Precision Measurement of the Stop Mass at the Linear Collider

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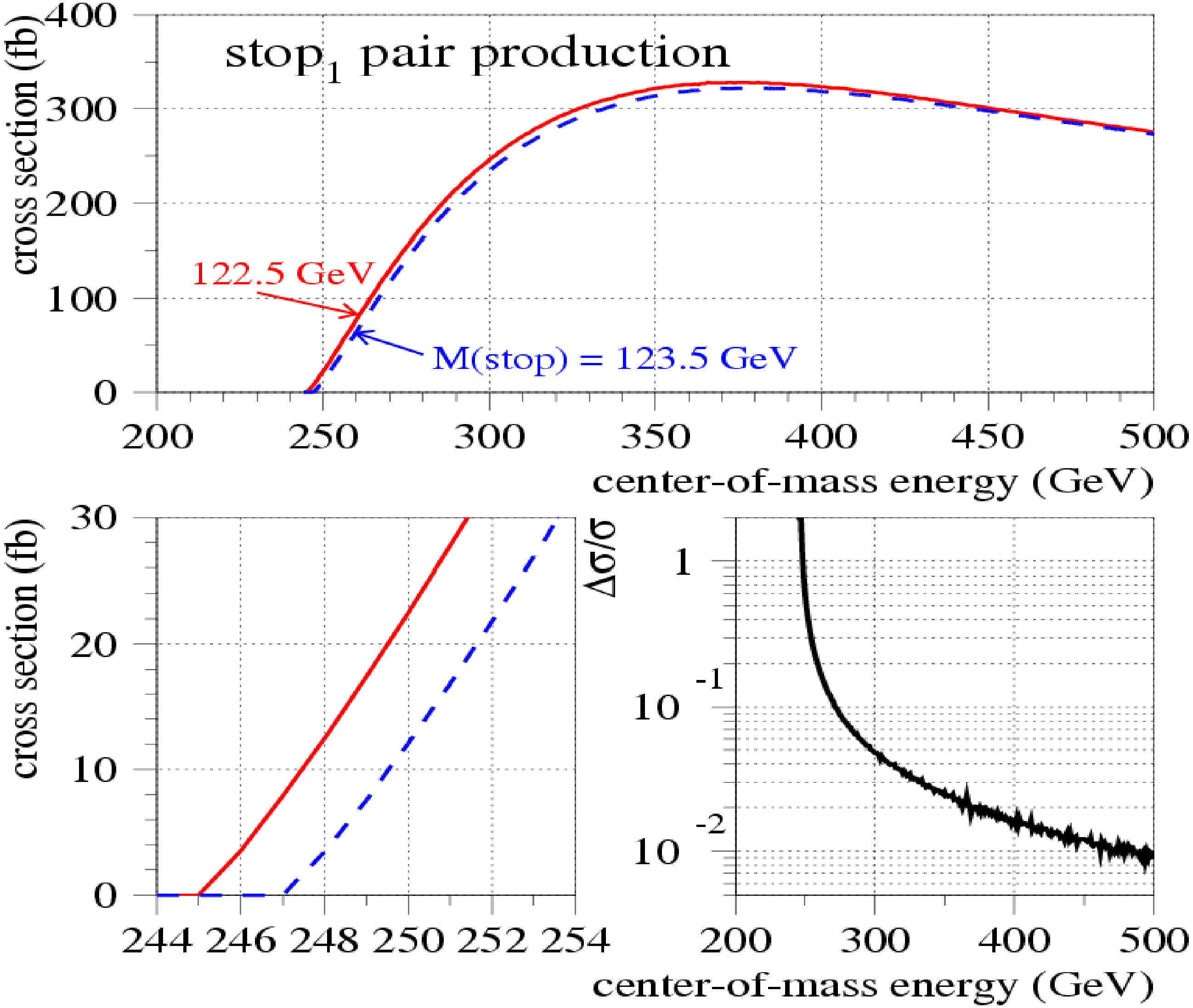
Publication in Preparation

