Revisiting Light String States in view of the 1053 GeV di-photon excess

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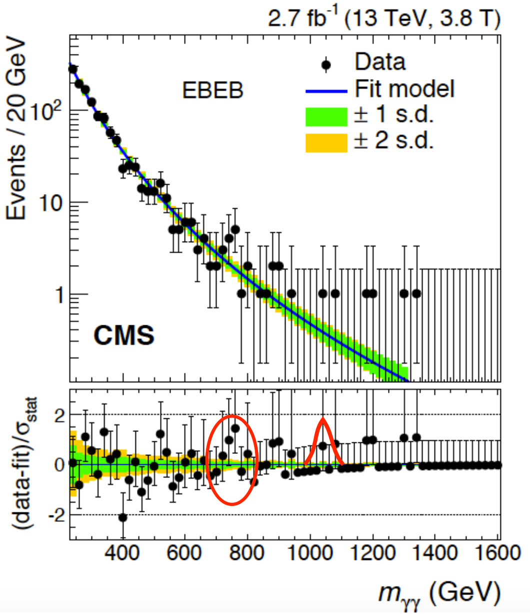
P. Anastasopoulos, M. B. arXiv:1601.07584
P. Anastasopoulos, M. B., D. Consoli *w.i.p.*
P. Anastasopoulos, M. B., R. Richter arXiv:1110.5424

Talk at String Pheno '16, Ioannina

Foreword

- String Theory is a theory of strings ... *Veneziano docet*
- Hallmark: higher spin excitations, Regge trajectories
- Yet, for intersecting / magnetised D-branes, lowest lying states: 'massive' replicas of (beyond) Standard Model particles
- Need low string tension [P. Antoniadis, N. Arkani-Hamed, S. Dimopoulos, G. Dvali] and 'small' intersection angles [P. Anastasopoulos, M. B., R. Richter]
- Probably we have already seen these lowest lying massive string states at LHC!

Di-photon excess(es) at LHC



Outline

- Introduction
- Character valued partition function
- States and vertex operators
  - Gauge sector
  - Massless sector
  - Massive multiplets
- SUSY transformations
  - Massless multiplets
  - Massive multiplets
- Interactions ... a glimpse [P. Anastasopoulos's talk!]
- Provisional conclusions

Introduction

- Unoriented open strings and intersecting/magnetized branes
- Low string tension $T_s = 1/\alpha' \approx 5\,TeV$, production and decay
- 'Standard' higher spin string excitations (Regge trajectories)

$$M^2_{A_1} = 0 \ , \quad \alpha' M^2_{H_2} = 1 \ , \quad \alpha' M^2_{H_3} = 2 \ \ldots$$

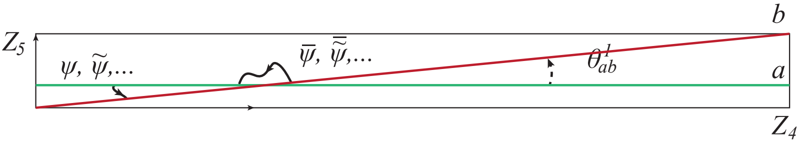
- At D-brane intersections: 'light' massive string states with 'same' spin as massless ground-state ($s \leq 1$)

$$M^2_{\psi_0} = 0 \ , \quad \alpha' M^2_{\psi_1} = \theta/\pi \ , \quad \alpha' M^2_{\psi_2} = 2\theta/\pi \ \ldots$$

- Stringy $M_n \sim \sqrt{n\ a/\alpha'}$ vs Kaluza-Klein $M_k \sim k/R$

Light String states

For small angles $\theta/\pi = a << 1$ [P. Anastasopoulos, M.B., R. Richter]



- "massless" Higgs $m_{H_0} = 125 GeV$
- "first" replica $m_{H_1} = 750 GeV$
- "second" replica $m_{H_2} = 1053 GeV = \sqrt{2 \times 750^2 - 125^2} = \sqrt{125^2 + 2 \times (750^2 - 125^2)}$
- ...

Unoriented open strings

- 1987-1997: Systematics ‘without’ and with D-branes
- Standard model embeddings and beyond
- Focus on intersecting D6-branes at $\theta_I = \pi a_I$ angles on factorizable tori/orbifolds with

$$a_1 > 0 \ , \quad a_2 > 0 \ , \quad a_3 > 0$$

  Supersymmetry: $a_1 + a_2 - a_3 = 0$
- Expect some universal behaviour
- Local vs Global (tadpole cancellation, moduli stabilisation, ... SUSY breaking, ...)
- Unoriented quiver theories, flavour and non-perturbative effects

Character valued partition function

Helicity super-trace: h vs m, $q = \exp 2\pi i\tau$, $z = \exp 2\pi i v$

$$\mathcal{Z} = \mathrm{STr}(z^h q^{\alpha' m^2}) = \sin \pi v \sum_a c_a^{GSO} \frac{\vartheta_a(v) \prod_I \vartheta_a(u_I)}{\vartheta_1(v) \prod_I \vartheta_1(u_I)}$$

where $u_I = a_I \tau$ with $\tau = iT/2$ for annulus[1].

