Non-Abelian kinetic mixing: transfer CP violation with dark photon

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Phase Transitions, Gravitational Waves, and Colliders (SPCS 2023)

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Electroweak baryogenesis

We want to explain baryon asymmetry in our universe (BAU)

$$Y_B \equiv \frac{n_b}{s} = (8.50 \pm 0.11) \times 10^{-11}$$

<u>Sakharov conditions:</u>

• Baryon number violation	electroweak sphalerons	✔
• C and CP violation	complex phases	✗
• Depature from thermal equilibrium	1st order phase transition	✗

Electroweak baryogenesis

EWPT: 1st order phase transition

The most economic way: introducing additional scalar(s)

singlet — **S. Profumo, M. J. Ramsey-Musolf, G. Shaughnessy, JHEP 08 (2007) 010**

doublet — **J. M. Cline, P. Lemieux, Phys. Rev. D 55 (1997) 3873**

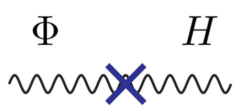
triplet — **H. H. Patel, M. J. Ramsey-Musolf, Phys. Rev. D 88 (2013) 035013**

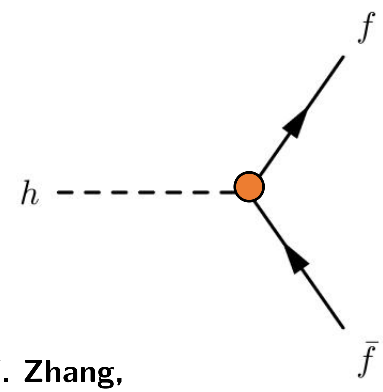
leptoquark — **B. Fu, S. F. King, JCAP 05 (2023) 055**

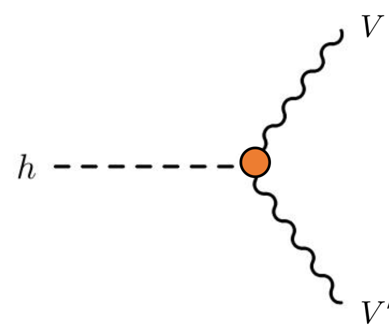
Electroweak baryogenesis

CPV: complex phases

anywhere in the SM sector, but mostly studied in





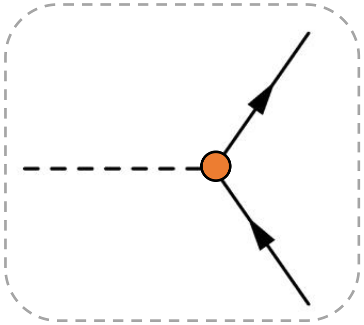


S. Inoue, M. J. Ramsey-Musolf, Y. Zhang, Phys.Rev.D 89 (2014) 115023

Electroweak baryogenesis

CPV: complex phases

less studied in the extended sector



Electroweak baryogenesis

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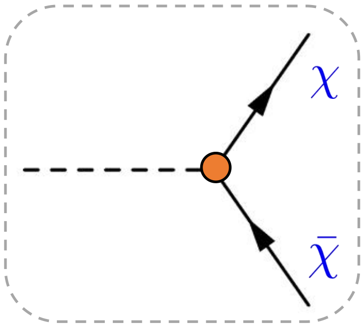


dark matter

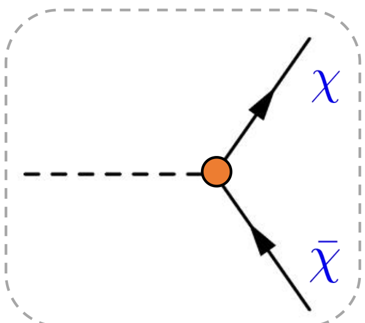
M. Carena, M. Quirós, Y. Zhang, Phys. Rev. Lett. 122, 201802 (2019)

Electroweak baryogenesis

CPV: complex phases

less studied in the extended sector

dark sector



visible sector

M. Carena, M. Quirós, Y. Zhang, Phys. Rev. Lett. 122, 201802 (2019)

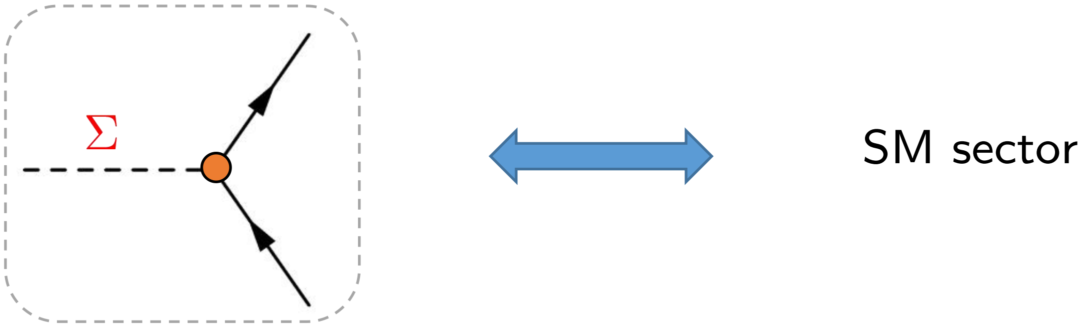
dark matter

challenge: transfer CP violation from the *dark* sector
to the *visible* sector

Electroweak baryogenesis

CPV: complex phases

less studied in the extended sector



real triplet scalar

Real tiplet scalar

Real triplet scalar (1, 3, 0):

$$\mathbf{\Sigma} = \frac{1}{2}\begin{pmatrix} \Sigma^0 & \sqrt{2}\Sigma^+ \\ \sqrt{2}\Sigma^- & -\Sigma^0 \end{pmatrix}$$

