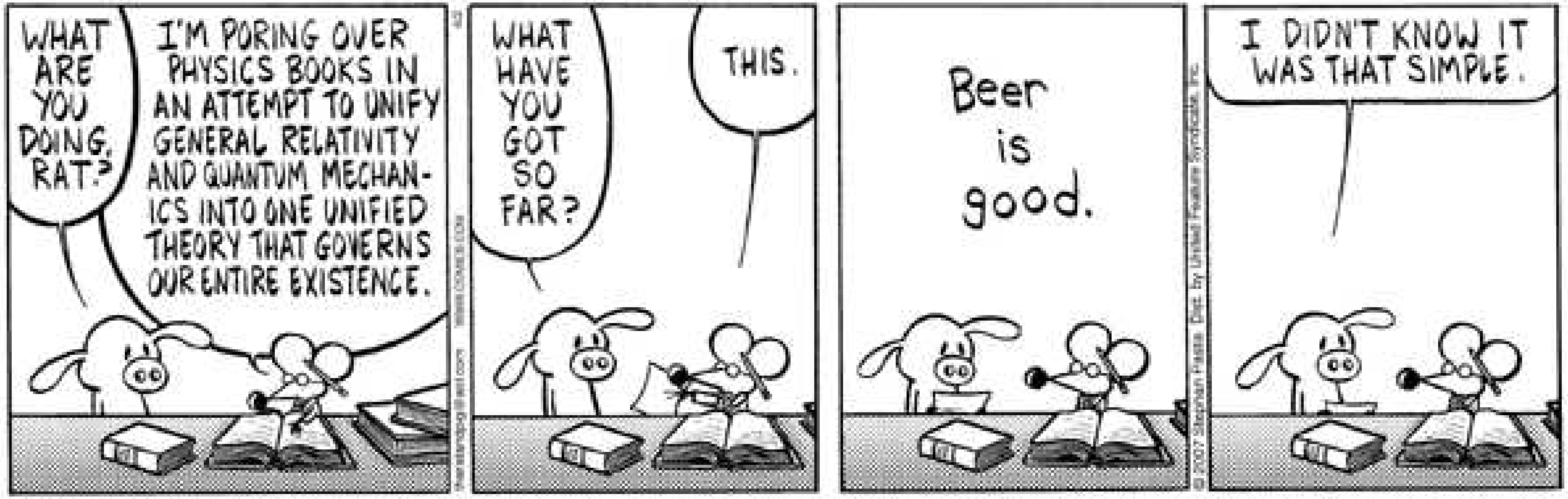
WHAT ARE YOU DOING, RAT?
I'M PORING OVER PHYSICS BOOKS IN AN ATTEMPT TO UNIFY GENERAL RELATIVITY AND QUANTUM MECHANICS INTO ONE UNIFIED THEORY THAT GOVERNS OUR ENTIRE EXISTENCE.
WHAT HAVE YOU GOT SO FAR?
THIS.
Beer is good.
I DIDN'T KNOW IT WAS THAT SIMPLE.

BSM Physics at the LHC

Sven Heinemeyer, IFCA (CSIC, Santander)

Barcelona, 09/2010

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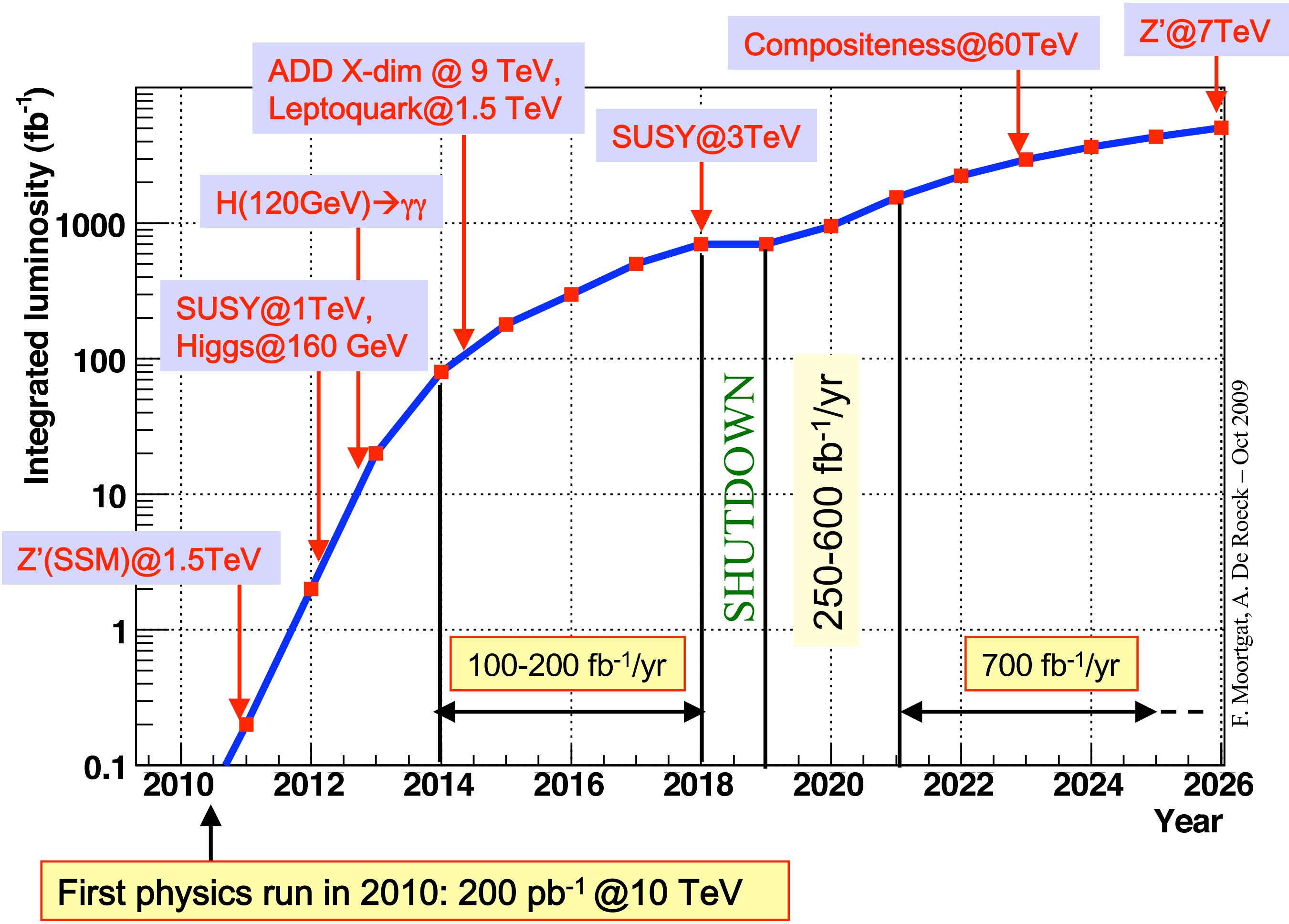
1. Introduction
2. Introduction to Supersymmetry
3. Supersymmetry at the LHC
4. More BSM phenomenology at the LHC
5. Conclusions

1. Introduction

[A. De Roeck et al. '09]



CERN TH institute 02/09: LHC2FC: From the LHC to Future Colliders

The (un)official (optimistic?) LHC time line:

2009: repairs, cool-down etc.,
first collisions by the end of the year!

2010 – 2011: $\lesssim 1\ \text{fb}^{-1}$ (at $\sqrt{s} = 7$ TeV) $\Rightarrow$ first physics results?

2012: shutdown, further splice checks, repairs, . . .

2013 – 2015: $10\ \text{fb}^{-1}$ per year $\Rightarrow$ physics results with "low" luminosity

2016 – ?: $100\ \text{fb}^{-1}$ per year $\Rightarrow$ physics results with "high" luminosity

2019 + X (X > 0): upgrade to SLHC?

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2019 + X (X > 0): upgrade to SLHC?

YOU live in an exciting time!!!

Physics at the LHC: basics

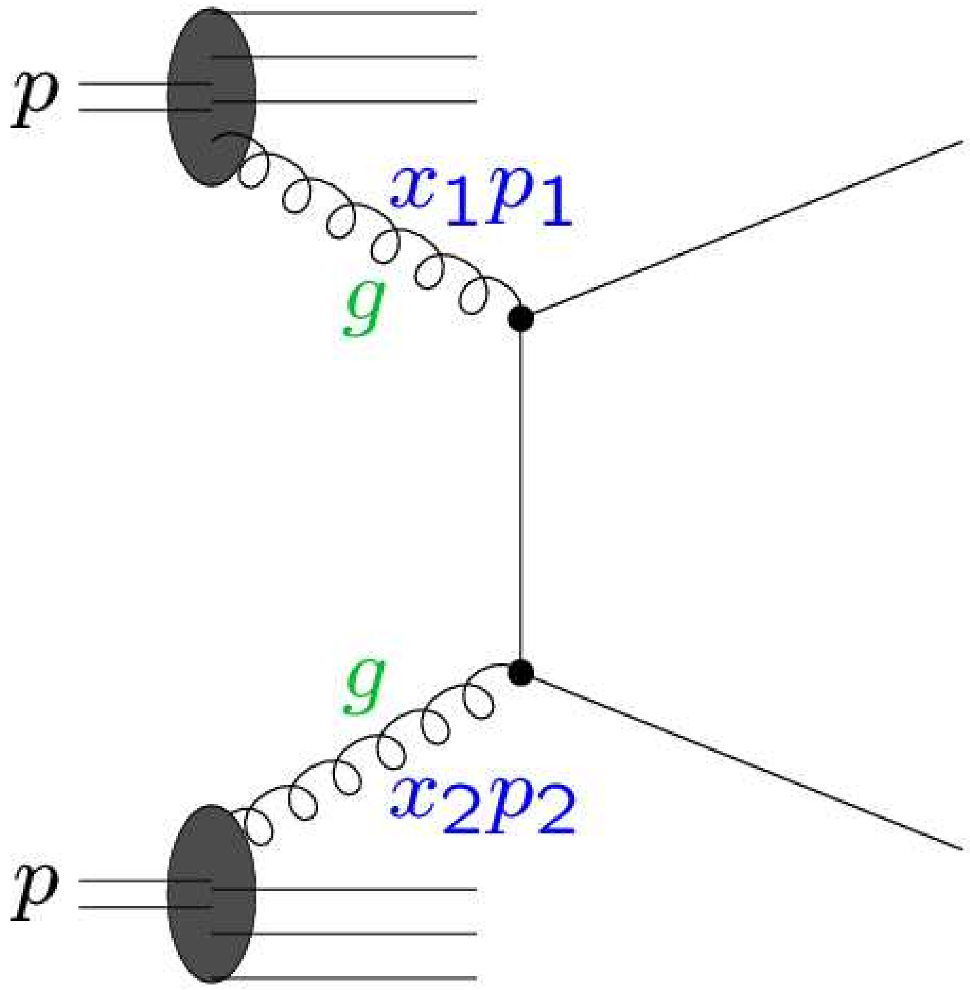
$p\,p$ scattering at $\sqrt{s} = 14$ TeV

