In Search of Extra Dimensions

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Extra dimensions: 96-year old idea!

- G. Nordström, 1914:

Unify pre-GR gravity and EM in 5D.

- Th. Kaluza, 1921:

Unify GR and EM in 5D.

- O. Klein, 1926:

Unify GR and EM with one *compact* extra dimension.

Extra dimensions in Recent Times

- String theory, since the 1980's.

- Quantum gravity.

- Consistency requires 10 or 11 dimension.

- Extra dimensions compactified near fundamental scale M_F ($M_P \sim 10^{19}$ GeV).

- Particle Physics, since the 1990's.

- Motivation: <u>the hierarchy</u>, $m_W/M_P \sim 10^{-17}$.

- Antoniadis, 1990: TeV^{-1} extra dimensions and SUSY breaking.

- Weak scale superstrings, Lykken, 1996.

- Large Extra Dimensions; Arkani-Hamed, Dimopoulos, Dvali, 1998: $m_W \lesssim M_F$.

- A Warped Extra Dimension; Randall, Sundrum, 1999: $m_W \sim e^{-k\pi r_c} M_P$; $k\pi r_c \sim 35$.

- TeV^{-1} Universal Extra Dimensions; Appelquist, Cheng, Dobrescu, 2000.

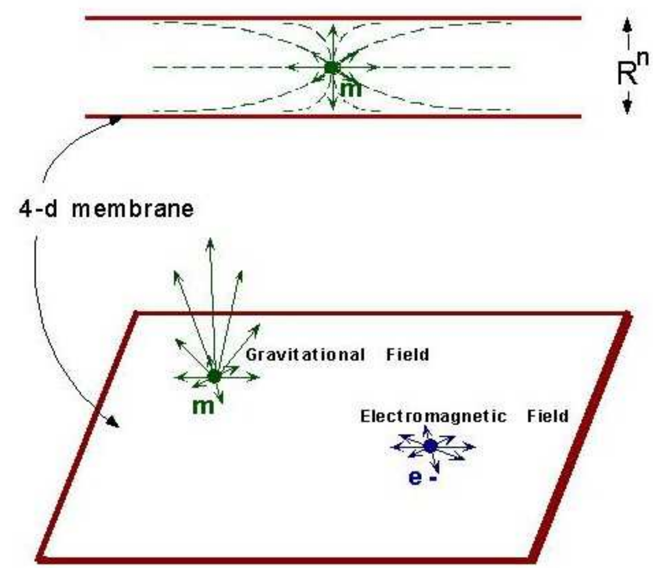
- . . .

Large Extra Dimensions (LED)

Arkani-Hamed, Dimopoulos, Dvali, 1998

- n compact extra dimensions, $M_F \sim$ TeV: $M_P^2 \sim R^n\, M_F^{n+2}$

- $R \lesssim$ mm (gravity tests) $\Rightarrow n \geq 2$.



- SM localized on a 3-brane (4D).

- Gravity propagates in all dimensions.

- Gravity "diluted" in extra dimensions.

- Graviton Kaluza-Klein (KK) modes.

- Quantized momenta in extra dimensions:

$m_{KK} = j/R; \quad j = 0, 1, 2, \ldots$

$\mathcal{L} = \frac{-1}{M_P} T^{\mu\nu} \sum_{\{\vec{j}\}} h_{\mu\nu}^{(\vec{j})}; \quad \text{fm} \lesssim R \lesssim \text{mm}; \quad 2 \leq n \leq 6.$

Key Signals for LED

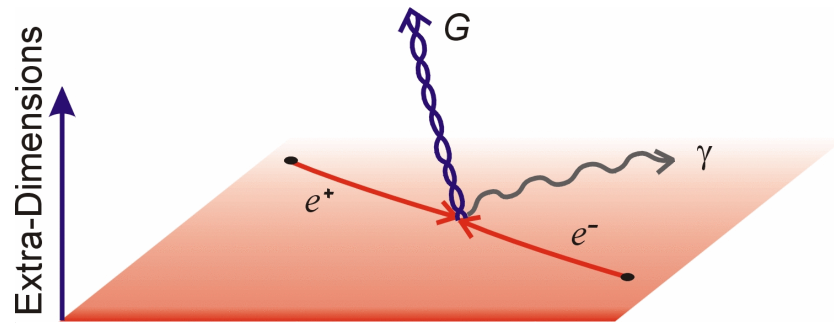
- Missing energy: KK gravitons escape into the "bulk."

$q\bar{q} \to j\, G_{KK}\, (\not{E}) \quad ; \quad e^+e^- \to \gamma\, G_{KK} \;\; \ldots$

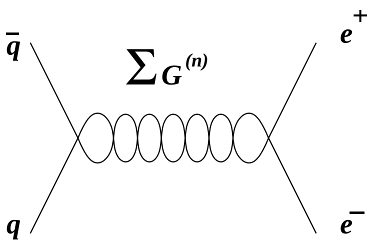
Missing E signature.

Giudice, Rattazzi, Wells 1998

Mirabelli, Perelstein, Peskin, 1998



- Virtual exchange of spin-2 tower.



Spin-2 mediated angular distributions.

Han, Lykken, Zhang, 1998
Hewett, 1998

- Black hole production for $\sqrt{s} \gg M_F$.

