Perspectives in Particle Physics

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PASCOS 2023
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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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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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Maxwell 1865 - 1873, Heaviside 1884

First unified field theory

The Beginning

Maxwell 1864 - 1873 Electromagnetism

The Beginning

Maxwell 1864 - 1873 Electromagnetism

Verification

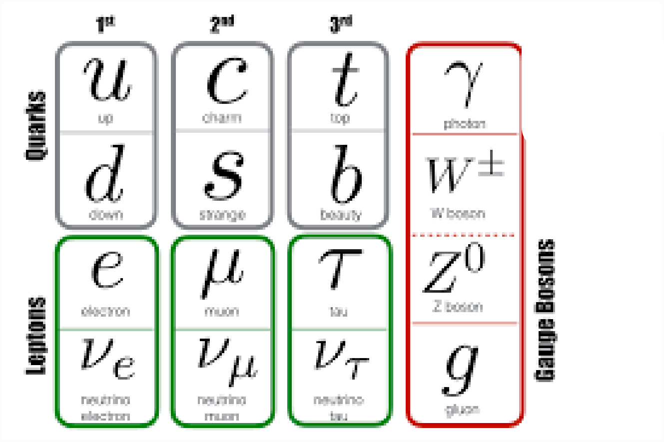
The Beginning

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

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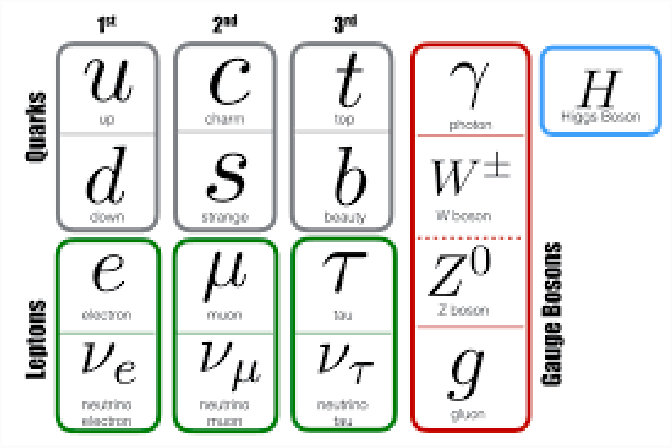

Final Verification

Higgs 2012

Glashow 1961, Weinberg & Salam 1967

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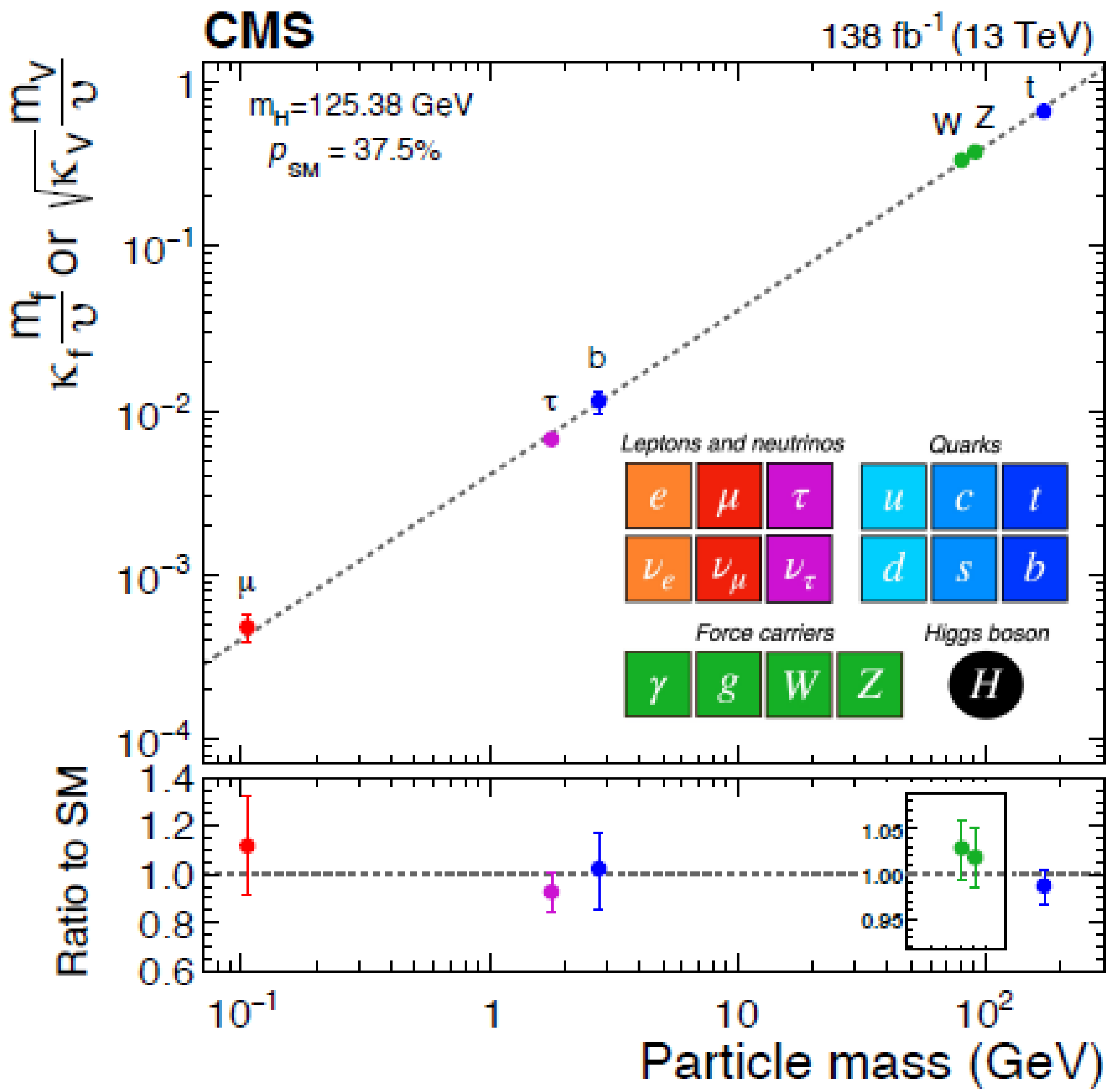
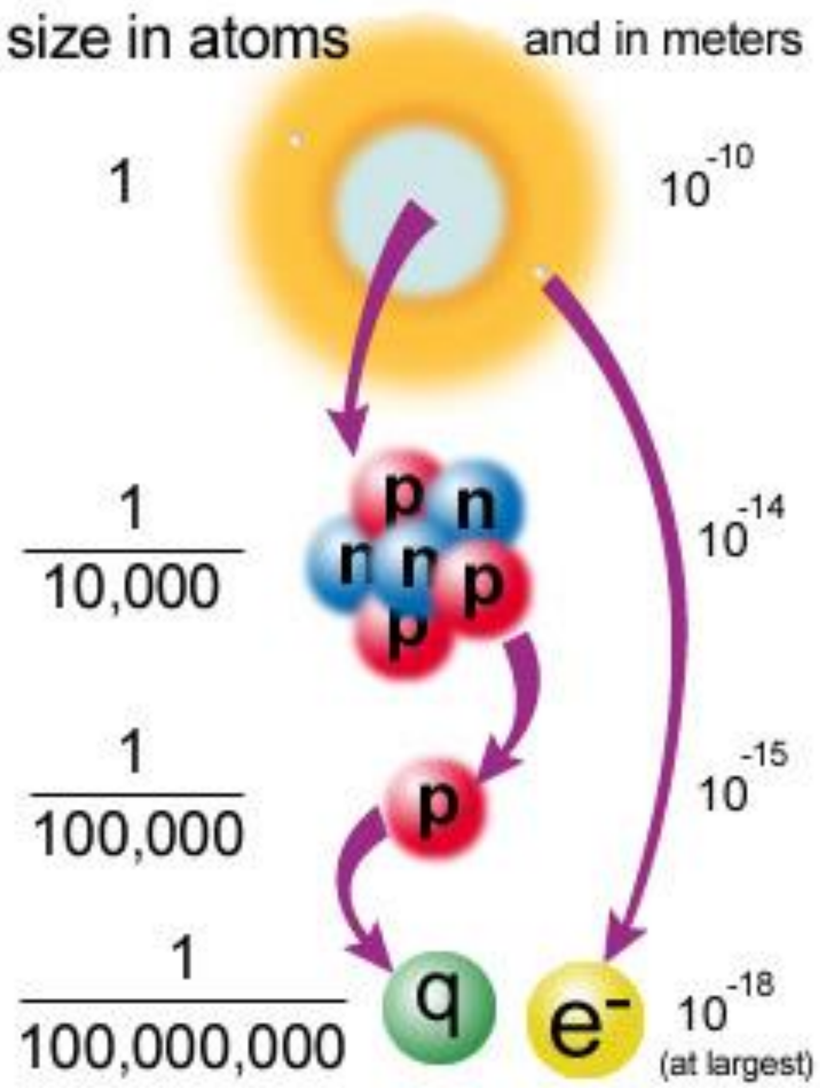


