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

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- Introduction
- Motivations
- Signal & Background Reduction
- Stop Discovery Reach
- Parameter Determination
- Dark Matter Prediction & WMAP Relic Density
- Outlook/Summary

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, small mass difference M (stop-neutralino)= 15-30 GeV, provides a 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 Detector , for FCAL .

2-Theoretical Motivation

- <u>Electroweak Baryogenesis:</u>

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:* $m\tilde{t}_1 < mt$

- <u>Dark Matter</u>

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

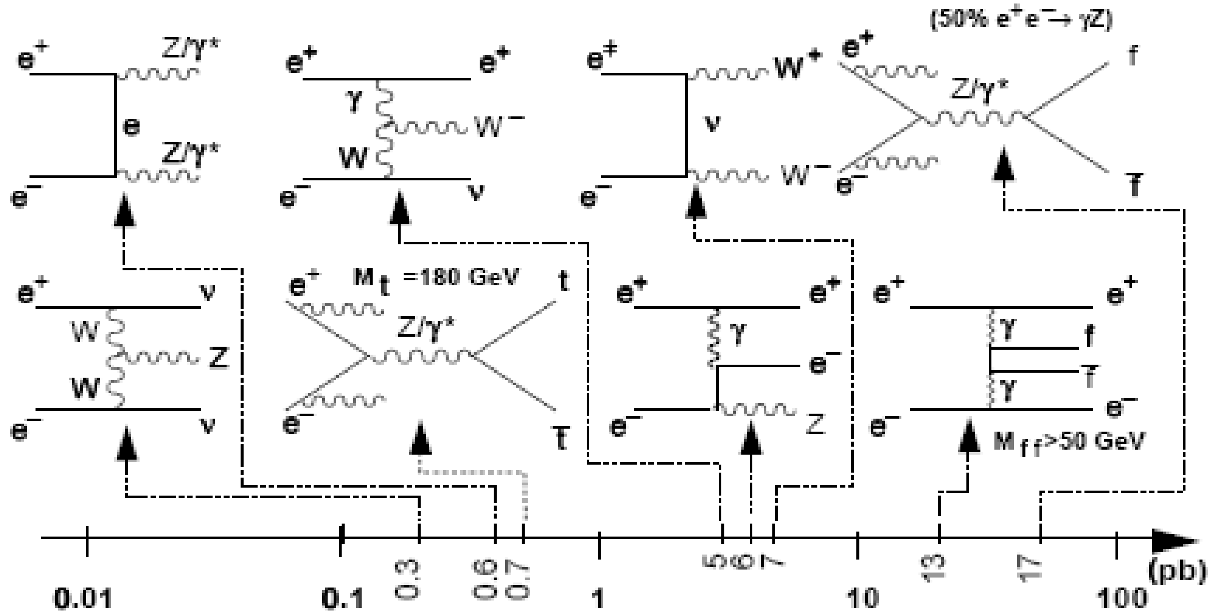
But for $m\tilde{t}_1$ - m X^0_1~15-30 GeV, there is co-annihilation between the $\tilde{t}_1$ and the X^0_1 →σ_a ($X^0_{1,}$, $\tilde{t}_1$)+ σ_a ($X^0_{1,}$, X^0_1) consistent with dark matter.

3-Signal/Background Reduction

Generated with Pythia; Detector Simulated with Simdet; Including Beamstrahlung with CIRCE; Luminosity $500 fb^{-1}$; E_{cm}=500 GeV

- Cross-Sections
  - Calculated @ Tree-level by A. Freitas to include Beamstrahlung & Bremsstrahlung, the QCD part being taken from Calvin
  - The Signal is given for $\cos\theta_{\tilde{t}}$ =0.5
  - σ(eez) && σ(Wev) are from Grace and do not include Beamstrahlung/ISR
- Selection: 2 stages
  - Pre-selection
  - Selection

Background- Channels



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

Signal And Background Cross-Sections (pb)

Process	σ(pb)		
	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
weν	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% ,

2 Stages Selection $e^+e^- \rightarrow \tilde{t}_1\overline{\tilde{t}}_1 \rightarrow c\tilde{\chi}_0^1\overline{c}\tilde{\chi}_0^1$

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

• <u>Signature: 2 soft charm jets + missing energy</u>

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

•100% Branching Ratio assumed

•Sequential cuts applied as a preselection first, allowed for larger samples to be produced and the cut refined at selection stage.

