Implications of LHC results on LC physics

G. Moortgat-Pick, Jenny List, Sabine Riemann

- **Status LHC results**

- **Impact from LHC findings**

- **Impact from (still) LHC non-findings**

- **Conclusions: possible steps and Outlook**

Status LHC results -- in short

- **Excess compatible with a SM-like Higgs around $m_H \sim 125$ GeV**
  - **Should become clear this year…..**
  - **Would be an absolute revolution!**

- **Limits in SUSY coloured sector (approx.):**
  - **mg>700 GeV,mq>800 GeV**
  - **3rd generation: much weaker**
  - **Results in $\Lambda > 31$ TeV in GMSB**

- **Limits on Z', W': ~2 TeV**

- **And more limits on ED, exotics, 4th generation etc.**

  Room left for a Linear Collider? Which energy steps?

Status LHC results -- in short

- **Excess compatible with a SM-like Higgs around m ≈ 125 GeV**

- **L**

- **L**

> • *Currently many new LC reports under work: CLIC CDR just finished, ILC TDR to be finished in end 2012 ….*
> *Please have a look for collider specific details.*
> • *This talk is a personal approach to outline possible first LC steps as reaction on the encouraging LHC results.*
> • *Therefore mainly talks of the recent LC Forum (only physics addressed) have been used*

- **And more limits in ED, exotics, 4th generation etc.**

Room left for a Linear Collider? Which energy steps?

Impact from LHC findings

- **If a Higgs at mH=125 GeV :**

The Higgs boson is a completely new type of particle that we have never encountered. The properties are experimentally totally unknown.

- **Rich phenomenology at LHC and a LC**
  - Distinction SM-Higgs vs. SUSY Higgs or something else
  - Precise measurement of couplings and BRs needed
  - Trilinear couplings measurement

- `The properties of the Higgs boson, to be discovered at the LHC, must be thoroughly investigated in a good condition at the ILC'* (K. Kawagoe)*

Which energy?

- **$E_{CM} \sim M_H + 120$ GeV($\sim$250 GeV)**
  - **Precise measurement of the mass and production cross section**
  - **Determination of the spin**
  - **Precise measurement of the decay branching fractions**

- **$E_{CM} \sim 500$ GeV or higher**

  - **Measurement of the Higgs self-coupling**

    - **Essential for the Higgs potential and EWSB mechanism**
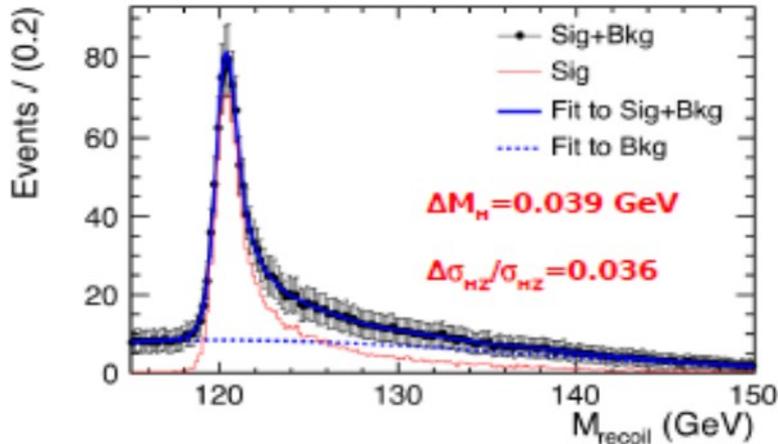
  - **Measurement of Top Yukawa coupling**

See talk K. Kawagoe at LCForum, Hamburg 2/2012
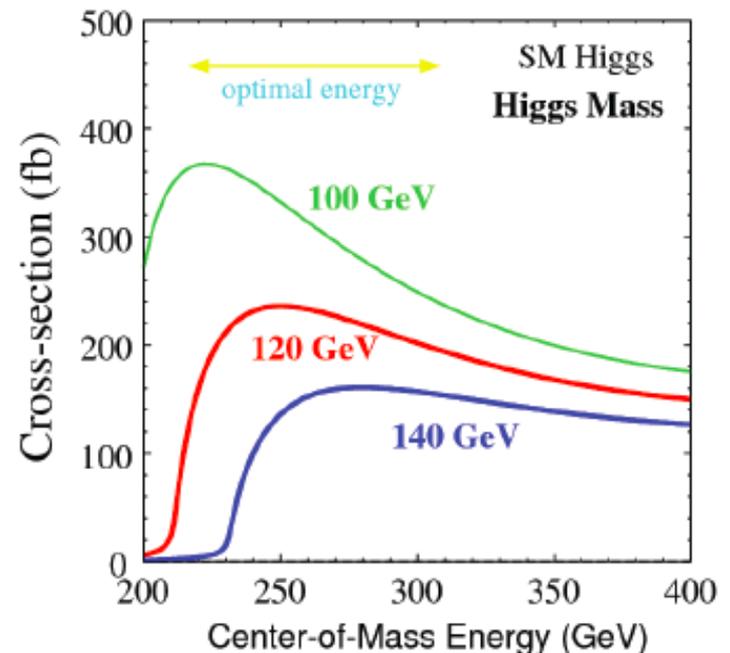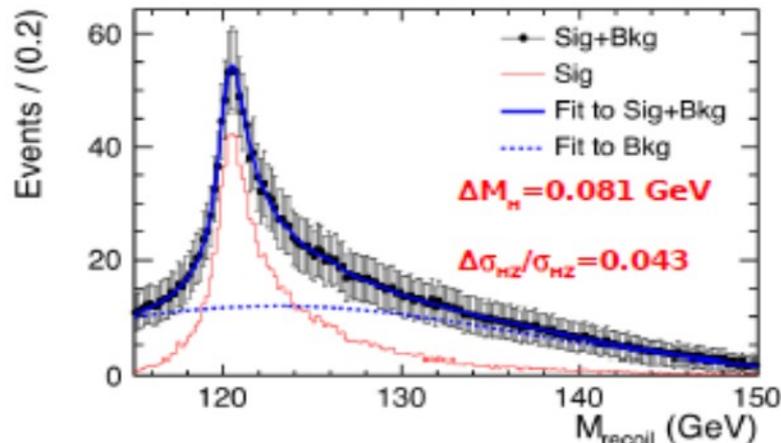
Task list of the LC -- some 'new' studies

