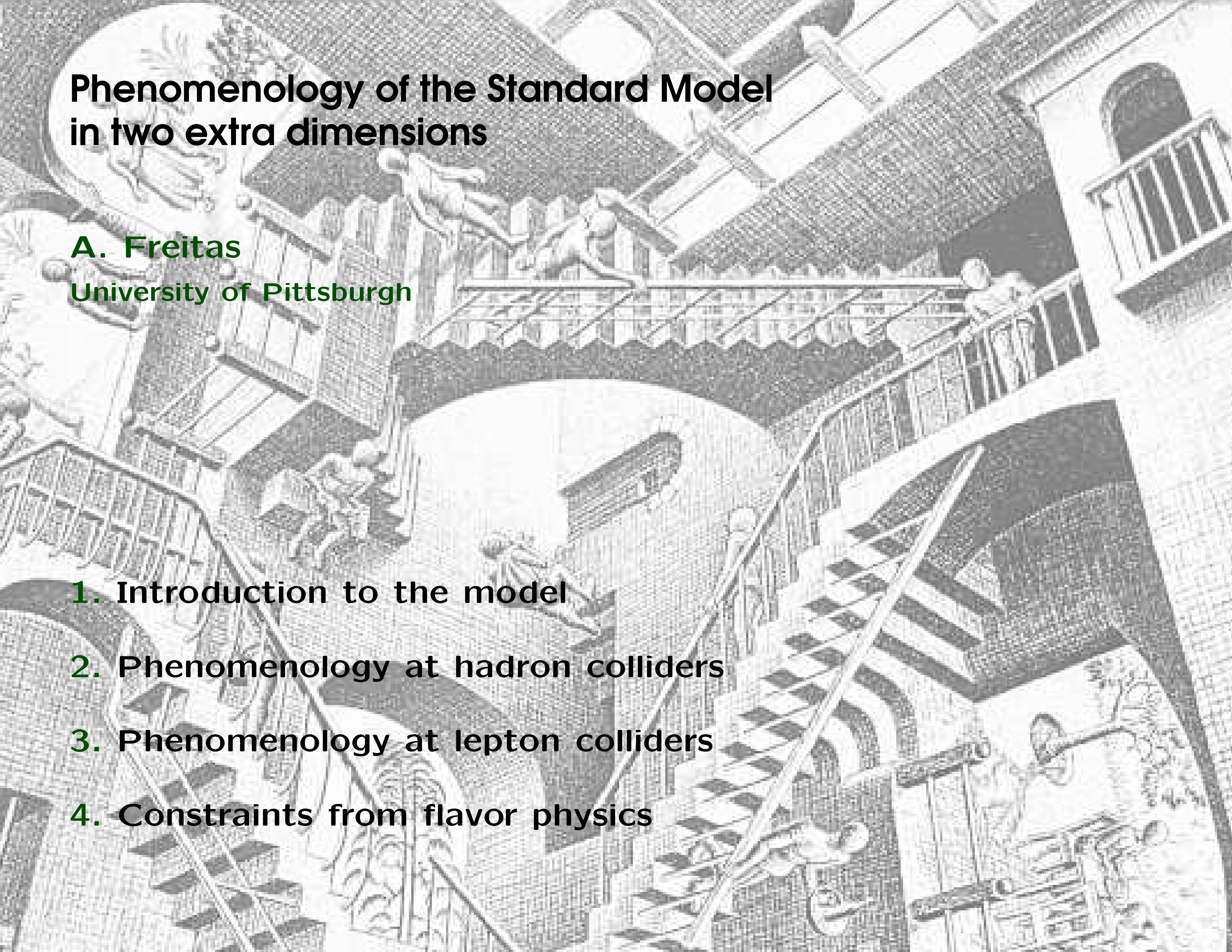

Phenomenology of the Standard Model in two extra dimensions

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1. Introduction to the model
2. Phenomenology at hadron colliders
3. Phenomenology at lepton colliders
4. Constraints from flavor physics

Two universal extra dimenions

Burdman, Ponton, Dobrescu '05

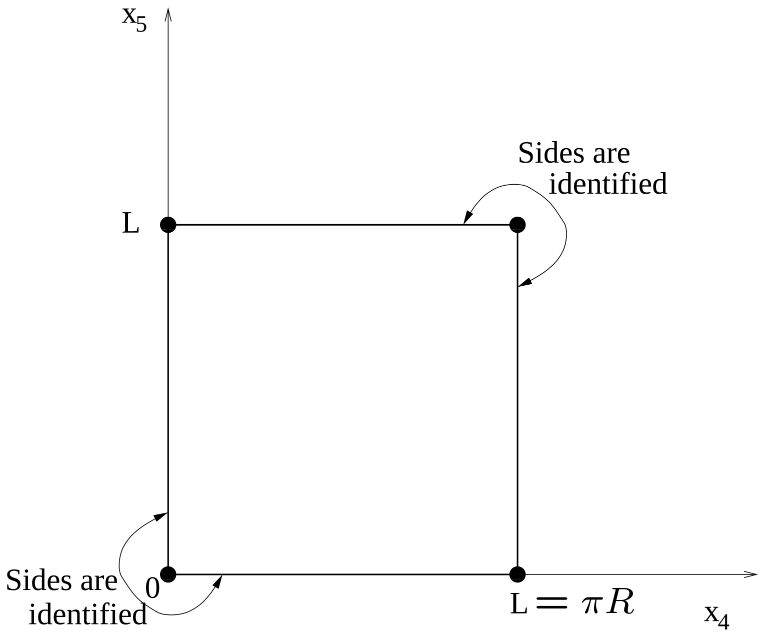
Several compactifications possible

Simple realistic choice: **chiral square**

→ Square that is folded along diagonal

→ Torus with 90° rotational orbifold symmetry T_2/Z_4

Choice of boundary conditions ensures **chiral** fermion zero-modes



Each gauge boson has **six** components A_μ, $\mu = 0, ..., 5$

Compactification leads to a tower of 4-component vector bosons $A_\nu^{(j,k)}$, $\nu = 0, ..., 3$

