University of Basel

SWISS NATIONAL SCIENCE FOUNDATION
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Lectures on **BSM in flavour**

Admir Greljo

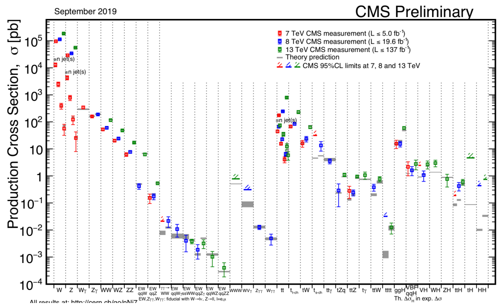
28.08.2023, Ljubljana

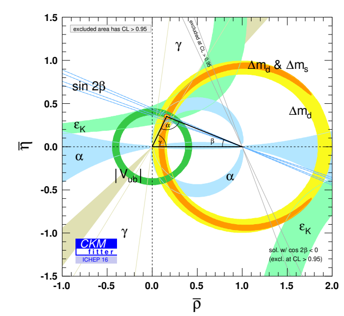
Literature

- The lecture notes by Yosef Nir:
  https://inspirehep.net/files/c8e5ccbd83d29b5d61fb2cb732886430
- Lecture series by Gino Isidori:
  https://indico.cern.ch/event/810847/
- The lecture notes by Jure Zupan:
  https://arxiv.org/pdf/1903.05062.pdf
- Lectures by Yuval Grossman & Filip Tanedo:
  https://arxiv.org/pdf/1711.03624.pdf

Confusing situation!

1. The SM: Experimental success!



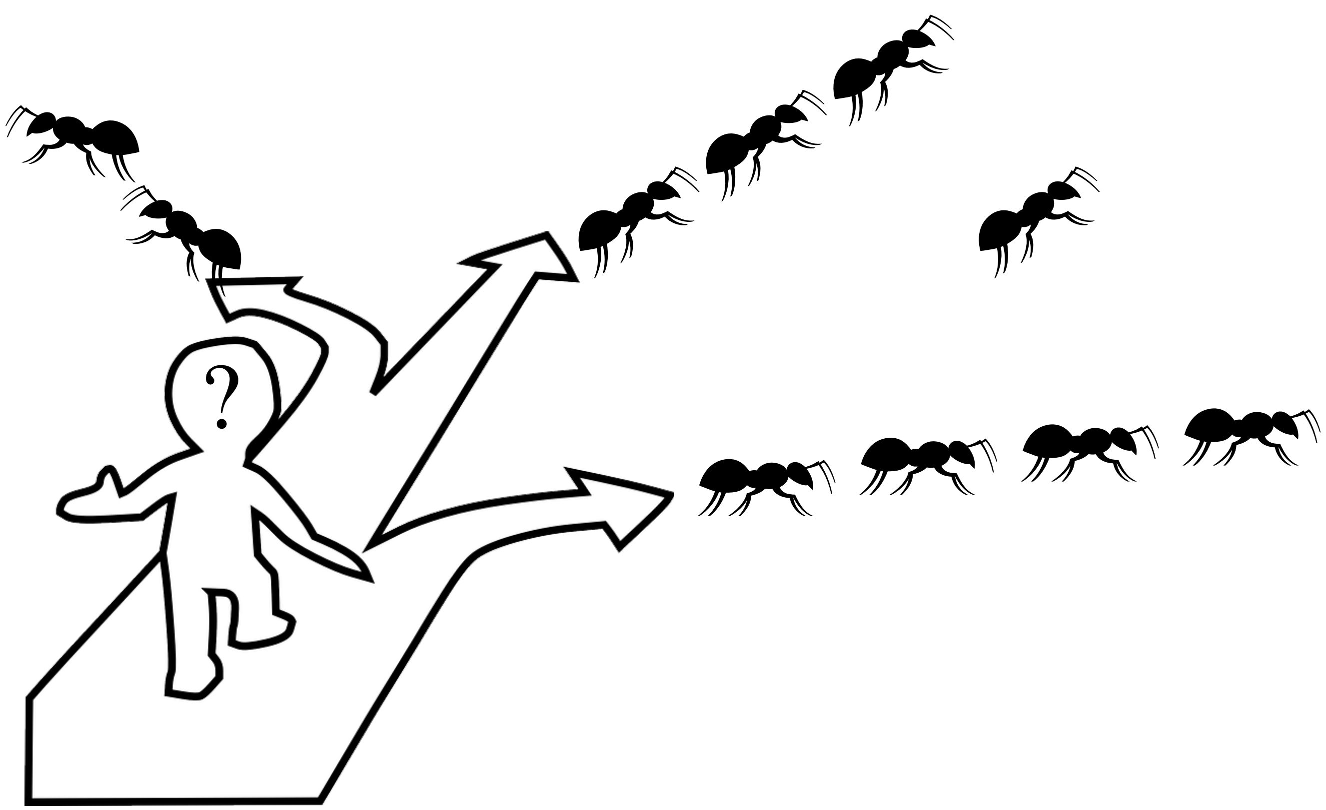


2. Yet, many open questions:

Hierarchy problem
Flavour puzzle
Strong CP problem
Charge quantization

Dark matter
Baryon asymmetry
Neutrino masses
Inflation

Dark energy
Quantum gravity
….



Beyond the SM

Why is flavour physics interesting for BSM?

1. **Indirect discovery**
   Flavor physics can discover new states before they are directly observed in colliders. Historical examples are charm and top quarks.

History

- Charm quark
  - Postulated to explain $\Gamma(K \to \mu\mu) \ll \Gamma(K \to \mu\nu)$ (GIM '70)
  - Mass estimated from Δm_K (GL '74)
  - Direct discovery (SLAC/BNL '74)
- Third-generation quarks
  - Postulated to explain $\epsilon_K \neq 0$ (KM '73)
  - Top quark mass estimated from Δm_B ('86)
  - Direct discovery: b (FNAL '77), t (FNAL '95)

Flavour physics:
a trailblazer for direct searches!

*Also, direct discovery possible, e.g. $K \to \pi a$

Why is flavour physics interesting for BSM?

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2. **CP violation**
   Baryogenesis tells us there must exist new sources of CP violation.

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   Peculiar structure of observed fermion masses and mixings. BSM explanation?

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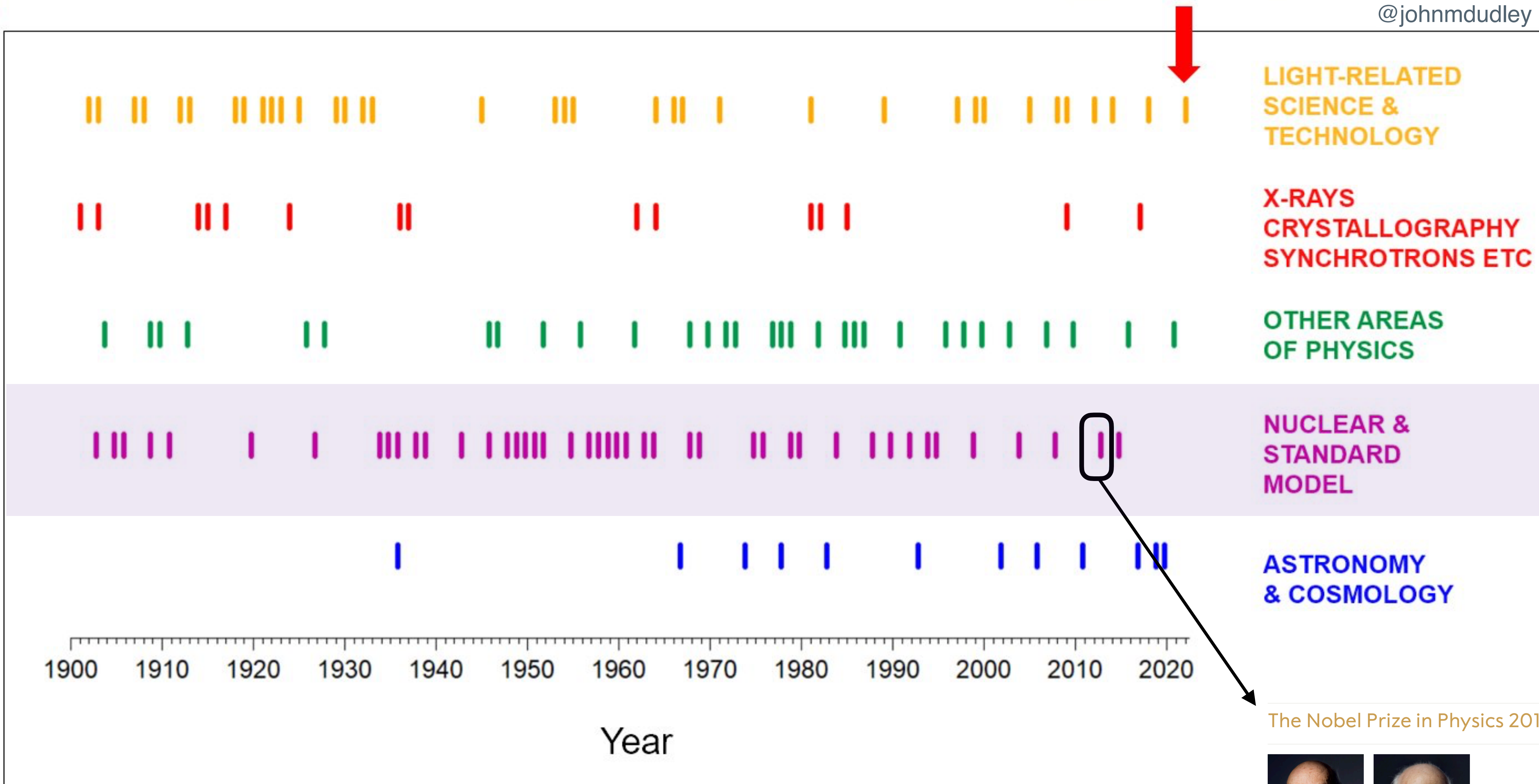
3. **The SM flavour puzzle**
   Peculiar structure of observed fermion masses and mixings. BSM explanation?
4. **The NP flavour puzzle**
   The fine-tuning problem of the Higgs mass implies that there exists new physics at, or below, the TeV scale. If such new physics had a generic flavor structure, it would contribute to FCNC processes orders of magnitude above the observed rates. Why is this not the case?

Part I

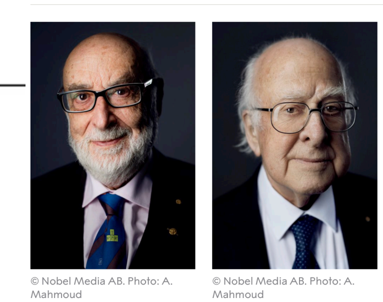
- Matter, Forces, Fields
- Flavour
- The Standard Model
- Global Flavor Symmetries
- Parameter counting
- Interaction & mass bases
- The CKM matrix
- Quiz

Matter, Forces, Fields

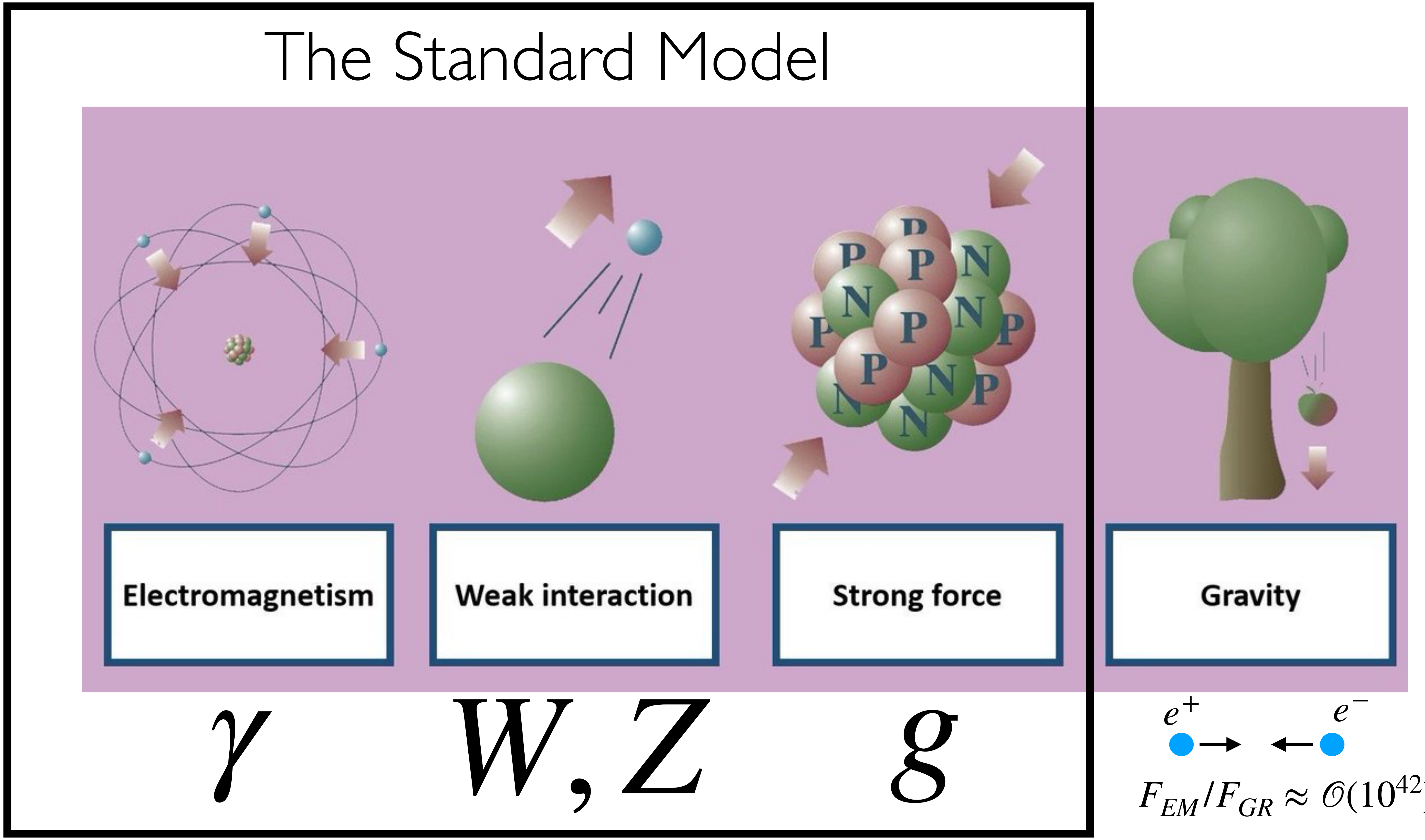
A timeline of the Nobel Prize



The Nobel Prize in Physics 2013



Fundamental forces



Gauge symmetry!

$$\phi(x) \to e^{i\alpha(x)}\phi(x)$$

Quantum fields

- The Basic Building Blocks of the Universe

Operator on the Hilbert space of particle states

$$\hat{\phi}(x)$$

Function of spacetime

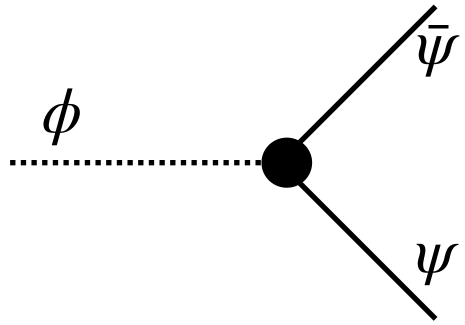
Quantum + Fields $=$ Particles are **ripples (excitations)** of fields tied into little parcels of energy due to quantum mechanics.

All electrons in the universe are identical copies of each other. They are excitations of a single electron field.

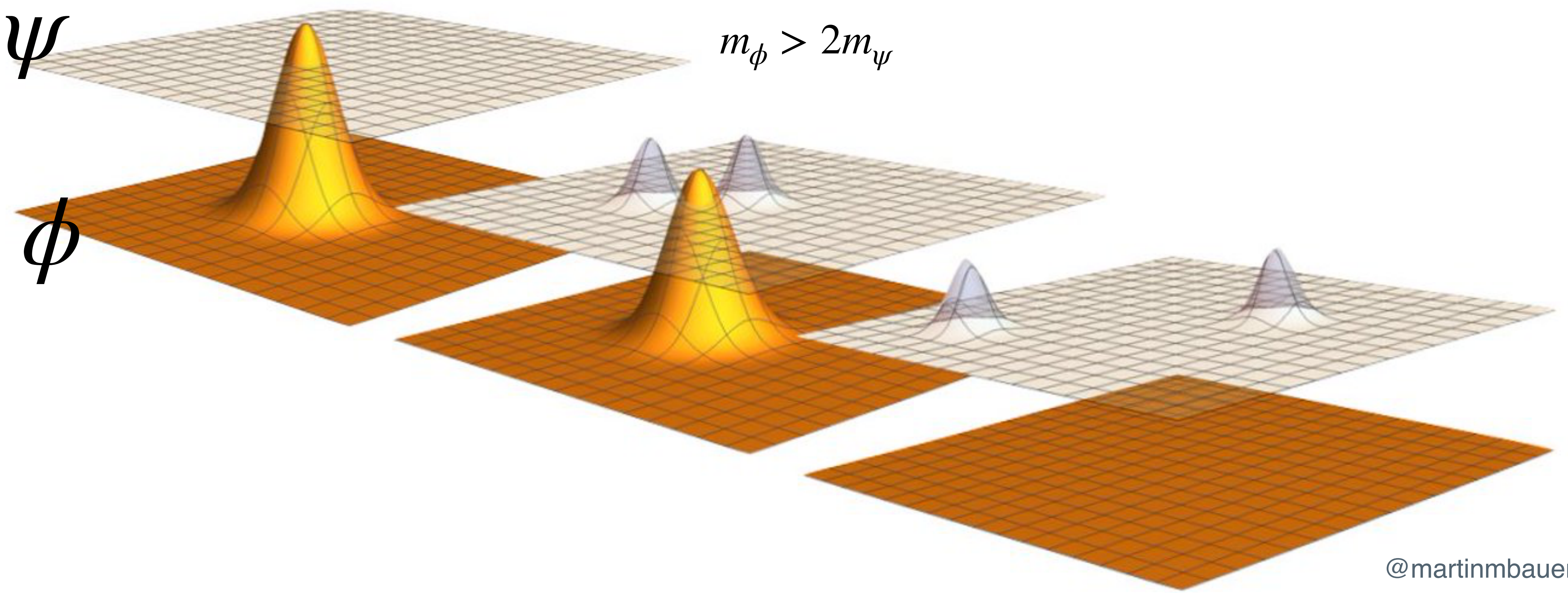
Quantum fields

- Local interactions:

$$\mathscr{L}(x) \supset y\,\phi(x)\bar{\psi}(x)\psi(x)$$



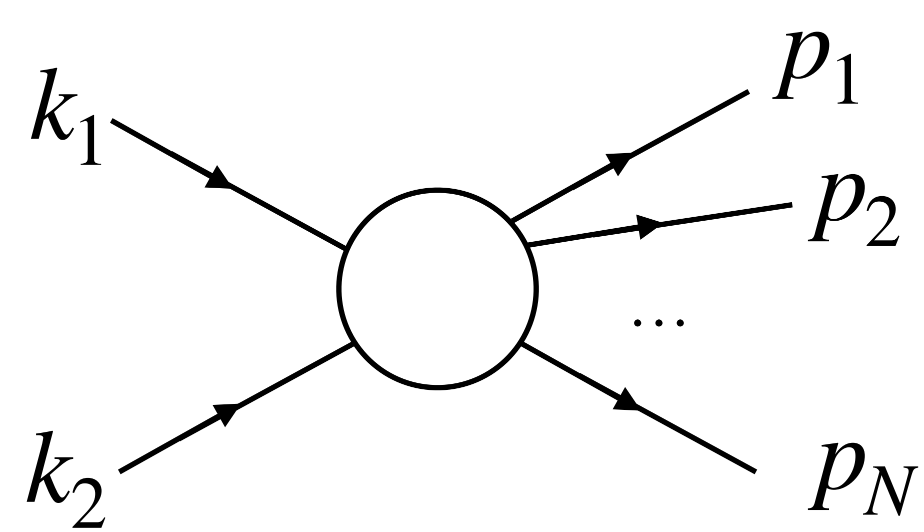
$\propto y$



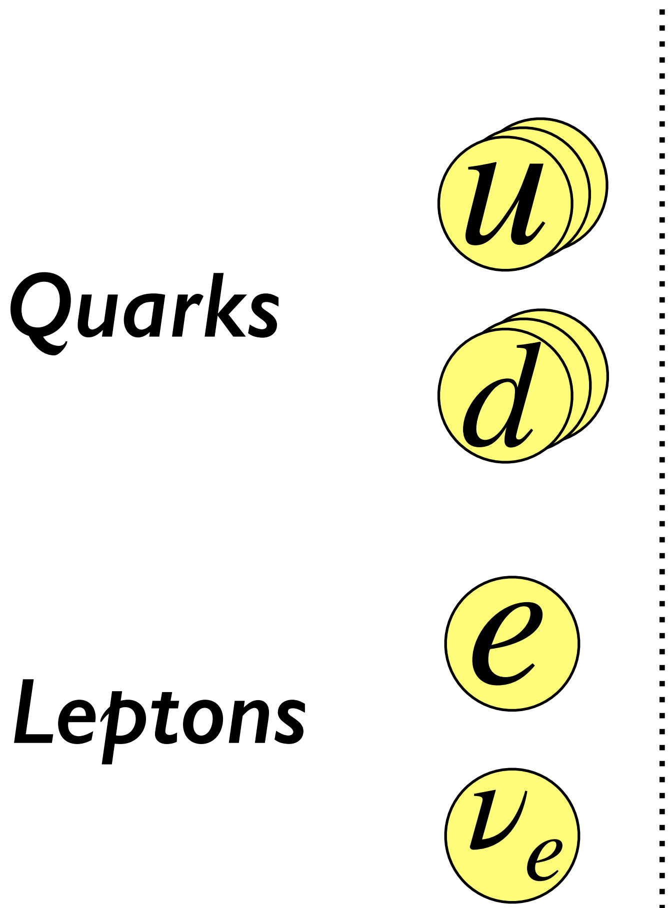
Decay: The ripple of the ϕ field excites ψ and $\bar{\psi}$ fields

QFT crash course

1. Lagrangian $\mathscr{L}(x)$ $\quad S = \int d^4x\, \mathscr{L}(x)$
2. Scattering amplitudes $\mathscr{M} \equiv \langle p_1 \ldots p_N | k_1 k_2 \rangle$
3. Cross sections $d\sigma \propto |\mathscr{M}|^2$
4. Events $dN = L \times d\sigma$



SM dynamics



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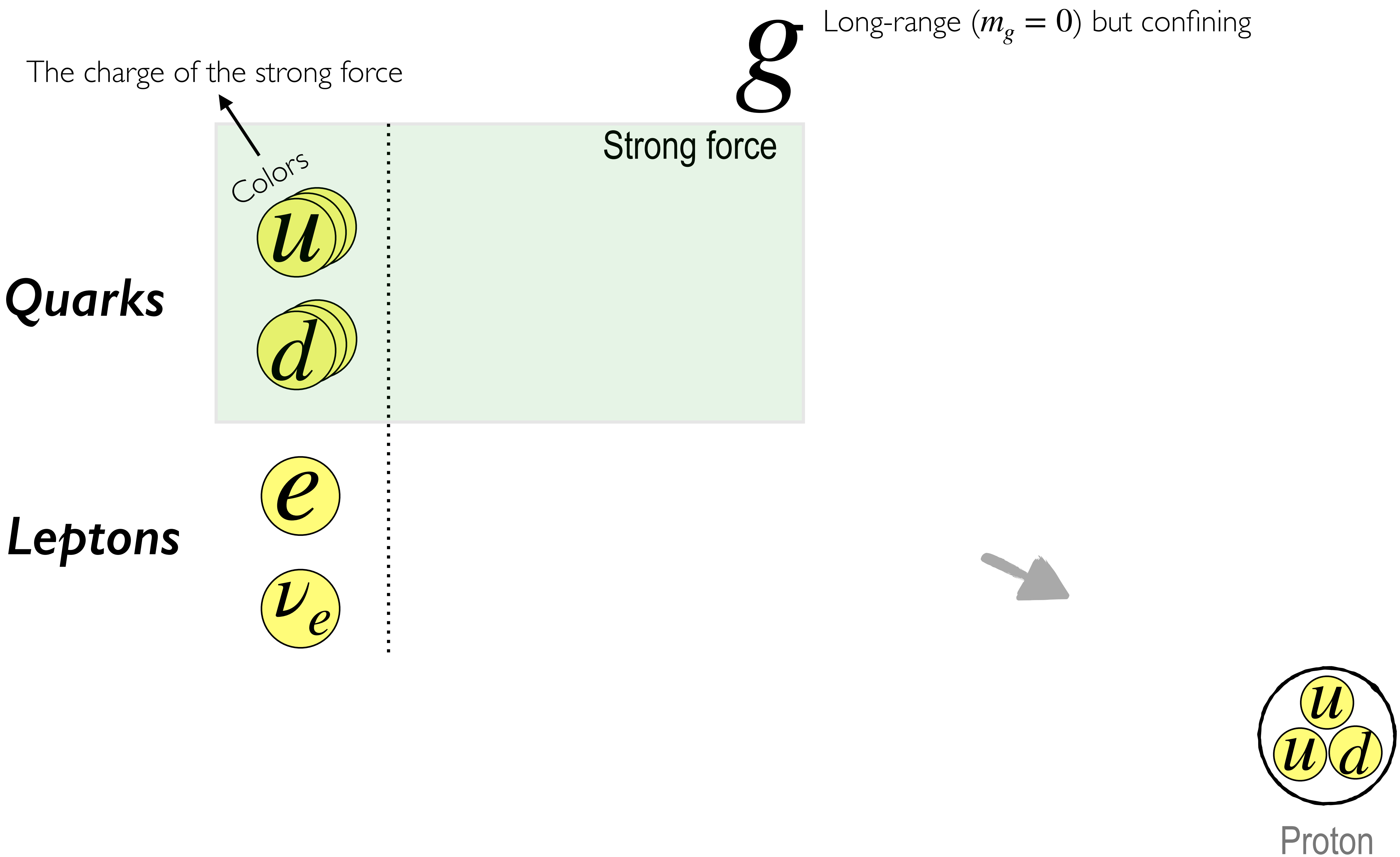
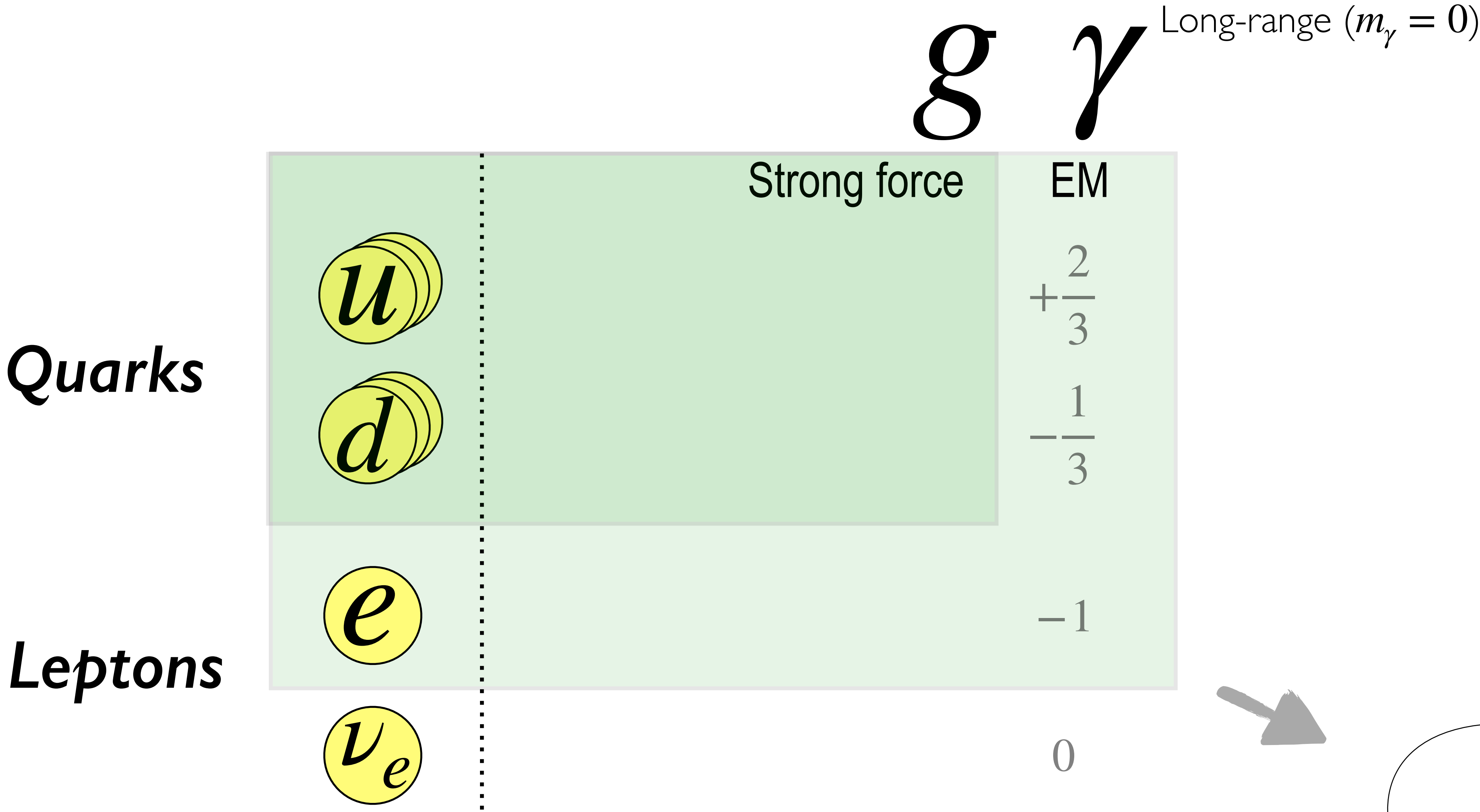
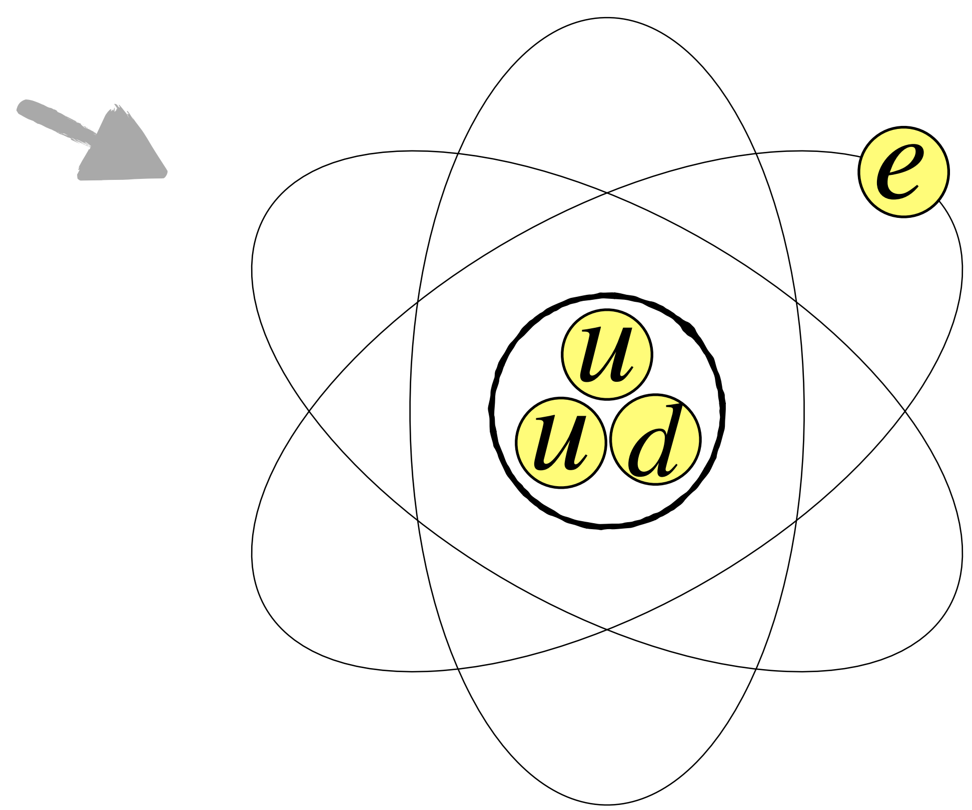


g
Long-range ($m_g = 0$) but confining
The charge of the strong force
Colors
Strong force
Quarks
u
d
Leptons
e
ν_e
u
u
d
Proton

