Precision Measurement of the Stop Mass at the Linear Collider

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In Collaboration with
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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 baryo-genesis 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 dm~1.2GeV including theoretical errors
- 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:

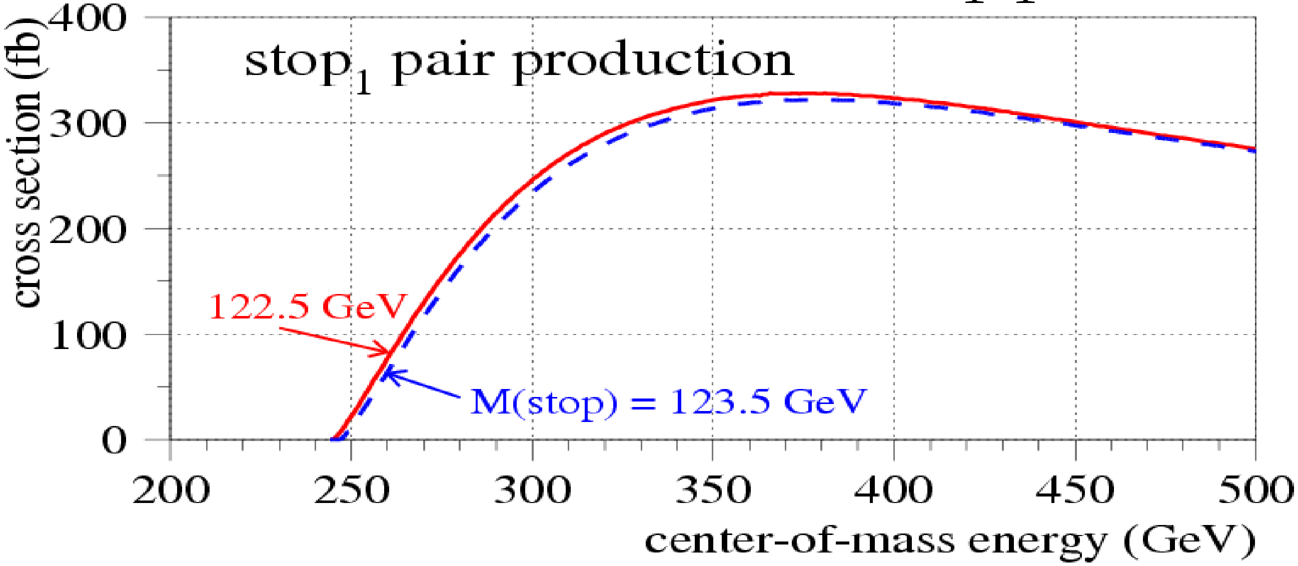
  a/ The systematic uncertainties are minimized by measuring the production cross-section at two energies→ cancellations .

  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:

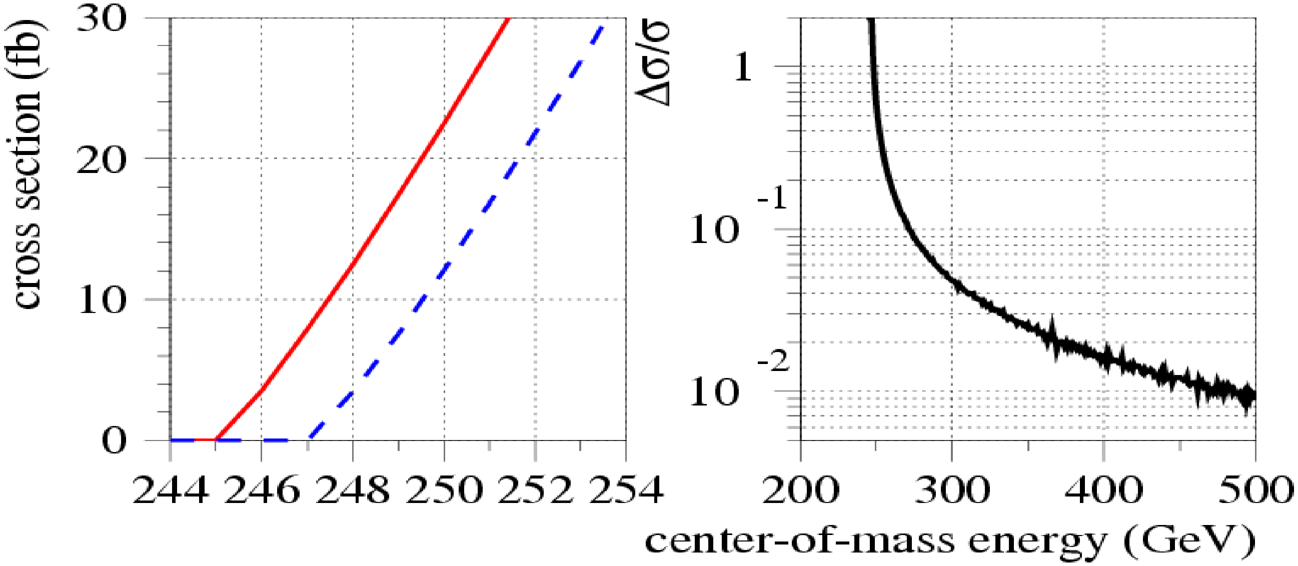
  the final number of jets increases- the c-tagging is now necessary to identify the charm jets (bench-marking for the vertex detector)
- Two approaches are used, a cut based analysis, a multi-parameters optimization analysis IDA
- The polarization improves further the signal to background ratio

