Do we need a LC to find BSM Physics?

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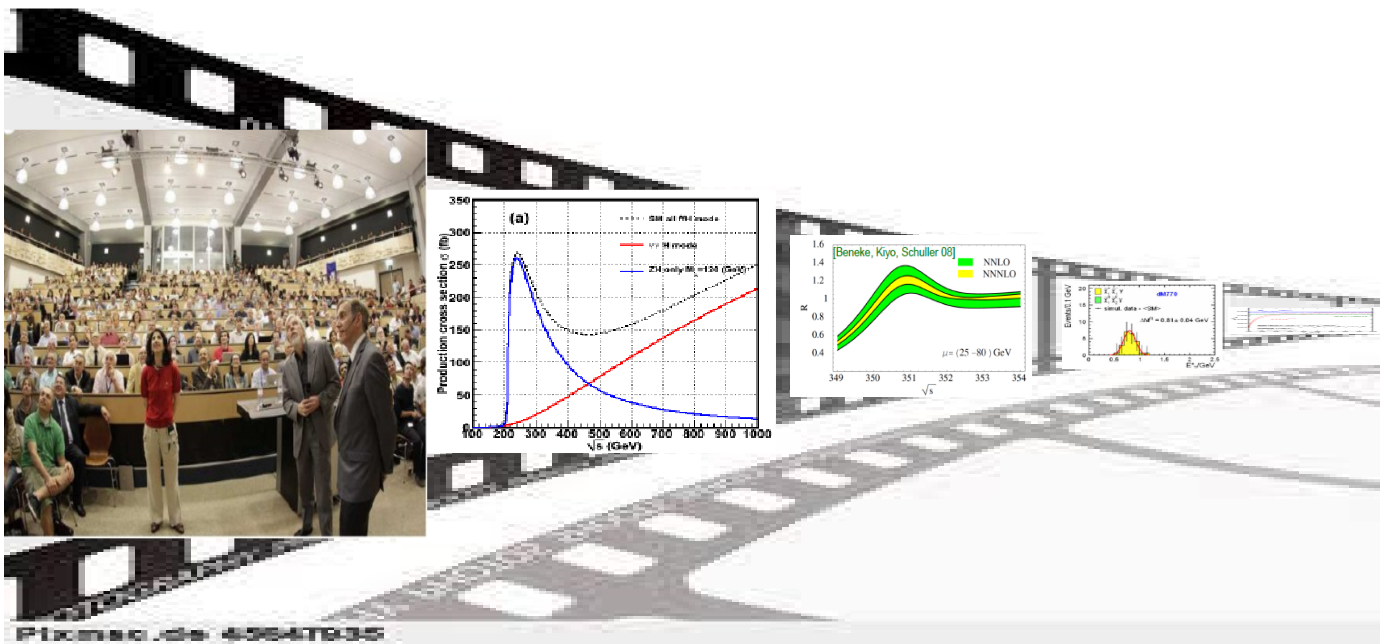


LINEAR COLLIDER COLLABORATION

Status LHC results -- in short

- **Discovery of a SM-like Higgs around m_H~125 GeV**
  - Is an absolute revolution!
  - Completely new type
  - Not clear whether a SM-Higgs
- **Limits in SUSY coloured sector (approx.):**
  - $m_g, m_q > 1$ TeV
  - 3rd generation: much weaker
- **Limits on Z', W': ~2 TeV**
- **And more limits on ED, exotics, 4th generation etc.**

`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, Feb 12)

Physics left for a Linear Collider? Which energy steps?

What is the motivation?

- We have a Higgs! That's great.
- Why do we need to know all its properties with best precision? Because that's the bridge between 'micro' and 'macro' cosmos.
- We have the Top! That's great.
- Why do we need to know all its properties with best precision? Because that's the bridge to understand dynamics of EWSB.
- Excellent top physics at LHC (and HL-LHC) That's great!
- Do we really also need the LC?

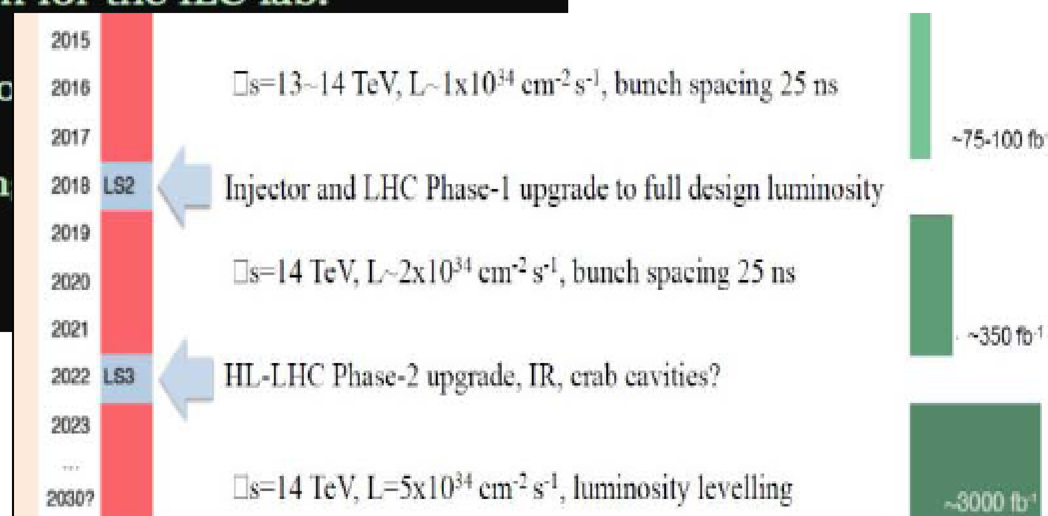
…a great chance might just be ahead….

