Little Kaluza-Klein Modes 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

arXiv:0908.1131 [hep-ph]

Introduction:

- EWSB in the SM via Higgs: $\langle H \rangle \sim m_H \sim 10^2$ GeV.

- Quantum corrections from UV scale Λ: $\delta m_H^2 \sim \Lambda^2$.

- Precision EW and flavor data: $\Lambda \gg 1$ TeV.

- Quantum gravity: $\Lambda \sim \bar{M}_P \sim 10^{18}$ GeV.

$\Rightarrow$ *The hierarchy problem: Why is $m_H \ll \Lambda$?*

$$\boxed{m_H/\bar{M}_P \sim 10^{-16}!}$$

- Proposals: Strong dynamics, SUSY, extra dimensions,. . . .

The Randall-Sundrum Model

Randall, Sundrum, 1999

- **A slice of AdS_5 spacetime.**

- Flat boundaries: Planck (UV), TeV (IR) branes.

- Gravity UV-localized, SM on TeV-brane.

- Dual to 4D strong dynamics.

(AdS/CFT, Maldacena, 1997)

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

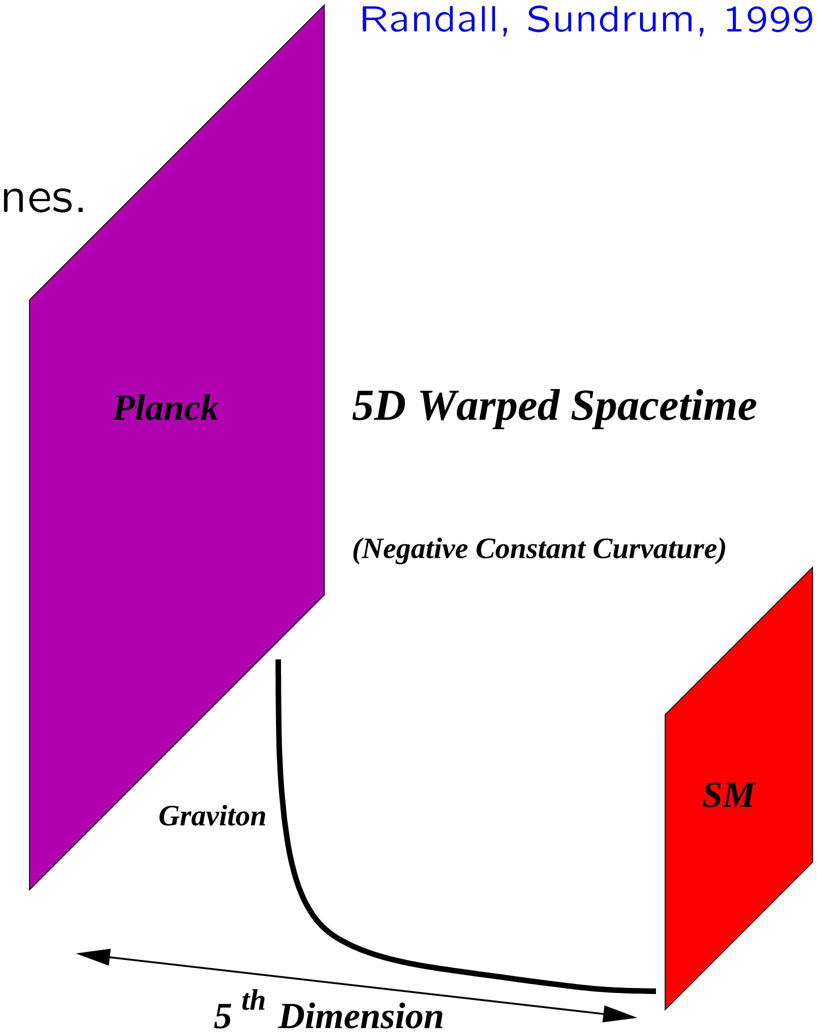
$kr_c\pi \approx 35$; hierarchy via exponentiation.

