The stop co-annihilation region at the ILC

A. Freitas
Fermilab

in collboration with
C. Milstène, M. Carena
Fermilab

A. Finch, A. Sopczak
Lancaster

H. Nowak
DESY

1. Introduction
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3. Parameter determination
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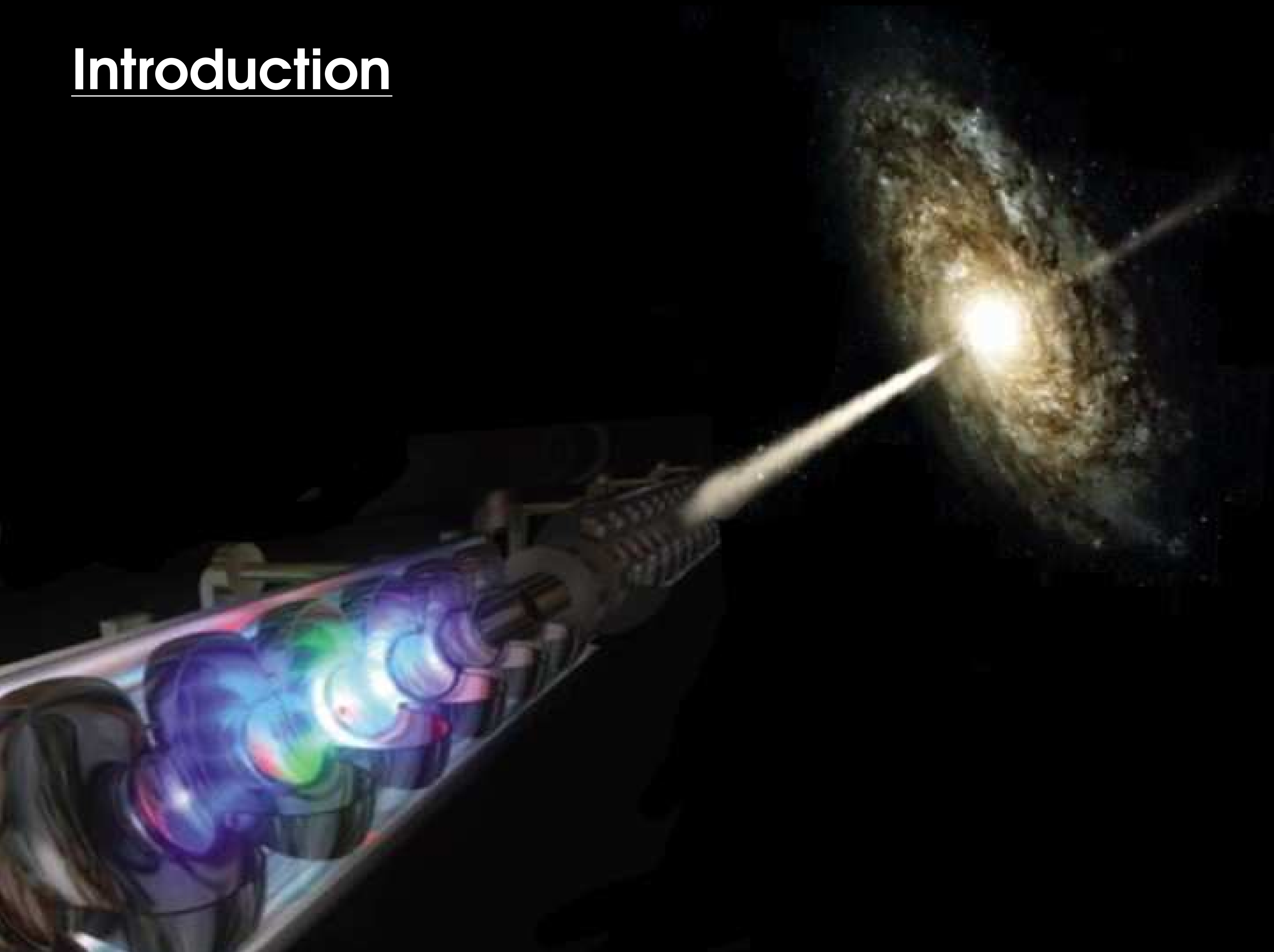
Introduction



Electroweak Baryogenesis

Sakharov conditions:

- Baryon number violation

  In Standard Model and extensions through non-perturbative sphaleron processes

- C and CP violation

  CP violation in Standard Model through CKM phase
  not sufficient to explain baryon asymmetry $\eta_{\mathrm{BBN}} \sim 6 \times 10^{-10}$

- Non-equilibrium

  Strongly first order electroweak phase transition necessary

$$\frac{v(T_{\mathrm{C}})}{T_{\mathrm{C}}} > 1$$

In Standard Model: $\frac{v(T_{\mathrm{C}})}{T_{\mathrm{C}}} \approx \frac{g^2}{4\pi\lambda}$ with $\lambda \propto \frac{M_{\mathrm{H}}^2}{v^2}$

→ not fulfilled for $M_{\mathrm{H}} \gtrsim 40$ GeV

Electroweak Baryogenesis and Supersymmetry

EW baryogenesis:

- new boson degrees of freedom with strong Higgs coupling
- new sources for CP violation

Supersymmetry provides natural framework for EW baryogenesis

Carena, Quirós, Wagner '96

Higgs potential modified by scalar top (stop) $\tilde{t}_1$:

Each stop has six degrees of freedom (3 color, 2 charge), coupling $\mathcal{O}(1)$ to Higgs

$$\frac{v(T_\mathrm{C})}{T_\mathrm{C}} \approx \frac{g^2 + 2y_\mathrm{t}^2}{4\pi\lambda}$$

- Higgs masses up to 120 GeV
- Lightest stop must have mass below top quark

Electroweak Baryogenesis and CP violation

CP violating source needed to generate chiral charge asymmetry

$\rightarrow$ particle currents coupling to the Higgs background

In Standard Model:
CP-violating CKM processes suppressed by Yukawa couplings $m_\mathrm{q}^2/M_\mathrm{W}^2$

Supersymmetry: Carena, Quirós, Riotto, Vilja, Wagner '97
Additional contribution from stop and chargino currents

