String derived Z' model at an Upgraded Superconducting Super Collider

- Collider physics under investigation
  Standard Model $\longrightarrow$ 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

Beyond the Standard Model 2023, Hurghada – Egypt, 7 November 2023

WHY?

DATA $\longrightarrow$ STANDARD MODEL $\longleftrightarrow$ HIGGS!

EWX –> PERTUBATIVE

STANDARD MODEL –> UNIFICATION

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

+ GRAVITY < –– > STRINGS

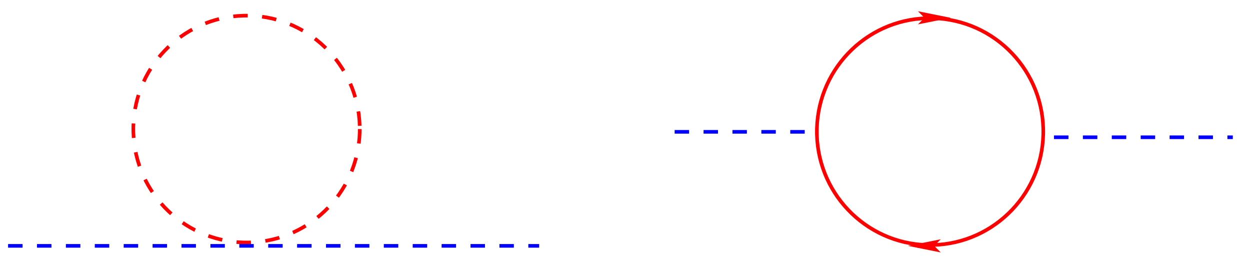
PRIMARY GUIDES:

3 generations
SO(10) embedding

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

$$L = mH^2 + g_1 f\bar{f}H + g_2 H^3 + g_3 H^4 + g_4 H\,V\,V + g_5 H\,H\,V\,V$$

$$+ \quad \cdots \quad \text{EFT}$$



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

$$\left|\delta m^2\right| < 1\ \text{TeV?}$$

Facilities

- **Europe:**
  HL–LHC ($\leq$ late 1930s);
  FCC–e^+e^- (100km ring) (250GeV CoM) (Precision Higgs Physics) ($\geq$ late 1940s);
  FCC–hh (100 TeV CoM) (Discovery Machine) ($\geq$ late 1950s);
  28TeV LHC
- **US:**
  ILC ($\geq$ late 1930s) (250GeV CoM) (Precision Higgs Physics)
  28TeV Fermilab 28T magnets
  Muon Collider (3TeV CoM) ($\geq$ 2070s?)
- **China:**
  CEPC; ($\geq$ late 1930s) (250GeV CoM) (Precision Higgs Physics)
  SPPC; ($\geq$ late 1940s) (100teV 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 1930s

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

  Discovery machine

Where:

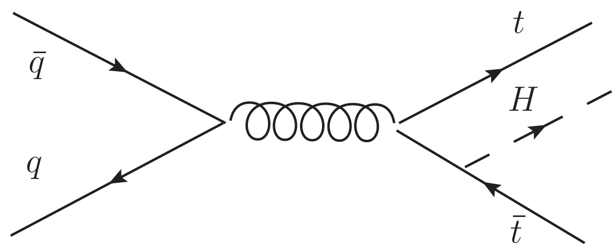
Given that Europe, the US and China have well established processes to determine their future accelerator physics programs, we propose that the USSC can be built in the Middle East SESAME facilty and funded by Saudi–Arabia and other regional and global interested parties.

