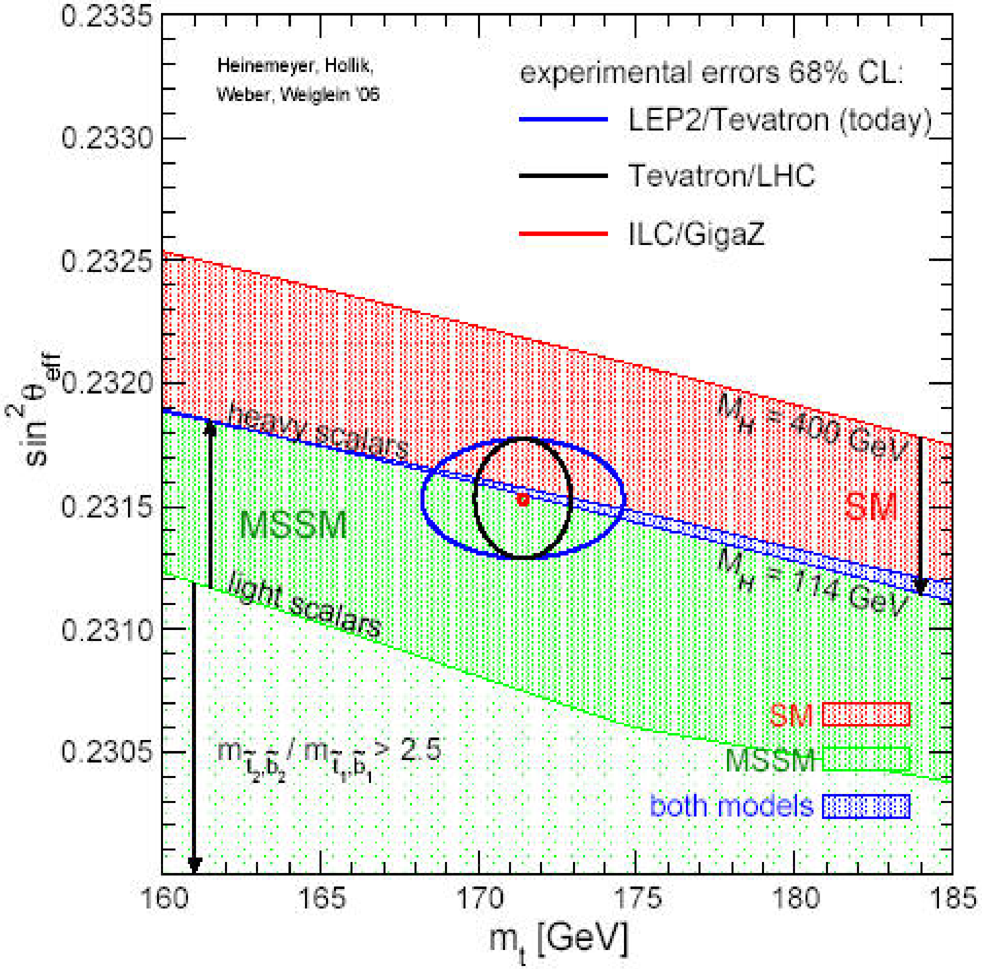
Summary: SUSY, New Physics, Cosmology and the ILC

- 34 great talks in these sessions!
- Disclaimer: I can't possibly cover them all – my apologies to those omitted

Supersymmetry: Predictions & Constraints

Symmetry Magazine

Prediction for $\sin^2\theta_{eff}$ in the SM and MSSM



[*S. Heinemeyer, W. Hollik, A.M. Weber, G. W. '07*]

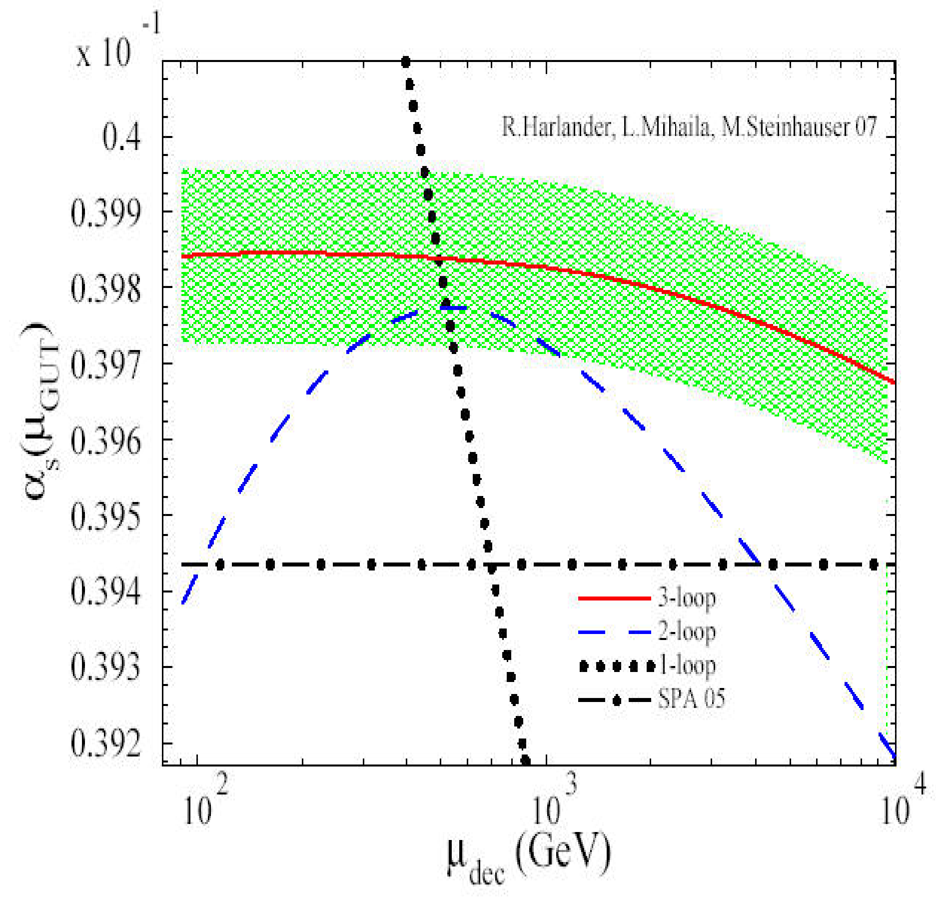
MSSM: SUSY parameters varied

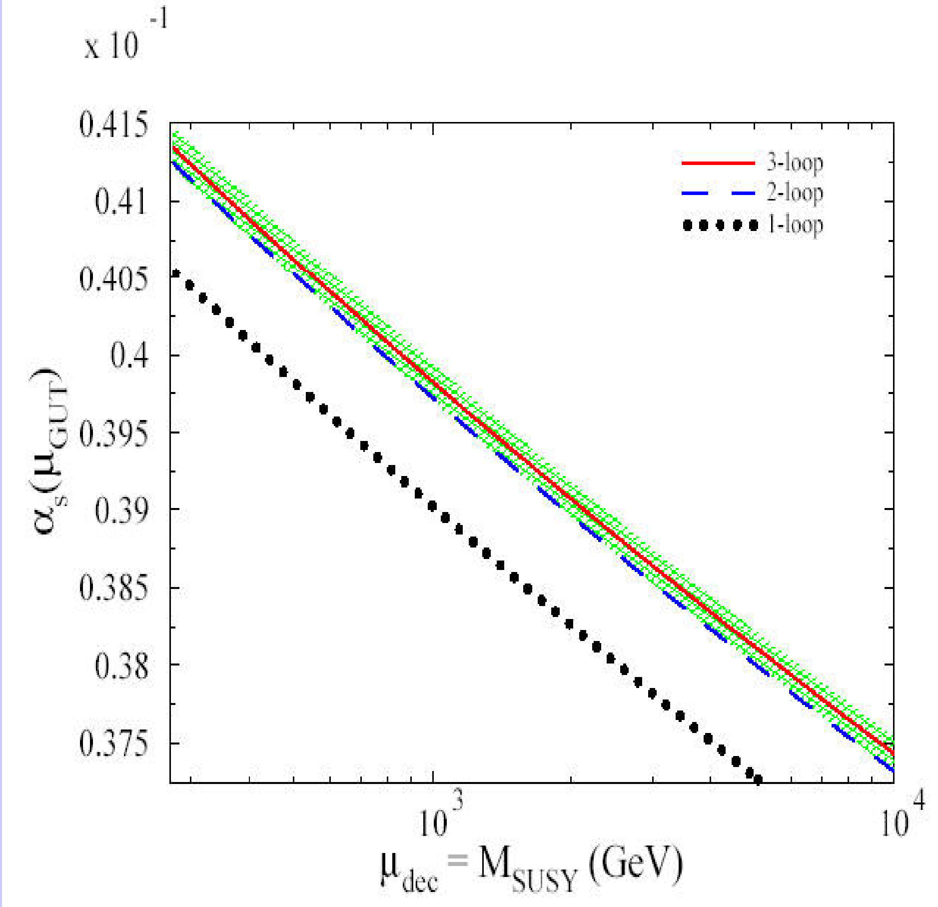
SM: M_H varied

L. Mihaila

3-Loop Evaluation of α_s in SUSY

Important for extrapolations to the GUT scale





S. Heinemeyer

Predictions for SUSY

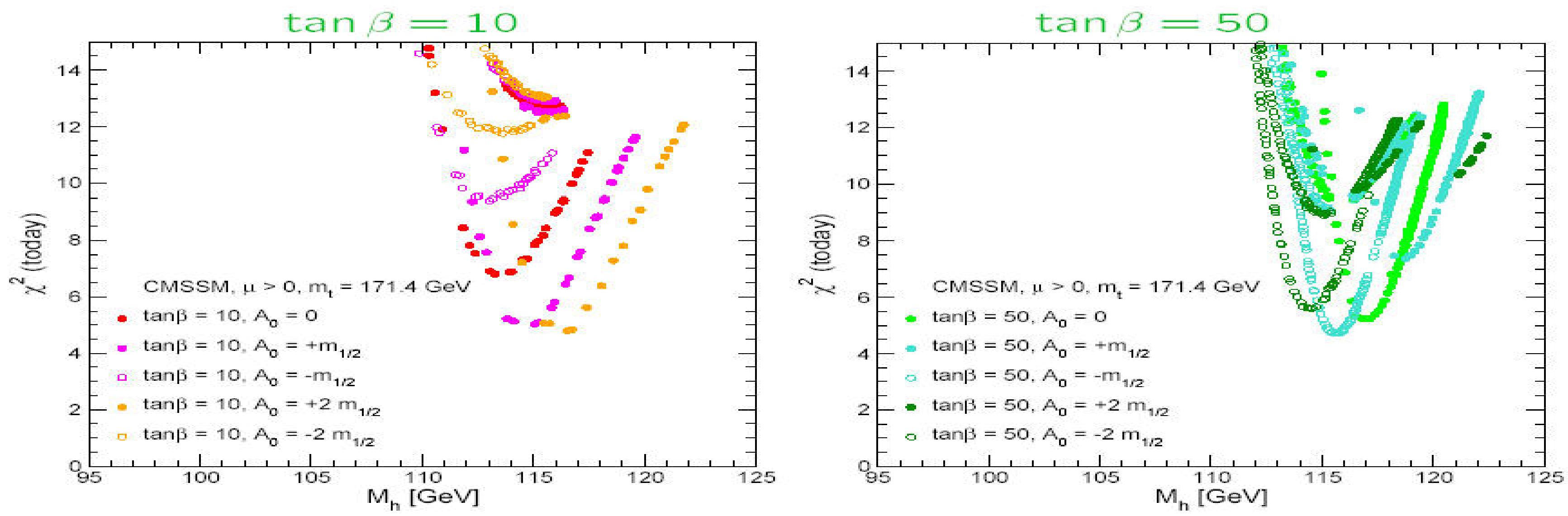
- Update global fit to include the observables:

  – Use existing data of M_W, $\sin^2\theta_{\rm eff}$, BR$(b \to s\gamma)$, $(g-2)_\mu$, M_h
  new observables: Γ_Z, BR$(B_s \to \mu^+\mu^-)$, BR$(B_u \to \tau\nu_\tau)$, ΔM_{B_s}

