Review of selected topics in Z'

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What kind of Z'?

The easiest kind (typical, ordinary, mundane, $\cdots Z'$)

- a new gauge boson of an anomaly-free $U(1)$ gauge symmetry, from a bottom-up approach

Z' can come from much wider sources.

- Non-Abelgian gauge groups (e.g. Z', W' from $SU(2)_R$)
- Extra dimension (Kaluza-Klein excitation of γ/Z)
- Dynamical symmetry breaking (Technimeson from Technicolor models)
- From top-down, GUT ($SO(10)$, E_6, $\cdots$)
- $\cdots$ and many other things

There are still too many typical, ordinary, mundane Z'.

(My apology for not covering all of them.)

Comprehensive review papers on Z' (a partial list)

1. J Hewett, T Rizzo (1989): Low-Energy Phenomenology of Superstring Inspired E_6 Models
2. A Leike (1998): The Phenomenology of extra neutral gauge bosons
3. P Langacker (2008): The Physics of Heavy Z' Gauge Bosons
4. PDG reviews on Z': periodically updated by various authors (most recently, MC Chen and B Dobrescu (2009))

Outline of Talk

In this talk, we will focus on only selected themes.

1. Z' as a Controller (of operators)
2. Z' as a Discovery tool (at the LHC)
3. Z' as a Connector (to Dark world)
4. Z' as a Long-range Force carrier

Z' as a Controller

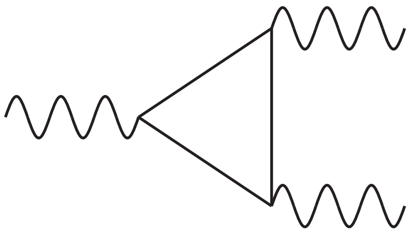
Residual discrete symmetries of $U(1)$ gauge symmetries

$U(1)$ in the SM

Y (hypercharge)

	Q	u_R	d_R	L	e_R	H
$6Y$	1	4	-2	-3	-6	-3

For the SM particle spectrum (without RH νs), hypercharge is uniquely determined by anomaly-free conditions. (It is not given by hand.)



$= 0$

Anomaly-free condition: powerful constraint on $U(1)$ charges and new particles.

Most popular $U(1)$ beyond-SM

$$(B-L)$$

	quarks	leptons
$B-L$	$1/3$	-1

Anomaly-free only with RH νs (one for each generation). Anomaly is cancelled generation-by-generation.

Extensive use in the literature: INSPIRE “B-L” keyword hits over 650 papers.

Matter Parity from $B-L$

After $U(1)$ is spontaneously broken, it can leave an unbroken Z_N.

$$U(1)_{B-L} \;\rightarrow\; Z_2 \;\text{(Matter Parity)}$$

if a scalar field (S) that breaks $U(1)_{B-L}$ has $Q'(S) = \pm 2/3$.

Matter Parity: $(-1)^{3(B-L)}$ [S Dimopoulos, H Georgi (1981)]

	(Matter)		(Non-matter)	
	quarks	leptons	Higgs boson	gauge boson
Z_2 (Matter Parity)	1	1	0	0

(Z_2 charge 1 = Odd under Parity, Z_2 charge 0 = Even under Parity)

Matter Parity in ‘simple (B-L) extended SM’: not very interesting.

Lightest Matter Parity odd particle: stable. (Lightest fermion is stable anyway.)

Matter Parity in beyond 'simple (B-L) extended SM'

(1) Supersymmetry (SUSY):

R-Parity: $(-1)^{3(B-L)+2S}$ [G Farrar, P Fayet (1978)]

	SM particles	SUSY partners
Z_2 (R-Parity)	0	1

Matter Parity is *equivalent* to R-Parity: $(-1)^{3(B-L)} = (-1)^{3(B-L)+2S}$

because of the angular momentum conservation at every vertex.

$\longrightarrow$ No difference in allowed/forbidden vertices. (This is what Z_N is all about.)

Lightest SUSY Particle (LSP): stable (popular DM candidate).

Renormalizable B, L violating terms are forbidden (helps proton stabilization).

(LQD^c, $U^cD^cD^c$ = odd + odd + odd = odd: forbidden by Matter Parity.)

(2) 4th-Generation (4G):

$B - L$ only in the 4G. ($B - L$ is anomaly-free in each generation.)

Z_2 in 4G only: $U(1)_{[B-L]_{4G}} \to Z_2$ (4G-Parity) [HSL, A Soni (in progress)]

	SM quarks	SM leptons	4G quarks	4G leptons
$(B-L)_{4G}$	0	0	$1/3$	-1
Z_2 (4G-Parity)	0	0	1	1

Lightest 4G Particle (L4P): stable

4G fermion decay modes are different from sequential 4G models.

(like SUSY particle decays modes under R-Parity.)

In short, Matter Parity can be very useful when we go beyond ‘simple (B-L) extended SM’.

Most general form of family-universal $U(1)$ beyond-SM

With no additional fermions (except for RH νs),

$$\alpha(B-L)+\beta Y$$

(i) Given by anomaly-free conditions.

(ii) Familiar form from GUT: $-\frac{5}{4}(B-L)+Y$ from $SO(10)\rightarrow SU(5)\times U(1)$.

(iii) Residual Z_N (Matter Parity, etc.) are not altered by arbitrary Y shift.

Family-nonuniversal $U(1)$

Anomaly-free family-nonuniversal choices without new fermions:

$$(L_e - L_\mu), \quad (L_\mu - L_\tau), \quad (L_\tau - L_e)$$

[XG He, G Joshi, H Lew, R Volkas (1990)]

These family-nonuniversal cases have been studied in many applications.

(ex-i) $L_\mu - L_\tau$ to explain $(g-2)_\mu$ deviation. $\left(\Delta(g-2)_\mu = \frac{g_{Z'}^2 m_\mu^2}{12\pi^2 M_{Z'}^2}\right)$

[E Ma, DP Roy, S Roy (1990)], [S Baek, N Deshpande, XG He, P Ko (2001)]

(ex-ii) $L_\mu - L_\tau$ for leptogenesis and neutrino physics. (lepton flavor symmetry)

[EJ Chun, K Turzynski (2007)], [J Heeck, W Rodejohann (2010)]

$U(1)$ without additional fermions (except for RH νs),

Any mixture of 2 anomaly-free charges is anomaly-free.

Any linear combination is also anomaly-free:

$$\begin{aligned} & a_0 Y + a_1(B-L) + a_2(L_e - L_\mu) + a_3(L_\mu - L_\tau) + a_4(L_\tau - L_e) \\ = \ & a_0 Y + a_1(B - x_e L_e - x_\mu L_\mu - x_\tau L_\tau) \end{aligned}$$

(Neutrino masses and mixings may constrain the choices.)