$\uparrow$ $\uparrow$

$\propto \mathrm{Im}(A_\mathrm{t}\mu)$ $\propto \mathrm{Im}(M_2\mu)$

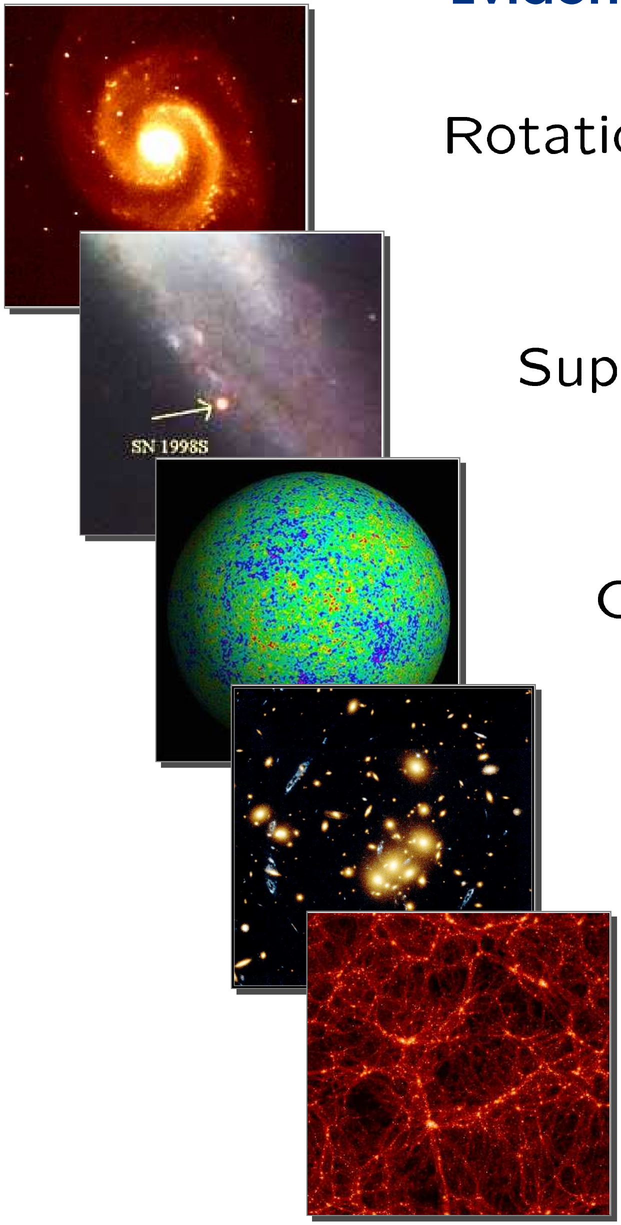
Higgs bound $M_{h^0} \gtrsim 114$ GeV: one stop eigen-state heavy

$\Rightarrow$ Charginos are dominant source if they are light

Phase can be rotated into μ parameter only

Dark matter

Evidence for dark matter from many sources:



Rotation curves of galaxies

Supernovae Ia redshift

CMB

Gravitational lensing

Large scale structure

$\sim$85% of matter
in universe is
dark

Dark matter and Supersymmetry

Dark matter has to be stable and weakly interacting

Supersymmetry has natural **dark matter** candidate:

lightest neutralino $\tilde{\chi}_1^0$ stable for R-parity conservation

- Dark matter particles freeze out when expanding universe cools
- After freeze-out dark matter particles annihilate
- Annihilation cross-section

$$\tilde{\chi}_1^0 \tilde{\chi}_1^0 \to X$$

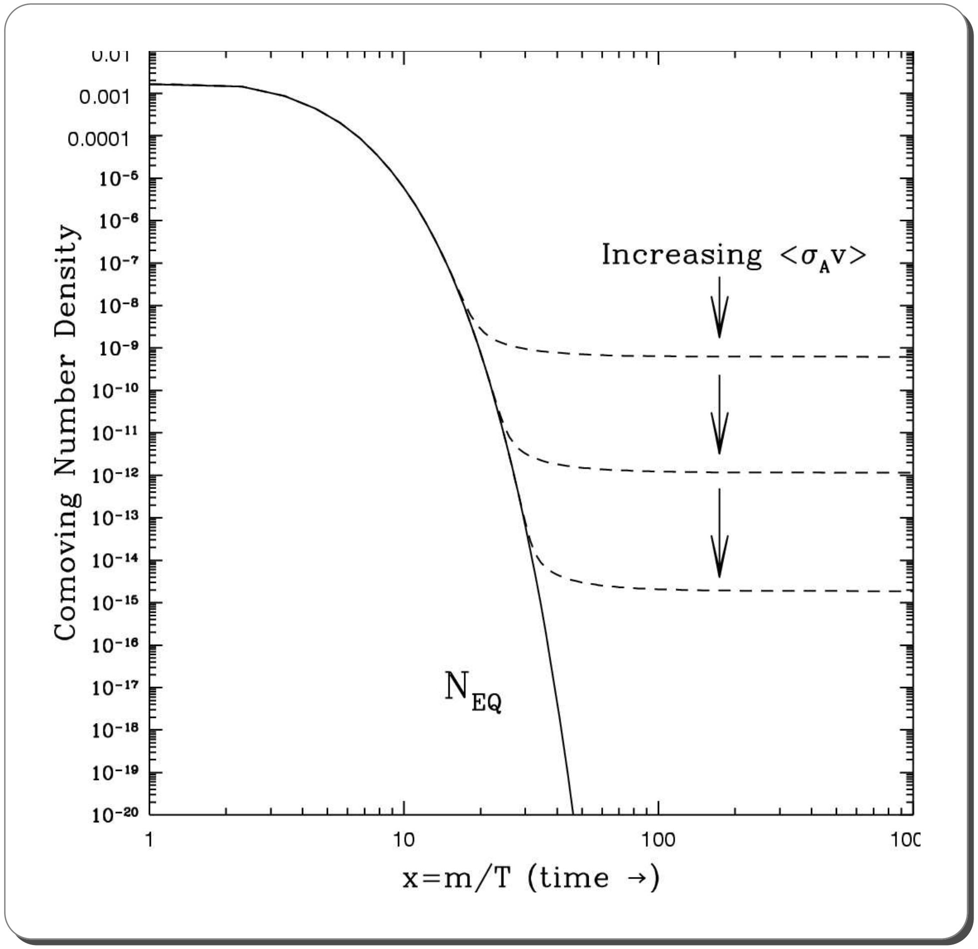
suppressed due to chirality conversation

→ Too large relic density in many SUSY scenarios

Co-annihilation

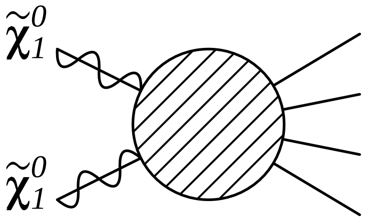
Mass of SUSY particle $\widetilde{X}$ close to lightest neutralino $\tilde{\chi}_1^0$

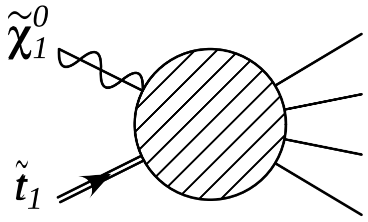
- Freeze-out of $\widetilde{X}$ and $\tilde{\chi}_1^0$ at roughly same temperature
- Annihilation in parallel (co-annihilation)
- Reduction of total dark matter density

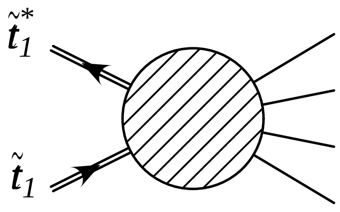


In framework of EW baryogenesis:

Co-annihilation with scalar top

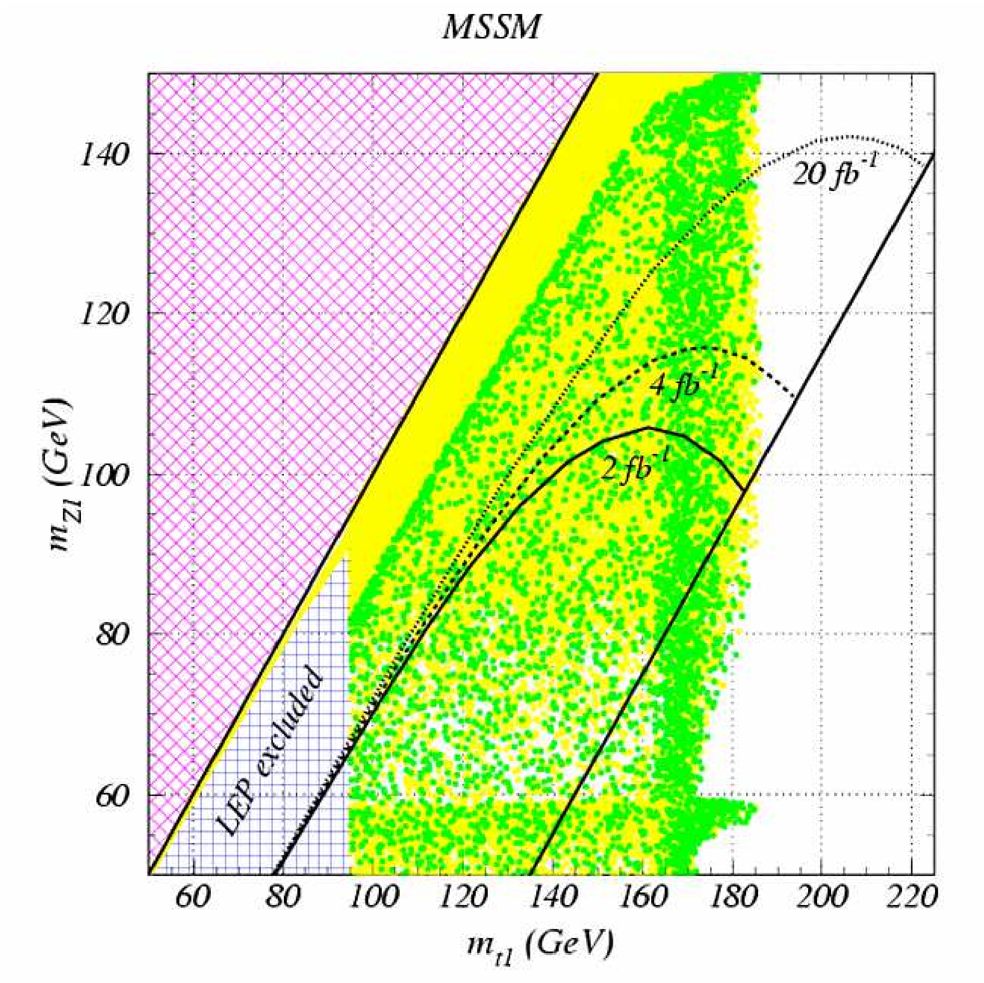






Typical parameter regions

Carena, Balázs, Wagner ’04



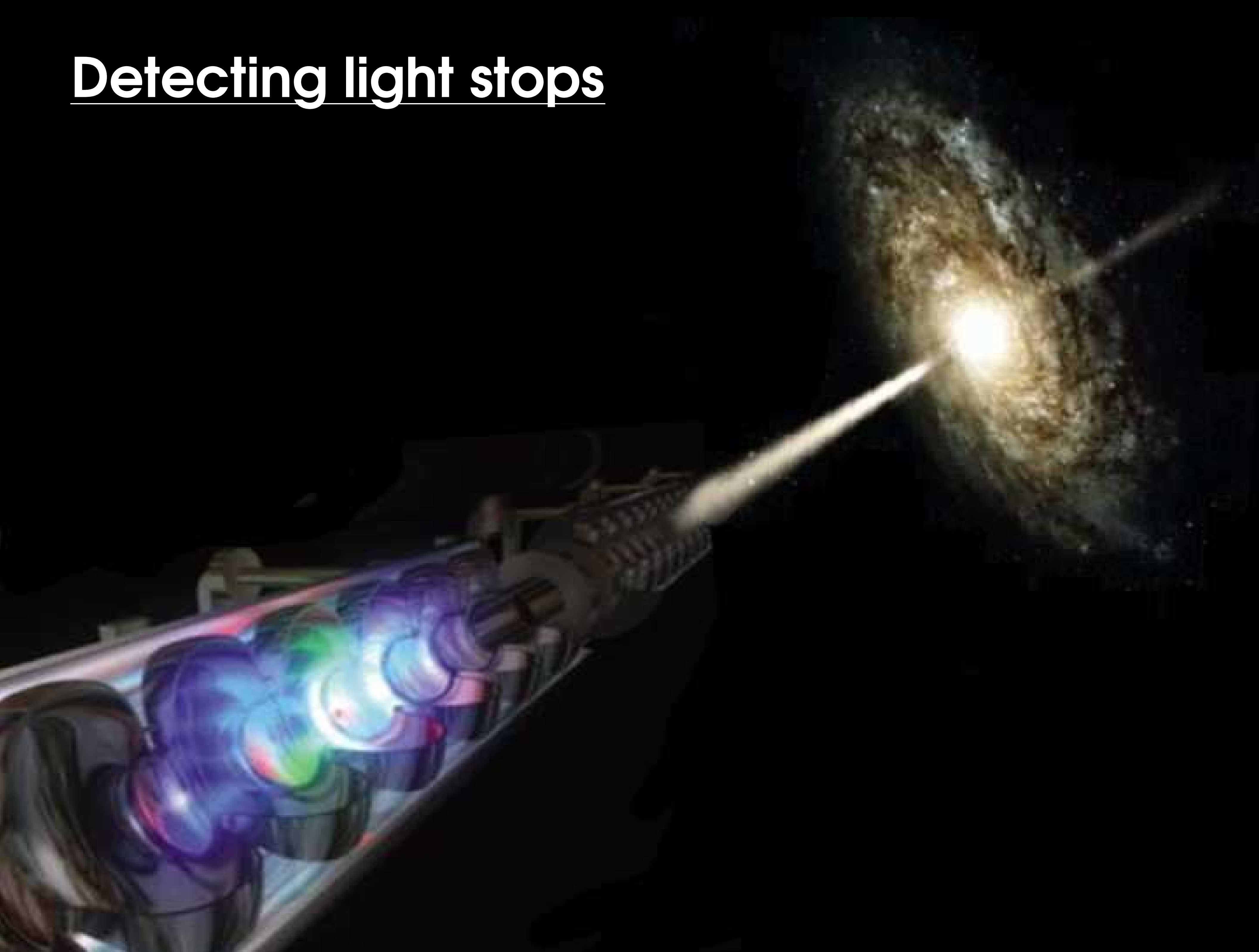
Green: Relic density consistent with WMAP

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

Difficult for searches at Tevatron

LHC will have similar difficulties (possible additional channel: $pp \to \tilde{g}\tilde{g} \to \tilde{t}_1 \tilde{t}_1 \, \bar{t}\, \bar{t}$)

Detecting light stops



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 $\mathcal{L} = 500$ 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	0.115	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
$\gamma\gamma$, $p_{\mathrm{t}} > 5$ GeV	936		

