SU(5) x U(1) Grand Unification with Minimal Seesaw and Z'-portal Dark Matter

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Ref: NO, S. Okada & D. Raut, Phys. Lett. B 780 (2018) 422

PHENO 2018 @ Univ. of Pittsburgh, May 7-9, 2018

Problems of the Standard Model

Although the Standard Model (SM) is the best theory so far, New Physics beyond SM is strongly suggested by both experimental & theoretical points of view

What is missing?

1. Neutrino masses and flavor mixings
2. Dark matter candidate

They must be supplemented by New Physics

Minimal gauged U(1)*x* extension of the Standard Model

$$\mathrm{SU}(3)_c \times \mathrm{SU}(2)_L \times \mathrm{U}(1)_Y \times \mathrm{U}(1)_X$$

- Generalization of the minimal U(1) B-L model
- Anomaly free requirement → 3 right-handed neutrinos (RHNs)
- A SM singlet Higgs → U(1)*x* symmetry breaking
  Majorana mass generation for RHNs
- Type I seesaw is implemented
- U(1)*x* breaking at TeV → LHC Physics for Z' boson

Introducing Z_2 symmetry for a Dark Matter candidate

$$\mathrm{SU}(3)_c \times \mathrm{SU}(2)_L \times \mathrm{U}(1)_Y \times \boxed{\mathrm{U}(1)_X \times Z_2}$$

Assigning Z_2-odd parity to one RHN, while even for all the others

J=1,2	$SU(3)_c$	$SU(2)_L$	$U(1)_Y$	$U(1)_X$	Z_2
N_R^j	1	1	0	-1	$+$
N_R	1	1	0	-1	$-$

NO & Seto, PRD 82 (2010) 023507

Anisimov & Di Bari, PRD 80 (2009) 073017

→ DM candidate

3 right-handed neutrinos → ``2+1 scheme''

- 2 RHNs for the Minimal Seesaw

King, NPB 576 (2000) 85; Frampton, Glashow & Yanagida, PLB 548 (2002) 119

✓ Neutrino oscillation data with one massless eigenstate

- Z_2-odd 1 RHN for thermal Dark Matter

TeV-scale minimal U(1)x model with RHN DM

NO & S. Okada,
PRD 95 (2017)035025

	$SU(3)_c$	$SU(2)_L$	$U(1)_Y$	$U(1)_X$	Z_2
q_L^i	$\mathbf{3}$	$\mathbf{2}$	$1/6$	$(1/6)x_H + (1/3)$	$+$
u_R^i	$\mathbf{3}$	$\mathbf{1}$	$2/3$	$(2/3)x_H + (1/3)$	$+$
d_R^i	$\mathbf{3}$	$\mathbf{1}$	$-1/3$	$-(1/3)x_H + (1/3)$	$+$
ℓ_L^i	$\mathbf{1}$	$\mathbf{2}$	$-1/2$	$(-1/2)x_H - 1$	$+$
e_R^i	$\mathbf{1}$	$\mathbf{1}$	-1	$(-1)x_H - 1$	$+$
H	$\mathbf{1}$	$\mathbf{2}$	$-1/2$	$(-1/2)x_H$	$+$
N_R^j	$\mathbf{1}$	$\mathbf{1}$	0	-1	$+$
N_R	$\mathbf{1}$	$\mathbf{1}$	0	-1	$-$
Φ	$\mathbf{1}$	$\mathbf{1}$	0	$+2$	$+$

J=1,2

- U(1)x charge: $Q_X = Y_f\, x_H + Q^f_{B-L}$
- The minimal B-L model is in the limit of $x_H \to 0$

New Yukawa terms in Lagrangian

$$\mathcal{L}_{Yukawa} \supset -\sum_{i=1}^{3}\sum_{j=1}^{2} Y_D^{ij}\overline{\ell_L^i} H N_R^j$$
$$-\frac{1}{2}\sum_{k=1}^{2} Y_N^k \Phi \overline{N_R^{k\ C}} N_R^k - \frac{1}{2} Y_N \Phi \overline{N_R^{\ C}} N_R$$