Multiplicity

- $\mathcal{I} = \mathcal{I}_L + \mathcal{I}_R$ degeneracy of ground-state = number of intersections or Landau levels
- $N\overline{M}$ Chan-Paton factors + $M\overline{N}$ from opposite orientation

For small angles $a_I \ll 1$, assuming (SUSY) $a_3 = a_1 + a_2 > a_2 \geq a_1$

$$\mathcal{Z} = (1 - z^{\mp 1/2})q^0 + (2 - z^{-1/2} - z^{1/2})(q^{a_1} + q^{a_2})$$
$$+(2 - z^{-1/2} - z^{1/2})(q^{2a_1} + q^{2a_2}) + (z^{-1} - 3z^{-1/2} + 4 - 3z^{1/2} + z^1)q^{a_1+a_2}$$
$$+(2 - z^{-1/2} - z^{1/2})(q^{3a_1} + q^{3a_2}) + (z^{-1} - 4z^{-1/2} + 6 - 4z^{1/2} + z^1)(q^{2a_1+a_2} + q^{a_1+2a_2})$$
$$+(2 - z^{-1/2} - z^{1/2})(q^{4a_1} + q^{4a_2}) + (z^{-1} - 4z^{-1/2} + 6 - 4z^{1/2} + z^1)(q^{3a_1+a_2} + q^{a_1+3a_2})$$
$$+(2z^{-1} - 7z^{-1/2} + 10 - 7z^{1/2} + 2z^1)q^{2a_1+2a_2} + \dots$$

[1] $\tau = iT/2 + 1/2$ for Möbius-strip

Lowest lying states

- Massless states q^0: $\mathcal{I}_L$ chiral + $\mathcal{I}_R$ anti-chiral

$$\mathcal{Z}^{\text{massless}}_{\text{(anti)chiral}} = 1 - z^{\pm 1/2}$$

- Massive states with $\alpha' m^2 = ka_{1,2}$: $q^{ka_{1,2}}$, $k = 1, 2, \ldots$

$$\mathcal{Z}_{k,0/0,k} = \left(2 - z^{-1/2} - z^{1/2}\right) q^{ka_{1,2}}$$

  form massive chiral+anti-chiral multiplets.
- Massive states with $\alpha' m^2 = ka_1 + a_2 = a_3 + (k-1)a_1$ with $k = 1, 2, \ldots$

$$\mathcal{Z}_{k,1} = \{(2 - z^{-1/2} - z^{1/2}) + (2 - 2z^{-1/2} - 2z^{1/2} + z^{-1} + z^1)\} q^{ka_1 + a_2}$$

  form a massive chiral and a massive vector multiplet. Same for $\alpha' m^2 = a_1 + ka_2 = a_3 + (k-1)a_2$.
- Massive states with $\alpha' m^2 = 2a_3 = 2a_1 + 2a_2$ (from $q^{2a_1 + 2a_2}$)

$$\mathcal{Z}_{2,2} = \{3(2 - z^{-1/2} - z^{1/2}) + 2(2 - 2z^{-1/2} - 2z^{1/2} + z^{-1} + z^1)\} q^{2a_3}$$

  form three massive chiral and two massive vector multiplets.

States and vertex operators

- Massless chiral sector ($a_1 + a_2 = a_3$, $R_{\phi_0} = +1$, $R_{\chi_0} = -1/2$)

$$V_{\phi_0} = \phi_0(k)\sigma_{a_1}\sigma_{a_2}\sigma^\dagger_{a_3} e^{i[a_1\varphi_1 + a_2\varphi_2 + (1-a_3)\varphi_3]} e^{-\varphi} e^{ikX}$$

$$V_{\chi_0} = \chi_0^\alpha(k) S_\alpha \sigma_{a_1}\sigma_{a_2}\sigma^\dagger_{a_3} e^{i[(a_1-\frac{1}{2})\varphi_1 + (a_2-\frac{1}{2})\varphi_2 + (\frac{1}{2}-a_3)\varphi_3]} e^{-\varphi/2} e^{ikX}$$

  BRST invariance: $k^2 = 0$ and $k^{\dot{\alpha}\alpha}\chi^0_\alpha(k) = 0$.