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- dark matter candidate

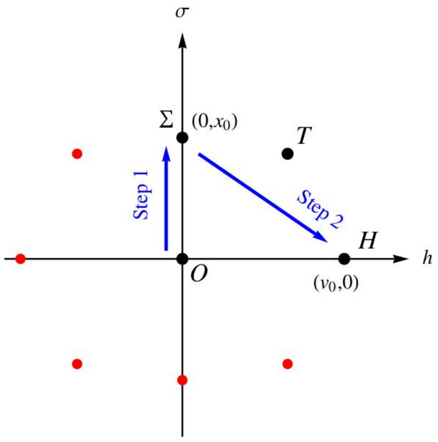
$$\langle \Sigma^0 \rangle = 0$$

M. Cirelli, N. Fornengo and A. Strumia, NPB 753, 178 (2006)
P. Fileviez Pérez, H. H. Patel, M. J. Ramsey-Musolf, K. Wang, Phys. Rev. D 79 (2009) 055024

- 1st order phase transition

$$\langle \Sigma^0 \rangle = x_0 \to 0$$

H. H. Patel, M. J. Ramsey-Musolf, Phys. Rev. D 88 (2013) 035013



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- neutrino masses?

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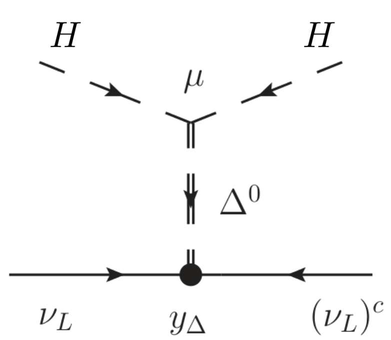
- neutrino masses?

In case of a complex triplet scalar (1, 3, 1)



$$\Delta = \begin{pmatrix} \frac{\Delta^+}{\sqrt{2}} & \Delta^{++} \\ \Delta^0 & -\frac{\Delta^+}{\sqrt{2}} \end{pmatrix} \qquad \mathcal{L} \supset -(Y_\Delta)_{ij}\,\overline{L_i^C} i\sigma^2 \Delta L_j + \text{ h.c.}$$

$\Delta^0 \to \langle \Delta^0 \rangle$ hypercharge: $-1/2 - 1/2 + 1 = 0$

neutrino mass in type-II seesaw mechanism

Real tiplet scalar

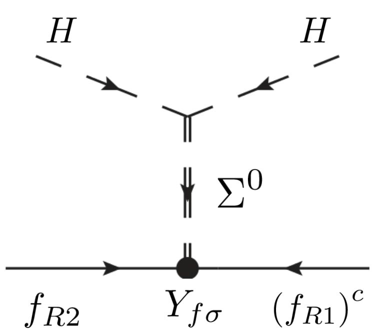
Real triplet scalar (1, 3, 0):

$$\Sigma = \frac{1}{2}\begin{pmatrix} \Sigma^0 & \sqrt{2}\Sigma^+ \\ \sqrt{2}\Sigma^- & -\Sigma^0 \end{pmatrix}$$

- neutrino masses?

$$4\,\mathrm{Tr}\left(\bar{f}^c_{Ri} Y_{f\sigma} \Sigma f_{Rj}\right) = i Y_{f\sigma} \bar{f}^a_{Li} \Sigma^b f^c_{Rj} \epsilon^{abc}$$

$$Y_{f\sigma 12}\left(\overline{\left(f^+_{R1}\right)^c} f^+_{R2} - \overline{\left(f^-_{R1}\right)^c} f^-_{R2}\right)\left(v_\Sigma + \Sigma^0\right)$$



$\Sigma^0 \to \langle \Sigma^0 \rangle$ hypercharge: $-1/2 + 1/2 + 0 = 0$

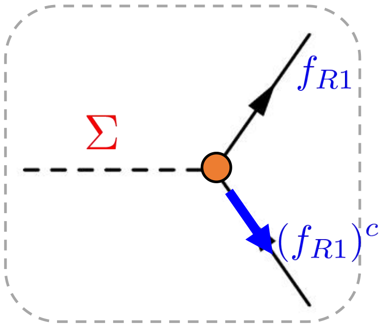
neutrino mass in type-III seesaw mechanism

