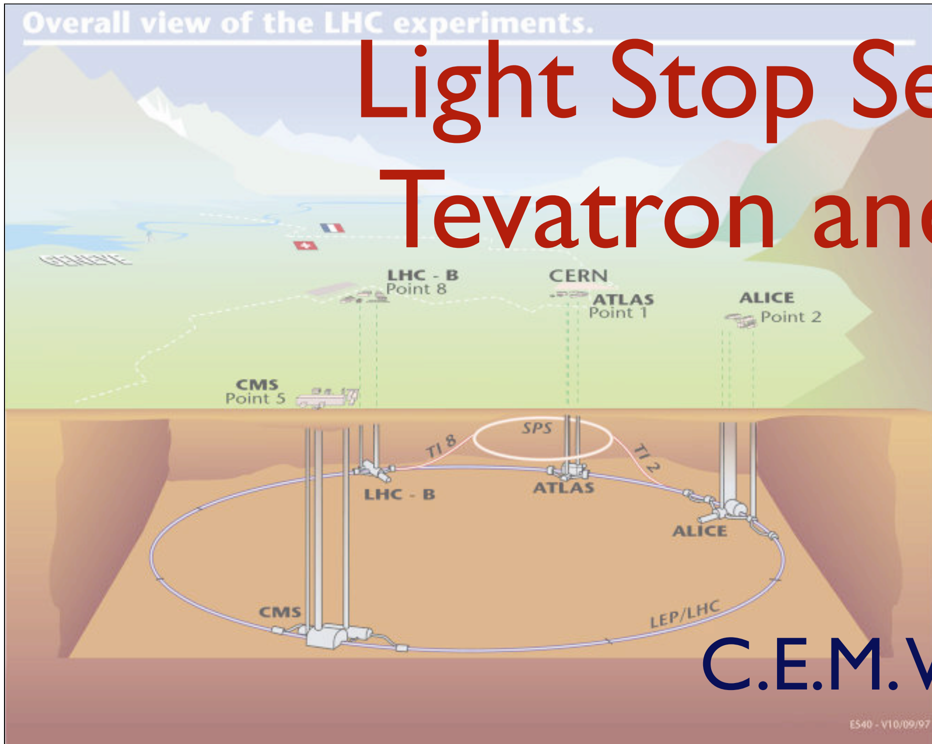
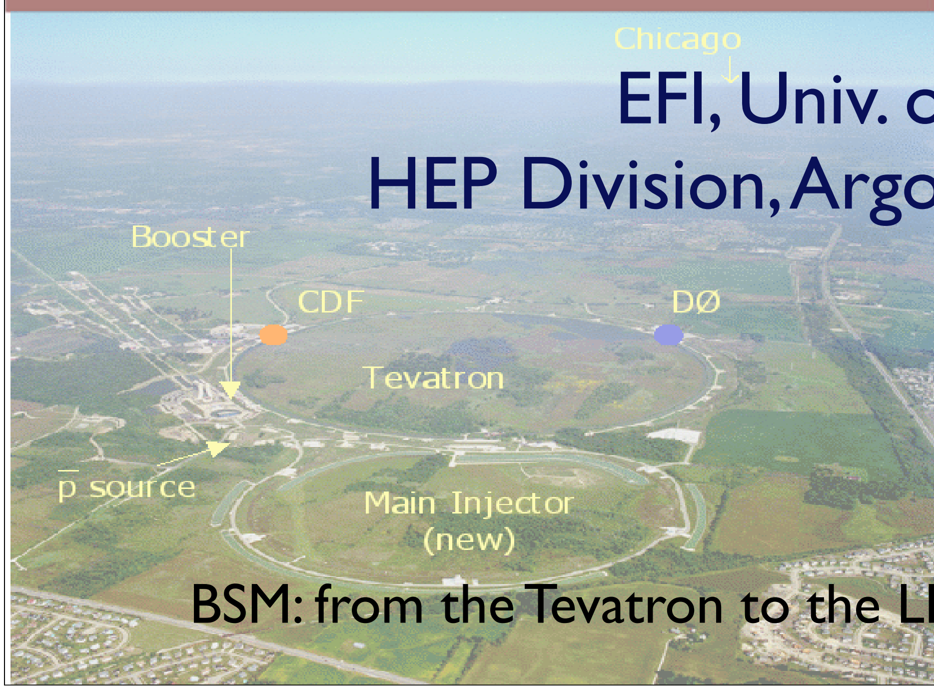
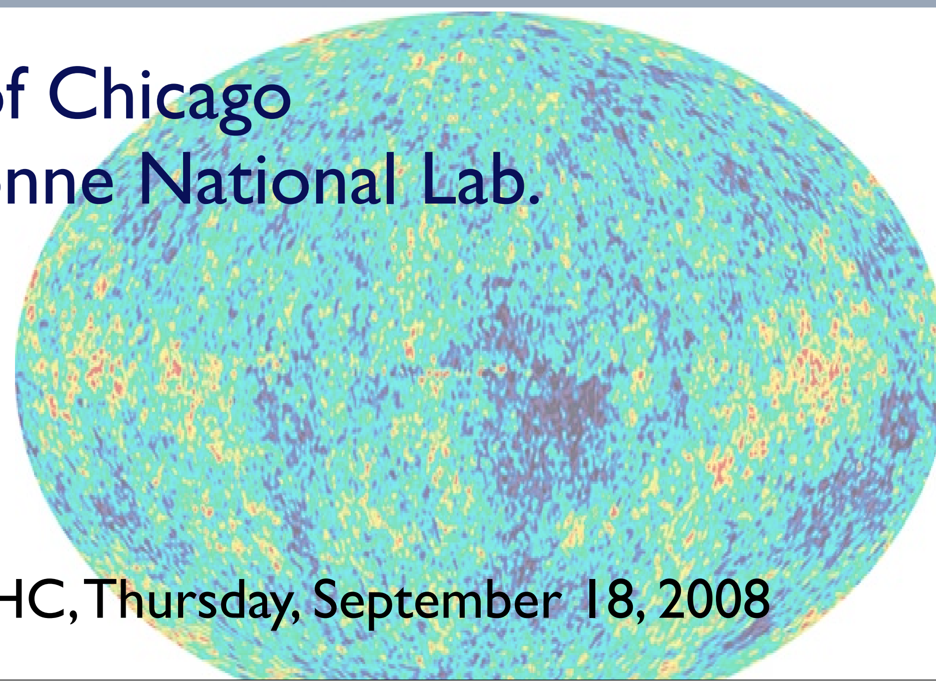
Light Stop Searches at the Tevatron and at the LHC



