Towards the Standard Model on Rigid D-Branes

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based on

- ongoing work with **Wieland Staessens** and **Martin Ripka**
- JHEP 1101 (2011) 091 with **Stefan Förste**

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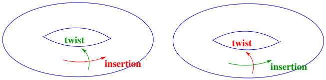
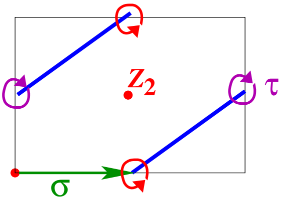
Rigid D-branes & discrete torsion

- **discrete torsion** on $T^6/\mathbb{Z}_K \times \mathbb{Z}_L$ orbifolds:
  phase $\eta = e^{2\pi i m/\gcd(K,L)}$ under $\mathbb{Z}_K$ in $\mathbb{Z}_L$ twisted sector
  here: $(K, L) = (2, 2M) \rightsquigarrow \boxed{\eta = \pm 1}$
- exchanges $h_{11} \leftrightarrow h_{21}$
  - new 3-cycles for D6-brane model building
    - D6-branes stuck at $\mathbb{Z}_2$ singularities
      $\rightsquigarrow$ no open string moduli: **rigid D-branes**
  - **less** closed string **moduli** on IIA/$\Omega\mathcal{R}$:
    - h_{21} complex structures $\rightsquigarrow$ some fixed by SUSY conditions
    - h_{11}^- Kähler moduli (but $(T^2)^3$ volumes still not fixed)
    - h_{11}^+ vectors (e.g. dark photon)
- worldsheet duality: $\eta = \eta_{\Omega\mathcal{R}} \prod_{i=1}^{3} \eta_{\Omega\mathcal{R}\mathbb{Z}_2^{(i)}} = -1$



  - one **exotic O6**-plane ($\eta_{\Omega\mathcal{R}\mathbb{Z}_2^{(i)}} = -1$)
  - three ordinary O6-planes ($\eta_{\Omega\mathcal{R}\mathbb{Z}_2^{(i)}} = +1$)

O6-planes, gauge enhancement & K-theory



- discrete param. of rigid D-brane at $\mathbb{Z}_2$ f.p.:
  - displacement σ
  - $\mathbb{Z}_2$ eigenvalue
  - Wilson lines τ
- $\Omega\mathcal{R}$ projection of $\mathbb{Z}_2^{(i)}$ sectors: $\eta_{(i)} \equiv \eta_{\Omega\mathcal{R}}\, \eta_{\Omega\mathcal{R}\mathbb{Z}_2^{(i)}}$

$c \parallel$ to	$\Omega\mathcal{R}$ invariant for $(\eta_{(1)}, \eta_{(2)}, \eta_{(3)}) \stackrel{!}{=}$
$\Omega\mathcal{R}$	$\left(-(-1)^{2(b_2\sigma_2\tau_2+b_3\sigma_3\tau_3)}, -(-1)^{2(b_1\sigma_1\tau_1+b_3\sigma_3\tau_3)}, -(-1)^{2(b_1\sigma_1\tau_1+b_2\sigma_2\tau_2)}\right)$
$\Omega\mathcal{R}\mathbb{Z}_2^{(1)}$	$\left(-(-1)^{2(b_2\sigma_2\tau_2+b_3\sigma_3\tau_3)}, (-1)^{2(b_1\sigma_1\tau_1+b_3\sigma_3\tau_3)}, (-1)^{2(b_1\sigma_1\tau_1+b_2\sigma_2\tau_2)}\right)$
$\Omega\mathcal{R}\mathbb{Z}_2^{(2)}$	$\left((-1)^{2(b_2\sigma_2\tau_2+b_3\sigma_3\tau_3)}, -(-1)^{2(b_1\sigma_1\tau_1+b_3\sigma_3\tau_3)}, (-1)^{2(b_1\sigma_1\tau_1+b_2\sigma_2\tau_2)}\right)$
$\Omega\mathcal{R}\mathbb{Z}_2^{(3)}$	$\left((-1)^{2(b_2\sigma_2\tau_2+b_3\sigma_3\tau_3)}, (-1)^{2(b_1\sigma_1\tau_1+b_3\sigma_3\tau_3)}, -(-1)^{2(b_1\sigma_1\tau_1+b_2\sigma_2\tau_2)}\right)$