Matter Parity from family-nonuniversal $U(1)$? → Yes.

Flavor-dependent gauge origin of Matter Parity

$U(1)_{B-x_iL_i} \;\longrightarrow\; Z_2$ (Matter Parity / R-Parity) [HSL, E Ma (2010)]

(i) $x_1 + x_2 + x_3 = 3$ from anomaly-free. ($x_1 = x_2 = x_3 = 1$: $B - L$)

(ii) $3x_i =$ odd from Z_N condition.

$$\longrightarrow x_i = (9, -3, -3),\ (-3, 3, 3),\ \cdots$$

$$\texttt{Br}(Z' \to e^+e^-) : \texttt{Br}(Z' \to \mu^+\mu^-) : \texttt{Br}(Z' \to \tau^+\tau^-) = x_1^2 : x_2^2 : x_3^2$$

(i) First Z' discovery at the LHC may depend on the flavor ($q\bar{q} \to Z' \to \ell^+\ell^-$).

(ii) The ratio might reveal the discrete symmetries inside.

More general discrete symmetries

Now, we discuss more general Z_N (other than Matter Parity) and its gauge origin.

Global symmetries may be violated by Planck scale physics (wormhole effect).
Discrete symmetries with gauge origin are protected from Planck scale physics.
[L Krauss, F Wilczek (1989)]

L Ibanez, G Ross (1992) did a systematic study for Z_N that are compatible with anomaly-free conditions.
(Put [$U(1)$ charge = Z_N charge + $N\times$integer] into anomaly-free conditions and get discrete anomaly-free conditions.)

Discrete symmetry compatible with MSSM sector

Most general Z_N of the MSSM sector [L Ibanez, G Ross (1992)] is

$$Z_N : \quad g_N = B_N^b L_N^\ell$$

with $B_N = e^{2\pi i \frac{q_B}{N}}, \quad L_N = e^{2\pi i \frac{q_L}{N}}$

	Q	U^c	D^c	L	E^c	N^c	H_u	H_d	meaning of q
B_N	0	-1	1	-1	2	0	1	-1	$-B + 2Y$
L_N	0	0	0	-1	1	1	0	0	$-L$

8 unknown discrete charges (Q, U^c, D^c, L, E^c, N^c, H_u, H_d)

- 5 superpotential terms ($H_u Q U^c$, $H_d Q D^c$, $H_d L E^c$, $H_u L N^c$, $H_u H_d$)

- 1 hypercharge shift invariance

= 2 free parameters (b, ℓ)

But only some of them can satisfy the discrete anomaly-free conditions:

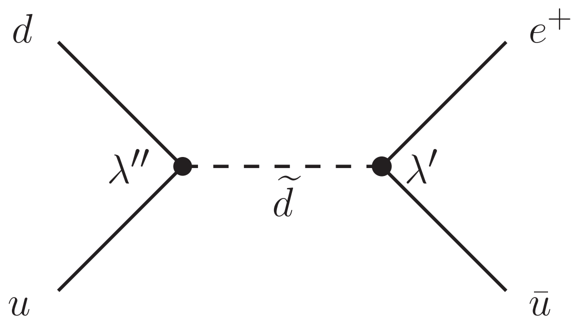
Z_2: $B_2L_2^{-1}$ (Matter Parity)

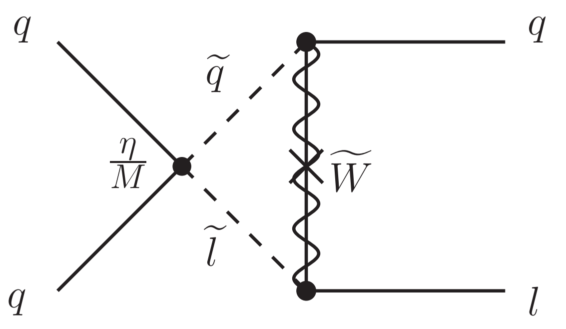
Z_3: B_3 (Baryon Triality), L_3 (Lepton Triality), $\cdots$

(For instance, B_2 (Baryon Parity) is not allowed by discrete anomaly-free conditions.)

We will take a close look at B_3.

Proton decay





[Dim 4 L violation $\&$ Dim 4 B violation]

$\lambda LLE^c + \lambda' LQD^c \;\&\; \lambda'' U^c D^c D^c$

[Dim 5 $B\&L$ violation]

$\frac{\eta_1}{\Lambda} QQQL + \frac{\eta_2}{\Lambda} U^c U^c D^c E^c$

To satisfy τ_p (proton lifetime) $\gtrsim 10^{29}$ years,

- Dim 4: $|\lambda_{LV} \cdot \lambda_{BV}| \lesssim 10^{-27}$ (if one is 0, the other can be sizable)
- Dim 5: $|\eta| \lesssim 10^{-7}$ $($for $\Lambda = M_{\rm Pl})$ [S Weinberg (1982)], [N Sakai, T Yanagida (1982)]

B_3 (Baryon Triality)

	Q	U^c	D^c	L	E^c	N^c	H_u	H_d	meaning of B_3 charge
B_3	0	-1	1	-1	-1	0	1	-1	$-B + 2Y \mod 3$

Dim-4 B violation: $U^c D^c D^c$: total $q \neq 0$. (Forbidden)

Dim-4 L violation: LLE^c, LQD^c, LH_u: total $q = 0$. (Allowed)

Dim-5 $B\&L$ violation: $QQQL, U^c U^c D^c E^c, U^c D^c D^c N^c$: total $q \neq 0$. (Forbidden)

$\longrightarrow$ Proton is safe with Dim-4 and Dim-5 operator under B_3.

Selection rule of discrete symmetries.

D Catano, S Martin (1994) noted the selection rule of B_3. B can be violated only by $\Delta B = 3 \times$ integer in any operator (independent of dimensions of operators).

Where does the selection rule come from?

Every operator should be neutral under B_3.

(B_3 charge is $-B + 2Y \mod 3$. Y is independently conserved.)

$\longrightarrow$ For any operator, $\Delta B \mod 3 = 0$ (i.e. $\Delta B = 3 \times$ integer).

$\longrightarrow$ Not possible to construct a proton decay operator ($\Delta B = 1$).

$\longrightarrow$ Proton decay ($\Delta B = 1$) never happens under B_3 (as the LSP decay never happens under R-Parity.)

