

Anomaly driven signatures of extra $U(1)$'s

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- 1 motivations
- 2 anomalies and Chern-Simons terms \Rightarrow new dimensionless coupling
- 3 axion alternatives and optical experiments
I.A.-Boyarsky-Ruchayskiy '06, '07
- 4 anomaly driven signatures at LHC
I.A.-Boyarsky-Espahbodi-Rucharsky-Wells '09
Dudas-Mambrini-Pokorski-Romagnoli '09

Extra $U(1)$'s: present in many SM extensions

- GUTs with rank > 4
- general feature of string compactifications
 - e.g. in D-brane models: $U(N)$ groups away from orientifolds

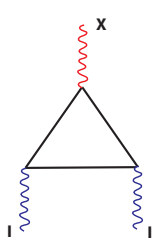
Masses and couplings:

- $m_X = g_X v \leftarrow$ VEV of a Higgs field breaking $U(1)_X$
- $m_X = g_X M \leftarrow$ string (or new physics) scale
- ① X couples to Standard Model fermions \Rightarrow
 - standard LHC signals e.g. Z' -type phenomenology
 - or light with suppressed couplings \rightarrow 5th force experiments
- ② All Standard Model fermions neutral under $X \Rightarrow$ hidden?
 - No if anomaly driven signatures

challenging case: all new fermions charged under SM and X unobservable
either heavier than LHC energy or very weakly coupled

naive expectation from decoupling \Rightarrow

at low energies double suppression: coupling + mass



e.g. X coupling to SM gauge bosons:

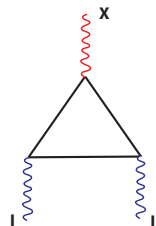
loop factor $\times E^2/M_f^2$

dim-6 effective operator $F_X F_I F_I$

exception: mixed $U(1)$ anomalies

- Non trivial anomaly cancellation \rightarrow new dimensionless coupling
 $\Rightarrow U(1)_X$ may couple to SM gauge bosons with no mass suppression

4d anomalies and Green-Schwarz mechanism



$$= k_I^X \sim \text{Tr} Q_X Q_I^2 \rightarrow \text{axion } \theta : \delta X = d\Lambda \quad \delta\theta = -m_X \Lambda$$

$$-\frac{1}{4g_I^2} F_I^2 - \frac{1}{2} (d\theta + m_X X)^2 + \frac{\theta}{m_X} k_I^X \text{Tr} F_I \wedge F_I$$

cancel the anomaly

string theory: $\theta = \text{Poincaré dual of a 2-form}$ $d\theta = *dB_2$

- Heterotic: single universal axion
- Type I: B_2 from the RR closed string sector \Rightarrow

global $U(1)_X$ symmetry remains in perturbation

e.g. Baryon or Lepton number

$U(1)_X \times U(1)_A$ example and Chern-Simons terms

X anomalous, A anomaly free : cancel mixed anomalies

⇒ also possible Chern-Simons terms: I.A.-Kiritsis-Tomaras '00

Coriano-Irges-Kiritsis '05, Anastasopoulos-Bianchi-Dudas-Kiritsis '06

$$\mathcal{L} = -\frac{1}{4}F_A^2 - \frac{1}{4}F_X^2 + \frac{1}{2}(D\theta_X)^2 - \frac{\kappa}{m_X} D\theta_X \wedge A \wedge F_A + \dots \quad D = d + m_X X$$

- $A \equiv \gamma \Rightarrow$ effects in optical experiments
- $A \equiv Z, W \Rightarrow$ LHC physics [10]

$X \wedge A \wedge F_A \Rightarrow$ XA mixing in the presence of magnetic field $F_A \neq 0$

linearly polarized photon gets a mass \Rightarrow axion behavior, interesting effects

\rightarrow unitary gauge: $-\frac{1}{4}F_A^2 - \frac{1}{4}F_X^2 + \frac{m_X^2}{2}X^2 - \kappa X \wedge A \wedge F_A + \dots$