- Mass generation for RHNs and Z' boson by $\langle \Phi \rangle = \frac{v_X}{\sqrt{2}}$

$$m_N^j = \frac{Y_N^j}{\sqrt{2}} v_X, \quad m_{DM} = \frac{Y_N}{\sqrt{2}} v_X,$$

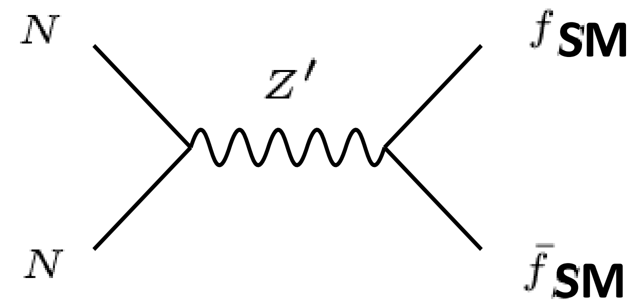
$$m_{Z'} = g_X \sqrt{4 v_X^2 + \frac{v^2}{4}} \simeq 2 g_X v_X$$

- Minimal Seesaw mechanism after EW symmetry breaking

Phenomenology of TeV-scale minimal U(1)x model with RHN DM

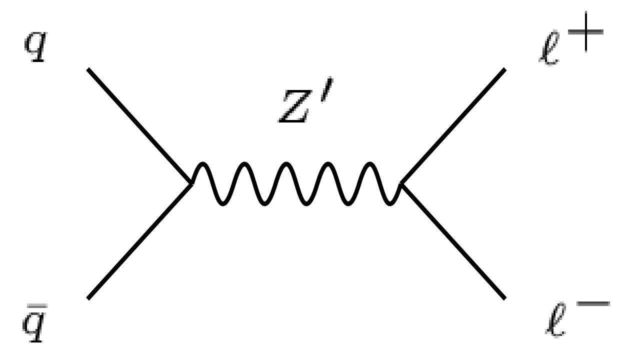
(1) Z'-portal RHN DM

RHN DM communicates with the SM particles through Z' boson mediated processes



(2) Z' boson search at the LHC Run-2

Search for a narrow resonance with the di-lepton final state at ATLAS and CMS with LHC Run-2



(3) Complementarity between DM physics and LHC physics

It turns out that both of DM physics and LHC physics are controlled by only 3 free parameters:

- U(1)X gauge coupling: $\alpha_X = \frac{g_X^2}{4\pi}$
- Z' boson mass: $m_{Z'}$
- SM Higgs U(1)x charge: x_H

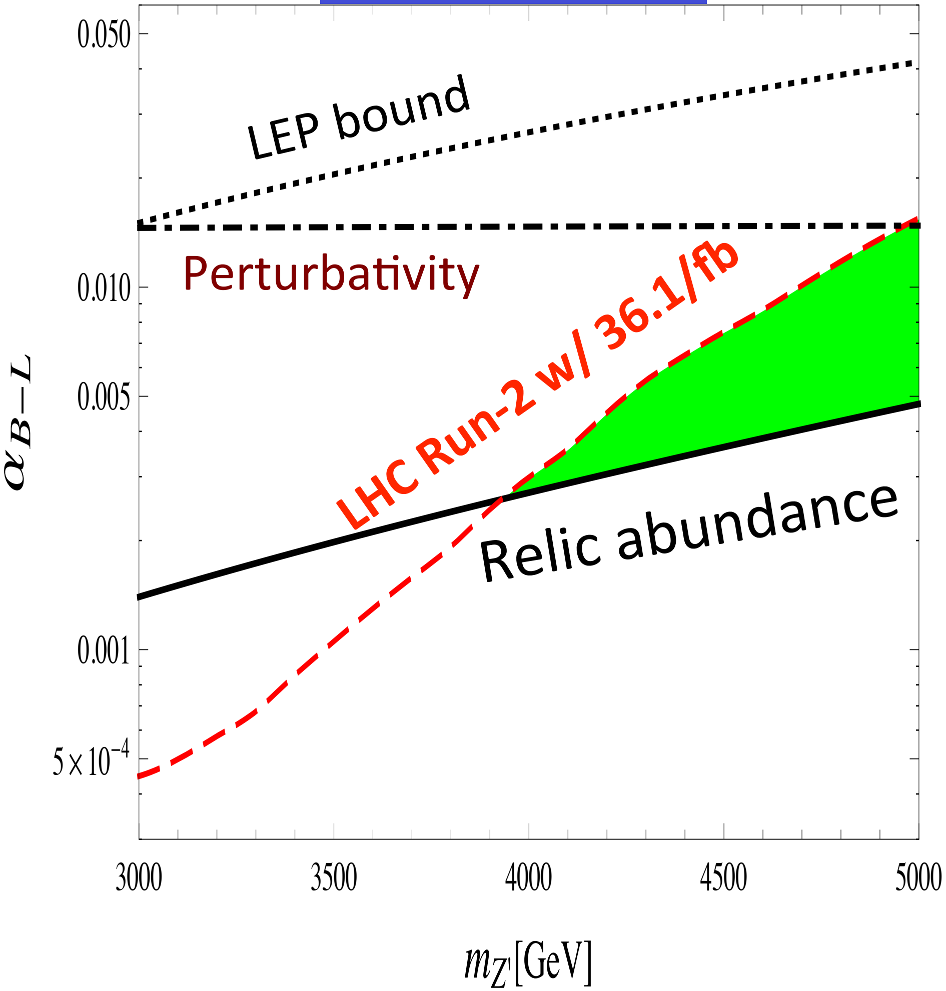
* To reproduce the observed DM abundance, $m_{\rm DM} \simeq m_{Z'}/2$

