




# **SUSY Studies**

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# Outline

- ☞ Key questions
- ☞ Why SUSY
- ☞ Activities
- ☞ The frame
- ☞ Recent progress
- ☞ What if ...
- ☞ Summary and outlook

# Key questions

- ☞ Origin of mass? Is it the Higgs mechanism, or ...?
  - ☞ Origin of matter-antimatter asymmetry?
  - ☞ Properties of neutrinos?
  - ☞ Unification of forces, including gravity?
  - ☞ Dark matter, dark energy?
- 
- SUSY may be related to all these questions
  - SUSY can be tested at colliders
  - the ILC provides essential tools for discovery answers

☞ **Discovering SUSY – a revolution in particle physics**

# Why SUSY ?

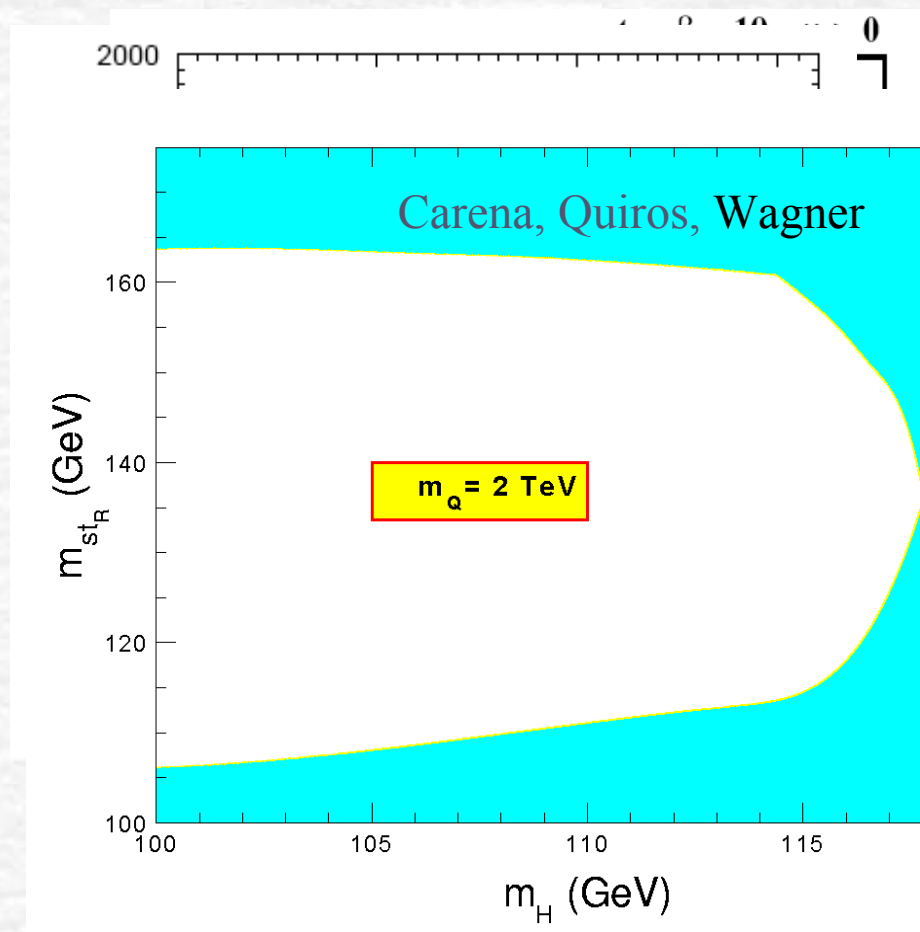
Pros:

- predicts gauge unification
- dark matter candidate
  - WMAP constrains models, e.g.
  - but neutralinos are visible at ILC
- naturally consistent with EW data
- relaxing model assumptions
- electroweak baryogenesis

Cons:

A ‘little hierarchy’ problem?

- non-minimal SUSY, extra gauge factors, ..
- remove scalars → Split SUSY



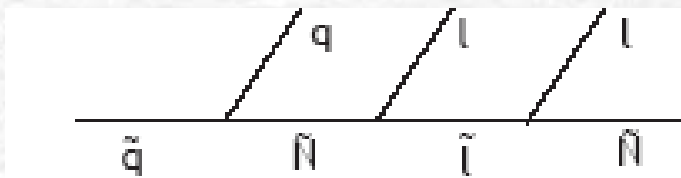
# Activities

## SUSY WG talks:

- W. Hollik - Supersymmetry Parameter Analysis: SPA Convention and Project
- P. Bechtle - Supersymmetry Parameter Analysis with Fittino
- D. Stockinger - Renormalization and Regularization of SUSY theories
- K. Kovarik - Precise Predictions for SUSY Processes at the ILC
- W. Kilian - Split Supersymmetry at the Linear Collider
- G. Moortgat-Pick - Distinguishing Between MSSM and NMSSM via Combined LHC/ILC Analyses
- H. Baer - Crazy SUSY Scenarios for the ILC That Just Might be True
- M.A. Diaz - Neutrinos in Supersymmetry
- N. Haba - Higgs Mass in the Gauge-Higgs Unification Theory
- A. Birkedal - Complementarity of Precision Studies at the LHC and the ILC
- P. Osland - Supersymmetric Cascade Decays
- R. Godbole/S. Kraml - Fermion Polarization in Sfermion Decays
- E. Boos - Impact of Tau Polarization for Study of the MSSM Charged Higgses in Top Quark Decays at ILC
- B. Schumm - Forward Selectron Production and Detector Performance
- K.C. Kong - Impact of Beamstrahlung on Precision Measurements of New Physics at
- H. Nowak - Studies on Scalar Top Quarks, Chargino and Scalar Lepton Production at LC
- U. Nauenberg - The Importance of Positron Polarization and the Deleterious Effects of Beam/Bremmstrahlung on the Measurement of Supersymmetric Particle Masses
- C. Wagner - Low Energy Supersymmetry and Electroweak Baryogenesis
- C. Milstene - Analysis of Stop Quarks With Small Stop-Neutralino Mass Difference at LC
- J.L. Kneur - Updated Constraints on the mSUGRA and Prospects for Sparticle Production at the ILC
- G. Weiglein - Indirect Sensitivities to the Scale of SupersymmetrySS

