

# Discovery and identification of universal extra dimensions at colliders

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- 1. Introduction to universal extra dimensions (UED)**
- 2. UED constraints from precision observables**
- 3. UED collider phenomenology**

# Introduction to universal extra dimensions

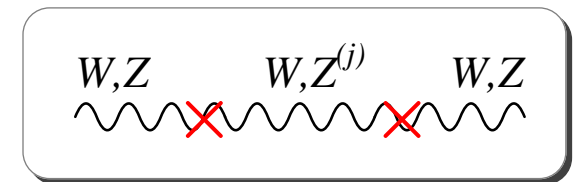
## Constraints on TeV-scale extra dimensions

Antoniadis '90

Confinement of Higgs or fermion fields on boundary induces tree-level interactions with KK modes

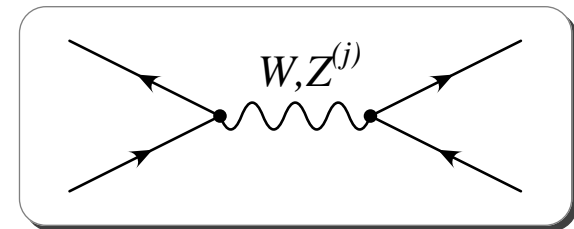
- **Higgs on boundary:**

Mixing between SM gauge bosons and their KK excitations



- **Fermions on boundary:**

KK exchange in 4-fermion interactions



→ Strong constraints from electroweak precision data

Delgado, Pomarol, Quiros '99

$R^{-1} > 2...5 \text{ TeV}$  (depending on choice of boundary-localized fields)

- Geometry of extra dimension is flat
- All SM fields propagate in the extra dimension

Remnant of Lorentz inv in 5th dim.: **KK-number  $j$  is conserved**

→ Constraint on allowed vertices:

$$\int_0^{2\pi R} dx_4 \Phi_j \Phi_k \Phi_l \neq 0 \quad \text{only for } j \pm k \pm l = 0$$

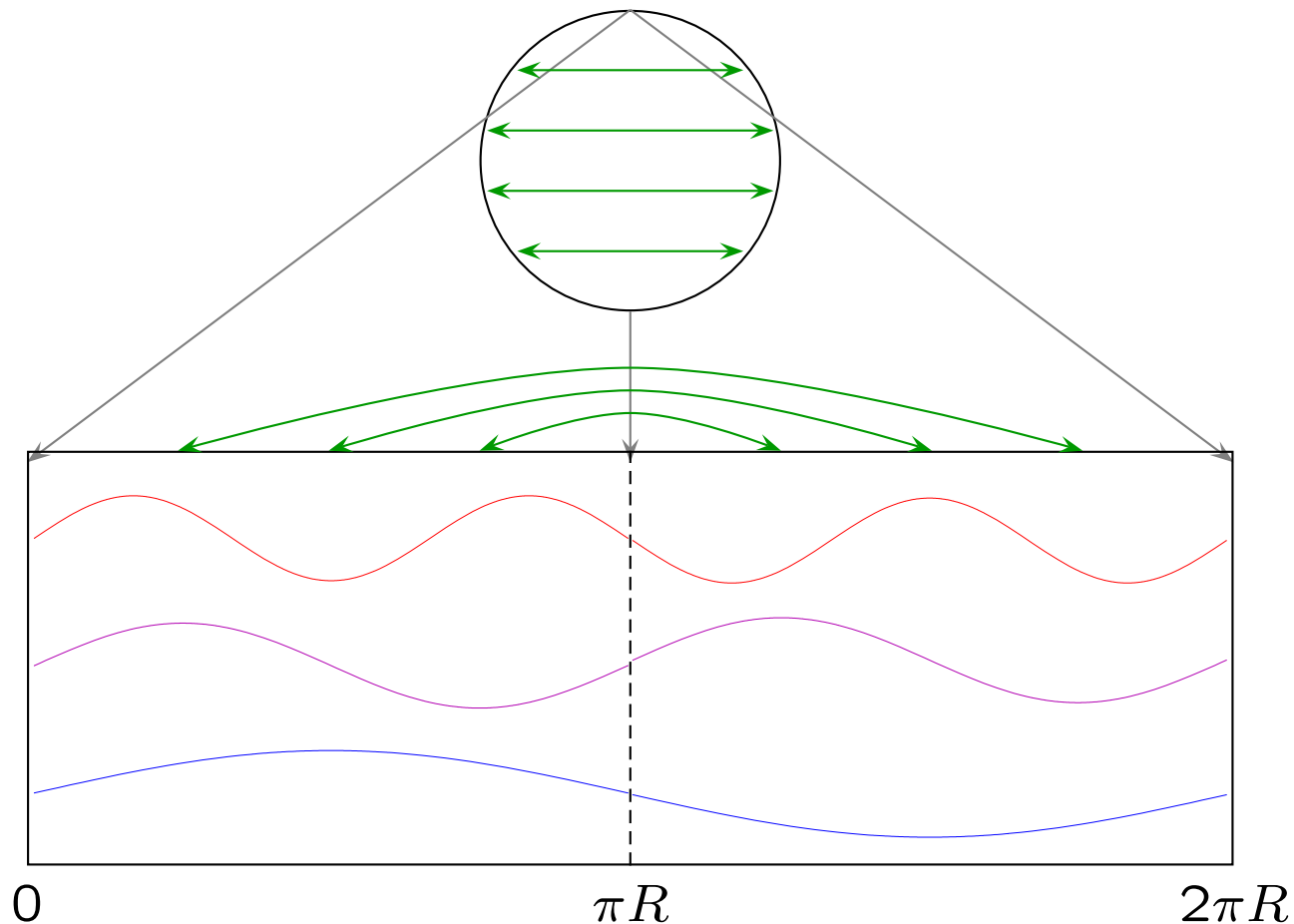
→ No tree-level contributions to precision observables

