Standard Model^{++}

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Outline

- Motivation
- String Theory, D-Branes, and all that...
- $SU(3)_C \times SU(2)_L \times U(1)_B \times U(1)_L \times U(1)_{I_R}$
- LHC Phenomenology
- Neutrino Cosmology Redux ☞ in Haim's talk on Wednesday
- Conclusions

LAA, Antoniadis, Goldberg, Huang, Lüst, Taylor, Vlcek, arXiv:1206.2537

Collateral Damage

- With turn on of LHC ☞ a new era of discovery has just begun
- $SU(3)_C \times SU(2)_L \times U(1)_Y$ was once again severely tested with $L \sim 4.9\ \mathrm{fb}^{-1}$ of pp collisions collected at $\sqrt{s} = 7\ \mathrm{TeV}$
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However ☞ there is another side to the story...

- Neutrino physics has wounded SM
  Convincing experimental evidence exists for $\nu_\alpha \leftrightharpoons \nu_\beta$
  oscillatory transitions between different neutrino flavors
- Cosmology may continue process and pierce SM's resistant armor
  flat expanding universe containing 5% baryons, 20% dark matter, and 75% dark energy continues to be put on a firmer footing
  – dark radiation too?!? –

Oases in the Desert?

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- Major driving force behind consideration of physics beyond SM is huge disparity between strength of gravity and of SM forces
- This hierarchy problem may signal new physics at TeV-scale
  To be more specific ☞ due to quadratic sensitivity of Higgs mass to quantum corrections from an aribitrarily high mass scale with no new physics between $M_{\rm EW} \sim 1~{\rm TeV}$ and $M_{\rm Pl} \sim 10^{19}~{\rm GeV}$ Higgs mass must be fine-tuned to an accuracy of $\mathcal{O}(10^{32})$

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- Therefore ☞ it is of interest to identify univocal footprints that can plausible arise in theories with capacity to describe physics over this enormous desert

SM Meets Gravity

- Among various attempts in this direction ☞ superstring theory is most successful candidate and also most ambitious approach since besides Standard Model gauge interactions it also includes gravitational force at quantum level
- In recent years there has been achieved substantial progress to marry string theory with particle physics and cosmology
- Important advances were fueled by realization of vital role played by D-branes in connecting string theory to phenomenology
- D-brane string compactifications provide collection of building block rules that can be used to build up SM or something very close to it

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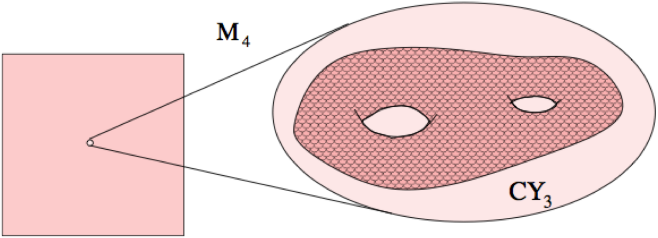
For an authoritative review see:
Blumenhagen, Körs, Lüst, Stieberger, Phys. Rept. **445** (2007) 1

Intersecting D-brane Models

- Basic unit of gauge invariance for oriented strings is a $U(1)$ field ☞ stack of N identical D-branes eventually generates $U(N)$ theory with associated $U(N)$ gauge group
- In presence of many D-brane types ➤ gauge group becomes $\prod U(N_P)$ ☞ N_P reflects number of D-branes in each stack
- Specific configuration ☞ K stacks of intersecting D$(p+3)$-branes filling 4-d Minkowski spacetime M_4 and wrapping p-cycles of CY_3
- Closed string degrees of freedom reside in entire 10-d space (gravitons + geometric scalar moduli fields of internal space CY_3)
- Open string degrees of freedom give rise to gauge theory on D$(p+3)$-brane world-volumes with gauge group $\prod U(N_P)$
- In orientifold brane configurations open strings come unoriented ☞ $U(2)$ can be replaced by symplectic representation of $SU(2)$

