Precision Measurement of the Stop Quark Mass at the ILC

-preliminary results-

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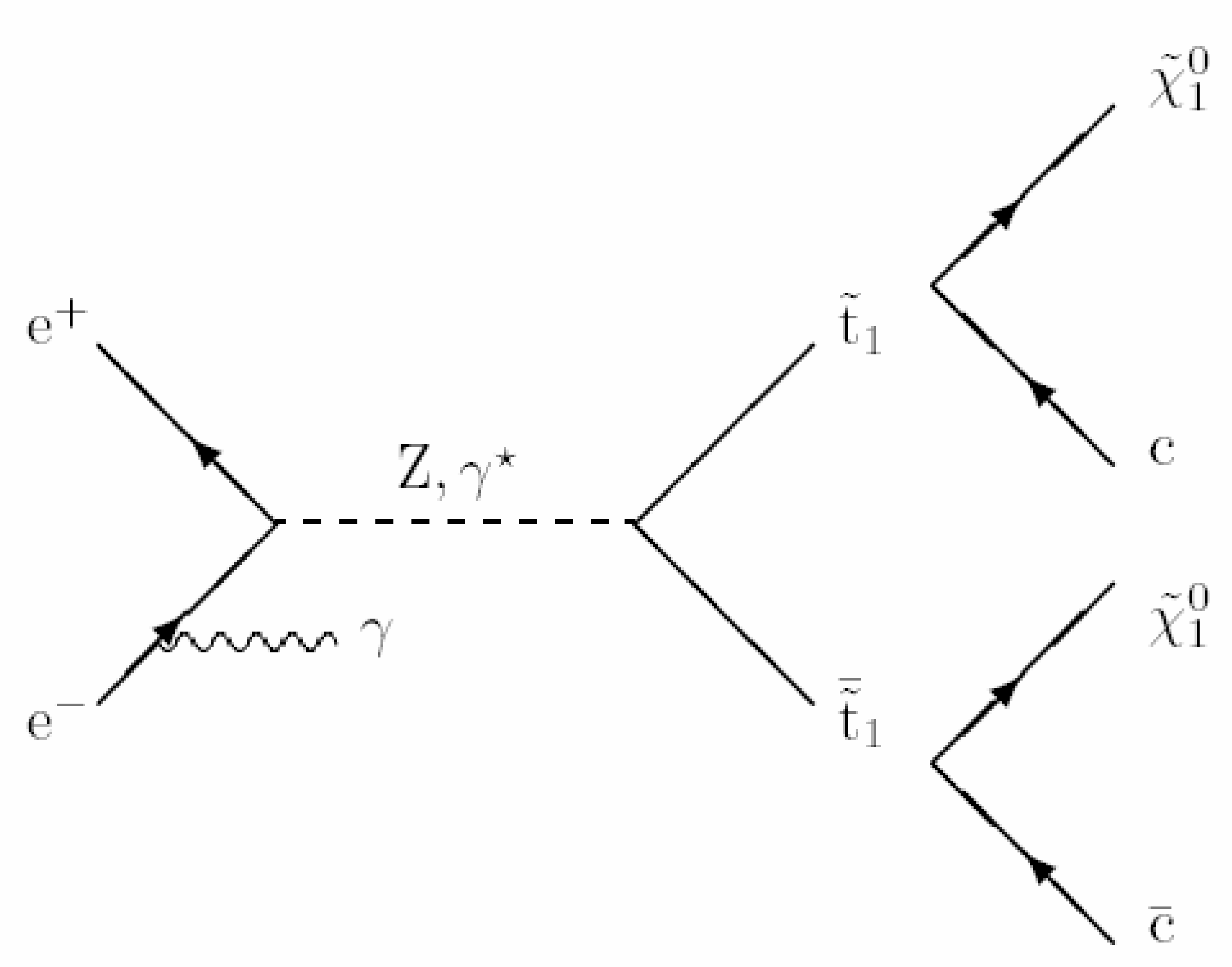
Outline

- Introduction
- Previous methods to determine the scalar top quark mass.
- New method using measurements at 260 and 500 GeV center-of-mass energies.
- Iterative Discriminant Analysis (IDA) versus sequential-cut analysis for event selection.
- MSSM interpretation for dark matter annihilation.
- Conclusions

Introduction

- Supersymmetric models predict new particles within the reach of the future Linear Collider.
- To understand the model structure and the mechanism(s) of symmetry breaking, it is important to know the masses of the new particles precisely.
- The mass determination of the scalar partner of the top quark (stop) at an e^+e^- collider is studied.
- A relatively light stop is motivated by attempts to explain electroweak baryogenesis and can play an important role in Cold Dark Matter (CDM) annihilation.
- Stop mass precision crucial for CDM prediction at the ILC.
- A new method makes use of cross-section measurements near the pair-production threshold as well as at higher center-of-mass energies.

Signal Signature



Previous Methods to Determine Scalar Top Mass at the ILC

Recent overview of ILC Scalar Top studies:

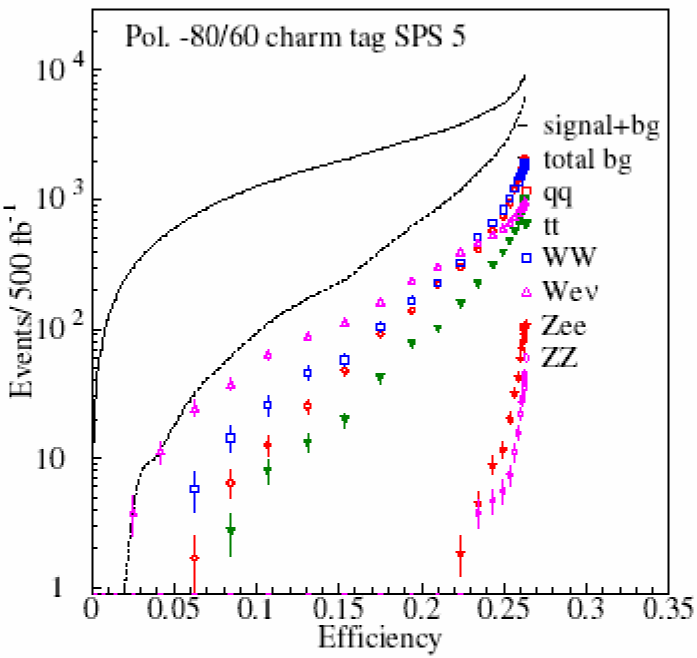
LCWS'07 contribution May 31, 2007 (AS).

