WG4 Discussion on Warped-space KK guage bosons

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Talk Outline

- Focus on heavy EW spin-1 resonances
- Warped (RS) model
  - $SU(3)_{QCD} \times SU(2)_L \times SU(2)_R \times U(1)_X$ bulk gauge group
  - Precision electroweak observables require $M_{Z'}$, $M_{W_1^\pm} \gtrsim 2$ TeV
    - Makes discovery challenging at the LHC
- Equivalently, 4-D strongly coupled theory (AdS/CFT Corresp.)
- What are the general issues at colliders?

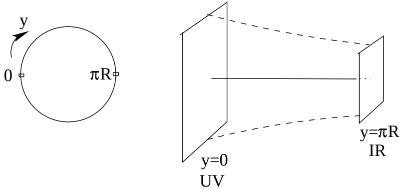
5D Warped Space

[Randall, Sundrum, 99]

$ds^2 = e^{-2k|y|}(\eta_{\mu\nu} dx^\mu dx^\nu) + dy^2$

Z_2 Orbifold -

- Planck (UV) Brane
- TeV (IR) Brane



R : radius of Ex. Dim.

k : curvature

Hierarchy prob soln:

- TeV Brane Higgs : $M_{EW} \sim k e^{-k\pi R}$: Choose $k\pi R \sim 34$

Bulk fields →AdS/CFT

Bulk Fermions explain flavor (in FCNC safe way)

Constraints

EWPT constraint [Csaki, Erlich, Terning - 02] [Agashe, Delgado, May, Sundrum - 03]

Bulk $SU(2)_L \times SU(2)_R \times U(1)_X$ and 3rd gen quarks $(2,2)$

- T and $Zb\bar{b}$ protected. S constraint [Agashe, Contino, DaRold, Pomarol - 06]
- EWPT $\Rightarrow M_{Z'} \gtrsim 2-3$ TeV [Carena, Ponton, Santiago, Wagner - 06,07]

Note that: $M_{Z'} = 2TeV \quad \Rightarrow \quad M_{KK\ Grav} = 3TeV$.

FCNC constraint [Agashe, Perez, Soni, 04] [Casagrande, Goertz, Haish, Neubert, Pfoh, 08]

Non-trivial flavor structure needed [Fitzpatrick, Perez, Randall - 07]

[Csaki, Falkowski, Weiler, 08]

Studies of KK states at the LHC

Our study on Electroweak KK

Agashe, Davoudiasl, SG, Han, Huang, Perez, Si, Soni.

arXiv:0709.0007 & 0810.1497

For KK Glue and Graviton see:

- KK Gluon at the LHC

  $L = 100\ fb^{-1}$ LHC reach is 4 TeV

  [Agashe, Belyaev, Krupovnickas,Perez,Virzi, 06] [Lillie, Randall, Wang, 07] [Lillie, Shu, Tait, 07]

- KK Graviton at LHC

  $L = 300\ fb^{-1}$ LHC reach is about 2 TeV

  [Agashe, Davoudiasl, Perez, Soni 07] [Fitzpatrick, Kaplan, Randall, Wang , 07]

- Associated Prod.

  [Guchait, Mahmoudi, Sridhar, 08]

[Other Refs. later]

EW Gauge Sector

Bulk Gauge group : $SU(2)_L \times SU(2)_R \times U(1)_X$

- Three neutral gauge bosons: $(W_L^3, W_R^3, X) \;\rightarrow\; Z'$
- Two charged gauge bosons: $(W_L^{\pm}, W_R^{\pm}) \;\rightarrow\; W'$

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Kaluza-Klein (KK) expansion: $A(x,y) = \sum_0^\infty f_n(y)\, A^{(n)}(x)$

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Kaluza-Klein (KK) expansion: $A(x,y) = \sum_0^\infty f_n(y)\, A^{(n)}(x)$

