Neutralino contributions to Dark Matter, LHC and future Linear Collider searches

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PLATON FORTRAN codes from http://dtp.physics.auth.gr

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•Neutralinos: very plausible DM components.
In addition to their astrophysical signatures, we need to study their LHC and LC production properties . Only then, we will be certain…

•An important **indirect** DM neutralino signature comes from a continuous γ-spectrum arising from $\tilde{\chi}_i^0 \tilde{\chi}_j^0 \to \gamma ...$

•Great if sharp discrete photons are also observed from

$$\tilde{\chi}_i^0 \tilde{\chi}_j^0 \to \gamma\gamma \ , \gamma Z \ , \gamma + \text{higgs}$$

•But then important to study reverse neutralino production at the LC

$$e^- e^+ \to \tilde{\chi}_i^0 \tilde{\chi}_j^0 \ , \quad \gamma\gamma \to \tilde{\chi}_i^0 \tilde{\chi}_j^0$$

•or the LHC processes

$$q\bar{q} \to \tilde{\chi}_i^0 \tilde{\chi}_j^0 \ , \quad gg \to \tilde{\chi}_i^0 \tilde{\chi}_j^0$$

$$q\bar{q} \to \tilde{\chi}_i^0 \tilde{g} \ , \quad gq \to \tilde{\chi}_i^0 \tilde{q}_{L,R} \ , \quad q\bar{q}' \to \tilde{\chi}_i^0 \tilde{\chi}_a^{\pm} \ , \quad gg \to \tilde{\chi}_i^0 \tilde{g}$$

$$\tilde{\chi}_i^0 \tilde{\chi}_j^0 \to \gamma\gamma \ , \gamma Z \ , \ gg$$

$$e^- e^+ \to \tilde{\chi}_i^0 \tilde{\chi}_j^0 \ , \quad \gamma\gamma \to \tilde{\chi}_i^0 \tilde{\chi}_j^0$$

$$q\bar{q} \to \tilde{\chi}_i^0 \tilde{\chi}_j^0 \ , \quad gg \to \tilde{\chi}_i^0 \tilde{\chi}_j^0$$

$$q\bar{q} \to \tilde{\chi}_i^0 \tilde{g} \ , \ gq \to \tilde{\chi}_i^0 \tilde{q}_{L,R} \ , \ q\bar{q}' \to \tilde{\chi}_i^0 \tilde{\chi}_a^\pm \ , \ gg \to \tilde{\chi}_i^0 \tilde{g}$$

•Al results in MSSM. Green processes studied to complete 1-loop, while magenta to tree level including 1-loop leading ln and $\ln^2$ terms.

•1-loop processes are so complicated, that cannot be written explicitly. FORTRAN codes are therefore released valid for any set of real MSSM parameters at the EW scale.

•Neutralino fermionic antisymmetry, and γγ or $g_a g_a$ bose statistics are instrumental for simplifying the calculation; (a=gluon color index) .

$$\tilde{\chi}_i^0(\lambda_1)\tilde{\chi}_j^0(\lambda_2) \to \gamma(\mu_1)\gamma(\mu_2) \Rightarrow F^{ij}_{\lambda_1\lambda_2\mu_1\mu_2}(\theta_{cm})$$

$$F^{ij}_{\lambda_1\lambda_2\mu_1\mu_2}(\theta_{cm}) = (-1)^{\mu_1-\mu_2} F^{ji}_{\lambda_2\lambda_1\mu_1\mu_2}(\pi-\theta_{cm}) \leftarrow \tilde{\chi}_i^0\tilde{\chi}_j^0$$ antisymmetry

$$F^{ij}_{\lambda_1\lambda_2\mu_1\mu_2}(\theta_{cm}) = (-1)^{\lambda_1-\lambda_2} F^{ij}_{\lambda_1\lambda_2\mu_2\mu_1}(\pi-\theta_{cm}) \leftarrow \gamma\gamma$$ bose symmetry

$$F^{ij}_{-\lambda_1,-\lambda_2,-\mu_1,-\mu_2,}(\theta_{cm}) = (-1)^{\lambda_1-\lambda_2-\mu_1+\mu_2}\eta_i\eta_j F^{ij}_{\lambda_1\lambda_2\mu_1\mu_2}(\theta_{cm}) \leftarrow CP$$ symmetry

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$$\tilde{\chi}_i^0(\lambda_1)\tilde{\chi}_j^0(\lambda_2) \to \gamma(\mu_1)Z(\mu_2) \Rightarrow F^{ij}_{\lambda_1\lambda_2\mu_1\mu_2}(\theta_{cm})$$