- **Stabilization $\rightarrow$ Radion scalar.**

Goldberger, Wise, 1999

- **Distinct TeV-scale collider signals:**

Kaluza-Klein (KK) spin-2 resonances (gravitons). H.D., Hewett, Rizzo, 1999



Warped Hierarchy/Flavor Models

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

- **Modified KK couplings.**
  - Gauge KK couplings: $(k\pi r_c \approx 35)$

UV-brane (*e.g.* e, u): $\sim g/\sqrt{k\pi r_c}$

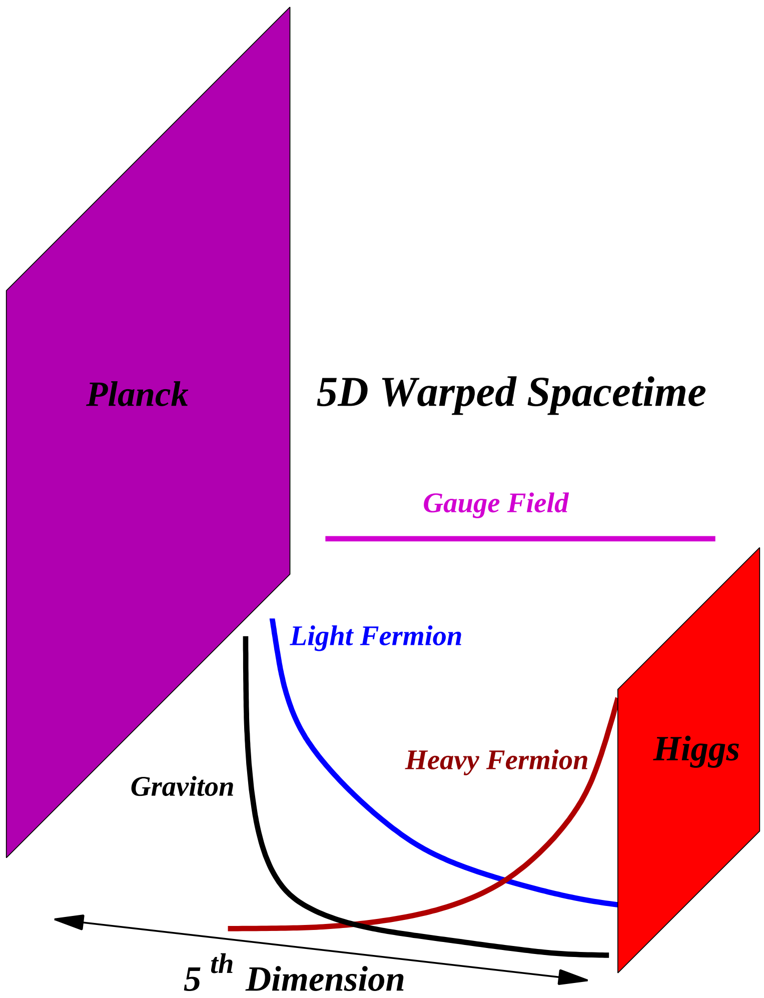
IR-brane (*e.g.* H, t_R): $\sim g\sqrt{k\pi r_c}$

  - Graviton KK couplings in $\sim$TeV^{-1}:

Light fermions: $\sim$ Yukawa.

IR-brane (*e.g.* H, t_R): ~ 1.

Gauge fields (g, γ): $\sim 1/(k\pi r_c)$.



- **Collider Signals: more challenging.**
  - Golden decays modes, *e.g.* $e^{\pm}, \mu^{\pm}$, suppressed.

Constraints on Warped Hierarchy/Flavor Models

- Control δT: 5D custodial $G_c = SU(2)_L \times SU(2)_R \times U(1)_X$.

Agashe, Delgado, May, Sundrum, 2003

- $Zb\bar{b}$: $G_c \times \mathbb{Z}_2$ Agashe, Contino, Da Rold, Pomarol, 2006

- Gauge KK mass $m_{KK} \gtrsim 2 - 3$ TeV. Carena, Pontón, Santiago, Wagner, 2007

- KK gluon exchange contribution to ϵ_K: Agashe, Perez, Soni, 2004
Csaki, Falkowski, Weiler, 2008

- $m_{KK} \gtrsim 20$ TeV; $\mathcal{O}(30\%)$ uncertainty

Further 5D flavor structure for $m_{KK} \sim$ TeV. *E.g.* Fitzpatrick, Perez, Randall, 2007

Summary of the LHC Prospects

($\sqrt{s} = 14$ TeV)

- KK gluons: ~ 3 TeV with 25 fb^{-1}

Agashe, Belyaev, Krupovnickas, Perez, Virzi, 2006
Lillie, Randall, Wang, 2007

- KK gravitons: $\lesssim 2$ TeV with $\mathcal{O}(100)$ fb^{-1}

Fitzpatrick, Kaplan, Randall, Wang, 2007
Agashe, H.D., Perez, Soni, 2007

- The electroweak sector: 5D $SU(2)_L \times SU(2)_R \times U(1)_X$.

