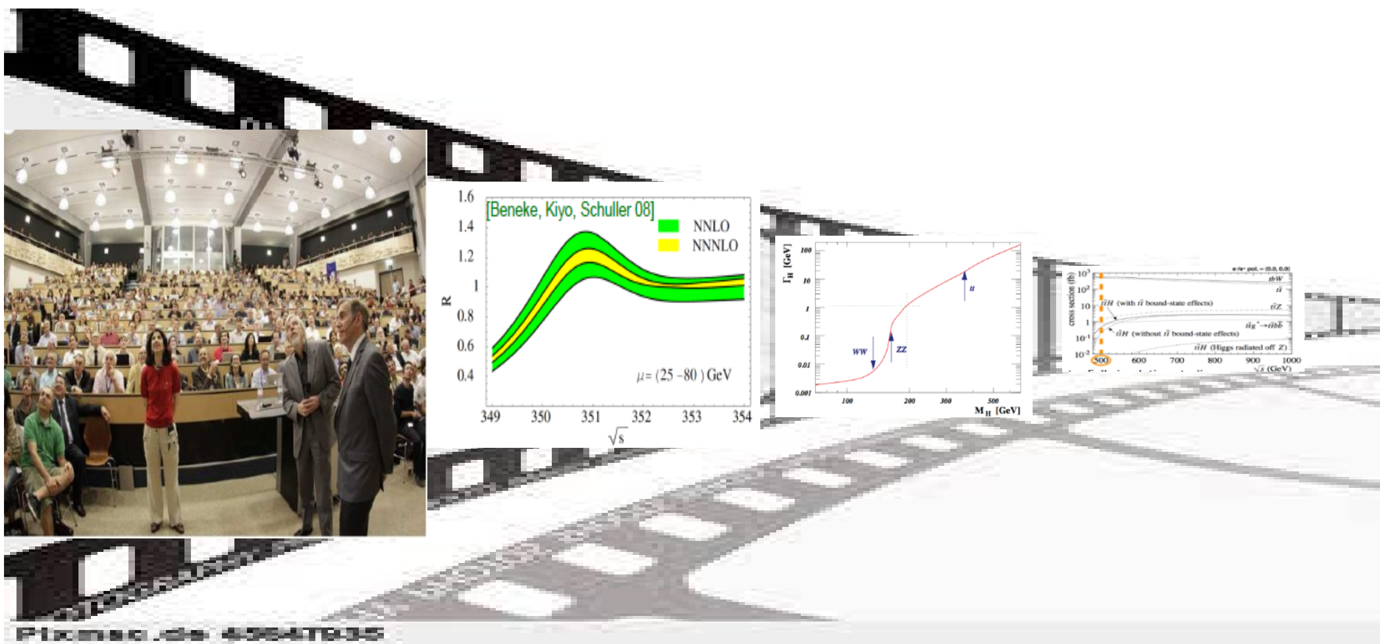
Do we need a LC to find BSM Physics?

G. Moortgat-Pick

(Uni Hamburg/DESY)



LINEAR COLLIDER COLLABORATION

Status LHC results -- in short

- **Discovery of a SM-like Higgs around m_H~125 GeV**
  - Is an absolute revolution!
  - Completely new type
  - Still not clear whether a pure SM-Higgs

`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)

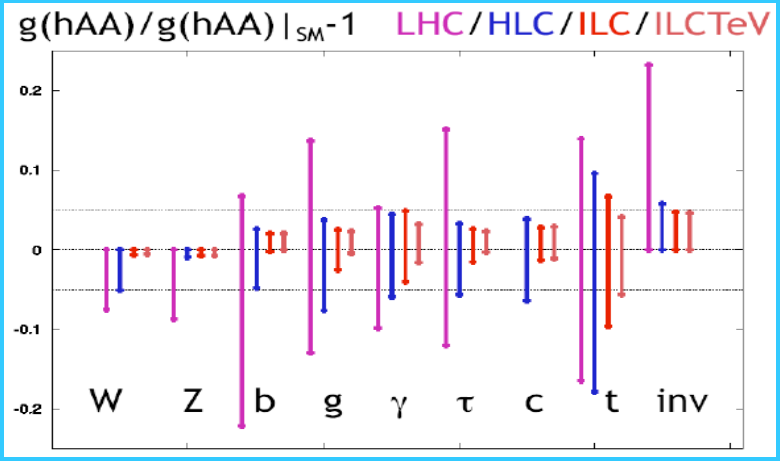
- **Limits in SUSY coloured sector (approx.):**
  - mg>700 GeV,mq>800 GeV
  - 3^{rd} generation: much weaker
- **Limits on Z', W': ~2 TeV**
- **And more limits on ED, exotics, 4^{th} generation etc.**

Physics left for a Linear Collider? Which energy steps?

Status LC -- in short

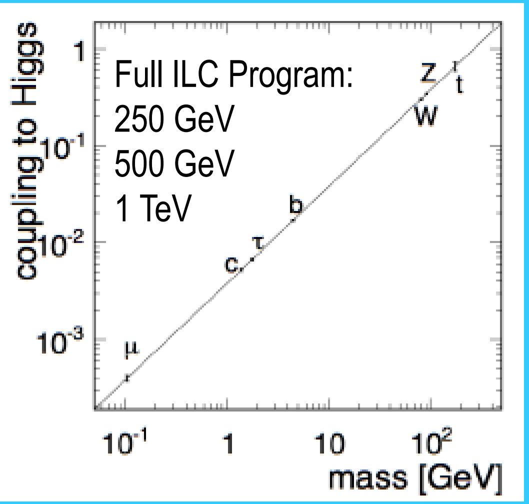
Physics

As e.g. Δm_{top}~0.1 GeV, $coup_{tth}$~6.5%
H: BR's~ 3-12% ,Γ_h~6%, $\Delta\lambda$~24%,
CP, mixed states



Details and more examples in the many new LC reports:

- CLIC CDR finished
- ILC TDR sent to PAC
- General LC review report



This talk personal choice of

- just new results in tricky scenarios
- only BSM/SUSY

Status LC -- in short

Politics

- **ILC newsline, 7.2.13:**

On Friday, 18 January, Hakubun Shimomura, Japan's Minister of MEXT (Ministry of Education, Culture, Sports, Science and Technology), the funding agency for Japan's high-energy physics programme, stated Japan's intention to invite the ILC […] Shimomura said […] I wish to carry forward to cooperate with countries concerned, and hopefully to invite it to Japan," . Japanese government would start a preparation to start discussion, including the distribution of the construction cost, with countries concerned in the first half of 2013.

