Analysis of Stop Quark with Small Stop-Neutralino Mass Difference at the ILC

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1-Introduction

• Scalar top studies for small visible energy in the detector.

•Theoretical motivation: Electroweak symmetry in particle physics and the nature of dark matter and baryogenesis in cosmology both suggest the existence of new symmetries within the reach of the next generation of colliders.

• Recently, the universe dark matter energy density has been precisely measured by the Wilkinson Microwave Anisotropy Probe (WMAP) to be $\Omega_{CDM}h^2$ =0.1126+0.0161/-0.0181.

•The super-symmetry with R parity conservation provides a stable neutral dark matter candidate, the Neutralino with mass and σ ~E.W energy scale.

•The Neutralino-Stop co-annihilation region is characterized by a small mass difference M (stop-neutralino)= 15-30 GeV, with relic density compatible with the WMAP observation. ILC reach Complementary to LHC reach

•Of interest the stop decay into 2 soft charm jets and missing energy.

•Possible benchmark for vertex detectors and material budget.

2-Theoretical Motivation

- Electroweak Baryogenesis:

Sakharov Requirements:

1- Baryon Number Violation - (SM - Anomalous process)
2- C & CP violation - (SM-Quark CKM mixing)
3- Departure from Equilibrium - (SM-at EW phase transition)

Limitations of SM:

2)Not Enough CP violation & 3)→ M_{Higgs}<40 GeV ,LEP Bound M_{Higgs} >114.4 GeV

→ *Supersymmetry with light scalar top, below the top mass:* $m\tilde{t}_1 < mt$

- Dark Matter

The Supersymmetric Lightest particle (LSP), the neutralino X^0_1 is a candidate
The annihilation cross-section σ_a ($X^0_{1,}$, X^0_1) too small

But for $m\tilde{t}_1$ - m X^0_1~15-30 GeV, there is co-annihilation between the $\tilde{t}_1$ and the X^0_1 →σ_a ($X^0_{1,}$, $\tilde{t}_1$)+ σ_a ($X^0_{1,}$, X^0_1) consistent with dark matter.

3-Signal And Background Cross-Sections (pb)

Process	σ(pb)- A. Freitas+Calvin(QCD)		
	Pr(0,0)	Pr(-80%,+60%)	Pr(+80%,-60%)
$\tilde{t}\ \tilde{t}$- $M\tilde{t}_1$=120 GeV	0.115	0.153	0.187
$M\tilde{t}_1$=140 GeV	0.093	0.124	0.151
$M\tilde{t}_1$=180 GeV	0.049	0.065	0.079
$M\tilde{t}_1$=220 GeV	0.015	0.021	0.020
w^+w^-	8.55	24.54	0.77
wev	6.14	10.57	1.82
ZZ	0.49	1.02	0.44
eeZ	7.51	8.49	6.23
tt	0.55	1.13	0.50
qq, q≠t	13.14	25.35	14.85
γγ ,pT>5GeV	936		

Table 1-P(e-)/P(e+)=-80%/+60% ;P(e-)/P(e+)=+80%/-60% ,σ(eez) && σ(Wev) are from Grace and do not include Beamstrahlung/ISR The Signal is given for $\cos\theta_{\tilde{t}}$ =0.5

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4- Selection $e^+e^- \to \tilde{t}_1\bar{\tilde{t}}_1 \to c\tilde{\chi}_0^1\bar{c}\tilde{\chi}_0^1$

• Pythia with Simdet/Tesla was used for the simulations of both signal and background with CIRCE for the Beamstrahlung.

• Signature: 2 soft charm jets + missing energy

•Luminosity=500 Fb^{-1} ; $\sqrt{s}$ =500 GeV

•A short list of the sequential cuts applied as a preselection first, allowed larger samples to be produced and the cut refined at selection stage.

Pre-selection:

•4<Number of Charged tracks<50

•Pt> 5 GeV

•$\cos\theta_{Thrust}$ <0.8

•$|P_{l,tot}/P|$<0.9

•E_{vis}<380 GeV

•M(inv)<200 GeV

Selection:

•Njets =2

•Cos (Φ_A-coplanarity) >-0.9

•$\cos\theta_{Thrust}$<0.7 , P_t >12 revisited:

•$E_{vis}<0.4\sqrt{s}$

•$60GeV^2 < Minv_{jets} < 90 GeV^2$

•c-tagging- From T. Khul

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5a-Pre-selection: Efficiency Each Cut

