Higgs and Electroweak Symmetry Breaking

Summary

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Higgs Sector Studies

Traditionally, Higgs sector studies address either one of two possibilities:

1. Weakly interacting Higgs sector.

   This contains a Higgs boson, possibly more associated scalars, leads to a renormalizable theory, can be stabilized by SUSY, and fits precision data.

2. Strongly interacting Higgs sector.

   This contains no Higgs boson but possibly some other scalars, does not lead directly to a renormalizable theory, does not need SUSY, and may or may not fit precision data (since they are not really calculable).

Today, this separation looks too simplistic:

- More recent models (topcolor, little Higgs, EDM, ...) allow for intermediate-mass Higgs bosons and incorporate both strong and weak interactions. Other models incorporate SUSY, but still have strongly-interacting sectors.

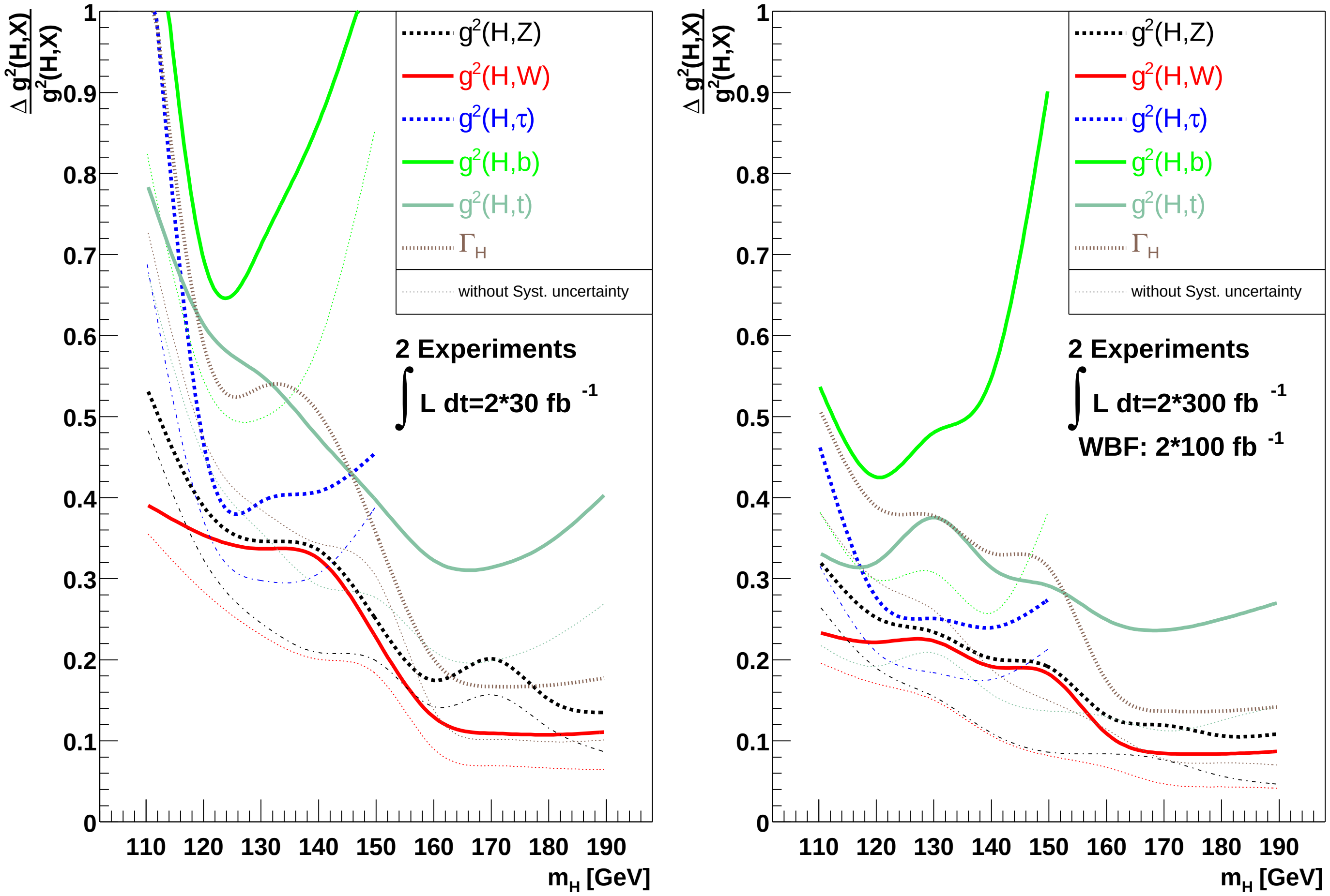
Furthermore:

- Higgs processes are well understood (theory + experiment). We are now looking at ϵ^2 effects, and Higgs processes become benchmark processes for loop calculations and detector.

LHC Benchmark

Less than 5 years! LHC will take data, will determine the type of Higgs sector we are facing.

