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Flavor gauge models below the Fermi scale

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Flavor Physics

Can there be flavor mediators at a low scale???

Flavor physics is definitely heavy

With minimal flavor violation: above TeV scale

Without minimal flavor violation: above 1000 TeV scale

see e.g. D'Ambrosio, Giudice, Isidori, Strumia 2002

Is it?

(

Studies for (B+)L_μ-L_τ at low energies

Heeck Rodejohann 2011, Altmannshofer et al 2014, Altmannshofer et al 2015, Farzan 2015, Farzan Shoemaker 2015, Heeck 2016, Altmannshofer et al 2016, Forero Huang 2016, …

Motivation:

$(g\text{-}2)_\mu$, proton radius, large neutrino matter effects (NSI), h to τ μ

Non **S**tandard **I**nteractions:

$$2\sqrt{2}G_F\varepsilon^f_{\alpha\alpha}\left(\bar{\nu}_{\alpha L}\gamma_\mu\nu_{\alpha L}\right)\left(\bar{f}\gamma^\mu f\right)$$

No SU(2) invariance

Usual lore: restoring SU(2) mostly rule out NSIs observable at neutrino experiments

Studies for (B+)L_μ-L_τ at low energies

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Motivation:
$(g\text{-}2)_\mu$, proton radius, large neutrino matter effects (NSI), h to τ μ

Non **S**tandard **I**nteractions:

$$(\bar{L}\gamma_\mu L)(\bar{Q}_L\gamma^\mu Q_L) = (\bar{\nu}_L\gamma_\mu\nu_L)(\bar{Q}_L\gamma^\mu Q_L) + (\bar{\ell}_L\gamma_\mu\ell_L)(\bar{Q}_L\gamma^\mu Q_L)$$

Charged leptons will generically provide a much stronger bound

#	Dim. eight operator	$\mathcal{C}^{111}_{LLH}$	$\mathcal{C}^{331}_{LLH}$	$\mathcal{C}^{133}_{LLH}$	$\mathcal{C}^{313}_{LLH}$	$\mathcal{C}^{333}_{LLH}$	$\mathcal{O}_{\rm NSI}$?	Mediators
Combination $(\bar{L}^\beta L_\alpha)(\bar{L}^\delta L_\gamma)(H^\dagger H)$								
31	$(\bar{L}\gamma^\rho L)(\bar{L}\gamma_\rho L)(H^\dagger H)$	1						$\mathbf{1}^v_0$
32	$(\bar{L}\gamma^\rho \vec{\tau} L)(\bar{L}\gamma_\rho \vec{\tau} L)(H^\dagger H)$		1					$\mathbf{3}^v_0$
33	$(\bar{L}\gamma^\rho L)(\bar{L}\gamma_\rho \vec{\tau} L)(H^\dagger \vec{\tau} H)$			1				$\mathbf{1}^v_0 + \mathbf{3}^v_0$
34	$(\bar{L}\gamma^\rho \vec{\tau} L)(\bar{L}\gamma_\rho L)(H^\dagger \vec{\tau} H)$				1			$\mathbf{1}^v_0 + \mathbf{3}^v_0$
35	$(-\mathrm{i}\epsilon^{abc})(\bar{L}\gamma^\rho \tau^a L)\times$ $(\bar{L}\gamma_\rho \tau^b L)(H^\dagger \tau^c H)$					1	✓	$\mathbf{3}^v_0$
Combination $(\bar{L}^\beta L_\alpha)(\bar{L}^\delta H)(H^\dagger L_\gamma)$								
36	$(\bar{L}\gamma^\rho L)(\bar{L}H)(\gamma_\rho)(H^\dagger L)$	1/2		1/2			✓	$\mathbf{1}^v_0 + 1^R_0$
37	$(\bar{L}\gamma^\rho L)(\bar{L}\vec{\tau}H)(\gamma_\rho)(H^\dagger \vec{\tau} L)$	3/2		−1/2				$\mathbf{1}^v_0 + 3^{L/R}_0$
38	$(\bar{L}\gamma^\rho \vec{\tau} L)(\bar{L}\vec{\tau}H)(\gamma_\rho)(H^\dagger L)$		1/2		1/2	1/2	✓	$\mathbf{1}^v_0 + 1^R_0 + 3^{L/R}_0$
39	$(\bar{L}\gamma^\rho \vec{\tau} L)(\bar{L}H)(\gamma_\rho)(H^\dagger \vec{\tau} L)$		1/2		1/2	−1/2	✓	$\mathbf{1}^v_0 + 1^R_0 + 3^{L/R}_0$
40	$(-\mathrm{i}\epsilon^{abc})(\bar{L}\gamma^\rho \tau^a L)\times$ $(\bar{L}\tau^b H)(\gamma_\rho)(H^\dagger \tau^c L)$		1		−1			$\mathbf{3}^v_0 + 1^R_0 + 3^{L/R}_0$
Combination $(\bar{L}^\beta L_\alpha)(\bar{L}^\delta H^\dagger)(L_\gamma H)$								
41	$(\bar{L}\gamma^\rho L)(\bar{L}\mathrm{i}\tau^2 H^*)(\gamma_\rho)(H^T\mathrm{i}\tau^2 L)$	−1/2		1/2				$\mathbf{1}^v_0 + 1^{L/R}_{-1}$
42	$(\bar{L}\gamma^\rho L)(\bar{L}\vec{\tau}\mathrm{i}\tau^2 H^*)(\gamma_\rho)(H^T\mathrm{i}\tau^2 \vec{\tau} L)$	−3/2		−1/2				$\mathbf{1}^v_0 + 3^{L/R}_{-1}$
43	$(\bar{L}\gamma^\rho \vec{\tau} L)(\bar{L}\vec{\tau}\mathrm{i}\tau^2 H^*)(\gamma_\rho)(H^T\mathrm{i}\tau^2 L)$		−1/2		1/2	1/2		$\mathbf{3}^v_0 + 1^{L/R}_{-1} + 3^{L/R}_{-1}$
44	$(\bar{L}\gamma^\rho \vec{\tau} L)(\bar{L}\mathrm{i}\tau^2 H^*)(\gamma_\rho)(H^T\mathrm{i}\tau^2 \vec{\tau} L)$		−1/2		1/2	−1/2		$\mathbf{3}^v_0 + 1^{L/R}_{-1} + 3^{L/R}_{-1}$
45	$(-\mathrm{i}\epsilon^{abc})(\bar{L}\gamma^\rho \tau^a L)\times$ $(\bar{L}\tau^b\mathrm{i}\tau^2 H^*)(\gamma_\rho)(H^T\mathrm{i}\tau^2\tau^c L)$		−1		−1		✓	$\mathbf{3}^v_0 + 3^{L/R}_{-1}$
Combination $(\bar{L}^\beta (L^c)^\delta)((\overline{L^c})_\alpha L_\gamma)(H^\dagger H)$								
46	$(\bar{L}\mathrm{i}\tau^2 L^c)(\overline{L^c}\mathrm{i}\tau^2 L)(H^\dagger H)$	1/4	−1/4				✓	$\mathbf{1}^s_{-1}$
47	$(\bar{L}\vec{\tau}\mathrm{i}\tau^2 L^c)(\overline{L^c}\mathrm{i}\tau^2 \vec{\tau} L)(H^\dagger H)$	−3/4	−1/4					$\mathbf{3}^s_{-1}$
48	$(\bar{L}\mathrm{i}\tau^2 L^c)(\overline{L^c}\mathrm{i}\tau^2 \vec{\tau} L)(H^\dagger \vec{\tau} H)$			1/4	−1/4	−1/4	✓	$\mathbf{1}^s_{-1} + \mathbf{3}^s_{-1}$
49	$(\bar{L}\vec{\tau}\mathrm{i}\tau^2 L^c)(\overline{L^c}\mathrm{i}\tau^2 L)(H^\dagger \vec{\tau} H)$			−1/4	1/4	−1/4	✓	$\mathbf{1}^s_{-1} + \mathbf{3}^s_{-1}$
50	$(-\mathrm{i}\epsilon^{abc})(\bar{L}\tau^a\mathrm{i}\tau^2 L^c)\times$ $(\overline{L^c}\mathrm{i}\tau^2\tau^b L)(H^\dagger \tau^c H)$			−1/2	−1/2			$\mathbf{3}^s_{-1}$
Combination $(\bar{L}^\beta H^\dagger)((L^c)^\delta H)((\overline{L^c})_\alpha L_\gamma)$								
51	$(\bar{L}\mathrm{i}\tau^2 H^*)(H^T L^c)(\overline{L^c}\mathrm{i}\tau^2 L)$	1/8	−1/8	1/8	−1/8	1/8	✓	$\mathbf{1}^s_{-1} + 1^L_0 + 1^{L/R}_{-1}$
52	$(\bar{L}\vec{\tau}\mathrm{i}\tau^2 H^*)(H^T L^c\vec{\tau})(\overline{L^c}\mathrm{i}\tau^2 L)$	−3/8	3/8	1/8	−1/8	1/8	✓	$\mathbf{1}^s_{-1} + 3^{L/R}_0 + 1^{L/R}_{-1}$
53	$(\bar{L}\vec{\tau}\mathrm{i}\tau^2 H^*)(H^T L^c)(\overline{L^c}\mathrm{i}\tau^2 \vec{\tau} L)$	−3/8	−1/8	−3/8	−1/8	1/8	✓	$\mathbf{3}^s_{-1} + 1^L_0 + 3^{L/R}_{-1}$
54	$(\bar{L}\mathrm{i}\tau^2 H^*)(H^T \vec{\tau} L^c)(\overline{L^c}\mathrm{i}\tau^2 \vec{\tau} L)$	3/8	1/8	−1/8	−3/8	−1/8		$\mathbf{3}^s_{-1} + 3^{L/R}_0 + 1^{L/R}_{-1}$
55	$(-\mathrm{i}\epsilon^{abc})(\bar{L}\tau^a\mathrm{i}\tau^2 H^*)\times$ $(H^T\tau^b L^c)(\overline{L^c}\mathrm{i}\tau^2\tau^c L)$	3/4	1/4	−1/4	1/4	1/4		$\mathbf{3}^s_{-1} + 3^{L/R}_0 + 1^{L/R}_{-1}$
Combination $(\bar{L}^\beta (L^c)^\delta)(H^\dagger (\overline{L^c})_\alpha)(L_\gamma H)$								
56	$(\bar{L}\mathrm{i}\tau^2 L^c)(\overline{L^c} H^*)(H^T\mathrm{i}\tau^2 L)$	1/8	−1/8	−1/8	1/8	1/8	✓	$\mathbf{1}^s_{-1} + 1^L_0 + 1^{L/R}_{-1}$
57	$(\bar{L}\vec{\tau}\mathrm{i}\tau^2 L^c)(\overline{L^c}\vec{\tau} H^*)(H^T\mathrm{i}\tau^2 L)$	3/8	1/8	−3/8	−1/8	−1/8		$\mathbf{3}^s_{-1} + 3^{L/R}_0 + 1^{L/R}_{-1}$
58	$(\bar{L}\mathrm{i}\tau^2 L^c)(\overline{L^c}\vec{\tau} H^*)(H^T\mathrm{i}\tau^2 \vec{\tau} L)$	−3/8	3/8	−1/8	1/8	1/8	✓	$\mathbf{1}^s_{-1} + 3^{L/R}_0 + 3^{L/R}_{-1}$
59	$(\bar{L}\vec{\tau}\mathrm{i}\tau^2 L^c)(\overline{L^c} H^*)(H^T\mathrm{i}\tau^2 \vec{\tau} L)$	−3/8	−1/8	−1/8	−3/8	1/8	✓	$\mathbf{3}^s_{-1} + 1^L_0 + 3^{L/R}_{-1}$
60	$(-\mathrm{i}\epsilon^{abc})(\bar{L}\tau^a\mathrm{i}\tau^2 L^c)\times$ $(\overline{L^c}\tau^b H^*)(H^T\mathrm{i}\tau^2\tau^c L)$	3/4	1/4	1/4	−1/4	1/4		$\mathbf{3}^s_{-1} + 3^{L/R}_0 + 3^{L/R}_{-1}$

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53	$(\bar{L}\vec\tau{\rm i}\tau^2H^*)(H^TL^c)(\overline{L^c}{\rm i}\tau^2\vec\tau L)$	−3/8	−1/8	−3/8	−1/8	1/8	✓	$\mathbf{3}^s_{-1} + 1^L_0 + 3^{L/R}_{-1}$
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the neutrino sector. Since any model of new physics has to recover the Standard Model at low energies, we have required gauge invariance under the SM gauge group and studied the possible effective theories. The focus is set on purely leptonic NSI, that is, on operators in

In conclusion, we have demonstrated that the minimum complexity of a realistic model leading to large NSI and no charged lepton flavor violation requires at least two new fields inducing $d = 8$ NSI couplings. We have determined the possible SM charges of those medi-

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Flavor Physics

In the SM each family provides a
complete independent consistent realization of the model
(Anomalies cancel within each family)

Why such small mixing to third family quarks?

Maybe the third family is indeed special
and has its own gauge symmetry?

We will gauge B – L of the third family

$U(1)^{(3)}_{B-L}$ (let us refer to it as X)

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u, d, c, s	0
b, t	+1/3
e, μ, ν_e, ν_μ	0
τ, ν_τ	-1

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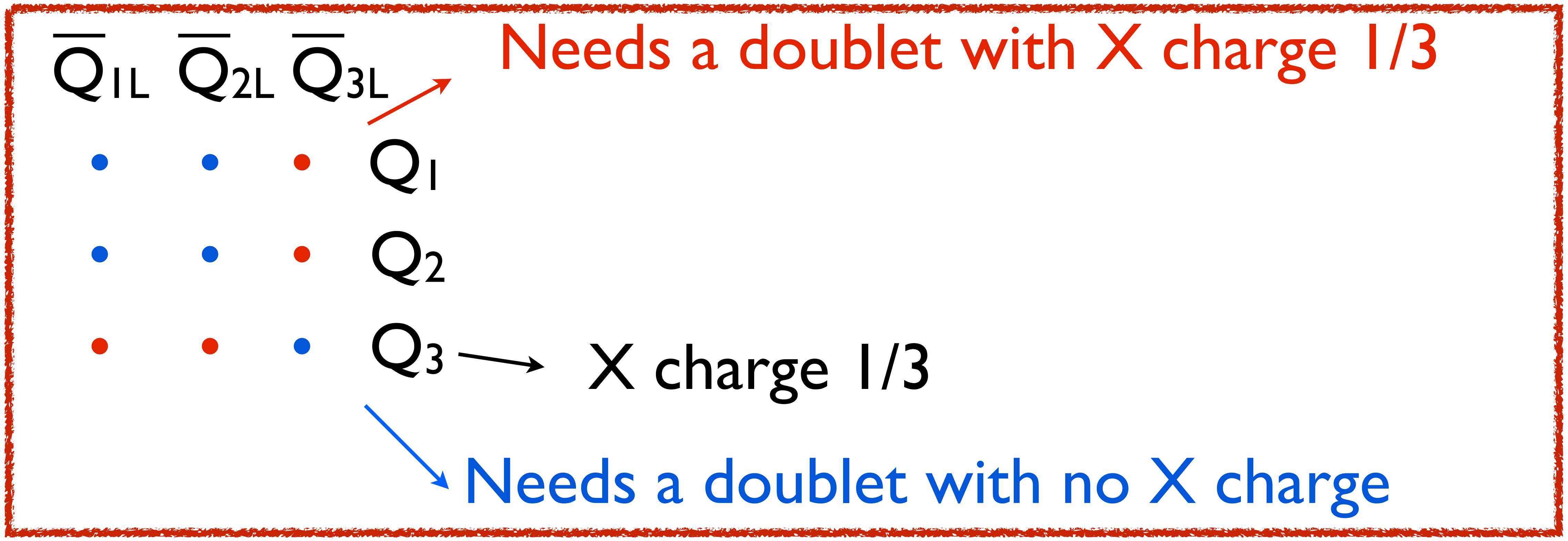

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CKM → extra doublet.
The flavor symmetry is broken by a Higgs doublet:
Its "natural" scale is EW

	ϕ_1	ϕ_2	s
$SU(2)_L$	$\mathbf{2}$	$\mathbf{2}$	$\mathbf{1}$
$U(1)_Y$	$+1$	$+1$	0
$U(1)^{(3)}_{B-L}$	$+1/3$	0	$+1/3$

generating CKM

$$\overline{\mathbf{Q}}_L \begin{pmatrix} y^u_{11}\widetilde{\phi}_2 & y^u_{12}\widetilde{\phi}_2 & y^u_{13}\widetilde{\phi}_1 \\ y^u_{21}\widetilde{\phi}_2 & y^u_{22}\widetilde{\phi}_2 & y^u_{23}\widetilde{\phi}_1 \\ 0 & 0 & y^u_{33}\widetilde{\phi}_2 \end{pmatrix} \mathbf{u}_R$$

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$$\begin{pmatrix} m^0_u & 0 & V^0_{ub}m^0_t \\ 0 & m^0_c & V^0_{cb}m^0_t \\ 0 & 0 & m^0_t \end{pmatrix} \qquad \begin{pmatrix} m^0_d & 0 & 0 \\ 0 & m^0_s & 0 \\ am^0_b & bm^0_b & m^0_b \end{pmatrix}$$

Generates flavor changing interactions in the quark sector

Flavor Physics

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$$\begin{pmatrix} m_u^0 & 0 & V_{ub}^0 m_t^0 \\ 0 & m_c^0 & V_{cb}^0 m_t^0 \\ 0 & 0 & m_t^0 \end{pmatrix} \qquad \begin{pmatrix} m_d^0 & 0 & 0 \\ 0 & m_s^0 & 0 \\ \cancel{a m_b^0} & \cancel{b m_b^0} & m_b^0 \end{pmatrix}$$

Generates flavor changing interactions in the quark sector

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Φ₁ induces mass mixing between X and Z gauge bosons

$$Z_\mu \simeq -s_w B_\mu + c_w W^3_\mu - s_X X^0_\mu,$$
$$X_\mu \simeq s_X(-s_w B_\mu + c_w W^3_\mu) + X^0_\mu,$$

$$M_X^2 = \frac{1}{9} g_X^2 \left(\frac{v_1^2 v_2^2}{v^2} + v_s^2 \right)$$

$$s_X \equiv \frac{2}{3} \frac{g_X}{\sqrt{g^2 + g'^2}} \frac{v_1^2}{v^2}$$

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Φ_1 induces mass mixing between X and Z gauge bosons

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$$M^2_X = \frac{1}{9} g^2_X \left(\frac{v_1^2 v_2^2}{v^2} + v_s^2 \right)$$

$$s_X \equiv \frac{2}{3} \frac{g_X}{\sqrt{g^2 + g'^2}} \frac{v_1^2}{v^2}$$

EWPT suggests small mixing, and thus small masses…

Flavor Physics

$$\mathcal{L}^{\ell}_{yuk} = y^{\ell}_{ij}\overline{L}_i\phi_2\ell_{Rj}$$

No flavor changing interactions in the lepton sector

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$$\mathcal{L}^{\ell}_{yuk} = y^{\ell}_{ij}\overline{L}_i\phi_2\ell_{Rj}$$

No flavor changing interactions in the lepton sector

Neutrino masses via effective operators

$$\frac{1}{\Lambda}\left(\bar{L}_{1,2}\tilde{\phi}_2\right)\left(\phi_2^\dagger\tilde{L}_{1,2}\right), \qquad \frac{1}{\Lambda^2}\left(\bar{L}_3\tilde{\phi}_1\right)\left(\phi_1^\dagger\tilde{L}_{1,2}\right)s^*$$

U(1): 0 0 0 0 -1 +1/3 +1/3 0 +1/3

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θ_{12}: D=5
θ_{13} and θ_{23}: D=6

No flavor changing interactions in the lepton sector!

