Experimental Particle Physics Priorities 2025:

A String Phenomenology Perspective

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- Particle Physics Priorities under investigation SnowMass2021; EPPP2025
  String Phenomenology $\rightarrow$ 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

String Phenomenology 2025, Boston MA, July 2025

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 – · · · (with Kounnas, Rizos & ... Percival, Matyas)
- .... Cosmology .... — (Kounnas, Partouche, Toumbas ...)

Fermion mass hierarchy

Fermion mass terms

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

c - calculable coefficients g - gauge coupling

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

$h \rightarrow$ light Higgs multiplets

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

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

Cabibbo mixing PLB 307 (1993) 305

Find anomaly free solution

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

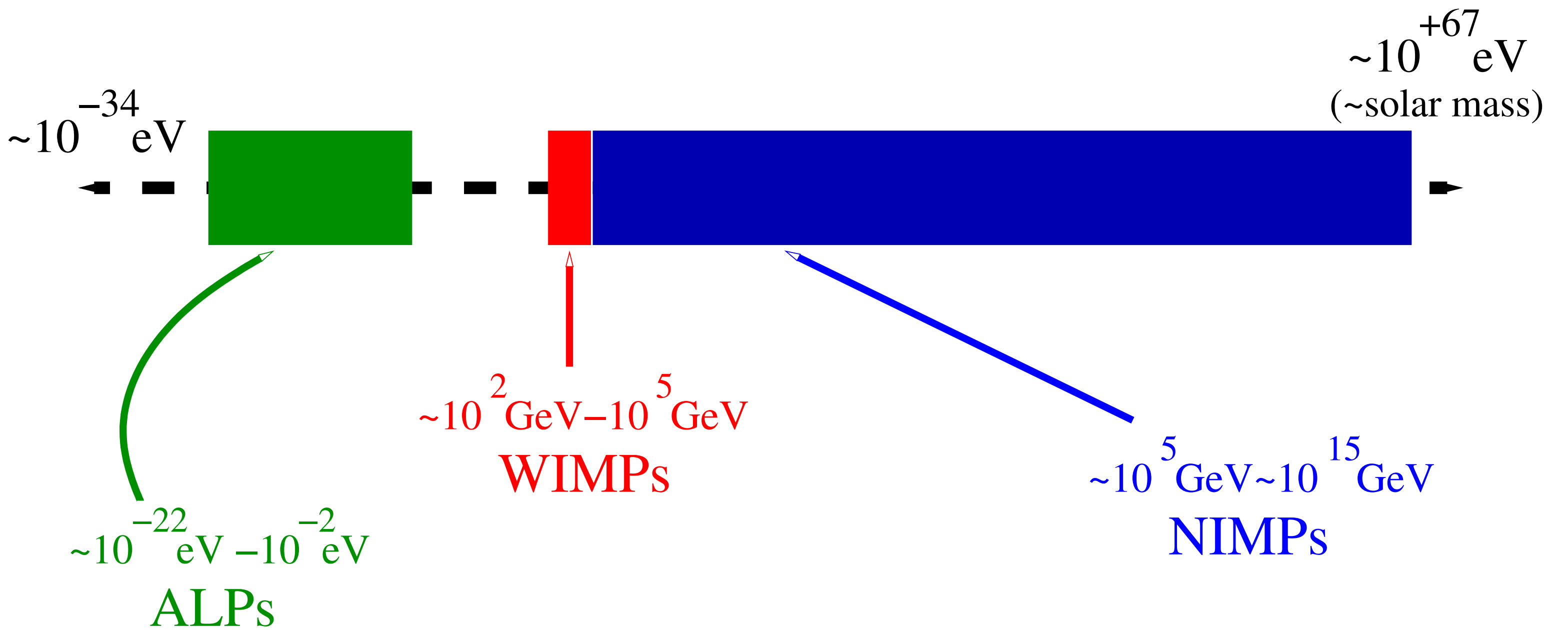
$$\epsilon < 10^{-8} \qquad \frac{V_2\bar{V}_3\Phi_{\alpha\beta}}{M^3} = \frac{\sqrt{5}\, g^6}{64\,\pi^3} \approx 2-3\times 10^{-4}.$$

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

Three generation mixing $\longrightarrow$ 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)

“Wilsonian” singlet dark matter   Delle Rose, AEF, Marzo, Rizos, 1704.02579

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

Several cases to consider :

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

2. $M >> M_{Z'}$ 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 $\Rightarrow M < 3$ 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 facilty and funded by Saudi–Arabia and other regional and global interested parties.