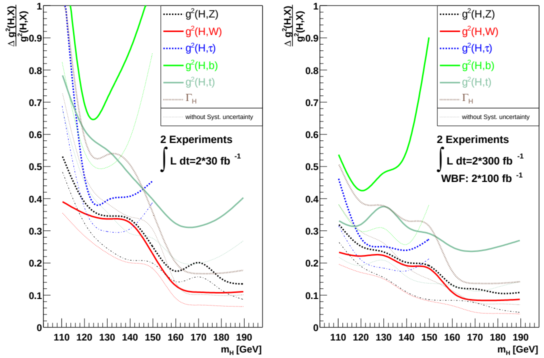
This might be the ultimate LHC reach: M. Dührssen et al., hep-ph/0407190



LHC Benchmark

In principle, at LHC you can get only ratios of BRs — where do these results come from?

To exctract absolute coupling values from LHC data, you need assumptions.



Assumptions in these plots:

1. $g_{HWW} \leq 1.05 \times g_{HWW}^{\text{SM}}$
2. The observed rates agree with SM predictions.

OK, but:

- $g_{HWW} \leq g_{HWW}^{\text{SM}}$ valid only in weakly-interacting models (unitarity)
- The observed rate in WBF might turn out to be significantly below (or even above) SM
- The interesting physics is in exactly this $5\,\%$ margin (heavy vector bosons, Higgs triplets, . . .)

⇒ These assumptions need to be tested *before* we draw conclusions from measurements.

⇒ This precision is probably not sufficient if looking for new-physics signals in the Higgs sector

ILC Charge: Higgs Physics

This LHC study tells us why the ILC is needed for Higgs physics.

- At the ILC, we can do a *inclusive* measurement of Higgs production:

  $$e^+e^- \to H + X \quad \text{(recoil spectrum)}$$

  This removes the model dependence from all LHC (and ILC) coupling measurements.

- At the ILC, we can determine couplings to better than $5\,\%$. In particular, $H \to b\bar{b}$ can be precisely measured.

Leaving the minimal SM paradigm, there is another crucial point:

- At the ILC, we can detect extra scalars in the Higgs sector (if not too heavy), complementing LHC searches. Many of their properties can be determined.

Finally:

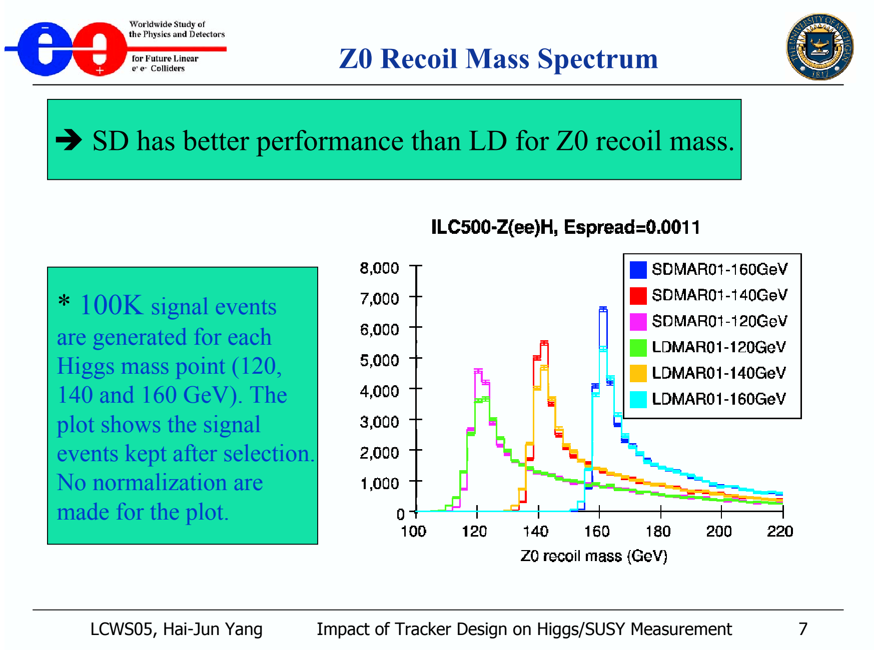
- At the ILC, the Higgs self-coupling can be measured (with low precision), if the Higgs is not too heavy. (For a Higgs boson above the WW threshold, this is more accessible at the LHC.)