Very encouraging politics!

Possible Timeline

- July 2013
  - Non-political evaluation of 2 Japanese candidate sites complete, followed by down-selecting to one
- End 2013
  - Japanese government announces its intent to bid
- 2013~2015
  - Inter-governmental negotiations
  - Completion of R&Ds, preparation for the ILC lab.
- ~2015
  - Inputs from LHC@14TeV, decisio
- 2015~16
  - Construction begins (incl. biddin
- 2026~27
  - Commissioning

LHC timeline



ILC might start @ times HL-LHC!

Preface

- **Discovery of a SM-like Higgs around m_H~125 GeV**
  - Is an absolute revolution!
  - Completely new type
  - Not clear whether a 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, Feb 12)

- **In short -- some LC capabilities:**

As e.g. Δm_{top}~0.1 GeV, $coup_{ttH}$~3%,
H: BR's~1(b)-7(c)%, Γ_h~5%, $\Delta\lambda$~17%

Further improvement via lumi-upgrade, see Tians'talk! ($coup_{ttH}$~2%, $\Delta\lambda$~10%)

- **Very active: many new LC studies and reports….**
  - *ILC TDR (since June 12, 2013)*
  - *CLIC CDR 2012*
  - *Collection of LC notes (DESY123h) online*
  - *2 more LC reviews under work*

Focus of my talk (in p. 1st article in Desy123h, 1210.0202)

The LC physics offer

- A `staged' approach:
  - √s=250 GeV, `Higgs cross section, mass + couplings'
  - √s=350 GeV, `Higgs width + top mass'
  - √s=500 GeV, `Special Higgs- and top couplings+BSM'
  - (√s=91 GeV, `Precision frontier + indirect BSM frontier')
  - √s≥1000 GeV, `Closing the Higgs picture? '
  - High rates!