- Massive multiplets BRST invariance $p^2 = -m^2$ + extra complications ... to be spelled out momentarily

For later use, unbroken SUSY charges

$$Q_\alpha^{(-1/2)} = \oint \frac{dz}{2\pi i} e^{-\varphi/2} S_\alpha \prod_{I=1}^{3} e^{i\varphi_I/2}$$

$$\tilde{Q}_{\dot{\alpha}}^{(+1/2)} = \oint \frac{dz}{2\pi i} e^{+\varphi/2} \left(C_{\dot{\alpha}} \partial Z_I^* \psi^I + \partial X_\mu S^\alpha \sigma^\mu_{\alpha\dot{\alpha}} \right) \prod_{I=1}^{3} e^{-i\varphi_I/2}$$

Massive multiplets with $\alpha' m^2 = a_1$

- Scalars vertex operators (+ opposite orientation)

$$V^{a_1}_{\tilde{\phi}^{1\dagger}_1} = \tilde{\phi}^{1\dagger}_1(p)\sigma_{a_1}\sigma_{a_2}\sigma^\dagger_{a_3} e^{i[a_1\varphi_1 + (a_2-1)\varphi_2 - a_3\varphi_3]} e^{-\varphi} e^{ipX}$$

$$V^{a_1}_{\phi^1_2} = \frac{1}{\sqrt{a_1}}\phi^1_2(p)\tau_{a_1}\sigma_{a_2}\sigma^\dagger_{a_3} e^{i[a_1\varphi_1 + a_2\varphi_2 + (1-a_3)\varphi_3]} e^{-\varphi} e^{ipX}$$

- Fermions vertex operators (+ opposite orientation)

$$V^{a_1}_{\tilde{\chi}^1_1} = \tilde{\chi}^{1\dot{\alpha}}_1(p) C_{\dot{\alpha}}\sigma_{a_1}\sigma_{a_2}\sigma^\dagger_{a_3} e^{i[(a_1+\frac{1}{2})\varphi_1 + (a_2-\frac{1}{2})\varphi_2 - (a_3-\frac{1}{2})\varphi_3]} e^{-\varphi} e^{ipX}$$

$$V^{a_1}_{\chi^1_2} = \frac{1}{\sqrt{a_1}}\chi^{1\alpha}_2(p) S_\alpha\tau_{a_1}\sigma_{a_2}\sigma^\dagger_{a_3} e^{i[(a_1-\frac{1}{2})\varphi_1 + (a_2-\frac{1}{2})\varphi_2 - (a_3-\frac{1}{2})\varphi_3]} e^{-\varphi} e^{ipX}$$

- BRST conditions ($\alpha' = 1$)
  - Scalars: $-p^2 = m^2 = a_1$
  - Fermions: $[\sqrt{a_1}\tilde{\chi}^1_{1\dot{\alpha}} + p_\mu(\chi^1_2)^\alpha\sigma^\mu_{\alpha\dot{\alpha}}]\ C^{\dot{\alpha}} = 0$
- Gauge invariant mass term

Scalars with $\alpha' m^2 = a_3 = a_1 + a_2$

$$V^{a_3}_{\phi^3_1} = \frac{1}{\sqrt{a_3}} \phi^3_1(p) \sigma_{a_1} \sigma_{a_2} \tau^\dagger_{a_3} e^{i[a_1\varphi_1 + a_2\varphi_2 + (1-a_3)\varphi_3]} e^{-\varphi} e^{ipX}$$

$$V^{a_3}_{\phi^3_2} = \frac{1}{\sqrt{a_1 a_2}} \phi^3_2(p) \tau_{a_1} \tau_{a_2} \sigma^\dagger_{a_3} e^{i[a_1\varphi_1 + a_2\varphi_2 + (1-a_3)\varphi_3]} e^{-\varphi} e^{ipX}$$

$$V^{a_3}_{\tilde\phi^{3\dagger}_3} = \frac{1}{\sqrt{a_1}} \phi^3_3(p) \tau_{a_1} \sigma_{a_2} \sigma^\dagger_{a_3} e^{i[(a_1-1)\varphi_1 + a_2\varphi_2 - a_3\varphi_3]} e^{-\varphi} e^{ipX}$$

$$V^{a_3}_{\tilde\phi^{3\dagger}_4} = \frac{1}{\sqrt{a_2}} \phi^3_4(p) \sigma_{a_1} \tau_{a_2} \sigma^\dagger_{a_3} e^{i[a_1\varphi_1 + (a_2-1)\varphi_2 - a_3\varphi_3]} e^{-\varphi} e^{ipX}$$

BRST invariance: *double* poles $\rightarrow \alpha' p^2 = -a_3$, simple poles

$$[Q_{BRST}, V^{a_3}_{\phi^3_1} + V^{a_3}_{\phi^3_2} + V^{a_3}_{\tilde\phi^{3\dagger}_3} + V^{a_3}_{\tilde\phi^{3\dagger}_4}] \rightarrow$$

$$\sigma_{a_1}\sigma_{a_2}\sigma^\dagger_{a_3}(\sqrt{a_3}\phi^3_1 + 0\phi^3_2 + \sqrt{a_1}\tilde\phi^{3\dagger}_3 + \sqrt{a_2}\tilde\phi^{3\dagger}_4) = 0$$

Three BRST invariant combinations, one BRST non-invariant mixes with massive vector ...