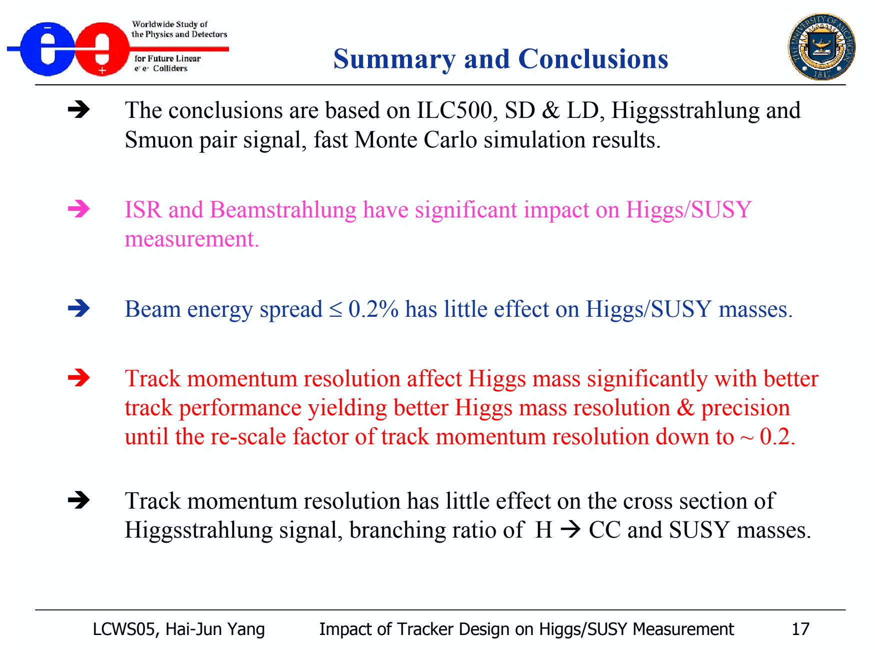
The Recoil Measurement

So, *how well are we prepared for these challenges?*

The recoil measurement: Higgs mass and cross section in $e^+e^-(\to ZX) \to e^+e^-X(\mu^+\mu^-X)$

- Hai-Jun Yang (Ann Arbor) with K. Riles: *Impact of tracker design on Higgs/SUSY measurement*
  - Fast simulation, look at effects of ISR/beamstrahlung, beam energy spread
  - Check SD and LD designs, investigate impact of tracker resolution

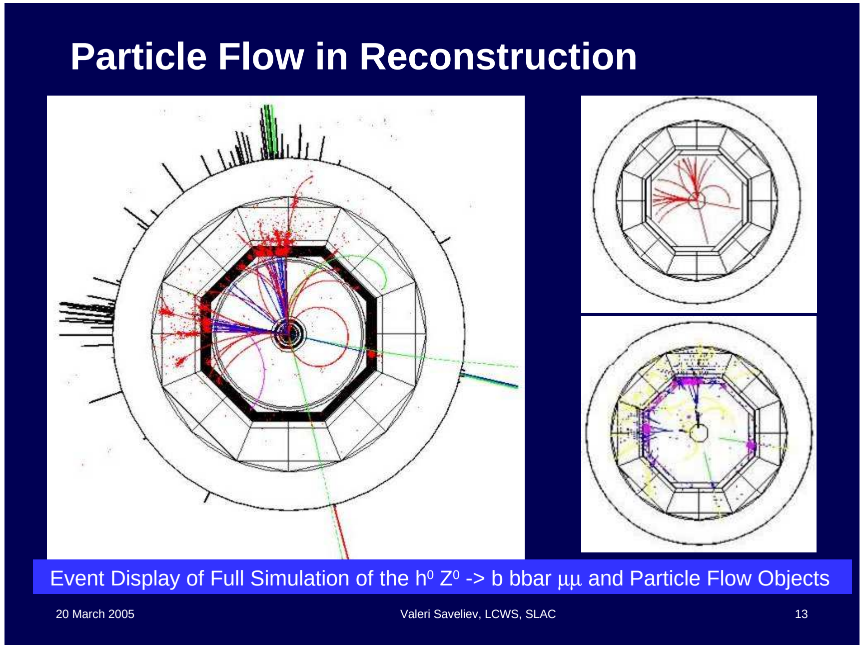


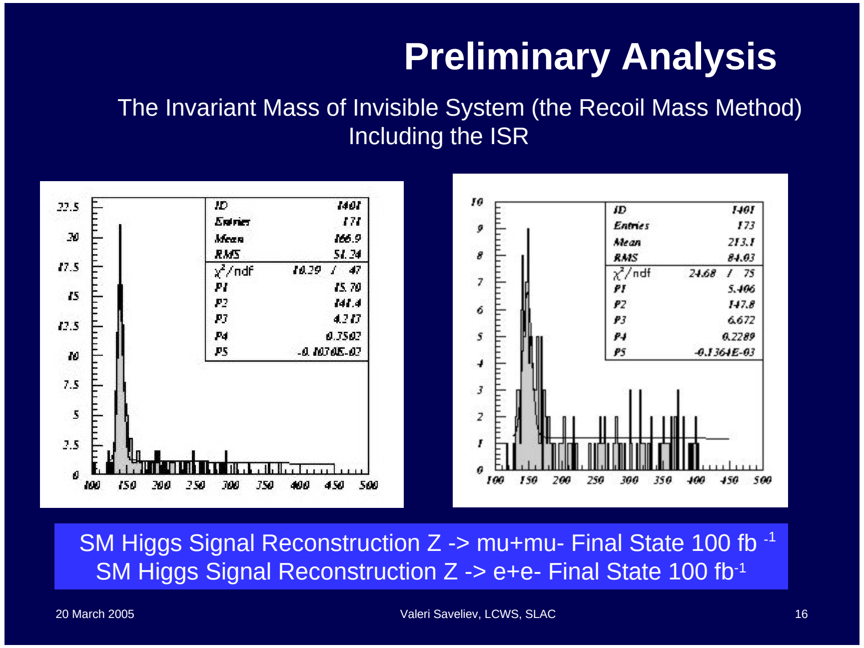


The Recoil Measurement

Higgs mass and cross section in $e^+e^-(\to ZX) \to e^+e^-X(\mu^+\mu^-X)$ (cont'd)

- Valeri Saveliev (DESY/Obninsk): *Study of SM Higgs sensitivity at ILC*
  - Full simulation (MOKKA)!





