Scalar Tops from Morioka'95 to DESY'07

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Outline

- Introduction: developments since Morioka'95
- Importance of polarization
- Vertex detector c-tagging
- Methods of scalar top mass determinations
- Small stop-neutralino mass differences
- Dark matter interpretations
- Precision mass determination near threshold
- Conclusions

Introduction

- Morioka'95: "Supersymmetric Top Discovery Potential at a 500 GeV LC", AS, Bartl, Eberl, Kraml, Majerotto, Porod(LEP-type detector).
- LCWS Munich'06: "Scalar Quark Mass and Mixing Angle Determination – an argument for beam polarization",

  AS, Bartl, Eberl, Kraml, Majerotto, Porod.
- "Production and Decay of Stops and Bottoms, and Determination of SUSY Parameters",

  Bartl, Eberl, Grjdosik, Kraml, Majerotto, Porod, AS, DESY 97-123E.
- "Search of Stops, Bottom, τ-Sneutrino, and Stau at an e^+e^- Linear Collider with 0.5 to 2 TeV", Z. Phys, C76 (1997) 549.
- LCWS Oxford'99: "Scalar Quark Study in the Neutralino Channel",AS.
- LCWS Obernai'99: "Scalar Quark Study in the Chargino Channel",AS.

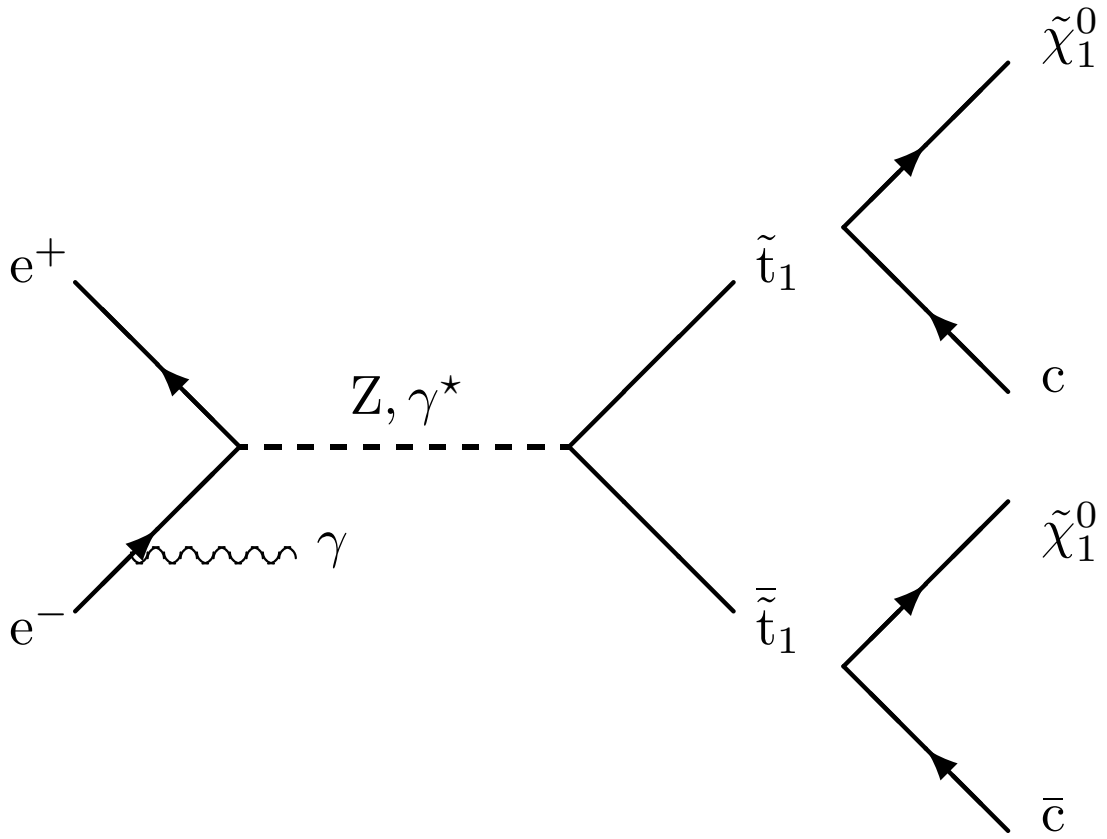
Iterative Discriminant Analyses

- LCWS Sitges'99: "Study of Scalar Top Quarks",
  a) Iterative Discriminant Analysis (IDA),
  b) Simulation Grand Vitesse (SGV), detailed LC det. description,
  Berggren, Keranen, Nowak, AS, EPJDirect C7 (2000) 1.
- LCWS Chicago'00, Scalar Top in the Neutralino and Chargino Channel, Nowak, AS.
- LCWS Snowmass'01, Scalar Top benchmark point SPS-5, AS.
- LCWS Jeju'02, "Precision measurements" SIMDET with LCFI vertex detector c-tagging,
  AS, Finch, Nowak.
- LCWS Amsterdam'03, "A new Scalar Top Analysis",
  AS, Finch, Nowak, hep-ph/0309235 (Kalinowski et al).
- LCWS Paris'04, "LCFI CCD Vertex Detector Charm-Tagging" and "Four Mass Determination Methods", AS, Finch, Nowak.

Dark Matter, Mass Precision

- LCWS Stanford'05 "Analysis of Stops with Small Stop-Neutralino Mass Difference", Milsténe, Carena, Finch, Freitas, Nowak, AS
- Snowmass'05: Scalar top studies as a benchmark for vertex detector c-quark tagging, Milsténe, AS, 2005-alcpg1431.
- Bangalore'06, "Small Visible Energy Scalar Top Interative Discrimiant Analysis" ($\sqrt{s} = 260$ GeV scenario), AS, Finch, Freitas, Milsténe, Schmitt
- SUSY'06, "Small Visible Energy Scalar Top Interative Discrimiant Analysis" ($\sqrt{s} = 500$ GeV scenario). AS, Finch, Freitas, Milsténe, Schmitt.
- LCWS DESY'07, **"Precision Measurements of the Stop Mass"**, Milsténe, Freitas, Schmitt, AS. Threshold, fragmentation effects, retuning of IDA, reduction of systematic uncertainties by $\sqrt{s} = 260$ and 500 GeV analyses.

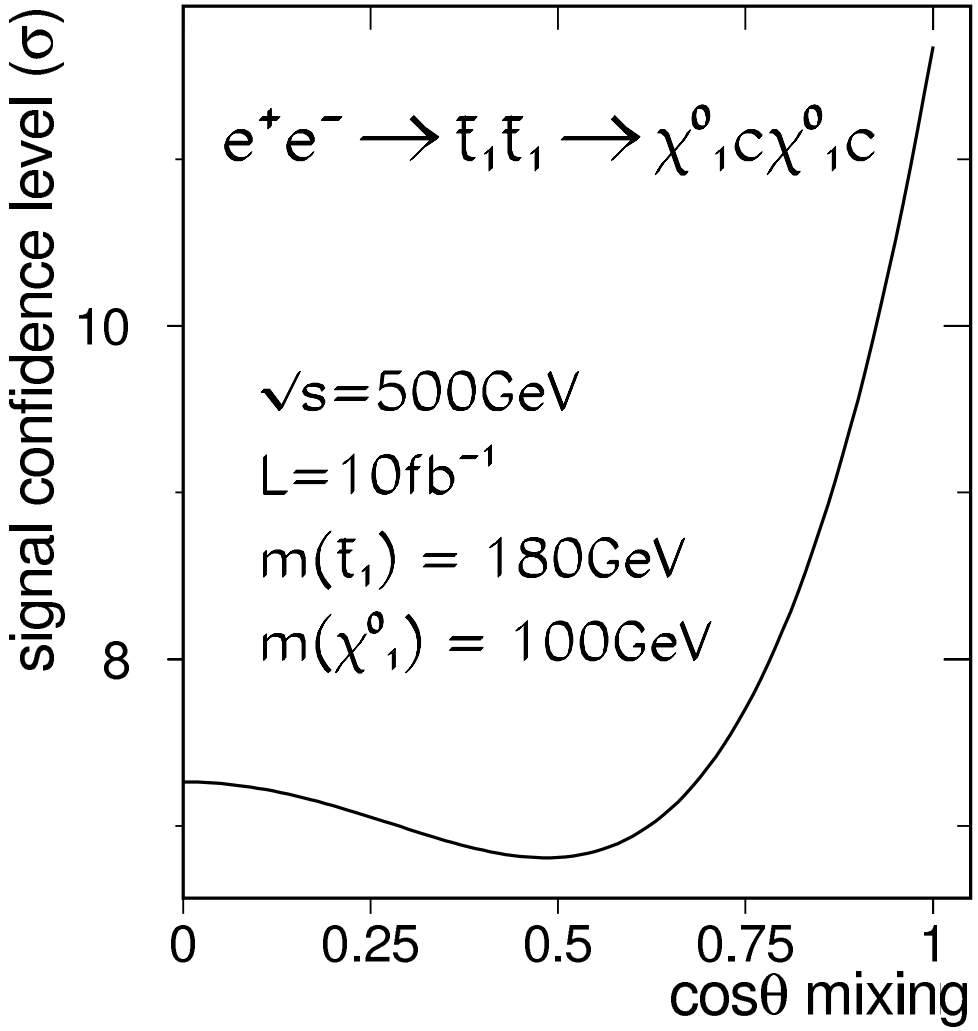
c-Quark Tagging: a Benchmark Reaction

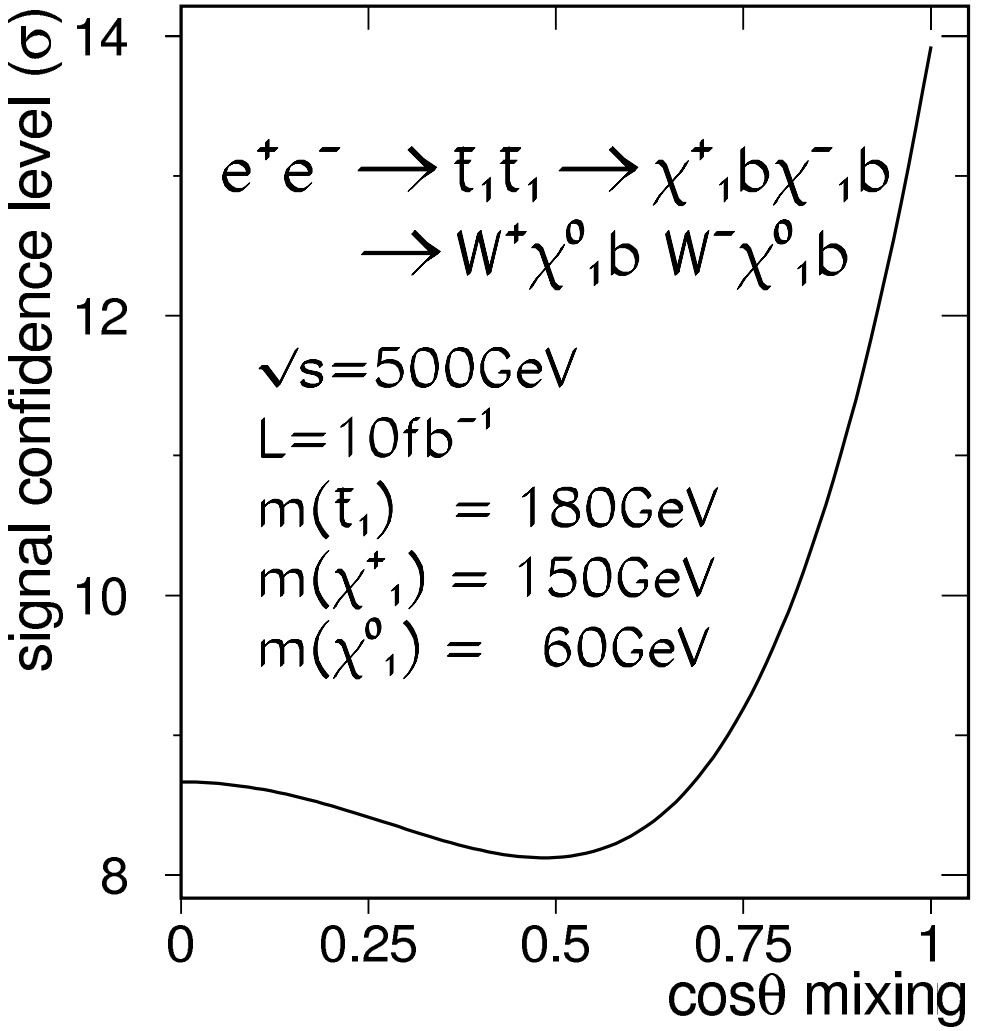


Signal: Two charm jets and missing energy.

