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Searching for New Physics in rare decays of meson $D^0 \to$ "invisible"

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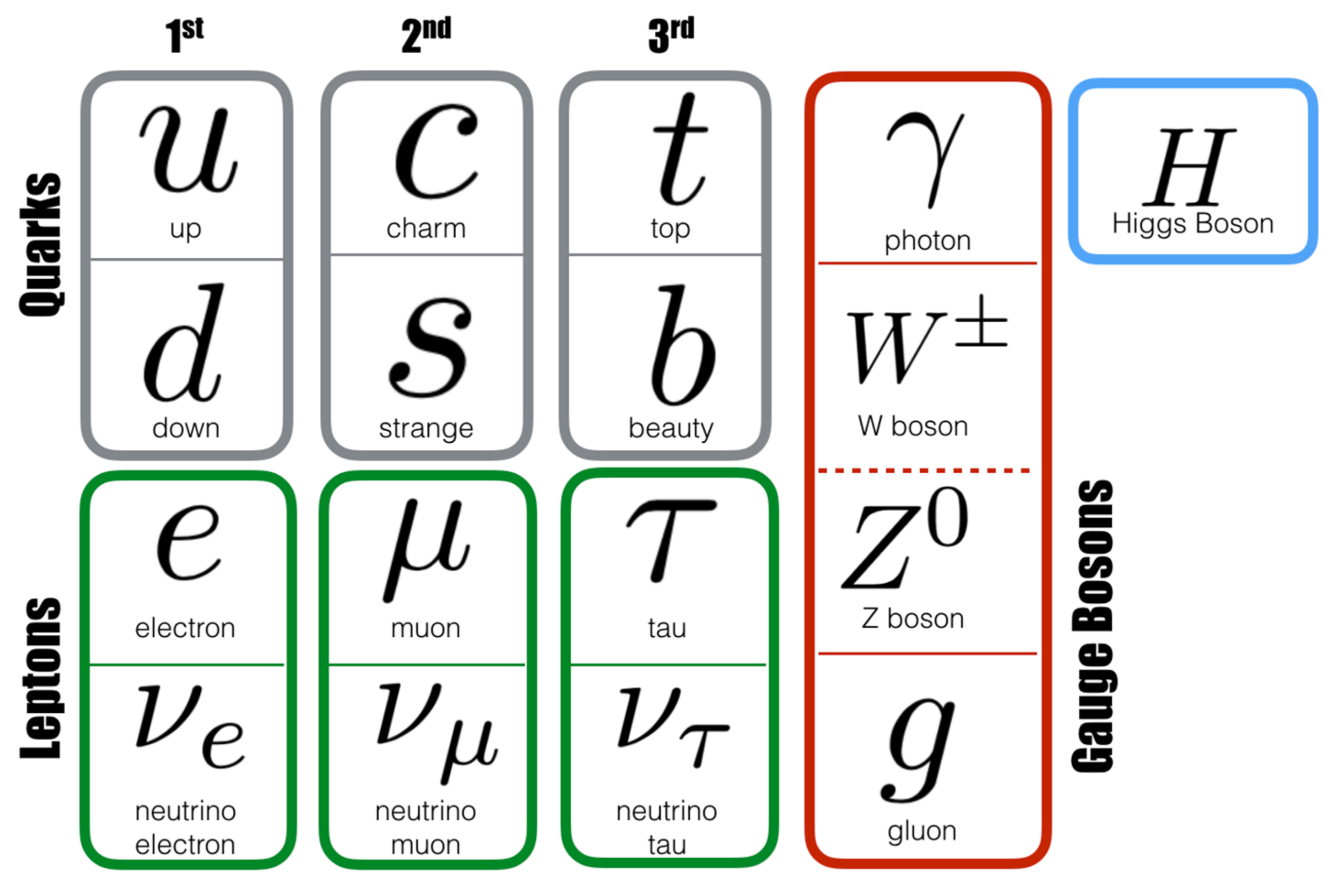
Standard Model (SM)

