Virtual Gravitons at the LHC

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ERG Heidelberg, June 2008

Outline

Large extra dimensions

Real and virtual gravitons at LHC

RG improved virtual gravitons

Outlook

Large extra dimensions

Large extra dimensions (ADD)

– new physics at LHC: cannot always look for supersymmetry

– Einstein–Hilbert action for low fundamental Planck scale

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

⇒ express the 4D Planck scale in terms of fundamental Planck scale

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

Numbers to make it work

– wanted $rM_D \gg 1$

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

– $M_D = 1$ TeV $\ll M_{\text{Planck}}$ fine for $n \gtrsim 2$

⇒ signatures of strong gravity in extra dimension?

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

Large extra dimensions at the LHC

Minimal model: only gravitons in extra dimensions

– only the interacting (tensor) graviton [QCD/QED massless, $M_D = 1$ TeV]

$$(\Box + m_k^2)\, G_{\mu\nu}^{(k)} = \frac{-T_{\mu\nu}}{M_{\text{Planck}}}$$

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

– KK graviton tower with mass splitting $\Delta m \ll$ GeV [below LHC resolution]
universal couplings via $-T_{\mu\nu}/M_{\text{Planck}}$

⇒ LHC effective theory: KK gravitons light, weakly coupled continuum

Real emission and virtual gravitons [Giudice, Rattazzi, Wells; Han, Lykken, Zhang;...]

– integration over continuous KK tower [$dm/d|k| = 1/r$; $(d\sigma) \propto 1/M_{\text{Planck}}^2$]

$$(d\sigma) \to \int dm\, (d\sigma)\, S_{n-1} m^{n-1} r^n = \int dm\, (d\sigma)\, \frac{S_{n-1}\, m^{n-1}}{(2\pi M_D)^n} \left(\frac{M_{\text{Planck}}}{M_D} \right)^2$$

$$\mathcal{A} = \frac{1}{M_{\text{Planck}}^2} \frac{1}{s - m^2} \to \frac{S_{n-1}}{2} \frac{\Lambda_{\text{cutoff}}^{n-2}}{M_D^{n+2}}$$

⇒ $1/M_D$ interaction after integration over KK tower

⇒ explicit UV cutoff Λ_{cutoff} or RG improvement?

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RG improvement

Outlook

Real gravitons at LHC

Effective theory of real gravitons [Giudice, Rattazzi, Wells; Vacavant, Hichliffe...]

– real graviton emission $pp \to G_{\text{KK}}$+jets [coupling $G \sim 1/M_D^{2+n}$]

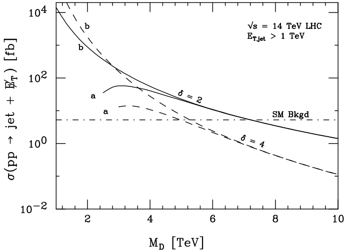
– recoil against hard jet [with $E_j \gtrsim M_D/4$]
background: radiation of $Z \to \nu\bar{\nu}$

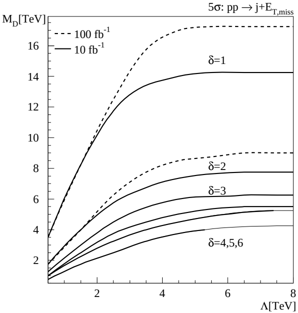
– towers of ADD gravitons $dN \propto S_{n-1} (M_{\text{Planck}}/M_D)^2 \, m^{n-1} dm$
cutoff $\mathcal{M}_{\text{KK}} = 0$ for $E_{\text{parton}} > \Lambda_{\text{cutoff}} \sim M_D$

– observables: total rate or 5σ discovery reach

– little UV sensitivity for $\Lambda_{\text{cutoff}} \to \infty$, small RG effects expected?

$\Rightarrow$ explicit cutoff irrelevant due to phase space [and gluon densities]



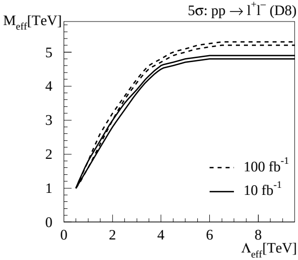


Virtual gravitons at LHC

Effective theory of virtual gravitons [Giudice & Strumia; Giudice, Strumia, TP; Kachelries & Plümacher,...]