One component gets eaten to give mass
(a longitudinal component) to the KK-vectors

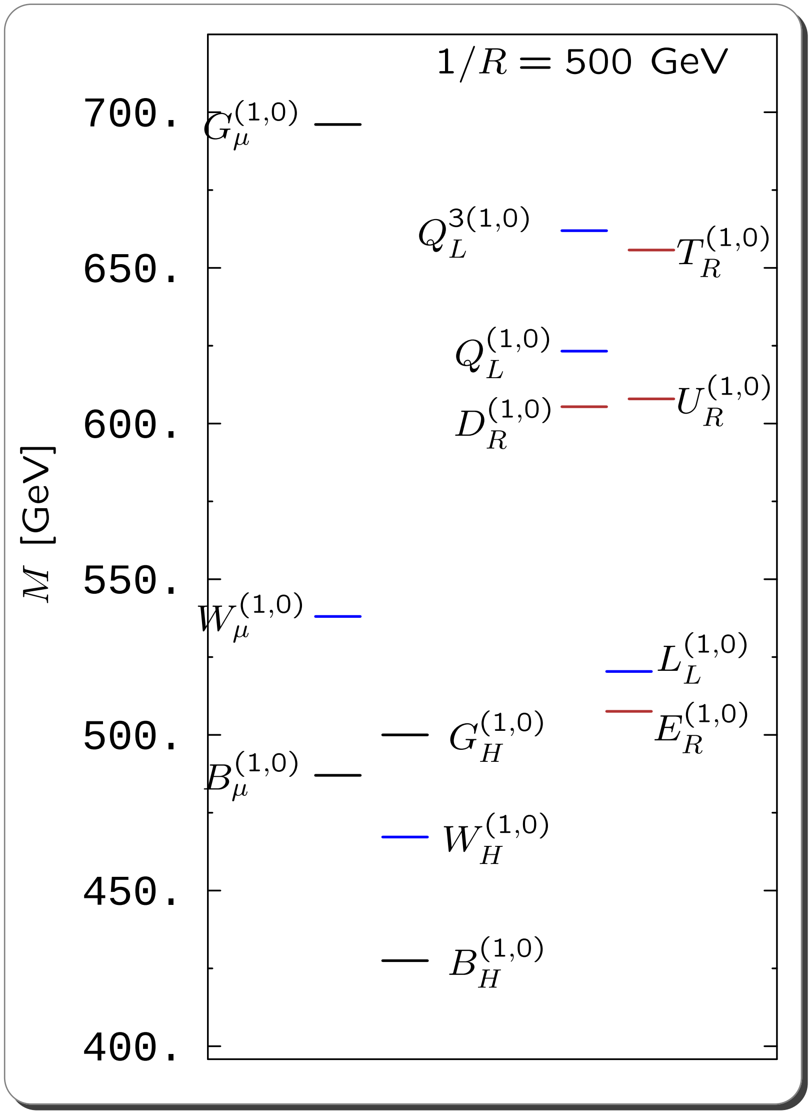
The remaining component forms a new scalar particle A_H

Mass spectrum

Cheng, Matchev, Schmaltz '02
Ponton, Wang '05

Masses of each KK-level: $M^2_{(j,k)} = (j^2+k^2)/R^2$

Radiative corrections generate localized operators that lift degeneracy within one KK-level



General form:

$$\delta M^2_{(j,k)} = const. \times \frac{g^2}{16\pi^2} \log \frac{\Lambda^2}{M^2_{(j,k)}}$$

Λ is a cut-off energy scale

Estimate $\Lambda \approx 10/R$
(couplings become strong)