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 its role 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.
- 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 → the c quark energy is spread out in the process of hadronization.
  the final number jets increases- the c-tagging is now a necessity 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

$$e^+e^- \to \tilde{t}_1\bar{\tilde{t}}_1$$



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

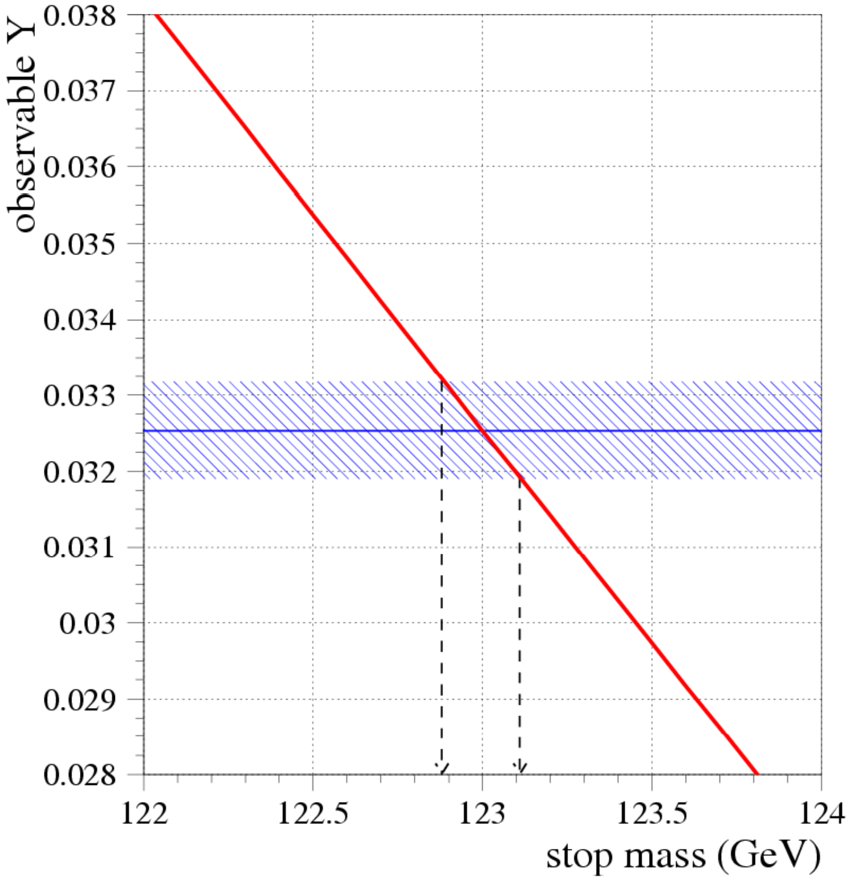
The Method

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

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

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
Y from the data the blue line.

As an example, Assume 2% precision for Y,
The blue hashed region → one obtains
→Precision $\Delta M_x = \pm 1\%$, 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)

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

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

•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 a <u>necessary tool</u> to identify
the charm jets (Vertex bench-marking)

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)

