

Selected Topics in BSM Physics

Cargese 2017

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1. Motivation for BSM
2. Introduction to Effective Field Theory
3. Dark matter direct detection
4. New physics in B decays



Motivation for BSM physics

1.1 Baryogenesis

↓ skip

Sakharov conditions:

- Baryon # violation
- C, CP violation
- Thermal non-equilibrium

1.2 Dark matter

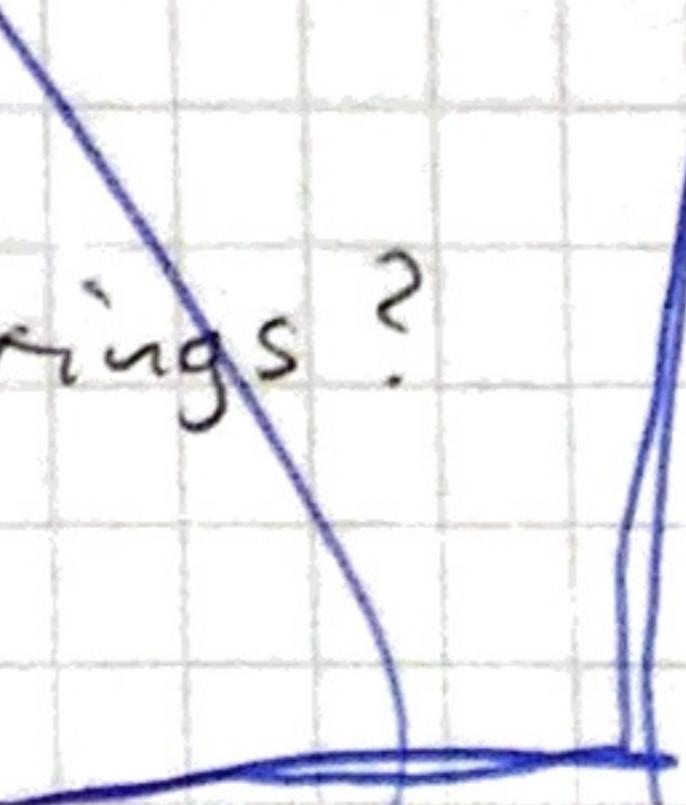
Experimental evidence:

- Galactic rotation curves
- Virialized galaxy clusters
- Existence of old galaxies
- Gravitational lensing
- CMB

DM must be neutral, non-baryonic, cold \Rightarrow BSM

1.3 Theoretical considerations

- Quantum gravity?
- Fermion masses and mixings?
- Strong CP problem?



2 Effective Theory

How do you search for something you don't know?

EFT - understand the physics that is relevant at accessible energy scales

Example: Non-relativistic volleyball

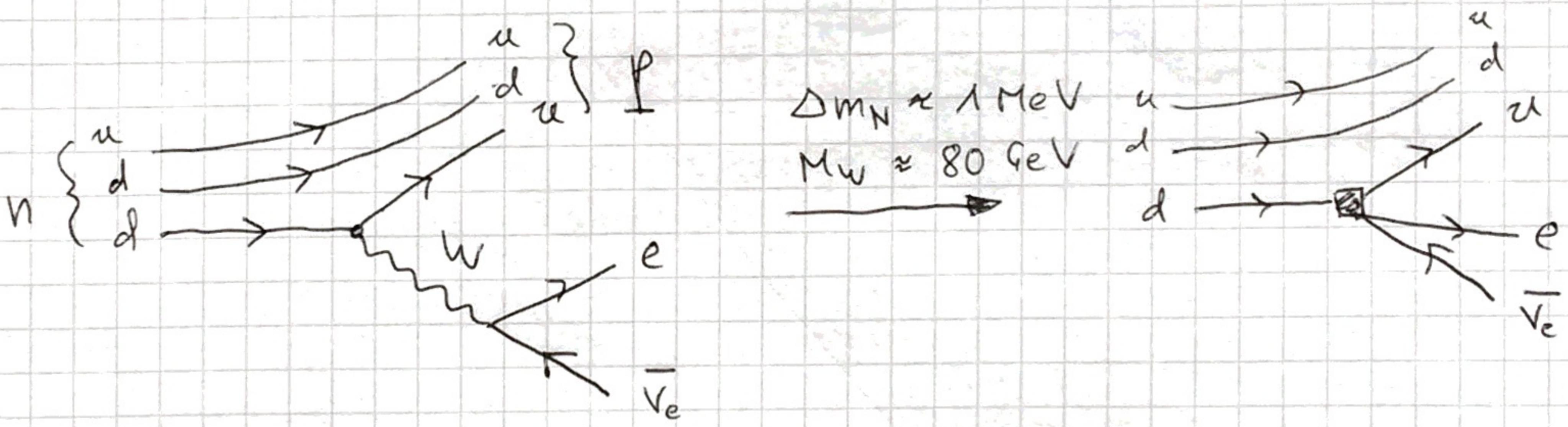
$$\begin{aligned} E_{\text{kin}} &= \left(m^2 c^4 + |\vec{p}|^2 c^2 \right)^{1/2} - mc^2 \\ &= mc^2 \left(1 + \frac{|\vec{p}|^2}{m^2 c^2} \right)^{1/2} - mc^2 \\ &= \frac{|\vec{p}|^2}{2m} + O\left(\frac{v^2}{c^2}\right) \quad (?.) \end{aligned}$$

NR Limit for $c \rightarrow \infty$; include corrections for $v \ll c$

If $v \approx c$, expansion breaks down!

(Quantum effects \Rightarrow Theory of renormalization)

Example: Fermi theory of β decay



$$\frac{1}{M_W^2 - p^2} \longrightarrow \frac{1}{M_W^2} + O\left(\frac{p^2}{M_W^4}\right)$$

history

Leading term for $p^2 \rightarrow 0$; can include corrections

If $p^2 \approx M_W^2$, expansion breaks down!



In general, ~~do~~ have expansion in small momenta

$$\frac{p^\mu}{m} \quad (\text{cf. expansion in small couplings!})$$

EFT is only valid at energies/momenta $\ll M$.

