Discovery Physics at the LHC

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Lecture Themes

I. Phenomenology beyond the Standard Model

- Empirical & theoretical limitations of the Standard Model
- Supersymmetry
- Extra Dimensions
- Little Higgs

II. Experimental Searches

- LHC, ATLAS and CMS: Experimental Challenges
- Searches at the LHC: SUSY, Extra Dimensions, Little Higgs

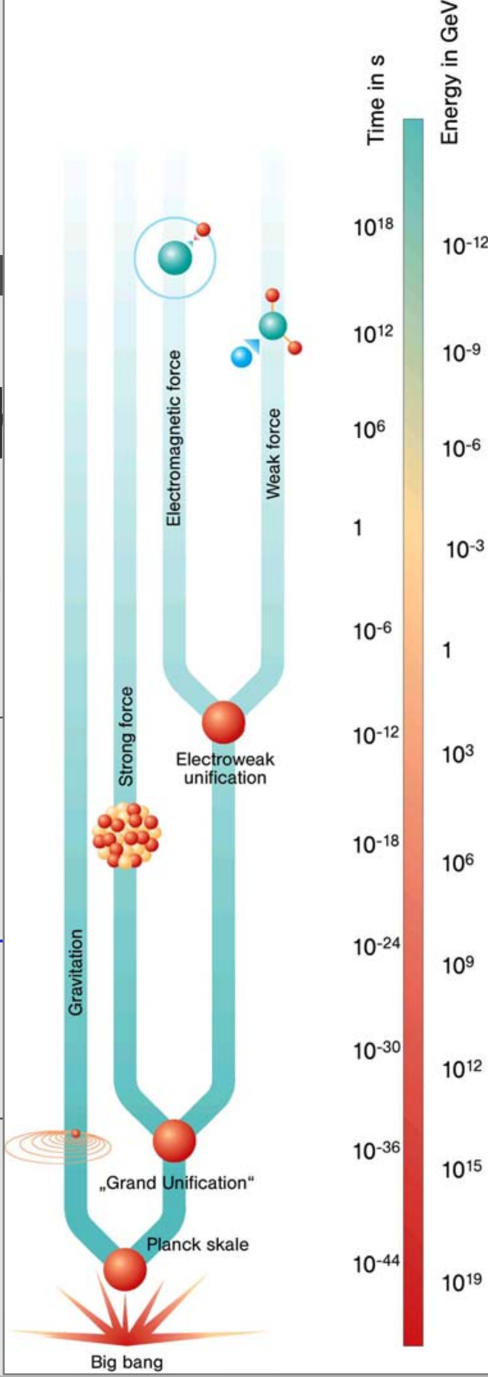
III. *CP* Violation and the Genesis of a Matter World
(out-of-series lecture)

Lectures based on many, many sources… please contact me for a list

Empirical and Theoretical

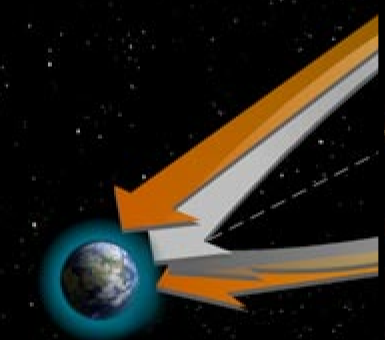
Limitations of th
Standard Mode

- Dark matter (and, perhaps, dark energy)
- Baryogenesis (CKM CPV too small)
- Grand Unification of the gauge couplings
- The gauge hierarchy Problem (Higgs sector, NP scale ~ 1
- The strong *CP* Problem (why is $\theta \sim 0$?)
- Neutrino masses

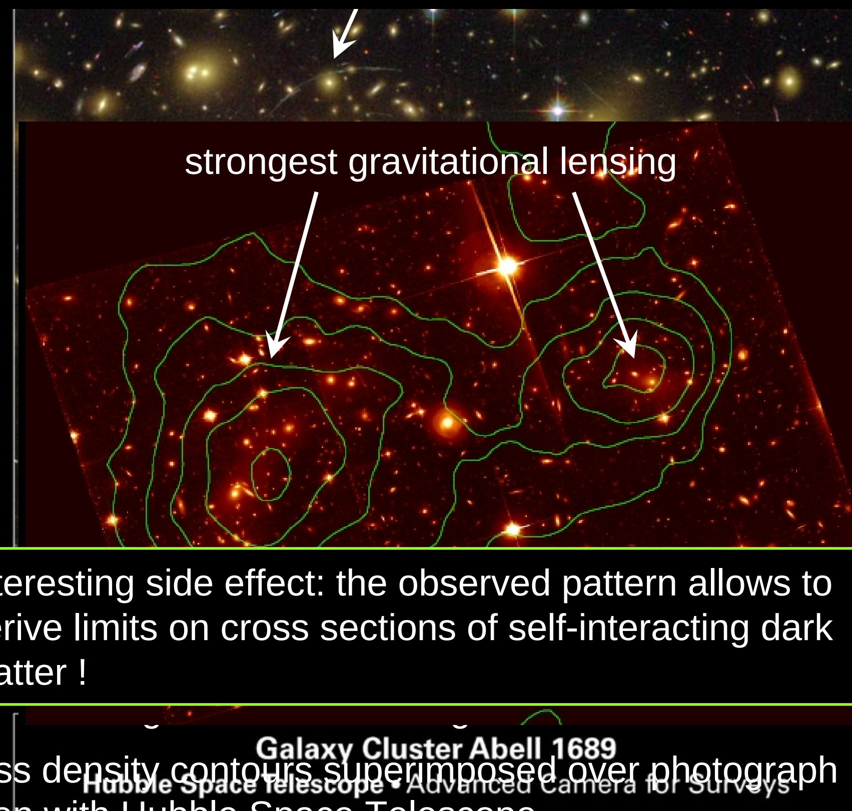


Dark Matter

- *Dark matter* does not emit or reflect sufficient electromagnetic radiation to be detected
- Evidence for dark matter stems from:
  - **gravitational lensing**
  - kinetics of galaxies
  - anisotropy of cosmic microwave background (blackbody) radiation



Bullet cluster: Collision of galaxy clusters: baryonic matter, stars – weakly affected by collisions – and strongly affected gas (pink in picture), and collisionless dark matter (blue)



Interesting side effect: the observed pattern allows to derive limits on cross sections of self-interacting dark matter !

Mass density contours superimposed over photograph taken with Hubble Space Telescope

NASA, N. Benitez (JHU), T. Broadhurst (The Hebrew University), H. Ford (JHU), M. Clampin(STScI), G. Hartig (STScI), G. Illingworth (UCO/Lick Observatory), the ACS Science Team and ESA
STScI-PRC03-01a

