Lectures on SM and SUSY Phenomenology

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- Introduction: on the way to the TeV scale
- The Standard Model and Supersymmetry (SUSY)
- Electroweak precision phyics
- Higgs physics
- SUSY phenomenology
- Conclusions and outlook

Not covered in these lectures

- QCD, pdfs, . . .
  $\longrightarrow$ *see lectures by M. Diehl, M. Knecht*

- Neutrino physics
  $\longrightarrow$ *see lectures by P. Vogel*

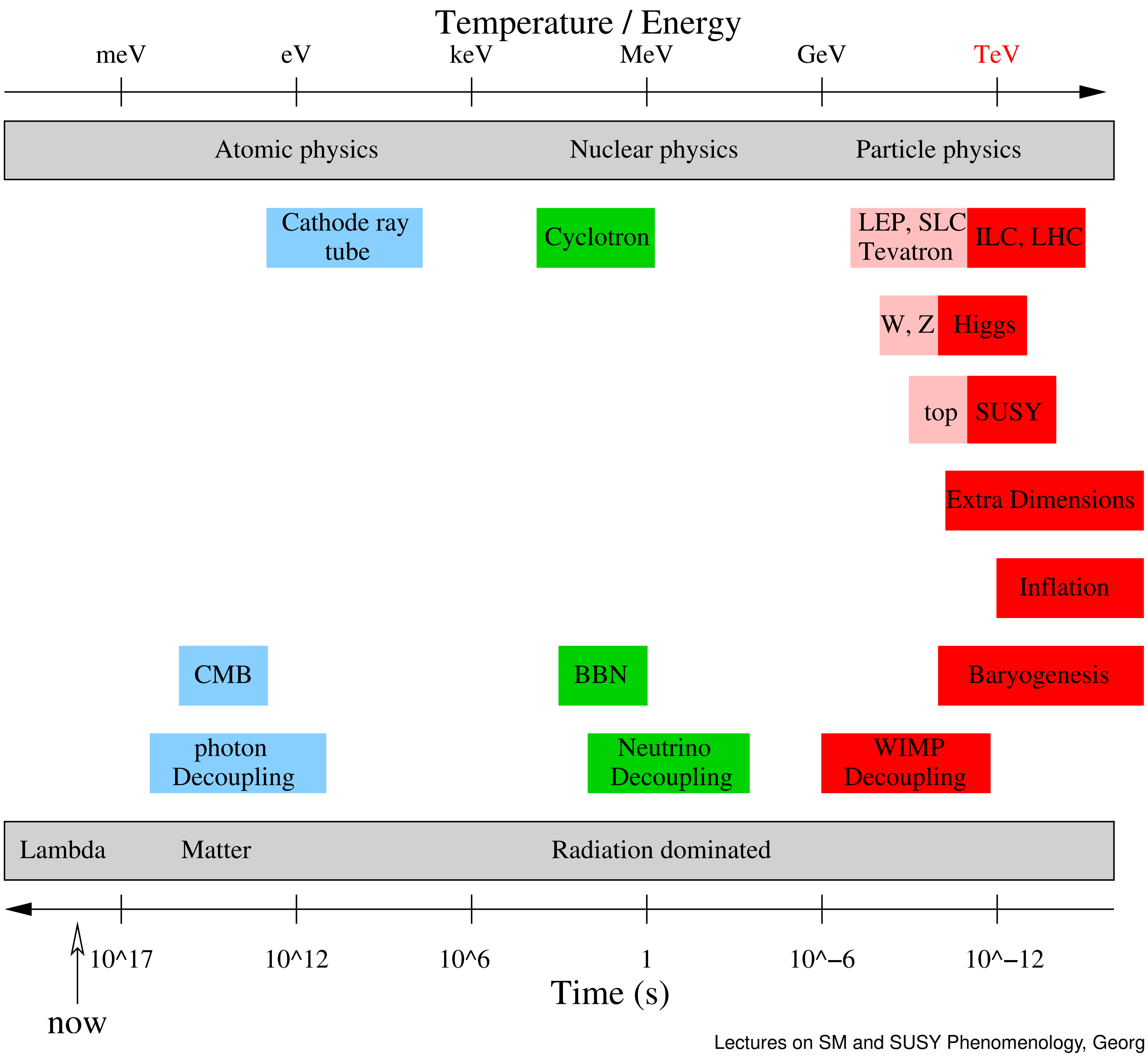
- Construction of SUSY field theories
  $\longrightarrow$ *see lectures by S. Bertolini*

- . . .

For more details on EWSB
$\longrightarrow$ *see lectures by W. Kilian*

Introduction: on the way to the TeV scale

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



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

- 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?
- . . .

What is the mechanism of electroweak symmetry breaking?

- Standard Model (SM), SUSY, . . . :
  Higgs mechanism, elementary scalar particle(s)
- Strong electroweak symmetry breaking (technicolour, . . .):
  new strong interaction, non-perturbative effects, resonances, . . .
- 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

$M_{\mathrm{H}} \lesssim 1 \ \mathrm{TeV}$ ("unitarity bound", see below)

The Standard Model cannot be the ultimate theory

- The Standard Model does not include gravity

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

- "Hierarchy problem": $M_{\mathrm{Planck}}/M_{\mathrm{weak}} \approx 10^{17}$

  How can two so different scales coexist in nature?

  Via quantum effects: physics at M_{weak} is affected by physics at M_{Planck}

  $\Rightarrow$ Instability of M_{weak}

  $\Rightarrow$ Would expect that all physics is driven up to the Planck scale

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

The hierarchy problem: quadratic divergences

SM: “effective theory”, can only be valid up to cutoff scale Λ

Higgs mass in the SM is a free parameter

Expect that in more fundamental theory the Higgs mass can be predicted

$\Rightarrow$ M_H in this theory is no longer a free parameter that can be set to the experimental value

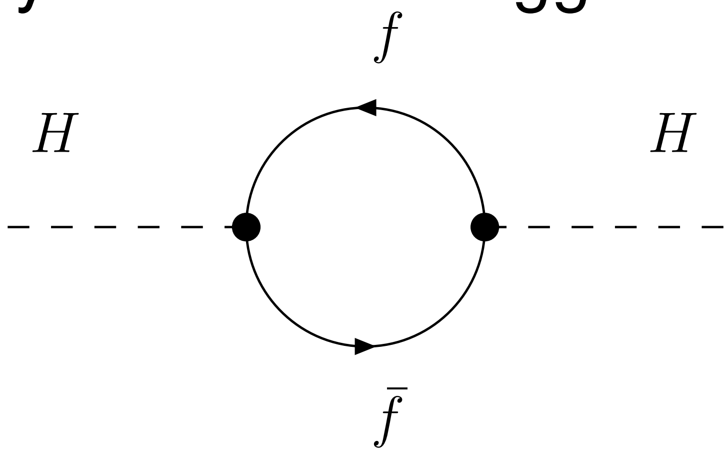
Physical value of M_H^2 is obtained as the sum of lowest-order contribution $+$ higher-order corrections

$$M_\mathrm{H}^2 = M_{\mathrm{H},0}^2 + \Delta M_{\mathrm{H},1}^2 + \Delta M_{\mathrm{H},2}^2 + \ldots$$

$\Rightarrow$ Calculation of corrections to M_H^2 in SM with cutoff Λ

Quadratic divergences

Contribution of heavy fermions to Higgs self-energy



$$\Sigma_f^H \sim -2\, N(f)\, \lambda_f^2 \int d^4k \left(\frac{1}{k^2 - m_f^2} + \frac{2m_f^2}{(k^2 - m_f^2)^2} \right)$$

for $\Lambda \to \infty$: $\Sigma_f^H \sim -2\, N(f)\, \lambda_f^2 \left(\underbrace{\int \frac{d^4k}{k^2}}_{\sim \Lambda^2} + 2m_{\mathrm{f}}^2 \underbrace{\int \frac{dk}{k}}_{\sim \ln \Lambda} \right)$

$\Rightarrow$ quadratically divergent!

The hierarchy problem: quadratic divergences

For $\Lambda = M_{\text{Planck}}$: $\Delta M_{\text{H}}^2 \sim M_{\text{Planck}}^2 \Rightarrow \Delta M_{\text{H}}^2 \approx 10^{30}\, M_{\text{H}}^2$
($M_{\text{H}} \lesssim 1$ TeV)

$\Rightarrow$ Hierarchy problem, extreme fine-tuning necessary between $M_{\text{H},0}^2$ and ΔM_{H}^2 to get small M_{H}

Example: Grand Unified Theory (GUT): $\Delta M_{\text{H}}^2 \approx \lambda \langle v_{\text{GUT}} \rangle^2$

Even if $\lambda = 0$ at tree level: non-zero coupling regenerated by radiative corrections: $\Delta M_{\text{H}}^2 \approx \mathcal{O}(\alpha/\pi) \langle v_{\text{GUT}} \rangle^2$
(cf. “Little Higgs” models)

Would need a symmetry to suppress many orders of perturbation theory

$\Rightarrow$ Expect new physics at the TeV scale

Hierarchy problem: how can the Planck scale be so much larger than the weak scale?

$\Rightarrow$ Expect new physics to stabilise the hierarchy

Supersymmetry:

Large corrections cancel out because of symmetry
fermions $\Leftrightarrow$ bosons

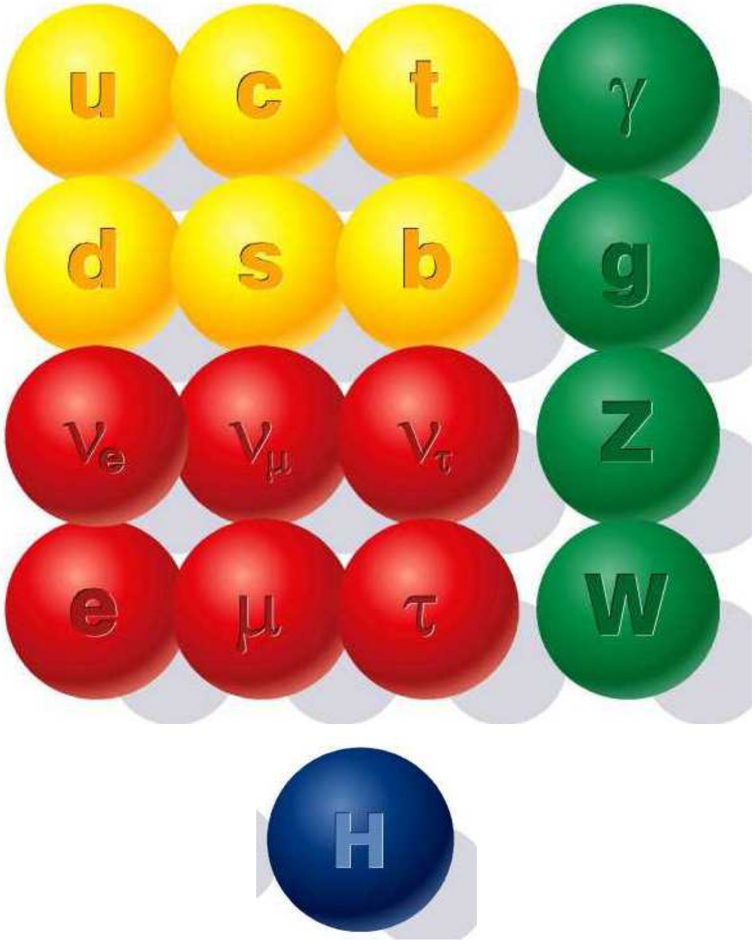
Extra dimensions of space:

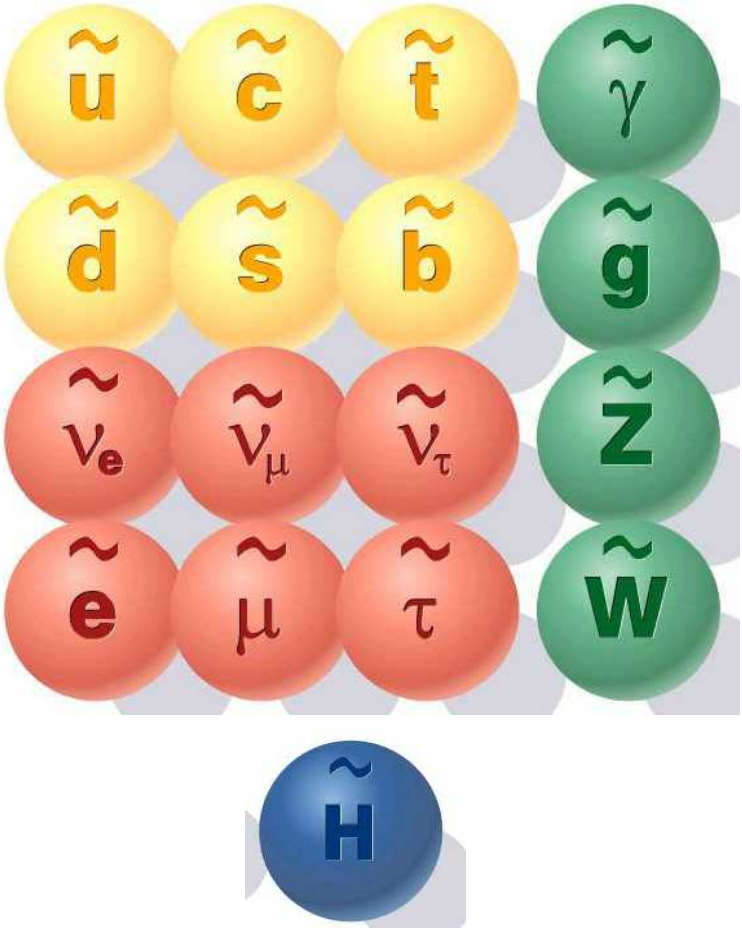
Fundamental Planck scale is $\sim \mathrm{TeV}$ (large extra dimensions),

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)

Superpartners for Standard Model particles:

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

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

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

$$\tilde{g} \quad \tilde{\chi}^{\pm}_{1,2} \quad \tilde{\chi}^{0}_{1,2,3,4} \qquad \text{Spin } \frac{1}{2}$$

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

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

Hierarchy problem $\Rightarrow$ expect observable effects at TeV scale

Supersymmetry (SUSY)

SUSY: unique possibility to connect space–time symmetry (Lorentz invariance) with internal symmetries (gauge invariance):

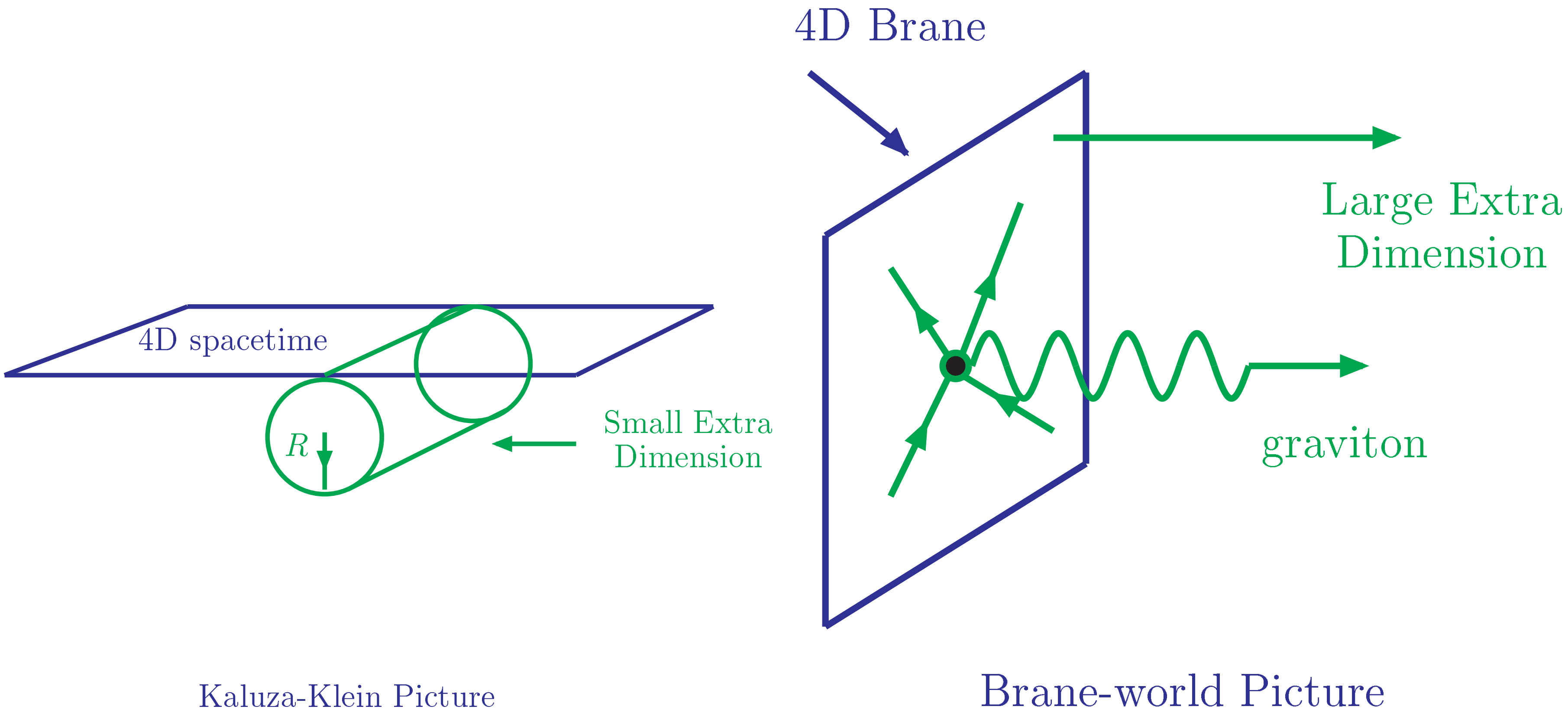
Unique extension of the Poincaré group of symmetries of $D = 4$ relativistic quantum field theories

Local SUSY includes gravity, called "supergravity"

Lightest superpartner (LSP) is stable if "R parity" is conserved
$\Rightarrow$ Candidate for cold dark matter in the Universe

Gauge coupling unification, $M_{\mathrm{GUT}} \sim 10^{16}$ GeV
neutrino masses: see-saw scale $\sim .01$–$.1\, M_{\mathrm{GUT}}$

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

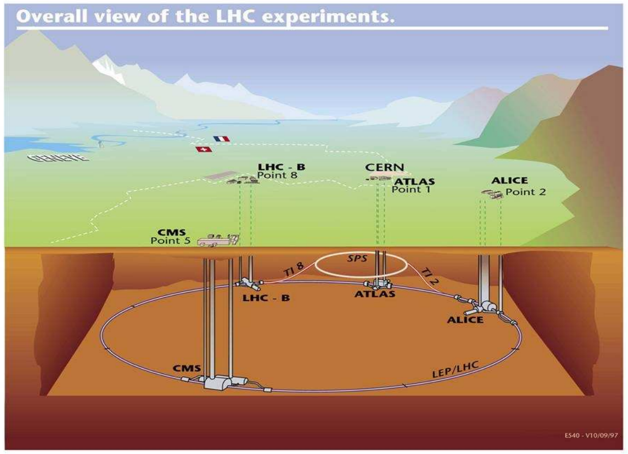
$\Rightarrow$ observable effects at the TeV scale

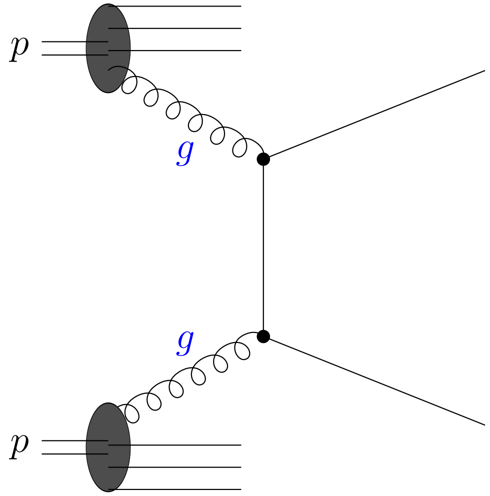
Exploring the TeV scale: the LHC

The Large Hadron Collider (LHC)

under construction at CERN (Geneva), scheduled to take first data next year

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





Complicated scattering process, difficult to interpret

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

Exploring the TeV scale: the ILC

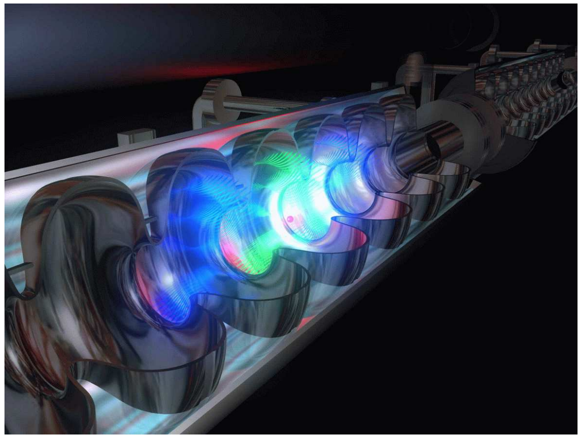
The International Linear Collider (ILC)

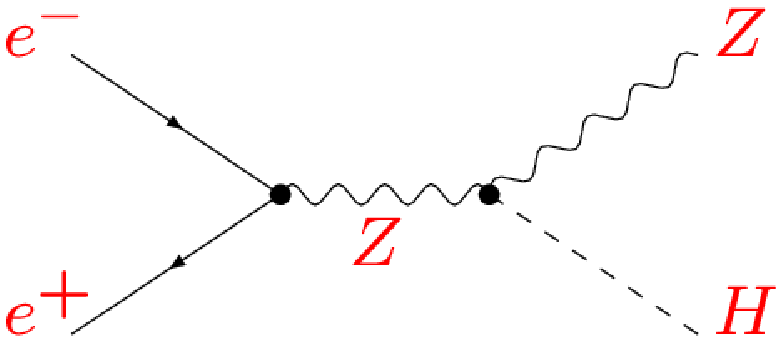
world-wide project, RDR ($+$ costing) issued earlier this year, Engineering Design Report in preparation

Electron–positron scattering at ≈0.5–1 TeV:

fundamental particles, point-like, electroweak interaction

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



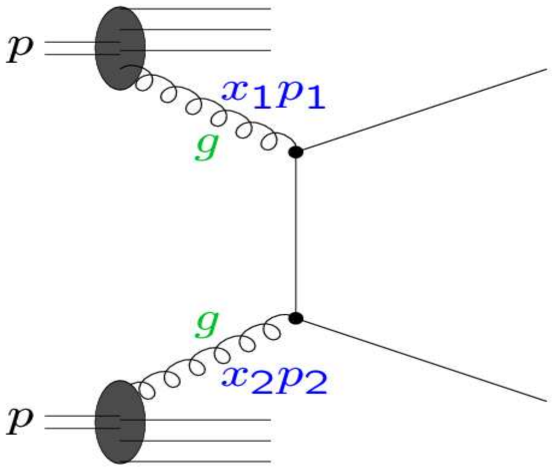


Results are easy to interpret, all events can be recorded

$\Rightarrow$ high-precision physics

Physics at the LHC and ILC in a nutshell

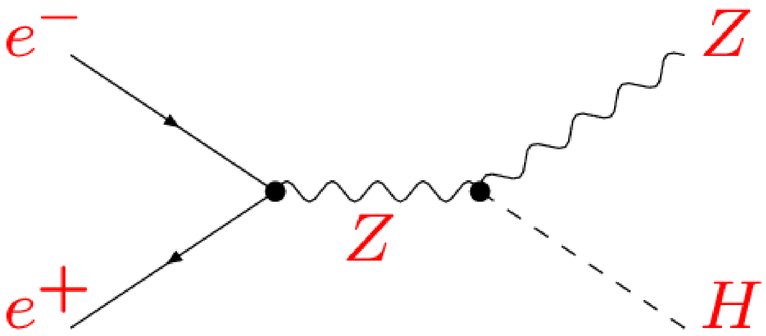
LHC: pp scattering at 14 TeV



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 $\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

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

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

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

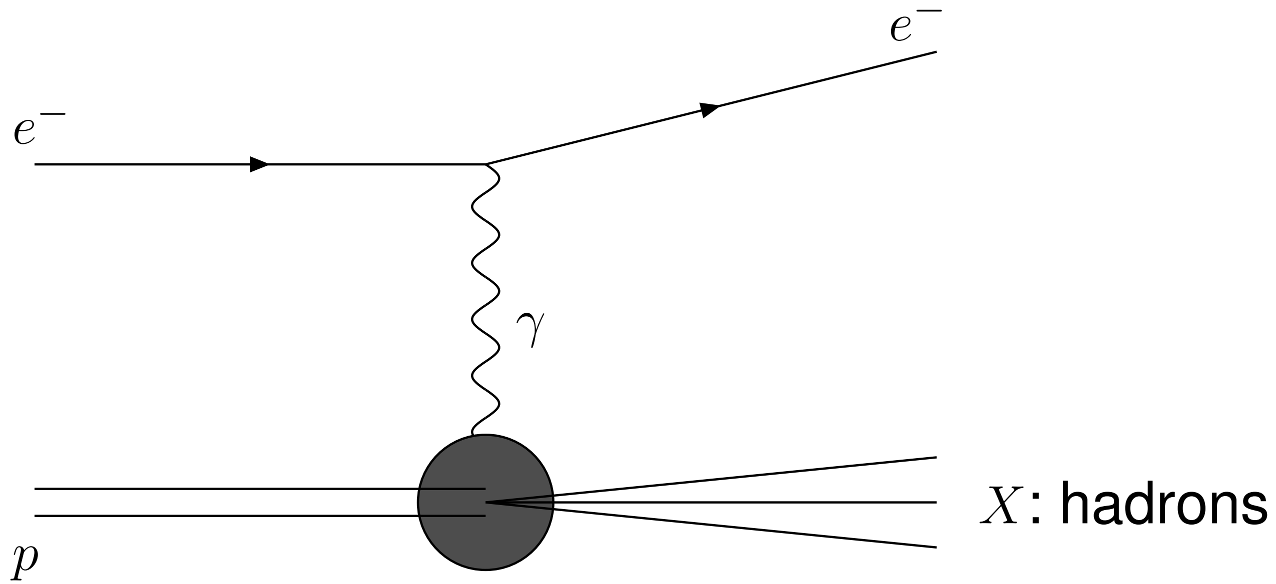
$\Rightarrow$ Sensitivity to indirect effects of TeV-scale physics

Hadronic collisions: HERA, Tevatron and the LHC

Electron–proton collider: HERA

e beam probes structure of the proton

$ep \to eX$: “deep inelastic scattering”



Electron–proton scattering

Total ep scattering cross section is the sum over all possible eq "partonic" sub-processes:

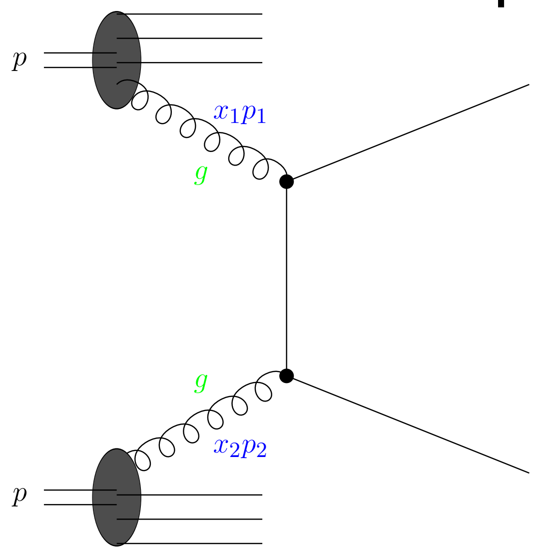
$$\sigma(ep) = \int_0^1 dx \sum_{q \text{ in proton}} \underbrace{q^p(x)}_{\text{parton density function}} \sigma(eq)$$

$q^h(x)\,dx$: probability of finding parton of type q inside hadron h carrying fraction of hadron momentum between x and $x + dx$

partons: quarks (valence and sea), anti-quarks, gluons

Proton – (anti-)proton scattering: Tevatron and the LHC

pp scattering contains "hard" collision process of partons q, $\bar{q}$, g, e.g.:



$$\text{LHC: } \sigma(pp) = \int_0^1 \int_0^1 dx_1 dx_2 \sum_{q_i, q_j} q_i^p(x_1)\, q_j^p(x_2)\, \sigma(q_i q_j)$$

Available $(\text{energy})^2$ for partonic sub-process: $\hat{s} = x_1 x_2 s$

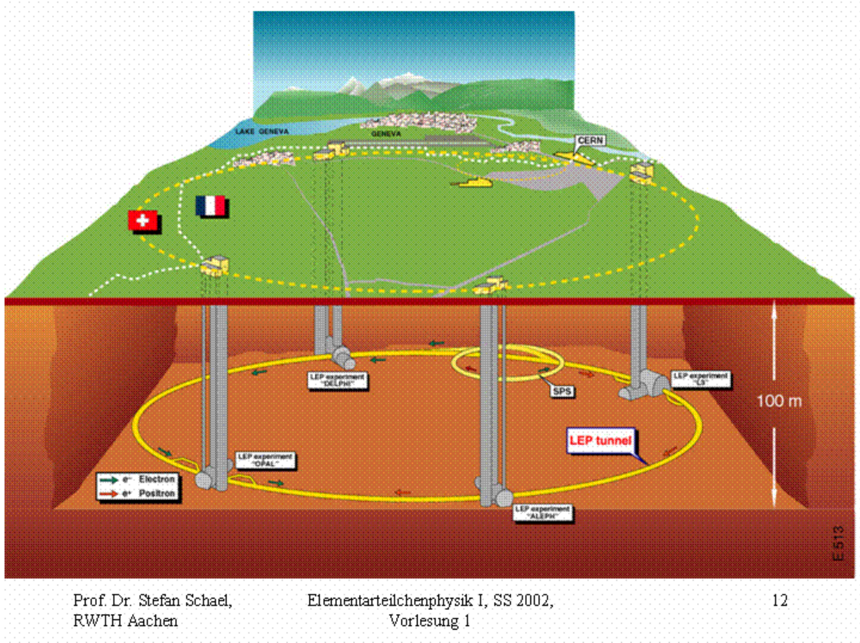
LHC: $\sqrt{s} = 14$ TeV; $\sqrt{\hat{s}}$ up to several TeV

most of available energy lost in beam pipe as proton remnant

Circular and linear colliders

LEP (≤ 2000): e^+e^- collider, $E_{\rm CM} \lesssim 206$ 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 $(m_\mathrm{e}/m_\mathrm{p})^4 \approx 10^{-13}$

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

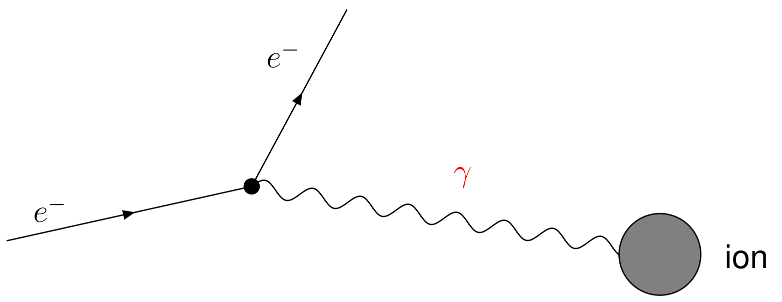
LHC ($\gtrsim 2008$): circular pp collider (in LEP tunnel), $E_\mathrm{CM} \approx 14~\mathrm{TeV}$

The Standard Model and Supersymmetry (SUSY)

Standard Model (SM): quantum field theory

Classical field theory (e.g. classical electrodynamics):

Quantum field theory (e.g. QED): field is quantised,
field quantum: photon



Interaction: exchange of field quanta

The SM: electroweak and strong interactions

Electroweak interaction:

Fermion fields: quarks: $\begin{pmatrix} u_L \\ d_L \end{pmatrix}, u_R, d_R,$ leptons: $\begin{pmatrix} \nu_L \\ e_L \end{pmatrix}, e_R$

3 generations: $u, d, \quad s, c \quad t, b$

$\nu_e, e \quad \nu_\mu, \mu \quad \nu_\tau, \tau$

gauge bosons: γ, Z, W^+, W^-

Gauge group: $\mathrm{SU(2)_I \times U(1)_Y \supset U(1)_{em}}$

Strong interaction: QCD

quarks: q_r, q_g, q_b, gauge bosons: $g_1, \ldots g_8$: gluons, $\mathrm{SU(3)_C}$

All postulated fermions and gauge bosons experimentally verified

Construction principle of the SM: gauge invariance

Example:

Quantum electrodynamics (QED)

free electron field: $\mathcal{L}_{\text{Dirac}} = i\overline{\Psi}\gamma_\mu\partial^\mu\Psi - m\overline{\Psi}\Psi$

invariant under global gauge transformation: $\Psi \to e^{i\theta}\Psi$

Requirement of local gauge invariance:

gauge field A_μ introduced, $\partial_\mu \to D_\mu = \partial_\mu - ieA_\mu$

gauge transformation: $\Psi \to e^{ie\lambda(x)}\Psi$, $A_\mu \to A_\mu + \partial_\mu\lambda(x)$

Construction of the QED Lagrangian

$\Rightarrow$ Lagrangian with interaction term:

$$\mathcal{L}_{\mathrm{QED}} = \underbrace{-\frac{1}{4} F_{\mu\nu} F^{\mu\nu}} + \underbrace{\overline{\Psi}(i\gamma_\mu \partial^\mu - m)\Psi} + \underbrace{\mathrm{e}\overline{\Psi}\gamma_\mu \Psi A^\mu}$$

free photon field free electron field interaction

invariant under local gauge transformations

mass term, $m^2 A^\mu A_\mu$: not gauge-invariant

$\Rightarrow$ A_μ: massless gauge field

Construction of a gauge-invariant Lagrangian for the SM

Problem: gauge fields Z, W^+, W^- are massive

explicit mass terms $\Leftrightarrow$ breaking of gauge invariance

$\Rightarrow$ Need additional concept:

Higgs mechanism, spontaneous electroweak symmetry breaking:

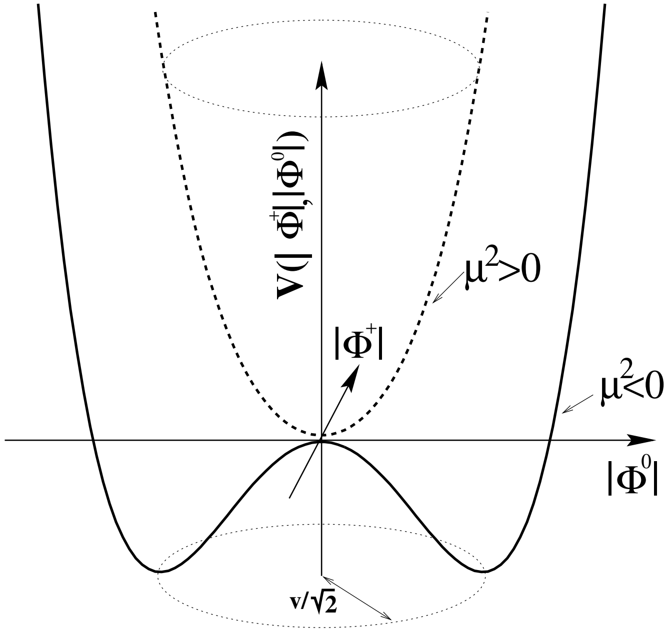
Scalar field postulated, gauge-invariant mass terms from coupling to Higgs field

Electroweak symmetry breaking in the SM

scalar SU(2) doublet: $\Phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix}$

Higgs potential: $V(\phi) = \mu^2 \left|\Phi^\dagger \Phi\right| + \lambda \left|\Phi^\dagger \Phi\right|^2, \quad \lambda > 0$

$\mu^2 < 0$: spontaneous symmetry breaking



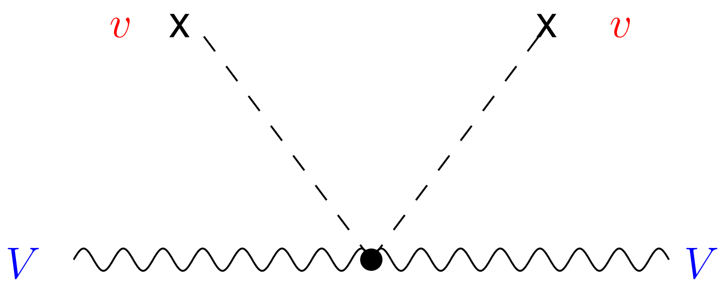
minimum of the potential at

$$\langle \Phi \rangle = \frac{1}{\sqrt{2}} \sqrt{\frac{-\mu^2}{\lambda}} \equiv \frac{v}{\sqrt{2}}$$

Gauge-invariant interaction with gauge fields

$$\mathcal{L}_{\text{Higgs}} = (D_\mu \Phi)^\dagger (D^\mu \Phi) - V(\Phi);$$ unitary gauge: $\Phi = \begin{pmatrix} 0 \\ v + H \end{pmatrix}$

$VV\Phi\Phi$ coupling:



$\Rightarrow$ VV mass terms: $\frac{1}{2} g_2^2 v^2 \equiv M_{\text{W}}^2, \quad \frac{1}{2}(g_1^2 + g_2^2) v^2 \equiv M_{\text{Z}}^2$