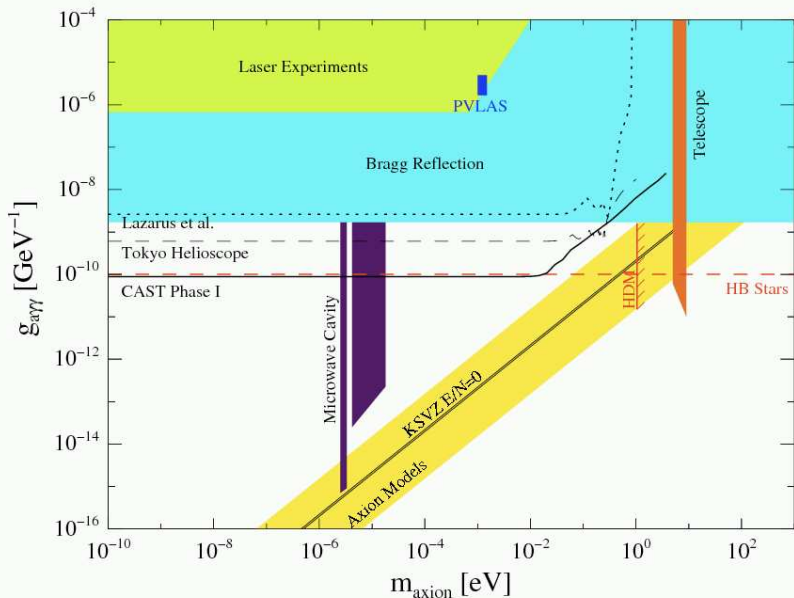
2 parameters: mass m_X , C-S coupling $\kappa \leftarrow$ dimensionless

$X_\mu \leftrightarrow$ axion: $a \equiv \theta_X$ with mass $m_a = m_X$ and decay constant $f_a \equiv \frac{m_X}{\kappa}$

however without axion constraint $m_a f_a = m_\pi f_\pi$

astrophysical constraints $\Rightarrow m_X/\kappa \gtrsim 10^{10}$ GeV

Experimental bounds on Axion Like Particles



Evading the astrophysics bounds

QED with photon mass: **em current conservation** \Rightarrow

high energy longitudinal γ emission suppressed by m_γ/E

not the case for the X -current: $j_X^\mu = \kappa \epsilon^{\mu\nu\lambda\rho} A_\nu F_{\lambda\rho}^A \Rightarrow \partial_\mu j_X^\mu = \kappa F_A \wedge F_A$

However \mathcal{L} effective up to a scale $\Lambda \lesssim m_X/\kappa$ (unitarity bound)

Idea: modify the theory at Λ so that j_X^μ becomes conserved

e.g. integrate massive fermions of mass $m_f \Rightarrow$

$$\delta\mathcal{L} = \kappa A \wedge X \wedge F_A + \kappa\theta_X \frac{m_f^2}{\square + m_f^2} F_A \wedge F_A - \kappa(\partial_\mu X^\mu) \frac{1}{\square + m_f^2} F_A \wedge F_A$$

$E \ll m_f$: $\kappa A \wedge X \wedge F_A + \kappa\theta_X F_A \wedge F_A \rightarrow \kappa A \wedge D\theta_X \wedge F_A$ as before

$E \gg m_f$: $\kappa A \wedge X \wedge F_A + \kappa(\partial_\mu X^\mu) \frac{1}{\square} F_A \wedge F_A$

X-current becomes at high energies:

$$j_X^\mu = \kappa \epsilon^{\mu\nu\lambda\rho} A_\nu F_{\lambda\rho}^A - \kappa \frac{\partial^\mu}{\square} F_A \tilde{F}_A \Rightarrow \partial_\mu j_X^\mu = 0$$

longitudinal X production is then suppressed by $(m_X/E)^2$

avoid astrophysical bounds $\Rightarrow m_f \lesssim \text{keV} \leftarrow$ stellar energies

$$\Rightarrow \kappa m_X \lesssim 10^{-10} \text{ eV}$$

- gauging axion shift \Rightarrow no $f_a \leftrightarrow m_a$ relation
- conserved current in star emission \Rightarrow weakened bound on f_a

