SUSY Lepton flavor Violating Signals at the Photon Collider

Mirco Cannoni

Università di Perugia e Istituto Nazionale di Fisica Nucleare
Sezione di Perugia

Firenze, September 14, 2007
ILC Physics in Florence

1. INTRODUCTION

1. INTRODUCTION

2. PHOTON BEAMS

3. $\gamma\gamma \to \ell\ell'$ WITH $\ell \neq \ell'$ AND $\ell, \ell' = e, \mu, \tau$, (ONE LOOP ORDER) IN THE SUSY SEE-SAW SCENARIO

1. INTRODUCTION
2. PHOTON BEAMS
3. $\gamma\gamma \to \ell\ell'$ WITH $\ell \neq \ell'$ AND $\ell, \ell' = e, \mu, \tau$, (ONE LOOP ORDER) IN THE SUSY SEE-SAW SCENARIO
4. $\gamma\gamma \to \mu\tau b\bar{b}$: HIGGS-MEDIATED LFV AT LARGE $\tan\beta$

1. Introduction
2. Photon Beams
3. $\gamma\gamma \to \ell\ell'$ with $\ell \neq \ell'$ and $\ell, \ell' = e, \mu, \tau$, (one loop order) in the SUSY see-saw scenario
4. $\gamma\gamma \to \mu\tau b\bar{b}$: Higgs-mediated LFV at large $\tan\beta$
5. Summary

Outline

1. Introduction
2. Photon Beams
3. $\gamma\gamma \to \ell\ell'$ with $\ell \neq \ell'$ and $\ell, \ell' = e, \mu, \tau$, (one loop order) in the SUSY see-saw scenario
4. $\gamma\gamma \to \mu\tau b\bar{b}$: Higgs-mediated LFV at large $\tan\beta$
5. Summary

Motivations

- Neutrino masses $\neq 0$ hint to lepton flavour violation (LFV) $\ell \to \ell' + \gamma$. However in the standard Model (SM) such processes are strongly suppressed: $Br \approx \mathcal{O}(10^{-40})$
- $Br(\mu \to e\gamma) < 1.2 \times 10^{-11}$ $Br(\tau \to e\gamma) < 3.9 \times 10^{-7}$
  $Br(\tau \to \mu\gamma) < 6.8 \times 10^{-8}$
- New Physics is needed to have rates which would be detectable. The SUSY see-saw mechanism provides sources of LFV potentially observable
- LFV reaction $\gamma\gamma \to \ell\ell'$ with $\ell \neq \ell'$ and $\ell, \ell' = e, \mu, \tau$, (one loop order) in the SUSY see-saw scenario [M. C., C. Carimalo, W. Da Silva and O. Panella, Phys. Rev. D **72**, 115004 (2005)]
- Study the lepton flavor violating reaction $\gamma\gamma \to \mu\tau b\bar{b}$ through Higgs-madieted LFV at large $\tan\beta$ [M. C., P. Paradisi and O. Panella, in preparation]

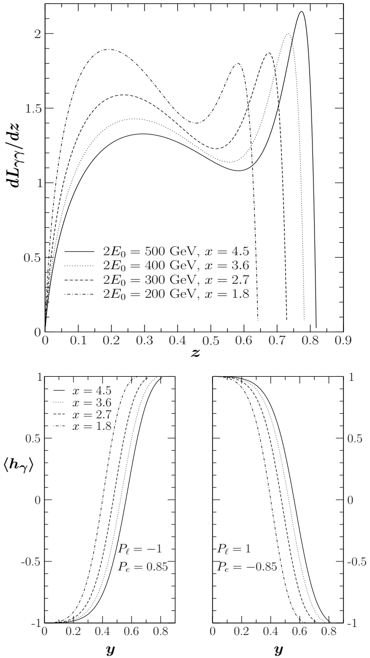
Outline

High Energy photon collisions

- High energy photons beams will be obtained from Compton back-scattered (CB) low energy laser photons with energy ω_0 off high energy electron beams with energy E_0.
- High energy photon beams *will not be* monochromatic but *will present* instead an energy spectrum, mainly determined by the Compton cross section, up to a maximum energy $y_m E_0$, where $y_m = x/(x+1)$ with $x = 4E_0\omega_0/m_e^2$.
- Full simulations show that there will be also a low energy broad peak (multiple compton scattering and beamstrahlung)
- However the high energy peak is well described by the analytical Compton spectrum