Scattering process of proton constituents (q, $\bar{q}$, g) with energy up to several TeV, strongly interacting

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

interaction rate of 10^9 events/s

$\Rightarrow$ can trigger on only 1 event in 10^7



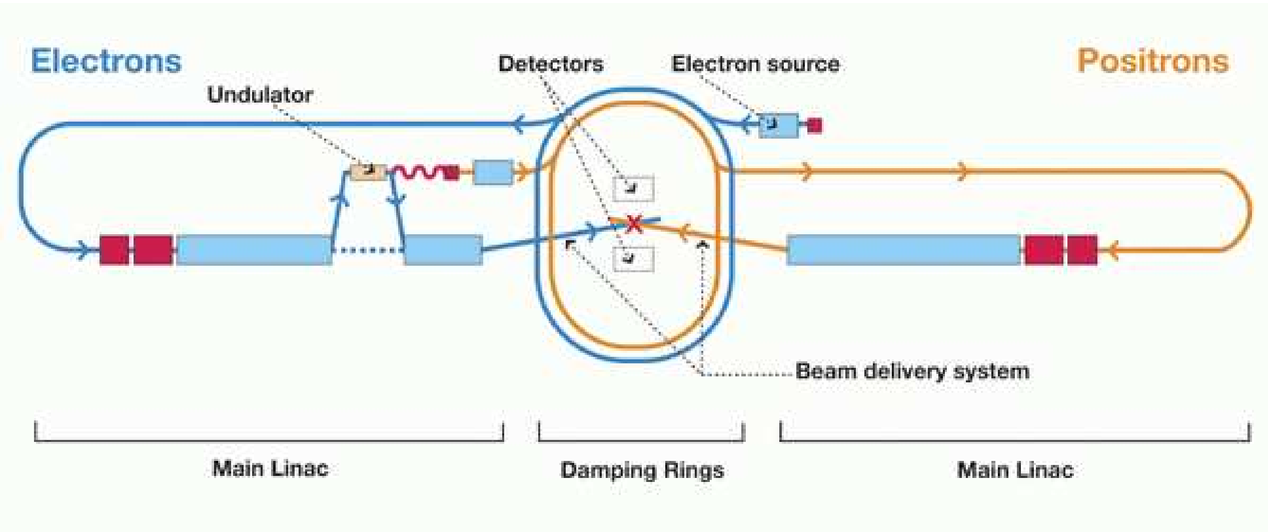
The "dirty" LHC might not be precise enough . . .   what then?

The “dirty” LHC might not be precise enough . . . what then?

Linear e^+e^- collider, $\sqrt{s} = 500 - 1000$ GeV

based on superconducting cavities (cold technology) (ITRP decision 2004)

Schematic:



– two detectors in one interaction region (push-pull)

– undulator based e^+ source

– polarized beams for e^- and e^+ ($P_{e^-} = 80\%$, $P_{e^+} = 60\%$)

Other options:

- GigaZ:
  running with high luminosity at low energies (Z pole, WW threshold)

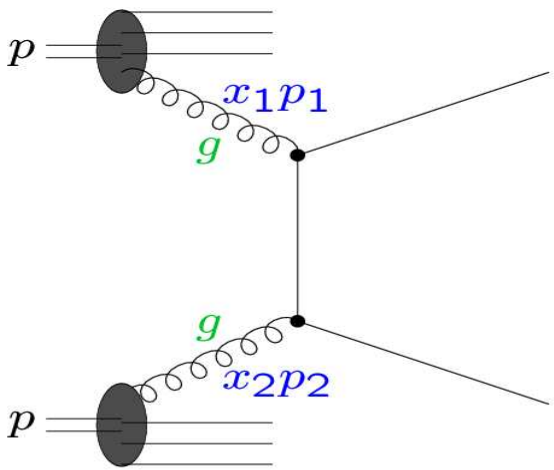
- e^-e^-:
  produce doubly charged particles in the s channel

- $e^-\gamma$:
  use one e^- beam to produce high-energy photons
  produce charged particles in the s channel

- $\gamma\gamma$:
  use both beams to produce high-energy photons
  (e.g. heavy Higgs production in the s channel)

Mini-comparison of LHC and ILC:

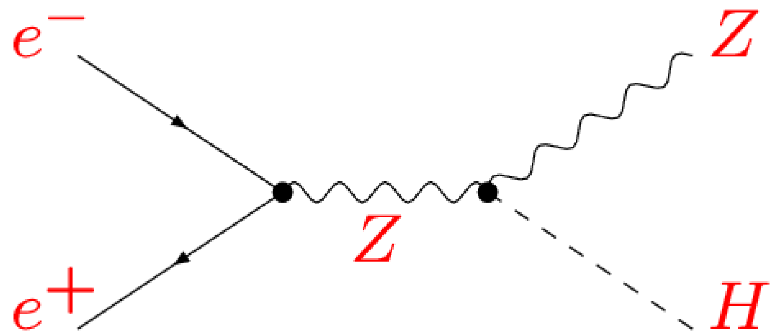
LHC: pp scattering at 14 TeV



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

⇒ huge QCD backgrounds,
low signal–to–background ratios

ILC: e^+e^- scattering
at ≈0.5–1 TeV

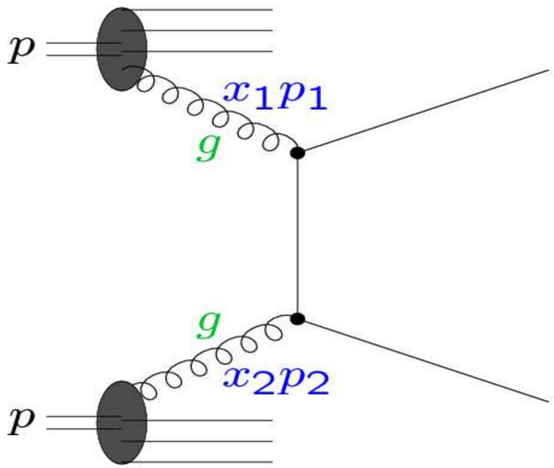


Clean exp. environment:
well-defined initial state,
tunable energy,
beam polarization, GigaZ,
$\gamma\gamma$, $e\gamma$, e^-e^- options, . . .

⇒ rel. small backgrounds
high-precision physics

Mini-comparison of LHC and ILC:

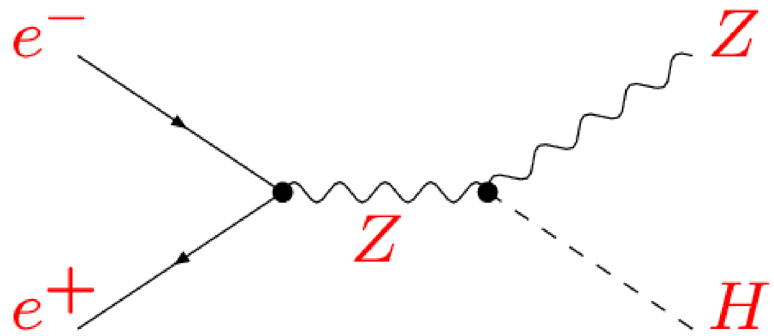
LHC: pp scattering at 14 TeV



interaction rate of 10^9 events/s

$\Rightarrow$ can trigger on only 1 event in 10^7

ILC: e^+e^- scattering at ≈0.5–1 TeV



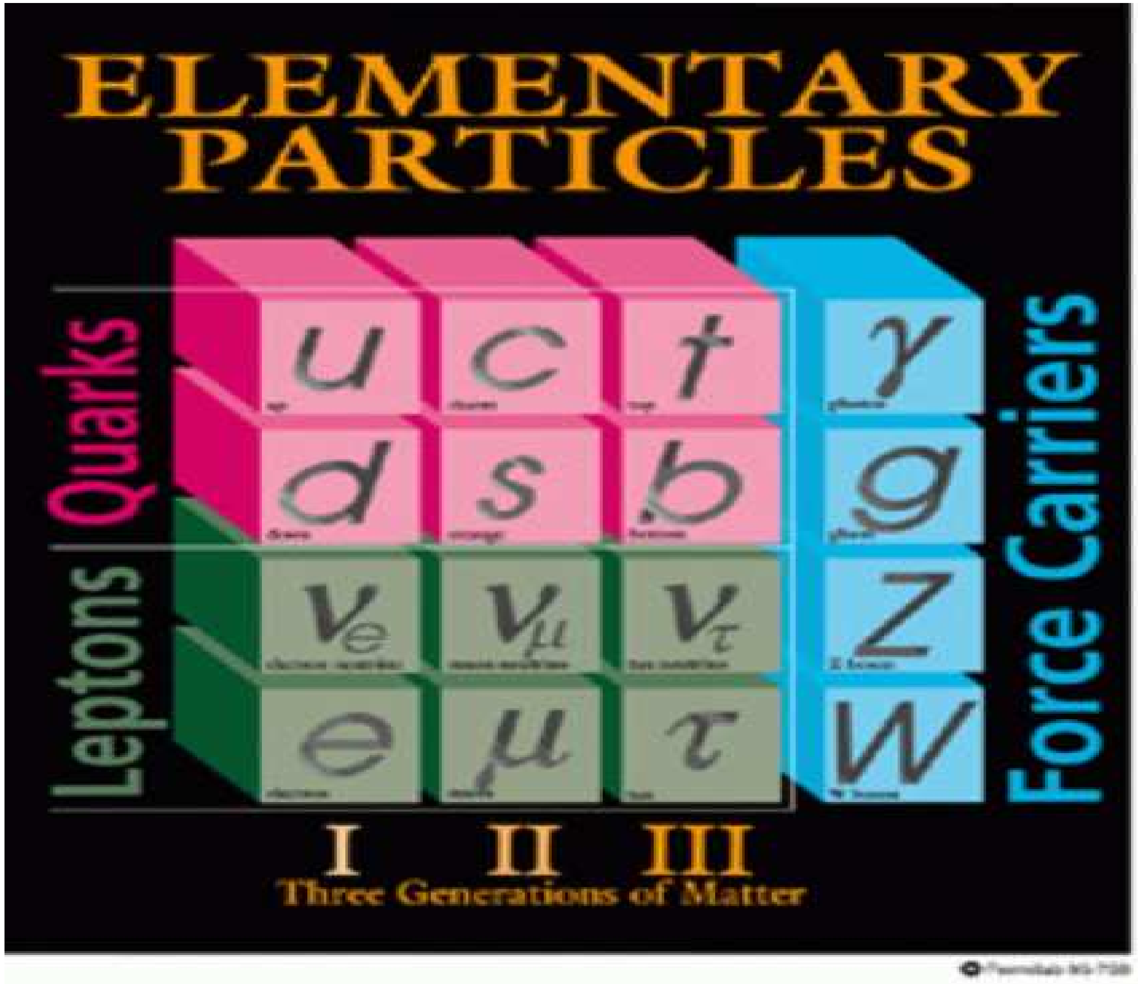
untriggered operation

$\Rightarrow$ can find signals of unexpected new physics (direct production + large indirect reach) that manifests itself in events that are not selected by the LHC trigger strategies

Why physics beyond the SM?

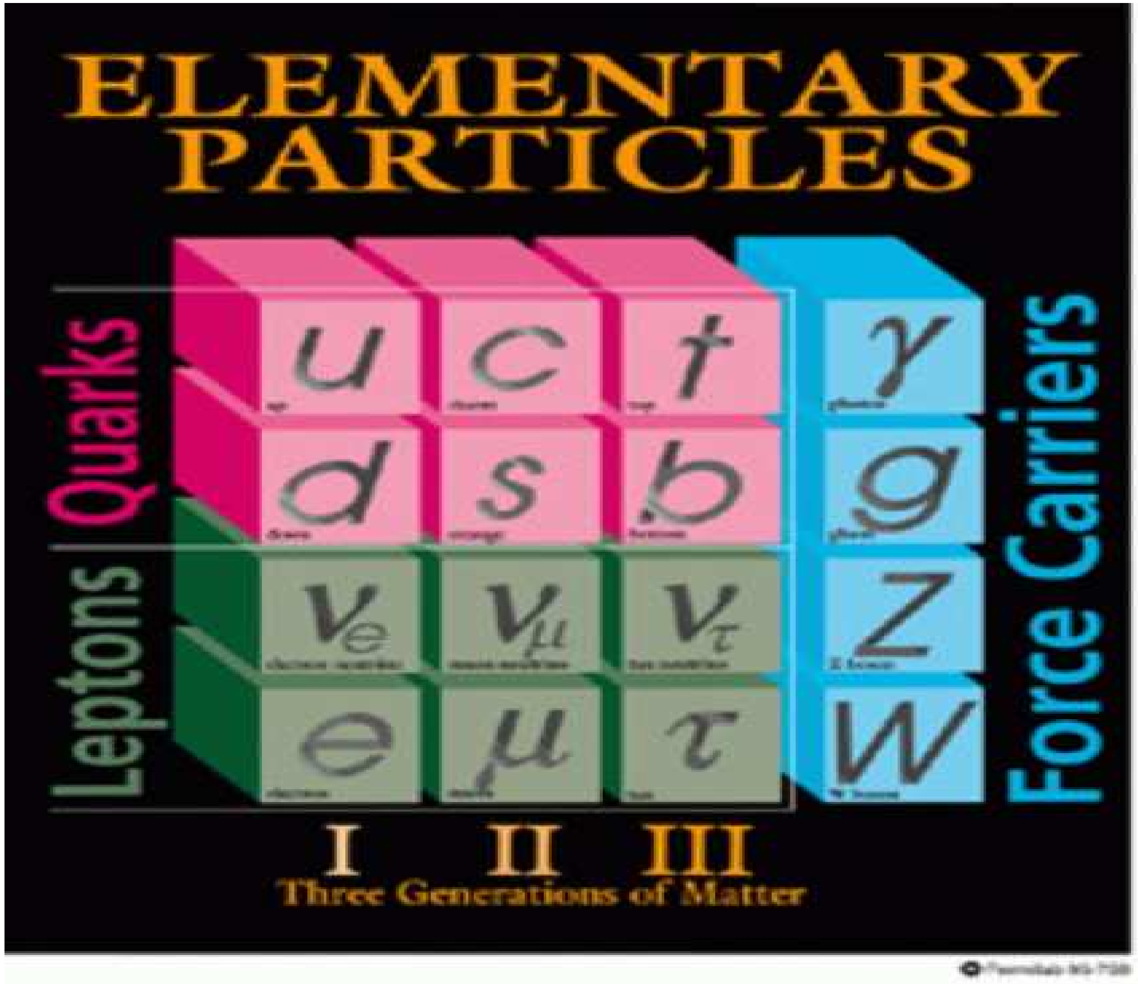
1. Check: status of the field (SM, . . .)
2. One finds: A Higgs (or something similar?) is missing
3. This introduces the hierarchy problem
   ⇒ physics beyond the SM required
4. Check all experimental constraints
5. One finds: some constraints require physics beyond the SM
6. ⇒ get an overview about New Physics Models
7. ⇒ NPM have to fulfill experimental constraints
8. ⇒ LHC phenomenology of BSM

Current status of knowledge: the Standard Model (SM)



⇒ all particles experimentally seen

Current status of knowledge: the Standard Model (SM)



⇒ all particles experimentally seen

⇒ but one particle is missing . . .

Problem:

Gauge fields Z, W^+, W^- are massive

explicite mass terms in the Lagrangian $\Leftrightarrow$ breaking of gauge invariance

Solution: Higgs mechanism

scalar field postulated, mass terms from coupling to Higgs field

Higgs sector in the Standard Model:

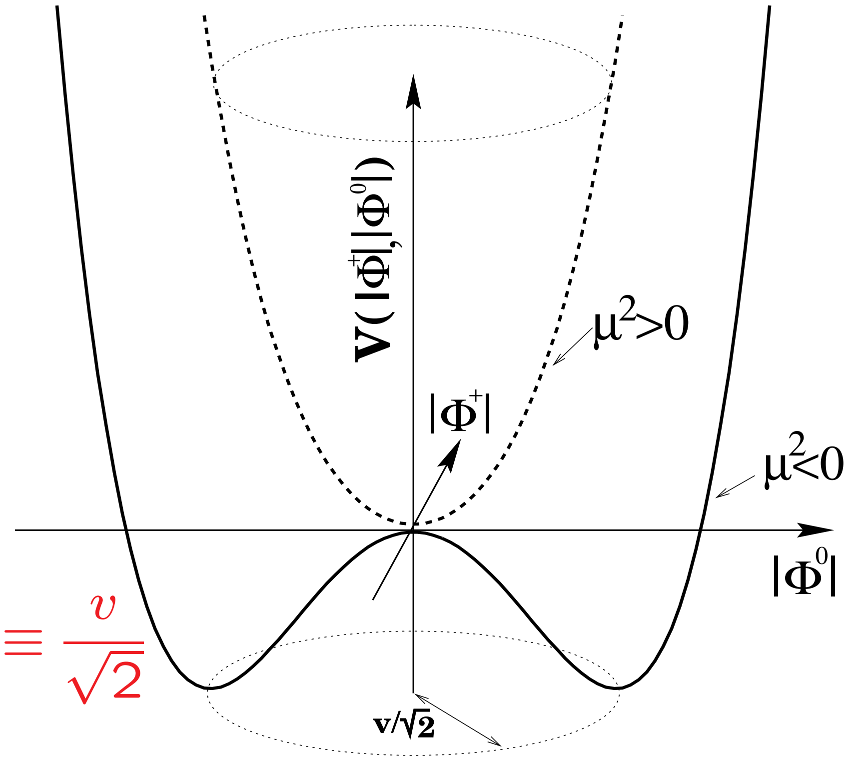
Scalar SU(2) doublet: $\Phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix}$

