Perspectives in Particle Physics

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Neutrino 2026
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THE OHIO STATE UNIVERSITY
DEPARTMENT OF PHYSICS

The Beginning

Ampere

$\nabla \times B$ [redacted] $= e\mu_0 j$

Faraday

$$\nabla \times E + \frac{\partial B}{\partial t} = 0$$

Coulomb / Gauss

$$\nabla \cdot E = e\frac{\rho}{\varepsilon_0}$$

No mag. monopoles

$$\nabla \cdot B = 0$$

The Beginning

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$$\nabla \times B - \frac{1}{c^2}\frac{\partial E}{\partial t} = e\mu_0 j$$

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Maxwell 1864 - 1873

Electromagnetism

The Beginning

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Coulomb / Gauss

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No mag. monopoles

$$\nabla \cdot B = 0$$

Heaviside took Maxwell's 20 equations in 20 different variables and rewrote them in terms of the 4 we now refer to as Maxwell's eqns. 1884

The Beginning

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$$\nabla \times B - \frac{1}{c^2}\frac{\partial E}{\partial t} = e\mu_0 j$$

Faraday

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No mag. monopoles

$$\nabla \cdot B = 0$$

Maxwell 1865 - 1873, Heaviside 1884

First unified field theory

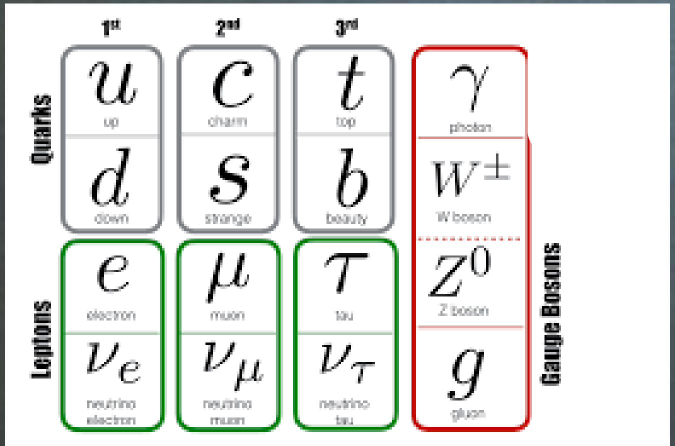
The Beginning

Maxwell 1864 - 1873 Electromagnetism

Verification

Hertz 1887 discovered E&M waves

The Standard Model



Glashow 1961, Weinberg & Salam 1967

Brout, Englert, Higgs, Hagen, Guralnik & Kibble 1964

Gell-Mann & Zweig 1964

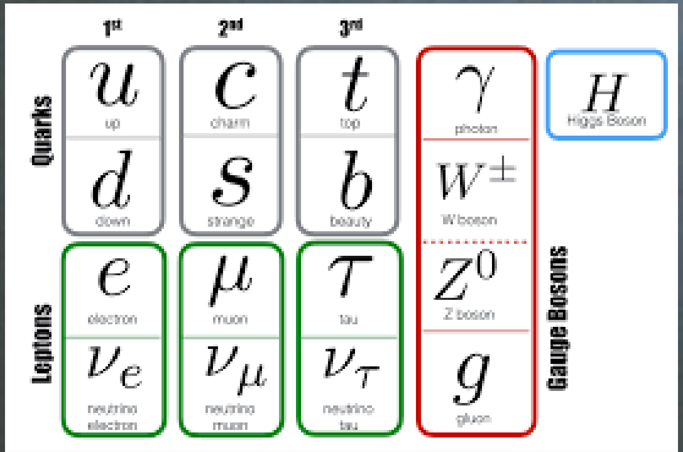
Glashow, Iliopoulos & Maiani 1970

't Hooft & Veltman 1972

Gross, Wilczek & Politzer 1973

Cabibbo 1963 / Kobayashi & Maskawa 1973

The Standard Model



Final Verification

Higgs 2012

Glashow 1961, Weinberg & Salam 1967

Brout, Englert, Higgs, Hagen, Guralnik & Kibble 1964

Gell-Mann & Zweig 1964

Glashow, Iliopoulos & Maiani 1970

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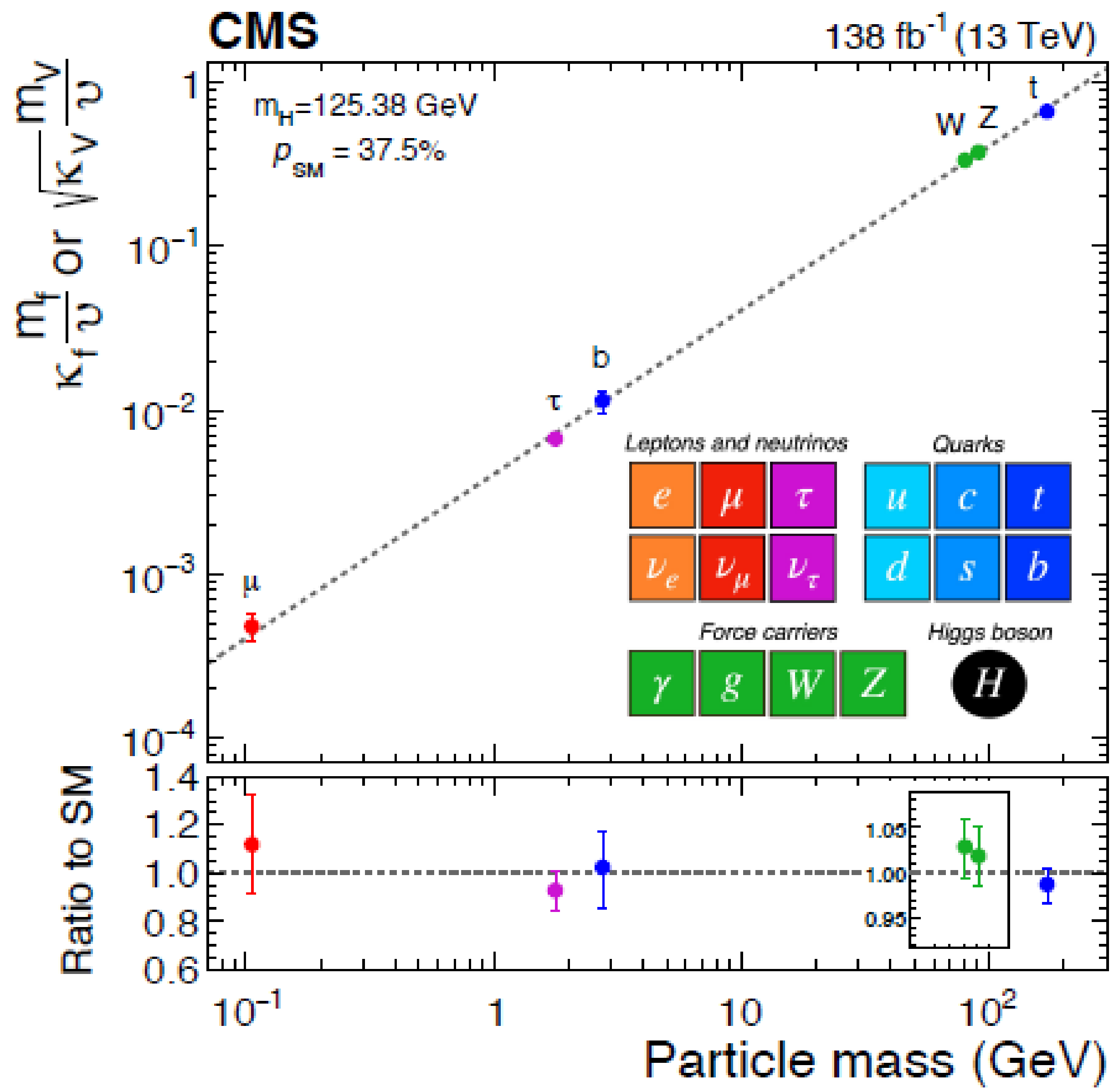
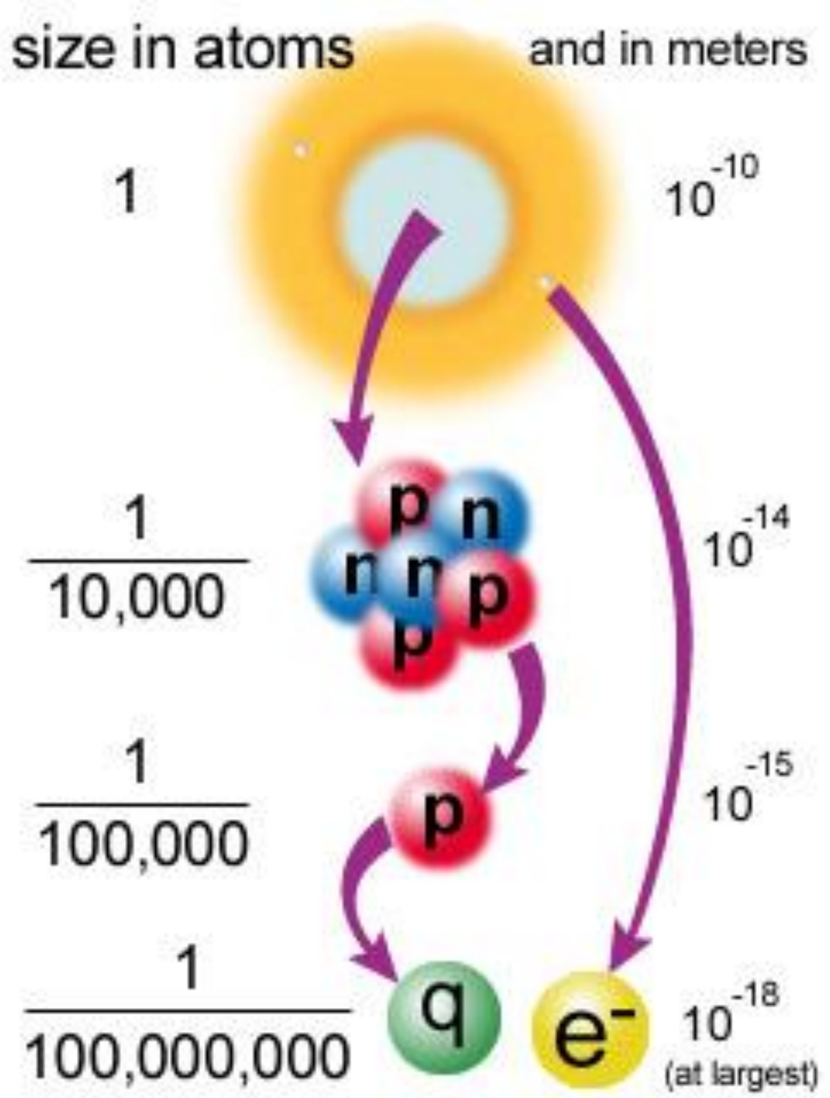


From the CMS webpage

