Beyond the LHC

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- Introduction
- What is the mechanism of electroweak symmetry breaking?
- Top and electroweak precision physics: windows to the structure of nature
- Example of TeV-scale physics: Supersymmetry
- Conclusions

Introduction

Beyond the LHC: why bother now?

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- How much sense does it make to talk about major facilities beyond the LHC in view of the funding crisis on both sides of the Atlantic Ocean?

Introduction

Beyond the LHC: why bother now?

- The LHC is about to start, why should one discuss now about possible physics in $\gtrsim$ 10 years from now?
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Will try to give some answers in the following . . .

On the way to the TeV scale

The LHC will open up the new territory of TeV-scale physics

$1\ \mathrm{TeV} \approx 1000 \times m_{\mathrm{proton}} \Leftrightarrow 2 \times 10^{-19}\,\mathrm{m}$

TeV-scale:

6 orders of magnitude above typical energy scale of nuclear physics

12 orders of magnitude above typical energy scale of atomic physics

“Extrapolation backwards in time” by 29 orders of magnitude

$1\ \mathrm{TeV} \Leftrightarrow 10^{-12}\,\mathrm{s}$ after the Big Bang

What can we learn from exploring the new territory of TeV-scale physics?

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- How do elementary particles obtain the property of mass: what is the mechanism of electroweak symmetry breaking?
- Do all the forces of nature arise from a single fundamental interaction?
- Are there more than three dimensions of space?
- Are space and time embedded into a “superspace”?
- Can dark matter be produced in the laboratory?
- . . .

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- Higgsless models in extra dimensions: boundary conditions for SM gauge bosons and fermions on Planck and TeV branes in higher-dimensional space

$\Rightarrow$ New phenomena required at the TeV scale

Electroweak symmetry breaking in the SM

Electroweak Standard Model (SM): Higgs is last missing ingredient

Higgs mechanism, spontaneous electroweak symmetry breaking:

Scalar field postulated, gauge-invariant mass terms from coupling to Higgs field

3 components of Higgs doublet $\longrightarrow$ longitudinal components of $W^{\pm}$, Z; H: elementary scalar field, Higgs boson

Fermion masses, gauge-boson masses from coupling to Higgs field

$\Rightarrow$ Higgs couplings proportional to masses of the particles

Mass of the Higgs boson: free parameter

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  $\Rightarrow$ breaks down at the latest at $M_{\mathrm{Planck}} \approx 10^{19}\ \mathrm{GeV}$

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- Nature has found a way to prevent this
  The Standard Model provides no explanation

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Large corrections cancel out because of symmetry
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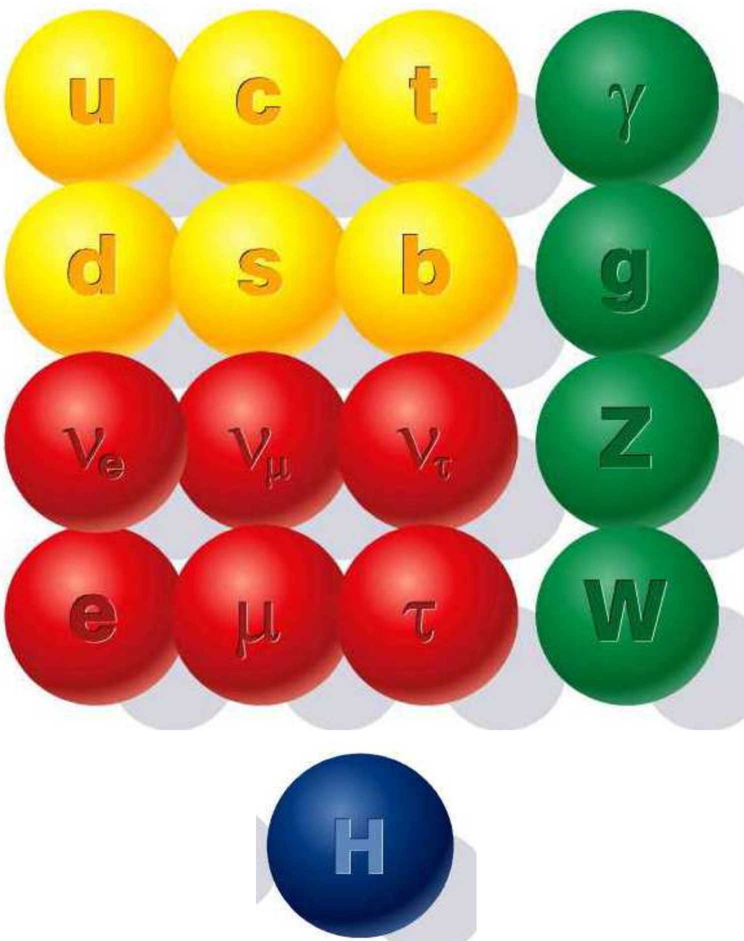
Extra dimensions of space:

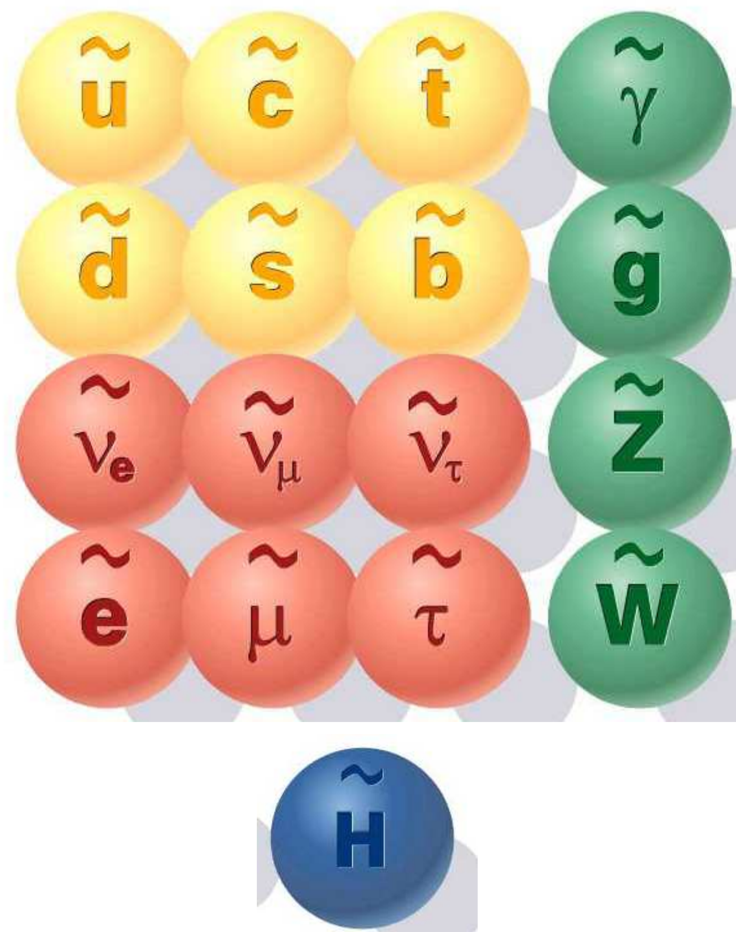
Fundamental Planck scale is $\sim \mathrm{TeV}$ (large extra dimensions),

hierarchy of scales is related to a “warp factor”
(“Randall–Sundrum” scenarios)

Supersymmetry (SUSY)

Supersymmetry: fermion $\longleftrightarrow$ boson symmetry,
leads to compensation of large quantum corrections





The Minimal Supersymmetric Standard Model (MSSM): internally consistent, valid up to very high scales

Superpartners for Standard Model particles:

$\left[u, d, c, s, t, b\right]_{L,R}$ $\left[e, \mu, \tau\right]_{L,R}$ $\left[\nu_{e,\mu,\tau}\right]_L$ Spin $\frac{1}{2}$

$\left[\tilde{u}, \tilde{d}, \tilde{c}, \tilde{s}, \tilde{t}, \tilde{b}\right]_{L,R}$ $\left[\tilde{e}, \tilde{\mu}, \tilde{\tau}\right]_{L,R}$ $\left[\tilde{\nu}_{e,\mu,\tau}\right]_L$ Spin 0

g $\underbrace{W^\pm, H^\pm}$ $\underbrace{\gamma, Z, H_1^0, H_2^0}$ Spin 1 / Spin 0

$\tilde{g}$ $\tilde{\chi}^\pm_{1,2}$ $\tilde{\chi}^0_{1,2,3,4}$ Spin $\frac{1}{2}$

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Enlarged Higgs sector: two Higgs doublets, physical states: $h^0, H^0, A^0, H^\pm$

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Enlarged Higgs sector: two Higgs doublets, physical states:
$h^0, H^0, A^0, H^{\pm}$

General parameterisation of possible SUSY-breaking terms
$\Rightarrow$ free parameters, no prediction for SUSY mass scale

How does SUSY breaking work?

MSSM: no particular SUSY breaking mechanism assumed, parameterisation of possible soft SUSY-breaking terms

$\Rightarrow$ relations between dimensionless couplings unchanged

$\Rightarrow$ cancellation of large quantum corrections preserved

Most general case: 105 new parameters

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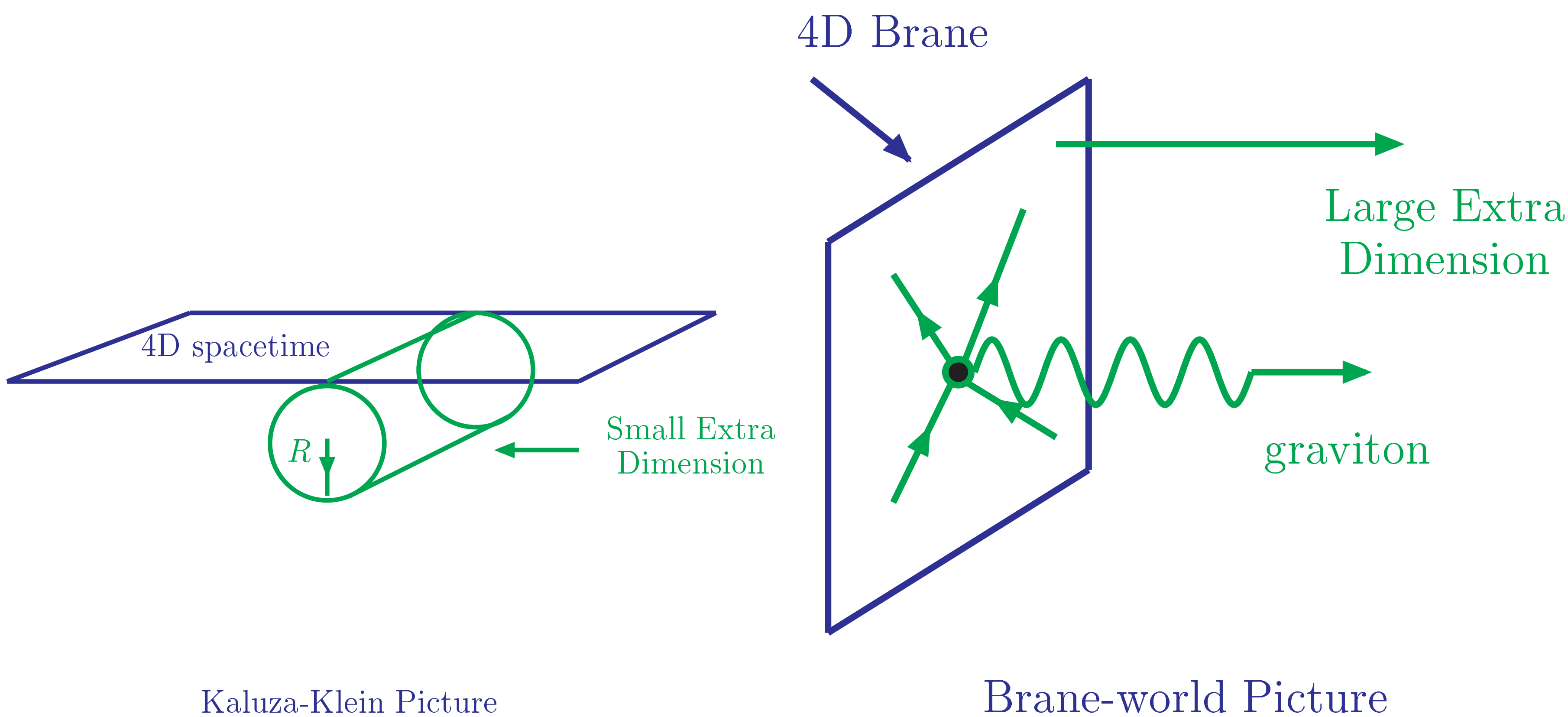
Strong phenomenological constraints on flavour off-diagonal SUSY-breaking terms

$\Rightarrow$ Good phenomenological description for universal SUSY-breaking terms ($\approx$ diagonal in flavour space)

