DESY.

2HDM subgroup

Phenomenology of a new gauge U boson

Directors: Pierre Fayet (LPENS, ENS)
&
Mikhail Shaposhnikov (LPPC, EPFL)

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María O. Olea Romacho

Contents

Abstract

- New fundamental interactions may exist
- Extra U(1) gauge group resulting in a new neutral gauge boson, the U boson
- Complete example of the scientific procedure in Beyond the Standard Model (BSM) physics
- Exclusion region from early beam dump experiments for the mass-coupling parameter space for an axially and feebly coupled light U boson

Motivation

- Study the simplest case of abelian symmetry groups associated to new neutral spin-1 mediators
- Natural consequence of a number of BSM theories
- The U boson, if light, is compatible with a role of mediator of light dark matter particles interactions

Framework

- General form of the extra U(1) generator before and after Higgs mechanism: restricted by gauge invariance of Yukawa couplings and the Higgs sector content
  - New current: vectorial or may also have an axial part
    Axially coupled U boson $\rightarrow$ much less explored situation
- Mass: generated by a Higgs singlet?
- Mixing effects: either heavy or feebly coupled U bosons
- Matter fields: DM or just SM particles?

Framework

- Summary:
  - **2 HIGGS DOUBLETS + 1 SINGLET**
  - Light ($\sim 1.02 - \sim 100\,\text{MeV}$) neutral gauge boson with feeble non-vanishing axial couplings to SM particles
- Probe this theory and point out the special qualitative and quantitative behavior of a light and axially coupled U boson in the ultra-relativistic limit

Theoretical background: General expression of the extra U(1) symmetry generator

$$\varphi_{u,d} = \begin{pmatrix} \varphi^{+}_{u,d} \\ \varphi^{0}_{u,d} \end{pmatrix} \qquad Y_{u,d} = 1$$

$$\left\langle \varphi^0_u \right\rangle = \frac{v_u}{\sqrt{2}}, \quad \left\langle \varphi^0_d \right\rangle = \frac{v_d}{\sqrt{2}}, \quad v^2 \quad \left(v_u^2 + v_d^2 \right) = \frac{1}{G_F \sqrt{2}} \simeq (246\,\mathrm{GeV})^2$$

$SU(2) \times U(1)_Y \times U(1)_F$ covariant derivative:

$$iD^{\mu} = i\partial^{\mu} - \left(gT \cdot W^{\mu} + \frac{1}{2} g' Y W'^{\mu} + \frac{1}{2} g'' F W''^{\mu} \right)$$

Theoretical background: General expression of the extra U(1) symmetry generator

$$\mathcal{L}_{\text{Yukawa}} =$$
$$-i\sqrt{2}\left[\frac{m_u}{v_u}\overline{u_R}\begin{pmatrix}\varphi_u{}^0, & -\varphi_u{}^+\end{pmatrix}\begin{pmatrix}u_L\\ d_L\end{pmatrix} + \frac{m_d}{v_d}\overline{d_R}\begin{pmatrix}\varphi_d{}^-, & \varphi_d{}^{0*}\end{pmatrix}\begin{pmatrix}u_L\\ d_L\end{pmatrix}\right.$$
$$\left.\frac{m_e}{v_d}\overline{e_R}\begin{pmatrix}\varphi_d{}^-, & \varphi_d{}^{0\,*}\end{pmatrix}\begin{pmatrix}\nu_L\\ e_L\end{pmatrix}\right]+\text{h.c.}$$

$$F_{ax} = \begin{cases} +1/2 & \text{for } u_L, d_L, \nu_L, e_L \\ -1/2 & \text{for } u_R, d_R, e_R \\ -1 & \text{for } \varphi_u \\ +1 & \text{for } \varphi_{d,e} \end{cases}$$

$$F = \alpha B + \beta L + \gamma Y + \mu F_{ax} \rightarrow \boldsymbol{F = F_{ax}}$$