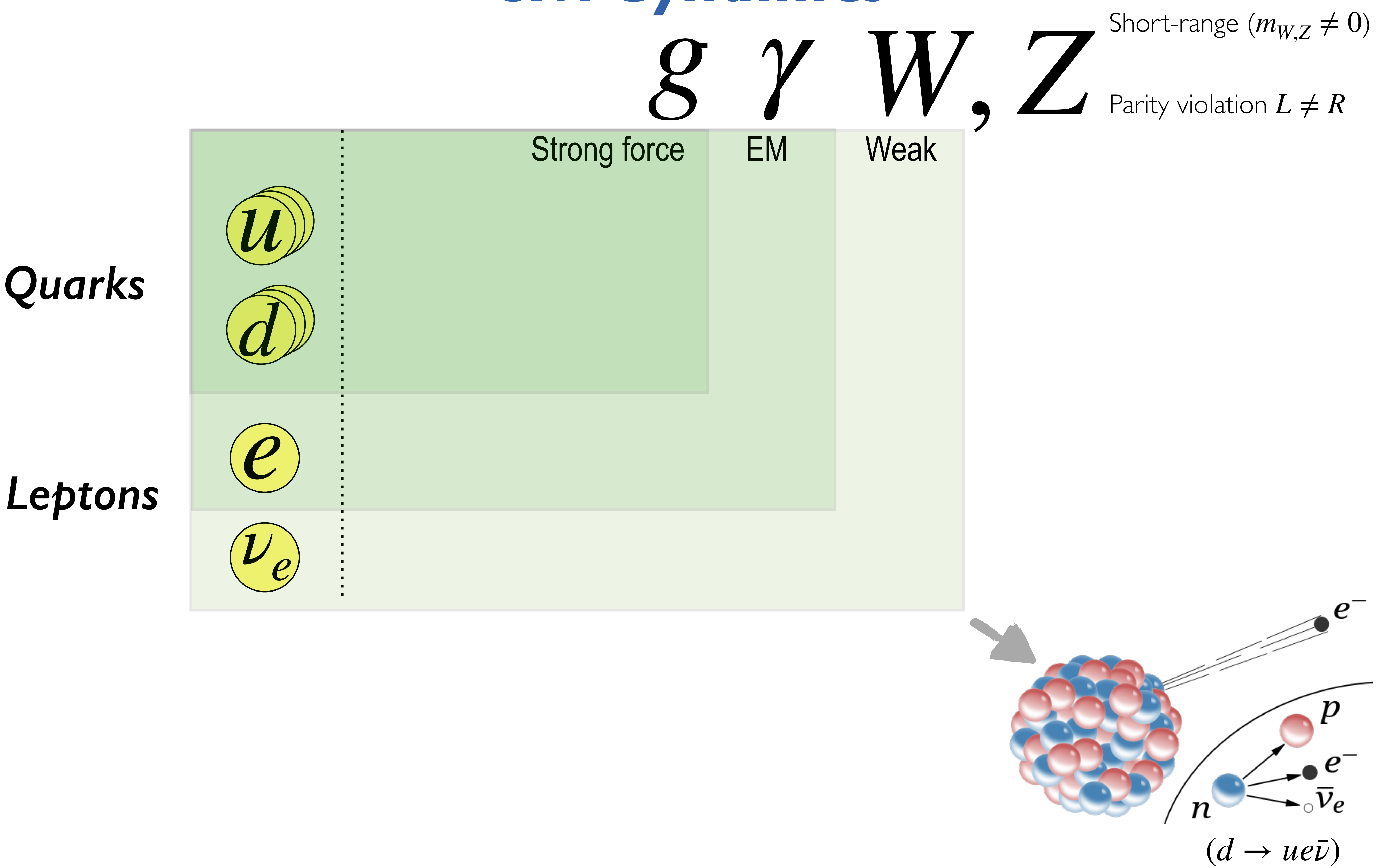
SM dynamics





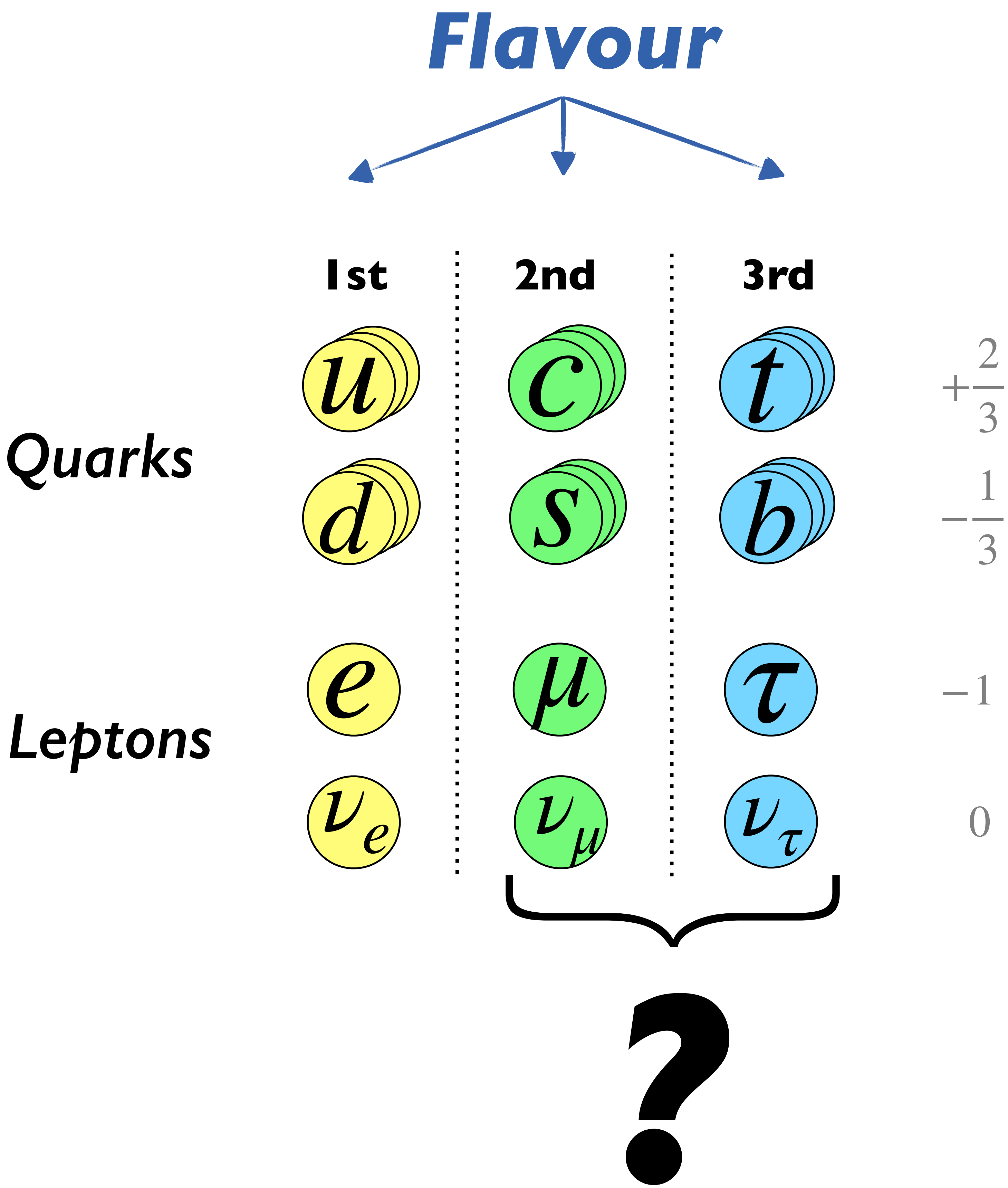
Hydrogen atom

SM dynamics



Radioactivity

Flavour



- Generations:

  Mysterious property of matter!

Terminology

- Flavour
  Several copies of the same gauge representation.

$$SU(3)_{QCD} \times U(1)_{QED} :$$

- Up-type quarks in the $(3)_{+2/3}$ representation: u, c, t;
- Down-type quarks in the $(3)_{-1/3}$ representation: d, s, b;
- Charged leptons in the $(1)_{-1}$ representation: e, μ, τ;
- Neutrinos in the $(1)_0$ representation: ν_1, ν_2, ν_3.

Terminology

- **Flavour**
  Several copies of the same gauge representation.

- **Flavour universal / blind**
  Proportional to the unit matrix in flavour space.

Example:
The kinetic terms in the SM Lagrangian! $\bar{f}_i \delta_{ij} i \not{D} f_j$

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  Number of particles of a certain flavour minus the number of anti-particles of the same flavour. *related to $U(1)_f$

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- **Flavour changing transitions**
  Initial and final flavour number in the process is different.

Example: $$B^0 : d\bar{b} \longleftrightarrow \bar{B}^0 : \bar{d}b$$

Neutral B meson oscillations: $\Delta B = 2$ process

Flavour Physics

for flavour-sensitive interactions

High-energy Frontier

CMS

ATLAS EXPERIMENT

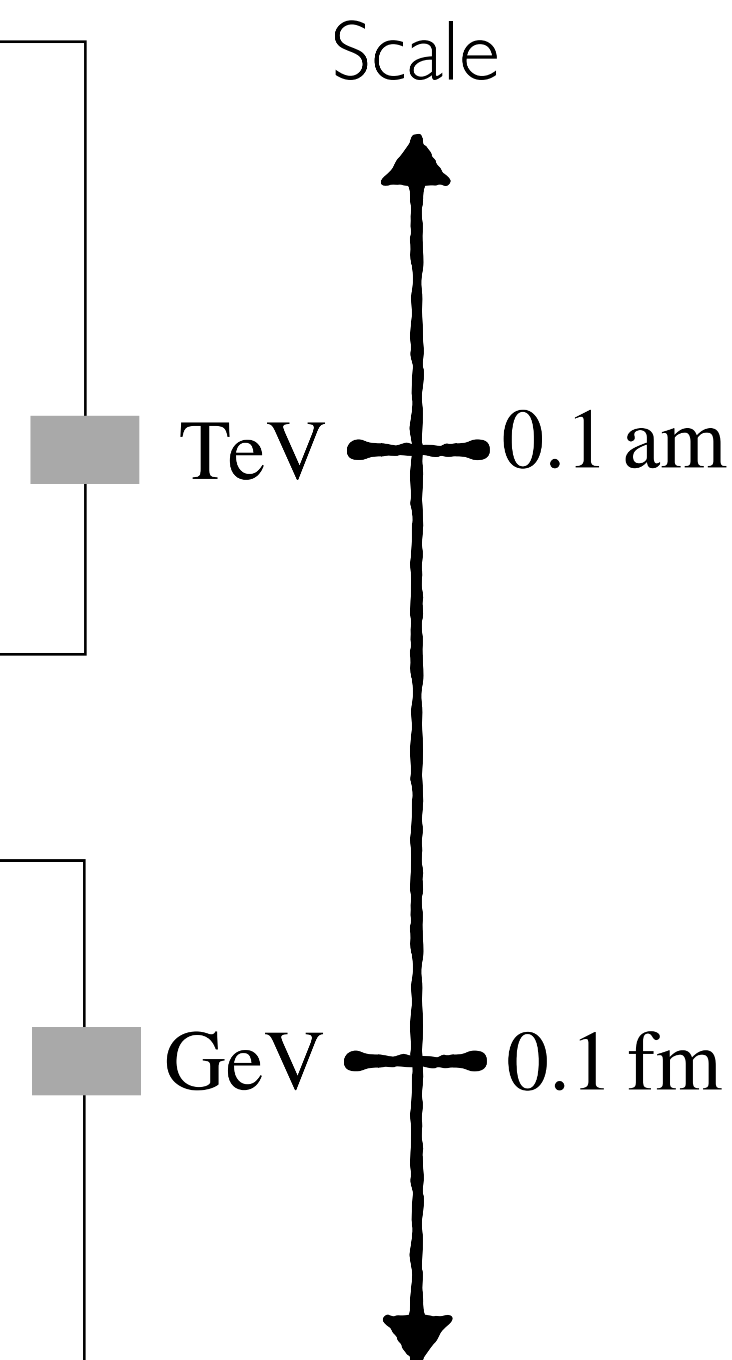
High-Intensity Frontier

LHCb

Belle II

BESIII

+ NA62, Koto, MEG II, Mu3e, …



Just a fraction of present and upcoming experiments!
Opportunities for data-driven progress!

Terminology

- **Flavour changing neutral currents (FCNC)**

  Involves either up-type or down-type flavours but not both.

  Examples:

$$\mu \to e\gamma \qquad \underset{s\bar{d}}{K_L} \to \mu^+\mu^- \qquad \begin{matrix} B \to \phi K \\ b \to s\bar{s}s \end{matrix}$$

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  Involves both types.

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- **Flavour violation**

  Related to the breaking of flavour symmetries, i.e. $U(1)^6$ for quarks.

The Standard Model

The Standard Model

Basic notions:

1. **"A" quantum field theory** *QFT = inevitable low-energy outcome of relativity + quantum mechanics + cluster decomposition

2. **Symmetries**

$$\overbrace{\text{Poincaré}}^{\text{Spacetime}} + \underbrace{SU(3)_C \times SU(2)_L \times U(1)_Y}_{\text{Gauge}}$$

3. **Field Content**

$$\phi \quad + \quad q_i, \ell_i, u_i, d_i, e_i$$

Flavour $i = 1,2,3$

$\boxed{\text{Complexity!}}$

4. **Renormalisability**

$$\dim \mathcal{O} \leq 4$$ *Turns out to be the leading terms in an EFT expansion

The Standard Model

– The symmetry is a local

$$G_{\rm SM} = SU(3)_C \times SU(2)_L \times U(1)_Y \quad .$$

– It is spontaneously broken by the VEV of a single Higgs scalar,

$$\phi(1,2)_{+1/2}, \quad (\langle\phi^0\rangle = v/\sqrt{2}) \quad ,$$

$$G_{\rm SM} \to SU(3)_C \times U(1)_{\rm EM} \quad (Q_{\rm EM} = T_3 + Y) \quad .$$

– There are three fermion generations, each consisting of five representations of $G_{\rm SM}$:

$$Q_{Li}(3,2)_{+1/6}, \;\; U_{Ri}(3,1)_{+2/3}, \;\; D_{Ri}(3,1)_{-1/3}, \;\; L_{Li}(1,2)_{-1/2}, \;\; E_{Ri}(1,1)_{-1} \quad .$$

Covariant derivative example:

$$D^\mu Q_{Li} \;=\; \left(\partial^\mu + \frac{i}{2} g_s G^\mu_a \lambda_a + \frac{i}{2} g W^\mu_b \tau_b + \frac{i}{6} g' B^\mu\right) Q_{Li}$$

The Standard Model

	G_μ^A	W_μ^a	B_μ
	$SU(3)$	$SU(2)$	$U(1)$
q_{Li}	$\mathbf{3}$	$\mathbf{2}$	$+1/6$
l_{Li}	$\mathbf{1}$	$\mathbf{2}$	$-1/2$
u_{Ri}	$\mathbf{3}$	$\mathbf{1}$	$+2/3$
d_{Ri}	$\mathbf{3}$	$\mathbf{1}$	$-1/3$
e_{Ri}	$\mathbf{1}$	$\mathbf{1}$	-1

$i = 1,2,3$

The Standard Model

Gauge sector

$$
\begin{aligned}
\mathcal{L}_{\rm SM} = & -\frac{1}{4}G^A_{\mu\nu}G^{A\ \mu\nu} - \frac{1}{4}W^a_{\mu\nu}W^{a\ \mu\nu} - \frac{1}{4}B_{\mu\nu}B^{\mu\nu} + \\
& + \bar{l}_{Li}\, i\not{D}\, l_{Li} + \bar{q}_{Li}\, i\not{D}\, q_{Li} + \bar{e}_{Ri}\, i\not{D}\, e_{Ri} + \bar{u}_{Ri}\, i\not{D}\, u_{Ri} + \bar{d}_{Ri}\, i\not{D}\, d_{Ri} + \\
& + (D_\mu\phi)^\dagger D^\mu\phi - V(\phi) - \left(\hat{y}^e_{ij}\ \bar{e}_{Ri}\phi l_{Lj} + \hat{y}^d_{ij}\ \bar{d}_{Ri}\phi q_{Lj} + \hat{y}^u_{ij}\ \bar{u}_{Ri}\tilde{\phi}^\dagger q_{Lj} + \text{h.c.}\right).
\end{aligned}
$$

Higgs sector

Yukawa sector

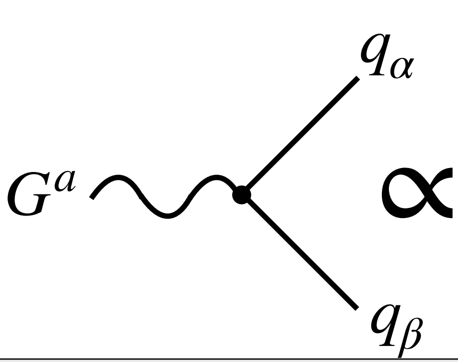
The Standard Model

Gauge sector

$$\mathcal{L}_{\rm SM} = -\frac{1}{4}G^A_{\mu\nu}G^{A\ \mu\nu} - \frac{1}{4}W^a_{\mu\nu}W^{a\ \mu\nu} - \frac{1}{4}B_{\mu\nu}B^{\mu\nu} + \\ + \bar{l}_{Li}\, i\not{D}\, l_{Li} + \bar{q}_{Li}\, i\not{D}\, q_{Li} + \bar{e}_{Ri}\, i\not{D}\, e_{Ri} + \bar{u}_{Ri}\, i\not{D}\, u_{Ri} + \bar{d}_{Ri}\, i\not{D}\, d_{Ri} + \\ + (D_\mu\phi)^\dagger D^\mu\phi - V(\phi) - \left(\hat{y}^e_{ij}\ \bar{e}_{Ri}\phi l_{Lj} + \hat{y}^d_{ij}\ \bar{d}_{Ri}\phi q_{Lj} + \hat{y}^u_{ij}\ \bar{u}_{Ri}\tilde{\phi}^\dagger q_{Lj} + \text{h.c.}\right).$$

Higgs sector

Yukawa sector

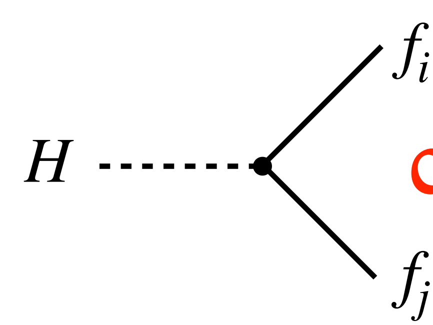


$\propto g_s$

Single free parameter

 # parameters:

- Gauge and Higgs sector: 5
- Yukawa sector: 13 *Would be 3 for a single generation



$\propto Y_f^{ij}$

All parameters free

$i, j = 1,2,3$

The Higgs field

- How do elementary particles get mass?

The Higgs mechanism

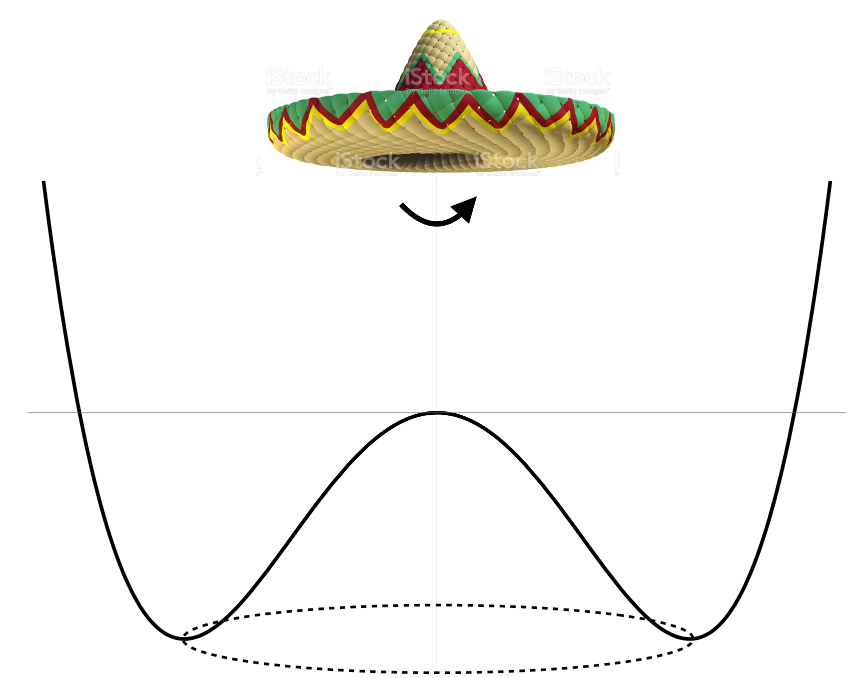
ϕ $\quad$ $\mathbf{1}$ $\quad$ $\mathbf{2}$ $\quad$ $+1/2$

$$\mathscr{V} = -\mu^2\phi^\dagger\phi + \lambda(\phi^\dagger\phi)^2$$

$$SU(3)\times SU(2)\times U(1)$$

SSB: $\langle\phi\rangle \neq 0$

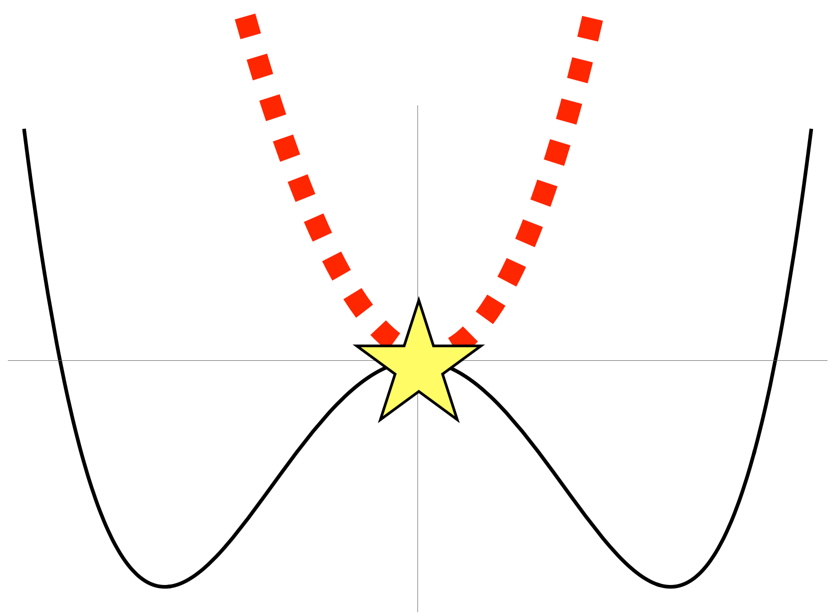
$$SU(3)\times U(1)_{em}$$



Cosmological event

- Electroweak phase transition

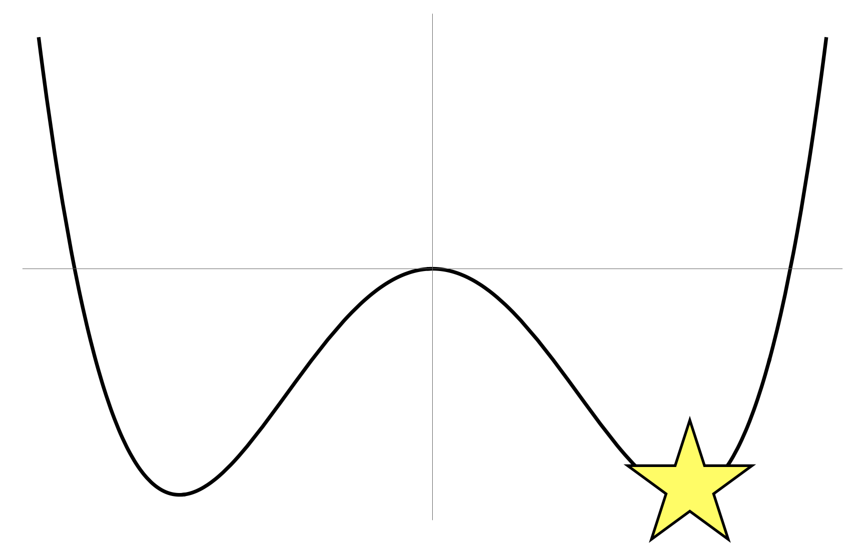
$T \gg T_{EW}$



$\langle \phi \rangle = 0$

10^{-10} sec after Big Bang

$T \ll T_{EW}$

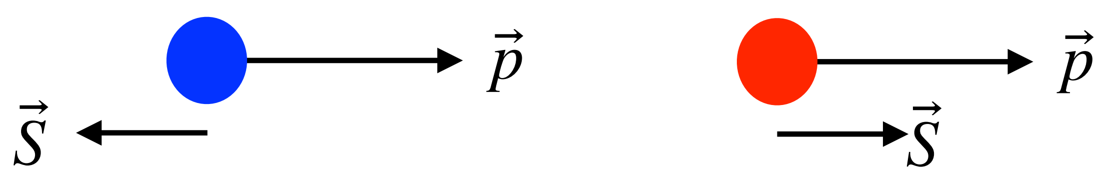


$\langle \phi \rangle \neq 0$

- Spacetime gets filled by a Higgs condensate
- Elementary particles get intrinsic masses

