# Physics Beyond the Standard Model

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Rogerio Rosenfeld
IFT-UNESP & ICTP-SAIFR

Lecture 1: The reasons for BSM and the agnostic approach
Lecture 2: Simple extensions of the Standard Model
→ Lecture 3: Naturalness guided BSM

# Electron self-energy

Lorentz – The theory of electrons (1916) – classical E&M

Electron self-energy (a is the radius of the electron):

$$E = \frac{1}{8\pi}\int dV\, \frac{4\pi\alpha}{r^4} = \frac{2\pi\alpha}{a} = 2\pi\alpha\Lambda$$

Naturalness would require $E<m_e$, that is, $a>2\text{x}10^{-12}$ cm and $\Lambda< 10$ MeV.

However, at LEP a limit from contact interactions gives $\Lambda>10$ TeV ($a < 2 \text{ x } 10^{-18}$ cm)! What is the solution?

# Electron self-energy

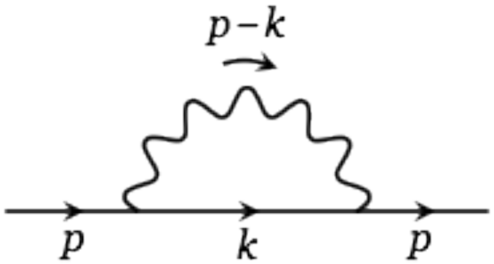
Solution is related to a symmetry: chiral symmetry

$$\psi \to e^{i\gamma_5 \alpha}\psi$$

Mass terms for fermions explicitly break chiral symmetry.

In QFT the correction to the electron mass is given by

$$\delta m_e \propto \alpha\ m_e\ \ln(m_e/\Lambda)$$



# Electron self-energy

Electron mass is "protected" by chiral symmetry:
the correction to the electron mass is proportional to the mass itself and vanishes in the chiral symmetric limit.

NATURALNESS, CHIRAL SYMMETRY, AND SPONTANEOUS

CHIRAL SYMMETRY BREAKING

G. 't Hooft

't Hooft (1980)

theories: the effective interactions at a large length scale, corresponding to a low energy scale $\mu_1$, should follow from the properties at a much smaller length scale, or higher energy scale $\mu_2$, without the requirement that various different parameters at the energy scale $\mu_2$ match with an accuracy of the order of $\mu_1/\mu_2$. That would be unnatural. On the other hand, if at the energy scale $\mu_2$ some parameters would be very small, say

$$\alpha(\mu_2) = \mathcal{O}(\mu_1/\mu_2) \ , \qquad \text{(III1)}$$

then this may still be natural, provided that this property would not be spoilt by any higher order effects. We now conjecture that the following dogma should be followed:

– at any energy scale $\mu$, a physical parameter or set of physical parameters $\alpha_i(\mu)$ is allowed to be very small only if the replacement $\alpha_i(\mu) = 0$ would increase the symmetry of the system. –

In what follows this is what we mean by naturalness. It is clearly ‘t Hooft (1980)

If within a set of small parameters one is several orders of magnitude smaller than another then the smallest must satisfy our "dogma" separately. As we will see, naturalness will put the severest restriction on the occurrence of scalar particles in renormalizable theories. In fact we conjecture that this is the reason why light, weakly interacting scalar particles are not seen.

Even ‘t Hooft can be wrong!

Naturalness dogma: Higgs mass must be protected by a symmetry.

# Naturalness

In an effective theory there is a physical cut-off $\Lambda$.

If SM is an effective theory, it is not natural to have $M_H << \Lambda$ because of quadratic divergencies.

Veltman (81): radiative corrections are supposed to be of the same order (or much smaller) than the actually observed values.

# Naturalness

SM is natural only if Λ<600 GeV- "Veltman's throat":

$$\delta M_H^2 = \frac{3\Lambda^2}{16\pi^2 \mathrm{v}^2}\left[M_H^2 + 2M_W^2 + M_Z^2 - 4m_t^2\right]$$

But LHC has ruled out New Physics at this scale.

LHC has shown that SM is not natural.

# Naturalness

This is the "naturalness"motivation to go BSM – find a mechanism that can explain why $M_H << \Lambda$ for large values of the cut-off representing a physical scale where New Physics should show up.

# Naturalness

New symmetries to protect a light Higgs:

- ✓ Supersymmetry
- ✓ Shift symmetry (Composite Models, Higgs~pNGB)
- ✓ Conformal symmetry (Higgs~dilaton)

or lower $\Lambda$:

- ✓ Extra-dimensions (with only gravity in xDim)
- ✓ Warped extra dimension

# Supersymmetry (SUSY) in 1 slide

- New symmetry of Nature: relates bosons and fermions
- For each SM particle it associates a SUSY partner

W-> wino, gluon-> gluino, top-> stop, ...

- Protects Higgs mass from quadratic divergences
- The Higgs mass at tree level must be lighter than the Z

tension with measurements – difference must come from loops

- Must have a second Higgs doublet: 5 physical Higgses
- Has a natural dark matter candidate – the LSP

requires R-parity; WIMP miracle

- Necessary ingredient in Superstring Theory
- Unification of coupling constants ($g_S$,g,g’)
- SUSY is broken in Nature!

Introduces several parameters to describe “soft” breaking

# SUSY

New symmetry of Nature with generators that carry spin :

$$Q_{\mathrm{SUSY}}|B\rangle \to |F\rangle$$

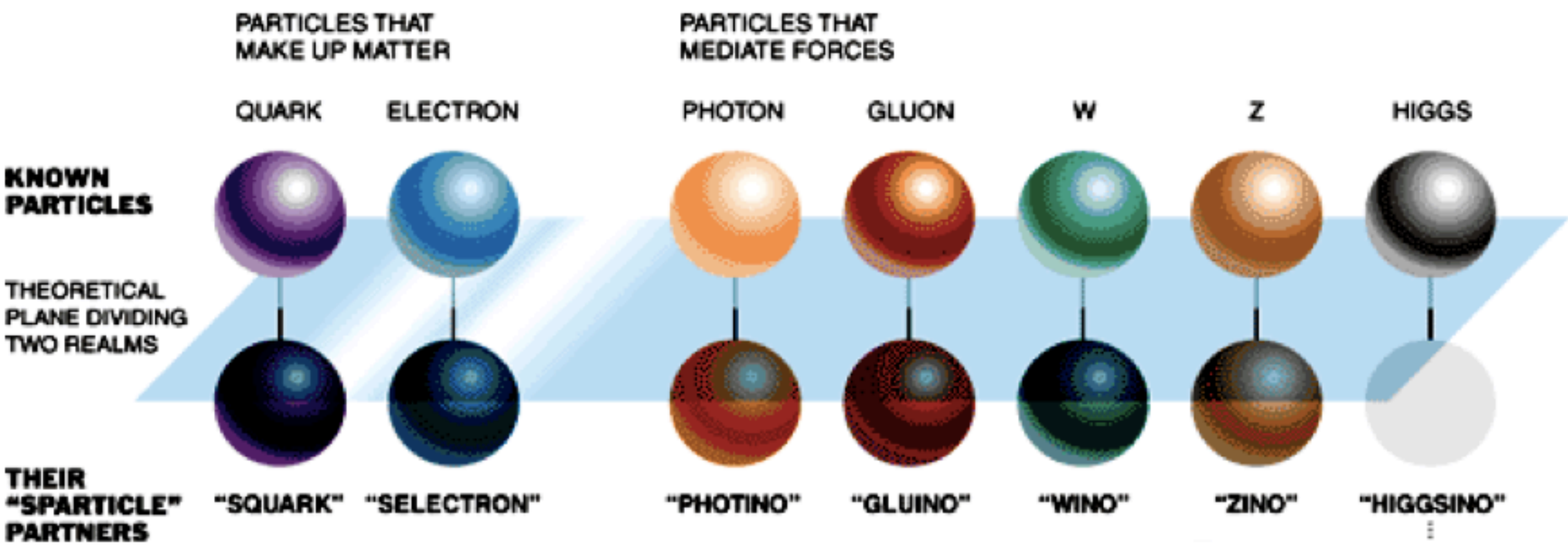
Symmetry: commutes with H $\qquad [Q_{\mathrm{SUSY}}, H] = 0$

