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

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Based on 0806.1057 [hep-ph]

Talk at IPMU, Kashiwa, Japan, June 26

Mini review of SUSY breaking

MSSM

MSSM is defined by

Supersymmetric Standard Model	+	O(100) soft SUSY breaking terms ???

This is analogous to

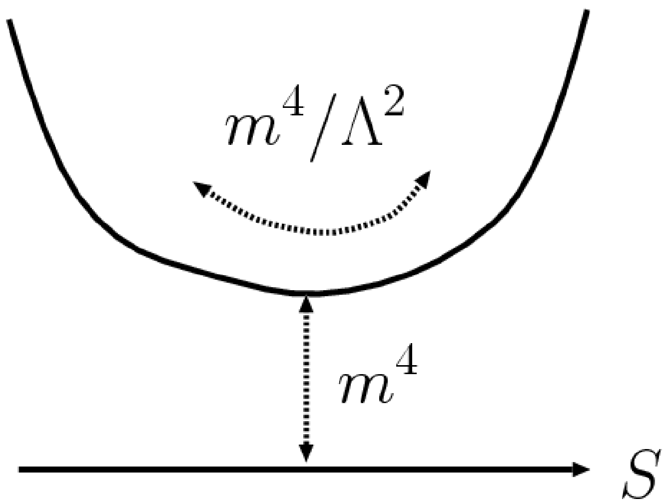
Standard Model	-	Higgs boson

SU(3)xSU(2)xU(1) gauge theory + fermion masses

W+Z boson masses

We want the Standard MSSM for this model to be a consistent theory.

SUSY breaking/mediation



$$K = S^\dagger S - \frac{(S^\dagger S)^2}{\Lambda^2} \qquad W = m^2 S$$

<u>Classification of the mediation models</u>

SUSY breaking sector

$$\mathcal{L} \ni f(S) F^{\mu\nu} F_{\mu\nu}$$

SM gauge fields

Gravity

$$f(S) = c_0 + \frac{c_1 S}{M_{\rm Pl}} + \cdots$$

Gauge

$$f(S) = c_0 + c_L \frac{\alpha}{4\pi} \log S + \cdots$$

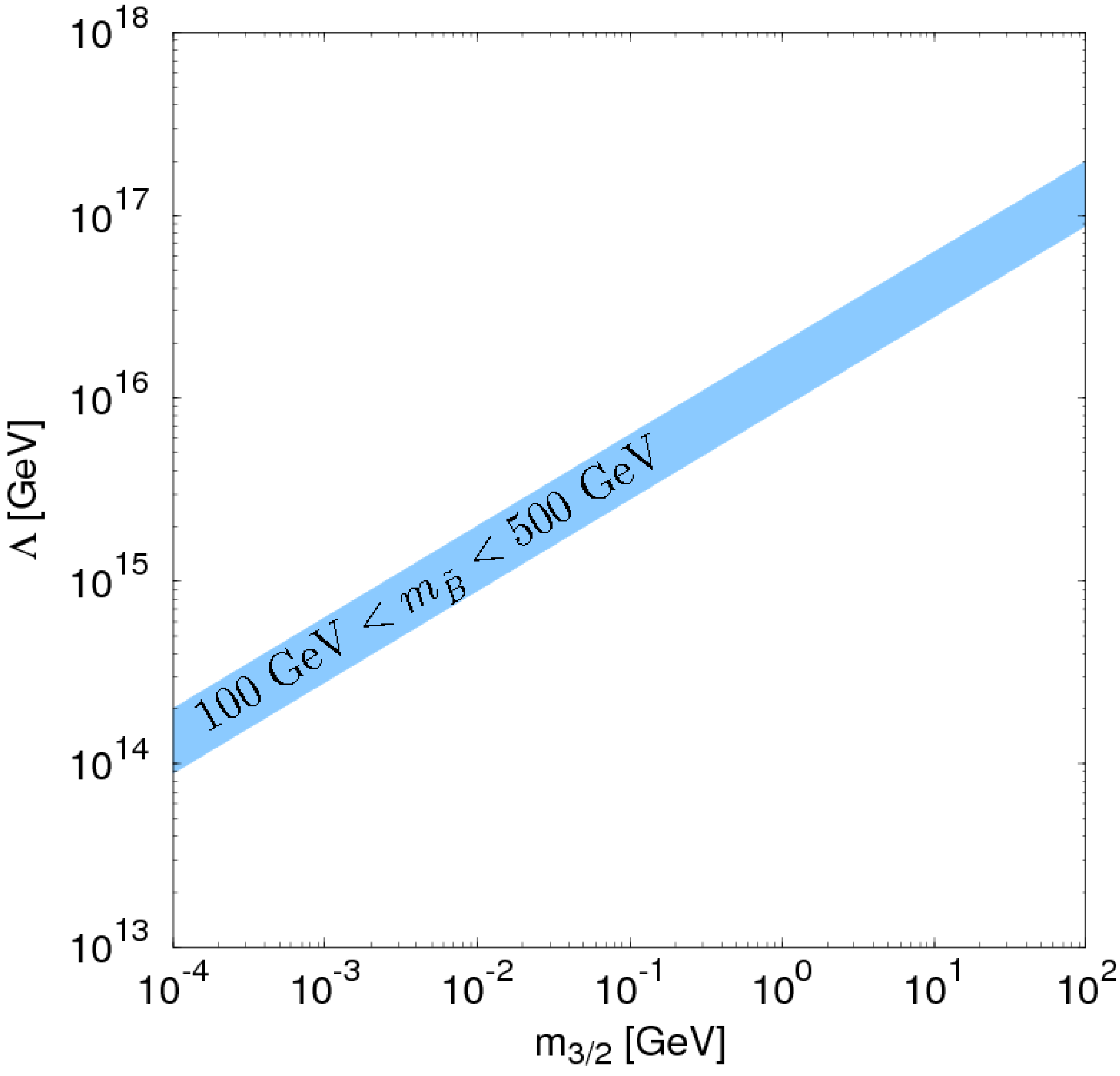
Anomaly

$$f(S) \simeq c_0$$

Sweet Spot Supersymmetry

[Ibe, RK '06]

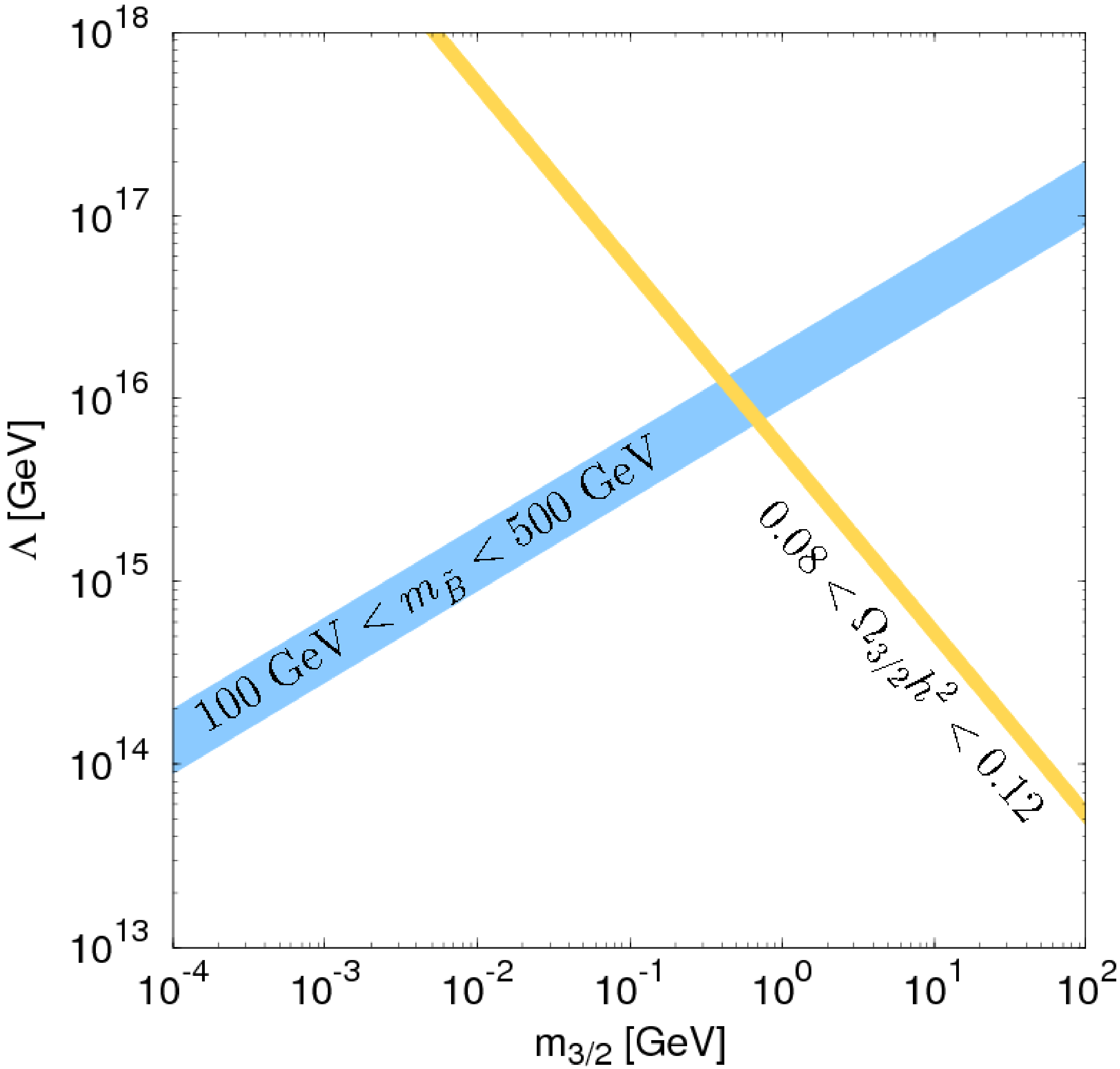
Gaugino masses



Sweet Spot Supersymmetry

[Ibe, RK '06]