Observed p-decay ($\Delta B = 1$) or n-$\bar{n}$ oscillation ($\Delta B = 2$)? Claim B_3 is ruled out.

Realization of TeV-scale $U(1)$ with B_3 in SUSY

TeV-scale $U(1)$ can be natural in SUSY due to extra D-term contribution (unless cancellations by multiple singlets occur.)

(i) For family-universal $U(1)$, to be anomaly-free, B_3 requires colored exotics, which are not uniquely determined. (Many different models can exist.)

[D Castano, S Martin (1994)]: B_3 with exotic colors

[HSL, C Luhn, K Matchev (2007)]: B_3, L_3, $\cdots$ with exotic colors

(ii) Take family-nonuniversal $U(1)$ $\longrightarrow$ Anomaly-free without exotics.

[HSL, E Ma (2010)]: $R_2 \times B_3$

[HSL (2010)]: B_3

Family-nonuniversal $U(1)$ can help keeping the model minimal (no exotic particles).

Relation between $U(1)$ and Z_N

$$U(1) \;\rightarrow\; Z_N$$

after $U(1)$ is broken by $\langle S\rangle$.

With integer $U(1)$ charges (by hypercharge shift and normalization),

(i) $N = |U(1)$ charge of $S|$ (G.C.D. for multiple S)

(ii) $[Z_N$ charge of $F_i] = [U(1)$ charge of $F_i] \mod N$.

As long as $N \neq 1$, $U(1)$ leaves Z_N after spontaneous symmetry breaking.

Leaving a remnant Z_N is a general property of $U(1)$.

Recap: Z' as a Controller

- $U(1)$ can allow/forbid some operators.
- Especially, its residual Z_N allows simple and powerful argument.

  (Do not worry about all possible nonrenormalizable operator effects.)

(i) If your model has $U(1)$, consider its residual discrete symmetry.

(ii) If your model has Z_N, consider its gauge origin. ($\longrightarrow Z'$ phenomenology)

Z' as a Discovery Tool

New resonances at Collider physics

Some experimental constraints on massive Z'

(i) Electroweak Precision Test (including precise Z pole measurement at LEP):

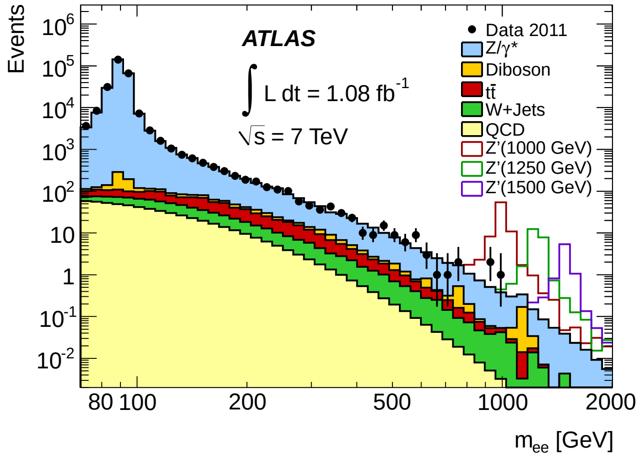
Z-Z' mixing angle $\lesssim 10^{-3}$. [Y Umeda, GC Cho, K Hagiwara (1998)], [J Erler, P Langacker, S Munir, E Rojas (2011)]

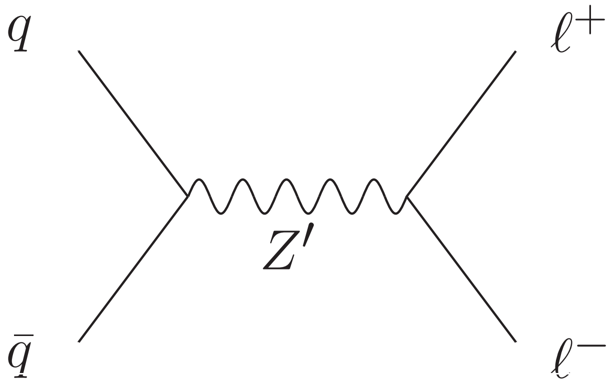
(ii) LEP contact interactions ($e^+e^- \longrightarrow f\bar{f}$ above Z pole):

$M_{Z'} > g_{Z'} \times (6 \ \ \mathrm{TeV})$ for $U(1)_{B-L}$. [LEP EW Working Group (2003)], [M Carena, A Daleo, B Dobrescu, T Tait (2004)]

(iii) Tevatron/LHC new resonance search ($q\bar{q} \longrightarrow Z' \longrightarrow f\bar{f}$)

Dilepton resonance search (Typical Z' search at hadron colliders)





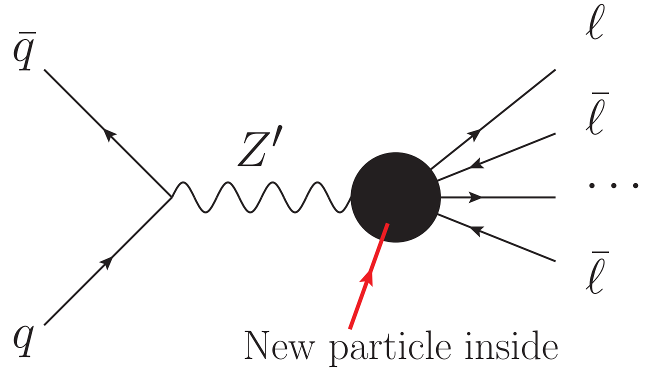
e^+e^- & $\mu^+\mu^-$ channel results are similar.

2 channels combined results: for sequential Z' model:

$M_{Z'} > 1.83$ TeV [ATLAS (2011. Aug)], 1.94 TeV [CMS (2011. July)]

Great performance (after only $\sim$ 1 year). Dilepton resonance is a golden channel because (i) cross section is enhanced by the resonance, and (ii) final leptons are a clean signal at hadron colliders.

