

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

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- 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; arXiv:2411.00595

Particle Physics Seminar, Liverpool University, Liverpool, 12 February 2025



 PhotoScan by Google Photos

## 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  $\langle \text{---} \rangle$  STRINGS

PRIMARY GUIDES:

3 generations

SO(10) embedding

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

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

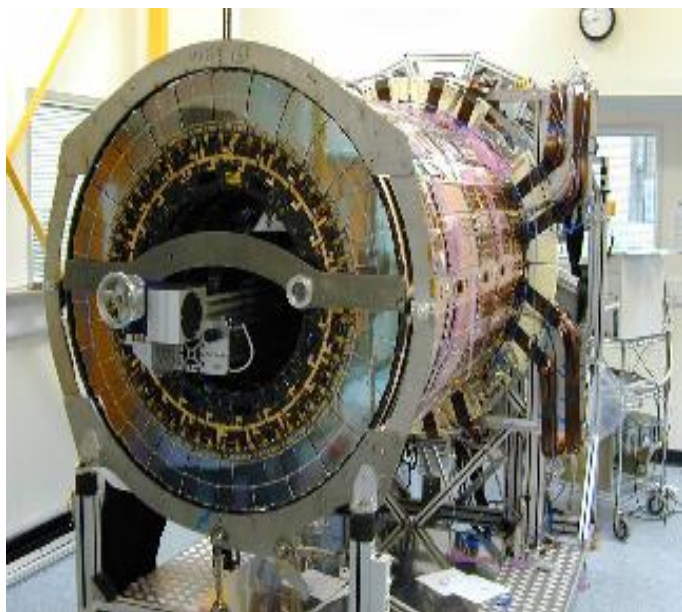
+ ... EFT



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

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

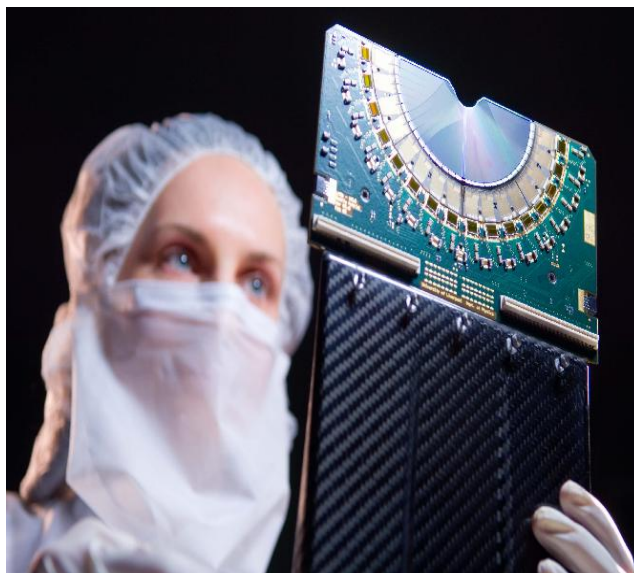
# Liverpool's contributions



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.*);

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 ~ 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

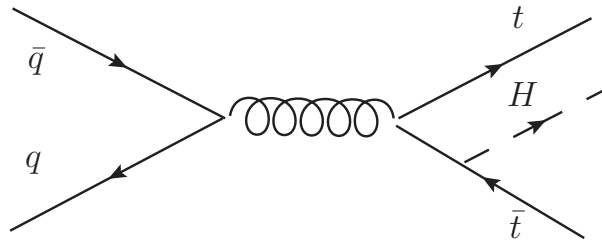
Under the leadership of the Arab Physical Society

(President Shaaban Khalil)