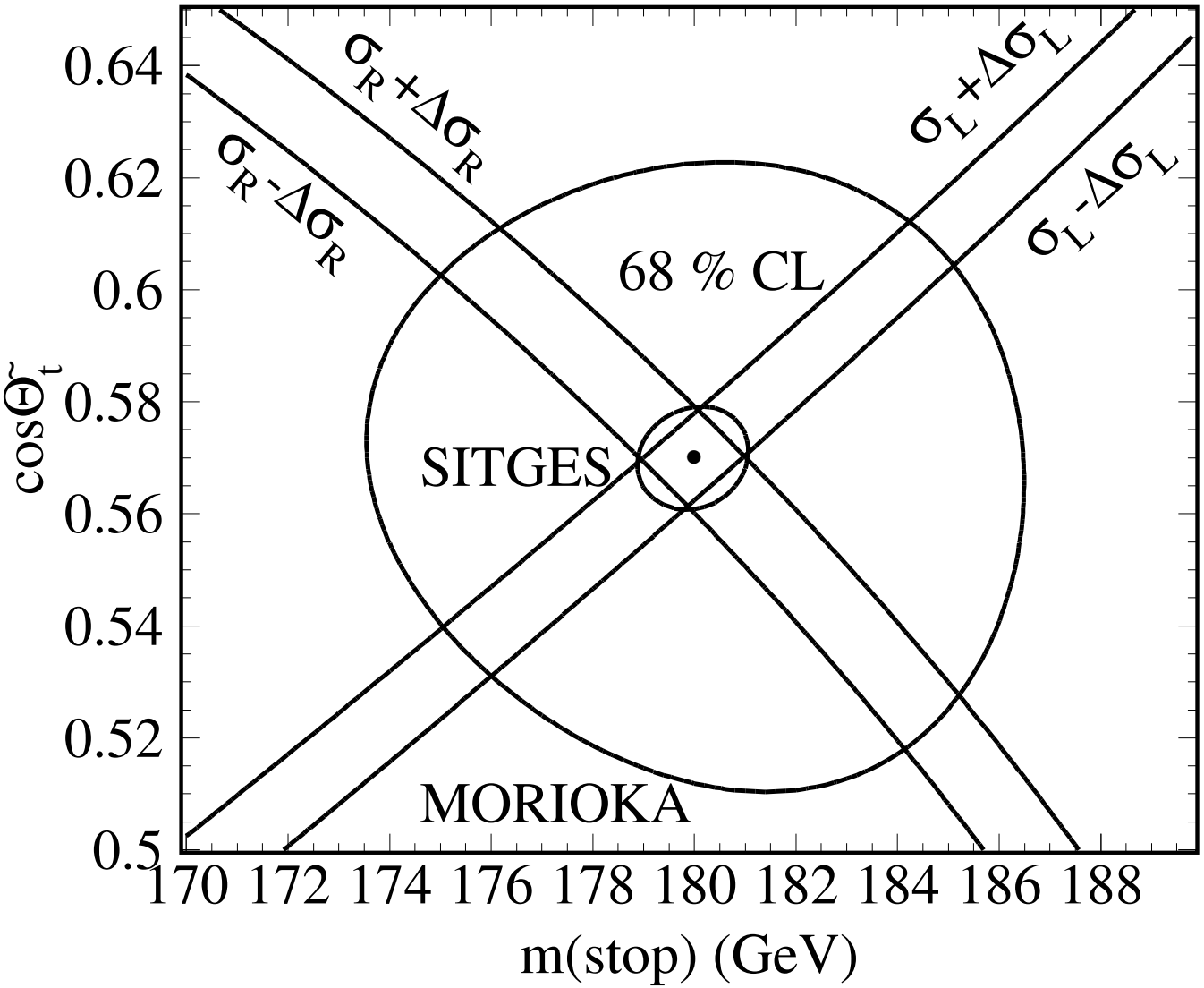
Benchmark reaction in the Supersymmetry framework: $e^+e^- \to \tilde{t}_1\bar{\tilde{t}}_1 \to c\tilde{\chi}_1^0\bar{c}\tilde{\chi}_1^0$

Expected LC Significance ($\sigma = s/\sqrt{b}$) Morioka'95





Development Morioka'95 to Sitges'99



- $L_{\mathrm{M}} = 10$ fb^{-1}
- $L_{\mathrm{S}} = 500$ fb^{-1}
- Morioka: sequential-cut based selection
- Sitges: IDA

Detector Aspects

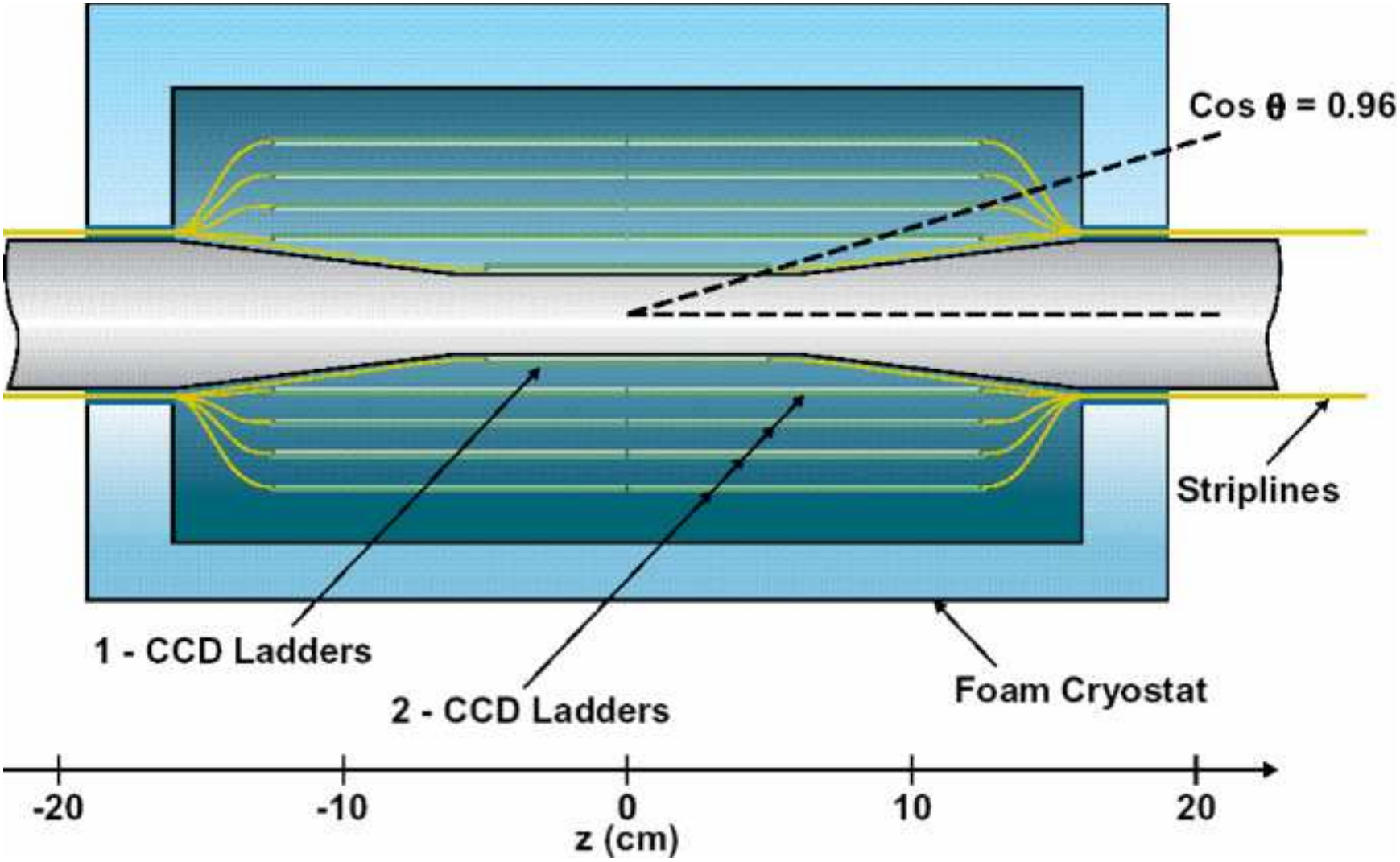
Major challenge to develop a vertex detector for a future LC.
Key aspects:

- Distance to interaction point of innermost layer is crucial (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 very important at a future LC:
Linear Collider Flavour Identification (LCFI) collaboration.
c-quark tagging is a benchmark for vertex detector developments.
New c-tagging Vertex Package just released (Sonja Hillert et al).

CCD Vertex Detector

LCFI Collaboration: Development of a CCD detector for a future LC.
This CCD detector is implemented in c-tagging simulations.



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

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):

$\tilde{t}_1\bar{\tilde{t}}_1(180/220.7)$	$We\nu$	WW	$q\bar{q}$	$t\bar{t}$	ZZ	eeZ
CALVIN32	GRACE	WOPPER	HERWIG	HERWIG	COMPHEP	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.