- **untilted tori** ($b_i \equiv 0$): $\Omega\mathcal{R}$ invariance only for $c \parallel$ exotic O6 & any $(\vec{\sigma}, \vec{\tau}) \rightsquigarrow USp(2N)$ $T^6/\mathbb{Z}_2 \times \mathbb{Z}_2$ Blumenhagen, Cvetič, Marchesano, Shiu '05
- **tilted tori** ($b_i \equiv \frac{1}{2}$): either $c \parallel$ exotic O6 $\rightsquigarrow USp(2N)$ only for $(\vec{\sigma}, \vec{\tau}) = (\vec{0}, \vec{0})$ or $SO(2N)$ only for $(\vec{\sigma}, \vec{\tau}) = (\vec{1}, \vec{1})$ or $c \perp$ exotic O6 vice versa G.H., Ripka, Staessens '12

Hodge numbers on $T^6/\mathbb{Z}_2 \times \mathbb{Z}_{2M}$ with(out) discrete torsion

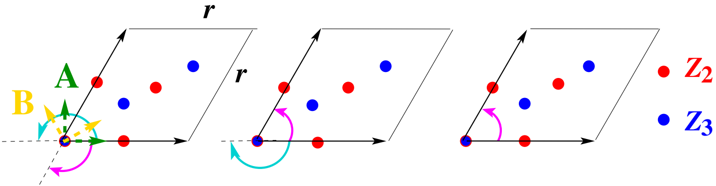
$T^6/$ torsion	lattice Hodge numbers	U	$\vec{w}$	$2\vec{w}$	$3\vec{w}$	$\vec{v}$	$(\vec{v}+\vec{w})$	$(\vec{v}+2\vec{w})$	$(\vec{v}+3\vec{w})$	total
$\mathbb{Z}_2 \times \mathbb{Z}_2$	$SU(2)^6$		$(0,\frac{1}{2},-\frac{1}{2})$			$(\frac{1}{2},-\frac{1}{2},0)$	$(\frac{1}{2},0,-\frac{1}{2})$			
$\eta=1$	h_{11}	3	16			16	16			51
	h_{21}	3	0			0	0			3
$\eta=-1$	h_{11}	3	0			0	0			3
	h_{21}	3	16			16	16			51
$\mathbb{Z}_2 \times \mathbb{Z}_4$	$SU(2)^2 \times SO(5)^2$		$(0,\frac{1}{4},-\frac{1}{4})$	$(0,\frac{1}{2},-\frac{1}{2})$		$(\frac{1}{2},-\frac{1}{2},0)$	$(\frac{1}{2},-\frac{1}{4},-\frac{1}{4})$	$(\frac{1}{2},0,-\frac{1}{2})$		
$\eta=1$	h_{11}	3	8	10		12	16	12		61
	h_{21}	1	0	0		0	0	0		1
$\eta=-1$	h_{11}	3	0	10		4	0	4		21
	h_{21}	1	8	0		0	0	0		1+8
$\mathbb{Z}_2 \times \mathbb{Z}_6$	$SU(2)^2 \times SU(3)^2$		$(0,\frac{1}{6},-\frac{1}{6})$	$(0,\frac{1}{3},-\frac{1}{3})$	$(0,\frac{1}{2},-\frac{1}{2})$	$(\frac{1}{2},-\frac{1}{2},0)$	$(\frac{1}{2},-\frac{1}{3},-\frac{1}{6})$	$(\frac{1}{2},-\frac{1}{6},-\frac{1}{3})$	$(\frac{1}{2},0,-\frac{1}{2})$	
$\eta=1$	h_{11}	3	2	8	6	8	8	8	8	51
	h_{21}	1	0	2	0	0	0	0	0	$1+2$
$\eta=-1$	h_{11}	3	0	8	0	0	4	4	0	19
	h_{21}	1	2	2	6	4	0	0	4	$15+4$
$\mathbb{Z}_2 \times \mathbb{Z}_6'$	$SU(3)^3$		$(-\frac{1}{3},\frac{1}{6},\frac{1}{6})$	$(-\frac{2}{3},\frac{1}{3},\frac{1}{3})$	$(0,\frac{1}{2},-\frac{1}{2})$	$(\frac{1}{2},-\frac{1}{2},0)$	$(\frac{1}{6},-\frac{1}{3},\frac{1}{6})$	$(-\frac{1}{6},-\frac{1}{6},\frac{1}{3})$	$(\frac{1}{2},0,-\frac{1}{2})$	
$\eta=1$	h_{11}	3	2	9	6	6	2	2	6	36
	h_{21}	0	0	0	0	0	0	0	0	0
$\eta=-1$	h_{11}	3	1	9	0	0	1	1	0	15
	h_{21}	0	0	0	5	5	0	0	5	15