. . . *work in progress*

Higgs Couplings

Standard (tree-level) couplings: HZZ, HWW, Hbb, Hcc, $H\tau\tau$

- Studies continue with improved (full) simulation, elaborate analysis tools, etc.

  ... and will continue until ILC starts (unless Higgs excluded by LHC)

And such results can be exploited to gather information on specific models:

Example: Little Higgs models (SM-like Higgs boson + extra heavy stuff)

- All ILC precision observables (fermions, W, Higgs, top) are modified and thus carry information on the heavy sector
- J. Conley (SLAC), with JoAnne Hewett: Look specifically at $e^+e^- \to f\bar{f}$ and $e^+e^- \to ZH$ (Z' exchange)

  $\Rightarrow$ $f\bar{f}$ at ILC covers full "Littlest Higgs" parameter space

  $\Rightarrow$ ZH covers not everything, but independent determination of model parameters

  $\Rightarrow$ ... in particular, if LHC information is used as an input

Higgs Couplings

Loop-type couplings: New results

- Bernd Kniehl (Hamburg) with F. Fugel, M. Steinhauser:

  $H\gamma\gamma$: Two-loop electroweak diagrams that involve a top quark

  - This adds to the know contributions: one-loop complete, two-loop QCD correction
  - technically: asymptotic expansion valid for $m_H = 80 \ldots 160$ GeV
  - comparable to 2-loop QCD (cancellation)

Comparison With $\mathcal{O}(\alpha_s)$ Correction

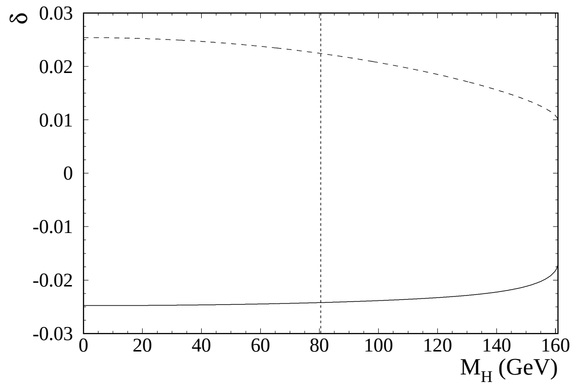


Figure 9: $\mathcal{O}(G_F M_t^2)$ (solid) and $\mathcal{O}(\alpha_s)$ (dashed) corrections to $\Gamma(H \to \gamma\gamma)$.

$\mathcal{O}(\alpha_s)$ gluon correction:

H. Zheng, D. Wu, Phys. Rev. D 42 (1990) 3760;
A. Djouadi, M. Spira, J.J. van der Bij, P.M. Zerwas, Phys. Lett. B 257 (1991) 187;
S. Dawson, R.P. Kauffman, Phys. Rev. D 47 (1993) 1264;
A. Djouadi, M. Spira, P.M. Zerwas, Phys. Lett. B 311 (1993) 255;
K. Melnikov, O.I. Yakovlev, Phys. Lett. B 312 (1993) 179;

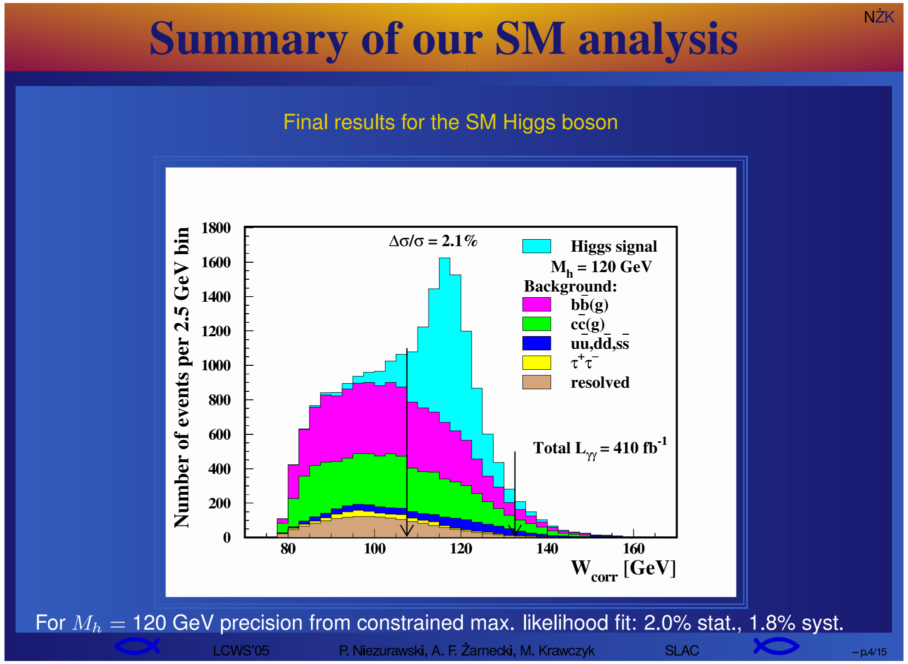
Bernd Kniehl: $\mathcal{O}(G_F M_t^2)$ Correction to $\Gamma(H \to \gamma\gamma)$ 13

Higgs Couplings

Loop-type couplings: New results on $\Gamma(H \to \gamma\gamma) \times B(H \to b\bar{b})$

- P. Niezurawski, with A. Zarnecki, M. Krawczyk
- Aura Rosca (DESY) [talk given by K. Mönig]:

$\Rightarrow$ Include all possible backgrounds, in particular overlay events.



