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Study of chargino-neutralino production at hadron colliders in a long-lived slepton scenario

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Motivation

A standard assumption of SUSY phenomenology: neutralino LSP

Why?
1. explains dark matter of the universe.
2. The Bino tends to be light due to a negative quantum correction.

But the gravitino LSP with stau NLSP is equally plausible.

1. explains dark matter of the universe.
2. The stau tends to be light due to a negative quantum correction through the Yukawa interaction.

Actually, the scenario of the thermal relic neutralino as dark matter has a big problem.

Bino LSP --> We must assume gravity mediation.

→ There is always a singlet field to give a mass to gauginos. The potential of the singlet field cannot be stabilized in a supersymmetric way to carry a SUSY breaking VEV.

→ Moduli problem!!! (Moduli decay too late and/or overproduce gravitinos.)

→ Inconsistent with the assumption in the thermal relic calculation. We need to carefully arrange the inflation sector such that moduli domination doesn't happen.

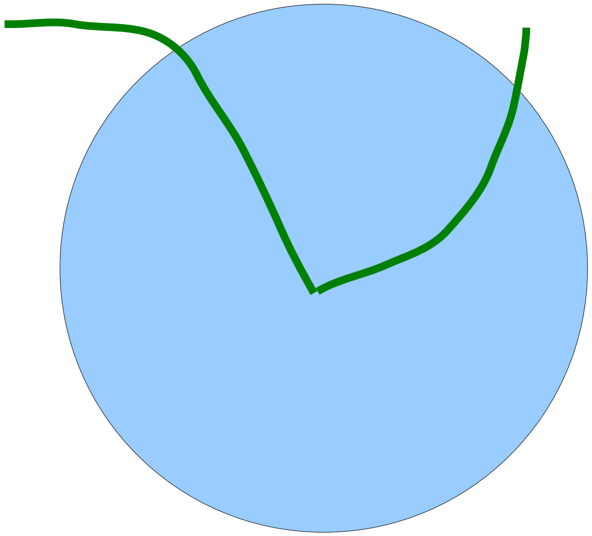
It's dangerous to believe that SUSY signatures at the LHC involves missing ET by neutralinos.

Overview of stau NLSP at LHC

[Drees, Tata '90][Feng, Moroi '97]
[Nisati, Petrarca, Salvini '97][Martin, Wells '98]
[Hinchliffe, Paige '98][Polesello, Rimoldi '99]
[Ambrosanio, Mele, Petrarca, Polesello, Rimoldi '00]

If the gravitino mass is large enough (>>100keV), staus decay outside the detector.

Stau looks like a muon which is a very nice particle for collider physics!



Very accurate mass (+-10-100MeV) and
momentum measurement (a few %) are possible
at ATLAS (and probably at CMS).
[Polesello, Rimoldi '99][Ambrosanio, Mele, Petrarca, Polesello, Rimoldi '00]

→ Lots of applications!

* Neutralino (and other sparticle) mass measurement

[Hinchliffe, Paige '98][Ellis, Raklev, Oye '06][Ibe, RK '06]

* Spin measurement

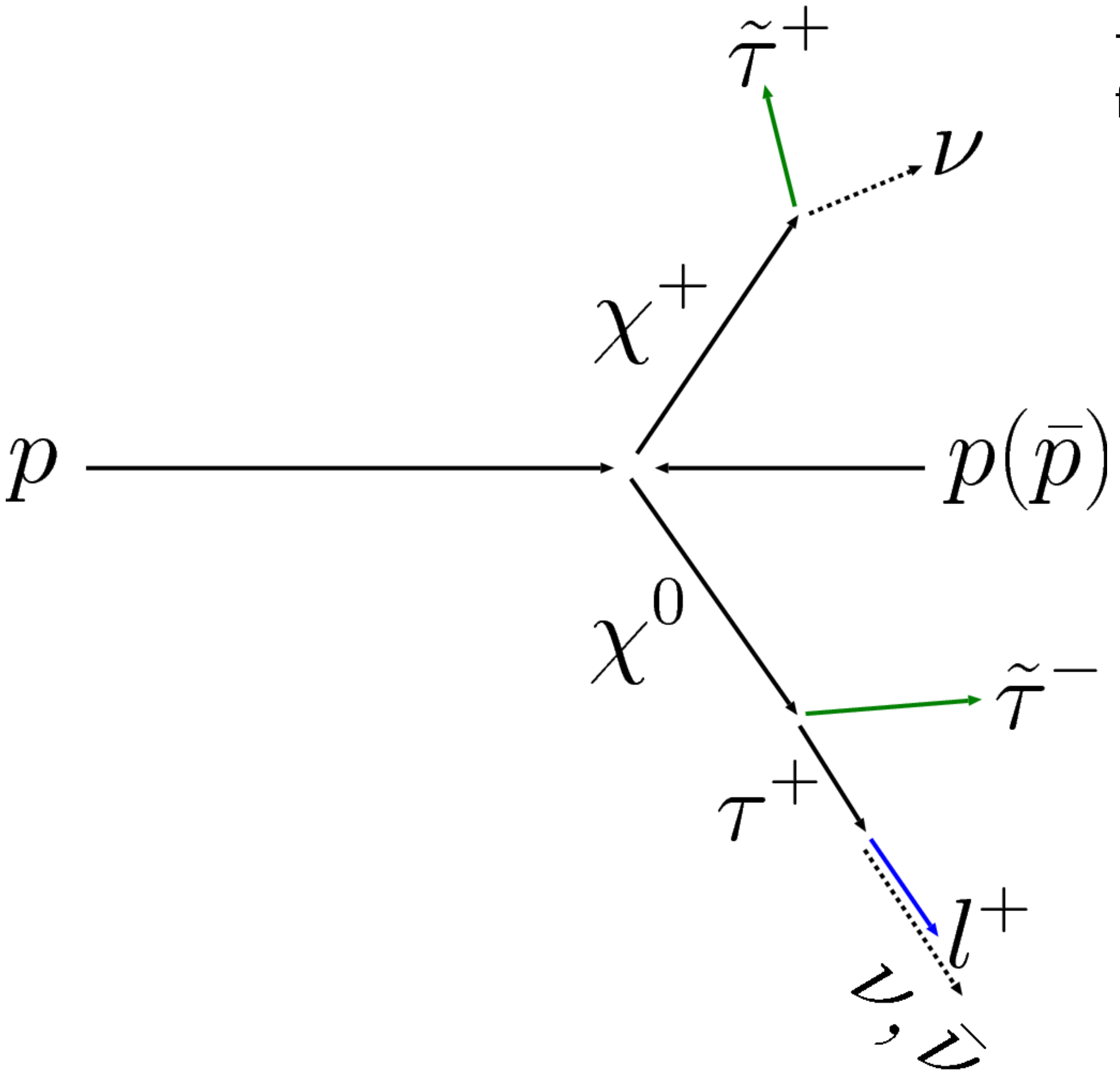
[Rajaraman, Smith '07]