Theoretical background: Z-U mixing effects and U boson mass

$F_{\varphi_{u,d}} = 0 \rightarrow$ No mixing effects

$$F_{\varphi_{u,d}} \neq 0 \rightarrow \mathcal{L}_m = -\frac{1}{8} \sum_{k=u,d} v_k^2 \left(-gW_3^\mu + g^{'} W'^{\mu} + g^{''} F_{\varphi_k} W''^{\mu}\right)^2$$

$$\mathcal{M}^2 = \frac{1}{4}\begin{pmatrix} \left(v_u^2+v_d^2\right)\left(g^2+g'^2\right) & -\left(v_u^2 F_u + v_d^2 F_d\right)\sqrt{g^2+g'^2}g'' \\ -\left(v_u^2 F_u + v_d^2 F_d\right)\sqrt{g^2+g'^2}g'' & \left(v_u^2+v_d^2\right) g''^2 \end{pmatrix}$$

$$\boldsymbol{v_u = v_d} \qquad \boldsymbol{F_u = 1,\ F_d = -1}$$

Theoretical background: Z-U mixing effects and U boson mass

Higgs singlet with a v.e.v. $\langle\sigma\rangle = \frac{w}{\sqrt{2}} \rightarrow$

$$m_U^2 = \underbrace{\frac{1}{4}g''v^2}_{\text{doublet}} + \underbrace{\boldsymbol{\frac{1}{4}g''^2 F_w^2 w^2}}_{\text{singlet}} = \frac{1}{4}g''^2 v^2/r^2$$

$$r^2 = \frac{1}{1+\left(\frac{F_w w}{v}\right)^2} \leq 1$$

Theoretical background: Z-U mixing effects and U boson mass

Due to $F = F_{ax} \rightarrow$ universal current:

$$J_U^\mu = \sum_{q,l\,(SM)} - \left(\frac{g''}{4}\right) \overline{q}\gamma^\mu\gamma_5 q - \left(\frac{g''}{4}\right) \overline{l}\gamma^\mu\gamma_5 l$$

$f_A = \frac{g''}{4} = \frac{\left(G_F\sqrt{2}\right)^{1/2}}{2} rm_U \simeq 2 \cdot 10^{-3} rm_U \,(\mathrm{GeV}/c^2)$ $\qquad e = (4\pi\alpha)^{1/2} \simeq 0.3$

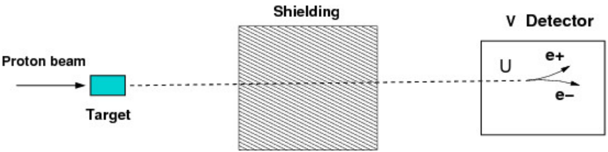
$$\alpha'' = \frac{f_A^2}{4\pi}$$

Theoretical background: anomalies

- Think of $G_{SM} \times U(1)_F$+SM matter+3 right-handed neutrinos as embedded in the $\underline{16}$ representation of $SO(10) \times U(1)$ and this one as if it was embedded in the $\underline{27}$ representation of E_6
- E_6 is an anomaly-free group in all its representations and so it is our extra U(1) gauge theory
- 11 new fermions for each generation of quarks and leptons

Experiment: Set-up

- Beam-dump experiment at BNL AGS in 1979



$$E = 28\,\mathrm{GeV} \qquad L = 45\,\mathrm{m}$$

Experiment: Limits

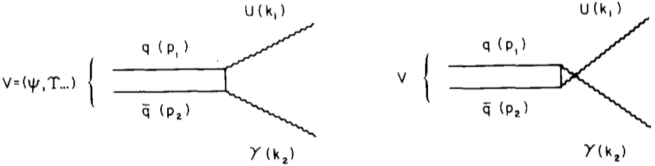
- Neutral current candidates:

$$\sigma_{prod}\sigma_{int} < 7 \times 10^{-68}\,\mathrm{cm}^4$$

- Unassociated e^+e^- pairs:

$$R_\pi = \frac{\sigma\left(pN \to a^0 X\right)}{\sigma\left(pN \to \pi^0 X\right)} < \left(2 \times 10^{-19}\,\mathrm{cm}^{-1}\right)\beta\gamma c\tau$$

Equivalence theorem



$$\epsilon^{\nu} \approx \epsilon_L^{\nu}(k_1) = \frac{k_1^{\nu}}{m_U} + \mathcal{O}\left(\frac{m_U}{E_{k_1}}\right)$$

