The Standard Model and beyond (6)
More SM extensions

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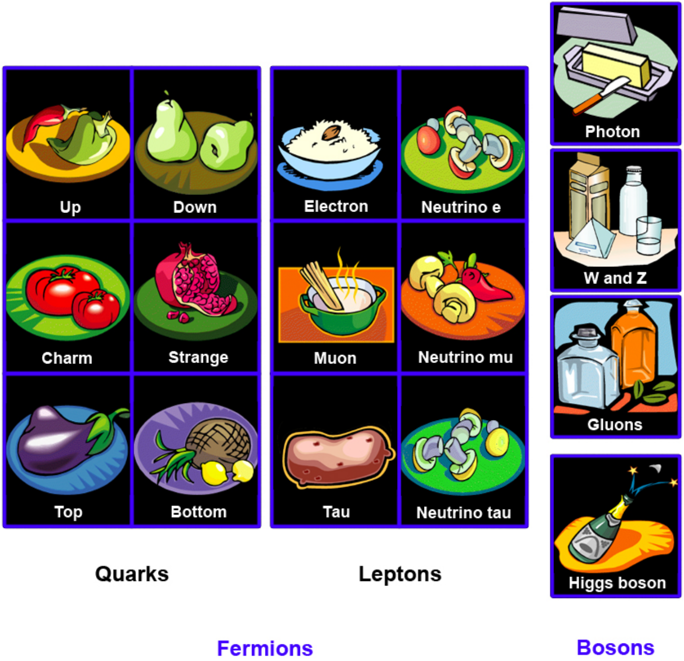

Up
Down
Electron
Neutrino e
Charm
Strange
Muon
Neutrino mu
Top
Bottom
Tau
Neutrino tau
Photon
W and Z
Gluons
Higgs boson
Quarks
Leptons
Fermions
Bosons

Fifth lecture

Limits of the SM

- lots of arbitrary params., with unexplained hierarchies (masses)
- why this gauge structure, partially unified, with these charges ?
- fine tuning related to presence of fundamental scalar field (Higgs)
- cosmology: matter/antimatter asymmetry, dark matter ?
- hints of violation of lepton universality ?

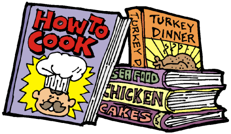
Supersymmetry

- additional symmetry relating bosons and fermions
- doubling of the spectrum of observed particles
- alleviate problems of fine tuning for the Higgs
- difficulty to break susy without generating large contributions to low-energy processes
- searched (and not found yet) at LHC through direct production

Other directions to extend the SM ?

Many different directions

- Fermion content (more “matter”)
- Gauge boson content (more “interactions”)
- Scalar sector (different symmetry breakings)
- Additional symmetries
- Additional dimensions



Main constraints

- Reproduce data within experimental and theoretical uncertainties
  $\Longrightarrow$Be close to SM up to currently tested energies
- Most new phenomena should occur only in untested processes
  $\Longrightarrow$Modify structure of the theory to push NP in these corners
- Built as decoupling theories: recover SM when $\Lambda_{NP} \to \infty$
  $\Longrightarrow$SM seen as effective theory, with NP corrections $O(\Lambda_{EW}/\Lambda_{NP})$

Grand unified theories

GUT: basic idea

Unifying phenomena has been a driving concept

- electricity and magentism in electrodynamics
- weak and electromagnetism unified in $SU_L(2) \times U_Y(1)$
- gauge couplings have similar values around 10^{16} GeV

why not unify all three SM interactions in a single gauge group ?

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For these Grand Unified Theories (GUTs), one needs

- a gauge group large enough to contain all SM gauge bosons
- a way of breaking down this large group down to $SU_C(3) \times SU_L(2) \times U_Y(1)$ somewhere above the EW scale

Several candidates: $SU(5)$, $SO(10)$, E_6
$\Longrightarrow$ Focus on the first one !