Schematic Representation of D-Brane Structure

Gauge fields are localized on D-branes wrapping certain compact cycles on underlying geometry whose intersection can give rise to chiral fermions



Where on the String Landscape

- This approach to string model building leads to variety of low energy theories including SM and its SUSY extensions

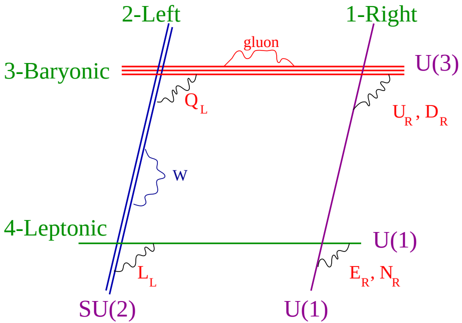
- Herein ➻ we will consider non-SUSY models all the way up to UV cutoff of effective theory ☞ though of course deep UV theory of quantum gravity may well be supersymmetric

- Though SUSY introduces advantages over non-SUSY theories ☞ our approach is distiguished by its simplicity to describe very appealing phenomenological possibilities that best display dynamics involving extra $U(1)$ symmetries

- Energy scale associated with string physics assumed to be near Planck mass ☞ $M_s \lesssim M_{\rm Pl}$

Engineering SM

- Minimal 4-stack model



- Open strings terminating on stack of "color" branes contain $SU(3)$ octet of gluons G^a_μ + extra $U(1)$ boson C_μ

Cremades, Ibañez, Marchesano, JHEP **0307** (2003) 038

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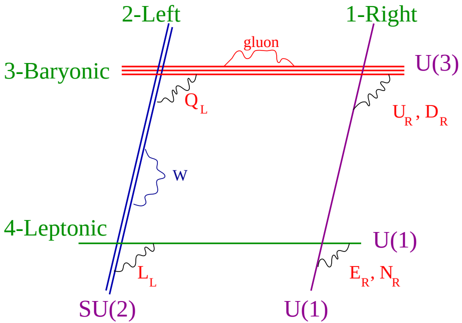

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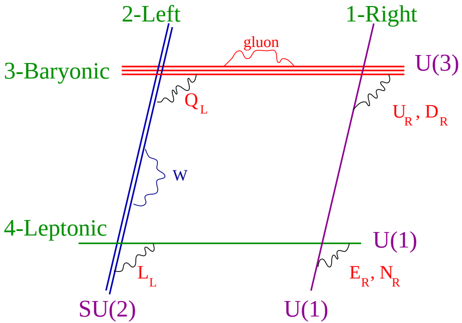

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- $SU(2)$ stack open strings correspond to weak gauge bosons W^a_μ
- $U(1)_{I_R}$ D-brane is a terminus for B_μ gauge boson and there is additional $U(1)$ field X_μ terminating on $U(1)_L$ brane

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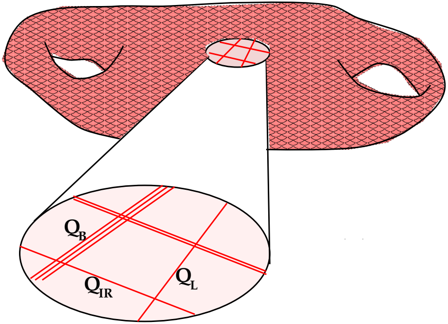
Gauge Symmetries



Resulting $U(1)$ content gauges:

- baryon number B ☞ with $U(1)_B \subset U(3)_B$
- lepton number L
- third additional abelian charge I_R
  which acts as third isospin component of $SU(2)_R$

The Dramatis Personae

Chiral spectrum consists of 6 sets of Weyl fermion-antifermion pairs

Label	Fields	Sector	Representation	Q_B	Q_L	Q_{I_R}
1	U_R	$3 \leftrightharpoons 1^*$	$(3, 1)$	1	0	1
2	D_R	$3 \leftrightharpoons 1$	$(3, 1)$	1	0	-1
3	L_L	$4 \leftrightharpoons 2$	$(1, 2)$	0	1	0
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Charges Q_B, Q_L, Q_{I_R} are mutually orthogonal in the fermion space

$$\sum_f Q_{i,f} Q_{j,f} = 0 \text{ for } i \neq j$$

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Right handed neutrino states ☞ singlets under hypercharge

