Coarse Deconstruction of AdS_5

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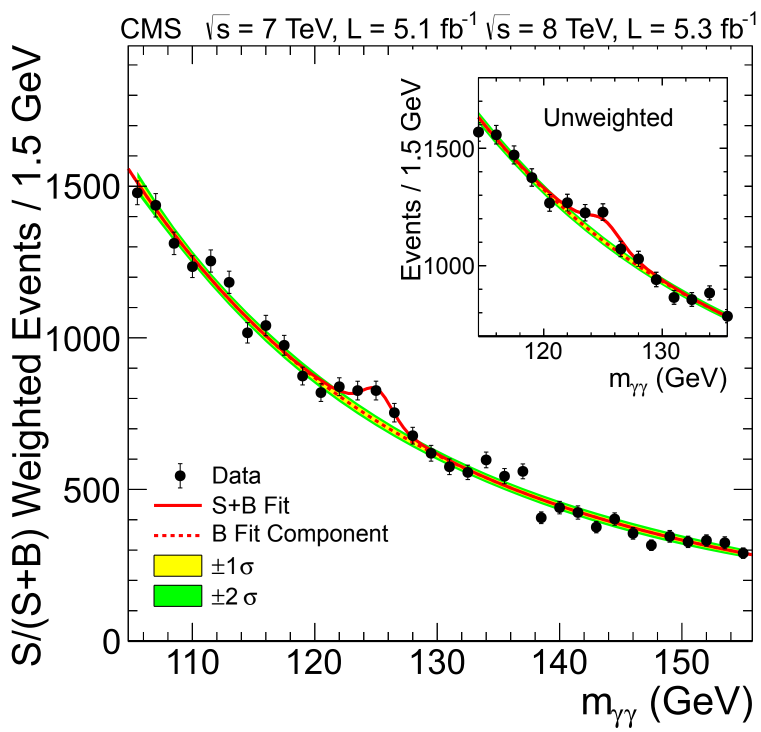
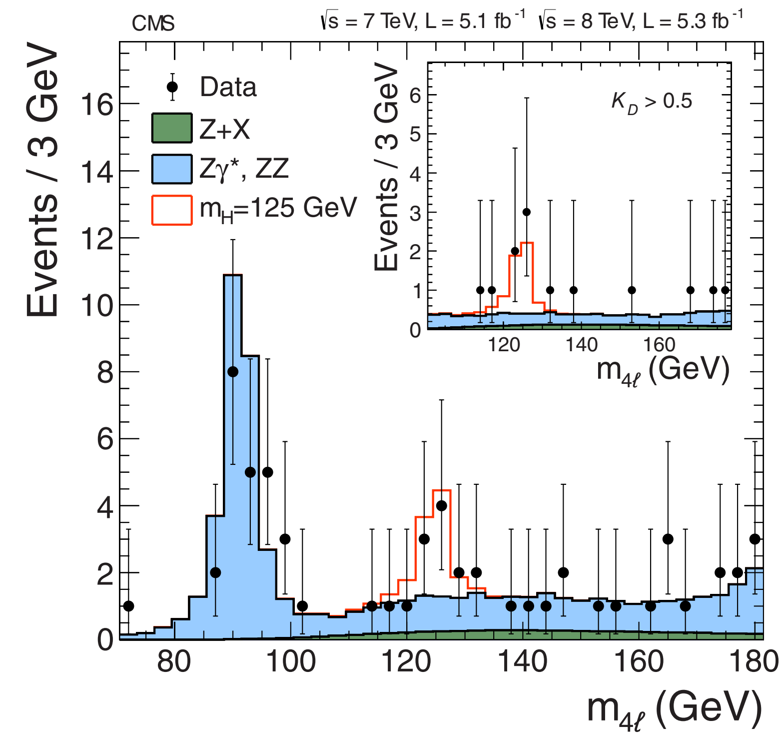
Outline

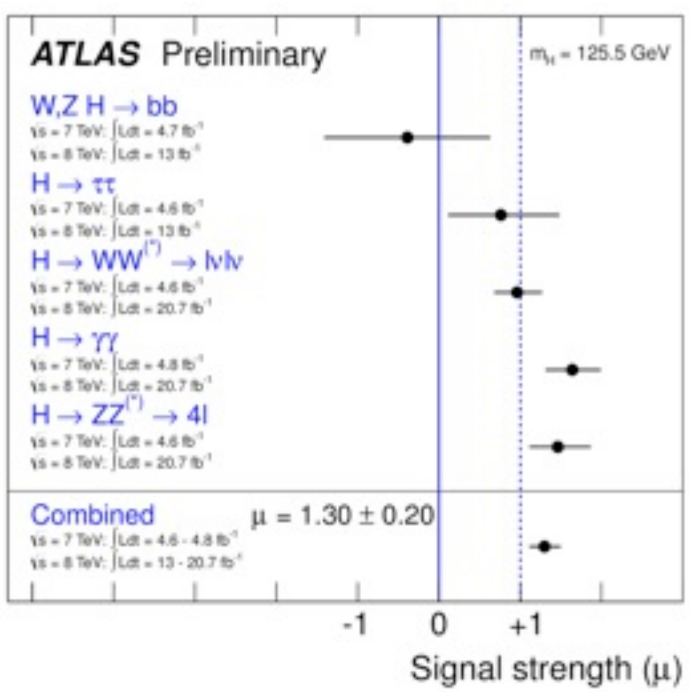
- Introduction/Motivation
- Deconstruction of AdS_5 : quiver theories of EWSB and fermion masses
- Phenomenology:
  - Flavor physics and EWPC
  - Bounds on Resonances
  - The (pNGB) Higgs
- Conclusions/Outlook

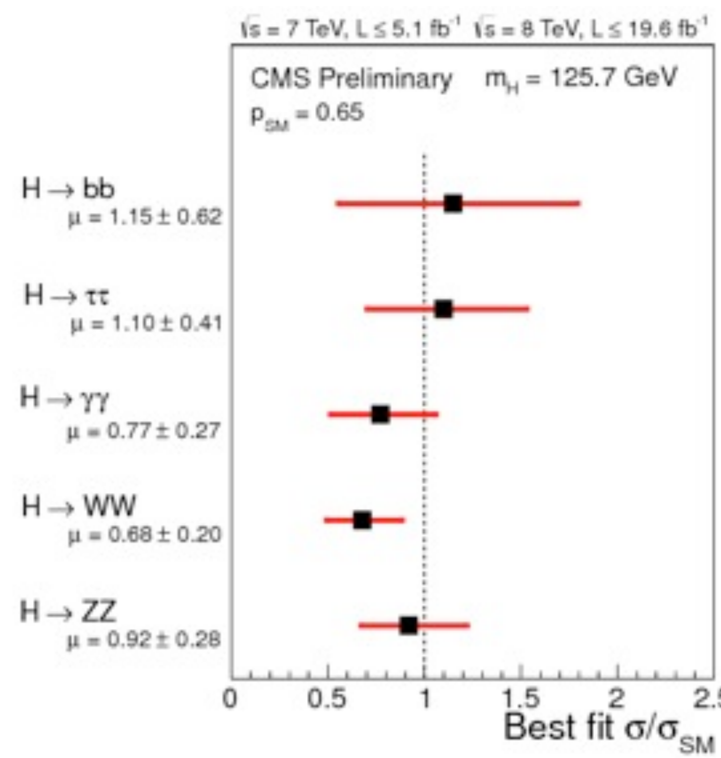
The Standard Model

<u>The Standard Model is now complete</u> $m_h \simeq 125\ \mathrm{GeV}$









Separation of Scales

Higgs is light compared to UV cutoff

If Higgs is a composite from an IR strong sector

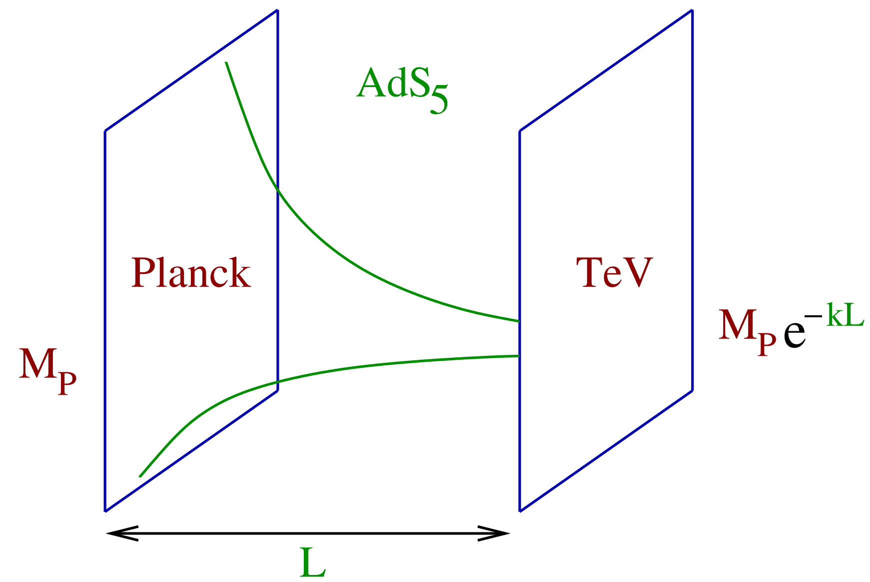
Why is $m_h \ll O(1)\ \mathrm{TeV}$?

Higgs should be a pNGB: scale of new physics is separated by $O(4\pi)$ from m_h

How do we model strong dynamics separating m_h from the UV and even from the TeV scale

Separation of Scales in AdS_5

- One compact extra dimension. Non-trivial metric induces a small energy scale from a high one. (Randall, Sundrum '99)



- Geometry of extra dimension generates exponential hierarchy

$$\Lambda_{\rm TeV} \sim M_{\rm Planck}\, e^{-k\,L}$$

- Higgs must be IR localized to solve HP.