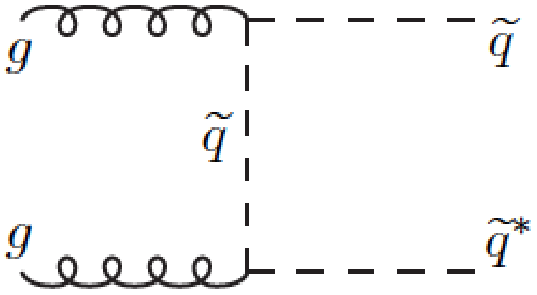
General Z' resonances



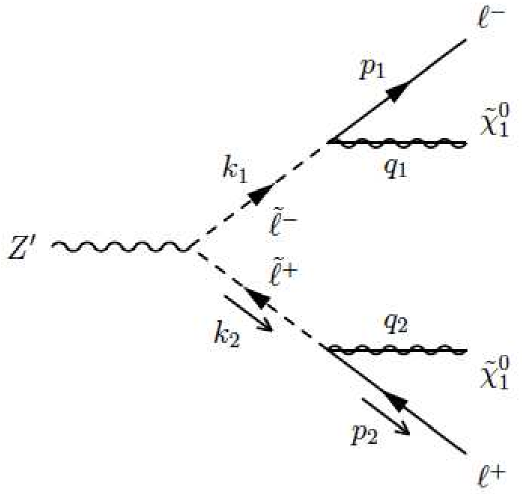
Put your favorite New particle between the Z' and final states to increase the production rate (using Z' resonance).

Z' resonance can help New particle search.

Z' as the slepton factory [M Baumgart, T Hartman, C Kilic, LT Wang (2006)]



[squark production]



[Z'-assisted slepton production]

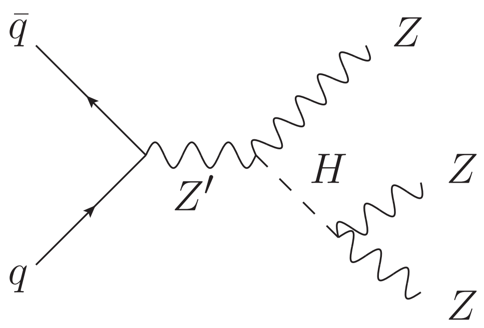
LHC is a hadron collider (gluons and quarks).

Compared to squark ($\widetilde{q}$) production, slepton ($\widetilde{\ell}$) production at LHC is limited.

Z' resonance can increase production of the sleptons without jets at the LHC.

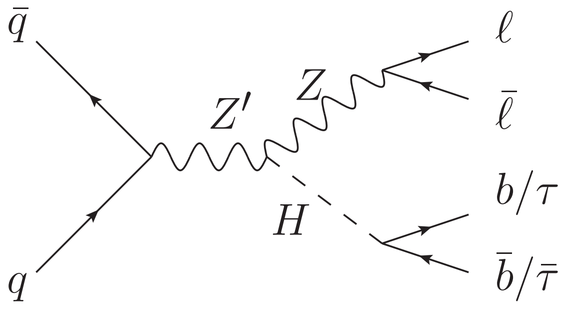
SUSY with R-parity model. Z' is motivated from the $U(1)_{B-L}$.

Z'-assisted Higgs search at the LHC



(for heavy Higgs)

[V Barger, P Langacker, HSL (2009)]



(for light Higgs)

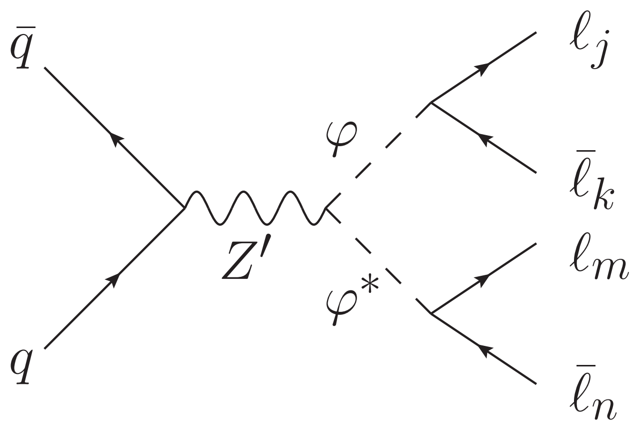
[A Katz, MH Son, B Tweedie (2010)]

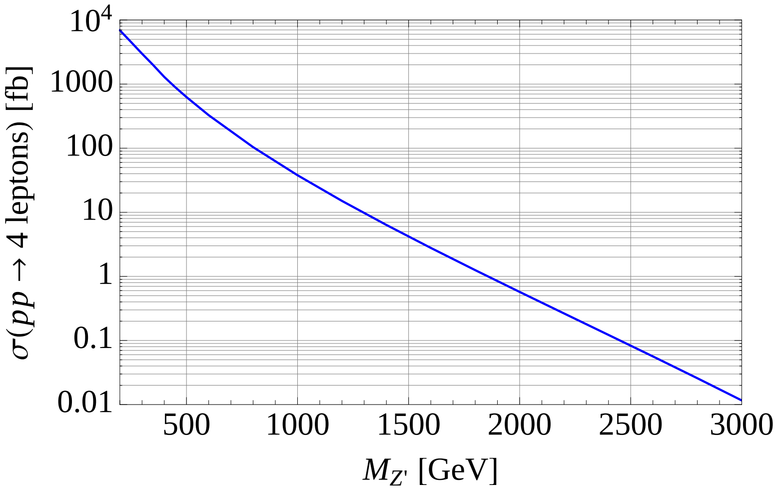
Z'-Z-H coupling can be sizable if Higgs has nonzero $U(1)$ charge.

$$\left|\left(\partial_\mu - \frac{i}{2} g_Z Z_\mu + i g_{Z'} Q'_H Z'_\mu\right) \frac{1}{\sqrt{2}}(H+v)\right|^2 = -g_Z g_{Z'} Q'_H v H Z_\mu Z'^\mu + \cdots$$

(R-Parity gauge origin may exist as $(B-L)+\alpha Y \ \rightarrow \ Q'_H \neq 0$.)

4-lepton Z' resonance (in a baryonic Z' model) [V Barger, HSL (2011)]





Gauged B is motivated to protect proton, especially in SUSY.

(B is accidentally conserved in SM $\longrightarrow$ Proton is stable in SM.)

[C Carone, H Murayama (1995)], [D Bailey, S Davidson (1995)], [P Fileviez-Perez, M Wise (2010)], [P Ko, Y Omura (2010)]

(Also see JH Song's talk about how a baryonic Z' ($M_{Z'} \sim 150\ \text{GeV}$) can address CDF Wjj excess. [K Cheung, JH Song (2011)])

In gauging B, additional fermions for anomaly cancellation.

(Most general family-universal $U(1)$ without exotics = $\alpha(B-L)+\beta Y$)

One possibility: an entire 4G family with B for all quarks.

	SM quarks	SM leptons	4G quarks	4G leptons
$U(1)_B$	$1/3$	0	$1/3$	-4

$U(1)\to B_4$ (Baryon Tetrality: 4G extension of the B_3) [HSL (2011)]

L is freely violated, but B can be violated only by $\Delta B = 4\times$ integer.

(i) Proton decay ($\Delta B = 1$) never occurs.

