Signatures for UV-complete Extra Dimensions

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Outline

Large extra dimensions

Effective Kaluza-Klein theory

String theory completion

UV fixed-point completion

Fixed-point black holes

Collider searches

Real particle production

- produce searched–for particle [like $pp \to$ single jet $+ \not{E}_T$]
- reconstruct decay products [or missing energy]
- measure mass, spin, branching ratios

⇒ high-energy regime

Virtual-particle effects

- produce known final state [like $pp \to \ell^+ \ell^-$]
- compare to Standard Model predictions
- trust in quantum theory and error estimates [new physics and old physics]

⇒ high-precision regime

Rare effect or rare decays [B physics, EDMs]

- produce something known [like B_s,...]
- find effect forbidden in Standard Model

⇒ not multi-purpose

⇒ form complete picture at LHC

Large extra dimensions

Remember the hierarchy problem

– fundamental scalars bad with high scale present

– weakness of gravity means large Planck scale $G_N = 1/(16\pi M_{\rm Planck})^2$

$\Rightarrow$ solution: another reason for huge non-fundamental $M_{\rm Planck}$

Large extra dimensions (ADD) [Antoniadis, Arkani-Hamed, Dimopoulos, Dvali]

– Einstein–Hilbert action for low fundamental Planck scale

$$\begin{aligned} S = -\frac{1}{2}\int d^4x\sqrt{|g|}\,M_D^2\,R \to -\frac{1}{2}\int d^{4+n}x\sqrt{|g|}\,M_D^{2+n}\,R \\ = -\frac{1}{2}(2\pi r)^n\int d^4x\sqrt{|g|}\,M_D^{2+n}\,R \\ \equiv -\frac{1}{2}\int d^4x\sqrt{|g|}\,M_{\rm Planck}^2\,R \end{aligned}$$

$\Rightarrow$ express $M_{\rm Planck}$ in terms of fundamental M_D

$$M_{\rm Planck} = M_D\,(2\pi r M_D)^{n/2}$$

Numbers to make it work

– free parameter $rM_D \gg 1$

– constraints from gravity tests above $\mathcal{O}$(mm)

$\Rightarrow$ most minimal solution of hierarchy problem

$M_D = 1$ TeV	
n	r
1	10^{12} m
2	10^{-3} m
3	10^{-8} m
...	...
6	10^{-11} m

Effective Kaluza-Klein theory

Bottom-up: only gravitons in extra dimensions

– expand the metric [graviton field h]

$$ds^2 = g_{MN}^{(4+n)} dx^M dx^N = \left(\eta_{MN} + \frac{1}{M_D^{n/2+1}} h_{MN} \right) dx^M dx^N$$

– 4D matter in Einstein's equation [no cosmological constant]

$$R_{AB} - \frac{1}{2+n} g_{AB} R = -\frac{1}{M_D^{2+n}} \begin{pmatrix} T_{\mu\nu}(x)\,\delta^{(n)}(y) & 0 \\ 0 & 0 \end{pmatrix}$$

– Fourier transformation of extra dimensions [periodic boundary conditions]

$$h_{AB}(x;y) = \sum_{m_1=-\infty}^{\infty} \cdots \sum_{m_j=-\infty}^{\infty} \frac{h_{AB}^{(m)}(x)}{\sqrt{(2\pi r)^n}} e^{i\frac{m_j y_j}{r}}$$

– universal interactions of KK excitations [$h_{AB} \to G_{\mu\nu}$, QCD massless]

$$(\Box + m_k^2)\, G_{\mu\nu}^{(k)} = \frac{1}{M_\text{Planck}} \left[-T_{\mu\nu} + \left(\frac{\partial_\mu \partial_\nu}{\hat{m}^2} + \eta_{\mu\nu} \right) \frac{T_\lambda^\lambda}{3} \right] = \frac{-T_{\mu\nu}}{M_\text{Planck}}$$

– tiny KK mass splitting [$M_D = 1$ TeV]

$$\delta m \sim \frac{1}{r} = 2\pi M_D \left(\frac{M_D}{M_\text{Planck}} \right)^{2/n} = \begin{cases} 0.003 \text{ eV} & (n=2) \\ 0.1 \text{ MeV} & (n=4) \\ 0.05 \text{ GeV} & (n=6) \end{cases}$$

⇒ continuum of weakly interacting gravitons at the LHC

Gravitons at the LHC

Effective theory predictions [Giudice, Rattazzi, Wells; Han, Lykken, Zhang; Hewett;...]

