Quantum Gravity at LHC Scales

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Outline

Standard–Model effective theory

Hadron colliders — the big guys

Large extra dimensions

Effective KK theory

String theory completion

Fixed-point completion

Warped extra dimensions

Fixed-point completion
Standard–Model effective theory

Data vs renormalizable Standard Model

- dark matter? [only solid evidence for new physics, weak–scale?]
- \((g - 2)_\mu\)? [loop effects around weak scale?]
- flavor physics? [new operators above \(10^4\) GeV?]
- neutrino masses? [see-saw at \(10^{11}\) GeV?]
- gauge–coupling unification? [something happening above \(10^{16}\) GeV?]
- gravity? [mostly negligible below \(10^{19}\) GeV]

⇒ obviously effective theory, cutoff negotiable

Problem with fundamental Higgs

- mass driven to cutoff: \(\delta m^2_H/m^2_H \propto g^2(2m^2_W + m^2_Z + m^2_H - 4m^2_t)\ \Lambda^2\)
- easy solution: tune counter term
- whole idea of gauge theories betrayed, evil
- or new physics at TeV scale: supersymmetry
  extra dimensions
  little Higgs, Higgsless, composite Higgs...
  typically cancellation by new states or discussing away high scale
- beautiful concepts, challenged at TeV scale

⇒ whatever is there - LHC’s job to sort it out
Collider searches

Real-particle production

– produce searched–for particle
– observe decay [before hadronization]
– reconstruct decay products [or missing energy]
– measure mass, spin, branching ratios
⇒ high-energy colliders

Virtual-particle effects

– produce and measure something known [like $pp \rightarrow \ell^+ \ell^-$]
– compare to Standard Model predictions
– trust in quantum theory and error estimates
– study deviations
⇒ high-precision colliders

Rare effect or rare decays [B physics, EDMs]

– produce something known [like $B_s$,...]
– find effect forbidden in Standard Model
⇒ well-chosen experiment, not multi-purpose
Collider searches

Everything you always wanted to know about LHC...

- signal: everything new, exciting and rare
- background: yesterday’s signal
- Standard Model: theory of background
- QCD: evil background theory trying to kill us
- trigger: no leptons/photons — not on tape

\[ N_{\text{events}} = \sigma \cdot L \cdot \epsilon \]

⇒ discovery statistical \( N_S / \sqrt{N_B} > 5 \)
Collider searches

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\[ \Rightarrow \text{discovery statistical } N_S / \sqrt{N_B} > 5 \]

Computing stuff for hadron colliders

- protons to first approximation valence quarks

\[ \sigma_{AB} = \sum_{a,b} \int_0^1 dx_a dx_b \ f_{a/A}(x_a) f_{b/B}(x_b) \ \hat{\sigma}_{ab} \]

(1) parton density \( f_{a/A}(x_a) \):
probability to find \( a \) with momentum fraction \( x_a \) in \( A \)

(2) partonic cross section \( \hat{\sigma}_{ab} \):
- perturbative in QCD [‘hard process’]
- integration over partonic energy scale

\[ \Rightarrow \text{energetic valence quarks ahead of many gluons} \]
Large extra dimensions

Remember the hierarchy problem

- fundamental scalars bad with high scale present
- weakness of gravity means large Planck scale $G_N = \frac{1}{(16\pi M_{\text{Planck}})^2}$

⇒ solution: another reason why we see huge non-fundamental $M_{\text{Planck}}$

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

- Einstein–Hilbert action for low fundamental Planck scale

$$S = -\frac{1}{2} \int d^4x \sqrt{|g|} M_D^2 R \rightarrow - \frac{1}{2} \int d^{4+n} \sqrt{|g|} M_D^{2+n} R$$

$$= - \frac{1}{2} (2\pi r)^n \int d^4x \sqrt{|g|} M_D^{2+n} R$$

$$\equiv - \frac{1}{2} \int d^4x \sqrt{|g|} M_{\text{Planck}}^2 R$$

⇒ express $M_{\text{Planck}}$ in terms of fundamental $M_D$

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

Numbers to make it work

- free parameter $r M_D \gg 1$
- constraints from gravity tests above $\mathcal{O}(\text{mm})$

⇒ signatures of strong gravity in extra dimension?