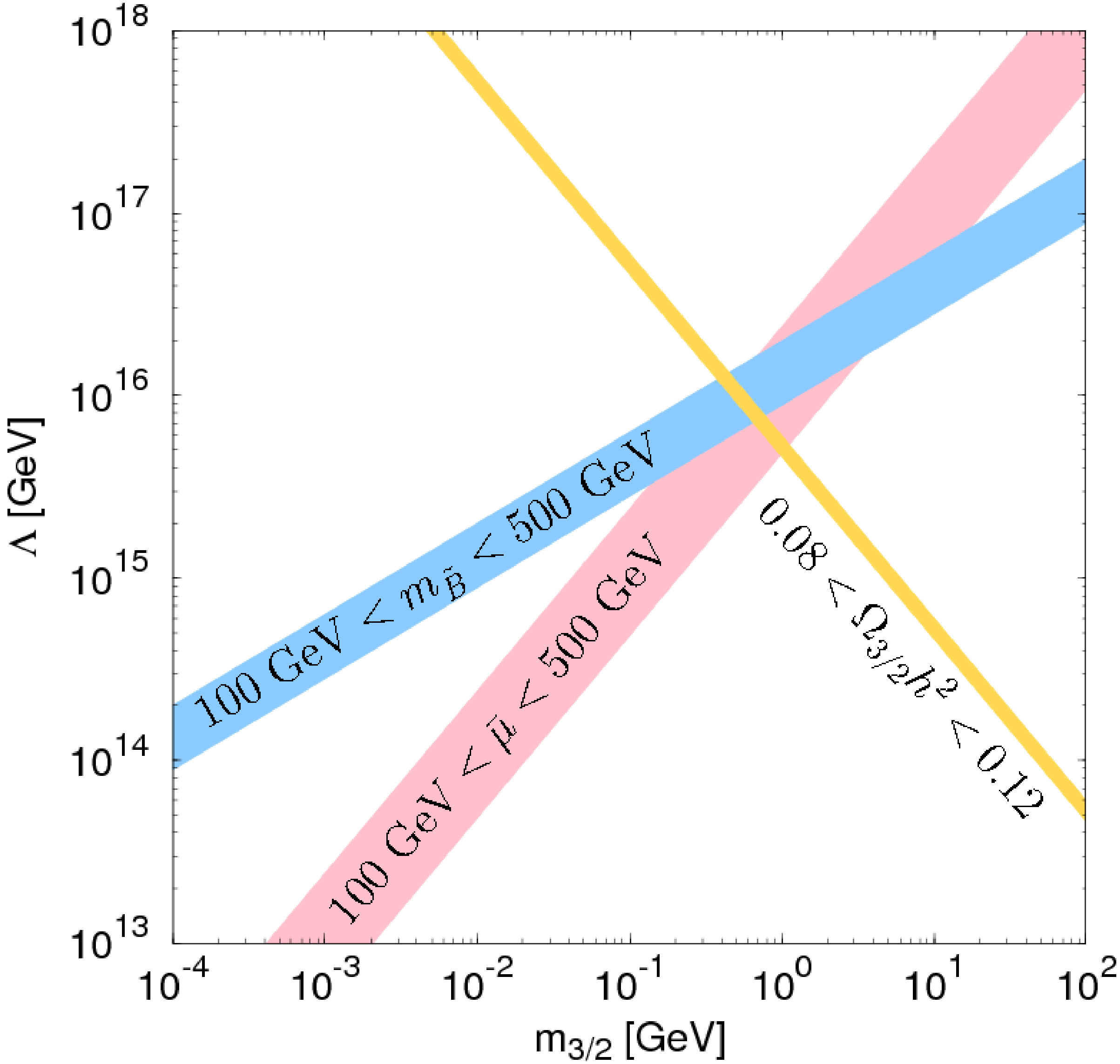
Dark Matter!



Sweet Spot Supersymmetry

[Ibe, RK '06]

μ-term

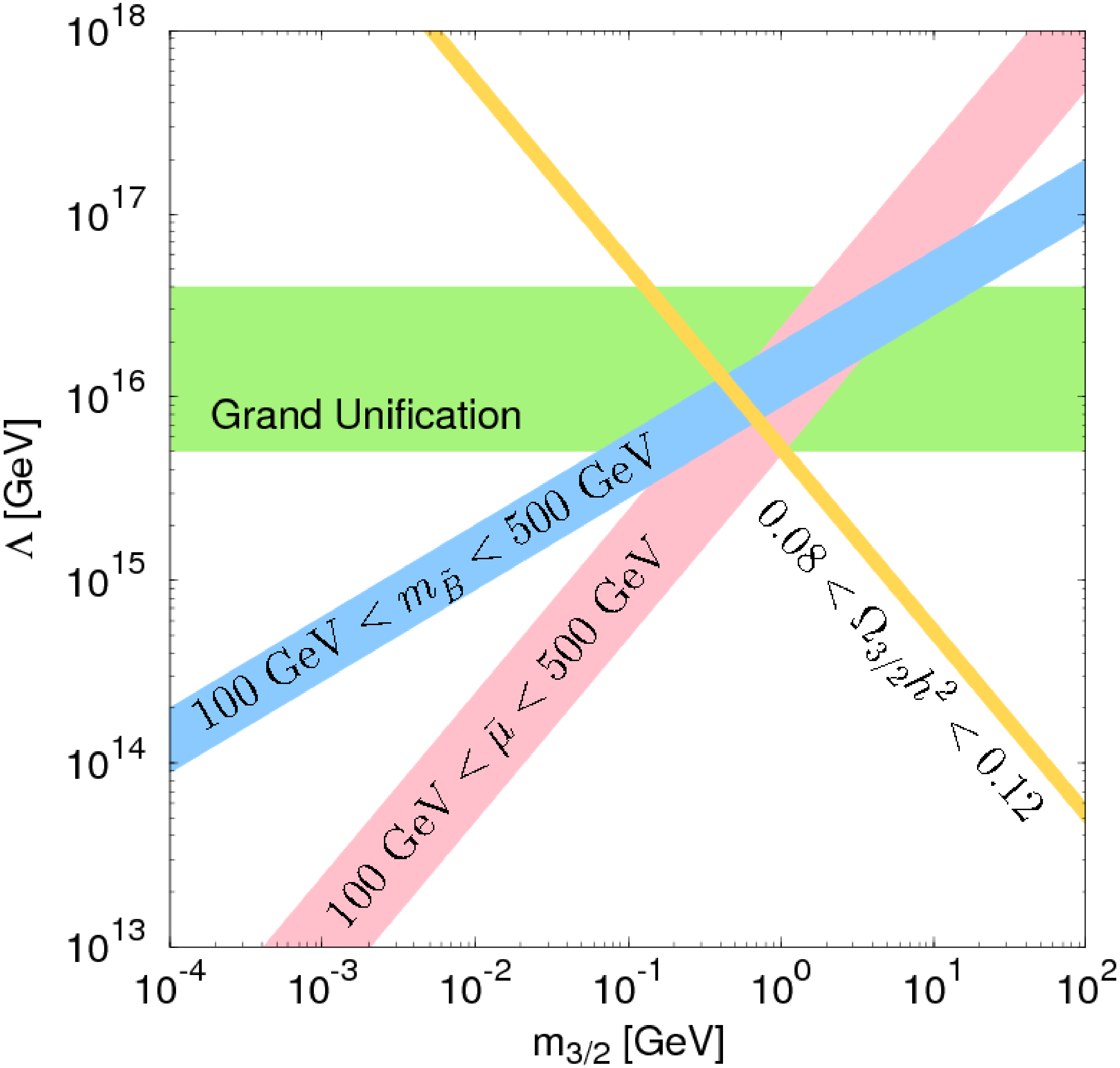


Assuming direct interaction between SUSY breaking and the Higgs fields.