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 potential at $|\langle \Phi_0 \rangle| = \sqrt{\frac{-\mu^2}{2\,\lambda}} \equiv \frac{v}{\sqrt{2}}$



$$\Phi = \begin{pmatrix} 0 \\ v + H \end{pmatrix} \quad \text{(unitary gauge)}$$

H: elementary scalar field, Higgs boson

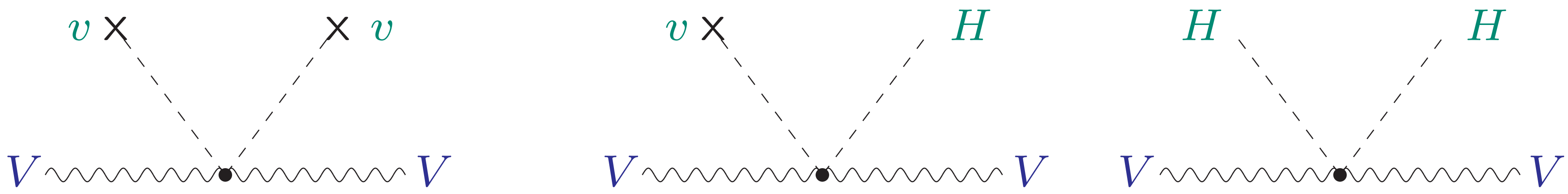
Lagrange density:

$$\mathcal{L}_{\text{Higgs}} = (D_\mu \Phi)^\dagger (D^\mu \Phi) - V(\Phi)$$

Gauge invariant coupling to gauge fields

$\Rightarrow$ mass terms for gauge bosons and fermions

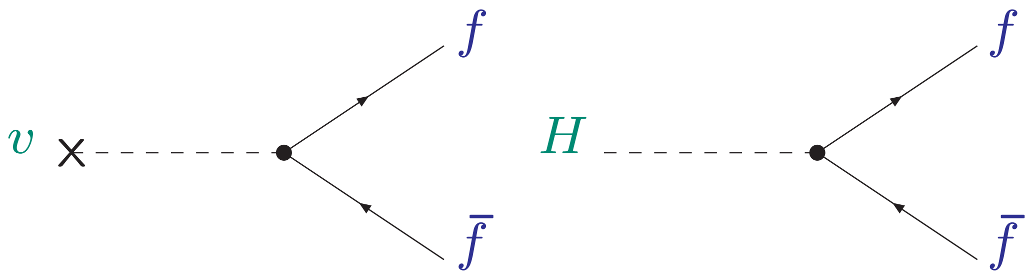
1.) $VV\Phi\Phi$ coupling:



$\Rightarrow$ VV mass terms $\qquad$ $\Rightarrow$ triple/quartic couplings to gauge bosons

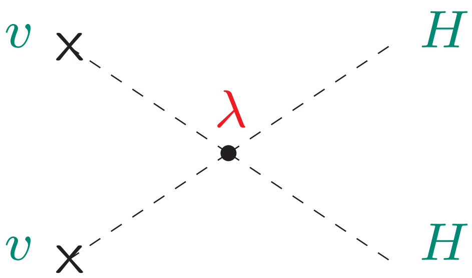
$g_2^2 v^2/2 \equiv M_W^2$, $(g_1^2 + g_2^2) v^2/2 \equiv M_Z^2$ $\Rightarrow$ coupling $\propto$ masses

2.) fermion mass terms: Yukawa couplings



$m_f = v\, g_f \Rightarrow$ coupling $\propto$ masses

3.) mass of the Higgs boson: self coupling



. . .

$\lambda = M_H^2/v$

$M_H = v\sqrt{\lambda}$ free parameter

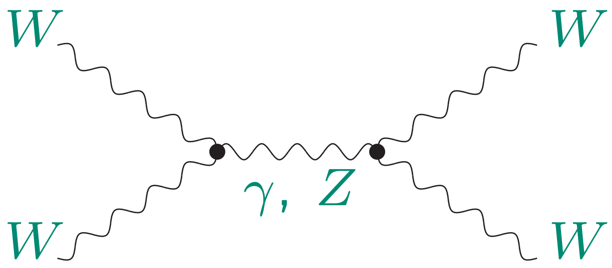
$\rightarrow$ last unknown parameter of the SM

$\Rightarrow$ establish Higgs mechanism $\equiv$ find the Higgs $\oplus$ measure its couplings

Another effect of the Higgs field:

Scattering of longitudinal W bosons: $W_L W_L \to W_L W_L$

$\mathcal{M}_V =$



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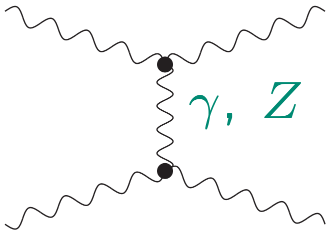

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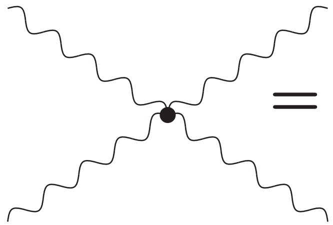
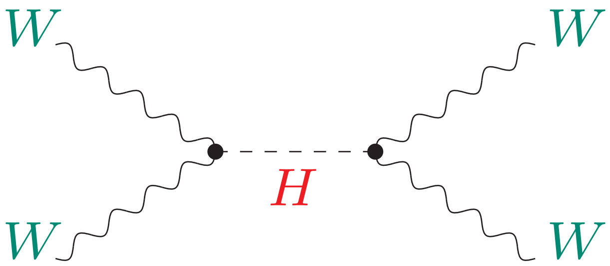


$= -g^2 \frac{E^2}{M_W^2} + \mathcal{O}(1)$ for $E \to \infty$

$\Rightarrow$ violation of unitarity

Contribution of a scalar particle with couplings prop. to the mass:

$\mathcal{M}_S =$



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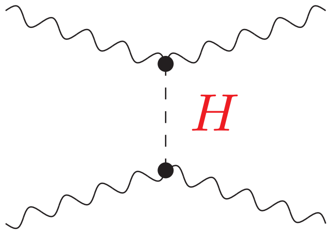


$= g_{WWH}^2 \frac{E^2}{M_W^4} + \mathcal{O}(1)$ for $E \to \infty$

$$\mathcal{M}_{\text{tot}} = \mathcal{M}_V + \mathcal{M}_S = \frac{E^2}{M_W^4}\left(g_{WWH}^2 - g^2\, M_W^2\right) + \ldots$$

$\Rightarrow$ compensation of terms with bad high-energy behavior for

$$g_{WWH} = g\, M_W$$

What else do we know about the Higgs boson?

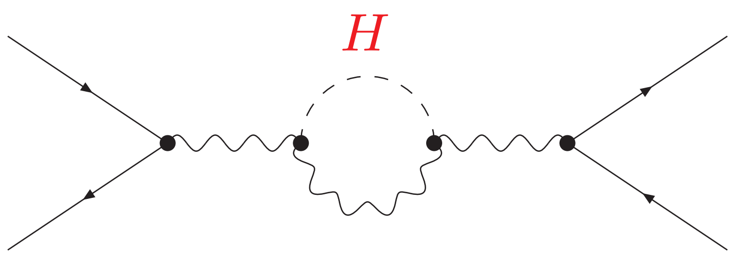
$\Rightarrow$ Indirect measurements via precision observables (POs):

Comparison of electro-weak precision observables with theory:

EW Precision data:	$\leftrightarrow$	Theory:
$M_W, \sin^2\theta_{\text{eff}}, \ldots$		SM, MSSM , . . .

$\Downarrow$

Test of theory at quantum level: Sensitivity to loop corrections



$\Downarrow$

All parameters of the model enter

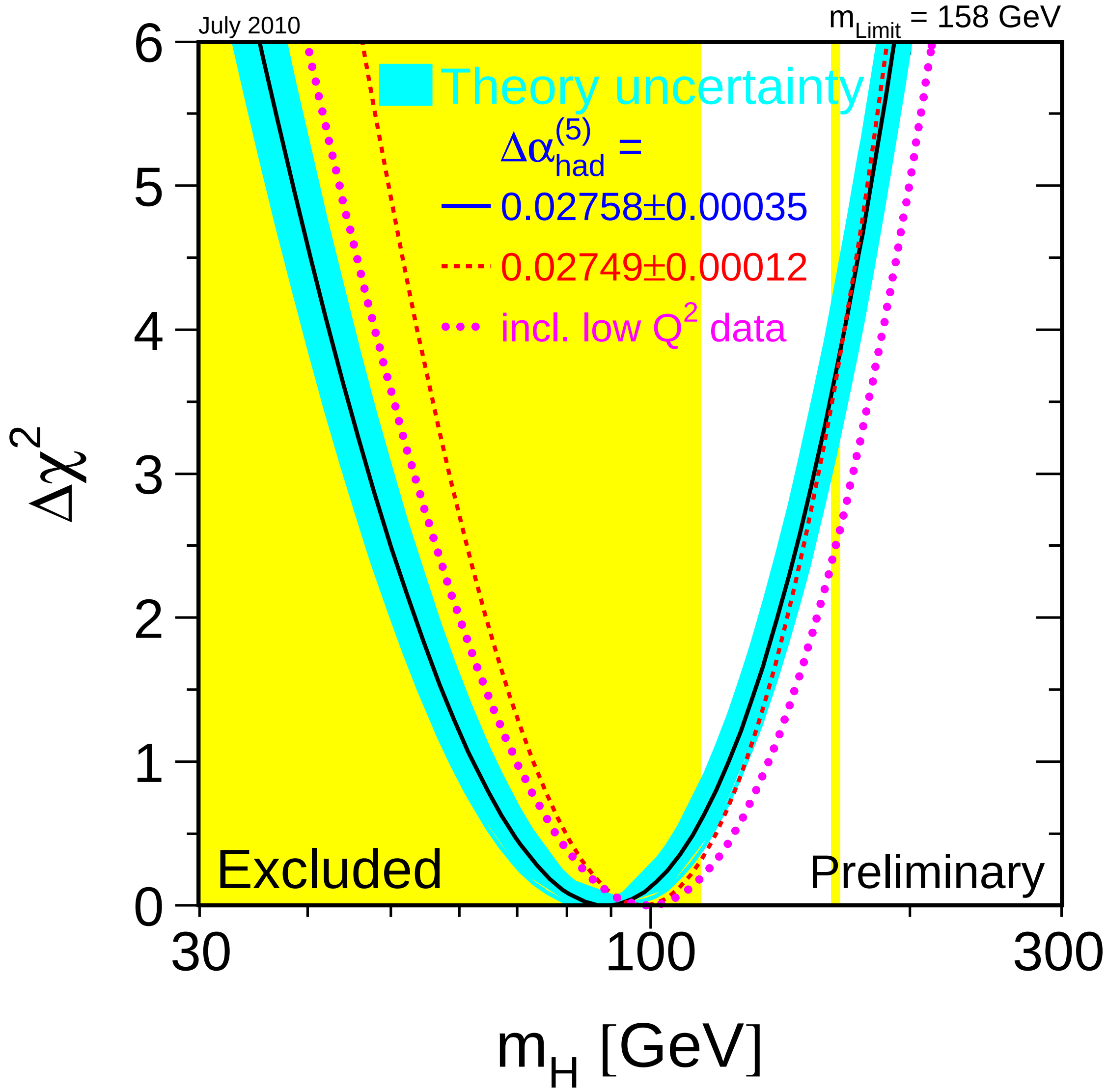
limits on M_H

Global fit to all SM data:

[*LEPEWWG '10*]

$\Rightarrow M_H = 89^{+35}_{-26}$ GeV

$M_H < 158$ GeV, 95% C.L.