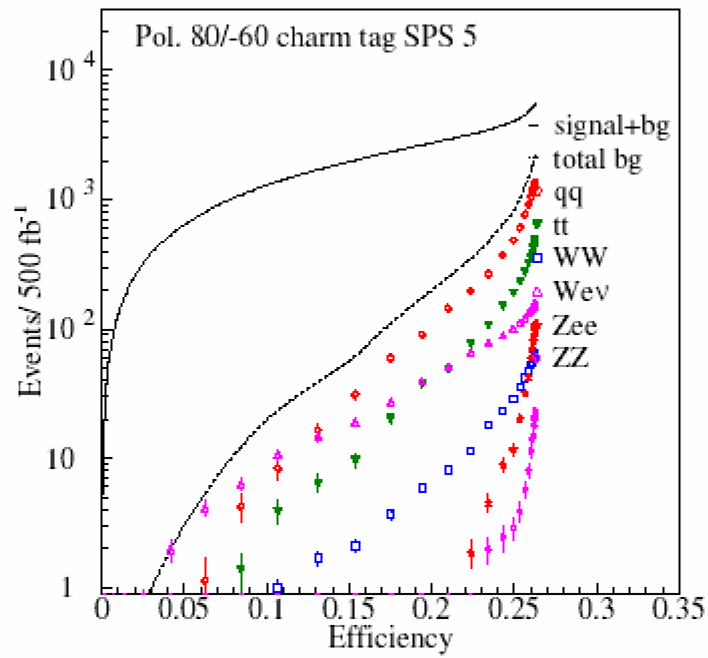
Methods:

1. Cross section determination for two different beam polarizations.
2. Threshold dependence on cross section.
3. Endpoint of jet energy spectrum.
4. Minimum Mass of jets (J.Feng).

Beam Polarization Method

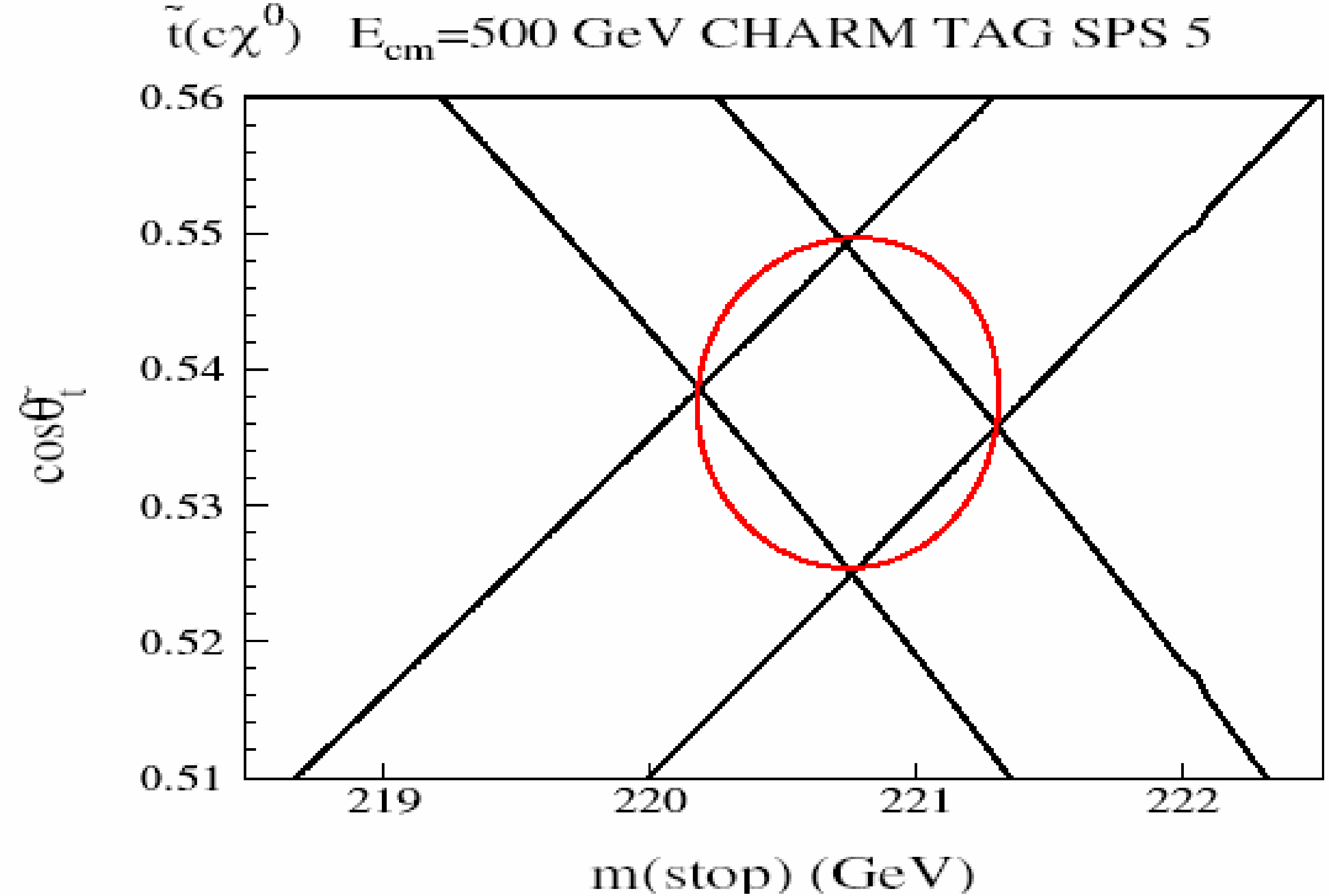
Finch, Nowak, AS





At 12% Efficiency		Pol. -80/60	Pol. 80/-60
	Signal:	1350	1500
	Background:	145	32