# The frame

- LHC will see SUSY if squarks/gluinos below 2-3 TeV
- Many channels from squark and gluino decays

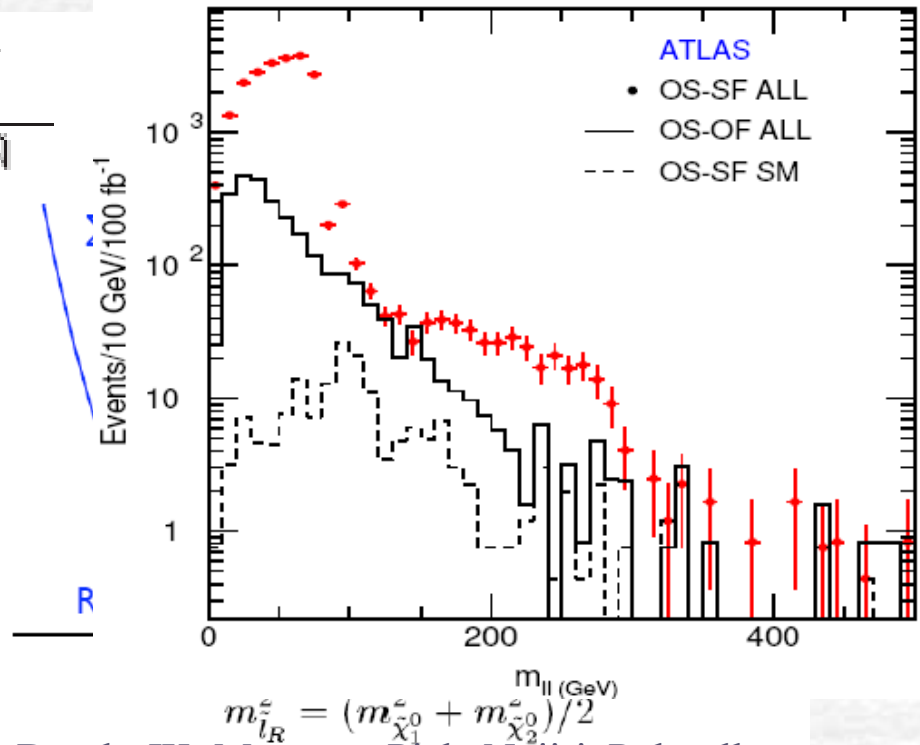


Moreover, ILC can help identifying heavy neutralino at LHC. Even if standard SUSY, false solutions may occur

Need ILC to eliminate them



Peskin



- ILC needed for precision and model-independent studies

# The frame

## From theory: important goals to achieve

- accurate theoretical calculations to match the experimental data
- model-independent reconstruction of Lagrange parameters and SUSY breaking mechanism
- SUSY – a bridge between EW and GUT/Planck scales

to achieve these goals

## **the SPA Project**

has been proposed



**<http://spa.desy.de/spa>**

- ☞ SPA Convention
  - renorm. schemes / LE parameters / observables**
- ☞ Program repository
  - th. & exp. analyses / LHC+ILC tools / Susy Les Houches Accord**
- ☞ Theoretical and experimental tasks
  - short- and long-term sub-projects**
- ☞ Reference point SPS1a'
  - derivative of SPS1a, consistent with all data**
- ☞ Current and future developments
  - CP-MSSM,  $R_pV$ , Split, nMSSM, effective string th., etc.**



# Recent progress

D. Stockinger  
hep-ph/0503129

## DRbar scheme:

1. DRED is mathematically inconsistent and there is no full proof that SUSY is preserved

⇒ Replace ordinary 4-dim space by yet another  $\infty$ -dimensional space with some 4-dim characteristics → “quasi-4-dim space”

quasi-4-dim space can be explicitly constructed ⇒ no mathematical problems, no inconsistency, unique results for calculations

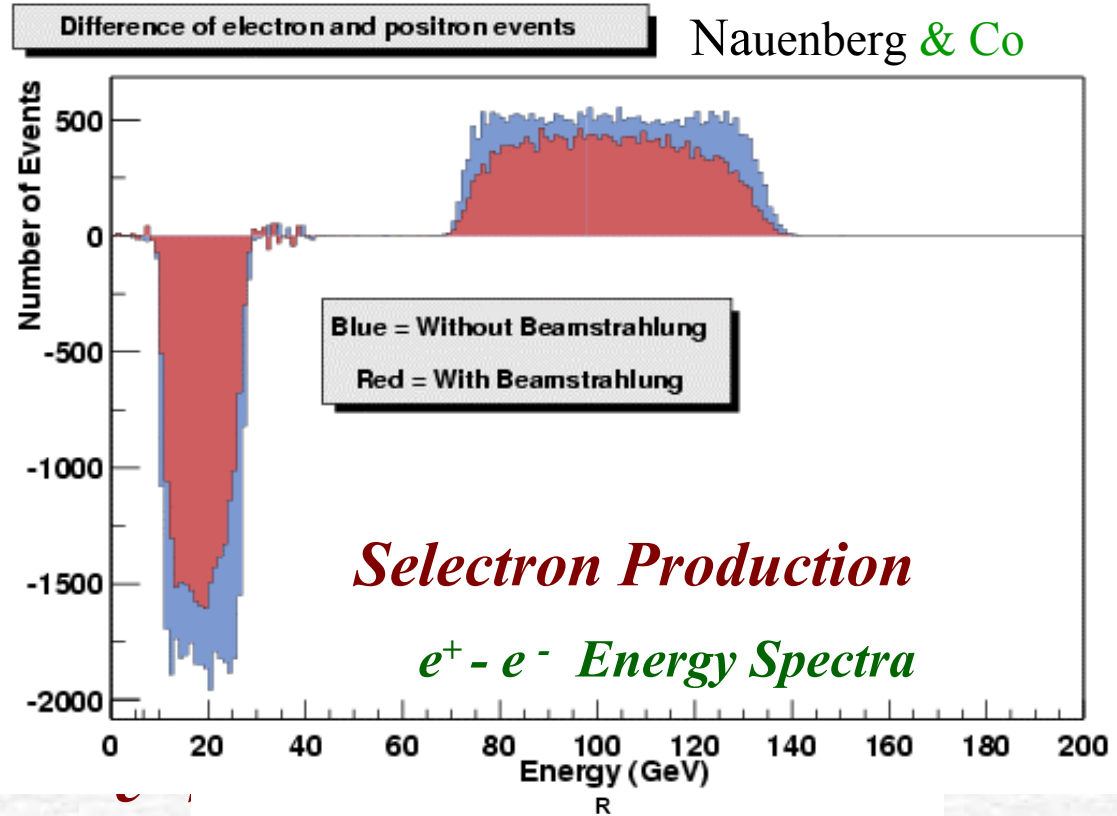
Check that DRED preserves SUSY in some interesting cases

