String derived $Z'$ model at an Upgraded Superconducting Super Collider

- Collider physics under investigation
  Standard Model $\rightarrow$ GUT/Planck Unification

- What is the mechanism that explains the lightness of the EW scale compared to the GUT/Planck scales?

- ... Supersymmetry? Technicolor? Extra Dimensions? $Z'$ ...

AEF, & John Rizos, NPB895 (2014) 233;
AEF, Marco Guzzi & Andrew McEntaggart, EPJC83 (2023) 590;
arXiv:2309.15707

UCSB, Santa Barbara CA, 11 April 2024
WHY?

DATA $\rightarrow$ STANDARD MODEL $\leftrightarrow$ HIGGS!

EWX $\rightarrow$ PERTUBATIVE

STANDARD MODEL $\rightarrow$ UNIFICATION

EVIDENCE: 16 of SO(10), Log running, proton stability, neutrino masses

+ GRAVITY $<-->$ STRINGS

PRIMARY GUIDES: 3 generations
SO(10) embedding

\[ L = mH^2 + g_1 f\bar{f}H + g_2 H^3 + g_3 H^4 + g_4 H V V + g_5 H H V V + \cdots \text{ EFT} \]

\[ \delta m^2 = (n_B - n_F) \lambda^2 \Lambda^2 + (m_B^2 - m_F^2) \]

\[ |\delta m^2| < 1 \text{ TeV?} \]
Liverpool’s contributions

Silicon Central Tracker

ATLAS

LHCb vertex detector
Facilities

- **Europe:**
  
  HL–LHC ($\leq$ late 2030s);
  
  FCC–$e^+e^-$ (100km ring) (250GeV CoM) (Precision Higgs Physics) ($\geq$ mid 2040s);
  
  FCC–$hh$ (100 TeV CoM) (Discovery Machine) ($\geq$ late 2060s);
  
  28TeV LHC

- **US:**

  ILC ($\geq$ late 2030s) (250GeV CoM) (Precision Higgs Physics)
  
  28TeV Fermilab 28T magnets Muon Collider (3TeV CoM) ($\geq$ 2070s?)

- **China:**

  CEPC; ($\geq$ mid 2040s) (250GeV CoM) (Precision Higgs Physics)
  
  SPPC; ($\geq$ late 2060s) (100TeV CoM) (Discovery Machine)

Sources:
SNOWMASS 2021 process (J.N. Butler et. al.);
European Strategy Group collaboration, 2020 Update, 10.17181/ESU2020
Our proposal: Upgraded Superconducting Super Collider (USSC)

- **Original SSC:**
  
  6T Magnets, 5cm bore; 87.1km ring; 40TeV CoM


  Cost: $ 6–11B

- **Upgraded SSC:**

  8–10T magnets; 5cm bore?; 87.1km?; 50–60TeV CoM

  10–15 years from decision to completion ~ mid to late 2030s

  Cost: $ 10–20B (from SNOWMASS 2021 estimates)

  Discovery machine
**Where:**

Given that Europe, the US and China have well established processes to determine their future accelerator physics programs, we propose that the USSC can be built in the Middle East SESAME facility and funded by Saudi–Arabia and other regional and global interested parties.

**COST:** $10–20\, \text{B} \times 5 = $50–100\, \text{B}

Under the leadership of the Arab Physical Society

(President Shaaban Khalil)

Alternatively: CERN FCC-ee $\leftrightarrow$ FCC–hh with LHC magnets
Physics case: Bread & Butter SM Physics

Process: \[ pp \rightarrow t\bar{t}H \rightarrow b\ell^+\nu \bar{b}\ell^-\nu H \quad (\ell = e, \mu) \]

(From Hong-Lei Li, Peng-Cheng Lu, Zong-Guo Si, Ying Wang, Associated Production of Higgs Boson and $t\bar{t}$ at LHC, 1509.06416)
Fermionic $\mathbb{Z}_2 \times \mathbb{Z}_2$ orbifolds

‘Phenomenology of the Standard Model and Unification’

- **Minimal Superstring Standard Model** NPB 335 (1990) 347
  (with Nanopoulos & Yuan)
- **Top quark mass $\sim 175$–$180$GeV** PLB 274 (1992) 47
- **Generation mass hierarchy** NPB 407 (1993) 57
- **CKM mixing** NPB 416 (1994) 63 (with Halyo)
- **Stringy seesaw mechanism** PLB 307 (1993) 311 (with Halyo)
- **Gauge coupling unification** NPB 457 (1995) 409 (with Dienes)
- **Proton stability** NPB 428 (1994) 111
- **Squark degeneracy** NPB 526 (1998) 21 (with Pati)
- **Moduli fixing** NPB 728 (2005) 83
- **Classification** 2003 – …
  (with Kounnas, Rizos & … Percival, Matyas)
- **…. Cosmology ….** (Kounnas, Partouche, Toumbas …)
REALISTIC STRING MODELS:

heterotic 10D $\rightarrow$ heterotic 4D

6D compactifications $(T^2 \times T^2 \times T^2)$

Orbifold $\rightarrow$ twists of flat 6D torus

\[ \frac{6}{2} = 1 + 1 + 1 \]

