Searching a signal beyond the Standard Model in Flavour Physics

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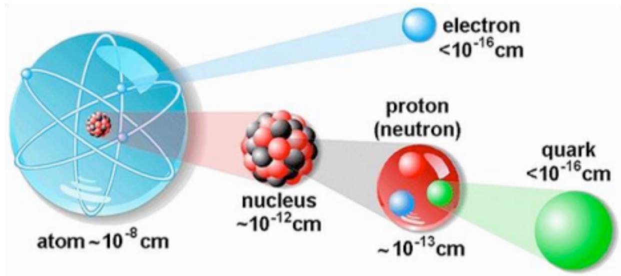
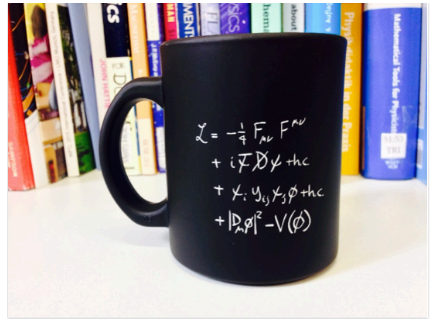
Introduction

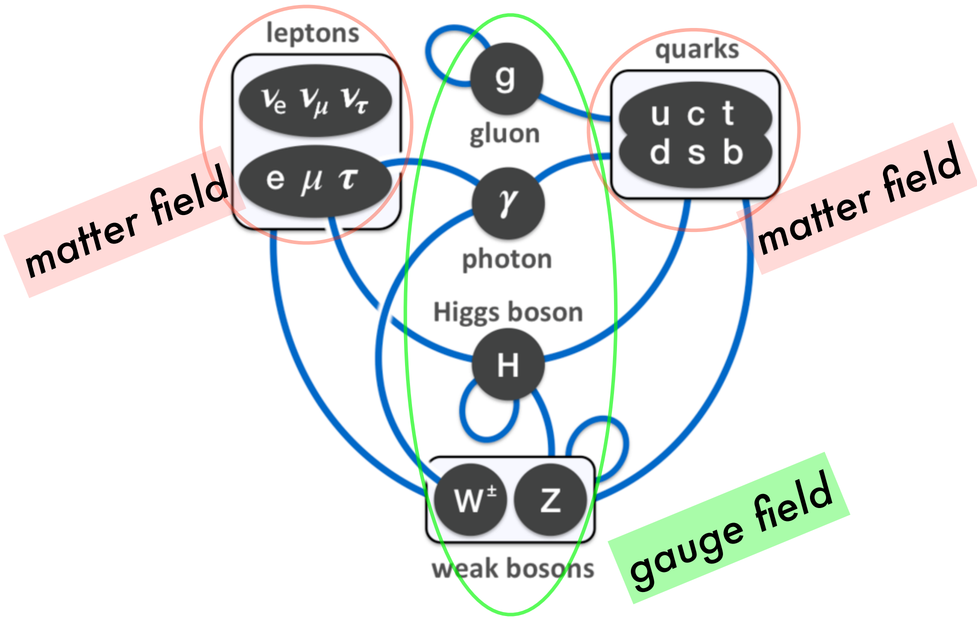
Particle physics





- Investigation of fundamental particles and their interactions
- Standard Model (SM) is a $SU(3)_C \times SU(2)_L \times U(1)_Y$ gauge theory

SM contains 19(26) free parameters, among which 13 (20) are to describe the flavour sector



	1st generation	2nd generation	3rd generation
up type charge 2/3	up 2.2±0.5MeV	charm 1.27±0.03GeV	top 173.21±0.87GeV
down type charge -1/3	down 4.7±0.5MeV	strange 96±6MeV	bottom 4.18±0.04GeV
charged lepton charge -1	electron 0.511MeV	μ 105.7MeV	τ 1.78GeV
neutrinos charge 0	ν_e <2.0eV	ν_μ <0.17eV	ν_τ <18.2eV

Flavour sector of SM

~ QUARKS ~

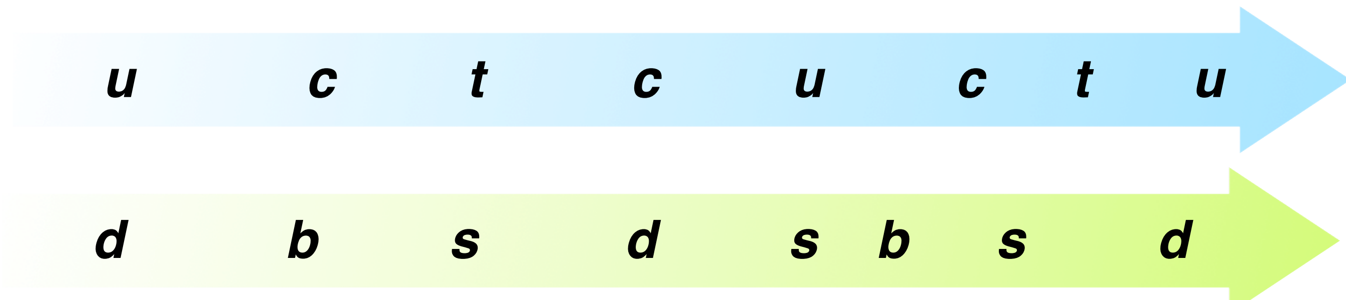
- The quark mass comes from the Yukawa coupling of SM.
- The Yukawa couplings are non-diagonal 3x3 (complex) matrix.

