

# Warped Extra Dimensions at the LHC

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Partially based on: K. Agashe, H.D., G. Perez, and A. Soni, hep-ph/0701186.

## Introduction:

- Key unresolved question: EWSB.
- SM:  $\langle H \rangle \sim 100 \text{ GeV}$ ; minimalistic, but unstable (hierarchy):

QM effects:  $\langle H \rangle \rightarrow \Lambda_{UV}, \quad \Lambda_{UV} = M_P, M_{GUT}, \dots$

## 5-d Resolution:

### Randall-Sundrum (RS) Model

Localized gravity in truncated  $\text{AdS}_5$ .

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

5-d SM: flavor from geometry.

AdS/CFT insights.

# RS with Realistic Flavor: Challenge for Colliders

Original RS discovery strategies must be reconsidered.

## Recent work:

- **KK gluon discovery at LHC.**

K. Agashe, A. Belyaev, T. Krupovnickas (BNL), G. Perez, J. Virzi, hep-ph/0612015.

Reach up to  $m_{KK}^g \simeq 4$  TeV with  $100 \text{ fb}^{-1}$ .

Current bounds:  $m_{KK}^g \gtrsim 2 - 3$  TeV  $\Rightarrow$  KK gluon promising signal.

- **KK graviton discovery at the LHC.**

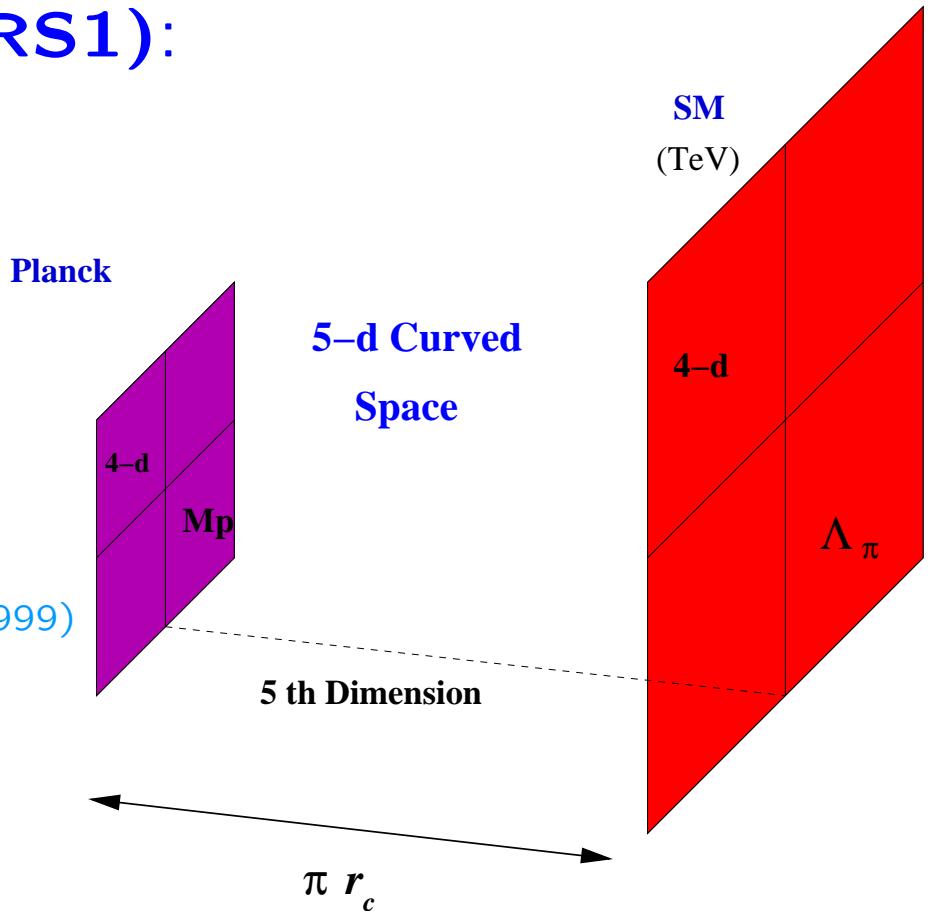
Distinct RS signature.

Fitzpatrick, Kaplan, Randall, Wang, hep-ph/0701150.

K. Agashe, H.D. (BNL), G. Perez, A. Soni (BNL), hep-ph/0701186 (this talk).

# The Original RS Model (RS1):

- $ds^2 = e^{-2\sigma} \eta_{\mu\nu} dx^\mu dx^\nu - dy^2$  ;  $\sigma = k|y|$
- $-\pi r_c \leq y \leq \pi r_c$  ;  $\mathbb{Z}_2$  orbifold
- $M_5 \sim M_P$
- $kr_c \sim 10$ : natural (Goldberger and Wise, 1999)
- $\Lambda_\pi = e^{-k\pi r_c} \bar{M}_P \sim \text{TeV}$ .
- Higgs localized at IR boundary.



