Physics with extra dimensions

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Part 2

- Large extra dimensions and low scale gravity
- Experimental signals
- Warped extra dimensions

Low scale gravity

Extra large $\perp$ dimensions can explain the apparent weakness of gravity

total force = observed force $\times$ volume $\perp$

total force $\simeq \mathcal{O}(1)$ at 1 TeV n dimensions of size $R_\perp$

$$\Rightarrow \text{volume } R_\perp^n = 10^{32} \text{ in TeV}^{-1} \text{ units}$$

$n = 1 : R_\perp \simeq 10^8$ km   excluded

$n = 2 : R_\perp \simeq 0.1$ mm $(10^{-12}$ GeV$)$

possible

$n = 6 : R_\perp \simeq 10^{-13}$ mm $(10^{-2}$ GeV$)$

- distances $> R_\perp$: gravity 3d

  however for $< R_\perp$: gravity (3+n)d [4]

- strong gravity at 10^{-16} cm $\leftrightarrow 10^3$ GeV

10^{30} times stronger than thought previously! [7]

Low scale gravity

Extra large $\perp$ dimensions can explain the apparent weakness of gravity

total force = observed force $\times$ volume $\perp$

$$\begin{array}{ccccc} \uparrow & & \uparrow & & \uparrow \\ G_N^* E^{2+n} & = & G_N E^2 & \times & V_\perp E^n \end{array}$$

$G_N^* = M_*^{-(2+n)}$: $(4+n)$-dim gravitational constant

total force $\simeq \mathcal{O}(1)$ at 1 TeV

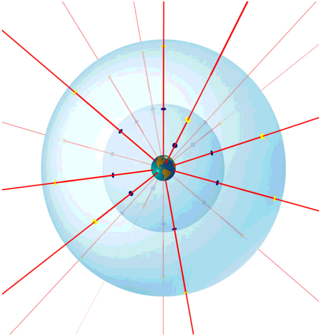
n dimensions of size $R_\perp$

$\Rightarrow \; V_\perp = R_\perp^n$

$\Rightarrow M_P^2 = M_*^{2+n} R_\perp^n$ for $M_* \simeq 1$ TeV $\Rightarrow (R_\perp M_*)^n \sim 10^{32}$

Gravity modification at submillimeter distances

Newton's law: force decreases with area



3d: force $\sim 1/r^2$

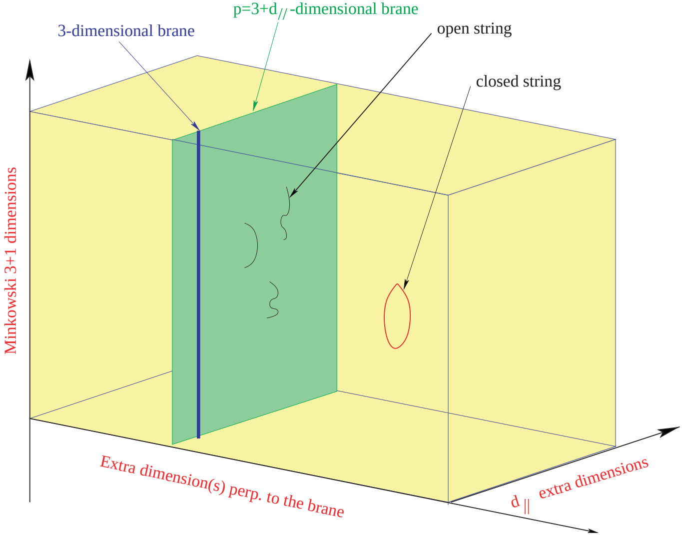
$(3+n)$d: force $\sim 1/r^{2+n}$

observable for $n = 2$: $1/r^4$ with $r << .1$ mm [2]

Braneworld

2 types of compact extra dimensions:

- parallel ($d_{\|}$): $\lesssim 10^{-16}$ cm (TeV) [6]
- transverse ($\perp$): $\lesssim 0.1$ mm (meV)