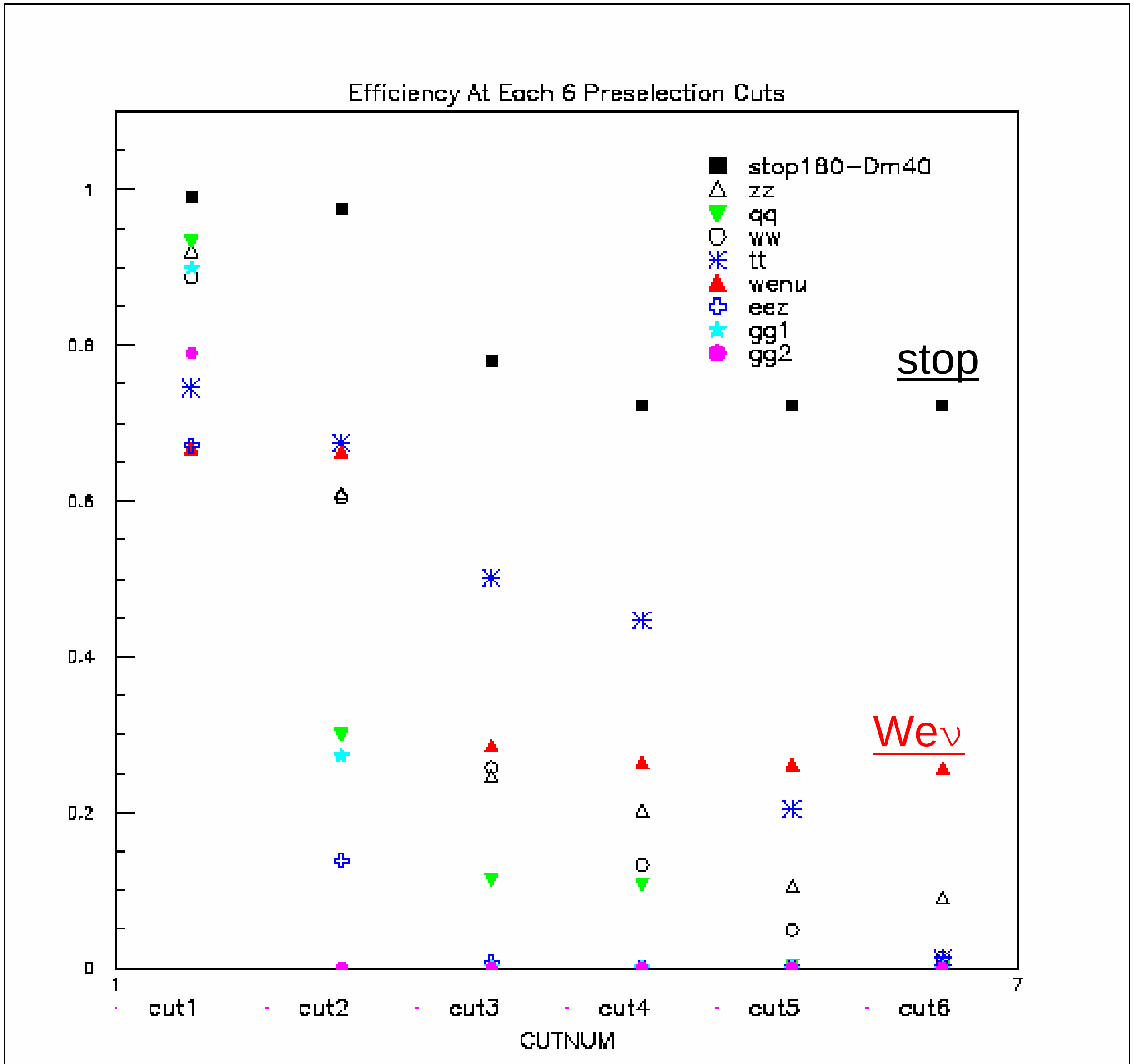

Fig 1

<u>Colour point</u>:
% of Background left after each cut, Reduced < 30%

<u>Black Points</u>:
% of signal left after each cut, Ends up to a
~70% signal left