Reduced Higgs coupling modifiers compared to their corresponding prediction from the Standard Model (SM). The error bars represent 68% CL intervals for the measured parameters. In the lower panel, the ratios of the measured coupling modifiers values to their SM predictions are shown.

Standard Model
Physics on scales from 10^{-18} to 10^{25} meters



Puzzle of Charge & Mass

$$Q = T_{3L} + \frac{Y}{2}$$

Charges

Charges	$q = \begin{pmatrix} u \\ d \end{pmatrix}$	$\overline{u}$	$\overline{d}$	$l = \begin{pmatrix} \nu_e \\ e \end{pmatrix}$	$\overline{e}$
Y	$\frac{1}{3}$	$-\frac{4}{3}$	$\frac{2}{3}$	-1	$+2$

Mass

ν_e	**e**	**u**	**d**
$\lesssim 10^{-7}$	1/2	2	5
ν_μ	μ	**c**	**s**
$\lesssim 10^{-7}$	105.6	1,300	120
ν_τ	τ	**t**	**b**
$\lesssim 10^{-7}$	1,777	174,000	4,500

$W^{\pm}$	80,000	Z^0	91,000	Higgs	125,000

The Standard Model

$$\mathcal{L}_{gauge-fermion} = [l^* \, i\bar{\sigma}_\mu D^\mu \, l + \bar{e}^* \, i\bar{\sigma}_\mu D^\mu \, \bar{e} + \bar{\nu}^* \, i\bar{\sigma}_\mu D^\mu \, \bar{\nu}$$
$$+q^* \, i\bar{\sigma}_\mu D^\mu \, q + \bar{u}^* \, i\bar{\sigma}_\mu D^\mu \, \bar{u} + \bar{d}^* \, i\bar{\sigma}_\mu D^\mu \, \bar{d}]$$
$$-\frac{1}{2} Tr(\tilde{\mathcal{G}}_{\mu\nu}\tilde{\mathcal{G}}^{\mu\nu}) - \frac{1}{2} Tr(\tilde{W}_{\mu\nu}\tilde{W}^{\mu\nu}) - \frac{1}{4} B_{\mu\nu}B^{\mu\nu}$$

$$D_\mu = (\partial_\mu + ig_s \mathcal{T}_A \mathcal{G}_{\mu A} + igT_a W_{\mu a} + ig' \, \frac{Y}{2} B_\mu)$$

$$Dirac \;\; fermion \;\; \Psi_e = \begin{pmatrix} e \\ i\sigma_2 \bar{e}^* \end{pmatrix}$$

The Standard Model

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$$-\mathscr{L}_{Yukawa} = \overline{e}_i Y_e^{ij} \ell_j H + \overline{d}_i Y_d^{ij} q_j H + \overline{u}_i Y_u^{ij} q_j H$$
$$+ \overline{\nu}_i Y_\nu^{ij} \ell_j H \qquad + h.c.$$

The Standard Model

$$\mathscr{L}_{gauge-fermion} = [l^* \, i\bar{\sigma}_\mu D^\mu \, l + \bar{e}^* \, i\bar{\sigma}_\mu D^\mu \, \bar{e} + \bar{\nu}^* \, i\bar{\sigma}_\mu D^\mu \, \bar{\nu}$$
$$+ q^* \, i\bar{\sigma}_\mu D^\mu \, q + \bar{u}^* \, i\bar{\sigma}_\mu D^\mu \, \bar{u} + \bar{d}^* \, i\bar{\sigma}_\mu D^\mu \, \bar{d}]$$
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$$+ \overline{\nu}_i Y_\nu^{ij} \ell_j H - \frac{1}{2} M_{ij} \bar{\nu}_i \bar{\nu}_j + h.c.$$

$$\mathscr{L}_{Higgs} = (D^\mu H_u)^* (D_\mu H_u) + (D^\mu H_d)^* (D_\mu H_d) - V(H_u, H_d)$$