Assumption for the fit:
SM incl. Higgs boson

$\Rightarrow$ no confirmation of
Higgs mechanism

$\Rightarrow$ Higgs boson seems to be light, $M_H \lesssim 160$ GeV

Physics beyond the SM:

The Standard Model (SM) cannot be the ultimate theory

- The SM does not contain gravity
- Hierarchy problem → more in a moment
- Cold Dark Matter exists, SM has no candidate
- neutrino masses (if not SM-like Dirac masses)
- $(g-2)_\mu$ shows a $\sim 3\,\sigma$ deviation from the SM

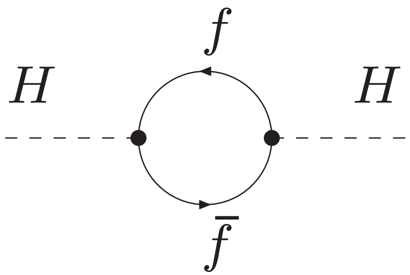
Experimental constraints:

- direct search limits
- indirect constraints from precision measurements
- are deviations from the SM improved?

Mass is what determines the properties of the free propagation of a particle

Free propagation: 

inverse propagator: $i(p^2 - M_H^2)$

Loop corrections: 

inverse propagator: $i(p^2 - M_H^2 + \Sigma_H^f)$

QM: integration over all possible loop momenta k

dimensional analysis:

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

$$\text{for } \Lambda \to \infty: \quad \Sigma_H^f \sim N_f \, \lambda_f^2 \left(\underbrace{\int \frac{d^4k}{k^2}}_{\sim \Lambda^2} + 2m_f^2 \underbrace{\int \frac{dk}{k}}_{\sim \ln \Lambda} \right)$$

$\Rightarrow$ quadratically divergent!

For $\Lambda = M_{\text{Pl}}$:

$$\Sigma_H^f \approx \delta M_H^2 \sim M_{\text{Pl}}^2 \quad \Rightarrow \quad \delta M_H^2 \approx 10^{30}\, M_H^2$$

(for $M_H \lesssim 1$ TeV)

– no additional symmetry for $M_H = 0$

– no protection against large corrections

$\Rightarrow$ Hierarchy problem is instability of small Higgs mass to large corrections in a theory with a large mass scale in addition to the weak scale

E.g.: Grand Unified Theory (GUT): $\delta M_H^2 \approx M_{\text{GUT}}^2$

Note however: there is another fine-tuning problem in nature, for which we have no clue so far – cosmological constant

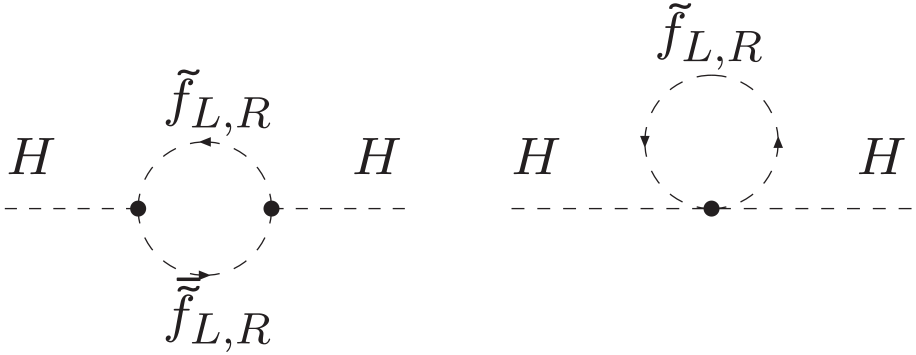
Supersymmetry:

Symmetry between fermions and bosons

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

Effectively: SM particles have SUSY partners (e.g. $f_{L,R} \to \tilde{f}_{L,R}$)

SUSY: additional contributions from scalar fields:



$$\Sigma_H^{\tilde{f}} \sim N_{\tilde{f}} \, \lambda_{\tilde{f}}^2 \int d^4k \left(\frac{1}{k^2 - m_{\tilde{f}_L}^2} + \frac{1}{k^2 - m_{\tilde{f}_R}^2} \right) + \text{ terms without quadratic div.}$$

for $\Lambda \to \infty$: $\quad \Sigma_H^{\tilde{f}} \sim N_{\tilde{f}} \, \lambda_{\tilde{f}}^2 \, \Lambda^2$

⇒ quadratic divergences cancel for

$$N_{\tilde{f}_L} = N_{\tilde{f}_R} \;=\; N_f$$
$$\lambda^2_{\tilde{f}} \;=\; \lambda^2_f$$

complete correction vanishes if furthermore

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

Soft SUSY breaking: $m^2_{\tilde{f}} = m^2_f + \Delta^2, \quad \lambda^2_{\tilde{f}} = \lambda^2_f$

$$\Rightarrow \; \Sigma_H^{f+\tilde{f}} \sim N_f \, \lambda^2_f \, \Delta^2 + \ldots$$

⇒ correction stays acceptably small if mass splitting is of weak scale

⇒ realized if mass scale of SUSY partners

$$M_{\mathrm{SUSY}} \lesssim 1\,\mathrm{TeV}$$

⇒ SUSY at TeV scale provides attractive solution of hierarchy problem

Physics beyond the SM: Interesting (new) physics models :

- 2HDM
- MSSM:
  - solves hierarchy problem
  - automatic electroweak symmetry breaking
  - gauge coupling unification
  - cold dark matter candidate
- extra gauge groups, Z'
- SM4: 4^{th} generation of fermions
- Extra dimensions:
  - solves the hierarchy problem
  - cold dark matter candidate
- Little Higgs:
  - (partially) solves the hierarchy problem
  - cold dark matter candidate
- ...

2. Introduction to Supersymmetry

Symmetry: a group of transformations that leaves the Lagrangian invariant

Generators of the group fulfill certain algebra

Examples:

0. Angular rotation: $\Psi \to \Psi e^{i\theta^a L_a}$
   theory is invariant under rotation
   generators: L_a, algebra: $[L_a, L_b] = i\varepsilon_{abc}L^c$
   Quantum numbers: (max. spin)^2, spin $[l(l+1), m = +l \ldots -l]$

1. Internal symmetry: $SU(3) \times SU(2) \times U(1)$
   gauge symmetry for the description of the strong and electroweak force
   generators: T_a, algebra: $[T_a, T_b] = i f_{abc} T^c$
   Quantum numbers: color, weak isospin, hyper charge

2. Poincaré symmetry (includes rotation)
   space–time symmetries:
   Lorentz transformations: $\Lambda^{\mu\nu}$, translations: P^ρ
   Quantum numbers: mass, spin

Our world (the SM) is described by:

– internal symmetry: T_a

– Poincaré symmetry: $\Lambda^{\mu\nu}$, P^ρ

internal symmetry is a trivial extension of the Poincaré symmetry:

$$[\Lambda^{\mu\nu}, T^a] = 0, \qquad [P^\rho, T^a] = 0$$

$\Rightarrow$ direct product: (Poincaré group) $\otimes$ (internal symmetry group)

Particle states characterized 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

Wanted: extension of the SM

Theorem # 1: No-go theorem [*Coleman, Mandula '67*]

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

$$|\underbrace{m, s; \vec{p}, s_3}_{\text{space–time}}; \underbrace{\tilde{g}, \ldots}_{\text{internal}}\rangle$$

quantum numbers

New group $\tilde{G}$ with generators Q^α and

$$[\Lambda^{\mu\nu}, Q^\alpha] \neq 0, \quad [P^\rho, Q^\alpha] \neq 0$$

impossible

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

$\Rightarrow$ new symmetry must predict new particles with the same mass and spin as in the SM

$\Rightarrow$ experimentally excluded, no such symmetry possible :-(

Theorem # 2: How-To-Avoid-the-No-go theorem

[Gol'fand, Likhtman '71] *[Volkov, Akulov '72]* *[Wess, Zumino '73]*

No go theorem can be evaded if instead of Lie-group (generators fulfill commutator relations):

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

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

$\Rightarrow$ Generator Q^α is fermionic (i.e. it has spin $\frac{1}{2}$)

$\Rightarrow$ Particles with different spin in one multiplet possible

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

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

E.g.:

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

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

⇒ $N = 1$ SUSY algebra:

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

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

⇒ SUSY: symmetry that relates bosons to fermions

unique extension of Poincaré group of symmetries of $D = 4$ relativistic QFT

Exercise # 1: a simple quantum mechanical SUSY example

Can SUSY be an exact symmetry?