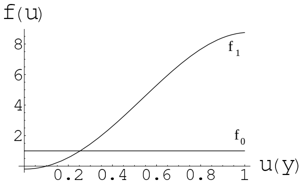
Symmetry breaking

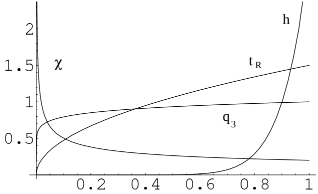
- $SU(2)_R \times U(1)_X \rightarrow U(1)_Y \quad \& \quad SU(2)_L \times U(1)_Y \rightarrow U(1)_{EM}$
  - Mixes zero-mode and KK-states
    - Mass eigenstates Z' and W'

Wave functions

Bulk field EOM gives profiles in extra-dimension

Fermion bulk mass (c parameter) controls localization





Overlap integral gives $\psi\psi V_\mu$: $\mathcal{I} = \int [dy]\, g_\psi(y)^2\, f_V(y)$

Compared to SM

- Z' couplings to h enhanced (also V_L by Equivalence Theorem!)
- Z' couplings to t_R enhanced
- Z'couplings to χ suppressed

Couplings

Define: $\xi \equiv \sqrt{k\pi R} \approx 5$

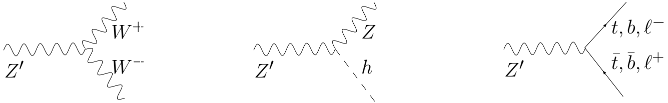
Z' overlap with Higgs $\longrightarrow \xi$

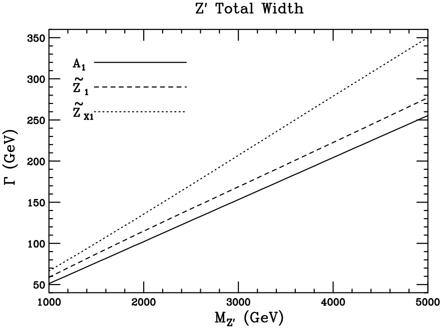
Z' overlap with fermions:

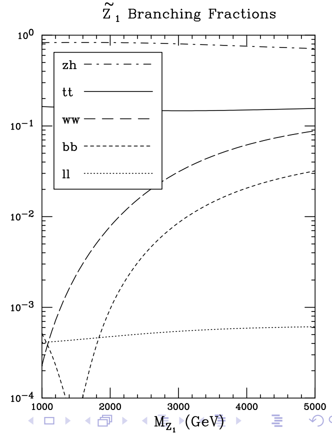
	Q_L^3	t_R	light fermions
$\mathcal{I}^+$	1	ξ	$-\frac{1}{\xi}$
$\mathcal{I}^-$	1	ξ	0

$$\bar{\psi}_{L,R}\gamma^\mu \Big[eQ\mathcal{I}A_{1\,\mu} + g_Z \left(T_L^3 - s_W^2 T_Q\right)\mathcal{I}Z_{1\,\mu} + g_{Z'}\left(T_R^3 - s'^2 T_Y\right)\mathcal{I}Z_{X1\,\mu}\Big]\psi_{L,R}$$

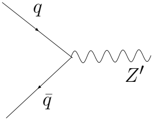
Z' decays and BR

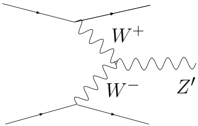


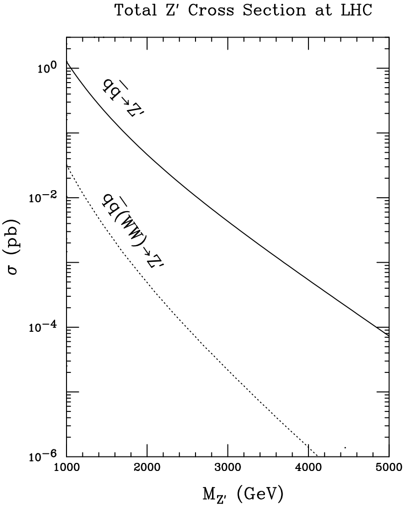




Z' production c.s. (LHC)





