Possible early signs of warped space at the LHC

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BASED ON:

- **Davoudiasl, Perez & A. S., arXiv:0802.0203** LRS
- **Davoudiasl, Gopalakrishna & A. S arXiv:0908.1131** KKZ'
- **Davoudiasl, McElmurry & A. S. (WIP)** ϕ KKg
- **See also:**
- **Bauer, Casagrande, Grunder, Haisch & Neubert, arXiv:0811.3678** ϵ_K
- **Rehermann & Tweedie, arXiv:1007.2221** KKg

Warped Hierarchy/Flavor Models

Courtesy HD

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

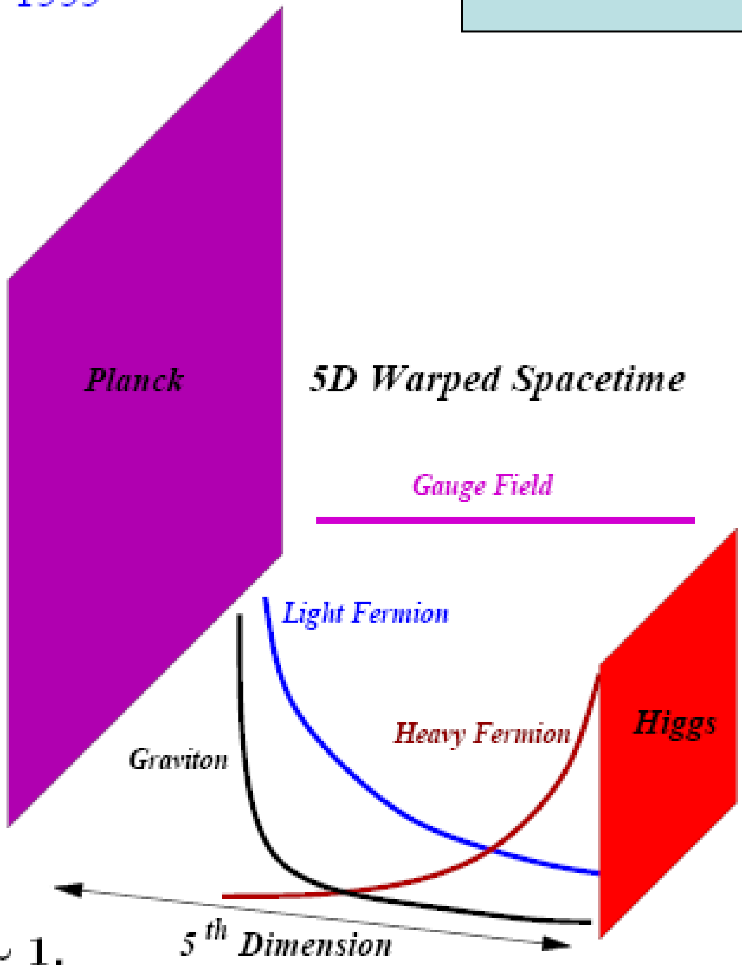
$k \gg 1$ TeV with $kr_c\pi \gtrsim 10$ (Hierarchy).

- **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

Fermion "geography" (localization) naturally explains:

Grossman&Neubert; Gherghetta&Pomarol; Davoudiasl, Hewett & Rizzo

- **Why they are light (or heavy)**
- **FCNC for light quarks are severely suppressed**
- **RS-GIM MECHANISM (Agashe, Perez,AS'04) flavor changing transitions though at the *tree level* (resulting from rotation from interaction to mass basis)are suppressed roughly to the same level as the loop in SM**
- **O(1) CP;…..in fact for neutron a (mild) CP problem**
- **Most flavor violations are driven by the top**

-> ENHANCED t-> cZ, (alsoD^0)….A VERY IMPORTANT "GENERIC" PREDICTION..Agashe, Perez, AS'06

EXTENSIVE RECENT STUDIES by BURAS et al and NEUBERT et al

Thus, RS represents an extremely interesting framework for a theory of flavor although an explicit consruction is still lacking

LRS@LHC

*(*Davoudiasl,Perez,AS,0802.0203*)*

- **LRS=Little Randall-Sundrum – a WARPED THEORY Of FLAVOR**
- **While the RS construction has a compelling appeal, as it allows a simultaneous resolution of SM (EW-Planck) and (EW-Flavor) puzzles, it is premised on a very strong assumption:**
- **Warping extends over many orders of magnitude w/o any basic change in physics, from the weak scale all the way to the Planck scale. Surely this assumption, no matter how appealing needs to be put to an experimental test.**
- **Is it possible, e.g. that the basic warped idea is used only for understanding EW-Flavor (>10^3 TeV) hierarchy via fermion localization, leaving open avenues for UV completion to Planck?**

