Precision Measurement of the Stop Mass at the Linear Collider

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Publication in Preparation

Introduction

- We have previously studied the light stop, with a small mass difference to the neutralino, in an attempt to understand EW baryogenesis the asymmetry matter anti-matter and the role of the stop in dark matter annihilation.

  Phys. rev. D 72,115008(2005)

  M. Carena, A. Finch, A. Freitas, C. Milstene, H. Nowak, A. Sopczak

  The mass precision measurement reached was δm~1.2GeV.

  This analysis aims at the minimization of the systematics while using more realistic data, stop hadronization/fragmentation included. We will show that:
- The precision is improved in two ways:

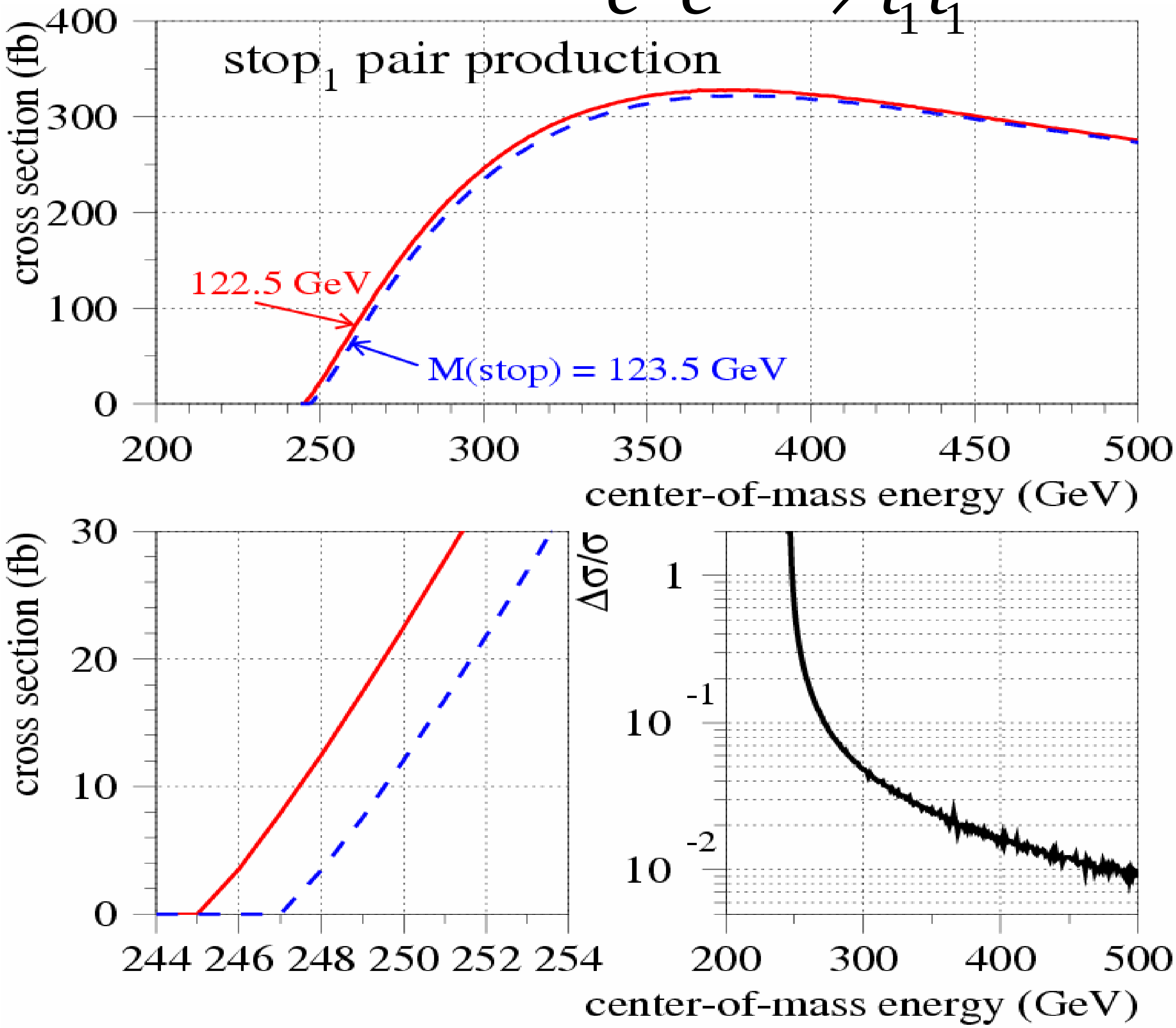
  a/ The systematic uncertainties are minimized by measuring the production cross-section at two energies→ cancellations .

  b/ The 2nd energy point chosen at or close to the production energy threshold → increased sensitivity to mass changes.
- The stop hadronization is included at production of the data → the c quark energy is spread out in the process of hadronization. As a result:

  the final number jets increases- the c-tagging is now necessary to identify the charm jets (bench-marking for the vertex detector)
- Two approaches are used, a cut based analysis, a multi-parameters optimization analysis IDA
- The polarization improves further the signal to background ratio

Cross-Section Precision In Production

$$e^+e^- \rightarrow \tilde{t}_1\tilde{t}_1$$



Cross-sections [fb] calculated up to NLO In MC software by Freitas et al EPJ C21(2001)361, EPJ C34(2004)487