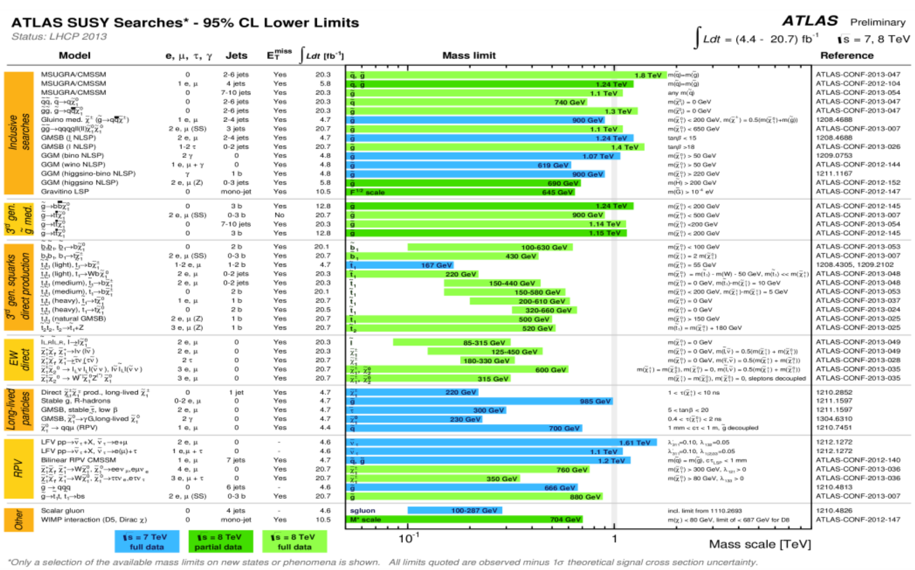
`

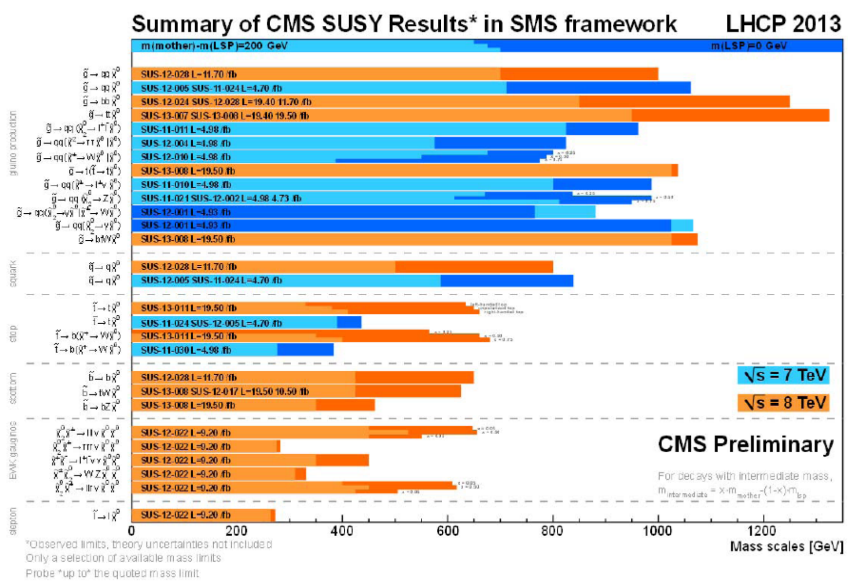
	250 GeV	350 GeV	500 GeV	1 TeV	1.5 TeV	3 TeV
$\sigma(e^+e^- \to ZH)$	240 fb	129 fb	57 fb	13 fb	6 fb	1 fb
$\sigma(e^+e^- \to H\nu_e\bar{\nu}_e)$	8 fb	30 fb	75 fb	210 fb	309 fb	484 fb
Int. $\mathcal{L}$	250 fb^{-1}	350 fb^{-1}	500 fb^{-1}	1000 fb^{-1}	1500 fb^{-1}	2000 fb^{-1}
# ZH events	60,000	45,500	28,500	13,000	7,500	2,000
# $H\nu_e\bar{\nu}_e$ events	2,000	10,500	37,500	210,000	460,000	970,000

- Plus `new' features:
  - Precise energy, threshold scans, polarization, γγ-option

Impact from LHC BSM limits

- **SUSY: still strongly motivated and beautiful, but**
  - **so far, no hints of a signal, only rather high exclusion limits in the coloured sector**
  - **Constrained models (CMSSM,…) + Simpl. Models under tension!**





- **Further hints from theory?**

Further SUSY facts

- Low energy experiments, $(g\text{-}2)_\mu$:
  - favours 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 all

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

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 and light higgsinos,…**

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

MSSM interpretation of light Higgs

- **Preferred values for stop masses from fits :**
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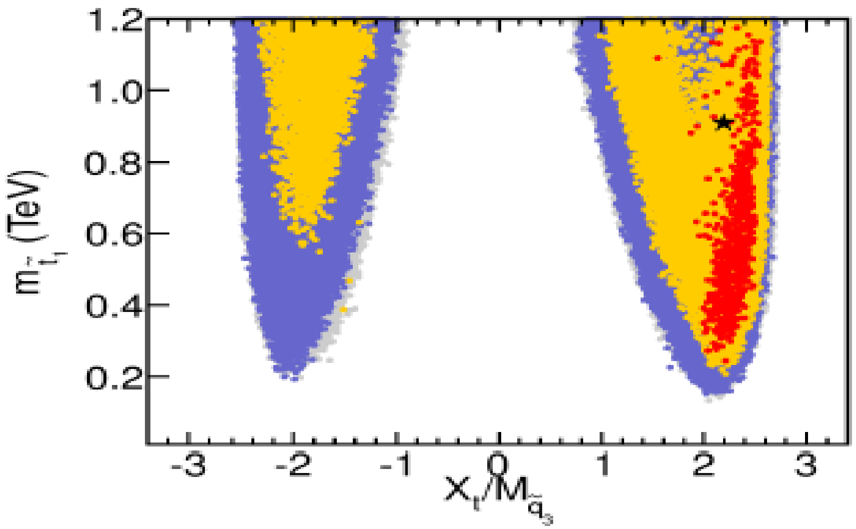
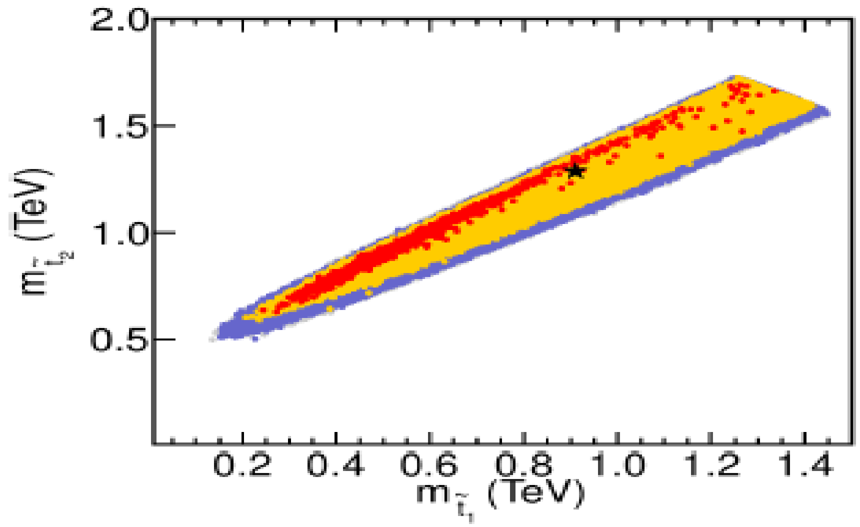
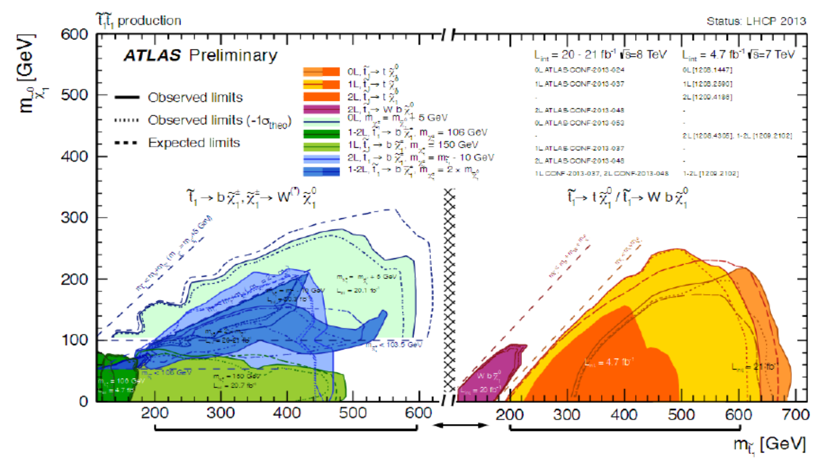
Bechtle, Heinemeyer,Stal,Stefaniak,Weiglein,Zeune '12