2d

2.1 EFT parameterizes NP

At low energies "you don't see what's in the black square"

⇒ Just write everything that's possible!

Possible = Allowed by symmetries (e.g. Lorentz)

Problem: There are ∞ many such interactions ("operators")

Solution: At each order in $\frac{P}{M}$ expansion only finite #.

"power counting scheme"

3 Dark Matter Direct Detection

If DM interacts with SM beyond gravitation, could observe nuclear recoil in DM-SM scattering process.

3.1 Cross section and scattering rate

Writing the S-matrix as $S_{p\alpha} = \delta(p - \alpha) = (2\pi)^4 i M_{p\alpha} \delta(\vec{p}_p - \vec{p}_\alpha)$

and normalizing states as $(\psi_{\vec{p}'}, \psi_{\vec{p}}) = (2\pi)^3 \delta^3(\vec{p}' - \vec{p})$,

the diff. cross section is (NR limit)

$$\frac{d\sigma}{dE_R} = \frac{M_A}{2\pi v^2} \frac{1}{2j_A+1} \frac{1}{2j_X+1} \sum_{\text{spins}} |M_{p\alpha}|^2 \quad (3.1)$$

To obtain E_R -- nucl. recoil energy, M_A -- nucleus mass,

v -- DM velocity, j_A -- nuclear / DM spin.

To obtain rate, multiply with flux of incoming DM:

$$d\Phi = \frac{\rho_0}{m_X} \cdot \frac{1}{v_0^3 \pi^{3/2}} \exp\left(-\frac{\vec{v}^2}{v_0^2}\right) d^3 v \quad (3.2)$$

$$\rho_0 \approx 0.47 \frac{\text{GeV}}{\text{cm}^3}$$

~~local~~ local DM energy density, $v_0 \approx 240 \text{ km/s}$ mean DM velocity

Integrate over angles, obtain diff. Rate / kg/day (4)

$$\frac{dR}{dE_R} = \frac{g_0}{m_A m_X} \int_{v_{\min}}^{\infty} dv v f(v) \cdot \frac{d\sigma}{dE_R}(v, E_R) \quad (3.3)$$

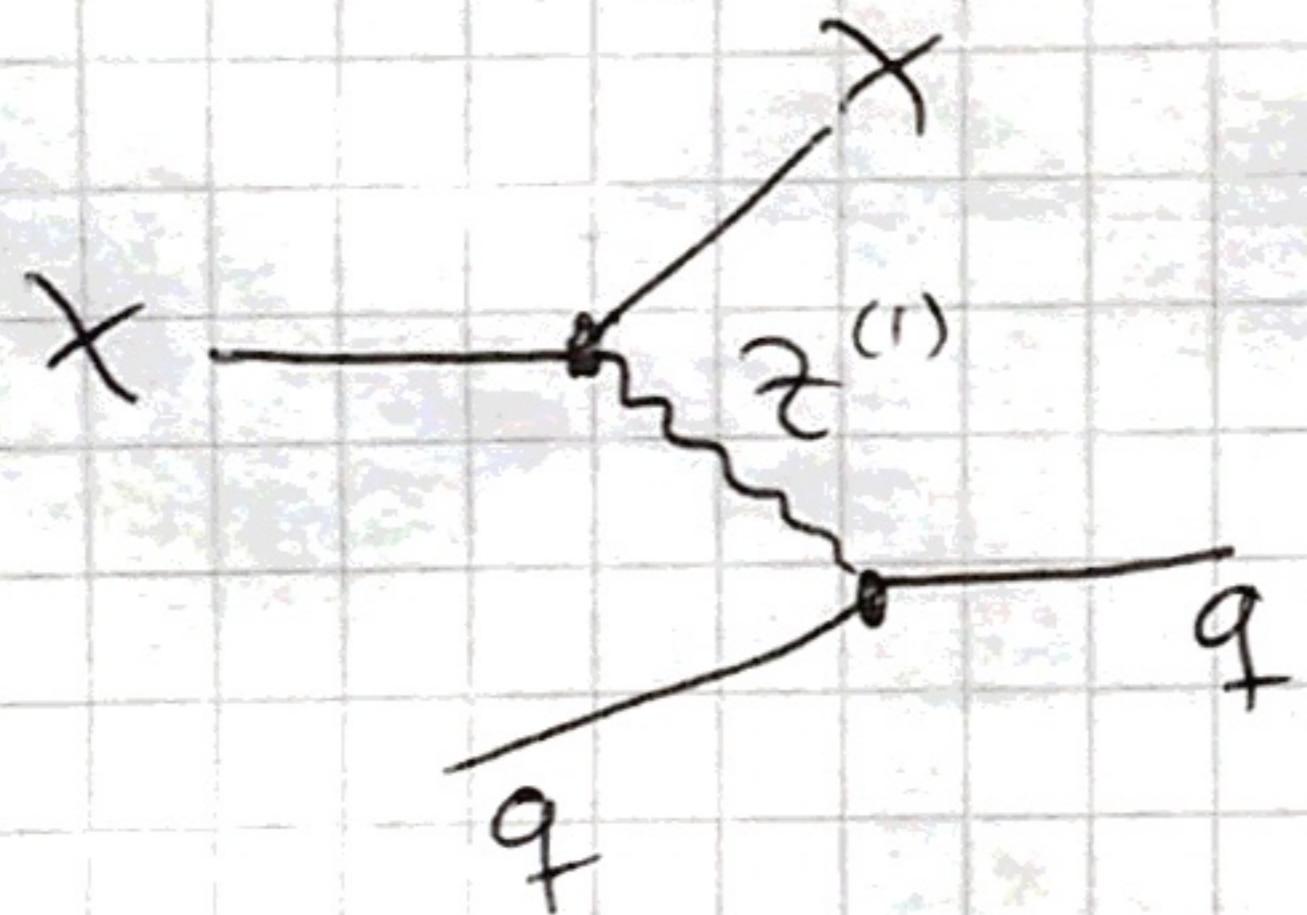
exp ↑
"astro" ↑
theo ↓

3.2 Microscopic cross sections

Assume DM is spin- $\frac{1}{2}$ WIMP (Dirac, Majorana)

How do we calculate the nuclear cross section?