E.g. Gauge-Higgs unification $\longleftrightarrow$ Composite Higgs models

Fermion Fields in AdS Bulk

- Massive fermion in curved 5D space

$$S_f = \int d^4x \, dy \, \sqrt{g} \left\{ \frac{i}{2} \bar{\Psi} \hat{\gamma}^M \left[\mathcal{D}_M - \overleftarrow{\mathcal{D}}_M \right] \Psi - \, M_f \, \bar{\Psi} \Psi \right\}$$

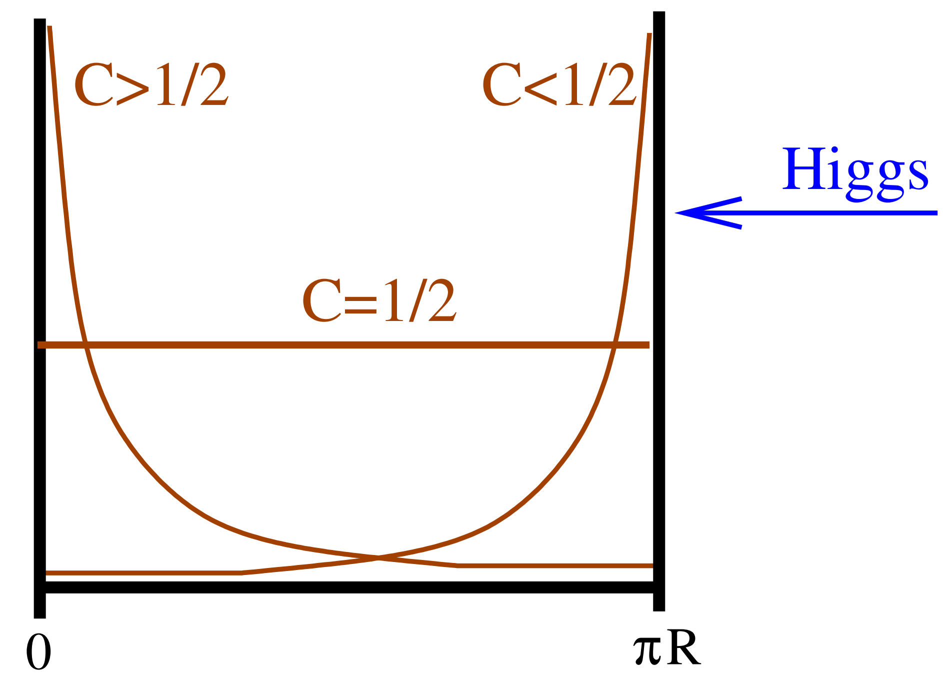
- To be natural $M_f \simeq O(1) k$

$M_f \equiv c_f \, k$ with $c_f \simeq O(1)$

- The parameter c_f determines the localization of the ZM fermion

Fermion Fields in AdS Bulk

O(1) flavor breaking in bulk can give fermion mass hierarchy



- Fermions localized near TeV brane have O(1) Yukawas
- Those localized near the Planck brane have highly suppressed Yukawas
- Flavor violation at tree level $\Longrightarrow$ stringent bounds

Hierarchies of Scales and Fermion Masses

AdS_5 is a representation of a strongly coupled 4D theory

Can we build a 4D representation
with the good features of AdS_5 ?

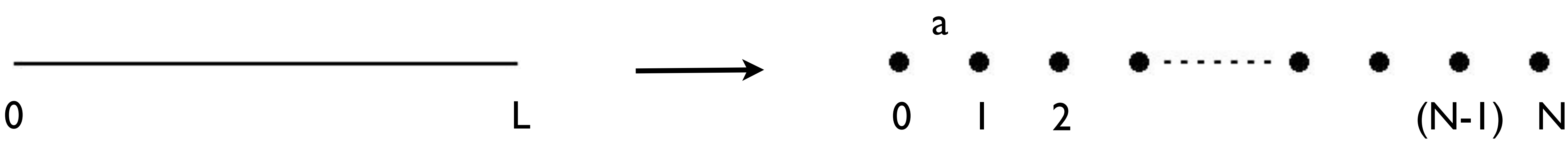
- Large scale separation
- Fermion hierarchies with small flavor violation
- A light Higgs + heavy new physics

Deconstructing AdS5

Gauge theory in AdS_5 (Randall, Shadmi, Weiner and Falkowski, Kim '02)

$$S_5 = \int d^4x \int_0^L dy \sqrt{g} \left[-\frac{1}{2\, g_5^2} \mathrm{Tr}[F_{MN}^2] + \cdots \right]$$

Discretize the extra dimension



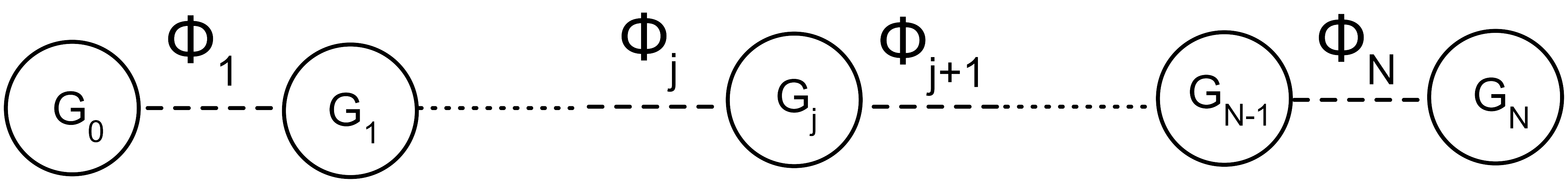
with $L = aN$

Deconstructing AdS$_5$

$$S_4 = \int d^4x \left\{ -\sum_{j=0}^{N} \frac{1}{2\,g_j^2}\,\mathrm{Tr}\left[F^j_{\mu\nu}F^{j\,\mu\nu}\right] + \sum_{j=1}^{N} \frac{1}{2}\,\mathrm{Tr}\left[v_j^2\,\left(A^j_\mu - A^{j-1}_\mu\right)^2\right] \right\}$$

Equivalent to (N+1) Gauge theories $F^j_{\mu\nu}$

N bi-fundamental scalar fields Φ_j



Quiver 4D Theory

Gauge Couplings

S_4 reproduces continuum limit if

$$g_0(v) = g_1(v_1) = \cdots = g_j(v_j) = g_{j+1}(v_{j+1}) = \cdots \equiv g$$

$$\Rightarrow \begin{cases} \text{matches the continuum} \\ \text{mimics (quasi) conformal behavior} \end{cases}$$

Quiver Theories

Link field Φ_j transforms as $(F, \bar{F})$ under $G_{j-1} \times G_j$

Breaks $G_{j-1} \times G_j \rightarrow G^D_{j-1,j}$

$$\Phi_j = \frac{v_j}{\sqrt{2}} e^{\sqrt{2}\,\pi_j / v_j}$$

To match discretized 5D theory we need

$$\frac{1}{g^2} \leftrightarrow \frac{a}{g_5^2}$$

$$v_j \leftrightarrow \frac{e^{-kaj}}{a}$$

Quiver Theories and Large Hierarchies

- 4D theories with N gauge "sites"

$$S_4 = \int d^4x \left\{ -\sum_{j=0}^{N} \frac{1}{2\,g^2}\,\mathrm{Tr}\left[F^j_{\mu\nu}F^{j\,\mu\nu}\right] + \sum_{j=1}^{N}\frac{1}{2}\,\mathrm{Tr}\left[v_j^2\,\left(A^j_\mu - A^{j-1}_\mu\right)^2\right]\right\}$$

- N Link fields break (N+1) gauge groups to $G^D_{0,\ldots N}$

$$\Rightarrow \begin{cases} \text{1 massless zero-mode} \\ \text{N massive gauge bosons} \end{cases}$$

- Mass Eigenstates :

$$A^{(n)}_\mu = \sum_{j=0}^{N} f^*_{j,n}\,A^j_\mu$$

Quiver Theories and Large Hierarchies

For instance, if we want M_P at UV and M_W at IR

$$k\,a\,N \simeq 35$$

<u>Continuum Limit</u>

$$k \ll \frac{1}{a}$$

$\Longrightarrow$ For $N \gg 35$ we recover AdS_5

Build theories in the coarse limit, small N

Quiver Theories and Large Hierarchies

- Large hierarchy between UV and IR (0 and N sites):

$$v_j = e^{-kaj} v \qquad \Longrightarrow \qquad \text{large } \; k\,a\,N$$

- Define $\quad q \equiv e^{-k\,a}$

Continuum limit $\;a \to 0, \quad N \to \infty$

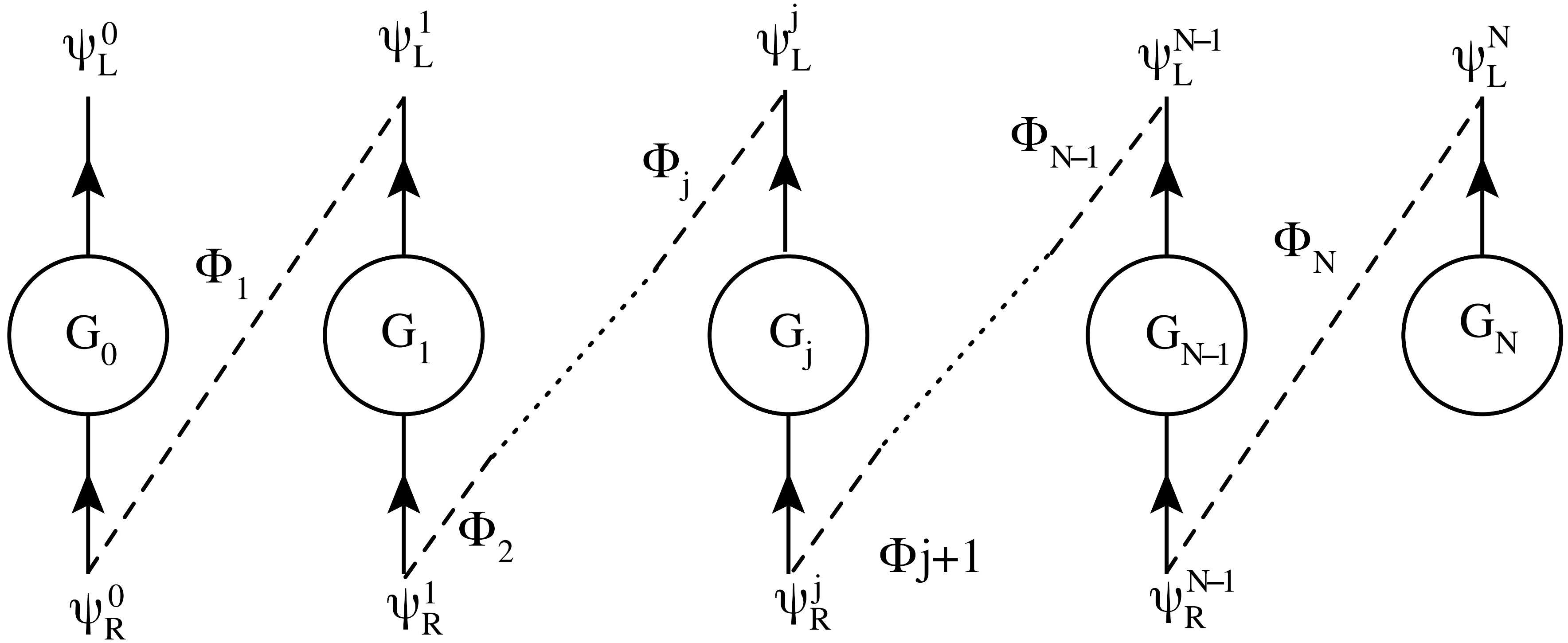
$$\Longrightarrow \qquad q \to 1_{-}$$

- Ordered vacua

$$v_j = q^j\, v$$

Fermion Masses in FHQT

(Bai, GB, Hill '09, De Curtis, Redi, Tesi '12)



