Doorways to New Physics

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CASE WESTERN RESERVE
UNIVERSITY EST. 1826
think beyond the possible

Standard Model at 50 years, CWRU, Cleveland, 2018

Current Status:

Thanks to the LHC we know that the masses for the W and Z gauge bosons, and charged fermions are generated through the Spontaneous Breaking of the Electroweak Gauge Symmetry

The Standard Model provides a good "explanation" for most of the current experimental results in particle physics and it is one of the most successful theories of nature !

Happy Birthday to the Standard Model !

Doors to New Physics

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P. Fileviez Perez

Some Questions:

What is the origin of Neutrino Masses ?

Why the SM interactions are so different ?

Why the fermion masses are so different ?

Why do we have three families of fermions ?

Why the Higgs boson is light?

How can we explain the Dark Matter in the Universe ?

How can we explain the matter-antimatter asymmetry ?

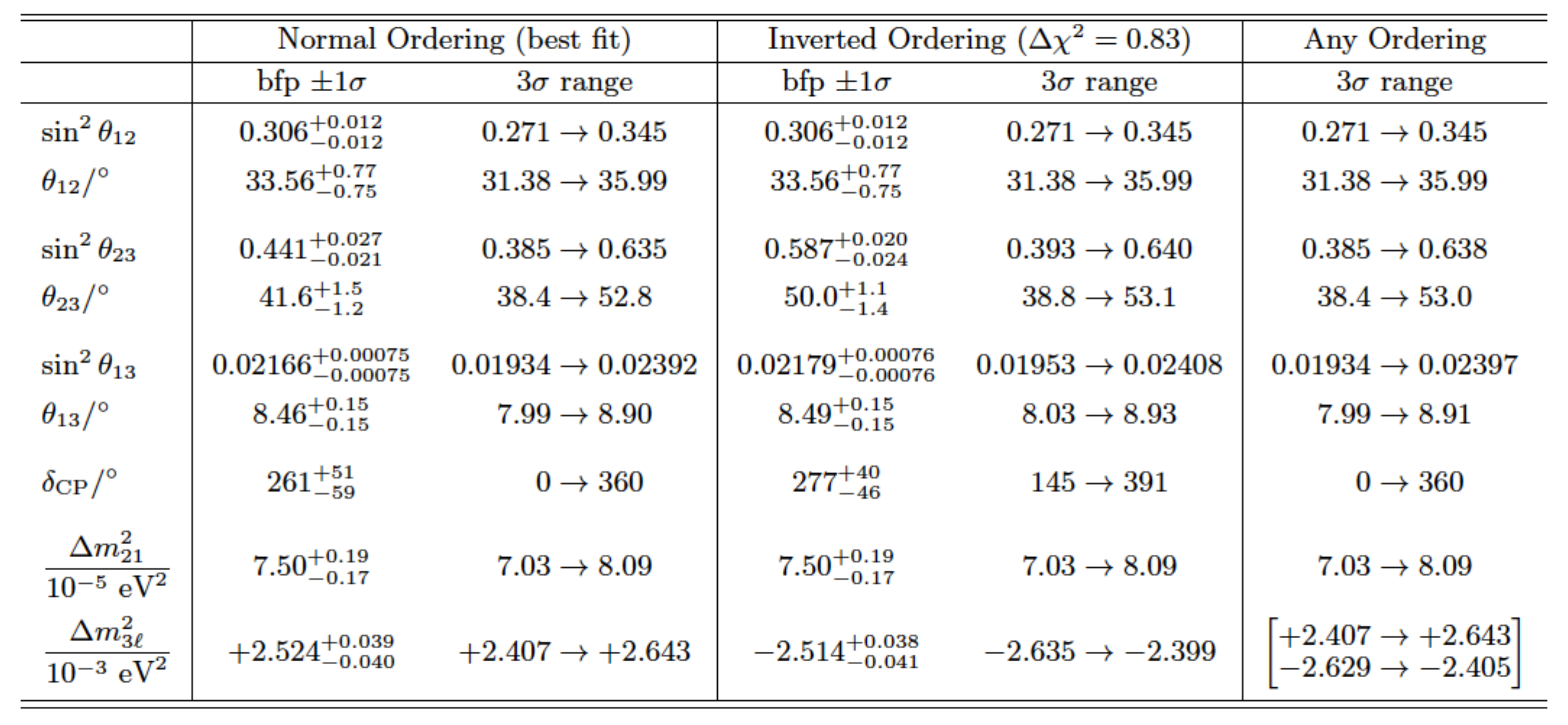
Neutrinos are Massive !

What is the origin of Neutrino Masses ?

How do we test the theory of Neutrino Masses ?

Massive Neutrinos

NuFit Collaboration



	Normal Ordering (best fit)		Inverted Ordering ($\Delta\chi^2 = 0.83$)		Any Ordering
	bfp ±1σ	3σ range	bfp ±1σ	3σ range	3σ range
$\sin^2\theta_{12}$	$0.306^{+0.012}_{-0.012}$	$0.271 \to 0.345$	$0.306^{+0.012}_{-0.012}$	$0.271 \to 0.345$	$0.271 \to 0.345$
$\theta_{12}/^\circ$	$33.56^{+0.77}_{-0.75}$	$31.38 \to 35.99$	$33.56^{+0.77}_{-0.75}$	$31.38 \to 35.99$	$31.38 \to 35.99$
$\sin^2\theta_{23}$	$0.441^{+0.027}_{-0.021}$	$0.385 \to 0.635$	$0.587^{+0.020}_{-0.024}$	$0.393 \to 0.640$	$0.385 \to 0.638$
$\theta_{23}/^\circ$	$41.6^{+1.5}_{-1.2}$	$38.4 \to 52.8$	$50.0^{+1.1}_{-1.4}$	$38.8 \to 53.1$	$38.4 \to 53.0$
$\sin^2\theta_{13}$	$0.02166^{+0.00075}_{-0.00075}$	$0.01934 \to 0.02392$	$0.02179^{+0.00076}_{-0.00076}$	$0.01953 \to 0.02408$	$0.01934 \to 0.02397$
$\theta_{13}/^\circ$	$8.46^{+0.15}_{-0.15}$	$7.99 \to 8.90$	$8.49^{+0.15}_{-0.15}$	$8.03 \to 8.93$	$7.99 \to 8.91$
$\delta_{\rm CP}/^\circ$	261^{+51}_{-59}	$0 \to 360$	277^{+40}_{-46}	$145 \to 391$	$0 \to 360$
$\dfrac{\Delta m^2_{21}}{10^{-5}\ \rm eV^2}$	$7.50^{+0.19}_{-0.17}$	$7.03 \to 8.09$	$7.50^{+0.19}_{-0.17}$	$7.03 \to 8.09$	$7.03 \to 8.09$
$\dfrac{\Delta m^2_{3\ell}}{10^{-3}\ \rm eV^2}$	$+2.524^{+0.039}_{-0.040}$	$+2.407 \to +2.643$	$-2.514^{+0.038}_{-0.041}$	$-2.635 \to -2.399$	$\begin{bmatrix} +2.407 \to +2.643 \\ -2.629 \to -2.405 \end{bmatrix}$

For neutrino experiments see talk by T. Kajita.