- **Couplings measurement: √s=250 GeV (LOI)**   √s=250 GeV

Muon Channel

ΔM$_H$=0.039 GeV

Δσ$_{HZ}$/σ$_{HZ}$=0.036

Very Precise Measurement
S/B = 8 in Peak Region

Electron Channel

ΔM$_H$=0.081 GeV

Δσ$_{HZ}$/σ$_{HZ}$=0.043

Less Precise
Bremsstrahlung in detector material

Combined: ΔM$_H$=0.035 GeV, Δσ$_{HZ}$/σ$_{HZ}$=0.027

See talk R. Poeschl at LCForum
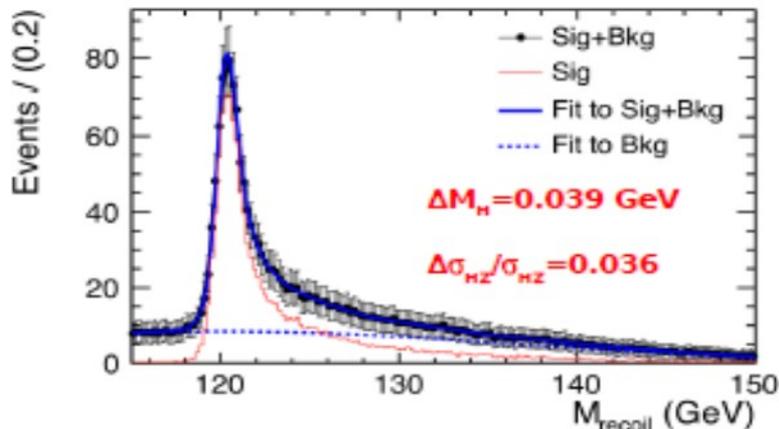

$$\sigma_{HZ} \sim g^2_{HZZ}$$
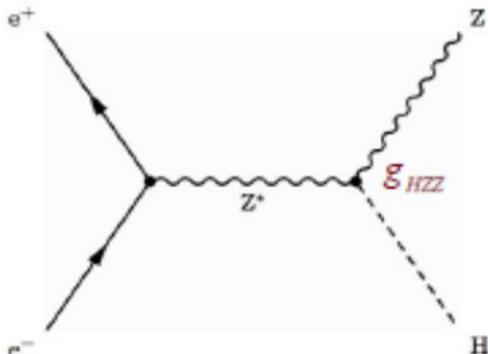
⇒ Precision in g$_{HZZ}$ coupling 1-2%

Sensitivity to 15% deviations
SM prediction of cross section
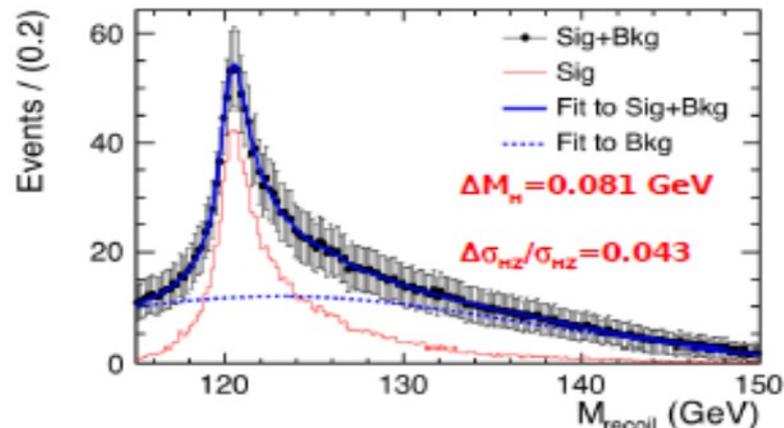
Task list of the LC -- some 'new' studies

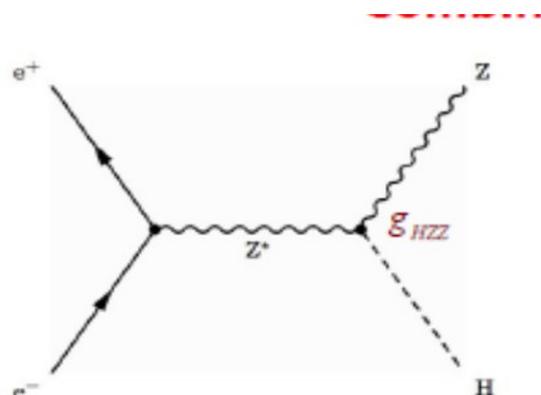- **Couplings measurement: √s=250 GeV (LOI)**   *√s=250 GeV*

Muon Channel

$\Delta M_H = 0.039$ GeV

$\Delta\sigma_{HZ}/\sigma_{HZ} = 0.036$

**Very Precise Measurement
S/B = 8 in Peak Region**

Electron Channel

$\Delta M_H = 0.081$ GeV

$\Delta\sigma_{HZ}/\sigma_{HZ} = 0.043$

**Less Precise
Bremsstrahlung in detector material**


Further results:

*See talk R. Poeschl
at LCForum*

- Higgs BR results
  $\Delta BR/BR(bb) \sim 3\%$
  $\Delta BR/BR(cc) \sim 9\%$
  $\Delta BR/BR(gg) \sim 10\%$
  Error includes $\Delta\sigma_{HZ}$

Exciting Higgs story not yet finished

- **Since $m_H \sim$ free parameter in SM at tree level**

  – Crucial relations exist, however, between m_{top}, m_W and $\sin^2\theta_{eff}$

  – If nothing else appears in the electroweak sector, these relations have to be urgently checked in order to

      a) distinguish between SM and Higgs in BSM models (remember Abdels talk, $\Delta m_H \sim m^4_{top}$!

      b) Close the SM picture

- **Which strategy should one aim?**

  – exploit **precision observables** and check, whether the measured values fit together at quantum level

  – m_Z, m_W, α_{had}, $\sin^2\theta_{eff}$ und m_{top}

Higgs story has just started …
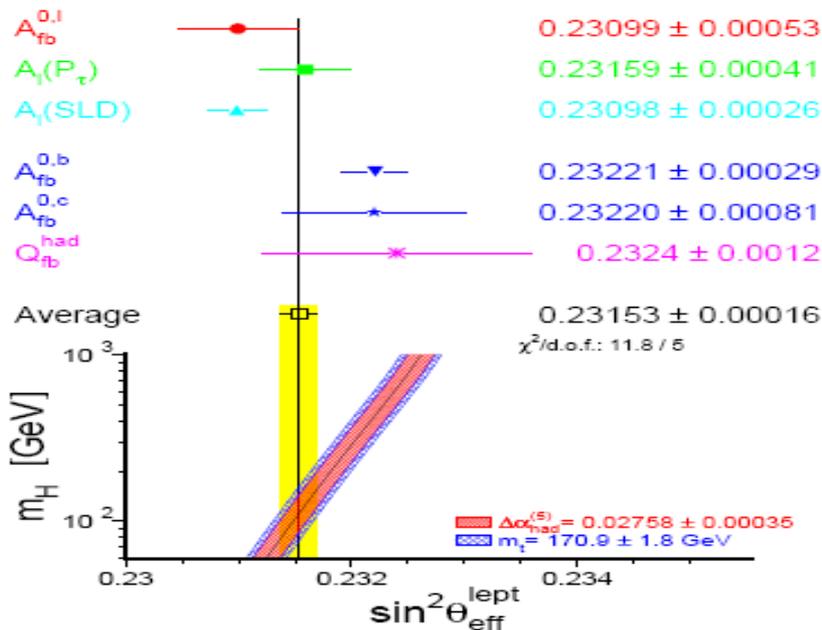
LEP:

$\sin^2\theta_{eff}(A_{FB}^b) = 0.23221 \pm 0.00029$

SLC:

$\sin^2\theta_{eff}(A_{LR}) = 0.23098 \pm 0.00026$

World average:

$\sin^2\theta_{eff} = 0.23153 \pm 0.00016$

- **Uncertainties from input parameters: Δm_Z, $\Delta\alpha_{had}$, m_{top}**

Heinemeyer, Weiglein

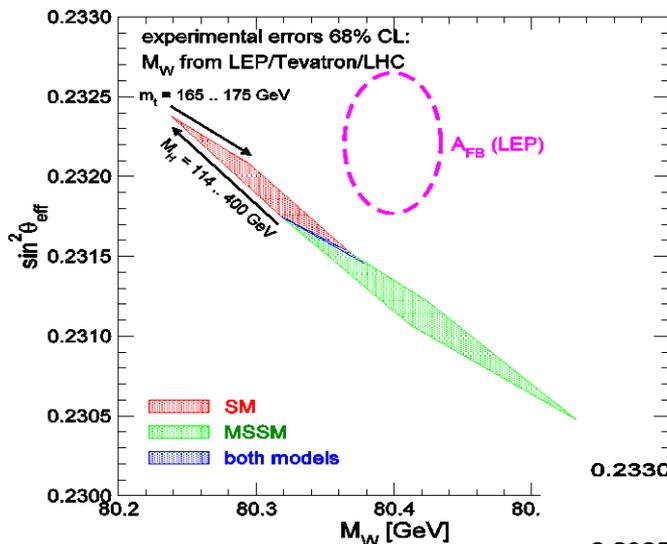- $\Delta m_Z = 2.1$ MeV: $\Delta\sin^2\theta_{eff}^{para} \sim 1.4 \times 10^{-5}$
- $\Delta\alpha_{had} \sim$ **10 (5 future) x 10^{-5}**: $\Delta\sin^2\theta_{eff}^{para} \sim 3.6$ (1.8 future)$\times 10^{-5}$
- $\Delta m_{top} \sim 1$ GeV (Tevatron/LHC): $\Delta\sin^2\theta_{eff}^{para} \sim 3 \times 10^{-5}$
- $\Delta m_{top} \sim 0.1$ GeV (ILC): $\Delta\sin^2\theta_{eff}^{para} \sim 0.3 \times 10^{-5}$
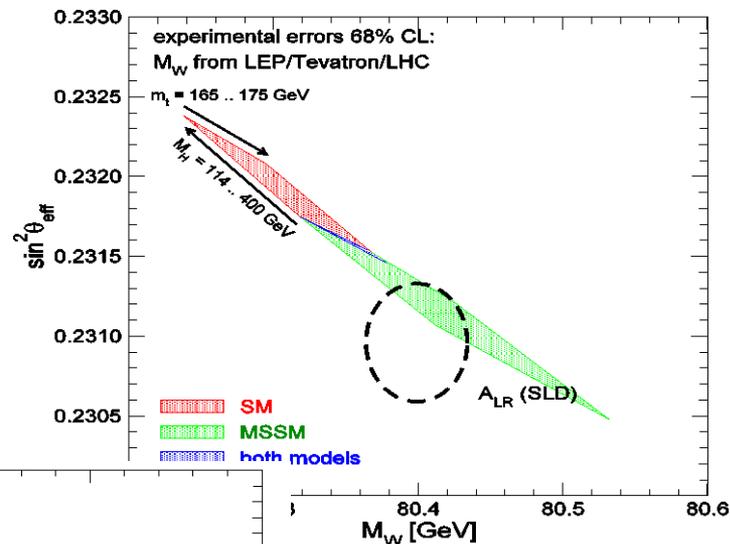
To close the story... √s=92 GeV

1. Measure $\sin^2\theta_{eff}$ via A_{LR}, A_{FB} with high precision

See talk S. Heinemeyer at LCForum

← LEP value disfavours both, SM+MSSM
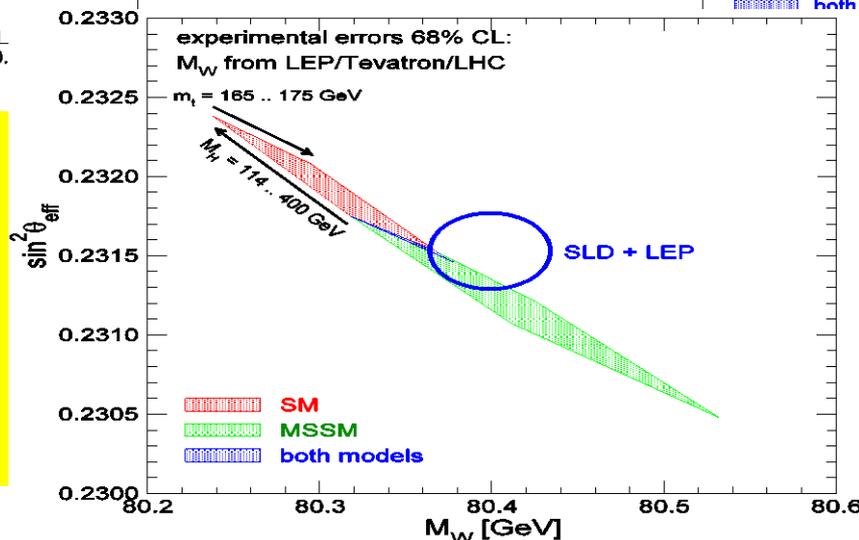
World average → happy with both!

Central value has large impact !!!

