SUSY Scalar Tops:
Small Visible Energy – A Challenging Task

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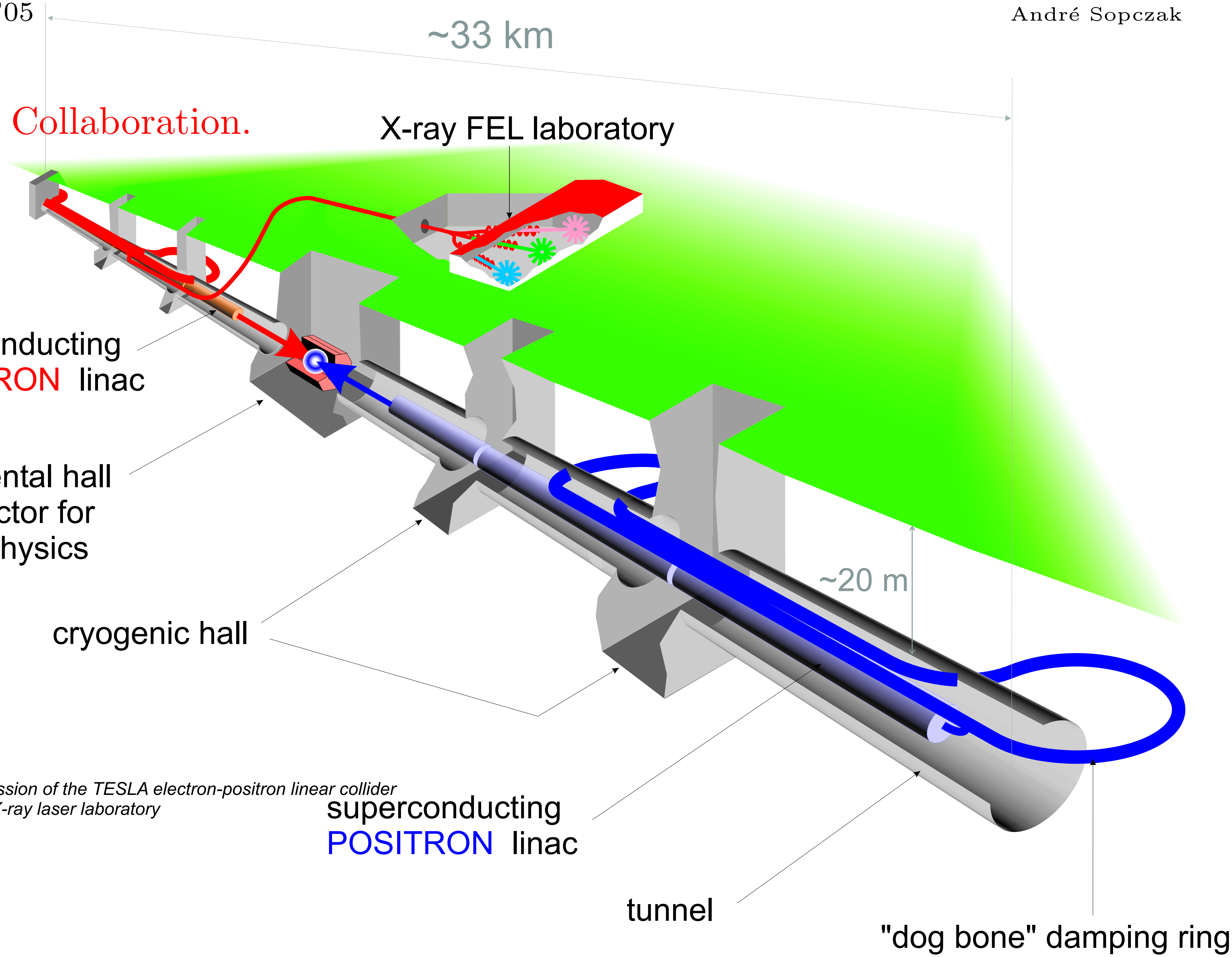
International Collaboration.



An artist's impression of the TESLA electron-positron linear collider with integrated X-ray laser laboratory

Outline

- The Basic Process
- Vertex Detector c-Tagging
- Mass Determinations
- Reduced Stop-Neutralino Mass Differences
- DM Interpretations
- Conclusions

Introduction

Large challenge to develop a vertex detector for a future LC.

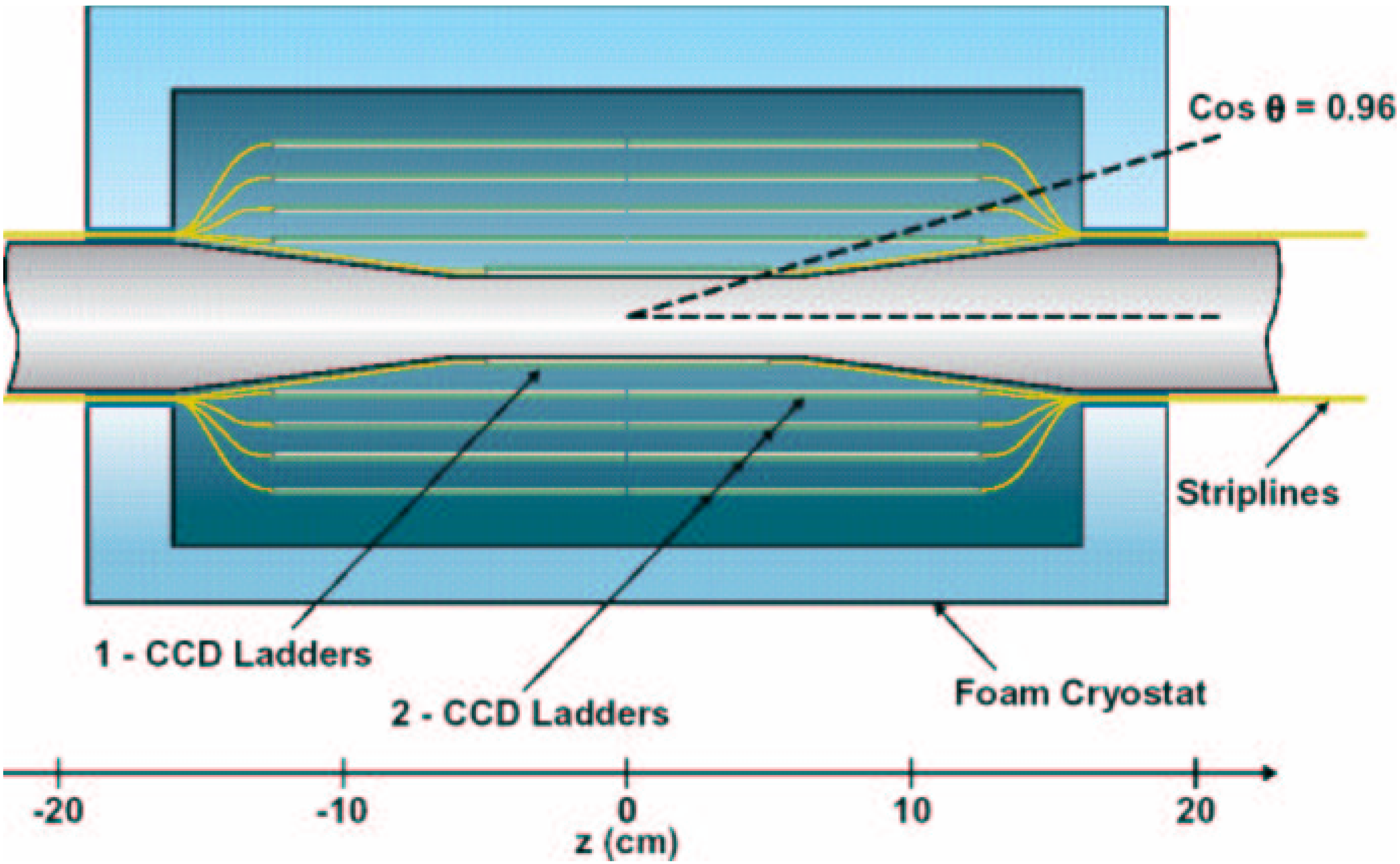
Key aspects:

- Distance to interaction point of innermost layer (radiation hardness, beam background).
- Material absorption length (multiple scattering).
- Tagging performance.

While at previous and current accelerators (e.g. SLC, LEP, Tevatron) b-quark tagging has revolutionized many searches and measurements, c-quark tagging will be a very important tool at a future LC.

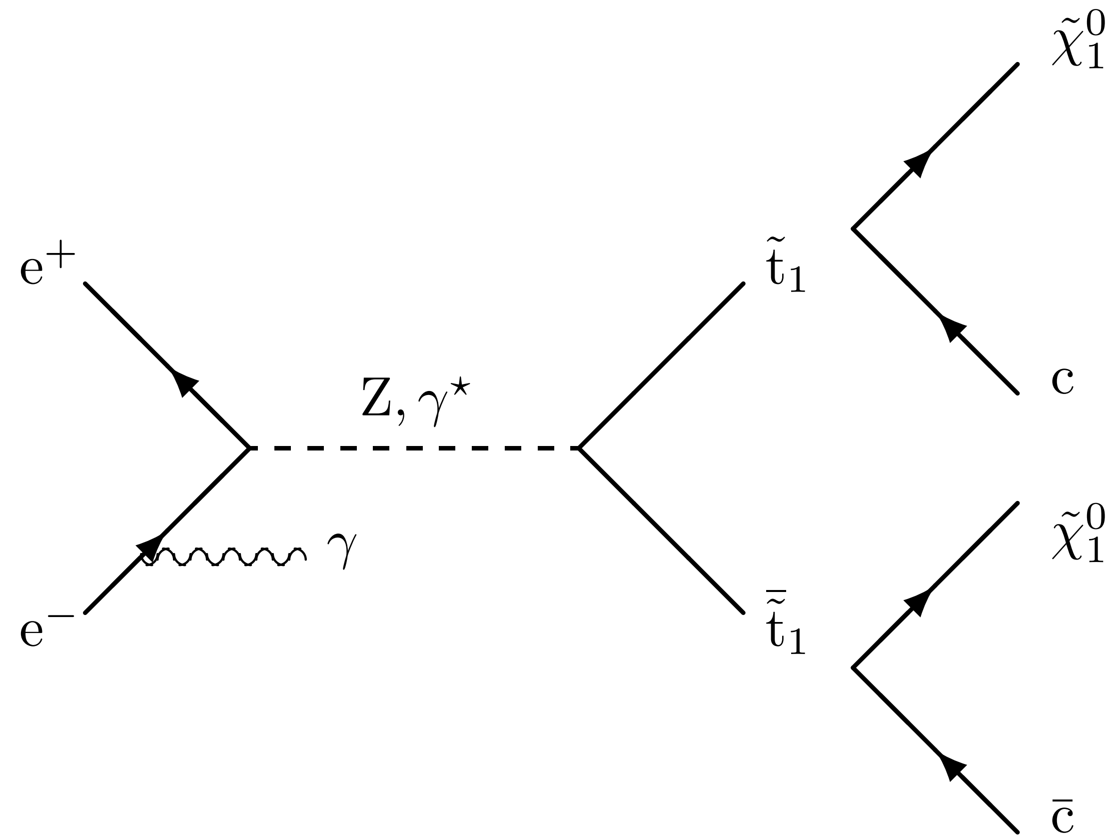
CDD Vertex Detector

LCFI Collaboration: Development of a CCD detector for a future LC.