Consider fermionic state $|f\rangle$ with mass m
$\Rightarrow$ there is a bosonic state $|b\rangle = Q_\alpha |f\rangle$

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

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

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

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

$\Rightarrow$ still experimentally excluded

$\Rightarrow$ SUSY must be broken

Superfields and Superspace

Translation transformation: P_μ , parameter: x^μ

SUSY transformation: $Q_\alpha, \bar{Q}_{\dot{\alpha}}$, parameter: $\theta, \bar{\theta} \rightarrow$ anticommuting c-numbers

("Grassmann variables")

$\Rightarrow$ 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: $\phi(x^\mu, \theta^\alpha, \bar{\theta}^{\dot{\alpha}})$

Grassmann variables:

SUSY transformation: $Q_\alpha, \bar{Q}_{\dot\alpha}$, parameter: $\theta, \bar\theta \to$ anticommuting c-numbers
("Grassmann variables")

Without spinor index:

$$\{\theta, \theta\} = 0 \;\Rightarrow\; \theta\theta = 0$$

With two-component spinor index (as it is our case):

$$\theta\theta \equiv \theta^\alpha\theta_\alpha = \epsilon_{\alpha\beta}\theta^\alpha\theta^\beta \;\Rightarrow\; \theta\theta \neq 0, \; (\theta^1\theta_2 \neq 0)$$

Taylor expansion in Grassmann variable: $\theta^\alpha\theta^\beta\theta^\gamma = 0$ $(\alpha, \beta, \gamma = 1, 2)$

$\Rightarrow$ Taylor expansion terminates after second term, i.e. $\phi(\theta) = a + \theta\psi + \theta\theta\, f$

Integration: $\int d\theta = 0$, $\int d\theta\, \theta = 1$

$d^2\theta = -\frac{1}{4}\epsilon_{\alpha\beta} d\theta^\alpha d\theta^\beta$

$$\Rightarrow \quad \int d^2\theta\, \phi(\theta) = \int d^2\theta (a + \theta\psi + \theta\theta\, f) = f$$

Simplified example: (simplified) left-handed chiral superfield

$$\phi_L(x,\theta) \;=\; \varphi(x) + \sqrt{2}\theta\,\psi(x) - (\theta\theta)F(x)$$

mass dimensions: $[\varphi] = 1$, $[\psi] = \frac{3}{2}$, $[F] = 2$

$\theta\theta = \varepsilon^{\alpha\beta}\theta_\alpha\theta_\beta, \qquad \theta^\alpha\theta_\alpha = -\theta_1\theta_2 + \theta_2\theta_1$

Infinitesimal SUSY transformations: (ε infinitesimal)

$$\theta^\alpha \to \theta^\alpha + \varepsilon^\alpha$$
$$x^\mu \to x^\mu + 2i\theta\sigma^\mu\bar{\varepsilon}$$

$$\Rightarrow \delta\phi_L = \left(\varepsilon\frac{\partial}{\partial\theta} + \bar{\varepsilon}\frac{\partial}{\partial\bar{\theta}} + 2i\theta\sigma^\mu\bar{\varepsilon}\partial_\mu\right)\phi_L$$

NR: $\varepsilon^\alpha\frac{\partial}{\partial\theta^\alpha}\theta^\beta\varepsilon_{\beta\gamma}\theta^\gamma = \ldots = 2\varepsilon^\alpha\theta_\alpha$ (*)

Remember:
a SUSY Lagrangian must be invariant under SUSY transformations

$$\delta\phi_L = 2i\theta\sigma^\mu\bar{\varepsilon}\partial_\mu\varphi$$
$$+\sqrt{2}\varepsilon^\alpha\psi_\alpha + \sqrt{2}2i\theta\sigma^\mu\bar{\varepsilon}\partial_\mu\theta^\alpha\psi_\alpha$$
$$+^{(*)}\,2\varepsilon^\alpha\theta_\alpha F + \mathcal{O}\left(\theta^3\right)$$

NR: $\theta^\beta(\sigma^\mu)_{\beta\dot{\beta}}\bar{\varepsilon}^{\dot{\beta}}\theta^\alpha = \ldots = -\frac{1}{2}\theta\theta(\sigma^\mu)^{\alpha}_{\dot{\beta}}\bar{\varepsilon}^{\dot{\beta}}$ (**)

$$\delta\phi_L = 2i\theta\sigma^\mu\bar{\varepsilon}\partial_\mu\varphi$$
$$+\sqrt{2}\varepsilon^\alpha\psi_\alpha -^{(**)}\sqrt{2}i(\theta\theta)(\sigma^\mu)^{\alpha}_{\dot{\beta}}\bar{\varepsilon}^{\dot{\beta}}\partial_\mu\psi_\alpha$$
$$+2\varepsilon^\alpha\theta_\alpha F + \mathcal{O}\left(\theta^3\right)$$
$$\overset{!}{=} \delta\varphi + \sqrt{2}\theta^\alpha\delta\psi_\alpha + (\theta\theta)\delta F$$

SUSY transformation of a LHχSF should yield a LHχSF!

Comparison of θ components:

$$\theta^0 : \delta\varphi = \sqrt{2}\varepsilon\psi$$ boson $\to$ fermion

$$\theta^1 : \delta\psi_\alpha = \sqrt{2}\varepsilon_\alpha F + i\sqrt{2}(\sigma^\mu)_{\alpha\dot{\alpha}}\bar{\varepsilon}^{\dot{\alpha}}\partial\varphi$$ fermion $\to$ boson

$$\theta^2 : \delta F = -i\sqrt{2}\partial\left((\sigma^\mu)^{\alpha}_{\dot{\beta}}\,\bar{\varepsilon}^{\dot{\beta}}\psi_\alpha\right)$$ total derivative!

F transforms as total derivative

F is the component with the highest power in θ

$\Rightarrow$ Construction of $\mathcal{L}$ (invariant under SUSY transformations)
with highest component

Overview about superfields:

$\bar{D}_{\dot{\alpha}}\Phi = 0$: left-handed chiral superfield (LHχSF)

$D_\alpha\Phi = 0$: right-handed chiral superfield (RHχSF)

$\Phi = \Phi^\dagger$: vector superfield

$\Rightarrow$ chiral superfields describe left- or right-handed component of SM fermion
+ scalar partner

LHχSF in components:

$$\begin{aligned}\phi(x,\theta,\bar{\theta}) &= \varphi(x) + \sqrt{2}\theta\psi(x) - i\theta\sigma^\mu\bar{\theta}\partial_\mu\varphi(x) + \frac{i}{\sqrt{2}}(\theta\theta)(\partial_\mu\psi(x)\sigma^\mu\bar{\theta}) \\ &\quad - \frac{1}{4}(\theta\theta)(\bar{\theta}\bar{\theta})\partial^\mu\partial_\mu\varphi(x) - (\theta\theta)F(x)\end{aligned}$$

φ, F: scalar fields , ψ: Weyl-spinor field

LHχSF: Transf. of component fields with infinitesimal SUSY param. $\xi, \bar{\xi}$:

$$\delta\phi(x,\theta,\bar{\theta}) = i(\xi Q + \bar{\xi}\bar{Q})\phi(x,\theta,\bar{\theta})$$

Comparison with

$$\delta\phi(x,\theta,\bar{\theta}) \;=\; \delta\varphi(x) + \sqrt{2}\theta\delta\psi(x) - i\theta\sigma^\mu\bar{\theta}\partial_\mu\delta\varphi(x) + \frac{i}{\sqrt{2}}(\theta\theta)(\partial_\mu\delta\psi(x)\sigma^\mu\bar{\theta}) - \frac{1}{4}(\theta\theta)(\bar{\theta}\bar{\theta})\partial^\mu\partial_\mu\delta\varphi(x) - (\theta\theta)\delta F(x)$$

$\Rightarrow$ determination of $\delta\varphi$, $\delta\psi$, δF:

$$\delta\varphi = \sqrt{2}\xi\psi \qquad \text{boson} \to \text{fermion}$$

$$\delta\psi_\alpha = -\sqrt{2}F\xi_\alpha - i\sqrt{2}(\sigma^\mu\bar{\xi})_\alpha\partial_\mu\varphi \qquad \text{fermion} \to \text{boson}$$

$$\delta F = \partial_\mu(-i\sqrt{2}\psi\sigma^\mu\bar{\xi}\,) \qquad F \to \text{total derivative}$$

RHχSF: analogously

Vector superfield in components:

$$\begin{aligned} V(x,\theta,\bar\theta) &= c(x) + i\theta\chi(x) - i\bar\theta\bar\chi(x) + \theta\sigma^\mu\bar\theta v_\mu(x) \\ &+ \frac{i}{2}(\theta\theta)(M(x)+iN(x)) - \frac{i}{2}(\bar\theta\bar\theta)(M(x)-iN(x)) \\ &+ i(\theta\theta)\bar\theta\left(\bar\lambda(x) + \frac{i}{2}\partial_\mu\chi(x)\sigma^\mu\right) - i(\bar\theta\bar\theta)\theta\left(\lambda(x) - \frac{i}{2}\sigma^\mu\partial_\mu\bar\chi(x)\right) \\ &+ \frac{1}{2}(\theta\theta)(\bar\theta\bar\theta)\left(D(x) - \frac{1}{2}\partial^\mu\partial_\mu c(x)\right) \end{aligned}$$

Number of components can be reduced by SUSY gauge transformation:

Wess-Zumino gauge: $\chi(x) = c(x) = M(x) = N(x) \equiv 0$

Vector SF: $V(x,\theta,\bar\theta) = \ldots + i(\theta\theta)\bar\theta\bar\lambda(x) - i(\bar\theta\bar\theta)\theta\lambda(x) + \frac{1}{2}(\theta\theta)(\bar\theta\bar\theta)D(x) + \ldots$