* lifetime measurement

[Buchmuller, Hamaguchi, Ratz, Yangida '04]
[Hamaguchi, Kuno, Nakaya, Nojiri '04][Feng, Smith '04]

Chargino-neutralino production with long-lived stau

With long-lived staus in the final state, we can do studies of exclusive processes at hadron colliders just like at a Linear Collider!



This process has a purely leptonic final state. Clean!

If we know the neutralino and chargino masses, we can fully reconstruct the event up to a two-fold ambiguity.

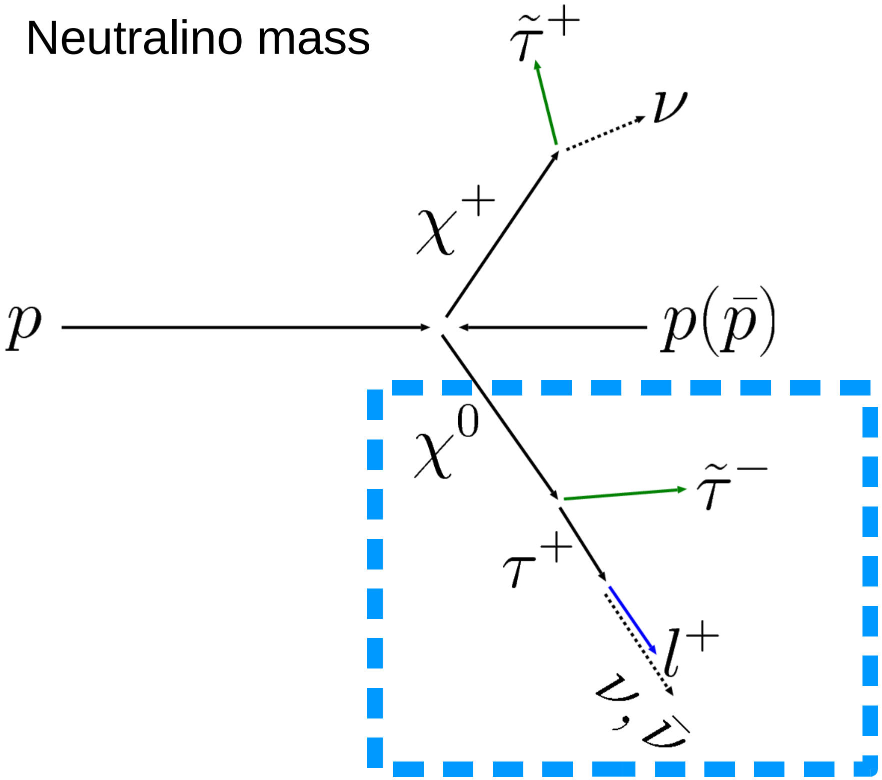
We can do many things!

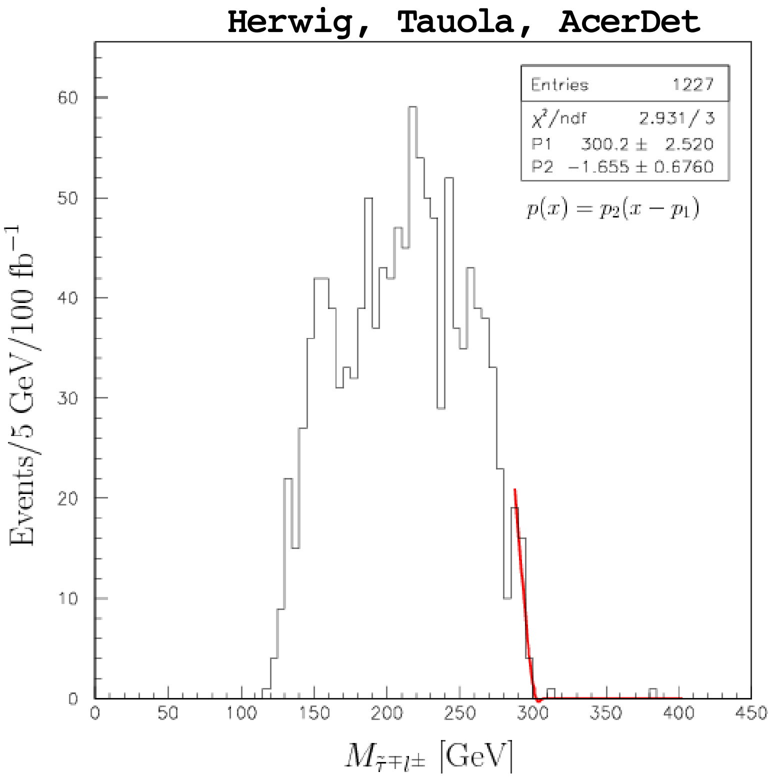
- mass measurements
- spin measurements
- P violation measurements
- CP violation measurements

They are going to be excellent tests of supersymmetry!!!

