New Physics Subgroup

第1回ミーティング

日時：　5月30日　13:30〜

場所：　KEK　4号館　414

New Physics Subgroup の立ち上げ

目的：　1TeV 領域へのエネルギー増強の意義、LHCとの同時運転のメリットの明確化を念頭に、リニアコライダーでのNew Physicsについて 理論・実験共同で検討を進める。

テーマ：（当面）これまで詳しい解析などがあまり行われてこなかったExtra Dimensionの物理を中心としてのSTUDY

これまでの議論の把握

典型的なExtra Dimension模型

現象論の議論

問題点など

これからの議論

これまでの議論の発展

新しいアイデア、トピックス

模型そのものの発達

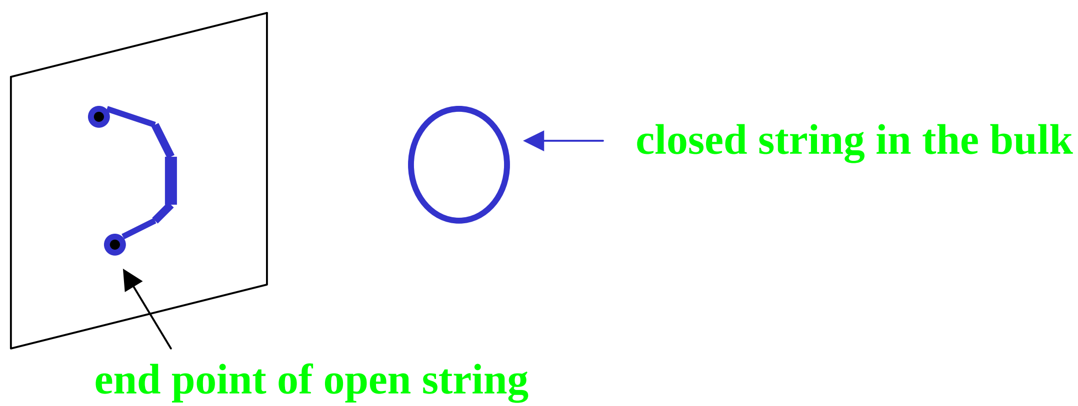
Extra Dimension 以外のNew Physics

Brief Review: Phenomenology of Brane World Physics

1. Brane World Scenario

String Theory : classical solution (Polchinski '95)

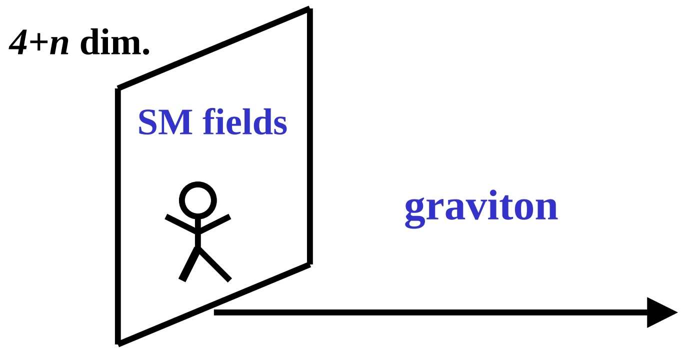
D-brane: D+1 dim. object embedded in higher dim. space time



Open string → fermion, boson, gauge on D-brane

Closed string → graviton in the bulk

<u>Phenomenological model</u>



We are confined on "3-brane"

Graviton lives in the bulk

<u>Beyond the standard model</u> → **Brane World Scenario**

4+n dimension

New property

"geometry"

Typical Scenario: **Large (flat) Extra Dimension** (Arkani-Hamed-Dimopoulos-Dvali, '98)

Warped (small) Extra Dimension (Randall-Sundrum, '99)

2. Large (flat) Extra Dimension Scenario

Alternative solution to hierarchy problem

without SUSY, TC, etc.

$M_W \sim 10^2\mathrm{GeV} \ll M_4 \sim 10^{19}\mathrm{GeV}$ **If** $M_W \sim M_{4+n} \Rightarrow$ **O.K.**

Low scale gravity model

$$S_{4+n} = M_{4+n}^{2+n} \int d^4x d^n y \sqrt{-g_{4+n}} R_{4+n}$$
$$= M_4^2 \int d^4x \sqrt{g_4} R_4$$

$M_4^2 = M_{4+n}^{2+n} V_n$ **V_n : volume of n extra-dim.**

$V_n = (2\pi r)^n$ (compactified on T^n)

For $M_{4+n} \sim 1\mathrm{TeV}$

n	r	
1	10^{13} cm	excluded
2	10^{-1} mm	allowed
3	10^{-6} mm	allowed

← **r < 218 μ*m***

Hoyle et al., PRL 86 (2001) 1418

Phenomenology

- $M_{4+n} \sim O$ (1TeV)
- many graviton KK modes

$$G_{\mu\nu}(x^\mu, y^1, y^2, .., y^n) = \sum_n g_{\mu\nu}^{(\vec{n})}(x^\mu)\, \chi^{(\vec{n})}(\vec{y})$$

$$\chi^{(n)} \propto e^{i\frac{\vec{n}\cdot\vec{y}}{r}}\ , \quad \left(m_{KK}^{(\vec{n})}\right)^2 = \frac{|\vec{n}|^2}{r^2}$$