Dark Matter

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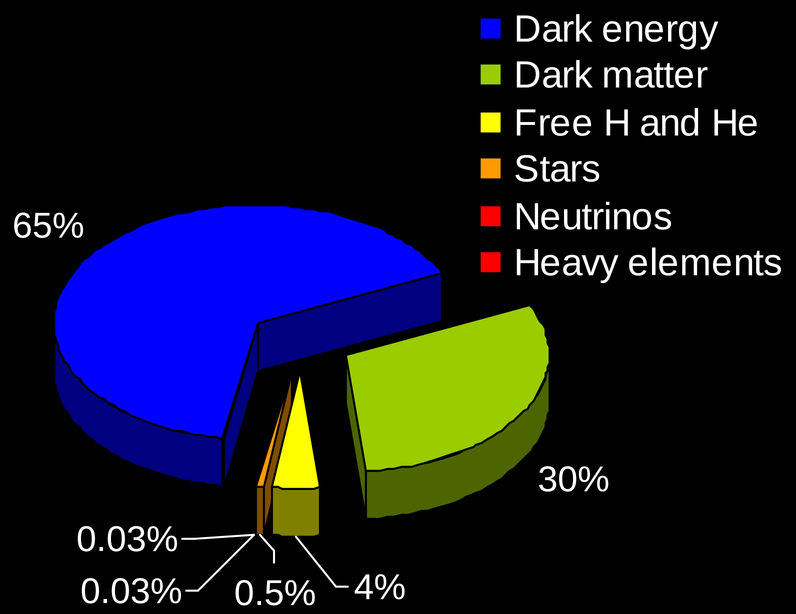
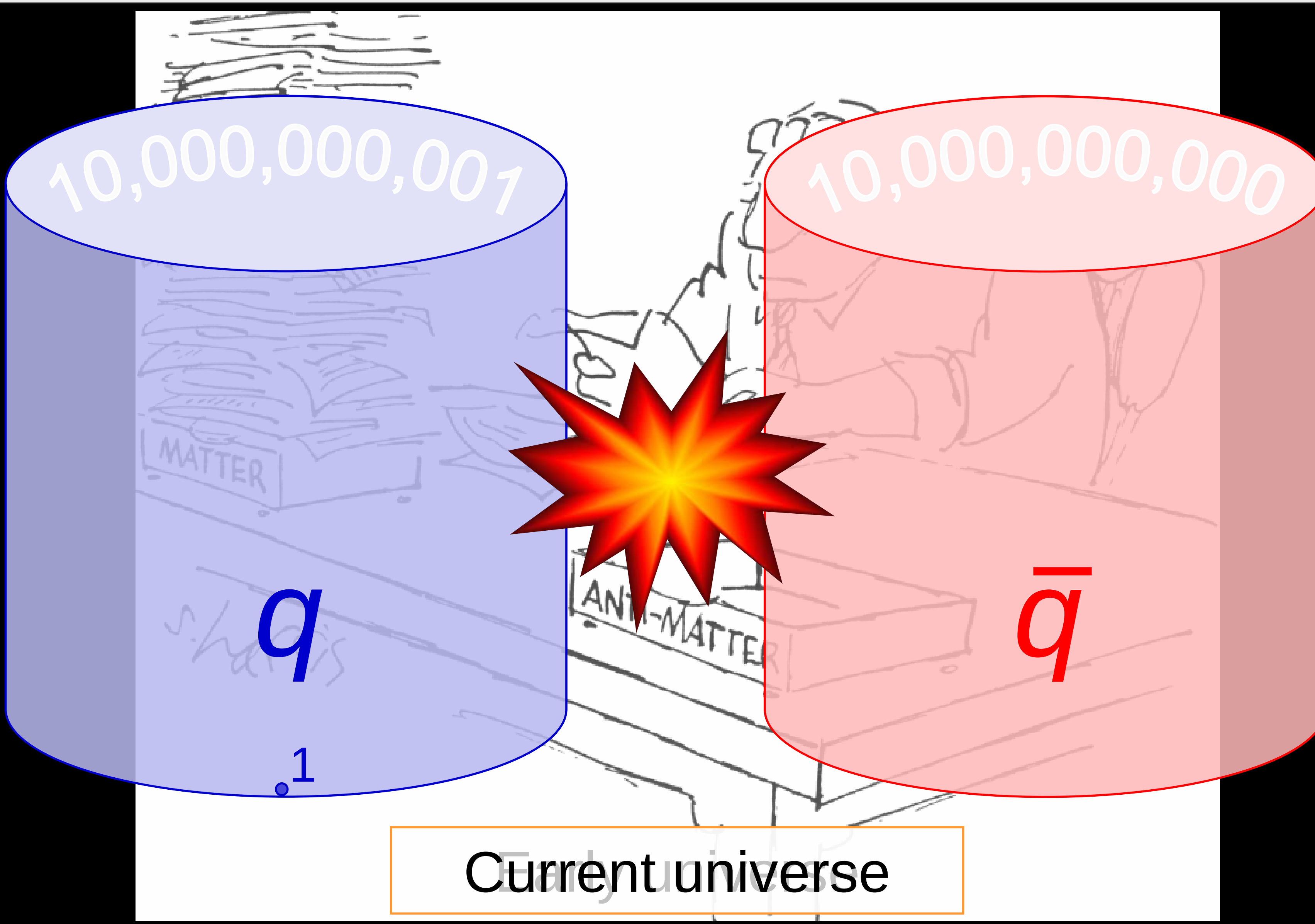
→ 2006 Nobel Price in Physics:
John C. Mather, and George F. Smoot
(COBE satellite)



- First peak determines curvature of universe
- Second peak (ratio of odd-to-even peaks) determines reduced baryon density
- Third peak is related to dark matter density !

➡ **Data analysis reveals a flat universe and lots of unknown matter and energy !**

Matter-Antimatter Asymmetry



Sakharov Conditions

- Is baryon asymmetry initial condition ? Possible ?
- Dynamically generated ?

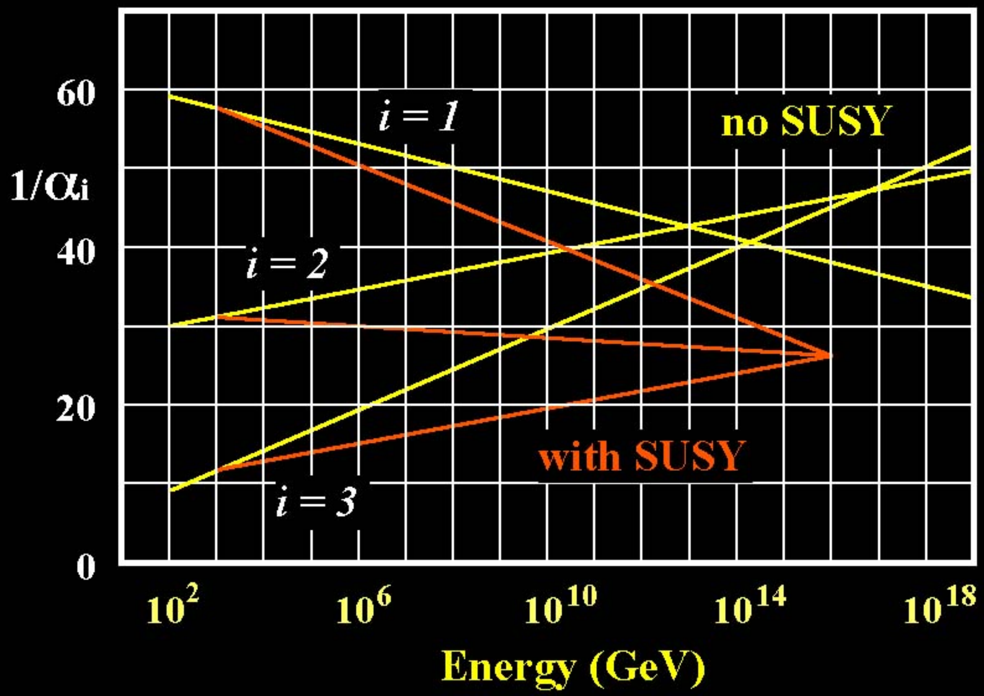
Sakharov conditions (1967) for Baryogenesis

1. Baryon number violation → new physics !
2. *C* and *CP* violation → (probably) new physics !
3. Departure from thermodynamic equilibrium (non-stationary system)

Grand Unification of the Gauge Couplings (GUT)

- Electromagnetic and weak couplings unify at E ~100 GeV
- When computing the renormalization group equations (=running) for the unified SU(3)×SU(2)×U(1) couplings α_1 (EM/hypercharge) α_2 (weak), and α_3 (strong), one finds that all three almost meet at E ~10^{15} GeV, but not quite !
- SM extensions such as Supersymmetry (SUSY) with a characteristic mass scale of ~1000 GeV can have the right properties to adjust the RGEs and allow for GUT at E ~10^{16} GeV

T. Kondo (KEK)

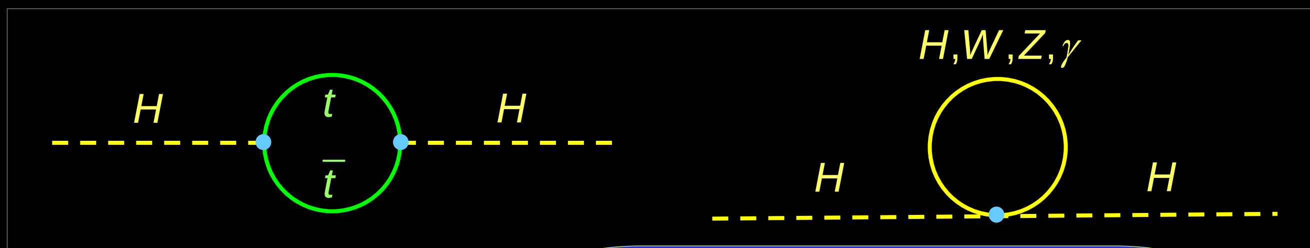


➡ **Exact unification does not need to occur, but wouldn't it be very appealing if it did ?**

It would be consistent with the speculation that the three couplings (forces) are in effect different manifestations of a single overarching gauge symmetry

A Light Higgs ?