Experimental predictions

- No little hierarchy problem:

  radiative electroweak symmetry breaking with no logs

  $\Lambda \sim$ a few TeV and $m_H^2 =$ a loop factor $\times \Lambda^2$

- particle accelerators

  - Large TeV dimensions   seen by gauge interactions [17]

  - Extra large hidden dimensions   transverse $\Rightarrow$ strong gravity

  - other accelerator signatures

- microgravity experiments

  - gravity modifications at short distances

  - new submillimeter forces

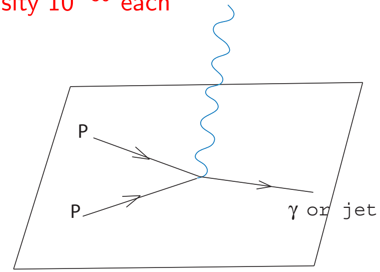
Hidden submillimeter dimensions

⇛ strong gravity at the TeV: gravitational radiation in the bulk

3d: Kaluza Klein gravitons very light

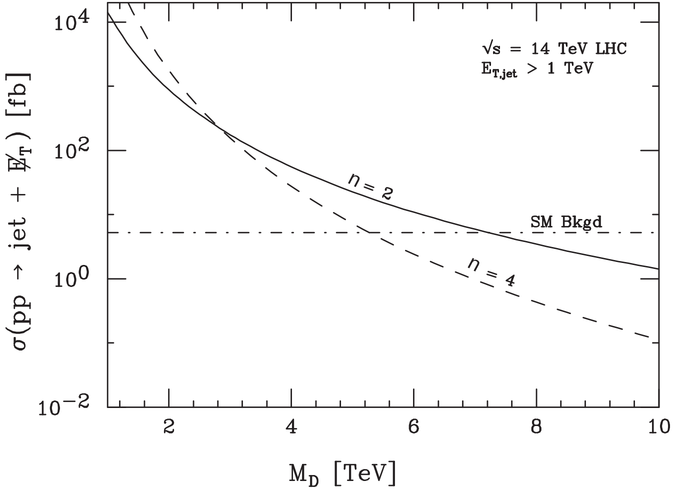
⇛ high energy: huge number of particles produced

LHC: 10^{30} massive gravitons of intensity 10^{-30} each



Signal: missing energy

Angular distribution ⇛ spin of the graviton



- no observation $\Rightarrow$ $R_\perp \lesssim 10^{-2} - 10^{-12}$ mm ($n = 2 - 6$); 95% CL

- more dimensions $\Rightarrow$ weaker limits

Angular distribution for graviton emission

Sum over KK modes:

$$\sum_{k_\perp} = R^n \int d^n m = \frac{1}{2}\Omega_n R^n \int (m^2)^{(n-2)/2} d\, m^2$$
$$= \Omega_n \frac{M_p^2}{2M_*^{(n+2)}} \int (m^2)^{(n-2)/2} d\, m^2$$

$\Omega_n = \frac{2\pi^{n/2}}{\Gamma(n/2)}$: volume of n-sphere of unit radius

Angular distribution for graviton emission

$$|\mathcal{M}(q\bar{q} \to gG_m)|^2 = \frac{1}{18M_p^2}\frac{\alpha_s}{1-m^2/s}\Bigg[(2-\frac{4ut}{(s-m^2)^2})\left(1+(\frac{m^2}{s})^4\right)$$
$$+ \left(2\frac{(s-m^2)^2}{4ut}-5+4\frac{4ut}{(s-m^2)^2}\right)\frac{m^2}{s}\left(1+(\frac{m^2}{s})^2\right)$$
$$+ 6\left(\frac{u-t}{s-m^2}\right)^2(\frac{m^2}{s})^2\Bigg]$$