$$u_L = \begin{pmatrix} u_L \\ c_L \\ t_L \end{pmatrix} \quad d_L = \begin{pmatrix} d_L \\ s_L \\ b_L \end{pmatrix} \quad u_R = \begin{pmatrix} u_R \\ c_R \\ t_R \end{pmatrix} \quad d_R = \begin{pmatrix} d_R \\ s_R \\ b_R \end{pmatrix}$$

Weak eigenstate

$$\mathscr{L}^Y \propto \bar{u}_L \underbrace{\begin{pmatrix} ? & ? & ? \\ ? & ? & ? \\ ? & ? & ? \end{pmatrix}}_{Y_u} u_R + \bar{d}_L \underbrace{\begin{pmatrix} ? & ? & ? \\ ? & ? & ? \\ ? & ? & ? \end{pmatrix}}_{Y_d} d_R$$

Oscillating among different flavours



Flavour sector of SM

~ QUARKS ~

- Observed mass hierarchy is the result of the diagonalisation of this matrix

Mass eigenstate

$$\mathscr{L}^Y = \bar{u}_L^{(m)} \begin{pmatrix} m_u & 0 & 0 \\ 0 & m_c & 0 \\ 0 & 0 & m_t \end{pmatrix} u_R^{(m)} + \bar{d}_L^{(m)} \begin{pmatrix} m_d & 0 & 0 \\ 0 & m_s & 0 \\ 0 & 0 & m_b \end{pmatrix} d_R^{(m)}$$

$$u_L = U_L^u u_L^{(m)} \quad d_L = U_L^d d_L^{(m)} \quad u_R = U_R^u u_R^{(m)} \quad d_R = U_R^d d_R^{(m)}$$

$U_L^u, U_L^d, U_R^u, U_R^d$: the rotation matrix (unitary)

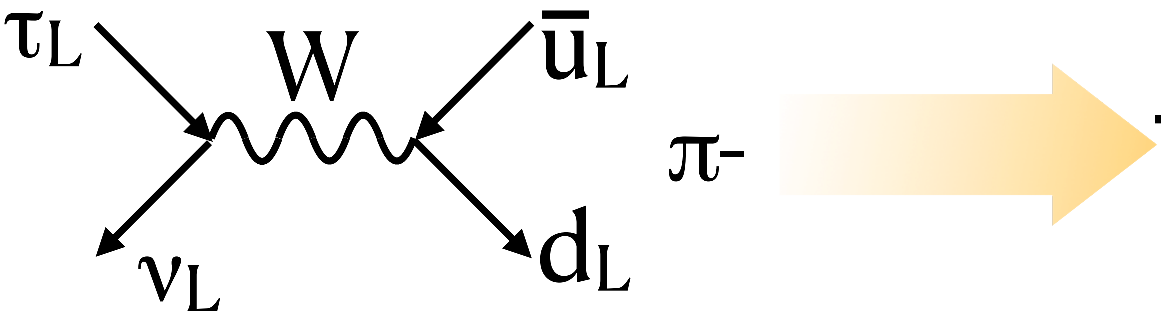
Flavour sector of SM

~ QUARKS ~


- Observed quark flavours are in the mass eigenstate.

Weak interaction

$$\mathscr{L}^{Cc} \propto W^{\mu}\bar{u}_L \gamma_{\mu} d_L$$



$$\bar{u}_L^{m} \underbrace{(U_L^{u})^{\dagger} U_L^{d}}_{=U_{CKM}} d_L^{m}$$

- When flavour is identified, the production probability is multiplied by the product of the up and down mixing matrix: CKM (Cabibbo-Kobayashi-Maskawa) matrix.
- The complex phase in U_{CKM} is the source of the CP violation in quark sector

Flavour sector of SM

~ LEPTONS ~

- Let us decouple the heavy Majorana neutrinos.
- Then, we can describe the lepton sector equivalently.

$$\nu_L = \begin{pmatrix} \nu^e{}_L \\ \nu^\mu{}_L \\ \nu^\tau{}_L \end{pmatrix} \quad l_L = \begin{pmatrix} e_L \\ \mu_L \\ \tau_L \end{pmatrix} \quad \nu_R = \begin{pmatrix} \nu^e{}_R \\ \nu^\mu{}_R \\ \nu^\tau{}_R \end{pmatrix} \quad l_R = \begin{pmatrix} e_R \\ \mu_R \\ \tau_R \end{pmatrix}$$

