# Flavour Physics

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# Outline

1. Flavour in the Standard Model
   - The Flavour Problem
2. Flavour Beyond the Standard Model
   - The Flavour Solution (?)
3. Conclusion

# The Standard Model

Gauge group: $SU(3)_C \times SU(2)_L \times U(1)_Y$

Chiral spin $1/2$ fermions (left and right)
Quarks: colour triplets of $SU(3)_C$
Left fermions are doublets of $SU(2)_L$
Spin 0 scalar, doublet of $SU(2)_L$

# The Standard Model (1 generation)

Gauge group: $SU(3)_C \times SU(2)_L \times U(1)_Y$

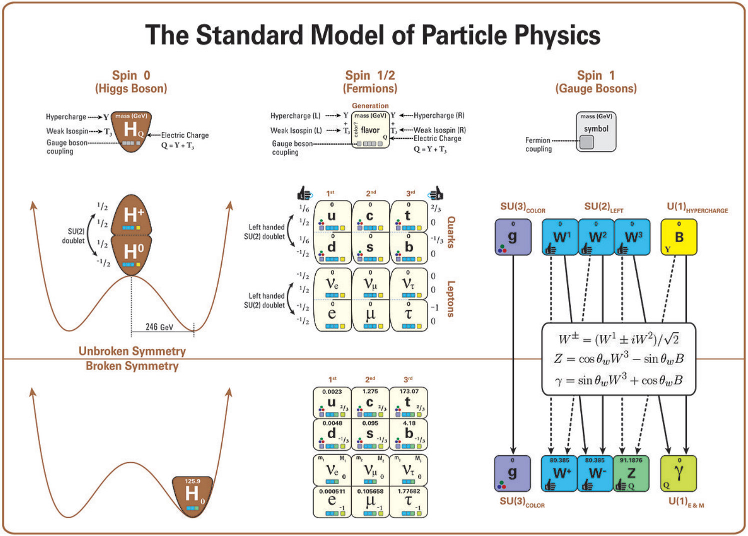
Quarks ($Q$, $u_R$, $d_R$): colour triplets of $SU(3)_C$
LH fields ($Q$ and $L$): doublets of $SU(2)_L$
$e_R$ just $U(1)_Y$
($\nu$SM: add $\nu_R$, complete singlet)

Scalar $H$ also doublet of $SU(2)_L$
$\langle H \rangle$ breaks $SU(2)_L \times U(1)_Y \to U(1)_{em}$

Mass terms: $m_f F_\alpha f_R$ not invariant under $SU(2)_L$

But $y_f(\epsilon^{\alpha\beta} H_\alpha F_\beta) f_R$ is...
$y_f \langle H \rangle F f_R \to m_f F f_R$ with $m_f = y_f \langle H \rangle$

# The Standard Model summary



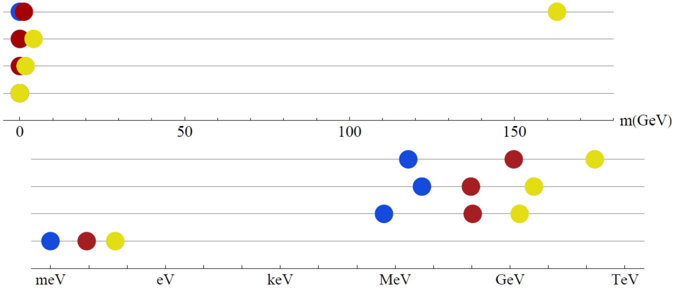
# The Standard Model is very successful but...

- Neutrinos have masses ($\nu$SM)
- Dark matter (no viable explanation)
- Matter / antimatter asymmetry (no viable explanation)
- Hierarchy problem (fine-tuning between parameters)
- Strong CP problem (fine-tuning between parameters)
- Gauge couplings (additional free parameters) - GUT?
- Flavour problem (many additional free parameters) - FS?

BSM solutions involve additional fields and symmetries

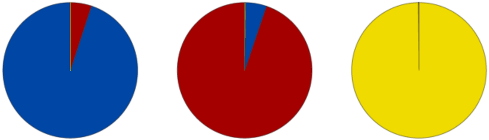
# The Standard Model flavour problem: masses

3 fermion generations? Masses span orders of magnitude?