Beam Polarization Method



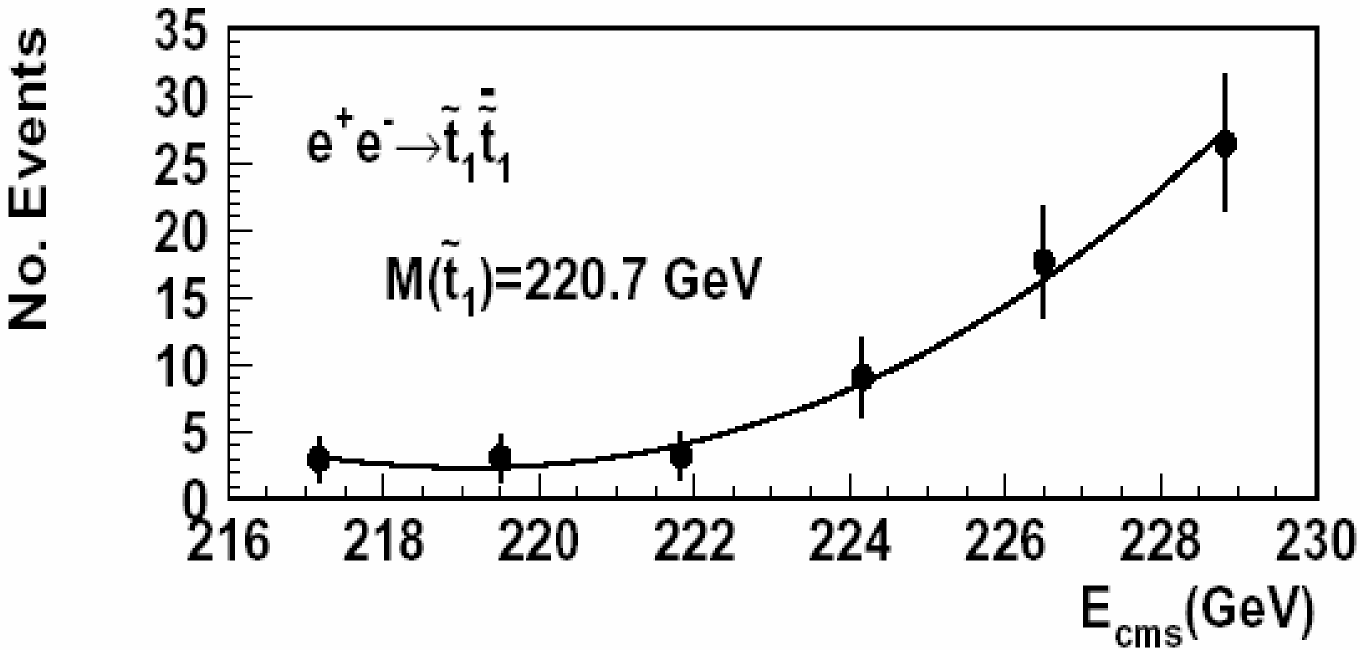
$500\,\mathrm{fb}^{-1}$ for each polarization: $\Delta m_{\tilde{t}_1} = \pm 0.57\mathrm{GeV}$ $\Delta\cos\theta_{\tilde{t}} = \pm 0.012$

Threshold Scan

Use 'right-handed polarization' to reduce backgrounds

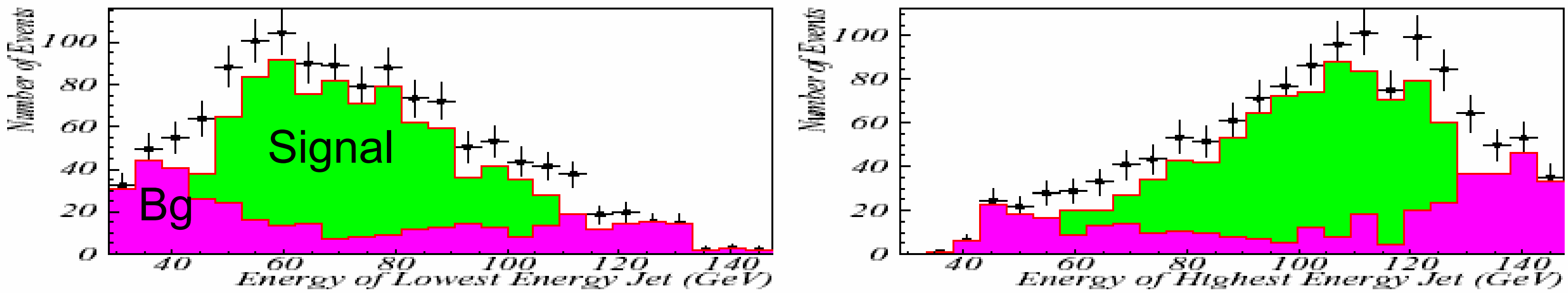
Measure cross section close to threshold

6 points with 50 fb^{-1} per point.

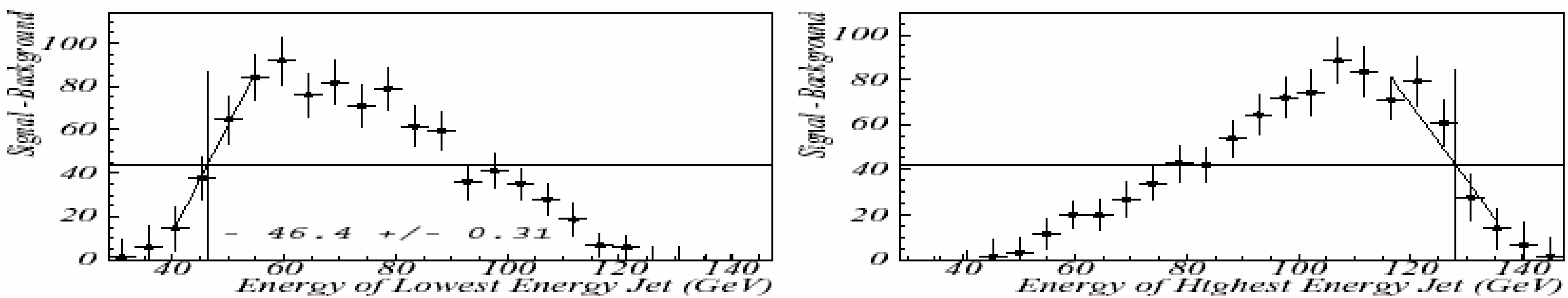


Mass from fit to shape: 220.9 ± 1.2 GeV

Jet Energy Method



Subtract Background. Straight line fit to decreasing and increasing slopes.



Measure Endpoints at Half Height Position (statistical uncertainty is small).