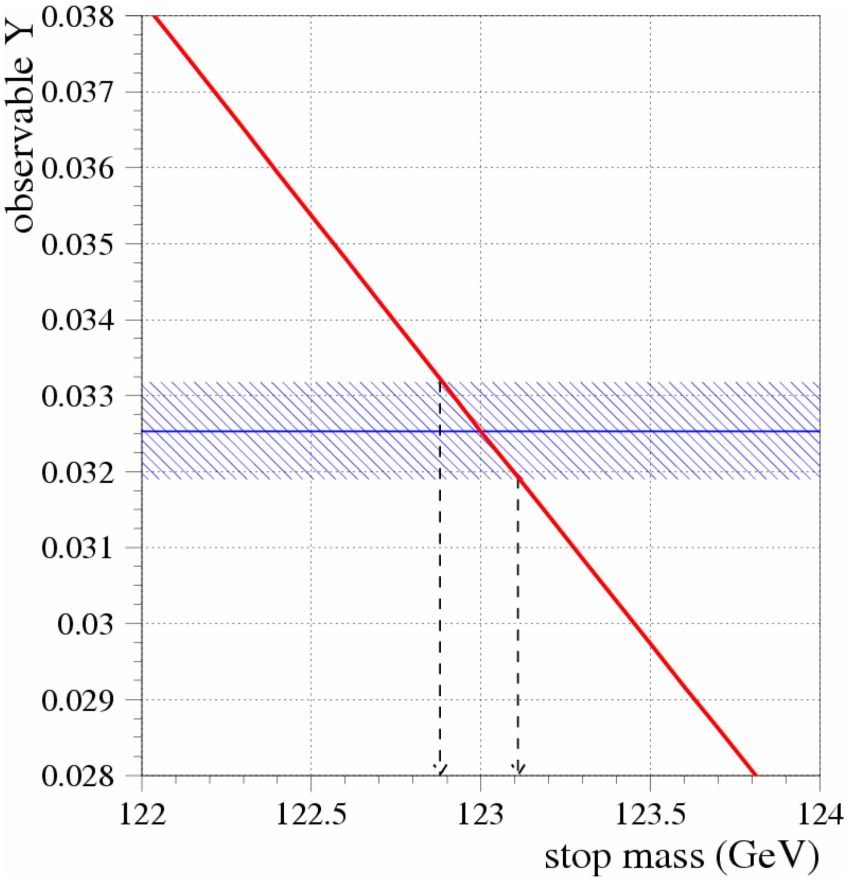
The Method

$$\sigma = \frac{N - B}{\varepsilon L}$$

$$Y(M_x \sqrt{s_{th}}) = \frac{N_{th} - B_{th}}{N_{pk} - B_{pk}} = \frac{\sigma(\sqrt{s_{th}})}{\sigma(\sqrt{s_{pk}})}$$

σ the cross-section [fb]
N the number of selected data events
B number of estimated background events
s Square of the energy in center of Mass
N_{th}, B_{th}, s_{th} at or close to production threshold
N_{pk}, B_{pk}, s_{pk}, at peak value
ε total efficiency & acceptance
L Integrated luminosity
M_x: Mass to be determined with high precision.
Y ratio of cross-section σ_{th} and σ_{pk} → Allows Reduction of systematic uncertainty as well as uncertainties from L measurement.
Remark: yield close to threshold is very sensitive to M_x → choice of N_{th} and B_{th} ..

Determination of the Stop Mass



Y=f (M_x) from the theoretical cross-section is be drawn in Red (NLO)
Y from the data the blue line.

As an example, Assume 2% precision for Y,
The blue hashed region → one obtains
→Precision ΔM_x ~±0.1%, the 2 vertical arrows

The Scenario depicted:
E_{CM}=260GeV with σ=9.2 fb and σ=77fb at peak

Remark: Assumed luminosities
L_{th}=50fb^{-1} (260 GeV), L_{pk}=500fb^{-1}(500 GeV)

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

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), in the MSSM, the neutralino X^0_1 is a candidate

  However, 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.

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

A scan in the super-symmetry parameter space

(hep-ph/0403224v2-2004) C. Balazs, M. Carena, C. Wagner)

Baryogenesis→ (m$\tilde{t}$1 <mtop && m$\tilde{t}$1 > 120 GeV) ;Higgs involved in the symmetry breaking mechanism mHiggs ≤ 114.4 GeV

→ Our points m$\tilde{t}_1$=122.5 GeV; mX_0^1 =107.2 GeV ; Δm=15.3 GeV

•Stop Hadronization→ the final state jets smeared :
due to Radiation + Fragmentation

Events Final State :

•Soft Multi-jets in the final state

•Stop Hadronization → the final state jets smeared :
due to gluon radiation + fragmentation

•At ECM=260 GeV mostly 2 jets, carry the charm.

•At ECM=500 GeV 2jets →2,3,4 jets (more energy available in the CM)
→the Charm tagging (*T. Kuhl*) a necessary tool
to identify the charm jets (Vertex bench-marking)

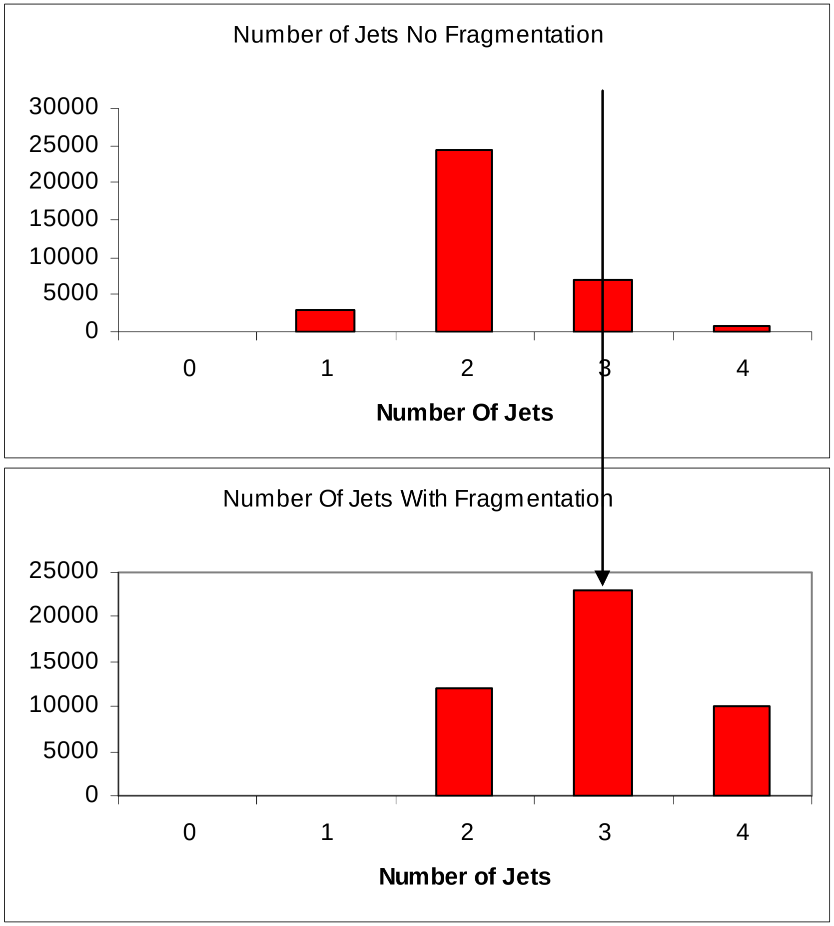
•Analysis uses N-tuple tool incorporating jet finding algorithm (*T. Kuhl*)