GUT: gauge bosons in $SU(5)$

24 generators (5×5 matrices): $W_\mu = W_\mu^A T^A$ with $A = 1 \dots 24$

$$W_\mu = \left(\begin{array}{ccc|cc} & & & X_\mu^1 & Y_\mu^1 \\ & G_\mu^a \frac{\lambda^a}{2} - \frac{1}{\sqrt{15}} B_\mu \mathbf{1}_3 & & X_\mu^2 & Y_\mu^2 \\ & & & X_\mu^3 & Y_\mu^3 \\ \hline X_\mu^{1*} & X_\mu^{2*} & X_\mu^{3*} & \frac{1}{2} W_\mu^3 + \sqrt{\frac{3}{20}} B_\mu & W_\mu^+ \\ Y_\mu^{1*} & Y_\mu^{2*} & Y_\mu^{3*} & W_\mu^- & -\frac{1}{2} W_\mu^3 + \sqrt{\frac{3}{20}} B_\mu \end{array}\right)$$

- 8 $SU_C(3)$ gluons G_μ^a
- 3 $SU_L(2)$ weak bosons $W_\mu^{\pm,3}$
- 1 $U_Y(1)$ weak bosons B_μ
- 12 new bosons X, Y carrying both colour and weak isospin

  (vector) leptoquarks: can decay into a lepton and a quark

GUT: fermions in $SU(5)$

All fermions in two representations

- $\bar{5}$: conjugate of fundamental representation 5
- 10: antisymmetric part of 5×5

$$\psi_{\bar{5}} \sim \begin{pmatrix} d_1^c \\ d_2^c \\ d_3^c \\ e^- \\ -\nu_e \end{pmatrix}_L \qquad \psi_{10} \sim \begin{pmatrix} 0 & u_3^c & -u_2^c & -u^1 & -d^1 \\ -u_3^c & 0 & u_1^c & -u^2 & -d^2 \\ u_2^c & -u_1^c & 0 & -u^3 & -d^3 \\ u_1 & u_2 & u_3 & 0 & -e^+ \\ d_1 & d_2 & d_3 & e^+ & 0 \end{pmatrix}_L$$

- $u_{a=1,2,3}, d_{a=1,2,3}$ for the colour of the quarks
- Right-handed part from $\psi_R^c = C\overline{\psi_L}^T$ (with C conjugation matrix)

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$\Longrightarrow$Baryon number $B = 1/3(n_q - n_{\bar{q}})$ and lepton number $L = n_\ell - n_{\bar{\ell}}$, conserved in SM, are not good quantum numbers here !

GUT: Symmetry breaking in $SU(5)$

- At $M_{GUT} \simeq 10^{15}$ GeV, breaking $SU(5) \to SU(3) \times SU(2) \times U(1)$ via a Higgs field in (adjoint) representation 24

$$\langle 0|\Phi_{24}|0\rangle = \left(\begin{array}{ccc|cc} V & & & & \\ & V & & & \\ & & V & & \\ \hline & & & -\frac{3V}{2} & \\ & & & & -\frac{3V}{2} \end{array}\right) \qquad M_X^2 = M_Y^2 = \frac{25}{8} g_5^2 V^2$$

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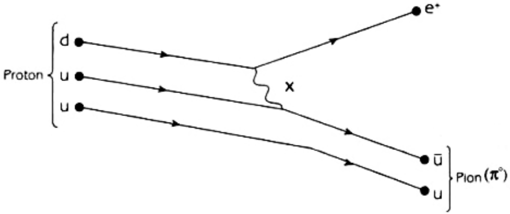
- At ew scale, breaking via Higgs in (fundamental) representation 5

$$H_5 \sim \left(\begin{array}{c} \Phi_1 \\ \Phi_2 \\ \Phi_3 \\ \hline \phi^+ \\ \phi^0 \end{array}\right) \qquad \langle 0|H_5|0\rangle = \left(\begin{array}{c} 0 \\ 0 \\ 0 \\ \hline 0 \\ v/\sqrt{2} \end{array}\right)$$