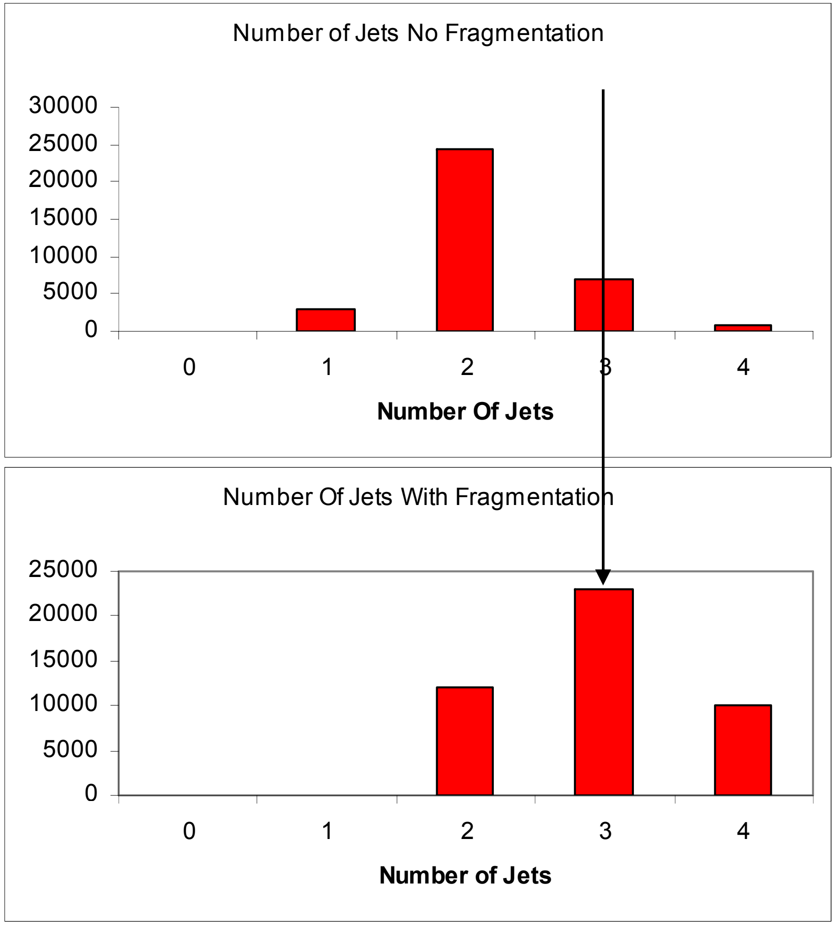
  - The $\tilde{t}$ fragmentation is simulated using Torbjorn code

  //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 $\varepsilon\_b=-0.0050 +/- 0.0015$ *following (OPAL,EPJ C6:225)*