Massive Neutrinos

- Dirac Fermions *B-L Conservation !*

$$-\mathcal{L}_D = Y_\nu^D \ \bar{\ell}_L i\sigma_2 H^* \nu_R + \text{h.c.}$$

- Majorana Fermions *B-L Violation !*

$$-\mathcal{L}_M = Y_\nu^D \ \bar{\ell}_L i\sigma_2 H^* \nu_R + \frac{1}{2} M_R \nu_R^T C \nu_R + \text{h.c.}$$

P. Fileviez Perez, SM@50, CWRU

(Minkowski, Mohapatra, Senjanovic, Glashow, Yanagida, Gell-Mann, Ramond, Slansky)

Majorana Neutrinos

$$-\mathcal{L}_M = Y_\nu^D \ \bar{\ell}_L i\sigma_2 H^* \nu_R + \frac{1}{2} M_R \nu_R^T C \nu_R + \text{h.c.}$$ Type I Seesaw

⇒ $$M_\nu = m_D M_R^{-1} m_D^T$$

if $m_D \sim 10^2 \text{GeV}$ ⇒ $M_R \lesssim 10^{14-15} \text{GeV}$ (Seesaw Scale)

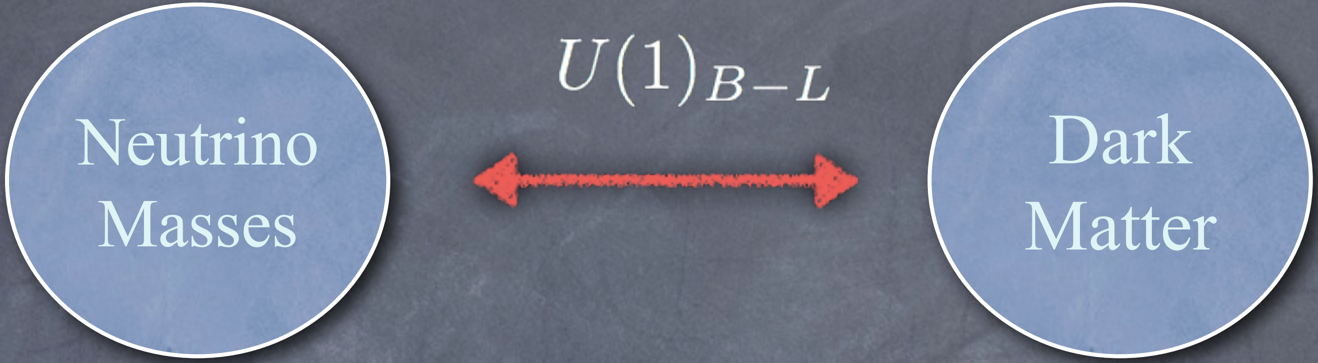
How do we test the Theory of Neutrino Masses at Colliders? (Keung, Senjanovic)

Maybe $M_R \sim 1 \text{ TeV}$ if $m_D \sim 10^{-3} - 10^{-4} \text{GeV}$

The testability of the theory of neutrino masses is crucial to complete our understanding of the origin of fermion masses !

P. F. P., C. Murgui, arXiv:1803.07462

Seesaw Scale and Dark Matter

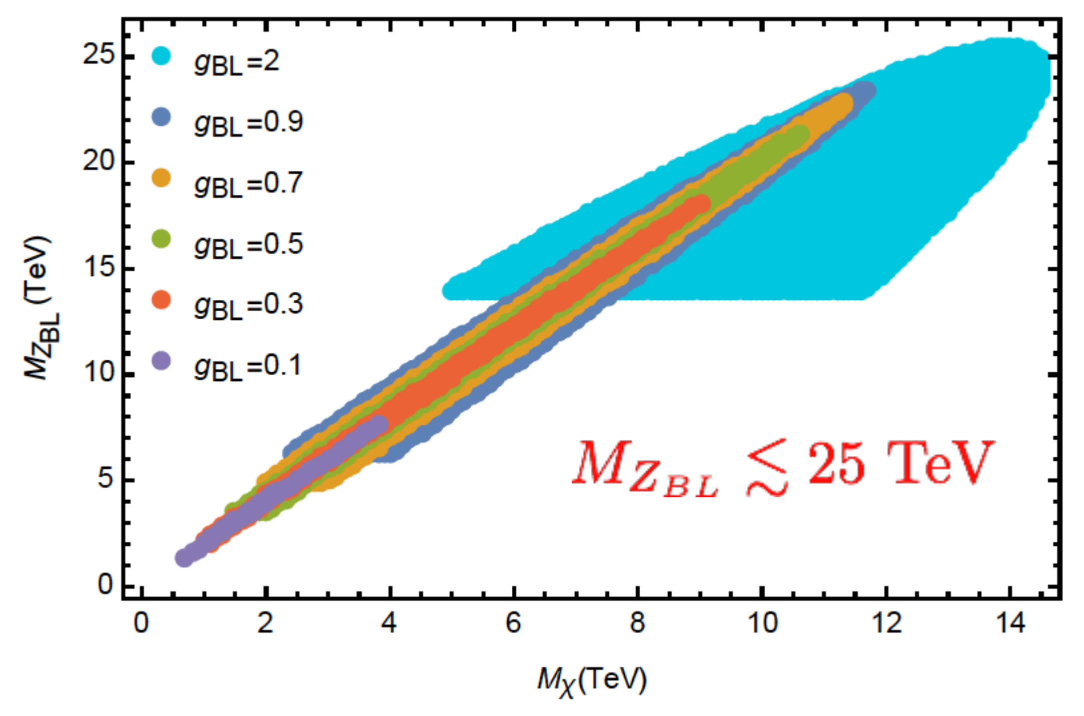


$$\mathcal{L}_\nu^{DM} \supset -\frac{1}{4} F^{BL}_{\mu\nu} F^{BL}_{\alpha\beta} g^{\alpha\mu} g^{\beta\nu} + i\overline{\chi}_L \gamma^\mu D_\mu \chi_L + i\overline{\chi}_R \gamma^\mu D_\mu \chi_R + (D_\mu S_{BL})^\dagger (D^\mu S_{BL})$$
$$- \left(Y_\nu \, \bar{\ell}_L i\sigma_2 H^* \nu_R \, + \, \lambda_R \, \nu_R^T C \nu_R S_{BL} + M_\chi \bar{\chi}_L \chi_R + \text{h.c.}\right),$$

$$M_R = \sqrt{2}\lambda_R v_{BL} \qquad M_{Z_{BL}} = 2 g_{BL} v_{BL}$$

P. F. P., C. Murgui, arXiv:1803.07462

$$\Omega_{DM} h^2 \leq 0.1199 \pm 0.0027$$



$$\begin{aligned}\bar{\chi}\chi &\rightarrow Z^*_{BL} \rightarrow \bar{u}_i u_i, \bar{d}_i d_i, \bar{e}_i e_i, \bar{\nu}_i \nu_i, \bar{N}_i N_i, \\ \bar{\chi}\chi &\rightarrow Z_{BL} Z_{BL}, Z_{BL} h_1, Z_{BL} h_2,\end{aligned}$$

There is a hope to test the origin of neutrinos masses at Colliders !