$-$ = L

$+$ = R

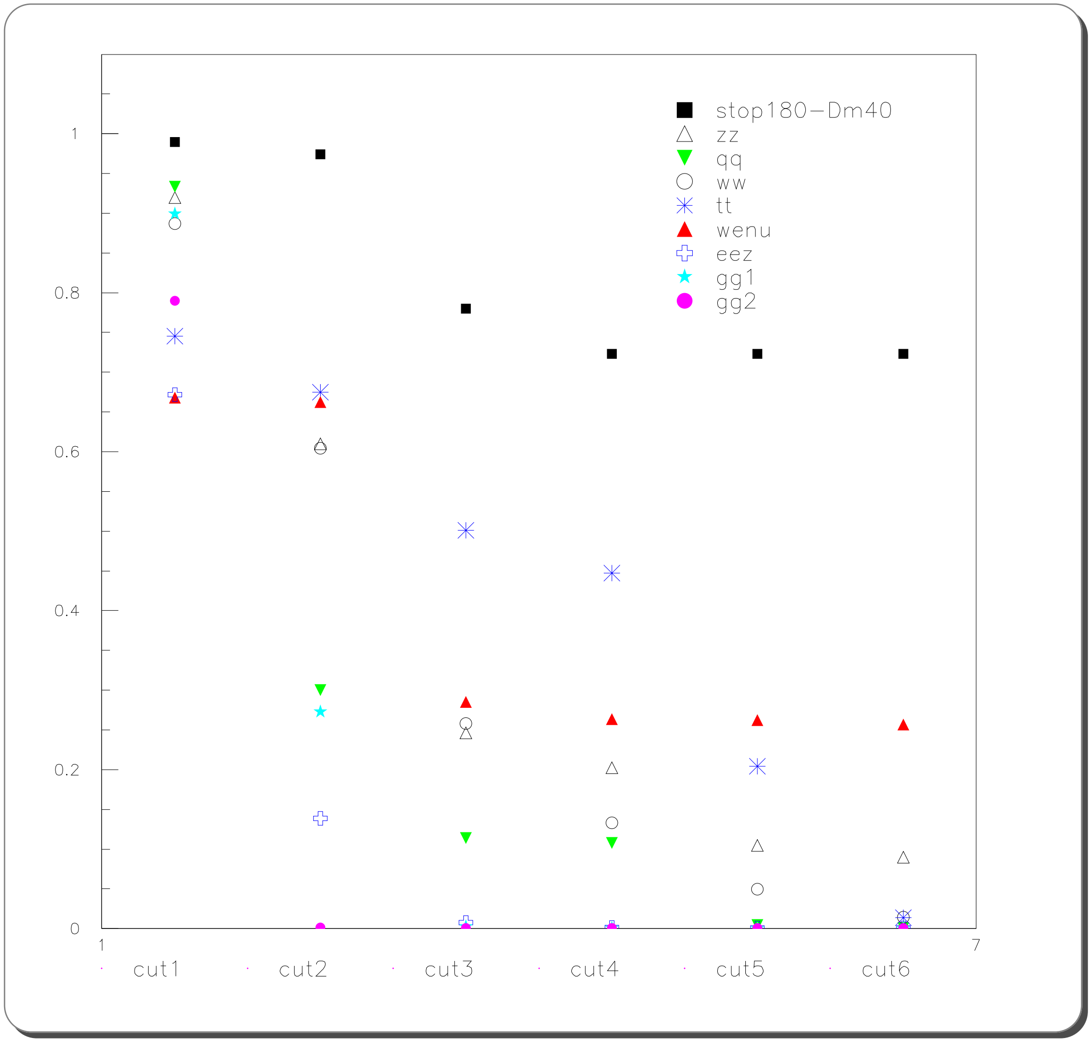
$\sin\theta_{\tilde{t}} = 0.5$

Large Standard Model backgrounds!

Reduction of background

Preselection:

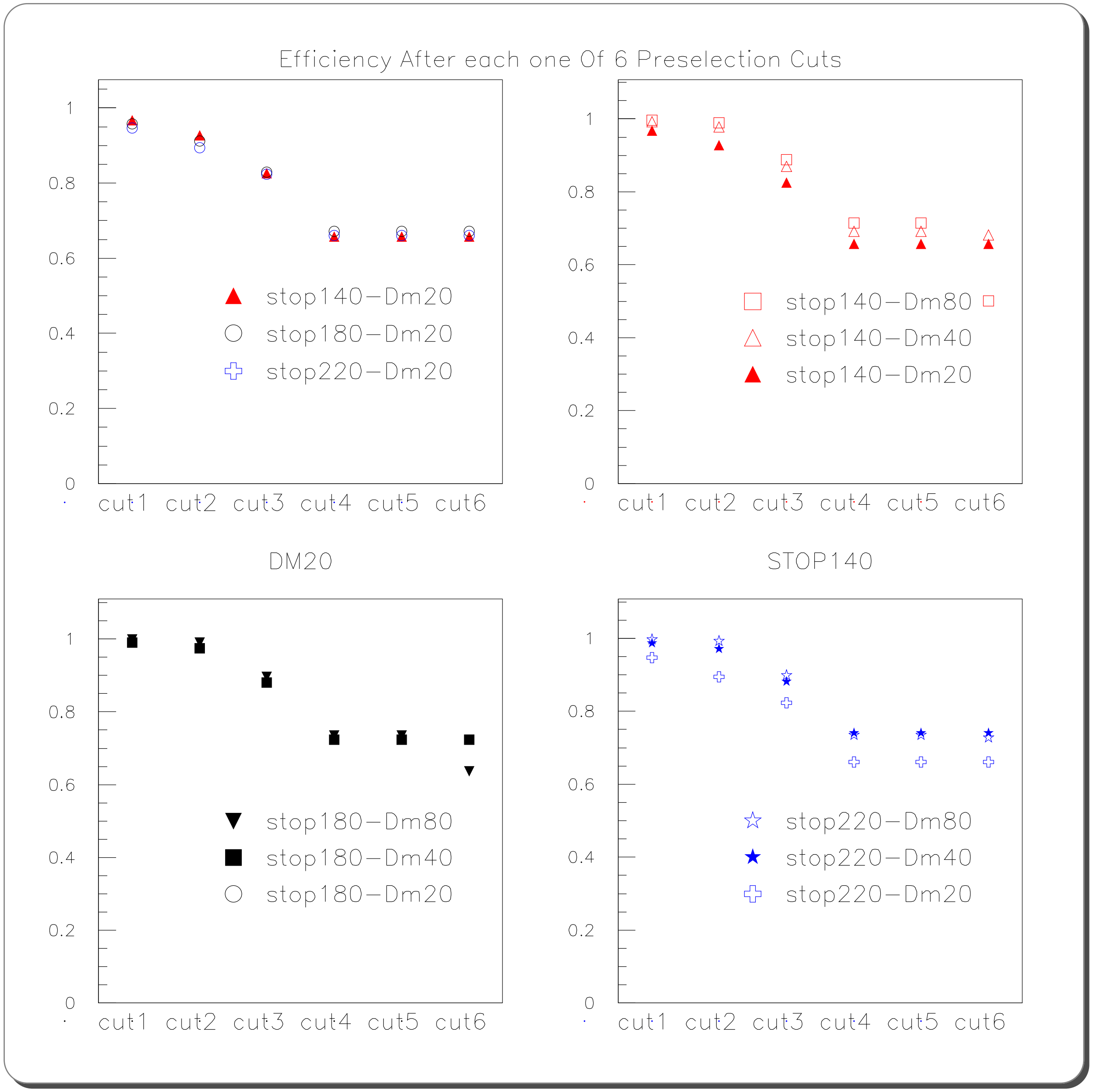
1. $4 < N_{\text{chargedtracks}} < 50$
2. $p_{\text{t}} > 5\ \text{GeV}$
3. $|\cos\theta_{\text{Thrust}} < 0.8|$
4. $|p_{\text{long,tot}}/p_{\text{tot}}| < 0.9$
5. $E_{\text{vis}} < 0.75\sqrt{s}$
6. $m_{\text{inv}} < 200\ \text{GeV}$