Ginzburg, Kotkin, Serbo and Telnov, Ginzburg, Kotkin, Panfil, Serbo and Telnov

Differential CB luminosity



- The high energy peak is almost independent from technological details and ≈ by the product of two CB spectra ($y_{1,2} = E_{\gamma_{1,2}/E_0}$):

$$\frac{dL^{CB}_{\gamma\gamma}}{dy_1\, dy_2} = F_c(x, y_1)\, F_c(x, y_2)$$

- The theoretical differential luminosity spectrum is:

$$\frac{dL^{CB}_{\gamma\gamma}}{dz} = 2z \int_{-\ln\frac{y_m}{z}}^{\ln\frac{y_m}{z}} d\eta F_c(x, ze^{+\eta}) F_c(x, ze^{-\eta})$$

$(z = \sqrt{y_1 y_2} = W_{\gamma\gamma}/2E_0 = \sqrt{s_{\gamma\gamma}/s_{ee}}$ and $\eta = \ln\sqrt{y_1/y_2})$

- Photons also show an helicity spectrum. In the high energy peak ($y \approx y_m$) photons have a high degree of circular polarization $P_\gamma = -P_\ell = P_{laser}$

Normalization of Luminosity spectrum

- $\gamma\gamma$ peak luminosities $L_{\gamma\gamma}(z > 0.8 z_m)$ of TESLA

$\sqrt{s_{ee}} = 2E_0$	$L_{\gamma\gamma}$ 10^{34} cm^{-2} s^{-1}	$L_{\gamma\gamma}$ fb^{-1}yr^{-1}
200 GeV	19.1	130
500 GeV	1.15	340
800 GeV	1.7	530

Badelek *et al.* [ECFA/DESY Photon Collider Working Group], "TESLA TDR, Part VI, Chapter 1: Photon collider at TESLA,

- We normalize the ideal spectrum to TESLA luminosities. T he *effective* cross is:

$$\sigma^{effective} = \int_{z_{min}}^{z_{max}} dz \frac{dL_{\gamma\gamma}^{norm}}{dz} \sigma(W_{\gamma\gamma})$$

- The total number of events is given by

$$N_{events} = L_{\gamma\gamma} \times \sigma^{effective}$$

Outline

SUSY SEE-SAW MECHANISM

- The superpotential W contains three $SU(2)_L$ singlet neutrino superfields N_i with the following couplings:

$$W = (Y_\nu)_{ij}\varepsilon_{\alpha\beta}H_2^\alpha N_i L_j^\beta + \frac{1}{2}(M_R)_i N_i N_i.$$

  H_2 is a Higgs doublet superfield, L_i are the $SU(2)_L$ doublet lepton superfields, Y_ν is a Yukawa coupling matrix and M_R is the $SU(2)_L$ singlet neutrino mass matrix.

- With the additional Yukawa couplings and the new mass scale (M_R) the RGE evolution from the GUT scale down to M_R induce *off-diagonal* matrix elements in charged sleptons mass matrix $(m^2_{\tilde{L}})_{ij}$.

SUSY SEE-SAW MECHANISM

- In the one loop approximation the off-diagonal elements of the charged sleptons mass matrix are [Borzumati,Masiero, Hisano]

$$(m^2_{\tilde{L}})_{ij} \simeq -\frac{1}{8\pi^2}(3+a_0^2)m_0^2(Y_\nu^\dagger Y_\nu)_{ij}\ln\left(\frac{M_{GUT}}{M_R}\right).$$

  where a_0 is a dimensionless parameter appearing in the matrix of trilinear mass terms $A_\ell = Y_\ell a_0 m_0$ contained in V_{soft}.
- These off diagonal matrix elements can be potentially large because they are not directly related to the mass of the light neutrinos, but only through the seesaw relation $m_\nu \simeq m_D^2/M_R = v^2 Y_\nu^2/M_R$.