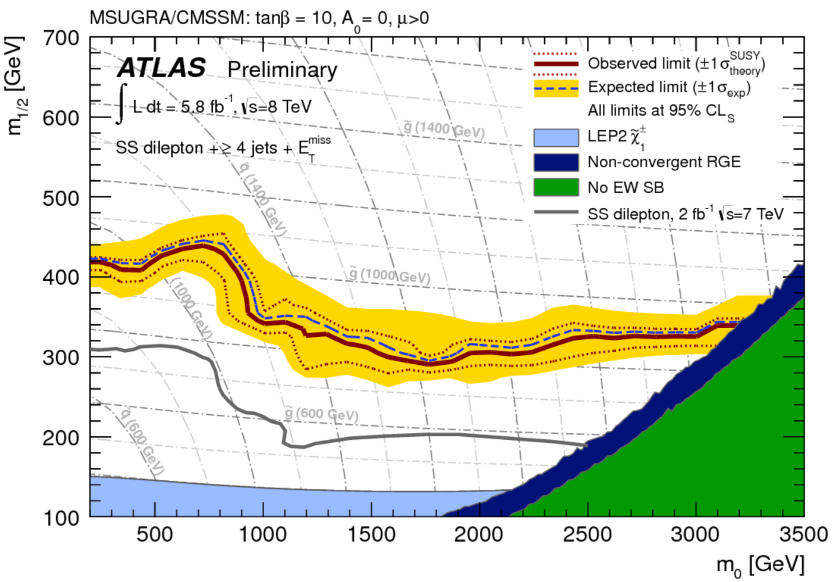
- **B. Foster, PECFA CERN 11/12:**

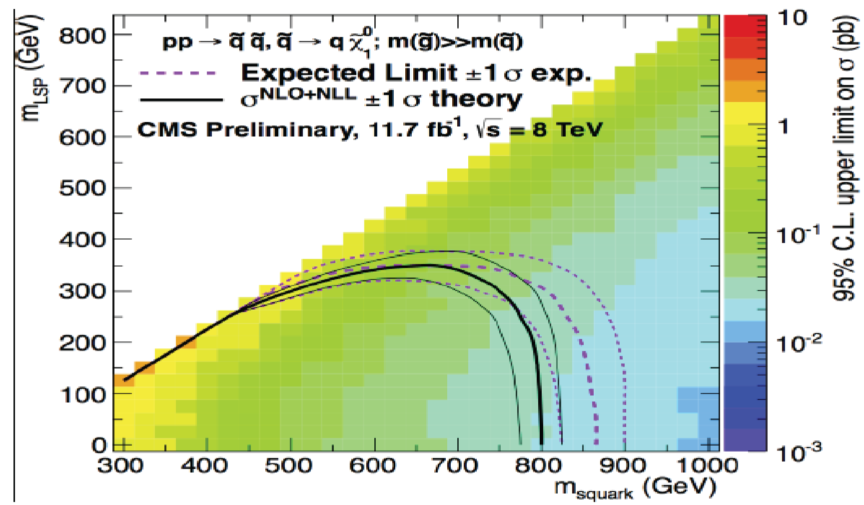
- Japanese HEP community proposes to host ILC based on the "staging scenario" to the Japanese Government.
  - ILC starts as a 250GeV Higgs factory, and will evolve to a 500GeV machine.
  - Technical extendability to 1TeV is to be preserved.
- It is assumed that one half of the cost of the 500GeV machine is to be covered by Japanese Government. However, the share has to be referred to inter-governmental negotiation.

Looks absolutely striking ….. So back to physics!

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
  - Constrained models (mSUGRA, CMSSM, Simpl. M) under tension!





- **Further hints from theory?**

Further SUSY facts

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

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

    - C very model dependent, SUSY/ED ~ O(α/4π …)
  - LHC results prefer rather heavy coloured sector in 1st +2nd generation
  - Way out: rather simple
    - Decouple uncoloured and coloured sector and/or take hybrid models of SUSY breaking
    - Just leave out the constrained minimal models, that's al

Remember: Minimal SUSY contains 105 new parameter… why should nature be too simple ?

Example: New TDR benchmarks

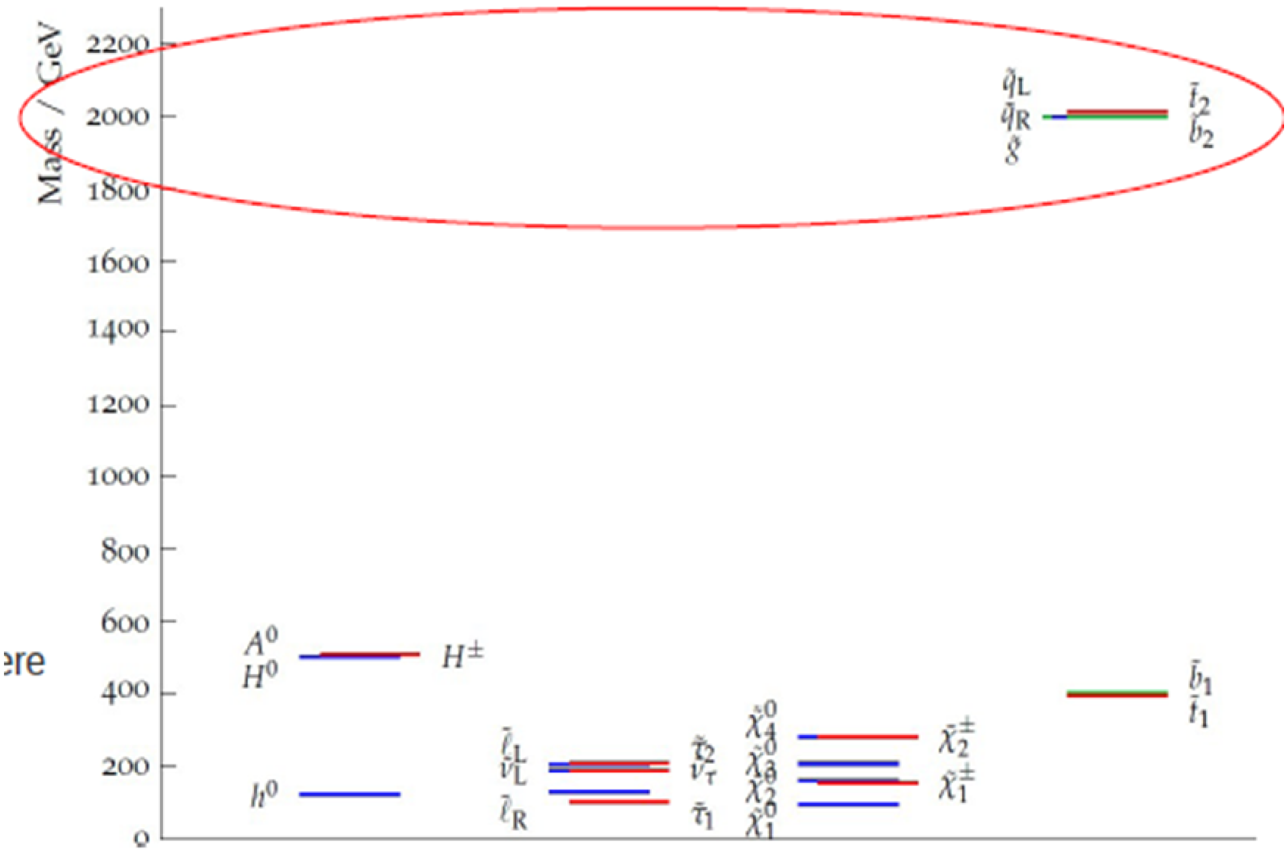
$\sqrt{s}$=500 GeV

Berggren, List, Rolbiecki '12

m_H=125 GeV:

tanβ=10
M_2=225 GeV
μ=200 GeV,…

Wonderful spectrum with rich phenomenology!