- **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 !**

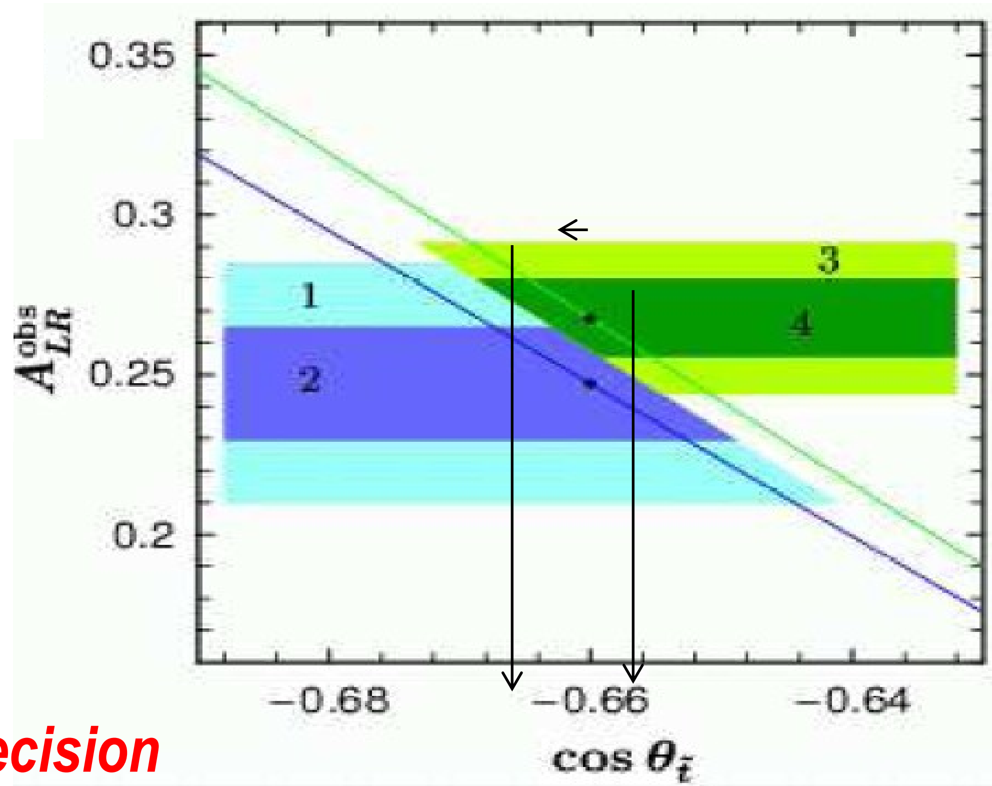


Start with stops: features at a LC

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

Eberl, Kraml,'05

$\mathcal{L}_{int}$	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!*

Higgsino-like scenarios

- **Can be embedded in hybrid gauge-gravity mediation**
  - ‘M’ driven by gauge-mediation
  - ‘μ’ driven by gravity mediation
- **Two examples as ‘prototypes’ under study**

Bruemmer,List,GMP, Rolbiecki,Sert’13

$$M_1 = 1.70\,\text{TeV},\ M_2 = 4.36\,\text{TeV},\ \mu = 165.66\,\text{GeV},\ \tan\beta|_{m_Z} = 44,$$
$$M_{\tilde\chi_1^\pm} = 165.77\,\text{GeV},\ M_{\tilde\chi_1^0} = 164.17\,\text{GeV},\ M_{\tilde\chi_2^0} = 166.87\,\text{GeV},\ m_h = 124\,\text{GeV};$$
$$M_1 = 5.30\,\text{TeV},\ M_2 = 9.51\,\text{TeV},\ \mu = 167.22\,\text{GeV},\ \tan\beta|_{m_Z} = 48,$$
$$M_{\tilde\chi_1^\pm} = 167.36\,\text{GeV},\ M_{\tilde\chi_1^0} = 166.59\,\text{GeV},\ M_{\tilde\chi_2^0} = 167.63\,\text{GeV},\ m_h = 127\,\text{GeV}.$$

