Electroweak Physics at the ILC

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Manchester, 07/2007

- Introduction
- Higgs physics at the ILC
- Top and electroweak precision physics
- New results for electroweak precision observables in the MSSM
- Conclusions

Introduction

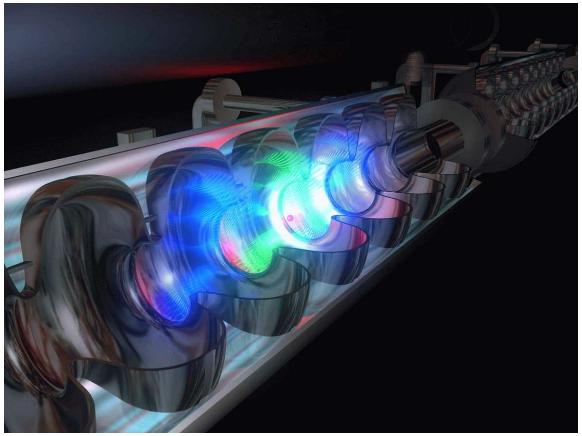
The International Linear Collider (ILC)

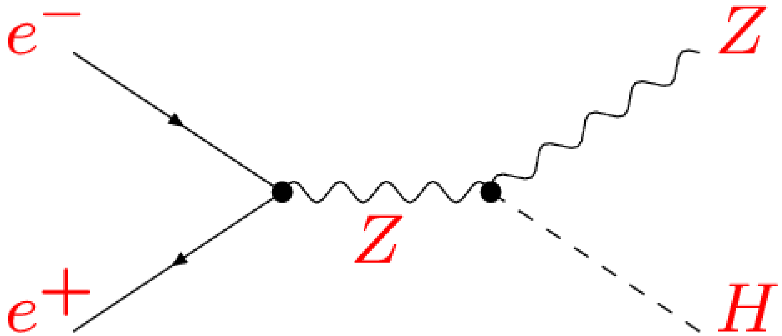
world-wide project, RDR ($+$ costing) issued earlier this year, Engineering Design Report in preparation

Electron–positron scattering at $\approx$0.5–1 TeV:

fundamental particles, point-like, electroweak interaction

well-defined initial state, full collision energy usable, tunable



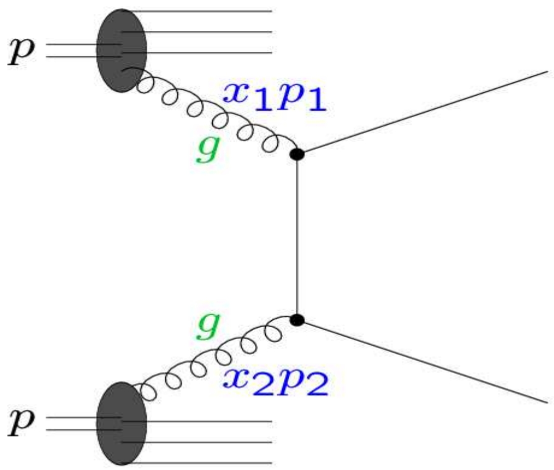


Results are easy to interpret, all events can be recorded

$\Rightarrow$ high-precision physics

Physics at the LHC and ILC in a nutshell

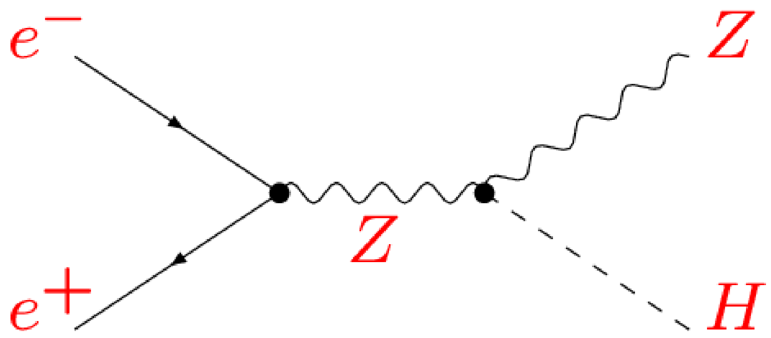
LHC: pp scattering at 14 TeV



Scattering process of proton constituents with energy up to several TeV,
strongly interacting

$\Rightarrow$ huge QCD backgrounds, low signal–to–background ratios

ILC: e^+e^- scattering at ≈0.5–1 TeV



Clean exp. environment:
well-defined initial state,
tunable energy,
beam polarization, GigaZ,
$\gamma\gamma$, $e\gamma$, e^-e^- options, . . .

$\Rightarrow$ rel. small backgrounds
high-precision physics

LHC / ILC complementarity

The results of LHC and ILC will be highly complementary

LHC: good prospects for producing new heavy states
(in particular strongly interacting new particles)

ILC: direct production (in particular colour-neutral new particles)
$\oplus$ high sensitivity to effects of new physics via precision measurements

Many examples for LHC / ILC interplay:

LHC / ILC Study Group Report

[*G. W. et al., hep-ph/0410364, Phys. Rept. 426 (2006) 47*]

www.ippp.dur.ac.uk/$\sim$georg/lhcilc

ILC Baseline Parameters

- Baseline parameters were established by a WWS committee in 2003 and reexamined in 2006
- Maximum energy should be $500\ \mathrm{GeV}$, with energy range for physics between $200\ \mathrm{GeV}$ and $500\ \mathrm{GeV}$

  $\Rightarrow$ energy scans possible at all cms energies
- Luminosity and reliability such that $500\,\mathrm{fb}^{-1}$ can be collected in first four years
- Electron polarisation of at least 80%

“Options” to ILC Baseline

- Energy should be upgradeable to approx. $1\ \mathrm{TeV}$
- Doubling of integrated luminosity to a total of $1\,\mathrm{ab}^{-1}$ within two additional years of running
- Positron polarisation at or above 50% in whole energy range
- Running at Z resonance and WW threshold with high lumi (“GigaZ” running)
- e^-e^-, $e\gamma$, $\gamma\gamma$ collisions

Reexamination of ILC baseline parameters and options

- No modification of original baseline parameters necessary

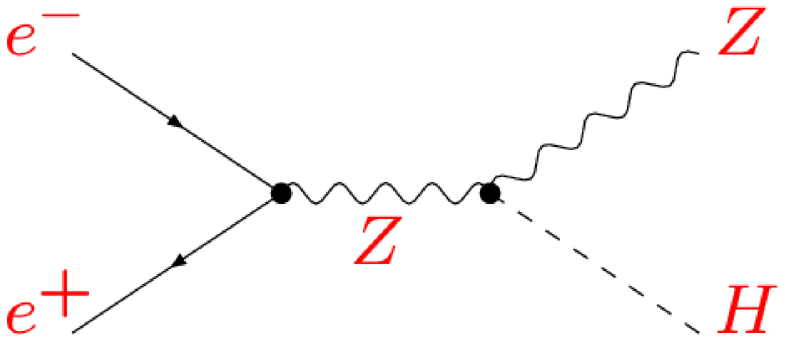
- Positron polarisation yields significant physics gain