- Gauge group $SU(3)_C \times SU(2)_L \times U(1)_Y$
- 12 elementary particles (fermions) interacting with strong, weak and electromagnetic interaction through exchange of gauge bosons



Particles of SM. [1]

- Yukawa interaction (Higgs with fermions): mass terms of fermions
- Quarks are bound in hadrons: mesons ($q\bar{q}$) and baryons (qqq)

Physics beyond SM

- Observational facts SM fails to explain: massive neutrinos, baryon asymmetry of the Universe, dark matter candidate

- Searching for the presence of New Physics (NP):

  - Direct production of new particles in colliders

  - Indirect searching in the decays of SM particles and analysing deviations between SM prediction and experimental data

- From experimental date the constraints on NP models are obtained

Useful relations

- Differential decay rate for decay of initial state i to final states f:

$$d\Gamma = \frac{1}{2m_i}\left(\prod_f \frac{d^3p_f}{(2\pi)^3}\frac{1}{2E_f}\right)|\mathscr{M}(i\to f)|^2(2\pi)^4\delta^{(4)}(p_i - \sum p_f)$$

- The amplitude $\mathscr{M}(i\to f)$ is obtained from S-matrix:

$$\langle f|i\rangle = \lim_{T\to\infty}\left\langle f|e^{-iH(2T)}|i\right\rangle = \langle f|S|i\rangle = \langle f|i\rangle + (2\pi)^4\delta^{(4)}(p_i - \sum p_f)i\mathscr{M}(i\to f)$$

- Amplitude with Feynman rules:

$i\mathscr{M} =$ sum of all connected, amputated diagrams

- Branching fraction:

$$\mathscr{B} \equiv \frac{\Gamma_i}{\Gamma} \qquad \Gamma = \sum_i \Gamma_i = \frac{1}{\tau}$$

τ : lifetime of the decaying particle

Effective theory approach

- Enables separation of the effects coming from different scales in weak mesonic decays.

- Effective Lagrangian:

$$\mathscr{L}_{\textbf{eff}} = \sum_i \mathscr{C}_i(\mu)\mathscr{O}_i(\mu)$$

Wilson coefficients encode short distance interactions

fermion operators containing only contributions from light fields propagating over large distances

- Amplitude for transition between initial and final states:

$$\mathscr{M}(i \to f) \sim \sum_i \mathscr{C}_i(\mu)\langle f \,|\, \mathscr{O}_i \,|\, i\rangle(\mu)$$

- NP contributions could lead to shifts in the value of $\mathscr{C}_i$ or by adding non-standard operators to $\mathscr{L}_{\text{eff}}$.

Leptoquarks (LQ)

- LQ are hypothetical particles (scalar or vector) that can turn quarks into leptons and vice versa.

- LQ are defined by the SM gauge group transformational properties $(SU(3),\ SU(2),\ U(1))$, where the hyper charge is defined as $Y = Q - T^3$.

$S=0:\ R_2\quad \tilde{R}_2\quad S_1\quad \bar{S}_1\quad \tilde{S}_1\quad S_3$ $\qquad S=1:\ U_1\quad \tilde{U}_1\quad \bar{U}_1\quad U_3\quad \tilde{V}_2\quad V_2$

- Fermionic multiplets:

$e_R \equiv (\mathbf{1},\mathbf{1},-1)$

$Q_L \equiv (\mathbf{3},\mathbf{2},1/6) = (u_L\ d_L)^T$

$u_R \equiv (\mathbf{3},\mathbf{1},2/3)$

$L_L \equiv (\mathbf{1},\mathbf{2},-1/2) = (\nu_L\ e_L)^T$

$d_R \equiv (\mathbf{3},\mathbf{1},-1/3)$

$+\quad \nu_R \equiv (\mathbf{1},\mathbf{1},0)$

- $\bar{S}_1 = (\bar{\mathbf{3}},\mathbf{1},-2/3)$ can also interact with ν_R :

$$\mathscr{L}_{\textbf{int}} = \bar{y}_{1ij}^{\overline{RR}}\bar{u}_R^{Ci}\bar{S}_1\nu_R^j + \bar{z}_{1ij}^{\overline{RR}}\bar{d}_R^{Ci}\bar{S}_1^* d_R^j + \textbf{h.c.}$$