If 6 dim. ➔ $\frac{1}{r} \sim 10^{-4}\mathrm{eV}$

(i) Perturbative process

KK graviton: emission & mediated

$$\mathcal{L}_{int}^{KK} = -\frac{1}{M_4}\left(\sum_{\vec{n}} g_{\mu\nu}^{(\vec{n})}\right) T^{\mu\nu} \qquad \sqrt{s} \ll M_{4+n}$$

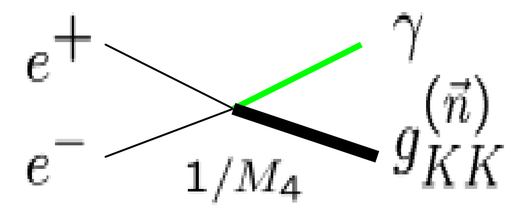
Each process is suppressed by $1/M_4^2$

But × # **of KK modes** $\Longrightarrow \dfrac{1}{M_{4+n}^2}$

KK graviton emission

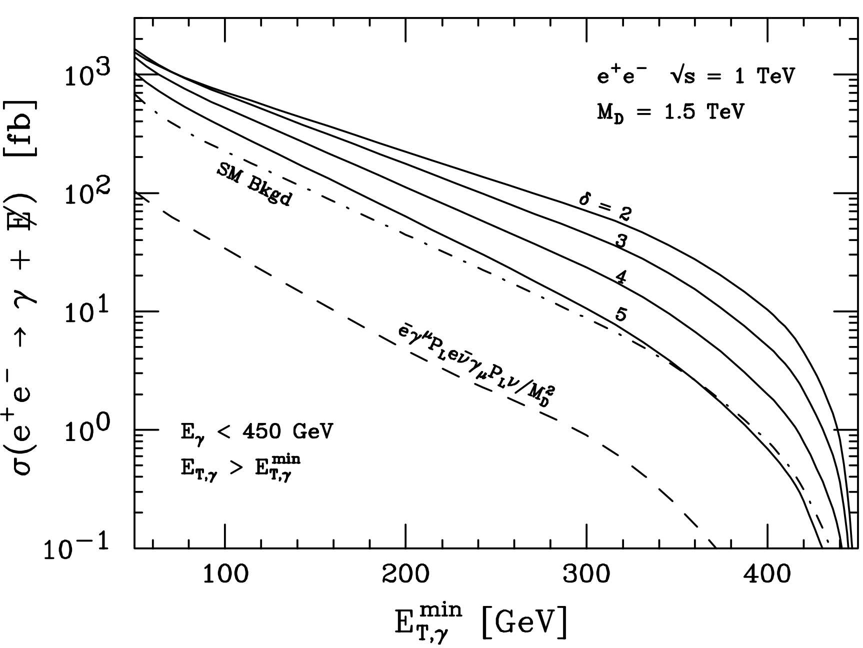
Emitted KK graviton → non-interacting & stable particle