SLD value disfavours SM

and…

2. measure the top mass   *See talk P. Uwer at LCForum*

- **LHC: Difficult (if not impossible) to go below Δm_{top}<1 GeV**
  - Because of non perturbative corrections, intrinsic uncertainty generator mass $\leftarrow \rightarrow$ pole mass, higher order corrections

- **Since top quark does not appear as asymptotic state: m_{top} is just a parameter, i.e. renormalisation scheme dependent**

- **only indirect determination possible**

- **Observable should show good sensitivity to m:**

$$\frac{\Delta O}{O} \leftrightarrow \frac{\Delta m_t}{m_t}$$

- **LC: Peak position remains stable: m_t=100 MeV estimate still valid!**

- **However: dedicated threshold scan required!**

- **Threshold scan meets all the requirements, theory is still improving**

- **Alternative approaches are in principle possible, however reachable accuracy not yet clear**

and...

2. measure the top mass

See talk P. Uwer at LCForum

[Beneke, Kiyo, Schuller 08]

NNLO
NNNLO

$\mu = (25 - 80)$ GeV
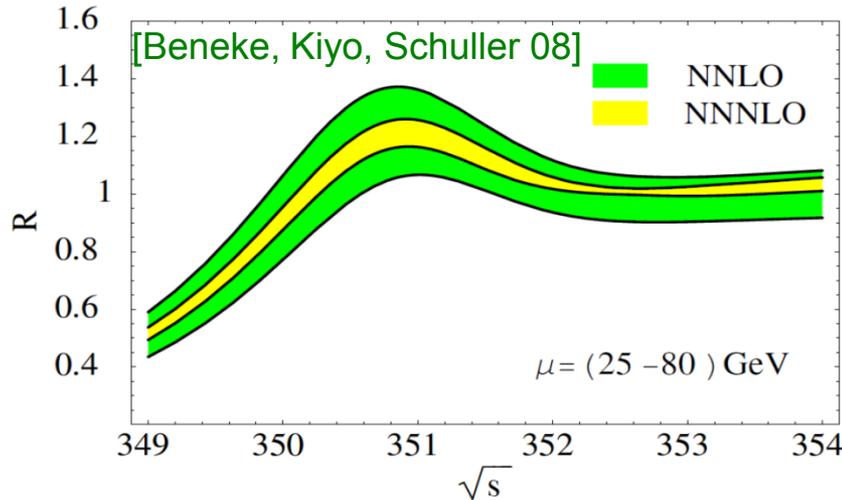
Important shift due to non-logarithmic NNNLO terms

- – **LC: Peak position remains stable: m_t=100 MeV estimate still valid!**
- – **However: dedicated threshold scan required!**
- – **Threshold scan meets all the requirements, theory is still improving**
- – **Alternative approaches are in principle possible, however reachable accuracy not yet clear**

Why Higgs self coupling?

$\sqrt{s} \gtrsim 500$ GeV

- **Needed to determine the Higgs potential**

- **May also be important to distinguish nature of Higgs sector, THDM or SUSY!**

See talk J. Tian at LCForum

Higgs Potential:
$$V(\eta_H) = \frac{1}{2} m_H^2 \eta_H^2 + \boxed{\lambda v \eta_H^3} + \frac{1}{4} \lambda \eta_H^4$$
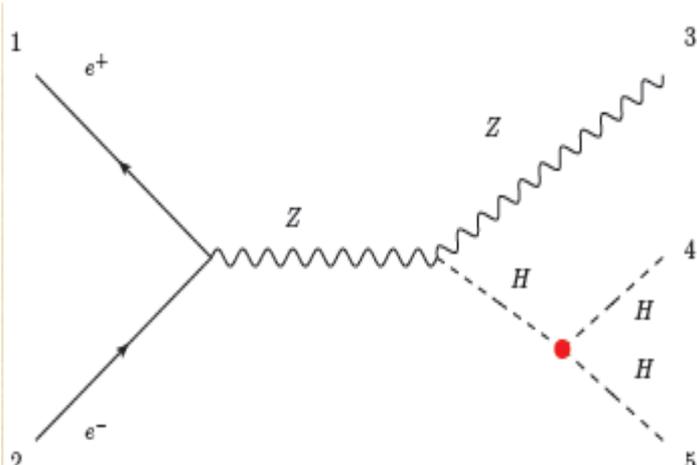
physical Higgs field   mass term   trilinear coupling   quartic Higgs coupling, which is difficult to measure at both LHC and ILC, even SLHC!

SM: $\lambda = \lambda_{SM} = \frac{m_H^2}{2v^2}$ $v \sim 246$ GeV
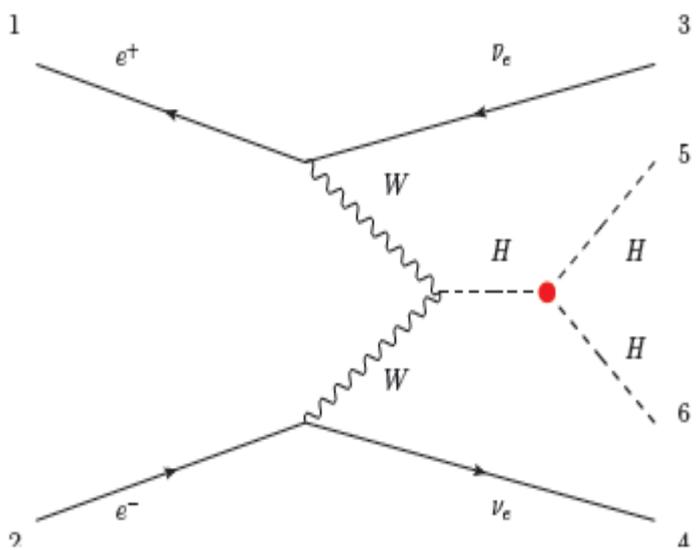
Full simulation study under work

