Particle Physics from Extra Dimensions

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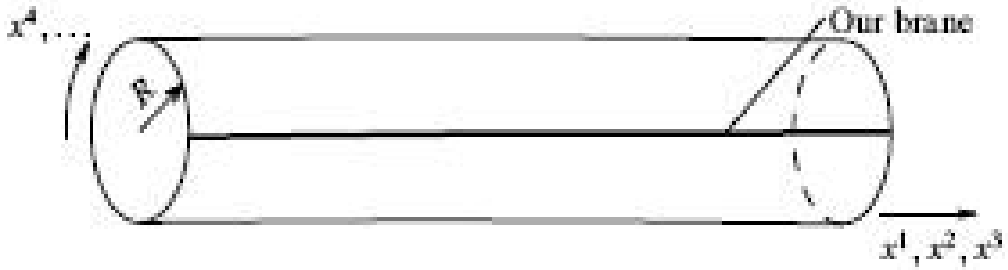
Extra dimensions but why?

- Extra dimensions for Quantum Gravity from Superstring Theory
- Hierarchy problem for Higgs particle mass and cosmological constant – to lower the Planck scale of natural cutoff in SM
- Mass generation without Higgses
- New way for gauge and super-symmetry breaking to provide a lower scale for (SUSY) Grand Unification

And how to realize?

- Extra dimensions may be small, compact to stay invisible: gravity background – curvature of extra-dim space, may be not essential.



- On a torus: Fourier expansion, tower of massive KK states for graviton

$$h_n = \exp\left(i\omega t - i\, p_i x^i\right) \exp\left(-i\,\frac{x^4}{R}\, n_4\right) \ldots \exp\left(-i\,\frac{x^N}{R}\, n_N\right)$$

$$m^2_{KK} = {}^{(4)}p^2 \equiv \omega^2 - {}^{(3)}\mathbf{p}^2 = \frac{\mathbf{n}^2}{R^2}\,.$$

Graviton wave function

? $\quad R \lesssim (\mathrm{TeV})^{-1} \sim 10^{-17}\ \mathrm{cm}$

- Gravity in the bulk but matter on a brane at a point in extra dim. ?

In what follows a number of extra dimensions $N - 4 \equiv d \equiv \delta \equiv n$

Size of extra dimensions

- Planck scale transmutation due to large volume $\sim R^d$

$$(RM_*)^d = \frac{M_{\rm Pl}^2}{M_*^2}\,. \qquad M_{Pl} \simeq 10^{16} TeV \Rightarrow M_* \simeq 1 TeV$$

Gravity in 4 dim and in (4+d) dim

$d = 1$

$R \sim 10^{15}$ cm;

No!

$d = 2$

$R \sim 0.1$ cm

No?!

Table-top exp.!

Indirect evidences:

Successful calculations of big-bang nucleosynthesis

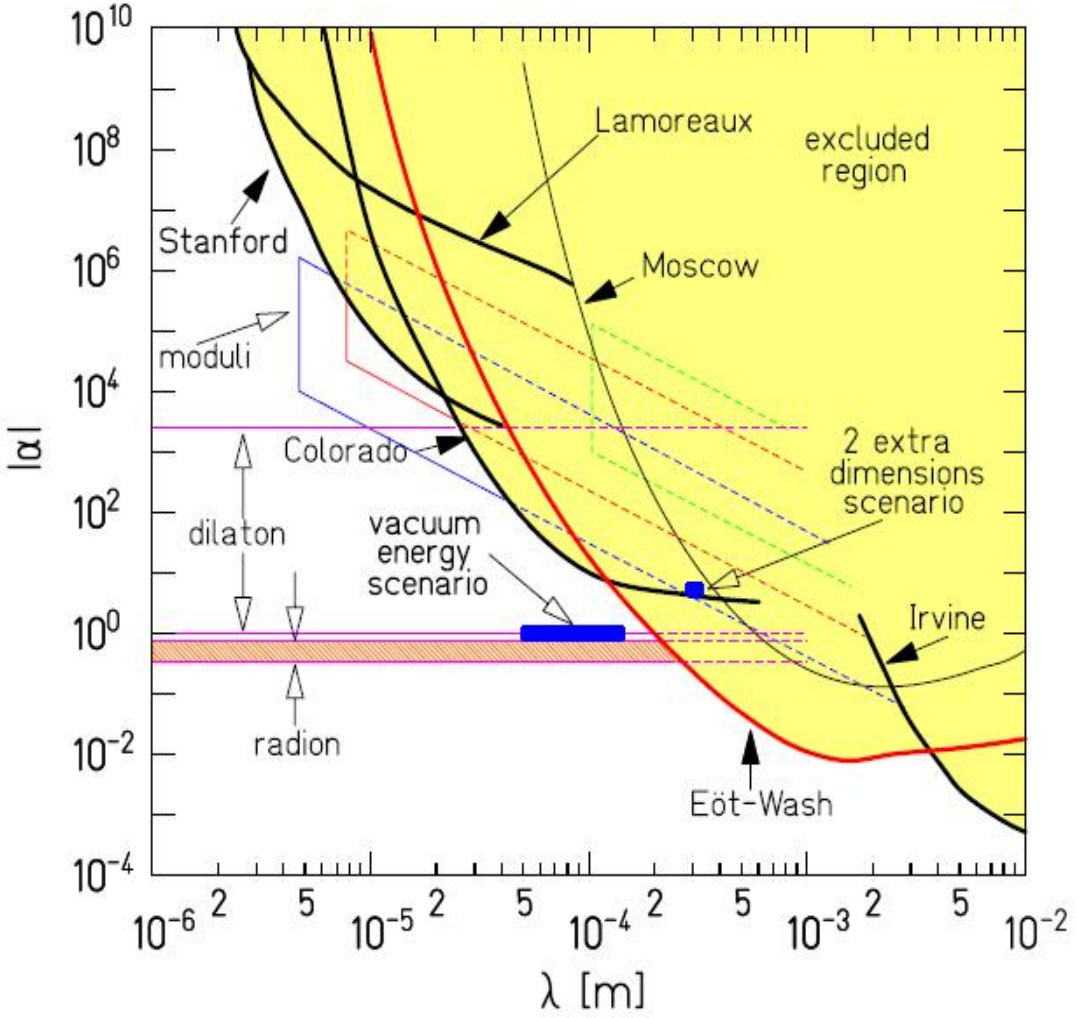
$R < 2\ \mu$m d = 3

Absence of diffuse background of cosmological Gamma rays

$R < 0.05\ \mu$m d = 3

Maybe!

- Spectrum of KK gravitons $\longrightarrow$ modification of the Newton law at short distances



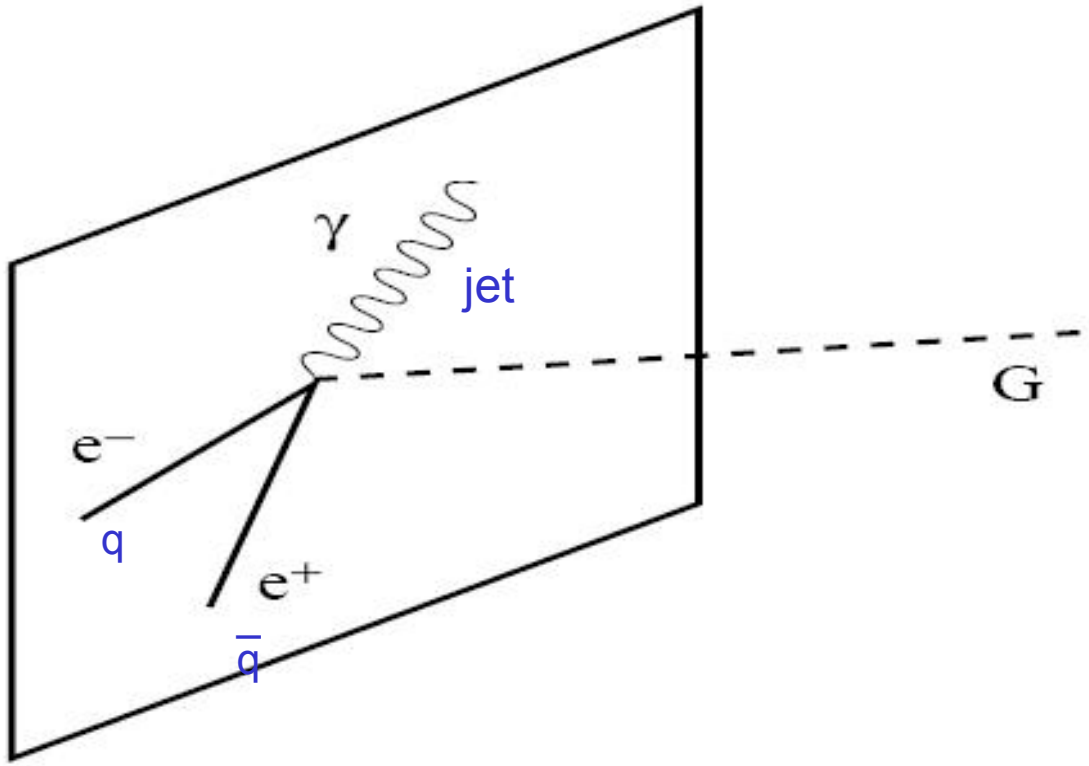
$$V(r) = -\frac{G_N m}{r}\left(1 + \alpha\, e^{-\frac{r}{\lambda}}\right)$$