Assume DM interacts with SM via heavy vector boson exchange (e.g. MSSM neutralino and Z exchange)



Effective Lagrangian (Lorentz invariant!)

$$\begin{aligned} \mathcal{L} = & e_{1q} (\bar{X} \gamma^\mu X) (\bar{q} \gamma^\mu q) + e_{2q} (\bar{X} \gamma^\mu \gamma_5 X) (\bar{q} \gamma^\mu q) \\ & + e_{3q} (\bar{X} \gamma_\mu X) (\bar{q} \gamma^\mu \gamma_5 q) + e_{4q} (\bar{X} \gamma_\mu \gamma_5 X) (\bar{q} \gamma^\mu q) \end{aligned} \quad (3.4)$$

e_{iq} fixed by Z ~~interaction~~ ^{couplings} and mass. For neutralino,
~~all $e_{iq} = 0$ apart from $e_{4q} \neq 0$. [~~ $e_{2q} \neq 0$ but tiny δ]

$$e_{1q} = e_{3q} = 0 .$$

3.3 Low-energy limit
Need $T M |^2$, ~~for propagator~~

4a

First step: Make DM \propto non-relativistic [... HQET, HDMET]

Write momentum $p = mv + k$, $k \ll mv$.

~~derivation of massless~~

Expand propagator for small k :

$$\frac{i(p+m)}{p^2 - m^2 + i\epsilon} = i \frac{mv + m + k}{m^2 + 2mv \cdot k + k^2 - m^2 + i\epsilon}$$

$$\Rightarrow i \underbrace{\frac{1+x}{2}}_{\text{P}_v} \cdot \frac{1}{v \cdot k} + \text{non } O\left(\frac{k^2}{m}\right)$$

P_v , projector $P_v \cdot P_v = P_v$

In rest frame: $v^\mu = (1, 0, 0, 0)$, ~~Dirac~~ rep. of γ^μ :

~~Dirac~~ $\gamma^0 = \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix}, \quad \vec{\gamma} = \begin{pmatrix} 0 & \vec{\sigma} \\ \vec{\sigma} & 0 \end{pmatrix}, \quad \gamma_5 = \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix}$

$$\chi(\vec{p}) = \begin{pmatrix} (1+\dots)\xi \\ (0+\dots)\eta \end{pmatrix}, \quad P_v = \begin{pmatrix} 1 & 0 \\ 0 & 0 \end{pmatrix}$$

P_v projects on particle spinor (no antiparticle).

$$\gamma^0 \vec{\gamma} \cdot \gamma_5 = \begin{pmatrix} \vec{\sigma} & 0 \\ 0 & -\vec{\sigma} \end{pmatrix} \Rightarrow \bar{\chi} \gamma_\mu \gamma_5 \chi = \xi^+ \vec{\sigma} \xi = 2 \xi^+ \vec{\sigma} \xi.$$

Axial-vector ~~int~~ currents lead to spin-dependent interactions.

Second step:

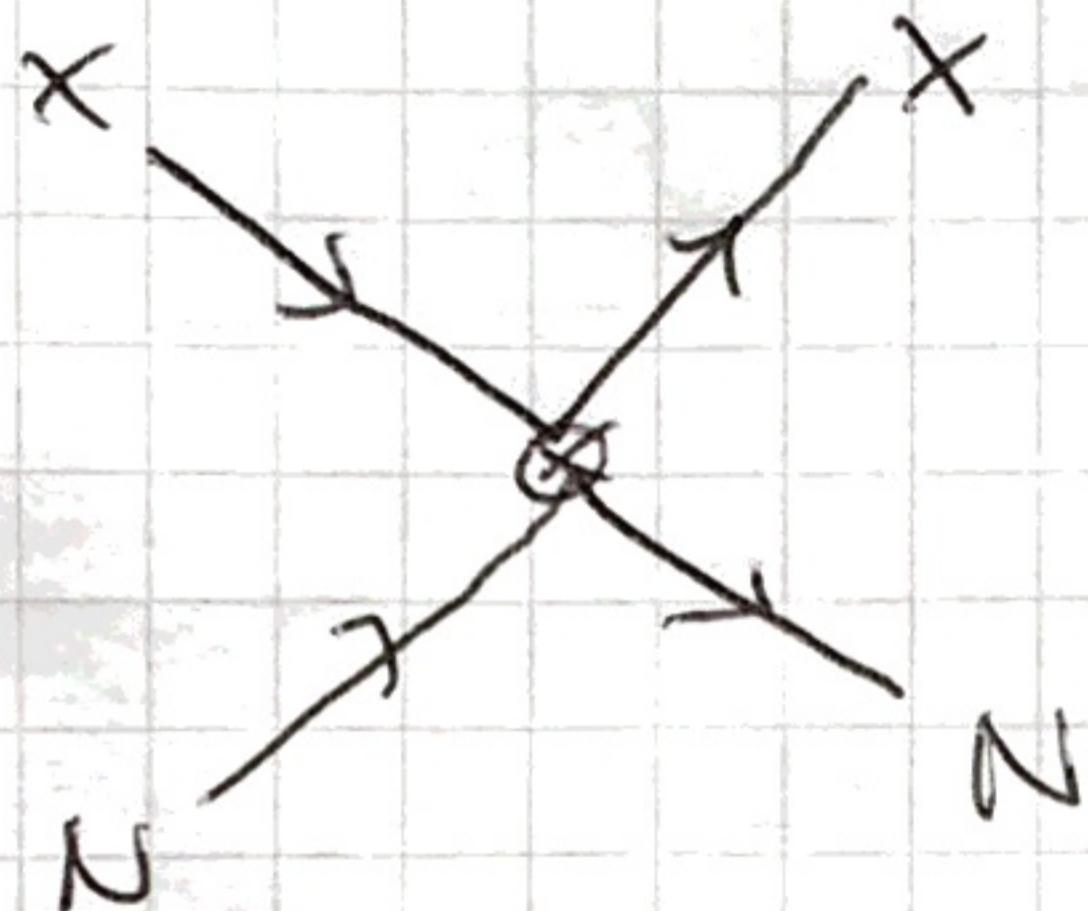
(4b)