Mass measurements

Neutralino mass

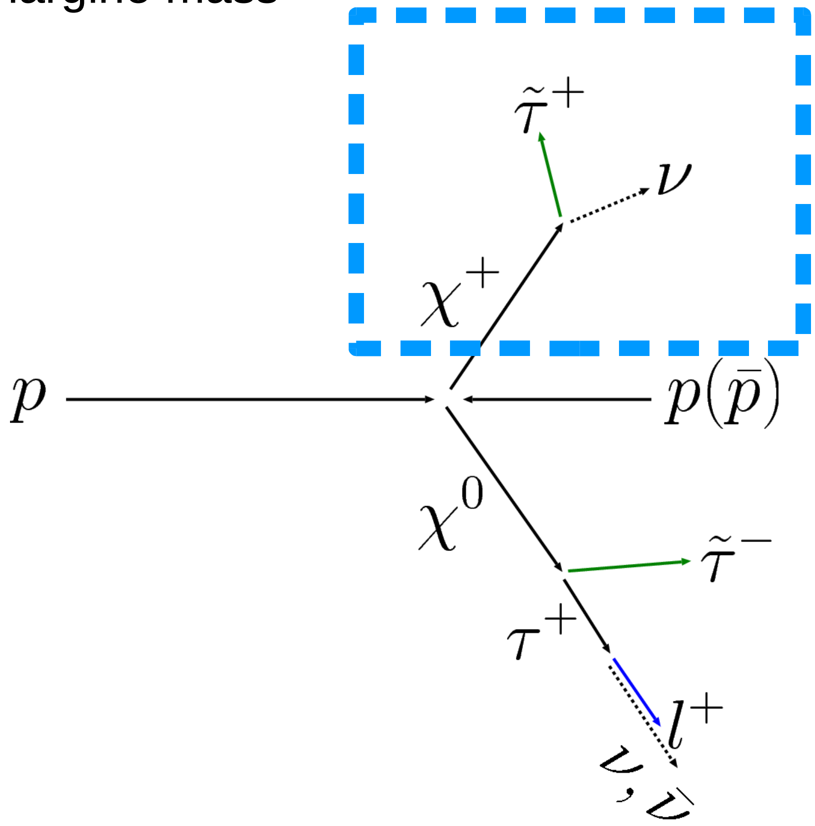




δM=3 GeV

(Pure Higgsino model with μ=300GeV
and right-handed m(stau)=109GeV)

Chargino mass



Once we know the neutralino mass, we know the rescaling factor of the lepton momeutum.

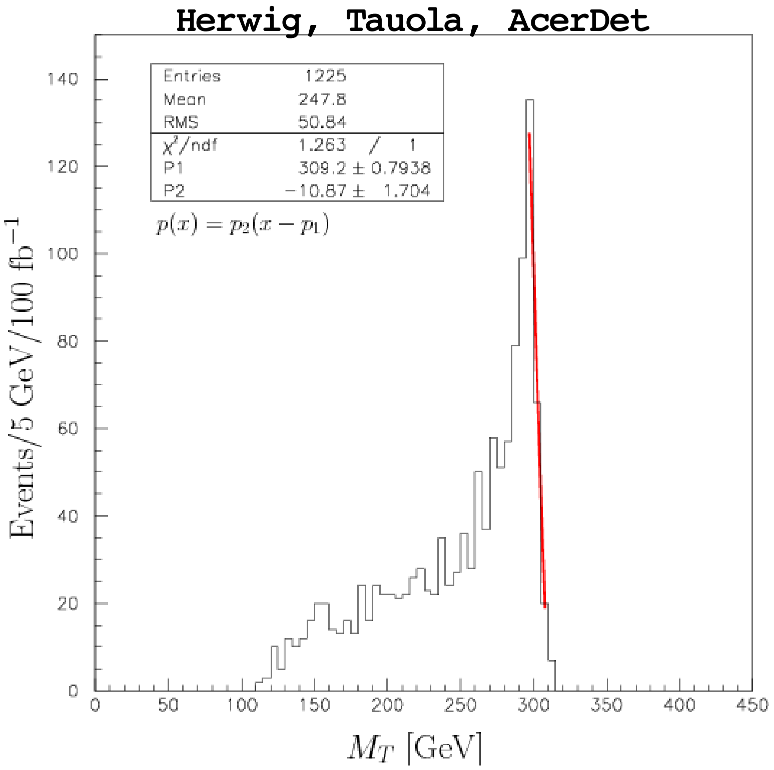
$$z_l \equiv \frac{E_l}{E_\tau}, \qquad \left(P_{\tilde\tau^-} + \frac{P_l}{z_l}\right)^2 = m_{\chi^0}^2$$

Transverse momentum of the neutrino from the chargino decay can be solved.