<u>Pre-selection</u>

<u>Selection</u>:

Pre-selection: Efficiency Each Cut

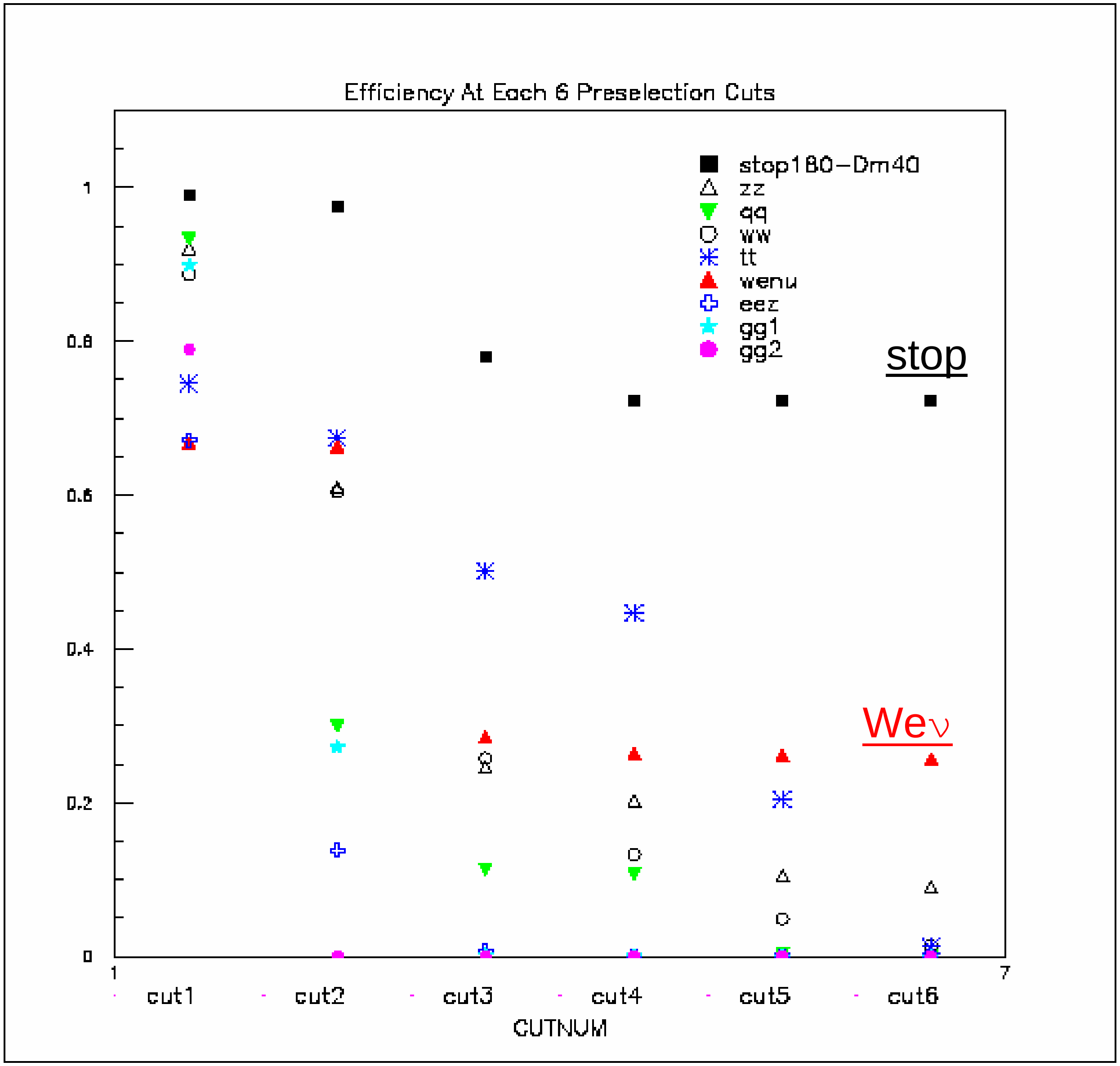


Fig 1

Pre-selection Cuts

- 4<Num. Charged tracks<50
- Pt> 5 GeV
- cosθThrust <0.8
- |Pl,tot /P|<0.9
- Evis<380 GeV
- M(inv)<200 GeV