$\lambda < 150\ \mu\text{m} \quad (95\%\ \text{CL})$

$M_* \simeq 1TeV$

Regions in the $\alpha - \lambda$ plane excluded by table top searches for deviations from Newtonian gravity

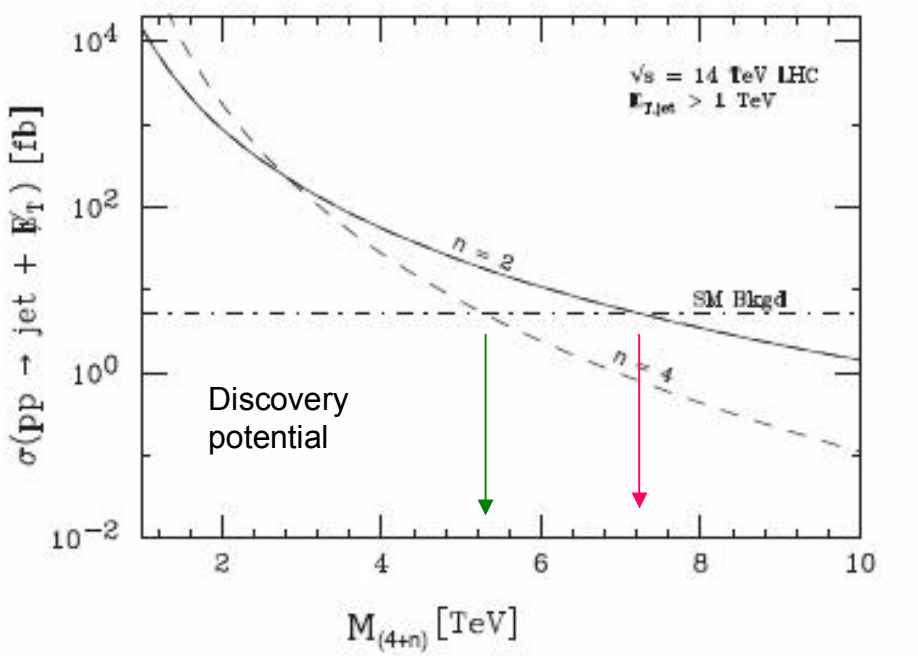
- Missing energy events = predictions of new Planck scale



$$q\bar{q} \rightarrow \text{jet} + \not{E}_T$$

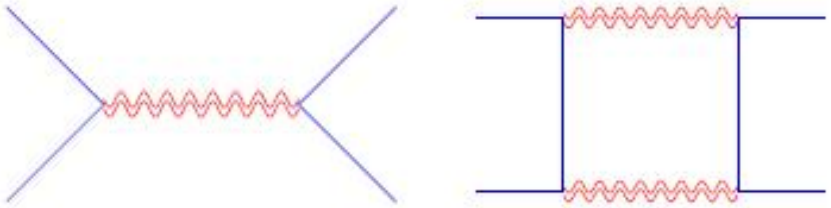
$$\sigma(e^+e^- \rightarrow \gamma + \not{E}_T) \sim \frac{\alpha}{M_{Pl}^2} N(E) \sim \frac{\alpha}{E^2} \left(\frac{E}{M}\right)^{d+2}$$

$N(E)$ is the number of KK gravitons with masses below E



Planck scale in extra-dimensions

• KK graviton exchange: specific four-fermion interaction.