SM + neutrino masses + dark matter

1. Higgs coupling

$$\bar{e}_i Y_e^{ij} \ell_j H \rightarrow Y_e^{ij} \left(\frac{v}{\sqrt{2}} + h \right) \bar{e}_i e_j = m_e^{ij} \left(1 + \frac{\sqrt{2}\, h}{v} \right) \bar{e}_i e_j$$

diagonal in mass basis !! GIM suppressed FCNC

2. Effective operators $\dfrac{\left(Y_\nu \ell H \right)^2}{M}$ **See-Saw**

$M \sim 10^{10-14}$ GeV or M=0, $Y_\nu < 10^{-7}\, Y_e \approx 3 \times 10^{-13}$

3. Dark Matter & Dark Energy ??

m_u, m_d, m_e, m_ν

3×3 complex mass matrices $\Rightarrow$ 4×18 arbitrary para's

$$m_u^D = U_u^\dagger m_u U_q \ , \ m_d^D = U_d^\dagger m_d U_d \quad \Rightarrow \ V_{CKM} = U_q^\dagger U_d$$

$$m_e^D = U_e^\dagger m_e U_\ell \ , \qquad m_\nu = U_\ell^T m_\nu^T M^{-1} m_\nu U_\ell$$

neutrino flavor basis

$$\tilde{m}_\nu^D = U^T \tilde{m}_\nu U \equiv \begin{pmatrix} m_1 & 0 & 0 \\ 0 & m_2 & 0 \\ 0 & 0 & m_3 \end{pmatrix} \quad U \equiv U_{PMNS}$$

$$V_{CKM} \equiv U_q^\dagger \, U_d$$

$$V_{CKM} \sim \begin{pmatrix} 1-\frac{\lambda^2}{2} & \lambda & A\,\lambda^3\,(\rho - i\eta) \\ -\lambda & 1-\frac{\lambda^2}{2} & A\,\lambda^2 \\ A\,\lambda^3\,(1-\rho-i\eta) & -A\,\lambda^2 & 1 \end{pmatrix}$$

$$\lambda \sim 0.22, \;\; A \sim 0.8, \sqrt{\rho^2+\eta^2} \sim 0.4$$

$$U_{PMNS} = \begin{pmatrix} c_{12}\,c_{13} & s_{12}\,c_{13} & s_{13}\,e^{-i\delta} \\ -s_{12}\,c_{23} - c_{12}\,s_{13}\,s_{23}\,e^{i\delta} & c_{12}\,c_{23} - s_{12}\,s_{13}\,s_{23}\,e^{i\delta} & c_{13}\,s_{23} \\ s_{12}\,s_{23} - c_{12}\,s_{13}\,c_{23}\,e^{i\delta} & -c_{12}\,s_{23} - s_{12}\,s_{13}\,c_{23}\,e^{i\delta} & c_{13}\,c_{23} \end{pmatrix}$$

$$\sin^2(\theta_{12}) \sim 0.3, \;\; \sin^2(\theta_{23}) \sim 0.5, \;\; \sin^2(\theta_{13}) \sim 0.024, \;\; \delta \sim -90^\circ$$

$$\Delta m_{21}^2 \sim 7.4\times 10^{-5}\,\text{eV}^2, \;\; \left|\Delta m_{31}^2\right| \sim 2.5\times 10^{-3}\,\text{eV}^2$$

Fermion masses are hierarchical

$$m_f \sim \begin{pmatrix} \lambda^4 & \lambda^3 & \lambda^2 \\ \lambda^3 & \lambda^2 & \lambda \\ \lambda^2 & \lambda & 1 \end{pmatrix} \frac{\mathrm{v}}{\sqrt{2}}$$

Suggestive of family symmetry breaking
a la Froggatt-Nielsen

Quark & Lepton masses and mixing

Hierarchical $\lambda\, q_3\, \overline{u_3}\, H_u$ $\lambda \sim \mathrm{O}(1)$

$$q_i\, \overline{u_j}\, H_u \left(\frac{\mathrm{S}}{\mathrm{M_P}}\right)^{n(i,j)}$$ Froggatt-Nielsen

Flavor symmetry breaking

$U(1)$ or non-Abelian SU(2), SU(3)

$$\mathrm{S}_3 \approx D_3,\ D_4,\ A_4,\ \Delta(27),\ \Delta(54)$$

Modular invariance SL(2,Z) Feruglio, 1706.08749 [hep-ph]

Eclectic Flavor symmetry (Nilles, Ramos-Sanchez Vaudrevange)

Combining standard flavor symmetries with Discrete modular groups

The Standard Model is incomplete

Neutrinos have mass and Dark Matter exists

Dark Energy is a difficult problem

3 families ? And hierarchical mass matrices ?

Higgs discovered with mass ~ 125 GeV

But a fundamental scalar's mass is unprotected from radiative corrections proportional to some new large mass scale.

So why is it so light ??

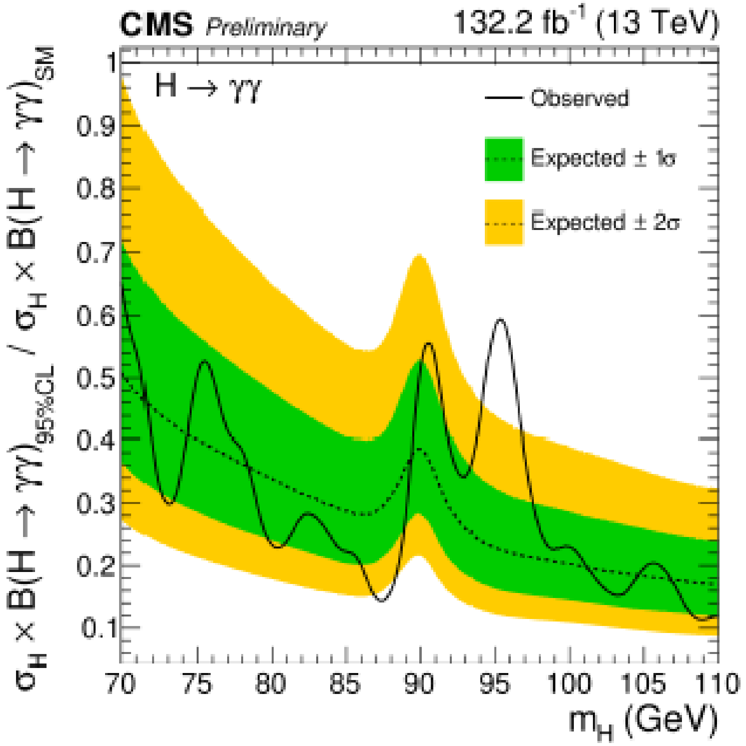
If just the SM, then vacuum instability of Higgs potential

& Radiative corrections fine-tuned 1 part in 10^{32} compared to new high scale, GUT or Planck