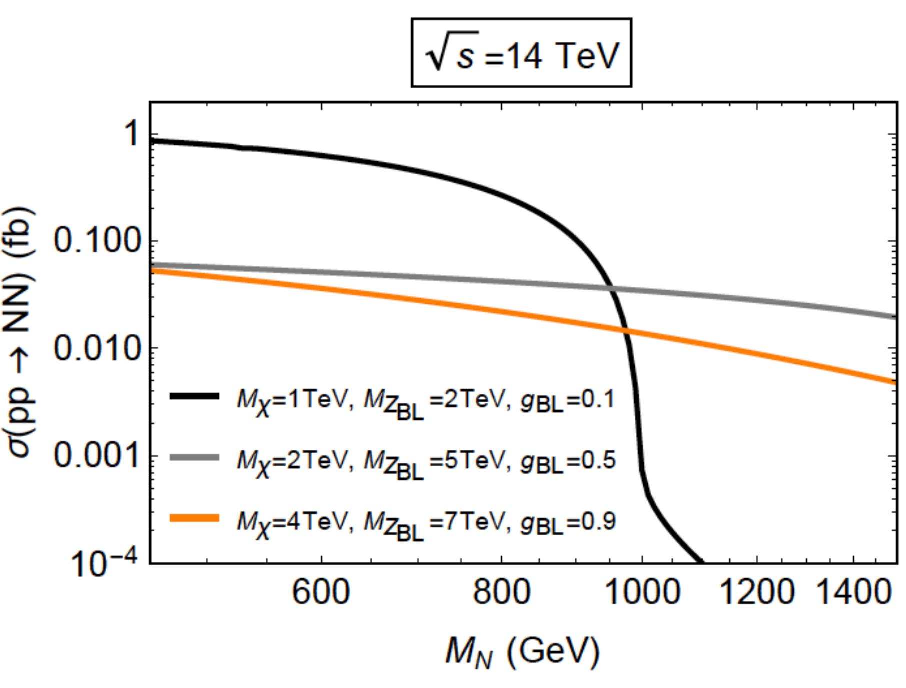
$$pp \rightarrow Z^*_{BL} \rightarrow N_i N_i \rightarrow e^{\pm}_j W^{\mp} e^{\pm}_k W^{\mp} \rightarrow e^{\pm}_j e^{\pm}_k 4j.$$

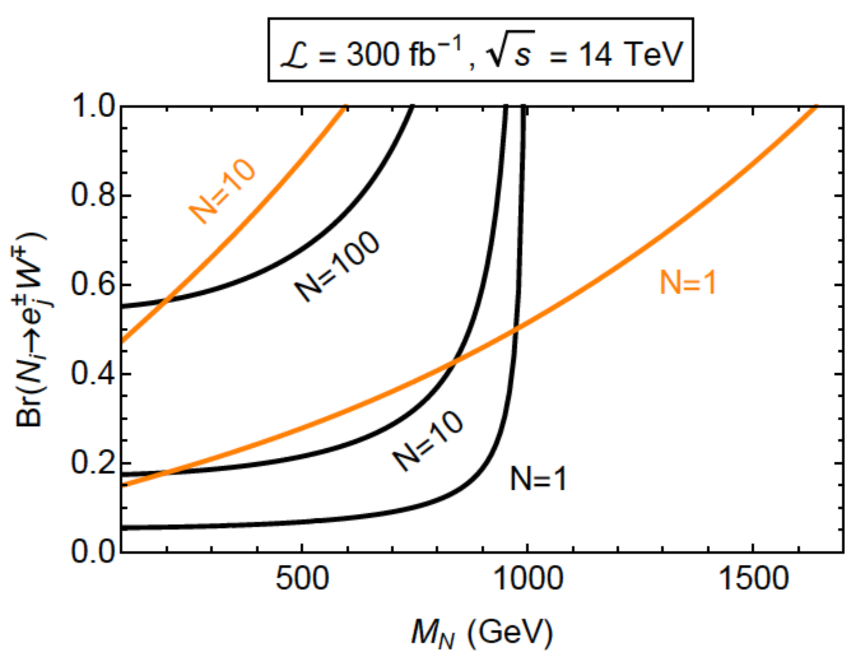
P. F. P., T. Han, T. Li

P. F. P., C. Murgui, arXiv:1803.07462

Testability at the LHC

$$pp \to Z_{BL}^{*} \to N_i N_i \to e_j^{\pm} W^{\mp} e_k^{\pm} W^{\mp} \to e_j^{\pm} e_k^{\pm} 4j.$$





The LHC could see these events in the near future !

The testability of the theory of neutrino masses is crucial to complete our understanding of the origin of fermion masses !

Why the SM interactions are so different ?

Why the SM interactions are so different ?

The strong, weak and electromagnetic interactions are just different manifestations of the same fundamental interaction at low energies !

H. Georgi, S. Glashow

$$SU(3)_C \otimes SU(2)_L \otimes U(1)_Y \quad \Longrightarrow \quad SU(5)$$

$$\Lambda_{\rm Weak} \sim 100 \ {\rm GeV} \qquad\qquad \Lambda_{\rm GUT} \sim 10^{15-16} \ {\rm GeV}$$