The goal of LC phenomenology: fixing the structure of the underlying model and parameters!

Why 'should' light SUSY be preferred?

- **Minimization of 1-loop Higgs Potential:**

$$\frac{M_Z^2}{2} = \frac{m_{H_d}^2 + \Sigma_d^d - (m_{H_u}^2 + \Sigma_u^u)\tan^2\beta}{\tan^2\beta - 1} - \mu^2 \simeq -(m_{H_u}^2 + \Sigma_u^u) - \mu^2$$

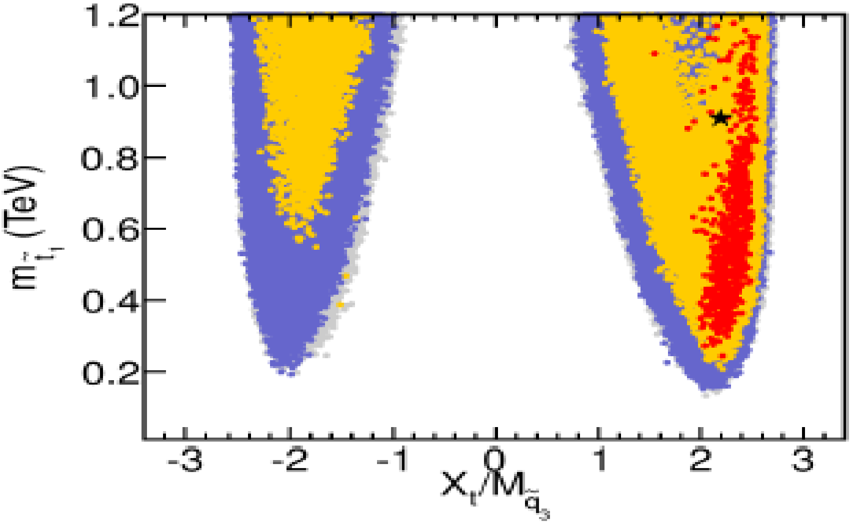
- **To keep EWFT ~ 3%:**
  - rather small μ (~200 GeV) required
  - 'naturalness'
  - Several 'natural' scenarios: light stops, light higgsinos or light sleptons

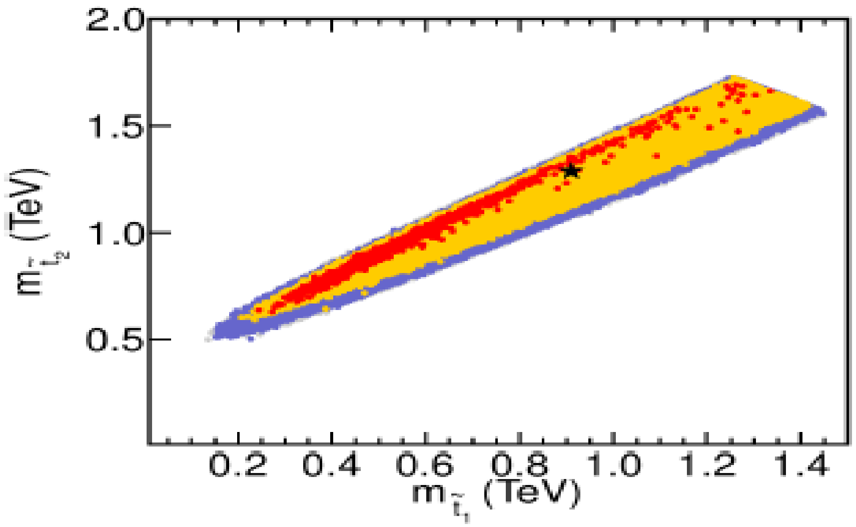
Papucci,Ruderman,Weiler 2011
Baer,Barger,Huang, Tata, 2012

MSSM interpretation of light Higgs

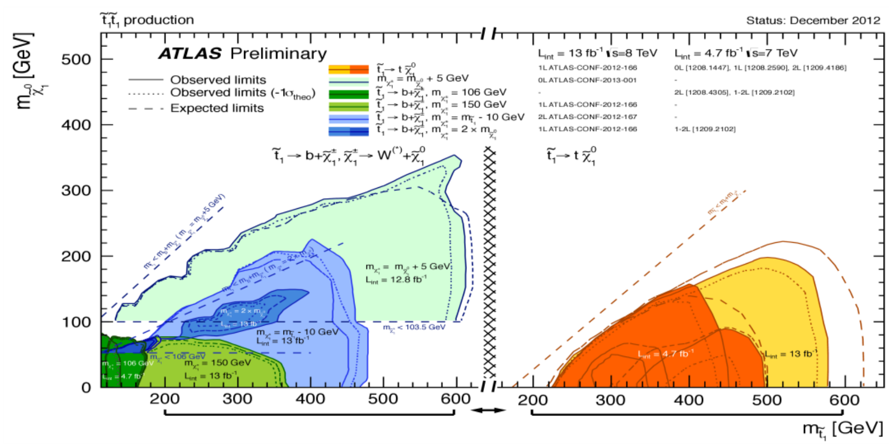
- Preferred values for stop masses from fits :
- \