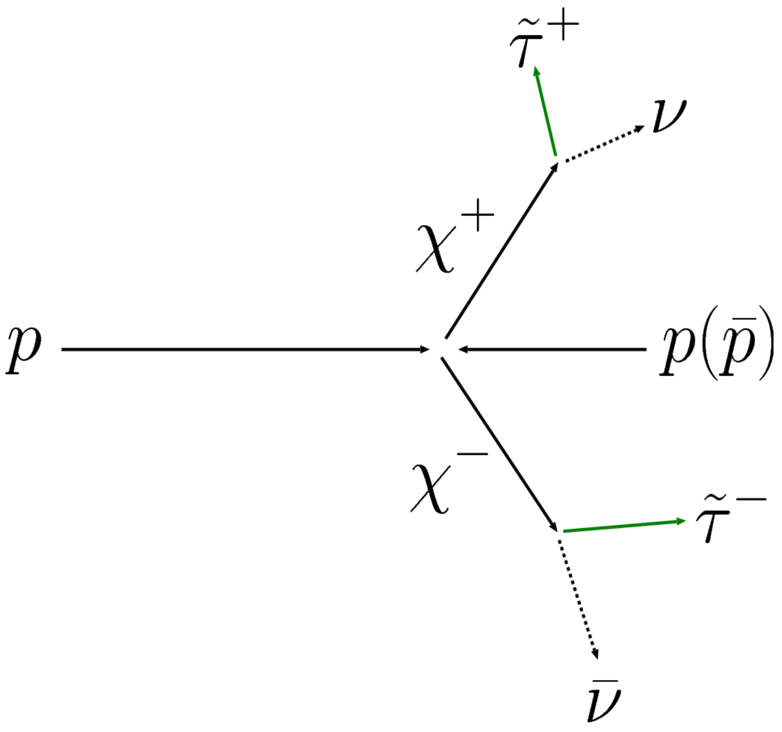
Transverse mass

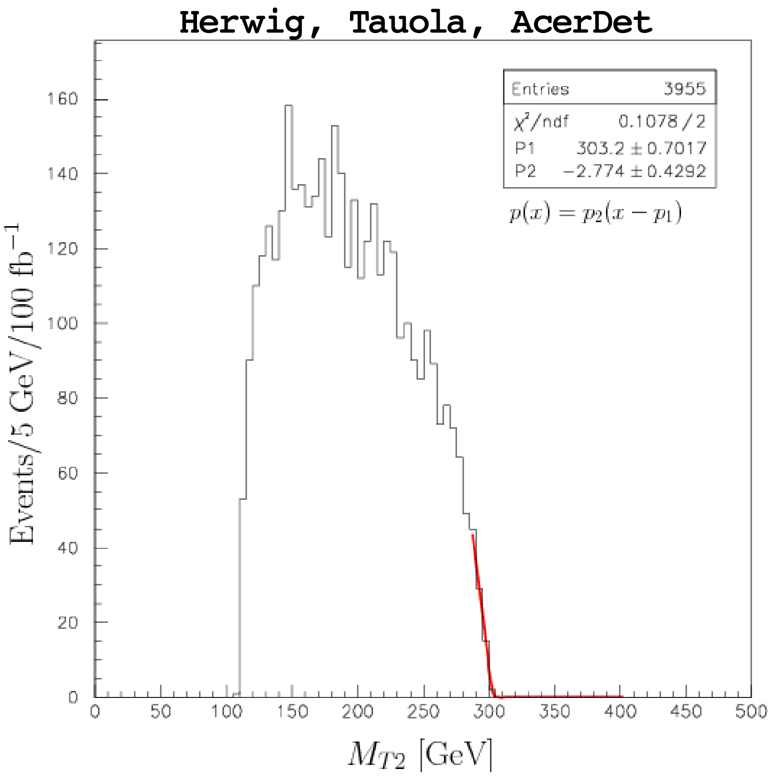
δM=0.8 GeV

(although it will depend on the resolution of the missing momentum measurement.)



By the way, the chargino mass can also be measured by using chargino-pair production events.



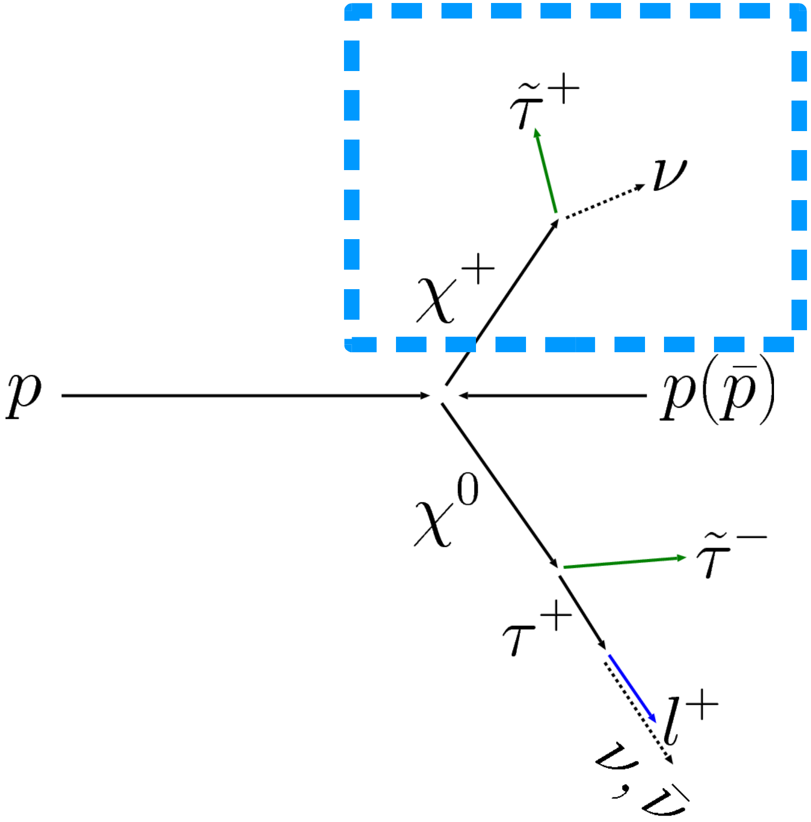


The M_{T2} variable can be used for this process.

[Lester, Summers '99]

This method directly measures the chargino mass.

Now with the knowledge of the chargino mass, z-direction of the neutrino momentum from the chargino decay can be solved:



$$(P_{\tilde{\tau}^+} + P_\nu)^2 = m_{\chi^+}^2$$

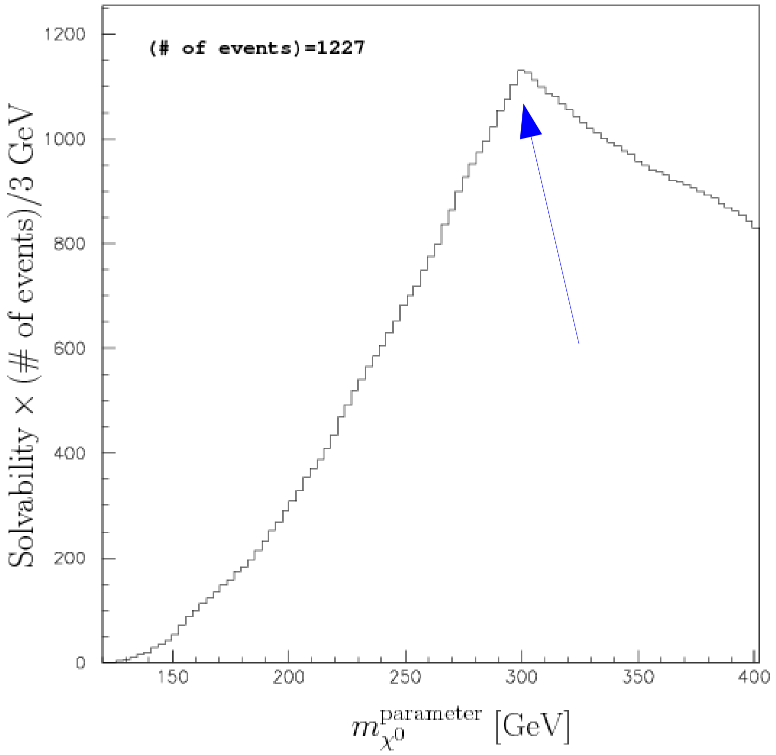
Unfortunately, we have two solutions to this equation.