Two generation model

- Assume for the mass matrix of the charged left-sleptons (and sneutrinos):

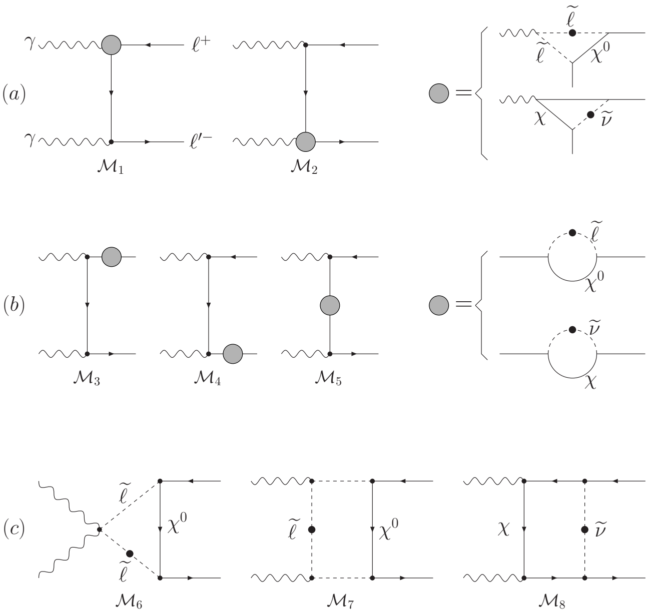
$$\widetilde{m}_L^2 = \begin{pmatrix} \widetilde{m}^2 & \Delta m^2 \\ \Delta m^2 & \widetilde{m}^2 \end{pmatrix},$$

with eigenvalues: $\widetilde{m}_\pm^2 = \widetilde{m}^2 \pm \Delta m^2$ and maximal mixing.

- After diagonalization of the mass matrix the LFV propagator for a scalar line is

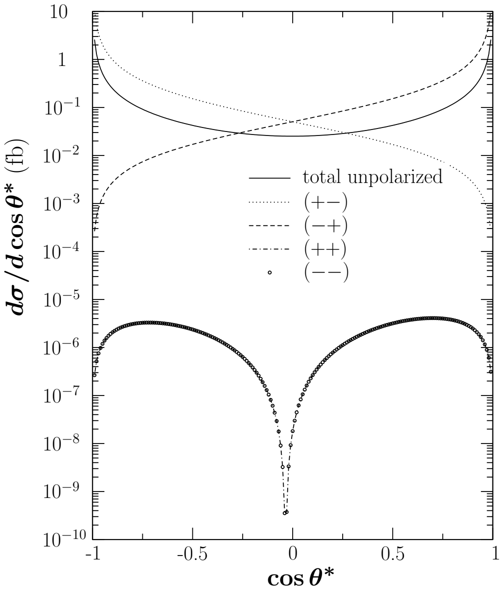
$$\langle \tilde{\ell}_i \tilde{\ell}_j^\dagger \rangle_0 = \frac{i}{2}\left(\frac{1}{p^2 - \widetilde{m}_+^2} - \frac{1}{p^2 - \widetilde{m}_-^2}\right) = i\frac{\Delta m^2}{(p^2 - \widetilde{m}_+^2)(p^2 - \widetilde{m}_-^2)}$$

- The quantity $\delta_{LL} = \Delta m^2 / \widetilde{m}^2$ is the dimension-less parameter that controls the magnitude of the LFV effect.
- Our propagator corresponds to the one in the Mass Insertion Approximation (MIA) when one assumes equal diagonal mass squared (good at EW scale due to degeneracy of sleptons) and $\Delta m^2 \ll \widetilde{m}^2$ which is necessary for the expansion in power of δ_{LL}
- This approach allows us to study the signal in a quite model-independent way by means of scans in the parameter space – the $\widetilde{m}, \delta_{LL}$ plane – which is already constrained by the experimental bounds of radiative lepton decay processes.