5b-Pre-selection Efficiency: Stop

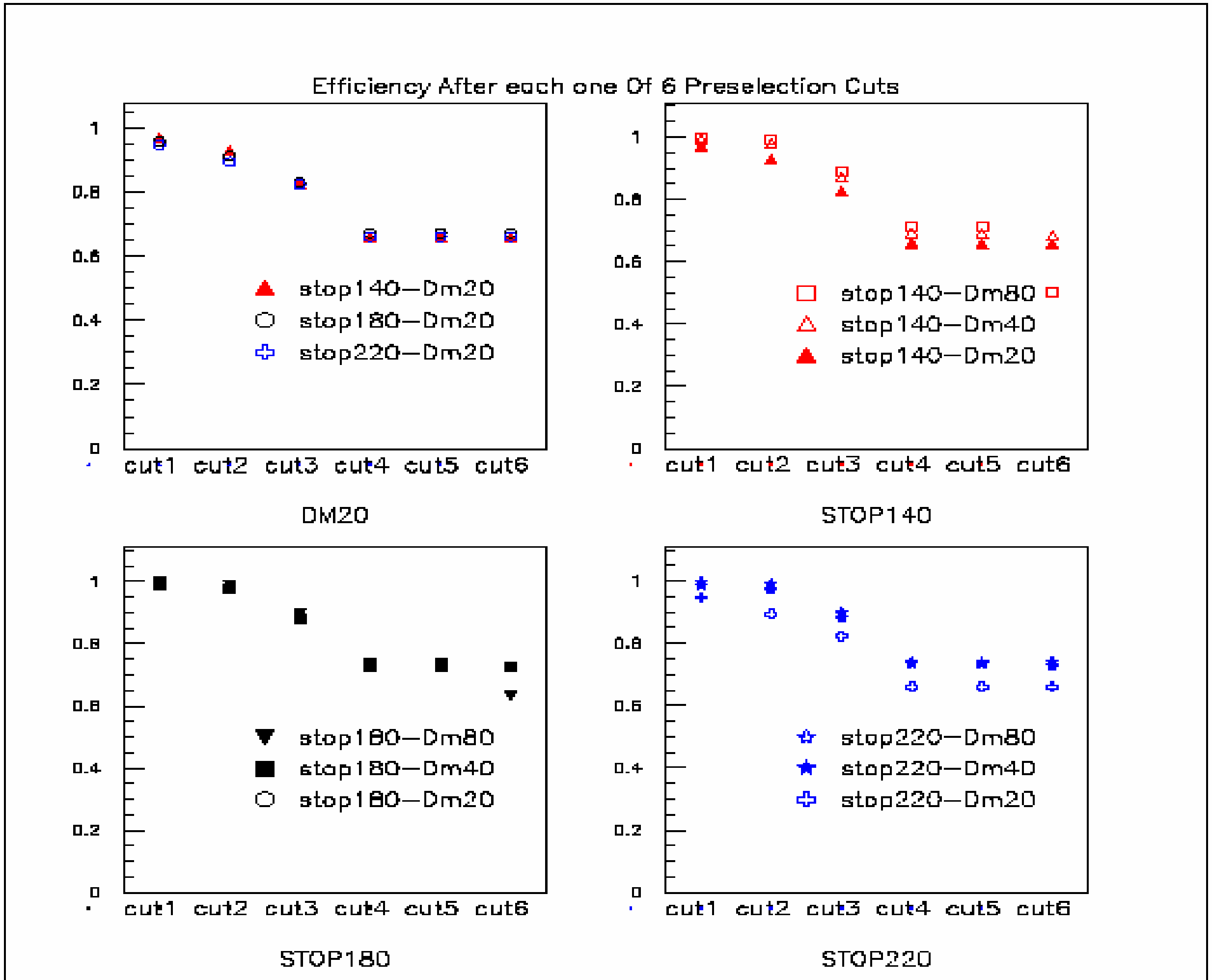

Fig. 2

<u>Upper Left</u>:

$\Delta M(\tilde{t}_1-X0)=20GeV$

$M\tilde{t}_1$ = 140GeV

$M\tilde{t}_1$ = 180GeV

$M\tilde{t}_1$ = 220GeV

Independent of $M\tilde{t}1$

<u>Others:</u>

$\Delta M(\tilde{t}_1-X0)=$ 20,40, 80 GeV

Separatly for ≠ $M\tilde{t}1$

~***Independent*** of $\Delta M(\tilde{t}1-X0)$

6a-Selection: The Background Rejection

Background	% Left - End Presel	Number Gen. Selection	Num Events Left after End Sel. – For 500 fb^-1	
γγ	0.06%	8.00 Millions	0.	< 164.
zz	9%	0.03 M	35.	257.
qq, q≠t	0.09%	0.35 M	8.	160.
ww	1.45%	0.21 M	8.	145.
tt	1.36%	0.18 M	25.	38.
wev	25.70%	0.21 M	345	5044.
eez	0.06%	0.21 M	2	36.