with Φ_a coloured scalar with $q = -1/3$ and ϕ SM Higgs doublet

GUT: Consequences

Proton decay



Not observed

$\Longrightarrow$Preference for $M_X \geq 10^{15}$ GeV

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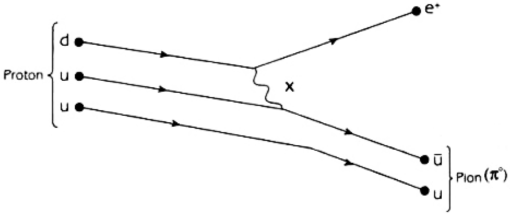

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- gauge couplings $\quad g = \sqrt{\frac{5}{3}} g' = g_s = g_5 \qquad \sin^2 \theta_W = \frac{3}{8}$
- Yukawa couplings $\quad m_d = m_e \qquad m_s = m_\mu \qquad m_b = m_\tau$

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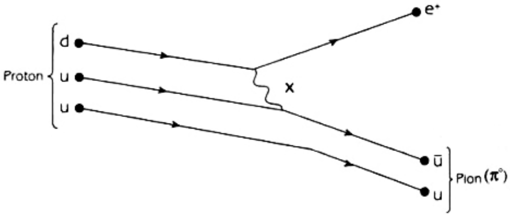

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Running from $M_X \simeq 10^{14}$ GeV down to electroweak scale

- Zeroth order prediction reasonable for m_b/m_τ and $\sin^2\theta_W$
- Other predictions harder to tune
  $\Longrightarrow$ susy, more Higgs, other grand unification groups

Leptoquarks

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- GUT theory: gauge bosons coupling to both quarks and leptons
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  - 1 non-coloured (lepton) and 1 coloured (quark): must be coloured
  - combine weak singlets (right-handed) and/or doublets (left-handed): can yield weak singlet, doublet, triplet

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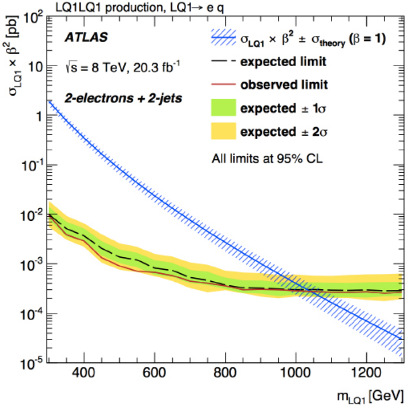
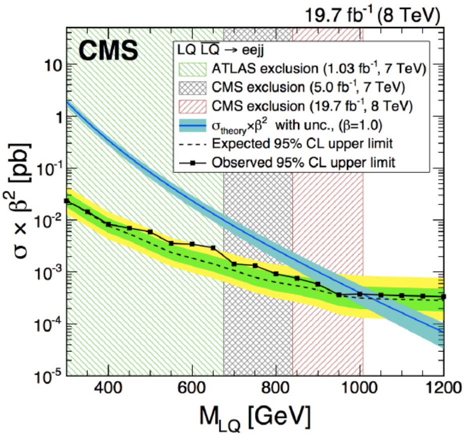
Spin	$SU_C(3)$	$SU_L(2)$	$U_Y(1)$	Symbol
0	$\bar{3}$	3	$1/3$	S_3
0	3	2	$7/6, 1/6$	$R_2, \tilde{R}_2$
0	$\bar{3}$	1	$4/3, 1/3, -2/3$	$\tilde{S}_1, S_1, \bar{S}_1$
1	3	3	$2/3$	U_3
1	$\bar{3}$	2	$5/6, -1/6$	$V_2, \tilde{V}_2$
1	3	1	$5/3, 2/3, -1/3$	$\tilde{U}_1, U_1, \bar{U}_1$

with different couplings to quarks and leptons from different gener.