From the CMS webpage

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	$q = \begin{pmatrix} u \\ d \end{pmatrix}$	$\overline{u}$	$\overline{d}$	$l = \begin{pmatrix} \nu_e \\ e \end{pmatrix}$	$\overline{e}$
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

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

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

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$$\boxed{D_\mu = (\partial_\mu + i g_s \mathcal{T}_A \mathcal{G}_{\mu A} + i g T_a W_{\mu a} + i g' \, \frac{Y}{2} B_\mu)}$$

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

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

The Standard Model

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$$+ \overline{\nu}_i Y_\nu^{ij} \, \ell_j \, H - \frac{1}{2} M_{ij} \, \bar{\nu}_i \, \bar{\nu}_j + h.c.$$

The Standard Model

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

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

SM + neutrino masses + dark matter

1. Higgs coupling

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

diagonal in mass basis !! GIM suppressed FCNC

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

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

3. Dark Matter & Dark Energy ??

$m_u\,,\ m_d\,,\ m_e\,,\ m_\nu$

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

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

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

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

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

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

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

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

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)

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

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 ??

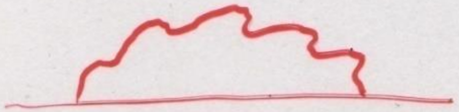
If just the SM, then vacuum instability of Higgs potential

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

Gauge Hierarchy Problem

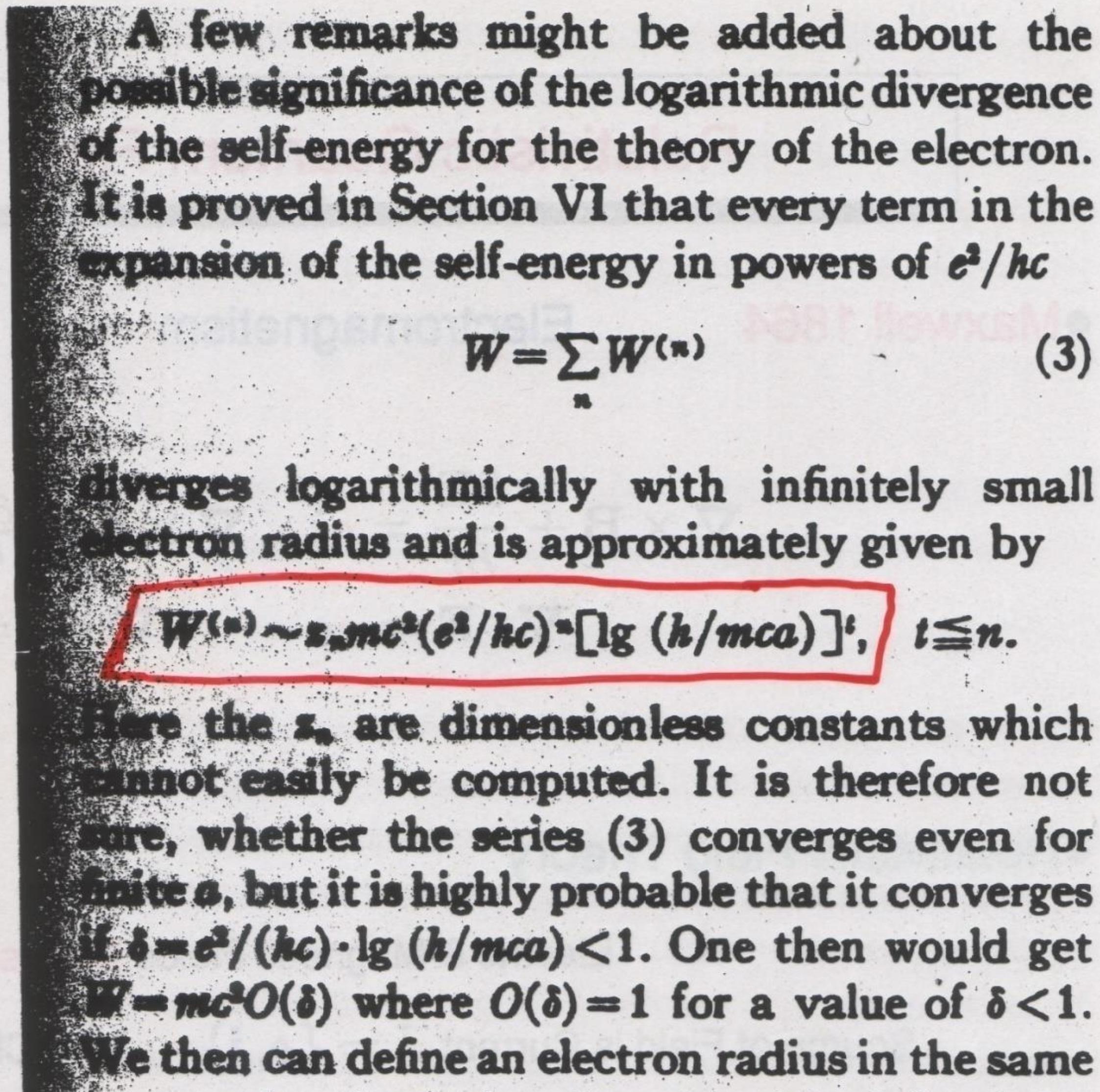
V.F. Weisskopf

Phys. Rev. 56,
72 (1939)



$\delta m_e \sim \alpha m_e \ln \frac{\Lambda}{m_e}$

$\Lambda \sim \frac{1}{a}$



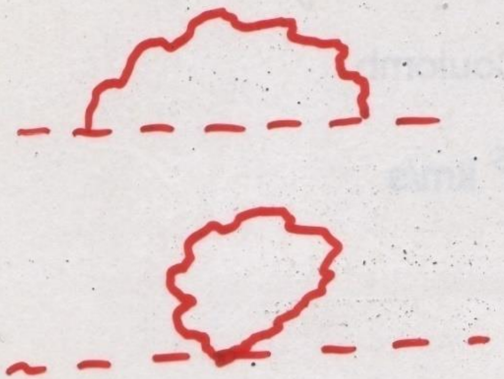
A few remarks might be added about the possible significance of the logarithmic divergence of the self-energy for the theory of the electron. It is proved in Section VI that every term in the expansion of the self-energy in powers of e^2/hc

$$W = \sum_n W^{(n)} \qquad (3)$$

diverges logarithmically with infinitely small electron radius and is approximately given by