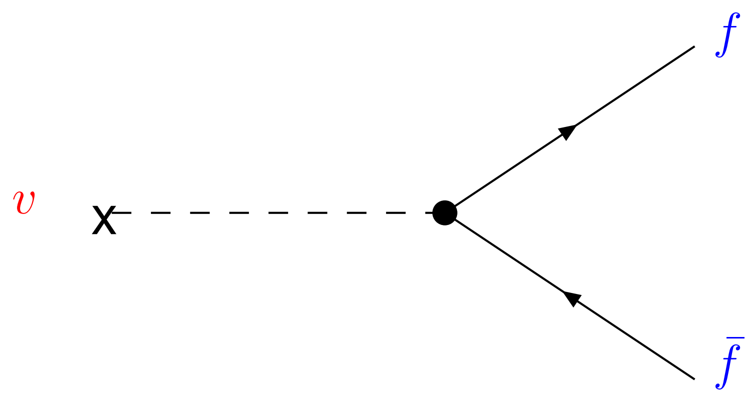
3 components of Higgs doublet

$\longrightarrow$ longitudinal components of $W^\pm$, Z

H: elementary scalar field, Higgs boson

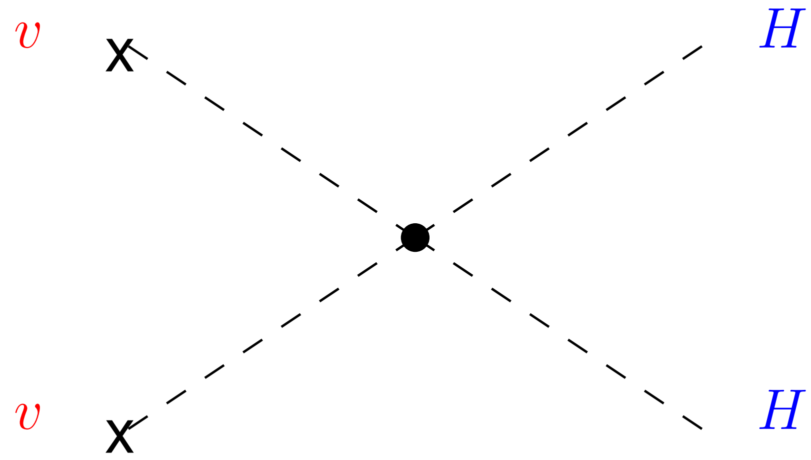
Fermion masses, Higgs mass

Fermion mass terms: Yukawa couplings



$m_f = v\, g_f$ free parameters

Mass of the Higgs boson: self-interaction



$M_{\rm H} = v\sqrt{\lambda}$ free parameter

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

Fermion masses in the SM

Fermion mass terms in SM Lagrangian:

$$\mathcal{L}_{\mathrm{SM}} = \underbrace{m_d \bar{Q}_L H d_R}_{\text{d-quark mass}} + \underbrace{m_u \bar{Q}_L \tilde{H} u_R}_{\text{u-quark mass}}, \quad Q_L = \begin{pmatrix} u \\ d \end{pmatrix}_L$$

$\Rightarrow$ Would at first sight expect that two doublets are needed

"Trick" used in the SM:

$$\tilde{H} = i\sigma_2 H^\dagger, \quad H \to \begin{pmatrix} 0 \\ v \end{pmatrix}, \quad \tilde{H} \to \begin{pmatrix} v \\ 0 \end{pmatrix}$$

$\Rightarrow$ One Higgs doublet sufficient to give mass to both up-type and down-type fermions

The Higgs boson of the Standard Model

The Higgs boson is the last missing ingredient of the SM

M_{H} is a free parameter; not directly predicted by the model

Exclusion limit on SM Higgs from experimental search at LEP:

$M_{\mathrm{H}} > 114.4$ GeV (95% C.L.), 1.7σ excess at $M_{\mathrm{H}} \approx 115$ GeV

The requirement of probability conservation leads to a "unitarity bound" of $M_{\mathrm{H}} \lesssim 1$ TeV

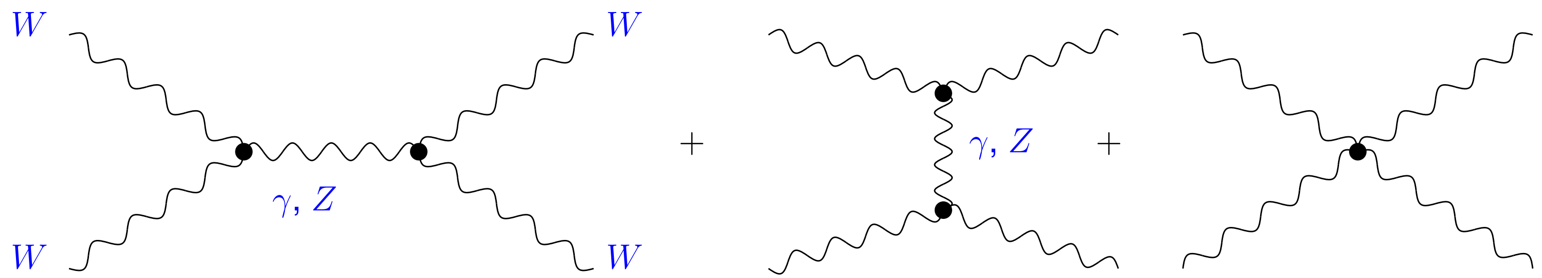
$\Rightarrow$ If no fundamental Higgs boson exists, there must be other new physics at the TeV scale to restore unitarity

Further constraints on the mass of the SM Higgs can be inferred from electroweak precision physics (see below)

Unitarity bound on the Higgs mass

E.g.: WW scattering, longitudinally polarised: $W_L W_L \to W_L W_L$

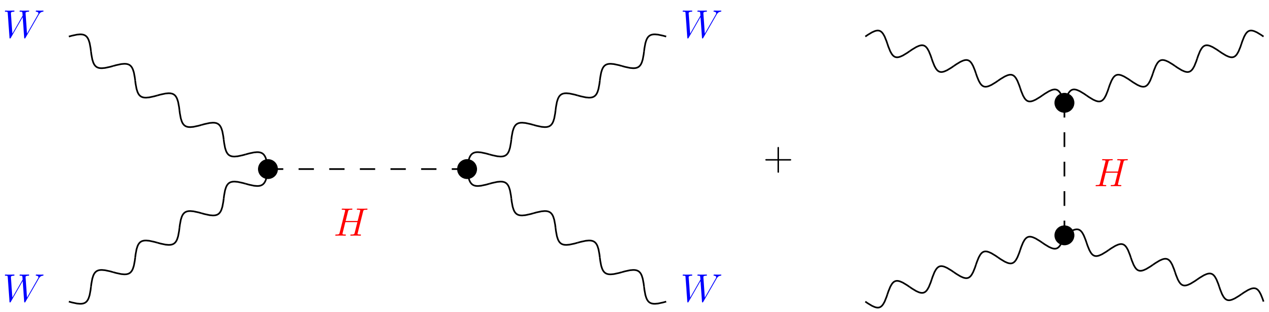
$\mathcal{M}_V =$



$$= -g^2 \frac{E^2}{M_\mathrm{W}^2} + \mathcal{O}(1) \text{ for } E \to \infty \;\Rightarrow \text{violation of probability conservation}$$

Compensated by Higgs contribution:

$\mathcal{M}_S =$



$$= g_{WWH}^2 \frac{E^2}{M_\mathrm{W}^4} + \mathcal{O}(1) \text{ for } E \to \infty, \; g_{WWH} = g\, M_\mathrm{W}$$

Unitarity bound on the Higgs mass

$\Rightarrow$ Upper limit on M_{H} (unitarity bound): $M_{\mathrm{H}} \lesssim 1$ TeV

Does not guarantee the existence of a fundamental Higgs,

but something has to happen when we probe the TeV scale

If no fundamental Higgs field exists:

strong interaction in gauge-boson sector for $E \gtrsim 1$ TeV

probability conservation via non-perturbative effects

Experimental tests: effects in W and Z scattering processes at high energy, resonances, . . .

Gauge-invariant Lagrangian of the SM

$$\mathcal{L}_{\mathrm{EW}}(\underbrace{g_2, g_1, v}_{M_\mathrm{W},\, M_\mathrm{Z},\, \alpha}, \underbrace{\lambda}_{M_\mathrm{H}}, \underbrace{g_f}_{m_f}) + \mathcal{L}_{\mathrm{QCD}}(\alpha_\mathrm{s})$$

Gauge invariance $\Rightarrow$ theory is renormalisable

[*G. 't Hooft '71*] [*G. 't Hooft, M. Veltman '72*] *Nobel prize '99*

$\Rightarrow$ theory can consistently been treated as a quantised field theory:

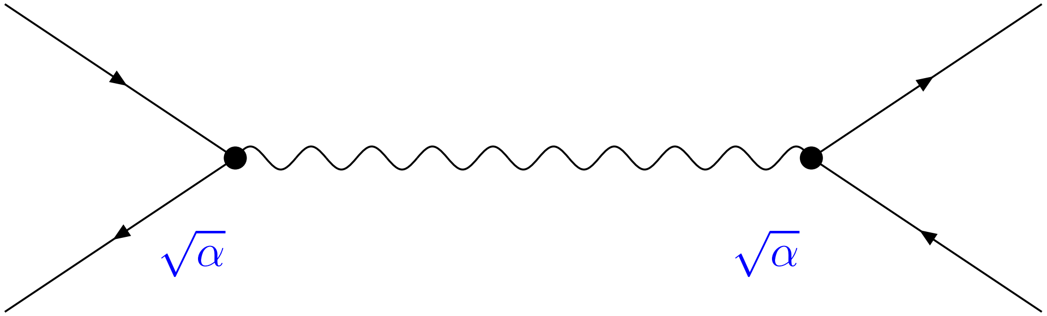
$\Rightarrow$ quantum effects can be evaluated

Perturbative evaluation of quantum field theories

Expansion in coupling constant: $\alpha \approx \frac{1}{137} \ll 1$

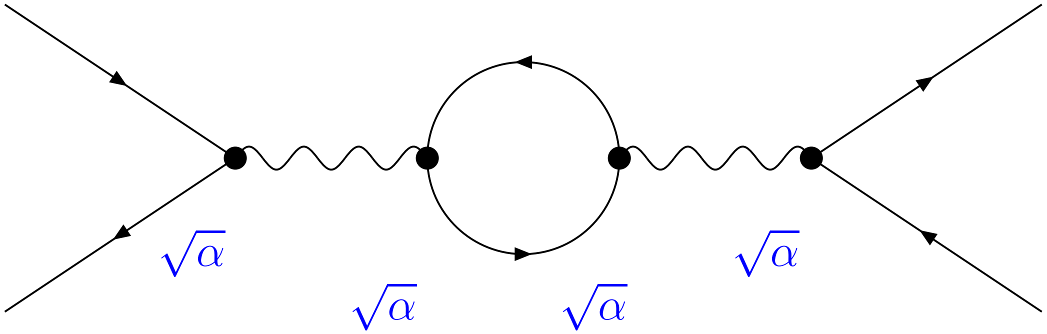
$\Leftrightarrow$ expansion about theory without interaction

lowest order,
classical limit



$\alpha \approx \frac{1}{137}$

quantum
corrections:
loop diagrams



$\mathcal{O}(\alpha)$ relative to lowest order

What can one learn from quantum corrections?

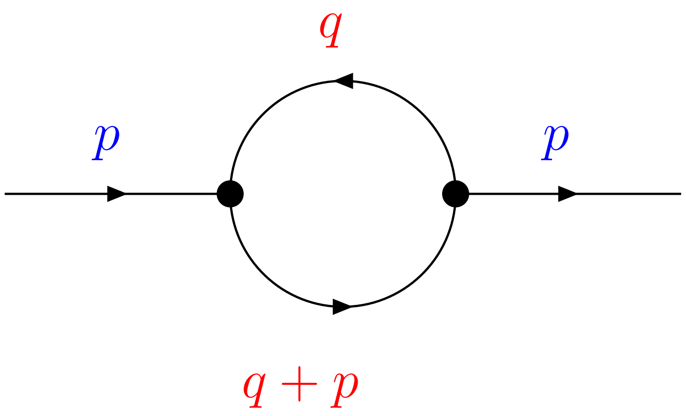
- Inclusion of quantum effects $\Leftrightarrow$ more accurate theoretical predictions

  Large loop corrections:

  - QCD corrections are often of $\mathcal{O}(100\%)$
  - EW enhancement factors: m_t^2, m_t^4, $\ldots$,
    large logarithms (involving two very different scales)
  - Per mille level corrections needed to match EW precision measurements

- Quantum effects provide sensitivity to the underlying structure of the theory

Quantum corrections: regularisation and renormalisation



$$\sim \int d^4q \frac{1}{(q^2 - m_1^2 + i\varepsilon)\left[(q+k)^2 - m_2^2 + i\varepsilon\right]}$$

$$q \to \infty: \quad \sim \int_0^\infty \frac{q^3 dq}{q^4} = \int_0^\infty \frac{dq}{q} \quad \to \infty$$

$\Rightarrow$ integral diverges for large q!

$\Rightarrow$ theory in this form not physically meaningful

$\Rightarrow$ further concept needed: renormalisation

Renormalisable theories: infinities can consistently be absorbed into parameters of theory

Two step procedure: regularisation

Regularisation:

theory modified such that expressions become mathematically meaningful

$\Rightarrow$ "regulator" introduced, removed at the end

e.g. cut-off in loop integral

$$\int_0^\infty d^4q \quad \to \int_0^\Lambda d^4q; \quad \Lambda \to \infty \text{ at the end}$$

technically more convenient: dimensional regularisation

$$\int d^4q \quad \to \int d^Dq, \quad D = 4 - \varepsilon; \quad D \to 4 \text{ at the end}$$

Two step procedure: renormalisation

Renormalisation:

original “bare” parameters replaced by renormalised parameters $+$ counterterms

reparametrization: $$\underbrace{g_0}_{\text{bare parameter}} = \underbrace{g}_{\text{renormalised parameter}} + \underbrace{\delta g}_{\text{counterterm}}$$

Renormalisable theory:

divergences compensated by counterterms

Two aspects of renormalisation:

- Absorption of divergences
- Determination of physical meaning of parameters order by order in perturbation theory

Why do the parameters (and fields) have to be renormalised?

- The SM Lagrangian contains free parameters that are not predicted by the theory:

  α, M_{W}, M_{Z}, M_{H} + fermion masses + four parameters of the quark-mixing matrix (+ four parameters of the lepton-mixing matrix if right-handed neutrinos are included)

- The bare parameters appearing in the Lagrangian have no physical meaning

- One needs n physical observables (masses, cross sections, . . .) to fix n free parameters of the Lagrangian (further observables $\Leftrightarrow$ test of the theory)

Why do the parameters (and fields) have to be renormalised?

- Only relations between observables are physically meaningful, not relations between observables and bare parameters

- Relations between physical observables include loop effects to all orders; one cannot "switch off" the interactions in nature

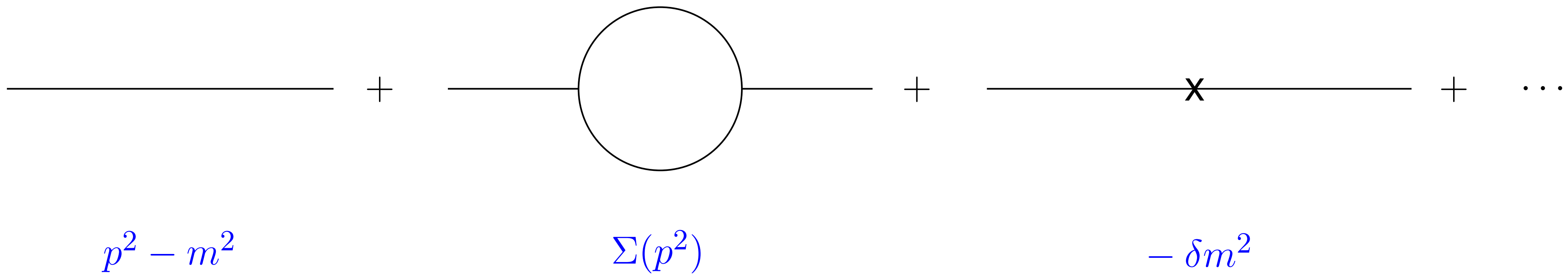
$\Rightarrow$ Need to define the meaning of the parameters in the Lagrangian in every loop order

Example: mass renormalisation

Renormalisation of the mass parameter: $m_0^2 = m^2 + \delta m^2$

Physical mass: pole of propagator

inverse propagator up to 1-loop order:



Pole of the propagator: $p^2 - m^2 + \Sigma(p^2) - \delta m^2 = 0$

On-shell and MS renormalisation

"On-shell renormalisation": $\delta m^2 = \Sigma(p^2)\big|_{p^2=m^2}$

$\Rightarrow$ pole of propagator for $p^2 = m^2 \Rightarrow m$: "pole mass"

Counterterm contains divergence: expansion in $\varepsilon \equiv 4 - D$, 1-loop:

$$\delta m^2 = \underbrace{a\,\frac{1}{\varepsilon}}_{} + \underbrace{b\,\varepsilon^0}_{} + \underbrace{c\,\varepsilon}_{} + \ldots$$

divergent for $D \to 4$ finite $\to 0$ for $D \to 4$

Other renormalisation prescription:

$\delta m^2 = a\frac{1}{\varepsilon}$ "minimal subtraction" (MS)

Renormalisation group equations

Different renormalisation prescriptions $\Leftrightarrow$ different parametrizations of result

Physical result must be independent of renormalisation prescription, e.g.

$$\Sigma^{\text{ren}}(p^2 = \underbrace{\mu^2}_{\text{renormalisation scale}}) \equiv \Sigma(p^2 = \mu^2) - \delta m^2 = 0$$

$\Rightarrow$ for physical observable σ:

$$\mu \frac{d}{d\mu} \sigma \left(p_i, g(\mu), m(\mu), \mu\right) = 0$$

"renormalisation group equation"

Renormalisation group equations

$\Rightarrow$ Explicit dependence of σ on μ compensated by μ-dependence of $g(\mu)$, $m(\mu)$

$$\frac{1}{g^2(\mu^2)} = \frac{1}{g^2(\mu_0^2)} + \beta \ln\left(\frac{\mu^2}{\mu_0^2}\right), \quad \beta = \text{const.}$$

$g(\mu)$: “running coupling”, $m(\mu)$: “running mass”

$\Rightarrow$ effective coupling $\alpha(Q)$ varies with scale Q

In exact theory (incl. all orders) all schemes are equivalent

Truncation of perturbative expansion at certain order

$\Rightarrow$ results depend on ren. scheme, ren. scale μ

renormalisation scheme dependence is of the order of uncalculated higher orders

Running coupling of QED

$$\alpha(Q) = \frac{\alpha(Q_0)}{1 + 4\pi\beta\,\alpha(Q_0)\,\ln\left(\frac{Q^2}{Q_0^2}\right)}$$

$\beta < 0$ in QED: $\beta \equiv b/(16\pi^2)$, $b = -4/3$ (1-loop)

$\Rightarrow$ $\alpha(Q)$ increases for increasing Q ($Q > Q_0$),

$\alpha(m_\mathrm{e}) \approx 1/137$, $\alpha(M_\mathrm{Z}) \approx 1/128$

Scale Λ_QED where QED coupling becomes strong:

$$\alpha(Q) = \frac{1}{4\pi\beta\,\ln\left(\frac{Q^2}{\Lambda^2_\mathrm{QED}}\right)}$$

$\Lambda_\mathrm{QED} \approx 10^{274}\ \mathrm{GeV} \gg M_\mathrm{Pl}(\approx 10^{19}\ \mathrm{GeV})$

$\Rightarrow$ QED is weakly coupled up to the Planck-scale

Running coupling of QCD

$$b^{\mathrm{QCD}} = \frac{1}{3}(11N_C - 2n_f) > 0 \text{ for } n_f = 6$$

$\Rightarrow \alpha_{\mathrm{s}}(Q) \to 0$ for $Q \to \infty$: "asymptotic freedom"

For large Q: perturbation theory applicable, description in terms of quarks and gluons useful

$\alpha_{\mathrm{s}}(Q)$ becomes strong for small Q:

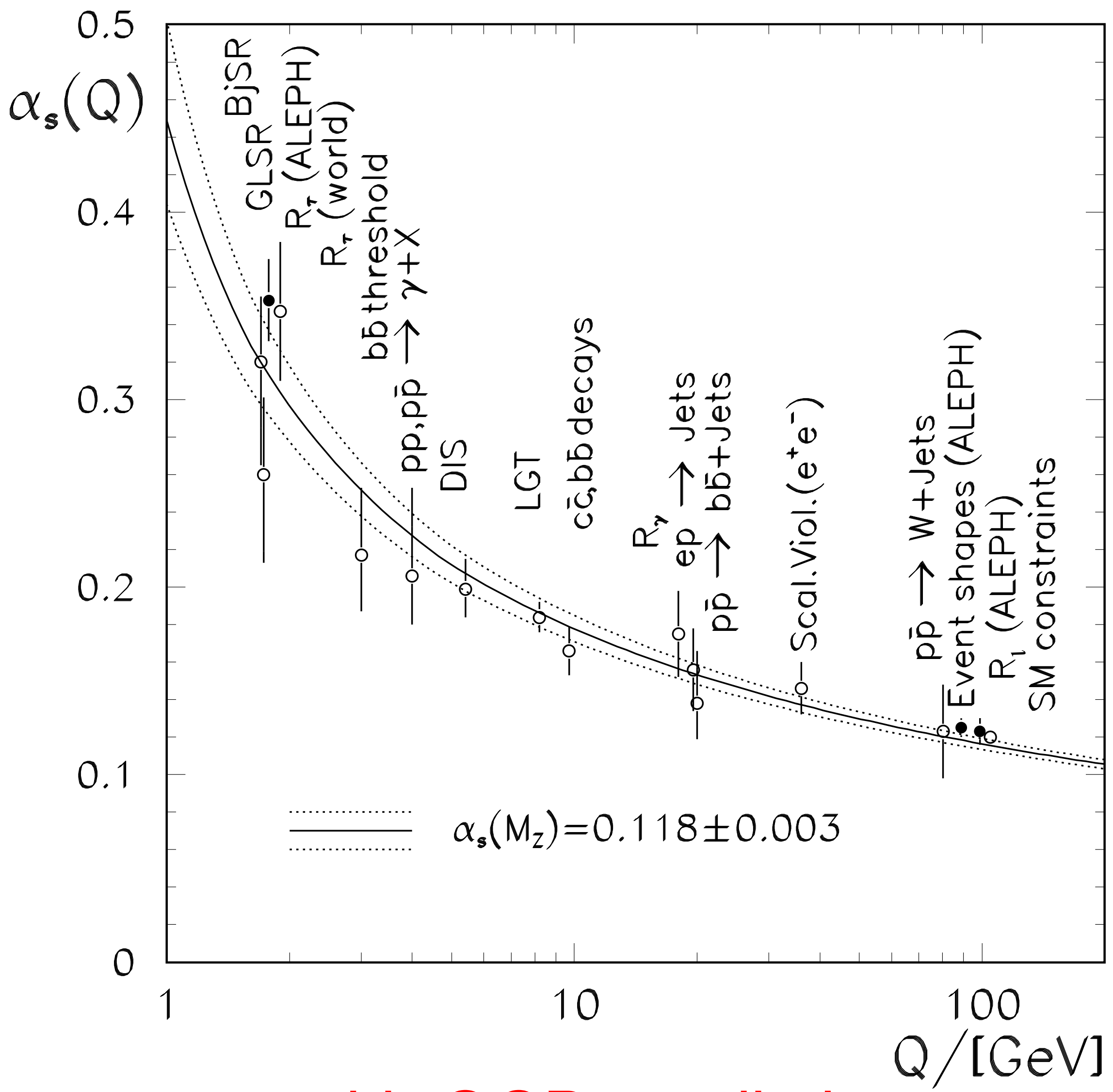
quarks and gluons bound together to form colourless hadrons

$\Rightarrow$ "confinement"

$$\alpha_{\mathrm{s}}(Q) = \frac{12\pi}{(11N_C - 2n_f)\ln\left(\frac{Q^2}{\Lambda^2_{\mathrm{QCD}}}\right)}$$

For scales of $\mathcal{O}(\Lambda_{\mathrm{QCD}}) \approx 100$ MeV: $\alpha_{\mathrm{s}}(Q)$ so large that perturbation theory not applicable

Running of $\alpha_s(Q)$*:*



$\Rightarrow$ Very good agreement with QCD prediction

What is the mass of an unstable particle?

Particle masses are not directly physical observables

Can only measure cross sections, branching ratios, kinematical distributions, ...

$\Rightarrow$ masses are “pseudo-observables”

Need to define what is meant by M_{Z}, M_{W}, m_{t}, ...:

$\overline{\mathrm{MS}}$ mass, pole mass (real pole, real part of complex pole, Breit–Wigner shape with running or constant width), ...

$\Rightarrow$ Determination of M_{Z}, M_{W}, m_{t}, ... involves deconvolution procedure (unfolding)

Mass obtained from comparison data – Monte Carlo

$\Rightarrow$ M_{Z}, M_{W}, m_{t}, ... are not strictly model-independent

What is the mass of an unstable particle?

The experimental value of M_Z is (slightly) model-dependent

In the SM: Dependence on the value of the Higgs mass

$\delta M_\mathrm{Z} = \pm 0.2$ MeV for $100\ \mathrm{GeV} \leq M_\mathrm{H} \leq 1\ \mathrm{TeV}$

$\Rightarrow M_\mathrm{Z}^\mathrm{SM}$ (slightly) differs from $M_\mathrm{Z}^\mathrm{MSSM}$

Differences could be much bigger, in principle, for $\alpha_s(M_\mathrm{Z})$

Numerical differences between the various mass definitions for M_W, M_Z are relatively large

(Running / constant width in Breit–Wigner $\Rightarrow \Delta M_\mathrm{W} = 27\ \mathrm{MeV}$)

$\Rightarrow$ Important to always refer to the same definition

Renormalisation of M_{W}, M_{Z} at the two-loop level

Expansion of amplitude around complex pole:

$$\mathcal{A}(e^+e^- \to f\bar{f}) = \frac{R}{s - \mathcal{M}_{\mathrm{Z}}^2} + S + (s - \mathcal{M}_{\mathrm{Z}}^2)\, S' + \cdots$$

$$\mathcal{M}_{\mathrm{Z}}^2 = \overline{M}_{\mathrm{Z}}^2 - i\overline{M}_{\mathrm{Z}}\,\overline{\Gamma}_{\mathrm{Z}}$$

Expanding up to $\mathcal{O}(\alpha^2)$ using $\mathcal{O}(\overline{\Gamma}_{\mathrm{Z}}/\overline{M}_{\mathrm{Z}}) = \mathcal{O}(\alpha)$

From 2-loop order on:

real part of complex pole, $\overline{M}_{\mathrm{Z}} \neq$ pole of real part, $\widetilde{M}_{\mathrm{Z}}^2$

$$\delta\overline{M}_{(2)}^2 = \delta\widetilde{M}_{(2)}^2 + \underbrace{\mathrm{Im}\left\{\Sigma'_{\mathrm{T},(1)}(M^2)\right\}\ \mathrm{Im}\left\{\Sigma_{\mathrm{T},(1)}(M^2)\right\}}_{\text{gauge-parameter dependent!}}$$

Renormalisation of M_{W}, M_{Z} at the two-loop level

$\Rightarrow$ Only the complex pole is gauge-invariant

Expansion around the complex pole leads to a Breit–Wigner shape with constant width

For historical reasons, the experimental values of M_{Z}, M_{W} are defined according to a Breit–Wigner shape with running width

$\Rightarrow$ Need to correct for the difference in definition when comparing theory with experiment

The 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

What is the mass of the top quark?

Additional problem for m_{t}: what is the mass of a coloured object?

Top pole mass is not "IR safe" (affected by large long-distance contributions), cannot be determined to better than $\mathcal{O}(\Lambda_{\mathrm{QCD}})$

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?

Measured mass should be "close to the pole mass", but how close?

Issue not yet settled, effects of $\mathcal{O}(\Gamma_{\mathrm{t}})$ are not fully under control

Measurement of the top-quark mass at the ILC

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

$\Rightarrow$ Measurement of a "threshold mass parameter" with high precision: $\lesssim 20\ \mathrm{MeV}$

$+$ transition to suitably defined (short-distance) top-quark mass, e.g. $\overline{\mathrm{MS}}$ mass

$\Rightarrow \quad \delta m_{\mathrm{t}}^{\mathrm{exp}} \lesssim 100\ \mathrm{MeV}$ (dominated by theory uncertainty)

Quark mixing and $\mathcal{CP}$-violation

Weak eigenstates (d', s', b') of quarks differ from mass eigenstates d, s, b:

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix} \equiv V_{\mathrm{CKM}} \begin{pmatrix} d \\ s \\ b \end{pmatrix} .$$

V_{CKM}: unitary transformation, Cabibbo-Kobayashi-Maskawa (CKM) matrix

GIM Mechanism:

unitarity of CKM-matrix, $V_{\mathrm{CKM}}^{\dagger} V_{\mathrm{CKM}} = 1$

$\Rightarrow$ no flavour changing neutral current transitions at tree level

$\Rightarrow$ $b \to s\gamma, \ldots$ are loop-induced in SM

$\Rightarrow$ high sensitivity to new physics effects

$\mathcal{CP}$ violation

$V_{\mathrm{CKM}}^{\dagger} V_{\mathrm{CKM}} = 1 \Rightarrow$ parametrised by 3 angles $\underbrace{+\ 1\ \text{phase}}$

gives rise to $\mathcal{CP}$-violation in SM

$\Rightarrow$ Weak interaction violates $\mathcal{C}$, $\mathcal{P}$ and $\mathcal{CP}$

SM: CKM phase is the only source of $\mathcal{CP}$-violation

Almost all models of new physics contain new sources of $\mathcal{CP}$-violation

Cosmology: baryogenesis ($\longrightarrow$ matter – antimatter imbalance in universe) requires further sources of $\mathcal{CP}$-violation beyond CKM phase

The unitarity triangle

$\mathcal{CP}$-violation discovered in neutral kaon system (1964)

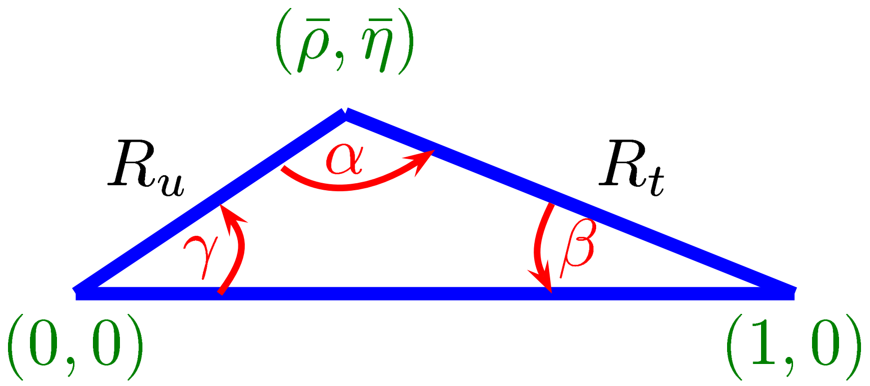
During the last years also established in B-meson decays at "b factories"

Unitarity triangles:

$V_{\rm CKM}^{\dagger} V_{\rm CKM} = 1 \Rightarrow V_{ud} V_{ub}^{*} + V_{cd} V_{cb}^{*} + V_{td} V_{tb}^{*} = 0$, etc.

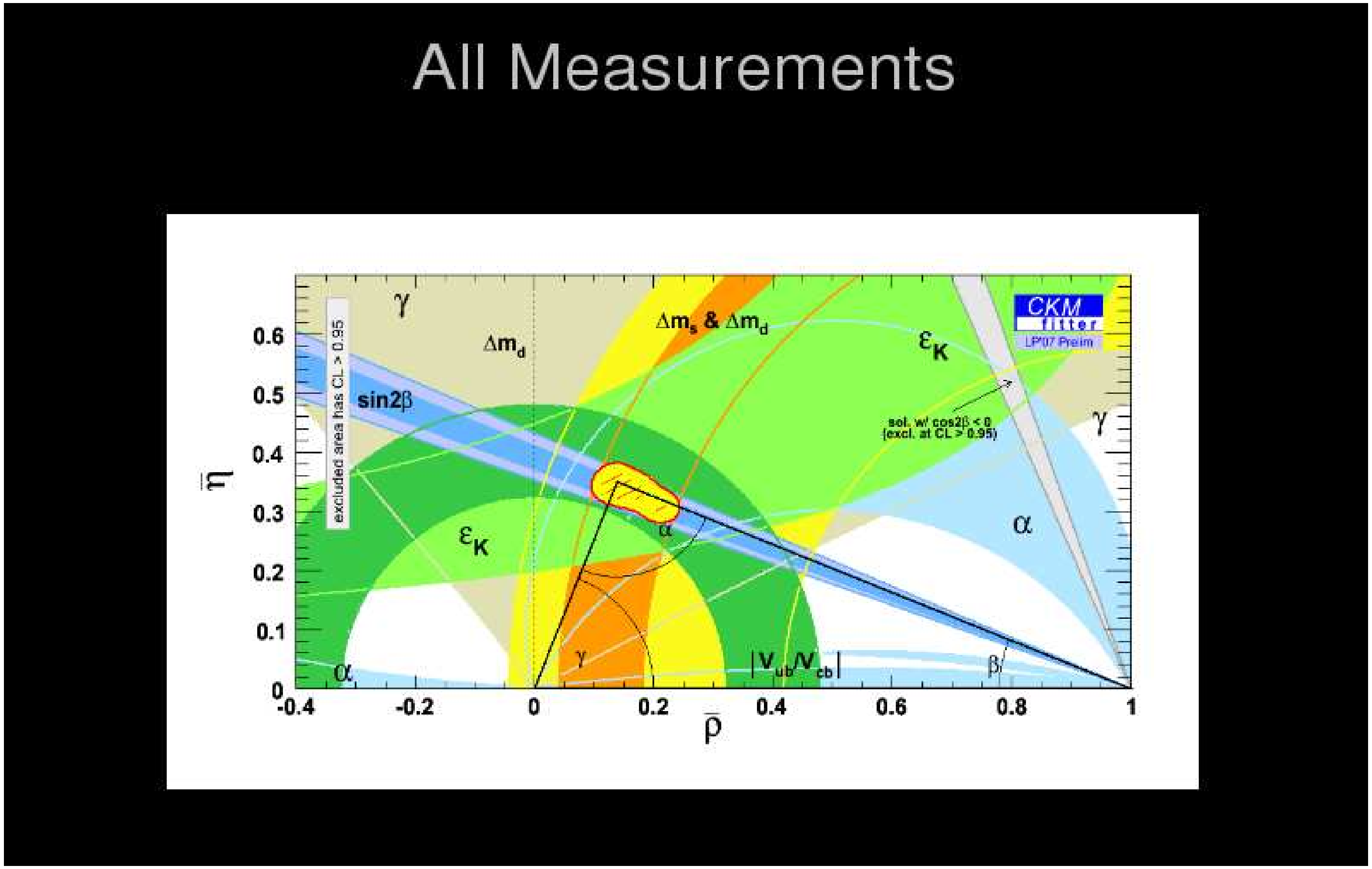
$\Rightarrow$ triangle relation in complex plane

after reparametrisation:



Current experimental information on unitarity triangle

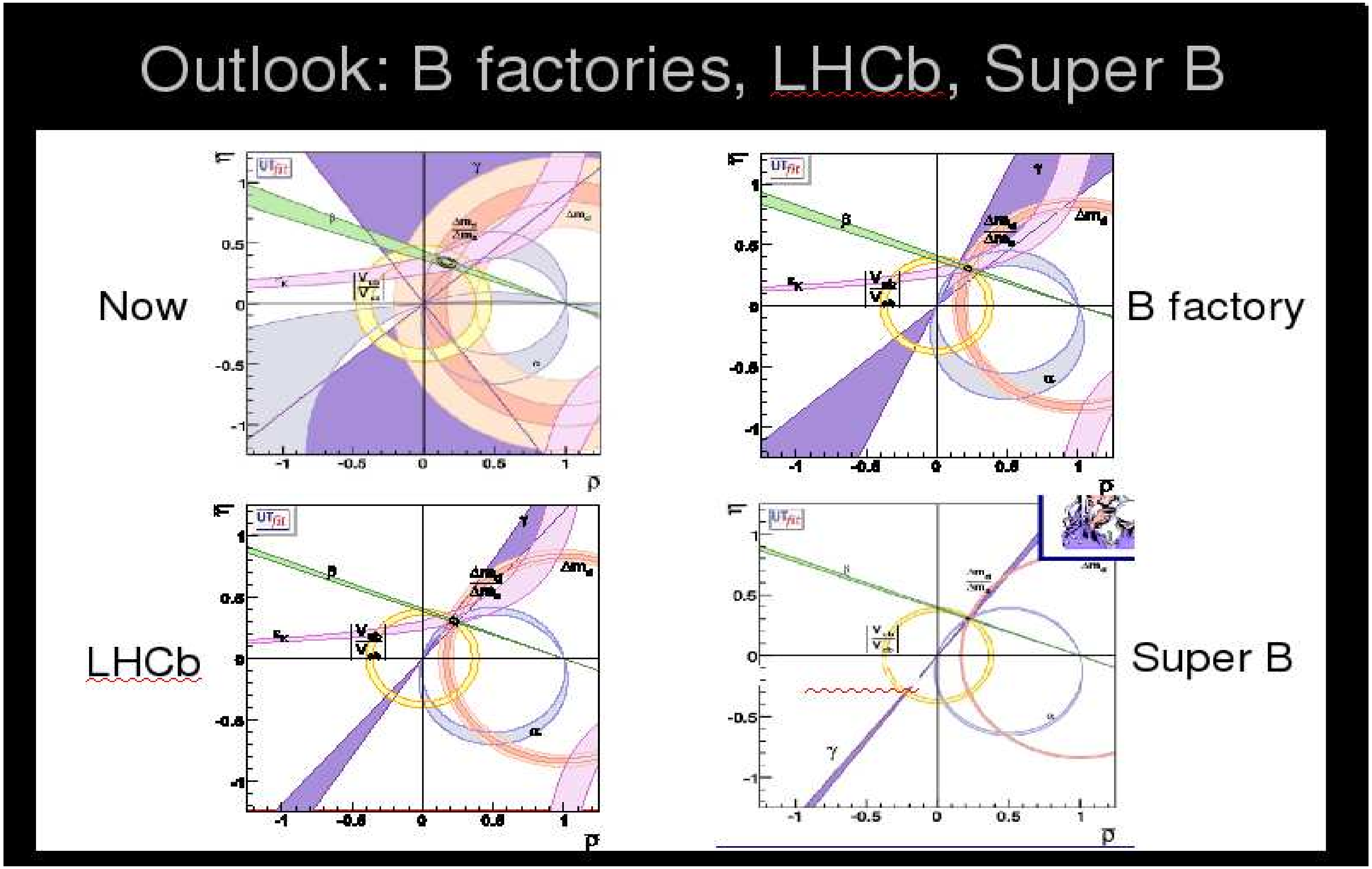
[*Y.-K. Kim, summary talk at LP07*]



⇒ $\mathcal{CP}$ violation induced by SM CKM matrix is well established
stringent constraints on new physics

Unitarity triangle: future sensitivities

[*Y.-K. Kim, summary talk at LP07*]

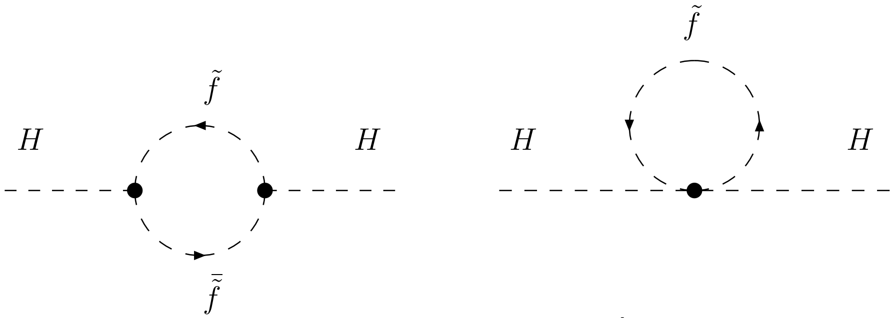


Supersymmetry (SUSY): Cancellation of quadratic divergences

SUSY: symmetry between fermions and bosons

$$Q|\text{boson}\rangle = |\text{fermion}\rangle$$
$$Q|\text{fermion}\rangle = |\text{boson}\rangle$$

SUSY: additional contributions from scalar fields:



$$\Sigma^H_{\tilde{f}} \sim N(\tilde{f})\,\tilde{\lambda}_f \int d^4k \left(\frac{1}{k^2 - m^2_{\tilde{f}_L}} + \frac{1}{k^2 - m^2_{\tilde{f}_R}} \right)$$

$+$ terms without quadratic div.

for $\Lambda \to \infty$: $\Sigma^H_{\tilde{f}} \sim 2\,N(\tilde{f})\,\tilde{\lambda}_f\,\Lambda^2$

Cancellation of quadratic divergences

$\Rightarrow$ quadratic divergences cancel for

$$\begin{aligned} N(\tilde{f}_L) = N(\tilde{f}_R) &= N(f) \\ \tilde{\lambda}_f &= \lambda_f^2 \end{aligned}$$

complete correction vanishes if furthermore

$$m_{\tilde{f}} = m_f$$

For $m^2_{\tilde{f}} = m^2_f + \Delta^2, \quad \tilde{\lambda}_f = \lambda^2_f,$ "soft SUSY breaking"

$$\Rightarrow \; \Sigma^H_{f+\tilde{f}} \sim N(f)\,\lambda^2_f\,\Delta^2 + \ldots$$

$\Rightarrow$ correction stays acceptably small if mass splitting is of weak scale

$\Rightarrow$ realised if mass scale of SUSY partners $M_{\mathrm{SUSY}} \lesssim 1\,\mathrm{TeV}$

$\Rightarrow$ SUSY at TeV scale provides attractive solution of hierarchy problem

The SUSY algebra

Symmetry: a group of transformations that leave Lagrangian invariant

generators of the group fulfill certain algebra

Noether's theorem: symmetries $\Leftrightarrow$ conservation laws

Unification of fundamental interactions?