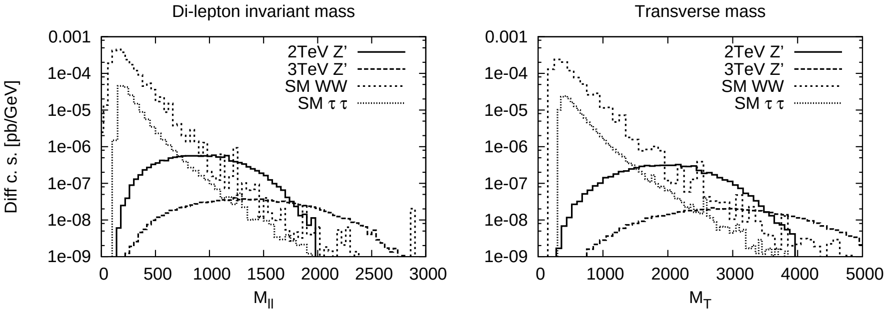


LHC Channels

$\mathcal{L}$ needed : $(\ldots, \ldots)\, fb^{-1}$ for (2 TeV, 3 TeV) is shown below

- $pp \to Z' \to W^+W^-$ $(100,\ 1000)\ fb^{-1}$
  - Fully leptonic : $W \to \ell\nu$; $W \to \ell\nu$
  - Semi leptonic : $W \to \ell\nu$; $W \to (j\,j)$
- $pp \to Z' \to Z\,h$
  - $m_h = 120\text{GeV}$: $Z \to \ell^+\ell^-$; $h \to b\,\bar{b}$ $(200,\ 1000)\ fb^{-1}$
  - $m_h = 150\text{GeV}$:
    $Z \to (j\,j)$; $h \to W^+\,W^- \to (j\,j)\ \ell\nu$ $(< 100,\ 300)\ fb^{-1}$
- $pp \to Z' \to \ell^+\ell^-$
  - Clean but needs high luminosity $(1000,\ -)\ fb^{-1}$
- $pp \to Z' \to t\,\bar{t}\ ,\ b\,\bar{b}$ [Djouadi, Moreau, Singh - 07]
  - KK gluon degenerate

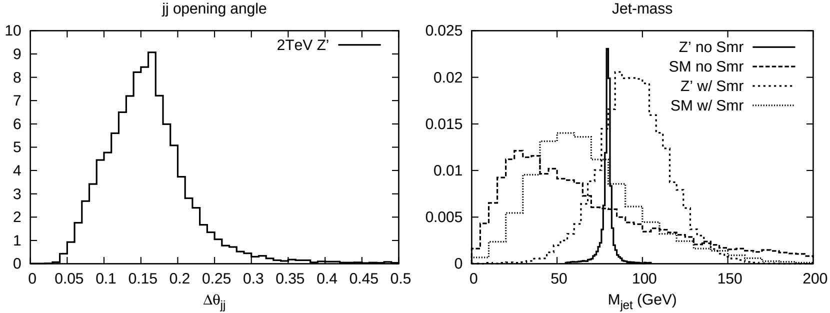
2 ν's $\Rightarrow$ cannot reconstruct event



$$M_{eff} \equiv p_{T_{\ell_1}} + p_{T_{\ell_2}} + \not{p}_T \qquad M_{T_{WW}} \equiv 2\sqrt{p^2_{T_{\ell\ell}} + M^2_{\ell\ell}}$$

$\mathcal{L}$ needed: 100 fb^{-1} (2 TeV) ; 1000 fb^{-1} (3 TeV)

$pp \to Z' \to W^+W^- \to \ell\,\nu\,j\,j$



j j Collimation implies forming m_W nontrivial : use jet-mass

In our study: Jet-mass after Parton shower in Pythia

[Discussions w/ Frank Paige] [Almeida, Lee, Perez, Sterman, Sung, Virzi, 08]

To account for (HCal) expt. uncert.