The Higgs mechanism

Matter: Quarks and Leptons



- The *left-handed* and the *right-handed* fields have different $U(1)_Y$ phases:

$$\theta_{f_L} \neq \theta_{f_R} \quad \Longrightarrow \quad \text{The mass } m_f \bar{f}_L f_R \text{ is forbidden!}$$

- The Higgs field saves the day, $\theta_H + \theta_{f_R} = \theta_{f_L}$

$$\mathscr{L} \supset - y_f \, \bar{f}_L f_R \, \phi \quad \overset{\text{SSB}}{\Longrightarrow} \quad m_f = y_f \langle \phi \rangle$$

- The mass $\propto$ the strength of the interaction with the Higgs field

The SM spectrum

Table 1: The SM particles

particle	spin	color	$Q_{\rm EM}$	mass $[v]$
$W^\pm$	1	(1)	± 1	$\frac{1}{2}g$
Z^0	1	(1)	0	$\frac{1}{2}\sqrt{g^2+g'^2}$
A^0	1	(1)	0	0
g	1	(8)	0	0
h	0	(1)	0	$\sqrt{2\lambda}$
e,μ,τ	$1/2$	(1)	-1	$y_{e,\mu,\tau}/\sqrt{2}$
ν_e,ν_μ,ν_τ	$1/2$	(1)	0	0
u,c,t	$1/2$	(3)	$+2/3$	$y_{u,c,t}/\sqrt{2}$
d,s,b	$1/2$	(3)	$-1/3$	$y_{d,s,b}/\sqrt{2}$

Global flavour symmetries

Global flavour symmetries

- $\mathscr{L}_4$ sans Yukawa

$g_S \sim 1, g_W \sim 0.6, g_Y \sim 0.3, \lambda_H \sim 0.2$
$\theta \lesssim 10^{-10}$ - The strong CP problem

ψ : 3 generations of q_i, U_i, D_i, l_i, E_i

<u>Accidental symmetry</u>

$U(3)_q \times U(3)_U \times U(3)_D \times U(3)_l \times U(3)_E$

$$\mathcal{L}_4 = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} + i \bar{\Psi} \not{D} \Psi + h.c. + \bar{\Psi}_i y_{ij} \Psi_j \phi + h.c. + |D_\mu \phi|^2 - V(\phi)$$

Global flavour symmetries

$$\mathcal{L}_4 = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} + i \bar{\psi} \not{D} \psi + h.c. + \bar{\psi}_i y_{ij} \psi_j \phi + h.c. + |D_\mu \phi|^2 - V(\phi)$$

Yukawas break $U(3)^5$

Global flavour symmetries

- The kinetic Lagrangian (flavor and CP conserving)

$$
\begin{aligned}
\mathcal{L}_{\rm kin}^{\rm SM} \quad = \quad & -\frac{1}{4}G_a^{\mu\nu}G_{a\mu\nu} - \frac{1}{4}W_b^{\mu\nu}W_{b\mu\nu} - \frac{1}{4}B^{\mu\nu}B_{\mu\nu} \\
& -i\overline{Q_{Li}}\not{D}Q_{Li} - i\overline{U_{Ri}}\not{D}U_{Ri} - i\overline{D_{Ri}}\not{D}D_{Ri} - i\overline{L_{Li}}\not{D}L_{Li} - i\overline{E_{Ri}}\not{D}E_{Ri} \\
& -(D^\mu\phi)^\dagger(D_\mu\phi) \quad .
\end{aligned}
$$

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- The global symmetry

$$
G_{\rm global}^{\rm SM}(Y^{u,d,e} = 0) = SU(3)_q^3 \times SU(3)_\ell^2 \times U(1)^5
$$

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$$

- Reminder:

$$U(1) : \phi \to e^{i\alpha Q}\phi$$

$$\phi^\dagger\phi \to \phi^\dagger e^{-i\alpha Q}e^{i\alpha Q}\phi = \phi^\dagger\phi$$

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\begin{aligned}
\mathcal{L}_{\rm kin}^{\rm SM} \;=\;& -\frac{1}{4}G_a^{\mu\nu}G_{a\mu\nu} - \frac{1}{4}W_b^{\mu\nu}W_{b\mu\nu} - \frac{1}{4}B^{\mu\nu}B_{\mu\nu} \\
& -i\overline{Q_{Li}}\not{D}Q_{Li} - i\overline{U_{Ri}}\not{D}U_{Ri} - i\overline{D_{Ri}}\not{D}D_{Ri} - i\overline{L_{Li}}\not{D}L_{Li} - i\overline{E_{Ri}}\not{D}E_{Ri} \\
& -(D^\mu\phi)^\dagger(D_\mu\phi) \quad .
\end{aligned}
$$

- The global symmetry

$$G_{\rm global}^{\rm SM}(Y^{u,d,e}=0) = SU(3)_q^3 \times SU(3)_\ell^2 \times U(1)^5$$

- Reminder:

$$U(1) : \phi \to e^{i\alpha Q}\phi$$

$$\phi^\dagger\phi \to \phi^\dagger e^{-i\alpha Q}e^{i\alpha Q}\phi = \phi^\dagger\phi$$

$$U(N) = SU(N) \times U(1)$$

$SU(N)$: group of $N \times N$ unitary matrices with $\det = 1$

$$U^\dagger U = 1 \;, \det U = 1$$

Global flavour symmetries

- The kinetic Lagrangian (flavor and CP conserving)

$$\begin{aligned}\mathcal{L}_{\rm kin}^{\rm SM} = & -\frac{1}{4}G_a^{\mu\nu}G_{a\mu\nu} - \frac{1}{4}W_b^{\mu\nu}W_{b\mu\nu} - \frac{1}{4}B^{\mu\nu}B_{\mu\nu} \\ & -i\overline{Q_{Li}}\not{D}Q_{Li} - i\overline{U_{Ri}}\not{D}U_{Ri} - i\overline{D_{Ri}}\not{D}D_{Ri} - i\overline{L_{Li}}\not{D}L_{Li} - i\overline{E_{Ri}}\not{D}E_{Ri} \\ & -(D^\mu\phi)^\dagger(D_\mu\phi) \quad .\end{aligned}$$

- The global symmetry

$$G_{\rm global}^{\rm SM}(Y^{u,d,e} = 0) = SU(3)_q^3 \times SU(3)_\ell^2 \times U(1)^5$$

- Reminder:

$$U(1) : \phi \to e^{i\alpha Q}\phi$$

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$$U(N) = SU(N) \times U(1)$$

$SU(N)$: group of $N \times N$ unitary matrices with det = 1

$$U^\dagger U = 1 \text{ , det } U = 1$$

$$U = e^{i\alpha^a T^a} \qquad a : 1,\ldots,N^2 - 1$$

$$SU(N) : \quad \phi_i \to U_{ij}\phi_j \qquad i,j : 1,\ldots,N$$

$$\phi^\dagger\phi \to \phi^\dagger U^\dagger U\phi = \phi^\dagger\phi$$

Global flavour symmetries

- Flavour and CP violation is in the **Yukawa Lagrangian**

$$-\mathscr{L}_{\text{Yuk}} = \bar{Q}Y^u\tilde{\phi}U + \bar{Q}Y^d\phi D + \bar{L}Y^e\phi E$$

- Flavour breaking **spurions**

$$Y^u \sim (3, \bar{3}, 1)_{SU(3)^3_q} \quad , \quad Y^d \sim (3, 1, \bar{3})_{SU(3)^3_q} \quad ,$$

$$Y^e \sim (3, \bar{3})_{SU(3)^2_\ell}$$

Global flavour symmetries

*Fermionic kinetic terms

- Flavour symmetry $G^f = U(3)_q \times U(3)_\ell \times U(3)_u \times U(3)_d \times U(3)_e$

- G^f equivalency classes, $Y^u \sim U_q Y^u U_u^\dagger$, etc. $\Longrightarrow$ $54 \to 13$ physical parameters

*By G^f and SVD theorem

$$-\mathscr{L}_{\text{Yuk}} = \bar{q} V^\dagger \hat{Y}^u \tilde{\phi} u + \bar{q} \hat{Y}^d \phi d + \bar{\ell} \hat{Y}^e \phi e$$

13 parameters

- *6* quark and *3* charged lepton masses
- The CKM: *3* angles + *1* CPV phase

$$V_{ij} \to e^{i(\theta_u^i - \theta_d^j)} V_{ij}$$

- The Yukawa sector breaks $G^f \to U(1)_B \times U(1)_e \times U(1)_\mu \times U(1)_\tau$

*Exact (classical) accidental symmetry of the SM

Parameter counting

*It is a bit technical, sorry

Parameter counting: Leptons

(If there was a right-handed neutrino)

- Dirac case

$$L_L = \begin{pmatrix} \nu_L \\ e_L \end{pmatrix}, \quad e_R, \quad \nu_R \qquad \tilde{H} = i\sigma_2 H^*$$

$$-\mathcal{L} \supset \bar{L}_L^i H Y_e^{ij} e_R^j + \bar{L}_L^i \tilde{H} Y_\nu^{ij} \nu_R^j + h.c.$$

$$i,j = 1,2,3$$

$$\text{SSB} \quad \langle H^0 \rangle = \frac{v}{\sqrt{2}} \Rightarrow$$

$$-\mathcal{L} \supset \bar{e}_L^i M_{ij}^e e_R^j + \bar{\nu}_L^i M_{ij}^\nu \nu_R^j$$

M^ν – complex

M^e – complex

Singular value decomposition

$$U M V^\dagger = M_{diag}$$

U: unitary; M: arbitrary complex; V: unitary

M_{diag}: diagonal with real non-negative entries

Parameter counting: Leptons

(If there was a right-handed neutrino)

From kinetic terms:

$$\mathcal{L} \supset \bar{e}_L i\partial\!\!\!/ e_L + \bar{e}_R i\partial\!\!\!/ e_R + \bar{\nu}_L i\partial\!\!\!/ \nu_L + \bar{\nu}_R i\partial\!\!\!/ \nu_R$$

- Four unitary rotations

$$e'_{L/R} = U_{e_{L/R}} e_{L/R} \qquad \nu'_{L/R} = U_{\nu_{L/R}} \nu_{L/R}$$

$$U^\dagger_{e_L} M^e U_{e_R} = M^e_{diag}$$

- 3 charged lepton masses

$$U^\dagger_{\nu_L} M^\nu U_{\nu_R} = M^\nu_{diag}$$

- 3 neutrino masses

- The "rotations" cancel everywhere else in the SM unitary lagrangian except

$$\mathcal{L}_W = \frac{g}{\sqrt{2}} W_\mu \bar{\nu}_L U^\dagger_{\nu_L} U_{e_L} \gamma^\mu e_L + h.c.$$

$$V_{PMNS} = U^\dagger_{\nu_L} U_{e_L} \qquad V^\dagger V = 1 \quad \text{unitary} \to \begin{cases} 3 \text{ real} \\ 6 \text{ imaginary} \end{cases}$$

Parameter counting: Leptons

(If there was a right-handed neutrino)

• There is still freedom to

$$\begin{pmatrix} \bar{e}_L & \bar{\mu}_L & \bar{\tau}_L \end{pmatrix} \begin{pmatrix} e^{i\theta_e} & & \\ & e^{i\theta_\mu} & \\ & & e^{i\theta_\tau} \end{pmatrix}^{\dagger} \begin{pmatrix} e^{i\theta_e} & & \\ & e^{i\theta_\mu} & \\ & & e^{i\theta_\tau} \end{pmatrix} \begin{pmatrix} e_R \\ \mu_R \\ \tau_R \end{pmatrix}$$

and the same for neutrinos. These transformations leave all terms invariant except for $\cancel{W} \bar{\nu}_L e_L$. Only Lepton number, i.e. $\theta_e = \theta_\mu = \theta_\tau = \theta_{\nu_e} = \theta_{\nu_\mu} = \theta_{\nu_\tau}$ is a full symmetry. Thus five phases can be used to remove parameters in the PMNS.

Finally: 3 angles, 1 phase

Parameter counting: Leptons

(If there was a right-handed neutrino)

Group theory approach

$\mathcal{L}_{SM}$ without Y_e and Y_ν enjoys

$U(3)_{L_L} \times U(3)_{e_R} \times U(3)_{\nu_R}$ global symmetry

which is broken to $U(1)_L$ when Y_e and Y_ν are present.

$$Y_e = 9R + 9I$$

$$Y_\nu = 9R + 9I$$

in general

- Freedom to change basis by broken

$$U(3)_L \times U(3)_e \times U(3)_\nu \to U(1)_L$$

9 angles & 17 phases

Parameter counting: Leptons

(If there was a right-handed neutrino)

- There is a basis with
  $18 - 9 = 9$ real params
  $18 - 17 = 1$ imaginary param

$$\underbrace{\begin{array}{l} \bullet\ 3\ m^e_i \\ \bullet\ 3\ m^\nu_i \\ \bullet\ 3 \text{ mixings in PMNS} \\ \bullet\ 1 \text{ phases in PMNS} \end{array}}_{\text{physical parameters}}$$

- Usefull BSM trick:
  In the unbroaken phase (before EWSB) we can start in the basis $L = \begin{pmatrix} \nu_L \\ V e_L \end{pmatrix}$: ν_L, e_L in the mass basis

$$\sim \bar{L}_L H V \hat{Y}_e e_R + \bar{L}_L \tilde{H} \hat{Y}_\nu \nu_R$$

$\hat{}$ – diagonal matrix

$\leftarrow$ up-alignment $L = \begin{pmatrix} \nu_L \\ V e_L \end{pmatrix}$

down-alignment $L = \begin{pmatrix} V^\dagger \nu_L \\ e_L \end{pmatrix}$

$\bar{L} \hat{Y}_e H e_R + \bar{L} V^\dagger \hat{Y}_\nu \tilde{H} \nu_R$

- Similarly for the quark sector

Parameter counting: Leptons

(No right-handed neutrino)

- Majorana case

$$L_L = \begin{pmatrix} \nu_L \\ e_L \end{pmatrix}, \quad e_R$$

$L = (2, -\frac{1}{2})$

$H = (2, \frac{1}{2})$

$\varepsilon = \begin{pmatrix} 0 & 1 \\ -1 & 0 \end{pmatrix}$

SU(2) invariant:

$\psi^T \varepsilon \chi = \psi_1 \chi_2 - \psi_2 \chi_1$

$$-\mathcal{L} \supset \bar{L}_L^i H Y_e^{ij} e_R^j + \frac{Y_\nu^{ij}}{\Lambda} \left(\bar{L}_i^c \varepsilon H\right)\left(H \varepsilon L_j\right) + h.c.$$

$$\langle H \rangle = \frac{v}{\sqrt{2}} \Rightarrow$$

$\psi^c = -i\gamma_2 \psi^*$

charge conjugation

$\bar{\psi} \chi = \overline{\chi^c} \psi^c$

fermionic field identity

$$-\mathcal{L} \supset \bar{e}_L^i M_{ij}^e e_R^j + \bar{\nu}_L^{c\,i} M_{ij}^\nu \nu_L^j$$

M^ν – complex symmetric $M^{\nu T} = M^\nu$

M^e – complex

Parameter counting: Leptons

(No right-handed neutrino)

Singular value decomposition

$$\underset{\text{unitary}}{U}\ \underset{\text{arbitrary complex}}{M}\ \underset{\text{unitary}}{V^{\dagger}} = M_{diag}$$ → diagonal with real non-negative entries

- If $M^T = M \Rightarrow U = V^*$

$$V^* M U^T = U M V^{\dagger}$$

From kinetic terms:

$$\mathcal{L} \supset \bar{e}_L i \not{\partial} e_L + \bar{e}_R i \not{\partial} e_R + \bar{\nu}_L i \not{\partial} \nu_L$$

- three unitary rotations

$e'_{L/R} = U_{e_{L/R}} e_{L/R} \qquad \nu'_L = U_\nu \nu_L$

$$U_{e_L}^{\dagger} M^e U_{e_R} = M^e_{diag}$$

- 3 charged lepton masses

$$U_\nu^T M^\nu U_\nu = M^\nu_{diag}$$

- 3 neutrino masses

Parameter counting: Leptons

(No right-handed neutrino)

- The "rotations" cancel everywhere else in the SM unitary lagrangian except

$$\mathcal{L}_W = \frac{g}{\sqrt{2}} W_\mu \, \bar{\nu}_L U_\nu^\dagger U_{e_L} \gamma^\mu e_L + h.c.$$

$$V_{PMNS} = U_\nu^\dagger U_{e_L} \qquad V^\dagger V = 1 \quad \text{unitary} \nearrow \begin{matrix} 3 \text{ real} \\ 6 \text{ imaginary} \end{matrix}$$

- No more phase rotations in the neutrino sector possible.
  $(\mathcal{L} \supset -M \, \psi^T \epsilon \psi)$
- Three phases in the charged lepton sector

$$(\bar{e}_L \; \bar{\mu}_L \; \bar{\tau}_L) \begin{pmatrix} e^{i\theta_e} & & \\ & e^{i\theta_\mu} & \\ & & e^{i\theta_\tau} \end{pmatrix}^\dagger \begin{pmatrix} e^{i\theta_e} & & \\ & e^{i\theta_\mu} & \\ & & e^{i\theta_\tau} \end{pmatrix} \begin{pmatrix} e_R \\ \mu_R \\ \tau_R \end{pmatrix}$$

- Used to remove 3 phases in the PMNS.
  That is, we are left with 3 angles and 3 phases!

Parameter counting: Leptons

(No right-handed neutrino)

Group theory approach

$\mathcal{L}_{SM}$ without Y_e and Y_ν enjoys

$U(3)_L \times U(3)_e$ global symmetry

which is broken to $\emptyset$ when Y_e and Y_ν are present.

$Y_e = 9R + 9I$ in general

$Y_\nu = 6R + 6I$ (symmetric)

- Freedom to change basis by broken
  $U(3)_L \times U(3)_e$
  6 angles & 12 phases

- There is a basis with
  $15 - 6 = 9$ real params
  $15 - 12 = 3$ imaginary params

- 3 m^e_i
- 3 m^ν_i
- 3 mixings in PMNS
- 3 phases in PMNS

physical parameters

- we can start in a basis $L = \begin{pmatrix} \nu_L \\ e_L \end{pmatrix}$

$$\bar{L}_L H V \hat{Y}_e e_R + \frac{\hat{Y}_\nu}{\Lambda} (\bar{L}^c \varepsilon H)(H \varepsilon L)$$

$\wedge$ – diagonal

Interaction & Mass bases

Flavour Bases

$$-\mathscr{L}_{\mathrm{Yuk}} = \bar{q} V^{\dagger} \hat{Y}^{u} \tilde{\phi} U + \bar{q} \hat{Y}^{d} \phi D + \bar{l} \hat{Y}^{e} \phi E$$

*Suitable interaction basis

[$U(3)^5$ transformation and a singular value decomposition theorem]

Flavour Bases

$$-\mathscr{L}_{\text{Yuk}} = \bar{q} V^\dagger \hat{Y}^u \tilde{\phi} U + \bar{q} \hat{Y}^d \phi D + \bar{l} \hat{Y}^e \phi E$$

[$U(3)^5$ transformation and a singular value decomposition theorem]

- After EWSB, rotate from the interaction to the mass basis

$$\mathcal{L}^u_{\text{Yuk}} = \underline{(\overline{u_{dL}}\ \overline{u_{sL}}\ \overline{u_{bL}})} V^\dagger \hat{Y}^u \begin{pmatrix} u_R \\ c_R \\ t_R \end{pmatrix} \quad \longrightarrow \quad \underline{\begin{pmatrix} u_L \\ c_L \\ t_L \end{pmatrix} = V \begin{pmatrix} u_{dL} \\ u_{sL} \\ u_{bL} \end{pmatrix}}$$

Flavour Bases

$$-\mathscr{L}_{\text{Yuk}} = \bar{q} V^\dagger \hat{Y}^u \tilde{\phi} U + \bar{q} \hat{Y}^d \phi D + \bar{l} \hat{Y}^e \phi E$$

[$U(3)^5$ transformation and a singular value decomposition theorem]

- After EWSB, rotate from the interaction to the mass basis

$$\mathcal{L}^u_{\text{Yuk}} = \underline{(\overline{u_{dL}}\ \overline{u_{sL}}\ \overline{u_{bL}})} V^\dagger \hat{Y}^u \begin{pmatrix} u_R \\ c_R \\ t_R \end{pmatrix} \longrightarrow \underline{\begin{pmatrix} u_L \\ c_L \\ t_L \end{pmatrix} = V \begin{pmatrix} u_{dL} \\ u_{sL} \\ u_{bL} \end{pmatrix}}$$

- $V \mathbf{1} V^\dagger = 1 \implies \bar{u}^i_L Z\, u^i_L$ universality!

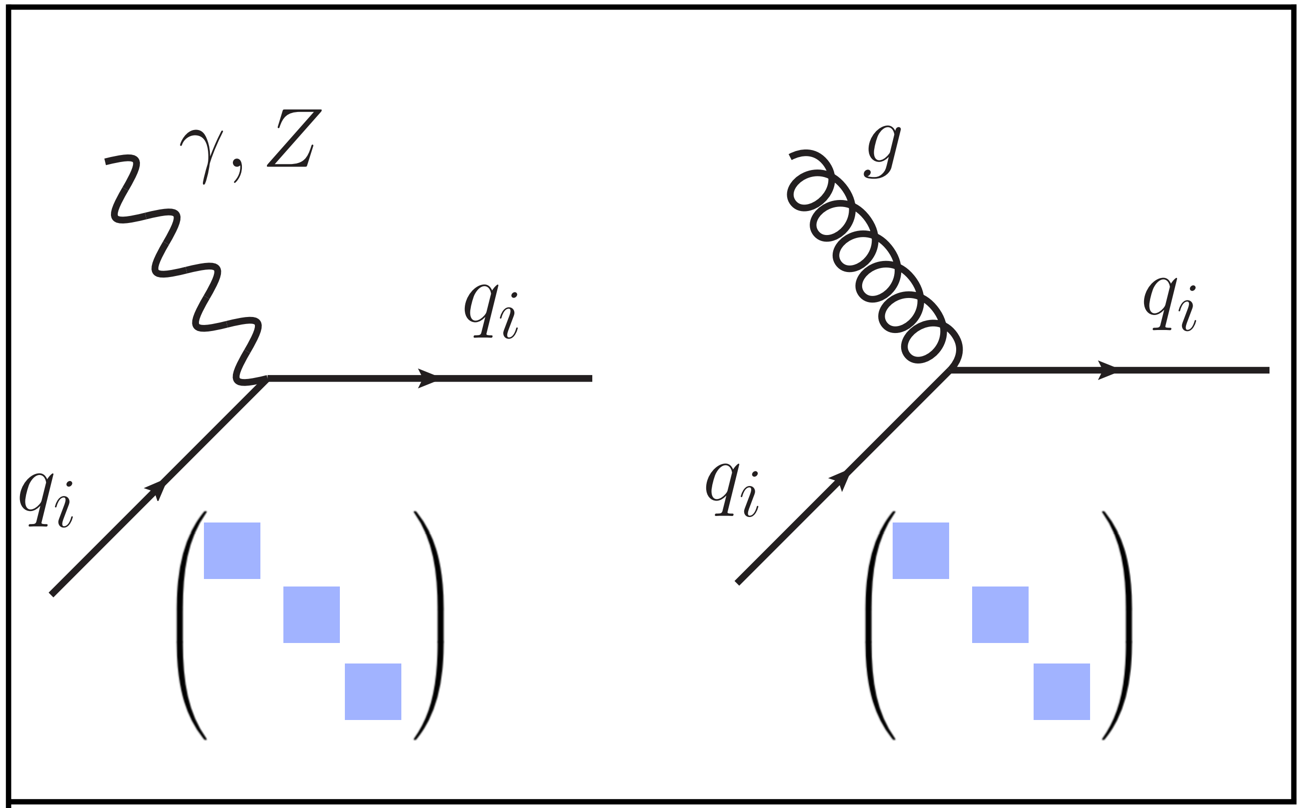
- It only appears in the $\bar{u}_L \gamma^\mu d_L W_\mu$ interactions, not in γ, g, Z, h

No FCNC at tree-level **!**

They are suppressed in the SM.