Electroweak and strong interactions:

described by gauge theories: internal symmetries

γ, Z, $W^{\pm}$: spin 1

Gravity:

described by general relativity: invariance under space–time transformations

graviton G: spin 2

Space–time symmetries: Poincaré group

Lorentz transformations: continous group, "Lie-group"

$M^{\rho\nu} = -M^{\nu\rho}$ (6 generators), translations P^ρ (4 generators)

particle states characterised by eigenvalues of mass and spin

Describe spin $\frac{1}{2}$ particles not in terms of 4-component "Dirac spinors" but in terms two 2-component "Weyl spinors"

$\Rightarrow$ Spinor representation of the Lorentz group:

Form (complex) linear combinations of the generators of rotations and Lorentz boosts such that commutation relations become

$$\left[J_i^\pm, J_j^\pm\right] = i\epsilon_{ijk} J^{\pm,k}; \qquad \left[J_i^+, J_j^-\right] = 0$$

$\Rightarrow$ two SU(2) algebras, commute with each other

$\Rightarrow$ Lorentz group is equivalent to a (complexified) version of SU(2) $\times$ SU(2) ($\rightarrow$ SL(2, C))

Spinor representation of the Lorentz group

$\Rightarrow$ Representations of Lorentz group are labelled by two 'spins', j_1, j_2, where $j_1, j_2 = 0, \frac{1}{2}, 1, \ldots$ as usual for SU(2)

Basic representations:

$(\frac{1}{2}, 0)$: LEFT-handed 2-component Weyl spinor, ψ_α

$(0, \frac{1}{2})$: RIGHT-handed 2-component Weyl spinor, $\bar{\psi}^{\dot{\alpha}}$

The two component Weyl spinors ψ_α (left-handed) and $\bar{\psi}^{\dot{\alpha}}$ (right-handed) transform under Lorentz transformations as:

$$\psi'_\alpha = M_\alpha{}^\beta \psi_\beta; \qquad \bar{\psi}'_{\dot{\alpha}} = (M^*)_{\dot{\alpha}}{}^{\dot{\beta}} \bar{\psi}_{\dot{\beta}}$$

$$\psi'^\alpha = (M^{-1})_\beta{}^\alpha \psi^\beta; \qquad \bar{\psi}'^{\dot{\alpha}} = (M^{*-1})_{\dot{\beta}}{}^{\dot{\alpha}} \bar{\psi}^{\dot{\beta}}$$

where $M = \exp(i\frac{\vec{\sigma}}{2}(\vec{\vartheta} - i\vec{\varphi}))$ and $\vec{\vartheta}$ and $\vec{\varphi}$ are the three rotation angles and boost parameters, respectively

Internal symmetries, e.g. gauge symmetries

QED: $\psi \to e^{iQ\lambda}\psi$, $A_\mu \to A_\mu + \partial_\mu \lambda$, generator: Q, group U(1)

QCD: SU(3), SM: SU(2) $\times$ U(1)

generators T^a of internal symmetries satisfy Lie algebra, $[T^a, T^b] = if^{abc}T_c$

'Trivial' extension of Poincaré group, T^a commute with Poincaré generators, $[P^\mu, T^a] = 0$, $[M^{\mu\nu}, T^a] = 0$

$\Rightarrow$ direct product (Poincaré group) $\otimes$ (internal symm. group)

Particle states characterised by maximal set of commuting observables:

$$|\underbrace{m, s; \vec{p}, s_3;}_{\text{space–time}} \ \underbrace{Q, I, I_3, Y, \ldots}_{\text{internal}}\rangle$$

quantum numbers

"No go" theorems

Direct product $\Rightarrow$ no irreducible multiplets containing particles with different mass or different spin

$\Rightarrow$ Look for extension of space–time symmetry with new generators Q_α such that $[Q_\alpha, M^{\mu\nu}] \neq 0$ or $[Q_\alpha, P^\mu] \neq 0$

But: general "no go theorems"

Coleman–Mandula theorem '67:

Any Lie-group containing Poincaré group P and internal symmetry group G must be direct product $P \otimes G$

The superalgebra

No go theorem can be evaded if instead of Lie-group (generators fulfill commutator relations):
[*Gol'fand, Likhtman '71*] [*Volkov, Akulov '72*] [*Wess, Zumino '73*]

$$[\ldots,\ldots] \to \{\ldots,\ldots\}$$

Anticommutator: $\{A, B\} = AB + BA$

$\Rightarrow$ "graded Lie algebra", "superalgebra"

Haag, Lopuszanski, Sohnius theorem '75:

no direct symmetry transformations between fields with different integer spins

$\Rightarrow$ particles with different spin in the same multiplet only possible for SUSY theories,

$Q|\text{boson}\rangle = |\text{fermion}\rangle$, $Q|\text{fermion}\rangle = |\text{boson}\rangle$

SUSY transformations

Symmetry generator Q:

fermionic operator, needs to have spin $1/2$

E.g.:

spin 2	$\longrightarrow$	spin $\frac{3}{2}$	$\longrightarrow$	spin 1
graviton		gravitino		photon

Q changes spin (behavior under spatial rotations) by $\frac{1}{2}$

$\Rightarrow$ SUSY transformation influences in general both space–time and internal quantum numbers

$N = 1$ *SUSY algebra*

Simplest case: only one fermionic generator Q_α (and conjugate $\bar{Q}_{\dot{\beta}}$, $\alpha = 1, 2$, $\dot{\beta} = 1, 2$)

$\Rightarrow N = 1$ SUSY algebra:

$$
\begin{aligned}
[Q_\alpha, P_\mu] = \left[\bar{Q}_{\dot{\beta}}, P_\mu\right] &= 0 \\
[Q_\alpha, M^{\mu\nu}] &= i\,(\sigma^{\mu\nu})_\alpha{}^\beta\, Q_\beta \\
\{Q_\alpha, Q_\beta\} = \left\{\bar{Q}_{\dot{\alpha}}, \bar{Q}_{\dot{\beta}}\right\} &= 0 \\
\{Q_\alpha, \bar{Q}_{\dot{\alpha}}\} &= 2(\sigma^\mu)_{\alpha\dot{\alpha}} P_\mu
\end{aligned}
$$

where $(\sigma^\mu)_{\alpha\dot{\alpha}} \equiv \{1, \sigma^1, \sigma^2, \sigma^3\}_{\alpha\dot{\alpha}}$, $(\bar{\sigma}^\mu)_{\alpha\dot{\alpha}} \equiv \{1, -\sigma^1, -\sigma^2, -\sigma^3\}_{\alpha\dot{\alpha}}$, $\sigma^{\mu\nu} \equiv \frac{1}{4}\left(\sigma^\mu\bar{\sigma}^\nu - \sigma^\nu\bar{\sigma}^\mu\right)$

$P_0 = H$, $[Q_\alpha, H] = 0 \Rightarrow$ conserved charge

$N = 1$ ***SUSY***

Haag, Lopuszanski, Sohnius theorem: $N = 1$ SUSY algebra is unique extension of Poincaré group of symmetries of $D = 4$ relativistic QFT

$\Rightarrow$ SUSY:

Symmetry that relates bosons to fermions

"generalises classical notion of a dimension to quantum domain"

"so beautiful it must be true . . . "

Consequences of the SUSY algebra

Global SUSY transformation:

$$\{Q_\alpha, \bar{Q}_{\dot{\alpha}}\} = \underbrace{2(\sigma^\mu)_{\alpha\dot{\alpha}} P_\mu}_{}$$

constant translation in space–time

If SUSY transformations are made local
$\Rightarrow$ space–time transformation differing from point to point

Invariance under local SUSY transformations:

$\Rightarrow$ invariance under local coordinate change

$\Rightarrow$ general relativity

$\Rightarrow$ local SUSY includes gravity, called “supergravity”

Consequences of the SUSY algebra

Q_α changes spin of particle by $\frac{1}{2}$

$Q_\alpha|\text{boson}\rangle = |\text{fermion}\rangle$, $Q_\alpha|\text{fermion}\rangle = |\text{boson}\rangle$

Consider fermionic state $|f\rangle$ with mass m:

$\Rightarrow$ bosonic state $|b\rangle = Q_\alpha|f\rangle$

$P^2|f\rangle = m^2|f\rangle$

$\Rightarrow$ $P^2|b\rangle = P^2 Q_\alpha|f\rangle = Q_\alpha P^2|f\rangle = Q_\alpha m^2|f\rangle = m^2|b\rangle$

$\Rightarrow$ For each fermionic state there is a bosonic state with the same mass

$\Rightarrow$ States are paired bosonic $\leftrightarrow$ fermionic

Consequences of the SUSY algebra

$$\left\{Q_\alpha, \bar{Q}_{\dot\beta}\right\} = 2\sigma^\mu_{\alpha\dot\beta} P_\mu$$

$$\Rightarrow \left\{Q_\alpha, \bar{Q}_{\dot\beta}\right\} \bar{\sigma}_\nu^{\dot\beta\alpha} = 2\, \underbrace{\sigma^\mu_{\alpha\dot\beta} \bar{\sigma}_\nu^{\dot\beta\alpha}}_{2 g^\mu{}_\nu} P_\mu = 4 P_\nu$$

$$\nu = 0 \Rightarrow H = P_0 = \tfrac{1}{4} \left\{Q_\alpha, \bar{Q}_{\dot\beta}\right\} \bar{\sigma}_0^{\dot\beta\alpha} = \tfrac{1}{4} \left(\left\{Q_1, Q_1^\dagger\right\} + \left\{Q_2, Q_2^\dagger\right\} \right)$$

where $\bar{Q}_{\dot\alpha} = (Q_\alpha)^\dagger$

$\left\{Q_i, Q_i^\dagger\right\} = Q_i Q_i^\dagger + Q_i^\dagger Q_i$: hermitean operator, eigenvalues ≥ 0

$\Rightarrow$ for any state $|\alpha\rangle$: $\langle\alpha|H|\alpha\rangle \geq 0$

$\Rightarrow$ spectrum of H is bounded from below, ≥ 0

$\Rightarrow$ no negative eigenvalues

Consequences of the SUSY algebra

State with lowest energy: vacuum state $|0\rangle$

if vacuum state is symmetric, i.e. $Q|0\rangle = 0$, $Q^\dagger|0\rangle = 0$ for all Q

$\Rightarrow$ vacuum has zero energy, $\langle 0|H|0\rangle = E_{\text{vac}} = 0$

For spontaneous symmetry breaking: vacuum state is not invariant

$\Rightarrow$ If (global) SUSY is spontaneously broken, i.e. $Q_\alpha|0\rangle \neq 0$, then $\langle 0|H|0\rangle = E_{\text{vac}} > 0$

$\Rightarrow$ non-vanishing vacuum energy

Construction of SUSY field theories

Superspace and superfields:

For compact representation of SUSY transformations

$\Rightarrow$ "fermionic variables" θ^α, $\bar{\theta}^{\dot{\alpha}}$ introduced: anticommuting c-numbers (Grassmann variables)

E.g.: translations, generators P_μ, parameters of transf. x^μ

$N = 1$ SUSY, generators Q_α, $\bar{Q}_{\dot{\alpha}}$, parameters of transf. θ^α, $\bar{\theta}^{\dot{\alpha}}$

$\Rightarrow$ Extension of 4-dim. space–time by coordinates θ^α, $\bar{\theta}^{\dot{\alpha}}$: superspace

Point in superspace: $X = (x^\mu, \theta^\alpha, \bar{\theta}^{\dot{\alpha}})$, Superfield: $\phi(x^\mu, \theta^\alpha, \bar{\theta}^{\dot{\alpha}})$

$\Rightarrow$ Construct an action that is invariant both under SUSY and gauge transformations: $\delta \int d^4x \mathcal{L}(x) = 0$

SUSY breaking

MSSM: no particular SUSY breaking mechanism assumed, parametrisation 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

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

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

Simplest ansatz: the CMSSM

Assume universality at high energy scale (M_{GUT}, M_{Pl}, ...)

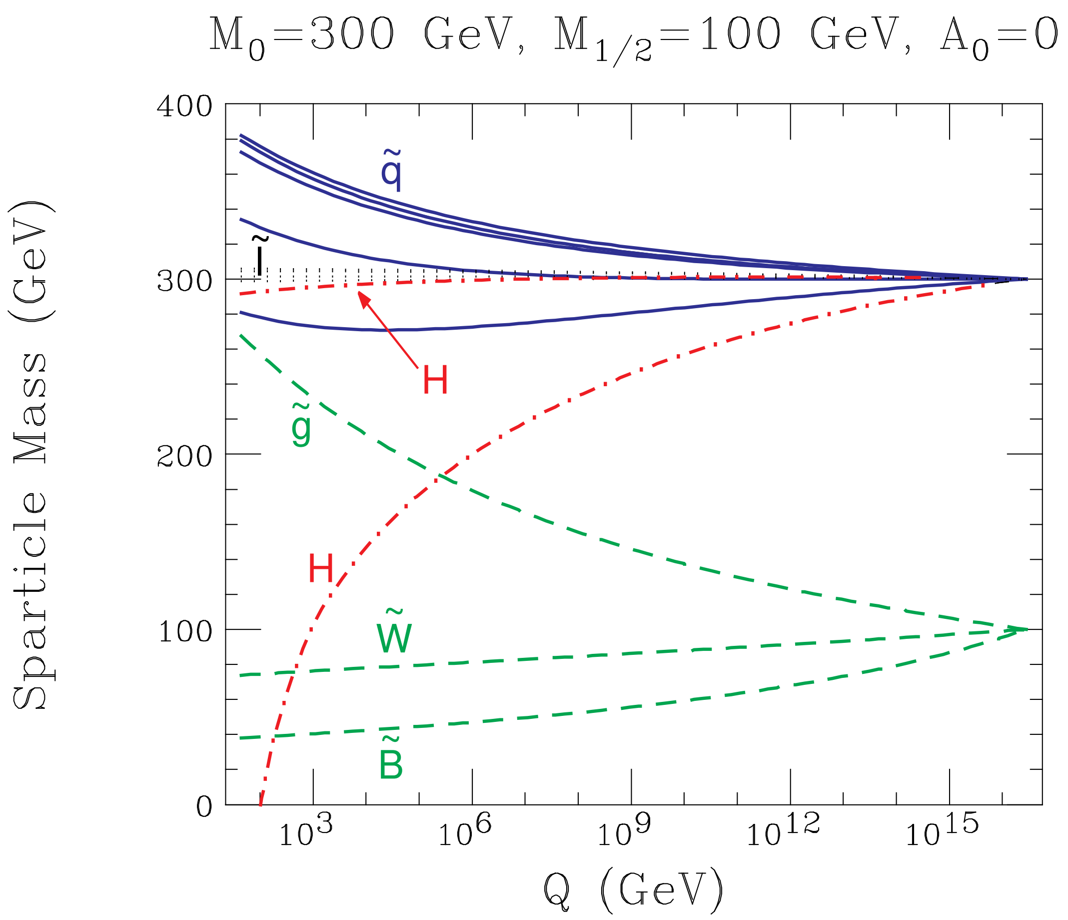
- Universal scalar masses: $\tilde{m}^2 = m_0^2$
- Universal gaugino masses: $M_i = m_{1/2}$ (“GUT relation”)
- Universality of soft-breaking trilinear terms:

$$\mathcal{L}_{\mathrm{tri}} = A_0(H_U Q y_u \bar{u} + H_D Q y_d \bar{d} + H_D L y_l \bar{e})$$

y_u, y_d, ... are the same matrices that appear in Yukawa couplings (“proportionality”)

Radiative electroweak symmetry breaking

Universal boundary conditions at GUT scale,
renormalisation group running down to weak scale



large corrections from top-quark Yukawa coupling

$\Rightarrow$ $m^2_{H_u}$ driven to negative values

$\Rightarrow$ ew symmetry breaking

emerges naturally at scale $\sim 10^2$ GeV for
$100 \text{ GeV} \lesssim m_{\rm t} \lesssim 200 \text{ GeV}$

The Constrained MSSM (CMSSM)

Universality ansatz results in five parameters, if possible phases are ignored:

$$m_0^2,\ m_{1/2},\ A_0,\ b,\ \mu$$

Require correct value of M_Z

$\Rightarrow$ $|\mu|$, b given in terms of $\tan\beta \equiv v_u/v_d$, $\mathrm{sign}\,\mu$

$\Rightarrow$ CMSSM characterised by

$$m_0^2,\ m_{1/2},\ A_0,\ \tan\beta,\ \mathrm{sign}\,\mu$$

SUSY-breaking scenarios

"Hidden sector":	$\longrightarrow$	Visible sector:
SUSY breaking		MSSM

"Gravity-mediated": SUGRA
"Gauge-mediated": GMSB
"Anomaly-mediated": AMSB
"Gaugino-mediated"
...

SUGRA: mediating interactions are gravitational

GMSB: mediating interactions are ordinary electroweak and QCD gauge interactions

AMSB, Gaugino-mediation: SUSY breaking happens on a different brane in a higher-dimensional theory

SUGRA

SUGRA: mediating interactions are gravitational

$\Leftrightarrow$ Connection of gravity and electroweak physics

Flavour off-diagonal and $\mathcal{CP}$-violating effects?

SUGRA with universality assumptions $\Rightarrow$ CMSSM, $\tilde{\chi}_1^0$ LSP

Other possibility:

Gravitino LSP, compatible with CDM, $\tilde{\tau}$ NLSP

$\tilde{\tau}$ could be long-lived charged particle, $\tilde{\tau} \to \tau \tilde{G}$, interesting phenomenology

CMSSM phenomenology

SUGRA with universality assumptions $\Rightarrow$ CMSSM

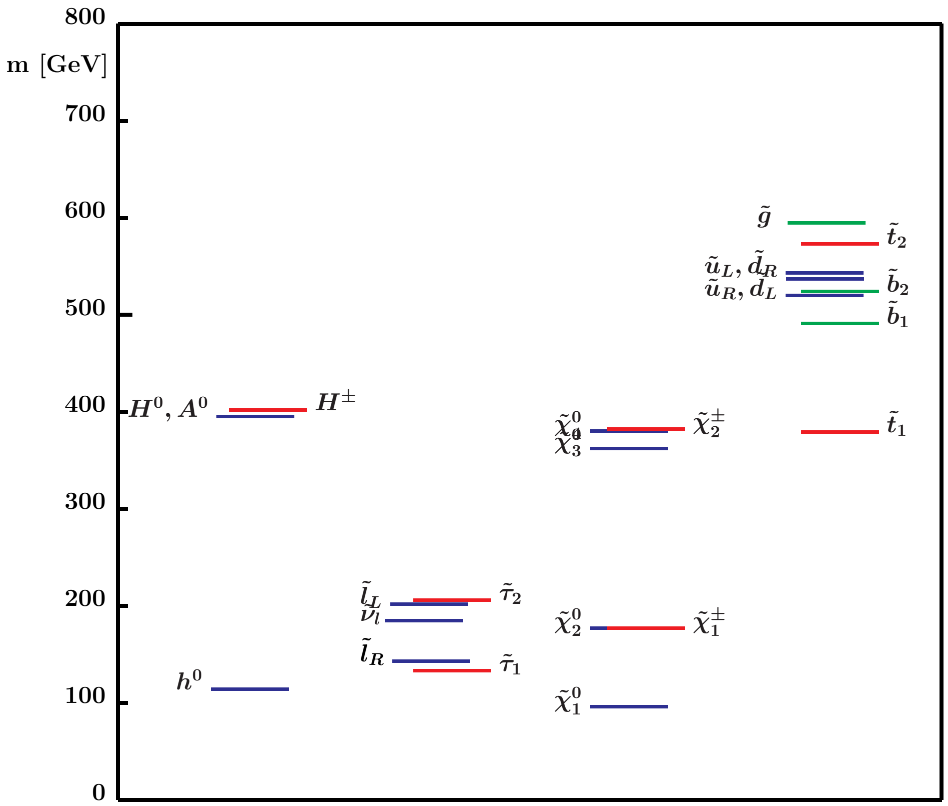
m_0, $m_{1/2}$, A_0: GUT scale parameters

$\Rightarrow$ Spectra from renormalisation group running to weak scale

Lightest SUSY particle (LSP) is usually lightest neutralino

Gaugino masses run in same way as gauge couplings
$\Rightarrow$ gluino heavier than charginos, neutralinos

"Typical" CMSSM scenario (SPS 1a benchmark scen.):



CMSSM phenomenology

CMSSM is in agreement with all experimental constraints

Electroweak precision observables (EWPO) + dark matter constraint

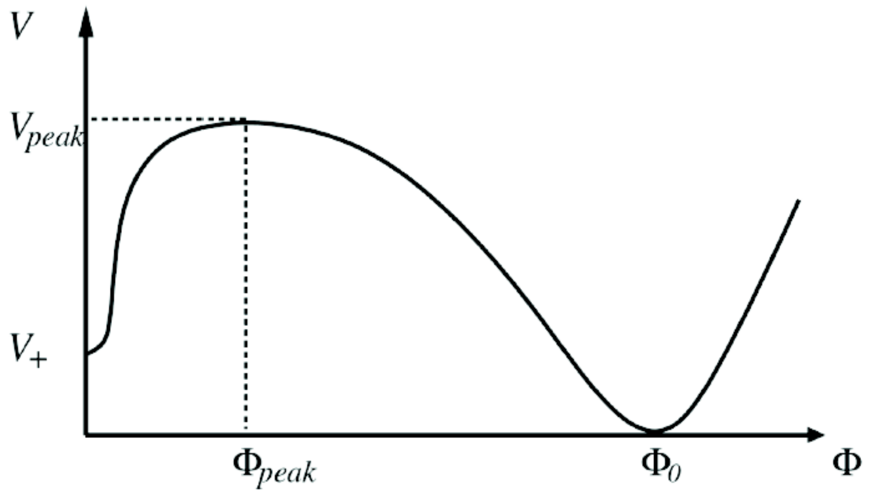
⇒ Preference for relatively light SUSY scale

[*J. Ellis, S. Heinemeyer, K. Olive, G. W. '05, '06*]
[*J. Ellis, K. Olive, Y. Santoso, V. Spanos '04*] [*B. Allanach, C. Lester '06*]
[*B. Allanach '06*] [*B. Allanach, C. Lester, A. Weber '06, '07*]
[*R. de Austri, R. Trotta, L. Roszkowski '06*] [*G. Isidori, F. Mescia, P. Paradisi, D. Temes '07*] [*M. Carena, A. Menon, C. Wagner '07*] . . .

(see below)

Meta-stable vacua

Suppose we live in a SUSY-breaking meta-stable vacuum, while the global minimum has exact SUSY



Recent developments: meta-stable vacua arise as generic feature of SUSY QCD with massive flavours

Meta-stable SUSY-breaking vacua are “generic” in local SUSY / string theory, can have cosmologically long life times [*Intriligator, Seiberg, Shih ’06*], . . .

⇒ Large activity in model building

Gauge-mediated SUSY breaking

GMSB: mediating interactions are ordinary electroweak and QCD gauge interactions

$\Rightarrow$ preserve flavour structure
(but "μ problem" not addressed, see below)

Meta-stable vacua

$\Rightarrow$ "simplified" GMSB models with generic superpotentials
[*H. Murayama, Y. Nomura '06*], . . .

GMSB phenomenology

Gaugino and scalar masses arise from loop contributions involving messenger fields

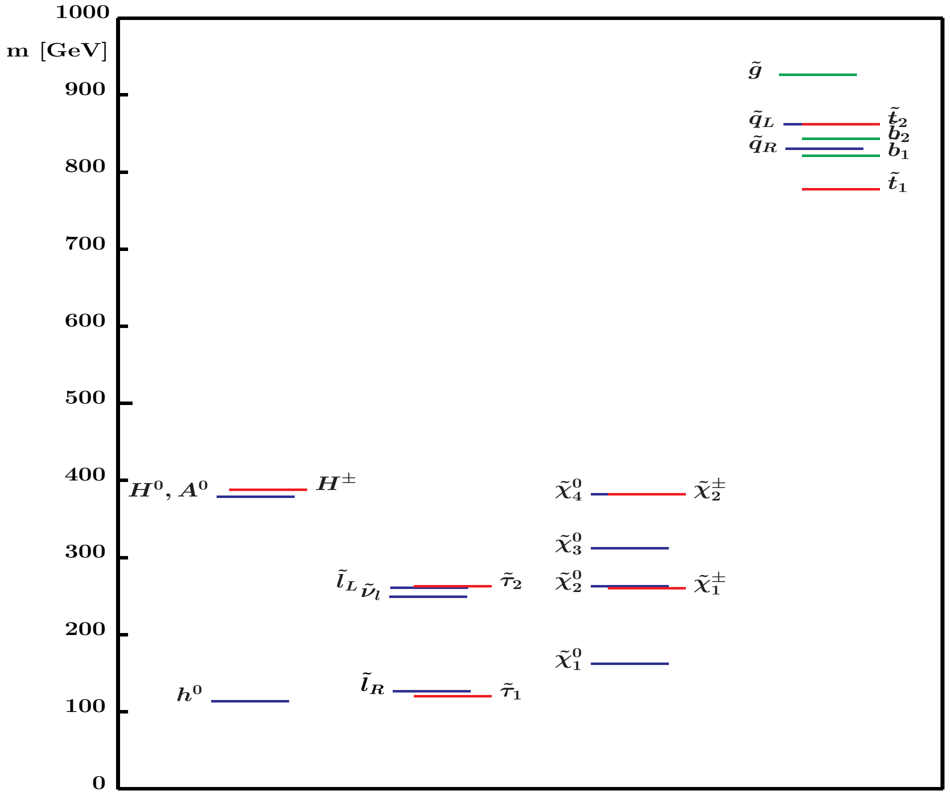
$\Rightarrow$ Typical mass hierarchy in GMSB scenario between strongly interacting and weakly interacting particles $\sim \alpha_3/\alpha_2/\alpha_1$

LSP is always the gravitino (also possible in SUGRA)

next-to-lightest SUSY particle (NLSP): $\tilde{\chi}_1^0$ or $\tilde{\tau}_1$

can decay into LSP inside or outside the detector

GMSB scenario with $\tilde{\tau}$ NLSP (SPS 7 benchmark scen.):



Anomaly-mediated SUSY breaking

AMSB: SUSY breaking happens on a different brane in a higher-dimensional theory

Problem of tachyonic slepton masses

$\Rightarrow$ further source of SUSY breaking needed

Recent proposal: mixed Modulus–Anomaly-Mediation scheme: “Mirage Mediation”

[*Choi, Jeong, Okumura ’05*]

[*Loaiza, Martin, Nilles, Ratz ’05*]

Summary on SUSY-breaking scenarios

We are still far away from a “Standard Model of SUSY breaking”

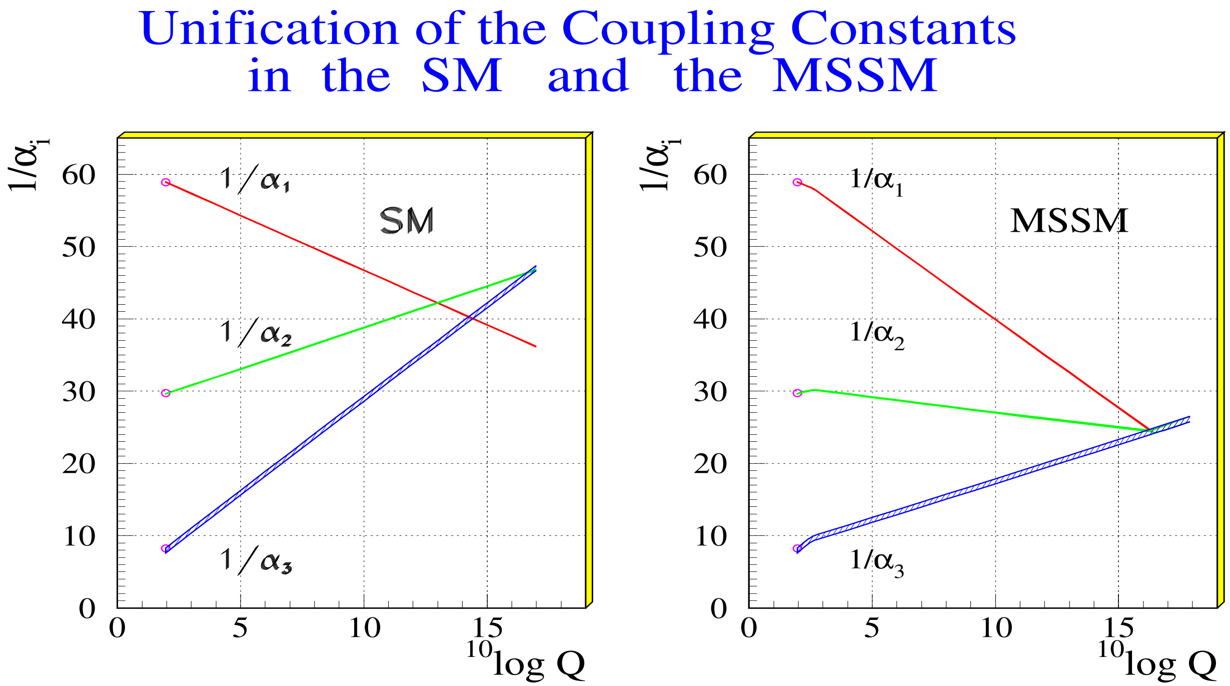
Eagerly waiting for a possible clue from data!

Generic features of SUSY theories

Gauge coupling unification:

Running of gauge couplings: $\dfrac{1}{g^2(\mu^2)} = \dfrac{1}{g^2(\mu_0^2)} + \beta \ln\left(\dfrac{\mu^2}{\mu_0^2}\right)$

Unification of couplings at high scale $\Leftrightarrow$ "Grand unified theories" (GUTs); e.g.: SO(10) GUTs, can naturally accomodate right-handed neutrinos



[*U. Amaldi, W. de Boer, H. Fürstenau '91*]

$\Rightarrow$ Coupling constant unification in MSSM for $M_{\rm SUSY} \lesssim 1$ TeV

R parity

Most general gauge-invariant and renormalizable superpotential with chiral superfields of the MSSM:

$$\mathcal{V} = \mathcal{V}_{\text{MSSM}} + \underbrace{\frac{1}{2}\lambda^{ijk} L_i L_j E_k + \lambda'^{ijk} L_i Q_j D_k + \mu'^i L_i H_u}_{\text{violate lepton number}} + \underbrace{\frac{1}{2}\lambda''^{ijk} U_i D_j D_k}_{\text{violates baryon number}}$$

If both lepton and baryon number are violated

$\Rightarrow$ rapid proton decay

Minimal choice (MSSM) contains only terms in the Lagrangian with even number of SUSY particles $\Rightarrow$ additional symmetry: “R parity”

$\Rightarrow$ all SM particles have even R parity, all SUSY particles have odd R parity

Phenomenological consequences of R parity conservation

- SUSY particles can only be pair-produced, e.g. $gg \to \tilde{g}\tilde{g}$
- Decay of SUSY particles into SM particles $+$ odd number of SUSY particles $\Rightarrow$ Lightest SUSY particle (LSP) is stable
- All SUSY particles will eventually decay into LSP

  $\Rightarrow$ Decay cascades of heavy SUSY particles
- LSP stable $\Rightarrow$ some LSP must have survived from Big Bang

  $\Rightarrow$ Weakly interacting massive particle ("WIMP")
  (otherwise ruled out from bounds on exotic isotopes etc.)

  $\Rightarrow$ Candidate for cold dark matter in the Universe
- LSP neutral, uncoloured $\Rightarrow$ leaves no traces in collider detectors $\Rightarrow$ Typical SUSY signatures: "missing energy"

Relations between SUSY parameters

Symmetry properties of MSSM Lagrangian (SUSY, gauge invariance) give rise to coupling and mass relations

Soft SUSY breaking does not affect SUSY relations between dimensionless couplings

E.g.:

gauge boson–fermion coupling

$=$

gaugino–fermion–sfermion coupling

for U(1), SU(2), SU(3) gauge groups

Squark and slepton mixing

$$\mathbf{M}_{\tilde{t}} = \begin{pmatrix} M_{\tilde{t}_L}^2 + m_t^2 + M_Z^2 c_{2\beta}(T_t^3 - Q_t s_\mathrm{W}^2) & m_t X_q^* \\ m_t X_q & M_{\tilde{t}_R}^2 + m_t^2 + M_Z^2 c_{2\beta} Q_t s_\mathrm{W}^2 \end{pmatrix}$$

$$\Rightarrow \; m_{\tilde{\mathrm{t}}_1}, m_{\tilde{\mathrm{t}}_2}, \theta_{\tilde{\mathrm{t}}}$$

$$\mathbf{M}_{\tilde{b}} = \begin{pmatrix} M_{\tilde{b}_L}^2 + m_b^2 + M_Z^2 c_{2\beta}(T_b^3 - Q_b s_\mathrm{W}^2) & m_b X_q^* \\ m_b X_q & M_{\tilde{b}_R}^2 + m_b^2 + M_Z^2 c_{2\beta} Q_b s_\mathrm{W}^2 \end{pmatrix}$$

$$\Rightarrow \; m_{\tilde{\mathrm{b}}_1}, m_{\tilde{\mathrm{b}}_2}, \theta_{\tilde{\mathrm{b}}}$$

with $X_q = A_q - \mu^* \kappa$, $\kappa = \{\cot\beta, \tan\beta\}$ for $q = t, b$, $\tan\beta \equiv v_u/v_d$

Off-diagonal element is prop. to mass of partner quark

$\Rightarrow$ mixing important in $\tilde{\mathrm{t}}$ sector, for large $\tan\beta$ also in $\tilde{\mathrm{b}}$, $\tilde{\tau}$ sect.