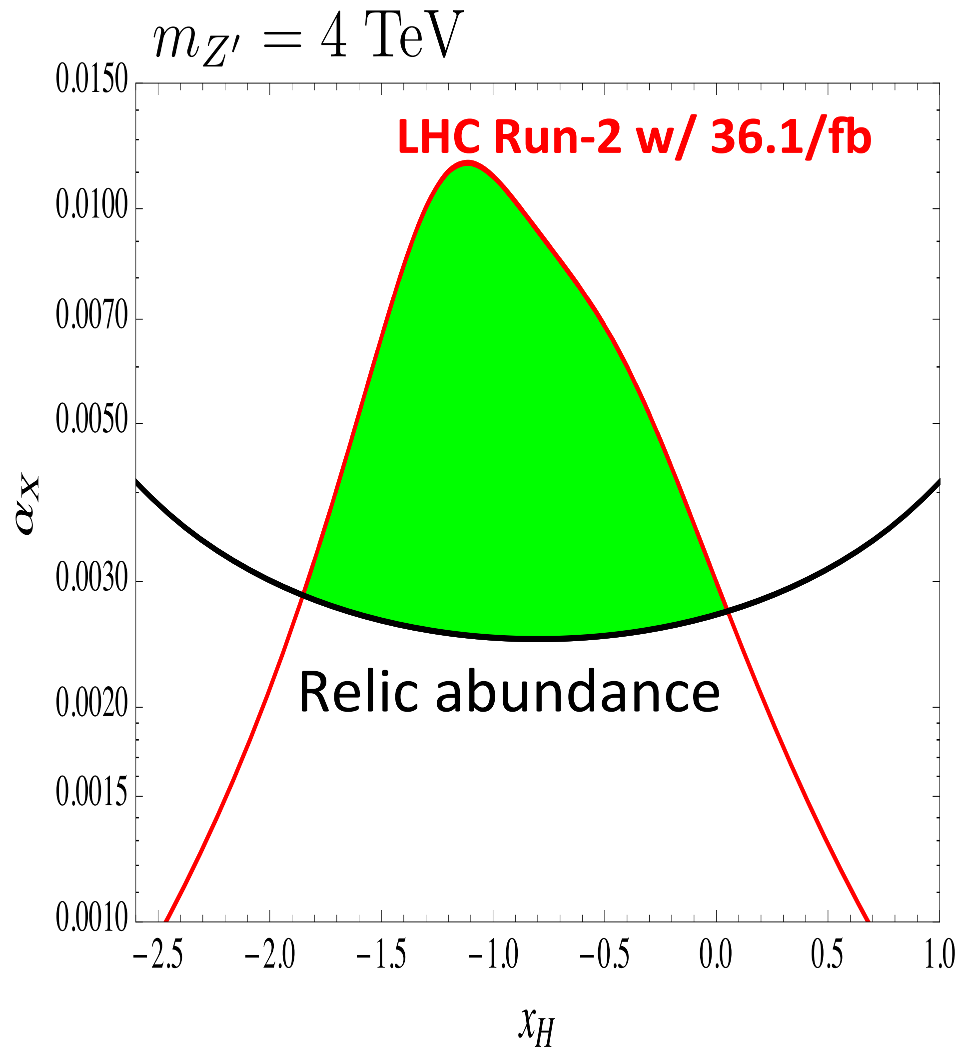
** For simplicity, 2 RHN mass = mz'

Complementarity

- DM relic abundance → upper bound on α_X
- LHC bound from Z’ boson search → upper bound on α_X

x_H=0 (B-L limit)





We now propose

Grand unified SU(5) x U(1)*x* model

into which the our U(1)*x* model is embedded.