Degenerate states: if $H|B\rangle = E_B|B\rangle$

$$Q_{\mathrm{SUSY}} H|B\rangle = Q_{\mathrm{SUSY}} E_B|B\rangle \implies H|F\rangle = E_B|F\rangle$$

At zero momenta, SUSY implies $m_B = m_F$

# supersymmetry


*Photino, Zino and Neutral Higgsino: Neutralinos*

*Charged Wino, charged Higgsino: Charginos*

C. Wagner

# SUSY

Building blocks are so-called superfields:

chiral multiplets (fermions and sfermions, Higgs and higgsinos)

vector multiplets (gauge bosons and gauginos).

Particle content in the Minimal Supersymmetric Standard Model

| | |
|---|---|
| spin-$\frac{1}{2}$ $(\nu_L, e_L); e_R$ | spin-0 $(\tilde{\nu}_L, \tilde{e}_L); \tilde{e}_R$ $\times$ generations |
| spin-$\frac{1}{2}$ $(u_L, d_L); e_R$ | spin-0 $(\tilde{u}_L, \tilde{d}_L); \tilde{d}_R$ $\times$ generations |
| spin-1 $(g, \gamma, W^{\pm}, Z)$ | spin-$\frac{1}{2}$ $(\tilde{g}, \tilde{\gamma}, \widetilde{W}^{\pm}, \widetilde{Z})$ |
| spin-0 Higgs bosons $(h^0, H^0, A^0, H^{\pm})$ | spin-$\frac{1}{2}$ higgsinos $(\tilde{H}_u^+, \tilde{H}_u^0)$, $(\tilde{H}_d^-, \tilde{H}_d^0)$ |

Masses are not predicted

# SUSY

Discrete symmetry must be imposed to avoid terms that violate B and L: R-parity.

All SM particles are even and all the SUSY partners are odd under R-parity.

Lightest SUSY particle (LSP) is stable.

Natural DM candidate (neutralino)

Collider signatures of SUSY involve missing energy!

# SUSY

Higgs sector of MSSM contains 2 Higgs doublets (required by anomaly cancellation).

5 physical particles: 2 scalars (h, H), 1 pseudoscalar (A), 2 charged Higgs ($H^{\pm}$)

Lightest scalar (h) is identified with the 125 GeV scalar

Free parameter given by the ratio of the vev's of the 2 doublets:

$$\tan\beta = \frac{v_2}{v_1}$$

# SUSY

SUSY is a beautiful theory. But we know SUSY must be broken if it has anything with the real world.

This is where complications arise.

There are a few models that describe SUSY breaking (e.g., gravity-mediated, gauge-mediated and anomaly-mediated). The breaking must be “soft” (preserve cancellation of quadratic divergences)

Pragmatic approach: parametrize soft-SUSY breaking.

# SUSY

Many “MSSM” models:

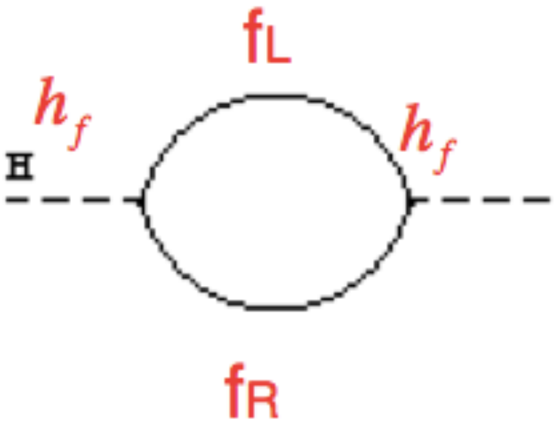
Full unconstrained MSSM – all possible soft-SUSY breaking terms
105 new parameters!

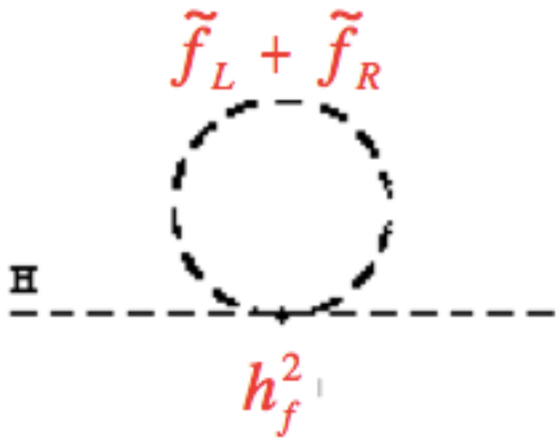
Phenomenological MSSM (pMSSM) – no new source of CP, no FCNC, universality in the 1st and 2nd generations:
19 new parameters

Constrained MSSM (cMSSM) or mSUGRA – universal gaugino masses, scalar masses and trilinear couplings.
5 parameters: tan $\beta$, $m_{1/2}$, $m_0$, $A_0$, sign($\mu$)

# SUSY

Magic of SUSY I – relation among couplings (Yukawa and quartic) that results in the cancellation of quadratic divergences for the Higgs mass (only log-divergence remains):




$$\delta m_H^2 = \frac{N_C h_f^2}{16\pi^2}\left[-2\Lambda^2 + 3m_f^2 \log\left(\frac{\Lambda^2}{m_f^2}\right) + 2\Lambda^2 - 2m_{\tilde{f}}^2 \log\left(\frac{\Lambda^2}{m_{\tilde{f}}^2}\right)\right]$$

C. Wagner

# SUSY

Magic of SUSY II – relation among couplings (gauge and Higgs quartic coupling) results in an upper bound at tree-level for the mass of the lightest Higgs scalar:

$$m_h^2 = M_Z^2 \cos^2 2\beta \Longrightarrow m_h < 91 GeV$$

SUSY favors a light Higgs boson.

Since we now know that $m_h$ > 125 GeV, large radiative corrections are necessary – problems with naturalness!

# SUSY

## Naturalness and SUSY:

$$m_h^2 = \underbrace{M_Z^2 \cos^2 2\beta}_{\leq M_Z^2} + \underbrace{\frac{3g^2 m_t^4}{4\pi^2 M_W^2} \log\left(\frac{\tilde{m}}{m_t}\right)}_{\geq (86 \text{ GeV})^2}$$

Same order as tree level!