Models with extra dimensions of space



Hierarchy between M_{Planck} and M_{weak} is related to the volume or the geometrical structure of additional dimensions of space

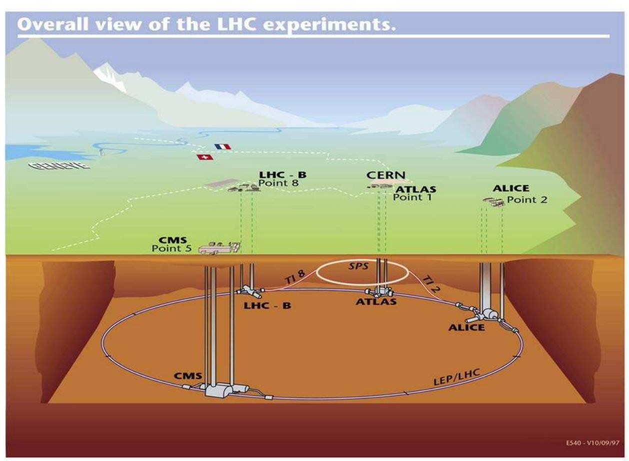
$\Rightarrow$ observable effects at the TeV scale

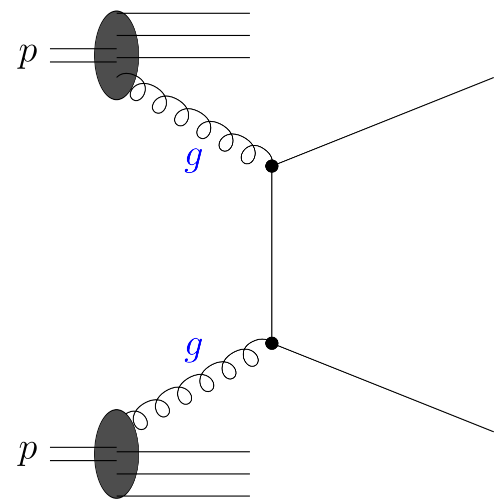
Exploring the TeV scale: the LHC

The Large Hadron Collider (LHC)

Construction nearing completion, scheduled to take first data this year

Proton–proton scattering at 14 TeV: composite objects of quarks and gluons, bound together by strong interaction





Complicated scattering process

10^9 scattering events$/s \Rightarrow$ only 1 event in 10^7 will be recorded

LHC luminosity upgrade: the SLHC

SuperLHC (SLHC): upgrade of LHC design luminosity by a factor of 10 to about $10^{35}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$

- Moderate extension of LHC mass reach
- More precise measurements of processes that are statistically limited
- Extended reach for rare processes

Difficult experimental environment: higher radiation levels in the detectors, increased pile-up background

Upgrades of ATLAS and CMS required

Exploring the TeV scale: the ILC

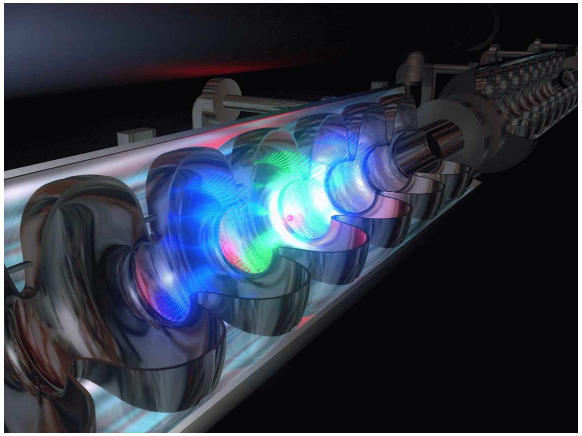
The International Linear Collider (ILC)

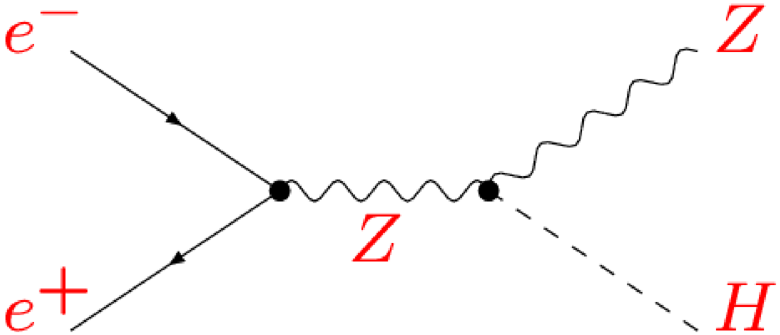
world-wide project, RDR (+ costing) issued in 2007, Engineering Design Report in preparation

Electron–positron scattering at ≈0.5–1 TeV:

fundamental particles, point-like, electroweak interaction

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



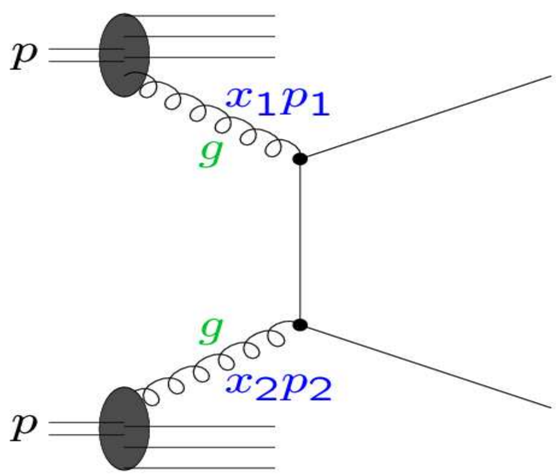


Results are easy to interpret, all events can be recorded

⇒ high-precision physics

Physics at the LHC and ILC in a nutshell

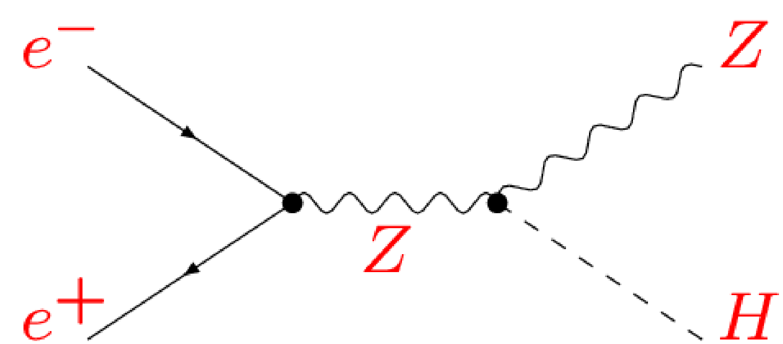
LHC: pp scattering at 14 TeV



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 $\approx$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

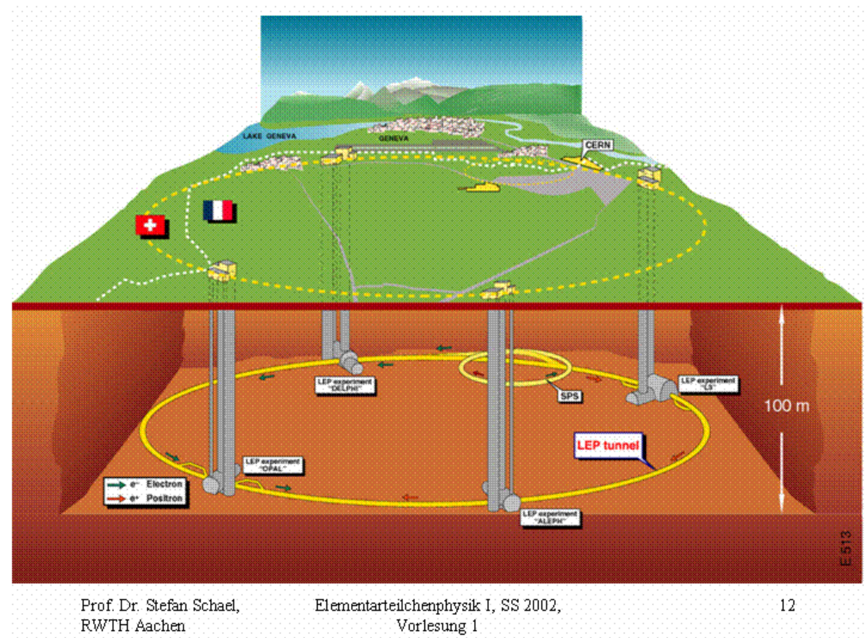
LHC: good prospects for producing new heavy states
(in particular strongly interacting new particles)

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

Circular and linear colliders

LEP (≤ 2000): e^+e^- collider, $E_{\text{CM}} \lesssim 206$ GeV

circular accelerator, ≈ 28 km long



Energy loss due to synchrotron radiation: $\Delta E \sim \dfrac{E^4}{m^4\, r}$

Circular and linear colliders

Synchrotron radiation loss $\Delta E \sim \dfrac{E^4}{m^4\, r}$

$\Rightarrow$ High energy e^+e^- collider can only be realised as Linear Collider (LC): ILC, CLIC

Synchrotron radiation loss smaller for proton by factor $(m_{\rm e}/m_{\rm p})^4 \approx 10^{-13}$

Tevatron, Run II (≥ 2001): circular $p\bar{p}$ collider, $E_{\rm CM} \approx 2$ TeV

LHC ($\gtrsim 2008$): circular pp collider (in LEP tunnel), $E_{\rm CM} \approx 14$ TeV

The ILC: global science collaboration

World-wide consensus (ECFA, ACFA, HEPAP, ICFA, GSF, . . .):

A linear collider of up to at least 400 (500) GeV, upgradeable to about a TeV, should be the next major project at the high-energy frontier

Original regional designs TESLA, NLC and JLC were based on different linac RF technologies: superconducting cavities (TESLA), room-temperature copper cavities (NLC, JLC)

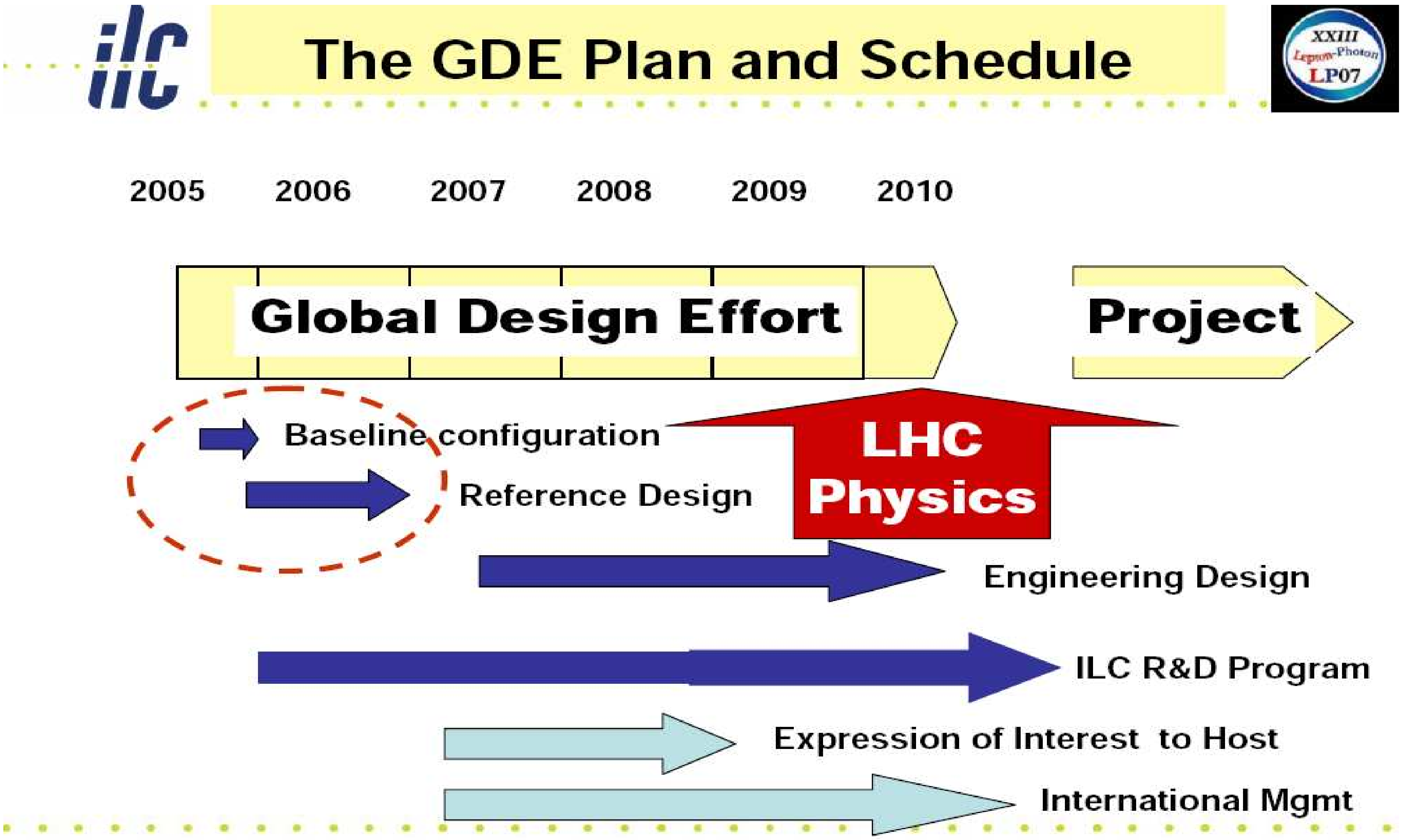
"International Technology Recommendation Panel" (ITRP), 2003–2004:

Decision for superconducting technology
Global Design Effort for the ILC

see *www.linearcollider.org*

The ILC Global Design Effort

[B. Barish, Lepton–Photon '07]



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

Exploring the TeV scale: CLIC, DLHC, VLHC, LHeC and the muon collider

- CLIC: e^+e^- collider, energy up to ~ 3 TeV
- DLHC: energy doubling of the LHC
- VLHC: energy in 100 TeV range
- Muon collider: energy in 10 TeV range, s-channel Higgs production
- LHeC: electron–proton collisions in the LHC tunnel
- …

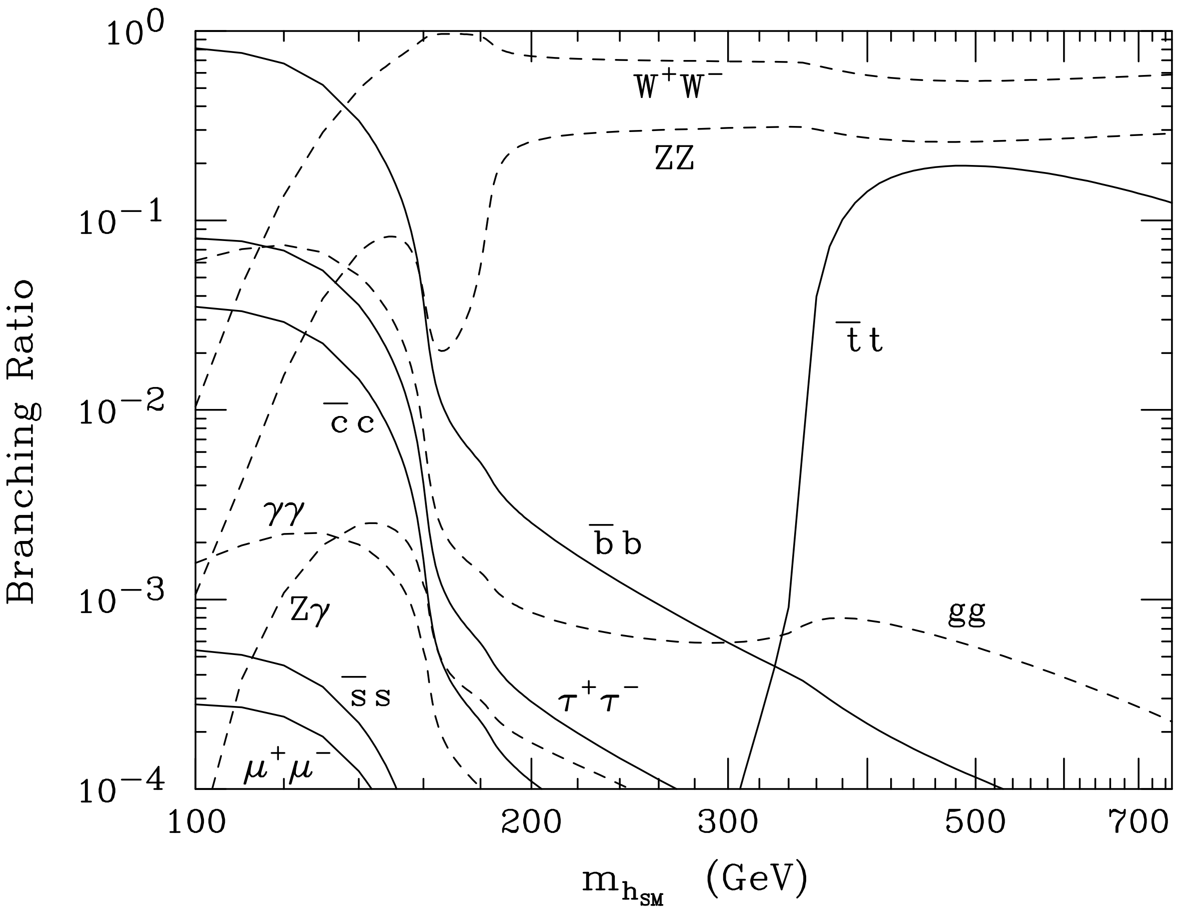
Precision measurements: M_Z, M_W, α_{em}, G_μ, $\sin^2\theta_{eff}$, $(g-2)_\mu$, $BR(b \to s\gamma)$, $BR(B_u \to \tau\nu_\tau)$, EDMs, …

$\Rightarrow$ Sensitivity to indirect effects of TeV-scale physics

What is the mechanism of electroweak symmetry breaking?

Standard Model: a single parameter determines the whole Higgs phenomenology: M_{H}

Branching ratios of the SM Higgs:



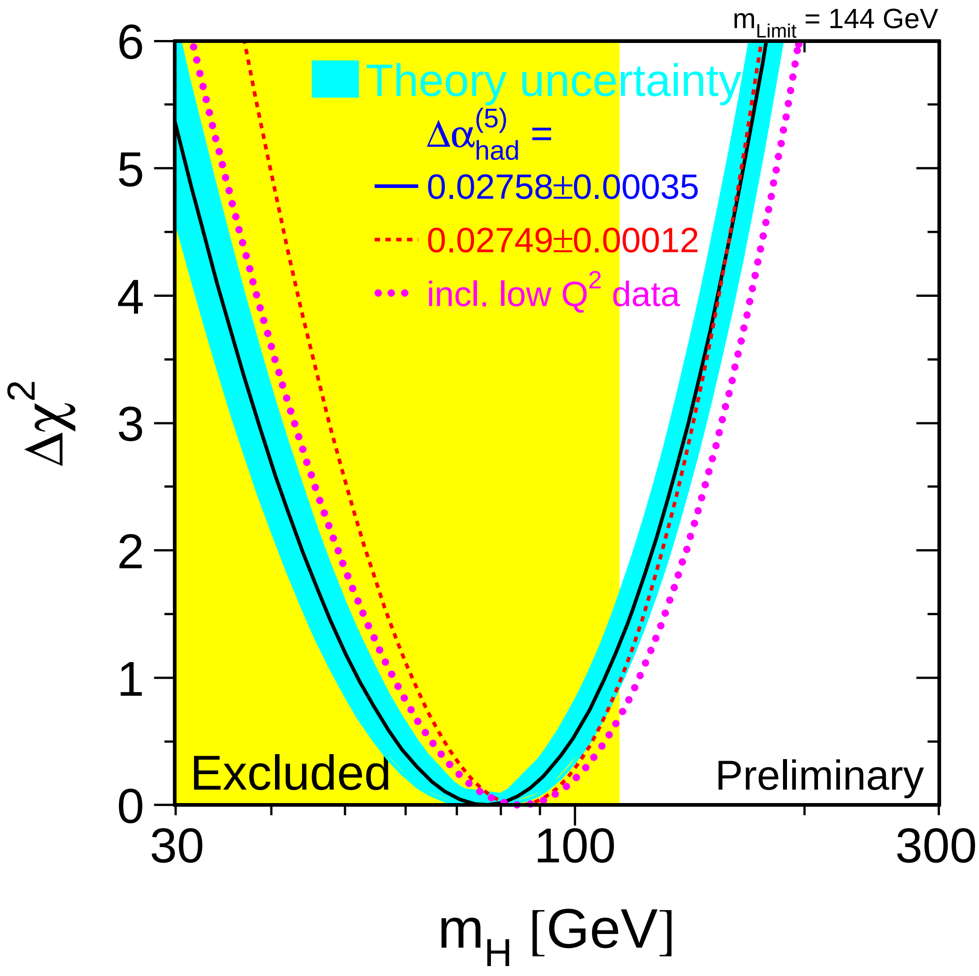
$\Rightarrow$ dominant BRs:

$M_{\mathrm{H}} \lesssim 140$ GeV:
$H \to b\bar{b}$

$M_{\mathrm{H}} \gtrsim 140$ GeV:
$H \to W^+W^-, ZZ$

SM Higgs: indirect constraints on $M_{\rm H}$ vs. direct search limit

[LEPEWWG '07]



$\Rightarrow$ Tension between indirect bounds on $M_{\rm H}$ in the SM and direct search limit has increased

Higgs physics in Supersymmetry

“Simplest” extension of the minimal Higgs sector:

Minimal Supersymmetric Standard Model (MSSM)

- Two doublets to give masses to up-type and down-type fermions (extra symmetry forbids to use same doublet)
- SUSY imposes relations between the parameters

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⇒ Two parameters instead of one: $\tan\beta \equiv \frac{v_u}{v_d}$, M_A (or $M_{\mathrm{H}^\pm}$)

⇒ Upper bound on lightest Higgs mass, M_h (*FeynHiggs*):
[*S. Heinemeyer, W. Hollik, G. W. '99*], [*G. Degrassi, S. Heinemeyer, W. Hollik, P. Slavich, G. W. '02*]

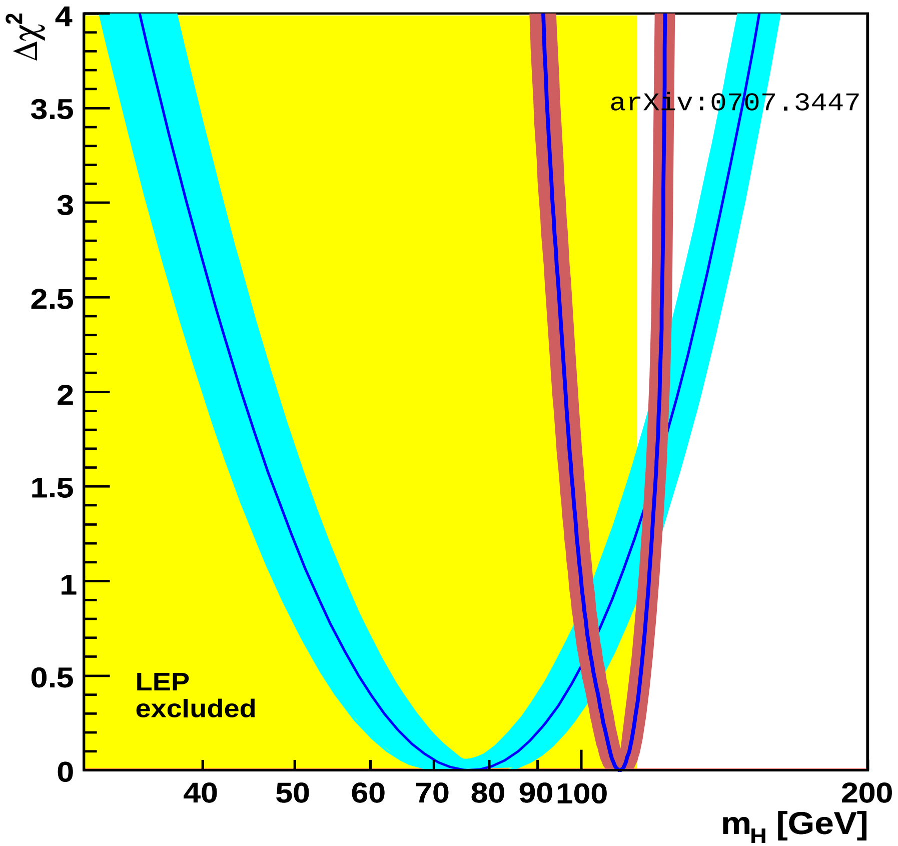
$$M_\mathrm{h} \lesssim 130\,\mathrm{GeV}$$

Very rich phenomenology

Indirect limits on the light Higgs mass in the CMSSM: EWPO + BPO + dark matter constraints

χ^2 fit for M_h, without imposing direct search limit [*O. Buchmueller, R. Cavanaugh, A. De Roeck, S. Heinemeyer, G. Isidori, P. Paradisi, F. Ronga, A. Weber, G. W. '07*]

SM CMSSM



$\Rightarrow$ High sensitivity, less tension than in SM

Higgs physics beyond the SM

In the SM the same Higgs doublet is used “twice” to give masses both to up-type and down-type fermions

$\Rightarrow$ extensions of the Higgs sector having (at least) two doublets are “natural” (and quite typical)

$\Rightarrow$ We need to look for more than just one Higgs boson

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Example: SUSY in the "decoupling limit"

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Example: SUSY in the "decoupling limit"

But there is also the possibility that none of the Higgs bosons is SM-like

Higgs physics beyond the SM

- Scenarios with a SM-like Higgs + additional states:
  - We may see only one Higgs that looks SM-like, but has a totally different physical origin

    How can one distinguish the SM-like state from the SM-Higgs?
  - How can one detect the other states?