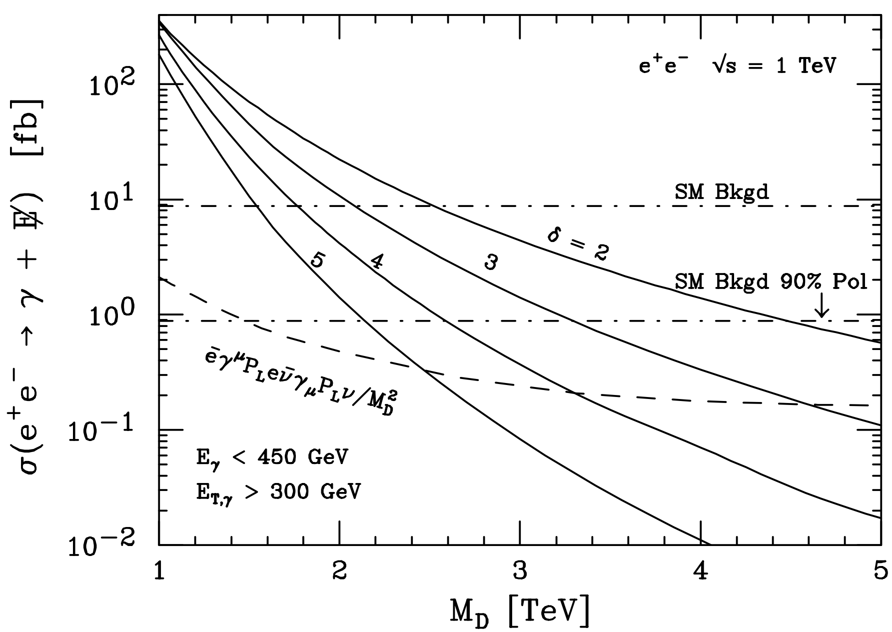
→ missing energy event



Example: $e^+e^- \to \gamma + \text{nothing}$

SM background: $e^+e^- \to \gamma\bar{\nu}\nu$



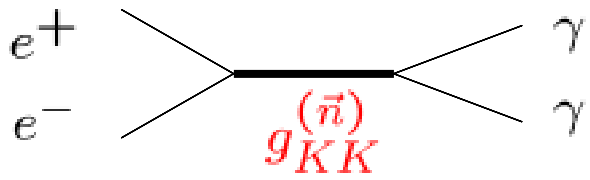


$\sqrt{s} = 1\text{TeV}\,,\quad M_{4+n} = 1.5\text{TeV}$

Giudice, Rattazzi & Wells,

NPB 544 (1999) 3

Virtual KK graviton mediated process

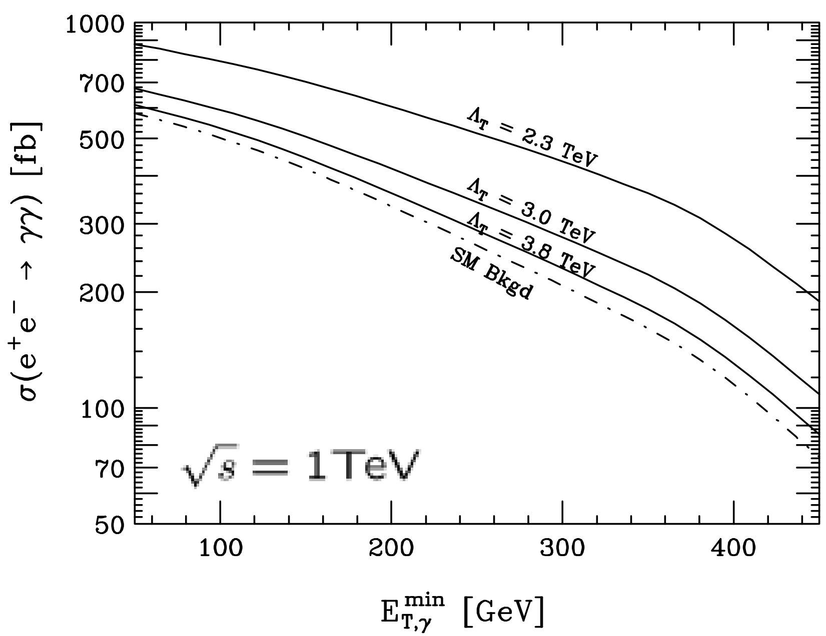


$$\sum_{\vec{n}} \frac{1}{s - \left(m_{KK}^{(\vec{n})}\right)^2} \to \infty \quad (\text{for } n \geq 2)$$

Need regularization

Naïve: Cut Off by $m_{KK}^{MAX} \sim M_{4+n}$

Finite Brane Tension / Fat Brane (Bando et al. ’99 / Hisano-Okada, ’99)



$$\mathcal{L}_{int} = \frac{4\pi}{\Lambda_T^4} T_{\mu\nu} T^{\mu\nu}$$

$\Lambda_T =$ 2.3 TeV

3.0

3.8

Giudice, Rattazzi & Wells,

NPB 544 (1999) 3

<u>Related topic</u>: Higgs physics

Graviscalar, Radion-Higgs mixing

$$G_{MN} \longrightarrow \quad \frac{(4+n)(1+n)}{2}$$

field	spin	d.o.f.
$G_{\mu\nu}^{(\vec{n})}$	2	5
$V_{\mu j}^{(\vec{n})}$	1	$(n-1)\times 3$
$S_{jk}^{(\vec{n})}$	0	$\frac{n^2-n-2}{2}$
$\phi^{(\vec{n})}$	0	1 ←graviscalar

In general, we can add

$$S_{add} = \xi \int d^4x \sqrt{g_{vis}} R(g_{vis}) H^\dagger H$$

Graviscalar-Higgs kinetic mixing

$$\mathcal{L}_{\phi-h}^{free} = -\frac{1}{2}\left(1+6\gamma^2\xi\right)\phi^{(\vec{n})}\partial^2\phi^{(\vec{n})} - \frac{1}{2}\frac{|\vec{n}|^2}{r^2}\phi^{(\vec{n})}\phi^{(\vec{n})}$$
$$- \frac{1}{2}h_0\left(\partial^2 + (2\lambda v_0^2)\right)h_0 - 6\gamma\xi\phi^{(\vec{n})}\partial^2 h_0$$

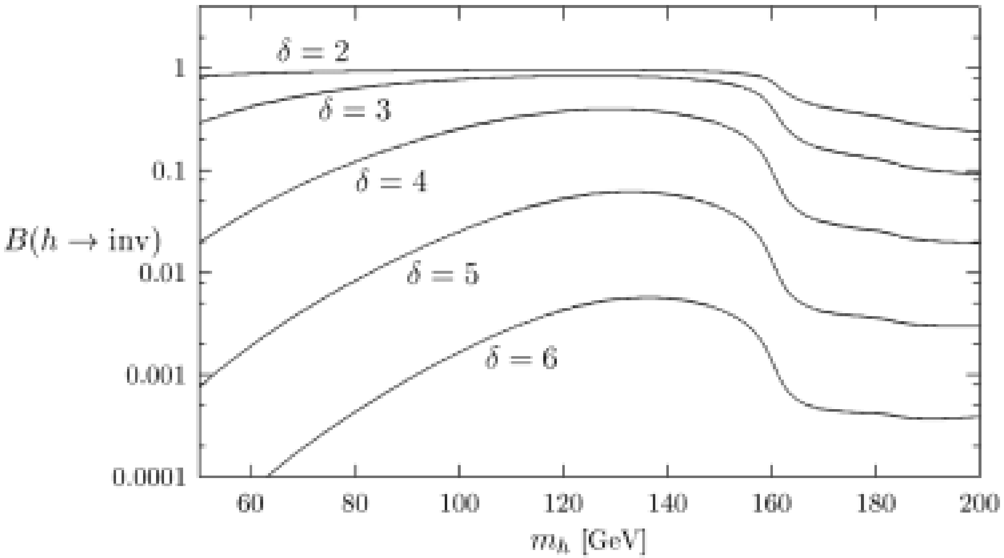
$$\gamma = \frac{v_0}{M_4}$$

$$\mathcal{L}_{int} = \frac{1}{3M_4}\sqrt{\frac{3(n-1)}{n+2}}\phi^{(\vec{n})}T^{\mu}_{\mu}$$