Minimum Jet Endpoint $= 45.7 \pm 1.0$ GeV

Maximum Jet Endpoint $= 130.2 \pm 1.5$ GeV

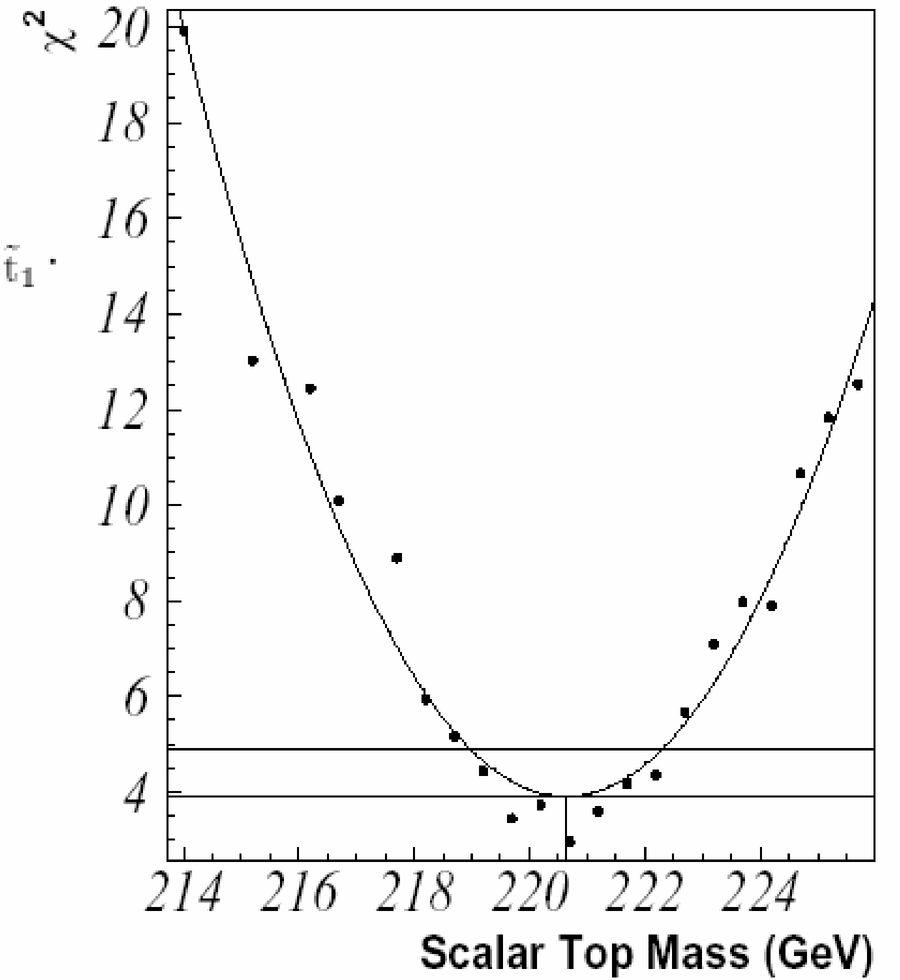
$m_{\tilde{t}_1} = 219.3 \pm 1.7$ GeV

$m_{\tilde{\chi}_1^0} = 119.4 \pm 1.6$ GeV

Minimum Mass

If $m_{\tilde{\chi}^0_1}$ is known:
calculate minimum allowed mass of the two jets; it peaks at $m_{\tilde{t}_1}$.

- Monte Carlo samples - varying $m_{\tilde{t}_1}$
- Fit minimum mass distribution.
- Result: $m_{\tilde{t}_1} = 220.5 \pm 1.5$ GeV



Previous SPS-5 Mass Precision

Method	Δ_m (GeV)	luminosity	comment
Polarization	0.57	2×500 fb^{-1}	no theory errors included
Threshold Scan	1.2	300 fb^{-1}	right hand polarization
End Point	1.7	500 fb^{-1}	
Minimum Mass	1.5	500 fb^{-1}	assumes $m_{\tilde{\chi}_1^0}$ known

Small Stop-Neutralino Mass Difference

Motivation:

- Baryongenesis (Carena, Quiros, Wagner '96): $m_{\tilde{t}_1} < m_t$
- Dark Matter (Carena, Balazs, Wagner '04):
  correct Cold Dark Matter for small mass difference.

Example: Phys. Rev. D 72,115008 (2005) and Snowmass Conf. Proc. (2005)
M. Carena, A. Finch, A. Freitas, C. Milstene, H. Nowak, A. Sopczak

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

<u>Mass spectrum:</u>

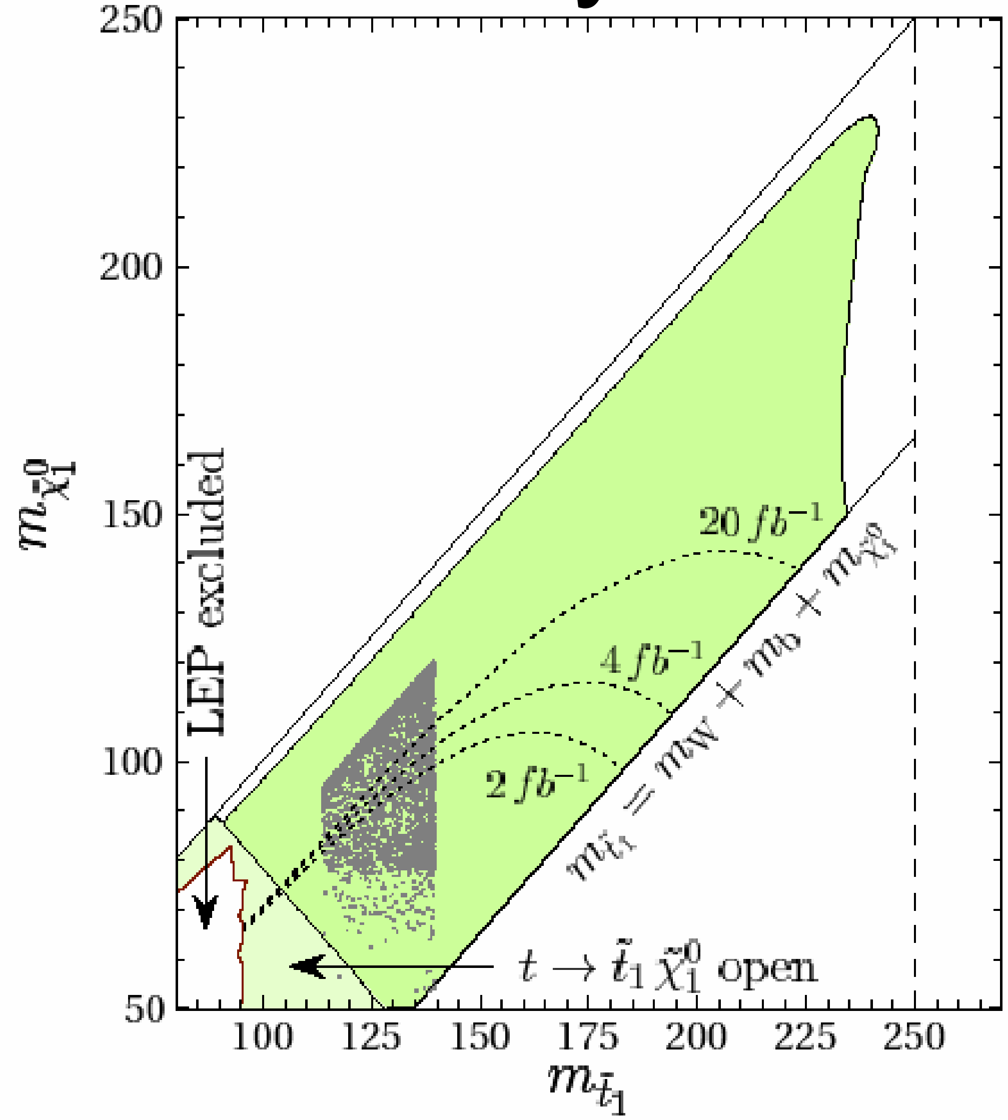
$m_{\tilde{t}_1}$ =122.5 GeV (lightest stop quark)

