Open Questions in High-Energy Physics

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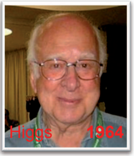
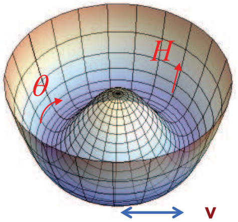
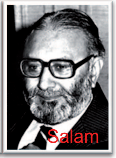
L IMFP & 15 CPAN Days (Santander, 2–6 October 2023)

Great success of the Standard Model

BEGHHK (≡ Higgs) Mechanism







$SU(2)_L \otimes U(1)_Y$ v = 246 GeV

Fundación
Príncipe de Asturias

$$M_Z \cos\theta_W = M_W = \frac{1}{2} \mathrm{v}\, g$$

The last missing ingredient of the SM has been found

What's next?

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What's next?

History mistakes strike back:

In this field, almost everything is already discovered, and all that remains is to fill a few unimportant holes (Philipp von Jolly, 1878)

The more important fundamental laws and facts of physical science have all been discovered, and these are now so firmly established that the possibility of their ever being supplanted in consequence of new discoveries is exceedingly remote... our future discoveries are to be looked for in the sixth place of decimals (Albert A. Michelson, 1894)

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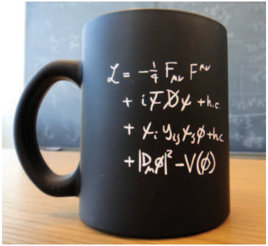
Many open questions remain to be answered

The SM in a Nutshell

$SU(3)_C \otimes SU(2)_L \otimes U(1)_Y$

Lagrangian



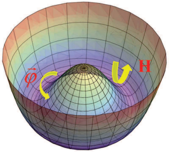
Gauge

Yukawas

EWSB

	Quarks		Leptons	
	$Q = \frac{2}{3}$	$Q = -\frac{1}{3}$	$Q = 0$	$Q = -1$
MATTER	0.002 Up	0.005 Down	< 0.000000001 ν_e Neutrino e	0.0005 Electron
	~ 1.3 Charm	~ 0.1 Strange	< 0.000000001 ν_μ Neutrino μ	0.1 Muon
	173 Top	~ 4.2 Beauty	< 0.000000001 ν_τ Neutrino τ	1.8 Tau
FORCES	0 Photon	0 Gluons	91 80 Z^0 , $W^\pm$	125 Higgs

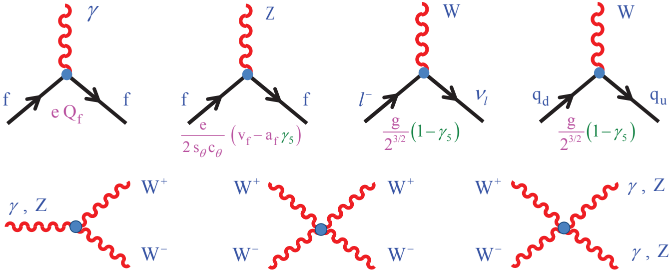
EWSB



Gauge Theories

Local Symmetries ➡ Interactions

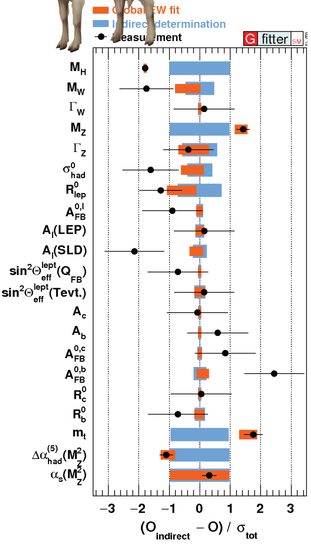
Great Achievement: QED, QCD, EW (GR also)

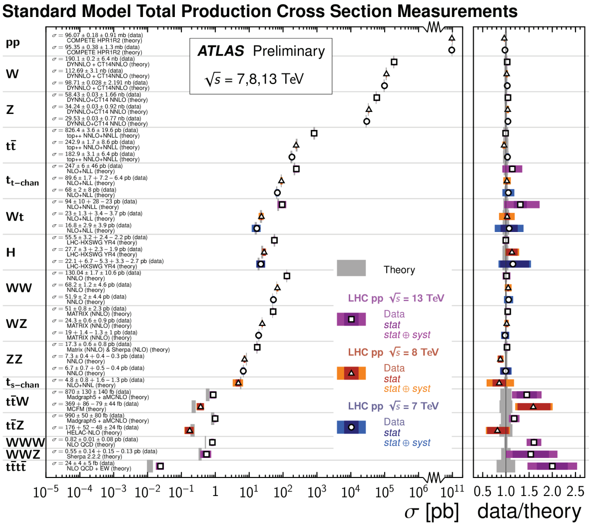


Elegant, simple and correct (3 inputs only: α_s, α, θ_W)

Everything looks SM-like at LHC

SM Greatest Of All Theories





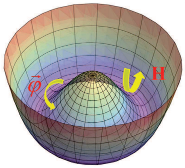
The EW symmetry needs to be broken (but not explicitly)
otherwise all fundamental particles would be massless

→

Spontaneous Symmetry Breaking

$$SU(3)_C \otimes SU(2)_L \otimes U(1)_Y \;\to\; SU(3)_C \otimes U(1)_{\rm em}$$

The SM introduces EWSB in the simplest way: (renormalizable)



1 scalar doublet (4 dof) → $\begin{cases} W_L^\pm, Z_L & (3) \\ H & (1) \end{cases}$

The Higgs arises because there is 1 dof too much

But there exist alternative options. Why this particular one?