Georgi-Glashow Model

Georgi, Glashow, Phys.Rev.Lett.32:438-441,1974

$$G_{SM} = SU(3) \bigotimes SU(2) \bigotimes U(1) \subset SU(5)$$

$$\alpha_3 \qquad \alpha_2 \qquad \alpha_1 \quad \rightarrow \quad \alpha_5$$

Matter Assignment

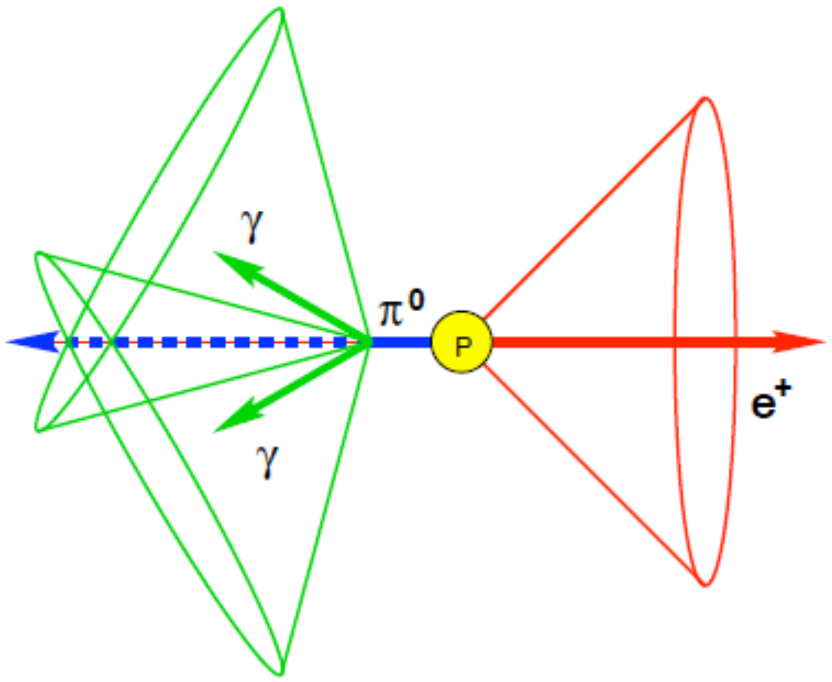
$$\bar{\mathbf{5}} = \begin{pmatrix} d_1^C \\ d_2^C \\ d_3^C \\ e \\ -\nu \end{pmatrix}_L \qquad \mathbf{10} = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 & u_3^C & -u_2^C & u_1 & d_1 \\ -u_3^C & 0 & u_1^C & u_2 & u_2 \\ u_2^C & -u_1^C & 0 & u_3 & d_3 \\ -u_1 & -u_2 & -u_3 & 0 & e^C \\ -d_1 & -d_2 & -d_3 & -e^C & 0 \end{pmatrix}_L$$

Higgs Bosons 5_H 24_H

B and L are explicitly broken !

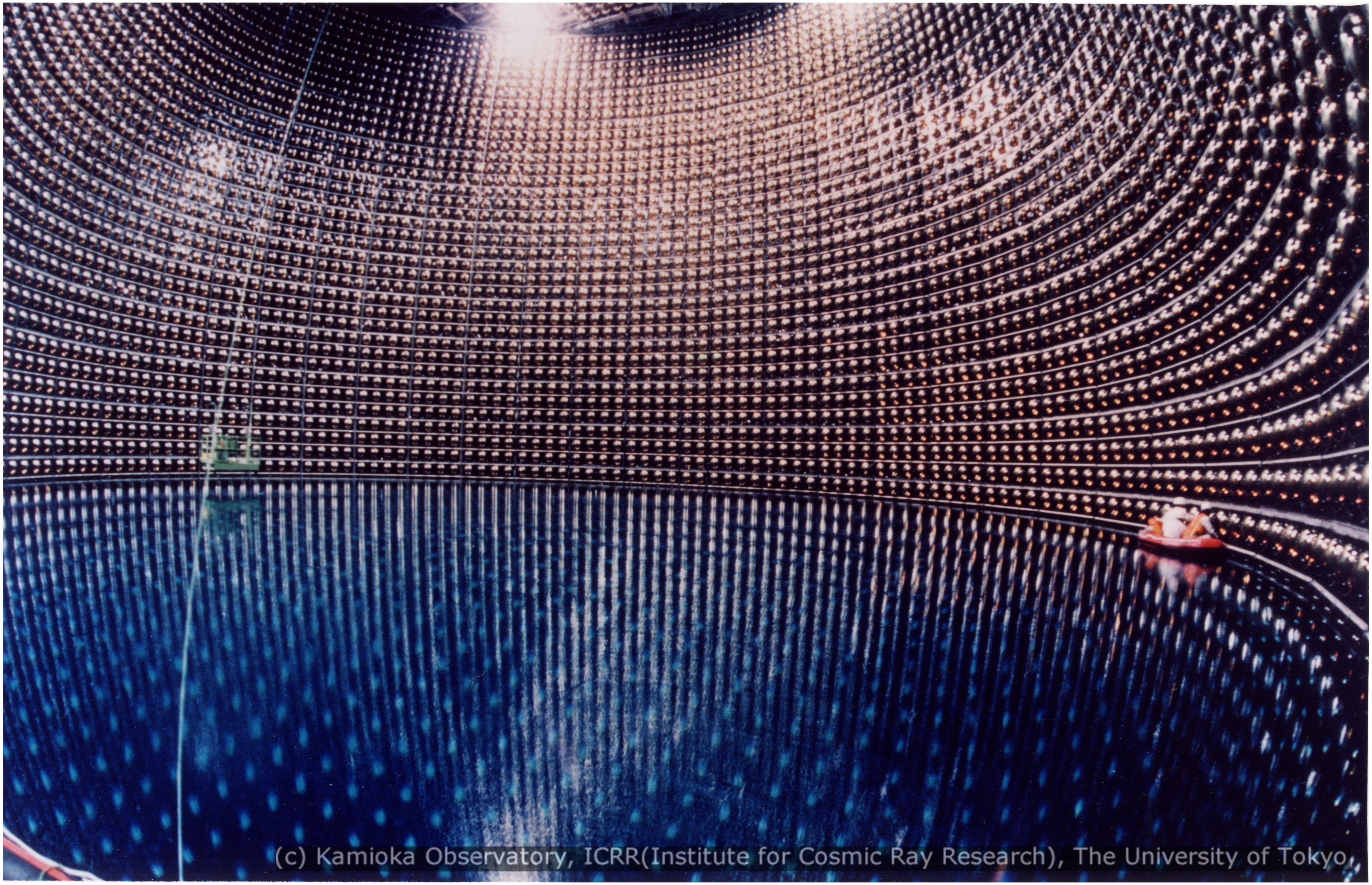
New Baryon and Lepton Number Violating Interactions

$$g_5\overline{(e^c)_L}\gamma^\mu X_\mu d_L + g_5\overline{u}_L\gamma^\mu X_\mu (u^c)_L \;+\; \text{h.c.}$$