Weak eigenstate

$$\mathscr{L}^Y \propto \bar{\nu}_L \begin{pmatrix} ? & ? & ? \\ ? & Y_\nu & ? \\ ? & ? & ? \end{pmatrix} \nu_R + \bar{l}_L \begin{pmatrix} ? & ? & ? \\ ? & Y_l & ? \\ ? & ? & ? \end{pmatrix} l_R$$

$$\nu_L = U_L{}^\nu \nu_L^{(m)} \quad l_L = U_L{}^l l_L^{(m)} \quad \nu_R = U_R{}^\nu \nu_R^{(m)} \quad l_R = U_R{}^l l_R^{(m)}$$

Flavour sector of SM

~ LEPTONS ~

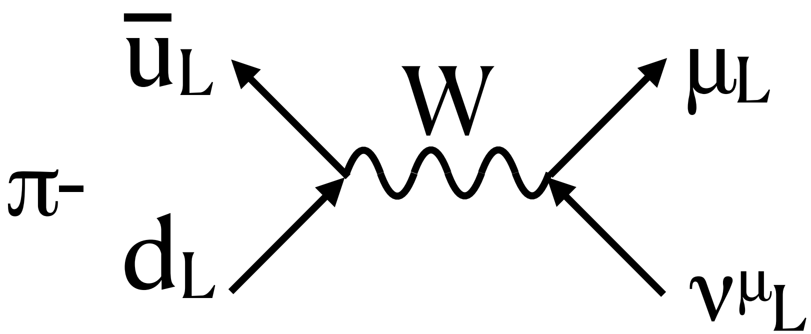
- For leptons, we can not identify the flavour of neutrinos. It is only defined as the type of the charged lepton produced together.

Weak interaction

$$\mathscr{L}^{CC} \propto W^{\mu}\bar{\nu}_L \gamma_\mu l_L$$

$$\bar{\nu}_L^{(m)} (U_L^{\nu})^{\dagger} U_L^{d}\, l_L^{(m)}$$

$$= U_{PMNS}$$



By definition →

$$\bar{\nu}_L^{(I)} (1)\; l_L^{(m)}$$

- The new "interaction basis" can be related to the neutrino mass basis with PMNS (Pontecorvo-Maki-Nakagawa-Sakata) matrix!

$$\nu_L^{(I)} = U_{PMNS}\, \nu_L^{(m)}$$

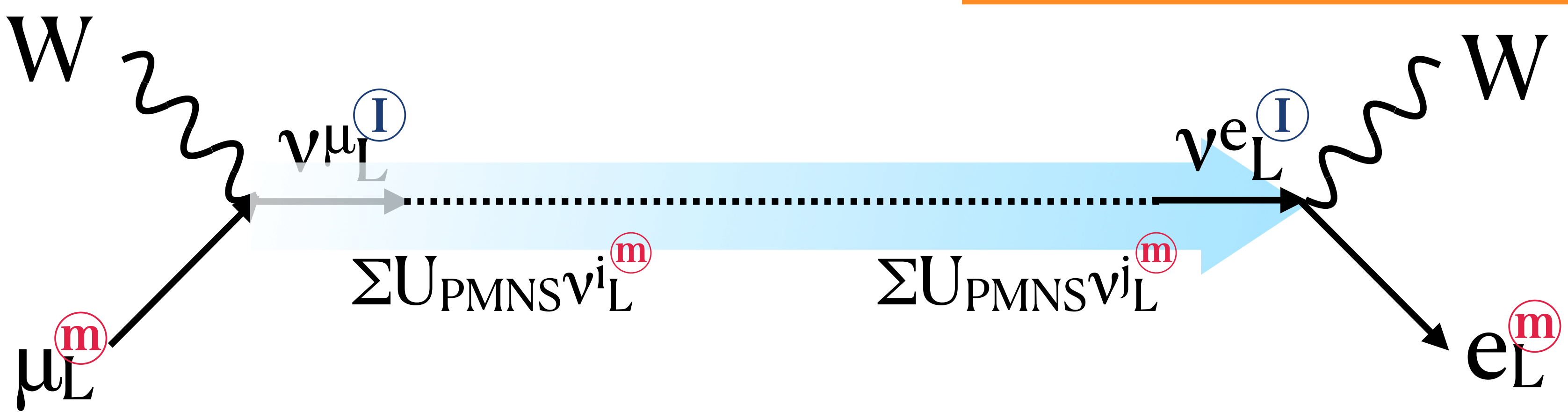
Flavour sector of SM

~ LEPTONS ~

- The PMNS matrix is not measurable from the weak decay.
- However, it can be measured from the neutrino oscillation!

$$P_{\mu e}=|\langle\nu_e|\nu_\mu\rangle|=|\Sigma\Sigma U^*_{\mu i}U_{ej}\langle\nu_j|\nu_i\rangle|^2$$

$|\langle\nu_j|\nu_i\rangle|^2$ is function of $\Delta m_{ij}^2\, L/E$



Testing the flavour sector of the SM

Flavour physics in SM

- Measurable quantities (* so far…)
  - ✓ quark: masses and the CKM matrix
  - ✓ lepton: mass differences* and the (unitary*) PMNS matrix
- What justifies this (single) Yukawa interaction picture?