Simulation Characteristics

- Signal and Background generated with: Pythia (6.129)
  Simdet (4-0-3)– Circe(1.0)
  - Hadronisation of the c quark and the $\tilde{t}$ from the Lund string fragmentation Pythia uses Peterson fragmentation
  (Peterson et al PR D27:105)
  - The $\tilde{t}$ fragmentation is simulated using Torbjorn 's code
  //http://www.thep.lu.se/torbjorn/pythia/main73.f
  The $\tilde{t}_1$ quark is **set stable** until **after fragmentation** where it is Allowed to **decay again** as described in (*Kraan, EPJ C37:91)*

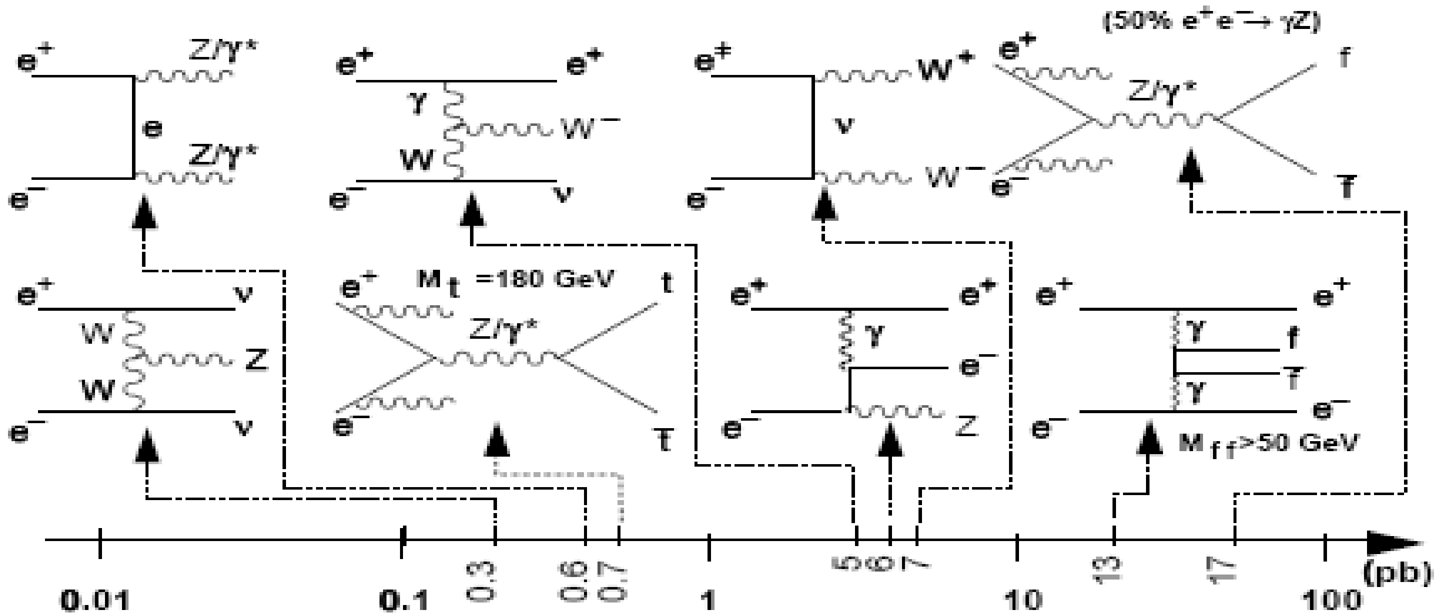
- Signal and Background are generated in each channel for the given luminosity in conjunction to the cross-sections

Jet Multiplicity – Without/With Fragmentation



- Stop fragmentation simulated using Torbjorn code *//http://www.thep.lu.se/torbjorn/pythia/main73.f*
- *The stop fragmentation parameter is set relative to the bottom fragmentation parameter*
  $\varepsilon_{\tilde{t}} = \varepsilon\_b * m_b^2 / m_{\tilde{t}}^2$
  And ε_b=-0.0050+ /- 0.0015 following (OPAL,EPJ C6:225)
- *The jet Multiplicity <u>without Fragmentation</u> Upper figure*
  ~ 70% 2 jets
- *The jet Multiplicity <u>with t̃ Fragmentation</u> Lower Figure*
  ~ 50% 3 jets
  & bigger admixture of 4jets

Background- Channels @500 GeV



Z Phys. C 76 (1997) 549- A.Bartl, H. Eberl,S. Kraml, W.Majerotto,W.Porod,A. Sopczak