$m_{\tilde{\chi}^0_1}$ = 107.2 GeV (lightest neutralino)

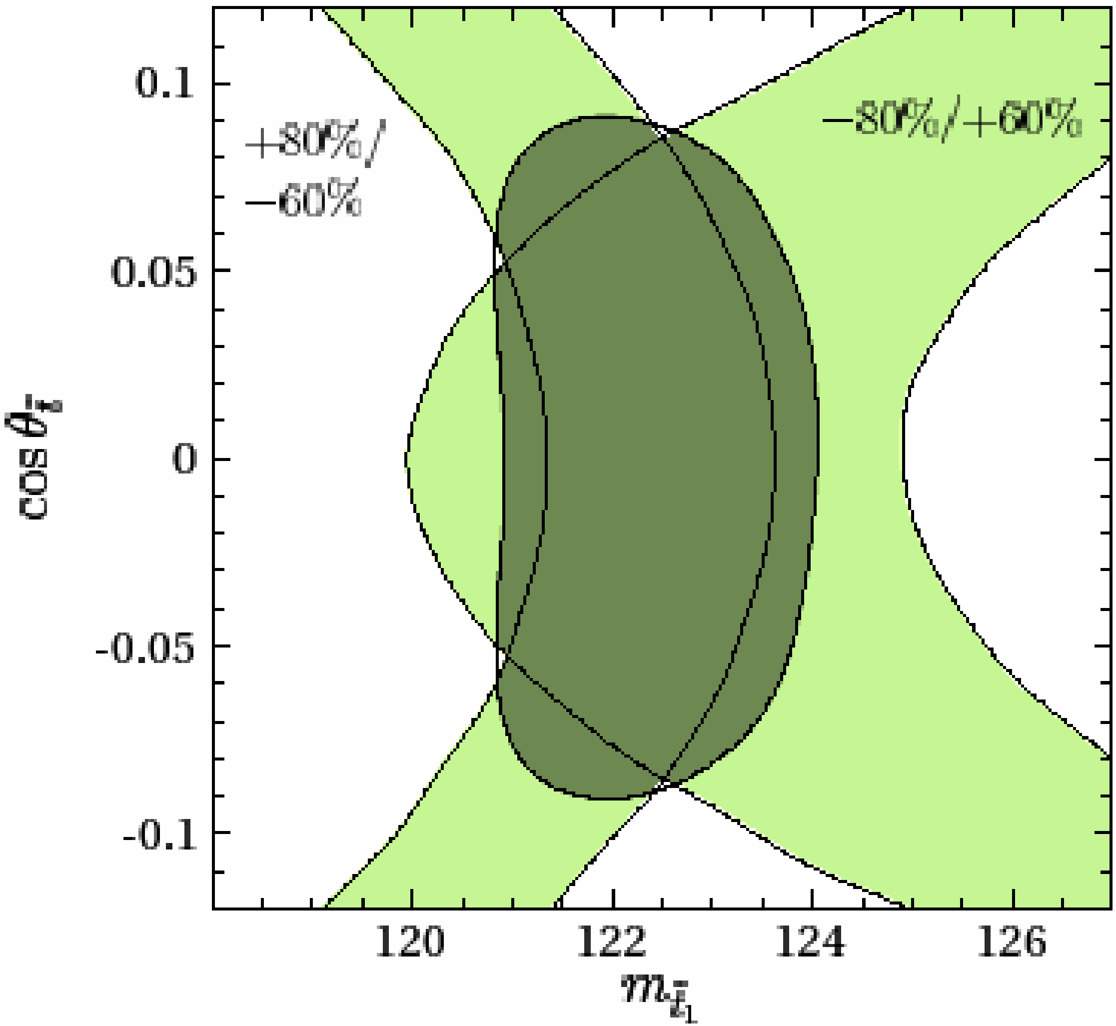
→ Δm=15.3 GeV

$\cos\theta_{\tilde{t}}$ = 0.0105, thus $\tilde{t}$ is right-handed

Discovery Reach



Mass Resolution in Previous Study



Δm(stop)=±1.0 GeV

Mass uncertainty dominates uncertainty on CDM prediction.