- Z' (3 neutral states): 3 TeV with $\gtrsim 300$ fb^{-1} Agashe, *et al.*, 2007
- W' (4 charged states): similar to Z'.

Agashe, Gopalakrishna, Han, Huang, Soni , 2008

- Challenge: heavy highly-boosted SM final states dominate.

- Decay products merge.
- Large reducible backgrounds.

E.g., $W\,W(\rightarrow jj)$ appears as Wj.

- Study of jet morphology.

Some Recent Works on Background Reduction

Top jets:

- J. Thaler and L.-T. Wang,
JHEP 0807:092,2008.
e-Print: arXiv:0806.0023 [hep-ph].

- D. Kaplan, K. Rehermann, M. Schwartz, and B. Tweedie,
Phys.Rev.Lett.101:142001,2008.
e-Print: arXiv:0806.0848 [hep-ph].

- L. Almeida, S. Lee, G. Perez, I. Sung, and J.Virzi,
Phys.Rev.D79:074012,2009.
e-Print: arXiv:0810.0934 [hep-ph].

- D. Krohn, J. Shelton, and L.-T. Wang,
e-Print: arXiv:0909.3855 [hep-ph].

Substructure of high-p_T Jets:

- L. Almeida, S. Lee, G. Perez, G. Sterman, I. Sung, J. Virzi,
Phys.Rev.D79:074017,2009.
e-Print: arXiv:0807.0234 [hep-ph].

- Y. Hatta and T. Ueda,
e-Print: arXiv:0909.0056 [hep-ph].

Little Randall-Sundrum (LRS) Models

H.D., Perez, Soni, 2008

- RS as a model of flavor: $M_5 \ll \bar{M}_P$ viable option.
- $M_5 \gg$ TeV needed to suppress unwanted (FCNC,...) operators.
- Volume-truncated RS models: $1 \ll kr_c\pi \ll 35$.

- Truncation: some unwanted contributions suppressed.

- tree-level oblique parameter $T_{\text{tree}} \propto kr_c\pi$ in RS models.

- $\delta Zb\bar{b}$ from zero-mode-KK mixing after EWSB $\sim kr_c\pi$.

- ...

- $m_{KK} \gtrsim 3$ TeV: 5D custodial symmetry to remove δT from UV-sensitive loops.

Agashe, Delgado, May, Sundrum, 2003

- Explain $\langle H \rangle / M_5 \ll 1$ hierarchy $\Rightarrow$ warped TeV-scale KK modes.

- LRS: significant improvement in *clean* collider signals.

- 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

Dilepton Little Z' Signals

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

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

(i) KK modes become narrower: $\Gamma \sim 1/y$ IR-coupling-dominated

(ii) Width into light states $(e^+e^-, u\bar{u}, \ldots)$ grows $\sim y$

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

(i) $\oplus$ (ii) $\oplus$ (iii): $\boxed{\mathcal{S} \sim y^3}$ and $\boxed{\mathcal{S}/\mathcal{B} \sim y^4}$! Background: $\mathcal{B} \sim 1/y$ (<u>over width</u>)

- Experimental sensitivity to the <u>UV-brane</u> scale.

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

Assume that a TeV-scale KK mode has been observed.

Question:

Is the Planck-weak hierarchy resolved?

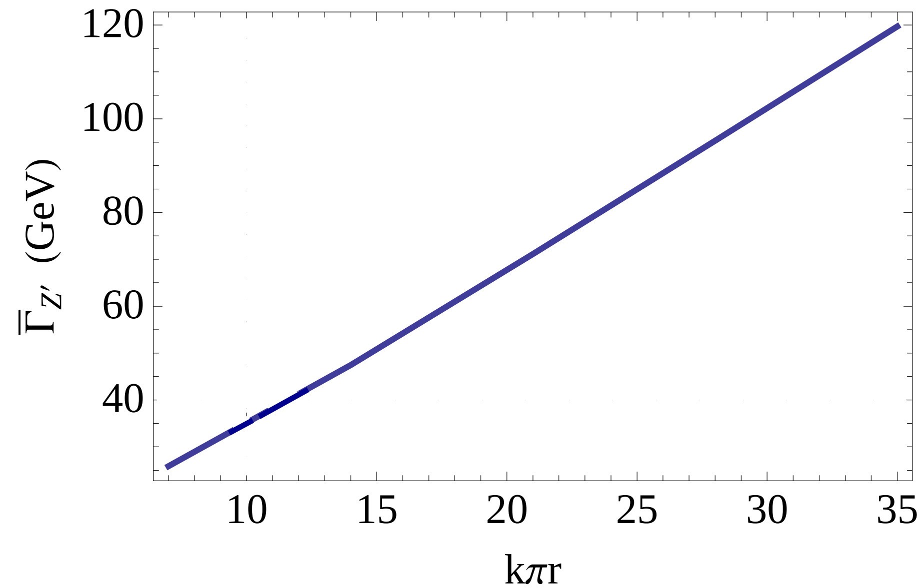
Clean dilepton Z' signals sensitive to truncation.