Table 2-The cut efficiency- And the number of background particles left normalized to 500fb^-1 are shown in the next figure for each BG channel separately. Largest remaining Background :Wev , already reduced by a factor 2 by c-tagging

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6b-Selection: The Background Rejection

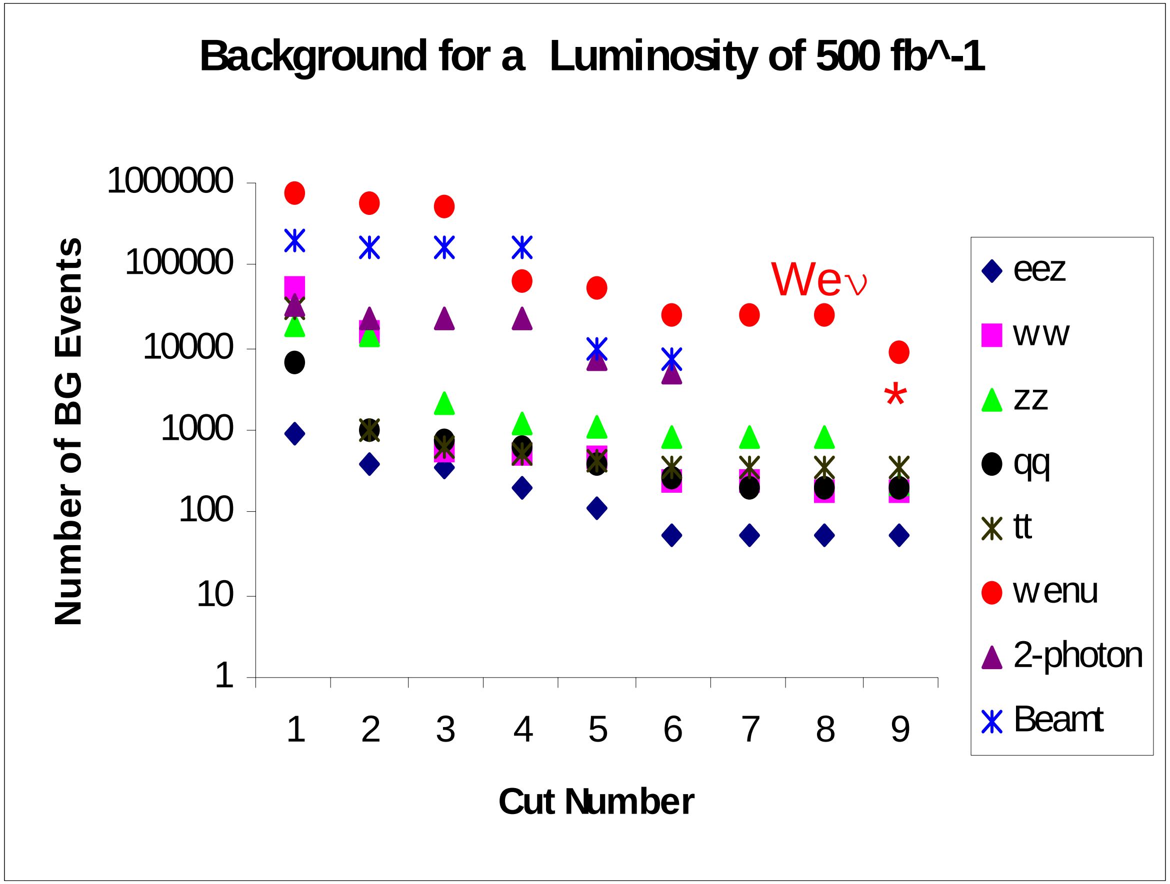

Fig. 3

For a Luminosity of 500 fb^-1. the number of BG events left are reported after each of the 9 selection cuts
The c-taging reduces the Wev background to half its previous value, the red Star in the plot. It is the leading background

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7a-Selection: The Signal Efficiency

Background	% Left - End Presel	Number Gen. Selection	% Left - End Sel.	Num. Left – For 500 fb^-1
Mstop=140				
Dm=20	68.5	50000	20.9	9720
Dm=40	71.8	50000	10.1	4700
Dm=80	51.8	50000	10.4	4840
Mstop=180				
Dm=20	68 .0	25000	28.4	6960
Dm=40	72.7	25000	20.1	4925
Dm=60	63.3	25000	15.0	3675
Mstop=220				
Dm =20	66.2	10000	34.6	2600
Dm=40	72.5	10000	24.2	1815
Dm=60	73.1	10000	18.8	1410

Table 3

7b-Signal Efficiency

Δm (GeV)	$M\tilde{t}_1$=120GeV	$M\tilde{t}_1$ =140GeV	$M\tilde{t}_1$=180GeV	$M\tilde{t}_1$=220GeV
80		10%	15%	19%
40		10%	20%	24%
20	17%	21%	28%	35%
10	19%	20%	19%	35%
5	2.5%	1.1%	0.3%	0.1%

Table 4

•Highest Signal efficiencies are reached for Δm=10-20 GeV and the efficiency increases for higher $m\tilde{t}_1$.
•Overall Signal for 500fb^{-1}, after selection cuts ~O(10^3)-O(10^4), remaining background O(10^3)
•Dm=5 GeV were not included in the cuts optimization(besides c-tagging)