## Orbifolding

**Problem:** 5D Lorentz invariance does not allow **chiral fermions**

→ Need additional breaking in compactification

**Orbifolding:** Symmetry under mirror transformation along special brane



Fields can be even/  
odd under orbifold  
transformation

Odd fields have **no  
zero mode**

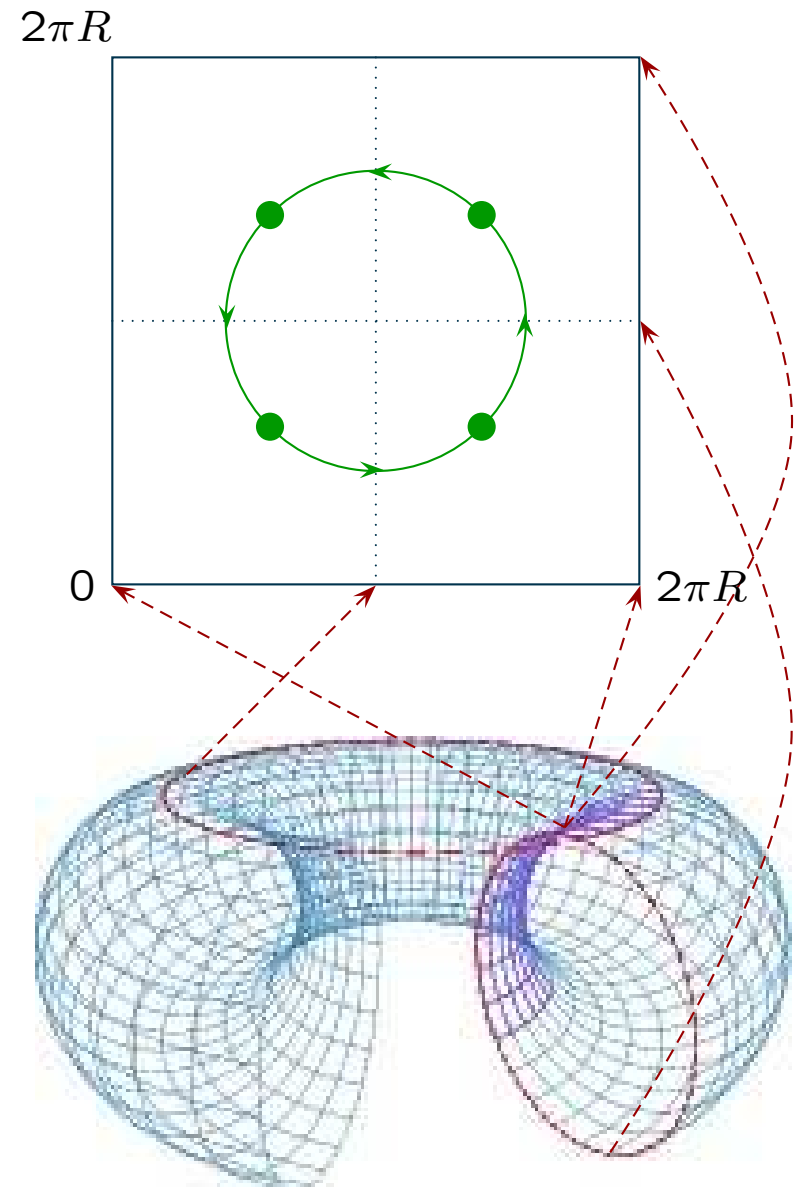
→ Chiral fermions  
at low energies

# Two universal extra dimensions

Dobrescu, Ponton '04

Several compactifications possible

Simple choice: Torus with discrete  $90^\circ$  rotational symmetry ( $T_2/Z_4$ )

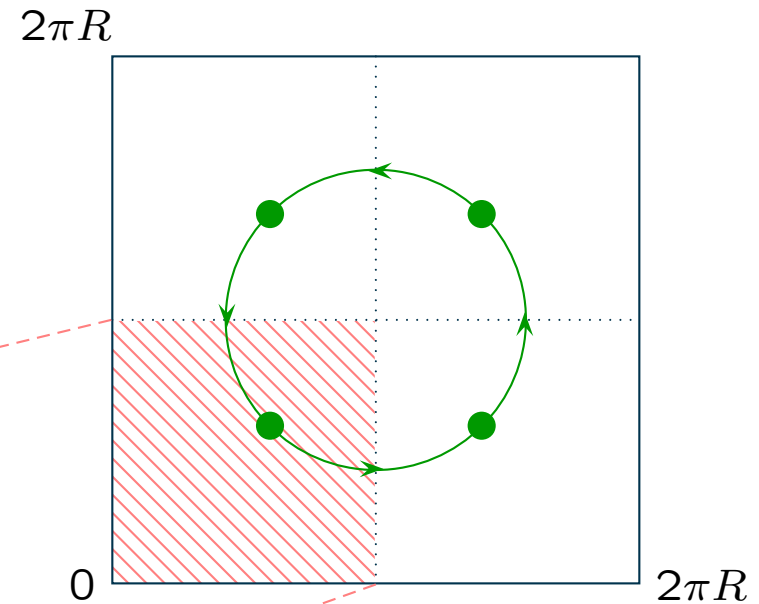
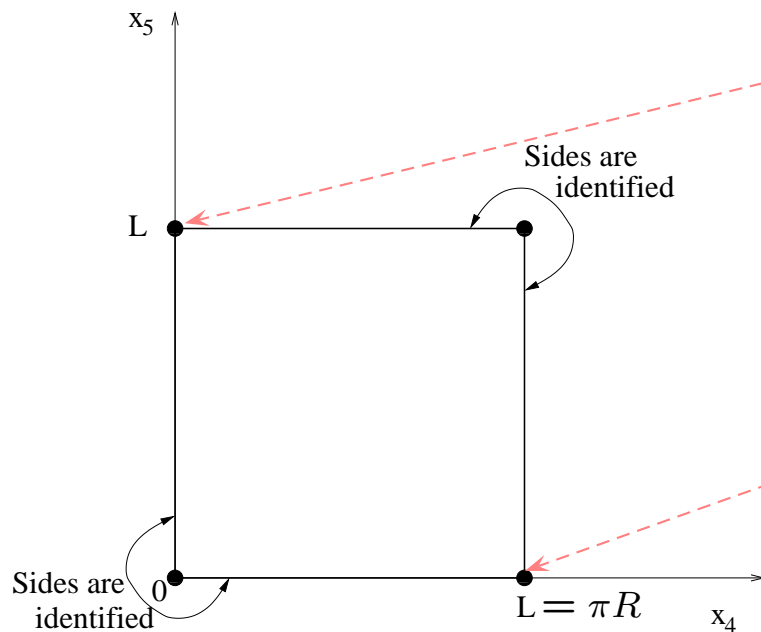