  Already in baseline design (undulator-based positron source): $\approx 30\%$ positron polarisation exploitable for physics

Higgs physics at the ILC

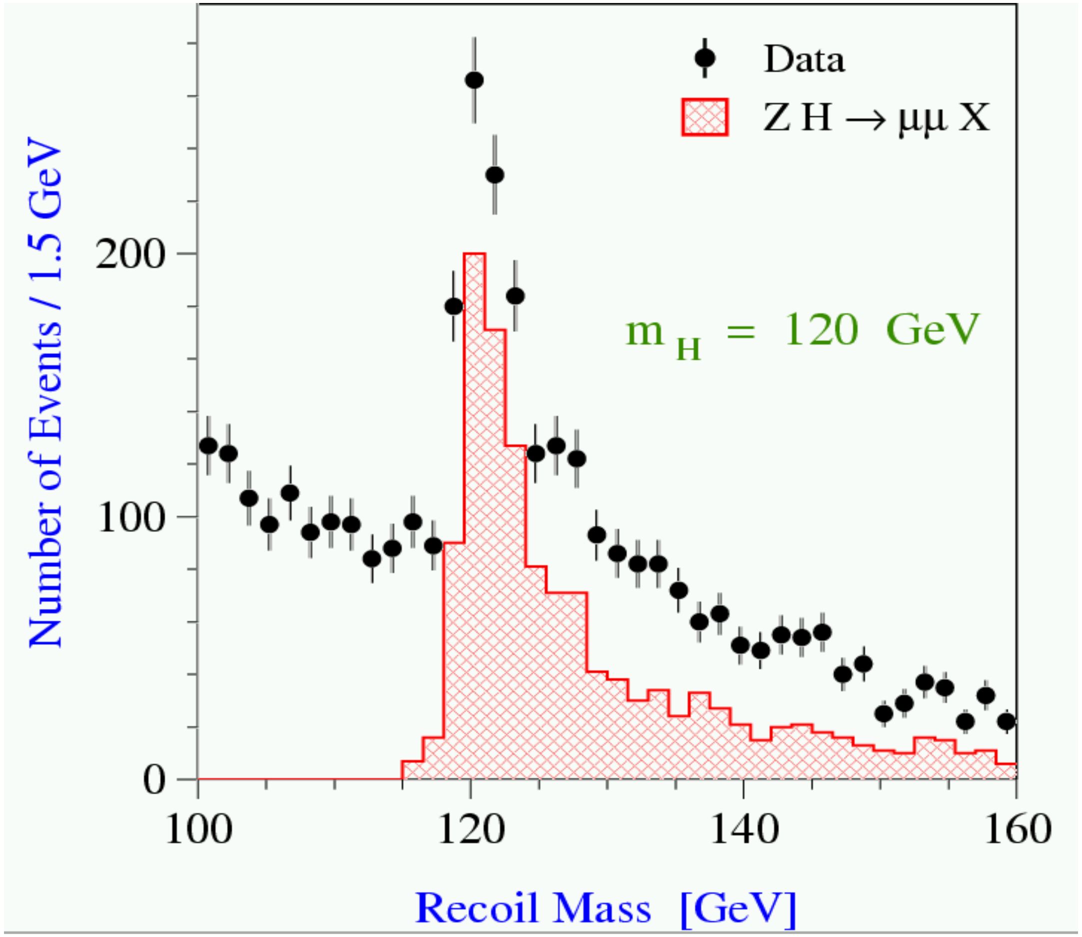
“Golden” production channel: $e^+e^- \to ZH$, $Z \to e^+e^-, \mu^+\mu^-$

Higgs discovery possible independently of decay modes (from recoil against Z boson)



$\Delta\sigma_{\mathrm{HZ}}/\sigma_{\mathrm{HZ}} \approx 2\%$
($E_{\mathrm{CM}} = 350$ GeV,
$\int \mathcal{L}dt = 500$ fb^{-1})

[P. Garcia-Abia, W. Lohmann ’00]



The ILC will be a "Higgs factory"

Example: $E_{\mathrm{CM}} = 800$ GeV, 1000 fb^{-1}, $M_{\mathrm{H}} = 120$ GeV:

$\Rightarrow$ ≈ 160000 Higgs events in "clean" experimental environment

$\Rightarrow$ Precise measurement of Higgs mass and couplings,
determination of Higgs spin and quantum numbers, . . .
Mass determination for a light Higgs:

$$\delta M_{\mathrm{H}}^{\mathrm{exp}} \approx 0.05 \text{ GeV}$$

$\Rightarrow$ Verification of Higgs mechanism in model-independent way

distinction between different possible manifestations:
extended Higgs sector, invisible decays, Higgs–radion mixing, . . .

Example: Higgs coupling determination

LHC: no absolute measurement of total production cross section (no recoil method like LEP, ILC: $e^+e^- \to ZH$, $Z \to e^+e^-, \mu^+\mu^-$)

Production $\times$ decay at the LHC yields combinations of Higgs couplings ($\Gamma_{\text{prod, decay}} \sim g^2_{\text{prod, decay}}$):

$$\sigma(H) \times \text{BR}(H \to a + b) \sim \frac{\Gamma_{\text{prod}}\Gamma_{\text{decay}}}{\Gamma_{\text{tot}}},$$

Large uncertainty on dominant decay for light Higgs: $H \to b\bar{b}$

$\Rightarrow$ LHC can directly determine only ratios of couplings, e.g. $g^2_{H\tau\tau}/g^2_{HWW}$

Higgs coupling determination at the LHC

Need additional (mild) theory assumption to obtain absolute values of the couplings at the LHC:

[*M. Dührssen, S. Heinemeyer, H. Logan, D. Rainwater, G. W., D. Zeppenfeld '04*]

$$g^2_{HVV} \leq (g^2_{HVV})^{\mathrm{SM}}, \quad V = W, Z$$

$\Rightarrow$ Upper bound on Γ_V

Observation of Higgs production

$\Rightarrow$ Lower bound on production couplings and Γ_{tot}

Observation of $H \to VV$ in WBF

$\Rightarrow$ Determines $\Gamma^2_V/\Gamma_{\mathrm{tot}}$ $\Rightarrow$ Upper bound on Γ_{tot}

$\Rightarrow$ Absolute determination of Γ_{tot} and Higgs couplings

Higgs coupling determination at the ILC

Absolute determination of couplings (Z, W, t, b, c, τ) with 1–5% accuracy, no theory assumptions needed