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

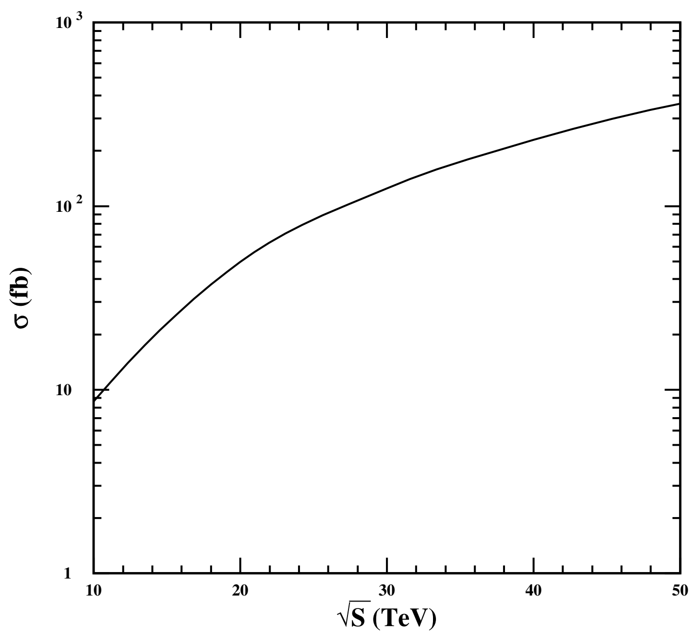
Under the leadership of the Arab Physical Society

(President Shaaban Khalil)

Physics case: Bread & Butter SM Physics



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



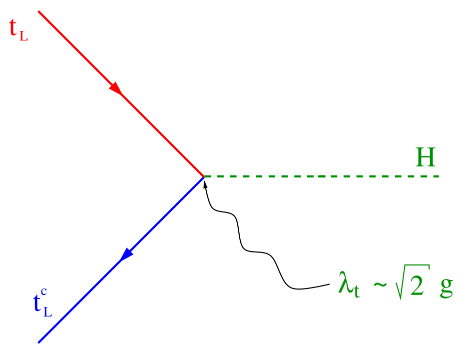
(From Hong-Lei Li, Peng-Cheng Lu, Zong-Guo Si, Ying Wang, *Associated Production of Higgs Boson and $t\bar{t}$ at LHC*, 1509.06416)

Fermionic $Z_2 \times Z_2$ orbifolds

'Phenomenology of the Standard Model and Unification'

- Minimal Superstring Standard Model — NPB 335 (1990) 347 (with Nanopoulos & Yuan)
- Top quark mass $\sim$ 175–180GeV — 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 – $\cdot\cdot\cdot$ (with Kounnas, Rizos & ... Percival, Matyas)
- .... Cosmology .... (Kounnas, Partouche, Toumbas ...)

Top Quark Mass Prediction



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

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

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

Evolve λ_t , λ_b to low energies

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

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

$$m_t \;=\; \lambda_t(m_t)\, \frac{v_0}{\sqrt{2}}\, \frac{\tan\beta}{(1+\tan^2\beta)^{\frac{1}{2}}} \Longrightarrow$$

ysics Letters B 274 (1992) 47–52
orth-Holland

PHYSICS LETTERS B

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 $\lambda_b = \lambda_\tau \sim \frac{1}{2}\lambda_t$ 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 juarks and leptons. Especially difficult to understand within the context of the standard model is the big split-ing in the heaviest generation. Experimental limits [1] indicate the top mass to be above 80 GeV, while the oottom and tau lepton masses are found at 5 GeV and 1.78 GeV respectively. Possible extensions to the standard nodel are grand unified theories. Although the main prediction of GUTs, proton decay, has not yet been ob-erved, calculations of $\sin^2\theta_w$ and of the mass ratio m_b/m_τ support their validity. Recent calculations seem to upport supersymmetric GUTs versus nonsupersymmetric ones [2]. In spite of the success of SUSY GUTs in onfronting LEP data [2], an understanding of the mass splitting between the top quark and the lighter quarks ind leptons is still lacking. The next level in which such an understanding may be developed is in the context of uperstring theory [3].

Low scale Z' in heterotic–string models:

- $E_6 \rightarrow SM \times U(1)_A \times U(1)_B \implies$ 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 $\Rightarrow$ Anomaly free $U(1)_A \in E_6$.

