Collider Phenomenology of

Extra Dimensions

APS April Meeting, Philadelphia

Why theorists expect physics beyond the SM

Unanswered theoretical problems

(1) Flavor problem: Why THREE families? Origin of fermion masses?

(2) Grand Unification

$$\begin{array}{ccccc} & & \text{strong} & & \\ & & \Downarrow & & \\ \text{EM} & \Longrightarrow & \text{Final theory} & \Longleftarrow & \text{weak} \\ & & \Uparrow & & \\ & & \text{gravity} & & \end{array}$$

(3) Large Hierarchy: $M_{\rm Planck} \gg M_W$.

• New physics needed to stabilize the hierarchy, e.g., Supersymmetry.

Recent developments in string theories and extra dimensions transform the hierarchy into geometry stabilization.

Observational Hints for physics beyond the SM

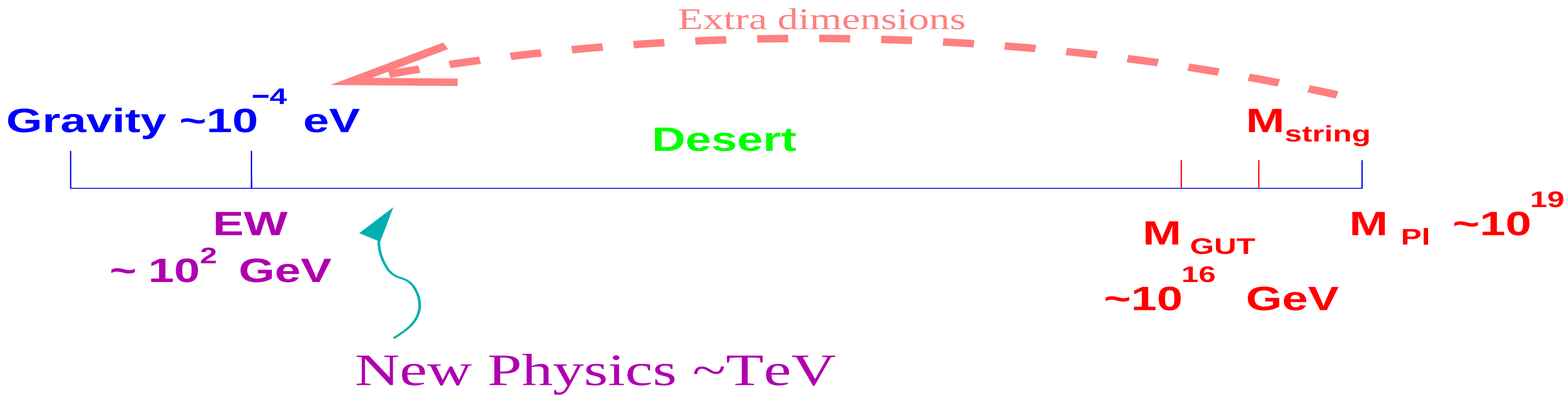
- ⋆ ν masses and oscillations
- ⋆ Existence of dark matter
- ⋆ Inflation, dark energy (cosmological constant)
- ⋆ Baryogenesis:

SM not enough CP violation and first order thermal transition

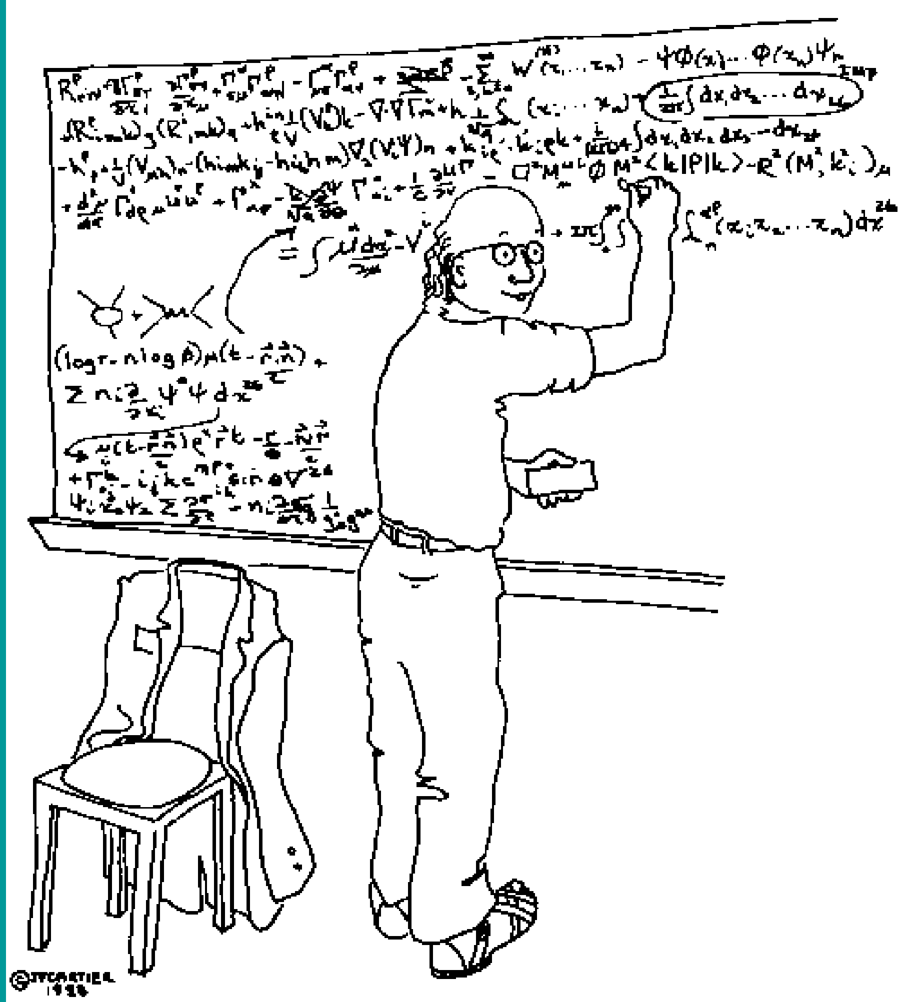
Outline

- Why we need extra dimensions.
- Compact flat large extra dimensions (ADD model)
  - Sub-Planckian signatures.
  - Trans-Planckian signals
- Warped extra dimensions (Randall-Sundrum model)
- Gauge bosons in TeV^{-1}-sized extra dimensions
- Universal extra dimensions
- An 5D SU(5) Supersymmetric GUT in an AdS slice

Extra Dimensions

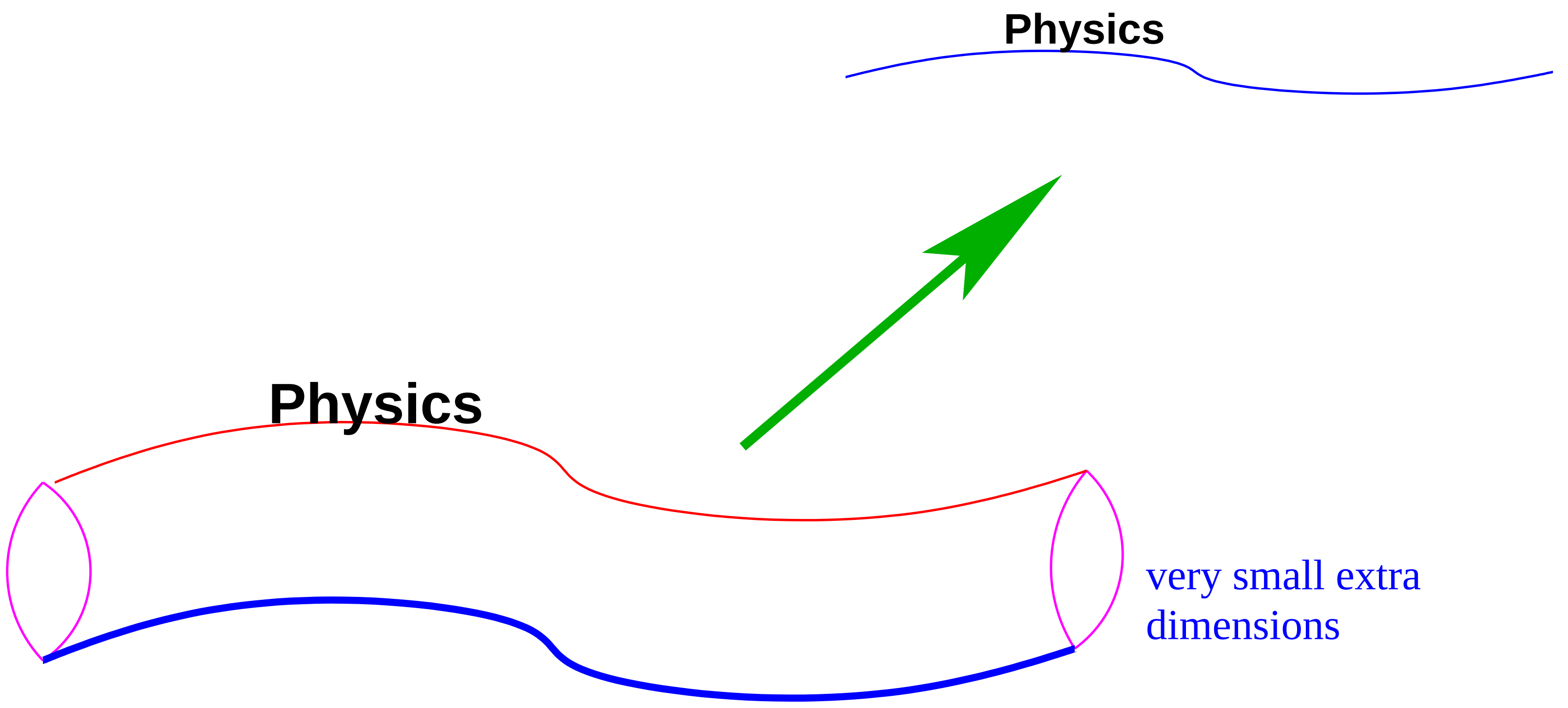


- Huge difference between $M_{\rm EW}$ and $M_{\rm Pl}$.
- New physics at $\sim$ TeV, e.g. SUSY.
- New ideas using extra dimensions can bring $M_{\rm Pl}$ down to TeV.

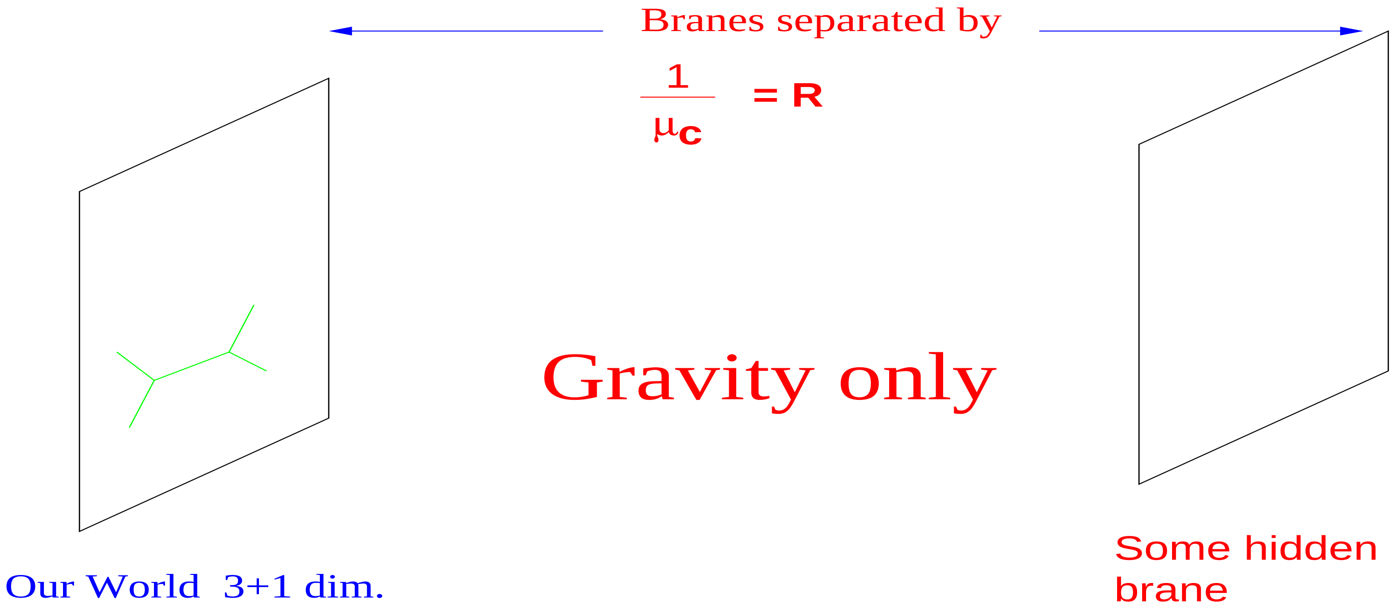


"At this point we notice that this equation is beautifully simplified if we assume that space–time has 92 dimensions."

Why we do not see extra dimensions



ADD model



Proposed by Arkani et al. the size of the extra dimensions can be as large as $R \lesssim 1$ mm.

$$\mu_c \equiv R^{-1} \gtrsim 10^{-4}\ \mathrm{eV} \ll M_{\rm EW}$$

$$M_{\rm Pl}^2 \sim M_D^{n+2}\, R^n \qquad \text{(Gauss)}$$

- $M_{*,D}$ is the fundamental Planck scale, as low as TeV.

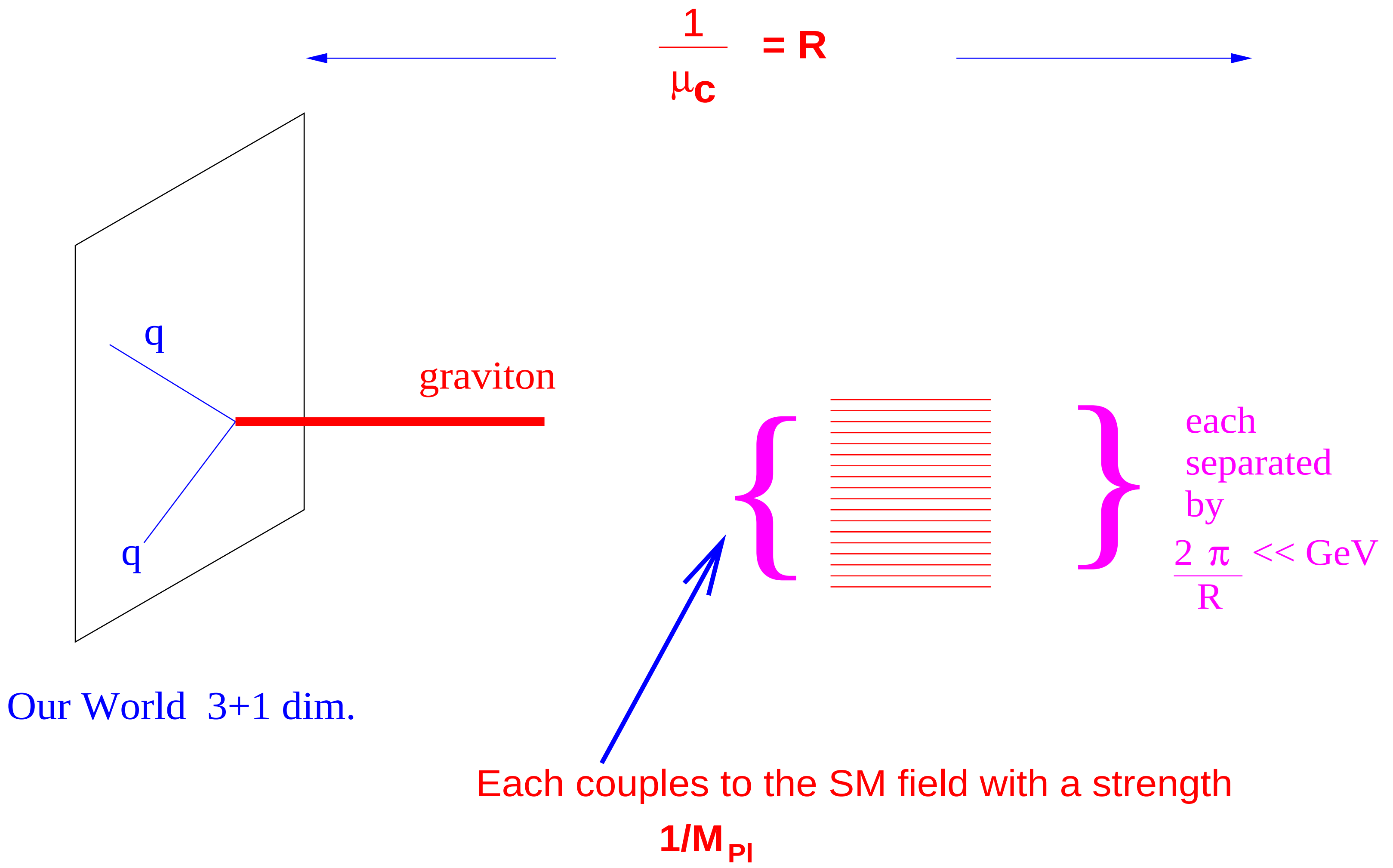
Solve the hierarchy.

- Allow only gravity in the bulk.

In 4-D, the graviton becomes towers of Kaluza-Klein states

$$M_n = \frac{2\pi n}{R}$$

- SM particles confined to a brane.



- Effectively, interaction $\sim \frac{1}{M_D} = (1\text{TeV})^{-1}$.

Sub-Planckian Signatures

- Graviton emission into extra dimensions.
- Graviton exchange processes: interference with the SM.

Trans-Planckian Physics

- Black holes
- String balls
- p-branes

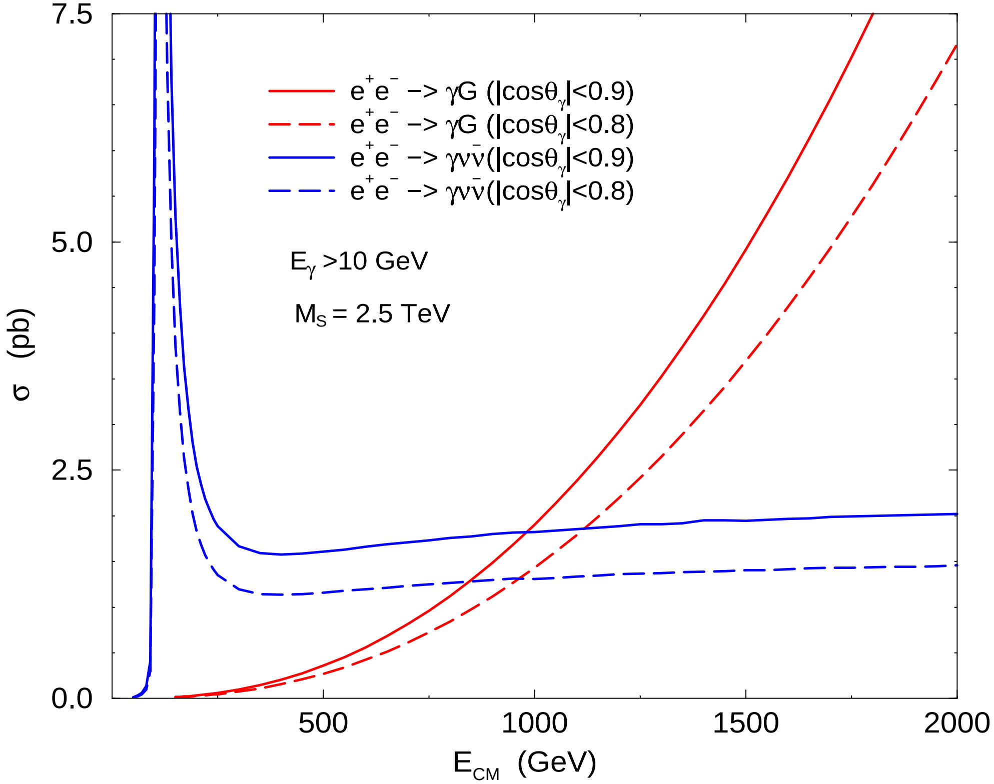
The energy scale is $\gg M_D, M_s$

Sub-Planckian

Novel signatures: Graviton Emissions

$$
\begin{aligned}
e^+e^-,\ \ p\bar{p} \quad &\longrightarrow \quad \gamma G, jG \qquad \text{(Mirabelli et al.; Giudice et al.)} \\
&\longrightarrow \quad ZG \qquad \text{(Cheung, Keung)} \\
&\longrightarrow \quad WG \qquad \text{(Balazs et al.)} \\
&\longrightarrow \quad f\bar{f}G \qquad \text{(Balazs et al.; Atwood et al.)}
\end{aligned}
$$

$e^+e^- \to \gamma G, ZG$: Single-photon (Z) plus missing E_T.