- If a Higgs boson with mass < 1 TeV is discovered, the Standard Model is complete !
- However, when computing radiative corrections to the bare Higgs mass a problem occurs:



Higgs radiative corrections

$$\Rightarrow \quad m_H^2 = m_0^2 + \delta m_H^2$$ where: δ

At the Planck mass scale the gravitational radius is equal to the Compton length divided by π:

$$M_{Pl} = \sqrt{hc/G} = 1.22 \times 10^{19} \text{ GeV}/c^2$$

- The cut-off sets the scale where new particles and physical laws must come in
- Above the EW scale we only know of two scales: GUT (~10^{16} GeV) and Planck (~10^{19} GeV)
- Such a cut-off would require an incredible amount of finetuning to keep m_H light and stable

$$m_H^2 \overset{?}{=} 120 \text{ GeV} = m_0^2 + C \cdot \Lambda_{\text{cut-off}}^2$$

The natural Higgs mass seems to be M_{Pl} rather than the experimentally favoured value…

Digression: Arguments for a light (but not too light) Higgs

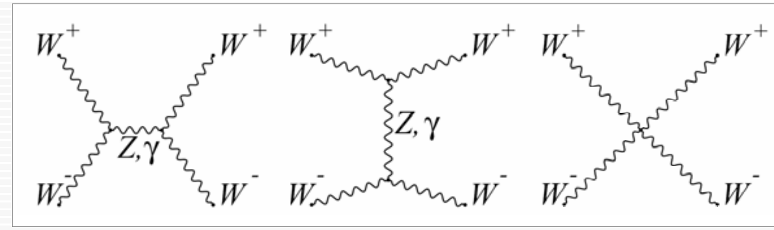
Several theoretical arguments favour a Higgs mass below ~1000 GeV (= 1 TeV)

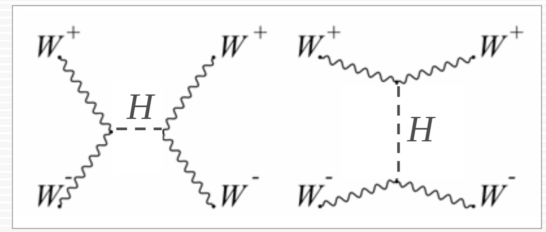
- **Unitarity**: if only Z and γ are exchanged, the amplitude of (longitudinal) W^+W^- scattering is:

$$A_{Z,\gamma}\left(W^+W^- \to W^+W^-\right) \propto \sqrt{2}G_F\left(s+t\right)$$

violating unitarity. The Higgs contributes with:

$$A_H\left(W^+W^- \to W^+W^-\right) \propto -\sqrt{2}G_F m_H^2\left(\frac{s}{s-m_H^2}+\frac{t}{t-m_H^2}\right)$$





Higgs regularises total amplitude, if m_H not too large !

- **Landau Pole**: neglecting fermion/boson loops, Higgs field is "trivial" $|\phi|^4$ theory:

Fermi scale

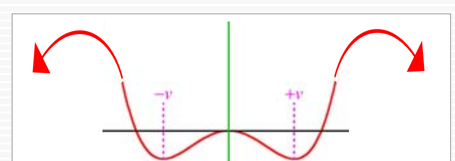
$$V(\phi) = \mu^2\,|\,\phi\,|^2 + \lambda\,|\,\phi\,|^4,$$ vacuum expectation value of Higgs field: $$\left\langle\phi\right\rangle = \frac{1}{\sqrt{2}}\begin{pmatrix}0\\ \upsilon\end{pmatrix},\quad \upsilon = \sqrt{-\frac{\mu^2}{2\lambda}} = \frac{1}{\sqrt{\sqrt{2}G_F}} = 246\text{ GeV}$$

coupling λ increases with mass μ: $$\frac{d\lambda}{d\ln\mu} \propto \lambda^2 \;\Rightarrow\; \lambda(\mu) = \frac{\lambda(\mu_0)}{1-(\ldots)\lambda(\mu_0)\ln(\mu/\mu_0)}$$

denominator can be =0 → Landau pole!

Landau pole leads to upper limit: $m_H^2 \propto \lambda(\upsilon) < 53\cdot\upsilon^2\ln^{-1}(\Lambda/\upsilon) \approx 300\ (1500)\text{ GeV}\ \left\{\Lambda = 10^{19}\ (10^3)\text{ GeV}\right\}$

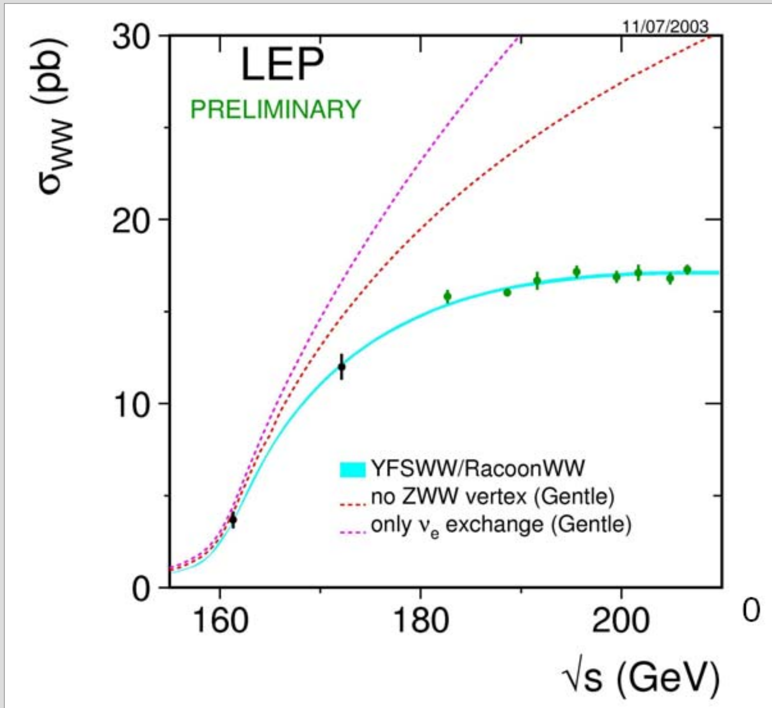
- **Stability**: for light Higgs (small λ), top quark contributions can decrease λ and make it negative; stability requirement leads to lower limit on m_H

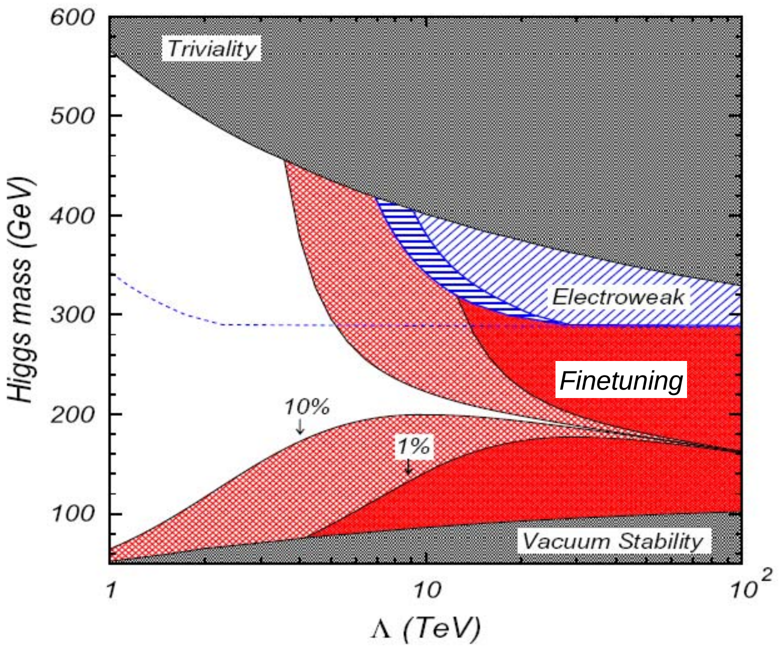


$$m_H^2 \propto \lambda(\upsilon) > 1.2\cdot\frac{m_{\text{top}}^2}{2\upsilon^2}$$

Digression: A Light Standard Model Higgs Boson

- If indeed the mass of the Higgs is light it will be produced at the LHC
  → see Oliver Buchmüller's lecture





Higgs mass from fit to electroweak data

Experimental result: $e^+e^- \to W^+W^-$ cross section measured at LEP2. Contribution which grows like $s \cdot m_e^2$ is cancelled by Higgs amplitude

Higgs mass as a function of cut-off scale Λ

The Hierarchy Problem

The Gauge Hierarchy Problem…

- …denotes this finetuning of parameters, and the stro
weak scale on the physics at (presumably) much hig
- If the loops are cut off at the scale of gravity, why is
breaking so different from the scale of gravity? Why
- Equivalently, why is gravity so weak? $G_F = \frac{g^2}{4\sqrt{2}m_W^2}$

Possible solutions to the hierarchy problem:

- New physics appears not much above the EW scale and regularises the quadratic divergences. The “desert” between the EW and GUT/Planck scales is not empty!