# The Standard Model flavour problem: mixing

3 generations of quarks, small mixing



3 generations of leptons, large and peculiar mixing

(mixing between weak and mass eigenstates)

# Summary of data: quark mixing

## Wolfenstein parametrisation

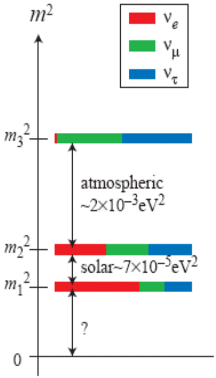
$$V_{CKM} \simeq \begin{pmatrix} 1 & \lambda & \lambda^3 \\ -\lambda & 1 & \lambda^2 \\ \lambda^3 & -\lambda^2 & 1 \end{pmatrix}$$

$\lambda \simeq 0.23$ (Sine of the Cabibbo angle)

# Summary of data: lepton mixing

## Tri-bi-maximal (TBM) mixing

$$V_{PMNS} \simeq \begin{pmatrix} -\sqrt{\frac{2}{3}} & \sqrt{\frac{1}{3}} & 0 \\ \sqrt{\frac{1}{6}} & \sqrt{\frac{1}{3}} & \sqrt{\frac{1}{2}} \\ \sqrt{\frac{1}{6}} & \sqrt{\frac{1}{3}} & -\sqrt{\frac{1}{2}} \end{pmatrix}$$



# Beyond the Standard Model with Family Symmetry

Without $y_f H F f_R$, $\mathcal{L}_{\nu SM}$ has accidental symmetry $SU(3)^6$

FS: upgrade subgroup of $SU(3)^6$ to actual symmetry of $\mathcal{L}$

1. Generations charged differently under FS
2. Yukawa couplings no longer invariant
3. FS must be broken somehow...

# Abelian example: $U(1)$ FS + single familon

## $U(1)$ assignments

| Field | $U(1)$ |
|---|---|
| $H$ | **0** |
| $\phi$ | **$-1$** |
| $Q_3$ | **0** |
| $d_{R3}$ | **0** |
| $Q_2$ | **1** |
| $d_{R2}$ | **1** |
| $Q_1$ | **2** |
| $d_{R1}$ | **2** |

$$\mathcal{L}_d = H(y_{33} Q_3 d_{R3} + \\ y_{23}(\phi/M_X) Q_2 d_{R3} + \\ y_{32}(\phi/M_X) Q_3 d_{R2} + \\ y_{22}(\phi/M_X)^2 Q_2 d_{R2} + \ldots)$$

## Respective mass matrix

$$M_d \sim m_b \begin{pmatrix} \epsilon^4 & \epsilon^3 & \epsilon^2 \\ \epsilon^3 & \epsilon^2 & \epsilon \\ \epsilon^2 & \epsilon & 1 \end{pmatrix}$$

$$\frac{\langle\phi\rangle}{M_X} = \epsilon$$

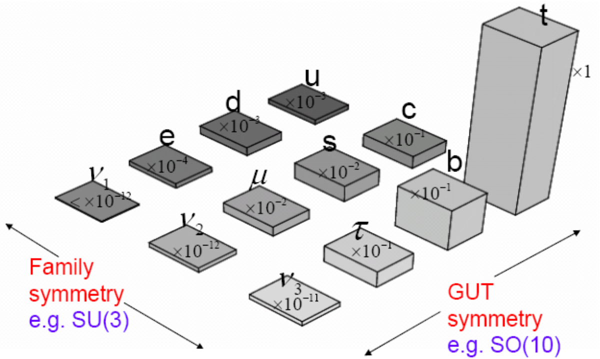
Each entry has a $y_{ij}$ parameter!

# Non-Abelian?

## 3 reasons

- 3 generations explained naturally
- $\nu$SM: FS $\subset SU(3)^6$; $SO(10)$ GUT: FS $\subset SU(3)$
- Lepton mixing strongly suggests non-Abelian FS

# $SO(10) \times SU(3)$?



# Discrete?

## 2 generation example

- $V = -m^2(\varphi^i \varphi_i^\dagger) + \lambda(\varphi^i \varphi_i^\dagger)(\varphi^j \varphi_j^\dagger)$ continuous vaccua
  $\pm d(\varphi^i \varphi_i^\dagger \varphi^i \varphi_i^\dagger)$ discrete vaccua, special directions
- Extrema of $|\varphi_1|^4 + |\varphi_2|^4$ for fixed magnitude $v$:
  Positive: $\propto (1,1)/\sqrt{2} \rightarrow V \sim +2v^4/4$
  Negative: $\propto (0,1) \rightarrow V \sim -v^4$

# Summary FS

**Interlude**

- Discrete symmetries have some interesting advantages
- Magnitudes: Abelian; predictions: non-Abelian
- Very natural extension beyond the SM