Cross-Section Precision In Production

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



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



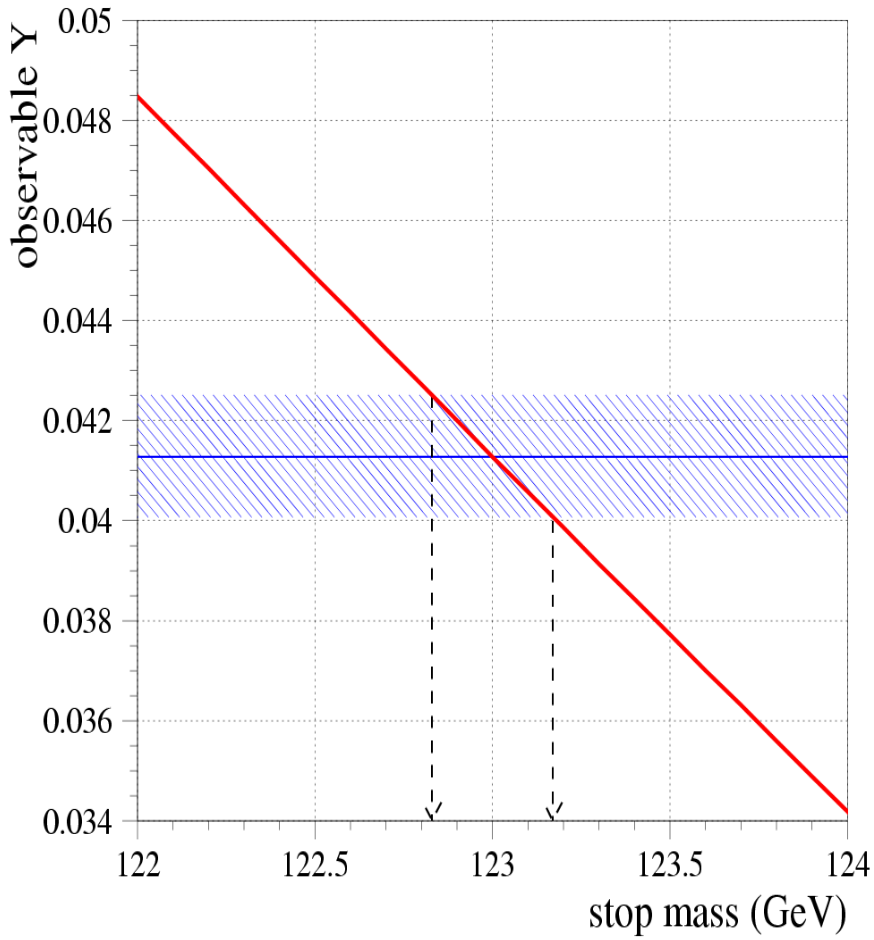
The Method

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

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

s - 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
$e_{th,}$and e_{pk} - total efficiency & acceptance threshold & peak
$L_{th;}$ and $_{;}L_{pk}$ -Integrated luminosity
M_x: Mass to be determined with high precision.
Y- ratio of signals at threshold and peak → 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



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

As an example, Assume 3% variation of Y,
The blue hashed region → one obtains
→Precision $\Delta M_x \sim \pm 0.016$, the 2 vertical arrows

The Scenario depicted:
E_{CM}=260GeV with s=9.2 fb and s=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 s_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 →s_a (X^0_1, $\tilde{t}_1$)+ s_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

Events Final State :

- •Stop Hadronization→ the final state jets smeared :
  due to Radiation + Fragmentation
- •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 and fragmentatrion of the $\tilde{t}$ and the fragmentation of the c quark 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)*
  - *The stop fragmentation parameter is set relative to the bottom fragmentation Parameter, e$\tilde{t}$=e_b*mb2/m$\tilde{t}$2 ; e_b=-0.0050+ /- 0.0015 following (OPAL,EPJ C6:225)*
  - *Newer:*
    e_b=-0.0031+ /- 0.0006-ALEPH-phys.lett B152,30(2001)
    e_b=-0.0041+ /- 0.0004(OPAL)-Eu.Phys.J,C29,463(2003)
  - *Variation in e_b was too big by a factor 4, it will be corrected for in the systematics*
- Signal and Background are generated in each channel for the given luminosity in conjunction to the cross-sections

The cross-sections

Process	s [pb] at ECM=260GeV			s [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

<u>Pre-selection</u>: 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	$N_{jets} = 2$	$N_{jets} = 2$ & E_n <25 GeV n=3,4
Number of charged tracks	$5 = N_{tracks} = 25$	$5 = N_{tracks} = 20$
Transverse Momentum p_t	$15 < p_t < 45$ GeV	$22 < p_t < 50$ GeV
Thrust T	$0.77 < T < 0.97$	$0.55 < T < 0.90$
Longitudinal Momentum	$\lvert p_L / p_{tot} \rvert < 0.85$	$\lvert p_L/p_{tot} \rvert < 0.85$
Visible Energy E_{vis}	$0.1 < E_{vis}$ /ECM <0.3	$0.1 < E_{vis}$ /ECM <0.3
Acoplanarity F_{acop}	$\lvert\cos(acop)\rvert < 0.9$	$\lvert\cos(acop)\rvert < 0.9$
Invariant mass of jet pair m_{jj}	$m_{jj}^2 < 5500\ GeV^2$ or $m_{jj}^2 > 8000GeV^2$	$m_{jj}^2 < 5500\ GeV^2$ or $m_{jj}^2 > 10000GeV^2$
Charm tagging likelihood P_c	$P_c > 0.6$	$P_c > 0.6$
Signal Efficiency	*0.340*	*0.212*