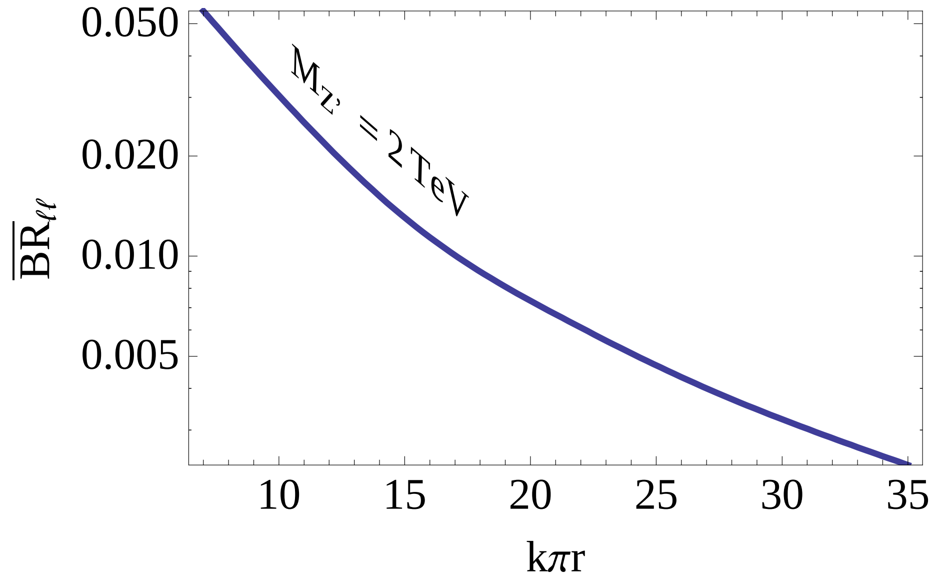
Experimental handle on $kr_c\pi$ (M_5) in typical models.

Early LRS Signals at the LHC

H.D., Gopalakrishna, Soni, arXiv:0908.1131 [hep-ph]

- Width $\bar{\Gamma}_{Z'}$ and leptonic Br$_\ell$ ($\ell = e$ or μ) as a function of $kr_c\pi$.