Lagrangian

Classical gauge invariant Lagrangian can be decomposed as

$$\mathscr{L}_{\rm SM^{++}} = \mathscr{L}_{\rm s} + \mathscr{L}_{\rm YM} + \sum_{\rm generations} (\mathscr{L}_{f} + \mathscr{L}_{\rm Y}) + \mathscr{L}_{\rm stringy}$$

$$\begin{aligned}
\mathscr{L}_s &= (\mathcal{D}^\mu H)^\dagger \mathcal{D}_\mu H + (\mathcal{D}^\mu H'')^\dagger \mathcal{D}_\mu H'' - V(H, H'') \\
\mathcal{D}_\mu &= \partial_\mu - i g_3 T^a G^a_\mu - i g'_3 Q_B C_\mu - i g_W \tau^a W^a_\mu - i g'_1 Q_{I_R} B_\mu - i g'_4 Q_L X_\mu \\
\mathscr{L}_{\rm YM} &= -\frac{1}{4}\left(G^a_{\mu\nu} G^{\mu\nu}_a + W^a_{\mu\nu} W^{\mu\nu}_a + F^{(1)}_{\mu\nu} F^{\mu\nu}_{(1)} + F^{(3)}_{\mu\nu} F^{\mu\nu}_{(3)} + F^{(4)}_{\mu\nu} F^{\mu\nu}_{(4)}\right) \\
\mathscr{L}_f &= i\overline{Q_L}\gamma_\mu \mathcal{D}^\mu Q_L + i\overline{U_R}\gamma_\mu \mathcal{D}^\mu U_R + i\overline{D_R}\gamma_\mu \mathcal{D}^\mu D_R + i\overline{L_L}\gamma_\mu \mathcal{D}^\mu L_L \\
&+ i\overline{E_R}\gamma_\mu \mathcal{D}^\mu E_R + i\overline{N_R}\gamma_\mu \mathcal{D}^\mu N_R \\
\mathscr{L}_{\rm Y} &= -Y_d \left(\overline{Q_L} H\right) D_R - Y_u \left(\overline{Q_L} i\sigma^2 H^*\right) U_R - Y_e \left(\overline{L_L} H\right) E_R \\
&- Y_N \left(\overline{L_L} i\sigma^2 H^*\right) N_R + \text{h.c.}
\end{aligned}$$

$i\sigma_2 H^*$ transforms in fundamental representation of $SU(2)$

Rotation to Basis Diagonal in Hypercharge

- Fields $C_\mu, \ X_\mu, \ B_\mu$ are related to $Y_\mu, \ Y_\mu{}', \ Y_\mu{}''$ by

$$\mathbb{R} = \begin{pmatrix} C_\theta C_\psi & -C_\phi S_\psi + S_\phi S_\theta C_\psi & S_\phi S_\psi + C_\phi S_\theta C_\psi \\ C_\theta S_\psi & C_\phi C_\psi + S_\phi S_\theta S_\psi & -S_\phi C_\psi + C_\phi S_\theta S_\psi \\ -S_\theta & S_\phi C_\theta & C_\phi C_\theta \end{pmatrix}$$

- Covariant derivative for the $U(1)$ fields can be rewritten as

$$\begin{aligned} \mathcal{D}_\mu = \ & \partial_\mu - iY_\mu \left(-S_\theta g_1' Q_{I_R} + C_\theta S_\psi g_4' Q_L + C_\theta C_\psi g_3' Q_B\right) \\ - \ & iY_\mu' \left[C_\theta S_\phi g_1' Q_{I_R} + \left(C_\phi C_\psi + S_\theta S_\phi S_\psi\right) g_4' Q_L + (C_\psi S_\theta S_\phi - C_\phi S_\psi) g_3' Q_B\right] \\ - \ & iY_\mu'' \left[C_\theta C_\phi g_1' Q_{I_R} + \left(-C_\psi S_\phi + C_\phi S_\theta S_\psi\right) g_4' Q_L + \left(C_\phi C_\psi S_\theta + S_\phi S_\psi\right) g_3' Q_B\right] \end{aligned}$$