# Two universal extra dimensions

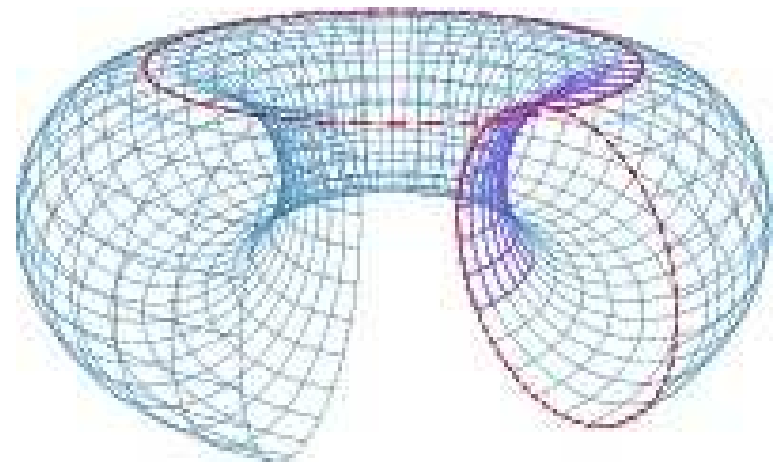
Dobrescu, Ponton '04

Several compactifications possible

Simple choice: Torus with discrete  $90^\circ$  rotational symmetry ( $T_2/Z_4$ )



Topologically equivalent to square with adjacent sides identified (**chiral square**)



## KK-parity and dark matter

Orbifolding breaks Lorentz invariance in extra dimension

→ KK-number is violated

→ But **KK-parity** remains as sub-symmetry:

KK-number even → KK-parity +1

KK-number odd → KK-parity -1

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

→ Good candidate for **dark matter**

## Particle content

- Each SM particle has a tower of KK excitations, with one **KK-number**  $j, k, \dots$  for each extra dimension and tree-level masses  $M_{(j,k,\dots)}^2 = (j^2 + k^2 + \dots)/R^2$
- KK fermions are vector fermions (except for zero modes)

- Each gauge boson has  $D$  components  $A_\mu, \mu = 0, \dots, D$

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

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

The remaining components form a new adjoint scalars  $A_H^{(j,k,\dots)}$

$D = 5$ : no extra scalar

$D = 6$ : one extra scalar

...

# Mass spectrum

Radiative corrections generate mass shifts, lifting degeneracy among one KK-level