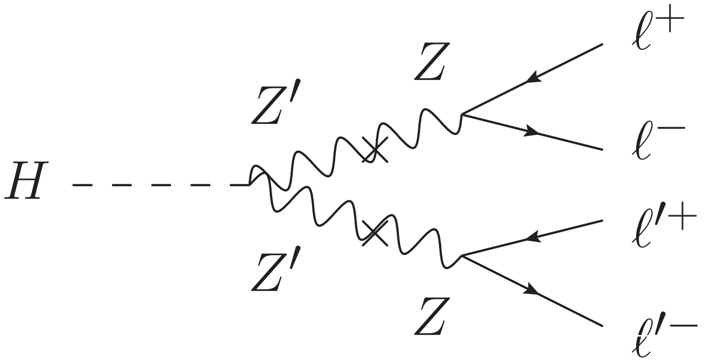
(ii) $Z' \to ee, \mu\mu, \tau\tau$ are absent. (No dilepton resonance)

(iii) $Z' \to \widetilde{\nu}_4 \widetilde{\nu}_4^*$ with $\widetilde{\nu}_4 \to 2\ell$ (L violation) is possible. (4-lepton resonance)

Multi-lepton Z' resonance without 2-lepton resonance is possible (with large cross-section).

4-lepton Higgs signal via Hidden sector Z' [S Gopalakrishnaa, SH Jung, J Wells (2008)]

(another way to obtain 4-lepton signals through Z')



An effect of Hidden sector Z' (with no direct coupling to SM fermions) may appear in the Higgs decay via mixing effect: $H \to Z'Z' \to 4\ell$

It is possible through mixing of Higgs doublet and singlet ($|H|^2|S|^2$) and kinetic mixing of Z and Z' ($F^{\mu\nu}F'_{\mu\nu}$).

Recap: Z' as a Discovery tool

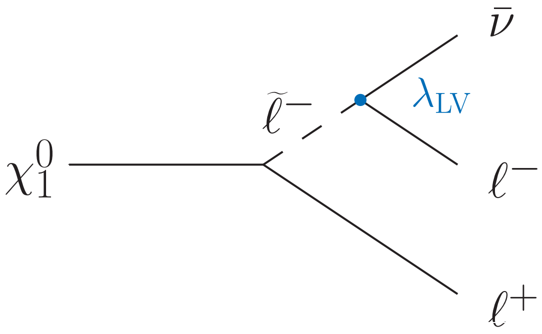
- Z' can be a factory of New particles.
- Non-typical Z' resonances might exist and worth to search for, since (i) New Physics are likely attached (besides the Z' itself), and (ii) resonance can help early discovery.

Z' as a Connector

Z' connection to Dark matter physics

Dark matter stabilization

$\tau_{\rm DM} \gtrsim 14 \times 10^9$ years (Universe age) ⟶ DM needs a stabilization mechanism.



$$\Gamma = \lambda^2 \frac{\alpha}{128\pi^2} \frac{m_\chi^5}{m_{\tilde{f}}^4} \quad \text{(for } \chi_1^0 = \tilde{\gamma}\text{)}$$

For instance, in the MSSM, we need R-Parity for LSP DM than for proton.

(i) LSP DM stability: $|\lambda_{\rm LV}|,\ |\lambda_{\rm BV}| \lesssim 10^{-20}$

(ii) proton stability: $|\lambda_{\rm LV} \cdot \lambda_{\rm BV}| \lesssim 10^{-27}$

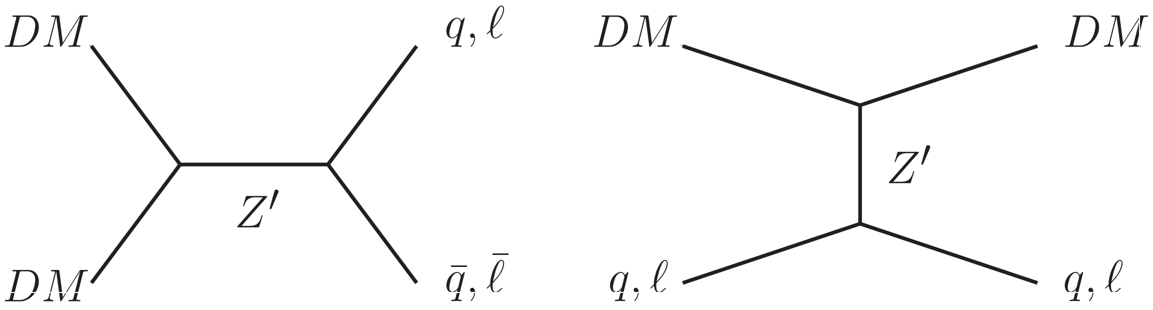
Stable WIMP-type DM demands a discrete symmetry (Z_N).

$U(1)$ is well-motivated as a gauge origin of Z_N for DM stabilization.

($U(1)_{B-L} \ \longrightarrow\ R$-Parity for LSP DM candidate.)

Simple picture of Dark Connection of Z'

Once we have Z' from a gauge origin of DM stabilization mechanism, we get a simple picture how it can affect DM physics further.



(Annihilation) (Direct detection)

Especially, for Hidden sector DM candidates (SM singlets), Z' can be a dominant Annihilation/Direct-detection channel.

Z' can (i) stabilize DM, and (ii) connect DM to the SM particles naturally.

(See also $\widetilde{Z}'$ (Z'-ino) connection for the RH $\widetilde{\nu}$-type DM [P Bandyopadhyay, EJ Chun, JC Park (2011)].)

Hidden sector discrete symmetries out of $U(1)$

Hidden sector DM models with Hidden sector Parity: [J Kubo, D Suematsu (2006)], [T Hur, HSL, S Nasri (2007)], [S Gopalakrishna, SJ Lee, J Wells (2009)], ...

$U(1) \rightarrow Z_2$ (Hidden sector Parity)

	SM/MSSM fields	Hidden sector fields
Z_2 (Hidden sector Parity)	0	1

Lightest Hidden sector Particle: stable

Hidden sector particle (SM singlet) may not decay fast (due to lack of enough interactions), but Z_N makes argument simple.

Flexible DM properties

Z'-connected DM can accommodate many kinds of properties.