Let's B Modest

Simple LRS models

- RS warping considered purely as a model of flavor i.e. $M_5 \sim M_{flavor}$, phenomenologically a viable possibility
- To suppress FCNC sufficiently, TeV<< M_{flavor}<< M_{planck} ; so in LRS, 1<< $k\pi r_c$ <<35
- Flavor constraints on LRS from ε_K , $k\pi r_c$ > ~ 6,

i.e.10^4 TeV see Bauer, Casagrande, Grunder, Haisch, Neubert, 2008

. Truncation alleviates some difficulty wrt EWPT,

e.g. $T_{tree} \propto k r_c \pi$ in RS models

. as usual invoke 5D custodial symmetry to suppress δT from UV-sensitive loops -> m_{KK} > ~ 3 TeV see Agashe, Delgado, May, Sundrum, 2003; Carena, Ponton, Santiago, Wagner, 2007

- LRS truncation factor: $y \equiv (kr_c|RS)/(kr_c\,|LRS)$ (y >> 1),

For numerics will take y ~6

NOTE: SIMPLE LRS ….NO BRANE KINETIC TERMS

Significant differences in phenomenology result in switching from RS as a theory of flavor to LRS as theory of flavor

LRS Phenomenology and Golden Modes

Courtesy HD

- $g_{KK}|_{UV} \sim g_4/\sqrt{kr_c\pi}, \quad g_{KK}|_{IR} \sim g_4\sqrt{kr_c\pi}.$

(i) Broad KK states become narrower by y.

(ii) Width into light states $(e^+e^-, u\bar{u}, \ldots)$ enhanced by $y \rightarrow$ BR$\sim y^2$.

(iii) $\sigma(f_i\bar{f}_j \rightarrow KK \rightarrow f_k\bar{f}_l) \propto \Gamma(KK \rightarrow f_i\bar{f}_j)\text{BR}(KK \rightarrow f_k\bar{f}_l)$

(i) $\oplus$ (ii) $\oplus$ (iii) $\Rightarrow \mathcal{S} \sim y^3$ and $\mathcal{B} \sim 1/y$ (over the width); $\mathcal{S}/\mathcal{B} \sim y^4$.

LRS, $y \approx 6 \Rightarrow \mathcal{S} \rightarrow \mathcal{O}(100)\mathcal{S} \quad ; \quad \mathcal{S}/\mathcal{B} \rightarrow \mathcal{O}(1000)\mathcal{S}/\mathcal{B}$!

$M_{Z'} \sim 4$ TeV and L $= 100$ fb^{-1}: $Z' \rightarrow \ell^+\ell^-$, $\ell = e, \mu$.

Compare with RS: $M_{Z'} \sim 2$ TeV and L $=$ 1000 fb^{-1}. Agashe *et al.*, 2007

Revived prospects for golden modes!

Dual picture

- **LRS model is holographically dual to dynamics with number of colors larger by the truncation factor (y)**

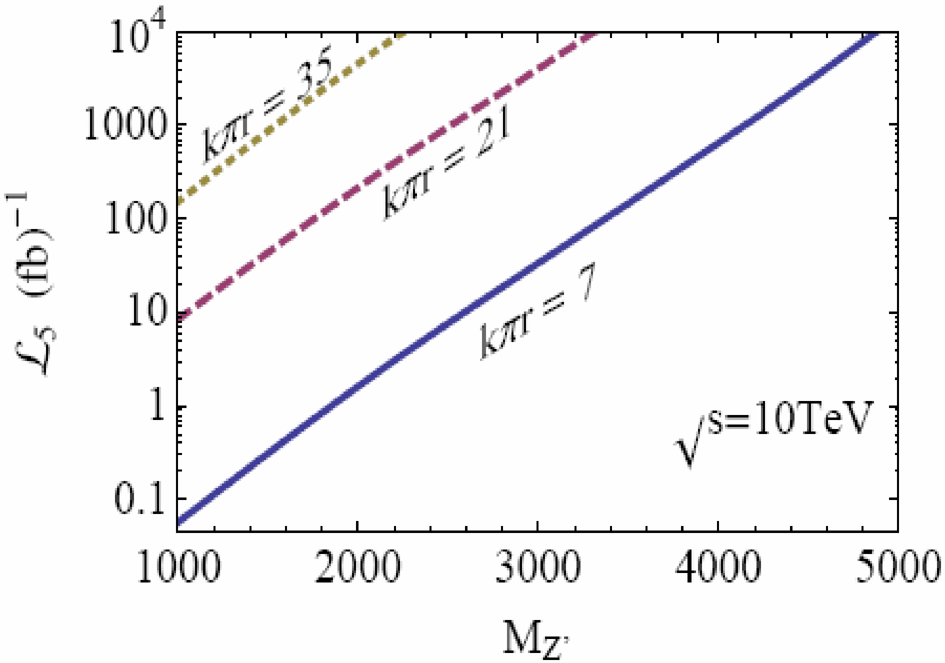
  -> enhancment of "golden" modes follows from the larger "ρ-γ" mixing and a weaker inter-composite coupling (each by a factor of y)