Y. Cheng, X.-G. He, M. J. Ramsey-Musolf, J. Sun, Phys.Rev.D 105 (2022) 095010

Electroweak baryogenesis

CPV: complex phases

less studied in the extended sector

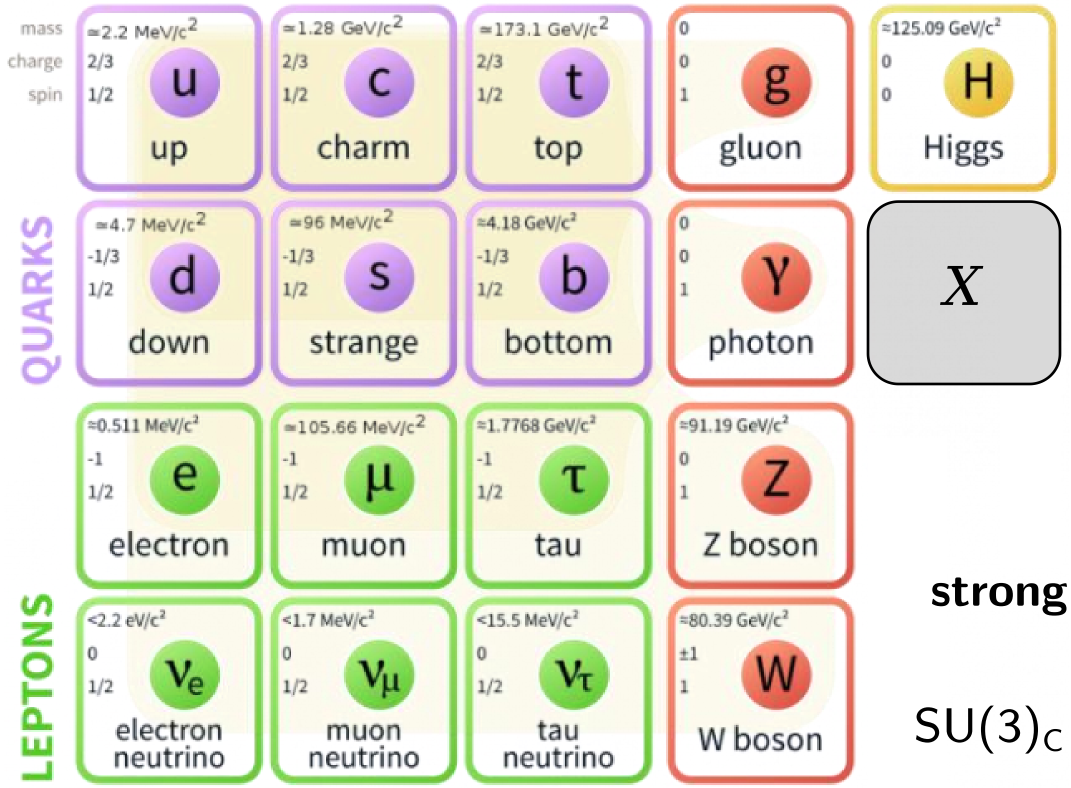


real triplet scalar

SM sector

task : **finding a suitable mechanism** to transfer CP violation from the extended sector to the SM sector

Dark photon as a simple extension



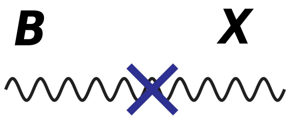
strong	**weak**	**EM**	
$SU(3)_C \otimes$	$SU(2)_L \otimes$	$U(1)_Y \otimes$	$U(1)_x$
g	W/Z	γ	X

Dark photon as a simple extension

- kinetic mixing

Abelian case:

$$\mathcal{L} \supset -\frac{1}{4}B_{\mu\nu}B^{\mu\nu} - \frac{1}{4}X_{\mu\nu}X^{\mu\nu} - \frac{\sigma}{2}X_{\mu\nu}B^{\mu\nu}$$



B. Holdom, Phys. Lett. B166, 196 (1986)
R. Foot, X.-G. He Phys.Lett. B267 (1991) 509

- Where does σ comes from?

Dark photon as a simple extension

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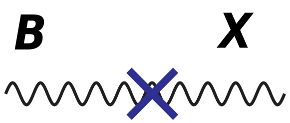
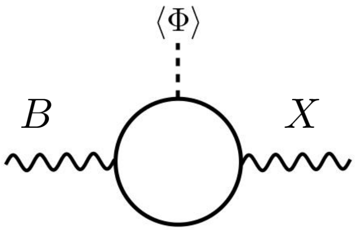


If $U(1)_x$ is fundamental, σ exists in the UV

If $U(1)_x$ is from other symmetry breaking

B. Holdom, Phys. Lett. B166, 196 (1986)
R. Foot, X.-G. He Phys.Lett. B267 (1991) 509



- Where does σ comes from?

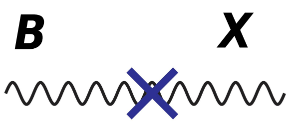
$$\sigma \sim \left(16\pi^2\right)^{-1} g_Y g_X$$

Dark photon as a simple extension

- kinetic mixing

Abelian case:

$$\mathcal{L} \supset -\frac{1}{4}B_{\mu\nu}B^{\mu\nu} - \frac{1}{4}X_{\mu\nu}X^{\mu\nu} - \frac{\sigma}{2}X_{\mu\nu}B^{\mu\nu}$$



$$\mathcal{L} \supset -\frac{1}{4}\hat{B}_{\mu\nu}\hat{B}^{\mu\nu} - \frac{1}{4}\hat{X}_{\mu\nu}\hat{X}^{\mu\nu}$$

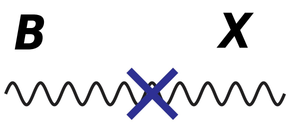
B. Holdom, Phys. Lett. B166, 196 (1986)
R. Foot, X.-G. He Phys.Lett. B267 (1991) 509

- Where does σ go?

Dark photon as a simple extension

- kinetic mixing

Abelian case:



$$\mathcal{L} \supset -\frac{1}{4}B_{\mu\nu}B^{\mu\nu} - \frac{1}{4}X_{\mu\nu}X^{\mu\nu} - \frac{\sigma}{2}X_{\mu\nu}B^{\mu\nu}$$

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R. Foot, X.-G. He Phys.Lett. B267 (1991) 509

- Where does σ go?