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 $Y=(N_{th}-B_{th})/(N_{pk}-B_{pk})$)

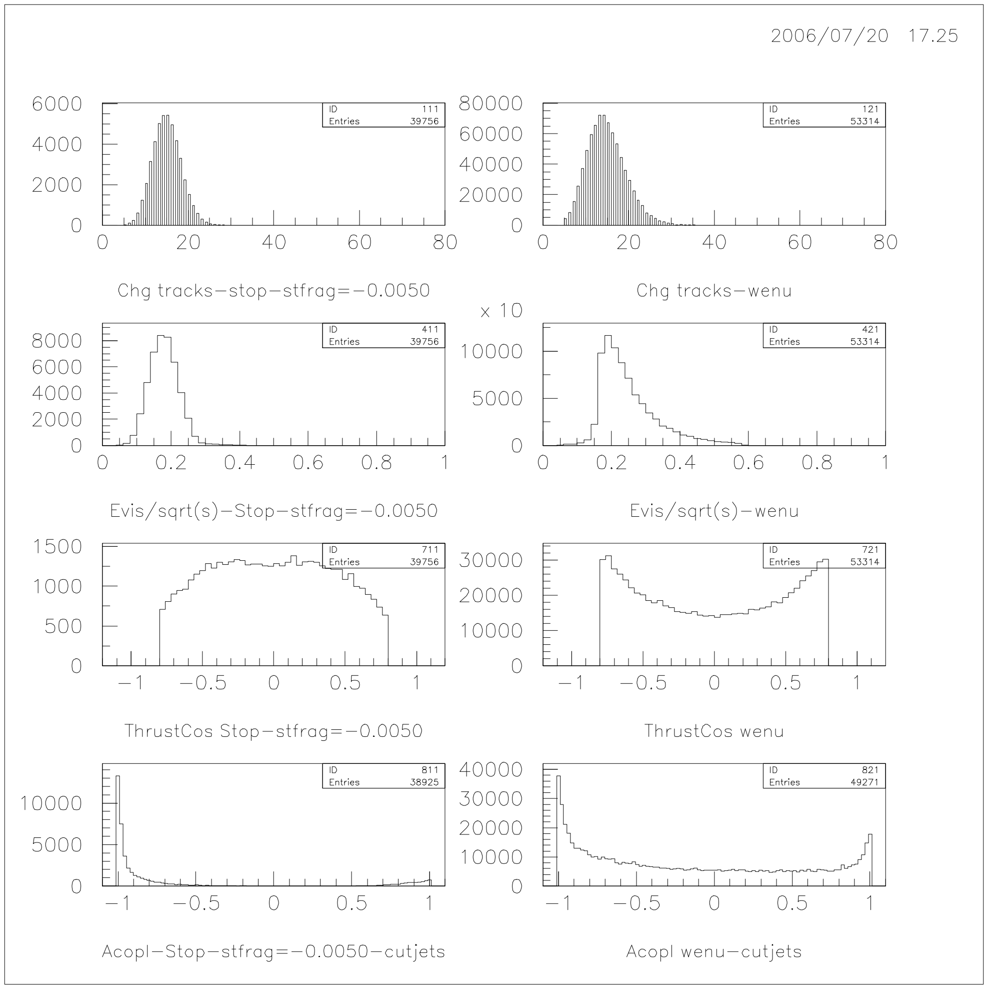
The two-photons background did require a 5GeV p_t pre-selection cut.

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	543	1309	50000	12514	29270
WW	180000	38	4	210000	91	8
ZZ	30000	8	7	30000	90	81
Wenu	210000	208	60	210000	18540	5495
eeZ	210000	2	2	210000	<18	<15
qq, q≠t	350000	42	45	350000	37	43
tt	-	0	0	180000	18	17
2-Photons	$1.6\ 10^6$	53	53	8.5×10^6	31	31
Total backgrd	-	351	171	-	18807	5781
S/B		1.5	7.6		0.7	5.2