~ $\frac{c_\tau}{2}\left(T_{\mu\nu}T^{\mu\nu} - \frac{T^\mu_\mu T^\nu_\nu}{2+\delta}\right)$ $T_{\mu\nu}$ is the energy-momentum tensor

Vertex of dim-8 $\Longrightarrow$ Fast increasing of fermion-fermion cross sections

$$\left(\frac{8}{|c_\tau|}\right)^{\frac{1}{4}} > 1.3 \text{ TeV}$$ (Giudice, Strumia)

- Black hole creation and their evaporation

Total cross section

$$\hat{\sigma}(\hat{s} = M_{\rm BH}^2) \approx \pi\, r_{\rm BH}^2$$

of order $1/\mathrm{TeV}^2 \sim 400$ pb

Black hole radius for $M_{\rm PL} = 1$ TeV

$$r_{\rm BH} \sim \frac{1}{M_{\rm PL}} \left(\frac{M_{\rm BH}}{M_{\rm PL}} \right)^{\frac{1}{n+1}} \sim 10^{-3} \text{ fm}$$

LHC would produce about 10^7 black holes per year!

Topology		Total Cross Section (fb)
5 TeV black hole	$n = 2$	62,000
	$n = 4$	37,000
	$n = 6$	34,000
8 TeV black hole	$n = 2$	580
	$n = 4$	310
	$n = 6$	270
10 TeV black hole	$n = 2$	6.7
	$n = 4$	3.4
	$n = 6$	2.9

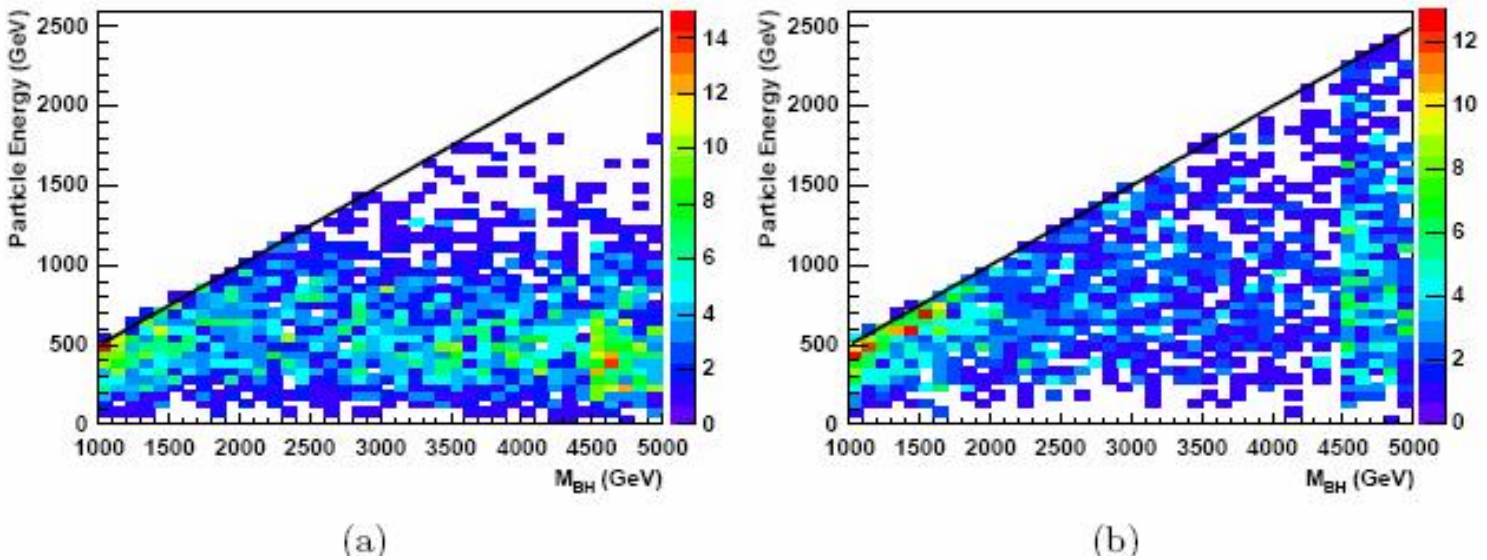
The black hole production cross sections at the LHC for $M_{\rm PL} = 1$ TeV

Black hole decay (evaporation)

Almost black body radiation

$$\frac{dN}{dE} \propto \frac{E^2\gamma}{\left(e^{E/T_H} \mp 1\right) T_H^{n+6}}$$

With a Hawking temperature $T_H = \frac{n+1}{4\pi r_{\mathrm{BH}}}$



Energy of the generator level decay products in the rest frame of the black hole for a 5 TeV black hole and 1000 events. The colour scale indicates the number of particles in each bin. (a) for $n = 2$ the kinematic limit ($E = M_{\mathrm{BH}}/2$, black lines) constricts the energy distribution at low masses. (b) for $n = 4$ the kinematic limit clearly affects the energy distribution at all masses.