$\psi^C = C\bar{\psi}^T$

$\bar{\psi}^C = -\psi^T C^{-1}$

$C = i\gamma^2\gamma^0$

$D^0 \to$ "invisible"

- "invisible" = weakly interacting particles: left-handed neutrinos (SM), right-handed neutrinos, dark matter particles

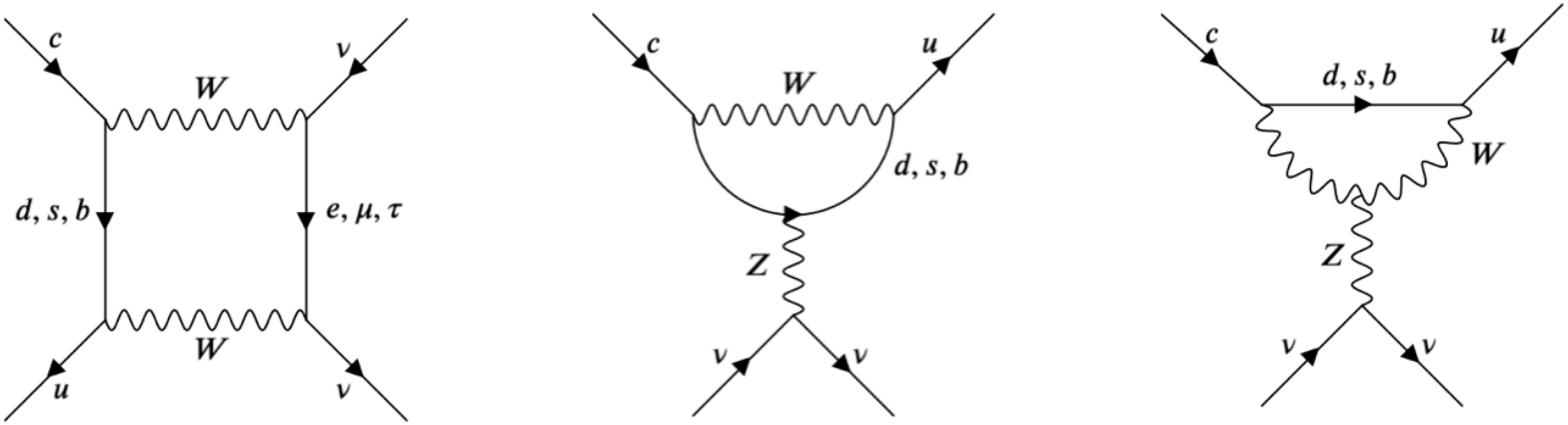
- Flavour Changing Neutral Current (FCNC): quark decays to another quark of the same electric charge, highly suppressed in the SM: loop level, Glashow-Iliopoulis-Maiani (GIM) mechanism

- The experimental upper bound on the branching fraction:

  $\mathscr{B}(D^0 \to \textbf{“invisible”}) < 9.4 \times 10^{-5}$

$D^0 \to$ "invisible": SM

- Feynman diagrams for $D^0 \to \bar{\nu}\nu$ in SM



- Effective Hamiltonian:

$$\mathscr{H}_{\textbf{eff}} = \frac{4G_F}{\sqrt{2}} \frac{\alpha}{2\pi \sin^2\theta_W} \sum_{l=e,\mu,\tau} \sum_k \lambda_k X^l(x_k)(\bar{u}_L\gamma^\mu c_L)(\bar{\nu}^l_L \gamma_\mu \nu^l_L)$$