Squark and slepton mixing

$$\mathbf{M}_{\tilde{t}} = \begin{pmatrix} M^2_{\tilde{t}_L} + m_t^2 + M_Z^2 c_{2\beta}(T_t^3 - Q_t s_\mathrm{w}^2) & m_t X_q^* \\ m_t X_q & M^2_{\tilde{t}_R} + m_t^2 + M_Z^2 c_{2\beta} Q_t s_\mathrm{w}^2 \end{pmatrix}$$

$$\Rightarrow \; m_{\tilde{\mathrm{t}}_1}, m_{\tilde{\mathrm{t}}_2}, \theta_{\tilde{\mathrm{t}}}$$

$$\mathbf{M}_{\tilde{b}} = \begin{pmatrix} M^2_{\tilde{b}_L} + m_b^2 + M_Z^2 c_{2\beta}(T_b^3 - Q_b s_\mathrm{w}^2) & m_b X_q^* \\ m_b X_q & M^2_{\tilde{b}_R} + m_b^2 + M_Z^2 c_{2\beta} Q_b s_\mathrm{w}^2 \end{pmatrix}$$

$$\Rightarrow \; m_{\tilde{\mathrm{b}}_1}, m_{\tilde{\mathrm{b}}_2}, \theta_{\tilde{\mathrm{b}}}$$

with $X_q = A_q - \mu^* \kappa$, $\kappa = \{\cot\beta, \tan\beta\}$ for $q = t, b$, $\tan\beta \equiv v_u/v_d$

Gauge invariance $\Rightarrow M_{\tilde{t}_L} = M_{\tilde{b}_L}$

$\Rightarrow$ relation between $m_{\tilde{\mathrm{t}}_1}, m_{\tilde{\mathrm{t}}_2}, \theta_{\tilde{\mathrm{t}}}, m_{\tilde{\mathrm{b}}_1}, m_{\tilde{\mathrm{b}}_2}, \theta_{\tilde{\mathrm{b}}}$

Mass relations in the MSSM

SM: all masses are free input parameters (except $M_{\rm W}$-$M_{\rm Z}$ rel.)

MSSM:

- Sfermion mass relations, e.g.

$$m^2_{\tilde{e}_L} = m^2_{\tilde{\nu}_L} - M^2_{\rm W} \cos(2\beta)$$

- Relations between neutralino and chargino masses
- Upper bound on mass of lightest $\mathcal{CP}$-even Higgs boson

All relations receive corrections from loop effects

$\Leftrightarrow$ effects of soft SUSY breaking, ew symmetry breaking

$\Rightarrow$ Experimental verification of parameter relations is a crucial test of SUSY!

The Higgs sector of the MSSM

'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 for both)
- Supersymmetry imposes relations between the parameters

$\Rightarrow$ Two parameters instead of one:

$$\tan\beta \equiv \frac{v_u}{v_d}, \qquad M_\mathrm{A} \text{ (or } M_{\mathrm{H}^\pm})$$

Higgs potential of the MSSM

MSSM Higgs potential contains two Higgs doublets:

$$V = \left(|\mu|^2 + m_{H_u}^2\right)\left(|h_u^0|^2 + |h_u^+|^2\right) + \left(|\mu|^2 + m_{H_d}^2\right)\left(|h_d^0|^2 + |h_d^-|^2\right)$$

$$+ \left[b\left(h_u^+ h_d^- - h_u^0 h_d^0\right) + \text{h.c.}\right]$$

$$+ \underbrace{\frac{g^2 + g'^2}{8}}\left(|h_u^0|^2 + |h_u^+|^2 - |h_d^0|^2 - |h_d^-|^2\right)^2 + \underbrace{\frac{g'^2}{2}}\left|h_u^+ h_d^{0*} + h_u^0 h_d^{-*}\right|^2$$

gauge couplings, in contrast to the SM

Five physical states: $h^0, H^0, A^0, H^\pm$

Parameters (besides g, g'):

μ: mixing term of the two Higgs doublets in superpotential, $\mu H_d H_u$

m_{H_u}, m_{H_d}, b: soft SUSY-breaking parameters

Parameters in MSSM Higgs potential (besides g, g')

$$v_d,\ v_u,\ \left(|\mu|^2 + m_{H_u}^2\right),\ \left(|\mu|^2 + m_{H_d}^2\right),\ b$$

Relation for M_W^2, M_Z^2 yields 1 condition:

$$M_\mathrm{W}^2 = \frac{1}{2} g'^2 (v_d^2 + v_u^2), \qquad M_\mathrm{Z}^2 = \frac{1}{2}(g^2 + g'^2)(v_d^2 + v_u^2)$$

Minimization of V w.r.t. neutral Higgs fields h_d^0, h_u^0

⇒ 2 conditions

⇒ only two free parameters remain in the Higgs potential, conventionally chosen as

$$\tan\beta \equiv \frac{v_u}{v_d}, \qquad M_\mathrm{A}^2 = -b(\tan\beta + \cot\beta)$$

⇒ M_h, M_H, mixing angle α, $M_{\mathrm{H}^\pm}$: derived quantities can be predicted

E.g., lowest-order prediction: $M_{\mathrm{H}^\pm}^2 = M_\mathrm{A}^2 + M_\mathrm{W}^2$

Conditions on MSSM Higgs potential

Potential has to be bounded from below

$$\Rightarrow \quad 2b < 2|\mu|^2 + m_{H_u}^2 + m_{H_d}^2$$

EW symmetry breaking $\Leftrightarrow h_u^0 = h_d^0 = 0$ must not be stable minimum

$$\Rightarrow \quad b^2 > \left(|\mu|^2 + m_{H_u}^2\right)\left(|\mu|^2 + m_{H_d}^2\right)$$

The two conditions above cannot be satisfied simultaneously if $b = m_{H_u} = m_{H_d} = 0$

$\Rightarrow$ SUSY breaking required for EW symmetry breaking

The "μ problem"

MSSM contains term $\mu H_d H_u$ in superpotential

μ: dimensionful parameter

For EW symmetry breaking required: $\mu \sim$ electroweak scale

But: no a priori reason for $\mu \neq 0$, $\mu \ll M_{\mathrm{Pl}}$

Possible solution: μ related to v.e.v. of additional field

$\Rightarrow$ Introduction of extra singlet field S, v.e.v. $s \Rightarrow$ “NMSSM”

Superpotential: $\mathcal{V} = \lambda H_d H_u S + \frac{1}{3}\kappa S^3 + \ldots$

Physical states in NMSSM Higgs-sector:

S_1, S_2, S_3 (CP-even), P_1, P_2 (CP-odd), $H^\pm$

Higgs mass bound in the MSSM

Prediction for M_h, M_H, $\ldots$

Tree-level result for M_h, M_H:

$$M^2_{\mathrm{H,h}} = \frac{1}{2}\left[M_\mathrm{A}^2 + M_\mathrm{Z}^2 \pm \sqrt{(M_\mathrm{A}^2 + M_\mathrm{Z}^2)^2 - 4M_\mathrm{Z}^2 M_\mathrm{A}^2 \cos^2 2\beta}\right]$$

$\Rightarrow M_\mathrm{h} \leq M_\mathrm{Z}$ at tree level

MSSM tree-level bound (gauge sector): excluded by LEP!

Large radiative corrections (Yukawa sector, $\ldots$):

Yukawa couplings: $\frac{\mathrm{e}\, m_\mathrm{t}}{2M_\mathrm{W} s_\mathrm{W}}$, $\frac{\mathrm{e}\, m_\mathrm{t}^2}{M_\mathrm{W} s_\mathrm{W}}$, $\ldots$

$\Rightarrow$ Dominant one-loop corrections: $G_\mu m_\mathrm{t}^4 \ln\left(\frac{m_{\tilde{\mathrm{t}}_1} m_{\tilde{\mathrm{t}}_2}}{m_\mathrm{t}^2}\right)$, $\quad \mathcal{O}(100\%)$!

Higgs mass bound in the MSSM

Present status of $M_{\rm h}$ prediction in the MSSM:

Complete one-loop $+$ "almost complete" two-loop result available

Upper bound on $M_{\rm h}$ (*FeynHiggs*):

[*S. Heinemeyer, W. Hollik, G. W. '99*], [*M. Frank, S. Heinemeyer, W. Hollik, G. W. '02*] [*G. Degrassi, S. Heinemeyer, W. Hollik, P. Slavich, G. W. '02*]

$$M_{\rm h} \lesssim 135\,{\rm GeV}$$

Extensions of the MSSM: $M_{\rm h} \lesssim 200~{\rm GeV}$ (if couplings stay perturbative up to high scale)

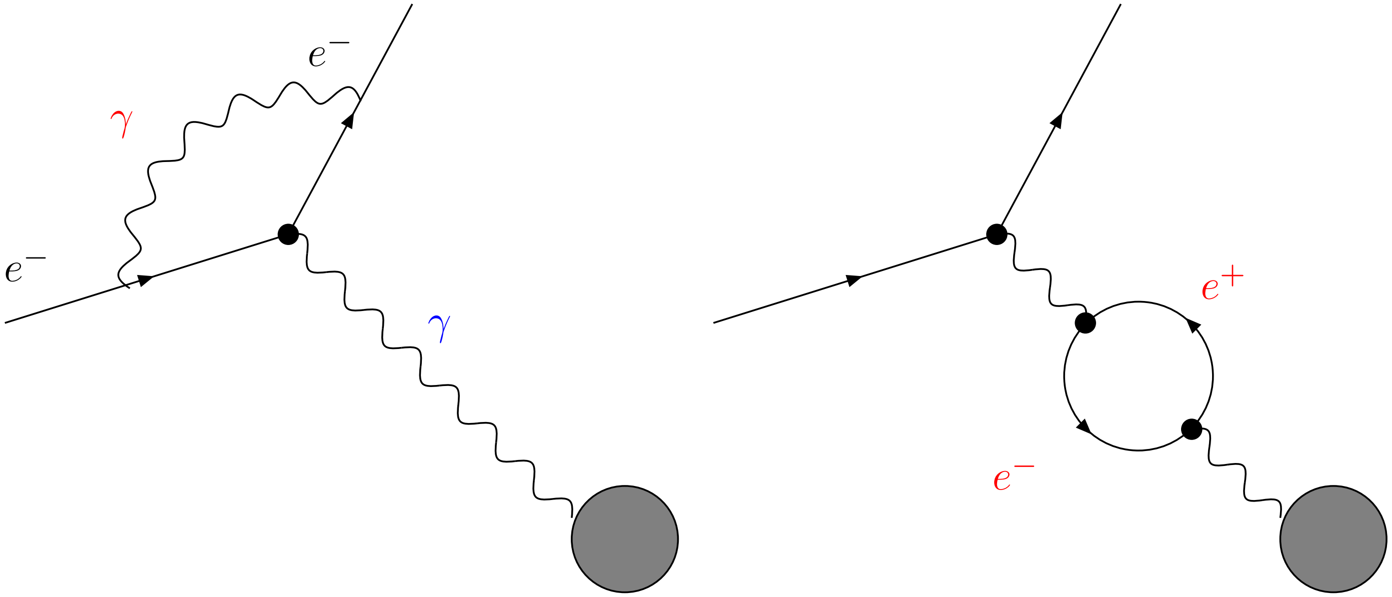
$\Rightarrow$ SUSY requires a light Higgs boson

Definite and robust prediction, testable at LHC and ILC

Electroweak precision physics

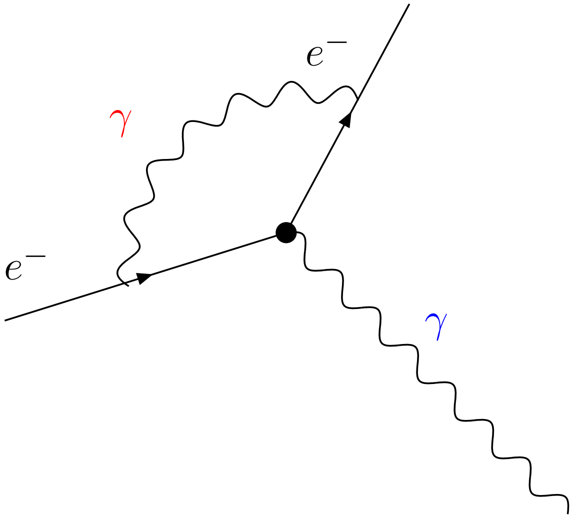
Historical: QED

Lamb shift:



nucleus

$g-2$:



$$a = \frac{1}{2}(g-2)$$

$$a_{\text{exp}} = 1\,159\,652\,188(\pm 4) \times 10^{-12}$$

$$a_{\text{theo}} = 1\,159\,652\,157(\pm 28) \times 10^{-12}$$

Electroweak precision measurements

- LEP1/SLC: e^+e^- annihilation at the Z-boson resonance

  LEP1: $\sim 4 \times 10^6$ events/experiment

- LEP2: $e^+e^- \to W^+W^-$

- Tevatron: $q\bar{q}' \to W \to l\bar{\nu},\ q\bar{q}'$

  $$q\bar{q} \to t\bar{t},\ t \to W^+b \to \ldots$$

- low-energy experiments: muon decay, $g_\mu - 2$, b physics, . . .

Electroweak precision physics

Electroweak precision measurements:

$M_\mathrm{W}[\,\mathrm{GeV}]$	$=$	80.398 ± 0.025	0.03%
$\sin^2\theta_\mathrm{eff}^\mathrm{lept}$	$=$	0.23153 ± 0.00016	0.07%
$\Gamma_\mathrm{Z}[\,\mathrm{GeV}]$	$=$	2.4952 ± 0.0023	0.09%
$M_\mathrm{Z}[\,\mathrm{GeV}]$	$=$	91.1875 ± 0.0021	0.002%
$G_\mu[\,\mathrm{GeV}^{-2}]$	$=$	$1.16637(1)\,10^{-5}$	0.0009%
$m_\mathrm{t}[\,\mathrm{GeV}]$	$=$	170.9 ± 1.8	1.1%
$\ldots$			

Quantum effects of the theory:

Loop corrections to M_W, $\sin^2\theta_\mathrm{eff}$, Γ_Z, $\ldots$: $\sim \mathcal{O}(1\%)$

$\Rightarrow$ EW prec. measurements test quantum effects of the theory

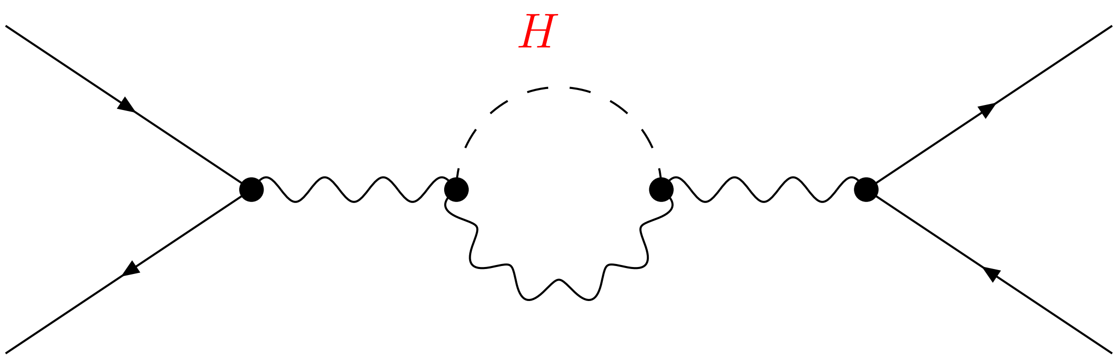
Comparison of electroweak precision data with theory predictions

EW precision data:
$M_Z, M_W, \sin^2\theta_{\mathrm{eff}}^{\mathrm{lept}}, \ldots$

Theory:
SM, MSSM, ...

$\Downarrow$

Test of theory at quantum level: sensitivity to loop corrections



$\Downarrow$

Indirect constraints on unknown parameters: $M_H, \ldots$

Effects of "new physics"?

Indirect determination of m_t from precision data vs. direct measurement

Indirect det. of m_t from precision data: $m_\mathrm{t} = 178^{+12}_{-9}\ \mathrm{GeV}$

Direct measurement: $m_\mathrm{t} = 170.9 \pm 1.8\ \mathrm{GeV}$

Leading corrections to precision observables:

$$\sim m_\mathrm{t}^2$$

$$\sim \ln M_\mathrm{H}$$

$\Rightarrow$ For constraints on M_H, SUSY, . . . : very high accuracy of measurements and theoretical predictions needed

Theoretical uncertainties:

– unknown higher-order corrections

– experimental error of input parameters: m_t, $\Delta\alpha_\mathrm{had}$, . . .

Observables with the highest sensitivity to the Higgs-boson mass: M_W, $\sin^2\theta_\mathrm{eff}$

M_W: Comparison of prediction for muon decay with experiment (Fermi constant G_μ)

$$\Rightarrow \qquad M_\mathrm{W}^2\left(1-\frac{M_\mathrm{W}^2}{M_\mathrm{Z}^2}\right)=\frac{\pi\alpha}{\sqrt{2}G_\mu}\left(1+\underset{\substack{\Updownarrow\\ \text{loop corrections}}}{\Delta r}\right),$$

$\Rightarrow$ Theo. prediction for M_W in terms of M_Z, α, G_μ, $\Delta r(m_\mathrm{t}, m_{\tilde{\mathrm{t}}}, \ldots)$

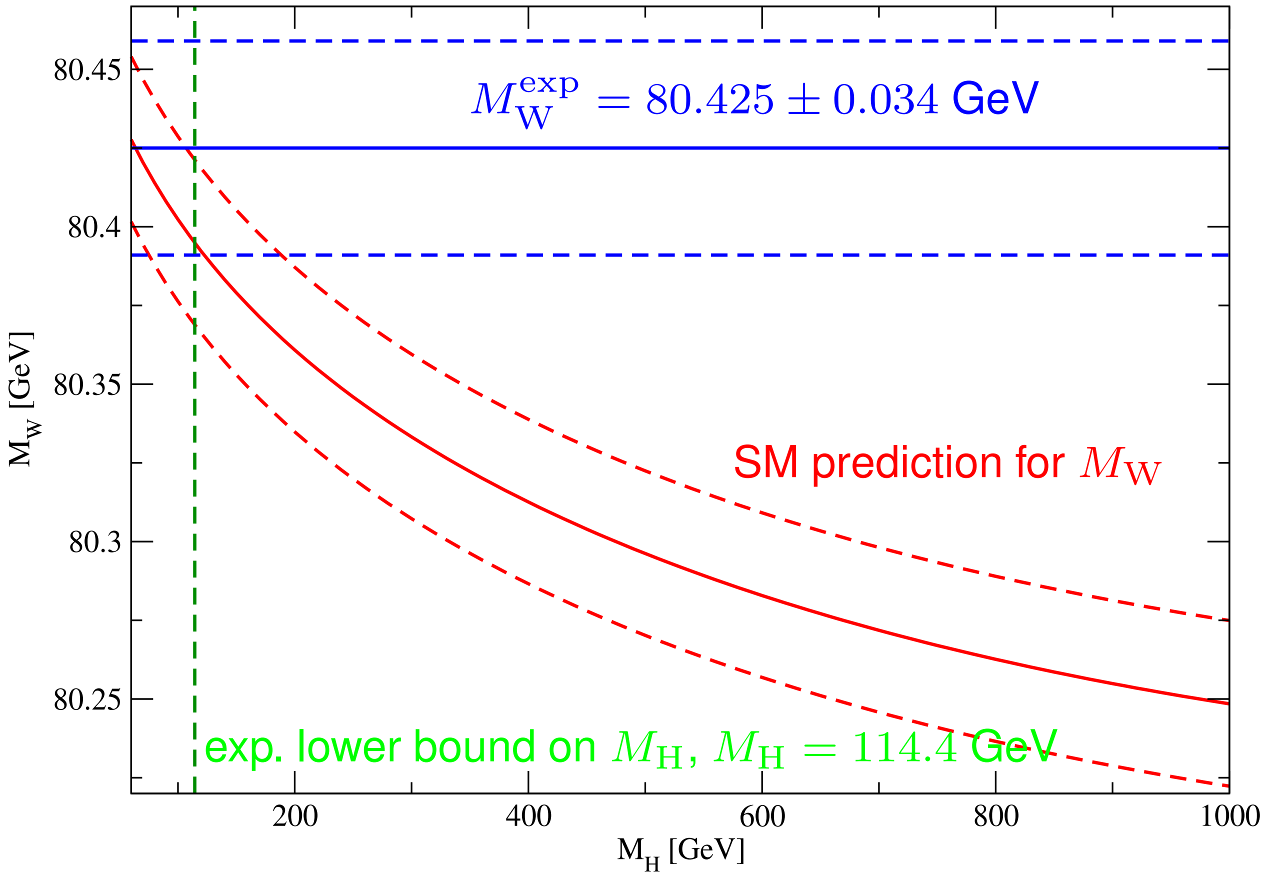
$\sin^2\theta_\mathrm{eff}$: Effective couplings at the Z resonance:

$$\Rightarrow \qquad \sin^2\theta_\mathrm{eff}=\frac{1}{4}\left(1-\mathrm{Re}\,\frac{g_V}{g_A}\right)=\left(1-\frac{M_\mathrm{W}^2}{M_\mathrm{Z}^2}\right)\mathrm{Re}\,\kappa_l(s=M_\mathrm{Z}^2)$$

Complete 2-loop results $+$ leading higher-order corrections known for M_W, $\sin^2\theta_\mathrm{eff}$ in the SM

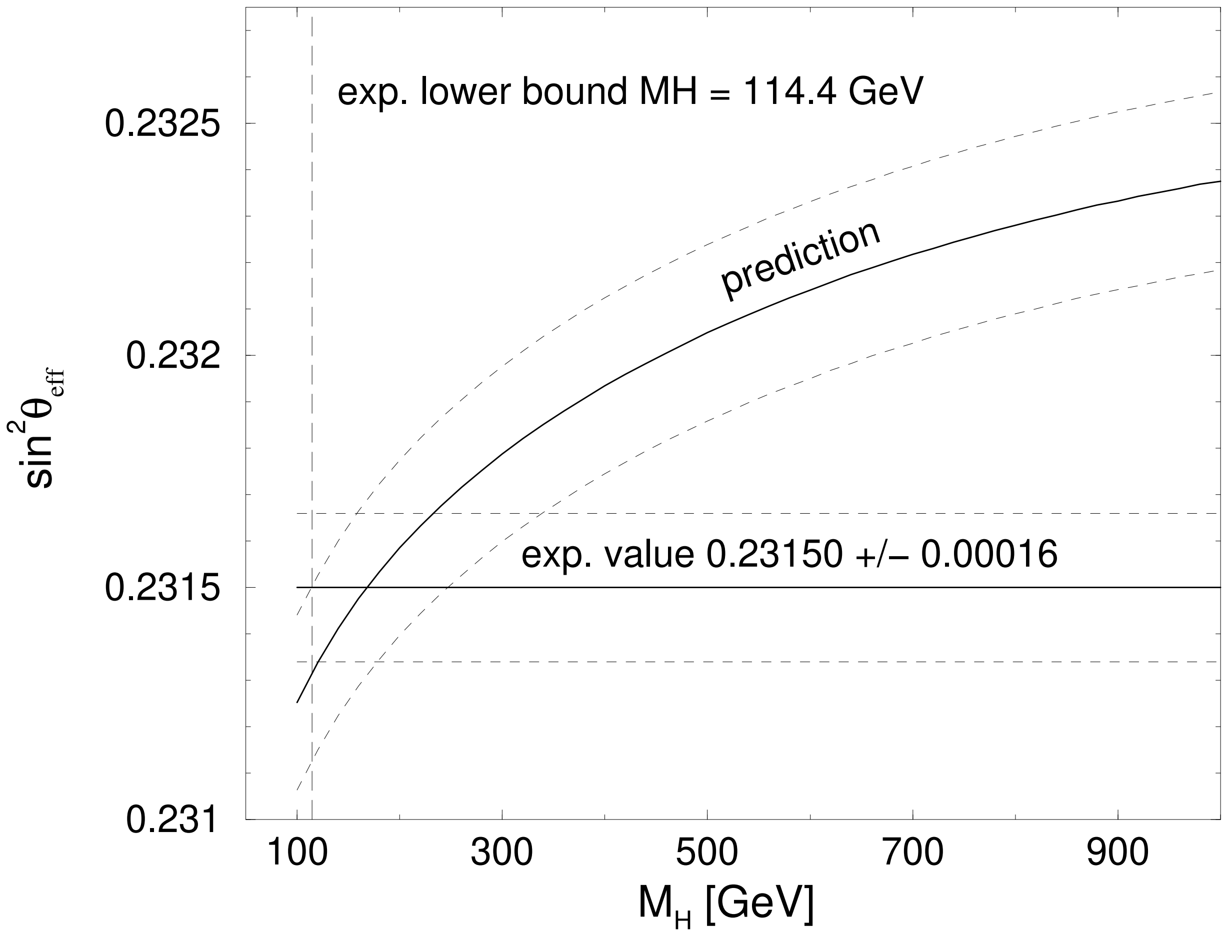
SM prediction for $M_{\rm W}$ (complete 2-loop result) vs. experimental result

[M. Awramik, M. Czakon, A. Freitas, G.W. '04]



$\Rightarrow$ Preference for light Higgs

SM prediction for $\sin^2\theta_{\mathrm{eff}}$ vs. experimental result

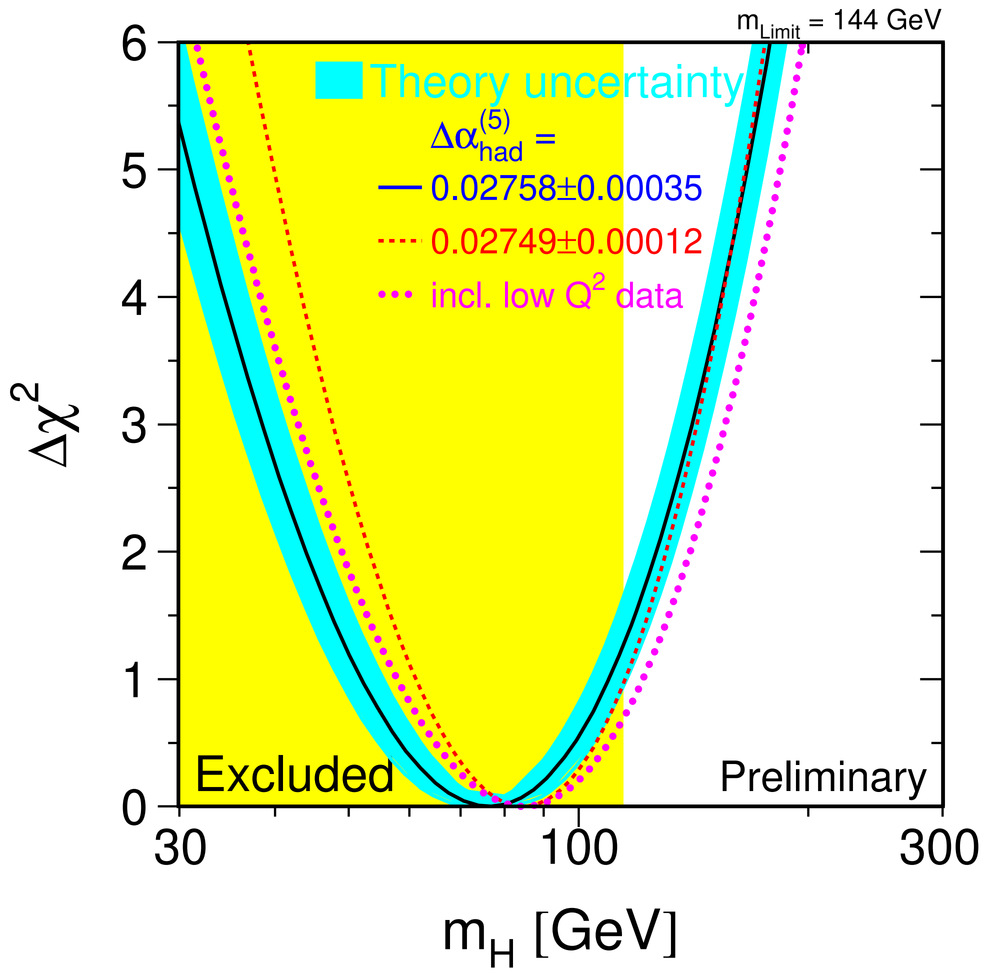


[*M. Awramik, M. Czakon, A. Freitas, G.W. '04*]

$\Rightarrow$ Preference for light Higgs

Global fit to all data in the SM: indirect constraints on M_H vs. direct search limit

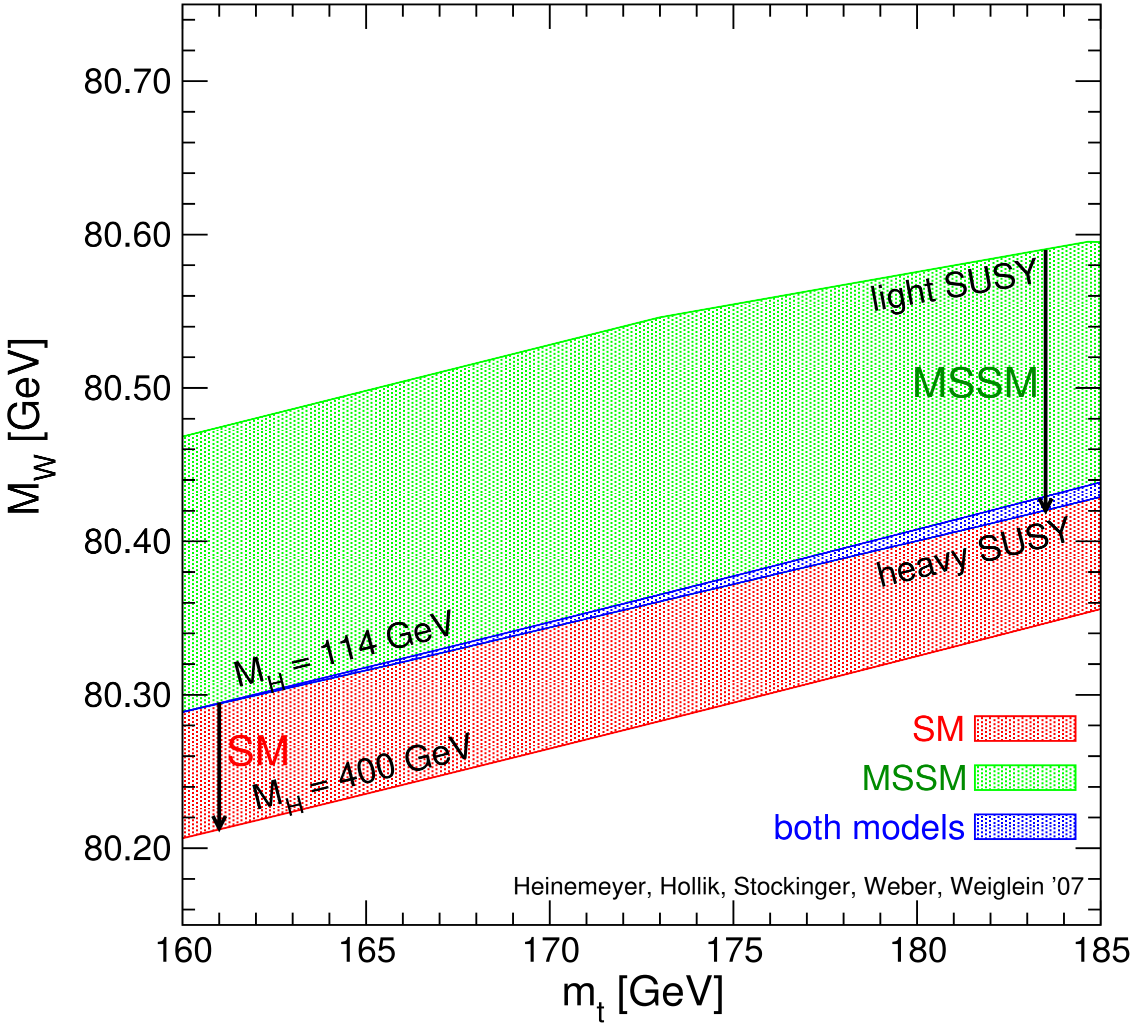
[*LEPEWWG '07*]



$\Rightarrow$ Tension between indirect bounds on M_H in the SM and direct search limit has increased

Prediction for M_W (parameter scan): SM vs. MSSM

Prediction for M_W in the SM and the MSSM:



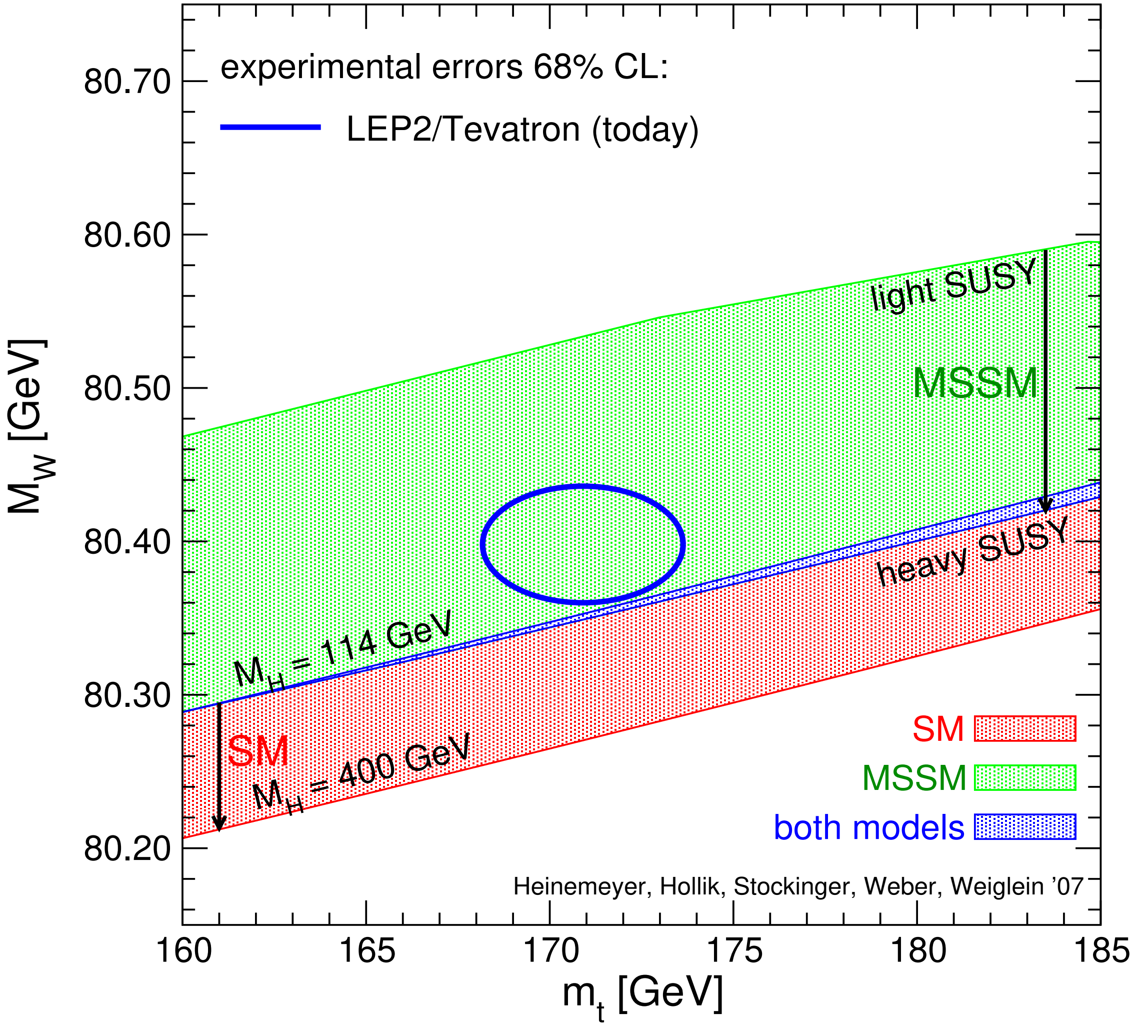
[*S. Heinemeyer, W. Hollik, A.M. Weber, G. W. '07*]

MSSM: SUSY parameters varied

SM: M_H varied

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*]