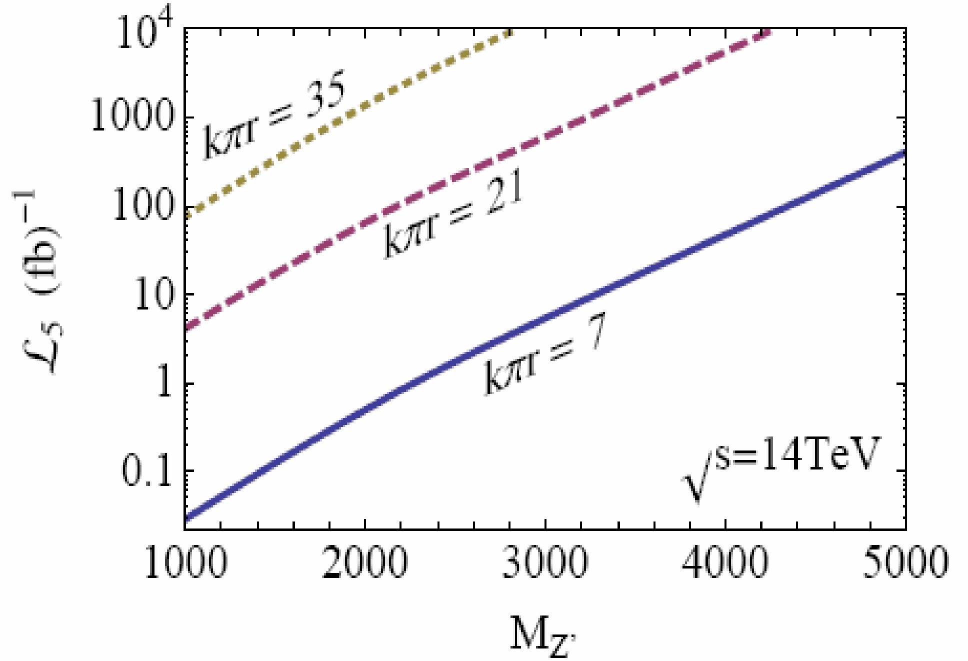
Experimental handle on truncation

- Clean signals into the golden modes are thus very sensitive to truncation
- Endowing us with an experimental handle on $kr_c\pi$ (M_5) in simple models
- Thus in case a TeV scale KK mode is discovered, we can quantitatively address whether it is relevant to the Planck-weak hierarchy or to some other large scale, such as flavor or in fact something else

LHC reach for the Little Z' via the clean dilepton channel

(Davoudiasl, Gopalakrishna and A.S. arXiv:0908.1131)





- $\mathcal{L}_5$: $\int L\,dt$ 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}.**