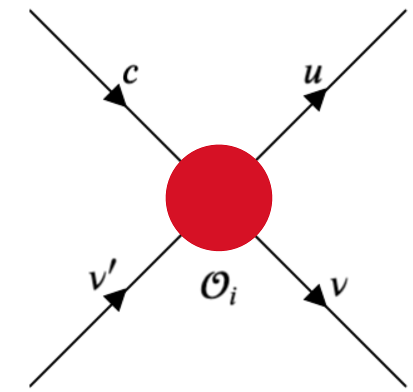
- Branching fraction ($m_{\nu_i} \leq 0.62$ eV)

$$\mathscr{B}^{SM}(D^0 \to \bar{\nu}\nu) = 1.1 \times 10^{-30}$$

$D^0 \to$ "invisible": NP

- Effective Lagrangian for $\bar{u}c \to \bar{\nu}\nu'$ transition

$$\mathscr{L}_{eff} = \sqrt{2}G_F\Big[c^{LL}(\bar{u}_L\gamma_\mu c_L)(\bar{\nu}_L\gamma^\mu\nu'_L) + c^{RR}(\bar{u}_R\gamma_\mu c_R)(\bar{\nu}_R\gamma^\mu\nu'_R)$$
$$+c^{LR}(\bar{u}_L\gamma_\mu c_L)(\bar{\nu}_R\gamma^\mu\nu'_R) + c^{RL}(\bar{u}_R\gamma_\mu c_R)(\bar{\nu}_L\gamma^\mu\nu'_L)$$
$$+g^{LL}(\bar{u}_L c_R)(\bar{\nu}_L\nu'_R) + g^{RR}(\bar{u}_R c_L)(\bar{\nu}_R\nu'_L)$$
$$+g^{LR}(\bar{u}_L c_R)(\bar{\nu}_R\nu'_L) + g^{RL}(\bar{u}_R c_L)(\bar{\nu}_L\nu'_R)$$
$$+h^{LL}(\bar{u}_L\sigma^{\mu\nu}c_R)(\bar{\nu}_L\sigma_{\mu\nu}\nu'_R) + h^{RR}(\bar{u}_R\sigma^{\mu\nu}c_L)(\bar{\nu}_R\sigma_{\mu\nu}\nu'_L)\Big] + \textbf{h. c.}$$



$\bar{u}c \to \bar{\nu}\nu'$ in effective theory

- Amplitude: $\mathscr{M} = \sqrt{2}G_F c^{RR}\langle \nu(p_1)\bar{\nu}(p_2)\,|\,(\bar{u}_R\gamma_\mu c_R)(\bar{\nu}_R\gamma^\mu\nu_R)\,|\,D^0(P)\rangle$

- Two body decay: $d\Gamma = \dfrac{1}{32\pi^2}|\mathscr{M}|^2\dfrac{\mathbf{p_1}}{M_D^2}d\Omega$

- Branching fraction:

$$\mathscr{B}(D^0 \to \bar{\nu}_R\nu_R) = \frac{1}{\Gamma_D}\frac{G_F^2 f_D^2 M_D}{16\pi}|c^{RR}|^2 m^2\sqrt{(1-\frac{4m^2}{M_D^2})}$$

$$|c^{RR}| < 0.0452$$

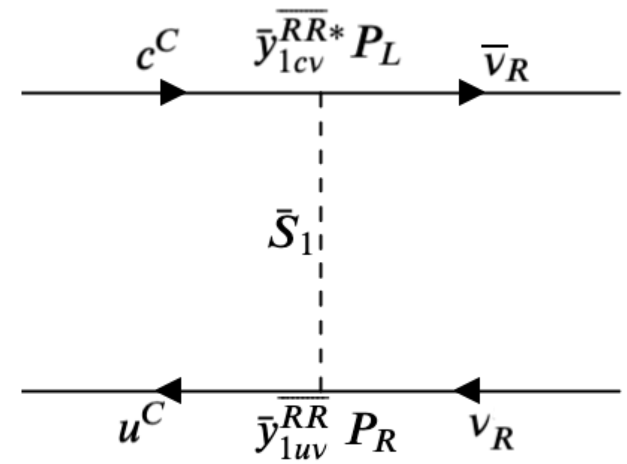
$D^0 \to$ "invisible": LQ $\bar{S}_1$

- Relevant terms of Lagrangian:

$$\mathscr{L}_{int} \supset \bar{y}^{\overline{RR}}_{1u\nu} \bar{u}^C_R \bar{S}_1 \nu_R + (\bar{y}^{\overline{RR}}_{1c\nu})^* \bar{\nu}_R \bar{S}^*_1 c^C_R$$