Cheung and Keung

William Orejudos, LBNL
ICHEP 2002

CDF search with ɔ 2 Missing E_T

Graviton emission:

$q\bar{q} \Downarrow G_{kk}\, \nu$

E_T^{ν} } 55 GeV

Missing E_T } 45 GeV

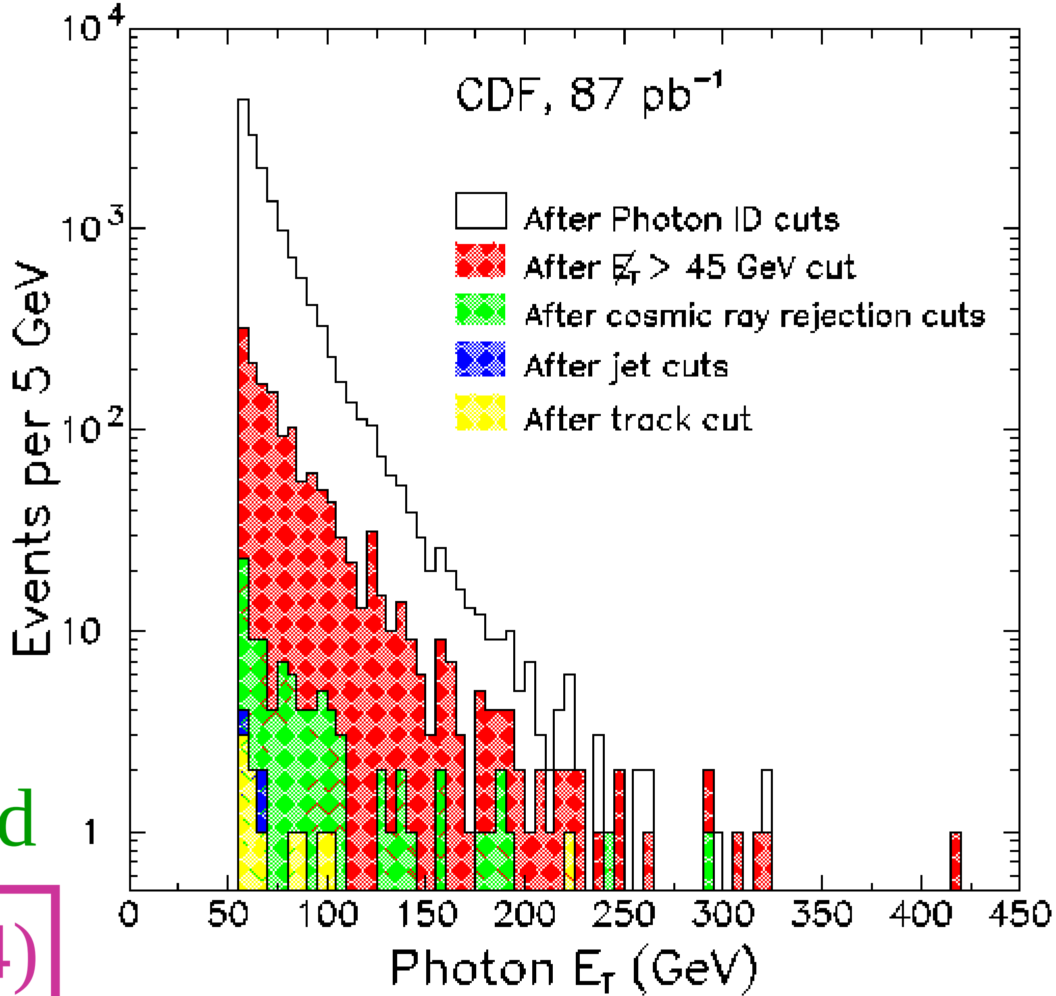
No jets with E_T } 15 GeV

No tracks with p_T } 5 GeV/c

Main bckgnd : Cosmic Rays,

$Z \Downarrow \Upsilon\bar{\Upsilon}\nu$

11.0 ∂ 2.2 expected, 11 observed



M_s } 549 GeV/c^2 (n | 4)

M_s } 581 GeV/c^2 (n | 6)

M_s } 602 GeV/c^2 (n | 8)

William Orejudos, LBNL
ICHEP 2002

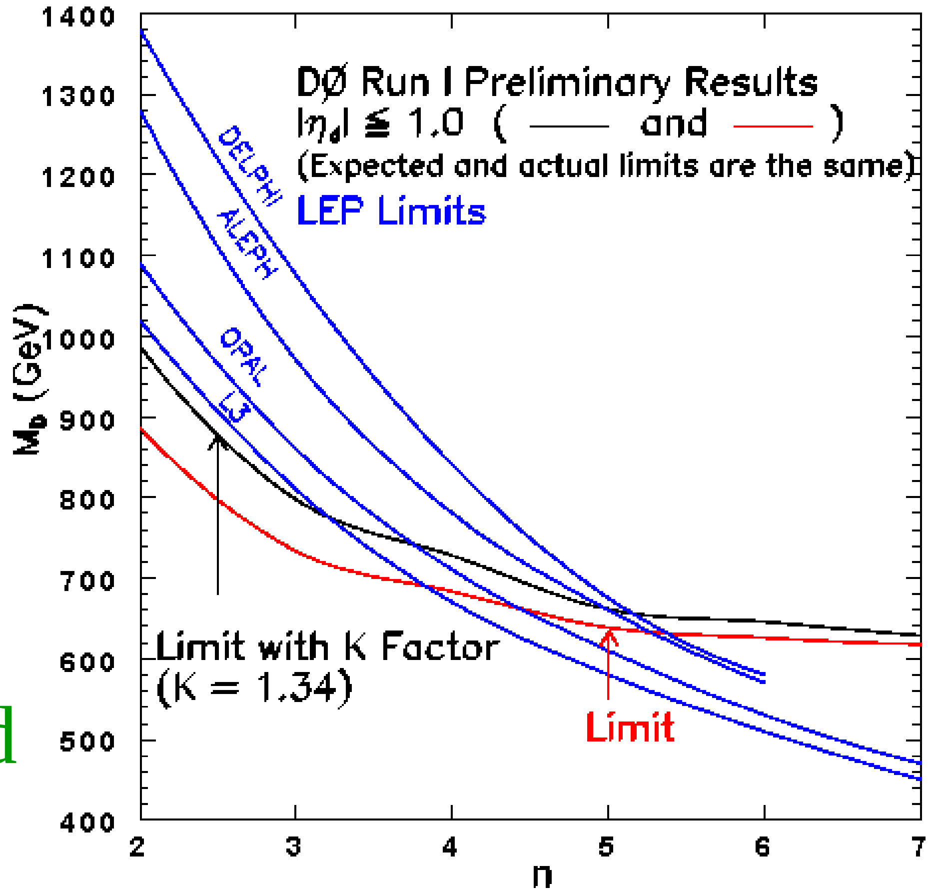
D0 search with jets and missing E_T

LED search, $G_{KK}g$ final state

E_T (jet1) > 150 GeV
E_T (jet2) < 50 GeV
Missing E_T > 150 GeV
Missing E_T, jet2 > 15^o apart
No isolated muons
Main bckgnd : Z ⇓ $\Upsilon\bar{\Upsilon}$ *jets*
QCD/Cosmics
W ⇓ $\vartheta\Upsilon$ *jets*

38.0 ∂ 9.6 expected, 38 observed

M_s } 886 GeV/c^2(n | 2)
M_s } 617 GeV/c^2(n | 7)

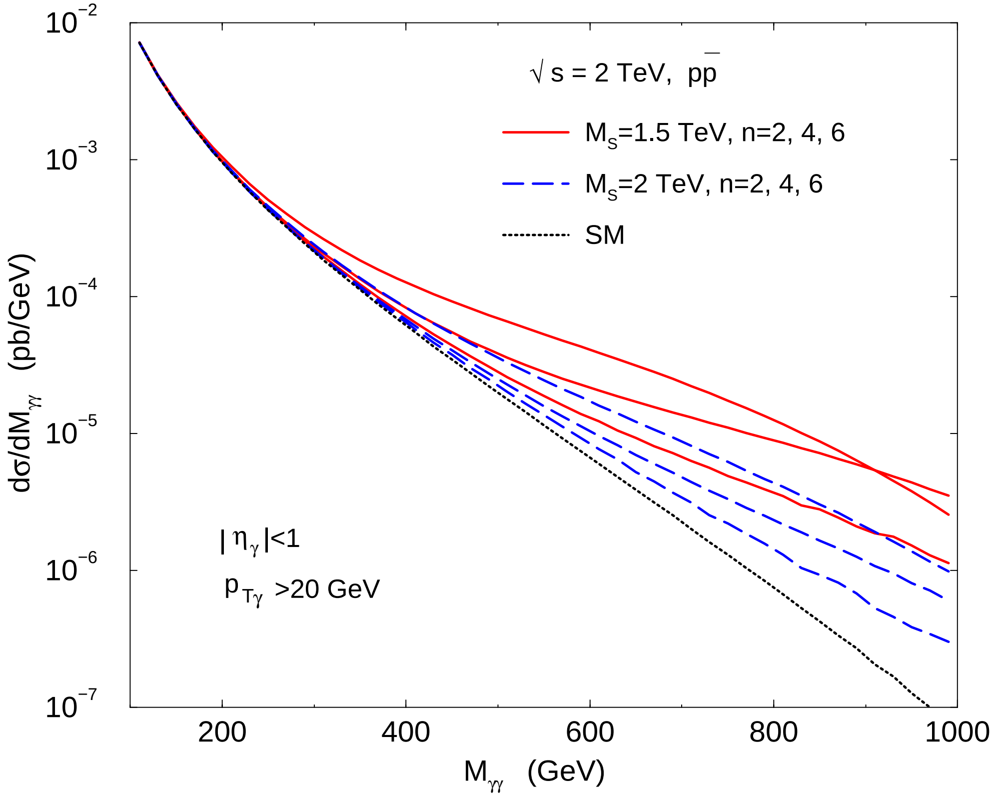


Virtual Exchanges of Graviton

$$
\begin{aligned}
e^+e^-,\ \ p\bar{p} &\longrightarrow \gamma\gamma,\ WW,\ ZZ,\ ... \\
q\bar{q} &\longrightarrow \ell^+\ell^- \\
\ell^+\ell^- &\longrightarrow q\bar{q} \\
ep &\longrightarrow eX,\ \nu X \\
q\bar{q} &\longrightarrow jj, t\bar{t}
\end{aligned}
$$

Giudice et al.; Han et al.; Nussinov et al.; Hewett; Rizzo; Agashe, Deshpande; Cheung; Lee et al.; Mathews et al.; Davoudiasl et al.; Guptal et al.; Atwood et al.; Ghosh et al.; Cheng et al.; He.

$\gamma\gamma \to \gamma\gamma\ , \qquad p\bar{p} \to \gamma\gamma, \ell^+\ell^-$