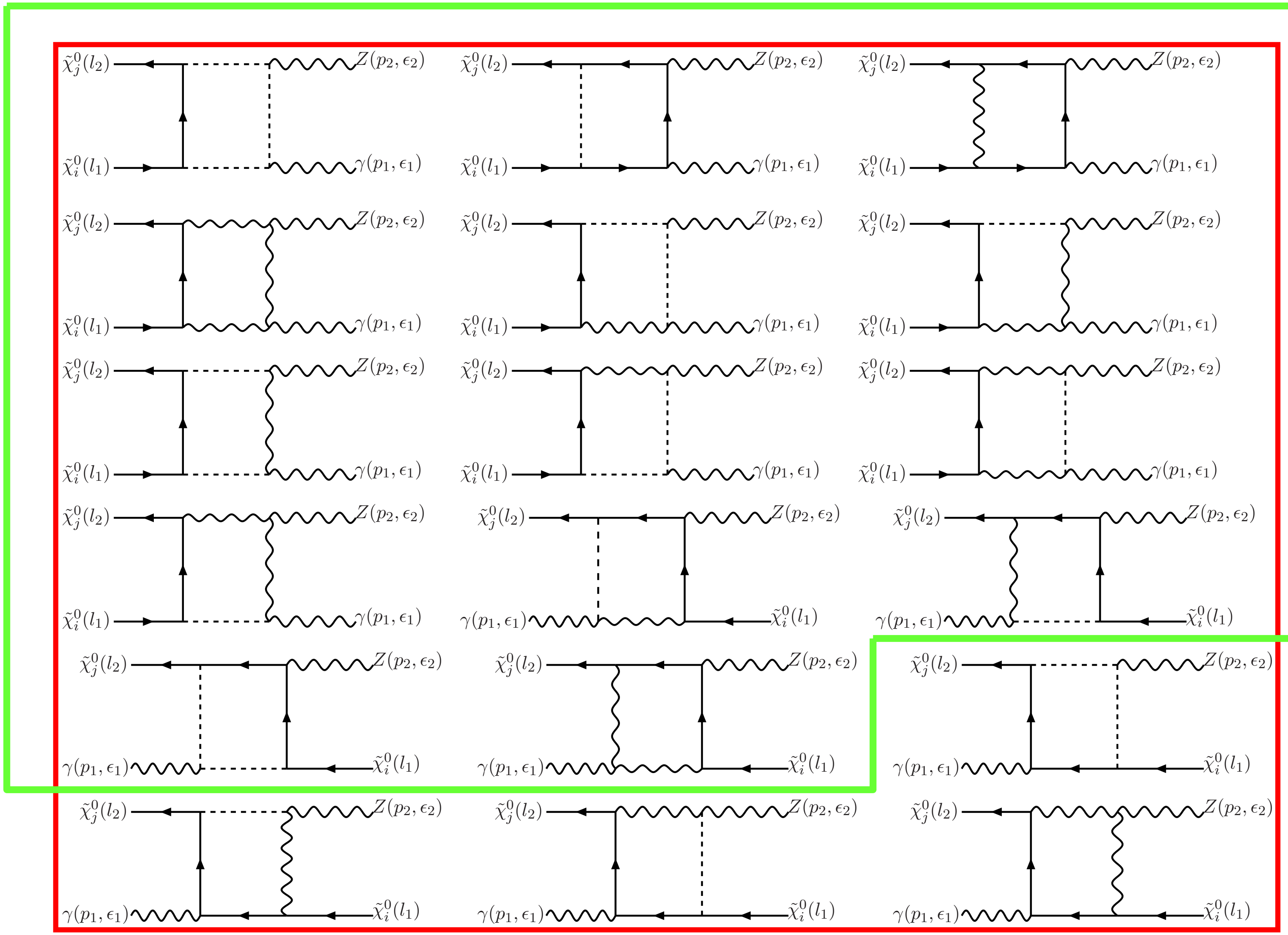
$$F^{ij}_{\lambda_1\lambda_2\mu_1\mu_2}(\theta_{cm}) = (-1)^{\mu_1-\mu_2} F^{ji}_{\lambda_2\lambda_1\mu_1\mu_2}(\pi-\theta_{cm}) \leftarrow \tilde{\chi}_i^0\tilde{\chi}_j^0$$ antisymmetry

$$F^{ij}_{-\lambda_1,-\lambda_2,-\mu_1,-\mu_2}(\theta_{cm}) = (-1)^{\lambda_1-\lambda_2-\mu_1+\mu_2}\eta_i\eta_j F^{ij}_{\lambda_1\lambda_2\mu_1\mu_2}(\theta_{cm}) \leftarrow CP$$ symmetry

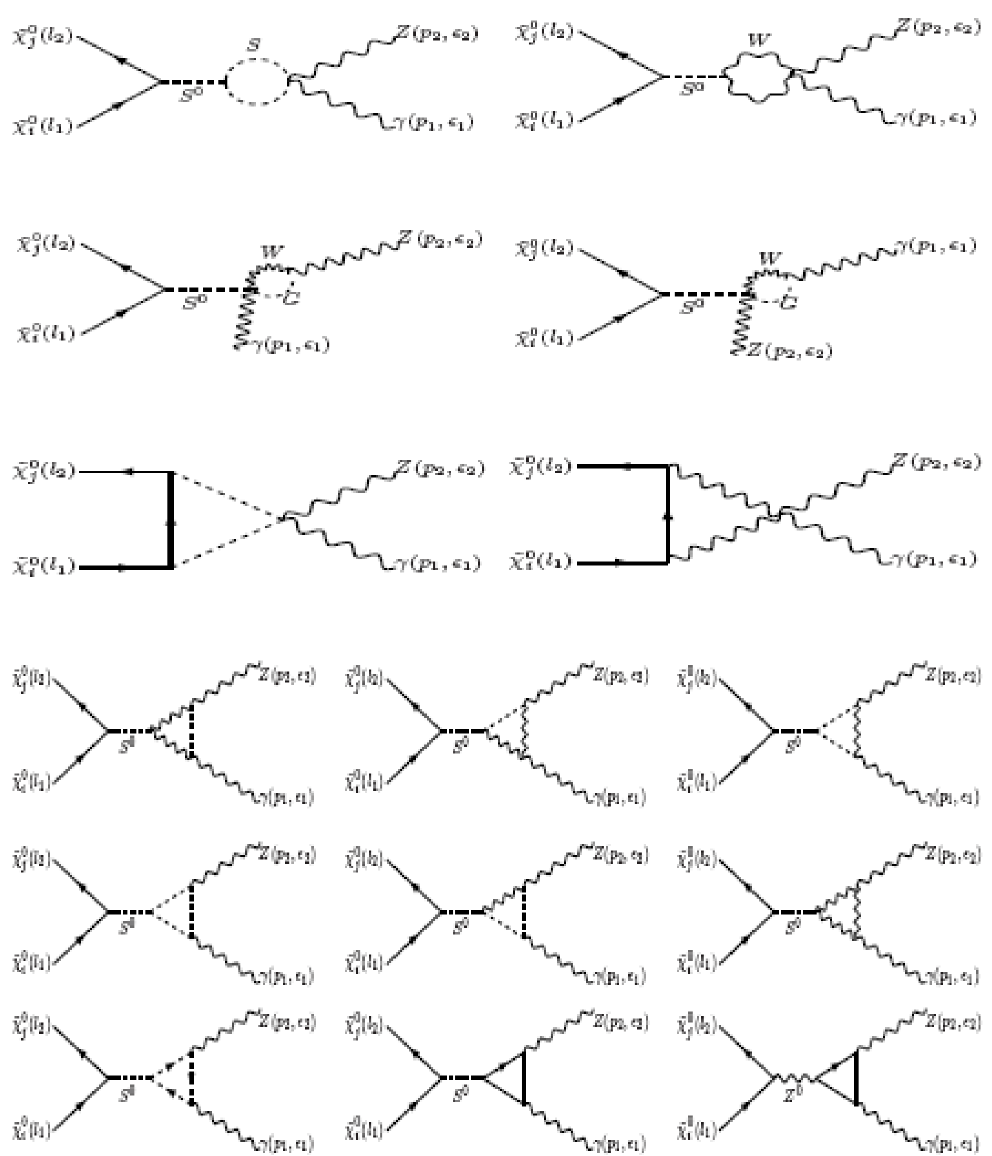
$\tilde{\chi}_i^0 \tilde{\chi}_j^0 \to \gamma\gamma$