$\delta D = -\xi\sigma^\mu\partial_\mu\bar\lambda(x) - \partial_\mu\lambda(x)\sigma^\mu\bar\xi$ $\quad D \to$ total derivative

Supersymmetric Lagrangians

Aim: construct an action that is invariant under SUSY transformations:

$$\delta \int d^4x \mathcal{L}(x) = 0$$

Satisfied if $\mathcal{L} \longrightarrow \mathcal{L} +$ total derivative

F and D terms (the terms with the largest number of θ and $\bar{\theta}$ factors) of chiral and vector superfields transform into a total derivative under SUSY transformations

$\Rightarrow$ Use F-terms (LHχSF, RHχSF) and D-terms (Vector SF) to construct an invariant action:

$$S = \int d^4x \left(\int d^2\theta \mathcal{L}_F + \int d^2\theta d^2\bar{\theta} \mathcal{L}_D \right)$$

If Φ is a LHχSF $\Rightarrow$ Φ^n is also a LHχSF (since $\bar{D}_{\dot{\alpha}} \Phi^n = 0$ for $\bar{D}_{\dot{\alpha}} \Phi = 0$)

$\Rightarrow$ products of chiral superfields are chiral superfields, products of vector superfields are vector superfields

F-term Lagrangian:

$$\mathcal{L}_F = \int d^2\theta \sum_{ijk} \left(a_i \Phi_i + \frac{1}{2} m_{ij} \Phi_i \Phi_j + \frac{1}{3} \lambda_{ijk} \Phi_i \Phi_j \Phi_k \right) + \text{ h.c.}$$

Terms of higher order in Φ_i lead to non-renormalizable Lagrangians

$\Rightarrow$ F-term Lagrangian contains mass terms, scalar–fermion interactions ($\rightarrow$ superpotential), but no kinetic terms

D-term Lagrangian:

$$\mathcal{L}_D = \int d^2\theta d^2\bar{\theta} V$$

$\Rightarrow$ D-term Lagrangian contains kinetic terms

Example: the Wess–Zumino Lagrangian

Construction of Lagrangian from chiral superfields Φ_i

$\Rightarrow$ Φ_i, $\Phi_i\Phi_j$, $\Phi_i\Phi_j\Phi_k$

$\Phi_i^\dagger\Phi_i$: vector superfield, $(\Phi_i^\dagger\Phi_i)^\dagger = \Phi_i^\dagger\Phi_i$

$$\left[\Phi_i^\dagger\Phi_i\right]_{\theta\theta\bar\theta\bar\theta} = F^\dagger F + (\partial_\mu\varphi^*)(\partial^\mu\varphi) + \frac{i}{2}(\psi\sigma^\mu\partial_\mu\bar\psi - \partial_\mu\psi\sigma^\mu\bar\psi) + \partial_\mu(\ldots)$$

Auxiliary field F can be eliminated via equations of motion

$$\text{abelian}: \quad F = m\varphi^* + g\varphi^{*2}$$
$$\text{non-abelian, gauge group } G: \quad D^G = \ldots \sum_a g_G\left(\varphi_i^\dagger (T_G)^a \varphi_i\right)$$

(internal indices of T_G, φ_i suppressed)

$$\Rightarrow \quad \mathcal{L}_D = F\,F^* + \frac{1}{2}\sum_G D^G (D^G)^\dagger + \ldots$$

Putting everything together:

$$
\begin{aligned}
\Rightarrow \quad \mathcal{L}_D \;=\; & \frac{i}{2}(\psi_i \sigma^\mu \partial_\mu \bar{\psi}_i - (\partial_\mu \psi_i)\sigma^\mu \bar{\psi}_i) - \frac{1}{2} m_{ij}(\psi_i \psi_j + \bar{\psi}_i \bar{\psi}_j) \\
& + (\partial_\mu \varphi_i^*)(\partial^\mu \varphi_i) - \sum_i \left| a_i + \frac{1}{2} m_{ij} \varphi_j + \frac{1}{3} \lambda_{ijk} \varphi_j \varphi_k \right|^2 \\
& - \lambda_{ijk} \varphi_i \psi_j \psi_k - \lambda^\dagger_{ijk} \varphi_i^* \bar{\psi}_j \bar{\psi}_k
\end{aligned}
$$

Putting everything together:

$$\Rightarrow \quad \mathcal{L}_D = \frac{i}{2}(\psi_i \sigma^\mu \partial_\mu \bar{\psi}_i - (\partial_\mu \psi_i)\sigma^\mu \bar{\psi}_i) - \frac{1}{2} m_{ij}(\psi_i \psi_j + \bar{\psi}_i \bar{\psi}_j)$$
$$+ (\partial_\mu \varphi_i^*)(\partial^\mu \varphi_i) - \sum_i \left| a_i + \frac{1}{2} m_{ij} \varphi_j + \frac{1}{3} \lambda_{ijk} \varphi_j \varphi_k \right|^2$$
$$- \lambda_{ijk} \varphi_i \psi_j \psi_k - \lambda^\dagger_{ijk} \varphi_i^* \bar{\psi}_j \bar{\psi}_k$$

Lagrangian for scalar fields φ_i and spinor fields ψ_i with the same mass m_{ii}

contains couplings of type $h f \bar{f}$ and $\tilde{h} \tilde{f} \bar{f}$ with the same strength

Putting everything together:

$$\Rightarrow \quad \mathcal{L}_D = \frac{i}{2}(\psi_i\sigma^\mu\partial_\mu\bar{\psi}_i - (\partial_\mu\psi_i)\sigma^\mu\bar{\psi}_i) - \frac{1}{2}m_{ij}(\psi_i\psi_j + \bar{\psi}_i\bar{\psi}_j)$$
$$+ (\partial_\mu\varphi_i^*)(\partial^\mu\varphi_i) - \sum_i \left| a_i + \frac{1}{2}m_{ij}\varphi_j + \frac{1}{3}\lambda_{ijk}\varphi_j\varphi_k \right|^2$$
$$- \lambda_{ijk}\varphi_i\psi_j\psi_k - \lambda^\dagger_{ijk}\varphi_i^*\bar{\psi}_j\bar{\psi}_k$$

Lagrangian for scalar fields φ_i and spinor fields ψ_i with the same mass m_{ii}

contains couplings of type $hf\bar{f}$ and $\tilde{h}\tilde{f}\bar{f}$ with the same strength

$\Rightarrow$ SUSY implies relations between masses and couplings

Putting everything together:

$$
\begin{aligned}
\Rightarrow \quad \mathcal{L}_D \;=\; & \frac{i}{2}(\psi_i \sigma^\mu \partial_\mu \bar{\psi}_i - (\partial_\mu \psi_i)\sigma^\mu \bar{\psi}_i) - \frac{1}{2} m_{ij}(\psi_i \psi_j + \bar{\psi}_i \bar{\psi}_j) \\
& + (\partial_\mu \varphi_i^*)(\partial^\mu \varphi_i) - \sum_i \left| a_i + \frac{1}{2} m_{ij} \varphi_j + \frac{1}{3} \lambda_{ijk} \varphi_j \varphi_k \right|^2 \\
& - \lambda_{ijk} \varphi_i \psi_j \psi_k - \lambda^\dagger_{ijk} \varphi_i^* \bar{\psi}_j \bar{\psi}_k
\end{aligned}
$$

Lagrangian for scalar fields φ_i and spinor fields ψ_i with the same mass m_{ii}

contains couplings of type $hf\bar{f}$ and $\tilde{h}\tilde{f}\bar{f}$ with the same strength

$\Rightarrow$ SUSY implies relations between masses and couplings

Collider phenomenology can directly be deduced from theoretical basis of the model!

$\mathcal{L}$ can be rewritten as kinetic part + contribution of superpotential $\mathcal{V}$:

$$\mathcal{V}(\varphi_i) = a_i\varphi_i + \frac{1}{2}m_{ij}\varphi_i\varphi_j + \frac{1}{3}\lambda_{ijk}\varphi_i\varphi_j\varphi_k$$

$$\Rightarrow \quad \mathcal{L} \; = \; \frac{i}{2}(\psi_i\sigma^\mu\partial_\mu\bar{\psi}_i - (\partial_\mu\psi_i)\sigma^\mu\bar{\psi}_i) + (\partial_\mu\varphi_i^*)(\partial^\mu\varphi_i)$$
$$-\sum_i \left|\frac{\partial\mathcal{V}}{\partial\varphi_i}\right|^2 - \frac{1}{2}\frac{\partial^2\mathcal{V}}{\partial\varphi_i\partial\varphi_j}\psi_i\psi_j - \frac{1}{2}\frac{\partial^2\mathcal{V}^*}{\partial\varphi_i^*\partial\varphi_j^*}\bar{\psi}_i\bar{\psi}_j$$

$\mathcal{V}$ determines all interactions and mass terms

Without proof:

characteristics of $\mathcal{V}$ = characteristics of $\mathcal{L}$

Special case $a_i = 0$: Wess–Zumino model

Soft SUSY-breaking

Exact SUSY: $m_f = m_{\tilde{f}}, \; \ldots$

$\Rightarrow$ in a realistic model: SUSY must be broken

Only satisfactory way for model of SUSY breaking:

spontaneous SUSY breaking

Specific SUSY-breaking schemes (see below) in general yield effective Lagrangian at low energies, which is supersymmetric except for explicit soft SUSY-breaking terms

Soft SUSY-breaking terms: do not alter dimensionless couplings

(i.e. dimension of coupling constants of soft SUSY-breaking terms > 0)
otherwise: re-introduction of the hierarchy problem

$\Rightarrow$ no quadratic divergences (in all orders of perturbation theory)

scale of SUSY-breaking terms: $M_{\text{SUSY}} \lesssim 1$ TeV

Classification of possible soft breaking terms:

[*L. Girardello, M. Grisaru '82*]

