A lightning course on Flavor Physics

II - FCNCs and sensitivity to New Physics

Jorge Martin Camalich

Instituto de Astrofísica de Canarias · IAC

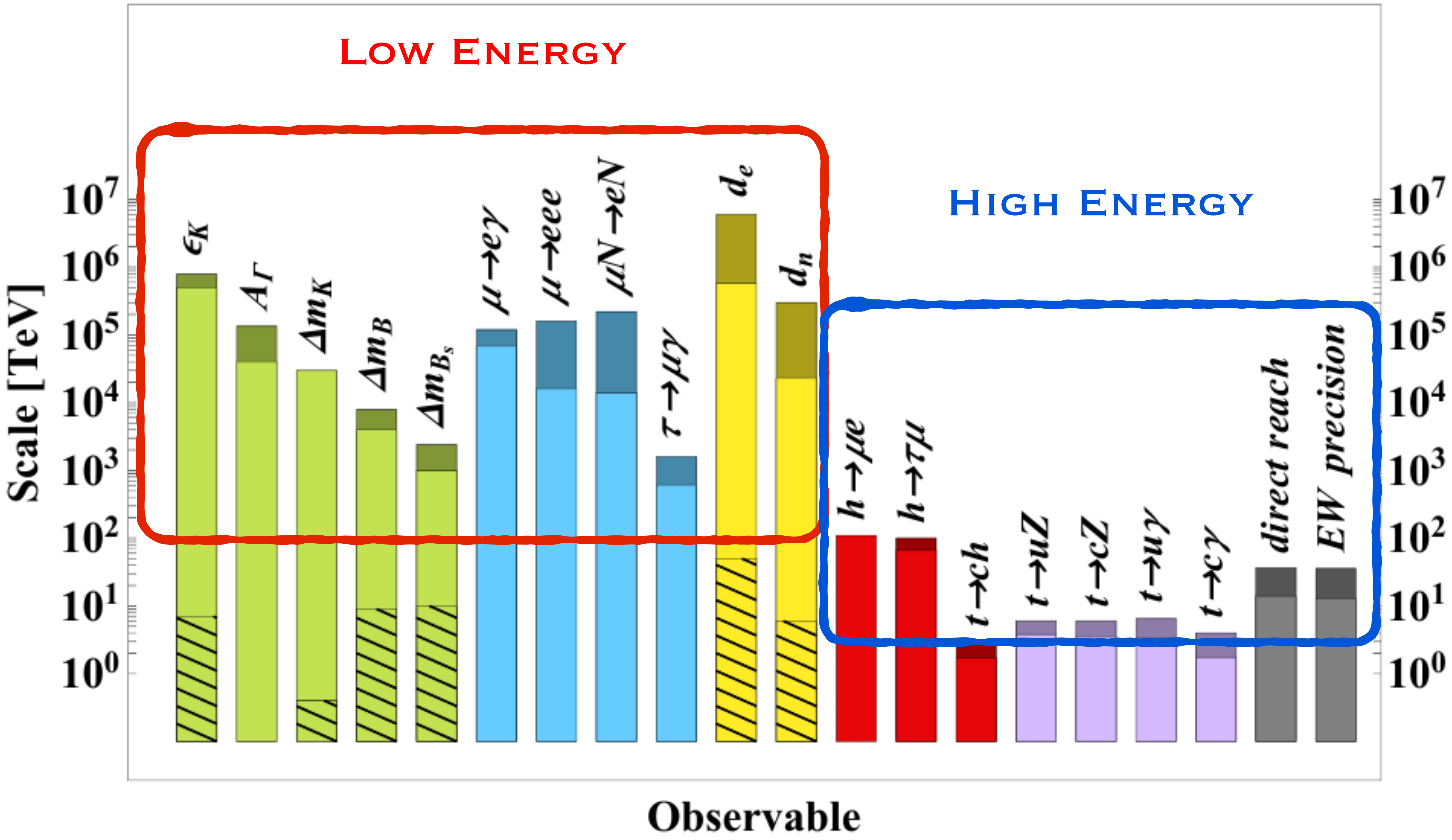
Universidad de La Laguna

FCNCs as probes of BSM

- FCNCs can provide null tests of the SM

  Null test: *Observational test that would contradict the model*

- FCNCs are very sensitive to BSM with *non-standard* gauge or flavor structure
  - Searching for FCNCs in experiment could herald the discovery of New Physics!
  - Null searches are typically expressed as lower-bounds on mass scales of the putative BSM



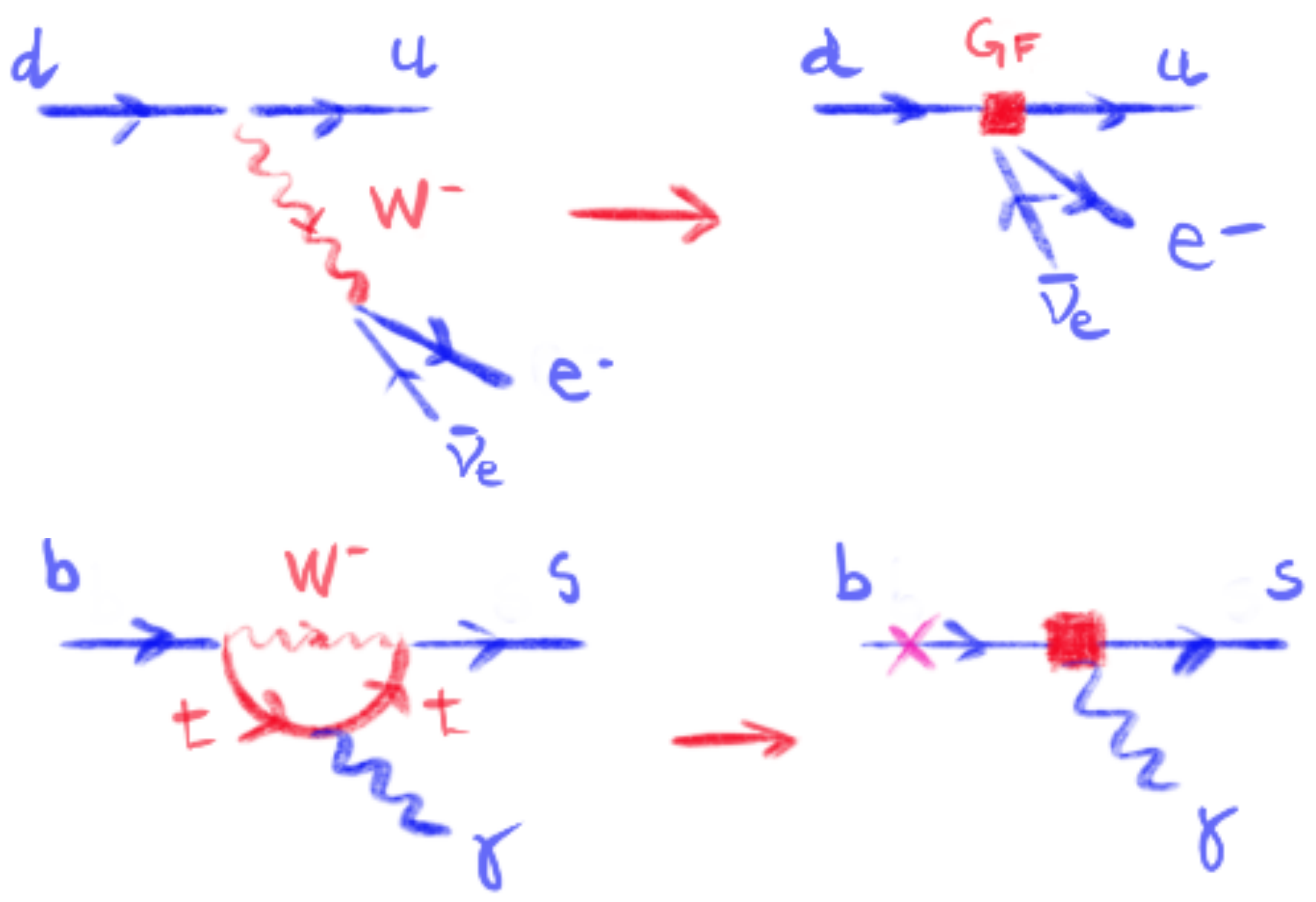
- Flavor physics **is mostly a low-E endeavour**
- Flavor is sensitive to **BSM scales orders of magnitude higher** than direct searches or EW precision tests