Most backgrounds (color) strongly reduced

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

Effect of preselection for various signal parameters



for $m_{\tilde{t}_1} = 140,$
$180,$
220 GeV

and $\Delta m = 20,$
$40,$
80 GeV

Signal efficiencies after pre-selection 65–75%

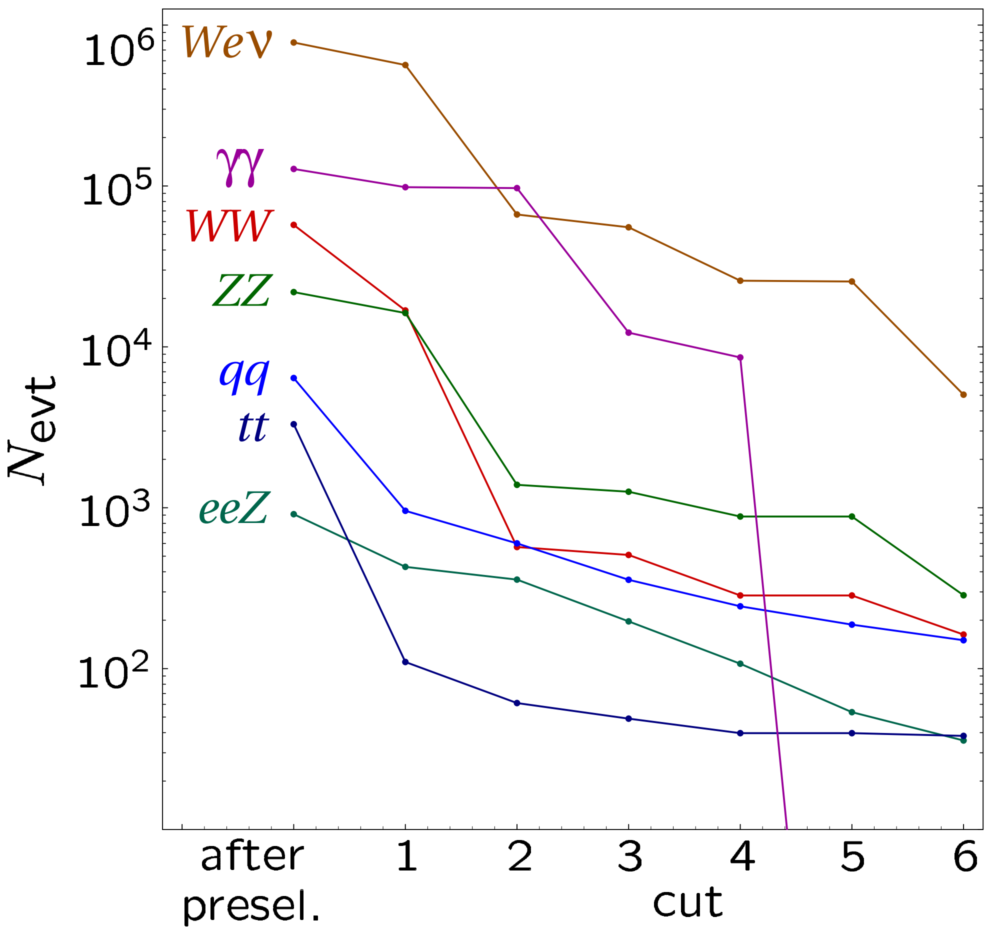
Reduction of background

Preselection:

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

Selection:

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



Remaining background levels

Background	N_{evt} generated	N_{evt} after selection	scaled to 500 fb^{-1}
W^+W^-	210,000	10	145
ZZ	30,000	30	257
$We\nu$	210,000	624	5044
eeZ	210,000	3	36
$q\bar{q},\ q \neq t$	350,000	10	200
$t\bar{t}$	180,000	25	38
$\gamma\gamma$	8,000,000	0	< 164

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

Distributions in thrust, acoplanarity, jet angles, etc. similar to signal

Only cut in window around $m_{\text{inv}} \sim M_{\text{W}}$ and c-tagging effective

Signal efficiency

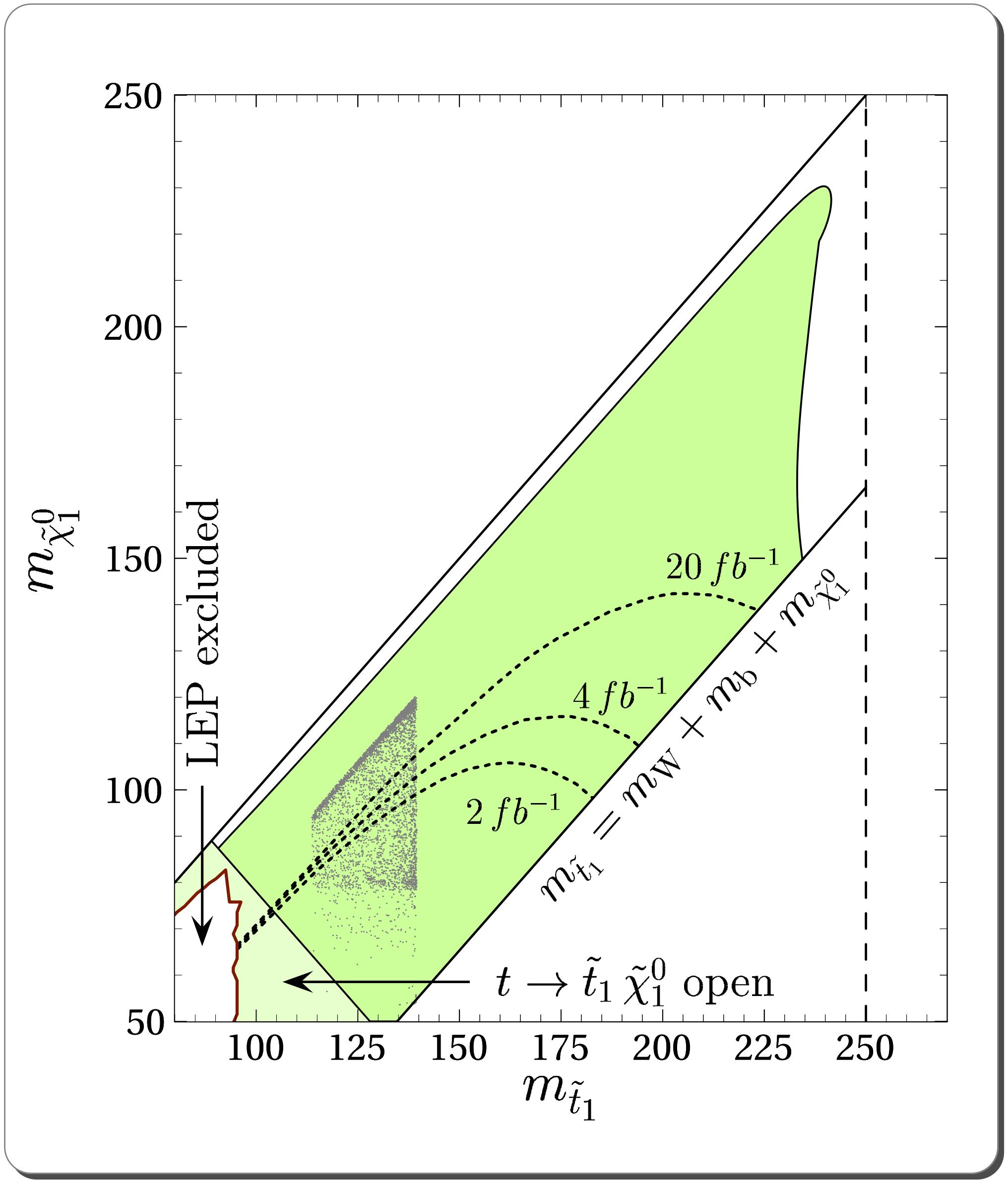
Δm	$m_{\tilde{t}_1} =$ 120 GeV	140 GeV	180 GeV	220 GeV
80 GeV		10%	15%	19%
40 GeV		10%	20%	24%
20 GeV	17%	21%	28%	35%
10 GeV	19%	20%	19%	35%
5 GeV	2.5%	1.1%	0.3%	0.1%

