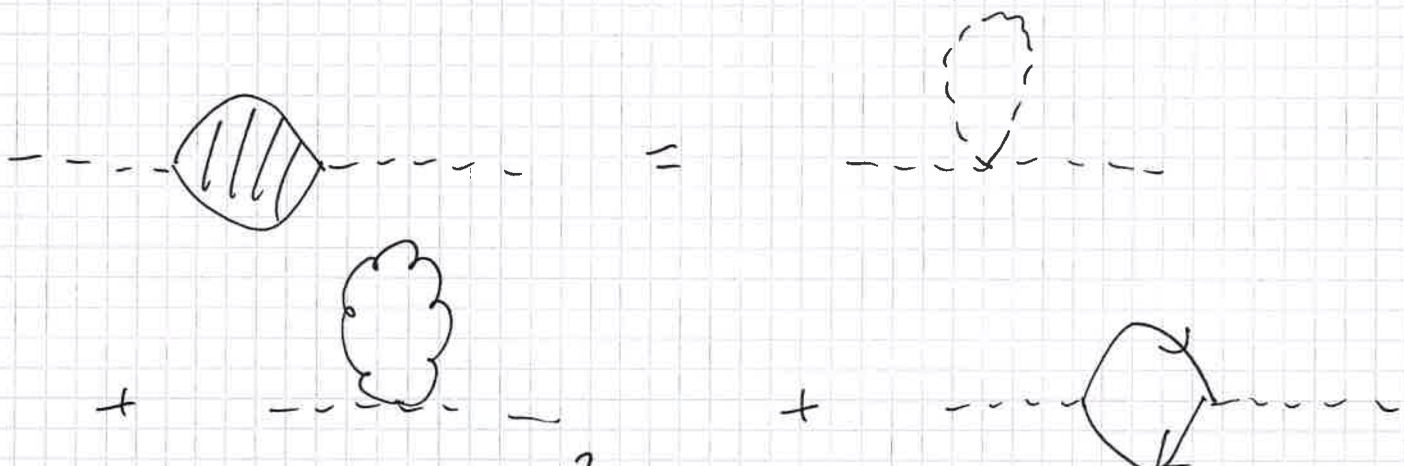
BEYOND THE STANDARD MODEL

CSABA CSA'KI

HIERARCHY PROBLEM

$$\int \frac{d^4k}{(2\pi)^4} \frac{1}{k^2-m^2}$$



$$\delta m^2 \sim \frac{\Lambda^2}{32\pi^2} \left(6\lambda + \ldots \right)$$

$\Lambda \gg 10$ TeV

<u>fermions</u>: new symmetry $m_e \to 0$

$$\Delta m_e \propto m_e \log\left(\frac{\Lambda}{m_e}\right)$$

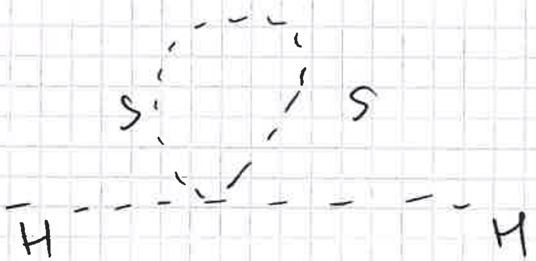
<u>gauge bosons</u>: $\Delta M_W^2 \propto M_W^2 \log\left(\frac{\Lambda}{M_W}\right)$

<u>Meaning of Λ^2 sensitivity?</u> Λ cutoff scale of validity of SM

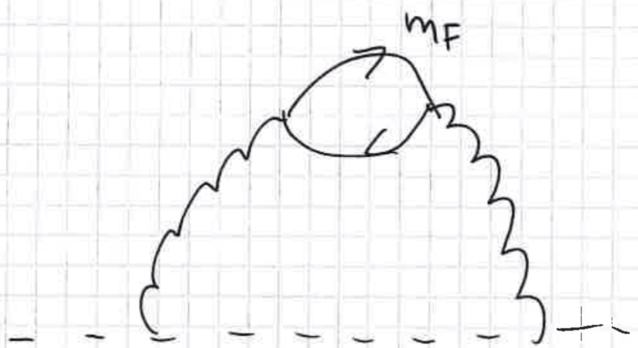
at scale Λ there will be new particles
(GUT bosons (...))

Λ represents <u>finite</u> contributions of very heavy particles

Ex. very heavy scalar $\qquad \lambda_S |H|^2 |S|^2$



$$\delta m_H^2 = \frac{\lambda_S}{16\pi^2}\Big[\cancel{\Lambda_{UV}^2} \to 0$$
$$- 2 m_S^2 \log\left(\frac{\Lambda_{UV}}{m_S}\right) + \text{finite} \Big]$$



$$\delta m_H^2 \sim \frac{g^4}{(16\pi^2)^2}\Big[m_F^2 \log\left(\frac{\Lambda}{m_F}\right) + \dots$$

$$m_F \sim 10^{16}\ \text{GeV}$$

is setting $\longrightarrow \delta m_H^2 \sim (10^{16}\ \text{GeV})^2$

$v = 246\ \text{GeV}$ $\qquad m_H^2 = m_{0\,\text{tree}}^2 + \overset{(10^{16}\,\text{GeV})^2}{\overset{\downarrow}{\delta m_H^2}} \sim (246\ \text{GeV})^2$