## 2. Problem with factorization -- needs further study

# Recent progress

$\tilde{e}^+ \tilde{e}^- \rightarrow all e e$  Boos, Bunichev, Carena, Wagner, Nauenberg & Co

$\pi$ -meson energy spectrum for MSSM intense coupling point  
 $\tan \beta = 30$   $M_{\tilde{t}\tilde{t}} = 146$  GeV with  $Br(t \rightarrow H^+ b) = 6.9\%$



- positron polarisation

- slepton masses

$e^+$  80%

- $f \tilde{f} \chi$  chiral structure in

$\tilde{\tau} \rightarrow \chi \tau$  decays

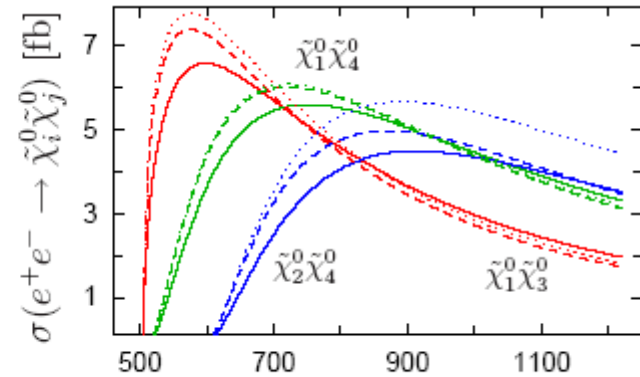
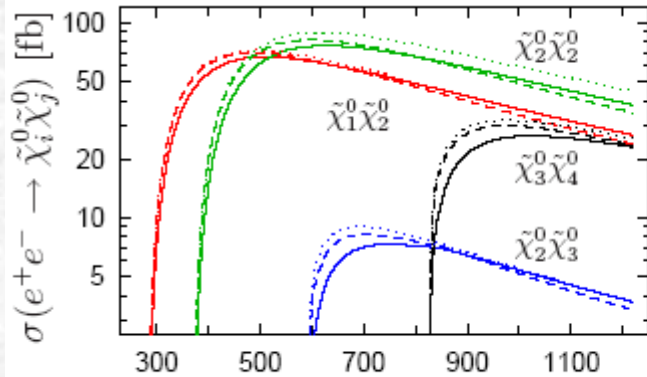
- $t \rightarrow H^+ b, H^+ \rightarrow \tau \nu$

$e^+$  0%

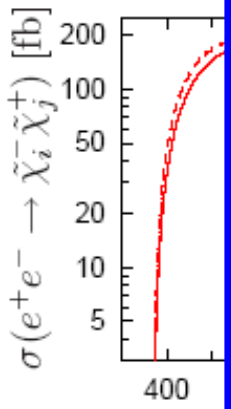
# Recent progress

K. Kovarik

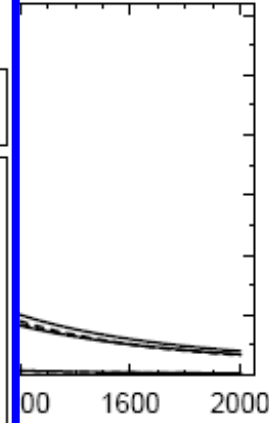
Loop corrections are needed to match experimental precision



shift  $M = 1$  TeV to 100 GeV  $\Rightarrow$  next loop!



Particle	Mass	$\delta_{\text{scale}}$	Particle	Mass	$\delta_{\text{scale}}$
$h^0$	115.4	1.3	$\tilde{u}_R$	547.7	9.4
$\tilde{\chi}_1^0$	97.75	0.4	$\tilde{t}_1$	368.9	5.4
$\tilde{\chi}_2^0$	184.4	1.2	$\tilde{g}$	607.6	1.4
$\tilde{e}_R$	125.2	1.2			