The SM interactions

- Universality of γ, g interactions is guaranteed by the unbroken QCD x QED in any extension of the SM.
- However, the Z universality is an accident of the SM field content.
- Eg. add a heavy vector-like quark weak singlet $(U_L, U_R)_{Y=2/3}$



- Flavour universal / blind

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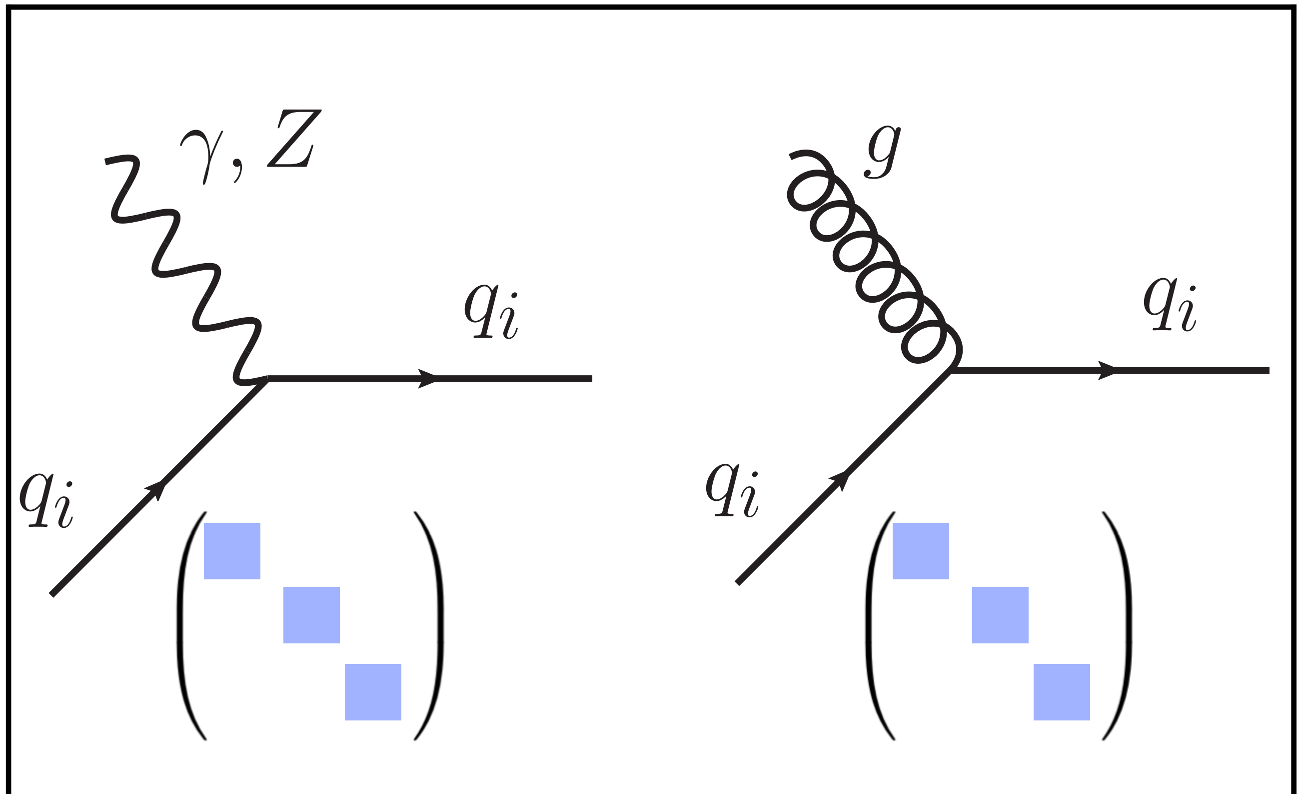


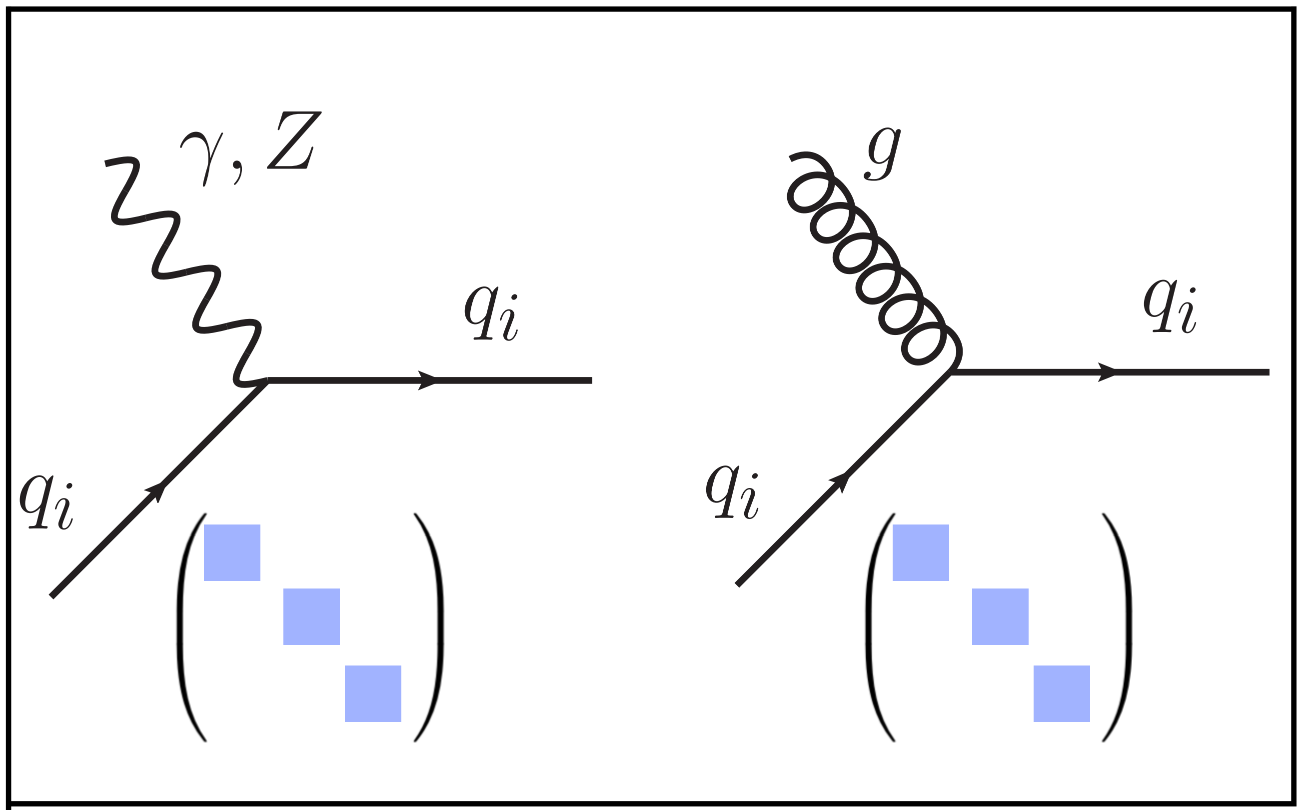
PDG

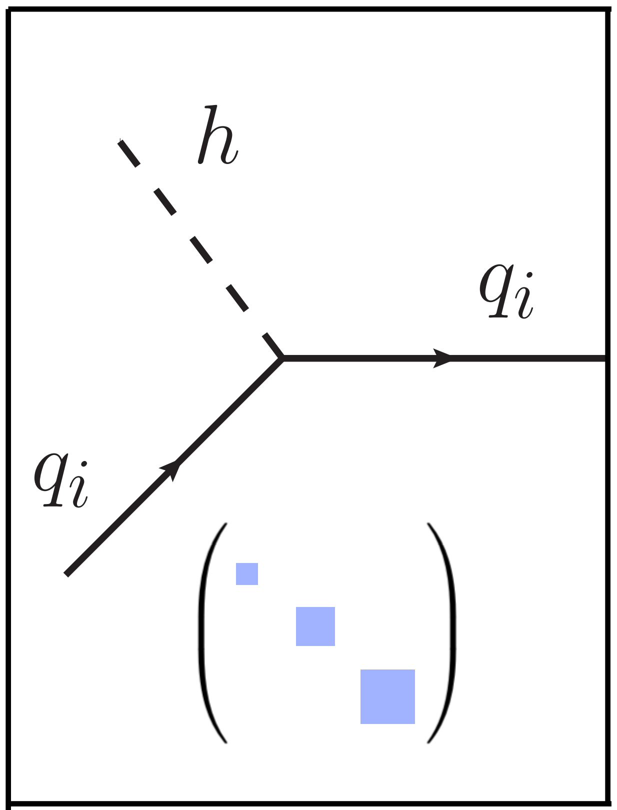
$$
\begin{aligned}
\Gamma(\mu^+\mu^-)/\Gamma(e^+e^-) &= 1.0009 \pm 0.0028 \\
\Gamma(\tau^+\tau^-)/\Gamma(e^+e^-) &= 1.0019 \pm 0.0032
\end{aligned}
$$

$$
\begin{aligned}
BR(Z \to e^+\mu^-) &< 7.5 \times 10^{-7} \quad , \\
BR(Z \to e^+\tau^-) &< 9.8 \times 10^{-6} \quad , \\
BR(Z \to \mu^+\tau^-) &< 1.2 \times 10^{-5} \quad .
\end{aligned}
$$

- Flavour universal / blind

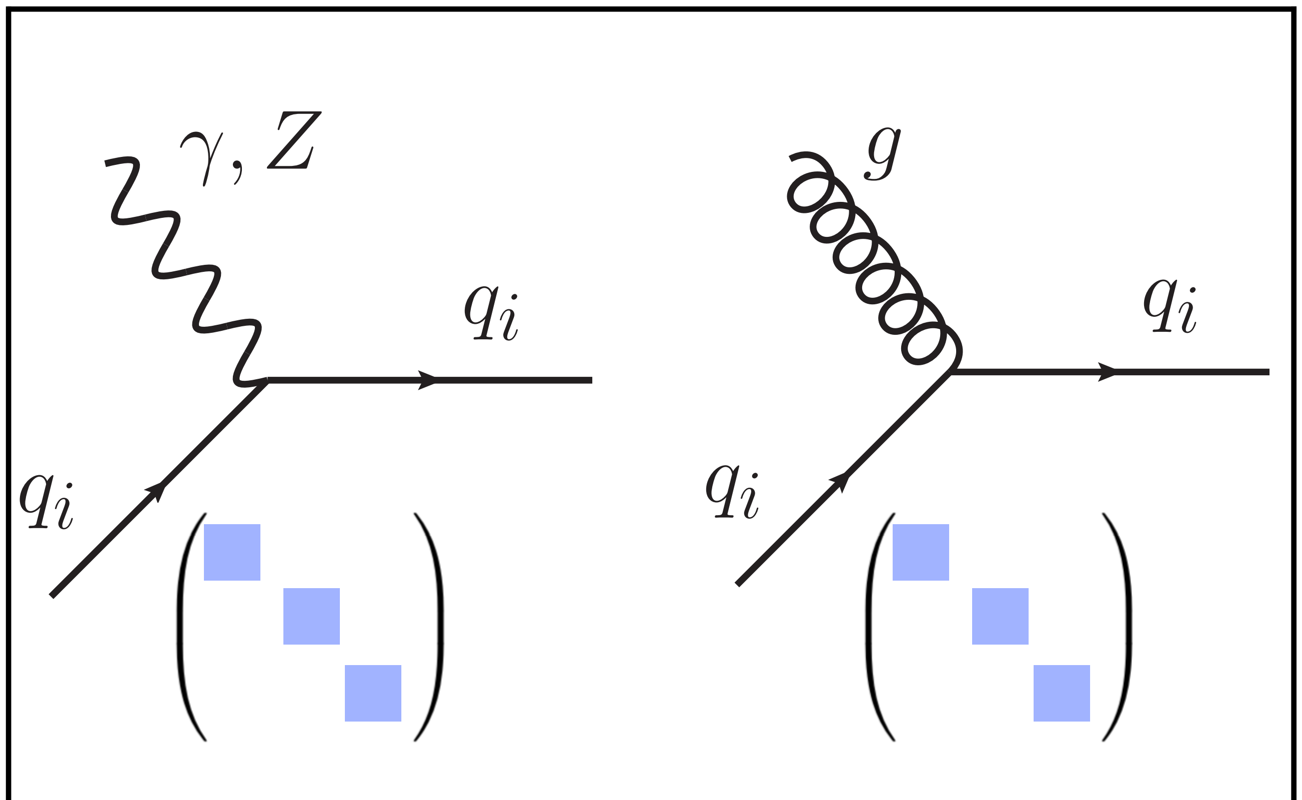
The SM interactions



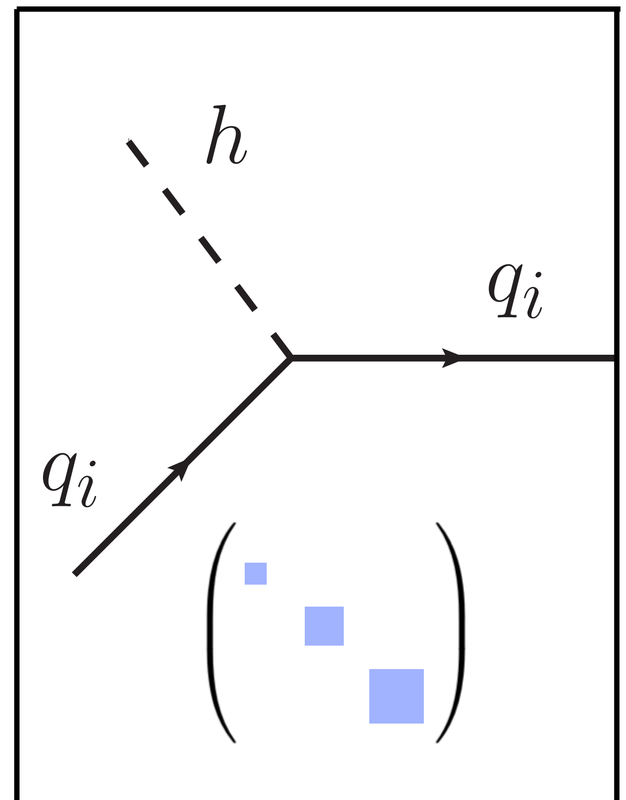


- Flavour universal / blind
- Flavour diagonal non-universal, $\propto m_f$

The SM interactions

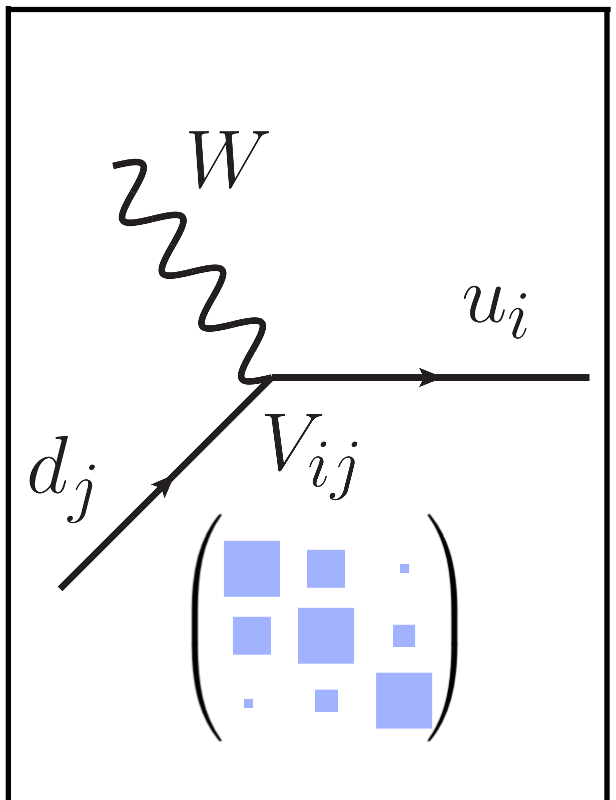


- Flavour universal / blind



- Flavour diagonal non-universal, $\propto m_f$

CKM matrix V



- Flavour changing / violating

The CKM matrix

The CKM matrix

- **Permutations**: fixed by ordering the up and the down quarks by their masses

$$\mathscr{L} \supset \frac{g}{\sqrt{2}} \bar{u}_L^i V_{ij} \gamma_\mu d_L^j W^\mu \qquad V = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

The CKM matrix

- **Permutations**: fixed by ordering the up and the down quarks by their masses

$$\mathscr{L} \supset \frac{g}{\sqrt{2}} \bar{u}_L^i V_{ij} \gamma_\mu d_L^j W^\mu \qquad V = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

- **Rephasing**: $V_{ij} \to e^{i(\theta_u^i - \theta_d^j)} V_{ij}$

$$V_{ij} = (+1, -1) \text{ spurion under } U(1)_{u_i} \times U(1)_{d_j}$$

the only source of breaking

The CKM matrix

- **Permutations**: fixed by ordering the up and the down quarks by their masses

$$\mathscr{L} \supset \frac{g}{\sqrt{2}} \bar{u}_L^i V_{ij} \gamma_\mu d_L^j W^\mu \qquad V = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

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the only source of breaking

- There is a single physical phase δ

The CKM matrix

- **Permutations**: fixed by ordering the up and the down quarks by their masses

$$\mathscr{L} \supset \frac{g}{\sqrt{2}} \bar{u}^i_L V_{ij} \gamma_\mu d^j_L W^\mu \qquad V = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

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$$V_{ij} = (+1, -1) \text{ spurion under } U(1)_{u_i} \times U(1)_{d_j}$$

the only source of breaking

- There is a single physical phase δ

$$Y_{ij} \bar{\psi}^i_L H \psi^j_R + Y^*_{ij} \bar{\psi}^j_R H^\dagger \psi^i_L \xrightarrow{\text{CP}} Y_{ij} \bar{\psi}^j_R H^\dagger \psi^i_L + Y^*_{ij} \bar{\psi}^i_L H \psi^j_R.$$

The CP is conserved, if Yukawa couplings are real, $Y^*_{ij} = Y_{ij}$.

The CKM matrix

- **Permutations**: fixed by ordering the up and the down quarks by their masses

$$\mathscr{L} \supset \frac{g}{\sqrt{2}} \bar{u}_L^i V_{ij} \gamma_\mu d_L^j W^\mu \qquad V = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

- **Rephasing:** $V_{ij} \to e^{i(\theta_u^i - \theta_d^j)} V_{ij}$

$$V_{ij} = (+1, -1) \text{ spurion under } U(1)_{u_i} \times U(1)_{d_j}$$

the only source of breaking

- There is a single physical phase δ

$$Y_{ij} \bar{\psi}_L^i H \psi_R^j + Y_{ij}^* \bar{\psi}_R^j H^\dagger \psi_L^i \xrightarrow{\text{CP}} Y_{ij} \bar{\psi}_R^j H^\dagger \psi_L^i + Y_{ij}^* \bar{\psi}_L^i H \psi_R^j.$$

The CP is conserved, if Yukawa couplings are real, $Y_{ij}^* = Y_{ij}$.

- All CP violation is controlled by a single phase δ - prediction!

The CKM matrix

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

Experimentally:

$$\begin{array}{ccccccc} s_{13} & \ll & s_{23} & \ll & s_{12} & \ll & 1 \\ 0.2^3 & & 0.2^2 & & 0.2 & & \end{array}$$

The CKM matrix

- The Wolfenstein parametrization: $s_{13} \ll s_{23} \ll s_{12} \ll 1$

$$V = \begin{pmatrix} 1-\frac{1}{2}\lambda^2-\frac{1}{8}\lambda^4 & \lambda & A\lambda^3(\rho-i\eta) \\ -\lambda+\frac{1}{2}A^2\lambda^5[1-2(\rho+i\eta)] & 1-\frac{1}{2}\lambda^2-\frac{1}{8}\lambda^4(1+4A^2) & A\lambda^2 \\ A\lambda^3[1-(1-\frac{1}{2}\lambda^2)(\rho+i\eta)] & -A\lambda^2+\frac{1}{2}A\lambda^4[1-2(\rho+i\eta)] & 1-\frac{1}{2}A^2\lambda^4 \end{pmatrix}$$

$$\begin{aligned} \lambda &= 0.2251 \pm 0.0005 \\ A &= 0.81 \pm 0.03 \\ \rho &= +0.160 \pm 0.007 \\ \eta &= +0.350 \pm 0.006 \end{aligned}$$

The CKM matrix

- The Wolfenstein parametrization: $s_{13} \ll s_{23} \ll s_{12} \ll 1$

$$V = \begin{pmatrix} 1-\frac{1}{2}\lambda^2-\frac{1}{8}\lambda^4 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda+\frac{1}{2}A^2\lambda^5[1-2(\rho+i\eta)] & 1-\frac{1}{2}\lambda^2-\frac{1}{8}\lambda^4(1+4A^2) & A\lambda^2 \\ A\lambda^3[1-(1-\frac{1}{2}\lambda^2)(\rho+i\eta)] & -A\lambda^2+\frac{1}{2}A\lambda^4[1-2(\rho+i\eta)] & 1-\frac{1}{2}A^2\lambda^4 \end{pmatrix}$$

$$\begin{aligned} \lambda &= 0.2251 \pm 0.0005 \\ A &= 0.81 \pm 0.03 \\ \rho &= +0.160 \pm 0.007 \\ \eta &= +0.350 \pm 0.006 \end{aligned}$$

- The unitarity triangles $VV^\dagger = 1$

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

The CKM matrix

- The Wolfenstein parametrization: $s_{13} \ll s_{23} \ll s_{12} \ll 1$

$$V = \begin{pmatrix} 1-\frac{1}{2}\lambda^2-\frac{1}{8}\lambda^4 & \lambda & A\lambda^3(\rho-i\eta) \\ -\lambda+\frac{1}{2}A^2\lambda^5[1-2(\rho+i\eta)] & 1-\frac{1}{2}\lambda^2-\frac{1}{8}\lambda^4(1+4A^2) & A\lambda^2 \\ A\lambda^3[1-(1-\frac{1}{2}\lambda^2)(\rho+i\eta)] & -A\lambda^2+\frac{1}{2}A\lambda^4[1-2(\rho+i\eta)] & 1-\frac{1}{2}A^2\lambda^4 \end{pmatrix}$$

$$\begin{aligned} \lambda &= 0.2251 \pm 0.0005 \\ A &= 0.81 \pm 0.03 \\ \rho &= +0.160 \pm 0.007 \\ \eta &= +0.350 \pm 0.006 \end{aligned}$$

- The unitarity triangles $VV^\dagger = 1$

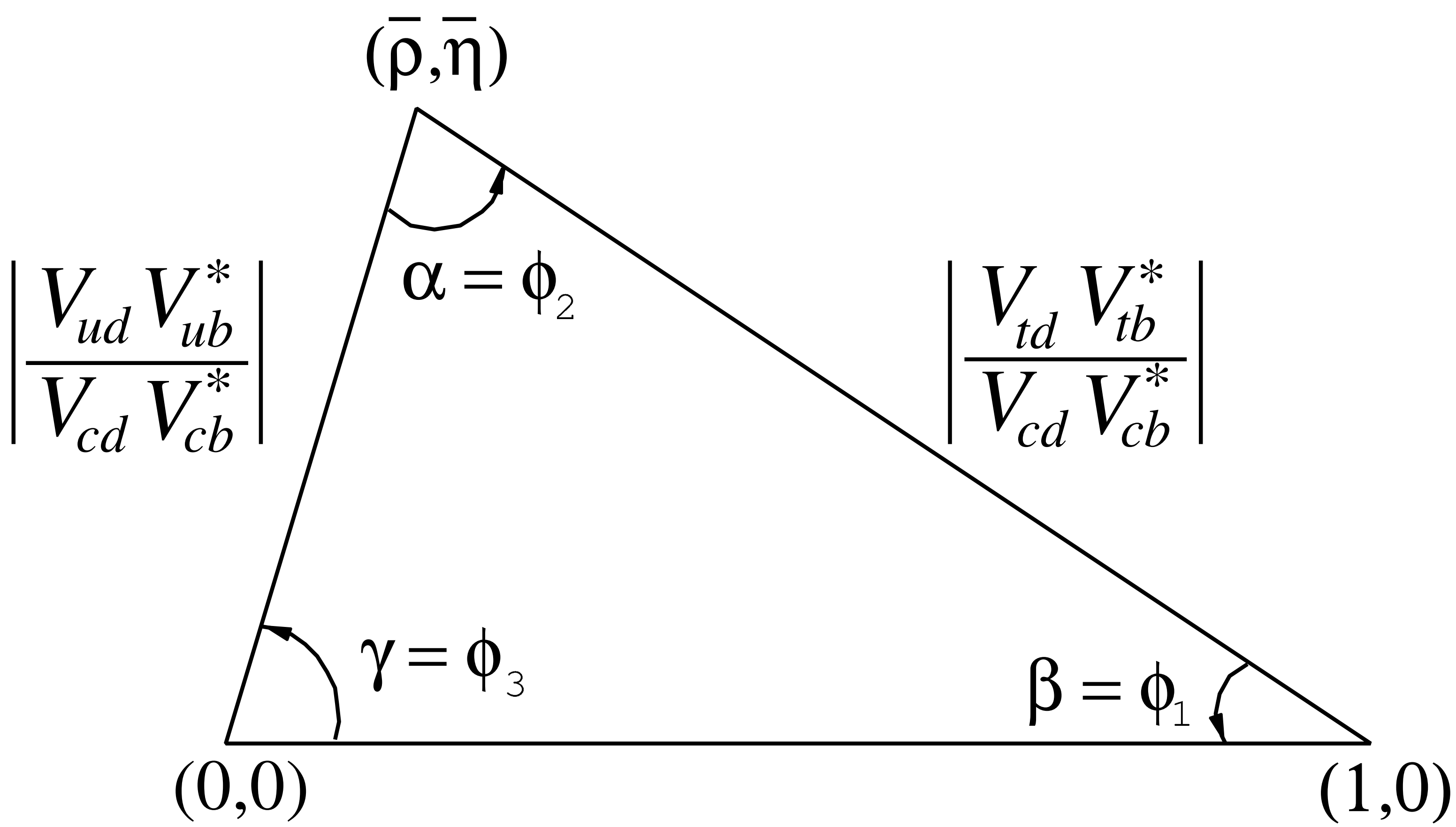
$$V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0$$

- Physical parameters. Invariant under $V_{ij} \to e^{i(\theta_u^i - \theta_d^j)} V_{ij}$

$$R_u \equiv \left| \frac{V_{ud}V_{ub}}{V_{cd}V_{cb}} \right| = \sqrt{\rho^2+\eta^2} \quad , \quad R_t \equiv \left| \frac{V_{td}V_{tb}}{V_{cd}V_{cb}} \right| = \sqrt{(1-\rho)^2+\eta^2}$$

$$\alpha \equiv \arg\left[-\frac{V_{td}V_{tb}^*}{V_{ud}V_{ub}^*}\right] \quad , \quad \beta \equiv \arg\left[-\frac{V_{cd}V_{cb}^*}{V_{td}V_{tb}^*}\right] \quad , \quad \gamma \equiv \arg\left[-\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}\right]$$

The CKM matrix

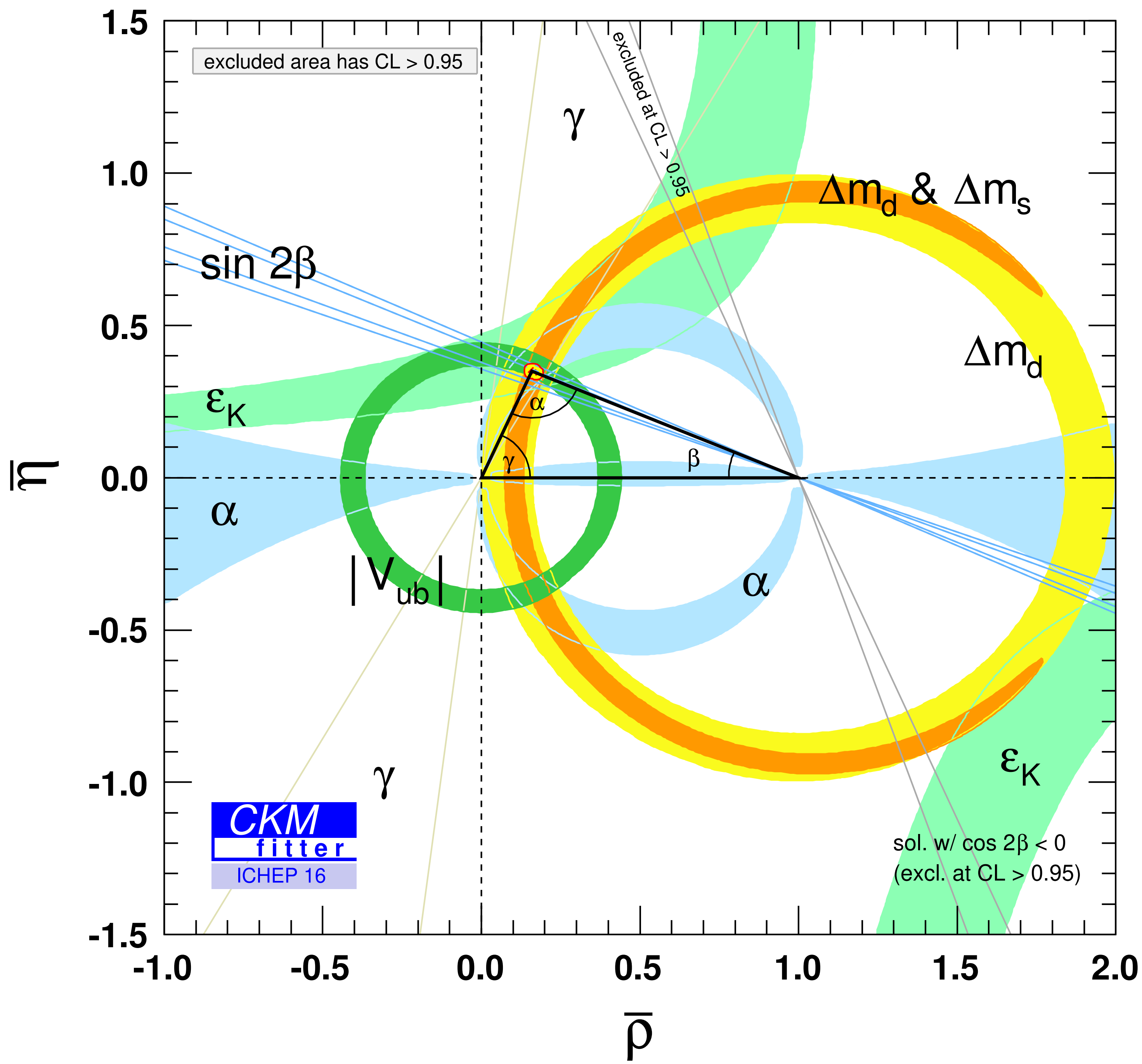


The CKM matrix: Experiment

Table 4: FCCC processes and CKM entries

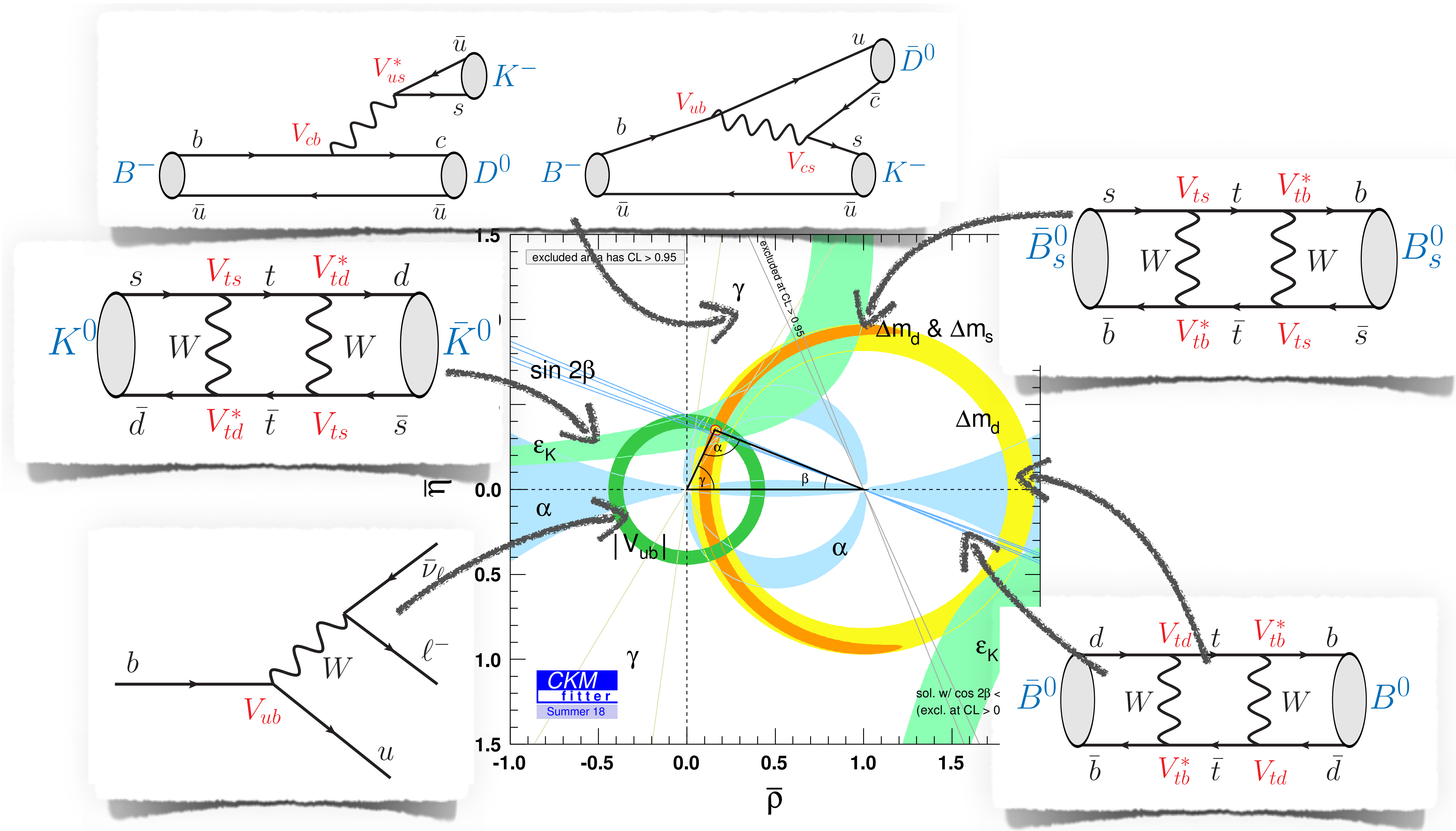
Process	CKM
$u \to d\ell^+\nu$	$\vert V_{ud}\vert = 0.97417 \pm 0.00021$
$s \to u\ell^-\bar{\nu}$	$\vert V_{us}\vert = 0.2248 \pm 0.0006$
$c \to d\ell^+\nu$ or $\nu_\mu + d \to c + \mu^-$	$\vert V_{cd}\vert = 0.220 \pm 0.005$
$c \to s\ell^+\nu$ or $c\bar{s} \to \ell^+\nu$	$\vert V_{cs}\vert = 0.995 \pm 0.016$
$b \to c\ell^-\bar{\nu}$	$\vert V_{cb}\vert = 0.0405 \pm 0.0015$
$b \to u\ell^-\bar{\nu}$	$\vert V_{ub}\vert = 0.0041 \pm 0.0004$
$pp \to tX$	$\vert V_{tb}\vert = 1.01 \pm 0.03$
$b \to sc\bar{u}$ and $b \to su\bar{c}$	$\gamma = 73 \pm 5^o$

The CKM matrix: Experiment



The great triumph of the SM!