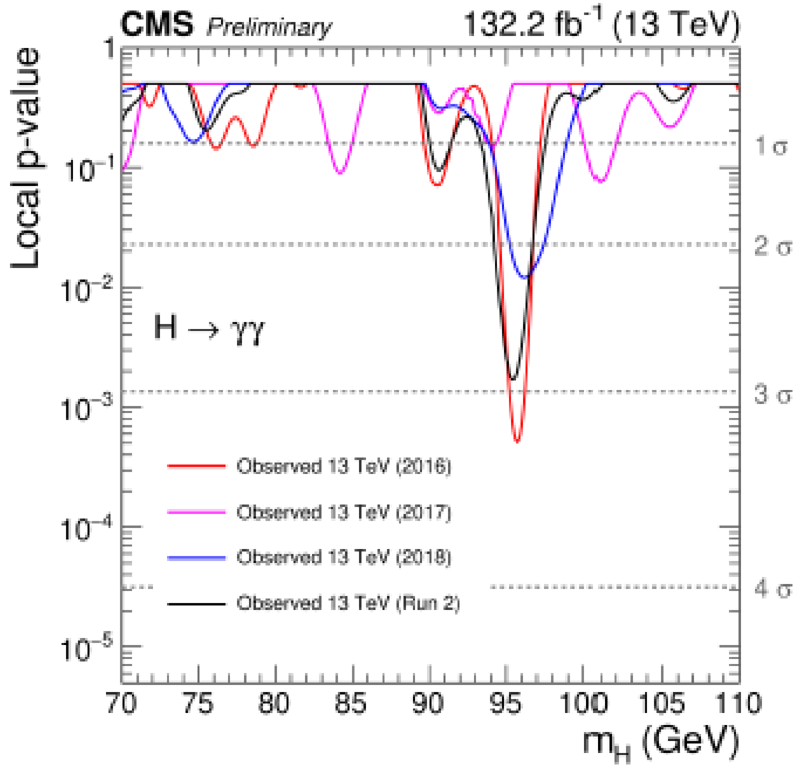
Where are we

- Standard Model well established
- few anomalies - $(g\text{-}2)_\mu$, W mass,
  lepton non-universality, CKM , extra Higgs ???

BSM Higgs physics hidden in plain sight?



Expected and observed exclusion limits (95% CL, in the asymptotic approximation) on the product of the production cross section and branching fraction into two photons for an additional SM-like Higgs boson, from the analysis of the combined data from 2016, 2017, and 2018. The inner and outer bands indicate the regions containing the distribution of limits located within ±1 and 2σ, respectively, of the expectation under the background-only hypothesis.



The observed local p-values for an additional SM-like Higgs boson as a function of m_H, from the analysis of the data from 2016, 2017, 2018, and their combination. Taken from CMS-PAS-HIG-20-002 (20 March 2023).

Where are we

- Standard Model well established
- few anomalies - ~~$(g-2)_\mu$~~ , W ~~mass~~,
  lepton ~~non~~-universality, CKM, extra Higgs ???
- SM is incomplete - Dark matter, origin of baryon asymmetry, why 3 families, quark & charged lepton masses and mixing, strong CP problem, neutrino masses & mixing, charge quantization, Hierarchy problem !
- Standard Cosmological model is well established ΛCDM - Dark Energy, Dark matter, inflation ?
- few anomalies - # DwarfSG, Cusp problem, H_0,
  Λ may not be constant afterall !

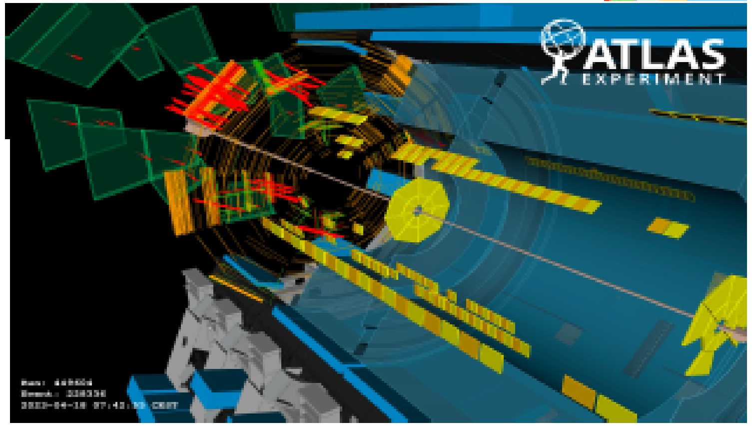
Where are we

Experimental program is robust

- Searches for new particles – SUSY, Scalars, etc.
- Dark matter (direct, indirect, spin independent vs spin dependent)
- ALPs, $0\nu\beta\beta$ decay
- Gravitational waves, multi-messenger cosmology ! UHE cosmic rays
- Neutrinos (NH, IH, CP)
- Proton decay

The second year of Run3 started in April 2023

Run2 data are still being exploited.



Particle	Produced in 139 fb^{-1} at $\sqrt{s}$ = 13 TeV	
Higgs boson	7.7 million	
Top quark	275 million	
Z boson	2.8 billion	($\rightarrow \ell\ell$, 290 million)
W boson	12 billion	($\rightarrow \ell\nu$, 3.7 billion)
Bottom quark	~40 trillion	(significantly reduced by acceptance)

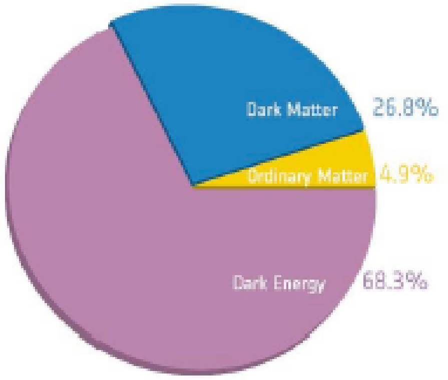
For ATLAS&CMS

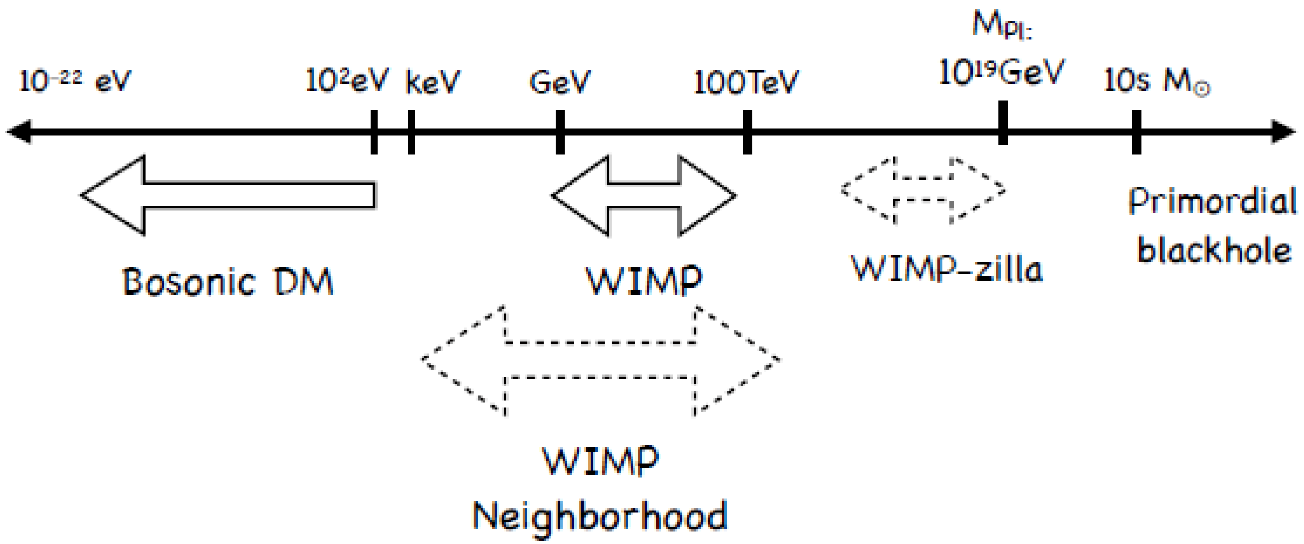
Run 3+2 (2022 end of 2025) ~500 1/fb (factor ~4)

Run 4+3+2 (2029 end of 2032) ~1000 1/fb (factor ~7)

Run 5+4+3+2 (– end of 2041*) ~3000 1/fb (factor ~20)

Dark world





None of above?

