SUSY, GUTs, and their Implications

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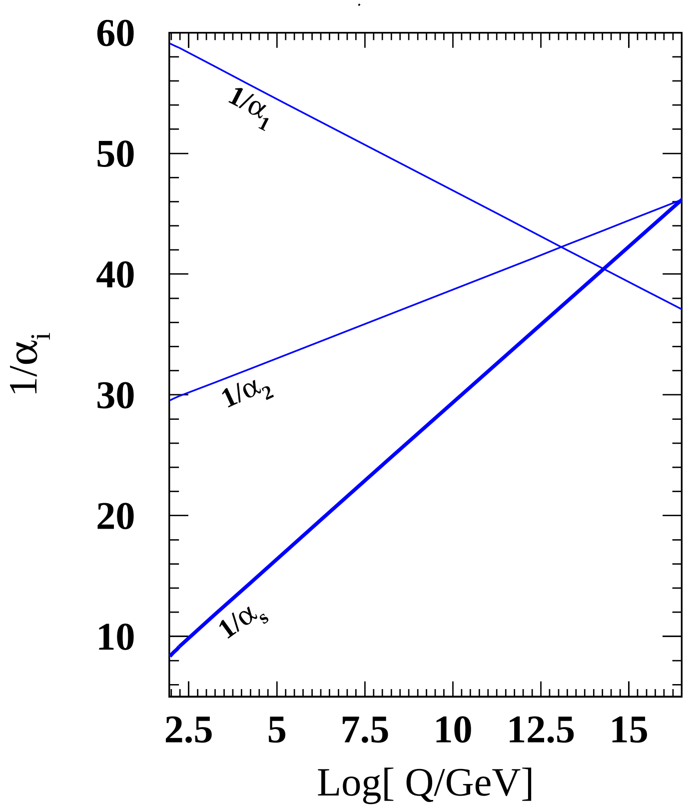
Outline

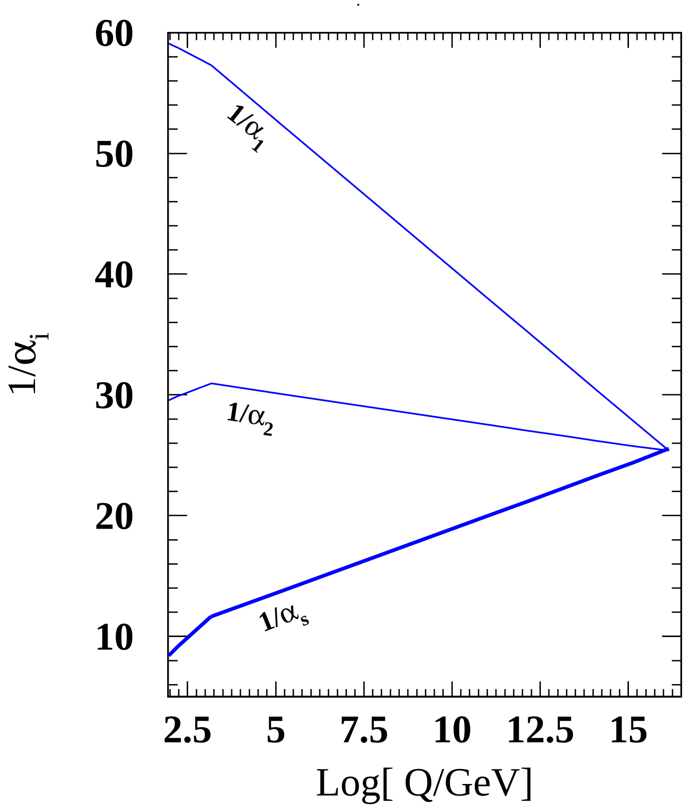
- ❑Motivation
- ❑GUT Models
- ❑SO(10) Models and Fermion Masses
- ❑Proton Decays
- ❑Predictions in Neutrino Physics, Lepton Flavor Violation
- ❑Implications in *B* Physics: $\Delta M_{B_s^0}$
- ❑Collider Signals
- ❑Conclusion

Motivation

Grand unification of couplings:

In SM, a near miss... **But It is not hard to unify**





The unification can also happen if we bring a LR scale (motivated by Neutrino physics: Seesaw scale).

- **But SUSY at the electroweak scale is required to cure the Higgs mass problem.**

- **The Dark matter content of the Universe: 23%[WMAP]**
  In SUSY models, $\tilde{\chi}_1^0$- the lightest neutralino as a stable dark matter candidate (R-parity invariant SUSY model).

- **This neutralino can give rise to the right amount of cold dark matter of the universe.**

- **The relic density of these neutralinos is given by:**

$$\Omega_{\tilde{\chi}_1^0} h^2 \sim \int_0^{x_f} dx (< \sigma_{ann} v >)^{-1}$$

- **Using $\Omega_{DM} \sim 0.2$ we obtain $< \sigma_{ann} v > \sim 0.9$ pb.**
  $< \sigma v > = \pi \alpha^2 / 8 m^2 \Rightarrow m \sim 100$ **GeV.**

Models at the Unification scale

The physics at the Unification scale can be described by Unifying groups e.g. SU(5), flipped SU(5), SO(10), E6 etc.

- **All these groups can arise from E_8.**
- **Higher symmetry groups encloses SM $\Rightarrow$ grand unifying groups.**
- **Major constraints and Implications:**
  Proton decay: dimension 5,6 operators[quark-lepton unification, new gauge bosons, colored Higgs bosons] threshold correction to the gauge couplings.
  Effect of quark lepton unifications in Lepton Flavor violating modes, Neutrino physics, B_s^0-$\bar{B}_s^0$ mixing, B-decay physics, collider signal.

Choosing a GUT Model

- **SU(5) vs SO(10): Right handed neutrinos are natural in SO(10): part of the fundemental particle content in SO(10). In SU(5) the right handed neutrino is a singlet. The particles are: $\bar{5}$ and 10 i.e. 15 SM particles/generation.**

- **$\mathbf{16}$: quarks, leptons plus right-handed neutrinos.**

  The Higgs: $\mathbf{10}$: In the very minimal representaion.

  If there is just one 10: we have $\lambda_t = \lambda_b = \lambda_\tau$ (GUT scale).

  For the 3rd generation, it is alright, but for the other generations we need to break this realtionship$\longrightarrow$ we need more Higgs. Electroweak symmetry breaking is a big constraint for this relatinship.

Model Requirements

We construct the Higgs sector of the model in such a way so that:

- All quarks and charged lepton masses are correctly reproduced. The CKM mixing is correctly generated.
- The light neutrino mass difference hierarchies are correctly generated i.e. $0.02 \leq \frac{\Delta m^2_{12(solar)}}{\Delta m^2_{23(atmos)}} \leq 0.06$.
- The neutrino mixing is reproduced with the feature: $U_{e3} \leq 0.26$, $sin^2 2\theta_A \geq 0.9$, $0.3 \leq tan^2\theta_{12} \leq 0.6$.
- Proton decay contstraints are satisfied.
- Gauge coupling unification is still maintained.

The light neutrno masses ($m_\nu << m_u, m_d, m_e$) are generated using seesaw mechanism: Minkowski, Yanagida, Gellman, Slansky, Ramond, Mohaptra, Senjanovic

- ν_R has a large Majorana mass and gives rise to the following light neutrino mass:

$$\mathcal{M}_\nu^{\mathrm{I}} = -M_\nu^D M_R^{-1} (M_\nu^D)^T \text{ : Type I Seesaw}$$

$M_\nu^D \Rightarrow$ Dirac neutrino mass matrix,
$M_R \Rightarrow$ right-handed Majorana matrix.

- The origin of M_R: $f\nu^c\nu^c < \Delta_R >$,
  ν^c: Right-handed neutrino, Δ_R: A new type of Higgs.
  The VEV of Δ_R corresponds to a symmetry breaking scale.

- $f\nu\nu < \Delta_L >$ terms also exist in these models. $< \Delta_L > \propto v_{ew}^2 / v_{GUT}$ (minimization of the Higgs potential)= sub-eV.

- The light neutrino mass has two contributions: $f < \Delta_L >$ and $M_\nu^D M_R^{-1} (M_\nu^D)^T$.

- $\mathcal{M}_\nu^{\rm II} = M_L - M_\nu^D M_R^{-1} (M_\nu^D)^T$: TypeII $M_L = f < \Delta_L >$. Lazarides, Shafi, Watterich, '81.

- For heavy right-handed Majorana masses, Type I contribution is neglected.

- 3 scenarios are possible: Type I: $M_\nu^D M_R^{-1} (M_\nu^D)^T$, Type II: $M_L - M_\nu^D M_R^{-1} (M_\nu^D)^T$, Pure Type II: M_L.

A Grand Unified Model: SO(10)

- All fermions +ν^c are in 16
  $SO(10) \rightarrow SU(5) \rightarrow SU(3)_c \times SU(2)_L \times U(1)_Y$,
  $SO(10) \rightarrow SU(4)_c \times SU(2)_L \times SU(2)_R \rightarrow$
  $SU(3)_c \times SU(2)_L \times SU(2)_R \times U(1)_{B-L} \rightarrow$
  $SU(3)_c \times SU(2)_L \times U(1)_Y$,
  $SO(10) \rightarrow SU(5) \times U(1)_X \rightarrow$ SM...
- Fields e.g. 126, $\overline{126}$, 45, 54, 210 develop VEVS to break SO(10)
- $M_{GUT} \simeq M_I >> M_{SM}$.
- Seesaw scale is linked to the grand unification.
- SO(10) grand unification of " MSSM+ Seesaw" makes the model predictive.