- **Higgsino masses:** $m_{\chi 0_1}$ ~165 GeV, $m_{\chi 0_2}$~167 GeV, $m_{\chi\pm_1}$~166 GeV
- **Feature:** $\Delta m(_{\chi\pm 1-\chi 01})$~770 MeV (1.6 GeV), $\Delta m(_{\chi 02-\chi 01})$~1.04 (2.7) GeV
  - Challenges: mass degeneration, many π’s, soft γ, E_{miss} from decay
  - How to resolve such scenarios?

Apply ISR method

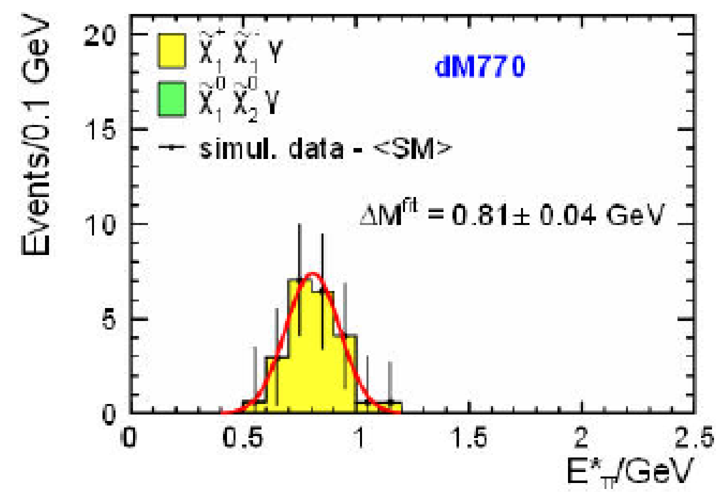
- **Accessible processes:** e+e- → $\chi^0_1\chi^0_2$, $\chi^+_1\chi^-_1$
  - Decays: χ^-_1 mainly hadronic, χ^0_2 mainly in γ's
- **Measure masses via ISR method:**
  - Take only events with hard γ from ISR
  - Get also rid of SM background two photons
- **Measure process at two energies, √s=350 and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

Berggren, List, Sert

→ ***Determine MSSM parameters***

$\sqrt{s} = 500$ GeV		input	lower	upper
2/ab	M_1 [TeV]	5.3	~ 3	110
	M_2 [TeV]	9.51	~ 7	~ 15
	μ [GeV]	167.22	165.2	167.4

→

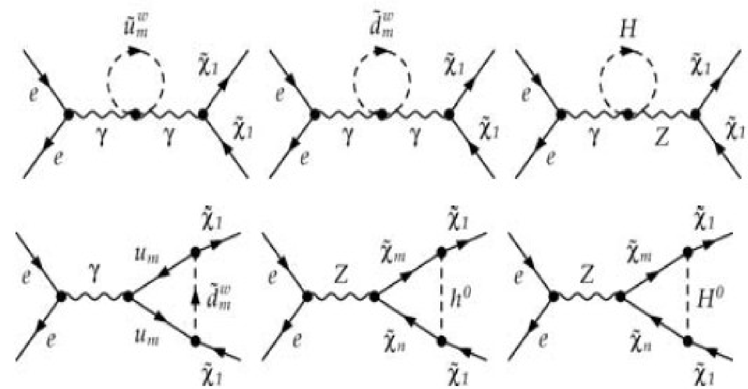


LC: Parameters from $e^+e^- \to \tilde{\chi}^+_1 \tilde{\chi}^-_1$@NLO

- **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

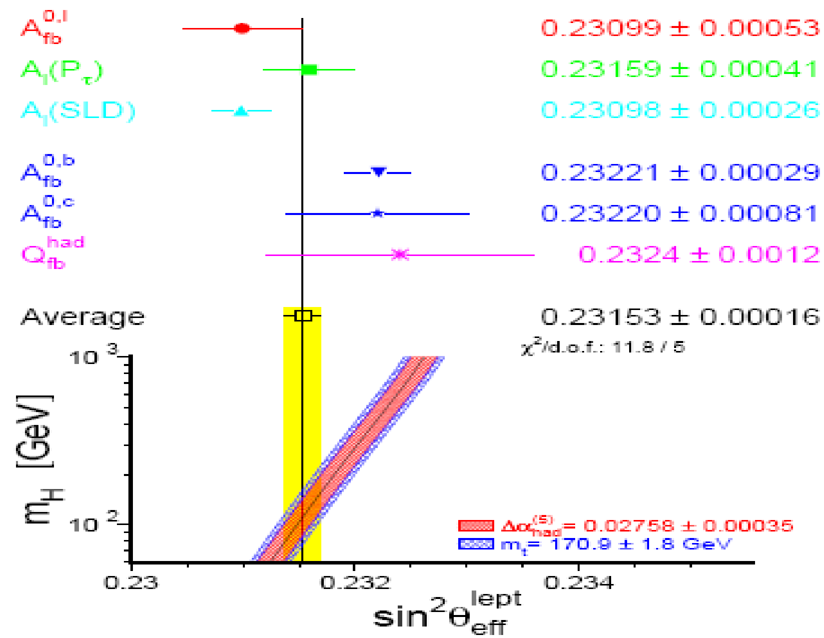
- **Impact also on dark matter prediction:**
  - Precision needed for accurate DM prediction: accuracy of the NLO corrected parameters → 5% uncertainty in DM prediction

What if nothing else than H is found now?