5 CCD layers at 15, 26, 37, 48 and 60 mm. Each layer $< 0.1\%\ X_0$.

c-Quark Tagging: a Benchmark Reaction



Signal: Two charm jets and missing energy.

Benchmark reaction in the Supersymmetry framework: $e^+e^- \rightarrow \tilde{t}_1\bar{\tilde{t}}_1 \rightarrow c\tilde{\chi}_1^0\bar{c}\tilde{\chi}_1^0$

(Other benchmark reactions, e.g. in Higgs sector, $H \rightarrow c\bar{c}$)

Signal and Background Cross Section

Two scenarios:

1. Comparison previous SGV study: $m_{\tilde{t}_1} = 180\,\text{GeV}$, $m_{\tilde{\chi}_1^0} = 100\,\text{GeV}$
2. SPS-5 SUSY parameters: $m_{\tilde{t}_1} = 220.7$ GeV, $m_{\tilde{\chi}_1^0} = 120$ GeV

Decays mode (kinematics) $\tilde{t}_1 \to \tilde{\chi}_1^0 c$.

Signal and background cross section (pb):

$\tilde{t}_1\bar{\tilde{t}}_1$(180/220.7) CALVIN32	$We\nu$ GRACE	WW WOPPER	$q\bar{q}$ HERWIG	$t\bar{t}$ HERWIG	ZZ COMPHEP	eeZ PYTHIA
0.0532/0.0164	5.59	7.86	12.1	0.574	0.864	0.6

For this performance study: no beam polarization.

However, beam polarization is very important for mass and mixing angle determination.

Analysis Strategy

- Signal and Background generated for 500 fb^{-1} and $\sqrt{s} = 500\text{GeV}$
- Detector Simulation: SIMDET 4.03 (J. Schreiber et al.)
- b/c tagging algorithm (T. Kuhl et al.)
- Iterative Discriminant Analysis (IDA) for selection optimization
- Different Vertex Detector configurations

SIMDET Detector Simulation (cf. SGV)

$\tilde{t}_1 \to c\tilde{\chi}^0_1$ and 1000 fb $^{-1}$ Standard Model background simulated (180 GeV).

Channel	Generated	Preselection/500 fb^{-1}	Previous SGV
$c\tilde{\chi}^0_1$	50 k	48%	47%
$q\bar{q}$	12169 k	64963	46788
$t\bar{t}$	620 k	32715	43759
eeZ	5740 k	24864	4069
ZZ	560 k	3100	4027
Weν	4859 k	252367	252189
WW	6800 k	122621	115243
Total bg		500631	466075

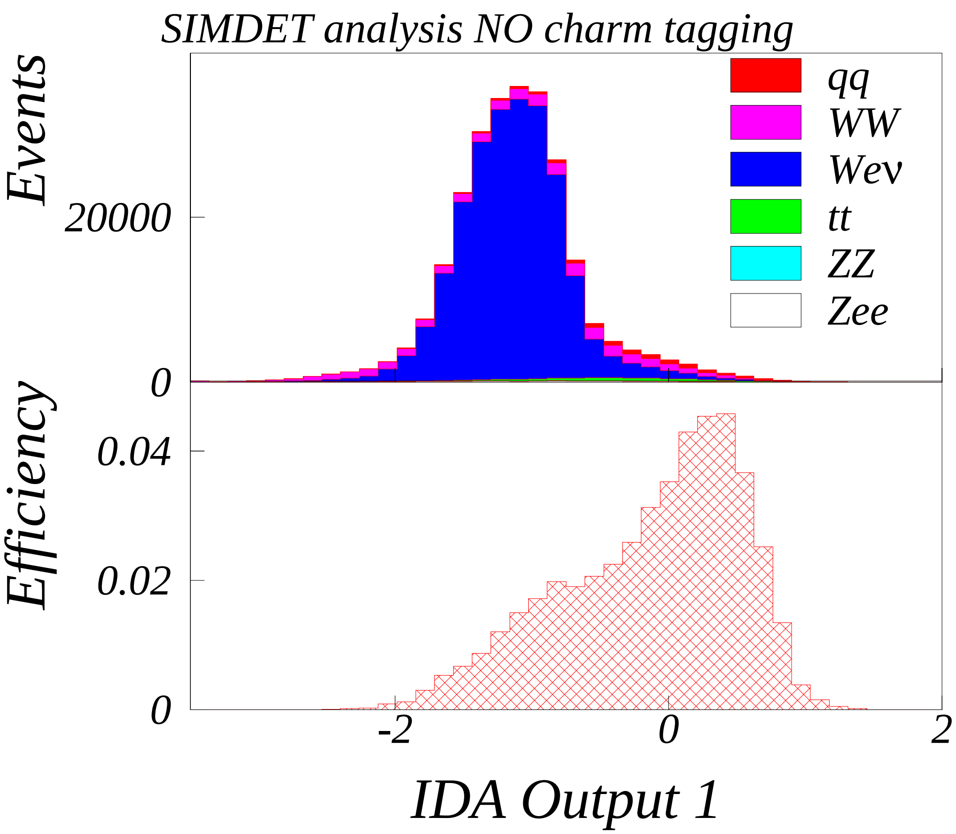
After additional preselection ($E_{\rm vis}/E_{\rm cms} < 0.52$, $P_{\rm t}/E_{\rm vis} > 0.05$):

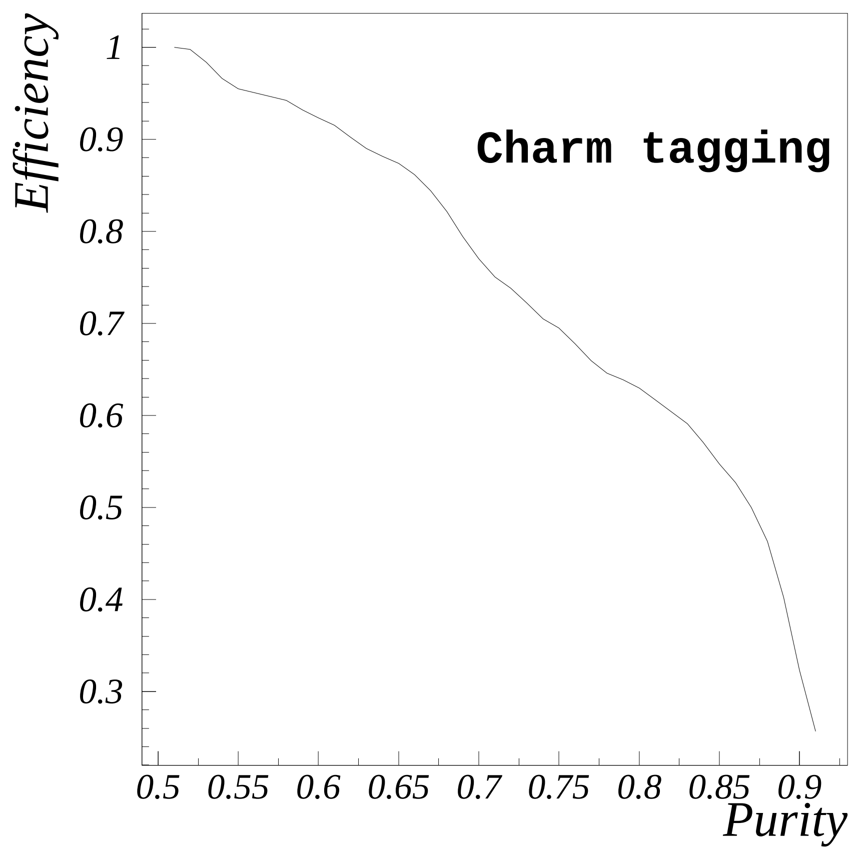
Channel	$q\bar{q}$	WW	Weν	$t\bar{t}$	ZZ	eeZ	Total
	6801	23278	226070	5267	125	2147	263691

(cf. SGV: 278377 events).

Iterative Discriminant Analysis (IDA)

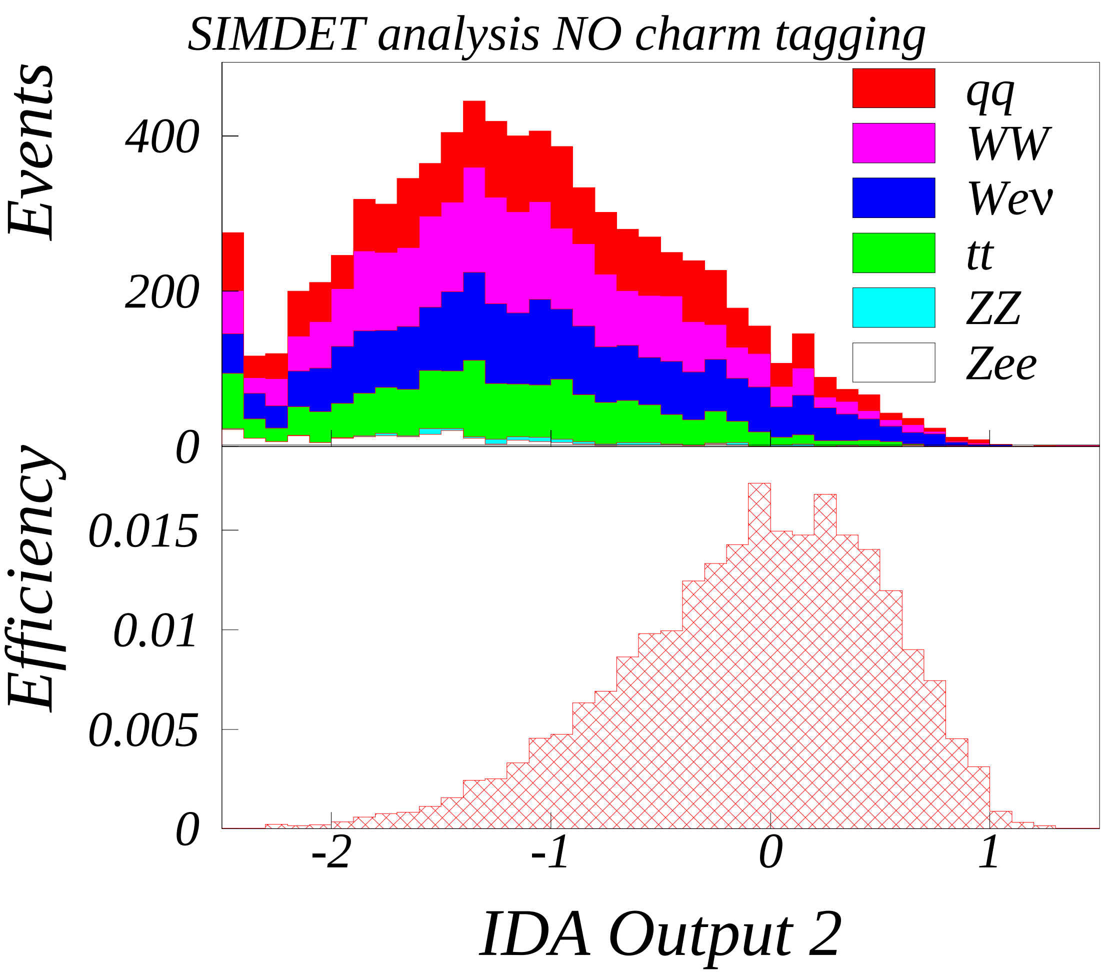
- First half-sample for training.
  Second part for signal efficiency and backgrund rate determination.
- Two step process: IDA 1: signal reduced to 50% efficiency; IDA 2: fine-tuning





Without charm tag 7815 (cf. SGV 7265). With charm tag 3600 background events.

