

Experimental Particle Physics Priorities 2025:

A String Phenomenology Perspective



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- Particle Physics Priorities under investigation SnowMass2021; EPPP2025
String Phenomenology → Higgs @ USSC/FCC-LHC
AEF, Marco Guzzi, Andrew McEntaggart, arXiv:2309.15707;
AEF, arXiv: 2411.00595;
Jonathan DeMont, AEF, Mark Goodsell, Marco Guzzi, arXiv:2505.12965

Corfu Summer Institute 2025, Corfu, 26 August 2025

WHY?

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

EWX $\rightarrow$ PERTUBATIVE

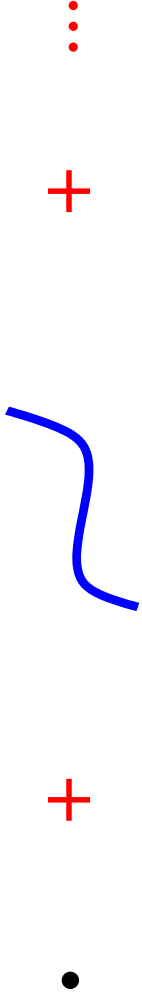
STANDARD MODEL $\rightarrow$ UNIFICATION

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

+ GRAVITY $\leftrightarrow$ STRINGS

Higgs : Fundamental? Composite? SM? Multi? SSC?!

What is string theory?



$$\int d\tau \int d\sigma$$

Worldline

Worldsheet

A consistent perturbative theory of Quantum Gravity

A well defined perturbative particle theory with well defined physical attributes

What is a vacuum?

Fermionic $Z_2 \times Z_2$ orbifolds

‘Phenomenology of the Standard Model and Unification’

- Minimal Superstring Standard Model NPB 335 (1990) 347
(with Nanopoulos & Yuan)
- Top quark mass $\sim 175\text{--}180\text{GeV}$ 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, Rizoş & ... Percival, Matyas, Detraux)
- ... vacuum stability ... (with Matyas, Percival, Avalos–Diaz, Detraux...)

Fermion mass hierarchy

Fermion mass terms

$$cg f_i f_j h \left(\frac{\langle \phi \rangle}{M} \right)^{N-3}$$

c - calculable coefficients g - gauge coupling

$$f_i, f_j \in b_j \quad j = 1, 2, 3$$

$h \rightarrow$ light Higgs multiplets $\longleftrightarrow$ FUNDAMENTAL STATES

$$M \sim 10^{18} \text{ GeV}$$

$\langle \phi \rangle$ generalized VEVs, several sources

Find anomaly free solution

$$M_d \sim \begin{pmatrix} \epsilon & \frac{V_2 \bar{V}_3 \Phi_{\alpha\beta}}{M^3} & 0 \\ \frac{V_2 \bar{V}_3 \Phi_{\alpha\beta} \xi_1}{M^4} & \frac{\bar{\Phi}_2^- \xi_1}{M^2} & 0 \\ 0 & 0 & \frac{\Phi_1^+ \xi_2}{M^2} \end{pmatrix} v_2,$$