How do we reach these conclusions and what does this mean?

The theorist's tool kit: Effective field theories

- Energies involved in hadron decays $m_h \ll m_W$

Rigorous and **systematic expansion** in the small parameter $\epsilon \approx m_h / m_W$ within the Effective Field Theory (EFT)



- Modern subnuclear extension of Fermi Theory
  - Neutron β decay

$$\mathcal{M}_\beta \approx G_F \, C_\beta \, \left(\bar{u}\gamma^\mu P_L d\right) \, \left(\bar{e}\gamma_\mu P_L \nu\right)$$

- Extended also to FCNCs
  - Radiative B-meson decays (e.g. $B^0 \to K^* \gamma$)

$$\mathcal{M}_\gamma \approx \frac{e \, m_b}{4\pi^2} G_F C_\gamma \, \bar{s}\sigma^{\mu\nu} P_R \, b \, F_{\mu\nu}$$

- **We work with low-energy effective Lagrangians:**
  - **Dimensionful constant:** Scale of dynamics that have been *integrated out* - $G_F \approx 1/m_W^2$
  - **Wilson coefficient:** Structure and constants of UV theory - $C_\beta \approx V_{ud}$, $C_\gamma = V_{tb}V_{ts}^* f(x_t)$
  - **Non-renormalizable operators:** with $d \geq 5$ and composed of dynamical fields at $E \ll m_W$

EFT for BSM: Low energies

- EFTs can be also used to parametrize new physics

Recipe for the construction of the EFT of the BSM

1. List **fields** that can be made *on-shell* at the energies of interest
2. List **gauge symmetries** manifest at the energies of interest
3. Construct all **gauge invariant operators** with these fields up to a given dimension d

Power counting: Ordering of the ∞ operators according to power n in $(E/\Lambda_{\rm BSM})^n$

- Only a **finite number of operators** needed for a given precision!

- EFTs of UV new physics are phenomenologist's 2nd best friend
  - **Top-down perspective:** One can readily test a model with low-energy data by *matching* to the EFT
  - **Bottom-up perspective:** *All* UV BSM models are subsumed within the EFT

  Two caveats about bottom-up usage of EFT

  1. Not *all* combinations of EFT operators can be accommodated by sensible UV models
  2. Only grasps the *shapes* of the UV physics

Low-energy EFT of the CC quark-lepton interactions

- Ingredients for e.g. neutron β decay
    1. **Degrees of freedom at $m_n \sim$ 1 GeV:** *up* and *down* quarks, electron, neutrinos and photons
    2. **Gauge symmetries:** $SU(3)_c \times U(1)_{\rm EM}$
    3. **Power counting:** Leading contribution at $n = 2$ (dimension-6 operators)

$$\mathscr{L}_\beta = \frac{4G_F V_{ud}}{\sqrt{2}}\Big(C_{LL}(\bar{u}\gamma^\mu P_L d)(\bar{e}\gamma_\mu P_L \nu) + C_{RL}(\bar{u}\gamma^\mu P_L d)(\bar{e}\gamma_\mu P_L \nu)$$
$$+ C_{S_L S_L}(\bar{u}P_L d)(\bar{e}P_L \nu) + C_{S_R S_L}(\bar{u}P_L d)(\bar{e}P_L \nu) + C_{T_L T_L}(\bar{u}\sigma^{\mu\nu}P_L d)(\bar{e}\sigma_{\mu\nu}P_L \nu)\Big)$$

- *Any* UV contribution to β decay must be described by these **5 dimension operators** at leading order
- Operators distinguished by their Lorentz and chiral structure
- If we added **right-handed neutrinos** we would need **5 more operators** (replace $P_L \to P_R$ in leptons)

Actually, it is very old technology: Equivalent effective Lagrangians led to the discovery of the $V - A$ interaction! (see S. Weinberg´s "V-A was the key")

Two concepts in the EFT

- **Matching:** Procedure by which we transition from a QFT to an EFT with less dynamical d.o.f. at a UV scale Λ_{NP}
  - One *integrates out* heavy d.o.f. and the **short distance** (**UV**) information is frozen in the Wilson coefficients
  - The **long distance** (**IR**) information is described dynamically at the operator level
- **RGE evolution of operators**
  - EFT is nonrenormalizable *but* can be renormalized order by order
  - **Renormalization Group Equation** provides the renormalization scale evolution of the **Wilson coefficients**

$$\frac{d\vec{C}(\mu)}{d\log\mu} = \gamma^T(\alpha_{\text{em}}, \alpha_s)\vec{C}(\mu)$$