Color point:
% of Background left after each cut,
Reduced < 30%

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

Pre-selection Efficiency: Stop

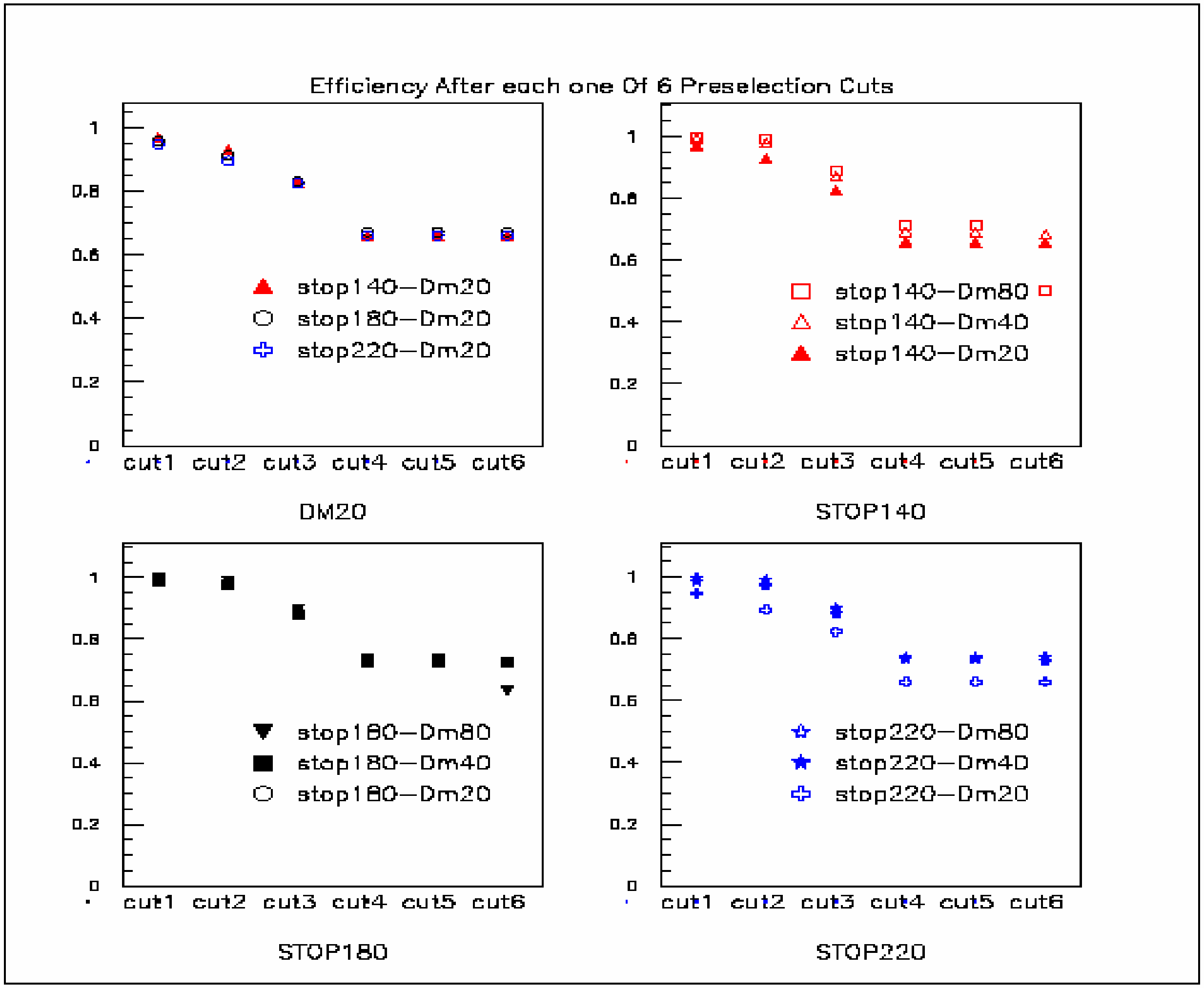
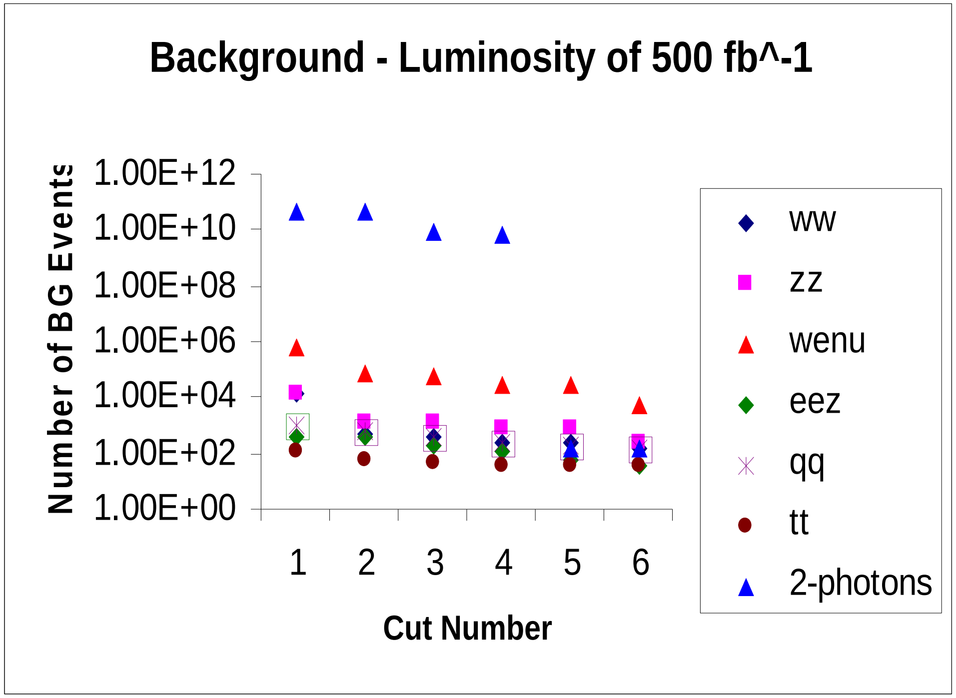