8-Stop Discovery Reach

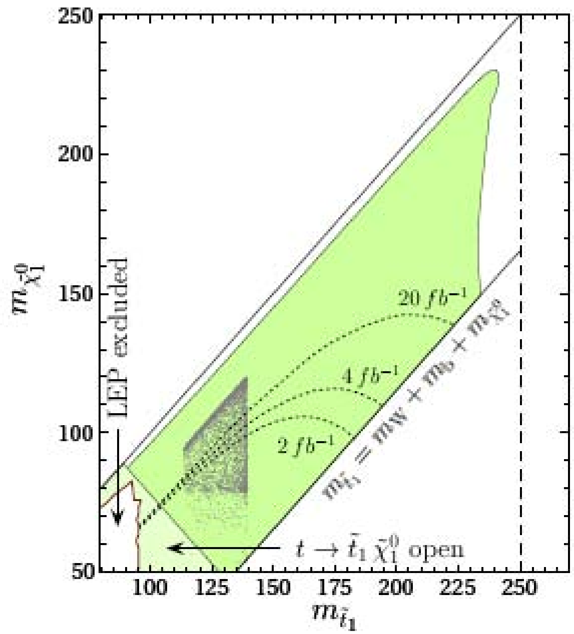

Fig 4a-Luminosity: 500 fb^{-1}

E_{cm}=500 GeV

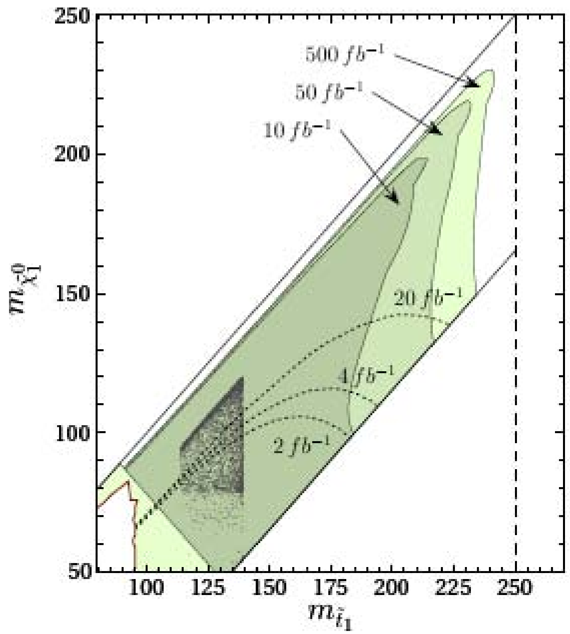

Fig 4b-Lumi. 500 fb^{-1}, 50 fb^{-1} ,10 fb^{-1}

From Simulations:
strong green region:

$$e^+e^- \to \tilde{t}_1\bar{\tilde{t}}_1 \to c\tilde{\chi}^1_0\bar{c}\tilde{\chi}^1_0$$

And Significance:
$(S/\sqrt{(S+B)}) > 5$
Background B
Signal S=εσL
For ε , Signal efficiency
For σ, Theoretical cross-section
dark gray region:
Consistent with DM
And Baryogenesis

*Simulations with: Pythia + Simdet +CIRCE

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9a-Sample Parameter Point

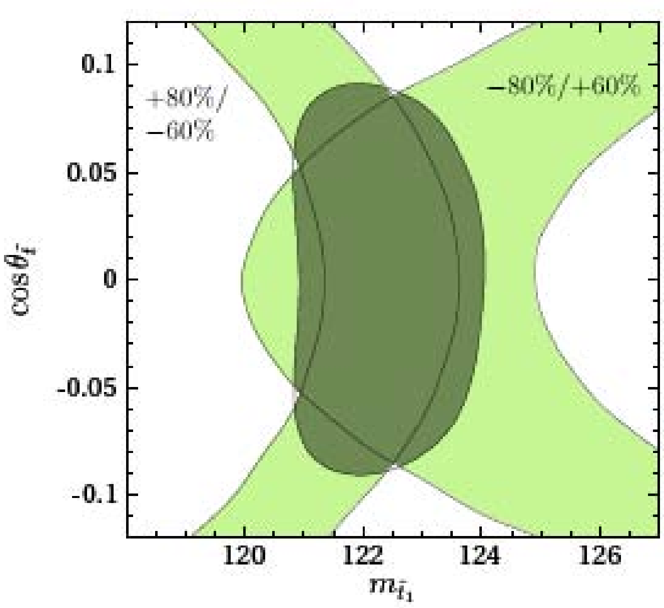
- $m_{\tilde{U}3}{}^2$ = -99^2 GeV^2
- $m_{\tilde{Q}3}$ =- 4200 GeV
- A_t = -1050 GeV
- M_1 = 112.6 GeV
- M_2 = 225 GeV
- |μ| = 320 GeV
- Φμ = 0.2
- tan β= 5