## Gravitational Redshift:

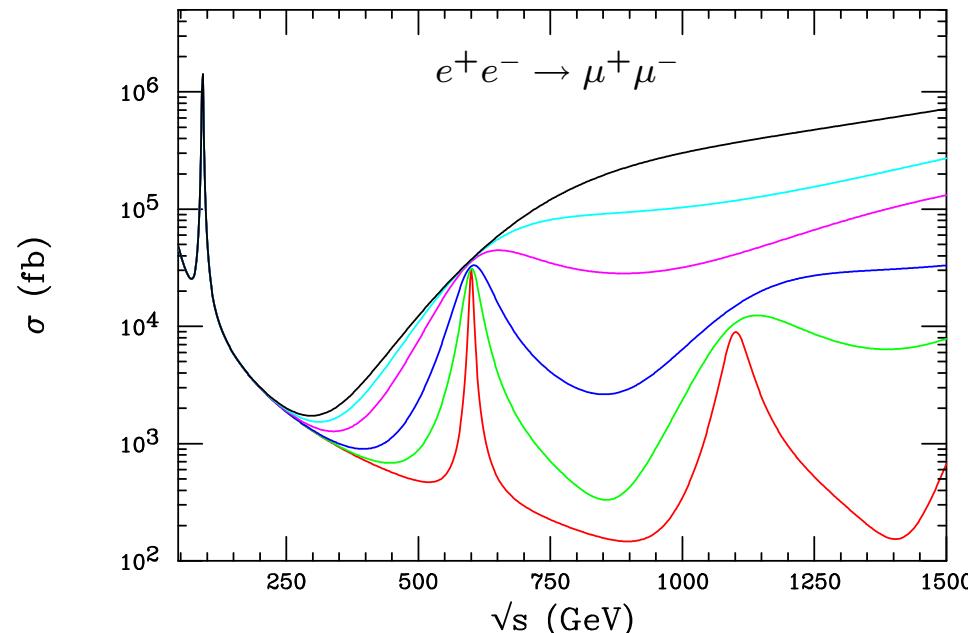
$$\langle H \rangle_5 \sim \bar{M}_P \rightarrow \langle H \rangle_4 \sim m_W$$

# RS1 Phenomenology:

- All SM couples to KK gravitons with  $1/\Lambda_\pi \sim 1/\text{TeV}$ .
- Graviton KK masses: TeV-scale.

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

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



- **Problem:** TeV-cutoff scale  $\rightarrow$  FCNC, Precision EW conflict.
  - **Solution:** 1<sup>st</sup> and 2<sup>nd</sup> generation Planck-brane-localized.
    - Higher dimension operators suppressed by  $M \gg \Lambda_\pi \sim \text{TeV}$ .
    - Natural 4-d Yukawa couplings: small overlap with Higgs, IR brane.
  - **Latest realistic models:** 5-d  $SU(2)_L \times SU(2)_R \times U(1)_X$ .
    - Custodial symmetry:  $T$ -parameter and  $Z b\bar{b}$  constraints.
    - Current bounds on the weak gauge-sector:  $m_{KK} \gtrsim 2 - 3 \text{ TeV}$ .
    - Rich collider phenomenology of the new KK towers.
- H.D., S. Gopalakrishna, A. Soni  $\oplus$  other collaborators.
- **KK Gravitons (distinct signature):** challenge in realistic models.

K. Agashe, H.D., G. Perez, and A. Soni, hep-ph/0701186.

## 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.
- $Z_L Z_L \rightarrow 4\ell$  ( $\ell = e, \mu$ ) a golden channel.
- VBF production subdominant to  $gg$ -channel.