– virtual graviton in s channel $pp \to \mu^+\mu^-$
– reconstructed $m_{\mu\mu}$ for photon, Z, graviton
– divergent D8 operator [leading constant in $\sqrt{s}/\Lambda_{\text{cutoff}}$]

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



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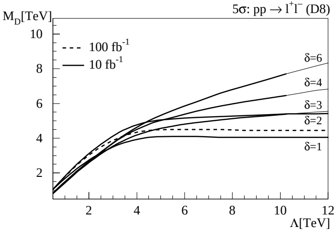
– scaling of rates $M_D^{\text{max}} \sim \Lambda_{\text{cutoff}}^{(n-2)/(n+2)}$

$\Rightarrow$ explicit cutoff needed for virtual gravitons



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

– Veneziano form factor

$$\frac{\Gamma(1-\alpha' s)\,\Gamma(1-\alpha' t)}{\Gamma(1-\alpha'(s+t))} = \frac{\Gamma(1-s/M_S^2)\,\Gamma(1-t/M_S^2)}{\Gamma(1-(s+t)/M_S^2)} = 1 - \frac{\pi^2}{6}\,\frac{st}{M_S^4} + \mathcal{O}\left(M_S^{-6}\right)$$

– string resonances above Λ_{cutoff}: $\sqrt{n}\, M_S$

Graviational fixed point

Matched graviton propagator [Reuter; Fischer & Litim]

- effective action: $\Gamma_k = 1/(16\pi G_k) \int d^{4+n}x \sqrt{g} \, [-R(g) + \cdots]$ [Percacci's talk]
- gravity weak enough at high energies?
- IR — no running; M_D regime — strong effects; UV — fixed point
- iterative approach: start with anomalous dimension of graviton propagator

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

- IR and UV contributions by virtual gravitons [UV: gluon pdf $\to$ leading in $\sqrt{s}/m$]

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

- needed and not needed:
  (1) gravitational coupling $G \sim 1/M_D^{2+n}$
  (2) transition scale $k_{\text{trans}} \sim M_D$
  (3) no artificial UV cutoff Λ_{cutoff} [setting $\mathcal{M}_{\text{KK}} = 0$]

$\Rightarrow$ UV fixed point regularizes KK integral

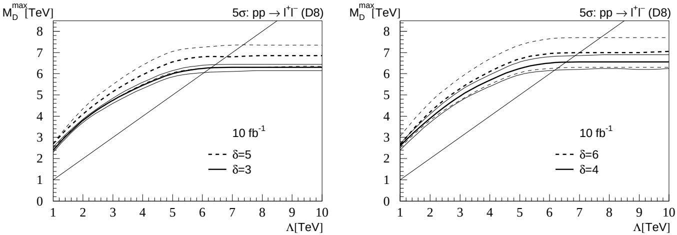
LHC signature

test artificial Λ_{cutoff} setting $\mathcal{M}_{\text{KK}} = 0$

– perfect decoupling, as expected [similar to real emission]

– mild effects for $k_{\text{trans}} = M_D \pm 10\%$ [more details to be studied]

– reach largely independent of n



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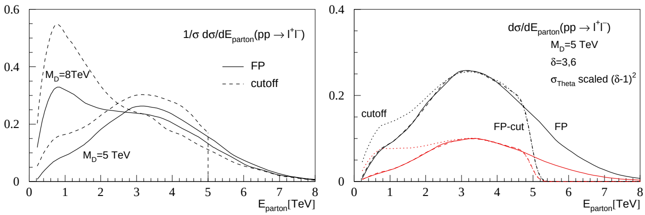
Shape of graviton kernel

- non-trivial structure from interference [shown $n = 3$]
  small $m_{\ell\ell}$: factor $\mathcal{S} \propto (n-1)$
  large $m_{\ell\ell}$: factor $\mathcal{S}^2 \propto (n-1)^2$
- UV contribution not negligible



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predicted LHC rates

– $\mathcal{S}^{(\text{FP})}$: UV regime in addition to $\mathcal{S}^{(\Theta)} \equiv \mathcal{S}^{\text{IR}}$

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

$\Rightarrow$ fixed–point graviton effect stable and large

Outlook

Gravitons at LHC

– effective field theory:

(1) real emission accidentally well defined

(2) virtual–graviton predictions cutoff dependent

– fixed point picture: gravity weak at large scales [non-perturbative asymptotic safety]

leading effect: anomalous dimension [Hewett & Rizzo: running coupling]

KK theory well defined without explicit cutoff

$\Rightarrow$ testable at the LHC [Litim & TP, to appear tomorrow morning]