The CKM matrix: Experiment



Quiz

Flavour data

$$\begin{aligned}
\mathrm{Br}(B \to X\mu\nu) &= 0.1086(16) \\
\mathrm{Br}(B \to Xe\nu) &= 0.1086(16) \\
\mathrm{Br}(B \to X_s\gamma) &= 3.49(19) \times 10^{-4} \\
\hline
\mathrm{Br}(B_s \to \mu^+\mu^-) &= 2.4(8) \times 10^{-9} \\
\mathrm{Br}(B^+ \to \bar{D}^0\ell^+\nu) &= 2.27(11) \times 10^{-2} \\
\mathrm{Br}(B^- \to \pi^0\ell^-\bar{\nu}) &= 7.80(27) \times 10^{-5} \\
\mathrm{Br}(K_L \to \mu^+\mu^-) &= 6.84(11) \times 10^{-9} \\
\mathrm{Br}(K^+ \to \mu^+\nu) &= 0.6356(11) \\
\mathrm{Br}(\psi \to \mu^+\mu^-) &= 5.961(33) \times 10^{-2} \\
\mathrm{Br}(D \to \mu^+\mu^-) &< 6.2 \times 10^{-9} \;.
\end{aligned}$$

[PDG]

Stare at these for a moment—do you see a pattern?

The big part of PDG is about flavour…

Flavour data

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[PDG]

?

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[PDG]

1. **Lepton universality**. Swapping one generation of leptons with another does not appear to affect the branching ratios of these transitions.

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[PDG]

1. **Lepton universality**. Swapping one generation of leptons with another does not appear to affect the branching ratios of these transitions.
2. **Flavor-changing neutral currents are small**. On the other hand, processes that change flavor are suppressed for charge-neutral transitions compared to transitions between hadrons of different charge.

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2. **Flavor-changing neutral currents are small**. On the other hand, processes that change flavor are suppressed for charge-neutral transitions compared to transitions between hadrons of different charge.
3. **Generation hierarchy**. Decays between third and first generation are suppressed compared to that of third to second generation.

Part II

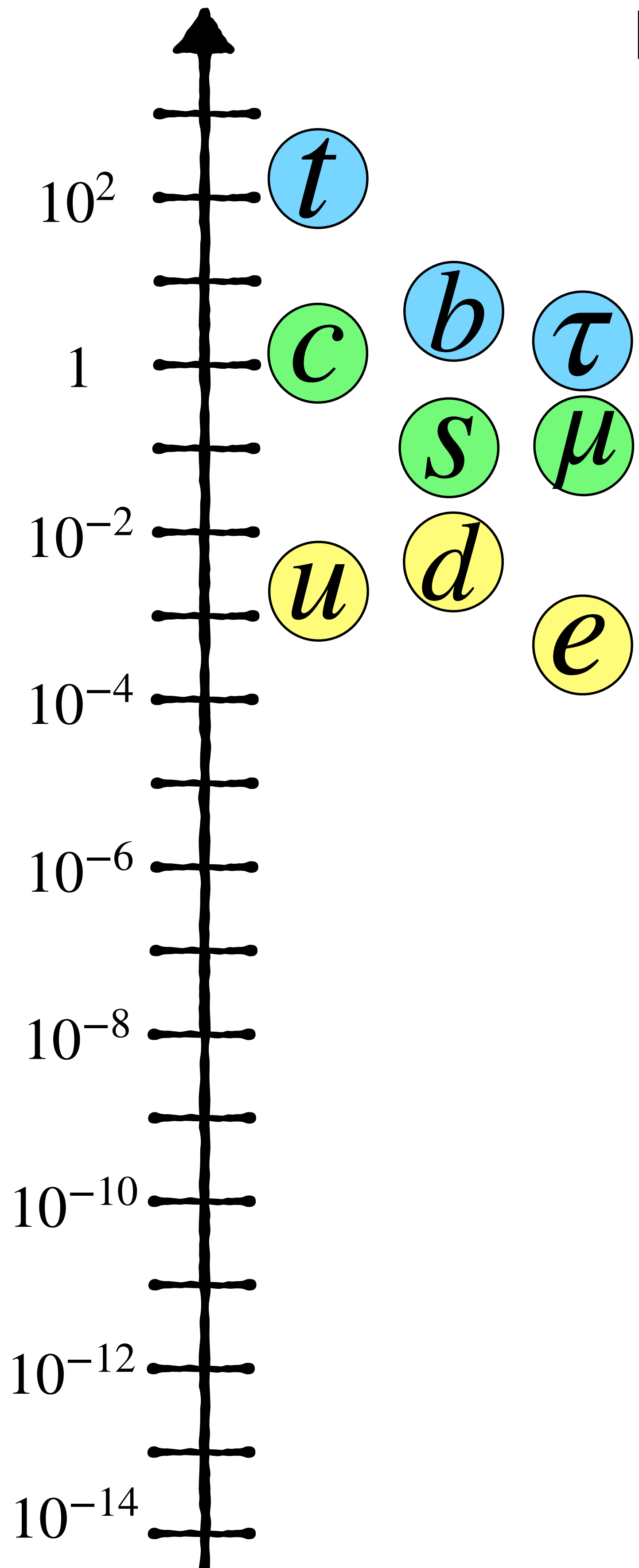
- The flavour puzzle
- EFT
- SMEFT
- New physics flavour puzzle
- Flavour vs Collider
- Extras…

The flavour puzzle

Flavour Puzzle

Empirical

Mass [GeV]



Hierarchy!

The Weak Force Mixing:

$V_{\text{CKM}} \sim$ 

Y^u / Y^d **Alignment!**

$$-\mathcal{L}_{\text{SM}} \supset \bar{q}_i Y_u^{ij} u_j \tilde{H} + \bar{q}_i Y_d^{ij} d_j H + \bar{\ell}_i Y_e^{ij} e_j H$$

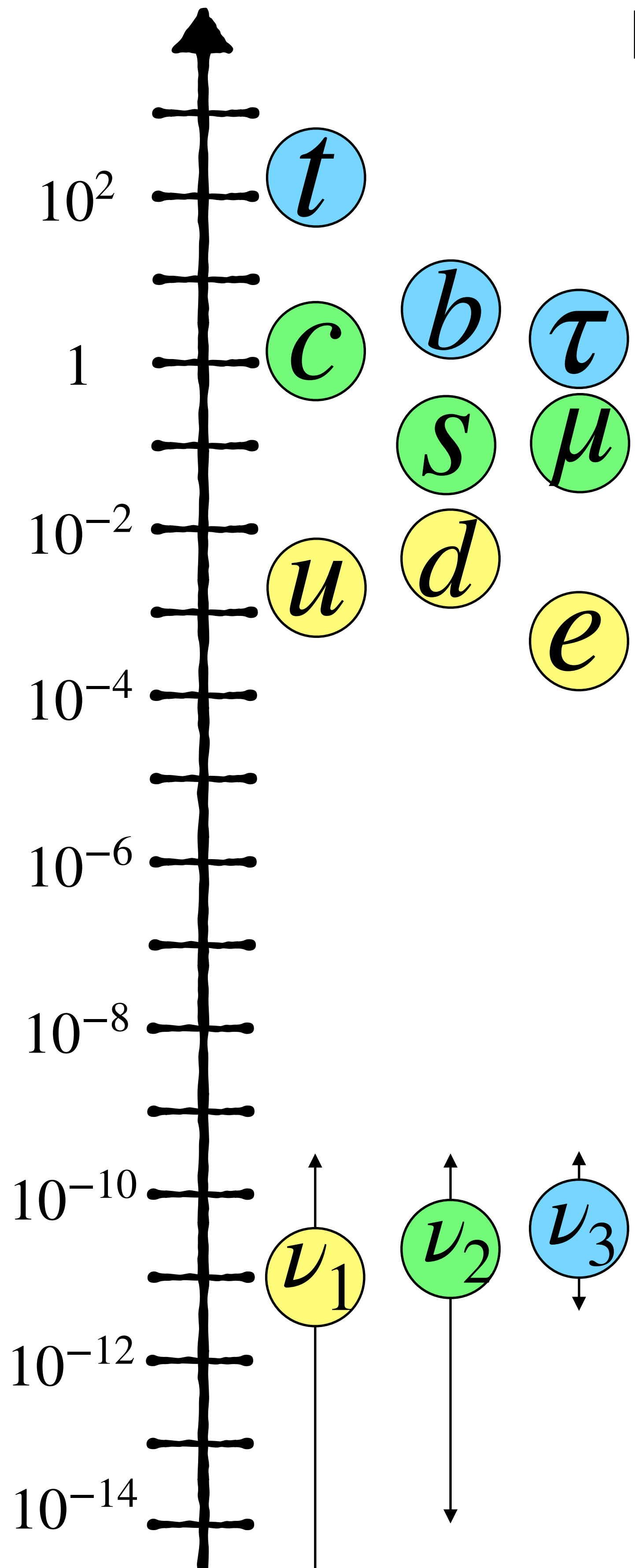
$$\Im \det[Y_d Y_d^\dagger, Y_u Y_u^\dagger] \approx \mathcal{O}(10^{-22})$$

*sample uniformly in [0,1] interval $\approx \mathcal{O}(1)$

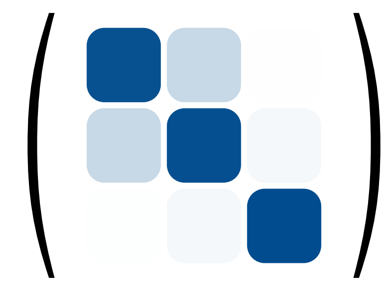
Flavour Puzzle

Empirical

Mass [GeV]

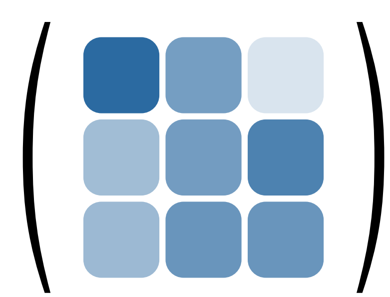


The Weak Force Mixing:

$V_{\text{CKM}} \sim$ 

$$-\mathcal{L}_{\rm SM} \supset \bar{q}_i Y_u^{ij} u_j \tilde{H} + \bar{q}_i Y_d^{ij} d_j H + \bar{\ell}_i Y_e^{ij} e_j H$$

$$-\mathcal{L}_{\rm SMEFT} \supset \frac{1}{\Lambda_\nu} \ell_i Y_\nu^{ij} \ell_j H H$$

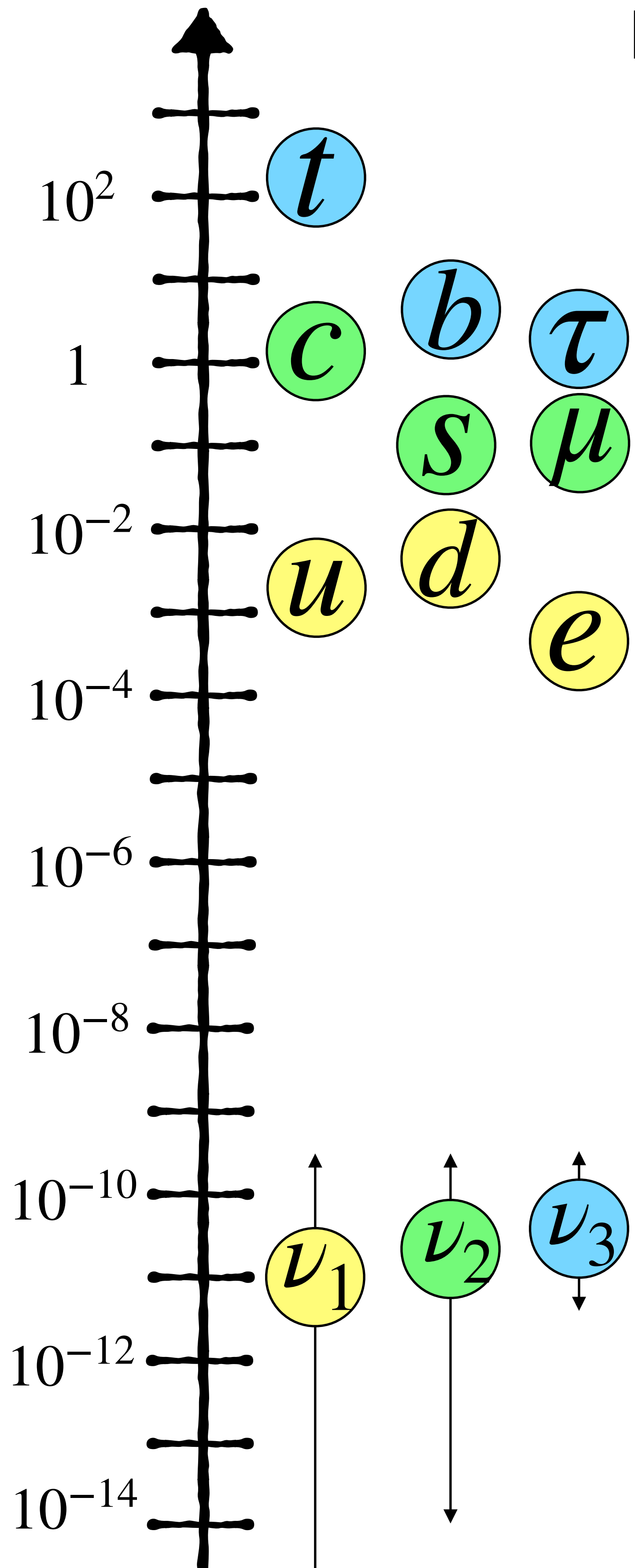
$V_{\text{PMNS}} \sim$ 

SM predicts massless neutrinos?!

Flavour Puzzle

Empirical

Mass [GeV]



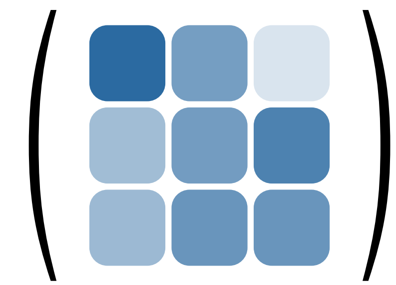
The Weak Force Mixing:

$V_{\mathrm{CKM}} \sim$ 

?

Pattern

Analogy:
The periodic table of elements

$V_{\mathrm{PMNS}} \sim$ 

Flavour Model Building

- Explain (fully or partially) the peculiar flavour patterns

- Warped compactification

  hep-ph/9905221, hep-ph/9903417, hep-ph/0003129, hep-ph/9912408, hep-ph/0408134, 0903.2415, 1004.2037, 1509.02539, 2203.01952, …

- (Gauged) flavour symmetries

  hep-ph/9512388, hep-ph/9507462, 1009.2049, 1105.2296, 1505.03862, 1609.05902, 1611.02703, 1807.03285, 1805.07341, 2201.07245, …

- Partial compositeness

  hep-ph/030625, 0804.1954, 1404.7137, 1506.01961, 1506.00623, 1607.01659, 1908.09312, 1911.05454, …

- Froggatt-Nielsen

  Froggatt:1978nt, hep-ph/9212278, hep-ph/9310320, 1909.05336, 1907.10063, 2009.05587, 2002.04623, 2010.03297, …

- Multi-scale flavour

  1603.06609, 1712.01368, 2011.01946, 2203.01952…

- Clockwork flavour

  1610.07962, 1711.05393, 1807.09792, 2106.09869, …

- Radiative masses

  Weinberg:1972ws, hep-ph/9601262, 1409.2522, 2001.06582, 2012.10458, …

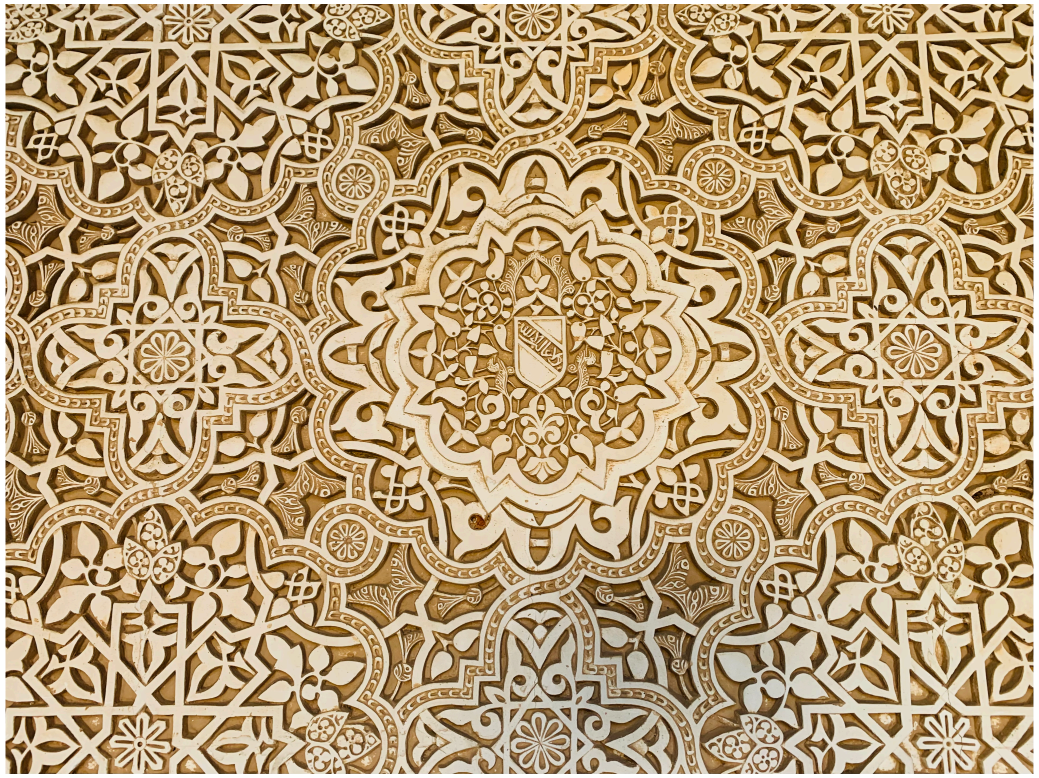
- …

Patterns <> Symmetries

Selection rules

- Flavour patterns observed in the Yukawa sector
  $\Longrightarrow$ *Approximate flavour symmetries in the SM*

Bottom-up:
The largest parameter $y_t = Y^u_{33} \sim 1$ breaks
$U(3)_q \times U(3)_u \to U(2)^2 \times U(1)$, etc…



Alhambra of **Granada**

1 Important to understand the SM phenomenology:

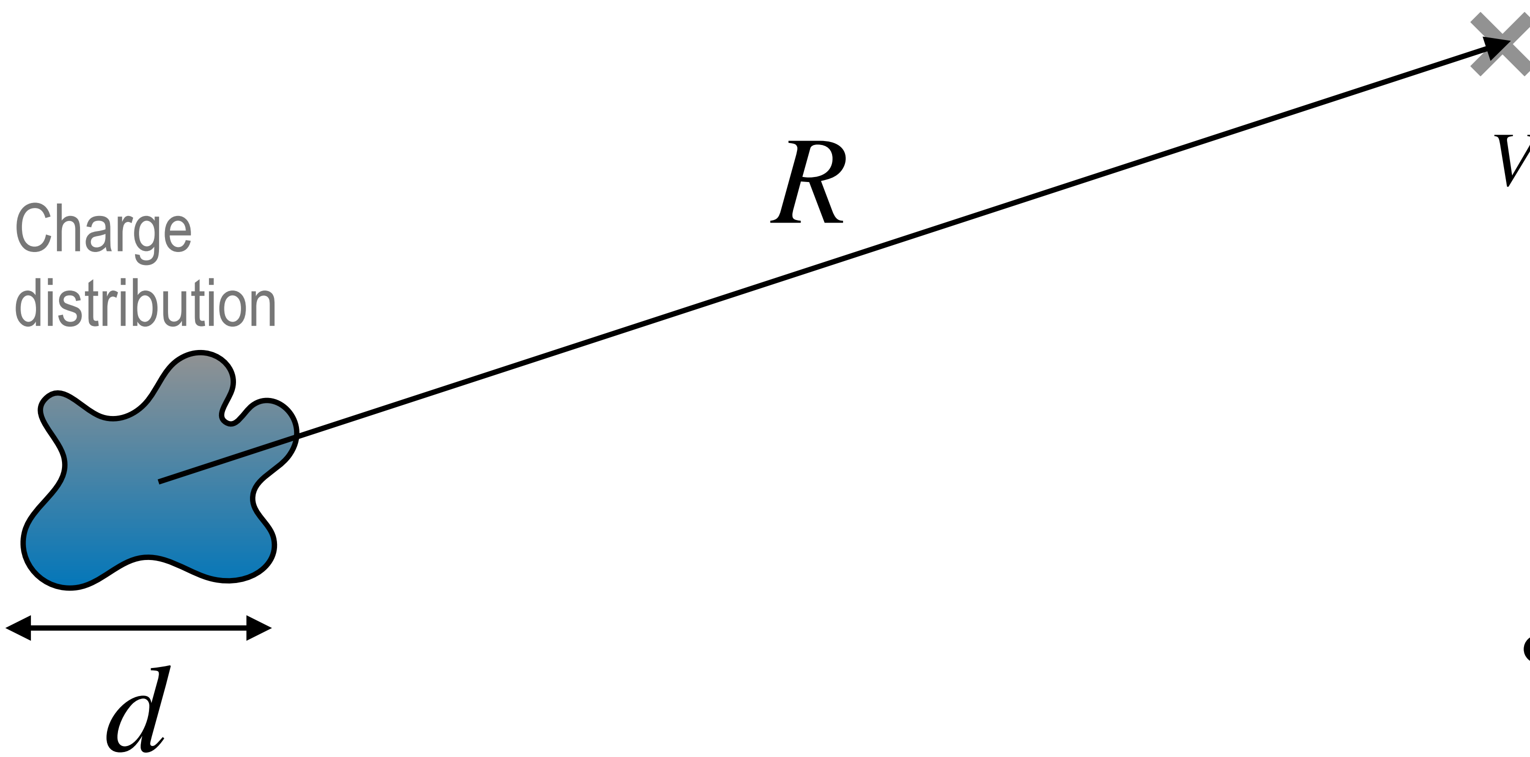
- *isospin, SU(3), heavy-quark symmetries, GIM, …*

2 Stringent tests of the SM
— a window to new physics.

Effective Field Theory

Effective theories: Electrostatics

- Scale separation $d \ll R$



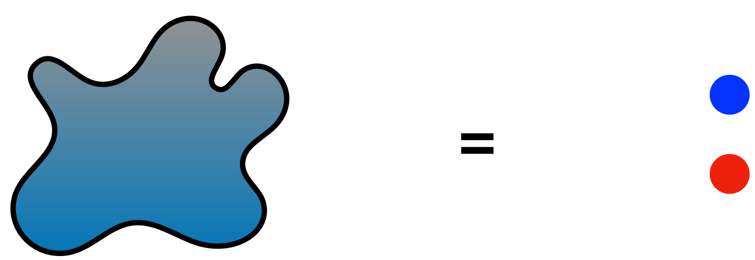
$$V(R) = C_1 \frac{d}{R} + C_2 \frac{d^2}{R^2} + C_3 \frac{d^3}{R^3} + \dots$$

Multipole expansion

- Precision/Distance interplay

EFT imprints of a UV Model

- Constructing a theoretical model within the framework of quantum field theory to solve (some) of the SM shortcomings

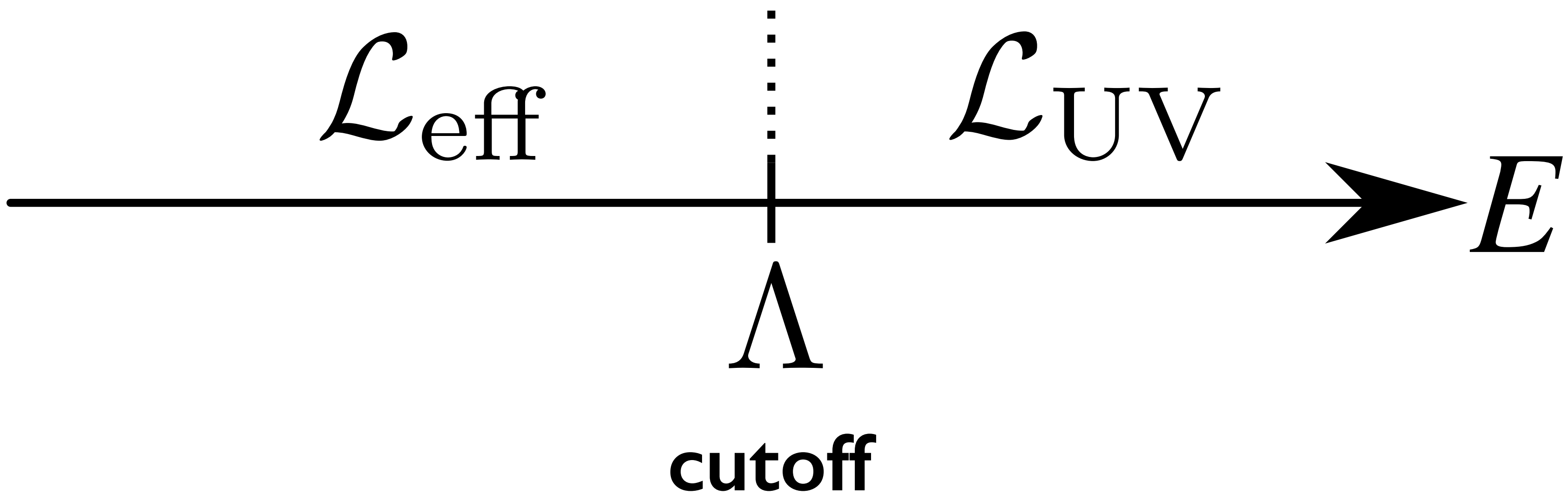


Symmetries = selection rules!