The cross-sections

Process	σ[pb] at ECM=260GeV			σ[pb] at ECM=500GeV		
P(e-)/ P(e+)	0/0	-80%/+60%	+80%/-60%	0/0	-80%/+60%	+80%/-60%
$\tilde{t}_1\ \tilde{t}_1^*$	0.032	0.017	0.077	0.118	0.072	0.276
W W	16.9	48.6	1.77	8.6	24.5	0.77
Z Z	1.12	2.28	0.99	0.49	1.02	0.44
Wenu	1.73	3.04	0.50	6.14	10.6	1.82
eeZ	5.1	6.0	4.3	7.5	8.5	6.2
qq, qq ≠ tt	49.5	92.7	53.1	13.1	25.4	14.9
tt	0.0	0.0	0.0	0.55	1.13	0.50
2γ (p_t > 5 GeV)	786			936		

Table 1

A. Freitas et al EPJ C21(2001)361, EPJ C34(2004)487 and GRACE and COMPHEP -Next to leading order, assuming a stop mixing angle (0.01)

Pre-Selection Cuts

- A short list of the sequential cuts applied as a pre-selection first, allowed larger samples to be produced
- The pre-selection cuts are the same at the 500 and 260 GeV unless listed in parenthesis for 500 GeV

Pre-selection: 260GeV ;(500 GeV)

- 4 < Number of Charged tracks < 50
- Pt> 5 GeV
- $\cos\theta_{Thrust} < 0.8$
- $|P_l / P_{tot}| < 0.9$
- $E_{vis} <$ 0.40 ECM; ($E_{vis} <$ 0.76 ECM)
- M(inv)<200 GeV

The cuts were refined further at Selection as shown next

Selection Cuts at E_{CM}=260, 500 GeV

Variable	ECM 260 GeV	ECM 500 GeV
Number of jets	N_{jets}=2	$N_{jets} \geq 2$ & E_n <25 GeV n=3,4
Transverse Momentum p_t	p_t > 10 GeV	p_t > 12 GeV
Thrust T	-	T > 0.8
$\cos\theta_{Thrust}$	$\lvert\cos\theta_{Thrust}\rvert < 0.7$	$\lvert\cos\theta_{Thrust}\rvert < 0.7$
Visible Energy E_{vis}	E_{vis} < 0.175 *ECM	E_{vis} < 0.4 *ECM
Acoplanarity Φ_{acop}	|cos(acop)| < 0.9	|cos(acop)| < 0.9
Invariant mass of jet pair m_{jj}	m_{jj} < 25.5GeV; 90GeV >m_{jj}	m_{jj} < 60GeV; 90GeV >m_{jj}
Charm tagging likelihood P_c	P_c > 40%	P_c > 40%

Table 2

In order to optimize the cancellation of the systematics we aim to have a selection as similar as possible at the two energies. (cancellation in $Y=(N_{th}-\sigma_{th})/(N_{pk}-\sigma_{pk})$)
The two-photons background did require a 5GeV pt cut.

Events Generated and After Sequential cuts

	$L=50fb^{-1}$ at ECM=260GeV			$L= 500fb^{-1}$ at ECM=500GeV		
P (e-)/ P(e+)	Generated	0/0	+80%/-60%	Generated	0/0	+80%/-60%
$\tilde{t}_1 \tilde{t}_1^*$	50000	382	921 (24%eff.)	50000	11300	26430 (19%eff.)
WW	180000	<5	<1	210000	102	9
ZZ	30000	<2	<2	30000	250	224
Wenu	210000	36	4	210000	10102	2994
eeZ	210000	<1	<1	210000	<18	<15
qq, q≠t	350000	<7	<8	350000	19	22
tt	-	0	0	180000	21	19
2-Photons	$1.6\ 10^6$	12	12	$8.5x10^6$	120	120

