A Fourth Generation at a Muon collider

Gustavo Burdman

FermiLab and University of São Paulo

Muon Collider Workshop, Fermilab, November 10-12 2009

New Physics at the LHC

Discoveries at the LHC:

- New Interactions (new gauge bosons, scalar sectors, . . .)
- New Fermions:
  - Vector-like: Little Higgs, KK fermions, ...
  - Chiral: 4th Generation

A Chiral Fourth Generation

Motivation:

Why not ?

- 4G with $300\ \mathrm{GeV} \lesssim m_4 \lesssim 600\ \mathrm{GeV}$ not excluded by EWPT, if $\Delta m \leq M_W$
- Flavor bounds can be accommodated by suppressed mixings

Why ?

- Simplest (dumbest) extension of the standard model
- Fourth generation could be associated to EWSB. Large Yukawas naturally associated with strongly coupled sector.

A Chiral Fourth Generation

Motivation:

Why not ?

- 4G with $300\ \mathrm{GeV} \lesssim m_4 \lesssim 600\ \mathrm{GeV}$ not excluded by EWPT, if $\Delta m \leq M_W$
- Flavor bounds can be accommodated by suppressed mixings

Why ?

- Simplest (dumbest) extension of the standard model
- Fourth generation could be associated to EWSB. Large Yukawas naturally associated with strongly coupled sector.
- Why not ?

Strongly Coupled Heavy Fermions

Heavy Chiral Fermions: strongly coupled to EWSB sector

- Top quark:

$$m_t \simeq v \qquad \Rightarrow \qquad y_t \sim 1$$

- If Heavy Fourth Generation $\Rightarrow y_4 > 1$

Higgs sector is strongly coupled

- Natural to assume composite Higgs sector

Fourth Generation may be related to EWSB

EWSB from Fourth Generation Condensation

Breaking the Electroweak Symmetry:

- A Chiral Fourth Generation: $Q_4, U_{4R}, D_{4R}, L_4, E_{4R}, N_{4R}$
- New strong interaction at the $O(1)$ TeV scale:
  - E.g. Broken gauge symmetry $M \sim TeV$
  - Strongly coupled to 4th gen. $\Rightarrow \langle \bar{F}_4 F_4 \rangle \neq 0$
- Fermion masses: higher dimensional operators like

$$\frac{x_{ij}}{\Lambda^2} \; \bar{f}^i_L f^j_R \; \bar{U}_R U_L$$

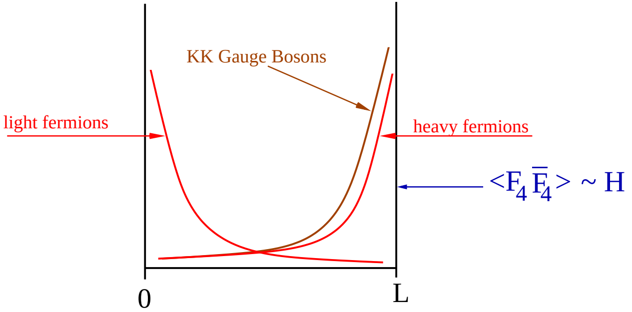
Fourth Generation in a Warped Extra Dimension

Complete Model of 4G Condensation: (G.B. Da Rold '07)

- Compact extra dimension with AdS metric
- Bulk gauge theory: $SU(3) \times SU(2)_L \times SU(2)_R \times U(1)_X$
- Four generations of SM fermions:
  - UV-localized light SM fermions
  - Q^3, $t_R \sim$ IR-localized
  - IR-localized 4th Generation

Flavor Violation in AdS_5 Models

KK Gauge Bosons couple stronger to heavier fermions



$\Rightarrow$ Heavier fermions couple strongly to KK gauge bosons

Strongly Coupled Fourth Generation

Generically we have:

- 4G Fermions strongly coupled to $O(1)$ TeV gauge bosons
  - 4G quarks U_4, D_4 strongly coupled to color-octet (e.g. $G^{(1)}$) $\Rightarrow$ e.g. $\langle \bar{U}_4 U_4 \rangle$ and EWSB
  - 4G leptons N_4, E_4 strongly coupled to color-singlet $O(1)$ TeV gauge bosons e.g. $\gamma^{(1)}, Z^{(1)}, \ldots$
- A heavy Higgs: $m_h \gtrsim m_4^{\mathrm{dyn.}} \simeq 600\ \mathrm{GeV}$

Fourth Generation at the LHC

At the LHC: (G.B., Da Rold, Eboli, Haluch, Matheus, '08,'09)

Quarks

- Easy to produce 4G quarks U_4, D_4 via QCD. Early discovery.
- *Not Possible* to see color-octet (KK gluon) contribution. Too small/broad.