- scalar mass terms: $m^2_{\phi_i} |\phi_i|^2$
- trilinear scalar interactions: $A_{ijk}\phi_i\phi_j\phi_k + \text{h.c.}$
- gaugino mass terms: $\frac{1}{2}m\bar{\lambda}\lambda$
- bilinear terms: $B_{ij}\phi_i\phi_j + \text{h.c.}$
- linear terms: $C_i\phi_i$

$\Rightarrow$ relations between dimensionless couplings unchanged

no additional mass terms for chiral fermions

A. Unconstrained models (MSSM):

agnostic about how SUSY breaking is achieved

no particular SUSY breaking mechanism assumed, parameterization of possible soft SUSY-breaking terms

$\Rightarrow$ relations between dimensionless couplings unchanged
no quadratic divergences

most general case:

$\Rightarrow$ 105 new parameters: masses, mixing angles, phases

Good phenomenological description for universal breaking terms

B. Constrained models (mSUGRA, . . .):

assumption on the scenario that achieves spontaneous SUSY breaking
$\Rightarrow$ prediction for soft SUSY-breaking terms
in terms of small set of parameters

Experimental determination of SUSY parameters

$\Rightarrow$ Patterns of SUSY breaking

“Hidden sector”: $\longrightarrow$ Visible sector:

SUSY breaking MSSM

“Gravity-mediated”: mSUGRA
“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

Particle Content & Collider phenomenology

MSSM: superpartners for SM fields

1. Fermions, sfermions:

left-handed chiral superfields give SM fermions/sfermions
($\Rightarrow$ the conjugates of right-handed ones appear)

LHχSF Q: quark, squark SU(2) doublets

LHχSF U: up-type quark, squark singlets

LHχSF D: down-type quark, squark singlets

LHχSF L: lepton, slepton SU(2) doublets

LHχSF E: lepton, slepton singlets

$\Rightarrow$ one generation of SM fermions and their superpartners described by five LHχSFs

2. Gauge bosons, gauginos:

Vector superfields:

– gluons g and gluinos $\tilde{g}$

– W bosons $W^{\pm}$, W^0 and winos $\tilde{W}^{\pm}$, $\tilde{W}^0$

– B boson B^0 and bino $\tilde{B}^0$

3. Higgs bosons, higgsinos:

LHχSF

In MSSM: two Higgs doublets needed $\Rightarrow$ two LHχSFs

Chiral supermultiplets		spin 0	spin $\frac{1}{2}$	$(SU(3)_c, SU(2), U(1)_Y)$
squarks and quarks	Q	$(\tilde{u}_L, \tilde{d}_L)$	(u_L, d_L)	$(3, 2, \frac{1}{6})$
	U	$\tilde{u}_R^*$	$u_R^\dagger$	$(\bar{3}, 1, -\frac{2}{3})$
	D	$\tilde{d}_R^*$	$d_R^\dagger$	$(\bar{3}, 1, \frac{1}{3})$
sleptons and leptons	L	$(\tilde{\nu}, \tilde{e}_L)$	(ν, e_L)	$(1, 2, -\frac{1}{2})$
	E	$\tilde{e}_R^*$	$e_R^\dagger$	$(1, 1, 1)$
higgs and higgsinos	H_u	(h_u^+, h_u^0)	$(\tilde{h}_u^+, \tilde{h}_u^0)$	$(1, 2, \frac{1}{2})$
	H_d	(h_d^0, h_d^-)	$(\tilde{h}_d^0, \tilde{h}_d^-)$	$(1, 2, -\frac{1}{2})$

Vector supermultiplets	spin $\frac{1}{2}$	spin 1	$(SU(3)_c, SU(2), U(1)_Y)$
gluinos and gluons	$\tilde{g}$	g	$(8, 1, 0)$
winos and W-bosons	$\widetilde{W}^\pm, \widetilde{W}^0$	$W^\pm, W^0$	$(1, 3, 0)$
bino and B-boson	$\widetilde{B}$	B	$(1, 1, 0)$

Soft breaking terms:

$$
\begin{aligned}
\mathcal{L}_{\text{soft}} = & -\frac{1}{2}\Big(M_1 \tilde{B}\tilde{B} + M_2 \widetilde{W}\widetilde{W} + M_3 \tilde{g}\tilde{g} \Big) + \text{h.c.} \\
& - (m_{H_u}^2 + |\mu|^2) H_u^+ H_u - (m_{H_d}^2 + |\mu|^2) H_d^+ H_d - (b H_u H_d + \text{h.c.}) \\
& - \Big(\tilde{u}_R \mathbf{a_u} \tilde{Q} H_u - \tilde{d}_R \mathbf{a_d} \tilde{Q} H_d - \tilde{e}_R \mathbf{a_e} \tilde{L} H_d \Big) + \text{h.c.} \\
& - \tilde{Q}^+ \mathbf{m_Q^2} \tilde{Q} - \tilde{L}^+ \mathbf{m_L^2} \tilde{L} - \tilde{u}_R \mathbf{m_u^2} \tilde{u}_R^* - \tilde{d}_R \mathbf{m_d^2} \tilde{d}_R^* - \tilde{e}_R \mathbf{m_e^2} \tilde{e}_R^*
\end{aligned}
$$

Most general parameterization of SUSY-breaking terms that keep relations between dimensionless couplings unchanged
$\Rightarrow$ no quadratic divergences

$\mathbf{m_i^2}, \mathbf{a_j}$: 3×3 matrices in family space

$\Rightarrow$ many new parameters

Particle content of the MSSM:

Superpartners for Standard Model particles:

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

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

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

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

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

as usual: Breaking of SU(2) $\times$ U(1)$_Y$ (electroweak symmetry breaking)

$\Rightarrow$ fields with different SU(2) $\times$ U(1)$_Y$ quantum numbers can mix if they have the same SU(3)$_c$, U(1)$_{\text{em}}$ quantum numbers

Squark mixing:

Stop, sbottom mass matrices ($X_t = A_t - \mu/\tan\beta$, $X_b = A_b - \mu\tan\beta$):

$$\mathcal{M}^2_{\tilde{t}} = \begin{pmatrix} M^2_{\tilde{t}_L} + m_t^2 + DT_{t_1} & m_t X_t \\ m_t X_t & M^2_{\tilde{t}_R} + m_t^2 + DT_{t_2} \end{pmatrix} \xrightarrow{\theta_{\tilde{t}}} \begin{pmatrix} m^2_{\tilde{t}_1} & 0 \\ 0 & m^2_{\tilde{t}_2} \end{pmatrix}$$

$$\mathcal{M}^2_{\tilde{b}} = \begin{pmatrix} M^2_{\tilde{b}_L} + m_b^2 + DT_{b_1} & m_b X_b \\ m_b X_b & M^2_{\tilde{b}_R} + m_b^2 + DT_{b_2} \end{pmatrix} \xrightarrow{\theta_{\tilde{b}}} \begin{pmatrix} m^2_{\tilde{b}_1} & 0 \\ 0 & m^2_{\tilde{b}_2} \end{pmatrix}$$

off-diagonal element prop. to mass of partner quark ($\tan\beta \equiv v_u/v_d$)

$\Rightarrow$ mixing important in stop sector (also in sbottom sector for large $\tan\beta$)

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

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

$\Rightarrow$ prediction for collider phenomenology!

Neutralinos and charginos:

Higgsinos and electroweak gauginos mix

charged:

$$\tilde{W}^+, \tilde{h}_u^+ \to \tilde{\chi}_1^+, \tilde{\chi}_2^+, \qquad \tilde{W}^-, \tilde{h}_d^- \to \tilde{\chi}_1^-, \tilde{\chi}_2^-$$

⇒ charginos: mass eigenstates

mass matrix given in terms of M_2, μ, $\tan\beta$

neutral:

$$\underbrace{\tilde{\gamma}, \tilde{Z},}_{\tilde{W}^0, \tilde{B}^0} \tilde{h}_u^0, \tilde{h}_d^0 \to \tilde{\chi}_1^0, \tilde{\chi}_2^0, \tilde{\chi}_3^0, \tilde{\chi}_4^0$$

⇒ neutralinos: mass eigenstates

mass matrix given in terms of M_1, M_2, μ, $\tan\beta$

⇒ only one new parameter

⇒ MSSM predicts mass relations between neutralinos and charginos
⇒ prediction for collider phenomenology!

R parity

Most general gauge-invariant and renormalizable superpotential with chiral superfields of the MSSM: → exercise # 2

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

If both lepton and baryon number are violated

⇒ rapid proton decay

Minimal choice (MSSM) contains only terms in the Lagrangian with even number of SUSY particles

⇒ additional symmetry: "R parity"

⇒ all SM particles have even R parity, all SUSY particles have odd R parity

R-parity $\Rightarrow$ the LSP

MSSM has further symmetry: "R-parity"

all SM-particles and Higgs bosons: even R-parity, $P_R = +1$

all superpartners: odd R-parity, $P_R = -1$

$\Rightarrow$ SUSY particles appear only in pairs, e.g. $e^+e^- \to \tilde{\chi}_1^+ \tilde{\chi}_1^-$

$\Rightarrow$ lightest SUSY particle (LSP) is stable

(usually the lightest neutralino)

good candidate for Cold Dark Matter

$\Rightarrow M_{\text{SUSY}} \lesssim 1$ TeV

LSP neutral, uncolored $\Rightarrow$ leaves no traces in collider detectors

$\Rightarrow$ Typical SUSY signatures: "missing energy"

$\Rightarrow$ prediction for collider phenomenology!

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

⇒ prediction for collider phenomenology!

In SM: all masses are free input parameters
(except M_W–M_Z interdependence)

MSSM:

- Upper bound on mass of lightest $\mathcal{CP}$-even Higgs boson

- Relations between neutralino and chargino masses

- Sfermion mass relations, e.g.

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

All relations receive corrections from loop effects

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

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

$\Rightarrow$ prediction for collider phenomenology!