C.E.M. Wagner

EFI, Univ. of Chicago
HEP Division, Argonne National Lab.





BSM: from the Tevatron to the LHC, Thursday, September 18, 2008

Information on New Physics at LHC reach

Baryogenesis at the weak scale

- Under natural assumptions, there are three conditions, enunciated by Sakharov, that need to be fulfilled for baryogenesis. The SM fulfills them :
- Baryon number violation: Anomalous Processes
- C and CP violation: Quark CKM mixing
- Non-equilibrium: Possible at the electroweak phase transition.

Baryon Number Violation at finite T

- Anomalous processes violate both baryon and lepton number, but preserve B – L. Relevant for the explanation of the Universe baryon asymmetry.

$$\partial^\mu j_\mu^{B,L} = \frac{N_g}{32\pi^2} Tr(\varepsilon^{\mu\nu\alpha\beta} F_{\mu\nu} F_{\alpha\beta})$$

$$S_{inst} = \frac{2\pi}{\alpha_W} \qquad \Gamma_{\Delta B\neq 0} \propto \exp(-S_{inst})$$

- At zero T baryon number violating processes highly suppressed

- At finite T, only Boltzman suppression

$$\Gamma(\Delta B\neq 0) \propto A\,T \exp\left(-\frac{E_{sph}}{T}\right) \qquad \mathbf{E_{sph}} \propto \frac{\mathbf{8\pi\, v}}{\mathbf{g}}$$

Klinkhamer and Manton '85, Arnold and Mc Lerran '88

Baryon Asymmetry Preservation

If Baryon number generated at the electroweak phase transition,

$$\frac{n_B}{s} = \frac{n_B(T_c)}{s} \exp\left(-\frac{10^{16}}{\mathrm{T_c(GeV)}} \exp\left(-\frac{\mathrm{E_{sph}}(\mathrm{T_c})}{\mathrm{T_c}}\right)\right)$$

Kuzmin, Rubakov and Shaposhnikov, '85—'87

Baryon number erased unless the baryon number violating processes are out of equilibrium in the broken phase.

Therefore, to preserve the baryon asymmetry, a strongly first order phase transition is necessary:

$$\frac{\mathrm{v}(T_c)}{T_c} > 1$$

Preservation of the Baryon Asymmetry

- EW Baryogenesis requires new boson degrees of freedom with strong couplings to the Higgs.
- Supersymmetry provides a natural framework for this scenario. Huet, Nelson '91; Giudice '91, Espinosa, Quiros,Zwirner '93.
- Relevant SUSY particle: Superpartner of the top
- Each stop has six degrees of freedom (3 of color, two of charge) and coupling of order one to the Higgs

$$E_{SUSY} = \frac{g_w^3}{4\pi} + \frac{h_t^3}{2\pi} \approx 8\, E_{SM}$$

$$\frac{v(T_c)}{T_c} \approx \frac{E}{\lambda} \quad , \quad \text{with} \quad \lambda \propto \frac{m_H^2}{v^2}$$