Fig. 2

<u>Upper Left</u>:
$\Delta M(\tilde{t}_1\text{-}X0)$=20GeV
$M\tilde{t}_1$ = 140GeV
$M\tilde{t}_1$ = 180GeV
$M\tilde{t}_1$ = 220GeV
<u>*Independent*</u> of $M\tilde{t}1$

<u>Others:</u>
$\Delta M(\tilde{t}_1\text{-}X0)$=
20,40, 80 GeV
Separatly for ≠ $M\tilde{t}1$
~<u>*Independent*</u> of
$\Delta M(\tilde{t}1\text{-}X0)$

Selection: The Background Rejection



Selection Cuts:

- Njets =2
- Evis<0.4 √s and

  70 < Minvjets < 90 GeV2
- Cos (Φ_A-coplanarity) >-0.9
- cosθThrust<0.7 (revisited)
- Pt >12 (revisited)
- 60 < Minvjets < 90 GeV2
- c-tagging- From T. Khul

Luminosity of 500 fb^-1

The main background left with our cuts is the wev-

The Background Rejection: Remarks

The background left has been reported after each cut

- The Cos (Φ_A-coplanarity) >-0.9 cut is powerful in the back to back processes, qq and 2-photons background.
- The 2-photons background rejection, ~20% reduction, for the signal as well, especially for the lower values of the light stop with a small Δm in our analysis, and a pt cut is still necessary to overcome the huge 2-photons processes cross-section .

  A better understanding of the Beamstrahlung and Bremsstrahlung and other back to back processes should allow to improve our cuts and therefore, the signal to background rejection consequently.

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.
weν	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 were shown in the previous figure for each BG channel separately. Largest remaining Background :Weν , already reduced by a factor 2 by c-tagging

Selection: Signal Efficiency For $500fb^{-1}$

Background	% Left - End Presel	Number Gen. Selection	% Left - End Sel. – For 500 fb^-1	Num. Left
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

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 $m\tilde{t}_1$.The lightest stop signal efficiency would benefit from a better understanding of the back to back processes
- Overall Signal for 500fb^{-1}, after selection cuts ~O(10^3)-O(10^4), remaining background O(10^3)

Stop Discovery reach at the Linear Collider

- From the simulations with Ecm=500 GeV
- Assuming 100% cross-section to the process

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

- The efficiencies are calculated interpolating the parameter points of Table 3, ($m\tilde{t}$,mX_0^1), together with the production cross-section and the Luminosity to calculate the number of events. One covers to whole parameter region which gives, together with the background information, the $\tilde{t}$ discovery region shown next slide