Digression: What the New Physics Should Be

Three diagrams give the largest contributions to the diverging Higgs radiative corrections…

top loop	$-(3/8\pi^2)\lambda_t^2\Lambda^2$	~ $(2\ \mathrm{TeV})^2$
gauge boson loop	$(9/64\pi^2)g^2\Lambda^2$	~ $(700\ \mathrm{GeV})^2$
Higgs loop	$-(1/16\pi^2)\lambda^2\Lambda^2$	~ $(500\ \mathrm{GeV})^2$

Contributions of diagrams, assuming $\Lambda_{\text{cut-off}}$ ~ 10 TeV

- The total mass-squared of the Higgs is the sum of these contributions and the tree-level
- What would be the cut-off (= new physics) scales if only small (~10%) finetuning existed

  → Λ_{top} < 2 TeV, Λ_{gauge} < 5 TeV, Λ_{Higgs} < 10 TeV
- Hence… with a new physics sensitivity of ~3 TeV, the LHC could discover the new physics !
- To naturally cancel these divergences, the new physics should couple to the Higgs and should be related to the particles in the loop (top, gauge, Higgs) by some symmetry

Extending the Standard Model ?

Some Observations Beforehand …

- The hierarchy problem (among others) of the SM Higgs sector can be turned into a prediction that **new physics** is expected at the TeV scale
- Since precision data do not give hints for new physics, we can use the data to constrain "**effective models**" that have the particle content of the SM, and where new physics is

And… by the way… the Higgs is not yet discovered ;-)

Broken symmetry	Operators	$O(\Lambda)$
baryon, lepton number	$(QQQL)/\Lambda^2$	10^{12} TeV
flavour (1^{st},2^{nd} family), *CP*	$(dsds)/\Lambda^2$	10^4 TeV
flavour (1^{st},3^{rd} family), *CP*	$(dbdb)/\Lambda^2$	10^3 TeV
flavour (2^{nd},3^{rd} family), *CP*	$m_b(s\sigma_{\mu\nu}F^{\mu\nu}b)/\Lambda^2$	50 TeV

example only… many more indirect constraints

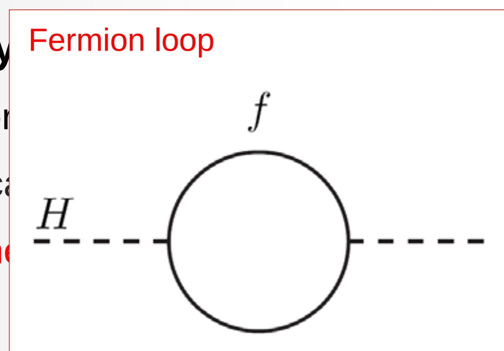
- The question is: **how to stabilize the light Higgs without violating the above bounds ?**
- The answer to this is by no means trivial, and the SM extensions discussed in the following only partially succeed in doing so … some apparent finetuning seems to be always involved

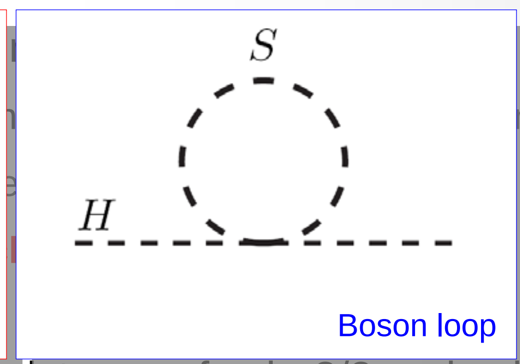
Extending the Standard Model

- **Supersymmetry**
- Extra dimensions
- Little Higgs

Supersymmetry (SUSY)

- We have seen that the light scalar Higgs boson is unprotected at GUT/ Planck scales
- On the contrary, all the *other* light particles of the SM *are* protected against large scales:
  - Due to chiral symmetry, their mass corrections are logarithmic in *E* (and not quadratic)
  - Gauge symmetry protects the bosons (no correction to photon or gluon masses)
- Fermion and boson loops contribute with different signs to the Higgs radiative corrections: if there existed a **symmetry** relating these two, this could protect the masses of the scalar !
- **Supersymmetry**
  - SUSY transfor … mass is protected
  - Hence, the sca …
  - ➡ This solves the …





- Local gauge invariance of SUSY requires existence of spin-3/2 and spin-2 particles
  - This naturally introduces the spin-2 graviton, assumed to mediate the gravitational force

Minimal Supersymmetric Standard Model – MSSM

- Standard SUSY has: N_{dof} (bosons) = N_{dof} (fermions) [*cf*. SM: N_{dof}(bosons) = N_{dof} (fermions)]
  - To create ***supermultiplets***, we need to add one ***superpartner*** to each SM particle
  - Need to introduce an **additional Higgs doublet** to the non-SUSY side
  - Mutual superpartners have **equal masses and couplings**

Spin 0	Spin 1/2	Spin 1	Spin 3/2	Spin 0
Higgs	Higgsino		Gravitino	Graviton
sLepton	Lepton			
sQuark	Quark			
	Gluino	Gluon		
	Photino	Photon		
	Zino	Z		
	Wino	W		

SM | SUSY

The MSSM Supermultiplets

Eigenstates

Superfield	Spin 0	Spin 1/2	Spin 1	$SU(3)_C \times SU(2)_L \times U(1)_Y$
Q				
E^c				
H_1				
H_2				
B				
W				
G	–	$\tilde{g}^0_a$	g_a	$(8,1,0)$

Eigenstates

Spin 0	Spin 1/2	Spin 1
	$\tilde{g}^0_a$	g_a
	$\tilde{\chi}^0_1, \tilde{\chi}^0_2, \tilde{\chi}^0_3, \tilde{\chi}^0_4$	$\gamma, Z^0, W^\pm$
	$\tilde{\chi}^\pm_1, \tilde{\chi}^\pm_2$	

__Note__: all scalar particles with same *e*-charge, *R*-parity and colour quantum number, can mix !

The gauge-mixed physical states that propagate in space and time and that can be experienced.

Neutralinos: mass eigenstates of photinos, zinos, neutral higgsinos

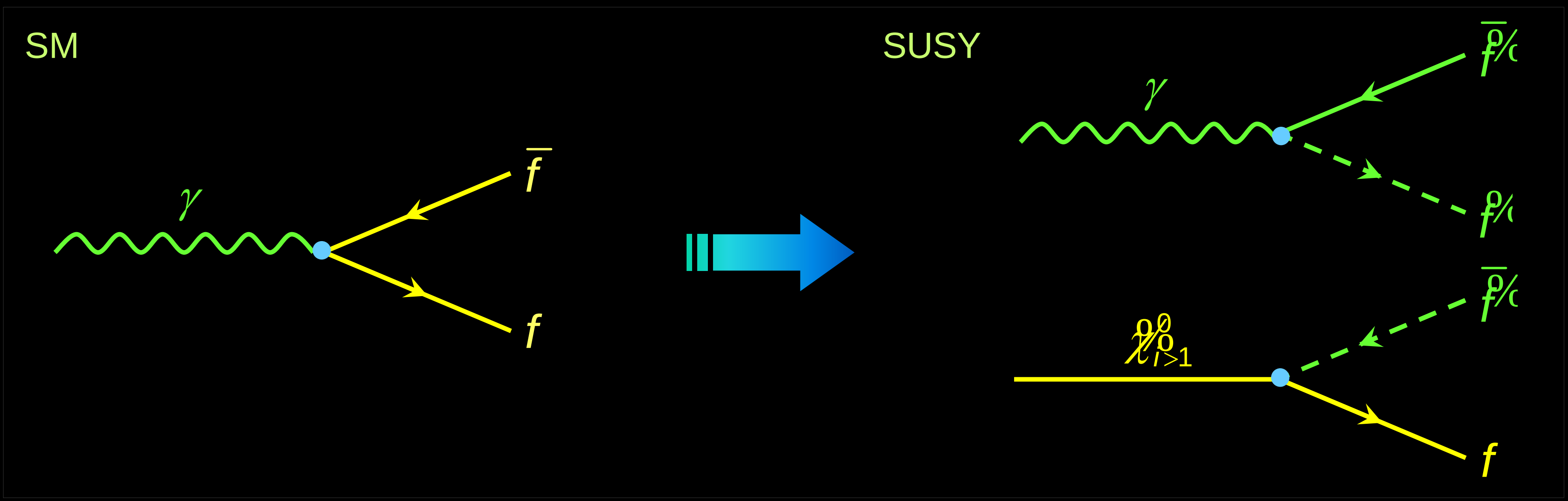
Charginos : mass eigenstates of winos and charged higgsinos

multiplets

Gauge Super-multiplets

The full particle content of the MSSM: each SM helicity state has a corresponding "spartner" (the indices indicate the helicities of the SM parther)

