H\tilde{\chi}\tilde{\chi}} \simeq -\frac{m_Z s_W t_W}{M_1^2 - \mu^2} \mu \cos 2 \beta. \quad (4)$$

Notice that this perturbative calculation breaks down if $|M_1 - |\mu|| \lesssim m_Z$. 

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Weak contribution to muon (g-2)
Hadronic contribution to muon (g-2)

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The Electroweak Sector of the pMSSM in the Light of LHC - 8 T
1 and 2-loop QED contribution to muon (g-2)
• SM contribution (almost saturates the experimental value) → $t - W^\pm$ loop.

• MSSM contribution:
  1. $\tilde{\chi}^\pm - \tilde{t}$ loop:
     \[
     BR(b \to s\gamma)|_{\tilde{\chi}^\pm} = \mu A_t \tan \beta f(m_{\tilde{t}_1}, m_{\tilde{t}_2}, m_{\tilde{\chi}^\pm}) \frac{m_b}{v(1+\Delta m_b)}
     \]
  2. $H^\pm - t$ loop:
     \[
     BR(b \to s\gamma)|_{H^\pm} = \frac{m_b(y_t \cos \beta - \delta y_t \sin \beta)}{v \cos \beta (1+\Delta m_b)} g(m_{H^\pm}, m_t) \text{ where,}
     \]
     \[
     \delta y_t = y_t \frac{2\alpha_s}{3\pi} \mu M_{\tilde{g}} \tan \beta (\cos^2 \theta_t I(m_{\tilde{s}_L}, m_{\tilde{t}_2}, M_{\tilde{g}}) + \sin^2 \theta_t I(m_{\tilde{s}_L}, m_{\tilde{t}_1}, M_{\tilde{g}}))
     \]
     destructive interference for $A_t \mu < 0 \to$ prefered.

• NLO contributions (from squark-gluino loops: due to the corrections of top and bottom yukawa couplings) become important at large $\mu$ or large $\tan \beta$. 

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\[ B_s \rightarrow \mu^+ \mu^- \]

- dominant SM contribution from: Z penguin top loop & W box diagram.
- SM value: \( BR(B_s \rightarrow \mu^+ \mu^-) = 3.23 \pm 0.27 \times 10^{-9} \).
- LHCb result: \( 3.2^{+1.4}_{-1.2}^{(stat.)} +^{0.5}_{-0.3}^{(syst.)} \) → no room for large deviation.
- \( BR(B_s \rightarrow \mu^+ \mu^-)_{SUSY} \propto \frac{\tan^6 \beta}{m_a^4} \)