In this case, we can't even start to look for them.

Lian Tao Wang

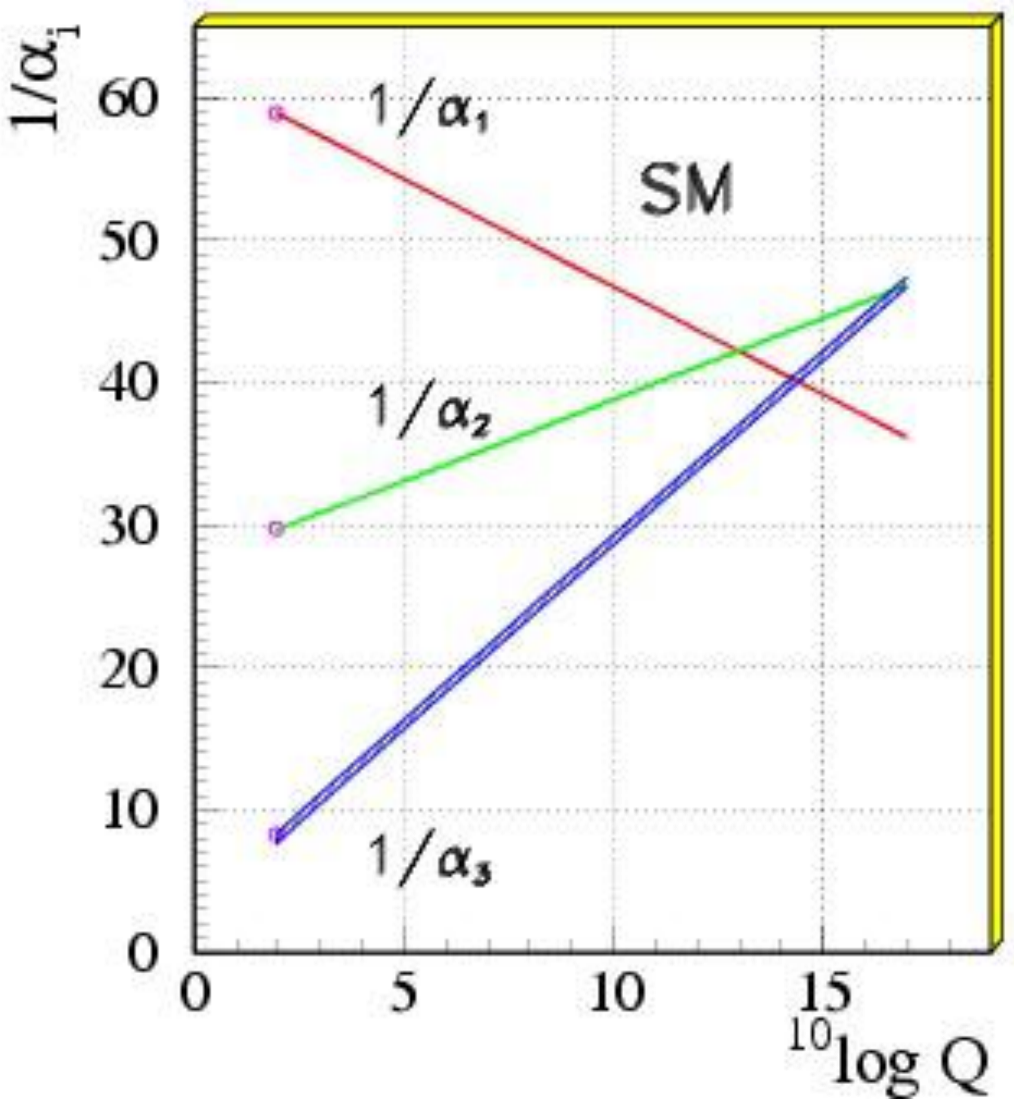
Where are we

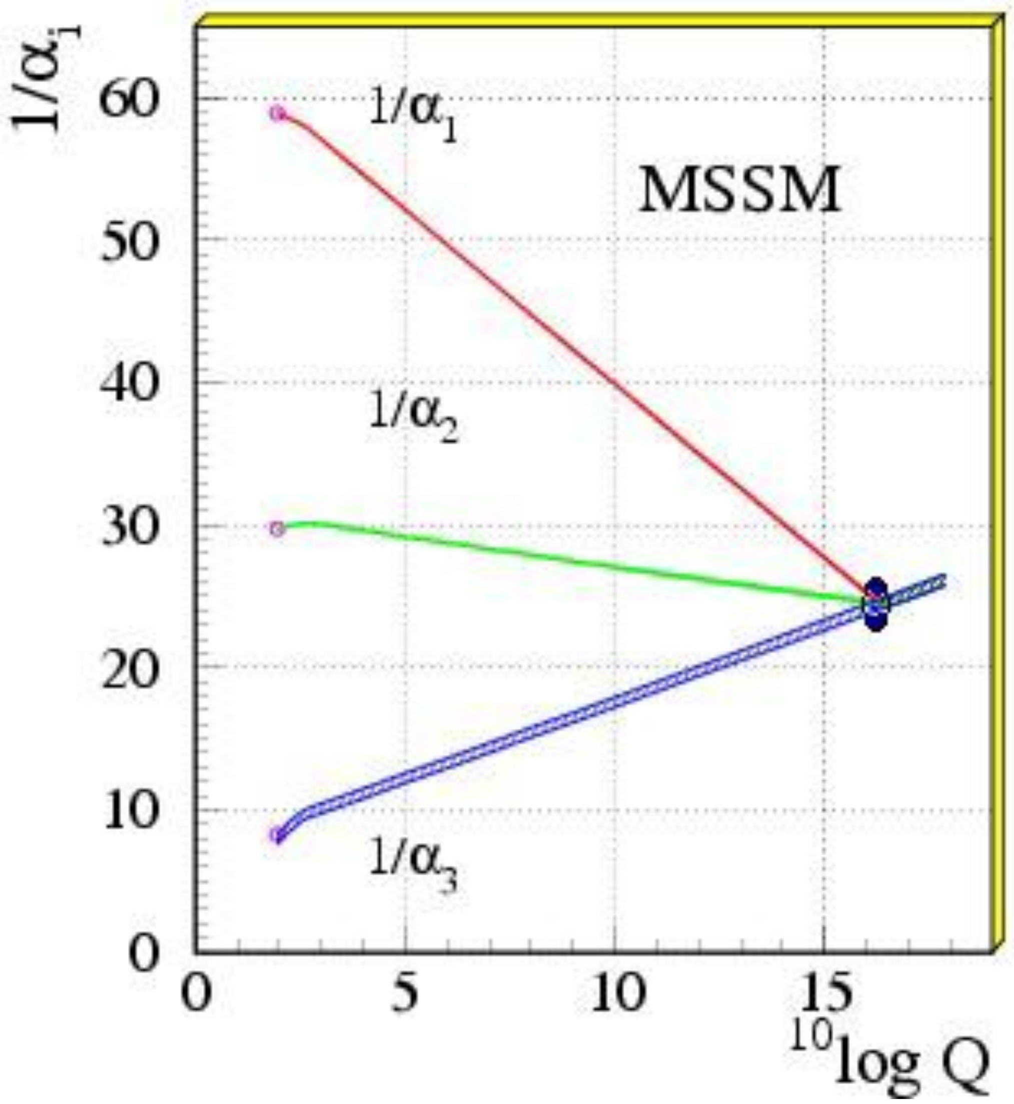
Theoretical program is robust

- Models for - fermion masses and discrete symmetries
- axions, inflation, baryogenesis, lepto-genesis, axio-genesis, ...
- primordial black holes , DM, signals of Grav. Waves
- Supersymmetry
- String models and Swampland

Gauge coupling unification gives first hint of SUSY LEP 1991

Dimopoulos, Raby and Wilczek, Phys. Rev. D24, 1681 (1981)
Dimopoulos and Georgi, *Nucl.Phys. B*193, 150 (1981)

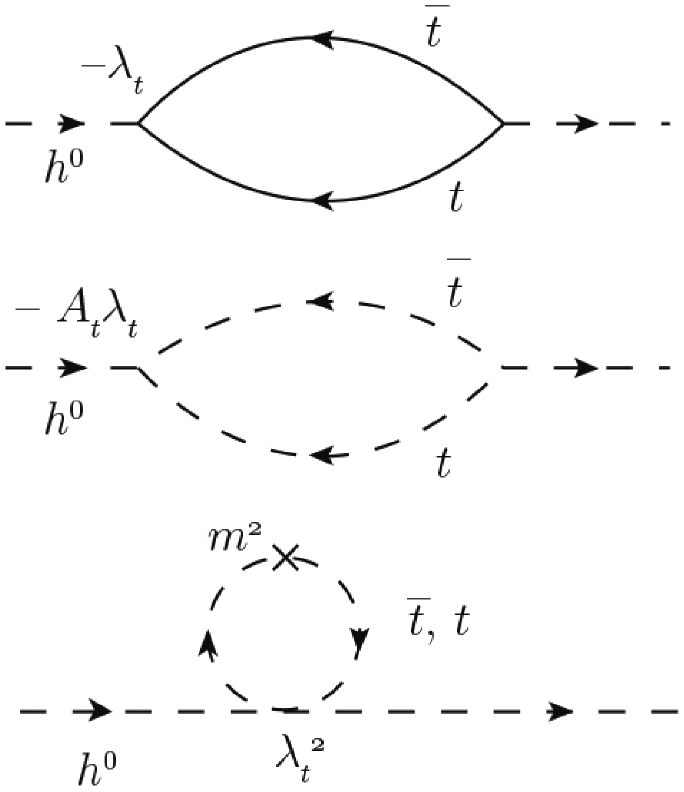




Radiative Electroweak symmetry breakiung

i.e. renormalization from $M_G \rightarrow \sim M_Z$ drives $\mathrm{m}_{h_u}{}^2 < 0$

Ibanez and Ross, Phys. Lett. B110, 215 (1982)



$$+\ 3\lambda_t^2\left(\tilde{m}_{h_u}^2 + \tilde{m}_t^2 + \tilde{m}_{t^c}^2 + A_t^2\right)$$

↑ 3 colors

$m_t \geq 50$ GeV

Ibanez and Lopez, Phys. Lett. B126, 54 (1983)

At tree level $m_h < M_Z |\cos 2\beta|$