The SO(10) Framework

- $\mathbf{16}$: **quarks, leptons plus right-handed neutrinos.**

  The superpotential for the Yukawa interactions:

$$W_Y = \frac{1}{2} h_{ij} \psi_i \psi_j H_{10} + \frac{1}{2} f_{ij} \psi_i \psi_j \overline{\Delta}_{\overline{126}} + \frac{1}{2} h'_{ij} \psi_i \psi_j A_{120}.$$

- h, f: **complex symmetric matrices.**

  h': **complex anti-symmetric matrix.**

- **The SO(10) model(Without h'): Babu, Mohapatra,'93; Matsuda, Koide, Fukuyama,'01; 02; Fukuyama, et al,'03; Bajc, Senjanovic, Vissani,'03; 04; Goh, Mohapatra, Ng,'03; Aulakh, Gridhar,'03; 04; B.D., Mimura, Mohapatra,'04, Babu, Macesanu,'05;... (With h'): Bertolini et al.'04,'05,'06, B.D., Mimura, Mohapatra,'04; Yang,Wang,'04...**

The SO(10) Framework...

- SO(10) symmetry breaks down to the Standard Model symmetry:

  The Standard Model Higgs pair arises:
  $H_{10}(1,2,2)$, $\overline{\Delta}_{126}(15,2,2)$, $\Delta_{126}(15,2,2)$, D_{120} $[(1,2,2)+(15,2,2)]$ and $\phi_{210}(10,2,2)$ Higgs fields.

- Mass of one pair of their linear combinations: H_u and H_d: $\sim$ O(weak scale)

  The other pairs: $\sim$ O(GUT scale) (We require this.)

$$(H_u, \cdots) = V^*(H_u^{10}, D_u^1, D_u^2, \Delta_u, \overline{\Delta}_u, \Phi_u),$$

$$(H_d, \cdots) = U^*(H_d^{10}, D_d^1, D_d^2, \overline{\Delta}_d, \Delta_d, \Phi_d),$$

- Intermediate scales can be accommodated.

- **The MSSM Yukawa couplings and left- and right-handed Majorana neutrino mass terms are**

$$W_Y \supset Y^u_{ij} Q_i U^c_j H_u + Y^d_{ij} Q_i D^c_j H_d + Y^e_{ij} L_i E^c_j H_d + Y^\nu_{ij} L_i \nu^c_j H_u + \frac{1}{2} f_{ij} L_i L_j \overline{\Delta}_L + \frac{1}{2} f_{ij} \nu^c_i \nu^c_j \overline{\Delta}^0_R,$$

$Q, U^c, D^c, L, E^c, \nu^c$: **quark and lepton superfields**
$\overline{\Delta}_L$ **is an** $SU(2)_L$: **triplet Higgs field;** $\overline{\Delta}^0_R$ **is a neutral Higgs field.**

- **A large vacuum expectation value of the** $\overline{126}$ **Higgs field is necessary to acquire the right-handed Majorana mass.** $M_R \propto f v_R$ **:** v_R **is expected to be close to the GUT scale.**

Fermion Masses

- The quark and lepton Dirac massses are

$$Y_u = \bar{h} + r_2 \bar{f} + r_3 \bar{h}',$$

$$Y_d = r_1(\bar{h} + \bar{f} + \bar{h}'),$$

[Similarly Y_e and Y_ν^D]
with

$$\bar{h} = V_{11} h,\ r_1 = U_{11}/V_{11},\ r_2 = r_1 V_{15}/U_{14}, ...$$

- V, U are diagonalizing matrices.

- The Majorana masses: $M_L \propto f v_L, \quad M_R \propto f v_R$,
$v_L \sim v^2_{\text{weak}}/(\lambda M_{GUT})$, $v_R \sim$ GUT scale.

Parameters

- So far we have 31 parameters.(No predictions)
- We introduce a parity symmetry:
- Under the parity symmetry, the mass parameters and the couplings in the Higgs potential are real.
- No EDM problem any more.
- The Dirac mass matrix is hermitian .
  ($\bar{h}$ and $\bar{f}$ are real symm. matrices, $\bar{h}'$ is a anti-symm. matrix whose all components are pure imaginary)
- The nos. of parameters : 17 and will be reduced furher by the proton decay constraint) .

Proton Decay

- This minimal SO(10) model has severe proton decay constraint. [Mohapatra et al.]
  Only small $tan\beta \leq 5$ is allowed with severe fine tunings.

- The proton decay is induced by the dimension 5 operators induced by the Higgs triplets (superpotential terms):
  $C_L^{ijkl} Q_k Q_l Q_i L_j, C_R^{ijkl} E_k^c U_l^c U_i^c D_j^c$

- The integrated out triplet Higgs fields:
  $\varphi_T = (H_T, D_T, D'_T, \Delta_T, \overline{\Delta}_T, \overline{\Delta}'_T, \Phi_T)$,$\varphi_{\overline{T}}$,
  $\varphi_{\overline{C}} = (D_{\overline{C}}, \Delta_{\overline{C}})$ and $\varphi_C = (D_C, \overline{\Delta}_C)$.

Proton Decay...

- **Yukawa couplings for proton decay:**

$$W_Y^{\text{trip.}} = hH_{\overline{T}}\,(QL + U^cD^c) + ... +$$

$$f\overline{\Delta}_{\overline{T}}\,(QL - U^cD^c) + f\overline{\Delta}_T\,(\frac{1}{2}QQ - E^cU^c) + ...$$

$$+\sqrt{2}h'D_{\overline{T}}\,U^cD^c + \sqrt{2}h'D'_{\overline{T}}QL + ...$$

- h, h', f **appear again.**

- **The dimension five operators:**

$$C_L^{ijkl} = c\,h_{ij}h_{kl} + x_1 f_{ij}f_{kl} + x_2 h_{ij}f_{kl} + ...$$

$$C_R^{ijkl} = c\,h_{ij}h_{kl} + y_1 f_{ij}f_{kl} + y_2 h_{ij}f_{kl} + ...$$

- h, f and h' appear in $Y_{u,d,e}$ with $r_{1,2,3}$ [e.g.,$Y_e = r_1(\bar{h} - 3\bar{f} + c_e\bar{h}')$ etc]

- Particular textures are needed to suppress proton decay.

- Textures : $\bar{h} \simeq$ diag$(0, 0, O(1))$,

$$\bar{f} \simeq \begin{pmatrix} \sim 0 & \sim 0 & \lambda^3 \\ \sim 0 & \lambda^2 & \lambda^2 \\ \lambda^3 & \lambda^2 & \lambda^2 \end{pmatrix}, \bar{h}' \simeq i \begin{pmatrix} 0 & \lambda^3 & \lambda^3 \\ -\lambda^3 & 0 & \lambda^2 \\ -\lambda^3 & -\lambda^2 & 0 \end{pmatrix},$$

where $\lambda \sim 0.2$. [Dutta, Mimura, Mohapatra, PRL;05.]

- r_2 and r_3 needs to be small, $r_3 = 0$, r_2 is fixed as $r_2 m_s/m_b \simeq \lambda_c$ ($r_2 \simeq 0.1$) to generate the correct charm mass.

- $f_{11,12} \sim 0$ to ensure small values of $h_{11,12}$, h'_{12} generates the down-quark mass and θ_c.

Suppression of Proton Decay

- **Proton Decay Amplitude:**
  $A = \alpha_2 \beta_p / (4\pi M_T m_{SUSY}) \tilde{A}$, $\beta_p \sim 0.01$,
  $M_T \sim 2 \times 10^{16}$ **GeV [Color Higgs mass scale].**

  $$\tilde{A} = c\tilde{A}_{hh} + x_1 \tilde{A}_{ff} + x_2 \tilde{A}_{hf} + x_3 \tilde{A}_{fh} + x_4 \tilde{A}_{h'h} + \cdots .$$

  $x_i = X_{1j} Y_{1k}$, X_{ij}, Y_{ij} **diagonalize the colored Higgsino mass matrices**

- $\tilde{A}_{hh}$ **can become much smaller than** 10^{-8}**. The bound:** $\tilde{A}_{hh} < 5 \cdot 10^{-8}$.

- **The contribution of the other components e.g.** $\tilde{A}_{ff,hf,fh,h'f,h'}$ **are associated with the colored Higgs mixing angles:**
  [$x_1 \tilde{A}_{ff} + x_2 \tilde{A}_{hf} \cdots$]
  x_i **can be suppressed by choosing VEVs and the Higgs couplings.**

Neutrino Sector

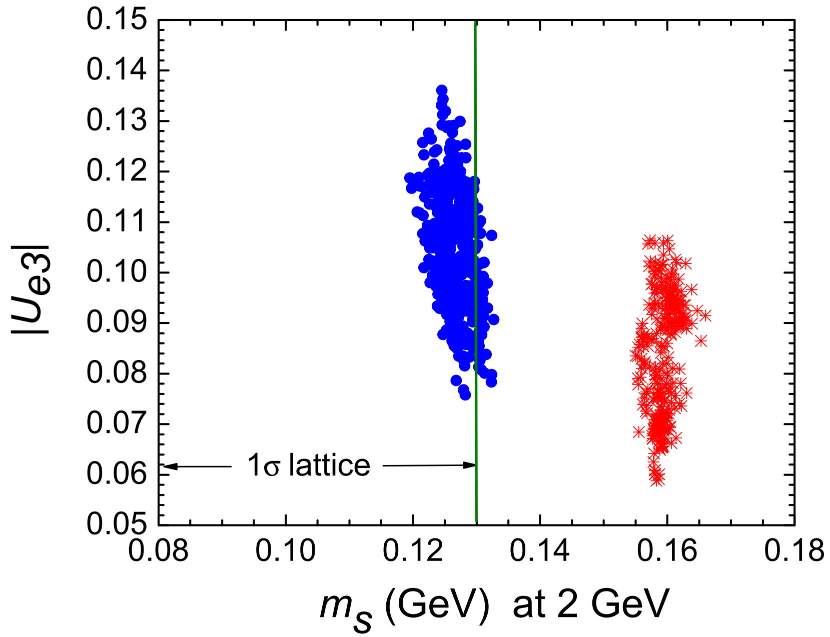
- **Using the textures we can explain the quark, lepton masses and mixing angles.**

- **We use the following input:** $m_{e,\mu,\tau}$, $V_{us,cb,ub}$, $m_{u,c,t}$, δ_{CKM}, θ_A, θ_{12}: **12. The proton decay constraint has reduced the relevant parameters down to 12.**