See talk J. Tian

√*s=500 GeV*

√*s=1000 GeV*

$$\frac{\Delta\lambda}{\lambda} = 1.8\frac{\Delta\sigma}{\sigma}$$

$$\sigma = a\lambda^2 + b\lambda + c$$

$$\frac{\Delta\lambda}{\lambda} = 0.85\frac{\Delta\sigma}{\sigma}$$

$\sigma(e^+e^- \rightarrow ZHH)$

M(H)=120GeV
√s=500GeV

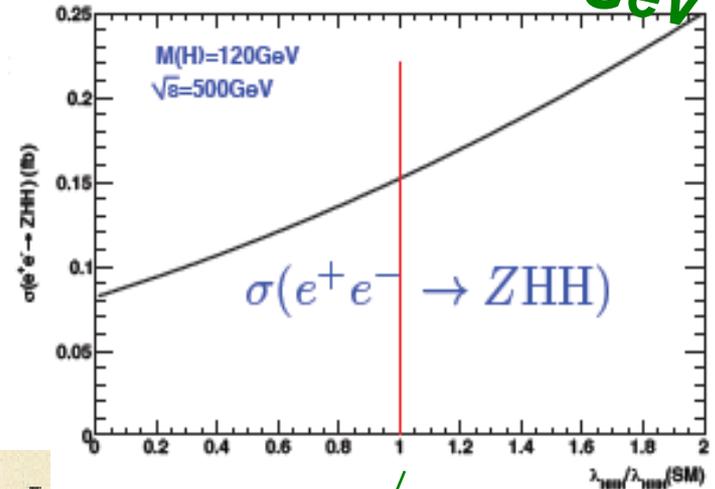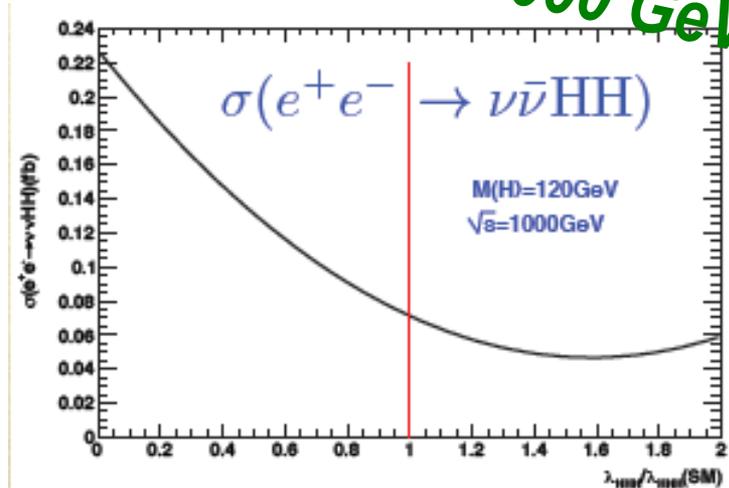$\sigma(e^+e^- \rightarrow \nu\bar{\nu}HH)$

M(H)=120GeV
√s=1000GeV

Full simulation study under work

See talk J. Tian

$\sqrt{s}=500$ GeV

$$\frac{\Delta\lambda}{\lambda} = 1.8\frac{\Delta\sigma}{\sigma}$$

$$\frac{\delta\sigma}{\sigma} = 20\%$$

$$\frac{\delta\lambda}{\lambda} = 36\%$$

$$\sigma = a\lambda^2 + b\lambda + c$$

$\sqrt{s}=1000$ GeV

$$\frac{\Delta\lambda}{\lambda} = 0.85\frac{\Delta\sigma}{\sigma}$$

Full sim under work, end 2012
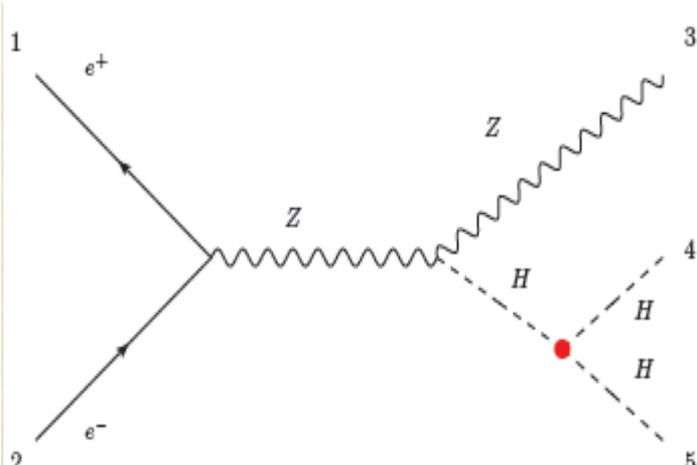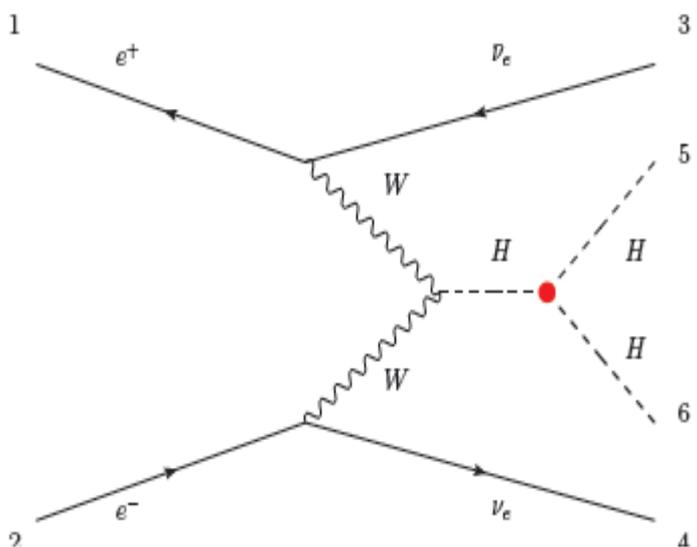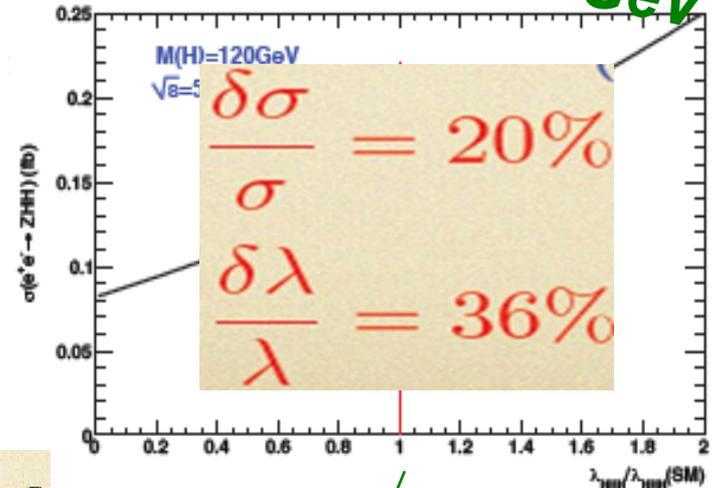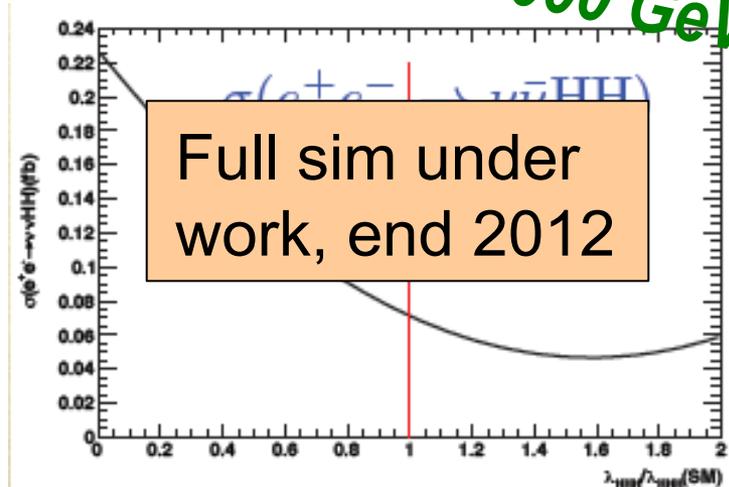
Impact from (still) LHC non-findings