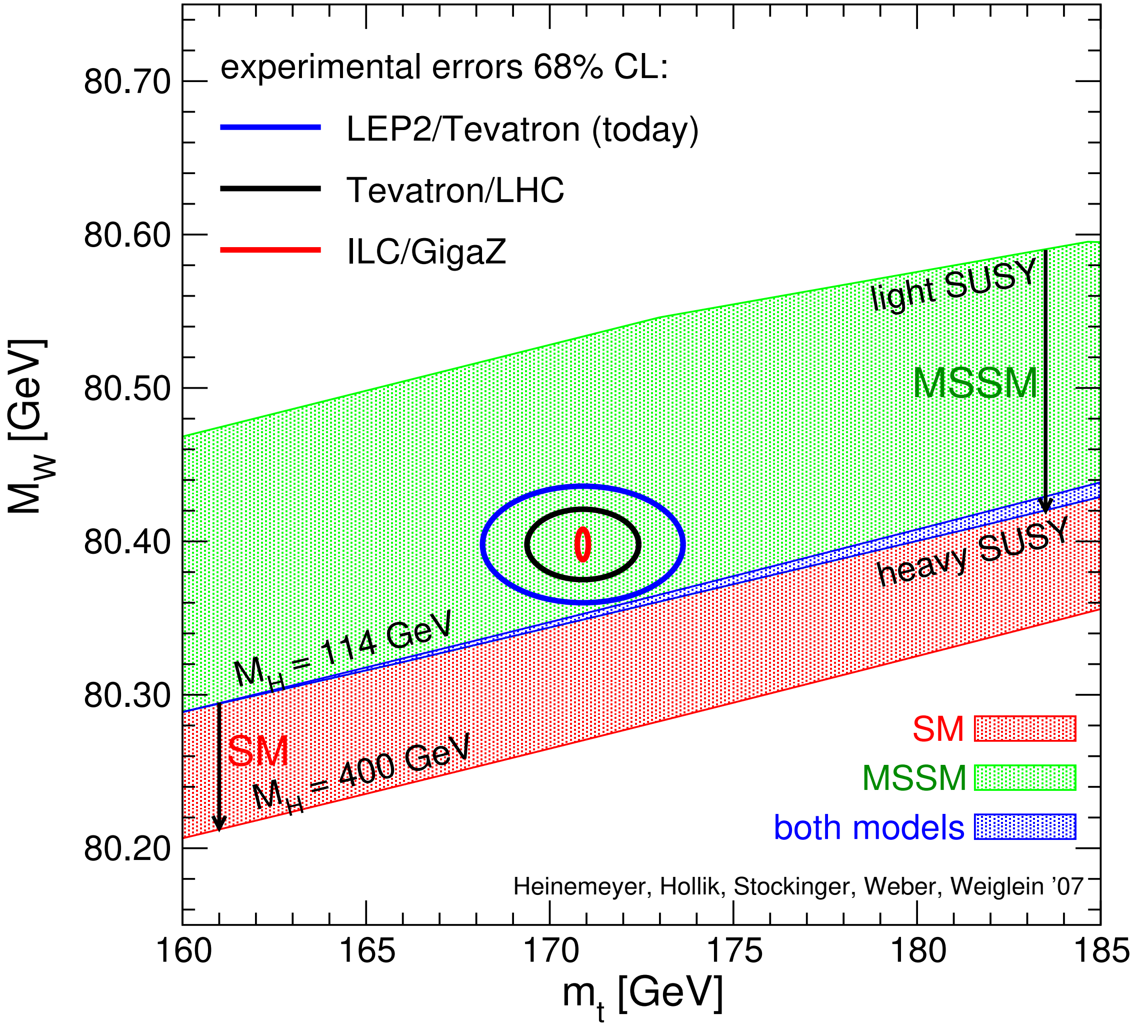
MSSM: SUSY parameters varied

SM: M_H varied

$\Rightarrow$ Slight preference for MSSM over SM

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*]

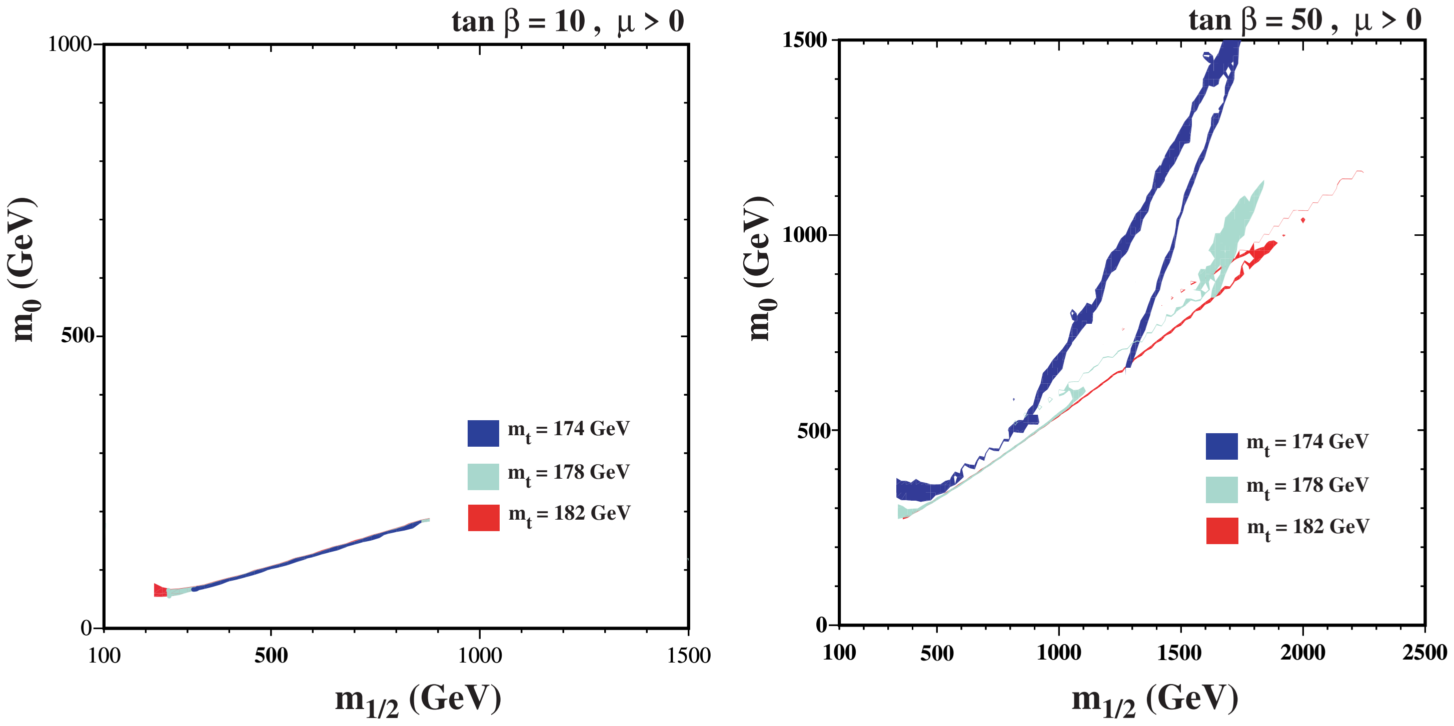
MSSM: SUSY parameters varied

SM: M_{H} varied

$\Rightarrow$ Slight preference for MSSM over SM

Constrained MSSM (CMSSM) with restrictions from dark matter relic density

Allowed region in $(m_{1/2}, m_0)$ plane (fixed A_0, different m_t):



⇒ narrow “WMAP strips”

⇒ effectively reduces dimensionality of parameter space

⇒ analyse CMSSM along WMAP strips

Sensitivity to the scale of Supersymmetry

CMSSM with restrictions from dark matter relic density:
$m_{1/2}$, m_0, A_0 (GUT scale), $\tan\beta$, $\mathrm{sign}(\mu)$ (weak scale)

$\Rightarrow$ Low-energy spectrum from renormalisation group running

Cold dark matter (CDM) density (WMAP, . . .):

$$0.094 < \Omega_{\mathrm{CDM}}\, h^2 < 0.129$$

$\Rightarrow$ Constraints on SUSY parameter space

$\Rightarrow$ χ^2 fit in the CMSSM with dark matter constraints
Electroweak precision observables (EWPO):
M_{W}, $\sin^2\theta_{\mathrm{eff}}$, Γ_{Z}, $(g-2)_\mu$, M_{h}
B-physics observables (BPO):
$\mathrm{BR}(b \to s\gamma)$, $\mathrm{BR}(B_{\mathrm{s}} \to \mu^+\mu^-)$, $\mathrm{BR}(B_{\mathrm{u}} \to \tau\nu_\tau)$, $\Delta M_{B_{\mathrm{s}}}$

The anomalous magnetic moment of the muon:

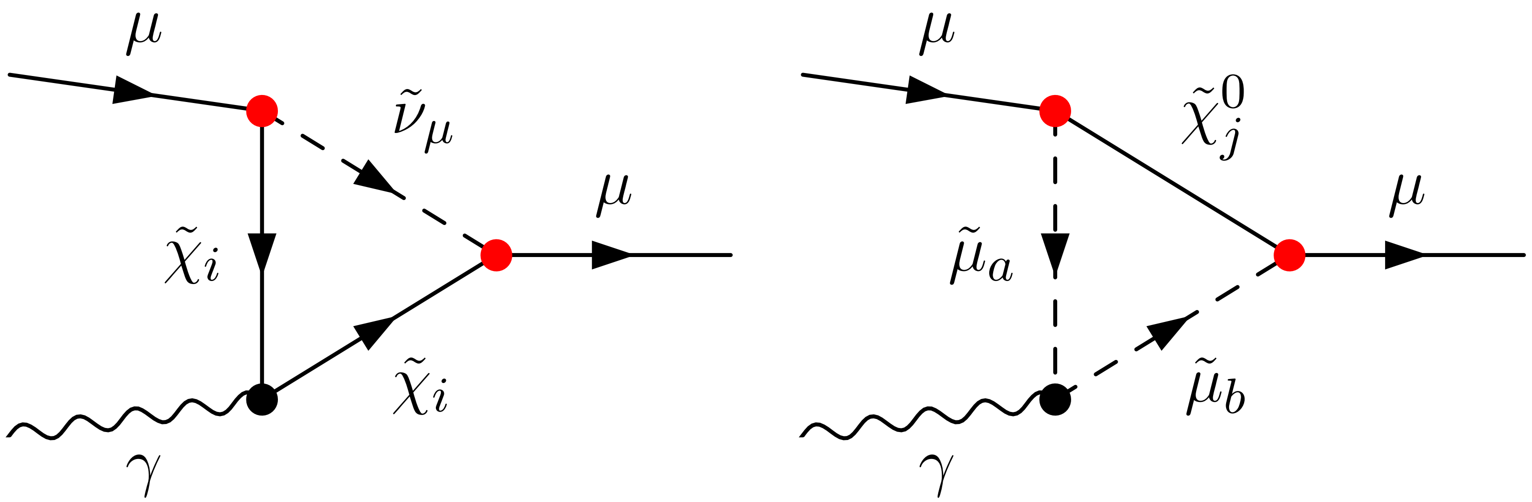
$$(g-2)_\mu \equiv 2a_\mu$$

Experimental result for a_μ vs. SM prediction (using e^+e^- data for hadronic vacuum polarisation):

$$a_\mu^{\rm exp} - a_\mu^{\rm theo} = (27.5 \pm 8.4) \times 10^{-10} \;\; : \;\; 3.3\,\sigma \; .$$

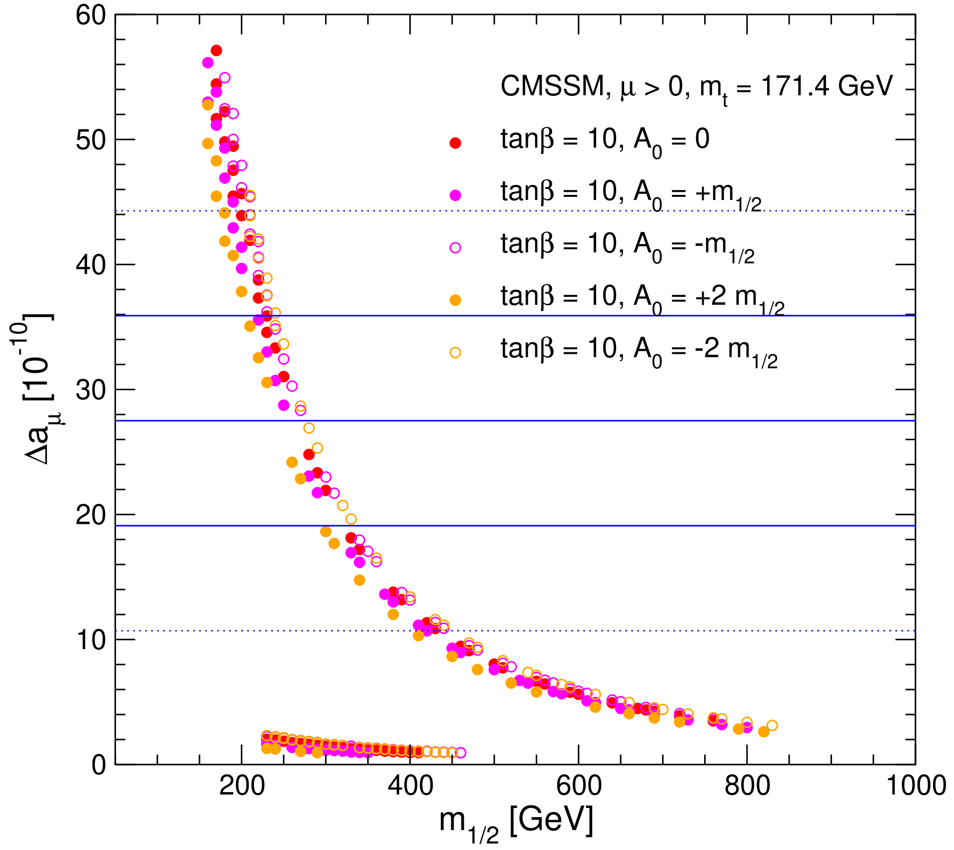
Better agreement between theory and experiment possible in models of physics beyond the SM

Example: one-loop contributions of superpartners of fermions and gauge bosons

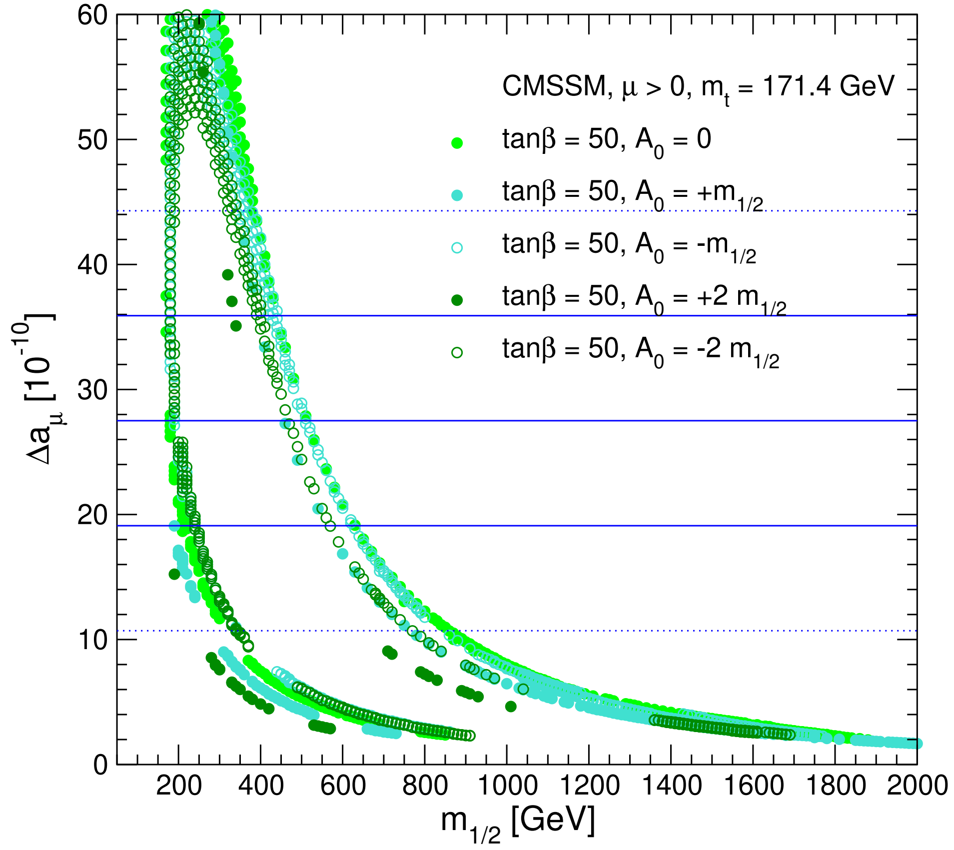


CMSSM prediction for Δa_μ vs. experimental result (1σ and 2σ bands)

$\tan\beta = 10$:



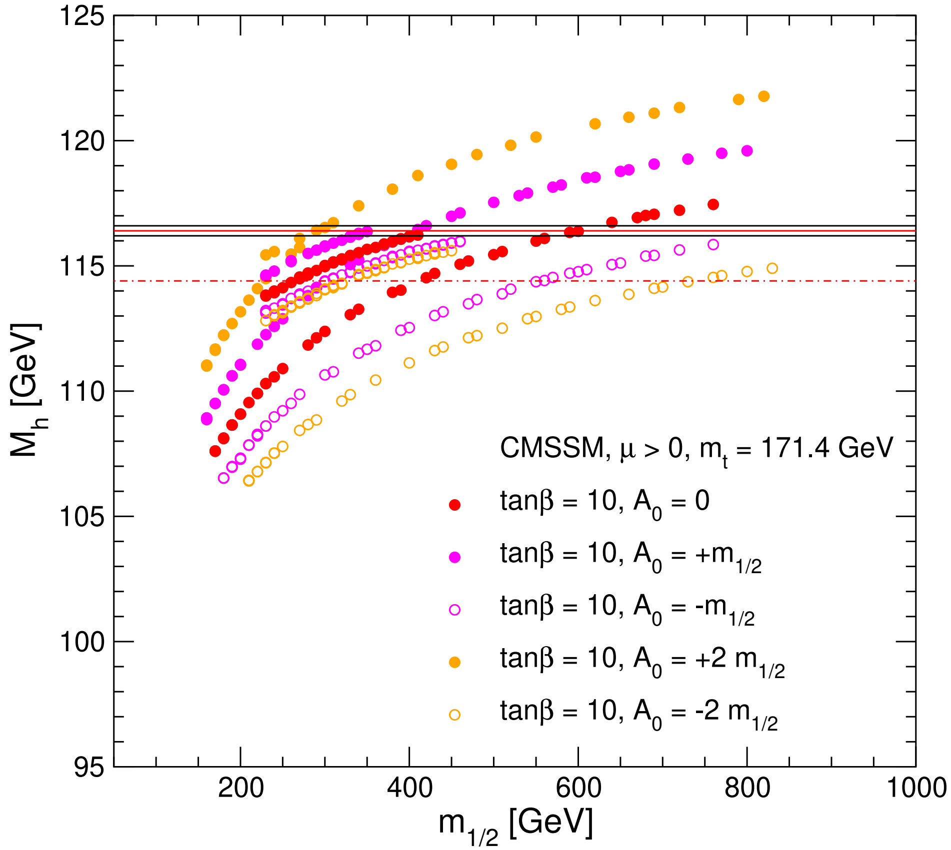
$\tan\beta = 50$:



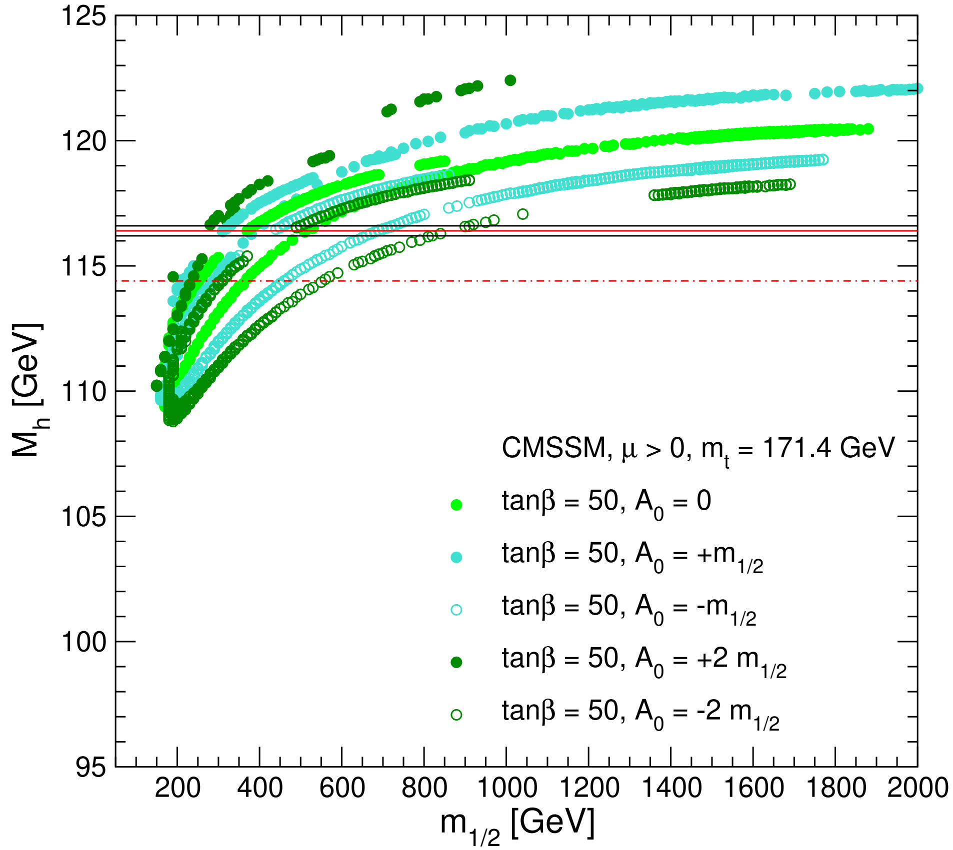
$\Rightarrow$ Preference for relatively light SUSY scale

CMSSM prediction for M_h vs. LEP bound and hypothetical experimental result

$\tan\beta = 10$:



$\tan\beta = 50$:

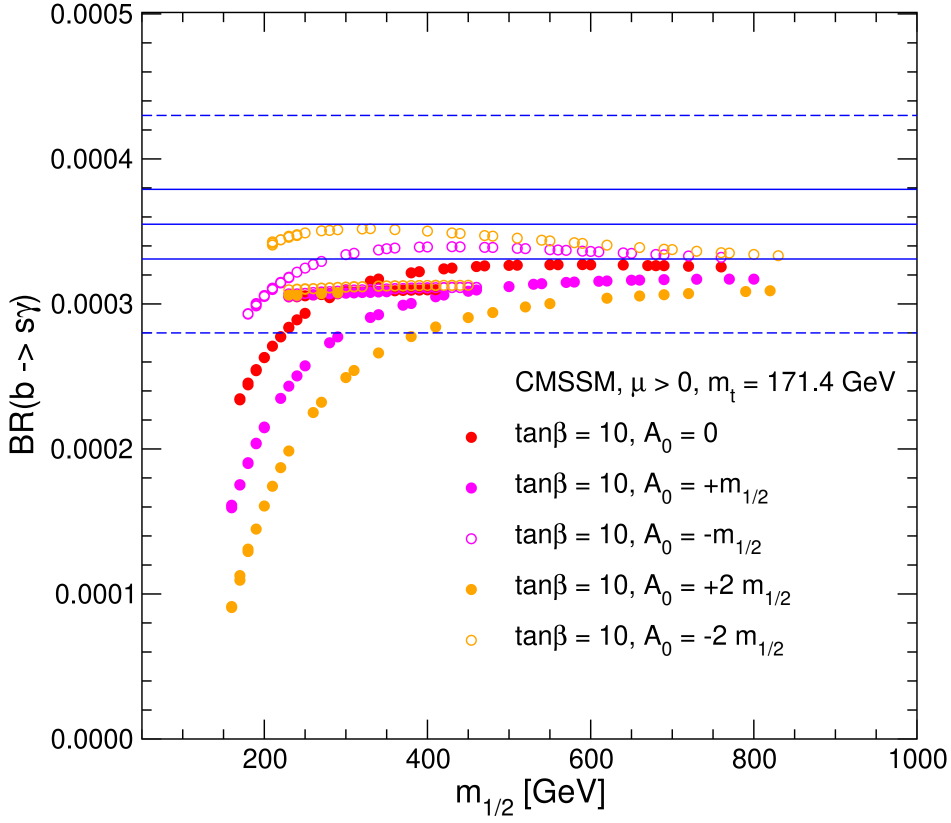


$\Rightarrow$ High sensitivity to variations of $m_{1/2}$, A_0

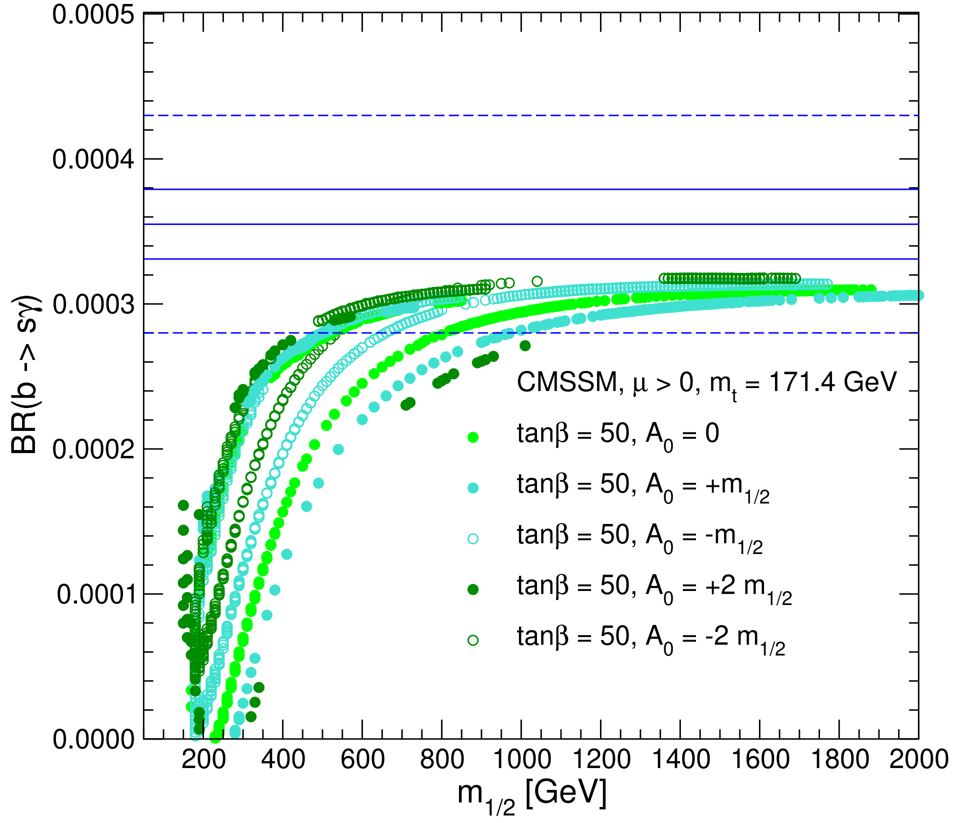
Relatively small values of $m_{1/2}$ allowed

CMSSM prediction for $\mathrm{BR}(b \to s\gamma)$ *vs. exp. result, exp. error* $+$ *theory uncertainty*

$\tan\beta = 10$:



$\tan\beta = 50$:



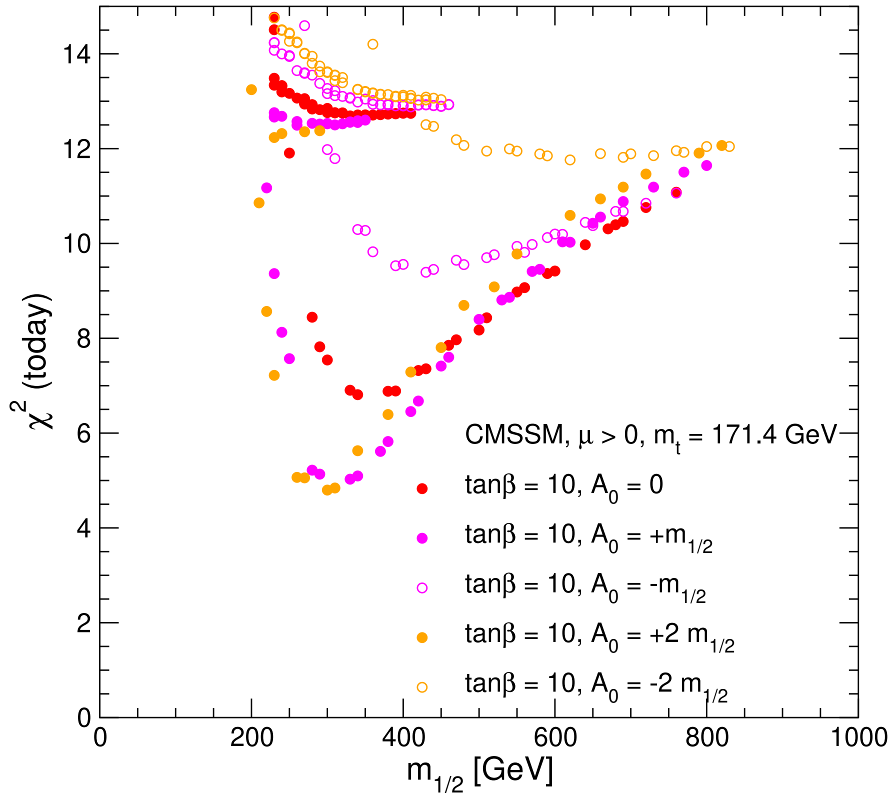
$\Rightarrow$ Preference for relatively heavy SUSY scale

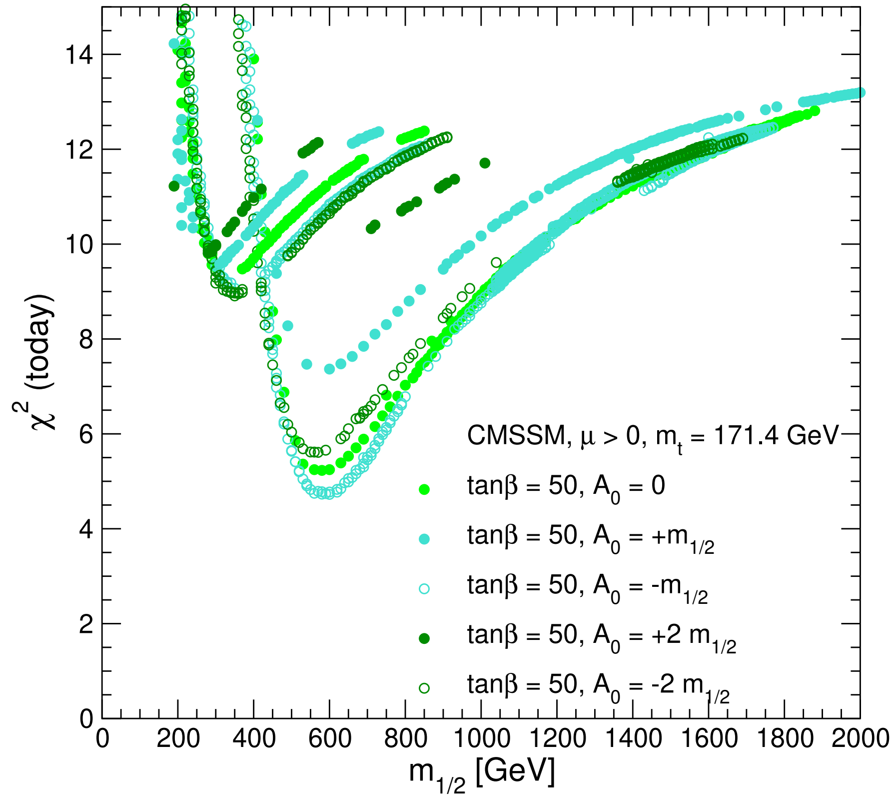
Slight tension with EWPO

χ^2 ***fit in the CMSSM, EWPO + BPO:*** M_W, $\sin^2\theta_{\rm eff}$, Γ_Z, $(g-2)_\mu$, M_h, BR$(b \to s\gamma)$, BR$(B_s \to \mu^+\mu^-)$, BR$(B_u \to \tau\nu_\tau)$, ΔM_{B_s}

[*J. Ellis, S. Heinemeyer, K. Olive, A. Weber, G. W. '07*]

$\tan\beta = 10$: $\tan\beta = 50$:





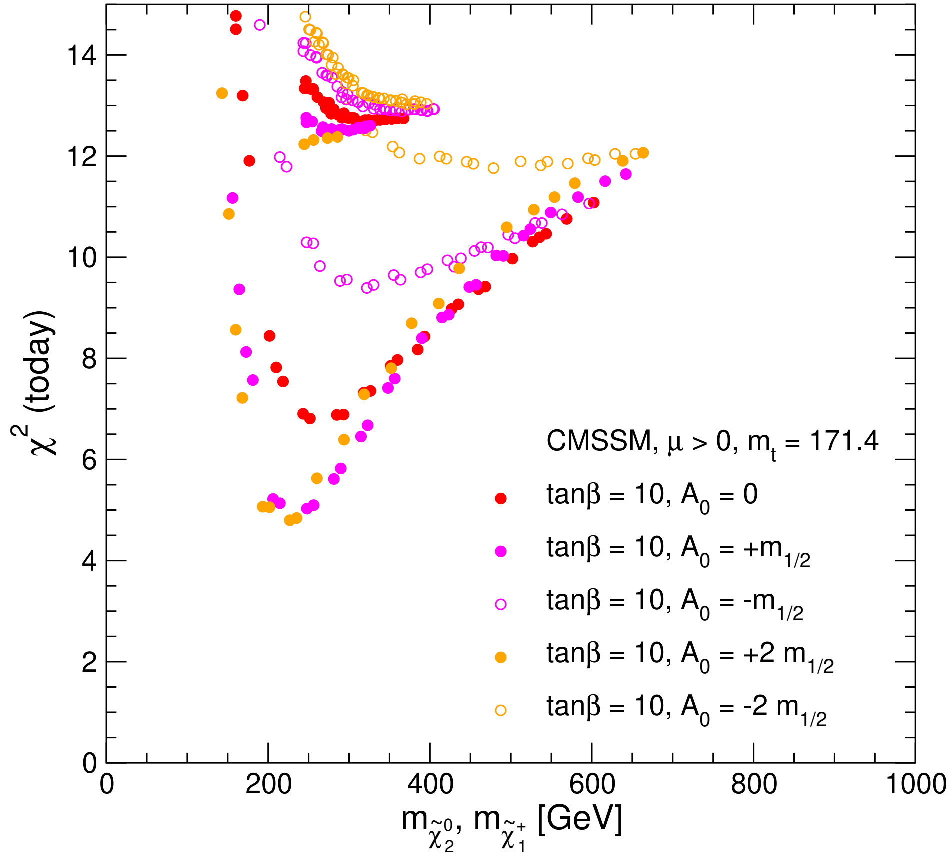
$\Rightarrow$ Good description of the data

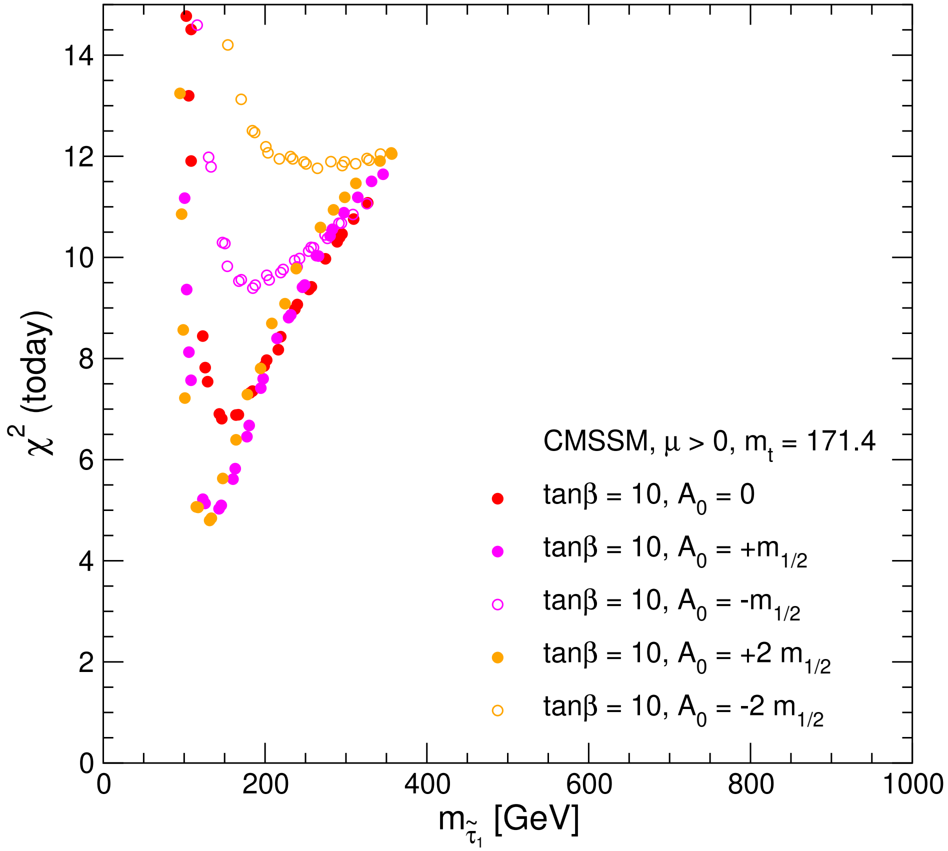
Preference for relatively light SUSY scale