KK number broken,
but **KK parity** preserved

Decays

Due to conservation of K-parity, the **lightest K-odd particle is stable**

Typically the scalar component of the hypercharge gauge boson $B_H^{(1,0)}$

→ Good **DM candidate** for $R^{-1} \lesssim 600$ GeV

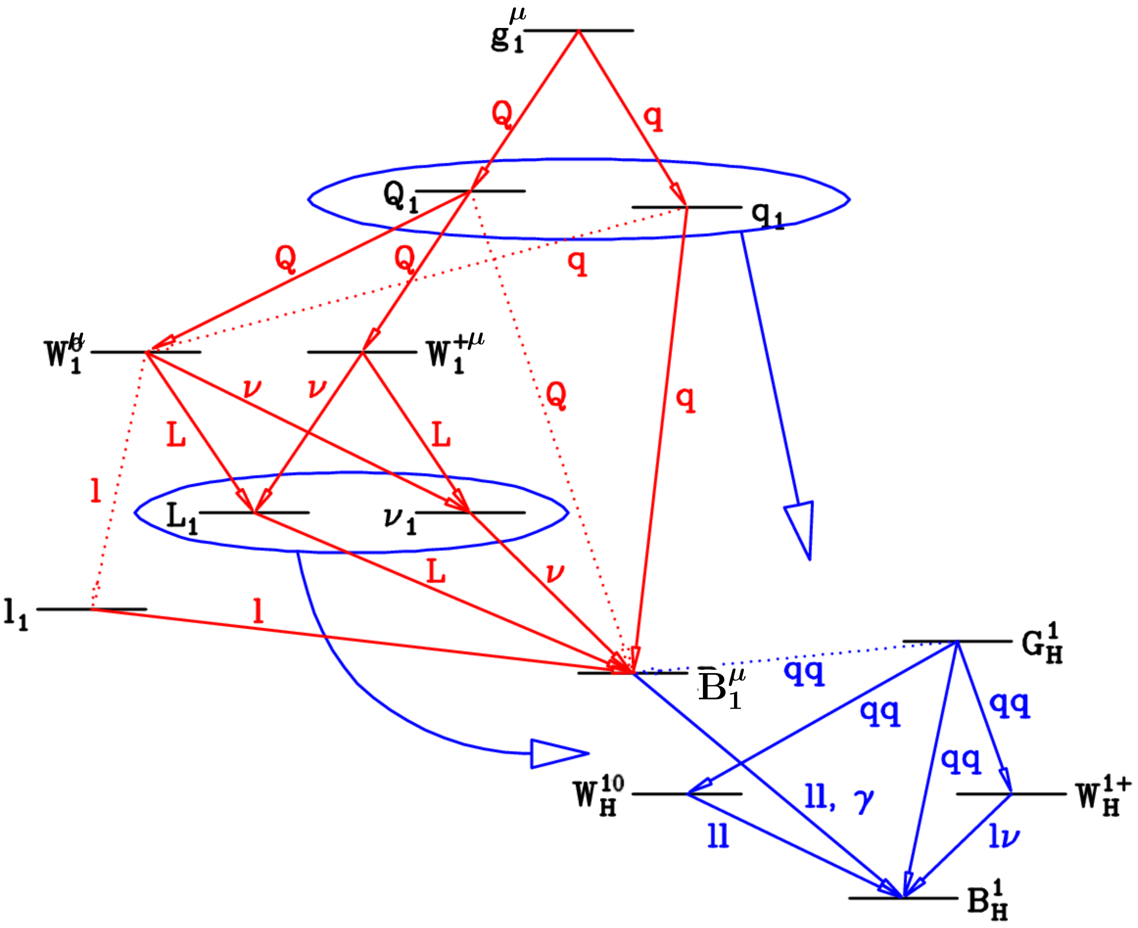
Dobrescu, Hooper, Kong, Mahbubani '07

All other level (1,0) particles decay into $B_H^{(1,0)}$

Decay channels with hadrons often dominant

KK-Leptons and KK-W-bosons have large decay fractions with leptons

$B_\mu^{(1,0)}$ can decay via a loop:
$B_\mu^{(1,0)} \to B_H^{(1,0)} + \gamma$

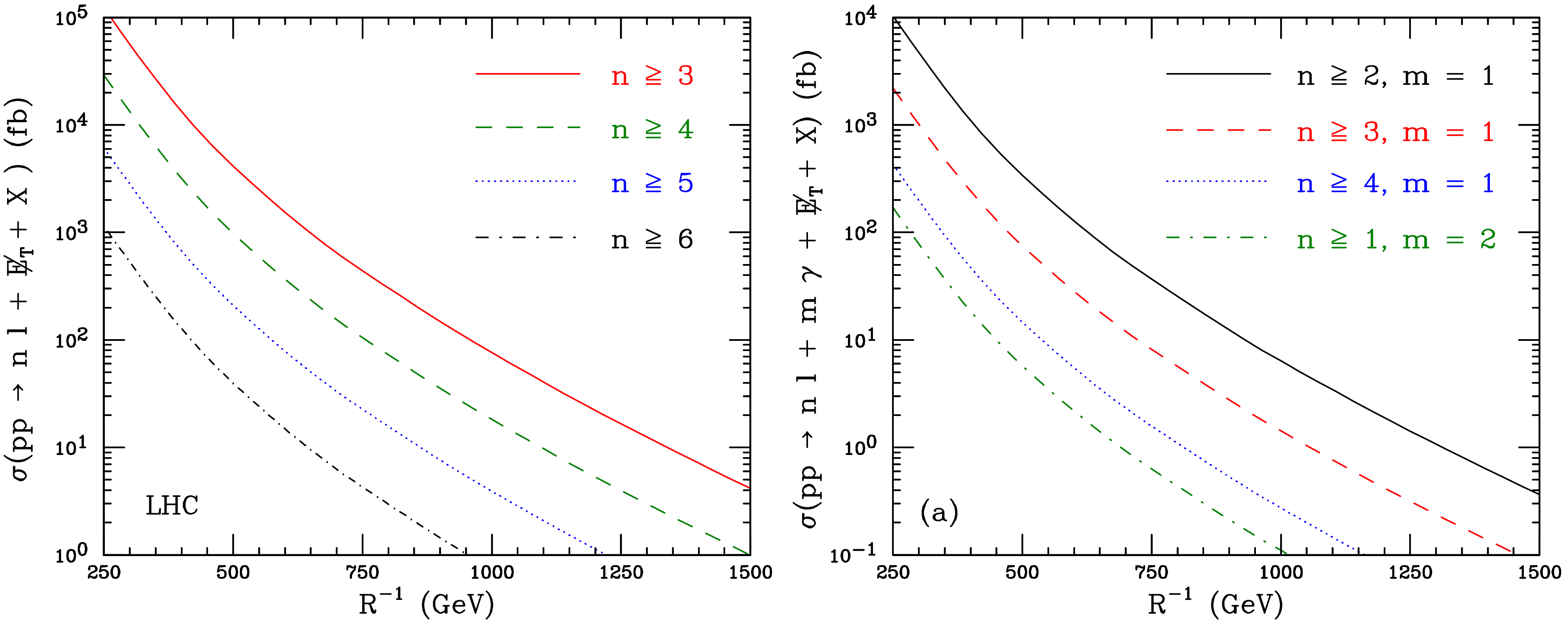


Signals at LHC

Dobrescu, Kong, Mahbubani '07

Production of level (1,0) particles can lead to distinct signal with many **leptons** and **photons**:

$pp \rightarrow n\,l + m\,\gamma + \not{E}_T + X$, X = hadrons (jets)