$\vec{C}(\mu)$ → **Vector** of Wilson coefficients

$\frac{d}{d\log\mu}$ → Renormalization scale dependence

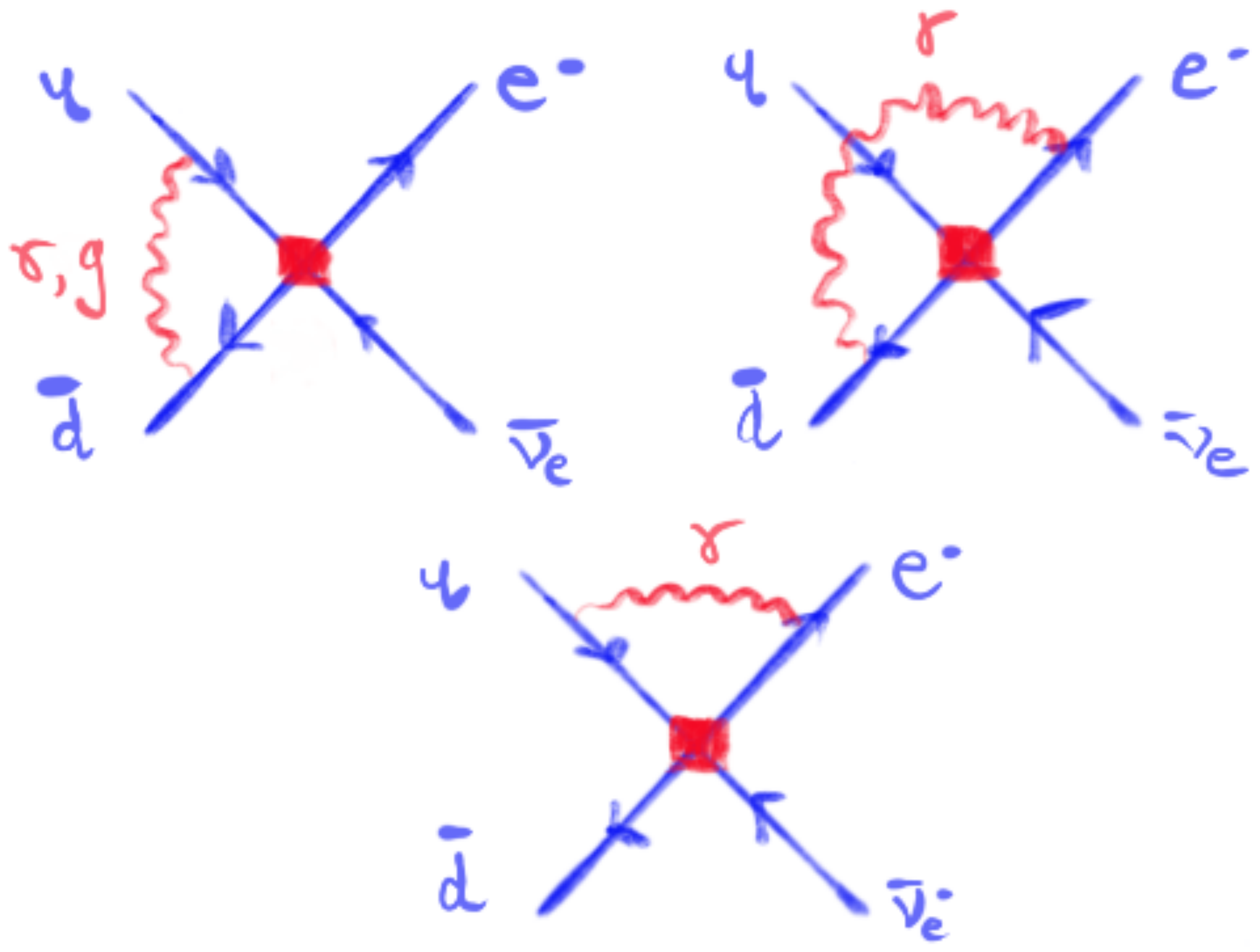
$\gamma^T(\alpha_{\text{em}}, \alpha_s)$ → Anomalous dimensions **matrix**
Coefficients of UV divergences

- **Matching** provides the initial conditions $\vec{C}(\Lambda_{\text{NP}})$ for the RGE flow
- Operators suffer **rescaling** and **mixing** when connecting the UV and IR scales! … Unless symmetry protection!

RGE in β decays and similar transitions

- Corrections at 1-loop given by QED and QCD

$$\vec{C}^T = \left(C_{LL}, C_{RL}, C_{S_RS_L}, C_{S_LS_L}, C_{T_LT_L}\right)$$



$$\gamma^T_{\rm QED} = \begin{pmatrix} -2 & 0 & 0 & 0 & 0 \\ 0 & -1 & 0 & 0 & 0 \\ 0 & 0 & \frac{2}{3} & 0 & 0 \\ 0 & 0 & 0 & \frac{2}{3} & 4 \\ 0 & 0 & 0 & \frac{1}{12} & -\frac{20}{9} \end{pmatrix}$$

$$\gamma^T_{\rm QCD} = {\rm diag}\,(0,0,-4,-4,4/3)$$

- Final RGE between 2 GeV and Z-pole mass

$$\begin{pmatrix} C_{LL} \\ C_{RL} \\ C_{S_RS_L} \\ C_{S_LS_L} \\ C_{T_LT_L} \end{pmatrix}(\mu = 2\ {\rm GeV}) = \begin{pmatrix} 1.005 & 0 & 0 & 0 & 0 \\ 0 & 1.005 & 0 & 0 & 0 \\ 0 & 0 & 1.72 & 0 & 0 \\ 0 & 0 & 0 & 1.72 & -0.0242 \\ 0 & 0 & 0 & 0 & 0.825 \end{pmatrix} \begin{pmatrix} C_{LL} \\ C_{RL} \\ C_{S_RS_L} \\ C_{S_LS_L} \\ C_{T_LT_L} \end{pmatrix}(\mu = m_Z)$$

- General comments
  - **QED rescales all operators and mix scalar-tensor**

    (QED/QCD vectorial ⇒ Do not mix different chiralities!)
  - **QCD only rescales scalar and tensor**

    (Conservation vector current prevents RGE of vectors!)

RGE needs to be taken into account when connecting our UV models to phenomenology!

EFT above EW scale: SMEFT

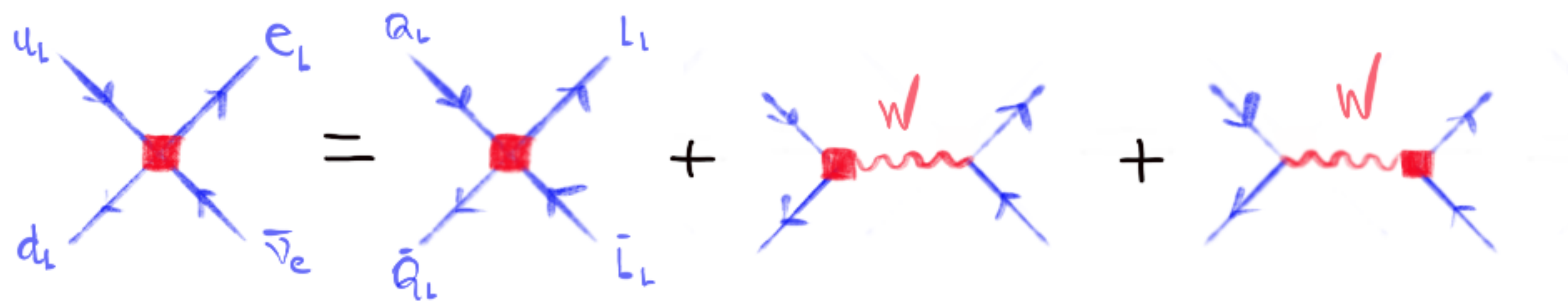
- **SMEFT:** EFT built with the ***full*** SM gauge group and field content

  Example: Current-current operators

  4-fermion - $\mathcal{O}^{(3)}_{LQ} = \left(\bar{L}_L\gamma^\mu\tau^I L_L\right)\left(\bar{Q}_L\gamma_\mu\tau^I Q_L\right)$

  Vertex corrections -
$$\begin{cases} \mathcal{O}^{(3)}_{HQ} = \left(H^\dagger D^I_\mu H\right)\left(\bar{Q}_L\gamma^\mu\tau^I Q_L\right) \\ \mathcal{O}^{(3)}_{HL} = \left(H^\dagger D^I_\mu H\right)\left(\bar{L}_L\gamma^\mu\tau^I L_L\right) \\ \mathcal{O}^{(3)}_{Hud} = \left(\tilde{H}^\dagger D_\mu H\right)\left(\bar{u}_R\gamma^\mu d_R\right) \end{cases}$$

  - **At scales** $\approx v_{\rm ew}$ **we need to *switch* EFTs!**



$$C^{ij,\alpha\beta}_{LL} \simeq -\left[\bar{C}^{(3)}_{LQ}\cdot V\right]^{ij,\alpha\beta} + \left[\bar{C}^{(3)}_{HQ}\cdot V\right]^{ij} + \left[\bar{C}^{(3)}_{HL}\right]^{\alpha\beta}$$
$$C^{ij,\alpha\beta}_{RL} \simeq \left[\bar{C}^{(3)}_{Hud}\right]^{ij}\delta^{\alpha\beta}$$

  - **More symmetry in SMEFT:** There are relations among low-energy EFT Wilson coefficients!