- Amplitude for this process:

$$i\mathscr{M} = \bar{u}^C \bar{y}^{\overline{RR}}_{1u\nu} P_R \nu_R \frac{i}{q^2 - m^2_{\bar{S}_1}} \bar{\nu}_R \bar{y}^{\overline{RR}*}_{1c\nu} P_L c^C$$



Feynman diagram from $\mathscr{L}_{int}$

- After Fierz relation, charge conjugation and $q^2 \ll m^2_{\bar{S}_1}$

$$i\mathscr{M} \simeq i\frac{1}{2} \bar{y}^{\overline{RR}}_{1u\nu} \bar{y}^{\overline{RR}*}_{1c\nu} \frac{1}{m^2_{\bar{S}_1}} (\bar{c}_R \gamma_\mu u_R)(\bar{\nu}_R \gamma^\mu \nu_R)$$

$$\frac{1}{2} \bar{y}^{\overline{RR}}_{1u\nu} \bar{y}^{\overline{RR}*}_{1c\nu} \frac{1}{m^2_{\bar{S}_1}} = \sqrt{2} G_F c^{RR}$$

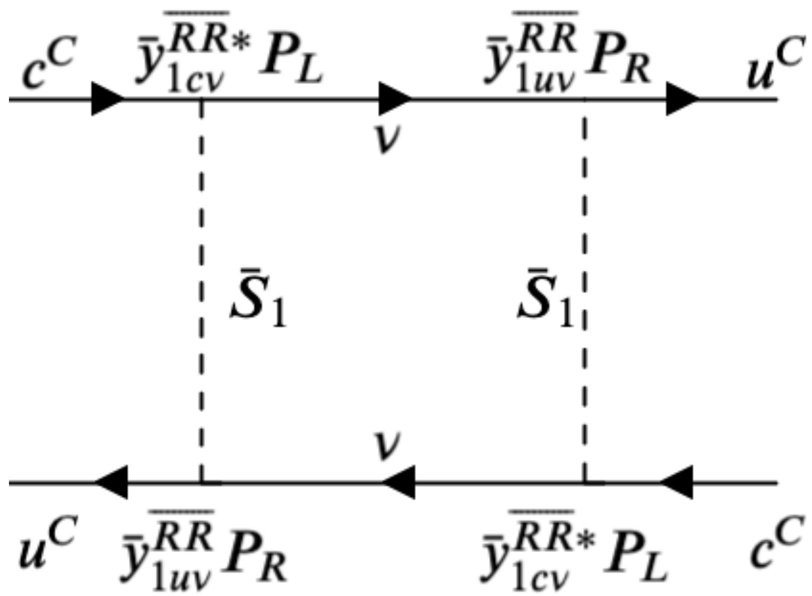
$$\longrightarrow \quad c^{RR} = \frac{v^2}{2m^2_{\bar{S}_1}} \bar{y}^{\overline{RR}}_{1c\nu} \bar{y}^{\overline{RR}*}_{1u\nu}$$

- $m_{\bar{S}_1} = 1.5$ TeV, $c^{RR} = 0.0452$

$$\boxed{\bar{y}^{\overline{RR}}_{1c\nu} \bar{y}^{\overline{RR}*}_{1u\nu} < 3.361}$$

$D^0 - \bar{D}^0$ mixing

- Amplitude:



$$i\mathcal{M} = \int \frac{d^4q}{(2\pi)^4} \bar{u}^C \bar{y}_{1u\nu}^{\overline{RR}} P_R \frac{i(\gamma^\mu q_\mu + m)}{q^2 - m^2} \bar{y}_{1c\nu}^{\overline{RR}*} P_L c^C \times$$

$$\times \bar{u}^C \bar{y}_{1u\nu}^{\overline{RR}} P_R \frac{i(\gamma^\mu q_\mu + m)}{q^2 - m^2} \bar{y}_{1c\nu}^{\overline{RR}*} P_L c^C \left(\frac{i}{q^2 - m_{\bar{S}_1}^2} \right)^2$$