Leptoquarks: searches

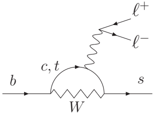




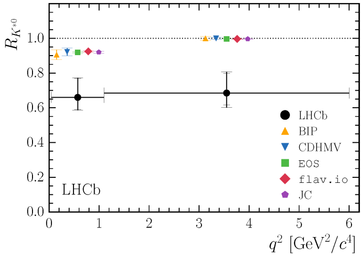
- Currently actively searched at LHC
  limits on LQ prod cross section $\times$ LQ decay rate in given
- Many indirect constraints (proton decay, $\mu \to e\gamma \ldots$)

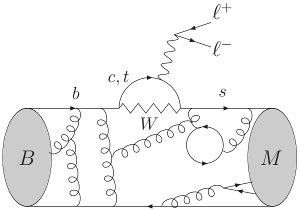
Leptoquarks: violation of lepton universality

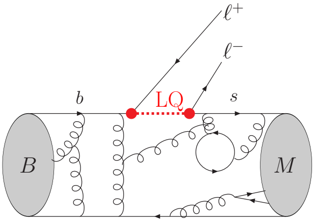
- Hints of violation of lepton universality in *b*-decays
- (Scalar and vector) leptoquarks coupling predominantly to second and third generations of fermions ?



$$R_{K(*)} = \frac{Br(B \to K(*)\mu\mu)}{Br(B \to K(*)ee)}$$







Two-Higgs doublet models

2HDM: basic idea

Scalar sector

- SM: simplest choice with a single scalar doublet ϕ
- Susy: need for 2 different scalar doublets H_u and H_d
- Why not allow more complicated scalar sectors ?

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Impact on electroweak symmetry breaking

- N scalar fields H_i
- weak isospin I_i (singlet, doublet, triplet... under $SU_L(2)$)
- hypercharge Y_i under $U_Y(1)$
- one neutral component with $Q = 0$ which acquires a vacuum expectation value v_i

$$\rho = \frac{M_W^2}{M_Z^2 \cos^2\theta_W} = \frac{1}{2}\frac{\sum_{i=1}^N [4 I_i(I_i+1) - Y_i^2] v_i}{\sum_{i=1}^N Y_i^2 v_i}$$

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$\rho \simeq 1$ (exp, ratio of neutral to charged currents) easily obeyed
if only singlets ($I = 0$, $Y = 0$) or doublets ($I = 1/2$, $Y = \pm 1$)

2HDM: scalar potential and symmetry breaking

Φ_1 and Φ_2 two complex Higgs doublets with $Y = 1$, with a potential

$$V = m_{11}^2\Phi_1^\dagger\Phi_1 + m_{22}^2\Phi_2^\dagger\Phi_2 - m_{12}^2(\Phi_1^\dagger\Phi_2 + \Phi_2^\dagger\Phi_1) + \frac{\lambda_1}{2}(\Phi_1^\dagger\Phi_1)^2$$
$$+\frac{\lambda_2}{2}(\Phi_2^\dagger\Phi_2)^2 + \lambda_3\Phi_1^\dagger\Phi_1\Phi_2^\dagger\Phi_2 + \lambda_4\Phi_1^\dagger\Phi_2\Phi_2^\dagger\Phi_1 + \frac{\lambda_5}{2}[(\Phi_1^\dagger\Phi_2)^2 + (\Phi_2^\dagger\Phi_1)^2]$$

with vaccum exp values and decomposition around this minimum

$$\langle 0|\Phi_a|0\rangle = \begin{pmatrix} 0 \\ \frac{v_i}{\sqrt{2}} \end{pmatrix} \qquad \Phi_a = \begin{pmatrix} \phi_a^+ \\ (v_a + \rho_a^0 + i\eta_a^0)/\sqrt{2} \end{pmatrix}$$

- Three degrees of freedom used to give masses to $W^\pm, Z^0$
- 1 charged scalar particle
- 2 neutral scalar particles (the light one similar to SM Higgs boson)
- 1 neutral pseudoscalar particle (odd under parity)