Signal vs. Background: c-Quark Tagging



After second IDA step, remaining backgrounds for 12% efficiency (180 GeV)

Without charm tag 680
(cf. SGV 400 events)

With charm tag 165 events.

SPS-5 Results (220.7 GeV)

Events remaining after 1st Iteration of IDA (25% efficiency):

Signal	Background	Charm Tagging
3800	5400	No
3800	2500	Yes

Events remaining after 2nd Iteration of IDA (12% efficiency):

Signal	Background	Charm Tagging
1800	170	No
1800	68	Yes

Varying Vertex Detector Design

Vertex detector absorption length:

- Normal thickness (TESLA TDR)
- Double thickness

Number of vertex detector layers:

- 5 layers - innermost layer at 15 mm (like TDR)
- 4 layers - innermost layer at 26 mm (Layer 1 removed)

For SPS-5 parameters (220.7 GeV):

Thickness	Layers	Remaining background events (12% Signal)	Remaining background events (25% Signal)
Normal	5	68	2300
Normal	4	82	2681
Double	5	69	2332
Double	4	92	2765

Four Different Methods of Mass Determination

- 'IDA' based selection -
  Optimum Signal/Background ratio:
  - Cross section with different polarizations
  - Threshold dependence of cross section
- Cuts based selection -
  Minimum distortion of final state observables
  - Endpoint of jet energy spectrum
  - Minimum Mass of jets

Iterative Discriminant Analysis - 'IDA'

A method to weight each event to optimize signal / background separation using n discriminant variables.

Construct: vector x containing the n variables and
$(n^2 - n)/2$ products of those variables.

Calculate:	V	Variance matrix
	$\Delta\mu$	Difference in the mean values between signal and background
	$a = V^{-1}\Delta\mu$	
	$D^0 = x^T \cdot a \cdot x$	provides the maximum separation between Signal and Background.

Weighted such that signal and background have equal importance.

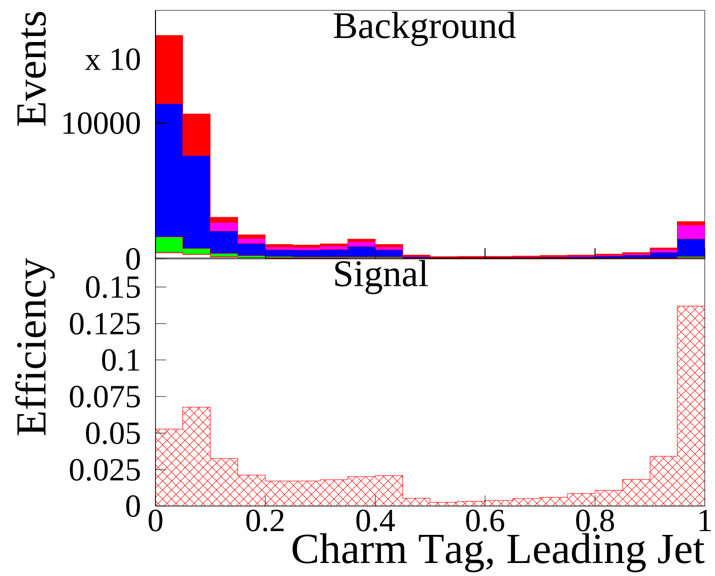
Find the value of D^0 which selects a predetermined fraction of the signal (e.g. 50%), and cut on it.

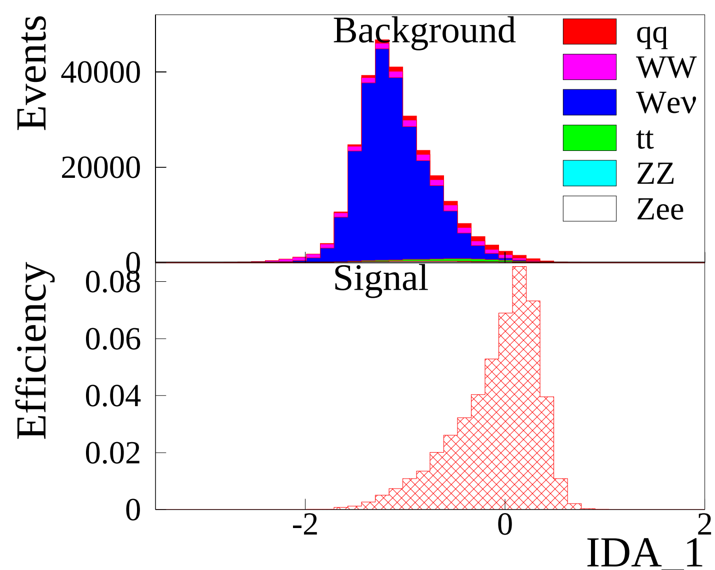
Do this process once again for events passing the cut.

IDA Analysis

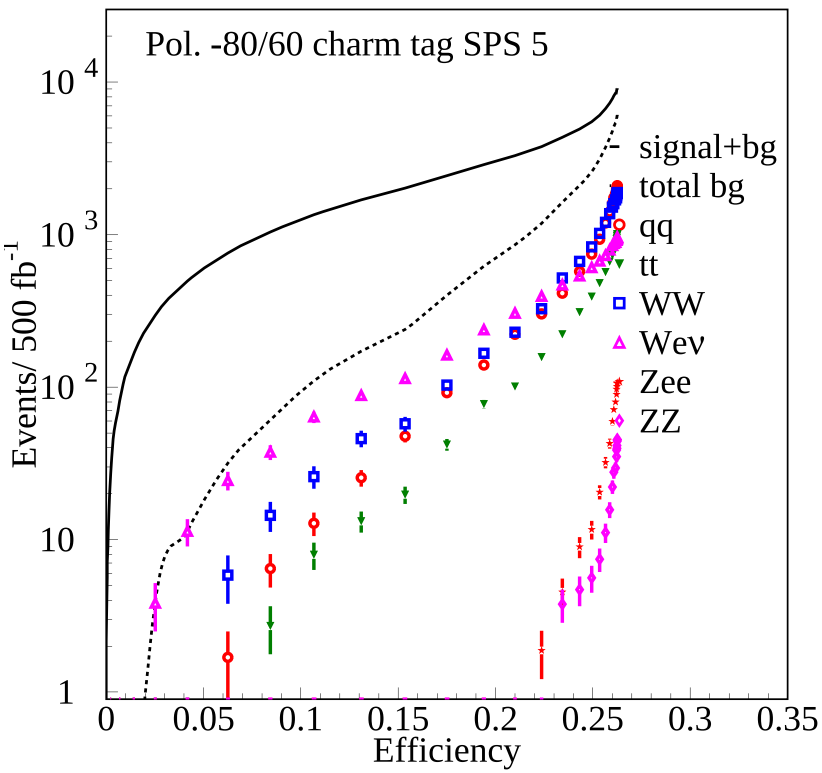
Discrimination Variables

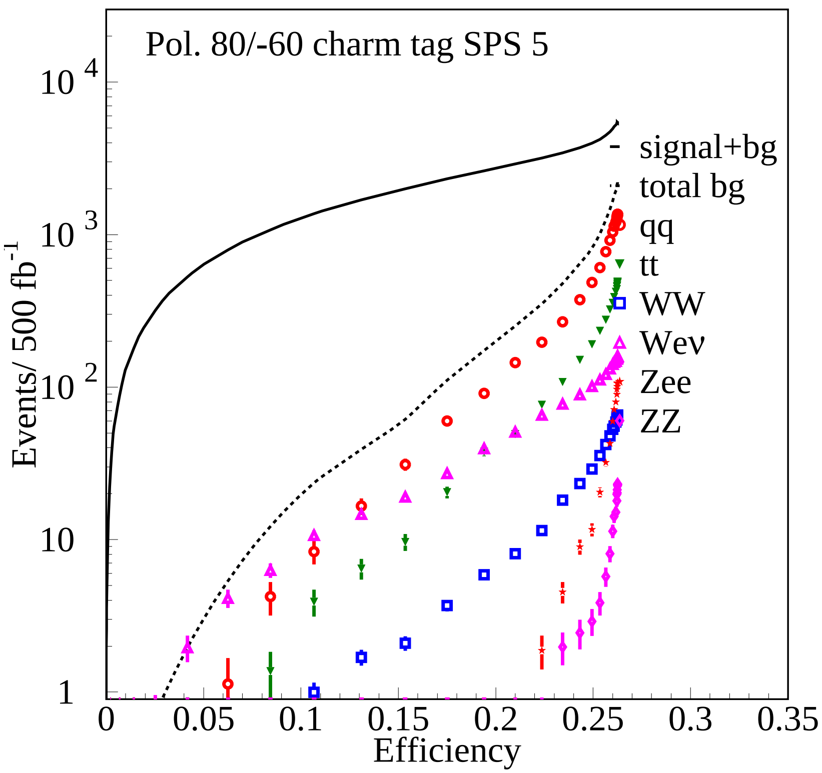
- visible energy
- number of jets
- thrust value
- thrust direction
- number of energy flow objects
- transverse momentum imbalance
- parallel momentum imbalance
- acoplanarity of the two highest energy jets.
- invariant mass of the two highest energy jets.
- Charm Tag of Jet 1
- Charm Tag of Jet 2