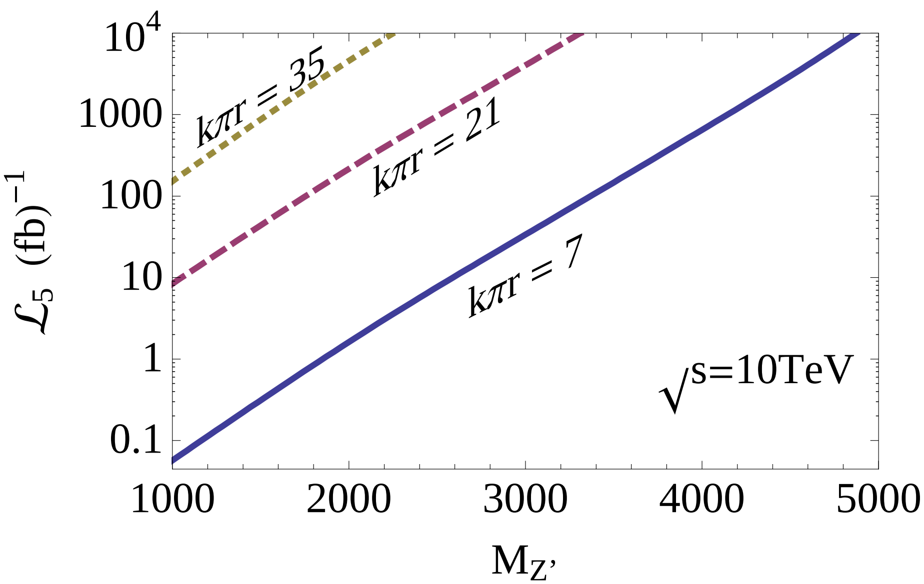


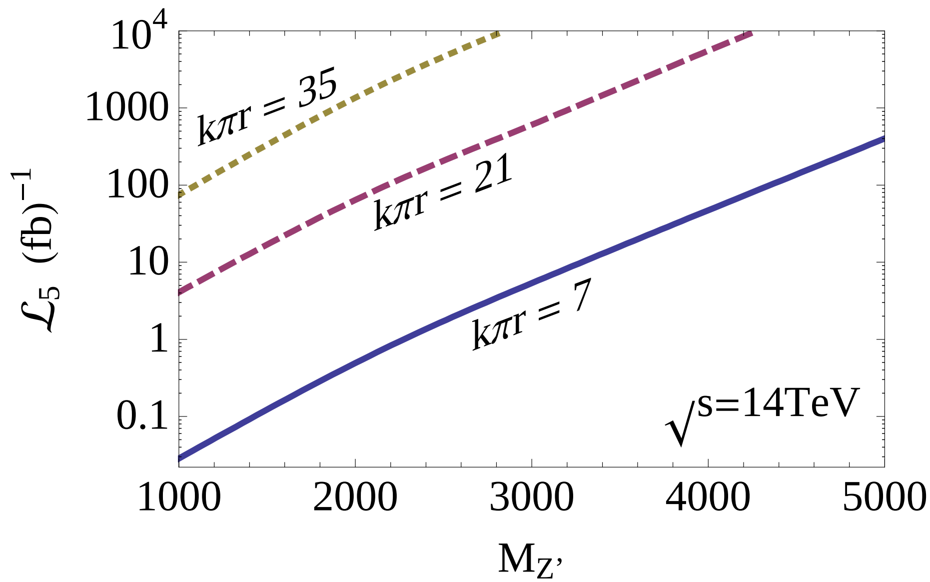


- Averaged over three states, $M_{Z'} = 2$ TeV.
- We will consider the clean process $q\bar{q} \to Z' \to \ell^+\ell^-$ at the LHC.
- Gluon KK modes: complicated $t\bar{t}$ final state; more later.

Dilepton Channel LHC Reach for the Little Z'

H.D., Gopalakrishna, Soni, arXiv:0908.1131 [hep-ph]





- 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 (≥ 3 events) in $pp \to \ell^+\ell^-$ ($\ell = e$ *or* μ).
- Early Little Z' discovery, for $kr_c\pi \approx 7$: EW data: $M_{Z'} \gtrsim 2-3$ TeV

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

- Compare with original RS ($kr_c\pi \approx 35$): $M_{Z'} \approx 3$ TeV, $\sqrt{s} = 14$ TeV, <u>300 fb^{-1}</u>.

Detecting Z''

- $R \equiv M_{Z'}/M_{Z''}$: information about warping.

- $kr_c\pi = (7, 35) \Rightarrow R \simeq (2.65/5.80, 2.45/5.57) \simeq (0.46, 0.44)$

- $\delta M \sim 5\%$ could be Measurable in e^+e^- channel.

- $kr_c\pi = 7$: $M_{Z'} = 2$ TeV $\Rightarrow M_{Z''} = 4.3$ TeV .

$\Rightarrow Z''$ discovery with ~ 100 fb^{-1} at $\sqrt{s} = 14$ TeV.

Little KK gluons

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

- Light quark decay modes overwhelmed by large QCD background.

- No equivalent to leptonic clean mode for $g^{(1)}$.

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

- Roughly, expect the width $\sim 1/y$, but $\mathcal{S} \sim y$ and $\mathcal{S}/\mathcal{B} \sim y^2$.

- Total cross section $pp \to t\bar{t}$ (no top decays):

- Cuts: $p_{T_t} > 1100$ GeV, $|y_t| < 3$, $M = 3$ TeV.