- **Since m_H is 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 $\Delta m_H \sim m^4_{top}$ in BSM!)
    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}
- **Exploit `GigaZ' option: high lumi run at $\sqrt{s}$ = 91 GeV**

Pe-=80% and Pe+=60% required ! (If only Pe-=90% : precision ~factor 4 less!)

Higgs story has just started … $\sqrt{s}=91$ GeV



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

Goal GigaZ: $\Delta\sin\theta=1.3\ 10^{-5}$

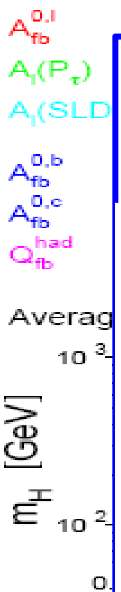
- **Uncertainties from input parameters: Δm_Z, $\Delta\alpha_{had}$, m_{top} ,…**

Heinemeyer, Kraml, Porod, Weiglein

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

Higgs story has just started …

$\sqrt{s}$=91 GeV



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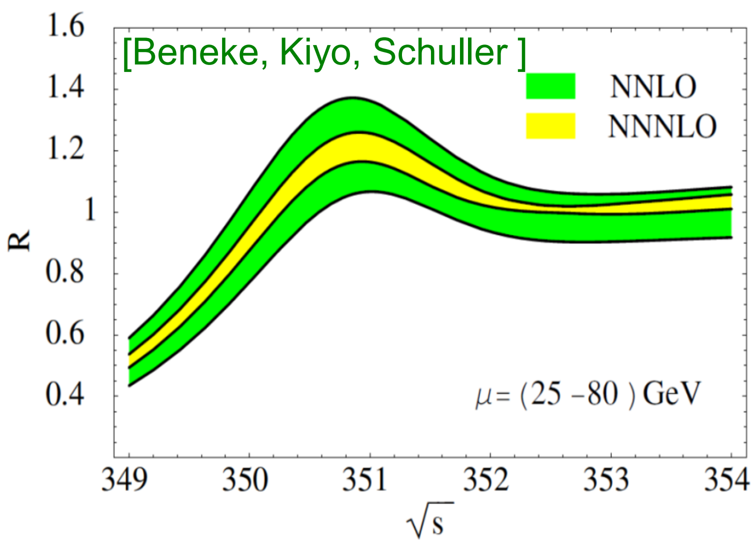
- But such a precision requires Δm_{top}=0.1 GeV



$\sqrt{s}$=350 GeV

Important shift due to non-logarithmic NNNLO terms

- Unce

Weiglein

- LC: Peak position remains stable: Δm_t=100 MeV
- includ. exp uncertainty + theo. uncertainty !
- expected accuracy confirmed by full simulation studies!
- Dedicated threshold scan required with about ~100fb^{-1}

