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 effecive theory

Data vs renormalizable Standard Model

– dark matter? [only solid evidence for new physics, weak–scale?]

– $(g-2)_\mu$? [loop effects around weak scale?]

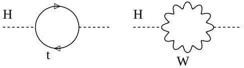
– flavor physics? [new operators above 10^4 GeV?]

– neutrino masses? [see-saw at 10^{11} GeV?]

– gauge–coupling unification? [something happening above 10^{16} GeV?]

– gravity? [mostly negligible below 10^{19} GeV]

$\Rightarrow$ obviously effective theory, cutoff negotiable



Problem with fundamental Higgs

– mass driven to cutoff: $\delta m_H^2 / m_H^2 \propto g^2 (2m_W^2 + m_Z^2 + m_H^2 - 4m_t^2)\, \Lambda^2$

– 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

$\Rightarrow$ 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 $pp \to \ell^+ \ell^-$]
– 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]

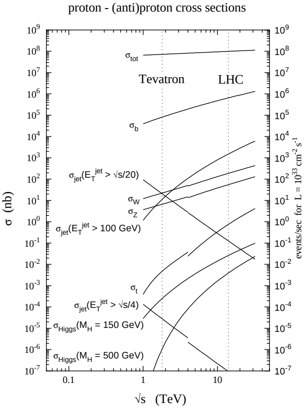
– produce something known [like B_s,...]
– find effect forbidden in Standard Model
⇒ well-chosen experiment, not multi-purpose

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
- $N_\text{events} = \sigma \cdot \mathcal{L} \cdot \epsilon$

$\Rightarrow$ discovery statistical $N_S/\sqrt{N_B} > 5$



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Computing stuff for hadron colliders

– protons to first approximation valence quarks

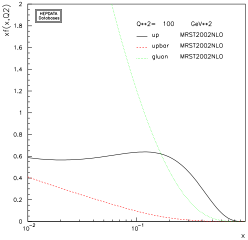
$$\sigma_{AB} = \sum_{a,b} \int_0^1 dx_a dx_b \; f_{a/A}(x_a) \; f_{b/B}(x_b) \;\; \hat{\sigma}_{ab}$$

(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

$\Rightarrow$ 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 $G_N = 1/(16\pi M_{\text{Planck}})^2$

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

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

– Einstein–Hilbert action for low fundamental Planck scale

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

$\Rightarrow$ express M_{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 $rM_D \gg 1$

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

$\Rightarrow$ 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

Effective KK theory

Toy model: only gravitons in extra dimensions

– expand the metric [graviton field h]

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

– 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 [KK excitations for 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 gravitons [$h_{AB} \to G_{\mu\nu}$, 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]

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

$\Rightarrow$ 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 [$dm/d|k| = 1/r$; $(d\sigma) \propto 1/M^2_{\text{Planck}}$]

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

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

$$\mathcal{A} = \frac{1}{M^2_{\text{Planck}}} \frac{1}{s - m^2_{\text{KK}}} \to \frac{S_{\delta-1}}{2} \frac{\Lambda^{n-2}}{M_D^{n+2}}$$

– $1/M_D^2$ interactions for KK tower

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

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

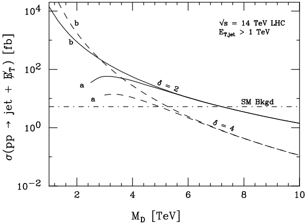
– recoil against hard jet [$E_j \sim M_D$]
background: radiation of $Z \to \nu\bar{\nu}$

– $\mathcal{M} = 0$ for $E_{\text{parton}} > \Lambda_{\text{cutoff}}$
$\mathcal{M} = 0$ automatically for $m_{\text{KK}} > E_{\text{parton}}$

– effective cutoff: steep gluon density

– little UV sensitivity for $\Lambda_{\text{cutoff}} \to \infty$

$\Rightarrow$ explicit cutoff not crucial



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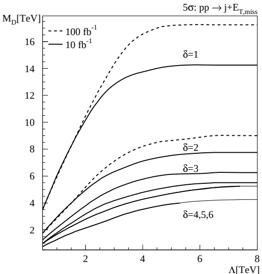


Virtual gravitons at LHC

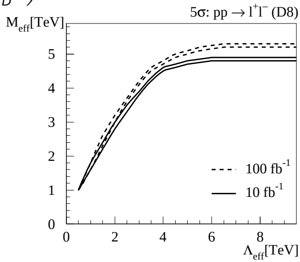
Effective theory of virtual gravitons [Giudice & Strumia; Giudice, Strumia, TP; Kachelries & Plümacher,...]