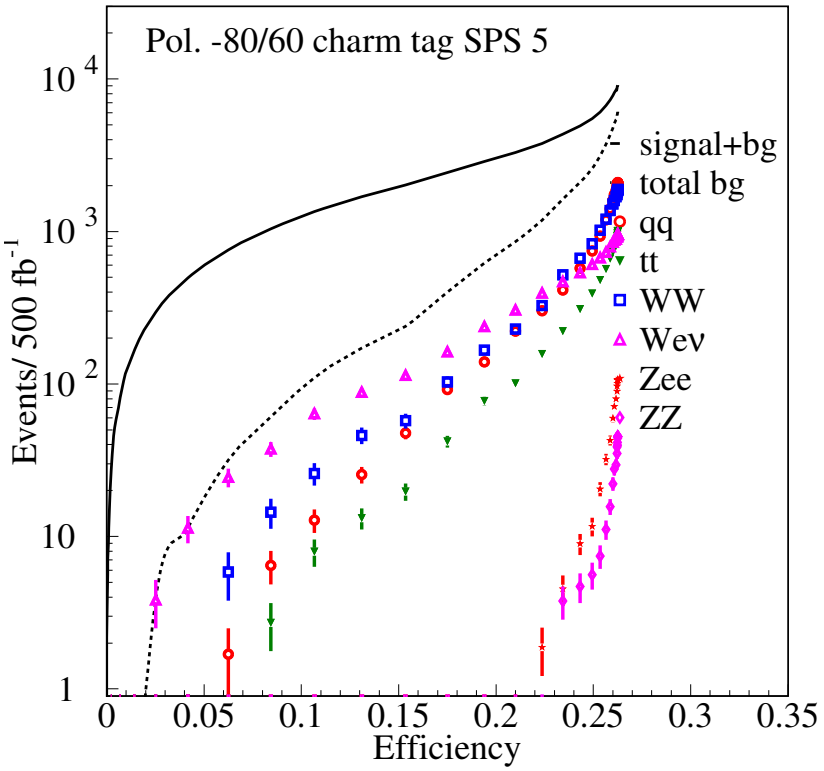
Typical Analysis Strategy

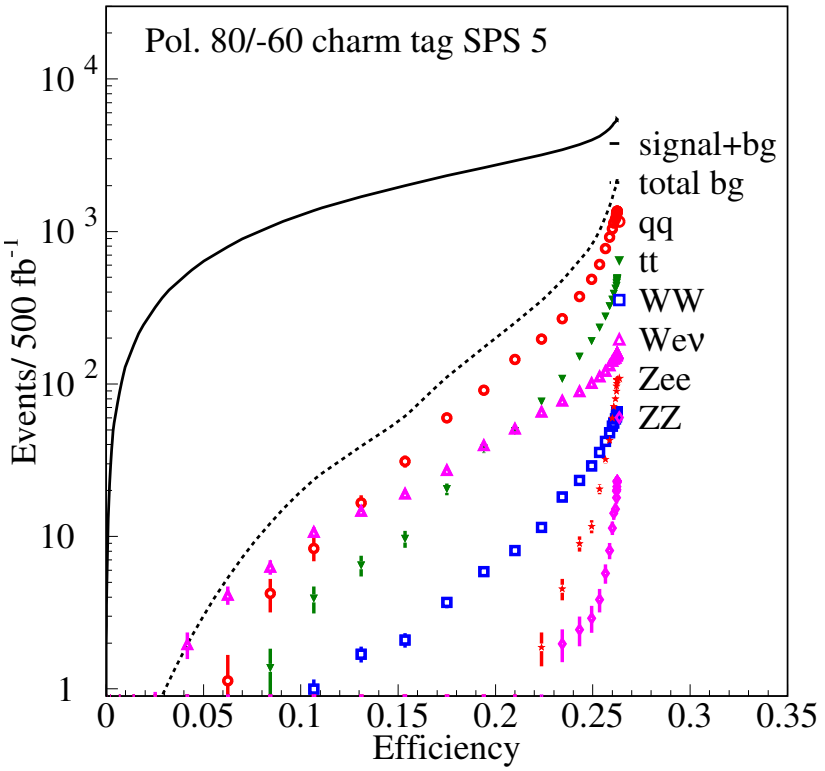
- Signal and Background generated for 500 fb^{-1} and $\sqrt{s} = 500\mathrm{GeV}$
- Detector Simulation: SIMDET 4.03 (J. Schreiber et al.)
- b/c tagging algorithm (T. Kuhl et al.)
- Iterative Discriminant Analysis (IDA) for selection optimization
- Different Vertex Detector configurations

Four Different Methods of Mass Determination

- Two 'IDA' based selection -
  Optimum Signal/Background ratio:
  - Cross section with different polarizations
  - Threshold dependence of cross section
- Two cut based selection -
  Minimum distortion of final state observables
  - Endpoint of jet energy spectrum
  - Minimum Mass of jets (J. Feng)

Selection Efficiency for Different Beam Polarizations

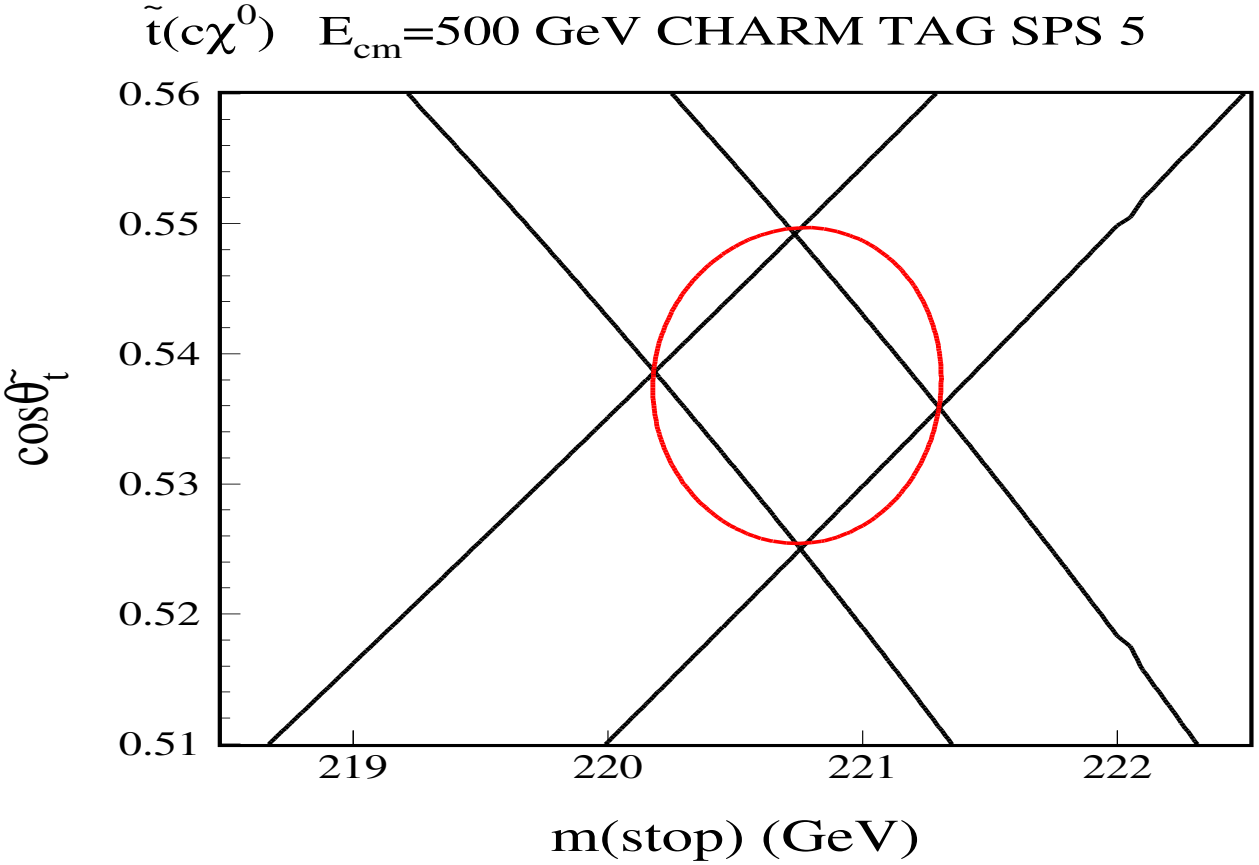




At 12%	Signal:	1350	1500
Efficiency	Background:	145	32

Results from Polarization Method

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



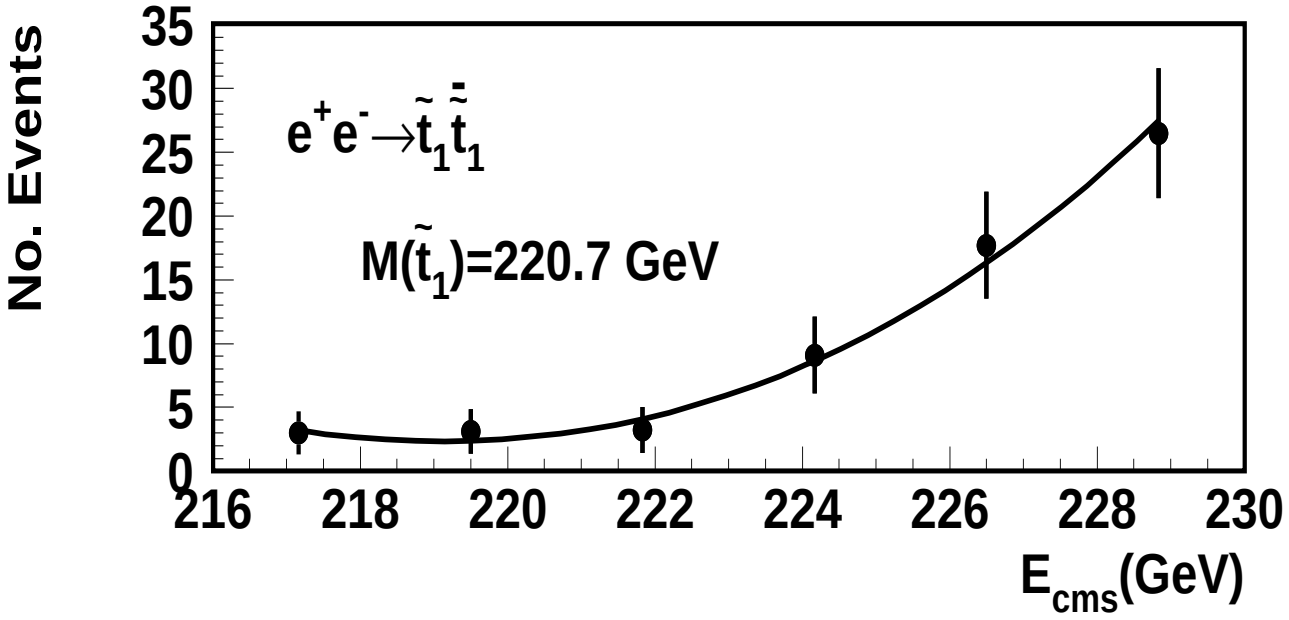
$500\,\mathrm{fb}^{-1}$ for each polarization: $\Delta m_{\tilde{t}_1} = \pm 0.57\mathrm{GeV}$ $\Delta\cos\theta_{\tilde{t}} = \pm 0.012$