other terms in the Lagrangian

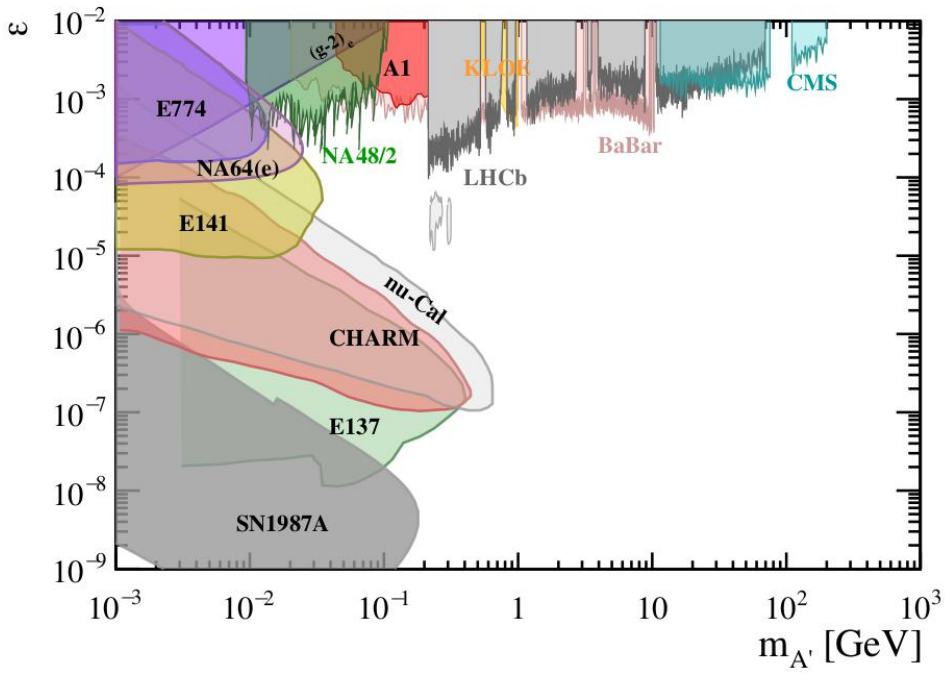
$$\mathcal{L} \supset j_B^\mu B_\mu + j_X^\mu X_\mu$$

Special attention should be paid if dark photon is exactly massless

J.-X. Pan, M. He, X.-G. He, GL, Nucl.Phys.B 953 (2020) 114968

Dark photon as a simple extension

- various constraints and (projected) searches



M. Fabbrichesi, E. Gabrielli, G. Lanfranchi, 2005.01515

Dark photon as a simple extension

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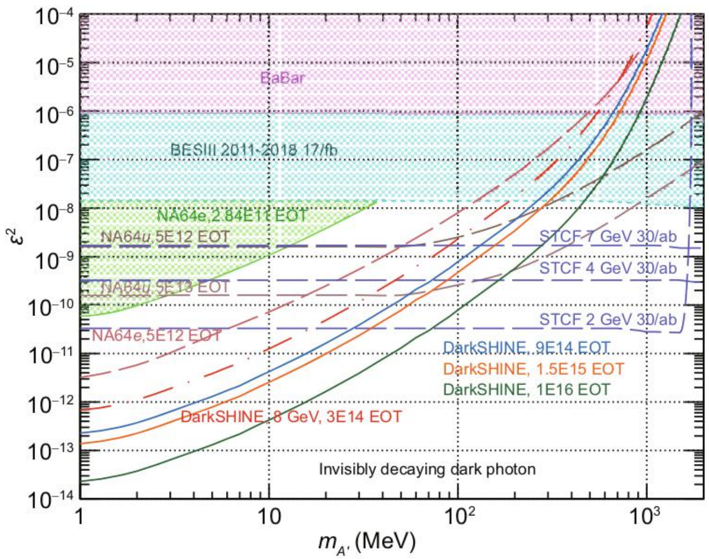
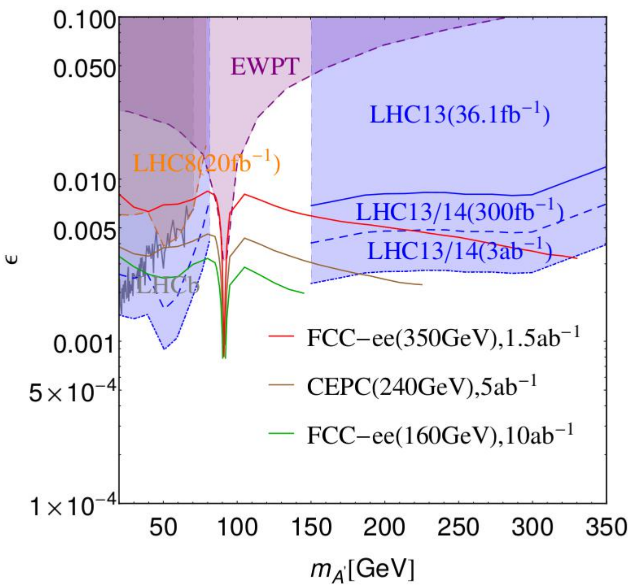


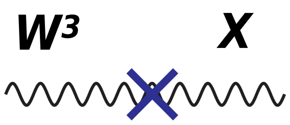


DarkSHINE experiment, Sci.China Phys.Mech.Astron. 66 (2023) 1, 211062

M. He, X.-G. He, C.-K. Huang, GL, JHEP 03 (2018) 139

Non-Abelian kinetic mixing

- Effective field theory



$$\mathcal{L} \supset -\frac{1}{4} X_{\mu\nu} X^{\mu\nu} - \frac{\beta}{\Lambda} \mathrm{Tr}\left[W_{\mu\nu}\Sigma\right] X^{\mu\nu}$$

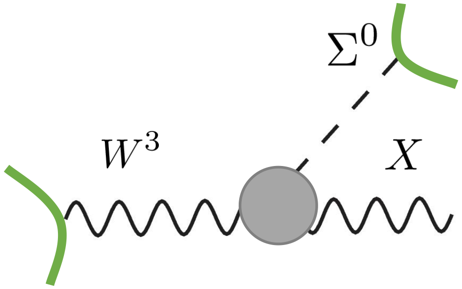
$$W_{\mu\nu} = W^a_{\mu\nu}\tau^a/2 \qquad \Sigma = \frac{1}{2}\begin{pmatrix} \Sigma^0 & \sqrt{2}\Sigma^+ \\ \sqrt{2}\Sigma^- & -\Sigma^0 \end{pmatrix}$$