**Higher order calculations mandatory**



## SPS1a'- derivative of the SPS1a point

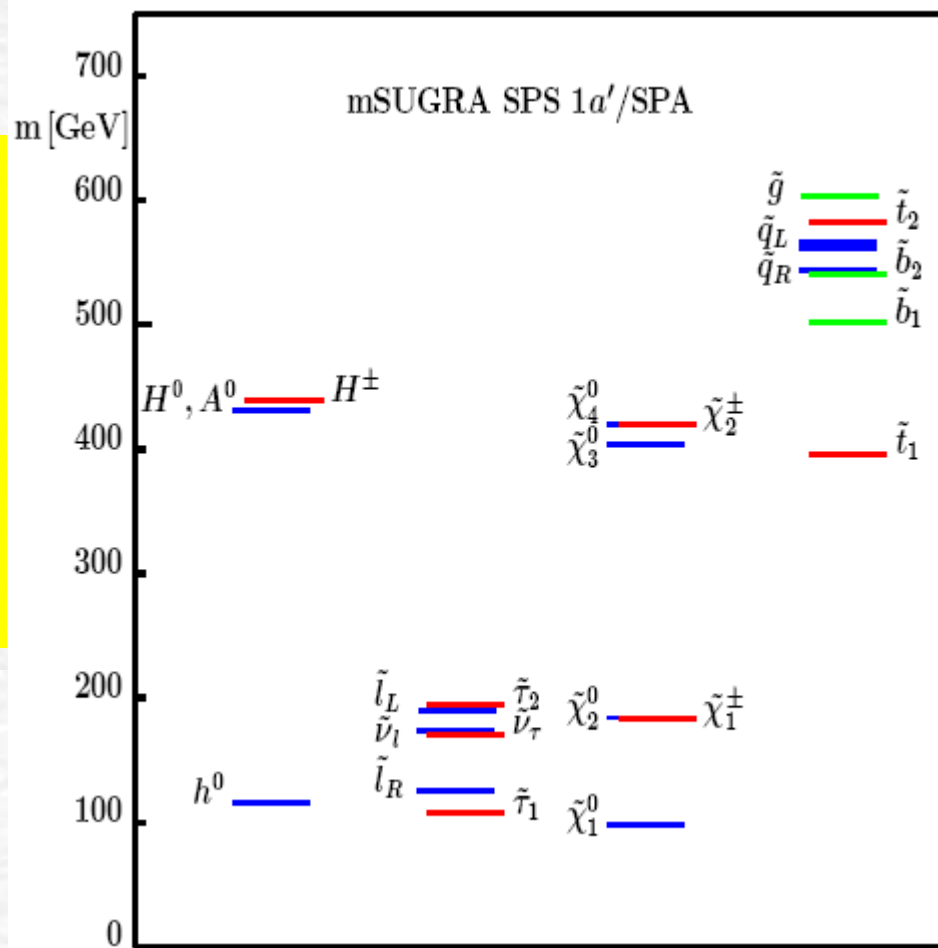
mSUGRA values:

$m_0$	70 GeV
$m_{1/2}$	250 GeV
$A_0$	-300 GeV
$\tan \beta$	10
$\text{sign } \mu$	+

$$BR(b \rightarrow s\gamma) = 3.0 \times 10^{-4}$$

$$\Delta[g_\mu - 2]/2 = 33 \times 10^{-10}$$

$$\Omega_{cdm} h^2 = 0.10$$



# Reconstructing Lagrange param.

global analysis codes:

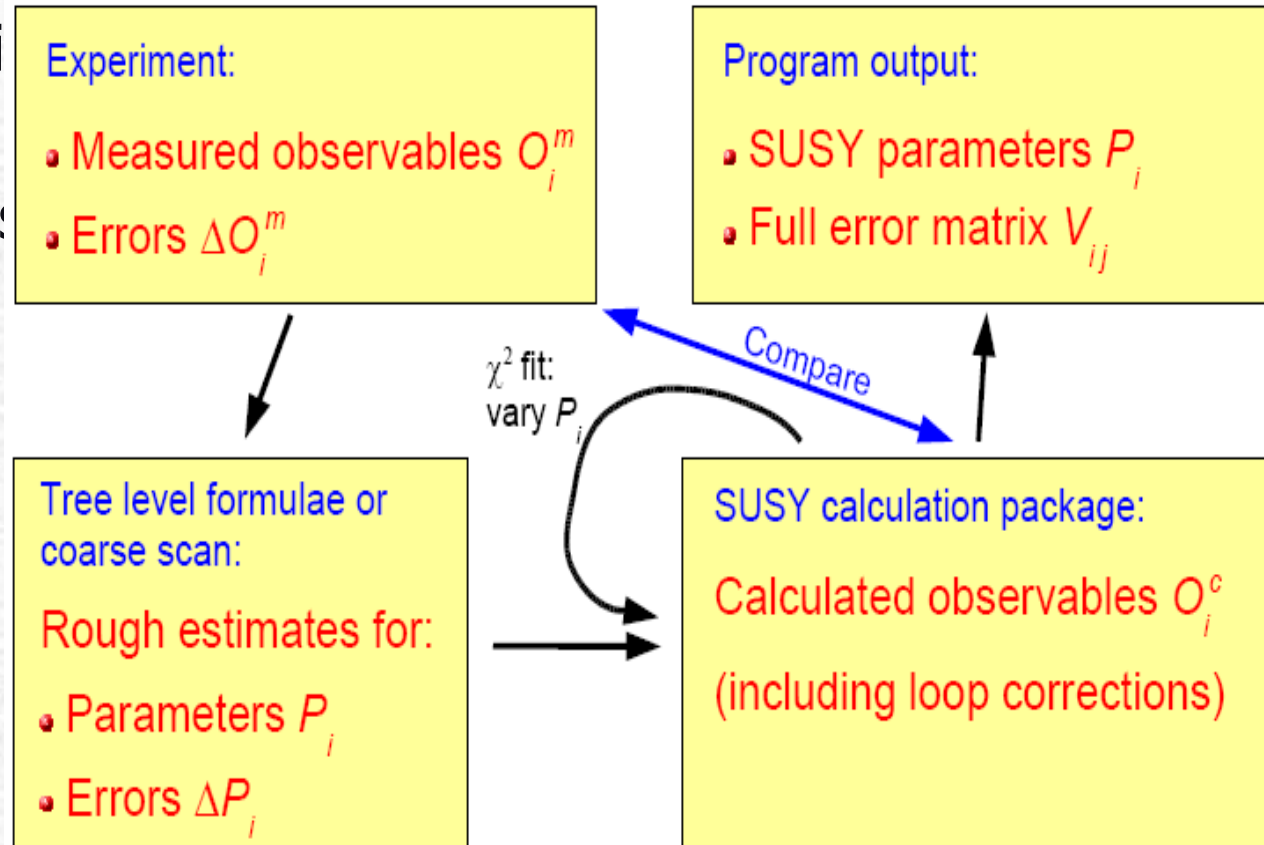
**SFitter** (R. Lafaye, T. Plehn and D. Zerwas)