Giddings, Thomas, 2001

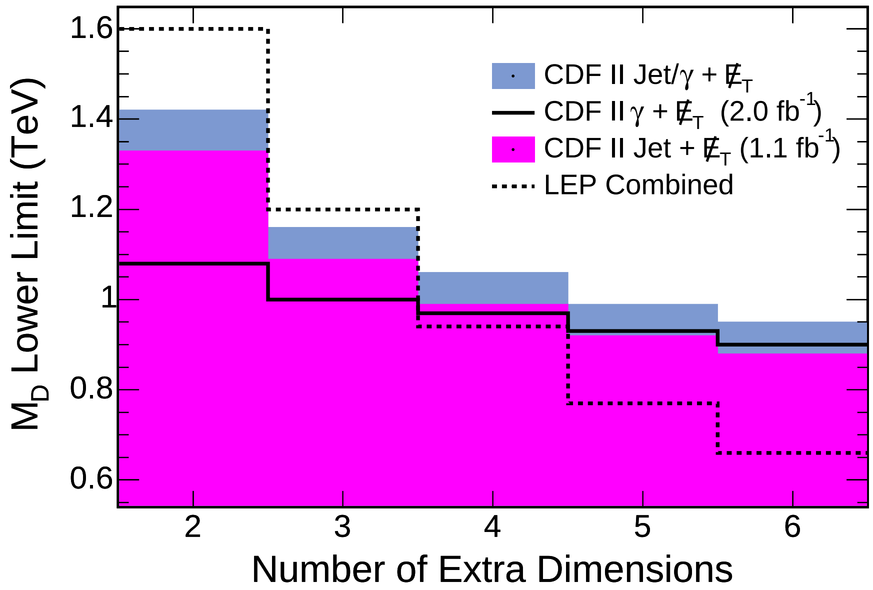
Dimopoulos, Landsberg, 2001

- Potentially spectacular signals: energetic multi-jets, leptons, ...
- Under debate.

e.g. Meade, Randall, 2007: $2 \to 2$ quantum gravity effects more likely at the LHC.

LED: Current Bounds and Future Prospects

- Collider limits:



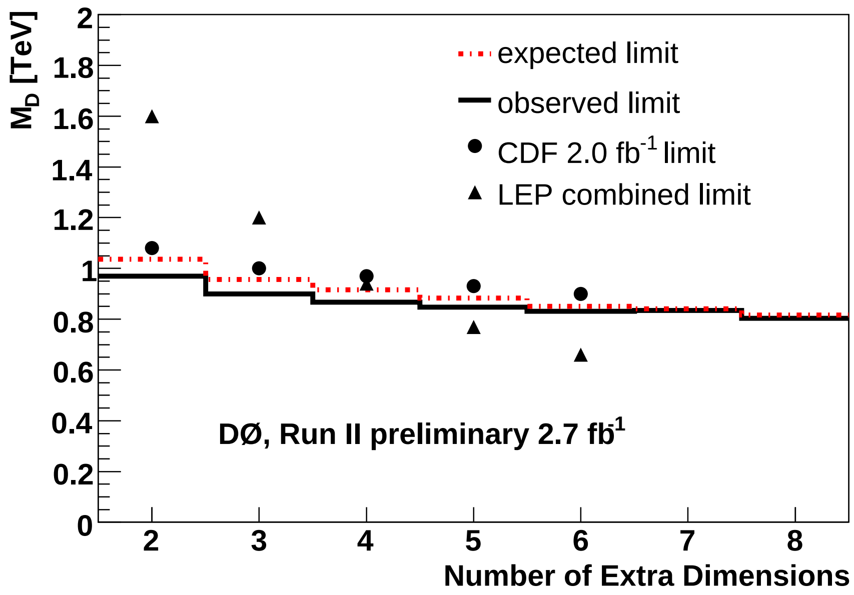
Jets/$\gamma + \not{E}_T$

CDF Collaboration (T. Aaltonen et al.),

Phys.Rev.Lett.101:181602,2008

DØ Collaboration; $\gamma + \not{E}$

DØ Note 5729-CONF, 2008



- Cosmology and Astrophysics: Arkani-Hamed, Dimopoulos, Dvali, 1998

- Cosmology: Typically $T_{reheat} \lesssim 1$ GeV for $M_F \sim 1$ TeV.

- SN 1987A, energy loss: $M_F \gtrsim 50$ TeV for $n = 2$.
Cullen, Perelstein, 1998

- Neutron star, excess heat from KK-could: $M_F \gtrsim 700(30)$ TeV, $n = 2(3)$.
Hannestad, Raffelt, 2001 & 2003

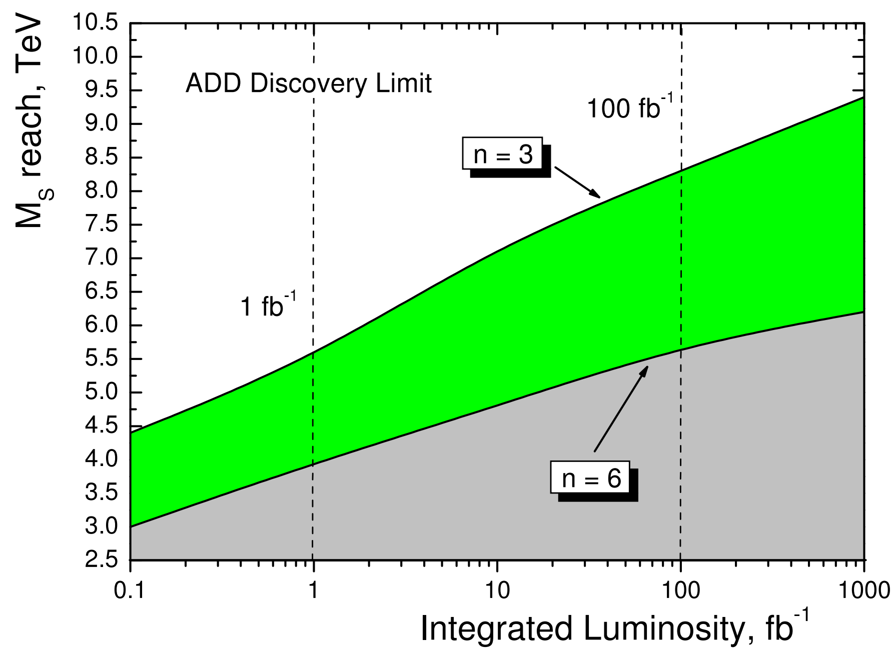
- 5σ LHC reach:

Kabachenko, Miagkov, Zenin, ATL-PHYS-2001-012

channel	n		2	3	4	5
	luminosiy					
$\gamma\gamma$	10 fb^{-1}	M_S^{max} (TeV)	6.3	5.6	5.1	4.9
		S/B	36/18	36/18	39/25	34/13
	100 fb^{-1}	M_S^{max} (TeV)	7.9	7.3	6.7	6.3
		S/B	50/53	62/96	55/72	51/53
l^+l^-	10 fb^{-1}	M_S^{max} (TeV)	6.6	5.9	5.4	5.1
		S/B	33/11	31/8	30/6	30/6
	100 fb^{-1}	M_S^{max} (TeV)	7.9	7.5	7.0	6.6
		S/B	49/48	38/21	36/16	29/6
$\gamma\gamma + l^+l^-$	10 fb^{-1}	M_S^{max} (TeV)	7.0	6.3	5.7	5.4
	100 fb^{-1}	M_S^{max} (TeV)	8.1	7.9	7.4	7.0

Dimuon channel

I. Belotelov *et al.*, CMS Note 2006/076



Universal Extra Dimensions (UED)

Appelquist, Cheng, Dobrescu, 2000

- All SM in TeV^{-1} extra dimensions.

- Bulk momentum conservation: 4D KK number preserved.

- KK particles not singly produced.

- Only loop contributions to EW precision data.

- Less stringent bounds on $1/R$.

- Chiral fermions via $\mathbb{Z}_2$ orbifolds: KK number $\rightarrow$ KK-parity.

- Compactification: Lorentz violation along extra dimensions.

- Loops around compact directions: δm_{KK}.

Cheng, Matchev, Schmaltz, 2002

- Lightest KK particle (LKP) stable, dark matter candidate.

- Can mimic supersymmetry at the LHC!

Cheng, Matchev, Schmaltz, 2002

UED: Current Status and LHC Prospects

- EW precision:

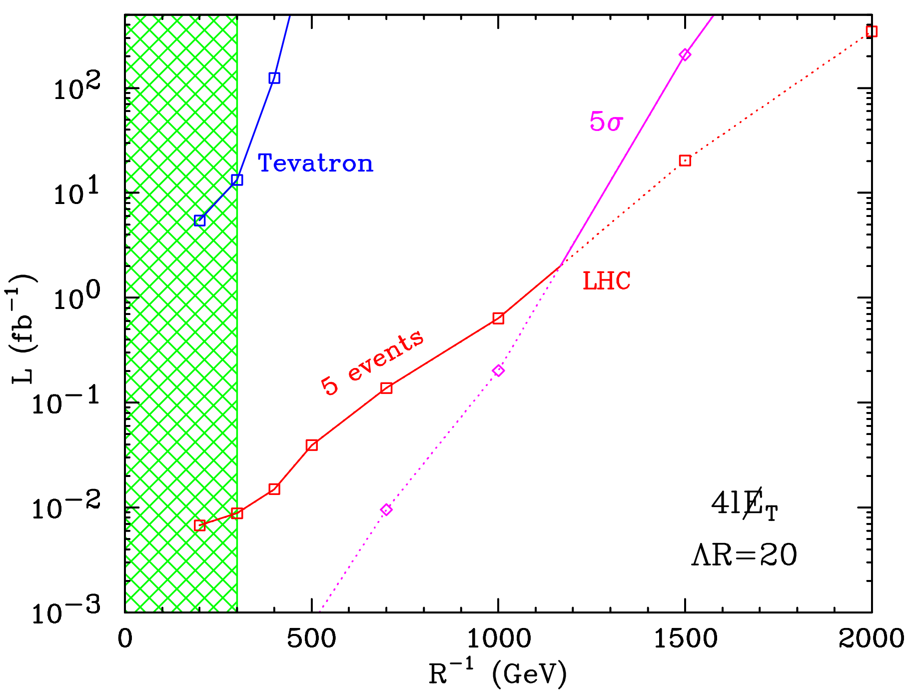
Hooper and Profumo, Phys.Rept.453:29-115,2007

- Tevatron: CDF, Run IB

$m_{KK} \gtrsim 280$ GeV

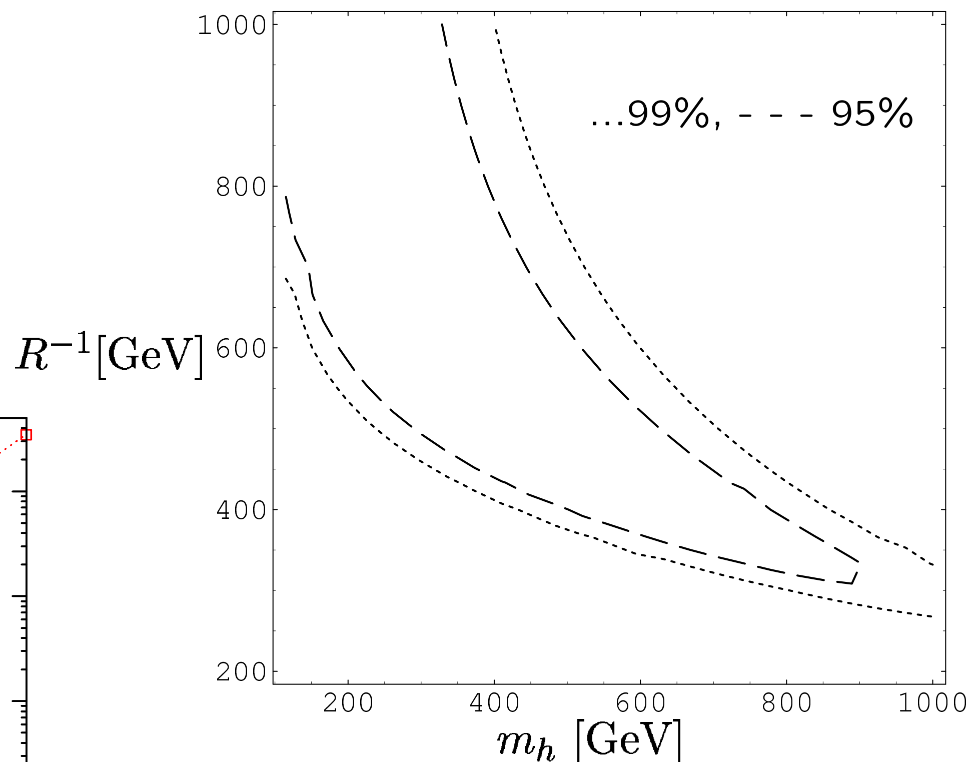
Lin, 2005

- LHC Prospects:



Cheng, Matchev, Schmaltz, Phys.Rev.D66:056006,2002

Flacke, Hooper, March-Russell, 2006



Warped Models

- The Randall-Sundrum (RS) Model

Randall, Sundrum, 1999

- 5D warped model of hierarchy, $M_5 \sim M_P$.