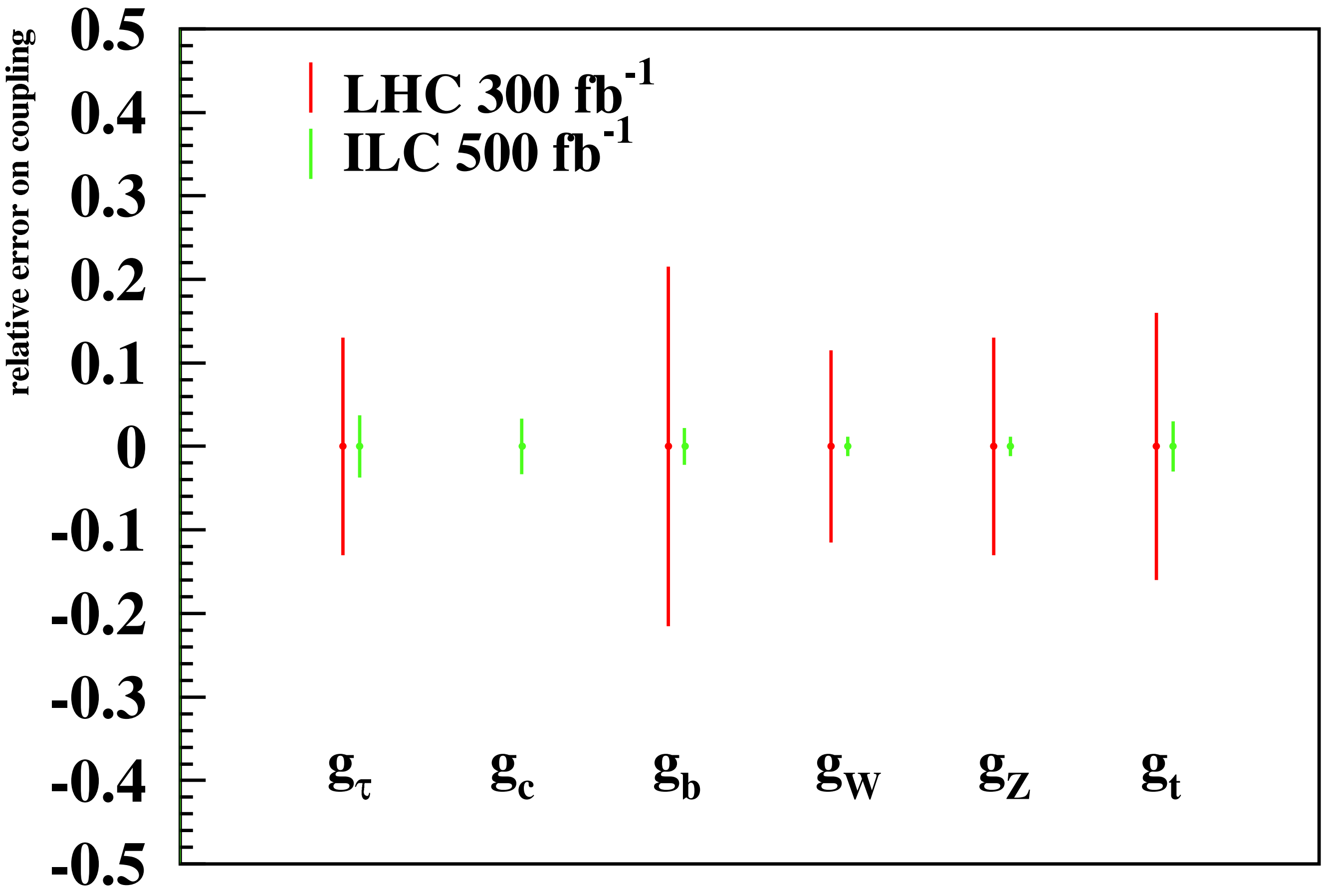
Model-independent measurement of the total width

$\Gamma_{\gamma\gamma}$: 2% measurement at photon collider option

Higgs coupling determination: LHC vs. ILC

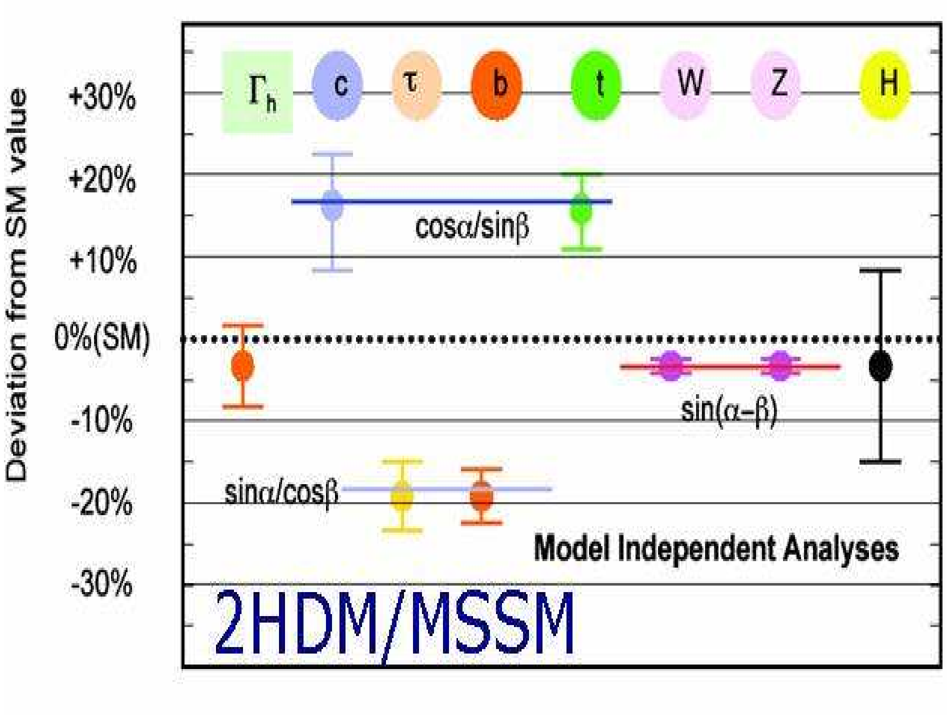
Comparison: LHC (with mild theory assumptions) vs. ILC (model-independent)