    There are no **lepton non-universal** C_{RL} interactions! (only quark vertex corrections)

Operators live in flavor space!

1. The $\bar{C}$ are **tensors in flavor space** of Wilson coefficients
2. Anomalous dimensions have to be re-calculated in SMEFT above $\approx v_{\rm ew}$

Imposing a flavor ansatz: Minimal Flavor violation

- **SMEFT is a full-fledged flavored EFT**
  - There are **59** flavor-diagonal operator *vs.* **2499** operators in the full flavor SMEFT at dim-6!

It is often practical to impose flavor ansatz in $\bar{C}$ to guide the model building

- **Minimal Flavor Violation (MFV):** *All* the flavor violation in SM+BSM stems from *just* the SM Yukawas
  - One can implement MFV in the EFT using the **spurion analysis**

Impose an additional global symmetry $\mathscr{G} = U(3)_Q \times U(3)_u \times U(3)_d$ to $\mathscr{L}_{\text{SMEFT}}$

$$Q_L \sim (3,1,1), \quad u_R \sim (1,3,1), \quad d_R \sim (1,1,3), \quad y_u \sim (3,\bar{3},1), \quad y_d \sim (3,1,\bar{3})$$

  - MFV is useful because it transfers the flavor component of the GIM suppression to BSM

Example: **Contribution to the FCNC $b \to s\gamma$**

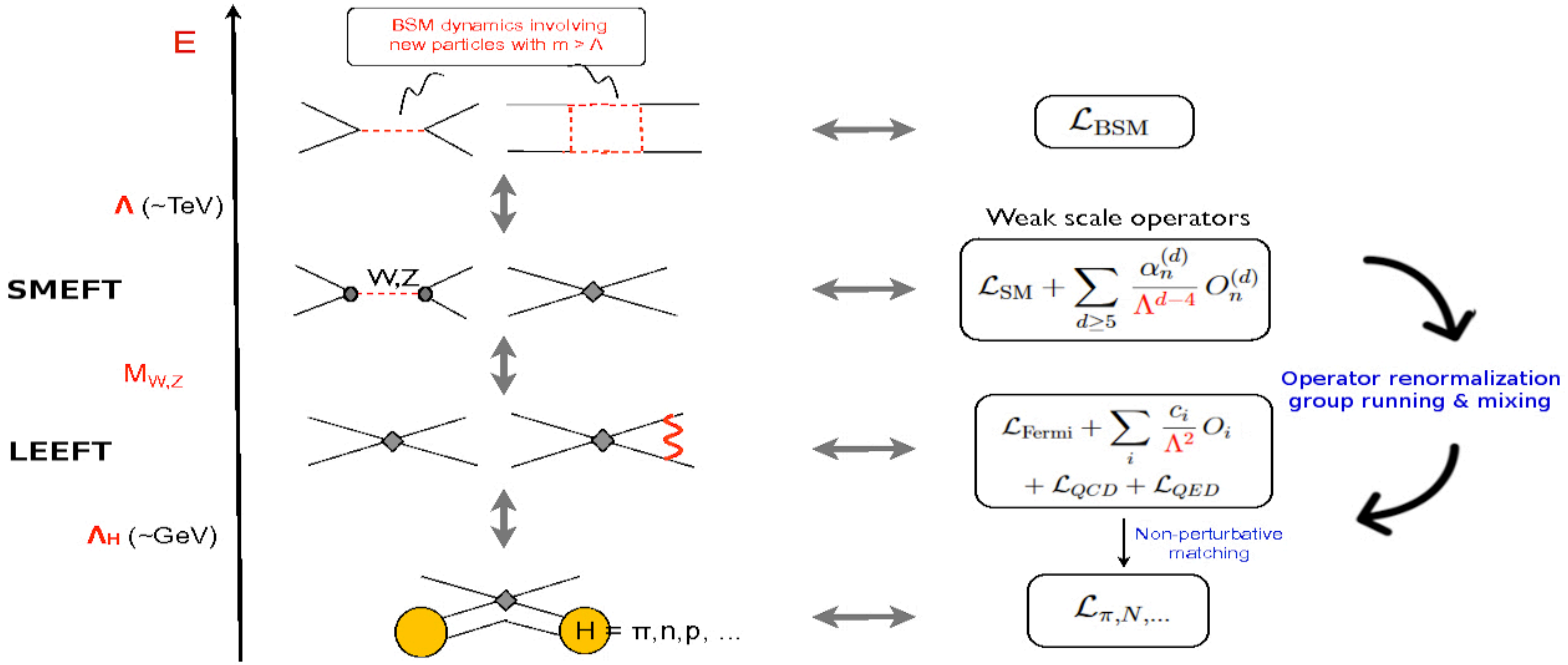
$$\frac{e\,\bar{c}}{\Lambda_{\text{NP}}^2} F_{\mu\nu} \bar{Q}_L \sigma^{\mu\nu} \underbrace{y_u y_u^\dagger y_d}_{} b_R \quad \Rightarrow \quad \frac{e\,\bar{c}}{\Lambda_{\text{NP}}^2} F_{\mu\nu} \begin{pmatrix} \bar{U}_L \\ \bar{D}_L V^\dagger \end{pmatrix} \sigma^{\mu\nu} m_u^2\, V\, m_d\, b_R$$

y_d alone is to small

Same yukawa suppression as in the SM!

$$C_\gamma = \frac{e\,\bar{c}}{\Lambda_{\text{NP}}^2}\, m_b\, y_t^2\, V_{ts}^* V_{tb}$$

