Scalar top signal: efficiency versus purity
as a vehicle for detector optimization

A. Finch, A. Sopczak (Lancaster University)

M. Carena, A. Freitas, C. Milsténe (Fermilab)

H. Nowak (DESY Zeuthen)

Outline

- Introduction
- Vertex Detector c-Tagging
- Small Stop-Neutralino Mass Differences (Dark Matter Interpretations)
- Variation of Vertex Detector Design
- Conclusions

Introduction

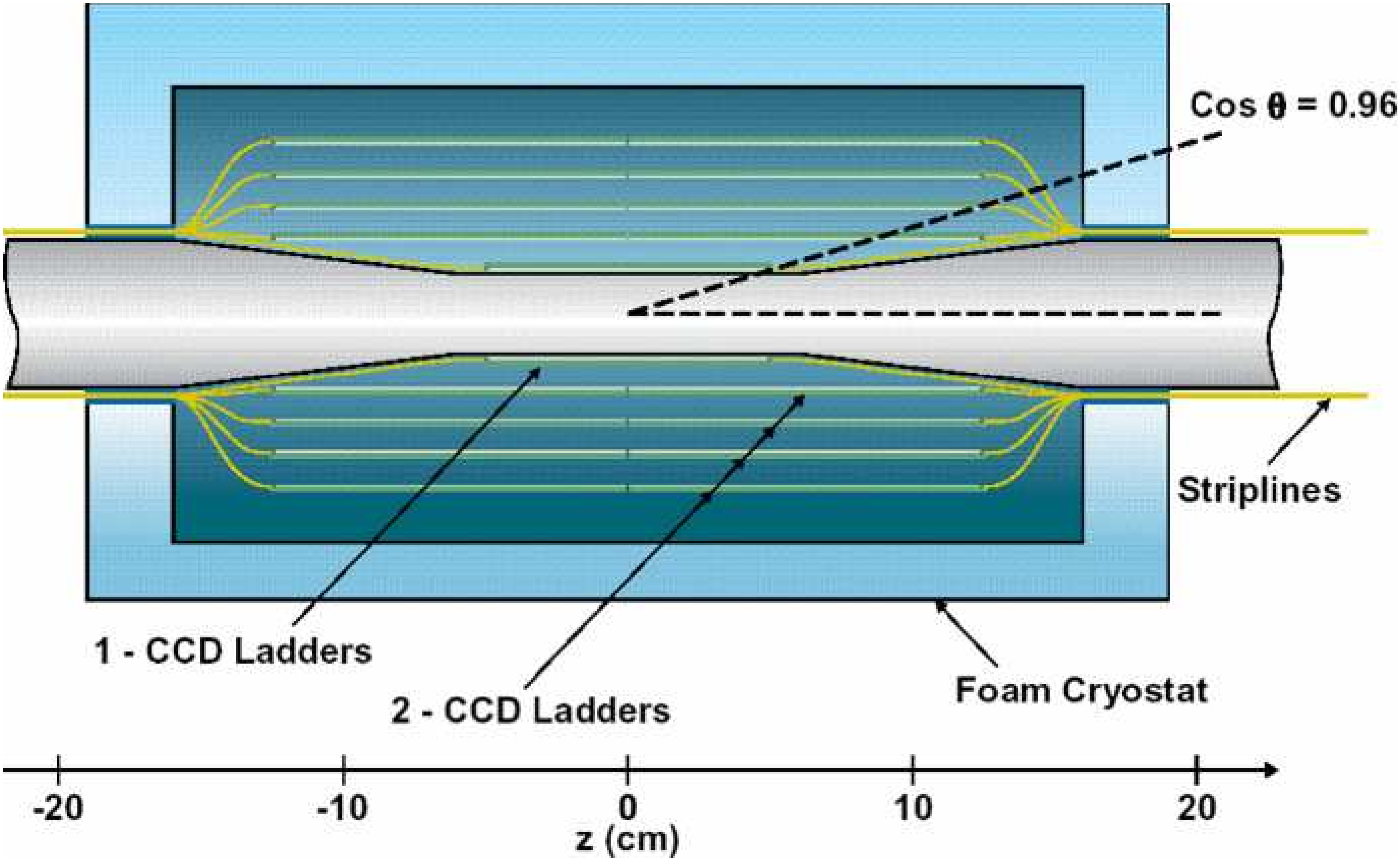
Large challenge to develop a vertex detector for a future LC.