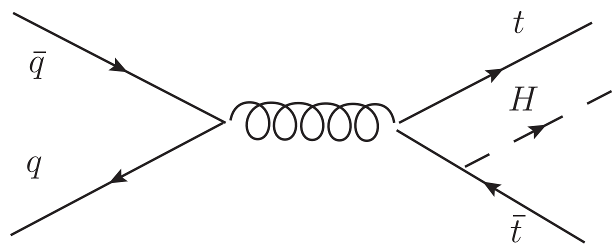
COST: $\$ 10–20$ B $\times 5 = \$ 50–100$ B

Under the leadership of the Arab Physical Society

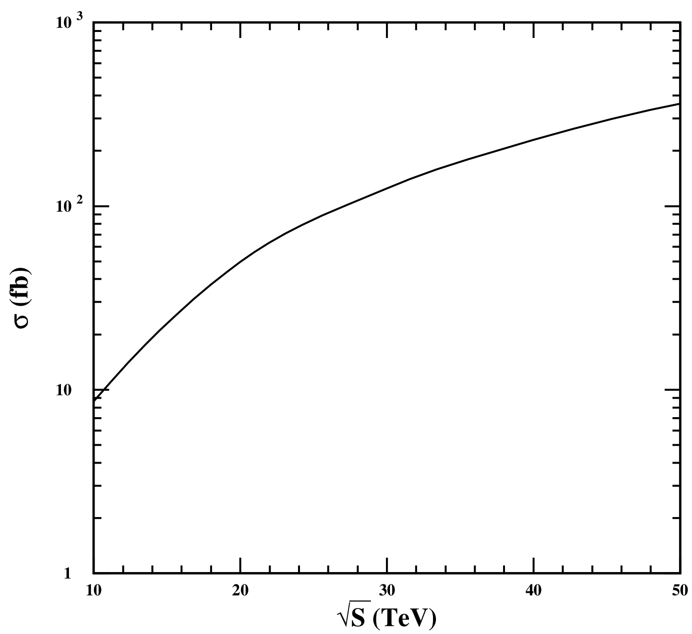
(President Shaaban Khalil)

Alternatively: CERN FCC-ee $\longleftrightarrow$ FCC–hh with LHC magnets (Plan B)