Same for quark current... $\langle N | \bar{q} \gamma^\mu \gamma_5 q | N \rangle = ?$

Use lattice QCD. Obtain

$$\langle N | \bar{q} \vec{\gamma} \gamma_5 q | N \rangle = \vec{s}_N \cdot \Delta q_N .$$

In total, have contact interaction, leading in $\frac{P}{m}$



$$\sim \vec{s}_X \cdot \vec{s}_N \sim \left(\frac{P}{m} \right)^0$$

3.3 Low-energy limit Chiral EFT

(5)

At small energies, quarks and gluons are bound into hadrons (p, n, π, \dots) ... non-perturbative physics.

Cannot calculate — use symmetries and construct EFT!
Symmetries of QCD for $m_q \rightarrow 0$ ($q = u, d, s$): $m_q \ll \Lambda_{QCD}$

$$\begin{aligned} \mathcal{L} &= \bar{u} i\not{\partial} u + \bar{d} i\not{\partial} d + \bar{s} i\not{\partial} s \\ &= \sum_{q=u,d,s} (\bar{q}_L i\not{\partial} q_L + \bar{q}_R i\not{\partial} q_R) \not{\partial} \bar{Q}_L \\ &\equiv \bar{Q}_L i\not{\partial} Q_L + \bar{Q}_R i\not{\partial} Q_R \quad (3.5) \end{aligned}$$

$$Q = (u, d, s), \quad Q_L = \frac{1}{2}(1 + \gamma_5) Q.$$

(3.5) is invariant if we rotate $Q_L \rightarrow V_L Q_L$, $Q_R \rightarrow V_R Q_R$, $Q \rightarrow e^{i\alpha} Q$, $Q \rightarrow e^{i\alpha} \gamma_5 Q$; $\alpha \text{ -- const.}$

$V_L \in \text{SU}(3)_L$, $V_R \in \text{SU}(3)_R$. (Exercise!)

Symmetry group: $\text{SU}(3)_L \times \text{SU}(3)_R \times U(1) \times U(1)_A$

Is it realized in nature??

1. $U(1)$... baryon number conservation $j^\mu = \bar{Q} \gamma^\mu Q$
2. $V_L = V_R \in \text{SU}(3)_L \times \text{SU}(3)_R$... $\text{SU}(3)$ flavor \rightarrow isospin $\begin{matrix} u \leftrightarrow d \\ p \leftrightarrow n \end{matrix}$
3. $U(1)_A$ is anomalous
4. $V_L \neq V_R$: No parity doubling of hadron spectrum;
spontaneously broken
 \Rightarrow Pions as Goldstone bosons

Strategy: Construct EFT out of pion and nucleon fields, with exactly same symmetry structure.

The effective Lagrangian can be written in terms of Goldstone fields as follows: Define $\Pi \equiv \sum_a \pi^a \lambda^a$ Gell-Mann,

$$\Pi = \begin{pmatrix} \frac{\pi^0}{\sqrt{2}} + \frac{\eta^8}{\sqrt{6}} & \pi^+ & K^+ \\ \pi^- & -\frac{\pi^0}{\sqrt{2}} + \frac{\eta^8}{\sqrt{6}} & K^0 \\ K^- & \overline{K^0} & -\frac{2\eta^8}{\sqrt{6}} \end{pmatrix} \quad (3.6)$$

and

$$U = \exp \left[\frac{i\sqrt{2}}{f} \Pi \right] \quad (3.7)$$

\nwarrow pion decay const.

U transforms as $U \rightarrow V_R U V_L^\dagger$, and the Lagrangian is

$$\mathcal{L}_{\text{ChPT}} = \frac{f^2}{4} \text{Tr} (\partial_\mu U^\dagger \partial^\mu U) + \dots \quad (3.8)$$

Now we need to add DM! Trick: We rewrite (3.4) as

$$\mathcal{L} = \bar{Q} \gamma^\mu [v_\mu + \gamma_5 q_\mu] Q, \quad (3.9)$$

where

$$v_\mu = e_1 (\bar{x} \gamma_\mu x) + e_2 (\bar{x} \gamma_\mu \gamma_5 x), \quad (3.10)$$

$$q_\mu = e_3 (\bar{x} \gamma_\mu x) + e_4 (\bar{x} \gamma_\mu \gamma_5 x), \quad (3.11)$$