M. Carena, M. Quiros, C.W. '96, '98
Delepine et al '96
J. Cline, K. Kainulainen '96
M. Laine '96; M. Losada '96

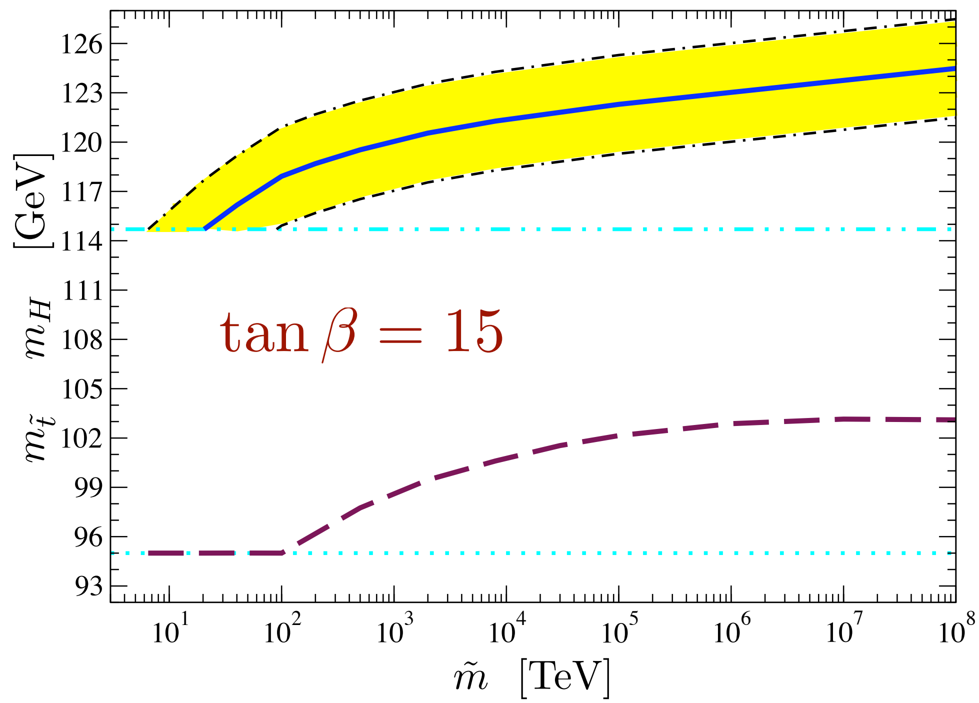
- Since

Higgs masses up to 120 GeV may be

Allowed parameter space for Electroweak Baryogenesis

M. Carena, G. Nardini, M. Quiros, C.W. in preparation

- Values of $\tan\beta \geq 5$ preferred to keep the Higgs mass large
- Values of At cannot be too large to keep the phase transition strongly first order
- Higgs remains light, with values below 125 GeV.



In general, a light stop with a mass below 125 GeV is required.

Other arguments for a light stop

- Relatively light stops appear naturally in SUSY models
- Stops are pushed to lower values than other squarks via RG evolution, by the same Yukawa effects that induce electroweak symmetry breaking.
- If gluino mass parameter is smaller than the wino one at the GUT scale, stop becomes naturally light
  (Compressed SUSY. Martin'06)
- In addition, stops can have large mixing, further pushing the mass down and increasing the Higgs mass.
- Light stop can lead to further annihilation channels for the neutralino dark matter.

Stop-Neutralino Mass Difference: Information from the Cosmos

M. Carena, C. Balazs, C.W., PRD70:015007, 2004

M. Carena, C. Balazs, A. Menon, D. Morrissey, C.W., Phys. Rev. D71:075002, 2005.

- If the neutralino provides the observed dark matter relic density, then it must be stable and lighter than the light stop.

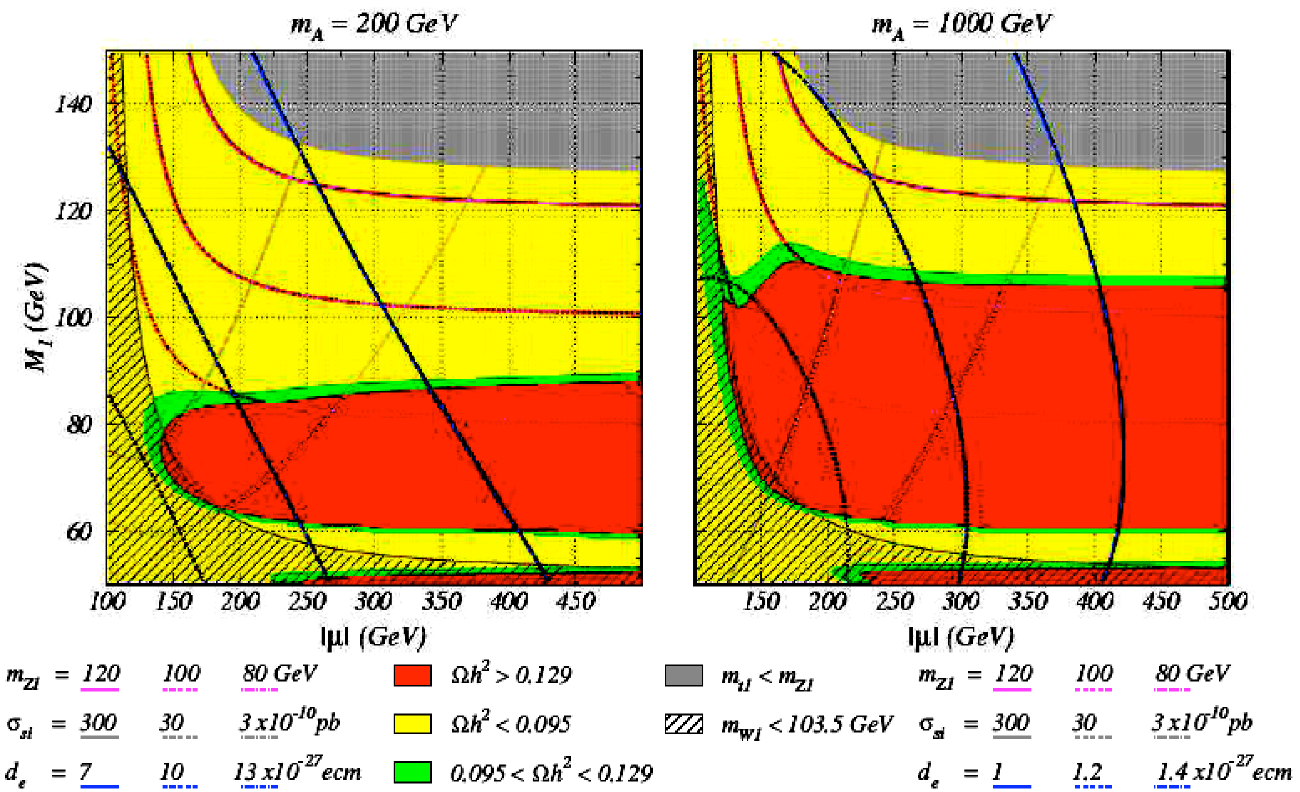
- Relic density is inversely proportional to the neutralino annihilation cross section.