Possible Scenarios of EWSB

❶ **SM Higgs:** Favoured by EW precision tests

❷ **Alternative perturbative EWSB:**

Scalar Doublets and singlets $\rho_{\text{tree}} = \frac{M_W^2}{M_Z^2 c_W^2} = \frac{\sum_i v_i^2 [T_i(T_i+1) - Y_i^2]}{2 \sum_i v_i^2 Y_i^2}$

❸ **Dynamical (non-perturbative) EWSB:**

Pseudo-Goldstone Higgs

Scalar Resonance

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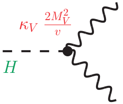
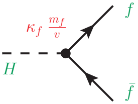
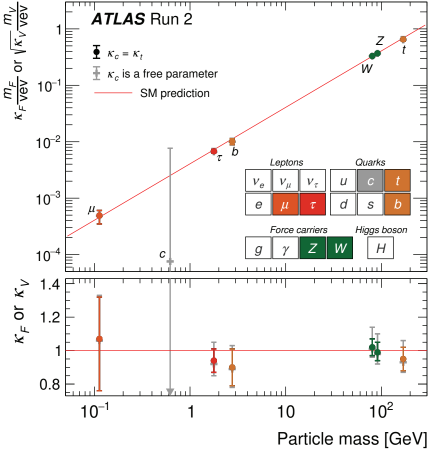
Scalar Resonance

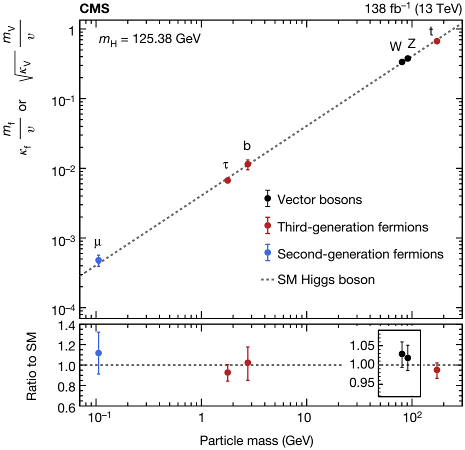
It is a Higgs





Nature 607, 52-68 (2022)



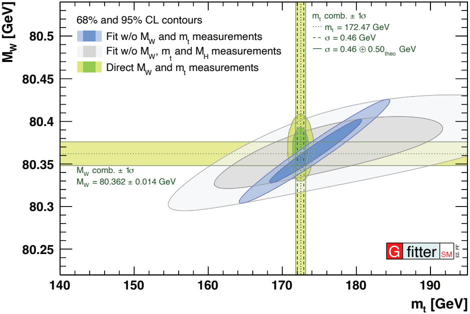


SM Higgs

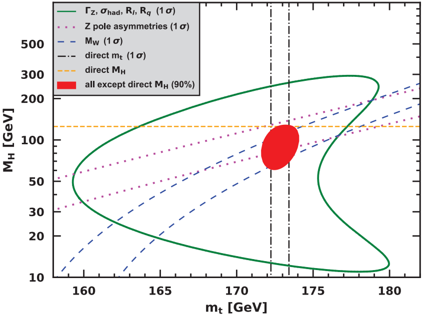
$$M_H = (125.11 \pm 0.09 \pm 0.06)\ \mathrm{GeV}$$

ATLAS 2308.04775

Yannick Fischer, EPS-HEP 2023

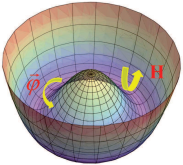


PDG 2022



Favoured by EW precision tests

SM Higgs Potential



$$\Phi(x) \;=\; \exp\left\{\frac{i}{v}\,\vec{\sigma}\,\vec{\varphi}(x)\right\}\;\frac{1}{\sqrt{2}}\;\left[\begin{array}{c} 0 \\ v + H(x)\end{array}\right]$$

$$V(\Phi) + \frac{\lambda}{4}\,v^4 \;=\; \lambda\,\left(|\Phi|^2 - \frac{v^2}{2}\right)^2 \;=\; \frac{1}{2}\,M_H^2\,H^2 \;+\; \frac{M_H^2}{2v}\,H^3 \;+\; \frac{M_H^2}{8v^2}\,H^4$$

$$v \;=\; \left(\sqrt{2}\,G_F\right)^{-1/2} \;=\; 246\ \mathrm{GeV}$$

$$M_H = (125.25 \pm 0.17)\ \mathrm{GeV} \quad \longrightarrow \quad \lambda \;=\; \frac{M_H^2}{2v^2} \;=\; 0.13$$