Λ not far from electroweak scale!

Usual comments at this point:

This is ruled out

It is ok if one makes the gauge coupling tiny (cheating…)

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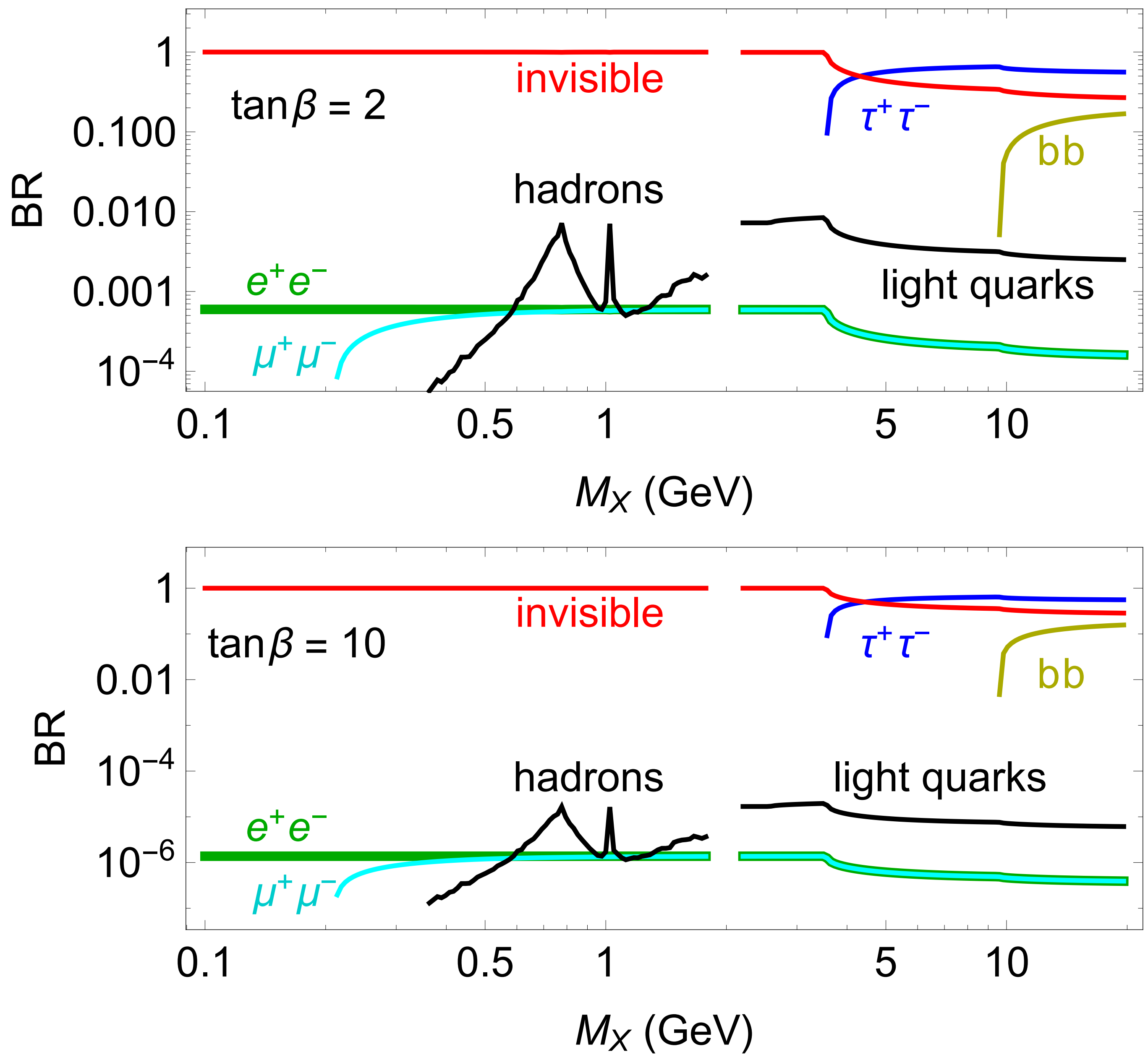
It is ok if one makes the gauge coupling tiny (cheating…) ✗

Flavor Physics



$$c_\alpha = q_\alpha c_w e\,\varepsilon + \left(g_X q_\alpha^X + s_X\sqrt{g^2+g'^2}\,q_\alpha^Z\right)$$

$$q_\alpha^Z = I_3^\alpha - s_w^2 q_\alpha$$

$$s_X \equiv \frac{2}{3}\frac{g_X}{\sqrt{g^2+g'^2}}\frac{v_1^2}{v^2}$$

Light X: $\nu_\tau\nu_\tau$ dominates

Hadronic cross section:

$$\Gamma(X \to \text{hadrons}) = \Gamma(X \to \mu^+\mu^-)R(s = M_X^2)$$

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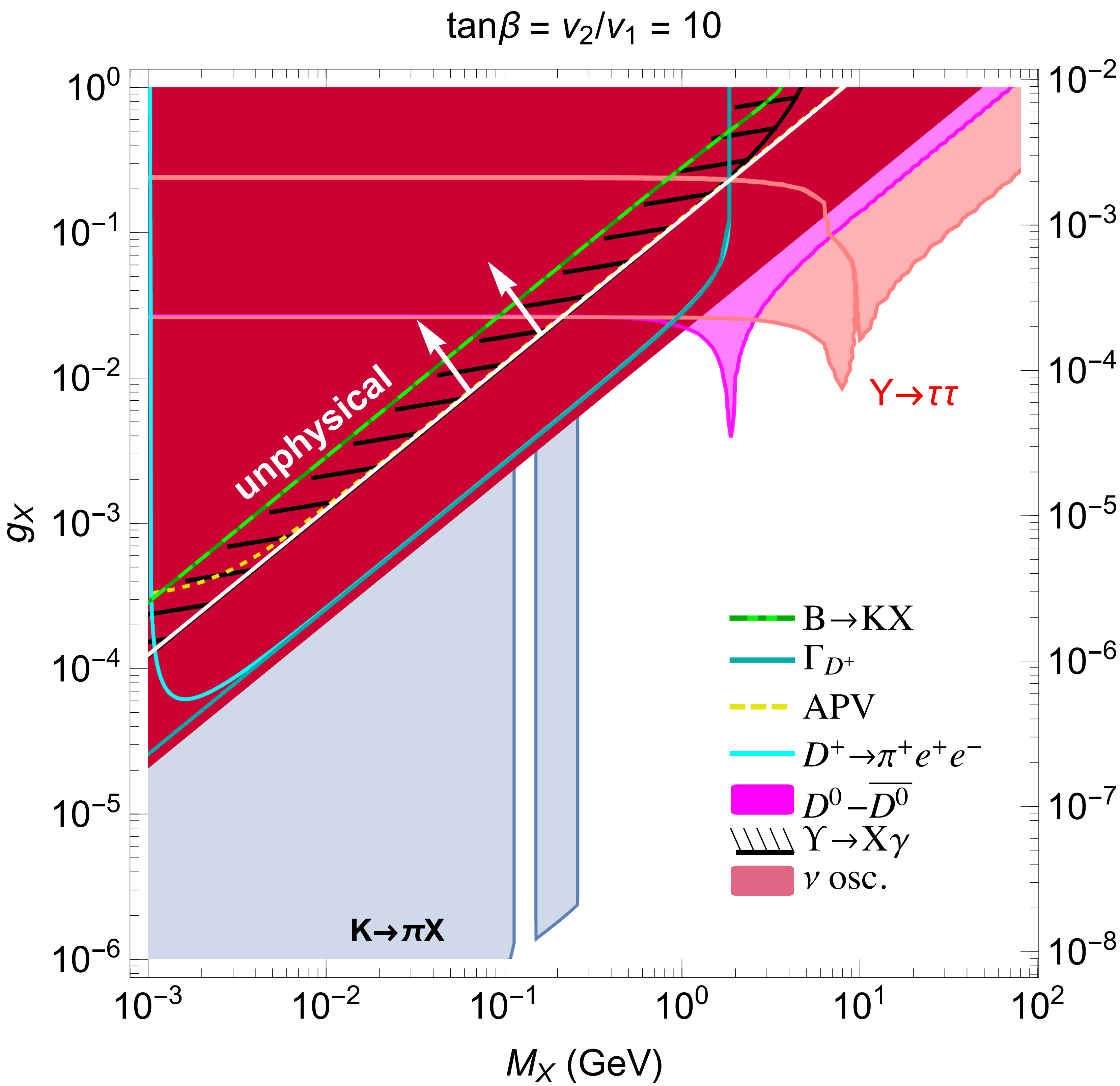
Flavor Physics



U(1) B – L of the third family

Complete model, including scalar sector and CKM generation

$$Z_\mu \simeq -s_w B_\mu + c_w W^3_\mu - s_X X^0_\mu,$$
$$X_\mu \simeq s_X(-s_w B_\mu + c_w W^3_\mu) + X^0_\mu,$$

$$s_X \equiv \frac{2}{3}\frac{g_X}{\sqrt{g^2+g'^2}}\frac{v_1^2}{v^2}$$

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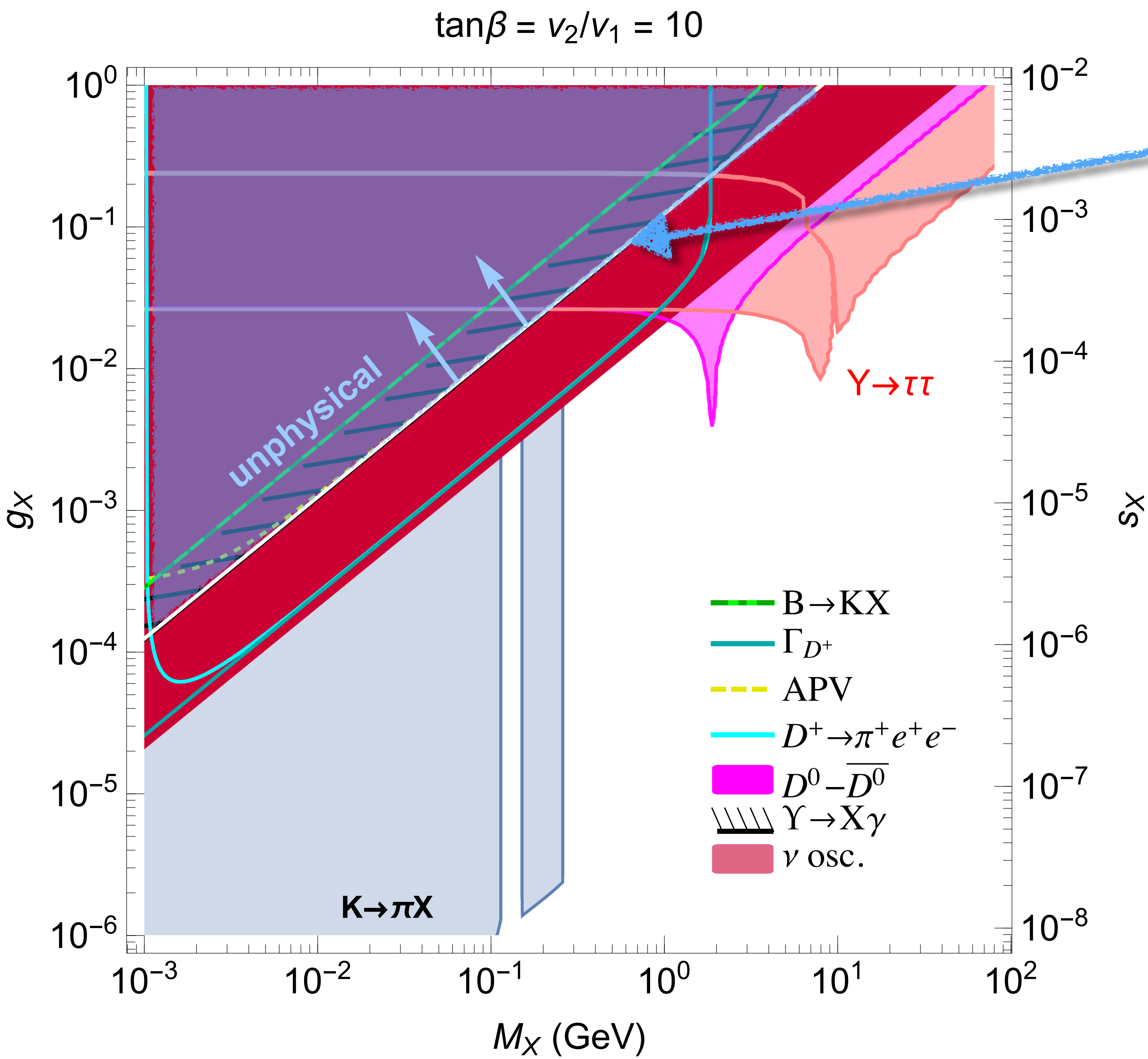
Flavor Physics



$$M_X^2 = \frac{1}{9} g_X^2 \left(\frac{v_1^2 v_2^2}{v^2} + v_s^2 \right)$$

t_β fixes v_1 and v_2

M_X has a lower value

$$Z_\mu \simeq -s_w B_\mu + c_w W_\mu^3 - s_X X_\mu^0,$$
$$X_\mu \simeq s_X(-s_w B_\mu + c_w W_\mu^3) + X_\mu^0,$$

$$s_X \equiv \frac{2}{3} \frac{g_X}{\sqrt{g^2 + g'^2}} \frac{v_1^2}{v^2}$$

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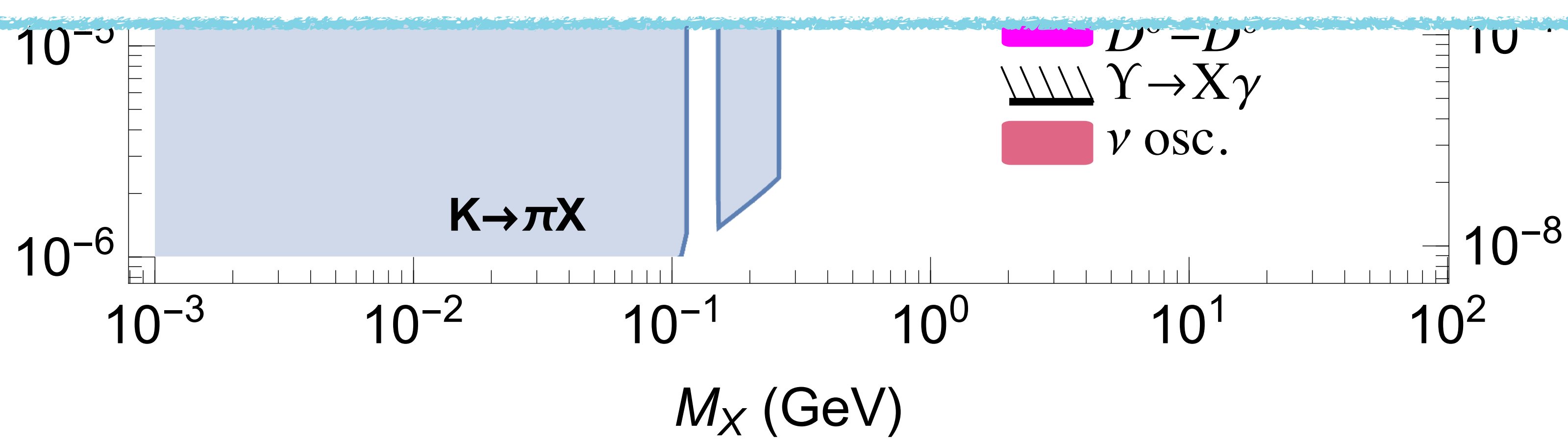
tanβ = v_2/v_1 = 10

At high energies, external longitudinal modes can be replaced by the Goldstone boson associated with the breaking of the symmetry (Equivalence theorem)

$$G_X = \frac{1}{3}\frac{g_X}{M_X v^2}\left[-v_1 v_2^2\,\mathrm{Im}(\phi_1^0) + v_1^2 v_2\,\mathrm{Im}(\phi_2^0) - v^2 v_s\,\mathrm{Im}(s^0)\right]$$

$$\mathcal{L}_{G_X} = iG_X\frac{g_X}{3}\frac{m_t}{M_X}\left[-\frac{v_1^2}{v^2}\bar{t}\gamma_5 t + V_{cb}(\bar{c}_L t_R - \bar{t}_R c_L) + V_{ub}V_{cb}(\bar{c}_L u_R - \bar{u}_R c_L)\right] - iG_X\frac{g_X}{3}\frac{m_\tau}{M_X}\frac{v_1^2}{v^2}\bar{\tau}\gamma_5\tau + \ldots$$

$$\mathcal{L}_{hXX} = \frac{g_X^2}{9}\frac{v_1^2 v_2^2}{v^3}\mathrm{Re}(H^0)X_\mu X^\mu$$