Fermions with mass $\alpha' m^2 = a_3$

Vertex operators

$$V^{a_3}_{\tilde\chi^3_1} = \tilde\chi^{3\dot\alpha}_1(p) C_{\dot\alpha} \sigma_{a_1}\sigma_{a_2}\sigma^\dagger_{a_3} e^{i[(a_1-\frac{1}{2})\varphi_1+(a_2-\frac{1}{2})\varphi_2-(a_3+\frac{1}{2})\varphi_3]} e^{-\varphi/2} e^{ipX}$$

$$V^{a_3}_{\chi^3_2} = \frac{1}{\sqrt{a_3}} \chi^{3\alpha}_2(p) S_{\alpha} \sigma_{a_1}\sigma_{a_2}\tilde\tau^\dagger_{a_3} e^{i[(a_1-\frac{1}{2})\varphi_1+(a_2-\frac{1}{2})\varphi_2+(\frac{1}{2}-a_3)\varphi_3]} e^{-\varphi/2} e^{ipX}$$

$$V^{a_3}_{\chi^3_3} = \chi^{3\alpha}_3(p) S_{\alpha} \sigma_{a_1}\sigma_{a_2}\sigma^\dagger_{a_3} e^{i[(a_1+\frac{1}{2})\varphi_1+(a_2+\frac{1}{2})\varphi_2+(\frac{1}{2}-a_3)\varphi_3]} e^{-\varphi/2} e^{ipX}$$

$$V^{a_3}_{\tilde\chi^3_4} = \frac{1}{\sqrt{a_1}} \tilde\chi^{3\dot\alpha}_4(p) C_{\dot\alpha} \tau_{a_1}\sigma_{a_2}\sigma^\dagger_{a_3} e^{i[(a_1-\frac{1}{2})\varphi_1+(a_2+\frac{1}{2})\varphi_2+(\frac{1}{2}-a_3)\varphi_3]} e^{-\varphi/2} e^{ipX}$$

$$V^{a_3}_{\tilde\chi^3_5} = \frac{1}{\sqrt{a_2}} \tilde\chi^{3\dot\alpha}_5(p) C_{\dot\alpha} \sigma_{a_1}\tau_{a_2}\sigma^\dagger_{a_3} e^{i[(a_1+\frac{1}{2})\varphi_1+(a_2-\frac{1}{2})\varphi_2+(\frac{1}{2}-a_3)\varphi_3]} e^{-\varphi/2} e^{ipX}$$

$$V^{a_3}_{\chi^3_6} = \frac{1}{\sqrt{a_1 a_2}} \chi^{3\alpha}_6(p) S_{\alpha} \tau_{a_1}\tau_{a_2}\sigma^\dagger_{a_3} e^{i[(a_1-\frac{1}{2})\varphi_1+(a_2-\frac{1}{2})\varphi_2+(\frac{1}{2}-a_3)\varphi_3]} e^{-\varphi/2} e^{ipX}$$

BRST invariance: *simple* poles and *double* poles.
Absence of *simple* poles:

$$\alpha' p_\mu (\tilde{\chi}_1^3)_{\dot{\alpha}}(p) \bar{\sigma}_\mu^{\dot{\alpha}\alpha} - \sqrt{a_3} (\chi_2^3)^\alpha (p) = 0$$

$$\frac{\alpha' p_\mu}{\sqrt{a_3}} (\chi_2^3)^\alpha (p) \sigma_{\alpha\dot{\alpha}}^\mu + (\tilde{\chi}_1^3)_{\dot{\alpha}}(p) = 0$$

$$\alpha' p_\mu (\chi_3^3)^\alpha (p) \sigma_{\alpha\dot{\alpha}}^\mu + (\tilde{\chi}_4^3)_{\dot{\alpha}}(p) + (\tilde{\chi}_5^3)_{\dot{\alpha}}(p) = 0$$

$$\alpha' p_\mu (\tilde{\chi}_4^3)_{\dot{\alpha}}(p) \bar{\sigma}_\mu^{\dot{\alpha}\alpha} - a_1 (\chi_3^3)^\alpha (p) + (\chi_6^3)^\alpha (p) = 0$$

$$\alpha' p_\mu (\tilde{\chi}_5^3)_{\dot{\alpha}}(p) \bar{\sigma}_\mu^{\dot{\alpha}\alpha} - a_2 (\chi_3^3)^\alpha (p) - (\chi_6^3)^\alpha (p) = 0$$

$$\alpha' p_\mu (\chi_6^3)^\alpha (p) \sigma_{\alpha\dot{\alpha}}^\mu - a_2 (\tilde{\chi}_4^3)_{\dot{\alpha}}(p) + a_1 (\tilde{\chi}_5^3)_{\dot{\alpha}}(p) = 0$$