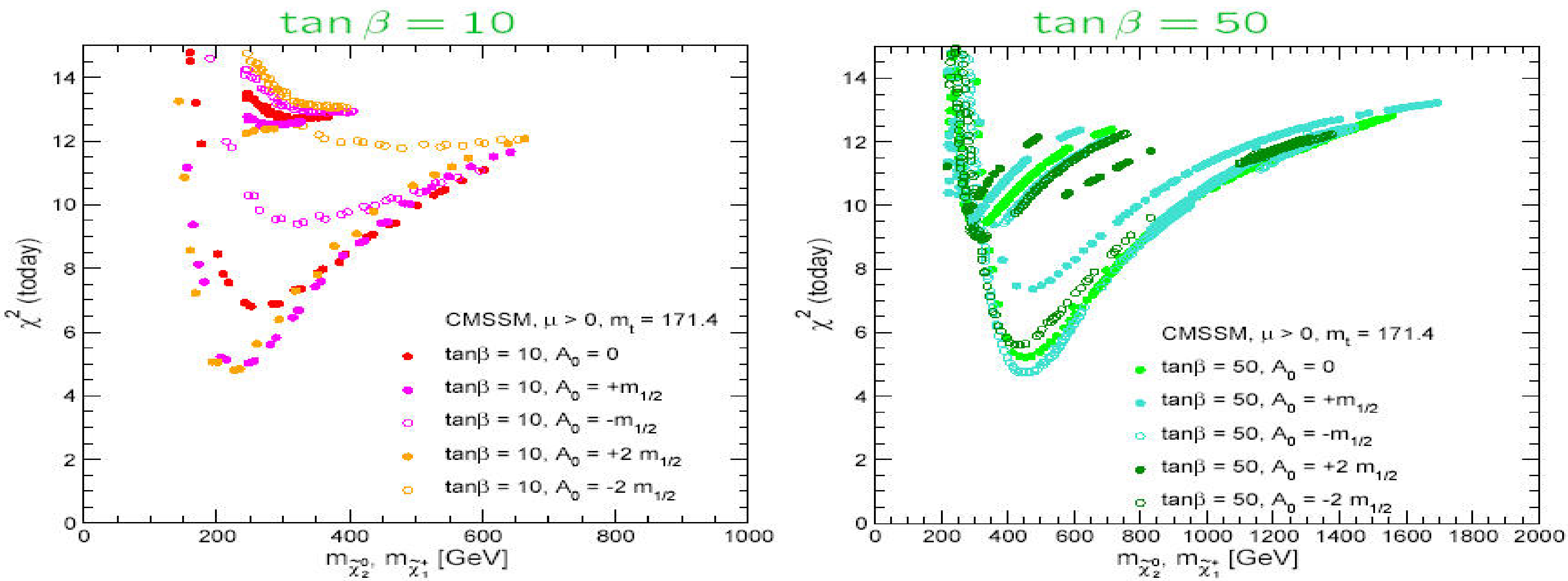
- For the CMSSM and NUHM

m_0, $m_{1/2}$, A_0, $\tan\beta$, sign μ and M_A and μ

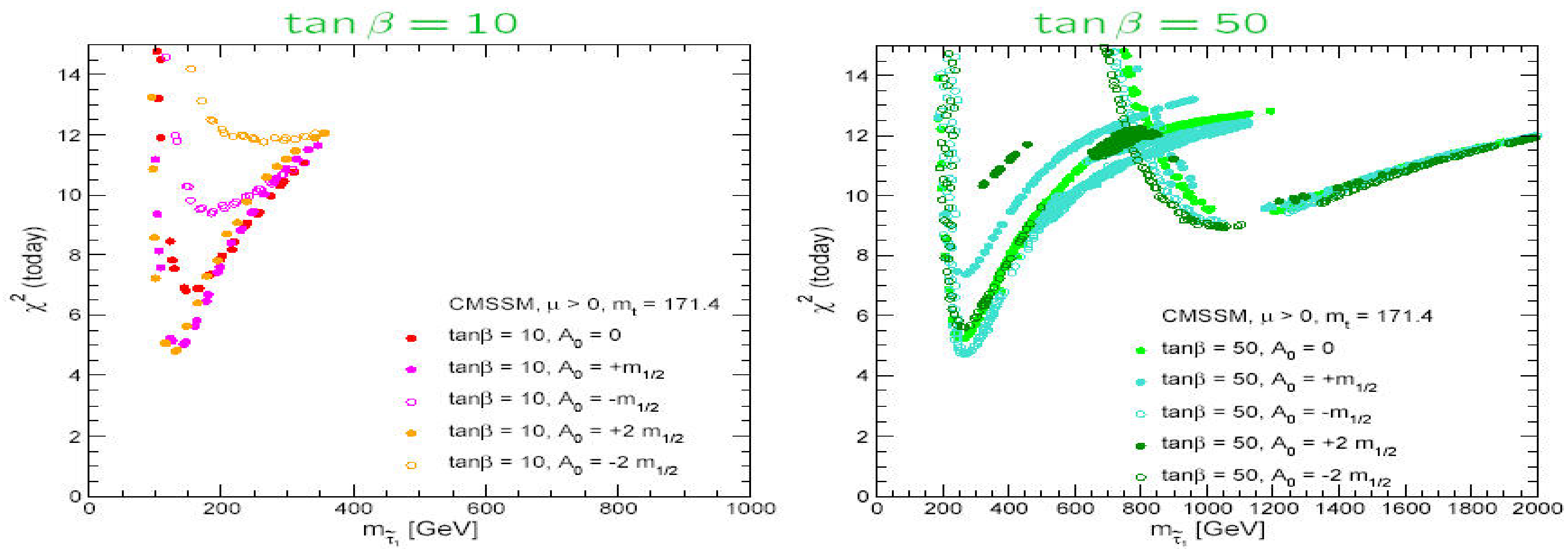
Results: CMSSM: prediction for M_h



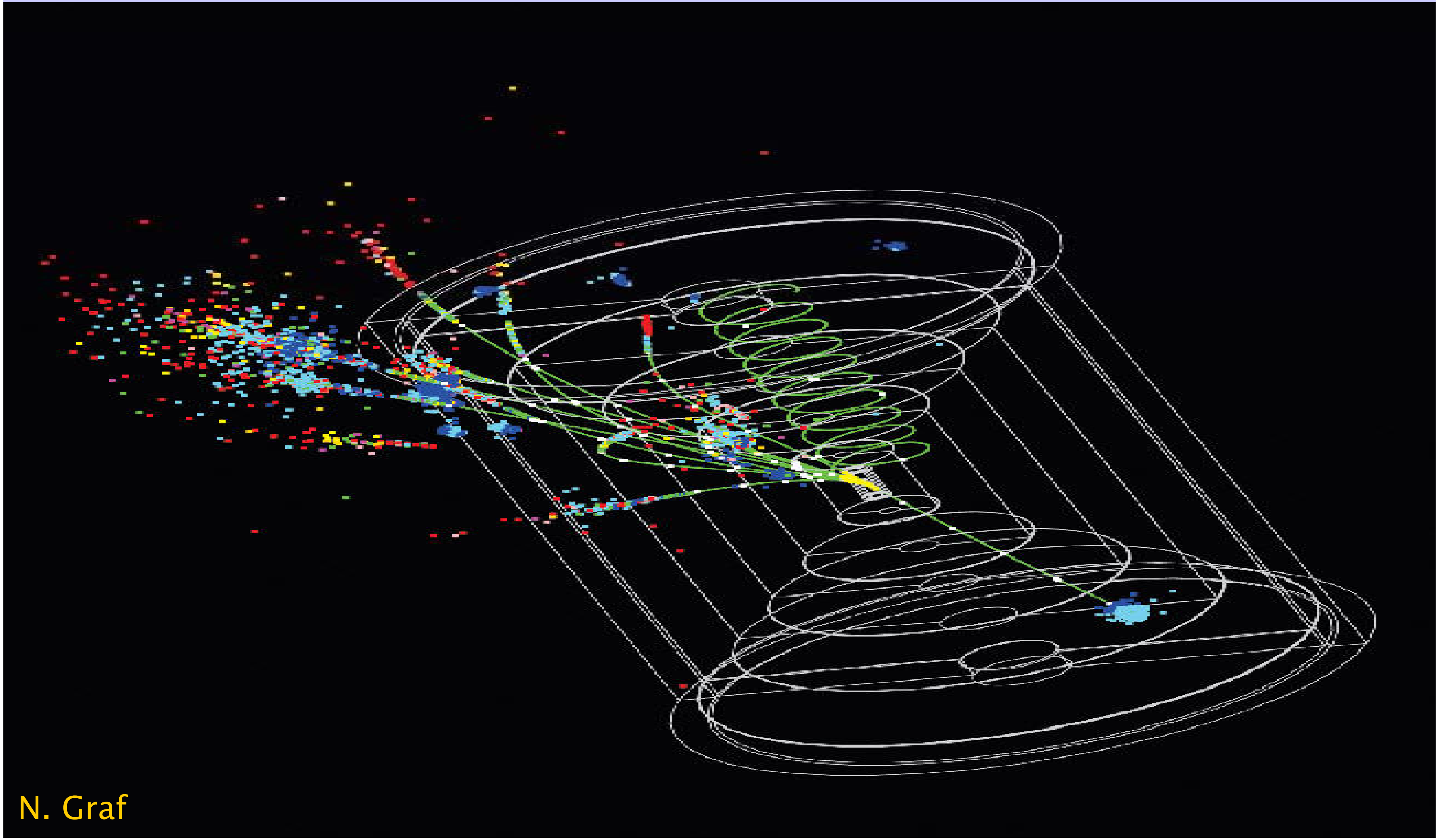
Results: CMSSM: prediction for $m_{\tilde{\chi}_2^0} \approx m_{\tilde{\chi}_1^\pm}$



Results: CMSSM: prediction for $m_{\tilde{\tau}_1}$



Supersymmetry: Production @ ILC



N. Graf

J. Reuter

Corrections to SUSY Production

- Off-shell kinematics for signal
- Irreducible bckgrnd from SUSY
- Reducible SM bckgrnd

Factorization in $2 \to 2$ production and decay insufficient/wrong

Off-shell effects and interferences affect results (especially with cuts)

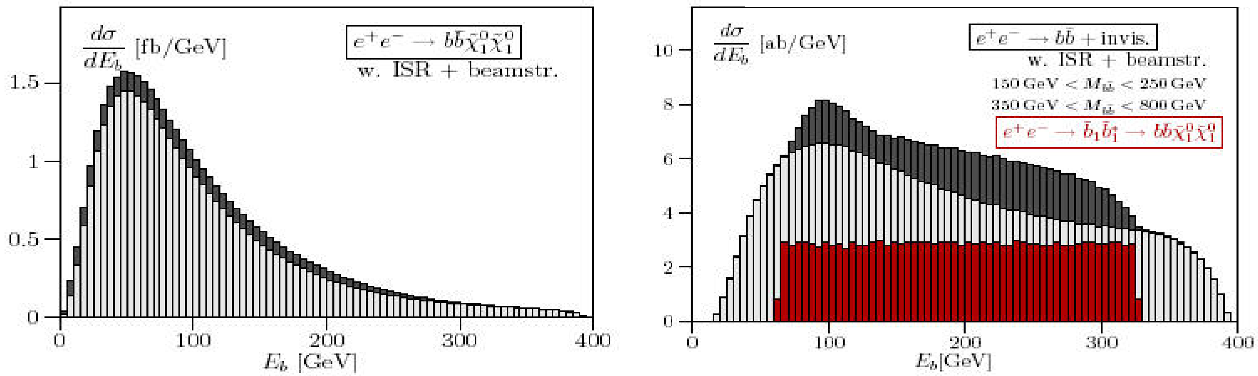
Use full matrix elements

Tools are available for ILC/LHC: Whizard/O'Mega

- More channels contribute to $e^+e^- \to b\bar{b}\tilde{\chi}_1^0\tilde{\chi}_1^0$:

  $e^+e^- \to Zh, ZH, Ah, HA, \tilde{\chi}_1^0\tilde{\chi}_2^0, \tilde{\chi}_1^0\tilde{\chi}_3^0, \tilde{\chi}_1^0\tilde{\chi}_4^0, \tilde{b}_1\tilde{b}_1^*, \tilde{b}_1\tilde{b}_2^*$ (412 diagrams)
- Irreducible SM background: $e^+e^- \to b\bar{b}\nu_i\bar{\nu}_i$ (WW fusion, Zh, ZZ)

$\tilde{b}_1 \to b\tilde{\chi}_1^0$ decay kinematics affected



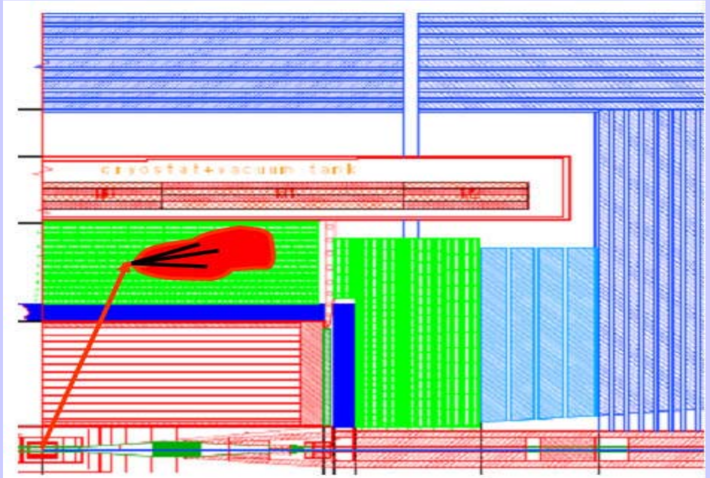
Example:
b-squark production
@$\sqrt{s}$ = 800 GeV

U. Martyn

Metastable Staus & Gravitinos

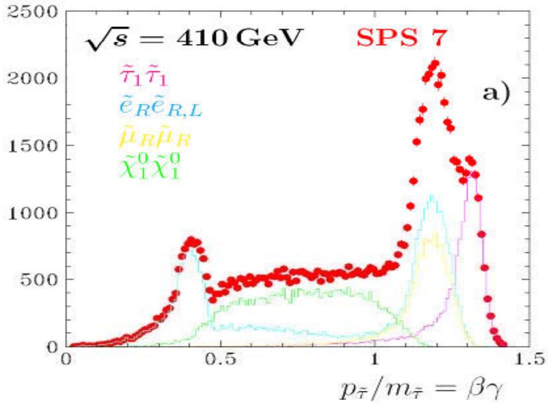
- Present in gauge/gaugino mediation
- Gravitino is good DM candidate

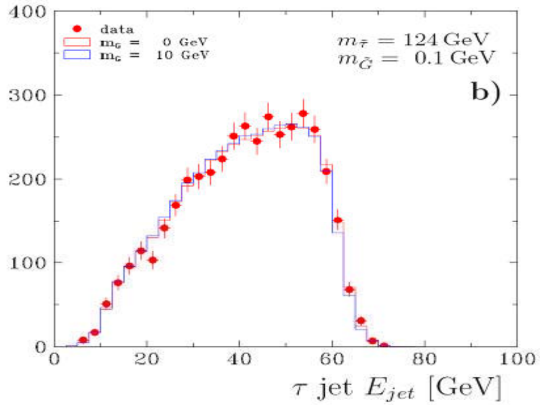
$$\tilde{\tau} \longrightarrow \tau \tilde{G}$$



- Stau stops
- Stau decays (record lifetime)
- Measure recoil spectra

Difficult @ LHC!