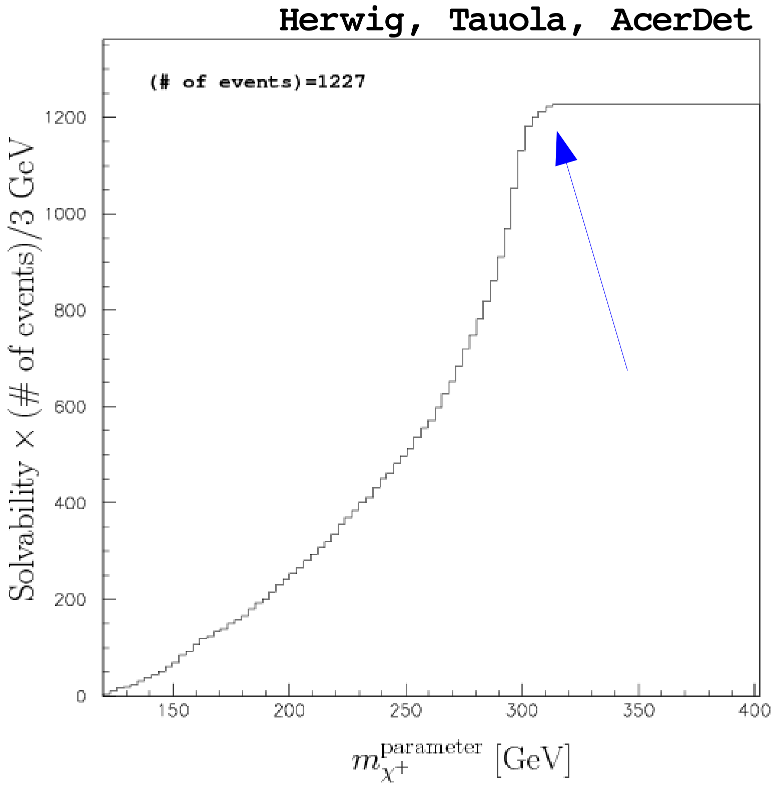
But anyway, we can fully reconstruct the event up to a two-fold ambiguity once the neutralino and chargino masses are known.

In this situation, we can do mass measurement in a more direct method.

Solvability analysis for neutralino and chargino masses

[Kawagoe, Nojiri, Polsello '04]
[Davis et al, (CMS collaboration) '06]
[Cheng, Gunion, Han, Marandella, McElrath '07]





Try to solve kinematics with various input masses. Solvability is defined as the probability to have a physical solution, i.e., $P_z(\nu)$ is a real number and $0<z_l<1$.

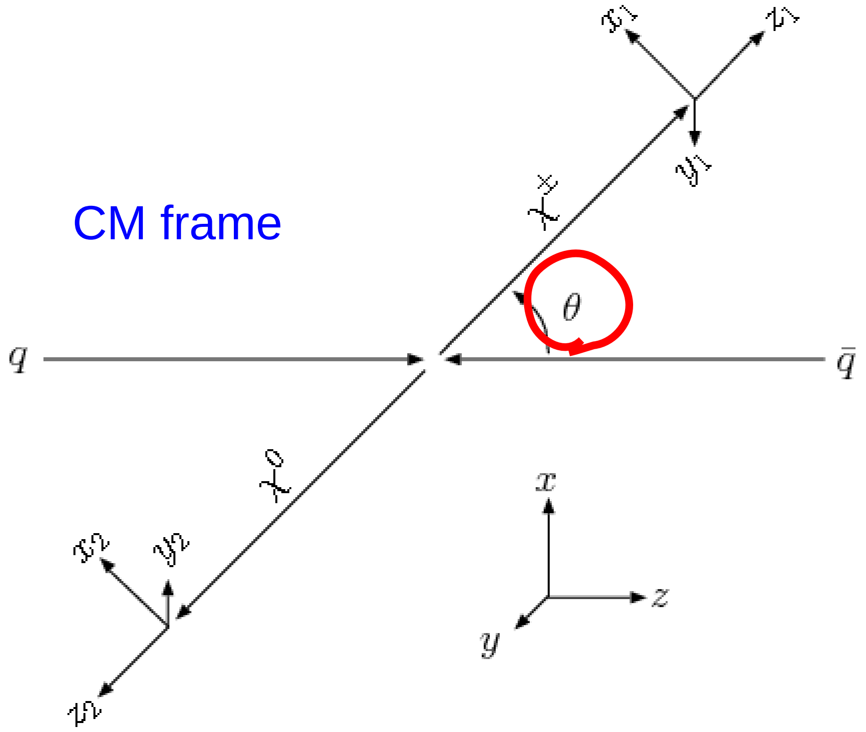
By looking for a peak or a point where solvability saturates, we can get masses.

δM~a few GeV.

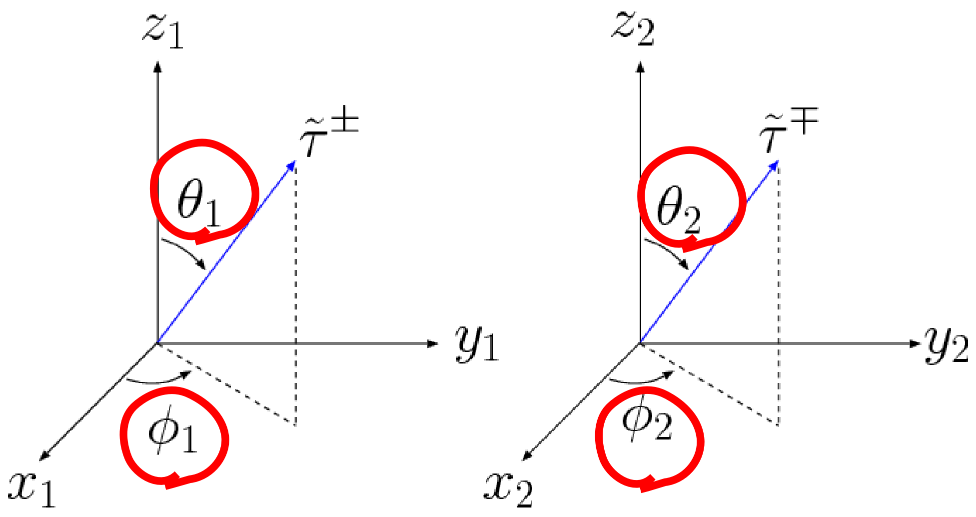
Various distributions

Define kinematic variables

CM frame



Rest frame of chargino



Rest frame of neutralino

Lepton energy fraction in leptonic tau decay

$$z_l \equiv \frac{E_l}{E_\tau}, \qquad 0 \leq z_l \leq 1$$

There are six kinematic variables.

The cross section formula

The formula is pretty simple.