Completing the Higgs Sector

. . . *there's more than the SM-like Higgs to investigate*

Next-to-Standard: Add a second doublet, in particular the MSSM Higgs sector

- In the MSSM, all Higgs masses and couplings can be calculated. All parameters of the MSSM enter (latest, at 2-loop order)

  Therefore, an accurate spectrum calculation in terms of MSSM parameters is complicated and needs automated tools. Recent progress:

  - Thomas Hahn (MPI): *Precise Higgs masses with FeynHiggs 2.2*
  - Sven Heinemeyer (CERN): *Recent higher-order corrections in the r/cMSSM Higgs sector*

Completing the Higgs Sector

Corrections included in FeynHiggs 2.2

$$\begin{pmatrix} q^2 - M_h^2 + \hat{\Sigma}_{hh} & \hat{\Sigma}_{hH} & \hat{\Sigma}_{hA} \\ \hat{\Sigma}_{Hh} & q^2 - M_H^2 + \hat{\Sigma}_{HH} & \hat{\Sigma}_{HA} \\ \hat{\Sigma}_{Ah} & \hat{\Sigma}_{AH} & q^2 - M_A^2 + \hat{\Sigma}_{AA} \end{pmatrix}$$

- **Most up-to-date leading $\mathcal{O}(\alpha_s\alpha_t, \alpha_t^2)$ + subleading $\mathcal{O}(\alpha_s\alpha_b, \alpha_t\alpha_b, \alpha_b^2)$ two-loop corrections in the rMSSM (complex effects only partially included in two-loop part).**

  Degrassi, Slavich, Zwirner 2001 – Brignole, Degrassi, Slavich, Zwirner 2001, 02
  Dedes, Degrassi, Slavich 2003

- **Full one-loop evaluation (all phases included).**
- **Complete q^2 dependence.**
- **Full one-loop corrections for the charged Higgs sector.**

  Frank, Heinemeyer, Hollik, Weiglein 2002

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    - MSSM with complex phases: two-loop electroweak ($\alpha_t \alpha_s$)
    - detailed investigation of resummation effects, scheme dependence, etc.

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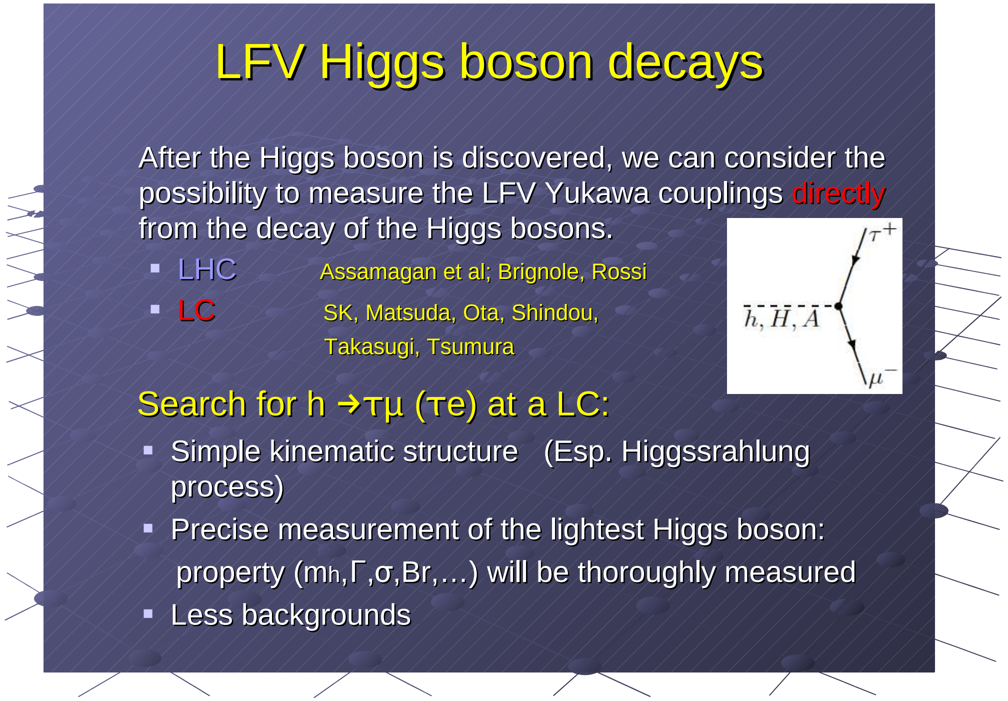
- Precision low-energy data ($g-2$, $b \to s\gamma$, τ *decays*) constrain 2HDM parameter space