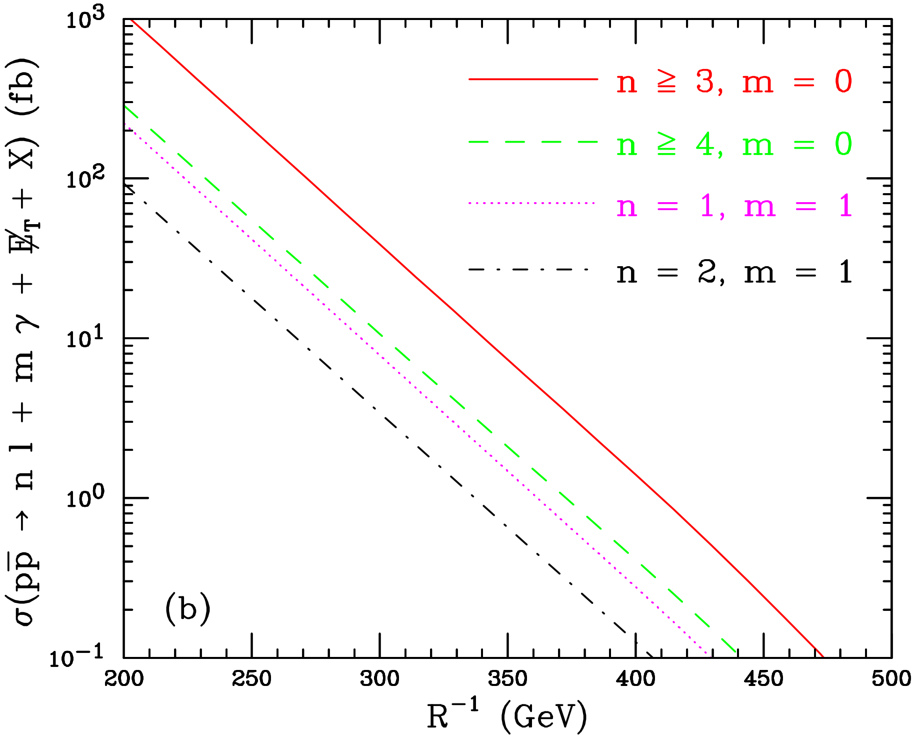


Several 100-1000 events observables in multi-lepton or lepton+photon channels for $R^{-1} \lesssim 1000$ GeV, with small SM backgrounds

Signals at the Tevatron

Dobrescu, Kong, Mahbubani ’07

Cross-section are lower and allow sensitivity only for small R^{-1}



Searches in $3l$ and $l + \gamma$ channels
give constraint $R^{-1} \lesssim 270$ GeV

CDF, D0 ’07

Spin determination at an e^+e^- collider

Special feature of Standard Model with two extra dimensions: dark matter candidate $B_H^{(1,0)}$ is a **scalar**

In SM with one extra dimension: $B_\mu^{(1,0)}$ (**vector**)

Supersymmetry: $\tilde{\chi}_1^0$ (**fermion**)

Ideal environment for this task is a 1 TeV e^+e^- collider (**ILC**)

Spin determination at an e^+e^- collider

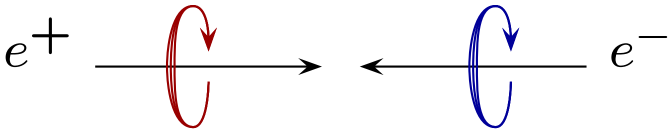
Freitas, Kong '07

Study production of KK-excitations of right-handed electrons, $e_R^{(1,0)}$

For comparison:

6DSM:	$e^+e^- \to e_R^{(1,0)+} e_R^{(1,0)-}$	$e_R^{(1,0)\pm} \to e^\pm B_H^{(1,0)}$
5DSM:	$e^+e^- \to e_R^{1+} e_R^{1-}$	$e_R^{1\pm} \to e^\pm B_\mu^1$
SUSY:	$e^+e^- \to \tilde{e}_R^+ \tilde{e}_R^-$	$\tilde{e}_R^\pm \to e^\pm \tilde{\chi}_1^0$

Make use of polarized beams: create spin-1 state



Coupling structure:

6DSM: $e_R^{(1,0)-} \to e^- B_H^{(1,0)}$ procudes right-handed e^-

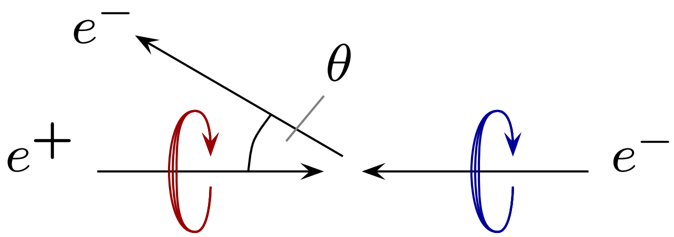
$\Rightarrow$ e^- go in **forward** direction