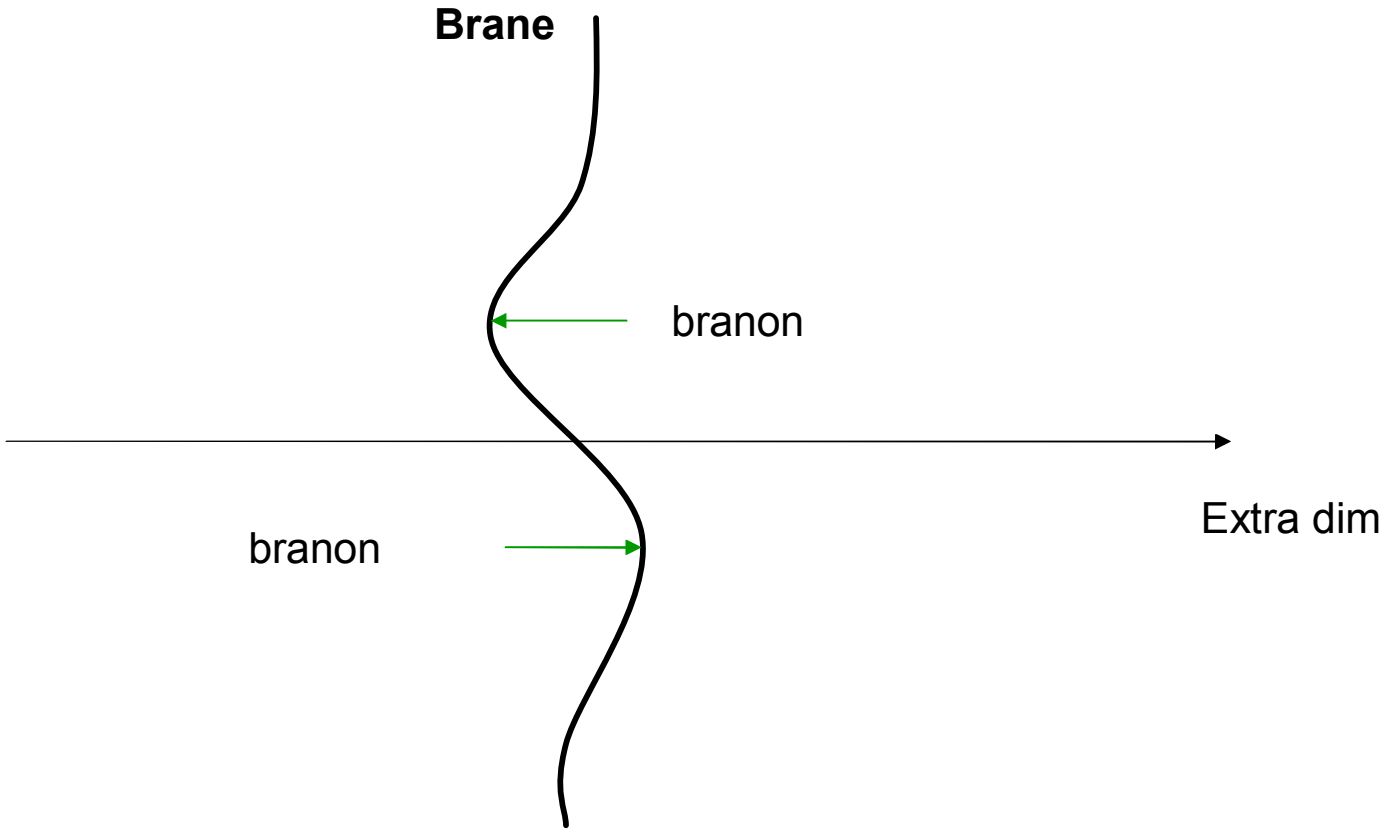
- Extra dimensions: longitudinal for (some of?) SM particles (the latter called universal), transversal + longitudinal for gravity .