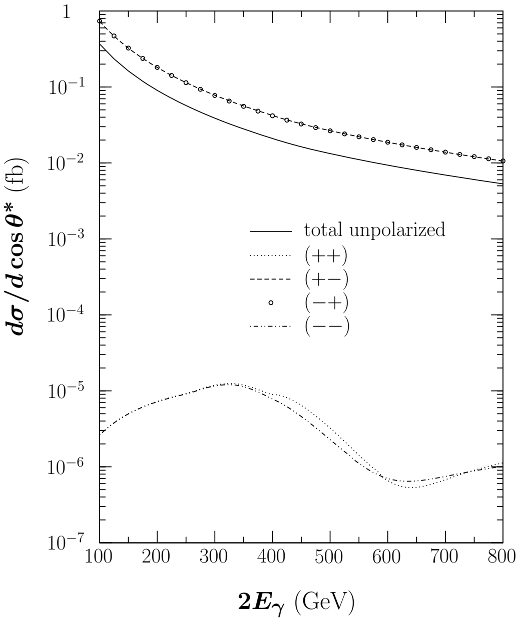
- (a) Penguin
- (b) Self-energy
- (c) Sea-gull and Box diagrams
- The full black circle stands for a LFV propagator

Monochromatic angular distributions



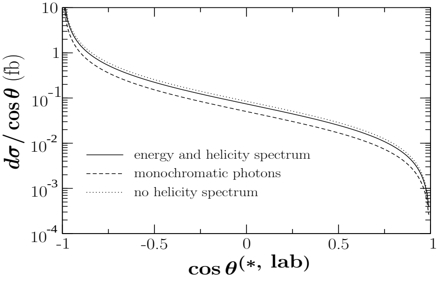
- $\mathcal{M}^{(+,-)}$ peaked in the backward direction $\mathcal{M}^{(-,+)}$ peaked in the forward direction ($J_z = \pm 2$)
- Dominance of diagrams with exchange of a massless lepton in t and u channel
- M^{++} and M^{--} ($J_z = 0$) are suppressed !
- The values of the masses are: $M_1 = 100$, $M_2 = 200$, $\langle \widetilde{m}_\ell \rangle = 150$ GeV, $\Delta m^2 = 6000$ GeV^2, $\sqrt{s_{\gamma\gamma}} = 128$ GeV

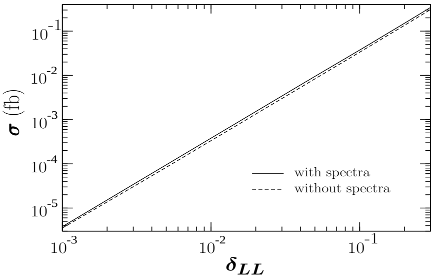
Monochromatic total cross-sections



- Configurations with opposite helicity photons $\sigma_{(+,-)}$ and $\sigma_{(-,+)}$ $(J_z = \pm 2)$ in the initial state dominate the signal.
- Those with same helicity photons $(J_z = 0)$ give a negligible cross sections
- The values of the masses are: $M_1 = 100$, $M_2 = 200$, $\langle \widetilde{m}_\ell \rangle = 150$ GeV, $\Delta m^2 = 6000$ GeV^2

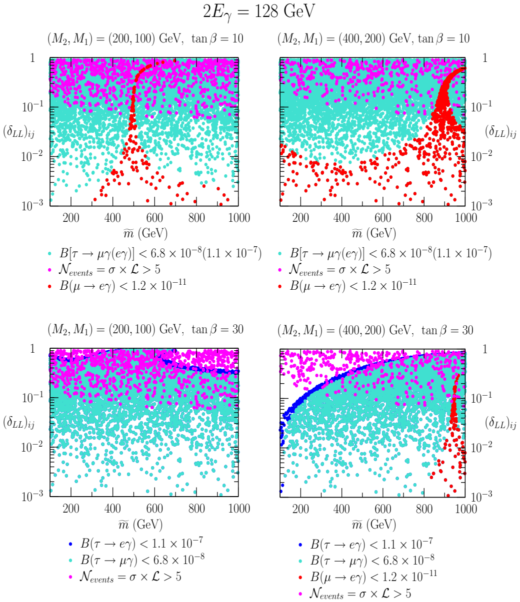
Effect of spectra





- The effect of photon spectra is small: use monochromatic photons at the maximum energy

Scan of the SUSY parameter space $(\widetilde{m}, \delta_{LL})$



- $\widetilde{m}$ and δ_{LL} varied freely, for fixed value of gaugino masses
- Cyan region ($\approx$ whole plane) is allowed by $Br(\tau \to \mu\gamma) < 6.8 \times 10^{-}$ $Br(\tau \to e\gamma) < 3.9 \times 10^{-7}$
- Red region is allowed by $Br(\mu \to e\gamma) < 1.2 \times 10^{-11}$
- magenta region is where a PC can provide a positive signal of LFV: $N_{events} = L_{\gamma\gamma} \times \sigma_{signal} > 5$
- Little overlap (tail in the $\delta_{LL} \approx 1$ part). Observation in the $(e\mu)$ channel is essentially excluded by the non observation of the $\mu \to e\gamma$ decay. The LFV signal is observabl only in the $e\tau$ or $(\mu\tau)$ channels.