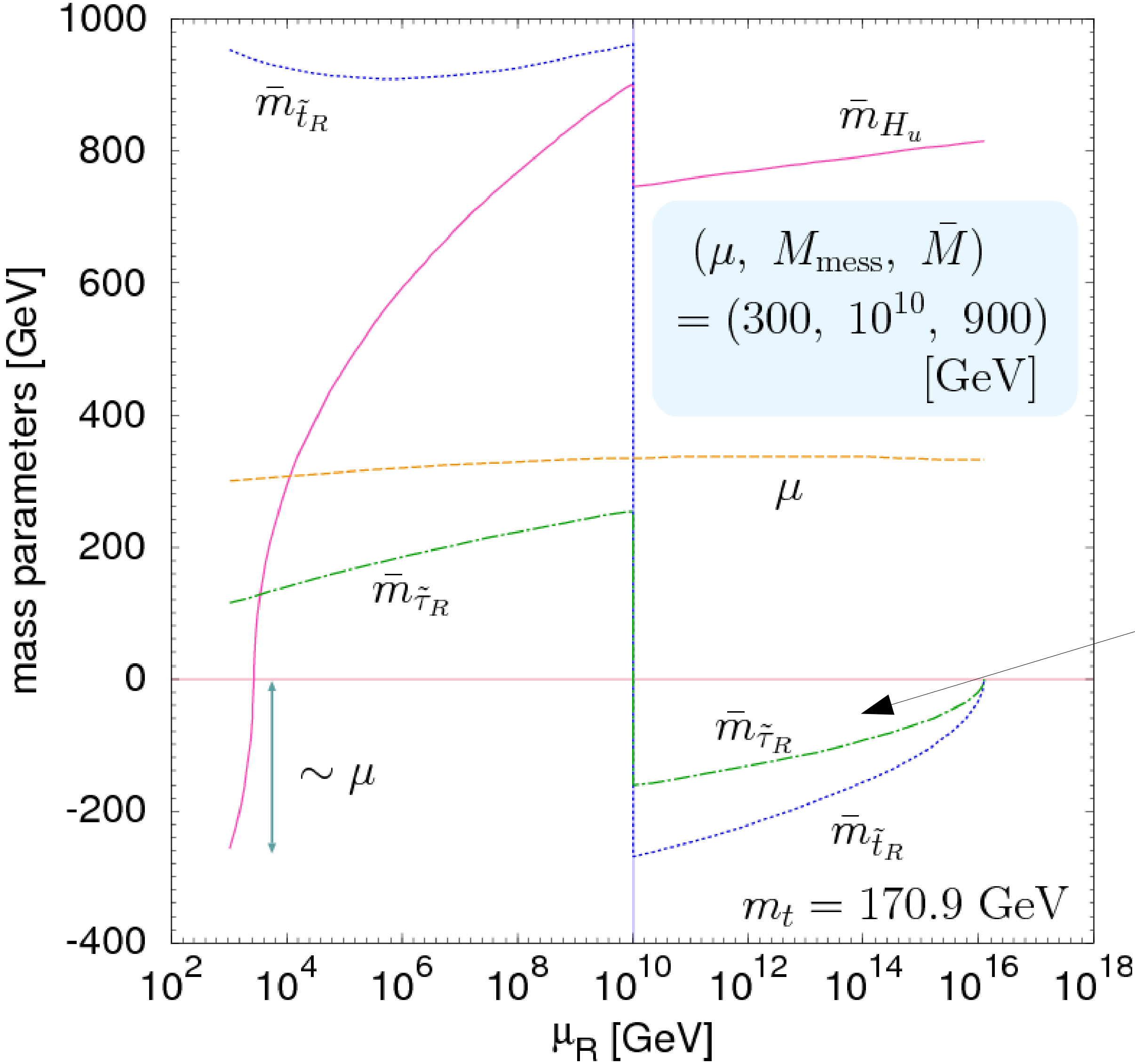
Sweet Spot Supersymmetry

[Ibe, RK '06]

Grand Unification!



Sweet Spot and stau NLSP



Negative contributions through the Yukawa interaction.

It is a result of a specific (but almost unique successful) model, but it is in general true that the Yukawa interaction can make stau lighter than other superparticles.

Given that there is no strong motivation to believe in gravity mediation, the stau NLSP scenario is I think worth looking at.

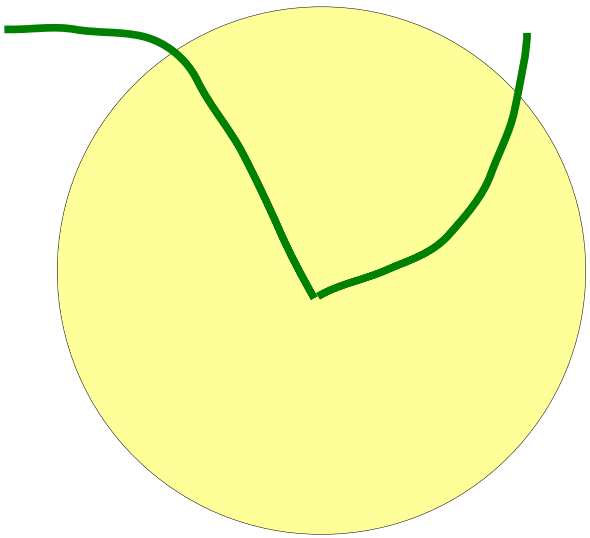
The LHC signatures are very different from conventional (and unmotivated) scenarios.

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]

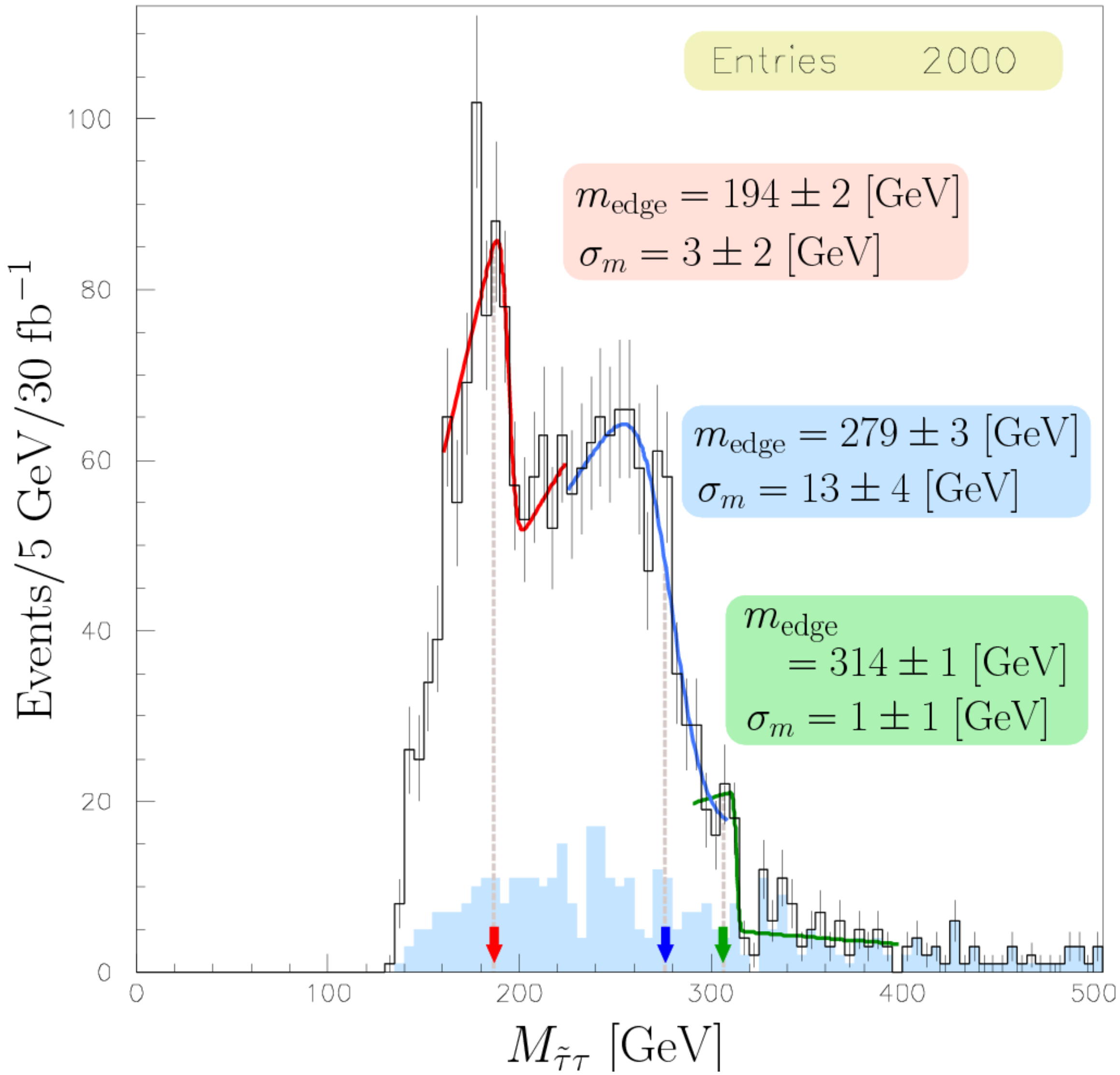
* New search for Lepton Flavor Violation

  [Hamaguchi, Ibarra '04][RK '08]