E.g.:left-handed zero mode

$$S_f = \int d^4x \sum_{j=0}^{N} \left\{ \bar{\psi}_L^j i\not{D}_j \psi_L^j + \bar{\psi}_R^j i\not{D}_j \psi_R^j - (\mu_j \bar{\psi}_L^j \psi_R^j + \lambda_j \bar{\psi}_R^{j-1} \Phi_j \psi_L^j + \text{h.c.}) \right\}$$

Tuesday, July 9, 2013

Fermion Masses in FHQT

- Diagonalization of fermion masses: 1 zero mode + excited states

$$\chi^{(n)}_{L,R} = \sum_{j=0}^{N} h^{*j,n}_{L,R}\, \psi^{j}_{L,R}$$

- Equations of Motion

$$\begin{aligned}
(\mu_j^2 + \frac{\lambda_j^2\, v_j^2}{2} - m_n^2)\, h_L^{j,n} - \frac{\lambda_j\, v_j}{\sqrt{2}}\mu_{j-1}\, h_L^{j-1,n} - \frac{\lambda_{j+1}\, v_{j+1}}{\sqrt{2}}\mu_j h_L^{j+1,n} &= 0 \\
(\mu_j^2 + \frac{\lambda_{j+1}^2\, v_{j+1}^2}{2} - m_n^2)\, h_R^{j,n} - \frac{\lambda_j\, v_j}{\sqrt{2}}\mu_j\, h_R^{j-1,n} - \frac{\lambda_{j+1}\, v_{j+1}}{\sqrt{2}}\mu_{j+1}\, h_R^{j+1,n} &= 0
\end{aligned}$$

$\Rightarrow$ difference eqns. for $h^{j,n}$

Fermion Zero-Modes

- For $m_n = 0$

$$\mu_j\, h_L^{j,0} + \frac{\lambda_{j+1}}{\sqrt{2}}\, v_{j+1}\, h_L^{j+1,0} = 0$$

$$\mu_j\, h_R^{j,0} + \frac{\lambda_j}{\sqrt{2}}\, v_j\, h_R^{j-1,0} = 0$$

Freedom in the choice of μ_j's and λ_j's

$\Longrightarrow$ localize zero-mode fermions in quiver

$$\sqrt{2}\,\frac{\mu_j}{v\,\lambda_{j+1}} \equiv -q^{j+c_L+1/2} \qquad \Longrightarrow \qquad \frac{h_L^{j+1,0}}{h_L^{j,0}} = q^{c_L-1/2}$$

$$\sqrt{2}\,\frac{\mu_j}{v\,\lambda_j} = -q^{j+c_R+1/2} \qquad \Longrightarrow \qquad \frac{h_R^{j,0}}{h_R^{j-1,0}} = q^{-(c_R+1/2)}$$

Fermion Zero-Modes

Localization parameters $c_L, \ c_R$

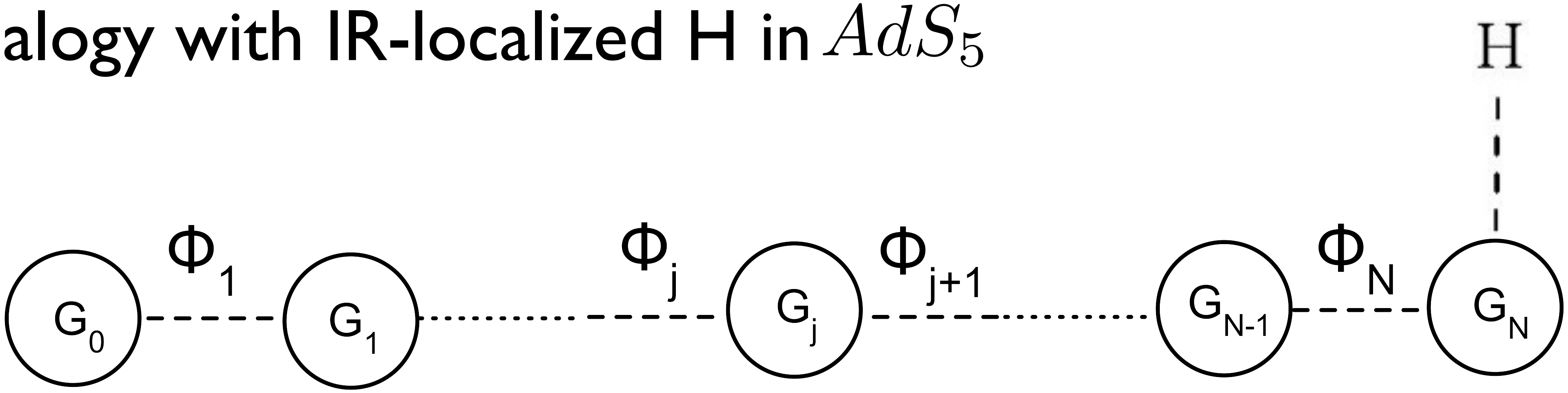
how much of each $\psi^{,j}_{L,R}$ is the zero mode

It determines $\begin{cases} \text{Couplings to gauge excited states } A_\mu^{(n)} \\ \text{Couplings to Higgs} \end{cases}$

Higgs Sector in Quiver Theories

Need Higgs mostly close to Nth site

Analogy with IR-localized H in AdS_5



Dynamical origin of N-site localization:

H is remnant of breaking with "defective" G_0 and G_N

E.g.: $(SU(2) \times U(1))_0 \times \cdots SU(3)_j \cdots (SU(2) \times U(1))_N$

$\Longrightarrow$ H is a pNGB similar to composite H models

Phenomenology of Quiver Theories

- Flavor Violation: can we build models with good FV properties ?
- EWPT: Compatibility with S and T
- Higgs sector
- Current direct bounds from LHC
- Predictions for the LHC

Flavor Violation

- Tree-level FV from couplings of ZM fermions to excited gauge bosons

- Compute coupling to first excited state of gauge bosons

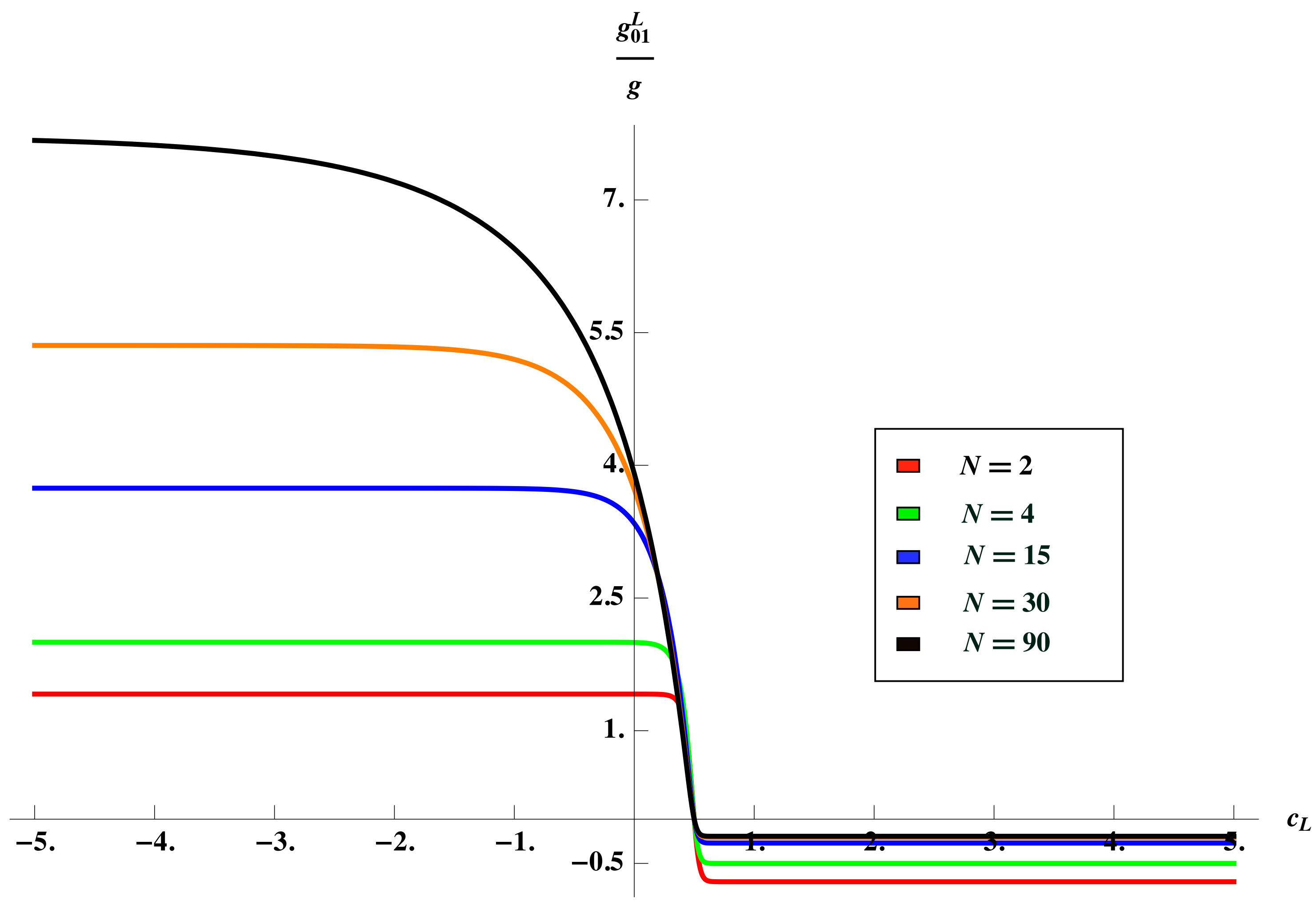
$$g^{01}_{L,R} \;\; \bar{\chi}^{(0)}_{L,R} \gamma^{\mu} A^{(1)}_{\mu} \, \chi^{(0)}_{L,R}$$

with

$$g^{01}_{L,R} = \sum_{j=0}^{N} g_j \, \left| h^{j,0}_{L,R} \right|^2 \, f_{j,1}$$