Threshold Scan Method

Use 'right-handed polarization' to reduce backgrounds

Measure cross section close to threshold

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

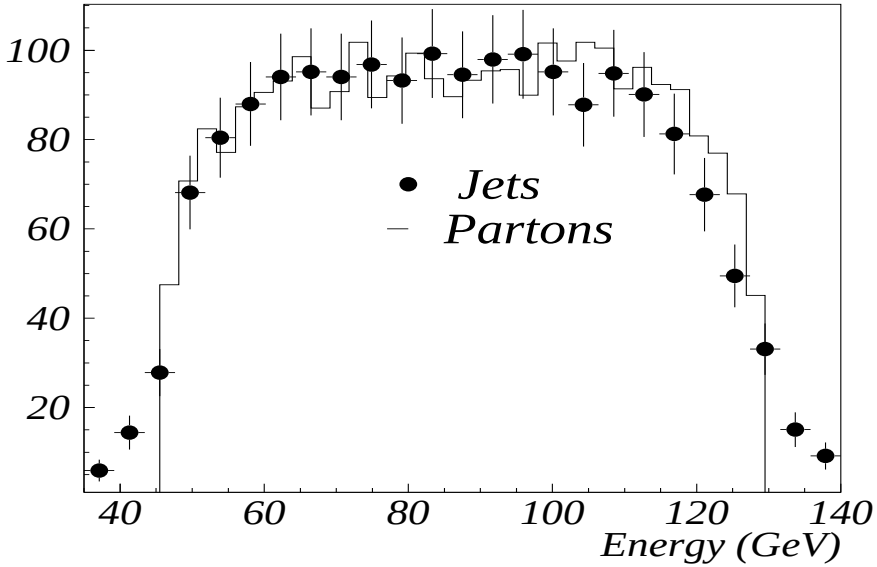


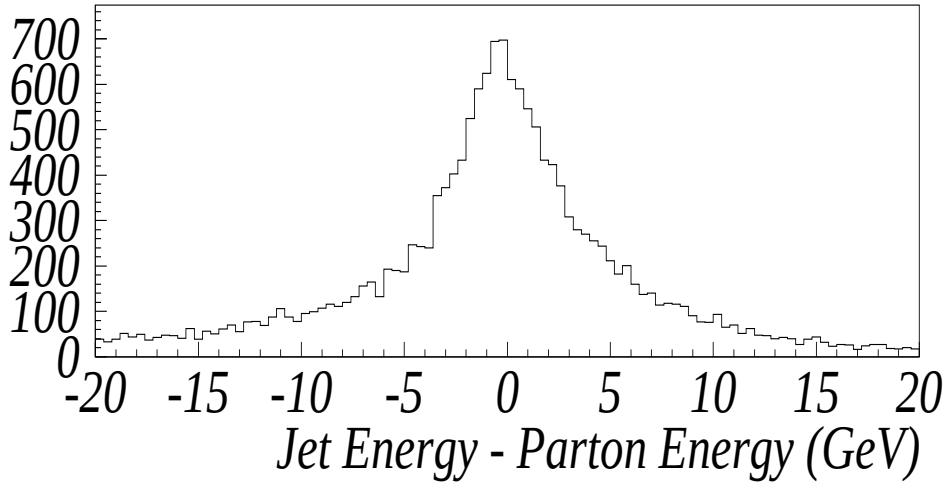
Mass from fit to shape: 220.9 ± 1.2 GeV

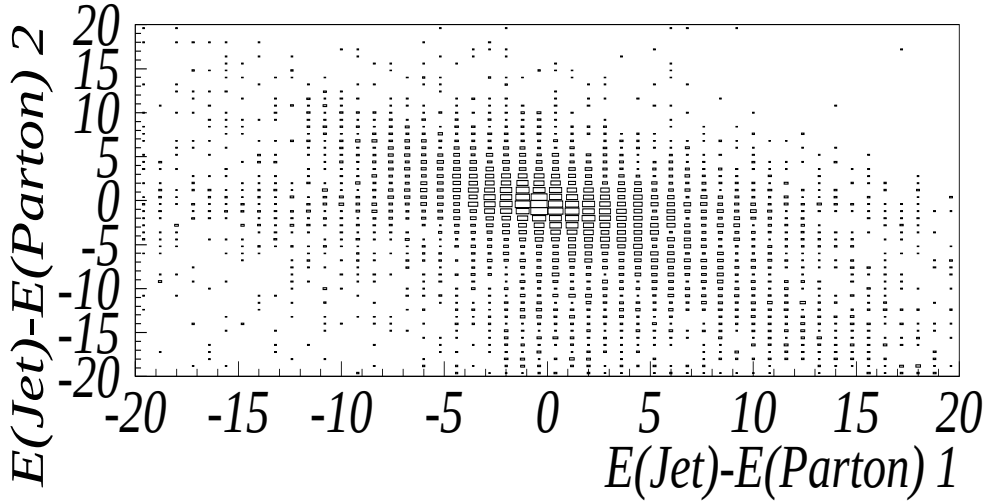
Direct Measurements from Jet Energies

'End Point Method' and 'Minimum Mass Method'

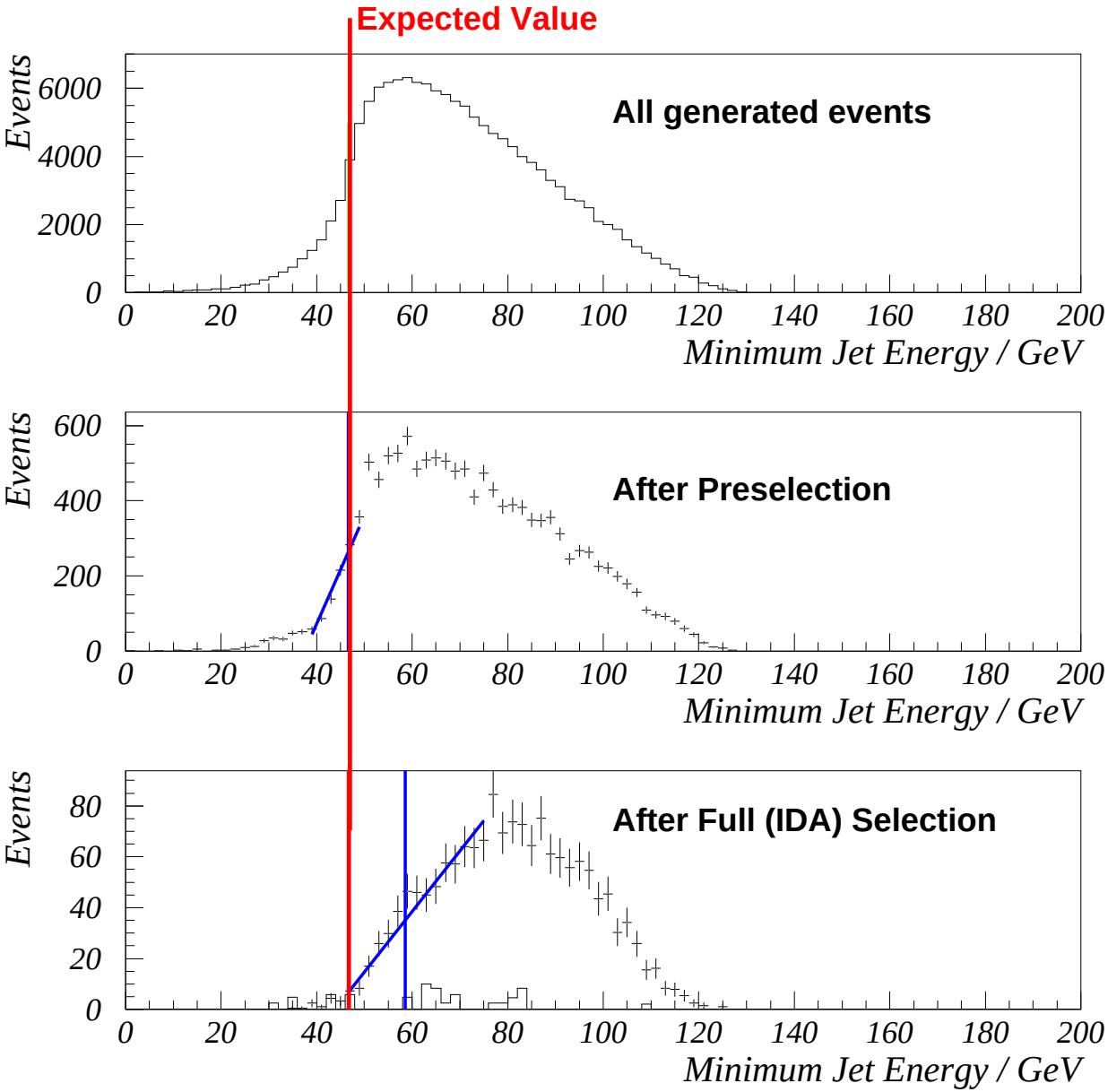
Require quark energies, but one measures jets.