$$\boxed{W^{(n)} \sim z_n mc^2 (e^2/hc)^n [\lg (h/mca)]^t,} \quad t \leqq n.$$

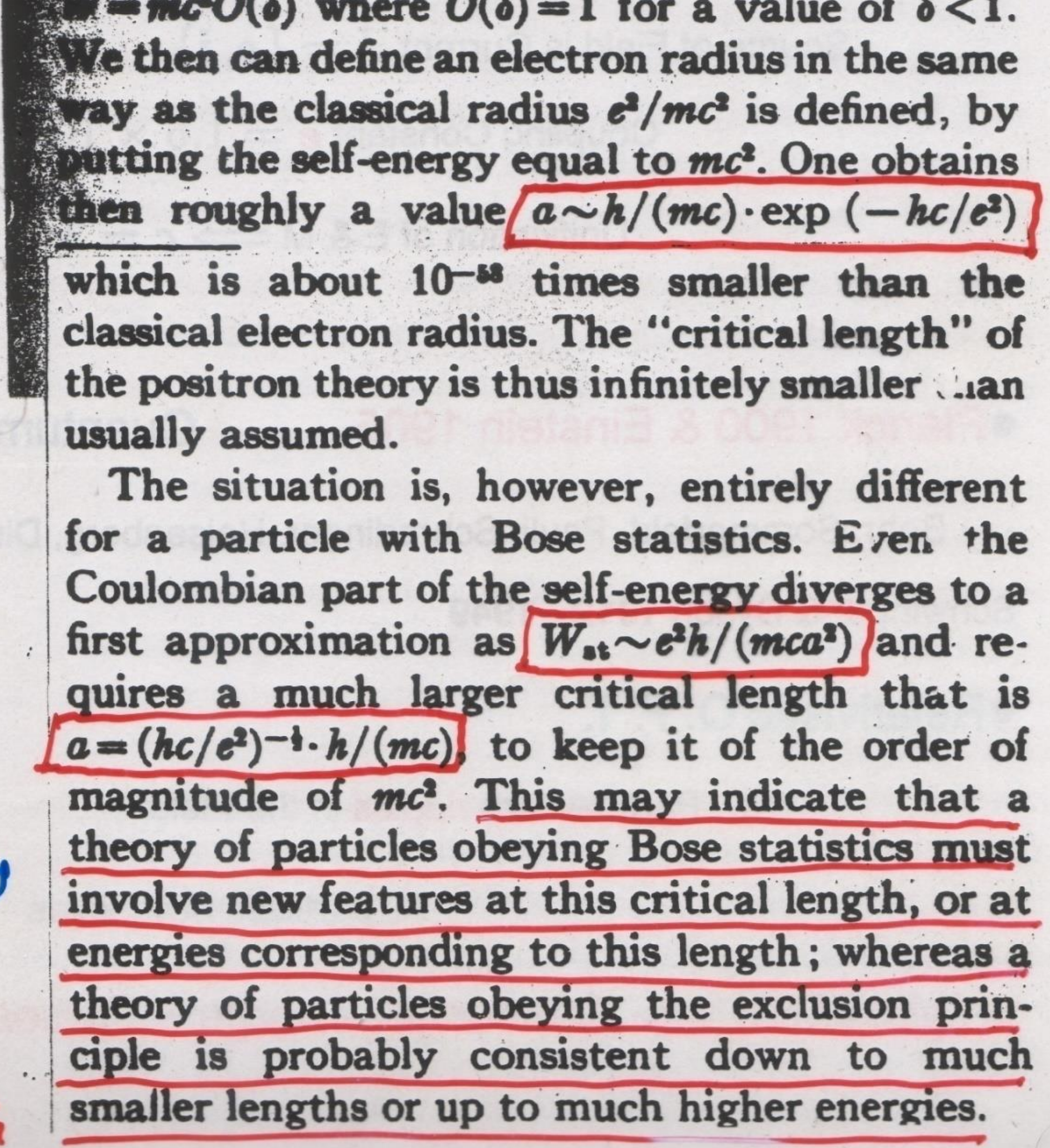
Here the z_n are dimensionless constants which cannot easily be computed. It is therefore not sure, whether the series (3) converges even for finite a, but it is highly probable that it converges if $\delta = e^2/(hc) \cdot \lg (h/mca) < 1$. One then would get $W = mc^2 O(\delta)$ where $O(\delta) = 1$ for a value of $\delta < 1$. We then can define an electron radius in the same



$\delta m_s^2 \sim \alpha \Lambda^2$

Gauge Hierarchy Problem

$M_Z \sim m_{Higgs} \ll M_G$



$W = mc^2 O(\delta)$ where $O(\delta) = 1$ for a value of $\delta < 1$. We then can define an electron radius in the same way as the classical radius e^2/mc^2 is defined, by putting the self-energy equal to mc^2. One obtains then roughly a value $\boxed{a \sim h/(mc) \cdot \exp(-hc/e^2)}$ which is about 10^{-58} times smaller than the classical electron radius. The "critical length" of the positron theory is thus infinitely smaller than usually assumed.

The situation is, however, entirely different for a particle with Bose statistics. Even the Coulombian part of the self-energy diverges to a first approximation as $\boxed{W_{st} \sim e^2 h/(mca^2)}$ and requires a much larger critical length that is $\boxed{a = (hc/e^2)^{-\frac{1}{2}} \cdot h/(mc)}$, to keep it of the order of magnitude of mc^2. This may indicate that a theory of particles obeying Bose statistics must involve new features at this critical length, or at energies corresponding to this length; whereas a theory of particles obeying the exclusion principle is probably consistent down to much smaller lengths or up to much higher energies.

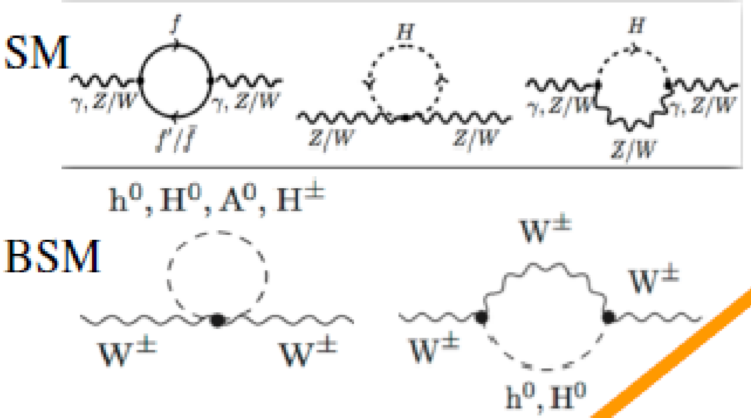
New physics at $\Lambda \sim 10$ TeV ??