Flavor Violation at Tree Level

Coupling of first
gauge excitation
to zero-mode fermion

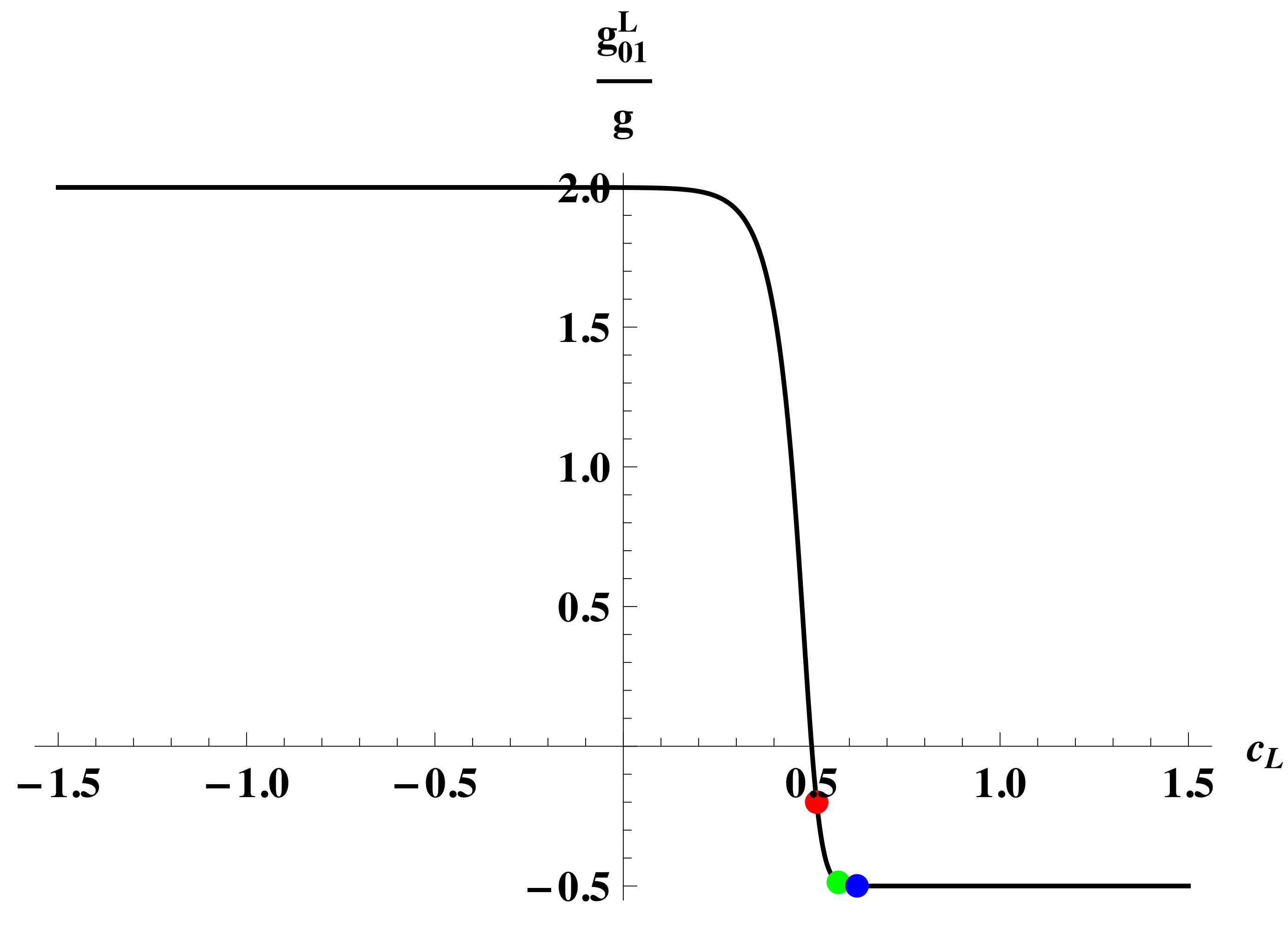


Flavor Violation

Tree-level couplings of ZM fermions to 1st excited state

N=4 (5 sites)