- **SUSY: still strongly motivated and beautiful, but**

  – **so far, nothing, only rather heavy exclusion limits in the coloured sector**

  – **just constrained models (mSUGRA, CMSSM) under tension !**
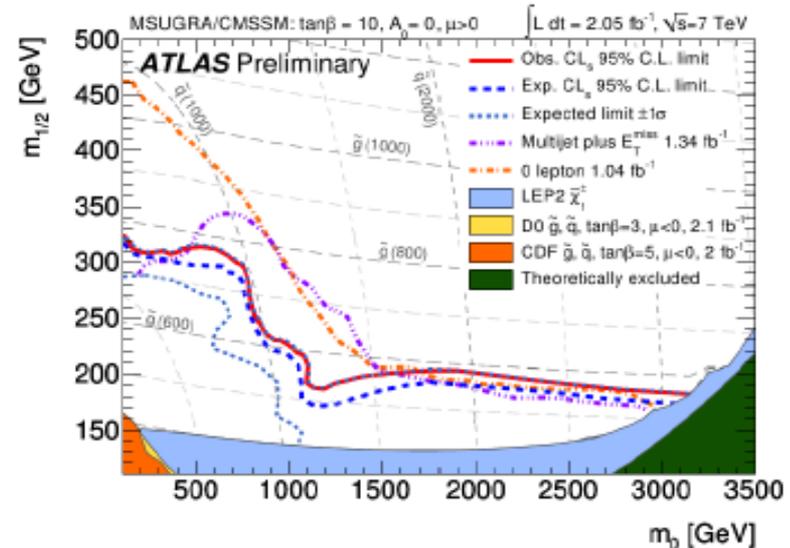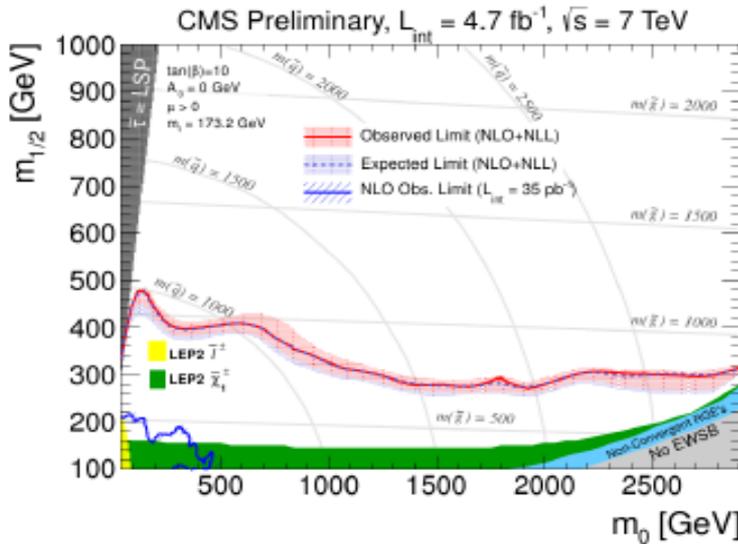
- **What can a LC do? Which further input do we have?**

What could be the 1ˢᵗ step in such scenarios?

- **Assume only Higgs@LHC but no hints for SUSY**
  - **Really SM?**
  - **Help from $\sin^2\theta_{eff}$?**

- **If GigaZ precision:**
  - **i.e. $\Delta m_{top}=0.1$ GeV…**
  - **Deviations measurable**