$$m_h^2 \simeq M_Z^2 + \frac{3G_F m_t^4}{\sqrt{2}\pi^2}\left(\log\frac{m_{\tilde{t}}^2}{m_t^2} + X_t^2\left(1 - \frac{X_t^2}{12}\right)\right),$$

$$X_t^2 = \frac{|A_t - \mu/\tan\beta|^2}{M_S}$$

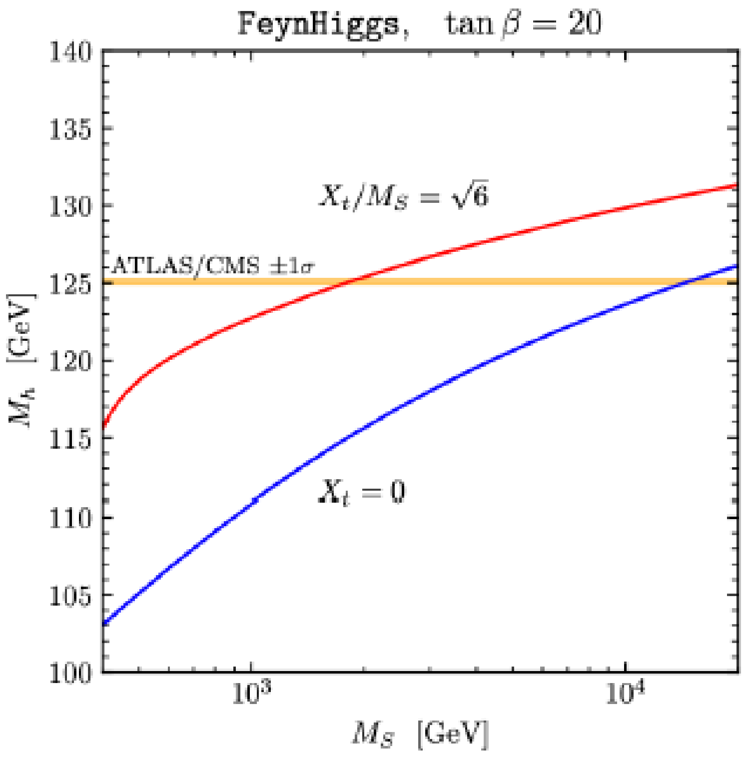
Okada, Yamaguchi and Yanagida, Prog. Theor. Phys. 85, 1 (1991)
Ellis, Ridolfi and Zwirner, Phys. Lett. B257, 83 (1991)
Haber and Hempfling, Phys Rev Lett.66.1815 (1991)

The Higgs boson as a portal to BSM physics

1. Supersymmetry (SUSY)

The MSSM employs a 2HDM Higgs sector and provides a (potentially) natural framework for electroweak symmetry breaking. The observed Higgs mass of 125 GeV is a prediction of the MSSM as a function of MSSM parameters.

The most recent precision Higgs mass calculations suggest that the SUSY scale M_S may be out of reach of LHC searches.



Taken from P. Slavich, S. Heinemeyer, et al., arXiv:2012.15629

Supersymmetry

- MSSM

  gravitino problem => M_{SUSY} > 40 TeV (gravity med.)
  or light gravitino dark matter (gauge med.)
  Flavor and CP => heavier SUSY scale and flavor syms.