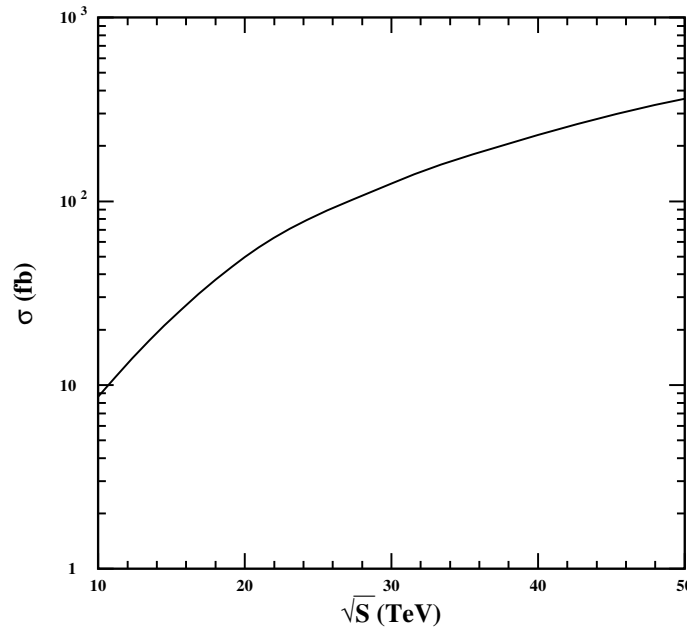
Alternatively: CERN FCC-ee  $\longleftrightarrow$  FCC-hh with LHC magnets



# Physics case: Bread & Butter SM Physics



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



(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)

## 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)
- .... Cosmology .... (Kounnas, Partouche, Toumbas ...)

# REALISTIC STRING MODELS :

heterotic 10D  $\rightarrow$  heterotic 4D

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

Orbifold – twists of flat 6D torus

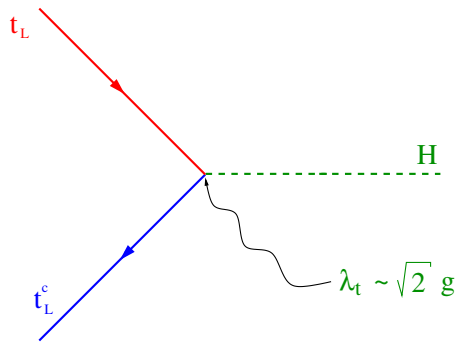


FREE FERMIONIC MODELS –

$Z_2 \times Z_2$  Orbifold  $\rightarrow U(1)_Y \in SO(10)$

$$\frac{6}{2} = 1+1+1$$

# 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

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

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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Received 30 September 1991

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  $\lambda_b = \lambda_\tau \sim \frac{1}{3}\lambda_t$  at the unification scale. A naive estimate yields  $m_t \sim 175\text{--}180\text{ GeV}$ .

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 split-

## 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  $U(1)_B$   
 $\implies U(1)_A ; U(1)_B \notin$  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  $U(1)_A \in E_6$ .