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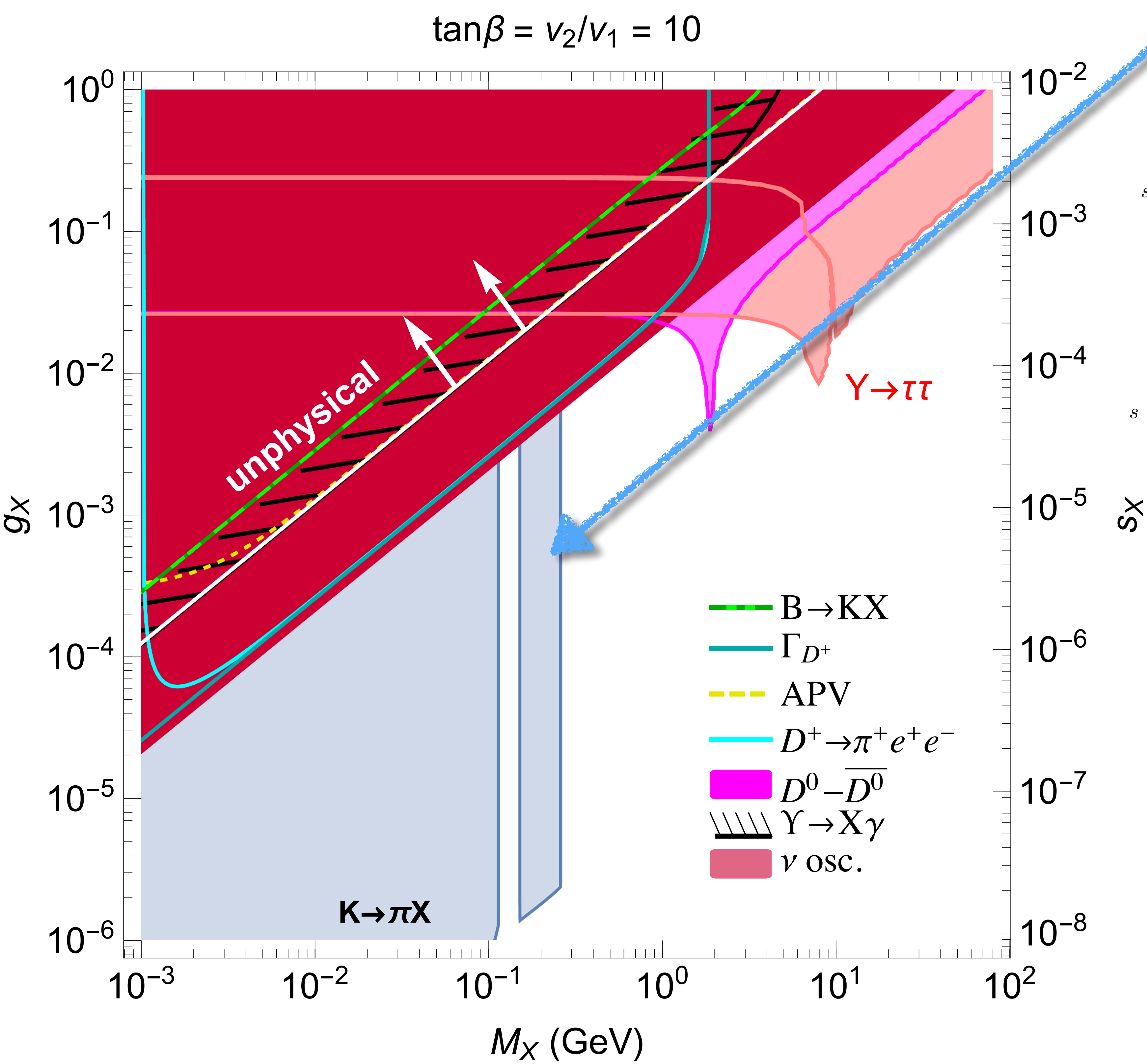
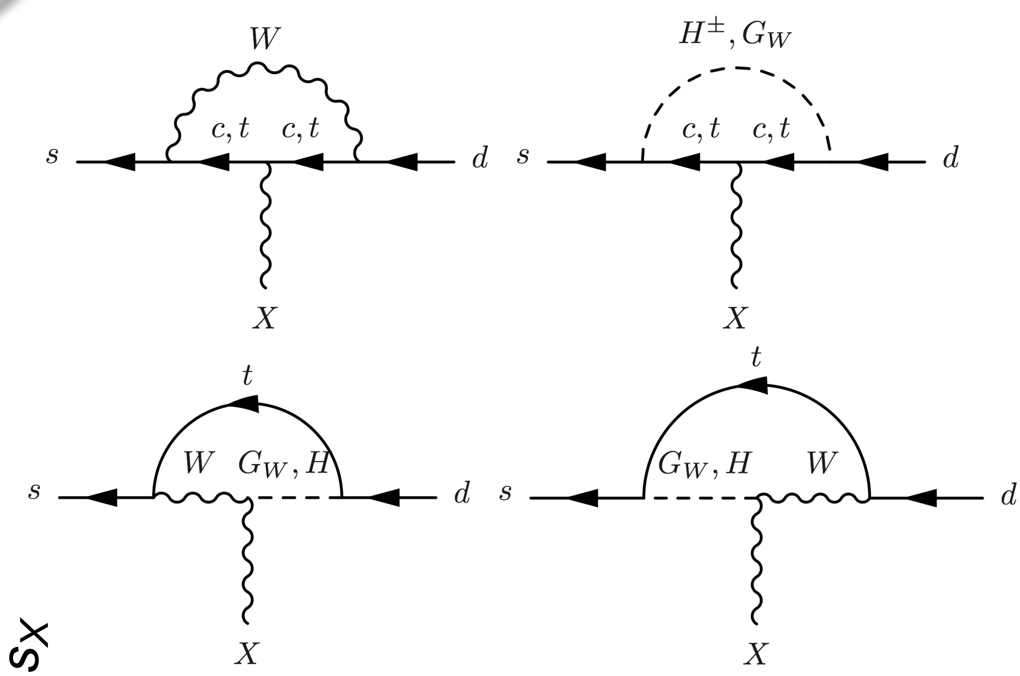


$K \to \pi X \to \pi \nu \nu$

Longitudinal enhancement



Inami Lim 1981
Hall Wise 1981
Frere Vermaseren Gavela 1981
Freytsis Ligeti Thaler 2010
E949 2008

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Flavor Physics

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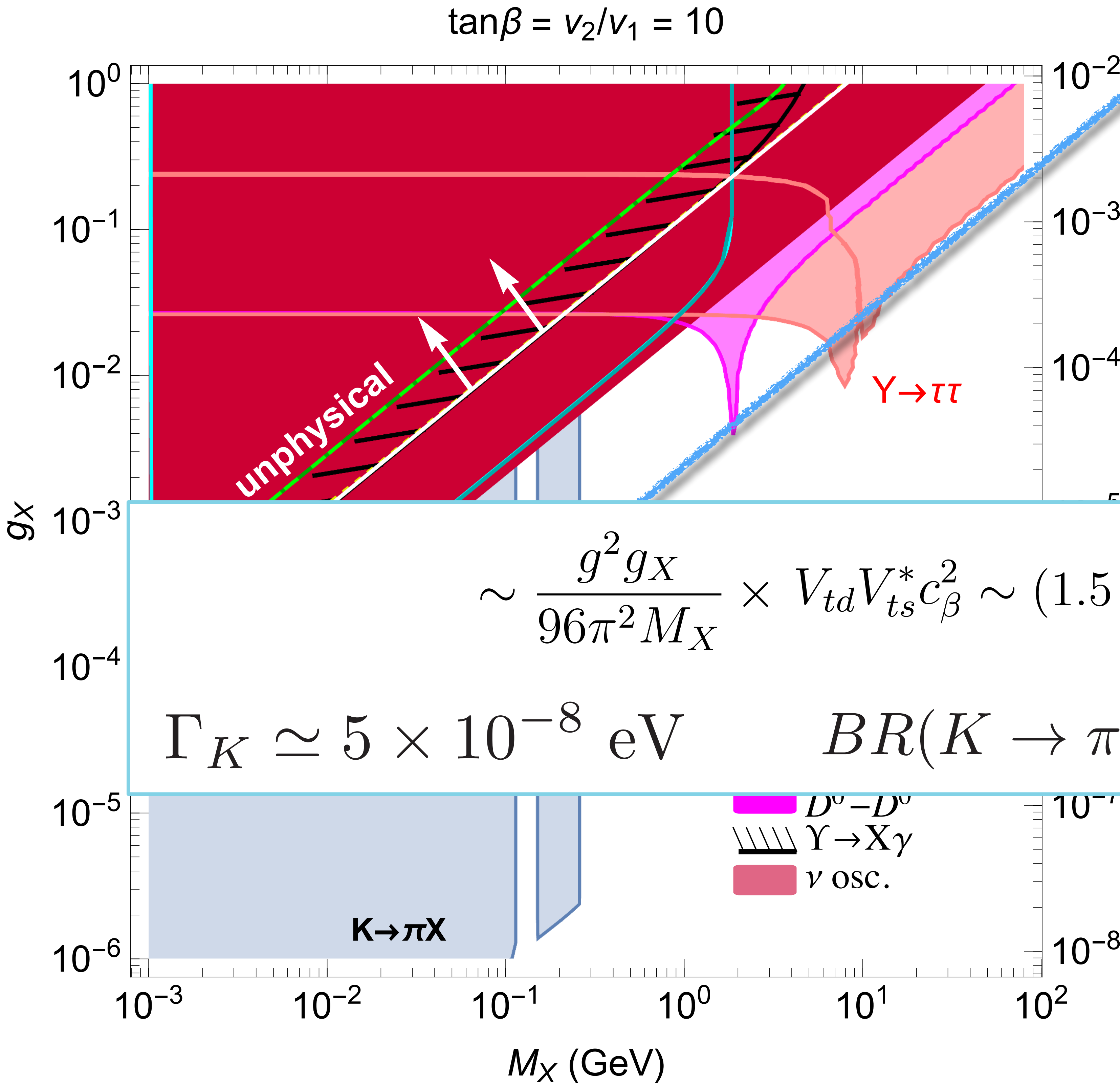

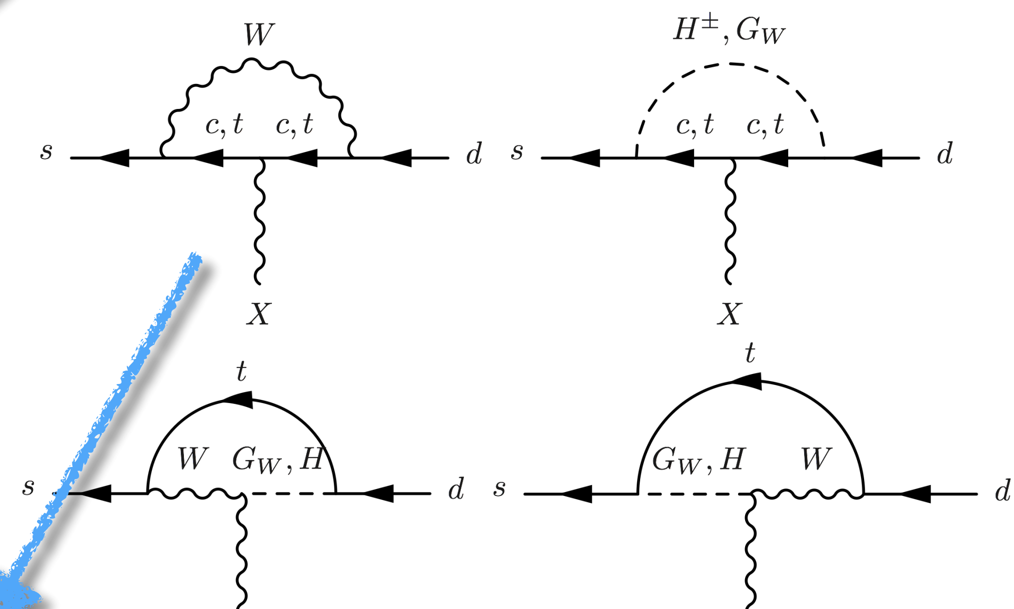

$$\sim \frac{g^2 g_X}{96\pi^2 M_X} \times V_{td} V_{ts}^* c_\beta^2 \sim (1.5 - 0.6i) 10^{-7} \frac{g_X}{M_X} c_\beta^2$$

$$\Gamma_K \simeq 5 \times 10^{-8}\ \text{eV} \qquad BR(K \to \pi\nu\nu) = (1.7 \pm 1.1) \times 10^{-10}$$

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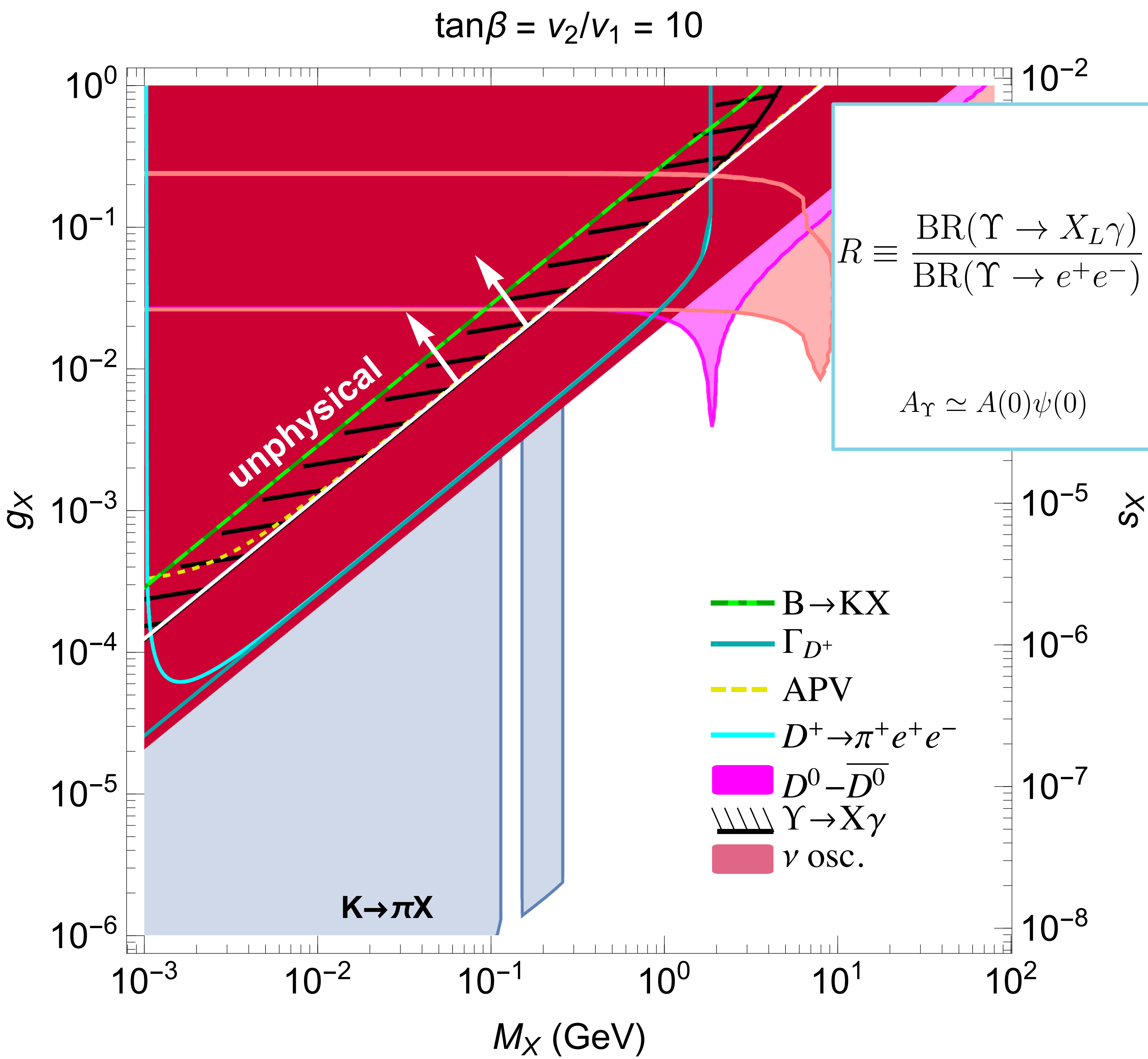
E949 2008

Υ to $X\gamma$

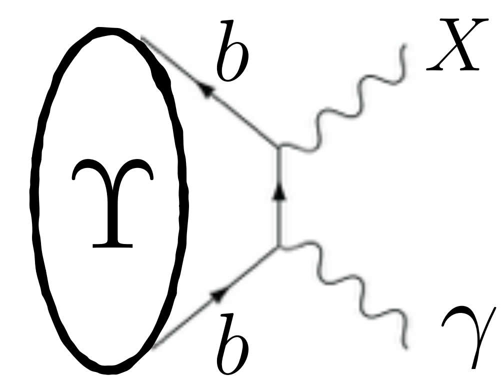
Longitudinal enhancement



$$R \equiv \frac{\mathrm{BR}(\Upsilon \to X_L \gamma)}{\mathrm{BR}(\Upsilon \to e^+e^-)} = \frac{|\psi(0)|^2 \left|A(0; b\bar{b} \to X_L\gamma)\right|^2}{|\psi(0)|^2 \left|A(0; b\bar{b} \to e^+e^-)\right|} \simeq \frac{2g_X^2 v_1^4 m_b^2}{9e^2 v^4 M_X^2}$$