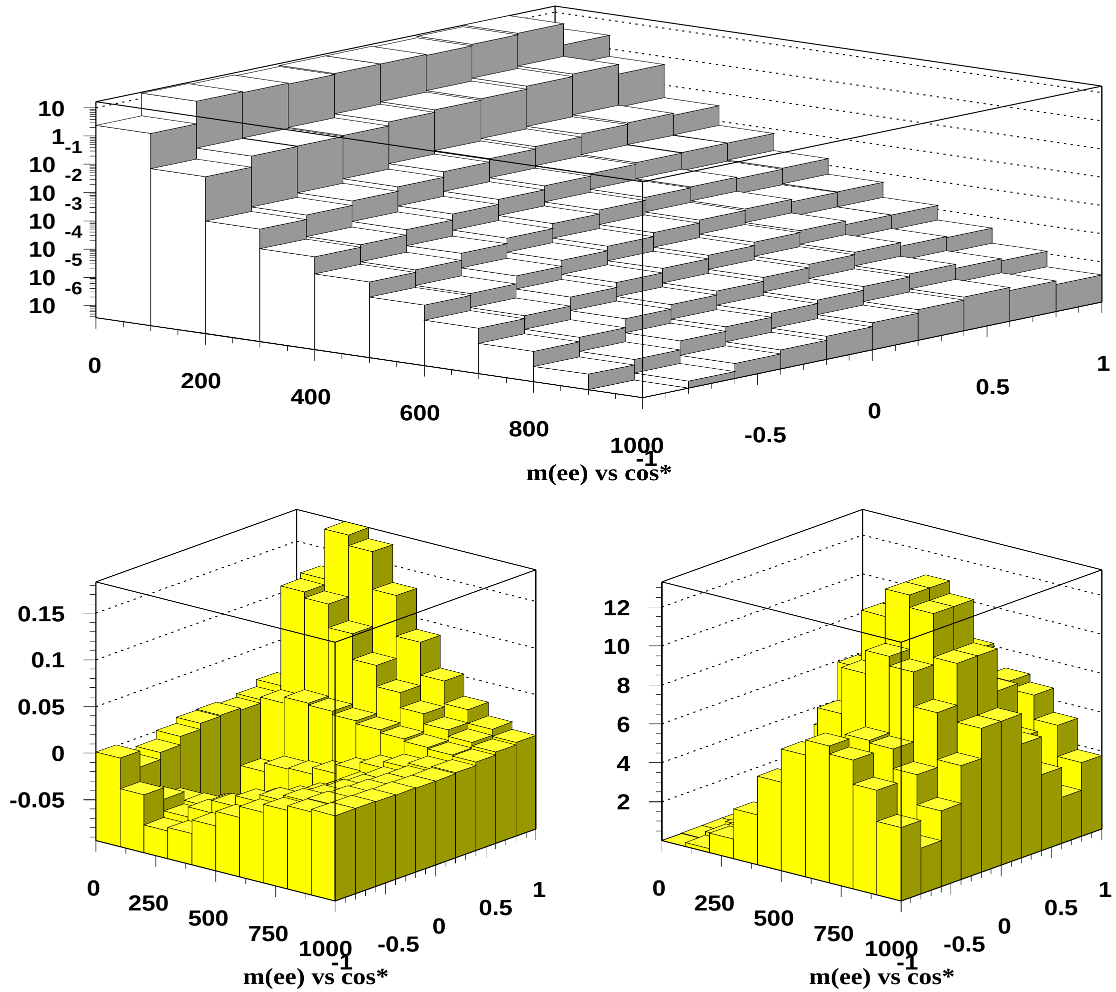
Cheung

Recent experimental results

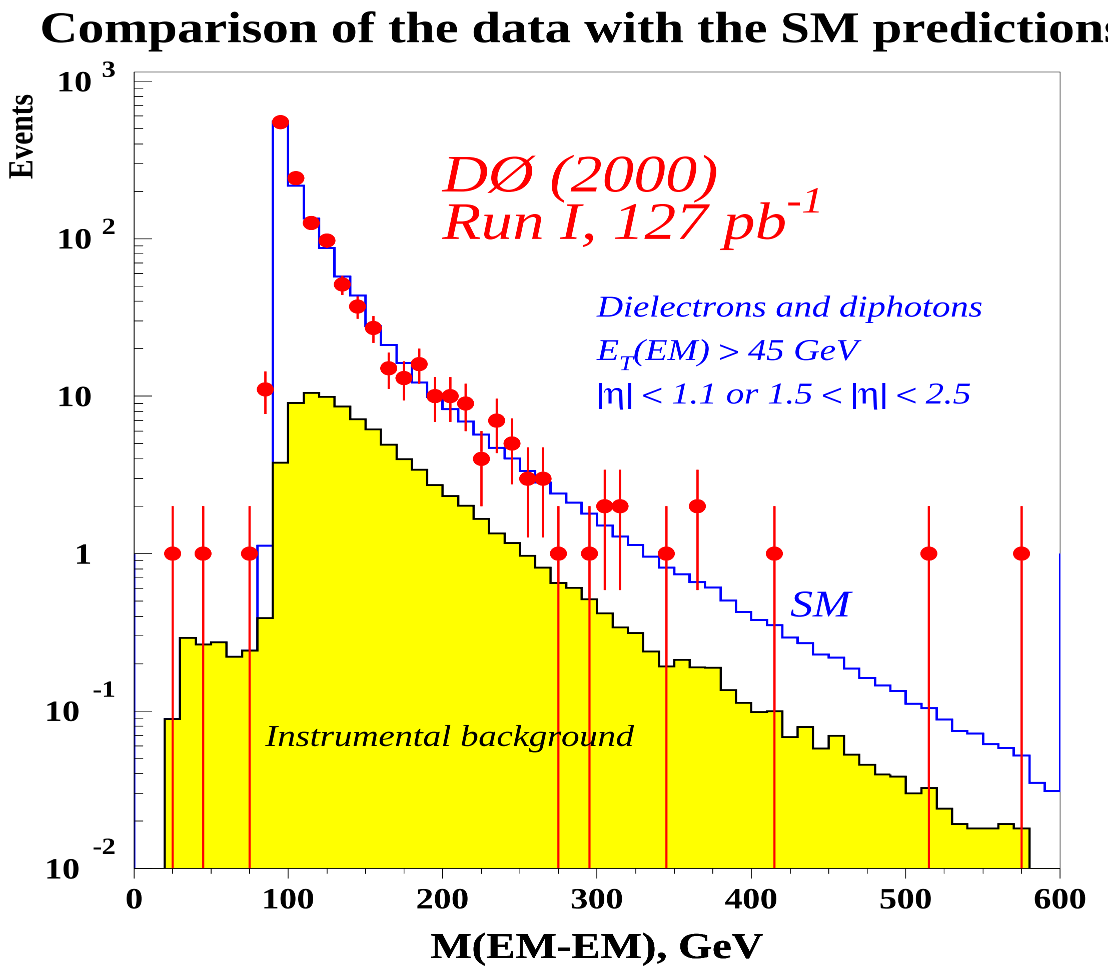
Tevatron

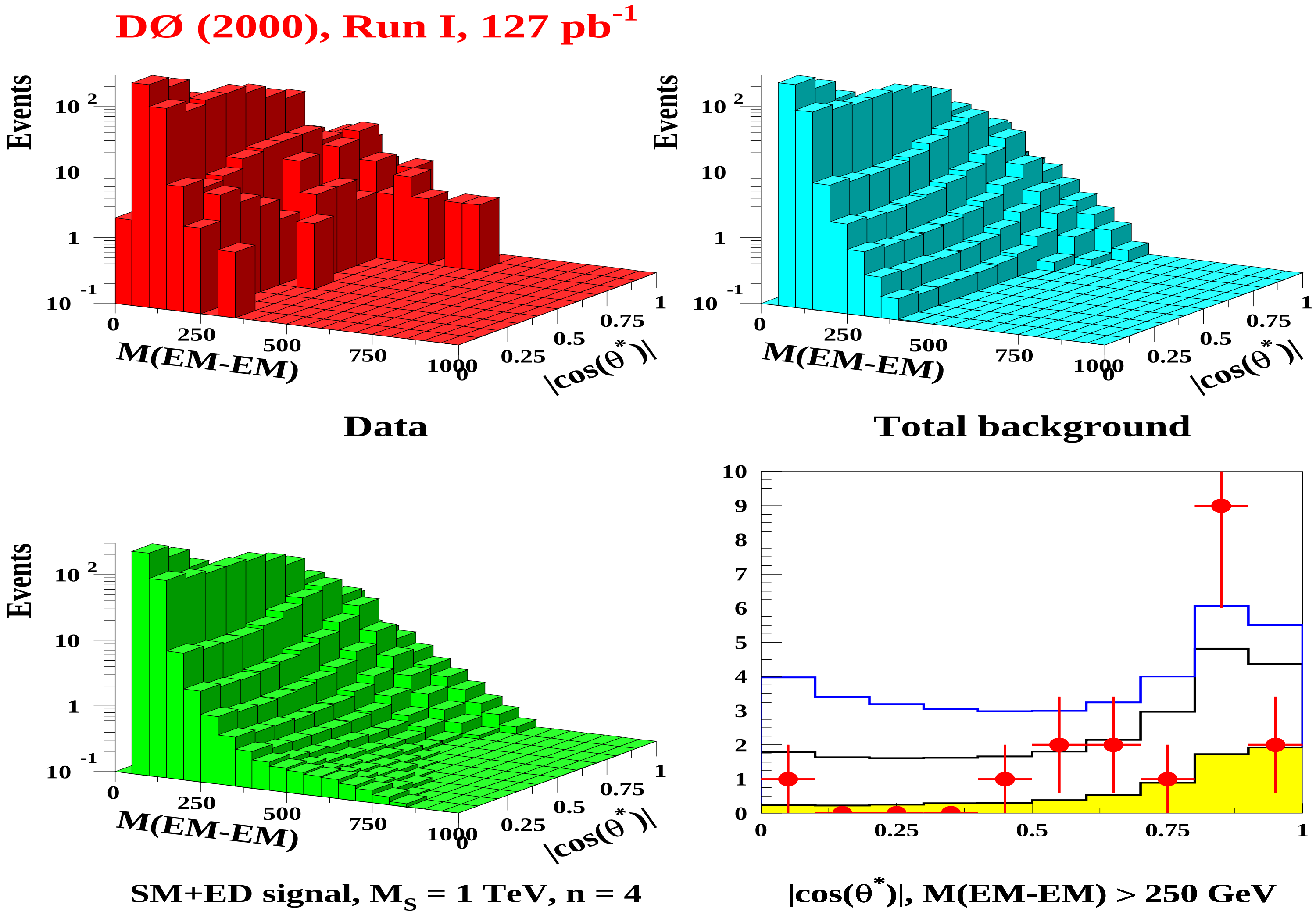
- Large extra dimensions

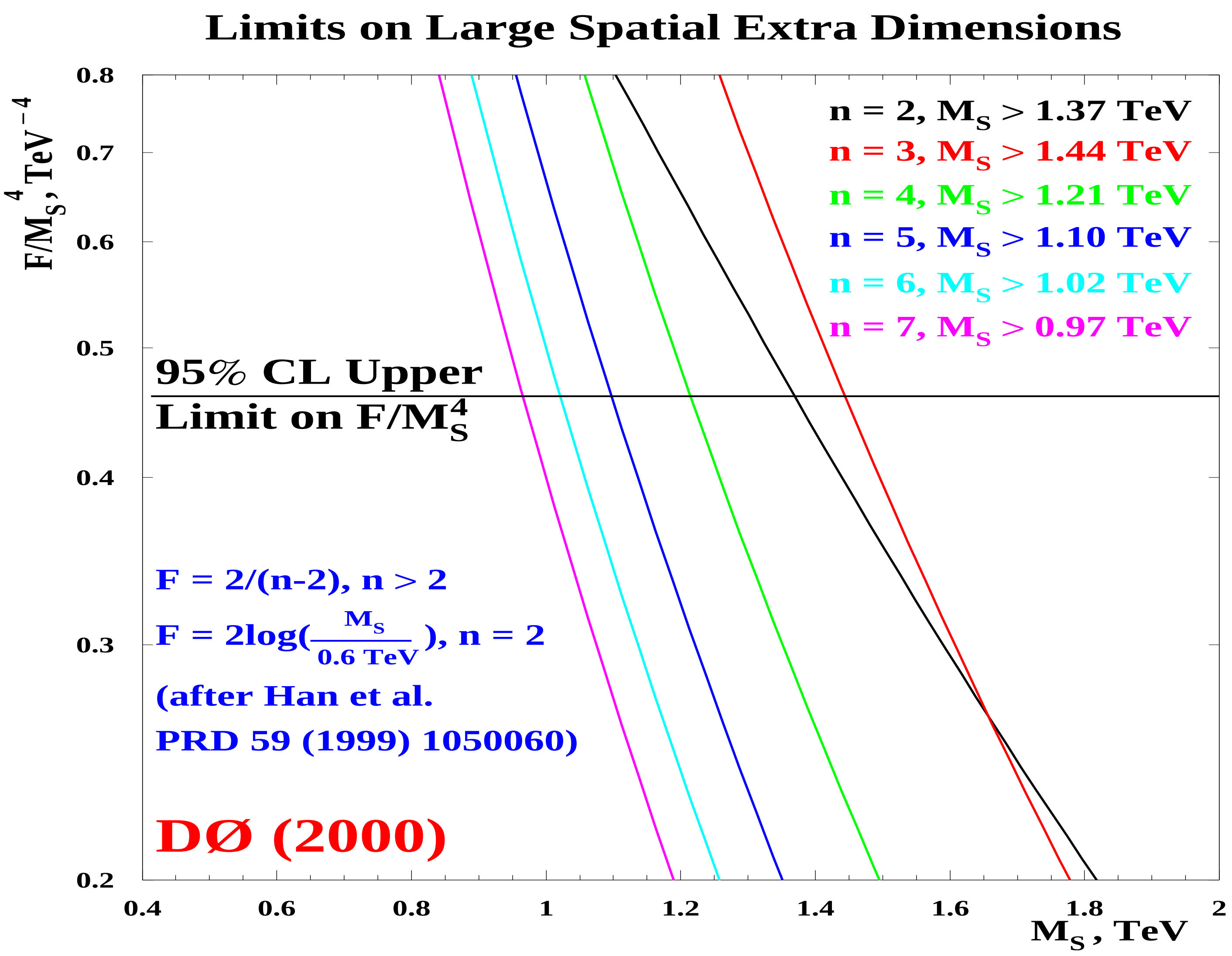
Diphoton and dilepton production are useful probes of extra dimensions (Cheung).
Use the double differential distribution to maximize the effects (Cheung+Landsberg)


10
1
10 -1
10 -2
10 -3
10 -4
10 -5
10 -6
0
200
400
600
800
1000
-1
-0.5
0
0.5
1
m(ee) vs cos*
0.15
0.1
0.05
0
-0.05
0
250
500
750
1000
-1
-0.5
0
0.5
1
m(ee) vs cos*
12
10
8
6
4
2
0
250
500
750
1000
-1
-0.5
0
0.5
1
m(ee) vs cos*

DØ used the dilepton and diphoton production to search for the effect of large extra dimensions.




DØ (2000), Run I, 127 pb-1
Events
M(EM-EM)
|cos(θ*)|
Data
Total background
SM+ED signal, MS = 1 TeV, n = 4
|cos(θ*)|, M(EM-EM) > 250 GeV

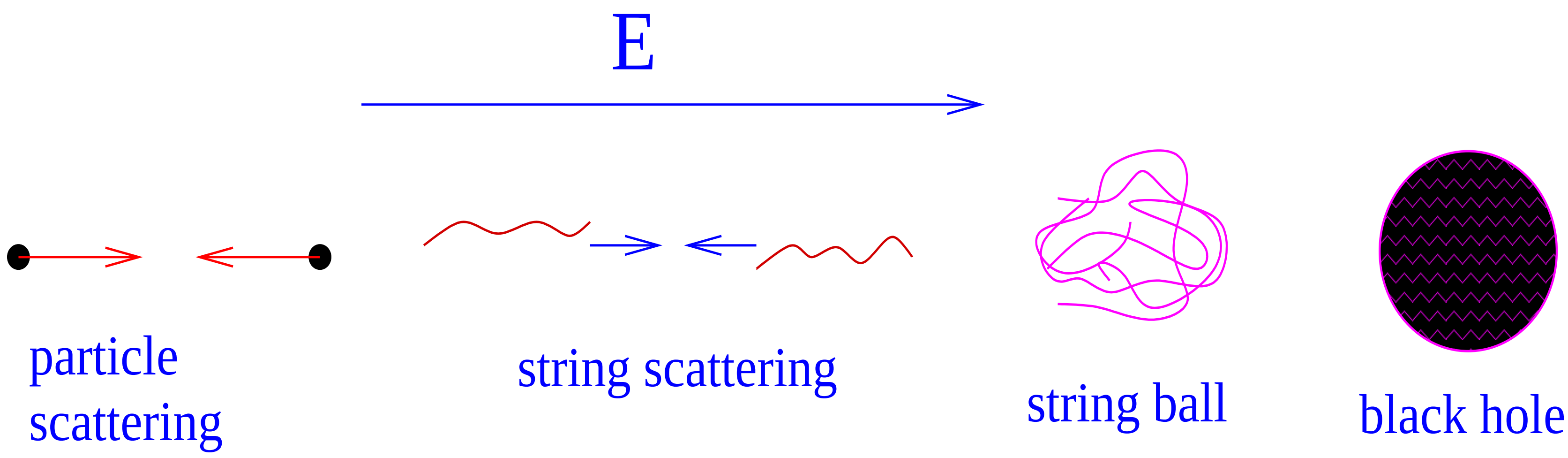

Limits on Large Spatial Extra Dimensions
F/M_S^4, TeV^{-4}
0.8
0.7
0.6
0.5
0.4
0.3
0.2
n = 2, M_S > 1.37 TeV
n = 3, M_S > 1.44 TeV
n = 4, M_S > 1.21 TeV
n = 5, M_S > 1.10 TeV
n = 6, M_S > 1.02 TeV
n = 7, M_S > 0.97 TeV
95% CL Upper Limit on F/M_S^4
F = 2/(n-2), n > 2
$F = 2\log(\frac{M_S}{0.6\ \mathrm{TeV}})$, n = 2
(after Han et al.
PRD 59 (1999) 1050060)
DØ (2000)
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2
M_S, TeV

Sensitivity to M_S using diphoton and dilepton modes

	M_S (TeV)					
	$n=2$	$n=4$	$n=6$	$n=2$	$n=4$	$n=6$
	Run I					
Dilepton	1.2	1.1	0.93			
Diphoton	1.4	1.2	1.0			
Combined	1.5	1.3	1.1			
	Run IIa			Run IIb		
Dilepton	1.9	1.6	1.3	2.7	2.1	1.8
Diphoton	2.4	1.9	1.6	3.4	2.5	2.1
Combined	2.5	1.9	1.6	3.5	2.6	2.2
	LHC					
Dilepton	10	8.2	6.9			
Diphoton	12	9.5	8.0			
Combined	13	9.9	8.3			

Trans-Planckian

Giddings and Thomas; Dimopoulos and Landsberg; Hossenfelder et al.; Cheung; Casadio and Harms; Park and Song; Giudice, Rattazzi, and Wells; Rizzo; Voloshin; Cheung and Chou; Feng and Shapere; Anchordoqui et al.; Dimopoulos and Emparan; Ringwald and Tu; Uehara; Jain et al.; Kowalski et al.; Alvarez-Muniz; ... ...


E
particle scattering
string scattering
string ball
black hole

Black Holes

A BH is characterized by

- mass $M_{\rm BH} \Rightarrow R_{\rm BH}, S_{\rm BH}, \tau$,
- Charge Q,
- Angular Momentum $J(=0)$.

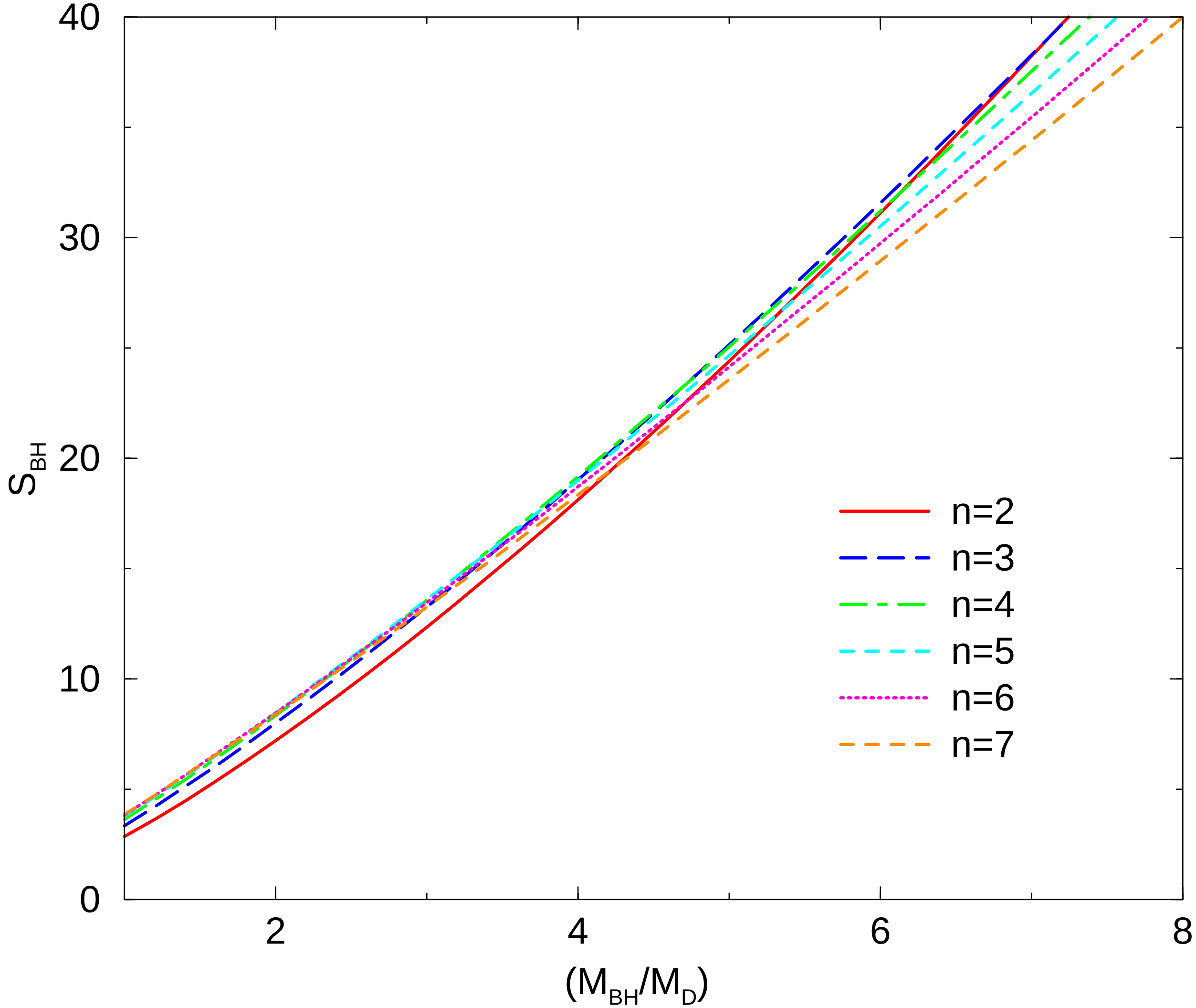
Minimum $M_{\rm BH} \sim$ a few $\times M_D$, in order that large entropy is fulfilled.

$$R_{\rm BH} = \frac{1}{M_D} \left(\frac{M_{\rm BH}}{M_D}\right)^{\frac{1}{n+1}} \left(\frac{2^n \pi^{\frac{n-3}{2}} \Gamma(\frac{n+3}{2})}{n+2}\right)^{\frac{1}{n+1}}$$

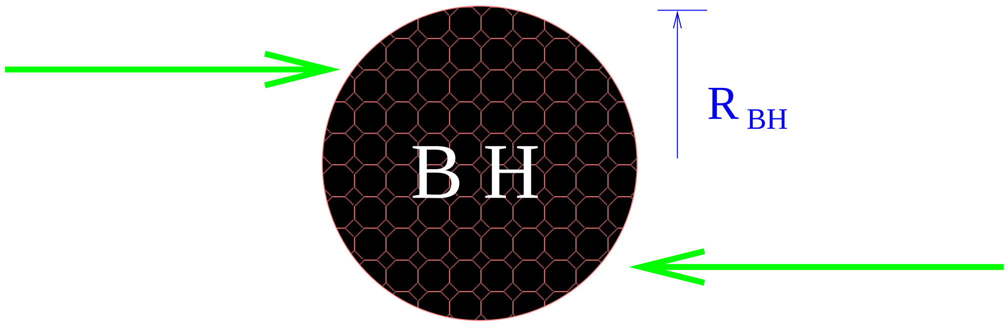
$$S_{\rm BH} = \frac{4\pi}{n+2} \left(\frac{M_{\rm BH}}{M_D}\right)^{\frac{n+2}{n+1}} \left(\frac{2^n \pi^{\frac{n-3}{2}} \Gamma(\frac{n+3}{2})}{n+2}\right)^{\frac{1}{n+1}} .$$

$M_{\rm BH} \gtrsim 5 M_D$ for $S_{\rm BH} \gtrsim 25$

Entropy $S_{\rm BH}$ versus $(M_{\rm BH}/M_D)$

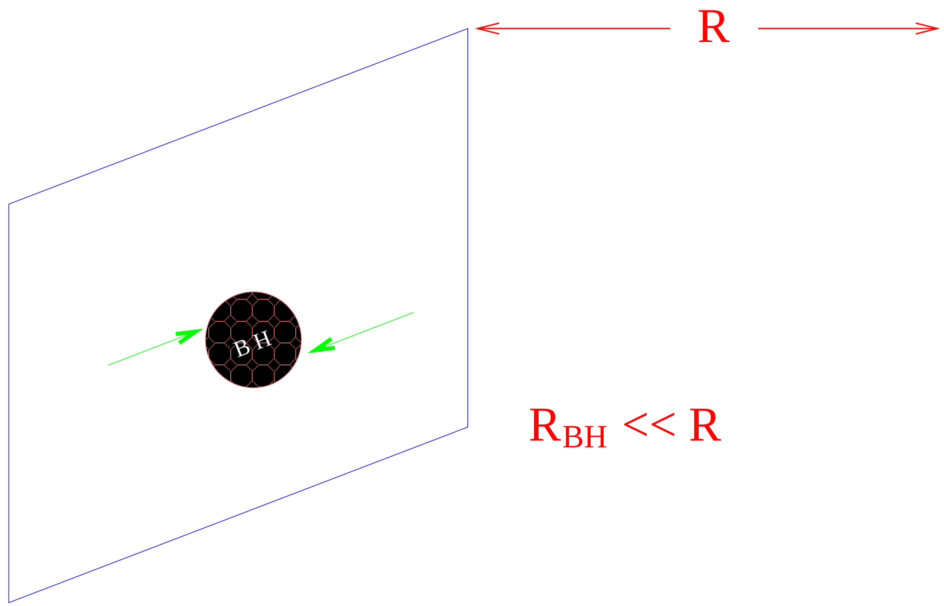


Production cross sections



$$\sigma(M_{\rm BH}^2) \approx \pi R_{\rm BH}^2$$

Decay Signature of BH



• λ corresponding to the Hawking temp. much larger than $R_{\rm BH}$, BH evaporates like a s-wave point source. Equally into brane and bulk modes. Expect:

$$\mathrm{BH} \rightarrow \mathrm{SM\ particles}$$

Emparan, Horowitz, and Myers

A BH decays "blindly". The main phase is the Hawking Evaporation, according to the degrees of freedom.

$$Z, W, H, \gamma, g; \;\; u, d, s, c, b, t; \;\; e, \mu, \tau, \nu_e, \nu_\mu, \nu_\tau = 30 : 72 : 18$$

Hadronic : leptonic $\sim 5 : 1$

A nonrotating BH decays isothermally. E.g., a BH with $M_{\rm BH} \sim$ a few TeV decays into $\sim 30 - 50$ particles. Each has about a few 100 GeV, like

A spherical fireball

Cross section in pb $2 \to 2$ ($2 \to 1$)

	$n = 4$	$n = 5$	$n = 6$
$M_D = 1.5$ TeV			
$y = 1$	571 (8650)	820 (12400)	1090 (16600)
$y = 2$	62.8 (831)	87.1 (1150)	113 (1490)
$y = 3$	6.3 (105)	8.6 (142)	10.9 (180)
$y = 4$	0.49 (11.8)	0.65 (15.7)	0.82 (19.8)
$y = 5$	0.024 (0.97)	0.032 (1.3)	0.039 (1.6)
$M_D = 3$ TeV			
$y = 1$	11.9 (157)	17.3 (228)	23.1 (305)
$y = 2$	0.09 (2.2)	0.13 (3.1)	0.17 (4.1)
$y = 3$	1.0×10^{-4} (0.0084)	1.4×10^{-4} (0.011)	1.8×10^{-4} (0.015)
$y = 4$	1.1×10^{-10} (2.6×10^{-7})	1.4×10^{-10} (3.5×10^{-7})	1.8×10^{-10} (4.5×10^{-7})
$y = 5$	-	-	-

$$M_{\rm BH}^{\rm min} = y M_D$$

String Balls

• Dimopoulos and Emparan pointed out that when a BH reaches a minimum mass, it transits into a state of highly excited and jagged strings – string balls (SB).

$$M_{\rm BH}^{\rm min} = M_s/g_s^2$$

• SBs are the stringy progenitors of BHs.