Key aspects:

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

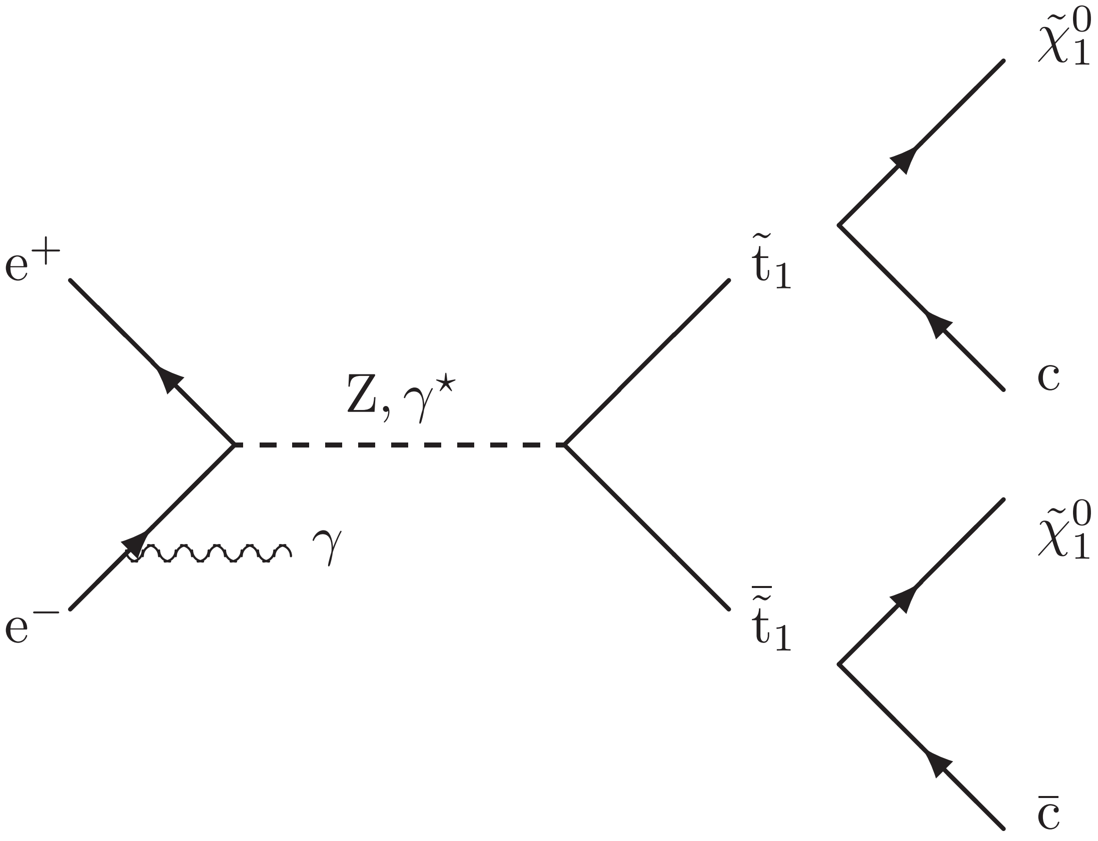
CCD Vertex Detector

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 $< 0.1\%\ X_0$.