SUSY scale: $\tilde{m} \approx 20 \times m_t \approx 3.5 \text{ TeV}$

## SUSY corrections to the Higgs mass is a bit more complicated:

For moderate to large values of tan beta and large non-standard Scalar boson masses

$$m_h^2 \cong M_Z^2 \cos^2 2\beta + \frac{3}{4\pi^2}\frac{m_t^4}{v^2}\left[\frac{1}{2}\tilde{X}_t + t + \frac{1}{16\pi^2}\left(\frac{3}{2}\frac{m_t^2}{v^2} - 32\pi\alpha_3\right)\left(\tilde{X}_t t + t^2\right)\right]$$

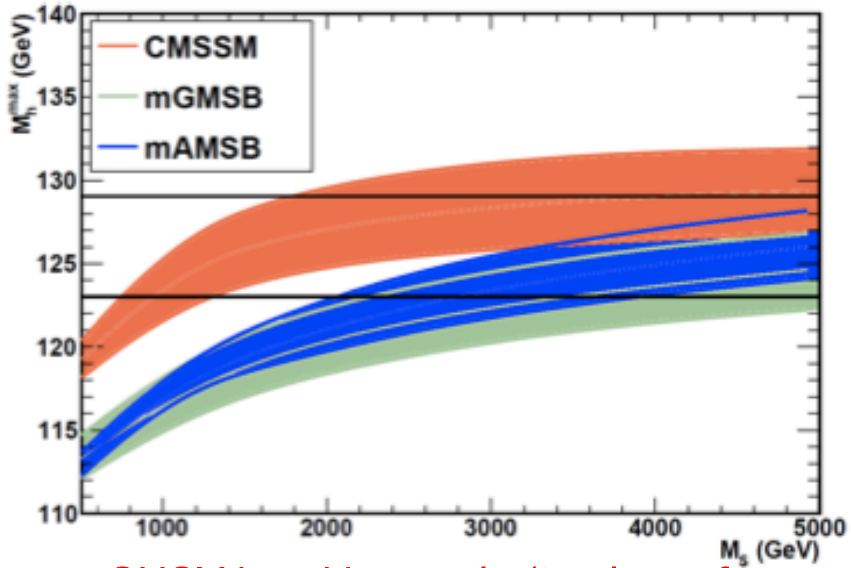
$$t = \log(M_{SUSY}^2 / m_t^2) \qquad \tilde{X}_t = \frac{2X_t^2}{M_{SUSY}^2}\left(1 - \frac{X_t^2}{12 M_{SUSY}^2}\right) \qquad X_t = A_t - \mu/\tan\beta \rightarrow \text{LR stop mixing}$$

$$m_h \leq 130 \text{ GeV}$$ (for sparticles of ~ 1 TeV)

M. Carena

# Not easy to have a heavy higgs in SUSY

There are different SUSY models




arXiv:1211.2794

SUSY breaking scale (too large for naturalness)

**Figure 3:** Maximal Higgs mass in mSUGRA, mAMSB and mGMSB, as a function of $M_S$ for the top quark mass varied in the range $m_t = 170 - 176$ GeV.

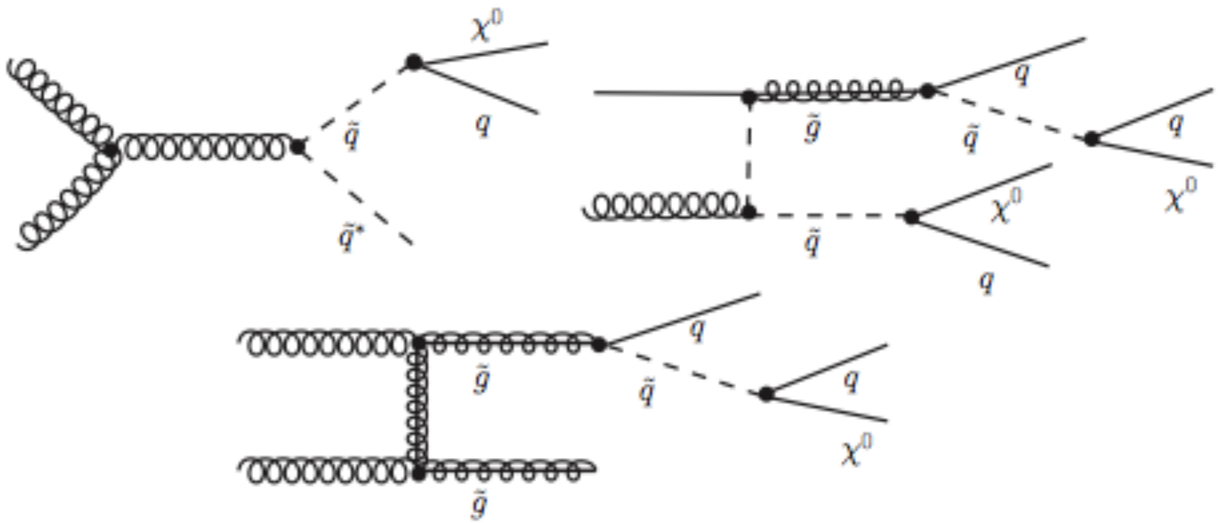
SUSY is becoming unnatural!

# SUSY beeing looked for since 1985


(aka SUSY)