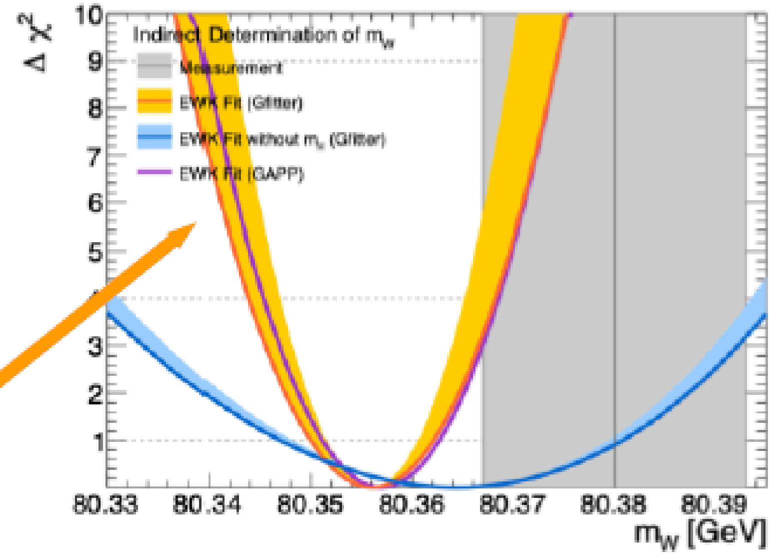
Where are we

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

Planck2023 Scale and the LHC, prospects

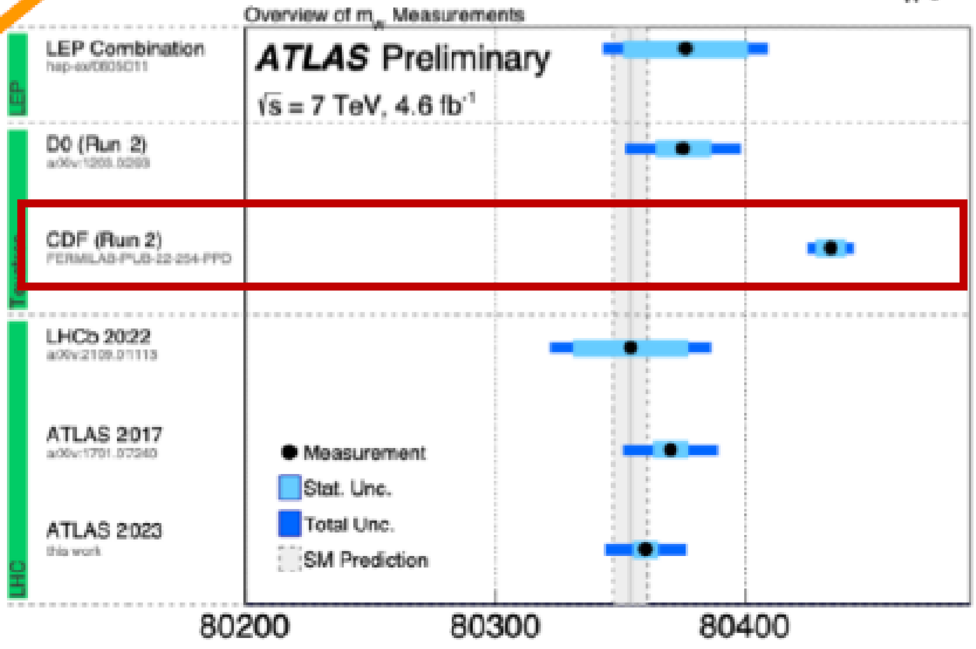
EWSB: M_W, M_H, M_{top}





4 parameters of the EW sector (α_{em}, G_F, m_Z, $\sin^2\theta_W$) + m_H and m_{top} → predict m_W within the SM Δm_W =7 MeV

New M_W measurement from ATLAS is very SM-like.
(ATLAS-CONF-2023-004)



m_W = 80360±5(stat.) ±15(syst.) = 80360 ±16 MeV

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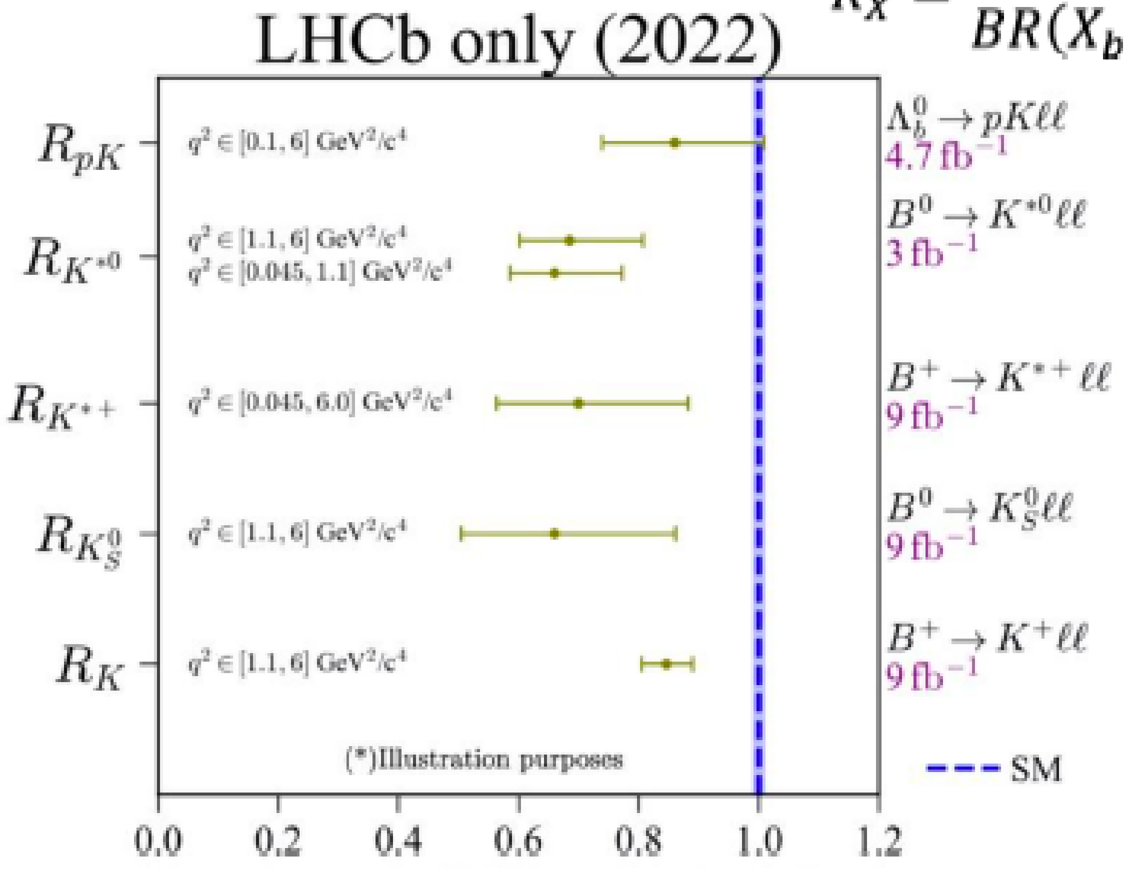
Tests of Lepton Flavour Universality

$$R_X = \frac{BR(X_b \to X_s \mu^+ \mu^-)}{BR(X_b \to X_s e^+ e^-)}$$

arXiv:2212.09152
arXiv:2212.09153

Pre Dec 2022



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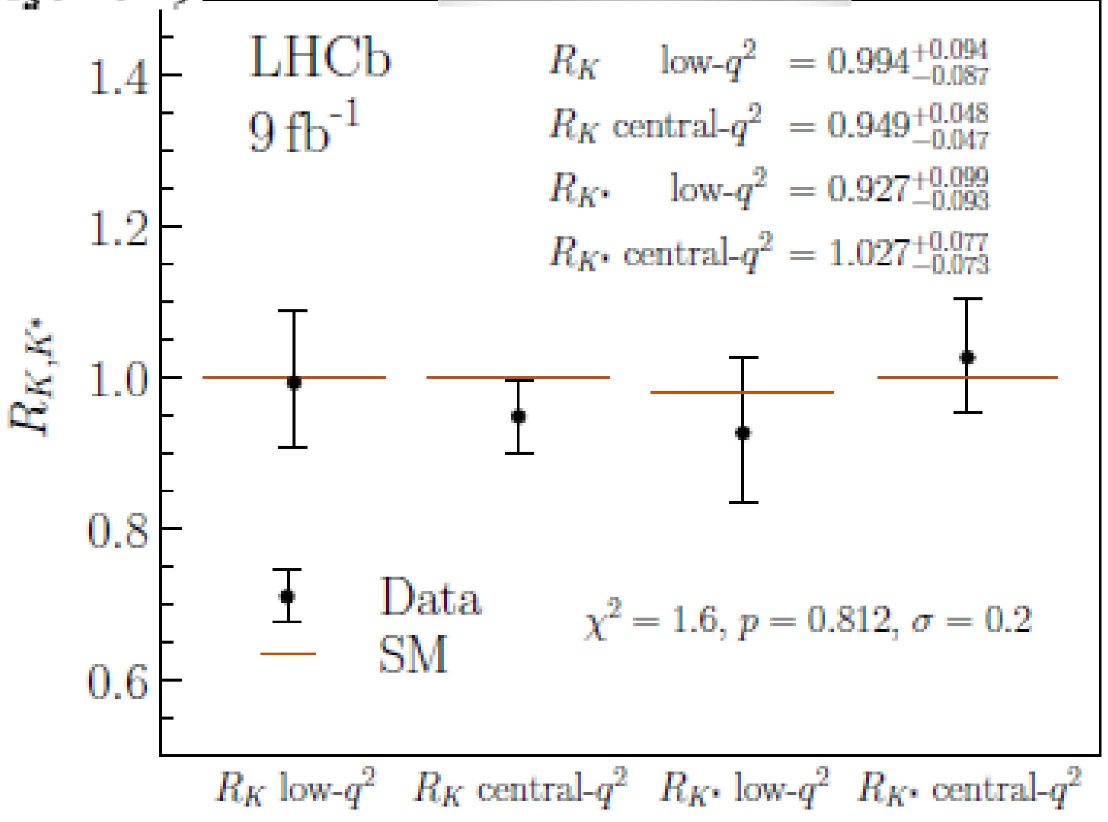