**Fittino** (P. Bechtle, K. Desch, P. Wienemann)

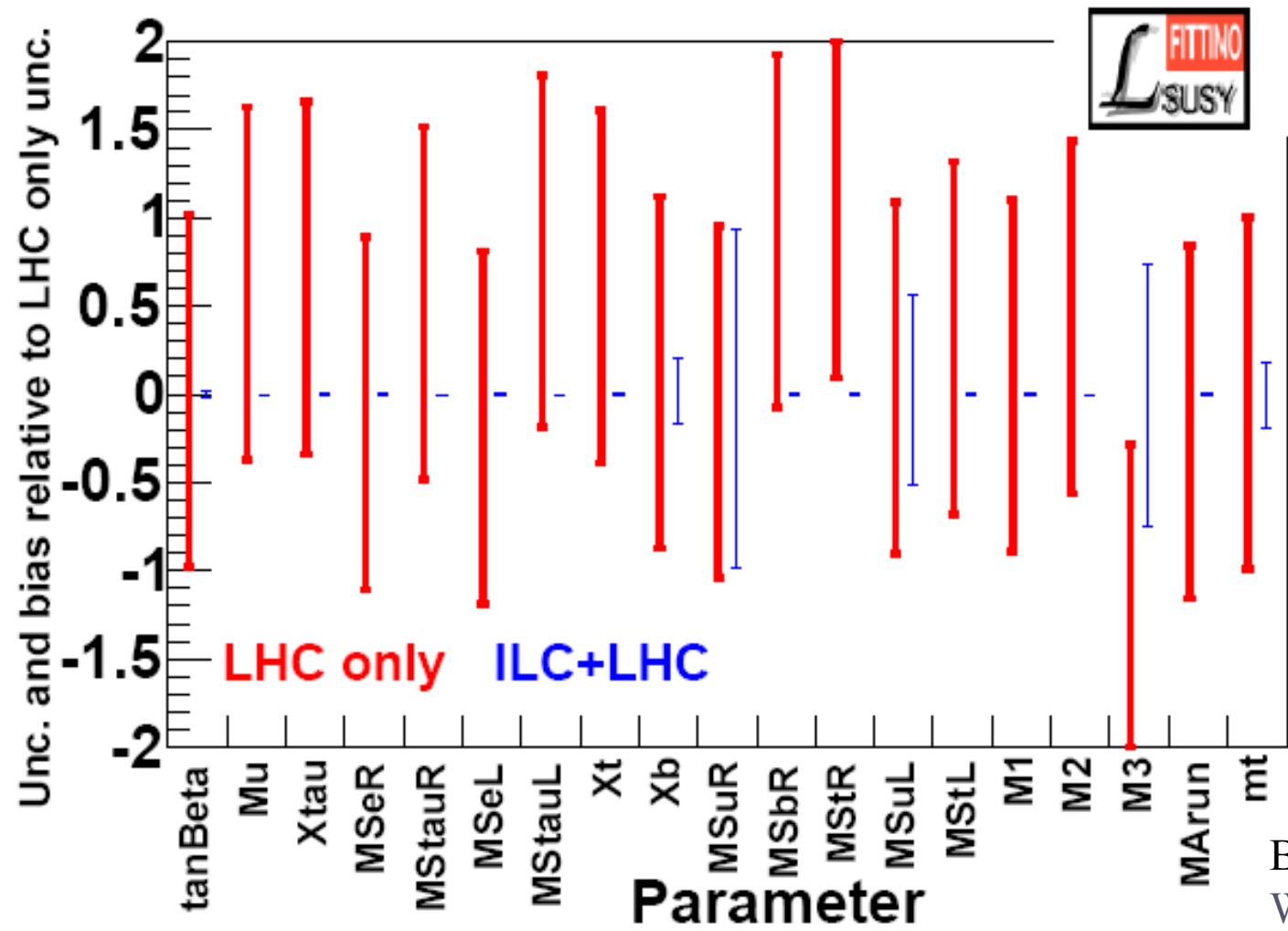
fit masses + xsection  
and BR

radiative corrections

ex: Fittino



# Comparison of LHC and ILC+LHC



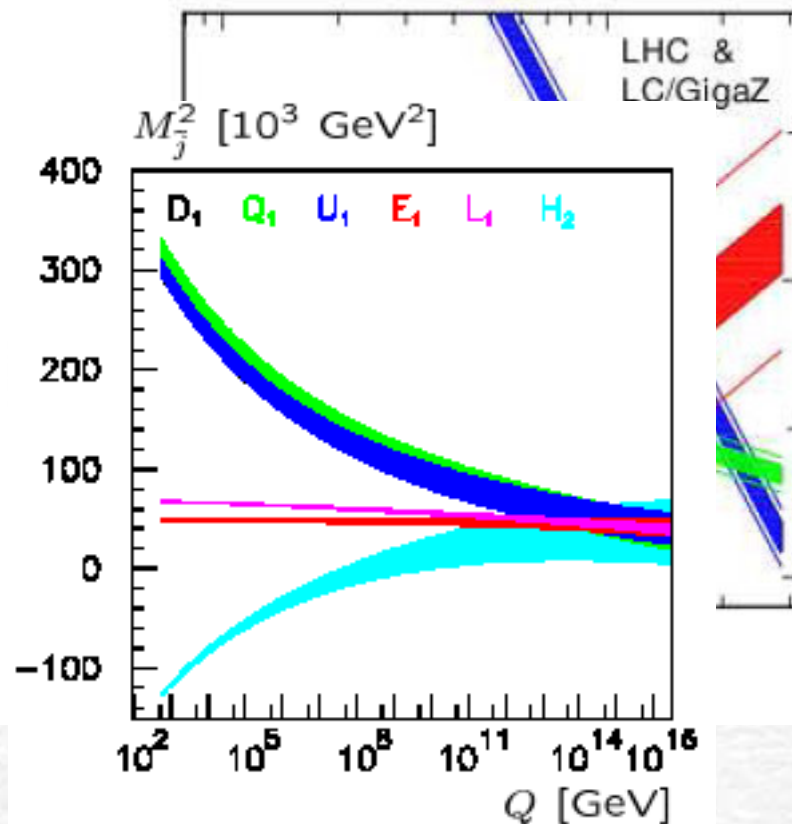
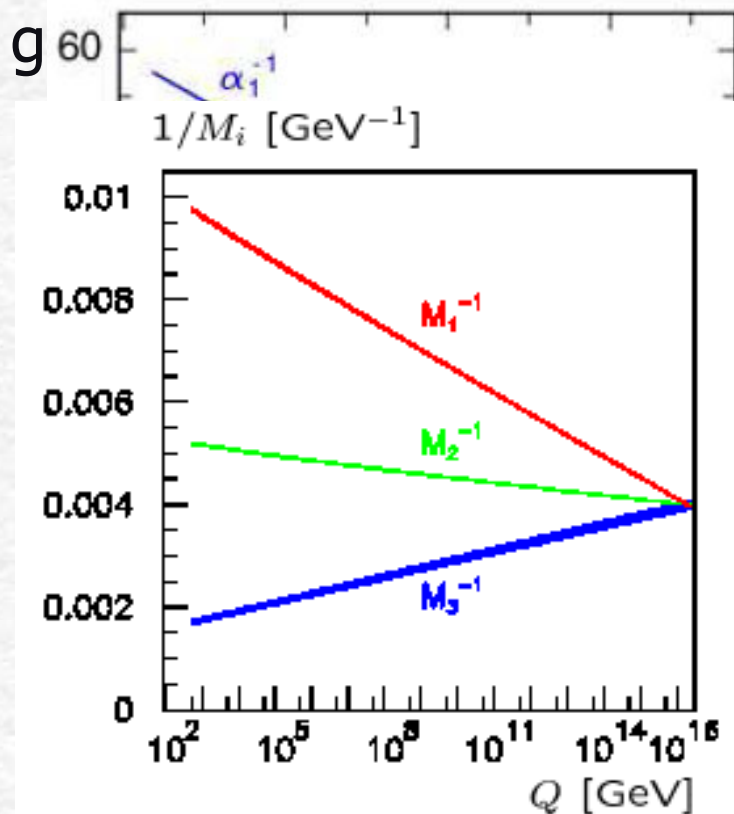
Bechtle, Desch  
Wienemann



Philip Bechtle, LCWS 05, 19.03.2005 - p.16

# High-scale extrapolation

- gauge couplings  $\alpha^{-1}$



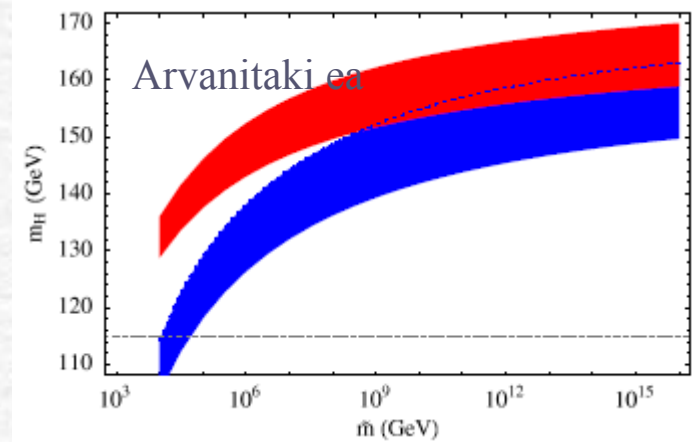
- universality can be tested in bottom-up approach