- virtual graviton in s channel $pp \to \mu^+\mu^-$ [$q\bar{q}$ and gg initial states]
- reconstructed $m_{\mu\mu}$ for photon, Z, graviton
- loop-induced D6 operator [axial vector–axial vector]

$$\mathcal{O} = \frac{1}{16}\,\frac{1}{M_D^2}\,\frac{\pi^{n-2}}{\Gamma^2(n/2)}\left(\frac{\Lambda_\text{cutoff}}{M_D}\right)^{2n+2}$$

- tree-induced 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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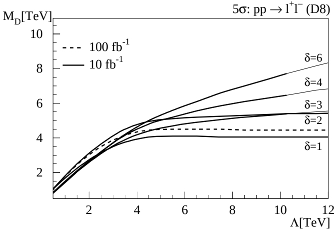
– two-dimensional integration over (m, s)
cutoff requiring $m \lesssim M_D$
additional cutoff for $\sqrt{s} \lesssim M_D$

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

$\Rightarrow$ breakdown of effective theory



String theory completion

String theory as UV completion [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 [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

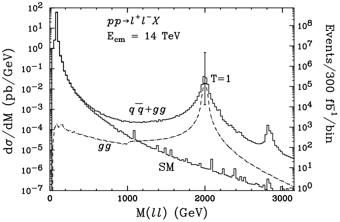
$$\mathcal{S}(s,t) = \frac{\Gamma(1-\alpha' s) \, \Gamma(1-\alpha' t)}{\Gamma(1-\alpha'(s+t))} = \frac{\Gamma(1-s/M_S^2) \, \Gamma(1-t/M_S^2)}{\Gamma(1-(s+t)/M_S^2)}$$

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

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

– effective operator below string scale

– string resonances: $\sqrt{n}\, M_S$



Fixed-point completion

Modified graviton propagator [Reuter; Fischer & Litim]

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

– 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

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

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

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

– needed and not needed:

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

(2) no artificial Λ_{cutoff} for m integration

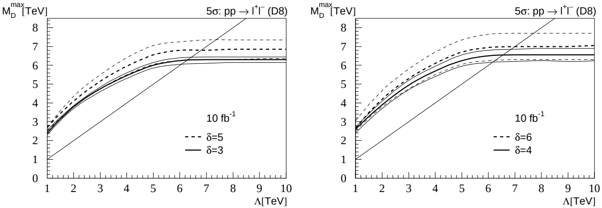
(3) matching/cutoff for s integration

⇒ UV fixed point indeed solution to our problems

Fixed-point completion

test with 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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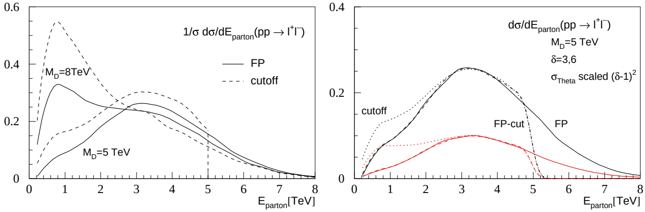
Shape of graviton kernel

- shift to larger $m_{\ell\ell}$ [shown $n = 3$]
  small $m_{\ell\ell}$: factor $\mathcal{S} \propto (n-1)$
  large $m_{\ell\ell}$: factor $\mathcal{S}^2 \propto (n-1)^2$
- UV contribution predicted and 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

$\Rightarrow$ proof of concept quantitatively very promising

Fixed point

Alternative: start with form factor [Hewett & Rizzo]