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- Scenarios with non SM-type phenomenology:
  - What do we need to be prepared for?
  - Search strategies?
  - How do we identify the underlying physics?

Phenomenology of scenarios with a SM-like Higgs

"Typical" features:

- A light Higgs with SM-like properties, couples with about SM-strength to gauge bosons
- Heavy Higgs states that decouple from the gauge bosons

For "non-standard" Higgs states:

$\Rightarrow$ Cannot use ZH, weak-boson fusion channels for production

$\Rightarrow$ Possible production channels: $e^+e^- \to H_1H_2$, $\gamma\gamma \to H$, $gg \to H$, $b\bar{b}H$, $\ldots$

Cannot use LHC "gold plated" decay mode $H \to ZZ \to 4\mu$

Phenomenology of scenarios *without* a SM-like Higgs

- Higgs may be much lighter than $114\ \mathrm{GeV}$ (e.g. SUSY with $\mathcal{CP}$-violation) $\Rightarrow$ no firm experimental lower bound on M_{H}
- Significant suppression / enhancement of various couplings possible with respect to the SM
  Example: large enhancement of $H\bar{b}b$ coupling
  $\Rightarrow$ large suppression of BR($h \to \gamma\gamma$), BR($h \to WW^*$), ...
- Higgs decays into non-standard particles
  Examples: $H \to$ invisible, $H \to$ soft jets, ...
- Mixing between different Higgs states, “continuum” Higgs models, mixing with exotic states, ...

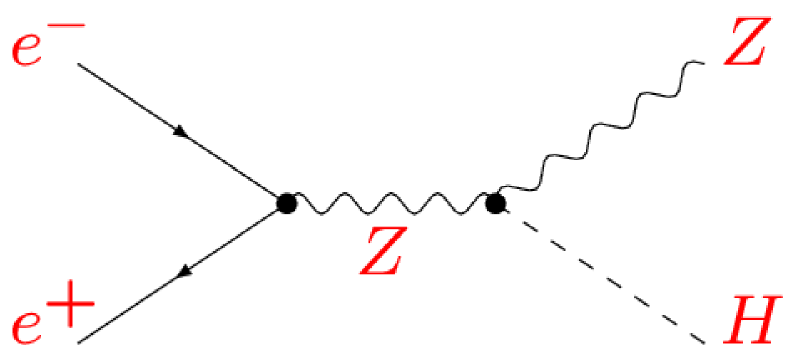
$\Rightarrow$ Higgs phenomenology can drastically differ from SM case

Expect at least one Higgs state with significant coupling to gauge bosons

Higgs physics at the ILC

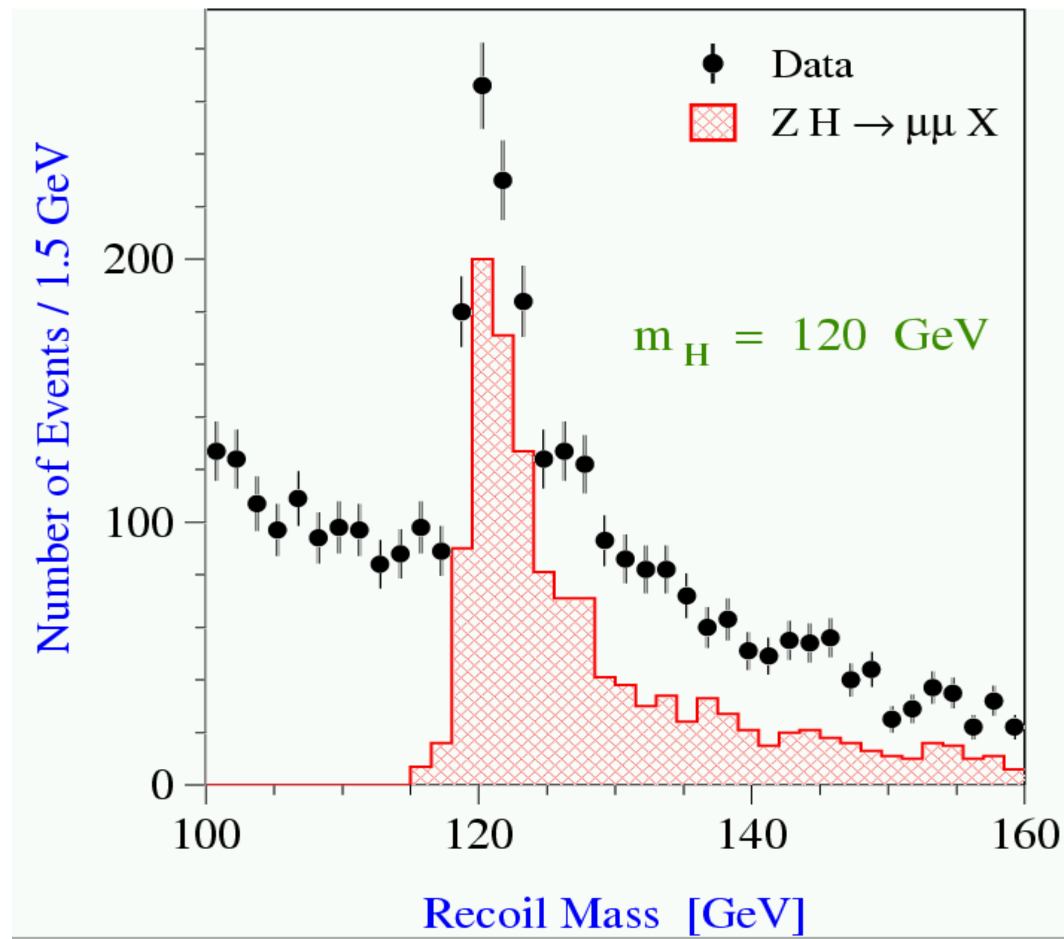
"Golden" production channel: $e^+e^- \to ZH$, $Z \to e^+e^-, \mu^+\mu^-$

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

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

$\Rightarrow$ Verification of Higgs mechanism in model-independent way
distinction between different possible manifestations: extended Higgs sector, invisible decays, Higgs–radion mixing, . . .

If a Higgs candidate has been detected: experimental questions

- Is it a Higgs boson?
- What are its mass, spin and $\mathcal{CP}$ properties?
- What are its couplings to fermions and gauge bosons? Are they really proportional to the masses of the particles?
- What are its self-couplings?
- Are its properties compatible with the SM, the MSSM, the NMSSM, . . . ?
- Are there indications that there are more than one Higgs bosons?
- Are there indications for other new states that influence Higgs physics?

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

Absolute values of the couplings at the LHC can be obtained with an additional (mild) theory assumption:
[*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 $\Gamma_V^2/\Gamma_{\mathrm{tot}}$ $\Rightarrow$ 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

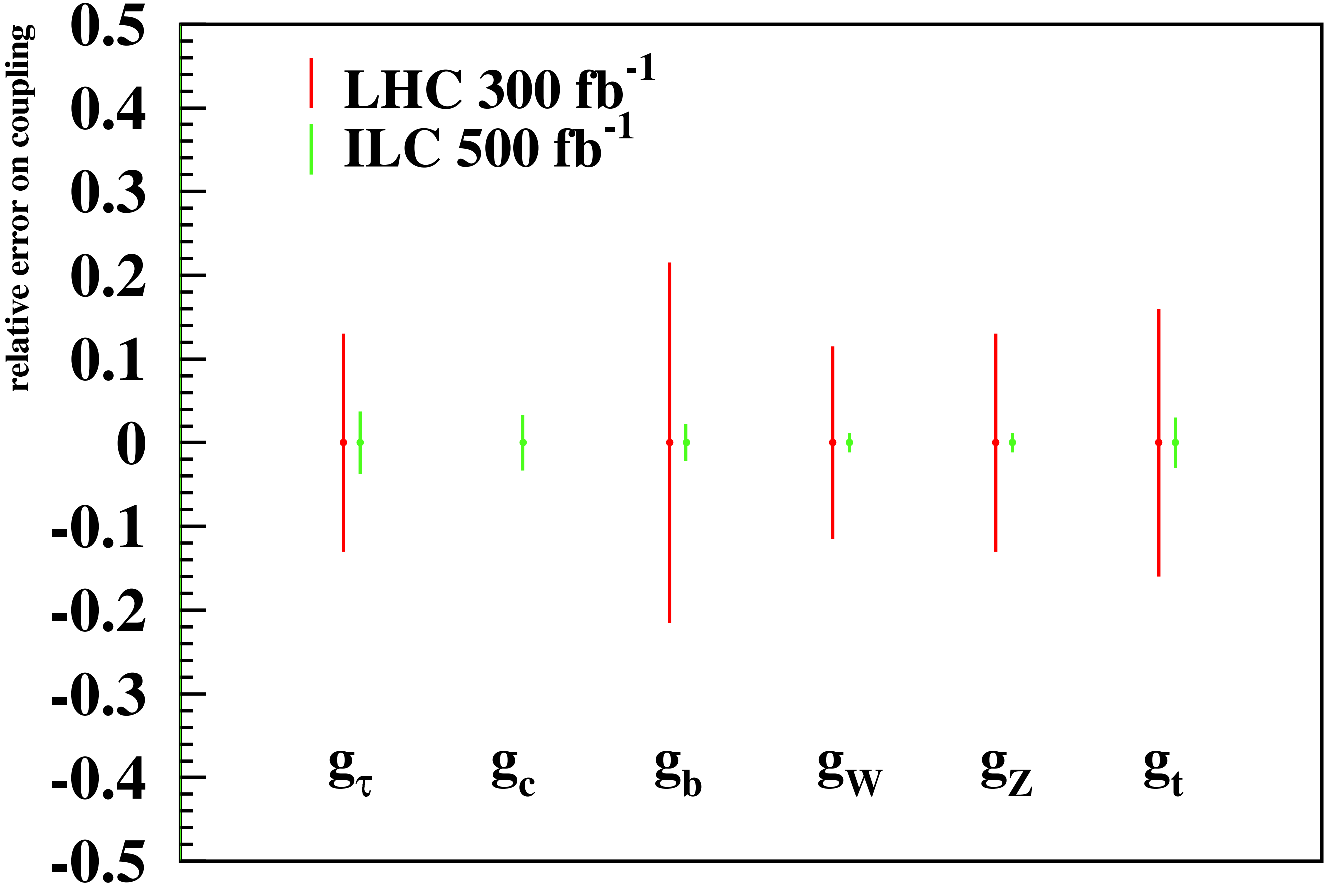
Model-independent measurement of the total width

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

Higgs coupling determination: LHC vs. ILC

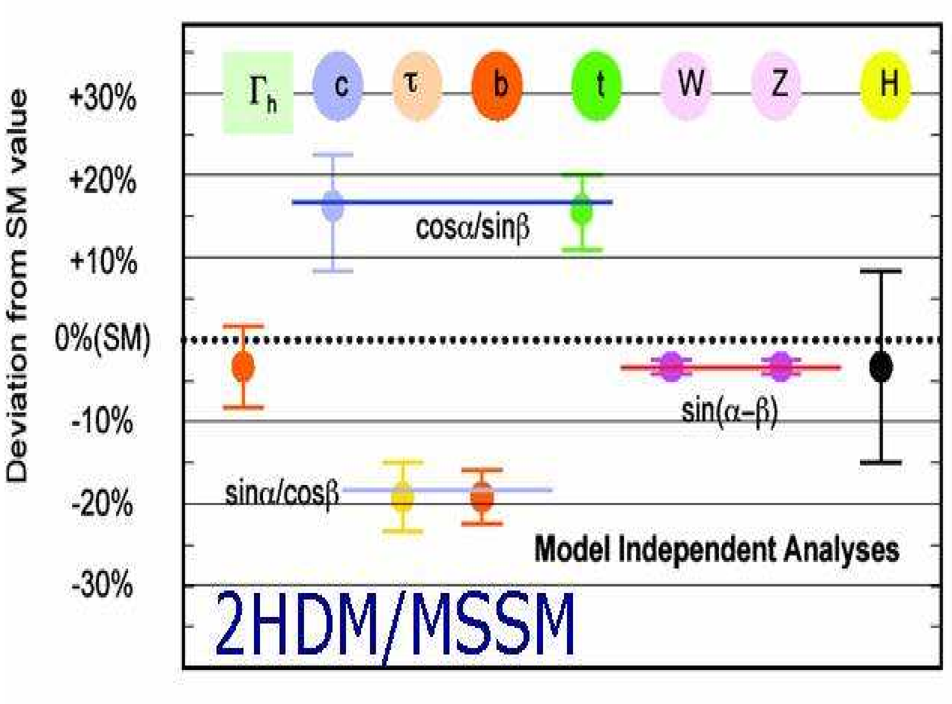
Comparison: LHC (with mild theory assumptions) vs. ILC (model-independent)