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<tr>
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<th>$r$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
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<tr>
<td>2</td>
<td>$10^{-3}$ m</td>
</tr>
<tr>
<td>3</td>
<td>$10^{-8}$ m</td>
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<tr>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>6</td>
<td>$10^{-11}$ m</td>
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</table>
Effective KK theory

Toy model: only gravitons in extra dimensions

- expand the metric \([\text{graviton field } h]\)
  \[
  ds^2 = g_{MN}^{(4+n)} dx^M dx^N = \left( \eta_{MN} + \frac{1}{M_D^{n/2+1}} h_{MN} \right) dx^M dx^N
  \]

- matter in Einstein’s equation \([\text{no cosmological constant}]\)
  \[
  R_{AB} - \frac{1}{2+n} g_{AB} R = - \frac{1}{M_D^{2+n}} \left( \begin{array}{cc} T_{\mu \nu}(x) \delta^{(n)}(y) & 0 \\ 0 & 0 \end{array} \right)
  \]

- Fourier transformation of extra dimensions \([\text{KK excitations for periodic boundary conditions}]\)
  \[
  h_{AB}(x; y) = \sum_{m_1=-\infty}^{\infty} \cdots \sum_{m_j=-\infty}^{\infty} \frac{h^{(m)}_{AB}(x)}{\sqrt{(2\pi r)^n}} e^{i \frac{m_j y_j}{r}}
  \]

- universal interactions of KK gravitons \([h_{AB} \rightarrow G_{\mu \nu}, \text{QCD massless}]\)
  \[
  \left( \Box + m_k^2 \right) G^{(k)}_{\mu \nu} = \frac{1}{M_{\text{Planck}}} \left[ -T_{\mu \nu} + \left( \frac{\partial_\mu \partial_\nu}{\hat{m}^2} + \eta_{\mu \nu} \right) \frac{T^\lambda_{\lambda}}{3} \right] = -\frac{T_{\mu \nu}}{M_{\text{Planck}}}
  \]

- tiny KK mass splitting \([M_D = 1 \, \text{TeV}]\)
  \[
  \delta m \sim \frac{1}{r} = 2\pi M_D \left( \frac{M_D}{M_{\text{Planck}}} \right)^{2/n} = \left\{ \begin{array}{ll}
  0.003 \, \text{eV} & (n = 2) \\
  0.1 \, \text{MeV} & (n = 4) \\
  0.05 \, \text{GeV} & (n = 6)
  \end{array} \right.
  \]

\Rightarrow \text{continuum of weakly interacting gravitons at the LHC}
Large extra dimensions

**Effective KK theory** [Giudice, Rattazzi, Wells; Han, Lykken, Zhang;...]

- real radiation of continuous KK tower \[ \frac{d\sigma}{dk} = \frac{1}{r}; (d\sigma) \propto \frac{1}{M^2_{\text{Planck}}} \]
  \[
  (d\sigma) \to \int dm (d\sigma) S_{n-1} m^{n-1} r^n = \int dm (d\sigma) \frac{S_{n-1} m^{n-1}}{(2\pi M_D)^n} \left( \frac{M_{\text{Planck}}}{M_D} \right)^2
  \]
- higher-dimensional operator from virtual graviton exchange \[ s\text{-channel in DY} \]
  \[
  A = \frac{1}{M_{\text{Planck}}^2} \frac{1}{s - m_{\text{KK}}^2} \to \frac{S_{n-1}}{2} \frac{\Lambda^{n-2}}{M_D^{n+2}}
  \]
- \(1/M_D^2\) interactions for KK tower
  \[
  \Rightarrow \text{like any effective theory valid for } E < M_D
  \]