– real radiation of KK tower $[dm/d|k| = 1/r; d\sigma \propto 1/M_{\rm Planck}^2]$

$$d\sigma^{\rm tower} \sim S_{n-1} r^n \int dm\, m^{n-1}\, d\sigma^{\rm graviton} = \frac{S_{n-1}}{(2\pi M_D)^n} \int dm\, m^{n-1}\, \frac{d\sigma^{\rm graviton} M_{\rm Planck}^2}{M_D^2}$$

– higher-dimensional operator from virtual KK tower [s–channel in DY]

$$\mathcal{S}(s) = \frac{S_{n-1}}{M_D^{2+n}} \int^\Lambda dm \frac{m^{n-1}}{s-m^2} \sim \frac{S_{\delta-1}}{2} \frac{\Lambda^{n-2}}{M_D^{n+2}} \neq \frac{S_{\delta-1}}{2} \frac{1}{M_D^4}$$

– saving grace: $1/M_D^2$ interactions of KK tower

$\Rightarrow$ effective theory valid for $E < M_D$

(1) Real emission $pp \to G_{\rm KK}$+jets [Giudice, Rattazzi, Wells; Vacavant, Hichliffe...]

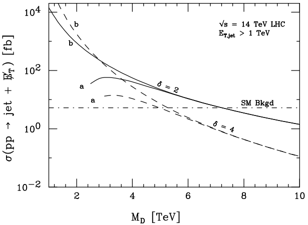
– background: radiation of $Z \to \nu\bar{\nu}$

– $\mathcal{M} = 0$ for $E_{\rm parton} > \Lambda$

$\mathcal{M} = 0$ automatically for $m_{\rm KK} > E_{\rm parton}$

– effective cutoff: steep gluon density

$\Rightarrow$ explicit cutoff only for $M_D \lesssim 3$ GeV



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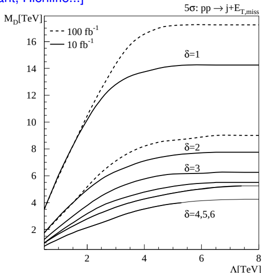

Signatures for UV-complete Extra Dimensions

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Large dimensions

Effective theory

String theory

UV fixed point

Black holes

Virtual gravitons at LHC

(2) Virtual exchange $pp \to \mu^+\mu^-$ [Giudice & Strumia; Giudice, Strumia, TP;...]

- Drell–Yan as standard candle [$q\bar{q}$ and gg initial states]
- reconstructed $m_{\mu\mu}$ for photon, Z, graviton
- loop-induced D6 operator [axial vector–axial vector]

$$\frac{1}{16}\,\frac{1}{M_D^2}\,\frac{\pi^{n-2}}{\Gamma^2(n/2)}\,\left(\frac{\Lambda}{M_D}\right)^{2n+2}$$

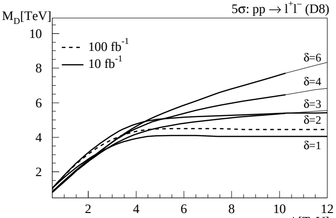
- tree-induced D8 operator [leading constant in $\sqrt{s}/\Lambda$]

$$\mathcal{S}(s) = \frac{S_{n-1}}{M_D^{2+n}} \int^\Lambda dm\, \frac{m^{n-1}}{s+m^2} = \begin{cases} \dfrac{4\pi}{M_\text{eff}^4} + \cdots & \text{effective scale} \\ \dfrac{S_{n-1}}{M_D^4}\,\dfrac{1}{2}\left(\dfrac{\Lambda}{M_D}\right)^{n-2} + \cdots & \text{NDA} \\ \dfrac{S_{n-1}}{M_D^4}\,\dfrac{1}{n-2}\left(\dfrac{\Lambda}{M_D}\right)^{n-2} + \cdots & \text{cutoff } \Theta(\Lambda - m) \end{cases}$$

- two-dimensional integration over (m, s)
  cutoff requiring $m \lesssim M_D$
  additional cutoff for $\sqrt{s} \lesssim M_D$
- constant rate $M_D^\text{max} \sim \Lambda^{(n-2)/(n+2)}$

$\Rightarrow$ breakdown of effective theory

[UHECR: Plümacher & Kachelrieß]



String theory completion

String theory as UV completion [e.g. Cullen, Perelstein, Peskin; Antoniadis, Benakli, Laugier...]