Bechtle, Heinemeyer,Stal,Stefaniak,Weiglein,Zeune '12





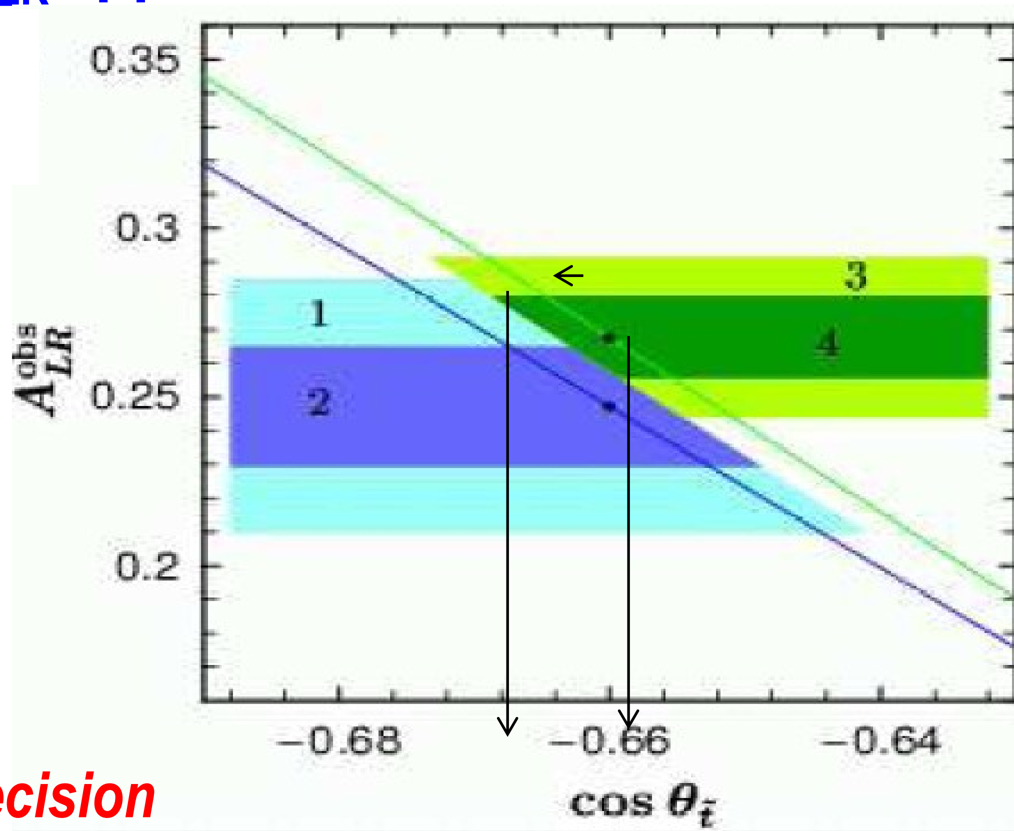
- M_h~125 GeV requires large stop mixing ~ large X_t
  - Rather large $X_t=A_t-\mu \cot\beta$
- But $m_{\tilde{t}}$ can still be light !



Start with stops: features at a LC

- **With polarized beams: A_{LR} applicable**

$\mathcal{L}_{int}$	P_{e^-}	P_{e^+}	$\Delta m_{\tilde{t}_1}$	$\Delta \cos\theta_{\tilde{t}}$
100 fb^{-1}	∓ 0.9	0	1.1%	2.3%
500 fb^{-1}	∓ 0.9	0	0.5%	1.1%
100 fb^{-1}	∓ 0.9	± 0.6	0.8%	1.4%
500 fb^{-1}	∓ 0.9	± 0.6	0.4%	0.7%



- **Mixing angle $\Delta\cos\theta_t$<1%**
  - **If $\Delta X_t \pm 1\%$: $\Delta m_h = \pm 0.2$GeV**

⟶ ***matches long-term LHC precision***

  - **If $\Delta X_t \pm 10\%$: $\Delta m_h = \pm 1.5$GeV**

⟶ ***Too big to check the consistency of the model!***

Next: Higgsino-like scenarios

- Can be embedded in hybrid gauge-gravity mediation
  - ‘M’ driven by gauge-mediation
  - ‘μ’ driven by gravity mediation

Bruemmer,List,GMP, Rolbiecki,Sert

- Two examples as ‘prototypes’ under study

Scen $m_h = 124$-Parameter:

M_1	M_2	μ	$\tan\beta$	$\tilde{e}_L$	$\tilde{e}_R$	$\tilde{\nu}$
1697	4361	165.8	45	3652	1685	3651

Scen $m_h = 127$-Parameter:

M_1	M_2	μ	$\tan\beta$	$\tilde{e}_L$	$\tilde{e}_R$	$\tilde{\nu}$
5299	9514.5	167.15	48	7730	4597	7729

- Higgsino masses: $m_{\chi 0_1}$ ~165 GeV, $m_{\chi 0_2}$~167 GeV, $m_{\chi \pm_1}$~166 GeV
- Common feature: $\Delta m(_{\chi\pm 1-\chi 01})$~1 GeV
  - Challenges: mass degeneration, many π’s, soft γ, E_{miss} from decay
  - How to resolve such scenarios?

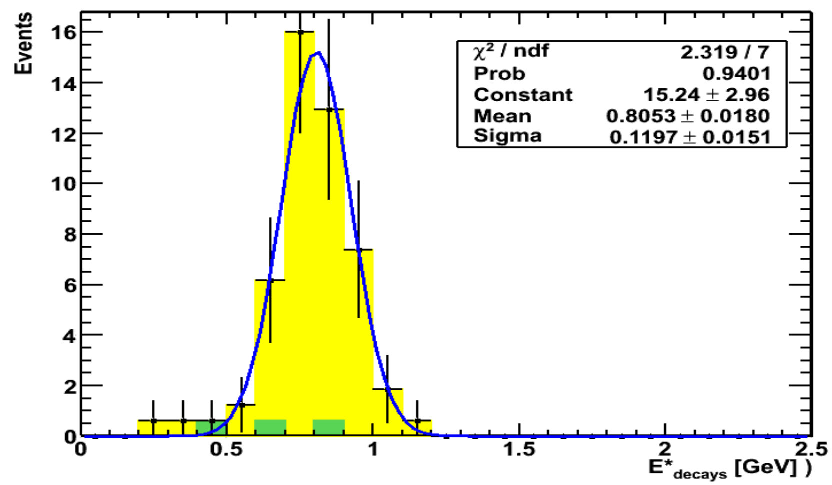
Apply ISR method

- **Accessible processes:** $e^+e^- \to \chi^0_1\chi^0_2, \chi^+_1\chi^-_1$
  - Decays: χ^-_1 mainly hadronic, χ^0_2 mainly in γ's
- **Measure masses via ISR method:**
  - Take only events with hard γ from ISR
  - Get also rid of SM background two photons
- **Measure process at two energies, $\sqrt{s}$=350 and 500 GeV**
  - Use recoil mass and semihadronic channel

Berggren, List, Sert

Mean value of fit gives the $\Delta M(\tilde{\chi}^\pm_1, \tilde{\chi}^0_1)$

- $\Delta M^{true} = 0.77$ GeV
- $\Delta M^{fit} \approx 0.80 \pm 0.02$ GeV



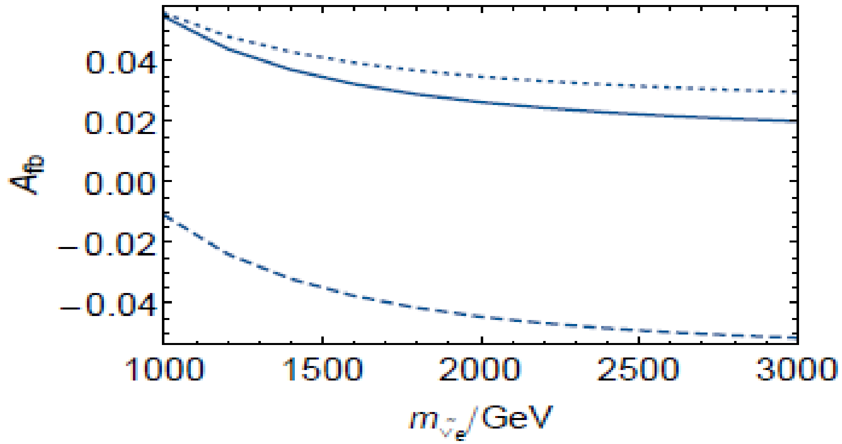
→ *Determine MSSM parameters*

LC: Parameters from $e^+e^- \to \tilde{\chi}^+_1 \tilde{\chi}^-_1$@NLO

- **In the past:** parameter determination at tree level
  - Extracted from $\sigma_{L,R}$ polarized cross sections and masses $m\tilde{\chi}_1$ and $m\tilde{\chi}^0_1$ with 500 fb^{-1}

SUSY Parameters				Mass Predictions		
M_1	M_2	μ	$\tan\beta$	$m_{\tilde{\chi}^\pm_2}$	$m_{\tilde{\chi}^0_3}$	$m_{\tilde{\chi}^0_4}$
99.1 ± 0.2	192.7 ± 0.6	352.8 ± 8.9	10.3 ± 1.5	378.8 ± 7.8	359.2 ± 8.6	378.2 ± 8.1

- **However:** Loop effects known to be relevant
  - Sensitivity to parameters arising from loops, e.g. stop-sector



Bharucha, Kalinowski, Moortgat-Pick, Rolbiecki, Weiglein 2012

- **Now:** Strategies for parameter determination still applicable?