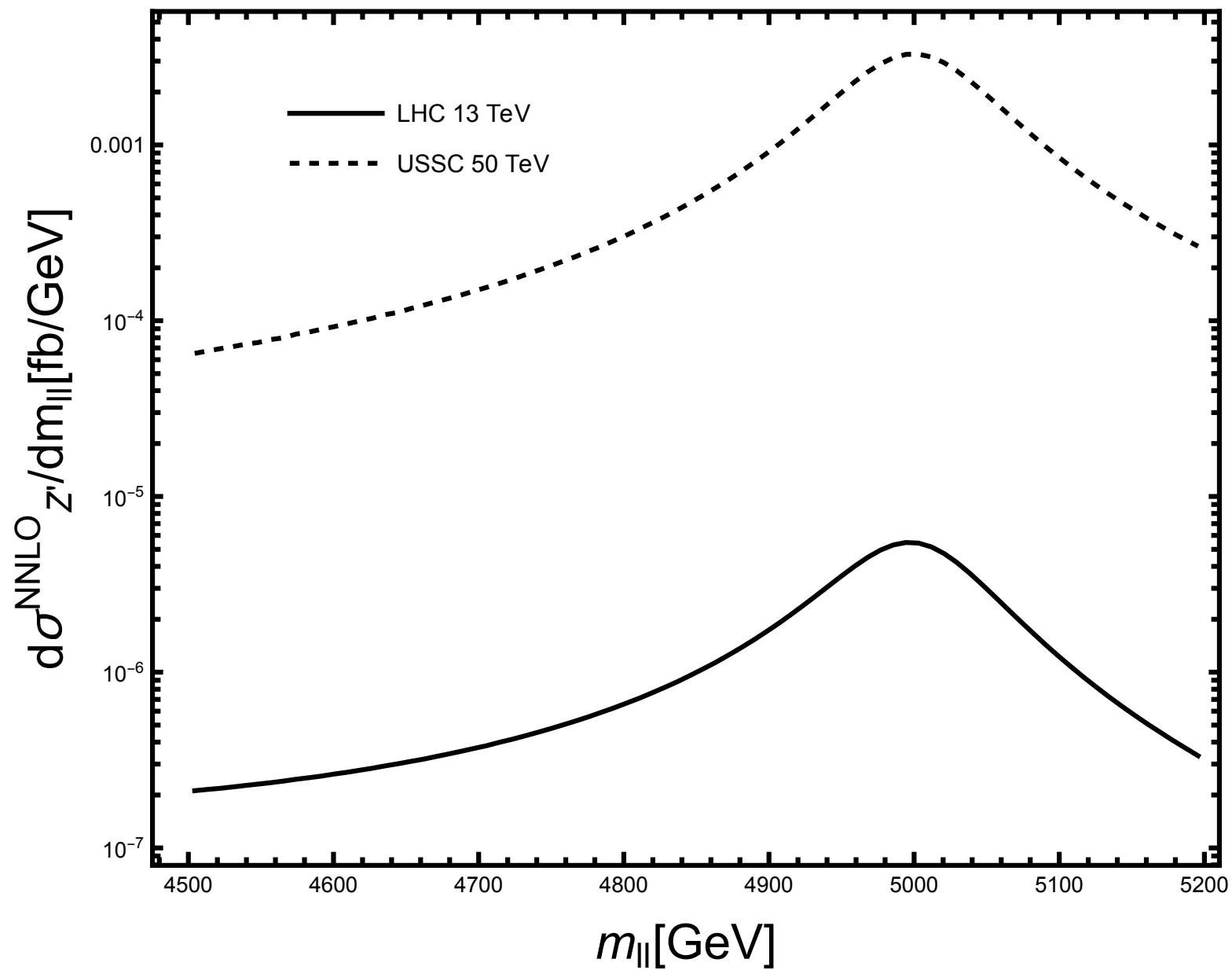
Z' model at low scales Heavy Higgs  $\langle \mathcal{N} \rangle \sim M_{\text{String}} \rightarrow$  high seesaw  $\rightarrow$  Z'

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	$+\frac{1}{2}$	$+\frac{4}{5}$
$\phi$	1	1	0	-1
$\bar{\phi}$	1	1	0	+1
$\zeta^i$	1	1	0	0