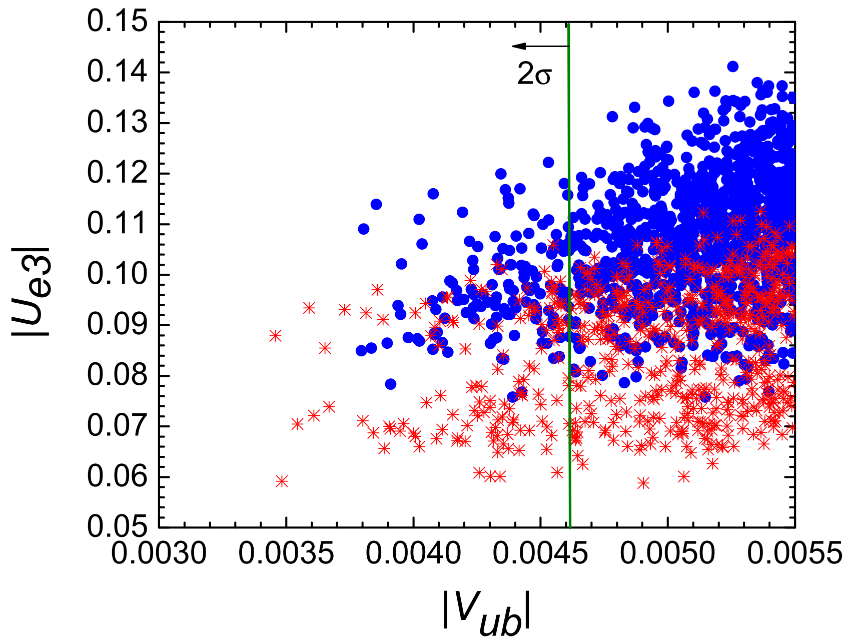
- **Several relations:**
$$m_s \sim m_\mu/3(1 \pm 3\lambda^2),$$
$$\Delta m_s^2/\Delta m_A^2 \simeq (1 - \tan^4\theta_{12})/tan^2\theta_{12}U_{e3}^2$$
$$U_{e3} \simeq 1/\sqrt{2}V_{ub}/V_{cb}$$
$$Sin\delta_{MNSP} \simeq 1/\sqrt{2}S_{12}^e/U_{e3}Sin[Arg(M_e)_{12}]$$

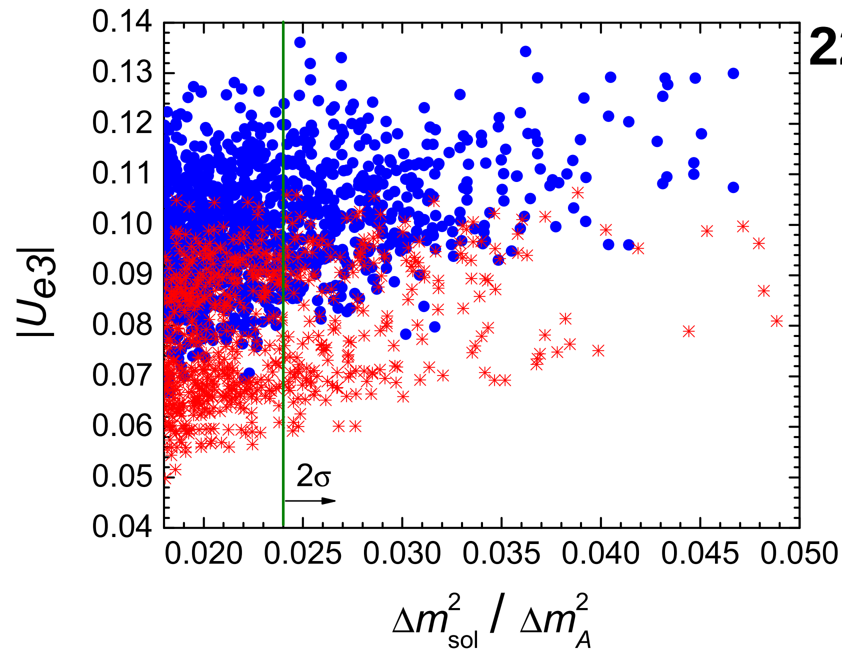
- U_{e3} **is restricted to a range due to the mass ratio and** V_{ub}**.**

Predictions



- **The predicted value of strange quark mass has two separate regions, roughly $m_s \sim 1/3\, m_\mu(1 \pm O(\lambda^2))$.**
- **larger values of strange mass prefers lower values of U_{e3}.**
- **The bottom-tau Yukawa couplings needs to be unified within several percent.**





$|U_{e3}|$ vs V_{ub} $|U_{e3}|$ vs $\Delta m_s^2/\Delta m_A^2$

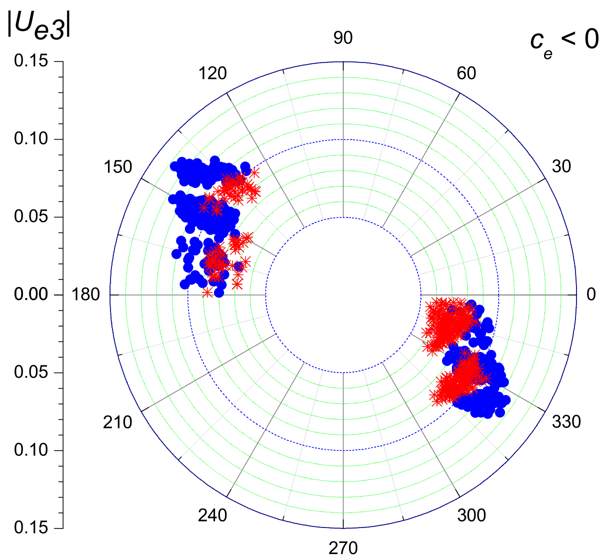
[Dutta, Mimura, Mohapatra, PRD;05.]

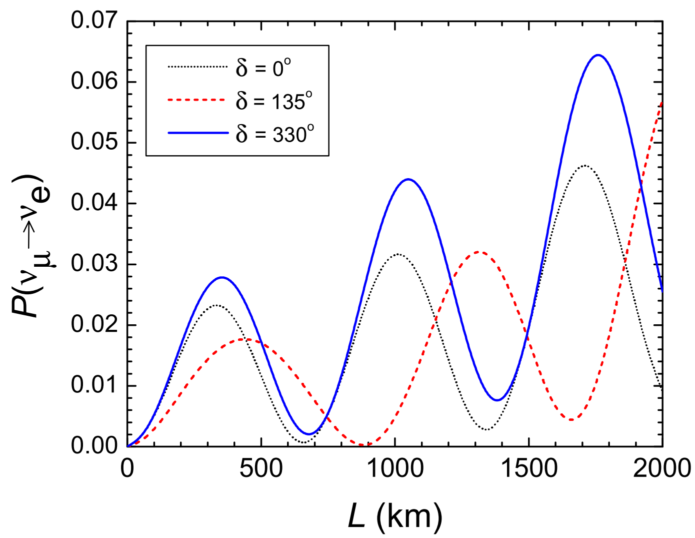
- $V_{ub} < 0.0046$ **and** $\Delta m_s^2/\Delta m_A^2 > 0.022$
- U_{e3} **is bounded: 0.06-0.11.**
- **We use type II for our fit.**

- The MNSP phase is given by the approximate expression:

$$\sin\delta_{\rm MNSP} \sim \frac{1}{\sqrt{2}}\frac{\sin\theta^e_{12}}{\sin\theta^\nu_{13}}\sin\left(\tan^{-1}\frac{c_e\bar{h}'_{12}}{3\bar{f}_{12}}\right),$$

Approximately, $\sin\theta^\nu_{13} \simeq |U_{e3}|$.





- The location of $\delta_{\rm MNSP}$ in the 2nd or 4th quadrant has impact on the probability of ν_μ to ν_e oscillation ($P_{\nu_\mu\to\nu_e}$)

Lepton Flavor Violating Processes

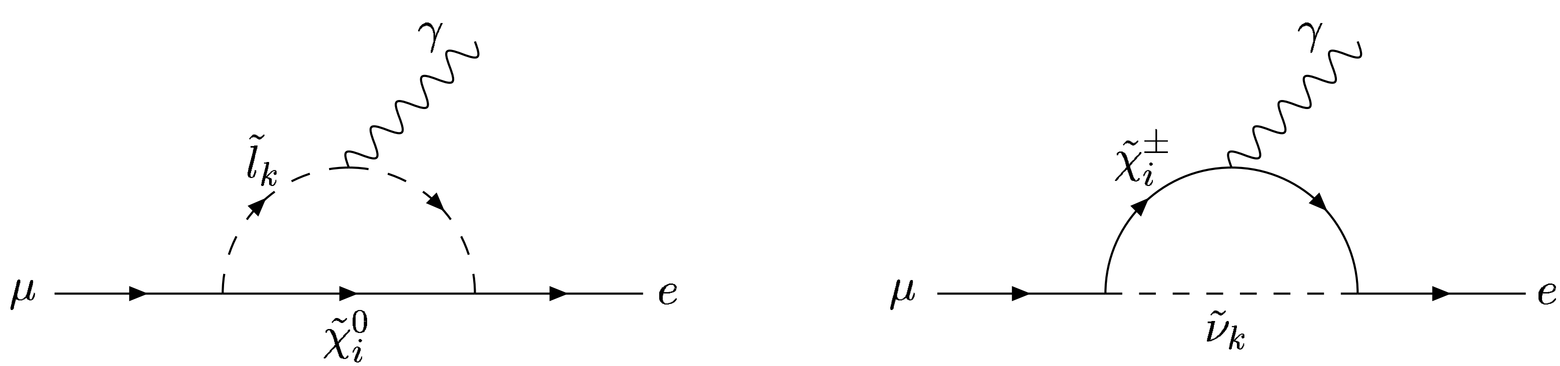
- **The decay width for $l_i \rightarrow l_j + \gamma$ can be written as:**

$$\Gamma(l_i \rightarrow l_j + \gamma) = \frac{m_{l_i} e^2}{64\pi} \left(|a_l|^2 + |a_r|^2\right)$$