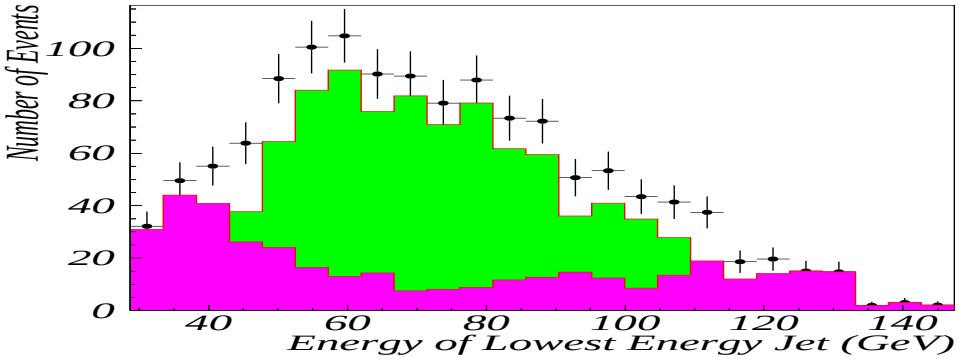


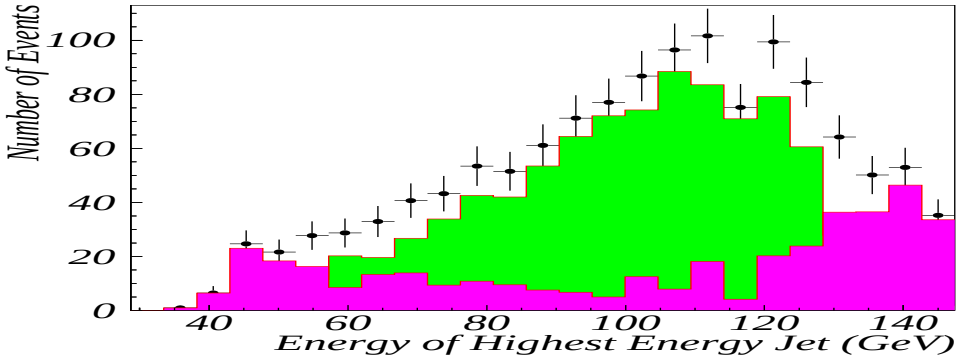


Effect of IDA Selection on Min. Jet Energy

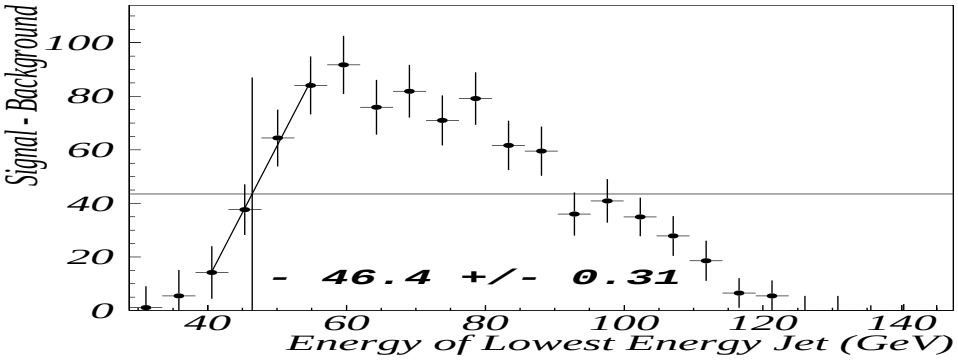


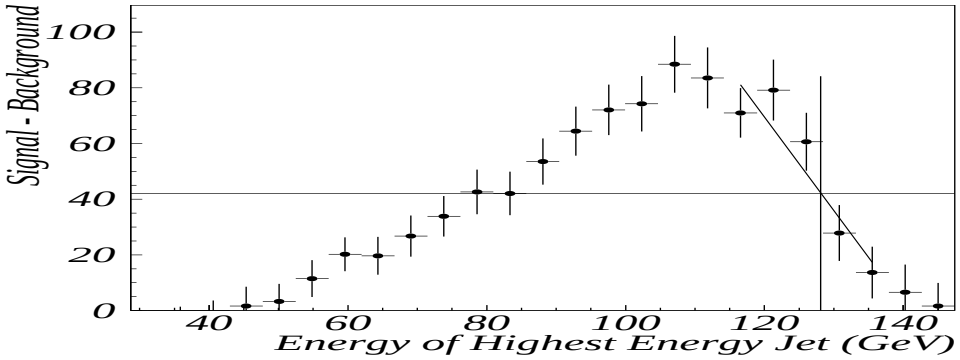
Jet Energy using Selection Cuts at SPS5





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

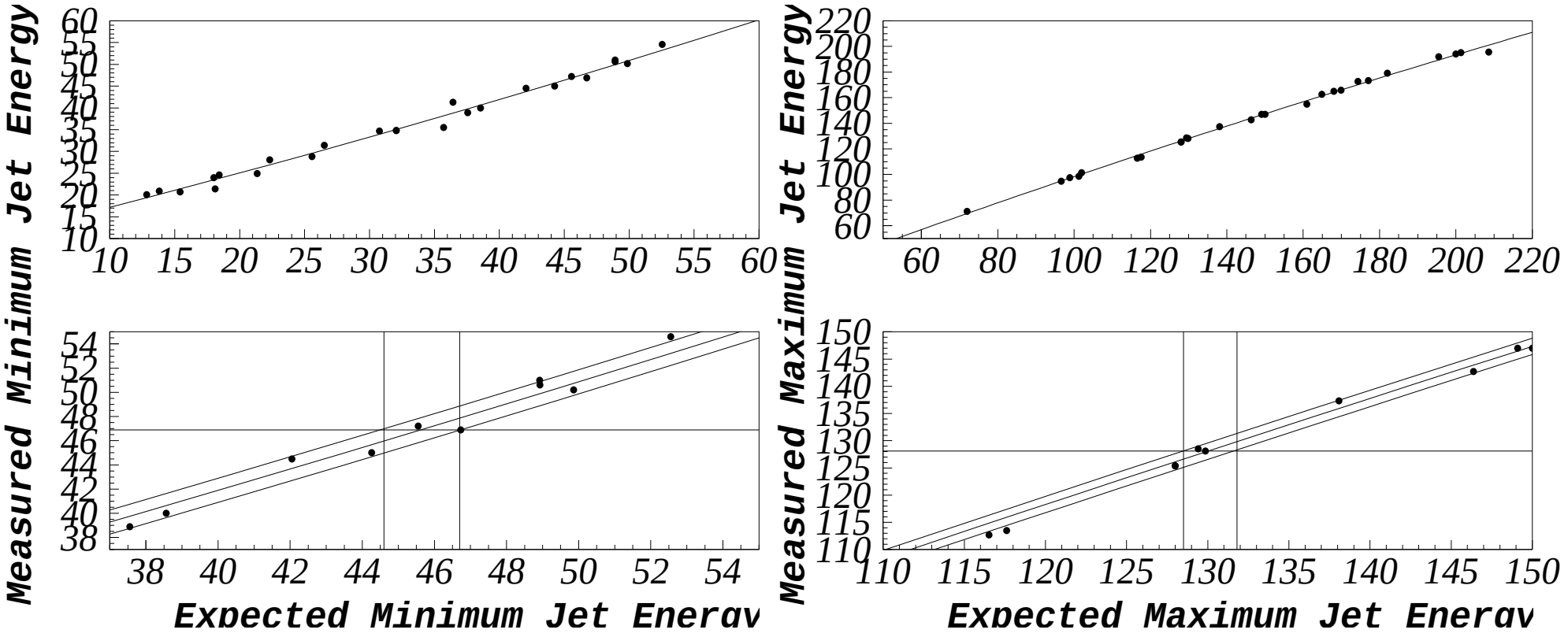




Measure Endpoints at Half Height Position (statistical uncertainty is small).

Jet Energy using Selection Cuts at SPS5

Generate several samples to obtain 'calibration curves'



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

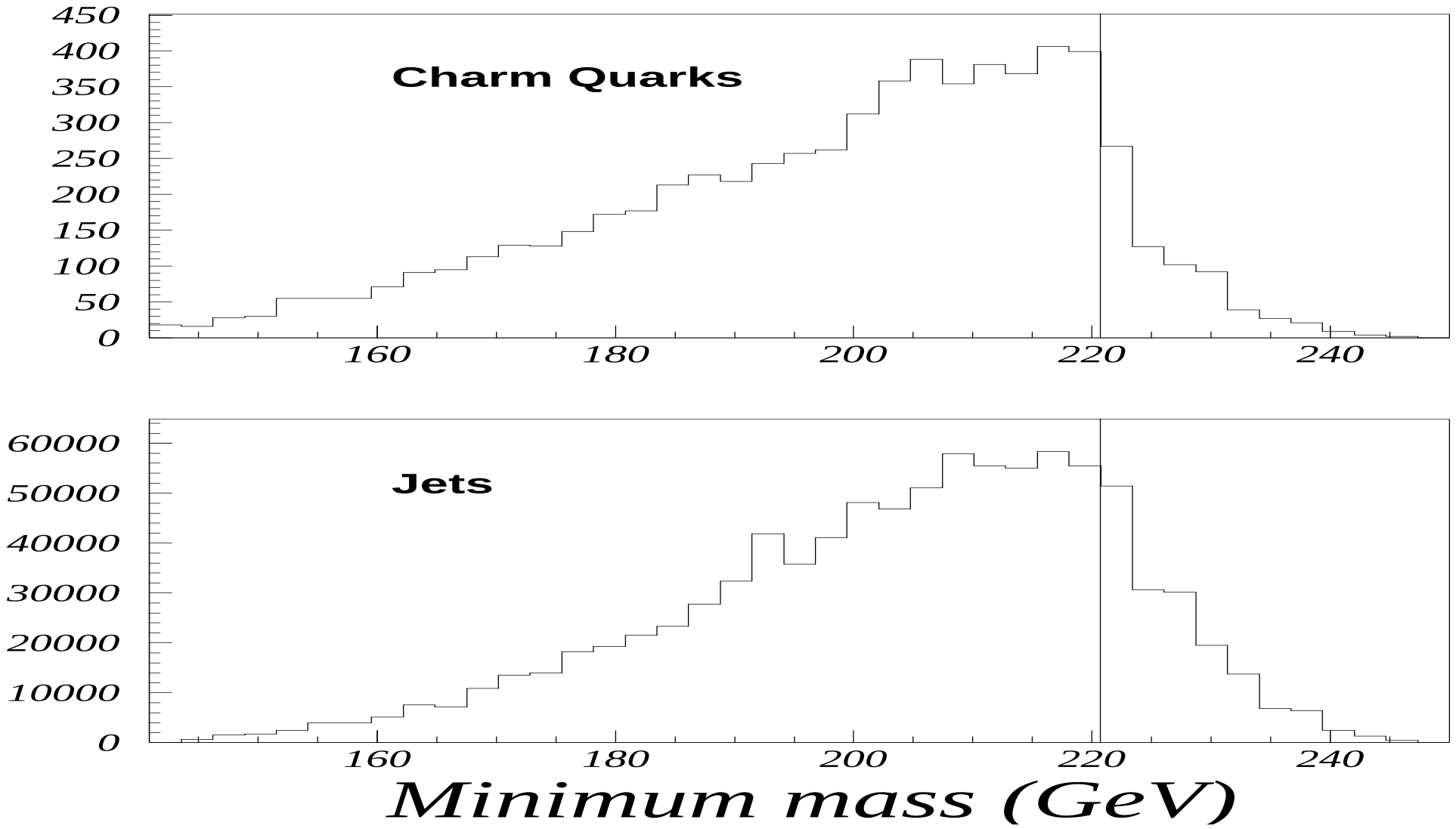
$$\text{Maximum Jet Endpoint} = 130.2 \pm 1.5 \text{ GeV}$$