Ref: NO, S. Okada and D. Raut, PLB 780 (2018) 422-426

Grand Unified Theory paradigm

- Unification of all the SM gauge interactions
- Electric charge quantization
- Mathematical beauty
- Prediction of proton decay

1. Embedding the U(1)*x* model into SU(5) x U(1)*x*

Left-handed fermion content:

	$SU(3)_C$	$SU(2)_L$	$U(1)_Y$	$U(1)_X$	Z_2
q_L^i	$\mathbf{3}$	$\mathbf{2}$	$1/6$	$(1/6)x_H + 1/3$	$+$
$(u_R^i)^c$	$\mathbf{3}^*$	$\mathbf{1}$	$-2/3$	$(-2/3)x_H - 1/3$	$+$
$(d_R^i)^c$	$\mathbf{3}^*$	$\mathbf{1}$	$+1/3$	$(+1/3)x_H - 1/3$	$+$
ℓ_L^i	$\mathbf{1}$	$\mathbf{2}$	$-1/2$	$(-1/2)x_H - 1$	$+$
$(e_R^i)^c$	$\mathbf{1}$	$\mathbf{1}$	-1	$(+1)x_H + 1$	$+$
J=1,2 $(N_R^j)^c$	$\mathbf{1}$	$\mathbf{1}$	0	$+1$	$+$
$(N_R)^c$	$\mathbf{1}$	$\mathbf{1}$	0	$+1$	$-$

Left-handed fermion content with x_H=-4/5

	$SU(3)_C$	$SU(2)_L$	$U(1)_Y$	$U(1)_X$	Z_2
q_L^i	$\mathbf{3}$	$\mathbf{2}$	$1/6$	$1/5$	$+$
$(u_R^i)^c$	$\mathbf{3}^*$	$\mathbf{1}$	$-2/3$	$1/5$	$+$
$(d_R^i)^c$	$\mathbf{3}^*$	$\mathbf{1}$	$+1/3$	$-3/5$	$+$
ℓ_L^i	$\mathbf{1}$	$\mathbf{2}$	$-1/2$	$-3/5$	$+$
$(e_R^i)^c$	$\mathbf{1}$	$\mathbf{1}$	$+1$	$1/5$	$+$
J=1,2 $(N_R^j)^c$	$\mathbf{1}$	$\mathbf{1}$	0	$+1$	$+$
$(N_R)^c$	$\mathbf{1}$	$\mathbf{1}$	0	$+1$	$-$

(red box) → **5*** in SU(5)

(blue box) → **10** in SU(5)

(green box) → **1** in SU(5)

Successful Unification of the matters into SU(5) x U(1)*x*

$$\overline{F_5}^i: \; (\mathbf{5}^*, -3/5) \supset (d_R^i)^c \oplus \ell_L^i$$
$$F_{10}^i: \; (\mathbf{10}, 1/5) \supset q_L^i \oplus (u_R^i)^c \oplus (e_R^i)^c$$

xH=-4/5

- In the presence of 3 RHNs, this GUT model is free from all gauge and mixed-gravitational anomalies.
- Electric charge quantization as usual SU(5) GUT
- x_H is also quantized by this unification

  * In terms of SO(10) unification, this is $\mathrm{SO}(10) \supset \mathrm{SU}(5) \times \mathrm{U}(1)$

The Standard SU(5) GUT by Georgi-Glashw is supplemented with the minimal seesaw for the neutrino mass matrix & Z'-portal RHN Dark Matter: Grand Unified SU(5) x U(1)*x* model