Stop Discovery Reach

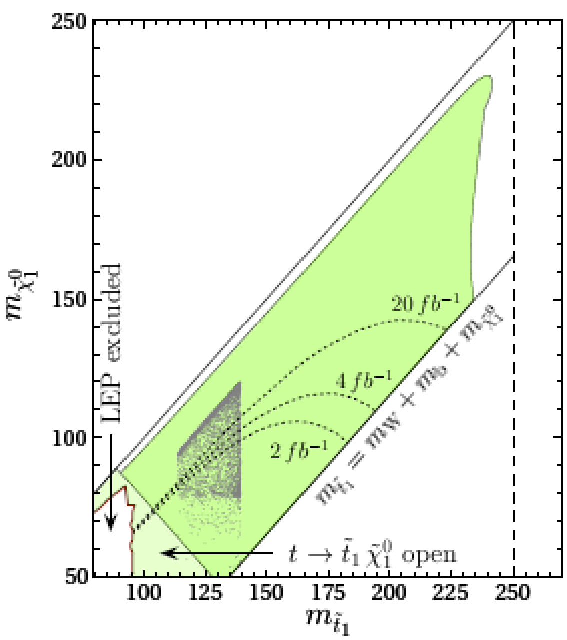


Fig 4a-Luminosity: 500 fb^{-1}

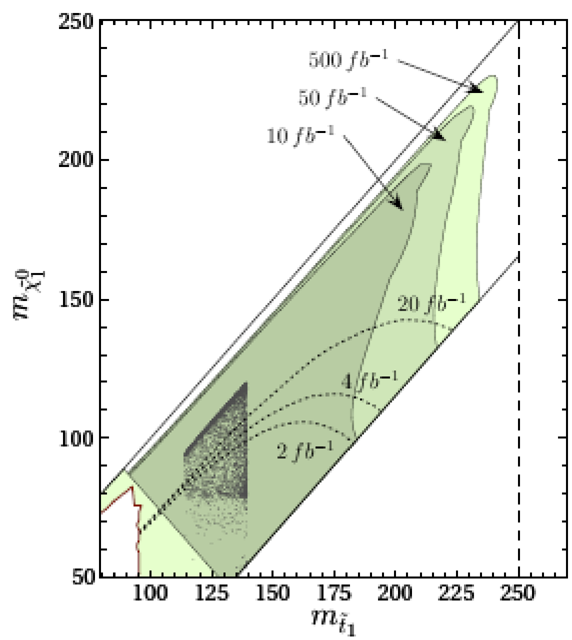


Fig 4b-Lumi. 500 fb^{-1}, 50 fb^{-1} ,10 fb^{-1}

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/√(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

Next to be done

- The region where the stop is so light that the top decay to the stop and neutralino has not been studied yet
- The region of the phase-space where a heavier stop decays into a W, b and neutralino.

Parameter Determination

- Sample parameter point
- Light Stop Mass and Mixing angle

A Sample Parameter Point

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

<u>Which gives:</u>

$m\tilde{t}_1$ =122.5 GeV; $m\tilde{t}_2$ =4203 GeV;

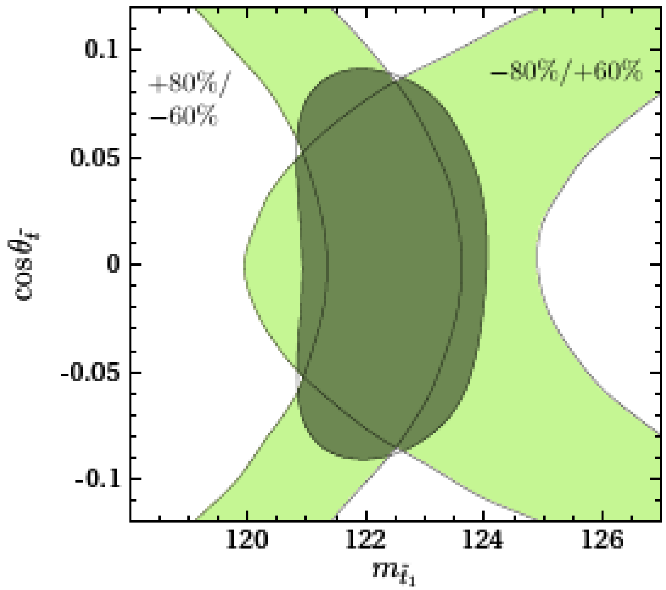
$m\tilde{\chi}_1^0$ = 107.2 GeV; $m\tilde{\chi}_1^+$ = 194.3 GeV; $m\tilde{\chi}_2^0$=196.1 GeV