C. A. Argüelles, X.-G. He, G. Ovanesyan, T. Peng, M. J. Ramsey-Musolf, Phys.Lett. B770 (2017) 101

- X interacts with the SM only through the non-Abelian kinetic mixing

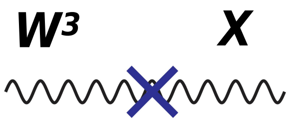
$$\langle \Sigma^0 \rangle = v_\Sigma$$

- Σ can also interact with th SM through the mixing $\Sigma - H$



Non-Abelian kinetic mixing

- Effective field theory



$$\mathcal{L} \supset -\frac{1}{4} X_{\mu\nu} X^{\mu\nu} - \frac{\beta}{\Lambda} \mathrm{Tr}\left[W_{\mu\nu}\Sigma\right] X^{\mu\nu} \boxed{- \frac{\tilde{\beta}}{\Lambda} \mathrm{Tr}\left[W_{\mu\nu}\Sigma\right] \tilde{X}^{\mu\nu}}$$

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K. Fuyuto, X.-G. He, GL, M. J. Ramsey-Musolf, Phys.Rev.D 101 (2020) 075016

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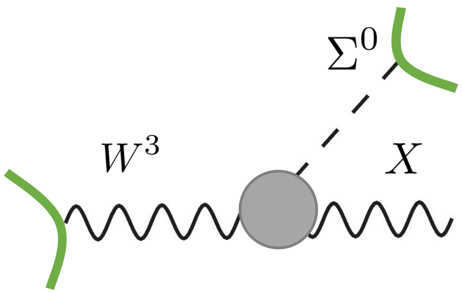
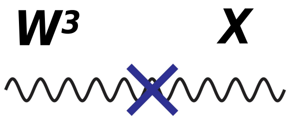


Non-Abelian kinetic mixing

- Effective field theory



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K. Fuyuto, X.-G. He, GL, M. J. Ramsey-Musolf, Phys.Rev.D 101 (2020) 075016

$$\boxed{-\frac{\beta}{\Lambda}\mathrm{Tr}[W_{\mu\nu}\Sigma]X^{\mu\nu} - \frac{\tilde{\beta}}{\Lambda}\mathrm{Tr}[W_{\mu\nu}\Sigma]\tilde{X}^{\mu\nu}}$$

$$W^3_{\mu\nu} = \partial_\mu W^3_\nu - \partial_\mu W^3_\nu + g\epsilon^{3bc} W^b_\mu W^c_\nu$$

vev

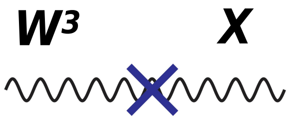
Σ^0

vev (Σ^0)

$\boxed{X\text{-}W^3 \text{ mixing}}$ $\boxed{\text{CPV } \Sigma^0 W^3 X \text{ int.}}$ $\boxed{\text{CPV } X(\Sigma^0)W^+W^- \text{ int.}}$

Non-Abelian kinetic mixing

- Effective field theory



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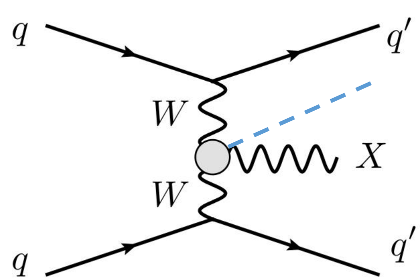
K. Fuyuto, X.-G. He, GL, M. J. Ramsey-Musolf, Phys.Rev.D 101 (2020) 075016

Observable:

CPV asymmetry at colliders

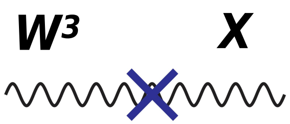
CPV $X(\Sigma^0)W^+W^-$ int.



azimuthal angle distribution: sensitivity is insufficient

Non-Abelian kinetic mixing

- Effective field theory



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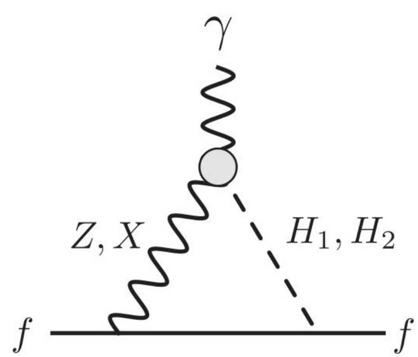
K. Fuyuto, X.-G. He, GL, M. J. Ramsey-Musolf, Phys.Rev.D 101 (2020) 075016

Observable:

electric dipole moments $\mathcal{L}^{\mathrm{EDM}} = -\frac{i}{2} d_f \bar{f} \sigma^{\mu\nu} \gamma_5 f F_{\mu\nu}$

CPV $\Sigma^0 W^3 X$ int.