	1st generation	2nd generation	3rd generation
up type charge 2/3	up 2.2±0.5MeV	charm 1.27±0.03GeV	top 173.21±0.87GeV
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	down	strange	bottom
up	Vub 0.97370±0.0001 4	Vus 0.2245±0.0008	Vub 0.00382±0.000 24
charm	Vcd 0.221±0.004	Vcs 0.987±0.011	Vcb 0.0410±0.0014
top	Vtd 0.0088±0.0003	Vts 0.0388±0.0011	Vtb 1.013 ± 0.030

Flavour physics in SM

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	ν_e	ν_μ	ν_τ
Electron	U_{e1} 0.803~0.845	U_{e2} 0.514~0.578	U_{e3} 0.142~0.155
Mu	$U_{\mu 1}$ 0.233~0.505	$V_{\mu 2}$ 0.460~0.693	$V_{\mu 3}$ 0.630~0.779
Tau	$U_{\tau 1}$ 0.262~0.525	$U_{\tau 2}$ 0.473~0.702	$U_{\tau 3}$ 0.610~0.762

Test 1: CP violation

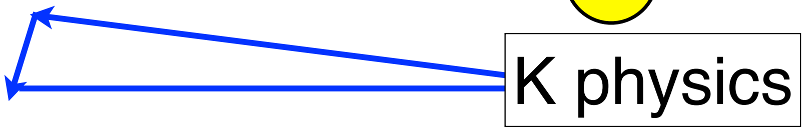
- If there are more than 3 generations, we must observe a CP violation!
  - ✓ quark: **done!**
  - ✓ lepton: (almost) done!
- This is assuring (counter example: strong CP, $\theta_{strong} \lesssim 10^{-10}$)!

Test 2: Unitarity of CKM matrix

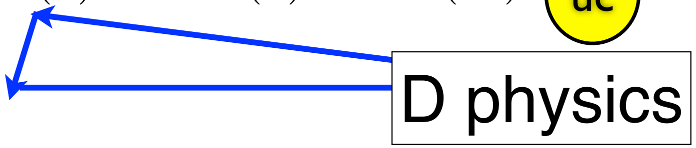
- CKM matrix is a product of up and down type quark mass matrices.
- It is an *unitary matrix* with 3 mixing angle and 1 CP violating phase.
- We can test the unitarity by fitting these 4 parameters by using measurements of independent flavour and CP violating phenomena.

Unitarity triangles

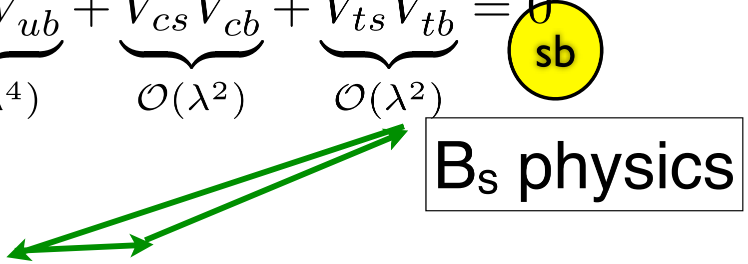
$$\underbrace{V_{ud}V_{us}^*}_{\mathcal{O}(\lambda)} + \underbrace{V_{cd}V_{cs}^*}_{\mathcal{O}(\lambda)} + \underbrace{V_{td}V_{ts}^*}_{\mathcal{O}(\lambda^5)} = 0$$



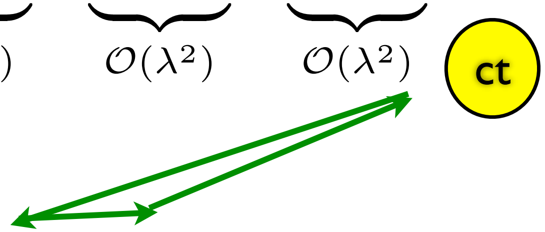
$$\underbrace{V_{ud}V_{cd}^*}_{\mathcal{O}(\lambda)} + \underbrace{V_{us}V_{cs}^*}_{\mathcal{O}(\lambda)} + \underbrace{V_{ub}V_{cb}^*}_{\mathcal{O}(\lambda^5)} = 0$$



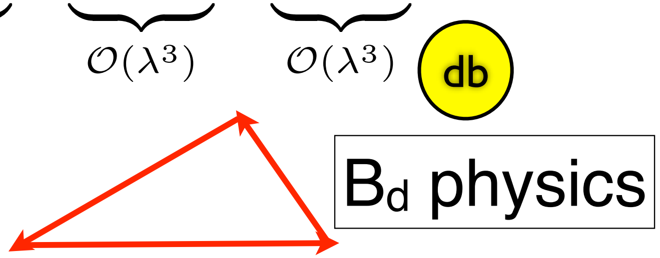
$$\underbrace{V_{us}V_{ub}^*}_{\mathcal{O}(\lambda^4)} + \underbrace{V_{cs}V_{cb}^*}_{\mathcal{O}(\lambda^2)} + \underbrace{V_{ts}V_{tb}^*}_{\mathcal{O}(\lambda^2)} = 0$$