•*The jet Multiplicity <u>without Fragmentation</u> Upper figure*

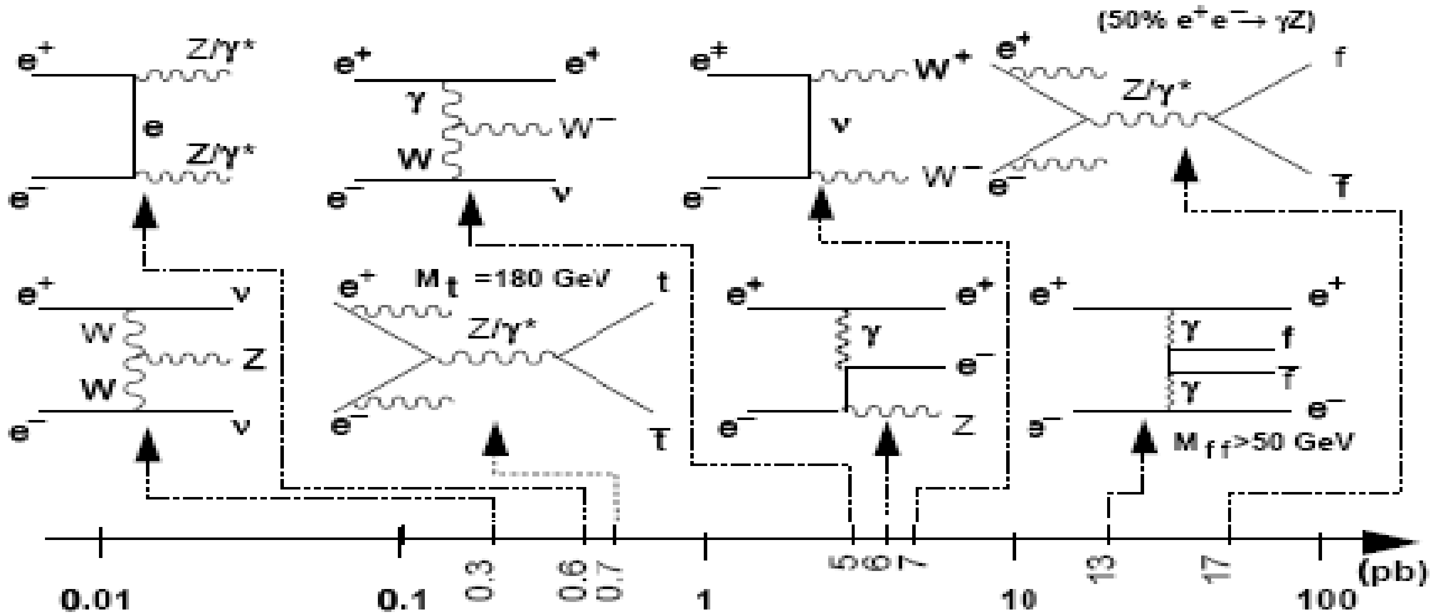
~ 70% 2 jets

•*The jet Multiplicity <u>with $\tilde{t}$ 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)

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 Thrust T $\cos\theta_{Thrust}$ Visible Energy E_{vis} Acoplanarity Φ_{acop} Invariant mass of jet pair m_{jj} Charm tagging likelihood P_c	p_t > 10 GeV - $\lvert\cos\theta_{Thrust}\rvert < 0.7$ E_{vis} < 0.175 *ECM $\lvert\Phi_{acop}\rvert < 0.9$ 25.5 GeV<m_{jj} <90 GeV P_c > 40%	p_t > 12 GeV T > 0.8 $\lvert\cos\theta_{Thrust}\rvert < 0.7$ E_{vis} < 0.4 *ECM $\lvert\Phi_{acop}\rvert < 0.9$ 60 GeV<m_{jj} <90 GeV 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)
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	$8.5\text{x}10^6$	120 120