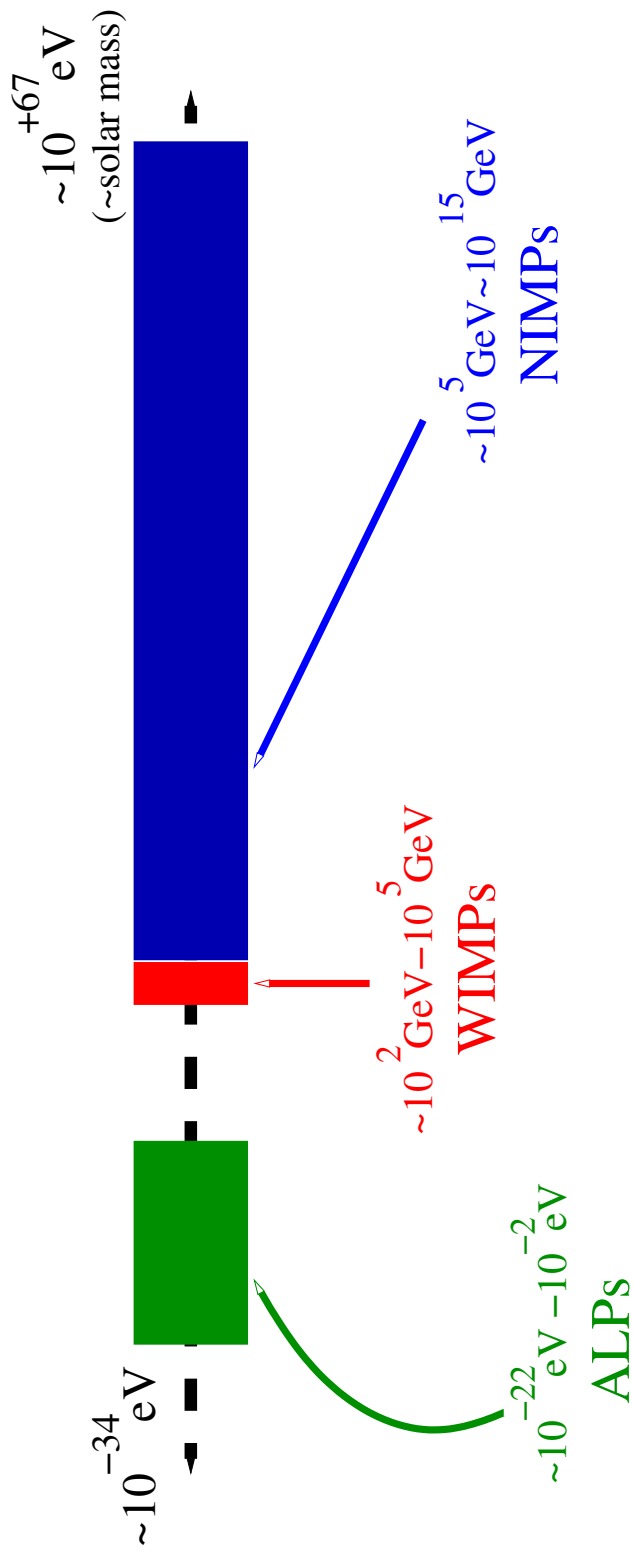
$$\epsilon < 10^{-8} \qquad \frac{V_2 \bar{V}_3 \Phi_{\alpha\beta}}{M^3} = \frac{\sqrt{5} \, g^6}{64 \, \pi^3} \approx 2 - 3 \times 10^{-4}.$$

$$\Rightarrow \quad |V| \sim \begin{pmatrix} 0.98 & 0.2 & 0 \\ 0.2 & 0.98 & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

$$\text{Three generation mixing} \quad \longrightarrow \quad \text{NPB 416 (1994) 63} \quad |J| \sim 10^{-6}$$

THE DARK MATTER LANDSCAPE *(in mass)*

Energy budget: 70% dark energy
25% dark matter
5% visible matter



Exotic matter :

In realistic string models

Unifying gauge group $\Rightarrow$ broken by “Wilson lines” .
 $\Rightarrow$ non-GUT physical states.

$\Rightarrow$ Meta-stable heavy string relics

$\rightarrow$ Dark Mater

NPB 477 (1996) 65

(with Coriano and Chang)

UHECR candidates

NPB 614 (2001) 233

(with Coriano and Plümacher)

Z' model at low scales Heavy Higgs $\langle \mathcal{N} \rangle \sim M_{\text{String}}$ $\rightarrow$ high seesaw $\rightarrow$ Z'

Field	$SU(3)_C$	$\times SU(2)_L$	$U(1)_Y$	$U(1)_{Z'}$
Q_L^i	3	2	$+\frac{1}{6}$	$-\frac{2}{5}$
u_L^i	$\bar{3}$	1	$-\frac{2}{3}$	$-\frac{2}{5}$
d_L^i	$\bar{3}$	1	$+\frac{1}{3}$	$-\frac{4}{5}$
e_L^i	1	1	+1	$-\frac{2}{5}$
L_L^i	1	2	$-\frac{1}{2}$	$-\frac{4}{5}$
D^i	3	1	$-\frac{1}{3}$	$+\frac{4}{5}$
$\bar{D}^i$	$\bar{3}$	1	$+\frac{1}{3}$	$+\frac{6}{5}$
H^i	1	2	$-\frac{1}{2}$	$+\frac{6}{5}$
$\bar{H}^i$	1	2	$+\frac{1}{2}$	$+\frac{4}{5}$
S^i	1	1	0	-2
h	1	2	$-\frac{1}{2}$	$-\frac{4}{5}$
$\bar{h}$	1	2	$+\frac{1}{2}$	$+\frac{4}{5}$
ϕ	1	1	0	-1
$\bar{\phi}$	1	1	0	+1
ζ^i	1	1	0	0

Additional matter states at $U(1)_{Z'}$ breaking scale

Relevant for: *e.g.* Sterile neutrinos; $g_\mu - 2$; Lepton universality; ...