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

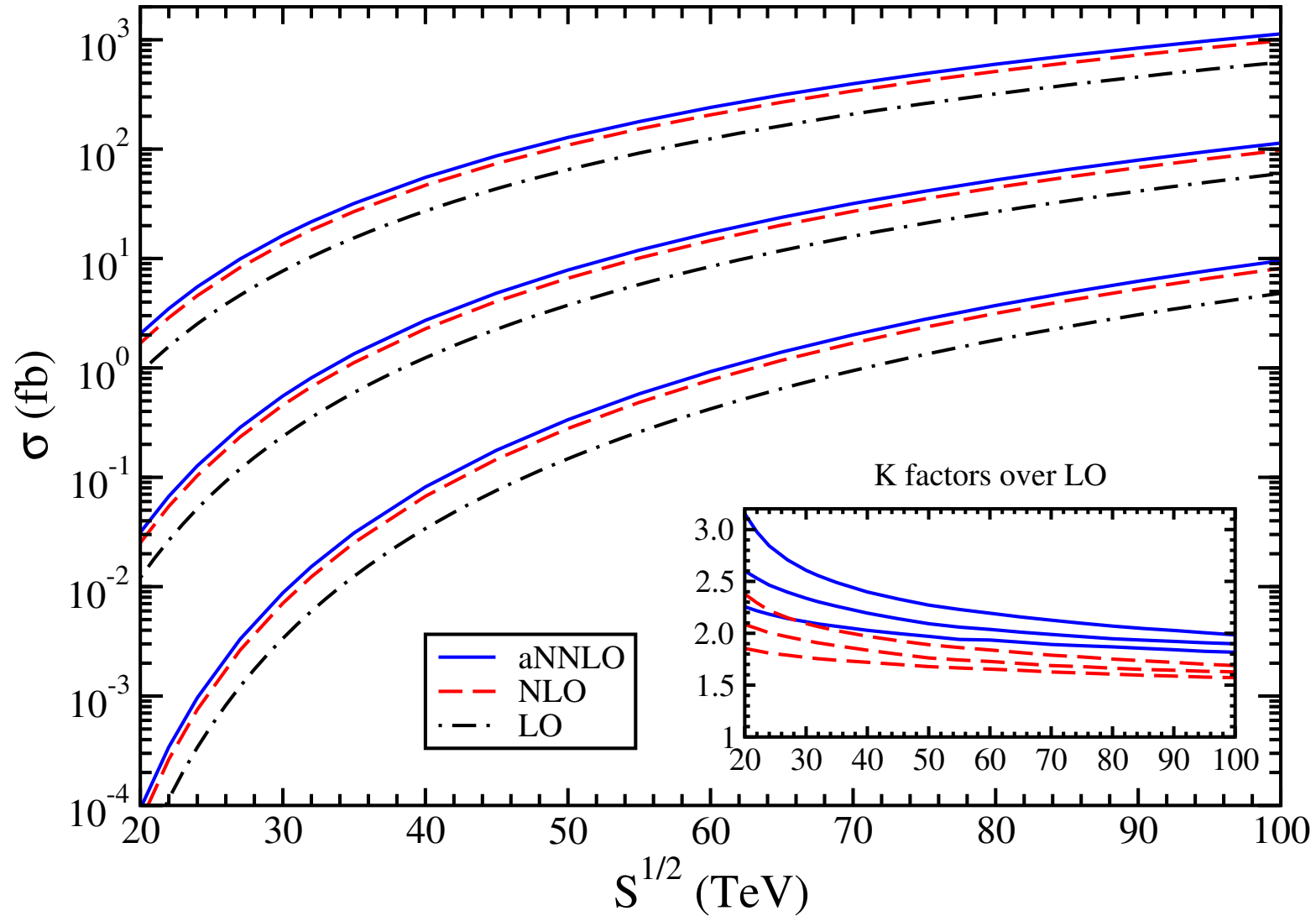
Relevant for: *e.g.* Sterile neutrinos;  $g_\mu - 2$ ; Lepton universality; ...

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





$gt \rightarrow tZ'$  in pp collisions  $m_{Z'}=3, 5, 8 \text{ TeV}$   $g_{Z'}=1$   
 NNPDF3.1 NNLO pdf  $\mu=m_{Z'}$   $m_t=172.5 \text{ GeV}$



(From Marco Guzzi, Nikolaos Kidonakis,  
 *$tZ'$  production at hadron colliders, 1904.10071*)

## What's next?

- Technical design & Physics case by Winter 2025
- Technical design: SSC + upgraded magnets
- Physics case:

SM (EW; QCD; Flavour) &

BSM (SUSY; Compositness;  $Z'$ ; ...) Phenomenology

- Possibly dedicated workshop in Summer 2025
- 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/FCC–LHC will seek B&B SM Physics
- It may discover new physics associated with EWSB by 2040
- Experimental Particle Physics Priorities 2025, A String Phenomenology Perspective, arXiv:2503.?????. Higgs: fundamental or composite? single or multi? interactions? flavour couplings? self-couplings? vacuum? hierarchy? New particles? → USSC/FCC–LHC

**THANK YOU**