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

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

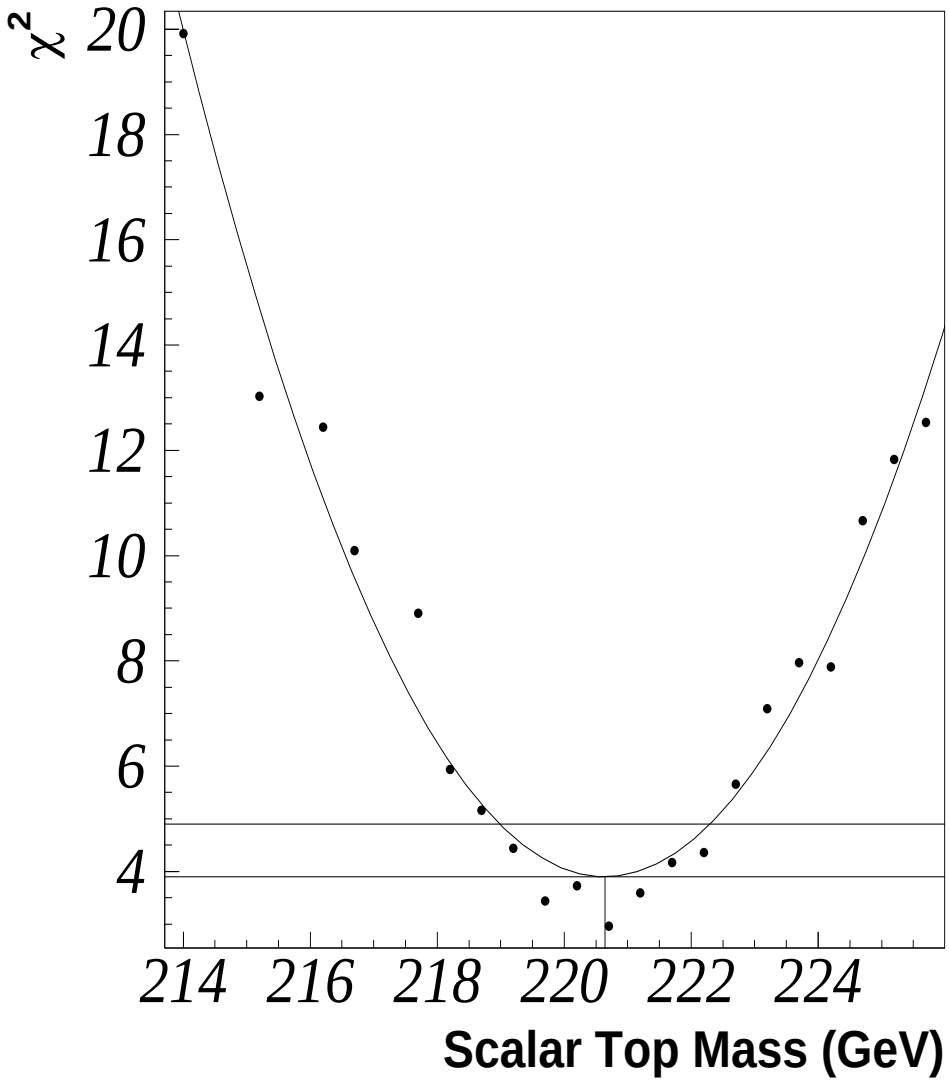
Minimum Mass Method

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 for SPS-5

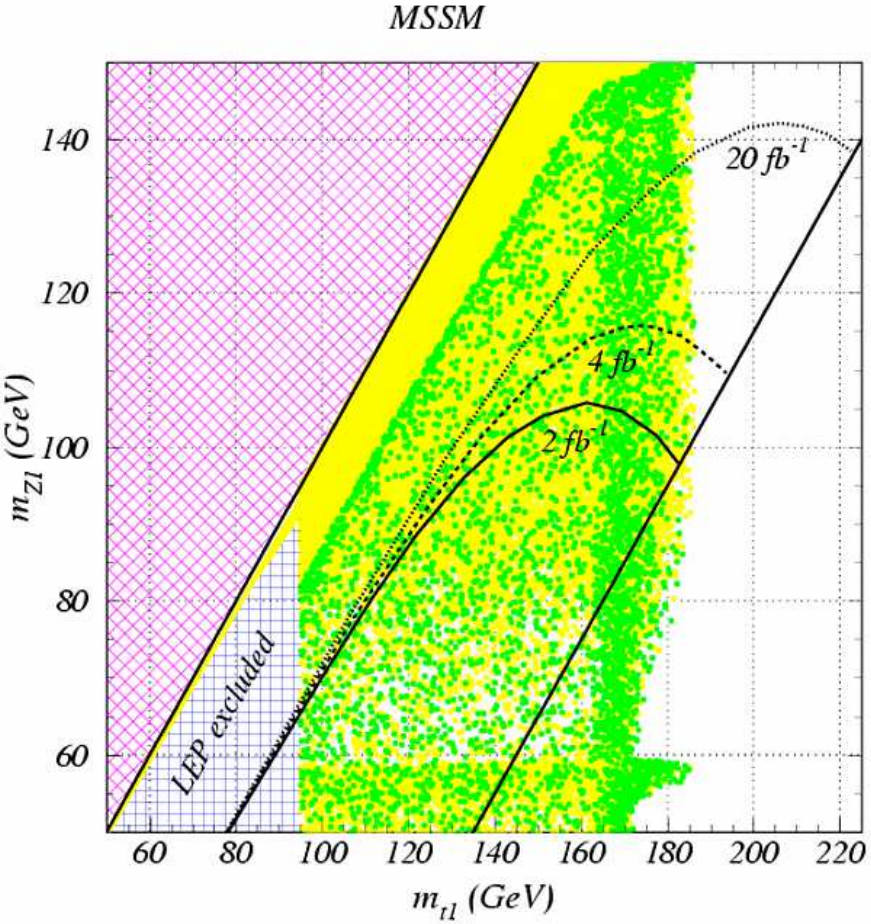
- IDA selection provides high purity and efficiency.
- Allows $m_{\tilde{t}_1}$ measurement via:
  1. Combining Different Beam Polarizations
  2. Threshold Scan
- Selection cuts reduce distortions of Jet Energy Spectrum
- Allows $m_{\tilde{t}_1}$ measurement via:
  1. End Point Method
  2. Minimum Mass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

Small Stop-Neutralino Mass Difference Studies

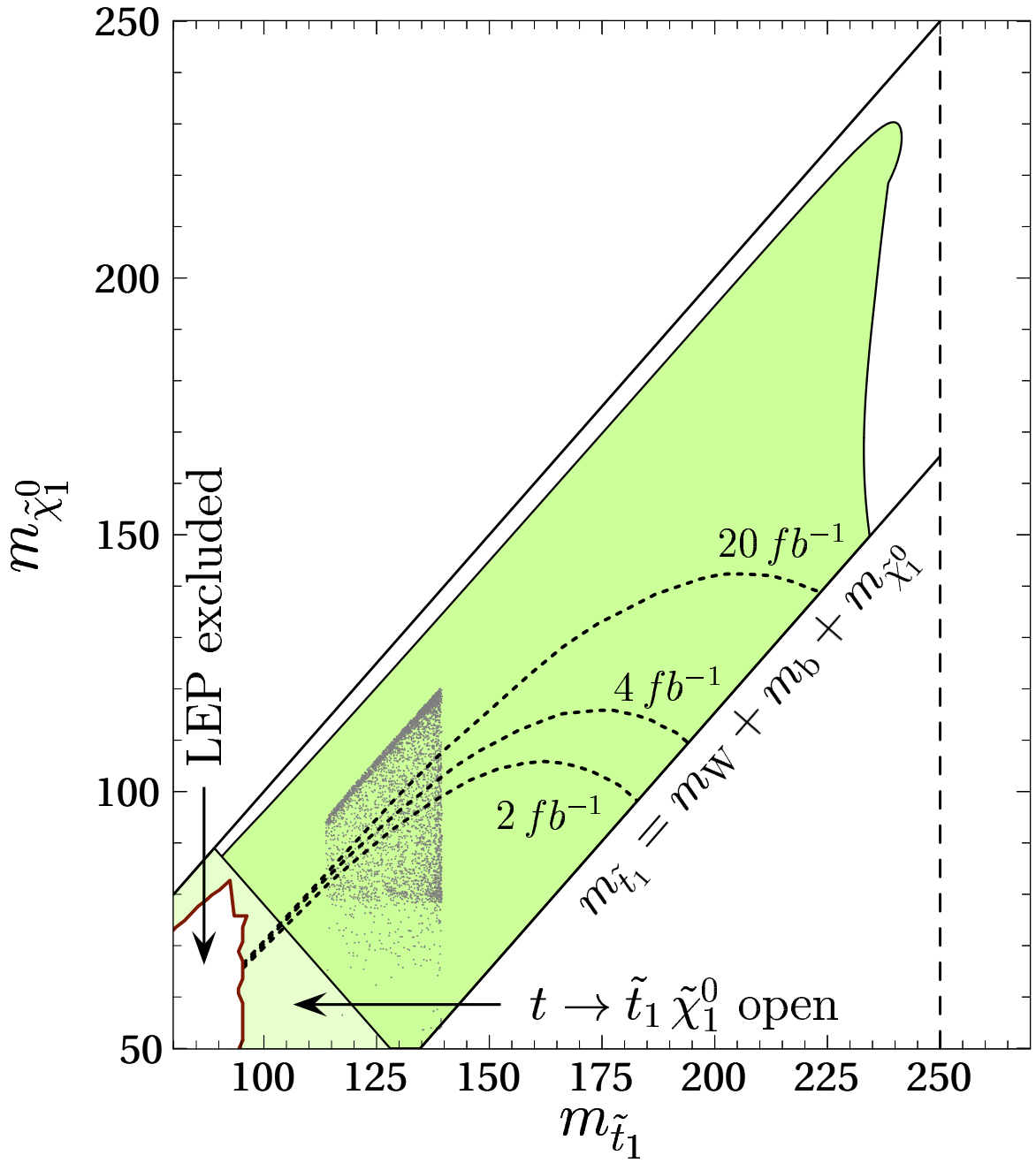
Motivations:

- Baryogenesis (Carena, Quirós, Wagner '96): $m_{\tilde{t}_1} < m_t$
- Dark Matter (Carena, Balázs, Wagner '04): $\tilde{\chi}_1^0$ is Cold Dark Matter (CDM) candidate. Correct CDM rate for small $\tilde{t}_1 - \tilde{\chi}_1^0$ mass difference (co-annihilation).
- Small and large visible energy: radius of innermost Vertex Detector layer most important, physics/0609017 (Milsténe, AS).

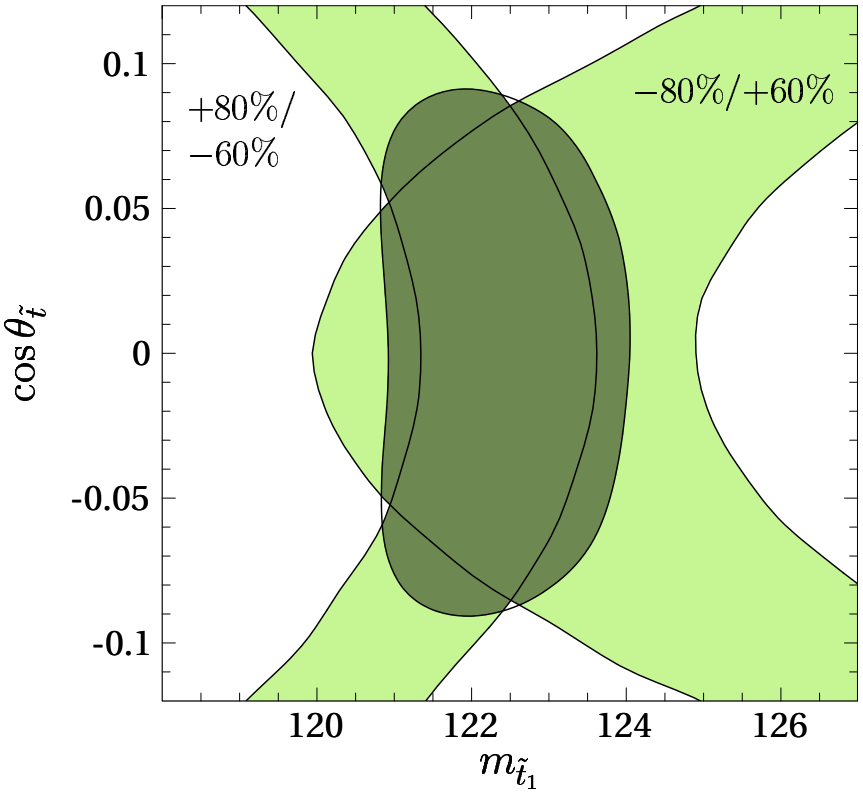


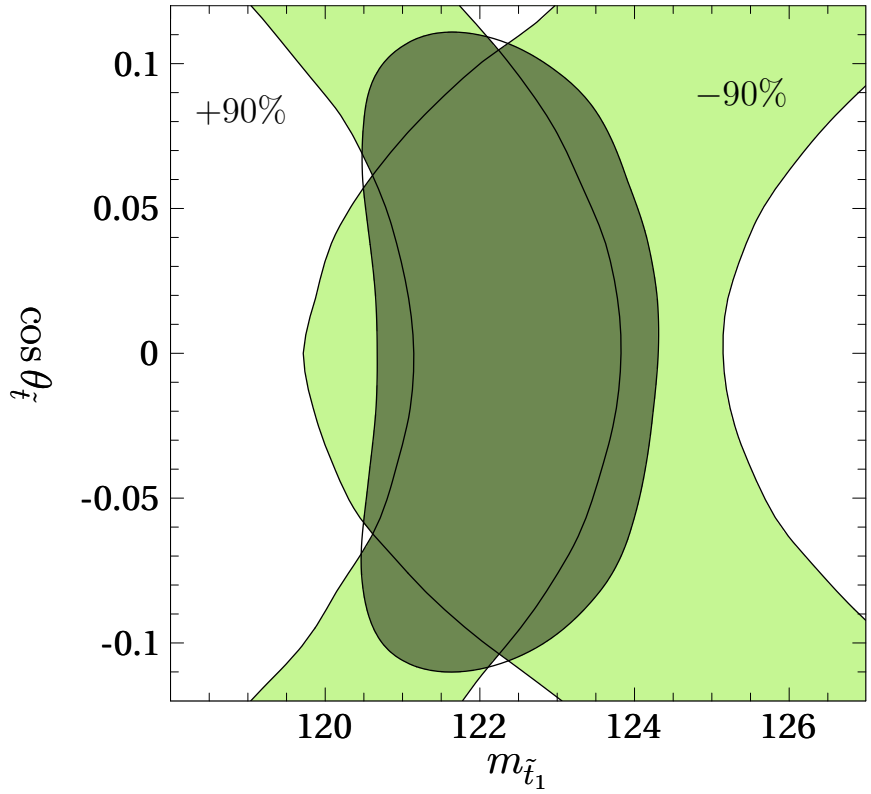
- Green: Relic density consistent with WMAP
- Co-annihilation for small $\Delta m = m_{\text{stop}} - m_{\text{neutralino}_1}$
- Difficult for searches at the Tevatron and LHC

Discovery Reach



Determination of Stop Mass and Mixing Angle





e^- and e^+ polarization: $\Delta m_{\rm stop} = 1.0$ GeV, $\|\cos\theta\| < 0.074$.

e^- polarization only: $\Delta m_{\rm stop} = 1.25$ GeV, $\|\cos\theta\| < 0.091$.