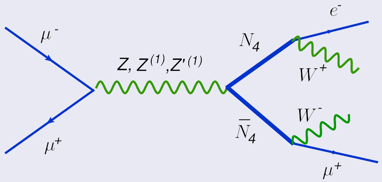
Leptons

- Contributions from strongly coupled gauge bosons are larger ($\sim 1/3$)
- $\sigma(pp \to N_4 \bar{N}_4 \to e^\pm \mu^\mp W^+ W^-) \simeq O(\text{few})\ fb$. Hard ($\gtrsim 100\ fb^{-1}$) to see above backgrounds.
- $pp \to E_4^+ E_4^- \to W^+ W^- \nu \bar{\nu}$: Larger cross section, but even harder.

The Fourth-Generation at a Muon Collider

Consider $\sqrt{s} = 3$ TeV

N_4 pair production



For $m_{N_4} = 300$ GeV:

- $\sigma(\mu^+\mu^- \to N_4\bar{N}_4)_{\mathrm{SM}} = 2.7\ fb\ (0.3R)$
- Including massive vector bosons with $M_V = 2.5$ TeV $\sigma(\mu^+\mu^- \to N_4\bar{N}_4) = 16\ fb\ (1.7R)$

The Fourth-Generation Leptons at a Muon Collider

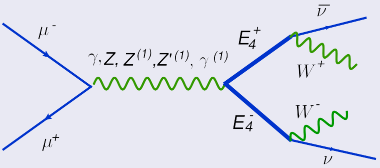
N_4 pair production (cont.)

- E.g. Decaying the W's to jets we have (with 20° cut) $\sigma(\mu^+\mu^- \to N_4\bar{N}_4 \to e^\mp\mu^\pm W(jj)W(jj)) = 1.4\ fb\ (0.15R)$
- Assuming $\mathcal{L} = 10^{34}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1} = 100\,\mathrm{fb}^{-1}/\mathrm{year}$

  $$\Rightarrow O(100)\ \text{events/year}$$
- If only the SM contributes, $10's$ events/year
- Physics backgrounds are manageable

The Fourth-Generation Leptons at a Muon Collider

$E_4^{\pm}$ pair production



- Larger cross section: for $m_{E_4} = 300$ GeV, $\sigma(\mu^+\mu^- \to E_4^+ E_4^-) \simeq 38 fb$
- Assuming $\Delta_m \equiv |m_{E_4} - m_{N_4}| < M_W$, 2-body decays dominate over 4G transition $E_4 \leftrightarrow N_4$
- Pure SM contributions:

$$\sigma(\mu^+\mu^- \to E_4^+ E_4^-)_{\rm SM} \simeq 4 fb$$

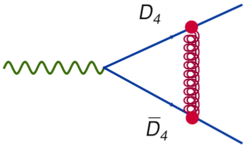
The Fourth-Generation Leptons at a Muon Collider

$E_4^{\pm}$ pair production (cont.)

- Assuming both W's decay to jets
  $\sigma(\mu^+\mu^- \to E_4^+ E_4^- \to W(jj)W(jj)\nu\bar{\nu}) \simeq 17 fb$
- $\Rightarrow 1000's$ events/year
- Harder backgrounds, no reconstruction of E_4

Fourth Generation Quarks

- Even larger cross sections but already seen at LHC
  E.g. $\sigma(\mu^+\mu^- \to D_4\bar{D}_4 \to t\bar{t}W^+W^-) \simeq 25\,\mathrm{fb}$
  ($\simeq 4\,\mathrm{fb}$ if only SM)
- Can we "see" their interaction to the color-octet (KK gluon) via threshold effects ?



It implies scanning at around $2m_{D_4} \simeq 1$ TeV

Summary/Outlook

- Existence of 4th Generation suggests special role in EWSB
- Easy to see 4G at LHC, hard to see new strong interaction
- Also hard to see lepton sector
- Lepton sector and strongly coupled heavy vector bosons at μ collider with $\sqrt{s} = 3$ TeV, $100\,\mathrm{fb}^{-1}$/year
- Need serious simulation of physics backgrounds
- Compute threshold effect from color-octet (KK gluon) interaction in quark pair production