5DSM: $e_R^{(1,0)-} \to e^- B_\mu^1$ procudes left-handed e^-

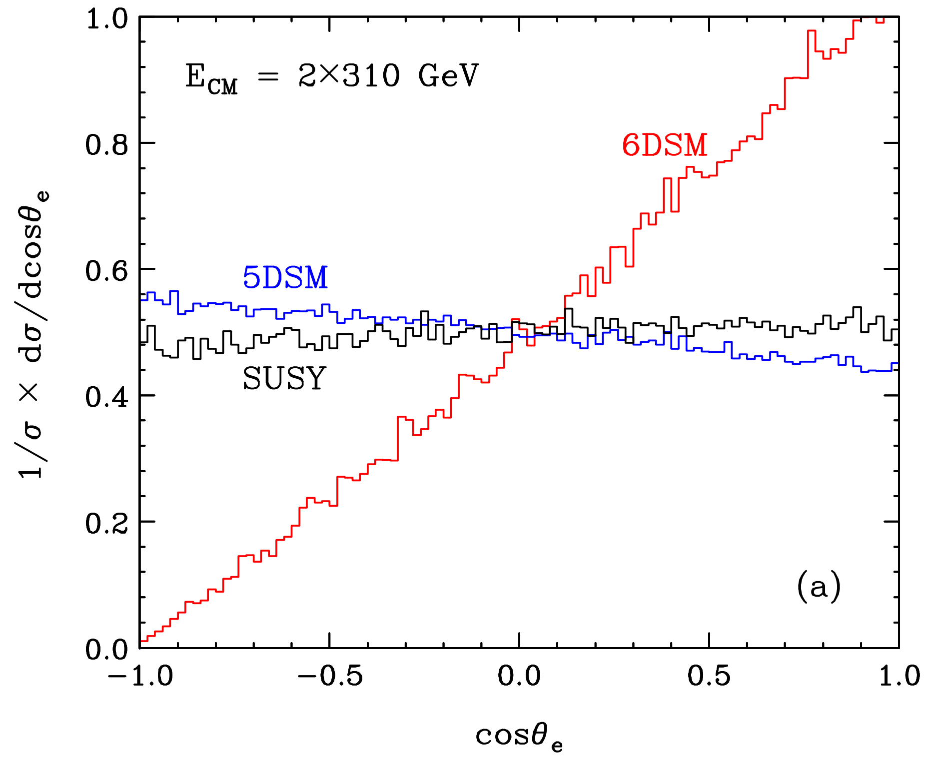
$\Rightarrow$ e^- go in **backward** direction

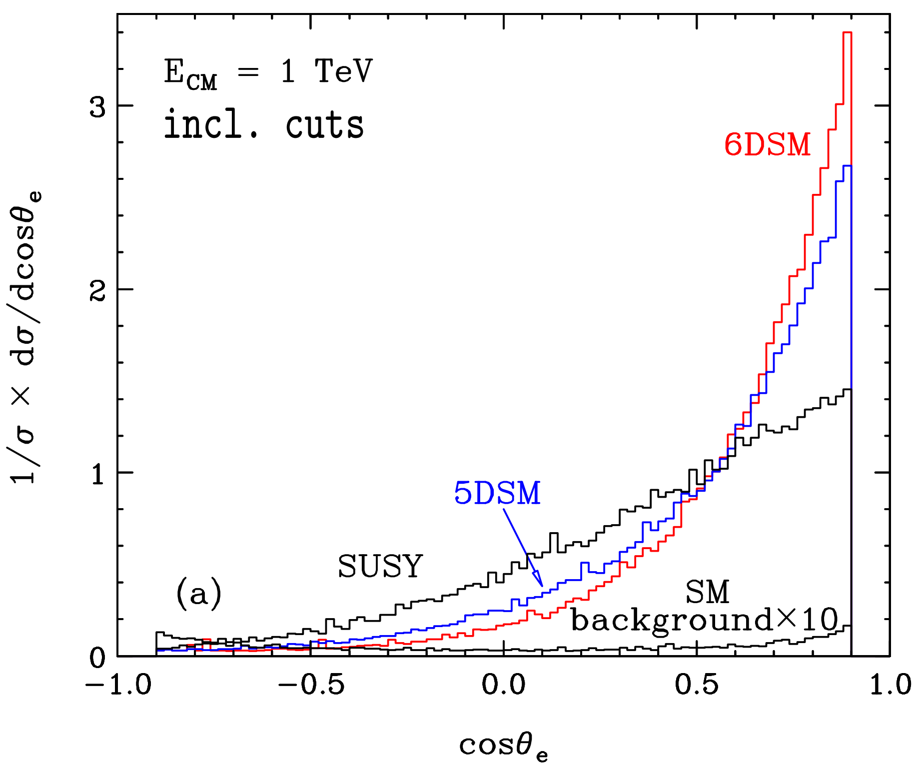
Spin determination at an e^+e^- collider

Freitas, Kong '07



$$m_{B_H^{(1,0)}} = m_{B_\mu^1} = m_{\tilde{\chi}_1^0} = 256.6 \text{ GeV}$$
$$m_{e_R^{(1,0)}} = m_{e_R^1} = m_{\tilde{e}} = 304.5 \text{ GeV}$$