Interactions of SUSY Particles

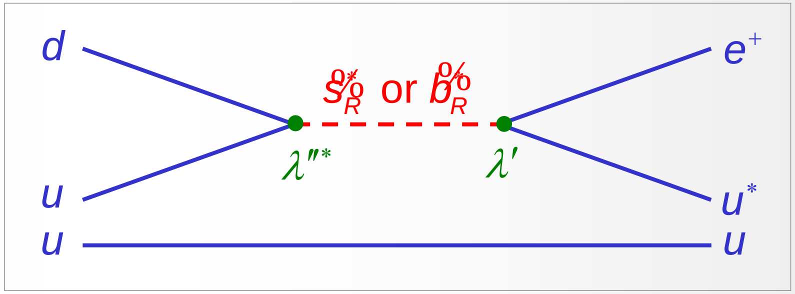


R-Parity

- The *superpotential* contains new lepton- or baryon number violating couplings of the form:

$$\left[\frac{1}{2}\lambda\cdot LLE^c + \lambda'\cdot LQD^c + \mu'\cdot LH_2\right]_{\Delta L=1}$$

$$\left[\frac{1}{2}\lambda''\cdot U^cD^cD^c\right]_{\Delta B=1}$$



Proton decay

Unless couplings very small – or sfermions very heavy

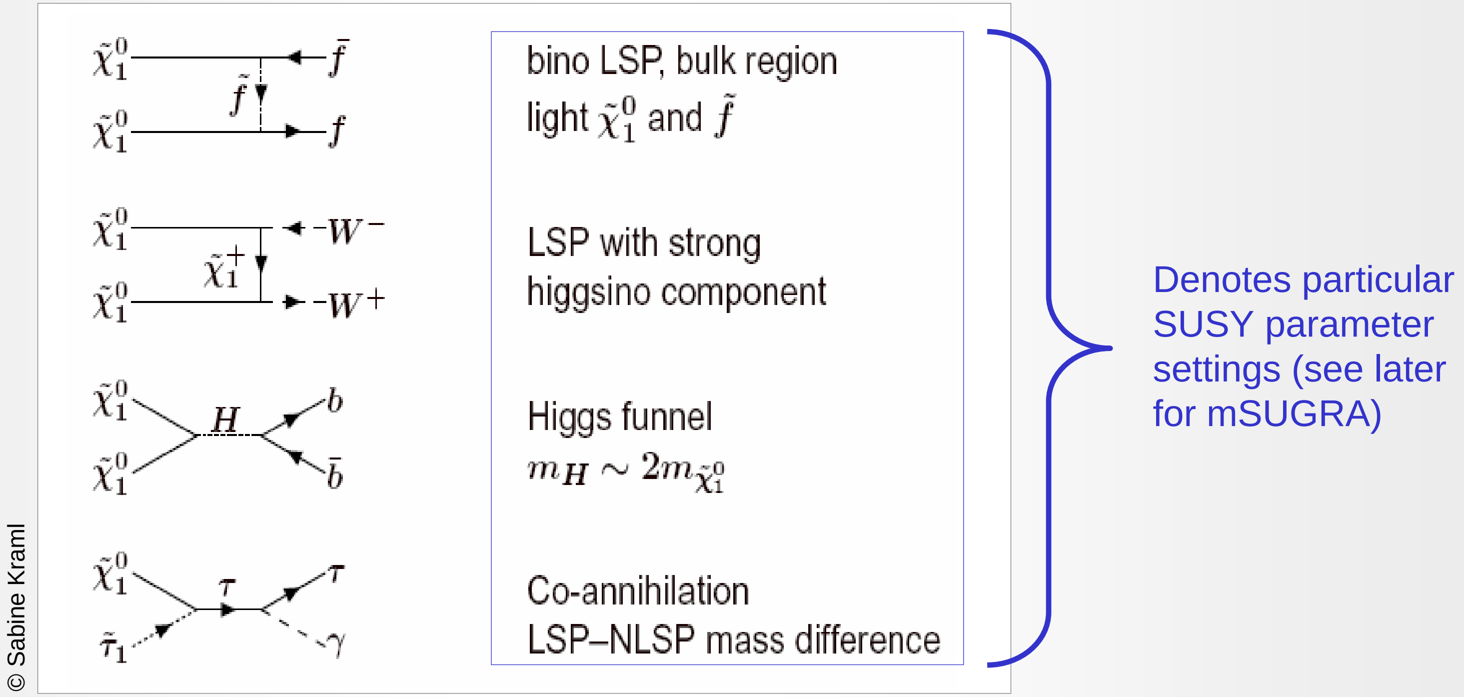
- **Throughout this lecture, we will assume that *R*-parity is conserved**

  - All interactions with odd numbers of SUSY particles are forbidden (SUSY production in pairs !)
  - The lightest SUSY particle (LSP) is stable
  - SUSY naturally provides a dark matter candidate (should be neutral (WIMP) → $\tilde{\chi}_1^0$ LSP candidate)

- *R*-parity has important phenomenological and <u>experimental</u> consequences (see later)

Dark Matter

- *R*-parity provides **dark matter candiates**: sneutrino (ruled out?), gravitino and **neutralino**
- The χ^0 **LSP** as **thermal relic**: relic density computed as thermally avaraged cross section of all χ^0 annihilation channels → **Cold dark matter density:** $\Omega_{DM}h^2 \sim \langle\sigma v\rangle^{-1} \sim 1\ \text{pb}^{-1}$



➡ CMB measurement: $0.094 < \Omega_{DM}h^2 < 0.129$ strongly bounds SUSY parameter space
[However, bounds are model-dependent: MSSM parameters, *R*-parity, other DM candidates, ...]

Observations

- If SUSY is unbroken (and *R*-parity is conserved), the MSSM has only a single additional parameter arising from the new Higgs doublet
- This is however not realised in nature:
  - EW symmetry breaking would be impossible (positive or zero Higgs potential)
  - In a given multiplet, the masses of the (s)particles are identical, but no scalar electron is observed
- ➜ SUSY – if it exists – must be broken in the vacuum state chosen by *our* nature !

- Spontaneous SUSY breaking is much more complicated than the EWSB in the SM
- Masses are added by hand to the SUSY Lagrangian ("soft" symmetry beaking)
  - Unlike massive fermions, massive sfermions do not break gauge symmetry of the Lagrangian

$\tilde{A}^{\dagger}\mathbf{m}_A^2\tilde{A}$, where: $\tilde{A} = \tilde{Q}, \tilde{L}, \tilde{U}^*, \tilde{D}^*, \tilde{E}^*$	squark and slepton terms ($\mathbf{m}^2_A$: 3×3 matrix)
$m_{H_1}^2 H_1^* H_1 + m_{H_2}^2 H_2^* H_2 + (\mu B \cdot H_1 H_2 + \text{h.c.})$	Higgs boson mass terms
$\tilde{U}^* \mathbf{A}_u \tilde{Q} H_2 + \tilde{D}^* \mathbf{A}_d \tilde{Q} H_1 + \tilde{E}^* \mathbf{A}_e \tilde{L} H_1 + \text{h.c.}$	trilinear Yukawa couplings ($\mathbf{A}_i$: 3×3 matrices)
$M_1 \tilde{B}\tilde{B} + M_2 \tilde{W}\tilde{W} + M_3 \tilde{g}_a \tilde{g}_a + \text{c.c.}$	gaugino mass terms

MSSM Parameters

- The MSSM defined by these soft SSB terms has a large number of free parameters
- The flavour-independent sector has:
  - 3 real gaugino couplings and 3 com… masses
  - H … and m_{H1}, m_{H2}
  - R
- The fl
  - 6 … gs)
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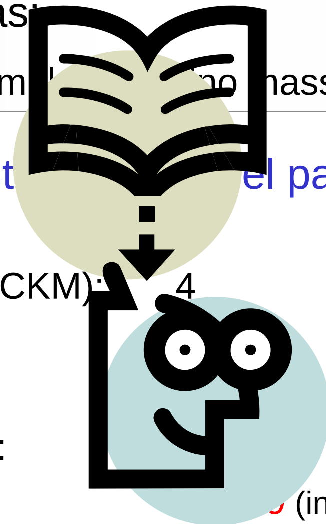
  - T … nd using
    u

Let's first recall the free St… el parameters:

fermion masses:
quark-mixing matrix (CKM): 4
boson masses:
coupling constants:
strong *CP* parameter:

(included in the MSSM parameters)



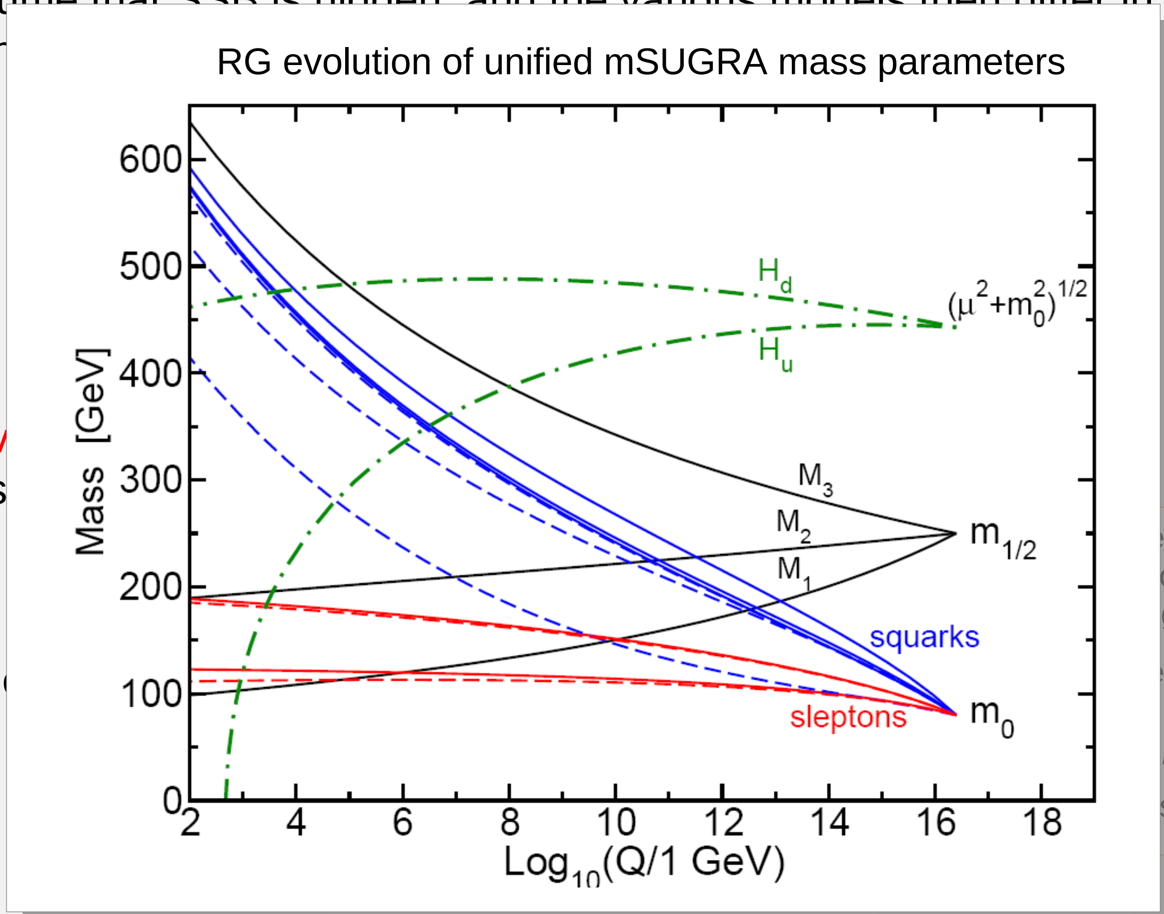
- Hence, the generic MSSM has **123 free parameters** (of which 44 are *CP*-violating phases!)
- Many of these parameters are already constrained from experiment:
  - lepton sector: electric dipole moments (EDMs), magnetic moments, charged-lepton flavour violation
  - quark sector: n-EDM, rare (radiative) *B* decays, flavour-changing neutral currents, *CP* violation

It is very difficult to introduce SSB without creating a conflict with experimental data

On the other hand, if SUSY is discovered, we'd already know much about its flavours

C(onstrained)MSSMs: Modeling SUSY Breaking

- One can assume that SSB is hidden, and the various models then differ in how the SSB is transmitted th



- Through grav … has only 5 parameters

At GUT scal

…normalisation group …ons govern the …g to the EW scale

… loop all M_i/α_i are …so that:

$m_{\tilde{\chi}_L} \approx m_{\tilde{\chi}} < m_{\tilde{\chi}_R}$

…st neutralino is LSP

- Through gauge interaction (GMSB): “messenger fields” transmit the SSB to the MSSM
  - The SSB scale is much smaller than in SUGRA
  - Very light gravitino is LSP, different experimental signature than SUGRA (where $m_{3/2} \sim m_{soft}$)

The Supersymmetric Higgs Sector

- At least 2 Higgs doublets with opposite hypercharge (Y_H) are necessary to realise EWSB

$$H_1^{Y_{H_1}=-1} = \begin{pmatrix} H_1^0 \\ H_1^- \end{pmatrix}, \quad H_2^{Y_{H_2}=+1} = \begin{pmatrix} H_2^+ \\ H_2^0 \end{pmatrix}$$

- Remember, the SM Higgs potential reads:
- The MSSM potential involving the Higgs fields then reads $(m_{1(2)}^2 = m_{H_{1(2)}}^2 + |\mu|^2,\ m_{12}^2 = \mu B)$

$$V_H = \mu^2 |H|^2 + \lambda |H|^4$$

$$V_H = \frac{1}{8}\left(g^2 + g'^2\right)\left(|H_1|^2 - |H_2|^2\right)^2 + \frac{1}{2} g^2 \left|H_1^\dagger H_2\right|^2 + m_1^2 |H_1|^2 + m_2^2 |H_2|^2 - m_{12}^2 \varepsilon_{ij}\left(H_1^i H_2^j + H_1^{*i} H_2^{*j}\right)$$

SM: λ

- The only free parameters are the m_i. Quartic couplings of the Higgs are constrained by the gauge coupling constants, g, g', in SUSY, while they are free (parameterised by λ) in the SM
- Contrary to the SM, the lightest Higgs mass can be predicted in SUSY !

SUSY Higgs Doublet – Species & Masses

- The vacuum expectation values (VEV) of the neutral Higgs fields are:

$$\langle H_1^0 \rangle = v_1/\sqrt{2}, \ \langle H_2^0 \rangle = v_2/\sqrt{2} \quad \text{with} \quad v_1^2 + v_2^2 = v^2 = \frac{2m_Z^2}{g^2 + g'^2} = (246 \text{ GeV})^2$$

  - $v_{1(2)}$ gives mass to fermions with isospin $I_z = -1/2(+1/2)$
  - The ratio of VEVs determines the mixing parameter: $\tan\beta = v_2 / v_1$

- After EWSB, 5 out of 8 degrees of freedom stay massive, and are the physical Higgs field

$$h,\ H_{CP=+1},\ A_{CP=-1},\ H^+,\ H^-$$

  - As in the SM, the remaining 3 degrees of freedom become the bosons W^+, W^- and Z^0

- The 6 parameters of the MSSM Higgs sector reduce to 2 ! By convention use: **tanβ, m_A**