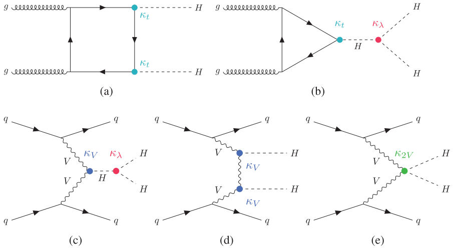
Only the valley (Goldstone modes) has been tested up to now

Higgs self-couplings needed to test the SM potential

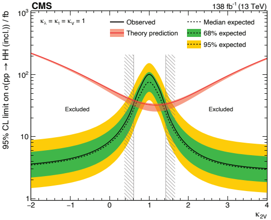
Higgs Self-coupling

Di-Higgs production

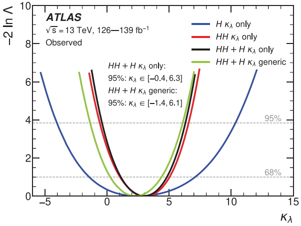
$\kappa_X \equiv g_X / g_X^{\rm SM}$



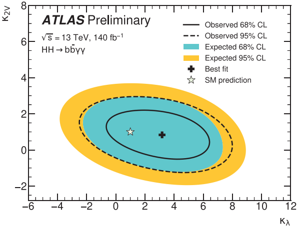
CMS 2207.00043



ATLAS 2211.01216



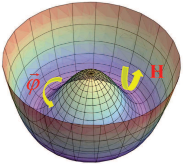
ATLAS-CONF-2023-050



$\kappa_{2V} = 0$ excluded at $6.6\,\sigma$

$\mu_{HH} \equiv \sigma(pp \to HH)/\sigma^{\rm SM} < 2.4$ (95% CL)

SM Higgs Potential



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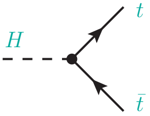
Loop corrections: $\frac{M_H^2}{2v^2} \;=\; \lambda(\mu) \;+\; \frac{2y_t^2}{(4\pi)^2}\;\left[\lambda + 3\left(y_t^2 - \lambda\right)\,\log\left(\mu/m_t\right)\right] + \cdots \qquad \left(y_t \;=\; \frac{\sqrt{2}\,m_t}{v} \approx 1\right)$

$\lambda(\mu)$ is a free parameter $\longrightarrow$ **M_H could take any value**

The heavier mass scale (top) pulls the Higgs mass $\longrightarrow$ **$M_H \sim \mathcal{O}(m_t)$**

This is not a problem. It is an experimental fact!

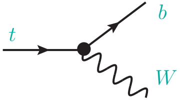
The Heaviest Mass Scale



$$y_t = \frac{\sqrt{2}}{v}\, m_t = 2^{3/4} G_F^{1/2} m_t \approx 1 \qquad (0.995)$$

The top quark:

- **Sensitive probe of Electroweak Symmetry Breaking**
- **Non-perturbative (strong) dynamics?**
- **Very different from other quarks:** $y_b = 0.025\,,\; y_c = 0.007\,\ldots$
- **Is it really a SM quark?**



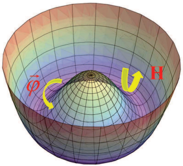
So far, we only know the decay $\mathbf{t \to W^+ b}$

$$|V_{tb}| = 1.014 \pm 0.029$$

Custodial Symmetry

$$\Sigma \equiv (\Phi^c, \Phi) = \begin{pmatrix} \Phi^{0*} & \Phi^+ \\ -\Phi^- & \Phi^0 \end{pmatrix} \equiv \frac{1}{\sqrt{2}} (v + H)\, U(\vec{\varphi})$$

$$U(\vec{\varphi}) \equiv \exp\left\{ i\, \vec{\sigma} \cdot \frac{\vec{\varphi}}{v} \right\}$$



$$\begin{aligned} \mathcal{L}_\Phi &= (D_\mu \Phi)^\dagger D^\mu \Phi - \lambda \left(|\Phi|^2 - \frac{v^2}{2} \right)^2 \\ &= \frac{1}{2} \mathrm{Tr} \left[(D^\mu \Sigma)^\dagger D_\mu \Sigma \right] - \frac{\lambda}{4} \left(\mathrm{Tr}\left[\Sigma^\dagger \Sigma \right] - v^2 \right)^2 \\ &= \frac{v^2}{4} \mathrm{Tr} \left[(D^\mu U)^\dagger D_\mu U \right] + O(H/v) \end{aligned}$$

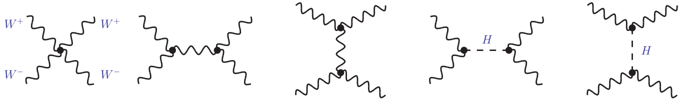
$SU(2)_L \otimes SU(2)_R \to SU(2)_{L+R}$ **Global Symmetry:** $\Sigma \to g_L\, \Sigma\, g_R^\dagger$

Same Goldstone Lagrangian as QCD pions $(f_\pi \to v\ ,\ \vec{\pi} \to \vec{\varphi} \to W_L^\pm, Z_L\ )$

EW Goldstones are responsible for $M_{W,Z}$ **(not the Higgs!)**

$W_L^+ W_L^- \to W_L^+ W_L^-$:

$\epsilon_L^\mu(\vec{k}) \sim \frac{k^\mu}{M_W}$ ➡ $T \sim g^2 \, \frac{|\vec{k}|^4}{M_W^4}$



$$T_{\rm SM} = \frac{1}{v^2}\left\{ s + t - \frac{s^2}{s - M_H^2} - \frac{t^2}{t - M_H^2} \right\} = -\frac{M_H^2}{v^2}\left\{ \frac{s}{s - M_H^2} + \frac{t}{t - M_H^2} \right\}$$

- **Exact gauge cancellation among the first 3 diagrams**

  Equivalence theorem: $T_{\rm Gauge} = T(\varphi^+\varphi^- \to \varphi^+\varphi^-) = \frac{s+t}{v^2} + \mathcal{O}\left(\frac{M_W}{\sqrt{s}}\right)$

  Goldstone dynamics ⟷ derivative interactions ⟷ $T \sim E^2$

- **Higgs-exchange exactly cancels the O(s, t) terms in the SM**

  When $s \gg M_H^2$: $T_{\rm SM} \approx -\frac{2M_H^2}{v^2}$, $a_0 \equiv \frac{1}{32\pi}\int_{-1}^{1} d\cos\theta \; T_{\rm SM} \approx -\frac{M_H^2}{8\pi v^2}$

- **Perturbative unitarity:** $|a_0| \leq 1$ ➡ $\mathbf{M_H < \sqrt{8\pi}\,v} \; \underbrace{\sqrt{2/3}}_{W^+W^-,\, ZZ,\, HH} \approx$ **1 TeV**

$W_L^+ W_L^- \to W_L^+ W_L^-$:

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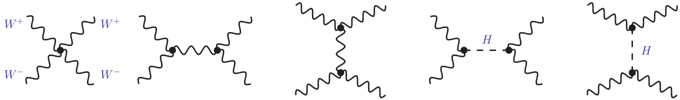

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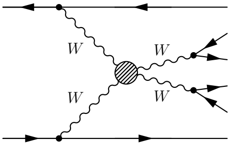
Deviations from the SM couplings imply bad UV behaviours

➡ **New states needed to restore unitarity**

Highly sensitive test but very challenging experimentally



Small signal

Huge backgrounds

Polarization

Flavour Dynamics: $N_G = 3$ Fermion Families

$$\Phi = \begin{pmatrix} \phi^{(+)} \\ \phi^{(0)} \end{pmatrix} \rightarrow \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v + H \end{pmatrix} \qquad , \qquad \tilde{\Phi} \equiv i\tau_2 \Phi^* = \begin{pmatrix} \phi^{(0)\dagger} \\ -\phi^{(+)\dagger} \end{pmatrix} \rightarrow \frac{1}{\sqrt{2}} \begin{pmatrix} v + H \\ 0 \end{pmatrix}$$

$$\mathcal{L}_Y = -\sum_{jk} \left\{ (\bar{u}'_j, \bar{d}'_j)_L \left[c^{(d)}_{jk}\, \Phi\, d'_{kR} + c^{(u)}_{jk}\, \tilde{\Phi}\, u'_{kR} \right] - (\bar{\nu}'_j, \bar{\ell}'_j)_L\, c^{(\ell)}_{jk}\, \Phi\, \ell'_{kR} \right\} + \text{h.c.}$$

↓ **SSB**

$$\mathcal{L}_Y = -\left(1 + \frac{H}{v}\right) \left\{ \bar{d}'_L \cdot M'_d \cdot d'_R + u'_L \cdot M'_u \cdot u'_R + \ell'_L \cdot M'_\ell \cdot \ell'_R + \text{h.c.} \right\}$$

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$\mathcal{L}_Y$ breaks the huge flavour symmetry of the SM Gauge Theory

$$U(N_G)_{L_L} \otimes U(N_G)_{Q_L} \otimes U(N_G)_{\ell_R} \otimes U(N_G)_{u_R} \otimes U(N_G)_{d_R}$$

Main source of unknown parameters in the SM framework

What's the dynamical origin of the Yukawa couplings $c_{jk}^{(d)}$?

Flavour Dynamics: $N_G = 3$ Fermion Families

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↓ SSB

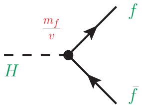
$$\mathcal{L}_Y = -\left(1 + \frac{H}{v}\right) \left\{ \bar d'_L \cdot M'_d \cdot d'_R + u'_L \cdot M'_u \cdot u'_R + \ell'_L \cdot M'_\ell \cdot \ell'_R + \text{h.c.} \right\}$$

Arbitrary (non-diagonal, complex) Yukawa couplings/mass matrices

$$(M'_f)_{jk} = c^{(f)}_{jk}\, \frac{v}{2}$$

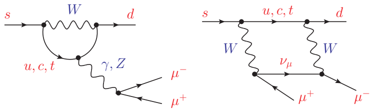
Diagonalization ⟶

- $g_{Hff} = m_f / v$
- **CKM Quark Mixing**
- **CP violation**
- **GIM Mechanism**