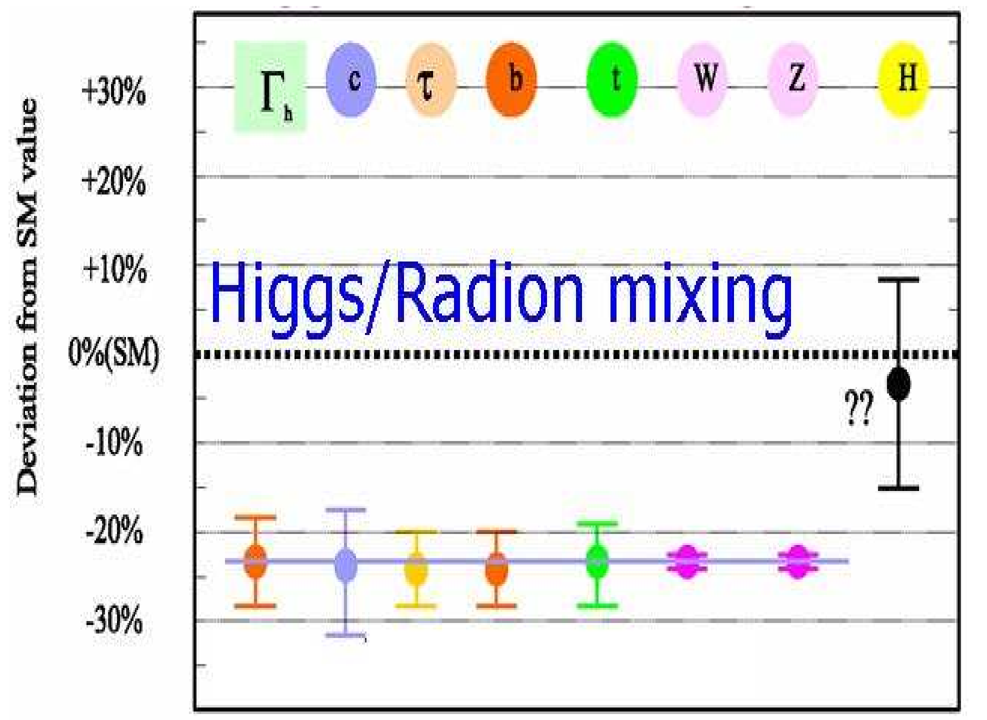
[*M. Dührssen, S. Heinemeyer, H. Logan, D. Rainwater, G. W., D. Zeppenfeld '04*]
[*K. Desch '06*]



Impact of ILC precision for the Higgs couplings

SM vs. BSM physics:

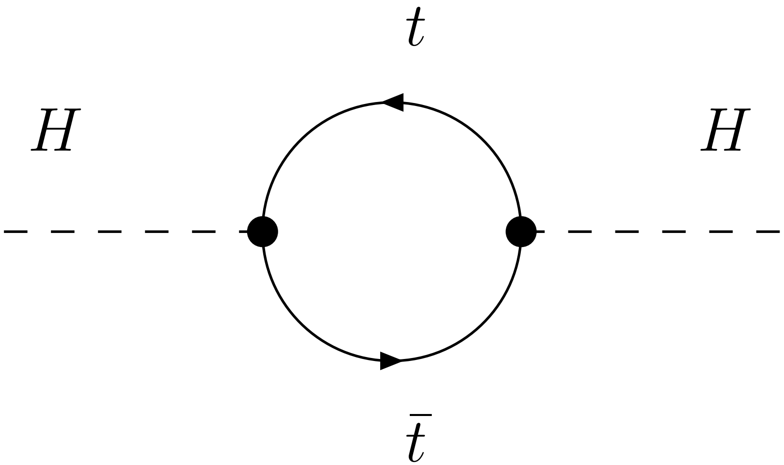




⇒ Precision measurement of Higgs couplings allows distinction between different models

Precision Higgs physics

Large coupling of Higgs to top quark



One-loop correction $\sim G_\mu m_t^4$

$\Rightarrow$ 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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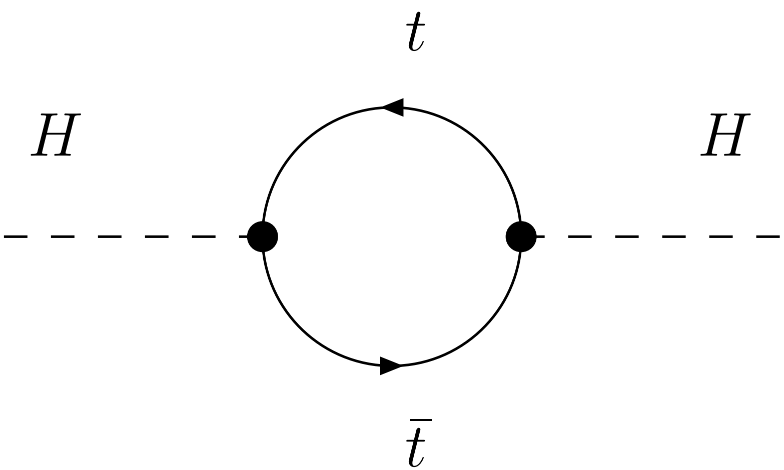

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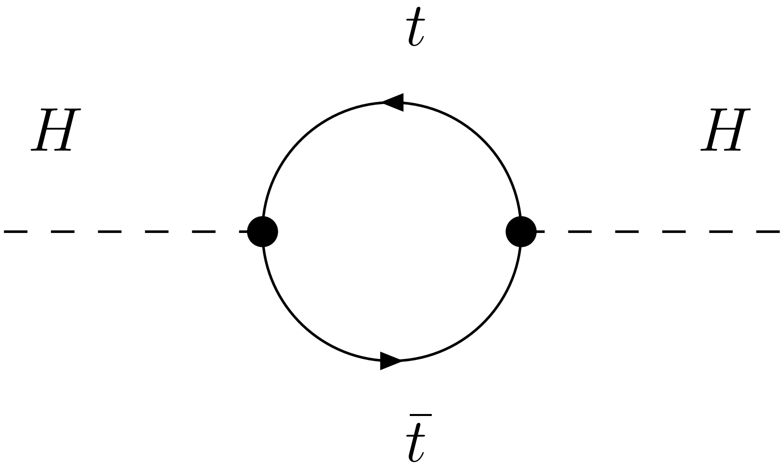

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$\Rightarrow$ Precision Higgs physics needs precision top physics

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

The Higgs as a composite object

Renewed interest in composite Higgs models, mostly from extra dimensions

[*N. Arkani-Hamed, A. Cohen, H. Georgi '01*]

[*K. Agashe, R. Contino, A. Pomarol '05*], . . .

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Correspondence (AdS/CFT):

Warped gravity model $\Leftrightarrow$ Technicolour-like theory in 4D

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Signatures at LHC: new resonances, W', Z', t', KK excitations

Under pressure from electroweak precision tests

Effective field-theory description of a composite Higgs

Agreement with electroweak precision data can be improved if there is a strongly interacting light Higgs, e.g.

Little Higgs [*N. Arkani-Hamed, A. Cohen, E. Katz, A. Nelson '02*]

Holographic Higgs [*R. Contino, Y. Nomura, A. Pomarol '03*], [*K. Agashe, R. Contino, A. Pomarol '05*], . . .

Effective Lagrangian formalism for model-independent analysis of effects of a Strongly-Interacting Light Higgs (SILH) [*G. Giudice, C. Grojean, A. Pomarol, R. Ratazzi '07*]

$\Rightarrow$ Specific pattern of modified Higgs couplings

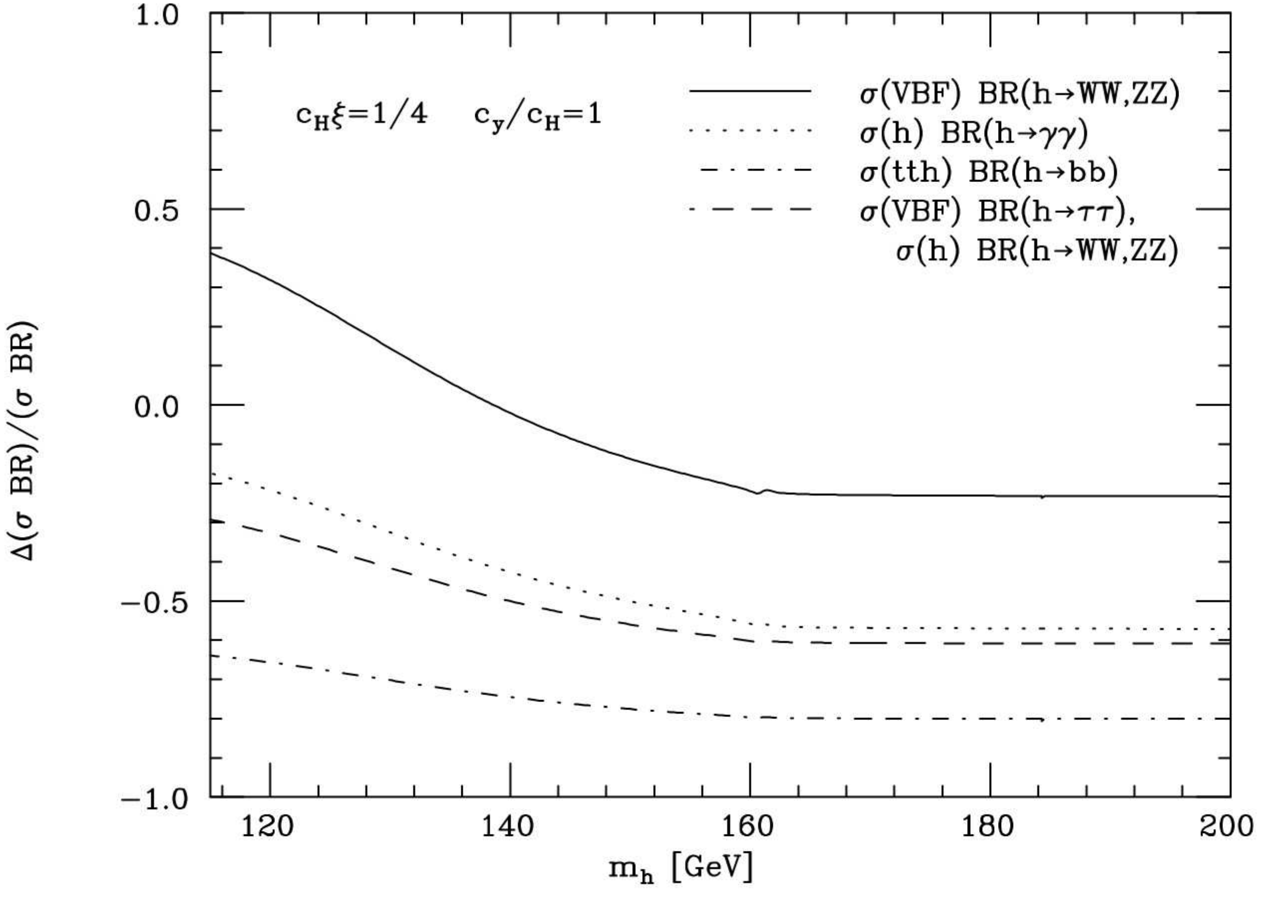
Strong WW scattering at high energies despite light Higgs

$\Rightarrow$ Need precision measurement of Higgs couplings

$+$ test of longitudinal gauge-boson scattering

Strongly-Interacting Light Higgs: deviation of $\sigma \times \mathrm{BR}$ *from the case of a SM Higgs*

[*G. Giudice, C. Grojean, A. Pomarol, R. Ratazzi '07*]



Sensitivity at LHC: 20–40%, ILC: 1%

$\Rightarrow$ ILC can test scales up to ~ 30 TeV

A Higgs-like state does not need to be a Higgs boson

Example: Higgs–radion mixing

Models with 3-branes in extra dimensions predict radion ϕ, can mix with the Higgs

$\Rightarrow$ Higgs properties modified

$\Rightarrow$ Higgs can be difficult to detect at the LHC
[*M. Battaglia, S. De Curtis, A. De Roeck, D. Dominici, J. Gunion '03*]

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$\Rightarrow$ precision measurements at ILC crucial to disentangle the nature of the observed state

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LHC: large sensitivity to production of KK excitations

Electroweak symmetry breaking without Higgs

If no light Higgs boson exists

$\Rightarrow$ dynamics of electroweak symmetry breaking can be probed in quasi-elastic scattering processes of W and Z at high energies