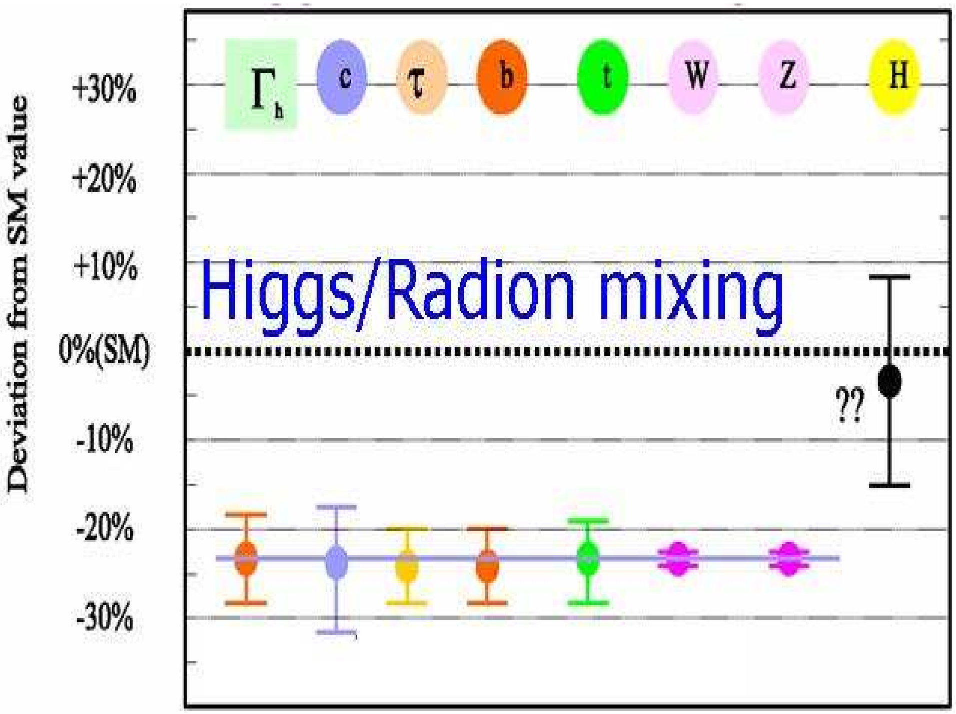
[*M. Dührssen, S. Heinemeyer, H. Logan, D. Rainwater, G. W., D. Zeppenfeld ’04*]
[*K. Desch ’06*]



Impact of ILC precision for the Higgs couplings

SM vs. BSM physics:

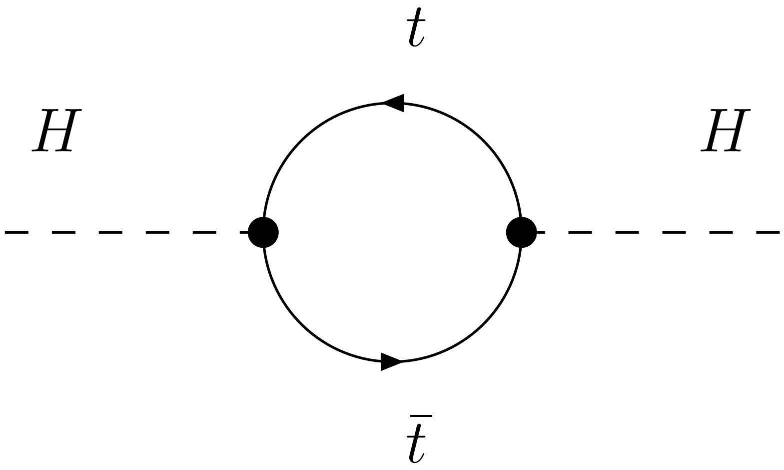




⇒ Precision measurement of Higgs couplings allows distinction between different models

Precision Higgs physics

Large coupling of Higgs to top quark



One-loop correction $\sim G_\mu m_\mathrm{t}^4$

$\Rightarrow$ M_H depends sensitively on m_t in all models where M_H can be predicted (SM: M_H is free parameter)

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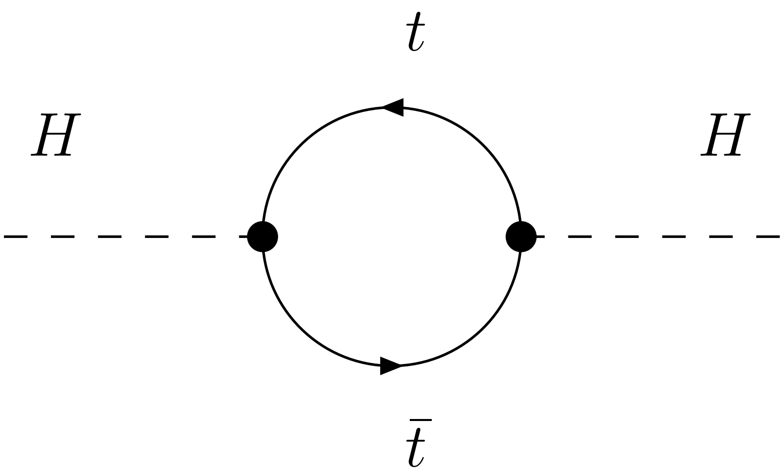

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SUSY as an example: $\Delta m_t \approx \pm 2\ \mathrm{GeV} \Rightarrow \Delta m_h \approx \pm 2\ \mathrm{GeV}$

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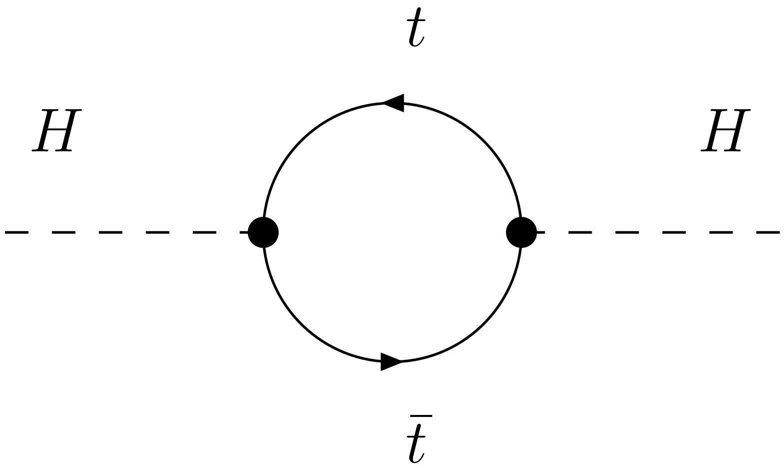

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SUSY as an example: $\Delta m_\mathrm{t} \approx \pm 2~\mathrm{GeV}$ $\Rightarrow$ $\Delta m_\mathrm{h} \approx \pm 2~\mathrm{GeV}$

$\Rightarrow$ Precision Higgs physics needs precision top physics

LHC: $\Delta m_\mathrm{h} \approx 0.2~\mathrm{GeV}$, $\Delta m_\mathrm{t} \gtrsim 1~\mathrm{GeV}$, ILC: $\Delta m_\mathrm{t} \lesssim 0.1~\mathrm{GeV}$

Top and electroweak precision physics

EW precision data:

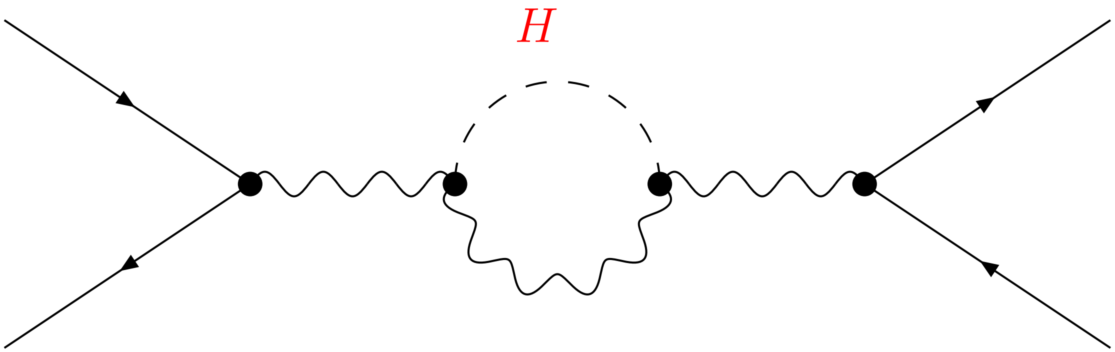
$M_Z, M_W, \sin^2\theta_{\rm eff}^{\rm lept}, \ldots$

Theory:

SM, MSSM, . . .

$\Downarrow$

Test of theory at quantum level: sensitivity to loop corrections



$\Downarrow$

Indirect constraints on unknown parameters: M_H, . . .

Effects of “new physics”?

Top-quark physics and eletroweak precision observables: $\sin^2\theta_{\rm eff}$, $M_{\rm W}$, . . . , $\sigma(e^+e^- \to f\bar{f})$, . . .

$\sin^2\theta_{\rm eff}, M_{\rm W}, \ldots$: Electroweak precision observables, high sensitivity to effects of new physics

$\Rightarrow$ test of the theory, discrimination between models

Top quark: By far the largest quark mass, largest mass of all known fundamental particles $\Rightarrow$ window to new physics?

$\Rightarrow$ large coupling to the Higgs boson

important for physics of flavour

prediction of $m_{\rm t}$ from underlying theory?

Loop corrections $\Rightarrow$ non-decoupling effects prop. to $m_{\rm t}^2$, $m_{\rm t}^4$

$\Rightarrow$ Need to know $m_{\rm t}$ very precisely in order to have sensitivity to new physics

Precision top physics

Current exp. error on $m_{\rm t}$ from the Tevatron: $\delta m_{\rm t}^{\rm exp} = 1.8~{\rm GeV}$

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Current exp. error on m_t from the Tevatron: $\delta m_\mathrm{t}^\mathrm{exp} = 1.8\ \mathrm{GeV}$

Which mass is actually measured at the Tevatron and the LHC?

What is the mass of an unstable coloured particle?
Impact of higher-order effects?
The pole mass is not “IR safe”

Precision top physics

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ILC:

Measurement of ‘threshold mass’ with high precision:
$\lesssim 20~{\rm MeV}$ $+$ transition to suitably defined (short-distance) top-quark mass, e.g. $\overline{\rm MS}$ mass

ILC: $\delta m_{\rm t}^{\rm exp} \lesssim 100~{\rm MeV}$ (dominated by theory uncertainty)

Top-quark physics at the ILC

From running at $t\bar{t}$ threshold and in the continuum:

Precision measurements of

- top-quark mass
- top couplings to gauge bosons, el. charge, spin
- top Yukawa coupling
- $V_{\mathrm{td}}, V_{\mathrm{ts}}, V_{\mathrm{tb}}$
- total width
- top cross section
- . . .

Electroweak precision observables (EWPO): present status vs. GigaZ / MegaW precision

obs.	exp. cent. value	$\sigma^{\rm today}$	$\sigma^{\rm LHC}$	$\sigma^{\rm ILC}$
$M_{\rm W}$ [GeV]	80.398	0.025	0.015	0.007
$\sin^2\theta_{\rm eff}$	0.23153	0.00016	$20–14 \times 10^{-5}$	1.3×10^{-5}
Γ_Z [GeV]	2.4952	0.0023	—	0.001
R_l	20.767	0.025	—	0.01
R_b	0.21629	0.00066	—	0.00014
$\sigma^0_{\rm had}$	41.540	0.037	—	0.025

$\Rightarrow$ Large improvement at the ILC

Theoretical predictions for EWPO

Sources of theoretical uncertainties:

- Unknown higher-order corrections

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Sources of theoretical uncertainties:

- Unknown higher-order corrections

- Parametric uncertainty induced by the experimental errors of the input parameters

  Dominant effect: experimental error of m_{t}

  $\Rightarrow$ ILC will yield improvement by an order of magnitude

  exp. error on m_{t}: $\approx 1\ \mathrm{GeV} \xrightarrow{\text{ILC + GigaZ}} 0.1\ \mathrm{GeV}$

New results for electroweak precision observables in the MSSM

New results for M_W and Z observables $\sin^2\theta_\mathrm{eff}$, Γ_Z, R_l, R_b, σ^0_had:

Complete one-loop results with complex parameters $+$ inclusion of all available higher-order corrections

[*S. Heinemeyer, W. Hollik, D. Stöckinger, A.M. Weber, G. W. '06*]

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Theoretical evaluation in the SM is more advanced than in the MSSM ⇒ incorporation of state–of–the–art SM results using

$$O^\mathrm{MSSM} = \underbrace{O^\mathrm{SM}}_{(a)} + \underbrace{O^\mathrm{MSSM-SM}}_{(b)}$$

(a): full SM result

(b): difference between SM and MSSM, evaluated at the level of precision of the known MSSM corrections

Incorporation of higher-order corrections from the Higgs sector

Higgs sector enters EWPO only via loop corrections

$\Rightarrow$ For one-loop corrections to EWPO it would in principle be sufficient to treat the Higgs sector in leading order, i.e. at the tree level

However:

Tree-level mass of light MSSM Higgs boson is below the SM exclusion bound on M_{H}

$\Rightarrow$ Treating the MSSM Higgs sector at tree level leads to artificially large contributions to EWPO from the light MSSM Higgs boson

Incorporation of higher-order corrections from the Higgs sector

Large higher-order corrections in the MSSM Higgs sector:

$\Rightarrow$ Correction to upper bound on $m_{\rm h}$ of about 50%

large corrections to Higgs couplings

$\mathcal{CP}$-violating mixing

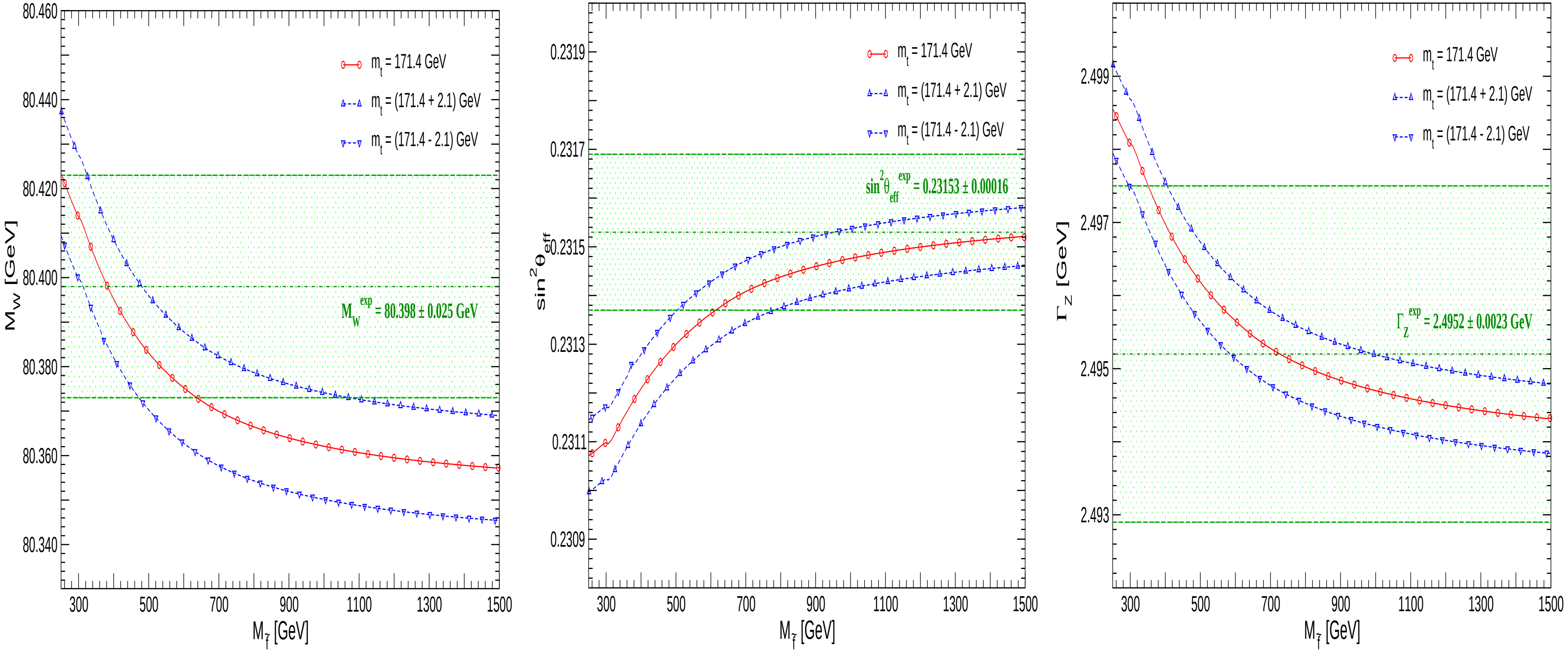
$\Rightarrow$ Incorporation of leading higher-order corrections in the MSSM Higgs sector into the predictions for the EWPO

Consistency checks: symmetry relations, UV-finiteness

Results for $M_{\rm W}$, $\sin^2\theta_{\rm eff}$, $\Gamma_{\rm Z}$

Dependence on the sfermion mass scale

[*S. Heinemeyer, W. Hollik, A.M. Weber, G. W. ’07*]

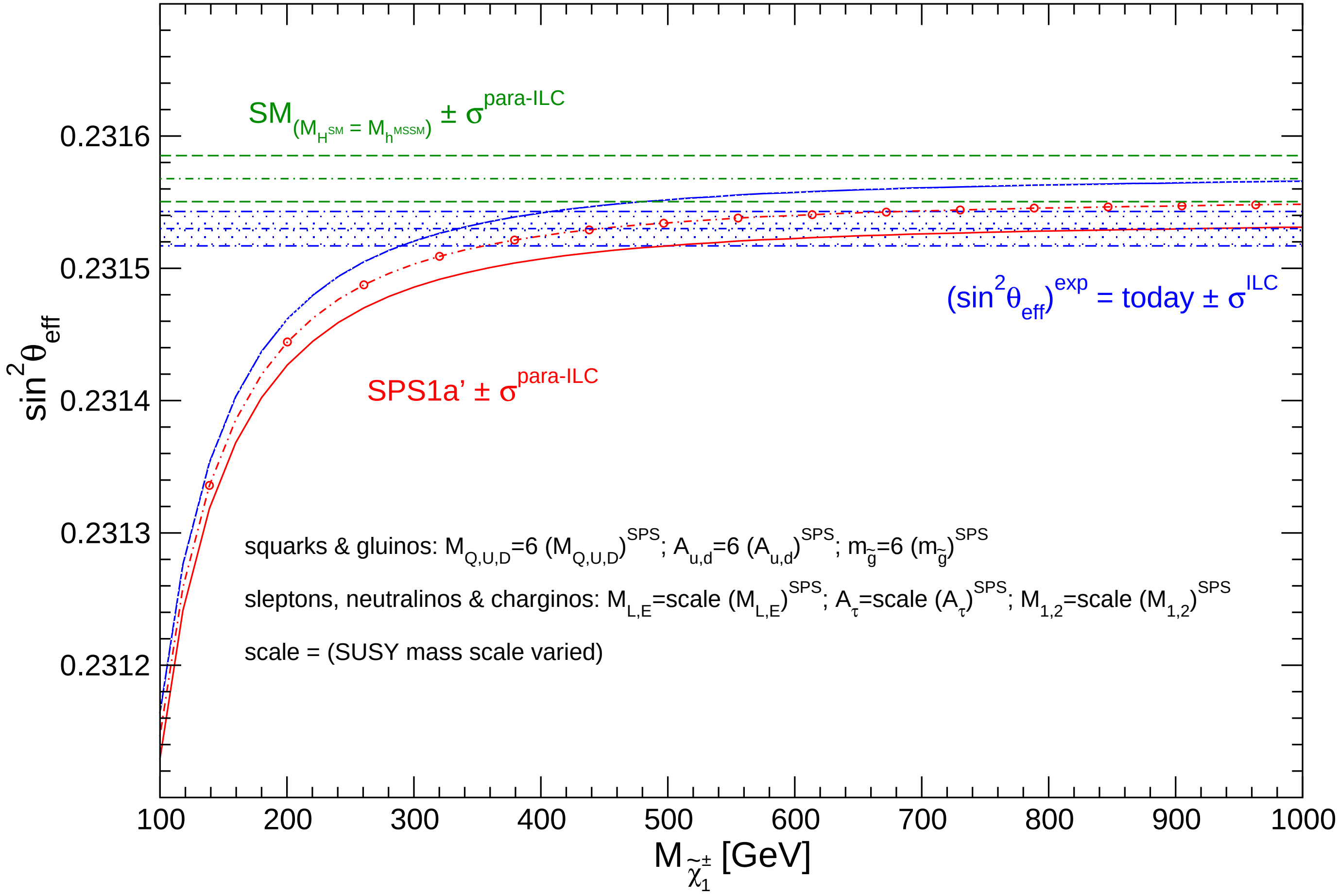


$\Rightarrow$ Sizable dependence on the sfermion mass scale

Drastic improvement with ILC prec. on $M_{\rm W}$, $\sin^2\theta_{\rm eff}$, $\Gamma_{\rm Z}$, $m_{\rm t}$