- can accommodate PVLAS type data

- $m_X \lesssim \text{eV}$: κ small may be obtained from millicharged keV fermions f

$A = Z, W \Rightarrow$ LHC signatures

I.A.-Boyarsky-Espahbodi-Ruchayskiy-Wells '09

2 axionic phases: $X \rightarrow \theta_X, A \rightarrow \theta_A \equiv$ SM Higgs \Rightarrow [5]

$$D\theta_X \wedge D\theta_A \wedge F_A \rightarrow \mathcal{L}_{\text{eff}} = c_1 D\theta_X \frac{H^\dagger DH}{|H|^2} F_Y + c_2 D\theta_X \frac{HF_W DH^\dagger}{|H|^2}$$

e.g. integrate out two sets of heavy fermions $f = \{\psi, \chi\}$

ψ : vector-like w.r.t. SM but chiral w.r.t. $U(1)_X$

χ : chiral w.r.t. SM but vector-like w.r.t. $U(1)_X$

\Rightarrow dim-4 effective interaction : $D\theta_X \wedge D\theta_I \wedge F_I$

D'Hoker-Farhi type terms

$$c_2 \rightarrow XW^+W^- \quad c_1 \rightarrow XZY \quad (XZ\gamma, XZZ) \quad \text{vertices}$$

\Rightarrow interesting LHC signatures : 3 vector boson final state (even $WZ\gamma$)

X phenomenology

1) **Production** mechanisms of X in hadron colliders similar to Higgs

dominant production: $qq' \rightarrow V^* \rightarrow XV'$ V, V' : SM gauge bosons

vector-boson fusion subdominant unlike Higgs: $qq' \rightarrow qq'VV' \rightarrow qq'X$

$VV' \rightarrow H$ enhanced over $V^* \rightarrow HV'$ for both V, V' longitudinal

this cannot be for $H \rightarrow X$

2) **Decay** channels $X \rightarrow VV'$ [14]

3) **Signatures** in colliders (LHC)

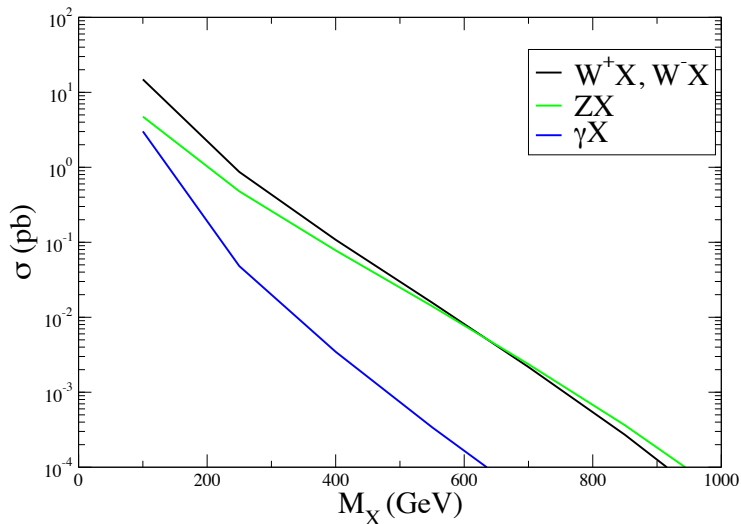
highest production/decay rate: $pp \rightarrow XW^\pm \rightarrow Z\gamma W^\pm$

