Clean Signals of Little Randall-Sundrum Models at the LHC

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Based on:

- H. D., G. Perez, and A. Soni

Phys.Lett.B665:67-71,2008, arXiv:0802.0203 [hep-ph]

- H. D., S. Gopalakrishna, and A. Soni

Phys.Lett.B686:239-243,2010, arXiv:0908.1131 [hep-ph]

- H. D., T. McElmurry, and A. Soni

Work in progress.

Santa Fe 2010 Summer Workshop

Introduction:

- SM effective theory below scale Λ.
- Precision EW: $\Lambda \gtrsim 10$ TeV; Flavor: $\Lambda \gtrsim 1000$ TeV.
- SM poses unresolved questions:
  - The hierarchy problem: Why is $m_H \ll \Lambda$?

$$\langle H \rangle \sim m_H \sim 10^2 \text{ GeV; QM} \Rightarrow \delta m_H^2 \sim \Lambda^2.$$

  - Flavor puzzle: pattern of fermion masses and mixing.
- Beyond SM: SUSY, strong dynamics, extra dimensions, ...

Warped Hierarchy/Flavor Models

- **Randall-Sundrum Model:** Randall, Sundrum, 1999

A slice of AdS_5.

Flat Planck (UV), TeV (IR) branes.

- **Metric:** $ds^2 = e^{-2ky}\eta_{\mu\nu}\, dx^\mu dx^\nu - dy^2$.

$k \lesssim M_5$ and $y \in [0, \pi r_c]$.

- **Redshift:** $e^{-kr_c\pi}\langle H_5\rangle \sim m_W$; $\langle H_5\rangle \sim k$.

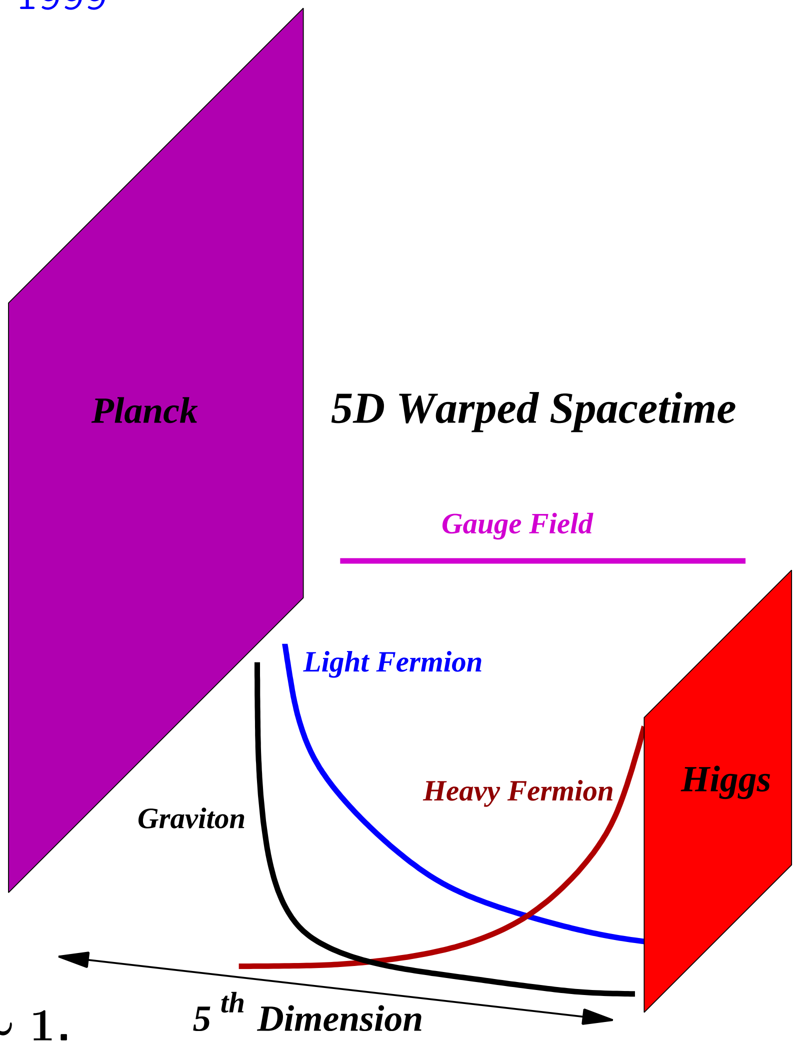
$k \gg 1$ TeV with $kr_c\pi \gtrsim 10$ (Hierarchy).