Independent Box diagrams for γZ and γγ

$\tilde{\chi}_i^0 \tilde{\chi}_j^0 \to \gamma Z$



Bubbles, initial and final triangles for γZ and γγ.



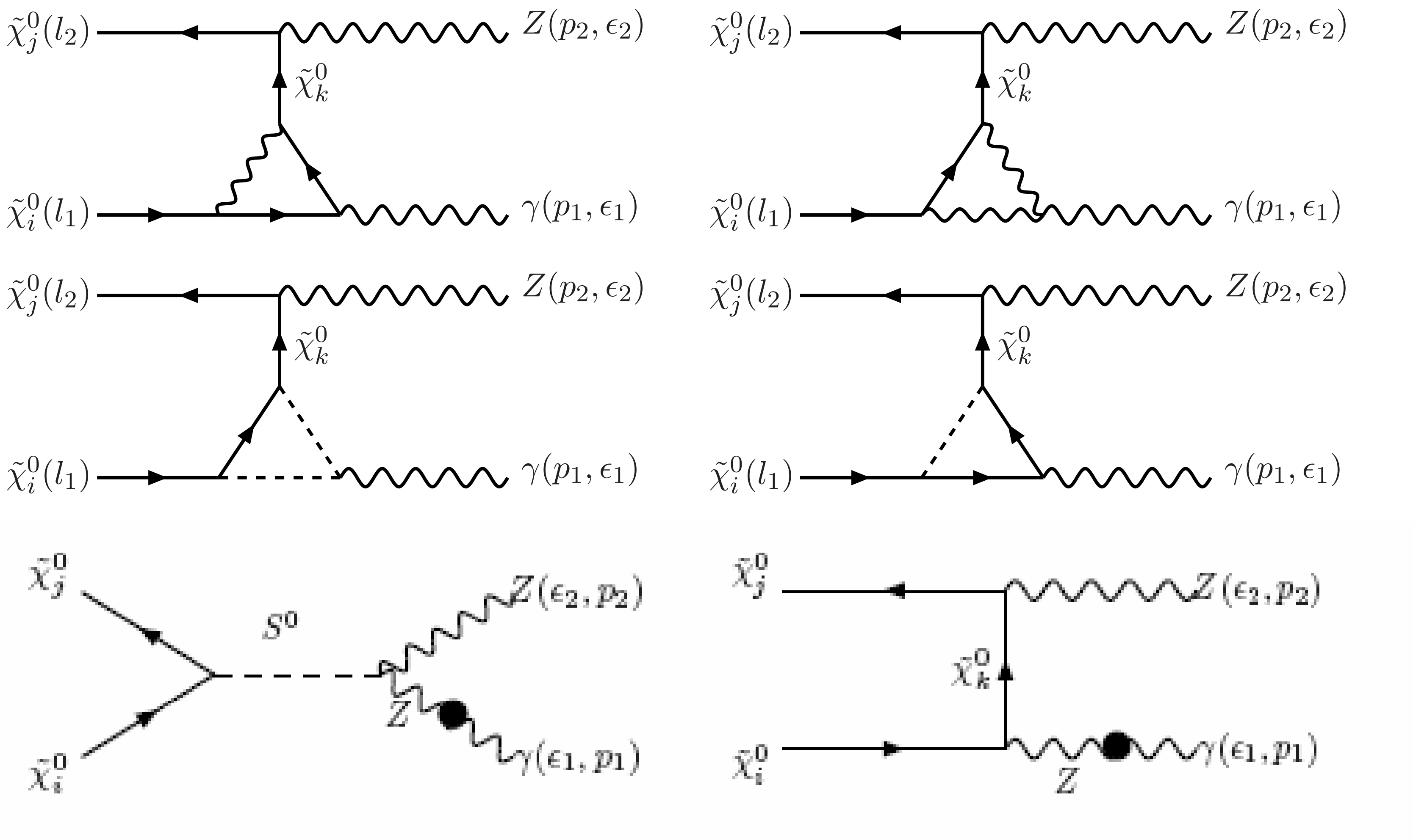
$$\tilde{\chi}_i^0 \tilde{\chi}_j^0 \rightarrow \gamma Z$$

Similarly for

$$\tilde{\chi}_i^0 \tilde{\chi}_j^0 \rightarrow \gamma \gamma$$

Additional independent diagrams for γZ only.

$$\tilde{\chi}_i^0 \tilde{\chi}_j^0 \rightarrow \gamma Z$$



The relevant quantity for DM searches is

$$v_{11} \sim 10^{-3}$$

$$v_{11}\sigma(\tilde{\chi}_1^0\tilde{\chi}_1^0 \to \gamma\gamma)\ ,\ v_{11}\sigma(\tilde{\chi}_1^0\tilde{\chi}_1^0 \to \gamma Z)\ \text{in}\ 10^{-27}\times cm^3 s^{-1}$$

$$v_{11}\sigma(\tilde{\chi}_1^0\tilde{\chi}_1^0 \to \gamma\gamma) \sim 10^{-5}\ ,\ \ 0.1\ ,\ \ 1\quad \text{for}\ \tilde{B}\ ,\ \tilde{H}^0\ ,\ \tilde{W}$$

$$v_{11}\sigma(\tilde{\chi}_1^0\tilde{\chi}_1^0 \to \gamma Z) \sim 10^{-5}\ ,\ \ 0.1-1\ ,\ \ 1-10\quad \text{for}\ \tilde{B}\ ,\ \tilde{H}^0\ ,\ \tilde{W}$$

But our codes also give results for any

$$v_{ij}\sigma(\tilde{\chi}_i^0\tilde{\chi}_j^0 \to \gamma\gamma)\ ,\ v_{ij}\sigma(\tilde{\chi}_i^0\tilde{\chi}_j^0 \to \gamma Z)\ ,$$

$$v_{ij}\sigma(\tilde{\chi}_i^0\tilde{\chi}_j^0 \to gg)$$

at small relative velocities.