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

- recoil against hard jet \[ E_j \sim M_D \]
  background: radiation of \(Z \to \nu\bar{\nu}\)
- \(M = 0\) for \(E_{\text{parton}} > \Lambda_{\text{cutoff}}\)
  \(M = 0\) automatically for \(m_{KK} > E_{\text{parton}}\)
- effective cutoff: steep gluon density
- little UV sensitivity for \(\Lambda_{\text{cutoff}} \to \infty\)
  \[
  \Rightarrow \text{explicit cutoff not crucial}
  \]
Large extra dimensions

**Effective KK theory**  [Giudice, Rattazzi, Wells; Han, Lykken, Zhang;...]

- real radiation of continuous KK tower \([dm/d|k| = 1/r; (d\sigma) \propto 1/M_{Planck}^2]\)

\[(d\sigma) \rightarrow \int dm (d\sigma) S_{n-1} m^{n-1} r^n = \int dm (d\sigma) \frac{S_{n-1} m^{n-1}}{(2\pi M_D)^n} \left( \frac{M_{Planck}}{M_D} \right)^2\]

- higher-dimensional operator from virtual graviton exchange  [s-channel in DY]

\[A = \frac{1}{M_{Planck}^2} \frac{1}{s - m_{KK}^2} \rightarrow \frac{S_{n-1}}{2} \frac{\Lambda^{n-2}}{M_{D}^{n+2}}\]

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\[\Rightarrow\] like any effective theory valid for \(E < M_D\)

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\[\Rightarrow\] explicit cutoff not crucial
Virtual gravitons at LHC

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

− virtual graviton in $s$ channel  $pp \rightarrow \mu^+ \mu^-$  [$q\bar{q}$ and $gg$ initial states]
− reconstructed $m_{\mu\mu}$ for photon, $Z$, graviton
− loop-induced D6 operator  [axial vector–axial vector]
  \[ \mathcal{O} = \frac{1}{16} \frac{1}{M_D^2} \pi^{n-2} \left( \frac{\Lambda_{\text{cutoff}}}{M_D} \right)^{2n+2} \]
− tree-induced D8 operator  [leading constant in $\sqrt{s}/\Lambda_{\text{cutoff}}$]
  \[ S = \frac{S_{n-1}}{M_D^{2+n}} \int dm \frac{m^{n-1}}{s + m^2} = \left\{ \begin{array}{l} \frac{4\pi}{M_D^4} \frac{1}{2} \left( \frac{\Lambda_{\text{cutoff}}}{M_D} \right)^{n-2} \\ \frac{S_{n-1}}{M_D^4} \frac{1}{n-2} \left( \frac{\Lambda_{\text{cutoff}}}{M_D} \right)^{n-2} \end{array} \right. \]  
  (effective scale)
  (NDA)
  (cutoff $\Theta$)

![Graph of $M_{\text{eff}}$ vs. $\Lambda_{\text{eff}}$ for $5\sigma: pp \rightarrow l^+l^-$ (D8)]

$S_{n-1}$: $pp \rightarrow l^+l^-$ (D8)

- $100 \text{ fb}^{-1}$
- $10 \text{ fb}^{-1}$
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- two-dimensional integration over \((m, s)\)
  - cutoff requiring \( m \lesssim M_D \)
  - additional cutoff for \( \sqrt{s} \lesssim M_D \)
- rates scaling \( M_D^{\max} \sim \Lambda_{\text{cutoff}}^{(n-2)/(n+2)} \)
  \( \Rightarrow \) breakdown of effective theory
String theory completion