No Flavour-Changing Neutral Currents

Successful Description of Flavour & CP



Rare Decays

$$\mathrm{Br}(K_L^0 \to \mu^+\mu^-) = 6.8 \times 10^{-9}$$

$$\mathrm{Br}(B_s^0 \to \mu^+\mu^-) = 3.0 \times 10^{-9}$$

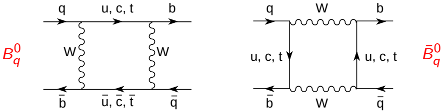
$$\mathrm{Br}(\bar{b} \to \bar{s}\gamma) = 3.1 \times 10^{-4}$$

Meson-Antimeson Mixing

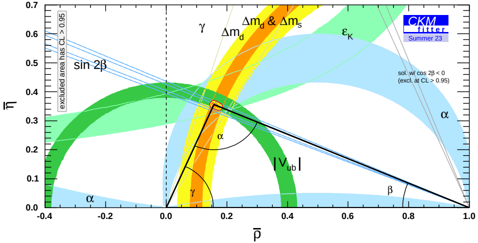
$$\Delta M_{K^0} / M_{K^0} = 7.0 \times 10^{-15}$$

$$\Delta M_{B_d^0} / M_{B_d^0} = 6.3 \times 10^{-14}$$

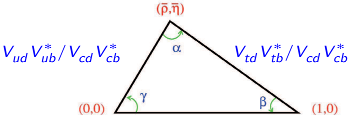
$$\Delta M_{B_s^0} / M_{B_s^0} = 2.2 \times 10^{-12}$$



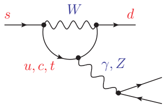
$$V_{ud} V_{ub}^* + V_{cd} V_{cb}^* + V_{td} V_{tb}^* = 0$$

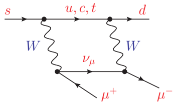


CKM Unitarity



Successful Description of Flavour & CP





Rare Decays

$$\mathrm{Br}(K_L^0 \to \mu^+\mu^-) = 6.8 \times 10^{-9}$$

$$\mathrm{Br}(B_s^0 \to \mu^+\mu^-) = 3.0 \times 10^{-9}$$

$$\mathrm{Br}(\bar{b} \to \bar{s}\gamma) = 3.1 \times 10^{-4}$$

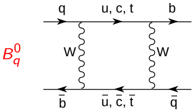
Sensitivity to (virtual) heavy scales

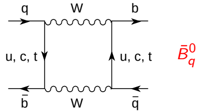
Meson-Antimeson Mixing

$\Delta M_{K^0}/M_{K^0} = 7.0 \times 10^{-15}$ ➡ m_c

$\Delta M_{B_d^0}/M_{B_d^0} = 6.3 \times 10^{-14}$ ➡ m_t

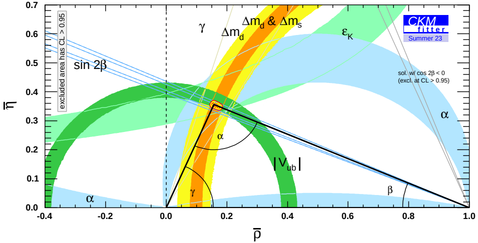
$\Delta M_{B_s^0}/M_{B_s^0} = 2.2 \times 10^{-12}$ ➡ m_t



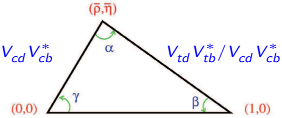


B_q^0 $\bar{B}_q^0$

$$V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0$$

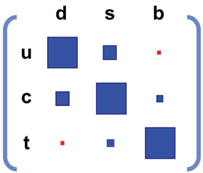


CKM Unitarity



$V_{ud}V_{ub}^*/V_{cd}V_{cb}^*$ $V_{td}V_{tb}^*/V_{cd}V_{cb}^*$

CKM Structure



Highly non-generic

$$\mathcal{CP} \sim J \approx A^2\lambda^6\eta < 10^{-4}$$

$$\mathbf{V} = \begin{bmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{bmatrix} + \mathcal{O}\left(\lambda^4\right)$$

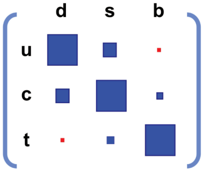
UT$_{fit}$

$$\bar{\eta} \equiv \eta\left(1-\tfrac{1}{2}\lambda^2\right) = 0.345 \pm 0.011$$

$$\bar{\rho} \equiv \rho\left(1-\tfrac{1}{2}\lambda^2\right) = 0.160 \pm 0.009$$

$$A = 0.827 \pm 0.010 \quad ; \quad \lambda = 0.2251 \pm 0.0008$$

CKM Structure



Highly non-generic

$$\not{C}\not{P} \sim J \approx A^2\lambda^6\eta < 10^{-4}$$

$$\mathbf{V} = \begin{bmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{bmatrix} + \mathcal{O}\left(\lambda^4\right)$$

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$$A = 0.827 \pm 0.010 \quad ; \quad \lambda = 0.2251 \pm 0.0008$$

Bounds on New Physics

(Isidori, 1302.0661)

$$\mathcal{L}_{\rm eff} = \mathcal{L}_{\rm SM} + \sum_{D>4}\sum_k \frac{c_k^{(D)}}{\Lambda_{\rm NP}^{D-4}}\, O_k^{(D)}$$