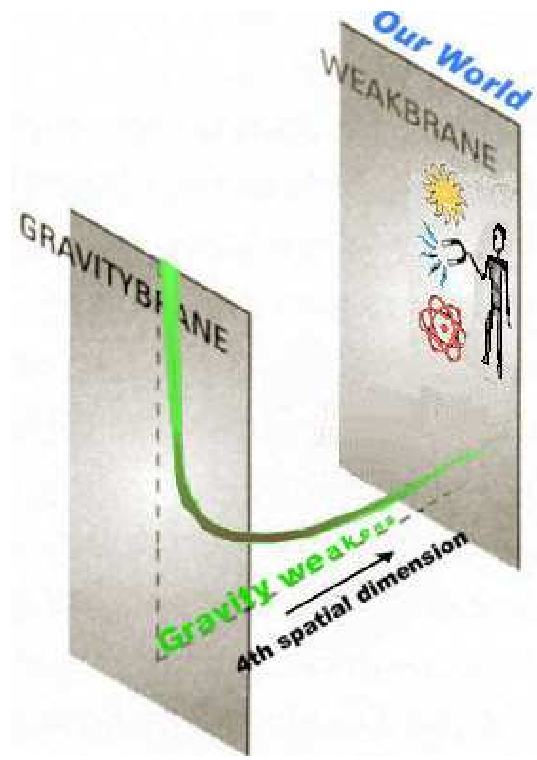
- A slice of AdS_5 spacetime.

- Negative constant curvature.

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

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

- AdS/CFT: Dual geometric picture of strong dynamics.
Maldacena, 1997



- Metric: $ds^2 = \underbrace{e^{-2ky}}_{\text{warp factor}} \eta_{\mu\nu}\, dx^\mu dx^\nu - dy^2$.

- $k \lesssim M_5$ and $y \in [0, \pi r_c]$.

- Redshift: $e^{-kr_c\pi}\langle H_5\rangle \sim m_W$; IR-localized Higgs, $\langle H_5\rangle \sim k$.

- $k\pi r_c \approx 35$; hierarchy via exponentiation.

RS Signatures with SM on the Wall

- TeV-scale tower of KK gravitons.

- KK masses $m_n = x_n k e^{-k\pi r_c}$

H.D., Hewett, Rizzo, 1999

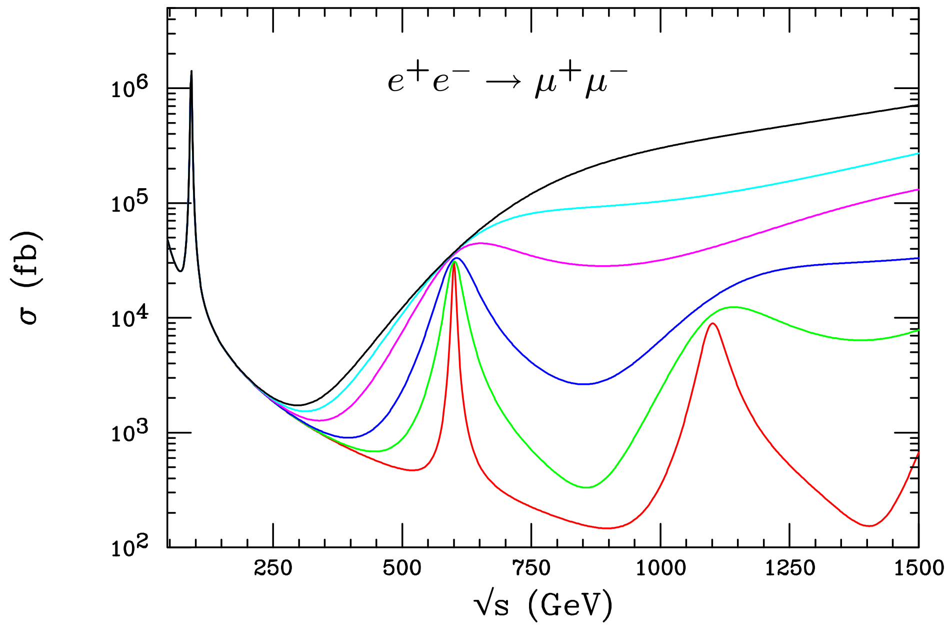
$x_n = 3.83, 7.02, \ldots$

- Coupling to SM-brane: $\sim$TeV^{-1}.

- KK graviton spin-2 resonances.

- Decay into e^+e^-, $\gamma\gamma$, ...

- Distinct signature.



- Stabilized geometry $\longrightarrow$ Radion scalar

Goldberger, Wise, 1999

- Typically lighter than KK modes.

- Couplings similar to Higgs.

- Can mix with Higgs through curvature-scalar coupling.