Neutralino production in *LC*

$$e^-(\tau_1)e^+(\tau_2)\rightarrow\tilde{\chi}_i^0(\lambda_1)\tilde{\chi}_j^0(\lambda_2)$$

Process appearing already at tree level.

It has been extensively studied…

Neutralino production in $LC_{\gamma\gamma}$

$$\gamma(\mu_1)\gamma(\mu_2) \to \tilde{\chi}_i^0(\lambda_1)\tilde{\chi}_j^0(\lambda_2) \Rightarrow \tilde{F}^{ij}_{\mu_1\mu_2\lambda_1\lambda_2}(\theta_{cm})$$

$$\tilde{F}^{ij}_{\mu_1\mu_2\lambda_1\lambda_2}(\theta_{cm}) = (-1)^{\mu_1-\mu_2}\tilde{F}^{ji}_{\mu_1\mu_2\lambda_2\lambda_1}(\pi-\theta_{cm}) \leftarrow \tilde{\chi}_i^0\tilde{\chi}_j^0$$ antisymmetry

$$\tilde{F}^{ij}_{\mu_1\mu_2\lambda_1\lambda_2}(\theta_{cm}) = (-1)^{\lambda_1-\lambda_2}\tilde{F}^{ij}_{\mu_2\mu_1\lambda_1\lambda_2}(\pi-\theta_{cm}) \leftarrow \gamma\gamma$$ bose symmetry

$$\tilde{F}^{ij}_{-\mu_1,-\mu_2,-\lambda_1,-\lambda_2}(\theta_{cm}) = (-1)^{\lambda_1-\lambda_2-\mu_1+\mu_2}\eta_i\eta_j\tilde{F}^{ij}_{\mu_1\mu_2\lambda_1\lambda_2}(\theta_{cm}) \leftarrow CP$$ symmetry

$$\begin{aligned}\frac{d\sigma(\gamma\gamma\to\tilde{\chi}_i^0\tilde{\chi}_j^0)}{d\tau\, d\cos\theta} \;=\; & \frac{d\bar{L}_{\gamma\gamma}}{d\tau}\Bigg\{\frac{d\sigma_0}{d\cos\theta} + \langle\xi_2\xi_2'\rangle\frac{d\sigma_{22}}{d\cos\theta} \\ & +\langle\xi_3\rangle\frac{d\sigma_3}{d\cos\theta}\cos 2\phi + \langle\xi_3'\rangle\frac{d\sigma_3'}{d\cos\theta}\cos 2\phi' \\ & +\langle\xi_3\xi_3'\rangle\left[\frac{d\sigma_{33}}{d\cos\theta}\cos(2[\phi+\phi']) + \frac{d\sigma_{33}'}{d\cos\theta*}\cos(2[\phi-\phi'])\right] \\ & +\langle\xi_3\xi_2'\rangle\frac{d\sigma_{23}}{d\cos\theta}\sin 2\phi + \langle\xi_2\xi_3'\rangle\frac{d\sigma'_{23}}{d\cos\theta}\sin 2\phi'\Bigg\}\quad .\end{aligned}$$

$$\frac{d\sigma_0}{d\cos\theta} = \left(\frac{C_{ij}}{128\pi s}\right)\sum_{\lambda_1\lambda_2}[\ |\tilde{F}_{++\lambda_1\lambda_2}|^2+|\tilde{F}_{--\lambda_1\lambda_2}|^2+|\tilde{F}_{+-\lambda_1\lambda_2}|^2+|\tilde{F}_{-+\lambda_1\lambda_2}|^2\ ]\ ,$$
$$= \left(\frac{C_{ij}}{64\pi s}\right)[\ |\tilde{F}_{++++}|^2+|\tilde{F}_{++--}|^2+|\tilde{F}_{+++-}|^2+|\tilde{F}_{++-+}|^2 + |\tilde{F}_{+-++}|^2+|\tilde{F}_{+---}|^2+|\tilde{F}_{+-+-}|^2+|\tilde{F}_{+--+}|^2\ ]\ ,$$

$$\frac{d\sigma_{22}}{d\cos\theta} = \left(\frac{C_{ij}}{128\pi s}\right)\sum_{\lambda_1\lambda_2}[\ |\tilde{F}_{++\lambda_1\lambda_2}|^2+|\tilde{F}_{--\lambda_1\lambda_2}|^2-|\tilde{F}_{+-\lambda_1\lambda_2}|^2-|\tilde{F}_{-+\lambda_1\lambda_2}|^2\ ]$$
$$= \left(\frac{C_{ij}}{64\pi s}\right)[\ |\tilde{F}_{++++}|^2+|\tilde{F}_{++--}|^2+|\tilde{F}_{+++-}|^2+|\tilde{F}_{++-+}|^2 -(|\tilde{F}_{+-++}|^2+|\tilde{F}_{+---}|^2+|\tilde{F}_{+-+-}|^2+|\tilde{F}_{+--+}|^2)\ ]\ ,$$

$$\frac{d\sigma_3}{d\cos\theta} = \left(\frac{-C_{ij}}{64\pi s}\right)\sum_{\lambda_1\lambda_2}[\tilde{F}_{++\lambda_1\lambda_2}\tilde{F}^*_{-+\lambda_1\lambda_2}+\tilde{F}_{+-\lambda_1\lambda_2}\tilde{F}^*_{--\lambda_1\lambda_2}]$$
$$= \left(\frac{-C_{ij}}{32\pi s}\right)Re[\tilde{F}_{++++}\tilde{F}^*_{+---}+\tilde{F}_{++--}\tilde{F}^*_{+-++} -\tilde{F}_{+++-}\tilde{F}^*_{+--+}-\tilde{F}_{++-+}\tilde{F}^*_{+-+-}]\eta_i\eta_j\ ,$$