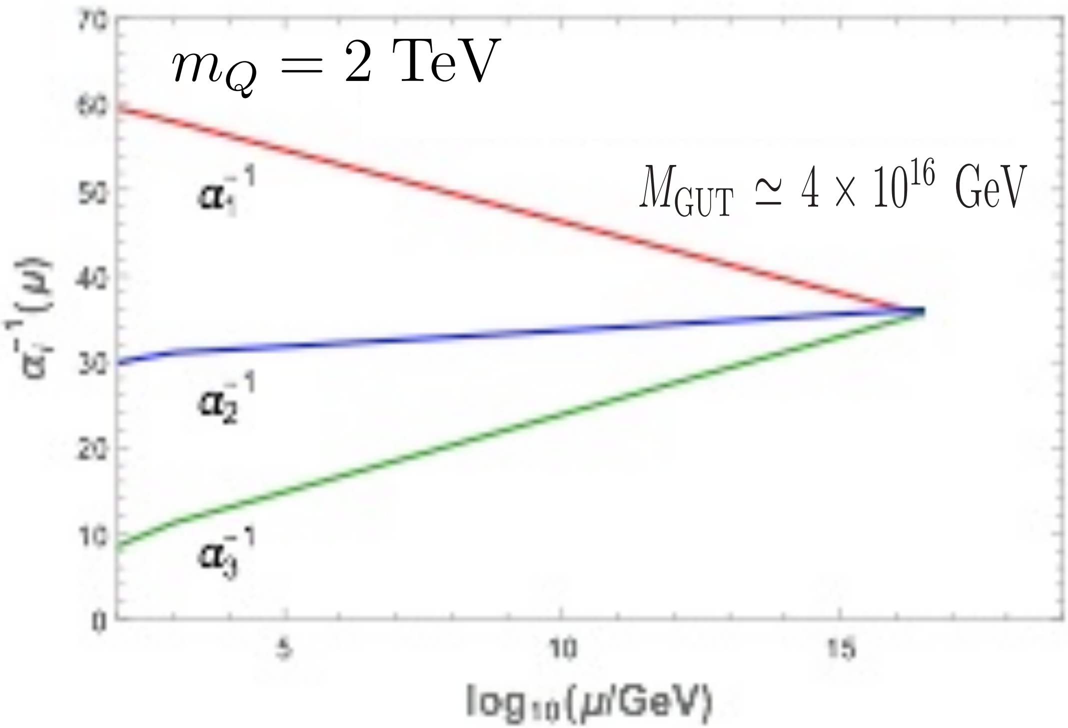
2. Phenomenological viability of SU(5) x U(1)*x* Model

- Successful gauge coupling unification?
- Realizing the SM at low energies?
- Theoretical consistency & consistency with the current experimental results?
- Future prospects?

2-1. Gauge coupling unification with extra-quarks

It is known that in the presence of vector-like heavy quarks with mass at the TeV scale, the successful gauge coupling can be achieved.

Amaldi et al., PLB 281 (1992) 374;
Chkareuli et al., PLB 340 (1994) 63;
Choudfury et al., PRD 65 (2002) 053002;
Gogoladze et al., PLB 690 (2010) 495



In the presence of vector-like quarks:

$D_L + D_R$: (**3, 1,** 1/3)
$Q_L + Q_R$: (**3, 2**, -1/6)

with mass of O(TeV)

$$\tau_p(p \to \pi^0 e^+) \simeq 10^{38} \text{ years}$$

2-2. Realizing the SM at low energies

- SU(5) symmetry breaking in the standard way with an SU(5) adjoint Higgs VEV at O(10^16) GeV

$$\langle \Sigma \rangle = v_{\rm GUT}\,{\rm diag}(1,1,1,-3/2,-3/2)$$

- SU(5) x U(1)*x* → SM x U(1)*x*
  U(1)*x* is broken at the TeV scale

- Realizing the vector-like quarks at the TeV with a mass splitting at the GUT scale

  $D_L + D_R^C$ and $Q_L + Q_R^C$ are unified into $F_5 + \overline{F_5}$ and $F_{10} + \overline{F_{10}}$

  We introducing Yukawa couplings and mass terms,

$$\mathcal{L}_Y = \overline{F_5}(Y_5\Sigma - M_5)F_5 + {\rm tr}\left[\overline{F_{10}}(Y_{10}\Sigma - M_{10})F_{10}\right]$$