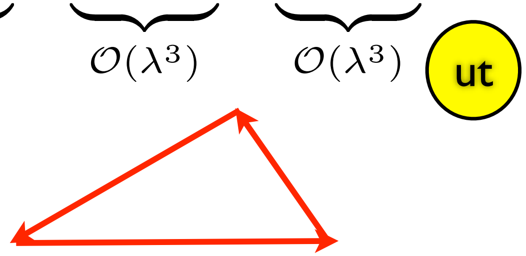
$$\underbrace{V_{td}V_{cd}^*}_{\mathcal{O}(\lambda^4)} + \underbrace{V_{ts}V_{cs}^*}_{\mathcal{O}(\lambda^2)} + \underbrace{V_{tb}V_{cb}^*}_{\mathcal{O}(\lambda^2)} = 0$$



$$\underbrace{V_{ud}^*V_{ub}}_{\mathcal{O}(\lambda^3)} + \underbrace{V_{cd}^*V_{cb}}_{\mathcal{O}(\lambda^3)} + \underbrace{V_{td}^*V_{tb}}_{\mathcal{O}(\lambda^3)} = 0$$

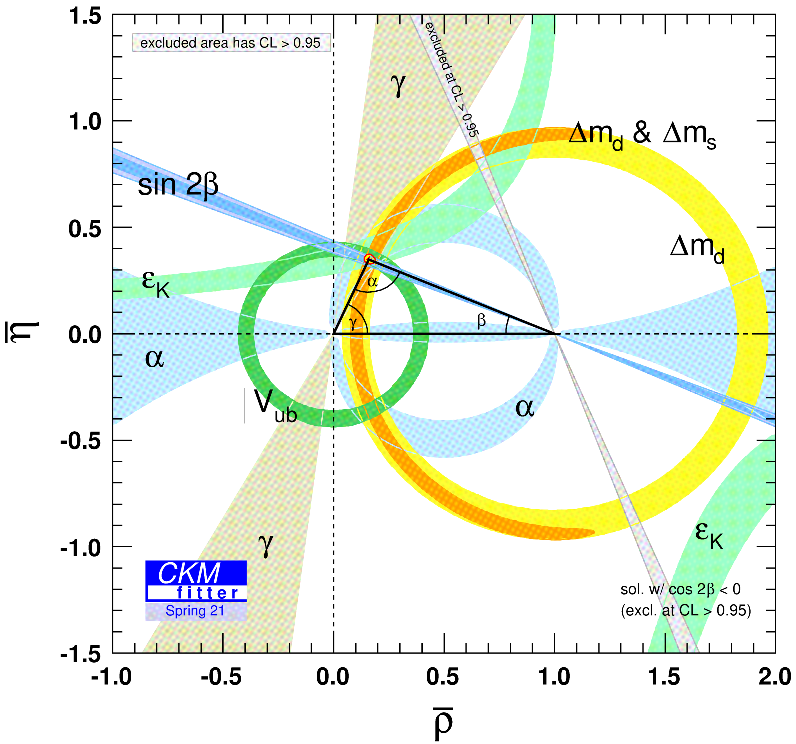


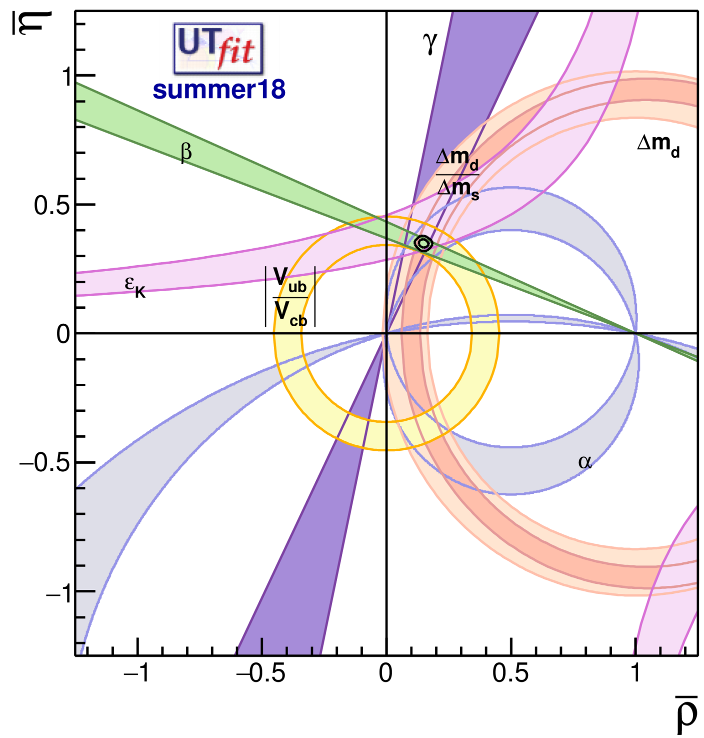
$$\underbrace{V_{td}V_{ud}^*}_{\mathcal{O}(\lambda^3)} + \underbrace{V_{ts}V_{us}^*}_{\mathcal{O}(\lambda^3)} + \underbrace{V_{tb}V_{ub}^*}_{\mathcal{O}(\lambda^3)} = 0$$