$A_\Upsilon \simeq A(0)\psi(0)$

~~Yang's theorem~~



$D^0 - \overline{D^0}$

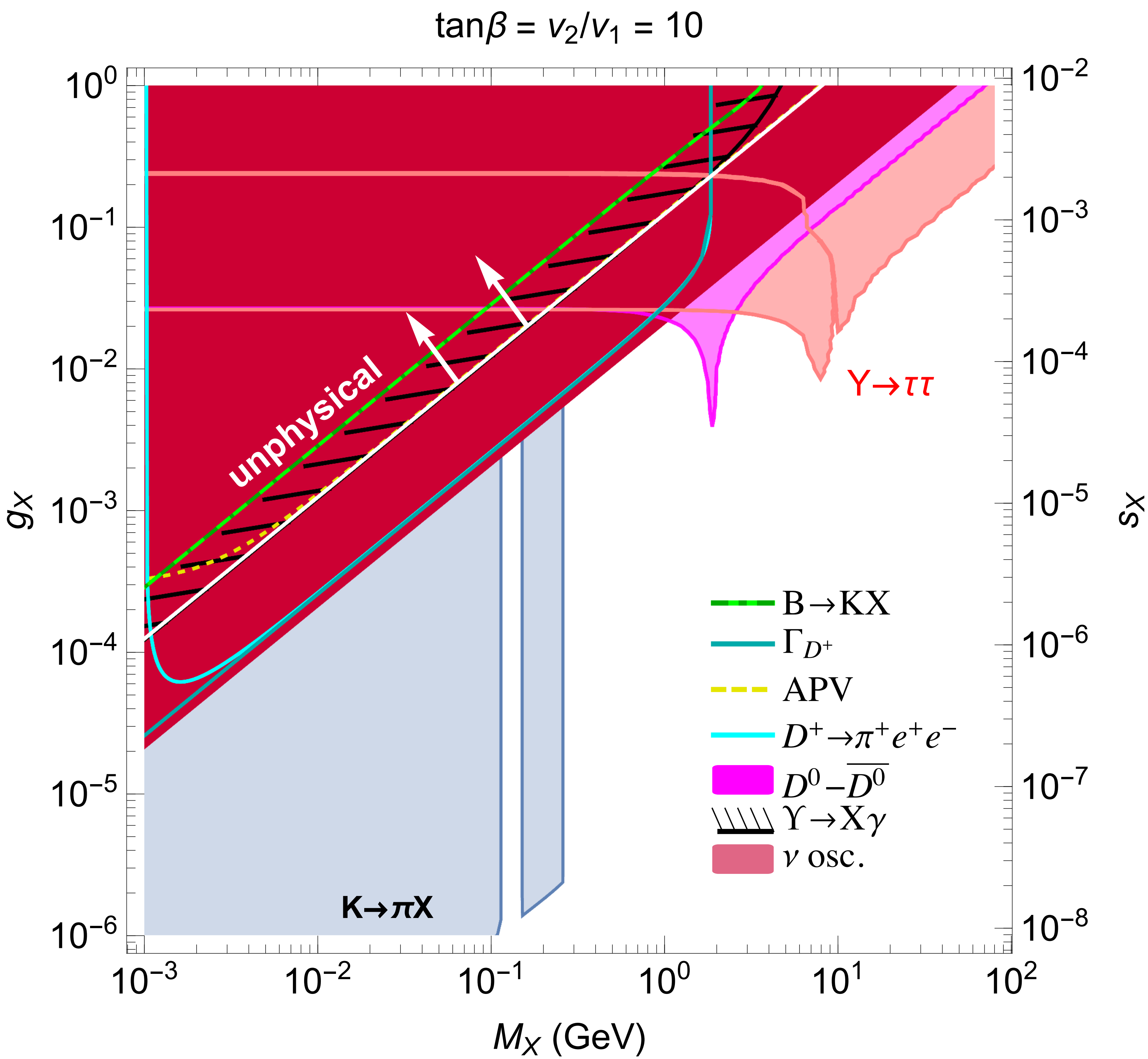
$$\mathcal{L}_{\text{eff}} = C(q^2)(\overline{u}_L \gamma_\mu c_L)^2$$

$$C(q^2) = \frac{g_X^2}{9} \frac{|V_{ub}V_{cb}|^2}{q^2 - M_X^2}$$

$$C(m_D^2) < \frac{5.9 \times 10^{-7}}{\text{TeV}^2}$$

Υ to ττ

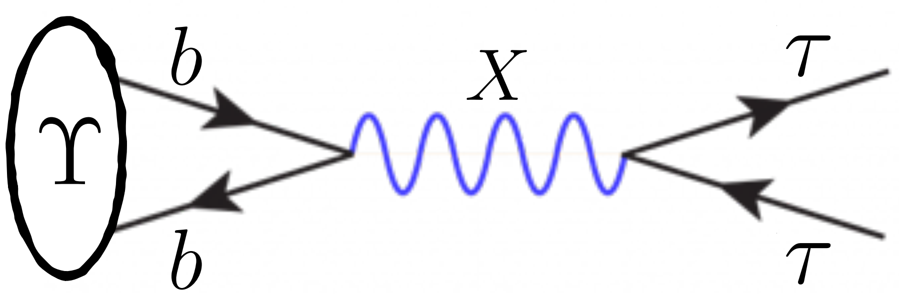
Only third family couplings



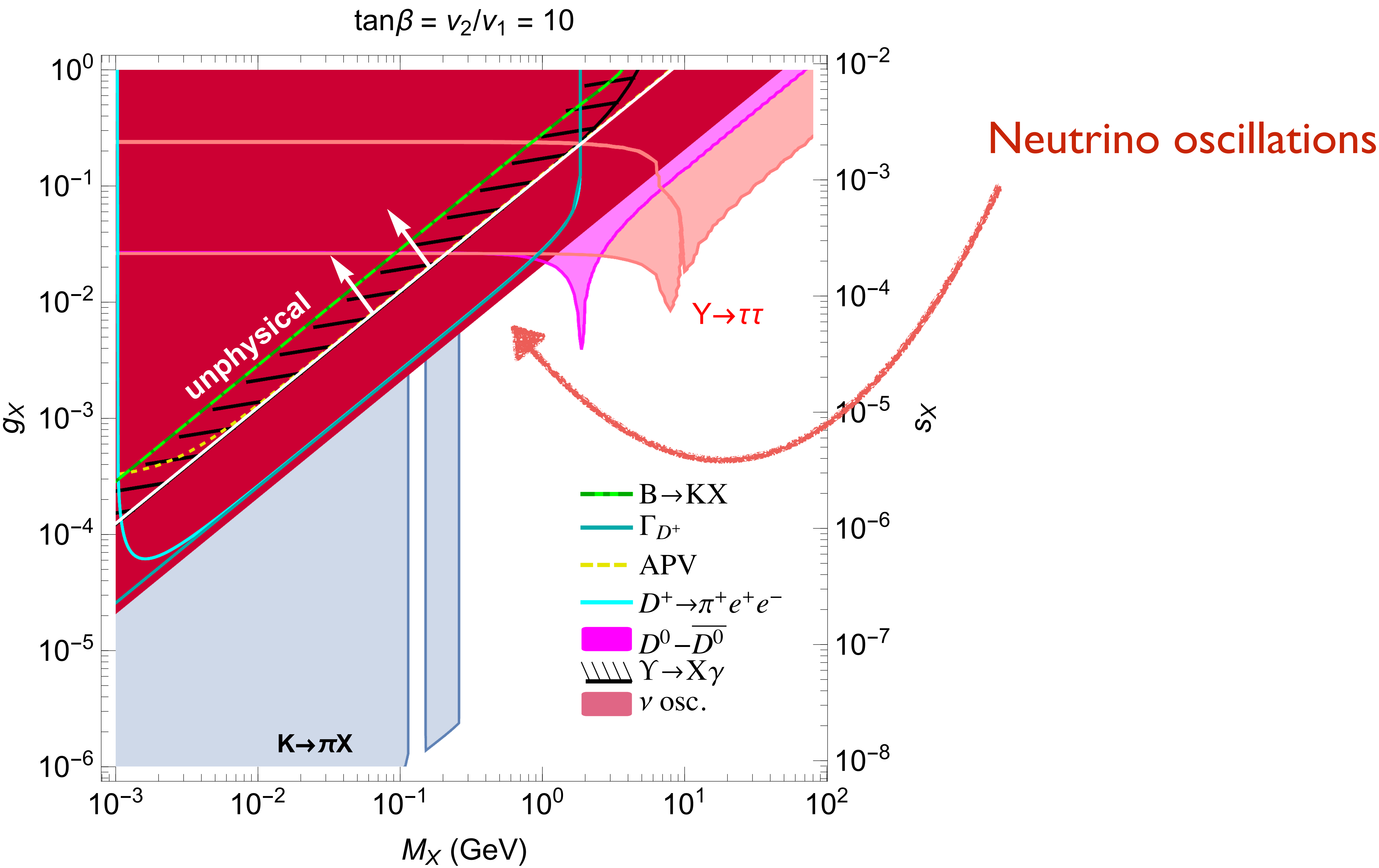
$$R_{\tau\mu} \equiv \frac{\Gamma(\Upsilon(1S) \to \tau^+\tau^-)}{\Gamma(\Upsilon(1S) \to \mu^+\mu^-)}$$

$$1.005 \pm 0.013(stat.) \pm 0.022(syst.)$$

$$R_{\tau\mu} \simeq 1 - 2\frac{g_X^2}{e^2}\frac{M_\Upsilon^2}{M_\Upsilon^2 - M_X^2}$$



Flavor Physics



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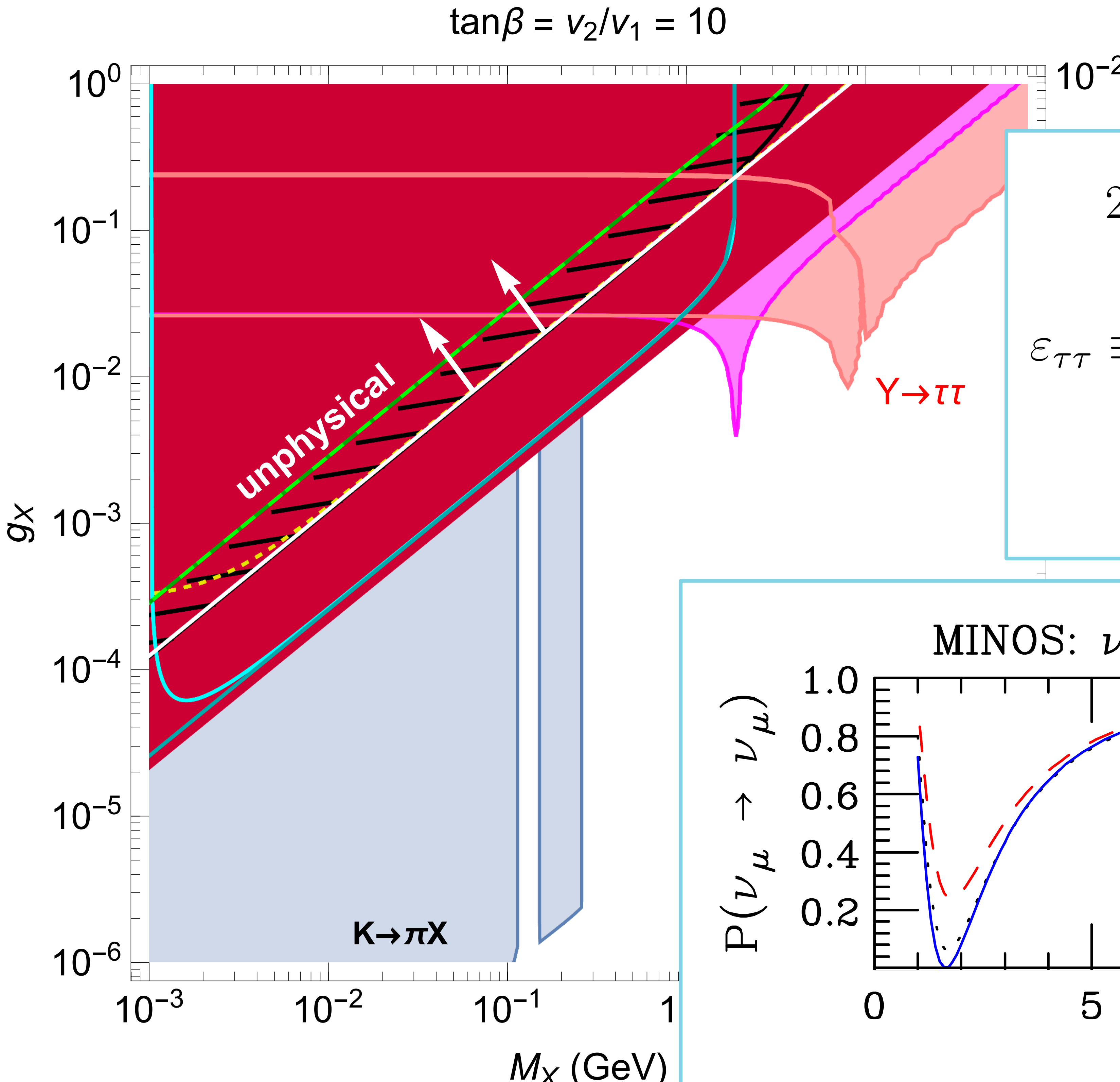
Flavor Physics



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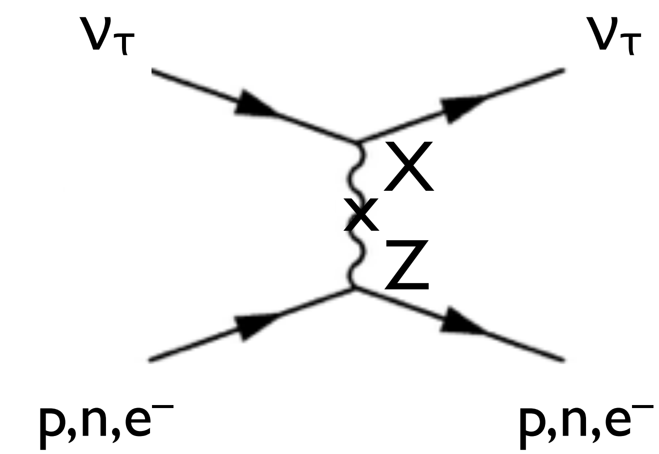
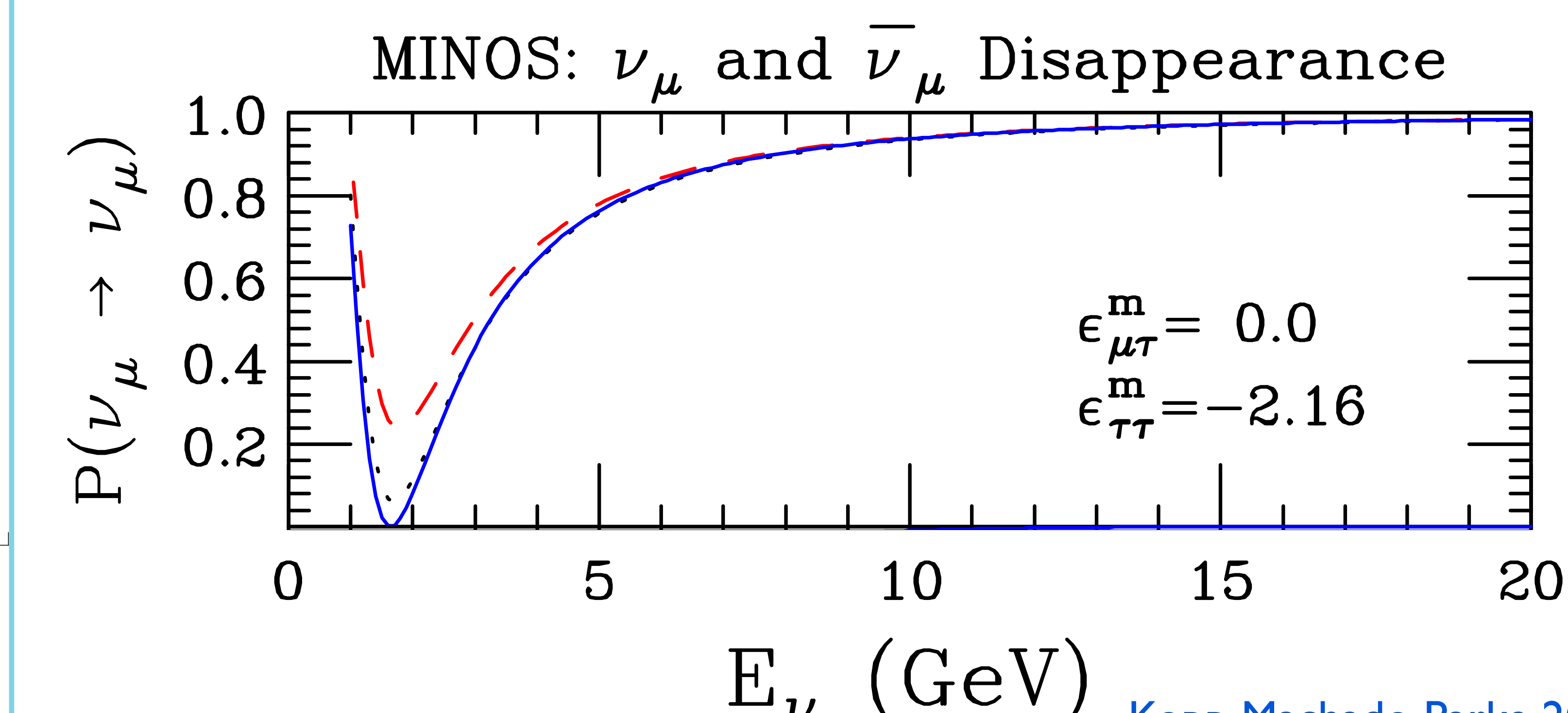


$$2\sqrt{2}G_F\varepsilon^f_{\alpha\alpha}\,\left(\bar{\nu}_{\alpha L}\gamma_\mu\nu_{\alpha L}\right)\left(\bar{f}\gamma^\mu f\right)$$

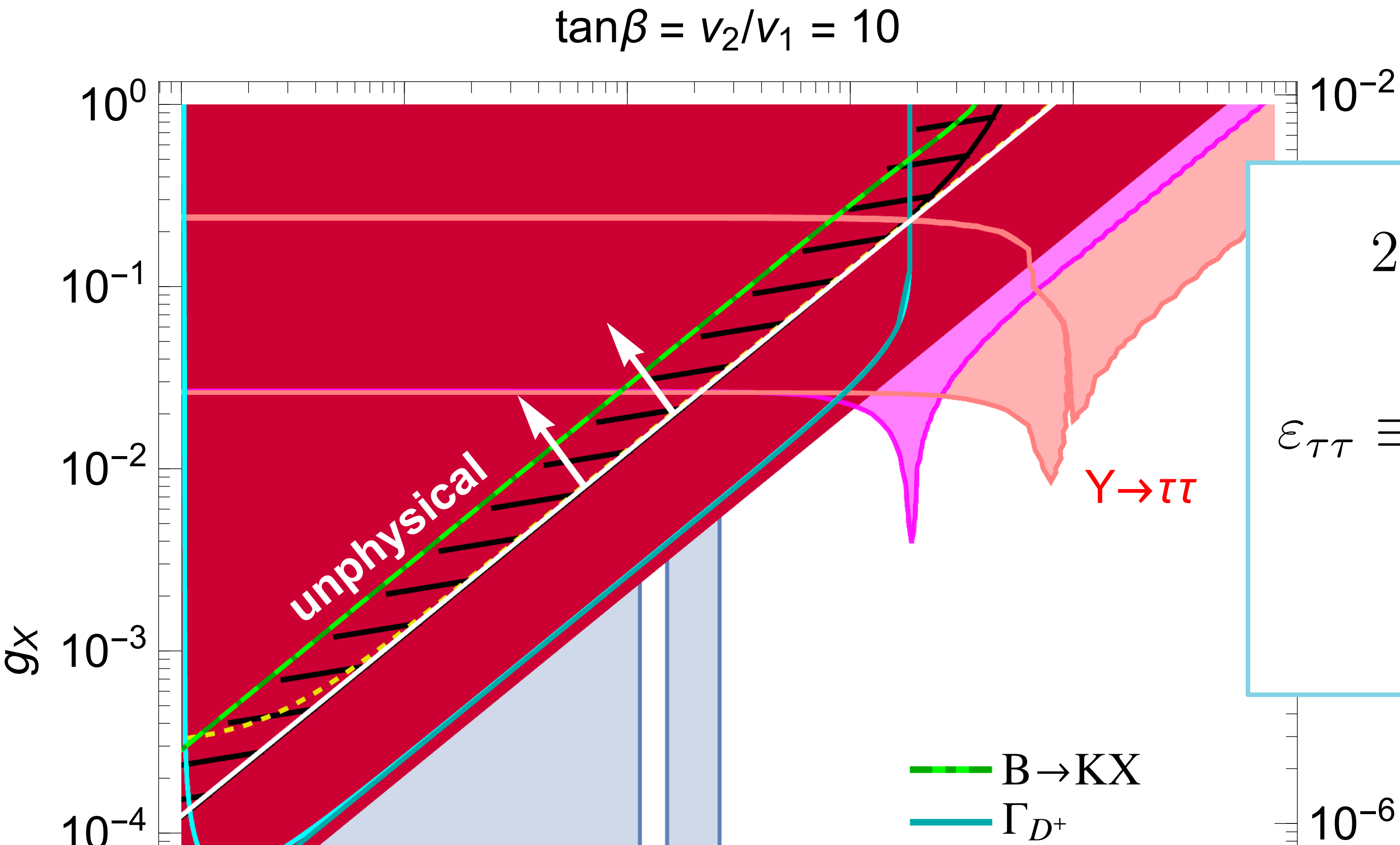
$$\varepsilon_{\tau\tau} \equiv \varepsilon^p_{\tau\tau} + \varepsilon^n_{\tau\tau} + \varepsilon^e_{\tau\tau} = 3\frac{v_1^2 v^2}{v_1^2 v_2^2 + v_s^2 v^2}$$

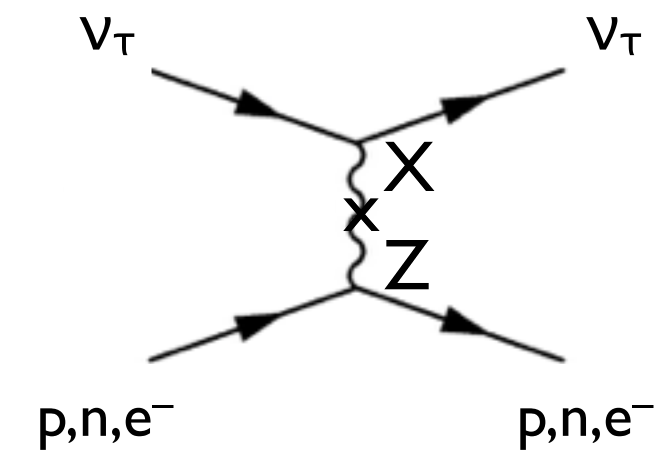
$$|\varepsilon_{\tau\tau}| < 0.09$$



Kopp Machado Parke 2010

Flavor Physics





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$$|\varepsilon_{\tau\tau}| < 0.09$$

The third family is not special!