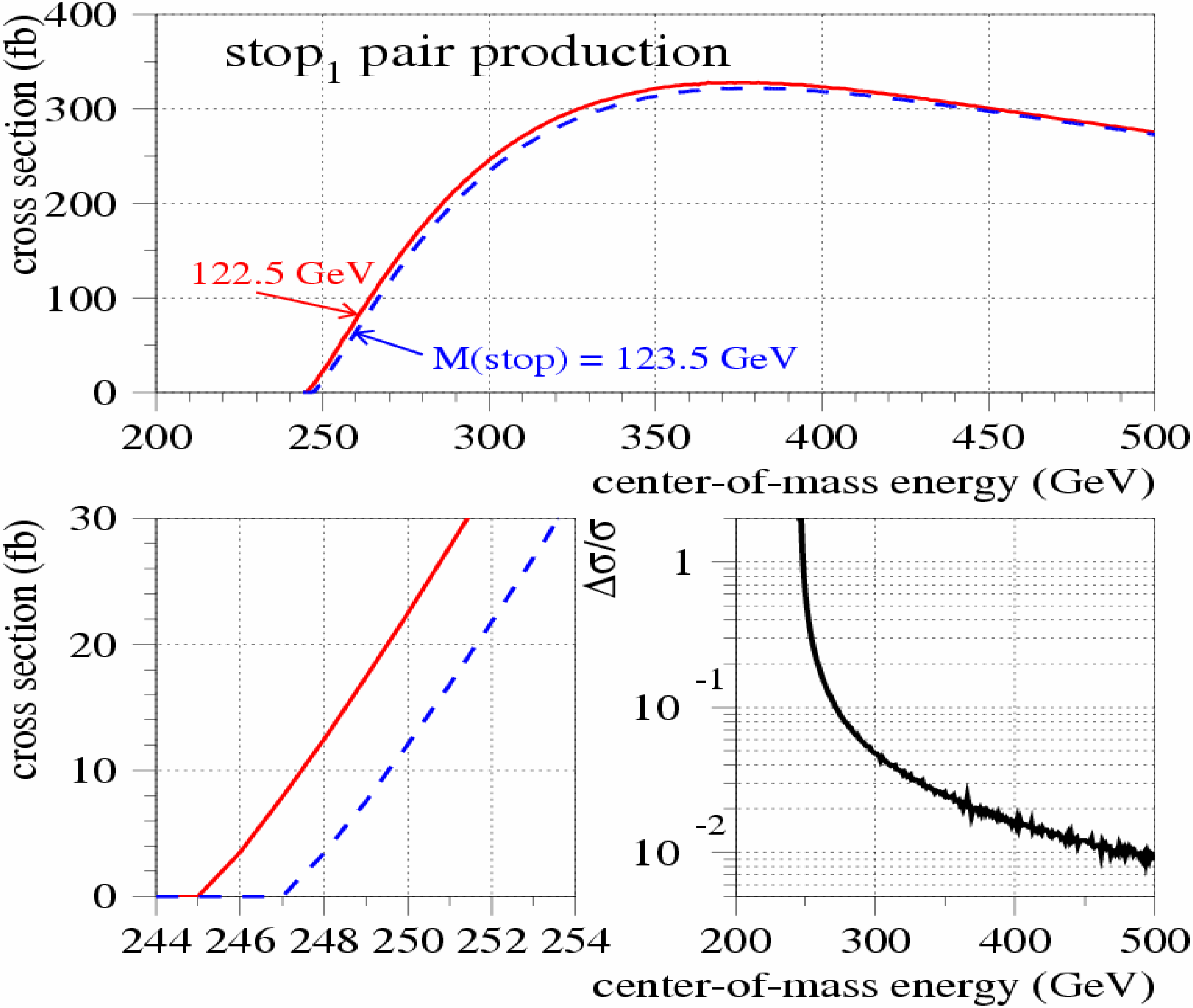
New Method to Determine Stop Mass

Determine stop pair production cross-section near threshold (th) and near the peak (pk) cross section. Use ratio *Y* to determine mass.

Cancellation of systematic uncertainties by using two cross-section measurements.

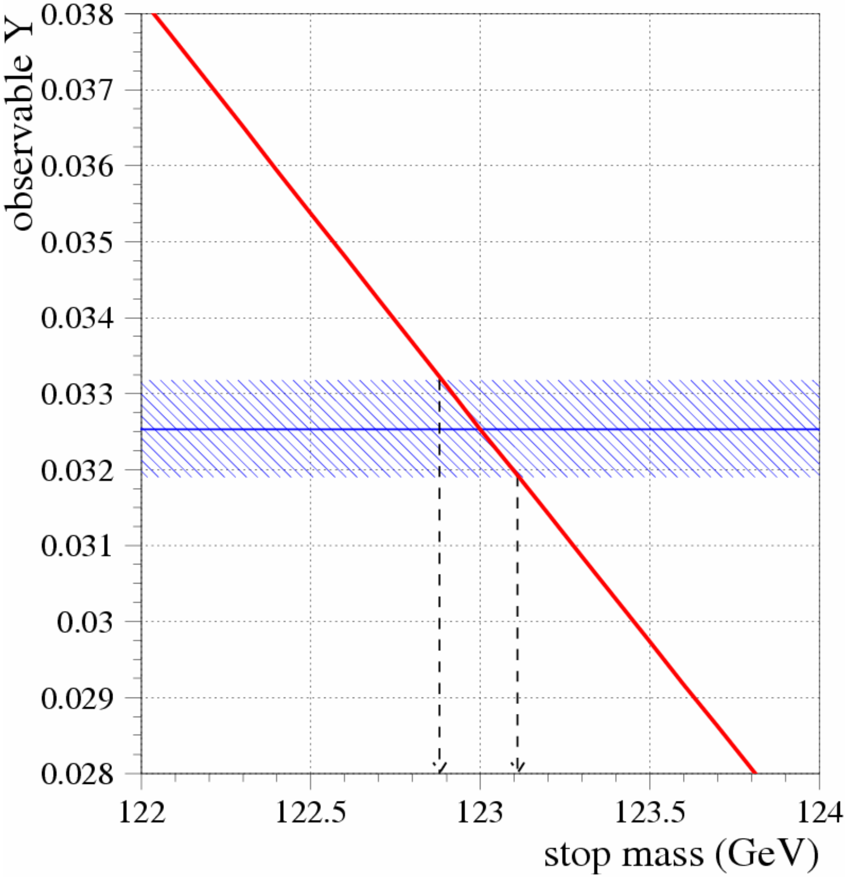
$$Y(M_X, \sqrt{s_{\rm th}}) \equiv \frac{N_{\rm th} - B_{\rm th}}{N_{\rm pk} - B_{\rm pk}} = \frac{\sigma_{\tilde{t}}(\sqrt{s_{\rm th}})}{\sigma_{\tilde{t}}(\sqrt{s_{\rm pk}})} \cdot \frac{\epsilon_{\rm th}}{\epsilon_{\rm pk}} \cdot \frac{\mathcal{L}_{\rm th}}{\mathcal{L}_{\rm pk}}$$

Cross Section vs √s



Cross-section very sensitive to stop mass in threshold region.

Principle of Method



- Expected $Y = f(m_{stop})$ from the theoretical cross-section (red line).
- *Y* from the simulated data (blue line).
- Uncertainty on *Y* determined uncertainty on stop mass.
- This scenario, at $\sqrt{s}$=260 GeV: σ=9.2 fb and at peak: σ=77fb.
- Assumed Background 4.3fb-1 (L_{th}=50fb^{-1}, L_{pk}=500fb^{-1} from our previous study.)

Production Cross-Section

Process	σ[pb] at √s=260GeV			σ[pb] at √s=500GeV		
P (e^-)/ P(e^+)	0/0	-80%/+60%	+80%/-60%	0/0	-80%/+60%	+80%/-60%
$st_1\ st_1^*$	.032	0.017	0.077	.118	.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
γγ (p_t > 5 GeV)	786			936		

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

Signal and Background Simulation

- Simulation: Pythia (gen.), Simdet (det.), Circe (photon rad.)
- Stop fragmentation influences accurate efficiency estimate:

1) Stop quarks live long enough to form stable hadrons, thus fragmentation of stop hadrons are included in the simulation.
2) When the stop hadron decays to charm and spectator quarks, the fragmentation of the charm quark is also simulated (Peterson fragmentation).
3) Several variables, such as the number of jets and their missing energy distributions, depend on this simultion.