- **The operator for $l_i \rightarrow l_j + \gamma$ is:**

$$\mathcal{L}_{l_i \rightarrow l_j \gamma} = \frac{ie}{2m_{l_i}} \overline{l_j}\, \sigma^{\mu\nu} q_\nu \left(a_l P_L + a_r P_R\right) l_i \cdot A_\mu + h.c.$$

- **The supersymmetric contributions include the neutralino and chargino diagrams.**



LFV in Type II case

- We work in the basis where the charged lepton masses are diagonal at the highest scale of the theory.
- Below v_R we have just MSSM and $M_{\rm GUT} \geq v_R$.
- The right handed masses Neutrino masses have hierarchies and therefore get decoupled at different scales.
- The flavor-violating pieces present in Y_ν induces flavor violations into the charged lepton couplings and into the soft SUSY breaking masses e.g. m^2 terms etc. through the following RGEs

$$dY_e/dt = \frac{1}{16\pi^2}(Y_\nu Y_\nu^\dagger + \cdots)Y_e$$

$$dm^2_{LL}/dt = \frac{1}{16\pi^2}(Y_\nu Y_\nu^\dagger m^2_{LL} + m^2_{LL} Y_\nu Y_\nu^\dagger + \cdots)$$

LFV in Type I case

- $v_R \sim\leq 10^{14}$ GeV for $\tan\beta = 40$.
- This requires the 2231 symmetry to be maintained between the GUT and the v_R scale.
- The right charged lepton and neutrino form a doublet under $SU(2)_R$.
- The right slepton masses get new flavor violating contributions through the flavor violating pieces present in Y_ν. dm^2_{RR}/dt=

$$\frac{1}{16\pi^2}(Y_\nu Y_\nu^\dagger m^2_{RR} + m^2_{RR} Y_\nu Y_\nu^\dagger + 2 Y_\nu m^2_{LL} Y_\nu^\dagger +$$

$$3/2[f f^\dagger m^2_{RR} + m^2_{RR} f f^\dagger + 2 f m^2_{RR} f^\dagger] + \cdots)$$

Minimal Supergravity (mSUGRA)

4 parameters + 1 sign

$m_{1/2}$	Gaugino mass at M_G
m_0	Scalar soft breaking mass at M_G
A_0	Cubic soft breaking mass at M_G
$\tan\beta$	$\langle H_2\rangle / \langle H_1\rangle$ at the electroweak scale
sign(μ)	Sign of Higgs mixing parameter ($W^{(2)} = \mu H_1 H_2$)

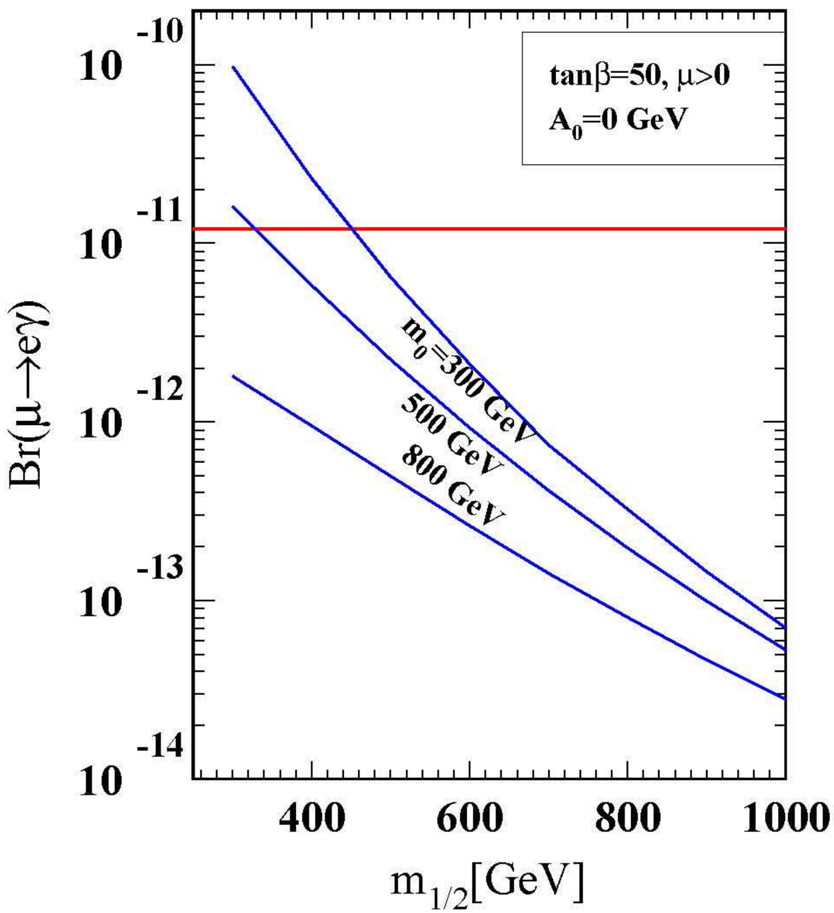
Experimental Constraints

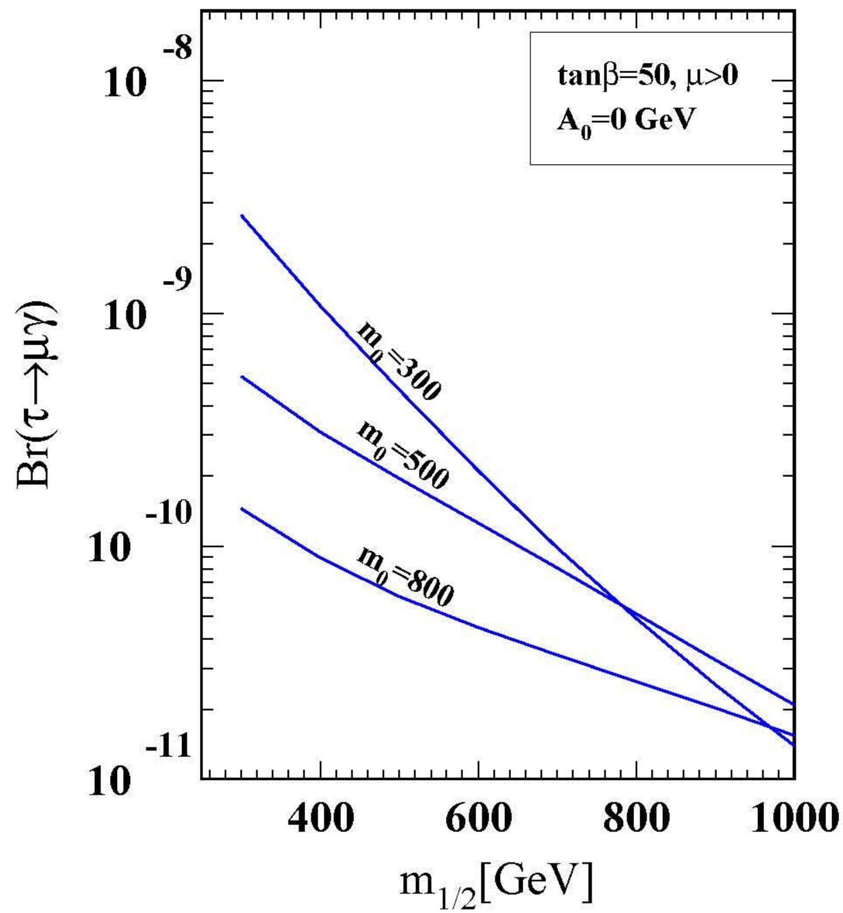
i. $M_{Higgs} > 114$ GeV $\quad M_{chargino} > 104$ GeV

ii. $2.2 \times 10^{-4} < Br\,(b \to s\,\gamma) < 4.5 \times 10^{-4}$

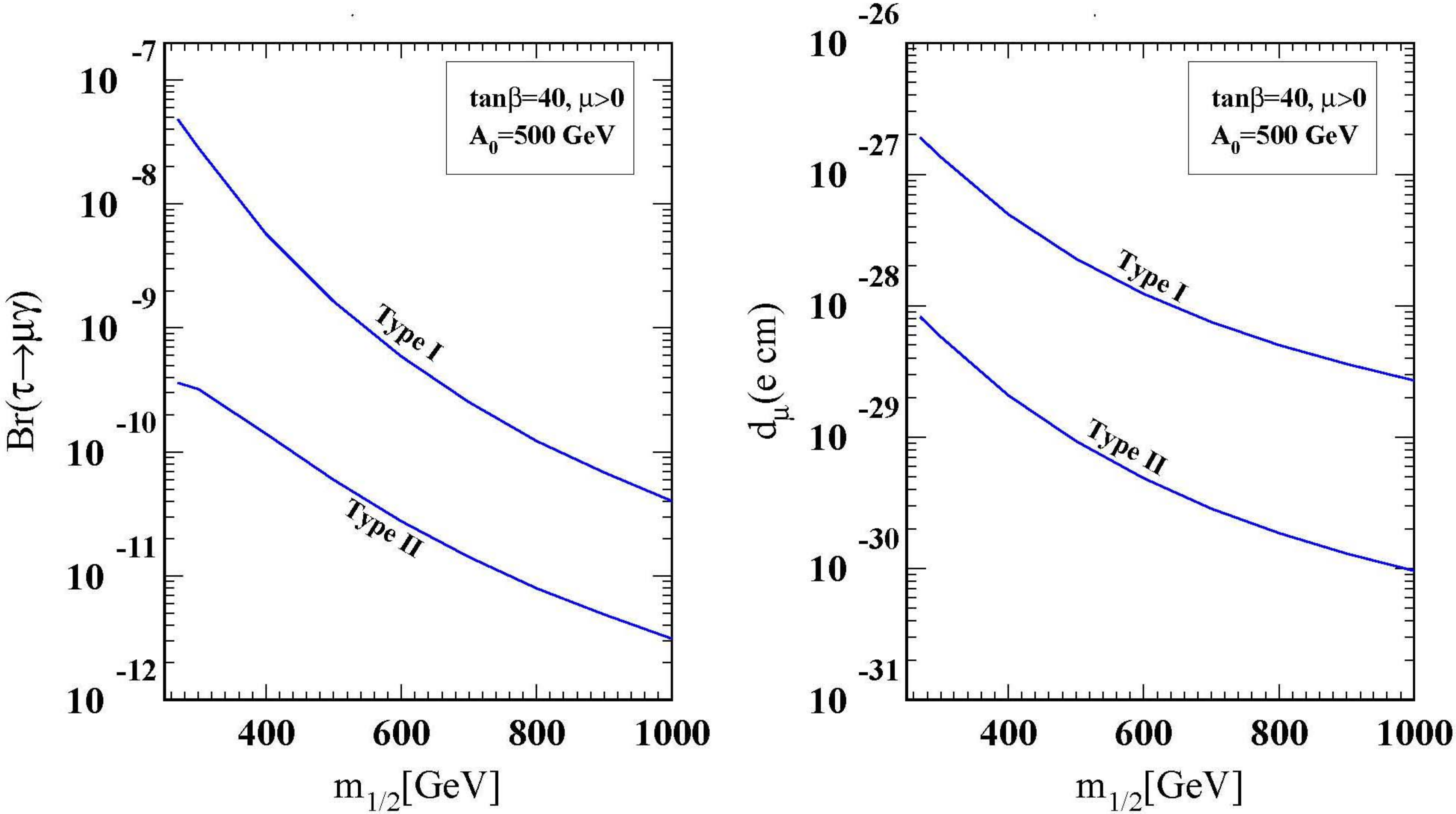
iii. $0.094 < \Omega_{\tilde{\chi}_1^0} h^2 < 0.129$