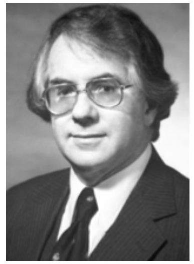
The Unitarity triangle: test of Unitarity

- Hundreds of observables (including dozens of CP violating ones) are consistently by the CKM matrix.





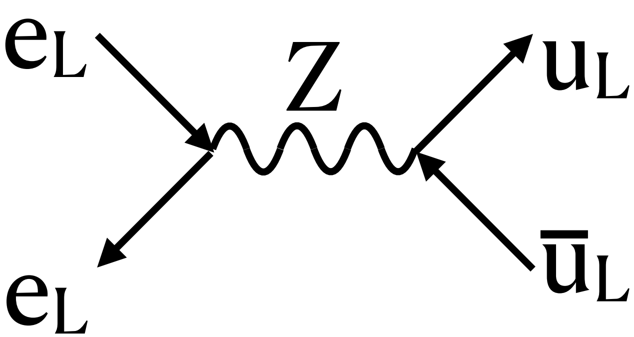
Test 3: FCNC process



- The unitarity of the mixing matrix predicts the suppression of Flavour Changing Neutral Current (FCNC) via GIM (Glashow, Illiopolous, Maiani) mechanism.

Weak interaction

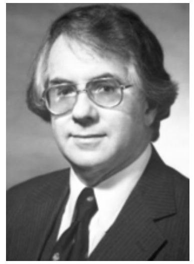
$$\mathscr{L}^{NC} \propto Z^{\mu}\bar{u}_L \gamma_{\mu} u_L + \ldots$$



$$\bar{u}_L^{m} (U_L^{u})^{\dagger} U_L^{u} u_L^{m}$$
$$= (1)$$

- For neutral current, flavour does **not change** even in the mass eigenstate.

Test 3: FCNC process



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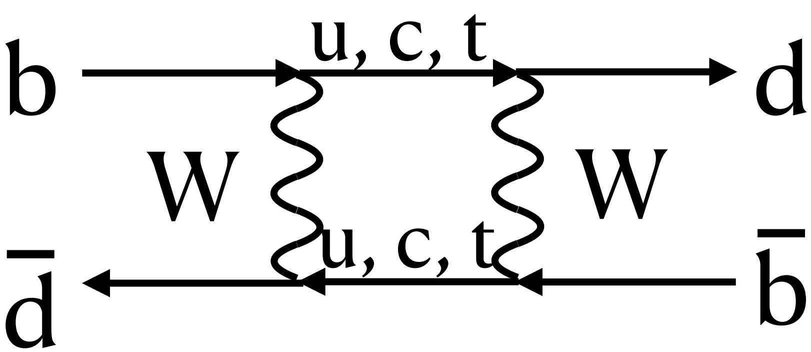
At the loop level…

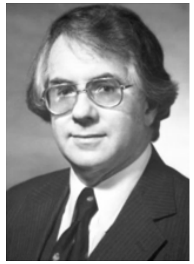


If the quark masses are the same…

$$\bar{d}^{(m)}_L \Sigma_{i=1,3}\, f(m_i)(U_L{}^d)^{\dagger}{}_{1j}(U_L{}^d)_{i3}\, b^{(m)}_L$$
$$= f(m_i)\,(1)$$

- Still no FCNC

Test 3: FCNC process



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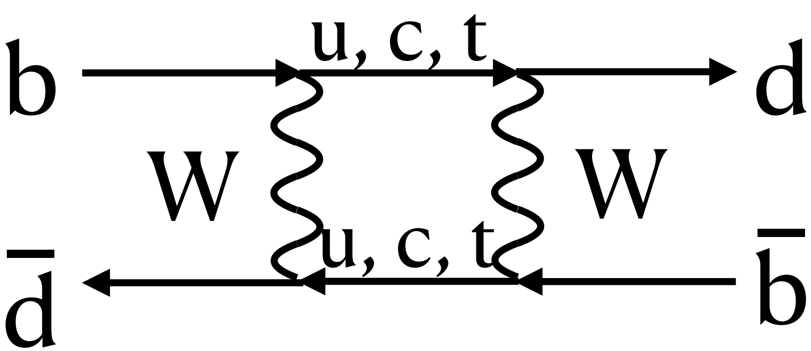


In reality, there is a huge mass difference!

$$\bar{d}_L^{\,m} \Sigma_{i=1,3}\, f(m_i)(U_L^{d})^{\dagger}_{1j}(U_L^{d})_{i3}\, b_L^{\,m}$$

$$= f(m_u)V_{ud}+f(m_c)V_{cd}+f(m_t)V_{td}$$

- Large top quark mass induces a relatively large FCNC!
- Observed as many **B meson and K meson rare decays**!