$$V(R) = C_1 \frac{d}{R} + C_2 \frac{d^2}{R^2} + \dots$$

$$SO(3) \supset SO(2) \supset \dots$$

Effective Field Theory



Infrared,
Long-distance,
Soft

Ultraviolet,
Short-distance,
Hard

Effective Field Theory

Toy example

Consider $M \gg E \gtrsim m$ where E is the collider's energy

$$\mathscr{L}_{\mathrm{UV}} \supset \bar{\psi}\,(iD - m)\,\psi$$
$$+\partial_\mu \Phi\, \partial^\mu \Phi - M^2 \Phi^\dagger \Phi$$
$$-y\,\bar{\psi}\psi\,\Phi$$

Degrees of freedom (in/out states): only ψ

Effective Field Theory

Toy example

Consider $M \gg E \gtrsim m$ where E is the collider's energy

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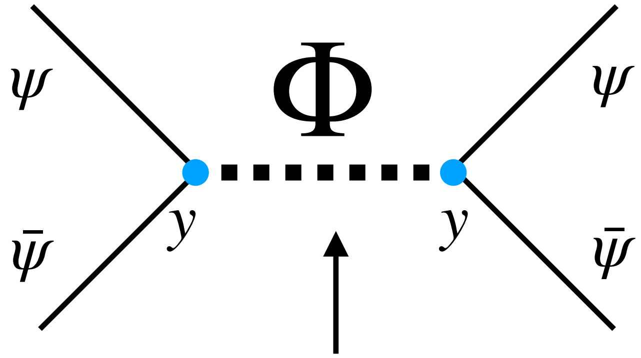


$$\langle 0 | T\{\Phi(0)\Phi(x)\} | 0\rangle = \int \frac{d^4k}{(2\pi)^4} e^{-ikx} \frac{i}{k^2 - M^2}$$

Degrees of freedom (in/out states): only ψ

Effective Field Theory

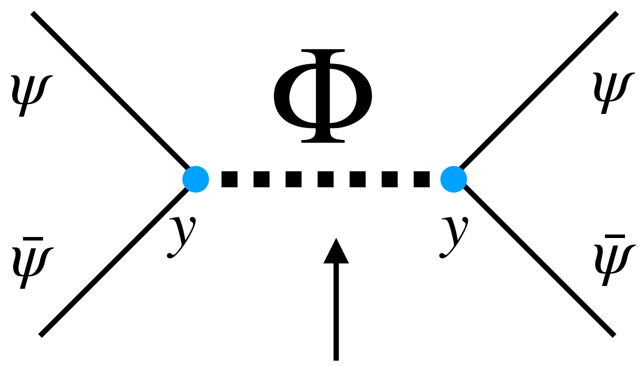
Toy example

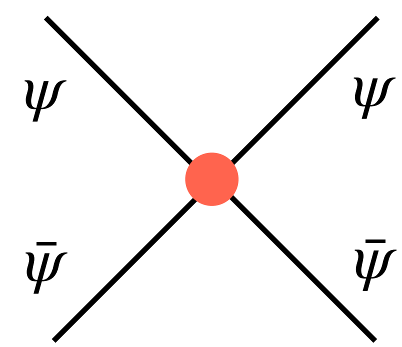
EFT

Consider $M \gg E \gtrsim m$ where E is the collider's energy

$$\mathscr{L}_{\rm UV} \supset \bar{\psi}\,(iD - m)\,\psi + \partial_\mu \Phi\, \partial^\mu \Phi - M^2 \Phi^\dagger \Phi - y\, \bar{\psi}\psi\, \Phi$$

$$\mathscr{L}_{\rm eft} \supset \bar{\psi}\,(iD - m)\,\psi - C\, \bar{\psi}\psi\, \bar{\psi}\psi + \dots$$





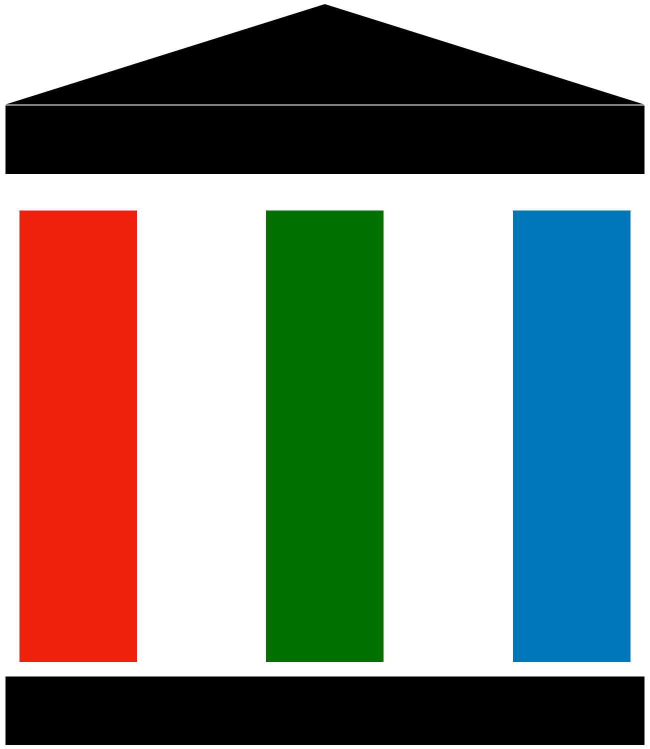
$+\dots$

$$\langle 0|T\{\Phi(0)\Phi(x)\}|0\rangle = \int \frac{d^4k}{(2\pi)^4} e^{-ikx} \frac{i}{k^2 - M^2} \xrightarrow{k^2 \sim \mathcal{O}(E^2) \ll M^2} -\frac{i}{M^2}\delta^{(4)}(x) + \dots$$

Degrees of freedom (in/out states): only ψ

Local interaction:
The Compton wavelength M^{-1} is very small.

Effective Field Theory

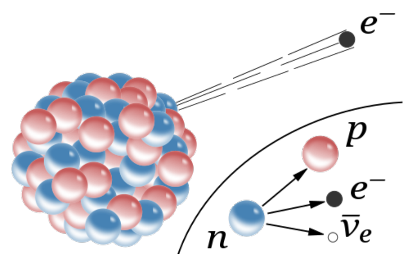


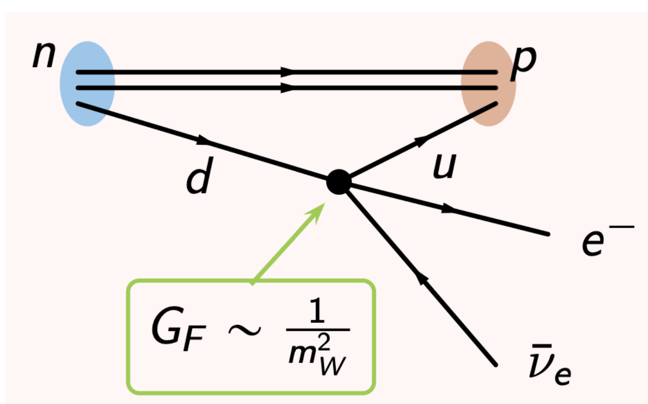
- **Degrees of freedom**
  Drop heavy fields and keep only the light ones. Heavy and light are defined by the **cutoff**.

- **Symmetries**
  Space-time, gauge symmetries. They shape the infinite series of **local** operators of the EFT.

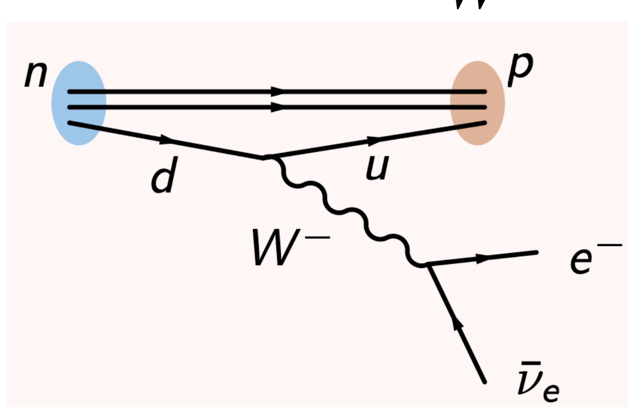
- **Power-counting**
  The expansion parameter gives meaning to the EFT series.

Fermi theory





$$q^2 \ll m_W^2$$



The Nobel Prize in Physics 1903

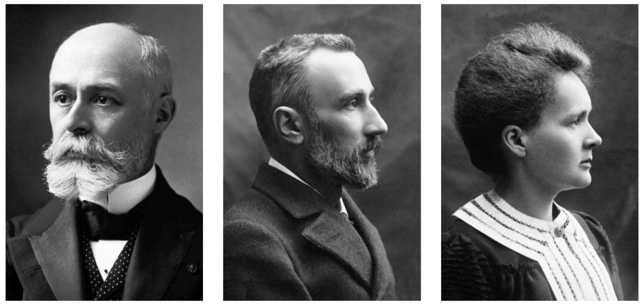


Photo from the Nobel Foundation archive.
Antoine Henri Becquerel
Prize share: 1/2

Photo from the Nobel Foundation archive.
Pierre Curie
Prize share: 1/4

Photo from the Nobel Foundation archive.
Marie Curie, née Sklodowska
Prize share: 1/4

The Nobel Prize in Physics 1938

Photo from the Nobel Foundation archive.
Enrico Fermi
Prize share: 1/1

The Nobel Prize in Physics 1979

Photo from the Nobel Foundation archive.
Sheldon Lee Glashow

Photo from the Nobel Foundation archive.
Abdus Salam

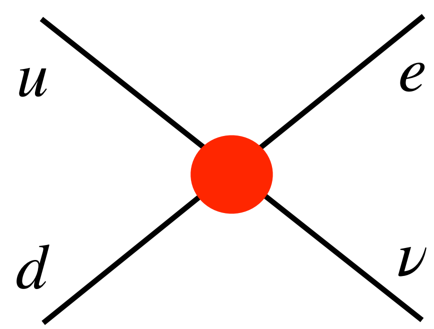
Photo from the Nobel Foundation archive.
Steven Weinberg

Fermi theory

- Violation of perturbative unitary

$$G_F \sim (100\,\mathrm{GeV})^{-2}$$

4-fermion scattering at energy E



$$\mathscr{M} \sim G_F\, E^2 \implies M_W \lesssim 1\,\mathrm{TeV}$$

- Important lesson!

Theory of weak decays

Effective Field Theory

Factorisation

$$\langle \mathscr{H}_{eff} \rangle \propto \langle Q(\mu) \rangle \; C(\mu)$$

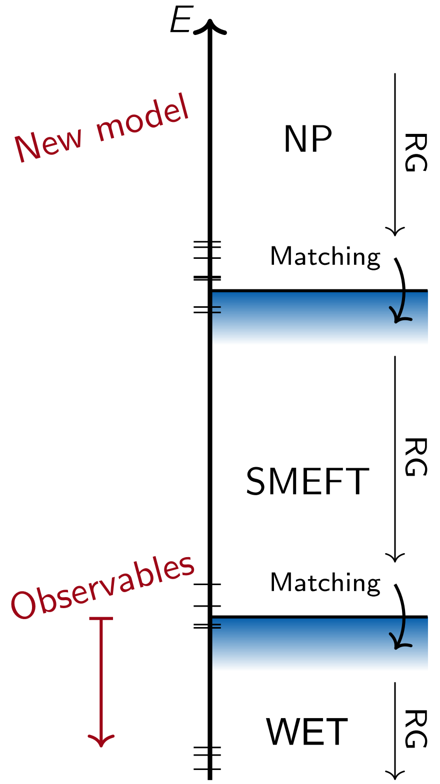
long-distance contributions $E < \mu$

short-distance contributions $E > \mu$

Hadronic matrix elements

2205.15373,	Lattice QCD, http://flag.unibe.ch/2021/
2205.13952,	Heavy quark effective theory,
2204.09091,	Heavy quark expansion,
2108.05589,	QCD factorisation,
1904.08731,	SCET,
1902.09553,	ChPT,
1908.09398,	QCD sum rules,
1912.09335,	Light-cone sum rules,
1908.07011,	…
2002.00020,	
2006.07287,	
2101.12028,	
2105.09330,	
2106.12168,	
2112.07685,	
2206.11281,	
…	

Wilson coefficients



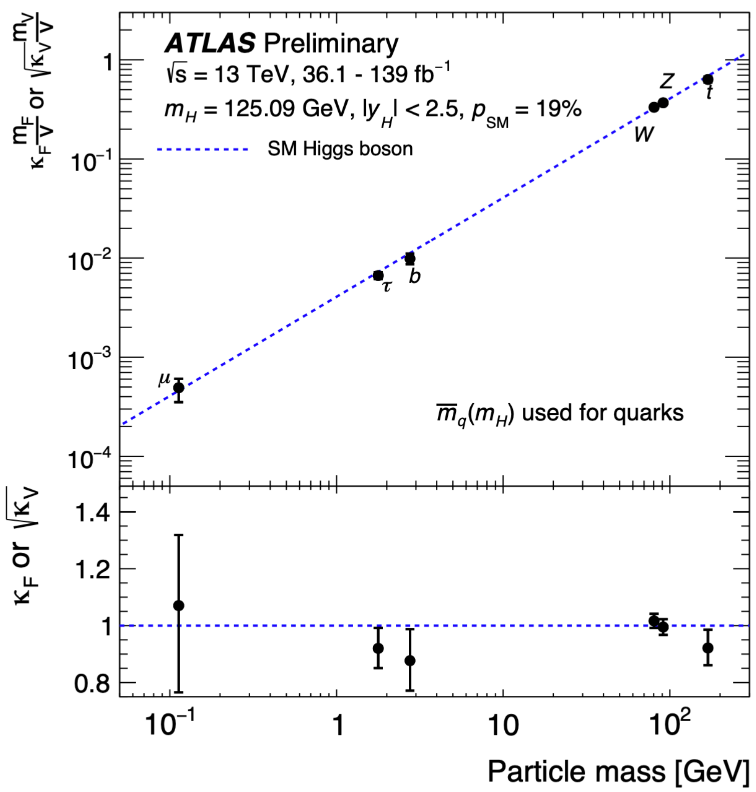
1308.2627,
1310.4838,
1312.2014,
1709.04486,
1711.05270,
1711.10391,
1710.06445,
1804.05033,
1908.05295,
2010.16341,
2012.08506,
2012.07851,
…

Standard Model Effective Field Theory

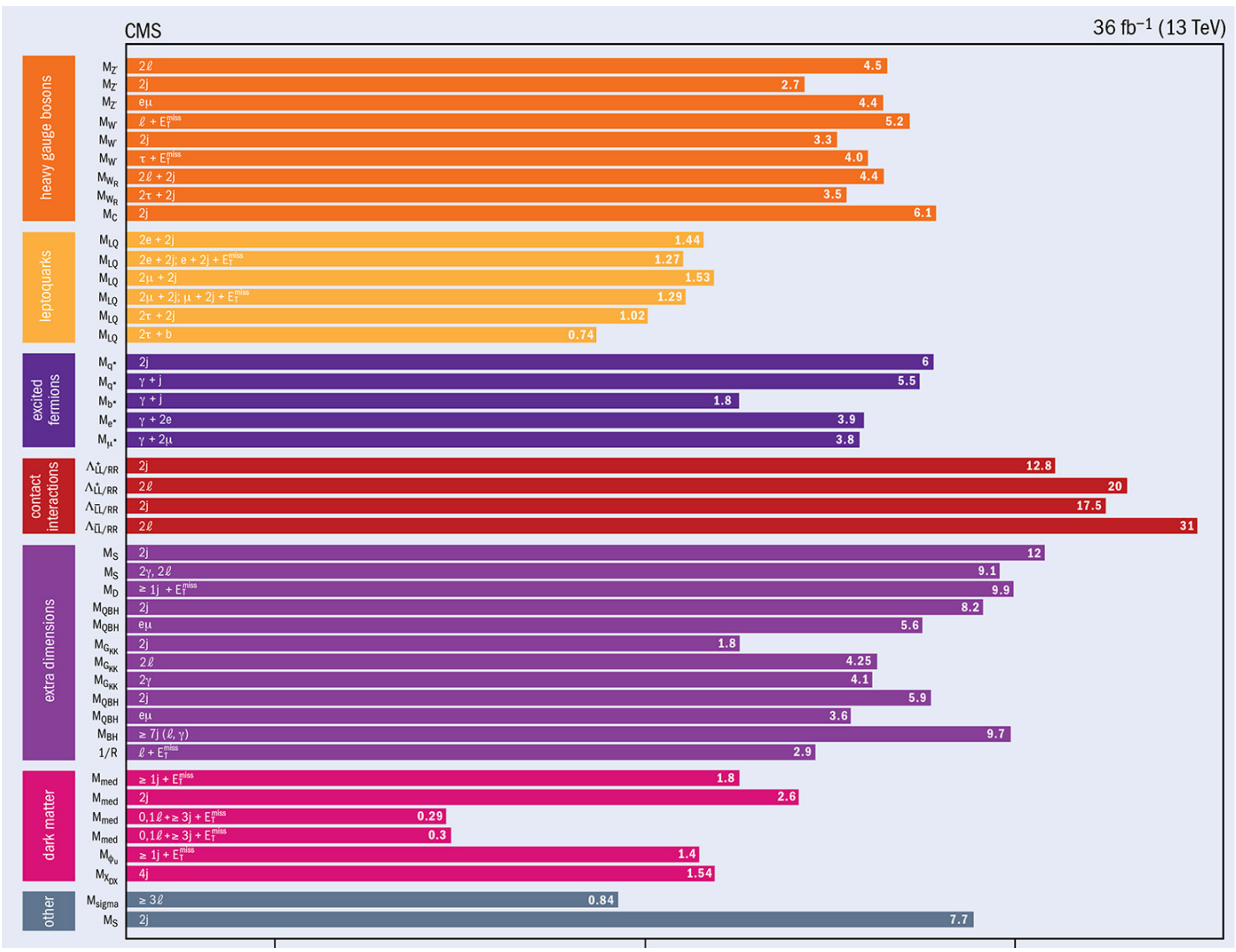
SMEFT

- SM fields & symmetries
- Scale separation $\Lambda_Q \gg v_{EW}$
- Higher-dimensional operators encode short-distance physics:

$$\mathscr{L} = \sum_Q \frac{C_Q}{\Lambda_Q^{[Q]-4}} Q$$

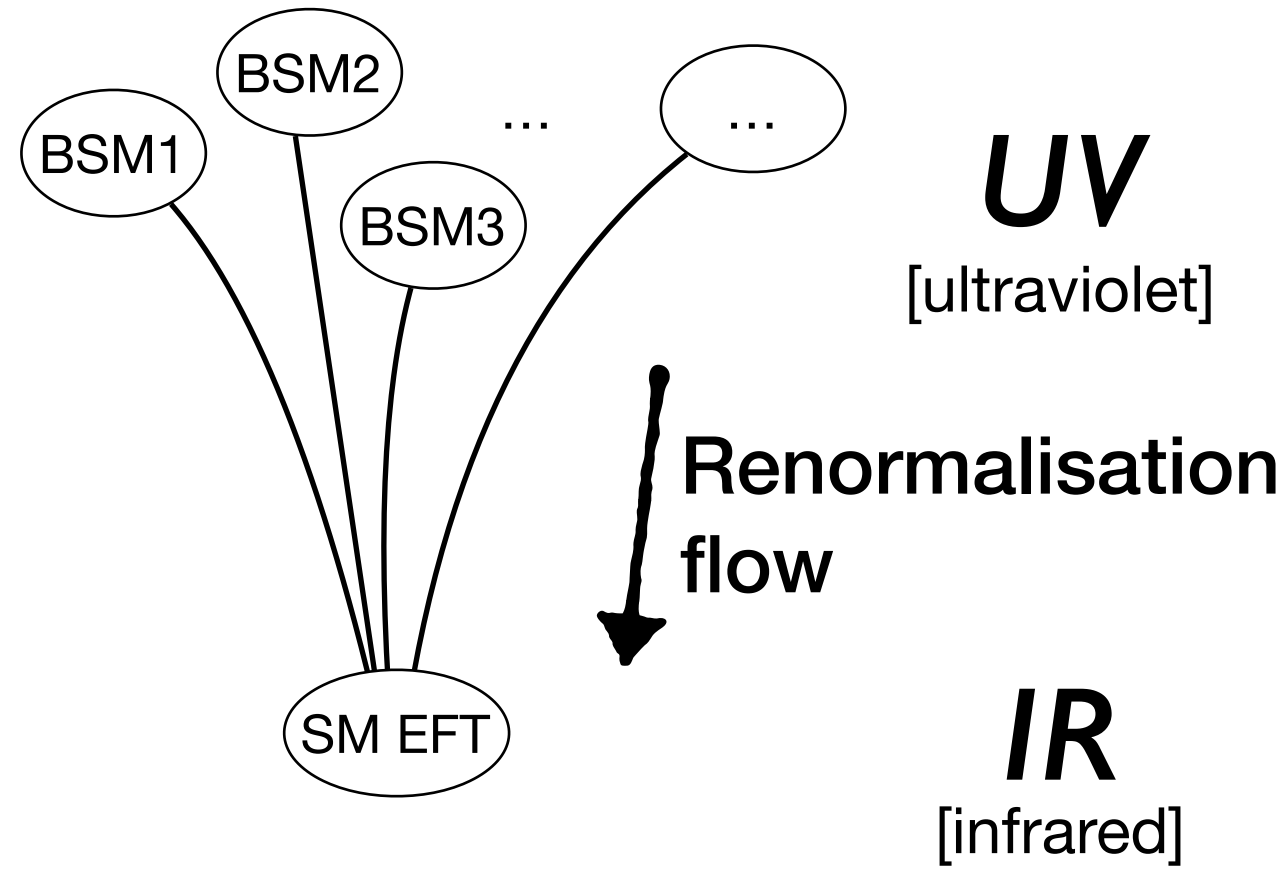


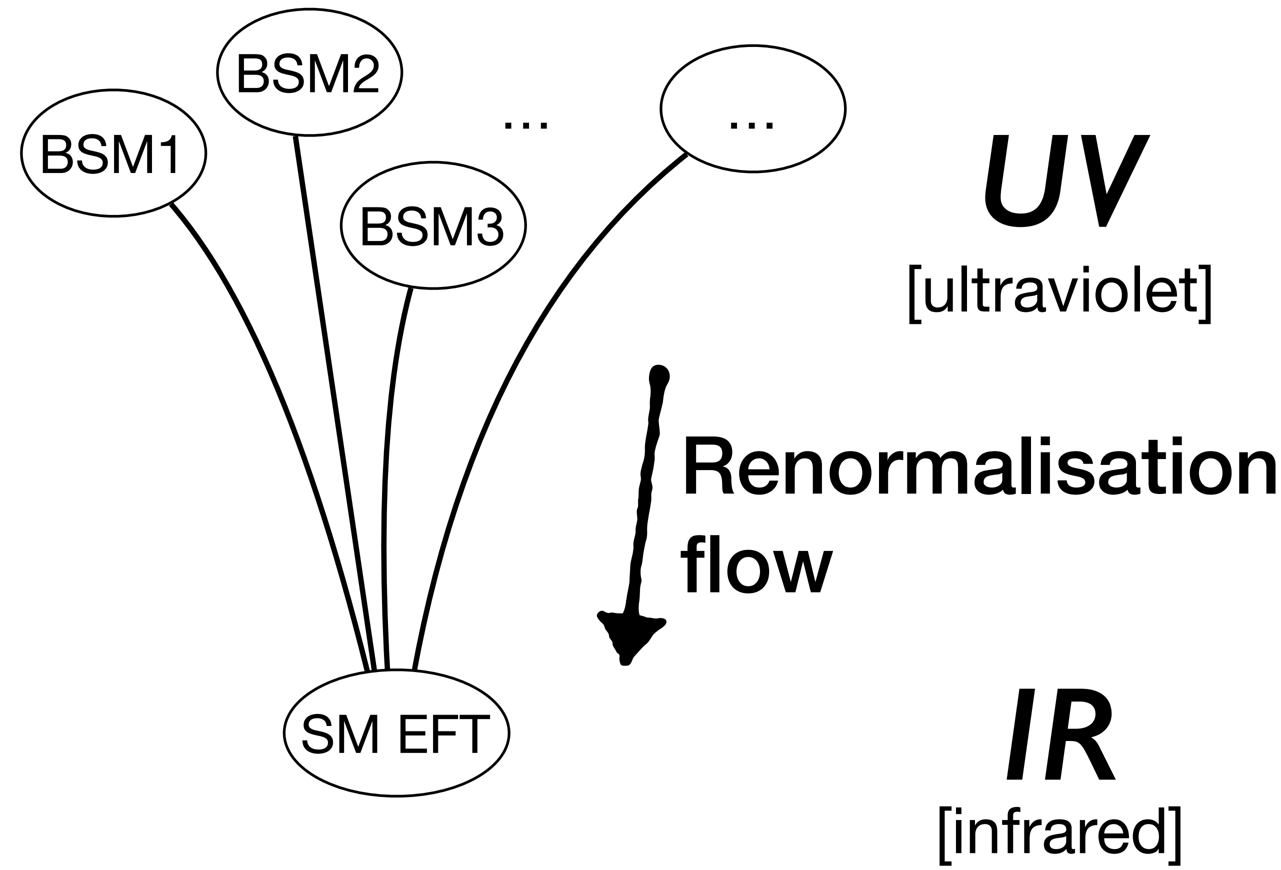
Linear EWSB?



NP mass gap?


SMEFT

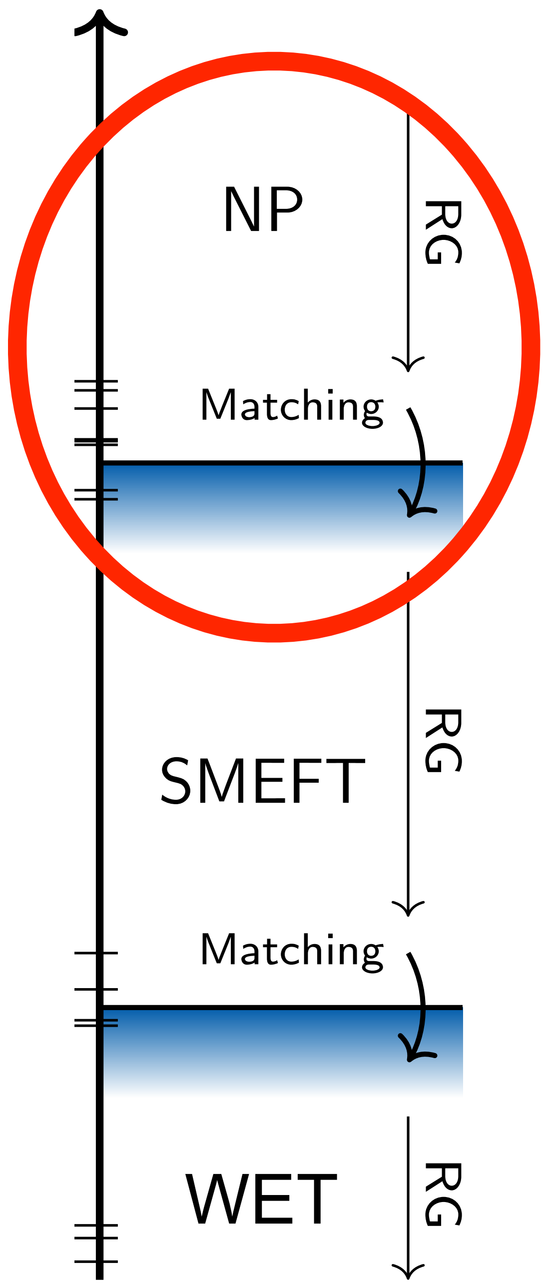

BSM1
BSM2
BSM3
...
...
SM EFT
UV
[ultraviolet]
Renormalisation flow
IR
[infrared]



<u>Reinforced by the current state of affairs</u>

1. No clear preferred BSM: Short-distance direction still the most compelling
2. SMEFT explains why SM works well: limited luminosity and energy so far
3. Experiments headed towards the precision era

SMEFT: Systematic BSM



New Physics

- **Strongly coupled**

Yet, SMEFT works provided the mass gap

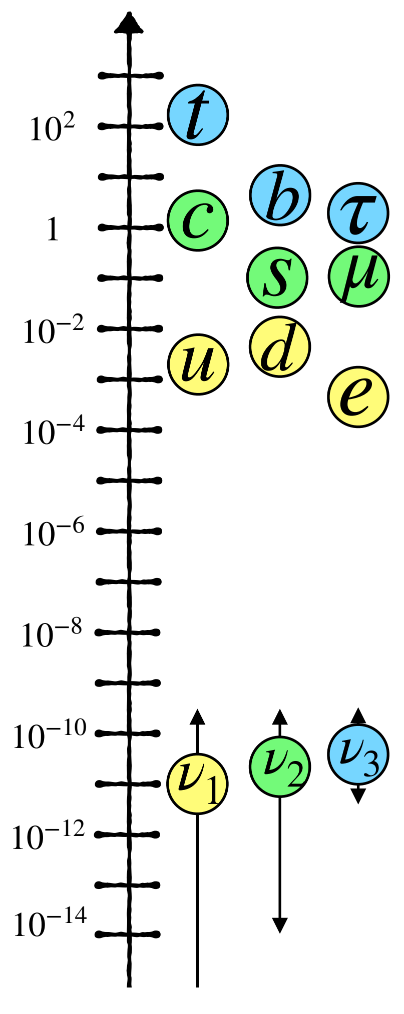
- **Perturbative**
  1. Tree-level
     Finite number of topologies, classified at dim-6.
  2. Loop-level
     Infinite but countable.