Absence of *double* poles: $-\alpha' p^2 = \alpha' m^2 = -a_3$

Diagonalizing

$$
\begin{aligned}
&\mathcal{P}\chi_2^3 = -\tilde{\chi}_1^3 \\
&\mathcal{P}^\dagger \tilde{\chi}_1^3 = a_3 \chi_2^3 \\
&\mathcal{P}\chi_3^3 = -(\tilde{\chi}_4^3 + \tilde{\chi}_5^3) \\
&\mathcal{P}^\dagger (\tilde{\chi}_4^3 + \tilde{\chi}_5^3) = (a_1 + a_2)\chi_3^3 \\
&\mathcal{P}\chi_6^3 = a_2 \tilde{\chi}_4^3 - a_1 \tilde{\chi}_5^3 \\
&\mathcal{P}^\dagger (-a_2 \tilde{\chi}_4^3 + a_1 \tilde{\chi}_5^3) = (a_1 + a_2)\chi_6^3
\end{aligned}
$$

with $\mathcal{P} = \sqrt{\alpha'} p^\mu \bar{\sigma}_\mu^{\dot{\alpha}\alpha}$, $\mathcal{P}^\dagger = \sqrt{\alpha'} p_\mu \sigma^\mu_{\alpha\dot{\alpha}}$ and $\mathcal{PP}^\dagger = \mathcal{P}^\dagger \mathcal{P} = \alpha' m^2$, get three massive Dirac fermions which are BRST invariant:

$$
\begin{pmatrix} (\chi_2^3)^\alpha_{[--+]} \\ (\tilde{\chi}_1^3)^{[---]}_{\dot{\alpha}} \end{pmatrix}
\begin{pmatrix} (\chi_3^3)^\alpha_{[+++]} \\ (\tilde{\chi}_4^3 + \tilde{\chi}_5^3)^{[\mp\pm+]}_{\dot{\alpha}} \end{pmatrix}
\begin{pmatrix} (\chi_6^3)^\alpha_{[--+]} \\ (-a_2\tilde{\chi}_4^3 + a_1 \tilde{\chi}_5^3)^{[\mp\pm+]}_{\dot{\alpha}} \end{pmatrix}
$$

R-charges $[2r_1, 2r_2, 2r_3] := [a_1 + r_1, a_2 + r_2, -a_3 + r_3]$, so that $R = r_1 + r_2 + r_3$, since $a_1 + a_2 - a_3 = 0$.

Vector with mass $\alpha' m^2 = a_3$

Vertex operator ($R_W = 0$)

$$V_W = W_\mu(p)\psi^\mu \sigma_{a_1}\sigma_{a_2}\sigma^\dagger_{a_3} e^{i[a_1\varphi_1 + a_2\varphi_2 - a_3\varphi_3]} e^{-\varphi} e^{ipX}$$

BRST invariance: $-p^2 = m^2 = a_3$ from *double* pole, $p \cdot W = 0$ from *simple* pole. Actually, mixing with the BRST non-invariant scalar that provides the "longitudinal" mode of the massive vector.

SUSY transformations, massless case

On-shell SUSY *e.g.* in $D = 10$ (q = superghost 'picture')

$$[\epsilon Q^{(-1/2)}, V_F^{(-1/2)}(\psi)] = V_B^{(-1)}(\delta_\epsilon \phi)$$

$$[\epsilon Q^{(+1/2)}, V_B^{(-1)}(\phi)] = V_F^{(-1/2)}(\delta_\epsilon \psi) = [\epsilon Q^{(-1/2)}, V_B^{(0)}(\phi)]$$

Massless multiplets in $D = 4$ ((q, r) = superghost, R-charge)

$$[\epsilon Q^{(+3/2,-1/2)}, V_\chi^{(-1/2,-1/2)}] = V_{\delta\phi=\chi\epsilon}^{(+1,-1)} \quad [\bar{\epsilon}\bar{Q}^{(-3/2,-1/2)}, V_\chi^{(-1/2,-1/2)}] = 0$$

$$[\epsilon Q^{(+3/2,+1/2)}, V_\phi^{(+1,-1)}] = 0 \quad [\bar{\epsilon}\bar{Q}^{(-3/2,+1/2)}, V_\phi^{(+1,-1)}] = V_{\delta\chi=\bar{\epsilon}k\phi}^{(-1/2,-1/2)}$$

SUSY transformations, massive case $\alpha' m^2 = a_1 = \theta_1/\pi$

Chiral multiplet[2]

$$V_B^{[001]} = \phi_1(p)\tau_1\sigma_2\sigma_3^\dagger e^{i[a_1\varphi_1 + a_2\varphi_2 + (1-a_3)\varphi_3]} e^{-\varphi} e^{ipX}$$

$$V_F^{[--+]} = \chi_1^\alpha(p) S_\alpha \tau_1\sigma_2\sigma_3^\dagger e^{i[(a_1-\frac{1}{2})\varphi_1 + (a_2-\frac{1}{2})\varphi_2 - (a_3-\frac{1}{2})\varphi_3]} e^{-\frac{\varphi}{2}} e^{ipX}$$

AND
anti-chiral multiplet

$$V_B^{[0-10]} = \tilde{\phi}_1^\dagger(p)\sigma_1\sigma_2\sigma_3^\dagger e^{i[a_1\varphi_1 + (a_2-1)\varphi_2 - a_3\varphi_3]} e^{-\varphi} e^{ipX}$$

$$V_F^{[+--+]} = \tilde{\chi}_1^{\dot\alpha}(p) C_{\dot\alpha}\sigma_1\sigma_2\sigma_3^\dagger e^{i[(a_1+\frac{1}{2})\varphi_1 + (a_2-\frac{1}{2})\varphi_2 - (a_3-\frac{1}{2})\varphi_3]} e^{-\frac{\varphi}{2}} e^{ipX}$$

Equivalently, chiral multiplet with opposite orientation in the $M\bar{N}$.
Gauge invariant mass term.