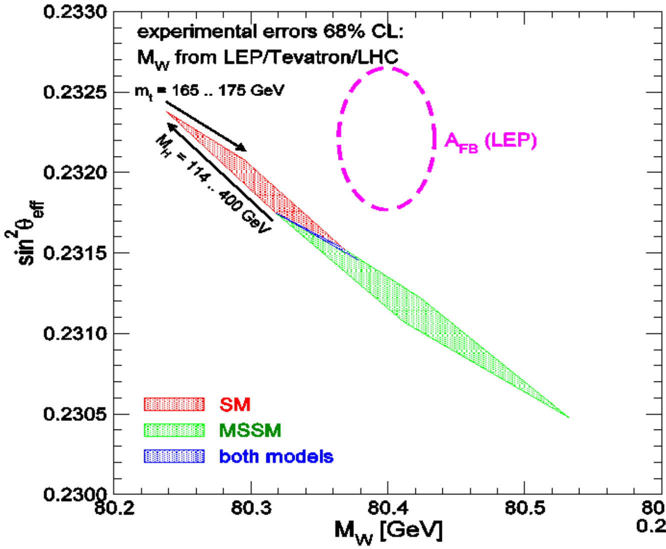
0^{-5}

- Δm_{top} … (ILC) … $\Delta \sin^2\theta_{eff}$ …

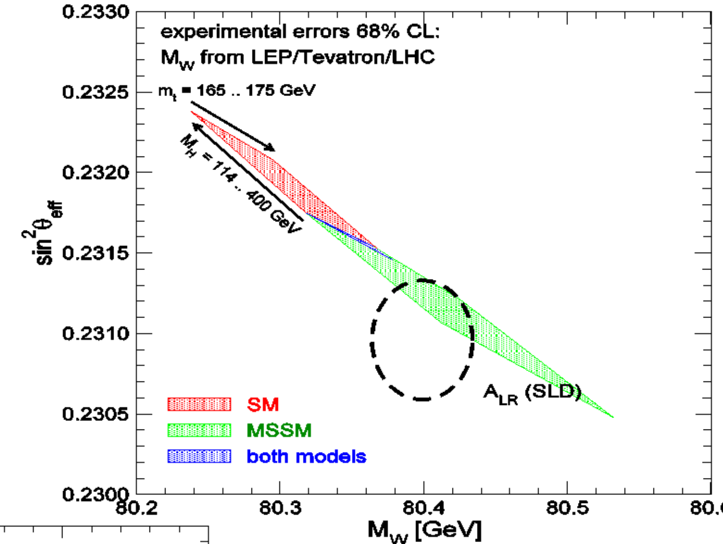
To close the story… GigaZ $\sqrt{s}=91$ GeV

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

Heinemeyer, Hollik, Weber, Weiglein



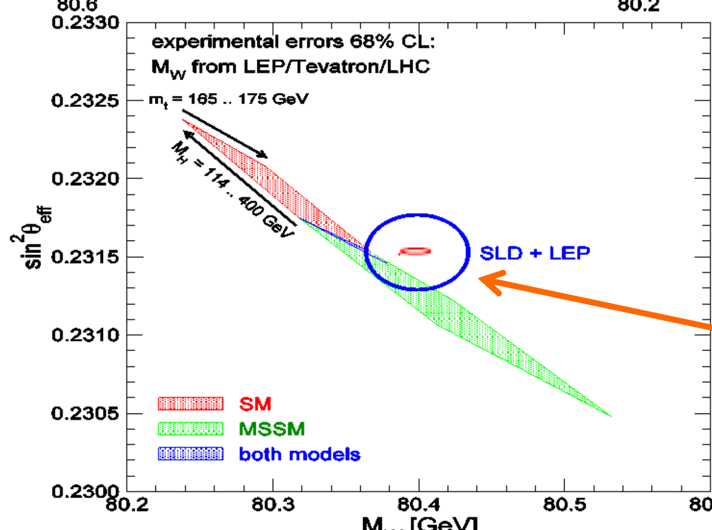
← LEP value disfavours both, SM+MSSM



↑ SLD value disfavours SM

World average → happy with both!

Central value has large impact !!!

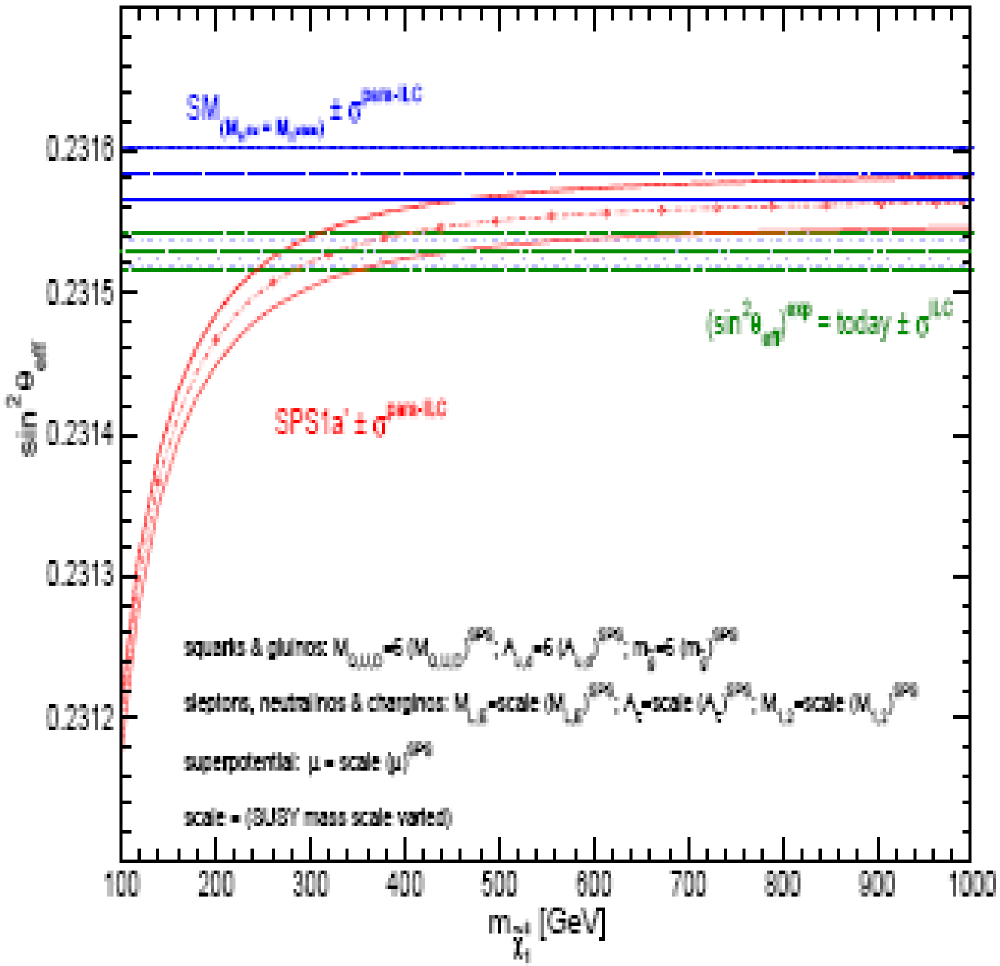


GigaZ precision!