Low q^2 :
$q^2 \in [0.1, 1.1]$ GeV$^2/c^4$

Central q^2 :
$q^2 \in [0.1, 1.1]$ GeV$^2/c^4$

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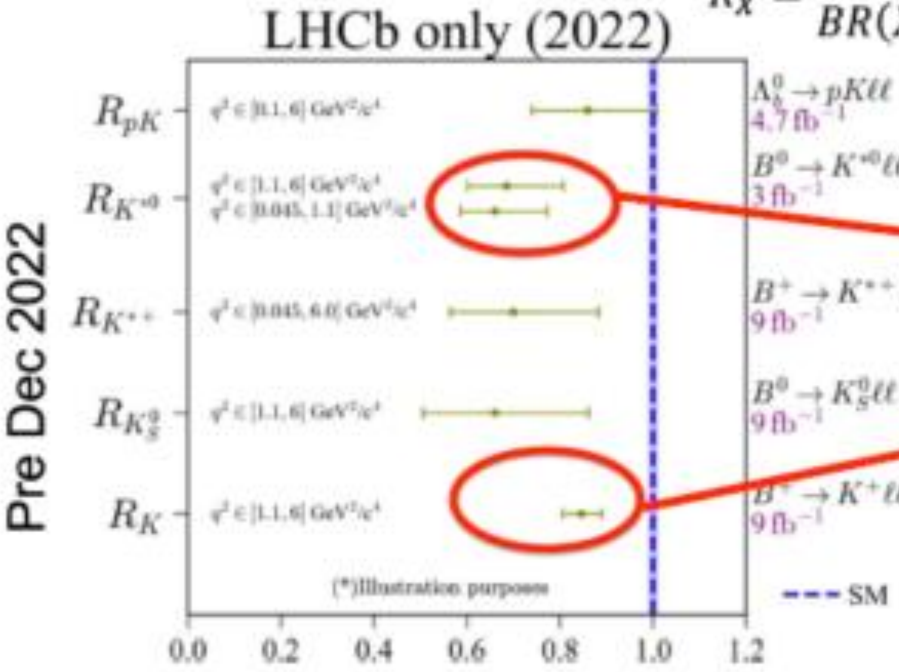
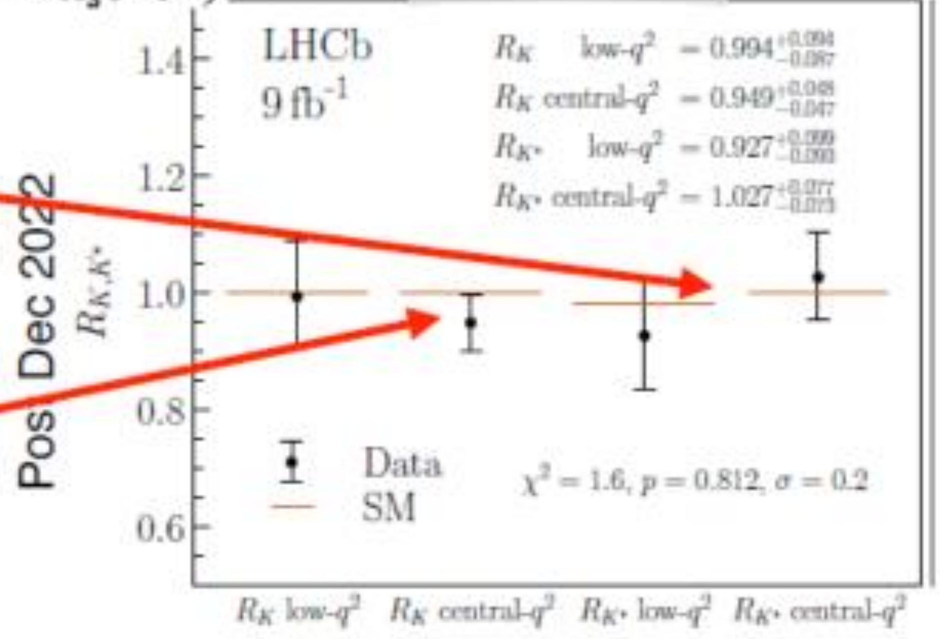
arXiv:2212.09152
arXiv:2212.09153





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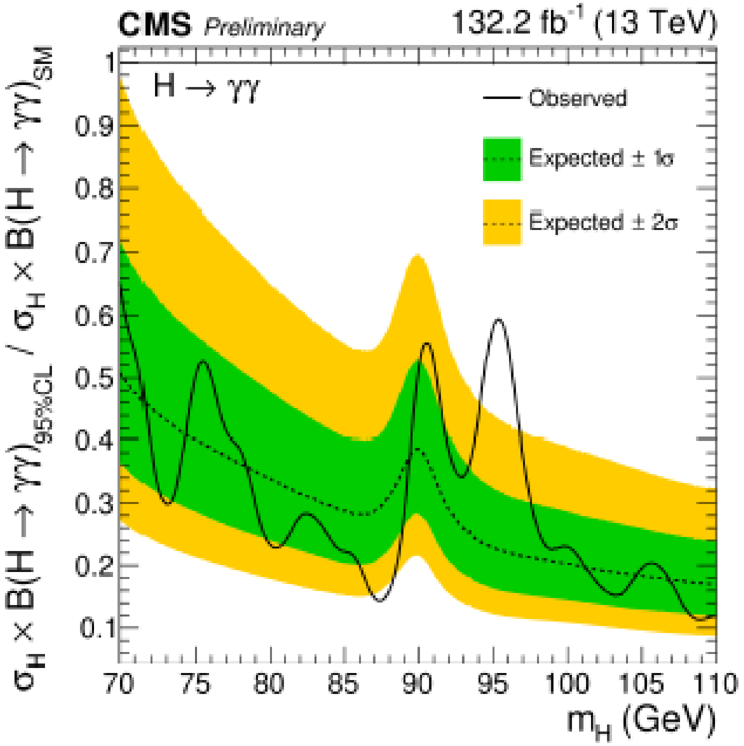
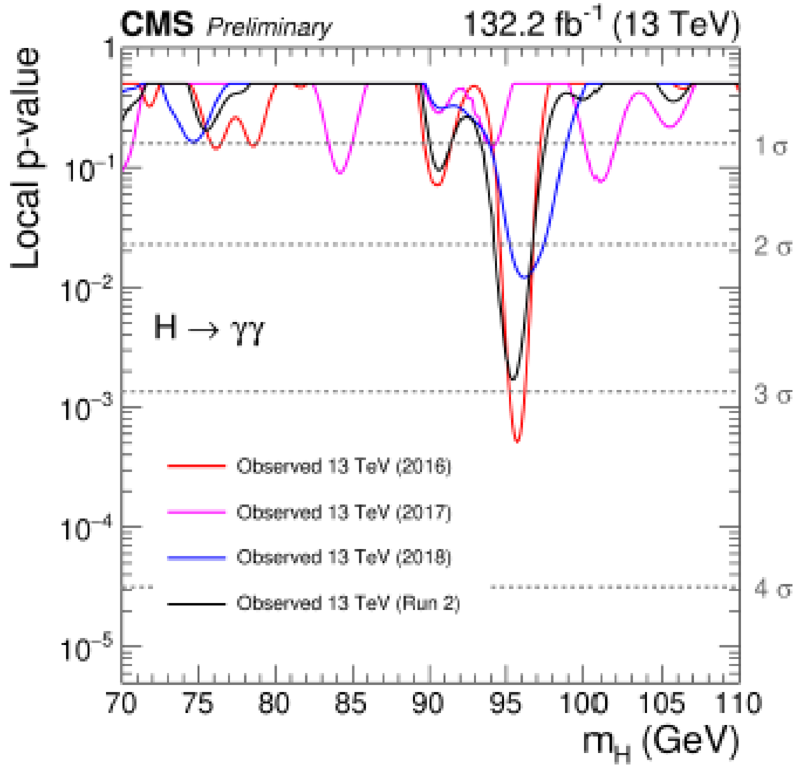
- few anomalies - # DwarfSG, Cusp problem, H_0

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).