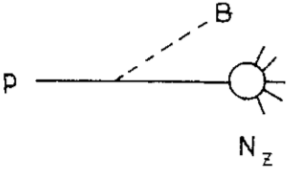
$$f_P = f_A \frac{2m_f}{m_U} = \left(G_F\sqrt{2}\right)^{1/2} m_f r, \quad \varepsilon_A = \frac{f_A}{e}, \quad \alpha_{ps} = \left(\frac{f_P^2}{4\pi}\right)$$

Summary: remarks on the Higgs sector

- **2 Higgs doublets**:
  - Making possible the existence of an axial invariance that can be gauged, enhancing the gauge boson interactions in the ultrarrelativistic limit due to the Equivalence Theorem.
- **1 Higgs singlet**:
  - Making possible to render the U boson invisible and explore a wider range in the parameter space.

Production

- **Direct production**:



- **Indirect production**: $\pi^0 \to \gamma\, U$ forbidden by charge conjugation if U coupled axially

Production

- We would like to estimate the quantity $R_\pi = \frac{\sigma(pN \to UX)}{\sigma(pN \to \pi^0 X)}$ to compare to the experimental limit

$$R_\pi = \frac{\sigma\left(pN \to a^0 X\right)}{\sigma\left(pN \to \pi^0 X\right)} < \left(2 \times 10^{-19}\,\mathrm{cm}^{-1}\right)\beta\gamma c\tau$$

- We split the R_π ratio in two contributions: $R_\pi\left(x\right) = \left(R_\pi\left(x\right)\right)_{/\!/} + \left(R_\pi\left(x\right)\right)_{\perp}$
- Benchmark value:

$$R_\pi(x) = \frac{\sigma\left(pp \to UX\right)}{\sigma\left(pp \to X\right)} \sim \frac{\alpha_U}{\pi}\frac{1}{\sigma_T}\sigma(x) = \left(\left(R_\pi\right)_{/\!/} + \left(R_\pi\right)_{\perp}\right)\frac{1}{\sigma_T}\sigma(x)$$

Production

$$R = \frac{\sigma\left(pp \to UX\right)}{\sigma\left(pp \to X\right)} \approx \begin{cases} \frac{\alpha_U}{3\pi} \\ \frac{\alpha_U}{\pi} \\ \alpha_U \\ 3\alpha_U \end{cases}$$

Formal treatment of the production cross section may induce potential corrections in R that we will treat as a source of uncertainty

Production: longitudinal contribution

- $\frac{\alpha_{ps}}{\pi} = \frac{1}{4\pi^2}\left(G_F\sqrt{2}r^2 m_q^2\right) \rightarrow$ We only consider production involving **strange quarks**

$$(R_\pi)_{/\!/} = \frac{\sigma\left(pN \rightarrow UX\right)_{/\!/}}{\sigma\left(pN \rightarrow \pi^0 X\right)} \approx \frac{\sigma\left(pp \rightarrow UX\right)_{/\!/}}{\sigma\left(pp \rightarrow X\right)}$$

$$= \frac{\sigma(pp \rightarrow UX)_{/\!/}}{\sigma(pp \rightarrow \text{strange particles } X)} \frac{\sigma(pp \rightarrow \text{strange particles } X)}{\sigma(pp \rightarrow X)} \approx \frac{1}{4\pi^2}\left(G_F\sqrt{2}r^2 m_s^2\right)\frac{1}{10}.$$

$$\mathbf{(R_\pi)_{/\!/} \approx 3.6 \times 10^{-10} r^2}$$

Production: transversal contribution

$$\left(R_\pi\right)_\perp \approx \frac{\sigma\left(pN \to UX\right)_\perp}{\sigma\left(pN \to \pi^0 X\right)} \approx \frac{\alpha''}{\pi} = \frac{1}{16\pi^2} G_F \sqrt{2} r^2 m_U^2$$

$$\left(R_\pi\right)_\perp \approx 1.0 \times 10^{-13} r^2 \left(m_U \left(\mathrm{MeV}/c^2\right)\right)^2$$

Production: energy dependence

- Phenomenological parametrization
- Assumption: energy distribution of the U boson in its production similar to the one of the pion
- Light U boson: production and interactions very much as those of the pseudoscalar Goldstone boson corresponding to the broken symmetry as if it was global rather than local
- Pions: lightest pseudoscalar particles known. Pseudo-Goldstone bosons and their interactions at leading order are described by axial currents