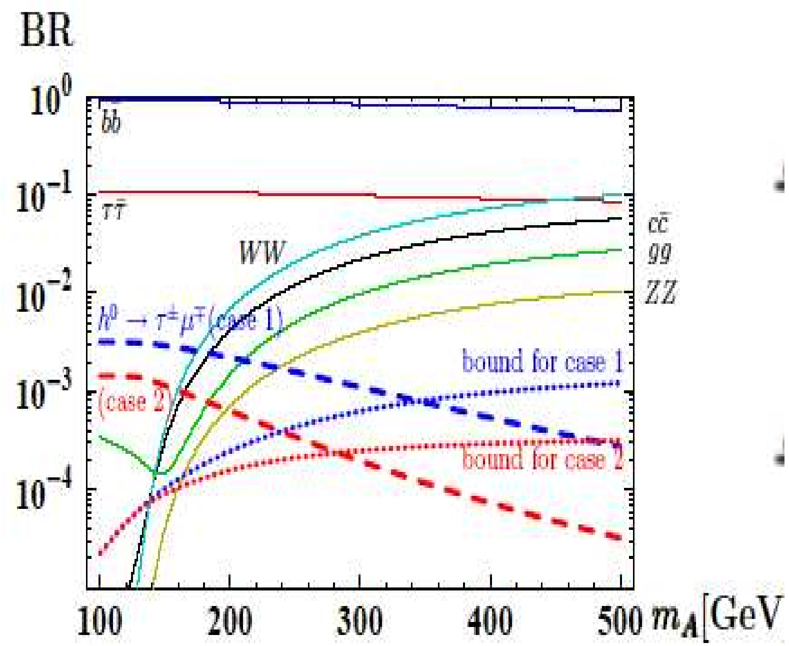
  – M. Krawczyk (Warsaw), with D. Temes: *Upper limit on the mass of $H^{\pm}$ from leptonic τ decays*

Completing the Higgs Sector

. . . *then, things can get even more interesting:*

- Shinya Kanemura (Osaka): *Measurement of lepton flavor violating Yukawa couplings at a linear collider*





- Fixed target @ ILC: $eN \to \tau X$ could improve LFV limit by 10^4

Pseudoscalars

Characteristic feature of Higgs sector extensions: Appearance of CP-odd scalars $(A^0, a, \eta, \ldots)$

⇒ Weakly-interacting and strongly-interacting models meet

⇒ CP violation: mixing of Higgs with CP-odd scalar

This has been looked at in various contexts:

- Andreas Imhof (DESY): *Higgs Parity from Angular Correlations in $H \to \tau\tau$ decays*
- P. Niezurawski, with A. Zarnecki, M. Krawczyk: $\gamma\gamma \to H, A \to b\bar{b}$
- R. Dermisek (Davis), with Jack Gunion: *NMSSM Higgs Physics: How to evade the fine-tuning and hierarchy problems in the NMSSM and the importance of $h \to aa$ decays*
- Jürgen Reuter (DESY), with WK, D. Rainwater: *Pseudo-Axions in little Higgs models*

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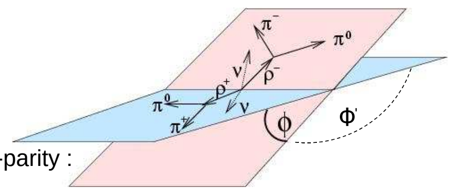
The observable



- Planes spanned by the 4-momenta of the pions
- Correlation sensitive to Higgs-parity :

the acoplanarity Φ.

- Use energies to distinguish between Φ and Φ' by the sign of $y_1 \cdot y_2$

$$y_1 = \frac{E_{\pi^+} - E_{\pi^0}}{E_{\pi^+} + E_{\pi^0}} \qquad y_2 = \frac{E_{\pi^-} - E_{\pi^0}}{E_{\pi^-} + E_{\pi^0}}$$

→ only direct accessible information from reconstructed momenta used.

THUS: precise reconstruction of the 4-momenta both for neutral (e.g. the photons from the π^0) and charged objects is essential.

→ Challenge to the performance of a high precision detector, especially to the calorimeter.

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Summary / Conclusion

∀ τ identification and reconstruction possible at high efficiency with anticipated detector

- Realistic measurement for CP in H → ττ performed
- Including
  - detector effects
  - full SM-background statistics
  - 2-photon backgrounds
  - full effects of ISR and FSR
- Significance to distinguish a CP-even from a CP-odd Higgs-Boson of 4.7 σ for 1 ab^{-1} can be expected
- Techniques like likelihoods, NN could enhance significances