Smearing by $\delta E = 80\%/\sqrt{E}$; $\delta\eta, \delta\phi = 0.05$

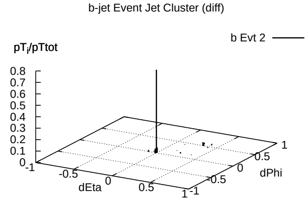
Tracker + ECal (2 cores?) have better resolutions [F. Paige] [M. Strassler]

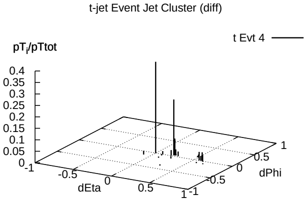
$\mathcal{L}$ needed: 100 fb^{-1} (2 TeV) ; 1000 fb^{-1} (3 TeV)

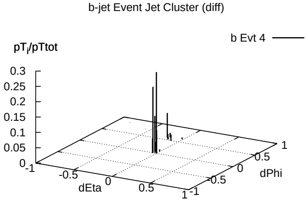
Signal c.s. $\sim 1 fb$

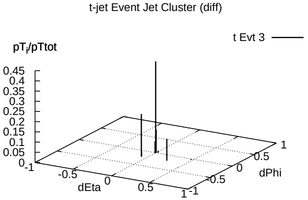
Bkgnd is single top + QCD W b b .... AND ...

$t\bar{t}$: hadronically decaying top can fake a b

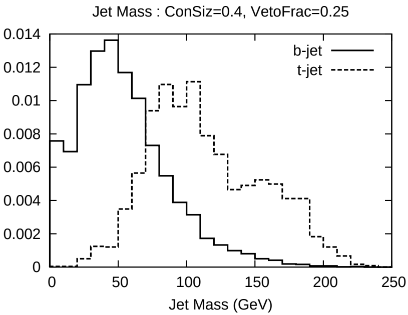


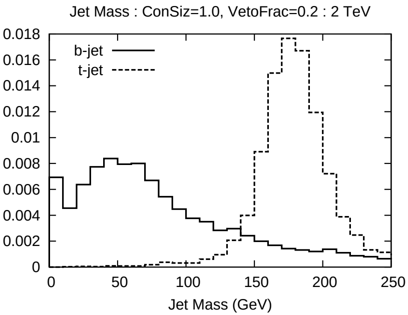






$W'^{\pm} \to t\, b \to \ell \nu b\, b$





Jet-mass cut: cone size 1.0 and $0 < j_M < 75 \Rightarrow$0.4% of *top* fakes *b*

$\mathcal{L}$ needed: 100 fb^{-1} (2 TeV)

Conclusions and Open questions

Conclusions

- Probing Z' and W' at the LHC challenging but possible
  - KK Grav needs large luminosity : SLHC?
- Improve reach by better "merged" jet reconstruction (jet mass)

Future Colliders (SLHC, VLHC, ILC, CLIC, muon collider)

- Can better detector resolutions give more suppression of QCD?
- Increased luminosity can give reasonable event samples
- What happens to signal vs. bkgnd with increasing $\sqrt{s}$?
- e^+e^- needs to have adequate $\sqrt{s}$ (EWPT constraints)

BACKUP SLIDES

Constraints

EWPT

Bulk $SU(2)_L \times U(1)_Y$

- $log\frac{M_{pl}}{M_{EW}}$ enhanced contributions to S, T [Csaki, Erlich, Terning - 02]
- $Zb\bar{b}$ coupling shifted

Bulk $SU(2)_L \times SU(2)_R \times U(1)_X$

- T-prarameter protected [Agashe, Delgado, May, Sundrum - 03]