  Little Hierarchy problem => $40 < M_{SUSY} < 100$ TeV

- Yukawa couplings given in Superpotential

$$\mathcal{W} = Y_e^{ij} H_d L_i \bar{E}_j + Y_d^{ij} H_d Q_i \bar{D}_j + Y_u^{ij} H_u Q_i \bar{U}_j + \kappa_{ij}^{(0)} H_u L_i H_u L_j$$

NO Dim. 4 proton decay $\mathbb{Z}_2$ matter parity

Searching for the standard model in the string landscape : SUSY GUTs

Heterotic orbifold models

Kobayashi, Raby & Zhang; Buchmuller, Hamaguchi, Lebedev & Ratz; Lebedev, Nilles, Raby, Ramos-Sanchez, Ratz, Vaudrevange & Wingerter ; Choi, Kim & Kyae; Farragi, ...

Heterotic CY3 models

Anderson, Braun, Donagi, Gray, He, Lukas, Ovrut, Palti, ...

F theory models

Beasley, Heckman & Vafa;   Donagi & Wijnholt; Marsano, Schafer-Nameki & Saulina; Blumenhagen, Cvetic, Grimm, Weigand, ...

Type II string models with Branes & Open strings

Ibanez, Schellekens, Uranga, Blumenhagen,Cvetic, Kachru, Weigand, ...

Challenges of String Model Building

- SU(3) x SU(2) x U(1) gauge group
- 3 families of quarks and leptons
- $H_u + H_d$ (Only vector –like states)
- Non-trivial Yukawa matrices
- Neutrino masses via See-Saw
- μ term of order weak scale
- Exact matter parity
- Dimension 5 B + L violation suppressed

$\mathbb{Z}_4^R$ symmetry explains low energy MSSM

SU(5)

q_{10}	$q_{\bar{5}}$	q_{H_u}	q_{H_d}
1	1	0	0

Lee, Raby, Ratz, Ross, Schieren, Schmidt-Hoberg & Vaudrevange
arXiv:1009.0905 [hep-ph]
arXiv:1102.3595 [hep-ph]

$$\mathcal{W}_p = Y_e^{ij} H_d L_i \bar{E}_j + Y_d^{ij} H_d Q_i \bar{D}_j + Y_u^{ij} H_u Q_i \bar{U}_j + \kappa_{ij}^{(0)} H_u L_i H_u L_j$$

$$\mathcal{W} = \mathcal{W}_p + \Delta \mathcal{W}_{non-perturbative}$$

$$\langle W \rangle_0 \big/ M_{Pl}^2 \sim m_{3/2}$$

$$\Delta W_{np} \propto B_0\, m_{3/2} M_{Pl}^2 + m_{3/2} H_u H_d + \frac{m_{3/2}}{M_{Pl}^2}\left(QQQL + \overline{U}\,\overline{U}\,\overline{D}\,\overline{E} \right)$$

$$\mu \approx m_{3/2}$$

$$\frac{1}{\Lambda} \approx \frac{m_{3/2}}{M_{Pl}^2} \approx 10^{-33}\ \mathrm{GeV}^{-1}$$

String Models with $\mathbb{Z}_4^R$ symmetry

- Heterotic string

  Kappl, Peterson, Raby, Ratz, Schieren & Vaudrevange

  1012.4574 [hep-th]

  Baur, Kade, Nilles, Ramos-Sanchez & Vaudrevange

  2104.03981 [hep-th]

- F theory

  Clemens and Raby

  1908.01913 [hep-th]

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- SU(3) x SU(2) x U(1) gauge group
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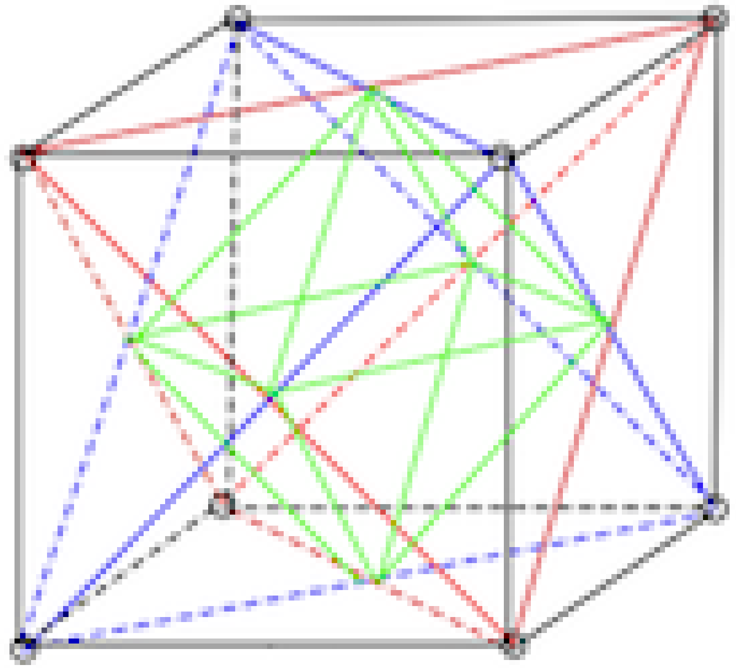
$\mathbb{Z}_4^R$

F theory with SU(5) gauge theory on a 7 brane
w/ 4 internal and 3 space dimensions + time

Internal 4 dimensions has the symmetry of a cube
Hence $\mathbb{Z}_4^R$ with matter with charge 1 and Higgs with charge 0

Clemens and Raby, 1908.01913 [hep-th]



SU(5) gauge theory broken to the SM gauge group with a Wilson line in the Hypercharge direction. This is possible due to a freely acting

$\mathbb{Z}_2$ *symmetry*

As a consequence, precise gauge coupling unification

Hebecker and Trapletti, 0411131 [hep-th]
Raby, Ratz and Schmidt-Hoberg, :0911.4249 [hep-ph]
Anandakrishnan and Raby, 1205.1228 [hep-ph]
Krippendorf, Nilles, Ratz and Winkler, 1306.0574 [hep-ph]