c-Quark Tagging: a Benchmark Reaction



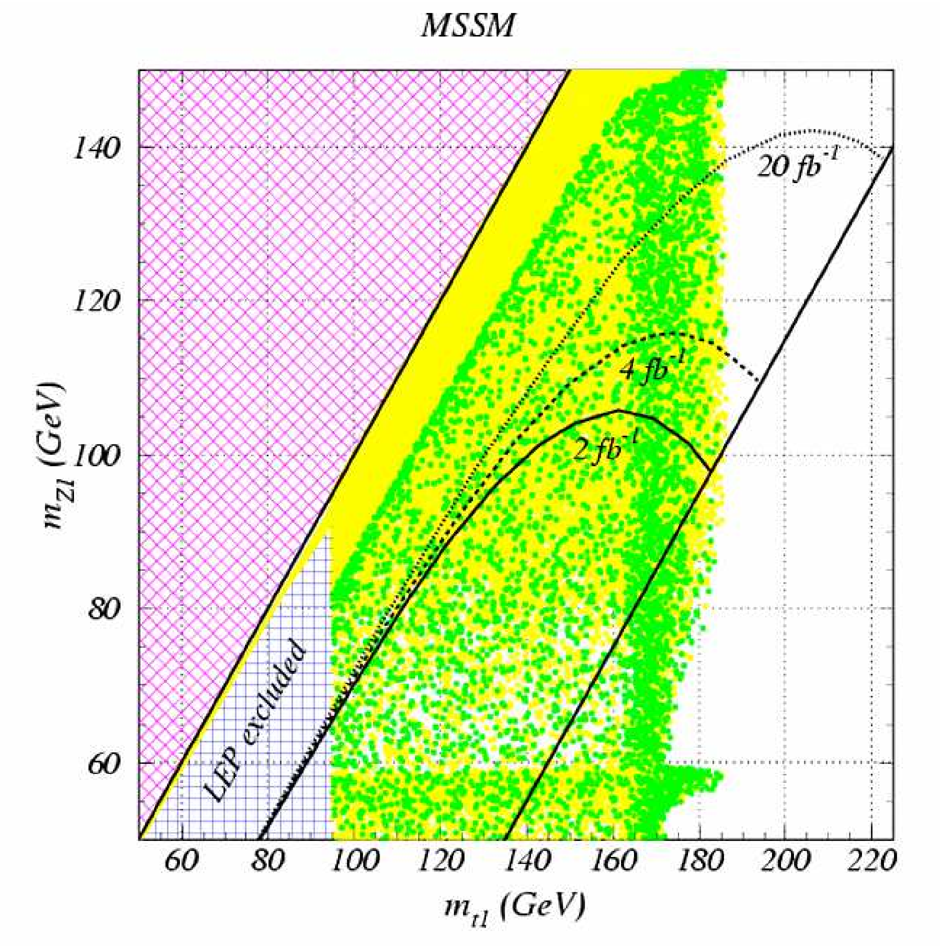
Signal: Two charm jets and missing energy.

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

Small Stop-Neutralino Mass Difference Studies

Motivations:

- Challenge for Vertex Detector
- 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).



- Green: Relic density consistent with WMAP
- Co-annihilation for small $\Delta m = m_{\rm stop} - m_{\rm neutralino_1}$
- Difficult for searches at the Tevatron and LHC

Signal(c=0.5) 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	0.115	0.153	0.187
$m_{\tilde{t}_1} = 140$ GeV	0.093	0.124	0.151
$m_{\tilde{t}_1} = 180$ GeV	0.049	0.065	0.079
$m_{\tilde{t}_1} = 220$ GeV	0.015	0.021	0.026
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
2-photon, $p_t > 5$ GeV	936		

Reduction of Background

1. Exactly 2 jets. Durham algorithm with jet resolution parameter $y_{\mathrm{cut}} = 0.003 \times \sqrt{s}/E_{\mathrm{vis}}$, tuned to most effectively reject four-jet $\mathrm{W^+W^-}$.
2. $E_{\mathrm{vis}} < 0.4\sqrt{s}$ to reduce $\mathrm{W^+W^-}$, ZZ and di-quark events. In addition, $70\ \mathrm{GeV} < m_{\mathrm{jet,inv}} < 90\ \mathrm{GeV}$ reduces large $\mathrm{We}\nu$ background.
3. $\cos\phi_{\mathrm{acol}} > -0.9$ reduces $\mathrm{e^+e^-} \rightarrow \mathrm{q\bar{q}}$ and $\gamma\gamma \rightarrow \mathrm{q\bar{q}}$ processes with back-to-back topology.
4. $|\cos\theta_{\mathrm{thrust}}| < 0.7$ reduces events with W bosons further.
5. Remaining two-photon background is almost completely removed by $p_{\mathrm{t}} > 12$ GeV.
6. c-quark tagging improves the signal-to-background ratio further. Neural network optimized for small Δm. And, excluded invariant jet mass window increased to $60\ \mathrm{GeV} < m_{\mathrm{jet,inv}} < 90\ \mathrm{GeV}$.