Matter potential → symmetry breaking scale

$$V_{CC} = \sqrt{2}G_F N_e, \quad G_F = \frac{1}{\sqrt{2}v^2}$$

NSI: $2\sqrt{2}G_F\varepsilon^f_{\alpha\alpha}\,(\bar\nu_{\alpha L}\gamma_\mu\nu_{\alpha L})\left(\bar f\gamma^\mu f\right)$ → 1% NSI translate into v’ ~ 10v

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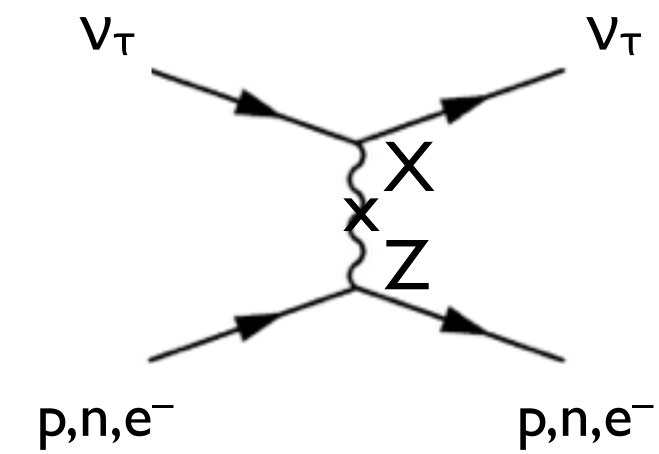
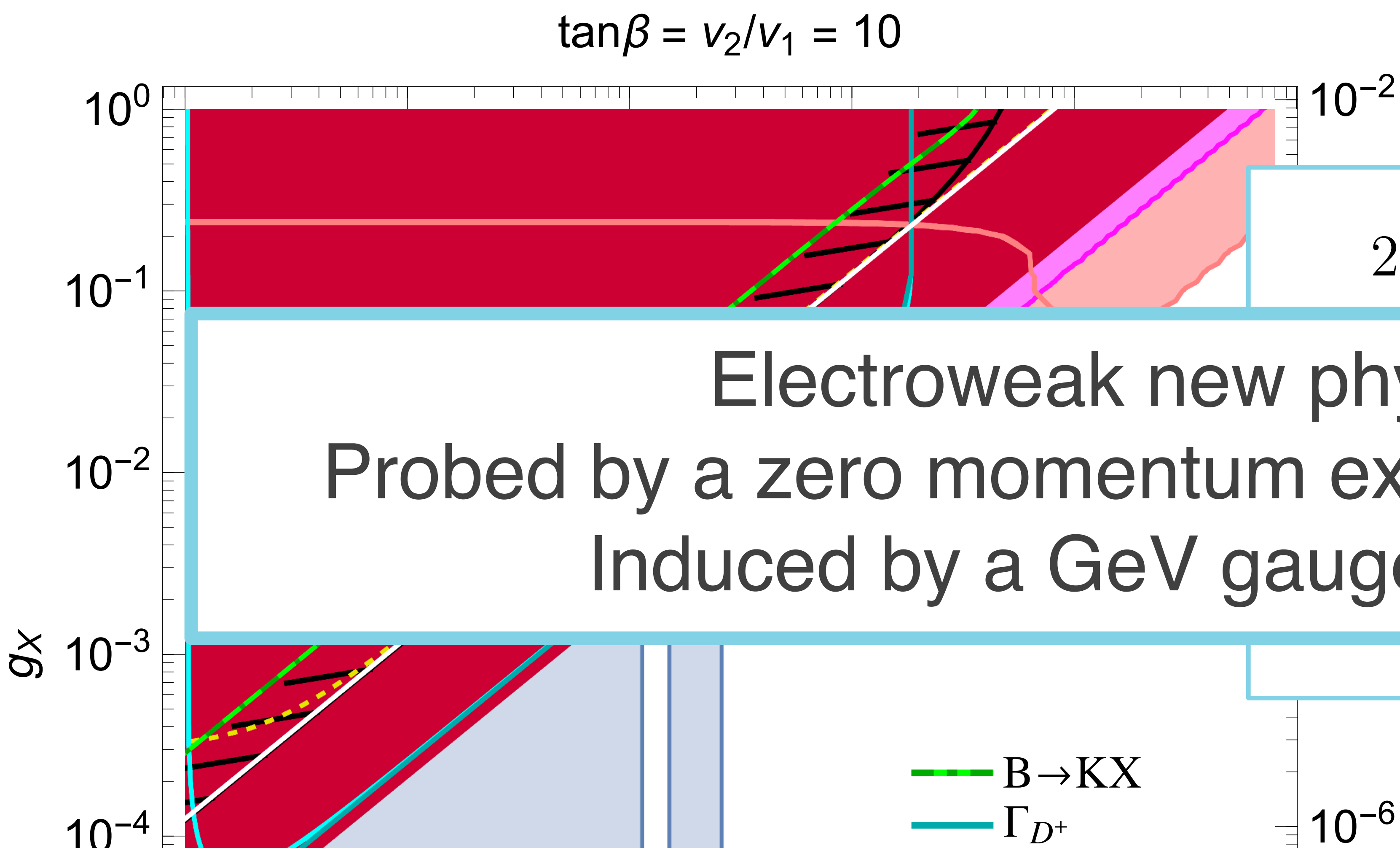
Flavor Physics





$$2\sqrt{2}G_F\varepsilon^f_{\alpha\alpha}\,(\bar{\nu}_{\alpha L}\gamma_\mu\nu_{\alpha L})\,(\bar{f}\gamma^\mu f)$$

v^2

$+ v_s^2 v^2$

Electroweak new physics
Probed by a zero momentum exchange process
Induced by a GeV gauge boson!

The third family is not special!

Matter potential → symmetry breaking scale

$$V_{CC} = \sqrt{2}G_F N_e, \quad G_F = \frac{1}{\sqrt{2}v^2}$$

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$\varepsilon_{\tau\tau}$ from atmospheric neutrinos: DUNE?

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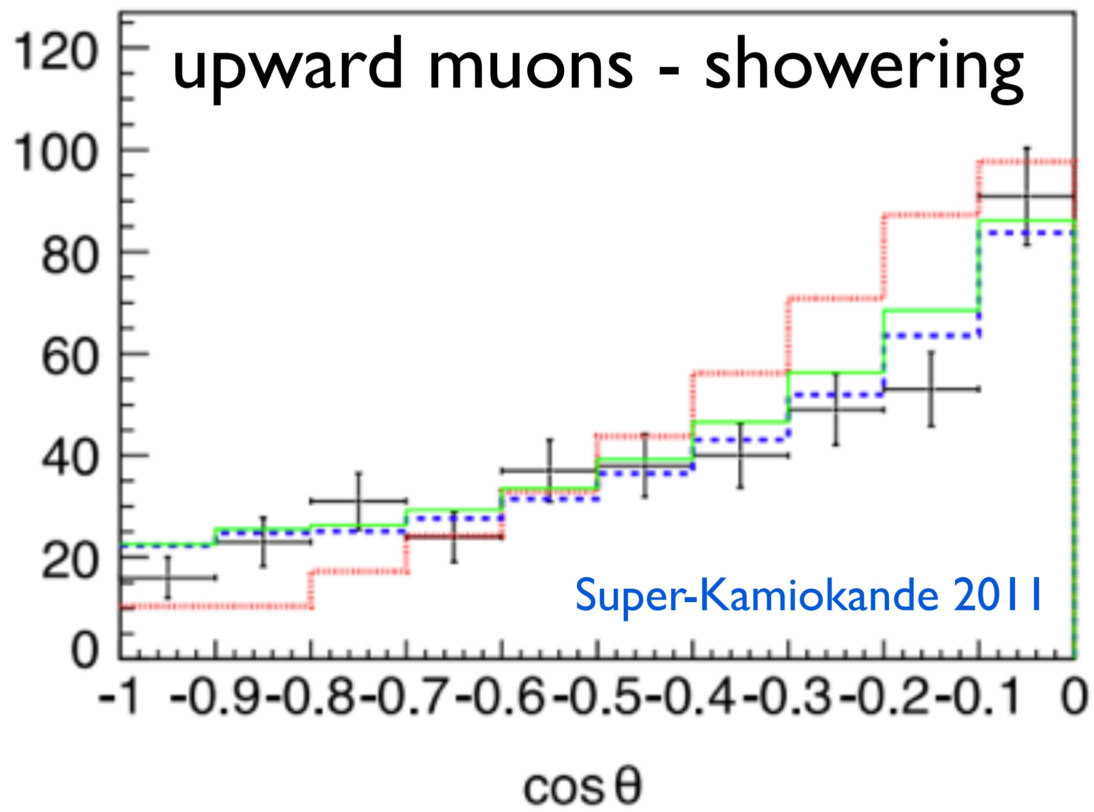