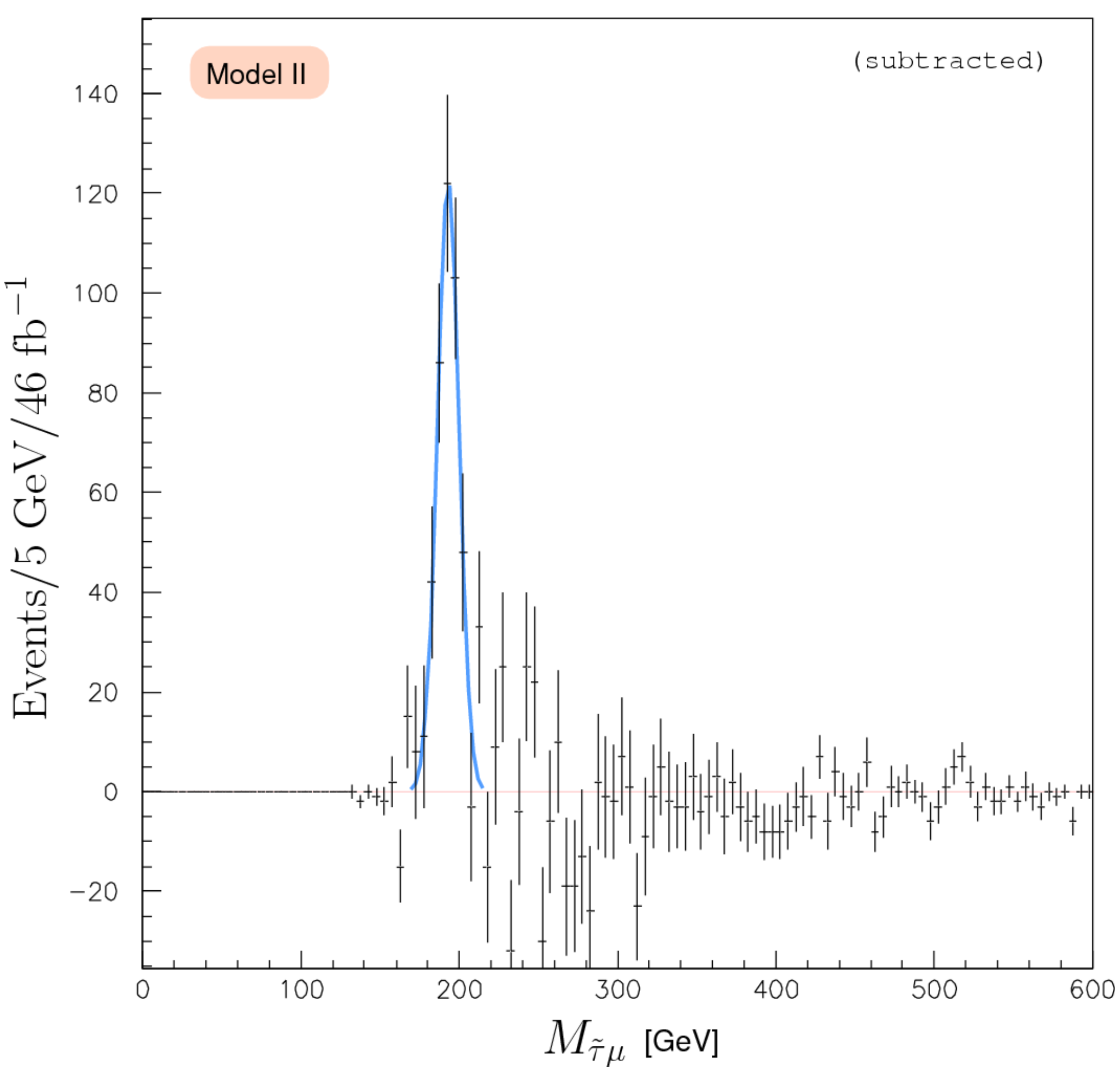
* lifetime measurement

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

Neutralino mass measurement (Sweet Spot example)

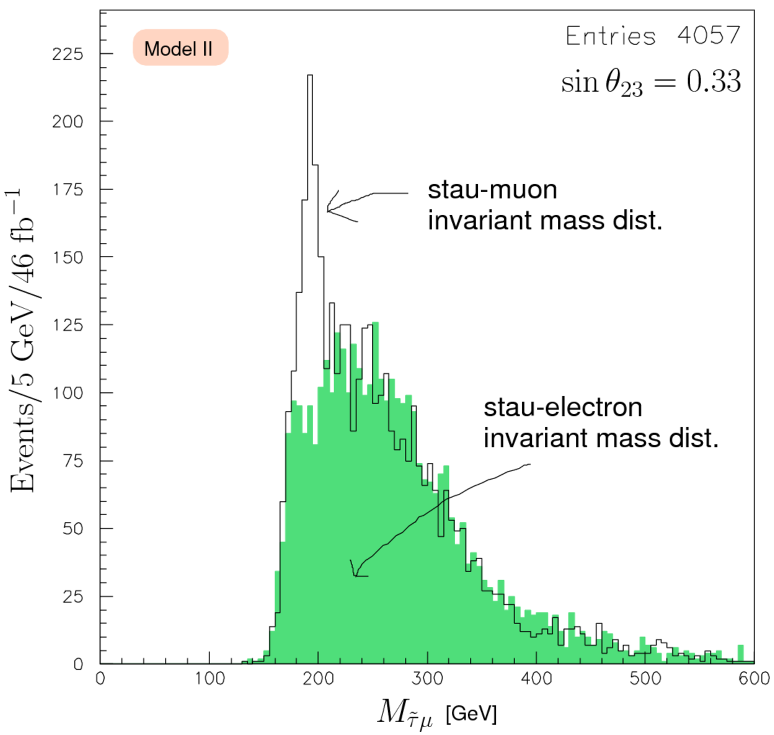


Search for LFV neutralino decay



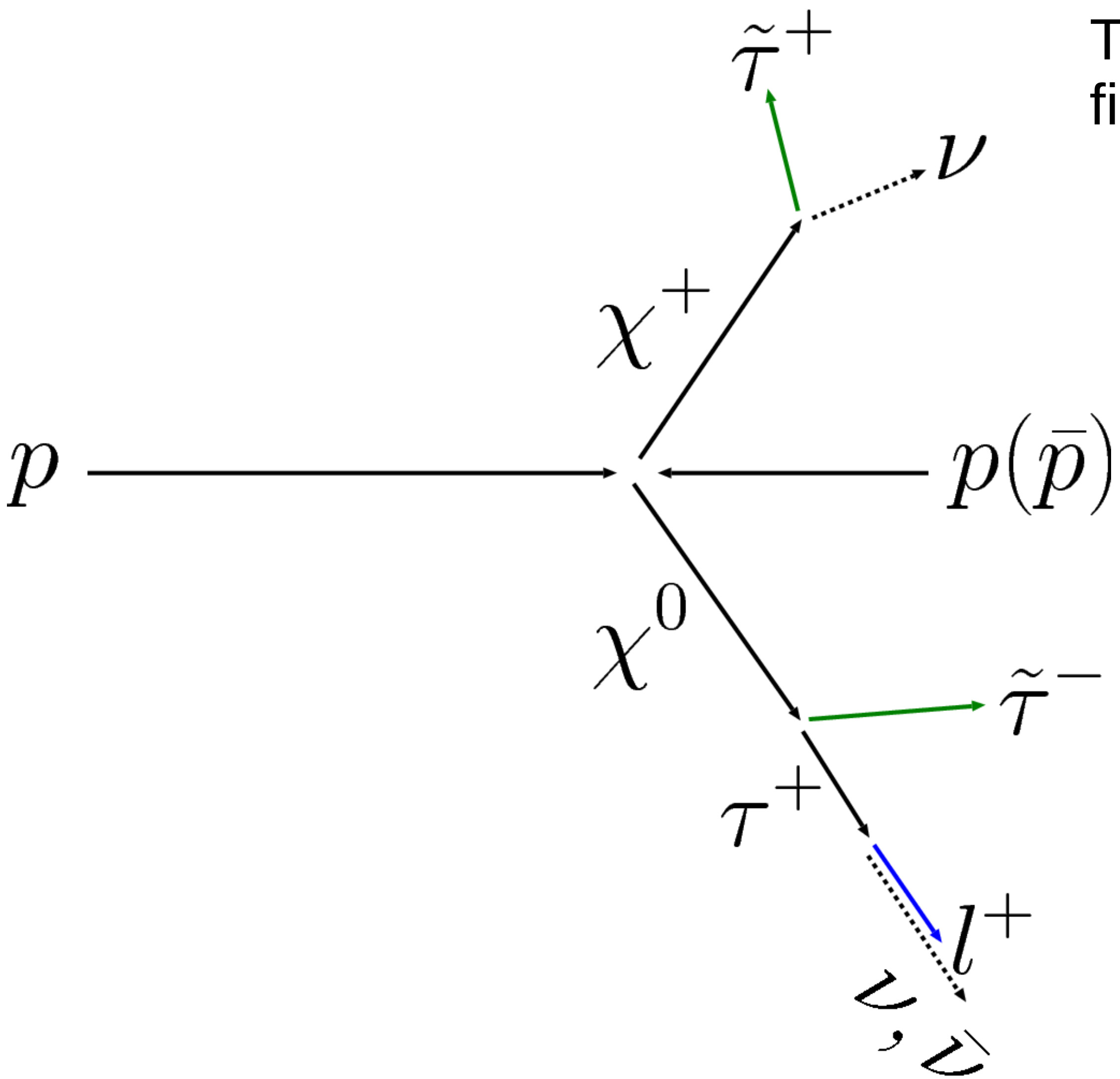
Sensitivity to the mixing angle is O(0.1).