$\rightarrow \gamma l^+ l^- l'^\pm + \text{missing energy}$

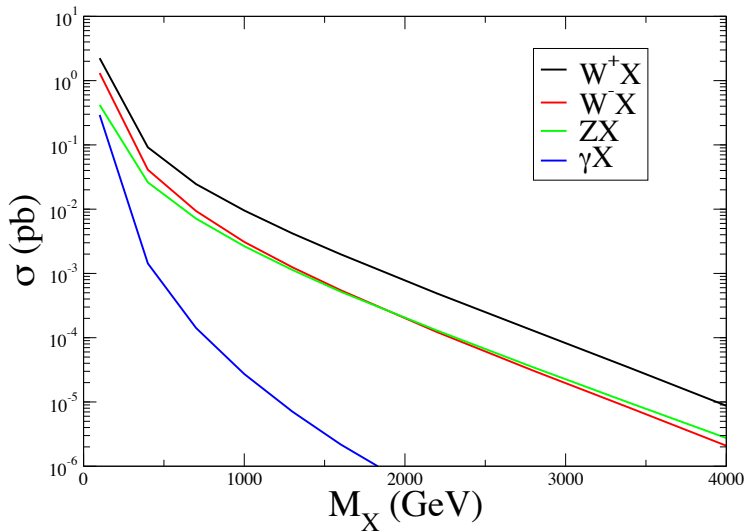
very little background when appropriate cuts

similar event from Higgs production but very suppressed [15]

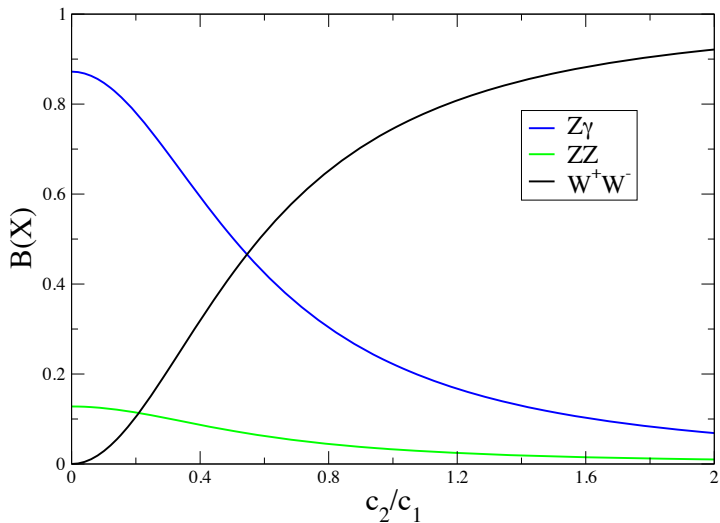
XV production cross-sections at Tevatron $c_1 = c_2 = 1$



XV production cross-sections at LHC $c_1 = c_2 = 0.1$



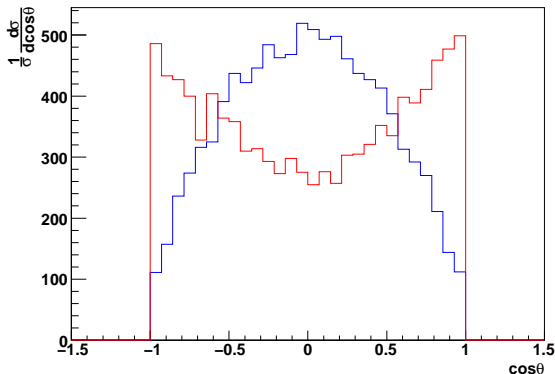
Branching ratios: $X \rightarrow WW$, $X \rightarrow \gamma Z$, $X \rightarrow ZZ$ [11]



spin determination

- angular distribution of photon in the rest frame of $X \rightarrow \gamma Z$
if X **scalar** \rightarrow **flat** but if **vector** \rightarrow **non-trivial**
- angular distribution of leptons in $Z \rightarrow l^+ l^-$

\rightarrow $\cos \theta_{l^-}$ distribution in the Z rest frame



Conclusions

Non trivial anomaly cancellation \rightarrow new dimensionless coupling

\Rightarrow extra 'hidden' $U(1)$'s may couple to SM gauge bosons V

with no mass suppression

- $V = \text{photon} \Rightarrow$ axion alternatives
avoiding mass/coupling relation and strong astrophysical bounds
- $V = W^\pm, Z \Rightarrow$ interesting LHC physics
main signature: $pp \rightarrow WZ\gamma$