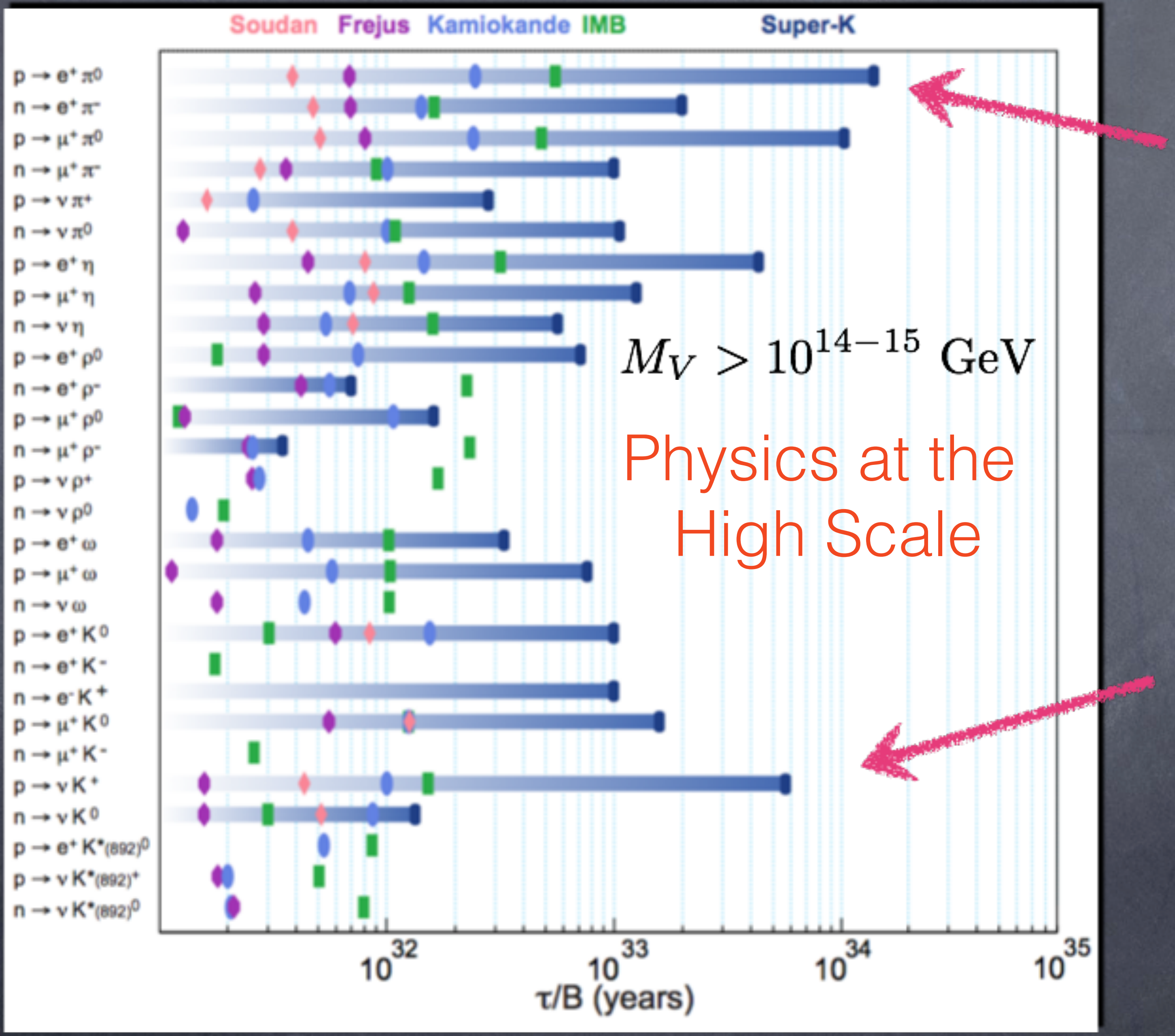


P. Nath, P. F. P., Physics Reports 441 (2007) 191

The Super-Kamiokande detector consists of a stainless-steel tank, 39m diameter and 42m tall, filled with 50,000 tons of ultra pure water. About 13,000 photo-multipliers are installed on the tank wall. The detector is located at 1000 meter underground in the Kamioka-mine, Hida-city, Gifu, Japan.


(c) Kamioka Observatory, ICRR(Institute for Cosmic Ray Research), The University of Tokyo

Proton Decay: $\Delta B = 1, \ \Delta L = \text{odd}$



$M_V > 10^{14-15}$ GeV

Physics at the High Scale

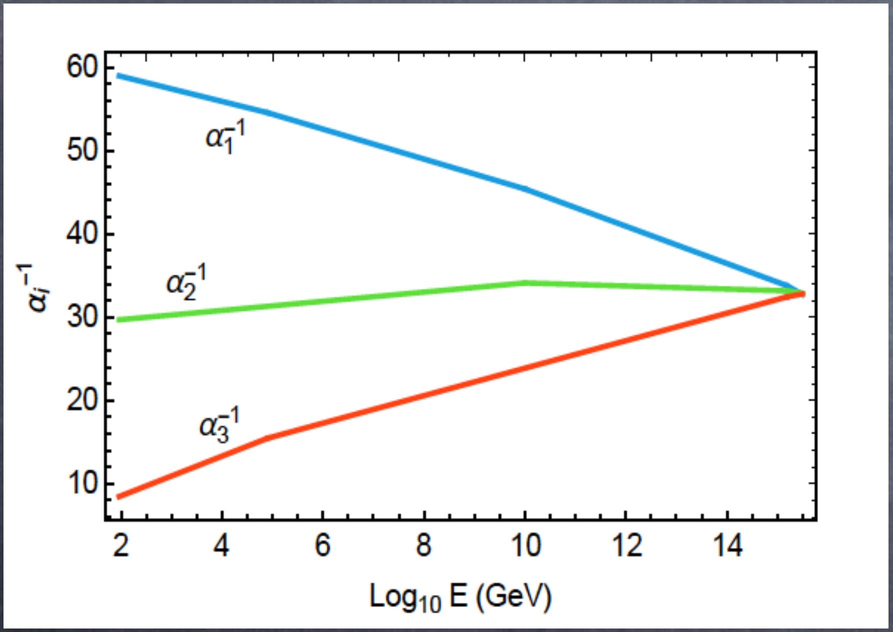
The Georgi-Glashow Model is ruled out !

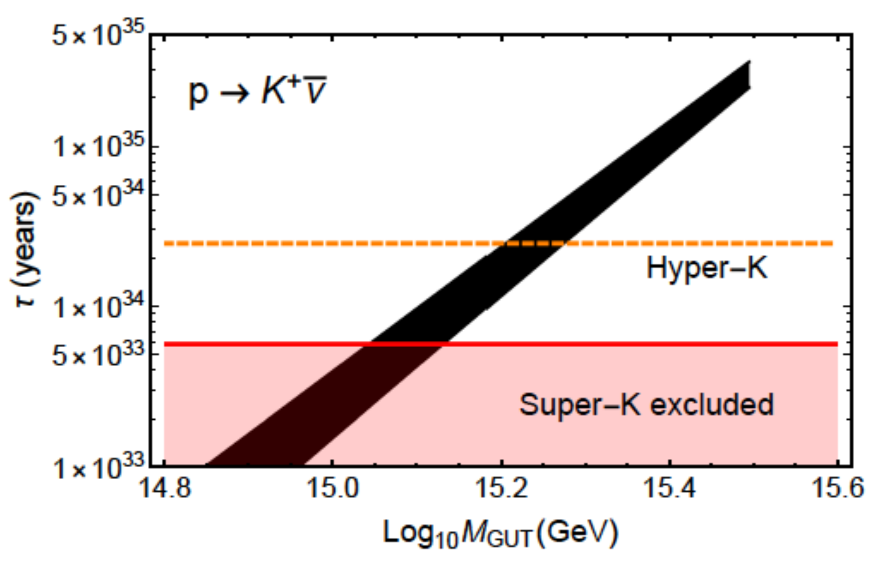
- The unification of gauge couplings in disagreement with the values of the couplings at the electroweak scale.
- Wrong relation between charged leptons and down quark masses.
- Neutrino are massless as in the SM.