Fit results for particle masses, $\tan\beta = 10$*:*

$$m_{\tilde{\chi}_1^+} \approx m_{\tilde{\chi}_2^0}, \quad m_{\tilde{\tau}_1}$$

[J. Ellis, S. Heinemeyer, K. Olive, A. Weber, G. W. '07]





$\Rightarrow$ Good prospects for the LHC and ILC

Global CMSSM fit, all CMSSM parameters and dark matter constraint included in the fit

Global χ^2 fit in the Constrained MSSM (CMSSM):

$m_{1/2}$, m_0, A_0 (GUT scale), $\tan\beta$, $\mathrm{sign}(\mu)$ (weak scale)

Fit includes:

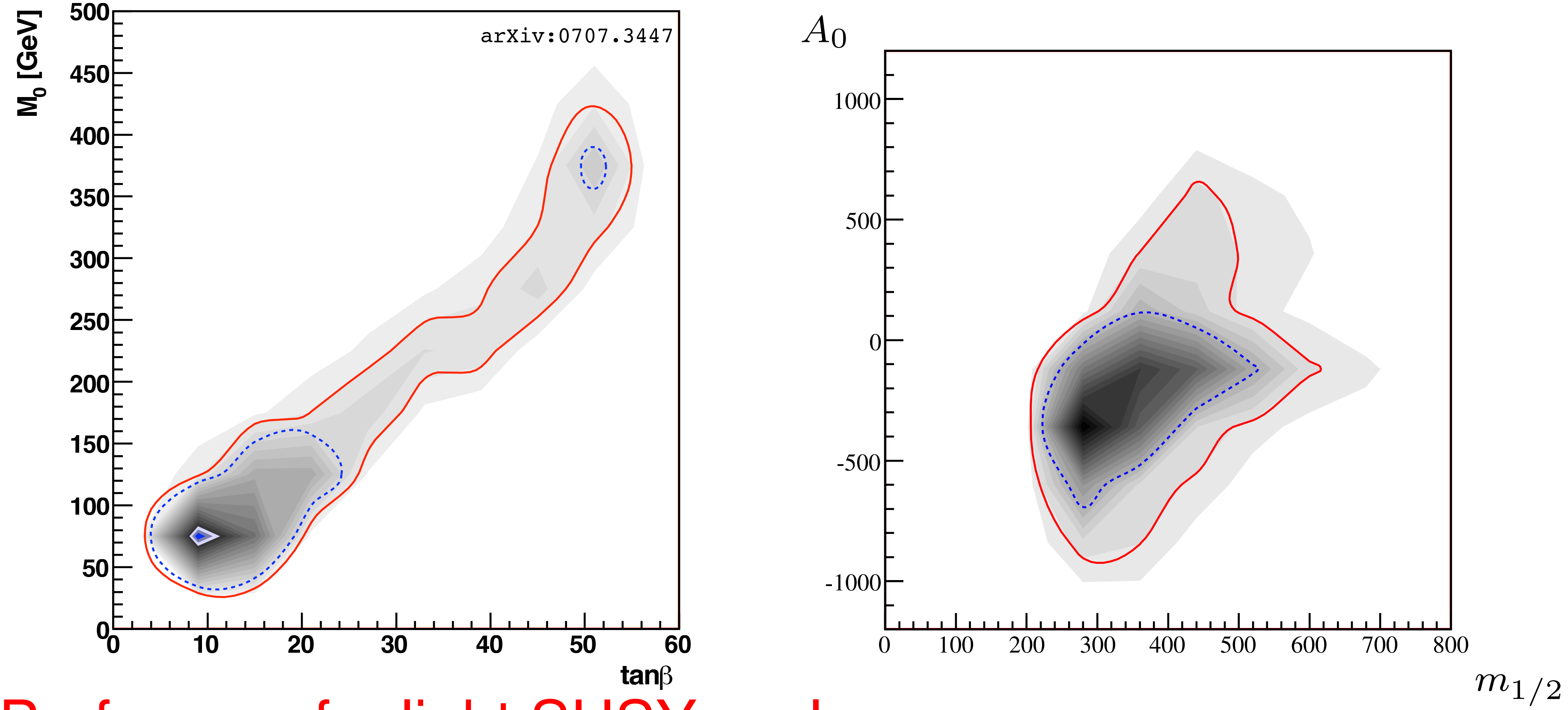
[*O. Buchmueller, R. Cavanaugh, A. De Roeck, S. Heinemeyer, G. Isidori, P. Paradisi, F. Ronga, A. Weber, G. W. '07*]

- All observables used in the SM fit of the LEPEWWG
- $+$ Cold dark matter (CDM) density (WMAP, . . .),
  $0.094 < \Omega_{\mathrm{CDM}}\, h^2 < 0.129$
- $+\ (g-2)_\mu$, $\mathrm{BR}(b \to s\gamma)$, $\mathrm{BR}(B_s \to \mu^+\mu^-)$

Global CMSSM fit

68% (dotted) and 95% (solid) confidence level regions

[O. Buchmueller, R. Cavanaugh, A. De Roeck, S. Heinemeyer, G. Isidori, P. Paradisi, F. Ronga, A. Weber, G. W. '07]



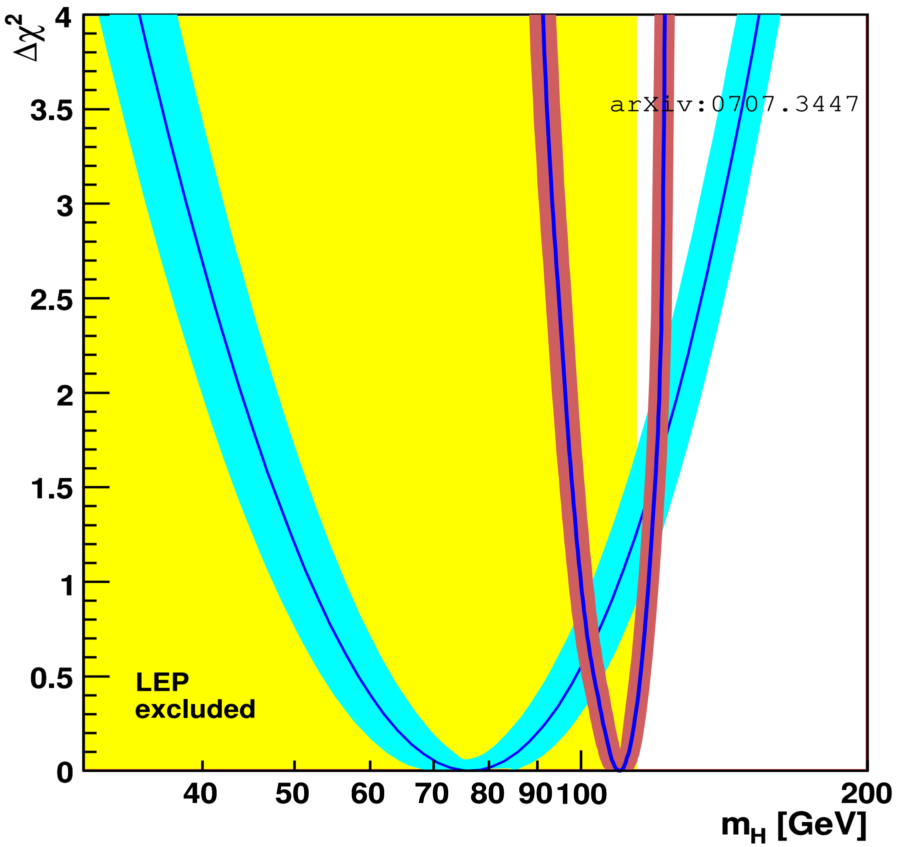
$\Rightarrow$ Preference for light SUSY scale

best fit values: $\tan\beta \approx 10$, $m_{1/2} \approx 300$ GeV

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*]

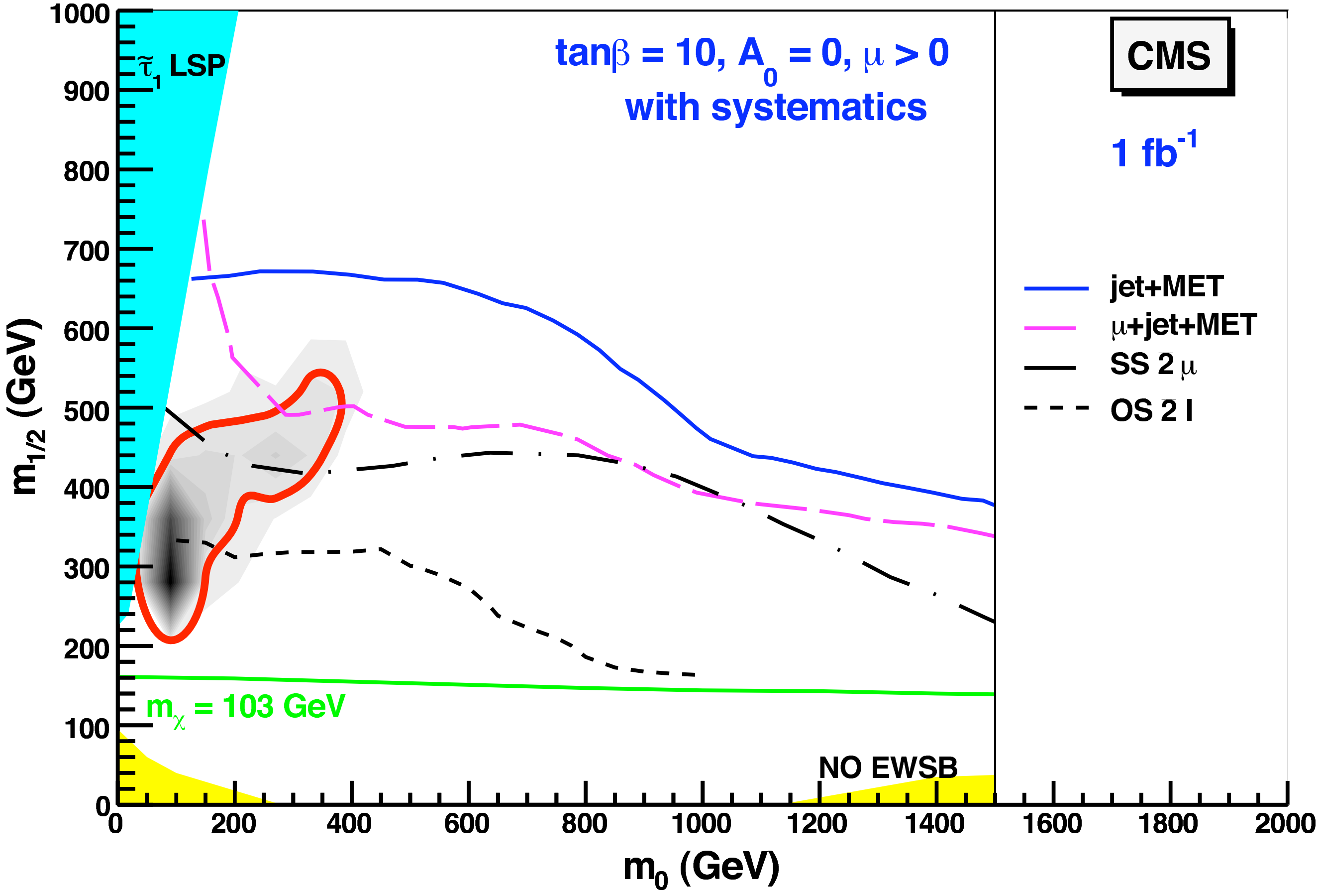
SM CMSSM



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

Comparison: preferred region in m_0–$m_{1/2}$ plane, LHC discovery reach for $1\ \mathrm{fb}^{-1}$ of understood data

[O. Buchmueller, R. Cavanaugh, A. De Roeck, S. Heinemeyer, G. Isidori, P. Paradisi, F. Ronga, A. Weber, G. W. '07]

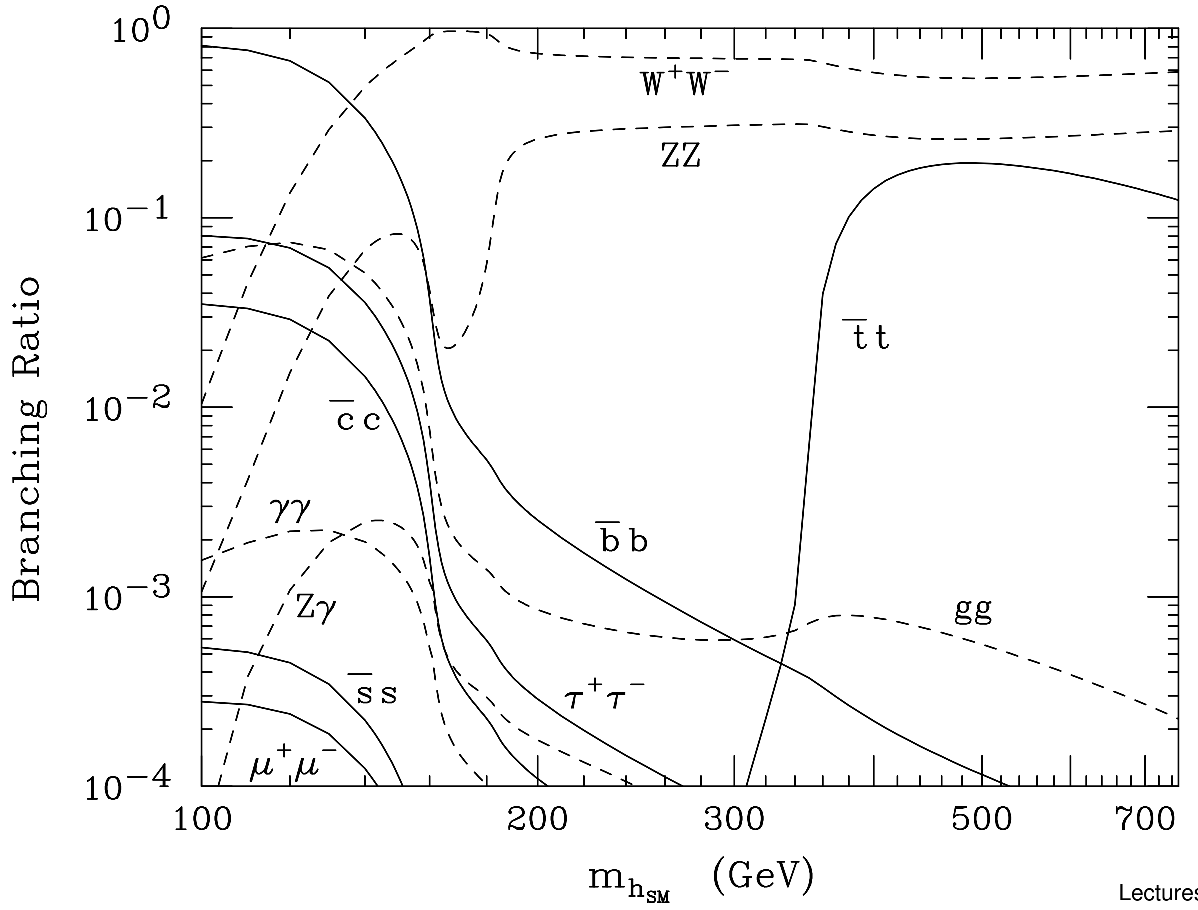


$\Rightarrow$ Preferred region would lead to early discovery

Higgs physics

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:

$H \to b\bar{b}$

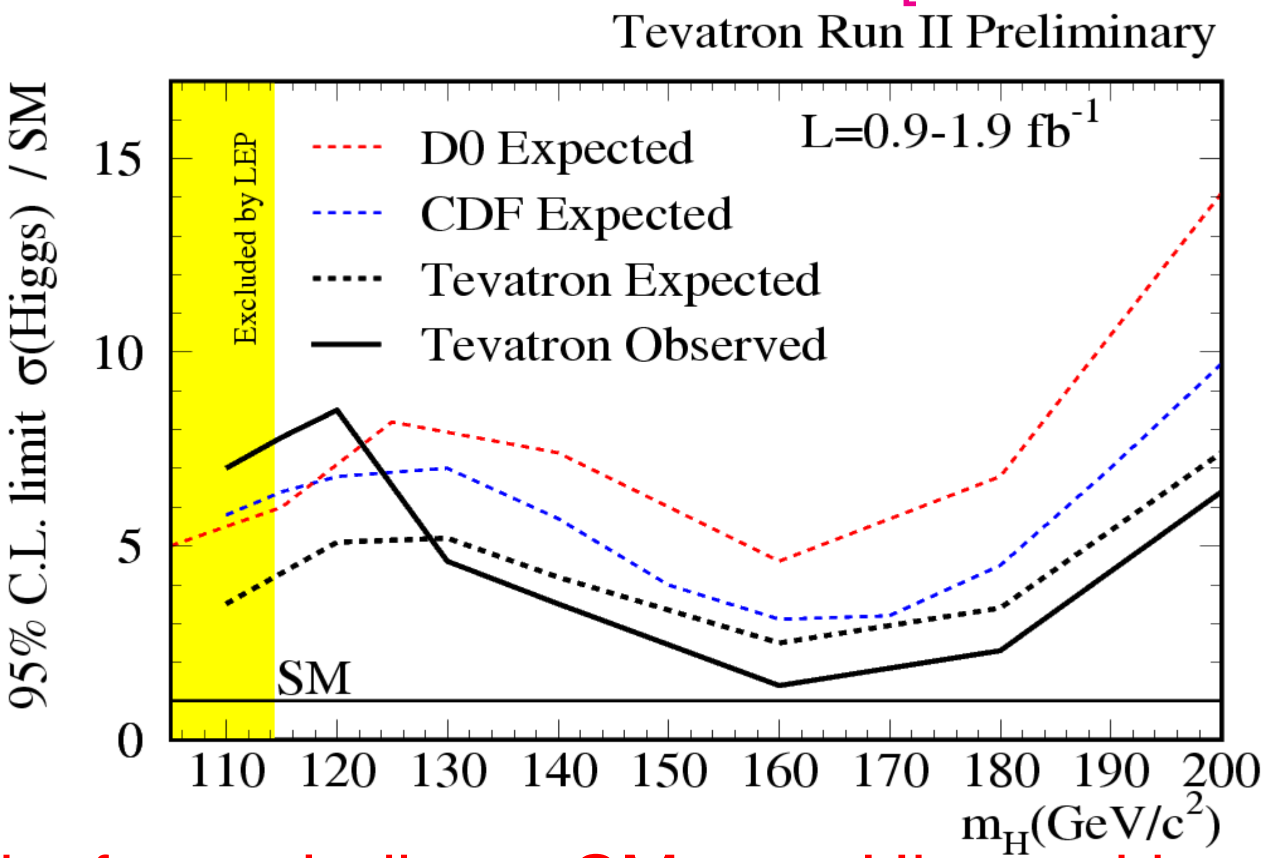
$M_\mathrm{H} \gtrsim 140$ GeV:

$H \to W^+W^-, ZZ$

Search for the SM Higgs at Tevatron, Run II

Dominant production processes: $gg \to H$, $qq' \to WH$

Combined CDF $+$ D0 cross section limit normalised to the SM cross section: [*TEVNPH Working Group '07*]

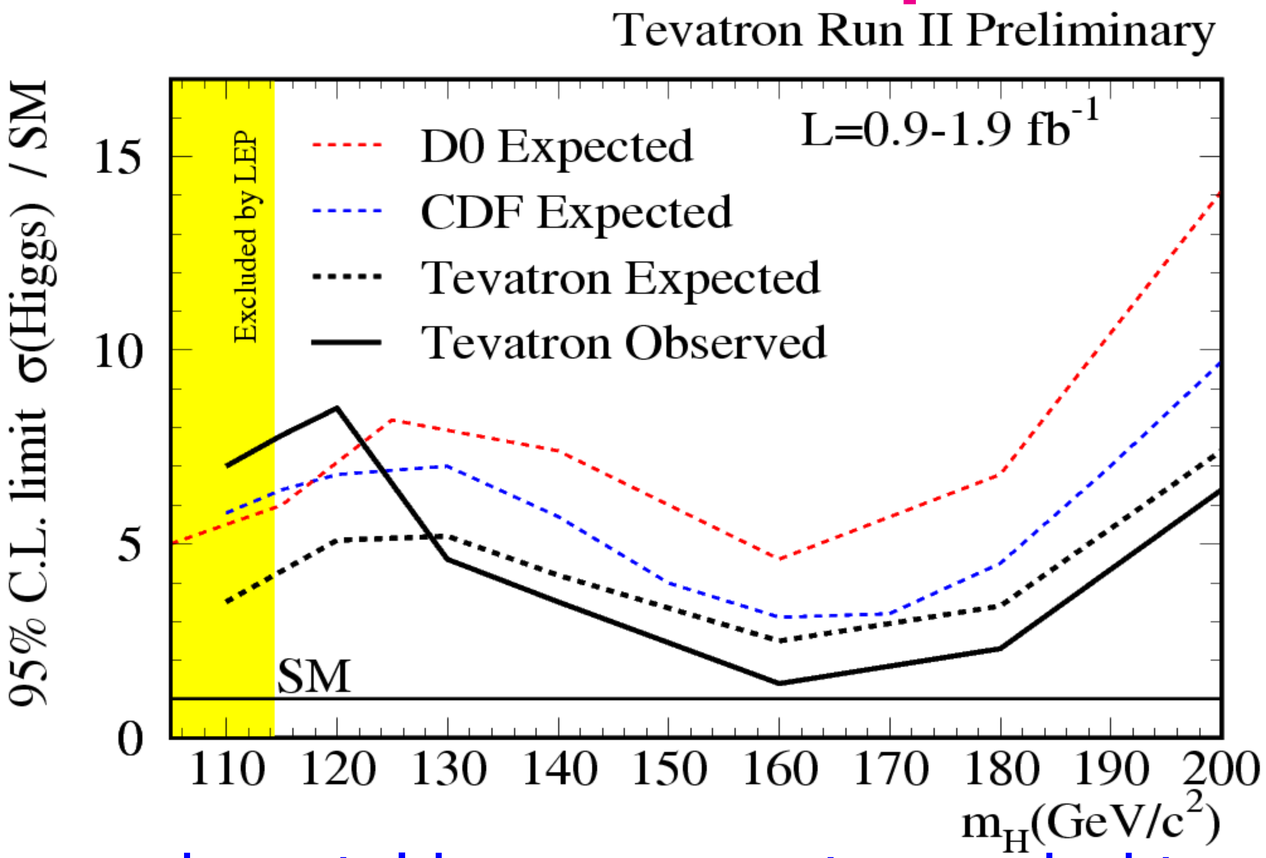


$\Rightarrow$ Sensitivity for excluding a SM-type Higgs with $M_{\mathrm{H}} \approx 160\ \mathrm{GeV}$ will soon be reached

Search for the SM Higgs at Tevatron, Run II

Dominant production processes: $gg \to H$, $qq' \to WH$

Combined CDF $+$ D0 cross section limit normalised to the SM cross section: [*TEVNPH Working Group '07*]

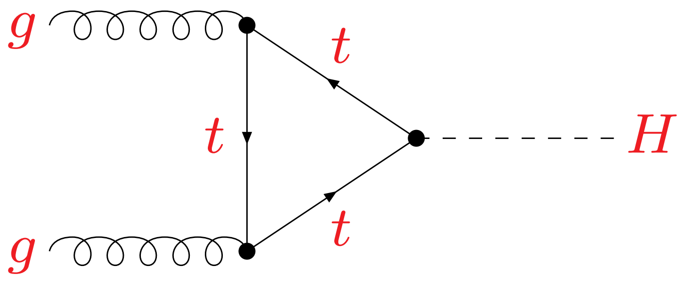


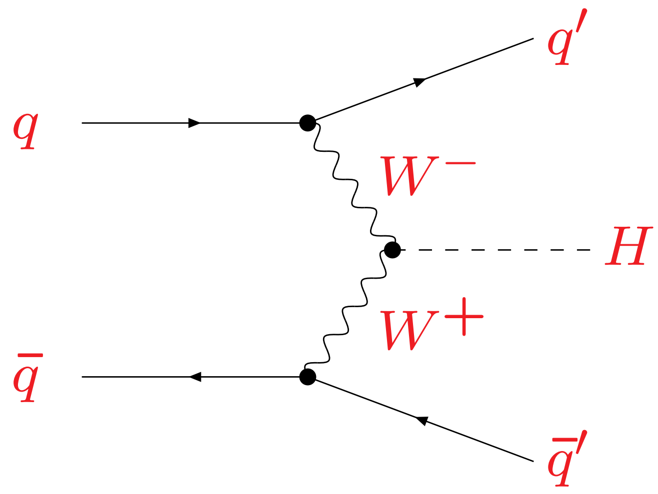
$\Rightarrow$ Further experimental improvements needed to probe the low-mass region above the LEP limit

SM Higgs production at the LHC

Dominant production processes:

gluon fusion: $gg \to H$, weak boson fusion (WBF): $q\bar{q} \to q'\bar{q}'H$





Higgs production at the LHC

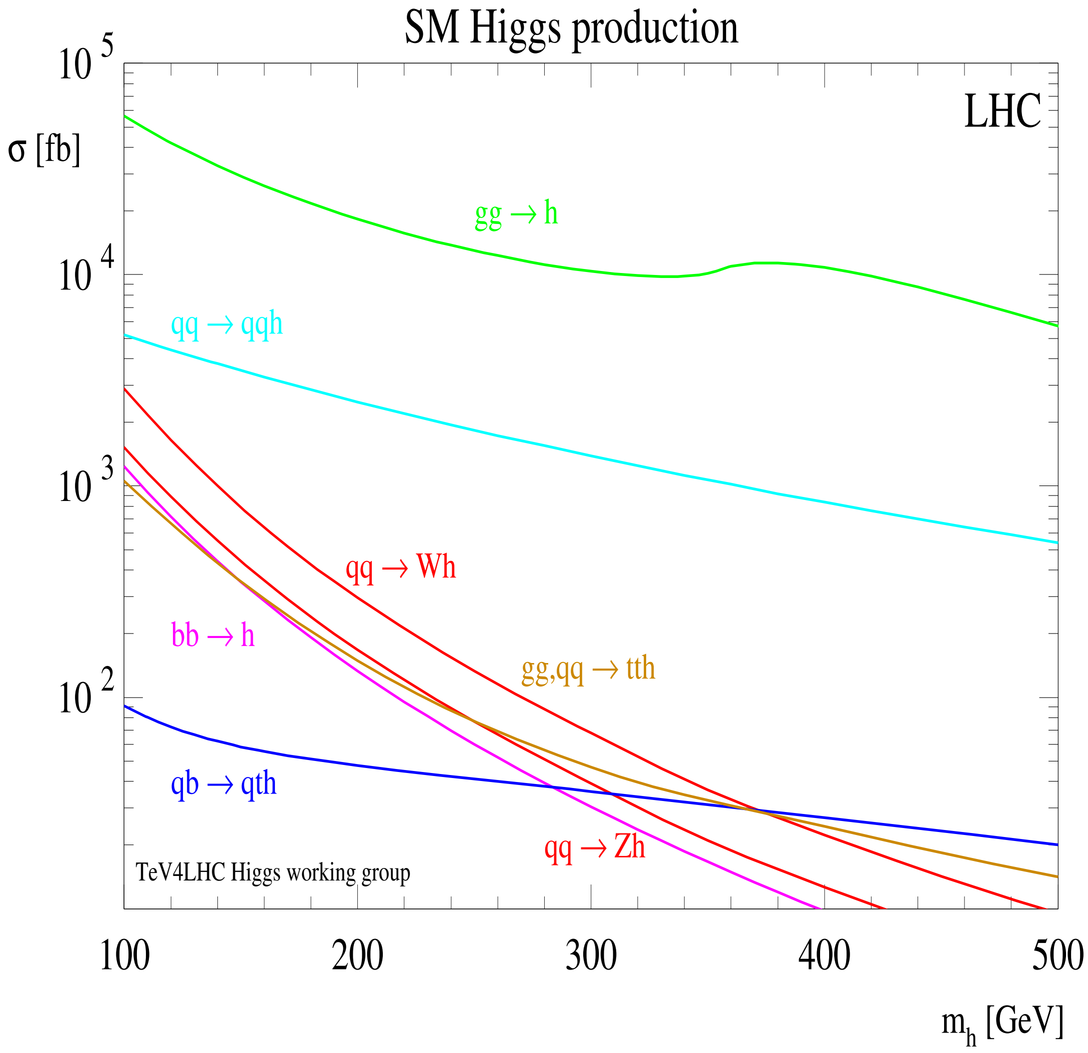
"Standard" production processes for SM-like Higgs:

Gluon fusion: $gg \to H$

Weak boson fusion (WBF): $q\bar{q} \to q'\bar{q}'H$

top-quark associated production: $gg, q\bar{q} \to t\bar{t}H$

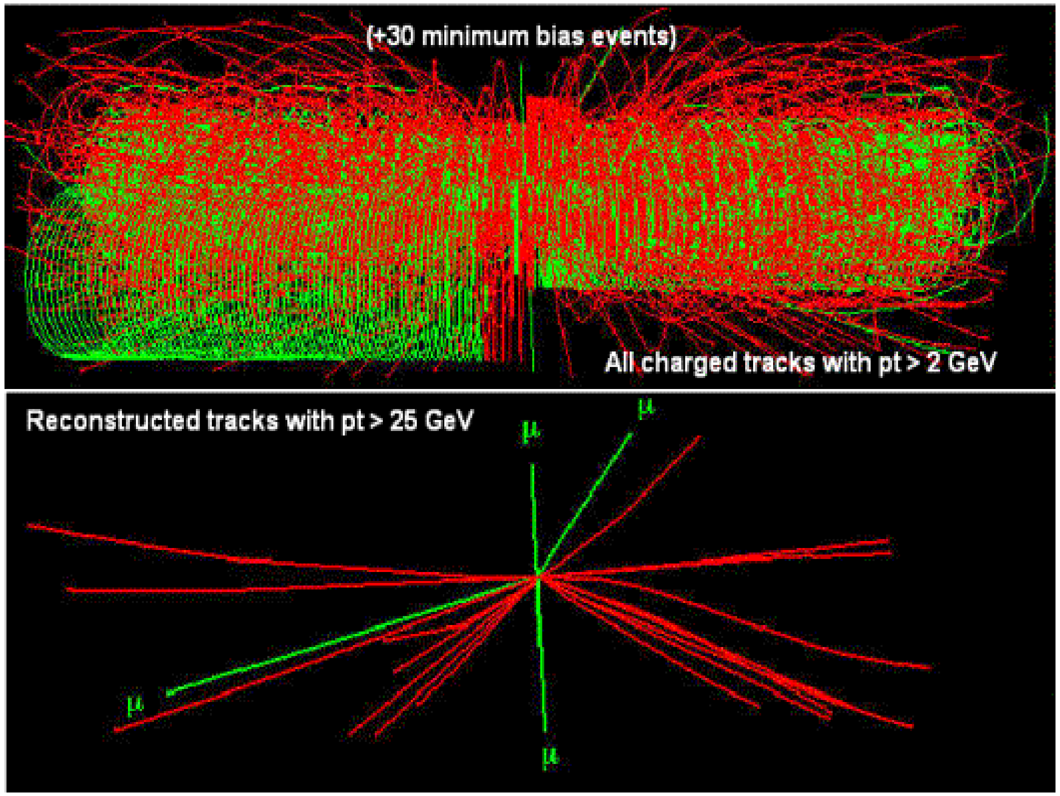
weak boson associated production: $q\bar{q}' \to WH, ZH$



Other possibility: Central exclusive diffractive (CED) Higgs production, $pp \to p + H + p$

Simulation of an LHC event: $gg \to H \to ZZ \to \mu^+\mu^-\mu^+\mu^-$

Computing in LHC experiments



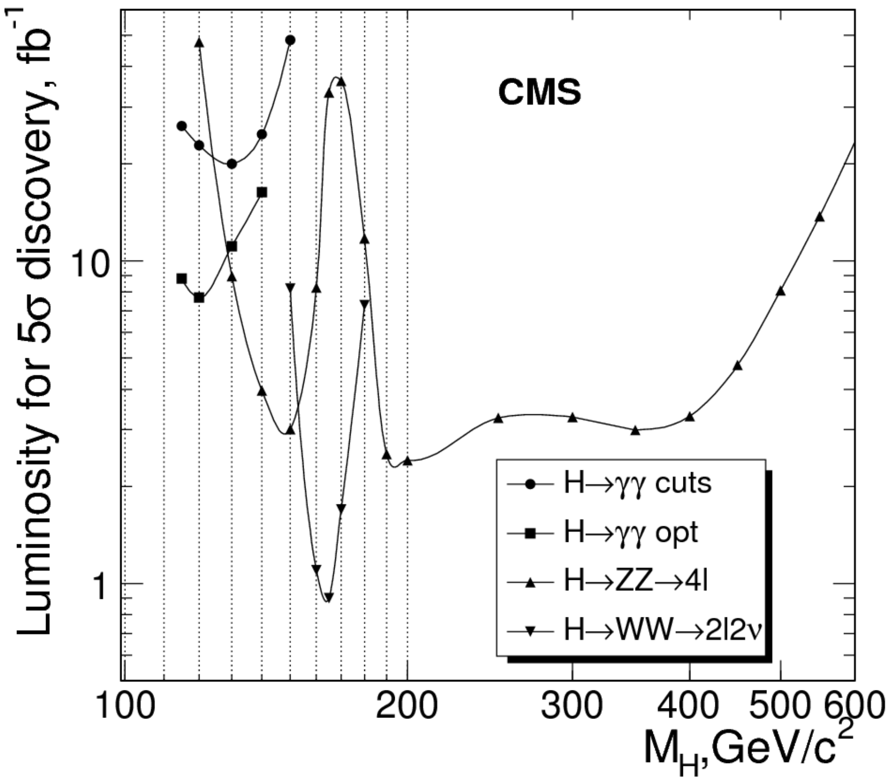
1 Higgs decay in 4 muons in 10^{13} events

1000 charged tracks/event, most of them p<0.5 GeV

Prof. Dr. Stefan Schael, RWTH Aachen | Vorlesung 1, Maria-Laach, September 2001 | 25

Search for the SM Higgs at the LHC

[*CMS '06*]

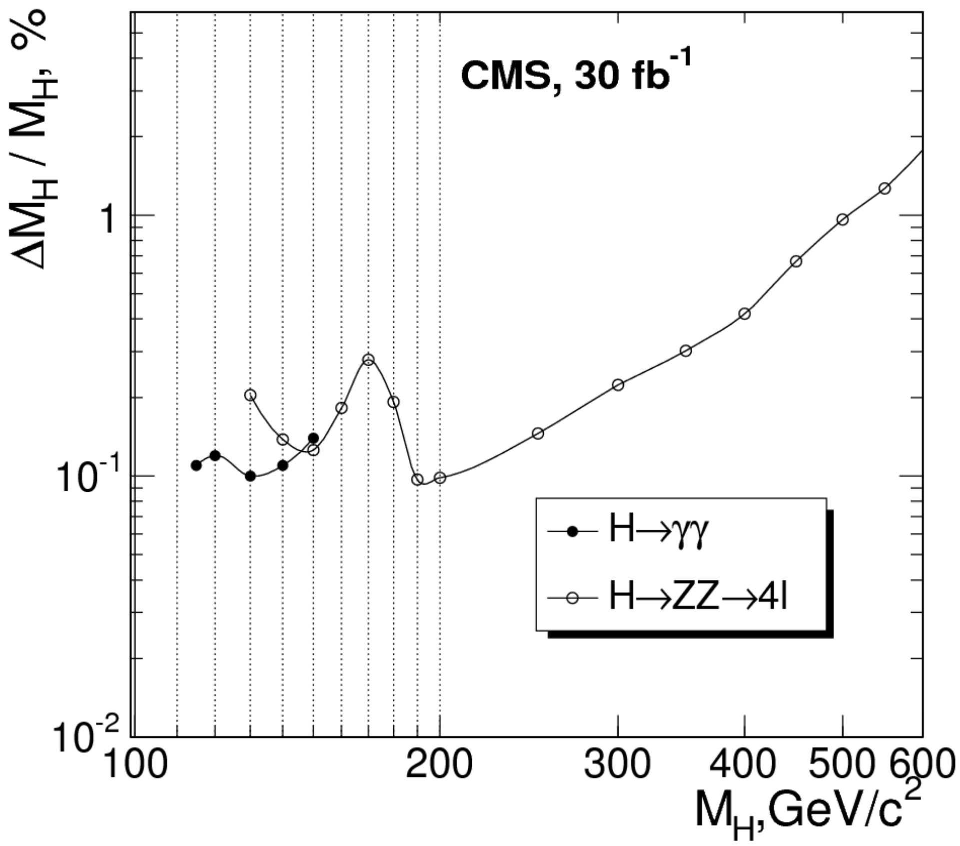


$\Rightarrow$ The LHC will discover a SM-like Higgs, covers whole range $M_{\mathrm{H}} \lesssim 1$ TeV

Low-mass region (just above LEP limit) is experimentally most challenging; $H \to b\bar{b}$ mode will be very difficult at the LHC