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ILC: detailed measurements of cross sections and angular distributions

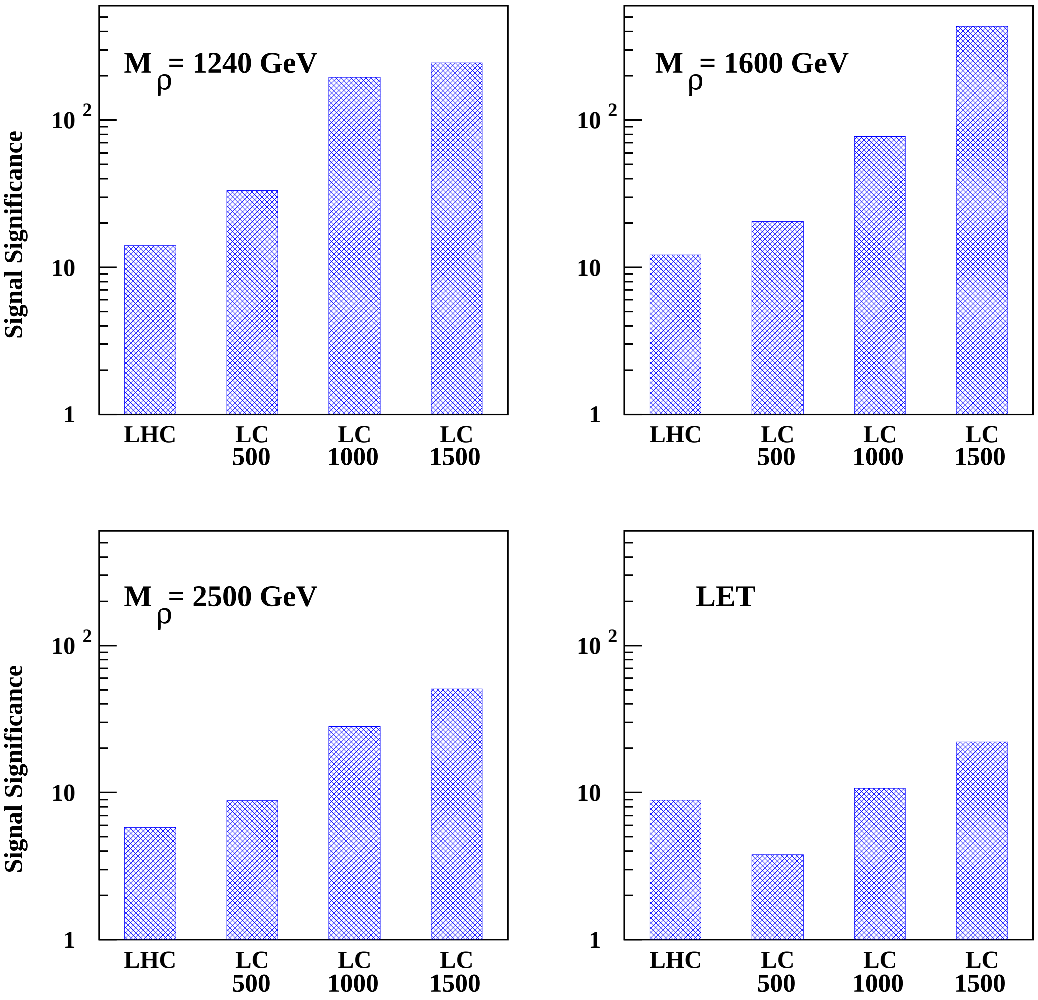
⇒ combination of LHC results with ILC data on cross-section rise essential for disentangling new states

Strong electroweak symmetry breaking

Sensitivity of LHC and ILC measurements to signals of strong electroweak symmetry breaking:

[*American LC WG '01*]

Signal significance in σ for various masses M_ρ of vector resonance in $W_L W_L$ scattering:



$\Rightarrow$ Strong electroweak symmetry breaking scenarios can be probed in detail at LHC $\oplus$ ILC

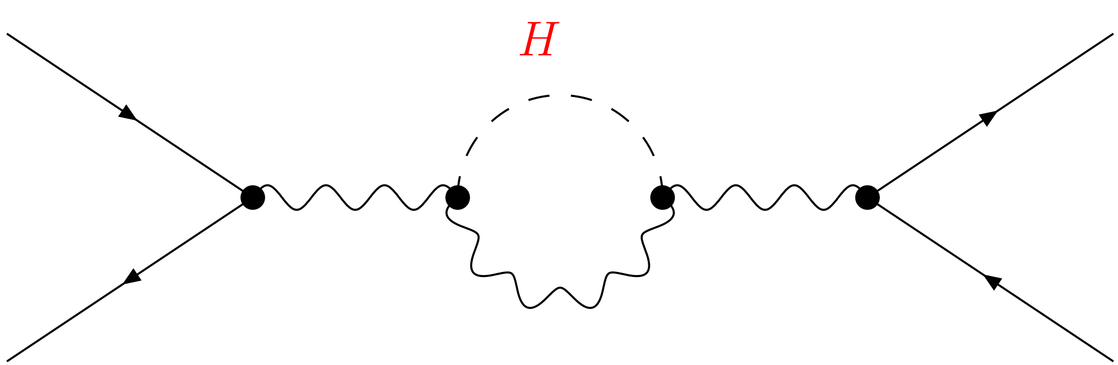
Top and electroweak precision physics: windows to the structure of nature

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: $\sin^2\theta_{\mathrm{eff}}$, M_{W}, ..., $\sigma(e^+e^- \to f\bar{f})$, ...

$\sin^2\theta_{\mathrm{eff}}, M_{\mathrm{W}}, \ldots$: 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_{t} from underlying theory?

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

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

Precision top physics

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

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

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

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Impact of higher-order effects?
The pole mass is not “IR safe”

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ILC:

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

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

Top-quark physics at the ILC

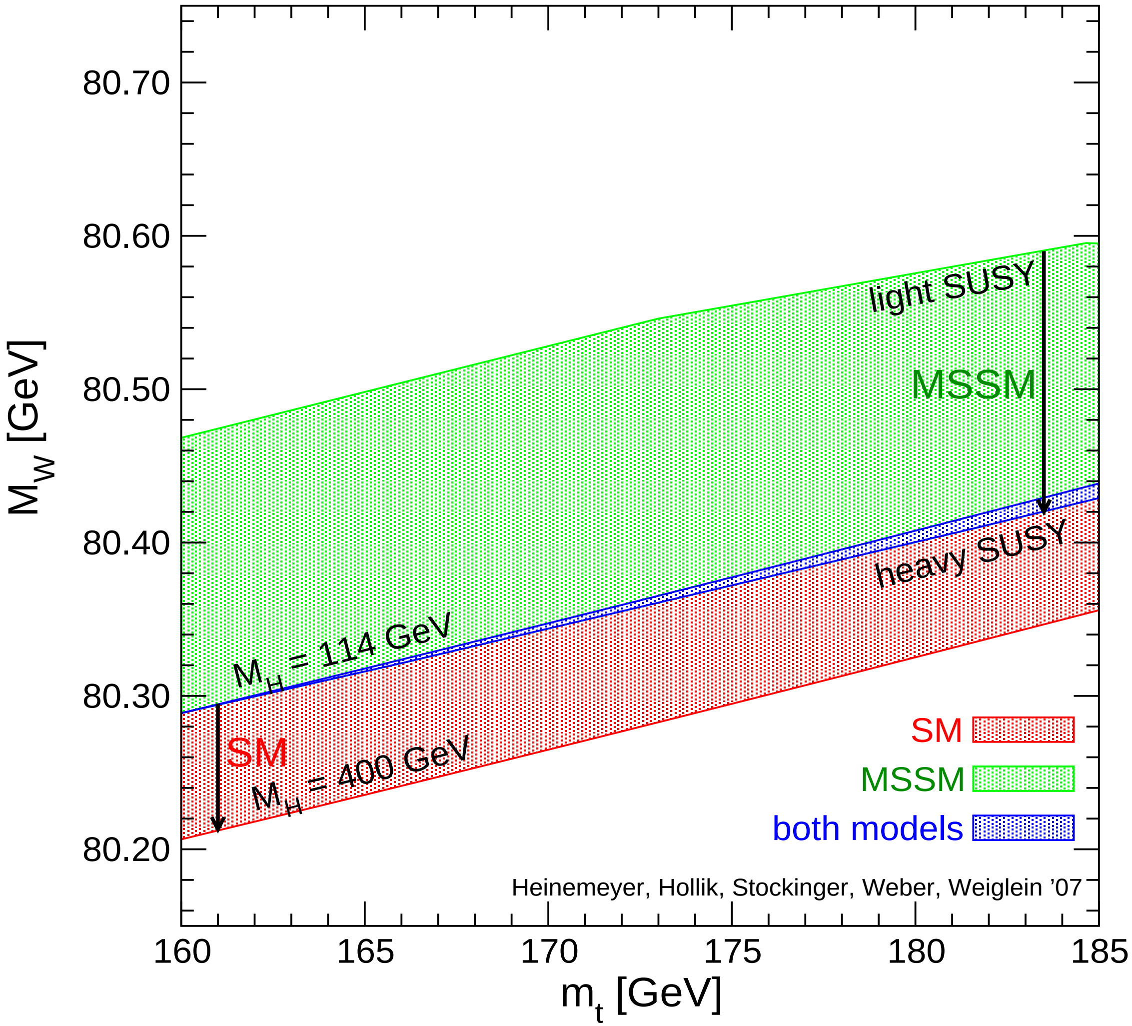
From running at $t\bar{t}$ threshold and in the continuum:

Precision measurements of

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

Prediction for M_{W} (parameter scan): SM vs. MSSM

Prediction for M_{W} in the SM and the MSSM:



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

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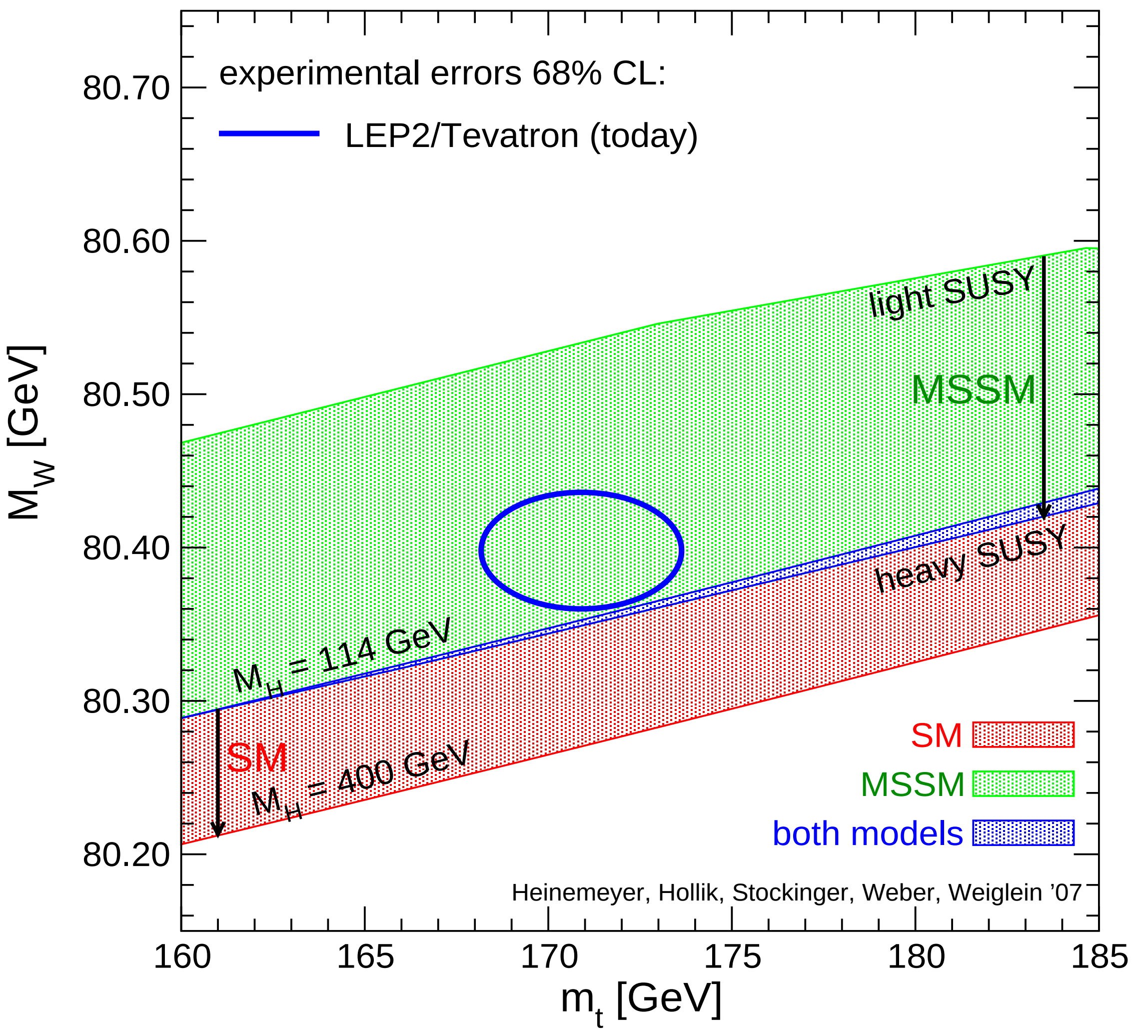