LC: Parameters from $e^+e^- \to \tilde{\chi}^+_1 \tilde{\chi}^-_1$ @NLO

- **Strategy:** Use NLO corrected masses and $\sigma_{L,R}$ at $\sqrt{s}$=350,500
  - Use in addition A_{FB}
  - Fit of M_1, M_2, μ, tanβ and stop sector mt_1, mt_2 and $\cos\theta_{\tilde{t}}$
  - Compare mass accuracy from
    - Threshold scans
    - Continuum measurement

Bharucha, Kalinowski, Moortgat-Pick, Rolbiecki, Weiglein 2012

Parameter	Threshold fit	Continuum fit
M_1	125 ± 0.3 (±0.7)	125 ± 0.6 (±1.2)
M_2	250 ± 0.6 (±1.3)	250 ± 1.6 (±3)
μ	180 ± 0.4 (±0.8)	180 ± 0.7 (±1.3)
$\tan\beta$	10 ± 0.5 (±1)	10 ± 1.3 (±2.6)
$m_{\tilde{\nu}}$	1500 ± 24 $\left({}^{+60}_{-40}\right)$	1500 ± 20 (±40)
$m_{\tilde{t}_1}$	400^{+180}_{-120} $\left({}^{\text{at limit}}_{\text{at limit}}\right)$	–
$m_{\tilde{t}_2}$	800^{+300}_{-170} $\left({}^{+1000}_{-290}\right)$	800^{+350}_{-220} $\left({}^{\text{at limit}}_{\text{at limit}}\right)$

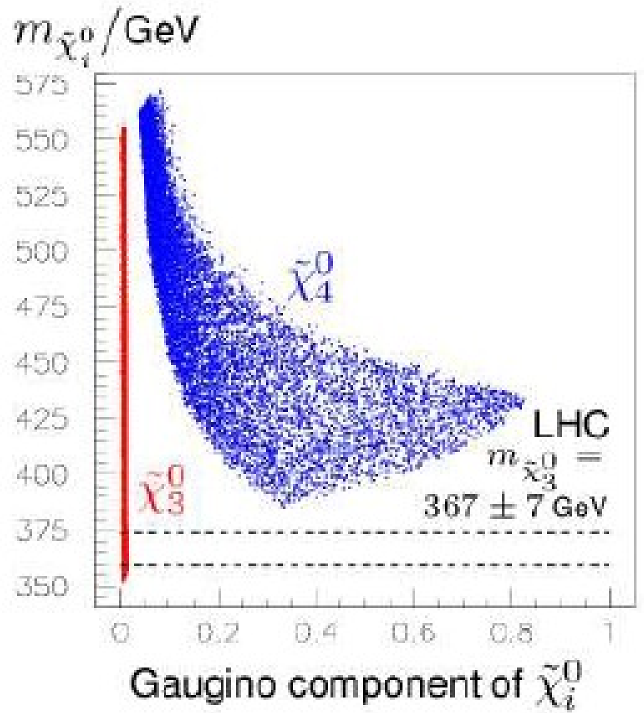
→ Relevance of threshold scans and sensitivity to heavy masses

- **Impact also on dark matter prediction:**
  - These uncertainties of the NLO corrected parameters cause 5% uncertainty in DM prediction (total uncertainty = 10%)

Challenge: MSSM vs NMSSM at LHC+LC?

- **NMSSM: Higgs singlet allows more freedom …**
  - *Choose tricky scenario with mh~124 GeV but singlet as 2nd lightest Higgs and M_1~370GeV, M_2~150 GeV, μ~360 GeV, tanβ~9,x~900 GeV*
  - **similar rates and masses**
  - **pretty 'MSSM-like' phenomenology**
- **How to distinguish the model?**
  - **First hints maybe from BR($\chi^0_{2} \rightarrow S\chi^0_{1}$)**
  - **Exploit gaugino sector:** *parameter determination, prediction of heavier states*
  - ***Model inconsistency clarifies the model !***

Hesselbach Franke Fraas, GMP '05, Levermann, List, Hartin,Porto, GMP

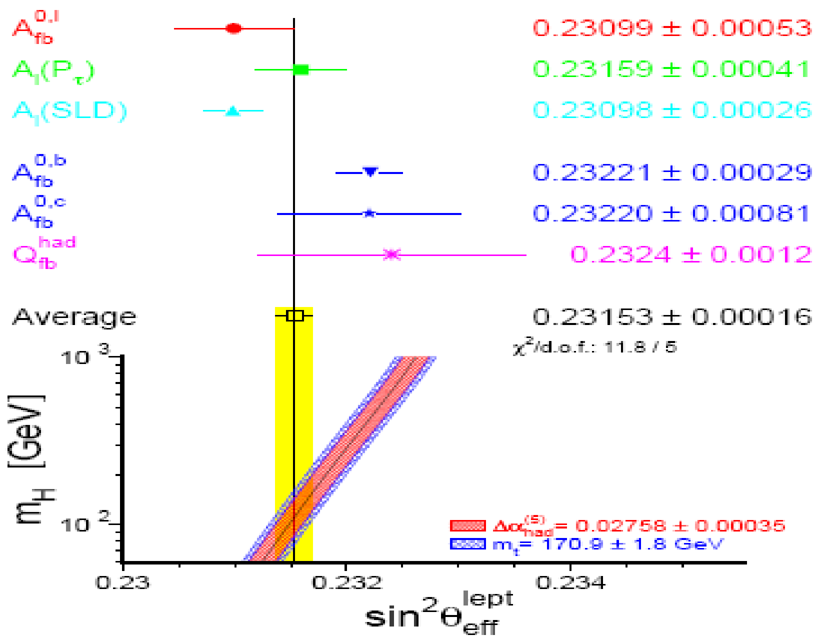


What if nothing else than H is found now?

But the exciting Higgs story has just started….