GigaZ: sensitivity to the scale of SUSY in a scenario where no SUSY particles are observed at the LHC

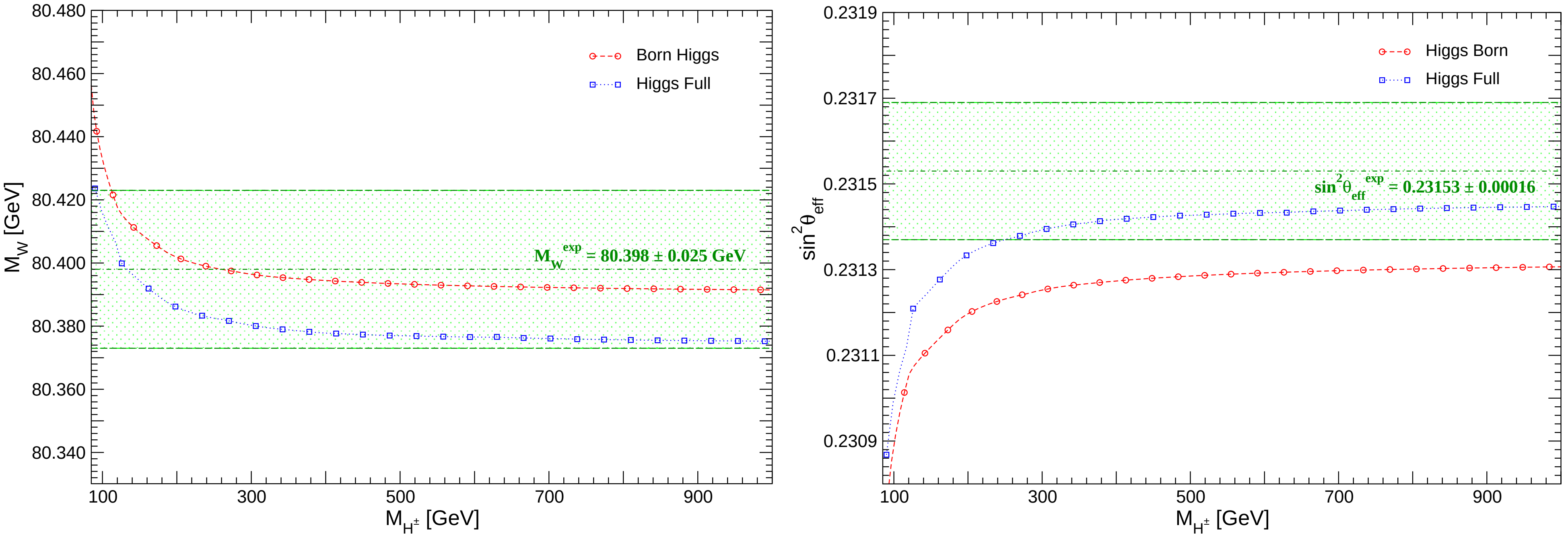
[S. Heinemeyer, W. Hollik, A.M. Weber, G. W. ’07]



⇒ GigaZ measurement provides sensitivity to SUSY scale, extends the direct search reach of ILC(500)

Higgs sector at higher orders: impact on M_{W} ***and*** $\sin^2\theta_{\mathrm{eff}}$

[*S. Heinemeyer, W. Hollik, A.M. Weber, G. W. ’07*]



$\Rightarrow$ Sizable effects

ILC can probe loop-induced effects from the Higgs sector

Impact of the complex phases ϕ_{A_t}, ϕ_{A_b} in the sfermion sector

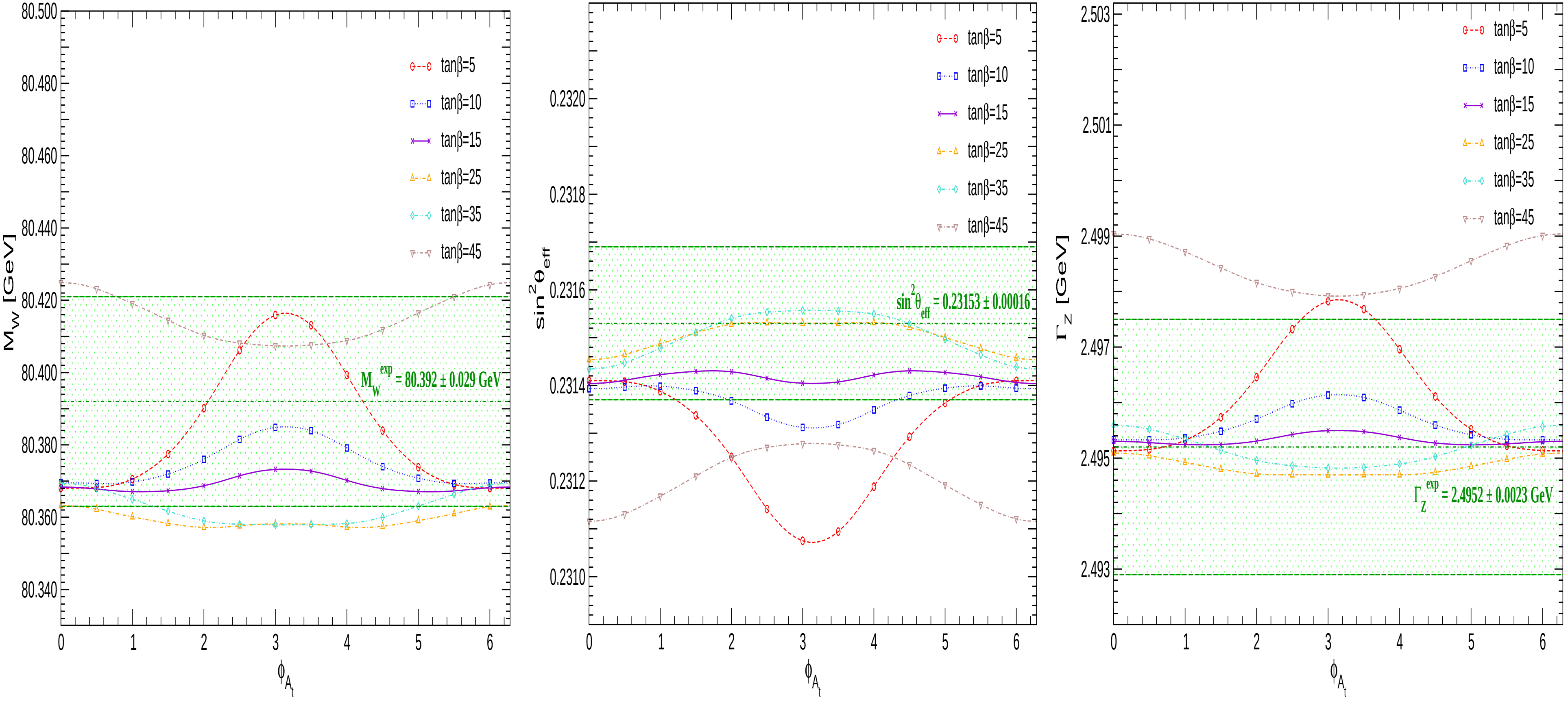
Enter leptonic observables M_W, $\sin^2\theta_\mathrm{eff}$, ... at 1-loop order only via