2HDM: Yukawa couplings

In absence of syms, both Higgs doublets couple to a given type of fermions (up-quarks, down-quarks, charged leptons)

$$\mathcal{L}_Y = y_{ij}^{(1)} \bar{\psi}_{i,L} \Phi_1 \psi_{j,R} + y_{ij}^{(2)} \bar{\psi}_{i,L} \Phi_2 \psi_{j,R}$$

with $i, j = 1, 2, 3$ generation indices, leading to mass matrices

$$M_{ij} = \frac{1}{\sqrt{2}} (y_{ij}^{(1)} v_1 + y_{ij}^{(2)} v_2)$$

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- Thus, in generic 2HDM, Flavour-Changing Neutral Currents scalar-fermion-fermion occur at tree level
- In SM, only one doublet, so diagonalising M is equivalent to diagonalising y for each type of fermion: no FCNC at tree level (only loop level, indeed small experimentally)

2HDM: several models

To avoid these FCNC

- Type I: All quarks couple to one of the Higgs doublets (say Φ_2)
- Type II: $Q = 2/3$ right-handed quarks couple to Φ_2 and $Q = -1/3$ right-handed quarks couple to Φ_1
- Possibility to choose couplings either to Φ_1 and Φ_2 for right-handed charged leptons
- (General) alignment: proportional Yukawa couplings to Φ_1 and Φ_2

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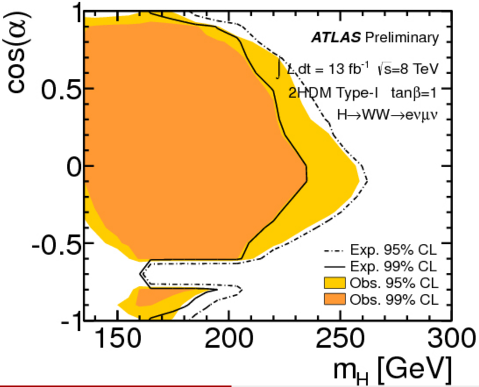
Scalar-fermion-fermion couplings in terms of

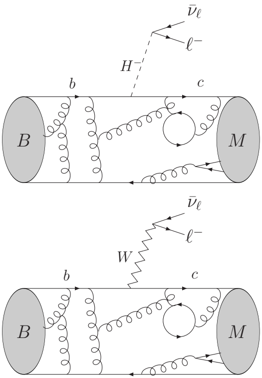
- fermion masses
- vaccum expectation value $v = \sqrt{v_1^2 + v_2^2}$
- β defined as $\cos\beta = v_1/v$ and $\sin\beta = v_2/v$
- α defined as rotation angle between ρ_1^0, ρ_2^0 and physical scalar h, H

$\Longrightarrow$Scalar interactions main probe of 2HDM

2HDM: experimental consequences

- Lightest scalar *h* identified to the observed *H* boson
- Searches for heavier scalar bosons (charged/neutral)
- Deviations in couplings of the observed *H* boson compared to SM
- Charged scalar contributions to low-energy processes
- The heavier the fermions, the stronger the coupling !





Extra-dimensions

Extra dimensions : basic idea

Some theories (like strings) prefer more than 4 dimensions

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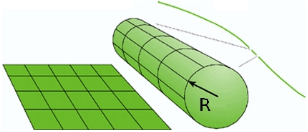
- Free massless scalar in 5D $\phi(x_\mu, y)$

$$\mathcal{L} = \partial_A \phi \partial^A \phi \qquad A = 0 \ldots 4$$

with y curled into a circle of radius R



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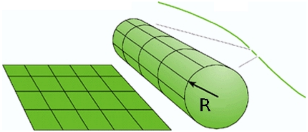