Triple couplings $h_0 - \phi^{(\vec{n})} - \phi^{(\vec{n})}$

Invisible Higgs decay width

$$B(h \to \text{invisible}) = \frac{\Gamma_G}{\Gamma_{SM} + \Gamma_G}$$



Giudice, Rattazzi & Wells,

NPB 595 (2001) 250

$$M_{4+n} = 2\text{TeV} \;, \quad \xi = 1$$

Constraints from Collider Experiments

Cullen, Perelstein & Peskin,

PRD 62 (2000) 0550212

Lower bound on M_{4+n}

Upper bound on r from missing energy event

LEPII: $e^+e^- \to \gamma + \text{nothing}$

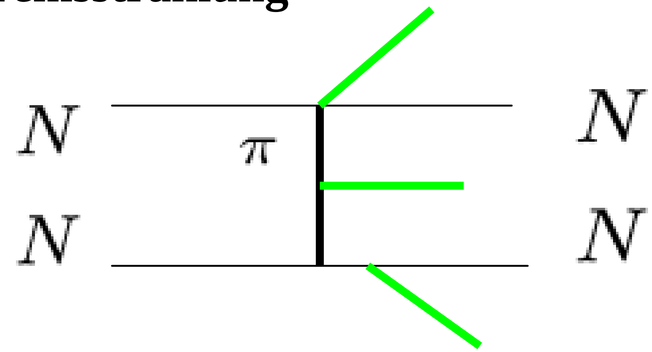
Tevatron: $q\bar{q} \to \gamma + \text{nothing}$

	$r(\text{cm})/M_{4+n}(\text{GeV})$		
LEPII	$4.8 \times 10^{-2}/1200$	$1.9 \times 10^{-9}/730$	$6.8 \times 10^{-12}/530$
Tevatron	$5.5 \times 10^{-2}/1140$	$1.4 \times 10^{-9}/860$	$4.1 \times 10^{-12}/780$
	n=2	n=4	n=6

Astrophysical and cosmological bounds

Anomalous SN cooling through gravi-bremsstrahlung

$$N + N \rightarrow N + N + g_{KK}^{(\vec{n})}$$



	$r(\text{cm})/M_{4+n}(\text{TeV})$		
SN1987A	$3 \times 10^{-6}/50$	$4 \times 10^{-9}/4$	$2 \times 10^{-10}/1$
	n=2	n=3	n=4

Primodial KK gravitons

Increase the amount of matter → CMBR

Decay in photons → CGRBR

$$M_{4+n} \geq \mathcal{O}(10\text{TeV}) \; , \; \; \mathcal{O}(1\text{TeV})$$
$$n = 2 \; , \quad n \geq 3$$

(ii) Non-perturbative process

$\sqrt{S} > M_{4+n}$ **TeV string, strong gravity**

4+n dim. Black Hole formation?

Giddings-Thormas '01

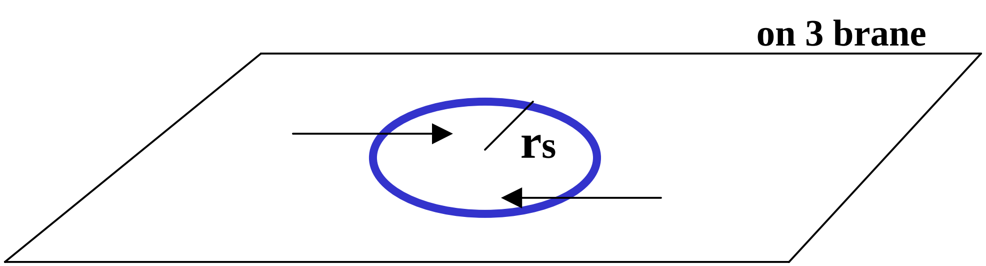
Dimopoulos-Lansberg

4+n dim. BH solution

$$ds^2 = -R(r)dt^2 + R(r)^{-1}dr^2 + r^2 d\Omega_{n+2}^2$$

$$R(r) = 1 - \left(\frac{r_s}{r}\right)^{n+1}$$

$$r_s = \frac{1}{\sqrt{\pi} M_{4+n}} \left(\frac{8\Gamma\left(\frac{n+2}{2}\right)}{n+2}\right)^{\frac{1}{n+1}} \left(\frac{M_{BH}}{M_{4+n}}\right)^{\frac{1}{n+1}}$$