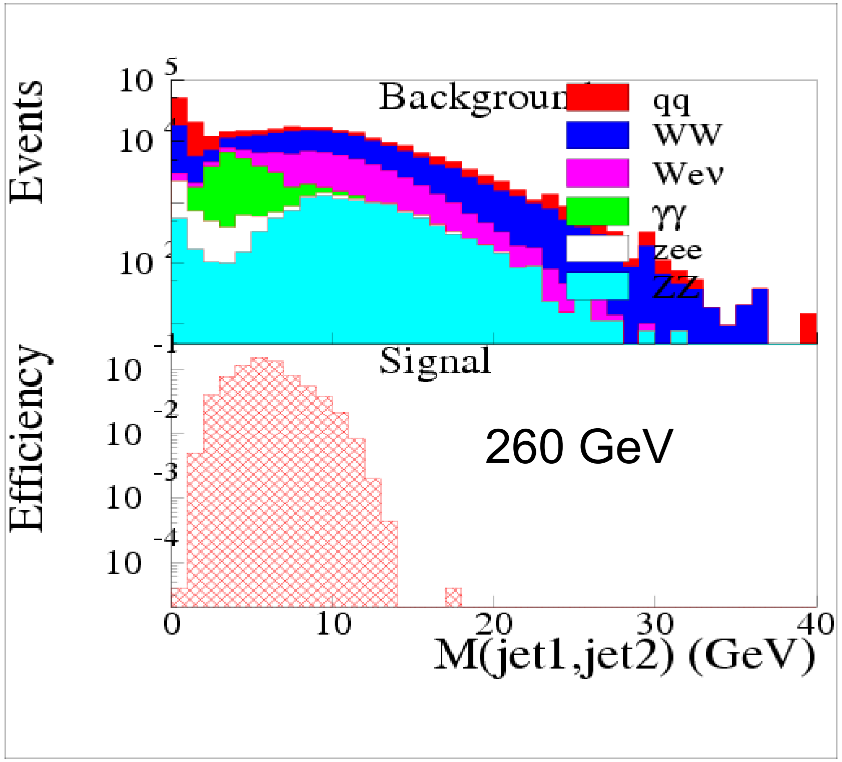
Table 3

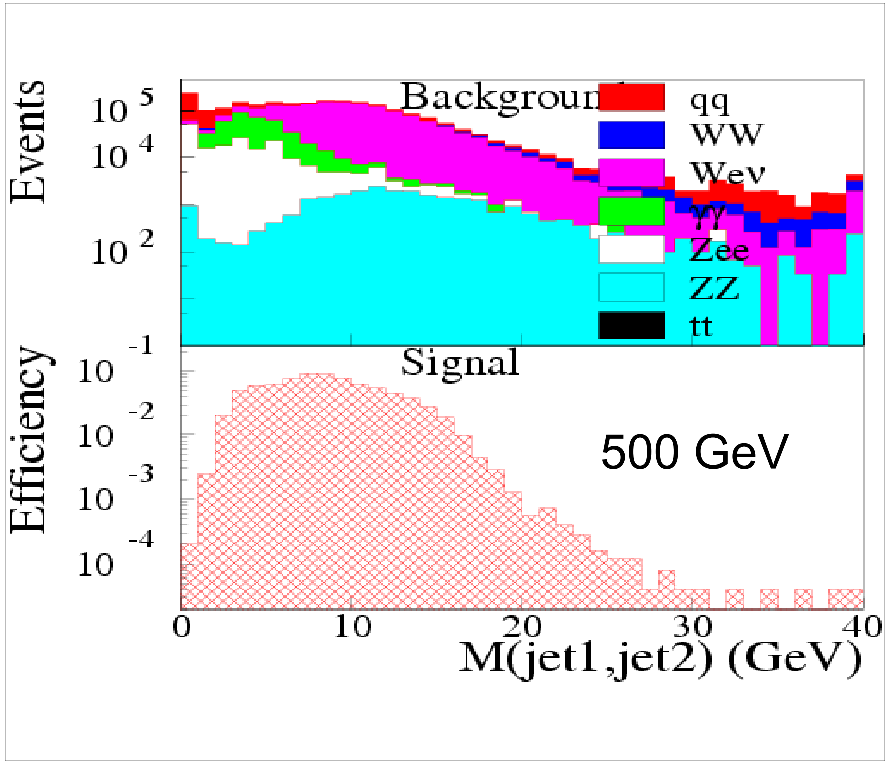
0/0 polarization beam → Unambiguous discovery
+80%/-60% polarization → Precision Measurement
Remark: $\tilde{t}_1$ fragmentation → the separation from the Wenu more difficult

Iterative Discriminant Analysis (IDA)