Signal beyond the SM?

Signal beyond the SM?

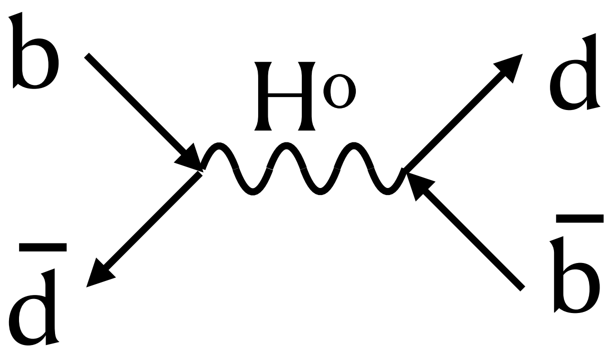
- Excess of CP violation
- Non-unitarity of CKM
- Excess of FCNC

Signal beyond the SM?

- The three outcome of the simple description of the flavour physics in SM is broken as soon as we add a particle Beyond the SM.

E.g.1: Two Higgs doublet model

- We can't diagonalise the two Yukawa matrix simultaneously.

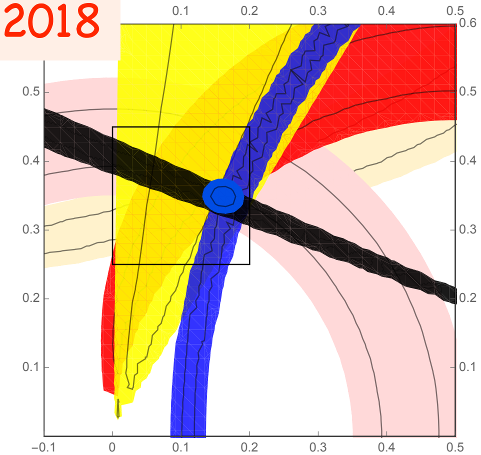


E.g.2: Extra fermion model

- CKM matrix is a part of $(3+n)_1 x (3+n_2)$ matrix.

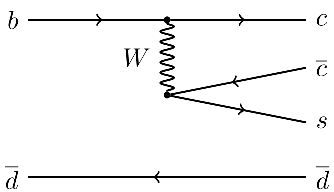
Future of the Unitarity Triangle

2018

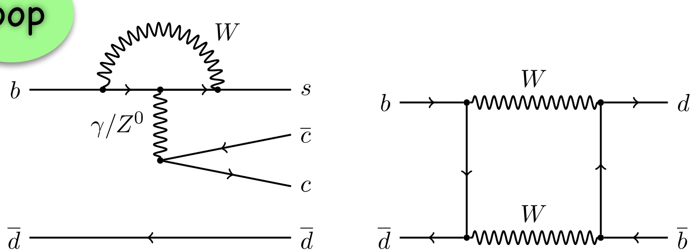


Consistent with SM

tree



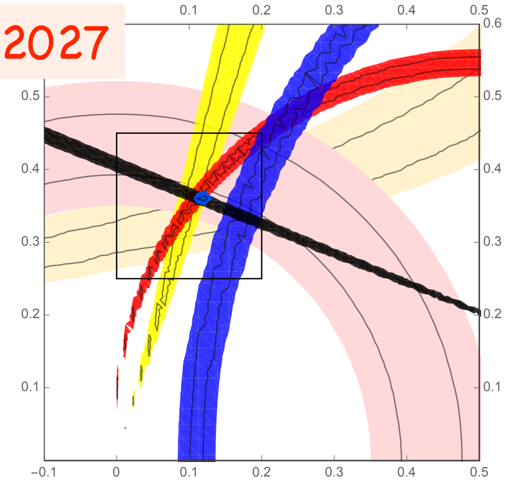
loop



If the central value remains exactly the same (though unlikely)...

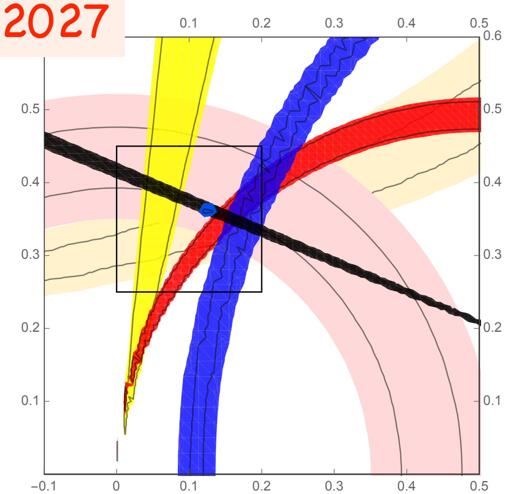
If 3 angles measurements move a little higher (within 1σ)...