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

- ‘In particular, the only known framework that allows for a self-consistent description of quantum gravity is string theory’
- Regge excitations of Standard Model  \[\text{[Burikham, Figy, Han]}\]
- compute different helicity contributions, like

\[
\mathcal{A}(e^+_Le^-_R \rightarrow \gamma_L\gamma_R) = -2e^2 \sqrt{\frac{u}{t}} \left( \frac{u}{s} + \frac{t}{s} - 1 \right) = 2e^2 \sqrt{\frac{u}{t}} \\
= -2e^2 \sqrt{\frac{u}{t}} \left( \frac{u}{s} S(s, t) + \frac{t}{s} S(s, u) - S(t, u) \right)
\]

- with Veneziano form factor

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

\[
= 1 - \frac{\pi^2}{6} \frac{st}{M_S^4} + \mathcal{O}(M_S^{-6})
\]

- dominant over KK because \(M_{\text{eff}} \gg M_S\)
- closed-string gravitons suppressed
- effective operator below string scale
- string resonances: \(\sqrt{nM_S}\)
Fixed-point completion

**Modified graviton propagator** [Reuter; Fischer & Litim]

- effective action: \[ \Gamma_k = \frac{1}{16\pi G_k} \int d^{4+n}x \sqrt{g} \left[ -R(g) + \cdots \right] \]
- 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

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

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

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

- needed and not needed:
  1. transition scale \( k_{\text{trans}} \sim M_D \) [anomalous dimension modeled]
  2. no artificial \( \Lambda_{\text{cutoff}} \) for \( m \) integration
  3. matching/cutoff for \( s \) integration

\[ \Rightarrow \text{UV fixed point indeed solution to our problems} \]
Fixed-point completion

test with artificial $\Lambda_{\text{cutoff}}$ setting $M_{KK} = 0$

- 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

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

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

- UV contribution predicted and not negligible
Fixed-point completion

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predicted LHC rates

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

<table>
<thead>
<tr>
<th>$\sigma$ [fb]</th>
<th>$n = 3$</th>
<th>$n = 6$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$M_D$</td>
<td>2 TeV</td>
<td>5 TeV</td>
</tr>
<tr>
<td>$S^{(\text{NDA})}$</td>
<td>43.6</td>
<td>0.18</td>
</tr>
<tr>
<td>$S^{(\Theta)}$</td>
<td>173</td>
<td>0.72</td>
</tr>
<tr>
<td>$S^{(\text{FP})}$</td>
<td>408</td>
<td>1.24</td>
</tr>
</tbody>
</table>

⇒ proof of concept quantitatively very promising
Fixed point

**Alternative: start with form factor** [Hewett & Rizzo]

- dress $s$-channel coupling with form factor

\[
\frac{1}{M_D^{2+n}} \rightarrow \frac{1}{M_D^{2+n}} F(s) = \frac{1}{M_D^{2+n}} \left( 1 + \left( \frac{\sqrt{s}}{tM_D} \right)^{2+n} \right)^{-1}
\]

- avoids matching of $s$ integration (unitarity)

\[
\frac{1}{M_D^{2+n}} F(s) \sim \frac{1}{M_D^{2+n}} \left( \frac{tM_D}{\sqrt{s}} \right)^{2+n} \sim \frac{1}{s^{1+n/2}}
\]

- improvement of $s$ integration/matching
- still cutoff in KK-mass integration
Fixed point

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- improvement of $s$ integration/matching
- still cutoff in KK-mass integration
- also applicable to graviton emission  [less impressive effect]

$\Rightarrow$ both, KK and energy integrations understood for fixed point
Warped extra dimensions

Another Solution to hierarchy problem  

- one extra dimension, not flat  
  
  \[ ds^2 = e^{-2k|y|} \eta_{\mu\nu} dx^\mu dx^\nu - dy^2 \quad \Leftrightarrow \quad g_{AB} = \begin{pmatrix} e^{-2k|y|} \eta_{\mu\nu} & 0 \\ 0 & \eta_{jk} \end{pmatrix} \]

- integration measure in our usual Lagrangian  
  \[ d^4\tilde{x} \ e^{-4kb} \]
  \[ \tilde{g}_{\mu\nu} = \eta_{\mu\nu} \]