- Jet multiplicity:

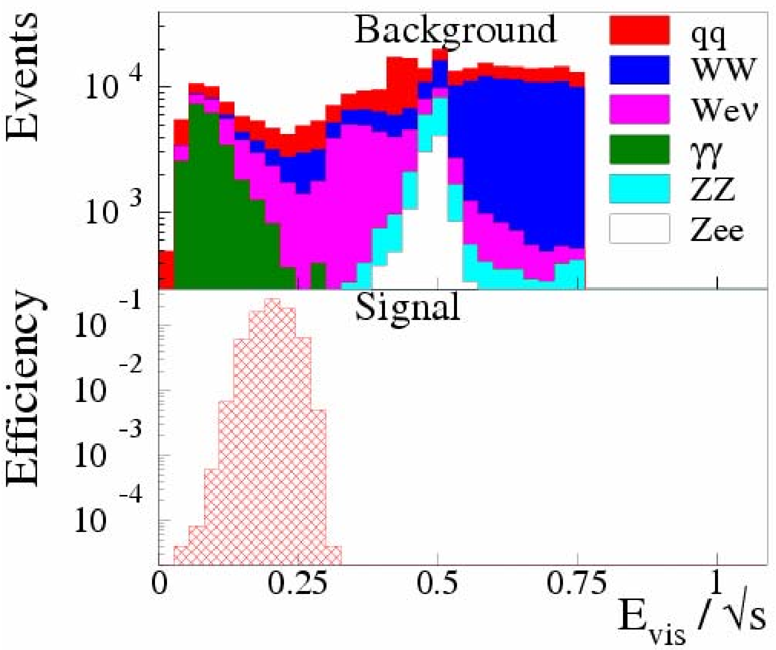
1) Without stop fragmentation: ≈70% 2-jet events
2) With stop fragmentation: ≈50% 2-jet events and larger number of multijet events

Sequential-Cut Analysis Results

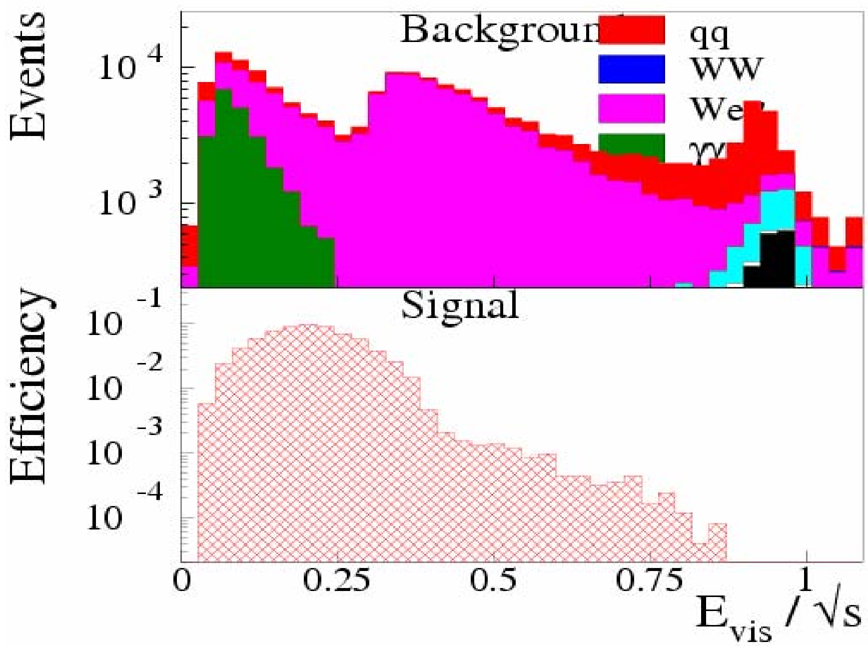
	L=50fb^{-1} at $\sqrt{s}$=260GeV			L= 500fb^{-1} at $\sqrt{s}$=500GeV		
P(e$^-$)/ P(e$^+$)	Generated	0/0	+80%/-60%	Generated	0/0	+80%/-60%
$st_1\ st_1^*$	50000	382	921*(24%eff.)*	50000	11300	26430*(19%eff.)*
WW	180000	<5	<1	210000	102	9
ZZ	30000	<2	<2	30000	250	224
Wenu	210000	36	4	210000	10102	2994
eeZ	210000	<1	<1	210000	<18	<15
qq, q≠t	350000	<7	<8	350000	19	22
tt	-	0	0	180000	21	19
$\gamma\gamma$	1.6 10^6	12	12	8.5×10^6	120	120

