Warped Gravitons at the LHC and Beyond

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Partially based on: K. Agashe, H.D., G. Perez, and A. Soni

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Introduction:

- *Key unresolved question: EWSB.*

- *SM:* $\langle H \rangle \sim 100$ *GeV; minimalistic, but unstable (hierarchy).*

⋆ 5-d Resolution:

Randall-Sundrum (RS1) Model

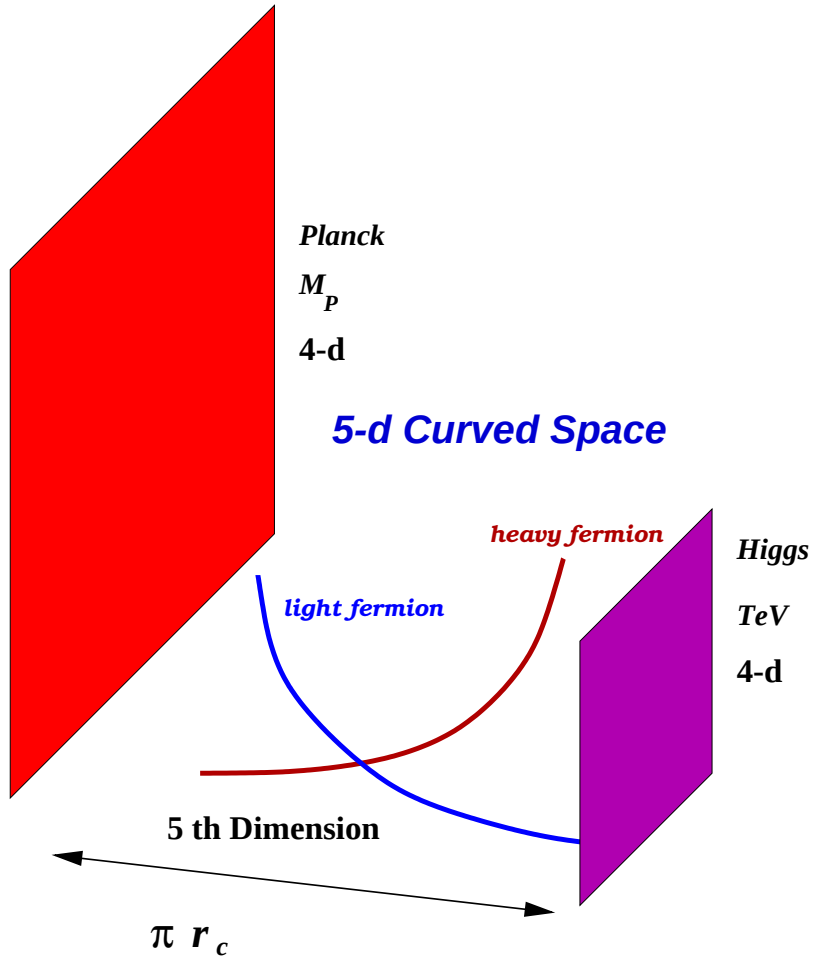
Localized gravity in truncated AdS$_5$.

Redshift $\Lambda_{UV} \rightarrow$ TeV, $O(1)$ parameters.

$\Lambda_\pi = e^{-k\pi r_c} \bar{M}_P \sim$ TeV ; $kr_c \sim 10$

5-d SM: flavor from geometry.

AdS/CFT insights.