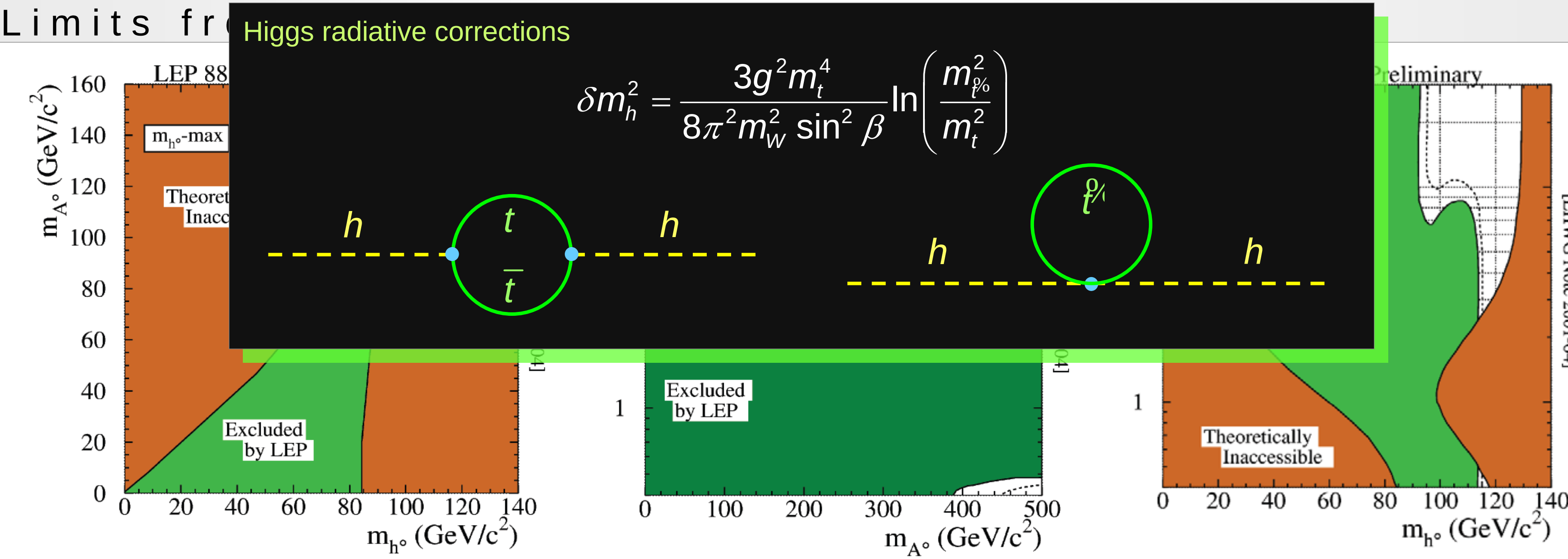
MSSM Higgs Searches at LEP

- The masses of the physical fields are obtained by minimising the Higgs potential; at Born level one finds in particular for the lightest SUSY Higgs:

$$m_h = \frac{1}{2}\left(m_A^2 + m_Z^2 - \sqrt{\left(m_A^2 + m_Z^2\right)^2 - 4m_A^2 m_Z^2 \cos 2\beta}\right)^{1/2} \leq m_Z$$

- If there weren't higher order corrections (m_h< 132 GeV) it would have been excluded already !

Limits fr



$$\delta m_h^2 = \frac{3g^2 m_t^4}{8\pi^2 m_W^2 \sin^2\beta} \ln\left(\frac{m_{\tilde{t}}^2}{m_t^2}\right)$$

Digression: SUSY Higgs – Couplings

- SUSY Higgs couplings to gauge bosons:
  - Trilinear couplings VVH_i, V=W,Z (do not exist for $H^\pm$ (charge conservation) A (*CP* invariance)):

    $g(VVh) \propto \sin(\alpha-\beta)$ and $g(VVH) \propto m_V \cos(\alpha-\beta)$ → $g(VVh)^2 + g(VVH)^2 = g(VVH)_{MS}$

    Note: no $\gamma\gamma H$ or γZH couplings ($m_\gamma = 0$), nor γZH coupling (*CP* invariance)
  - Trilinear couplings VH_iH_j:

    ZhA, ZHA, ZH^+H^-, γH^+H^-, and $WH^\pm h$, $WH^\pm H$, $WH^\pm A$

    Note: Zhh, ZHh, ZHH, ZAA forbidden (*CP* invariance)
  - Quartic couplings:

    ZZH_iH, $W^+W^-H_iH_j$, ($H_{i,j} = h, H, A, H^\pm$), $\gamma\gamma H^+H^-$, γZH^+H^-, $ZWH^\pm H_i$, $\gamma WH^\pm H_i$ ($H_{i,j} = h, H, A$),

- SUSY Higgs couplings to fermions:
  - Trilinear Yukawa couplings between Higgs and two fermions (dominated by heavy top, bottom quarks)

    $\lambda(H_ipp) \propto m_p \times f(\mathrm{trig}(\alpha)/\mathrm{trig}(\beta))$, where p=u,d-type, and $H_i = h, H, A$,

    $\lambda(H^\pm pq) \propto f(m_p, m_q) \times V_{CKM} \times f'(\mathrm{trig}(\alpha), \mathrm{trig}(\beta))$

    Note: A, $H^\pm$ couplings to down-type quarks increase with $\tan\beta$, while those to up-type quarks decrs.

    Couplings to τ also important for searches at LHC

SUSY – Résumé and Comments

- The MSSM naturally responds to a number of SM problems:
  - The quadratic divergence of the Higgs radiative corrections becomes logarithmic
  - SUSY “naturalizes” the Higgs and cures the hierarchy problem by introducing new fields at ~ O(TeV)
  - Grand unification of the forces at high scale is achieved
  - The existence of a spin-2 graviton (and a spin-3/2 gravitino) is naturally embedded in SUSY
  - SUSY provides a cold dark matter candidate → LSP

- However, no experimental evidence for SUSY so far, on the contrary (→ *flavour problem*)

- Other SUSY models exist, for example the controversial *Split Supersymmetry*

  From the observation that the m_{EW}-vs-M_{Pl} hierarchy problem is not the only one (there also is a huge gap between the cosmological constant ($\Lambda \sim (0.002\ \text{eV})^4$) and m_{EW}), it is suggested to neglect the necessity to cure the EW hierarchy problem with SUSY.

  Consequences:

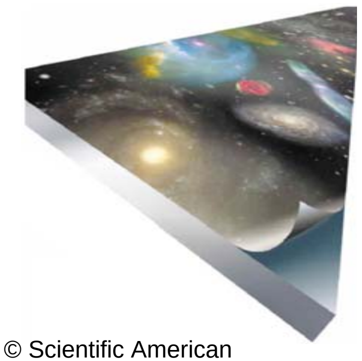
  - Lightest Higgs and gaugino sector light (keeps dark matter candidate and GUT)
  - Very heavy sfermions ~ 10^{10} GeV
  - Cures problem that no indirect SUSY hints have been observed
  - Very different phenomenology and experimental signature

Extending the Standard Model

- Supersymmetry
- **Extra dimensions**
- Little Higgs

Perhaps the problem with the hierarchy is that we use the wrong M_{Pl} ?

Could there be strong gravity at the TeV scale ?



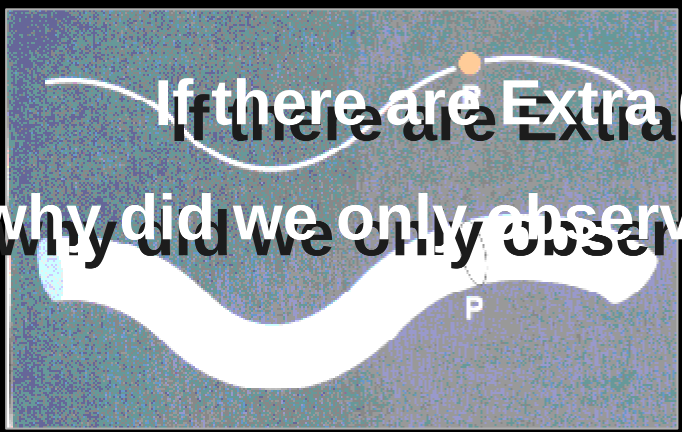
Quantity	Value
Planck Mass	1.2×10^{19} GeV/c^2
Planck Length	1.6×10^{-33} cm
Planck Time	5.4×10^{-44} s
Planck Temperature	1.4×10^{32} K

Extra Dimensions (EDs) ?

- Since the very end of the last century, an old theory (~1920), invented to unify gravitation and EM interaction was rediscovered to solve the hierarchy problem… the **Kaluza-Klein theory**
- ED theories associate “Kaluza-Klein towers” with the particles propagating in (compact) EDs
- String theory requires 10 – 11 space-time dimensions → **≤ 7 extra spatial dimensions (ED)** ?
- String theory acts at scale $M_{\mathrm{string}} \sim M_{\mathrm{Pl}} \sim 10^{19}$ GeV ~ 1.6 10^{-33} cm → not observable at LHC
- Up to $M_{\mathrm{EW}} \sim 10^{2}$ GeV ~ **1.6 10^{-16} cm [SM], and 10^{-2} cm [Gravitation] EDs can be excluded**
- Relatively large EDs in which gravitons propagate are thus not excluded; the SM particles could be confined in a smaller sub-space: a “**brane**”
- Gravity would allow us to probe the EDs
- Unfortunately, since gravity is a very weak force, and the EDs are small, we can hardly see the effects of them in a laboratory… **unless gravitation could be amplified making extra dimensions of up to a mm possible** ?

If there are Extra (spatial) Dimensions …

…why did we only observe 3 spatial dimensions so far ?



Extra space dimensions are hidden from view because they are "compactified“, *i.e.*, tightly rolled up. In this demonstration, a 2D surface is rolled up in a tube (bottom), becoming so tightly rolled that it looks like a 1D line (top). [Graphics by Mark McLellan].