FREE FERMIONIC MODELS $-$

$Z_2 \times Z_2$ Orbifold $\rightarrow$ $U(1)^Y \in SO(10)$
Top Quark Mass Prediction

Only $\lambda_t = \langle Q t_L^c H \rangle = \sqrt{2} g$ at $N = 3$

mass of lighter quarks and leptons $\rightarrow$ nonrenormalizable terms

$\lambda_b = \lambda_\tau = 0.35g^3 \sim \frac{1}{8} \lambda_t$

Evolve $\lambda_t, \lambda_b$ to low energies

$m_t = \lambda_t v_1 = \lambda_t \frac{v_0}{\sqrt{2}} \sin \beta \quad m_b = \lambda_b v_2 = \lambda_b \frac{v_0}{\sqrt{2}} \cos \beta$

where $v_0 = \frac{2m_W}{g_2(M_Z)} = 246\text{GeV}$ and $v_1^2 + v_2^2 = \frac{v_0^2}{2}$

$m_t = \lambda_t(m_t) \frac{v_0}{\sqrt{2}} \frac{\tan \beta}{(1 + \tan^2 \beta)^{\frac{1}{2}}} \implies$
Hierarchical top-bottom mass relation in a superstring derived standard-like model

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I propose a mechanism in a class of superstring standard-like models which explains the mass hierarchy between the top and bottom quarks. At the trilinear level of the superpotential only the top quark gets a nonvanishing mass term while the bottom quarks and tau lepton mass terms are obtained from nonrenormalizable terms. I construct a model which realized this mechanism. In this model the bottom quark and tau lepton Yukawa couplings are obtained from quartic order terms. I show that $\lambda_b = \lambda, \sim \frac{1}{\Lambda}$, at the unification scale. A naive estimate yields $m_t \sim 175-180$ GeV.

One of the unresolved puzzles of the standard model is the mass splitting between the top quark and the lighter quarks and leptons. Especially difficult to understand within the context of the standard model is the big splitting in the Yukawa couplings. Experimental limits [11] indicate the top mass to be above 80 GeV, while the origin of this mass remains a mystery.
Low scale $Z'$ in heterotic–string models:

- $E_6 \rightarrow SM \times U(1)_A \times U(1)_B \implies \text{anomalous } U(1)_A$; seesaw $U(1)_B$

  $\implies U(1)_A$; $U(1)_B \notin \text{low scale } U(1)_{Z'}$

- 1996-2013, Pati, AEF, Guzzi, Mehta, Athanasopoulos, $U(1) \notin E_6$

- On the other hand ...(AEF, Viraf Mehta, PRD88 (2013) 025006)

  $\sin^2 \theta_W(M_Z), \alpha_s(M_Z) \implies U(1)_{Z'} \in E_6$

- $Z'$ string derived model, (with Rizos) NPB 895 (2015) 233

  Self–dual under SVD; no $E_6$ enhancement $\implies$ Anomaly free $U(1)_A \in E_6$. 
\( Z^{'} \) model at low scales  \[ \langle N \rangle \sim M_{\text{String}} \rightarrow \text{high seesaw} \rightarrow Z' \]

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<th>( U(1)_Y )</th>
<th>( U(1)_{Z'} )</th>
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Additional matter states at \( U(1)_{Z'} \) breaking scale

Relevant for: \( e.g. \) Sterile neutrinos; \( g_\mu - 2 \); Lepton universality; ...
pp→Z'→μμ, g_{Z'} = g_Y, CT18NNLO PDFs
$gt \rightarrow tZ'$ in pp collisions, $m_{Z'}=3, 5, 8$ TeV, $g_{Z'}=1$

NPDF3.1 NNLO pdf, $\mu=m_{Z'}$, $m_t=172.5$ GeV

(From Marco Guzzi, Nikolaos Kidonakis, $tZ'$ production at hadron colliders, 1904.10071)
What’s next?

- Technical design & Physics case by Summer 2024
- Technical design: SSC + upgraded magnets
- Physics case:
  - SM (EW; QCD; Flavour) &
  - BSM (SUSY; Compositness; Z'; ...) Phenomenology
- Possibly dedicated workshop in Summer 2024
- Following discussions with David Gross:
  - Math&Phys Dep @ Liverpool Uni. & the Cockcroft Institute at Daresbury:
  - Dedicated MPhys 4 year undergraduate degree in accelerator physics
Conclusions

• Columbus sailed west seeking a route to India

• He discovered America

• The USSC will seek B&B SM Physics

• It may discover new physics associated with EWSB by 2040