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

→ same order as remaining background

Signal efficiency deteriorates for very small Δm

Stop discovery reach at linear collider



From simulations:

Background numbers B and 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

Parameter determination

Sample parameter point

Point with light stop, gauginos, selectron and CP violation
→ Use existing studies where possible

$M_1 = 112.6$ GeV
$M_2 = 225$ GeV
$|\mu| = 320$ GeV
$\phi_\mu = 0.2$

$M_{u3}^2 = -99^2$ GeV^2
$M_{q3} = 4200$ GeV
$A_\mathrm{t} = -1050$ GeV
$\tan\beta = 5$

1st/2nd generation squarks heavy

→ Consistent with e and n EDM, m_{h^0} bound, baryogenesis

Sparticle masses:

$m_{\tilde{\chi}_1^0} = 107.2$ GeV $\quad m_{\tilde{t}_1} = 122.5$ GeV $\quad \cos\theta_{\tilde{t}} = 0.0105$

$\Omega_\mathrm{CDM} h^2 \approx 0.112$

Stop parameters

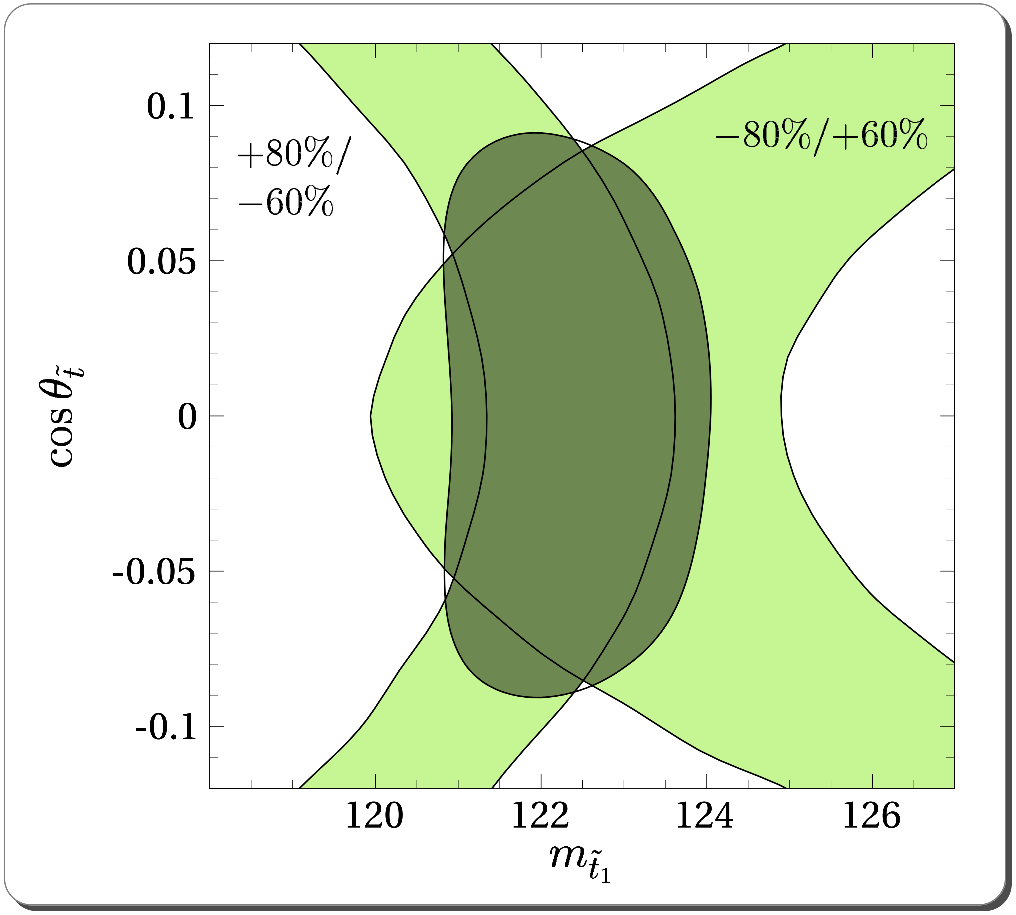
Use $e^+e^- \to \tilde{t}_1\tilde{t}_1^*$ cross-section measurements for two different beam polarizations:

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

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

Systematic errors:

- $\delta m_{\tilde{\chi}_1^0} = 0.1$ GeV
- $\delta P/P = 0.5\%$
- backgr. $\delta B/B = 0.3\%$
- $\delta\mathcal{L}/\mathcal{L} = 5 \times 10^{-4}$
- $\tilde{t}_1$ hadroniz./fragment.: ∼1%
- charm tagging/fragm.: 0.5%
- detector calibration: 0.5%
- beamstrahlung



Result: $m_{\tilde{t}_1} = 122.5 \pm 1.0$ GeV

$|\cos\theta_{\tilde{t}}| < 0.074$

$\Rightarrow |\sin\theta_{\tilde{t}}| > 0.9972$

Chargino/Neutralino parameters

Mass measurements:

- Heavy 1st/2nd generation squarks
  → Neutralino masses from squark cascades at LHC difficult
- Lightest neutralino $\tilde{\chi}_1^0$ mass from selectron and other decays at ILC → $\delta m_{\tilde{\chi}_1^0} = 0.11$ GeV
- Other neutralino/chargino masses from ILC threshold scans

LHC/ILC report '04

Most studies performed in SPS1a scenario
→ Scale errors with different cross-sections in our scenario

	$\tilde{\chi}_1^0$	$\tilde{\chi}_2^0$	$\tilde{\chi}_3^0$	$\tilde{\chi}_1^\pm$
δm	0.11	2.5	4	0.12 GeV

Cross-section measurements

Desch et al. ’04

$e^+e^- \to \tilde{\chi}_1^+\tilde{\chi}_1^-$ $\quad$ $P(e^-)/P(e^+) = -80\%/+60\%$ and $+80\%/-60\%$