- Project over Fourier modes and integrate over y

$$\phi(x_\mu, y + 2\pi R) = \phi(x_\mu, y) \Longrightarrow \phi(x_\mu, y) = \sum_{n=-\infty}^{+\infty} \phi_n(x_\mu) e^{iny/R}$$

$$\mathcal{L} = (2\pi R) \left[\partial_\mu \phi_0 \partial^\mu \phi_0 + 2 \sum_{n=1}^{+\infty} (\partial_\mu \phi_n \partial^\mu \phi_n - \frac{n^2}{R^2} \phi_n \phi_n) \right]$$

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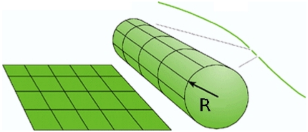

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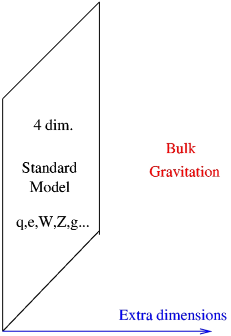
- "Massless" ϕ_0 and tower of Kaluza-Klein excitations of $m_n = n/R$

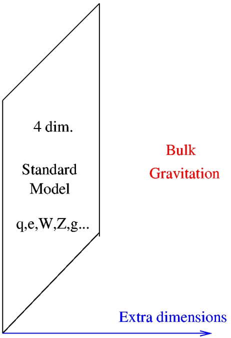
[if $1/R >$ a few TeV, only $\phi_0 \simeq$ SM seen up to now]

Extra dimensions : Gravitation and SM



- Extra dimensions used in "brane world" scenarios
  - SM particles on a brane (4D plane)
  - gravitation in the bulk ($n+4$ D space)

Extra dimensions : Gravitation and SM



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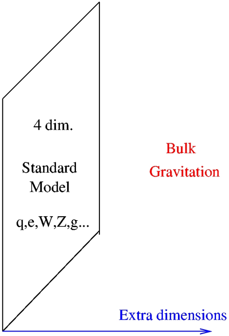

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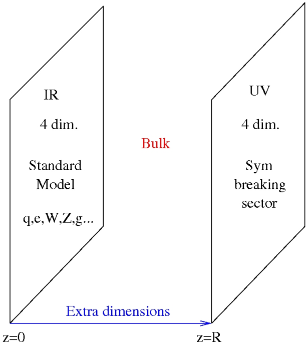
- Solve discrepancy between the Planck scale (gravitation) and the electroweak scale (3 other interactions)

$$\Lambda^2_{Planck} = \Lambda^{2+n}_{fund} (2\pi R)^n$$

$\ldots \Lambda_{fund} \simeq \Lambda_{ew}$ if R is small enough (but why should it be ?)

Extra dimensions : symmetry breaking



Further models introduce two branes

- IR brane at $z = 0$: (MS)SM particles
- UV brane at $z = R$: sector responsible for ew/susy breaking
- Geometry : flat in 4D, exponential suppression for x_5
- Only some mediator propagate in the bulk (gravity, gauge interactions)
- Yields flavour blind ew/susy brkg

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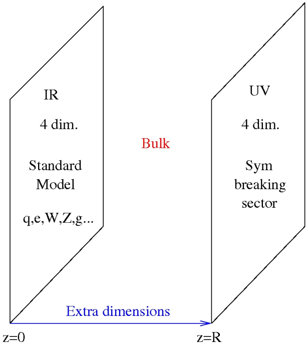

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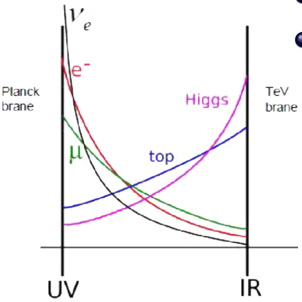
Hierarchy and fine-tuning translated into geometrical question

- why are some extra dimensions so large/small ?
- why is the metric so different in different directions ?
- why some fields are stuck on a brane, and not others ? ...