Remaining Background Events

Process	Total	After presel.	cut 1	cut 2	cut 3	cut 4	cut 5	cut 6	Scaled to 500 fb^{-1}
W^+W^-	210,000	2814	827	28	25	14	14	8	145
ZZ	30,000	2681	1987	170	154	108	108	35	257
$We\nu$	210,000	53314	38616	4548	3787	1763	1743	345	5044
eeZ	210,000	51	24	20	11	6	3	2	36
$q\bar{q},\ q \neq t$	350,000	341	51	32	19	13	10	8	160
$t\bar{t}$	180,000	2163	72	40	32	26	26	25	38
2-photon	8×10^6	4061	3125	3096	533	402	0	0	<164

Signal Efficiency(%) and Events

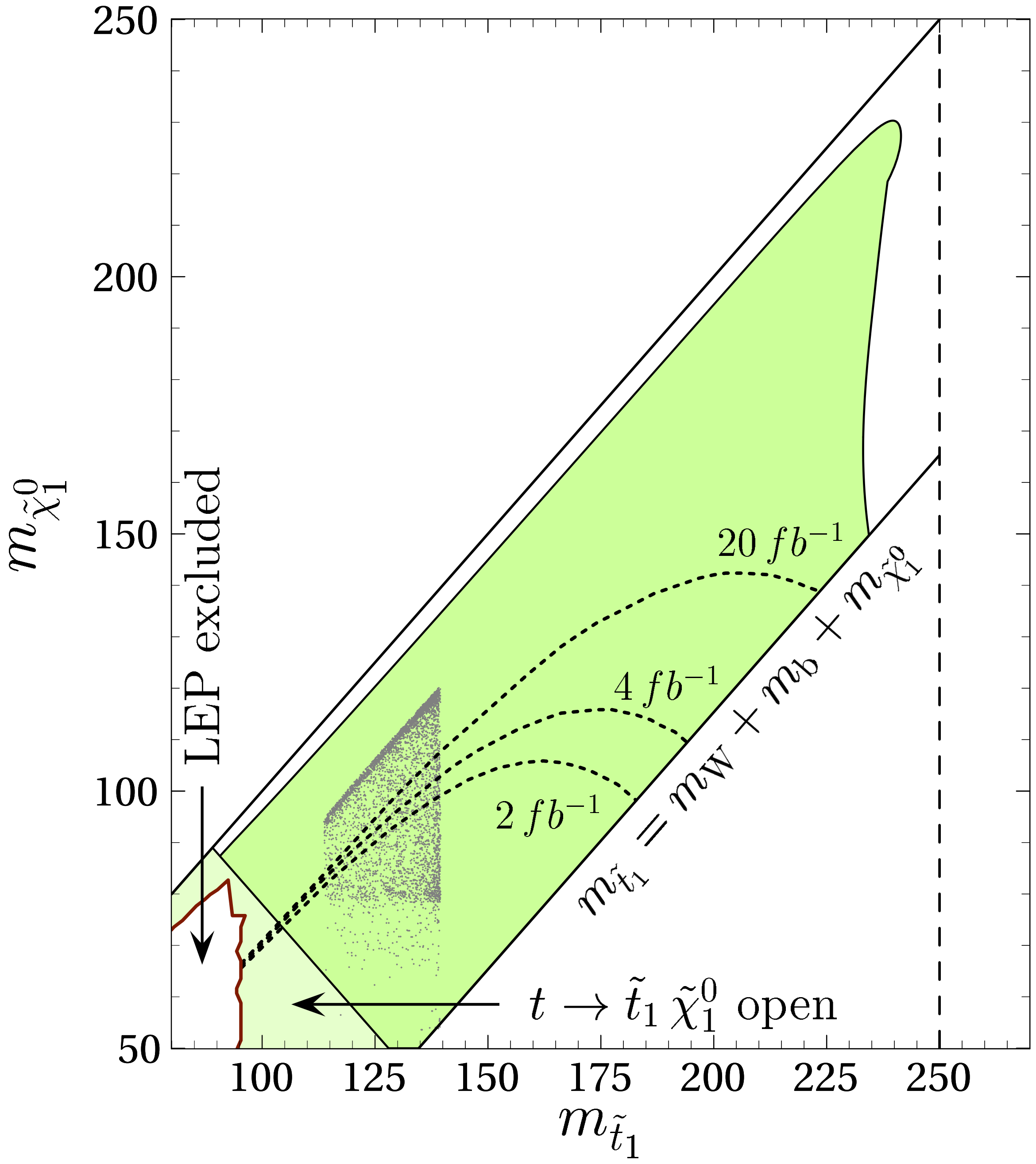
(GeV)	Total	After presel.	cut 1	cut 2	cut 3	cut 4	cut 5	cut 6	Scaled to 500 fb^{-1}
$m_{\tilde{t}_1} = 140$									
$\Delta m = 20$	50,000	68.5	48.8	42.1	33.4	27.9	27.3	20.9	9720
$\Delta m = 40$	50,000	71.8	47.0	40.2	30.3	24.5	24.4	10.1	4700
$\Delta m = 80$	50,000	51.8	34.0	23.6	20.1	16.4	16.4	10.4	4840
$m_{\tilde{t}_1} = 180$									
$\Delta m = 20$	25,000	68.0	51.4	49.4	42.4	36.5	34.9	28.4	6960
$\Delta m = 40$	25,000	72.7	50.7	42.4	35.5	28.5	28.4	20.1	4925
$\Delta m = 80$	25,000	63.3	43.0	33.4	29.6	23.9	23.9	15.0	3675
$m_{\tilde{t}_1} = 220$									
$\Delta m = 20$	10,000	66.2	53.5	53.5	48.5	42.8	39.9	34.6	2600
$\Delta m = 40$	10,000	72.5	55.3	47.0	42.9	34.3	34.2	24.2	1815
$\Delta m = 80$	10,000	73.1	51.6	42.7	37.9	30.3	30.3	18.8	1410