P. F. P., A. Gross, C. Murgui, arXiv:1804.07831

Realistic SU(5) Grand Unified Theory

$$\bar{5} = \begin{pmatrix} d^c \\ \ell \end{pmatrix}, \quad 10 = \begin{pmatrix} u^c & Q \\ Q & e^c \end{pmatrix}, \quad \bar{5}' = \begin{pmatrix} D^c \\ L \end{pmatrix}, \quad 5' = \begin{pmatrix} D \\ L^c \end{pmatrix}, \quad 24 = \begin{pmatrix} \rho_8 & \rho_{(3,2)} \\ \rho_{(\bar{3},2)} & \rho_3 \end{pmatrix} + \lambda_{24}\rho_0,$$





$$\tau(p \to K^+\bar{\nu}) \lesssim 3.4 \times 10^{35} \text{ and } \tau(p \to \pi^+\bar{\nu}) \lesssim 1.7 \times 10^{34} \text{ years}$$

$$M_{\rho_3} \leq 500 \text{ TeV}$$

High Scale Unification

- The proton is not stable !
- The SM gauge couplings unify at the high scale.
- One has a (SUSY) GUT based on SU(5), SO(10), ..

$$M_{GUT} > 10^{15}\ \mathrm{GeV}$$

Towards Low Scale Unification

Low Scale Unification

- The proton must be stable.

- The gauge couplings unify at the low scale.

- One has a ‘new’ Grand Unified Theory.

Baryon Number as a Local Gauge Symmetry

A. Pais, 1973

S. Rajpoot, 1988

R. Foot, G. C. Joshi, H. Lew, 1989

C. Carone, H. Murayama,1995

P. F. P., M. B. Wise, PRD82 (2010)011901; JHEP1108(2011)068

M. Duerr, P. F. P., M. B. Wise, Physical Review Letters 110 (2013) 231801

P. F. P., S. Ohmer, H. H. Patel, Phys. Rev. D90 (2014)3,037701

P.F.P., S. Ohmer, Phys. Lett. B768 (2017) 86-91

P. F. P., M. B. Wise

Breaking B and L at the TeV scale !

$$SU(3)_C \otimes SU(2)_L \otimes U(1)_Y \otimes U(1)_B \otimes U(1)_L$$

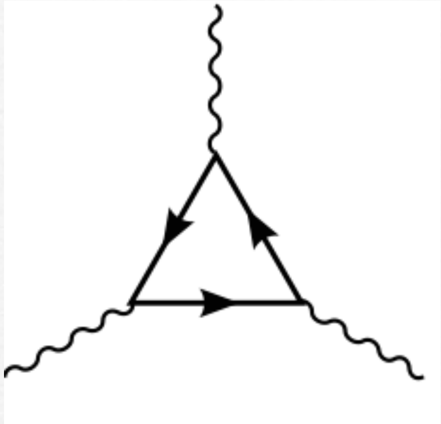
where $U(1)_B$ and $\mathrm{U}(1)_\mathrm{L}$ can be broken at the TeV Scale !

$B(\text{quark}) = 1/3$ $\quad$ $L(\text{lepton}) = 1$

How to define an anomaly free theory ?

Anomaly Cancellation

Baryonic Anomalies:



$$\mathcal{A}_1\left(SU(3)^2\otimes U(1)_B\right),\ \underline{\mathcal{A}_2\left(SU(2)^2\otimes U(1)_B\right)},$$
$$\underline{\mathcal{A}_3\left(U(1)_Y^2\otimes U(1)_B\right)},\ \mathcal{A}_4\left(U(1)_Y\otimes U(1)_B^2\right),$$
$$\mathcal{A}_5\left(U(1)_B\right),\ \mathcal{A}_6\left(U(1)_B^3\right),$$

In the SM: $\mathcal{A}_2=-\mathcal{A}_3=3/2$

P. Fileviez Perez, SM@50, CWRU

Different Solutions for Anomaly free theories:

- ~~Sequential Family~~
- ~~Mirror family~~
- Vector-like Fermions

P. F. P., M. B. Wise, PRD82 (2010)011901; JHEP1108(2011)068

M. Duerr, P. F. P., M. B. Wise, Phys. Rev. Lett. 110 (2013) 231801

P. F. P., S. Ohmer, H. H. Patel, Phys. Rev. D90 (2014)3,037701

P.F.P., S. Ohmer, Phys.Lett. B768 (2017) 86-91

P. Fileviez Perez, Physics Reports 597

Main Features:

- One can have the Spontaneous Breaking of Baryon and Lepton numbers at the Low Scale

- One can have a DM candidate

- A relation between the Baryon and Dark Matter Asymmetries is possible

- Since the proton is stable one could have unification at the low scale.

M. Duerr, **P. F. P.**, M. B. Wise, Phys. Rev. Lett.

One can define an anomaly free theory using the Fermionic Lepto-baryons:

Example:

$$\Psi_L \sim (1, 2, -1/2, B_1) \qquad \Psi_R \sim (1, 2, -1/2, B_2)$$

$$\eta_R \sim (1, 1, -1, B_1) \qquad \eta_L \sim (1, 1, -1, B_2)$$

$$\chi_R \sim (1, 1, 0, B_1) \qquad \chi_L \sim (1, 1, 0, B_2)$$

$$B_1 - B_2 = -3$$

They can have vector-like masses and cancel all anomalies !

M. Duerr, **P. F. P.**, M. B. Wise, Phys. Rev. Lett.

Mass Generation:

$$\mathcal{L}_B \supset \lambda_\Psi \bar{\Psi}_L \Psi_R S_B + \lambda_\eta \bar{\eta}_R \eta_L S_B + \lambda_\chi \bar{\chi}_R \chi_L S_B + \text{h.c.}$$