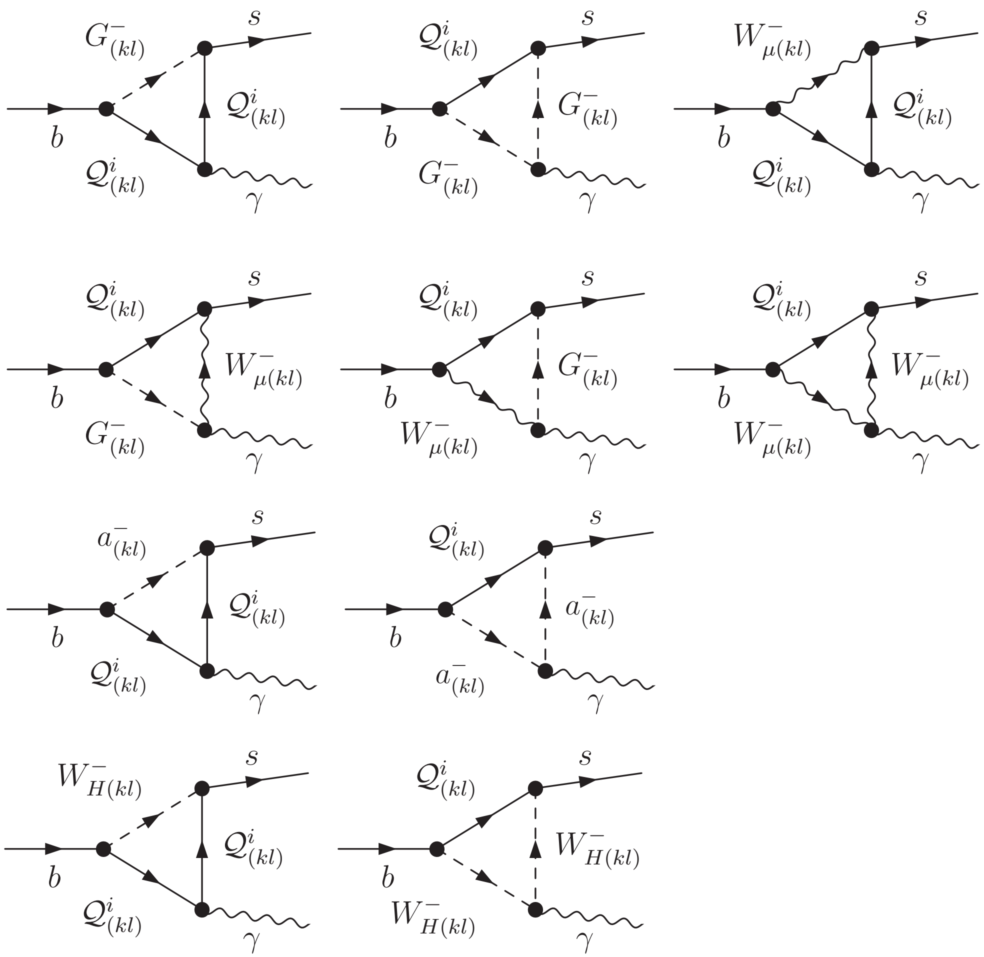


Clear distinction possible only 2–20 fb^{-1} of luminosity sufficient to distinguish spins (depending on cross-section)

Constraints from $B \to s\gamma$

Freitas, Haisch '08

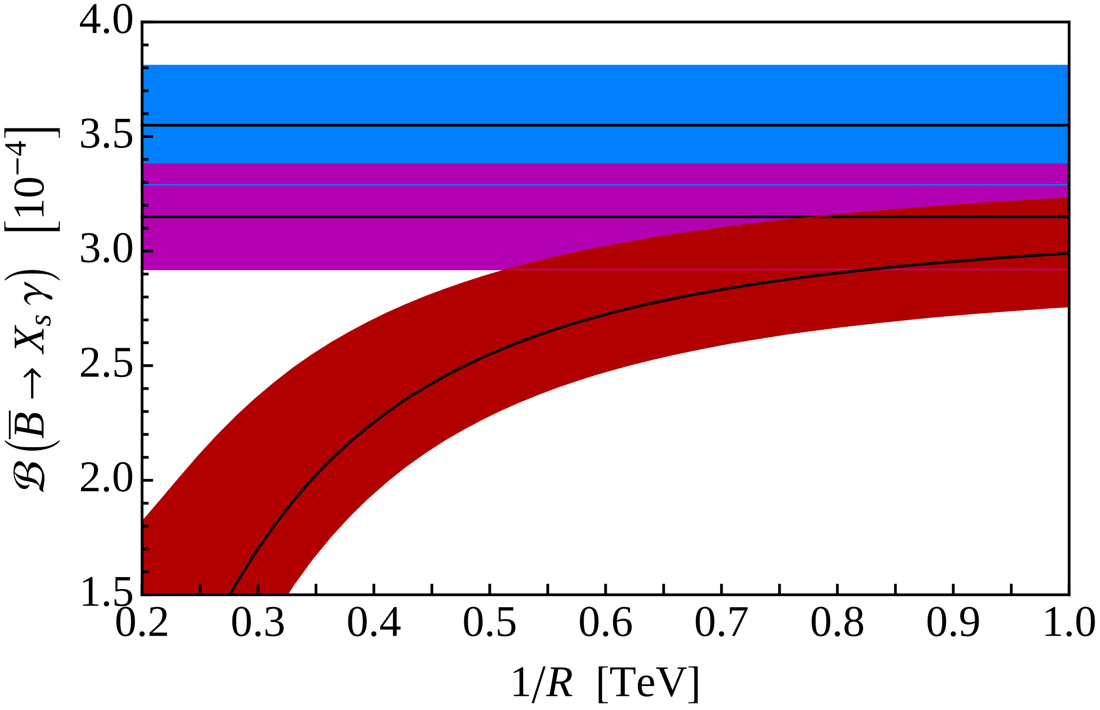
Assume **"minimal flavor violation"**,
i.e. no sources of flavor violation from high-scale physics



- Need to sum over KK-levels (k,l) in loop
- Sum does not converge for $k,l \to \infty$
- Introduce cutoff $k+l < N_{\text{KK}} = \Lambda\, R^{-1}$
- Vary $N_{\text{KK}} \in [5, 15]$ to parameterize uncertainty
- Same for mass corrections from localized operators

Constraints from $B \to s\gamma$

Freitas, Haisch '08



Experimental measurement:
$(3.55 \pm 0.24^{+0.09}_{-0.10} \pm 0.03) \times 10^{-4}$

SM prediction with NNLO QCD corr.:
$(3.15 \pm 0.23) \times 10^{-4}$

Result in 6DSM with theory uncertainty

Strong constraint $R^{-1} > 650$ GeV at 95% CL

→ Conflict with preferred parameter region from cosmological dark matter density ($R^{-1} < 600$ GeV)

UV operators

Models with extra dimensions break down at a high scale:

- Loops corrections to infinitely many operators are divergent (not renormalizable)
- Sum over KK modes is divergent for $D \gtrsim 6$
- 6D gauge couplings become strong for large energies