$m\tilde{\chi}_3^0$ = 325.0 GeV; $m\tilde{\chi}_2^+$ = 359.3 GeV

$\cos\theta\tilde{t}$ = 0.0105~ $\tilde{t}$ right handed

→ Δm=15.2 GeV

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, |cosθt̃|<0.074 ~Right Chiral state

Stop Parameters Evaluation

Systematic Errors

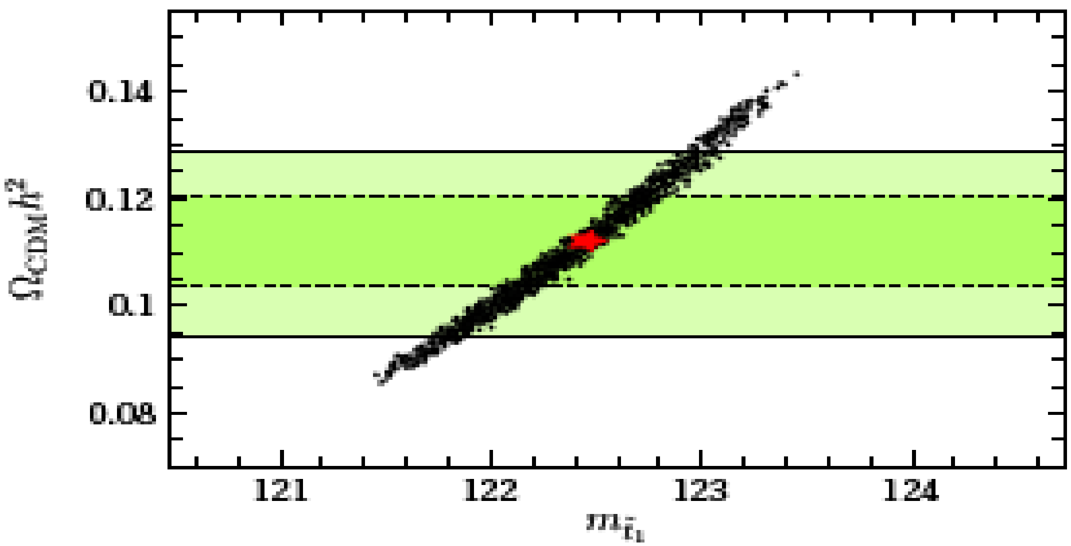
- $\Delta m(x_1^0)$=0.11GeV(0.1%);
- Beam Polar. Δp/p =0.5%
- Theoretical (Bg simul)=Δ(BG)/BG=0.3%
- Stop_Hadronization_Fragmentation (experimental data from ILC stop discovery)(1%)
- Charm tagging (Charm.Frag. Func.) samples charm jets from SM processes e.g. Z → cc_bar(<0.5%)
- Realistic simulation of the detector effects

  → limited by (1)simulation stat. &(2) Det. Calib., nowadays (2) only ~<0.5%(LEP2)
- Luminosity: d(L) / L = 2 *10^{-4} assumed - Technical Design Report
- For the computation of the cross-sections the Beamstrahlung effects needs to be understood precisely. The Beamstrshlung spectrum (from Bhabha scattering) → resulting error in the cross-section(0.02%)

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

Dark Matter Prediction

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



Using the previous stop parameters
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)
$0.086 < Ώ_{CDM}h2 < 0.143$

WMAP measurements (in green)
$0.095 < Ώ_{CDM}h2 < 0.129$

Dark Matter Prediction: Remarks

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

The precision on the determination of the Neutralino, and $\Phi\mu$ and $\theta\tilde{t}$ are also important.