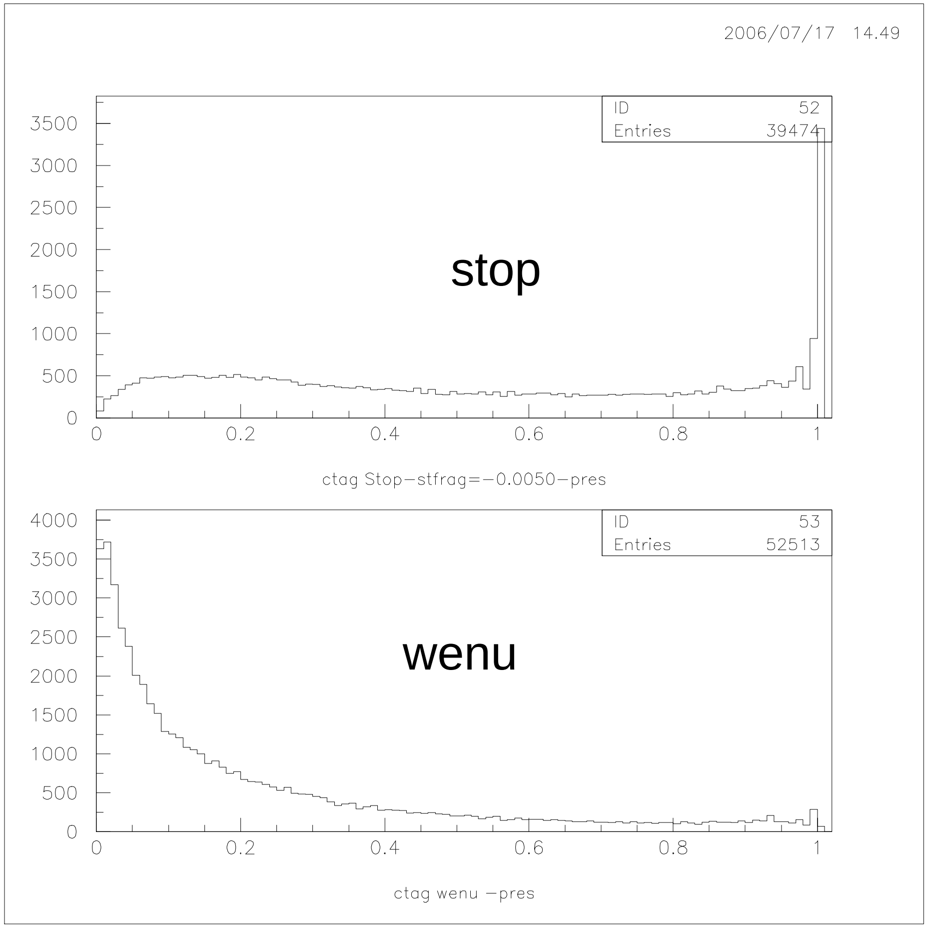
0/0 polarization beam → Unambiguous discovery
+80%/-60% polarization → Precision Measurement
Remark: $\tilde{t}_1$ fragmentation → the separation from the Wenu more difficult (we had 5044 Wenu at 0/0 polarization)

Stop/wenu- Variables Distributions



Left column: Stop
Right column: wenu (main Bg)