Extra dimensions : masses



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- with various wave functions
- mass hierarchy from different overlap with Higgs on the IR brane

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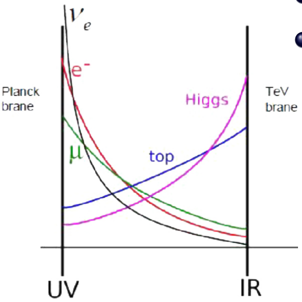

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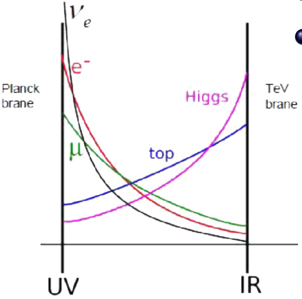

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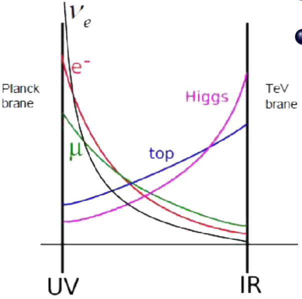

- SM fields extending in the bulk
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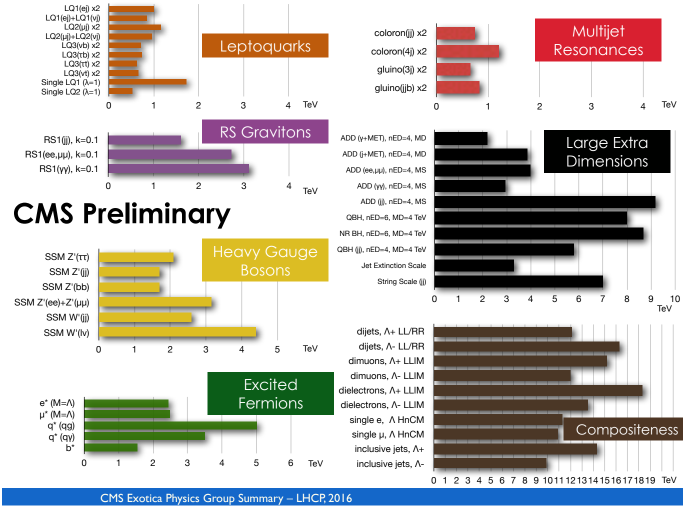
- Extra dim natural in some extensions of the SM (susy, strings)
- Kaluza-Klein excitations should be easy to spot
- No fully satisfying model for phenomenological applications (yet ?)

And much more...

- Additional gauge bosons (Z', W')
- Compositeness
- 4th generation
- Little Higgs
- Left-right symmetry...

Anything at LHC ?

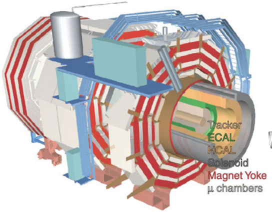


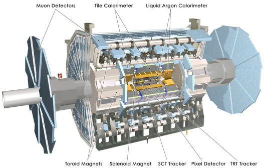
Many searches, peaks rise and drop, but no clear signal (yet ?)

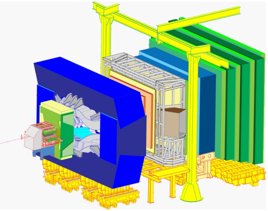
Pushing beyond the SM

Generally, similar problems occur

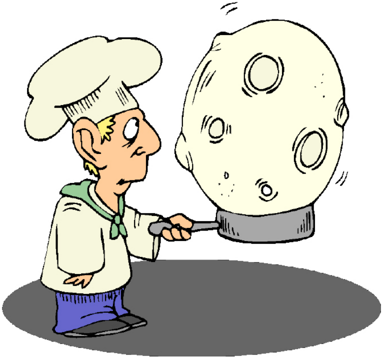
- Hard to reproduce low energy data for quarks and leptons
- Difficulties for some scenarios from direct searches
- Need to break the original (and unobserved) beautiful symmetries, providing many new parameters
- Experiment to drive towards one theory rather than opposite







It is your time to be the cook. . .



Have fun !