- $\mathbb{Z}_2$ sectors 'see' discrete torsion only for $T^6/\mathbb{Z}_2 \times \mathbb{Z}_{2M}$ with M odd $\rightsquigarrow$ potential for new SM or GUT vacua for $2M \in \{2, 6, 6'\}$

IIA/$\Omega\mathcal{R}$ on $T^6/\mathbb{Z}_2 \times \mathbb{Z}_6'$ with discrete torsion: geometry

Förste, G.H. JHEP 1101 (2011) 091

$\mathbb{Z}_2 \times \mathbb{Z}_6'$ generators: $\vec{v} = \frac{1}{2}(1,-1,0)$ $\quad \vec{w}' = \frac{1}{6}(-2,1,1)$ on $SU(3)^3$



- $\boxed{\Pi_a^{\rm rigid} = \frac{1}{4}\left(\Pi_a^{\rm bulk} + \sum_{i=1}^3 \Pi_a^{\mathbb{Z}_2^{(i)}}\right)}$
- $\boxed{\Pi_a^{\rm bulk} = X_a\,\rho_1 + Y_a\,\rho_2}$ with

$$X_a \equiv n_a^1 n_a^2 n_a^3 - m_a^1 m_a^2 m_a^3 - \sum_{i\neq j\neq k\neq i} n_a^i m_a^j m_a^k \in \mathbb{Z}, \qquad Y_a \equiv \sum_{i\neq j\neq k\neq i}\left(n_a^i n_a^j m_a^k + n_a^i m_a^j m_a^k\right) \in \mathbb{Z}$$

- $\boxed{\Pi^{\mathbb{Z}_2^{(i)}} = \sum_{\alpha=1}^5 \left(x_{\alpha,a}^i\,\varepsilon_\alpha^{(i)} + y_{\alpha,a}^i\,\tilde{\varepsilon}_\alpha^{(i)}\right)}$ with $(x_{\alpha,a}^i, y_{\alpha,a}^i) \sim (n_a^i, m_a^i)$

$T^6/\mathbb{Z}_2 \times \mathbb{Z}_6'$: RR tadpoles, SUSY & relations

lattice	Bulk RR tadpole cancellation $\sum_a N_a (\Pi_a + \Pi_a') = 4\,\Pi_{O6}$	Bulk SUSY: nec. & suff. $\int_{\Pi_a} \mathrm{Im}(\Omega) = 0$	$\int_{\Pi_a} \mathrm{Re}(\Omega) > 0$
AAA	$\sum_a N_a (2\,X_a + Y_a) = 4 \left(\eta_{\Omega\mathcal{R}} + 3 \sum_{i=1}^3 \eta_{\Omega\mathcal{R}\mathbb{Z}_2^{(i)}}\right)$	$Y_a = 0$	$2\,X_a + Y_a > 0$
ABB	$\sum_a N_a (X_a + 2\,Y_a) = 4 \left(\eta_{\Omega\mathcal{R}\mathbb{Z}_2^{(1)}} + 3 \sum_{i=0,2,3} \eta_{\Omega\mathcal{R}\mathbb{Z}_2^{(i)}}\right)$	$X_a = 0$	$X_a + 2\,Y_a > 0$
AAB	$\sum_a N_a (X_a + Y_a) = 4 \left(3\,\eta_{\Omega\mathcal{R}\mathbb{Z}_2^{(3)}} + \sum_{i=0}^2 \eta_{\Omega\mathcal{R}\mathbb{Z}_2^{(i)}}\right)$	$Y_a - X_a = 0$	$X_a + Y_a > 0$
BBB	$\sum_a N_a\, Y_a = 4 \left(3\,\eta_{\Omega\mathcal{R}} + \sum_{i=1}^3 \eta_{\Omega\mathcal{R}\mathbb{Z}_2^{(i)}}\right)$	$2\,X_a + Y_a = 0$	$Y_a > 0$