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

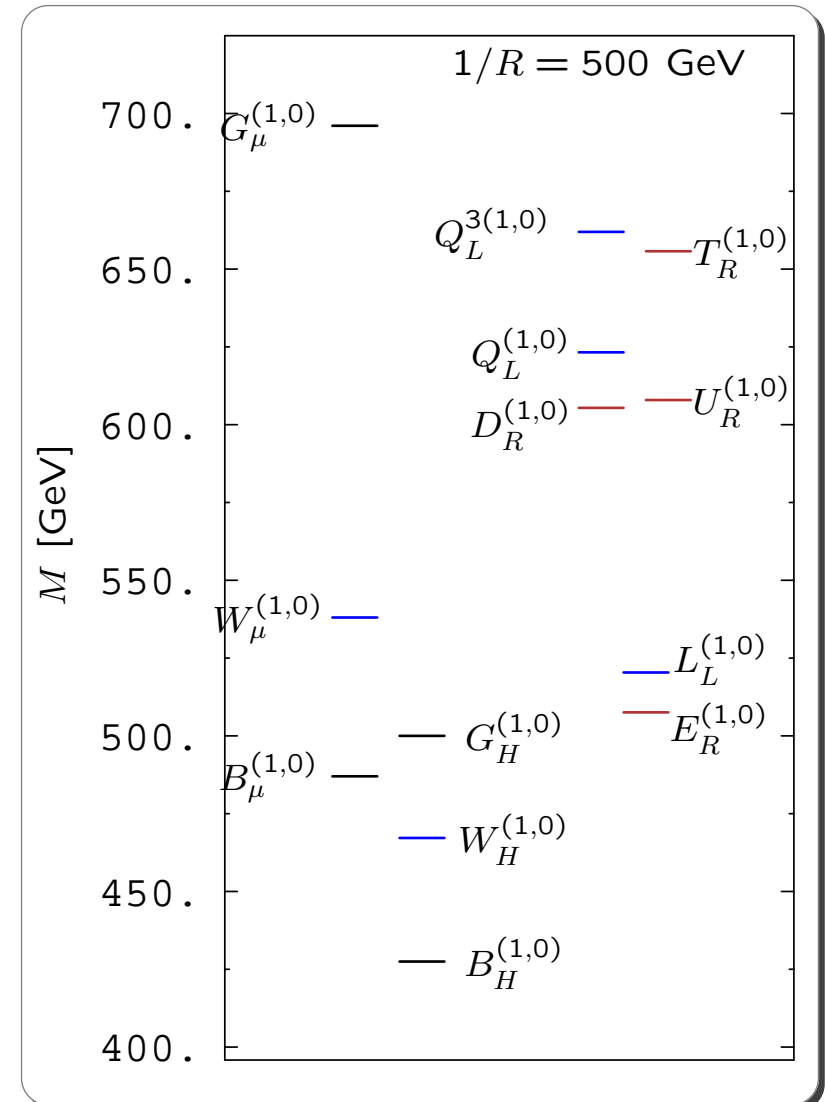
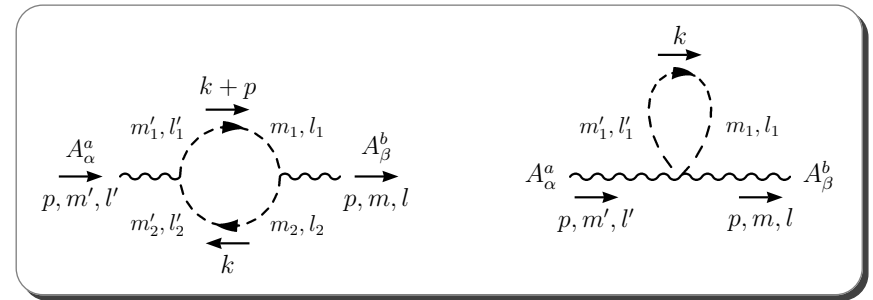
Sum over KK modes in loop **diverges**  
→ Need cut-off energy scale  $\Lambda$

General form:

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

Estimate  $\Lambda \approx 10/R$

(couplings become strong)