- **TeV-scale Kaluza-Klein (KK) modes**

Collider signals.

- **Stabilization: radion scalar ϕ.**

$m_\phi \lesssim m_{KK}$ Goldberger, Wise, 1999



- **Localized fermions via 5D masses, $m/k \sim 1$.**
- UV(IR)-localization: Light (heavy) fermion. Grossman, Neubert, 1999
- Large effective cutoff scales for UV-localized flavors. Gherghetta, Pomarol, 2000

Little Randall-Sundrum (LRS) Models

H.D., Perez, Soni, 2008

- RS as a model of **flavor**: $M_5 \sim M_{\text{flavor}}$ viable option.

- TeV $\ll M_{\text{falvor}} \ll \bar{M}_P$ needed to suppress unwanted (FCNC,. . .) operators.
- Volume-truncated **Little RS** models: $1 \ll k r_c \pi \ll 35$.

- Truncation: some unwanted contributions suppressed.

- *E.g.* tree-level oblique parameter $T_{\text{tree}} \propto k r_c \pi$ in RS models.
- $m_{KK} \sim 3$ TeV: 5D custodial symmetry to suppress δT from UV-sensitive loops.

Agashe, Delgado, May, Sundrum, 2003, Carena, Pontón, Santiago, Wagner, 2007

- Explain $\langle H \rangle \ll M_{\text{flavor}}$ hierarchy $\Rightarrow$ **TeV-scale** IR-brane, KK modes.

- Flavor constraints on LRS from ϵ_K: $k\pi r_c \gtrsim 7$ ($M_5 \gtrsim 10^4$ TeV).

Bauer, Casagrande, Grunder, Haisch, Neubert, 2008

Little Z' Couplings

- Simple models, no brane kinetic terms.

- LRS truncation factor: $\boldsymbol{y \equiv (kr_c|_{RS})/(kr_c|_{LRS}) \quad (y > 1)}$

- Gauge KK mode couplings:

$$\boldsymbol{g_{KK}|_{UV} \sim g_4/\sqrt{kr_c\pi} \quad (q, e, \ldots) \;\; ; \quad g_{KK}|_{IR} \sim g_4\sqrt{kr_c\pi} \quad (H, t, \ldots)}$$

Example: $\sigma(q\bar{q} \to Z' \to \ell^+\ell^-) \propto \overbrace{\Gamma(Z' \to q\bar{q})}^{\sim y} \overbrace{\mathrm{BR}(Z' \to \ell^+\ell^-)}^{\sim y^2}$

$\boxed{\mathcal{S} \sim y^3}$ and $\boxed{\mathcal{S}/\mathcal{B} \sim y^4}$ *!* Background: $\mathcal{B} \sim 1/y$ (over width)

- Experimental sensitivity to the **UV** scale $M_5 \sim k$.

$$\boldsymbol{y \approx 1 \Rightarrow M_5 \sim \bar{M}_P \;\; ; \;\; y \gg 1 \Rightarrow M_5 \ll \bar{M}_P.}$$

Assume a TeV-scale KK mode is discovered.