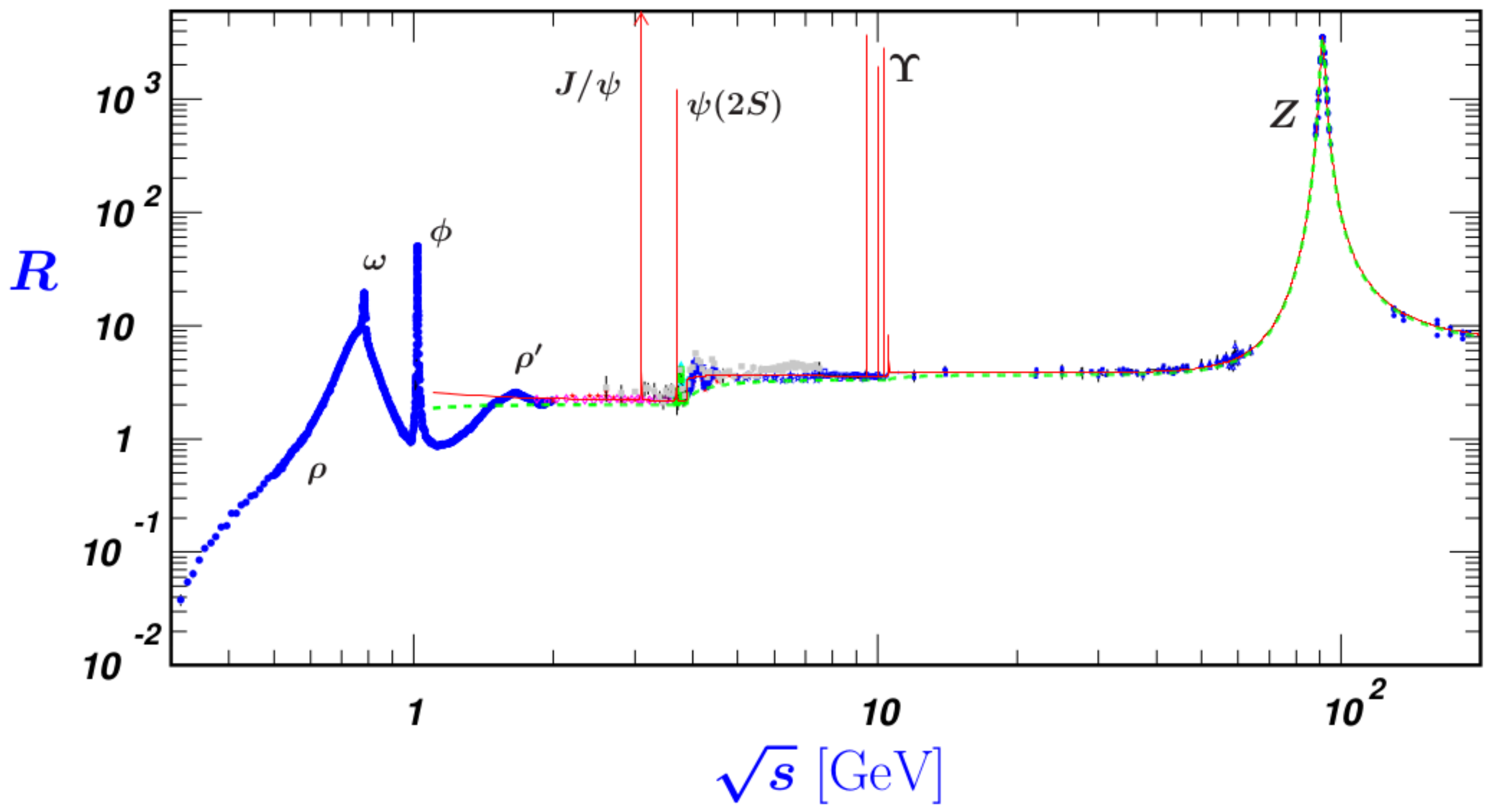
Summary of the EFT procedure



Cirigliano and Mussolf Prog.Part.Nucl.Phys. 71 (2013) 2-20

Low-energy: The realm of the hadrons

- QCD confines around and below energies ~ $\Lambda_{\mathrm{QCD}} \approx$ 200 MeV



Baryons qqq and Antibaryons $\bar{q}\bar{q}\bar{q}$

Baryons are fermionic hadrons.
There are about 120 types of baryons.

Symbol	Name	Quark content	Electric charge	Mass GeV/c^2	Spin
p	proton	uud	1	0.938	1/2
$\bar{p}$	anti-proton	$\bar{u}\bar{u}\bar{d}$	–1	0.938	1/2
n	neutron	udd	0	0.940	1/2
Λ	lambda	uds	0	1.116	1/2
Ω^-	omega	sss	–1	1.672	3/2

Mesons $q\bar{q}$

Mesons are bosonic hadrons.
There are about 140 types of mesons.

Symbol	Name	Quark content	Electric charge	Mass GeV/c^2	Spin
π^+	pion	$u\bar{d}$	+1	0.140	0
K^-	kaon	$s\bar{u}$	–1	0.494	0
ρ^+	rho	$u\bar{d}$	+1	0.770	1
B^0	B-zero	$d\bar{b}$	0	5.279	0
η_c	eta-c	$c\bar{c}$	0	2 .980	0

- Only the proton is (almost) really stable!

The thousands of different decay modes of these hundreds of particles are a **precious source of information**

The PDG is phenomenologist's 1st best friend!

- **Branching fraction** of a decay channel i of a hadron h

$$\mathrm{Br}_i = \Gamma_i / \Gamma_h = \tau_h \Gamma_i$$

- Only hadrons whose main decay channel is *weak*
  1. **Flavor violations !**
  2. **Sensitivity to** $E \gtrsim m_W$ **!**

Connecting to the observables of the hadronic world

- **Our Lagrangians are written in terms of quarks and our observables in terms of hadrons!**

Interactions: $\mathscr{L}(u, d, s, c, b, e, \nu, G, F)$ ***Asymptotic* states:** $|\pi^\pm, \pi^0, K^\pm, D^\pm, B^\pm, p, n, \Lambda, \ldots\rangle$

- By *asymptotic* we mean hadrons with **long life times** ($\tau_{\text{weak}} \approx \overbrace{10^{-8}}^{\text{Kaons}} - \overbrace{10^{-12}}^{B-\text{mesons}}$ s $vs.$ $\tau_{\text{EM}} \approx \overbrace{10^{-17}}^{\pi^0}$ s OR $\tau_{\text{strong}} \approx \overbrace{10^{-24}\,\text{s}}^{\rho-\text{resonance}}$)
- **Observables** defined in terms of matrix elements

$$\mathscr{M} \sim \langle e', \nu', \ldots; H_1', H_2', \ldots | \overbrace{\mathcal{O}_\ell \times \mathcal{O}_q}^{\mathscr{L}} | e, \nu, \ldots; H_1', H_2', \ldots \rangle$$

with $\text{Observables} \sim |\mathscr{M}|^2$

- **Factorization:** Wick's theorem *typically* leads to factorization of matrix element

$$\mathscr{M} \sim \langle e', \nu', \ldots | \mathcal{O}_\ell | e, \nu, \ldots \rangle \times \langle H_1', H_2', \ldots | \mathcal{O}_q | H_1', H_2', \ldots \rangle$$

Perturbative matrix element — Hadronic matrix element

- **Hadronic matrix elements:** Encapsulate all the nonperturbative-QCD information of the transition

Very difficult to compute! They limit our capacity to learn about short distances

Determinations of the hadronic brown muck

- **General strategy:**
  1. **Parametrize** the matrix element and **exploit discrete and Lorentz symmetries**
  2. **Exploit approximate symmetries of QCD** in perturbative (EFT) expansions