$$\sigma(M_{BH}) \sim \pi r_s^2$$

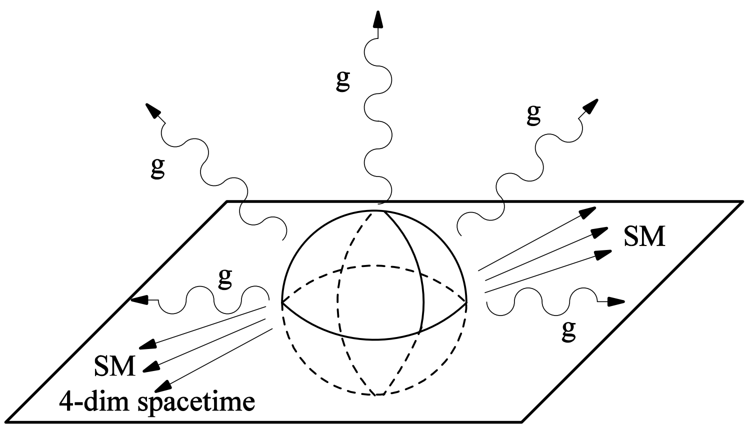
BH production @ LHC

$$\sigma_{pp\to BH}(x_m, n) \sim \sum_{ij} \int_{x_m}^{1} dx \int_{x}^{1} \frac{dy}{y} f_i(y,Q) f_j(x/y,Q) \times \sigma_{ij\to BH}(xs; n)$$

$$x_m = \frac{M_{BH}^{min}}{\sqrt{s}} \sim \frac{M_{4+n}}{\sqrt{s}}$$

BH decay

Evaporate by emitting Hawking Radiation



$$T_H = \frac{n+1}{4\pi r_s}$$

- particle blind
- E ~ T_H for each quanta
- emission rate → # of d.o.f

BH → quarks & gluons ~ 75 %

charged leptons ~ 10 %

neutrinos ~ 5 %

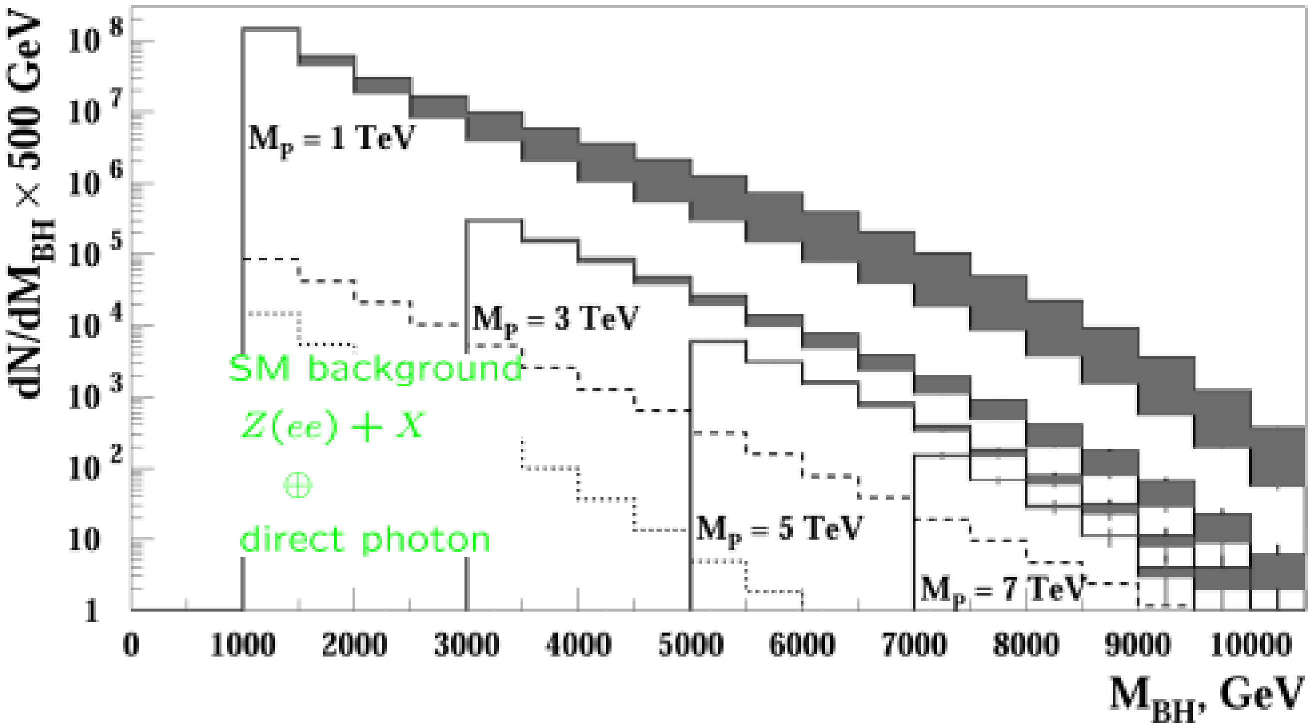
γ, W, Z ~ 2 % each

of produced BH @ LHC ($100 fb^{-1}$ integrated luminosity)

electron/photon decay channels

Dimopoulos-Landsberg,

PRL 87 (2001) 161602



$n = 1 \sim 7$

LHC can be "BH Factory"

if $M_{BH}^{min} \sim \mathcal{O}(1\,\mathrm{TeV})$

Far future …..