This can be better than $\tau \to \mu\gamma$ decay



Chargino-neutralino production with long-lived stau

With long-lived staus in the final state, we can do detailed 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.

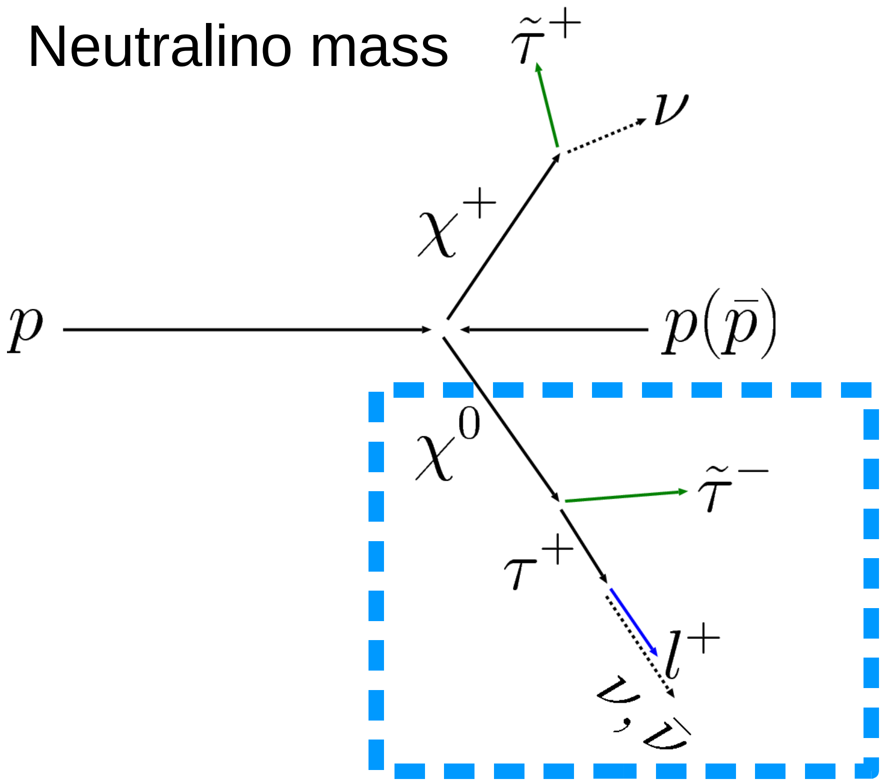
We can do many things!

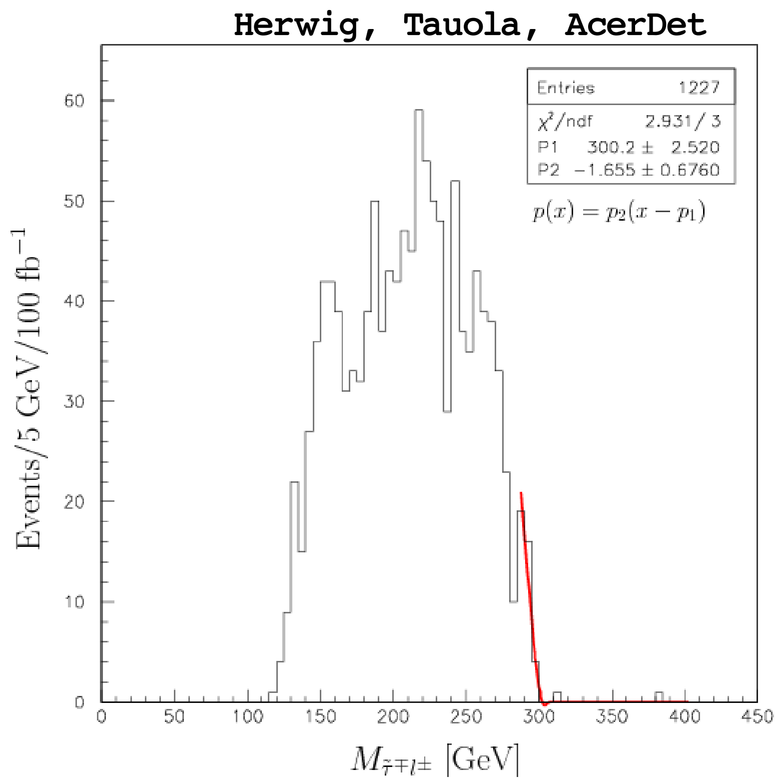
* mass measurements
* spin measurements
* P violation measurements
* CP violation measurements

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

Mass measurements

Neutralino mass

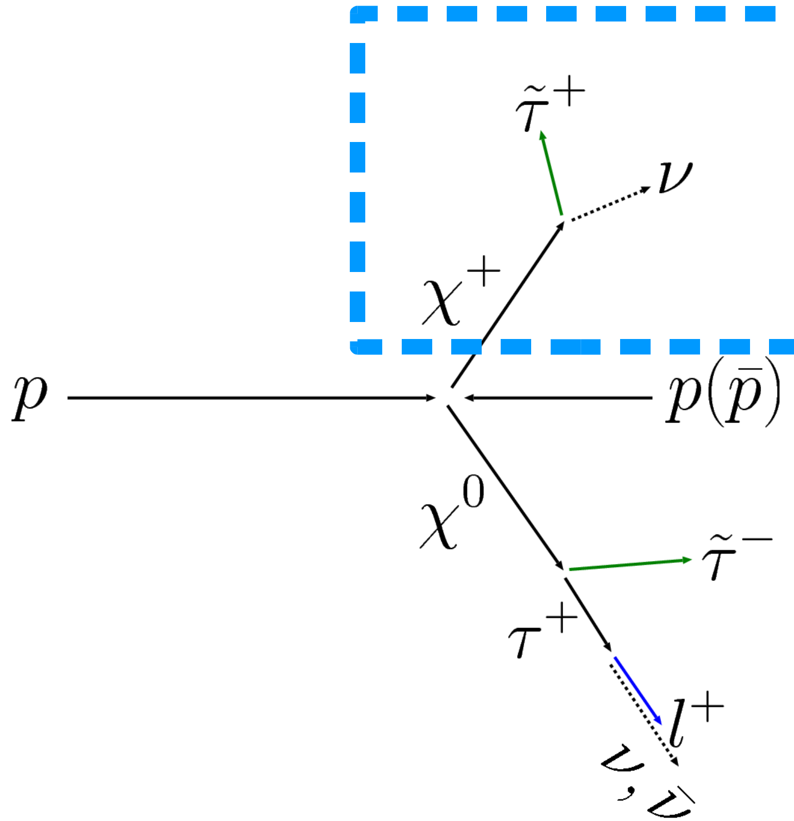




δM=3 GeV

(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.

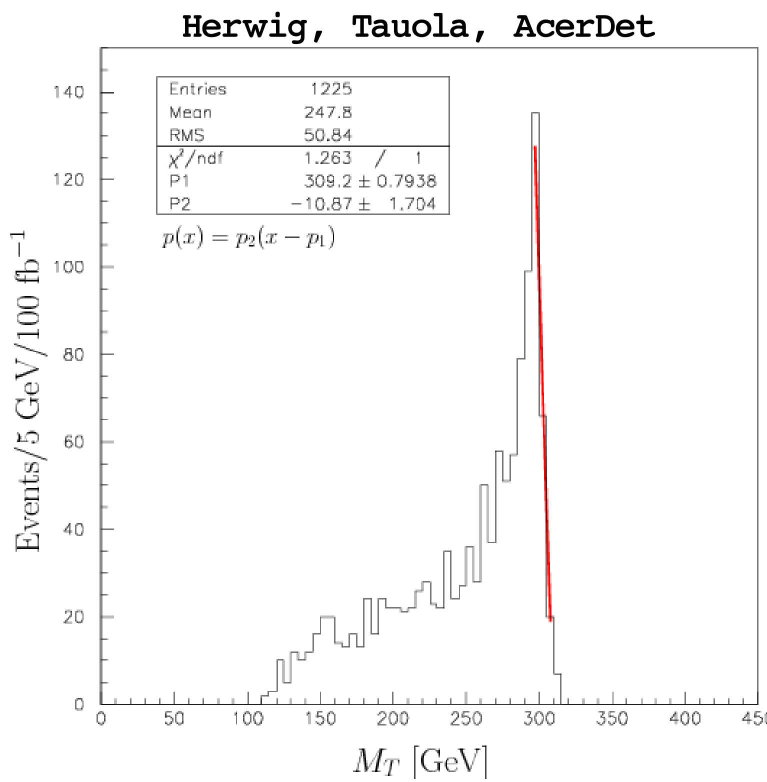
$$z_l \equiv \frac{E_l}{E_\tau}, \qquad \left(P_{\tilde{\tau}^-} + \frac{P_l}{z_l}\right)^2 = m_{\chi^0}^2$$

