Phenomenology of Extra Dimensions

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What do we expect at the Weak scale?

Higgs mass (hence EW scale) sensitive to high scale physics

Naturality: cutoff at around TeV $\longrightarrow$ new physics!

- Supersymmetry (superpartners)
- Extra Dimensions (Kaluza-Klein modes)
- Higgs as pseudo NGB

Look for new particles at high-energy colliders. Theories predict specific relations between new and observed particles.

- Often new interactions are related to SM ones
- Lorentz transformation properties predicted: spins
- But also lots of "model building freedom" and new parameters

Exciting prospect of seeing extra dimensional nature at colliders

Maybe a glimpse into even higher energies

Outline

- Overview of selected X-Dim. scenarios
- Can we see several KK levels?
- A six-dimensional example: UED's
  - Missing energy signals
  - Resonances
- Conclusions

Large "Gravitational" Dimensions

(Arkani-Hamed, Dimpoulous & Dvali)

ADD:
- δ flat, compact extra dimensions
- Invisible to SM, but accesible to gravity

$$M_{\rm Pl}^2 = V_\delta M_D^{2+\delta} \qquad M_D = \mathcal{O}(\mathrm{TeV})$$

Quantum gravity effects may lurk near the EW scale!

Almost a *continuum* of KK graviton states, with Planck suppressed couplings

Well defined couplings to matter: $\frac{1}{M_{\rm Pl}} h_{\mu\nu} T^{\mu\nu}$ or $\frac{1}{\Lambda_H^2} T^{\mu\nu} T_{\mu\nu}$

- Modifications of $f\bar{f}$ production in e^+e^- and pp collisions
- At LHC: Drell-Yan and diphoton production can probe scales up to a few TeV, depending on δ.

(Giudice, Rattazzi & Wells, Mirabelli, Perelstein & Peskin, ...)

- Graviton emisson: $pp \to \mathrm{jet} + \not{E}_T \;\; (qg \to qG)$

Warped Extra Dimensions

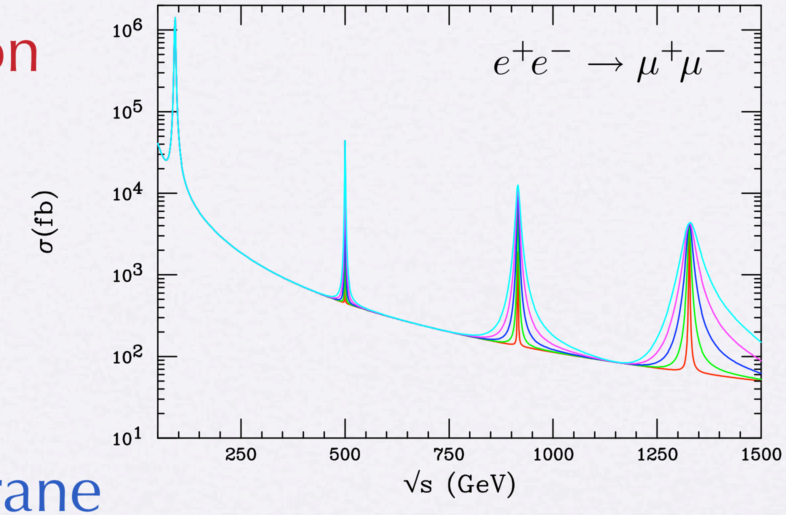
(Randall & Sundrum)

Solves hierarchy problem if Higgs on IR brane. Also $M_{\rm Pl}^2 \approx \frac{M^3}{k} e^{2k\pi r_c}$.

Signal very sensitive to fermion localization

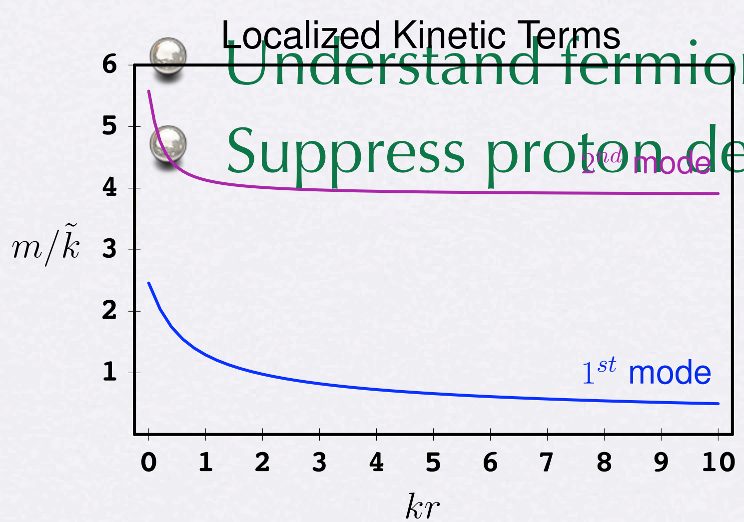
- If SM fermions localized on IR brane:

  Graviton resonances:
  EW scale masses and couplings



(from Davoudiasl, Hewett & Rizzo)

- Light fermions may be away from IR brane
  - Understand fermion mass hierarchies
  - Suppress proton decay or dangerous FCNC effects



(Carena, E.P,Tait & Wagner)

- But gauge and fermion KK towers
- Important constraints from EWPM
  Mixing due to localized Higgs
- First KK level may be within reach of LHC

Bulk Gauge Fields in TeV X-Dim

Gauge interactions get strong near the compactification scale

- Matter fields localized at certain points in extra dimensions
  - tree-level couplings to gauge fields
  - Important constraints from EWPM: 1/R > 5 TeV
  - Present collider bounds: 1/R > 1-2 TeV

Combined 7 TeV at 95% C.L. **(Cheung & Landsberg)**

Cutoff scale $\Lambda \rightarrow$ Higher dimensional effective theory breaks down near the weak scale

Hierarchy problem alleviated.

In general, "little hierarchy problem" remains

- All SM fields delocalized ⟶ Universal Extra Dimensions
  - Present constraints on the order of a few 100 GeV
  - Potential production of several KK levels!
- Some similarities with SUSY models with a degenerate spectrum **(Cheng, Matchev & Schmaltz)**
  - Superpartners ⟷ First KK level states
  - R-parity ⟷ KK-parity
  - "Small" EW corrections

Why 6 Dimensions?

Interesting theoretical constraints:

- Anomalies $\longrightarrow$
  - generations a multiple of three
  - predicts right-handed neutrinos

(Dobrescu & Poppitz)

- Discrete symmetries of the compactified theory
  - Z_2^{KK} : KK-Parity $\longrightarrow$ LKP is stable (similar to 5D)
  - Z_8 :
    - Nucleon decay suppressed
    - Neutrinos are Dirac fermions

(Appelquist, Dobrescu, E.P. & Yee)

These symmetries are tightly related to the higher dimensional Lorentz invariance

Useful to distinguish between

Tree-level effects

Loop-level effects

Tree-level Structure

Tree-level spectrum: $M_{j,k}^2 = \dfrac{j^2 + k^2}{R^2}$

- In detail: $1/R,\ \sqrt{2}/R,\ 2/R, \ldots$

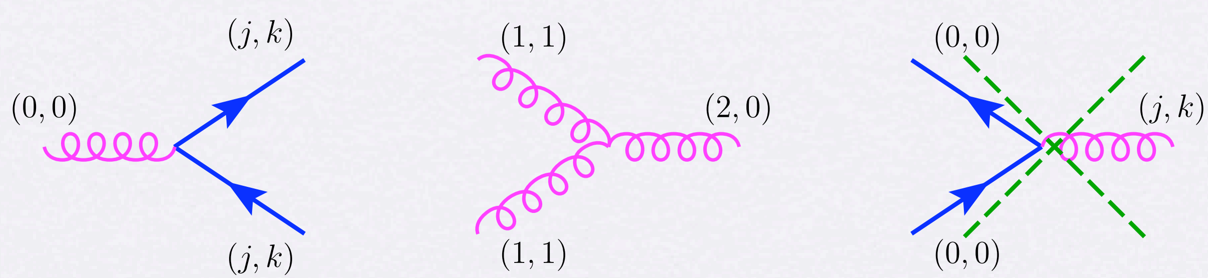
  (1,0) (1,1) (2,0)

  does not exist in 5D

- n-th KK level states degenerate at tree-level

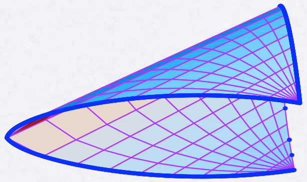
Couplings determined by wavefunction profiles (boundary cond.)

KK number conservation: related to momentum conservation



At tree-level: only pair production of KK modes!

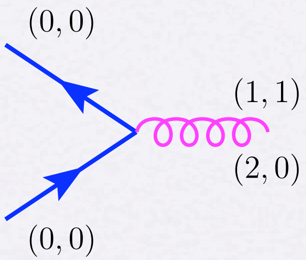
Radiative corrections



- Low-energy chiral theory requires "singularities"

  → Localized operators and new effects!

  - Mass splittings: depend on quantum numbers
  - New interactions, e.g.



$$P_{\mathrm{KK}} = (-1)^{j+k}$$

- Theory has a cutoff at $\Lambda \sim \mathcal{O}(10)/R$ (when QCD gets strong)
- Localized operators receive contributions from
  - Unknown UV completion at Λ (assume NDA philosophy)
  - "Known" physics below Λ (loop induced and logarithmically enhanced)

KK Spectrum in 6D

1-loop leading order mass corrections take the form

$$\delta M^F_{j,k} = \frac{1}{16\pi^2} \ln \frac{\Lambda^2}{\mu^2} C_F M_{j,k}$$

One finds:

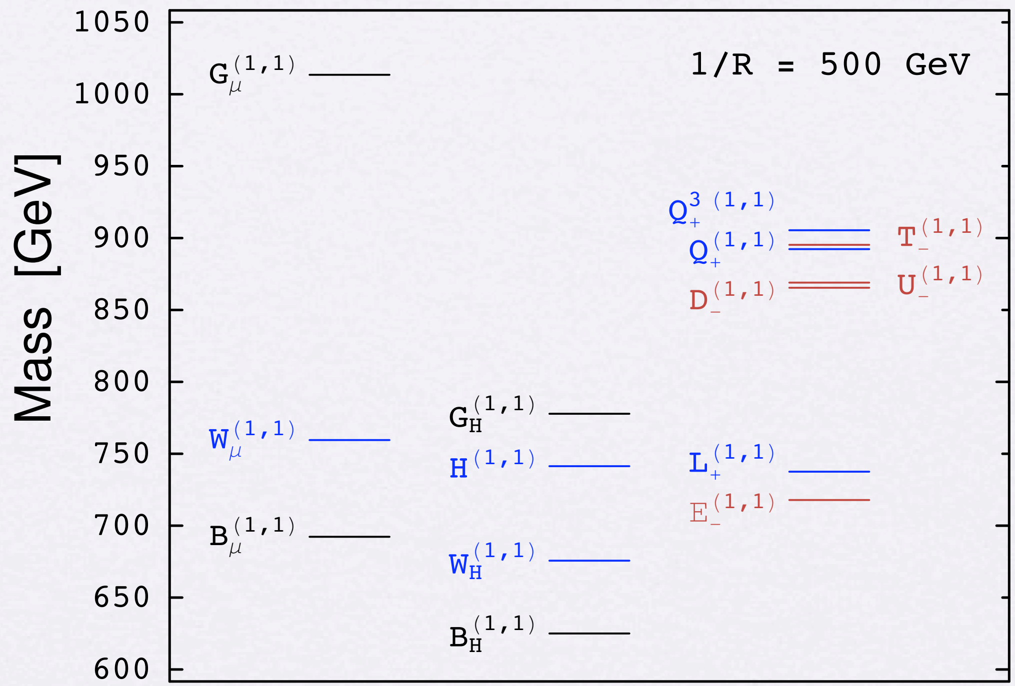
$$C_{A_\mu} = g_4^2 \left(\frac{17}{3} C(G) - \frac{2}{3} \sum_\Psi T(r) - \frac{1}{2} \sum_\Phi T(r) \right)$$

$$C_{A_H} = g_4^2 \left(9\, C(G) - 4 \sum_\Psi T(r) + \frac{7}{2} \sum_\Phi T(r) \right)$$

$$C_\Psi = 5 \sum_{\text{gauge}} g_4^2 C_2(\Psi) + \frac{3}{4} \sum_i |\lambda_{4,i}|^2$$

Take these as a guide keeping in mind theoretical uncertainties

(1,1) level states



(E.P. & Wang)

Quarks and gluons should receive larger corrections than leptons and electroweak gauge bosons.

Scalars from Gauge fields

$$A_M \rightarrow A_\mu^{(n)}, A_i^{(n)}$$

Spin-1 Spin-0

- One linear combination eaten by the massive gauge fields ➞ Higgs Mech.
  - 5D: nothing left
  - 6D and higher: new scalars
    ➞ "Spinless Adjoints"
- Interesting possibility: the Higgs from A_M ➞ enlarge gauge group
- Consider SM gauge group:

$$G_H^a \quad W_H^\pm \quad W_H^3 \quad B_H$$

- Interactions constrained by KK-parity and gauge invariance
  - No dimension-4 couplings to fermions or gluons
  - Higher dimension operators, e.g.

$$\overline{Q}\Gamma^M\Gamma^N\Gamma^L Q\, \partial_M G_{NL} \quad \text{or} \quad G_{MN}G^{NL}G_L^M$$

Scalars from Gauge fields

- The couplings to gluons vanish! $f^{abc} G_a^{\mu\nu} G^b_{\mu\nu} G_H^{(j,k)c} = 0$
- Couplings to fermions exist if $(-1)^{j+k} = +1$:

$$(\overline{q}\gamma^\mu T^a q)\ \partial_\mu G_H^{(j,k)a} \quad \longrightarrow \quad \text{couplings proportional to } m_q$$

No chirality flip

- The KK-parity even spinless adjoints are hard to produce from $\overline{q}q$ or gg initial states
- But they can be produced in decays of KK quarks or fermions
- They decay into top quarks almost always!
- In 6D, the LKP is expected to be $B_H^{(1,0)}$, a scalar