$e^+e^- \to \tilde{\chi}_1^0\tilde{\chi}_2^0$ $\quad$ at $\sqrt{s} = 500$ GeV

$e^+e^- \to \tilde{\chi}_2^0\tilde{\chi}_2^0$

Note: Light stop opens decay $\tilde{\chi}_1^+ \to \tilde{t}_1\bar{b}$
with experimentally unknown BR

→ Use only cross-section ratios for $\sigma(e^+e^- \to \tilde{\chi}_1^+\tilde{\chi}_1^-)$

Systematic errors in cross-sections:

- chargino/neutralino masses
- selectron/sneutrino masses in t-channel
- $\delta P/P = 0.5\%$

Experimental efficiency extrapolated from analysis for $e^+e^- \to \tilde{\chi}_1^0\tilde{\chi}_2^0$

M. Ball ’02

Chargino/Neutralino comprehensive analysis

Use χ^2 fit to extract fundamental SUSY parameters:

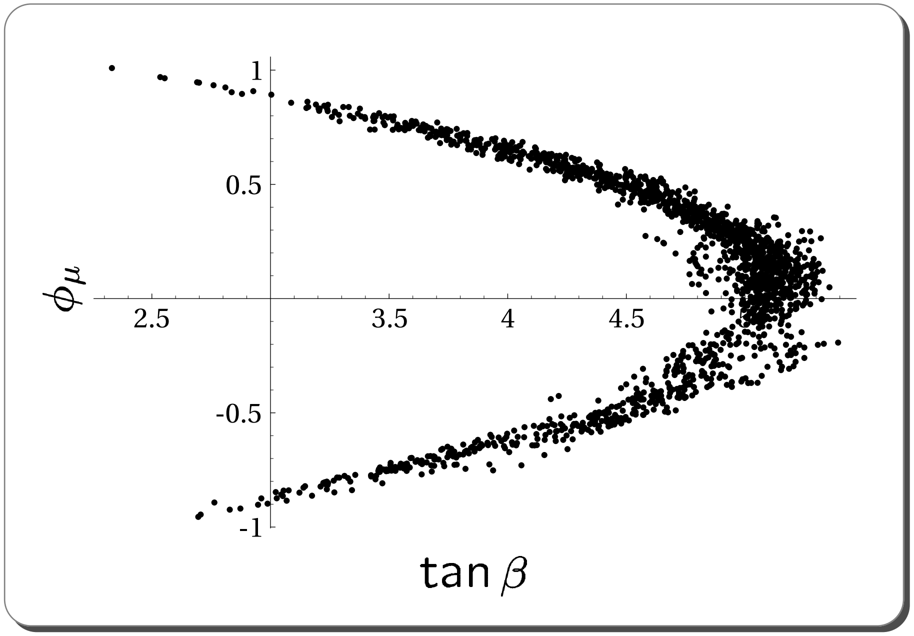
$$M_1 = 112.6 \pm 0.2 \text{ GeV} \qquad |\phi_\mu| < 1.0$$