• BH Correspondence principle: properties of a BH with a mass $M_{\rm BH}$ match those of a string ball of a string theory with $M_s/g_s^2 = M_{\rm BH}$.

$$\sigma(SB)|_{M_{SB}=M_s/g_s^2} = \sigma(BH)|_{M_{BH}=M_s/g_s^2}$$

Production cross sectons

$$\hat{\sigma}(\text{SB/BH}) = \begin{cases} \frac{\pi}{M_D^2} \left(\frac{M_{\text{BH}}}{M_D}\right)^{\frac{2}{n+1}} [f(n)]^2 & \frac{M_s}{g_s^2} \le M_{\text{BH}} \\ \\ \frac{\pi}{M_D^2} \left(\frac{M_s/g_s^2}{M_D}\right)^{\frac{2}{n+1}} [f(n)]^2 = \frac{\pi}{M_s^2} [f(n)]^2 & \frac{M_s}{g_s} \le M_{\text{SB}} \le \frac{M_s}{g_s^2} \\ \\ \frac{\pi g_s^2 M_{\text{SB}}^2}{M_s^4} [f(n)]^2 & M_s \ll M_{\text{SB}} \le \frac{M_s}{g_s} \end{cases}$$

• When the energy is above M_s but below M_s/g_s, the scattering is between two strings. The amplitude $\sim \hat{s}/M_s^4$.

• When the energy reaches M_s/g_s, saturation of unitarity sets σ constant until it hits the correspondence point.

p Branes

A BH is considered a 0-brane, so p-branes, in principle, can also be produced.

- Consider an uncharged, static p-brane with mass M_{pB} . The p-brane wraps on $r(\leq m)$ small extra dim. and on $p-r(\leq n-m)$ large extra dim.
- The radius of the p-brane is

$$R_{pB} = \frac{1}{\sqrt{\pi} M_*} \gamma(n,p) \, V_{pB}^{\frac{1}{1+n-p}} \left(\frac{M_{pB}}{M_*} \right)^{\frac{1}{1+n-p}}$$

$$V_{pB} = l_{n-m}^{p-r} \, l_m^r \approx \left(\frac{M_{\rm Pl}}{M_*} \right)^{\frac{2(p-r)}{n-m}} ,$$

$$\gamma(n,p) = \left[8\Gamma \left(\frac{3+n-p}{2} \right) \sqrt{\frac{1+p}{(n+2)(2+n-p)}} \right]^{\frac{1}{1+n-p}}$$

- $R_{pB} \to R_{\rm BH}$ in the limit $p=0$.

Production of p Branes

- $\sigma(p\mathrm{B}) \sim \sigma(\mathrm{BH})$, based on a naive geometric argument.

$$\hat{\sigma}(M_{p\mathrm{B}}) = \pi R_{p\mathrm{B}}^2$$

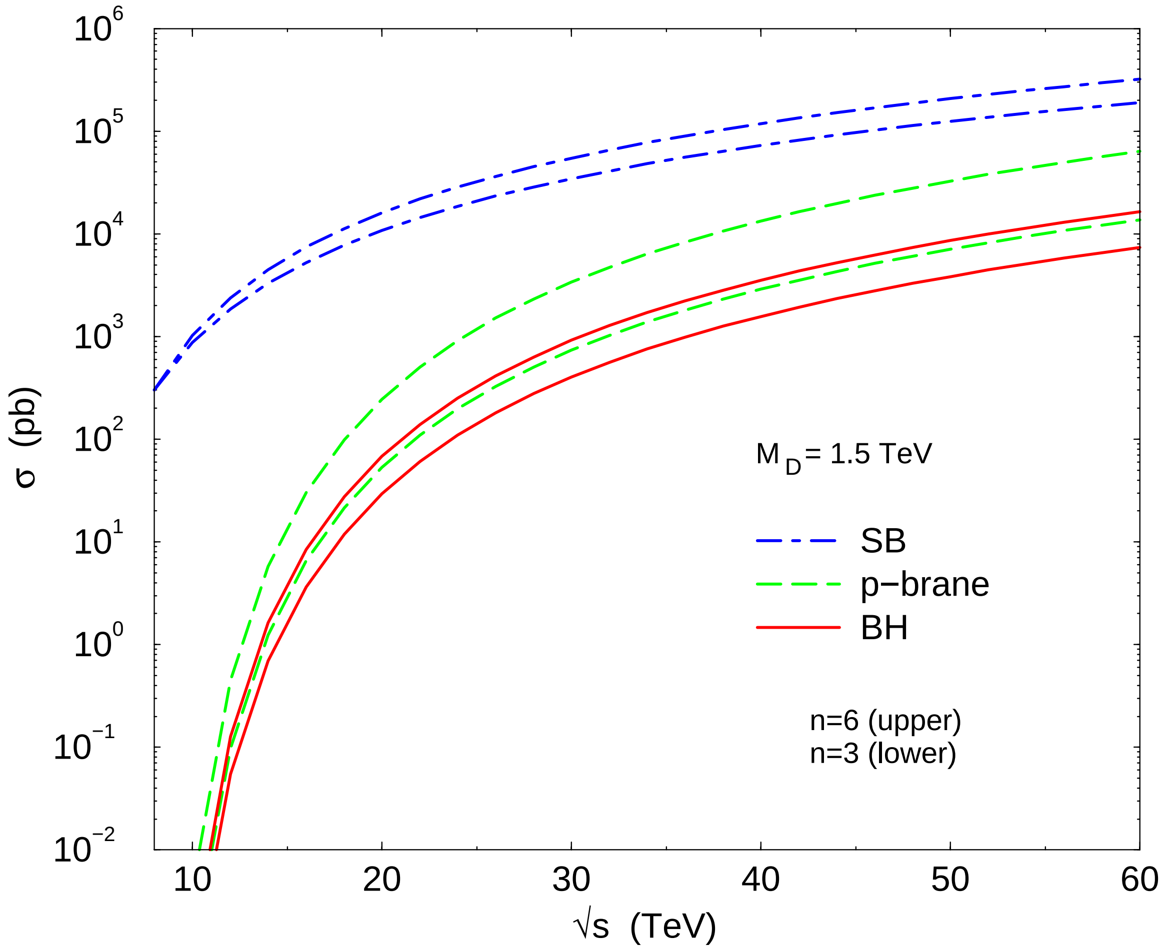
- $R_{p\mathrm{B}}$ of a p-brane is suppressed by some powers of the volume $V_{p\mathrm{B}}$ wrapped by the p-brane. Minimum $V_{p\mathrm{B}} = 1$ occurs when the p-brane wraps entirely on the small extra dimensions only,

$$r = p$$

- Compare $\sigma(\mathrm{BH})$ with $\sigma(p\mathrm{B})$

$$R \equiv \frac{\hat{\sigma}(M_{p\mathrm{B}}=M)}{\hat{\sigma}(M_{\mathrm{BH}}=M)} = \left(\frac{M_*}{M_{\mathrm{Pl}}}\right)^{\frac{4(p-r)}{(n-m)(1+n-p)}} \left(\frac{M}{M_*}\right)^{\frac{2p}{(1+n)(1+n-p)}} \left(\frac{\gamma(n,p)}{\gamma(n,0)}\right)^2$$

pp Collisions



$M_D = 1.5$ TeV, $M_{\rm BH}^{\rm min} = 5M_D$, $M_{\rm SB}^{\rm min} = 2M_s$.

Production via UHE Cosmic Rays

- UHECR as a beam, atmosphere as the target.

$$E_p \sim 10^{13} - 10^{21} \text{ eV}$$

$$pN \to BH \to \text{Giant Air shower}$$

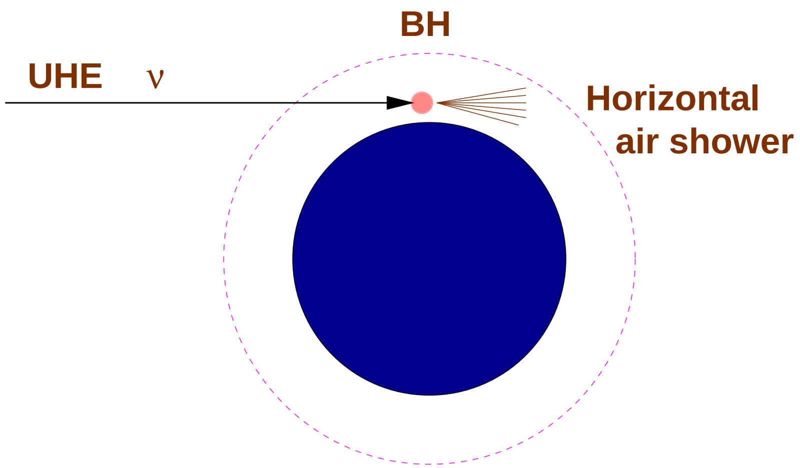
$$\nu N \to BH \to \text{horizontal air shower}$$

UHE neutrinos can deeply penetrate into atmosphere, because they are weakly interacting.

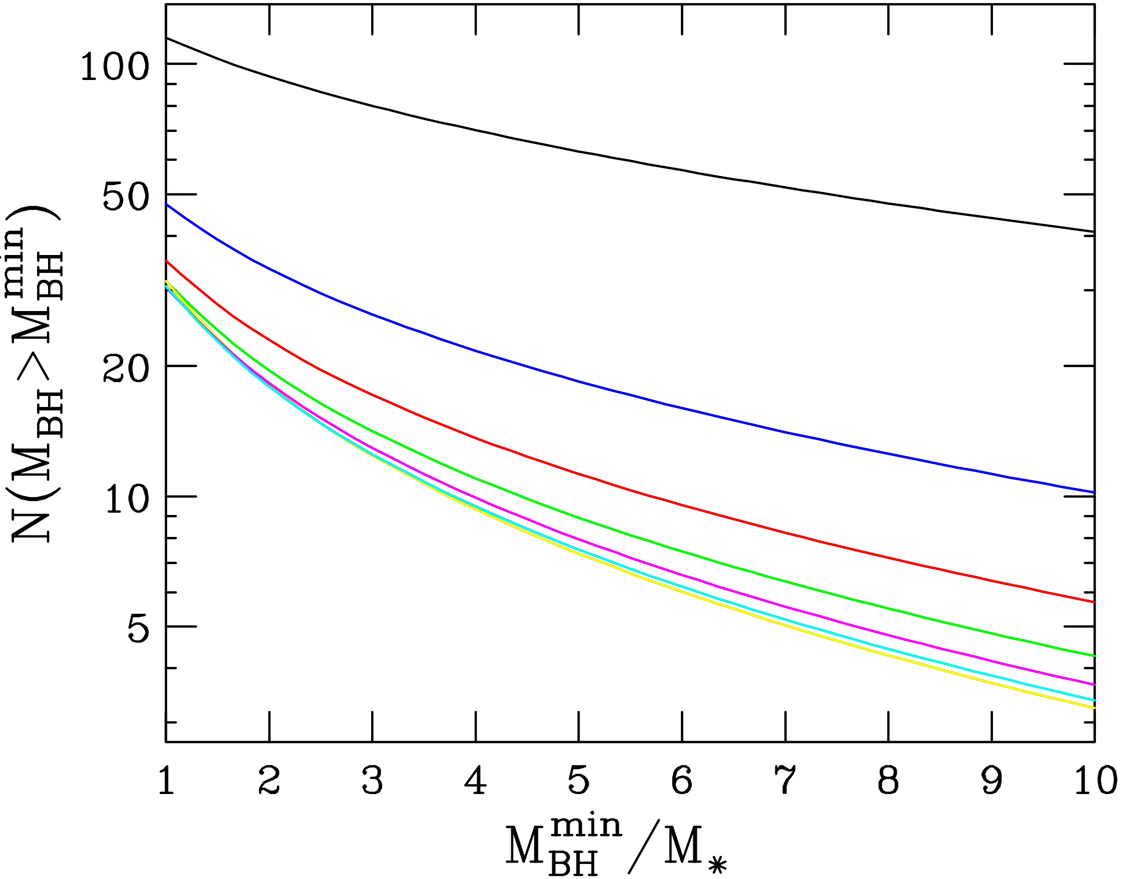
If large extra dimensions exist,

$$\nu \ N \ \longrightarrow \ BH \ \longrightarrow \ \text{SM particles}$$

It produces clean sign of HORIZONTAL air showers.



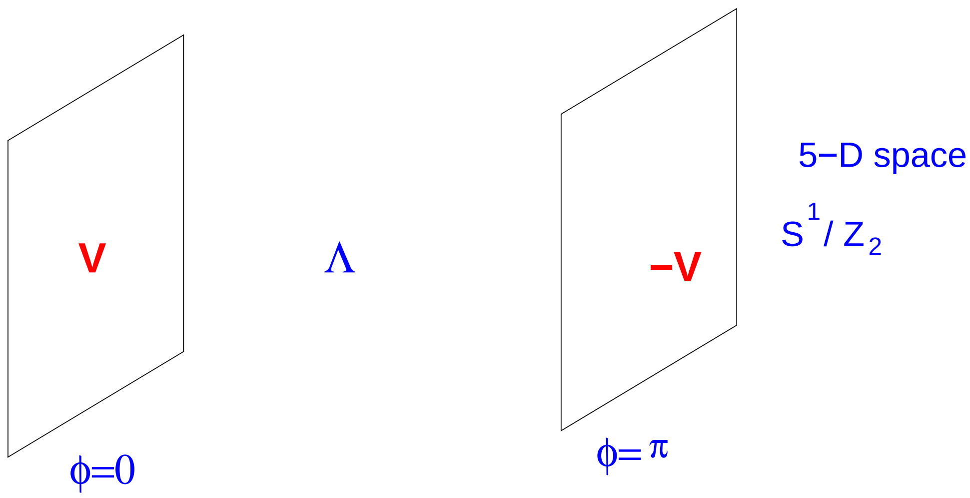
BH production rate



# of BH detected by the ground array in 5 Auger site-years for $n = 1 - 7$ from above.

Feng, Shapere

Randall-Sundrum model



With a nonfactorizable metric

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

$\overline{M_5}$ is the 5D fundamental Planck scale, k: curvature of the AdS space.

$$\overline{M_{\rm Pl}}^2 = \overline{M_5}/k$$

The scale $\Lambda_\pi \equiv \overline{M_{\rm Pl}}\,e^{-kr_c\pi}$ describes the scale of physical processes on the TeV brane.

The weak scale can be generated from the Planck scale for kr_c around 12.

Phenomenology of RS model

- Kaluza-Klein states of the Graviton, uneven spacing
- The radion
- The radion-Higgs mixing

RS Gravitons

The graviton field can be obtained by fluctuation of the metric

$$G_{\alpha\beta} = e^{-2ky}(\eta_{\alpha\beta} + 2h_{\alpha\beta}/M_5^{3/2})$$

After compactification, the KK states of the graviton has the spectrum

$$m_n = x_n \, k \, e^{-2r_c\pi} = x_n \, \Lambda_\pi \frac{k}{\overline{M}_{\rm Pl}}$$

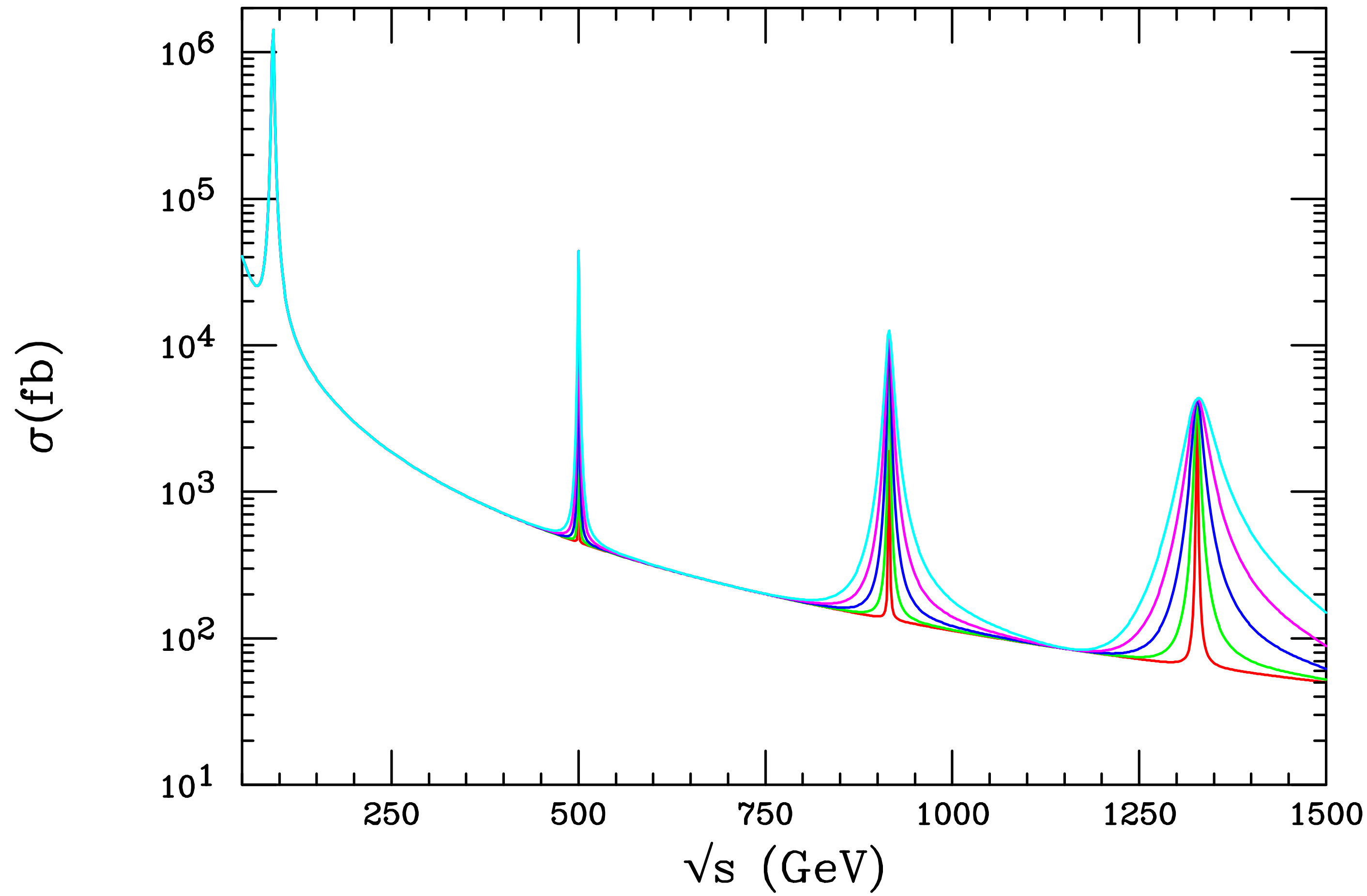
The interactions are given by

$$\mathcal{L} = -\frac{1}{\overline{M}_{\rm Pl}} T^{\mu\nu} h^{(0)}_{\mu\nu} - \frac{1}{\Lambda_\pi} T^{\mu\nu}(x) \sum_{n=1}^{\infty} h^{(n)}_{\mu\nu}(x)$$

The zeroth mode decouples, but the other has a coupling strength of 1/TeV.