If only stops, charginos and neutralinos are light, there are three main annihilation channels:

1. Coannihilation of neutralino with light stop or charginos: Small mass differences.
2. s-channel annihilation via Z or light CP-even Higgs boson
3. s-channel annihilation via heavy CP-even Higgs boson and CP-odd Higgs boson

Light Stop and Relic Density Constrain

In the presence of a light stop, the most relevant annihilation channel is the coannihilation between the stop and the neutralino at small mass differences. Relic density may be naturally of the observed size in this region of parameters.



$\tan\beta = 7$

C. Balazs, M. Carena, A. Menon, D. Morrissey, C.W. 05
Cirigliano, Profumo, Ramsey-Musolf 07, Martin'06--'07

Collider Tests of Electroweak Baryogenesis and Dark Matter

⁕ Higgs searches

Higgs properties: SM-like couplings to W and Z (agent of EWSB) and $m_h < 120$ GeV

- $\mathrm{h} \to \mathrm{b}\bar{\mathrm{b}}$ channel at the Tevatron :

may achieve a 3 sigma evidence with 6 fb^{-1} of data

- $\mathrm{h} \to \tau^+\tau^-$ and $\mathrm{h} \to \gamma\gamma$ channels at the LHC :

a definitive test of this scenario with the first 10 fb^{-1} of well understood data

⁕ Stop searches:

Light Stop models with Neutralino LSP Dark Matter ⟶ $\not{E}_T$ signal

⟶ dominant decay $\boxed{\tilde{t}_1 \to c\,\tilde{\chi}_1^0}$

For small Stop-Neutralino mass difference: co-annihilation region

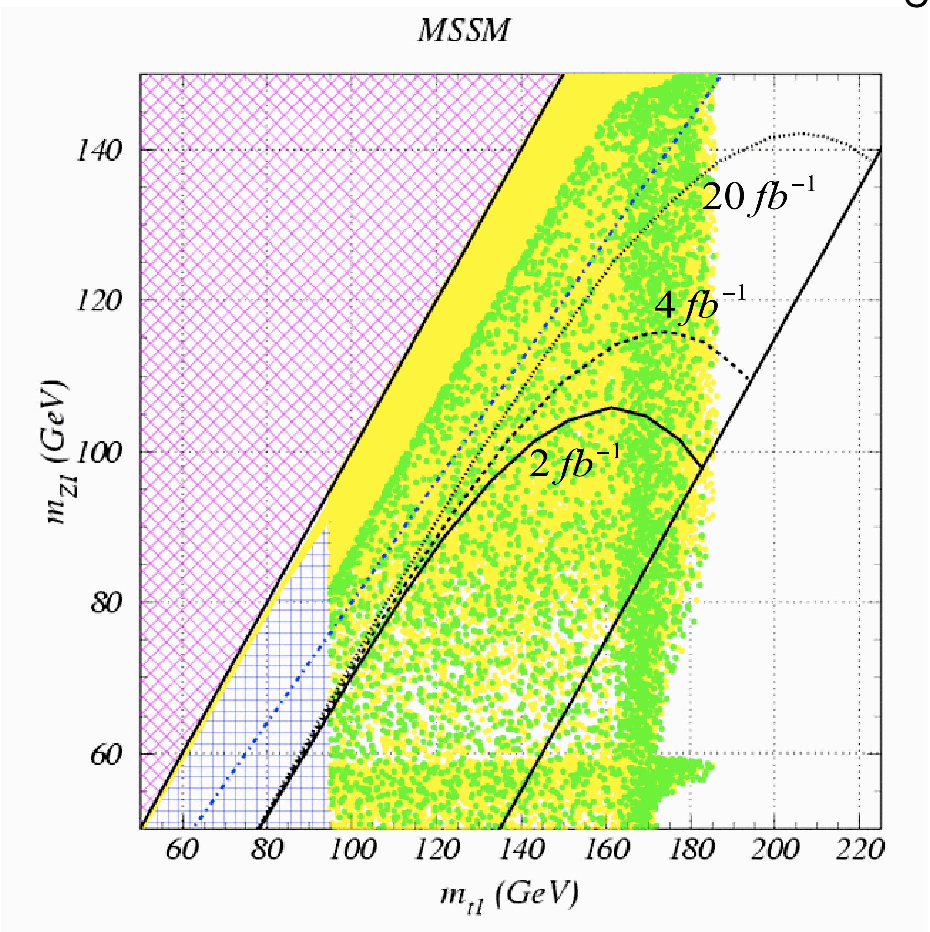
⟶ excellent agreement with WMAP data

Very challenging region for stop searches at hadron colliders


Chicago
Booster
CDF
DØ
Tevatron
p̄ source
Main Injector
(new)