  and arrange the parameters to leave only D’s and Q’s light

2-3. Theoretical consistency and Consistency with the current experiments

- Perturbativity of U(1)*x* gauge coupling up to the GUT scale

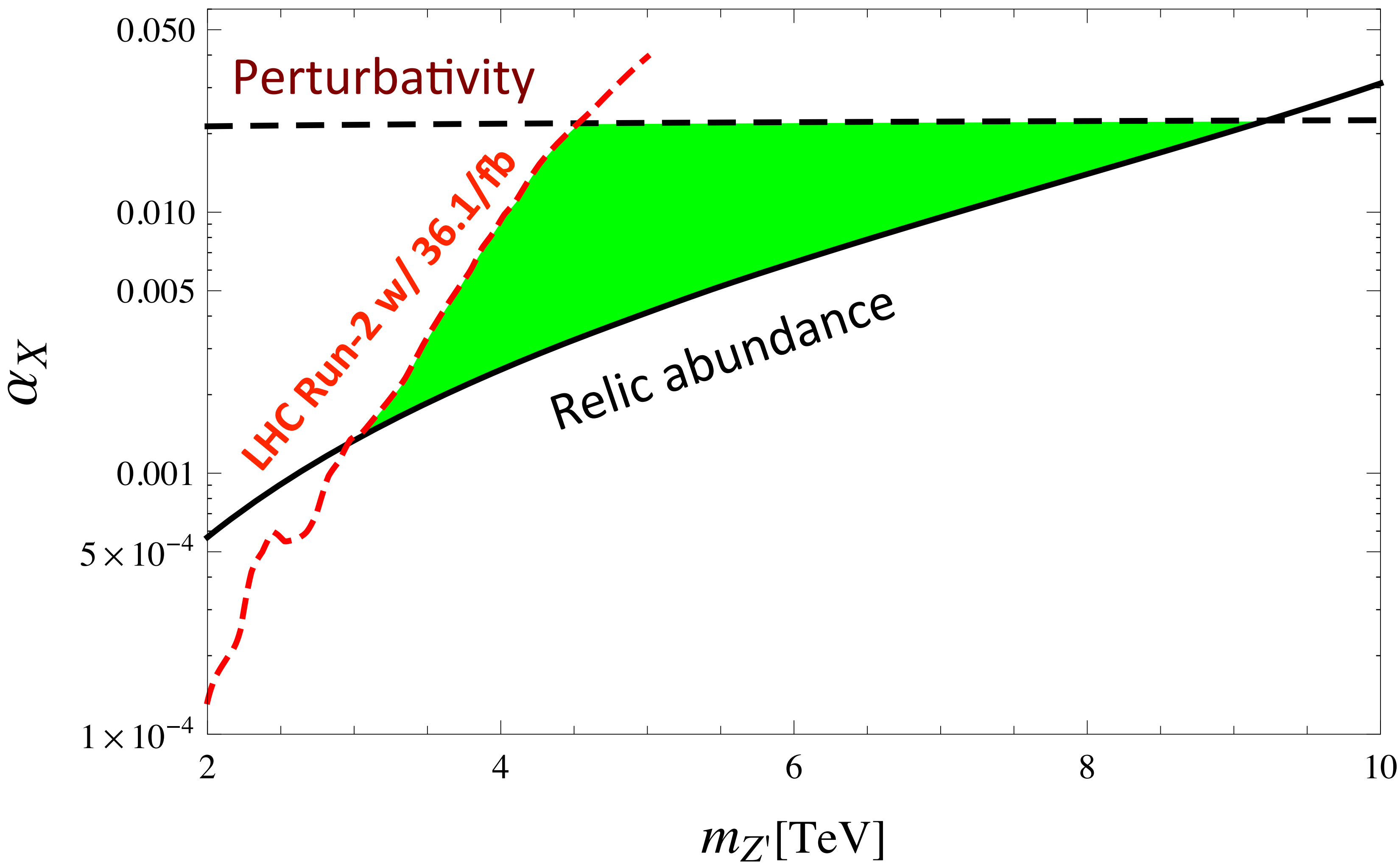
Solution to the Renormalization Group Equation for the U(1)x gauge coupling at 1-loop level:

$$\alpha_X(m_{Z'}) = \frac{\alpha_X(M_{\rm GUT})}{1 + \alpha_X(M_{\rm GUT})\frac{b_X}{2\pi}\ln\left[\frac{M_{\rm GUT}}{m_{Z'}}\right]}$$