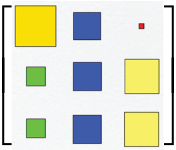
Operator	Bounds on Λ in TeV ($c_{\rm NP}=1$) Re	Im	Bounds on $c_{\rm NP}$ ($\Lambda = 1$ TeV) Re	Im	Observables
$(\bar{s}_L\gamma^\mu d_L)^2$	9.8×10^2	1.6×10^4	9.0×10^{-7}	3.4×10^{-9}	Δm_K; ϵ_K
$(\bar{s}_R d_L)(\bar{s}_L d_R)$	1.8×10^4	3.2×10^5	6.9×10^{-9}	2.6×10^{-11}	Δm_K; ϵ_K
$(\bar{c}_L\gamma^\mu u_L)^2$	1.2×10^3	2.9×10^3	5.6×10^{-7}	1.0×10^{-7}	Δm_D; $\lvert q/p\rvert, \phi_D$
$(\bar{c}_R u_L)(\bar{c}_L u_R)$	6.2×10^3	1.5×10^4	5.7×10^{-8}	1.1×10^{-8}	Δm_D; $\lvert q/p\rvert, \phi_D$
$(\bar{b}_L\gamma^\mu d_L)^2$	6.6×10^2	9.3×10^2	2.3×10^{-6}	1.1×10^{-6}	Δm_{B_d}; $S_{\psi K_S}$
$(\bar{b}_R d_L)(\bar{b}_L d_R)$	2.5×10^3	3.6×10^3	3.9×10^{-7}	1.9×10^{-7}	Δm_{B_d}; $S_{\psi K_S}$
$(\bar{b}_L\gamma^\mu s_L)^2$	1.4×10^2	2.5×10^2	5.0×10^{-5}	1.7×10^{-5}	Δm_{B_s}; $S_{\psi\phi}$
$(\bar{b}_R s_L)(\bar{b}_L s_R)$	4.8×10^2	8.3×10^2	8.8×10^{-6}	2.9×10^{-6}	Δm_{B_s}; $S_{\psi\phi}$

$\Lambda_{\rm NP} \sim \mathcal{O}(\rm TeV)$ **requires** $c_{\rm NP}$ **to inherit the strong SM suppressions (GIM)**

→ **Minimal Flavour Violation: The Yukawa matrices are the only source of quark-flavour symmetry breaking** (D'Ambrosio et al, Buras et al)

Lepton Mixing has a different structure

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} =$$



$$\begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

Flavour eigenstates ↑ ↑ Mass eigenstates

NuFIT 5.2 (2022)

$$|U|_{3\sigma}^{\text{with SK-atm}} = \begin{pmatrix} 0.803 \to 0.845 & 0.514 \to 0.578 & 0.143 \to 0.155 \\ 0.244 \to 0.498 & 0.502 \to 0.693 & 0.632 \to 0.768 \\ 0.272 \to 0.517 & 0.473 \to 0.672 & 0.623 \to 0.761 \end{pmatrix}$$

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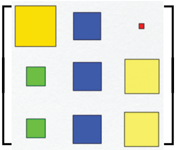

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$$\mathrm{Im}\left(U_{\alpha i} U^*_{\alpha j} U^*_{\beta i} U_{\beta j}\right) \equiv \sum_{\gamma=e,\mu,\tau} \sum_{k=1,2,3} J_{\mathrm{CP}}\, \epsilon_{\alpha\beta\gamma}\, \epsilon_{ijk} \equiv J_{\mathrm{CP}}^{\max} \sin\delta_{\mathrm{CP}}$$

PDG 2022: $J_{\mathrm{CP}}^{\max} = 0.03359 \pm 0.0006$ $(\pm 0.0019 \text{ at } 3\sigma)$

Data preference for $\delta_{\mathrm{CP}} \neq 0$ ➡ $J_{\mathrm{CP}}^{\mathrm{best}} = -0.019$

Flavour Puzzles

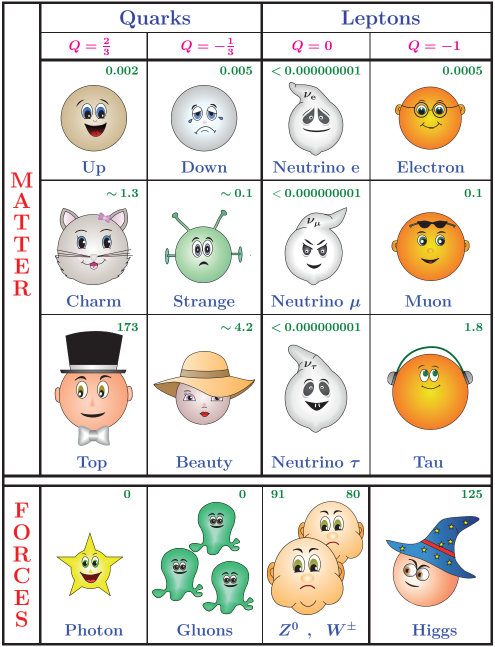
- **Dynamical origin of flavour**
- **Hierarchy of fermion masses**