Usual solutions to hierarchy:

$\Lambda \sim$ 1 TeV – few TeV & the new physics is special:

no additional large contributions

- <u>SUSY</u> relation between scalar & fermion
- relate scalar to gauge boson
  - gauge-higgs unif.
  - little higgs models
  - pseudo-GB higgs
- technicolor, higgsless $\times$ EWSB w/o elementary scalar
- composite Higgs
- fundamental scale $\Lambda = 1$ TeV (no other high scale)
  large extra dimensional models

INTRO TO SUSY

Ordinary symmetry : invariance of Lagrangian

internal symmetry : $\underset{\text{boson}}{\underset{\uparrow}{\varphi_i}} \longrightarrow i\,\epsilon^a T^a_{ij}\,\underset{\text{boson}}{\underset{\uparrow}{\varphi_j}}$

Space-time symmetries :

non-SUSY : spin does not change

SUSY : generators of symmetry are fermionic
mix fermions & bosons among each other!

Coleman-Mandula : no way to mix internal & space-time symmetries

SUSY 2 types of T's

$$\{Q_\alpha, Q^\dagger_{\dot\alpha}\} = 2P^\mu(\sigma_\mu)_{\alpha\dot\alpha}$$ SUSY algebra

$\Downarrow$

I. # fermions = # of bosons

II. mass fermion = mass of boson

III. If SUSY unbroken $\langle 0|H|0\rangle = 0$

$\uparrow$ P^0

Basic building blocks for SUSY theories!

SUPERFIELDS : basic objects "representations"

1.) chiral superfield
- 1 complex scalar
- 2 component spinor (Weyl spinor)

2.) vector superfield
- massless gauge boson (spin 1 object) $A^\mu \rightarrow 2$ DoF
- 2 component spinor $\longrightarrow 2$ DoF (particle + anti-part + 1 helicity)

Off-shell : chiral SF

complex scalar	2 DoF
Weyl spinor	4 DOF
auxiliary field F	2 DoF

VECTOR SF

Weyl spinor	4 DoF
A_μ	3 DoF
D auxiliary	1 DoF

Fix interaction & obtain a SUSY Lagrangian?

<u>Superfield</u> : φ , χ $\Rightarrow$ to build

Φ

<u>Superspace</u>

$$\underbrace{x^\mu P_\mu + \theta^\alpha Q_\alpha + \bar\theta^{\dot\alpha} \bar Q_{\dot\alpha}}$$

$$G(\theta, \xi, \bar\xi) \; \underbrace{F(x, \theta, \bar\theta)}$$

$$(x + i\theta\sigma^\mu\bar\xi - i\xi\sigma^\mu\bar\theta, \theta + \xi, \bar\theta + \bar\xi)$$

how much SUSY rotation

Superfield function $\boxed{F(x, \theta, \bar\theta)}$

fermionic

only contain finite # of terms!

$$\boxed{\begin{aligned} F(x,\theta,\bar\theta) &= f(x) + \theta\psi(x) + \bar\theta\bar\psi(x) \\ &+ \theta^2 m(x) + \bar\theta^2 \bar m(x) + \theta\sigma^\mu\bar\theta\, v_\mu(x) \\ &\quad \theta^2\bar\theta\lambda + \bar\theta^2\theta\xi + \theta^2\bar\theta^2 d \end{aligned}}$$

contains both vector & chiral

θ^α

$\theta^2 = \theta^1 . \theta^2$

Impose a condition that is SUSY

$V = V^\dagger \longrightarrow$ vector SF

$$\partial_\mu \to D_\alpha = \frac{\partial}{\partial\theta^\alpha} + i\bar\theta^{\dot\alpha}\sigma^\mu_{\alpha\dot\alpha}\partial_\mu$$

$$\Longrightarrow \boxed{\bar D\,\Phi = 0 \longrightarrow \text{chiral SF}}$$

$$\boxed{\Phi(y,\theta) = \varphi(y) + \sqrt2\,\theta\psi(y) + \theta^2 F(y)}$$

$$\delta_\xi \varphi = \sqrt{2}\, \cancel{\epsilon}\, \xi \psi$$

$$\delta_\xi \psi = \sqrt{2} i\, \sigma^\mu \bar{\xi}\, \partial_\mu \varphi + \sqrt{2}\, \xi F$$

$$\delta_\xi F = \sqrt{2} i\, \bar{\xi}\, \bar{\sigma}^\mu \partial_\mu \psi$$

Lagrangian? $\mathcal{L} = W(\phi)\big|_{\theta^2} \longrightarrow$ invariant

superpotential

Kinetic term? $\phi^\dagger \phi \big|_{\theta^2 \bar{\theta}^2} =$

$$= \left(\partial_\mu \varphi^*\right)^2 + i/2\, \partial_\mu \bar{\psi}\, \sigma^\mu \psi + \text{h.c.} + F F^*$$