- **$\sin^2\theta_{eff}$ can be the crucial quantity to outline the scale!**

Heinemeyer, Weber, Weiglein

√s=92 GeV
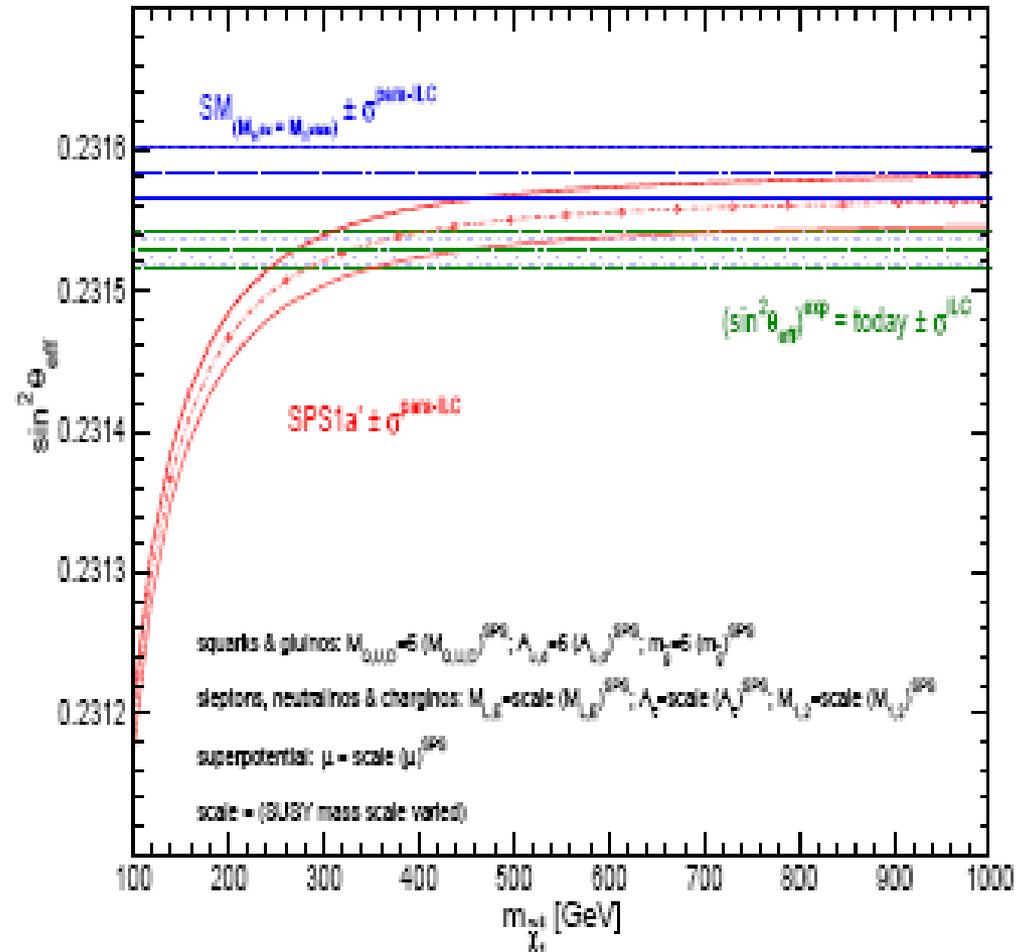
Further SUSY facts

- **Please remember (see talk, S. Heinemeyer, yesterday):**

  - **Low energy experiments, $(g-2)_\mu$, favour rather low SUSY masses in the electroweak sector:**

    $$\delta a_\mu(\text{N.P.}) = \mathcal{O}(C)\left(\frac{m_\mu}{M}\right)^2, \quad C = \frac{\delta m_\mu(\text{N.P.})}{m_\mu}$$

    See talk D. Stoeckinger at LCForum

    - **C very model dependent, SUSY/ED ~ O($\alpha/4\pi$ …)**

  - **LHC results prefer rather heavy coloured sector in 1st +2nd generation (m_g>800 GeV)**

  - **Way out: rather simple**

    - **Either just decouple uncoloured and coloured sector and take hybrid models of SUSY breaking**

    - **Just leave out the constrained minimal models, that's all**

  Personal remark: I am not worried at all, just enjoy LHC results

Simple way out, just one example

Normal scalar mass hierarchy

- (g-2)_mu needs light smuons

- BF(b->s gamma) needs heavy stops

- NMH model: m0(1)=m0(2)<<m0(3)

But decouple 3rd from 1st+2nd generation!

$m_0(1,2) = 100\text{GeV}, m_0(3) = 1400\text{GeV}, m_{1/2} = 550\text{GeV},$
$A_0 = 0, \tan\beta = 30, \mu > 0, m_t = 175\text{GeV}$

H. Baer, S. Belyaev, Kupnovnickas, Mustafayev

Further play: new TDR benchmark

$\sqrt{s}$=500 GeV

Berggren, List, Rolbiecki

m_H=125 GeV:

tanβ=10
M$_2$=225 GeV
μ=200 GeV,…

- **Wonderful spectrum with rich phenomenology!**
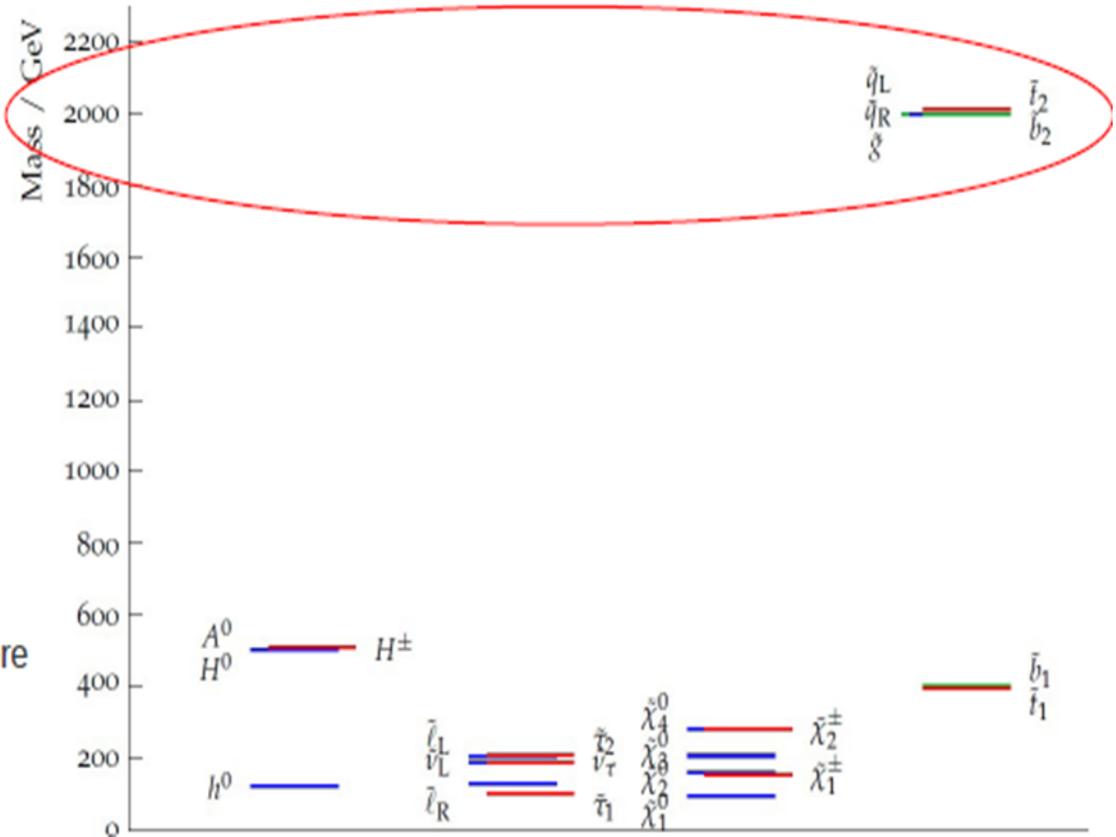
There is not really a problem with current LHC bounds vs SUSY !