Spin correlations

chargino-neutralino production

$$d\sigma \;\propto\; \frac{d\cos\theta}{2}\,\frac{d\Omega_1}{4\pi}\,\frac{d\Omega_2}{4\pi}\,dz_l \sum_{a,b=0}^{3} \underline{D_A^a(\theta_1,\phi_1)}\,\rho^{ab}(\theta)\,\underline{\widetilde{D}_B^b(\theta_2,\phi_2,z_l)}$$

chargino decay

neutralino decay

$$\widetilde{D}_B^b(\theta_2,\phi_2,z_l) = \frac{1}{3}(1-z_l)\left[(5+5z_l-4z_l^2)D_B^b(\theta_2,\phi_2) - a_N(1+z_l-8z_l^2)\delta^{b0}\right]$$

$$D_A^a = \begin{pmatrix} 1 \\ \pm a_C\sin\theta_1\cos\phi_1 \\ \pm a_C\sin\theta_1\sin\phi_1 \\ \pm a_C\cos\theta_1 \end{pmatrix}, \quad D_B^b = \begin{pmatrix} 1 \\ \mp a_N\sin\theta_2\cos\phi_2 \\ \mp a_N\sin\theta_2\sin\phi_2 \\ \mp a_N\cos\theta_2 \end{pmatrix}$$

← spin summed part

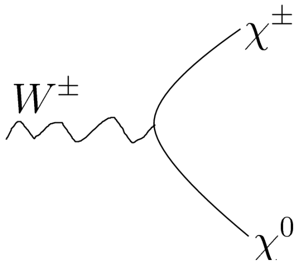
$$\rho^{ab}(\theta) = \cdots$$

← All the components are non-vanishing.

a_C and a_N are parity asymmetry parameter ($-1<a<1$) in the chargino decay and the neutralino decay, respectively. Non-trivial angular distribution measures parity violation.

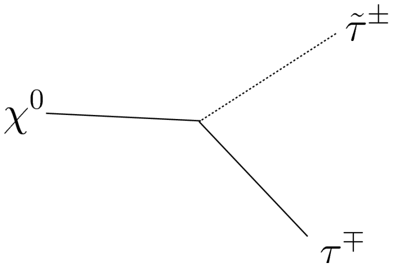
$a_C=1$ because neutrino has always the left-handed chirality (maximal parity violation).

Lagrangian and asymmetry parameters



* Chargino-neutralino production:

$$\mathcal{L}_W = \overline{\chi^0}\gamma^\mu(w_L P_L + w_R P_R)\chi^- W^+_\mu + \text{h.c.}$$



* neutralino decay:

$$\mathcal{L}_{\chi^0} = \overline{\chi^0}(n_R P_R + n_L P_L)\tau\tilde{\tau}^\dagger + \text{h.c.}$$

$$a_N \equiv \frac{|n_L|^2 - |n_R|^2}{|n_L|^2 + |n_R|^2}$$

← Parity violation in neutralino decay

$$a_W \equiv \frac{|w_L|^2 - |w_R|^2}{|w_L|^2 + |w_R|^2}$$

$$\xi_W \equiv \frac{2\text{Re}[w_L^* w_R]}{|w_L|^2 + |w_R|^2}$$

$$\eta_W \equiv \frac{2\text{Im}[w_L^* w_R]}{|w_L|^2 + |w_R|^2}$$

Parity violation in production

CP violation in production

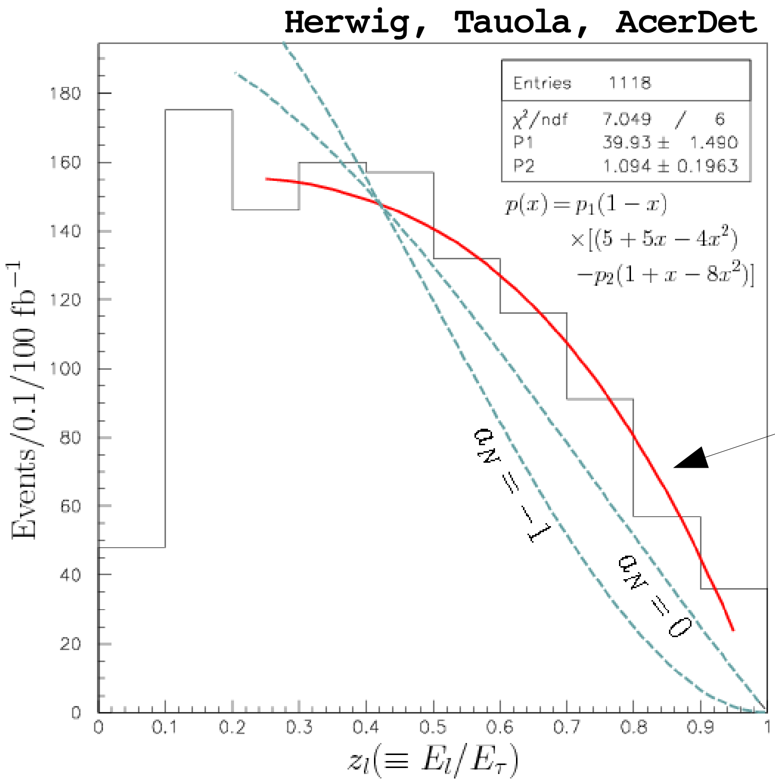
z_l distribution

z_l is a simple observable since it is a boost invariant quantity.
We can measure it in the lab frame. There is no two-fold ambiguity.

$$d\sigma \propto \frac{1}{3}(1-z_l)\left[(5+5z_l-4z_l^2)-a_N(1+z_l-8z_l^2)\right]dz_l$$

This is a well-known distribution of the polarized tau decay. [Bullock, Hagiwara, Martin '93]
This is true for both $\chi^+\chi^0$ and $\chi^-\chi^0$ productions.

Again, in the pure Higgsino with right-handed stau model,



τ is left-handed

Theory value is $a_N=1$. We can distinguish from other models.

$$a_N = 1.1 \pm 0.2$$

In general, this parameter has information on the LR mixing of the stau and the gaugino/higgsino mixing.