# SM Background at LHC:

## Irreducible Backgrounds:

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

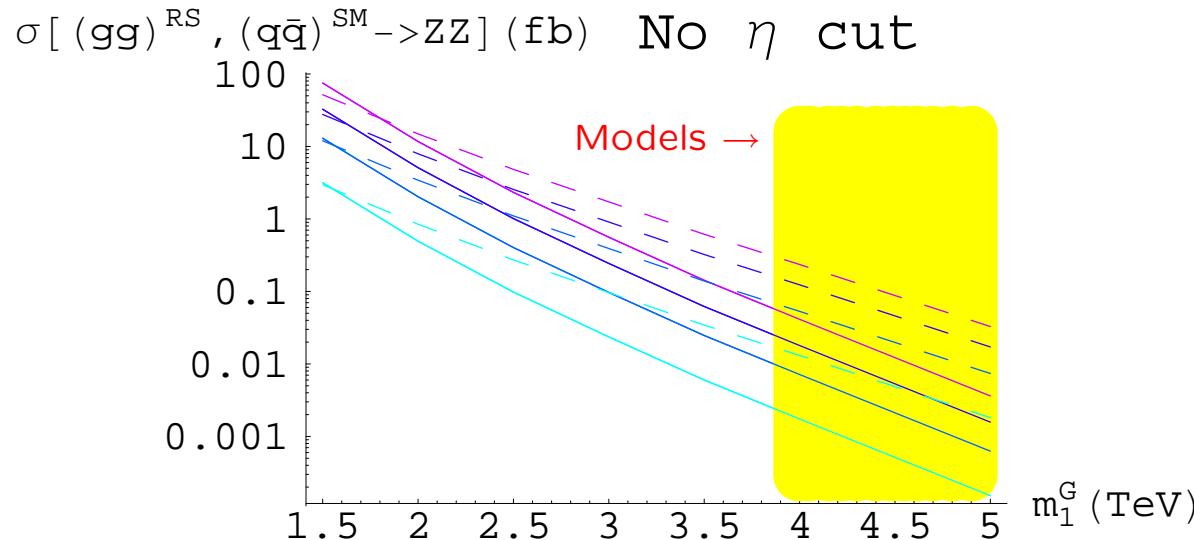
## Reducible Backgrounds:

- Hadronic  $ZZ$  decays: large QCD 4-jet background.
- $Z(\rightarrow jj)Z(\rightarrow \ell^+\ell^-)$  decays: large  $Z + j$  background.

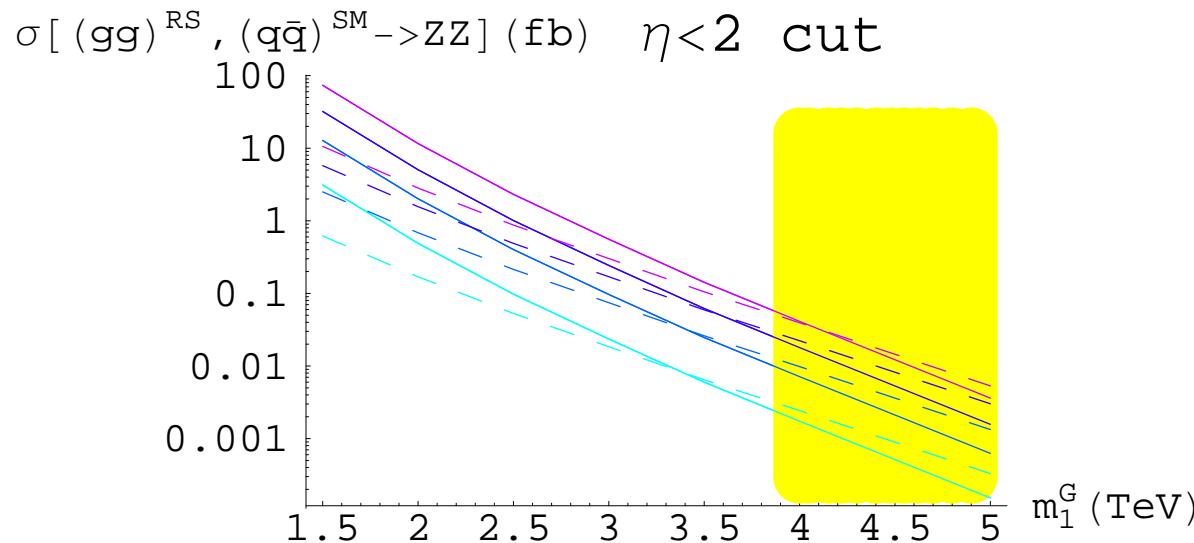
**Focus on  $ZZ \rightarrow 4\ell$  with irreducible  $B < S$ .**

**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).**



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

$c \equiv k/M_P$	0.5	1.0	1.5	2.0
$m_1^G \text{ (TeV)}$	< 1.5	1.6	1.9	2.2
$S/\sqrt{B}$	—	7.0	6.1	6.1

**SLHC with  $3 \text{ ab}^{-1}$ :**

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

## Concluding Remarks

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

### Challenging collider phenomenology.

- T. Krupovnickas and collaborators: KK gluon a promising signal.
- 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,  $L = 300 \text{ fb}^{-1}$ ,  $c = 2$ :  $m_1^G \approx 2 \text{ TeV}$ .
- SLHC reach,  $L = 3 \text{ ab}^{-1}$ ,  $c = 2$ :  $m_1^G \approx 3 \text{ TeV}$ .
- H.D., S. Gopalakrishna, and A. Soni: RS weak gauge bosons at the LHC.

### Multi-institute collaboration.

- BNL HET: very active in the rich phenomenology of warped models.