- Hypercharge condition fixes first column of $\mathbb{R}$

$$\begin{pmatrix} C_\mu \\ X_\mu \\ B_\mu \end{pmatrix} = \begin{pmatrix} Y_\mu \, \frac{g_Y}{6 \, g_3'} & \cdots \\ -Y_\mu \, \frac{g_Y}{2 \, g_4'} & \cdots \\ Y_\mu \, \frac{g_Y}{2 \, g_1'} & \cdots \end{pmatrix}$$

Constraints on Euler Angles and Abelian Couplings

- ... and determine value of two associated Euler angles

$$\theta = -\arcsin\left[\frac{g_Y}{2g'_1}\right] \qquad \psi = -\arcsin\left[\frac{g_Y}{2g'_4\, C_\theta}\right]$$

- Abelian couplings related through orthogonality condition

$$\frac{1}{g_Y^2} = \left(\frac{1}{2\,g'_4}\right)^2 + \left(\frac{1}{6\,g'_3}\right)^2 + \left(\frac{1}{2\,g'_1}\right)^2$$

  orthogonal charges mantain orthogonality relation to one loop

  without inducing kinetic mixing

- g'_3 fixed by the relation of $U(N)$ unification ➧ $g_3(M_s) = \sqrt{6}\, g'_3(M_s)$ hence ☞ determined at all energies through RG running
- Demanding Y'' couples to linear combination of I_R and $B - L$

$$\tan\phi = -S_\theta \frac{3\,g'_3\, C_\psi + g'_4\, S_\psi}{3\,g'_3\, S_\psi + g'_4\, C_\psi}$$

Anomalous (Mass)^2 Matrix

- Relevant parts of Lagrangian specifying anomalous mass

$$\mathscr{L} = \bar{f}^i_{L\,(R)} \gamma^\mu \mathbb{Q}^T \mathbb{G} \mathbb{X} f^i_{L\,(R)} + \tfrac{1}{2} \mathbb{X}^T \mathbb{M}^2 \mathbb{X}$$

- Under $\mathbb{R}$ rotation mass term becomes

$$\tfrac{1}{2} \mathbb{X}^T \mathbb{M}^2 \mathbb{X} = \tfrac{1}{2} \mathbb{Y}^T \, \overline{\mathbb{M}^2} \, \mathbb{Y} \qquad \text{with} \qquad \overline{\mathbb{M}^2} = \mathbb{R}^T \, \mathbb{M}^2 \, \mathbb{R}$$

- Additional constraint:
  fields Y_μ and Y''_μ are eigenstates of $\mathbb{M}^2$ with zero eigenvalue
- Poincare invariance requires complete diagonalization of $\mathbb{M}$ in order to deal with observables
- Therefore ☞ same $\mathbb{R}$ which rotates to couple Y_μ to hypercharge simultaneously diagonalizes $\mathbb{M}^2$ so that $\overline{\mathbb{M}^2} = \mathrm{diag}(0, M'^2, 0)$
- $\mathscr{L}_{\rm stringy}$ comes to the rescue ➽ Green-Schwarz mass term
  $M' \sim M_s$ ☞ Z' decouples from low energy physics

Higgs Sector

Fields	Sector	Representation	Q_B	Q_L	Q_{I_R}	Q_Y
H	$2 \leftrightharpoons 1$	$(1, 2)$	0	0	1	$\frac{1}{2}$
H''	$4 \leftrightharpoons 1$	$(1, 1)$	0	-1	-1	0

- There are no dimension 4 operators involving H'' that contribute to Yukawa Lagrangian ☞ this is very important: H'' carries ν_R quantum numbers and its VEV breaks L
- However ☞ breaking affects only higher-dimensional operators which are suppressed by M_s ➽ no phenomenological problem with experimental constraints for $M_s \gtrsim 10^{14}$ GeV