Question:

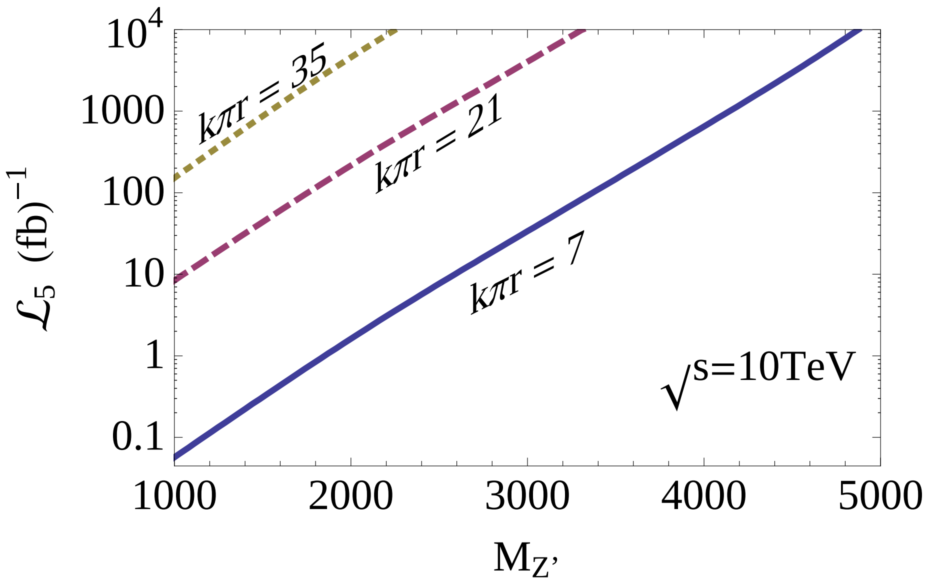
Is the Planck-weak hierarchy resolved?

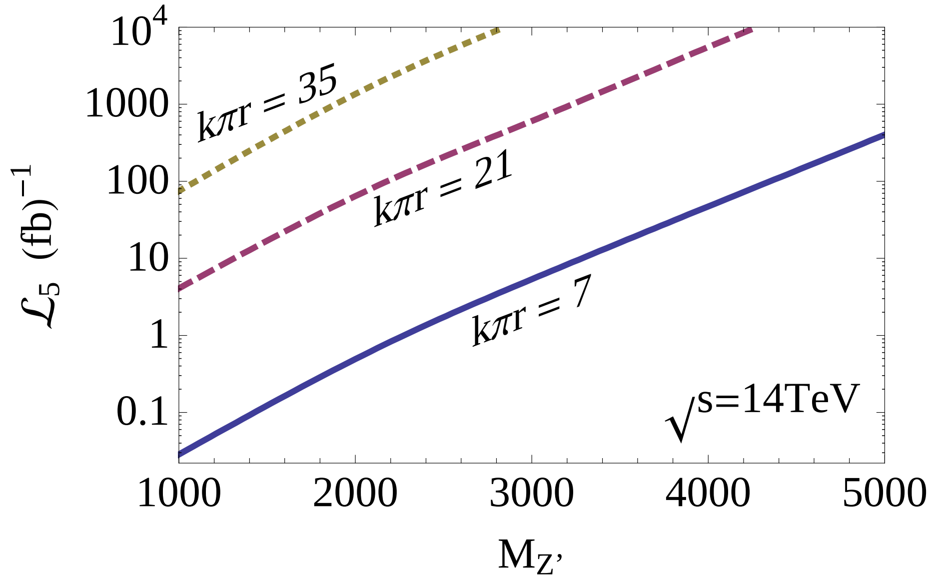
Some clean signals sensitive to truncation.

Experimental handle on $k r_c \pi$ (M_5) in simple models.

Dilepton Channel LHC Reach for the Little Z'

H.D., Gopalakrishna, Soni, Phys.Lett.B686:239-243,2010





- Cuts: $|\eta_\ell| < 3.0$, $p_{T_\ell} > 100$ GeV, $M_{\ell^+\ell^-}$ within $M_{Z'} \pm 100$ GeV.
- Background: irreducible SM only, due to low leptonic jet-fake rate (10^{-3}).
- $\mathcal{L}_5$: $\int L\, dt$ for 5σ signal ($\geq$ 3 events) in $pp \to \ell^+\ell^-$ ($\ell = e$ *or* μ).