Standard Model Background

- The $e\mu$ final state almost completely excluded by the strong bounds from the non observation of the radiative decay $\mu \to e\gamma$. Thus weconsider signals with τ's

$$(a)\ \gamma\gamma \to \tau^-\tau^+ \to \tau^-\nu_e\bar{\nu}_\tau e^+$$

$$(b)\ \gamma\gamma \to W^{-*}W^{+*} \to \tau^-\bar{\nu}_\tau\, e^+\nu_e$$

$$(c)\ \gamma\gamma \to e^+e^-\tau^+\tau^-$$

with similar processes for the production of $\mu\tau$ pairs.

- The signal has two back-to-back leptons *without missing transverse momentum and energy*.
- The angular cut $|\cos(\theta)| < 0.9$ ($\theta < 25.8°$) applied to the signal is also applied to the background.
- We impose the back-to-back condition on the background processes requiring $180° - \theta_{\ell\ell'} < 5°$.
- Leptons are required to have energy close to E_γ, at least 85% of the maximum photons energy $E^\gamma_{max} = y_{max}E_0$.

SM Background

$2E_0$ (GeV)	$\gamma\gamma \to \tau\tau \to \tau e \nu \bar{\nu}$	$\gamma\gamma \to WW \to e\tau\nu\bar{\nu}$	$\gamma\gamma \to \tau\tau ee$
200	0.58 fb 1.49×10^{-6} fb	2.3×10^{-1} //	36.7 pb 4.4×10^{-2} fb
300	3.1 fb 16.3×10^{-6} fb	0.48 pb //	38.9 pb 3.7×10^{-2} fb
400	4.9 fb 3.9×10^{-4} fb	0.69 pb 2.1×10^{-2}	39.5 pb 2.9×10^{-2} fb
500	6.1 fb 9.7×10^{-4} fb	0.77 pb 1.0×10^{-1}	39.9 pb 2.4×10^{-2} fb

$$SS = \frac{\mathcal{L}\sigma^{Sig}_{cut}}{\sqrt{\mathcal{L}\sigma^{BG}_{cut}}} \geq 3$$

This implies (with simulated annual luminosity for TESLA):

$$\sqrt{s_{ee}} = 200\,\mathrm{GeV} \Rightarrow \sigma^{Sig}_{cut} > 5.4 \times 10^{-2}\,\mathrm{fb} \Rightarrow \delta_{LL} \gtrsim 10^{-1}$$

$$\sqrt{s_{ee}} = 500\,\mathrm{GeV} \Rightarrow \sigma^{Sig}_{cut} > 2.5 \times 10^{-2}\mathrm{fb} \Rightarrow \delta_{LL} \gtrsim 10^{-1}$$

Outline

1. Introduction

2. Photon Beams

3. $\gamma\gamma \to \ell\ell'$ with $\ell \neq \ell'$ and $\ell, \ell' = e, \mu, \tau$, (one loop order) in the SUSY see-saw scenario

4. $\gamma\gamma \to \mu\tau b\bar{b}$: Higgs-mediated LFV at large $\tan\beta$

5. Summary

Parametrization of Higgs-mediated LFV

- The presence of a non zero μ term, coupled with SUSY breaking, induce non-holomorphic Yukawa interactions for quarks and leptons. If there is a source of LFV among the sleptons, Higgs-mediated LFV is unavoidable.
- In the mass-eigenstate basis for both leptons and Higgs bosons, the effective LFV interactions are described by the four dimension operators:

$$-\mathcal{L} \simeq (2G_F^2)^{\frac{1}{4}} \frac{m_{l_i}}{c_\beta^2} \left(\Delta_L^{ij} \bar{l}_R^i l_L^j + \Delta_R^{ij} \bar{l}_L^i l_R^j \right) \times \left(c_{\beta-\alpha} h^0 - s_{\beta-\alpha} H^0 - i A^0 \right)$$