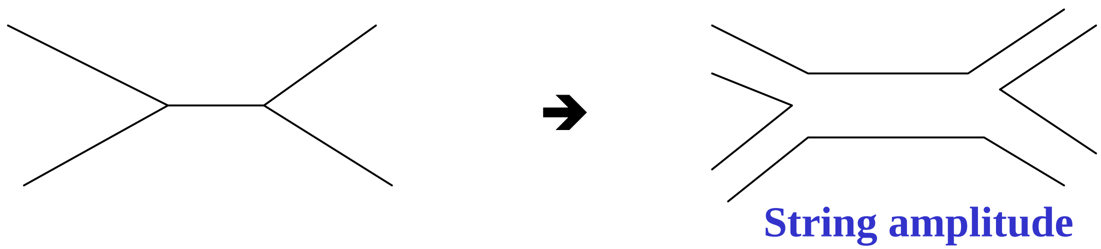
BH property has been known

Collider will be designed in order to

NOT produce BH

(iii) TeV scale string theory

Evidence of TeV scale string theory? $M_{4+n} \sim M_{st}$



(Perturbative) String Theory

Many states: **string Regge excitations**

$$M_n = \sqrt{n} M_{st} \; (n = 0, 1, 2, ...)$$
$$J = 0, 1/2, 1, 3/2, 2, 5/2......$$

Phenomenology of TeV string theory

string Regge excitations: **new contact terms** $\sqrt{s} \leq M_{st}$

string resonances $\sqrt{s} \geq M_{st}$

Stringy correction to scattering amplitudes

Cullen, Perelstein & Peskin,

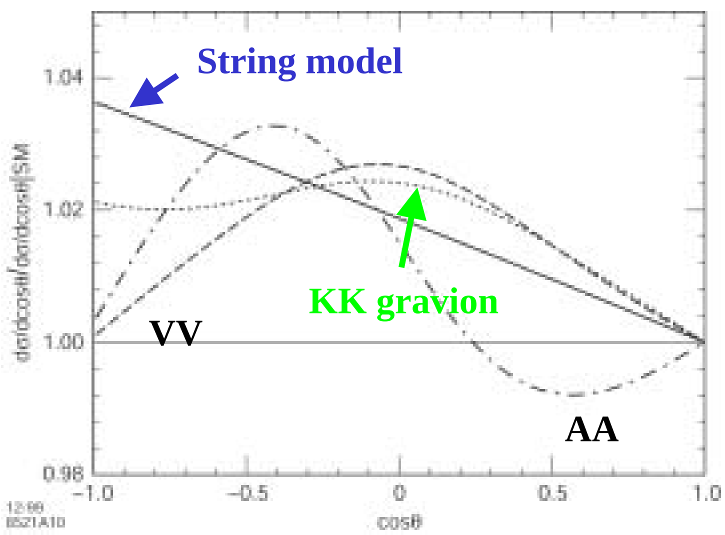
PRD 62 (2000) 0550212

$$\frac{d\sigma}{d\cos\theta} = \left(\frac{d\sigma}{d\cos\theta}\right)_{SM} |S(s,t)|^2$$

String form factor: $S(s,t) = \frac{\Gamma(1-s/M_{st}^2)\Gamma(1-t/M_{st}^2)}{\Gamma(1-s/M_{st}^2-t/M_{st}^2)}$

$\sqrt{s} \lesssim M_{st} \rightarrow$ **Contact interaction mediated SR excitations**

Example: Bhabha scattering @ 1TeV LC



$M_{st} = 3.1\text{TeV}$

$\Lambda_T = 6.2\text{TeV}$

VV contact with $\Lambda = 88\text{TeV}$

AA contact with $\Lambda = 62\text{TeV}$

$$\mathcal{L}_{KK} = i\frac{4}{\Lambda_T} T^{\mu\nu}T_{\mu\nu}$$

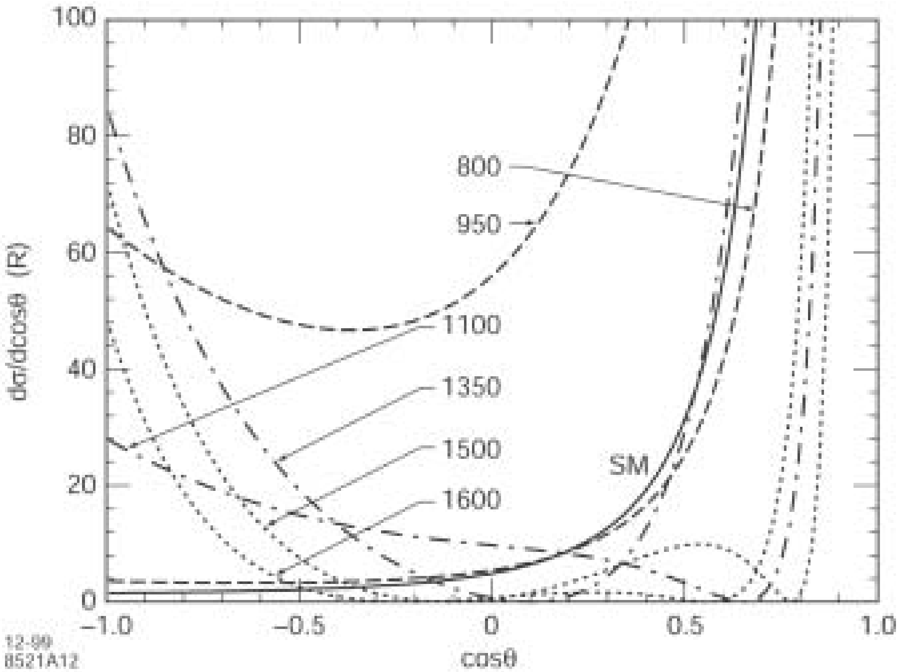
$$\mathcal{L}_{VV} = -\frac{4\pi}{2\Lambda^2}\overline{e_L}\gamma^\mu e_L \overline{e_L}\gamma_\mu e_L + \cdots$$