where $b_X = \frac{48}{5}$, including the vector-like quarks

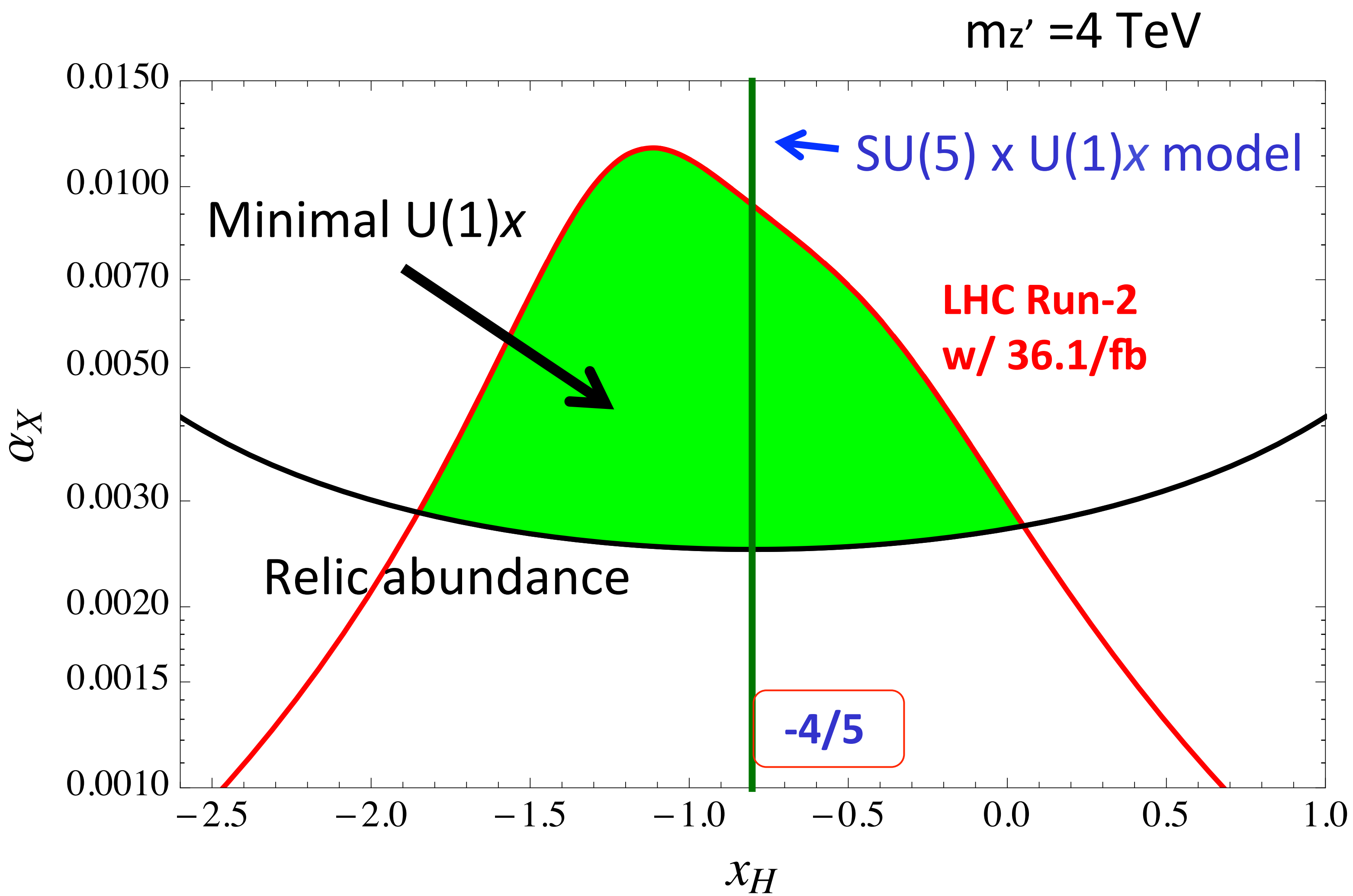
For a requirement, $\alpha_X(M_{\rm GUT}) \leq 4\pi$ we find $\alpha_X(m_{Z'}) \leq 0.022$ for $m_{Z'} \leq 10\ {\rm TeV}$