Signal Efficiency (in %)

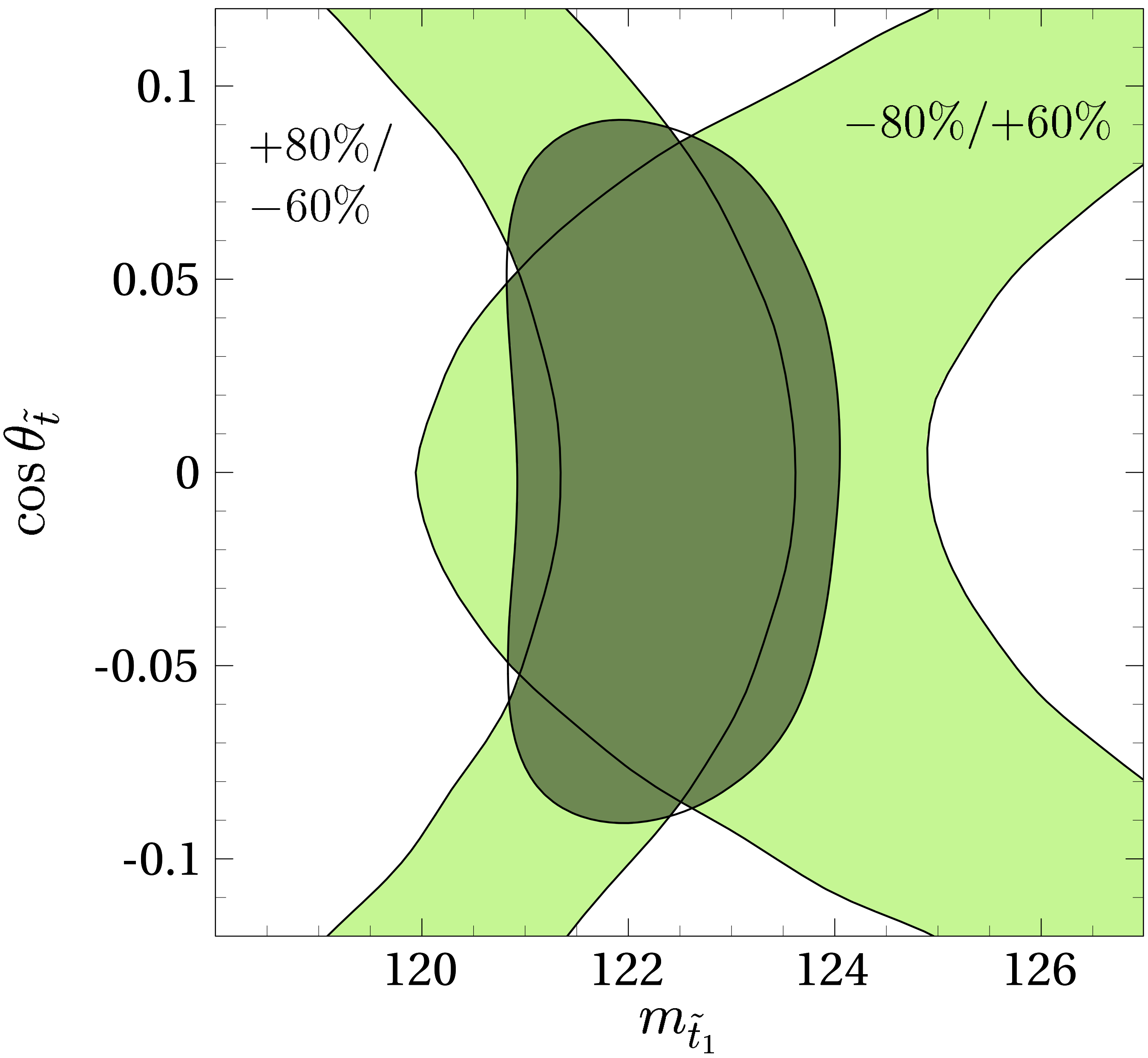
Δm	$m_{\tilde{t}_1} = 120$ GeV	140 GeV	180 GeV	220 GeV
80 GeV		10	15	19
40 GeV		10	20	24
20 GeV	17	21	28	35
10 GeV	19	20	19	35
5 GeV	2.5	1.1	0.3	0.1

For $\Delta m < 10$ GeV reduced efficiency due to $p_{\mathrm{t}} > 12$ GeV requirement.

Discovery Reach



Determination of Stop Mass and Mixing Angle



Systematic and Statistical Uncertainties

- $\delta m_{\tilde{\chi}^0_1} = 0.1$ GeV
- 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: $< 0.02\%$