# Desperately seeking SUSY

Smoking gun at the LHC: production of new colored particles squarks and gluinos

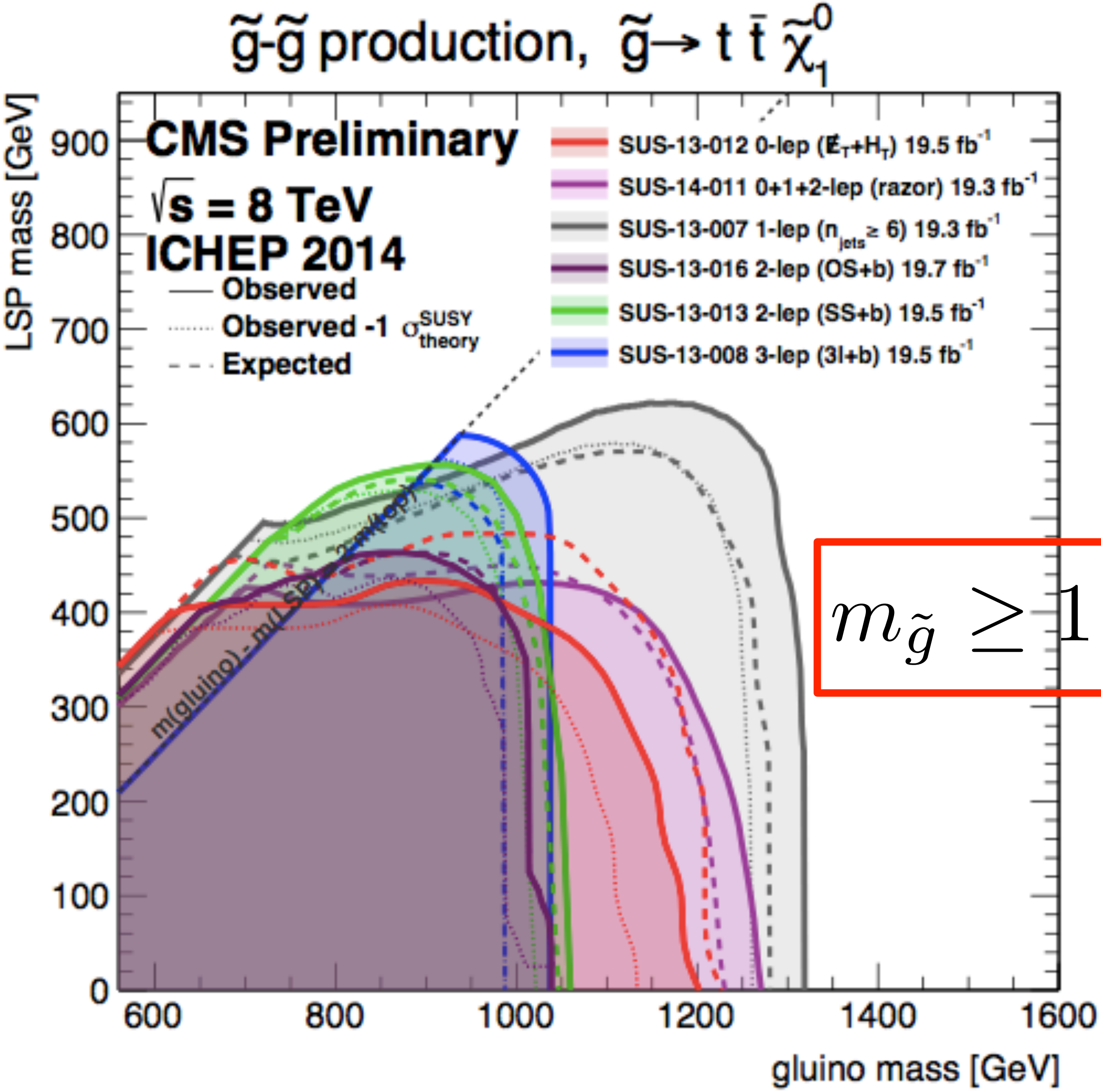



| Process | LHC8 | LHC 14 |
|---|---|---|
| Total | .1b | .1 b |
| $b\bar{b}$ ($p_T > 30$ GeV) | .3 $\mu$b | 1 $\mu$b |
| $t\bar{t}$ | 200 pb | 800 pb |
| $gg \to h$ | 15 pb | 50 pb |
| gluino ($m_{\tilde{g}} = 500$ GeV) | 4 pb | 30 pb |
| gluino ($m_{\tilde{g}} = 750$ GeV) | 200 fb | 3 pb |
| gluino ($m_{\tilde{g}} = 1$ TeV) | 20 fb | 400 fb |

FIG. 4: Production of colored superpartners. Clockwise from upper-left are representative diagrams for squark pair production, squark-gluino associated production and gluino pair production. Their decays are shown to quarks and the lightest supersymmetric particle, here assumed to be the neutralino. The result is a final state with jets and missing energy.

arXiv:1303.1142

# Desperately seeking SUSY




$m_{\tilde{g}} \geq 1.3$ TeV

# Split SUSY

Light SUSYparticles are higgsinos and gauginos. All other states (sfermions, A, H±) are heavy (scale $\tilde{m}$). Give up on hierarchy.

Giudice and Romanino (2004)

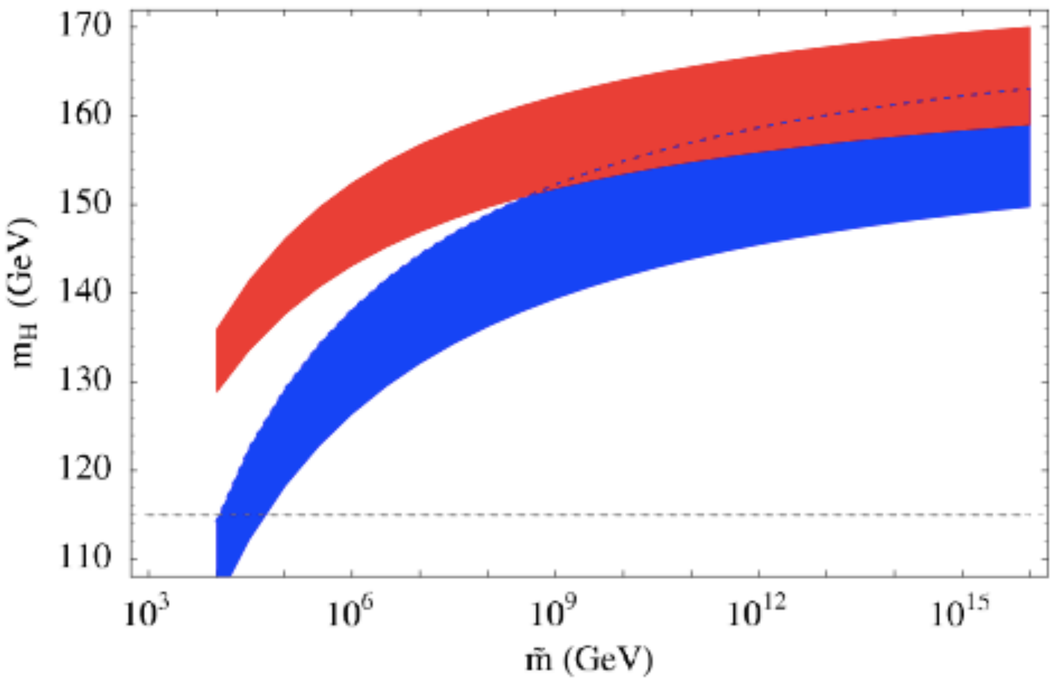



Figure 10: The value of the Higgs mass as a function of $\tilde{m}$. The bands include 1-$\sigma$ errors on $m_t$ and $\alpha_s(M_Z)$. The upper band corresponds to $\tan\beta = 50$ and the lower one to $\tan\beta = 1.5$.

# The ultimate SUSY model

arXiv.org > hep-th > arXiv:hep-th/0503249

Search or Article

**High Energy Physics – Theory**

## Supersplit Supersymmetry

P.J. Fox, D.E. Kaplan, E. Katz, E. Poppitz, V. Sanz, M. Schmaltz, M.D. Schwartz, N. Weiner

*(Submitted on 31 Mar 2005 (v1), last revised 1 Apr 2005 (this version, v2))*

The possible existence of an exponentially large number of vacua in string theory behooves one to consider possibilities beyond our traditional notions of naturalness. Such an approach to electroweak physics was recently used in "Split Supersymmetry", a model which shares some successes and cures some ills of traditional weak-scale supersymmetry by raising the masses of scalar superpartners significantly above a TeV. Here we suggest an extension – we raise, in addition to the scalars, the gaugino and higgsino masses to much higher scales. In addition to maintaining many of the successes of Split Supersymmetry – electroweak precision, flavor-changing neutral currents and CP violation, dimension-4 and 5 proton decay – the model also allows for natural Planck-scale supersymmetry breaking, solves the gluino-decay problem, and resolves the coincidence problem with respect to gaugino and Higgs masses. The lack of unification of couplings suggests a natural solution to possible problems from dimension-6 proton decay. While this model has no weak-scale dark matter candidate, a Peccei-Quinn axion or small black holes can be consistently incorporated in this framework.

Comments: 3 pages, 1 figure

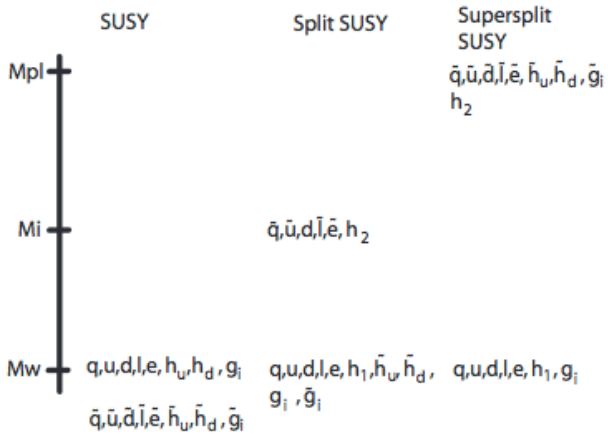



FIG. 1: Mass scales in the MSSM, Split SUSY and Supersplit SUSY.