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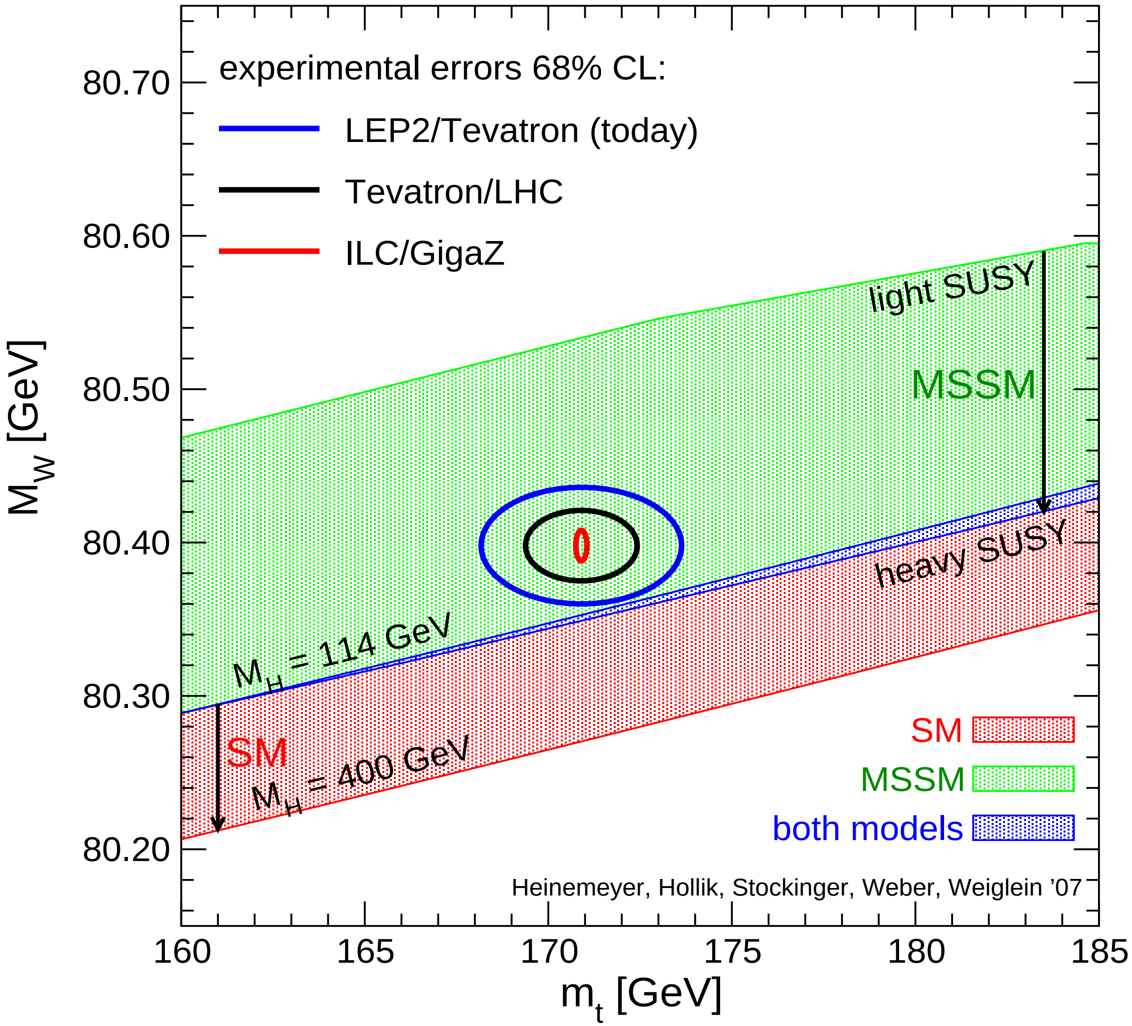

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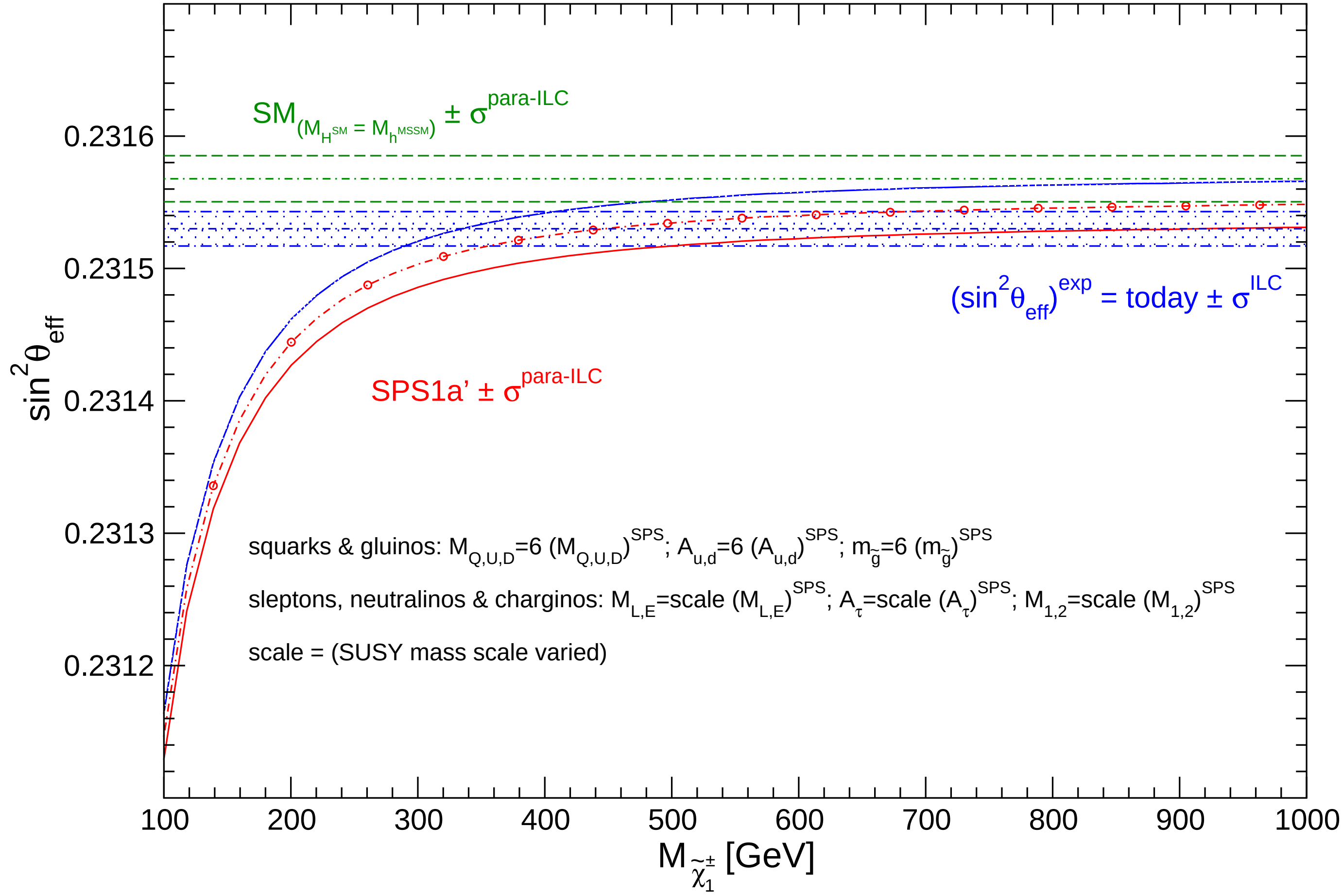
GigaZ: sensitivity to the scale of SUSY in a scenario where no SUSY particles are observed at the LHC

[*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)

Example of TeV-scale physics: Supersymmetry

LHC: good prospects for strongly interacting new particles

long decay chains $\Rightarrow$ complicated final states

e.g.: $\tilde{g} \to \bar{q}\tilde{q} \to \bar{q}q\tilde{\chi}_2^0 \to \bar{q}q\tilde{\tau}\tau \to \bar{q}q\tau\tau\tilde{\chi}_1^0$

Many states are produced at once, difficult to disentangle

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But ist it really SUSY? Which particles are actually produced?

Main background for determining SUSY properties at the LHC will be SUSY itself!

It quacks like SUSY, but . . .

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- does every SM particle really have a superpartner?
- do their spins differ by $1/2$?
- are their gauge quantum numbers the same?
- are their couplings identical?
- do the SUSY predictions for mass relations hold, . . . ?

Even when we are sure that it is actually SUSY, we will still want to know:

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- is the lightest SUSY particle really the neutralino, or the stau or the sneutrino, or the gravitino or . . . ?
- is it the MSSM, or the NMSSM, or the mNSSM, or the N^2MSSM, or . . . ?
- what are the experimental values of the 105 (or more) SUSY parameters?
- does SUSY give the right amount of dark matter?
- what is the mechanism of SUSY breaking?

We will ask similar questions for other kinds of new physics

Particle spins and $\mathcal{CP}$ properties

Determination of spin and $\mathcal{CP}$ prop. of observed new states will be crucial for establishing the SUSY nature of the signal

- Spin: establish fermion–boson symmetry, distinguish from universal extra dimensions (can have similar spectrum as in SUSY, but different spins), spin 2 excitations, . . .
- $\mathcal{CP}$ properties: pseudo-scalar Higgs, mixed states, . . .
- $\mathcal{CP}$ violation:

  Measure CPV effects in $\mathcal{CP}$-conserving observables?

  Access to $\mathcal{CP}$-violating observables: $\mathcal{CP}$ asymmetries, triple products, . . . ?

$\Rightarrow$ Very important information, but experimentally challenging at the LHC

SUSY parameter determination

Need a comprehensive and precise determination of as many SUSY parameters as possible in order to

- establish SUSY experimentally
- disentangle patterns of SUSY breaking

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How well can we identify particles in different decay chains?

Theory uncertainties?

How precisely do we need to know the SUSY parameters?

Dark matter relic density: measurement vs. prediction

Aim:

match the precision of the relic density measurement with the prediction based on collider data

$\Rightarrow$ sensitive test of SUSY dark matter hypothesis

Relic density measurement:

current (WMAP): $\approx 10\%$

future (Planck): $\approx 2\%$

Prediction of the dark matter density

We cannot assume a certain SUSY scenario (CMSSM), we have to test it

Need precision measurements of:

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- Higgs masses, Higgs couplings (“Higgs funnel region”)
- Prediction for “focus point region” depends extremely sensitively on m_t through RGE running: would need m_t with accuracy of $\mathcal{O}(20\ \mathrm{MeV})$
- ...