$Br(\mu \to e\gamma)$ & $Br(\tau \to \mu\gamma)$





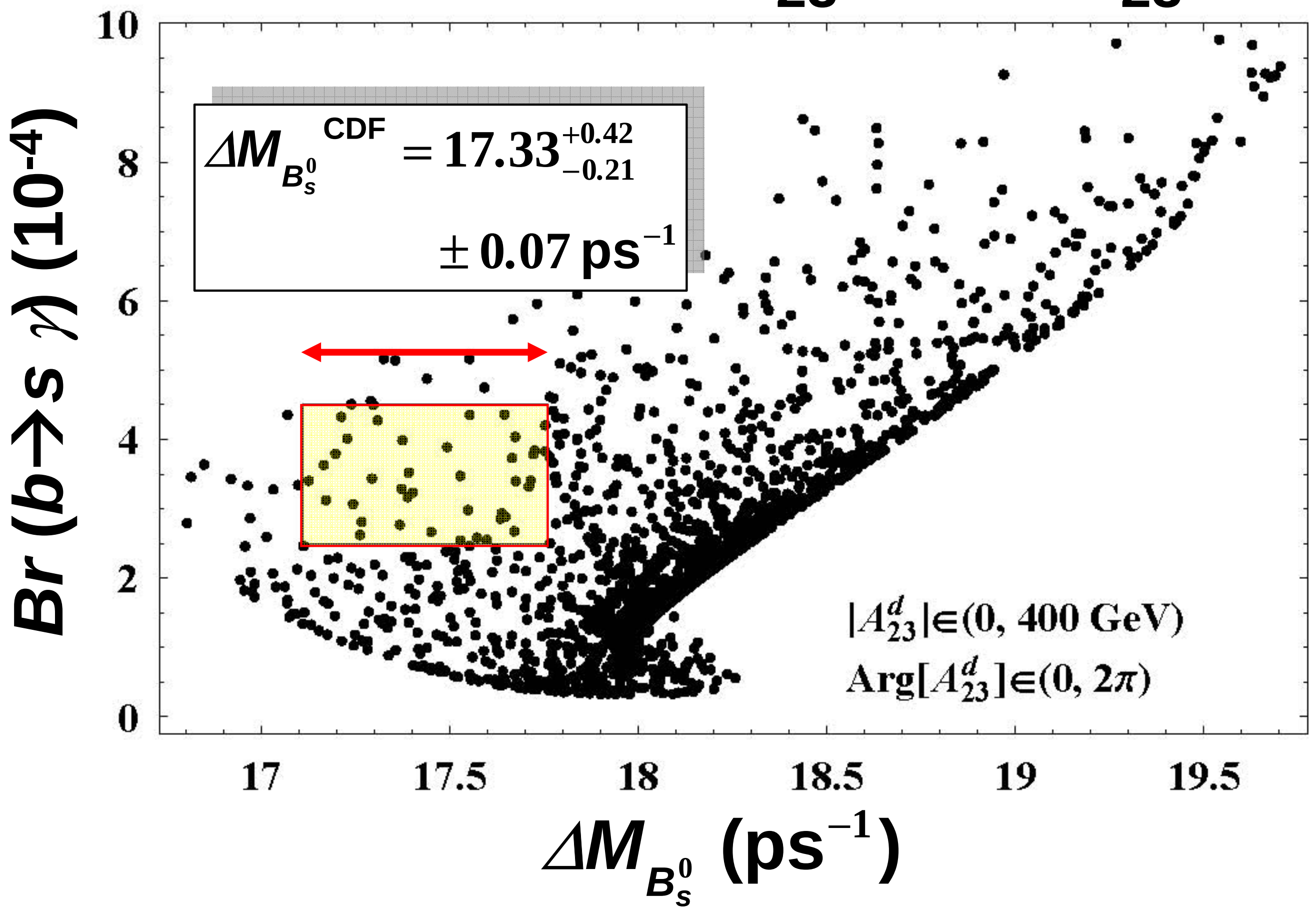
$Br(\tau \rightarrow \mu\gamma)$ & d_μ



B_s^0 - $\overline{B}_s^0$ Mixing

- [SM UTfitter] $\Delta M_{B_s^0} = 21.5 \pm 2.6\,\mathrm{ps}^{-1}$

  [SM CKMfitter] $\Delta M_{B_s^0} = 21.7^{+5.9}_{-4.2}\,\mathrm{ps}^{-1}$
- [SUSY] ΔM_B can be changed with non-zero soft mass matrix terms M_{23}^2 and A_{23}



- What are predictions of the Unification models?

  Let us first consider SU(5) like or SO(10) like boundary conditions:

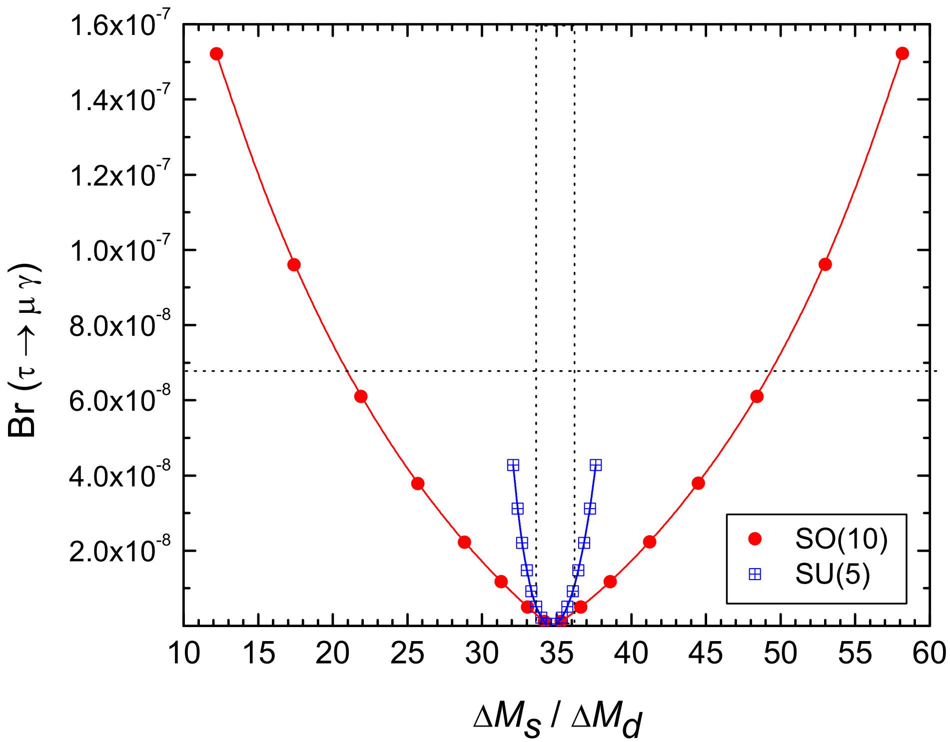
- SU(5) Boundary conditions: $M^2_{23,L} = M^2_{23,D^c} = M^2_{23,\bar{F}}$, $M^2_{23,E^c} = M^2_{23,U^c} = M^2_{23,Q} = M^2_{23,T}$ [$\bar{F}$: D^c, L, T: Q, E^c, U^c].