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

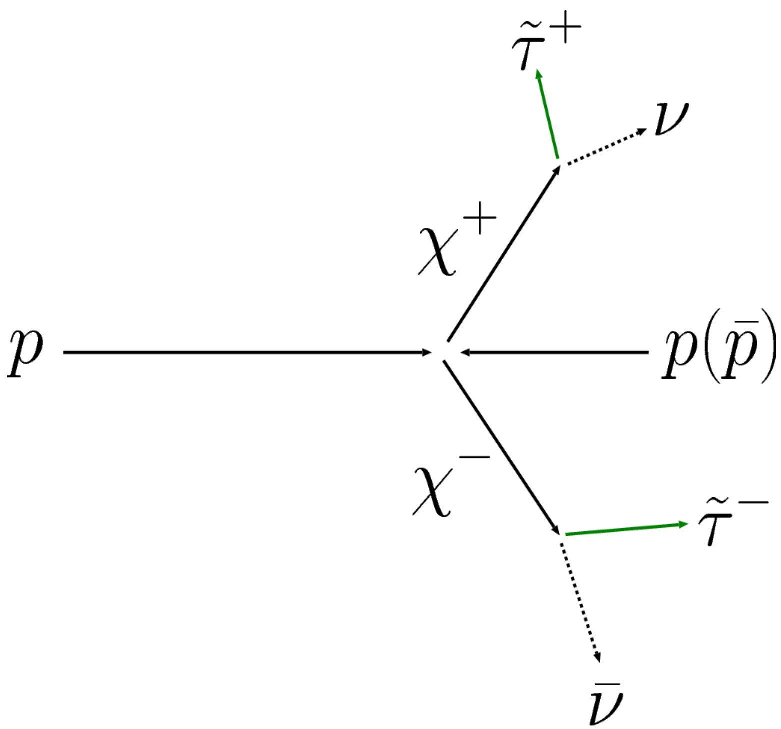
→ Transverse mass

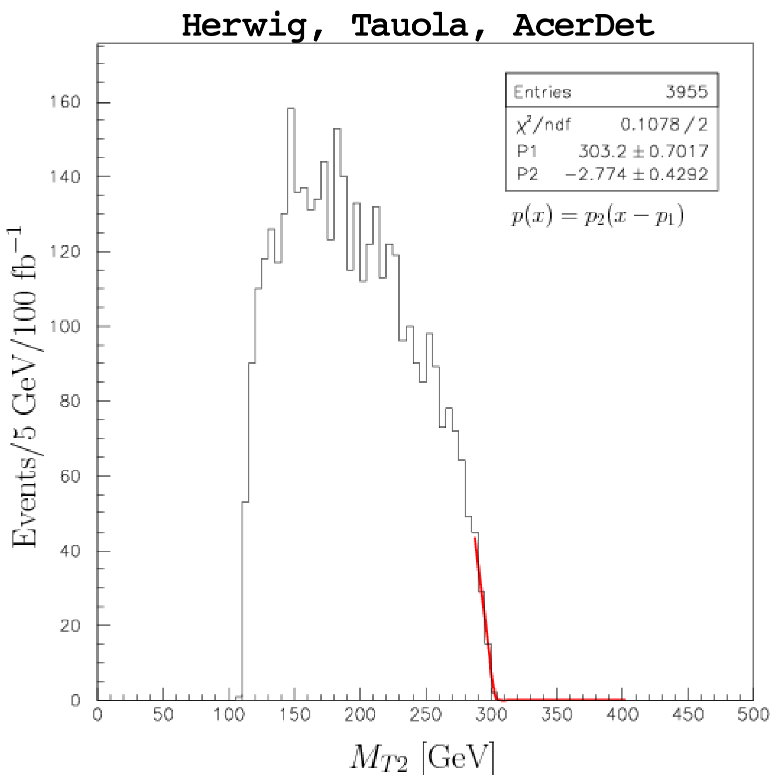
δM=0.8 GeV

(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.

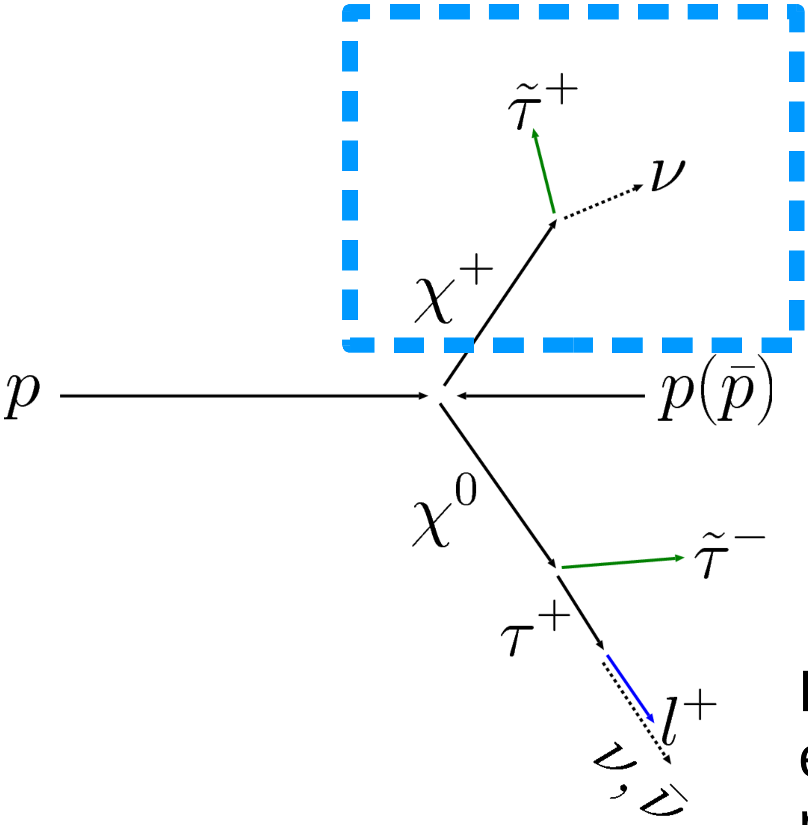




The M_{T2} variable can be used for this process.
[Lester, Summers '99]

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:



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

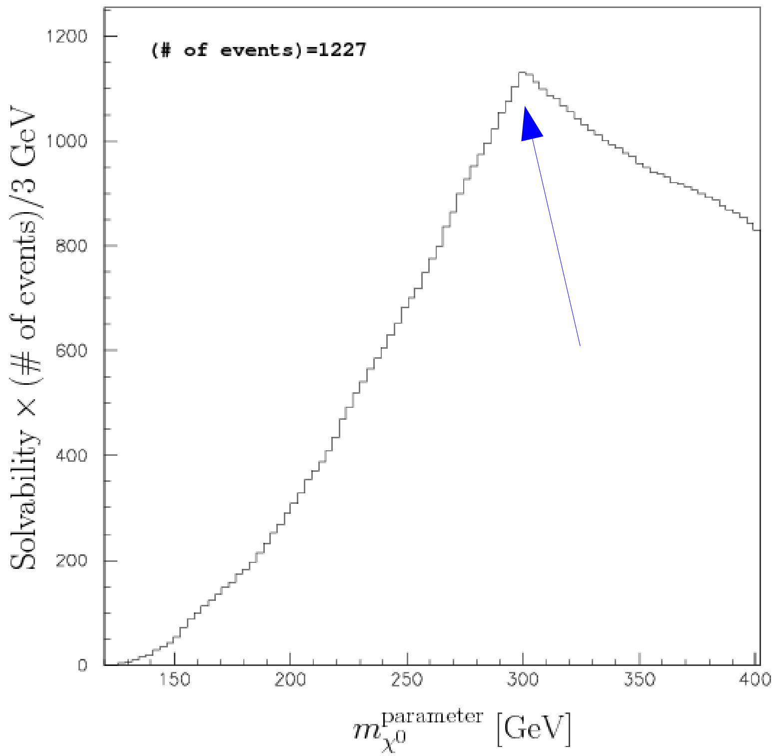
Unfortunately, we have two solutions to this equation.

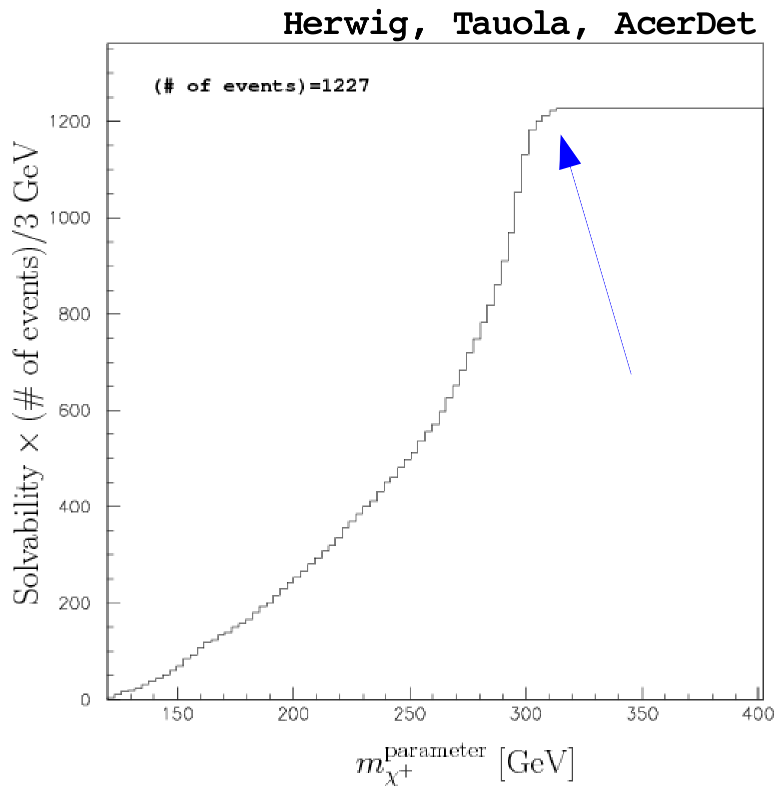
But anyway, we can fully reconstruct the event up to a two-fold ambiguity once the neutralino and chargino masses are known.