$$\frac{d\sigma'_3}{d\cos\theta} = \left(\frac{-C_{ij}}{64\pi s}\right)\sum_{\lambda_1\lambda_2}[\tilde{F}_{++\lambda_1\lambda_2}\tilde{F}^*_{+-\lambda_1\lambda_2}+\tilde{F}_{-+\lambda_1\lambda_2}\tilde{F}^*_{--\lambda_1\lambda_2}]$$
$$= \left(\frac{-C_{ij}}{32\pi s}\right)Re[\tilde{F}_{++++}\tilde{F}^*_{+-++}+\tilde{F}_{++--}\tilde{F}^*_{+---} +\tilde{F}_{+++-}\tilde{F}^*_{+-+-}+\tilde{F}_{++-+}\tilde{F}^*_{+--+}\ ]\ ,$$

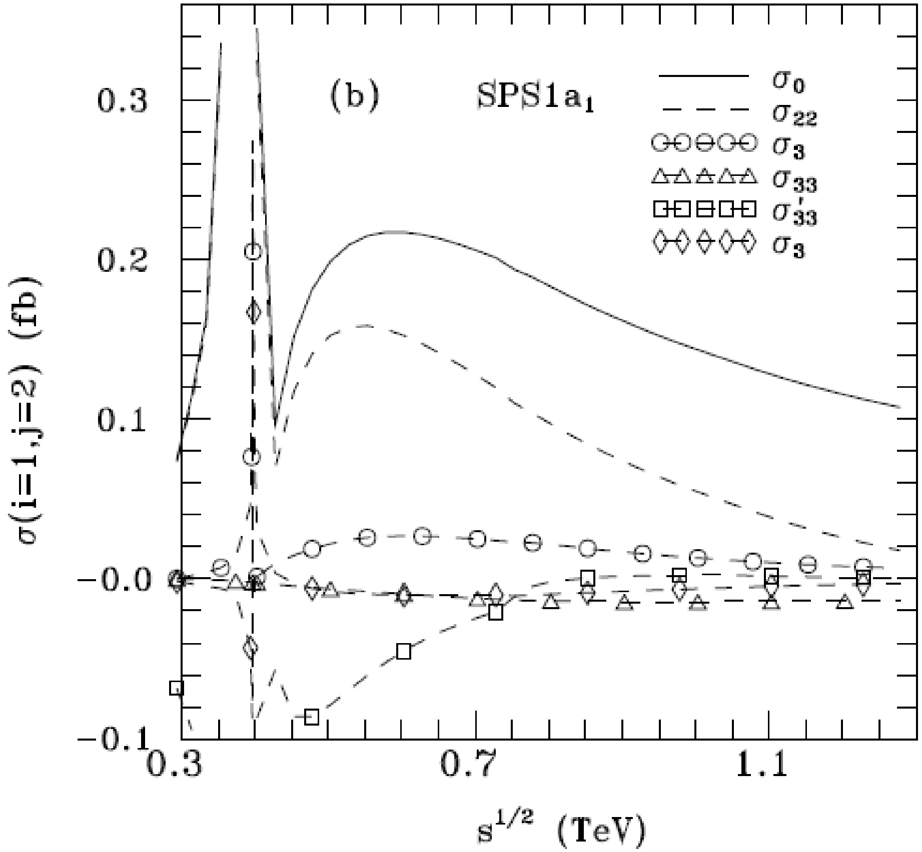
$$\frac{d\sigma_{33}}{d\cos\theta} = \left(\frac{C_{ij}}{32\pi s}\right)Re[\tilde{F}_{+---}\tilde{F}^*_{-+--}+\tilde{F}_{+-+-}\tilde{F}^*_{-++-}\ ]$$
$$= \left(\frac{C_{ij}}{32\pi s}\right)Re[\tilde{F}_{+---}\tilde{F}^*_{+-++}-\tilde{F}_{+-+-}\tilde{F}^*_{+--+}]\eta_i\eta_j\ ,$$

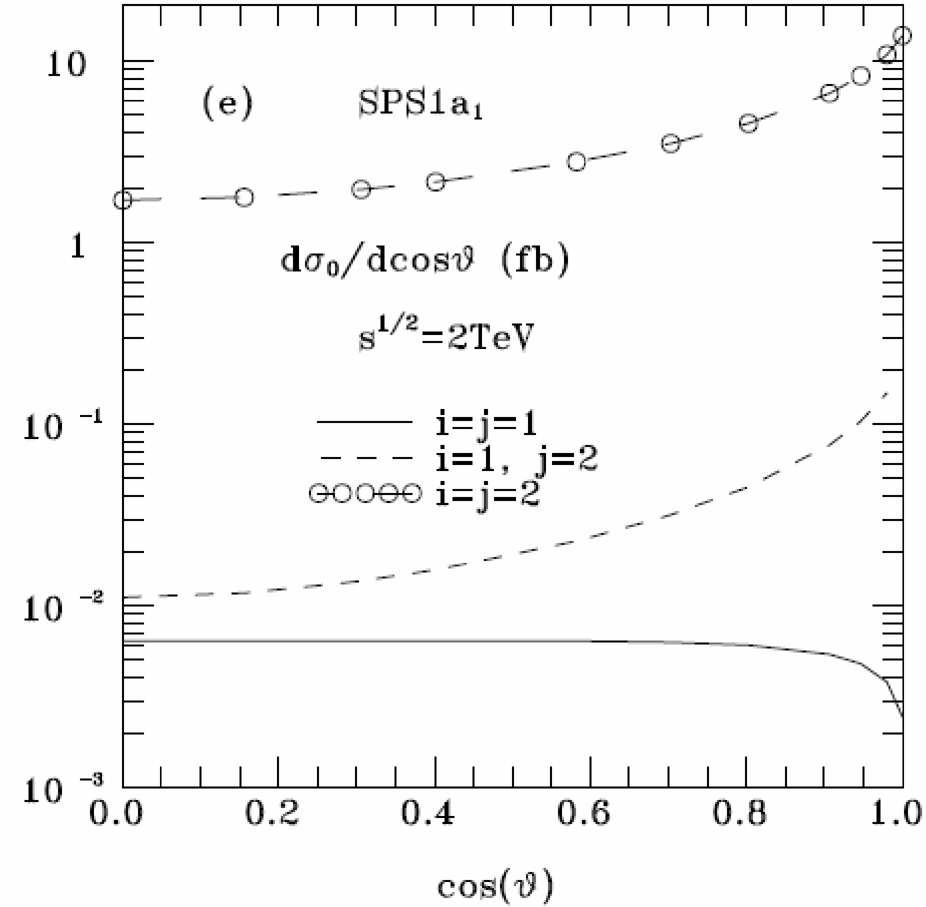
$$\frac{d\sigma'_{33}}{d\cos\theta} = \left(\frac{C_{ij}}{32\pi s}\right)Re[\tilde{F}_{++++}\tilde{F}^*_{--++}+\tilde{F}_{+++-}\tilde{F}^*_{--+-}\ ]$$
$$= \left(\frac{C_{ij}}{32\pi s}\right)Re[\tilde{F}_{++++}\tilde{F}^*_{++--}-\tilde{F}_{+++-}\tilde{F}^*_{++-+}]\eta_i\eta_j\ ,$$