Classification of fermionic $Z_2 \times Z_2$ orbifolds

Basis vectors:

$$1 = \{\psi^\mu,\ \chi^{1,\dots,6}, y^{1,\dots,6}, \omega^{1,\dots,6} \mid \bar{y}^{1,\dots,6}, \bar{\omega}^{1,\dots,6}, \bar{\eta}^{1,2,3}, \bar{\psi}^{1,\dots,5}, \bar{\phi}^{1,\dots,8}\}$$

$$S = \{\psi^\mu, \chi^{1,\dots,6}\},$$

$$z_1 = \{\bar{\phi}^{1,\dots,4}\},$$

$$z_2 = \{\bar{\phi}^{5,\dots,8}\},$$

$$e_i = \{y^i, \omega^i | \bar{y}^i, \bar{\omega}^i\},\ i = 1, \dots, 6,$$ $N = 4$ Vacua

$$b_1 = \{\chi^{34}, \chi^{56}, y^{34}, y^{56} | \bar{y}^{34}, \bar{y}^{56}, \bar{\eta}^1, \bar{\psi}^{1,\dots,5}\},$$ $N = 4 \to N = 2$

$$b_2 = \{\chi^{12}, \chi^{56}, y^{12}, y^{56} | \bar{y}^{12}, \bar{y}^{56}, \bar{\eta}^2, \bar{\psi}^{1,\dots,5}\},$$ $N = 2 \to N = 1$

$$\alpha = \{\bar{\psi}^{4,5}, \bar{\phi}^{1,2}\}$$ & $SO(10) \to SO(6) \times SO(4) \times \cdots$

$$\beta = \{\bar{\psi}^{1,\cdots,5} \equiv \tfrac{1}{2}, \cdots\}$$ & $SO(10) \to SU(5) \times U(1) \times \cdots$

light Z' heterotic–string model $c\left[{v_i \atop v_j}\right] = \exp[i\pi(v_i|v_j)]$:

$$
(v_i|v_j) \;=\; \begin{array}{c} \\ 1 \\ S \\ e_1 \\ e_2 \\ e_3 \\ e_4 \\ e_5 \\ e_6 \\ b_1 \\ b_2 \\ z_1 \\ z_2 \\ \alpha \end{array}
\begin{array}{c}
\begin{array}{ccccccccccccc} 1 & S & e_1 & e_2 & e_3 & e_4 & e_5 & e_6 & b_1 & b_2 & z_1 & z_2 & \alpha \end{array} \\
\left(\begin{array}{ccccccccccccc}
1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 \\
1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 \\
1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \\
1 & 1 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 1 & 0 \\
1 & 1 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 1 & 1 \\
1 & 1 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \\
1 & 1 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 1 & 1 \\
1 & 1 & 0 & 1 & 0 & 0 & 1 & 0 & 0 & 0 & 1 & 0 & 0 \\
1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 1 & 0 & 0 & 0 \\
1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 1 & 0 & 0 & 1 \\
1 & 1 & 0 & 0 & 0 & 1 & 0 & 1 & 0 & 0 & 1 & 1 & 0 \\
1 & 1 & 0 & 1 & 1 & 0 & 1 & 0 & 0 & 0 & 1 & 1 & 0 \\
1 & 1 & 1 & 0 & 1 & 0 & 1 & 0 & 1 & 0 & 1 & 0 & 1
\end{array}\right)
\end{array}
$$