Systematic and Statistical Uncertainties

- $\delta m_{\tilde{\chi}_1^0} = 0.3$ GeV (hep-ph/0608255 Carena, Freitas)
- Polarization: $\delta P(\mathrm{e}^{\pm})/P(\mathrm{e}^{\pm}) = 0.5\%$
- Background rate $\delta B/B = 0.3\%$
- Scalar top hadronization and fragmentation: $< 1\%$
- c-quark tagging: $< 0.5\%$
- Detector calibration: $< 0.5\%$
- Beamstrahlung: $< 0.02\%$

Sum of systematic uncertainty: 1.3%(l), 1.2% (r) reduces to 0.8%.
Statistical uncertaity: 0.8%.

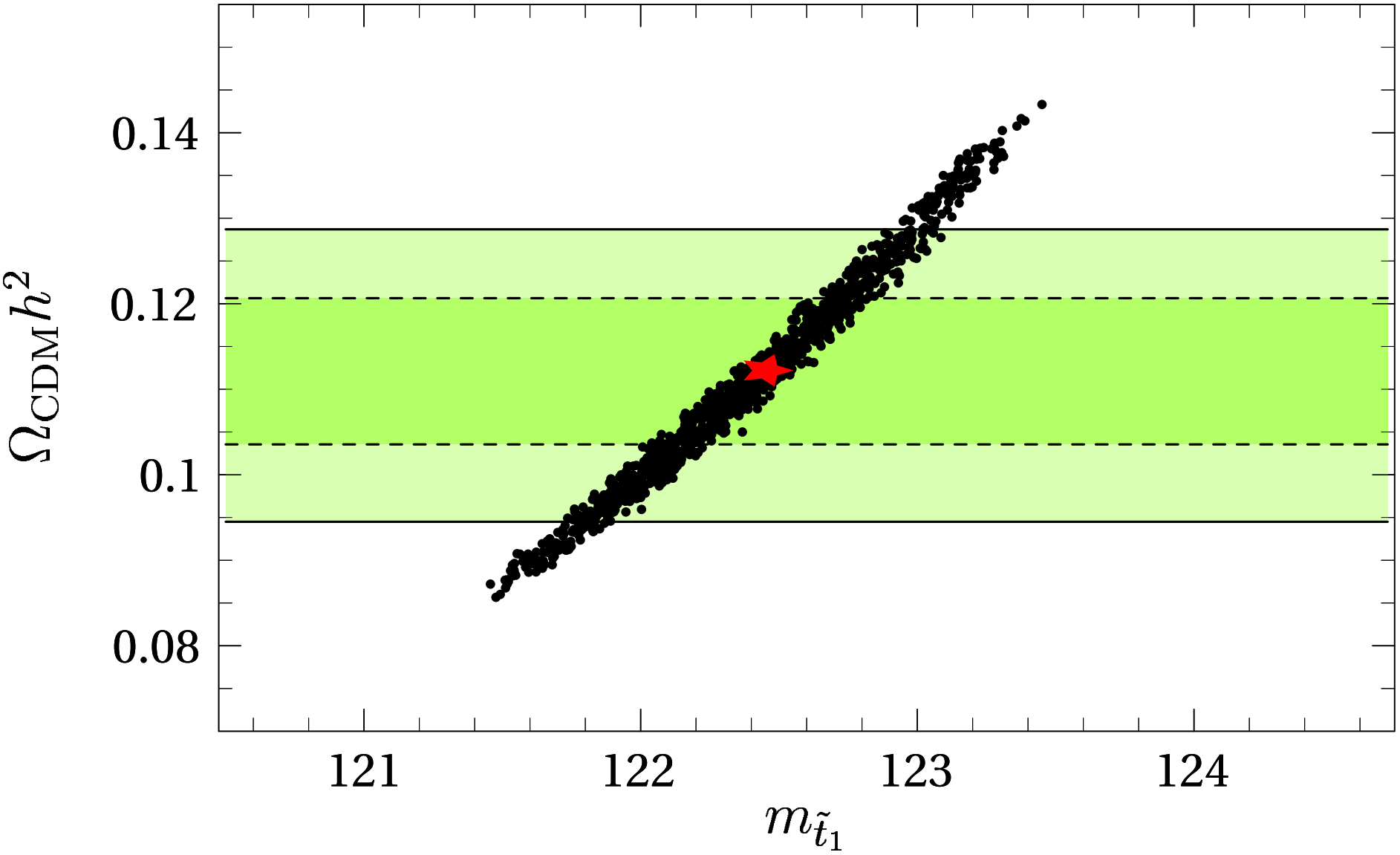
Typical small Δm (15 GeV) parameter point:
For $250\,\mathrm{fb}^{-1}$ for each polarization:

$m_{\tilde{\mathrm{t}}_1} = 122.5 \pm 1.0$ GeV $\qquad |\cos\theta_{\tilde{\mathrm{t}}}| < 0.074$

Dark Matter Prediction

Included all parameters and their errors (e.g. $\tilde{\chi}_1^0/\tilde{\chi}_1^+$ measurements).

Stop mass uncertainty is dominant for CDM co-annihilation precision.

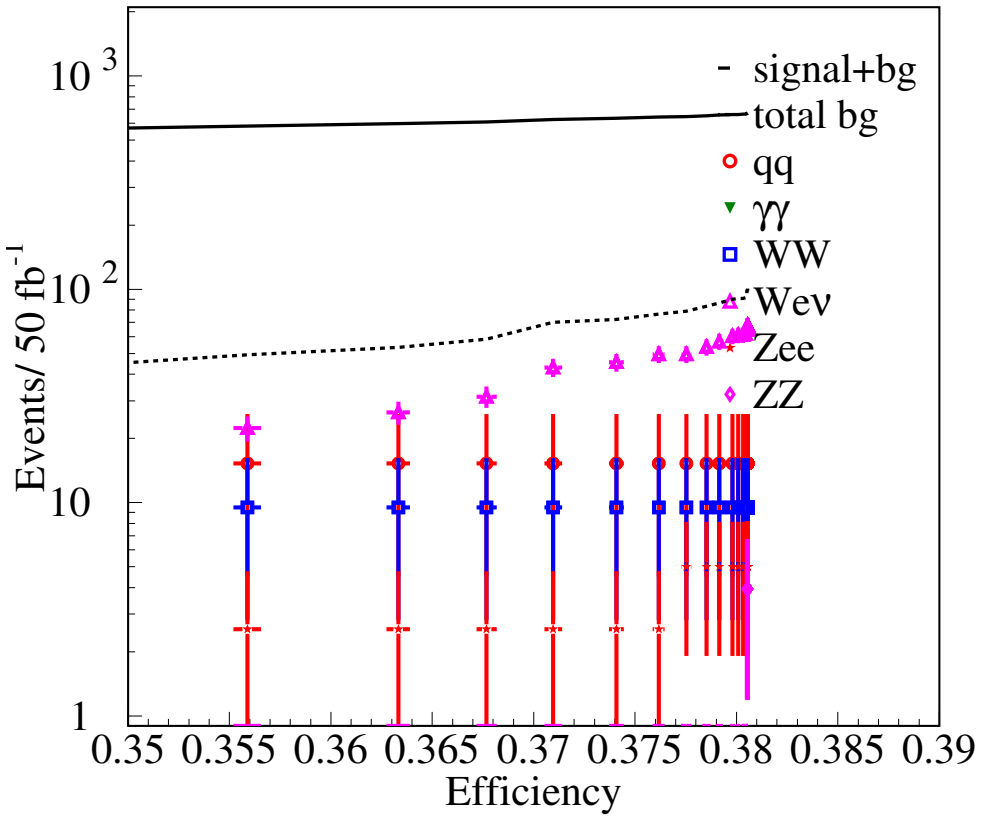


WMAP: 1, 2σ bands. LC: precision.

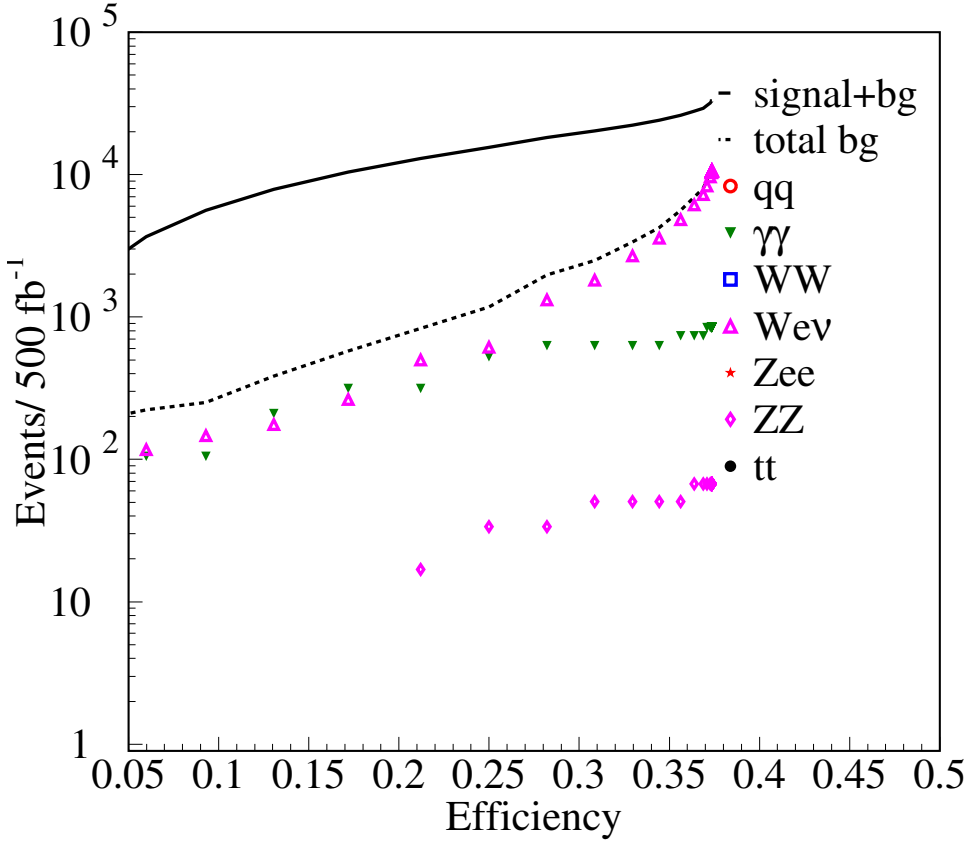
Precision Mass Determination → C. Milsténe SUSY session

Method: measure cross section at two $\sqrt{s}$, one of them near threshold to reduce systematic uncertainties. Stop hadronization effect included in new simulation.