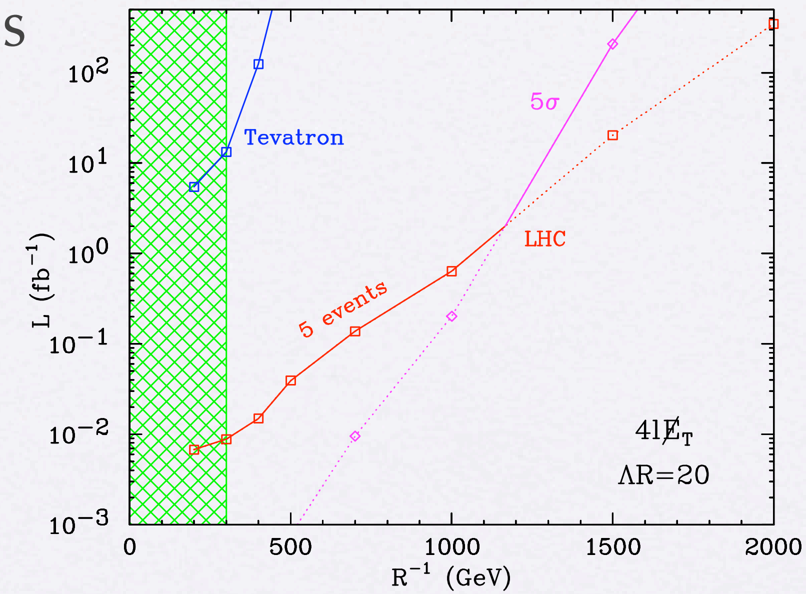
Pair Production: the SUSY-like case

Involves KK-number ***conserving*** interactions

- 1st level states: cascade decays to LKP
  - Strong production of $Q^1 Q^1$

    Soft jets ➞ hard!

    ➞ look for 3 or more lepton plus missing energy signal



(from Cheng, Matchev & Schmaltz)

  - Decays into $W_1^{\pm}$ and Z_1 ➞ leptons

    "Gold-plated" mode: $\not{E}_T + 4$ leptons

$$Q_1 \longrightarrow W_1 q$$
$$\hookrightarrow L_1 l$$
$$\hookrightarrow B_1 l$$

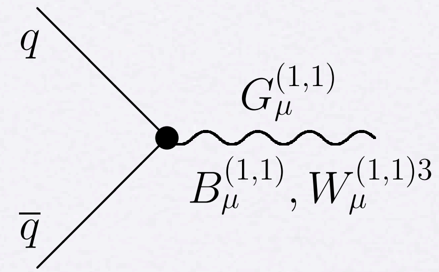
- Heavier KK states (phase space suppression)
- Spin Measurements at hadron collider are challenging!

(Smillie and Weber; Datta, Kong & Matchev)

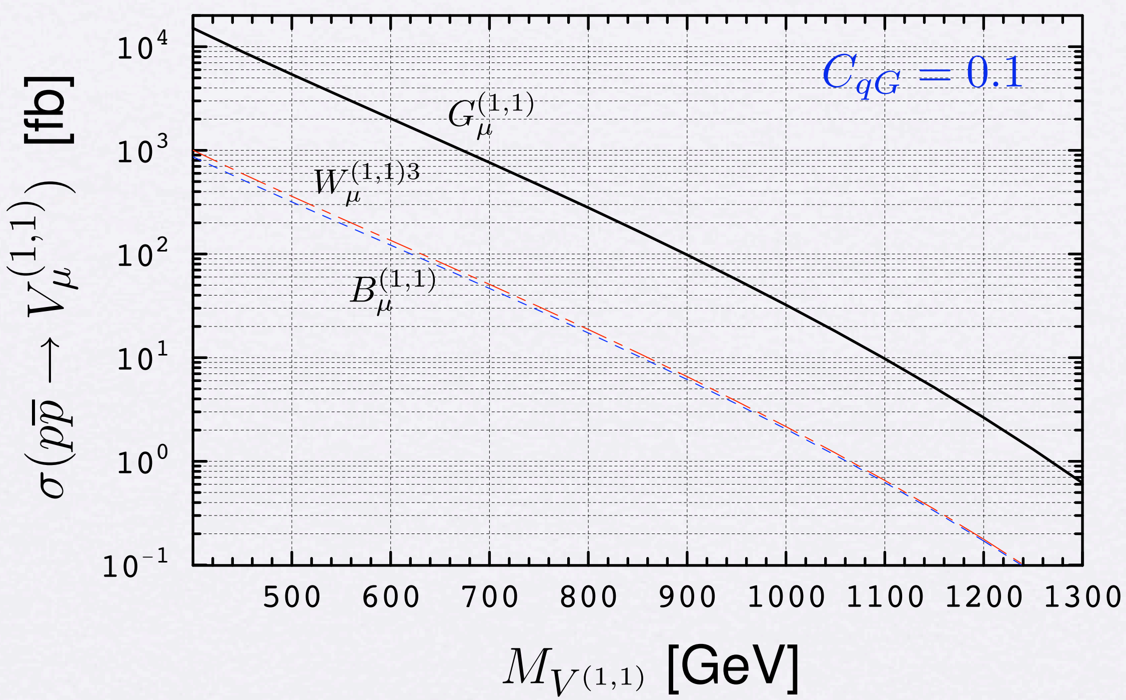
Vector Mode Production at the Tevatron

(Dobrescu, E.P & Burdman)