Extra Dimensions and Newton's Gravitation

- Let us consider d EDs with some size R, the distance r_{12} between two masses m_1 and m_2

  - If $r_{12} = R$, we live in a (4+d)D world with:

$$F^{(4+d)}(r_{12}) = \frac{G^{(4+d)} m_1 m_2}{r_{12}^{d+2}} = \frac{m_1 m_2}{M_{\mathrm{Pl}}^{d+2} \cdot r_{12}^{d+2}}$$

  - If r_{12} ? R, we live in a 4D world, where the EDs are integrated out, and is identified with Newton's law:

$$F^{(4+d)}(r_{12}) \propto \frac{G^{(4+d)} m_1 m_2}{R^d r_{12}^2} = \frac{G^{(4)} m_1 m_2}{r_{12}^2}$$

  - From continuity at $r_{12} = R$, one finds:

$$G^{(4)} = G^{(4+d)}/R^d \quad \text{and} \quad \left(M_{\mathrm{Pl}}^{(4)}\right)^2 = \left(M_{\mathrm{Pl}}^{(4+d)}\right)^{d+2} \cdot R^d$$

4D gravity is diluted by the extra dimension !

The Planck scale is no longer fundamental !

- At the LHC scale of $M_D \sim M_{\mathrm{Pl}}^{(4+d)} \sim 1$ TeV, one thus finds:

d=1: $R \sim 10^{15}$ cm (excluded from large scale gravitation tests)
d=2: $R \sim 10^{-1}$ cm (limit from gravitation tests) → only probes energy scale $R^{-1} \sim 2\ 10^{-4}$ eV !
d=3: $R \sim 10^{-6}$ cm (allowed)

Kaluza-Klein Towers

Suppose a massless scalar ϕ in a 5D space. 1D, y, is compactified on a circle with radius R

- We need to verify that: $\phi\left(x^{(4)}, y\right) = \phi\left(x^{(4)}, y + 2\pi R\right)$

  which translates into a quantification of the momentum in this dimension: $p = n/R,\ n \in \mathbb{Z}$

- Developing ϕ into Fourier series of y,

$$\phi\left(x^{(4)}, y\right) = \sum_n \phi_n = \sum_n \phi\left(x^{(4)}\right) e^{iny}$$

  one finds that the ensemble of ϕ_n represents a **Kaluza-Klein (KK) tower** associated with the field ϕ, and the mass-squared of the mode ϕ_n in 4D (solution of Klein-Gordon equation) is given by:

$$m_n^2 = m_0^2 + \left(\frac{n}{R}\right)^2 \quad \Rightarrow \quad \Delta m = \frac{1}{R} \overset{R \sim 2\times 10^{-17}\,\text{cm}}{\sim} 1\,\text{TeV}$$

- KK attempted in 1920 to unify EM interactions and gravitation with their theory: they have developed the metric between space-time and the 5th D around small perturbations proportional to the photon field A_μ.

- Computing the effective action with this metric in 4D, one recovers the 4D gravitation by identifying:

$$G^{(4)} = \frac{1}{2\pi R} G^{(5)}$$

➡ **In the KK theory, $G^{(4)}$ is only a reflection of the *real* gravitational constant $G^{(5)}$ (*i.e.*, the Planck scale), reduced by the extra dimension !**

The ADD Model

Universal Extra Dimensions

Arkani-Hamed, Dimopoulos, Dvali (1998)

Unfortunately, there is a little secret in the ADD model.

The original purpose of it to eliminate the hierarchy problem is missed: although the true (4+*d*) Planck scale is indeed of *O*(EW), one finds that $R \cdot M_D = (M_{Pl}/M_D)^{2/d}$ is a very large number (due to the large EDs).

→ ADD trades one hierarchy problem for another one !

energy by the large number of accessible KK states that is summed over
[remember: the mass difference of a KK towers is given by the (small) energy scale (R^{-1}) of the large ED]

- No momentum conservation per ED, *i.e.*, gravitons are emitted into ED by SM fields
- Main ADD ED signatures at the LHC:
  1. *pp* → jet + missing energy (from undetected sum of accessible KK graviton towers)
  2. gravitons can modify SM cross sections through loops (here: all KK towers are virtually accessible)

The RS Model (in 5D → 1 ED)

Randall, Sundrum (1999)

If discovered, to truly identify these spin-2 resonances as gravitons, one needs to demonstrate:

1. that it is indeed spin-2 (“easy” from angular distribution)
2. that couplings are universal (general relativity)
   → measure branching ratios

- Parameter k has dimension; basic assumption of RS: no mass hierarchies → $k \sim M_D \sim M_{Pl}$
- Solving Einstein’s equations and integrating out y, one finds for 4D: $M_{Pl}^2 = \frac{M_D^2}{k}\left(1 - e^{-2\pi k r_c}\right)$ “warp factor”
- If there is some mass $m_0 \sim M_{Pl}$, we on the SM brane see: $m = m_0 e^{-\pi k r_c}$!
  $O(10^{-15})$ for $kr_c \sim 11$ → large hierarchy is naturally explained by exponential factor !
- RS ED signature at the LHC: the KK gravitons-to-SM couplings are enhanced by warp factor
  - Weak scale graviton KKs with weak scale couplings should produce universal spin-2 resonances !

EDs in Astrophysics, Cosmology and HEP

- Large EDs would act only after the inflation period; they could influence:
  - Primordial nucleosynthesis
  - Cosmic microwave background – if the gravitons decay into photons by interacting with the SM brane
- A priori, nothing is known about cosmology when we enter the domain of strong gravitation. For example: non-perturbative effects could occur
- EDs could modify the ν-nucleon scattering cross section of ultra-high energetic cosmic ν's
- EDs could modify deflection angle of gravitational lensing [limit: for d=2, M_D > 4 TeV]
- EDs could influence the maximum allowed mass for neutron stars, and contribute to cooling of stars: limit on ED scale from super nova (SN1987A) [d=2, M_D > 50 TeV, d=4, M_D > 1 TeV]
- EDs modify Newton's gravitational law at small distances (→ dedicated experiments)
- EDs influence cross sections of standard accelerator processes (*e.g.*, $e^+e^- \to \gamma\gamma$)
- EDs allow direct production of gravitons, *e.g.*, $e^+e^- \to \gamma G$, ZG, and excited KK graviton states

Extending the Standard Model

- Supersymmetry
- Extra dimensions
- **Little Higgs**

Perhaps Higgs is Goldstone of new interaction at scale Λ ~ 10 TeV, so we didn't notice the interaction yet ? Its breaking could lead to new fields of mass ~ 1 TeV that stabilize the SM for the "little hierarchy": $v \rightarrow \Lambda$

Digression: A "Little" Higgs ?

- Seeks to solve the radiative instability of the SM Higgs sector
- In the "Little Higgs" model, the massless Higgs is generated (in analogy of the pion in QCD) through SSB of a new symmetry
- It's mass is acquired during EWSB. The new symmetry being still approximately valid, the mass is protected and stays small

- As new symmetry one could use SU(5), embedding the unified gauge group $(SU(2)\times U(1))^2$
  - Breaking SU(5) by a VEV into SO(5) creates 14 "Goldstone" bosons
  - Then, the group $(SU(2)\times U(1))^2$ is broken into $SU(2)_L\times U(1)_Y$, where 4 of the 14 Goldstone bosons are used to create massive longitudinal SM gauge fields ($W^{\pm}_H$, Z_H, A_H) of the broken gauge group
  - Among the remaining Goldstone bosons one finds a complex scalar doublet (SM Higgs), and a scalar triplet with 5 Higgs bosons: ϕ^0 , $\phi^{\pm}$, $\phi^{\pm\pm}$

- Breaking SU(5) requires at least one heavy, *O*(TeV), new particle for each particle contributing to the radiative corrections of the Higgs, which cancel the SM corrections
  - By construction: the $W^{\pm}_H$, Z_H cancel the weak divergence, a new quark *T* cancels the top-quark divergence, the new Higgs triplet cancels the SM Higgs divergence
  - The new heavy top and gauge bosons decay into their SM partners through associated Higgs production. These and the new Higgs fields could be discovered at the LHC

Conclusions

of the first lecture

Conclusions … of the first lecture

- Strong experimental and theoretical hints for physics beyond the SM exist from both astro physics and particle physics
- Dark matter, baryogenesis (& leptogenesis) and the hierarchy problem are the best ones
- Good new physics models can deal with all these problems at once
- Best candidate is Supersymmetry, but could also be several models at once!
- The experimentalists cannot restrict there search to one favourite model, but should search as inclusively as possible for the most diverse phenomena...

  … this will be the subject of the next (less difficult!) lecture.