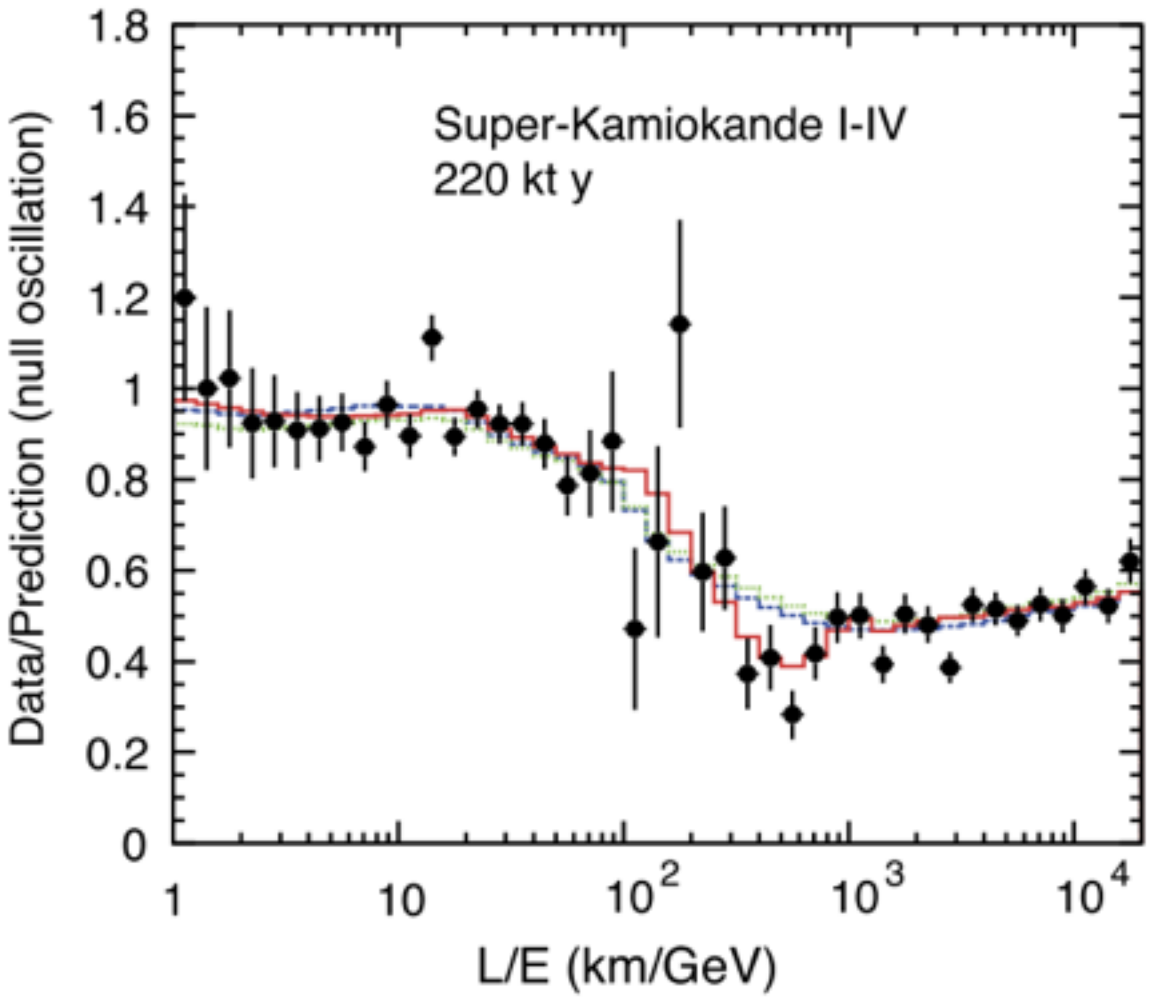

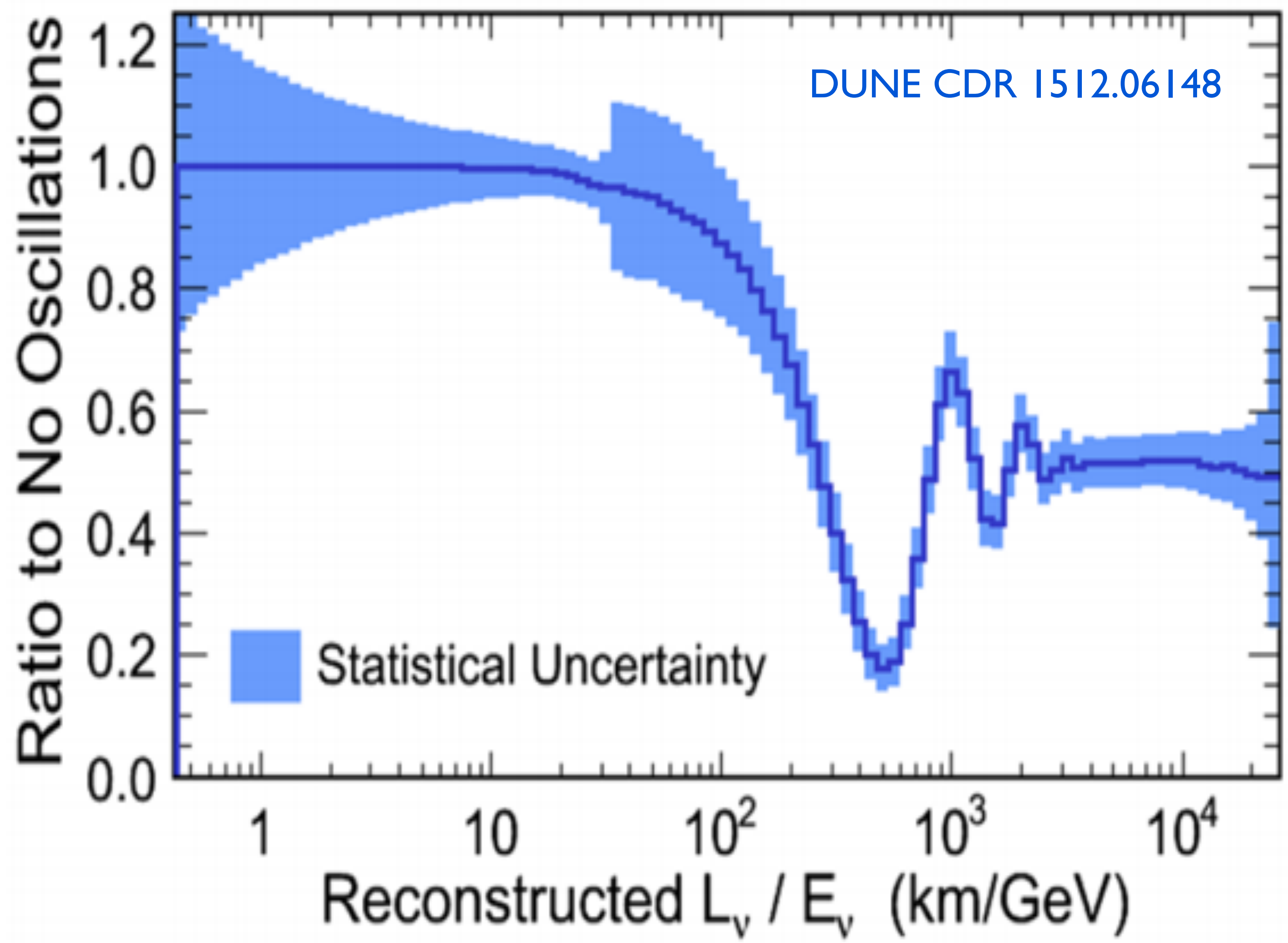

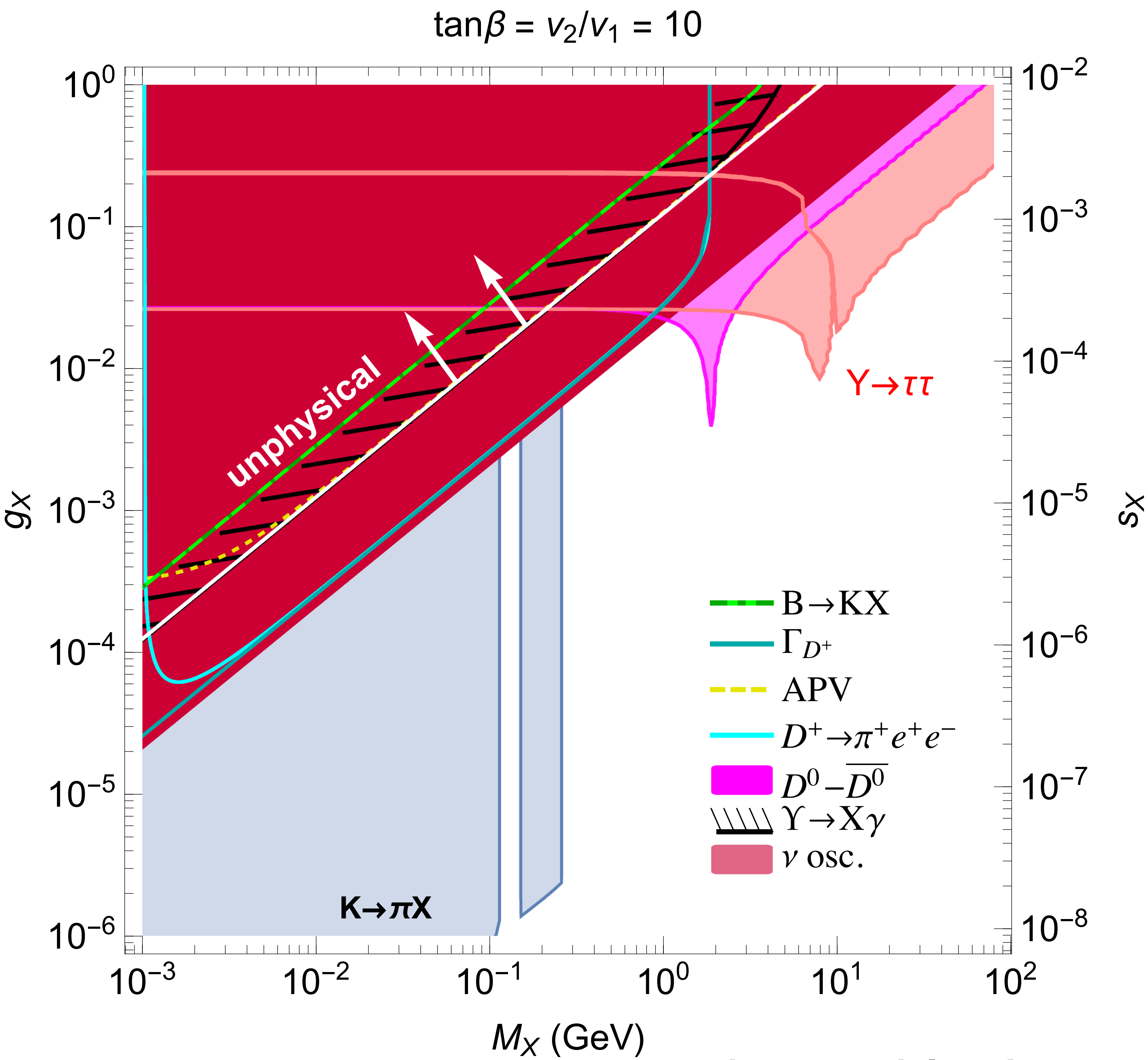

Neutrino scattering
X-Z mixing

Møller scattering
X-Z mixing

B, D, K decays
X-Z mixing

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h invisible decays
Longitudinal enhancement

Z to bbX, ττX
Transverse mode

Atomic parity violation
X-Z mixing

Top decays
longitudinal enhancement

X at the LHC
Non-standard Z' search

Meson oscillation
Probing FCNCs

BES-III
e^+e^- to $\tau^+\tau^-$

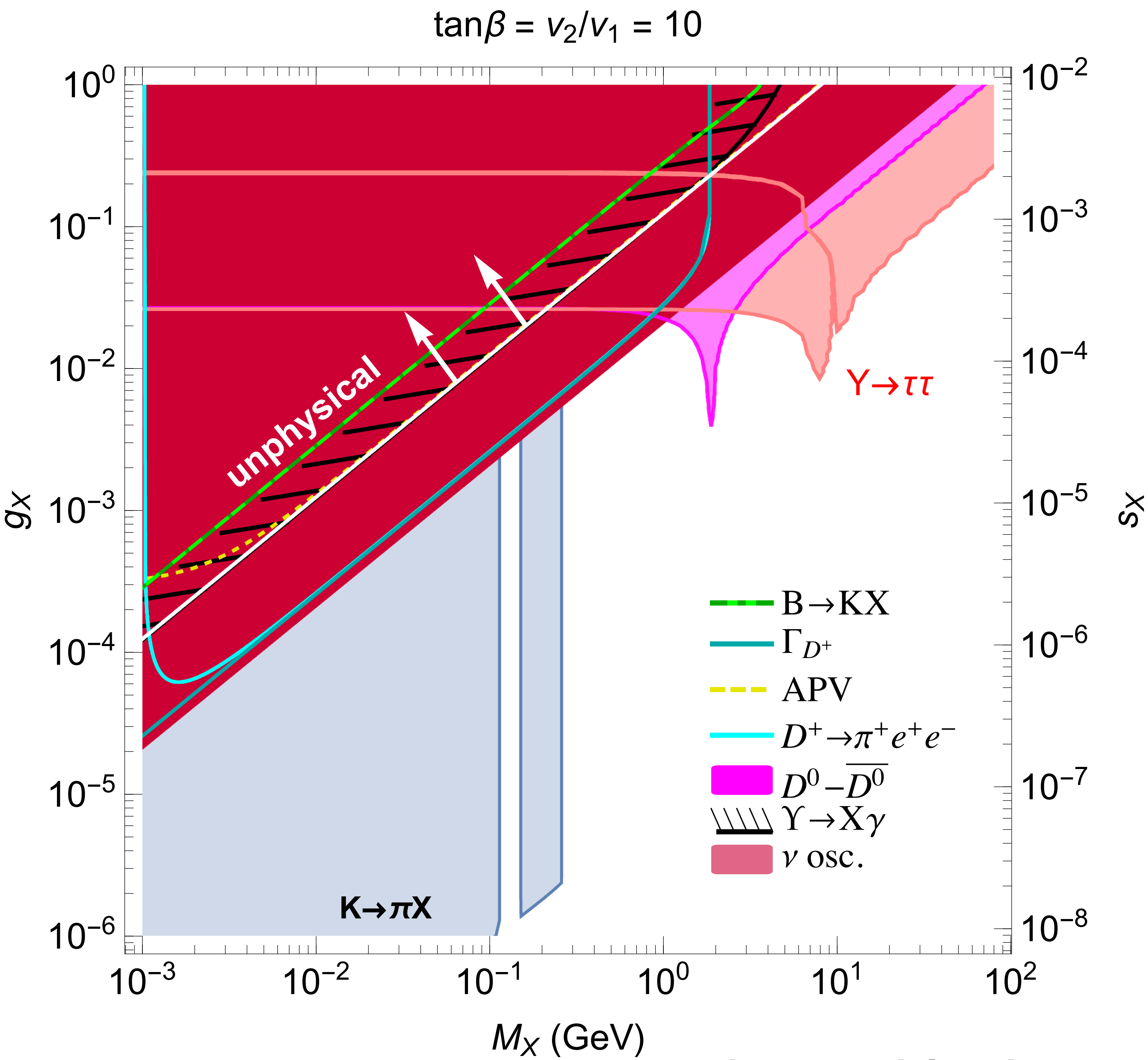
$(g-2)_\mu$
Does not decouple, but weak

Beam dump exps
X decays invisibly

W to τ ν X
longitudinal + transverse

LEP direct searches
Coupling to e^-

Upsilon decays
X-Z mixing / third family coupling



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Upsilon decays
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Conclusions

Low scale flavor models

There could be flavor dependent physics
below the electroweak scale

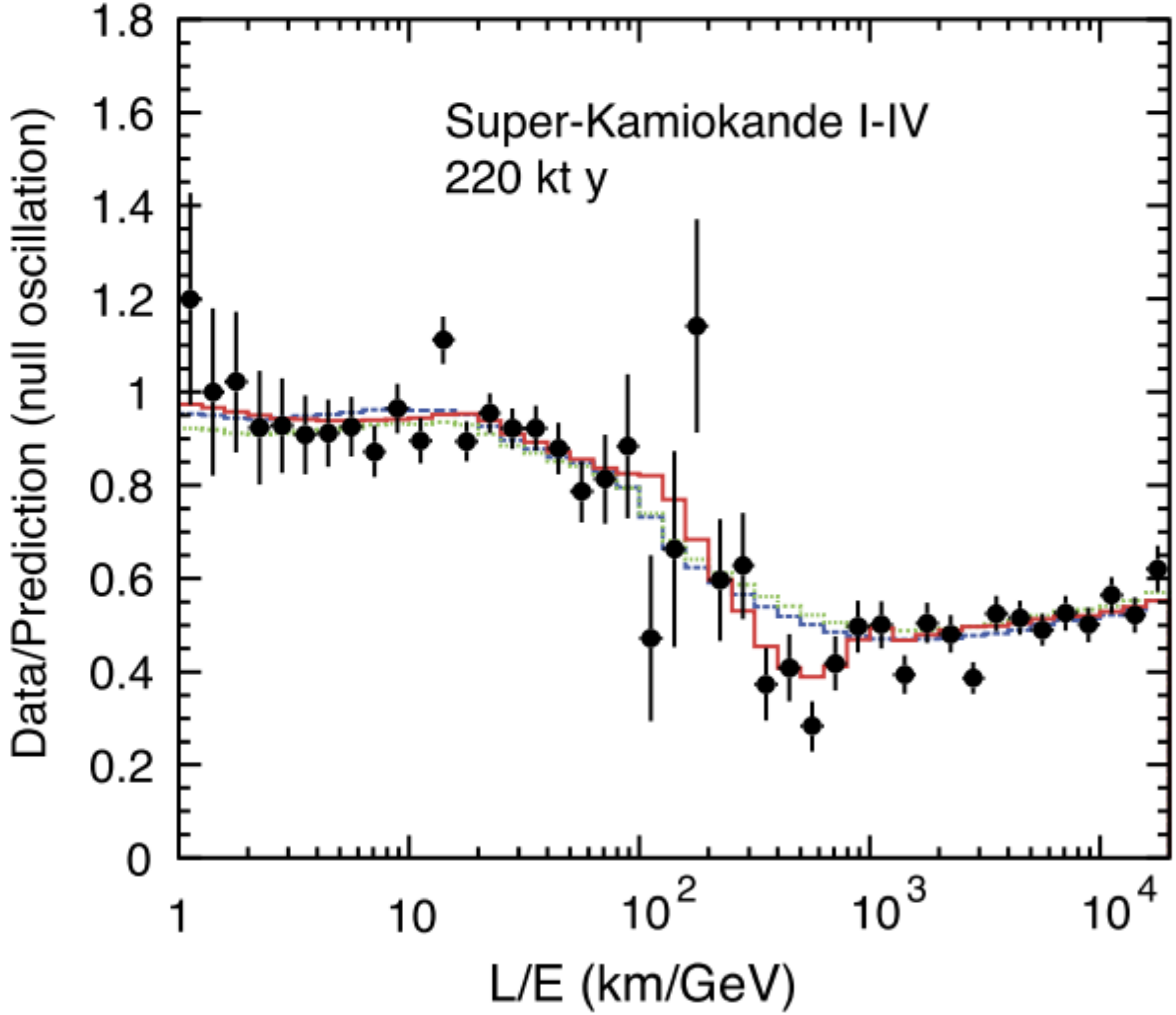
Synergy between vastly different physics:
neutrino oscillations, higgs decays, b-physics,
APV, meson oscillation and decays…

Neutrinos experiments can be sensitive to
physics beyond the reach of collider experiments

Do B anomalies point to a flavor dependent new interaction?

Backup

Best constraint on $\varepsilon_{\tau\tau}$ comes from atmospheric neutrinos
Will the current bound be improved by DUNE?



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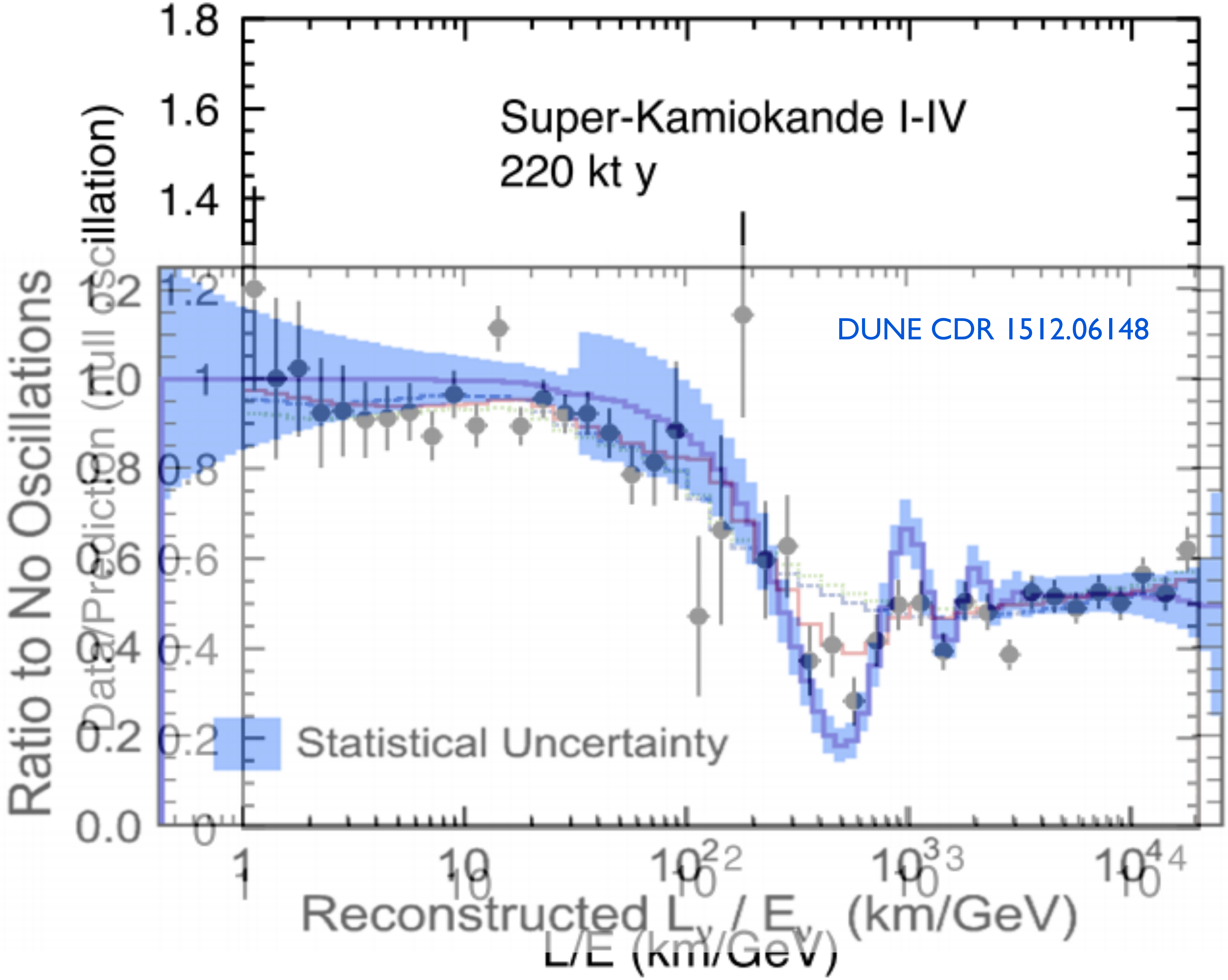
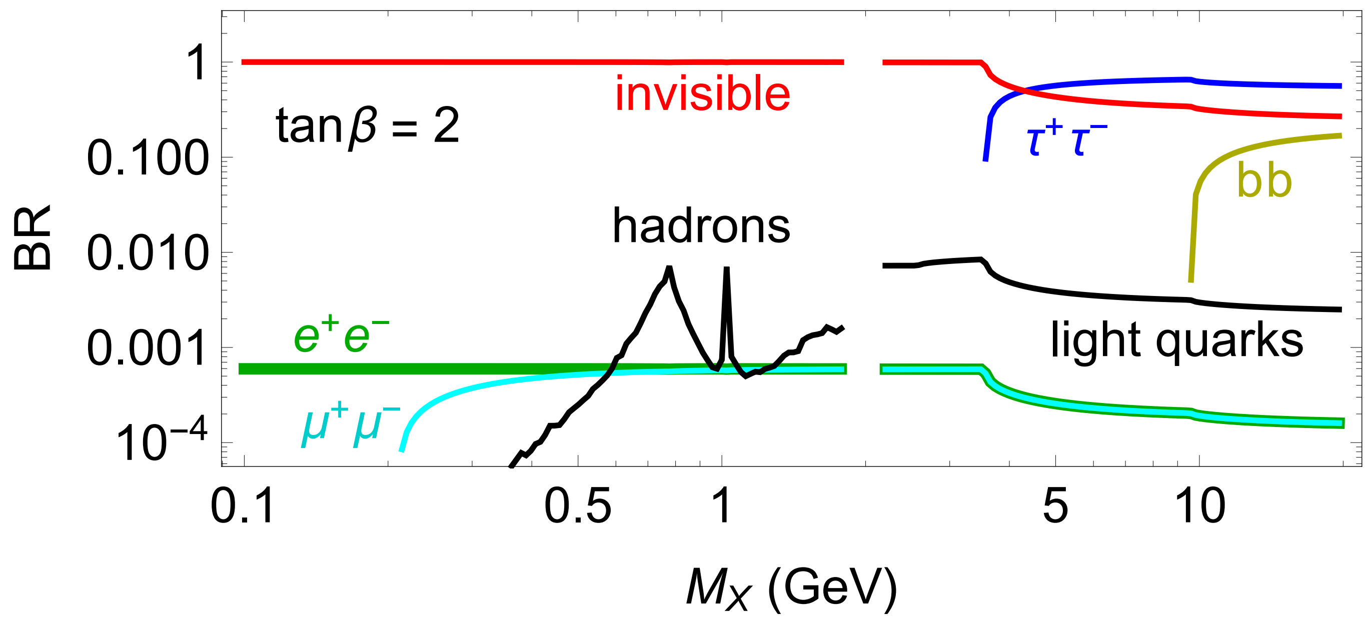
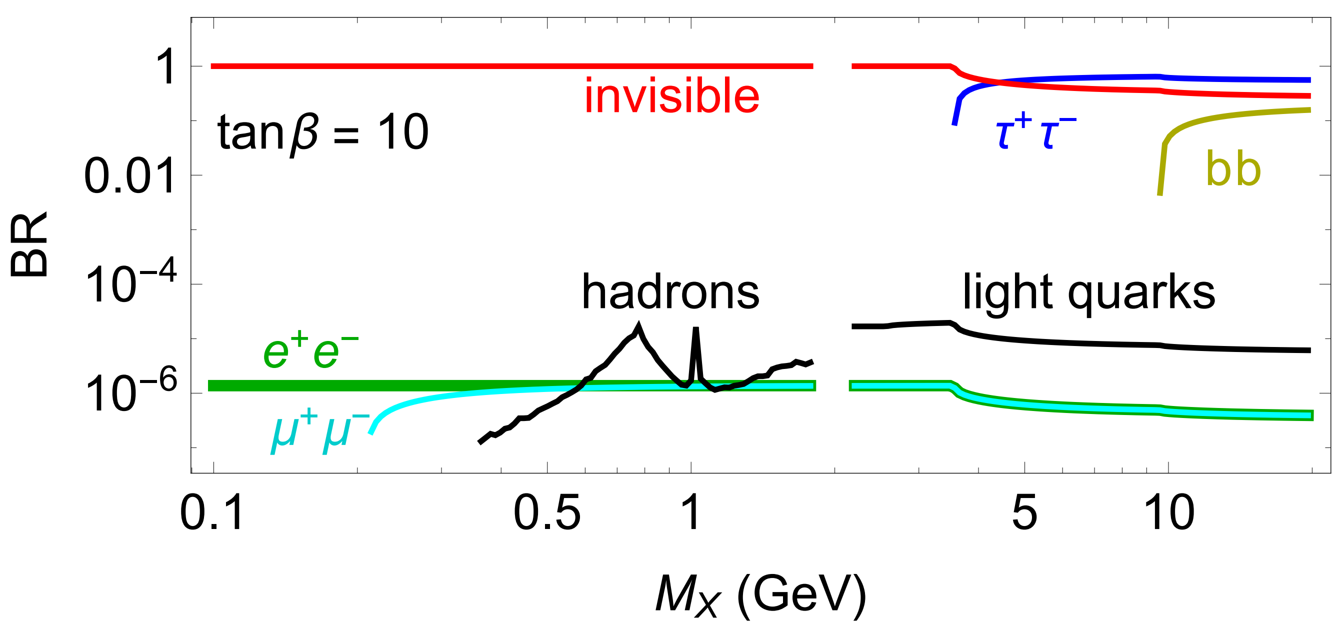