➢ Cosmological & LHC Run-2 constraints & perturbativity



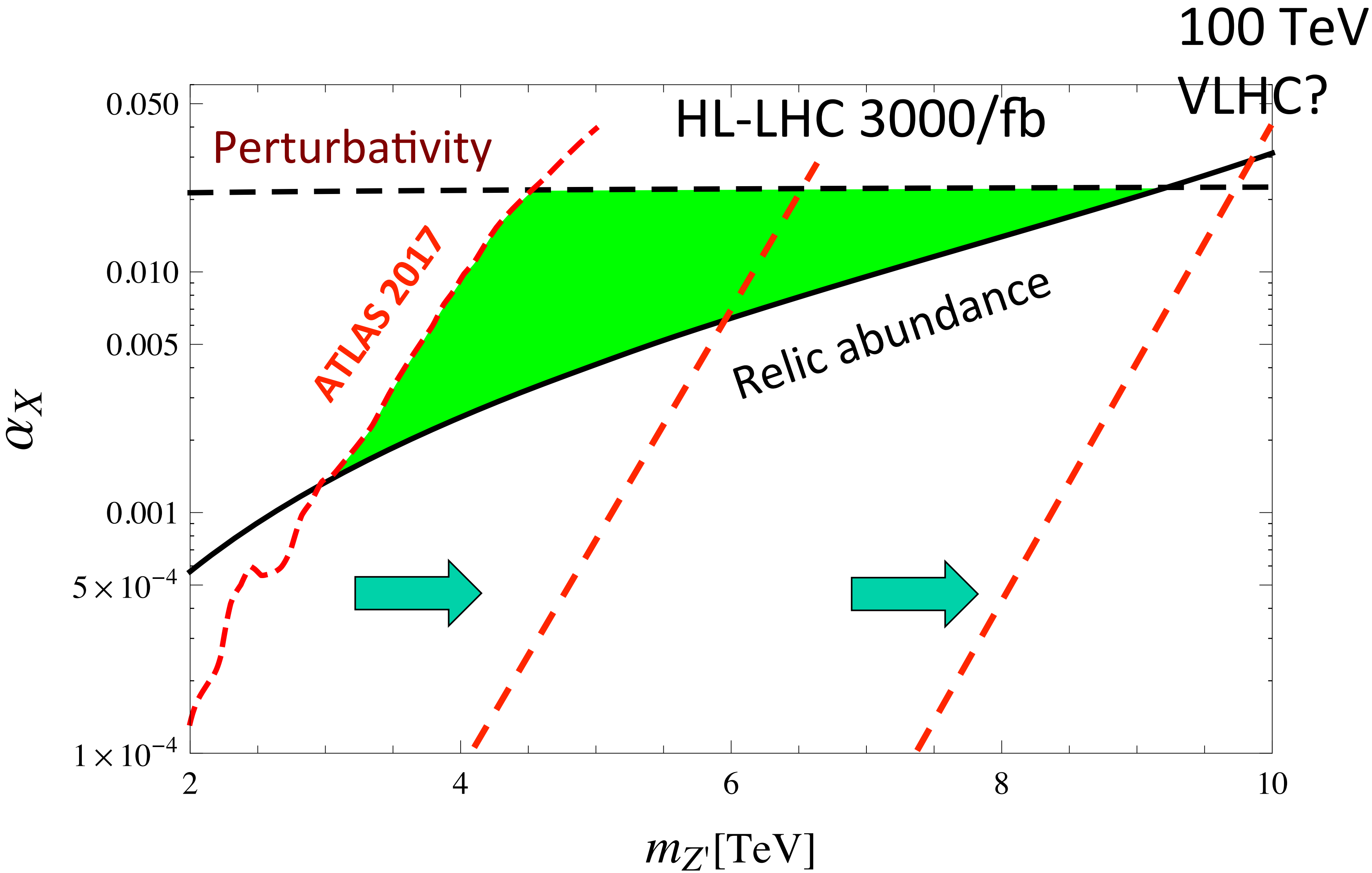
$$3.0 \leq m_{Z'}[\mathrm{TeV}] \leq 9.2$$

Is xH=-4/5 special?



Interestingly, xH=-4/5 is almost an ideal choice to survive the severe experimental constraints

2-4. Future prospects



$$3.0 \leq m_{Z'}[\mathrm{TeV}] \leq 9.2$$

Summary

- We have proposed a grand unified SU(5) x U(1)*x* model, where the standard grand unified SU(5) model is supplemented by minimal seesaw and Z'-portal dark matter.

- The SU(5) symmetry is broken at 10^16 GeV, while U(1)*x* symmetry is broken at the TeV scale.

- Phenomenological viabilities if this scenario has been investigated.

- The constraints from (i) the DM relic abundance (ii) the LHC search results for Z' boson and (iii) gauge coupling perturbativity are complementary to narrow down the Z' boson mass to the range of 3 TeV – 9.2 TeV, which will be explored in the near future.