Production: energy dependence

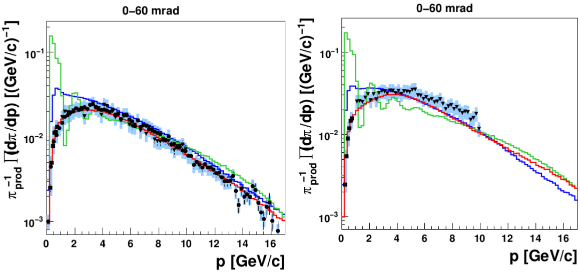


Figure: **Right** (**Left**): Momentum dependence of π^- (π^+) production cross-section in p+C collisions at 31 GeV. Circles, squares and triangles are experimental points. Vertical bars and boxes indicate statistical and systematic uncertainties, respectively.

Production

$R_\pi(x) = (R_\pi(x))_{/\!/} + (R_\pi(x))_\perp$ can be taken as

$$(R_\pi(x))_{/\!/} = 3.6 \times 10^{-10} r^2 \frac{1}{\sigma_T} \frac{\mathrm{d}\sigma\left(\mathrm{pC} \to \pi^0 X\right)}{\mathrm{d}x}$$

$$(R_\pi(x))_\perp = 1.0 \times 10^{-13} r^2 \left(m_U\left(\mathrm{MeV}/c^2\right)\right)^2 \frac{1}{\sigma_T} \frac{\mathrm{d}\sigma\left(\mathrm{pC} \to \pi^0 X\right)}{\mathrm{d}x},$$

where $\sigma_T = \sigma\left(\mathrm{pC} \to \pi^0 X\right)$ is the total cross section

Detection

- They might **interact** with the **active volume** of the detector, leaving a neutral current signature
- They might **decay into SM particles** inside the detector, leaving a 'displaced vertex' signature or an unassociated e^+e^- pair

Detection

$$\tau = \frac{1}{\Gamma} = \frac{12\pi\, B\left(\mathrm{U} \to \bar{f} f\right)}{f_A^2 m_U \beta_f^3}$$

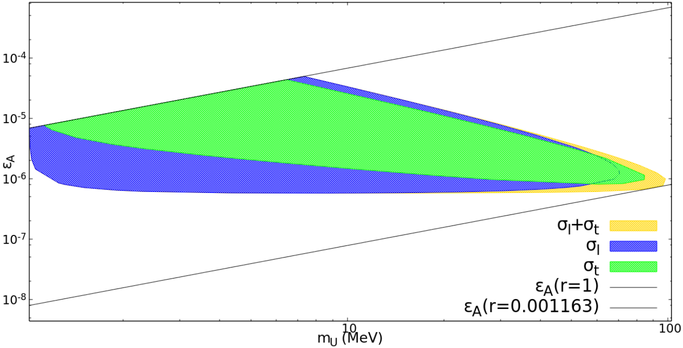
$$l = \gamma\, \tau\, \beta\, c = x \frac{E_T}{m_U} \frac{12\pi B\left(\mathrm{U} \to \bar{f} f\right)}{f_A^2 m_U \beta_f^3} \hbar c^2$$

$$B\left(U \to e^+ e^-\right) = 40\% \qquad B\left(U \to \overline{\nu}\nu\right) = 60\%$$

Overview

Detection Procedure	Experimental limit	Model observable
Neutral Current Signal	$\sigma_{prod}\sigma_{int} < 7 \times 10^{-68}\ \mathrm{cm}^4$	$\sigma_{prod}\sigma_{int} \approx 2.1 \times 10^{-70} r^4\ \mathrm{cm}^4$
Unass. Vertex	$R_\pi = \frac{\sigma\left(pN \to a^0 X\right)}{\sigma\left(pN \to \pi^0 X\right)} < \left(2 \times 10^{-19}\ \mathrm{cm}^{-1}\right) \beta\gamma c\tau$	$\int R_\pi(x)\, \frac{1}{l} e^{-\frac{L}{l}}\, dx < 2 \times 10^{-17}\ \mathrm{m}^{-1}$