A. Through $U(1)$ charge assignment (Q'[quarks], Q'[leptons]):

(i) DM coupling only to SM leptons (leptophilic DM) - motivated by positron excess at PAMELA [P Fox, E Poppitz (2009)], [S Baek, P Ko (2009)]

(ii) DM coupling only to SM quarks (leptophobic DM) - motivated by hint of light DM signals [P Gondolo, P Ko, Y Omura (2011)]

B. γ/Z-Z' kinetic mixing ($F^{\mu\nu} F'_{\mu\nu}$) [B Holdom (1986)]:

(i) Milicharged MeV DM - motivated by galactic 511 keV γ-ray anomaly: [JH Huh, JE Kim, JC Park, SC Park (2007)]

(ii) Constraints on kinetic mixing and predictions: [EJ Chun, JC Park, S Scopel (2010)]

Common gauge origin for proton stability and DM stability

In the MSSM, proton stability and LSP DM stability has a common mechanism: R-Parity (which can originate from $U(1)_{B-L}$).

Can we have a similar picture for a Hidden sector DM in SUSY?

$U(1)' \longrightarrow Z_6$ where $Z_6 = B_3 \times U_2$ [HSL (2008)]

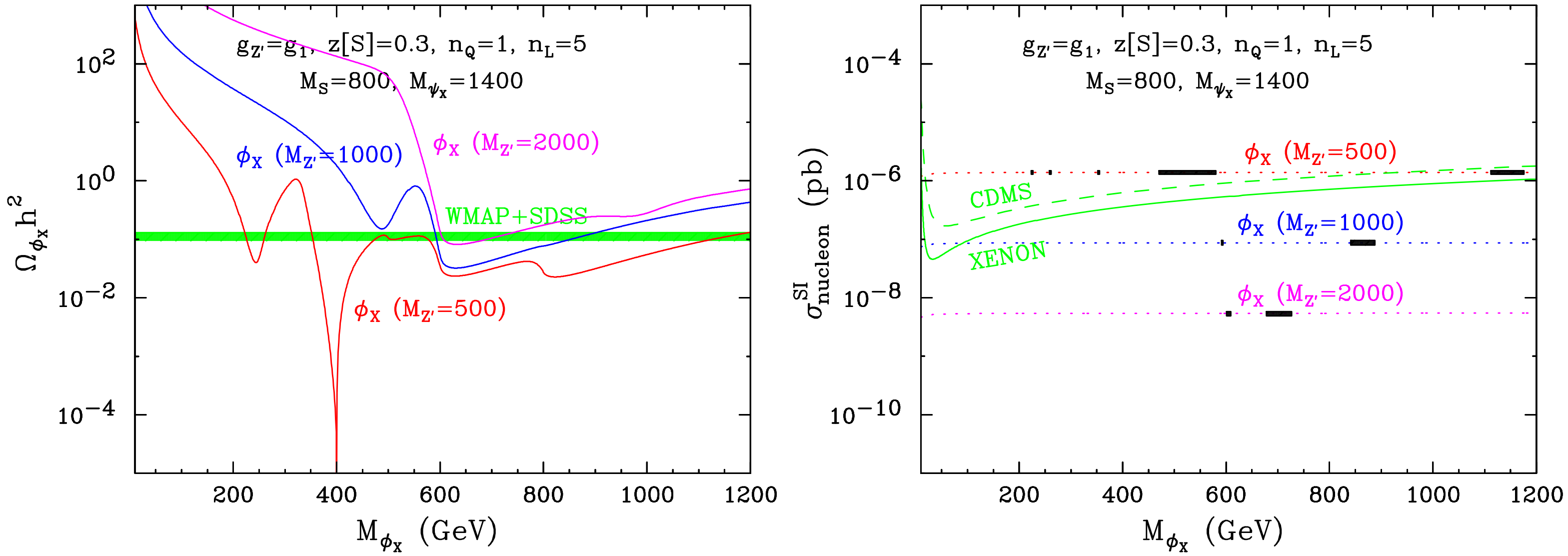
	Q	U^c	D^c	L	E^c	N^c	H_u	H_d	X
Z_6	0	-2	2	-2	-2	0	2	-2	-3

MSSM sector discrete symmetry: $B_3 \longrightarrow$ Proton is stable

Hidden sector discrete symmetry: $U_2 \longrightarrow$ Hidden sector DM is stable

Annihilation channels for the Hidden sector DM under $Z_6 = B_3 \times U_2$

1. DM+DM $\longrightarrow Z' \longrightarrow f\bar{f}$
2. DM+DM $\longrightarrow Z' \longrightarrow \widetilde{f}\widetilde{f}^* \longrightarrow$ SM particles (no R-Parity)



Hidden sector DM connected by Z' can satisfy both the relic density and direct detection constraints. (More annihilation channels open as more superpartners are kinematically allowed.)

Multiple Dark matters

In presence of multiple Z_N or $U(1)$, one may have multiple WIMP-type DMs.

[T Hur, HSL, S Nasri (2007)], [QH Cao, E Ma, J Wudka, CP Yuan (2007)], [P Ko, Y Omura (2011)]

For instance, SUSY version of $U(1)_B \times U(1)_L \longrightarrow$ 3 symmetries with 3 DMs (R-Parity, accidental $U(1)_{XB}, U(1)_{XL}$) [P Ko, Y Omura (2011)]

(i) DM$_1$ (leptophilic DM): explains PAMELA positron excess

(ii) DM$_2$ (leptophobic DM): explains CoGeNT light DM signals

No prevailing single DM candidate that can explain all DM signals.

$\longrightarrow$ DM world might be richer than a single DM picture.

$\longrightarrow$ Multiple DMs and their stabilizations suggest multiple extra $U(1)$s may exist.

Recap: Z' as a Connector

- DM stability motivates Z' (gauge origin of Z_N).
- Z' naturally connects DM to SM particles (especially for Hidden sector DM candidates) with flexible DM properties.

Z' as a Long-range Force carrier

Ultralight Z' (such as $M_{Z'} = 10^{-18}\ \mathrm{eV} \sim \frac{1}{\text{Sun-Earth distance}}$)

: Long-Range Interaction (LRI) effects in ν oscillation

Some relevant works on LRI

(i) LRI gets constraints from Eötvös-type experiments. [TD Lee, CN Yang (1955)]

Gravitation equivalence principle test: $ma = mg + F_{\rm LRI}$

LRI should be extremely weak: $\alpha' < 10^{-47}$ (baryons), $\alpha' < 10^{-49}$ (leptons).

LRI may need large (astronomical) source to have sizable effects.

Various analysis on LRI can be found in works by [L Okun, A Dolgov (1990's)]

(ii) Neutrino oscillation experiments are sensitive to a feeble LRI.

[A Joshipura, S Mohanty (2003)], [J Grifols, E Masso (2003)]

(iii) Recent interest in LRI to address MINOS anomaly (Disagreement in ν_μ and $\bar{\nu}_\mu$ in 2010 data of long-baseline ν oscillation [Fermilab to Soudan Mine]).