$$i\mathcal{M} = i \frac{-\left(\bar{y}_{1u\nu}^{\overline{RR}}\right)^2 \left(\bar{y}_{1c\nu}^{\overline{RR}*}\right)^2}{64\pi^2 m_{\bar{S}_1}^2} \bar{c}\gamma^\mu P_R u \bar{c}\gamma_\mu P_R u$$

$$\frac{-\left(\bar{y}_{1u\nu}^{\overline{RR}}\right)^2 \left(\bar{y}_{1c\nu}^{\overline{RR}*}\right)^2}{64\pi^2 m_{\bar{S}_1}^2} = \mathcal{C}_6$$

This form appears in Hamiltonian for $D^0 - \bar{D}^0$ mixing

$$\mathcal{C}_6 (\bar{u}_R \gamma^\mu c_R)(\bar{u}_R \gamma_\mu c_R)$$

- $m_{\bar{S}_1} = 1.5$ TeV, $|\mathcal{C}_6| < 2.5 \times 10^{-13}$ GeV^{-2}

$$\boxed{\bar{y}_{1u\nu}^{\overline{RR}} \bar{y}_{1c\nu}^{\overline{RR}*} < 0.0188}$$

$D^0 \to \pi^0 \bar{\nu}\nu$: SM

- Effective Hamiltonian

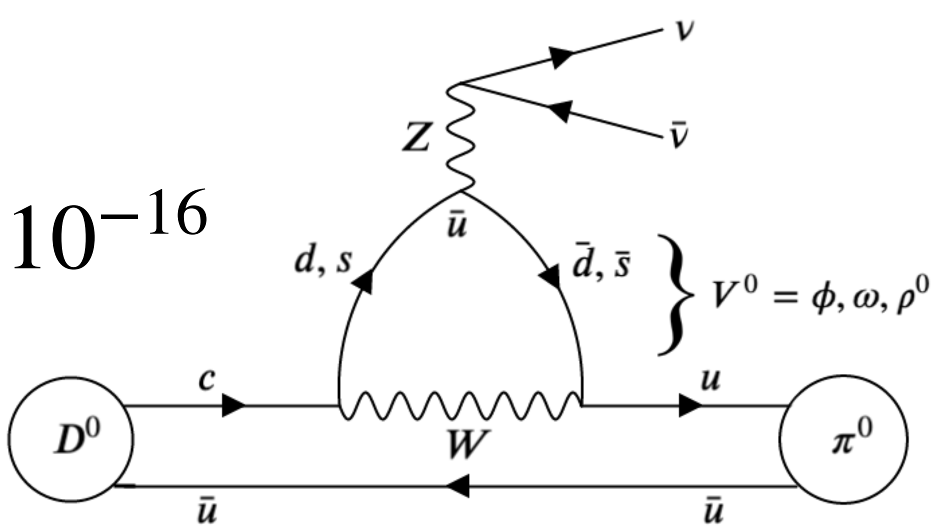
$$\mathscr{H}_{\text{eff}} \simeq \frac{G_F}{\sqrt{2}} \frac{\alpha}{2\pi \sin^2 \theta_W} V_{cs}^* V_{us} X^\tau(x_s)(\bar{u}_L \gamma_\mu c_L)(\bar{\nu}_L^l \gamma^\mu \nu_L^l)$$

- Branching fraction for $D^0 \to \pi^0 \bar{\nu}_L \nu_L$

$$\mathscr{B}^{SM}(D^0 \to \pi^0 \bar{\nu}_L \nu_L) \simeq 5.0 \times 10^{-16}$$

- Long distance contributions

$$\mathscr{B}^{SM}(D^0 \to \pi^0(\rho^0 \to \bar{\nu}_L \nu_L)) \simeq 2.55 \times 10^{-16}$$