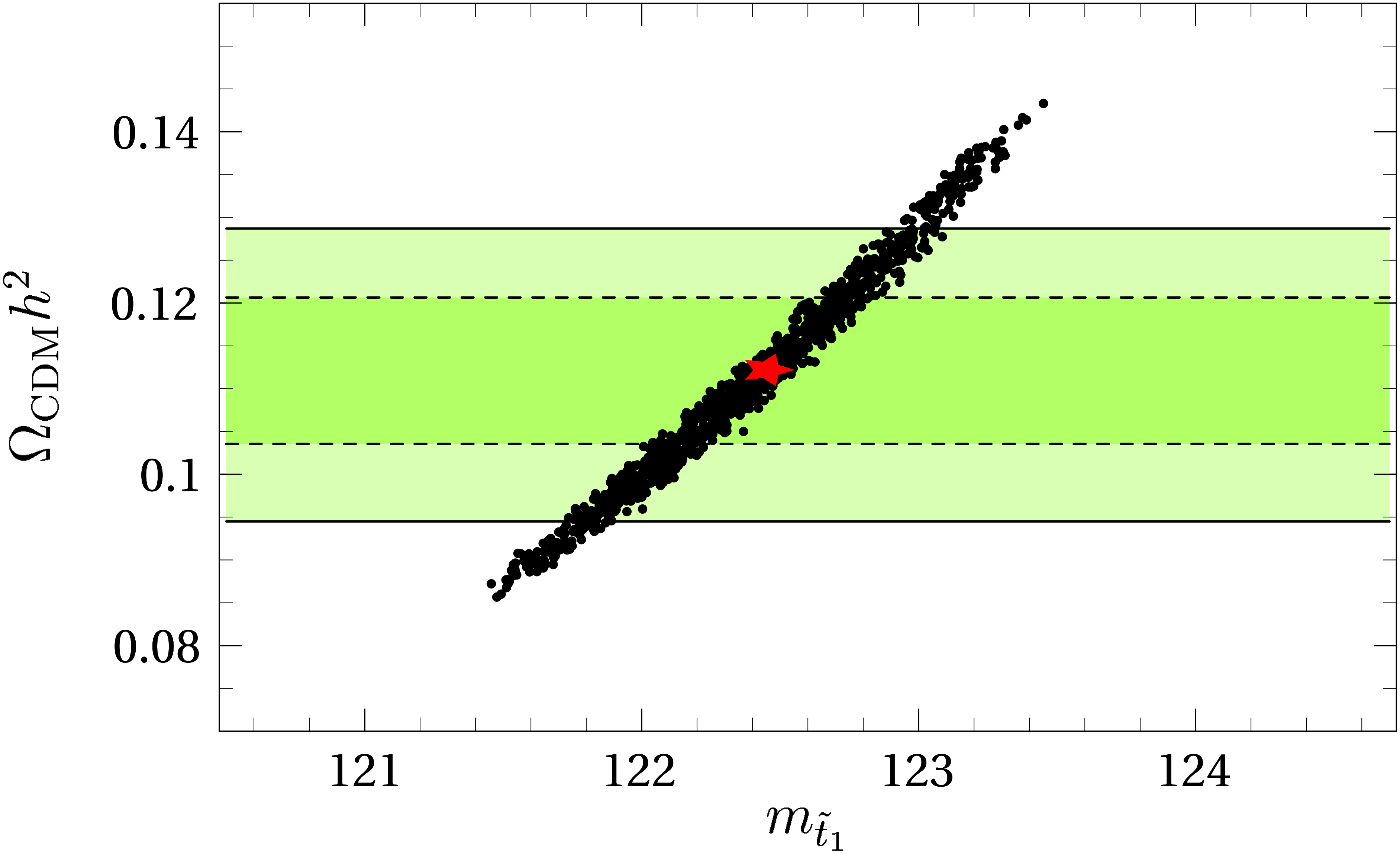
Sum of systematic uncertainty: 1.3%(l), 1.2% (r) reduces to 0.8%.
Statistical uncertaity: 0.8%.

Typical small Δm (15 GeV) parameter point:
Result for 250 fb^{-1} for each polarization:
$\Delta m_{\tilde{\mathrm{t}}_1} = 122.5 \pm 1.0$ GeV $|\cos\theta_{\tilde{\mathrm{t}}}| < 0.074$

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.