Iterative Discriminant Analysis

√s=260 GeV

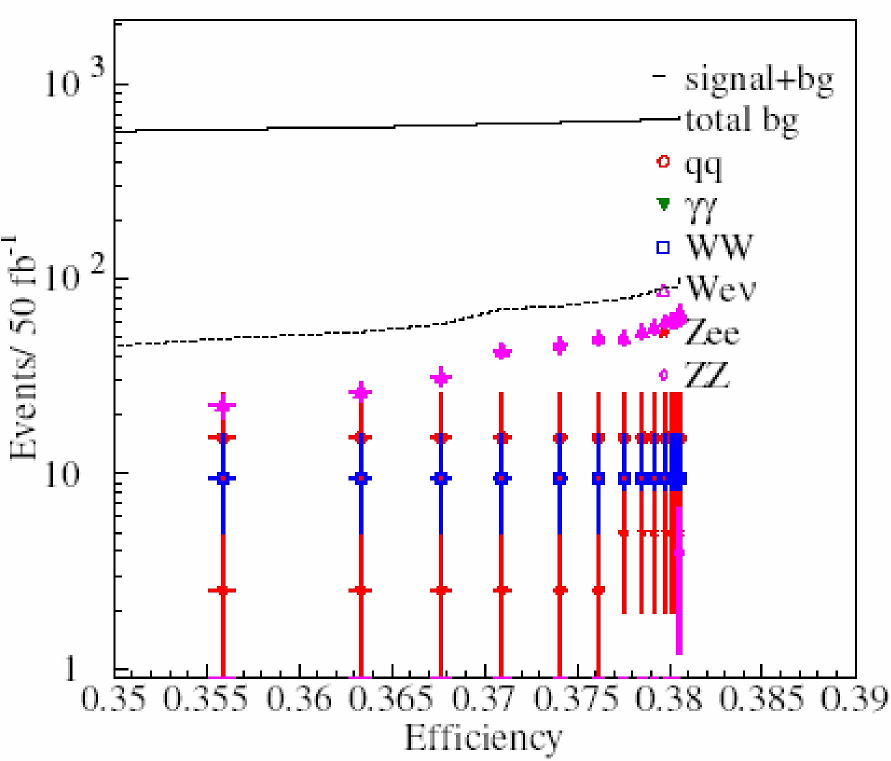


√s=500 GeV

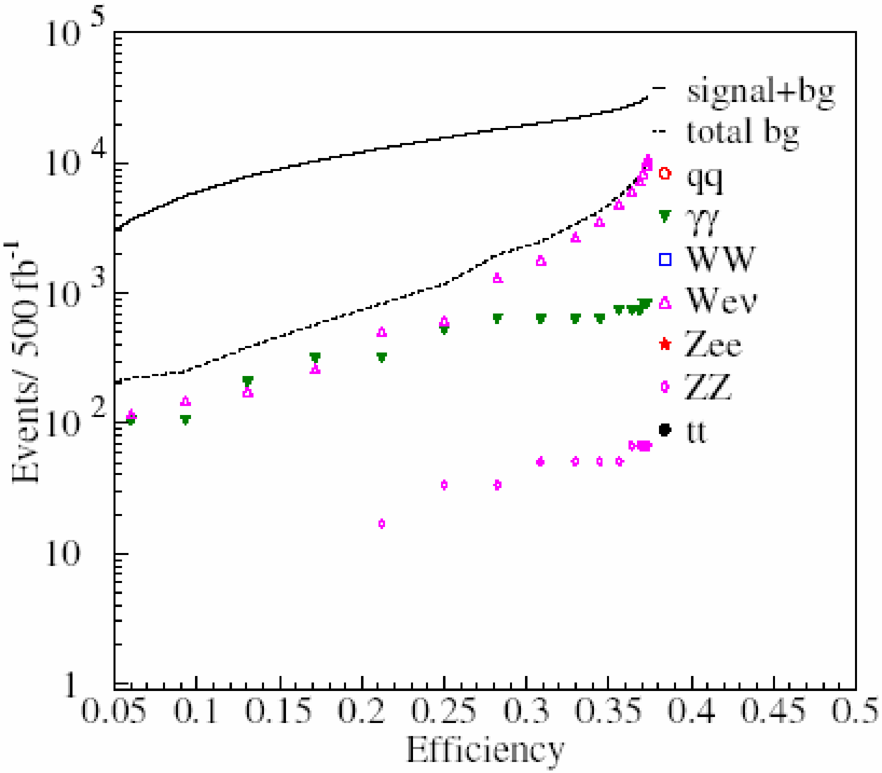


Iterative Discriminant Analysis

$\sqrt{s} = 260$ GeV



$\sqrt{s} = 500$ GeV



Weν is dominant background.

IDA Analysis Results

	L=50fb^{-1} at √s=260GeV		L= 500fb^{-1} at √s=500GeV	
P (e$^-$)/ P(e$^+$)	0/0	+80%/-60%	0/0	+80%/-60%
st_1 st_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

The signal over background ratios for the 260 and 500 GeV analyses improve with the IDA method.

Uncertainties on *Y*

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

Mass Determination

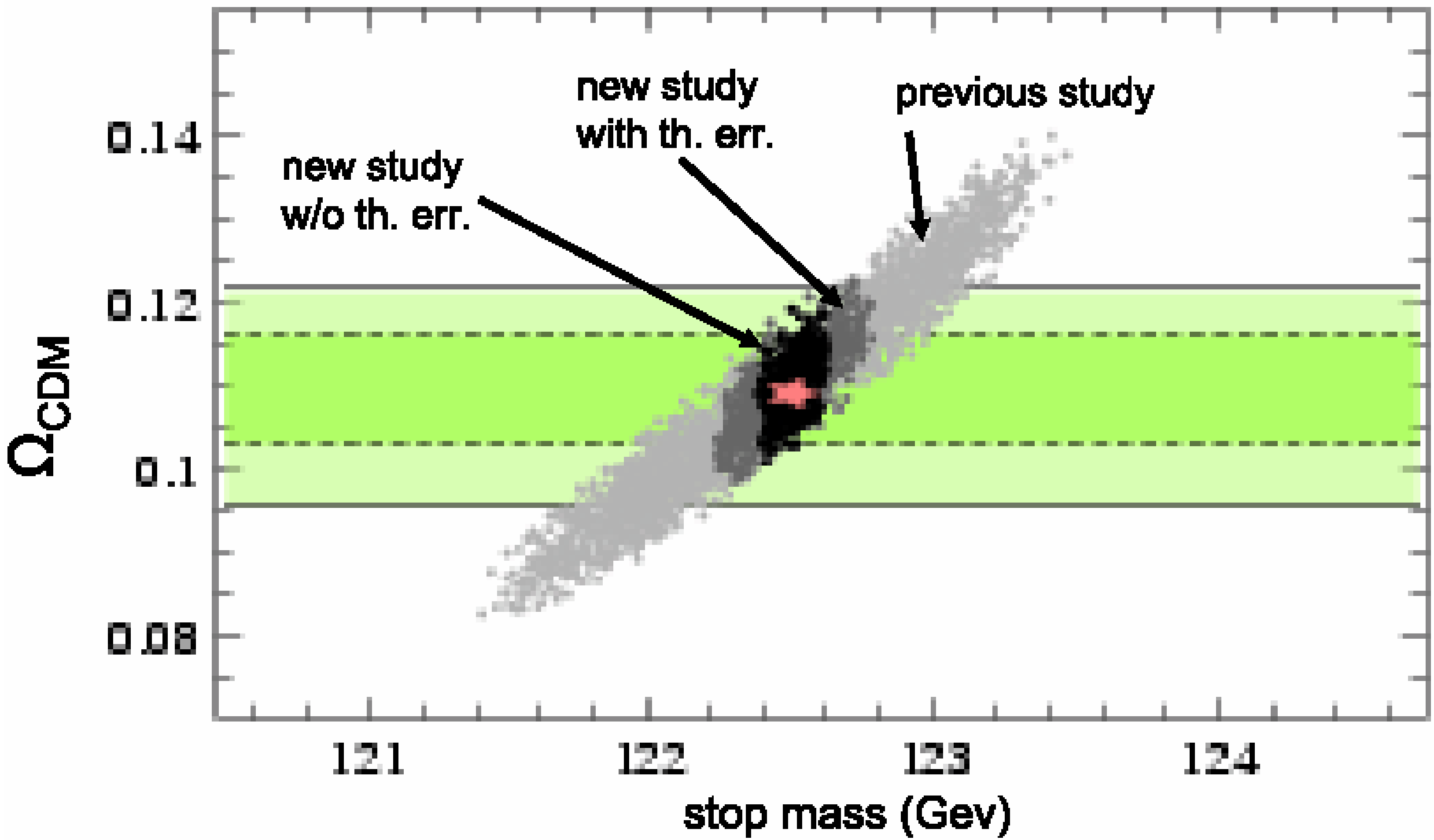
•ΔY=7.2%→ Δm(stop) ~ 0.3 GeV: (including theory uncertainty, which is expected to improve)

•ΔY=5.2%→ Δm(stop) ~ 0.2 GeV (cut-based experimental errors alone)

•ΔY=4.2%→ Δm(stop) ~ 0.15 GeV (IDA experimental errors alone with 1.2% stop fragment error)

About a factor 7 better compared to previous analysis.

MSSM CDM Interpretation



Other limiting factors start to contribute, e.g. neutralino mass Δm=0.3 GeV.

Conclusions

- Scalar top quarks could be studied with precision at a future Linear Collider.
- Simulations for small stop-neutralino mass difference motivated by cosmology.
- Precision mass determination possible with a method using two center-of-mass energies, e.g. $\sqrt{s}$=260 and 500 GeV.
- This method can also be applied to other analyses to improve the mass resolution.
- Expected LC precision on Ω_{CDM} comparable to current cosmological (WMAP) measurements.