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 give a physical solution, i.e., $P_z(\nu)$ is a real number and $0<z_l<1$.

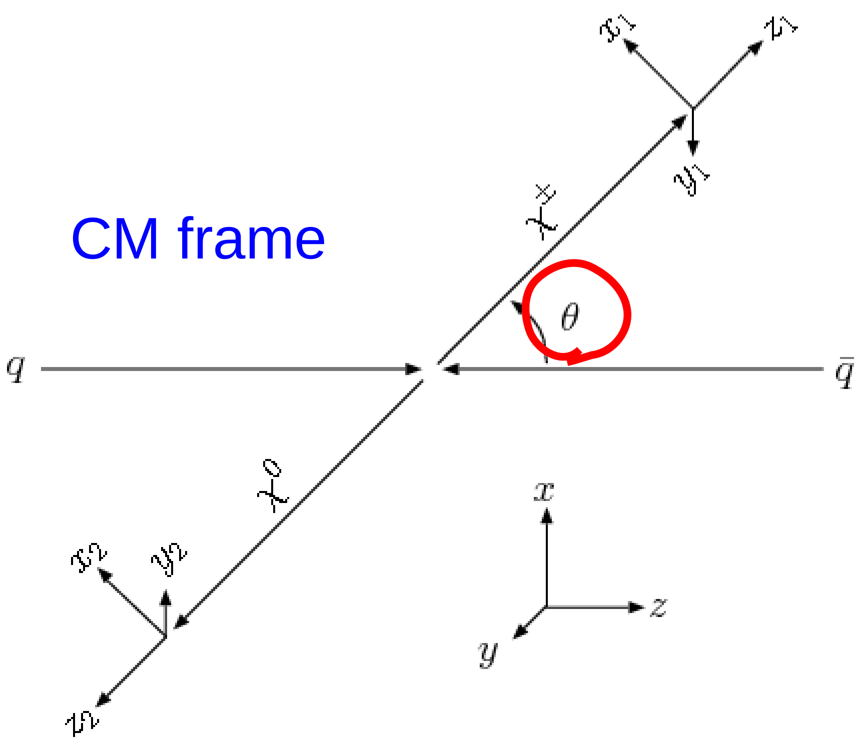
By looking for a peak or a point where solvability saturates, we can get masses.

δM~a few GeV.

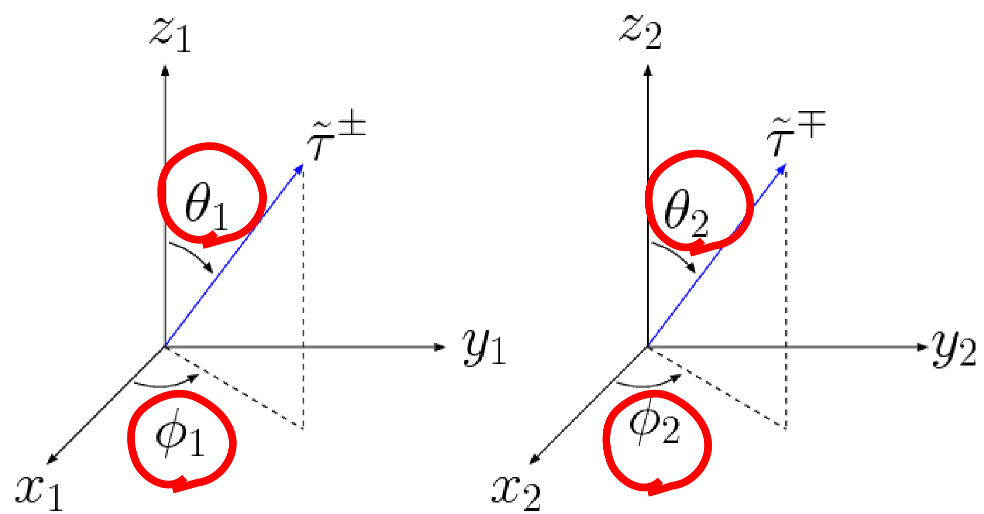
Various distributions

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.

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

Spin correlations

chargino-neutralino production

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

spin dependent part

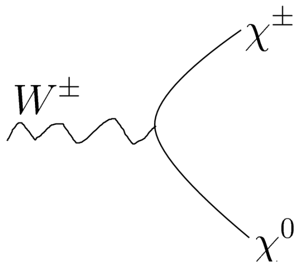
$$\rho^{ab}(\theta) = \cdots$$

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).

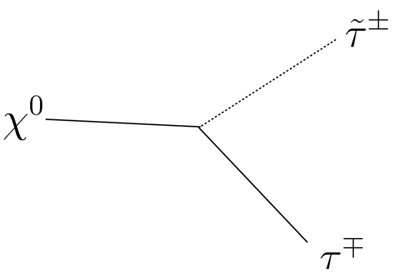
Lagrangian and asymmetry parameters



* 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

$$a_W \equiv \frac{|w_L|^2 - |w_R|^2}{|w_L|^2 + |w_R|^2} \qquad \xi_W \equiv \frac{2\mathrm{Re}[w_L^* w_R]}{|w_L|^2 + |w_R|^2} \qquad \eta_W \equiv \frac{2\mathrm{Im}[w_L^* w_R]}{|w_L|^2 + |w_R|^2}$$

Parity violation in production

CP violation in production

z_l distribution

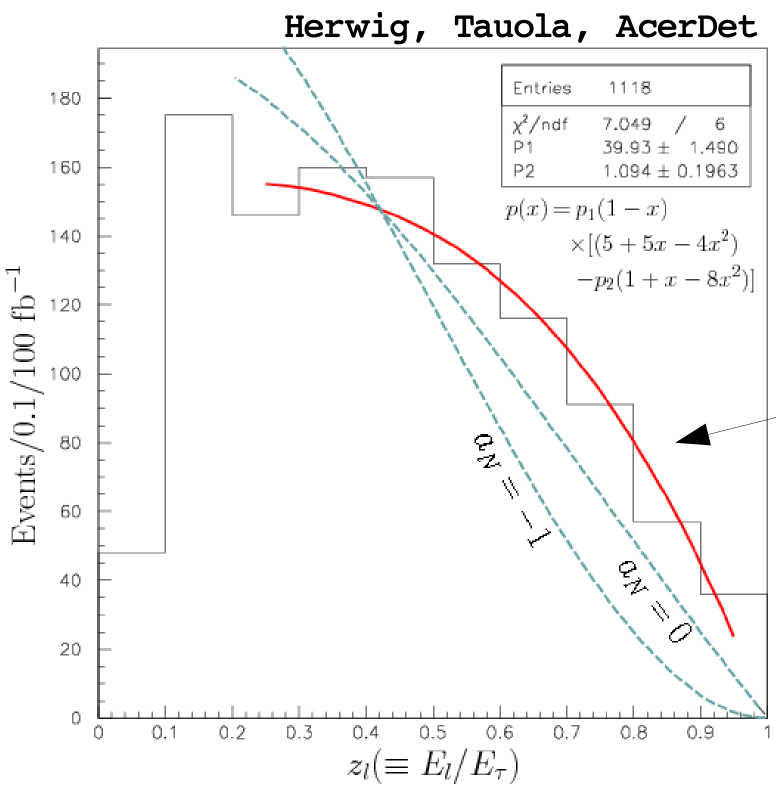
z_l is a simple observable since it is a boost invariant quantity. We can measure it in the lab frame. There is no two-fold ambiguity.

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

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.