$$c_\alpha = q_\alpha c_w e\,\varepsilon + \left(g_X q_\alpha^X + s_X\sqrt{g^2+g'^2}q_\alpha^Z\right)$$

Light X: $\nu_\tau\nu_\tau$ dominates



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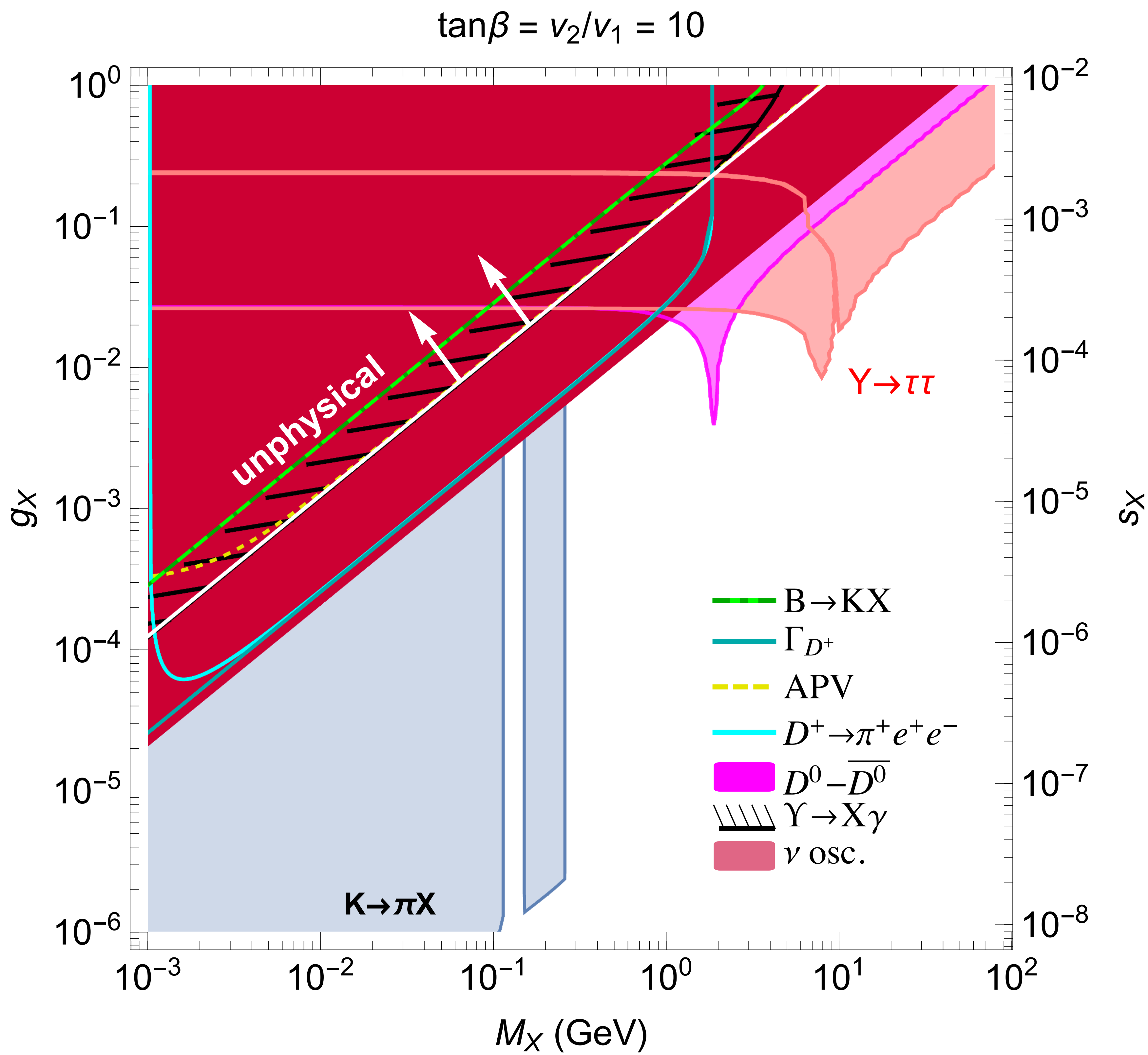

Electroweak T parameter

$$\Delta M_Z^2 \simeq \frac{g_X^2}{9}\frac{v_1^4}{v^2}$$

$$T \simeq \frac{1}{\alpha}\frac{\Delta M_Z^2}{M_Z^2} = 0.01 \pm 0.12$$

Υ to $\tau\tau$

Only third family couplings

$$R_{\tau\mu} \equiv \frac{\Gamma(\Upsilon(1S) \to \tau^+\tau^-)}{\Gamma(\Upsilon(1S) \to \mu^+\mu^-)}$$

$$1.005 \pm 0.013(stat.) \pm 0.022(syst.)$$

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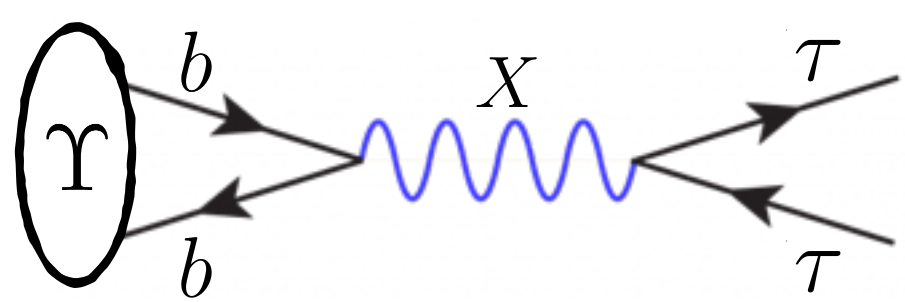
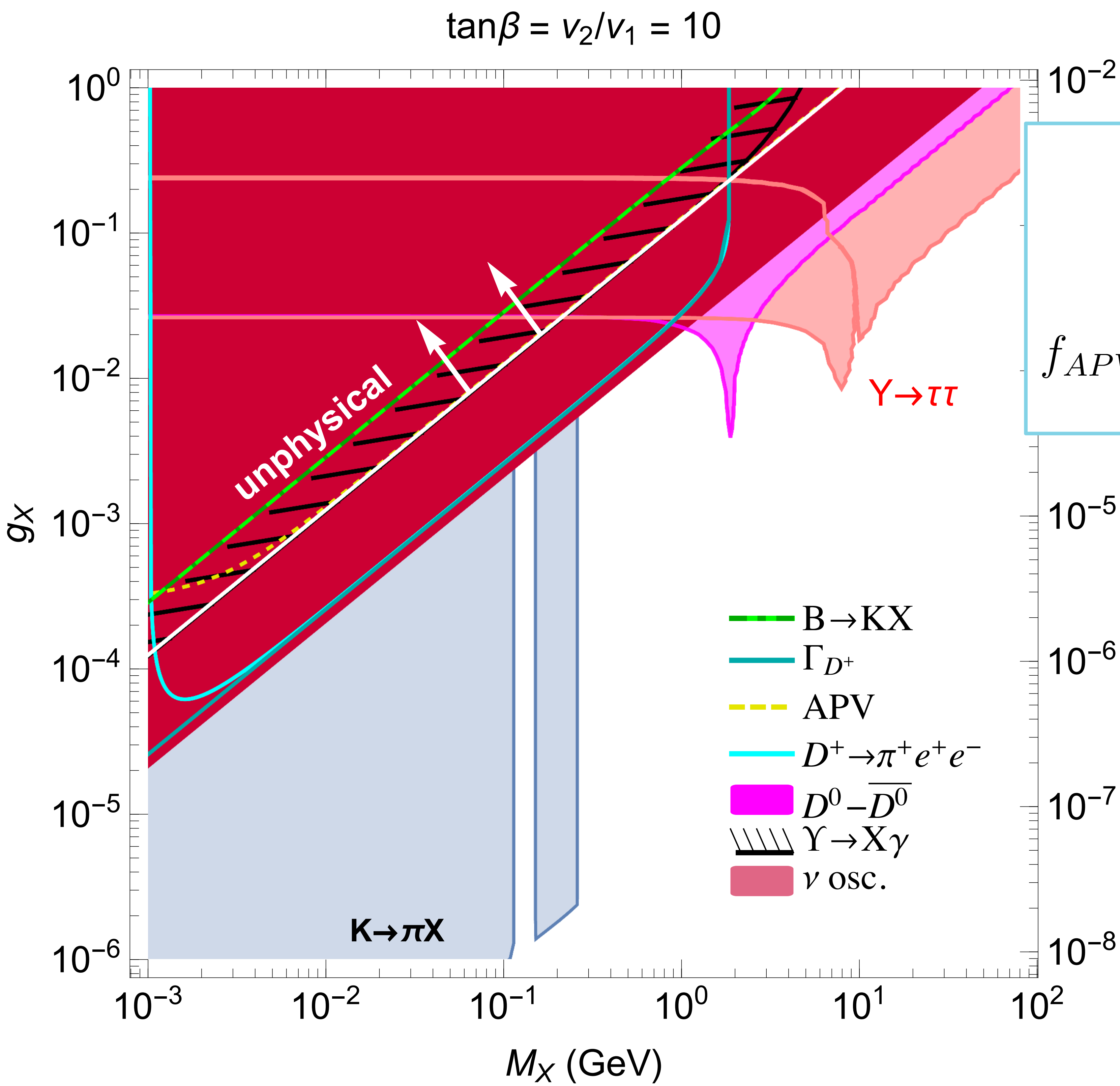


Atomic Parity Violation

mixing with Z boson



^{133}Cs weak charge

$$Q_W^{SM} = -73.16 \pm 0.3$$

$$f_{APV} = 1 + s_X^2 \frac{M_Z^2}{M_X^2 + q^2} = 1 \pm 0.0063$$

Fermilab

Scalar sector

$$V = m_{11}^2(\phi_1^\dagger\phi_1) + m_{22}^2(\phi_2^\dagger\phi_2) + m_s^2 s^* s + \frac{\lambda_1}{2}(\phi_1^\dagger\phi_1)^2 + \frac{\lambda_2}{2}(\phi_2^\dagger\phi_2)^2 + \lambda_3(\phi_1^\dagger\phi_1)(\phi_2^\dagger\phi_2) \tag{24}$$
$$+ \lambda_4(\phi_1^\dagger\phi_2)(\phi_2^\dagger\phi_1) + \frac{\lambda_s}{2}(s^* s)^2 + \lambda_{1s}(\phi_1^\dagger\phi_1)(s^* s) + \lambda_{2s}(\phi_2^\dagger\phi_2)(s^* s) - \left[\mu(\phi_2^\dagger\phi_1)s + \text{h.c.}\right].$$

$$m_A^2 = \mu\frac{v_1^2 v_2^2 + v_1^2 v_s^2 + v_2^2 v_s^2}{\sqrt{2}v_1 v_2 v_s} \qquad m_{H^\pm}^2 = \frac{1}{2}\lambda_4 v^2 + \mu\frac{v_s v^2}{\sqrt{2}v_1 v_2}$$

$$y_{ij}'^{u}\frac{H^\dagger H}{\Lambda^2}\bar{Q}_{iL}\tilde{H}u_{jR} + y_{ij}'^{d}\frac{H^\dagger H}{\Lambda^2}\bar{Q}_{iL}H d_{jR},$$

$$y'^{u,d} = y_t\begin{pmatrix} c_\beta m_u/m_t & 0 & -s_\beta V_{ub} \\ 0 & c_\beta m_c/m_t & -s_\beta V_{cb} \\ 0 & 0 & c_\beta \end{pmatrix}$$

Z to f f X

Light X (longitudinal enhancement):

$$\Gamma(Z \to f\bar{f}X) = \frac{N_c}{192\pi^3} M_Z |y_f^{G_X}|^2 \left[g_V^{f\,2}\left(1 + \log\frac{M_Z^2}{M_X^2}\right) + g_A^{f\,2}\left(-\frac{14}{3} + \log\frac{M_Z^2}{M_X^2}\right)\right]$$

Heavy X (transverse modes):

$$\frac{d\Gamma(Z \to f\bar{f}X)}{dx} = \frac{M_Z}{6\pi^3}\left[(g_V^f c_V^f + g_A^f c_A^f)^2 (h_1(x) + h_3(x))\right]$$

$$h_1(x) = 2x \log\frac{x + \sqrt{x^2 - 4R}}{x - \sqrt{x^2 - 4R}} + \sqrt{x^2 - 4R}\left(\frac{1}{R} + R - x - \frac{x}{R} + \frac{x^2}{12R} - \frac{7}{3}\right)$$

$$h_3(x) = \frac{4(1 + R - x)(1 + R)}{x} \log\frac{x + \sqrt{x^2 - 4R}}{x - \sqrt{x^2 - 4R}} - \sqrt{x^2 - 4R}\left(\frac{1}{R} + R - x - \frac{x}{R} + \frac{x^2}{12R} + \frac{5}{3}\right)$$

Marciano Wyler 1979

$$c_V^f \equiv (c_{fR} + c_{fL}), \quad c_A^f \equiv (c_{fR} - c_{fL})$$

$$g_V^\tau = \frac{g}{4c_w}(4s_w^2 - 1), \quad g_A^\tau = \frac{g}{4c_w}, \quad g_V^b = \frac{g}{4c_w}\left(\frac{4s_w^2}{3} - 1\right), \quad g_A^b = \frac{g}{4c_w}$$

Meson oscillation

$$(\Delta m_S)_X = \frac{\sqrt{2}}{6} G_F f_S^2 m_S B_S \eta_S \frac{M_Z^2}{m_S^2 - M_X^2} \left| \frac{2 g_X^2 U_{ij}^X / 3}{g / c_w} \right|^2$$

$$K - \bar{K} : \quad \left(\frac{100\,\text{GeV}}{m_\varphi} \right) \text{Re} \left(\frac{h_{21}^d}{\sqrt{2} m_s / v} \right) \lesssim 1.4 \times 10^{-2}$$

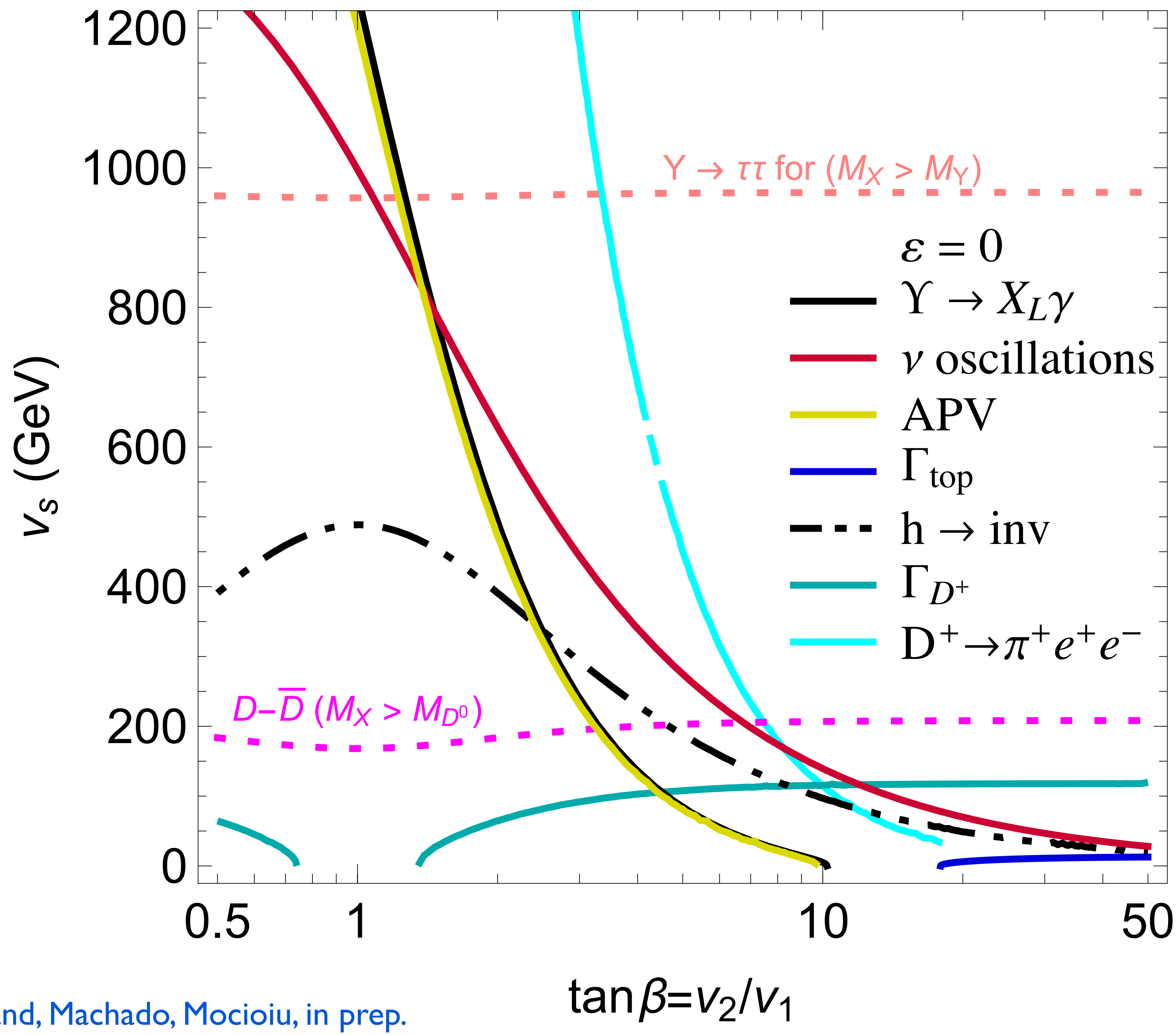
$$B_d - \bar{B}_d : \quad \left(\frac{100\,\text{GeV}}{m_\varphi} \right) \text{Re} \left(\frac{h_{31}^d}{\sqrt{2} m_b / v} \right) \lesssim 3.1 \times 10^{-3}$$

$$B_s - \bar{B}_s : \quad \left(\frac{100\,\text{GeV}}{m_\varphi} \right) \text{Re} \left(\frac{h_{32}^d}{\sqrt{2} m_b / v} \right) \lesssim 1.3 \times 10^{-2}$$