Tevatron stop searches and dark matter constraints

Carena, Balazs and C.W. '04



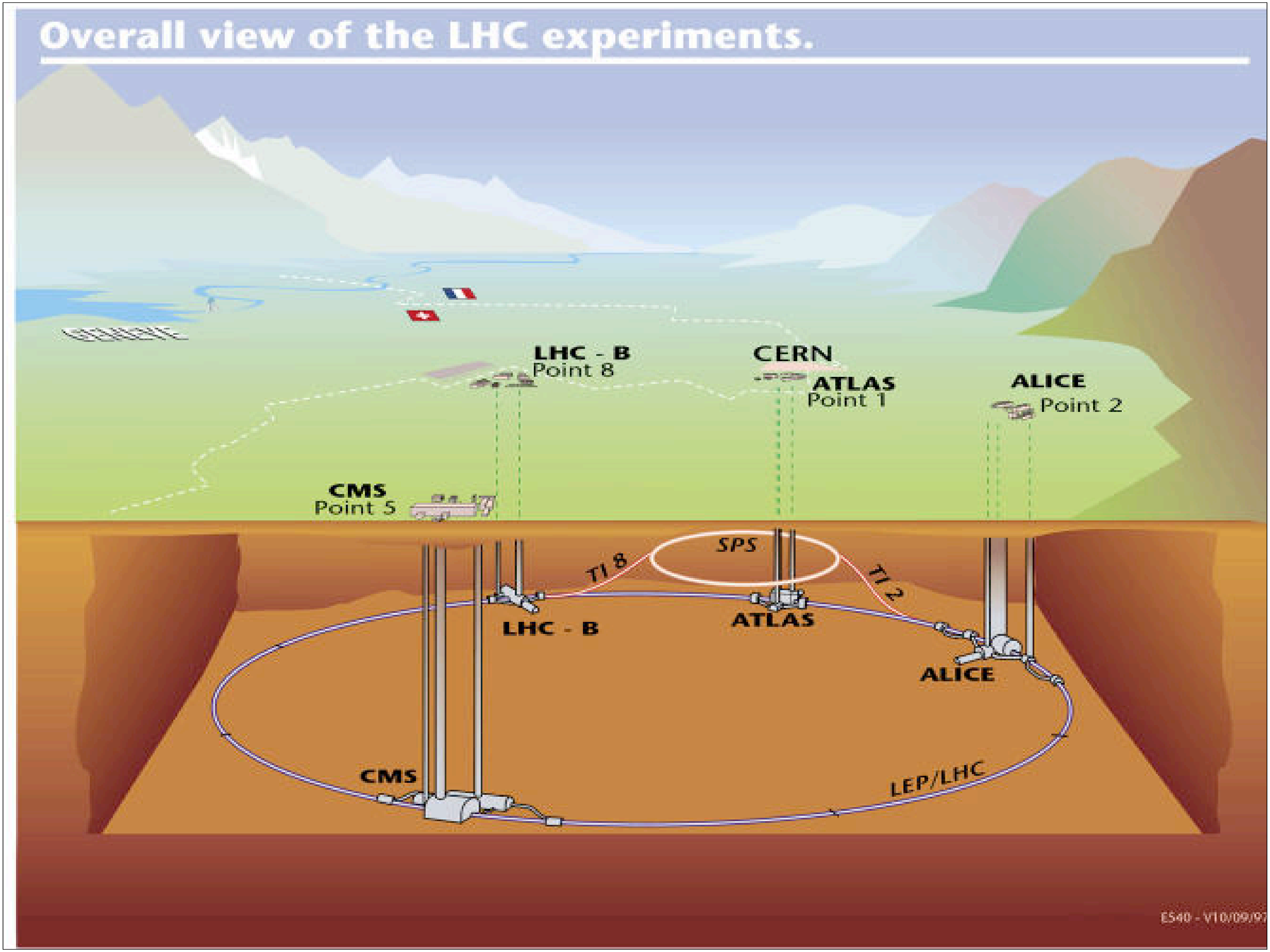
Green: Relic density consistent with WMAP measurements.

Searches for light stops difficult in stop-neutralino coannihilarion region.

LHC will have equal difficulties.

But, LHC can search for stops from gluino decays into stops and tops.
Stops may be discovered for gluino masses lower than 900 GeV, even if the stop-neutralino mass difference is as low as 10 GeV !

Kraml, Raklev '06, Martin 08

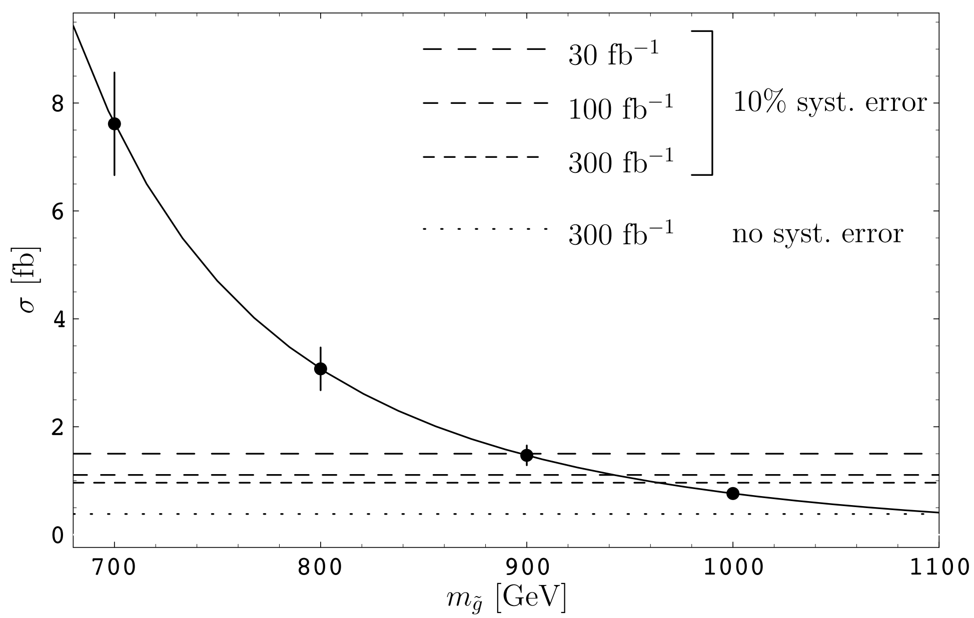

Overall view of the LHC experiments.
LHC - B
Point 8
CERN
ATLAS
Point 1
ALICE
Point 2
CMS
Point 5
SPS
TI 8
TI 2
LHC - B
ATLAS
ALICE
CMS
LEP/LHC
ES40 - V10/09/97