$$e_1 = (e_{1u}, e_{1d}, e_{1s}) \text{ etc.}$$

Spurion method: (3.9) is invariant under

$$Q = Q_L + Q_R \rightarrow V_L Q_L + V_R Q_R \quad \text{if (exercise!)}$$

$$v_\mu + q_\mu \rightarrow V_R (v_\mu + q_\mu) V_R^\dagger, \quad (3.12)$$

$$v_\mu - q_\mu \rightarrow V_L (v_\mu - q_\mu) V_L^\dagger. \quad (3.13)$$

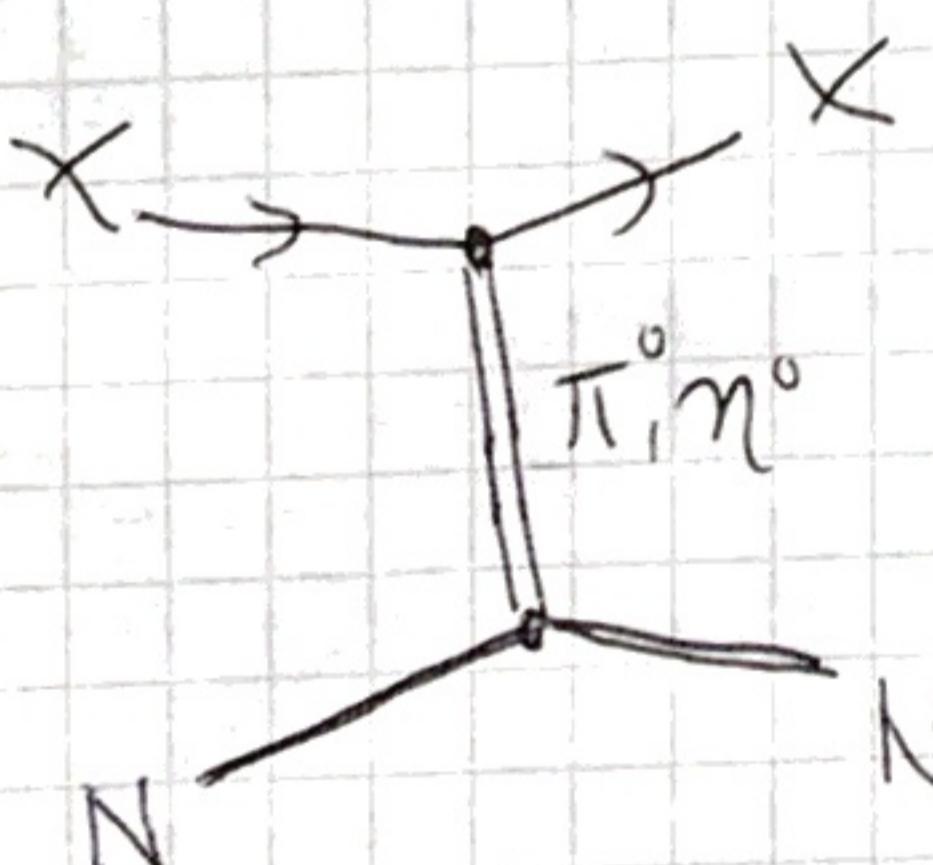
Including the corresponding terms in the chiral Lagrangian, we obtain

$$\mathcal{L}_{\text{ChPT}} = \frac{f^2}{4} \text{Tr} \left[\left(\partial_\mu U - i(v_\mu + q_\mu)U + iU(v_\mu - q_\mu) \right)^+ \times \left(\partial^\mu U - i(v_\mu + q_\mu)U + iU(v_\mu - q_\mu) \right) \right]. \quad (3.14)$$

Expanding the exponential in (3.7) and inserting into (3.14), we get

$$\mathcal{L}_{\text{ChPT}} = f (\bar{\chi} \gamma^\mu \gamma_5 \chi) \left[(e_{4d} - e_{4u}) \partial^\mu \pi^0 - (e_{4u} + e_{4d} - 2e_{4s}) \frac{\partial^\mu n}{\sqrt{3}} \right] + \dots \quad (3.15)$$

Effectively, we have generated a DM-pion coupling:



coupling to nucleus via meson exchange.

$$\sim \frac{P^2}{p^2} = (P)^0 - \text{also leading}$$

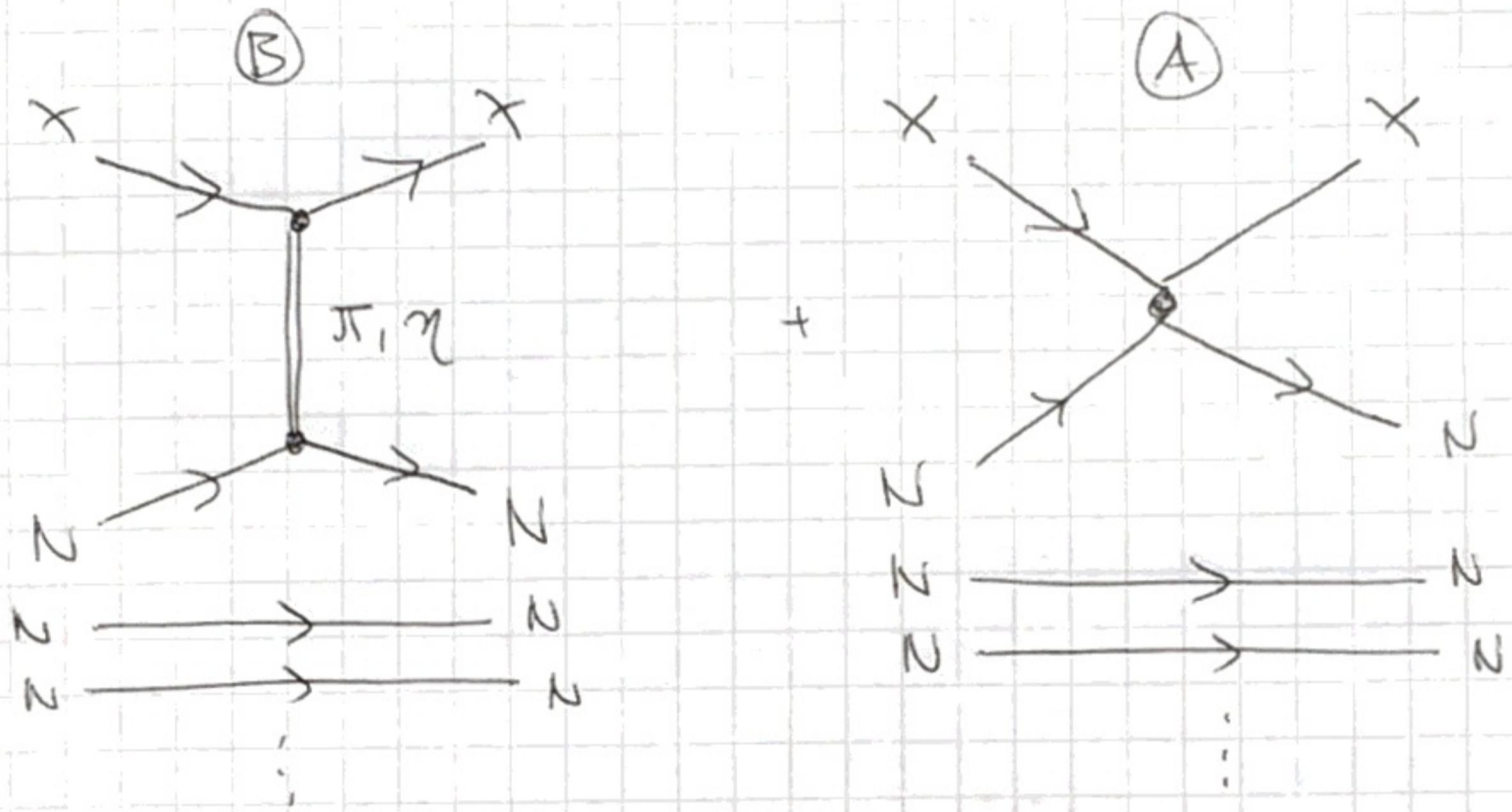
In addition, there is a direct "contact interaction" with the nucleus, obtained by inserting the quark current axial-vector current into a nucleon matrix element:

(8)

$$\langle N | \bar{q} \gamma^\mu q | N \rangle = s^\mu \Delta q_N . \quad (3.16)$$

Here, s^μ is the nucleon spin vector and Δq_N a non-perturbative constant that can be calculated using lattice QCD.

In total, have two contributions:



Can use a nuclear shell model to calculate the nuclear response, if DM hits a nucleus (complicated nuclear physics) [1203.3542]

- (A) is the standard "spin-spin" interaction of DM.
- (B) has been neglected up to now.

The interference between (A) and (B) can ~~basically~~ reduce the cross section.

E.g. for $\mathcal{L} = (\bar{q} \gamma_\mu q)(\bar{u} \gamma^\mu u) + (\bar{d} \gamma^\mu d)$

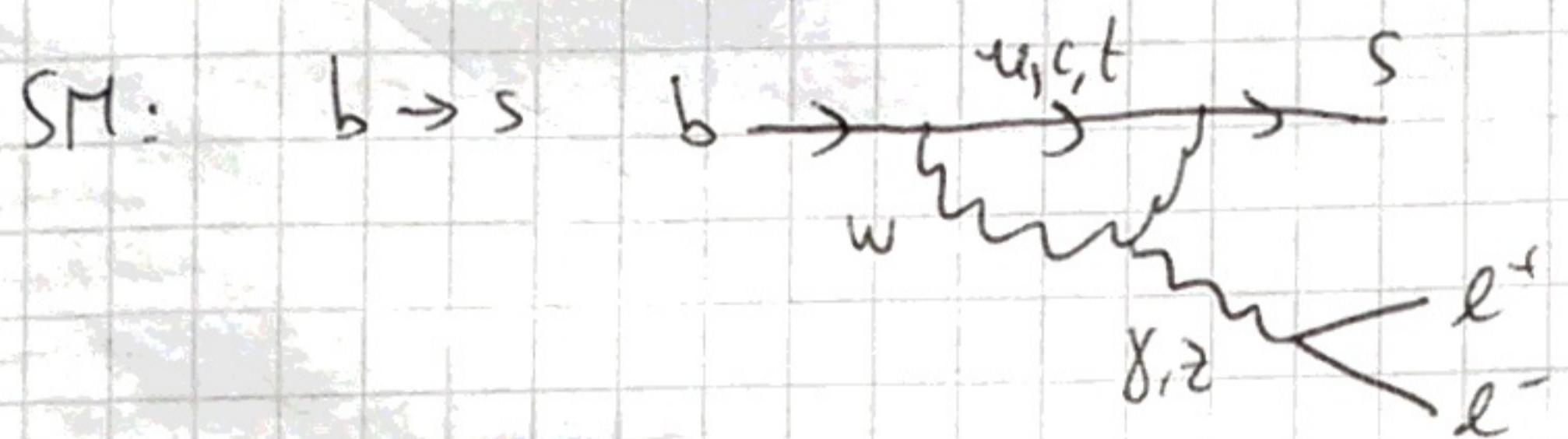
(9)

4 Anomalies in B physics

Precision tests of the SM. E.g. Lepton Flavor universality
Compare μ and e decay modes, for instance,

$$R_K \equiv \frac{\text{Br}(B^+ \rightarrow K^+ \mu^+ \mu^-)}{\text{Br}(B^+ \rightarrow K^+ e^+ e^-)} \stackrel{\text{exp.}}{=} 0.745^{+0.090}_{-0.074} \pm 0.036 \quad (4.1)$$

What is the theory prediction (SM / BSM) ?



For $\mu \approx M_B$, use EFT:

$$\mathcal{L}_{\text{eff}} = -\frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \frac{\alpha}{4\pi} \sum_i^6 C_i Q_i + \dots \sum_{i=1}^6 C_i Q_i + C_{7,g} + C_{8,g} \quad (4.2)$$

$$Q_9^\ell = (\bar{s}_L \gamma_\mu b_L) (\bar{\ell} \gamma^\mu \ell), \quad Q_{10}^\ell = (\bar{s}_L \gamma_\mu b_L) (\bar{\ell} \gamma^\mu \gamma_5 \ell)$$

$$Q_S^\ell = (\bar{s}_L b_R) (\bar{\ell} \ell), \quad Q_P^\ell = (\bar{s}_L b_R) (\bar{\ell} \gamma_5 \ell)$$