Long distance contribution to $D^0 \to \pi^0 \bar{\nu}\nu$

$D^0 \to \pi^0 \bar{\nu}\nu$: NP

- Amplitude for this process with $\sqrt{2} G_F c^{RR} (\bar{u}_R \gamma_\mu c_R)(\bar{\nu}_R \gamma^\mu \nu_R)$

$$\mathscr{M} = \sqrt{2} G_F c^{RR} \bar{u}(p_1) \gamma^\mu P_R v(p_2) \langle \pi^0(k) | \bar{u} \gamma_\mu P_R c | D^0(p) \rangle$$

- Form factors are used to parametrise hadron matrix elements

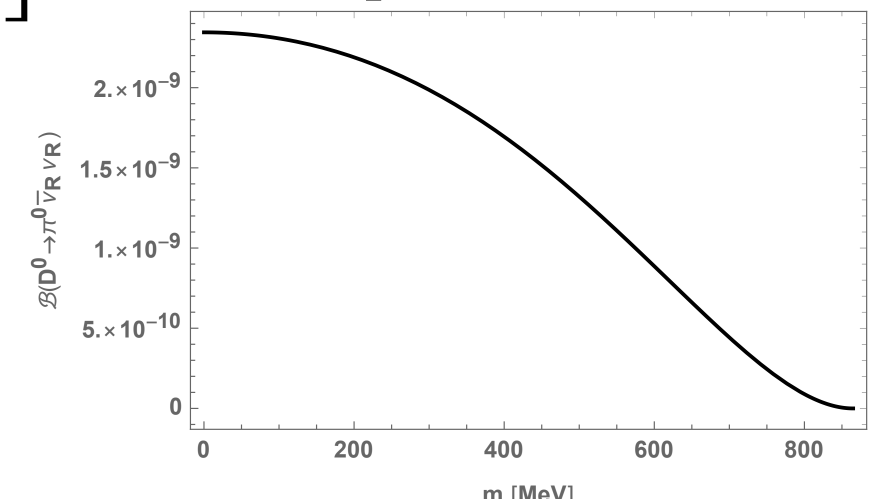
$$\langle \pi(k) | \bar{u} \gamma^\mu (1 \pm \gamma_5) c | D(p) \rangle = f_+(q^2) \left[(p+k)^\mu - \frac{M_D^2 - M_\pi^2}{q^2} q^\mu \right] + f_0(q^2) \frac{M_D^2 - M_\pi^2}{q^2} q^\mu$$

- Branching fraction

$$q = p - k = p_1 + p_2$$

$$\frac{d\mathscr{B}(D^0 \to \pi^0 \bar{\nu}_R \nu_R)}{dq^2} = \frac{1}{\Gamma_D} N \lambda^{1/2} \beta [2a(q^2) + \frac{2}{3} c(q^2)]$$

$$|c^{RR}| < 2.53 \times 10^{-4}$$



$\mathscr{B}(D^0 \to \pi^0 \bar{\nu}_R \nu_R)$ as a function of mass of right-handed neutrinos.

$$\mathscr{B}^{NP}(D^0 \to \pi^0 \bar{\nu}_R \nu_R) > \mathscr{B}^{SM}(D^0 \to \pi^0 \bar{\nu}_L \nu_L)$$

Conclusion

- Effects of NP can be investigated in rare mesonic decays $D^0 \to$ "invisible".
- NP contributions can be analysed using effective theory approach or in specific models (containing LQ).
- NP couplings are constrained with experimental data:

	$D^0 \to \bar{\nu}_R \nu_R$	$D^0 - \bar{D}^0$
$\bar{y}^{\overline{RR}}_{1u\nu} \bar{y}^{\overline{RR}*}_{1c\nu}$	3.361	0.0188
$\lvert c^{RR} \rvert$	0.0452	2.53×10^{-4}

- Prediction: $\mathscr{B}^{NP}(D^0 \to \pi^0 \bar{\nu}_R \nu_R) > \mathscr{B}^{SM}(D^0 \to \pi^0 \bar{\nu}_L \nu_L)$
- With more future data, models describing NP will be additionally constrained, providing better understanding of physics beyond the SM.

Thank you for your attention!

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