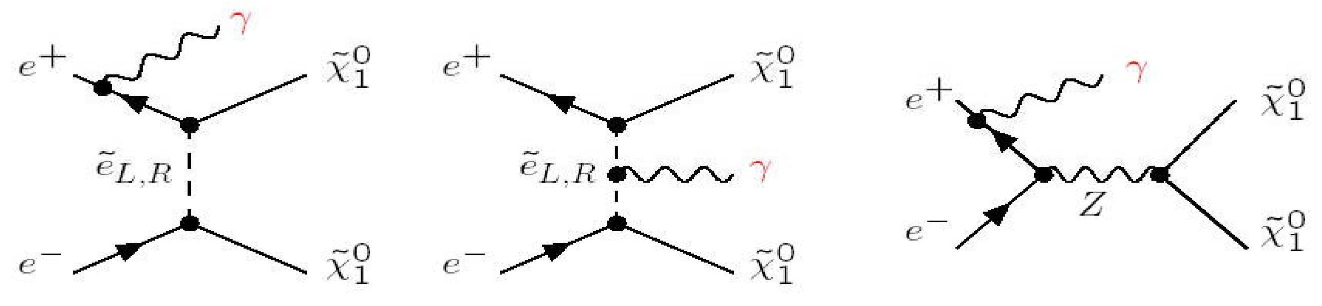
Pulse operation of detectors needs to be revised for long-lived particles

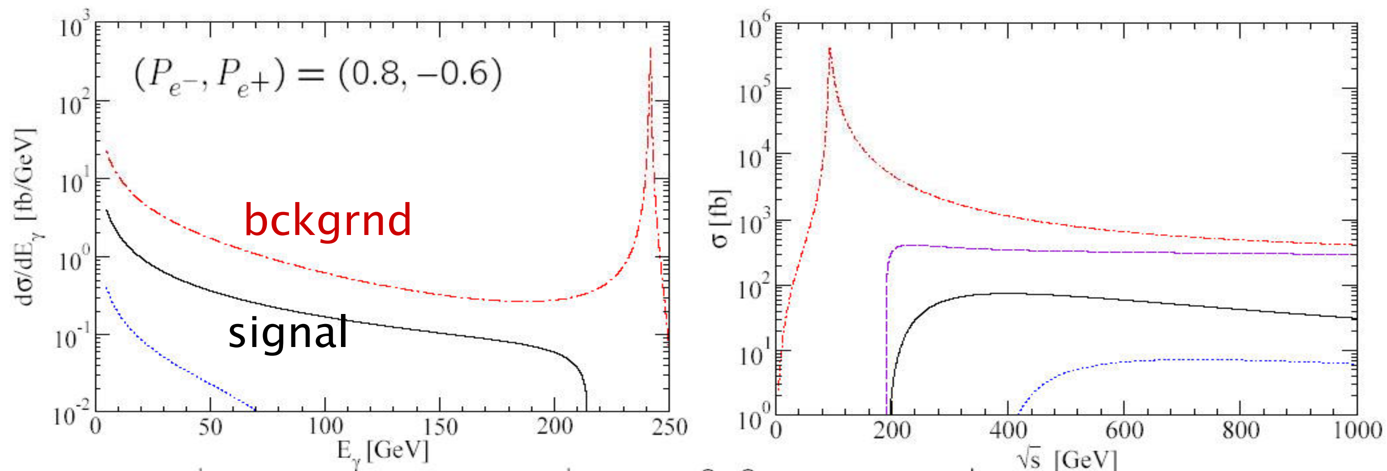
$m_{\tilde{\tau}}$ [GeV]	$t_{\tilde{\tau}}$ [s]	$m_{\tilde{G}}(\Gamma_{\tilde{\tau}})$	$m_{\tilde{G}}(E_\tau)$
124.3 ± 0.1	209.3 ± 2.4	0.1 ± 0.001	< 9
	$(2.1 \pm 0.02)\ 10^6$	10 ± 0.1	10 ± 5

O. Kittel

Radiative Neutralino Production

$e^+e^- \to \chi_1{}^0\chi_1{}^0 + \gamma$





solid: $e^+e^- \to \nu\bar{\nu}\gamma$, dashed: $e^+e^- \to \tilde{\chi}_1^0\tilde{\chi}_1^0\gamma$, dotted: $e^+e^- \to \tilde{\nu}\tilde{\nu}^*\gamma$

Is this observable?

Need full MC study…

Polarized beams enhance signal reduce bckgrnd

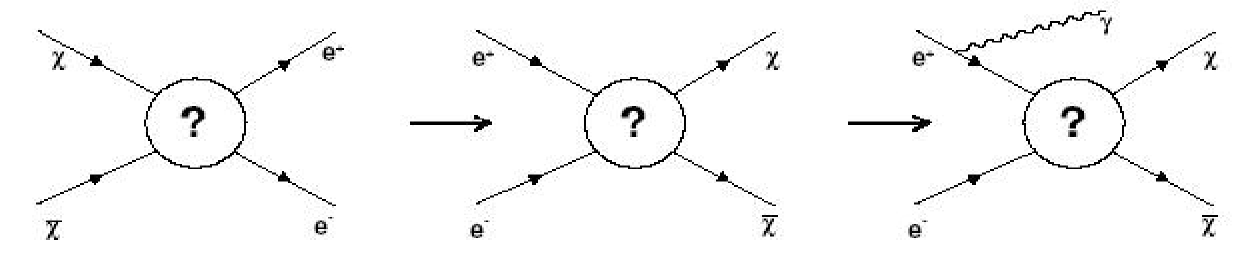
Results for sample msugra point

(P_{e^+}, P_{e^-})	(0|0)	(0|0.8)	(−0.3|0.8)	(0|0.9)	(−0.3|0.9)	(−0.6|0.8)
$\sigma(\tilde{\chi}_1^0\tilde{\chi}_1^0\gamma)$	4.7 fb	8.2 fb	11 fb	8.6 fb	11.2 fb	13 fb
$\sigma_B(\nu\bar{\nu}\gamma)$	3354 fb	689 fb	495 fb	356 fb	263 fb	301 fb
S	1.8	7	11	10	15	17
$R = \sigma/\sigma_B$	0.1%	1.2%	2.2%	2.4%	4.3%	4.4%

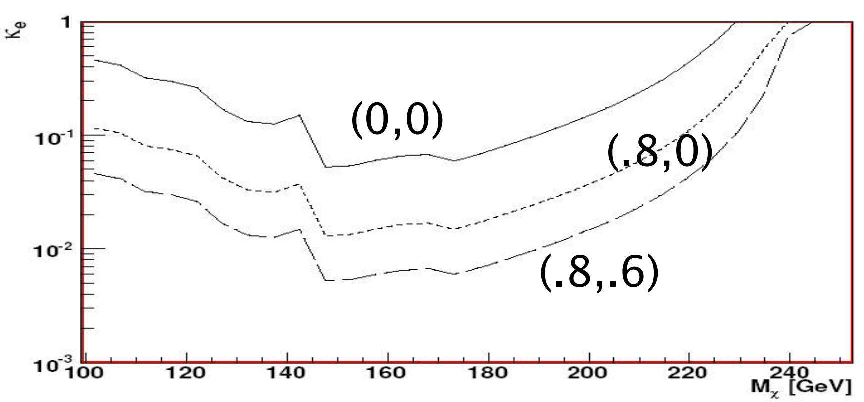
J. List

Model Independent WIMP Searches

No assumptions on nature of WIMP interactions



coupling: $e_R^- \; / \; e_L^+$



3σ Sensitivity in coupling strength – mass plane after full detector simulation of signal & background

Beam polarization enhances reach & mass resolution

WIMP (Case 2):

- P-wave annihilator (J=1), $S_\chi = \frac{1}{2}$
- couplings: $e_R^- \; / \; e_L^+$
- $M_\chi = 180$ GeV
- $\kappa_e = 0.3$

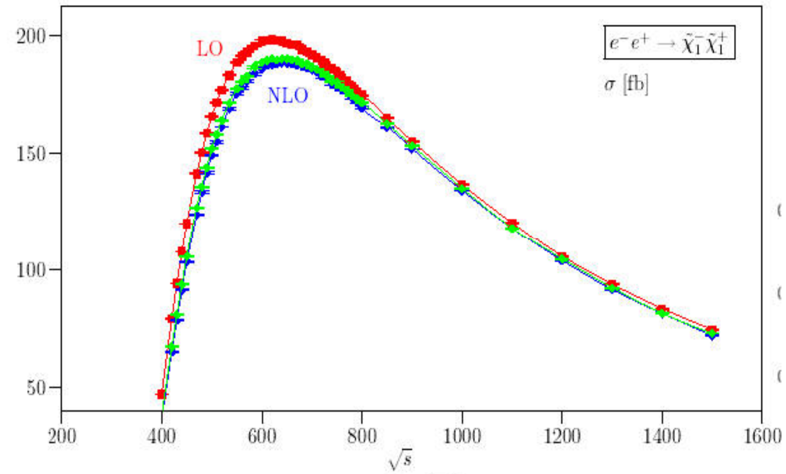
Mass resolution

- $P_{e^-} = 0.8, P_{e^+} = 0.0$: $M_\chi = 180.7 \pm 1.3$ GeV
- $P_{e^-} = 0.8, P_{e^+} = 0.6$: $M_\chi = 180.5 \pm 0.6$ GeV

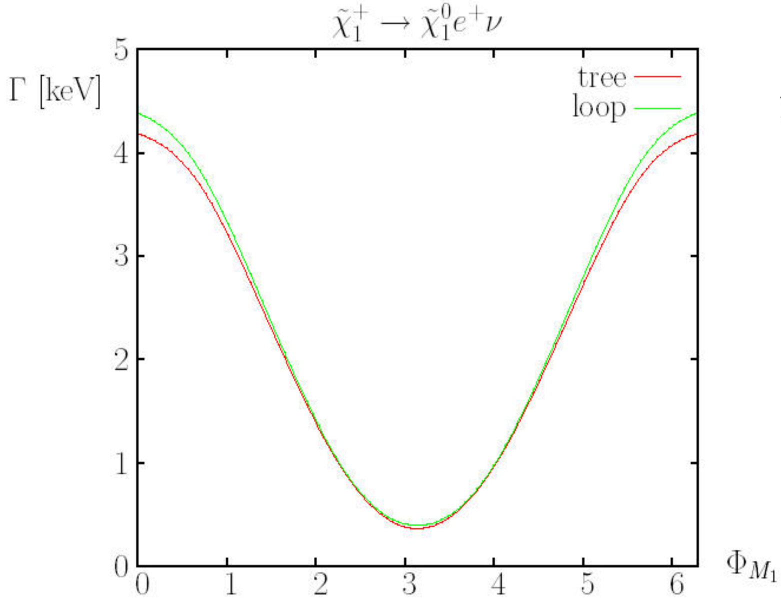
Chargino Production & Decay @ NLO

T. Robens

- Implement NLO corrections to production in WHIZARD
  - Theoretical precision match exp't precision
  - Agrees well with literature
  - Resum γ's allows soft cuts