  To get a large effect in weak decays:

- a large coupling
  Perturbativity
- a small mass
  Direct searches

dim 5 - *The first SMEFT's success?*

*Picture to be confirmed experimentally



The mass gap is explained if $\Lambda_\nu \gg v_{EW}$

$$-\mathcal{L}_{\rm SMEFT} \supset \frac{1}{\Lambda_\nu} \ell_i Y_\nu^{ij} \ell_j H H \qquad (\Delta L = 2)$$

New physics flavour puzzle

dim 6 - ***Fermionic operators***

Grzadkowski et al, 1008.4884

$(\bar{L}L)(\bar{L}L)$		$(\bar{R}R)(\bar{R}R)$		$(\bar{L}L)(\bar{R}R)$	
Q_{ll}	$(\bar{l}_p\gamma_\mu l_r)(\bar{l}_s\gamma^\mu l_t)$	Q_{ee}	$(\bar{e}_p\gamma_\mu e_r)(\bar{e}_s\gamma^\mu e_t)$	Q_{le}	$(\bar{l}_p\gamma_\mu l_r)(\bar{e}_s\gamma^\mu e_t)$
$Q_{qq}^{(1)}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{q}_s\gamma^\mu q_t)$	Q_{uu}	$(\bar{u}_p\gamma_\mu u_r)(\bar{u}_s\gamma^\mu u_t)$	Q_{lu}	$(\bar{l}_p\gamma_\mu l_r)(\bar{u}_s\gamma^\mu u_t)$
$Q_{qq}^{(3)}$	$(\bar{q}_p\gamma_\mu\tau^I q_r)(\bar{q}_s\gamma^\mu\tau^I q_t)$	Q_{dd}	$(\bar{d}_p\gamma_\mu d_r)(\bar{d}_s\gamma^\mu d_t)$	Q_{ld}	$(\bar{l}_p\gamma_\mu l_r)(\bar{d}_s\gamma^\mu d_t)$
$Q_{lq}^{(1)}$	$(\bar{l}_p\gamma_\mu l_r)(\bar{q}_s\gamma^\mu q_t)$	Q_{eu}	$(\bar{e}_p\gamma_\mu e_r)(\bar{u}_s\gamma^\mu u_t)$	Q_{qe}	$(\bar{q}_p\gamma_\mu q_r)(\bar{e}_s\gamma^\mu e_t)$
$Q_{lq}^{(3)}$	$(\bar{l}_p\gamma_\mu\tau^I l_r)(\bar{q}_s\gamma^\mu\tau^I q_t)$	Q_{ed}	$(\bar{e}_p\gamma_\mu e_r)(\bar{d}_s\gamma^\mu d_t)$	$Q_{qu}^{(1)}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{u}_s\gamma^\mu u_t)$
		$Q_{ud}^{(1)}$	$(\bar{u}_p\gamma_\mu u_r)(\bar{d}_s\gamma^\mu d_t)$	$Q_{qu}^{(8)}$	$(\bar{q}_p\gamma_\mu T^A q_r)(\bar{u}_s\gamma^\mu T^A u_t)$
		$Q_{ud}^{(8)}$	$(\bar{u}_p\gamma_\mu T^A u_r)(\bar{d}_s\gamma^\mu T^A d_t)$	$Q_{qd}^{(1)}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{d}_s\gamma^\mu d_t)$
				$Q_{qd}^{(8)}$	$(\bar{q}_p\gamma_\mu T^A q_r)(\bar{d}_s\gamma^\mu T^A d_t)$

$\psi^2\varphi^3$	
$Q_{e\varphi}$	$(\varphi^\dagger\varphi)(\bar{l}_p e_r\varphi)$
$Q_{u\varphi}$	$(\varphi^\dagger\varphi)(\bar{q}_p u_r\widetilde{\varphi})$
$Q_{d\varphi}$	$(\varphi^\dagger\varphi)(\bar{q}_p d_r\varphi)$

$(\bar{L}R)(\bar{R}L)$ and $(\bar{L}R)(\bar{L}R)$		-	B-violating
Q_{ledq}	$(\bar{l}_p^j e_r)(\bar{d}_s q_t^j)$	Q_{duq}	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(q_s^{\gamma j})^T C l_t^k\right]$
$Q_{quqd}^{(1)}$	$(\bar{q}_p^j u_r)\varepsilon_{jk}(\bar{q}_s^k d_t)$	Q_{qqu}	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(u_s^\gamma)^T C e_t\right]$
$Q_{quqd}^{(8)}$	$(\bar{q}_p^j T^A u_r)\varepsilon_{jk}(\bar{q}_s^k T^A d_t)$	Q_{qqq}	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jn}\varepsilon_{km}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(q_s^{\gamma m})^T C l_t^n\right]$
$Q_{lequ}^{(1)}$	$(\bar{l}_p^j e_r)\varepsilon_{jk}(\bar{q}_s^k u_t)$	Q_{duu}	$\varepsilon^{\alpha\beta\gamma}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(u_s^\gamma)^T C e_t\right]$
$Q_{lequ}^{(3)}$	$(\bar{l}_p^j\sigma_{\mu\nu}e_r)\varepsilon_{jk}(\bar{q}_s^k\sigma^{\mu\nu}u_t)$		

$\psi^2 X\varphi$		$\psi^2\varphi^2 D$	
Q_{eW}	$(\bar{l}_p\sigma^{\mu\nu}e_r)\tau^I\varphi W_{\mu\nu}^I$	$Q_{\varphi l}^{(1)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar{l}_p\gamma^\mu l_r)$
Q_{eB}	$(\bar{l}_p\sigma^{\mu\nu}e_r)\varphi B_{\mu\nu}$	$Q_{\varphi l}^{(3)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu^I\varphi)(\bar{l}_p\tau^I\gamma^\mu l_r)$
Q_{uG}	$(\bar{q}_p\sigma^{\mu\nu}T^A u_r)\widetilde{\varphi}\,G_{\mu\nu}^A$	$Q_{\varphi e}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar{e}_p\gamma^\mu e_r)$
Q_{uW}	$(\bar{q}_p\sigma^{\mu\nu}u_r)\tau^I\widetilde{\varphi}\,W_{\mu\nu}^I$	$Q_{\varphi q}^{(1)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar{q}_p\gamma^\mu q_r)$
Q_{uB}	$(\bar{q}_p\sigma^{\mu\nu}u_r)\widetilde{\varphi}\,B_{\mu\nu}$	$Q_{\varphi q}^{(3)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu^I\varphi)(\bar{q}_p\tau^I\gamma^\mu q_r)$
Q_{dG}	$(\bar{q}_p\sigma^{\mu\nu}T^A d_r)\varphi\,G_{\mu\nu}^A$	$Q_{\varphi u}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar{u}_p\gamma^\mu u_r)$
Q_{dW}	$(\bar{q}_p\sigma^{\mu\nu}d_r)\tau^I\varphi\,W_{\mu\nu}^I$	$Q_{\varphi d}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar{d}_p\gamma^\mu d_r)$
Q_{dB}	$(\bar{q}_p\sigma^{\mu\nu}d_r)\varphi\,B_{\mu\nu}$	$Q_{\varphi ud}$	$i(\widetilde{\varphi}^\dagger D_\mu\varphi)(\bar{u}_p\gamma^\mu d_r)$

$$\mathscr{L}_6 \supset \frac{1}{\Lambda^2}qqq\ell \qquad \underline{\Lambda > 10^{12}\,\text{TeV}}$$

Proton decay

dim 6 - *Fermionic operators*

Grzadkowski et al, 1008.4884

$(\bar{L}L)(\bar{L}L)$		$(\bar{R}R)(\bar{R}R)$		$(\bar{L}L)(\bar{R}R)$	
Q_{ll}	$(\bar{l}_p\gamma_\mu l_r)(\bar{l}_s\gamma^\mu l_t)$	Q_{ee}	$(\bar{e}_p\gamma_\mu e_r)(\bar{e}_s\gamma^\mu e_t)$	Q_{le}	$(\bar{l}_p\gamma_\mu l_r)(\bar{e}_s\gamma^\mu e_t)$
$Q_{qq}^{(1)}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{q}_s\gamma^\mu q_t)$	Q_{uu}	$(\bar{u}_p\gamma_\mu u_r)(\bar{u}_s\gamma^\mu u_t)$	Q_{lu}	$(\bar{l}_p\gamma_\mu l_r)(\bar{u}_s\gamma^\mu u_t)$
$Q_{qq}^{(3)}$	$(\bar{q}_p\gamma_\mu\tau^I q_r)(\bar{q}_s\gamma^\mu\tau^I q_t)$	Q_{dd}	$(\bar{d}_p\gamma_\mu d_r)(\bar{d}_s\gamma^\mu d_t)$	Q_{ld}	$(\bar{l}_p\gamma_\mu l_r)(\bar{d}_s\gamma^\mu d_t)$
$Q_{lq}^{(1)}$	$(\bar{l}_p\gamma_\mu l_r)(\bar{q}_s\gamma^\mu q_t)$	Q_{eu}	$(\bar{e}_p\gamma_\mu e_r)(\bar{u}_s\gamma^\mu u_t)$	Q_{qe}	$(\bar{q}_p\gamma_\mu q_r)(\bar{e}_s\gamma^\mu e_t)$
$Q_{lq}^{(3)}$	$(\bar{l}_p\gamma_\mu\tau^I l_r)(\bar{q}_s\gamma^\mu\tau^I q_t)$	Q_{ed}	$(\bar{e}_p\gamma_\mu e_r)(\bar{d}_s\gamma^\mu d_t)$	$Q_{qu}^{(1)}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{u}_s\gamma^\mu u_t)$
		$Q_{ud}^{(1)}$	$(\bar{u}_p\gamma_\mu u_r)(\bar{d}_s\gamma^\mu d_t)$	$Q_{qu}^{(8)}$	$(\bar{q}_p\gamma_\mu T^A q_r)(\bar{u}_s\gamma^\mu T^A u_t)$
		$Q_{ud}^{(8)}$	$(\bar{u}_p\gamma_\mu T^A u_r)(\bar{d}_s\gamma^\mu T^A d_t)$	$Q_{qd}^{(1)}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{d}_s\gamma^\mu d_t)$
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Q_{ledq}	$(\bar{l}_p^j e_r)(\bar{d}_s q_t^j)$
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$Q_{quqd}^{(8)}$	$(\bar{q}_p^j T^A u_r)\varepsilon_{jk}(\bar{q}_s^k T^A d_t)$
$Q_{lequ}^{(1)}$	$(\bar{l}_p^j e_r)\varepsilon_{jk}(\bar{q}_s^k u_t)$
$Q_{lequ}^{(3)}$	$(\bar{l}_p^j\sigma_{\mu\nu} e_r)\varepsilon_{jk}(\bar{q}_s^k\sigma^{\mu\nu} u_t)$

Impose B symmetry

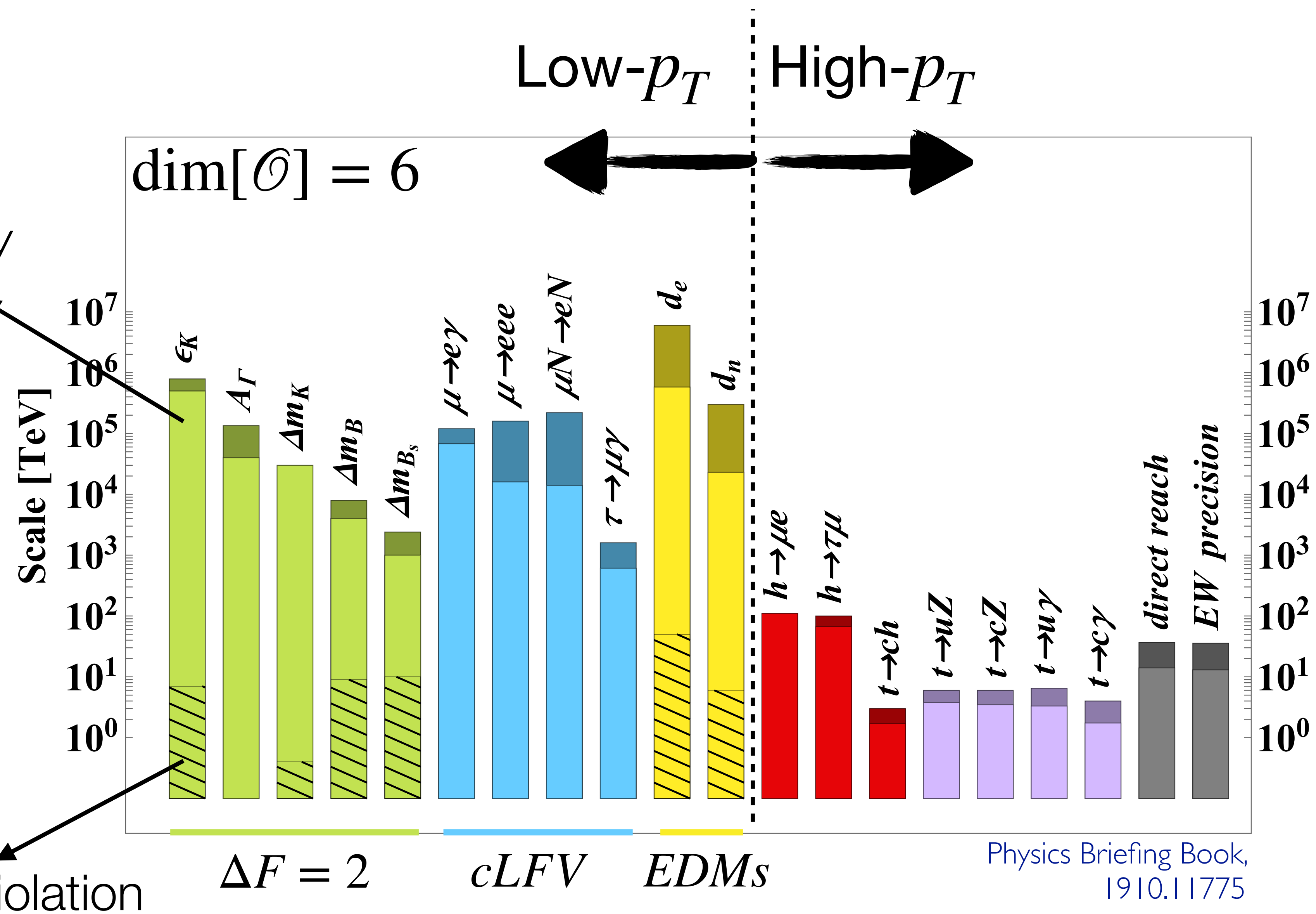
$\psi^2 X\varphi$		$\psi^2\varphi^2 D$	
Q_{eW}	$(\bar{l}_p\sigma^{\mu\nu}e_r)\tau^I\varphi W_{\mu\nu}^I$	$Q_{\varphi l}^{(1)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar{l}_p\gamma^\mu l_r)$
Q_{eB}	$(\bar{l}_p\sigma^{\mu\nu}e_r)\varphi B_{\mu\nu}$	$Q_{\varphi l}^{(3)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu^I\varphi)(\bar{l}_p\tau^I\gamma^\mu l_r)$
Q_{uG}	$(\bar{q}_p\sigma^{\mu\nu}T^A u_r)\widetilde{\varphi}\, G_{\mu\nu}^A$	$Q_{\varphi e}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar{e}_p\gamma^\mu e_r)$
Q_{uW}	$(\bar{q}_p\sigma^{\mu\nu}u_r)\tau^I\widetilde{\varphi}\, W_{\mu\nu}^I$	$Q_{\varphi q}^{(1)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar{q}_p\gamma^\mu q_r)$
Q_{uB}	$(\bar{q}_p\sigma^{\mu\nu}u_r)\widetilde{\varphi}\, B_{\mu\nu}$	$Q_{\varphi q}^{(3)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu^I\varphi)(\bar{q}_p\tau^I\gamma^\mu q_r)$
Q_{dG}	$(\bar{q}_p\sigma^{\mu\nu}T^A d_r)\varphi\, G_{\mu\nu}^A$	$Q_{\varphi u}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar{u}_p\gamma^\mu u_r)$
Q_{dW}	$(\bar{q}_p\sigma^{\mu\nu}d_r)\tau^I\varphi\, W_{\mu\nu}^I$	$Q_{\varphi d}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar{d}_p\gamma^\mu d_r)$
Q_{dB}	$(\bar{q}_p\sigma^{\mu\nu}d_r)\varphi\, B_{\mu\nu}$	$Q_{\varphi ud}$	$i(\widetilde{\varphi}^\dagger D_\mu\varphi)(\bar{u}_p\gamma^\mu d_r)$

- Challenge: **A large number of independent parameters!**
- 2499 $\dim[\mathcal{O}] = 6$ $\Delta B = \Delta L = 0$ independent operators
- Why? 3 flavours
- For a single generation, this would be 59

The importance of flavour violation!

- SMEFT at $\dim[\mathcal{O}] = 6$ - new sources of flavour violation
- Strong constraints from flavour experiments

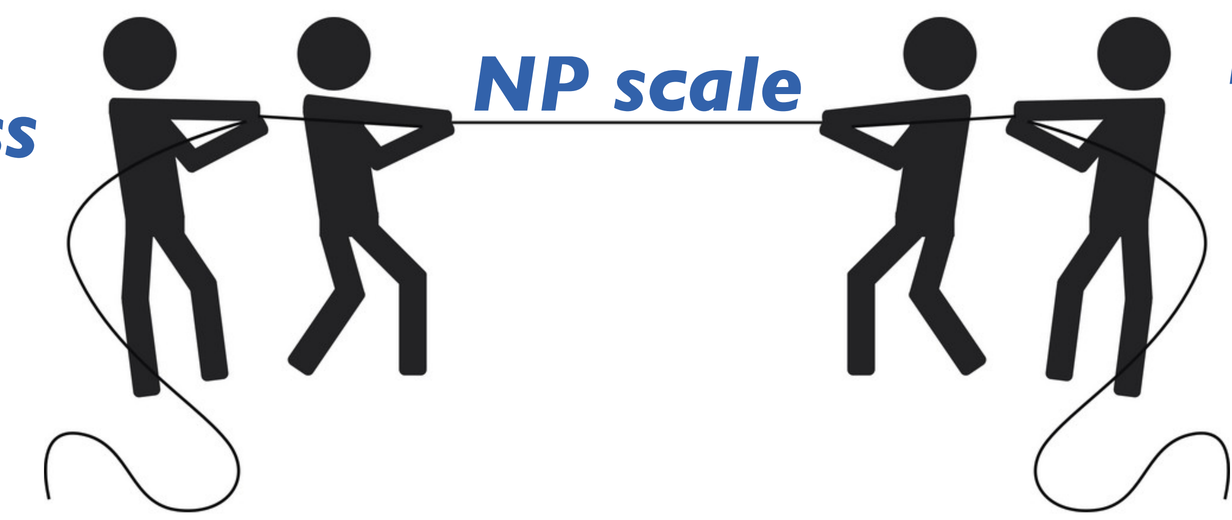
Flavour Anarchy



Physics Briefing Book, 1910.11775

Minimal Flavour Violation

D'Ambrosio, Giudice, Isidori, Strumia; hep-ph/0207036



- A viable BSM at the TeV-scale should have accidental symmetries similar to the SM.
- Key ingredients:
  Flavour symmetry and symmetry breaking patterns.

  * just like with the B number

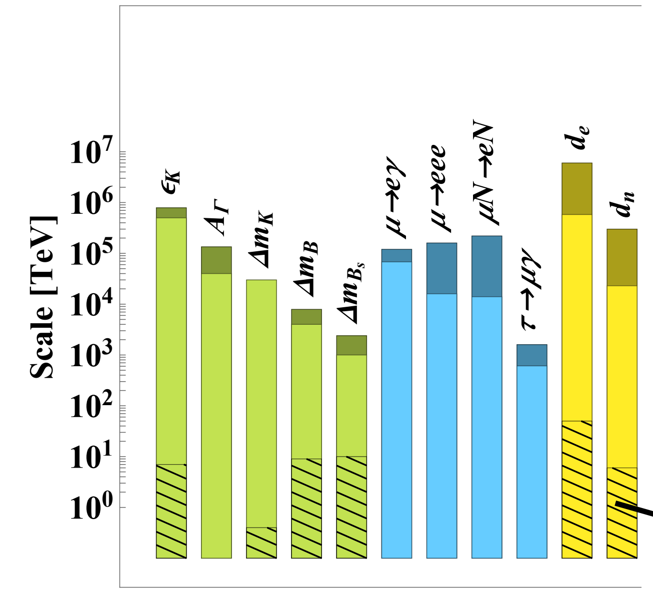
MFV

- The flavour breaking in the NP sector is also from the Yukawa matrices

$$G_Q = \mathrm{U}(3)_q \times \mathrm{U}(3)_u \times \mathrm{U}(3)_d$$

$$Y_u \sim (\mathbf{3}, \bar{\mathbf{3}}, \mathbf{1}), \quad Y_d \sim (\mathbf{3}, \mathbf{1}, \bar{\mathbf{3}}).$$

- The MFV allows for the NP cutoff as low as the TeV scale!



MFV

D'Ambrosio et al; hep-ph/0207036

MFV

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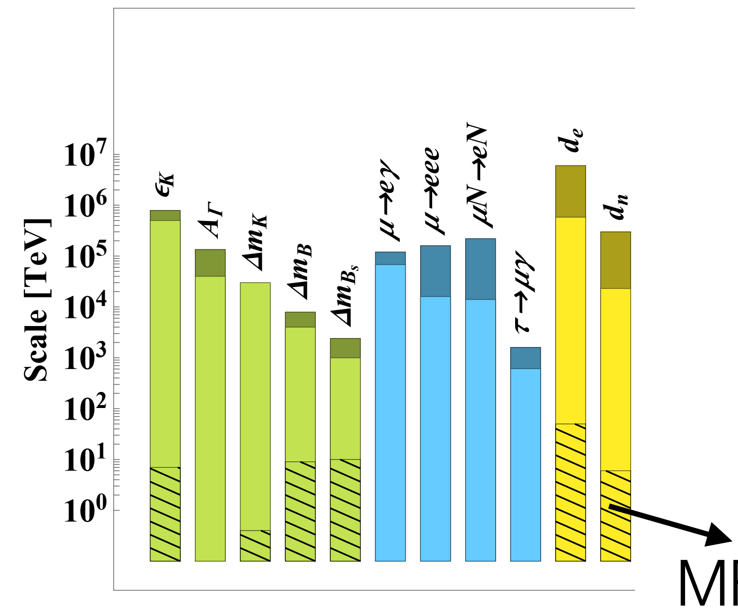


MFV

D'Ambrosio et al; hep-ph/0207036

U(2)

- Approximate symmetry of the SM
- Small breaking spurions (well-defined power counting)
- Also protects against dangerous FCNC but less restrictive than the MFV

$$G = \mathrm{U}(2)_q \times \mathrm{U}(2)_u \times \mathrm{U}(2)_d$$

$$V_q \sim (\mathbf{2}, \mathbf{1}, \mathbf{1})\ , \qquad \Delta_u \sim (\mathbf{2}, \bar{\mathbf{2}}, \mathbf{1})\ , \qquad \Delta_d \sim (\mathbf{2}, \mathbf{1}, \bar{\mathbf{2}})$$

Barbieri et at; 1105.2296

$$Y_{u,d} \sim \begin{pmatrix} \boxed{\Delta_{u,d}} & \boxed{V_q} \\ 0 \quad 0 & 1 \end{pmatrix}$$

$$\Delta \ll V \ll 1 \qquad V^\dagger \propto (V_{td}, V_{ts})$$

SMEFT flavour

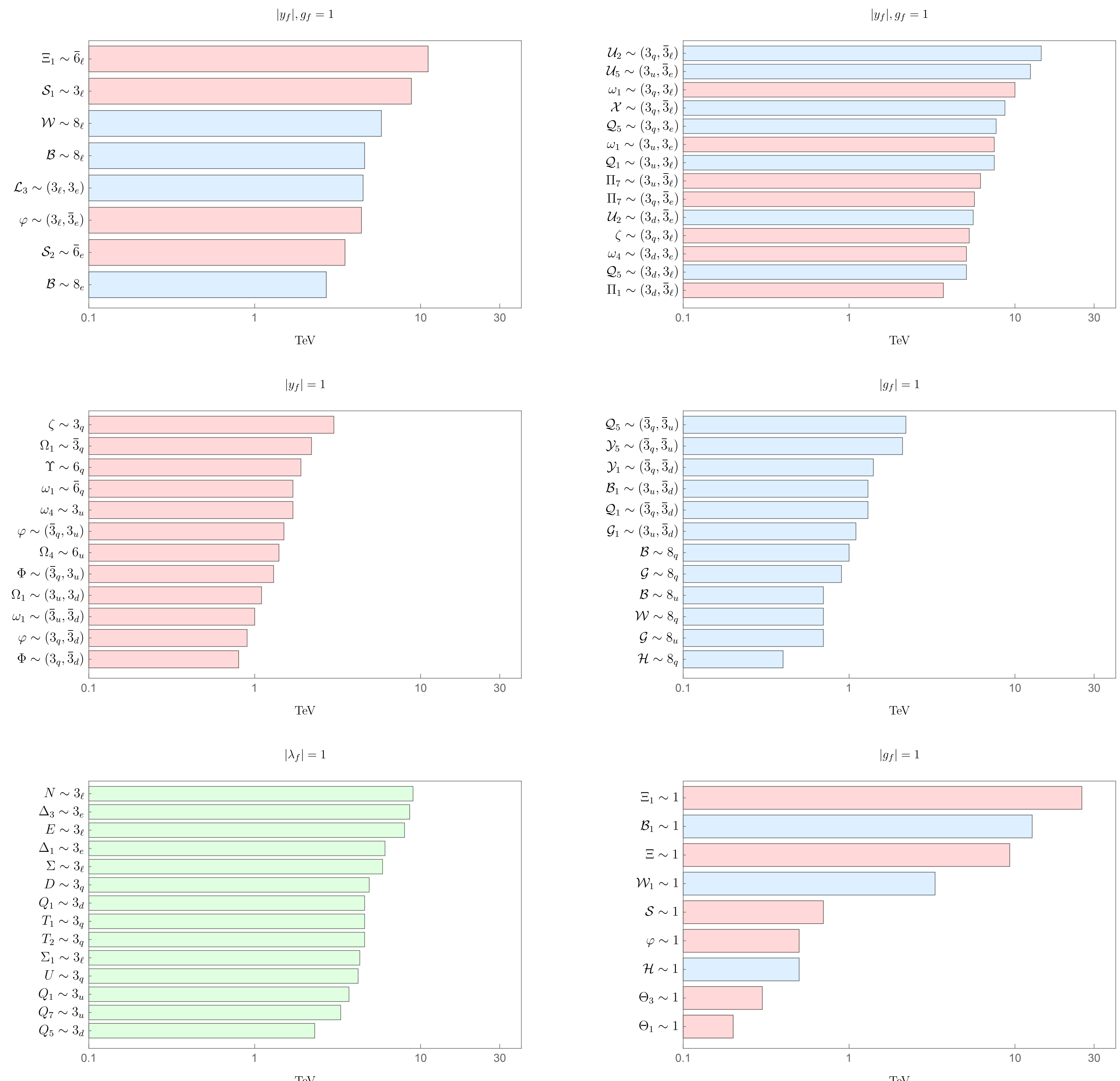
AG, Thomsen, Palavric; [2203.09561]

SMEFT $\mathcal{O}(1)$ terms (dim-6, $\Delta B = 0$)		Lepton sector							
		MFV_L	$\mathrm{U(3)}_V$	$\mathrm{U(2)}^2 \times \mathrm{U(1)}$	$\mathrm{U(2)}^2$	$\mathrm{U(2)}_V$	$\mathrm{U(1)}^6$	$\mathrm{U(1)}^3$	No symm.
Quark sector	MFV_Q	47	54	65	71	80	87	111	339
	$\mathrm{U(2)}^2 \times \mathrm{U(3)}_d$	82	93	105	115	128	132	168	450
	$\mathrm{U(2)}^3 \times \mathrm{U(1)}_{b_R}$	96	107	121	128	144	150	186	480
	$\mathrm{U(2)}^3$	110	123	135	147	162	164	206	512
	No symm.	1273	1334	1347	1407	1470	1425	1611	2499