# What if ...

## Split SUSY

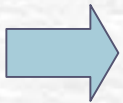
Arkani-Hamed, Dimopoulos

$$\begin{aligned} \mathcal{L} \supset & \tilde{B}(\kappa'_1 h^\dagger \tilde{H}_1 + \kappa'_2 h \tilde{H}_2) \\ & + \tilde{W}^a (\kappa_1 h^\dagger \tau^a \tilde{H}_1 + \kappa_2 \tilde{H}_2 \tau^a h) - \lambda |h|^4 \\ & - \mu \tilde{H}_1 \tilde{H}_2 - \frac{1}{2} (M_1 \tilde{B} \tilde{B} + M_2 \tilde{W} \tilde{W} + M_3 \tilde{g} \tilde{g}) \end{aligned}$$



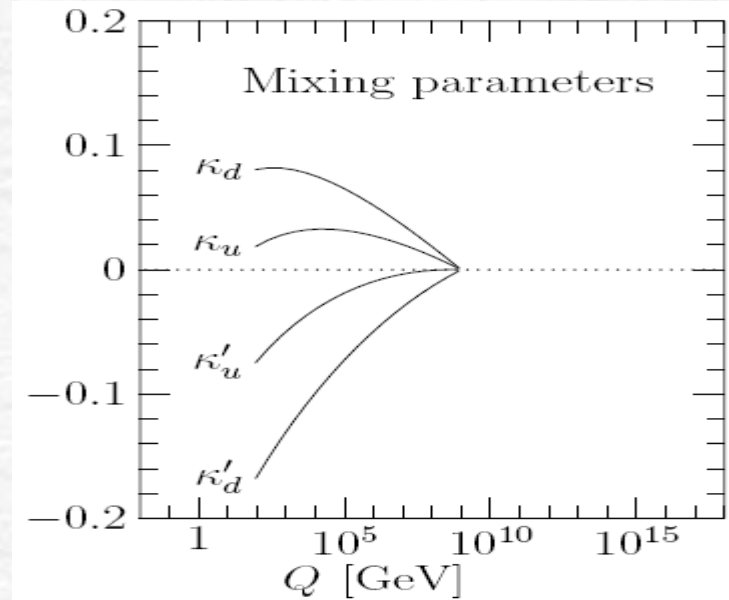
## Signature:

- heavier SM-like Higgs boson
- LHC: long-lived gluino
- ILC: measure Yukawa couplings



**testable at LHC+ILC**

Kilian, Plehn, Richardson, Schmidt  
hep-ph/0408088





# What if ...

Split SUSY

CP-violated MSSM

- CP-odd asymmetries in gaugino/higgsino

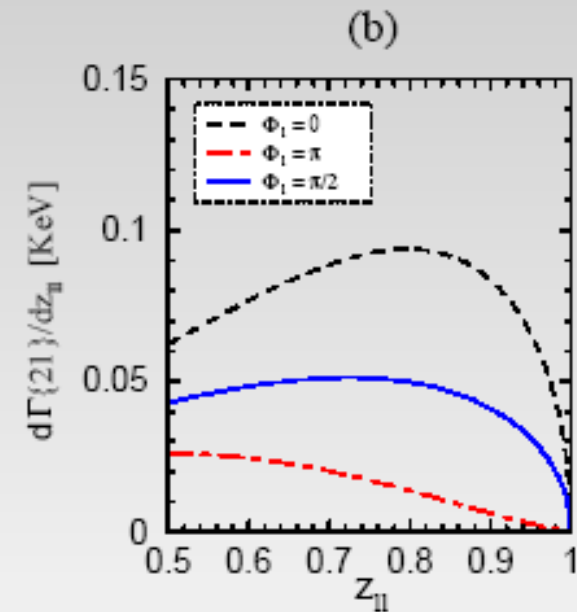
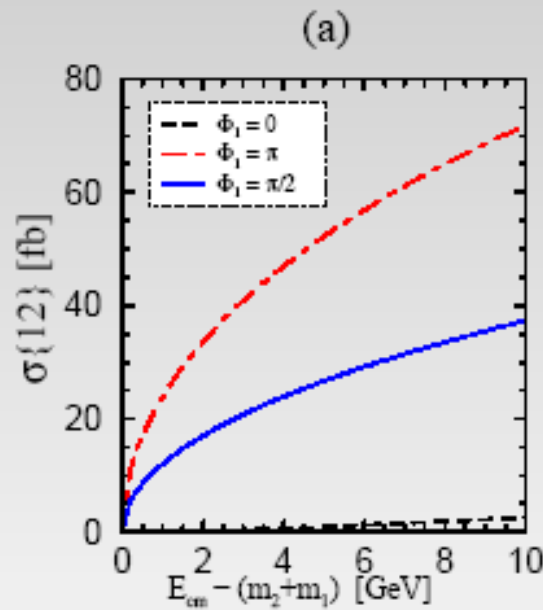
Hesselbach *et al.*

- Majorana nature in neutralino prod.+dec.

B. Chung *et al.*

## T-odd asymmetries in $\tilde{\chi}^\pm, \tilde{\chi}^0$ sectors

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



# What if ...

Split SUSY

CP-violated MSSM

NMSSM

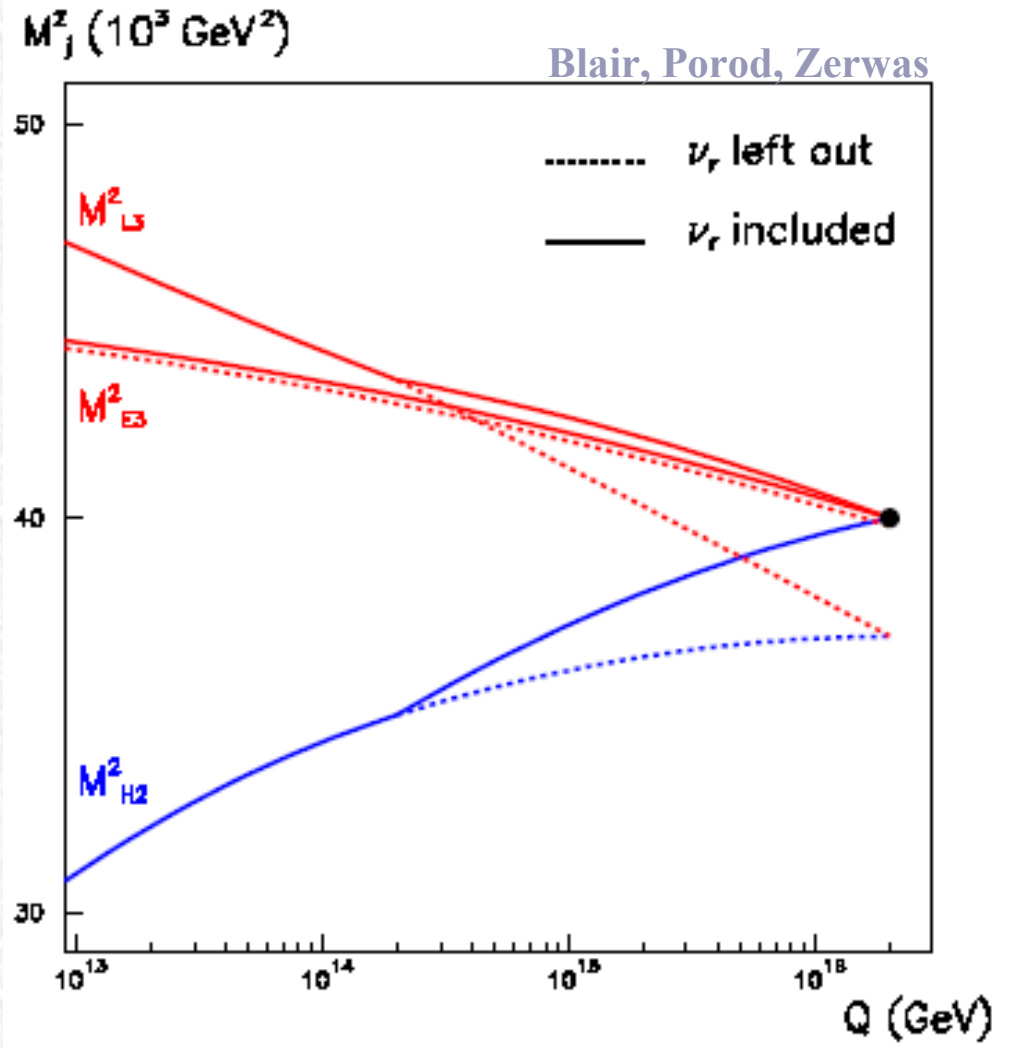
- two more Higgses  
and one more  
neutralino

Moortgat-Pick et al.