[J Heeck, W Rodejohann (2010)], [H Davoudiasl, HSL, W Marciano (2011)]

($\longrightarrow$ The anomaly disappeared with new 2011 data though.)

What type of $U(1)$ to affect ν oscillation?

$$H = H_{\text{vac}} + H_{\text{SM}} \quad \text{(for } \nu \text{ oscillation)}$$
$$H_{\text{SM}} = V_W(1,0,0) + V_Z(1,1,1)$$

with $V_W = \sqrt{2} G_F n_e, V_Z = -\frac{G_F}{\sqrt{2}} n_n$

Flavor-universal potential (such as by Z) is irrelevant to ν flavor oscillation.

$U(1)$ charge should be lepton-flavor-dependent to affect ν flavor oscillation.

(unless sterile ν, etc are introduced [N Engelhardt, A Nelson, J Walsh (2010)])

$$H_{\text{LRI}} = V_{Z'}(Q'_e, Q'_\mu, Q'_\tau)$$

$$Q' = \alpha Y + \beta(B-L) + a_1(L_e - L_\mu) + a_2(L_e - L_\tau) + a_3(L_\mu - L_\tau)$$

(i) $L_e - L_\mu$, $L_e - L_\tau$: couples to electrons in Sun, Earth

(ii) $L_\mu - L_\tau$: couples to neutrons through $Z - Z'$ mixing

(iii) $(B-L) + (L_\mu - L_\tau)$: couples to neutrons in Sun, Earth

Effective ν_μ survival probability (in 2-flavor oscillation limit)

[A Joshipura, S Mohanty (2003)]

$$P(\nu_\mu \to \nu_\mu) = 1 - \sin^2(2\tilde{\theta}_{23}) \sin^2 \left(\frac{\Delta \tilde{m}^2_{23} L}{4E_\nu} \right)$$

with effective mass splitting and mixing angle under New Potential

$$\begin{aligned} \Delta \tilde{m}^2_{23} &= \Delta m^2_{23} \sqrt{[\xi - \cos(2\theta_{23})]^2 + \sin^2(2\theta_{23})} \\ \sin^2(2\tilde{\theta}_{23}) &= \sin^2(2\theta_{23}) / \left([\xi - \cos(2\theta_{23})]^2 + \sin^2(2\theta_{23}) \right) \end{aligned}$$

$$\xi \equiv -\frac{2(Q'_\tau - Q'_\mu) V_{Z'} E_\nu}{\Delta m^2_{23}}$$

(In analogy of the standard matter effect in ν_e oscillation: $\xi = \frac{2\sqrt{2} G_F n_e E_\nu}{\Delta m^2}$)

(i) Standard Matter effect: Local electrons through W.

(ii) LRI: All particles in Earth/Sun through ultralight Z' (depending on Q').

Astronomical source of New Potential

For instance, $Q' = (B-L) + (L_\mu - L_\tau)$ case (coupling to neutrons)

Sun ($\odot$) $\longleftarrow r \longrightarrow$ Earth ($\oplus$)

$(N_n^\odot = 1.7 \times 10^{56})$ $(N_n^\oplus = 1.8 \times 10^{51})$

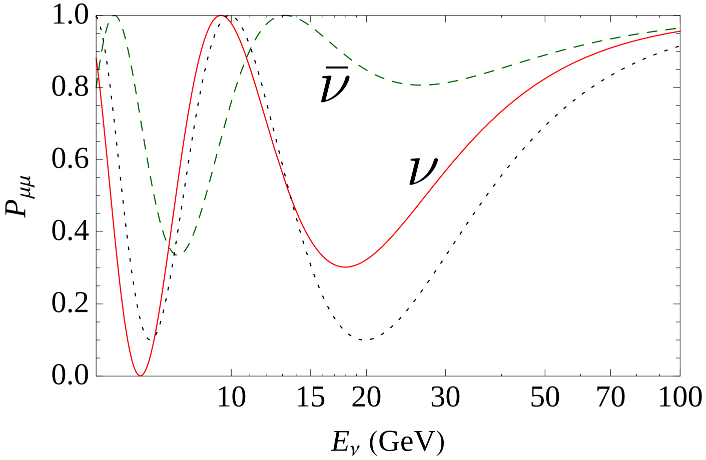
$$V_{Z'} = \alpha' \left(\frac{N_n^\odot}{r} + \frac{N_n^\oplus}{R_\oplus} \right) = \left(\frac{\alpha'}{10^{-50}}\right) \times \left(\frac{AU}{r} + 0.25\right) \times (2.2 \times 10^{-12}\ \mathrm{eV})$$
$$\sim \left(\frac{\alpha'}{10^{-50}}\right) \times \mathcal{O}(10^{-12}\ \mathrm{eV})$$

Since MINOS ν oscillation is relevant to $\frac{\Delta m^2_{23}}{E_\nu} \sim \mathcal{O}\left(\frac{10^{-3}\ \mathrm{eV}^2}{10^9\ \mathrm{eV}}\right) \sim \mathcal{O}(10^{-12}\ \mathrm{eV})$, LRI with $\alpha' \sim \mathcal{O}(10^{-50})$ level can affect MINOS experiments. (Anomaly is gone with new data.)

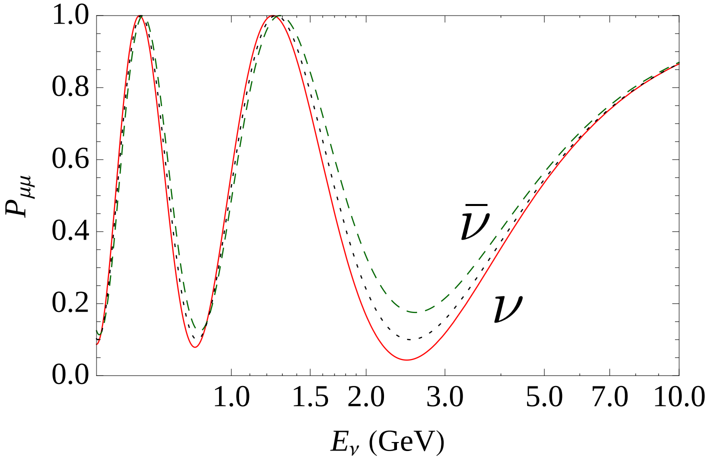
(In other words, ν oscillation is a good probe of an extremely weak LRI.)