$$|\mathcal{M}(qg \to qG_m)|^2 = \frac{\alpha_s}{48M_p^2}\frac{-t/s(1-m^2/s)}{(1-m^2/t)^2}\Bigg[(2-\frac{4us}{(t-m^2)^2})\left(1+(\frac{m^2}{t})^4\right)$$
$$+ \left(2\frac{(t-m^2)^2}{4us}-5+4\frac{4us}{(t-m^2)^2}\right)\frac{m^2}{t}\left(1+(\frac{m^2}{t})^2\right)$$
$$+ 6\left(\frac{s-u}{t-m^2}\right)^2(\frac{m^2}{t})^2\Bigg]$$

$t, u = -\frac{1}{2}s(1-m^2/s)(1\mp\cos\theta)$

Cross sections

$$\left.\boxed{\begin{array}{ccc} |\mathcal{M}(gg \to gg)|^2 & , & |\mathcal{M}(gg \to q\bar{q})|^2 \\ |\mathcal{M}(q\bar{q} \to gg)|^2 & , & |\mathcal{M}(qg \to qg)|^2 \end{array}}\right\}$$

model independent
for any compactification

$$|\mathcal{M}(gg \to gg)|^2 = g_{YM}^4 \left(\frac{1}{s^2} + \frac{1}{t^2} + \frac{1}{u^2}\right) \times \left[\frac{9}{4}\left(s^2 V_s^2 + t^2 V_t^2 + u^2 V_u^2\right) - \frac{1}{3}\left(sV_s + tV_t + uV_u\right)^2\right]$$

$$|\mathcal{M}(gg \to q\bar{q})|^2 = g_{YM}^4 \frac{t^2 + u^2}{s^2} \left[\frac{1}{6}\,\frac{1}{tu}\,(tV_t + uV_u)^2 - \frac{3}{8}\,V_t\,V_u\right]$$

$M_s = 1$

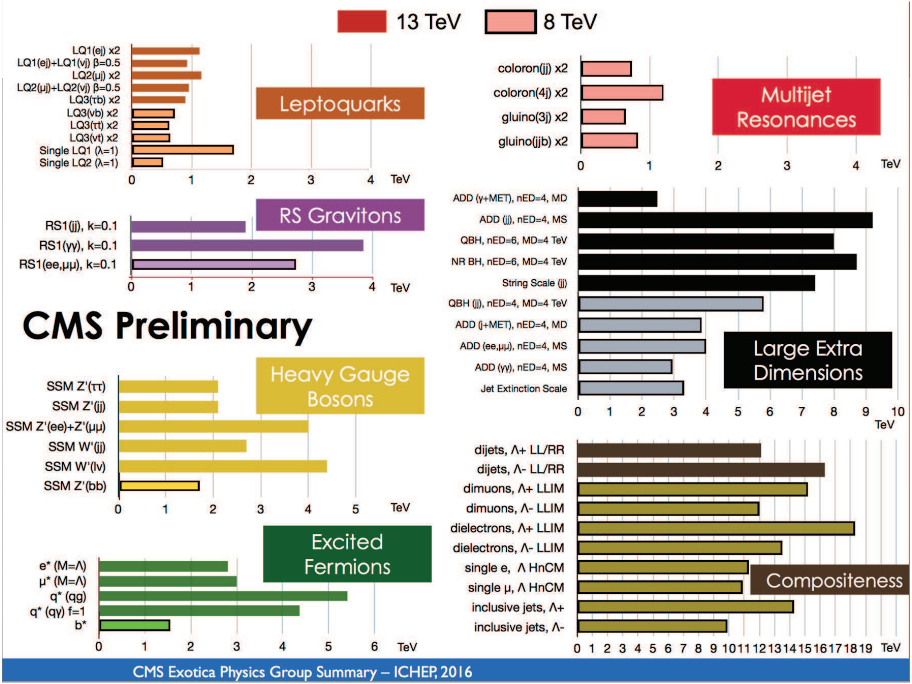
$V_s = -\frac{tu}{s}\,B(t,u) = 1 - \frac{2}{3}\pi^2\,tu + \ldots \qquad V_t : s \leftrightarrow t \qquad V_u : s \leftrightarrow u$