Csáki, Graesser, Kribs, 1999

Tevatron Bounds and LHC Prospects

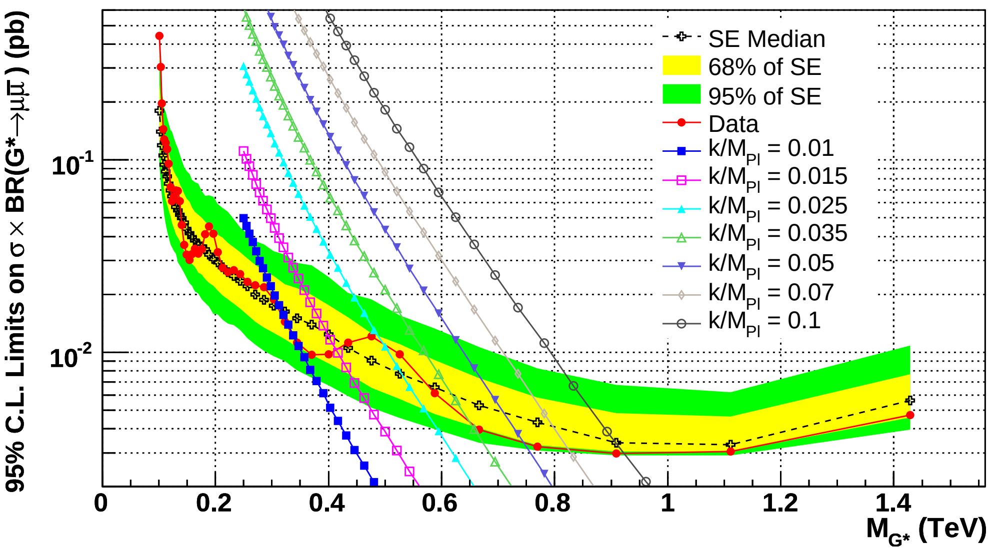
CDF Collaboration (Aaltonen *et al.*); di-muon channel

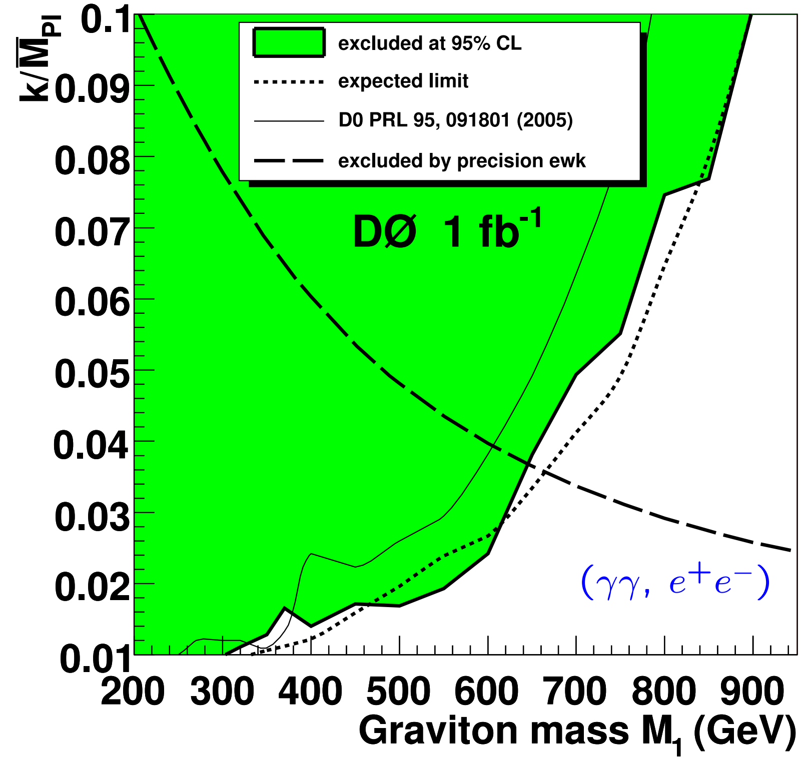
Phys.Rev.Lett.102:091805,2009

$m_G > 921$ GeV for $k/M_{Pl} = 0.1$; 2.3 fb^{-1}

D0 Collaboration (Abazov *et al.*)

Phys.Rev.Lett.100:091802,2008

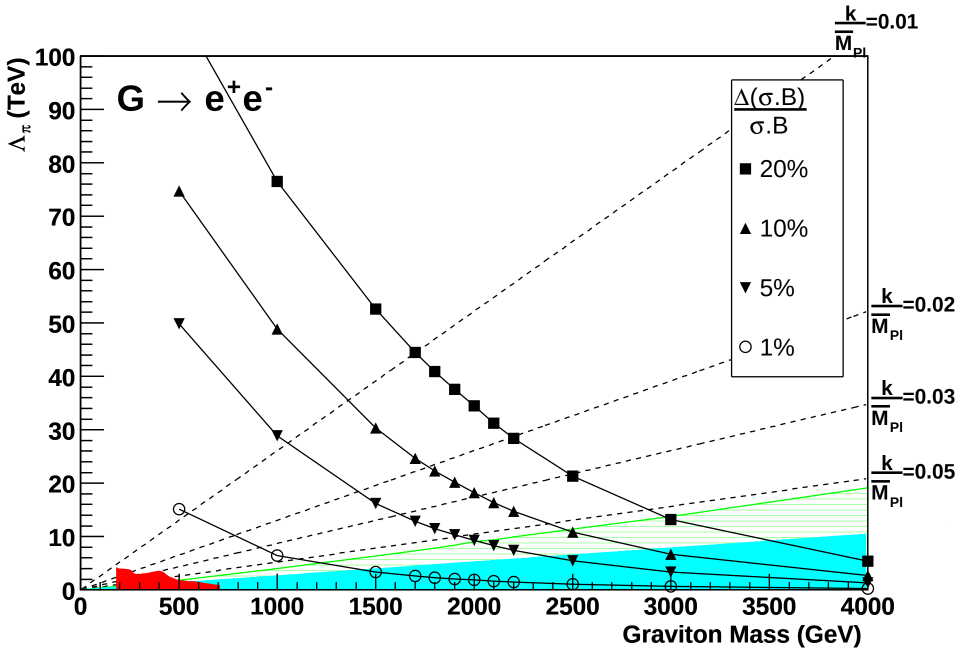




$(\gamma\gamma,\ e^+e^-)$

- ATLAS: 100 fb^{-1}, 3.5 TeV for $k/M_P \simeq 0.1$.