$$Q' = Q(L \leftrightarrow R)$$

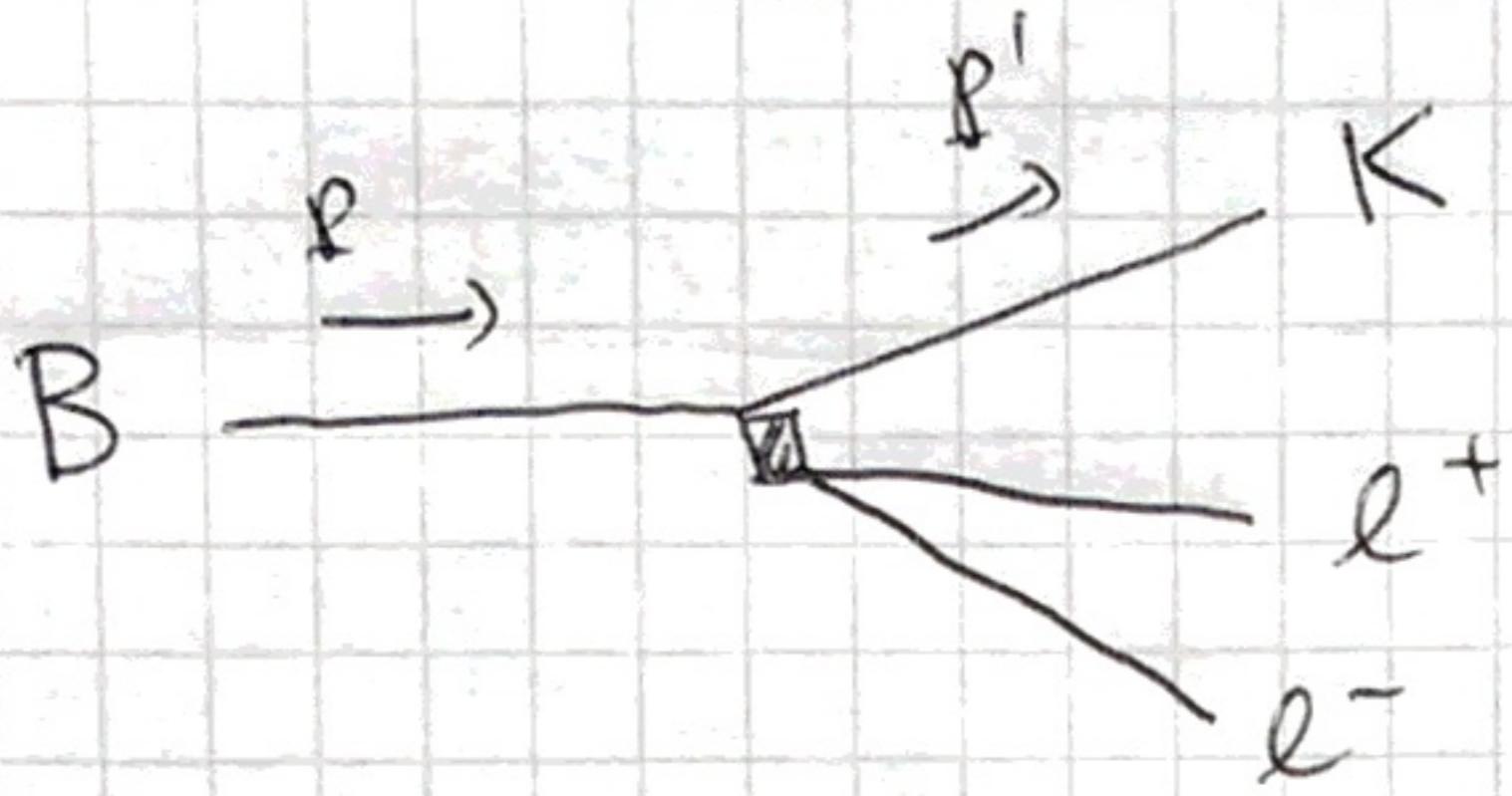
$$\text{SM: } C_9^{\text{SM}} = -C_{10}^{\text{SM}} = 4.2 \quad (\ell = e, \mu)$$

$$\frac{d\Gamma(B \rightarrow K \ell \ell)}{dq^2 d\cos\theta} \propto |\langle K \ell \ell | \mathcal{L}_{\text{eff}} | B \rangle|^2$$

= complicated function ($q^2, \cos\theta, M_B, M_K, m_\ell$)

involving non-perturbative QCD

Again, EFT helps! Decay kinematics:



$$q = p' - p$$

momentum transfer

small (large recoil of $(\bar{l}l)$, K fast)

If q^2 is large, outgoing K behaves like color singlet ("color transparency"). Form factors simplify

(technically expand in $\frac{1}{m_b}$, $\frac{1}{E}$) - universal f.f. $\xi(q^2)$.

$$R_K^{SM} = \frac{\Gamma_{e\mu}^{SM}}{\Gamma_e} \frac{\Gamma_\mu^{SM}}{\Gamma_e^{SM}}$$

$$q^2_{\text{max}} \sim 6 \text{ GeV}^2$$

$$\Gamma_e^{SM} \underset{q^2 \rightarrow 0}{\propto} \int dq^2 \xi(q^2) (|F_L|^2 + |F_V|^2) \times \left[1 + O\left(\frac{m_c^4}{q^4}\right) + \frac{M_e^2}{M_B^2} O\left(\alpha_S \frac{q^2}{M_B^2} \sqrt{\frac{\Lambda_{QCD}}{E}}\right) \right]$$

$$\Rightarrow R_K^{SM} = 1 \quad (+ \% + \text{cut-dep. QED } 0.0\%) \quad O(\text{few \%}) \quad (4.3)$$

compatible only

(4.1) and (4.3) not consistent at 2.6 σ

If the effect stays confirmed, need BSM physics!

In principle easy - lots of operators in (4.2)

Challenge - ~~keep all~~ consistency with other observables

In the following, let's focus on ~~scalar~~ ^{(axial-)vector} operators [1408.1627]

$\left(\begin{array}{c} \text{Tree-level scalar ruled out by } Br(\bar{B} \rightarrow \bar{K} ee) \\ \text{---} \text{---} \text{---} \text{---} \text{---} \\ \text{---} \text{---} \text{---} \text{---} \text{---} \end{array} \right)$

$$Br(\bar{B} \rightarrow X_5 ee), Br(\bar{B} \rightarrow \bar{K} ee)$$

(11)