$[(1, 0); (1, 0)]_{(0, \pm 1, 0)} \quad SO(10)$ singlets E_6 exotics

Several cases to consider :

1. $M \gg M_{Z'}$ without inflation $\Rightarrow M \leq 10^5 \text{ GeV}$

2. $M \gg M_{Z'}$ with inflation and $T_R > M_{Z'} \Rightarrow M > T_R \left[25 + \frac{1}{2} \ln \left(\frac{M}{T_R} \right) \right]$

3. $M < M_{Z'}$ without inflation $\Rightarrow M < 3 \text{ keV}$

4. $M < M_{Z'}$ with inflation

$$M \begin{cases} > T_R \left[25 + \frac{1}{2} \ln \left(\frac{M^5}{M_{Z'}^4 T_R} \right) \right], & T_R < M \\ < \frac{M_{Z'}^4}{T_R^3} 6.9 \times 10^{-25} \left(\frac{g_*}{200} \right)^{1.5} \frac{1}{N_{Z'} g_{\text{eff}}^2}, & T_R > M \end{cases}$$

Other candidates

- **Uniton** $\longrightarrow$ **Strongly interacting** $\longrightarrow$ **unification**
- $1/2$ fractionally charged leptons and hadrons $\longrightarrow$ hydrogen-like
- **Hidden sector glueballs**
- Axion-like candidates

Facilities

- Europe: (Plan A)

HL-LHC ($\leq$ late 2030s);

FCC- e^+e^- (90km ring) (250GeV CoM) (Precision Higgs Physics)
($\geq$ mid 2040s);

FCC- hh (90 TeV CoM) (Discovery Machine) ($\geq$ 2070s);

- US:

P5 $\longrightarrow$ Muon Collider (3TeV CoM) ($\geq$ 2070s?)

- China:

CEPC; ($\geq$ 2040s) (250GeV CoM) (Precision Higgs Physics)

SPPC; ($\geq$ late 2060s) (90TeV CoM) (Discovery Machine)

Sources:

SNOWMASS 2021 process (J.N. Butler *et. al.*);

Energy Frontier, arXiv:2211.11084; Accelerator Frontier, arXiv:2209.14136;

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

Decision: October 1988; Start: 1996–1999; Cancelled 10/1993

Cost: \$ 6–11B

- Upgraded SSC:

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

10–15 years from decision to completion $\sim$ mid to late 2030s

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

Discovery machine

Where:

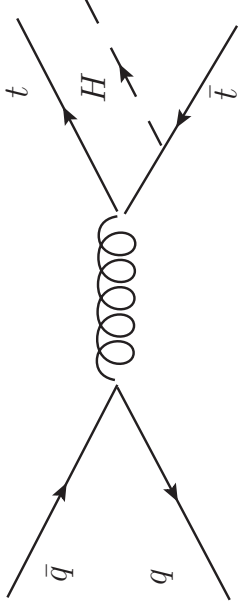
Given that Europe, the US and China have well established processes to determine their future accelerator physics programs, we propose that the USSC can be built in the Middle East SESAME facility and funded by Saudi-Arabia and other regional and global interested parties.

COST: \$ 10–20 B $\times$ 5 = \$ 50–100 B

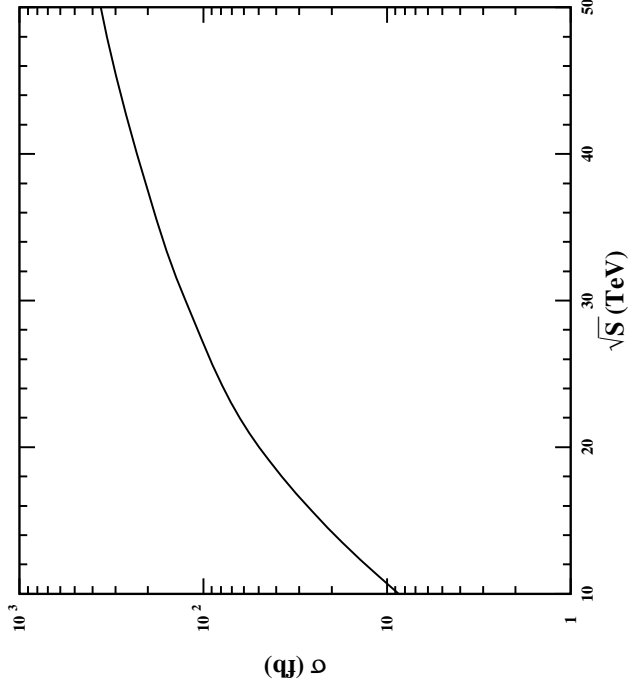
Under the leadership of the Arab Physical Society
(President Shaaban Khalil)