- write effective 4D theory on TeV brane scaling all fields  
  \[ \tilde{H} = e^{-kb} H \quad \text{scalars} \]
  \[ \tilde{A}_\mu = e^{-kb} A_\mu \quad \text{or} \quad \tilde{D}_\mu = e^{-kb} D_\mu \]
  \[ \tilde{\psi} = e^{-3kb/2} \psi \quad \text{fermions} \]
  \[ \tilde{m} = e^{-kb} m \quad \text{masses} \]
  \[ \tilde{v} = e^{-kb} v \]
  \[ \tilde{y} = y \quad \text{Yukawas} \]

- assume \( kb \sim 35 \) and large fundamental scales  
  \[ M_D \sim M_{\text{Planck}} \sim k \]

\[ \Rightarrow \quad \text{all scales on TeV brane lowered} \]

\[ \tilde{v} \sim e^{-kb} M_{\text{Planck}} \lesssim 1 \text{ TeV} \]
Warped extra dimensions

Gravitons in one warped extra dimension

- re-write the metric including 4D graviton

\[ ds^2 = \frac{1}{(1 + kz)^2} \left( \eta_{\mu\nu} + h_{\mu\nu}(x, z) \, dx^\mu \, dx^\nu - dz^2 \right) \]

- solve Einstein’s equations separating variables \( \tilde{h}_{\mu\nu}(x, z) = \hat{h}_{\mu\nu}(x) \Phi(z) \)

\[ \partial_\mu \partial^\mu \hat{h}_{\mu\nu} = m^2 \hat{h}_{\mu\nu} \]

\[ -\partial_z^2 \Phi + \frac{15}{4} \frac{k^2}{(kz + 1)^2} \Phi = m^2 \Phi \]

- masses given by roots of Bessel functions \( J_1(x_j) = 0 \)

\[ m_j = x_j \, k \, e^{-kb} \sim \text{TeV} \quad x_j = 3.8, 7.0, 10.2, 16.5, \ldots \]

- weak zero mode from wave-function overlap in \( z \) [approximately, neglect Bessel functions]

\[ \Phi(z) \bigg|_{\text{TeV}} \sim \sqrt{kz + 1} \bigg|_{\text{Planck}} \sim \frac{1}{\sqrt{eky} \bigg|_{\text{TeV}}} \sim \frac{1}{e^{kb/2}} \ll 1 \]

- roughly universal couplings for higher modes

\[ \mathcal{L} \sim \frac{1}{M_{\text{Planck}}} \, T^{\mu\nu} h^{(0)}_{\mu\nu} + \frac{1}{M_{\text{Planck}} \, e^{-kb}} \, T^{\mu\nu} \sum h^{(m)}_{\mu\nu} \]

\[ \Rightarrow \, Z' \text{ decays to leptons etc revisited...} \]
Fixed point completion

Screened coupling again [Hewett & Rizzo]

- mass and energy integrations not problematic
- UV problem with widths of KK resonances
  \[ \frac{\Gamma_j}{m_j} \propto x_j^2 \]

- form factor on mass pole implies constant widths
  \[ F^{-1} = 1 + \left( \frac{m_j}{t M_D e^{-k b}} \right)^3 \]
  implies
  \[ \Gamma_j \propto k e^{-k b} t^3 \]

- resonance structure also for high excitations at LHC

⇒ RS models with fixed point well behaved in UV
Outlook

**KK Gravitons at LHC**

- searches as part of puzzle of electroweak symmetry breaking
- effective field theory:
  - real emission accidentally well defined
  - virtual–graviton predictions cutoff dependent
- string theory:
  - solution not clear, but gravitons sub-leading anyhow
- fixed-point picture:
  - gravity weak at large scales [asymptotic safety]
  - effect on KK mass: graviton anomalous dimension
  - effect on energy: coupling form factor

⇒ UV-complete ADD/RS models possible for LHC
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LHC basics
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