Charm-tagging

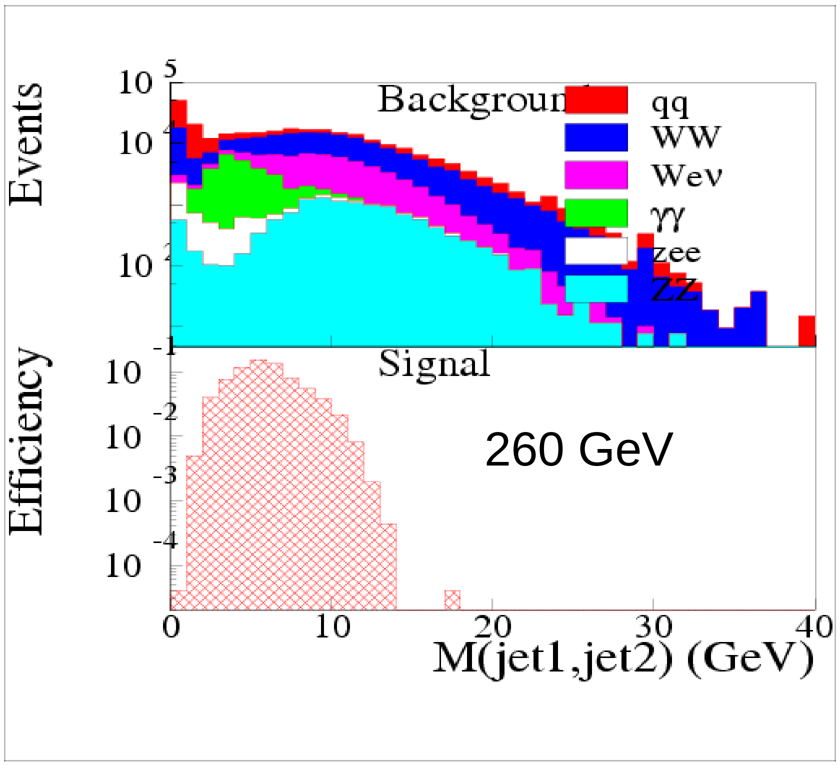


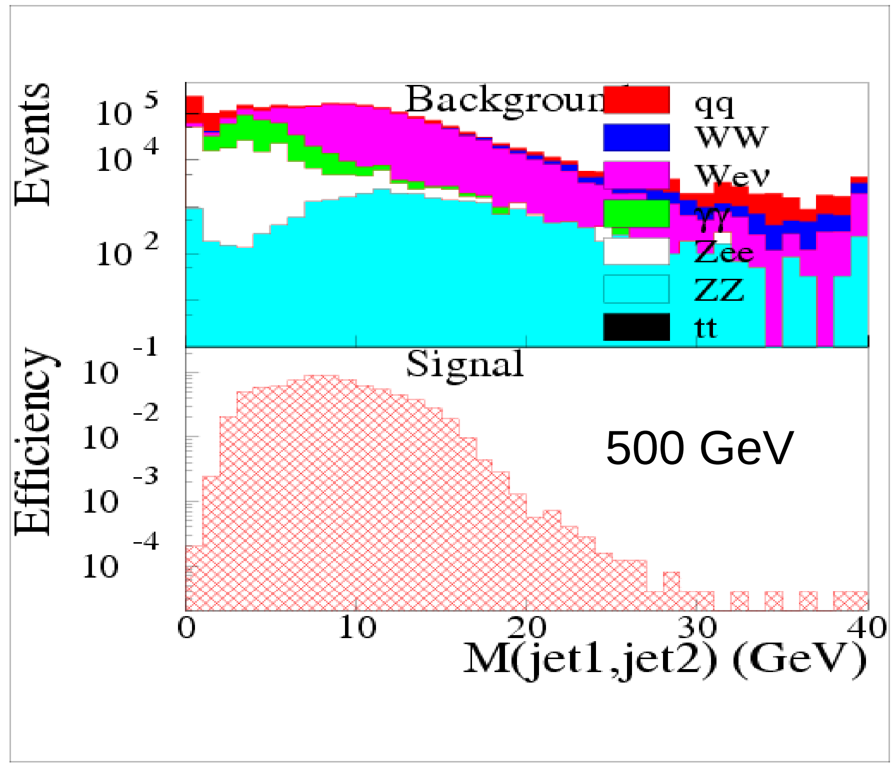
-The charm tagging provides
A good cut between signal
And wenu background
-It has been used here as a
tool to find the charm jets in
The multi-jet event

Iterative Discriminant Analysis (IDA)

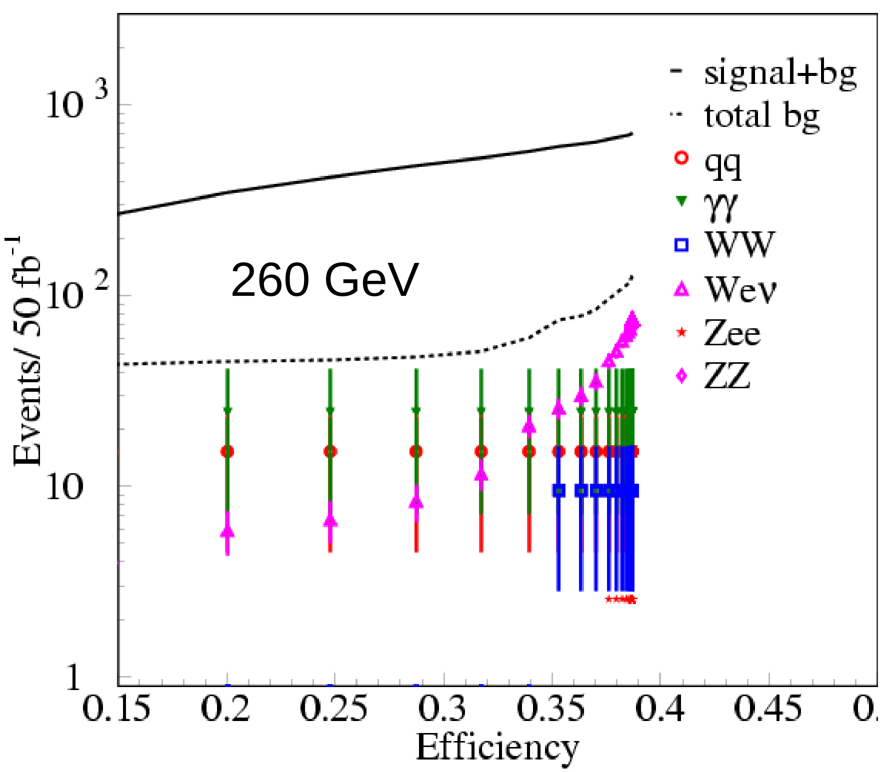
- A NN approach was also used the Iterative Discriminant Analysis (IDA) . (modified Fisher Disc. Analysis)
- IDA combines the kinematic variables in parallel. The same kinematical variables we used in the cut based analysis . A non linear discriminant function followed by iterations are enhancing the 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 1^{st} IDA iteration keeping 99% of the signal efficiency while cutting part of the Bg.
- The performance is shown in the two next figures at 260 and 500 GeV.