- Single production (through KK ***violating*** interactions) of (1,1) and (2,0) states, e.g.



$$q\bar{q} \to G_\mu^{(1,1)}, W_\mu^{(1,1)3}, B_\mu^{(1,1)}$$



In 6D:

- Couplings to fermions

$$g_s C_{qG} \left(\bar{q}\gamma^\mu T^a q\right) G_\mu^{(1,1)a}$$

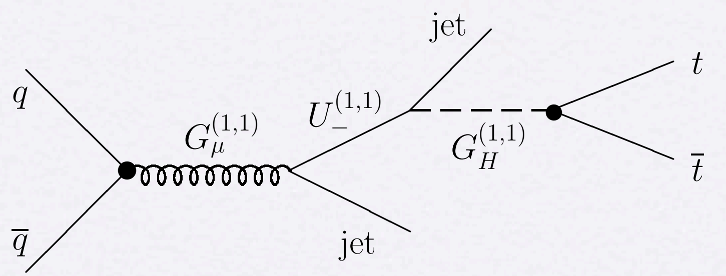
- Mass shifts

$$\delta M_{j,k}^2 / M_{j,k}^2$$

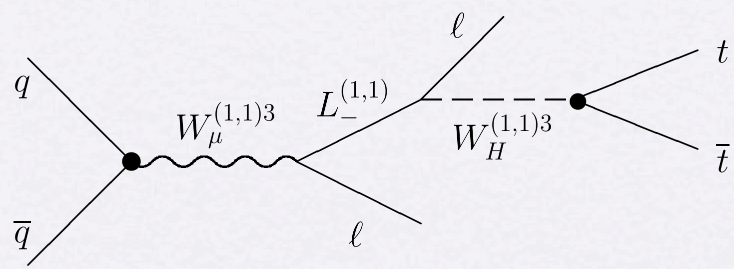
controlled by independent fundamental parameters

$t\bar{t}$ Resonances at the Tevatron

(1,1) excitations of the gauge bosons have large BR into spinless adjoints, hence into $t\bar{t}$

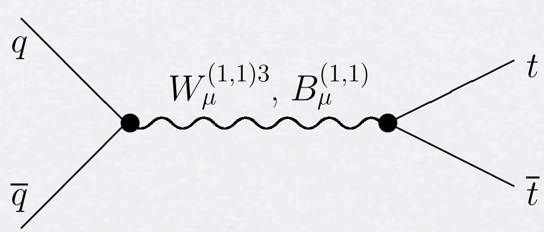


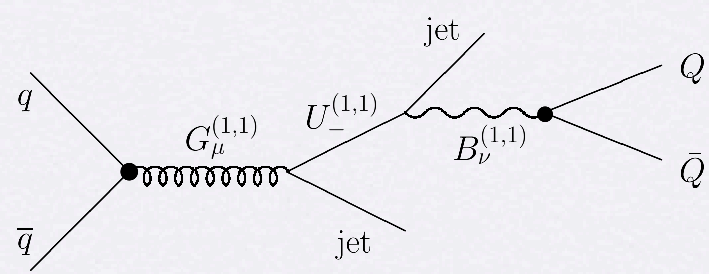
or also



decay modes	$G_\mu^{(1,1)}$
$G_H^{(1,1)}$ + jets	60.5
$W_H^{(1,1)3}$ + jets	3.2
$W_H^{(1,1)\pm}$ + jets	6.1
$B_H^{(1,1)}$ + jets	4.8
$W_\mu^{(1,1)3}$ + jets	4.3
$W_\mu^{(1,1)\pm}$ + jets	7.0
$B_\mu^{(1,1)}$ + jets	9.3
$t\bar{t}$	0.5
$b\bar{b}$	0.8
dijet (no $b\bar{b}$)	3.3