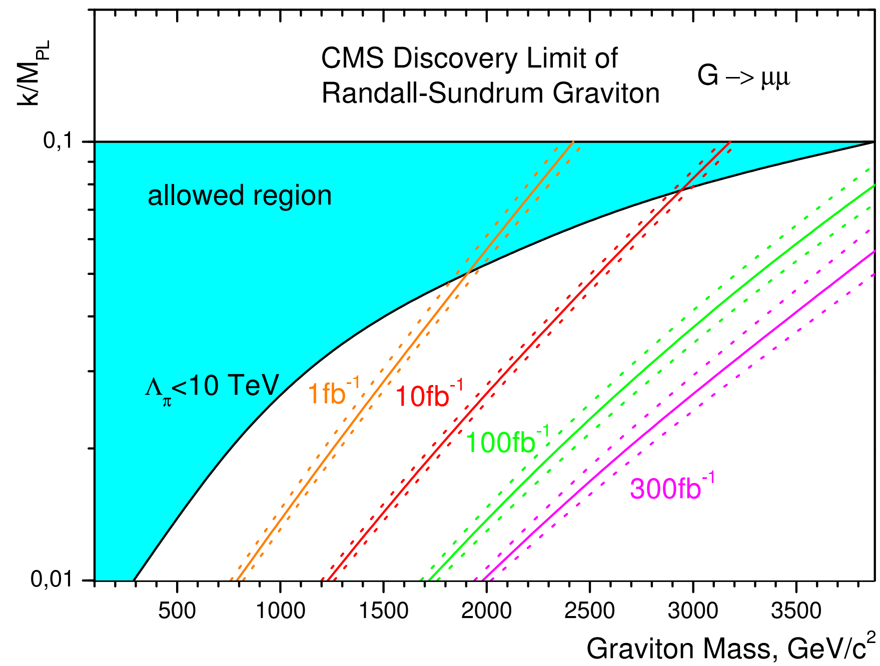
Allanach *et al.*, JHEP 0212:039,2002



- CMS:

100 fb^{-1}, 4 TeV for $k/M_P \simeq 0.1$.

Belotelov *et al.*, CMS Note 2006/104



The RS Model with 4D SM (1999)

Pros:

- Natural Planck-weak hierarchy.
- Striking signals.

Cons:

- Dangerous operators: Large IR cutoff-scales $\longrightarrow$ little hierarchy.
- Flavor still a mystery.

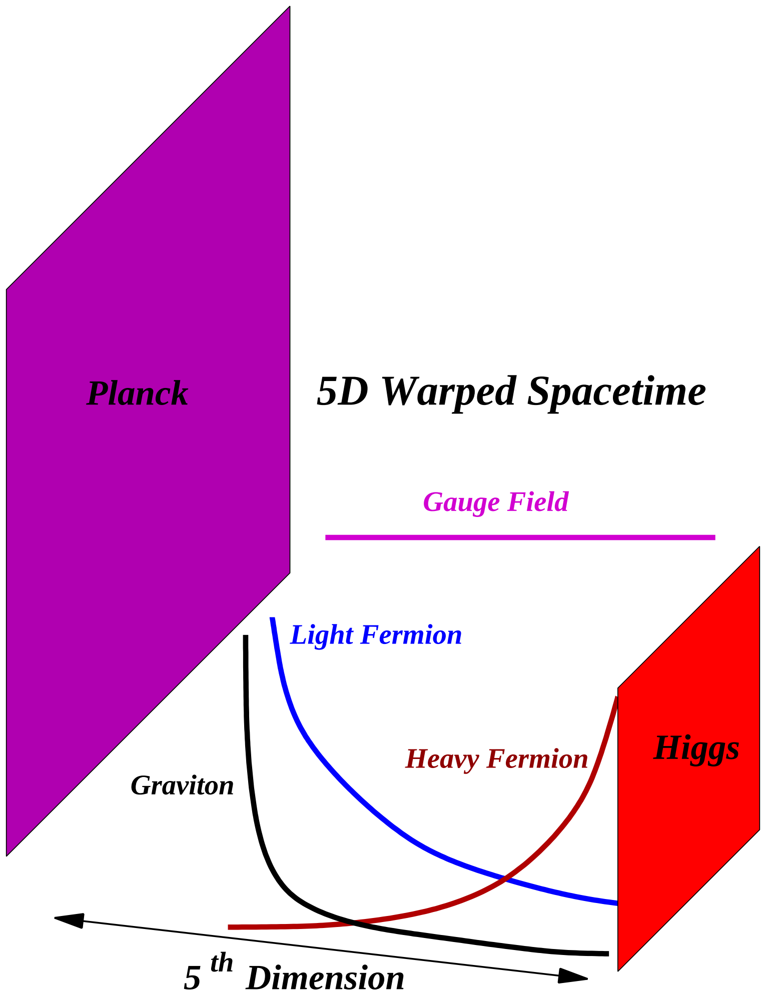
SM Flavor from a Warped Bulk

- 5D fermion masses, $m/k \sim 1 \rightarrow$ localization. Grossman, Neubert, 1999

- UV(IR)-localization (overlap with Higgs) $\rightarrow$ Light (heavy) fermion.

- UV-localization: Large effective cutoff scales. Gherghetta, Pomarol, 2000

$\therefore$ Unwanted light flavor operators suppressed.



- 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.

- Important production and decay channels 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

Collider Signals and Realistic Bulk Flavor

- The basic RS signals need to be revisited.