$\sigma(\sqrt{s})$



- NLO corrections to $\chi^{\pm}$ Decays with CP violating interactions
  - Calculated in on-shell scheme

K. Rolbiecki

S. Hesselbach

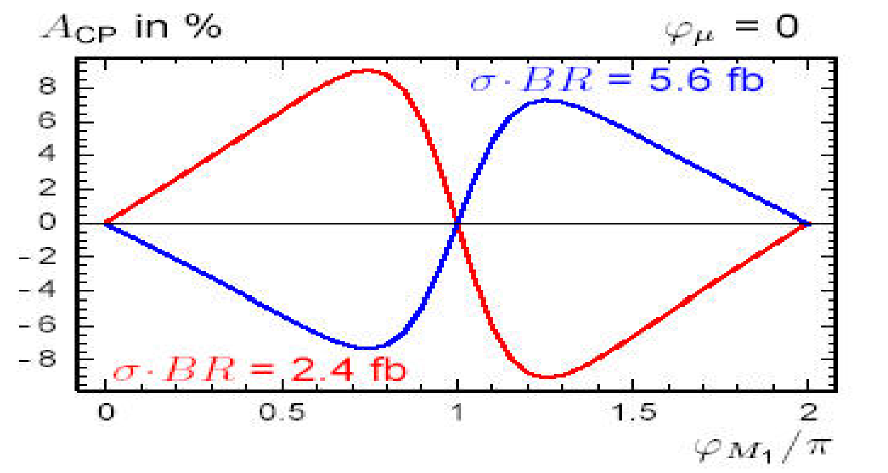
CP Violation in SUSY Production & Decay

- Determine phases & CP structure of SUSY
- Form CP-odd observables in $\chi^{\pm}$, χ^0 production & decay

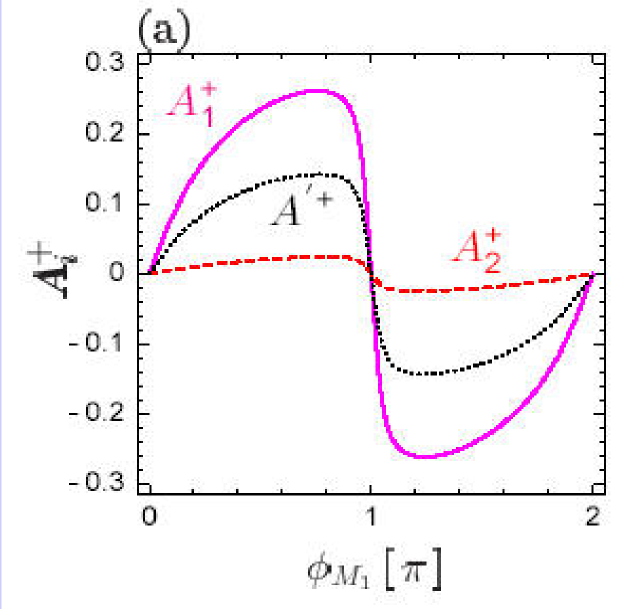
Triple product asymmetry in gaugino decay

Triple products: $\mathcal{T} = \vec{p}_{e^-} \cdot (\vec{p}_f \times \vec{p}_{\bar{f}^{(\prime)}})$ or $\mathcal{T} = \vec{p}_{e^-} \cdot (\vec{p}_{\tilde{\chi}_j} \times \vec{p}_f)$

T-odd asymmetry: $A_{\mathcal{T}} = \frac{\sigma(\mathcal{T} > 0) - \sigma(\mathcal{T} < 0)}{\sigma(\mathcal{T} > 0) + \sigma(\mathcal{T} < 0)}$

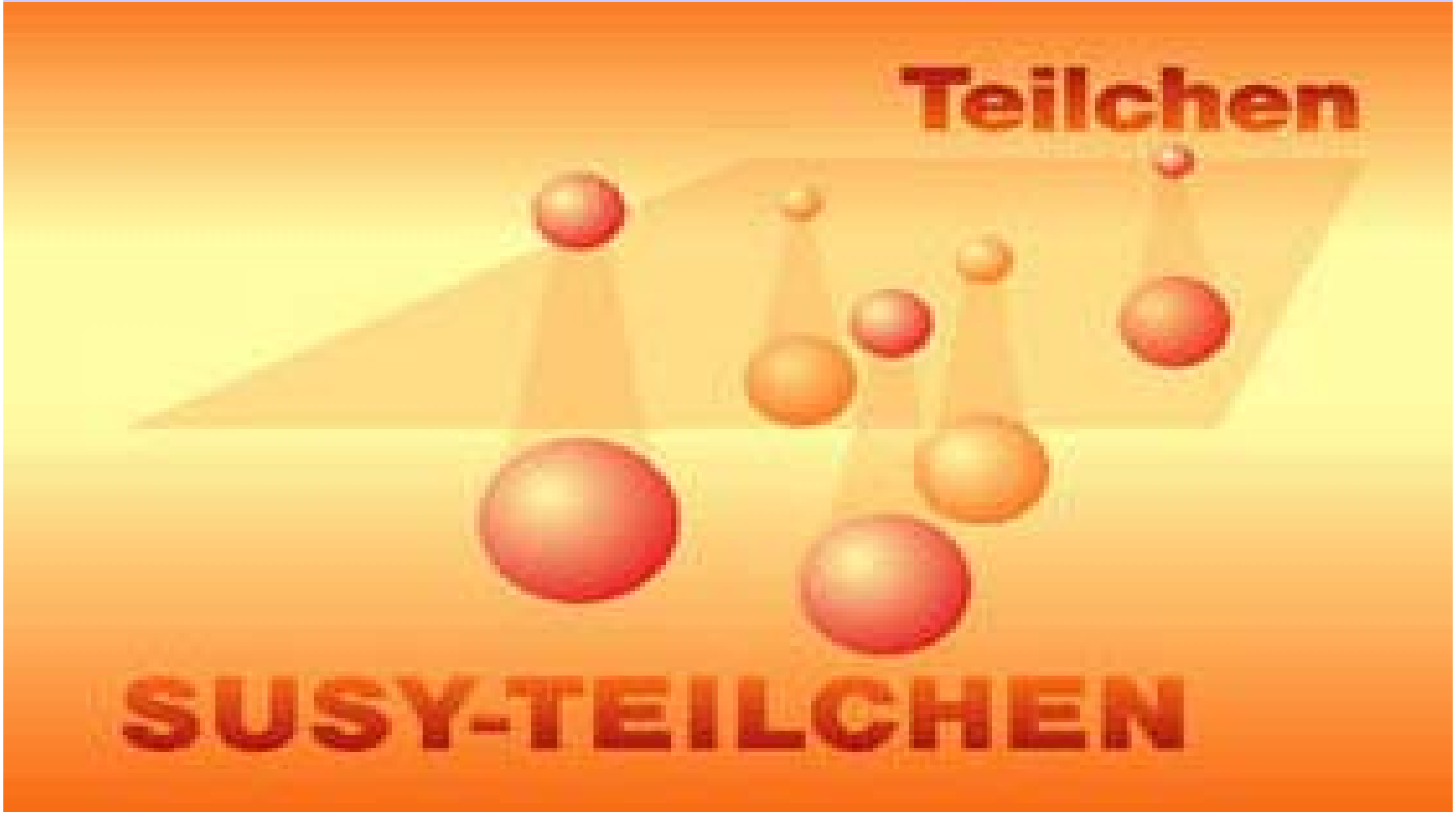


T-odd asymmetry with transverse beam pol



Asymmetries can be ~10-20%

Supersymmetry: Parameter Determination



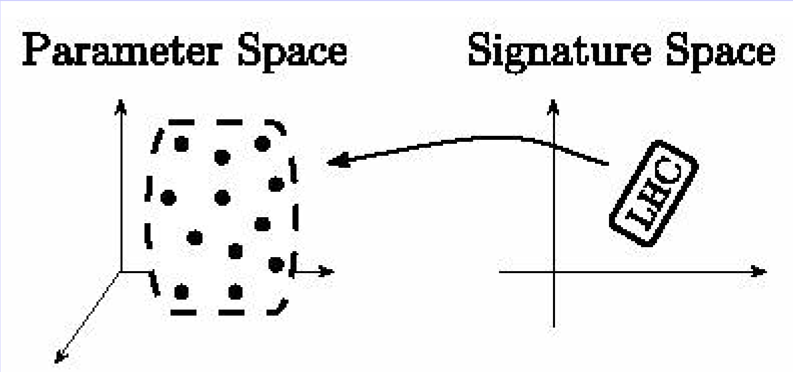
LHC Inverse Problem

Generate blind SUSY data and map it back to parameters in the fundamental Lagrangian

- Generated 43,026 models within MSSM for 10 fb^{-1} @ LHC
- For 15 parameters:

Inos :	$M_1,\ M_2,\ M_3,\ \mu$
Squarks :	$m_{\tilde{Q}_{1,2}},\ m_{\tilde{U}_{1,2}},\ m_{\tilde{D}_{1,2}},\ m_{\tilde{Q}_3},\ m_{\tilde{t}_R},\ m_{\tilde{b}_R}$
Sleptons :	$m_{\tilde{L}_{1,2}},\ m_{\tilde{E}_{1,2}},\ m_{\tilde{L}_3},\ m_{\tilde{\tau}_R}$

+ $\tan\beta$



Main result:
<degeneracies> ~ 242 models
A signature maps back into a number of small islands in parameter space

Begs the question.....

Arkani-Hamed, Kane, Thaler, Wang, hep-ph/0512190

$ILC = LHC^{-1}$?

Our Analysis:

- 10 simultaneous SUSY channels (Pythia & CompHEP) of 242 models
- Full SM bckgrnd (Whizard)
- ISR, Beamstrahlung, Beam energy spread
- SiD detector simulation
- Analyze 500 fb^{-1} "data" at 500 GeV with 80% P_{e-} and appropriate cuts

Several iterations necessary to find best cuts!

Our Results:

- Random SUSY signal smaller than SPS1a
- Many SPS1a cuts kill random SUSY signal
- Pythia underestimates SM bckgrnd
- Forward detector coverage critical
- Some difficult cases:

  close stau-LSP mass,

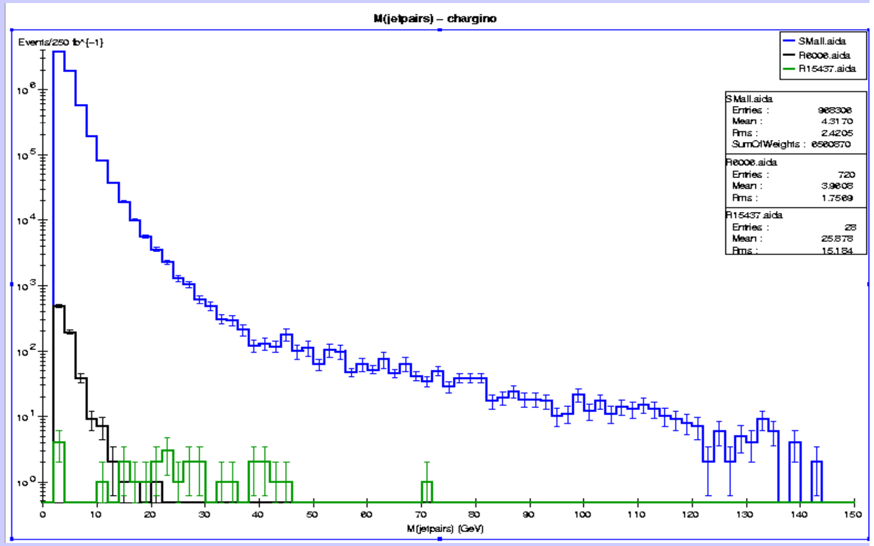
  $\chi_1^{\pm} \rightarrow W^{*}\chi_1^{0} \rightarrow jj\ \chi_1^{0}$

Random SUSY signal is not a piece of cake!