Observable gauge group: $SO(6) \times SO(4) \times U(1)_{1,2,3}$

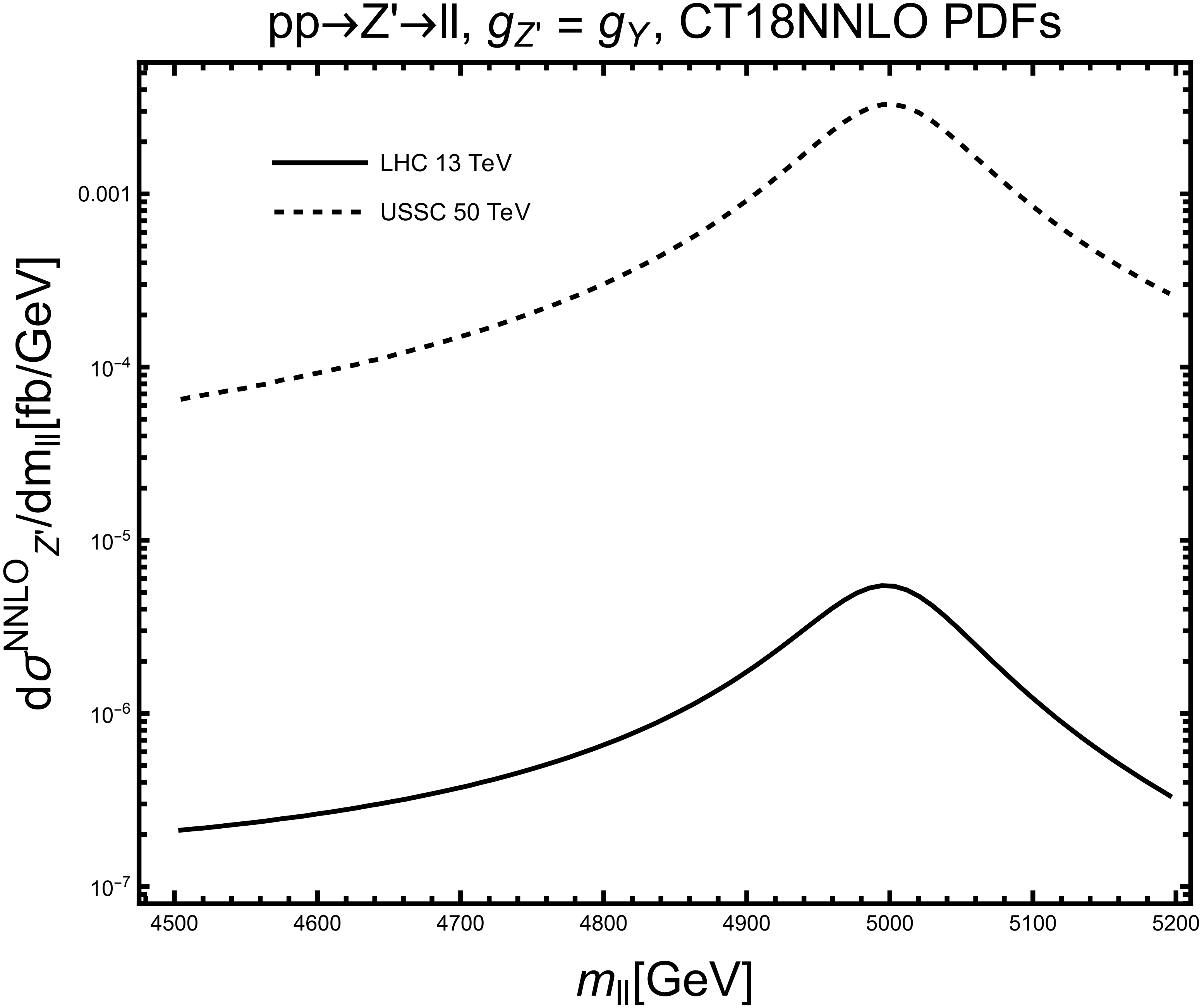
$U(1)_\zeta = U(1)_1 + U(1)_2 + U(1)_3$ is anomaly free