Left-handed

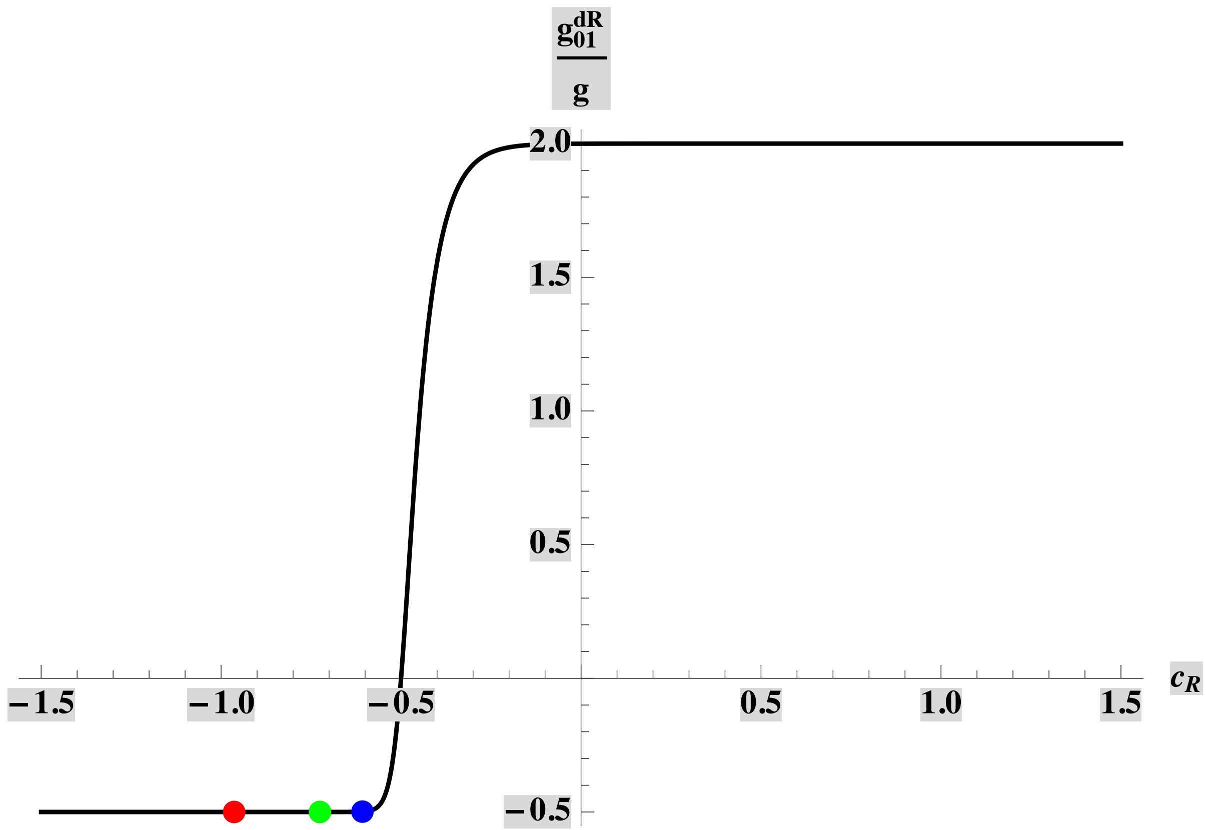


Flavor Violation

Tree-level couplings of ZM fermions to 1st excited state

N=4

Right-handed down



D_R sector is nearly universal

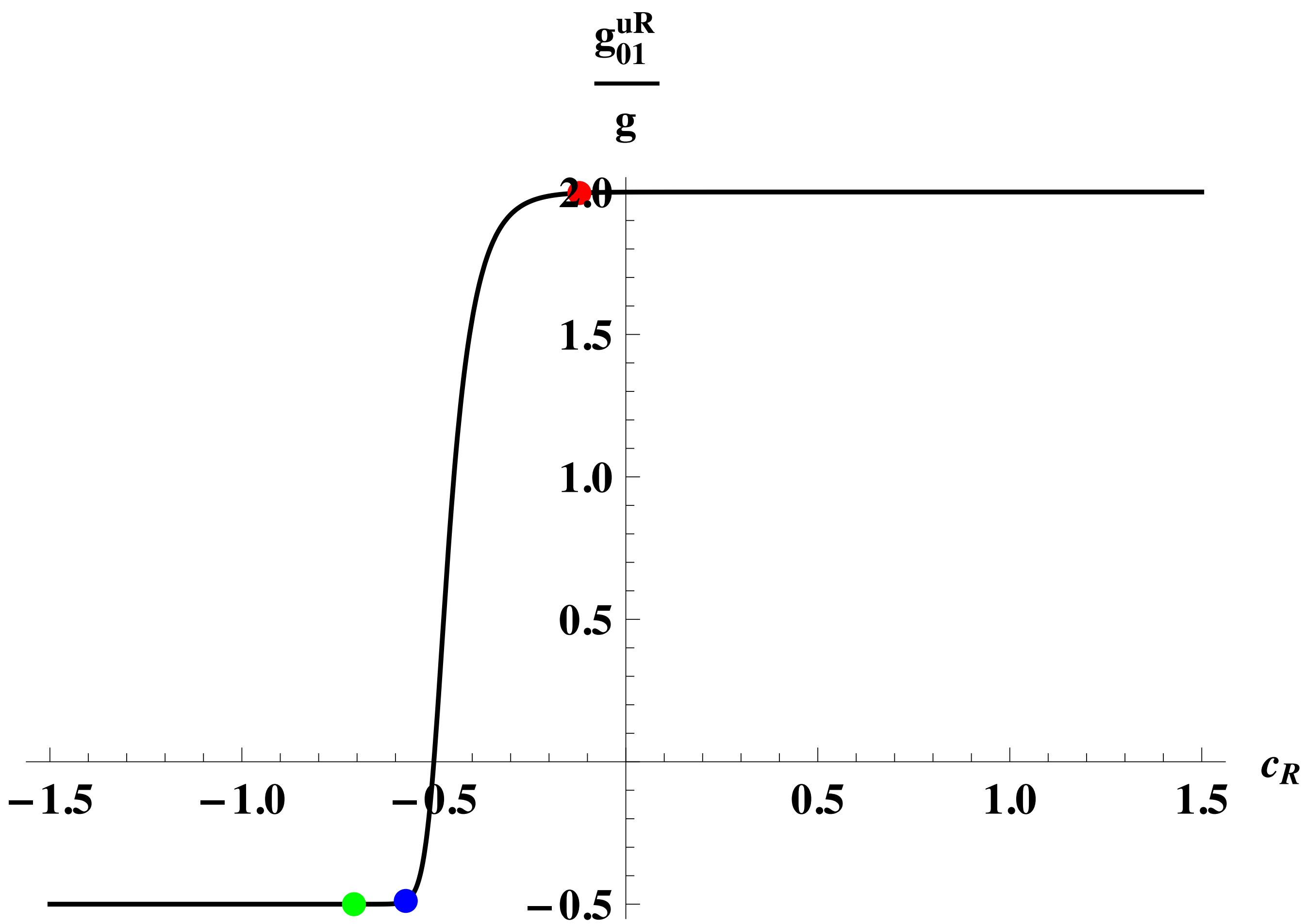
$\Longrightarrow$ no conflict with $K^0\bar{K}^0,\ B^0\bar{B}^0$

Flavor Violation

Tree-level couplings of ZM fermions to 1st excited state

N=4

Right-handed up



$\Longrightarrow$ largest flavor violation in the up sector

Flavor Violation Bounds

Bounds from $\Delta F = 2$ assuming $SU(3)_c$ propagates in quiver

Parameter	95% allowed range (GeV^{-2})	Lower limit on Λ (TeV) for arbitrary NP	Bound on Color-octect Mass in FHQT (TeV)
$\mathrm{Re}C_K^1$	$[-9.6, 9.6] \cdot 10^{-13}$	$1.0 \cdot 10^3$	0.2
$\mathrm{Re}C_K^4$	$[-3.6, 3.6] \cdot 10^{-15}$	$17 \cdot 10^3$	0.1
$\mathrm{Re}C_K^5$	$[-1.0, 1.0] \cdot 10^{-14}$	$10 \cdot 10^3$	0.1
$\mathrm{Im}C_K^1$	$[-2.6, 2.8] \cdot 10^{-15}$	$1.9 \cdot 10^4$	2.6
$\mathrm{Im}C_K^4$	$[-4.1, 3.6] \cdot 10^{-18}$	$49 \cdot 10^4$	3.0
$\mathrm{Im}C_K^5$	$[-1.2, 1.1] \cdot 10^{-17}$	$29 \cdot 10^4$	1.0
$\lvert C_D^1 \rvert$	$< 7.2 \cdot 10^{-13}$	$1.2 \cdot 10^3$	1.0
$\lvert C_D^4 \rvert$	$< 4.8 \cdot 10^{-14}$	$4.6 \cdot 10^3$	2.9
$\lvert C_D^5 \rvert$	$< 4.8 \cdot 10^{-13}$	$1.4 \cdot 10^3$	0.5
$\lvert C_{B_d}^1 \rvert$	$< 2.3 \cdot 10^{-11}$	$0.21 \cdot 10^3$	0.3
$\lvert C_{B_d}^4 \rvert$	$< 2.1 \cdot 10^{-13}$	$2.2 \cdot 10^3$	0.3
$\lvert C_{B_d}^5 \rvert$	$< 6.0 \cdot 10^{-13}$	$1.3 \cdot 10^3$	0.1
$\lvert C_{B_s}^1 \rvert$	$< 1.1 \cdot 10^{-9}$	30	0.1
$\lvert C_{B_s}^4 \rvert$	$< 1.6 \cdot 10^{-11}$	250	0.1
$\lvert C_{B_s}^5 \rvert$	$< 4.5 \cdot 10^{-11}$	150	0.03

UTFit collaboration

$M_{G^{(1)}}$

Flavor Violation Bounds

All flavor bounds satisfied for $M_1 > 3 \text{ TeV}$

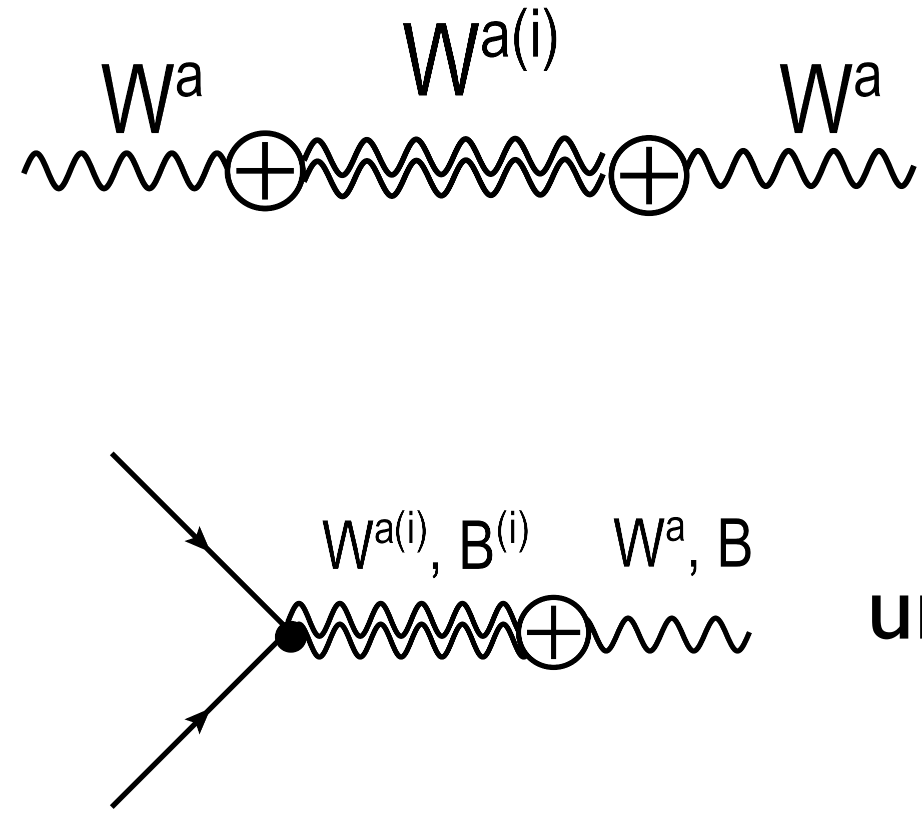
Bounds weaker if $SU(3)_c$ does not propagate in quiver

Electroweak Precision Bounds

In a generic model w.o. custodial symmetry

E.g.: $[SU(2) \times U(1)]^{N+1}$ i.e. the SM in the quiver

Leading contributions



exchange

universal vertex shift

Electroweak Precision Bounds

Tree-level contributions to S and T

E.g.: N=4

$$\left.\begin{aligned} S &\simeq 0.16 \left(\frac{3\ \mathrm{TeV}}{M_1}\right)^2 \\ T &\simeq 0.15 \left(\frac{3\ \mathrm{TeV}}{M_1}\right)^2 \end{aligned}\right\} \text{OK with fit}$$

- Custodial protection not forced by tree-level contributions to T
- Might be needed at one loop (fermions)

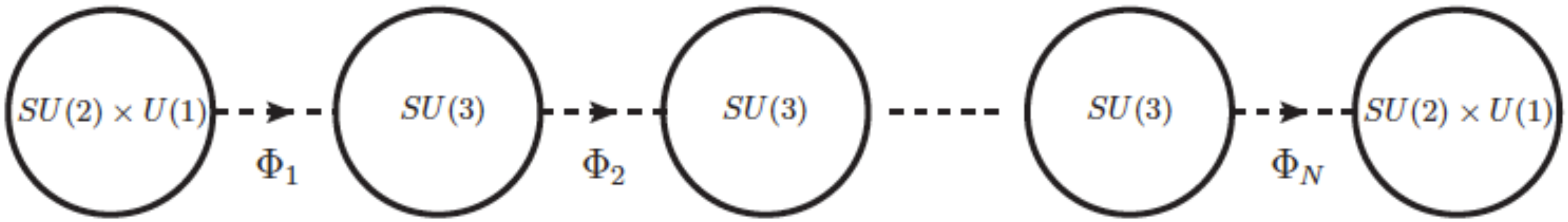
Higgs as a pseudo NGB

(in progress)

Dynamical origin of N-site localization:

H is remnant of breaking with "defective" G_0 and G_N

E.g.: $(SU(2)\times U(1))_0 \times \cdots SU(3)_j \cdots (SU(2)\times U(1))_N$



H: from excess d.o.f. in link fields $\Longrightarrow$ H is a pNGB

Higgs as a pseudo NGB

N-localization:

$$H^a = C \sum_{j=1}^{N} q^{N-j}\, \pi_j^a$$

Extract Higgs h from H^a

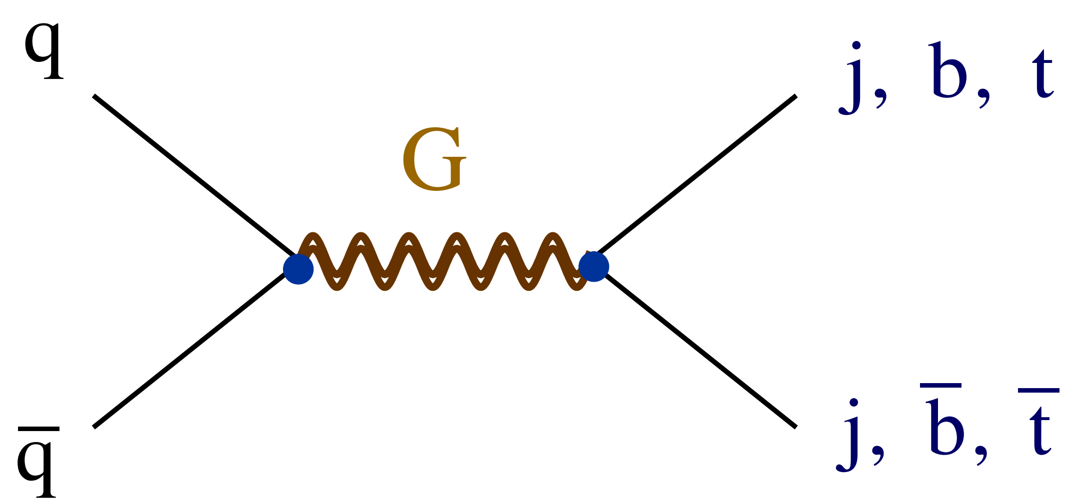
Small N $\Rightarrow h$ very localized close to site N

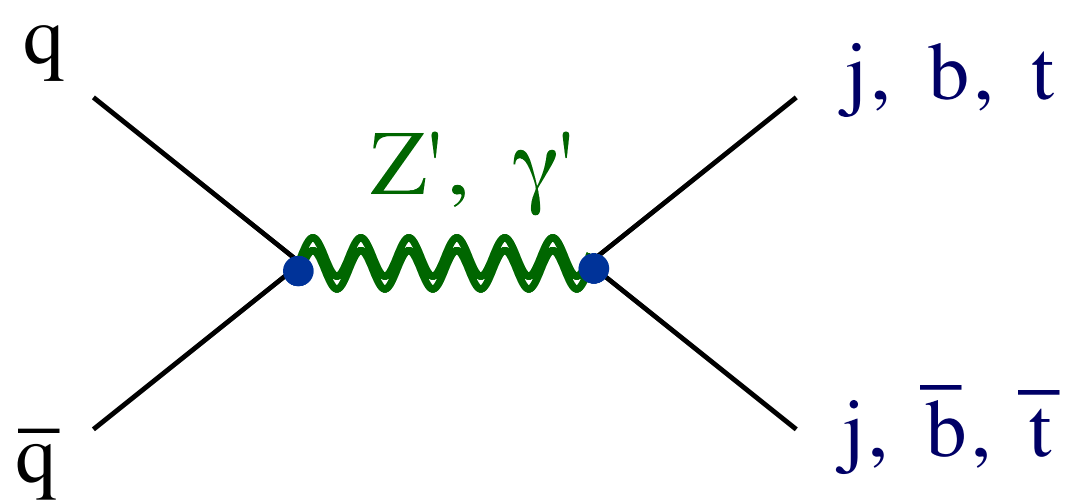
Compute $V_{\rm eff}$ $\longrightarrow$ tuning issues

Phenomenology at the LHC

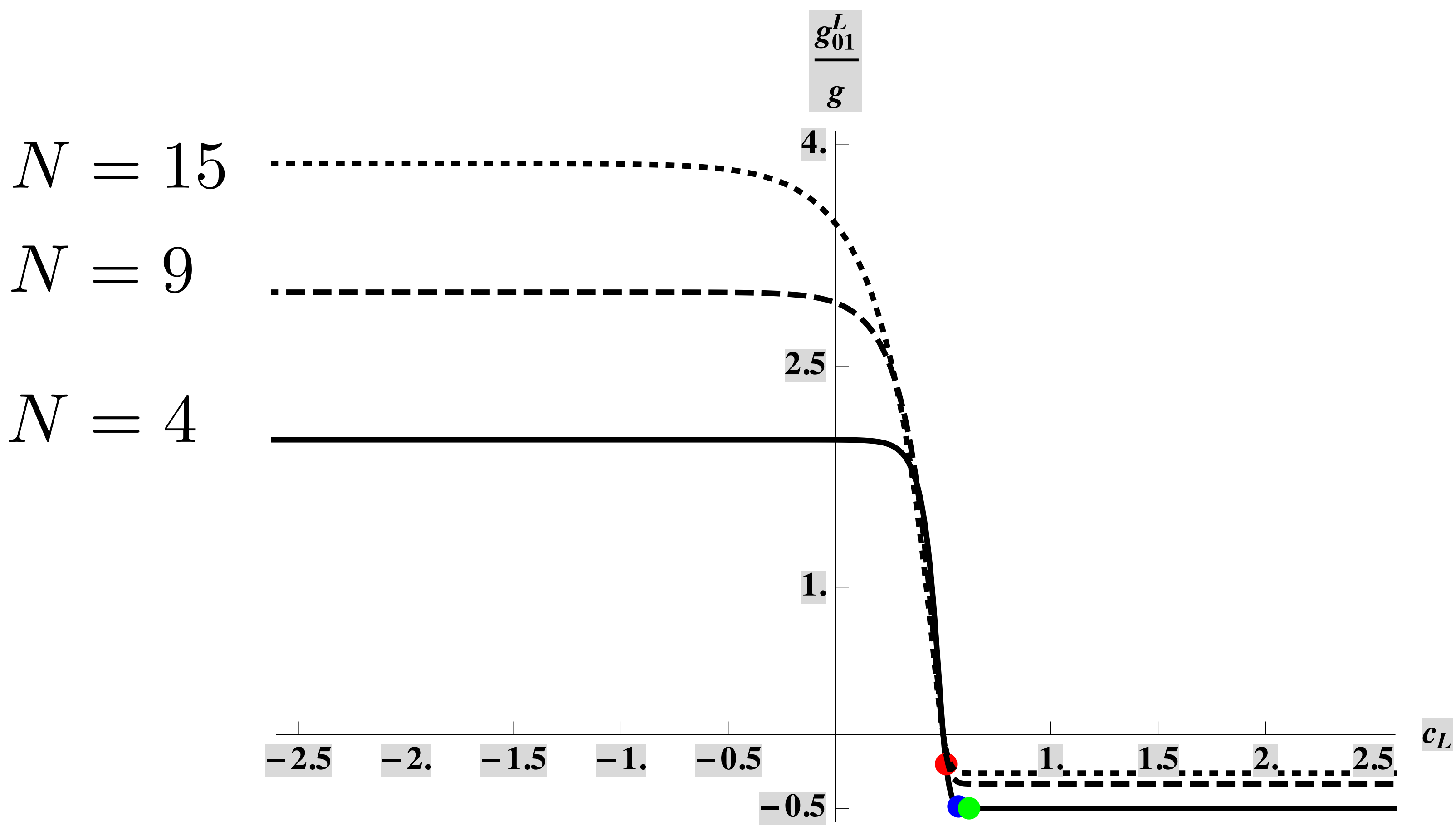
(with N. Fonseca and G. Lichtenstein)