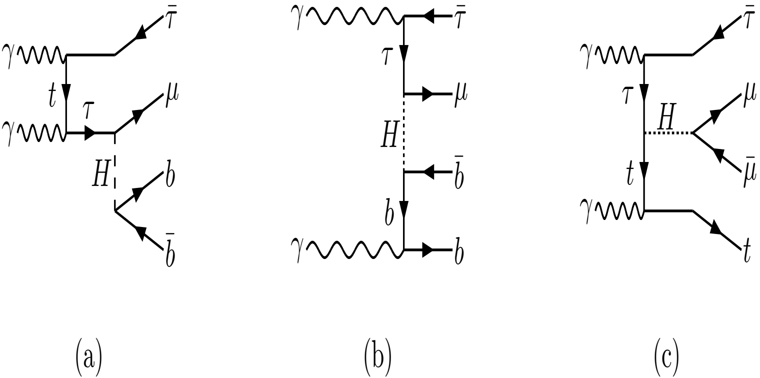
- Δ^{ij} terms are induced at one loop level by the exchange of gauginos and sleptons, provided a source of slepton mixing. In the MI approximation, $\Delta_{L,R}^{ij}$ are given by

$$\Delta_L^{ij} = -\frac{\alpha_1}{4\pi} \mu M_1 \delta_{LL}^{ij} m_L^2 \left[I^{'}(M_1^2, m_R^2, m_L^2) + \frac{1}{2} I^{'}(M_1^2, \mu^2, m_L^2) \right]$$

$$\Delta_R^{ij} = \frac{\alpha_1}{4\pi} \mu M_1 m_R^2 \delta_{RR}^{ij} \left[I^{'}(M_1^2, \mu^2, m_R^2) - (\mu \leftrightarrow m_L) \right]$$

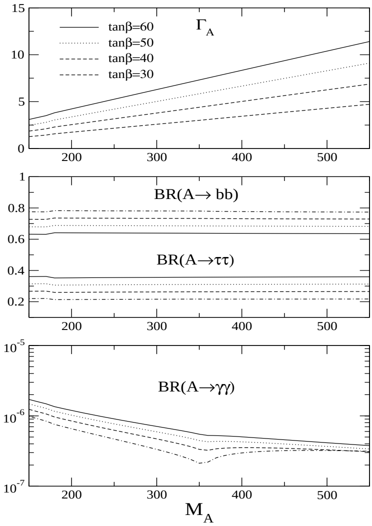
- depend only on the ratio of the susy mass scales and they do not decouple for large m_{SUSY} We treat the $\Delta_{L,R}^{ij}$ terms in a model independent way. $\Delta_{L,R}^{ij}$ parameters, their contributions to LFV processes do not exceed the experimental bounds.

Diagrams for $\gamma\gamma \to \mu\tau b\bar{b}$



(c): "$\mu - \tau$" fusion is the LFV analog of "$\tau - \tau$" fusion channel which is enhanced for large $\tan\beta$ [Choi, Kalinowski, Lee, Muhlleitner, Spira, Zerwas]

A/H DECAY WIDTHS AND BRANCHING RATIOS



-

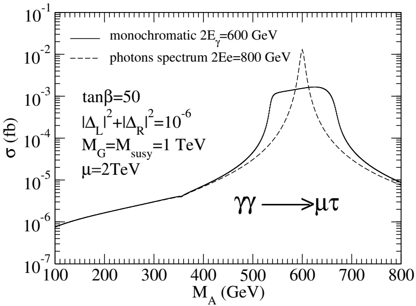
$$\Gamma(A \to \tau\mu) = \frac{\alpha_2}{8\pi} \frac{M_A}{M_W^2} m_\tau^2 t_\beta^4 (|\Delta_L|^2 + |\Delta_R|^2)$$

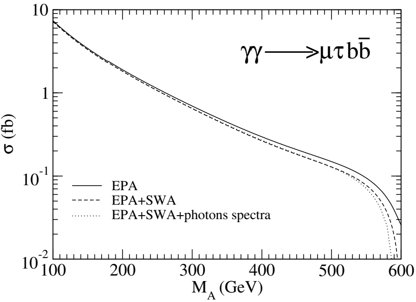
-

$$\mathcal{B}(A \to \mu^+\tau^-) = t_\beta^2 \, (|\Delta_L|^2 + |\Delta_R|^2)\mathcal{B}(A \to \tau^+\tau^-)$$

- For H (or h) there is a factor $(\mathrm{c}_{\beta-\alpha}/\mathrm{s}_\alpha)^2$ [or $(\mathrm{s}_{\beta-\alpha}/\mathrm{c}_\alpha)^2$]. $\mathcal{B}(A \to \mu\tau)$ can reach values of order 10^{-4}.