- $\prod_{i=0}^3 \eta_{\Omega\mathcal{R}\mathbb{Z}_2^{(i)}} = -1, \quad \eta_{\Omega\mathcal{R}\mathbb{Z}_2^{(i)}} = \begin{cases} 1 & \text{ordinary} \\ -1 & \text{exotic} \end{cases}$ O6-plane
- $(X_a\,,\ Y_a)^{\mathbf{AAA}}_{\mathbf{AAB}} = (X_a + Y_a\,,\ -X_a)^{\mathbf{ABB}}_{\mathbf{BBB}}$ and $\Omega\mathcal{R} \leftrightarrow \Omega\mathcal{R}\mathbb{Z}_2^{(1/3)}$
- pairwise relations carry over to $\mathbb{Z}_2^{(i)}$ sectors — G.H., Ripka, Staessens '12
- maximal SUSY rank

$$\mathbf{AAA} = \begin{cases} 16 & \eta_{\Omega\mathcal{R}} = -1 \\ 8 & \text{else} \end{cases} \qquad \mathbf{BBB} = \begin{cases} 8 & \text{else} \\ 0 & \eta_{\Omega\mathcal{R}} = -1 \end{cases}$$

Model building constraints

Closed string sector on **AAA** with exotic $\Omega\mathcal{R}$-plane:

- $h_{21} = 15$ complex structures ($\mathbb{Z}_2$)
- $h_{11}^- = 14$ Kähler moduli (3 bulk + 3 $\mathbb{Z}_2$ + 8 $\mathbb{Z}_3$)
- $h_{11}^+ = 1$ vector/dark photon ($\mathbb{Z}_3$)

Open strings:

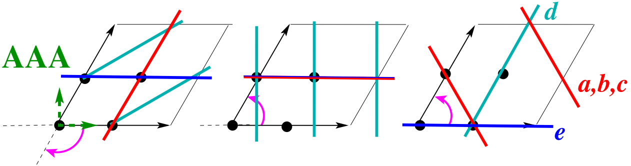
- no **Adj** $\rightsquigarrow$ only possible for the 3 shortest *bulk* cycles & special choices of $(\vec{\sigma}, \vec{\tau})$ $\quad I_{a(\omega a)} + \sum_{i=1}^{3} I_{a(\omega a)}^{\mathbb{Z}_2^{(i)}} \stackrel{!}{=} 0$
- no [**Sym** + $h.c.$] or [**Anti** + $h.c.$] of QCD stack $\rightsquigarrow$ only one shortest *bulk* cycle and $\eta_{\Omega\mathcal{R}} = -1$
- 3 generations $\rightsquigarrow$ same shortest *bulk* cycle for $SU(2)_L$

Comparison with **BBB**:

- no **Adj** ✓
- no [**Sym** + $h.c.$] or [**Anti** + $h.c$] ↯

A Pati-Salam model on $T^6/\mathbb{Z}_2 \times \mathbb{Z}_6'$

$SU(4) \times SU(2)_L \times SU(2)_R \times SU(2) \times SU(2)$ G.H., Ripka, Staessens '12



- Standard Model particles plus **one Higgs**

$$(\mathbf{4},\overline{\mathbf{2}},\mathbf{1};\mathbf{1},\mathbf{1})+2\,(\mathbf{4},\mathbf{2},\mathbf{1};\mathbf{1},\mathbf{1})+(\overline{\mathbf{4}},\mathbf{1},\mathbf{2};\mathbf{1},\mathbf{1})+2\,(\overline{\mathbf{4}},\mathbf{1},\overline{\mathbf{2}};\mathbf{1},\mathbf{1})+(\mathbf{1},\mathbf{2},\overline{\mathbf{2}};\mathbf{1},\mathbf{1})$$

$\rightsquigarrow$ **one massive generation** at leading order

- chiral w.r.t. anomalous $U(1)^5$

$$(\mathbf{1},\mathbf{2},\mathbf{1};\overline{\mathbf{2}},\mathbf{1})+3(\mathbf{1},\overline{\mathbf{2}},\mathbf{1};\overline{\mathbf{2}},\mathbf{1})+(\mathbf{1},\overline{\mathbf{2}},\mathbf{1};\mathbf{1},\overline{\mathbf{2}})+(\mathbf{1},\mathbf{1},\overline{\mathbf{2}};\mathbf{2},\mathbf{1})+3(\mathbf{1},\mathbf{1},\mathbf{2};\mathbf{2},\mathbf{1})+(\mathbf{1},\mathbf{1},\mathbf{2};\mathbf{1},\mathbf{2})$$