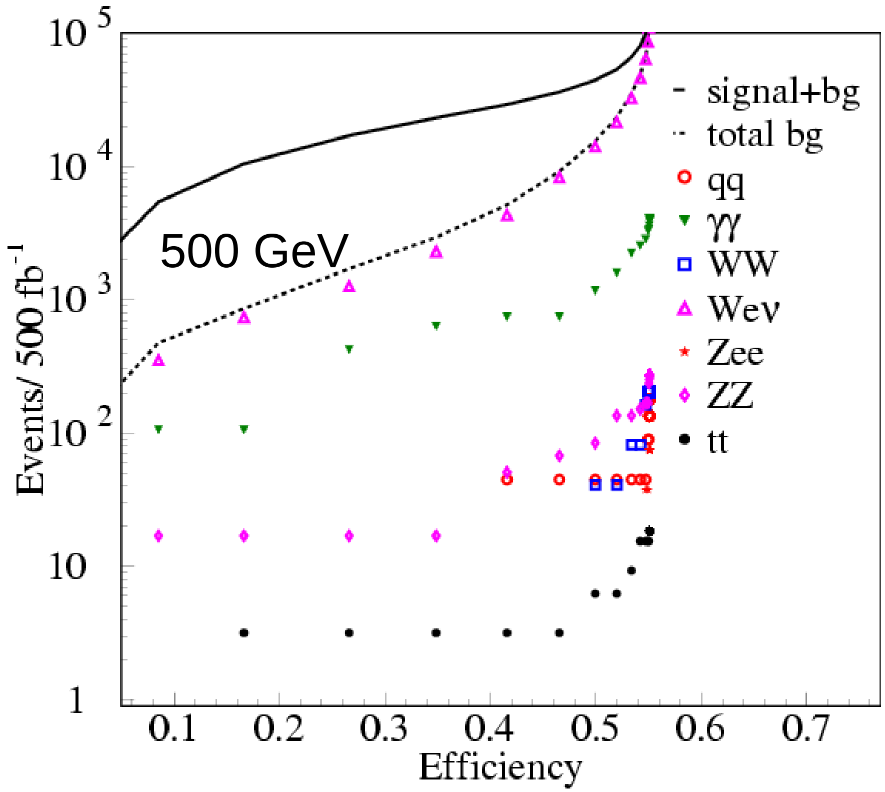
Invariant Mass Di-Jets 1 Step Before Final IDA





IDA Performance





Work in Progress

Systematic Uncertainty in Kinematics Cuts Variables

Variables	Error on Variable	Relative shift On signal eff √s = 260 GeV	Relative shift On signal eff √s = 500 GeV	Error on Y
energy scale	1%	3.7% (3.4%)	3.1% (1.3%)	<1% (2.1%)
N_{tracks}	0.5%	Negligible	Negligible	
Charm tagging	0.5%			
Luminosity	-	0.4%	0.2%	0.4%
Charm frag	0.011	0.3% (0.1%)	0.8% (0.6%)	<1%
Stop frag.	0.0015	2.4% (1.2%)	1.0% (3.5%)	2.7% (2.8%)
Background est.		0.8%	0.1%	<1%

All cuts are applied to hadronic and jet observables→ Calibration quantities are jet energy scale & jet angle.

Based on LEP, we assume 1% energy scale, 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

In parenthesis IDA's values if different

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

→e_c =-0.0031±0.0011

Stop fragmentation is set relative to bottom fragmentation, $e_{\tilde{t}1} = e_b(m_b/m_t)^2$

$e_{\tilde{t}1}$ =-0.0050±0.0015

de_c =± 35% → Error dY=0.2% (from new papers of OPAL and ALEPH)

$de_{\tilde{t}1}$=± 30% → Error dY=2.4% however "

Newer analysis from ALEPH and OPAL provide

e_b=-0.0031+ /- 0.0006-ALEPH-phys.lett B152,30(2001)

e_b=-0.0041+ /- 0.0004(OPAL)-Eu.Phys.J,C29,463(2003)

We assume an improvement of a factor ~4 in precision as a consequence we assume that the contribution of the stop fragmentation

→ Error dY~0.7%

→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→dY=5.5%

Combined Statistical and Systematic Errors

Error source for Y	Sequential Cuts	IDA- method
Statistical	3.1% (0.19 GeV)	2.7%(0.17 GeV)
Detector effects(syst.)	0.6%	2.1%
Charm fragmentation(syst.)	0.5%	0.5%
Stop fragmentation(syst.)	0.7%	0.7%
Background contr (syst.)	0.8%	0.1%
Sum Exp systematics	1.3%(0.08 GeV)	3.6%(0.14 GeV)
Sum of experimental errors	3.3% (0.20GeV)	3.5% (0.22 GeV)
Theory for Signal s	5.5%	5.5%
Total error dY	6.4%(0.40 GeV)	6.5%(0.41 GeV)

Results

Combining the statistical and systematic errors Table 6(*)

dY=6.4%→ dm $_{\tilde{t}1}$ ~0.40 GeV – a factor 3 better (*Phys. rev. D 72,115008(2005*)