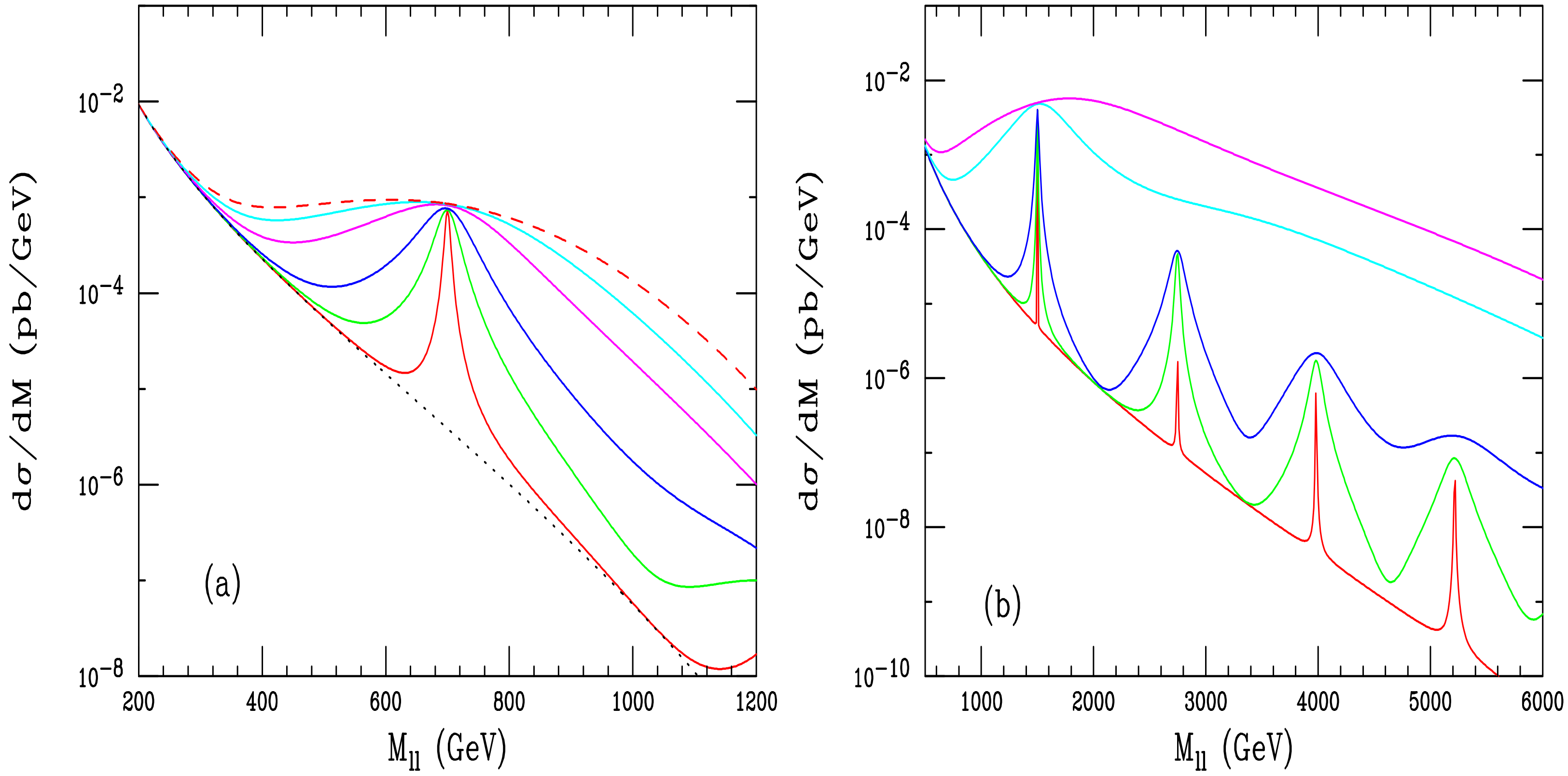
Signatures indicate discrete unevenly spaced resonaces.

$e^+e^- \to \mu^+\mu^-$



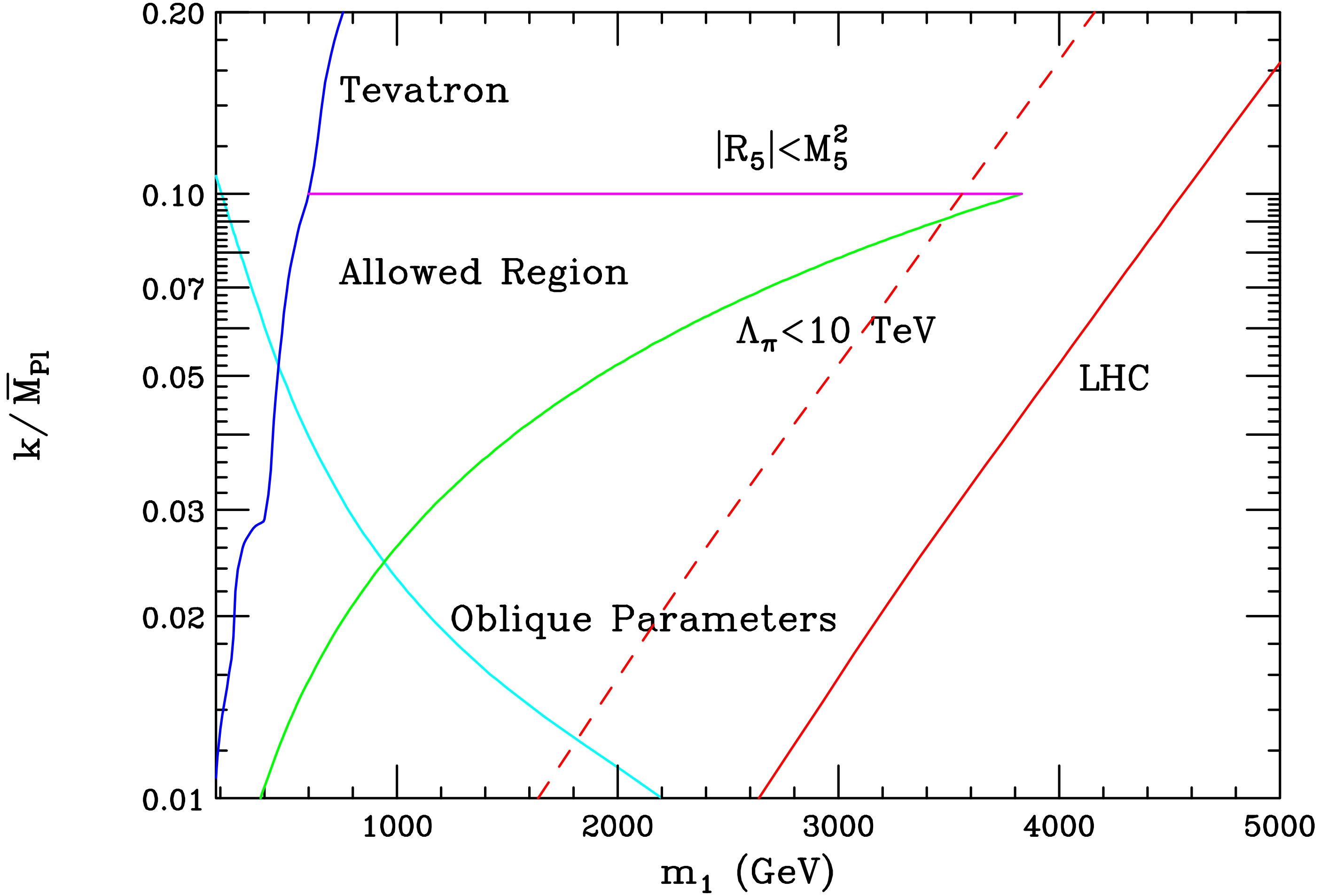
Hewett and Spiropulu, hep-ph/0205106

Drell-Yan



Davoudiasl, Hewett, and Rizzo

Constrained parameter space



Hewett and Spiropulu, hep-ph/0205106

RS Radion

The RS model also has a 4D massless scalar, radion, about the background metric

$$ds^2 = e^{-2k\phi T(x)} g_{\mu\nu}(x)\, dx^\mu dx^\nu - T^2(x) d\phi^2$$

$T(x)$ is the modulus field describing the distance between the two branes.

A stabilization mechanism (Goldberger and Wise) using a bulk scalar field to generate a potential.

The modulus field acquires a $O(0.1 - 1TeV)$ mass with a coupling strength 1/TeV.

Interactions of the Radion

$$\mathcal{L}_{\rm int} = \frac{\phi}{\Lambda_\phi}\, T^\mu_\mu({\rm SM}) \; ,$$

where $\Lambda_\phi = \langle \phi \rangle$ is of order TeV and

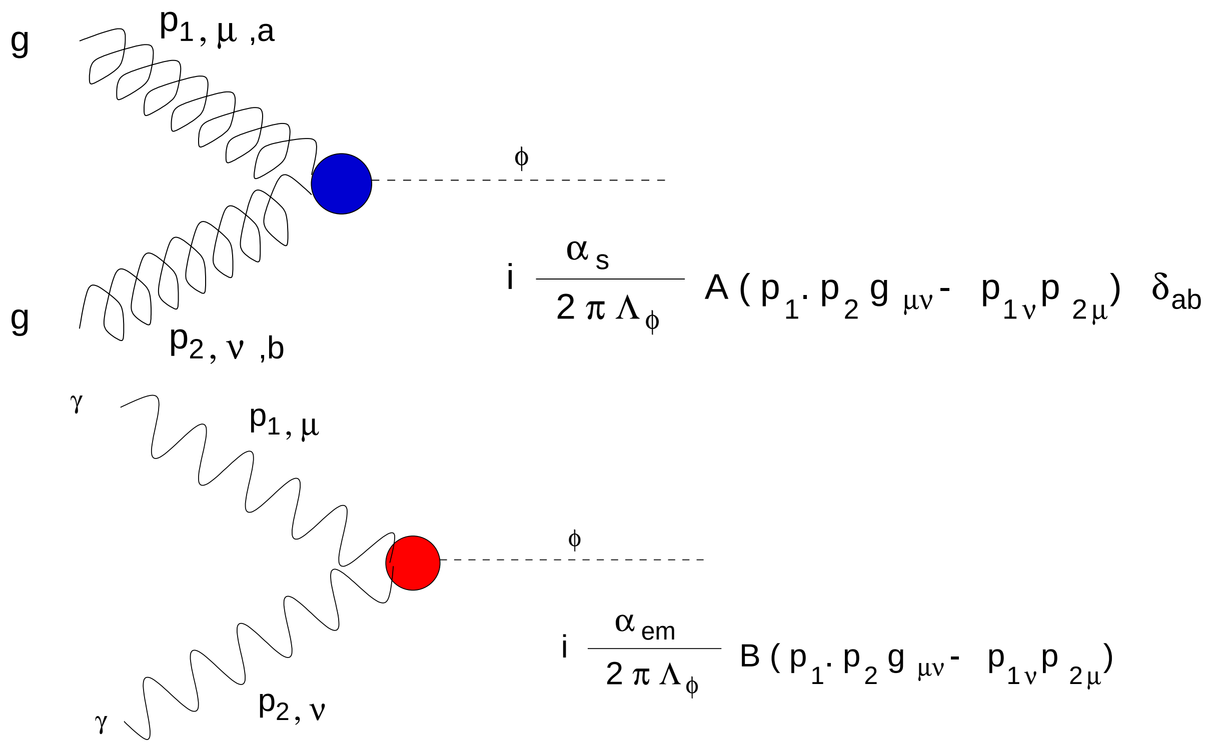
$$T^\mu_\mu({\rm SM}) = \sum_f m_f \bar f f - 2 m_W^2 W^+_\mu W^{-\mu} - m_Z^2 Z_\mu Z^\mu + (2 m_h^2 h^2 - \partial_\mu h \partial^\mu h) + \ldots ,$$

Coupling of the radion to a pair of gluons (photons), there are contributions from 1-loop diagrams with the top-quark (top-quark and W) in the loop, and from the trace anomaly.

$$T^\mu_\mu({\rm SM})^{\rm anom} = \sum_a \frac{\beta_a(g_a)}{2 g_a} F^a_{\mu\nu} F^{a\mu\nu} \; .$$

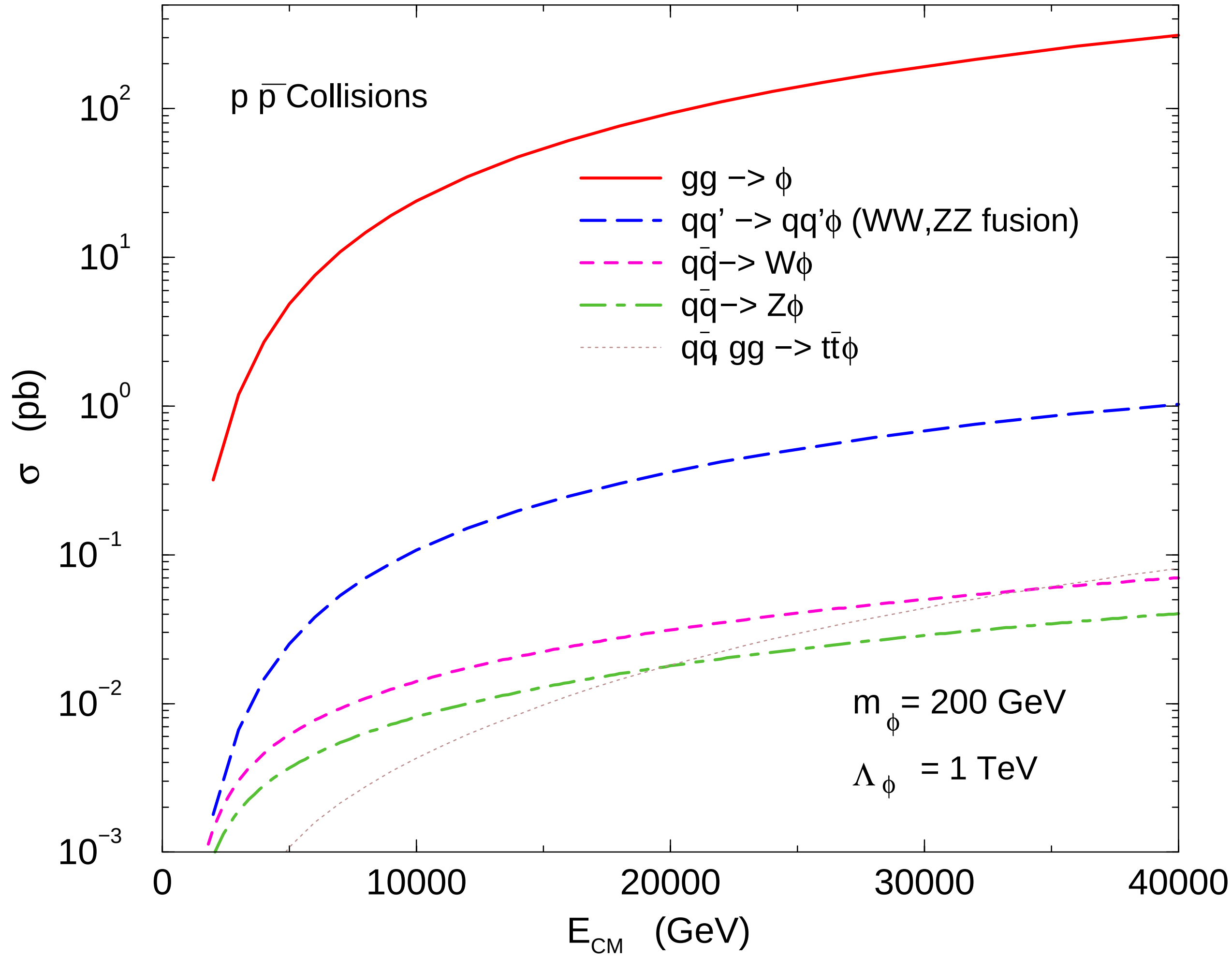
where

$$\beta_{\rm QCD}/2g_s = -(\alpha_s/8\pi) b_{\rm QCD} \quad {\rm and} \quad b_{\rm QCD} = 11 - 2 n_f/3$$