What else could we learn? $\sqrt{s}$=91 GeV

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

Heinemeyer, Hollik, Weber, Weiglein

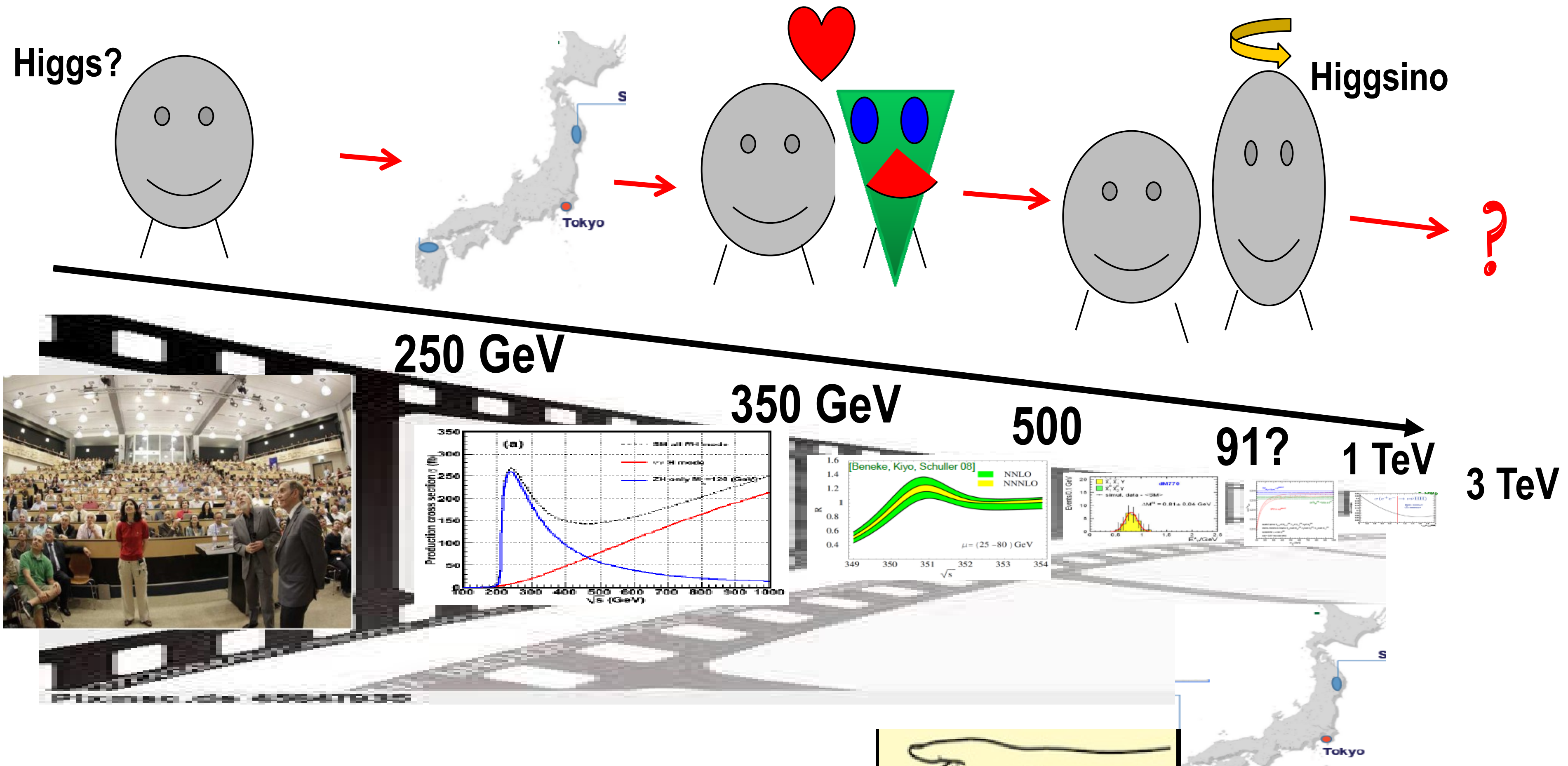


- **If GigaZ precision:**
  - **i.e. Δm_{top}=0.1 GeV…**
  - **Deviations measurable**

- **$\sin^2\theta_{eff}$ can be the crucial quantity to reveal effects of NP!**

In 20 years time……we could tell a story

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



LC Physics case is well justified!