YM limits agree with e.g. book "*Collider Physics*" by Barger, Phillips

Limits on $R_\perp$ in mm

Experiment	$R_\perp(n=2)$	$R_\perp(n=4)$	$R_\perp(n=6)$
Collider bounds			
LEP 2	4.8×10^{-1}	1.9×10^{-8}	6.8×10^{-11}
Tevatron	5.5×10^{-1}	1.4×10^{-8}	4.1×10^{-11}
LHC	4.5×10^{-3}	5.6×10^{-10}	2.7×10^{-12}
Astrophysics/cosmology bounds			
SN1987A	3×10^{-4}	1×10^{-8}	6×10^{-10}
COMPTEL	5×10^{-5}	-	-

present LHC bounds: $M_* \gtrsim 3 - 5$ TeV


13 TeV
8 TeV
LQ1(ej) x2
LQ1(ej)+LQ1(νj) β=0.5
LQ2(μj) x2
LQ2(μj)+LQ2(νj) β=0.5
LQ3(τb) x2
LQ3(νb) x2
LQ3(ττ) x2
LQ3(νt) x2
Single LQ1 (λ=1)
Single LQ2 (λ=1)
Leptoquarks
TeV
coloron(jj) x2
coloron(4j) x2
gluino(3j) x2
gluino(jjb) x2
Multijet Resonances
RS Gravitons
RS1(jj), k=0.1
RS1(γγ), k=0.1
RS1(ee,μμ), k=0.1
ADD (γ+MET), nED=4, MD
ADD (jj), nED=4, MS
QBH, nED=6, MD=4 TeV
NR BH, nED=6, MD=4 TeV
String Scale (jj)
QBH (jj), nED=4, MD=4 TeV
ADD (j+MET), nED=4, MD
ADD (ee,μμ), nED=4, MS
ADD (γγ), nED=4, MS
Jet Extinction Scale
Large Extra Dimensions
CMS Preliminary
Heavy Gauge Bosons
SSM Z'(ττ)
SSM Z'(jj)
SSM Z'(ee)+Z'(μμ)
SSM W'(jj)
SSM W'(lν)
SSM Z'(bb)
dijets, Λ+ LL/RR
dijets, Λ- LL/RR
dimuons, Λ+ LLIM
dimuons, Λ- LLIM
dielectrons, Λ+ LLIM
dielectrons, Λ- LLIM
single e, Λ HnCM
single μ, Λ HnCM
inclusive jets, Λ+
inclusive jets, Λ-
Compositeness
Excited Fermions
e* (M=Λ)
μ* (M=Λ)
q* (qg)
q* (qγ) f=1
b*
CMS Exotica Physics Group Summary – ICHEP, 2016

Supernova constraints

cooling due to graviton production   e.g. $NN \to NN$ + graviton

number of gravitons: $\sim (TR_\perp)^n$ $T >> R_\perp^{-1}$

$\nearrow$ ~ 10 MeV

$\Rightarrow$ production rate: $P_{\rm gr} \sim \frac{1}{M_P^2}(TR_\perp)^n \sim \frac{T^n}{M_*^{(2+n)}}$

$P_{\rm gr} < P_\nu \;\Rightarrow\; M_*\big|_{n=2} \gtrsim 50\ \mathrm{TeV} \;\Rightarrow\; M_s \gtrsim 10\ \mathrm{TeV}$

R-neutrinos: in the bulk

R-neutrino: $\nu_R(x,y)$ y: bulk coordinates

$$S_{int} = g_s \int d^4x\, H(x)\, L(x)\, \nu_R(x, y=0)$$

$\langle H \rangle = v \;\Rightarrow$ mass-term: $\dfrac{g_s v}{R_\perp^{n/2}} \nu_L \nu_R^0$ $\leftarrow$ 4d zero-mode

