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

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1. motivations, masses and couplings in string compactifications
2. mixed 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

$\rightarrow$ see also Dudas talk (Dudas, Mambrini, Pokorski, Romagnoli '09)

Extra $U(1)$'s: generic property of several BSM 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. anomalous $U(1)_X$ with Green-Schwarz anomaly cancellation
2. non anomalous in 4d but anomalous in 6d

1) X couples to Standard Model fermions $\Rightarrow$

standard LHC signals e.g. Z'-type phenomenology

or light with suppressed couplings $\to$ 5th force experiments

$m_X = g_X M \Rightarrow$ small mass from coupling suppression

e.g. in models with large extra dims if X propagates in (part of) the bulk

but localized mass from anomalies induced by localized chiral states

2) All Standard Model fermions neutral under $X \Rightarrow$ hidden?

No if anomaly driven signatures: low energy (optical experiments)

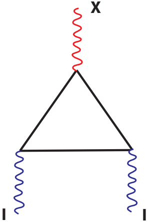
or high energy (LHC)

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



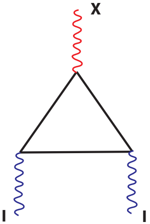
e.g. X coupling to SM gauge bosons:

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

dim-6 effective operator $F_X F_l F_l$

exception: mixed $U(1)$ anomalies

4d anomalies and Green-Schwarz mechanism



$= k_I^X \sim \mathrm{Tr}\, Q_X Q_I^2 \;\rightarrow$ axion θ : $\delta X = d\Lambda \quad \delta\theta = -M\Lambda$

$$-\frac{1}{4g_I^2} F_I^2 - \frac{1}{2}(d\theta + MX)^2 + \frac{\theta}{M} k_I^X \,\mathrm{Tr}\, F_I \wedge F_I$$

cancel the anomaly

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

- 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

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

X anomalous, A anomaly free $\Rightarrow$ 4d G-S mechanism $\Rightarrow$ X massive

cancel mixed anomalies: $XA^2 \sim \mathrm{Tr}\, Q_X Q_A^2 = k_A^X$ and $X^3 \sim \mathrm{Tr}\, Q_X^3 = k_X^X$

However it is still possible to have AX^2 anomalies $\sim \mathrm{Tr}\, Q_A Q_X^2 = k_X^A$

$$-\frac{1}{4g_I^2} F_I^2 - \frac{1}{2}(d\theta + MX)^2 + \frac{\theta}{M} k_I^X F_I \wedge F_I + k_X^A \left(A \wedge X \wedge F_X + \frac{\theta}{M} F_A \wedge F_X \right)$$

A, X — cancels AX^2 anomaly — $A \wedge D\theta \wedge F_X$ $(D = d + X)$

I.A.-Kiritsis-Tomaras '00, Anastasopoulos-Bianchi-Dudas-Kiritsis '06

Interesting physics $\rightarrow$ need $X \wedge A \wedge F_A$ term!

- $A \equiv \gamma \Rightarrow$ effects in optical experiments but need small photon mass?
- $A \equiv Z, W \Rightarrow$ LHC physics

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

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

Effective action: two axionic phases $X \to \theta_X$, $A \to \theta_\gamma$

$$\mathcal{L} = -\frac{1}{4}F_A^2 - \frac{1}{4}F_X^2 + \frac{m_X^2}{2}(D\theta_X)^2 + \frac{m_\gamma^2}{2}(D\theta_\gamma)^2 + \kappa\, D\theta_\gamma \wedge D\theta_X \wedge F_A$$

$\to$ unitary gauge: $-\frac{1}{4}F_X^2 + \frac{m_X^2}{2}X^2 - \frac{1}{4}F_A^2 + \frac{m_\gamma^2}{2}A^2 + \kappa\, A \wedge X \wedge F_A$ [12]

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 $m_a f_a = m_\pi f_\pi$ [9]

astrophysical constraints $\Rightarrow$ $m_X/\kappa \gtrsim 10^{10}$ GeV results independent on m_γ: small, finite

experimental upper bounds on m_γ: $10^{-14} - 10^{-16}$ eV

(Coulomb's law - magnetohydrodynamics of solar system)