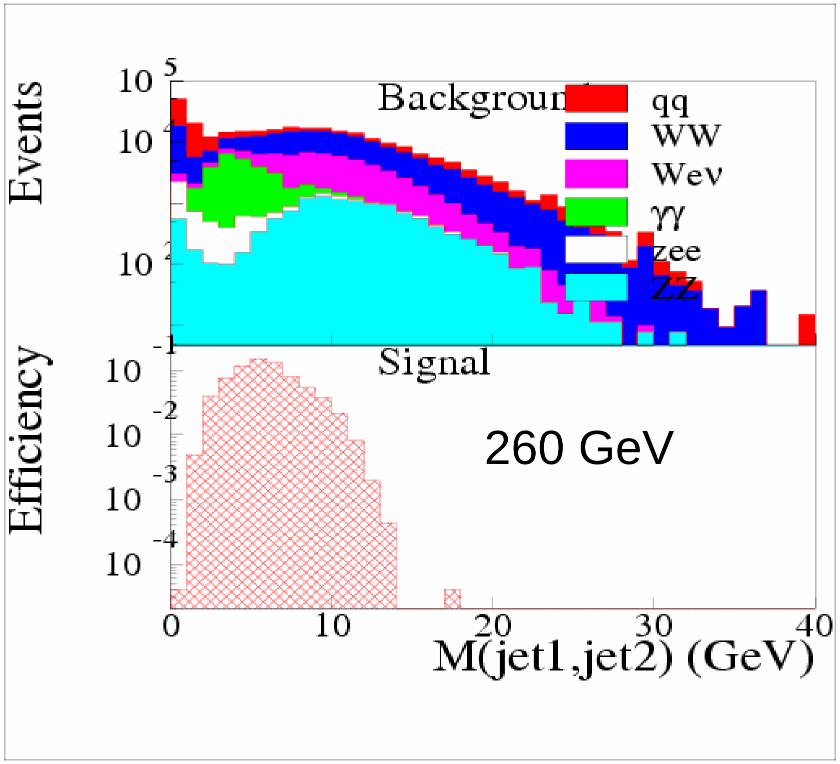
Table 3 *Preliminary Results*

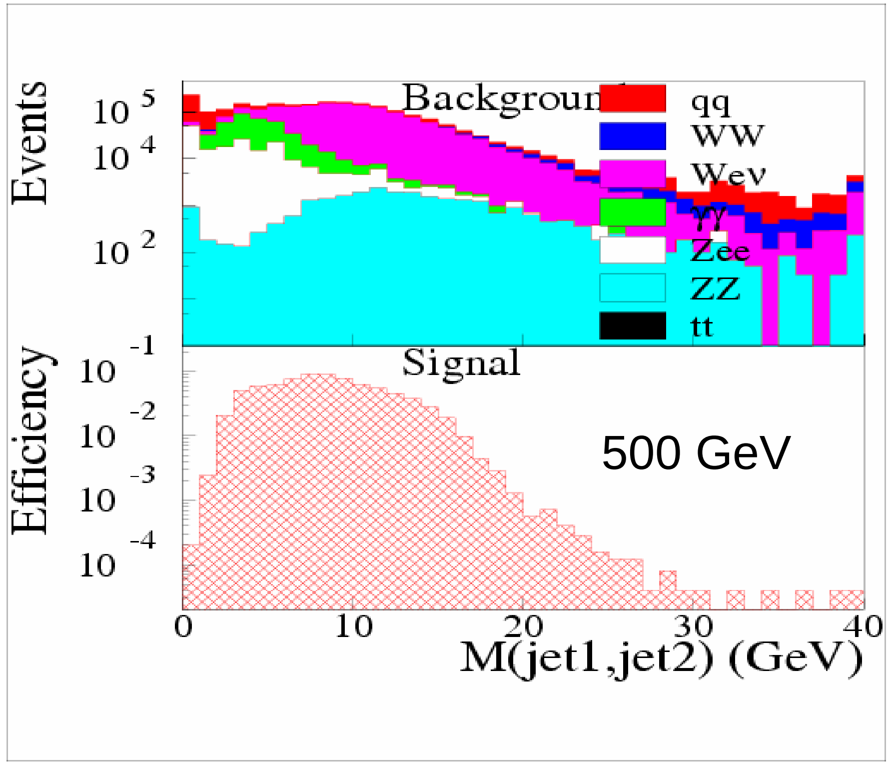
0/0 polarization beam → Unambiguous discovery
+80%/-60% polarization → Precision Measurement
Remark: $\tilde{t}_1$ fragmentation → the separation from the Wenu more difficult

Iterative Discriminant Analysis (IDA)

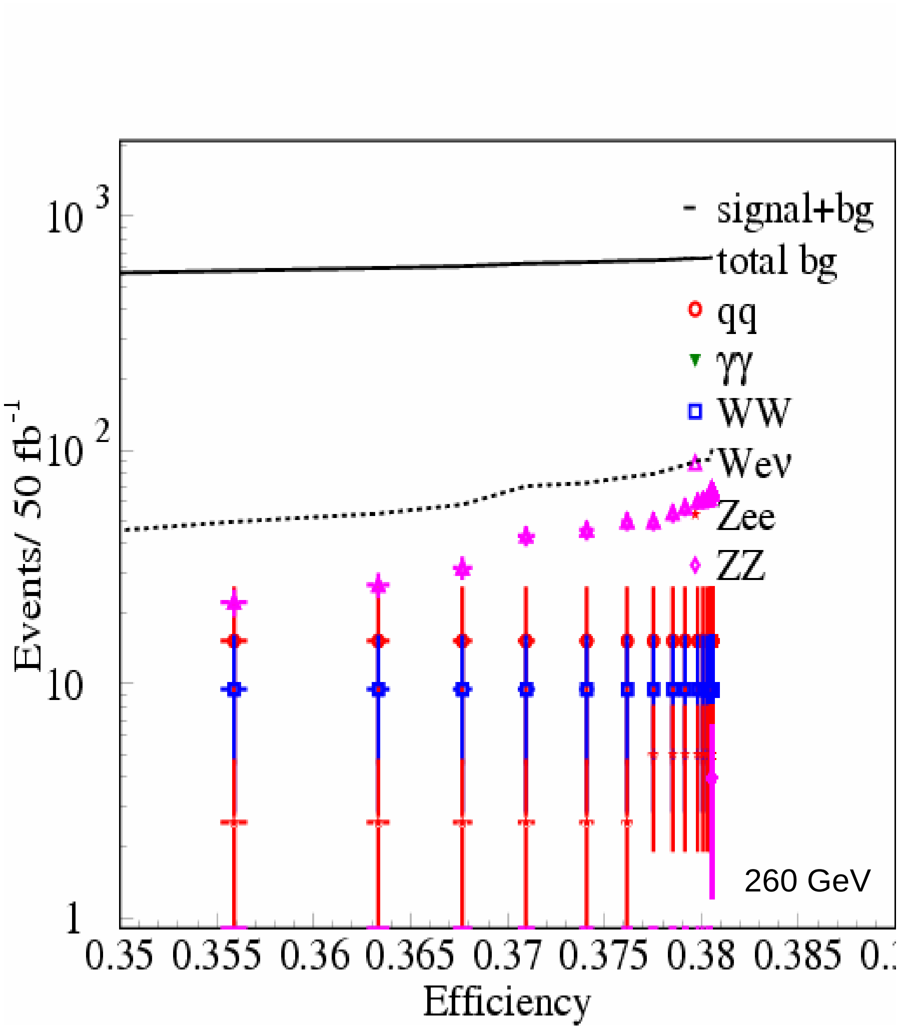
- Improves even more the precision in the $\tilde{t}_1$ mass measurement an Iterative Discriminant Analysis (IDA) is used. (modified Fisher Disc. Analysis)
- IDA combines the kinematic variables in parallel. The same variables and simulated events are used than in the cut based analysis . A non linear discriminant function followed by iterations are enhancing the separation between signal and background.
- Both the signal and background have been divided in two equally sized samples, one sample is used for training, the other as data.
- Two IDA steps have been performed, with a cut after the 1st IDA iteration keeping 99% of the signal efficiency.
- The performance is shown in the two next figures at 260 and 500 GeV.