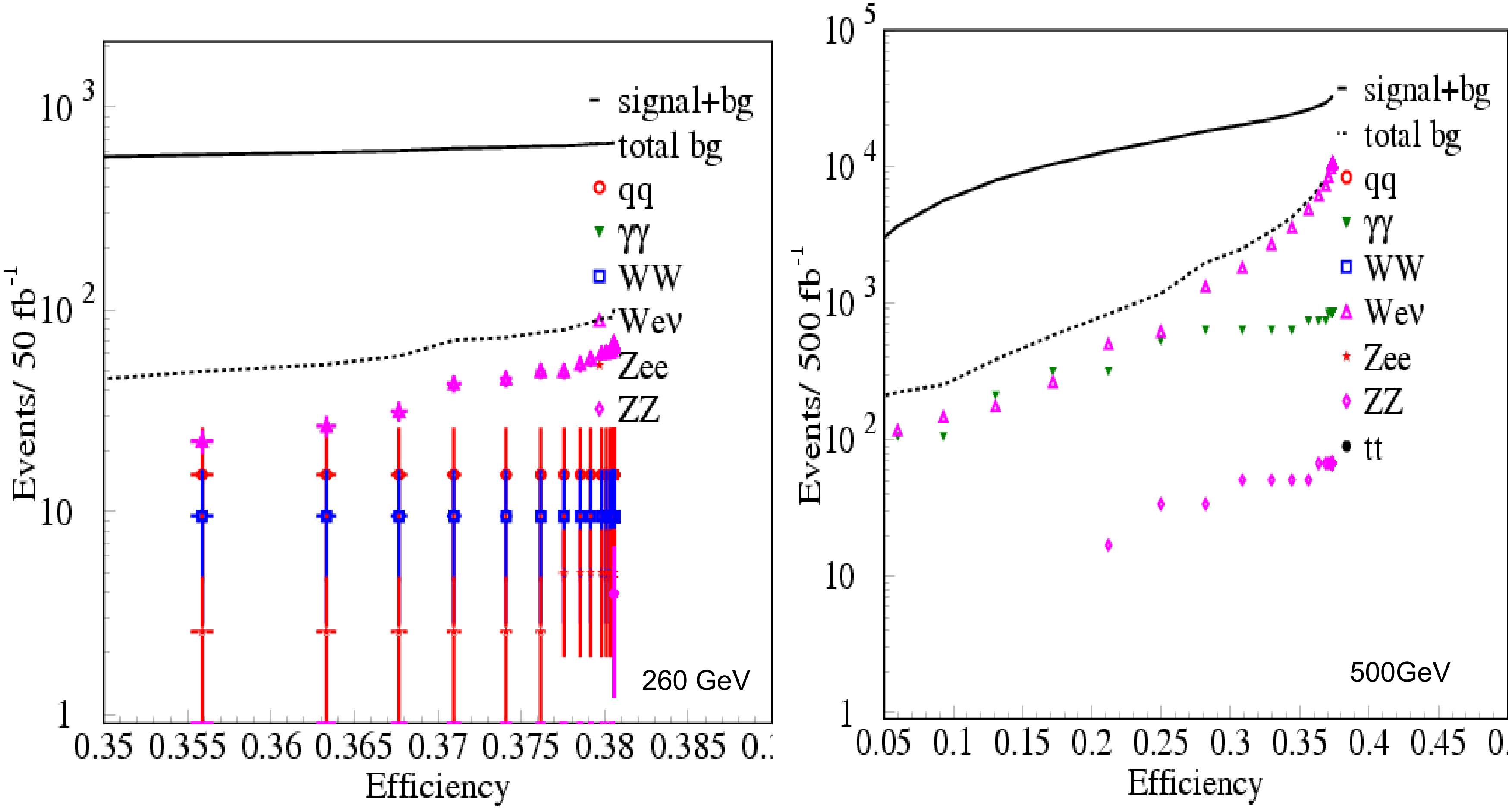
- Improves even more the precision in the $\tilde{t}_1$ mass measurement an Iterative Discriminant Analysis (IDA) is used. (modified Fisher Disc. Analysis)
- IDA combines the kinematic variables in parallel. The same variables and simulated events are used than in the cut based analysis . A non linear 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 Before Final IDA





IDA Performance



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

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±0.011
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±0.015
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
- Stop production receive large corrections from QCD gluon exchange
  Between the final state stops (bigger @Threshold) → Coulomb corr.
- NLO- QCD corrections ~100% @threshold down to 10% at high energies are included here
- NNLO-QCD corrections are expected 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)

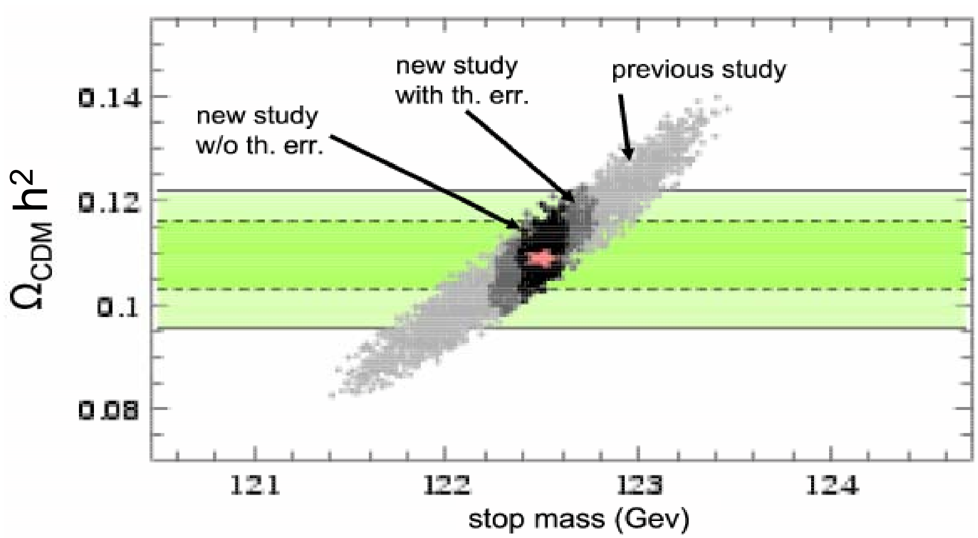
δY=5.2%→ $\delta m_{\tilde{t}1}$~ 0.2 GeV (cut based experimental errors alone)