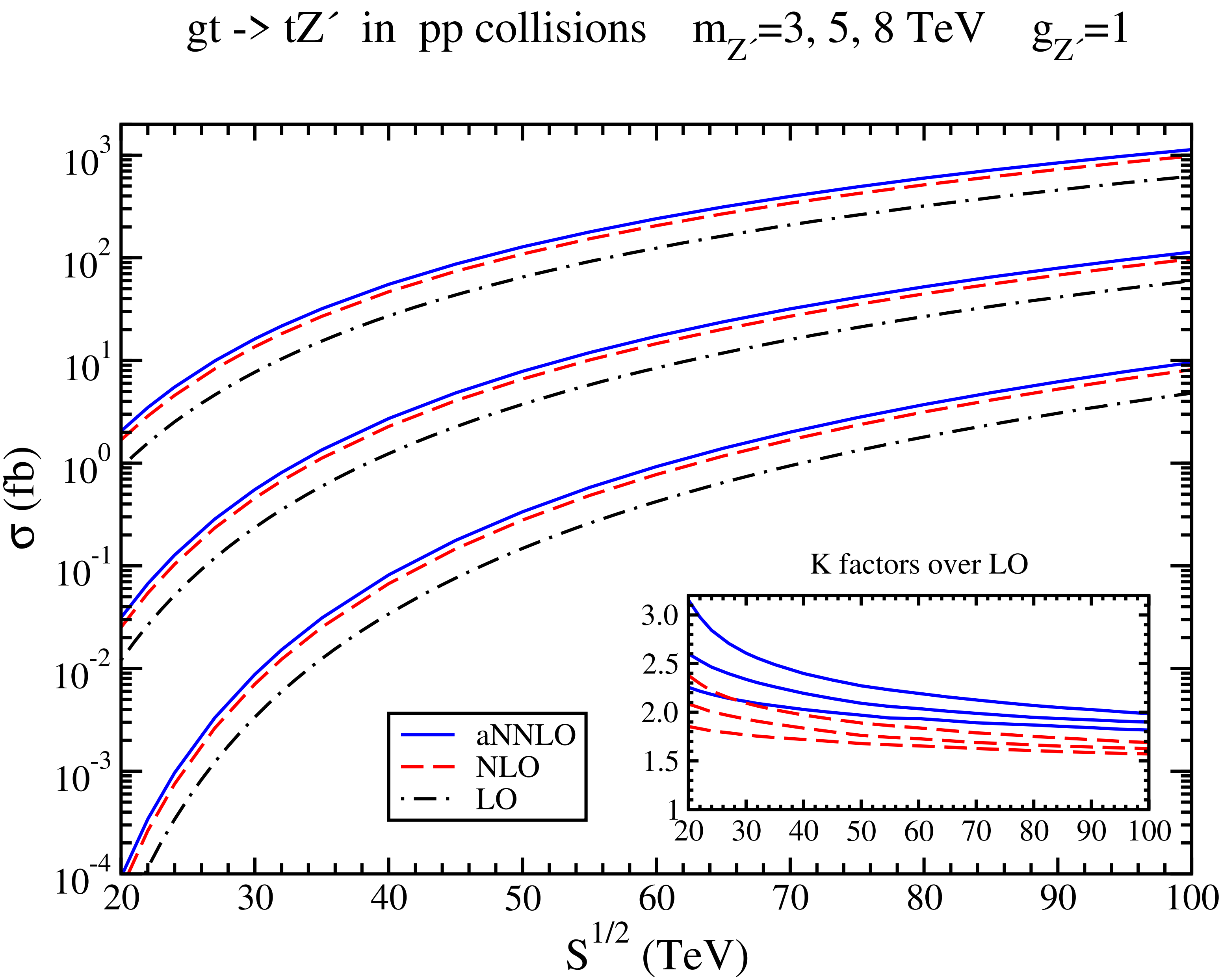
Z' model at low scales Heavy Higgs $\langle \mathcal{N} \rangle \sim M_{\rm String}$ $\rightarrow$ high seesaw $\rightarrow$ Z'

Field	$SU(3)_C$	$\times SU(2)_L$	$U(1)_Y$	$U(1)_{Z'}$
Q^i_L	3	2	$+\frac{1}{6}$	$-\frac{2}{5}$
u^i_L	$\bar{3}$	1	$-\frac{2}{3}$	$-\frac{2}{5}$
d^i_L	$\bar{3}$	1	$+\frac{1}{3}$	$-\frac{4}{5}$
e^i_L	1	1	$+1$	$-\frac{2}{5}$
L^i_L	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; ...


pp→Z'→ll, $g_{Z'}$ = g_Y, CT18NNLO PDFs
LHC 13 TeV
USSC 50 TeV
$d\sigma^{NNLO}_{Z'}/dm_{ll}$[fb/GeV]
0.001
10^{-4}
10^{-5}
10^{-6}
10^{-7}
4500
4600
4700
4800
4900
5000
5100
5200
m_{ll}[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

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