SM Higgs at the LHC: Higgs mass precision

[*CMS '06*]



For light SM-like Higgs, $H \to \gamma\gamma$ decay mode:

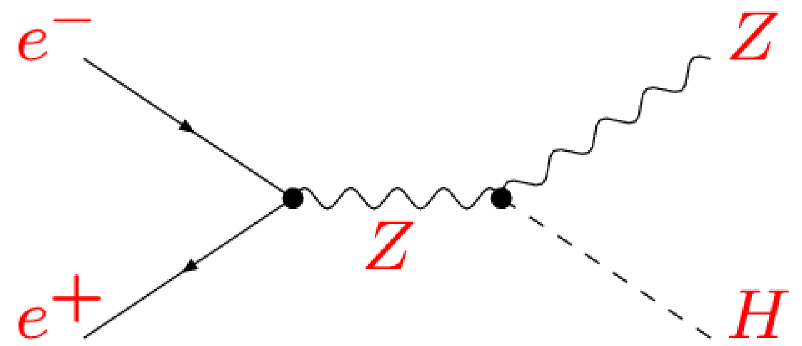
$\Rightarrow$ LHC can do first precision measurement in Higgs sector:

$$\delta M_{\mathrm{H}}^{\mathrm{exp}} \approx 0.2 \text{ GeV}$$

Higgs physics at the ILC

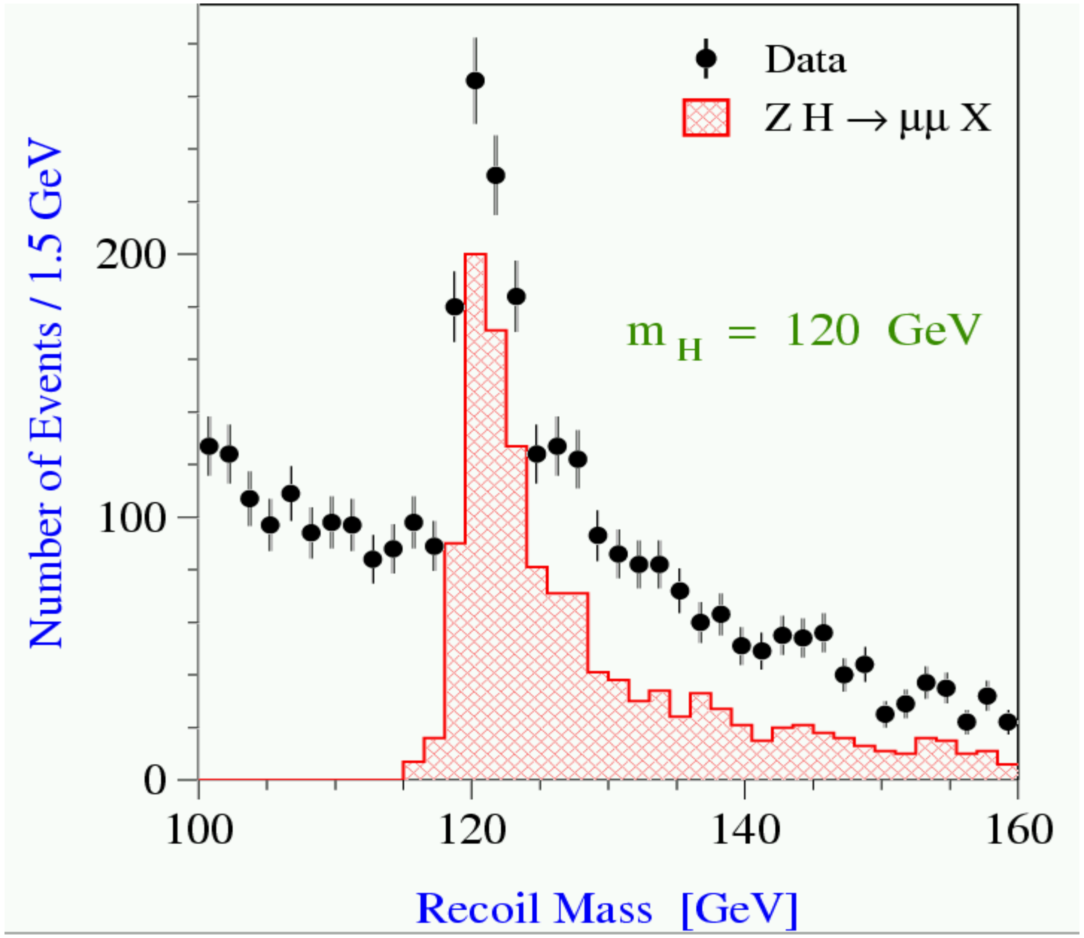
"Golden" production channel: $e^+e^- \to ZH$, $Z \to e^+e^-, \mu^+\mu^-$

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



$\Delta\sigma_{\rm HZ}/\sigma_{\rm HZ} \approx 2\%$
($E_{\rm CM} = 350$ 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

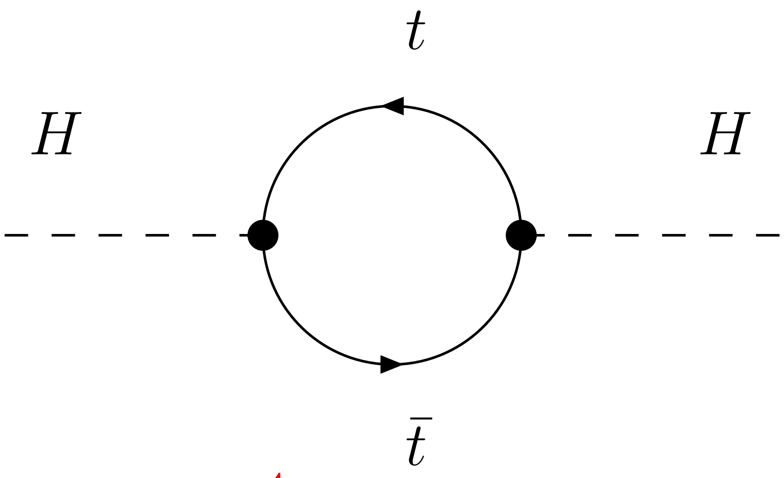
$\Rightarrow$ Precise measurement of Higgs mass and couplings, determination of Higgs spin and quantum numbers, ...
Mass determination for a light Higgs:

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

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

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)

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: $\Delta m_\mathrm{t} \lesssim 0.1~\mathrm{GeV}$

SUSY Higgs physics

MSSM Higgs sector:

“simplest” extension of SM Higgs sector

two parameters instead of one

But: MSSM Higgs physics has very rich phenomenology

Higgs couplings

Higgs couplings, tree level:

$$g_{\mathrm{hVV}} = \sin(\beta - \alpha)\, g_{\mathrm{HVV}}^{\mathrm{SM}}, \quad g_{\mathrm{HVV}} = \cos(\beta - \alpha)\, g_{\mathrm{HVV}}^{\mathrm{SM}}, \quad V = W^{\pm}, Z$$

$$g_{\mathrm{hAZ}} = \cos(\beta - \alpha)\, \frac{g'}{2\cos\theta_{\mathrm{W}}}, \quad g_{\mathrm{HAZ}} = \sin(\beta - \alpha)\, \frac{-g'}{2\cos\theta_{\mathrm{W}}}$$

$\Rightarrow$ $g_{\mathrm{hVV}} \leq g_{\mathrm{HVV}}^{\mathrm{SM}}$, $g_{\mathrm{hVV}}, g_{\mathrm{HVV}}, g_{\mathrm{hAZ}}, g_{\mathrm{HAZ}}$ cannot all be small

In decoupling limit, $M_{\mathrm{A}} \gg M_{\mathrm{Z}}$ (already realized for $M_{\mathrm{A}} \gtrsim 150$ GeV):
$\cos(\beta - \alpha) \to 0$

$\Rightarrow$ h is SM-like, H and A decouple from gauge bosons

$\Rightarrow$ Cannot use WBF channels for production of heavy SUSY Higgses; no $H \to ZZ \to 4\mu$ decay

Higgs couplings

- Tree-level couplings to fermions:

  large enhancement / suppression possible, $g_{Ab\bar{b}} \sim \tan\beta$

- Large loop effects:

  BR($h \to b\bar{b}$), BR($h \to \tau^+\tau^-$) $\to 0$ possible

- $\mathcal{CP}$ violation in the Higgs sector:

  MSSM Higgs sector is $\mathcal{CP}$-conserving at tree level, but complex parameters enter via loop corrections

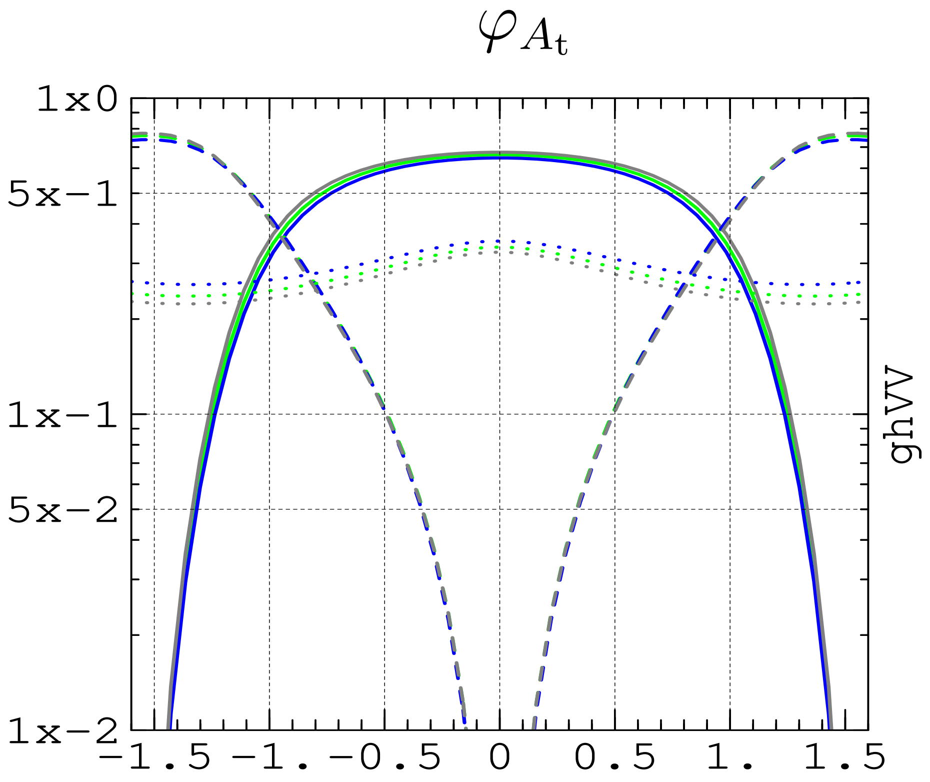
  $\Rightarrow$ can induce $\mathcal{CP}$-violating effects

  $\Rightarrow$ Mixing between neutral Higgs bosons h_1, h_2, h_3

  $\Rightarrow$ Complex phases can have large effects on Higgs couplings

$\mathcal{CP}$ *violation in the Higgs sector*

Example: g^2_{hVV} for h_1, h_2, h_3: [*M. Frank, S. Heinemeyer, W. Hollik, G. W. '03*]



full: h_1, dashed: h_2, dotted: h_3

Parameters:

$M_{\rm SUSY} = 500$ GeV,

$M_2 = 500$ GeV,

$\mu = 2000$ GeV,

$|A_{\rm t}| = 1000$ GeV,

$M_{\rm H^\pm} = 150$ GeV, $\tan\beta = 5$

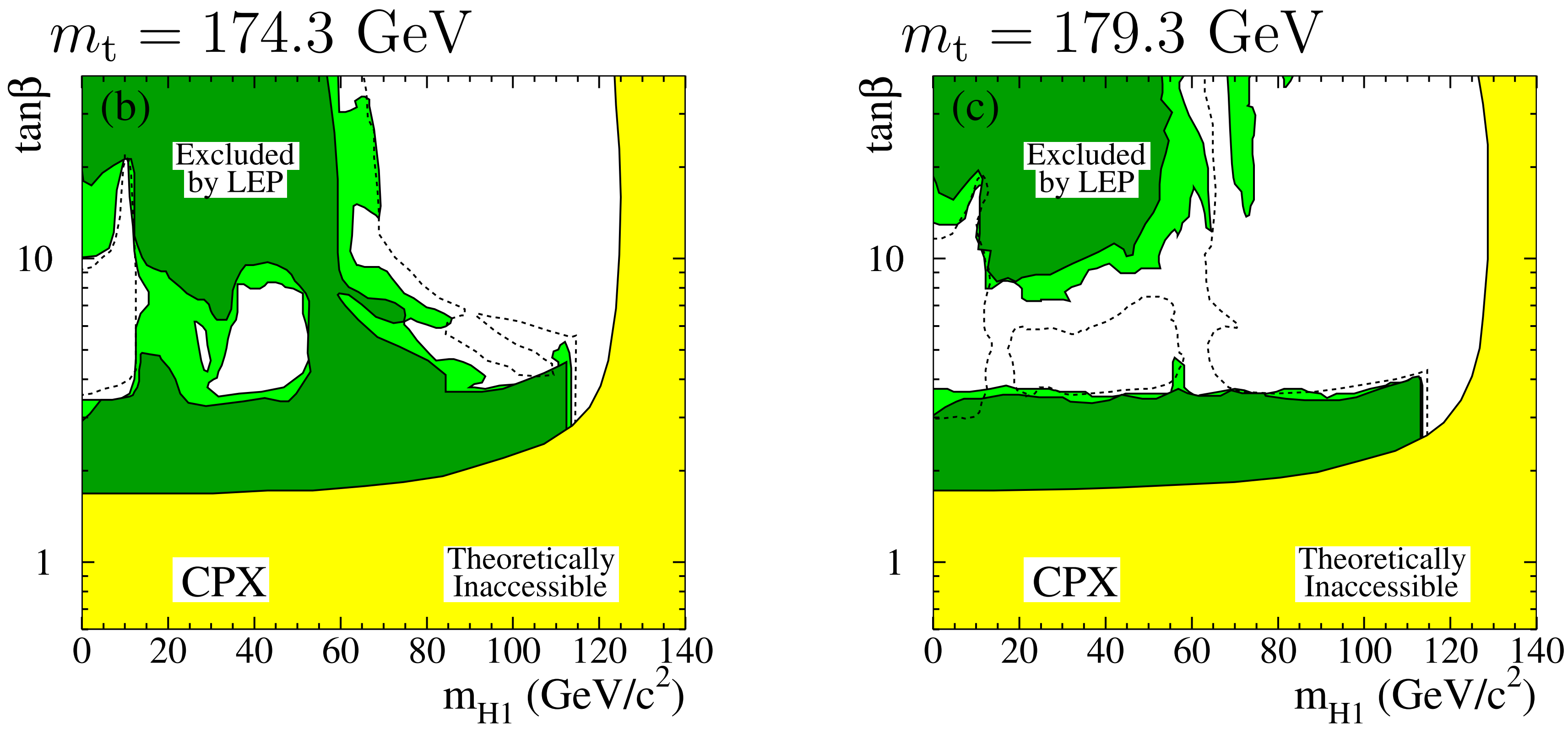
$\Rightarrow$ Complex phases can have large effects on Higgs couplings

$\mathcal{CP}$-violating case (CPX scenario): LEP exclusion bounds

Light Higgs, h_1: strongly suppressed h_1VV couplings

Second-lightest Higgs, h_2, possibly within LEP reach (with reduced VVh_2 coupling), h_3 beyond LEP reach

Large $\mathrm{BR}(h_2 \to h_1 h_1) \Rightarrow$ difficult final state [*LEP Higgs WG '06*]



$\Rightarrow$ no lower limit on M_{h_1}: light SUSY Higgs not ruled out!

Theoretical motivation for a very light Higgs

"Little hierarchy problem:"

Prediction for $M_{\rm h}$:

$$M_{\rm h}^2 \approx M_{\rm Z}^2 \cos^2 2\beta + \frac{3G_\mu}{\sqrt{2}\pi^2} m_{\rm t}^4 \ln(M_{\tilde{\rm t}}^2/m_{\rm t}^2) + \ldots$$

$\Rightarrow$ Need $M_{\tilde{\rm t}} \gtrsim 500~\rm GeV$ to satisfy exclusion bound on SM-like Higgs, $M_{\rm h} > 114.4~\rm GeV$

RG running from $M_{\rm GUT}$:

$$M_{\rm Z}^2 \approx 1.6\, M_{\tilde{\rm t}}^2 - 1.8\, \mu^2 + 5.9\, M_3^2 - 0.4\, M_2^2 - 1.2\, m_{H_u}^2 + \ldots$$

$\Rightarrow$ Need cancellations between soft SUSY-breaking parameters

$\Rightarrow$ (Slight) tension can be relaxed if Higgs is light

Other possibility: a light SM-like Higgs

Many theories have over large part of their parameter space a light Higgs with properties very similar to those of the SM Higgs boson

Example: SUSY in the “decoupling limit”, $M_\mathrm{A} \gg M_\mathrm{Z}$

Heavy Higgses may be difficult to detect

$\Rightarrow$ We may see only one Higgs that looks SM-like, but has a totally different physical origin

$\Rightarrow$ High-precision measurements of Higgs properties will be crucial to reveal the nature of EWSB

SUSY Higgs: non-standard heavy Higgses

"Typical" features of extended Higgs sectors:

- 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 weak-boson fusion channels for production

$\Rightarrow$ Possible production channels: $gg \to H$, $b\bar{b}H$, ...

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

$\Rightarrow$ Search for heavy Higgs bosons $H, A, H^{\pm}$ is very different from the SM case

Lesson for Higgs searches:
we cannot take a SM-type Higgs for granted

Higgs phenomenology can be drastically different from the SM case even in the MSSM:

- Higgs may be much lighter than $114\ \mathrm{GeV}$

  Example: SUSY with $\mathcal{CP}$-violation

  $\Rightarrow$ no firm experimental lower bound on M_{H}

  $\Rightarrow$ LHC needs to look also for light Higgs bosons

- 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($h \to WW^*$), ...

We cannot take a SM-type Higgs for granted

- Higgs decays into SUSY particles, $H \to$ invisible, $H \to$ soft jets, ...

- SUSY decays into Higgs, ...

NMSSM: $h \to aa$, singlet dominated light Higgs, ...

More exotic scenarios:
Higgs–radion mixing, "continuum" Higgs models, ...

$\Rightarrow$ Need to be prepared for non-standard phenomenology

Search for SUSY Higgses at the Tevatron

- Search for SM-type Higgs:

$$gg \to \phi, \quad \phi \to WW^*, \qquad q\bar{q} \to V\phi, \quad \phi \to b\bar{b} \quad (\phi = h, H)$$

If the Tevatron sets an exclusion bound on the SM Higgs that exceeds the LEP limit of $M_{\mathrm{H}} > 114.4$ at 95% C.L., this would have a big impact on the SUSY parameter space

- Search for heavy SUSY Higgses h, H, A in large $\tan\beta$ region:

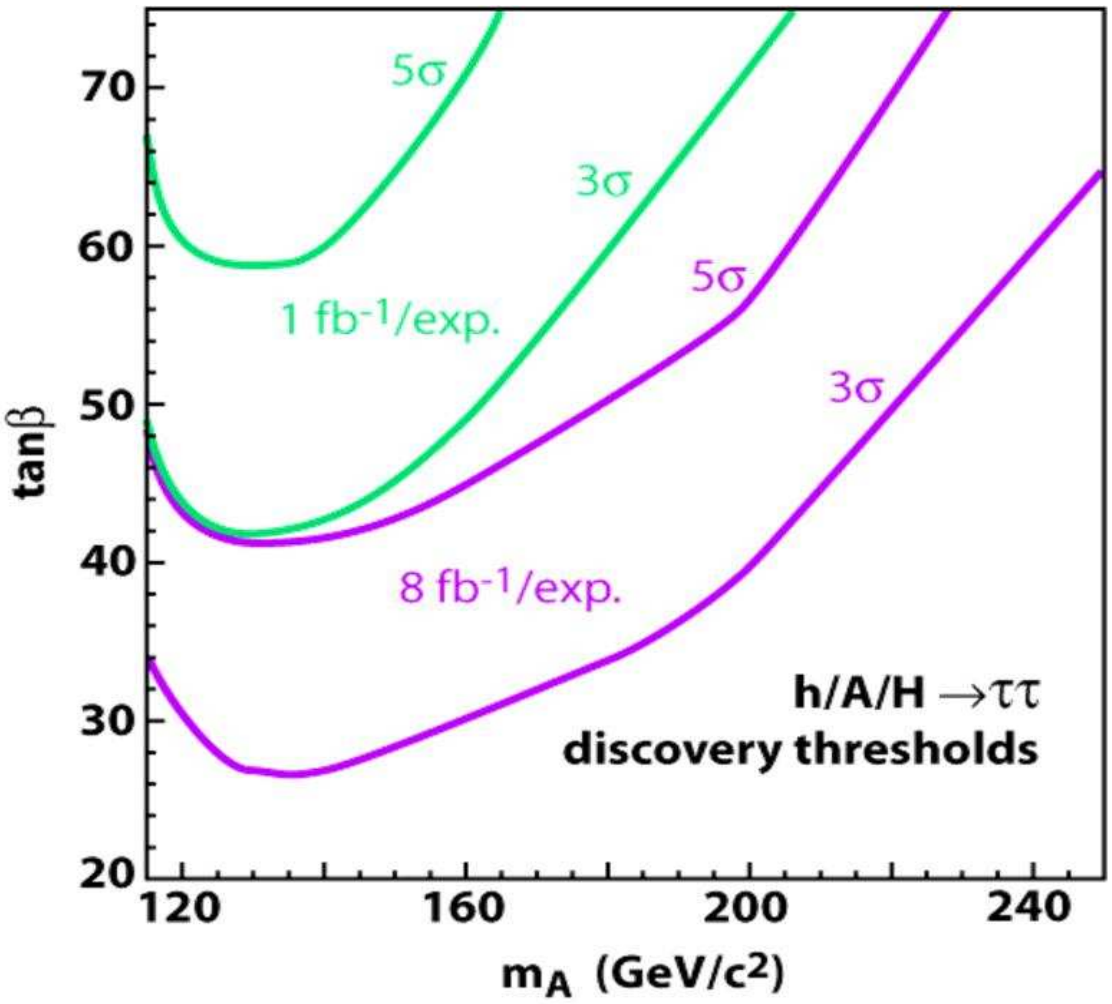
$$gg, q\bar{q} \to b\bar{b}\phi, \quad \phi \to b\bar{b} \quad (\phi = h, H, A)$$

Enhancement of $Ab\bar{b}$, $Hb\bar{b}$ couplings for large $\tan\beta$

$\Rightarrow$ Discovery potential in the region of small M_{A} and large $\tan\beta$

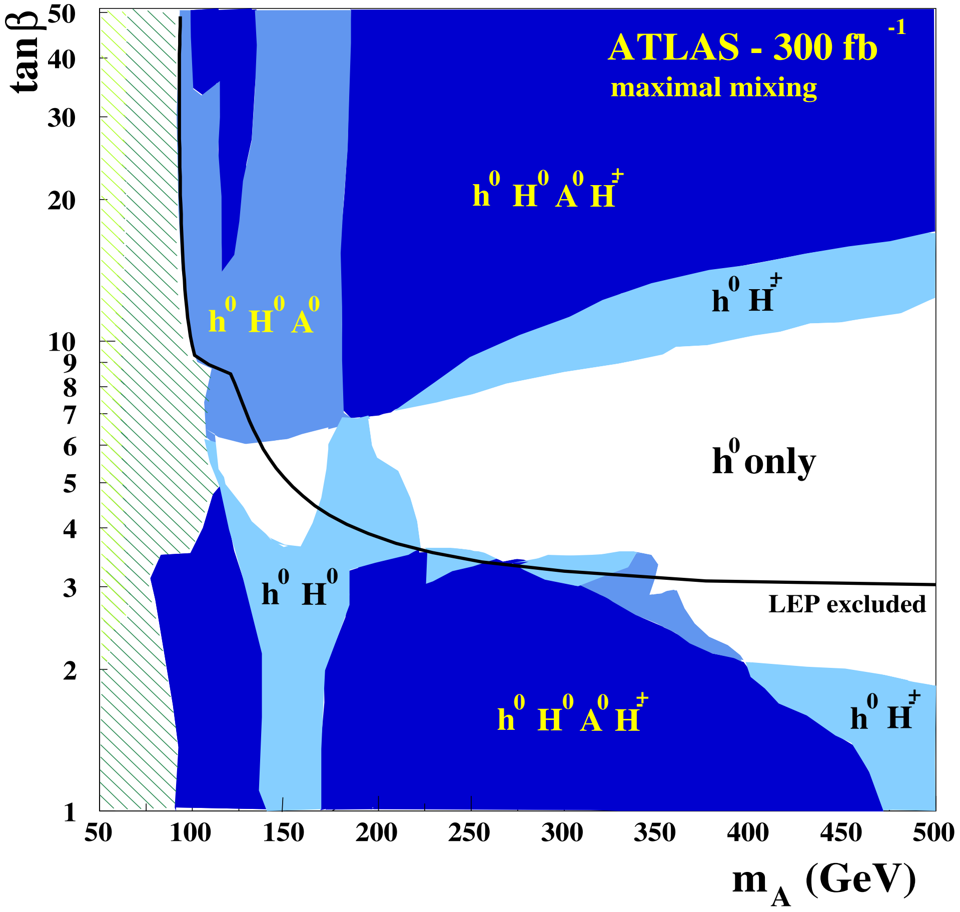
Tevatron discovery potential in $p\bar{p} \to \phi \to \tau^+\tau^-$ *channel* ($m_h^{\max}$ *scen.,* $\mu = +200$ GeV)

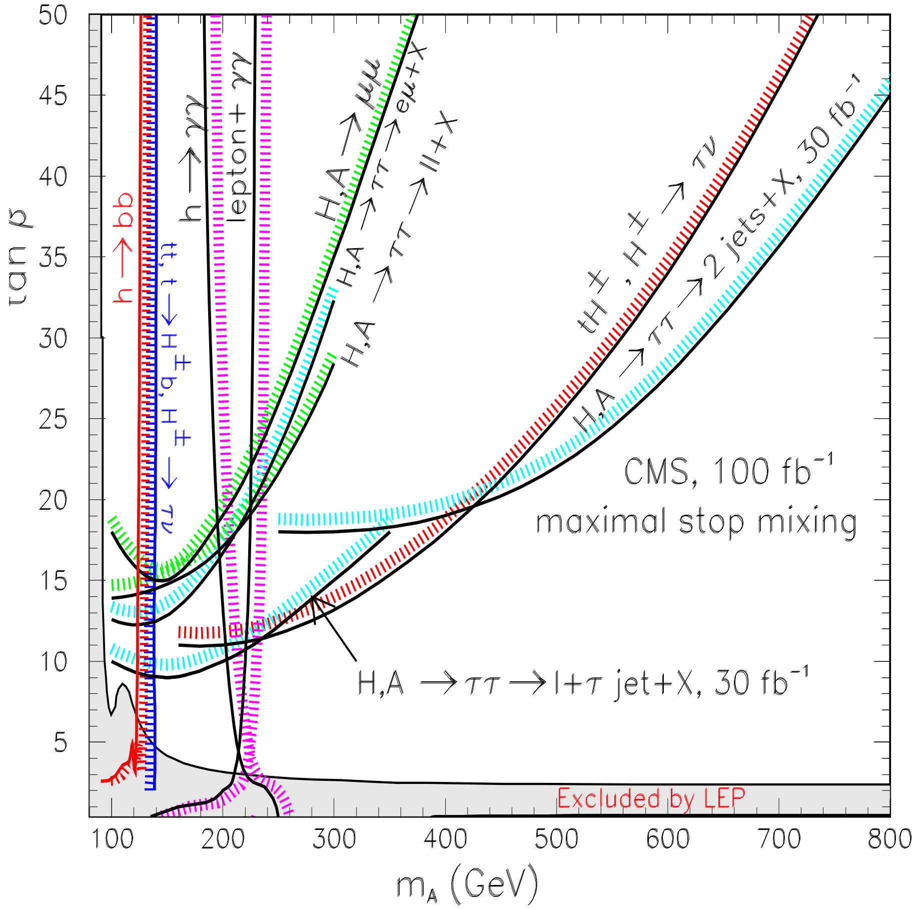
[*CDF Collab. '05*]



$\Rightarrow$ promising search reach

MSSM Higgs discovery contours at the LHC ($m_\mathrm{h}^\mathrm{max}$ benchmark scenario)





⇒ Discovery of at least one Higgs state “expected”

Significant region where only one SM-like Higgs can be detected at the LHC

Example for determination of Higgs properties: Higgs coupling determination at the LHC

LHC does not provide a measurement of the 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}

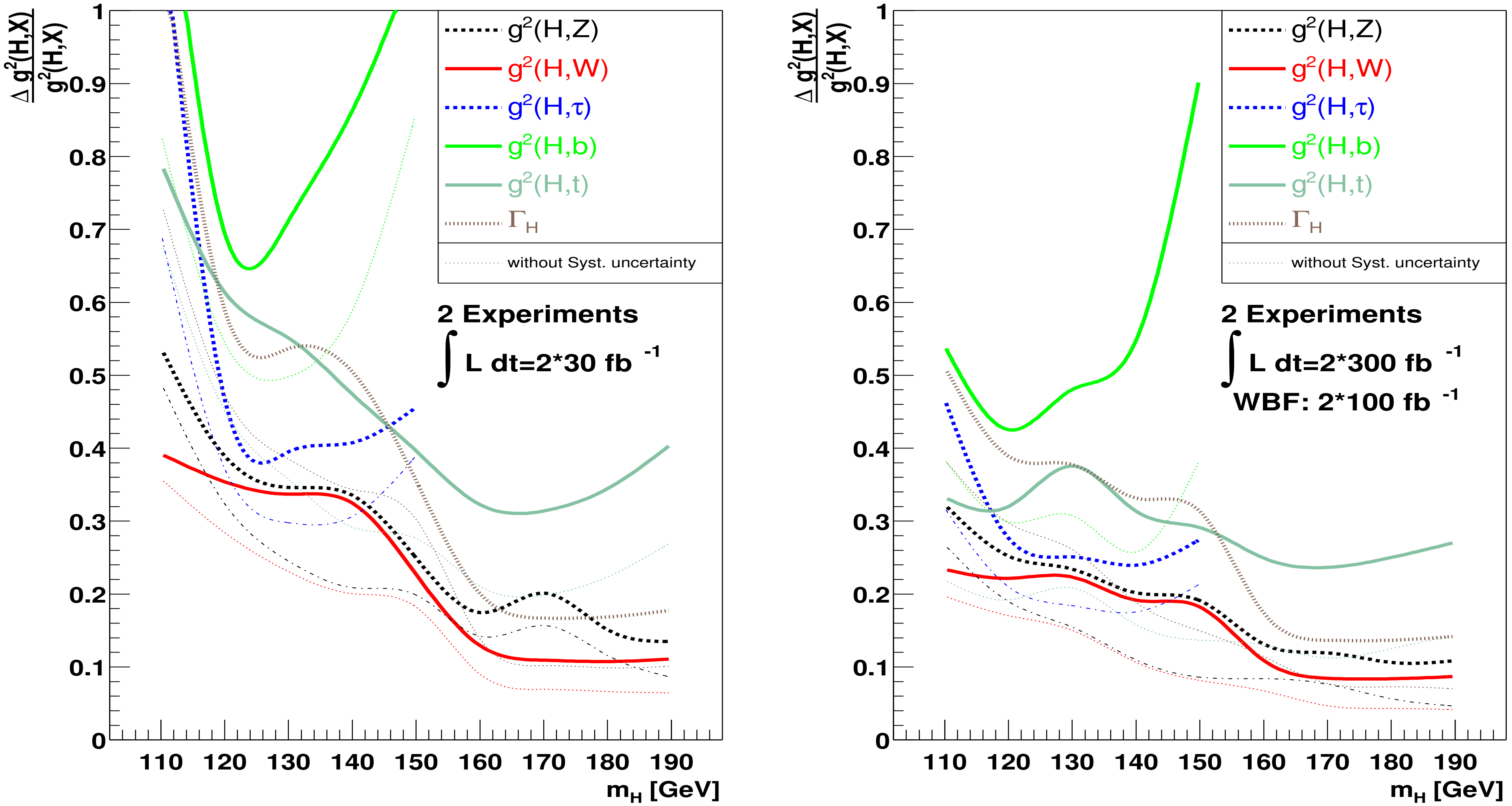
Observation of $H \to VV$ in WBF

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

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

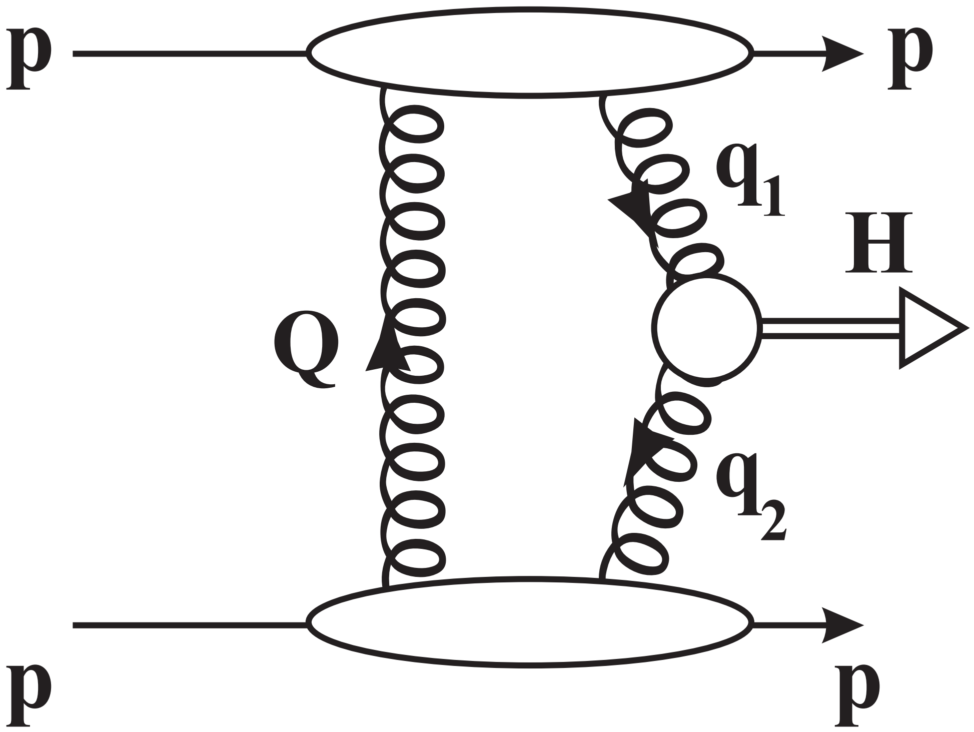
Absolute determination of Higgs couplings with (mild) theory assumption

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



⇒ Reachable for the couplings (with high lumi): ≈10–20%

Access to the $Hb\bar{b}$ coupling via central exclusive diffractive (CED) Higgs production, $pp \to p \oplus H \oplus p$



Protons remain undestroyed, forward proton tagging in “roman pot” detectors

exchange of colour-singlet

no hadronic activity between outgoing protons and Higgs decay products
$J_z = 0$ selection rule

$\Rightarrow$ Good mass resolution, access to $H \to b\bar{b}$ decay mode

$\Rightarrow$ Experimentally very challenging (pile-up, in particular at high lumi, . . .), but may yield interesting information