- The SO(10) like BCs are:
  $M^2_{23,L} = M^2_{23,D^c} = M^2_{23,Q} = M^2_{23,U^c} = M^2_{23,E^c} = M^2_{\psi}$

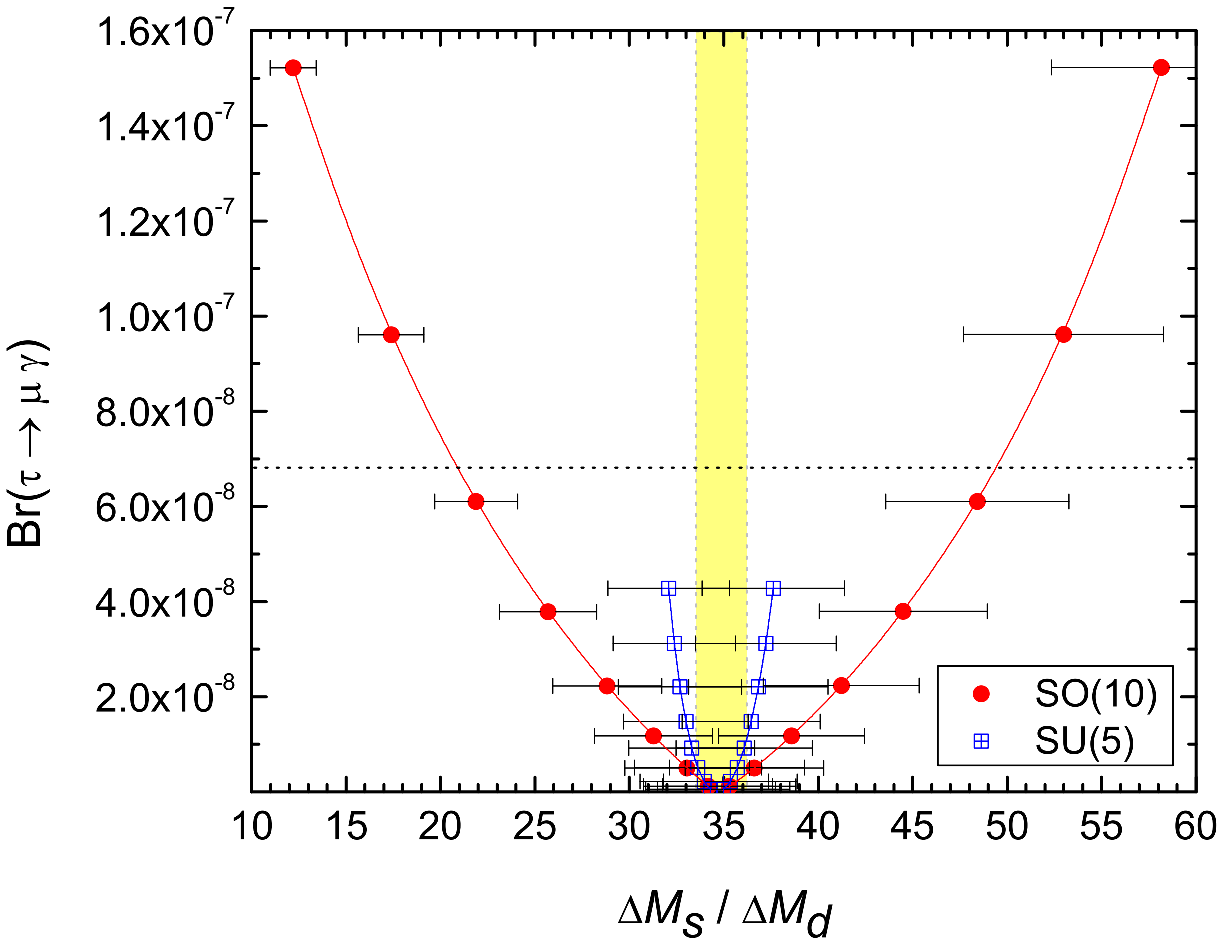
- Due to the quark lepton Unification, the $\tau \to \mu\gamma$ process also gets generated.

- We define $\delta_{23} = M^2_{23,L}/M^2$ and calculate the ΔM_{B_s} and the BR[$\tau \to \mu\gamma$].

- The plot is shown for $\xi = 1.23$ [$\xi \equiv \frac{f_{B_s}\sqrt{B_s}}{f_{B_d}\sqrt{B_d}}$]
  The JLQCD value: 1.23 ± 0.06.
- We vary δ_{23}: 0-0.8 [Phase : [0,2π]] to generate the plot.
  We show the maximum and minimum ratio.
- Experimental constraint on the ratio: 34.24-35.52.



- We now use the error of $\xi = 1.23 \pm 0.06$ [$\xi \equiv \frac{f_{B_s}\sqrt{B_s}}{f_{B_d}\sqrt{B_d}}$] to calculate the mass difference.



- **The origin of these mixings: $f\psi\psi\Delta$ ($16\,16\,\overline{126}$) will induce $m^2 f f^\dagger$ terms via RGEs.**
  f has flavor non-diagonal structure due to the Neutrino mixings.
  Similarly, Y_ν will also introduce flavor violation ($m^2 Y_\nu Y_\nu^\dagger$) via RGE's.

- **In the SU(5) case: the quark lepton unification and running up to the string scale/SO(10) scale will introduce flavor violation terms e.g. $\Delta M^{2E^c}_{ij} = V_{ti}\lambda_t^2 V^*_{tj} m^2$, $\Delta M^{2\bar{F}}_{ij} = m^2 Y_\nu Y_\nu^\dagger$ [$\lambda_\nu \bar{F} 1 F_H$].** **Raby, Hall, Barbieri,Hisano, Moroi,...**

- **It is also possible to have Pati-Salam scale below the GUT scale and quark lepton unification and the RGE effect on the scalar masses will introduce flavor violation.** **[Dutta, Deshpande, Keith,...]**

Collider Signal

- **The mSUGRA scenario: (Dark Matter allowed) Neutralino stau Coannihillation, focus point, A annihilation funnel.**
- **These features exist also in the non universal models.**
- **How to establish these regions?**
- **The low mass region is dominated by the neutralino stau coannihilation region.**
- **The signal has low energy taus. At the LHC the signal is : taus +jets +missing energy.**
- **How accurately can one establish the coannihilation region? Can one confirm that the relic density is not getting reduced by any other mechanism?**

Stau Neutralino Coannhilation and GUT scale

- In SUGRA models, the lightest stau seems to be naturally very close to the lightest neutralino mass especially for large $\tan\beta$.

- For example, the R- selectron ($\tilde{E}^c$) mass is related to the lightest neutralino ($\tilde{\chi}_1^0$) mass by the following relations at the electroweak scale:

$$m^2_{\tilde{E}^c} = m_0^2 + (6/5) f_1 m^2_{1/2} - \sin^2\theta_W M_W^2 \cos(2\beta)$$

$$m_{\tilde{\chi}_1^0} = (\alpha_1/\alpha_G) m_{1/2}$$

where $f_i = [1-(1+\beta_i t)^{-2}]/\beta_i, t = \ln(M_G/M_Z)^2$, β_1 is the $U(1)_Y$ β function coefficient (one loop), α_1 is the $U(1)_Y$ gauge coupling constant ($\times 5/3$) at the M_Z scale and α_G is the gauge coupling constant at M_G.

Stau Neutralino Coannhilation

- Numerically this gives e.g., for $\tan\beta = 5$

$$m^2_{\tilde{E}^c} = m_0^2 + 0.15 m^2_{1/2} + (37\,\mathrm{GeV})^2$$

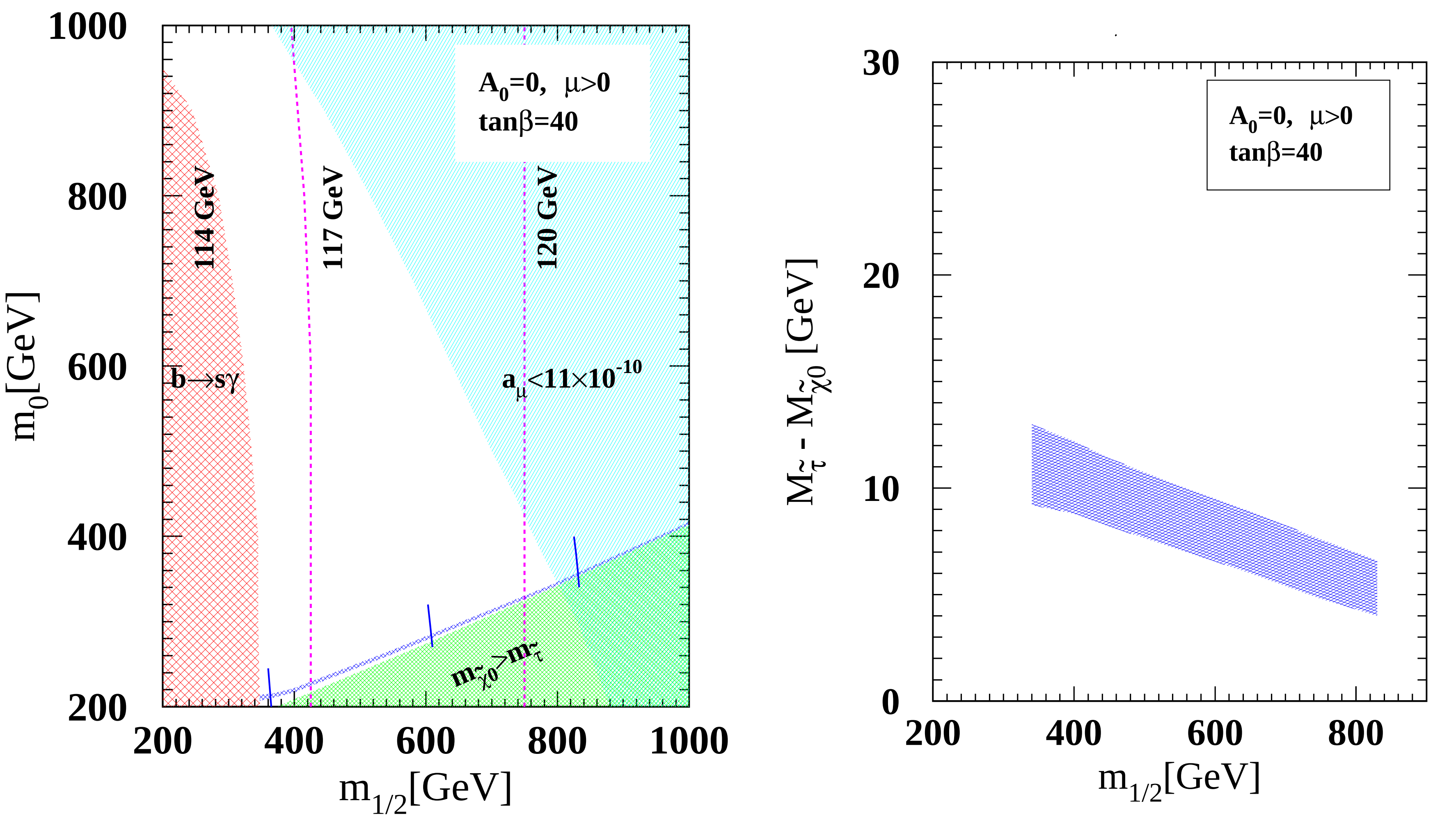
$$m^2_{\tilde{\chi}^0_1} = 0.16 m^2_{1/2}$$

- Thus for $m_0 = 0$, the mass of $\tilde{E}^c$ becomes degenerate with the $\tilde{\chi}^0_1$ at $m_{1/2} = 370$ GeV, i.e. co-annihilation effects roughly begin at $m_{1/2} \cong (350 - 400)$ GeV. (The numerical coefficients are determined by solving the renormalization group equations).