– see Antoniadis' talk, let me skip due to my complete ignorance...

– Regge excitations of Standard Model [Burikham, Figy, Han]

– compute different helicity contributions, like

$$\mathcal{A}(e_L^+ e_R^- \to \gamma_L \gamma_R) = -2e^2 \sqrt{\frac{u}{t}} \left(\frac{u}{s} + \frac{t}{s} - 1 \right) = 2e^2 \sqrt{\frac{u}{t}}$$

$$= -2e^2 \sqrt{\frac{u}{t}} \left(\frac{u}{s} \mathcal{S}(s,t) + \frac{t}{s} \mathcal{S}(s,u) - \mathcal{S}(t,u) \right)$$

– with Veneziano form factor

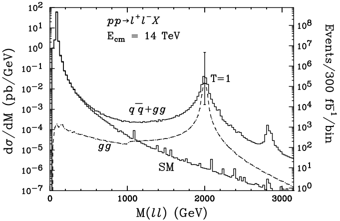
$$\mathcal{S}(s,t) = \frac{\Gamma(1-\alpha' s)\,\Gamma(1-\alpha' t)}{\Gamma(1-\alpha'(s+t))} = \frac{\Gamma(1-s/M_S^2)\,\Gamma(1-t/M_S^2)}{\Gamma(1-(s+t)/M_S^2)}$$

$$= 1 - \frac{\pi^2}{6} \frac{st}{M_S^4} + \mathcal{O}\left(M_S^{-6}\right)$$

– dominant over KK because $M_{\text{eff}} \gg M_S$ closed-string gravitons suppressed

– effective operator below string scale

– string resonances: $\sqrt{n}\, M_S$



UV fixed-point completion

Gravity as its own UV completion [Reuter; Percacci; Fischer & Litim;....]

– effective action: $\Gamma_k = 1/(16\pi G_k) \int d^{4+n}x \sqrt{g} \, [-R(g) + \cdots]$ [Wetterich]

– dimensionless running coupling $g(\mu) = G(\mu)\mu^{2+n} = G_0 \, Z_G^{-1}(\mu) \, \mu^{2+n}$

– UV fixed point [anomalous dimension: $\eta = -\mu\partial_\mu \log Z_G \propto g$]

$$\mu \frac{\partial}{\partial\mu} g(\mu) = (2+n+\eta(g)) \; g(\mu) = 0 \qquad \text{for} \qquad g \neq 0 \qquad \eta(g) = -2-n$$

– $G(\mu) < G_N$ weak enough at high energies? [Weinberg]

– IR — no running; M_D regime — strong effects; UV — fixed point

– iterative approach: start with anomalous dimension of graviton

$$P(s,m) = \begin{cases} \dfrac{1}{s+m^2} & \sqrt{s}, m < k_{\text{trans}} \\ \dfrac{M_D^{n+2}}{(s+m^2)^{n/2+2}} & \sqrt{s}, m > k_{\text{trans}} \end{cases}$$

– IR and UV contributions to D8 operator [leading in $\sqrt{s}/m$, matched to $1/s^2$]

$$\mathcal{S}^{(\text{FP})} = \frac{S_{n-1}}{M_D^4} \left(\frac{k_{\text{trans}}}{M_D} \right)^{n-2} \frac{n-1}{n-2} = (1+(n-2)) \; \mathcal{S}^{(\Theta)}$$

$\Rightarrow$ consistent and truly minimal SM extension

UV fixed-point completion

Predicted graviton kernel

– sizeable rate enhancement $\mathcal{S}^{(\text{FP})} = \mathcal{S}^{(\Theta)} + \mathcal{S}^{(\text{UV})}$:

σ[fb]	$n = 3$			$n = 6$		
M_D	2 TeV	5 TeV	8 TeV	2 TeV	5 TeV	8 TeV
$\mathcal{S}^{(\text{NDA})}$	43.6	0.18	0.0053	263	1.11	0.031
$\mathcal{S}^{(\Theta)}$	173	0.72	0.0204	66	0.28	0.008
$\mathcal{S}^{(\text{FP})}$	408	1.24	0.0317	398	1.21	0.031

– visible effect on $m_{\ell\ell}$

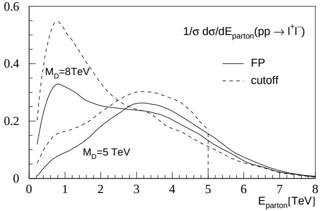
– shift to larger $m_{\ell\ell}$ [shown $n = 3$]

small $m_{\ell\ell}$: factor $\mathcal{S} \propto (n-1)$
large $m_{\ell\ell}$: factor $\mathcal{S}^2 \propto (n-1)^2$

– mild effects from $k_{\text{trans}} = M_D \pm 10\%$

– no resonance structure

$\Rightarrow$ clearly testable model



– needed and not needed:

(1) transition scale $k_{\text{trans}} \sim M_D$ [anomalous dimension modeled]

(2) no artificial Λ for m integration

(3) matching/cutoff for s integration [Minkowski picture?]

UV fixed point completion

Alternative: coupling form factor [Hewett & Rizzo: RS gravitons]

– dress s-channel coupling

$$\frac{1}{M_D^{2+n}} \longrightarrow \frac{1}{M_D^{2+n}} \, F(s) = \frac{1}{M_D^{2+n}} \left(1 + \left(\frac{\sqrt{s}}{M_D} \right)^{2+n} \right)^{-1}$$

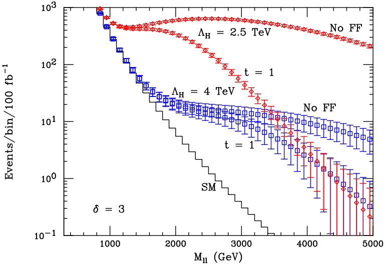
– no modified s integration (unitarity)

$$\frac{1}{M_D^{2+n}} \, F(s) \sim \frac{1}{M_D^{2+n}} \left(\frac{M_D}{\sqrt{s}} \right)^{2+n} \sim \frac{1}{s^{1+n/2}}$$

– still cutoff in m integration

– also applicable to graviton emission [less impressive effect]

⇒ KK and energy integrations understood for fixed point



Fixed-point black holes

Application to black holes [Falls, Litim, Raghuraman; to appear]

– classical Schwartzschild black holes $r_{\text{class}} = (G_N M)^{1/(n+1)}$ from

$$ds^2 = -f(r)dt^2 + f^{-1}(r)dr^2 + r^2 d\Omega^2 \quad \text{with } f = 1 - \frac{G_N M}{r^{n+1}}$$

– improved radius $r_{\text{FP}} < r_{\text{class}}$ from

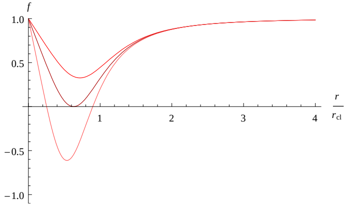
$$f(r_{\text{FP}}) \equiv 0 \quad \text{with } f(r) = 1 - \frac{G(r)M}{r^{n+1}}$$

– critical (minimal) black hole mass $M_{\text{crit}} \sim M_D$

$$(n+1)\; M_{\text{crit}} = r\frac{d}{dr}G(r)\bigg|_{r(M_{\text{crit}})}$$

– (1) no arbitrary small black holes
(2) stable remnant from large black holes

⇒ distinctive UV feature



Outlook

TeV-scale gravity at LHC

– most minimal extension of Standard Model

– effective field theory:

real emission accidentally well defined

virtual–graviton predictions poor

– string theory:

resonances and exponention suppression

gravitons sub-leading

– fixed-point gravity:

gravity asymptotically safe (weak at high energies)

effect on KK mass: graviton anomalous dimension
effect on energy: coupling form factor

application to black holes
lots more work to do [Gerwick, Litim, Plehn]

$\Rightarrow$ UV-complete extra dimensions needed and available