- non-chiral w.r.t. to full $U(4) \times U(2)^4$

$$2\left[(\mathbf{4},\mathbf{1},\mathbf{1};\overline{\mathbf{2}},\mathbf{1})+h.c.\right]+\left[(\mathbf{1},\mathbf{1},\mathbf{1};\mathbf{2},\mathbf{2})+h.c.\right]+2\,(\mathbf{1},\mathbf{1},\mathbf{1};\mathbf{4}_{\mathbf{Adj}},\mathbf{1})$$
$$+\,4\left[(\mathbf{1},\mathbf{1},\mathbf{1};\mathbf{3}_{\mathbf{S}},\mathbf{1})+(\mathbf{1},\mathbf{1},\mathbf{1};\mathbf{1}_{\mathbf{A}},\mathbf{1})+h.c.\right]+\left[(\mathbf{1},\mathbf{1},\mathbf{1};\mathbf{1},\mathbf{3}_{\mathbf{S}})+(\mathbf{1},\mathbf{1},\mathbf{1};\mathbf{1},\mathbf{1}_{\mathbf{A}})+h.c.\right]$$

Conclusions

- **Rigid D6-branes** on $T^6/\mathbb{Z}_2 \times \mathbb{Z}_{2M}$ with **discrete torsion**
  - $M = 6, 6'$ attractive for model building
  - new maps among lattice orientations $\rightsquigarrow$ economises SM search
  - reduction of closed & open string moduli
  - $M \neq 1$: bulk cycles have $\mathbb{Z}_{2M}$ images
    $\rightsquigarrow$ selection rules on Yukawa interactions ($\neq T^6$)

G.H., Vanhoof JHEP 1204 (2012) 085

- Example: **Pati-Salam** spectrum on $T^6/\mathbb{Z}_2 \times \mathbb{Z}_6'$
  - without **Adj** moduli
  - some vector-like states
  - perturbative Yukawa couplings for one particle generation only
  - gauge coupling unification at M_{string}

G.H., Ripka, Staessens to appear soon

Technical details of the Pati-Salam model on $T^6/\mathbb{Z}_2 \times \mathbb{Z}_6'$

G.H., Ripka, Staessens '12

brane	$(n^i, m^i)_{i=1,2,3}$	$\mathbb{Z}_2$ eigenv.	$(\vec{\tau})$	$(\vec{\sigma})$	group	(X, Y)
a	(0,1;1,0,1,-1)	$(+++)$	$(0,0,1)$	$(1,1,1)$	$U(4)$	(1,0)
b	(0,1;1,0,1,-1)	$(--+)$	$(0,1,1)$	$(1,1,1)$	$U(2)_L$	(1,0)
c	(0,1;1,0,1,-1)	$(-+-)$	$(1,0,1)$	$(1,1,1)$	$U(2)_R$	(1,0)
d	(1,1;1,-2;0,1)	$(+++)$	$(0,0,1)$	$(1,1,1)$	$U(2)_d$	(3,0)
e	(1,0;1,0;1,0)	$(+--)$	$(1,1,1)$	$(1,1,0)$	$U(2)_e$	(1,0)

- D6-branes a, b, c at angle $\pi(\frac{1}{3}, 0, -\frac{1}{3})$ w.r.t. $\Omega\mathcal{R}$-plane (plus two $\mathbb{Z}_6$ images at $\pi(-\frac{1}{3}, \frac{1}{3}, 0)$ and $\pi(0, -\frac{1}{3}, \frac{1}{3})$) differ in $\mathbb{Z}_2^{(i)}$ eigenvalues and discrete Wilson lines $(\vec{\tau})$
- d at angle $\pi(\frac{1}{6}, -\frac{1}{2}, \frac{1}{3})$
- e parallel to $\Omega\mathcal{R}$-plane, but $\mathbb{Z}_2^{(i)}$ sectors not invariant
- gauge coupling unification at M_{string}:

$$\frac{1}{g^2(M_{string})} \sim e^{-\phi_4} \sqrt{X^2 + XY + Y^2} = e^{-\phi_4} \times \begin{cases} 1 & a, b, c, e \\ 3 & d \end{cases}$$