$\gamma\gamma \to \mu\tau$ AND $\gamma\gamma \to \mu\tau b\bar{b}$





- Resonant s-channel loop production

$$\sigma = 8\pi \frac{\Gamma(A \to \gamma\gamma)\Gamma(A \to \tau\mu)}{(S_{\gamma\gamma} - M_A^2)^2 + (\Gamma_A M_A)^2}(1 + \lambda_1\lambda_2)$$

- "$\mu - \tau$" fusion with the Equivalent Particle Approximation

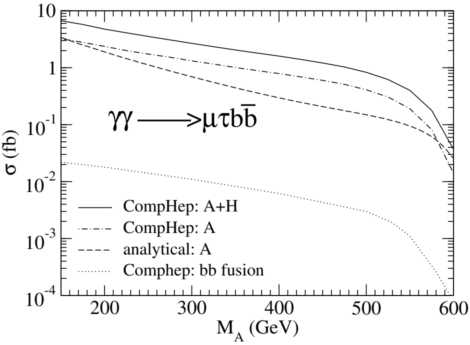
$$\sigma = \int dxdy P_{\gamma/\mu}(x) P_{\gamma/\tau}(y)$$
$$4\pi \frac{\Gamma(A \to \tau\mu)\Gamma(A \to b\bar{b})}{(S_{\mu\tau} - M_A^2)^2 + (\Gamma_A M_A)^2}$$

$P_{\gamma/l}(x)$ are photon's splitting functions

$$P_{\gamma\ell}(x) = \frac{\alpha}{2\pi}[x^2 + (1-x)^2] \log\left(\frac{\mu_F^2}{m_\ell^2}\right)$$

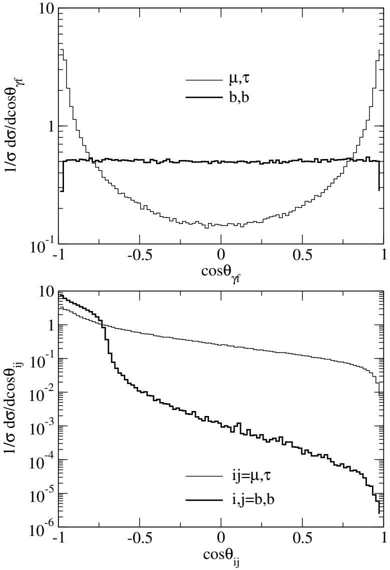
where the factorization scale is taken to be $\mu_F = M_A$.

Signal cross section



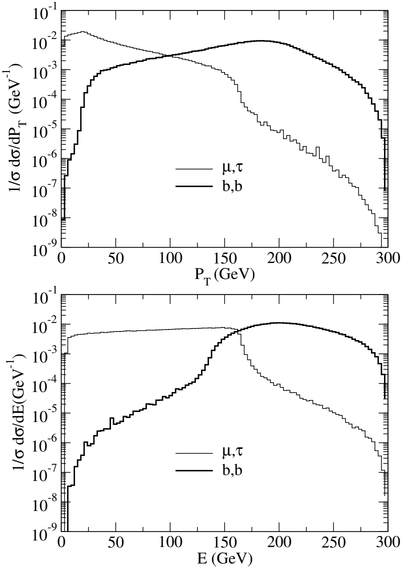
- The analytical formulas give the correct order of magnitude of the cross section
- In CompHEP all the diagrams are considered: the interference with the same diagrams with H give a factor of two in the cross section,
- “b-b fusion”, give a cross section two order of magnitude smaller because diagrams with the b attached to a photon line bring a charge factor $(1/3)^2$.