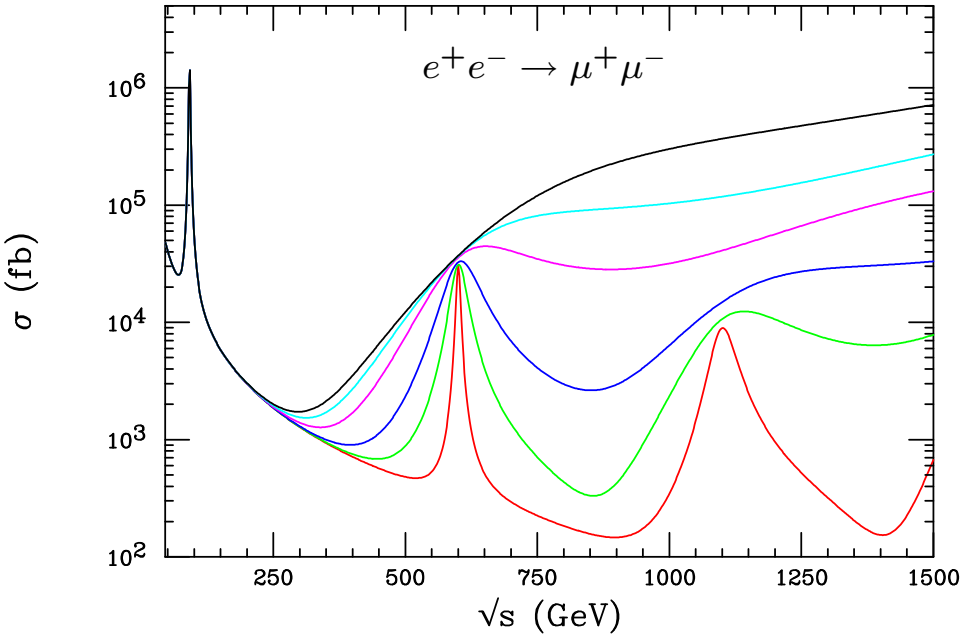
RS1 Phenomenology:

- All SM couples to KK gravitons with $1/\Lambda_\pi \sim 1/\mathrm{TeV}$.

- Graviton KK masses: TeV-scale.

$m_n^G = x_n^G k e^{-k\pi r_c}$; $x_n^G = 3.83, 7.02, \ldots$; $k e^{-k\pi r_c} \sim$ TeV.

Striking Signature: Spin-2, $\mathcal{O}(\mathrm{TeV})$ KK graviton resonances $(e^+e^-, q\bar{q}, gg, \ldots \to G^n)$: (H. D., Hewett, and Rizzo, 1999)



- **Problem**: TeV-cutoff scale $\rightarrow$ FCNC, Precision EW conflict.

- **Solution**: 1^{st} and 2^{nd} generation Planck-brane-localized.

- Higher dimension operators suppressed by $M \gg \Lambda_\pi \sim$ TeV.

- Natural 4-d Yukawa couplings: small overlap with Higgs, IR brane.

- **KK Gravitons (distinct signature)**: challenge in realistic models.

A. Fitzpatrick, J. Kaplan, L. Randall, L-T. Wang, hep-ph/0701150 .

K. Agashe, H.D., G. Perez, and A. Soni, hep-ph/0701186 (to appear in PRD); this talk.

Collider Discovery of KK Gravitons

- $q\bar{q}$ production $\sim$ Yukawa-suppressed.

- gg production volume suppressed, but non-negligible.

- *Golden* mode signals, $\ell^+\ell^-$ (Yukawa), $\gamma\gamma$ (volume) suppressed.

- Dominant coupling: top and Higgs (challenging detection).

Crucial observation: $W_L^{\pm}$ **and** Z_L **effectively in Higgs-sector.**

- $W_L^{\pm}/Z_L$ `near IR-brane, unsuppressed couplings.`
- $Z_L Z_L \to 4\ell$ $(\ell = e, \mu)$ `a golden channel.`
- VBF production subdominant to gg-channel.

$$\sigma(\text{VBF})/\sigma(gg) \sim [\alpha_{EW}/(4\pi)]^2 \times [\log(\bar{M}_P/\text{TeV})]^2 \times (u\text{PDF}/g\text{PDF})^2.$$

$$\sigma(\text{VBF}) \sim 0.1\sigma(gg).$$

We study $gg \to G^n \to Z_L Z_L$**.**

SM Background at LHC:

Irreducible Backgrounds:

- $pp \to ZZ$, dominated by $q\bar{q}$ annihilation (t/u channels).
- Forward/backward peaking (t/u exchange): η cut.

Reducible Backgrounds:

- Hadronic ZZ decays: large QCD 4-jet background.
- $Z(\to jj)Z(\to \ell^+\ell^-)$ decays: large $Z + j$ background ($\sim 10 \times S$).

$M_Z/\text{TeV} \ll 0.4$

More analysis, substructure of Z-jet, could make this channel useful.

Focus on $ZZ \to 4\ell$ with irreducible $B < S$.

Range of Parameters:

- Custodial symmetry for EWPT* and $Zb\bar{b}$**: $M_{KK}^{gauge} \gtrsim 2-3$ TeV***.