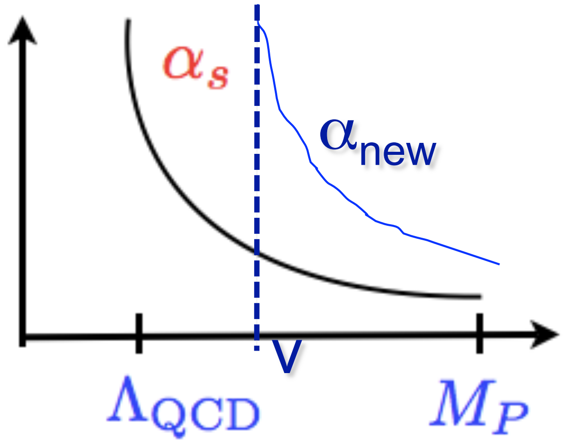
SUSY is a theory that obeys decoupling!

# Composite models

Inspired by QCD: electroweak symmetry is broken by new strong interactions.

QCD can have huge hierarchy between Planck scale and QCD scale naturally: log running of coupling constant.

Could the same mechanism happen in EW?



Lightest mesons are pseudo Nambu-Goldstone bosons: mass protected by symmetry.

Massless QCD with 2 flavors: chiral symmetry is broken by quark condensate: $\langle \bar{q} q \rangle = f_\pi^3$

$$SU(2)_L \times SU(2)_R \to SU(2)_V$$

3 pions are generated (3 broken generators).

Simplest technicolor model: scaled-up version of QCD by $v/f_\pi$

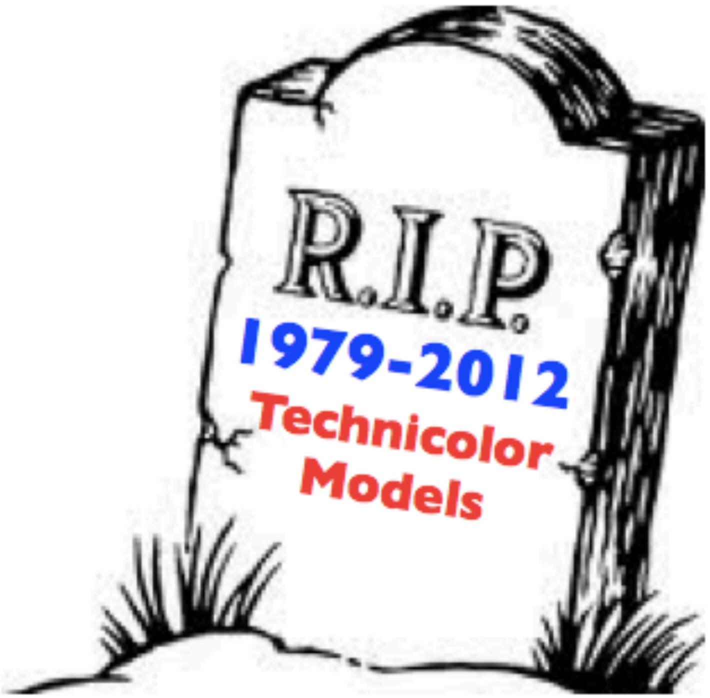
New techniquarks with a new interaction that induces chiral symmetry breaking $\langle \bar{q}_T q_T \rangle = v^3$

$$SU(2)_L \times SU(2)_R \to SU(2)_V$$

3 technipions are generated and are eaten by EW gauge bosons

Higgsless model

# Specially for fans of **Higgsless models:**




Pomarol – ICHEP 2012

# Composite Higgs models

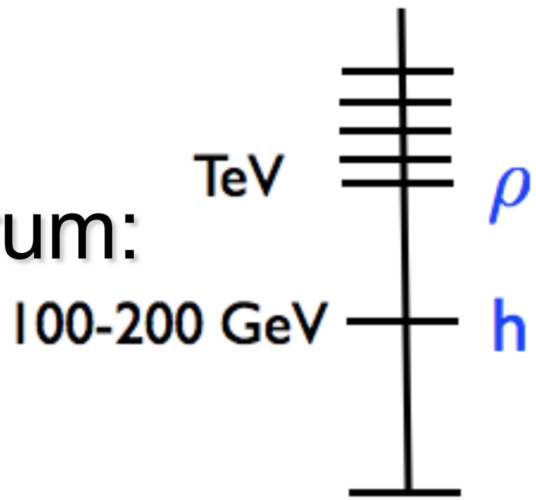
Larger symmetry breaking pattern: e.g.

$SO(N):\ \frac{N(N-1)}{2}$ generators

$$SO(5) \to SO(4)$$

4 technipions with the quantum numbers of a Higgs doublet are generated. Three are eaten by EW gauge bosons -> physical Higgs is a pNGB.

Spectrum:




Resonances (techni-rho) are a smoking gun for this model

Higgs potential generated radiatively

 as a pseudo- boson

Kind of a historical irony:

BROKEN SYMMETRIES, MASSLESS PARTICLES AND GAUGE FIELDS

P. W. HIGGS
*Tait Institute of Mathematical Physics, University of Edinburgh, Scotland*

Received 27 July 1964

$[k^2 n_\mu - k_\mu (nk)]\rho(k^2, nk)$. We have thus exorcised both Goldstone's zero-mass bosons and the "spurion" state (at $k_\mu = 0$) proposed by Klein and Lee.

A TWO-STEP SYMMETRY BREAKING:

$$SO(5) \xrightarrow{f} SO(4) \xrightarrow{v} SO(3)$$

composite doublet H — EWSB

Free parameter

$$\xi = \left(\frac{v}{f}\right)^2$$

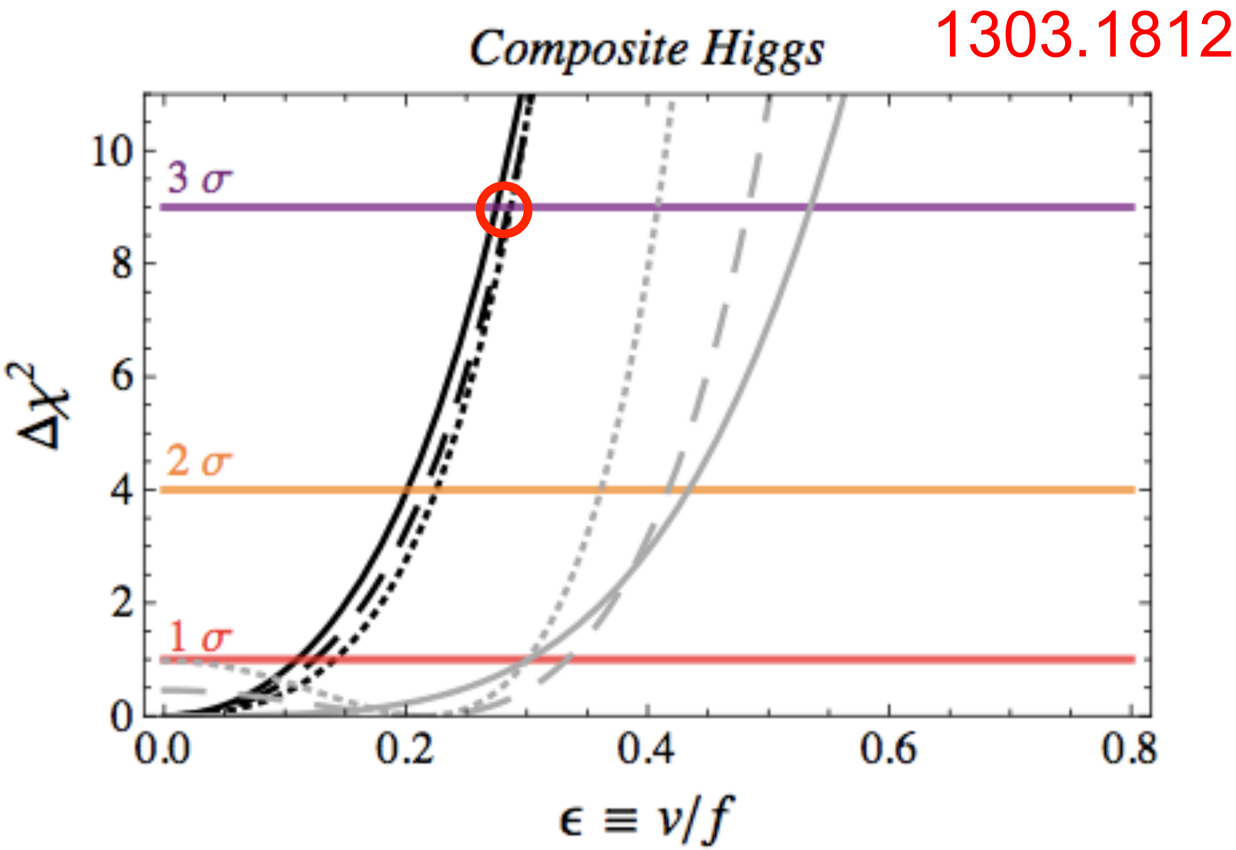
$$m_\rho \sim 4\pi f = 4\pi v/\sqrt{\xi}$$