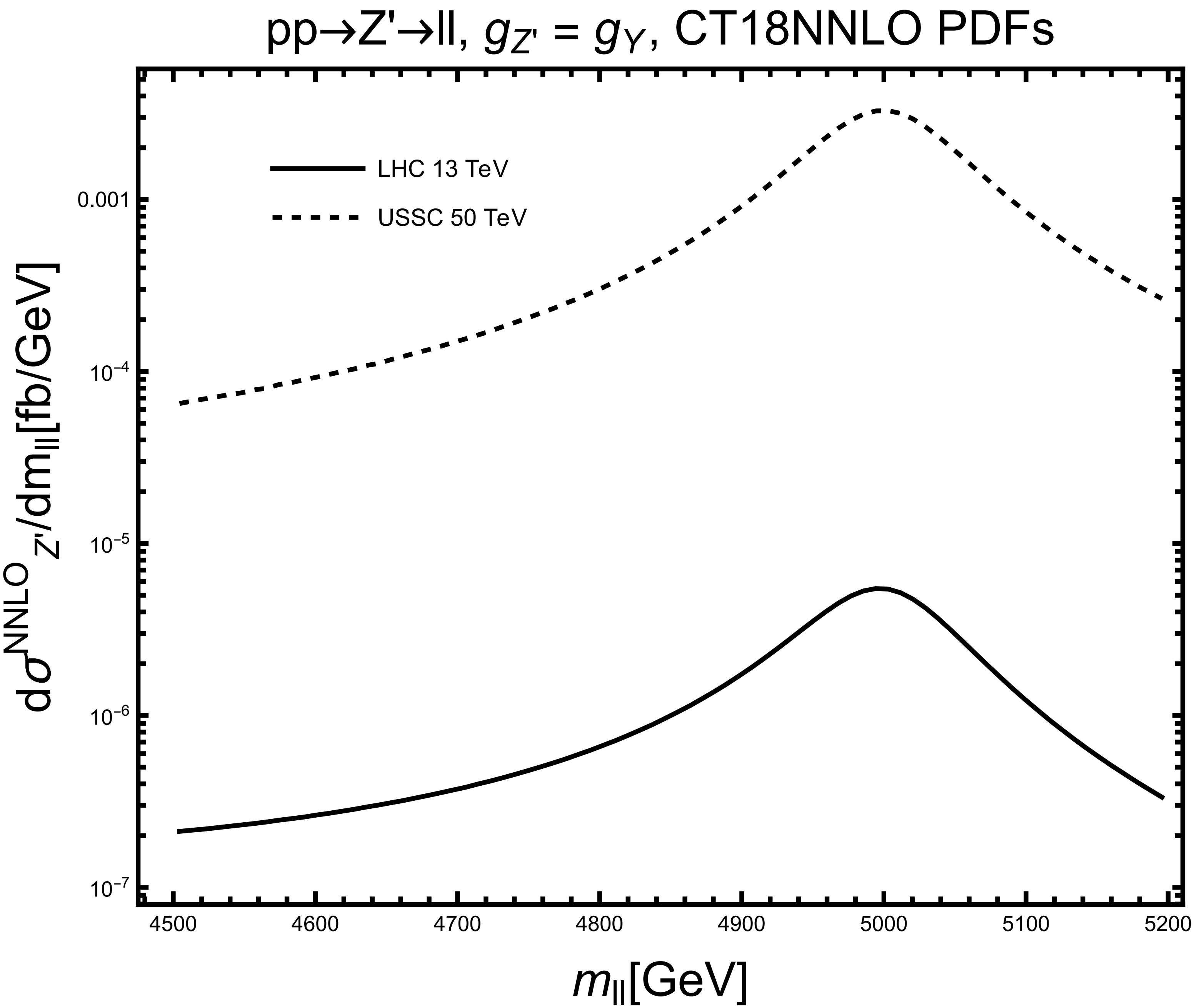
Physics case: Bread & Butter SM Physics

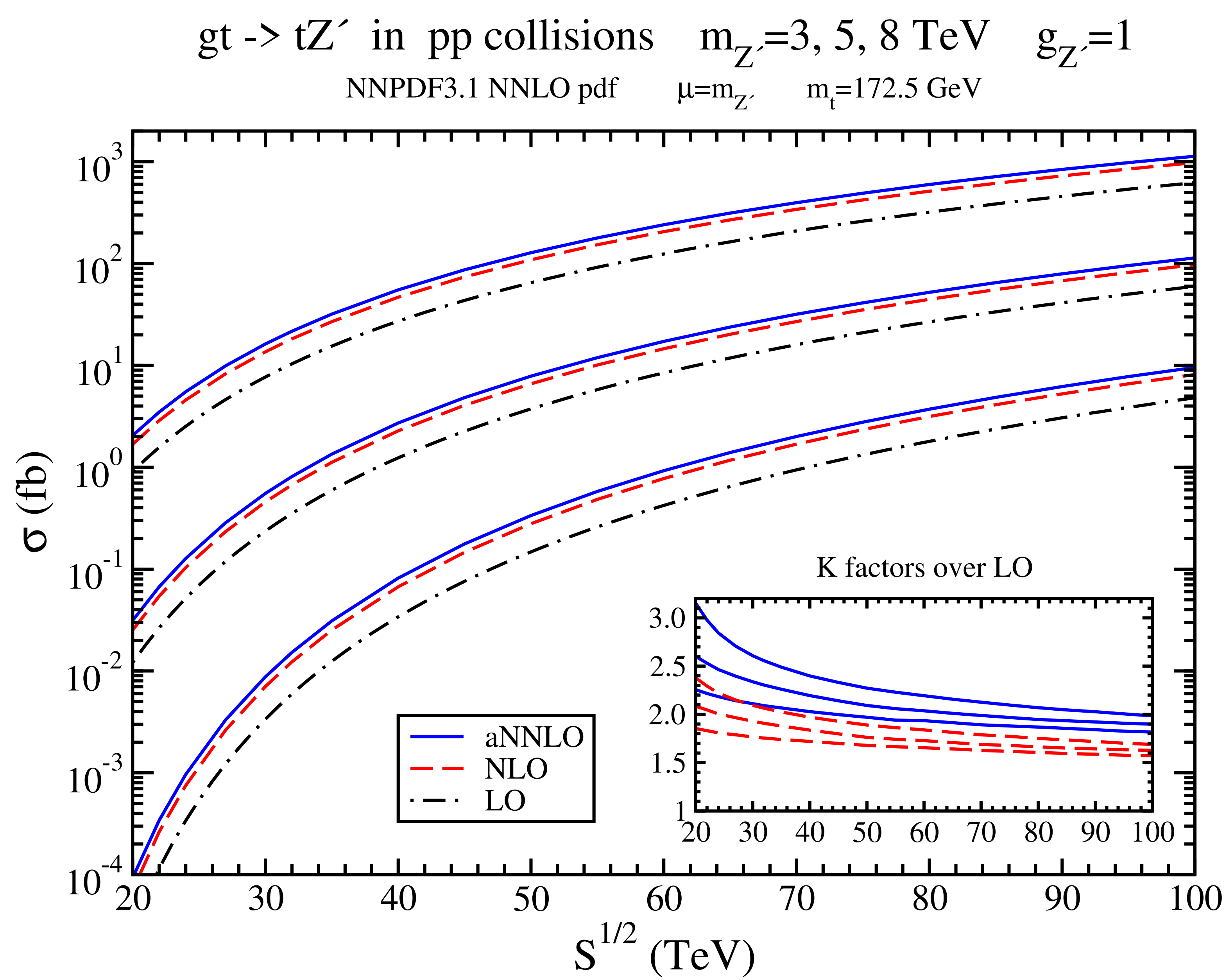


Process: $pp \to t\bar{t}H \to b\ell^+\nu\bar{b}\ell^-\nu H \qquad (\ell = e, \mu)$



(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)


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



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

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?

$\longrightarrow$ USSC/FCC–LHC

THANK YOU