$m_{\tilde{L}123}$ =2000 GeV
m_{R123} = 200 GeV→ Rsleptmass reachable@ILC
Ae,μ τ = 5 TeV. $e^{i\pi/2}$
$m_{\tilde{Q},\tilde{U},\tilde{D}12}$= 4000 GeV

Constrained by the electric dipole moment of e, n
(Important 1loop contrib. of $\tilde{f}$-X^0 ; $\tilde{f}$-X+ → $\tilde{q}$,$\tilde{l}$ of first 2 gener. heavy)
→ $\tilde{q}$ soft super symmetry breaking param. 2 first gener.
are heavy ~4TeV and left-chiral sleptons too

<u>Which gives:</u>
$m\tilde{t}_1$ =122.5 GeV; $m\tilde{t}_2$ =4203 GeV;
$m\tilde{\chi}_1^0$ = 107.2 GeV; $m\tilde{\chi}_1^+$ = 194.3 GeV; $m\tilde{\chi}_2^0$=196.1 GeV
$m\tilde{\chi}_3^0$ = 325.0 GeV; $m\tilde{\chi}_2^+$ = 359.3 GeV
$\cos\theta_{\tilde{t}}$ = 0.0105~ $\tilde{t}$ right handed
→ Δm=15.2 GeV

9b-Light Stop Mass and Mixing Angle



From: σ(e+ e- → $\tilde{t}_1$ $\tilde{t}_1^*$) and σ(Bg) measured for 2 beam Polarizations:
P(e-)/P(e+)= -80%/+60% ; +80%/-60%
L=250 fb-1 each
The green errors bands :
~1σ errors of the cross-sections combined into 1σ two-parameters allowed region: dark green
With statistical and systematical errors
No Radiative Corrections included but should be available at ILC time .

Mstop1=122.5 ±1.0 GeV, cosθ$\tilde{t}$<0.074 ~Right Chiral state

9c-Systematic Errors
Stop Parameters Evaluation

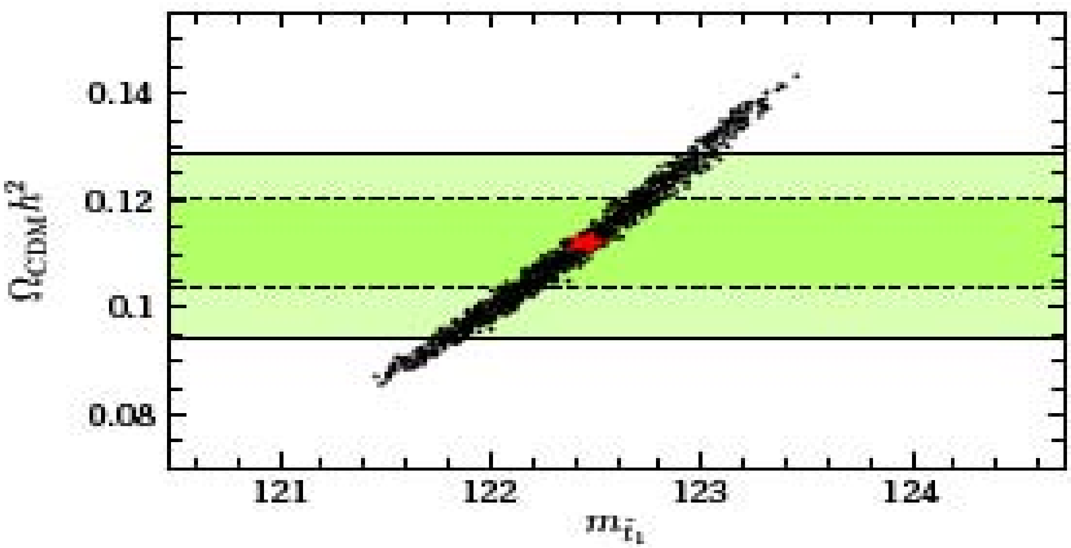
<u>The systematic errors include</u>

- $\Delta m(x_1^0)$=0.11GeV(0.1%); Beam Polar. Δp/p =0.5% (0.01%);
- Theoretical (Bg simul)=Δ(BG)/BG=0.3%(<0.5%)
- Stop_Hadronization_Fragmentation (experimental data from ILC stop discovery)(1%)
- Charm tagging (Charm.Frag. Func.) samples charm jets from SM processes e.g. Z → cc_bar (<0.5%)
- Realistic simulation of the detector effects→ limited by (1)simulation stat. &(2) Det. Calib., nowadays (2) only ~<0.5%(LEP2)
- Beamstrshlung spectrum (from Bhabha scattering)(0.02%)

→ 1.3% for (-80%/+60%) polarization and 1.2% for (+80%/-60%)