Selection Efficiency for Different Beam Polarizations

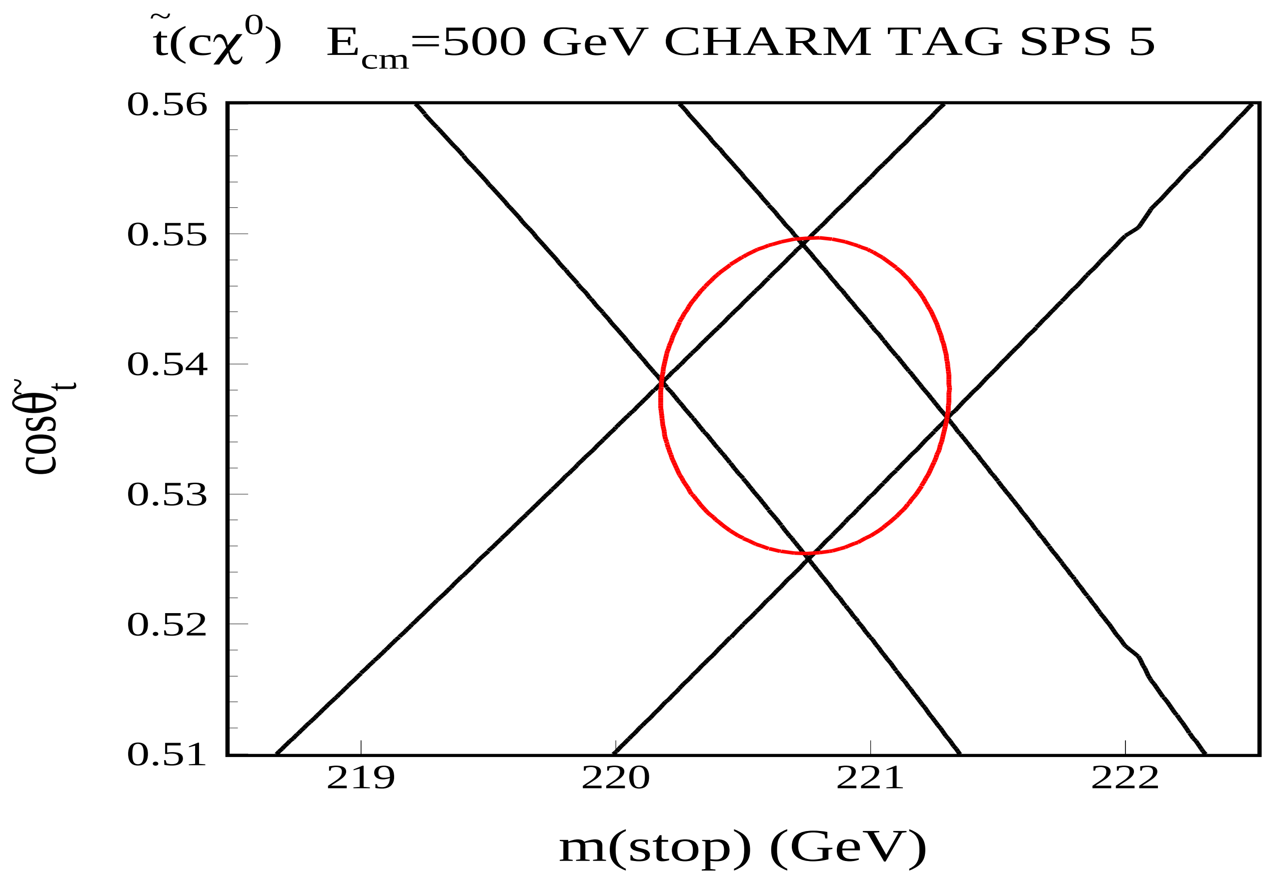




At 12% Efficiency {	Signal:	1350	1500
	Background:	145	32

Results from Polarization Method

Dependence of cross section on scalar top mass and mixing angle:



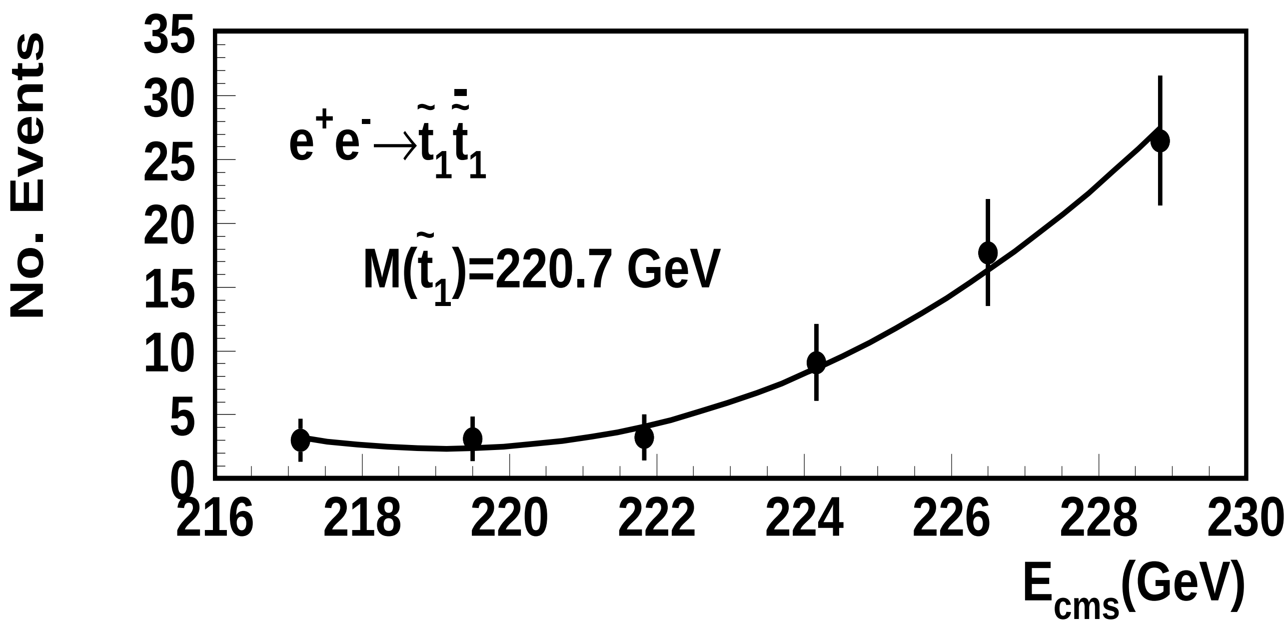
$500\,\mathrm{fb}^{-1}$ for each polarization: $\Delta m_{\tilde{t}_1} = \pm 0.57\mathrm{GeV}$ $\Delta \cos\theta_{\tilde{t}} = \pm 0.012$

Threshold Scan Method

Use 'right-handed polarization' to reduce backgrounds

Measure cross section close to threshold

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

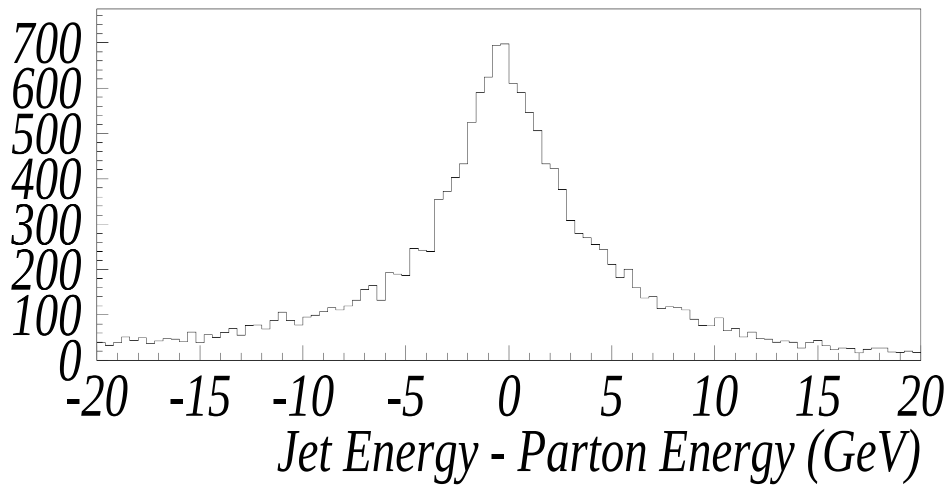


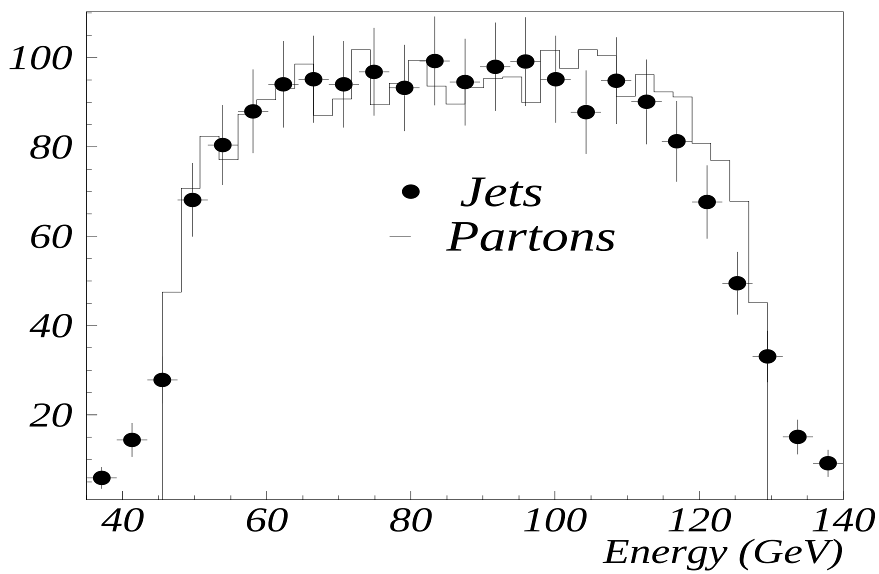
Mass from fit to shape: 220.9 ± 1.2 GeV

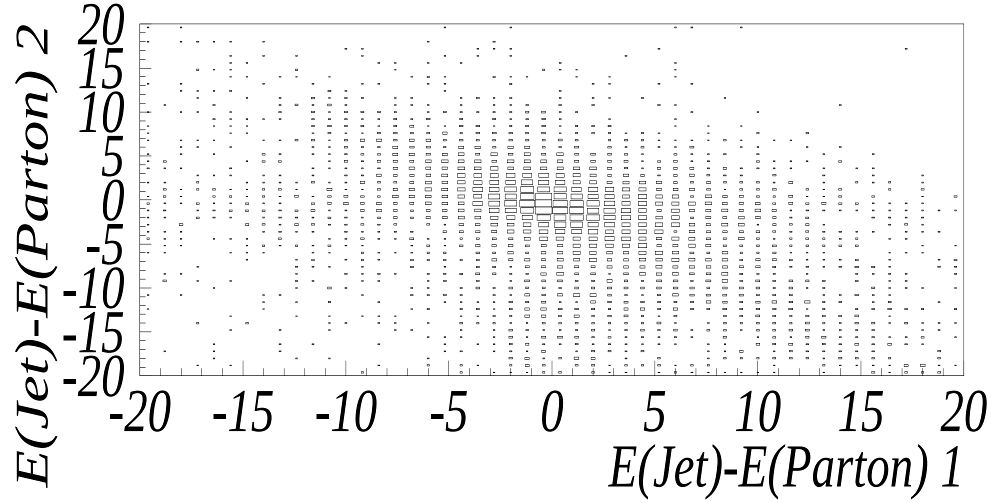
Direct Measurments from Jet Energies

'End Point Method' and 'Minimum Mass Method'