Alternatively: CERN FCC-ee $\longleftrightarrow$ FCC-hh with LHC magnets

Physics case: Bread & Butter SM Physics

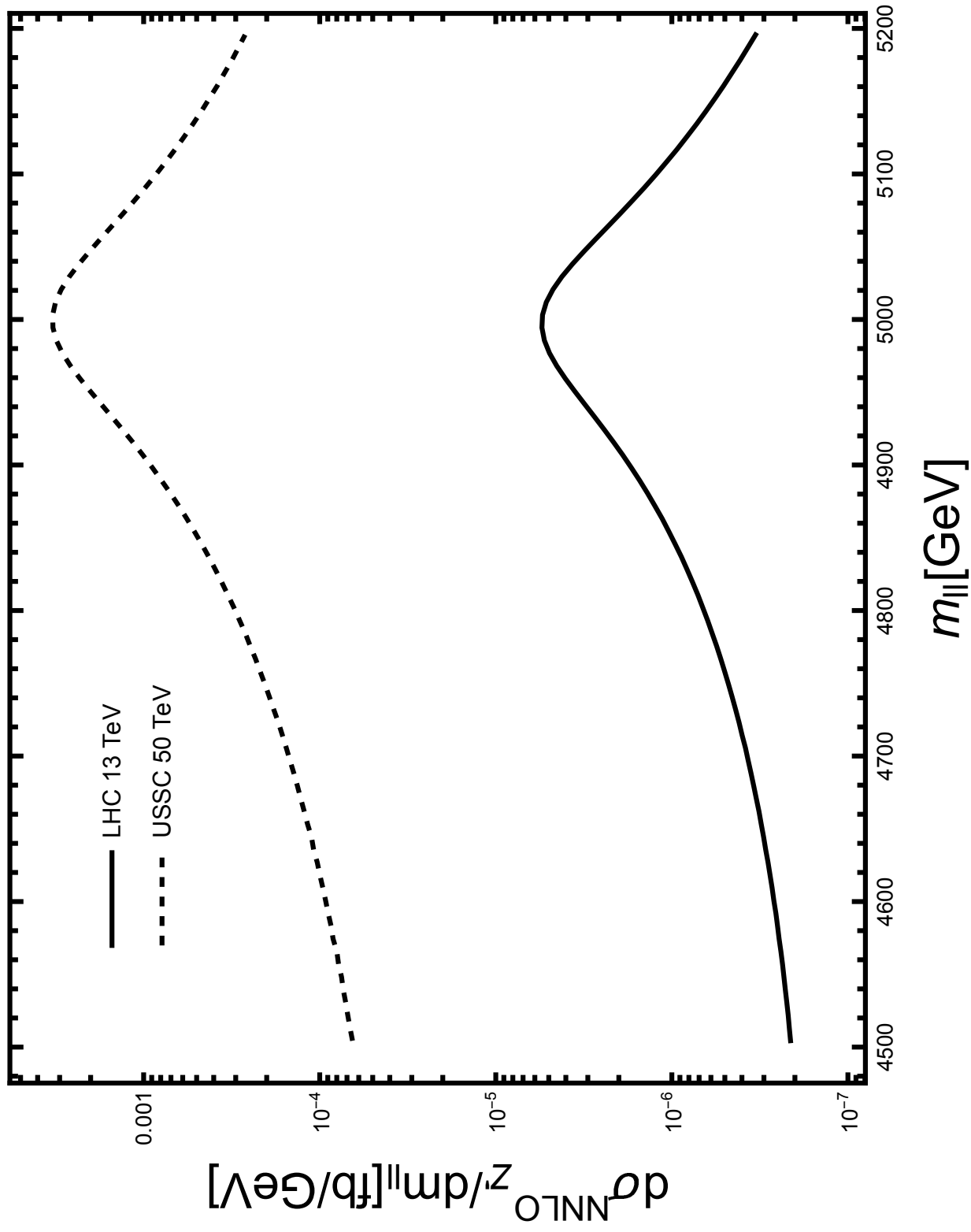


Process: $pp \rightarrow t\bar{t}H \rightarrow b\ell^+\nu\bar{b}\ell^-\nu H$ ($\ell = e, \mu$)



(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)

$$pp \rightarrow Z' \rightarrow \ell\ell, g_{Z'} = g_Y, \text{CT18NNLO PDFs}$$



Conclusions

- Experimental Particle Physics Priorities 2025:

A String Phenomenology Perspective, arXiv:2505.12965

Higgs: fundamental or composite? single or multi? interactions? flavour couplings? self-couplings? vacuum? hierarchy? New particles?

→ USSC/FCC-LHC

THANK YOU