- KK gluons:

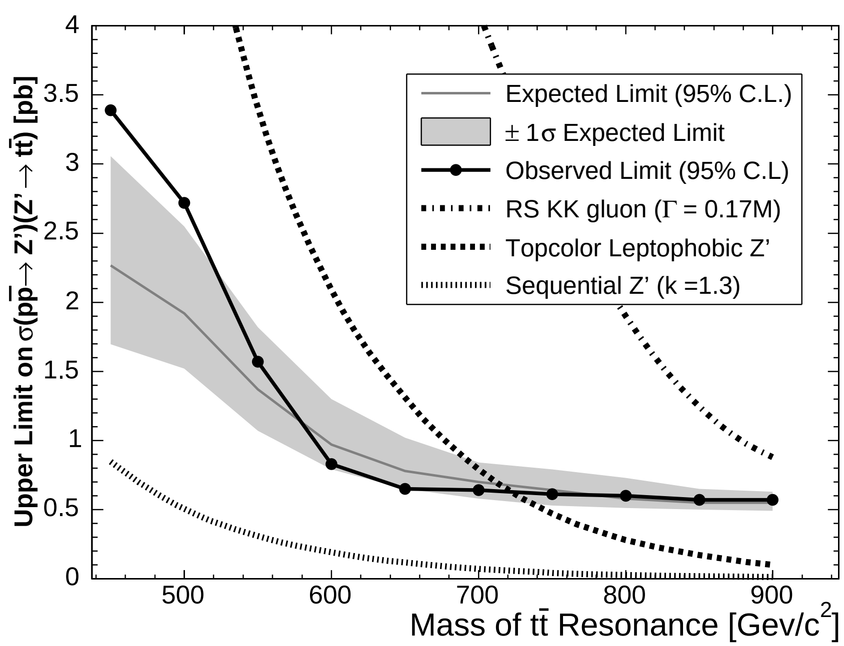
Agashe, Belyaev, Krupovnickas, Perez, Virzi, 2006

Lillie, Randall, Wang, 2007

- Production from light quark initial states, suppressed.
- Decay mostly to $t\bar{t}$, $\Gamma_{KK} \sim m_{KK}/6$.
- Top-polarization (different t_L and t_R KK gluon couplings) a handle.
- LHC reach 3-4 TeV with 100 fb^{-1}.

- Limits on narrow $t\bar{t}$ resonances:

CDF Collaboration (T. Aaltonen *et al.*)
Phys.Rev.D77:051102,2008 (995 pb^{-1})



$\star$ Light t^1 ($SU(2)_L \times SU(2)_R \times \mathbb{Z}_2$ models):

- Favored by EW data.

Carena, Pontón, Santiago, Wagner, 2006

- Larger Γ_{KK}, reduced BR($g^1 \to t\bar{t}$).

Carena, Medina, Panes, Shah, Wagner, 2008

Fitzpatrick, Kaplan, Randall, Wang, 2007

Agashe, H.D., Perez, Soni, 2007

- KK gravitons:

- Distinct RS signal.
- Production through gg initail state, volume suppressed.
- Golden (dilepton, diphoton) modes negligible.
- Decay through the Higgs (including Z_L/W_L) and top sectors.
- $gg \to G^1 \to Z_L Z_L \to 4\ell \Rightarrow$ LHC reach $\lesssim 2$ TeV with 300 fb^{-1}. ADPS, 2007
- $Z \to jj$ highly boosted ($E \sim 1$ TeV), dominated by $Z + j$ background.

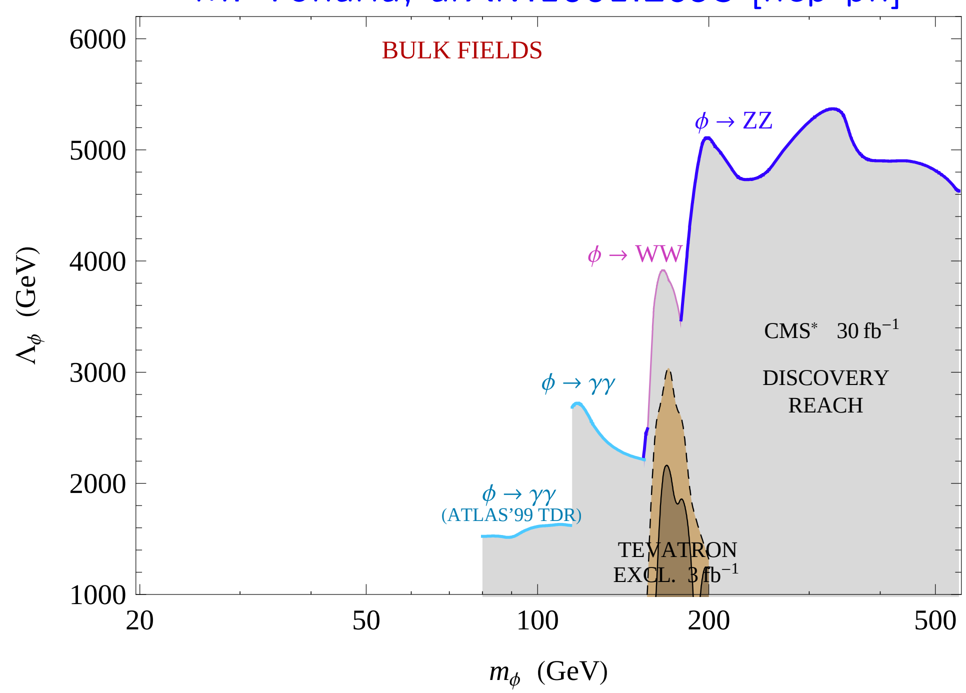
- The Radion:

- Associated with fluctuations of r_c.
- Typically the lightest new 5D state.
- 5D SM: new tree-level couplings.

Csáki, Hubisz, Lee, 2007

LHC reach from Higgs projections →

M. Toharia, arXiv:1001.2693 [hep-ph]



- The electroweak sector:

- 5D $SU(2)_L \times SU(2)_R \times U(1)_X$ to accommodate EW precision data.

- Z': Agashe, *et al.*, 2007

- At the TeV scale, 3 neutral states, collectively denoted by Z'.

- Production dominated by light quark initial states.

- Main decay channels IR-brane fields: H, W_L/Z_L, t.

- $Z' \to W_L^+ W_L^- \to \ell^+ \ell^- \not{E}_T$: LCH reach 2 TeV with 100 fb^{-1}.

- $W \to jj$ boosted dijet challenge, requires more detailed analysis.

(Use of EM calorimeter to find 2 EM cores a possibility.)

- $t\bar{t}$ dominated by KK gluon "background."

- W': Agashe, Gopalakrishna, Han, Huang, Soni , 2008

- 4 Charged states.