- The question:
  - MSSM - NMSSM separation with light particles
  - numerical example (including some exp. errors)
  - assumption: no separation@LC<sub>500</sub> possible
- The answer:
  - LHC/LC interplay
  - motivation for using LC<sub>650</sub>

# What if ...

- Split SUSY
- CP-violated MSSM
- NMSSM
- LR SUGRA
  - kink in evolution of 3rd generation



# What if ...

Split SUSY

CP-violated MSSM

NMSSM

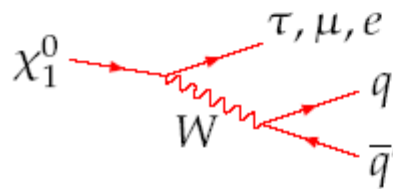
LR SUGRA

$R_p$  violation

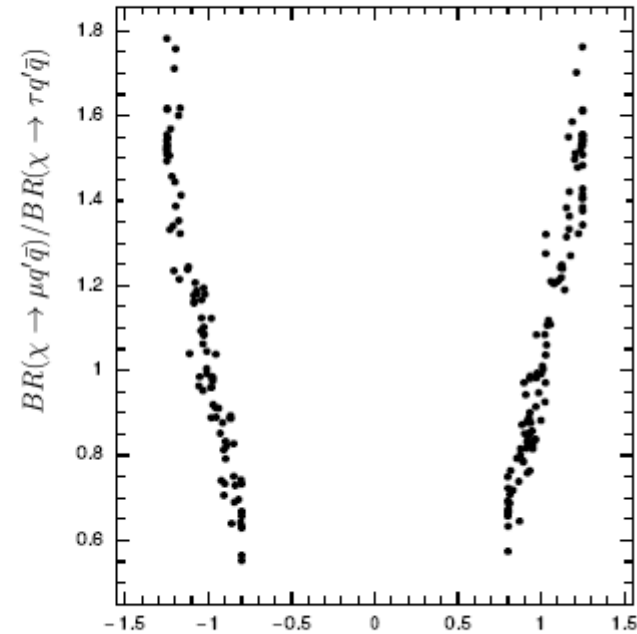
- neutrinos mix with neutralinos

## Neutralino Decays

In the presence of BRpV a neutralino LSP is not stable:



Ratios of BR are closely related to the  $\Lambda_i$  parameters.



Collider Physics  $\Leftrightarrow$  Neutrino Physics

Díaz, Hirsch, Porod, Romao, Valle

# What if ...

Split SUSY

CP-violated MSSM

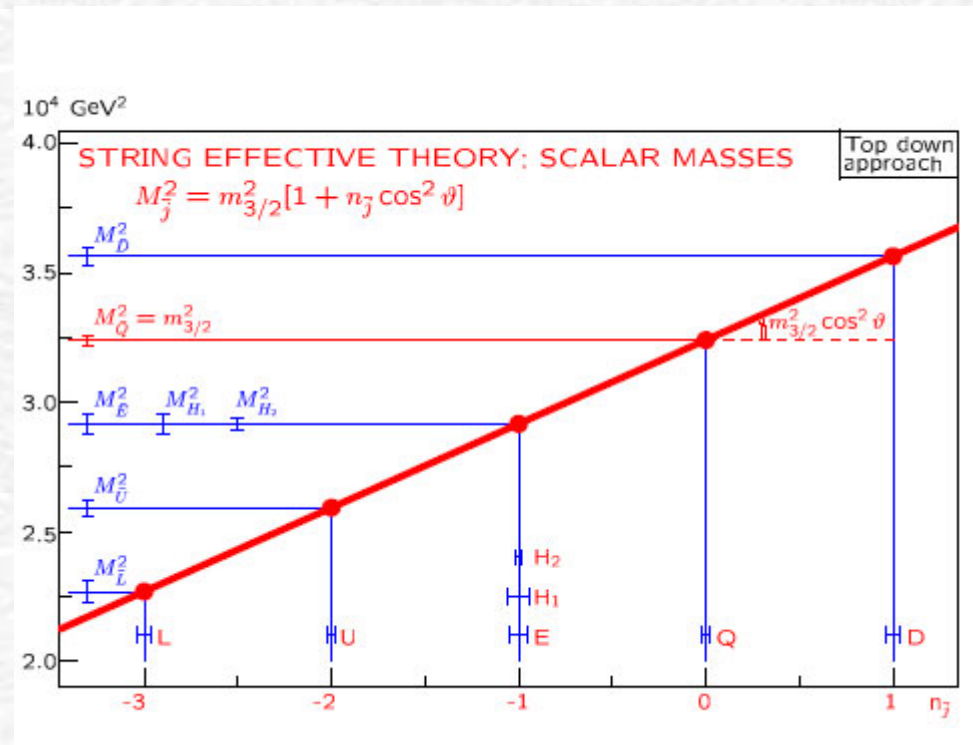
NMSSM

LR SUGRA

$R_p$  violation

Superstring eff. model

- integer modular weights



# Summary and outlook

- ☞ Many interesting avenues explored
- ☞ SPA: a joint interregional th. and exp. effort

## Bottom-up approach:

**max exploitation of measurements taking full account of theoretical knowledge**

- ☞ cosmology strongly constrains certain SUSY models
- ☞ precision LHC/ILC + WMAP/PLANCK → consistency checks on cosmological models
  - ☞ our next stop: ILC Workshop in Snowmass

☞ LHC+ILC – telescope to GUT/Planck physics