decoupling limit:

$$\xi \to 0$$

$$v = \text{fixed}$$

# Fit with Higgs + EW data




$\epsilon = v/f$ in sample composite Higgs models with (black) and without (gray) including EW precision data. The different lines correspond to the $SO(5)/SO(4)$ coset and fermionic representations with $m = 0$ and $n = 0$ (solid), $n = 1$ (dashed) and $n = 2$ (dot-dashed)."

# What is the Composite Higgs made of?

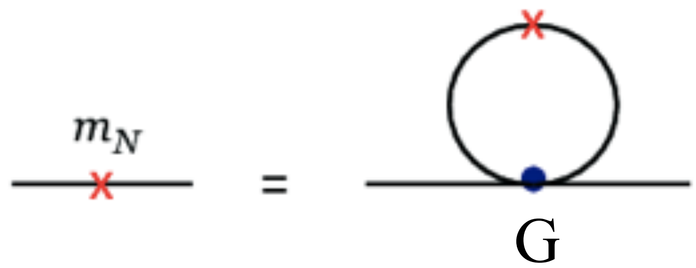
Gersdorff, Pontón and RR (1502.07340)

Chiral symmetry breaking can be triggered by a 4-fermion interaction (Nambu&Jona-Lasinio) – New fundamental interaction at scale $\Lambda$

$$\mathcal{L} = \mathcal{L}_{kin} + G(\bar{\psi}\psi)(\bar{\psi}\psi)$$

Cut-off scale

Gap equation: critical value for G

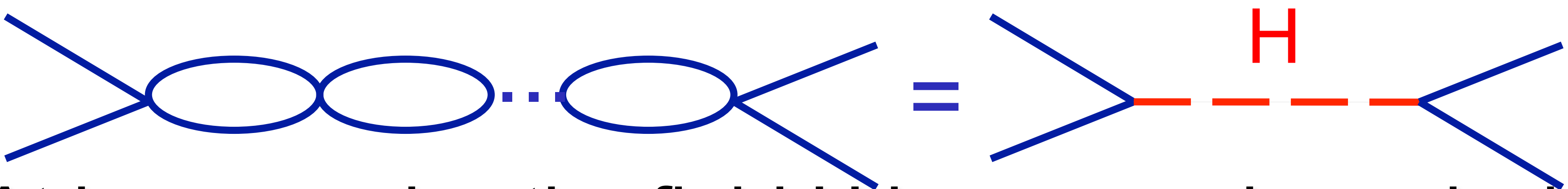


# What is the Composite Higgs made of?

One can introduce an auxiliary scalar field H:

$$\mathcal{L} = \mathcal{L}_{kin} + g(\bar{\psi}\psi H + h.c.) - m^2 H^\dagger H$$

with G = $(g/m)^2$




At low energies the field H becomes dynamical

(develops a kinetic term and a quartic term due to fermion loops).
Wave function renormalization and quartic coupling vanish as
$\mu \to \Lambda$ (compositeness boundary conditions).

# What is the Composite Higgs made of?

Pioneer work of Bardeen, Hill and Linder (1990): Higgs as a composite state of top quarks based on global breaking $SU(2)_L \times SU(2)_R \to SU(2)_V$

All GB's eaten by W,Z - Higgs is similar to the elusive $\sigma$ meson of QCD.

It does not work: too heavy top and Higgs.

# What is the Composite Higgs made of?

We study a NJL-like model which has the global symmetry breaking pattern of the minimal Composite Higgs model $SO(5) \to SO(4)$

Minimal field content: left-handed fermions in a 5 of SO(5) and one right-handed fermion singlet.