# Decays

Conservation of K-parity: **lightest K-odd particle (LKP) is stable**

$D = 5$ : KK hypercharge boson  $B_\mu^{(1)}$

$D = 6$ : KK hypercharge adjoint scalar  $B_H^{(1,0)}$

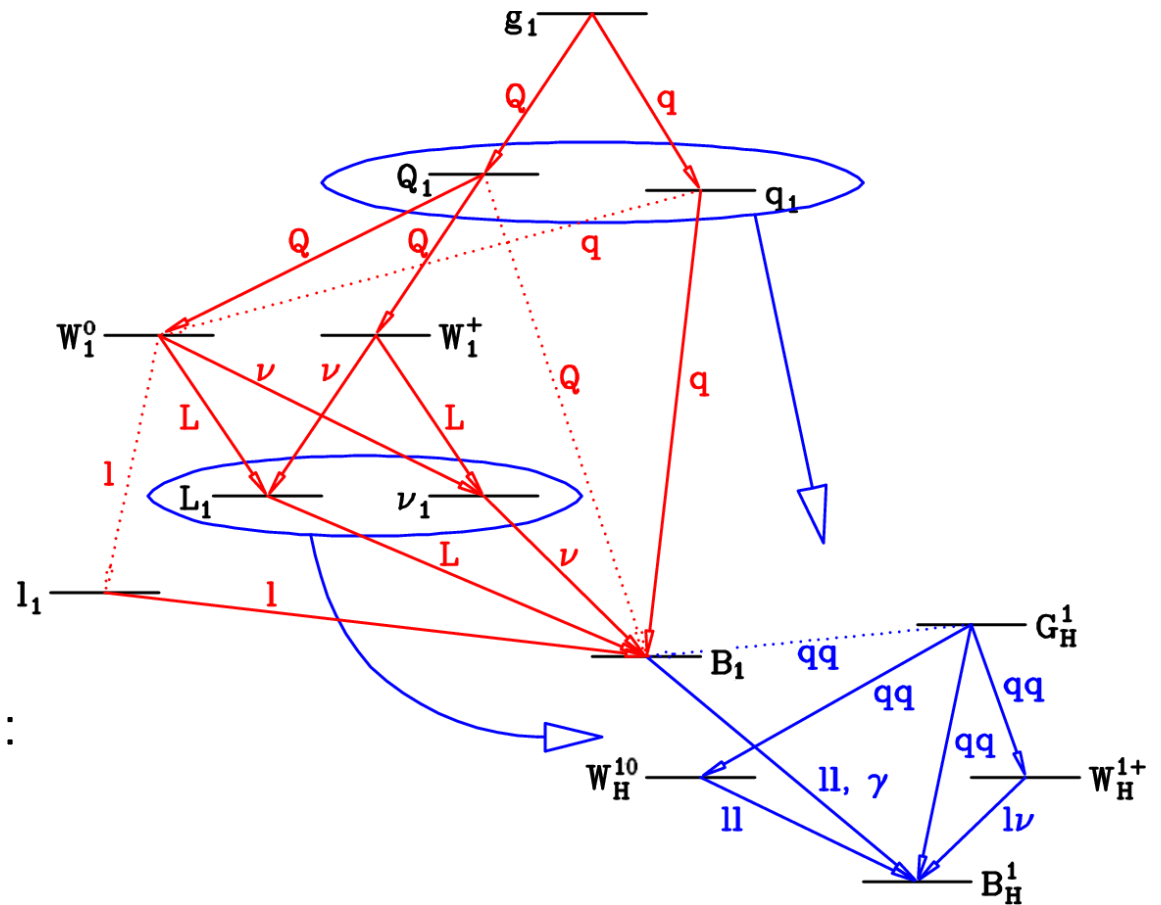
All other level-1 particles decay into LKP

Decay channels with hadrons often dominant

For  $D = 6$ :

The KK-gauge boson  $B_\mu^{(1,0)}$  can decay via a loop:

$$B_\mu^{(1,0)} \rightarrow B_H^{(1,0)} + \gamma$$



# Dark matter relic density

Compare measured dark matter relic density with model prediction:  
Requires calculation of annihilation rate in early universe

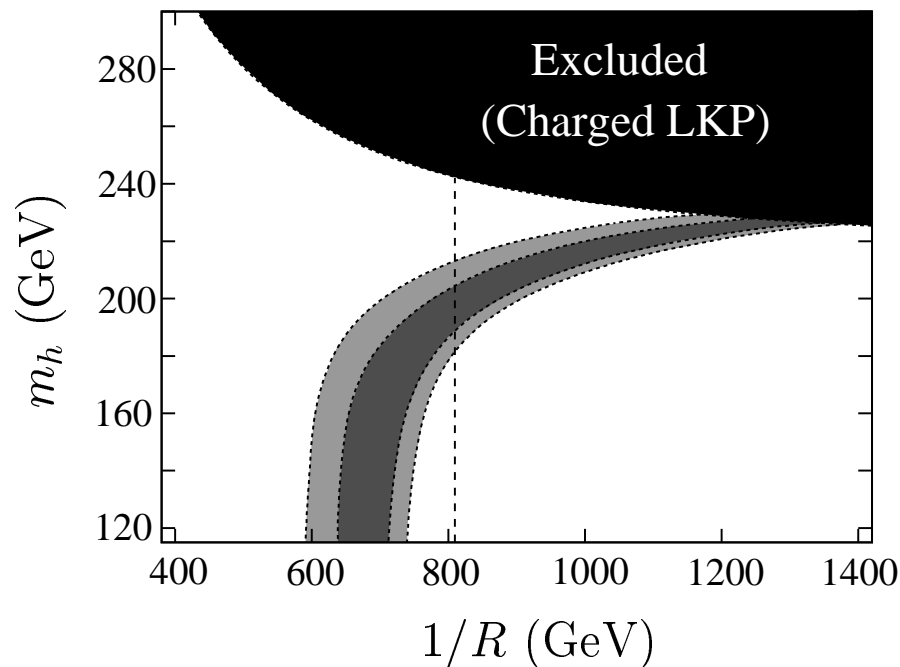
$D = 5$ :