[2] [...] R-charges

$$[\epsilon Q, V_F^{[--+]}(\chi_1(p))] = V_B(\phi^{[001]}(p) = \epsilon\chi_1(p)), \quad [\bar{\epsilon}\bar{Q}, V_F^{[--+]}(\chi_1(p))] = 0$$

$$[\epsilon Q, V_B^{[001]}(\phi_1(p))] = 0$$

$$[\bar{\epsilon}\bar{Q}, V_B^{[001]}(\phi_1(p))] = V_F^{[--+]}(\chi_1 = \sigma^\mu \bar{\epsilon} p_\mu \phi_1(p)) + V_F^{[+-+]}(\tilde{\chi}_1^\dagger = a_1 \phi_1(p)\bar{\epsilon})$$

$$[\epsilon Q, V_F^{[+-+]}(\tilde{\chi}_1^\dagger(p))] = 0, \quad [\bar{\epsilon}\bar{Q}, V_F^{[+-+]}(\tilde{\chi}_1^\dagger(p))] = V_B^{[0-10]}(\tilde{\phi}_1^\dagger(p) = \bar{\epsilon}\tilde{\chi}_1^\dagger(p))$$

$$[\epsilon Q, V_B^{[0-10]}(\tilde{\phi}_1^\dagger(p))] = V_F^{[+-+]}(\tilde{\chi}_1^\dagger = \epsilon\sigma^\mu p_\mu \tilde{\phi}_1^\dagger(p)) + V_F^{[--+]}(\chi_1 = \tilde{\phi}_1^\dagger(p)\epsilon)$$

$$[\bar{\epsilon}\bar{Q}, V_B^{[001]}(\tilde{\phi}_1^\dagger(p))] = 0$$

For the (on-shell) fields one has

$$\delta\phi_1(p) = \epsilon\chi_1(p)\,, \quad \delta\chi_1(p) = \sigma^\mu \bar{\epsilon} p_\mu \phi_1(p) + \tilde{\phi}_1^\dagger(p)\epsilon$$

and

$$\delta\tilde{\phi}_1^\dagger(p) = \bar{\epsilon}\tilde{\chi}_1^\dagger(p)\,, \quad \delta\tilde{\chi}_1^\dagger(p) = \epsilon\sigma^\mu p_\mu \tilde{\phi}_1^\dagger(p) + a_1\phi_1(p)\bar{\epsilon}$$

SUSY transformations, massive case $\alpha' m^2 = a_3 = \theta_3/\pi$

Acting on fermion vertex operators

$$[\epsilon Q, V_F^{[---]}(\bar{u}_1(p))] = V_B^{[000]}(W_\mu(p) = \epsilon\sigma_\mu \bar{u}_1(p)), \quad [\bar{\epsilon}\bar{Q}, V_F^{[---]}(\bar{u}_1(p))] = 0$$

$$[\epsilon Q, V_F^{[--+]}(u_2(p))] = V_B^{[001]}(\phi_1 = \epsilon u_2(p)), \qquad [\bar{\epsilon}\bar{Q}, V_F^{[--+]}(u_2(p))] = 0$$

$$[\epsilon Q, V_F^{[+++]}(u_3(p))] = 0, \quad [\bar{\epsilon}\bar{Q}, V_F^{[+++]}(u_3(p))] = V_B^{[000]}(W_\mu(p) = u_3(p)\sigma_\mu\bar{\epsilon})$$

$$[\epsilon Q, V_F^{[-++]}(\bar{u}_4(p))] = 0, \quad [\bar{Q}(\bar{\epsilon}), V_F^{[-++]}(\bar{u}_4(p))] = V_B^{[-100]}(\tilde{\phi}_3 = \bar{\epsilon}\bar{u}_4(p))$$

$$[\epsilon Q, V_F^{[+-+]}(\bar{u}_5(p))] = 0, \quad [\bar{Q}(\bar{\epsilon}), V_F^{[+-+]}(\bar{u}_5(p))] = V_B^{[0-10]}(\tilde{\phi}_4 = \bar{\epsilon}\bar{u}_4(p))$$

$$[\epsilon Q, V_F^{[--+]}(u_6(p))] = V_B^{[001]}(\phi_2 = \epsilon u_6(p)), \quad [\bar{\epsilon}\bar{Q}, V_F^{[--+]}(\chi_6)] = 0$$