(*) Agashe, Delgado, May, Sundrum, (2003)

(**) Agashe, Contino, Da Rold, Pomarol (2006)

(***) Carena, Ponton, Santiago, Wagner, (2006), (2007)

- In the simplest models $\Rightarrow m_1^G \gtrsim 4.5$ TeV.

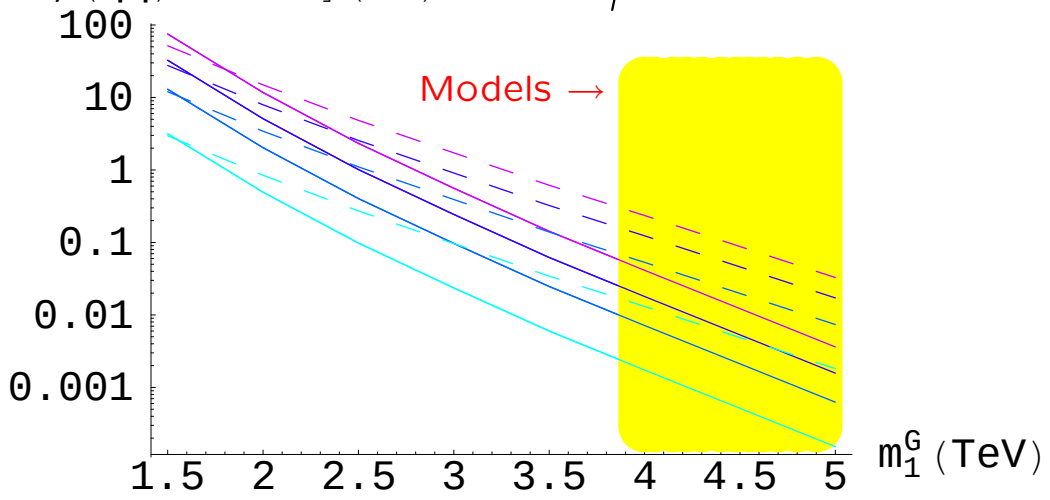
- Usually, $c \equiv k/\bar{M}_P < 1$ is assumed for a valid effective treatment.

- However, the cutoff Λ: all loops become unsuppressed.

- For $d = 5$, this means $\Lambda \sim 2\sqrt[3]{3}\,\pi M_5$. Chacko, Luty, Ponton, (1999)

- Effective description valid for $c \lesssim 3$.

$\sigma[(gg)^{RS},(qq)^{SM}\to ZZ]$(fb) No η cut

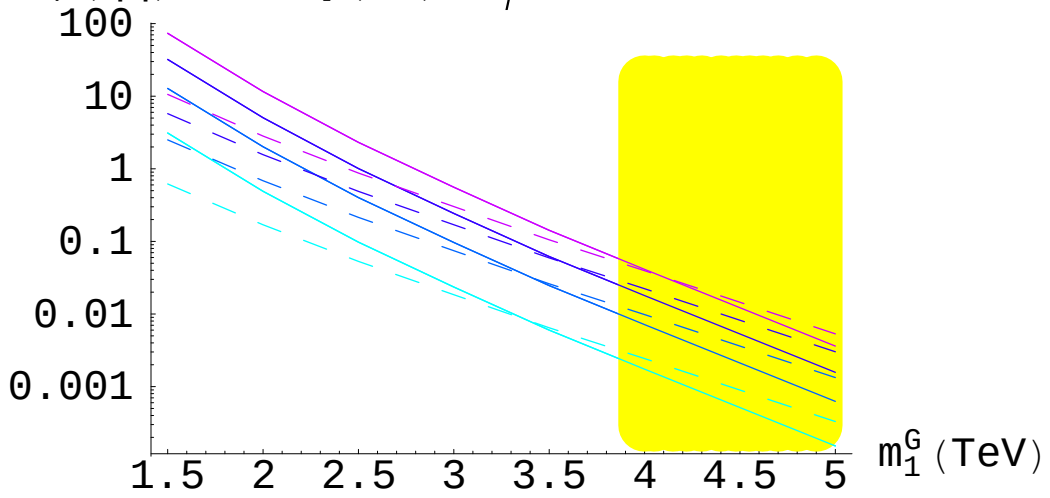


S,B: $m \pm \Gamma$

$\Gamma \propto c^2$

S: solid lines. SM B: dashed lines. $c \equiv k/M_P = 0.5, 1, 1.5, 2$ **(bottom to top).**