– dress s-channel coupling with form factor

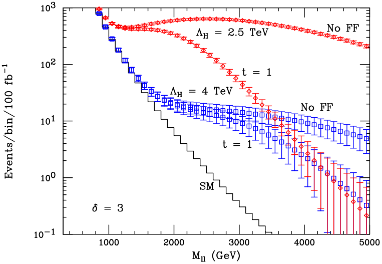
$$\frac{1}{M_D^{2+n}} \longrightarrow \frac{1}{M_D^{2+n}} F(s) = \frac{1}{M_D^{2+n}} \left(1 + \left(\frac{\sqrt{s}}{tM_D}\right)^{2+n}\right)^{-1}$$

– 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



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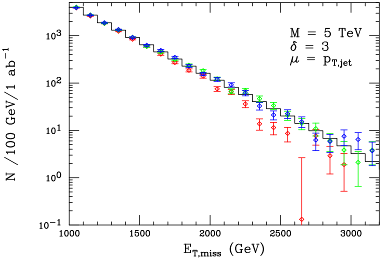
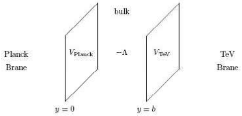
– also applicable to graviton emission [less impressive effect]

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



Warped extra dimensions



Another Solution to hierarchy problem [Randall & Sundrum]

– one extra dimension, not flat [TeV brane at $y = b$]

$$ds^2 = e^{-2k|y|}\eta_{\mu\nu}dx^\mu dx^\nu - dy^2 \quad \Leftrightarrow \quad g_{AB} = \begin{pmatrix} e^{-2k|y|}\eta_{\mu\nu} & 0 \\ 0 & \eta_{jk} \end{pmatrix}$$

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

$$S = \int dy\,\delta(y)\ d^4\tilde{x}\, e^{-4kb}\,\mathcal{L} = \int\ d^4\tilde{x}\, e^{-4kb}\ \left[|D_\mu H|^2 - \lambda(|H|^2 - v^2)^2 + \dots \right]$$

– write effecive 4D theory on TeV brane scaling all fields

$\tilde{H} = e^{-kb}H$	scalars
$\tilde{A}_\mu = e^{-kb}A_\mu$	or $\tilde{D}_\mu = e^{-kb}D_\mu$
$\tilde{\Psi} = e^{-3kb/2}\Psi$	fermions
$\tilde{m} = e^{-kb}m$	masses
$\tilde{v} = e^{-kb}v$	
$\tilde{y} = y$	Yukawas

– assume $kb \sim 35$ and large fundamental scales $M_D \sim M_{\rm Planck} \sim k$

$\Rightarrow$ all scales on TeV brane lowered

$$\tilde{v} \sim e^{-kb}\ M_{\rm Planck} \lesssim 1\ {\rm TeV}$$

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 $J_1(x_j) = 0$

$$m_j = x_j\, k\, e^{-kb} \sim \text{TeV} \qquad x_j = 3.8, 7.0, 10.2, 16.5, \dots$$

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

$$\frac{\Phi(z)\big|_{\text{TeV}}}{\Phi(z)\big|_{\text{Planck}}} \sim \frac{\sqrt{kz+1}\big|_{\text{Planck}}}{\sqrt{kz+1}\big|_{\text{TeV}}} \sim \frac{1}{\sqrt{e^{ky}}\big|_{\text{TeV}}} \sim \frac{1}{e^{kb/2}} \ll 1$$

– 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' 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

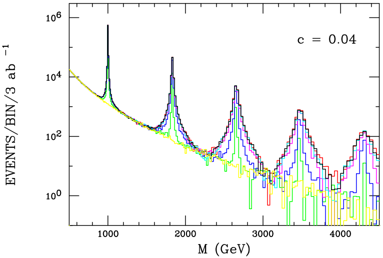
$$\frac{\Gamma_j}{m_j} \propto x_j^2$$

- form factor on mass pole implies constant widths

$$F^{-1} = 1 + \left(\frac{m_j}{t M_D e^{-kb}} \right)^3 \qquad \text{implies} \qquad \Gamma_j \propto k e^{-kb} t^3$$

- resonance structure also for high excitations at LHC

$\Rightarrow$ 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

$\Rightarrow$ UV-complete ADD/RS models possible for LHC