One gravitino DM induced example

- **See Sergei's talk later today: nightmare (LHC) scenario**

  - Gravitino LSP (DM)
  - Neutralino is the NLSP and Higgsino-like
  - Charginos are mass-degenerate with Neutralinos
  - Higgs mass around 125 GeV
  - All colored particles are inaccessible at the LHC

  Light chargino and neutralinos ~130 GeV, Further scalars>600 GeV Gluino etc, >1 TeV

- **Apply in future LC features to such a scenario:**

  Choi ,SY ea

  - **Precise fundamental SUSY parameter determination M_1, M_2, μ, tanβ possible, if only $m_{\chi^0_1}$, $m_{\chi^0_2}$ and $m_{\chi^+_1}$ is accessible**

  - **Required features: polarized beams, different beam energies, threshold scans**
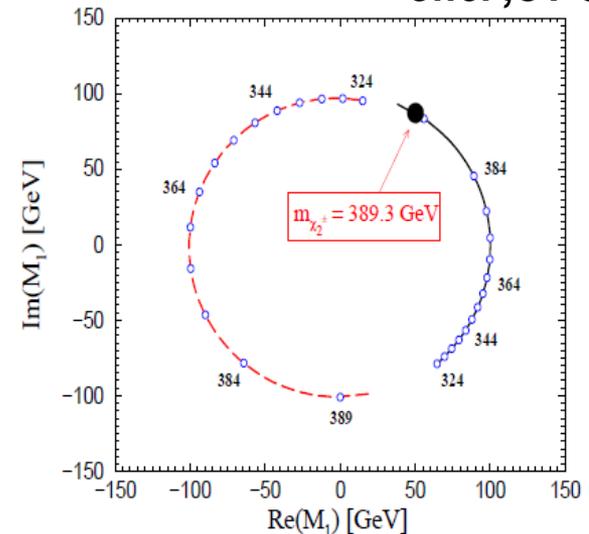
Assume hints for SUSY at LHC: task List LC

- **Precise determination of fundamental MSSM parameters**
  - Independent from the SUSY breaking scheme
  - Since masses and cross section O(% - ‰) level achievable, parameter determination also O(%)
  - Inclusion of electroweak higher order corrections required
  - Already under work now:
  - Why already now? Study, i.e. how strong the impact of mass measurements via threshold scans is etc.
  - Provide accurate predictions for heavier states!

See A. Bharucha talk at LCForum

e+e- to $\chi^+_1\chi^-_1$

Parameter	NLO result $\pm 1\sigma (\pm 2\sigma)$	LO result $\pm 1\sigma$
M_1 / GeV	$125.0 \pm 0.6\ (\pm 1.2)$	122.0 ± 0.5
M_2 / GeV	$250.0 \pm 1.6\ (\pm 3.0)$	260.7 ± 1.4
μ / GeV	$180.0 \pm 0.7\ (\pm 1.3)$	176.5 ± 0.5
$\tan\beta$	$10.0 \pm 1.3\ (\pm 2.6)$	27.0 ± 9.0
$m_{\tilde{\nu}}$ / GeV	$1500 \pm 20\ (\pm 40)$	2230 ± 50
$m_{\tilde{t}_2}$ / GeV	$800^{+220}_{-170}\ (^{+540}_{-280})$	–

Task List cont.

- **Goal: reveal the 'structure' of NP**
  - *Prove all predicted properties: couplings, mass relations, CP properties, spin, quantum numbers etc.*
  - **For some properties as e.g. spin verification, very good methods have been developed for the LHC** *(remember methods of Barr and of Rolbiecki, Tattersall etc.)*

- **However, 'model independence' and 'accuracy at quantum level' requires a LC**
  - *Remember the results of the LHCLC report, >400 pages,…….. still valid, nothing has really changed since then*

Conclusions: possible steps

- **LHC results are strongly encouraging !**

- **If new particle at $m_? = 125$ GeV confirmed:**

  – rich phenomenology for both LHC and LC

- **Reasonable steps:**

'elementary'

  – $\sqrt{s}$=250 GeV, 350 GeV and 92 GeV (do not forget, it might be crucial already now!)

'graduate'

  – $\sqrt{s}$= 500 GeV, 1 TeV *(if hints at LHC for NP found)*

'post-graduate'

  – $\sqrt{s}$=1.5 TeV and more *(if eg Z', ED, SUSY at LHC found)*

and Outlook

- **Physics prospects couldn't be better……**
  - **Maybe a Higgs at 125 GeV**
  - **LHC runs perfectly well**
  - **LC is ready to start**
  - **Encouraging activities in Japan towards a LC**

- **A LCreview** (*physics!*) **from 92 GeV to multi-TeV under work**
  - **Please have a look on** *lcforum.desy.de* **(more details on the web or ask S. Riemann, I. Fleck, F. Simon and myself)**
  - **Feel invited and encouraged to submit LCnotes (ILC,CLIC) on:**
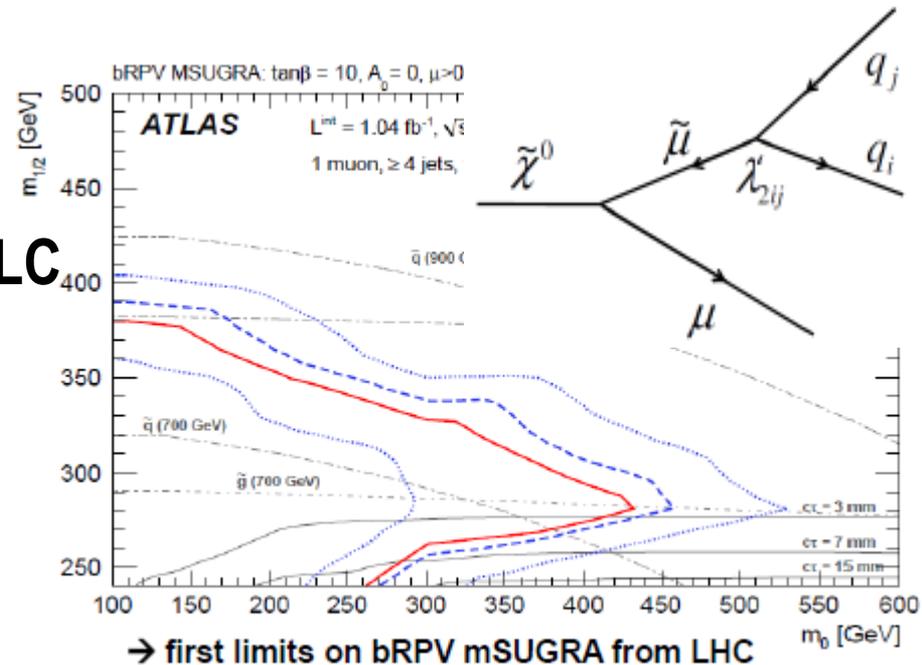 - *www-flc.desy.de/lcnotes*

This year is crucial to get answers to our physics questions!

R-parity violation

- ## Much lower mass bounds in such models:

  - ## RPV often leads to displaced vertices
  - ## Dedicated simulations also at LC

bRPV MSUGRA: tanβ = 10, A_0 = 0, μ>0

ATLAS L^{int} = 1.04 fb⁻¹, √3

1 muon, ≥ 4 jets,

→ first limits on bRPV mSUGRA from LHC

Conclusion

> R-parity violation is an interesting alternative to "normal" SUSY

> bRPV could explain neutrino parameters

> some RPV LHC searches ongoing

> especially for high squark masses: sensitivity of ILC expected to be better

See B. Vormwald talk at LCForum