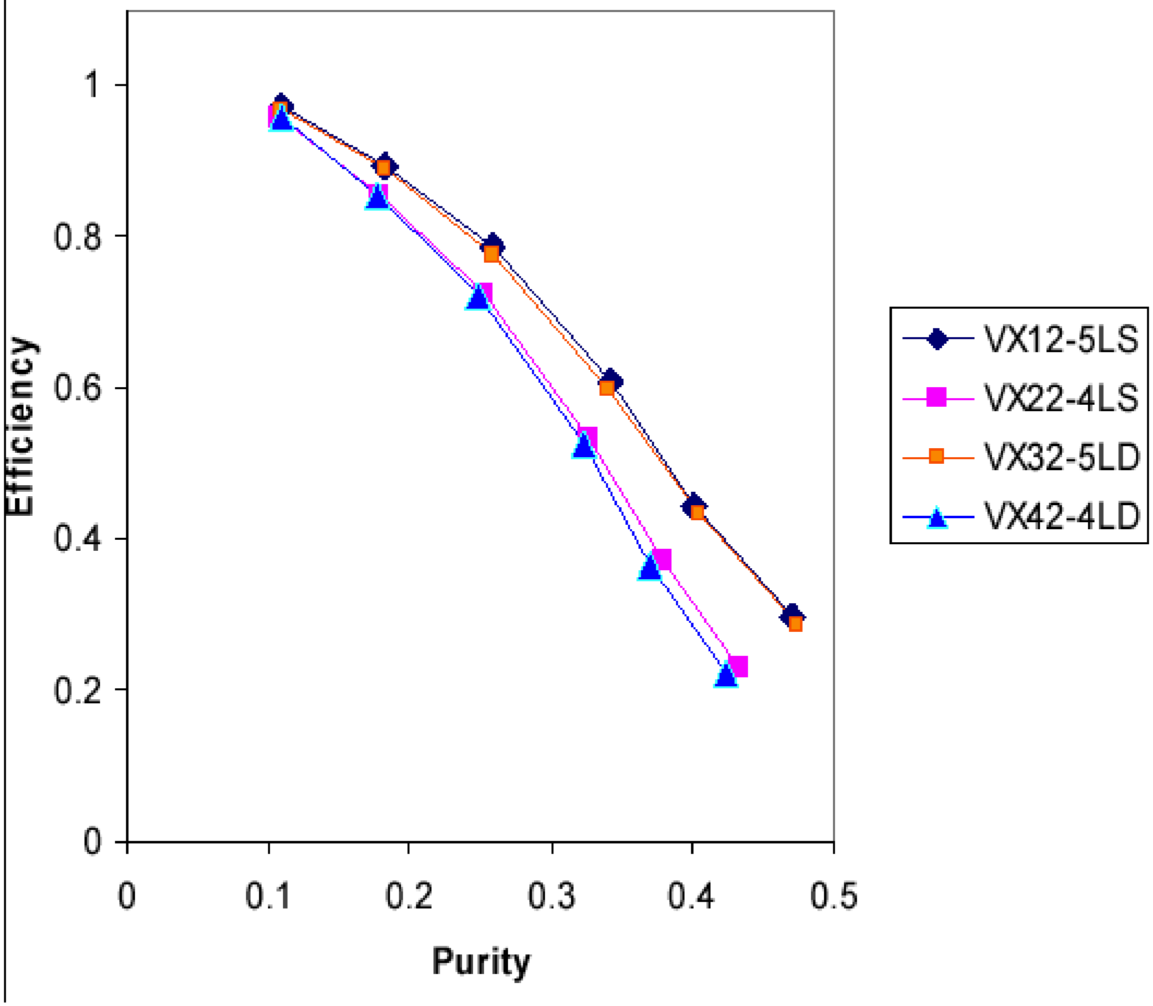
Varying Vertex Detector Design

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)



Recall: SPS-5 Varying Vertex Detector Design

Same result observed! 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

- Larger sensitivity on CCD design variations expected for reactions with smaller visible energy, e.g. small stop-neutralino mass difference!

Conclusions

- c-quark tagging as a benchmark for vertex detectors.
  In Supersymmetry: Scalar top quarks.
- SIMDET detector simulation: LCFI vertex detector.
- c-tagging reduces background by about a factor 2 to 3 for $\tilde{\chi}_1^0 c \tilde{\chi}_1^0 \bar{c}$.
- Simulations for small stop-neutralino mass difference, motivated by vertex detector studies and cosmology.
- Background depends on vertex detector design.
- Vertex detector design variation: large effect on radius of inner most layer.
- Plan: Small Δm analysis refinements, further variations of detector design.