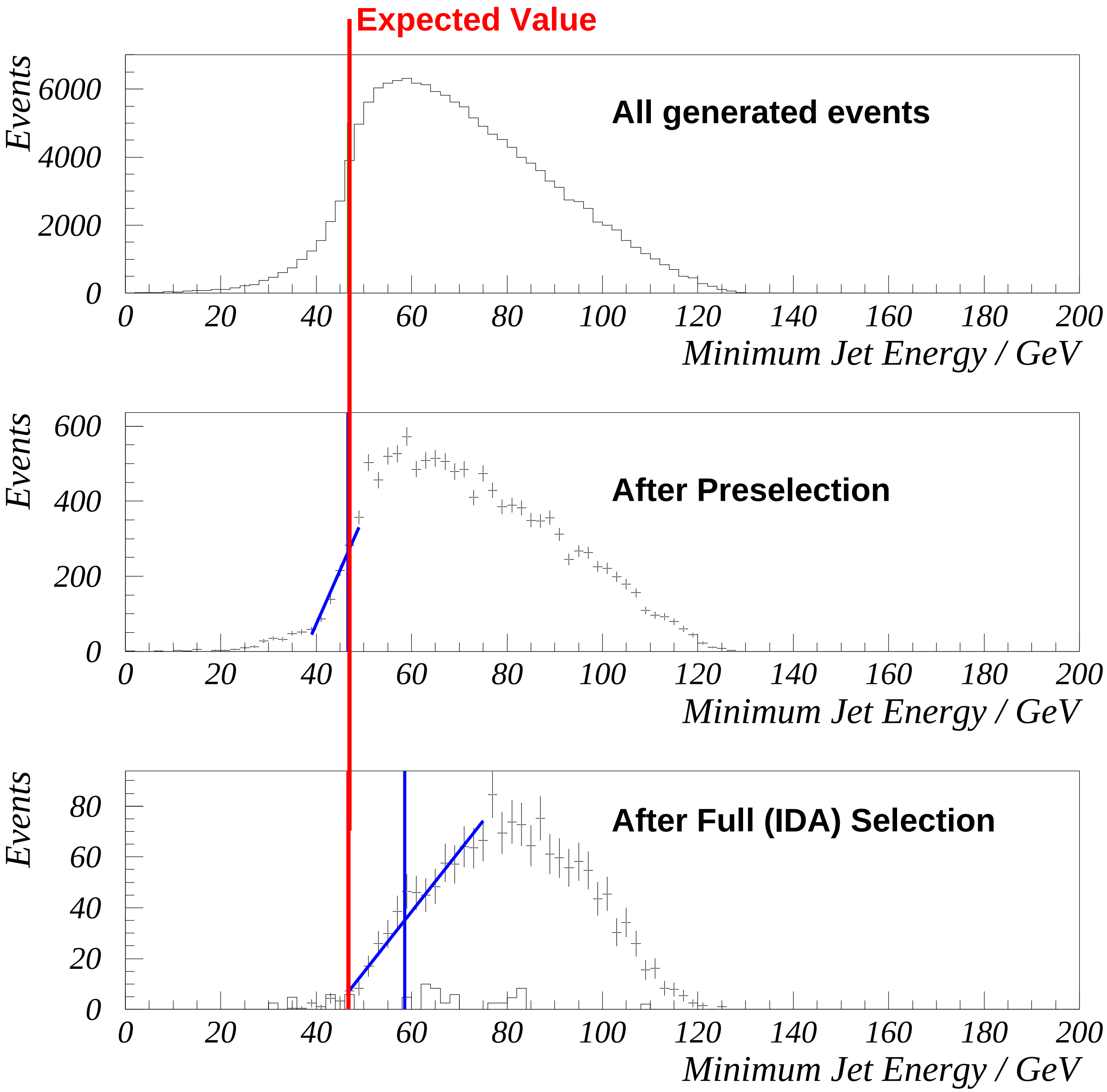
Require quark energies, but one measures jets.







Effect of IDA Selection on Min. Jet Energy



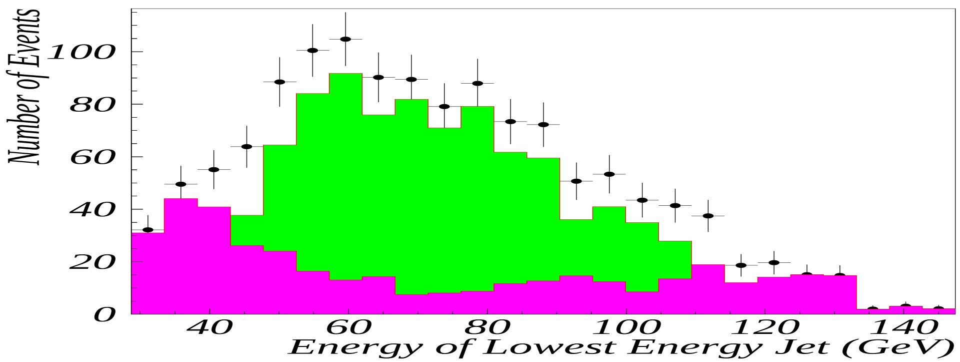
Use a Cuts based selection to reduce distortions

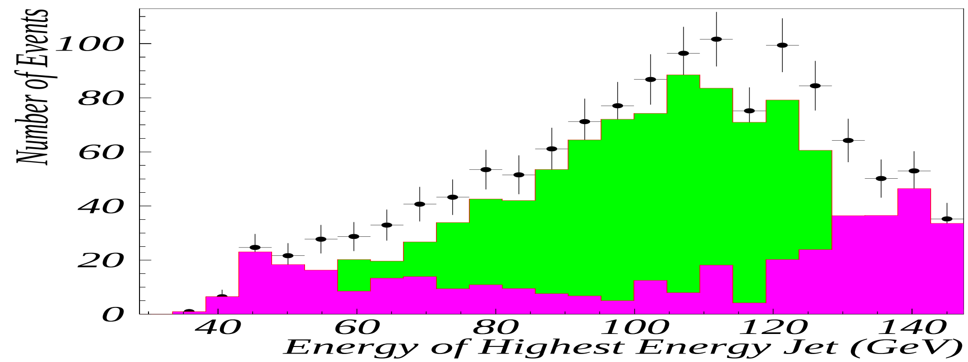
- $20 <$ Number of Energy Flow Objects < 90
- Visble Energy $< 0.8\sqrt{s}$
- Measured Longitudinal Momentum < 0.5 Visible Energy
- Thrust < 0.95
- Cosine of Thrust Axis relative to Beam Direction < 0.95
- Both Jet Charm Tags > 0.3
- At Least One Jet Charm Tag > 0.4
- Number of Jets < 4.
- Lowest Energy Jet > 35 GeV
- Highest Energy Jet < 140 GeV

Number of Signal Events Selected = 900 (=11 % efficiency)

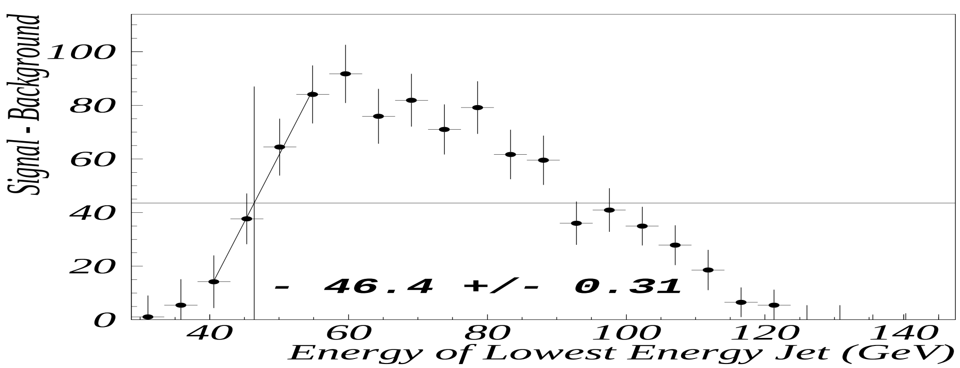
Number of Background Events Selected = 390 (=70% purity)

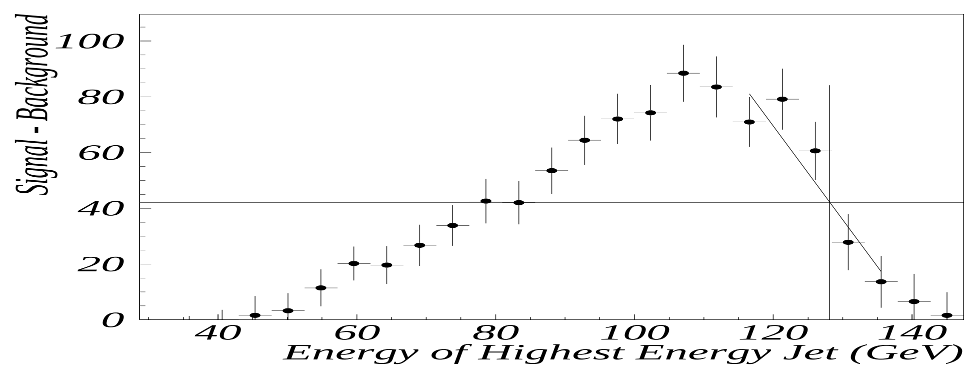
Jet Energy using Selection Cuts at SPS5





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

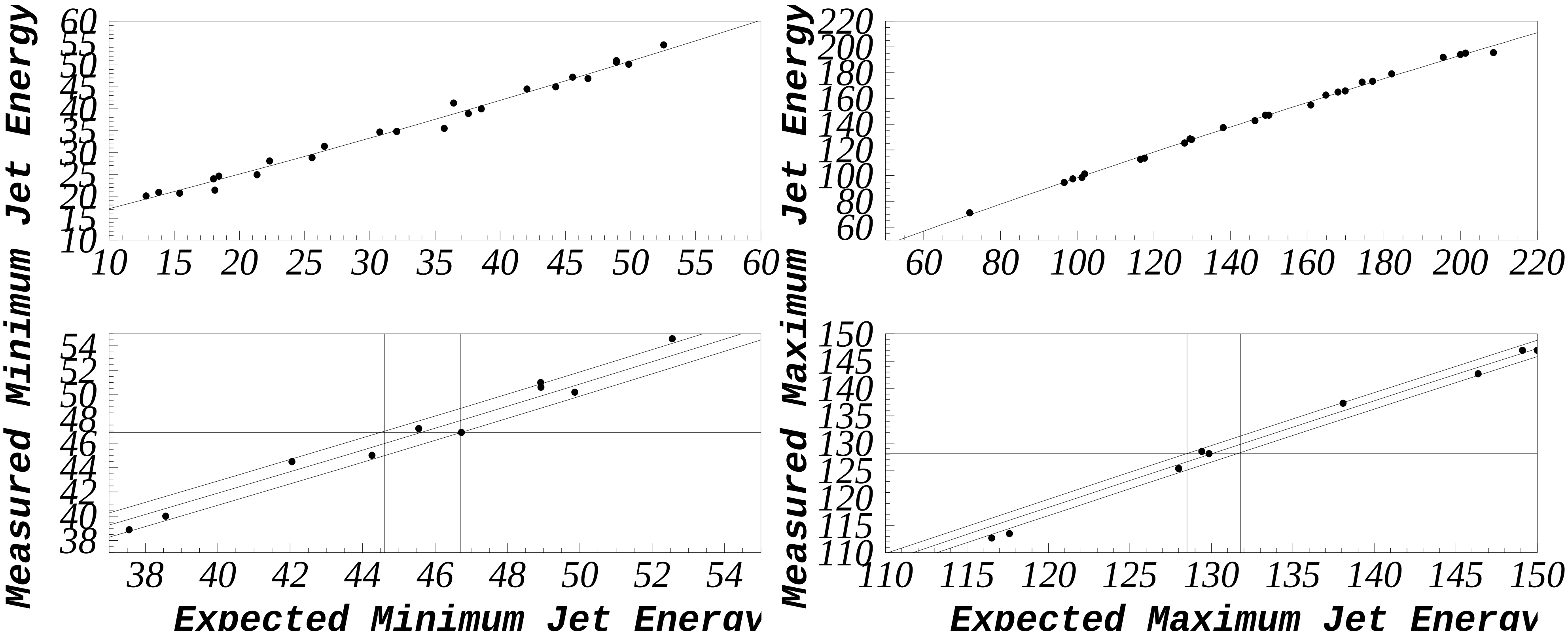




Measure Endpoints at Half Height Position (statistical uncertainty is small).