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- Higgs VEVs obtained after minimizing

$$V\left(H, H''\right) = \mu^2 \left|H\right|^2 + \mu'^2 \left|H''\right|^2 + \lambda_1 \left|H\right|^4 + \lambda_2 \left|H''\right|^4 + \lambda_3 \left|H\right|^2 \left|H''\right|^2$$

will be denoted by

$$\langle\, H \,\rangle = \begin{pmatrix} 0 \\ v \end{pmatrix} \quad \text{and} \quad \langle H'' \rangle = v''$$

Symmetry Breaking

- Higgs kinetic terms together with Green-Schwarz mass term lead to

$$\mathscr{B} = [\mathcal{D}_\mu^\dagger \, (0 \; v)] \left[\mathcal{D}^\mu \begin{pmatrix} 0 \\ v \end{pmatrix}\right] + (\mathcal{D}_\mu v'')^\dagger (\mathcal{D}^\mu v'') + \frac{1}{2} M'^2 Z'_\mu Z'^\mu$$

Expanded this gives

$$\begin{aligned} \mathscr{B} &= \frac{1}{4}(g_2\, v)^2 W_\mu^+ W^{-\mu} + \frac{1}{4}(g_2 v)^2 C_{\theta_W}^{-2} \, \overline{Z}_\mu \overline{Z}^\mu + g_1' C_\theta \left(S_\phi Z'_\mu + C_\phi Y''_\mu \right) g_2 \, v^2 C_{\theta_W}^{-1} \overline{Z}^\mu \\ &+ v''^2 \left\{ g_1' C_\theta (S_\phi \, Z'_\mu + C_\phi \, Y''_\mu) + g_4' \left[(C_\phi C_\psi + S_\theta S_\phi S_\psi) \, Z'_\mu + S_\psi S_\theta C_\phi \, Y''_\mu \right] \right\}^2 \\ &+ (g_1' v \, C_\theta)^2 \left(S_\phi Z'_\mu + C_\phi Y''_\mu \right) \left(S_\phi Z'^\mu + C_\phi Y''^\mu \right) + \frac{1}{2} M'^2 Z'_\mu Z'^\mu \\ &\simeq \frac{1}{4}(g_2\, v)^2 W_\mu^+ W^{-\mu} + \frac{1}{4}(g_2 v)^2 C_{\theta_W}^{-2} \, \overline{Z}_\mu \overline{Z}^\mu + g_1' C_\theta C_\phi Y''_\mu \, g_2 \, v^2 C_{\theta_W}^{-1} \overline{Z}^\mu \\ &+ v''^2 \left(g_1' C_\theta C_\phi \, Y''_\mu + g_4' S_\psi S_\theta C_\phi \, Y''_\mu \right)^2 + (g_1' v \, C_\theta C_\phi)^2 \, Y''_\mu Y''^\mu + \dots \end{aligned}$$

omitted terms pertain only to the Z' couplings at the string scale

- Expansion around $v/v'' \ll 1$ ☞ $\overline{Z}_\mu Y''^\mu$ mass matrix is render diagonal

$$\mathscr{B} = \left(\frac{g_2 v}{2}\right)^2 W_\mu^+ W^{-\mu} + \left(\frac{g_2 v}{2 C_{\theta_W}}\right)^2 Z_\mu Z^\mu + \left(\frac{g_1' \, C_\phi \, v''}{C_\theta}\right)^2 Z''_\mu Z''^\mu + \mathcal{O}\left(\left(\frac{v}{v''}\right)^2\right)$$

$Z'' \simeq Y'' +$ small corrections

Currents and Branching Fractions

- Take $M_s = 10^{14}\ \mathrm{GeV}$ as a reference point
  for running down g'_3 coupling to TeV region
- For $g'_1(M_s) = 0.999$ ☞ $U(1)$ vector bosons couple to currents

$$
\begin{aligned}
J_Y &= 1.8 \times 10^{-1}\ Q_{I_R} + 1.8 \times 10^{-1}\ (B - L) \\
J_{Z'} &= 1.6 \times 10^{-4}\ Q_{I_R} + 5.5 \times 10^{-1}\ B - 7.6 \times 10^{-2}\ L \\
J_{Z''} &= 3.6 \times 10^{-1}\ Q_{I_R} - 9.2 \times 10^{-2}\ (B - L)
\end{aligned}
$$