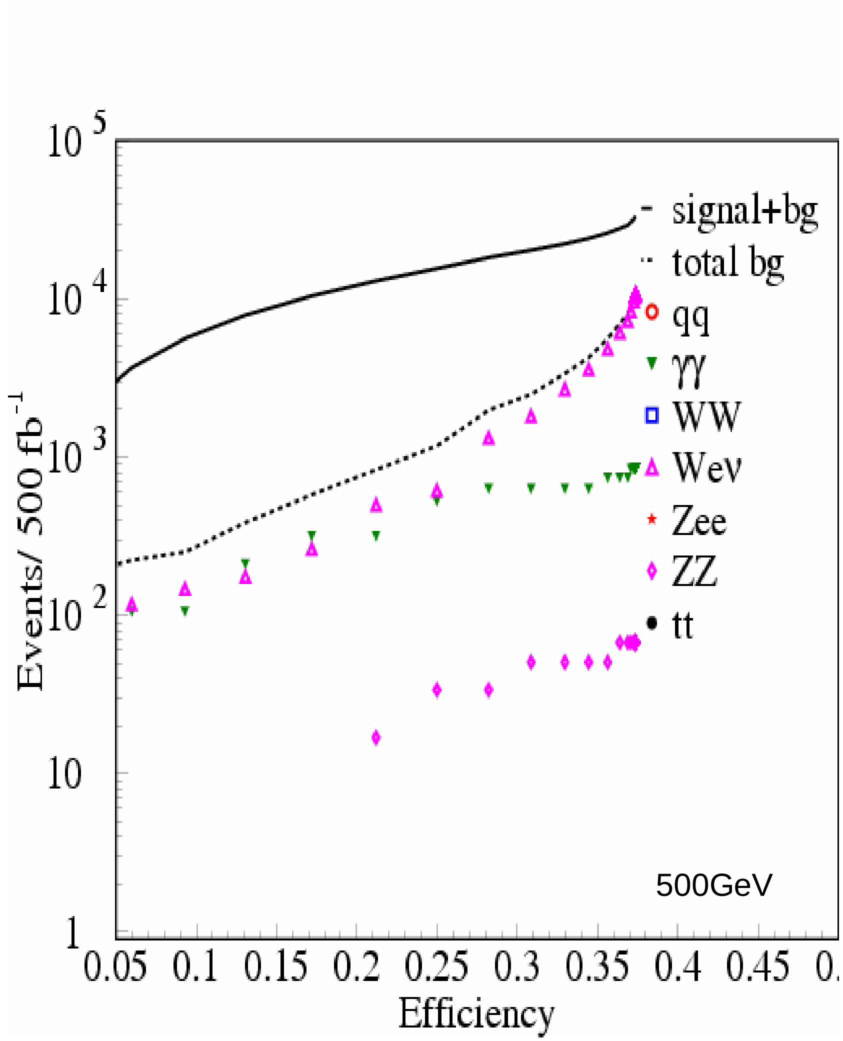
Invariant Mass Di-Jets 1 Step Before Final IDA





IDA Performance





Work in Progress

Events Generated and After IDA Selection

	L=50fb^{-1} at ECM=260GeV		L= 500fb^{-1} at ECM=500GeV	
P (e-)/ P(e+)	0/0	+80%/-60%	0/0	+80%/-60%
$\tilde{t}_1 \tilde{t}_1^*$	610	1470 (38%eff.)	21240	49700 (36%eff.)
WW	19	2	<41	<4
ZZ	7	7	67	60
Wenu	68	39	10640	3155
eeZ	10	8	<36	<30
qq, q≠t	30	32	<38	<43
tt	0	0	<3	<3
2-Photons	<25	<25	840	840

Table 4: *Preliminary Results- (In Progress)*

The efficiencies improves from 24% ,19% cut based → 38% ,36% IDA, while the background is of the same order of magnitude.

Systematic Uncertainty in Kinematics Cuts Variables

Variable	Error on variable	Error on Y
p_t	2%	0.28%
$\cos\theta_{Thrust}$	1.8%	0.18%
E_{vis}	2%	0
Φ_{acop}	1%	0.08%
m_{jj}	4%	0.61%

Table 5

•All cuts are applied to hadronic and jet observables→ Calibration quantities are jet energy scale & jet angle.
•Based on LEP, we assume 2% calibration error for jets, 1 deg for jet angle
•Effect on signal efficiency: Partial cancellation between 260 and 500 GeV
•We assume cancellation in total luminosity in Y between 260&500GeV

Effect of Stop and Charm Fragmentation

Comparison of the signal generated with and without gluon radiation
→The signal efficiency changes due to jet number cut is 2.5%
→We assume an error of 1% for the number of jets
Charm fragmentation parameters assumed as precise as for LEP/OPAL
→ε_c =-0.0031±0.0011
Stop fragmentation is set relative to bottom fragmentation, $\varepsilon_{\tilde{t}1} = \varepsilon_b (m_b/m_t)^2$
$\varepsilon_{\tilde{t}1}$ =-0.0050±0.0015
They don't cancel between the 2 energies but are small
Including the effects of the fragmentation at both energy points
$\delta\varepsilon_c$ =± 35% → Error δY=+1.2%-0.2%
$\delta\varepsilon_{\tilde{t}1}$=± 30% → Error δY=+0.4%+2.4%
→contribute an error O(few%)

Theoretical Uncertainties

- Precise cross-section calculations are needed
- $\tilde{t}1$ production receives large corrections from QCD gluon exchange
  Between the final state $\tilde{t}1$ (bigger @Threshold) → Coulomb corr.
- NLO- QCD corrections ~100% @threshold down to 10% at high energies are included here
- NNLO-QCD corrections are expected of to be same order than NLO
  based on the results for the top quark. The missing higher order
  correction ~7% @260GeV, 2.5% @500 GeV
- It is expected that theoretical uncertainties can be brought down by a
  factor 2
- Here we assume an uncertainty of 3.5% @260GeV and 1% @500 GeV
- The EW corrections : NLO ~several %, the NNLO ~1%
- Combined → ~4% @260 GeV and 1.5% @500GeV→δY=5.5%

Combined Statistic and systematic Errors

Error source for Y	Cut-based Analysis
Statistical	4.1%
Detector Effects	1.15%
Jet number	1%
Charm Fragmentation	1.2%
Stop Fragmentation	2.4%
Charm tagging algorithm	<0.5%
Sum of Experimental Errors	5.2%
Theory for signal σ	5.5%
Theory for background σ	0.5%
Total error δY	7.2%

Table 6

For IDA the determination of *systematic uncertainties* in progress.