Jet Energy using Selection Cuts at SPS5

Generate several samples to obtain 'calibration curves'



$$\text{Minimum Jet Endpoint} = 45.7 \pm 1.0 \text{ GeV}$$

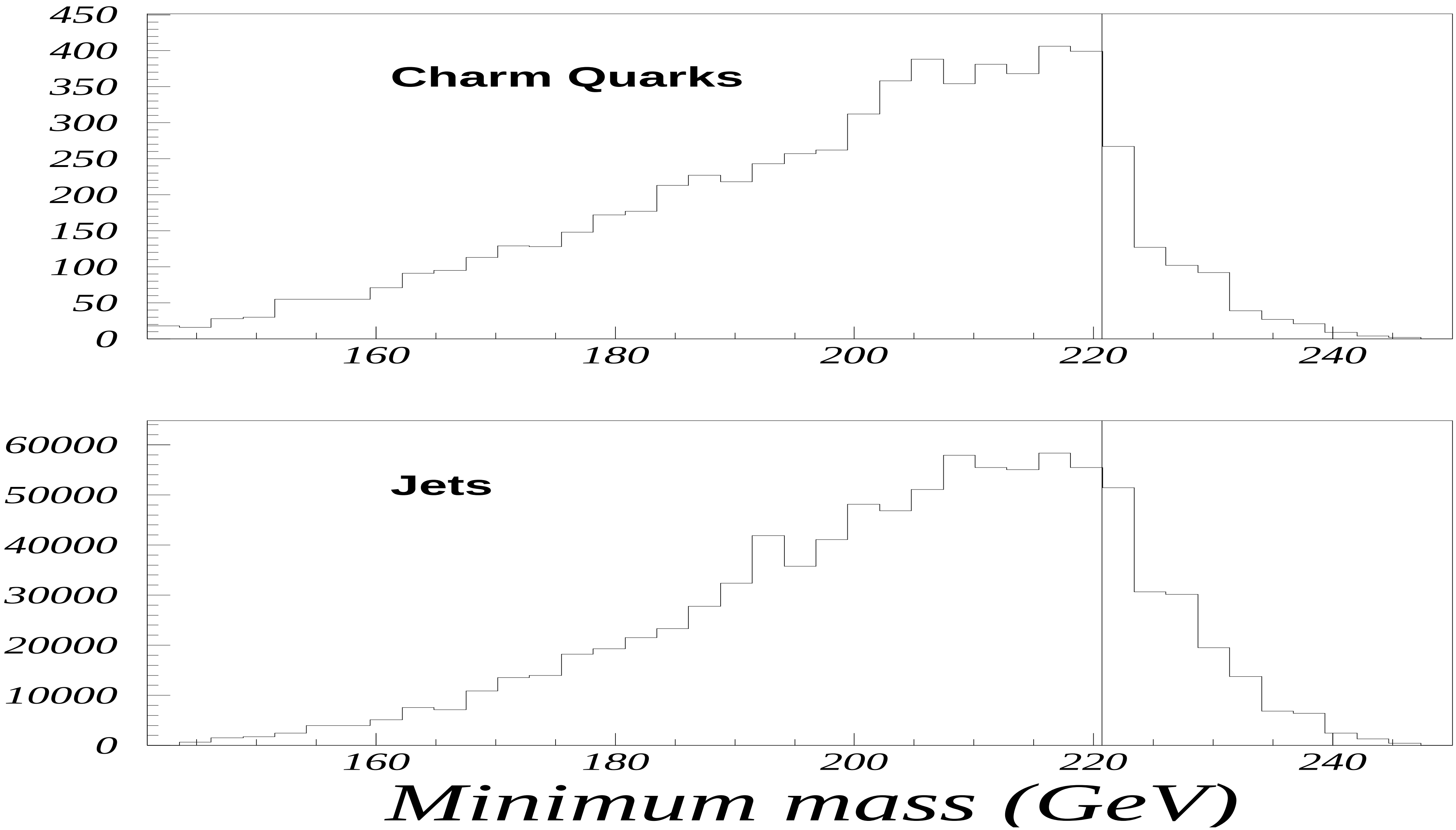
$$\text{Maximum Jet Endpoint} = 130.2 \pm 1.5 \text{ GeV}$$

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

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

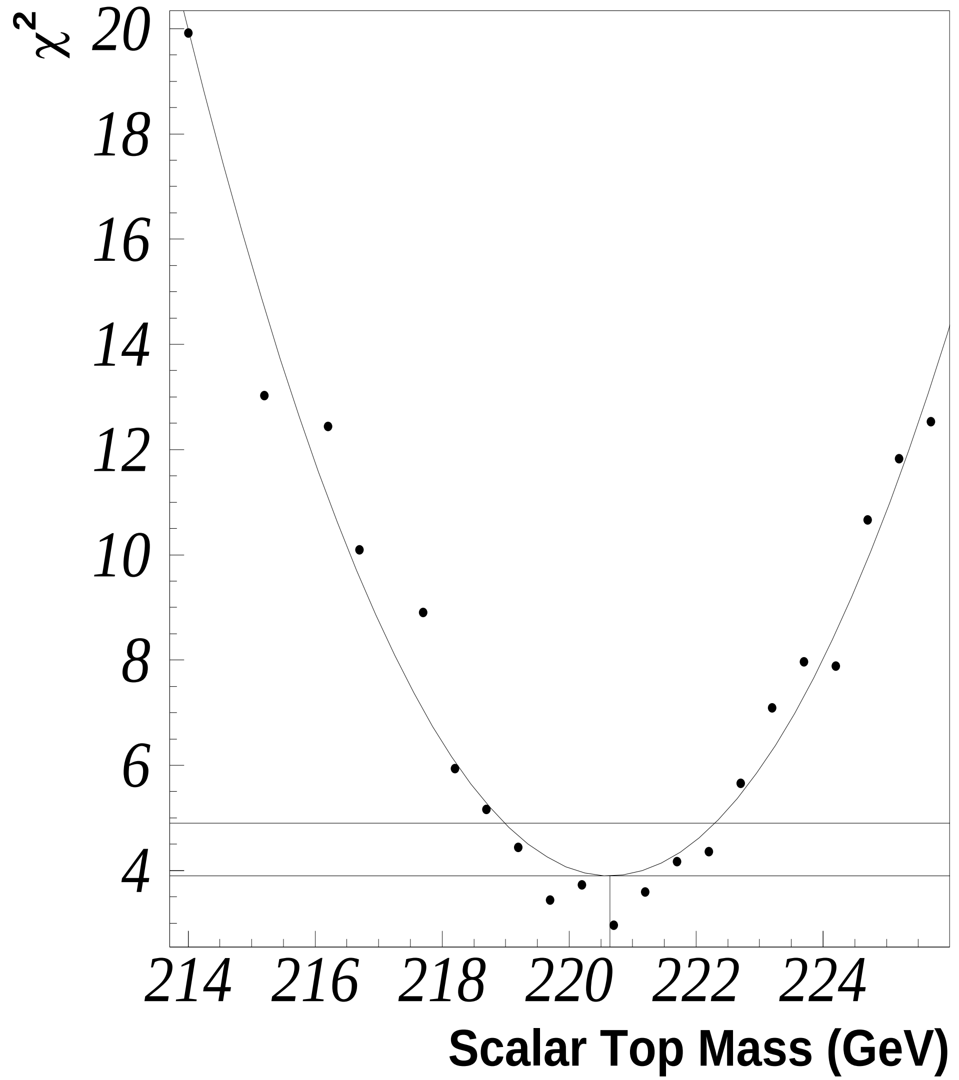
Minimum Mass Method

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



Fit to Find Error on Mass

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



Summary of Mass Determinations

- IDA selection provides high purity and efficiency.
- Allows $m_{\tilde{t}_1}$ measurement via:
  1. Combining Different Beam Polarizations
  2. Threshold Scan
- Selection cuts reduce distortions of Jet Energy Spectrum
- Allows $m_{\tilde{t}_1}$ measurement via:
  1. End Point Method
  2. Minimum Mass Method

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

Conclusions

- c-quark tagging as a benchmark for vertex detectors.
  In Supersymmetry: Scalar top quarks.
- SIMDET detector simulation: LCFI vertex detector.
- SIMDET and previous SGV kinematic distributions largely agree.
- c-tagging reduces background by about a factor 3 for $\tilde{\chi}_1^0 c \tilde{\chi}_1^0 \bar{c}$.
- Dedicated simulation with SPS-5 parameters:
  Possibility to compare with other vertex detector projects.
- Background depends on vertex detector design.
- Simulations for small stop-neutralino mass difference started
  (with Caroline Milstene).

The stop co-annihilation region at future colliders

A. Freitas, C. Milstène, M. Carena (Fermilab), A. Finch, A. Sopczak (Lancaster), H. Nowak (DESY)

1. Motivation
2. Detecting light stops
3. Parameter determination
4. Dark matter prediction

Electroweak Baryogenesis

Sakharov conditions:

- Baryon number violation
- C and CP violation
- Non-equilibrium →

Strongly first order electroweak phase transition necessary

$$\frac{v(T_C)}{T_C} > 1$$

Not possible in Standard Model,
but in Supersymmetry with light scalar top quarks (stops), $m_{\tilde{t}_1} < m_t$