- For larger $m_{1/2}$, the near degeneracy is maintained by increasing m_0, and we get:
  a corridor in the $m_0 - m_{1/2}$ plane.

Narrow Coannihilation Region

$\Delta M \sim 5 - 15$ GeV

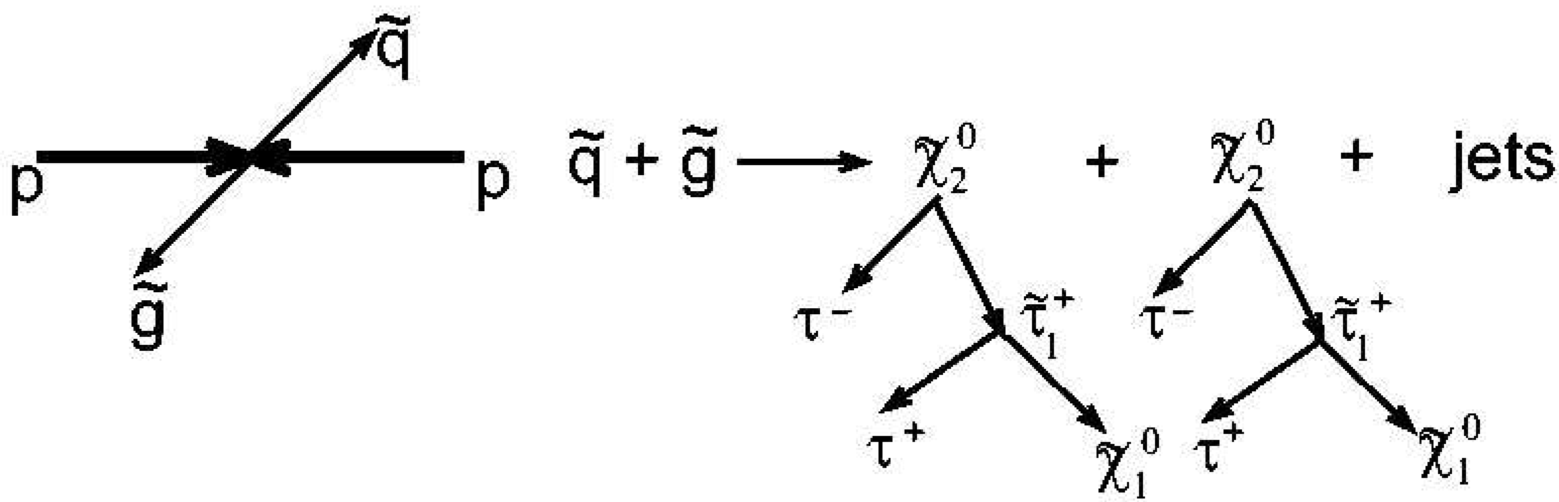


The (blue) vertical lines: ($\tilde{\chi}^0_1$-p cross-sections) (from left):
0.03 $\times 10^{-6}$ pb, 0.002 $\times 10^{-6}$ pb, 0.001 $\times 10^{-6}$ pb

Signals and Measurements at LHC

- Squark-gluino production cross section is very large.

- The Squark, Gluino decays, e.g.



- 4 τ (2 low energy and 2 high energy)+ jets+$\not{E}_T$.

- We choose: $m_{1/2}$ = 360 GeV, $\tan\beta = 40$, $\mu > 0$, $A_0 = 0$ and m_0: 210, 212, 215, 217, 220 (GeV).
Where: $M_{\tilde{\chi}_1^0}$: 144.2, $M_{\tilde{g}}$: 831, $M_{\tilde{u}_{R(L)}}$:740(765) (GeV),
$\Delta M(M_{\tilde{\tau}_1}$-$M_{\tilde{\chi}_1^0})$: 5.7, 7.6, 10.6, 12.5, 15.4 (GeV).

Signals and ...

- **Two different final states:**
  1) Two taus +2 jets +$\not{E}_T$; 2) three taus +1 jet +$\not{E}_T$.

- **We use ATLFAST MC and ISAJET event generator.**

- **Two observables :**
  (1) the number of OS—LS events ($N_{\mathrm{OS-LS}}$);
  (2) the peak position of the di-tau invariant mass $M_{\tau\tau}$ in OS—LS events.

- **We consider the SM $t\bar{t}$ background and develop cuts to reduce this background.**

- **fake effects : a jet may be misidentified as a tau. The fake rate we use is 1%.**
  The fake effect can be large since the SUSY cascade decays produce lots of jets.

Two tau $\not\!\!E_T$

Event selection:

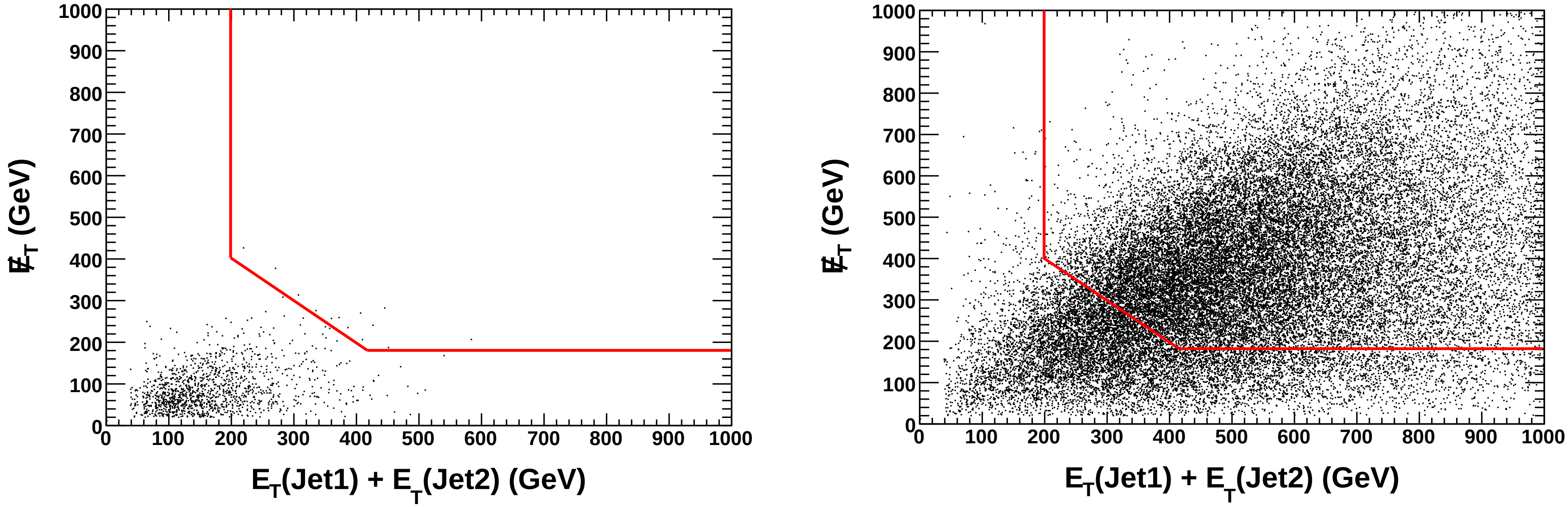
- The dominant background: $t\bar{t}$ pair production where each t decays: $t \to b\tau\nu$ to a final state of $\not\!\!E_T + 2b + 2\tau$. The additional τ may come from: $b \to c\tau\nu$.

- Choose two jets each with $E_T > 100$ and $\not\!\!E_T > 180\,\mathrm{GeV}$. Define $H_\mathrm{T} \equiv E_\mathrm{T}^\mathrm{jet1} + E_\mathrm{T}^\mathrm{jet2} + \not\!\!E_T$ to distinguish SUSY events from the top events and choose $H_\mathrm{T} > 600\,\mathrm{GeV}$.

- Require two reconstructed/identified τ's with ${p_T}^\mathrm{vis} > 20\,\mathrm{GeV}$ with one tau having ${p_T}^\mathrm{vis} > 40\,\mathrm{GeV}$. Reconstruction/identification efficiency is 50%.

$\not\!\!E_T$ vs $E_{\mathrm{T}}^{\mathrm{jet1}} + E_{\mathrm{T}}^{\mathrm{jet2}}$

- $t\bar{t}$(left) vs SUSY(right) Background; ΔM=10.6 GeV.