$\sigma[(gg)^{RS},(qq)^{SM}\to ZZ]$(fb) η<2 cut



Value of m_1^G yielding 10 signal events at the LHC with 300 fb^{-1} :

$c \equiv k/\bar{M}_P$	0.5	1.0	1.5	2.0
m_1^G (TeV)	< 1.5	1.6	1.9	2.2
$S/\sqrt{B}$	–	7.0	6.1	6.1

SLHC with 3 ab^{-1}:

$c \equiv k/\bar{M}_P$	0.5	1.0	1.5	2.0
m_1^G (TeV)	1.9	2.3	2.6	2.9
$S/\sqrt{B}$	6.1	4.3	4.3	4.3

- **Latest realistic models**: **5-d $SU(2)_L \times SU(2)_R \times U(1)_X$.**
- Custodial symmetry: T-parameter and $Zb\bar{b}$ constraints; $m_{KK} \gtrsim 2-3$ TeV..
- Rich collider phenomenology of the new EW KK towers.

K. Agashe, H.D., S. Gopalakrishna, T. Han, G. Huang, G. Perez, Z.G. Si, A. Soni

Preliminary

	A_1		$\tilde{Z}_1$		$\tilde{Z}_{X1}$	
	Γ	BR	Γ	BR	Γ	BR
$\bar{t}t$	60.5	0.53	18.86	0.15	58.09	0.4
$\bar{b}b$	0.97	8.6×10^{-3}	0.11	8.3×10^{-4}	30.1	0.21
$\bar{u}u$	0.28	2.45×10^{-3}	0.19	1.5×10^{-3}	0.06	3.9×10^{-4}
$\bar{d}d$	0.07	6.2×10^{-4}	0.25	2×10^{-3}	0.07	5.1×10^{-4}
$\ell^+\ell^-$	0.21	1.8×10^{-3}	0.057	4.5×10^{-4}	0.017	1.15×10^{-4}
$W_L W_L$	50.32	0.45	0.74	5.9×10^{-3}	55.1	0.38
$Z_L h$			105.1	0.83	1.82	0.012
Total	113.1		127.3		145.93	

- $t\bar{t}$ decay mode: KK gluon pollution.
- $Z_L h$ decay mode: significant, dependence on Higgs properties.
- $W_L W_L$ decay mode enhanced and free from KK gluon "background".

Recent work based on $t\bar{t}$ and $b\bar{b}$ decay modes:

A. Djouadi, G. Moreau, R.K. Singh arXiv:0706.4191 [hep-ph].

$pp \to WW \to (\ell\nu)jj$ cross section (fb) for $M_{Z'} = 2$ TeV and 100 fb^{-1}.

Preliminary

	p_T	η_{W^+,W^-}	$M_{T_{WW}}$	# Evts	S/B	$S/\sqrt{B}$
Signal	4.7	2.5	1.7	170		
W+1j	3×10^5	4.4×10^4	11.8	1180	0.14	5
WW	2×10^3	284	0.12	12		

$p_T > 100$ GeV; $-1 < \eta_{W^\pm} < 1$; 1800 GeV$< M_{T_{WW}} <$2200 GeV.

- Preliminary jet mass study: possibility of enhanced S/B.

Limits based on jet-mass require more detailed (NLO, detector,. . .) analysis.

- Previous work using jet mass:

Benchekroun, Driouichi, Hoummada, SN-ATLAS-2001-001. $m_{Z'}$ up to ~ 2 TeV

Skiba, Tucker-Smith (2007) Vector quarks at LHC

Concluding Remarks

- RS $\oplus$ bulk SM fermion localization: geometry $\rightarrow$ hierarchy and flavor.

Challenging collider phenomenology.

- Key signature, spin-2 KK graviton, difficult to detect at colliders.
- We found gg-production channel dominant over VBF.
- Clean signal: $gg \rightarrow Z_L Z_L \rightarrow 4\ell$, $\ell = e, \mu$.
- LHC reach, $L = 300$ fb^{-1}, $c = 2$: $m_1^G \approx 2$ TeV.
- SLHC reach, $L = 3$ ab^{-1}, $c = 2$: $m_1^G \approx 3$ TeV.
- RS neutral weak gauge boson KK modes at the LHC.

$Z' \rightarrow W_L W_L$: $\mathcal{O}(1)$ Br, KK gluon free final state.

$Z' \rightarrow Z_L h$: significant, dependence on Higgs properties.