- Since m_H~ 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 $\Delta m_H \sim m^4_{top}$!)
    - 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±0.00029

SLC:

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

World average:

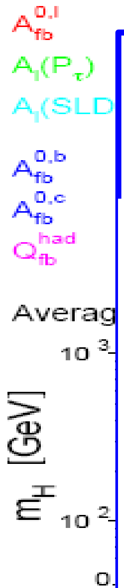
$\sin^2\theta_{eff}$ = 0.23153±0.00016

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

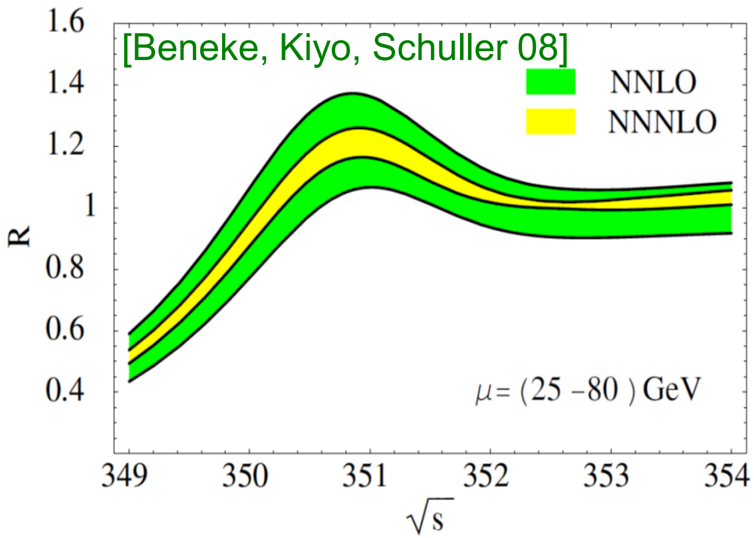
Heinemeyer, Weiglein

- Δm_Z=2.1 MeV: $\Delta\sin^2\theta_{eff}^{para}$~$1.4\text{x}10^{-5}$
- $\Delta\alpha_{had}$~10 (5 future) x 10^{-5} : $\Delta\sin^2\theta_{eff}^{para}$~3.6 (1.8 future)$\text{x}10^{-5}$
- Δm_{top}~1 GeV (Tevatron/LHC): $\Delta\sin^2\theta_{eff}^{para}$~$3\text{x}10^{-5}$
- Δm_{top}~0.1 GeV (ILC): $\Delta\sin^2\theta_{eff}^{para}$~$0.3\text{x}10^{-5}$

Higgs story has just started …



- But such a precision requires Δm_{top}=0.1 GeV



Important shift due to non-logarithmic NNNLO terms

$\sqrt{s}$=350 GeV

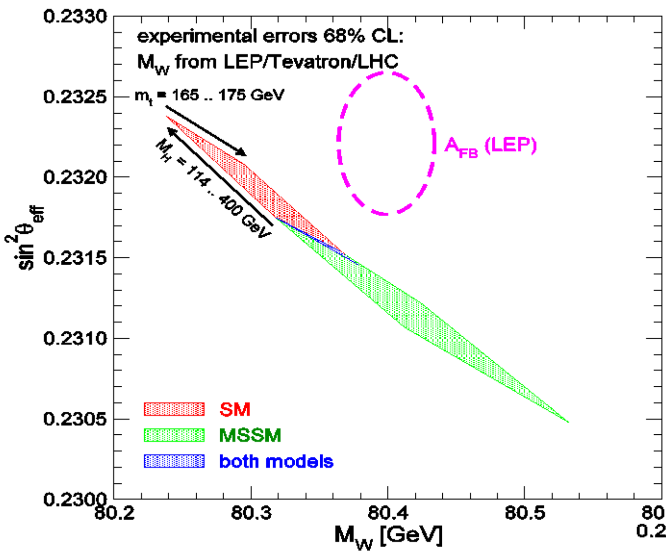
- LC: Peak position remains stable: m_t=100 MeV estimate still valid!
- However: dedicated threshold scan required!

- Unce

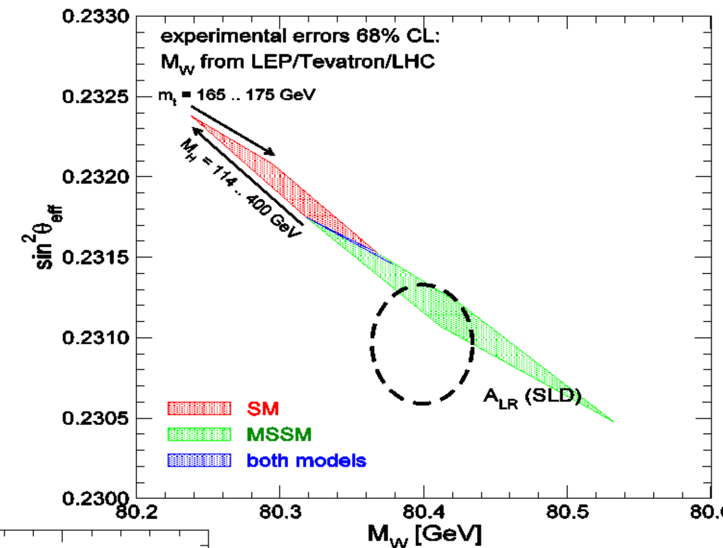
Weiglein

To close the story… GigaZ $\sqrt{s}=92$ GeV

- Measure $\sin^2\theta_{eff}$ via A_{LR} with high precision: $\Delta\sin\theta=1.3\ 10^{-5}$



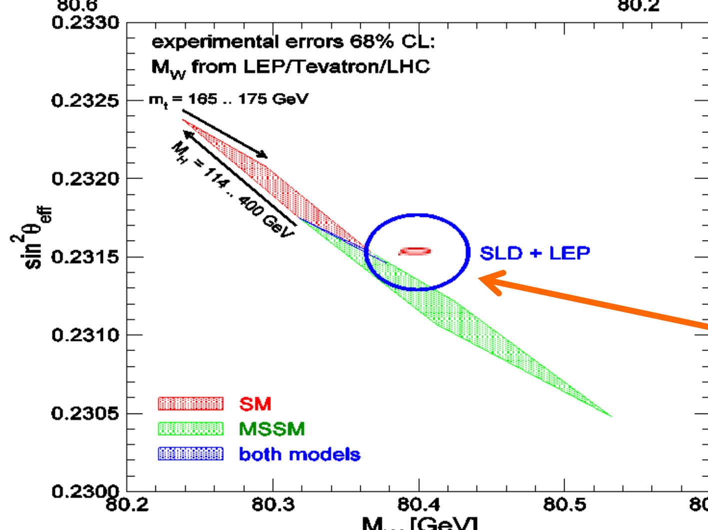
← LEP value disfavours both, SM+MSSM



↑ SLD value disfavours SM

World average → happy with both!

Central value has large impact !!!