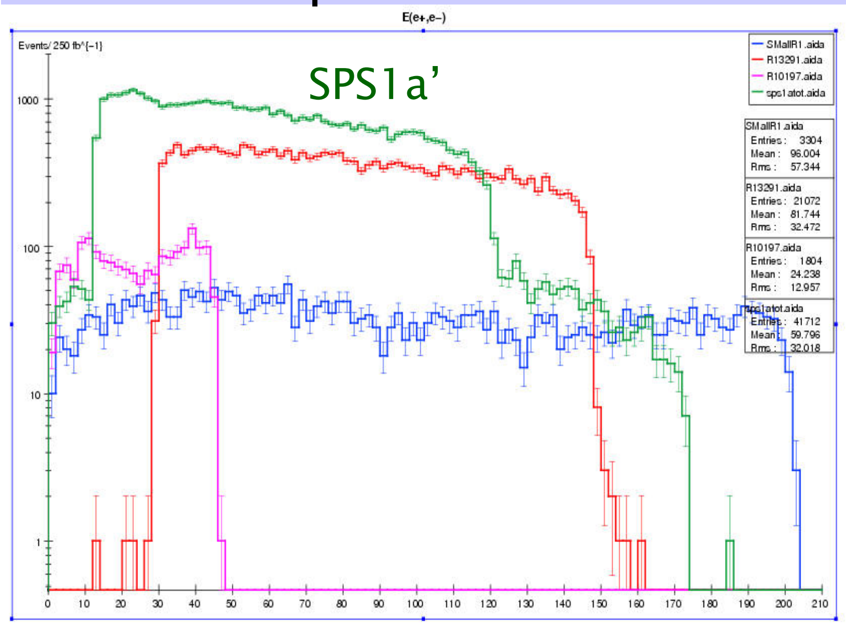
Berger, Gainer, JLH, Lillie, Rizzo

Sample Results

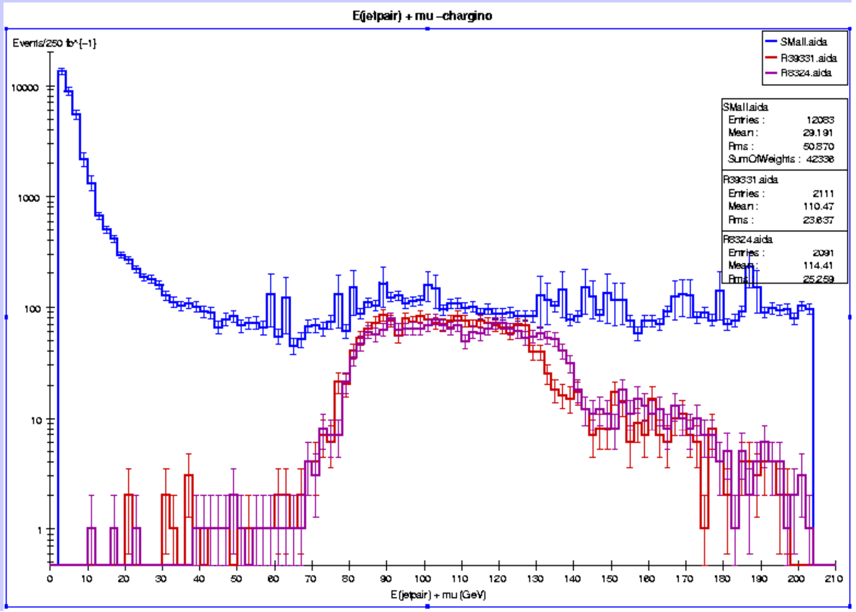
Chargino pair → jj jj + missing, off-shell W's



Selectron production



Blue = SM bckgrnd
Model A
Model B

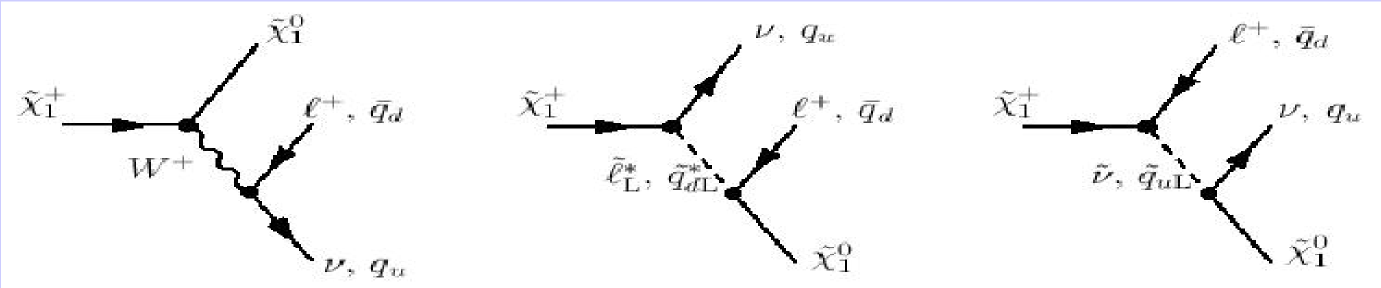


Chargino pair → jj + μ + missing, on-shell W's

G. Moortgat-Pick

SUSY with Heavy Sfermions

- Study light gaugino production



- Masses, production rates, A_{FB} of final leptons/squarks- sensitive to high scale virutal particles
- Precise mass & parameter determinations

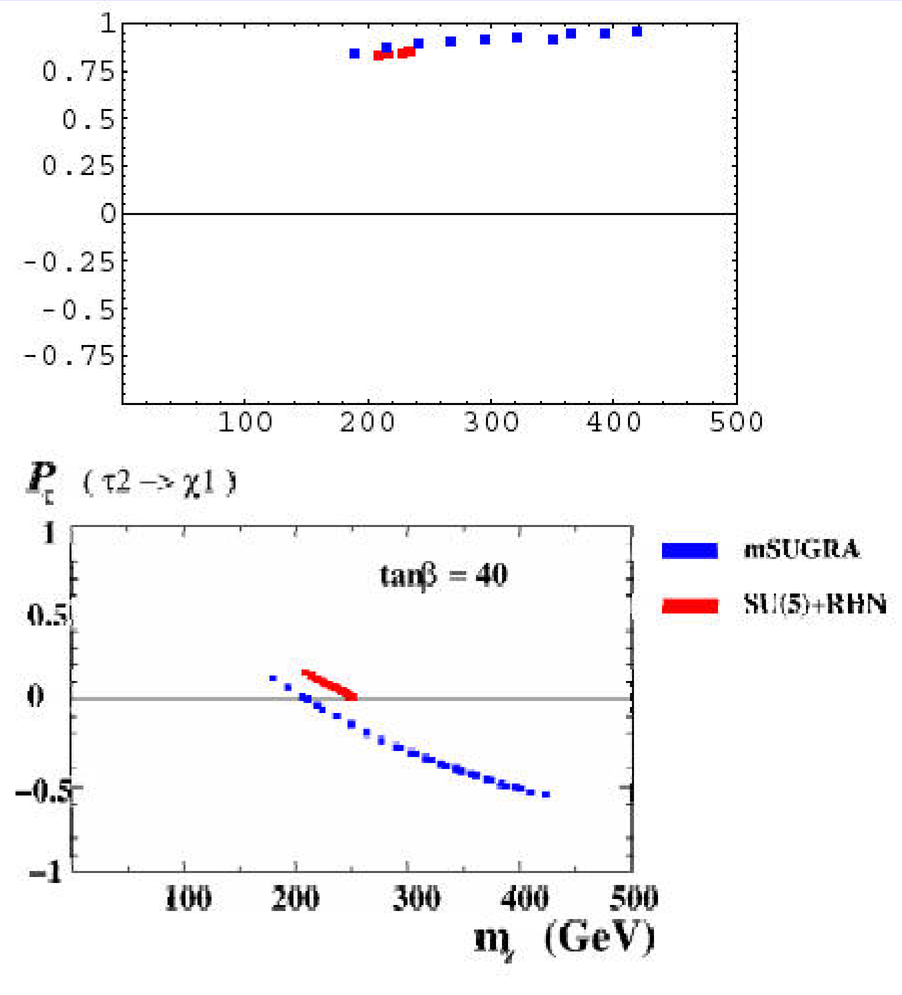
$$506 < m_{\tilde{\chi}^0_3} < 615\,GeV$$
$$512 < m_{\tilde{\chi}^0_4} < 619\,GeV$$
$$514 < m_{\tilde{\chi}^\pm_2} < 621\,GeV$$

$$59.7 \leq M_1 \leq 60.35 \text{ GeV}, \quad 119.9 \leq M_2 \leq 122.0 \text{ GeV},$$
$$500 \leq \mu \leq 610 \text{ GeV}, \quad 14 \leq \tan\beta \leq 31$$
$$1900 \leq m_{\tilde{\nu}_e} \leq 2100 \text{ GeV}$$

R. Godbole

Tau Polarization Observables

- Distinguish between msugra & SUSY-GUT models



- For $\tilde{\tau}_1 \to \tau\tilde{\chi}_1^0$ the P_τ is the same for mSUGRA and $SU(5)+$ RHN.

- For $\tilde{\tau}_2 \to \tau\tilde{\chi}_1^0$ is completely different.

Determination of SO(10) GUT parameters

- Low energy stau mass measurement

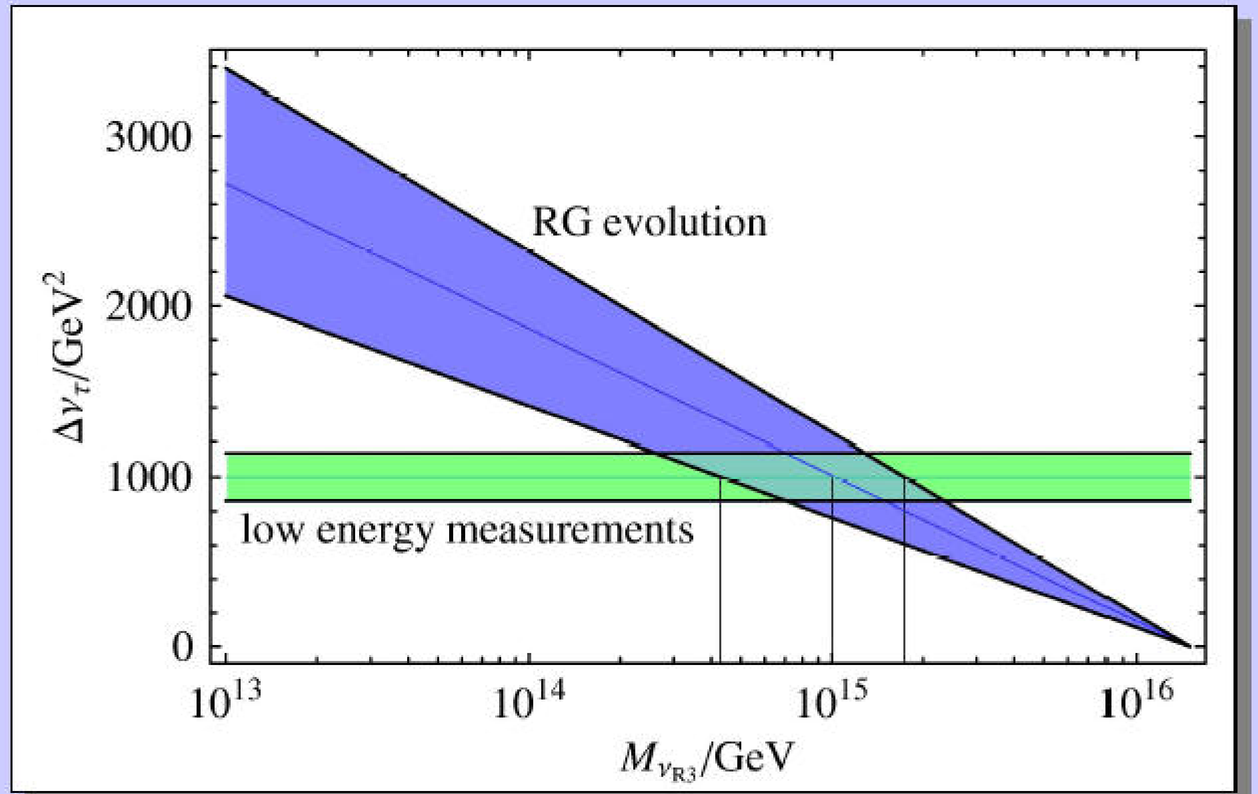
$$\Delta_{\nu_\tau} = (1.0 \pm 0.14) \cdot 10^3\,\mathrm{GeV}^2$$