Gauge excitations as s-channel resonances

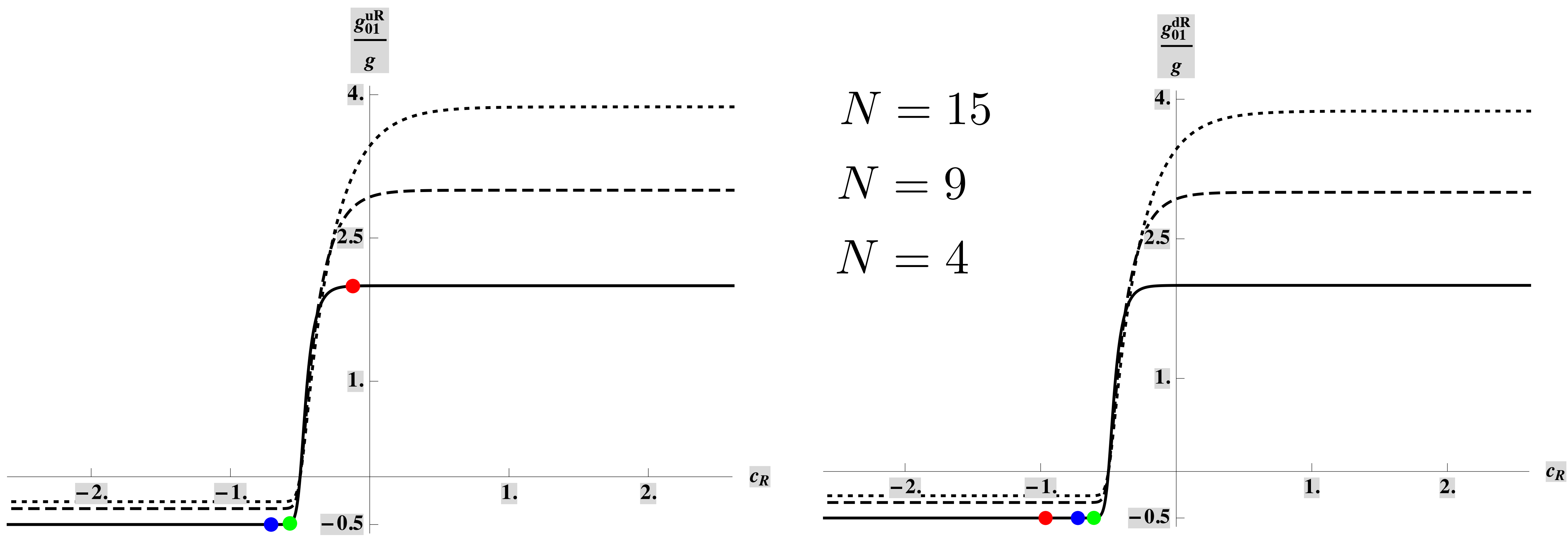




Couplings to Zero-mode Fermions



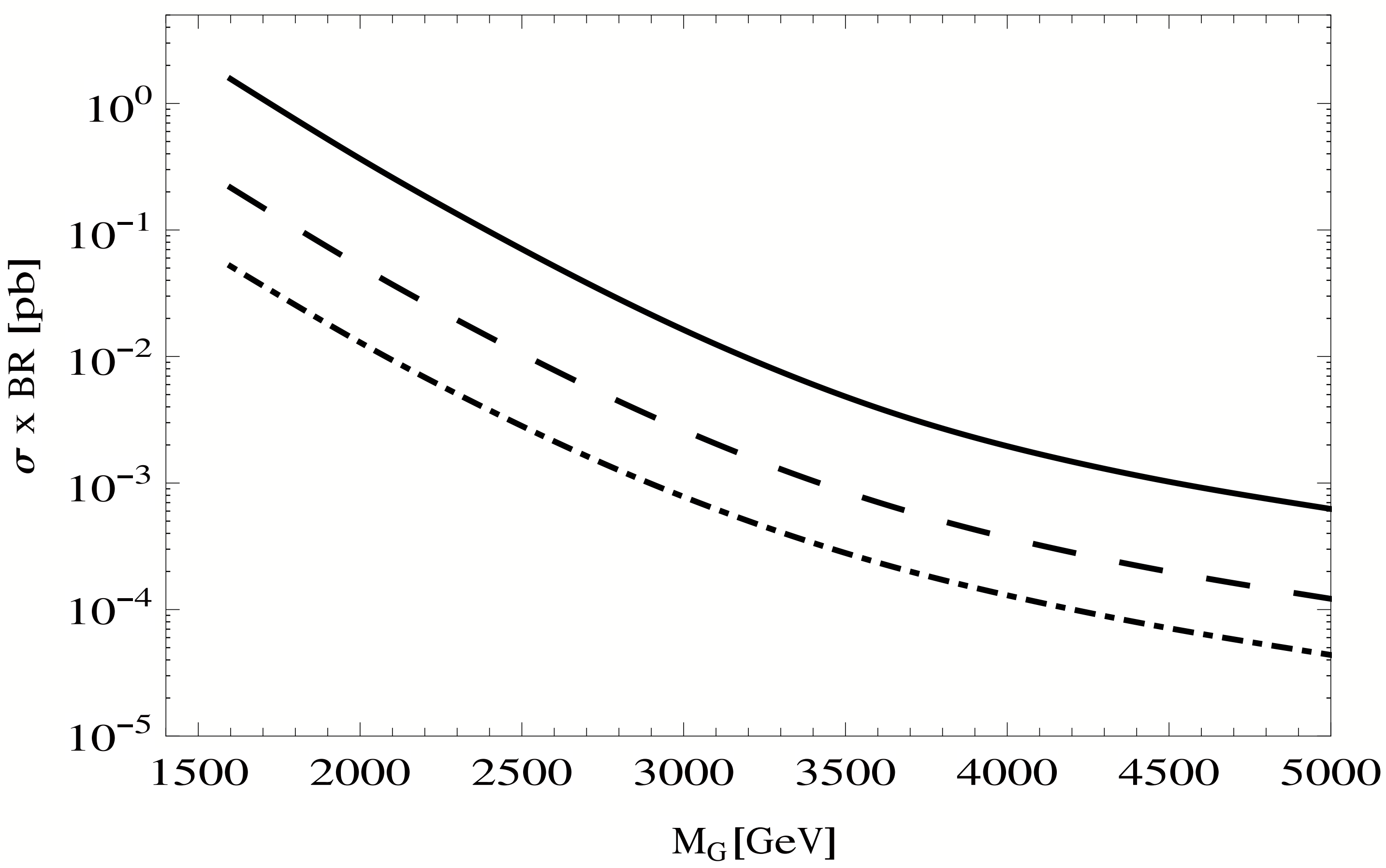
Couplings to Zero-mode Fermions



Resonances at the LHC

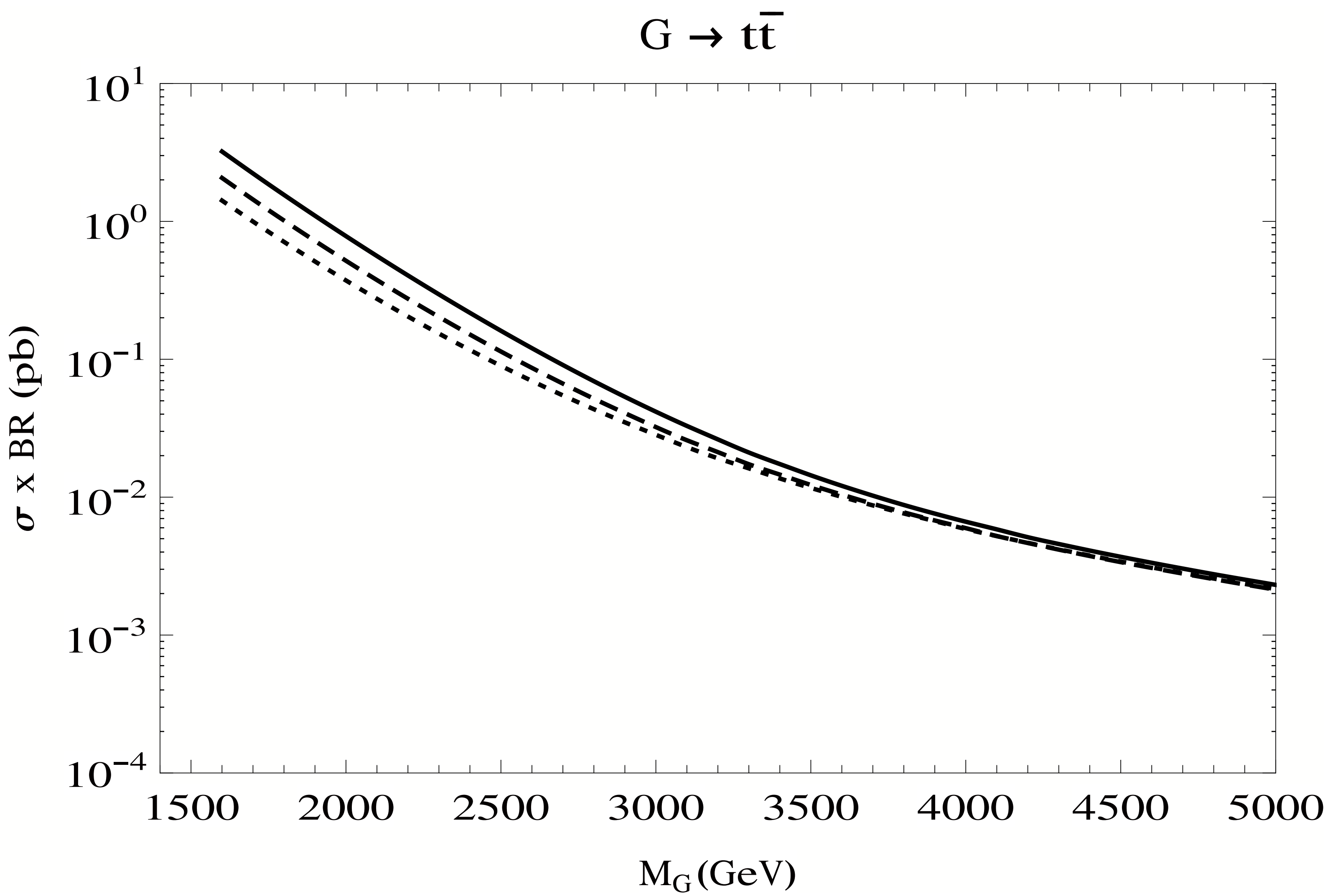
Production of color-octet $\sqrt{s} = 8\ \text{TeV}$

$$G \to jj$$



Resonances at the LHC

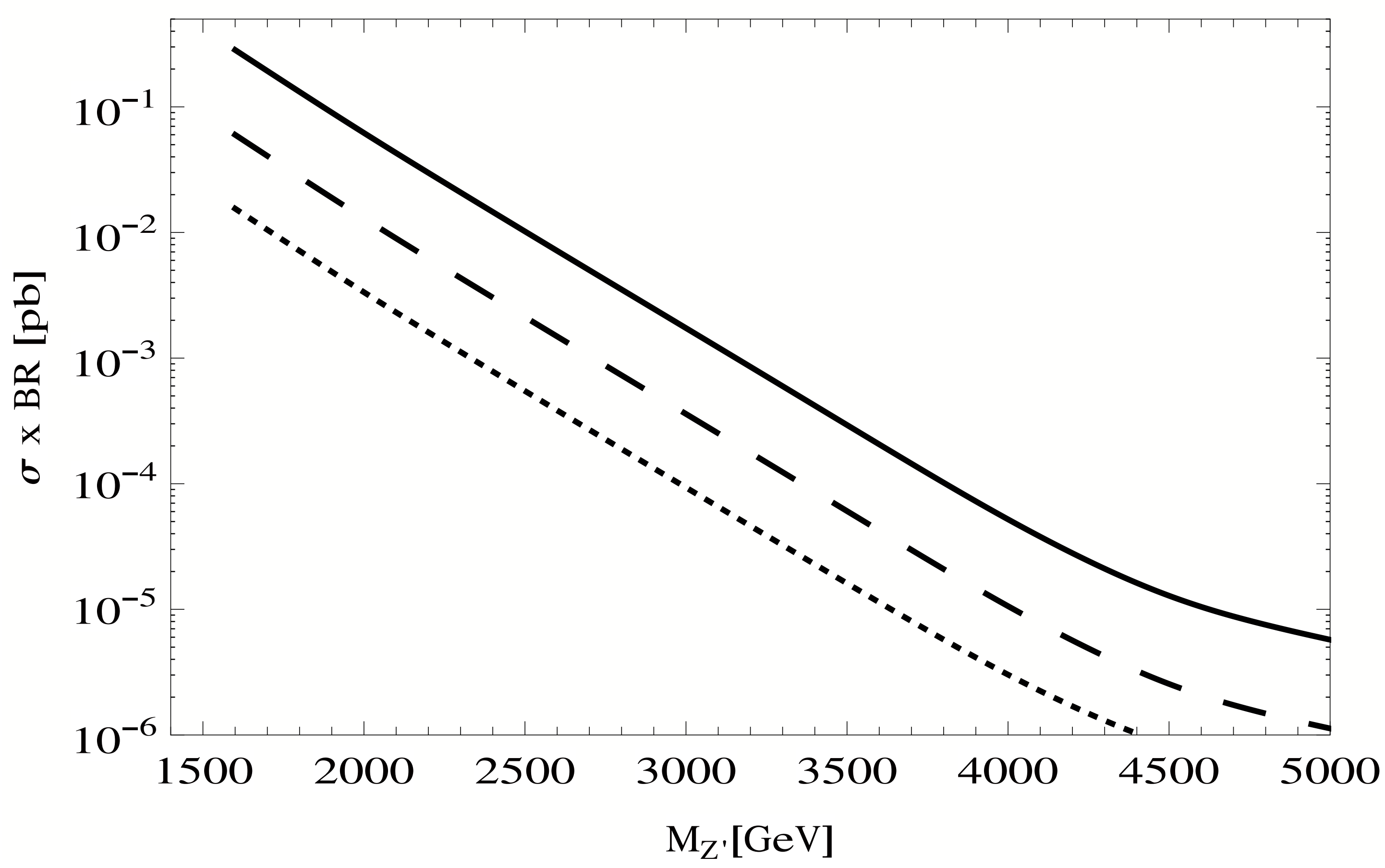
<u>Production of color-octet</u> $\sqrt{s} = 8\ \text{TeV}$