Results

Combining the statistical and systematic errors Table 6(*)

δY=7.2%→ $\delta m_{\tilde{t}1}$ ~ 0.3 GeV – a factor 4 better (*Phys. rev. D 72,115008(2005*)

(dominated by the theory, expected to improve for signal and background)

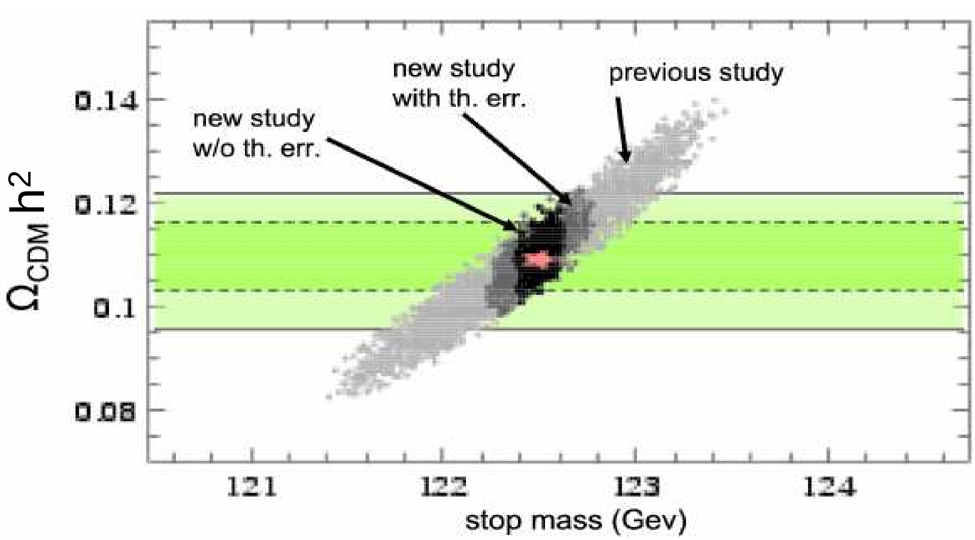
δY=5.2%→ $\delta m_{\tilde{t}1}$~ 0.21 GeV (cut based experimental errors alone)

δY=4.2%→ $\delta m_{\tilde{t}1}$ ~ 0.17 GeV (experimental errors & IDA) (expected)

→ Improvements in dark matter relic density due to improvement in $\delta m_{\tilde{t}1}$ is shown in the next figure.

Other limiting factors start to interplay, e.g. the precision on the neutralino mass $\delta m_{X1}{}^{0}$ ~ 0.3 GeV ,(hep-ph/0608255, M.Carena, A.Freitas)

Dark Matter Relic Abundance=f $(m_{\tilde{t}1})$



Dark Matter relic density accounting
The estimated experimental errors
For stop, Chargino, neutralino and
Higgs sector –(scan over 1σ)
versus $m_{\tilde{t}1}$ for

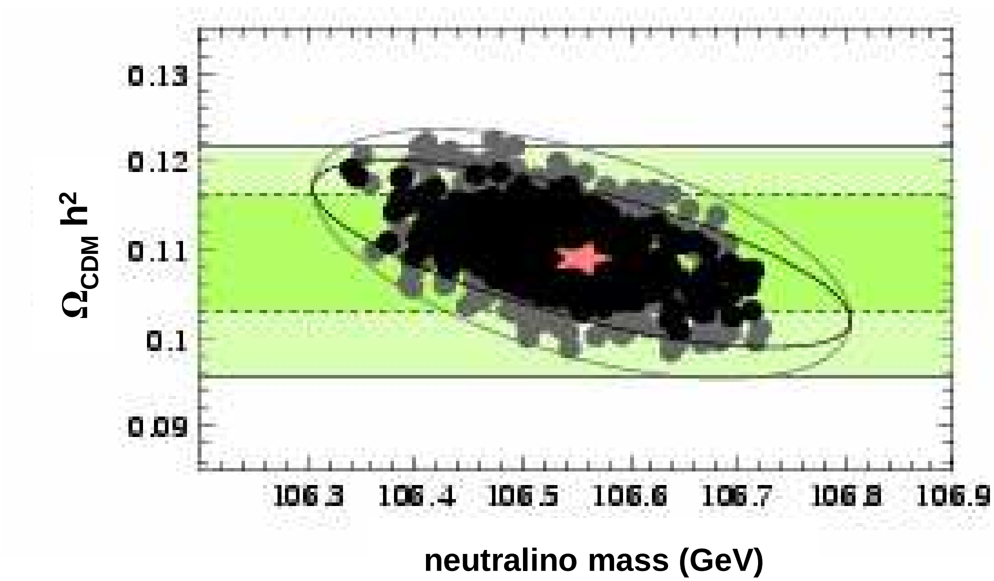
$\delta m_{\tilde{t}1}$=1.2 GeV light gray dot
Previous study

$\delta m_{\tilde{t}1}$=0.3 GeV dark gray dot
Now this study

$\delta m_{\tilde{t}1}$=0.17GeV black dots
Expected this study with IDA

$\delta m_{\tilde{t}1}$= 0.3 GeV → $\Omega_{CDM} h^2$ = 0.109+0.0013-0.010 Exp. Err.+ Th. Err.
$\delta m_{\tilde{t}1}$= 0.21 GeV → $\Omega_{CDM} h^2$= 0.109+0.0012-0.009 Exp. Err. Seq. cuts
$\delta m_{\tilde{t}1}$= 0.17 GeV → $\Omega_{CDM} h^2$=0.109+0.0011-0.009 Exp. Err. IDA