Bulk $SU(2)_L \times SU(2)_R \times U(1)_X$ and 3rd gen quarks $(2,2)$

- T and $Zb\bar{b}$ protected [Agashe, Contino, DaRold, Pomarol - 06]

EWPT $\Rightarrow M_{Z'} \gtrsim 2-3$ TeV [Carena, Ponton, Santiago, Wagner - 06,07]

FCNC constraint

Non-trivial flavor structure needed For MFV example see [Fitzpatrick, Perez, Randall - 07]

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- $SU(2)_R \times U(1)_X \rightarrow U(1)_Y$: $(W_L^3, W_R^3, X) \rightarrow (W_L^3, B, Z_X)$
  - $Z_X \equiv \frac{1}{\sqrt{g_x^2+g_R^2}}(g_R W_R^3 - g_X X) \rightarrow (-,+)$; $W_R^\pm \rightarrow (-,+)$
  - $B \equiv \frac{1}{\sqrt{g_x^2+g_R^2}}(g_X W_R^3 + g_R X) \rightarrow (+,+)$; $W_L^\pm \rightarrow (+,+)$

Symm breaking by BC: $Z_X(-,+)$ means $Z_X|_{y=0} = 0$; $\partial_y Z_X|_{y=\pi R} = 0$

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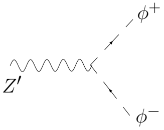
- $SU(2)_L \times U(1)_Y \rightarrow U(1)_{EM}$: $(W_L^3, B, Z_X) \rightarrow (A, Z, Z_X)$
  - By TeV brane Higgs

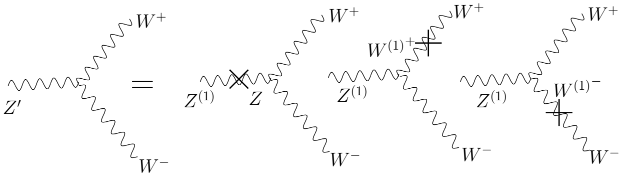
EWSB induced $Z'W^+W^-$ coupling

$Z^{(1)}V^{(0)}V^{(0)}$ is zero by orthogonality ...
... but induced after EWSB

Using Goldstone equivalence:



In Unitary Gauge:



Even though $\xi \cdot (\frac{v}{M_{KK}})^2$ suppressed ...
... can be overcome by $(\frac{M_{KK}}{m_Z})^2$ (from long. pol. vectors)

$W'^{\pm}$ LHC reach

Case (i): Channel	$M_{W_1^\pm}$ (TeV)	$\mathcal{L}$ (fb^{-1})	S/B	$S/\sqrt{B}$
$t\, b \longrightarrow \ell \nu b \bar{b}$	3	300	5.8 (0.9)	0.995 (0.95) CL
$Z\, W \longrightarrow \ell \ell \ell \nu$	3	1000	6	0.99 CL
$m_h = 120$: $W\, h \longrightarrow \ell \nu b \bar{b}$	3	300	1	0.99 CL
$m_h = 150$: $W\, h \longrightarrow (jj)\, \ell \nu\, (jj)$	3	300	2	0.9987 CL
Case (ii): Channel	$M_{W_1^\pm}$ (TeV)	$\mathcal{L}$ (fb^{-1})	S/B	$S/\sqrt{B}$
$t\, b \longrightarrow \ell \nu b \bar{b}$	2	1000	0.4 (0.2)	3.4 (2.5) σ
$Z\, W \longrightarrow \ell \ell \ell \nu$	3	1000	10	$>$ 0.9995 CL
$m_h = 120$: $W\, h \longrightarrow \ell \nu b \bar{b}$	3	300	2.4	$>$ 0.9995 CL
$m_h = 150$: $W\, h \longrightarrow (jj)\, \ell \nu\, (jj)$	3	300	4	$\gg$ 0.9995 CL