Acting on boson vertex operators, instead

$$[\epsilon Q, V_B^{[000]}(W(p))] = V_F^{[+++]}(\chi_3 = \epsilon\sigma^\mu\bar{\sigma}^\nu p_\mu W_\nu(p)) + V_F^{[+-+]}(\tilde{\chi}_4 = \epsilon\sigma^\mu W_\mu(p))$$

$$+V_F^{[-++]}(\tilde{\chi}_5 = -\epsilon\sigma^\mu W_\mu(p))$$

$$[\bar{\epsilon}\bar{Q}, V_B^{[000]}(W(p))] = V_F^{[---]}(\tilde{\chi}_1 = \bar{\epsilon}\bar{\sigma}^\mu\sigma^\nu p_\mu W_\nu(p)) + V_F^{[--+]}(\chi_2 = \sigma^\mu\bar{\epsilon}W_\mu(p))$$

$$[\epsilon Q, V_B^{[001]}(\phi_1(p))] = V_F^{[+++]}(\chi_3 = a_3\epsilon\phi_1(p))$$

$$[\bar{\epsilon}\bar{Q}, V_B^{[001]}(\phi_1(p))] = V_F^{[--+]}(\chi_2 = \sigma^\mu\bar{\epsilon}p_\mu\phi_1(p))$$

$$[\epsilon Q, V_B^{[001]}(\phi_2(p))] = 0$$

$$[\bar{\epsilon}\bar{Q}, V_B^{[001]}(\phi_2(p))] = V_F^{[--+]}(\chi_6 = \sigma^\mu\bar{\epsilon}p_\mu\phi_2(p)) + V_F^{[+-+]}(\tilde{\chi}_4 = a_2\bar{\epsilon}p_\mu\phi_2(p))$$

$$+V_F^{[-++]}(\tilde{\chi}_5 = a_1\bar{\epsilon}p_\mu\phi_2(p))$$

$$[\epsilon Q, V_B^{[-100]}(\tilde{\phi}_3(p))] = V_F^{[+-+]}(\tilde{\chi}_4 = \epsilon\sigma^\mu p_\mu\tilde{\phi}_3(p)) + V_F^{[--+]}(\chi_6 = \epsilon\tilde{\phi}_3(p))$$

$$[\bar{\epsilon}\bar{Q}\ , V_B^{[-100]}(\tilde{\phi}_3(p))] = V_F^{[---]}(\tilde{\chi}_1 = a_1\bar{\epsilon}\tilde{\phi}_3(p))$$

$$[\epsilon Q, V_B^{[0-10]}(\tilde{\phi}_4(p))] = V_F^{[-++]}(\tilde{\chi}_5 = \epsilon\sigma^\mu p_\mu\tilde{\phi}_3(p)) + V_F^{[--+]}(\chi_6 = \epsilon\tilde{\phi}_4(p))$$

$$[\bar{\epsilon}\bar{Q}\ , V_B^{[-100]}(\tilde{\phi}_3(p))] = V_F^{[---]}(\tilde{\chi}_1 = a_2\bar{\epsilon}\tilde{\phi}_4(p))$$

Combining bosons and fermions

$$\delta W_\mu(p) = \epsilon\sigma_\mu\tilde{\chi}_1(p) + \bar{\epsilon}\bar{\sigma}_\mu\chi_3(p)$$

$$\delta\phi_1(p) = \epsilon\chi_2(p)$$

$$\delta\phi_2(p) = \epsilon\chi_6(p)$$

$$\delta\tilde{\phi}_3(p) = \bar{\epsilon}\tilde{\chi}_4(p)$$

$$\delta\tilde{\phi}_4(p) = \bar{\epsilon}\tilde{\chi}_5(p)$$

$$\delta\tilde{\chi}_1(p) = W^{\mu\nu}(p)\bar{\sigma}_{\mu\nu}\bar{\epsilon} + (a_1\tilde{\phi}_3(p) - a_2\tilde{\phi}_4(p) + p\cdot W(p))\bar{\epsilon}$$

$$\delta\chi_2(p) = \sigma_\mu\bar{\epsilon}(W^\mu(p) + p^\mu\phi_1(p))$$

$$\delta\chi_3(p) = W^{\mu\nu}(p)\sigma_{\mu\nu}\epsilon + (a_3\phi_1(p) + p\cdot W(p))\epsilon$$

$$\delta\tilde{\chi}_4(p) = \epsilon\sigma_\mu(W^\mu(p) + p^\mu\tilde{\phi}_3(p)) + a_2\phi_2(p)\bar{\epsilon}$$

$$\delta\tilde{\chi}_5(p) = \epsilon\sigma_\mu(-W^\mu(p) + p^\mu\tilde{\phi}_4(p)) + a_1\phi_2(p)\bar{\epsilon}$$

$$\delta\chi_6(p) = \sigma_\mu\bar{\epsilon}p^\mu\phi_2(p) + (\tilde{\phi}_3(p) + \tilde{\phi}_4(p))\epsilon$$

Supermultiplet structure, massive case $\alpha' m^2 = a_3 = \theta_3/\pi$

- "Half hyper-multiplet" (one chiral + one anti-chiral): $\{\chi_6, \phi_2\}$ and $\{\tilde{\chi}_4 + \tilde{\chi}_5, \phi_3 + \phi_4\}$
- Vector multiplet: vector boson W_μ, two Left-Handed fermions (χ_2 and χ_3), two scalars (ϕ_1 and $a_1\phi_3 - a_2\phi_4$, a combination thereof is eaten by the vector) and two Right-Handed fermions ($\tilde{\chi}_1$ and $a_1\tilde{\chi}_4 - a_2\tilde{\chi}_5$).