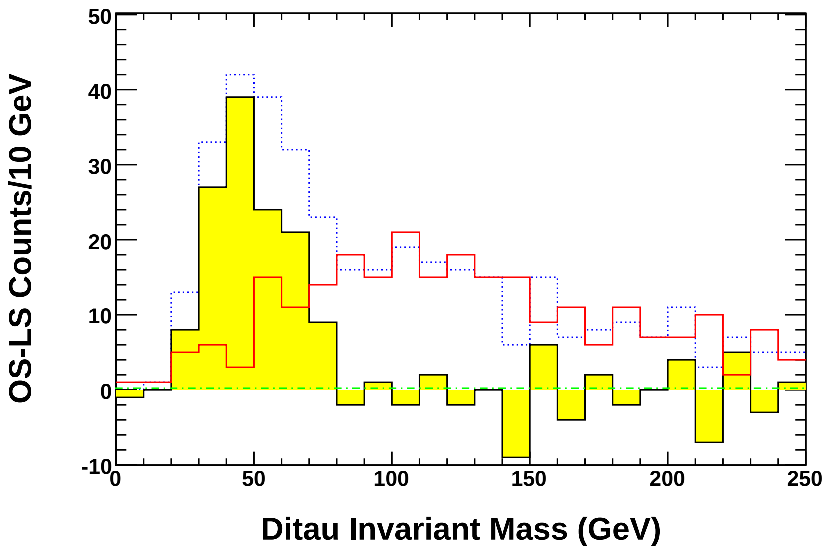
Require $E_{\mathrm{T}}^{\mathrm{jet1}} > 100\,\mathrm{GeV}$, $E_{\mathrm{T}}^{\mathrm{jet2}} > 100\,\mathrm{GeV}$,
$\not\!\!E_T > 180\,\mathrm{GeV}$, and $H_{\mathrm{T}} \equiv E_{\mathrm{T}}^{\mathrm{jet1}} + E_{\mathrm{T}}^{\mathrm{jet2}} + \not\!\!E_T >$ 600 GeV.

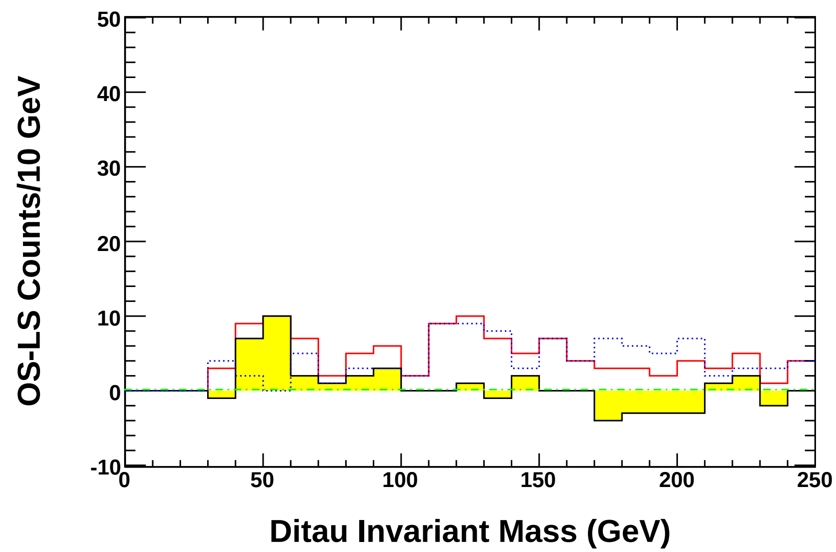
- Negligible $t\bar{t}$ background.

$M_{\tau\tau}^{\text{vis}}$

- **An invariant mass ($M_{\tau\tau}$) for each of possible combinational pairs of two τ's is calculated and categorized as opposite sign (OS) or like sign (LS) charge combinations. Example: $\Delta M = 10.6$ GeV (10 fb^{-1} luminosity):**

$p_T^{\text{vis}}(\tau) > 20$ GeV(Left); $p_T^{\text{vis}}(\tau) > 40$ GeV(Right);



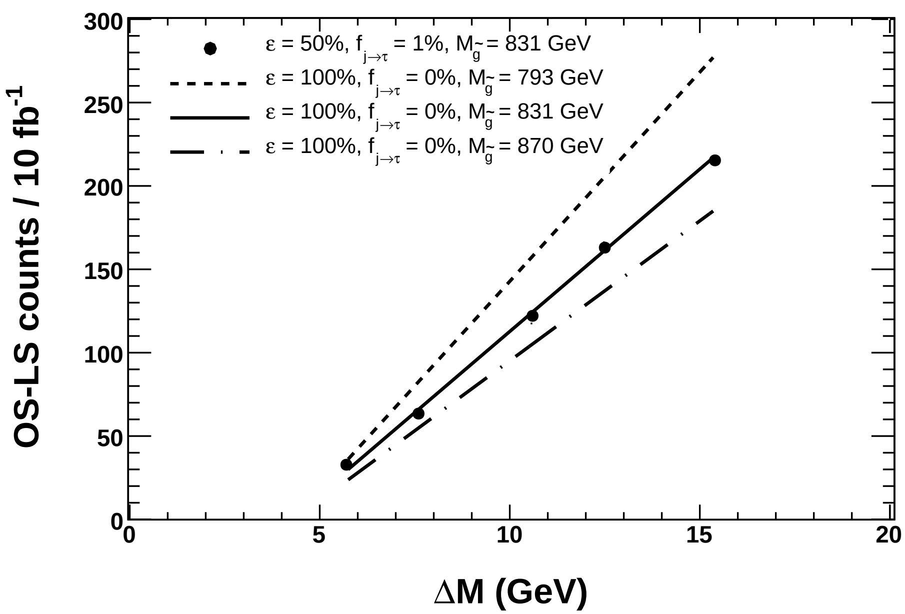


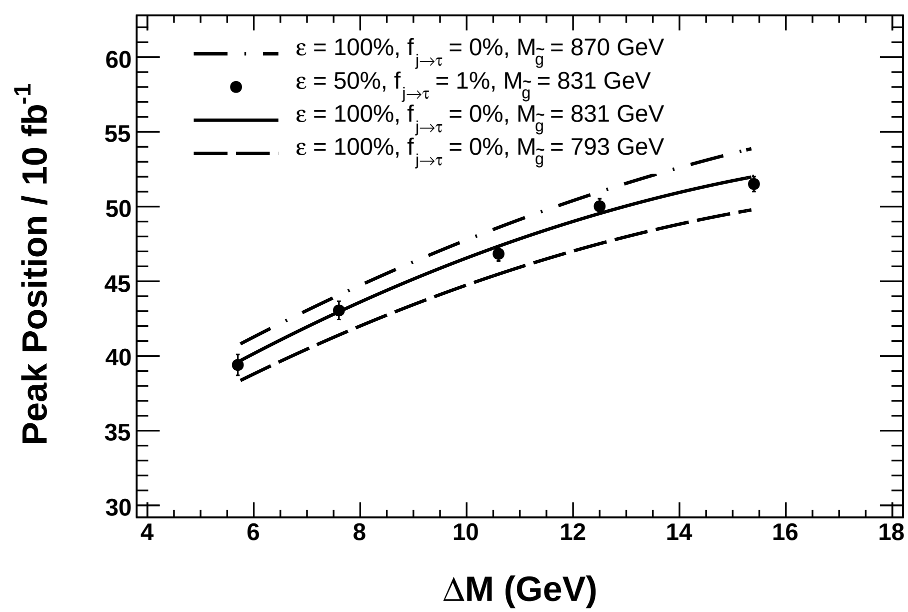
- **The expected end point position: 78.7 (GeV).**

- **The peak and the end points are due to $\tilde{\chi}_2^0 \to \tau\tilde{\tau}_1$.**

ΔM Dependence

- **The OS—LS counts change as a function of ΔM.**
- **The peak of the $M_{\tau\tau}^{\text{vis}}$ distributions of OS—LS shifts as a function of ΔM.**

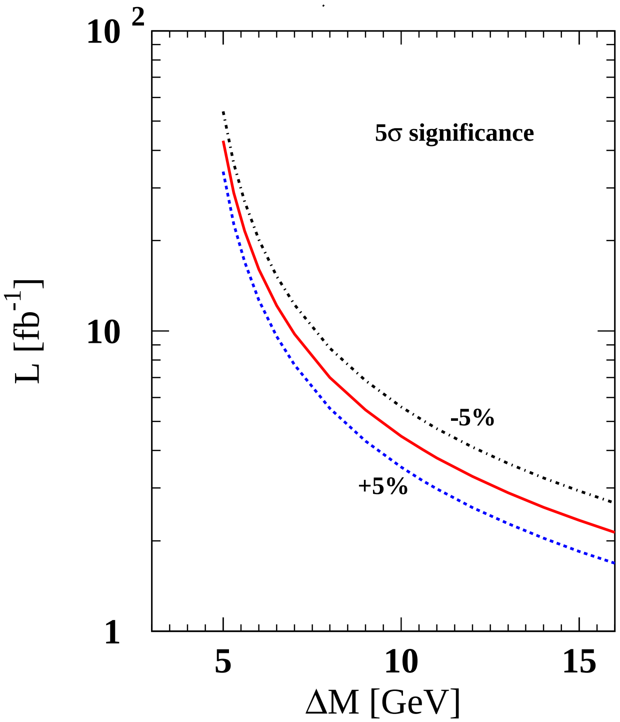




- **The gluino mass varies by 5%.**
- **The “fake” effect is negligible.**

Counting OS-LS pairs

- The 5σ significance reach for the coannihilation region as a function of luminosity (the gluino mass is varied by 5%).



- The error for ΔM measurement using peak position is about 20% for 5-15 GeV (10 fb^{-1} of luminosity). Comparison: 10% (ILC). [Arnowitt, Dutta, Kamon, Kolev, Toback,'05].

Conclusion

- The minimal renormalizable SO(10) models with 10, 126 and 120 Higgs multiplets explains the fermion masses and mixing angles.

- It is possible to reconcile the CKM model of CP violation with neutrino predictions.

- In the new model the proton decay rate is suppressed by a suitable choice of the texture.

- This model also gives rise to a large amount of lepton flavor violation.

- Recent results of $B_s^0 - \bar{B}_s^0$ mass difference allowes the flavor structure of this model.

Conclusion...

- Collider signals for small SUSY masses involves stau neutralino coannihalation region where the stau mass is very close to the neutralino mass.
- The key observables are:
  OS-LS counts and the peak of the ditau mass distribution as a function of ΔM.
- The observables are not affected by ”fake” effects.
- It is possible to have 5σ discovery in certain regions of the coannihilation channel even for 5 fb^{-1} of luminosity.
- The uncertainty in the ΔM measurement is about 20% (LHC), 10% (ILC).