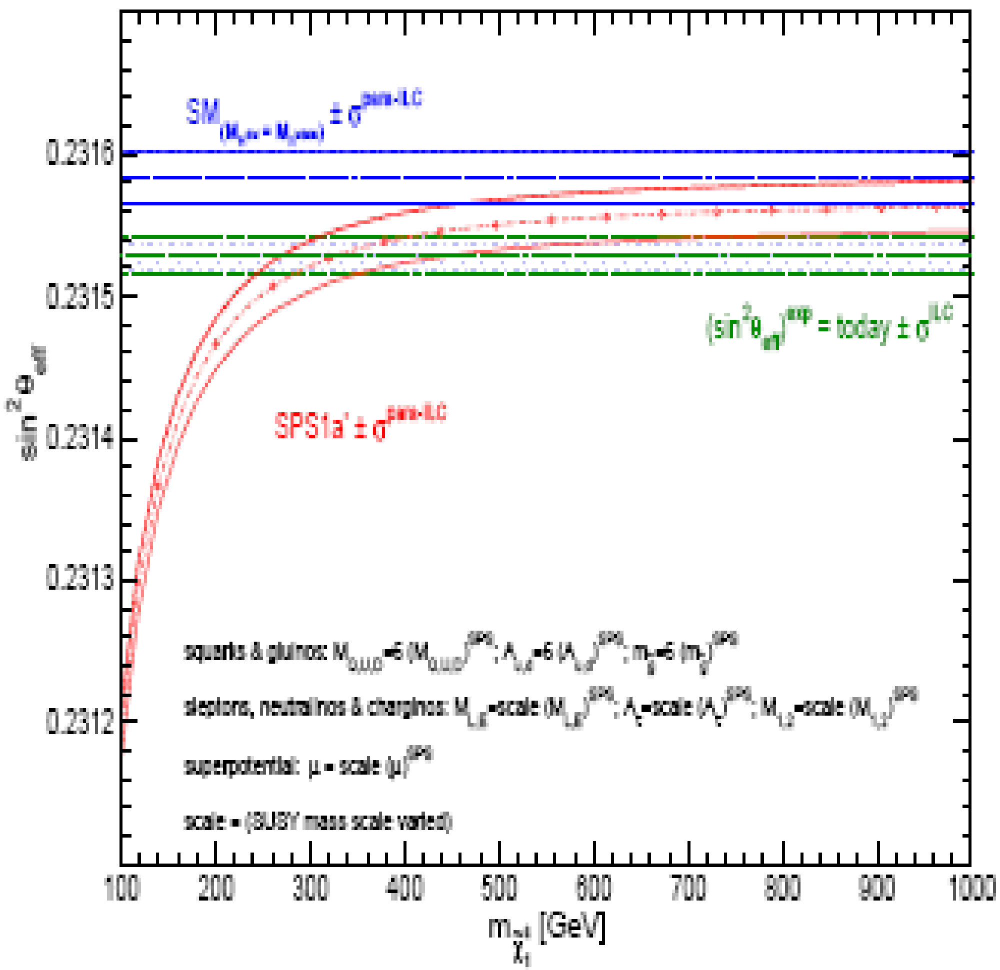


GigaZ precision!

What else could we learn? $\sqrt{s}$=92 GeV

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

Heinemeyer, Weber, Weiglein

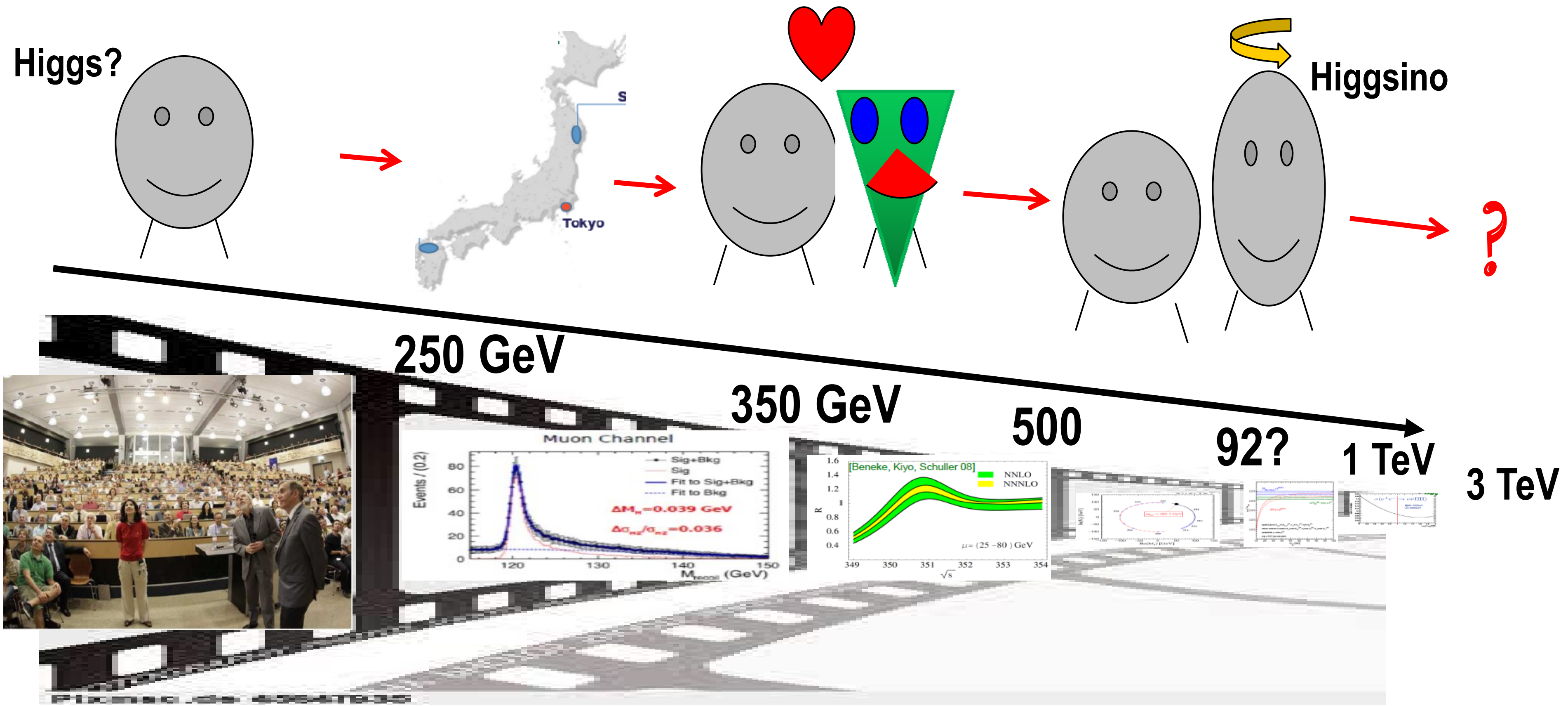


- **If GigaZ precision:**
  - **i.e. Δm_{top}=0.1 GeV…**
  - **Deviations measurable**

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

In 20 years time……we could tell a story

- Once upon a time –it was July 4th– …..



Let's do it !