$$B_{\mu}^{(1)} B_{\mu}^{(1)} \rightarrow \text{SM}$$

Servant, Tait '02

Kong, Matchev '05

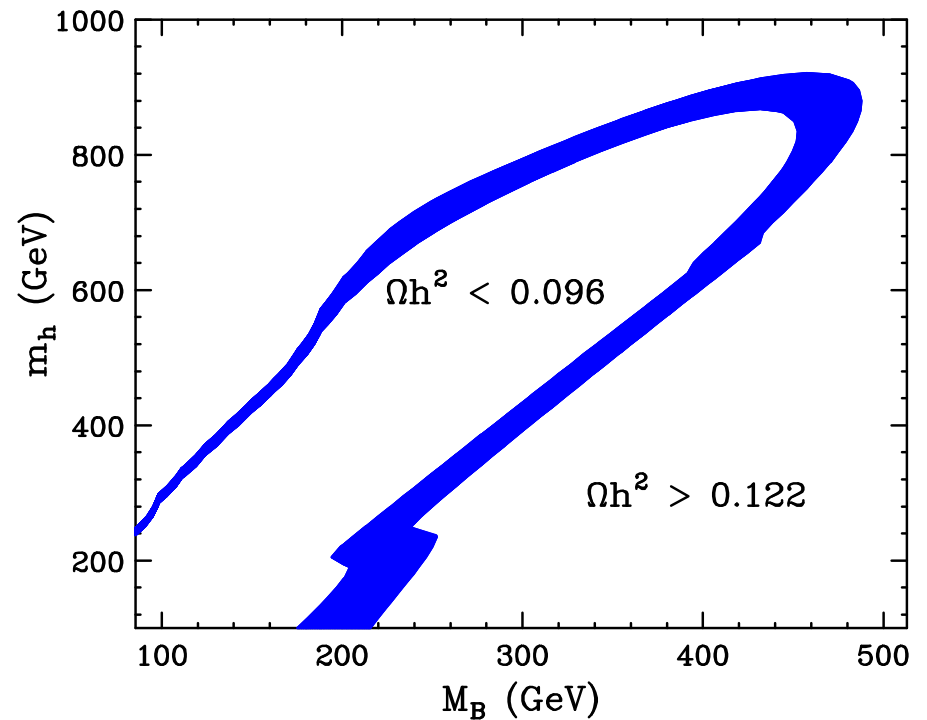
Kakizaki, Matsumoto, Senami '06



$D = 6$ :