Dark matter

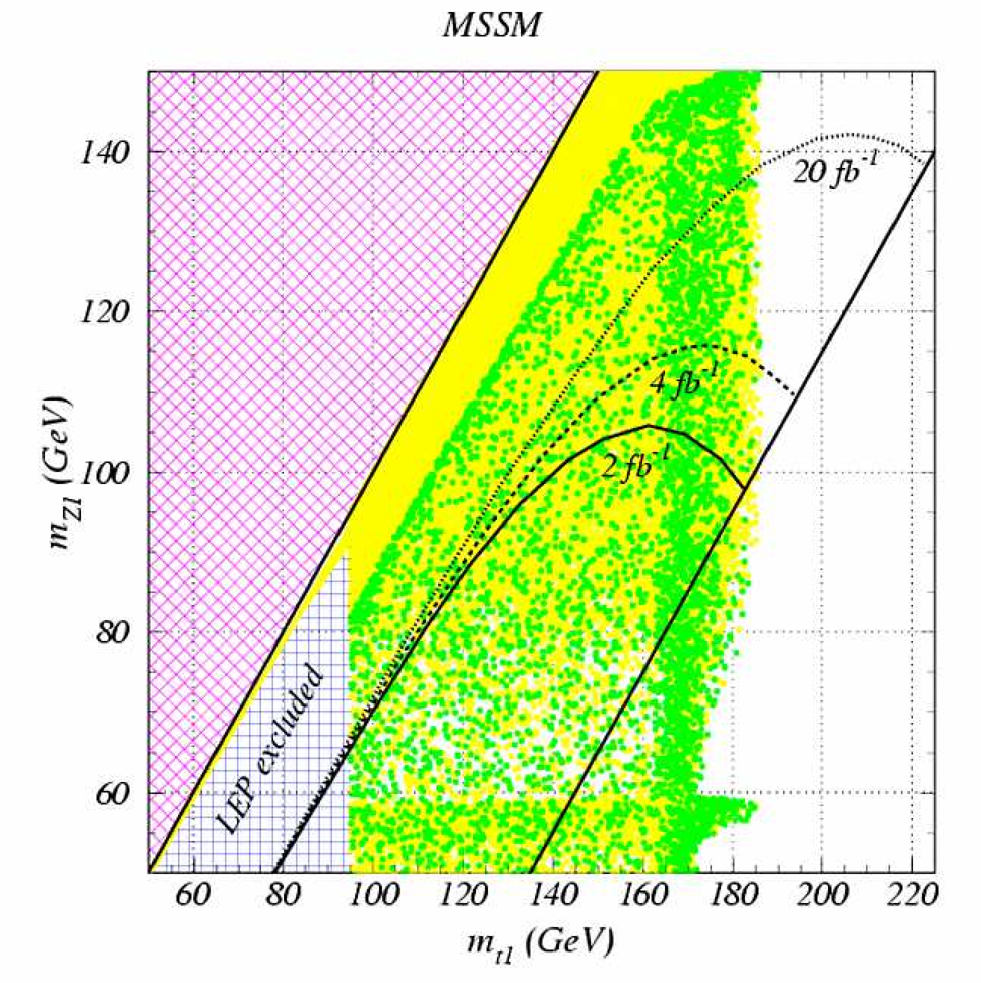
Lightest neutralino $\tilde{\chi}_1^0$ is natural dark matter candidate

Typically annihilation cross-section $\tilde{\chi}_1^0 \tilde{\chi}_1^0 \to X$ too small in MSSM

Enhancement of annihilation when $\tilde{t}_1$–$\tilde{\chi}_1^0$ mass difference Δm small
$\to$ co-annihilation

Typical parameter regions

Carena, Balázs, Wagner '04



Green: Relic density consistent with WMAP

Co-annihilation for $\Delta m \lesssim 30$ GeV

Difficult for searches at Tevatron

LHC will have similar difficulties

Light stop signature

Dominant decay for small mass differences $\Delta m = m_{\tilde{t}_1} - m_{\tilde{\chi}_1^0}$: $\tilde{t}_1 \to c\,\tilde{\chi}_1^0$

Assume 100% branching ratio for $\tilde{t}_1 \to c\,\tilde{\chi}_1^0$

Signature at linear collider: $e^+e^- \to \tilde{t}_1\,\tilde{t}_1^* \to c\,\bar{c}\,\tilde{\chi}_1^0\,\tilde{\chi}_1^0$

Two (soft) charm jets plus missing energy

Discrimination from background requires detector simulation

- Event generation with Pythia
- Detector effects with fast simulation
- Include beamstrahlung with Circe

Generate SM background from various sources

Assume $\mathcal{L} = 500\ \text{fb}^{-1}$ at $\sqrt{s} = 500$ GeV.

Signal and Background

process	cross-section [pb]		
	$P(e^-)/P(e^+) = 0/0$	$-80\%/+60\%$	$+80\%/-60\%$
$\tilde{t}_1\tilde{t}_1$, $m_{\tilde{t}_1} = 120$ GeV	0.280	0.374	0.456
$m_{\tilde{t}_1} = 140$ GeV	0.217	0.289	0.353
$m_{\tilde{t}_1} = 180$ GeV	0.105	0.140	0.171
$m_{\tilde{t}_1} = 220$ GeV	0.025	0.033	0.040
W^+W^-	8.55	24.54	0.77
ZZ	0.49	1.02	0.44
$We\nu$	6.14	10.57	1.82
eeZ	7.51	8.49	6.23
$q\bar{q}$, $q \neq t$	13.14	25.35	14.85
$t\bar{t}$	0.55	1.13	0.50
$\gamma\gamma$, $p_{\mathrm{t}} > 5$ GeV	936		

$-$ = L
$+$ = R

$\sin\theta_{\tilde{t}} = 0.5$

Large Standard Model backgrounds!

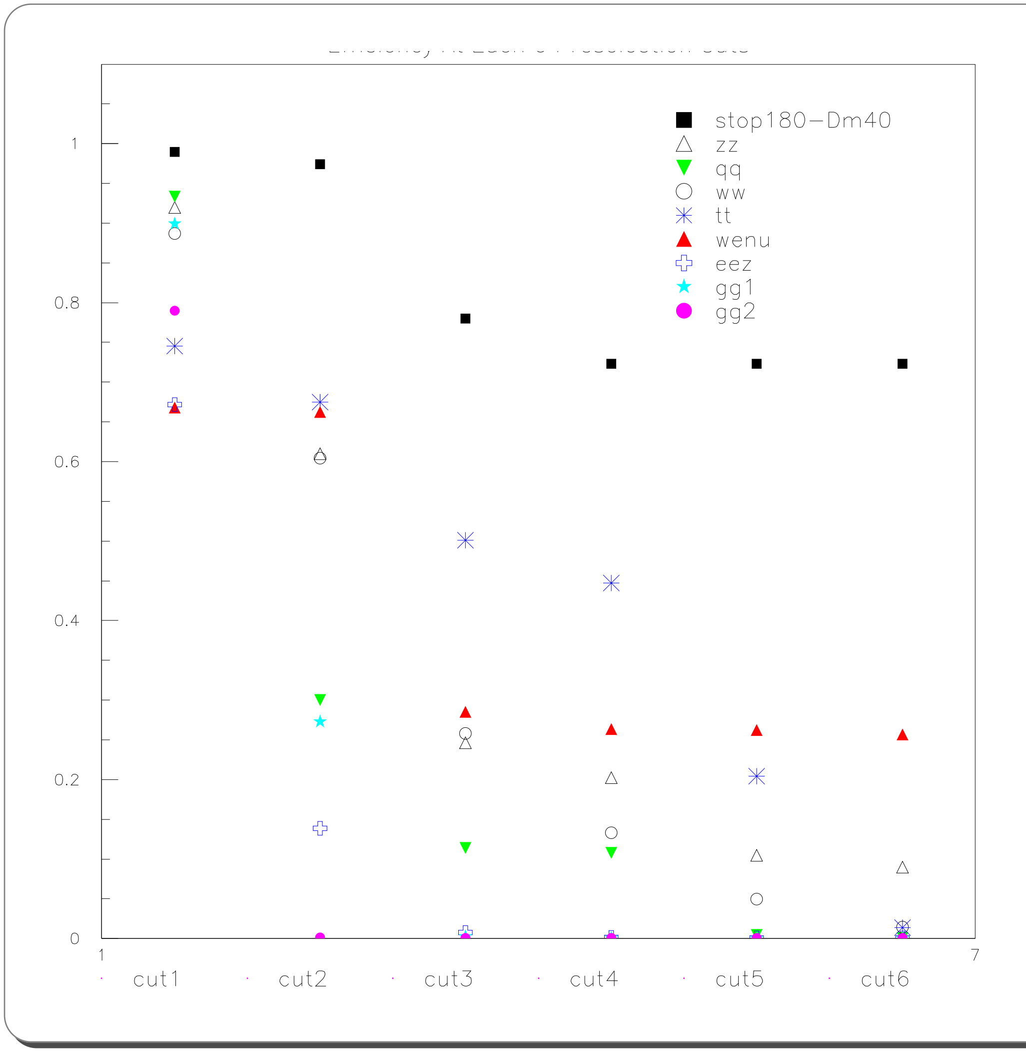
Reduction of background

Pre-selection:

1. $4 < N_{\mathrm{chargedtracks}} < 50$
2. $p_{\mathrm{t}} > 5$ GeV
3. $|\cos\theta_{\mathrm{Thrust}} < 0.8|$
4. $|p_{\mathrm{long,tot}}/p_{\mathrm{tot}}| < 0.9$
5. $E_{\mathrm{vis}} < 0.75\sqrt{s}$
6. $m_{\mathrm{inv}} < 200$ GeV

Most backgrounds (color) strongly reduced

Signal (**black**) to $\sim 70\%$



Reduction of background (ct'd)

Selection:

1. $N_{\text{jets}} = 2$ (Durham $y_{\text{cut}} = 0.003$)
2. $\cos\phi_{\text{aco}} > -0.9$
3. $p_{\text{t}} > 12$ GeV
4. $|\cos\theta_{\text{Thrust}} < 0.7|$
5. $E_{\text{vis}} < 0.4\sqrt{s}$
6. $3500\ \text{GeV}^2 < m^2_{\text{inv}} < 8000\ \text{GeV}^2$
7. c-tagging

Background	N_{evt} generated	N_{evt} after selection	scaled to 500 fb^{-1}
W^+W^-	210,000	8	145
ZZ	30,000	35	257
$We\nu$	210,000	345	5044
eeZ	210,000	2	36
$q\bar{q},\ q \neq t$	350,000	8	160
$t\bar{t}$	180,000	25	400
$\gamma\gamma$	5,500,000	0	< 164