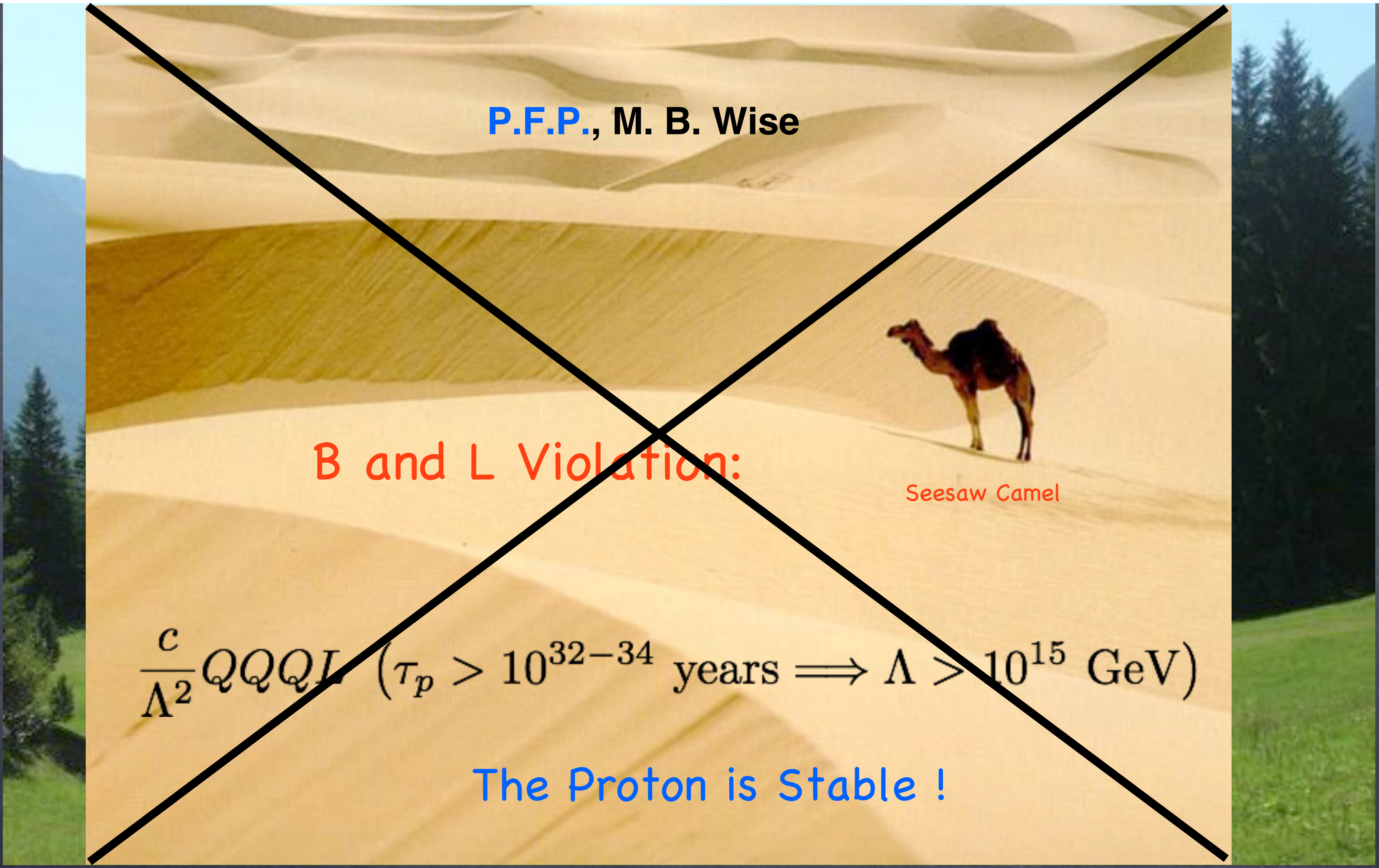
New Higgs: $S_B \sim (1, 1, 0, -3)$

$\Delta B = \pm 3$ → **Stable Proton !** → **NO DESERT !**

Spontaneous B and L Breaking !

LOW SCALE

HIGH SCALE



P.F.P., M. B. Wise

B and L Violation:

$$\frac{c}{\Lambda^2} QQQL \quad \left(\tau_p > 10^{32-34}\ \text{years} \Longrightarrow \Lambda > 10^{15}\ \text{GeV}\right)$$

The Proton is Stable !

Standard Model

$\Lambda_{\text{Weak}} \sim 100$ GeV

GUTs ?

$\Lambda \sim 10^{15-19}$ GeV

M. Duerr, **P. F. P.**, M. B. Wise, Phys. Rev. Lett.

Some Features:

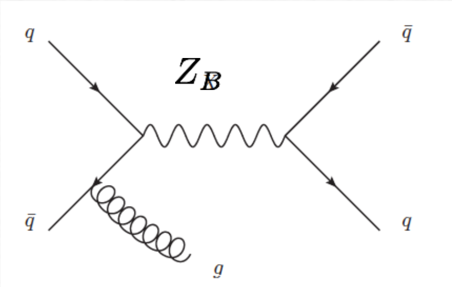
Dark Matter: $\chi = \chi_L + \chi_R$ cold dark matter candidate !

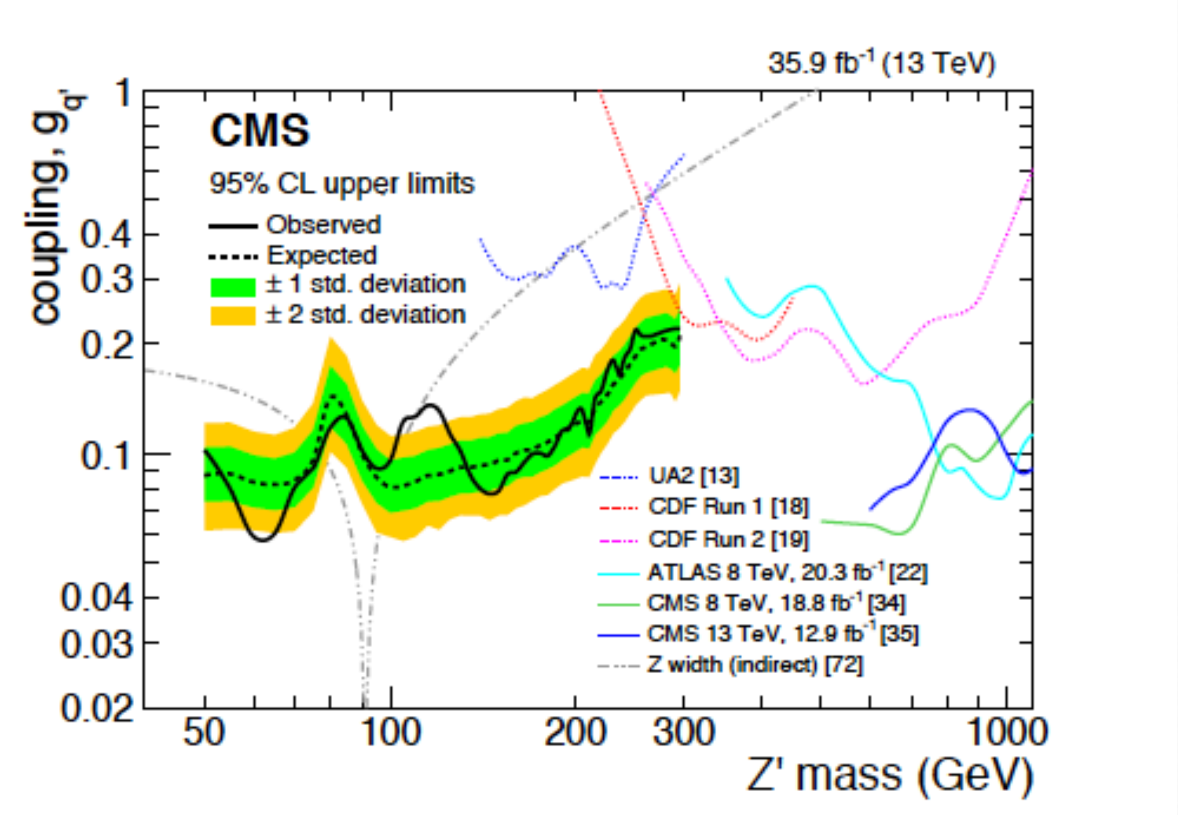
Leptophobic Gauge Boson: $Z_B \to \bar{q}q, \bar{\chi}\chi$