Angular distributions



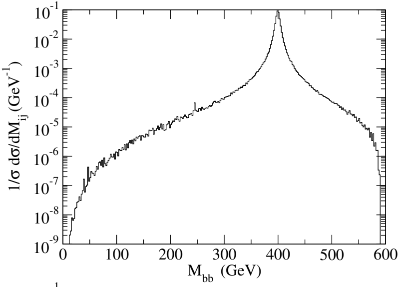
- $M_A \simeq M_H = 400$ GeV, $\tan\beta = 50$, $|\Delta_L|^2 + |\Delta_R|^2 = 10^{-6}$ and the other parameters as before.
- mild cut on leptons and jets for detector acceptance
- Distribution is almost flat for the quarks, peaked along the collision axis for the leptons.
- cosine of the angle among the leptons and among the quarks: both are peaked at -1, thus both the particles and the jets will be separated being back-to-back.

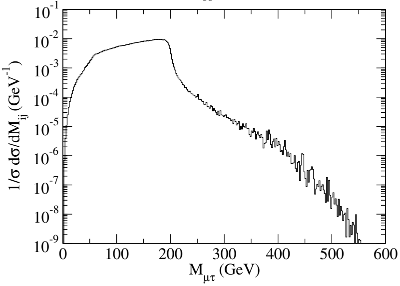
Transverse momentum and energy distributions



- Leptons have low p_T, the quarks have very high transverse momentum and energy peaking around $M_A/2$.
- A cut $p_{T_j} \geq 30$ GeV can be applied to the jets to suppress backgrounds without decreasing the signal cross section.

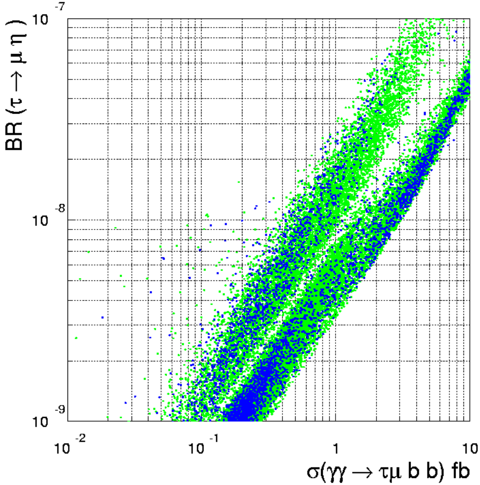
Invariant mass ditributions





- the distribution of mass for the bb pair is peaked at the Higgs mass
- that for the $\mu\tau$ pair at $M_A/2$.

Constraints from low energy flavor physics



- $(\mu, M_1, M_2, M_{\tilde{q}}, M_{\tilde{g}}, M_{\ell_L}, M_{\ell_R}) <$ 5TeV and $\tan\beta < 60$. Green dots: points of the parameter space satisfying all the constraints
- Blue dot: fulfill also $Br(\tau \to \mu\gamma) < 5 \times 10^{-9}$ and $Br(B_s \to \mu^+\mu^-) < 5 \times 10^{-9}$

Outline

Conclusions

1. In the range $\sqrt{s_{ee}} \approx 200 - 500$ GeV the cross section of the signal is $\sigma(\gamma\gamma \to \ell\ell') \approx \mathcal{O}(10^{-1} - 10^{-2})$ fb, (sparticle masses $\approx 90 - 200$ GeV) i.e. a light SUSY spectrum somehow hinted to by fits on standard model parameters and SUSY benchmark points.
2. Observation of $\gamma\gamma \to e\tau$, $(\mu\tau)$ is not excluded by present bounds on the radiative lepton decays $\tau \to e\gamma$, $\tau \to \mu\gamma$. However a $\delta_{LL} = \Delta m^2/\widetilde{m}_\ell^2 \approx \mathcal{O}(10^{-1})$ is required, (possible only within some specific models of the SUSY see-saw framework).
3. The $e\mu$ final state is almost excluded by $Br(\mu \to e\gamma) \leq 1.2 \times 10^{-11}$, four orders of magnitude smaller than $Br(\tau \to e\gamma)$, $Br(\tau \to \mu\gamma)$.
4. The heavy Higgs madiated LFV process $\gamma\gamma \to \mu\tau b\bar{b}$ at large $\tan\beta$ and heavy susy spctrum has large cross section!