motivations, masses and couplings in string compactifications

mixed anomalies and Chern-Simons terms

⇒ new dimensionless coupling

axion alternatives and optical experiments

anomaly driven signatures at LHC

→ 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 $\rightarrow$ 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:

\[
\text{loop factor } \times \frac{E^2}{M_f^2}
\]

dim-6 effective operator $F_X F_I F_I$

exception: mixed $U(1)$ anomalies
4d anomalies and Green-Schwarz mechanism

\[ k_I^X \sim \text{Tr} Q x Q_I^2 \rightarrow \text{axion } \theta : \delta X = d\Lambda \quad \delta \theta = -M\Lambda \]

\[ -\frac{1}{4g_I^2} F_I^2 - \frac{1}{2} (d\theta + MX)^2 + \frac{\theta}{M} k_I^X \text{Tr} F_I \wedge F_I \]

cancel the anomaly

string theory: \( \theta = \text{Poincaré dual of a 2-form} \quad d\theta = \ast dB_2 \)

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

global \( U(1)_\chi \) 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: $XA^2 \sim \text{Tr} Q_X Q_A^2 = k_A^X$ and $X^3 \sim \text{Tr} Q_X^3 = k_X^X$

However it is still possible to have $AX^2$ anomalies $\sim \text{Tr} Q_A Q_X^2 = k_A^X$

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

$A, X$ 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
$A = \gamma \Rightarrow \text{axion alternatives}$

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

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

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

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

$\rightarrow$ 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 $m_\gamma$: small, finite

experimental upper bounds on $m_\gamma$: $10^{-14} - 10^{-16}$ 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 $M \to \infty$
Evading the astrophysics bounds

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

high energy longitudinal $\gamma$ emission suppressed by $m_\gamma/E$

not the case for the $X$-current: $j^\mu_X = \kappa \epsilon^{\mu\nu\lambda\rho} A_\nu F^A_{\lambda\rho} \Rightarrow \partial_\mu j^\mu_X = \kappa F_A \tilde{F}_A$

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

Idea: modify the theory at $\Lambda$ so that $j^\mu_X$ becomes conserved

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

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

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

\[
j^\mu_X = \kappa \epsilon^{\mu\nu\lambda\rho} A_\nu F^{A}_{\chi\rho} - \kappa \partial^\mu \Box F^A_A \tilde{F}^A_A \Rightarrow \partial^\mu j^\mu_X = 0
\]

Longitudinal X production is then suppressed by \((m_X/E)^2\)

Avoid astrophysical bounds \(\Rightarrow m_f \lesssim \text{keV} \leftarrow \text{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
- \(m_X \lesssim \text{eV}: \kappa\) small may be obtained from millicharged keV fermions \(f\)
\[ A = Z, \ W \rightarrow \text{LHC signatures} \]

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

2 axionic phases: \( X \rightarrow \theta_X, \ A \rightarrow \theta_A \equiv \text{SM Higgs} \Rightarrow [7] \)

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

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

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

\( \chi \) : 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: $qq' \rightarrow V^* \rightarrow XV'$ \hspace{1cm} $V, V'$: 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
\hspace{1cm} this cannot be for $H \rightarrow X$

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

3) **Signatures** in colliders (LHC)
highest production/decay rate: $pp \rightarrow XW^\pm \rightarrow Z\gamma W^\pm$
\hspace{1cm} $\rightarrow \gamma l^+l^-l'^\pm + \text{missing energy}$
\hspace{1cm} very little background when appropriate cuts

similar event from Higgs production but very suppressed [17]
$c_1 = c_2 = 1$

$X\gamma$ production cross-sections at Tevatron

\[ \sigma (pb) \times 10^n \]

\[ M_X (GeV) \]

- $W^+X, W^-X$
- $ZX$
- $\gamma X$
XV production cross-sections at LHC \( c_1 = c_2 = 0.1 \)
Branching ratios: $X \rightarrow WW, X \rightarrow \gamma Z, X \rightarrow ZZ$  [13]
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 $Z \rightarrow l^+ l^-$
  - $\rightarrow \cos \theta_{l^+l^-}$ distribution in the $Z$ rest frame

![Graph showing angular distribution](image-url)
Non trivial anomaly cancellation $\rightarrow$ new dimensionless coupling

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

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