- For $kr_c\pi \approx 7$:

$M_{Z'} \approx 2(3)$ TeV at $\sqrt{s} = 10\,(14)$ TeV with 1 (4) fb^{-1}.

- $kr_c\pi \approx 35$ (RS), any channel: $M_{Z'} \approx 3$ TeV, $\sqrt{s} = 14$ TeV, 300 fb^{-1}.

Agashe *et al.*, 2007

Little KK gluons

- Expect same enhanced *production* (coupling to $q\bar{q}$) for $g^{(1)}$.

- Light quark decay modes overwhelmed by large QCD background.

$\Rightarrow$ Discovery signal: $g^{(1)} \to t\bar{t}$.

- 5σ discovery estimates for $g^{(1)}$: $pp \to t\bar{t} \to bW(jj)\,\bar{b}W(\ell\nu)$

- Hadronic t reconstruction efficiency 5%.

Agashe, Belyaev, Krupovnickas, Perez, Virzi, 2006

- Efficiency includes b-tagging and kinematic acceptance.

- Simple analysis, ignore large boost of tops.

- 3-TeV KK gluon ($\sqrt{s} = 14$ TeV):

(2,8,21) fb^{-1} for $kr_c\pi = (7, 21, 35)$.

- Good agreement with ABKPV results for $kr_c\pi = 35$.

A Light Little Radion

H.D., McElmurry, Soni, work in progress

- Radion ϕ: fluctuations of πr_c, coupling $\frac{\phi}{\Lambda_\phi}\theta^\mu_\mu$.

- Realistic phenomenology: $V(\phi) \Rightarrow m_\phi \neq 0$.

Goldberger, Wise, 1999

De Wolfe, Freedman, Gubser, Karch, 1999

Csáki, Graesser, Kribs, 2000

E.g., Golberger-Wise (GW) mechanism:

Bulk scalar with mass m and brane-localized potentials.

- Typically, lightest warped state $m_\phi \ll m_{KK}$.

GW: $\epsilon = m^2/(4k^2)$; $\quad k\pi r_c \sim 1/\epsilon$; $\quad m_\phi \sim \epsilon\, k\, e^{-k\pi r_c}$

$\Rightarrow m_\phi \sim k\, e^{-k\pi r_c}/(k\pi r_c)$; $\quad k\, e^{-k\pi r_c} \sim 1$ **TeV (RS, LRS)**

- $k\pi r_c \sim 7$ **(LRS):** $m_\phi \sim 100$ **GeV.**

Little Radion Couplings

- Bulk gauge fields $\Rightarrow$ tree and loop level couplings:

$$\mathcal{L} = -\frac{\phi}{\Lambda_\phi}\left(C_{gg} G_{\mu\nu} G^{\mu\nu} + C_{\gamma\gamma} F_{\mu\nu} F^{\mu\nu}\right)$$

$$C_{gg} = \frac{1}{4}\left[\frac{1}{k\pi r_c} + \frac{\alpha_s}{2\pi} b^s_{\text{light}}\right]; \qquad C_{\gamma\gamma} = \frac{1}{4}\left[\frac{1}{k\pi r_c} - \frac{\alpha}{2\pi} b^{EM}_{\text{light}}\right]$$

(No brane kinetic terms) Csáki, Hubisz, Lee, 2007

- $kr_c|_{\text{LRS}} < kr_c|_{\text{RS}} \Rightarrow$ enhanced LRS couplings C_{gg}, $C_{\gamma\gamma}$.

- Assume $m_\phi \lesssim 140$ GeV: $gg \to \phi \to \gamma\gamma$ important.

$\Rightarrow$ Little radion may be interesting for the $\sqrt{s} = 7$ TeV LHC run.

- $q\bar{q} \to W^*/Z^* \to W/Z\,\phi$.