δY=4.2%→ $\delta m_{\tilde{t}1}$ ~ 0.15 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 $\delta m_{X0}{}^{1}$ ~ 0.3 GeV ,(hep-ph/0608255, M.Carena, A.Freitas)

Dark Matter Relic Abundance=f(m_{stop})



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

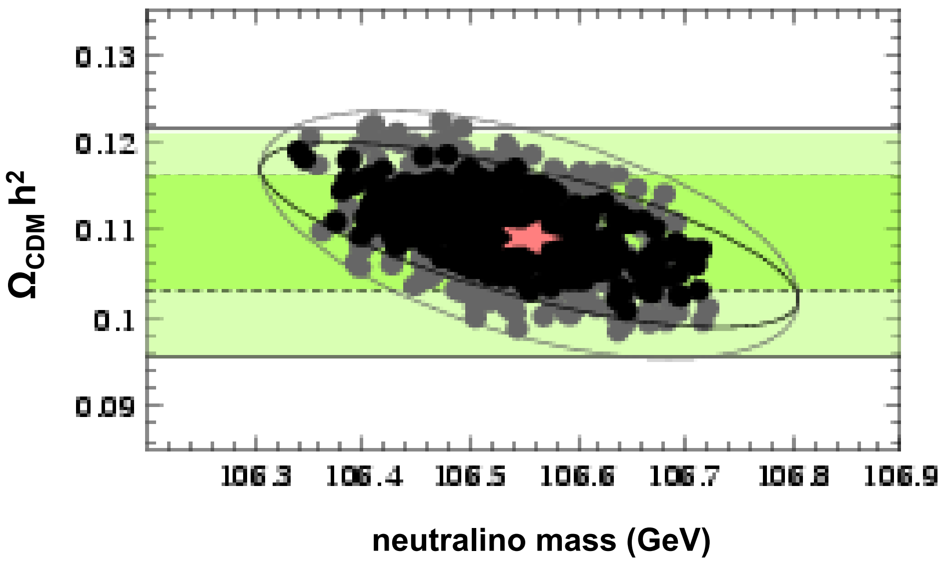
$\delta m_{\tilde{t}1}$=1.2 GeV light gray dot
Previous study

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

$\delta m_{\tilde{t}1}$=0.15GeV black dots
Expected this study
with IDA

δm_{st}^1= 0.3 GeV→$\Omega_{CDM}\,h^2$= 0.109+0.0013-0.010
δm_{st}^1= 0.2 GeV→$\Omega_{CDM}\,h^2$= 0.109+0.0012-0.009
δm_{st}^1= 0.15 GeV→$\Omega_{CDM}\,h^2$=0.109+0.0011-0.009

Relic Abundance as Function of $m_{\chi 0}{}^1$



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 $\delta m_{\tilde{t}1}=0.15$ This Study
Experiment. Err. and IDA

δmst1= 0.3 GeV→$\Omega_{CDM}\ h^2$ = 0.109+0.0013-0.010
δmst1= 0.15 GeV→$\Omega_{CDM}\ h^2$ = 0.109+0.0011-0.009
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 $\delta m_{st}{}^{1}$= 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 $\delta m_{st}{}^{1}$= 0.15 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 ,

  δmst1= 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 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