Annual modulation in New Potential due to $r = (1.47 \sim 1.52) \times 10^8\ \mathrm{km}$

LRI effect on neutrino oscillation



[$L = 2 \times 6400$ km (IceCube DeepCore)]



[$L = 1300$ km (Future LBNE)]

(for best-fit values to MINOS 2010 anomalous data)

(i) LRI effects on ν oscillations are energy-dependent.

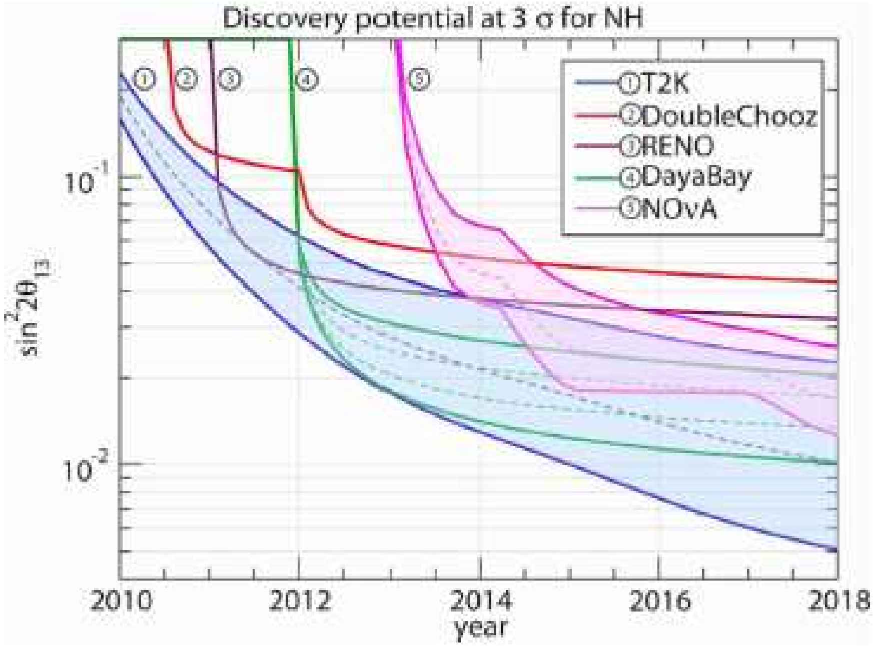
(ii) The effects on ν (red solid) and $\bar{\nu}$ (green dashed) are different.

(iii) Possible seasonal modulation if the source is the Sun.

If New Potential exists, the standard oscillation picture would under-describe the nature. (too few parameters)

Possible energy dependence of θ_{13}

The world is racing to measure θ_{13} now. (Already some indication of $\theta_{13} > 0$.)



With LRI, the θ_{13} values might vary with energy and baseline.

It is important to see if the θ_{13} measurements at reactor-based experiments ($L \sim 1\,\mathrm{km}$, $E_\nu \sim 1\,\mathrm{MeV}$) agree to the accelerator-based experiments ($L \sim 1000\,\mathrm{km}$, $E_\nu \sim 1\,\mathrm{GeV}$).

Recap: Z' as a Long-range Force carrier

- Long-Range Interaction with tiny coupling ($\alpha' \lesssim 10^{-50}$) can affect ν oscillation.

Things I could not cover (a partial list)

- Extended neutralino and Higgs sector
- Forward-Backward asymmetry
- $U(1)$ solution to the μ-problem
- Dirac ν with a naturally suppressed mass
- $U(1)$ symmetry breaking
- Z'-mediated FCNC
- $Z'/\widetilde{Z}'$-mediated SUSY breaking mechanism
- Dark photon
- Stueckelberg mechanism
- $\cdots$

Concluding Remarks

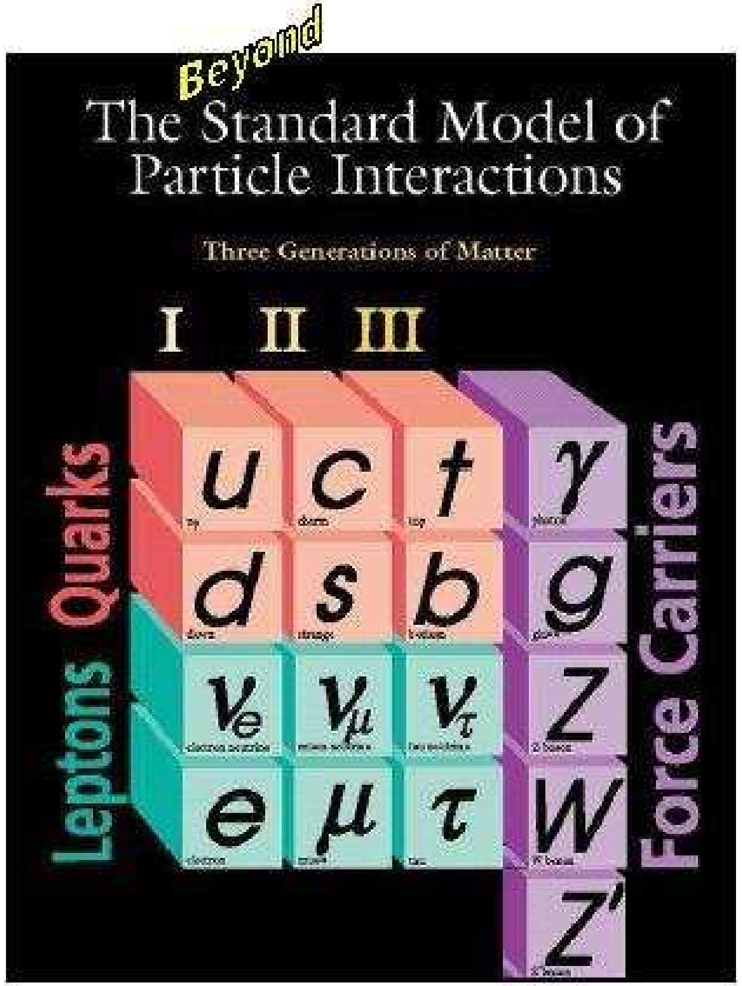
We went over only selected topics of the easiest kind Z'.

1. Z' as a Controller: $U(1) \rightarrow Z_N$
2. Z' as a Discovery tool: $pp \rightarrow Z'$ resonance → New particles
3. Z' as a Connector: New interaction and stabilization for DM candidates.
4. Z' as a Long-range Force carrier: LRI with a tiny coupling can still affect ν oscillation.

Z' is versatile (a useful tool for many purposes).

Z' is general (commonly predicted in many New physics models).

The future-SM will be likely



+ any incidental particles ...

- Thank you -