Polar angle distributions

Again, the same formula for both $\chi^+\chi^0$ and $\chi^-\chi^0$ productions.

$$d\sigma \propto \left[1 + a_W\langle f_1(\beta_A,\beta_B)\rangle\cos\theta_1 + a_W a_N\langle f_1(\beta_B,\beta_A)\rangle\cos\theta_2 + a_N\langle f_2(\beta_A,\beta_B)\rangle\cos\theta_1\cos\theta_2\right]\frac{d\cos\theta_1}{2}\frac{d\cos\theta_2}{2}$$

$0 < f_1 < 1$

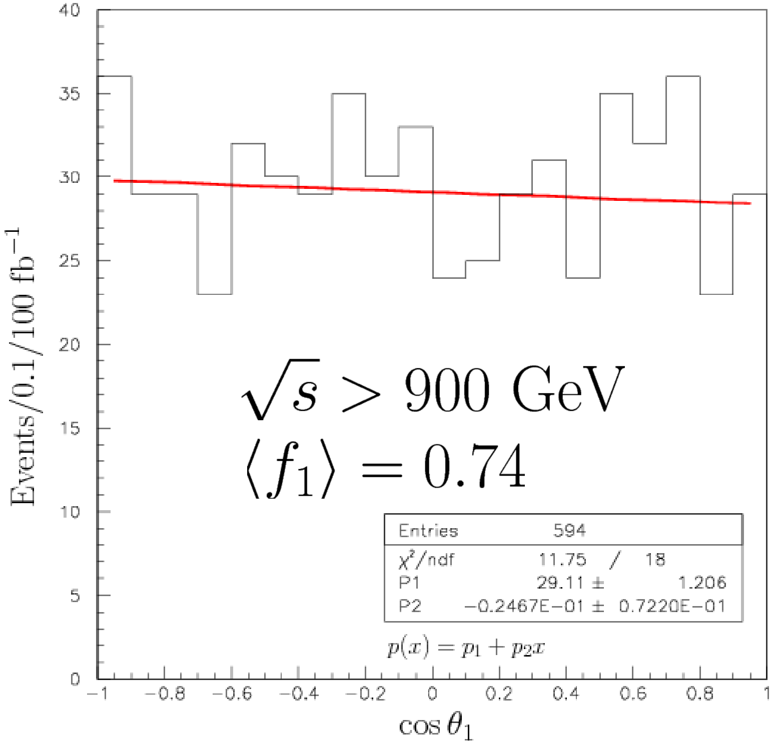
Threshold production

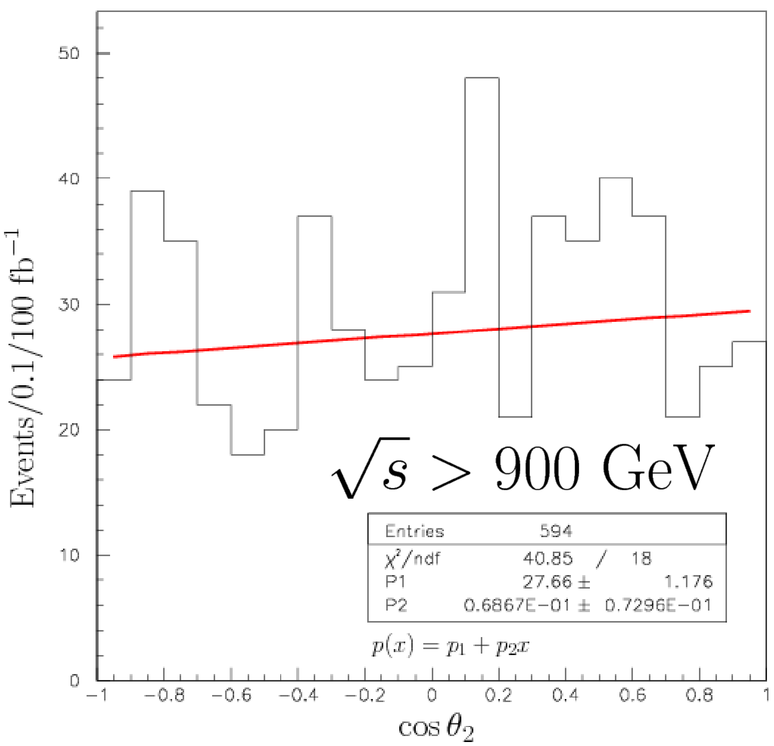
Boosted production

$1/3 < f_2 < 1$

Boosted production

Threshold production





Theoretical value:

$a_W = 0$

→ Flat distribution

False solutions are under control. Those are randomly distributed.

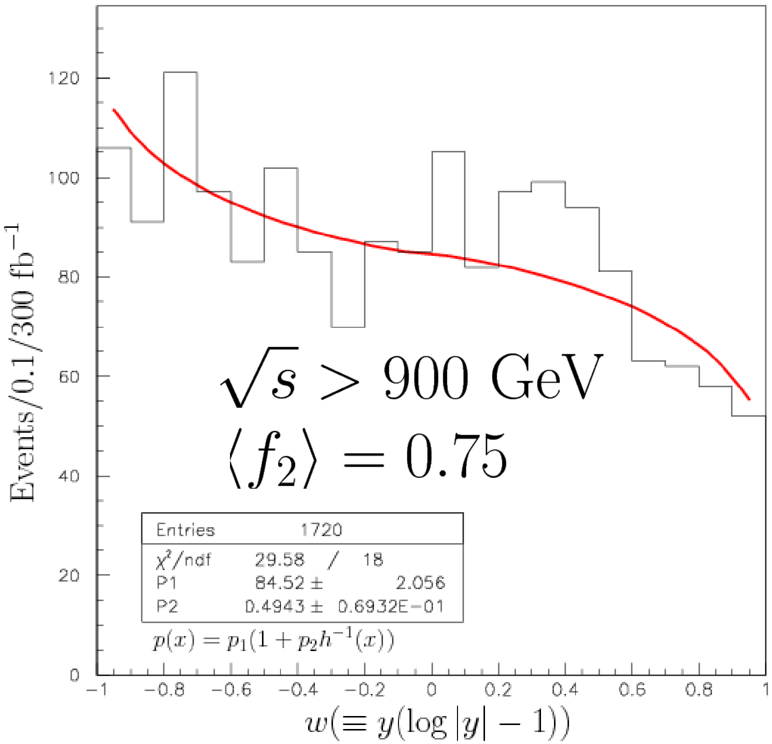
Angle-angle correlation

The $\cos\theta_1\cos\theta_2$ term gives a non-trivial correlation even if $a_W=0$.