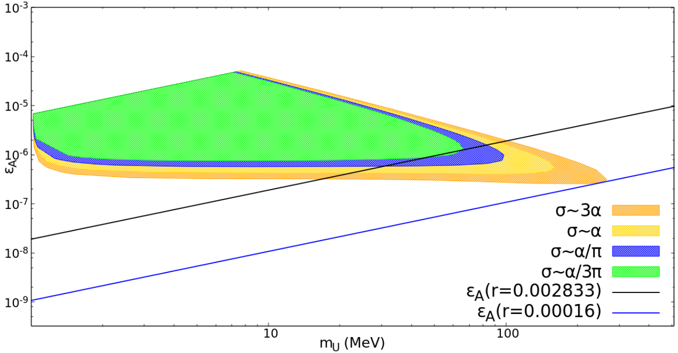
Exclusion regions



Lower part blue region$\rightarrow e^{-\frac{L}{l}} \approx 1, (R_\pi)_{/\!/} \sim r^2$ and $l \sim \frac{r^2}{\varepsilon_A^4} \rightarrow \frac{1}{l} \, (R_\pi)_{/\!/} \sim \varepsilon_A^4$

Lower part green region$\rightarrow e^{-\frac{L}{l}} \approx 1, (R_\pi)_\perp \sim \varepsilon_A^2$ and $l \sim \frac{1}{\varepsilon_A^2 m_U^2} \rightarrow \frac{1}{l} \, (R_\pi)_\perp \sim \varepsilon_A^4 m_U^2$

Exclusion regions



$$\begin{array}{l} \frac{\alpha_U}{3\pi} \\ \frac{\alpha_U}{\pi} \\ \alpha_U \\ 3\alpha_U \end{array} \rightarrow \begin{array}{l} [1.02 - 7.12]\ \mathrm{MeV} \\ [1.02 - 7.31]\ \mathrm{MeV} \\ [1.02 - 7.51]\ \mathrm{MeV} \\ [1.02 - 7.68]\ \mathrm{MeV} \end{array}$$

Exclusion regions

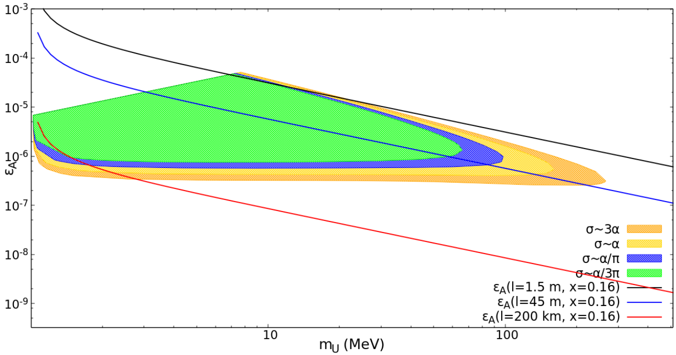
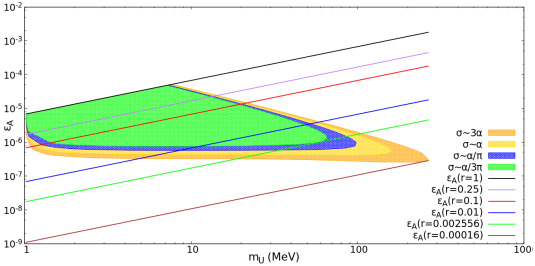


Figure: Excluded regions in the mass-coupling parameter space of the U boson for different proportionality factors for the R ratio with three curves at constant decay lenght, l, for U bosons with energy $x = 0.16$.

Conclusions



	m_U (MeV)	ε_A
$r = 1$ (no singlet)	$1.02 - 7.12$	$6.86 \times 10^{-6} - 4.78 \times 10^{-5}$
$r = 0.258$ ($\langle\sigma\rangle \sim 4v$)	$1.07 - 12.90$	$1.85 \times 10^{-6} - 2.23 \times 10^{-5}$
$r = 0.1$ ($\langle\sigma\rangle \sim 10v$)	$1.44 - 19.35$	$9.65 \times 10^{-7} - 1.30 \times 10^{-5}$
$r = 0.01$ ($\langle\sigma\rangle \sim 100v$)	$11.31 - 48.12$	$7.60 \times 10^{-7} - 3.23 \times 10^{-6}$

Conclusions

THANK YOU FOR YOUR ATTENTION