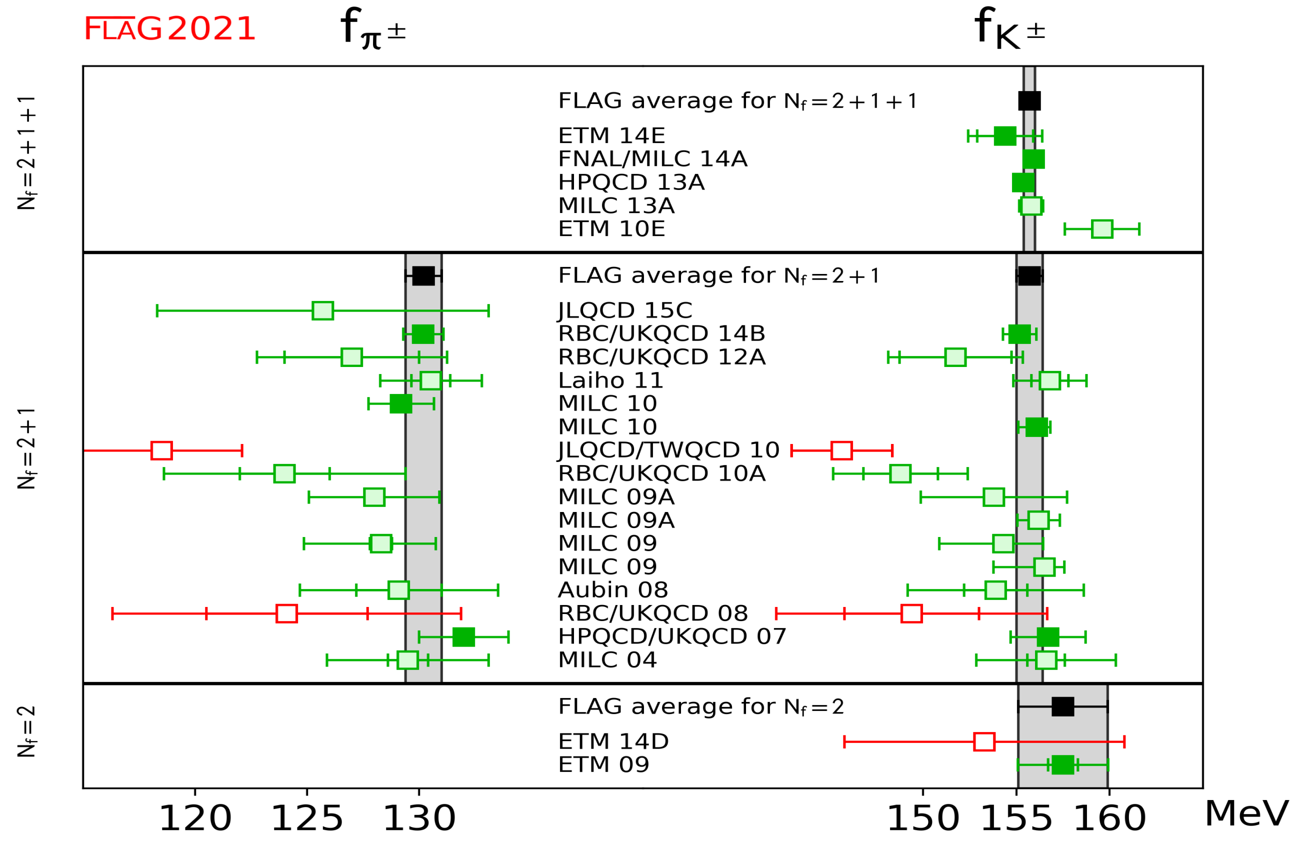
     Relations among hadronic elements that **increase predictability** in a **robust framework**
     - Isospin ($m_d \approx m_u$) and $SU(3)_F$ ($m_u \approx m_d \approx m_s$) in light quarks - Chiral Perturbation Theory
     - Heavy-quark symmetry ($m_{c,b} \gg \Lambda_{\rm QCD}$) - Heavy quark effective theory
  3. **Measure** or **calculate** hadronic matrix elements
     - Lattice QCD - systematic approximation to nonperturbative QCD from a discrete and finite space-time
     - QCD sum rules, quark models, Ads/CFT, etc … Allow to estimate semi-analytically

Example: **Leptonic pion decay $\pi^- \to e^- \bar{\nu}$**

$$\langle 0 | \bar{u}\gamma^\mu \gamma_5 d | \pi^-(p) \rangle = -ip^\mu f_\pi$$

- f_π is the pion decay constant $f_\pi \simeq 130$ MeV
- **Parity invariance:** Vector & Scalar are 0!
- **Lorentz invariance:** Tensor is 0!

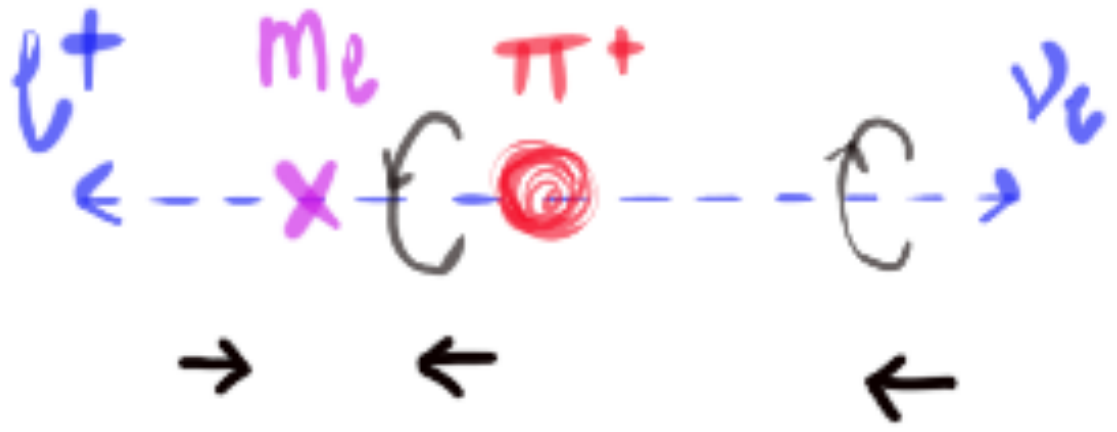
Check FLAG (Lattice "PDG")



More about the leptonic pion decay

- **Chiral suppression:** In the chiral limit $m_\ell \to 0$ the amplitude vanishes!

$$\mathcal{M} = \langle \ell^+ \nu_\ell | \mathcal{L}_{SM} | \pi^+ \rangle = \frac{4 G_F\, V_{ud}}{\sqrt{2}} \langle \ell^+ \nu_\ell | \bar{\nu}_L \gamma_\mu P_L \ell | 0 \rangle \langle 0 | \bar{d} \gamma^\mu P_L u | \pi^+ \rangle = \frac{G_F\, f_\pi V_{ud}}{\sqrt{2}}\, m_\ell\, \bar{\nu}_\ell P_R e$$



$$\mathrm{Br}(\pi^+ \to \mu^+ \nu_\mu) = 99.98770(4)\,\%$$
$$\mathrm{Br}(\pi^+ \to e^+ \nu_e) = 1.230(4) \times 10^{-4}$$

- **Pseudoscalar operator:** Contribution of $\bar{d}\gamma_5 u$?

Current algebra (PCAC): $\partial_\mu(\bar{d}\gamma^\mu \gamma_5 u) = i(m_d + m_u)\bar{d}\gamma_5 u \quad \Rightarrow \quad \langle 0 | \bar{d}\gamma_5 u | \pi^+ \rangle \equiv f_P = i f_\pi \dfrac{m_\pi^2}{m_d + m_u}$

  - Pseudoscalar operator is chirally flipping ⇒ **Not chirally suppressed!**

$$\Gamma_{\ell 2} = \frac{G_F\, |V_{ud}|^2 f_\pi^2}{8\pi} m_\pi\, m_\ell^2 \overbrace{\left(1 - \frac{m_\ell^2}{m_\pi^2}\right)^2}^{\text{Phase space}} \left| C_{LL} - C_{RR} - \frac{m_\pi^2}{m_e(m_d + m_s)} \left(C_{S_R S_L} - C_{S_L S_L} \right) \right|^2$$

Physical results

SM: $|V_{ud}| = 0.97438(12)$

BSM-Vector: $\Lambda_{LL} \approx$ **1 TeV**

BSM-Scalar: $\Lambda_{S_L S_L} \approx$ **1000 TeV!**

Form factors

- **Hadron → Hadron' transitions:** Hadronic matrix elements depend on Lorentz scalar $q^2 = (p - p')^2$
  - Can be **parametrized** in terms of q^2-dependent functions called form factors
    - Meson → Meson form factors

$$\langle \pi^0(p') | \bar{s}\gamma_\mu d | K^+(p) \rangle = f_+(q^2)(p_\mu + p'_\mu) + f_-(q^2)(p_\mu - p'_\mu), \qquad \langle \pi^0(p') | \bar{s}\sigma_{\mu\nu} d | K^+(p) \rangle = f_T(q^2)(p_\mu p'_\nu - p'_\mu p_\nu)$$

      - No **axial** form factors! **Scalar** obtained with **current algebra**

Only in BSM!