- Since $\mathrm{Tr}\,[Q_{I_R} B] = \mathrm{Tr}\,[Q_{I_R} L] = 0$ ☞ Z'' decay width is given by

$$
\begin{aligned}
\Gamma_{Z''} &= \Gamma_{Z'' \to Q_{I_R}} + \Gamma_{Z'' \to B-L} \\
&\propto (1.4 \times 10^{-1})^2\, \mathrm{Tr}[Q^2_{I_R}] + (9.2 \times 10^{-2})^2 \mathrm{Tr}\left[(B-L)^2\right] \\
&= 1.0 \times 10^{0} + 4.5 \times 10^{-2}
\end{aligned}
$$

- Corresponding branching fractions are

$$
\mathrm{BR}\ Z'' \to Q_{I_R} = 0.959 \qquad \text{and} \qquad \mathrm{BR}\ Z'' \to B - L = 0.041
$$

Cross Sections

Relevant Lagrangian part of $f\bar{f}Z''$ coupling is of form

$$\mathscr{L} = \frac{1}{2}\sqrt{g_Y^2 + g_2^2}\,\sum_f \left(\epsilon_{f_L^i}\,\bar{f}_L^i\gamma^\mu f_L^i + \epsilon_{f_R^i}\,\bar{f}_R^i\gamma^\mu f_R^i\right) Z''_\mu = \sum_f \left((g_{Y'}Q_{Y'})_{f_L^i}\,\bar{f}_L^i\gamma^\mu f_L^i + (g_{Y'}Q_{Y'})_{f_R^i}\,\bar{f}_R^i\gamma^\mu f_R^i\right) Z''_\mu$$

Fields	$g_Y Q_Y$	$g_{Y'} Q_{Y'}$	$g_{Y''} Q_{Y''}$
U_R	0.2434	0.1836	0.3321
D_R	−0.1214	0.1838	−0.3933
L_L	−0.1826	0.0759	0.0918
E_R	−0.3650	0.0760	−0.2709
Q_L	0.0610	0.1837	−0.0306
N_R	0.0000	0.0758	0.4545
H	0.1824	0.0000	0.3627
H''	0.0000	−0.0758	−0.4545

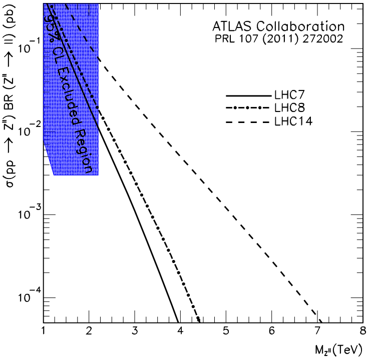
$$\frac{d\sigma}{dM} = M\tau \sum_{ijkl}\left[\int_{-Y_{\max}}^{0} dY\, f_i(x_a,\, M)\;\; f_j(x_b,\, M)\int_{-(y_{\max}+Y)}^{y_{\max}+Y} dy\, \left.\frac{d\sigma}{d\hat{t}}\right|_{ij\to kl}\frac{1}{\cosh^2 y}\right.$$
$$\left. + \int_0^{Y_{\max}} dY\, f_i(x_a,\, M)\, f_j(x_b, M)\int_{-(y_{\max}-Y)}^{y_{\max}-Y} dy\, \left.\frac{d\sigma}{d\hat{t}}\right|_{ij\to kl}\frac{1}{\cosh^2 y}\right]$$