Dirac neutrino masses: $m_\nu \simeq \dfrac{g_s v}{R_\perp^{n/2}} \simeq v \dfrac{M_*}{M_p}$

$\simeq 10^{-3} - 10^{-2}$ eV for $M_* \simeq 1 - 10$ TeV

$m_\nu << 1/R_\perp \Rightarrow$ KK modes unaffected

Black hole production

String-size black hole energy threshold : $M_{\rm BH} \simeq M_s/g_s^2$

- string size black hole: $r_H \sim l_s = M_s^{-1}$
- black hole mass: $M_{\rm BH} \sim r_H^{d-3}/G_N$ $\quad G_N \sim l_s^{d-2} g_s^2$

weakly coupled theory $\Rightarrow$ strong gravity effects occur much above M_s, M_*

$g_s \sim 0.1$ (gauge coupling) $\quad \Rightarrow \quad M_{\rm BH} \sim 100 M_s$

Comparison with Regge excitations : $M_n = M_s\sqrt{n} \Rightarrow$

production of $n \sim 1/g_s^4 \sim 10^4$ string states before reach $M_{\rm BH}$ [6]

Large TeV dimensions

longitudinal dimensions: $R^{-1} \lesssim M_s \Rightarrow R^{-1}$ first scale of new physics

increasing the energy

- could happen for some of the internal dims
- explain coupling constant ratios g_2/g_3
- susy breaking
- fermion masses displace light generations

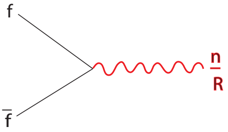
Massive tower of Kaluza Klein modes for Standard Model particles

$$M_n^2 = M_0^2 + \frac{n^2}{R^2} \quad ; \quad n = \pm 1, \pm 2, \ldots$$

$\Rightarrow$ excited states of photon, $W^{\pm}$, Z, gluons

Localized fermions (on 3-brane intersections)

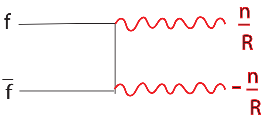
⇒ single production of KK modes



- strong bounds   indirect effects: $R^{-1} \gtrsim 4\,\mathrm{TeV}$
- new resonances   but at most $n = 1$

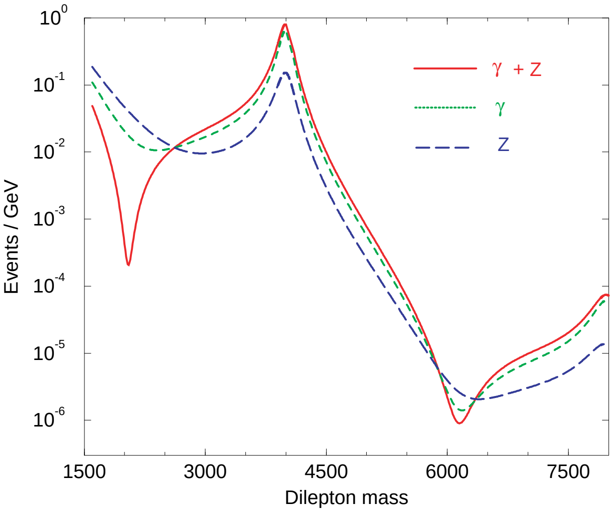
Otherwise KK momentum conservation [21]

⇒ pair production of KK modes (universal dims)



- weak bounds $R^{-1} \gtrsim 500$ GeV
- no resonances
- lightest KK stable ⇒ dark matter candidate

$R^{-1} = 4$ TeV



- no observation in dijets $\Rightarrow R^{-1} \gtrsim 20$ TeV ; 95% CL

- more than one dimension $\Rightarrow$ stronger limits

KK W-production at LHC in the $l\nu$ channel [18]