- We constructed explicit operator bases for several flavour hypotheses
- Systematic approach from MFV towards anarchy: $U(3) \supset U(2) \supset U(1)$
- Non-trivial interplay of Top/Higgs/EW with Flavour

Flavour blind directions in the SMEFT

- Classification of generic tree-level mediators with $U(3)^5$ flavour-symmetric interactions which match to **dim 6** SMEFT
- Flavor symmetry restrictions: **leading directions**
- Spin 0, 1/2, 1
- Protection against FCNC
- Compilation of experimental EFT limits =>



AG, Palavric; 2203.09561

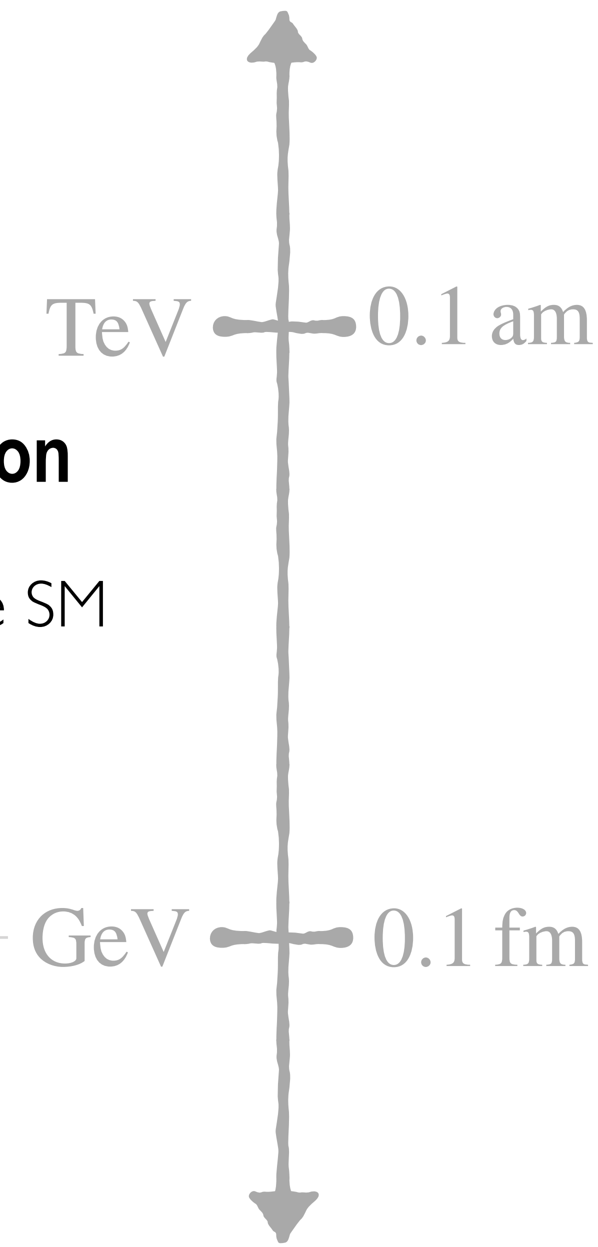
Flavour vs Collider

Complementarity
Flavor vs Collider

Example

Lepton Production
Status:
Consistent with the SM

***B*-hadron Decays to Leptons**
Status:
Discrepancy with the SM



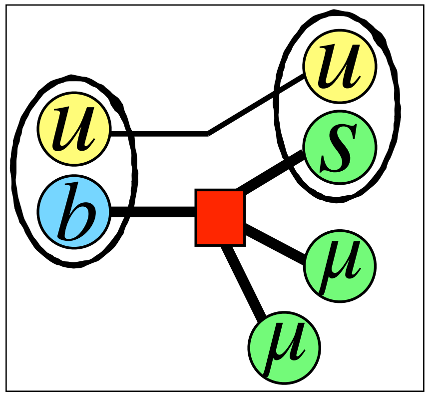
Methods

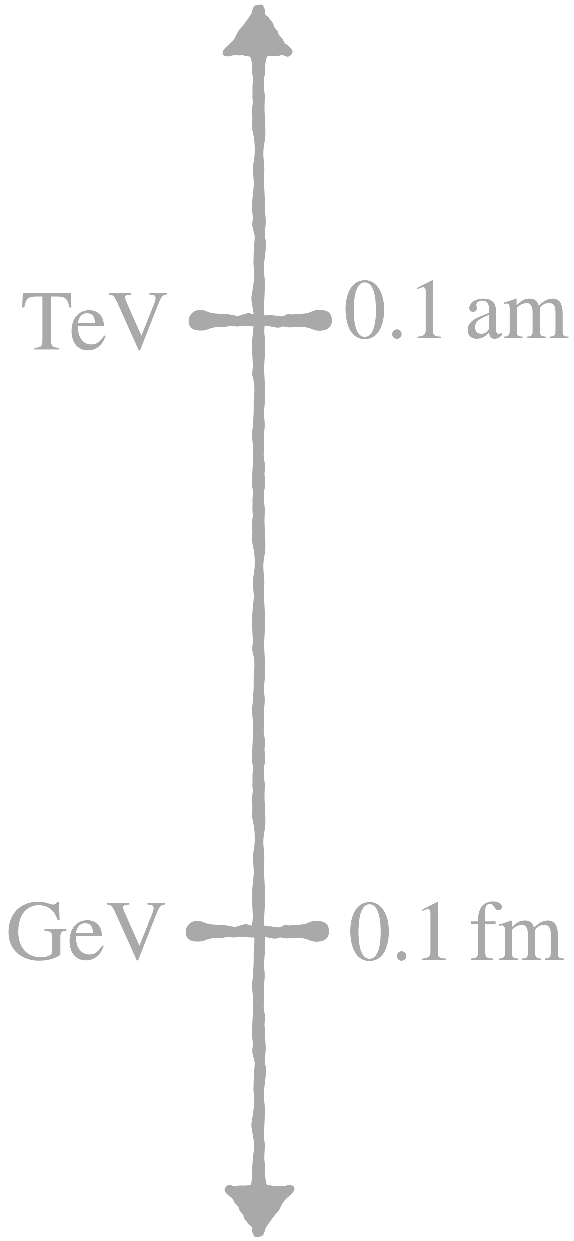
Effective Field Theory

New Contact Interaction

$$(\bar{Q}_i \gamma_\mu \sigma^a Q_j)(\bar{L}_k \gamma^\mu \sigma_a L_l)$$

$$B \to K \mu^+ \mu^-$$

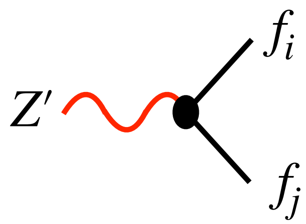




Methods

Simplified Model

New Force Mediator



Effective Field Theory

New Contact Interaction

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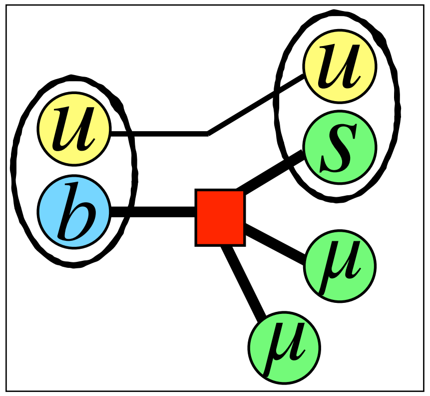
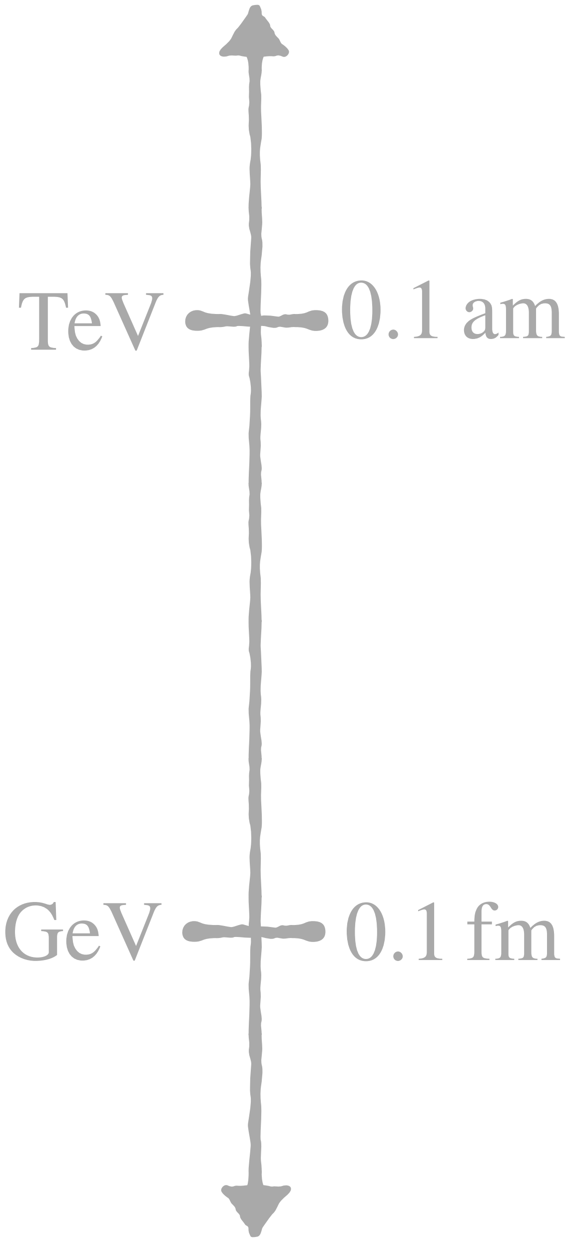




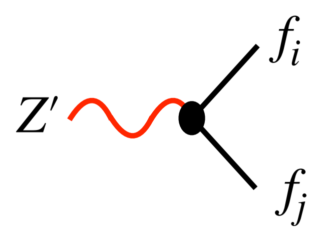
Methods

Complete Model

e.g. Gauged Flavour Symmetry

Simplified Model

New Force Mediator

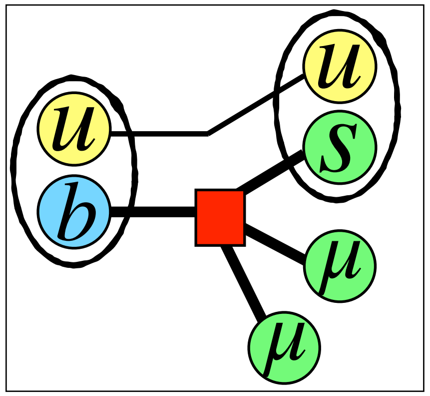


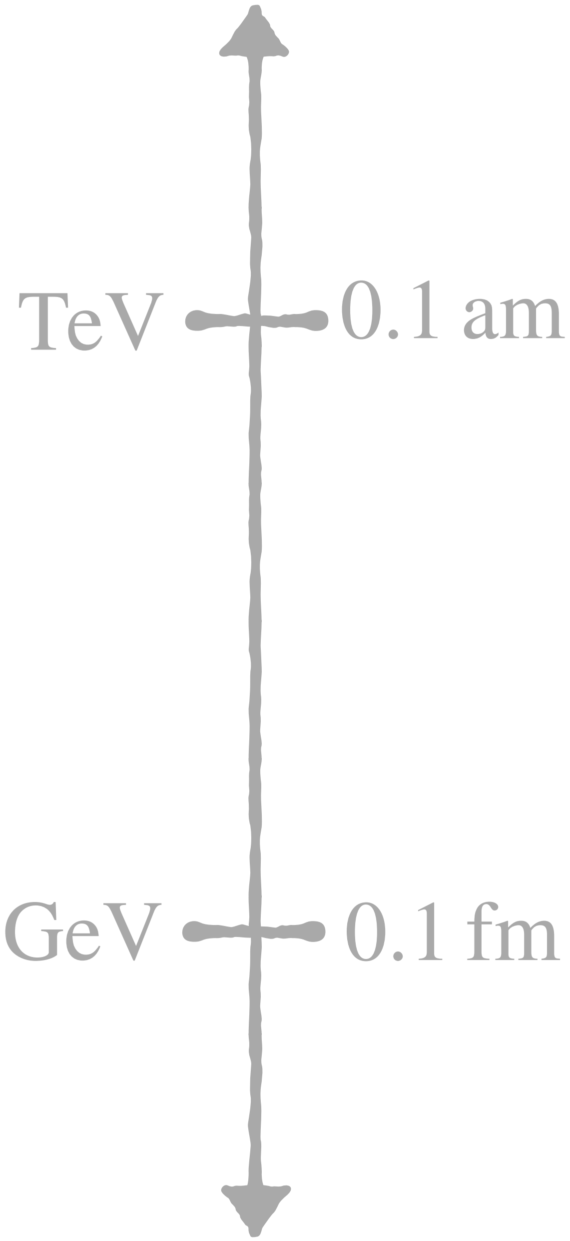
Effective Field Theory

New Contact Interaction

$$(\bar{Q}_i \gamma_\mu \sigma^a Q_j)(\bar{L}_k \gamma^\mu \sigma_a L_l)$$

$$B \to K \mu^+ \mu^-$$





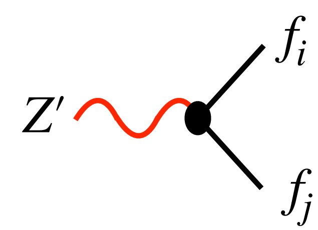
Methods

Complete Model

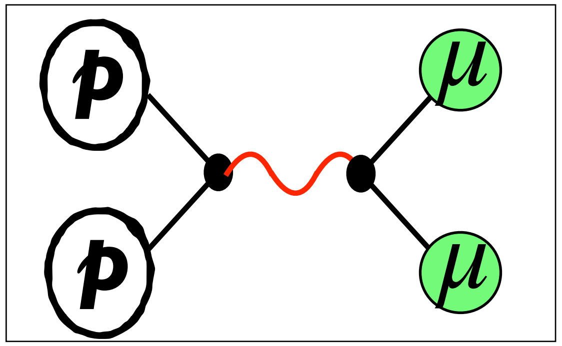
e.g. Gauged Flavour Symmetry

Simplified Model

New Force Mediator



$$p\,p \to \mu^+\mu^-$$

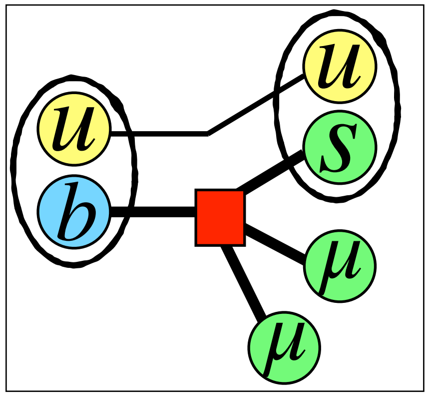


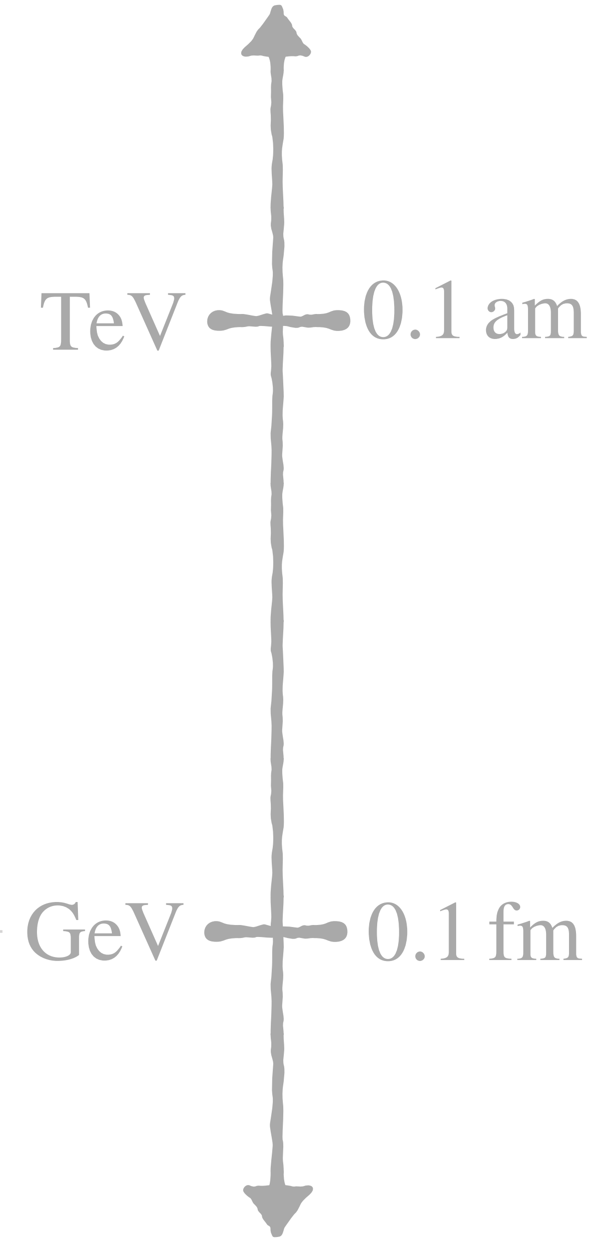
Effective Field Theory

New Contact Interaction

$$(\bar{Q}_i\gamma_\mu\sigma^a Q_j)(\bar{L}_k\gamma^\mu\sigma_a L_l)$$

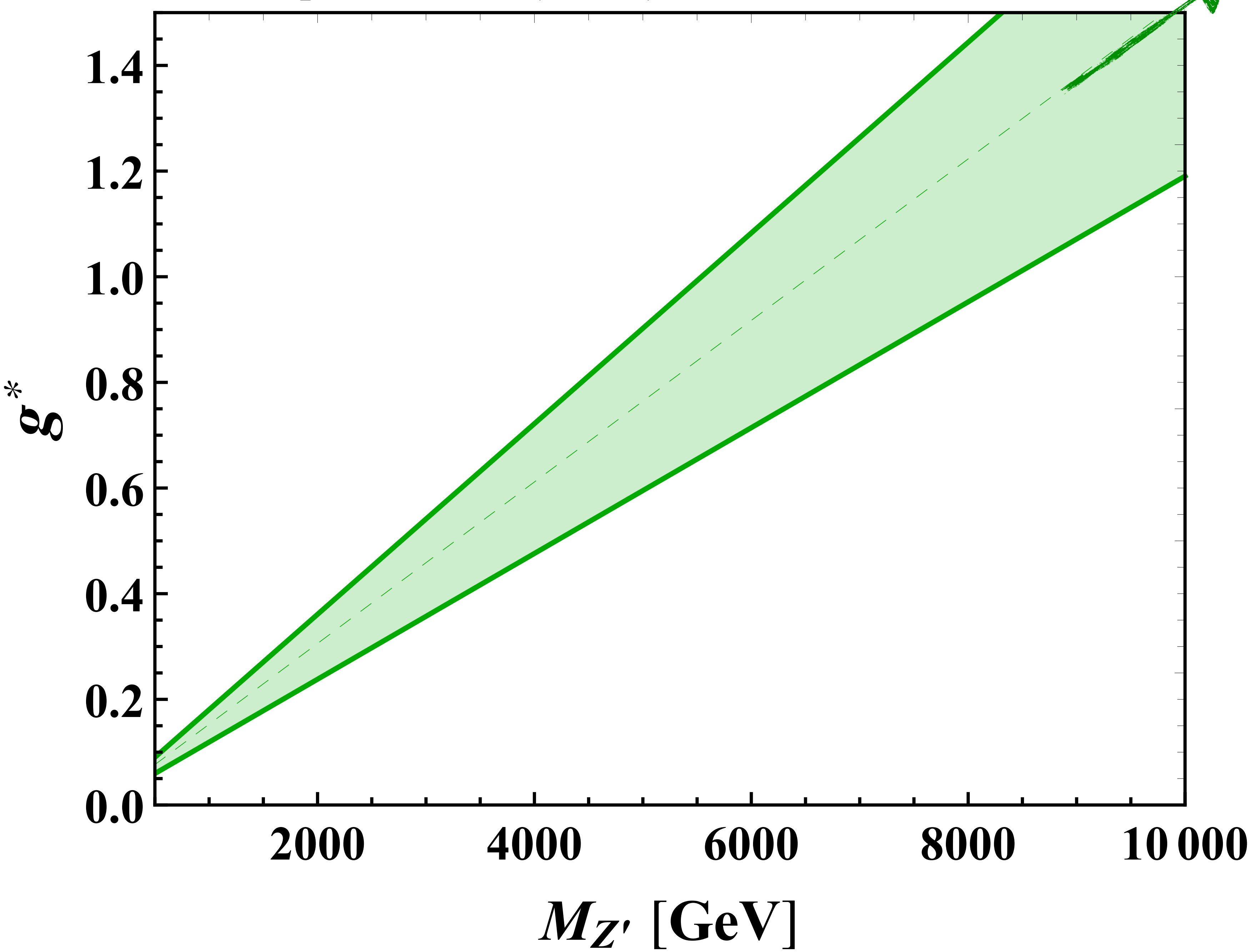
$$B \to K\mu^+\mu^-$$





Relevance

[**Greljo**, Marzocca]
Eur.Phys.J. C77 (2017) no.8, 548



Interaction strength

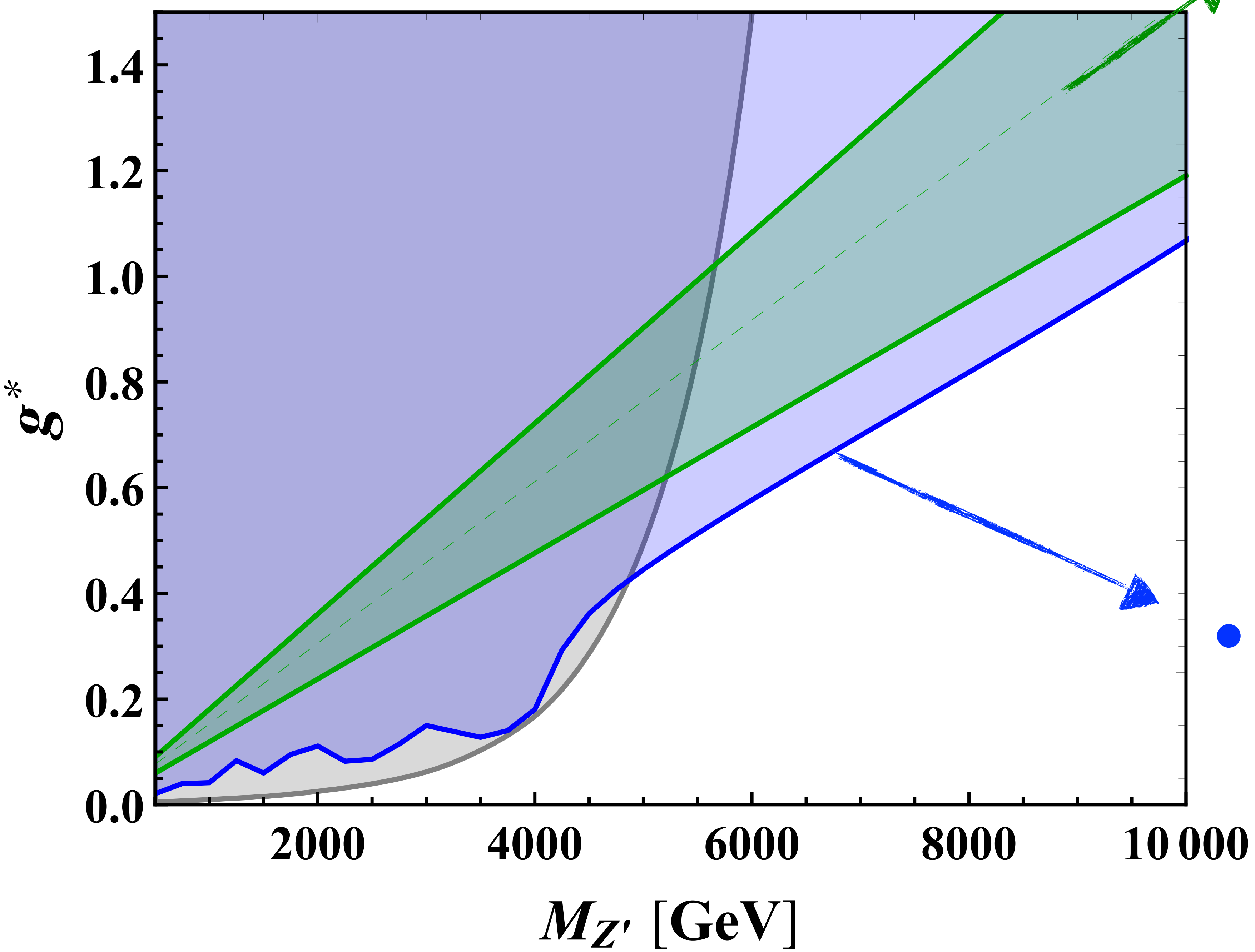
Mediator mass

- Low-energy preferred

A specific model example:

Relevance

[**Greljo**, Marzocca]
Eur.Phys.J. C77 (2017) no.8, 548



Interaction strength

Mediator mass

- Low-energy preferred
- High-energy excluded

A specific model example: Ruled out!

Challenges

Complete Model

- Uncountable
- Most imagination needed

Simplified Model

- Extra Higgs, Z', W', Leptoquark, Coloron, Quark and Lepton Partners
  + many more

- Many signatures

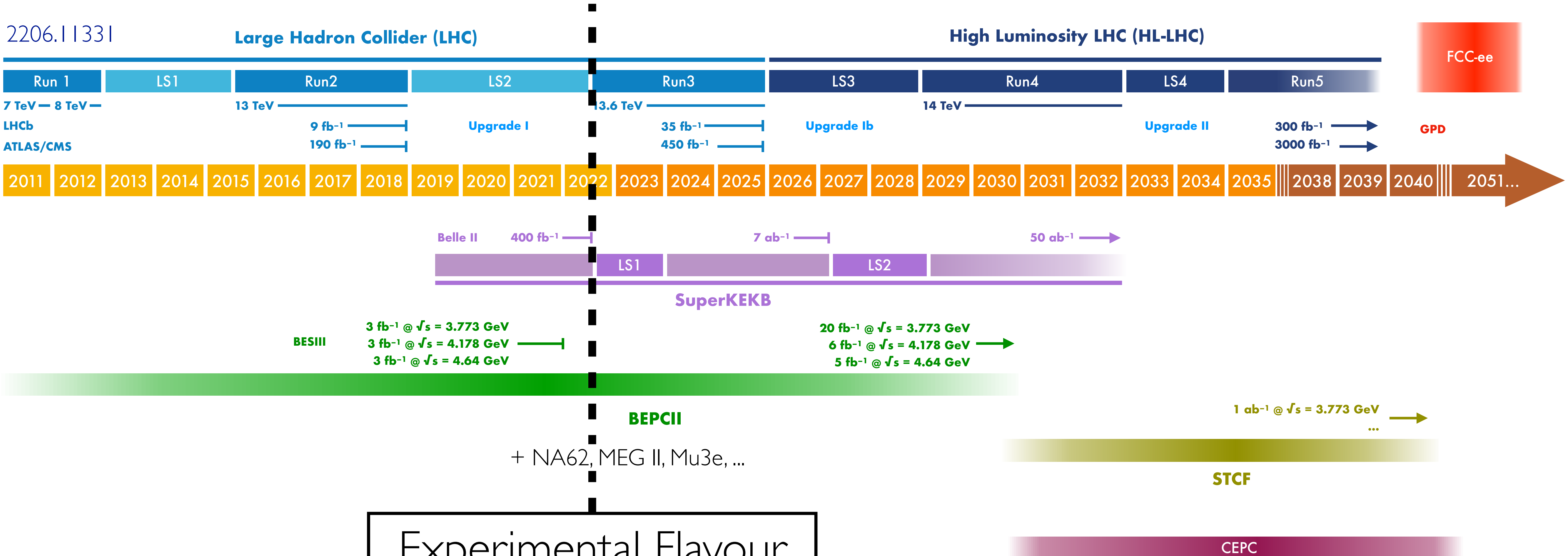
Effective Field Theory

- 2499 leading dim-6 operators
- Most are flavour-sensitive

- Many observables

Talk more often to your colleagues from different experiments and theory!

Outlook



Experimental Flavour Physics is in a full sprint

- ☐ Theoretical Flavour Physics
  - ☐ Precision calculations of flavour observables in and beyond the SM
    - to match the (foreseen) experimental precision
  - ☐ Flavour model building
    - to explain the SM and the new physics flavour puzzle, …

Extras…