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- Dark matter (direct, indirect, spin independent vs spin dependent)

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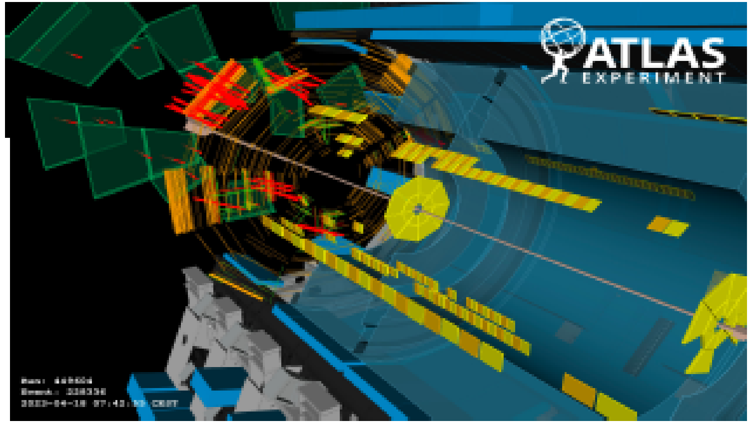
The second year of Run3 started in April 2023
Run2 data are still being exploited.

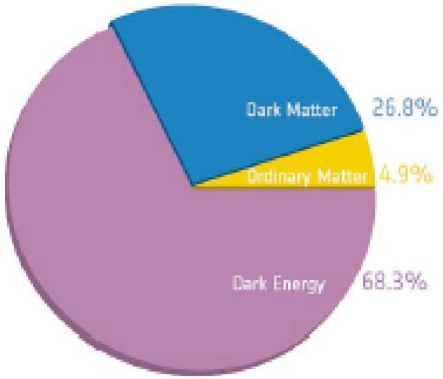


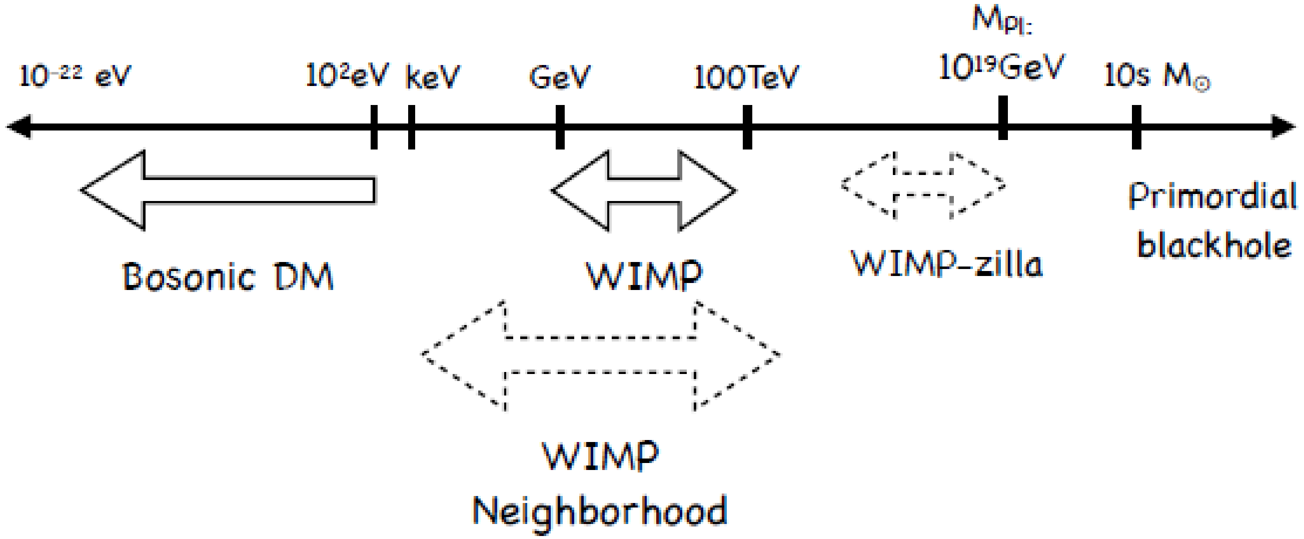
Particle	**Produced in 139 fb^{-1} at $\sqrt{s}$ = 13 TeV**	
Higgs boson	7.7 million	
Top quark	275 million	
Z boson	2.8 billion	($\rightarrow \ell\ell$, 290 million)
W boson	12 billion	($\rightarrow \ell\nu$, 3.7 billion)
Bottom quark	~40 trillion	(significantly reduced by acceptance)

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, ...
- primordial black holes (DM, signals of Grav. Waves)

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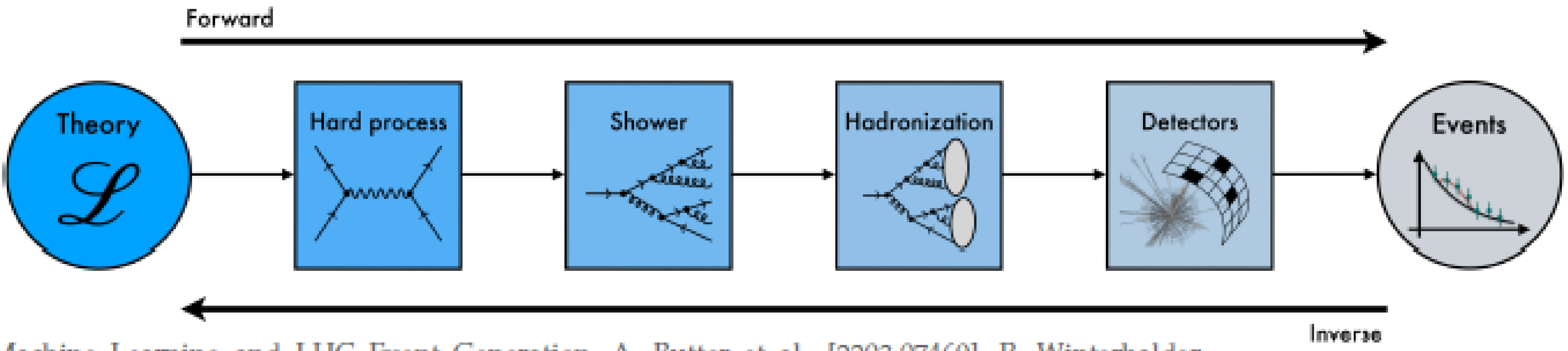
- Machine Learning

We want to understand the LHC data based on 1st principles.

What do we need to understand the data?

1. (a lot of) precise Simulations

2. optimized analyses for high-dimensional data



Machine Learning and LHC Event Generation, A. Butter et al. [2203.07460], R. Winterhalder

⇒ Machine Learning, as numerical tool, has a significant impact to every aspect of the simulation chain!

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- Machine Learning, SMEFTs

SMEFTs

- SMEFTs/Model Building (Buchmuller & Wyler 1986)
  There are 2499 dim. 6 ops. in the Warsaw basis which removes all redundant ops.
  Isidori, Wilsch & Wyler 2303.16922
- Flavor symmetries $SU(3)^5$ or $SU(2)^5$ or MFV
- RG improved, Wilson coefficiens (1 or 4π)
- Add new heavy scalars or fermions = model building