$\sigma_{pp\to t\bar{t}}$ (fb)	$kr_c\pi = 7$	$kr_c\pi = 21$	$kr_c\pi = 35$	SM
No cuts	197	127	91	4×10^5
p_{T_t}, y_t cuts	100	52	30	11

5σ Discovery Reach Estimates for $g^{(1)}$

- $pp \to t\bar{t} \to bW(jj)bW(\ell\nu)$

- 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):

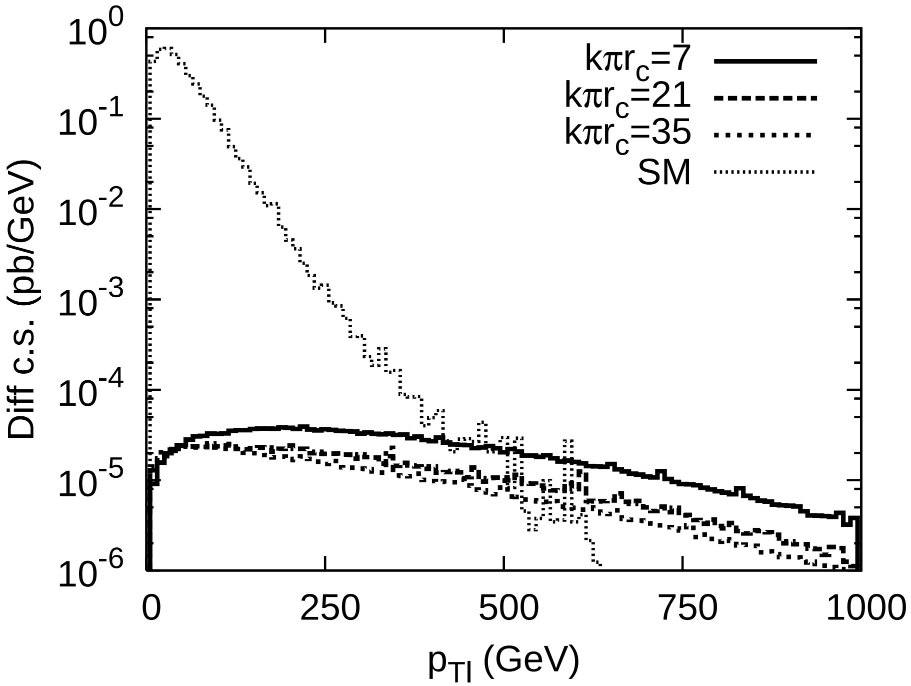
(2,8,21) fb^{-1} for $kr_c\pi = (7, 21, 35)$.

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

- Dilepton channel ($WW \to \ell\ell\nu\nu$).

- Not fully reconstructed (2 missing ν's).
- Lepton counting analysis.
- Hard cut: $p_{T_\ell} > 400$ GeV.
- Basic cuts: $|\eta_{\ell,b}| < 3$, $p_{T_b} > 20$ GeV.
- 3-TeV KK gluon ($\sqrt{s} = 14$ TeV):

(4,15,109) fb^{-1} for $kr_c\pi = (7, 21, 35)$.



- Early Little KK gluon discovery ($kr_c\pi \sim 7$):

- Challenging $t\bar{t}$ final state (missing energy, top jets).
- Similar to the Little $Z'(\to \ell^+\ell^-)$, but less straightforward.
- Better prospects with improved control over backgrounds (likely later stages).

A Few Words on Holography

- RS: dual to large N CFT, between M_5 and $\sim$ TeV.

- $1/g_4^2 = \tau_{\text{UV}} + \tau_{\text{IR}} + \underbrace{\log(k/\kappa)}_{kr_c\pi}/(kg_5^2) \Rightarrow kg_5^2 \sim 16\pi^2/N$.

- $\tau_{UV,IR}$ small QM corrections; $\kappa \equiv ke^{-kr_c\pi} \sim$ TeV

- g_4 fixed $\Rightarrow$ LRS dual to *larger* N CFT : $N^{LRS} \sim yN^{RS}$.

- LRS: Inter-composite interactions weaker with increasing N.

- Dual to weaker KK mode IR-brane couplings.

- Composite decay constant ($\rho - \gamma$ mixing) $\sim \sqrt{N}$; larger in LRS.

- Dual to larger coupling to UV-localized modes.

- Clean LRS signals: handle on the conformal range [TeV, M_5].

Concluding Remarks

- RS background an interesting framework for flavor.
- Volume-truncated LRS as a model of <u>flavor</u>:
  - The fundamental scale $M_5 \gg$ TeV can be much lower than $\bar{M}_P$.
  - Some constraints can be alleviated by volume truncation.
  - LRS still addresses Higgs-M_5 hierarchies $\rightarrow$ TeV-scale KK modes.
- Some clean LRS signals quite sensitive to the hierarchy (UV scale).
  - Simple models: value of M_5 may be inferred from weak scale data.
  - 4D CFT dual: experimental handle on UV conformal behavior.