$$\frac{d\sigma_{23}}{d\cos\theta} = \left(\frac{-C_{ij}}{32\pi s}\right)Im[\tilde{F}_{++++}\tilde{F}^*_{+---}+\tilde{F}_{++--}\tilde{F}^*_{+-++} -\tilde{F}_{+++-}\tilde{F}^*_{+--+}-\tilde{F}_{++-+}\tilde{F}^*_{+-+-}]\eta_i\eta_j\ ,$$

$$\frac{d\sigma'_{23}}{d\cos\theta} = \left(\frac{C_{ij}}{32\pi s}\right)Im[\tilde{F}_{++++}\tilde{F}^*_{+-++}+\tilde{F}_{++--}\tilde{F}^*_{+---} +\tilde{F}_{+++-}\tilde{F}^*_{+-+-}+\tilde{F}_{++-+}\tilde{F}^*_{+--+}]\ ,$$

$$C_{ij} = \beta_{ij}\left(1-\frac{\delta_{ij}}{2}\right)\ ,$$
$$\beta_{ij} = \sqrt{\left[1-\frac{(m_i-m_j)^2}{s}\right]\left[1-\frac{(m_i+m_j)^2}{s}\right]}$$





$SPS1a_1$

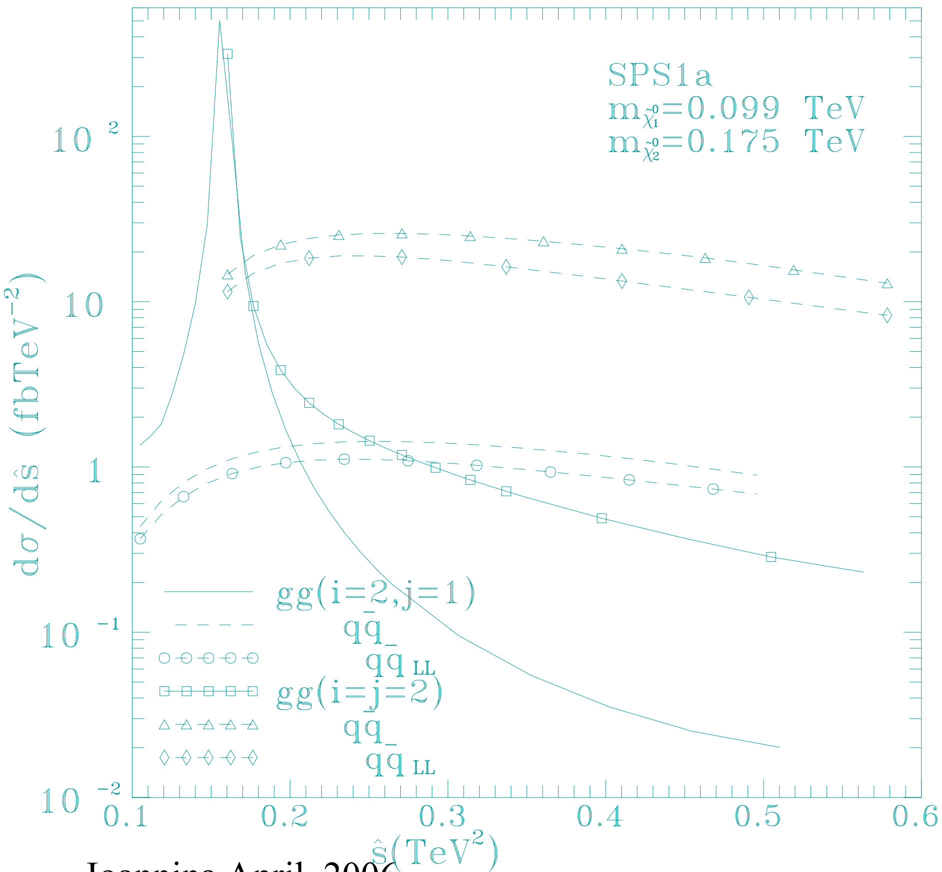
$m_{1/2} = 250$ GeV , $m_0 = 100$, $A_0 = -100$