Mass scale constraints

$$\frac{Br(\bar{B}_s \rightarrow l\bar{l})}{Br(\bar{B}_s \rightarrow l\bar{l})^{SM}} = |1 - \gamma_e (C_p^l - C_p^{l'})|^2 + |1 - \gamma_e (C_s^l - C_s^{l'})|^2$$

$$\frac{d\Gamma^e}{d\cos\theta} = \dots$$

We need $0.7 \lesssim \text{Re}[x^e - x^\mu] \lesssim 1.5$,

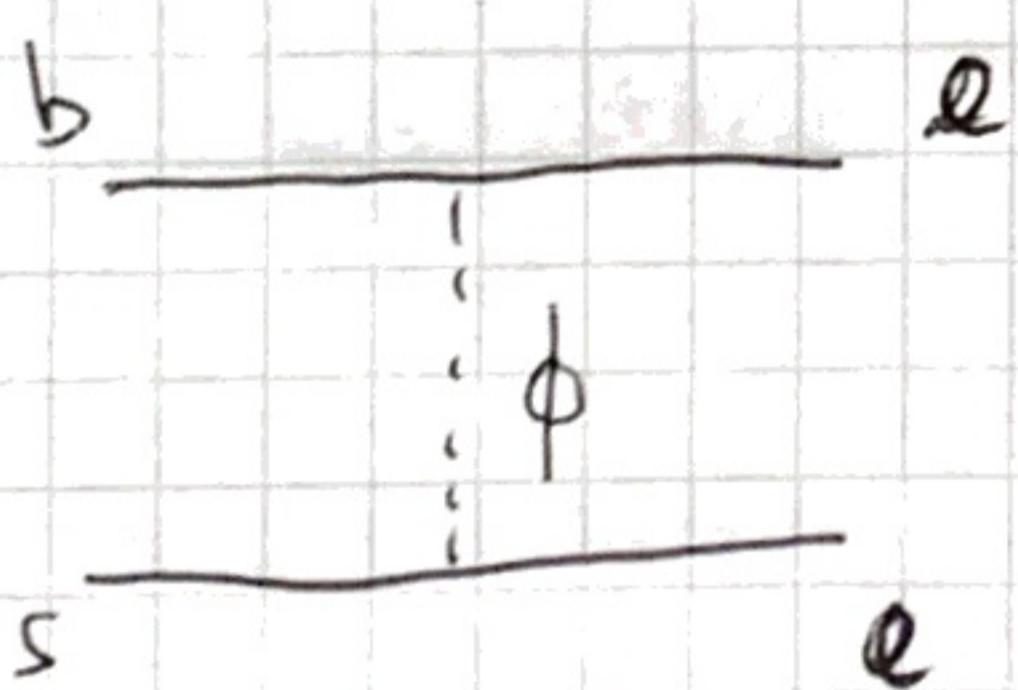
$$x^e = C_q^l + C_q^{l'} - (C_{10}^l + C_{10}^{l'}) \quad (\text{everything NP})$$

$C_{10}^{l\mu}$ is constrained (mainly from $B_s \rightarrow \mu\mu$)

Fits show $C_q^\mu \approx -C_q^{l\mu}$.

E.g. scalar leptoquark $\phi \sim (3, 2, \frac{1}{6})$ with

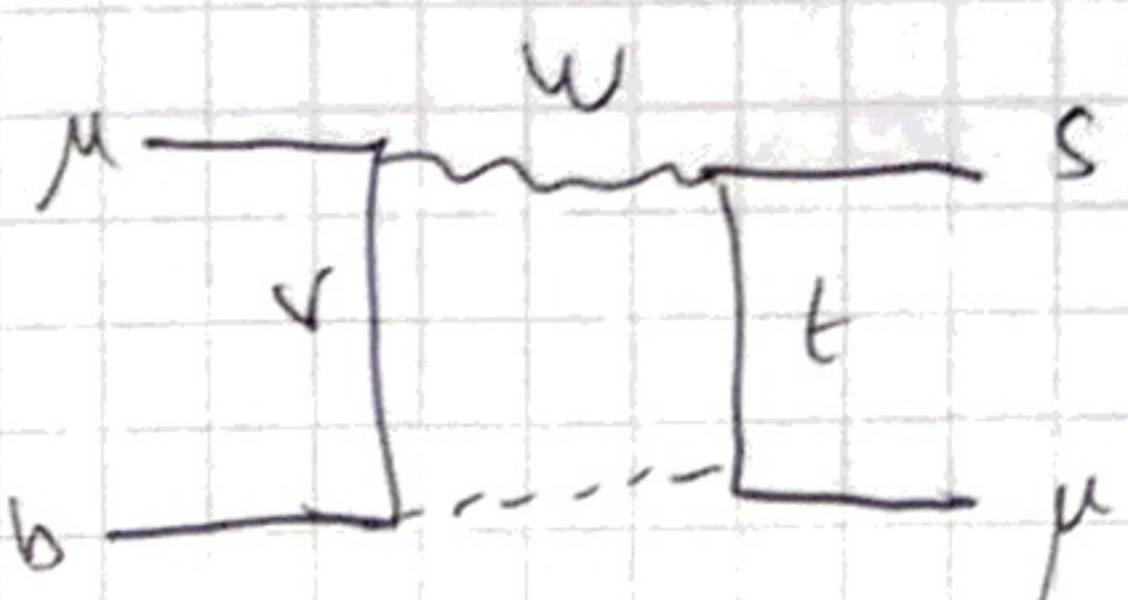
$$\mathcal{L} = -\lambda_{de} \phi (\bar{d}_R \not{L}) + \text{h.c.}, \quad d \dots b,s; \quad l \dots e,\mu$$



$$\text{gives } \mathcal{H}_{\text{eff}} = \frac{\lambda_{se}\lambda_{be}^*}{2M^2} (\bar{s}_R \gamma^\mu b_R)(\bar{\ell}_L \gamma_\mu \ell_L) + \text{h.c.}$$

$$\text{Can fit data with } \frac{M^2}{|\lambda_{se}\lambda_{be}^*|} \sim (24 \text{ TeV})^2$$

[1511.01900] scalar leptoquark $(3, 1, -\frac{1}{3})$, $M_\phi \sim 1 \text{ TeV}$



... explain R_K , $R_D^{(*)}$, $(g-2)_\mu$

Study several ratios (R_K, \dots) to test chirality