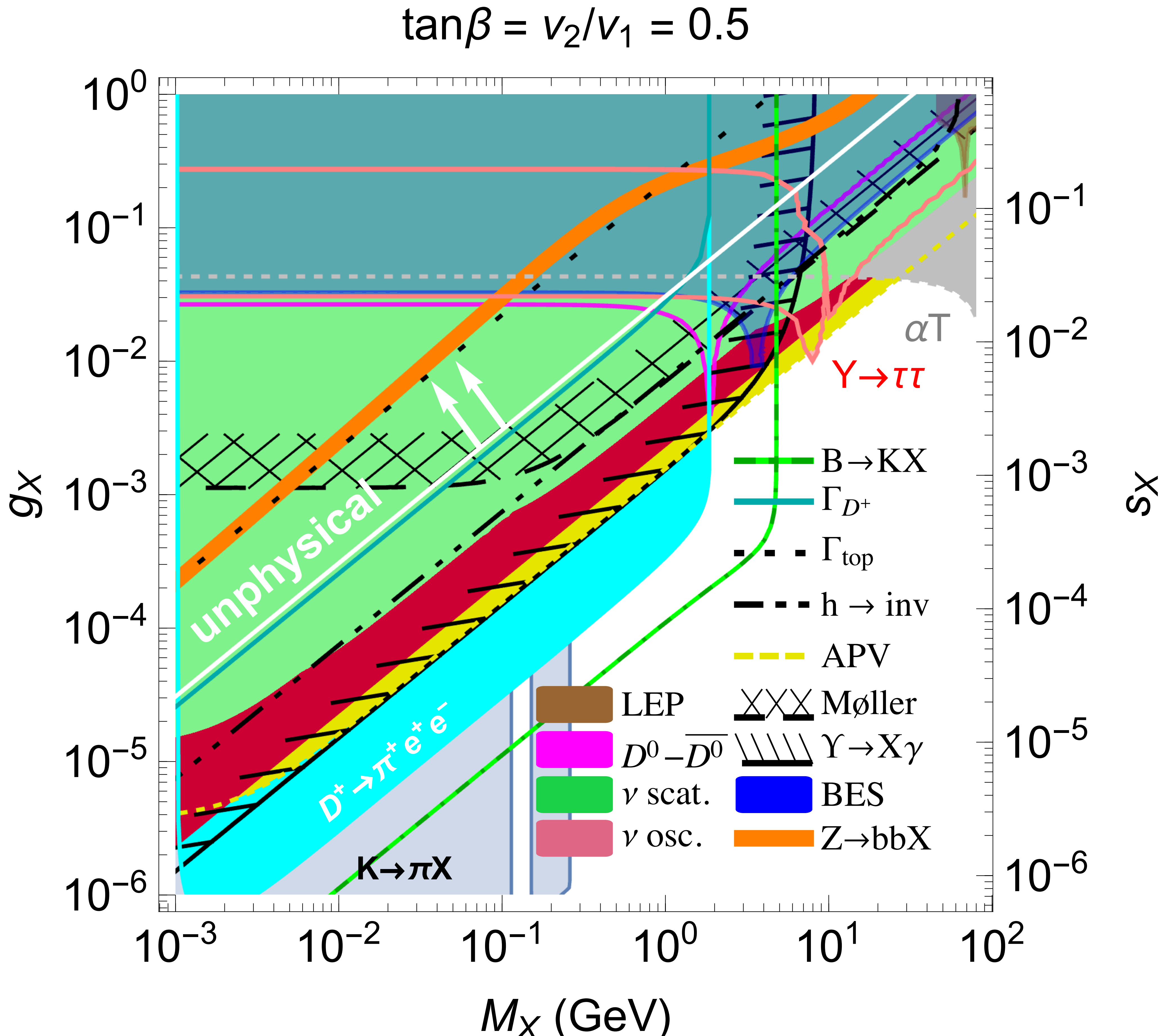
$$D - \bar{D} : \quad \left(\frac{100\,\text{GeV}}{m_\varphi} \right) \text{Re} \left(\frac{h_{12}^u}{\sqrt{2} m_c / v} \right) \lesssim 3.4 \times 10^{-3}$$

Babu Meng 2009
Babu Nandi 2000
Nir Silverman 1990
Buras Jamin Weisz 1990
Lenz 2012

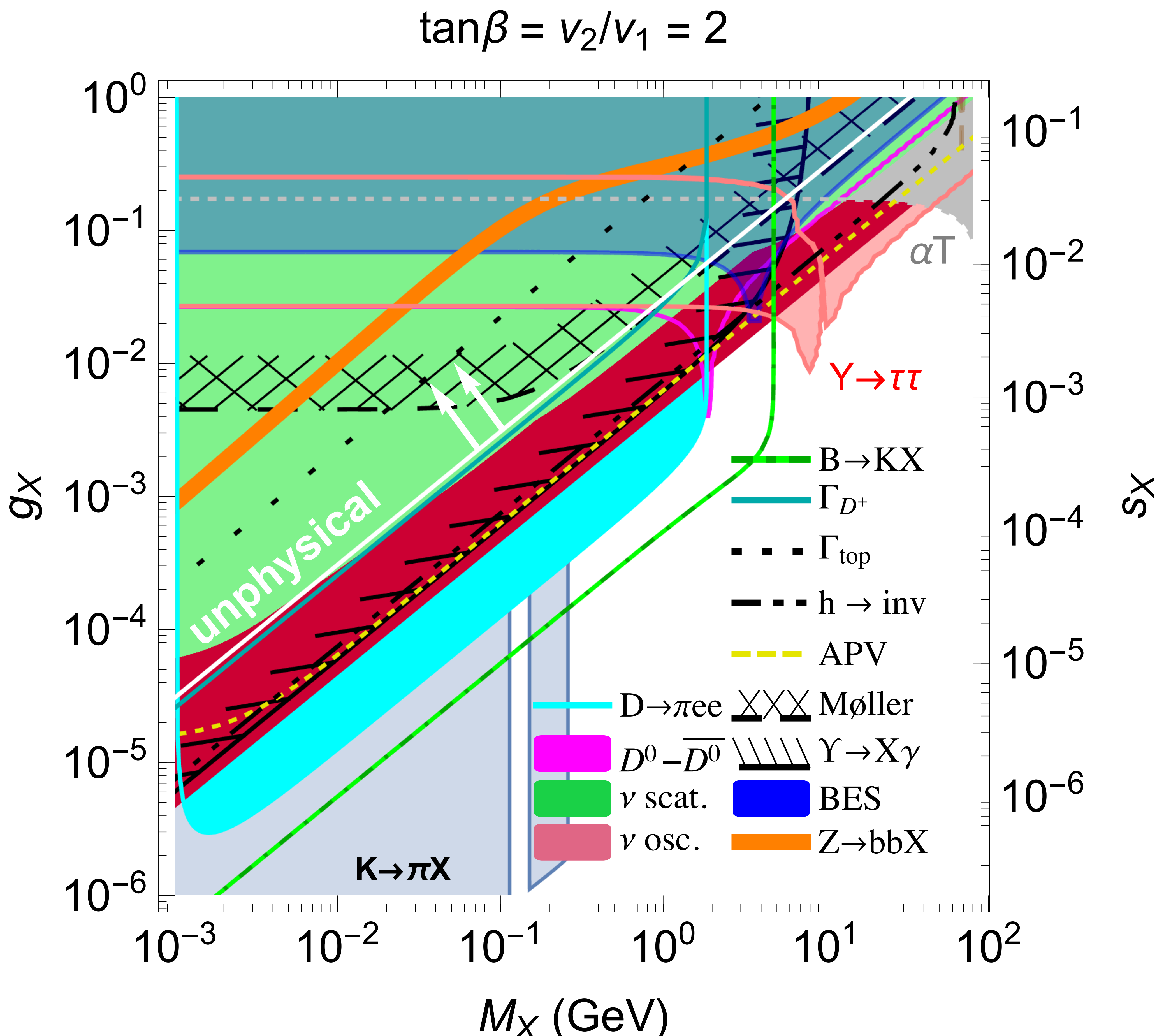
Phenomenology



Babu, Friedland, Machado, Mocioiu, in prep.

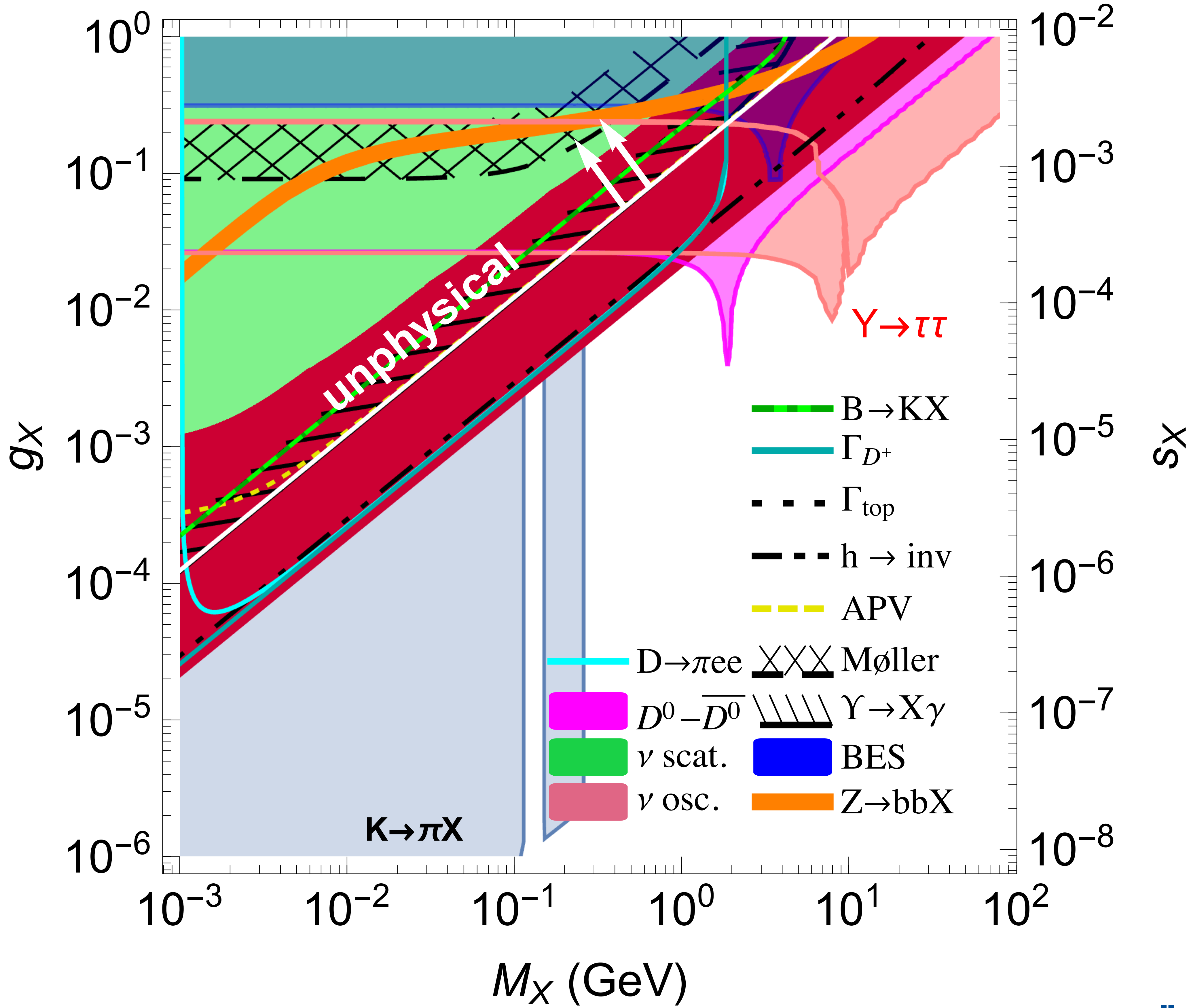


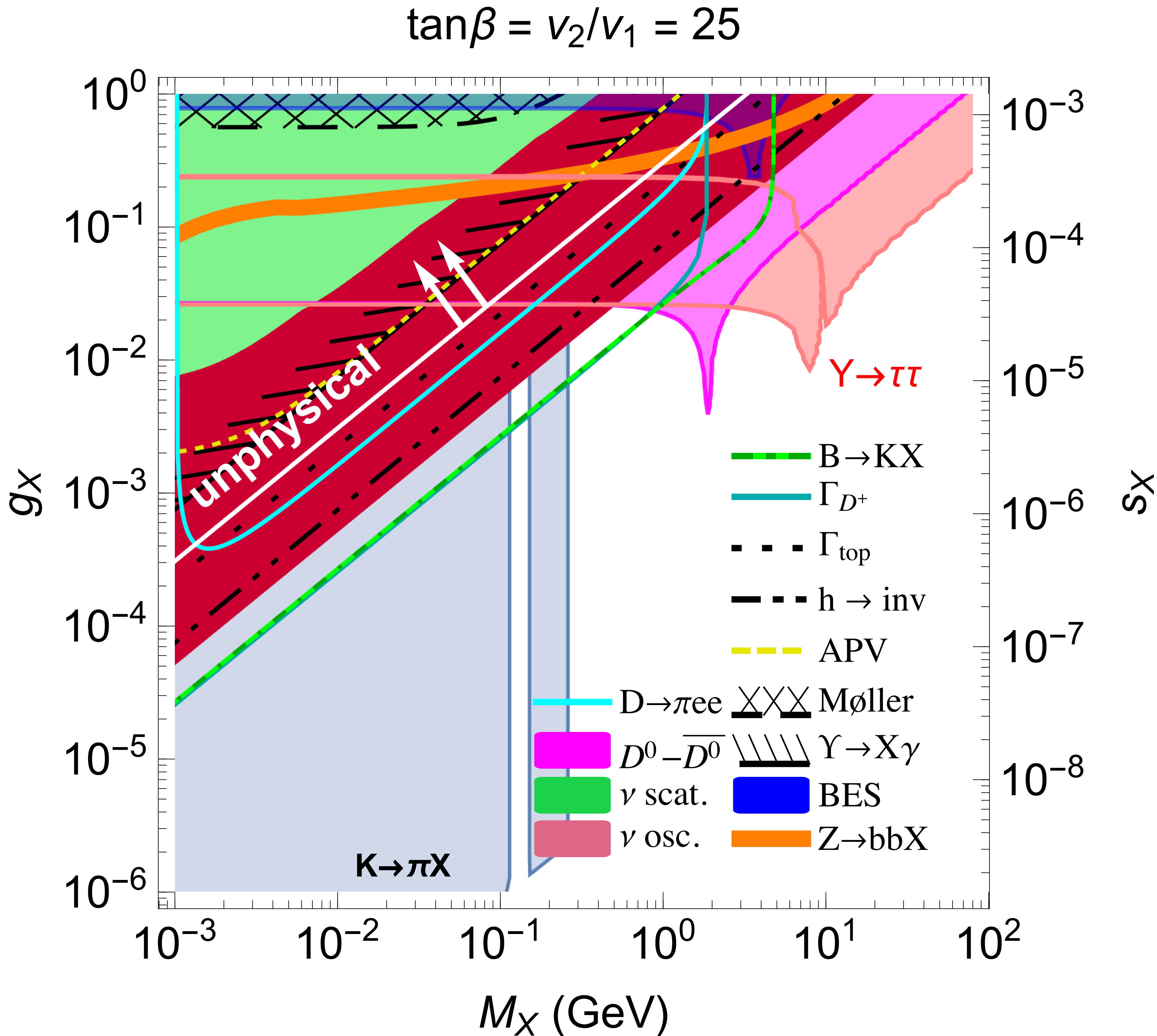
tanβ = v2/v1 = 0.5
gX
sX
MX (GeV)
unphysical
D+ → π+ e+ e−
K→πX
αT
ϒ→ττ
B→KX
ΓD+
Γtop
h → inv
APV
LEP
D0−D0
ν scat.
ν osc.
Møller
ϒ→Xγ
BES
Z→bbX



tanβ = v2/v1 = 2
gX
sX
MX (GeV)
unphysical
αT
Υ→ττ
B→KX
ΓD+
Γtop
h → inv
APV
D→πee
Møller
D0−D̄0
Υ→Xγ
ν scat.
BES
ν osc.
Z→bbX
K→πX

tan$\beta = v_2/v_1 = 10$





$\tan\beta = v_2/v_1 = 25$
g_X
s_X
M_X (GeV)
unphysical
$\Upsilon \to \tau\tau$
K→πX
B→KX
Γ_{D^+}
Γ_{top}
h → inv
APV
D→πee
Møller
$D^0 - \overline{D^0}$
Υ→Xγ
ν scat.
BES
ν osc.
Z→bbX