- No KK gluon pollution.

- LHC reach similar to Z'.

- Reach may be improved by better control over reducible backgrounds.

Little Randall-Sundrum (LRS) Models

H.D., Perez, Soni, 2008

- RS as a model of flavor: $M_5 \ll M_P$ viable option.
- $M_5 \gg$ TeV needed to suppress unwanted (FCNC,...) operators.
- Volume-truncated RS models: $1 \ll k r_c \pi \ll 35$.

- Truncation: some unwanted contributions suppressed.

Example: tree-level oblique parameter $T_{\text{tree}} \propto k r_c \pi$ in RS models.

(5D custodial symmetry to suppress δT from UV-sensitive loops.)

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

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

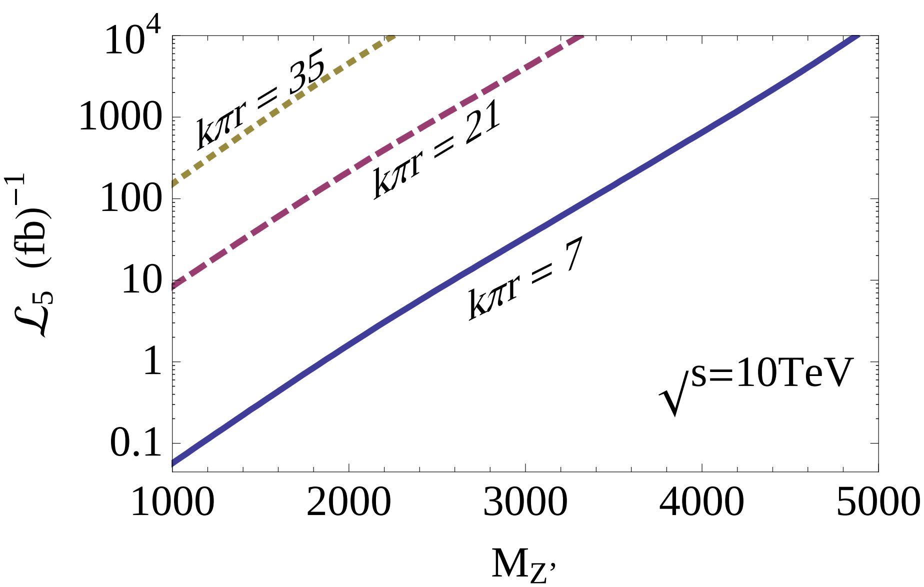
Example: $S \sim \sigma(q\bar{q} \to Z' \to \ell^+\ell^-) \propto 1/(k r_c \pi)^3$.

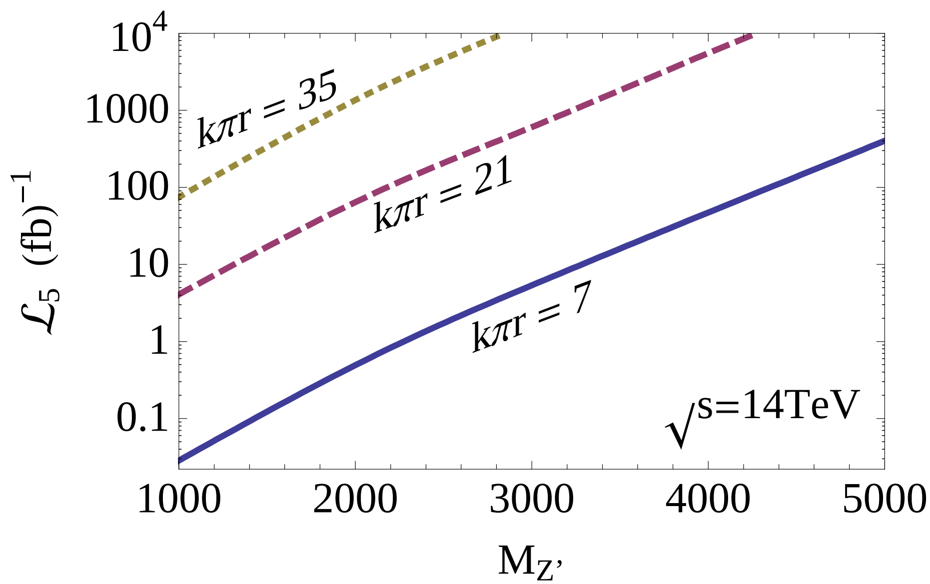
- Flavor constraints on LRS from ϵ_K: $k\pi r_c \gtrsim 7$ $(M_5 \gtrsim 10^4$ TeV).

Bauer, Casagrande, Grunder, Haisch, Neubert, 2008

Dilepton Channel LHC Reach for the Little Z'

H.D., Gopalakrishna, Soni, Phys.Lett.B686:239-243,2010





- 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).
- For $kr_c\pi \approx 7$: $M_{Z'} \approx 2(3)$ TeV at $\sqrt{s} = 10\,(14)$ TeV with $1\,(4)$ fb^{-1}.
- Original RS ($kr_c\pi \approx 35$): $M_{Z'} \approx 3$ TeV, $\sqrt{s} = 14$ TeV, <u>300 fb^{-1}</u> (any channel).
- Sensitivity to <u>$kr_c\pi$</u> can give clues about the UV scale M_5.

Conclusions

- Extra dimensions: possibilities for hierarchy and more.

- New phenomena at the TeV scale.

- Discovery a fundamental revolution in science.

- Various extra dimensional scenarios can be tested at the LHC.

- Signals could be more subtle or elusive than the first estimates.

Examples:

- LED: Black hole signals could be less obvious/likely.

- Warped models of hierarchy and flavor:

* Signals likely more challenging than in original models, mass scales larger.

* Larger m_{KK}: boosted dijets from decays ($E \gtrsim 1$ TeV), mono-jet backgrounds.

- Truncated warped bulk (conformal depth) $\leftrightarrow$ Enhanced clean signals.

- Observing TeV-scale KK modes: is Planck-weak hierarchy addressed?

- Little RS models: possible clues may be accessible at the LHC.