Representation	Type of multiplet	Cohomology group dimension
$(\mathbf{8},\mathbf{1})_0$	Vector	$h^2\left(S^\vee_{\mathrm{GUT}}, K_{S^\vee_{\mathrm{GUT}}}\right) = h^0\left(\mathcal{O}_{S^\vee_{\mathrm{GUT}}}\right) = 1$
$(\mathbf{1},\mathbf{3})_0$	Vector	$h^2\left(S^\vee_{\mathrm{GUT}}, K_{S^\vee_{\mathrm{GUT}}}\right) = h^0\left(\mathcal{O}_{S^\vee_{\mathrm{GUT}}}\right) = 1$
$(\mathbf{1},\mathbf{1})_0$	Vector	$h^2\left(S^\vee_{\mathrm{GUT}}, K_{S^\vee_{\mathrm{GUT}}}\right) = h^0\left(\mathcal{O}_{S^\vee_{\mathrm{GUT}}}\right) = 1$
$(\mathbf{8},\mathbf{1})_0$	Chiral	$h^0\left(S^\vee_{\mathrm{GUT}}, K_{S^\vee_{\mathrm{GUT}}}\right) \oplus h^1\left(S^\vee_{\mathrm{GUT}}, K_{S^\vee_{\mathrm{GUT}}}\right) = 0$
$(\mathbf{1},\mathbf{3})_0$	Chiral	$h^0\left(S^\vee_{\mathrm{GUT}}, K_{S^\vee_{\mathrm{GUT}}}\right) \oplus h^1\left(S^\vee_{\mathrm{GUT}}, K_{S^\vee_{\mathrm{GUT}}}\right) = 0$
$(\mathbf{1},\mathbf{1})_0$	Chiral	$h^0\left(S^\vee_{\mathrm{GUT}}, K_{S^\vee_{\mathrm{GUT}}}\right) \oplus h^1\left(S^\vee_{\mathrm{GUT}}, K_{S^\vee_{\mathrm{GUT}}}\right) = 0$
$(\mathbf{3},\mathbf{2})_{-5/6}$	Vector	$h^0\left(\mathcal{O}_{S^\vee_{\mathrm{GUT}} \times_{B^\vee_3} W^\vee_4}\left(\varepsilon_{u,v}\cdot\tilde{\tau} - \varepsilon_{u,v}\cdot\tilde{\zeta}\right)\right) = 0$
$(\bar{\mathbf{3}},\mathbf{2})_{5/6}$	Vector	$h^0\left(\mathcal{O}_{S^\vee_{\mathrm{GUT}} \times_{B^\vee_3} W^\vee_4}\left(\varepsilon_{u,v}\cdot\tilde{\tau} - \varepsilon_{u,v}\cdot\tilde{\zeta}\right)\right) = 0$
$(\mathbf{3},\mathbf{2})_{-5/6}$	Chiral	$h^1\left(\mathcal{O}_{S^\vee_{\mathrm{GUT}} \times_{B^\vee_3} W^\vee_4}\left(\varepsilon_{u,v}\cdot\tilde{\tau} - \varepsilon_{u,v}\cdot\tilde{\zeta}\right)\right) \oplus h^2(\ldots) = 0$
$(\bar{\mathbf{3}},\mathbf{2})_{5/6}$	Chiral	$h^1\left(\mathcal{O}_{S^\vee_{\mathrm{GUT}} \times_{B^\vee_3} W^\vee_4}\left(\varepsilon_{u,v}\cdot\tilde{\tau} - \varepsilon_{u,v}\cdot\tilde{\zeta}\right)\right) \oplus h^2(\ldots) = 0$

It naturally has 3 families & one pair of Higgs doublets

$\Sigma_{\mathbf{10}}^{(4)} = \{a_5 = z = 0\}$	$C_{u,v}$	L_Y	$\mathcal{L}_{Higgs}$	$SU(3) \times SU(2) \times U(1)_Y$
$h^0\left(\check{\mathcal{L}}_{\mathbf{10}}^{(4)[\pm 1]}\right)$	$+1$	$+1$	3	$(\mathbf{1},\mathbf{1})_{+1}$
	-1	-1		$(\mathbf{3},\mathbf{2})_{+1/6}$
	$+1$	$+1$		$(\bar{\mathbf{3}},\mathbf{1})_{-2/3}$
$h^1\left(\check{\mathcal{L}}_{\mathbf{10}}^{(4)[\pm 1]}\right)$	$+1$	$+1$	0	$(\mathbf{1},\mathbf{1})_{+1}$
	-1	-1		$(\bar{\mathbf{3}},\mathbf{2})_{+1/6}$
	$+1$	$+1$		$(\mathbf{3},\mathbf{1})_{+2/3}$

$\Sigma_{\bar{\mathbf{5}}}^{(41)} = \{a_{420} = z = 0\}$	$C_{u,v}$	L_Y	$\mathcal{L}_{Higgs}$	$SU(3) \times SU(2) \times U(1)_Y$
$h^0\left(\check{\mathcal{L}}_{\bar{\mathbf{5}}}^{(41)[\pm 1]}\right)$	$+1$	$+1$	3	$(\bar{\mathbf{3}},\mathbf{1})_{+1/3}$
	-1	-1		$(\mathbf{1},\mathbf{2})_{-1/2}$
$h^1\left(\check{\mathcal{L}}_{\bar{\mathbf{5}}}^{(41)[\pm 1]}\right)$	$+1$	$+1$	0	$(\mathbf{3},\mathbf{1})_{-1/3}$
	-1	-1		$(\mathbf{1},\mathbf{2})_{+1/2}$

As for the Higgs fields we have the following:

$\Sigma_{\bar{\mathbf{5}}}^{(44)} = \{a_4 a_3 + a_5 (a_0 - a_3) = z = 0\}$	$C_{u,v}$	L_Y	$\mathcal{L}_{Higgs}$	$SU(3) \times SU(2) \times U(1)_Y$
$h^0 \left(\check{\mathcal{L}}_{\bar{\mathbf{5}}}^{(44)[+1]}\right)$	$+1$	$+1$	0	$(\bar{\mathbf{3}}, \mathbf{1})_{+1/3}$
$h^0 \left(\check{\mathcal{L}}_{\bar{\mathbf{5}}}^{(44)[-1]}\right)$ H_d	-1	-1	1	$(\mathbf{1}, \mathbf{2})_{-1/2}$
$h^1 \left(\check{\mathcal{L}}_{\bar{\mathbf{5}}}^{(44)[+1]}\right)$	$+1$	$+1$	0	$(\mathbf{3}, \mathbf{1})_{-1/3}$
$h^1 \left(\check{\mathcal{L}}_{\bar{\mathbf{5}}}^{(44)[-1]}\right)$ H_u	-1	-1	1	$(\mathbf{1}, \mathbf{2})_{+1/2}$

The model also has a $U(1)_X$ symmetry which breaks to $\mathbb{Z}_2$ matter parity

$10_{+1},\ \bar{5}_{-3},\ H_{u-2}, H_{d+2},\ N_{+5}$ [4 RH neutrinos]

The model also has a complete Twin sector

Challenges of String Model Building

This all depends on SUSY breaking and Stabilizing all the moduli

Maxwell in his Introductory Lecture on Experimental Physics held at Cambridge in October 1871

"… the opinion seems to have got abroad, that in a few years all the great physical constants will have been approximately estimated, and that the only occupation which will then be left to men of science will be to carry on these measurements to another place of decimals. …

But we have no right to think thus of the unsearchable riches of creation, or of the untried fertility of those fresh minds into which these riches will continue to be poured. …

But the history of science shews that even during the phase of her progress in which she devotes herself to improving the accuracy of the numerical measurement of quantities with which she has long been familiar, she is preparing the materials for the subjugation of the new regions, which would have remained unknown if she had been contented with the rough methods of her early pioneers. I might bring forward instances gathered from every branch of science, shewing how the labour of careful measurement has been rewarded by the discovery of new fields of research, and by the development of new scientific ideas."

Soon after Maxwell made these comments a period of highly significant scientific break-throughs began with the discovery of

- radio waves by Hertz (1886-1889)
- X-rays by Roentgen (1895)
- nuclear radiation by Becquerel (1896)
- discovery of the electron by Thomson (1897)
- quanta by Planck (1900)
- relativity by Einstein (1905)
- Nucleus by Rutherford (1911)
- Atom by Bohr (1913)
- …

Where are we going

There is every reason to believe that in the next few years there may be some major discoveries.

What these will be, clearly, I do not know.

But I am certain that we will all be celebrating!!

Celebration !!!


Thank you