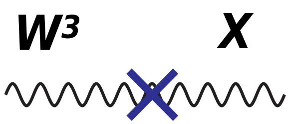


$$\begin{pmatrix} H_1 \\ H_2 \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} h \\ \Sigma^0 \end{pmatrix}$$

$$-\frac{\tilde{\beta}}{2\Lambda} s_W A_{\mu\nu} (c_\theta H_2 + s_\theta H_1)(c_\xi \tilde{X}^{\mu\nu} - s_\xi \tilde{Z}^{\mu\nu})$$

Non-Abelian kinetic mixing

- Effective field theory



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K. Fuyuto, X.-G. He, GL, M. J. Ramsey-Musolf, Phys.Rev.D 101 (2020) 075016

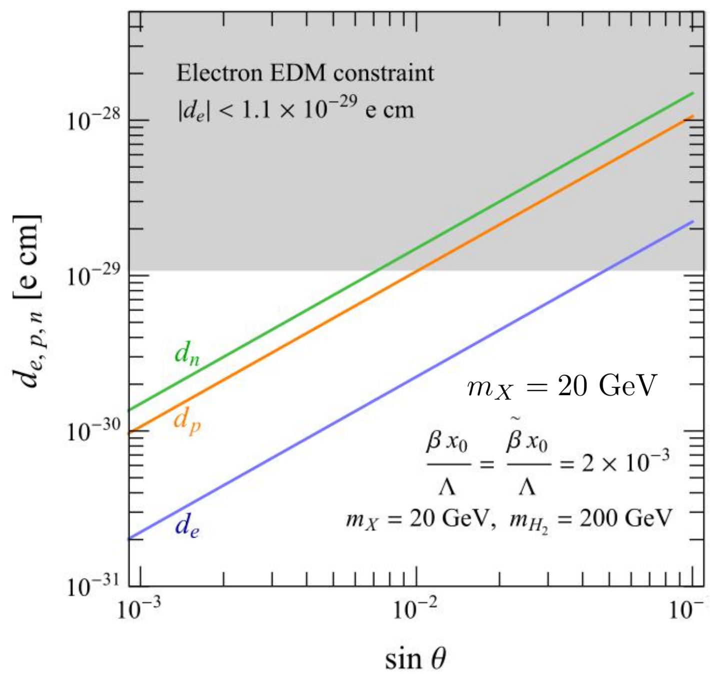
Observable:

electric dipole moments

$$d_f = \frac{e}{8\pi^2} \frac{m_f}{v} c_\theta s_\theta \Big[C_Z V_Z^f f\left(r_{ZH_1}, r_{ZH_2}\right) + C_X V_X^f f\left(r_{XH_1}, r_{XH_2}\right) \Big]$$

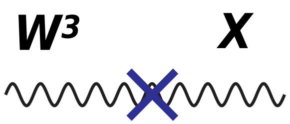
$$C_Z = \frac{\tilde{\beta}}{\Lambda} s_W s_\xi, \quad C_X = \frac{\tilde{\beta}}{\Lambda} s_W c_\xi$$

$$V_X = \left(c_\xi \alpha_{ZX} - s_\xi\right) v_Z + Q_f \alpha_{AX} c_\xi s_W c_W$$
$$A_X = \left(c_\xi \alpha_{ZX} - s_\xi\right) a_Z$$



Non-Abelian kinetic mixing

- Effective field theory



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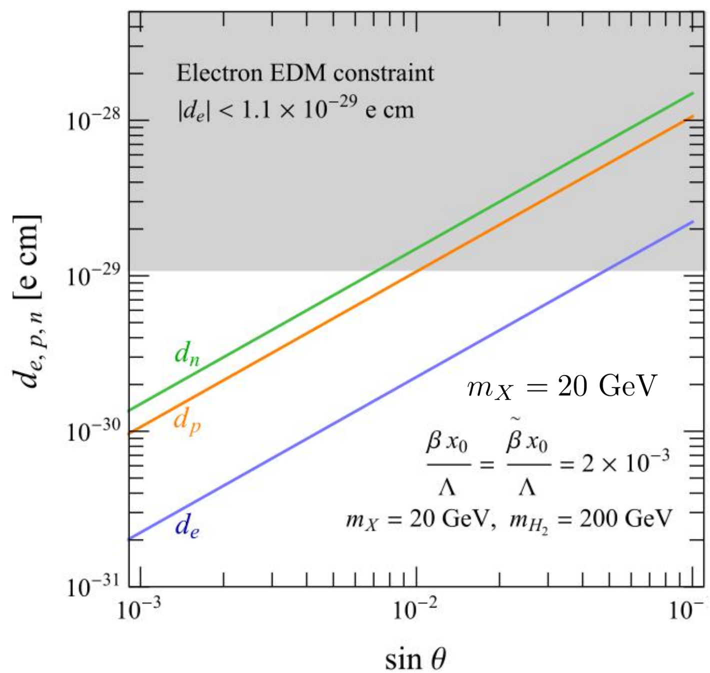
K. Fuyuto, X.-G. He, GL, M. J. Ramsey-Musolf, Phys.Rev.D 101 (2020) 075016

Observable:

electric dipole moments

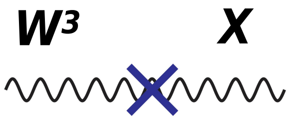
Feature:
new CPV source is associated to the **light** and weakly coupled new physics

Snowmass 2203.08103



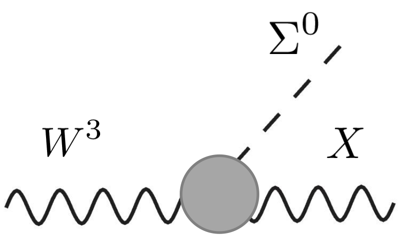
Non-Abelian kinetic mixing

- UV completion



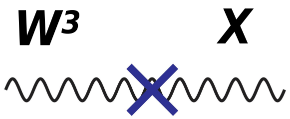
$$\mathcal{L} \supset -\frac{1}{4} X_{\mu\nu} X^{\mu\nu} - \frac{\beta}{\Lambda} \mathrm{Tr}\left[W_{\mu\nu}\Sigma\right] X^{\mu\nu} - \frac{\tilde{\beta}}{\Lambda} \mathrm{Tr}\left[W_{\mu\nu}\Sigma\right] \tilde{X}^{\mu\nu}$$

$$\boldsymbol{W_{\mu\nu} = W^a_{\mu\nu}\tau^a/2} \qquad \boldsymbol{\Sigma = \frac{1}{2}\begin{pmatrix} \Sigma^0 & \sqrt{2}\Sigma^+ \\ \sqrt{2}\Sigma^- & -\Sigma^0 \end{pmatrix}}$$