New Higgs Boson: $h_2 \to \bar{q}q, WW, ZZ, hh, \bar{\chi}\chi$

Missing Energy at the LHC: $pp \to Z_B h_2 \to \bar{t}t\bar{\chi}\chi \to \bar{t}tE_T^{\rm miss}$

Leptophobic Gauge Boson: $Z_B \to \bar{q}q$ arXiv:1710.00159

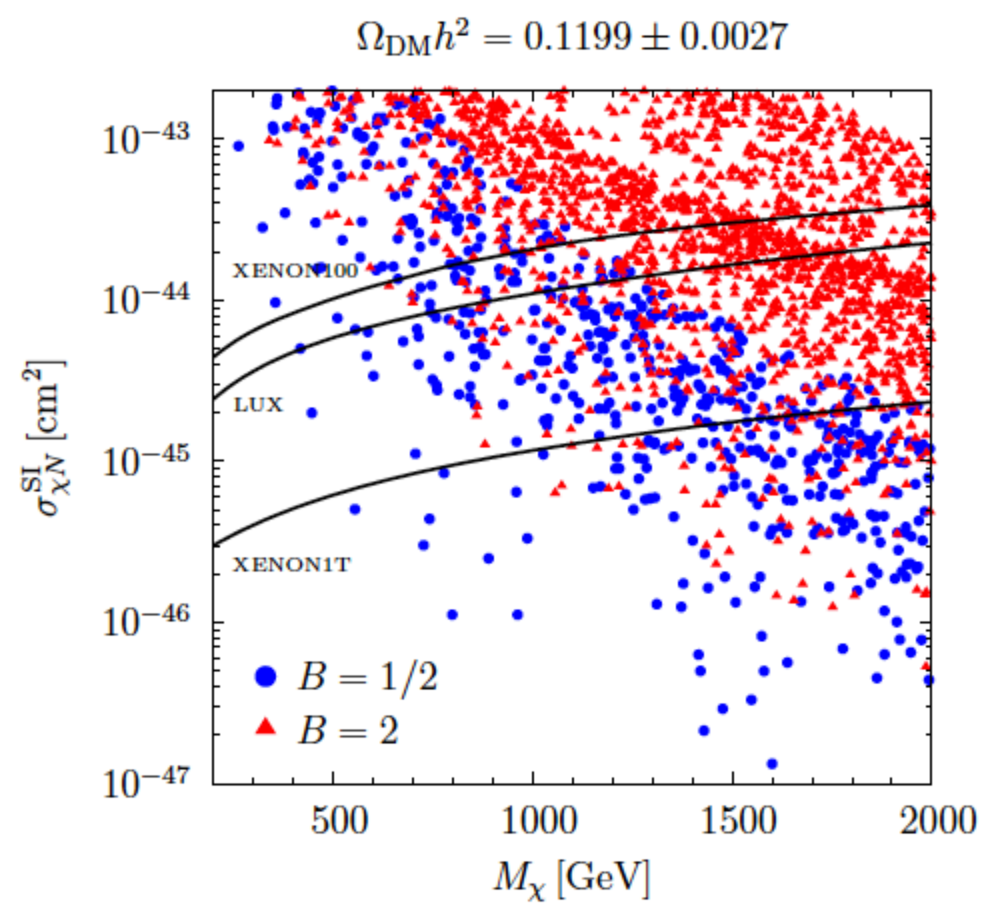




P. Fileviez Perez, SM@50, CWRU

Dirac Dark Matter

M. Duerr, P.F.P., PRD 91



Annihilation:

$$\bar{\chi}\chi \to Z_B \to \bar{q}q$$

Direct Detection:

$$\chi N \to Z_B \to \chi N$$

P. Fileviez Perez, SM@50, CWRU

Upper bound on the Symmetry Breaking Scale

DM relic density: $\Omega_{\rm DM} h^2 \leq 0.12$

➡ $M_{Z_B} \lesssim 36 \text{ TeV}$

☺

$(M_{Z_B} << M_{GUT})$

The Symmetry must be broken at the low scale !

B and L Violation

$$S_{BL} \sim (1,1,0,-3,-3)$$

$$\mathcal{L} \supset \frac{c}{\Lambda^{15}} (Q_L Q_L Q_L \ell_L)^3 S_{BL}$$

$\Delta B = \Delta L = \pm 3$

$$\begin{aligned} p+p+p &\rightarrow e^+ \, e^+ \, e^+ \\ n+n+n &\rightarrow \bar{\nu}\bar{\nu}\bar{\nu} \\ p+p+n &\rightarrow e^+ \, e^+ \, \bar{\nu} \\ p+n+n &\rightarrow e^+ \, \bar{\nu} \, \bar{\nu} \end{aligned}$$

HIGHLY suppressed !!!

The Theory predicts that the proton is stable

What about the Unification of Forces ?

P.F.P., M. B. Wise; B. Fornal, T. Tait

Towards Low Scale Unification

$$SU(3)_C \otimes SU(2)_L \otimes U(1)_Y \otimes U(1)_B$$

Key Idea:

$$SU(4)_C \to SU(3)_C \otimes U(1)_B$$

$$\begin{pmatrix} q_{SM} & \Psi \\ \tilde{\Psi} & q^{'} \end{pmatrix}$$

P.F.P., S. Ohmer, Phys.Lett. B768 (2017) 86-91

Towards Low Scale Unification

$$SU(4)_C \otimes SU(4)_L \otimes SU(4)_R$$

$$\Big\downarrow$$

$$SU(3)_C \otimes SU(3)_L \otimes SU(3)_R \otimes U(1)_B$$

$$\Big\downarrow$$

$$SU(3)_C \otimes SU(2)_L \otimes U(1)_Y \otimes U(1)_B$$

Low Scale Unification

- The proton must be stable.
- The gauge couplings unify at the low scale.
- One has a ‘new’ Grand Unified Theory.

Summary

It is crucial to understand the testability of the theories for neutrino masses. Using cosmology we can find an upper bound on the Seesaw Scale in the multi-TeV region and one can hope to test this mechanism at current or future colliders.

One can have the unification of the electromagnetic, strong and weak forces at the high scale in the context of grand unified theories. We have discussed a simple renormalizable grand unified theory which predicts an upper bound on the proton decay lifetime and can be probed at the Super-Kamiokande or Hyper-Kamiokande.

We have proposed new theories which predict the stability of the proton where the baryon number is a local symmetry spontaneously broken at the low scale. These theories make interesting predictions for cosmology and provide a famework to investigate the unification of gauge forces at the low scale.

Doors to New Physics

P. Fileviez Perez

Happy Birthday
to the Standard Model !