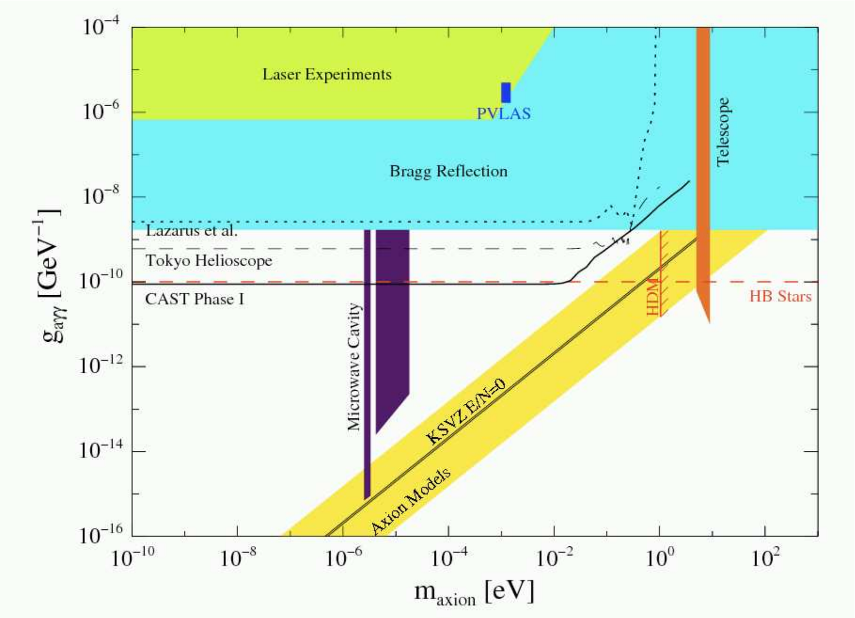
also astrophysics and cosmology bounds $\lesssim 10^{-27}$ eV but model dependent

Adelberger, Dvali, Gruzinov '03

or limit $m_\gamma \to 0$ with the constraint $F_A \wedge F_X = 0$

e.g. add $\phi F_A \wedge F_X + M^2\phi^2$ with $M \to \infty$

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: $j_X^\mu = \kappa\epsilon^{\mu\nu\lambda\rho}A_\nu F^A_{\lambda\rho} \Rightarrow \partial_\mu j_X^\mu = \kappa F_A \tilde{F}_A$

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 $\Rightarrow$

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

$E << m_f$: $\kappa\, A\wedge X\wedge F_A + \kappa\theta_X F_A\wedge F_A \rightarrow \kappa A\wedge d\theta_X\wedge F_A$ as before

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

X-current becomes at high energies:

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

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

avoid astrophysical bounds $\Rightarrow m_f \lesssim$ 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

- $m_X \lesssim$ 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: $X \to \theta_X$, $A \to \theta_A$ $\equiv$ SM Higgs $\Rightarrow$ [7]

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

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

$c_2 \to XW^+W^- \qquad c_1 \to XZY \quad (XZ\gamma, XZZ)$ 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: $qq' \to V^* \to XV'$ $\quad$ V, V': SM gauge bosons

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

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

this cannot be for $H \to X$

2) **Decay** channels $X \to VV'$ [16]

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

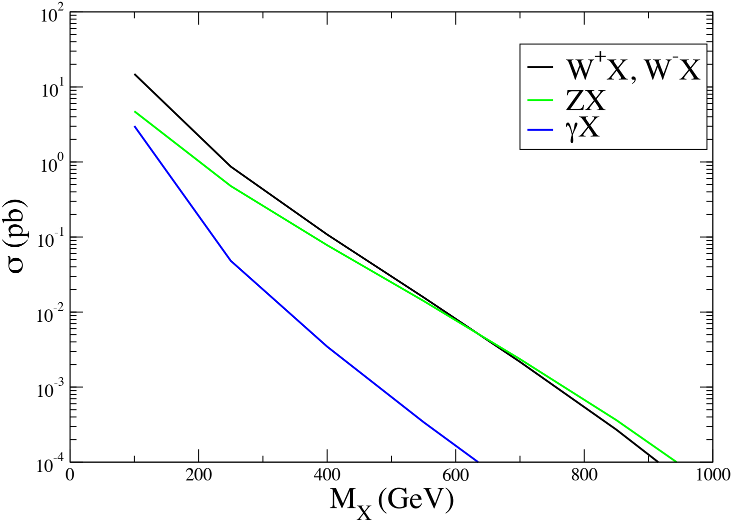
highest production/decay rate: $pp \to XW^\pm \to Z\gamma W^\pm$