By defining a variable:

$$w = h(y) \equiv y(\log y - 1) \qquad y \equiv \cos\theta_1 \cos\theta_2$$

$$\rightarrow \quad d\sigma \propto (1 + a_N \langle f_2 \rangle h^{-1}(w))dw$$



Deviation from the flat distribution is a sign of parity violation and the spin-spin correlation.

The non-trivial distribution is diluted by false solutions by about a factor of two.

Combine with the a_N measurement by z_l distribution, this will be an interesting test of spins!

Azimuthal angle distributions

For recent discussion,
[Buckley, Murayama, Klemm, Rentala '07]

$$d\sigma \propto \left[1 \pm \frac{\pi^2}{16}\langle g_1(\beta_A, \beta_B)\rangle \cos\phi_1 \pm \frac{\pi^2}{16}\eta_W \langle g_2(\beta_A, \beta_B)\rangle \sin\phi_1\right] \frac{d\phi_1}{2\pi}$$

$$d\sigma \propto \left[1 \mp \frac{\pi^2}{16} a_N \langle g_1(\beta_B, \beta_A)\rangle \cos\phi_2 \mp \frac{\pi^2}{16} a_N \eta_W \langle g_2(\beta_B, \beta_A)\rangle \sin\phi_2\right] \frac{d\phi_2}{2\pi}$$

$\sin\phi$ term measures CP (or T) violation.

Signs of the coefficients are opposite for $\chi^+\chi^0$ and $\chi^-\chi^0$ productions.

Effective polarization of the beam through the W-quark interaction and the parity violation in the decays make the distribution possible.

We need to know the direction of the intial (anti-)quark to define the azimuthal angle. (we know it only statistically at the LHC.)

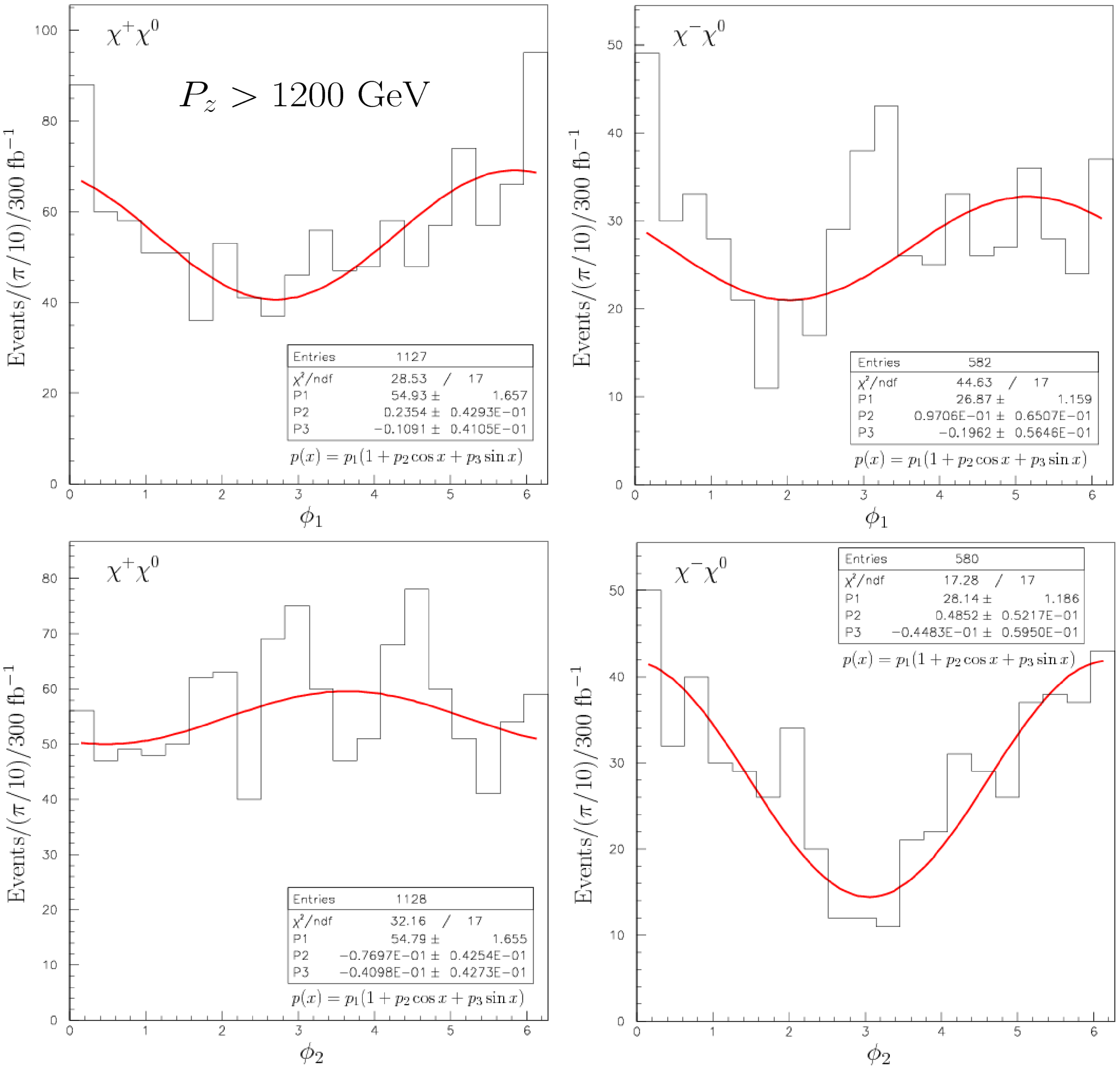
$0 < g_1 < 1$

boosted production

threshold production

$0 < g_2 < 0.31 \leftarrow \beta \sim 0.77$

Boosted and threshold production



Theoretical input:

$\eta W=0$

Qualitatively OK.

One can eliminate (or understand) the fake distribution by false solutions by using events with different charges.

$$\frac{\pi^2}{16}\langle g_1\rangle = 0.51$$

$$\frac{\pi^2}{16}\langle g_2\rangle = 0.16$$

Summary

* In the long-lived stau scenario, it is possible to perform a detailed analysis of exclusive processes.

* Masses of superparticles (not the mass differences) can be measured with a good accuracy.

* Chargino-neutralino production is a good process to test supersymmetry.

* P and CP (or T) violation can be measured. We can lean about model parameters such as gaugino/higgsino mixing and left-right mixing.

* Study of neutralino-pair production will also be important.