  $m_{\nu_i} < 0.8$ eV, $\sqrt{\Delta m^2_{21}} \sim 0.009$ eV

  $m_c \sim 1.3 \cdot 10^9$ eV, $m_t \sim 1.7 \cdot 10^{11}$ eV
- **Mixing structure**
- **CP violation**

  Matter-antimatter asymmetry
- **Sterile ν_R ? ν mass scale?**
- **Dirac or Majorana ν ?**
- **B and L conservation**

  Accidental symmetries of the SM



Interesting Anomalies

$b \to c\tau\nu$, $b \to s\,\mu^+\mu^-$, $\tau^\pm \to \pi^\pm K_S \nu$, $B \to K\nu\bar{\nu}$, V_{ub} , V_{ud} , V_{us} , $\Delta a^{D^0}_{\mathrm{CP}}$

$(g-2)_{\mu,e}$ (?), ν anomalies (LSND/MiniBooNE, Gallium experiments, $\cdots$), $\cdots$

Many already gone:

$B \to \tau\nu$, $W \to \tau\nu$, $\varepsilon'_K/\varepsilon_K$, ε_K , V_{cb} , R_K, $(g-2)_{\mu,e}$ (?), $\cdots$

Also in high-E searches: WW, multilepton, diphoton bumps (95, 152, 680 GeV), dijets, $\cdots$

Usual explanation: **statistical fluctuation, underestimated systematics, . . .**

Worth a careful investigation

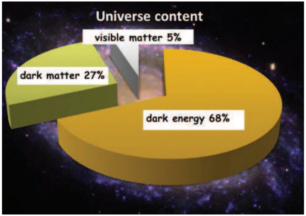
Precision measurements could uncover signals of new underlying dynamics

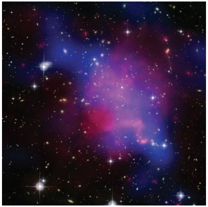
... and there is

Dark Matter

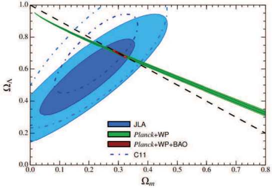
(and dark energy)

We only know 5% of the Universe





J. Liske, EPS-HEP 2023



DM does not emit light but has mass

Does it interact with the Higgs field?

Can it be produced at high-energy colliders?

Status & Outlook

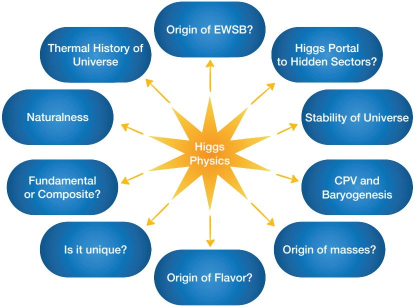
- The **SM** appears to be the **right theory at the EW scale**
- The ***H*(125)** behaves as the SM scalar boson
- The **CKM** mechanism works very well
- Neutrinos do have (tiny) masses. **Lepton flavour is violated**
- Different **flavour structure** for quarks & leptons
- **New physics needed** to explain many pending questions: **Flavour, CP, baryogenesis, dark matter, cosmology. . .**
- **The Higgs could be related to most of these questions**

- **Large room for New Physics nearby**
- **How far is the Scale of New-Physics?**
- **Which kind of New Physics?**

A New Force has been discovered

The Higgs field

- It is not a gauge interaction $(J = 0)$
- Related to many open questions
- We have just started to explore it



Higgs @ Snowmass 2021, 2209.07510

A thorough investigation of the Higgs force should be a priority goal of current and future HEP experiments

Awaiting great discoveries @ LHC
and/or Future Colliders

Backup

Beautiful Discovery

Boson, $J = 0$

Fermions = Matter ; Bosons = Forces

- **Fundamental Boson:** **New interaction which is not gauge**
- **Composite Boson:** **New underlying dynamics**

Beautiful Discovery

Boson, $J = 0$

Fermions = Matter ; Bosons = Forces

- **Fundamental Boson:** **New interaction which is not gauge**
- **Composite Boson:** **New underlying dynamics**

If New Physics exists at Λ_{NP}

$$\delta M_H^2 \sim \frac{g^2}{(4\pi)^2} \Lambda_{\mathrm{NP}}^2 \log\left(\frac{\Lambda_{\mathrm{NP}}^2}{M_H^2}\right)$$

Which symmetry keeps M_H away from Λ_{NP}?

- Fermions: Chiral Symmetry
- Gauge Bosons: Gauge Symmetry
- Scalar Bosons: Supersymmetry, Scale/Conformal Symmetry . . . ?

Which symmetry keeps M_H away from Λ_{NP} ?

Quantum Stability: Vectors/fermions protected by gauge/chiral symmetries

Spin, Mass & Degrees of Freedom

	$J = 1$	$J = \frac{1}{2}$	$J = 0$
$M = 0$	2 d.o.f. Trans. Pol.	2 d.o.f. ψ_L	1 d.o.f.
$M \neq 0$	3 d.o.f. Trans & Long.	4 d.o.f. ψ_L, ψ_R	1 d.o.f.