Non-Abelian kinetic mixing

- UV completion



$$\mathcal{L} \supset -\frac{1}{4} X_{\mu\nu} X^{\mu\nu} - \frac{\beta}{\Lambda} \mathrm{Tr}\left[W_{\mu\nu}\Sigma\right] X^{\mu\nu} - \frac{\tilde{\beta}}{\Lambda} \mathrm{Tr}\left[W_{\mu\nu}\Sigma\right] \tilde{X}^{\mu\nu}$$

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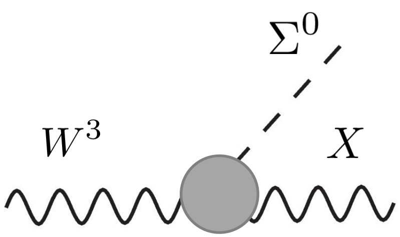
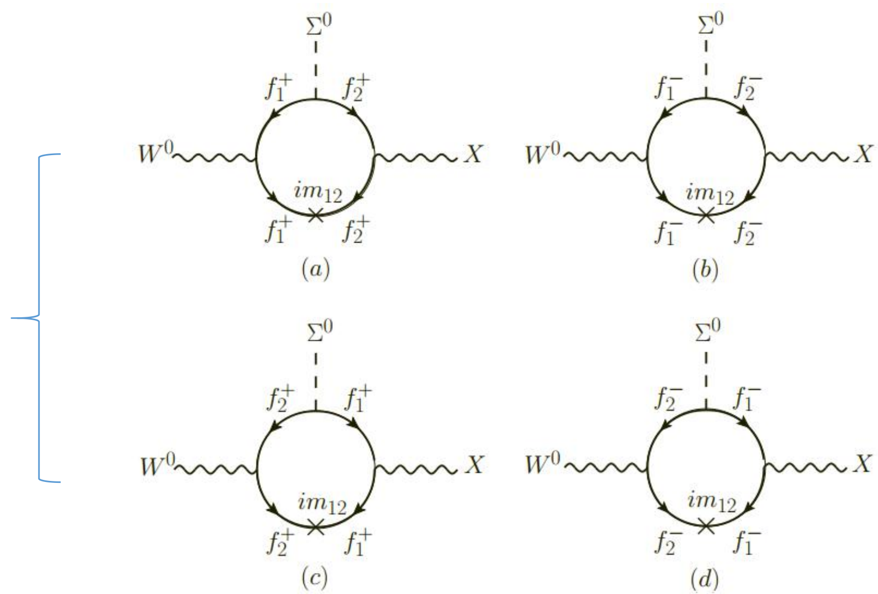
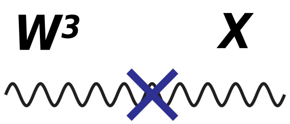




Non-Abelian kinetic mixing

- UV completion



$$\mathcal{L} \supset -\frac{1}{4} X_{\mu\nu} X^{\mu\nu} - \frac{\beta}{\Lambda} \mathrm{Tr}\left[W_{\mu\nu}\Sigma\right] X^{\mu\nu} - \frac{\tilde{\beta}}{\Lambda} \mathrm{Tr}\left[W_{\mu\nu}\Sigma\right] \tilde{X}^{\mu\nu}$$

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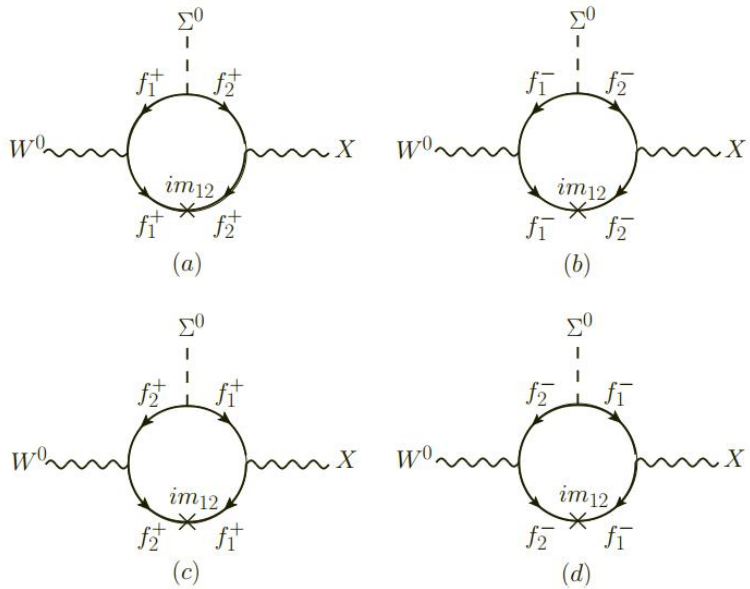
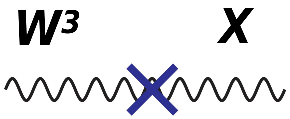
$$\frac{\tilde{\beta}_X}{\Lambda} = \frac{1}{2\pi^2} g g_X x_f \,\mathrm{Im}\left(m_{12} Y^*_{f\sigma}\right) \times \left[f\left(m_1, m_2, p_W, p_X\right) + f\left(m_2, m_1, p_W, p_X\right)\right]$$

$$\frac{\beta_X}{\Lambda} = \frac{1}{2\pi^2} g g_X x_f \,\mathrm{Re}\left(m_{12} Y^*_{f\sigma}\right) \times \left[f\left(m_1, m_2, p_W, p_X\right) + f\left(m_2, m_1, p_W, p_X\right)\right]$$