SUSY at the ILC

ILC: clean signatures, small backgrounds

$\Rightarrow$ precise determination of masses, spin, couplings, mixing angles, complex phases . . . ,

Good prospects for weakly interacting SUSY particles

Precision measurement of mass of lightest SUSY particle (factor 100 improvement)

$\Rightarrow$ Information from LHC and ILC will be complementary

LHC / ILC interplay $\Rightarrow$ enhanced physics gain, see

LHC / ILC Study Group Report

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

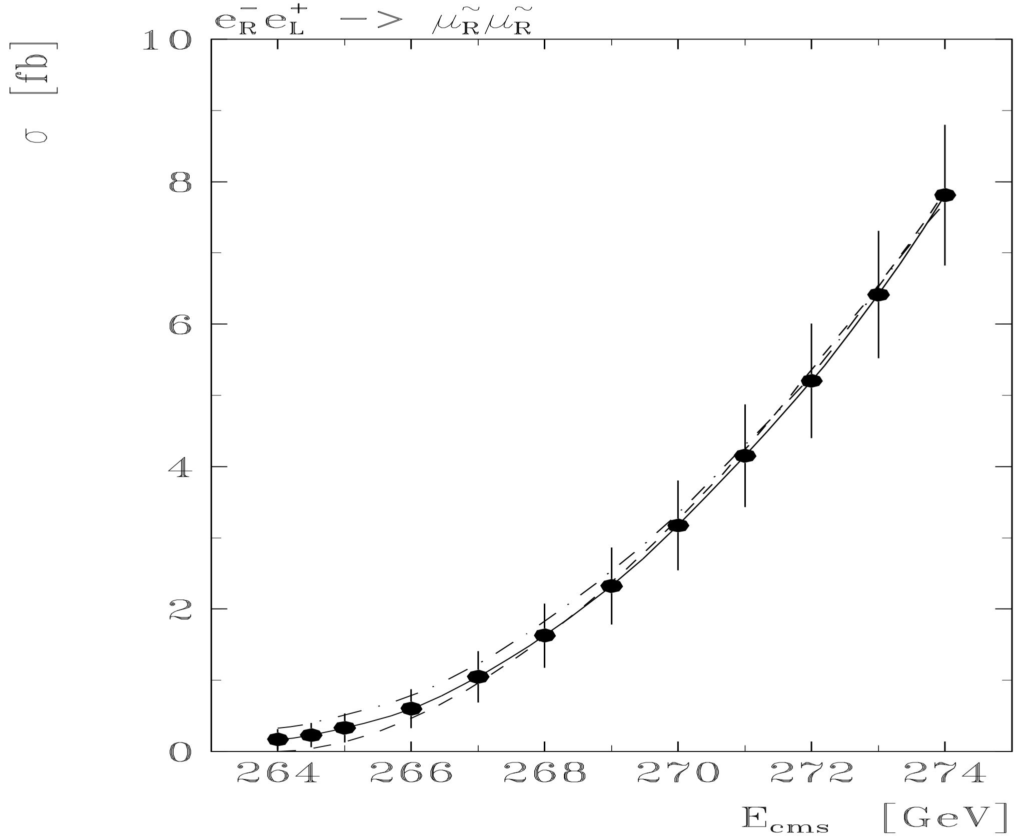
www.ippp.dur.ac.uk/$\sim$georg/lhcilc

Production of SUSY particles at the ILC

Tunable energy $\Rightarrow$ can run directly at threshold

Example: Determination of mass and spin of SUSY particle $\tilde{\mu}_R$ from production at threshold:

[*TESLA TDR '01*]

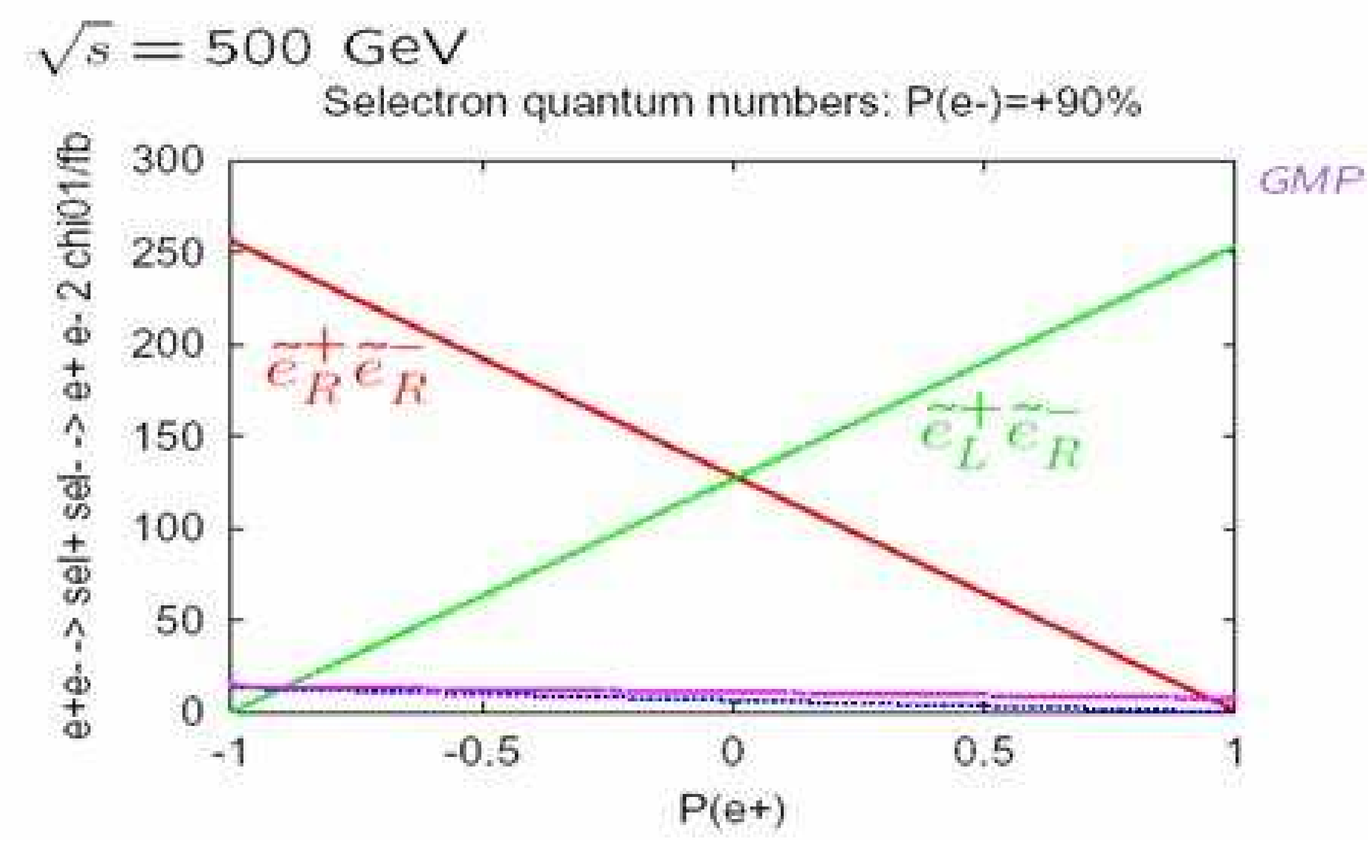


$$\Rightarrow \quad \frac{\Delta m_{\tilde{\mu}_R}}{m_{\tilde{\mu}_R}} < 1 \times 10^{-3}$$

$\Rightarrow$ test of $J = 0$ hypothesis

Determination of chiral quantum numbers

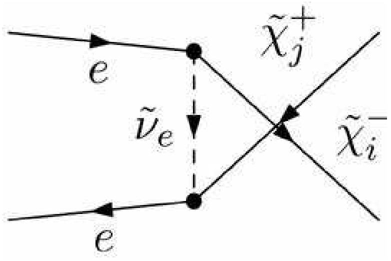
[*G. Moortgat-Pick '05*]



⇒ Experimental proof of SUSY relations
information on SUSY breaking patterns

Prediction of heavier states from measurement of light SUSY particles at ILC(500)

Example: $e^+e^- \to \tilde{\chi}_1^+\tilde{\chi}_1^-$



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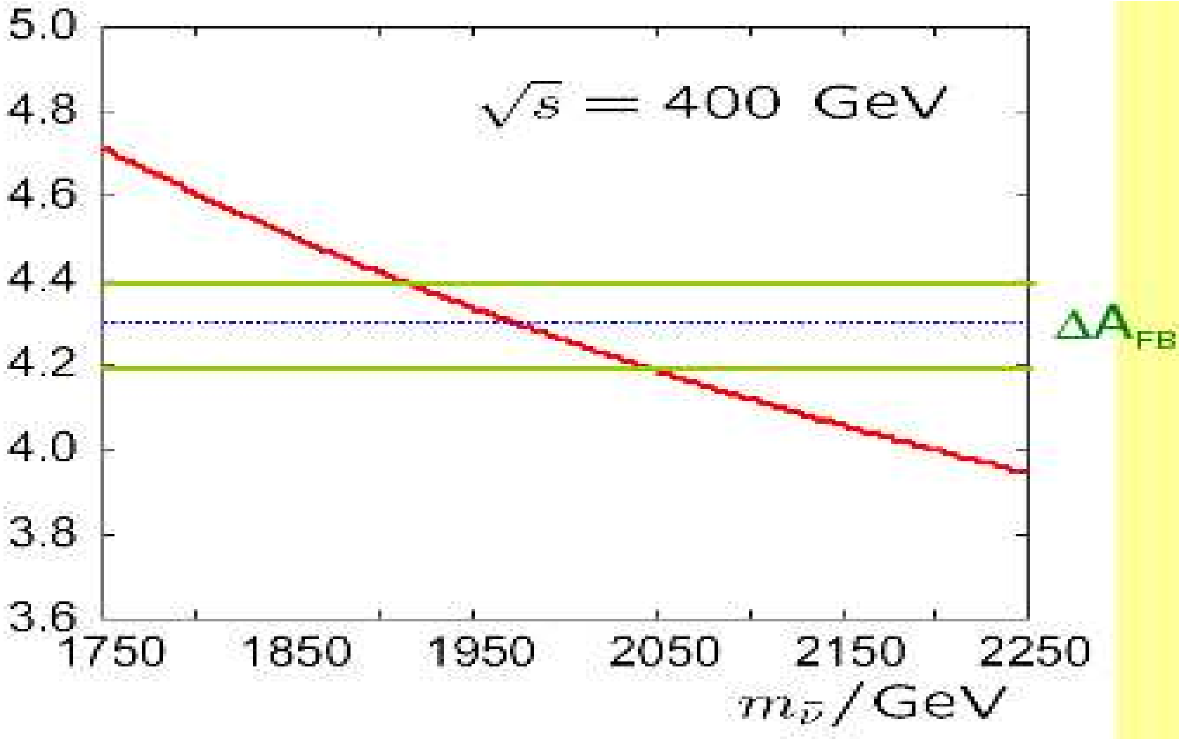
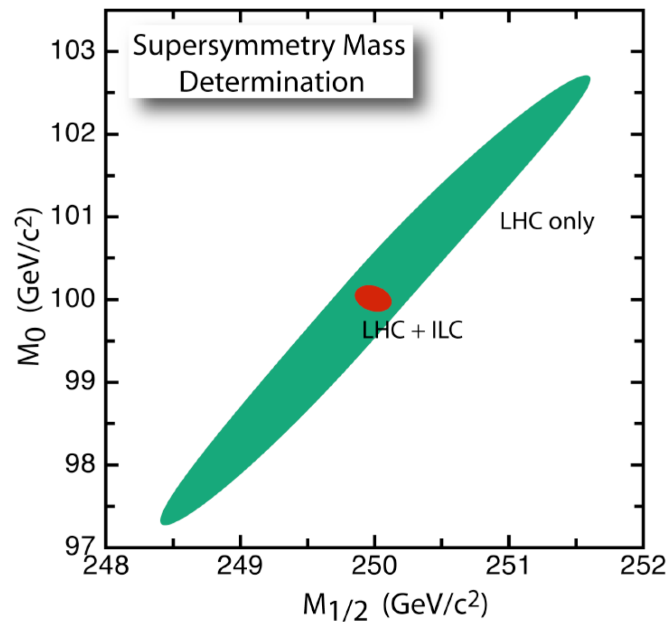


⇒ Indirect determination of sneutrino mass distinction between models: focus point vs. split SUSY

Determination of SUSY parameters at LHC $\oplus$ ILC

Constrained MSSM:

4 parameters + $\mathrm{sgn}(\mu)$



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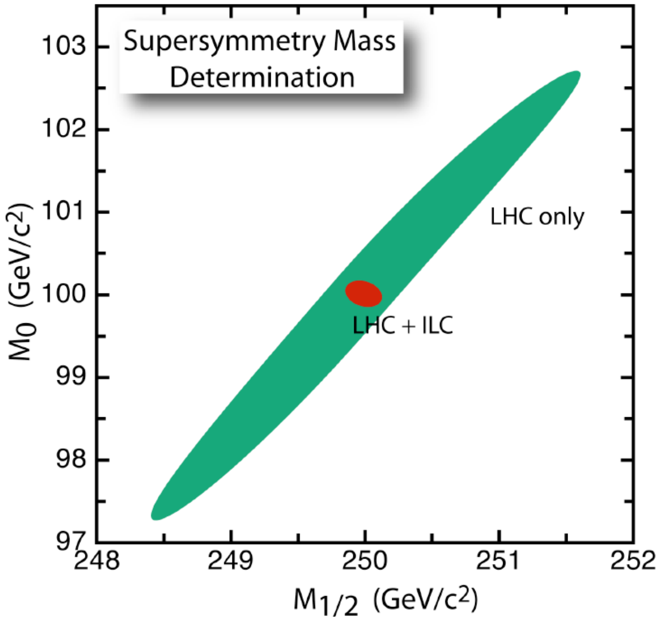

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Unconstrained MSSM:

most of the Lagrangian parameters can hardly be constrained by LHC data alone

LHC ⊕ ILC needed for precise det. of SUSY parameters

Conclusions

- The LHC will open the new territory of TeV-scale physics, where we expect to observe manifestations of the mechanism(s) responsible for EWSB and for stabilising the hierarchy between $M_{\rm weak}$ and $M_{\rm Planck}$

  $\Rightarrow$ Looking forward to exciting results from the LHC

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It is your future — take an active role in it!