Vector $(2 \neq 3)$ and fermion $(2 \neq 4)$ masses are safe

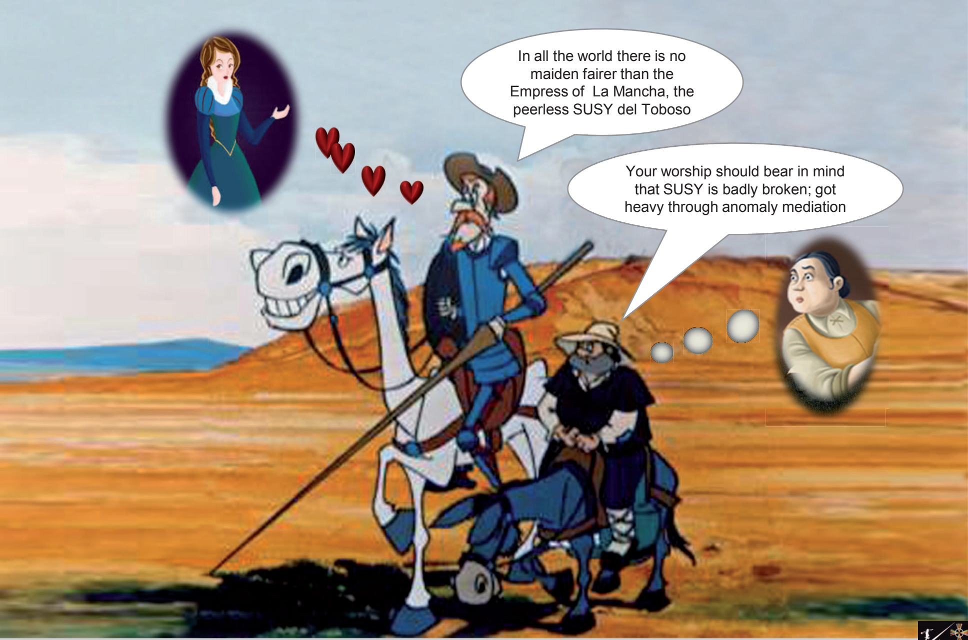
Scalar masses not protected (continuous $m \to 0$ limit)

Proposed Solutions:

- **SUSY.-** Symmetry relates bosons to fermions
- **Composite Higgs.-** Higgs made of fermion constituents
- **Pseudo-Goldstone Higgs.-**

Don Quixote and the Windmills

Desperately Seeking SUSY (Dulcinea)



Electroweak Symmetry Breaking

$$\mathcal{L}_2 = \frac{v^2}{4}\,\mathrm{Tr}\left(D_\mu U^\dagger D^\mu U\right) \quad \xrightarrow{U=1} \quad \mathcal{L}_2 = M_W^2\, W_\mu^\dagger W^\mu + \frac{1}{2}\, M_Z^2\, Z_\mu Z^\mu$$

$$\mathbf{M_W} = \mathbf{M_Z}\,\cos\theta_\mathbf{W} = \tfrac{1}{2}\,\mathbf{g\,v}$$

$$D^\mu U = \partial^\mu U - i\,\hat{W}^\mu U + i\,U\,\hat{B}^\mu \qquad , \qquad D^\mu U^\dagger = \partial^\mu U^\dagger + i\,U^\dagger \hat{W}^\mu - i\,\hat{B}^\mu U^\dagger$$

$$\hat{W}^\mu = -\tfrac{g}{2}\,\vec{\sigma}\cdot\vec{W}^\mu \qquad , \qquad \hat{B}^\mu = -\tfrac{g'}{2}\,\sigma_3\,B^\mu$$

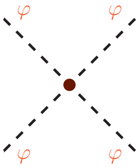
(explicit symmetry breaking)

- **EW Goldstones are responsible for $\mathbf{M_{W,Z}}$ (not the Higgs!)**
- **QCD pions also generate small W, Z masses:** $\delta_\pi \mathbf{M_W} = \dfrac{1}{2}\,\mathbf{g\,f_\pi}$

Goldstone interactions are determined by the underlying symmetry

$$U(\vec{\varphi}\,) \;\equiv\; \exp\left\{ i\,\vec{\sigma}\cdot\frac{\vec{\varphi}}{v}\right\}$$

$$\begin{aligned}
\frac{v^2}{4}\,\mathrm{Tr}\left(\partial_\mu U^\dagger \partial^\mu U\right) \;=\;& \partial_\mu\varphi^-\partial^\mu\varphi^+ + \frac{1}{2}\,\partial_\mu\varphi^0\partial^\mu\varphi^0 \\
&+\; \frac{1}{6v^2}\left\{\left(\varphi^+\overleftrightarrow{\partial}_\mu\,\varphi^-\right)\left(\varphi^+\overleftrightarrow{\partial}^\mu\varphi^-\right) + 2\left(\varphi^0\overleftrightarrow{\partial}_\mu\,\varphi^+\right)\left(\varphi^-\overleftrightarrow{\partial}^\mu\varphi^0\right)\right\} \\
&+\; O\left(\varphi^6/v^4\right)
\end{aligned}$$



$$T\left(\varphi^+\varphi^- \to \varphi^+\varphi^-\right) \;=\; \frac{s+t}{v^2}$$

Non-Linear Lagrangian: $2\varphi \to 2\varphi\,,\; 4\varphi\,,\;\cdots$ related