Stops from Gluino Decays

Kraml, Raklev '06, Martin 08

Take advantage of Majorana character of gluino: $\tilde{g} \to \tilde{t}_1 \bar{t},\ \tilde{t}_1^* t$. Production of equal sign tops

- Two same-sign leptons with $p_T > 20$ GeV.
- Two b-tagged jets with $p_T > 50$ GeV. (b-tag eff. 43%)
- $\not{E}_T > 100$ GeV. Invariant mass $m_{bl} < 160$ GeV



Efficient stop search channel up to gluino masses of about 1 TeV

Alternative Channels at the LHC

- When the stops and neutralino mass difference is small, the jets will be soft.
- One can look for the production of stops in association with jets or photons. Signature: Jets or photons plus missing energy

M. Carena, A. Freitas, C.W., arXiv:0808.2298

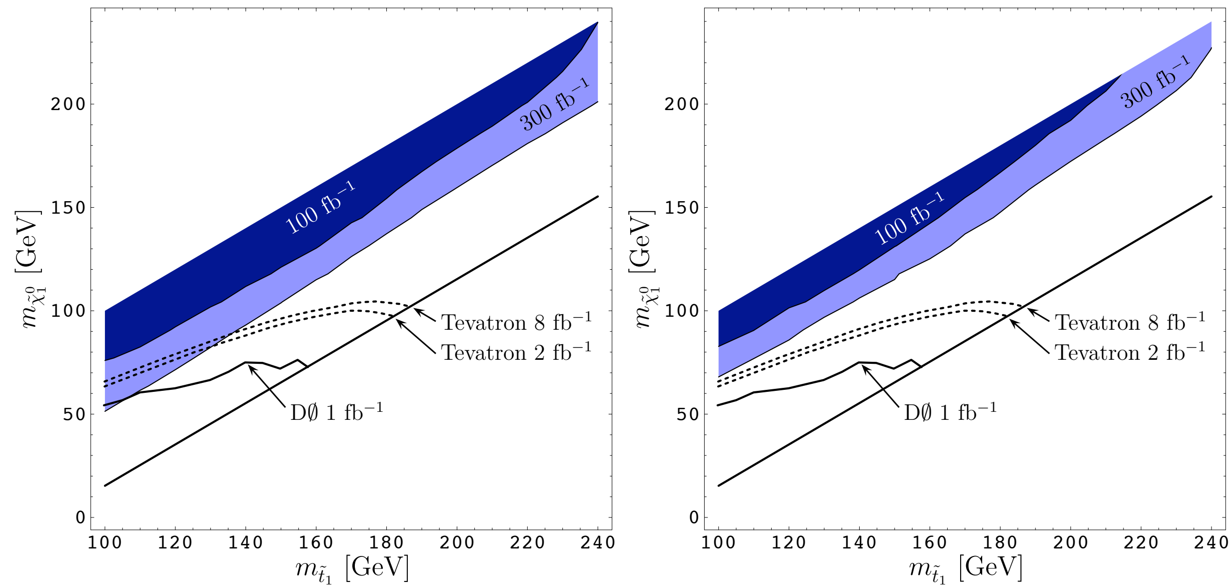
- Photon plus missing energy searches have the advantage of being cleaner, but they suffer from low statistics and large systematics
- Jet plus missing energy searches have larger backgrounds but have the advantage of having much larger production cross section compared to the photon case
- Hard photons and jets recoiling against missing energy have been simulated at the LHC experiments in the search for large extra dimensions, and we will make use of the backgrounds computed for that purpose.

Photons plus missing energy at the LHC

M. Carena, A. Freitas, C.W., arXiv:0808.2298

$$p\,p \to \tilde{t}_1\,\tilde{t}_1^*\,\gamma$$

1. Require one hard photon with $p_\mathrm{T} > 400$ GeV and pseudo-rapidity $|\eta| < 2.4$.
2. Missing energy requirement: $\not{E}_\mathrm{T} > 400$ GeV.
3. Veto against tracks with $p_\mathrm{T} > 40$ GeV.
4. Require back-to-back topology for photon and missing momentum: $\Delta\phi(\not{\vec{p}}_\mathrm{T}, \vec{p}_\gamma) > 2.5$.