$\to \gamma l^+ l^- l'^\pm +$ missing energy

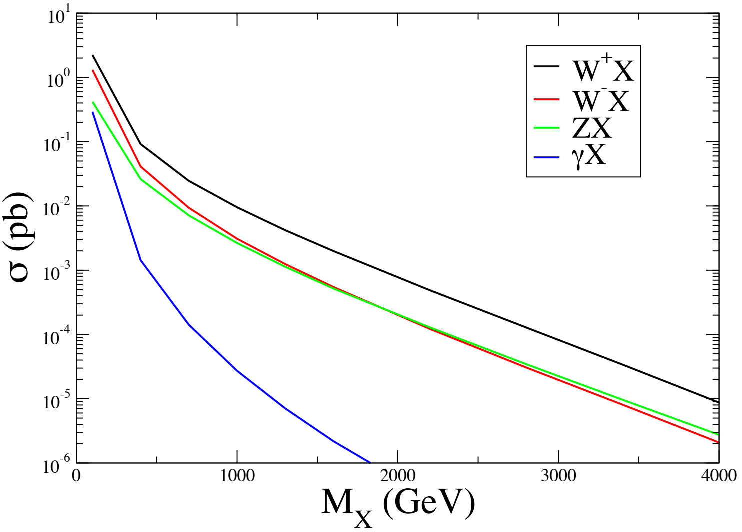
very little background when appropriate cuts

similar event from Higgs production but very suppressed [17]

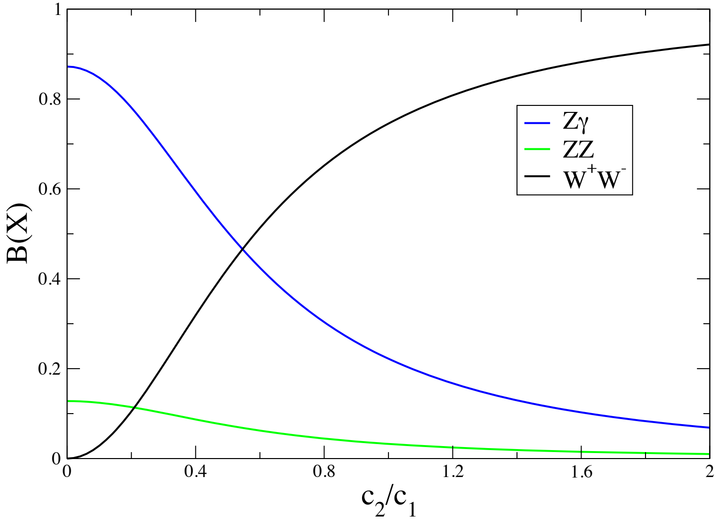
XV production cross-sections at Tevatron $c1 = c2 = 1$



XV production cross-sections at LHC $c1 = c2 = 0.1$



Branching ratios: $X \to WW$, $X \to \gamma Z$, $X \to ZZ$ [13]

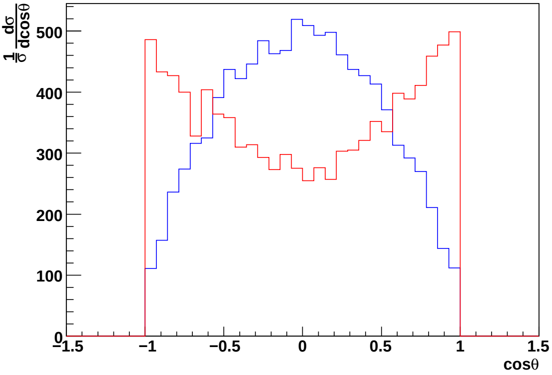


spin determination

- angular distribution of photon in the rest frame of $X \to \gamma Z$

  if X scalar $\to$ flat but if vector $\to$ non-trivial
- angular distribution of leptons in $Z \to l^+ l^-$

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



Conclusions

Non trivial anomaly cancellation $\longrightarrow$ new dimensionless coupling

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

with no mass suppression

- V = photon $\Rightarrow$ axion alternatives

  avoiding mass/coupling relation and strong astrophysical bounds

- $V = W^{\pm}, Z$ $\Rightarrow$ interesting LHC physics

  main signature: $pp \rightarrow WZ\gamma$