# What is the Composite Higgs made of?

Global symmetry breaking is obtained for $\langle \Phi \rangle = \hat{f}$

$$SO(5) \to SO(4)$$

4 GB's generated forming a doublet of $SU(2)_L$ and are identified with the SM Higgs doublet.

There is still a heavy "radial mode" in the spectrum

# What is the Composite Higgs made of?

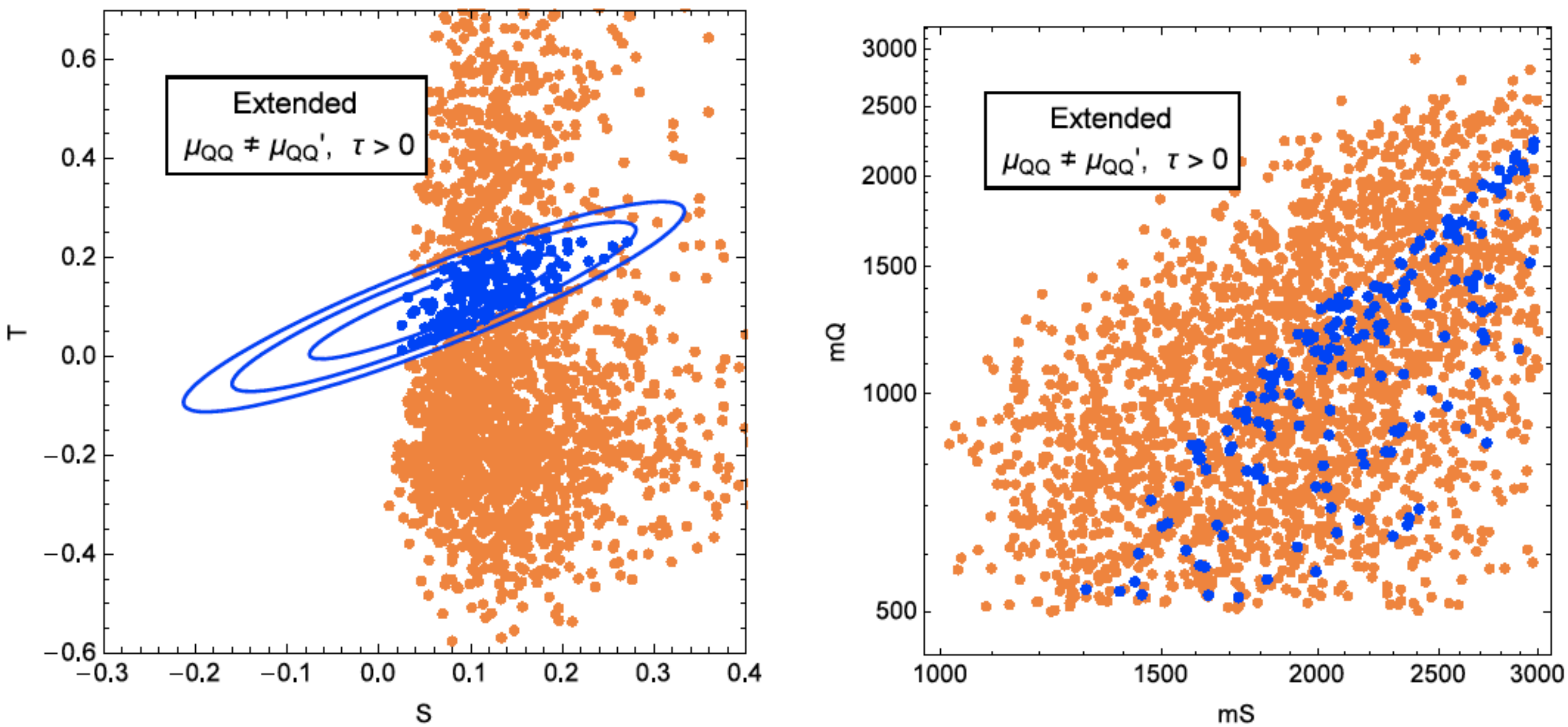
GB's are only derivatively coupled (shift symmetry) – no potential!

Global symmetry is broken by SM interactions and fermion and scalar mass terms.

Potential for pNGBs generated at loop-level.

# What is the Composite Higgs made of?

Scan over parameters: $v_{SM}$, $m_h$ and $m_t$ enforced



# Extra dimensions

Old idea since 1920's: Kaluza and Klein

Universe may have extra, compact dimensions
(motivated by string theory)

# Basic idea

Consider a free scalar field in 5 dimensions:

$$\phi(\vec{x}, y, t)$$

Action:

$$S = \int dt\, d^3x\, dy \sqrt{-g}\, \frac{1}{2}\left(\partial_M \phi\, \partial^M \phi\right)$$

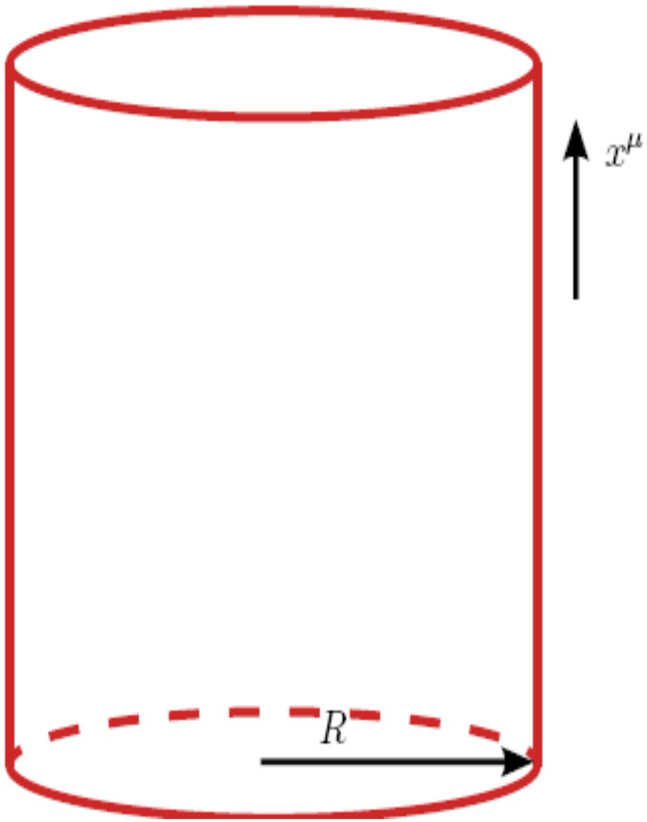
Flat metric: $g_{MN} = (-1,1,1,1,1)$

# Equation of motion for free massless scalar field:

$$\Box_{\mathrm{M}}\phi\left(\vec{x}, y, t\right) = 0 \Rightarrow$$

$$\Box\phi + \frac{\partial^2}{\partial y^2}\phi = 0$$

# Compactify extra dimension in a circle of radius R:




$$\phi(\vec{x}, y + 2\pi R, t) = \phi(\vec{x}, y, t)$$

Expand in a complete basis:

$$\phi(\vec{x}, y, t) = \sum_{n=0}^{\infty} \varphi_n(\vec{x}, t) e^{i\frac{n}{R}y}$$

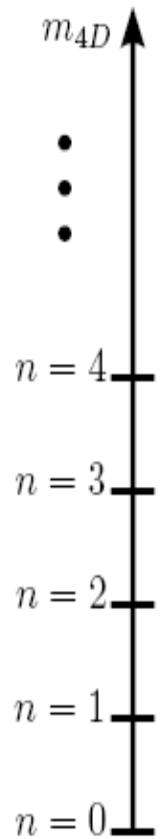
Equation of motion becomes:

$$\Box \varphi_n(\vec{x}, t) - \frac{n^2}{R^2} \varphi_n(\vec{x}, t) = 0$$

5d free massless scalar field = n free scalar fields in 4d of mass

$$m_n^2 = \frac{n^2}{R^2}$$

Kaluza-Klein (KK) tower




This is a general feature:
it happens in models with scalars, fermions and gauge fields!

Zero modes are identified with SM fields.

# Different models with extra dimensions

- Large extra dimensions (ADD)

only gravity propagates in the bulk

- Universal extra dimensions (UED)

All fields can propagate in flat extra dimensions

- Warped extra dimensions (RS)

can address issues of hierarchy in fermion masses with profiles of particles in the extra dimension

# New ideas on EWSB from extra dimensions:

Gauge-Higgs unification: Higgs can be identified with 5th component of a gauge field
(mass protected by 5d gauge invariance)

Higgsless models: EW symmetry broken by boundary conditions in 5th dim
(WW scattering unitarized by exchange of KK tower)

Top quark condensate models: EW symmetry broken by condensation of top quark due to exchange of KK gluons
(Dobrescu et al.)