$$
\begin{aligned}
|X_\mathrm{t}|^2 &= |A_\mathrm{t}|^2 + |\mu\cot\beta\,|^2 - 2|A_\mathrm{t}|\cdot|\mu|\cot\beta\ \cos(\phi_{A_\mathrm{t}} + \phi_\mu) \\
|X_\mathrm{b}|^2 &= |A_\mathrm{b}|^2 + |\mu\tan\beta|^2 - 2|A_\mathrm{b}|\cdot|\mu|\tan\beta\ \cos(\phi_{A_\mathrm{b}} + \phi_\mu)
\end{aligned}
$$

where $X_\mathrm{t} = A_\mathrm{t} - \mu^*/\tan\beta$, $X_\mathrm{b} = A_\mathrm{b} - \mu^*\tan\beta$, $\tan\beta \equiv v_2/v_1$

⇒ phase dependence only enters via the squark masses and mixing angles

Effects of varying the complex phase ϕ_{A_t} *on* M_W*,* $\sin^2\theta_\mathrm{eff}$*,* Γ_Z

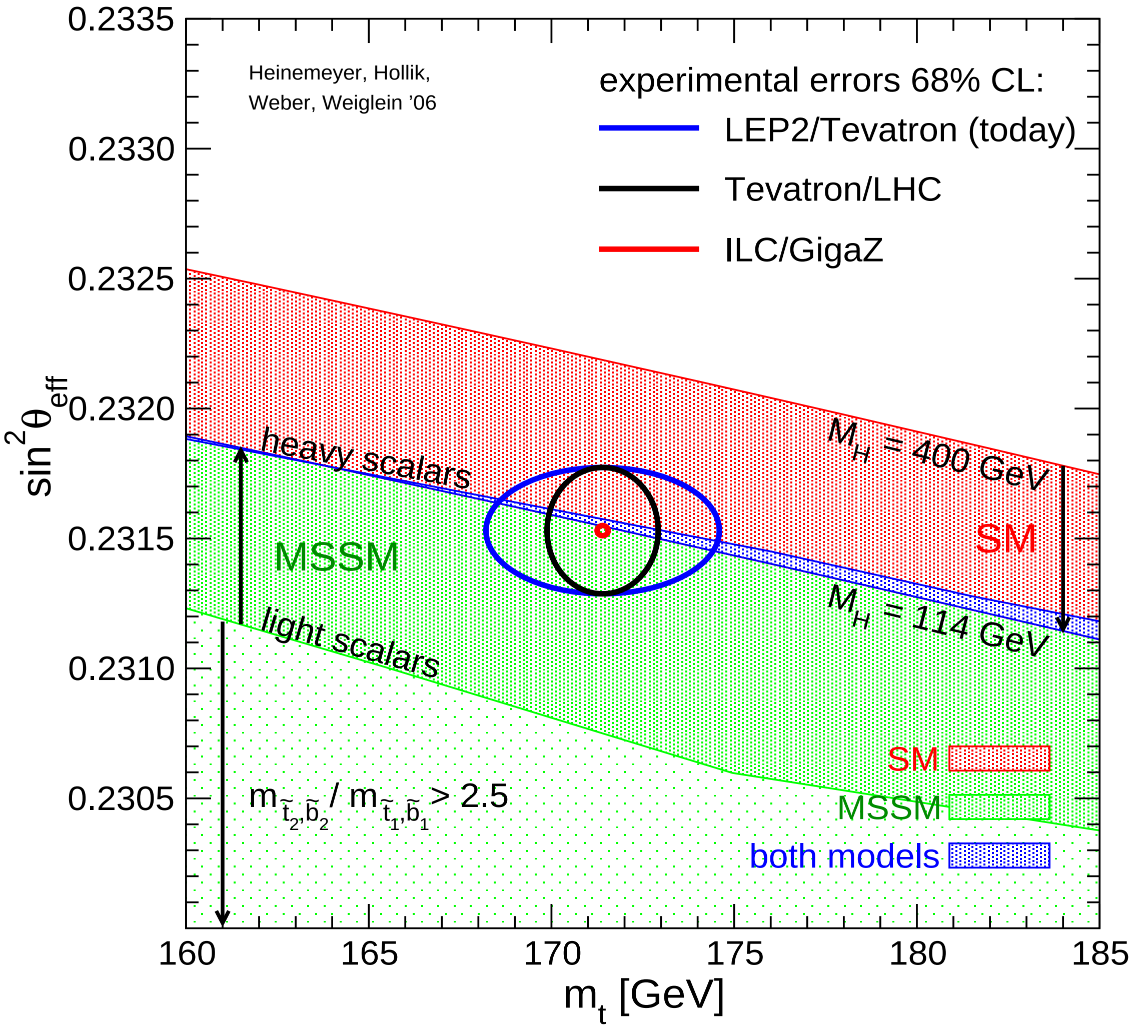


⇒ Shift in M_W, $\sin^2\theta_\mathrm{eff}$, Γ_Z predictions by 1–2 σ for small $\tan\beta$

Largely improved sensitivity at the ILC

Prediction for $\sin^2\theta_{\mathrm{eff}}$ (parameter scan): SM vs. MSSM

Prediction for $\sin^2\theta_{\mathrm{eff}}$ in the SM and the MSSM:



[S. Heinemeyer, W. Hollik, A.M. Weber, G. W. '07]

MSSM: SUSY parameters varied

SM: M_{H} varied

⇒ ILC precision on $\sin^2\theta_{\mathrm{eff}}$ and m_{t} yields drastic improvement

Conclusions

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- Sensitivity to higher-order effects drastically improves with ILC precision on EWPO and m_t

$\Rightarrow$ Electroweak physics at the ILC will be a very powerful tool for probing the structure of new physics