Non-Abelian kinetic mixing

- UV completion



$$\mathcal{L} \supset -\frac{1}{4} X_{\mu\nu} X^{\mu\nu} - \frac{\beta}{\Lambda} \mathrm{Tr}\left[W_{\mu\nu}\Sigma\right] X^{\mu\nu} - \frac{\tilde{\beta}}{\Lambda} \mathrm{Tr}\left[W_{\mu\nu}\Sigma\right] \tilde{X}^{\mu\nu}$$

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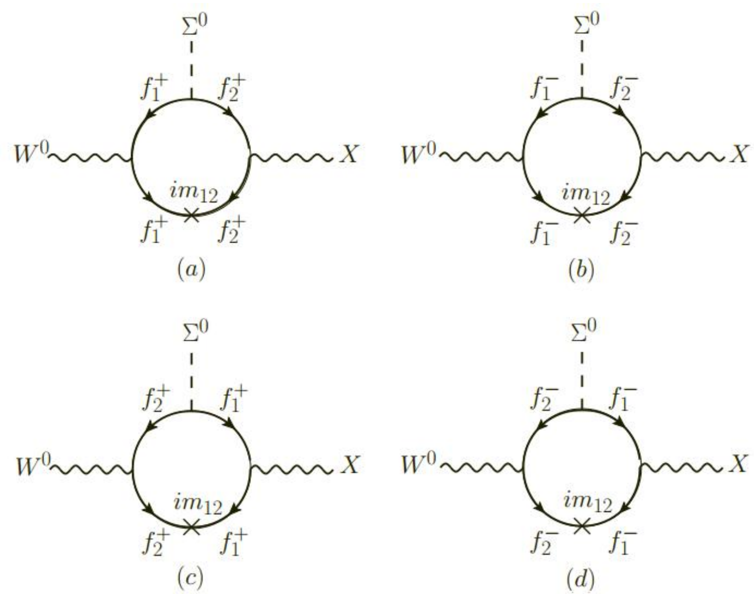
$$-\bar{L}_L Y_e \tilde{H} E_R - \bar{L}_L Y_{fL3} \tilde{H} f_{R3} - \bar{f}^c_{R1} Y_{fs1} S_X f_{R1}$$
$$-\bar{f}^c_{R2} Y_{fs2} S^\dagger_X f_{R2} - \bar{f}^c_{R_1} m_{12} f_{R2} - \bar{f}^c_{R3} m_{33} f_{R3}$$
$$-\bar{Q}_L Y_u H U_R - \bar{Q}_L Y_d \tilde{H} D_R.$$

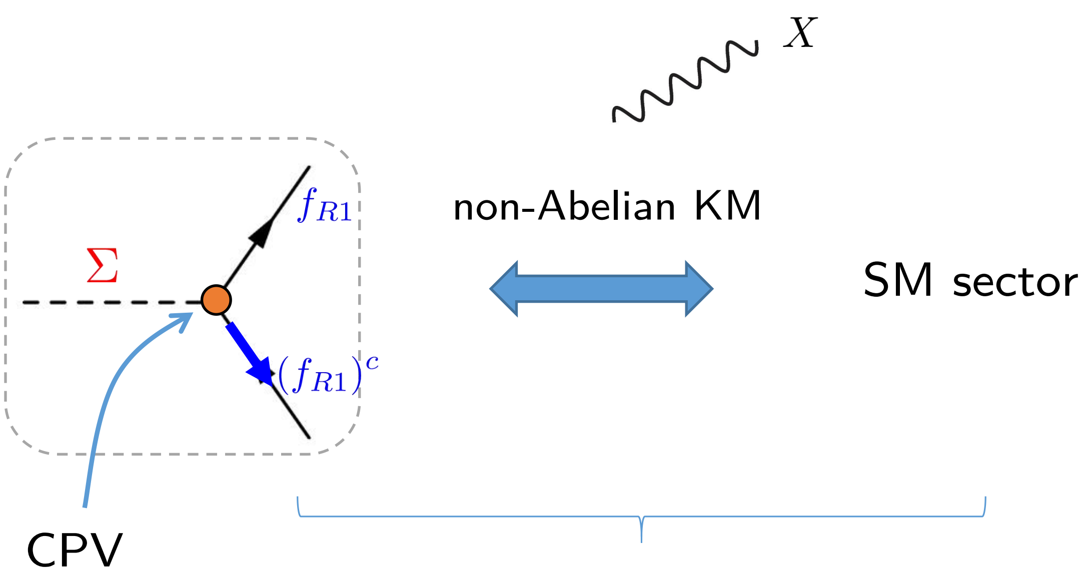


Neutrino masses:

$$\mathcal{L}_m = -\frac{1}{2}(\bar{\nu}_L, \bar{\nu}^c_R)\begin{pmatrix} 0 & M_D \\ M_D^T & M_R \end{pmatrix}\begin{pmatrix} \nu^c_L \\ \nu_R \end{pmatrix}$$
$$-(\bar{E}_L, \bar{f}_L)\begin{pmatrix} m_e & \sqrt{2}M_D \\ 0 & M_R \end{pmatrix}\begin{pmatrix} E_R \\ f_R \end{pmatrix}$$

Summary

- Real triplet scalar enables a strong 1st order phase transition
- The CPV interaction between real triplet scalar and triplet leptons can explain neutrino masses
- Non-Abelian kinetic mixing assisted with dark photon can transfer CP violation from the extended sector to the SM sector



a successful EW baryogenesis?