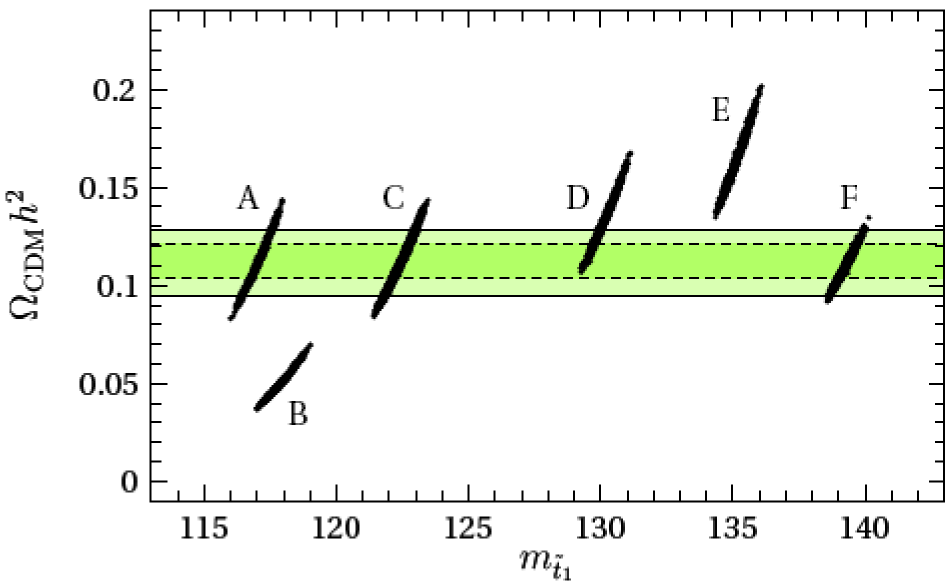
The Control of the main backgrounds is important.

Next to wev background, the 2photons and back to back processes are important since their cuts providing the biggest signal to background reduction in the selection cuts.

Other MSSM scenarios Compatible with EW Baryogenesis

	A	B	C	D	E	F
m_{U3}^2(GeV^2)	-99^2	-99^2	-99^2	-97^2	-90.5^2	-85.5^2
m_{Q3}(GeV)	2700	3700	4200	4900	4700	4300
A_t (GeV)	-860	-1150	-1050	-500	-400	0
M_1(GeV)	107.15	111.6	112.6	119.0	123.2	129.0
tan β	5.2	4	5	6	5.5	5.5
$A_{e,\mu,\tau}$	$5\ e^{i\pi/2}$	$3.7\ e^{i\pi/2}$	$5\ e^{i\pi/2}$	$5.8\ e^{i\pi/2}$	$5.2\ e^{i\pi/2}$	$5\ e^{i\pi/2}$
$m_{\tilde{t}1}$ (GeV)	117.1	118.0	122.5	130.2	135.2	139.4
$m_{\tilde{\chi}1^0}$ (GeV)	102.1	104.1	107.2	114.0	118.1	123.1
$\cos\theta_{\tilde{t}}$	0.0210	0.0150	0.0105	0.0038	0.0035	0.0005
m_{h0} (GeV)	115.1	115.0	117.0	117.1	116.2	115.1
$\Omega_{CDM}\ h^2$	0.113	0.060	0.112	0.144	0.166	0.112

Dark Matter Predictions In Considered MSSM Scenarios



Shown in black, Chi2 scan over super Symmetry parameters regions allowed for 1σ error for the different assumed scenarios

The green shaded bands are the 1σ and 2 σ constraints on WMAP measured relic density

Discussion

- For points A,C,F, the light neutralino with a light stop in the co-annihilation region, is the source of dark matter in the universe
- The point D, within 1σ errors will still be consistent with the WMAP results but imposes restriction on the parameter space (e.g. $m_{\tilde{t}}$<30 GeV)
- For E the dark matter density would be too large
- For B the dark matter density would be smaller than the WMAP results, which could be produced by another source of dark matter as well from a non-supersymmetric origin.

Summary/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, improving our cuts - improving our understanding of the 2-photons and back to back processes and further reduction of the wev background. For the computation of the cross-sections the Beamstrahlung effects needs to be understood precisely.

b) Inclusion of radiative corrections to the cross-section calculations

c) Scalar tops: possible benchmark reaction for the Luminosity Calorimeter Detector (FCAL) and for vertex detector projects (c-tagging) (e.g. Sopczak LCWS'04)

International Collaboration involving Fermilab (USA), Lancaster (UK) within the LCFI (Linear Collider Flavor Identification) and DESY (Germany), which can still expand !

Other Parameters Of Parameter Points

$m_{L1,2,3} = 2000$ GeV

$m_{R1,2,3} = 200$ GeV

$M_{Q,U,D1,2} = 4000$ GeV

$m_{A0} = 800$ GeV

$m_{D3} = 4000$ GeV

$A_{e,\mu,\tau} = 5\text{TeV}\ e^{i\pi/2}$

C- Tagging

- Appendix:

  C-tagging short description

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 Weν, 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