Theory only valid up to some cutoff scale Λ
$\longrightarrow$ Unkown new physics enters

Could generate observable effects at low energies, suppressed by Λ, but still important:

- Mass shifts of KK modes
- Flavor changing effects, *e.g.* to $B \to s\gamma$
  $\longrightarrow$ Would overwhelm SM contribution by factor **∼50**

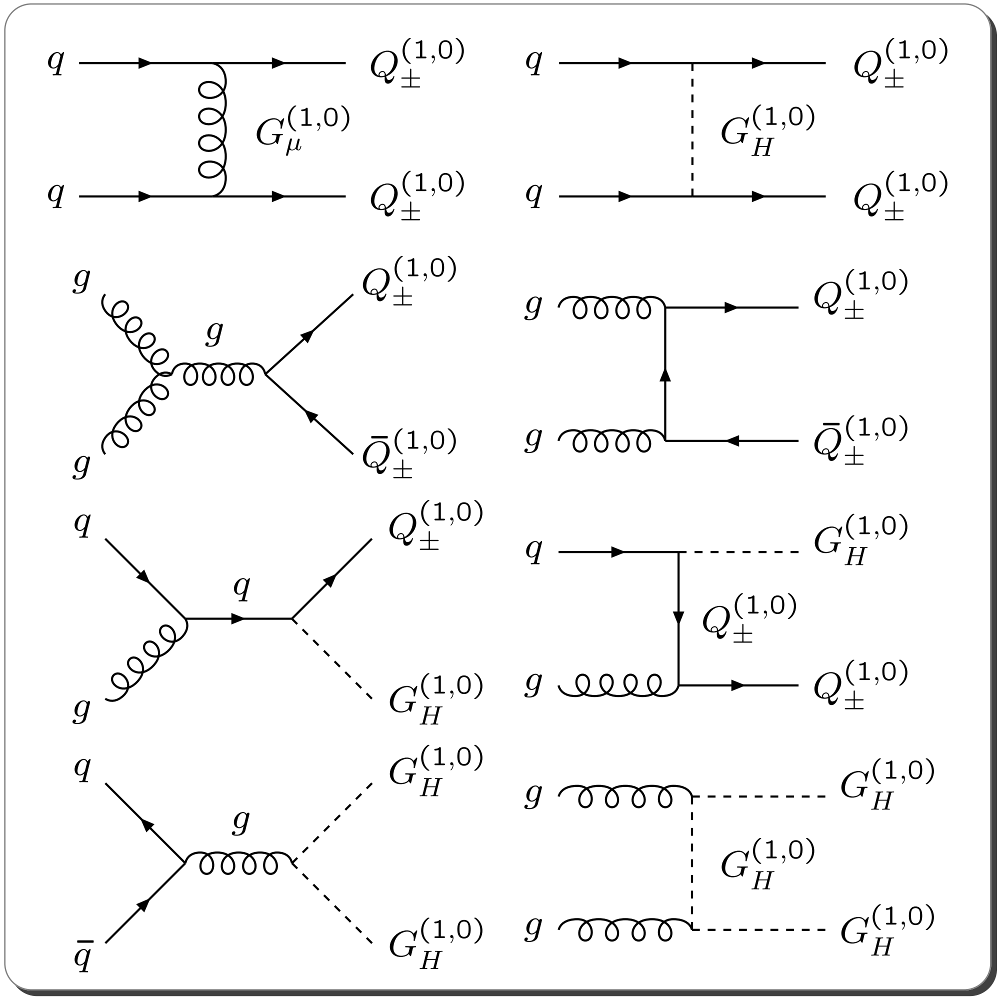
Conclusions

- Theories with universal extra dimensions provide a simple framework to extend the Standard Model into additional space dimensions
- Compactification of two extra dimensions on the "chiral square" reproduces the 4D Standard Model as a low-energy theory
- New particles within reach of the LHC/TeVLC are predicted, with distinct signatures and a rich phenomenology
- Explanation for dark matter, but in (moderate) disagreement with constraints from flavor physics
- The completion of the model with viable high-scale dynamics remains an unsolved theoretical problem

Production at LHC

Dobrescu, Kong, Mahbubani '07

- Large rates for KK-quark, KK-gluon and scalar KK-gluon production
- Expect between 1000 and 10^6 for 100 fb^{-1} luminosity for 500 $\lesssim R^{-1} \lesssim$ 1500 GeV
- Cascade decays via KK-W-bosons and KK-Leptons
- $B_H^{(1,0)}$ is stable and weakly interacting:
  escapes detector undetected as missing momentum