Couplings to vector V_μ depend on $k\pi r_c$, Λ_ϕ, and $k\,e^{-k\pi r_c}$:

$$\boldsymbol{\mathcal{L} = -\frac{\phi}{\Lambda_\phi}\left[m_V^2\left(1 - k\pi r_c\,\frac{m_V^2}{k^2 e^{-2k\pi r_c}}\right) + \frac{1}{4k\pi r_c}V_{\mu\nu}V^{\mu\nu}\right]}$$

- Gauge KK mass: $m_n = x_n k\,e^{-k\pi r_c}$; x_n weak dependence on $k\pi r_c$.

$$\text{KK mass} \Rightarrow \text{KK scale } k\,e^{-k\pi r_c}$$

- $m_\phi \sim 100$ GeV, $k\,e^{-k\pi r_c} \gtrsim 1$ TeV $\to$ main coupling $-\phi\frac{m_V^2}{\Lambda_\phi}$

- $q\bar{q} \to W^*/Z^* \to W/Z\,\phi$, $gg \to \phi \to \gamma\gamma$, KK scale

$$\boldsymbol{\Rightarrow \Lambda_\phi \textbf{ and } k r_c \pi.}$$

- Infer bulk volume $k\pi r_c$ (check versus KK data).

Holographic Interpretation of Warping

Arkani-Hamed, Porrati, Randall, 2001

Rattazzi, Zaffaroni, 2001

- 5D warped models:

Conformal dynamics below the cutoff UV scale $\sim k$.

- IR brane at scale $k\, e^{-k\pi r_c} \sim$ TeV:

Spontaneous conformal symmetry breaking (SCSB).

- Bulk SM gauge sector:

Weakly gauged global symmetry of the CFT.

- Radion: dilaton, pseudo-Goldstone associated with SCSB.

- LRS: truncated bulk $\rightarrow$ **"Conformal Depth"** TeV $\lesssim E \lesssim M_{\text{flavor}}$.

General Light Dilatons

- Walking gauge theories $\Rightarrow$ light dilaton. Appelquist, Bai, 2010

- Collider signatures of dilaton from SCSB. Goldberger, Grinstein, Skiba, 2007

  Fan, Goldberger, Ross, Skiba, 2008

Massless gauge field couplings; SM *embedded* in CFT:

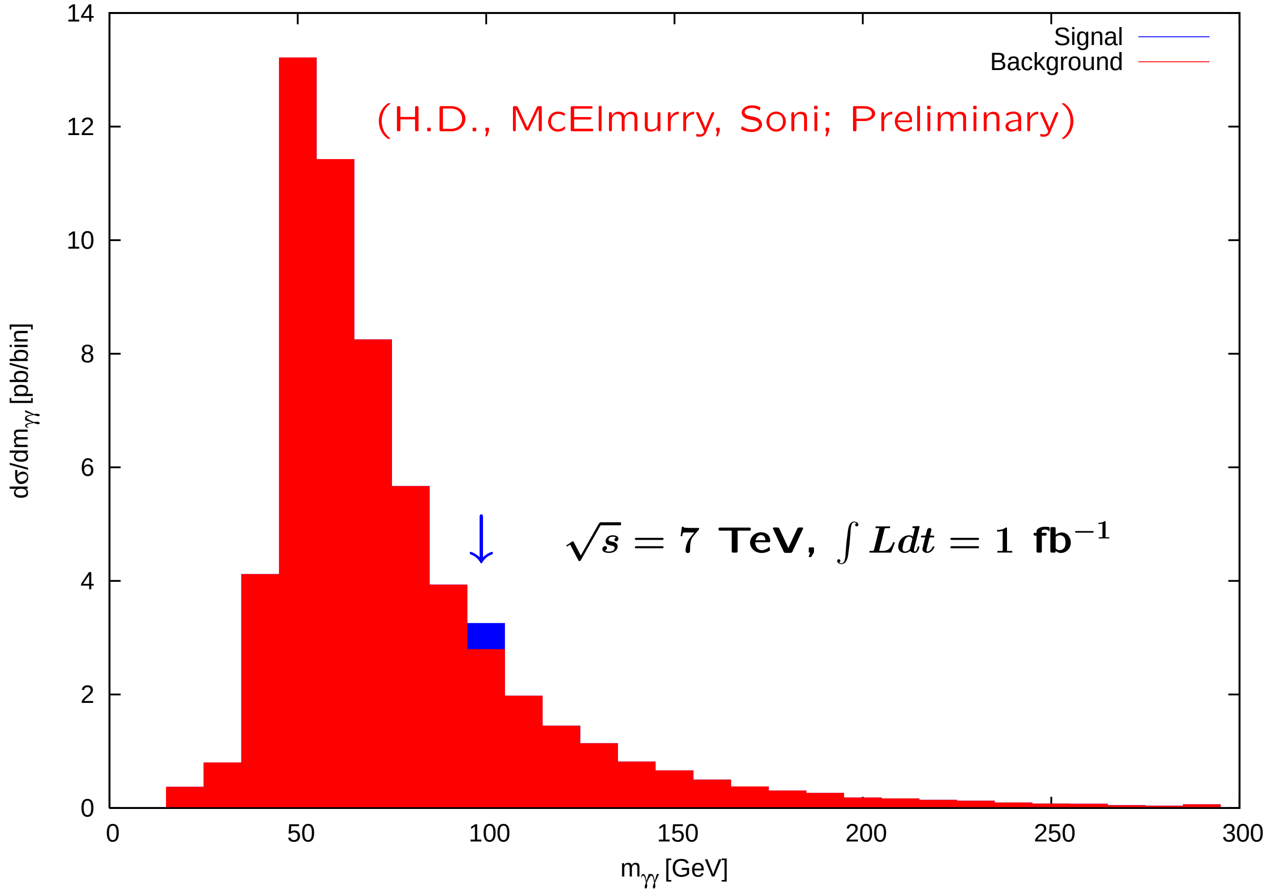
$C_{gg} = \frac{\alpha_s}{8\pi} b_{\text{light}}; \qquad b^s_{\text{light}} = (-11 + 2N_{\text{light}}/3);$

For Higgs: $\Lambda_\phi \to v$, $b^s_{\text{light}} \to b_{\text{heavy}}$ $(b^s_t = 2/3)$

$\Rightarrow$ Enhanced ϕ coupling for $\Lambda_\phi \sim v$ (LHC).

Note:
No analogue of the RS (LRS) tree-level couplings, UV cutoff $\to \infty$.

$$pp \to \phi \to \gamma\gamma$$



- $m_\phi = 100$ GeV, $\Lambda_\phi = 3$ TeV, $kr_c\pi = 7$ ($M_5 \sim 10^4$ TeV).
- Br($\phi \to gg, b\bar{b}, \gamma\gamma$) = 89.6%, 8.0%, 2.4%.
- $p_T(\gamma) > 20$ GeV, $|\eta| < 2.5$, isolation (0.4, 10 GeV):

$S \approx 460$ fb, $B \approx 60 \times 10^3$ fb (NLO).

- 90 GeV $< M_{\gamma\gamma} <$ 110 GeV $\Rightarrow S/B \approx 0.08$, $S/\sqrt{B} \approx 6$.

Concluding Remarks

- Volume-truncated **LRS** as a predictive model of **flavor**:
  - The UV scale $M_{\text{flavor}} \gg$ TeV can be much lower than $\bar{M}_P$.
  - $k\pi r_c$ not *a priori* known, experimental question.
  - Some constraints can be alleviated by volume truncation.
  - Natural Higgs-$M_{\text{flavor}}(M_5)$ hierarchy $\rightarrow$ TeV-scale KK modes.
- Some clean LRS signals quite sensitive to the hierarchy (UV scale).
- Light Little Radion good target for the 7-TeV LHC run.
- Simple models: bulk volume (geometry)/conformal depth (CFT) may be extracted from TeV-scale data.