$s = M_n^2 = nM_{st}^2 \rightarrow$ **String resonance**

$nM_{st}^2 < s < (n+1)M_{st}^2$ **behavior of string form factor**

In units of

$\frac{4\pi\alpha^2}{3s}$



$M_{st} = 1\mathrm{TeV}$

$s < M_{st}^2$

$M_{st}^2 < s < 2M_{st}^2$

$2M_{st}^2 < s < 3M_{st}^2$

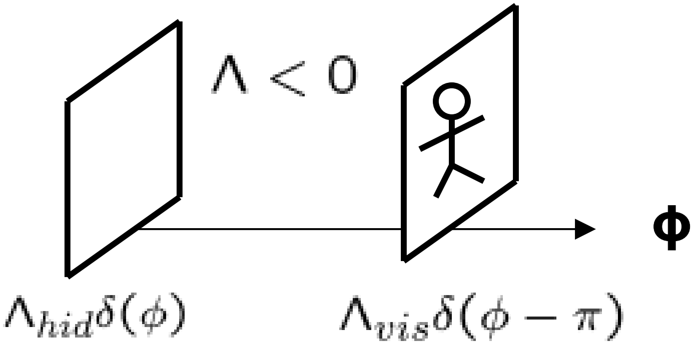
Cullen, Perelstein & Peskin,

PRD 62 (2000) 0550212

3. Warped (small) Extra Dimension Scenario

Randall-Sundrum, ’99

5-dim. Theory compactified on s^1/Z_2



slice of AdS_5

$$S_G = \int d^4x \int_{-\pi}^{\pi} d\phi \sqrt{-g}\,(2M_5R_5 - \Lambda)$$

$$S_{\frac{vis}{hid}} = \int d^4x \sqrt{-g_{\frac{vis}{hid}}}\left(\mathcal{L}_{\frac{vis}{hid}} - \Lambda_{\frac{vis}{hid}}\right)$$

Solution of Einstein Eqs.

$$ds^2 = e^{-2\kappa r_c|\phi|}\eta_{\mu\nu}dx^\mu dx^\nu + r_c^2 d\phi^2$$

If

$$\Lambda = -24M_5^3\kappa$$
$$\Lambda_{hid} = \Lambda_{vis} = 24M_5^3\kappa$$

4-dim. Planck scale

$$V_5 = \int_{-\pi}^{\pi} d\,\phi r_c\, e^{-2\kappa r_c|\phi|} = \frac{1}{\kappa}\left(1 - e^{-2\kappa r_c|\phi|}\right)$$

$$\rightarrow \quad M_4^2 = \frac{M_5^3}{\kappa}\left(1 - e^{-2\kappa r_c|\phi|}\right) \sim \begin{array}{ll} M_5/\kappa & \text{for } \kappa r_c\pi \gg 1 \\ M_5^3(2\pi r_c) & \text{for } \kappa r_c\pi \ll 1 \end{array}$$

Alternative solution to hierarchy problem

SM Higgs lives on the visible brane

$$S_{Higgs} = \int d^4x \sqrt{-g_{vis}} \left[g_{vis}^{\mu\nu}(D_\mu H)^\dagger(D^\mu H) - \lambda(H^\dagger H - v_0^2)^2\right]$$

$$\sqrt{-g_{vis}} g_{vis}^{\mu\nu} = e^{\kappa r_c \pi}\eta^{\mu\nu} \Longrightarrow H \rightarrow e^{\kappa r_c\pi} H$$ **rescale**

$$S_{Higgs} = \int d^4x \left[\eta^{\mu\nu}(D_\mu H)^\dagger(D^\mu H) - \lambda(H^\dagger H - v^2)^2\right]$$

$$v = v_0 \times e^{-\kappa r_c \pi}$$

Even if v0 ~M4, v can be the weak scale with $\kappa r_c \sim 12$

Mild hierarchy

Phenomenology

- $M_5 \sim M_4 \gg M_W$
- graviton KK mode mass $m_{KK}^{n} \sim \kappa e^{-\kappa r_c \pi} \sim \mathcal{O}(M_W)$

KK mode configuration

$$f^{(0)}(\phi) \sim e^{-\kappa r_c \pi}$$ **localize around hidden brane**

$$f^{(n)}(\phi) \sim e^{\kappa r_c \pi} J_2(m_{KK}^{(n)}/\kappa e^{\kappa r_c |\phi|})$$ **localize around visible brane**

$$\mathcal{L}_{int} = -\frac{1}{M_4} g_{\mu\nu}^{(0)} T^{\mu\nu} - \frac{1}{M_4 e^{-\kappa r_c \pi}} \sum_{n=1} g_{KK\,\mu\nu}^{(n)} T^{\mu\nu}$$