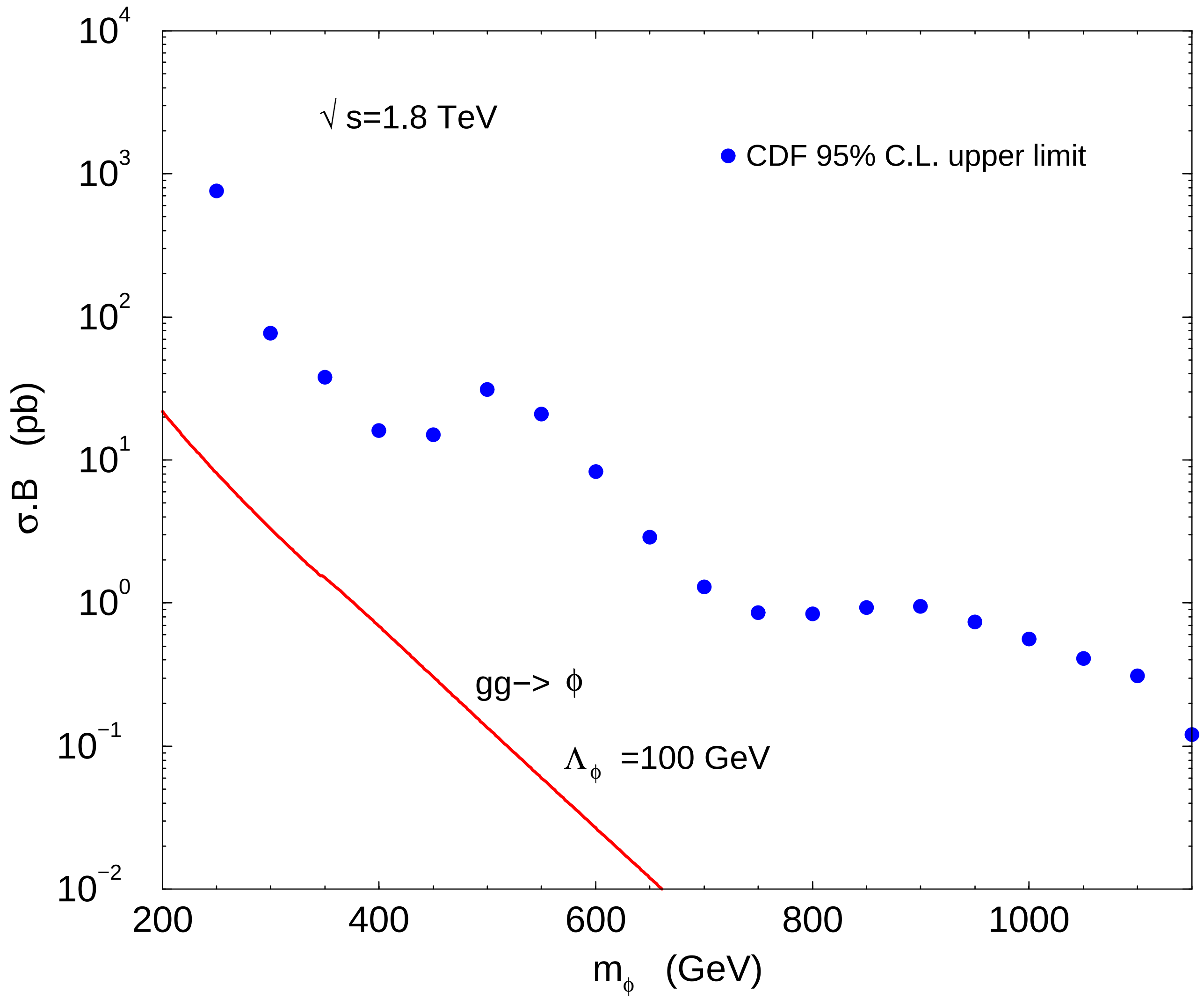


$A = b_{\rm QCD} + y_t(1 + (1 - y_t)f(y_t))$

$B = b_2 + b_Y - (2 + 3y_W + 3y_W(2 - y_W)f(y_W)) + \frac{8}{3}y_t(1 + (1 - y_t)f(y_t))$,
where $y_i = 4m_i^2/2p_1 \cdot p_2$.

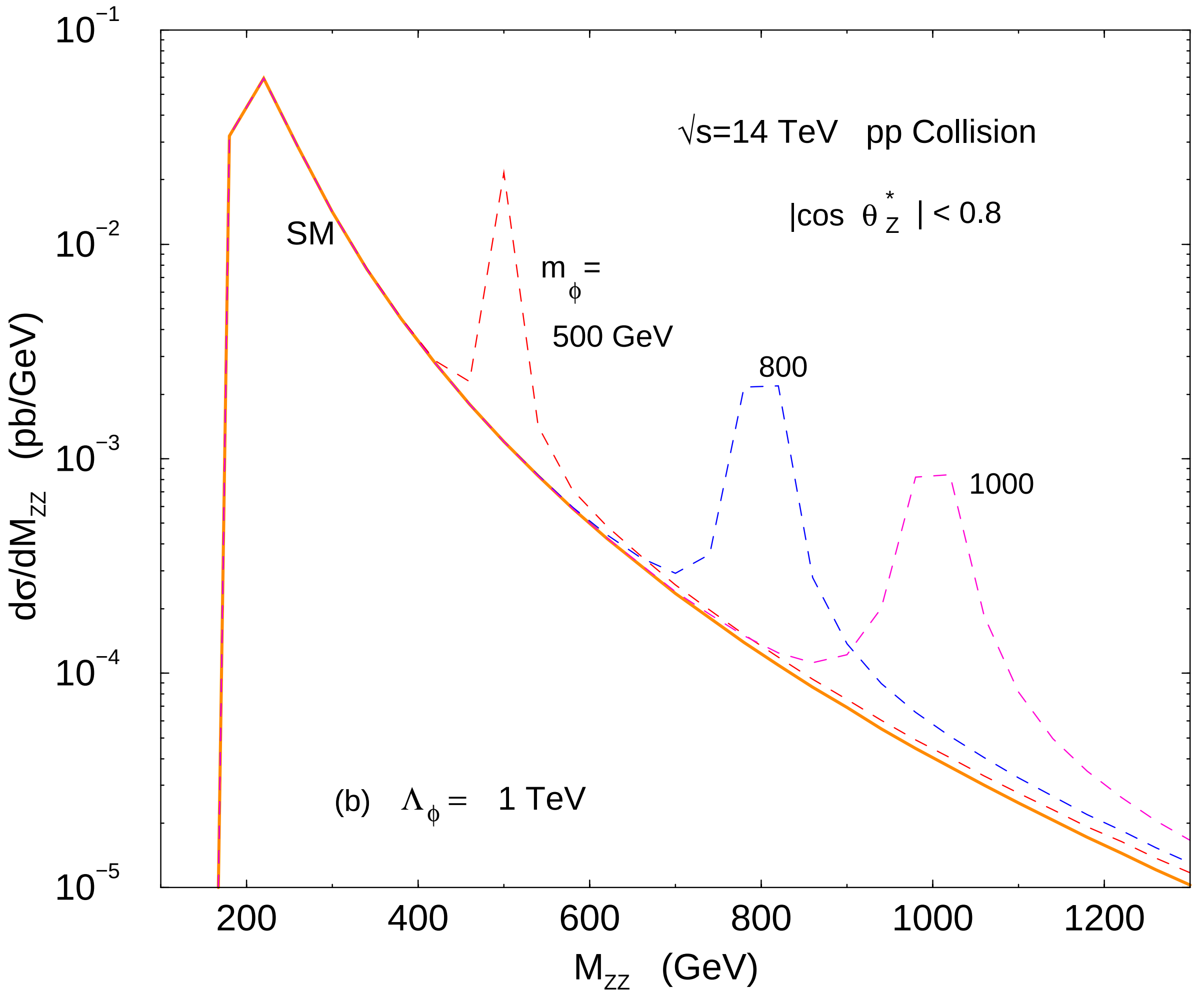

p p̄ Collisions
gg −> ϕ
qq' −> qq'ϕ (WW,ZZ fusion)
qq̄−> Wϕ
qq̄−> Zϕ
qq̄, gg −> tt̄ϕ
m_ϕ = 200 GeV
Λ_ϕ = 1 TeV
σ (pb)
10^2
10^1
10^0
10^−1
10^−2
10^−3
0
10000
20000
30000
40000
E_CM (GeV)

Cheung


√ s=1.8 TeV
CDF 95% C.L. upper limit
gg−> ϕ
Λϕ =100 GeV
σ.B (pb)
m ϕ (GeV)
10^4
10^3
10^2
10^1
10^0
10^−1
10^−2
200
400
600
800
1000

Cheung

$pp \longrightarrow \phi \longrightarrow ZZ$



Higgs-Radion Mixing

Gauge and Poincare invariance do not forbid the mixing between the gravity scalar and the Higgs boson:

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

where $R(g_{\rm vis})$ is the Ricci scalar for the induced metric on the visible brane.

The free Lagrangian of the Higgs and radion is

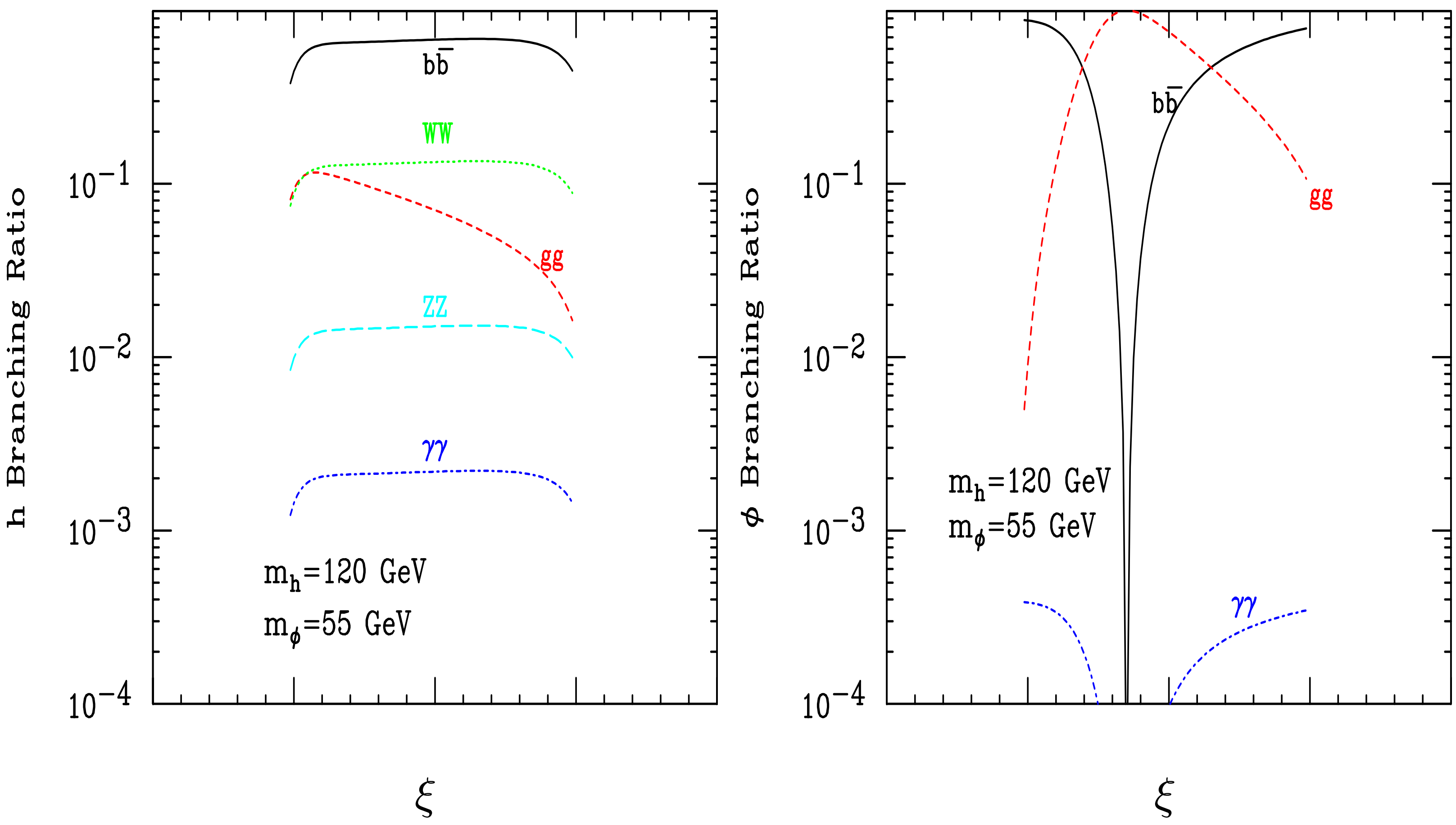
$$\mathcal{L}_0 = -\frac{1}{2}\left\{1 + 6\gamma^2\xi\right\}\phi_0 \Box \phi_0 - \frac{1}{2}\phi_0 m^2_{\phi_0}\phi_0 - \frac{1}{2}h_0(\Box + m^2_{h_0})h_0 - 6\gamma\xi\phi_0\Box h_0$$

⋆ A nonzero ξ will induce some triple couplings

$$h\text{-}\phi\text{-}\phi, \quad h^{(n)}_{\mu\nu}\text{-}h\text{-}\phi, \quad \phi\text{-}\phi\text{-}\phi, \quad h^{(n)}_{\mu\nu}\text{-}\phi\text{-}\phi$$

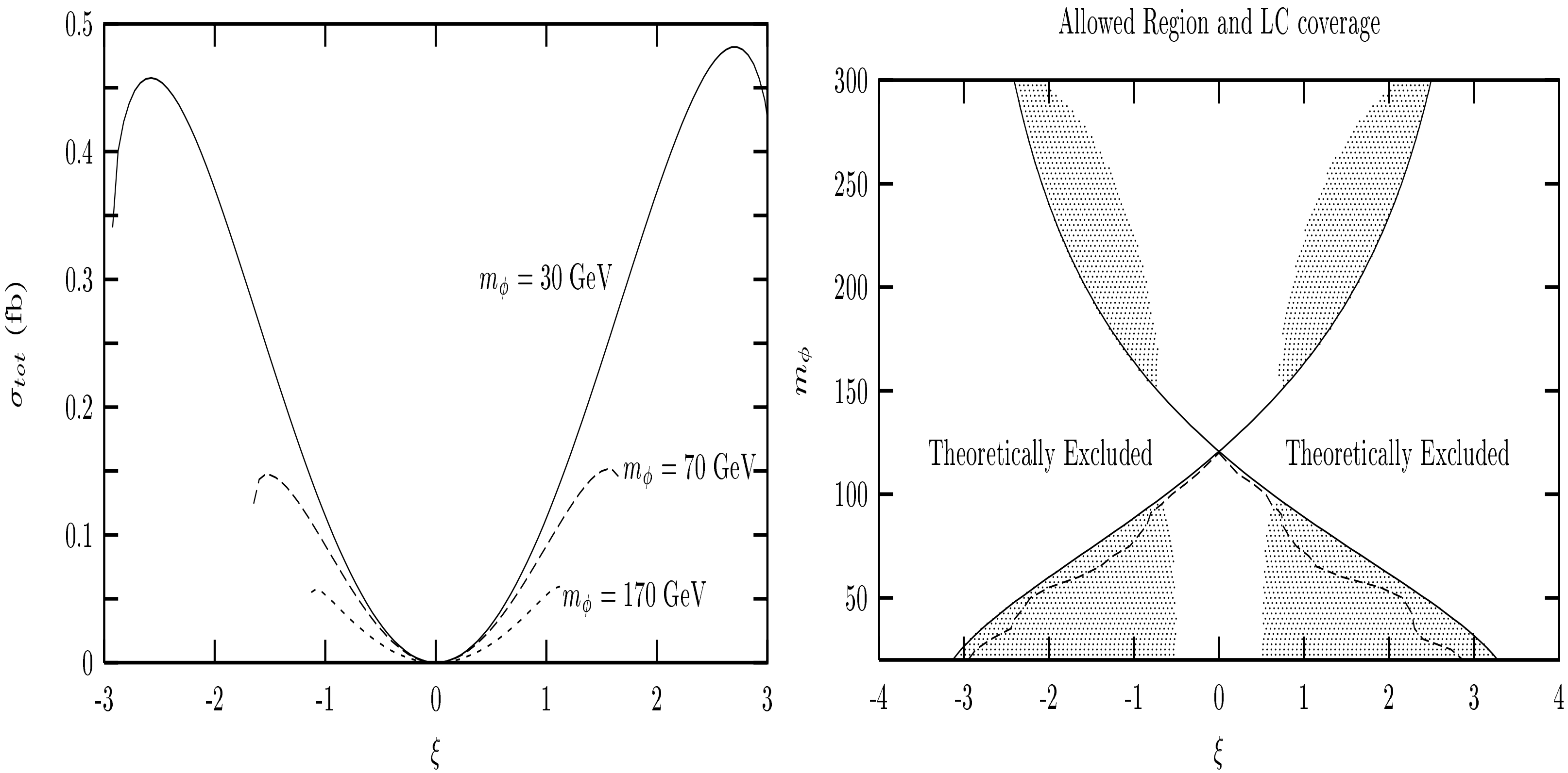
Giudice, Rattazzi, and Wells; Hewett and Rizzo; Dominici, Grzadkowshi, Gunion, and Toharia; Cheung, Kim, and Song

Branching ratios



Dominici, Grzadkowshi, Gunion, and Toharia

$e^+e^- \to G^{(n)} \to h\phi$



Cheung, Kim, Song

TeV^{-1} sized Extra Dimensions with Gauge Bosons

(Dienes, Dudas, Gherghetta)

With the gauge bosons in the bulk, the KK states have masses

$$m_n^2 = m_0^2 + \sum_i^{\delta} \frac{n_i^2}{R^2}$$

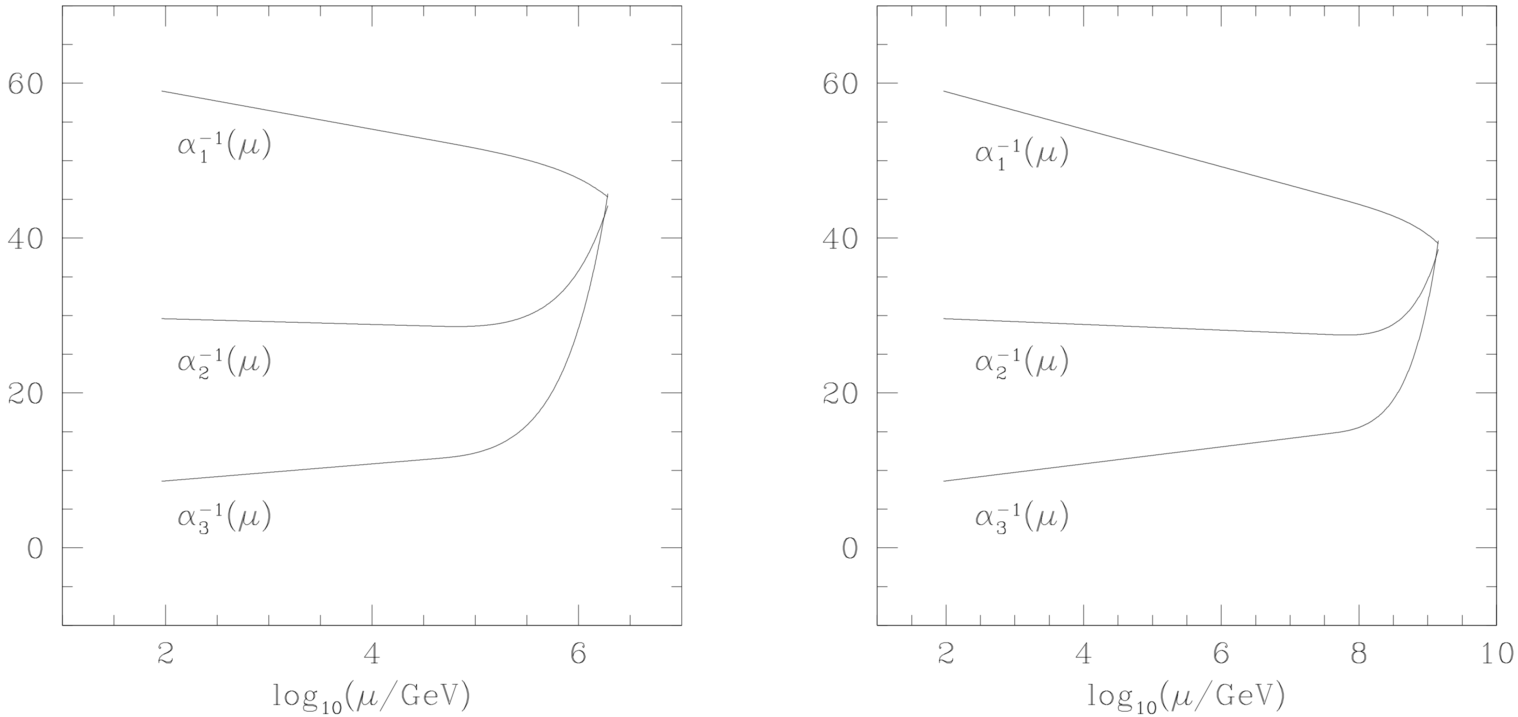
When the energy scale is above $\mu_0 \equiv 1/R$, KK states contribute to physical processes, e.g., the running of the couplings.

$$\alpha_i^{-1}(\Lambda) = \alpha_i^{-1}(M_Z) - \frac{b_i}{2\pi} \ln \frac{\Lambda}{M_Z}$$

$$+ \frac{\tilde{b}_i}{2\pi} \ln \frac{\Lambda}{\mu_0} - \frac{\tilde{b}_i X_\delta}{2\pi\delta} \left[\left(\frac{\Lambda}{\mu_0} \right)^{\delta} - 1 \right]$$

$(b_1, b_2, b_3) = (33/5, 1, -3)$; $(\tilde{b}_1, \tilde{b}_2, \tilde{b}_3) = (3/5, -3, -6)$; $X_\delta = \frac{2\pi^{\delta/2}}{\delta\Gamma(\delta/2)}$

Early Gauge Coupling Unification



$\delta = 1,\ \mu_0 = 10^5, 10^8$ GeV

Dienes, Dudas, Gherghetta

Phenomenology of KK gauge bosons

A Five-Dimensional Model, $\delta = 1$, with the extra dimension compactified on S^1/Z_2.