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

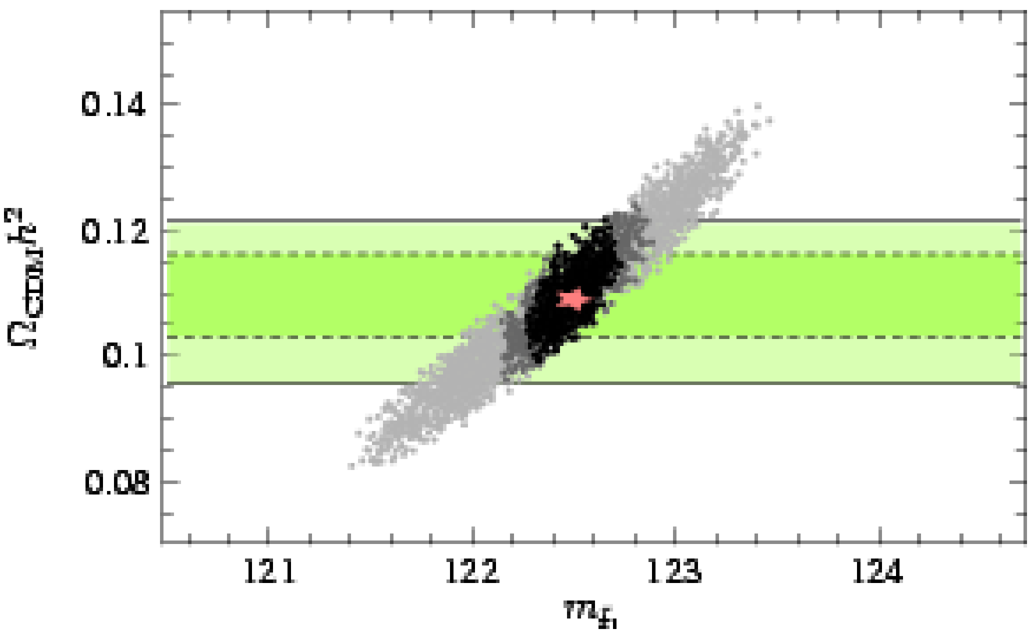
dY=3.3%→ dm $_{\tilde{t}1}$~ 0.20 GeV (cut based experimental errors alone)

dY=3.5%→ dm $_{\tilde{t}1}$ ~ 0.22 GeV (experimental errors alone& IDA)

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

Other limiting factors start to interplay, e.g. the precision on the neutralino mass $dm_{\chi_1^0}$ ~ 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 1s)
versus $m_{\tilde{t}1}$ for
$dm_{\tilde{t}1}$=1.2 GeV light gray dot
Previous study
$dm_{\tilde{t}1}$=0.40 GeV dark gray dot
Now this study
$dm_{\tilde{t}1}$=0.20GeV black dots
Expected this study
with seq. cuts

$dm_{\tilde{t}1}$= 0.40 GeV→O_{CDM} h ^{2} = 0.109+0.0013-0.012 Exp. Err.+ Th. Err.
$dm_{\tilde{t}1}$= 0.20 GeV→O_{CDM} h ^{2}= 0.109+0.0010-0.0007 Exp. Err. Seq. cuts
$dm_{\tilde{t}1}$= 0.22 GeV→OCDM h^2= 0.109+0.0010-0.0008 Exp. Err. Seq. cuts
WMAP: OCDM 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 $dm_{\tilde{t}1}$= 0.40 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)
- IDA and the sequentiel cuts give almost identical results. IDA gives better statistical uncertainties but worse systematics $dm_{\tilde{t}1}$= 0.20 GeV (0.22 GeV-IDA)
- 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 ,

$dm_{\tilde{t}1}$= 0.20 GeV→OCDM h2 = 0.109+0.0010-0.007

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

Backup slides

A Sample Parameter Point

- $m_{\tilde{U}3}{}^2 = -99^2\ GeV^2$
- $A_t = -1100$ GeV
- $M_1 = 112.6$ GeV
- $M_2 = 225$ GeV
- $|\mu| = 225$ GeV
- $F\mu = 0.2$
- $\tan ß = 5$

Which gives:
$m\tilde{t}_1 = 122.5$ GeV; $m\tilde{t}_2 = 4333$ GeV;
$m\tilde{\chi}_1^0 = 107.2$ GeV; $m\tilde{\chi}_1^+ = 162.7$ GeV; $m\tilde{\chi}_2^0 = 170.8$GeV
$m\tilde{\chi}_3^0 = 231.0$ GeV; $m\tilde{\chi}_2^+ = 170.8$ GeV
$\cos\theta_{\tilde{t}} = 0.010$~ $\tilde{t}$ right-handed
→ $\Delta m = 15.2$ GeV

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%
$\tilde{t}_1 \tilde{t}_1^*$	618	1489	24538	57394
WW	11	1	<20	<2
ZZ	<2	<2	51	46
Wenu	68	20	4262	1263
eeZ	3	2	<18	<15
qq, q≠t	16	17	45	52
tt	0	0	3	3
2-Photons	<25	<25	772	772
Total background	*125*	*67*	*5133*	*2136*
S/B	4.9	22	*4.7*	*27*

The efficiencies improves from 34% ,21.2% cut based → 38.7% ,41.6% IDA, while the background is of the same order of magnitude.