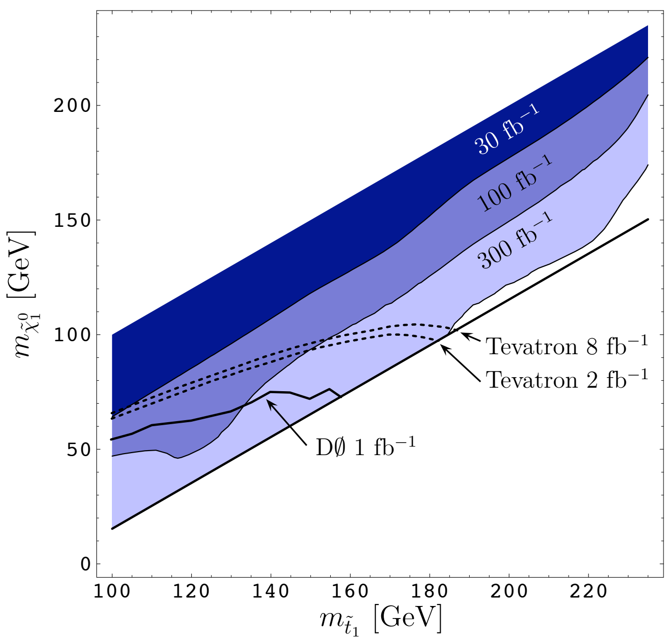


5-sigma discovery reach for the case in which systematic uncertainties associated with photon and missing energy determination are ignored (left) and taken into account (right). Total syst. uncertainty 6.5 %.

Jets plus missing Energy

M. Carena, A. Freitas, C.W., arXiv:0808.2298

1. Require one hard jet with $p_T > 100$ GeV and $|\eta| < 3.2$ for the trigger.
2. Large missing energy $\not{E}_T > 1000$ GeV.
3. Veto against electrons with $p_T > 5$ GeV and muons with $p_T > 6$ GeV in the visible region ($|\eta| < 2.5$).



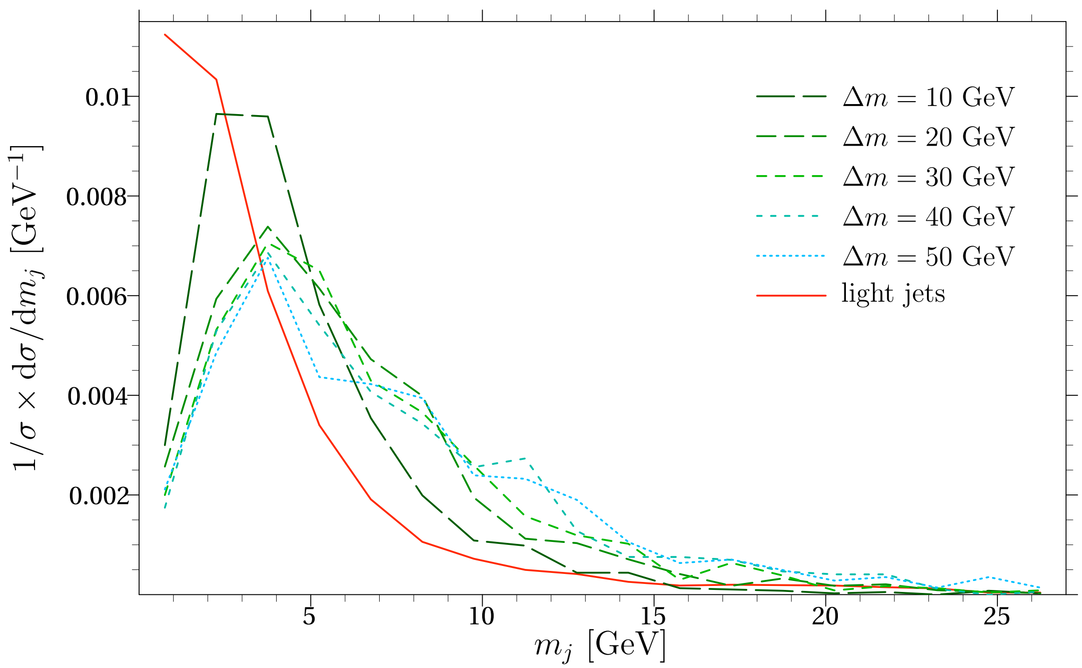
Including systematics associated with jet and missing energy determination. Dominant missing energy coming from Z's, calibrated with the electron channel.

Excellent reach until masses of the order of 220 GeV and larger.

Full region consistent with EWBG will be probed by combining the LHC with the Tevatron searches.