# Signals @ LHC

## KK recurrences of SM particles
## All in the few TeV range (precision measurements)

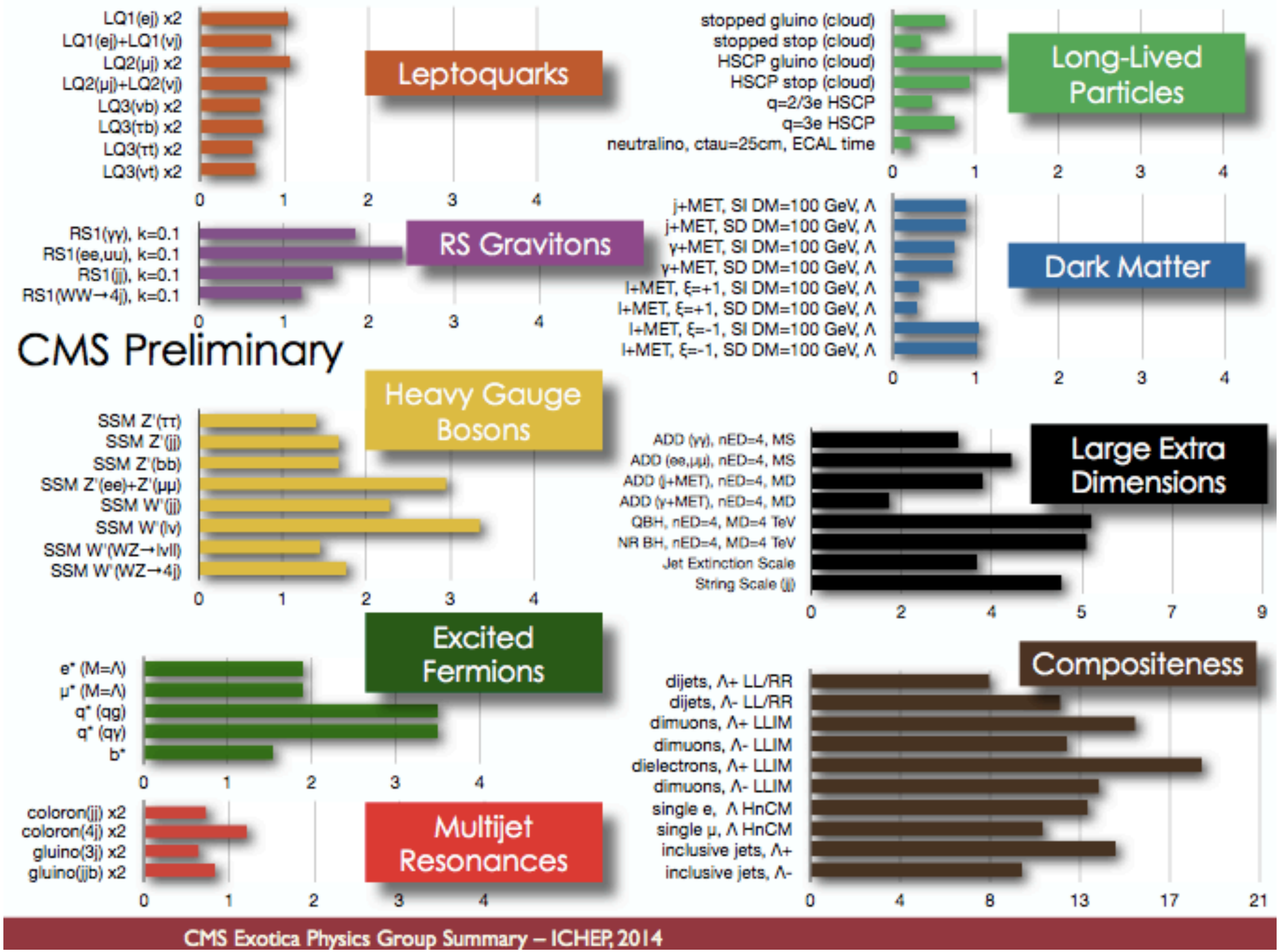
- KK gluons, KK W's and Z's

- KK fermions

- Light "custodians"

EW precision tests -> needs custodial symmetry to keep T small

# CMS results on searches for new particles



# Conclusion

At a Crossroad

“What has the LHC done to theory?”
Dimopoulos 2012

**LHC has shown that SM is not natural.**

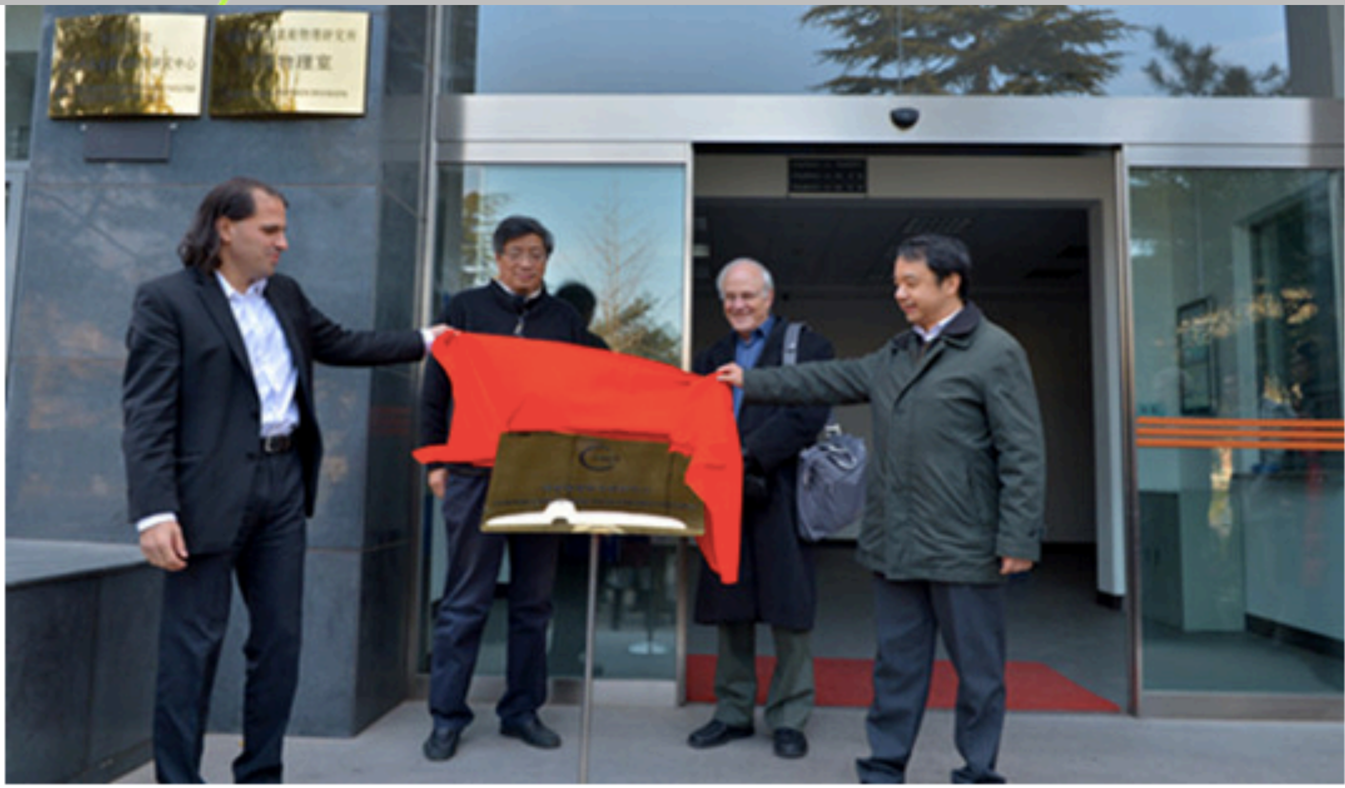

Wait for LHC14

OR

# 100 TeV Collider in China?

**Center for Future High Energy Physics**

高能物理前沿研究中心



The Center for Future High Energy Physics (CFHEP) was inaugurated in Beijing on December 17, 2013. The director of CFHEP, Prof. Nima Arkani-Hamed and the head of IHEP, Prof. Wang Yifang unveiled the foudation of the center.

**Director:** Nima Arkani-Hamed (IAS, USA)
**Deputy Director:** Cai-Dian Lu (IHEP, China)