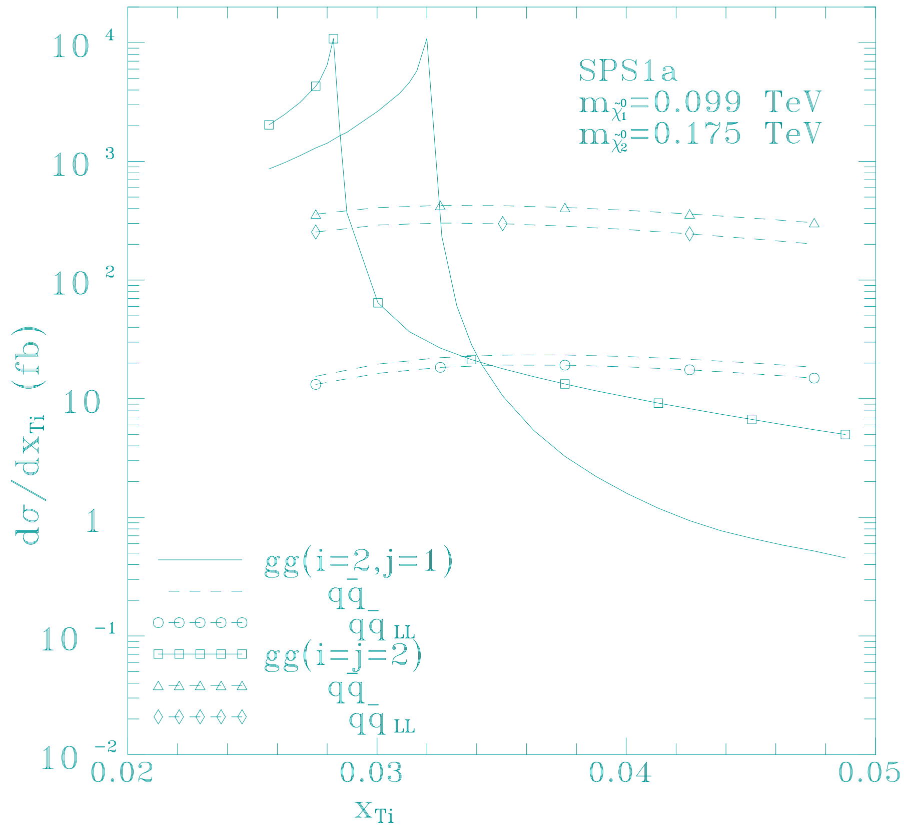
$\tan\beta = 5$, $\mu > 0$

Neutralino pair production at LHC:
The 1-loop (box, bubble, initial and final triangle) diagrams are similar to those studied above.

SPS1a
$m_{1/2} = 250$ GeV , $m_0 = 100$, $A_0 = -100$
$\tan\beta = 10$, $\mu > 0$

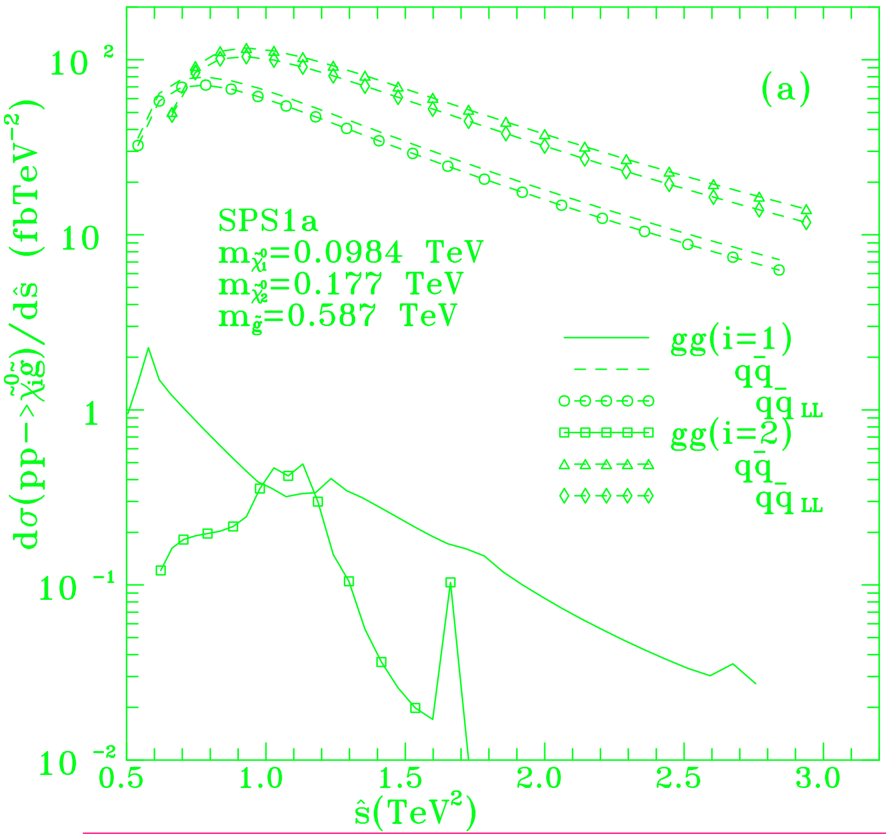
$$q\bar{q} \to \tilde{\chi}_i^0 \tilde{\chi}_j^0 \quad , \quad gg \to \tilde{\chi}_i^0 \tilde{\chi}_j^0$$