- Heavy neutrino mass

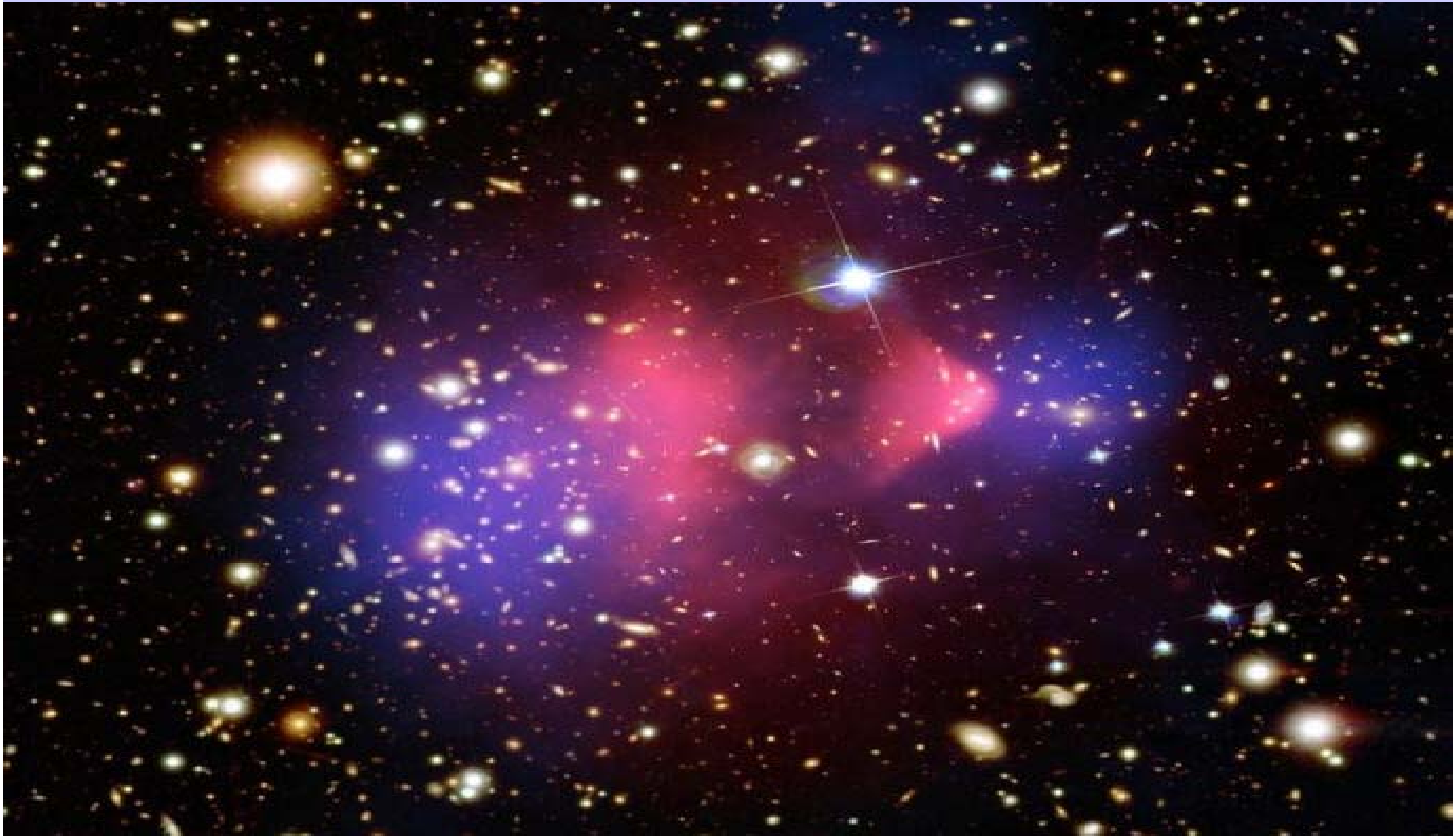
$$M_{\nu_{R3}} = (1.0 \pm 0.6) \cdot 10^{15}\,\mathrm{GeV}$$

- Light neutrino mass

$$m_{\nu_1} = (3.0^{+10}_{-2.0}) \cdot 10^{-3}\,\mathrm{eV}$$



Cosmology and the ILC



A Recent Comprehensive DM Study:

- Assume standard SUSY benchmark points
- Identify expected collider measurements
  - Masses, (polarized) production cross sections, FB asymmetries
- Generate 10^6 SUSY models consistent w/ experiment
  - 24 parameters, most general MSSM conserving flavor, CP
- Study range of properties relevant to Dark Matter
  - LHC
  - 500 GeV ILC
  - 1 TeV ILC

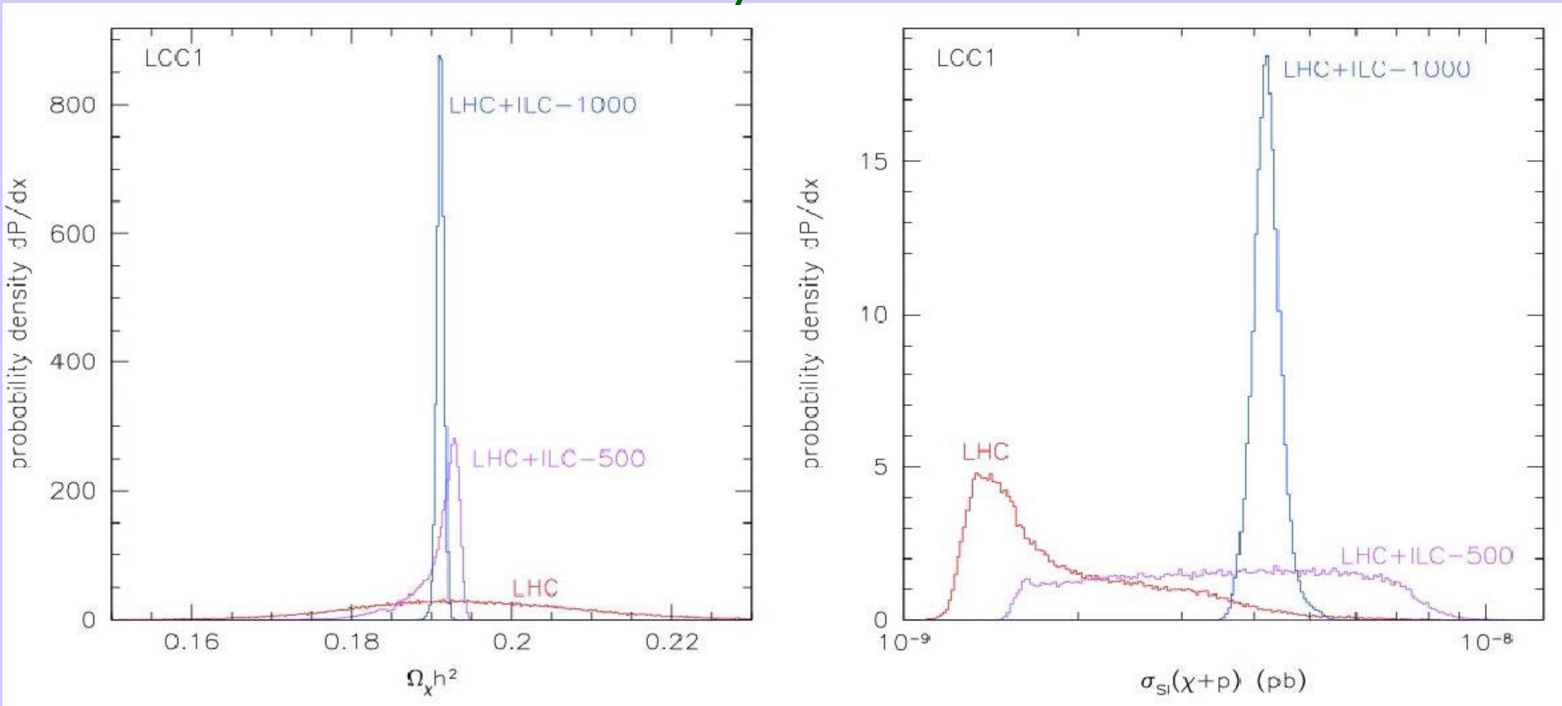
Baltz, Battaglia, Peskin, Wizansky, hep-ph/0602187

Example: SPS1a, "Bulk region"

- LHC discovers 3 neutralinos, all squarks (except stop), all sleptons (except heavy stau), light higgs
- ILC 500 discovers heavy stau, light chargino, electron sneutrino
- ILC 1000 discovers heavy chargino, light stop, heavy higgs

Prediction of relic density

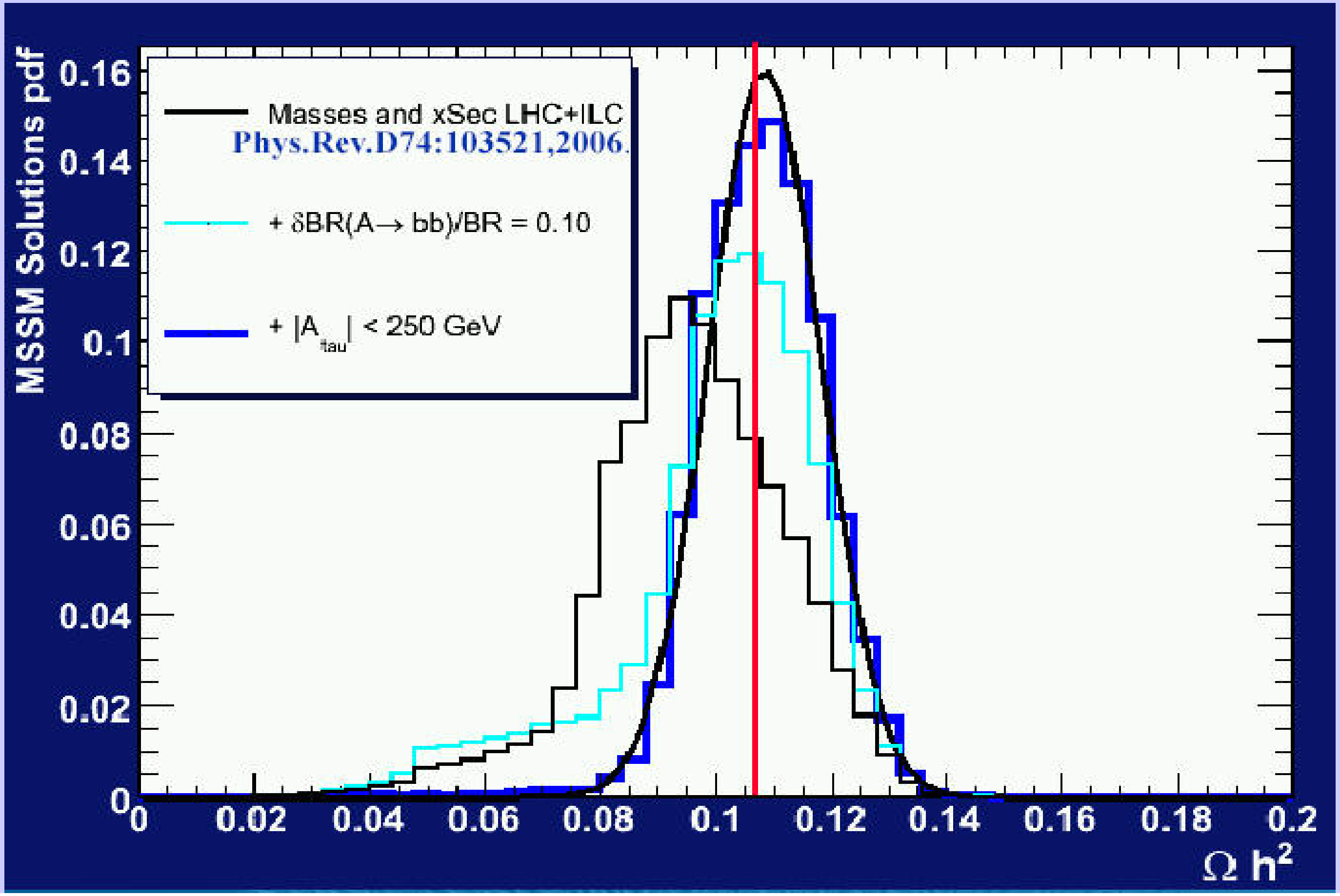
Direct detection



M. Battaglia

Evolution of Relic Density Determination for LCC4

- ILC-Cosmology Benchmark point LCC4
- Collider measurements for SUSY production @ LHC/ILC + Higgs property determinations