Stop Discovery Reach
Snowmass 2005

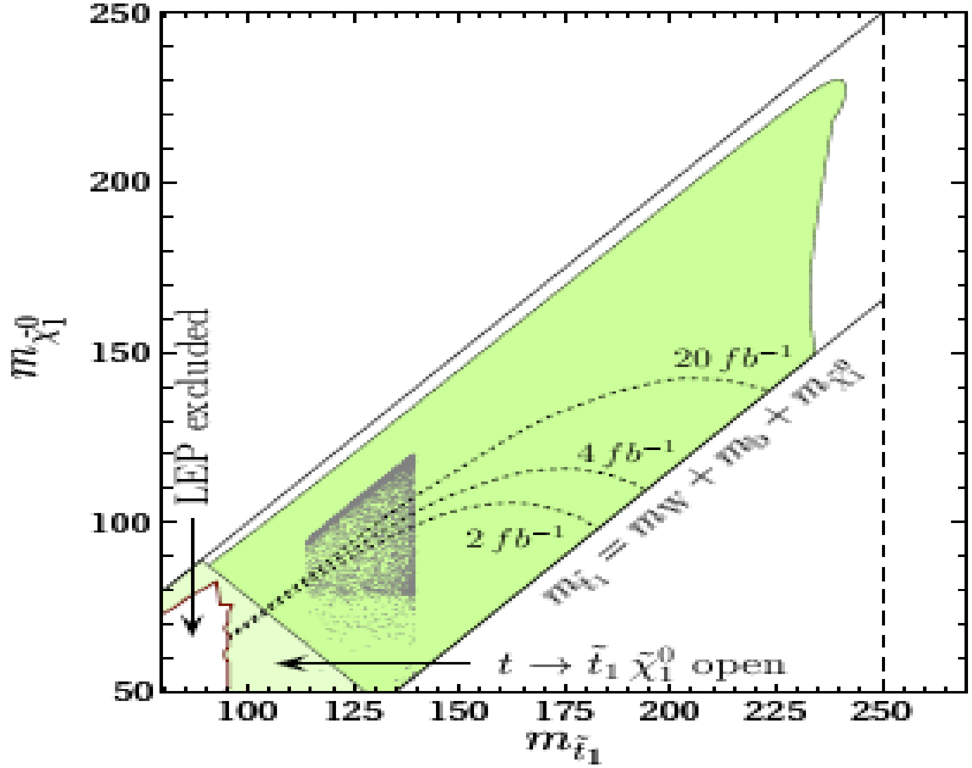


Fig 4a-Luminosity: 500 fb^{-1}

E_{cm}=500 GeV

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/v(S+B)) > 5

Background B

Signal S=esL

For e , Signal efficiency

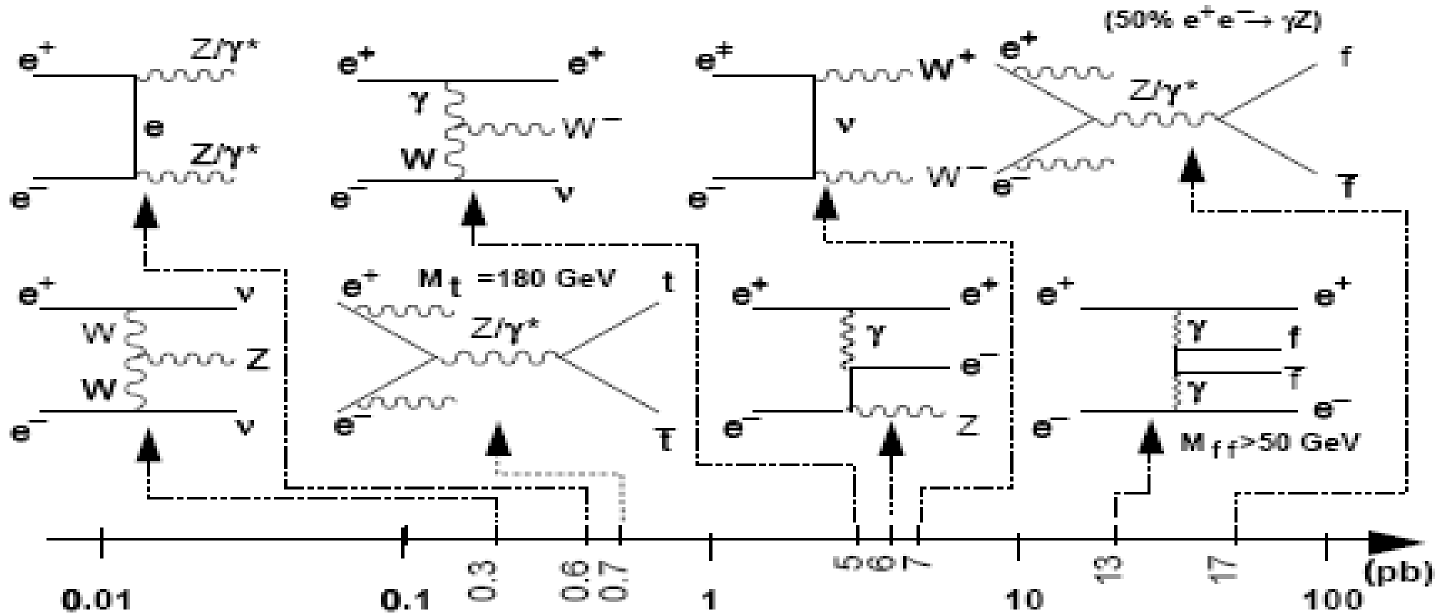
For s , Theoretical cross-section

dark gray region:

Consistent with DM

And Baryogenesis

Background- Channels @500 GeV



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

C-Tagging – The Data Samples

- *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-F plane (highest separation power) && their Impact parameters.
- The impact parameter significance & Impact parameters of the 2 tracks in z
- Their momenta
- The joint probability in r- F (tiny beamspot 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), the pt of the decay products perpendicular to the flight direction (between primary && secondary Vertex) && joint probability in r-F 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

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
F_{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