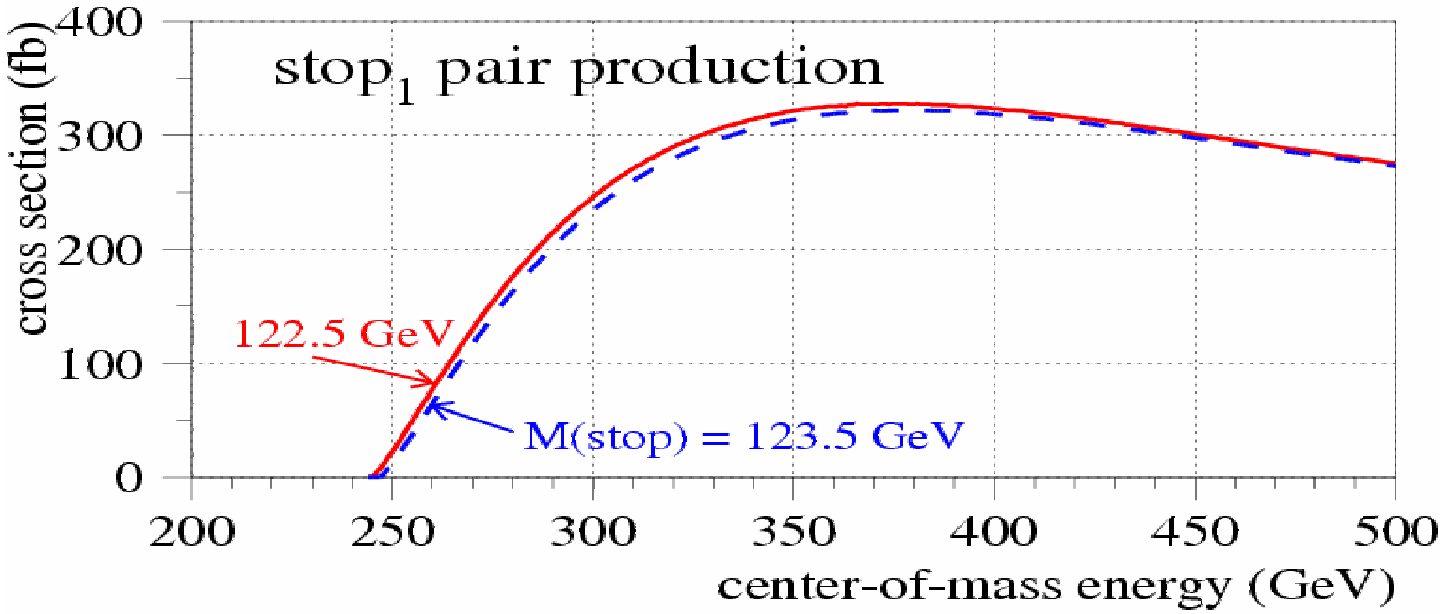
$\sqrt{s} = 260$ GeV

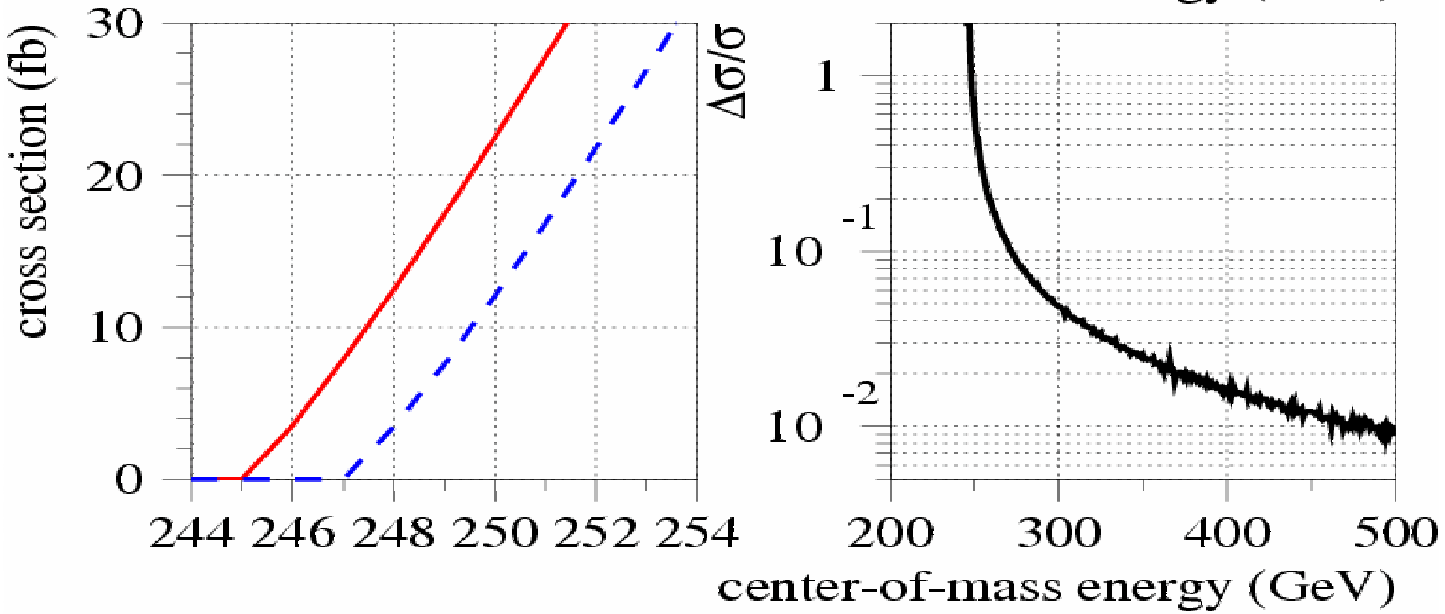


$\sqrt{s} = 500$ GeV

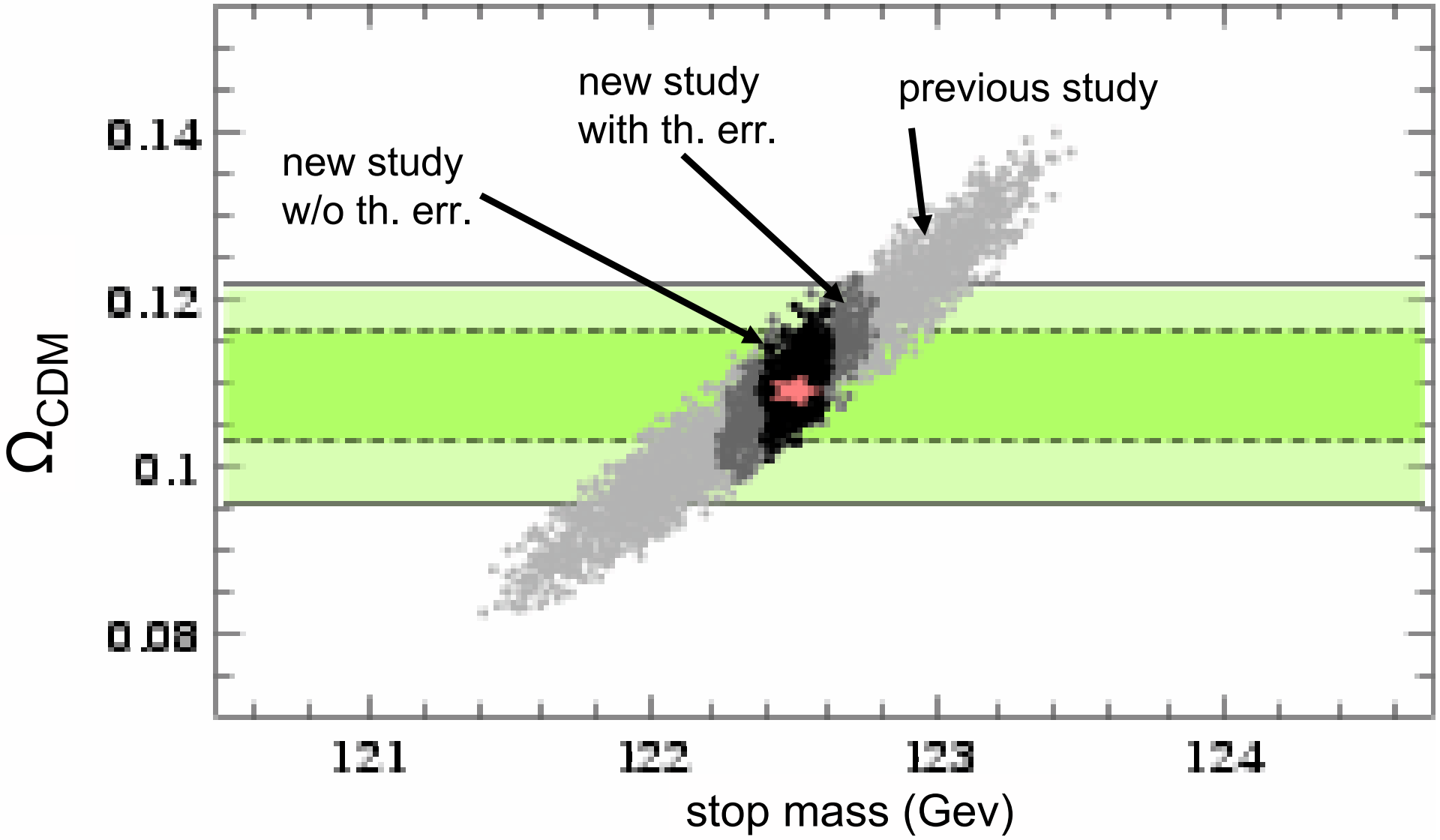


Threshold Scan Method → C. Milsténe SUSY session





Dark Matter Prediction → C. Milsténe SUSY session



Conclusions

- From expected detection sensitivity (Morioka'95) to precision mass determination and Dark Matter prediction.
- e^- beam polarization is important for mass and mixing angle determination, e^+ polarization contributes in addition.
- Detector simulations improved, c-quark tagging as a benchmark for vertex detectors, also to find c-jets in multi-jet scenarios.
- Background depends on vertex detector design.
- Different detector descriptions e.g. SIMDET and SGV agree.
- Dedicated simulation with SPS-5 parameters.
- Simulations for small stop-neutralino mass difference, cosmology.
- Precision mass determination possible with a method using two center-of-mass energies, e.g. $\sqrt{s} = 260$ and 500 GeV.
- Expected LC precision on $\Omega_{\rm CDM}$ comparable to cosmological (WMAP) measurements.