The 5-D Lagrangian is

$$\mathcal{L}_5 = -\frac{1}{4g_5} F_{MN}^2 + |D_M \phi_1|^2 + \left(i\bar{\psi}\sigma^\mu D_\mu \psi + |D_\mu \phi_2|^2 \right) \delta(x^5)$$

Compactifying the fifth dim. with

$$\Phi(x^\mu, x^5) = \sum_{n=0}^{\infty} \cos\left(\frac{nx^5}{R}\right) \Phi^{(n)}(x^\mu)$$

The resulting 4-D Lagrangian:

$$\mathcal{L}^{\rm CC} \quad = \quad \frac{g^2 v^2}{8} \left[W_1^2 + \cos^2\beta \sum_{n=1}^{\infty} (W_1^{(n)})^2 + 2\sqrt{2} \sin^2\beta W_1 \right.$$

$$
\begin{aligned}
& \times \sum_{n=1}^{\infty} W_1^{(n)} + 2\sin^2\beta \left(\sum_{n=1}^{\infty} W_1^{(n)} \right)^2 \Bigg] \\
+ \quad & \frac{1}{2} \sum_{n=1}^{\infty} n^2 M_c^2 (W_1^{(n)})^2 - g(W_1^{\mu} + \sqrt{2} \sum_{n=1}^{\infty} W_1^{(n)\mu}) J_{\mu}^1 + (1 \to 2) \\
\mathcal{L}^{\rm NC} \quad = \quad & \frac{g v^2}{8 c_\theta^2} \Bigg[Z^2 + \cos^2\beta \sum_{n=1}^{\infty} (Z^{(n)})^2 + 2\sqrt{2}\sin^2\beta Z \\
& \times \sum_{n=1}^{\infty} Z^{(n)} + 2\sin^2\beta \left(\sum_{n=1}^{\infty} Z^{(n)} \right)^2 \\
+ \quad & \frac{1}{2} \sum_{n=1}^{\infty} n^2 M_c^2 \left[(Z^{(n)})^2 + (A^{(n)})^2 \right] \\
- \quad & \frac{e}{s_\theta c_\theta} \left(Z^{\mu} + \sqrt{2} \sum_{n=1}^{\infty} Z^{(n)\mu} \right) J_{\mu}^{Z} - e \left(A^{\mu} + \sqrt{2} \sum_{n=1}^{\infty} A^{(n)\mu} \right) J_{\mu}^{\rm em}
\end{aligned}
$$

Pomarol and M. Quirós; Masip and Pomarol; Antoniadis, Benakli, and Quirós.

Effects on Precision Measurements

Mixing with SM gauge bosons

- KK states have the same quantum number as the SM gauge bosons.
- All the weak eigenstates mix to form mass eigenstates, e.g., $Z^{(0)}$ mix with all $Z^{(n)}$ $(n = 1 - \infty)$ through a series of mixing angles. Similar to Z' mixing.
- The lightest one is the Z observed at LEP. The couplings will be modified through the mixing angles. Place constraints on M_c.

Nath, Yamada, and Yamaguchi; Casalbuoni et al; Rizzo and Wells; Strumia; Carone; Delgado, A. Pomarol, and M. Quirós; Cornet, M. Relaño, and J. Rico.

Use equation of motion to eliminate $V^{(n)}$ from the 4-D Lagrangian

$$M_W^2 \quad = \quad M_W^2(1 - c_\theta^2 \sin^4_\beta X) \,, \qquad M_Z^2 = M_Z^2(1 - \sin^4_\beta X)$$

$$\begin{aligned}
\mathcal{L}_{\rm int}^{\rm CC} &= -gJ_\mu^1 W^{1\mu}(1 - \sin^2\beta c_\theta^2 X) - \frac{g^2}{2M_Z^2} X J_\mu^1 J^{1\mu} + (1 \to 2) \\
\mathcal{L}_{\rm int}^{\rm NC} &= -\frac{e}{s_\theta c_\theta} J_\mu^Z Z^\mu (1 - \sin^2\beta X) - \frac{e^2}{2 s_\theta^2 c_\theta^2 M_Z^2} X J_\mu^Z J^{Z\mu} \\
&\quad - e J_\mu^{\rm em} A^\mu - \frac{e^2}{2M_Z^2} X J_\mu^{\rm em} J^{{\rm em}\mu} \\
X &= \frac{\pi^2 M_Z^2}{3M_c^2}
\end{aligned}$$

The precision measurements are affected. For example,

$$G_F = \frac{\sqrt{2} g^2}{8 M_W^2} (1 + c_\theta^2 X)(1 - 2\sin^2\beta c_\theta^2 X)$$

$$\Gamma(Z \to f\bar{f}) = \frac{N_c M_Z}{12\pi} \frac{e^2}{s_\theta^2 c_\theta^2} (1 - 2\sin^2\beta X)(g_v^2 + g_a^2) ,$$

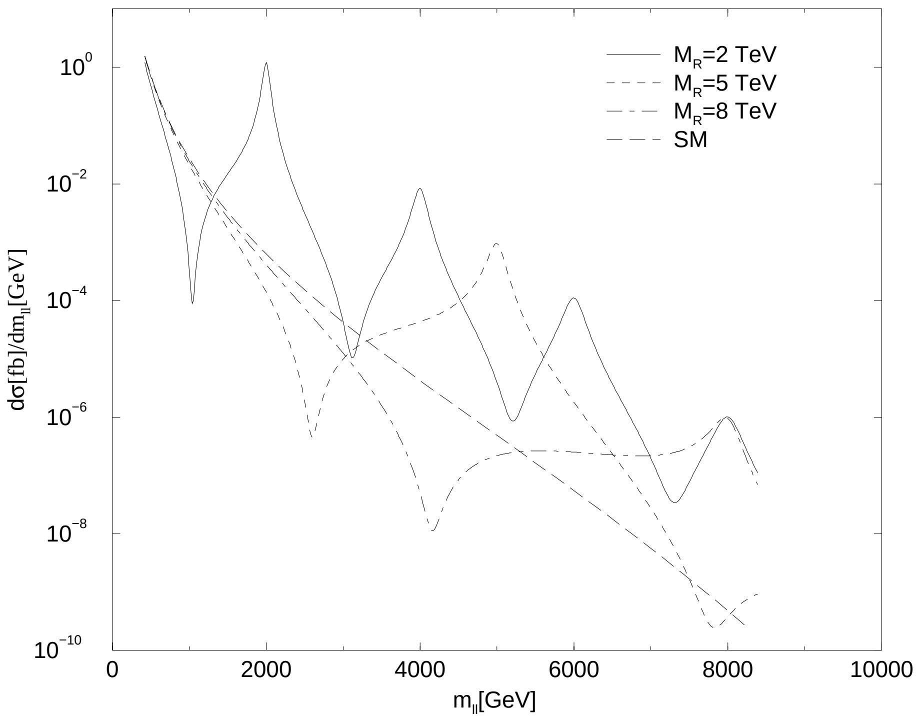
Casalbouoni et al. used EW fit parameters $\epsilon_{1,2,3}$, ΔQ_W, and $R_{\nu,\bar{\nu}}$ obtained a limit of

$$M_c \gtrsim 3.6 \text{ TeV}$$

Others got similar limits.

High Energy Processes

- $M_c < \sqrt{s}$: Resonances can be seen in Drell-yan production



Nath, Yamada, Yamaguchi

Constraints from present high energy data

(Cheung and Landsberg)

- $M_c > \sqrt{s}$: No resonance is seen.

Use the approximation:

$$M_c^2 \gg \hat{s}, |\hat{t}|, |\hat{u}|$$

$$\begin{aligned} M^{eq}_{\alpha\beta}(s) &= e^2 \left\{ \frac{Q_e Q_q}{s} + \frac{g^e_\alpha g^q_\beta}{\sin^2\theta_{\rm w}\cos^2\theta_{\rm w}} \frac{1}{s - M_Z^2} \right. \\ &- \left. \left(Q_e Q_q + \frac{g^e_\alpha g^q_\beta}{\sin^2\theta_{\rm w}\cos^2\theta_{\rm w}} \right) \frac{\pi^2}{3M_c^2} \right\} \end{aligned}$$

- Enhancement in large $\sqrt{s}$

Put

$$\eta = \frac{\pi^2}{3M_c^2}$$

into our fitting analysis.

Data sets

- Drell-yan production at Tevatron.
- HERA NC and CC DIS.
- LEPII hadronic, leptonic cross section, angular distributions.
  All the above are due to KK states of γ, Z, W
- Dijet cross section and angular distribution.
  This is mainly due to KK states of gluon, e.g.,

$$\overline{\sum} |\mathcal{M}(qq' \to qq')|^2 = \frac{4}{9} g_s^4 (\hat{s}^2 + \hat{u}^2) \left(\frac{1}{\hat{t}} - \frac{\pi^2}{3M_c^2} \right)^2$$

- $t\bar{t}$ production

Best-fit values of $\eta = \pi^2/(3M_C^2)$ and the 95% C.L. upper limits on M_c for individual data set and combinations.

	η (TeV^{-2})	M_C^{95} (TeV)
LEP 2:		
hadronic cross section, ang. dist., $R_{b,c}$	$-0.33^{+0.13}_{-0.13}$	5.3
μ, τ cross section & ang. dist.	$0.09^{+0.18}_{-0.18}$	2.8
ee cross section & ang. dist.	$-0.62^{+0.20}_{-0.20}$	4.5
LEP combined	$-0.28^{+0.092}_{-0.092}$	6.6
HERA:		
NC	$-2.74^{+1.49}_{-1.51}$	1.4
CC	$-0.057^{+1.28}_{-1.31}$	1.2
HERA combined	$-1.23^{+0.98}_{-0.99}$	1.6
TEVATRON:		
Drell-yan	$-0.87^{+1.12}_{-1.03}$	1.3
Tevatron dijet	$0.46^{+0.37}_{-0.58}$	1.8
Tevatron top production	$-0.53^{+0.51}_{-0.49}$	0.60
Tevatron combined	$-0.38^{+0.52}_{-0.48}$	2.3
All combined	$-0.29^{+0.090}_{-0.090}$	6.8

Sensitivity reach in M_c for Run 1, Run 2 of the Tevatron and at the LHC, using the dilepton channel.

	95% C.L. lower limit on M_C (TeV)
Run 1 (120 pb^{-1})	1.4
Run 2a (2 fb^{-1})	2.9
Run 2b (15 fb^{-1})	4.2
LHC (14 TeV, 100 fb^{-1}, 3% systematics)	13.5
LHC (14 TeV, 100 fb^{-1}, 1% systematics)	15.5

Universal Extra Dimensions

All SM particles are free to move in the extra dimensions. Translational invariance

$\Rightarrow$ Conservation of KK numbers (momentum)

Boundary breaks the momentum conservation down to a Z_2 parity,

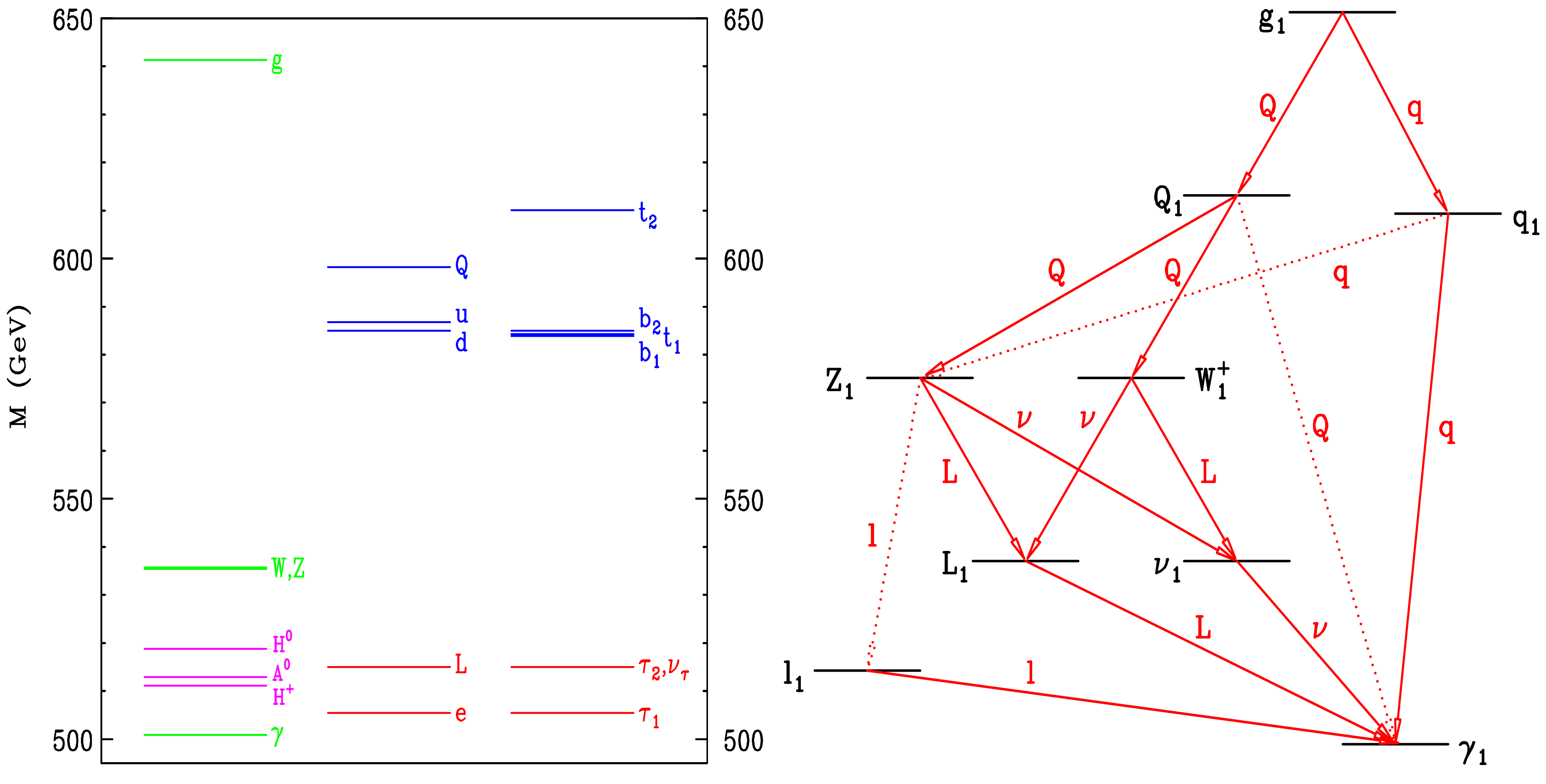
Conservation of KK parity

Radiation corrections and the boundart terms lift the mass degeneracy of KK states.

B^1, the first KK state of the hypercharge gauge boson, is the lightest KK particle

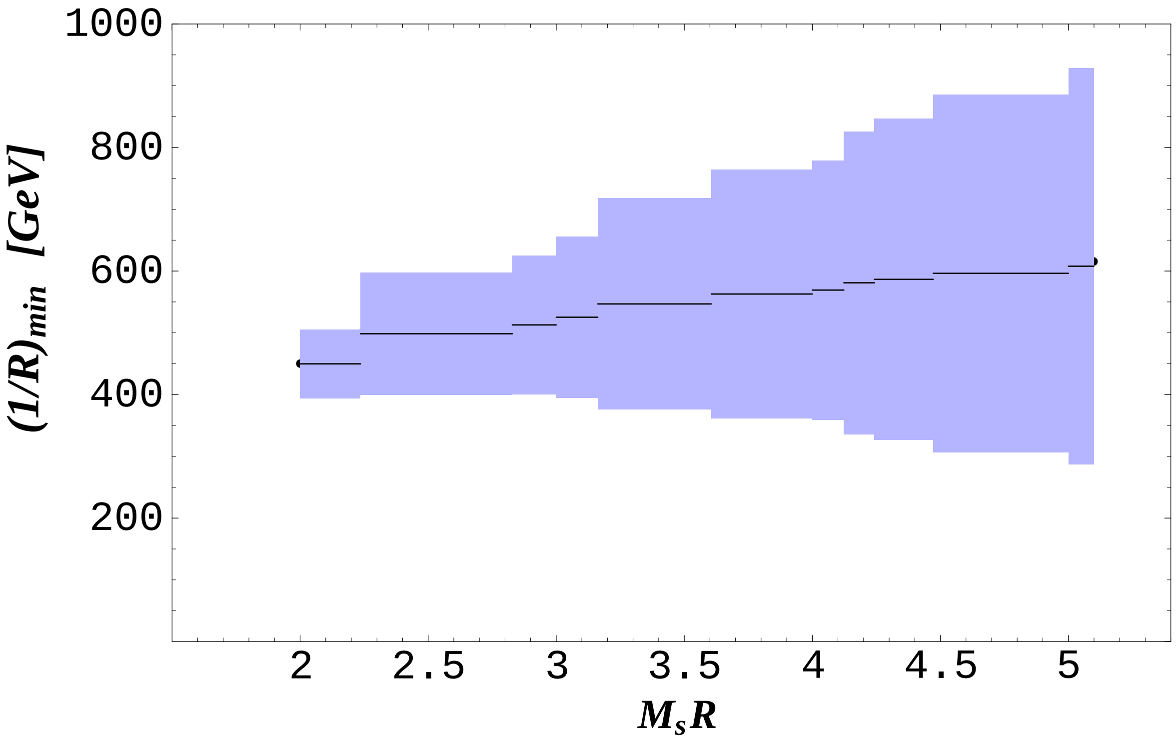
Appelquist, Cheng, Dobrescu

KK state spectrum



Cheng, Matchev, Schmaltz

Present Constraint



$\delta = 2$, M_s is the upper cutoff.

KK states must appear in pairs $\Rightarrow$ bounds are weak.