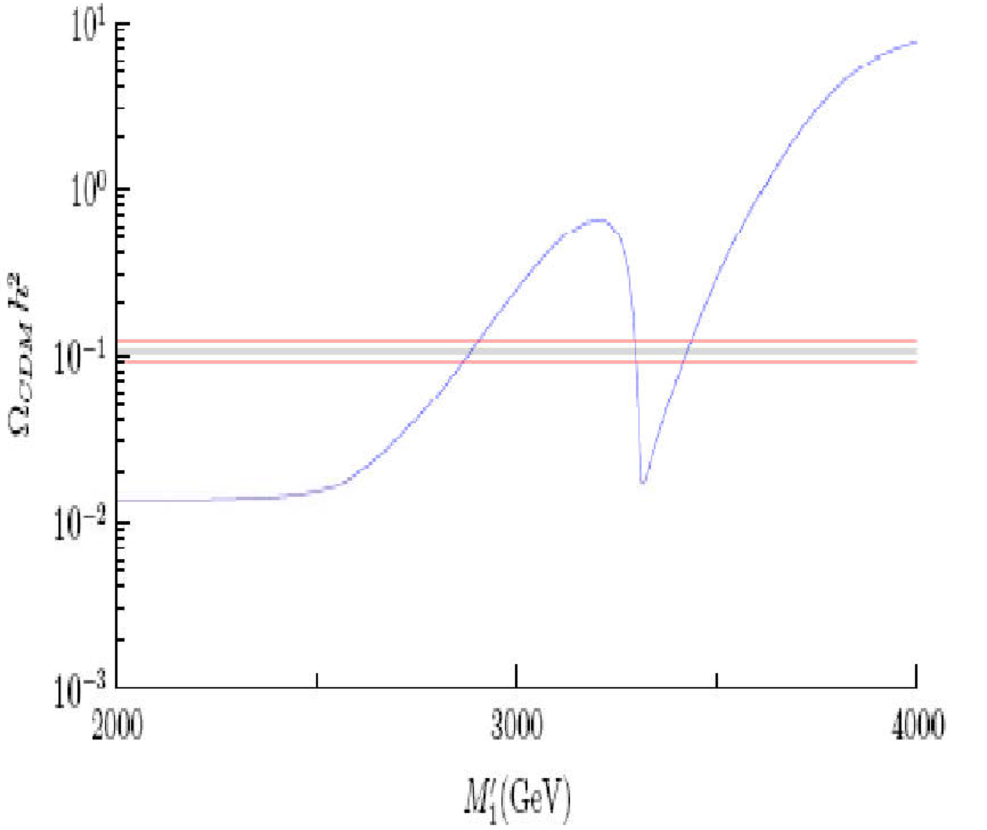
Full detector simulation

J. Kalinowski

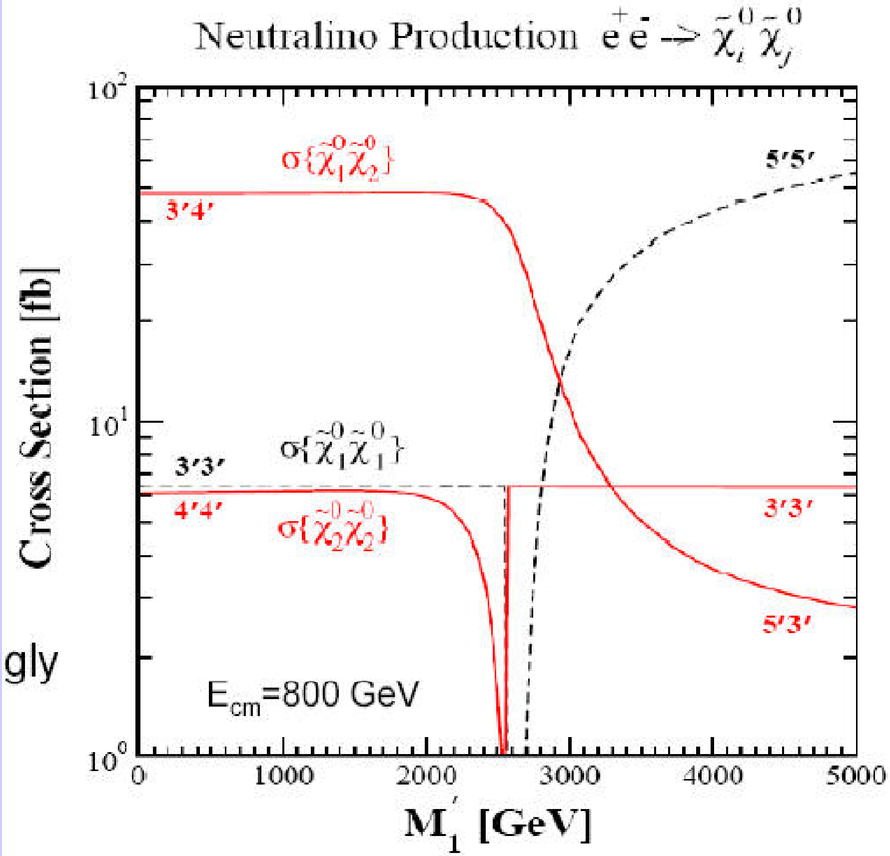
SUSY with extra U(1)

M_1' mass of new gaugino singlet (after mixing)

Relic Density Constraints



Influence on Collider Production



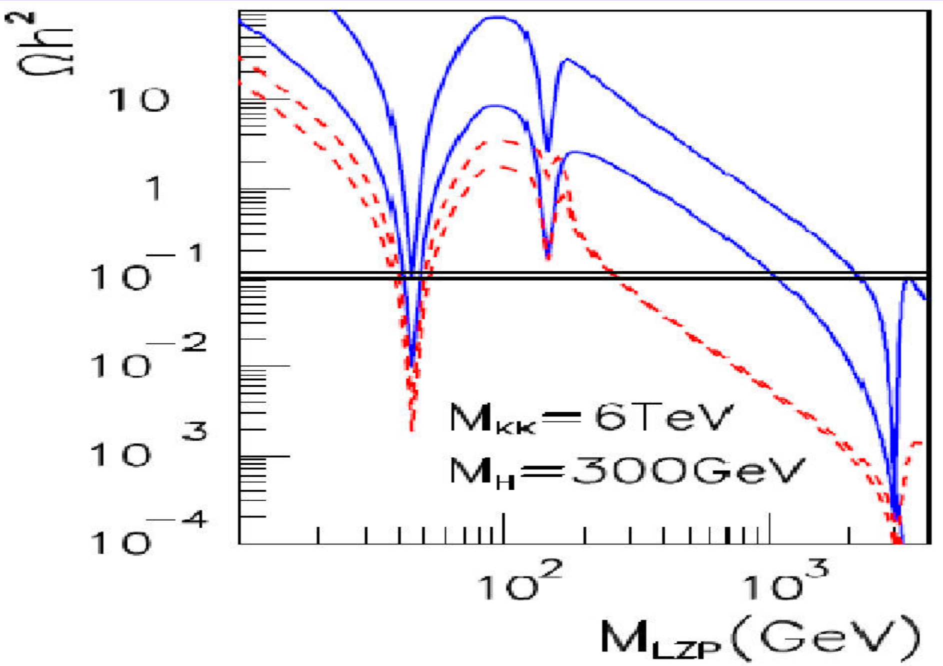
G. Belanger

Warped Extra Dimension with SO(10) in the bulk

- Splits families amongst 16 of SO(10) with different Z_3 charges: Baryon symmetry in bulk
- Lightest Z-odd particle, ν_R' KK state, is stable

$$\begin{pmatrix} \mathbf{u_L}\,,\mathbf{d_L} \\ u'^c_R \\ d'^c_R \\ \nu'_L\,,e'_L \\ e'^c_R \\ \nu'^c_R \end{pmatrix}_{B=1/3}, \quad \begin{pmatrix} u'_L\,,d'_L \\ \mathbf{u^c_R} \\ \mathbf{d^c_R} \\ \nu'_L\,,e'_L \\ e'^c_R \\ \nu'^c_R \end{pmatrix}_{-1/3}, \quad \begin{pmatrix} u'_L\,,d'_L \\ u'^c_R \\ d'^c_R \\ \boldsymbol{\nu_L}\,,\mathbf{e_L} \\ \mathbf{e^c_R} \\ \boldsymbol{\nu^c_R} \end{pmatrix}_0$$

Bold-face particles have zero-modes



Gives correct relic density for wide range of masses

Comparisons of DM scenarios

Scenario		SUSY1 bino	SUSY2 higgsino	SUSY3 gravitino	LZP ν_R	LTP heavy photon
LHC	Discovery precision	*** *	* No	** ?	* ?	** ?
ILC	Discovery precision	*** ***	** *	** ?	* ?	** ?
Direct		*	***	No	***	No
Indirect	γ or ν	*	***	No	**	***

New Physics @ the ILC

Kaluza-Klein (Invisible Architecture III)

Dawn Meson

J. Reuter

Probing New Phyisics in Quartic Gauge Couplings

Encode New Physics in EW Chiral Lagrangian

$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{min}} - \sum_{\psi} \overline{\psi}_L \Sigma M \psi_R + \beta_1 \mathcal{L}'_0 + \sum_i \alpha_i \mathcal{L}_i + \frac{1}{v} \sum_i \alpha_i^{(5)} \mathcal{L}^{(5)} + \frac{1}{v^2} \sum_i \alpha_i^{(6)} \mathcal{L}^{(6)} + \dots$$

$$\mathcal{L}'_0 = \frac{v^2}{4} \operatorname{tr}\{\mathbf{T}\mathbf{V}_\mu\} \operatorname{tr}\{\mathbf{T}\mathbf{V}^\mu\}$$

$$\mathcal{L}_1 = \operatorname{tr}\{\mathbf{B}_{\mu\nu}\mathbf{W}^{\mu\nu}\} \qquad \mathcal{L}_6 = \operatorname{tr}\{\mathbf{V}_\mu\mathbf{V}_\nu\}\operatorname{tr}\{\mathbf{T}\mathbf{V}^\mu\}\operatorname{tr}\{\mathbf{T}\mathbf{V}^\nu\}$$

$$\mathcal{L}_2 = \mathrm{i}\operatorname{tr}\{\mathbf{B}_{\mu\nu}[\mathbf{V}^\mu,\mathbf{V}^\nu]\} \qquad \mathcal{L}_7 = \operatorname{tr}\{\mathbf{V}_\mu\mathbf{V}^\mu\}\operatorname{tr}\{\mathbf{T}\mathbf{V}_\nu\}\operatorname{tr}\{\mathbf{T}\mathbf{V}^\nu\}$$

$$\mathcal{L}_3 = \mathrm{i}\operatorname{tr}\{\mathbf{W}_{\mu\nu}[\mathbf{V}^\mu,\mathbf{V}^\nu]\} \qquad \mathcal{L}_8 = \tfrac{1}{4}\operatorname{tr}\{\mathbf{T}\mathbf{W}_{\mu\nu}\}\operatorname{tr}\{\mathbf{T}\mathbf{W}^{\mu\nu}\}$$

$$\mathcal{L}_4 = \operatorname{tr}\{\mathbf{V}_\mu\mathbf{V}_\nu\}\operatorname{tr}\{\mathbf{V}^\mu\mathbf{V}^\nu\} \qquad \mathcal{L}_9 = \tfrac{\mathrm{i}}{2}\operatorname{tr}\{\mathbf{T}\mathbf{W}_{\mu\nu}\}\operatorname{tr}\{\mathbf{T}[\mathbf{V}^\mu,\mathbf{V}^\nu]\}$$

$$\mathcal{L}_5 = \operatorname{tr}\{\mathbf{V}_\mu\mathbf{V}^\mu\}\operatorname{tr}\{\mathbf{V}_\nu\mathbf{V}^\nu\} \qquad \mathcal{L}_{10} = \tfrac{1}{2}\left(\operatorname{tr}\{\mathbf{T}\mathbf{V}_\mu\}\operatorname{tr}\{\mathbf{T}\mathbf{V}^\mu\}\right)^2$$

Measure deviations in quartic couplings:
- Triple gauge production
- Vector boson scattering

Interpret quartic couplings as new resonances

Integrating out resonances

- leads to anomalous quartic couplings

$$\alpha_5 = g_\sigma^2 \left(\frac{v^2}{8M_\sigma^2}\right) \qquad \alpha_7 = 2 g_\sigma h_\sigma \left(\frac{v^2}{8M_\sigma^2}\right) \qquad \alpha_{10} = 2 h_\sigma^2 \left(\frac{v^2}{8M_\sigma^2}\right)$$

Final result:

Spin	$I=0$	$I=1$	$I=2$
0	1.55	–	1.95
1	–	2.49	–
2	3.29	–	4.30

Spin	$I=0$	$I=1$	$I=2$
0	1.39	1.55	1.95
1	1.74	2.67	–
2	3.00	3.01	5.84

Full signal & bckgrnd computed via WHIZARD

A. Manteuffel

Anomalous Couplings in $\gamma\gamma \to WW$

Gauge and gauge-Higgs anomalous couplings

$$\mathscr{L}_2 = \frac{1}{v^2}\left(h_W O_W + h_{\tilde{W}} O_{\tilde{W}} + h_{\varphi W} O_{\varphi W} + h_{\varphi \tilde{W}} O_{\varphi \tilde{W}} + h_{\varphi B} O_{\varphi B} + h_{\varphi \tilde{B}} O_{\varphi \tilde{B}} + h_{WB} O_{WB} + h_{\tilde{W}B} O_{\tilde{W}B} + h_\varphi^{(1)} O_\varphi^{(1)} + h_\varphi^{(3)} O_\varphi^{(3)}\right),$$

$$O_W = \epsilon_{ijk}\, W_\mu^{i\,\nu} W_\nu^{j\,\lambda} W_\lambda^{k\,\mu}, \qquad O_{\tilde{W}} = \epsilon_{ijk}\, \tilde{W}_\mu^{i\,\nu} W_\nu^{j\,\lambda} W_\lambda^{k\,\mu},$$