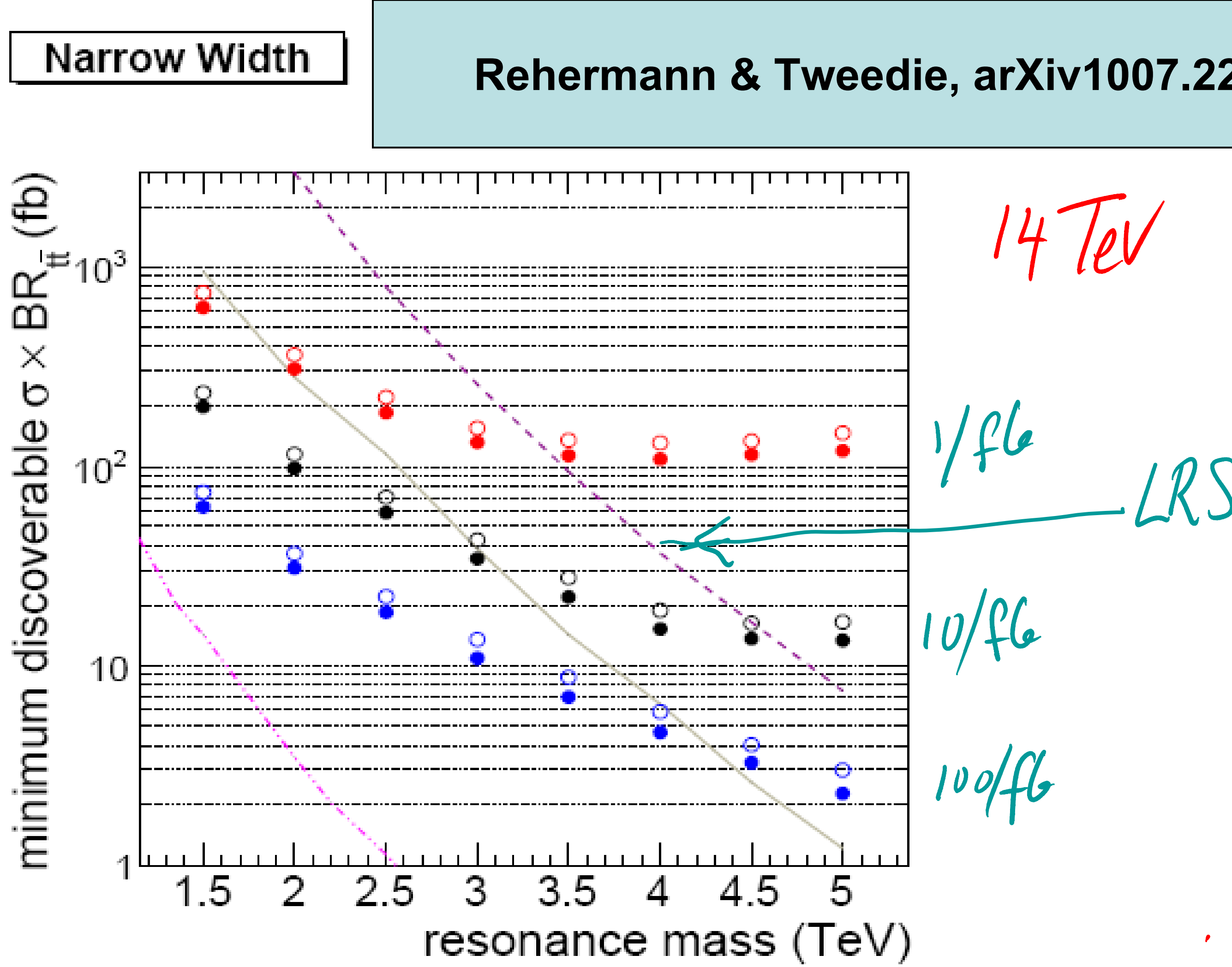
- $kr_c\pi \approx 35$ (RS), any channel: $M_{Z'} \approx 3$ TeV, $\sqrt{s} = 14$ TeV, 300 fb^{-1}.

Agashe *et al.*, 2007

Improved prospects for Little KK gluon @ the LHC

- Enhanced production by light quark pairs to $g^{(1)}$
- Decays to light quarks overwhelmed by backgrounds
- Discovery channel: $g^{(1)}$: $pp \to t\bar{t} \to bW(jj)\,\bar{b}W(\ell\nu)$
- RS case studied by Agashe, Belyaev, Krupvnickas, Perez, Virzi '06; Lillie, Randall, Wang '07
- LRS case briefly looked at by DGS '09
- Recently issue of efficient tagging of boosted top quarks via the semileptonic mode re-examined by Rehermann & Tweedie, see 1007.2221

Rehermann & Tweedie, arXiv1007.2221



LHC Reach

1/fb 3.5

10/fb 4.5 TeV

RT '10 were able to do a lot better than DGS'08; we got 3TeV needs 2/fb

A Light Little Radion

Radian is rather unique prediction of RS

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 Radian Signals

- Effective Langrangian:

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

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

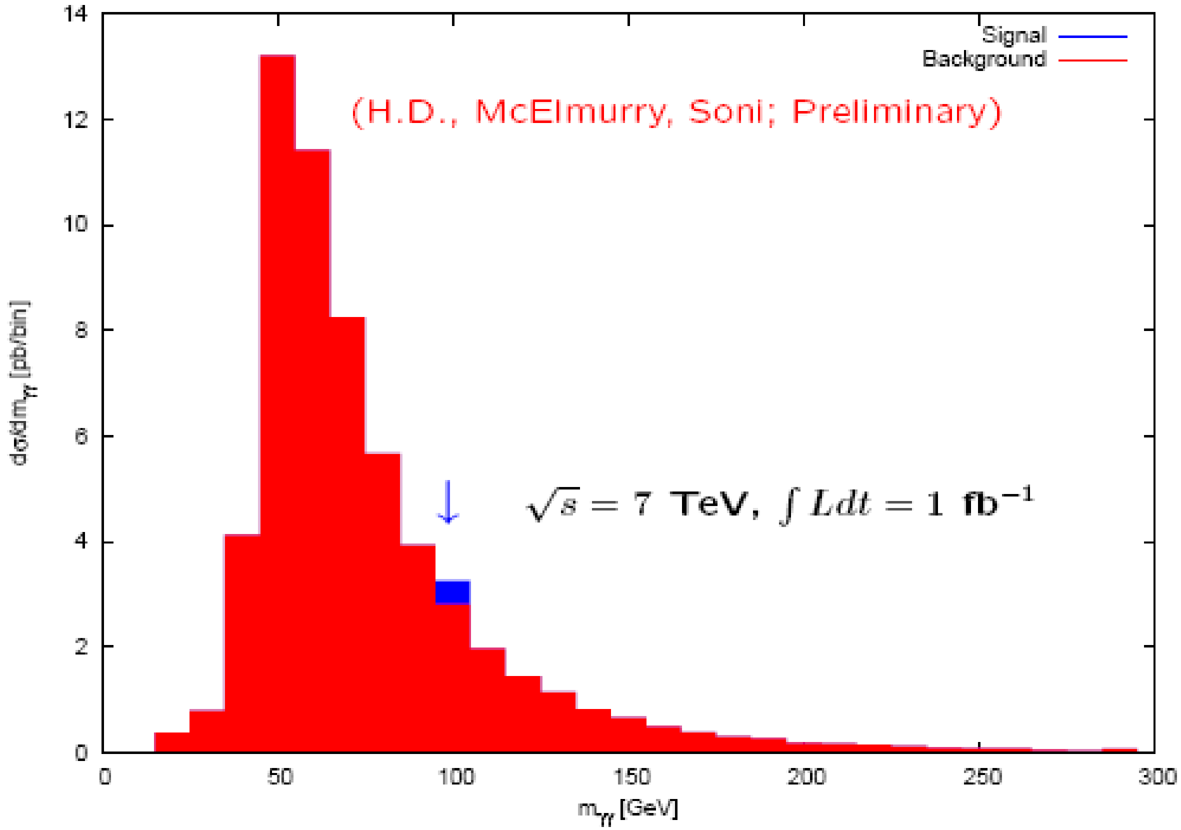
(No brane kinetic terms) Csáki, Hubisz, Lee, 2007 ⇒ PHENO. USUAL RS

For LRS couplings C's enhanced due $k\pi r_c$
Assume m_Φ < 140 GeV, then gg -> Φ -> γγ important signal
LITTLE RADIAN MAY BE ESPECIALLY INTERESTING FOR EARLY RUN @ 7 TeV

General light dilatons

- **In theories where the EW symmetry breaking originates from a spontaneously broken,nearly conformal sector, there is also a narrow scalar resonance, the psuedo-GB (pseudo-dilaton) of conformal symm breaking, properies much like Higgs.**
- **For collider signatures & distinction from Higgs, see: Goldberger,Grinstein,Skiba'07;Fan, Goldberger,Ross,Skiba'08**
- **Relation to walking technicolor, Applequist & Bai '10**

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



Courtesy HD

WORK IN PROGRESS

- $m_\phi = 100$ GeV, $\Lambda_\phi = 3$ TeV, $kr_c\pi = 7$ ($M_5 \sim 10^4$ TeV).
- $\text{Br}(\phi \to gg, b\bar{b}, \gamma\gamma) = 89.6\%, 8.0\%, 2.4\%$.
- $p_T(\gamma) > 20$ 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 $\Rightarrow S/B \approx 0.08$, $S/\sqrt{B} \approx 6$.

Summary

- Use basic warped space idea to formulate a theory for flavor
- A priori $k\pi r_c$ is an unknown; its rather an experimental question
- For a theory of flavor, the UV scale M_{flavor} >> TeV, but may be much lower than M_{Planck}
- Volume-truncated LRS is rather predictive model for flavor.
- Some EWP constraints get alleviated due volume truncation
- There are clean dilepton signals that are found to be very sensitive to the UV truncation.
- Light Little Radion, a unique prediction of the warped theory, Is an excellent target for the early LHC-run at 7 TeV.
- Also, with early LHC (7 TeV) -> Z' with mass~ 2TeV & with 14 TeV, Z' of 3 TeV and KKG of mass ~3.5 TeV may be accessible