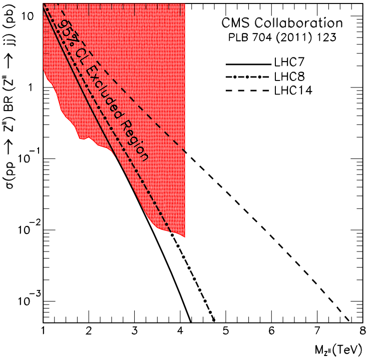
CTEQ6

$$|\mathcal{M}(ij\to kl)|^2 = 16\pi\hat{s}^2 \left.\frac{d\sigma}{d\hat{t}}\right|_{ij\to kl}$$

$$|\mathcal{M}(q\bar{q}\stackrel{Z''}{\to} q'\bar{q}')|^2 = \frac{1}{4}\left[g_{Y''}^2 Q_{Y''}^2(q_L) + g_{Y''}^2 Q_{Y''}^2(q_R) g_{Y''}^2 Q_{Y''}^2({q_L}') + g_{Y''}^2 Q_{Y''}^2({q_R}')\right]\left[\frac{2(u^2+t^2)}{(s-M_{Z''}^2)^2 + (\Gamma_{Z''}\,M_{Z''})^2}\right]$$

Bounds from LHC7 and predictions for LHC14





LHC14	10 fb^{-1}			100 fb^{-1}			1000 fb^{-1}		
$M_{Z''}$ (TeV)	$\mathcal{S}$	$\mathcal{B}$	$\mathcal{S}/\mathcal{N}$	$\mathcal{S}$	$\mathcal{B}$	$\mathcal{S}/\mathcal{N}$	$\mathcal{S}$	$\mathcal{B}$	$\mathcal{S}/\mathcal{N}$
3	244	2689	4.71	2443	26893	14.89	24427	268928	47.10
4	39	579	1.62	391	5789	5.14	3910	57895	16.25
5	7	176	0.50	67	1759	1.60	670	17590	5.05
6	1	66	0.14	11	664	0.44	113	6646	1.39

The Take-Home Message

- Studied phenomenology of $U(3)_B \times SU(2)_L \times U(1)_L \times U(1)_{I_R}$
- Initially free parameters consist of three couplings ☞ $g'_1,\ g'_3,\ g'_4$
- These are augmented by three Euler angles
  to allow for field rotation to coupling diagonal in hypercharge
- Diagonalization fixes two angles and orthogonal nature of $\mathbb{R}$
  introduces constraint on couplings $P(g_Y, g'_1, g'_3, g'_4) = 0$
- $g'_3 = \sqrt{1/6}\, g_3$ at scale of $U(N)$ unification
  and is therefore determined at all energies through RG running
- Third Euler angle determined by demanding Y'' couples
  to an anomalous free linear combination of I_R and $B - L$
- Model is fully predictive and can be confronted with LHC14 data

Dark Radiation ?!?

- WMAP + BOA + H_0 ☞ $N_\nu^{\rm eff} = 4.34 \pm^{+0.86}_{0.88}$ (2σ)
  WMAP Collaboration, Astrophys. J **192** (2011) 18
- ACP + BAO + H_0 ☞ $N_\nu^{\rm eff} = 4.56 \pm 0.75$ (68%CL)
  ACP Collaboration, Astrophys. J **739** (2011) 52
- SPT + BAO + H_0 ☞ $N_\nu^{\rm eff} = 3.86 \pm 0.42$ (1σ)
  SPT Collaboration, Astrophys. J **743** (2011) 28
- CMB + BBN + D/H ☞ $N_\nu^{\rm eff} = 3.9 \pm 0.44$ (1σ)
  Nollett & Holder, arXiv:1112.2683
- WMAP + SPT [ACT]+ $H(z)$ ☞ 3.5 ± 0.3 (1σ) [3.7 ± 0.4 (1σ)]
  Moresco, Verde, Pozzetti, Jimenez, Cimatti, arXiv:1201.6658

Task then becomes to explain why we don't see three extra r.d.o.f.

For certain ranges of $M_{Z''}$ ☞ ν_R decoupling occurs @ QCD crossover just so that they are only partially reheated compared to ν_L

LAA & Goldberg, Phys. Rev. Lett. **108** (2012) 081805