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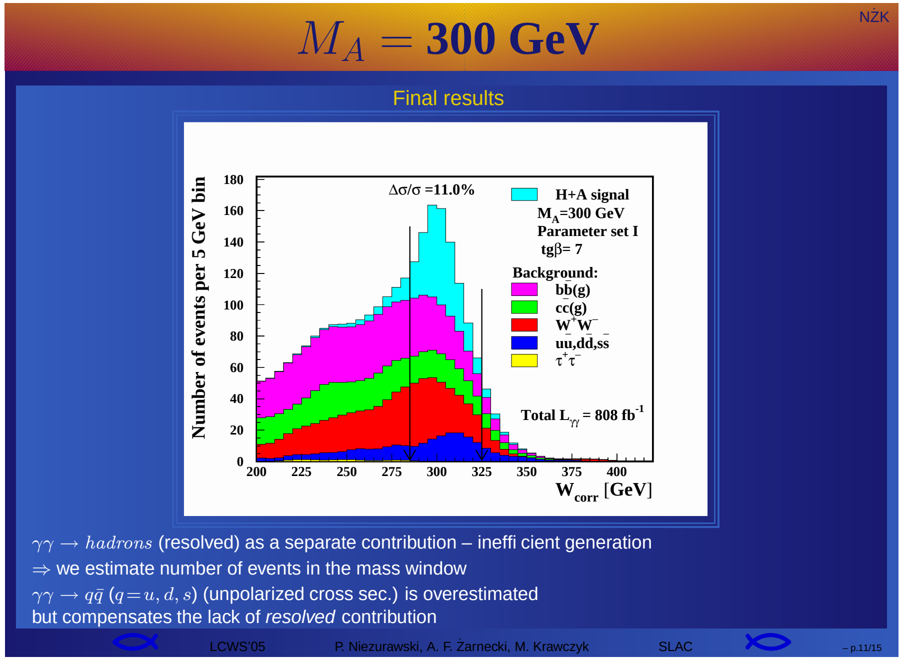

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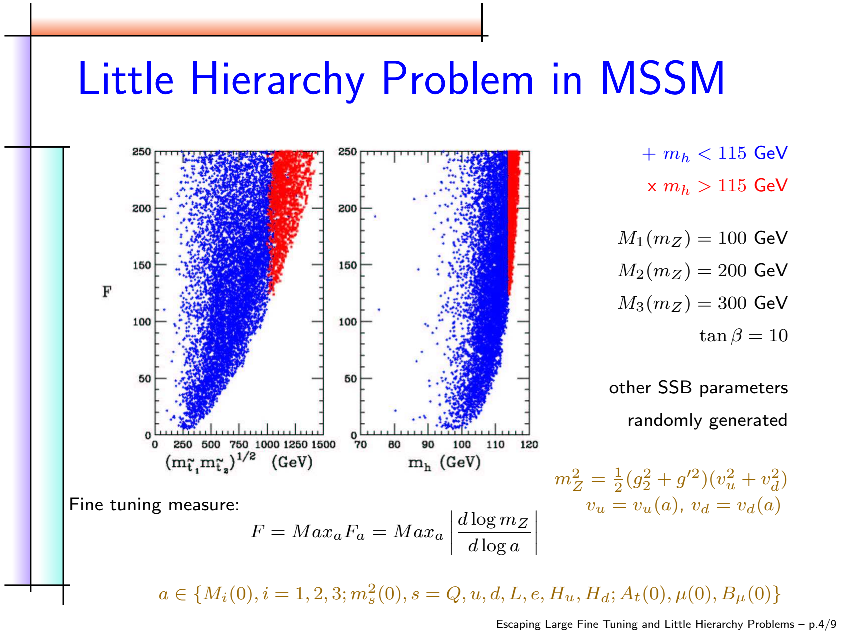