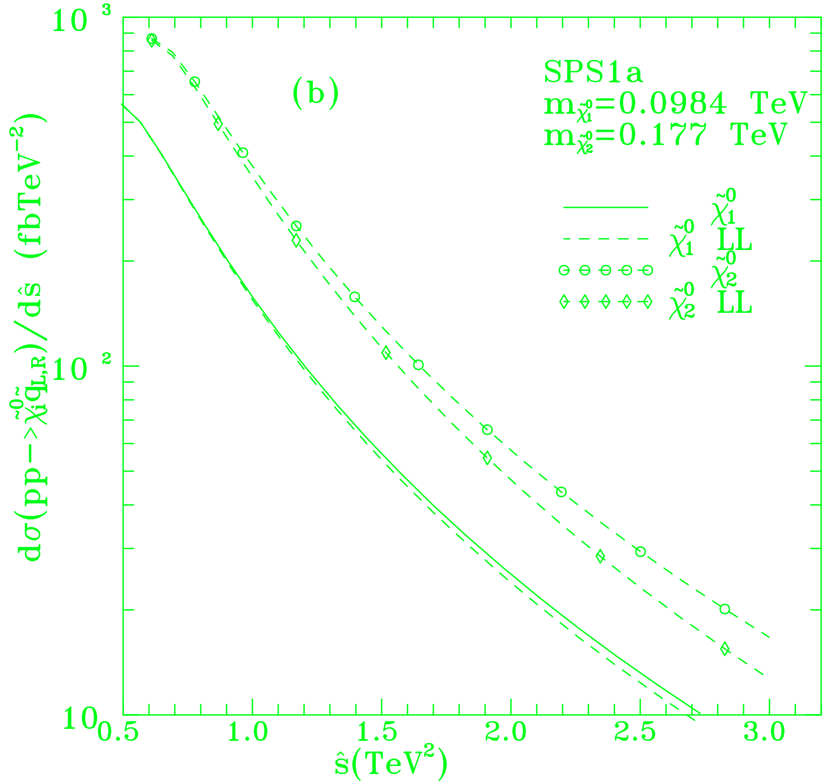




Single neutralino pair production at LHC; PLATONgluino

$$q\bar{q} \to \tilde{\chi}_i^0 \tilde{g} \;,\; gq \to \tilde{\chi}_i^0 \tilde{q}_{L,R} \;,\; q\bar{q}' \to \tilde{\chi}_i^0 \tilde{\chi}_a^{\pm} \;,\; gg \to \tilde{\chi}_i^0 \tilde{g}$$

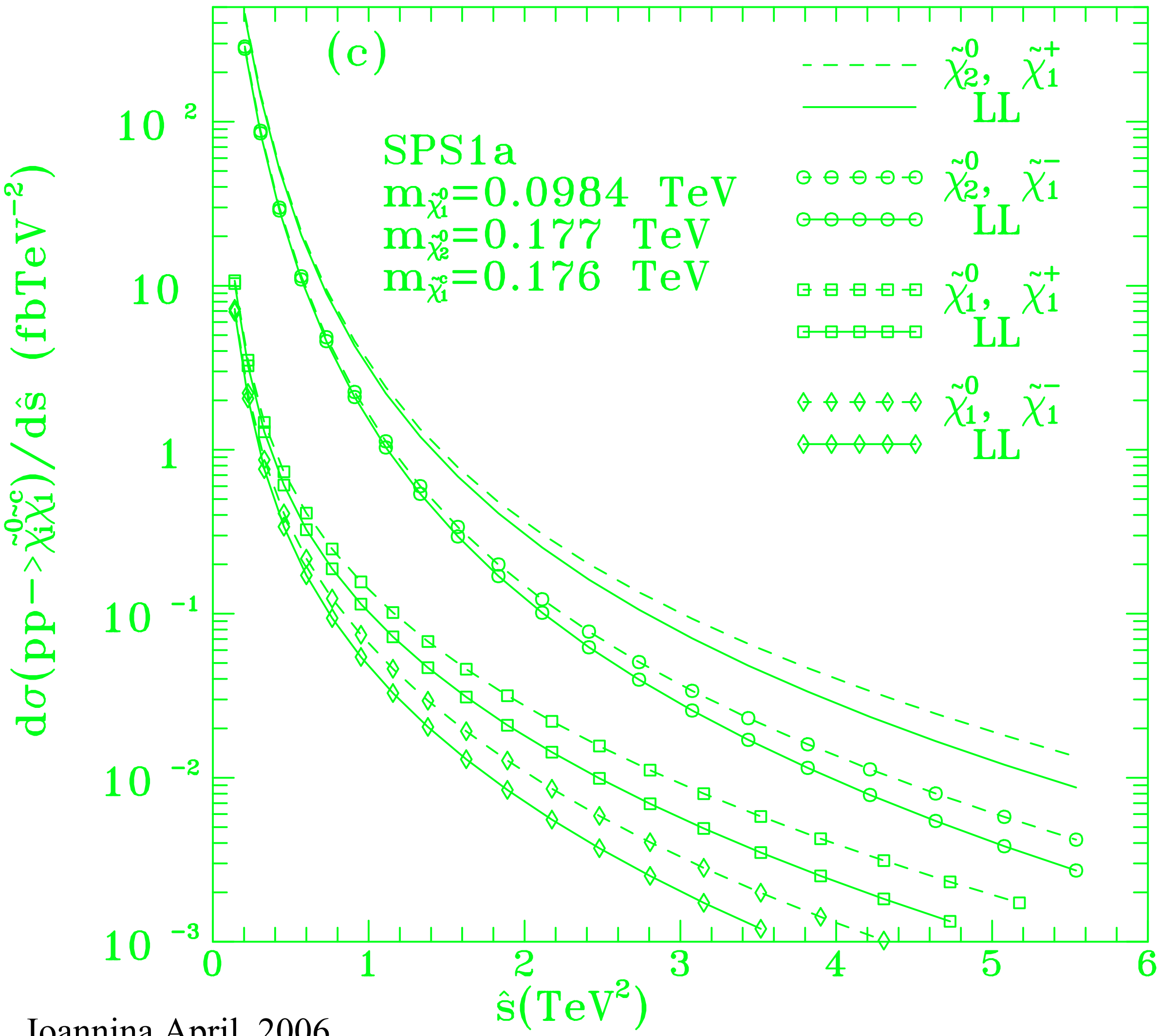




The 1-loop (box, bubble, initial and final triangle) diagrams are again similar to those studied above

Single neutralino pair production at LHC; PLATONgluino

$q\bar{q} \to \tilde{\chi}_i^0 \tilde{g}$, $gq \to \tilde{\chi}_i^0 \tilde{q}_{L,R}$, $q\bar{q}' \to \tilde{\chi}_i^0 \tilde{\chi}_a^\pm$, $gg \to \tilde{\chi}_i^0 \tilde{g}$



Neutralinos through cascades at LHC

$$\tilde{g} \to \bar{q}_1 \tilde{q}_1 \to \bar{q}_1 q'_2 \, \tilde{\chi}_a^{\pm} \to \bar{q}_1 q'_2 \, W^{\pm} \tilde{\chi}_1^0$$

$$\tilde{g} \to \bar{q}_1 \tilde{q}_1 \to \bar{q}_1 q_1 \tilde{\chi}_2^0 \to \bar{q}_1 q_1 Z \, \tilde{\chi}_1^0$$

Modes like this are the main ones for producing neutralinos at LHC. Already extensively studied…

Conclusions

An extensive study of 1-loop neutralino processes relevant for its identification in DM, LHC and $LC_{\gamma\gamma}$ has been completed and FORTRAN codes have been released in

http://dtp.physics.auth.gr

applying to MSSM with any real parameters.