EW gauge bosons can also decay into top pairs





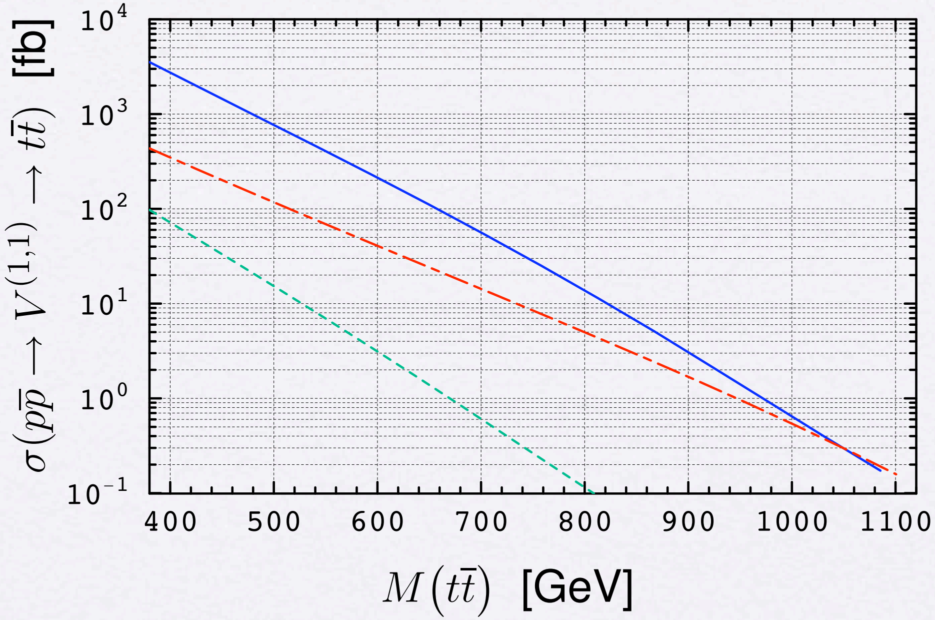
$t\bar{t}$ Resonances at the Tevatron

Three (potential) peaks:

$$G_H, W_\mu \rightarrow 1.1 \times M_{1,1}$$

$$W_H, B_\mu \rightarrow 0.97 \times M_{1,1}$$

$$B_H \rightarrow 0.86 \times M_{1,1}$$

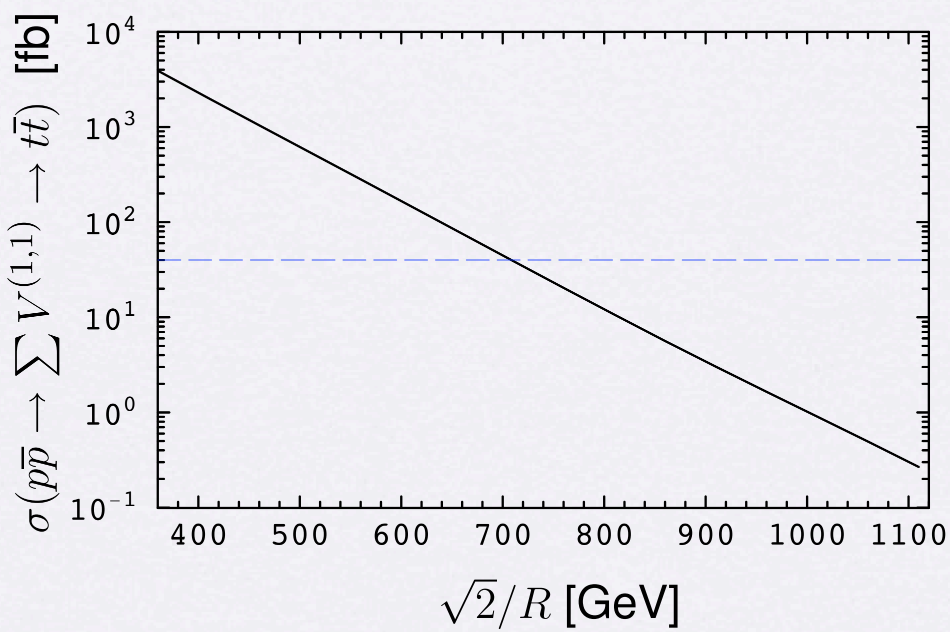


Current limit from CDF with $682\ \mathrm{pb}^{-1}$:

$> 1-2\ \mathrm{pb}$ at 95% C.L. for

$350\ \mathrm{GeV} < \mathrm{M}(\mathrm{t}\bar{\mathrm{t}}) < 600\ \mathrm{GeV}$

→ No limit on 1/R

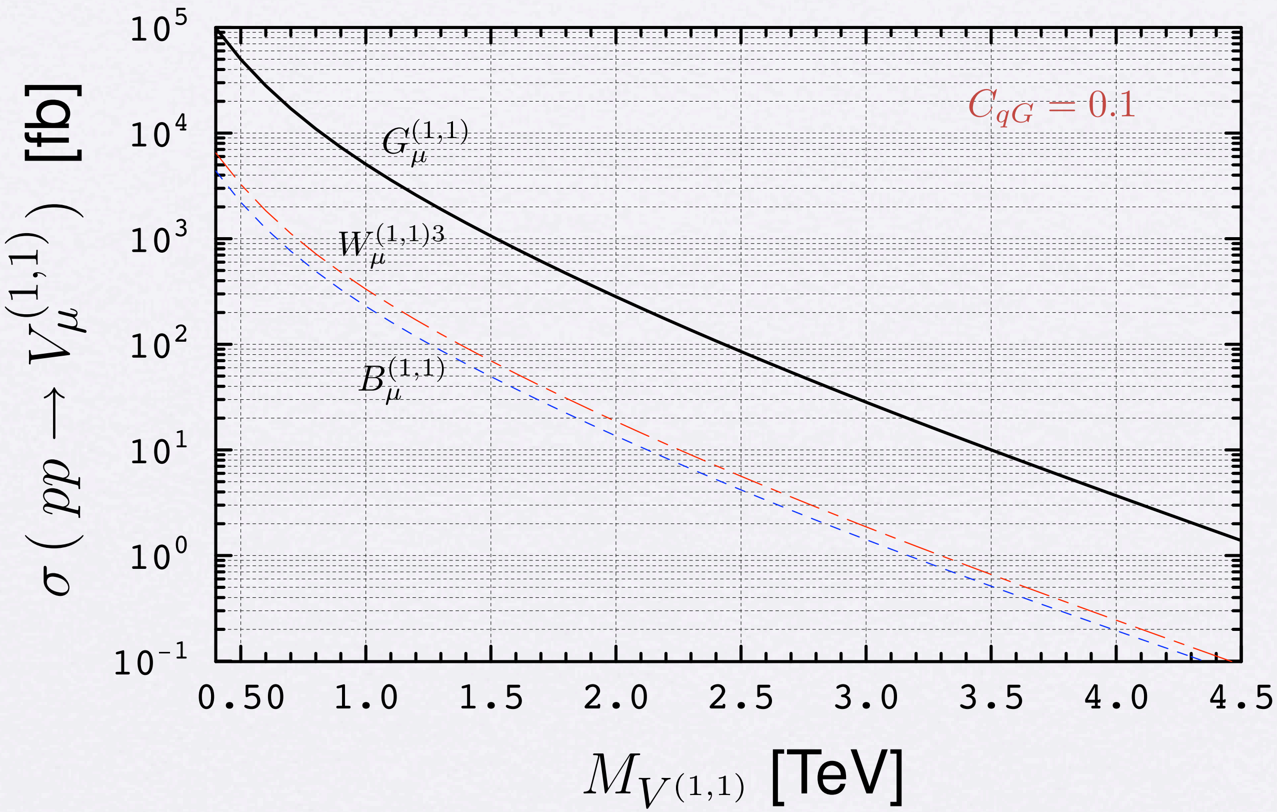


Vector Mode Production at the LHC

- Single production at the LHC

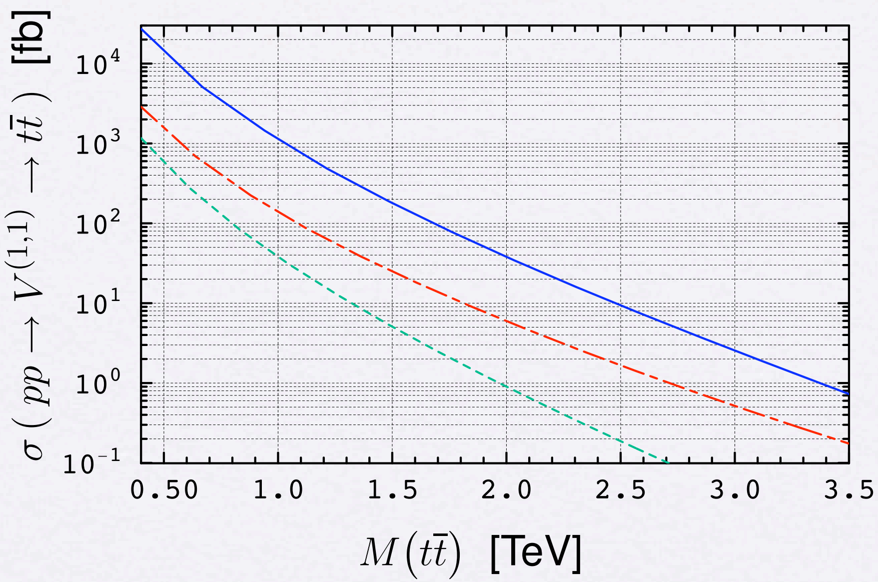
  Initial gg or qg $\to$ $\mathrm{G}^{(1,1)}$ (not log enhanced)

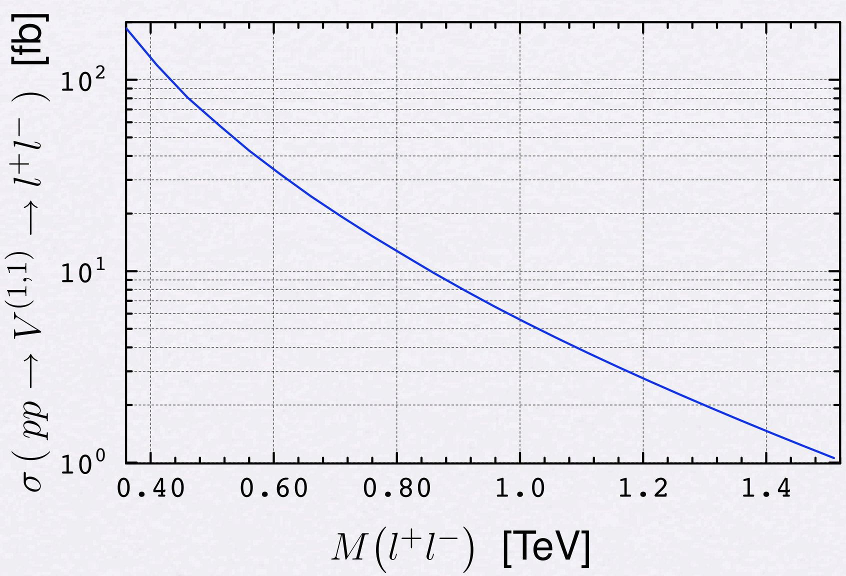
  $\to$ $q\bar{q} \to G^{(1,1)}, W^{(1,1)3}, B^{(1,1)}$ probably still dominant