10-Dark Matter Prediction

D. Morissey's program was used to calculate ΏCDM
(Balazs, Carena, Menon, Morissey, Wagner 04)



Using the stop parameters Detailed above and combining estimated errors for Chargino and Neutralino, the collider measurements of the stop and Chargino/Neutralino parameters Constrain, the relic density at the1-σ level (dark points) to:

$0.086 < Ώ_{CDM}h2 < 0.143$

WMAP measurements (in green)

$0.095 < Ώ_{CDM}h2 < 0.129$

So the overall precision is comparable to the direct WMAP determination. The uncertainty in the theoretical determination is dominated by the uncertainty in the stop mass, while the precision on the determination of the Neutralino, and $\Phi\mu$ and $\theta\tilde{t}$ are also important.

Dark Matter Determination

- Mass Measurements:

- Light $m(X_1^0)$ from selectron decay at ILC ẽ → e $X^0_{1,}$ (Ee spectrum) ,
  Threshold scan of m =f(√s). → Mx_1^0,Mx_2^0,Mx_3^0,Mx^{+1}
- Other neutralino/chargino masses from ILC threshold scans
  Mass Systematic errors estimated from LHC/ILC report 04

Remark: Heavy 1st/2nd generation of squarks, very little σ → difficult to measure neutralino Masses from squark cascades at LHC

- σ Measurements

For P(e⁻)/P(e⁺)=-80%/+60% ; +80%/-60% for √s=500, 600 GeV

Assuming dP/P=0.5% (Tesla Tech. report)

σ(e+ e- → $X_1^+ X_1^-$); σ(e+ e- → $X_1^0 X_2^0$); σ(e+ e- → $X_2^0 X_2^0$);

Analytical Estimate (S.Y. Choi et al), assuming systematic errors

And stat. errors, use a Chi2 to extract fundamental SUSY Parameters

- Mw, Mz, $\sin\theta_{W,}$ $\cos\theta_w$ from SM
- And from the parameters obtained at the parameter point $m\tilde{t}_1$; $\cos\theta\tilde{t}$, M_1; M_2; |μ| ; Φμ ; tanβ; sinα; mh^0 and assuming $m\tilde{t}_2$ >1000GeV

Outlook

The sensitivity to small mass differences is particularly important for the co-annihilation mechanism

We have shown that with the linear collider we can cover the region of co-annihilation down to mass differences ~O(5GeV).

We can determine the parameters accurately enough to reach comparable precisions for the dark matter predictions than the direct WMAP measurements

Next to be done

a) Further refinement of the analysis.

b) Inclusion of radiative corrections

c) Optimization of the cuts for Δm ~5 GeV and below

e) Scalar tops: possible benchmark reaction for vertex detector projects (e.g. Sopczak LCWS'04).

International Collaboration involving Fermilab (USA), Lancaster (UK) within the LCFI (Linear Collider Flavor Identification) Collaboration and DESY (Germany).

C-tagging-The Principle

A Vertex Identification followed by a Neural Network application Developed by T. Khul for LEP.

•*Vertex Identification:*

As a maximum in track overlapping (product of probability density tubes defined using the track parameters)

3 cases:

Case 1) Only a primary Vertex

Case 2) 1 secondary vertex

Case 3) >1 secondary vertex

•*Neural Network (NN):*

data used: 255000 stops, Mstop=120-220; Dm=5,10, 20 GeV

240000 Wev, the most resilient background

C-tagging-Neural Network Input

•Vertex Case 1:NN Input variables

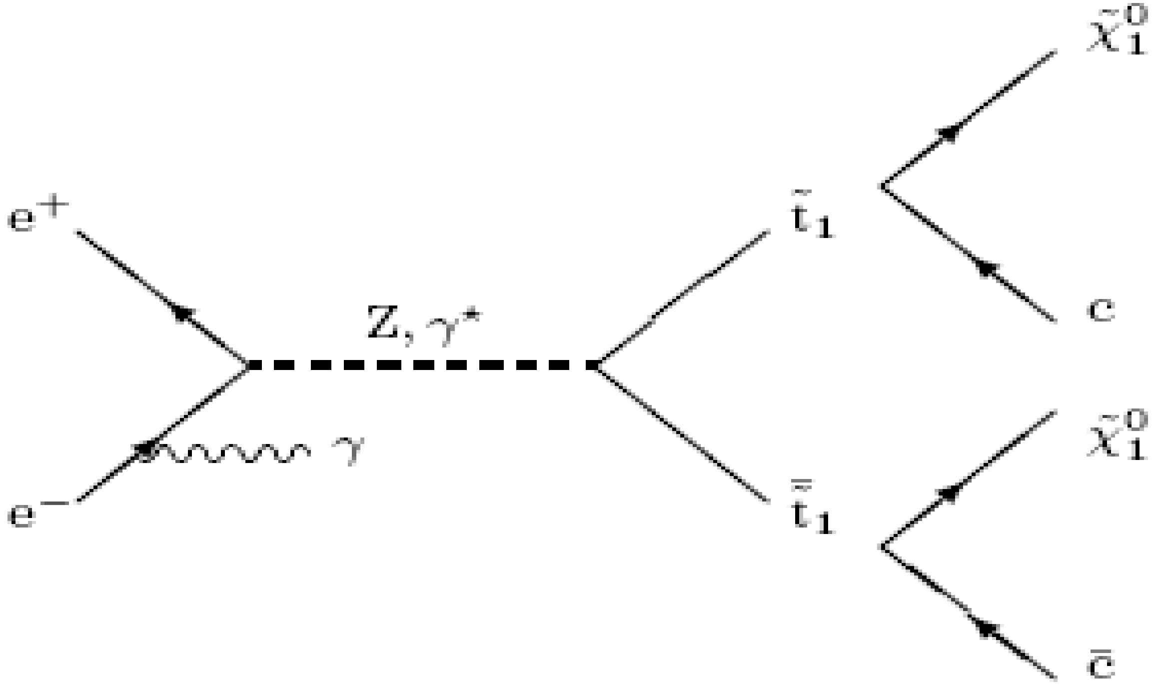
- *Impact parameter* significance (impact parameter/error) of the 2 most significant tracks in the r-Φ plane (tracks with the biggest separation) && their Impact parameters.
- The impact parameter significance & Impact parameters of the 2 tracks in z
- Their momenta
- The joint probability in r- Φ (tiny beam spot size in that plane)& z

•Vertex Case 2: NN Input variables (all of Case 1+below)

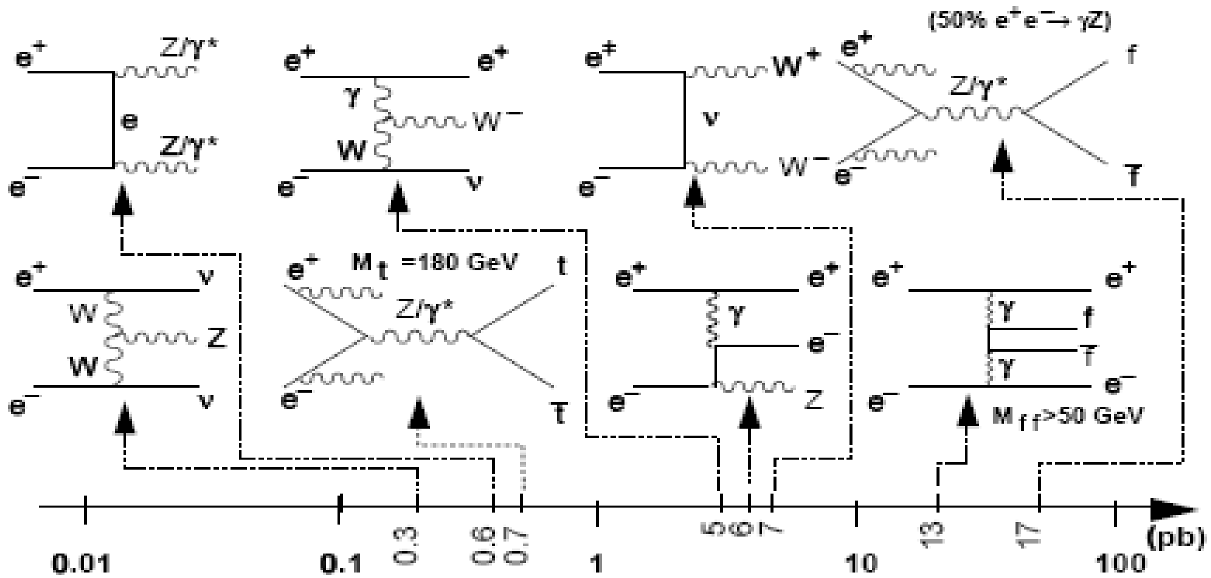
- *Decay Length* significance of the secondary vertex && Decay Length
- Momentum of all tracks associated to the secondary vertex && Multiplicity
- Pt corrected mass of secondary vertex (corrected for neutral hadrons&ν's), the pt of the decay products perpendicular to the flight direction (between primary && secondary Vertex) && joint probability in r-Φ and z

•Vertex Case 3: 2 secondary vertices, the tracks are assigned to the vertex closest to the primary vertex and the NN input variables are those of case 2

Two-Soft Charm Jets and Missing Energy



Background- Channels



hep-ph9701336-A.Bartl,H. Eberl,S. Kraml, W.Majerotto,W.Porod,A. Sopczak