Appelquist, Cheng, Dobrescu

Collider Phenomenology

The largest production comes from KK quarks and KK gluons

$$\begin{aligned} qq' &\to q^{(1)} q'^{(1)} \\ q\bar{q} &\to q^{(1)} \bar{q}^{(1)} \\ gg &\to g^{(1)} g^{(1)} \\ gg, q\bar{q} &\to q'^{(1)} \bar{q}'^{(1)} \end{aligned}$$

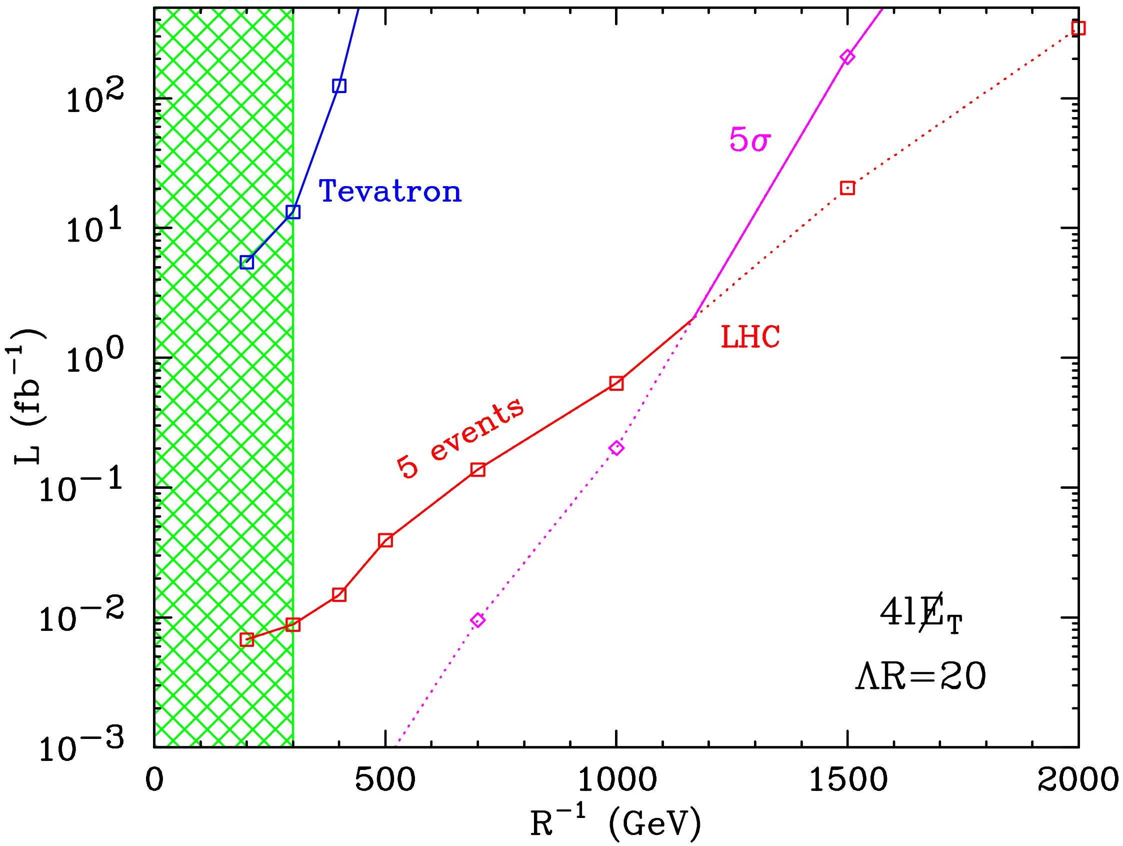
Each $q^{(1)}$ decays into jets and $\gamma^{(1)}$ eventually

$\Rightarrow$ jets+ $\not{E}_T$

Each $q^{(1)}$ also decays $W^{(1)}, Z^{(1)}$, which decay into leptons.

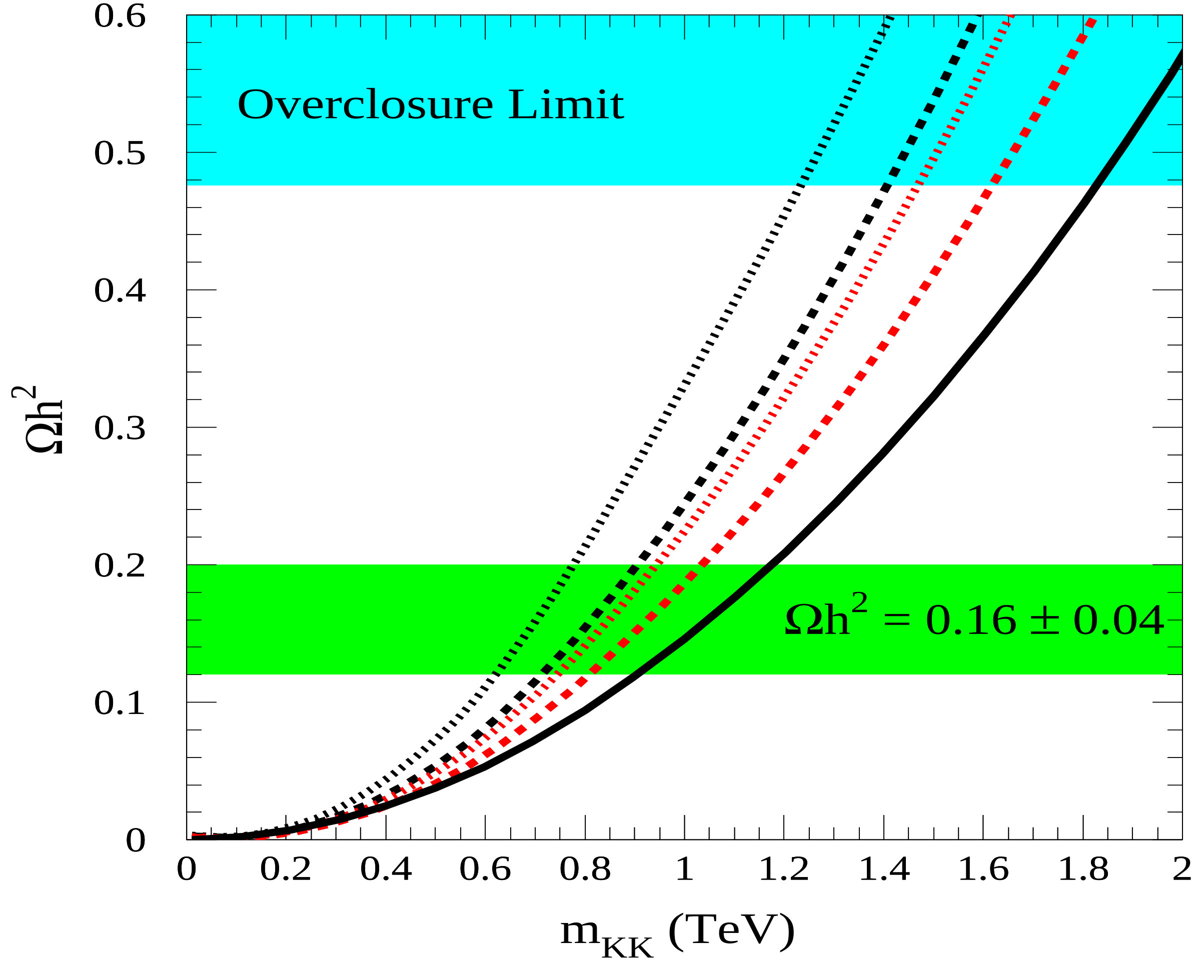
$\Rightarrow$ multi-leptons+ $\not{E}_T$

Sensitivity Reach



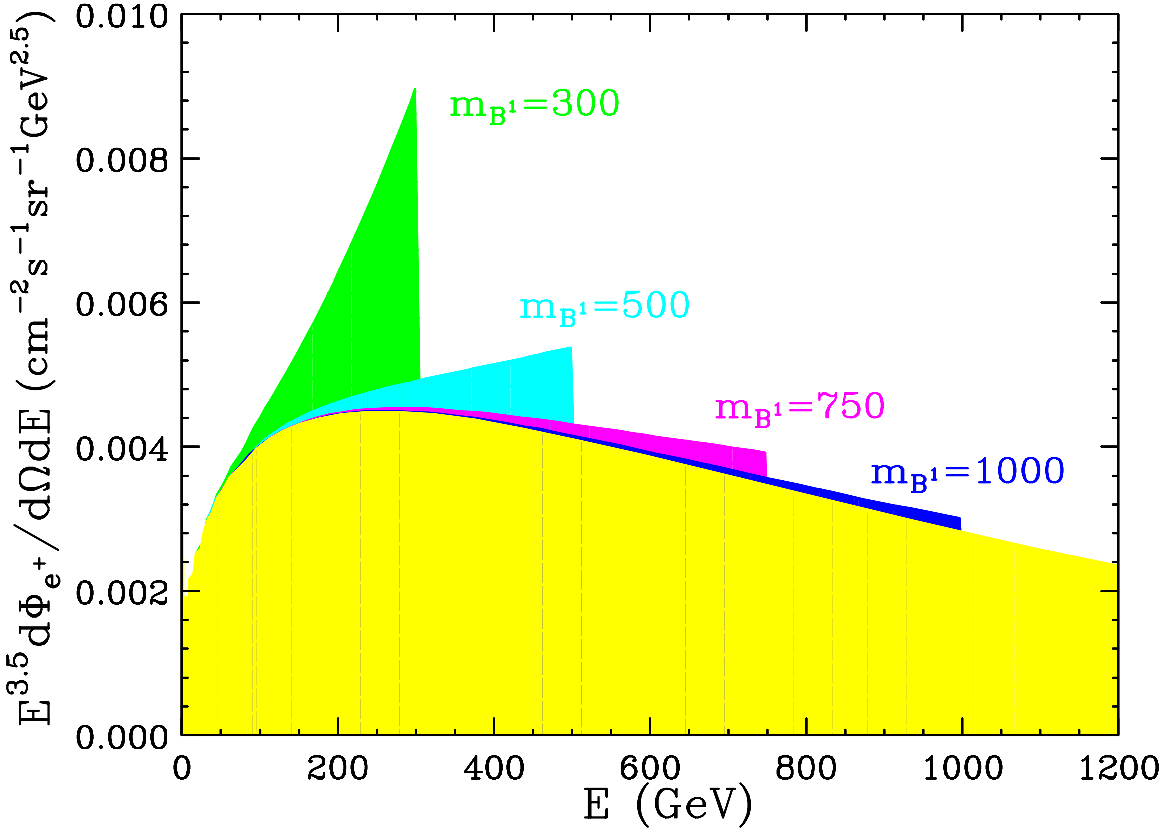
Cheng, Matchev, and Schmaltz

Lightest KK state as the Dark Matter



Servant and Tait

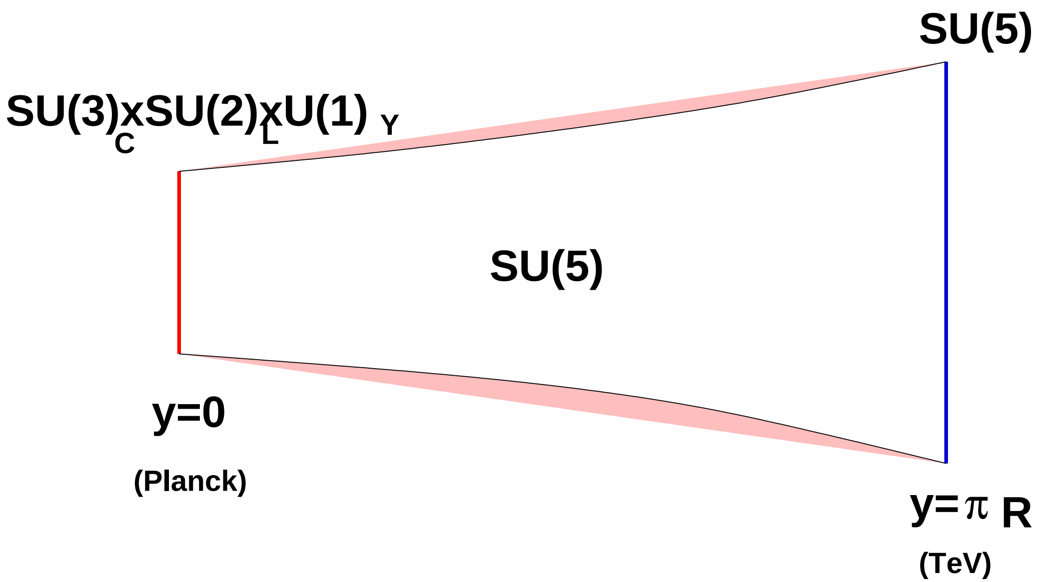
$B^1 B^1 \to e^+ e^-$



Monoenergetic positron signal, but broadened during propagation.

Cheng, Feng, Matchev

An 5D SU(5) SUSY GUT Model



Nomura, Goldberger, Smith

It is a SUSY SU(5) compactified on an orbifold S^1/Z_2 in the AdS space.

• The AdS warp factor generates the hierarachy of scales.

• Special boundary conditions break the SU(5) symmetry and provide a natural doublet-triplet splitting.

• By the boundary conditions, the color-triple Higgs field is automatically zero on the Planck brane (matter). Proton decay is safe.

• The mass of the color-triplet (and the XY) is given by the warp factor, $\sim$ TeV.

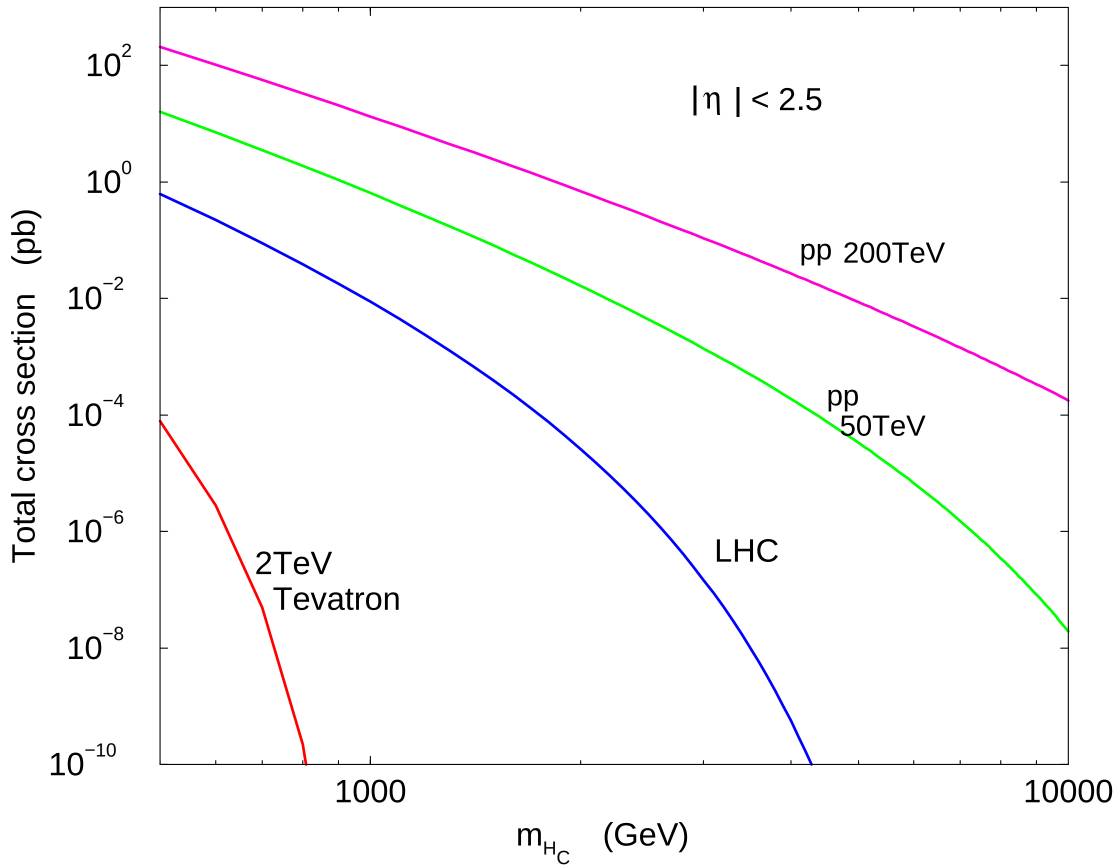
Alternative signature for GUT

TeV colored Higgs bosons

They can be copiously produced at the upcoming LHC.
They have a distinct signature:

- a massive stable charged particle,
- producing an ionized track in the central tracking chamber, and
- ionized in the outer muon chamber as well.
- like a "heavy muon".

Cheung and Cho



Cheung and Cho

Detection of Colored Higgs Bosons

Experimentally, the massive stable charged particle will produce a track in the central tracking and/or silicon vertex system, where dE/dx and p can be measured.

$$\beta\,\gamma = \frac{p}{E}\,\frac{E}{M} = \frac{p}{M} \lesssim 0.85$$

The particle is required to penetrate to the outer muon chamber.

$$0.25 - 0.5 \lesssim \beta\,\gamma$$

c.f. CDF Coll. used a criteria: $0.26 - 0.5 \lesssim \beta\gamma \lesssim 0.86$, but it is for a particle of mass of $50 - 500$ GeV only.

Event rates

Factors:

- $P = 1/2$ for the colored Higgs boson to hadronize into a charged particle.
- Require at least one colored Higgs boson to be in the detection range: $0.25 < \beta\gamma < 0.85$ and $|\eta| < 2.5$.
- An efficiency factor of 80% for seeing a track in the central tracking chamber.

The $\beta\gamma \equiv p/M > 0.25$ cut means $p > 250$ GeV for a 1 TeV particle. Make it background free from $\mu^\pm, K^\pm, \pi^\pm$.

m_{H_C} (TeV)	Tevatron ($\mathcal{L} = 20$ fb^{-1})	LHC ($\mathcal{L} = 100$ fb^{-1})	VLHC 50 TeV ($\mathcal{L} = 100$ fb^{-1})	VLHC 200 TeV ($\mathcal{L} = 100$ fb^{-1})
0.3	160	2.3×10^5	3.1×10^6	2.8×10^7
0.4	14	5.5×10^4	9.6×10^5	9.7×10^6
0.5	0.9	1.7×10^4	3.7×10^5	4.3×10^6
0.8	-	1200	4.7×10^4	7.1×10^5
1.0	-	285	1.6×10^4	2.9×10^5
1.5	-	15	2200	5.6×10^4
2.0	-	1.2	470	1.6×10^4
3.0	-	-	43	2700
4.0	-	-	6.4	690
6.0	-	-	-	90
8.0	-	-	-	19
9.0	-	-	-	9.7

Conclusions

- There have been extensive studies of sub-Planckian and trans-Planckian collider signatures for the large extra dimension model.

- Experimentally, there are already some limits around $M_D \sim 1 - 1.4$ TeV for the fundamental Planck scale.

- Randall-Sundrum model has a distinct unevenly spaced KK spectrum.

- The radion or radion-Higgs mixing phenomenology may be the first sign of RS model.

- TeV^{-1}-sized extra dimensions with gauge bosons will modify the gauge coupling running, and affect the precision measurements, and high energy scattering processes. The current best limit is about $M_c > 6.8$ TeV.

- Universal extra dimension has a stable lightest KK state, which gives a distinct $\not{E}_T$ signal and is a DM candidate.

- An 5D SU(5) SUSY GUT model in AdS can have safe proton decay, natural doublet-triplet splitting, and a TeV colored Higgs boson, which gives an interesting "heavy muon"-like signature.