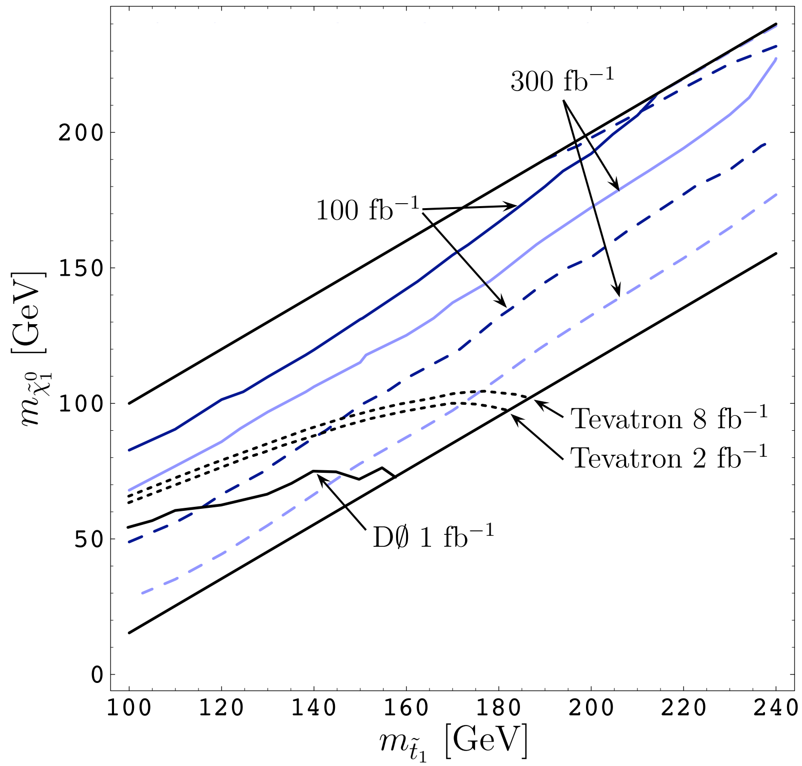
Stop Identification

- Can we detect the relatively soft jets coming from stop decay ?
- One can try to identify the charm-jets by the invariant mass and the track multiplicity
- Below we compare their invariant mass to the one of light jets coming from initial state radiation
- Cutting above 4.5 GeV leaves 60 % signal and only 25 % bkgd.



Improvement in Stop Searches by using charm identification in photon channel

M. Carena, A. Freitas, C.W., arXiv:0808.2298



Photons plus missing E_T
with charm tagging

We now demand one additional jet with pT > 20 GeV and with positive charm identification.

The charm identification
an additional improvement

Just like in the jet channel,
after charm i.d. one can
probe the whole region consistent
with electroweak baryogenesis

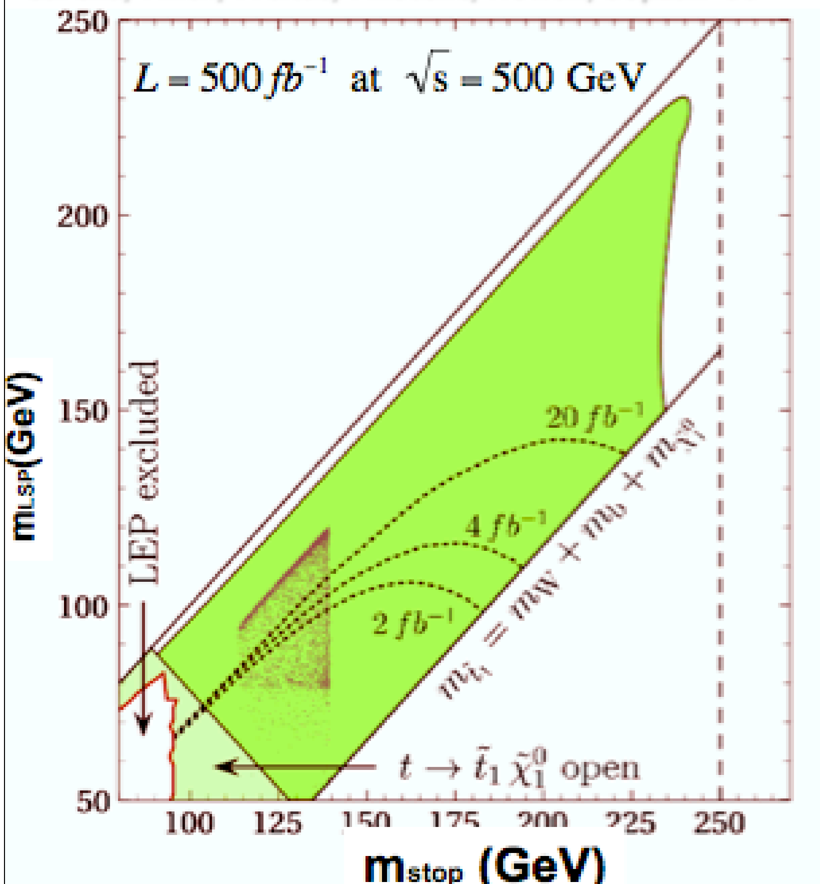
Conclusions

- Light stops are theoretically well motivated and consistent with the EWBG scenario in the MSSM
- If the mass difference with the neutralino is small, it can provide the dark matter density via co-annihilation
- Searches at the Tevatron become promising only if the mass difference is large
- Searches at the LHC can proceed in a variety of channels, including hard photons and/or jets plus missing energy
- The whole region consistent with EWBG may be probed by combining Tevatron and LHC searches

The power of the ILC

- Detect light stop in the whole regime compatible with DM and EWBG

Carena, Finch, Freitas, Milstene, Nowak, Sopzak '06



Assume 100% BR for $\tilde{t} \longrightarrow c + \tilde{\chi}^0$

Signature: 2 soft charm jets plus missing E

$$e^+e^- \to \tilde{t}_1\tilde{t}_1^* \to c\bar{c}\tilde{\chi}_1^0\tilde{\chi}_1^0$$

Discrimination of two-jet signature from B requires detector simulation

- Event generation with Pythia
- Detector Simulation with fast simulation Simdet for "typical" ILC detector
- Include beamstrahlung according to cold technology with Circe.

Green region: $\frac{S}{\sqrt{S+B}} > 5$ with $S = \varepsilon\sigma$

Detection of light stops possible for $\Delta_{m_{\tilde{t}\tilde{\chi}}}$ ~5 GeV

Direct detection

- Searches at colliders will be complemented by direct (and indirect) detection experiments
- These are based on nuclei--dark matter collisions and hence strongly dependent on these cross sections
- It is possible that these experiments will lead to a dark matter signature in the near future.

Direct Dark Matter Detection

- Neutralino DM is searched for in neutralino-nucleon scattering exp. detecting elastic recoil off nuclei
- Hatched region: Excluded by LEP2 chargino searches

Balazs, Carena, Menon, Morrissey, C.W.'04