~2027



3.5σ effect (=SM???)

~2027



7σ effect (≠SM)!

Strategy for discovery via precision

$$\Delta_{NP} = \text{Deviation from SM}$$
$$= (\text{exp. - SM}) \pm \sqrt{(\sigma_{exp})^2 + (\sigma_{SM})^2}$$

Strategy I: reducing the experimental uncertainty

- Belle II increases the luminosity (50 times by ~2035)
- Hadronic channels become available after LHCb upgrade (started in 2023!)
- Challenges: as statistic error will be at a per-mill level for many rare decays, controlling the systematic errors becomes essential!

Strategy for discovery via precision

$$\Delta_{NP} = \text{Deviation from SM}$$
$$= (\text{exp.} - \text{SM}) \pm \sqrt{(\sigma_{exp})^2 + (\sigma_{SM})^2}$$

Strategy II: reducing the theoretical uncertainty

- Theoretical development in QCD higher order corrections, Lattice QCD will allow to reduce the theoretical uncertainties.
- Improved measurements of "theoretical control channels" are very important to reduce the theoretical errors (**data driven**, excellent example, muon g-2).

Strategy for discovery via precision

$$\Delta_{NP} = \text{Deviation from SM}$$
$$= (\text{exp.} - \text{SM}) \pm \sqrt{(\sigma_{exp})^2+(\sigma_{SM})^2}$$

Strategy III: explore new observables!

- High statistics data or detector upgrade allow us to explore new observables which have never been studied before!

Strategy III: explore new observables!

arXiv:1808.10567 (PTEP 2019)
Belle II Physics Book (E.K. as an editor)

✴Angular/Dalitz distribution, time dependent measurement

Polarisation, CPV etc…

✴Null test

Unexpected CPV, LFV (e.g. $\tau \to \mu\gamma$), LFUV, Dark Photon, Axion…

✴(Ultra)-rare decays

B->$\boldsymbol{\gamma\gamma}$, K(*)$\boldsymbol{\nu\nu}$ (start seeing them at Belle II!), baryon decays (more and more available at LHCb) etc…

✴New hadronic resonances

More XYZ, more Pentaquarks!

Conclusions

- Flavour physics targets an **indirect** search of a signal beyond the Standard Model. It is a complementary method to the **direct** search at LHC.
- Main signatures we are looking at are
  - ✳ **Excess of CP violation**
  - ✳ **Non-unitarity of CKM**
  - ✳ **Excess of FCNC**

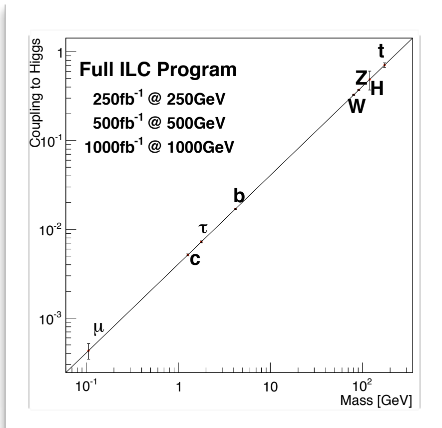
which can be induced **any (natural) extension** of the SM.

Backup

What has been confirmed?

Observed Quark masses

	1st generation	2nd generation	3rd generation
up type cha...	up	charm	top

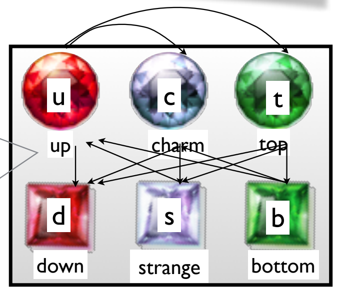


DBD 2012

Do fermion masses come entirely from the Yukawa coupling?

- ✓ SM does not say anything about the Yukawa coupling so the masses and the couplings are not predictable.
- ✓ **V_{CKM} has to be a 3x3 unitary matrix which includes only one complex phase.**
- ✓ N.B. LHC and LCs can tell us the linearity of the masse and the Higgs coupling.

Vckm: Cabibbo-Kobayashi-Maskawa matrix



Flavour Physics beyond SM

The indirect search of new physics through quantum effect: very powerful tool to search for new physics signal!

- This very simple picture does not exist in most of the extensions of SM: suppression of the FCNC is NOT automatic and also CP violation parameters can appear.
  N.B.: SM also has an "unwanted" CP parameter (strong CP problem).

SUSY: Quark and Squark mass matrices can not be diagonalized at the same time ---> FCNC and CP violation

Mutli-Higgs model, Left-Right symmetric model: Many Higgs appearing in this model ---> tree level FCNC and CP violation

Warped extra-dimension with flavour in bulk: Natural FCNC suppression though, K-K mixing might be too large due to the chiral enhancement