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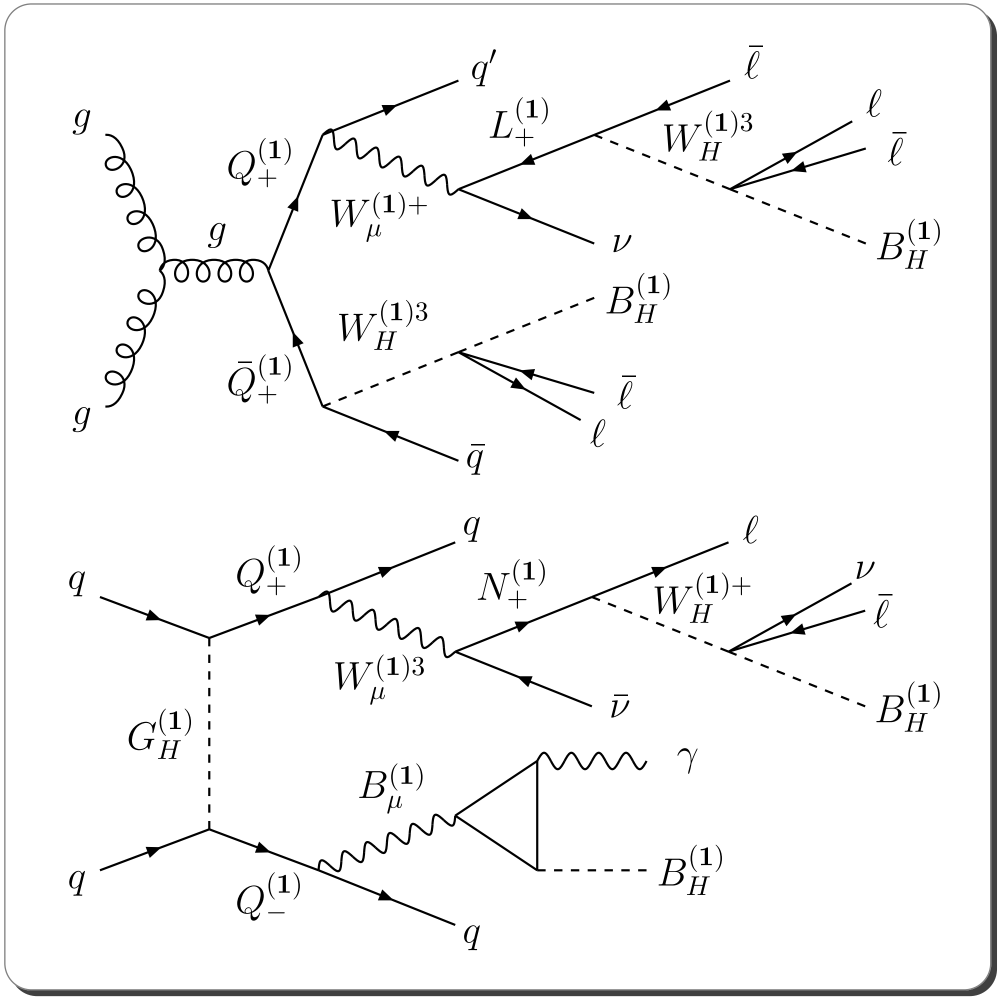

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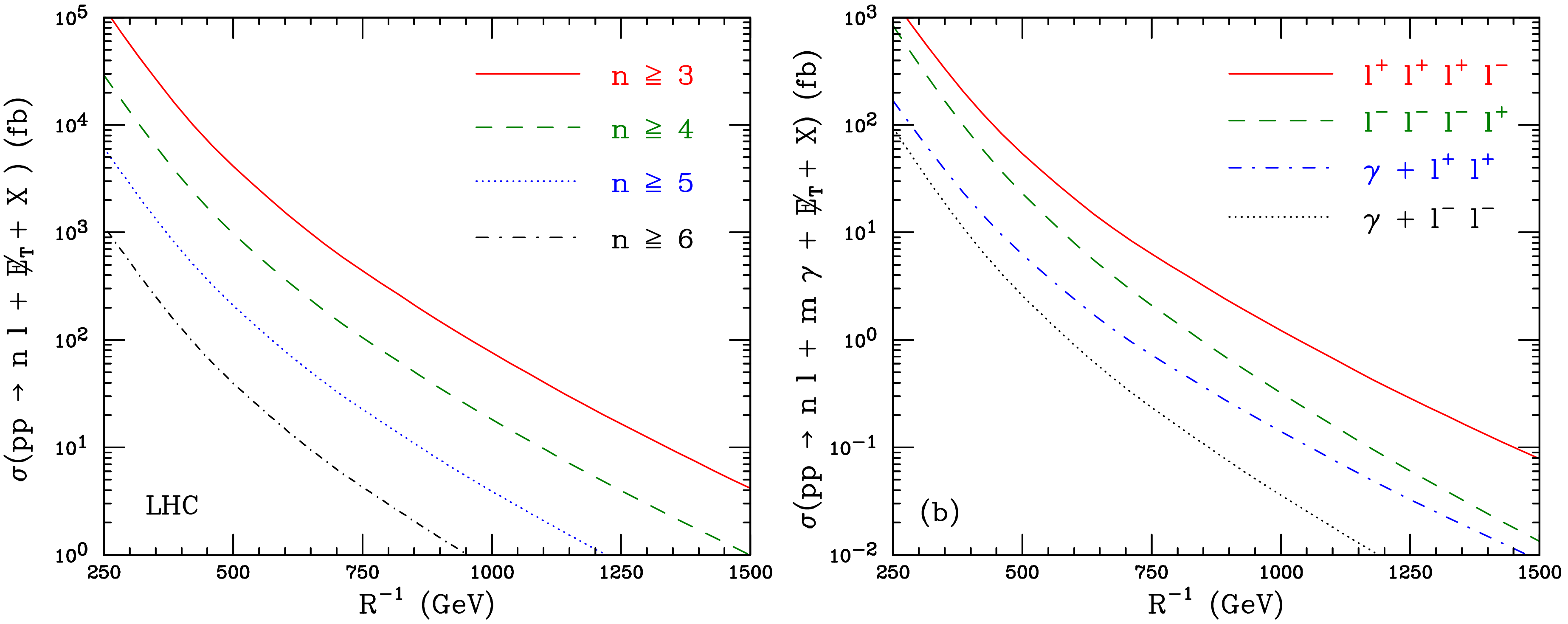

Several 100-1000 events observables in multi-lepton or lepton+photon channels for $R^{-1} \lesssim 1000$ GeV, with small SM backgrounds

Dark matter

Dobrescu, Hooper, Kong, Mahbubani ’07

Lightest KK-parity-odd particle $B_H^{(1,0)}$ is **stable** and **weakly interacting**

→ Can be source of dark matter in universe

Compare measured dark matter relic density with model prediction:

Depends on how fast $B_H^{(1,0)}$ particles annihilated in early universe