    - Baryon → Baryon form factors

$$\langle B_2(p') | \bar{d}\gamma_\mu u | B_1(p) \rangle = \bar{u}_2(p') \left[f_1(q^2)\gamma_\mu + i\frac{f_2(q^2)}{m_{B_1}}\sigma_{\mu\nu}q^\nu + \frac{f_3(q^2)}{m_{B_1}}q_\mu \right] u_1(p)$$

$$\langle B_2(p') | \bar{d}\gamma_\mu\gamma_5 u | B_1(p) \rangle = \bar{u}_2(p') \left[g_1(q^2)\gamma_\mu + i\frac{g_2(q^2)}{m_{B_1}}\sigma_{\mu\nu}q^\nu + \frac{g_3(q^2)}{m_{B_1}}q_\mu \right] \gamma_5 u_1(p)$$

      - ***Both* vector and axial form factors! (pseudo)scalar** with **current algebra** and **3 more tensor** form factors for BSM

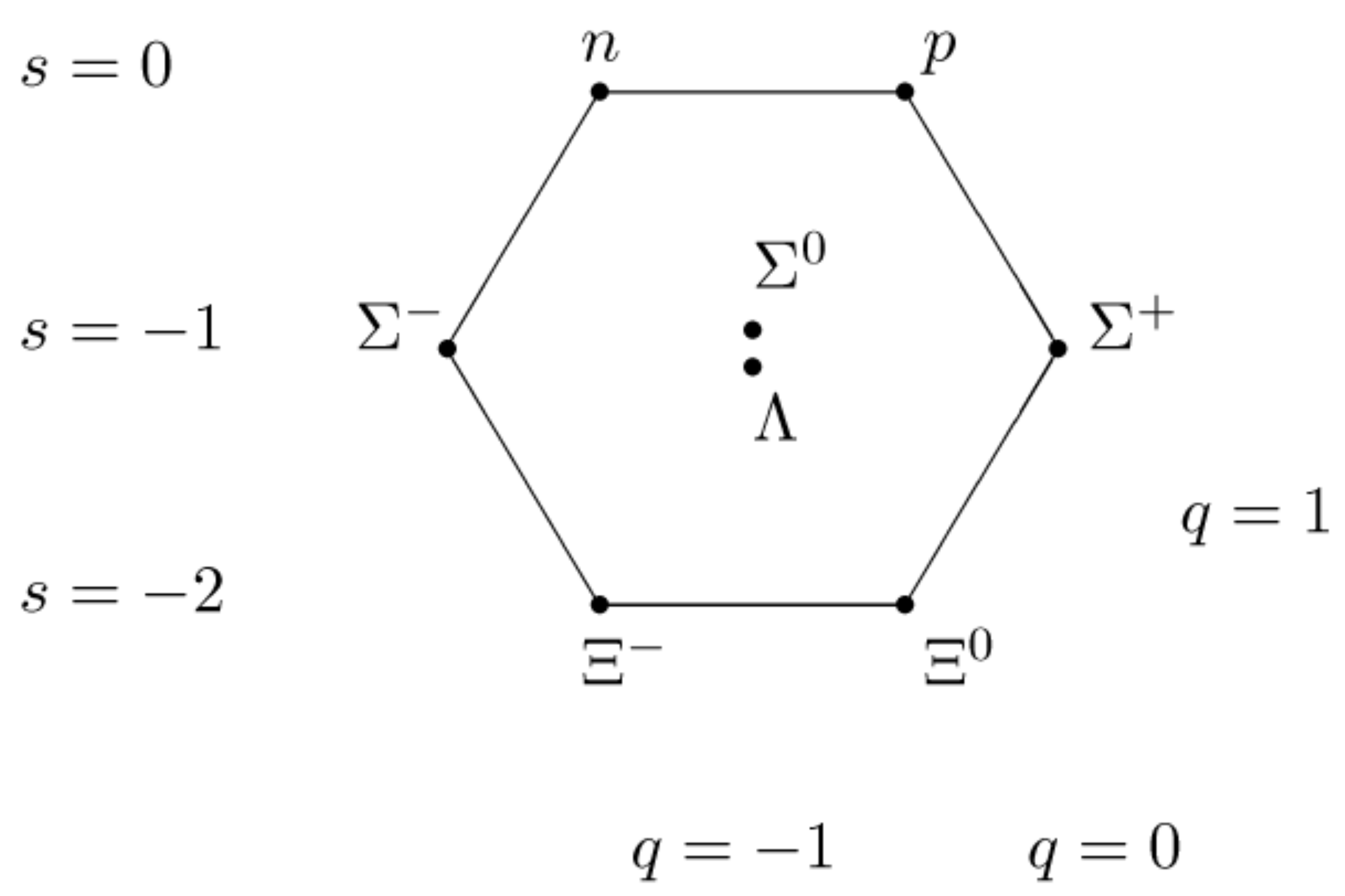
Total of **9 form factors!**

Important points about form factors and friends

1. Hadronic complexity can lead to extended sensitivity to UV physics
2. Use every trick under your sleeve to get rid of them!

Exploiting SU(3)F: e.g. hyperon FFs

- **Hyperon decays:** Form factors related by $SU(3)_F$ symmetry



- Semileptonic decays $B_1 \to B_2 e\bar{\nu}_e$ triggered by $s \to de^-\bar{\nu}_e$ decays
  - **5 decay channels:** Λp, $\Sigma^- n$, $\Xi^-\Lambda$, $\Xi^-\Sigma^0$, $\Xi^0\Sigma^+$
  - Only two $SU(3)_F$−singlets if $\mathcal{O}_{\text{EFT}}$ **lives in the octet**

$$\langle B_a | \mathcal{O}_c | B_b \rangle = F_{\mathcal{O}} f_{cab} + D_{\mathcal{O}} d_{cab}$$

Reduced ME

Group theory factors

  - Vector FFs **predicted** in terms of *p* and *n* EM charges!
  - Axial FFs **predicted** by axial np coupling and one extra channel

- **Further** $SU(3)_F$ expansions involve baryon-mass differences Δ!