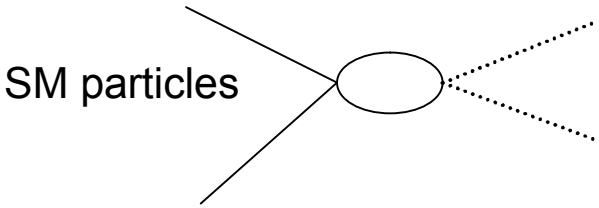
Simplest universal extra dimension

R^{-1}	ΛR	$M_{\mathcal{E}_1}$	$M_{\mathcal{E}_1}$	M_{W_1}	M_{Z_1}	M_{γ_1}
250	20	252.7	257.5	276.5	278.1	251.6
	50	253.6	259.7	280.6	281.9	251.9
350	20	353.8	360.4	379.0	379.7	351.4
	50	355.0	363.6	384.9	385.4	351.5
450	20	454.9	463.4	482.9	483.3	451.1
	50	456.4	467.5	490.6	490.8	451.1

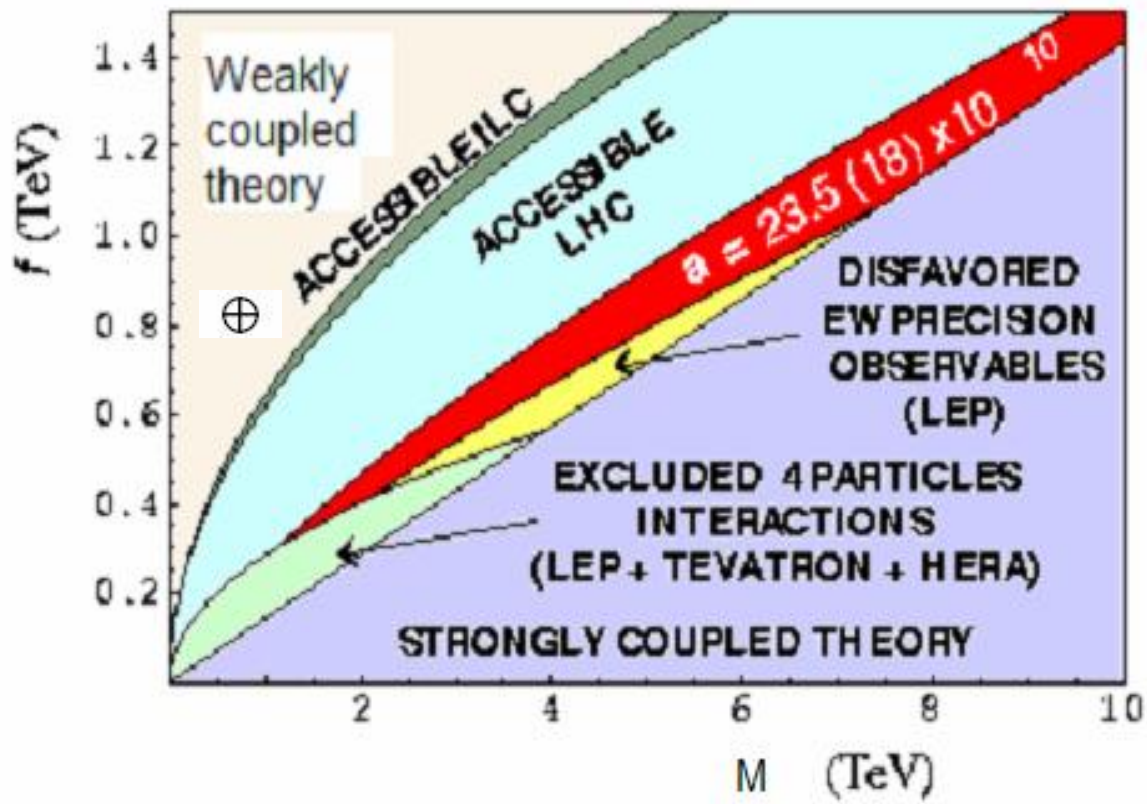
KK masses ($n = 1$) for different cases: excited electrons in SU(2) singlet and doublet representations, excited charged and neutral gauge bosons, respectively. All mass scales are in GeV.

- Gravity on a brane: lightest states = scalar branon + gravitons





pairs of branons !!



Discovery potential for branons (A.Dobado et al.)

f is a brane tension, M is a branon mass