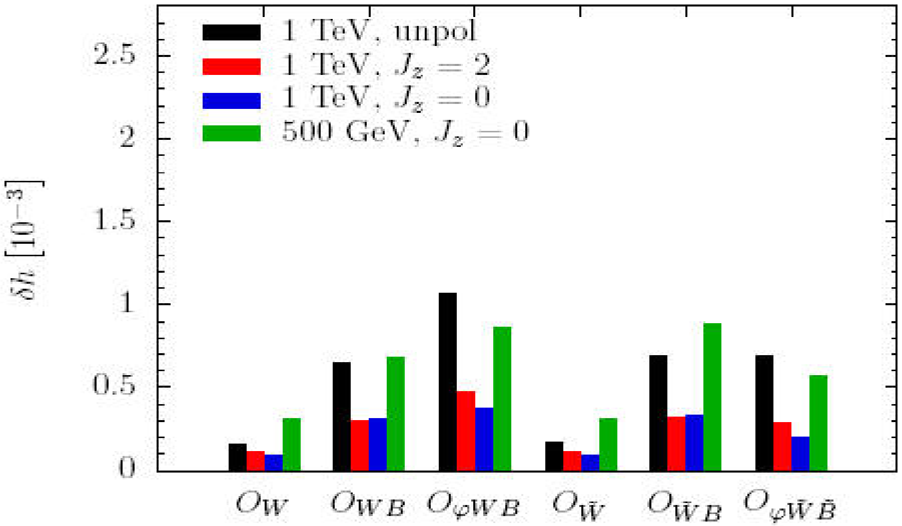
$$O_{\varphi W} = \frac{1}{2}\left(\varphi^\dagger \varphi\right) W^i_{\mu\nu} W^{i\,\mu\nu}, \qquad O_{\varphi \tilde{W}} = \left(\varphi^\dagger \varphi\right) \tilde{W}^i_{\mu\nu} W^{i\,\mu\nu},$$

$$O_{\varphi B} = \frac{1}{2}\left(\varphi^\dagger \varphi\right) B_{\mu\nu} B^{\mu\nu}, \qquad O_{\varphi \tilde{B}} = \left(\varphi^\dagger \varphi\right) \tilde{B}_{\mu\nu} B^{\mu\nu},$$

$$O_{WB} = \left(\varphi^\dagger \tau^i \varphi\right) W^i_{\mu\nu} B^{\mu\nu}, \qquad O_{\tilde{W}B} = \left(\varphi^\dagger \tau^i \varphi\right) \tilde{W}^i_{\mu\nu} B^{\mu\nu},$$

$$O_\varphi^{(1)} = \left(\varphi^\dagger \varphi\right) \left(\mathcal{D}_\mu \varphi\right)^\dagger \left(\mathcal{D}^\mu \varphi\right), \qquad O_\varphi^{(3)} = \left(\varphi^\dagger \mathcal{D}_\mu \varphi\right)^\dagger \left(\varphi^\dagger \mathcal{D}^\mu \varphi\right)$$

Sensitivity with polarized beams



Comparison of Sensitivities

	LEP & SLD (*) $h_i\ [10^{-3}]$	$ee \to WW$ (*) $\delta h_i\ [10^{-3}]$	$\gamma\gamma \to WW$ unpolarised $\delta h_i\ [10^{-3}]$	$\gamma\gamma \to WW$ $J_z = 0$ $\delta h_i\ [10^{-3}]$
h_W	-69 ± 39	0.3	0.6	0.3
h_{WB}	-0.06 ± 0.79	0.3	1.6	0.7
$h_{\varphi WB}$	×	×	2.2	0.9
$h_\varphi^{(3)}$	-1.15 ± 2.39	36.4	×	×
$h_{\tilde{W}}$	68 ± 81	0.3	0.7	0.3
$h_{\tilde{W}B}$	33 ± 84	2.2	2.0	0.9
$h_{\varphi \tilde{W}\tilde{B}}$	×	×	2.0	0.6

A. Alboteanu

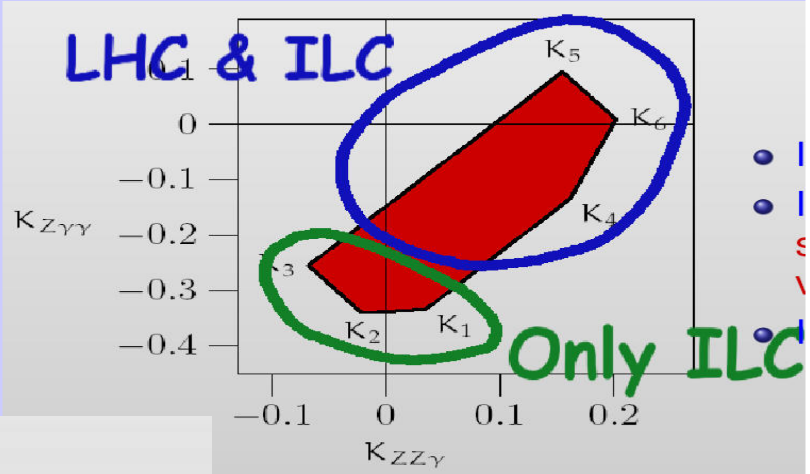
Non-Commutative Spacetime

- Postulate that spacetime coordinates do not commute
- Occurs in string theory in the presence of background fields

$$[\hat{x}_\mu, \hat{x}_\nu] = i\theta_{\mu\nu} = i\frac{C_{\mu\nu}}{\Lambda_{NC}^2} \quad \Rightarrow \quad \Delta\hat{x}_\mu \cdot \Delta\hat{x}_\nu \gtrsim \frac{\theta_{\mu\nu}}{2}$$

Characteristic NC scale

- Modifies SM interactions
- Induces new interactions among gauge fields



ILC sensitivity on Λ_{NC}:

$(K_{Z\gamma\gamma}, K_{ZZ\gamma})$	$\lvert\vec{E}\rvert^2 = 1, \vec{B} = 0$	$\vec{E} = 0, \lvert\vec{B}\rvert^2 = 1$
$K_0 \equiv (0, 0)$ (mNCSM)	$\Lambda_{NC} \gtrsim 2$ TeV	$\Lambda_{NC} \gtrsim 0.4$ TeV
$K_1 \equiv (-0.333, 0.035)$ (nmNCSM)	$\Lambda_{NC} \gtrsim 5.9$ TeV	$\Lambda_{NC} \gtrsim 0.9$ TeV
$K_5 \equiv (0.095, 0.155)$ (nmNCSM)	$\Lambda_{NC} \gtrsim 2.6$ TeV	$\Lambda_{NC} \gtrsim 0.25$ TeV
$K_3 \equiv (-0.254, -0.048)$(nmNCSM)	$\Lambda_{NC} \gtrsim 5.4$ TeV	$\Lambda_{NC} \gtrsim 0.9$ TeV

Studied Zγ production @ ILC and LHC

ILC: Positron Polarization from Beginning?

RDR: helical undulator

→ **Positron Polarization: ~30%** (60% upgrade value)

We will have a machine with both beams polarized from the beginning! Perfect start for physics!!

To maintain e+ polarization we need

- → spin rotation before and after DR (foreseen)
- → e+ polarimeter @ IP (foreseen)
- → **reversal of (+) and (-) helicity of positrons (not yet foreseen)**

Without e+ helicity reversal, 50% of the measurements would correspond to the wrong pairing of initial states (lower cross sections!!)

→ advantage of higher lumi is lost

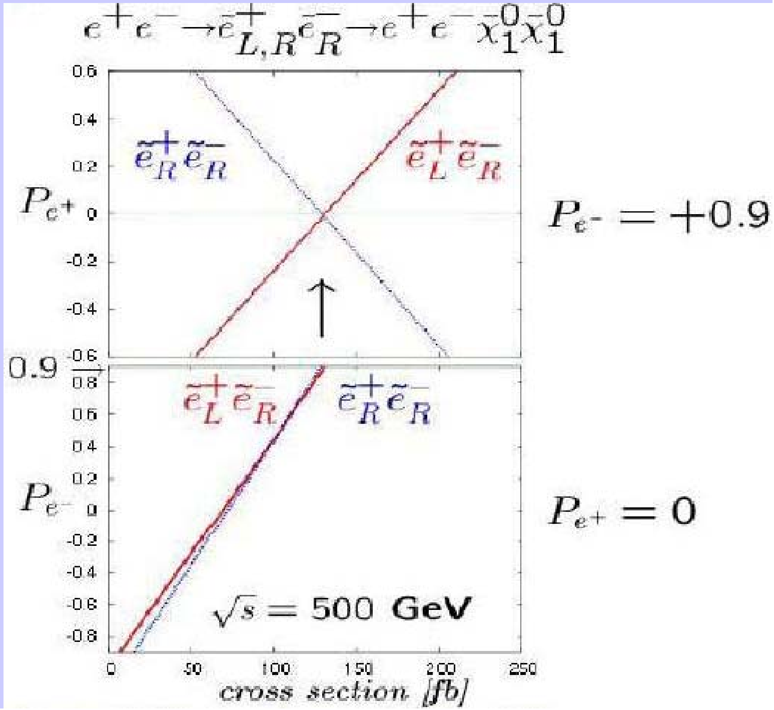
→ advantage of $P_{eff}=(P_{e-}+P_{e+})/(1+P_{e-}P_{e+})$ is lost

→ no reduction of polarization uncertainty ΔP_{eff}

ILC: e+ Polarization from Beginning?

To use the e+ polarization for physics we strongly ask to provide a machine with flexible helicity reversal also for the positron beam

No or very rare reversal of e+ helicity could be worse than no e+ polarization



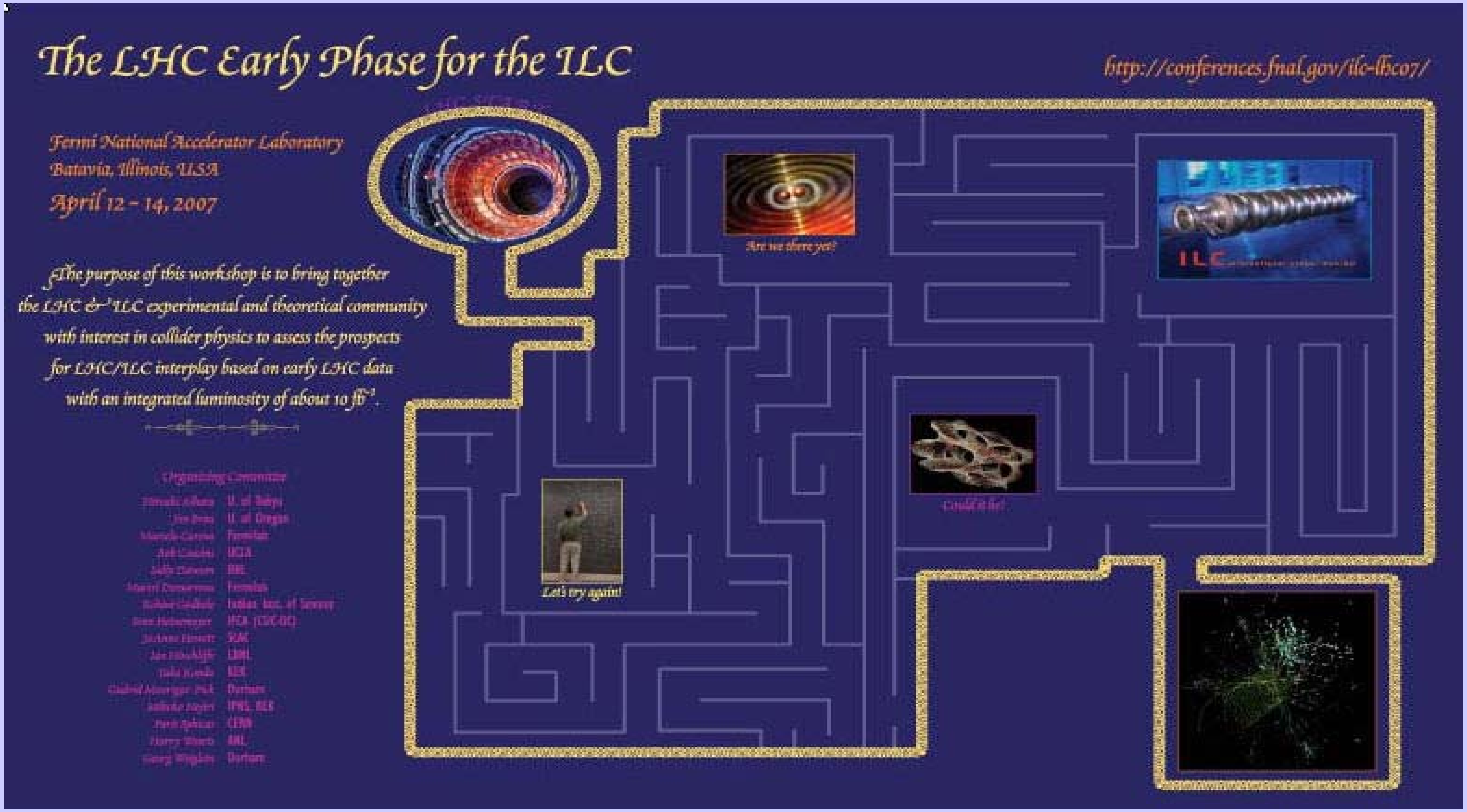
Reminder: Positron Pol is important for numerous physics channels

- Gain in production rate
- Reduction of Bckgrnd
- Access to new channels

Positron Pol WG

Next LHC/ILC Interplay Meeting:

SLAC, November 15-17, 2007



See you there!!!