Resonances at the LHC

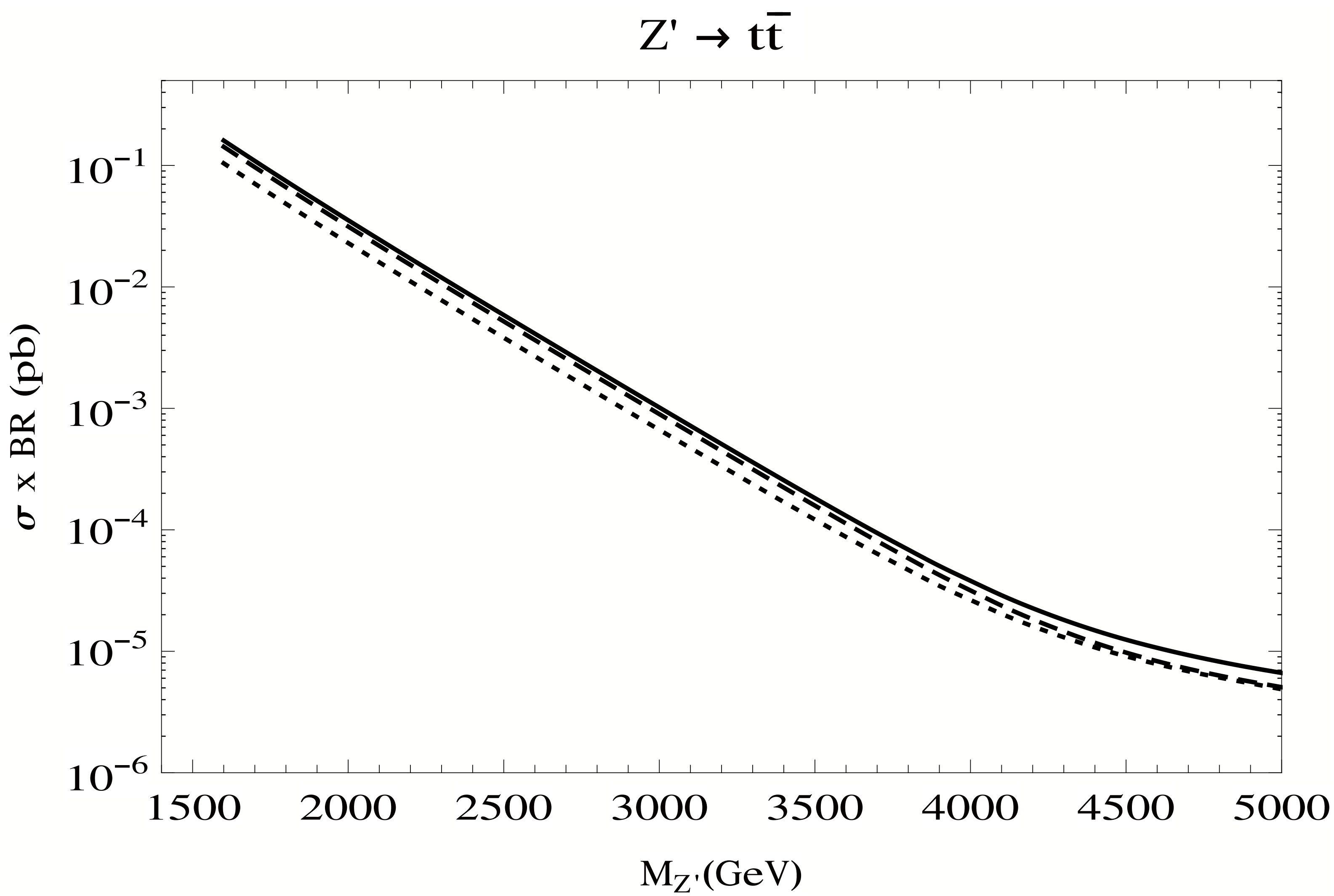
Production of $Z' + \gamma'$ $\sqrt{s} = 8 \text{ TeV}$

$$(Z' + \gamma') \to jj$$

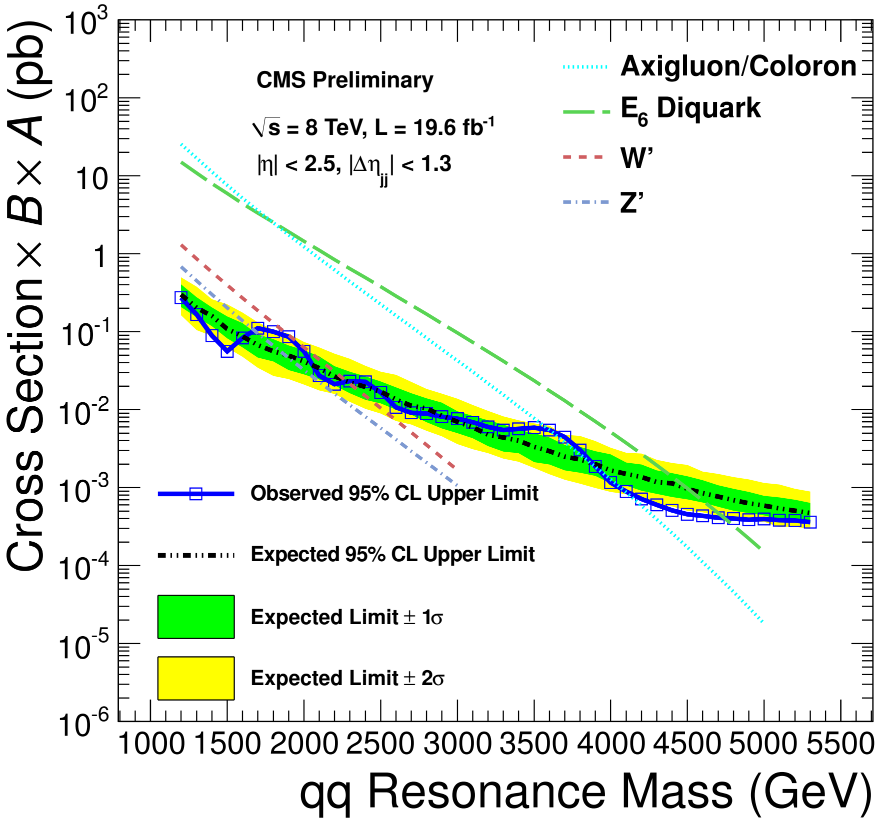


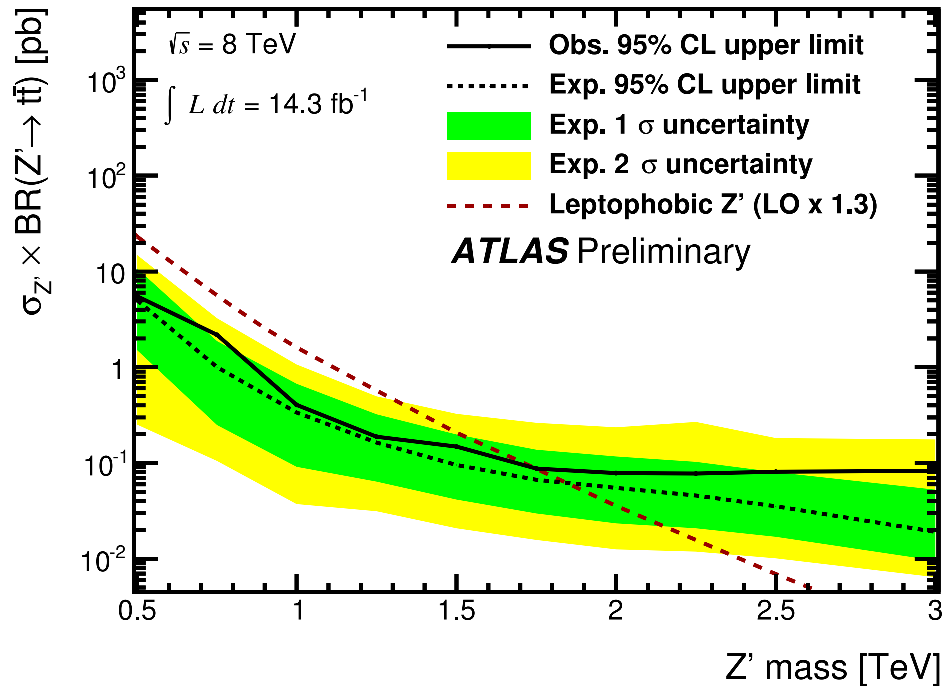
Resonances at the LHC

Production of $Z' + \gamma'$ $\sqrt{s} = 8\ \mathrm{TeV}$



Bounds on FHQT Resonances at the LHC





N	Dijet	$t\bar{t}$
4	3.0	2.7
9	1.6	2.6
15	–	2.5

Color-octet

N	Dijet	$t\bar{t}$
4	1.7	2.1
9	–	2.0
15	–	1.8

$(Z' + \gamma')$

Conclusions and Outlook

- FHQT with small N, complementary to AdS_5 models

- Distinct phenomenology

  Improved flavor violation behavior

  Passes EWPC even w.o. custodial protection (tree-level)

  At the LHC: different cross sections, BR, etc.

- To explore:

  Higgs sector, H as a pNGB (similar to CHM)

  Details of Model building (e.g. lepton sector, ...)