$$M_2 = 225.0 \pm 0.7 \text{ GeV} \qquad \tan\beta = 5^{+0.5}_{-2.6}$$

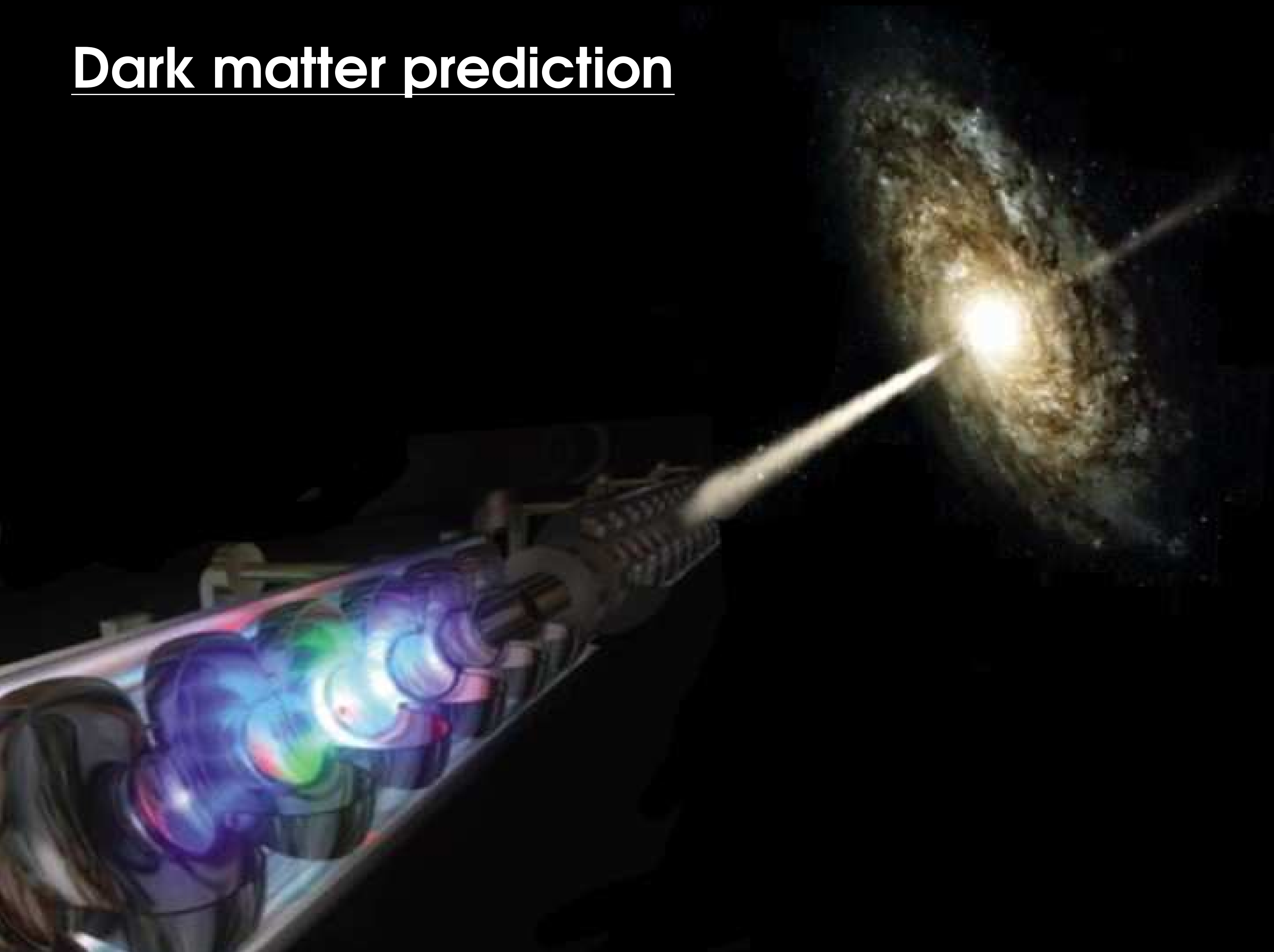
$$|\mu| = 320.0 \pm 3.3 \text{ GeV}$$

Large correlation between $\tan\beta$ and ϕ_μ

→ Not problematic for dark matter determination



Dark matter prediction



Computation of Ω_{CDM} from collider results

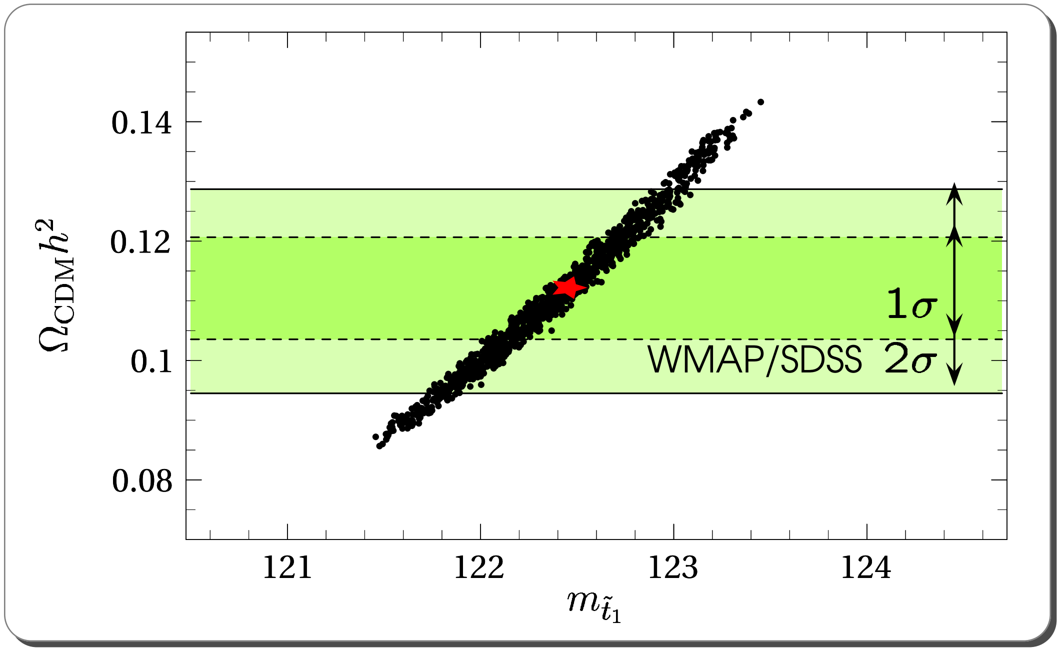
Use program by D. Morrissey for calculating Ω_{CDM}

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:

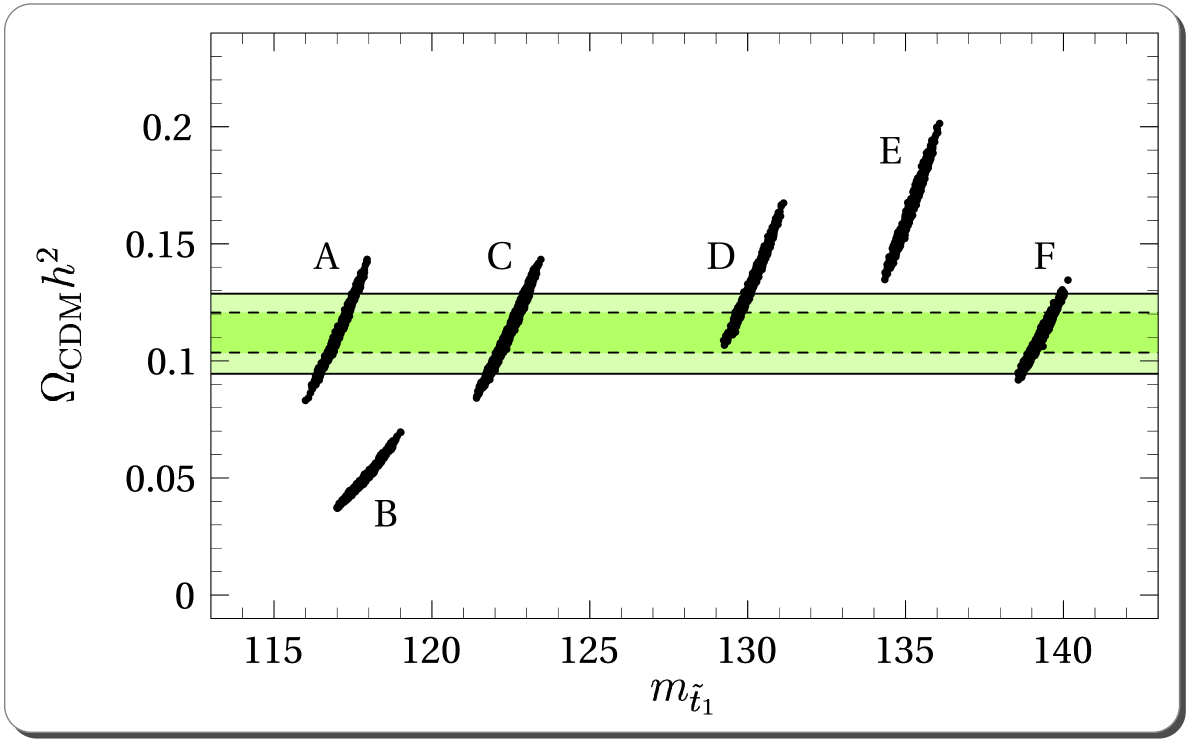
$0.086 < \Omega_{\text{CDM}}h^2 < 0.143$

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

WMAP/SDSS (95% CL):

$0.095 < \Omega_{\text{CDM}}h^2 < 0.129$

Different SUSY scenarios



ILC measurements could lead to different conclusions:

- Agreement with cosmological observations (A,C,E)
- SUSY predicts too little DM (B)
  → other sources?
- SUSY predicts too much DM (D,E)
  → constraints on parameters, revision of model of universe?

Conclusions

- ILC can cover complete stop-neutralino co-annihilation scenario
  Can explore mass differences down to
  $\Delta m = m_{\tilde{t}_1} - m_{\tilde{\chi}_1^0} \sim \mathcal{O}(5\ \mathrm{GeV})$
- Prediction of Ω_{CDM} in MSSM from collider measurements with precision comparable to cosmological measurements

Future avenues:

- Further refinements of the experimental analysis
- Analyze different dark matter scenarios
- Investigate effect of radiative corrections

Maybe at one point we will be able to figure out what this is

C-tagging – Concept

T. Kuhl ’03

Vertex identification followed by a Neural Network optimization

Vertex identification:

As a maximum in track overlapping (product of probability density tubes defined using the track parameters) 3 cases:

1. Only primary vertex
2. 1 secondary vertex
3. $>$1 secondary vertex

Neural Network (NN):

Data for training: 255000 $\tilde{t}_1\tilde{t}_1^*$ events, $m_{\tilde{t}_1} = 120$–220 GeV,
$\Delta m = 5, 10, 20$ GeV
240000 $We\nu$ events, the most resilient background

C-tagging – Neural Network Input

Vertex Case 1: NN input variables:

- impact parameters and their significance (impact parameter / error) of 2 most significant tracks
- track momenta
- joint probability in r-ϕ plane and z direction

Cases 2/3: NN input variables: **all of case 1 plus:**

- decay length and its significance of secondary vertex
- number/momenta of tracks associated to 2nd vertex
- p_t-corrected mass of 2nd vertex
  (corrected for neutral hadrons and ν's),
  p_t distribution relative 2nd vertex direction