Generalization to higher mass level, still with $m^2 < 1$, straightforward in principle, extremely laborious in practice (except for $m^2 = ka_{1/2}$ or $m^2 = ka_1 + a_2$)
At sufficiently high mass level, $m^2 = 1$, 'standard' higher-spin excitations start to appear, *e.g.* $H_{\mu\nu}$ ($s = 2$), H_0 and $C_{\mu\nu\rho} \sim C_0$ ($s = 0$)... [Anchordequoi, Lüst, Stieberger, Taylor; MB, Lopez, Richter; Schlotterer; ...] ... validity of soft theorems with massive insertions [MB, He, Huang, Wen; MB, Guerrieri]

Interactions ... a glimpse

In addition to the "standard" interactions $\ell\ell\ell$ (where ℓ light/massless), consider $H\ell\ell$ (H "heavy"/massive), $HH\ell$ or HHH. Focus on decay process $H \to \ell_1 \ell_2$ with H a boson and $\ell_{1,2}$ two massless fermions.

Vector boson

$$\mathcal{A}(W \to f_1^L f_2^R) = \mathcal{C}(1,2,3) W^\mu(p) \bar{v}_{\dot\alpha}(k_2) \bar{\sigma}_\mu^{\dot\alpha\alpha} u_\alpha(k_1) \quad .$$

Scalar

$$\mathcal{A}(\phi_a \to f_1^L f_2^L) = \mathcal{C}(1,2,3) \phi_a(p) u_2^\alpha(k_2) u_\alpha(k_1) \quad .$$

where $\quad \mathcal{C}(1,2,3) =$
$$\left(\Gamma\left[a_1^{(1)}, 1-a_1^{(2)}, a_1^{(3)}\right] \Gamma\left[a_2^{(1)}, 1-a_2^{(2)}, a_2^{(3)}\right] \Gamma\left[1-a_3^{(1)}, a_3^{(2)}, 1-a_3^{(3)}\right]\right)^{1/4}$$
with $\Gamma[a,b,c] = \frac{\Gamma(a)\Gamma(b)\Gamma(c)}{\Gamma(1-a)\Gamma(1-b)\Gamma(1-c)}$

Standard model Higgs and its replica(s)

Mutatis mutandis from Standard Model Higgs, "first" replica Higgs H_1 with mass 750 GeV into a fermion pair

$$\Gamma(H_1 \to f\bar{f}) = \frac{N_c(f) m_{H_1} |\mathcal{Y}_{H_1 ff}|^2}{8\pi} \left(1 - \frac{4m_f^2}{m_{H_1}^2}\right)^{3/2}$$

$N_c(f) = 3$ for quarks and $N_c(f) = 1$ for leptons. For large extra dimensions and small a_1^{ab}

$$\mathcal{Y}_{H_1 ff} \approx \mathcal{Y}_{H_0 ff} \frac{v^{(1)} \sin \pi a_1^{ab}}{e^{\frac{1}{2}|v^{(1)}|^2} \pi a_1^{ab}} = \frac{m_f v^{(1)} \sin \pi a_1^{ab}}{v_H e^{\frac{1}{2}|v^{(1)}|^2} \pi a_1^{ab}} < \frac{m_f}{v_H \sqrt{e}}$$

where $v_H = 246 GeV$. For small angles $\sin \pi a_1^{ab} / \pi a_1^{ab} \approx 1$ and the partial width is roughly $m_{H_1}/e m_{H_0} = 750/e125 \approx 2.207$ larger than the partial width of the SM Higgs.

The "second" replica H_2 with mass 1053 GeV can decay into massless, massive and "mixed" pairs of fermions or vector bosons at tree level.

Provisional conclusions ... attend Pascal Anastasopoulos's talk for the final word

- Intersecting/magnetized D-branes promising and calculable (!) setting for embedding (beyond) Standard Model with low string tension[3] $T_s > 5 TeV$
- Anisotropic compactifications with some intersection angles $\theta_1^{a,b} << \theta_2^{a,b} \sim \theta_3^{a,b}$ suggest lightest massive string states to be replicas of (b)SM particles NOT 'standard' higher spins (unfortunately ? !)
- Rich spectrum of massive chiral + anti-chiral $\approx$ half-hypers (like in superQCD) and vector multiplets ... $s \leq 1$!!!
- Can explain di-photon excess(es) at 750 AND 1053 GeV
- Exact width to be computed together with other interesting decay channels ... work in progress with P. Anastasopoulos and D. Consoli ... stay tuned

[3] Yet some remains between chirality and moduli stabilisation