Higgs coupling determination at the ILC

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

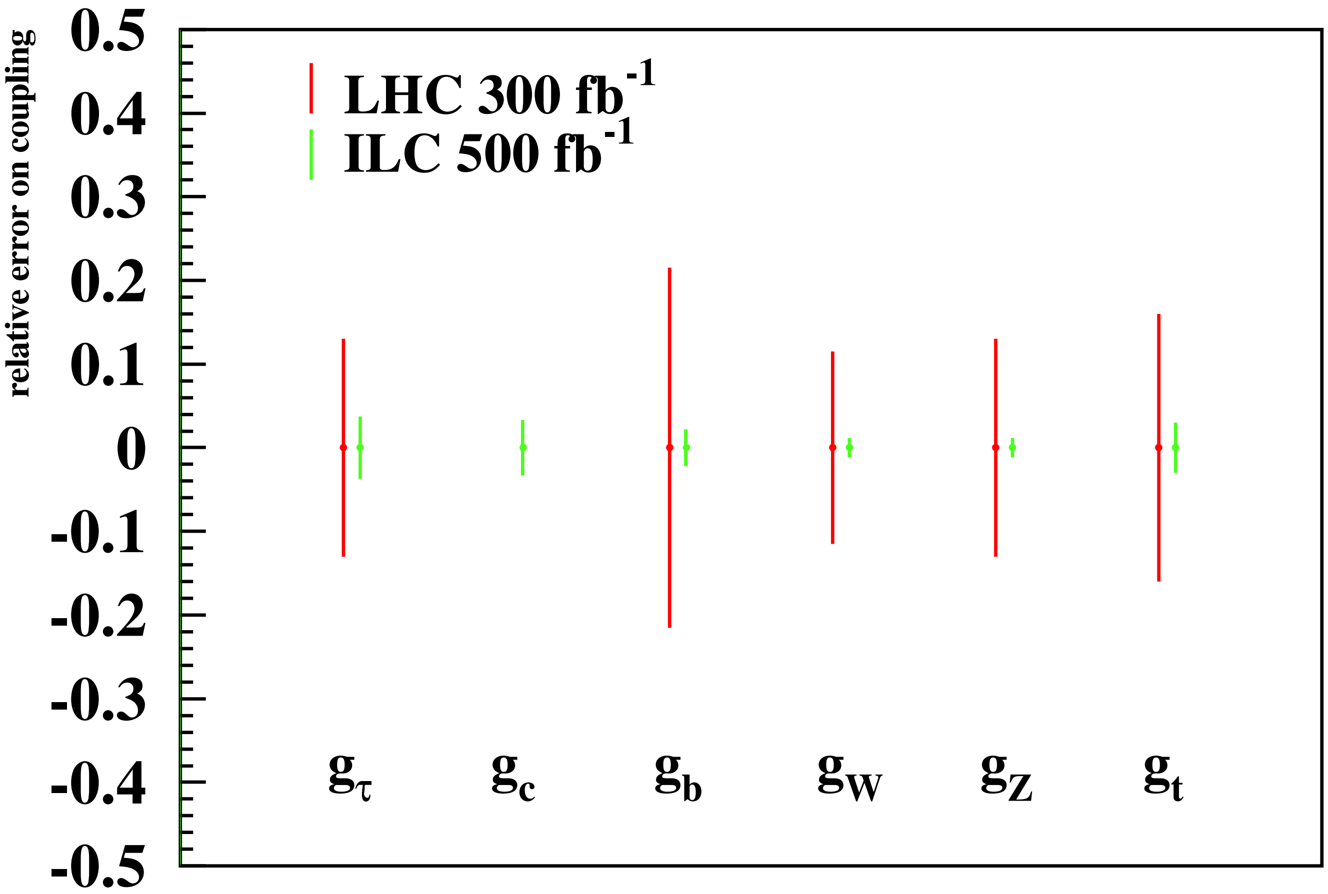
Model-independent measurement of the total width

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

Higgs coupling determination: LHC vs. ILC

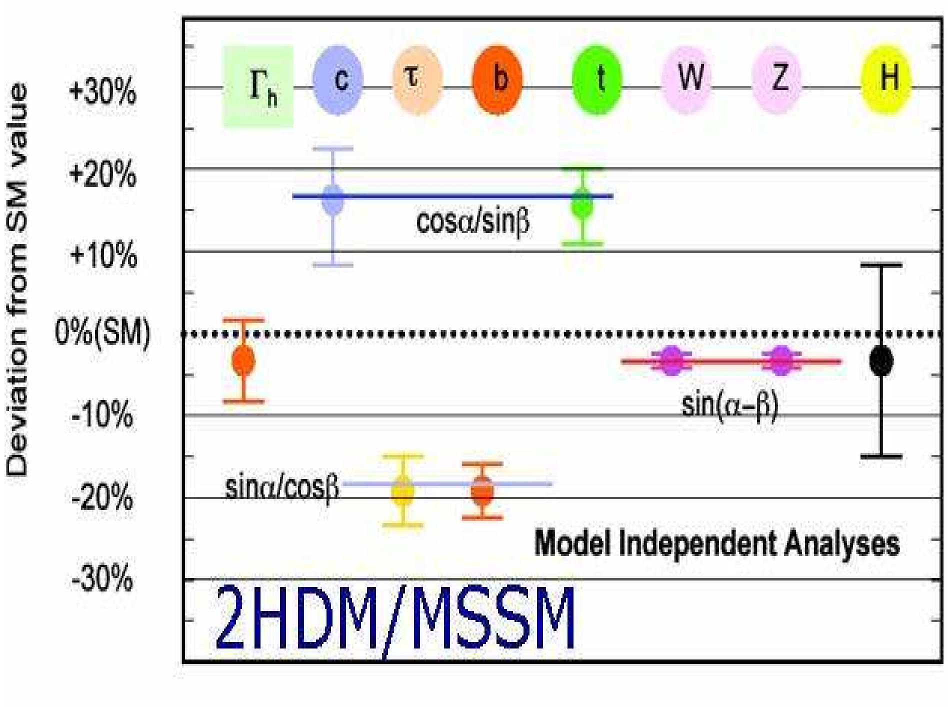
Comparison: LHC (with mild theory assumptions) vs. ILC (model-independent)

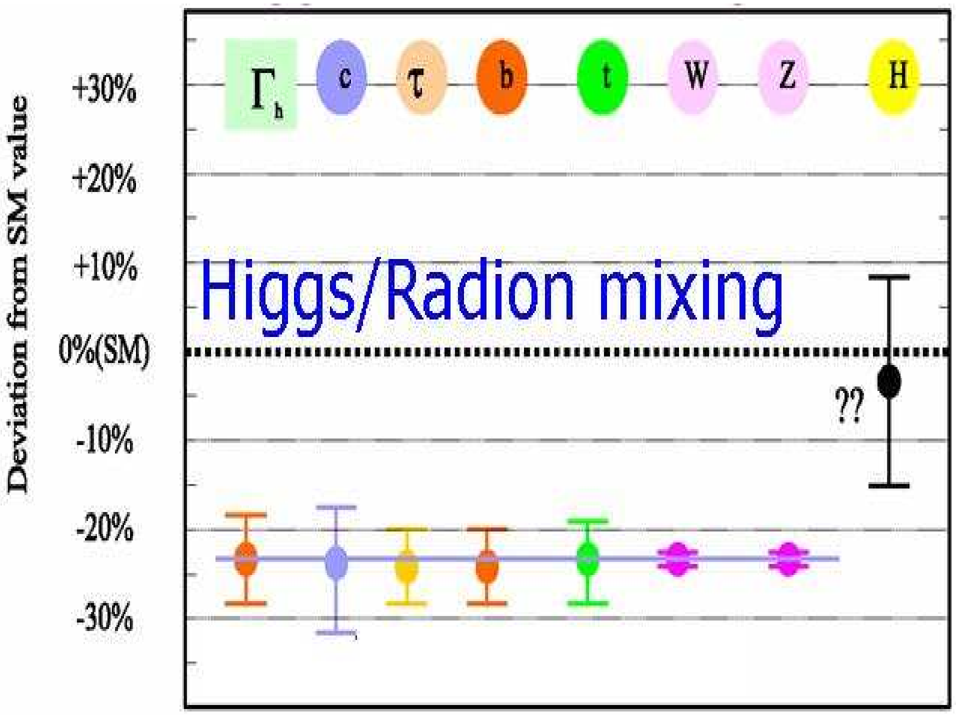
[*M. Dührssen, S. Heinemeyer, H. Logan, D. Rainwater, G. W., D. Zeppenfeld '04*]
[*K. Desch '06*]



Impact of ILC precision for the Higgs couplings

SM vs. BSM physics:

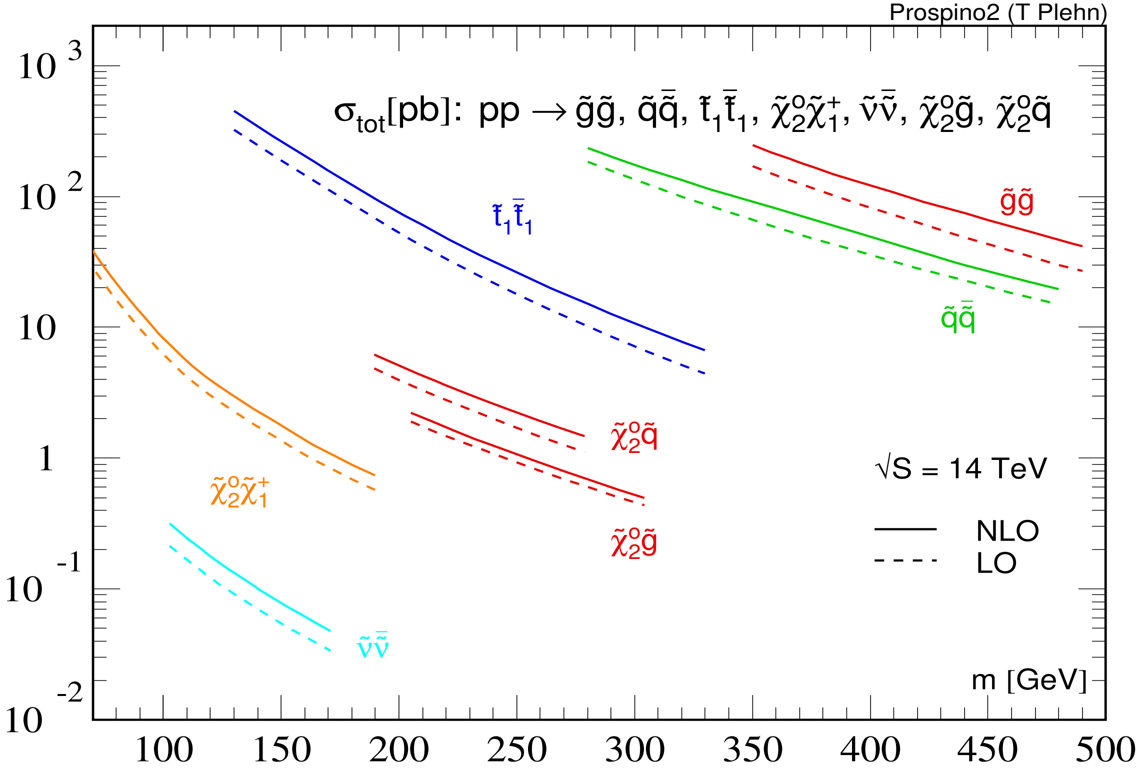




⇒ Precision measurement of Higgs couplings allows distinction between different models

SUSY phenomenology

SUSY production cross sections at the LHC:



Squark and gluino couplings $\sim \alpha_s$

Cross sections mainly determined by $m_{\tilde{q},\tilde{g}}$, small residual model dependence

$\sigma \approx 50\,\mathrm{pb}$ for $m_{\tilde{q},\tilde{g}} = 500$ GeV, $\sigma \approx 1\,\mathrm{pb}$ for $m_{\tilde{q},\tilde{g}} = 1$ TeV

SUSY searches at the LHC

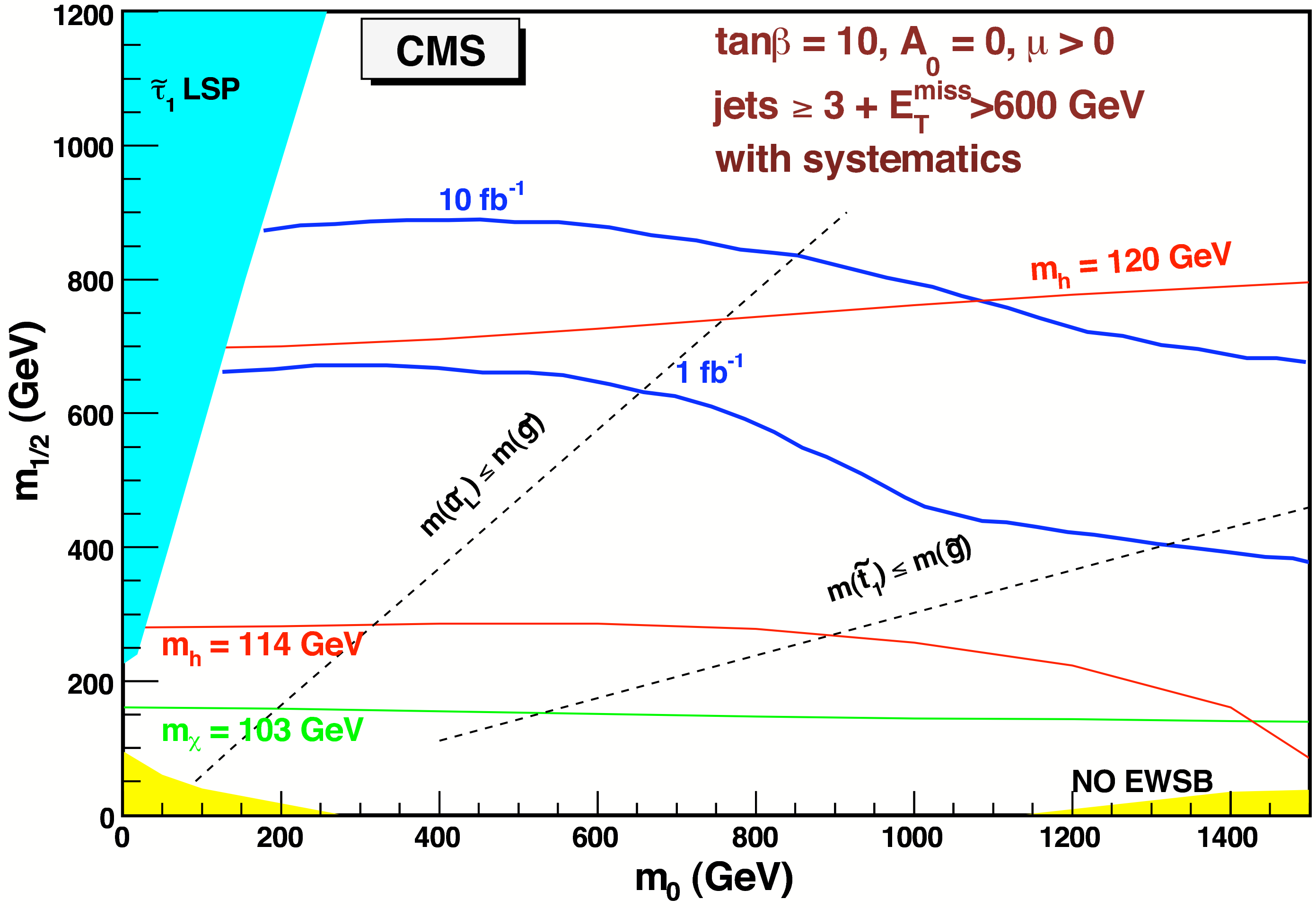
Dominated by production of coloured particles:
gluino, squarks

Very large mass reach in the searches for
jets $+$ missing energy
$\Rightarrow$ gluino, squarks accessible up to 2–3 TeV

$\Rightarrow$ very good prospects for discovering SUSY particles if low-energy SUSY is realised in nature

LHC discovery reach in m_0–$m_{1/2}$ plane of the CMSSM for jets + miss. energy, $1\ \mathrm{fb}^{-1}$ and $10\ \mathrm{fb}^{-1}$

[*CMS '06*]



$\Rightarrow$ Large coverage even with $1\ \mathrm{fb}^{-1}$ of understood data

SM backgrounds to missing energy signals

[*M. Mangano, SUSY07*]

Missing energy ⇒ νs ⇒ W/Z production

"Irreducible": individual events cannot be distinguished from the signal

Z+4jets, Z→ νν

"Reducible": individual events feature properties which distinguish them from the signal, but these can only be exploited with limited efficiency

W+3jets, W→ τν, τ→hadrons (jet)	τ jet has low multiplicity, and originates from a displaced vertex, because of τs lifetime
W+4jets, W→ e/μ ν, lepton undetected	e/μ can be detected, but cannot be vetoed with 100% efficiency, else the signal would be killed as well (e /μ may come from π conversions or decays)
tt → W+jets, with W→ leptons as above	In addition to the above, top decays have b's, but these cannot be detected and vetoed with 100% efficiency

Instrumental backgrounds

[*M. Mangano, SUSY07*]

"Instrumental": individual events resemble the signal because of instrumental "effects" (namely detector deficiencies, accidents, or non-collision bgs)

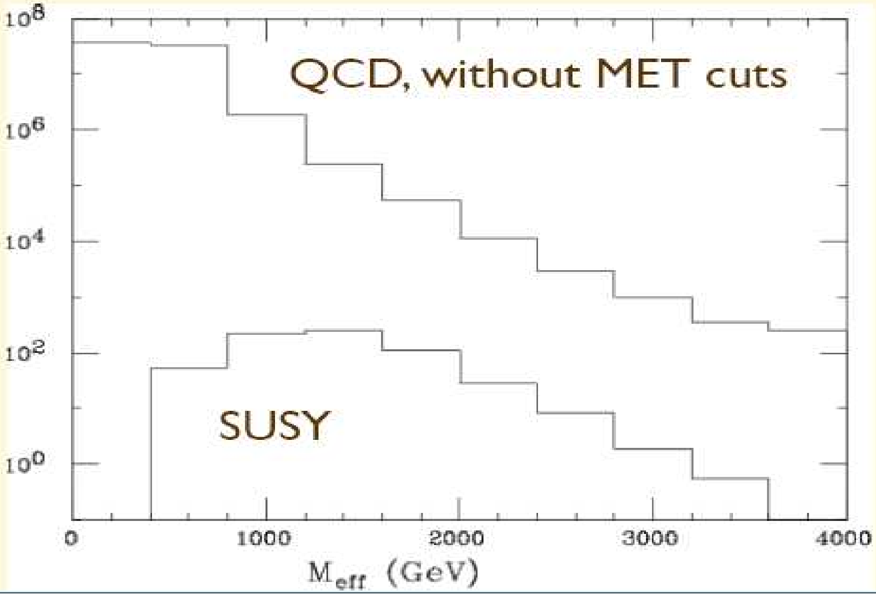
E.g.: Multijets

The missing ET may originate from several sources:

Mismeasurement of the energy of individual jets

Incomplete coverage in rapidity (forward jets undetected)

Accidental extra deposits of energy (cosmic rays on time, beam backgrounds, , electronic noise, etc.etc.etc.)



It is sufficient that these effects leave a permille fraction of the QCD rate for the signal to be washed away!

Determining backgrounds from data

[*M. Mangano, SUSY07*]

The prediction of each of these backgrounds, both physics and detector ones, and of possible additional ones, should be entirely based on the data themselves

Each search strategy should contain the definition of control samples and control observables to be used for

★ the direct determination of the backgrounds (e.g. by extrapolation of sidebands)

★ the validation of the MC tools,

and the proof that extrapolation is legitimate

Role of theoretical predictions

[*M. Mangano, SUSY07*]

- **accurate absolute predictions for inclusive quantities:**
  - E.g. W/Z total cross sections ⇒ luminosity determination, PDF measurements
  - E.g. Higgs and other new particles cross sections ⇒ extract couplings, BRs
  - ⇨ **require N(N)LO for reduced scale dependence**
- **complete description of final states**
  - complete description of SM processes with, e.g. ,
    - large jet multiplicities
    - associated production of multiple EW and QCD objects (t,b,g,H,W,...)
  - Goal is not first-principle predictability, but good agrement with data after tuning
  - ⇨ **require full MC generators, flexibility in the input param's for accurate tuning**

SUSY signals at the LHC

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

$\Rightarrow$ It quacks like SUSY!

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 . . .

- 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, . . . ?

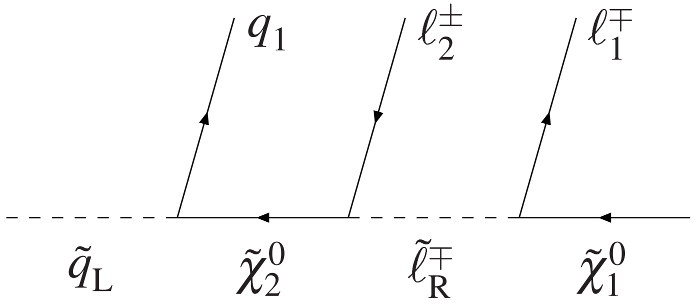
Even when we are sure that it is actually SUSY, we will still want to know:

- 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?

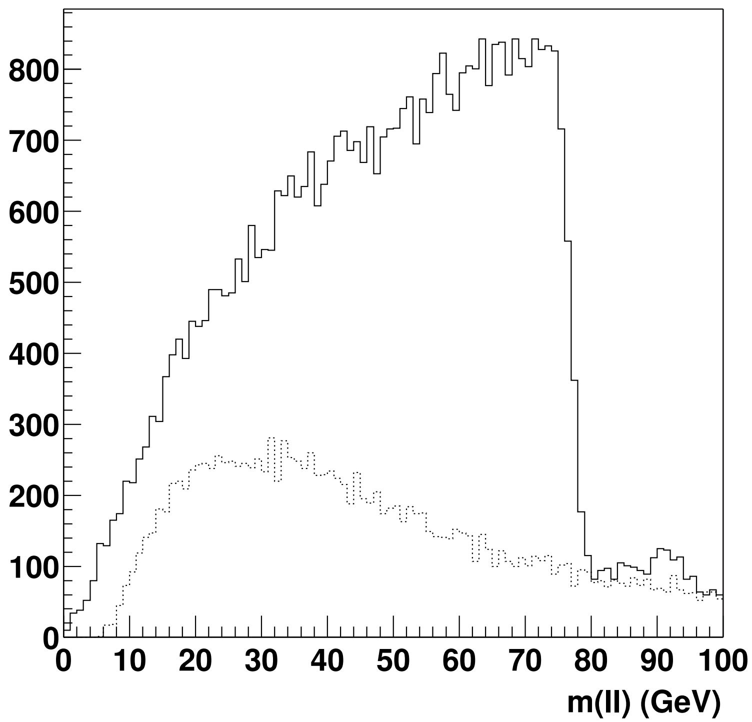
We will ask similar questions for other kinds of new physics

SUSY searches at the LHC

Cascade decays: complicated decay chains for squarks and gluinos



Main tool: dilepton "edge" from $\tilde{\chi}_2^0 \to \ell^+\ell^-\tilde{\chi}_1^0$



Information from kinematical edges and thresholds

$$(m^2_{ll})^{\text{edge}} = \frac{(m^2_{\tilde{\chi}^0_2} - m^2_{\tilde{l}_R})(m^2_{\tilde{l}_R} - m^2_{\tilde{\chi}^0_1})}{m^2_{\tilde{l}_R}}$$

$$(m^2_{qll})^{\text{edge}} = \frac{(m^2_{\tilde{q}_L} - m^2_{\tilde{\chi}^0_2})(m^2_{\tilde{\chi}^0_2} - m^2_{\tilde{\chi}^0_1})}{m^2_{\tilde{\chi}^0_2}}$$

$$(m^2_{ql})^{\text{edge}}_{\text{min}} = \frac{(m^2_{\tilde{q}_L} - m^2_{\tilde{\chi}^0_2})(m^2_{\tilde{\chi}^0_2} - m^2_{\tilde{l}_R})}{m^2_{\tilde{\chi}^0_2}}$$

$$(m^2_{ql})^{\text{edge}}_{\text{max}} = \frac{(m^2_{\tilde{q}_L} - m^2_{\tilde{\chi}^0_2})(m^2_{\tilde{l}_R} - m^2_{\tilde{\chi}^0_1})}{m^2_{\tilde{l}_R}}$$

$$\begin{aligned}(m^2_{qll})^{\text{thres}} = {} & [(m^2_{\tilde{q}_L} + m^2_{\tilde{\chi}^0_2})(m^2_{\tilde{\chi}^0_2} - m^2_{\tilde{l}_R})(m^2_{\tilde{l}_R} - m^2_{\tilde{\chi}^0_1}) \\ & -(m^2_{\tilde{q}_L} - m^2_{\tilde{\chi}^0_2})\sqrt{(m^2_{\tilde{\chi}^0_2} + m^2_{\tilde{l}_R})^2(m^2_{\tilde{l}_R} + m^2_{\tilde{\chi}^0_1})^2 - 16 m^2_{\tilde{\chi}^0_2} m^4_{\tilde{l}_R} m^2_{\tilde{\chi}^0_1}} \\ & +2m^2_{\tilde{l}_R}(m^2_{\tilde{q}_L} - m^2_{\tilde{\chi}^0_2})(m^2_{\tilde{\chi}^0_2} - m^2_{\tilde{\chi}^0_1})]/(4m^2_{\tilde{l}_R} m^2_{\tilde{\chi}^0_2})\end{aligned}$$

$\Rightarrow$ Precise information on mass squared differences

From overconstrained system $\Rightarrow$ absolute mass determination

Dilepton edges

- "Experimentalist's definition" of a lepton: $e^\pm$, $\mu^\pm$

  τ's are much more challenging

  However, most of the leptons are in fact τ's, completely dominate at high $\tan\beta$

  E.g.: SPS1a, $\tan\beta = 10$:

  $\mathrm{BR}(\tilde{\chi}_2^0 \to \tilde{e}^\pm e^\mp) = \mathrm{BR}(\tilde{\chi}_2^0 \to \tilde{\mu}^\pm \mu^\mp) = 6\%$

  $\mathrm{BR}(\tilde{\chi}_2^0 \to \tilde{\tau}^\pm \tau^\mp) = 88\%$

- Use more information than just the kinematic edges: complete shapes?

  What is the impact of Monte Carlo uncertainties, higher-order contributions?

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

SUSY contains many parameters that are not closely related to a specific experimental observable:

mixing angles, $\tan\beta$, complex phases, ...

Most observables depend on a variety of SUSY parameters

$\Rightarrow$ SUSY parameters need to be determined by global fits to a large set of observables

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:

- LSP mass — the dark matter particle
- LSP couplings
- NLSP–LSP mass difference ("coannihilation region"), down to $0.2\ \mathrm{GeV}$
- 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*]

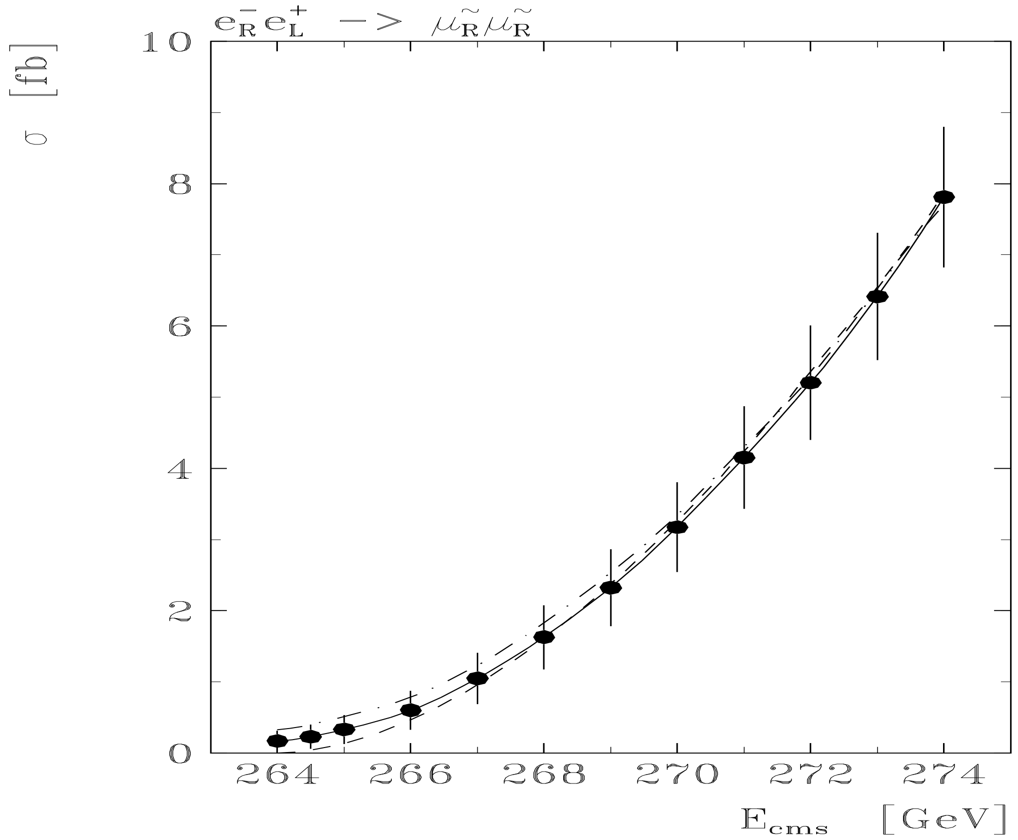
www.ippp.dur.ac.uk/$\sim$georg/lhcilc

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*]

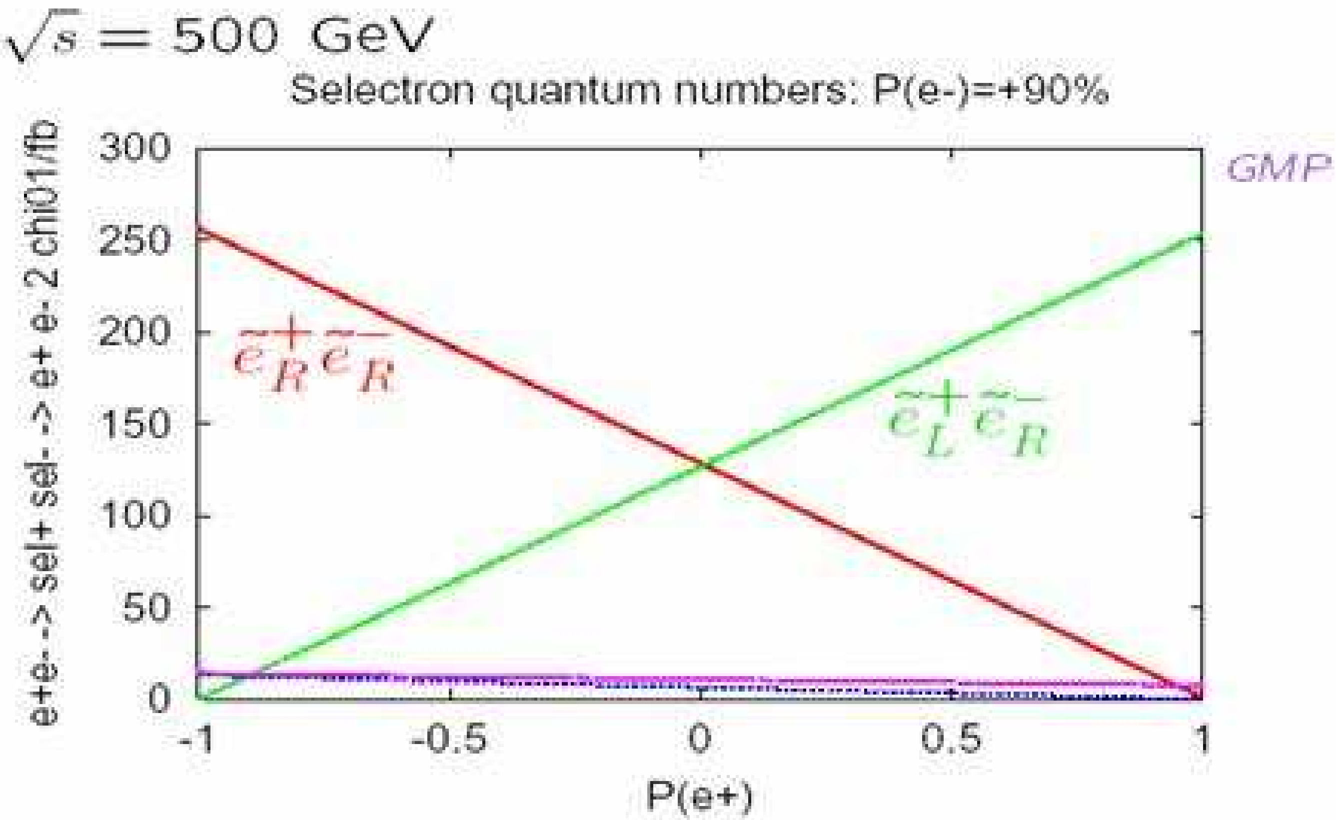


$$\Rightarrow \quad \frac{\Delta m_{\tilde{\mu}_R}}{m_{\tilde{\mu}_R}} < 1 \times 10^{-3}$$

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

Determination of chiral quantum numbers

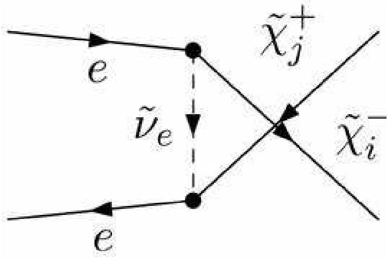
[*G. Moortgat-Pick '05*]



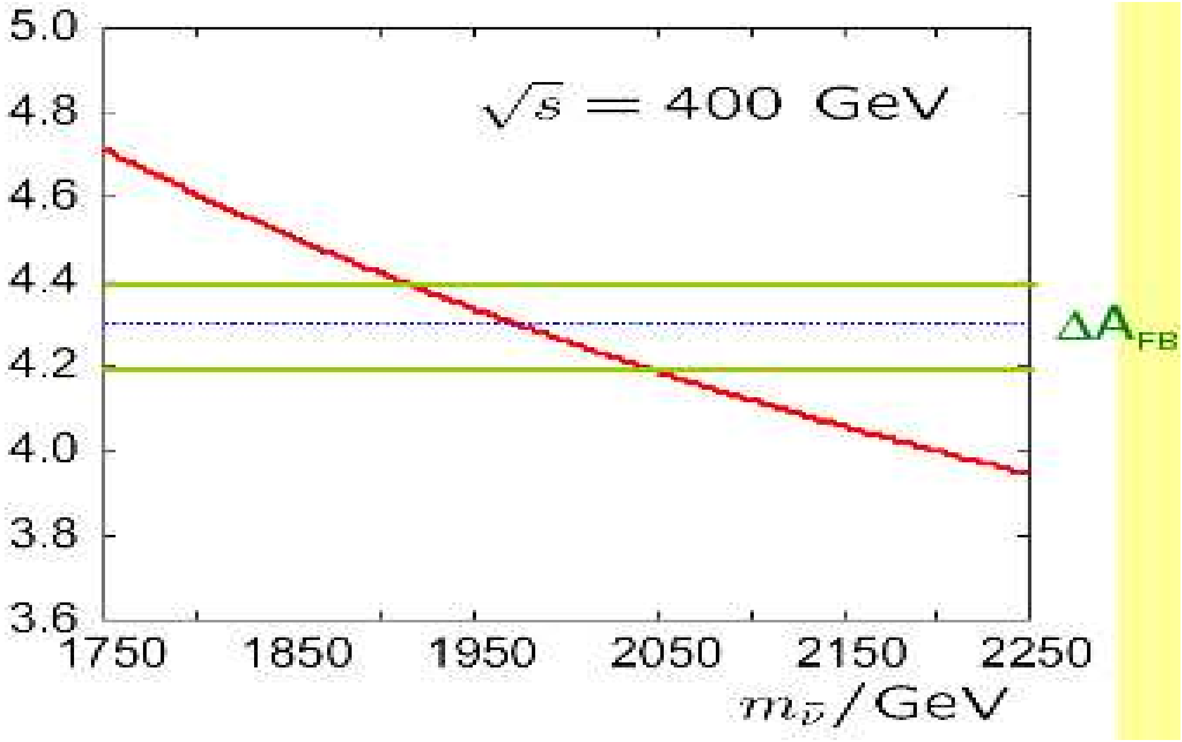
$\Rightarrow$ Experimental proof of SUSY relations
information on SUSY breaking patterns

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

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



[*G. Moortgat-Pick '05*]

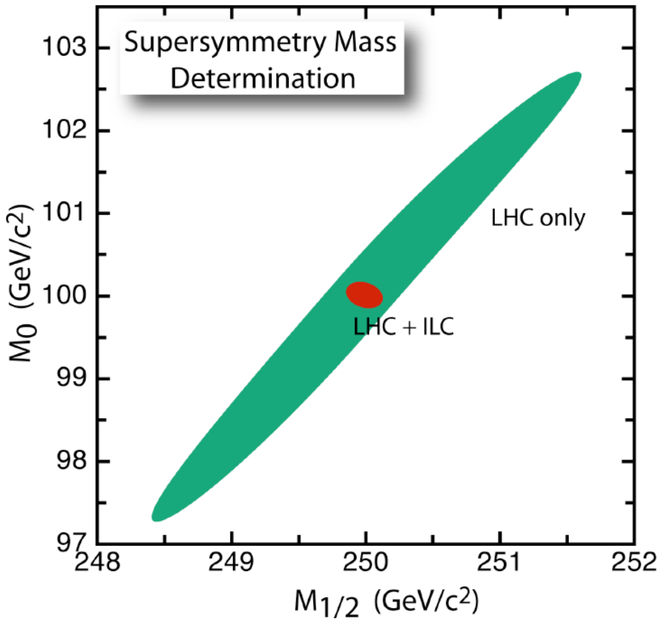


$\Rightarrow$ Indirect determination of sneutrino mass
distinction between models: focus point vs. split SUSY

Determination of SUSY parameters at LHC $\oplus$ ILC

Constrained MSSM:

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



$\Rightarrow$ LHC $\oplus$ ILC yields drastic improvement

Unconstrained MSSM:

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

LHC $\oplus$ ILC needed for precise det. of SUSY parameters

Conclusions and Outlook

- LHC will open the new territory of TeV-scale physics
- “Golden era” of the Standard Model is likely to end soon

  At the TeV scale we expect to observe manifestations of the mechanism(s) responsible for EWSB and for stabilising the hierarchy between M_{weak} and M_{Planck}
- Will the LHC be a “dark matter factory”?
- Low-energy SUSY continues to be our best bet for physics beyond the SM

  Good agreement with constraints from precision observables $+$ dark matter

Conclusions and Outlook

- Data rules: Experimental information from Tevatron, LHC, ILC, ν experiments, dark matter searches, low-energy exp., ... needed to verify / falsify models of new physics

- New physics can manifest itself in many (and maybe completely unexpected) ways

  $\Rightarrow$ Challenge for experiment and theory to figure out the nature of TeV-scale physics

- The experiments in the next years will bring a decisive test of our ideas about physics beyond the SM

  We should be prepared for surprises ...

Looking forward to very exciting times ahead of us!