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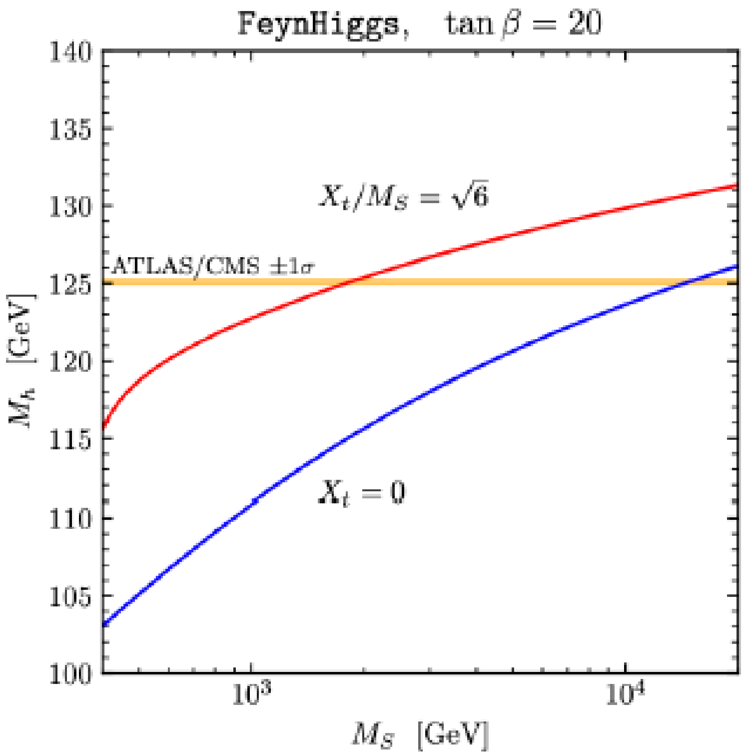
- Machine Learning, SMEFTs
- Supersymmetry
- String models and Swampland

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

Haber, PLANCK 2023

Many other BSM scenarios

There are many other models inspired by naturalness, but one can also entertain more general scenarios. SMEFT (and more generically HEFT) provides a model independent approach for probing BSM physics.

- Supersymmetry
- The Higgs boson as a pseudo-Goldstone boson
- Composite Higgs models
- Higgs boson as a component of an extra-dimensional gauge field
- Higgs portal to the dark sector
- Cosmological scalars

Early universe history (inflation, electroweak phase transition) provide an independent motivation for BSM Higgs physics. Future gravitational wave experiments open up a new avenue for exploration.

Supersymmetry

- CMSSM
  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

NOT “Natural” SUSY

NOT “Natural” SUSY

BUT SUSY does not completely decouple

NOT “Natural” SUSY

BUT SUSY does not completely decouple

NOT “Split” SUSY

NOT “Natural” SUSY

BUT SUSY does not completely decouple

NOT “Split” SUSY

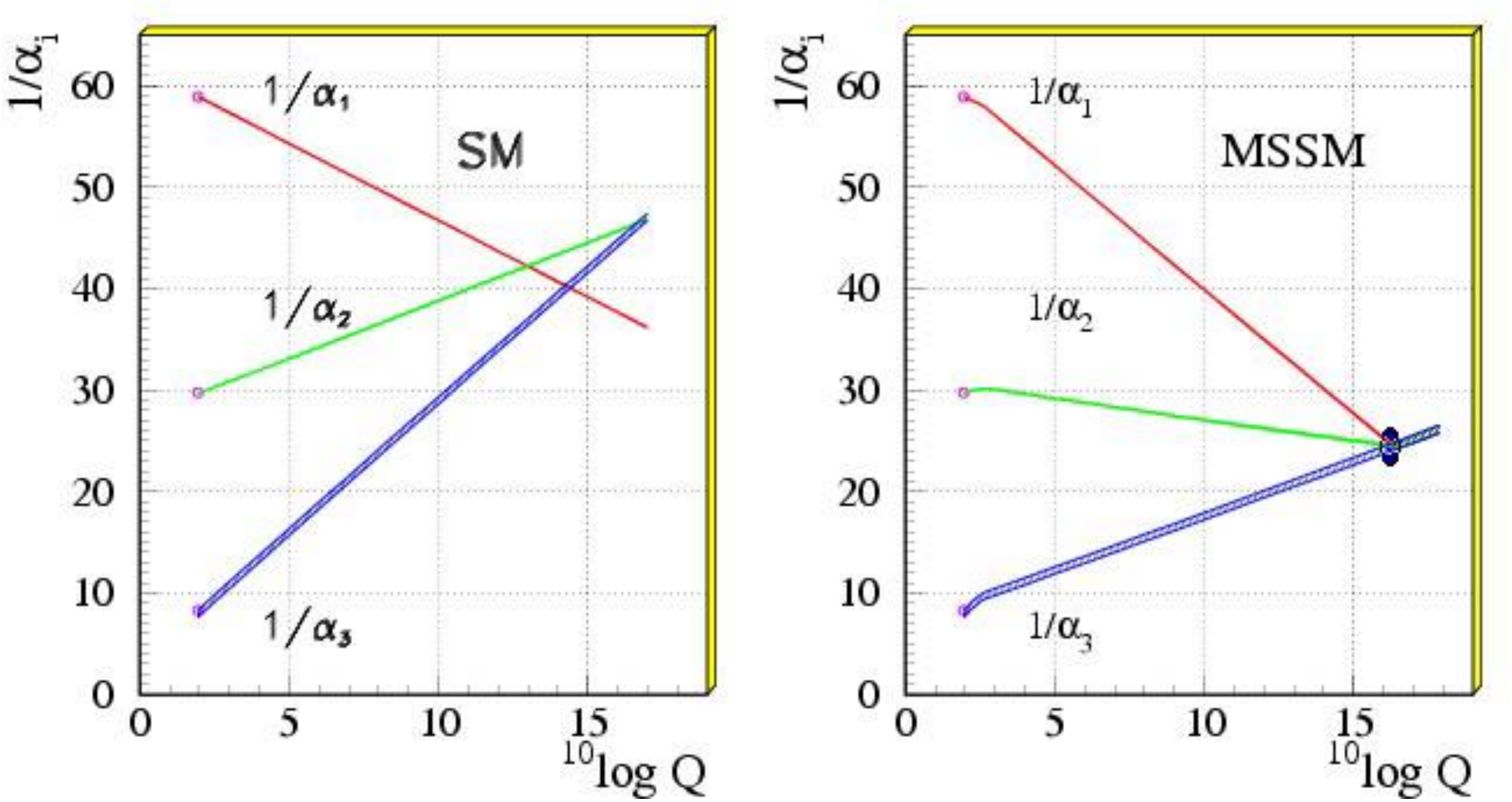
BUT gravitino & moduli sufficiently heavy
so NO cosmological problems

“SUSY on the Edge”

Poh & Raby 2016

painting by Hans Werner Sahm

Gauge coupling unification gives first hint of SUSY



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 exotics)
- Non-trivial Yukawa matrices
- Neutrino masses via See-Saw
- μ term of order weak scale
- Exact R parity
- Dimension 5 B + L violation suppressed
- Asymmetric 6D orbifold with one large dimension $\ell_{\mathrm{GUT}} \sim M_{\mathrm{GUT}}^{-1} \gg \ell_{\mathrm{string}} \sim M_{\mathrm{string}}^{-1}$

  $M_{\mathrm{GUT}} \sim 3\times 10^{16}\ \mathrm{GeV} \ll M_{\mathrm{string}} \sim 5\times 10^{17}\ \mathrm{GeV}$