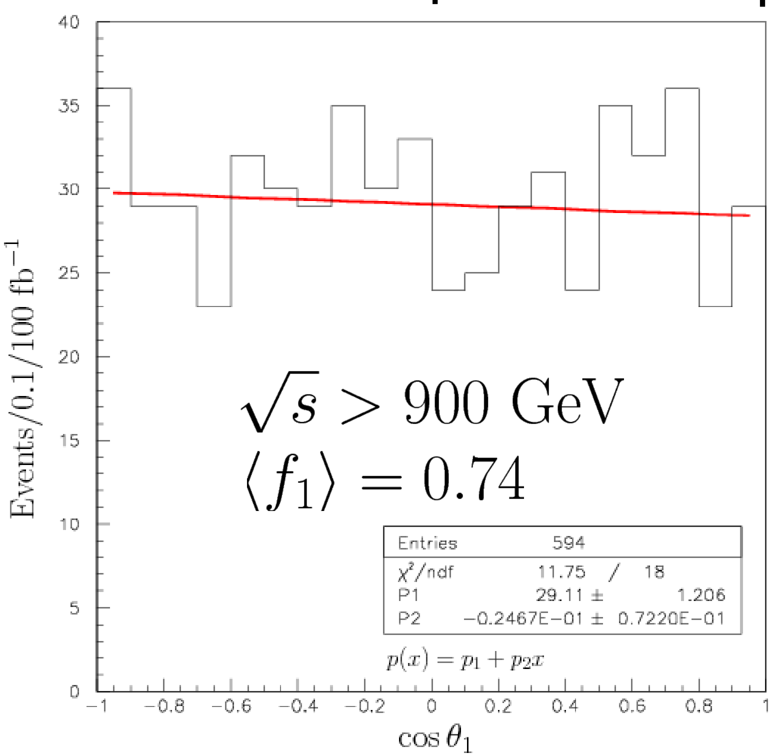
Polar angle distributions

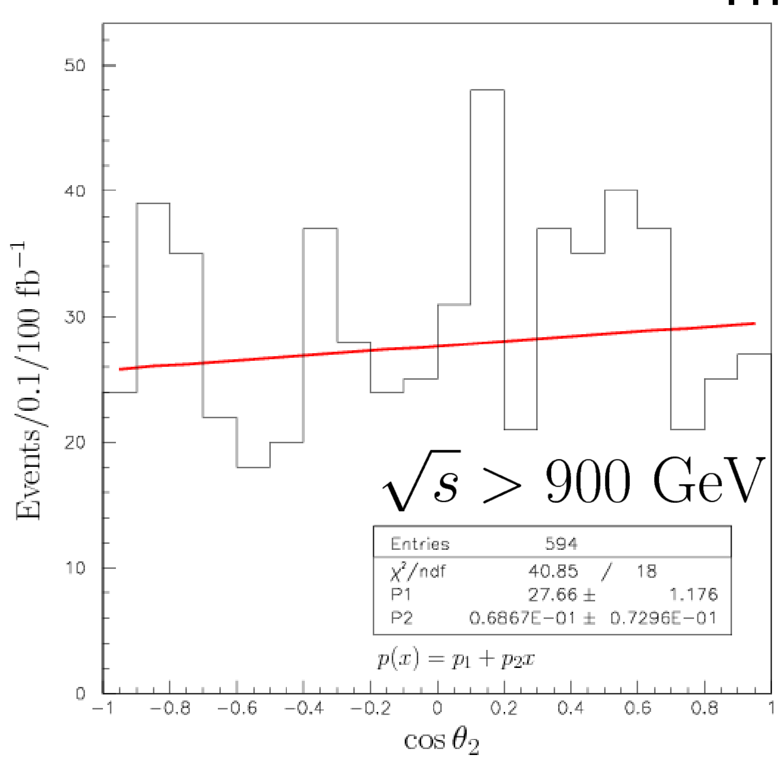
Again, the same formula for both χ+χ0 and χ-χ0 productions.

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

$0 < f_1 < 1$ — Threshold production → 0; Boosted production → 1

$1/3 < f_2 < 1$ — Threshold production → 1/3; Boosted production → 1





Theoretical value:

$a_W = 0$

→ Flat distribution

False solutions are under control. Those are randomly distributed.

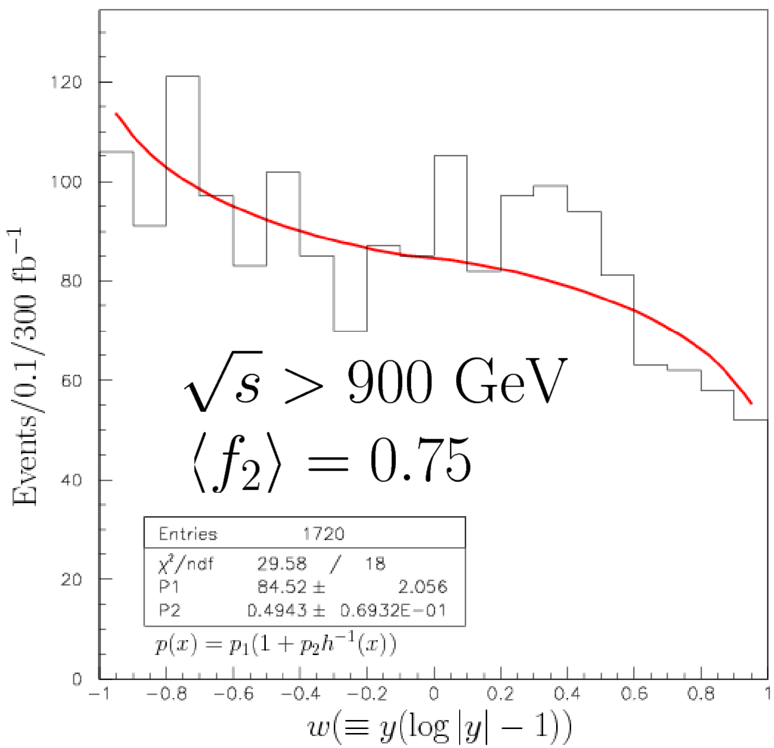
Angle-angle correlation

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.

Combining 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.

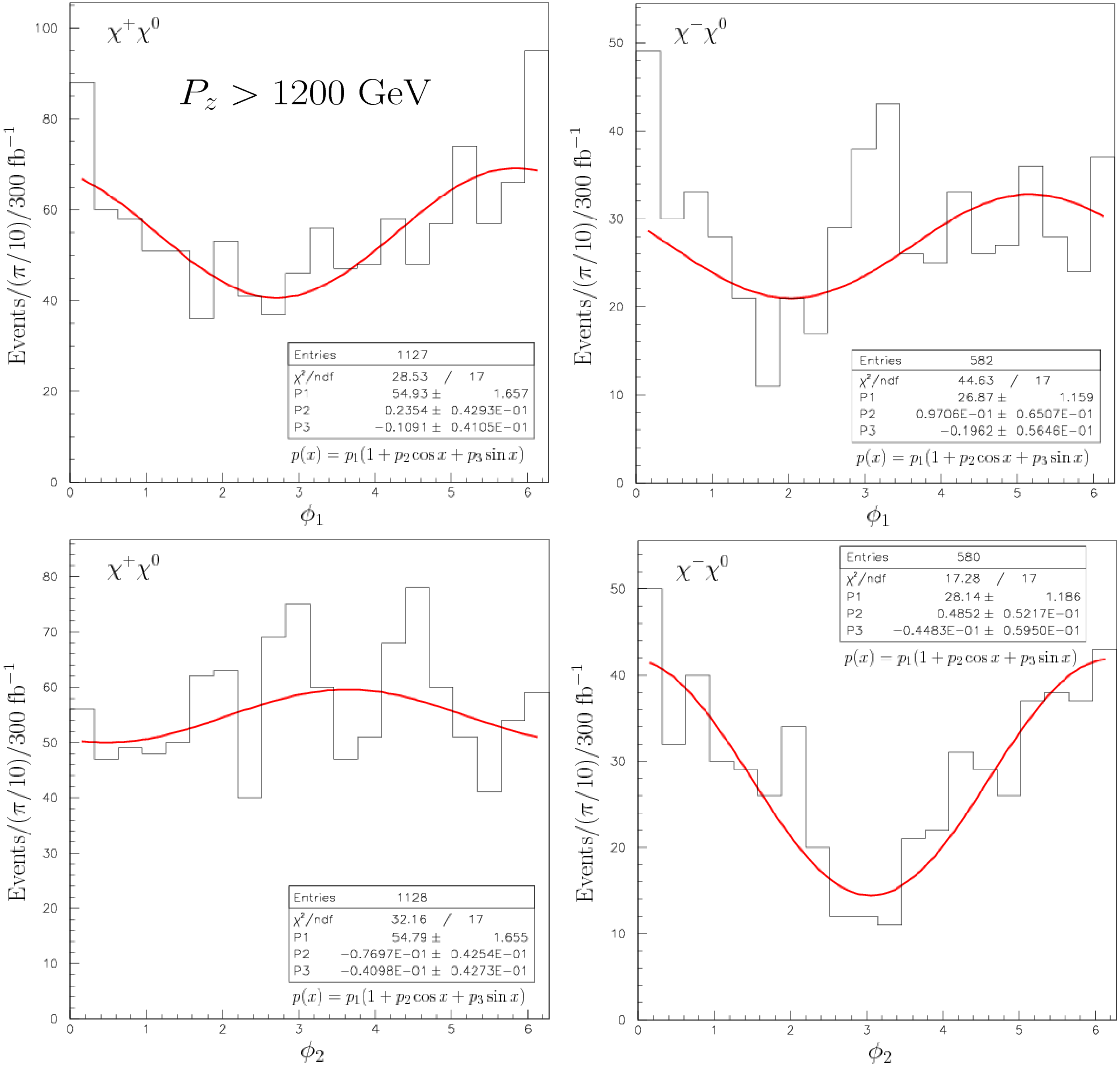
We need to know the direction of the intial (anti-)quark to define the azimuthal angle. (we know it only statistically at the LHC.)

$0 < g_1 < 1$

boosted production ← threshold production

$0 < g_2 < 0.31$ ← β~0.77

Boosted and threshold production



Theoretical input:

η_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.