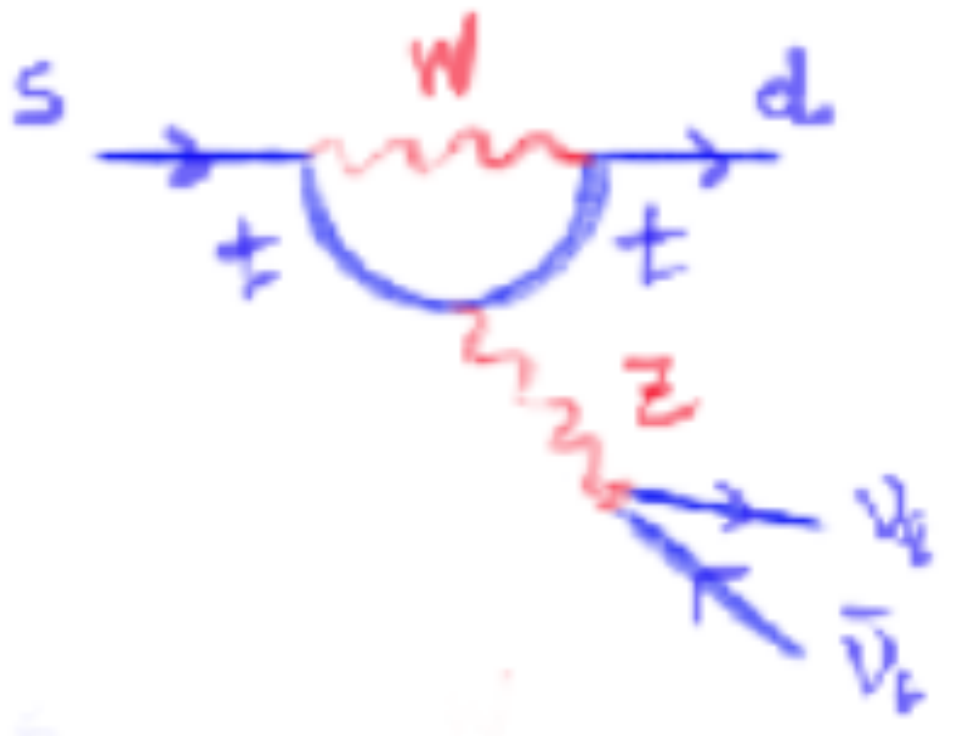
Rates of the **5 decay channels** depend only on **2 numbers!** (@ LO in $SU(3)_F$)

$$\Gamma \simeq \frac{G_F^2 |V_{us}|^2 \Delta^5}{60\pi^3} \left[f_1(0)^2 + 3g_1(0)^2\right]$$

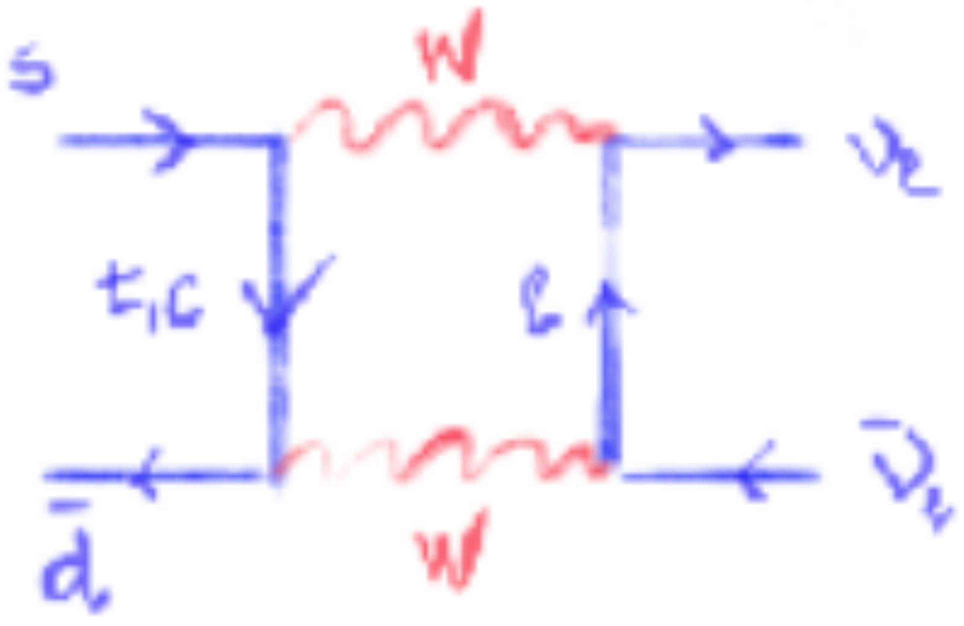
Flavor physics at work: $K^+ \to \pi^+ \nu\bar{\nu}$

- Prototypical very-rare kaon decay: $\Delta S = 1$ FCNC

Penguin diagram



Box diagram



- Effective Lagrangian

$$\mathscr{L}_{\rm SM} = -\frac{4G_F}{\sqrt{2}} V_{ts} V_{td}^* \frac{\alpha}{2\pi} \sum_\ell C_{\nu_\ell} (\bar{d}\gamma^\mu P_L d)(\bar{\nu}_\ell \gamma_\mu \nu_\ell)$$

Wilson Coefficient: $C_{\nu_\ell} = \frac{1}{s_w^2}\left(\frac{V_{cs}V_{cd}^*}{V_{ts}V_{td}^*} X_c^\ell + X_t\right)$

Inami-Lin function

- Relevant form factors related by isospin to CCs

$$\mathrm{Br}(K^+ \to \pi^+ \nu\bar{\nu}) = \frac{\alpha^2 |V_{ts}V_{td}^*|^2 \mathrm{Br}(\mathrm{K}^+ \to \pi^0 \mathrm{e}^+ \nu_\mathrm{e})}{2\pi^2 |V_{us}|^2} \sum_\ell \left|C_{\nu_\ell}\right|^2$$

$$\simeq \frac{\alpha^2}{2\pi^2} \lambda^{10} \sum_\ell \left|C_{\nu_\ell}\right|^2$$

Physical results

$$\mathrm{Br}(K^+ \to \pi^+ \nu\bar{\nu})_{\rm SM} = 8.55(4) \times 10^{-11}$$

$$\mathrm{Br}(K^+ \to \pi^+ \nu\bar{\nu})_{\rm expt} = 1.14(36) \times 10^{-10}$$

$\Lambda_{\rm NP} \gtrsim 100$ TeV!

Flavor at work: Tutorial

- Let´s connect a UV model to a $\mathrm{Br}(K^- \to \pi^- \nu \bar{\nu})$ an derive a bound on it´s mass scale
- We have a Z' boson of mass $m_{Z'}$ that is coupled to the SM with

$$\mathscr{L} \supset \left(g^Q_{ij} \bar{Q}^i_L \gamma^\mu Q^j_L + g^L \bar{L}^\alpha_L \gamma^\mu L^\alpha_L \right) Z'_\mu$$

g^Q is a matrix in general real matrix in flavor space and g_L a universal coupling for leptons.

Calculate

1. Matching of the UV model to an SMEFT operator.
2. Match the SMEFT operator to the operator in low-energy EFT ($C^{\mathrm{SM}}_{\nu_\ell} \simeq 10$)

$$\mathscr{L}_{\mathrm{EFT}} \supset -\frac{4G_F}{\sqrt{2}} V_{ts} V^*_{td} \frac{\alpha}{2\pi} \sum_\ell C_{\nu_\ell} (\bar{d}\gamma^\mu P_L d)(\bar{\nu}_\ell \gamma_\mu \nu_\ell)$$

3. *Estimate* the lower bound on $m_{Z'}$ given by $\mathrm{Br}(K^+ \to \pi^+ \nu \bar{\nu})_{\mathrm{expt}} = 1.14(36) \times 10^{-10}$
4. How does this bound change if we impose MFV?