Relic Abundance as Function of $m_{\chi_1^0}$



Dark Matter relic density as a function of the neutralino mass accounting for the estimated experimental errors as before but as function of the
Lightest neutralino mass $m_{\chi_0^1}$
Gray dots for $\delta m_{\tilde{t}1}=0.3$ This study
Errors from Experiment+theory
Black dots for $\delta m_{\tilde{t}1}=0.17$ This Study
Experiment. Err. and IDA

$\delta m_{\tilde{t}1}$= 0.3 GeV→$\Omega_{CDM}\, h^2$ = 0.109+0.0013-0.010 Exp. Err.+ Th. Err.
$\delta m_{\tilde{t}1}$= 0.17 GeV→$\Omega_{CDM}\, h^2$ = 0.109+0.0011-0.009 Exp. Err. IDA
WMAP: $\Omega_{CDM}\, h^2$ = 0.1106+0.0056-0.0075

Conclusion

- More realistic data were produced including hadronization/fragmentation
- The precision, however, improved by a factor three on our previous analysis with $\delta m_{\tilde{t}1}$= 0.3 GeV
- This method could be applied to other particles e.g. to measure the Higgs mass
- The method improves the precision to the mass determination in two ways
  a/ by reducing the systematics in Y- cancellation between the two energy points.
  b/ by choosing the energy at threshold, Y extremely sensitive to the mass
- The polarization separates the right-handed signal $\tilde{t}_1$ from background.
- Due to hadronization and fragmentation the c-tagging was a necessary tool to identify the charm jets at E_{CM}=500 GeV (benchmark for the vertex detector)
- Systematics in progress for the IDA a multi-parameters analysis, expected improvement to $\delta m_{\tilde{t}1}$= 0.17 GeV
- Progress in the theoretical calculations is expected and partly accounted for
- With that precision we become limited by other factors.
- With this mass precision, the calculated relic density is in accordance with WMAP and SLOAN ,

  $\delta m_{\tilde{t}1}$= 0.15 GeV→ΩCDM h2 = 0.109+0.0011-0.009

  WMAP: ΩCDM h^2 = 0.1106+0.0056-0.0075

Backup slides

A Sample Parameter Point

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

Which gives:

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

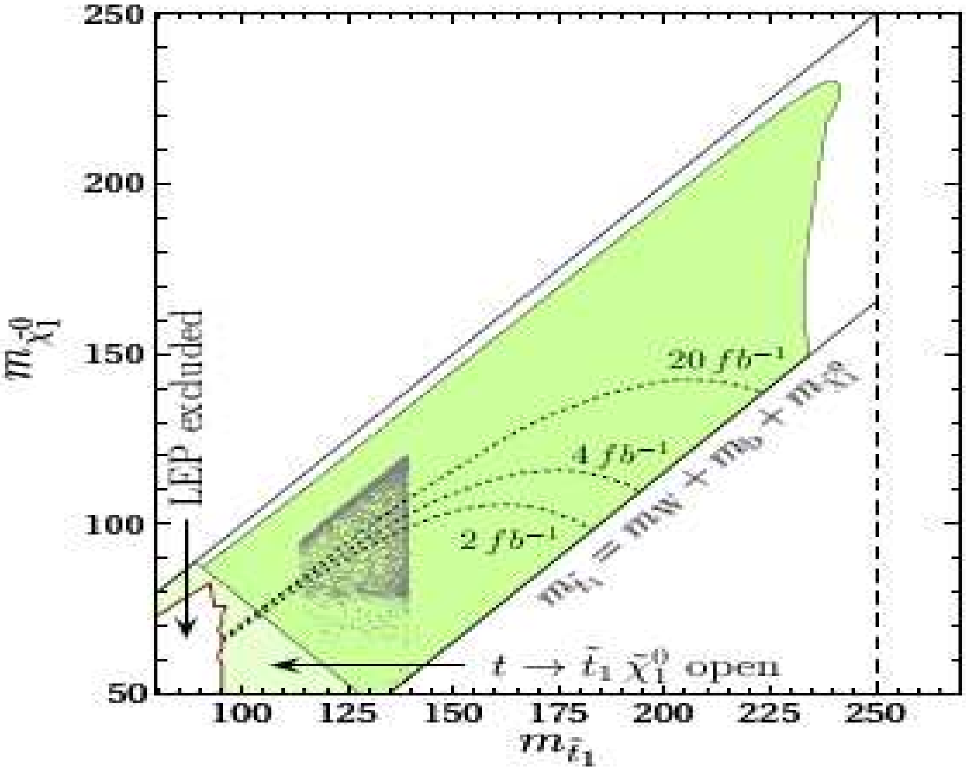
$m\tilde{\chi}_1^0$ = 107.2 GeV; $m\tilde{\chi}_1^+$ = 194.3 GeV; $m\tilde{\chi}_2^0$=196.1 GeV

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

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

→ Δm=15.2 GeV

Stop Discovery Reach
Snowmass 2005



From Simulations:
<u>strong green region</u>:

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

And Significance:
(S/√(S+B)) > 5
Background B
Signal S=εσL
For ε , Signal efficiency
For σ, Theoretical cross-section
<u>dark gray region</u>:
Consistent with DM
And Baryogenesis

Fig 4a-<u>Luminosity: 500 fb^{-1}</u>
E_{cm}=500 GeV

Fig 4b-<u>Lumi. 500 fb^{-1}, 50 fb^{-1} ,10 fb^{-1}</u>

C-Tagging – The Data Samples

- *<u>Neural Network (NN):</u>*

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

240000 Weν, the most resilient background