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

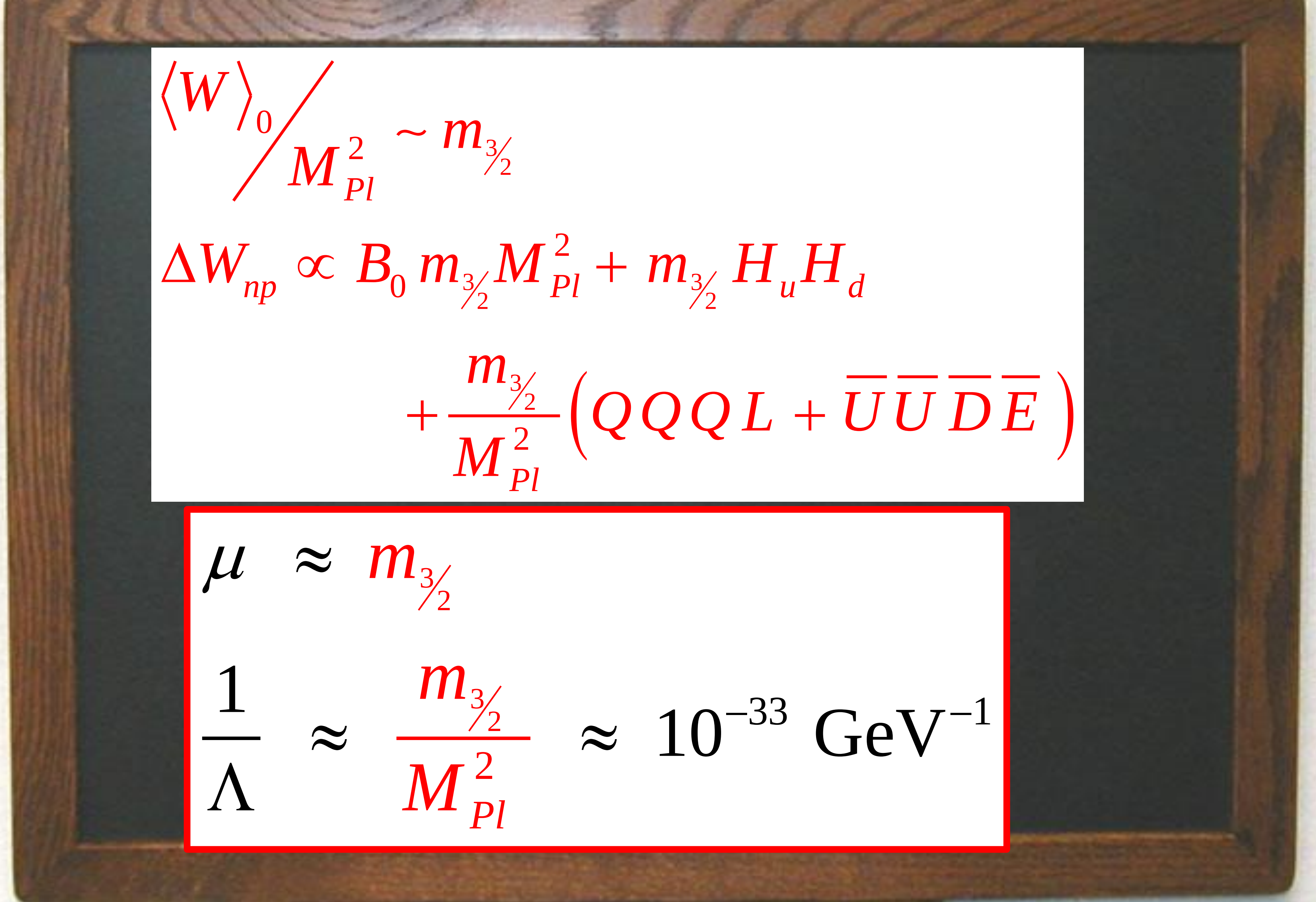
SU(5)

$q_{\mathbf{10}}$	$q_{\bar{\mathbf{5}}}$	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]

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

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



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

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

$$\boxed{\begin{aligned} \mu \ &\approx\ m_{3/2} \\ \frac{1}{\Lambda}\ &\approx\ \frac{m_{3/2}}{M_{Pl}^2}\ \approx\ 10^{-33}\ \mathrm{GeV}^{-1} \end{aligned}}$$

- Heterotic string

  Kappl, Peterson, Raby, Ratz, Schieren & Vaudrevange

  arXiv:1012.4574 [hep-th]

  Baur, Kade, Nilles, Ramos-Sanchez & Vaudrevange

  arXiv:2104.03981

- F theory

  Clemens and Raby

  arXiv:1908.01913 [hep-th]

Where are we going

Discrete gauge symmetries for fermion mass hierarchies have been found in Heterotic

- Kobayashi, Raby & Zhang; Buchmuller, Hamaguchi, Lebedev & Ratz; Lebedev, Nilles, Raby, Ramos-Sanchez, Ratz, Vaudrevange & Wingerter
- Kobayashi, Nilles, Ploeger, Raby & Ratz

and Type II Brane models

- Ibanez, Schellekens, Uranga

Eclectic Flavor Symmetries

Modular groups suggested by Feruglio

Eclectic flavor symmetries combine standard flavor symmetries with the modular groups in string theory

First complete example - Heterotic orbifold

Baur, Nilles, Ramos-Sanchez, Trautner & Vaudrevange

arXiv:2207.10677

Challenges of String Model Building

And 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

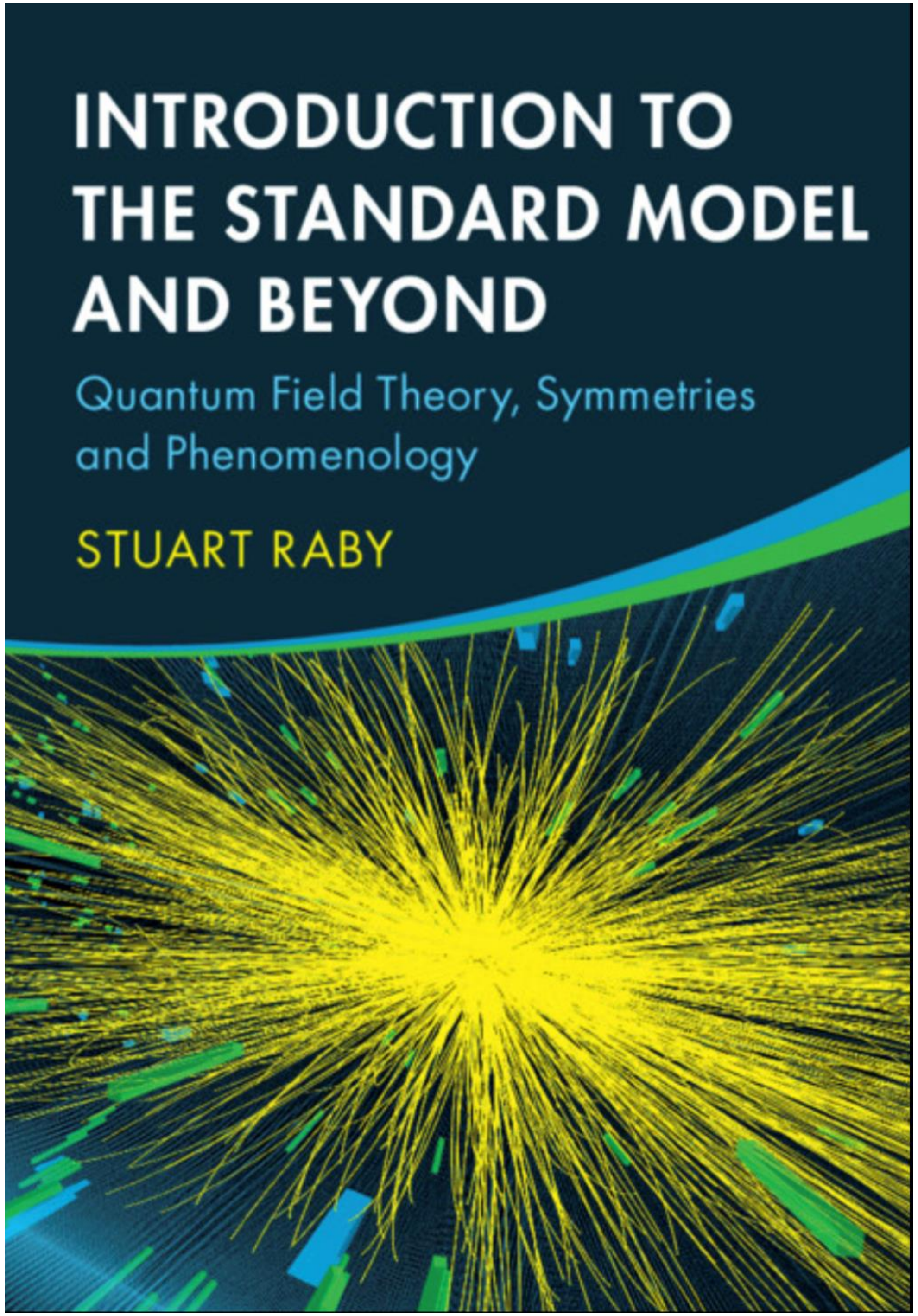
There is every reason to believe that in the next few years there may be some major discoveries.

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

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

Celebration !!!

Thank you



INTRODUCTION TO THE STANDARD MODEL AND BEYOND

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STUART RABY

Cambridge University Press 2021