← **Strong**

Collider physics

Davoudiasl, Hewett & Rizzo,

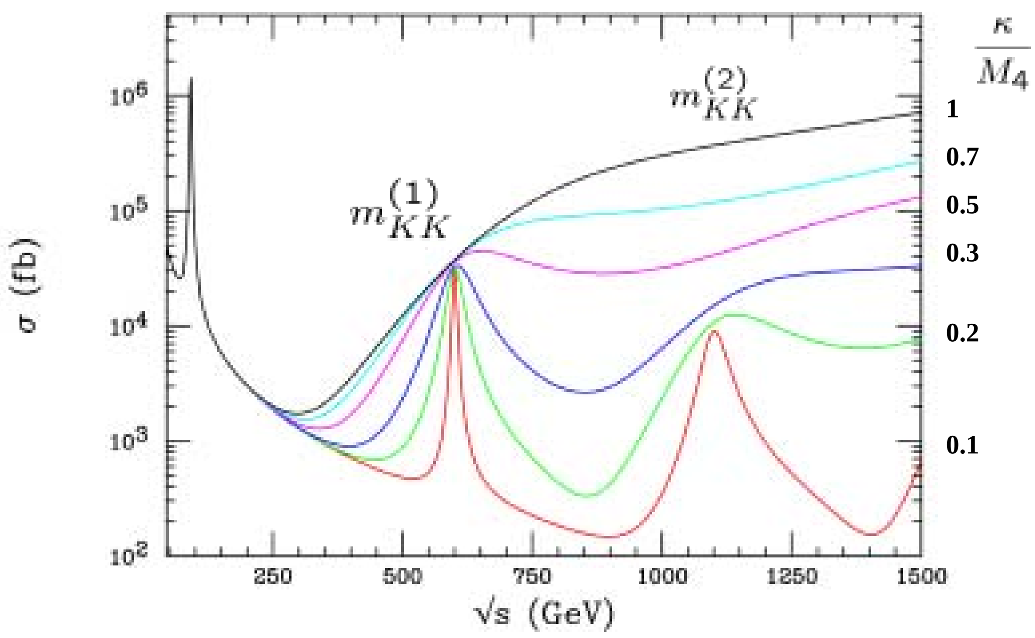
PRL 84 (2000) 2080

KK graviton resonance production

LC: $e^+e^- \to g_{KK}^{(1)} \to \mu^+\mu^-$

$$\mathcal{L}_{int}^{(1)} = -\frac{1}{M_4 e^{-\kappa r_c \pi}} g_{KK\,\mu\nu}^{(1)} T^{\mu\nu}\ , \qquad M_4 e^{-\kappa r_c \pi} \sim \frac{m_{KK}^{(1)}}{3.83}\frac{M_4}{\kappa}$$

$$m_{KK}^{(1)} = 600\text{GeV}$$

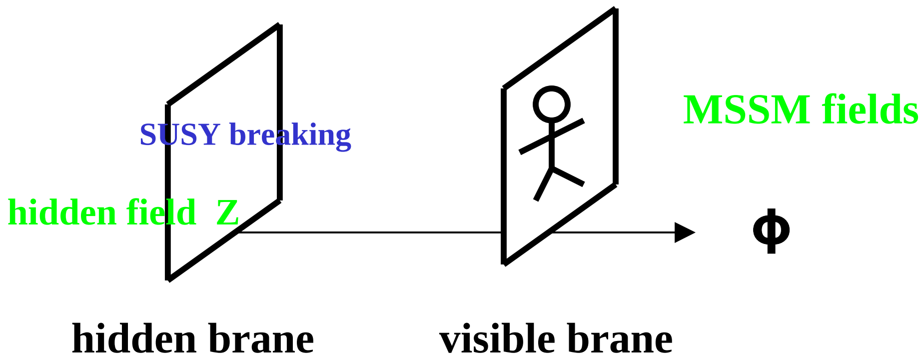


Width becomes large

as κ/M4 becomes large

4. SUSY + Extra Dimension

<u>Sequestering scenario</u> Randall-Sundrum, '99



$$\mathcal{L}_{cont} = \int d^4\theta \frac{Z^\dagger Z Q_i^\dagger Q_j}{M_4^2} \to m_{3/2}^2 \tilde{Q}_i^\dagger \tilde{Q}_j$$ **causes FCNC**

is forbidden by Geometry

SUSY breaking mediation → Anomaly Mediation Scenario

$$M_{\lambda_i} = \frac{b_i g_i^2}{16\pi^2} m_{3/2}$$ **<u>different soft mass spectrum</u>**

5. Discussions

Extra Dimension Model

Large Extra Dimension Scenario

Randall-Sundrum Scenario

TeV string

TeV gravity --- BH production

Universal Extra Dimension -- KK modes of SM fields

Story

$$\sqrt{s} \;\le\; M_{4+n} \text{ or } M_{st}$$

$$\sqrt{s} \;\ge\; M_{4+n} \text{ or } M_{st}$$

$(i)\sqrt{s} \leq M_{4+n}$ or M_{st}

KK graviton emission $m_{KK}^{(n)} \leq \sqrt{s}$

Graviscalar-Higgs mixing

Contact interaction $m_{KK}^{(n)} \geq \sqrt{s}$

KK graviton

string Regge

Angular distribution

information of intermediate fields

spin & mass

$(ii) \sqrt{s} \geq M_{4+n}$ or M_{st}

Randall-Sundrum model: KK graviton resonance

TeV string resonance

BH production @ LC

Search for # of extra dimensions

$T_H(n)\ ,\ \ M_{BH}(n)$ **as a function of *n***

Information of quantum gravity?

set c.m. energy $\sqrt{s} \leq M_{BH}^{min}$

how to extract quantum gravity information?

Check KK mode? --- coupling measurement etc.