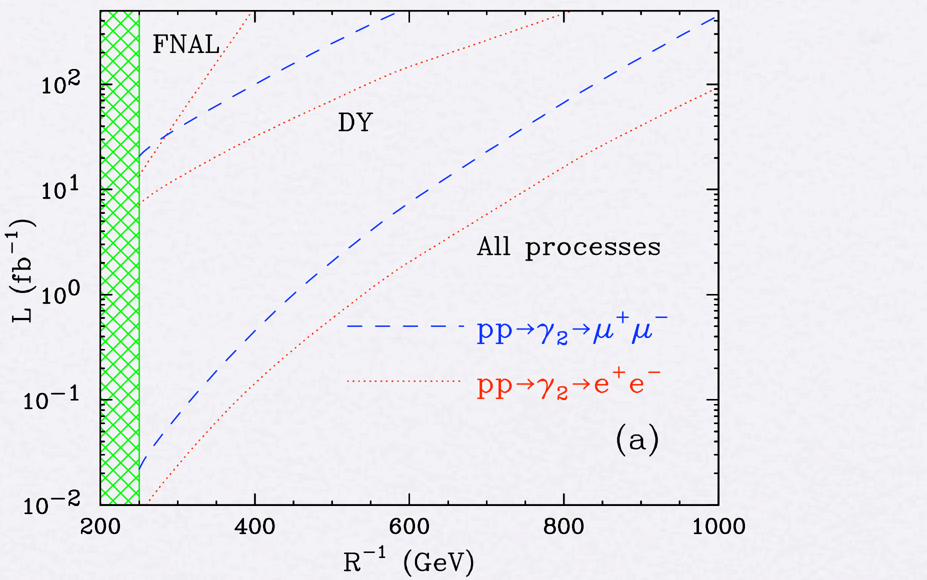
Resonances at the LHC

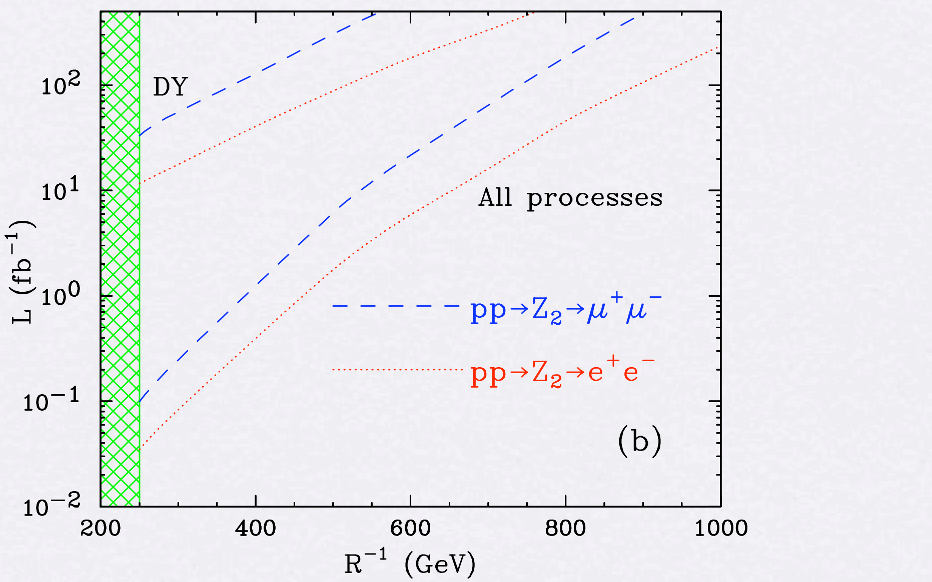
In 6D: (Dobrescu, E.P & Burdman)





In 5D: (from Datta, Kong & Matchev)





Conclusions

- Extra dimensions at the TeV scale are well motivated, and can be observed at high-energy colliders
- We may see several KK levels in UED scenarios!

  ➞ striking manifestation of extra dimensions

- Observation of (1,1) level at $\sim \sqrt{2}/R$ and (2,0) level at $\sim 2/R$ allows a clear distinction between 5D and 6D

  ➞ Should hold for $B_\mu^{(1,1)}$ (small corrections)

- New scalars in 6D with large couplings to tops

  ➞ Look for bumps in $t\bar{t}$ at the Tevatron and LHC!

- $B_\mu^{(1,1)}$ resonance in dilepton channel also promising
- The SUSY/UED "confusion" is probably resolvable at hadron colliders, even in the absence of a spin measurement