Largest remaining background from $e^+e^- \to W^\pm e^\mp \nu$

Signal efficiency

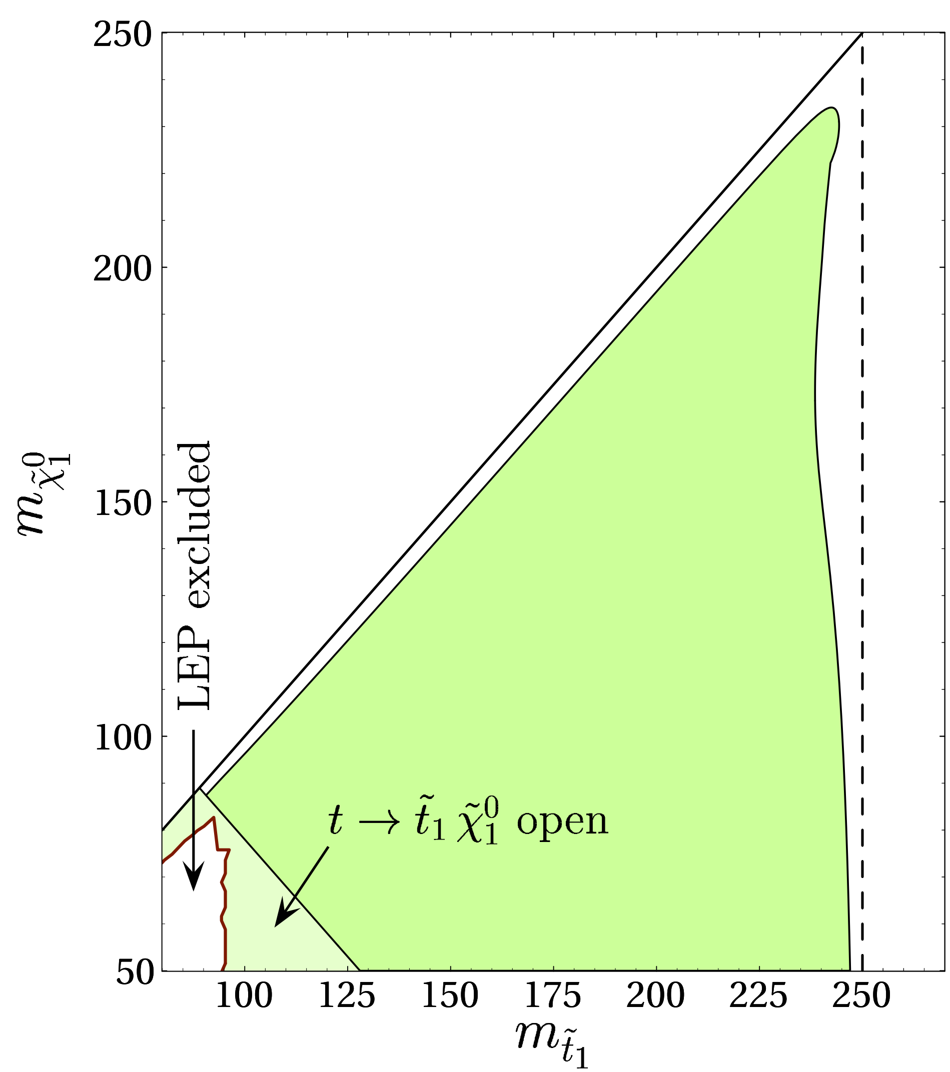
Δm	$m_{\tilde{t}_1} =$ 120 GeV	140 GeV	180 GeV	220 GeV
80 GeV		10%	15%	19%
40 GeV		10%	20%	24%
20 GeV	17%	21%	28%	35%
10 GeV	19%	20%	19%	35%
5 GeV	2.5%	1.1%	0.3%	0.1%

Typical signal event number remaining after selectron for 500 fb^{-1}, depending on $m_{\tilde{t}_1}$ and $\theta_{\tilde{t}}$: $N_{\text{sig}} \sim \mathcal{O}(10^3) - \mathcal{O}(10^4)$

$\longrightarrow$ same order as remaining background

Signal efficiency deteriorates for very small Δm

Stop discovery reach at linear collider



From simulations:

Background numbers B an
signal efficiencies ϵ
with theor. cross-section σ
yields signal number $S = \epsilon\sigma$

Green region: $\dfrac{S}{\sqrt{S+B}} > 5$

Light green:
decay $t \to \tilde{t}_1\tilde{\chi}_1^0$ open
(not yet studied)

Detection of light stops
possible for $\Delta m \sim \mathcal{O}(5\text{GeV}$

Cover complete
co-annihilation region

Sample parameter point

Point with light stop and CP violation

$\longrightarrow$ Use existing studies where possible

$M_1 = 137.2$ GeV	$M_{u3} = 0$	$M_{e1} = 200$ GeV
$M_2 = 260$ GeV	$M_{q3} = 1500$ GeV	$M_{l1} = 2000$ GeV
$\|\mu\| = 320$ GeV	$A_t = -570$ GeV	$A_e = 4.5$ TeV $\times e^{-i\pi/2}$
$\phi_\mu = 0.2$	$\tan\beta = 6$	

1st/2nd generation squarks heavy

$\longrightarrow$ Consistent with e and n EDM, m_{h^0} bound, baryogenesis

Sparticle masses:

$m_{\tilde{\chi}_1^0} = 133.4$ GeV $\quad m_{\tilde{t}_1} = 148.1$ GeV $\quad \sin\theta_{\tilde{t}} = 0.046$

$\Omega_{\mathrm{CDM}} h^2 = 0.115$

Stop parameters

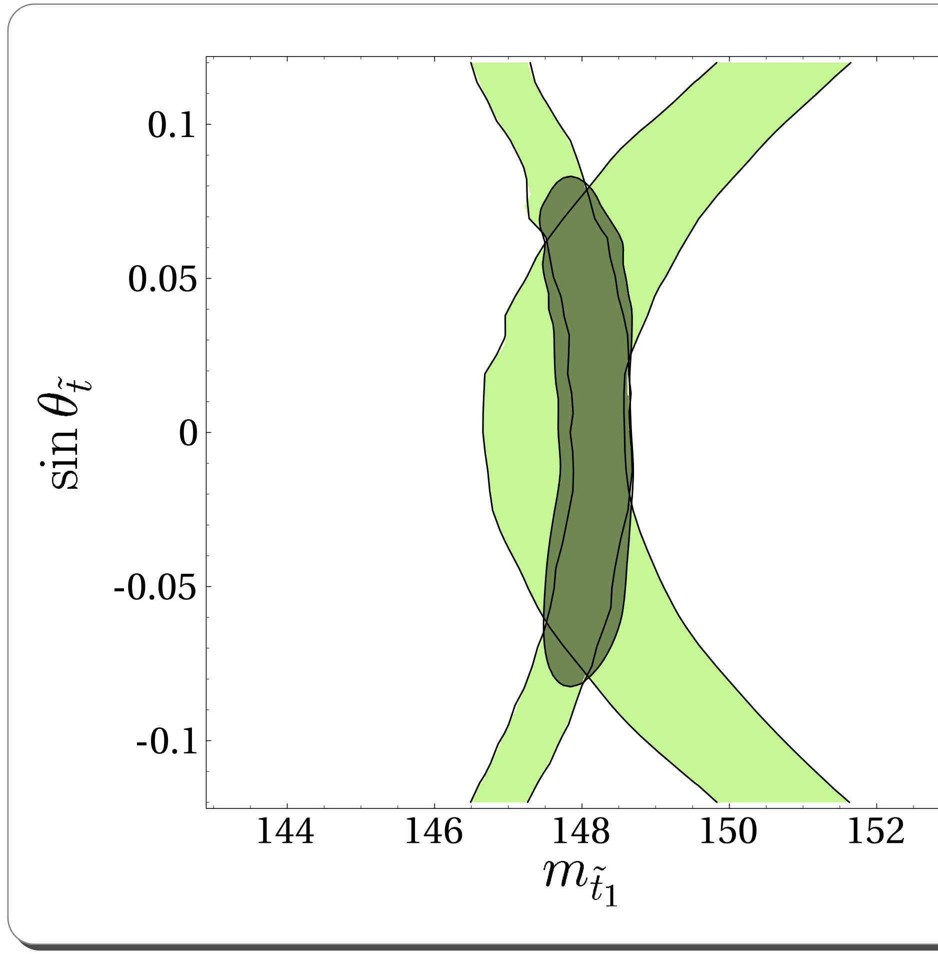
Use $e^+e^- \to \tilde{t}_1\tilde{t}_1^*$ cross-section measurements for two different beam polarizations:

$$P(e^-)/P(e^+) = -80\%/+60\%$$
$$+80\%/-60\%$$

$\mathcal{L} = 250\ \text{fb}^{-1}$ each

Systematic errors:

- $\delta m_{\tilde{\chi}_1^0} = 0.05$ GeV
- $\delta P/P = 0.5\%$
- backgr. simulation: $\delta B/B = 0.3\%$
- $\delta\mathcal{L}/\mathcal{L} = 2 \times 10^{-4}$



Result: $m_{\tilde{t}_1} = 148.1 \pm 0.4$ GeV

$|\sin\theta_{\tilde{t}}| < 0.07$

$\Rightarrow |\cos\theta_{\tilde{t}}| > 0.9975$

Computation of Ω_{CDM} from collider results

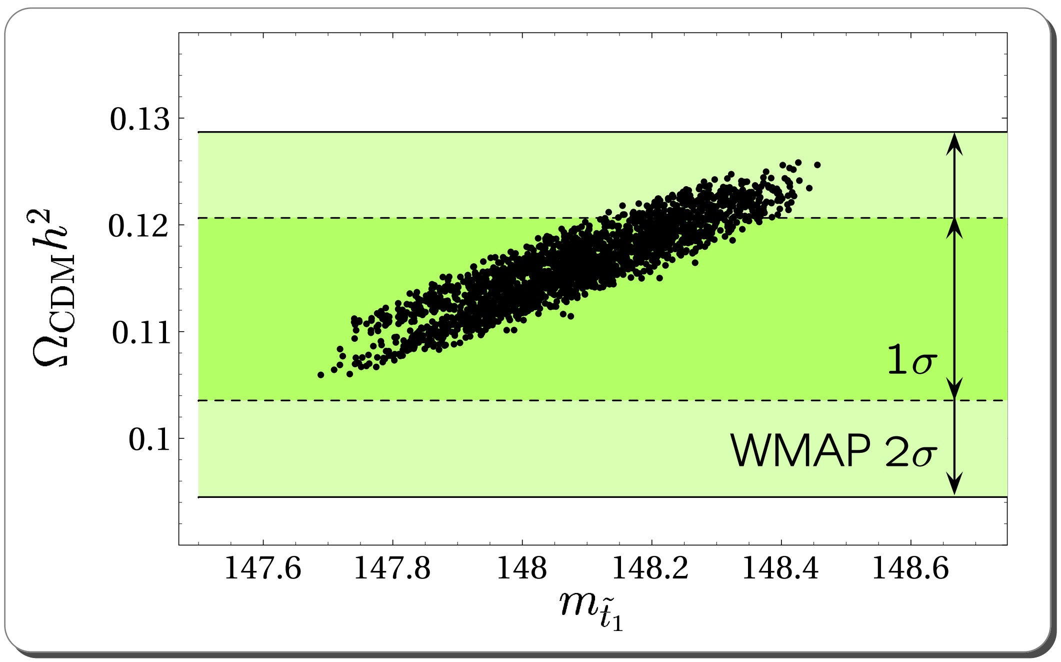
Use program by D. Morrissey for calculating Ω_{CDM}

Balázs, Carena, Menon, Morrissey, Wagner '04

Use inputs and propagate errors from

- Stop sector
- Chargino/neutralino sector
- Higgs sector

Account for correlations by using χ^2 fit



1σ constraints from ILC/LHC measurements:
$0.107 < \Omega_{\mathrm{CDM}} h^2 < 0.126$

dominated by error on $m_{\tilde{t}_1}$

WMAP (95% CL):
$0.095 < \Omega_{\mathrm{CDM}} h^2 < 0.129$

Conclusions

- ILC can cover complete stop-neutralino co-annihilation scenario
  Can explore mass differences down to
  $\Delta m = m_{\tilde{t}_1} - m_{\tilde{\chi}_1^0} \sim \mathcal{O}(5\ \text{GeV})$

- Prediction of Ω_{CDM} in MSSM from collider measurements with precision comparable to cosmological measurements

Future avenues:

- Further refinements of the experimental analysis
- Increase of efficiency at very low mass differences
- Analyze different dark matter scenarios
- Further studies of systematic uncertainties
- Comparasion with other DM calculations.