Distinction of mass degenerated ew'inos

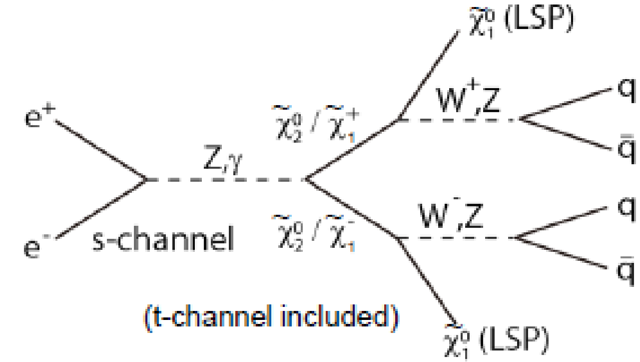
Chera, List, Suehara

- **Exploiting 'particle flow' at the LC:**

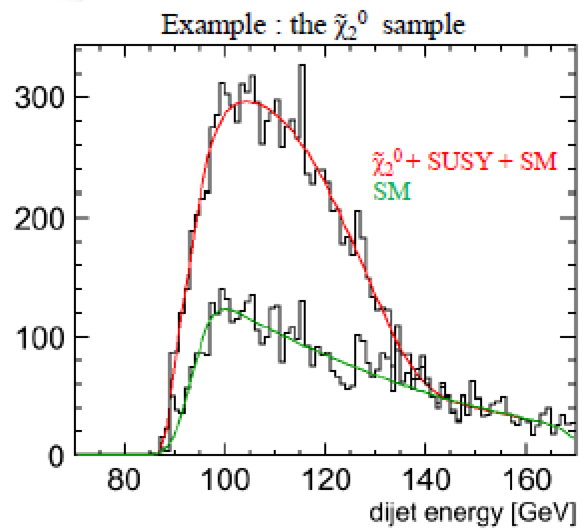
Gaugino masses: [GeV] (Spheno)

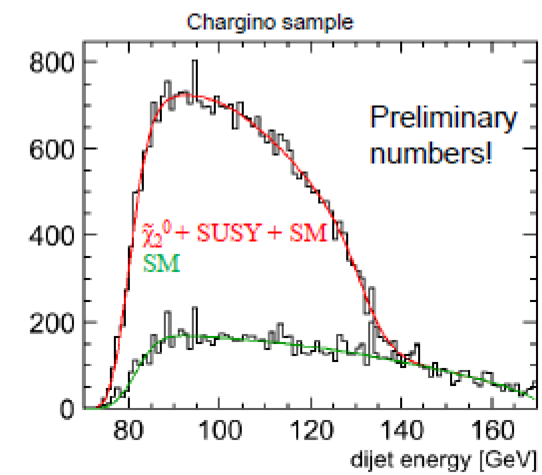
$\tilde{\chi}_1^0$	$\tilde{\chi}_1^\pm$	$\tilde{\chi}_2^0$	$\tilde{\chi}_3^0$
115.7	216.5	216.7	380

(mass degenerate)



- **Strategy (see LOI):**
  - determine $M\tilde{\chi}^\pm_1$ and $M\,\tilde{\chi}^0_2$ from the energy spectrum of W / Z candidates
  - separate $\tilde{\chi}_1^\pm$ and $\tilde{\chi}_2^0$ based on reconstructed dijet masses:

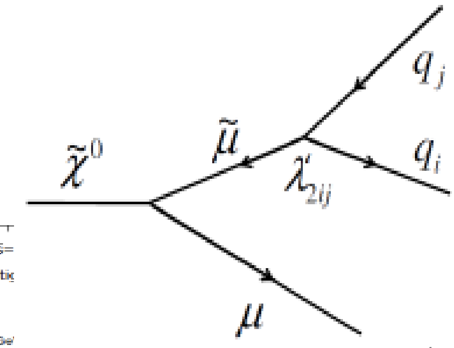




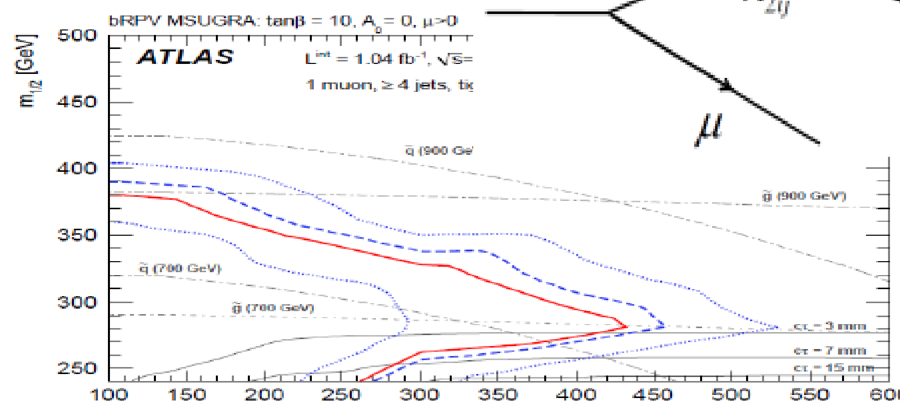
- **χ^0_2, χ^+_1 separated!**
  - **even in fully hadronic mode**

R-parity violation

- **Much lower mass bounds in such models:**

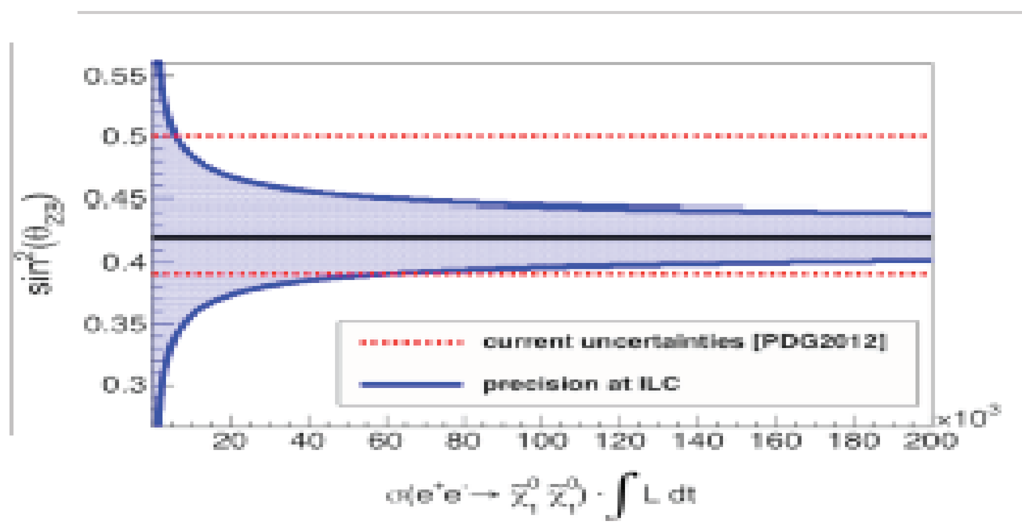


- **RPV often leads to displaced vertices**
- **Dedicated simulations also at LC**



→ first limits on bRPV mSUGRA from LHC

- **Since χ^0 and ν mix:**
  - **angle θ_{23} measurable very precise at LC**



Vormwald, List '12