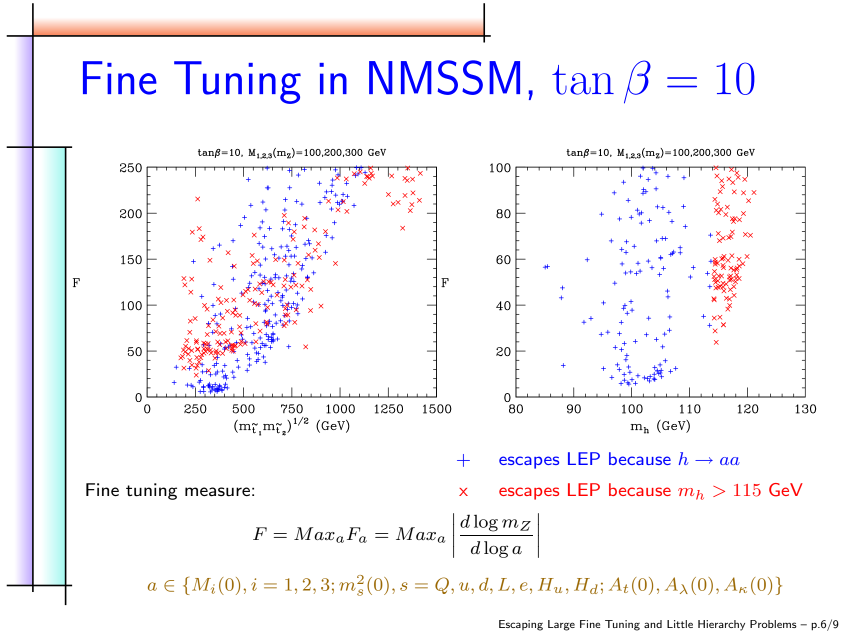

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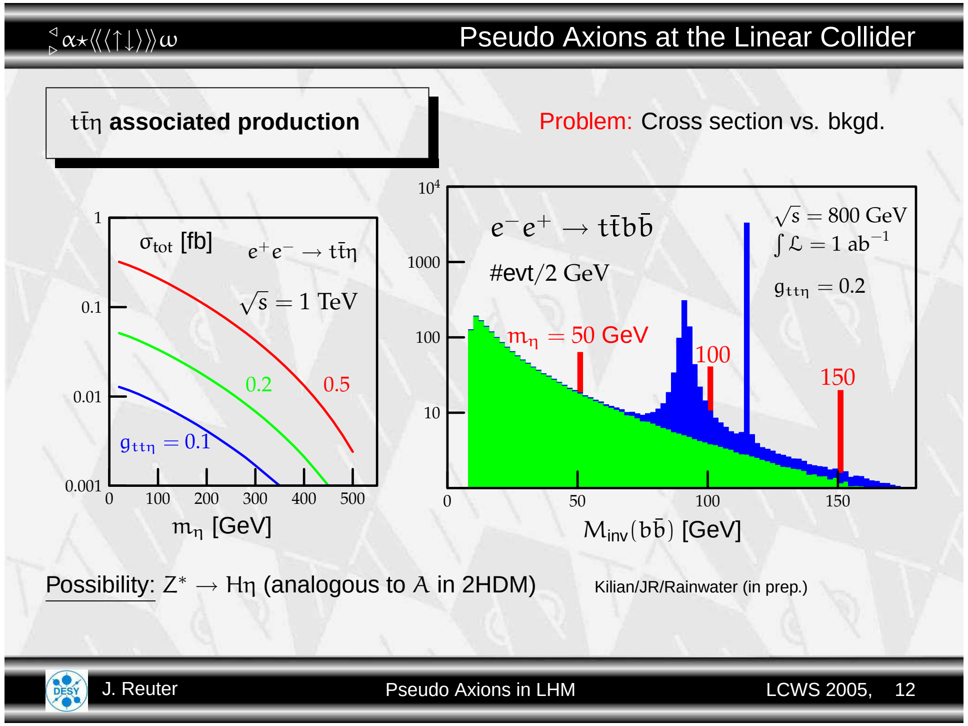


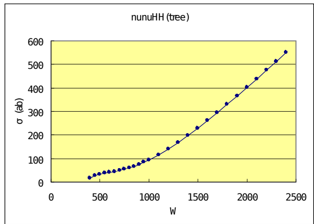
Higgs Self-Coupling

For not-too-heavy Higgs, the ILC opens the possibility to measure the Higgs self-coupling and thus the Higgs potential.

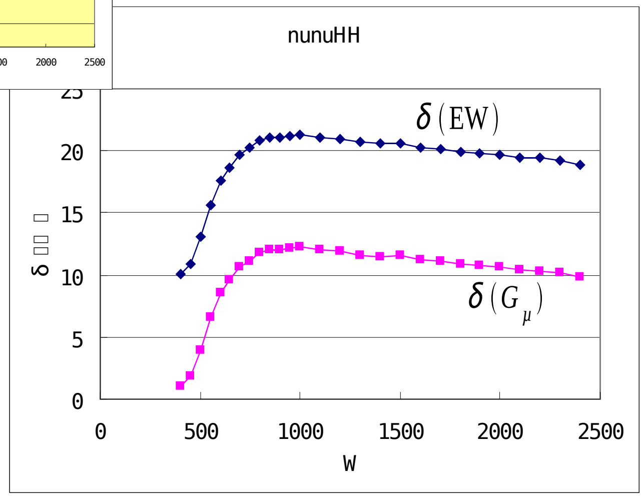
This is a very difficult measurement, and all systematic effects have to be under control.

News:

- Kiyoshi Kato (Kogakuin U.): *Electroweak Correction for the Study of Higgs Potential in LC* ($e^+e^- \to ZHH \;/\; \nu\bar{\nu}HH$)



$e^+e^- \to \nu\nu$ □□



Full calculation M_H=120GeV

Corrections comparable to experimental accuracy

Summary and Outlook

Higgs physics is a mature field. In particular, for the SM Higgs all important channels are being explored, and the emphasis is now on higher-order predictions and full simulation.

(Little has been done on the less important production channels (e.g., $ZZ \to H$, $W^+W^- \to ZH$) that have non-negligible rates, in particular at a $1\ \mathrm{TeV}$ ILC.)

The status of the MSSM Higgs sector is similar. The spectra are being computed to NNLO, many production and decay channels have been simulated (at least, superficially).

Note: Actual analyses tend to concentrate on few parameter points.

For beyond-(MS)SM scenarios, the range of studies ranges from model-building to theorists' estimate of collider sensitivities, but few experimental studies.

If it's not just the (MS)SM: Before doing precision studies, we'll have to sort out the particle content and quantum numbers, and ILC will play its role as a discovery (or exclusion?) machine .