$$B_H^{(1,0)} B_H^{(1,0)} \rightarrow \text{SM}$$

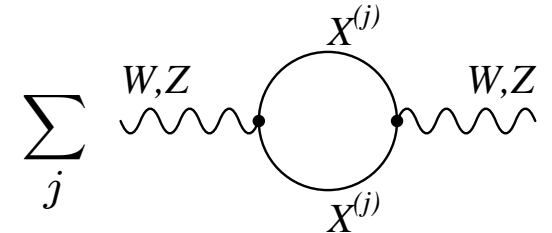
Dobrescu, Hooper, Kong, Mahbubani '07



# UED constraints from precision observables

KK particles contribute to  $S, T, U$ -parameters at one-loop level

→ Need to sum over KK indices in loops

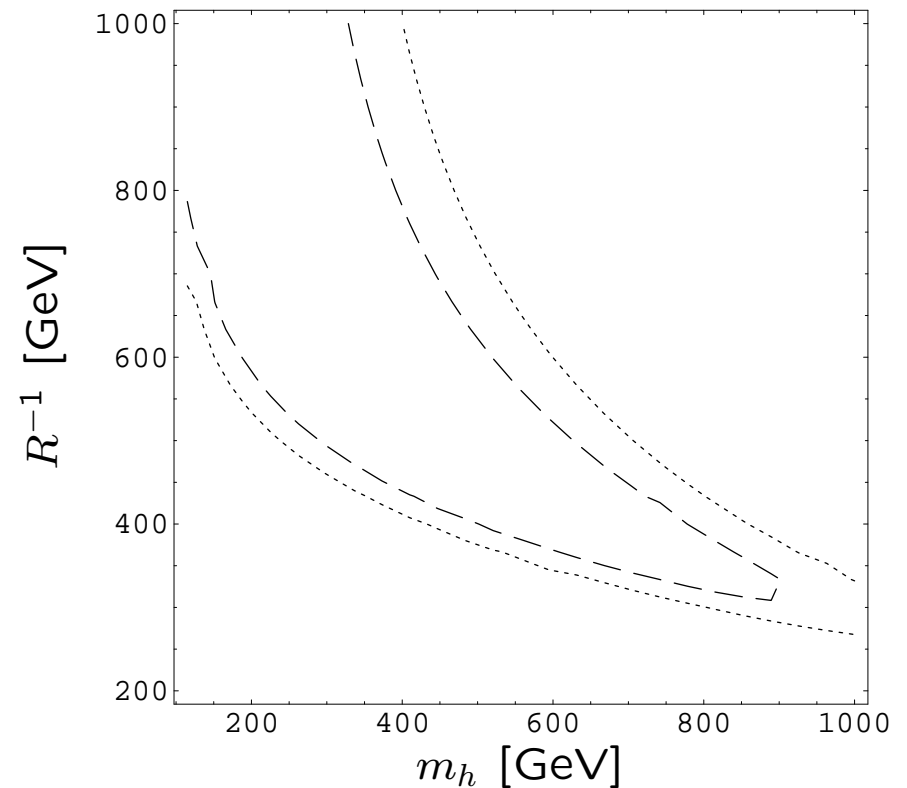


$D = 5$ :

- Sum converges fast
- Robust prediction for  $S, T, U$

Appelquist, Yee '02

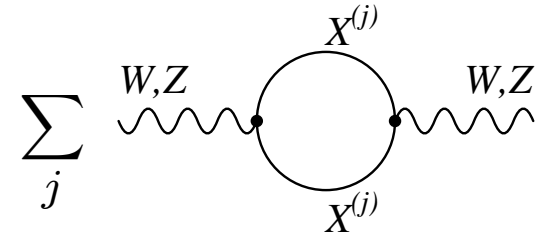
Flacke, Hooper, March-Russell '05



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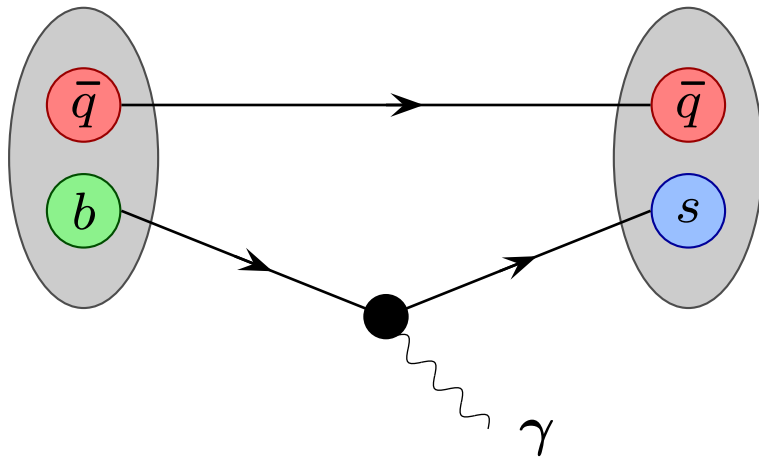
$D = 6$ :

- Sum over KK indices  $(j, k)$  does not converge
  - Introduce cutoff  $j + k < N_{\text{KK}} = \Lambda R^{-1}$
  - Vary  $N_{\text{KK}} \in [5, 15]$  to parameterize uncertainty
  - Same for mass corrections from localized operators
- Bound including this uncertainty:  $R^{-1} \gtrsim 250 \text{ GeV}$

# Constraints from rare decays of B-mesons

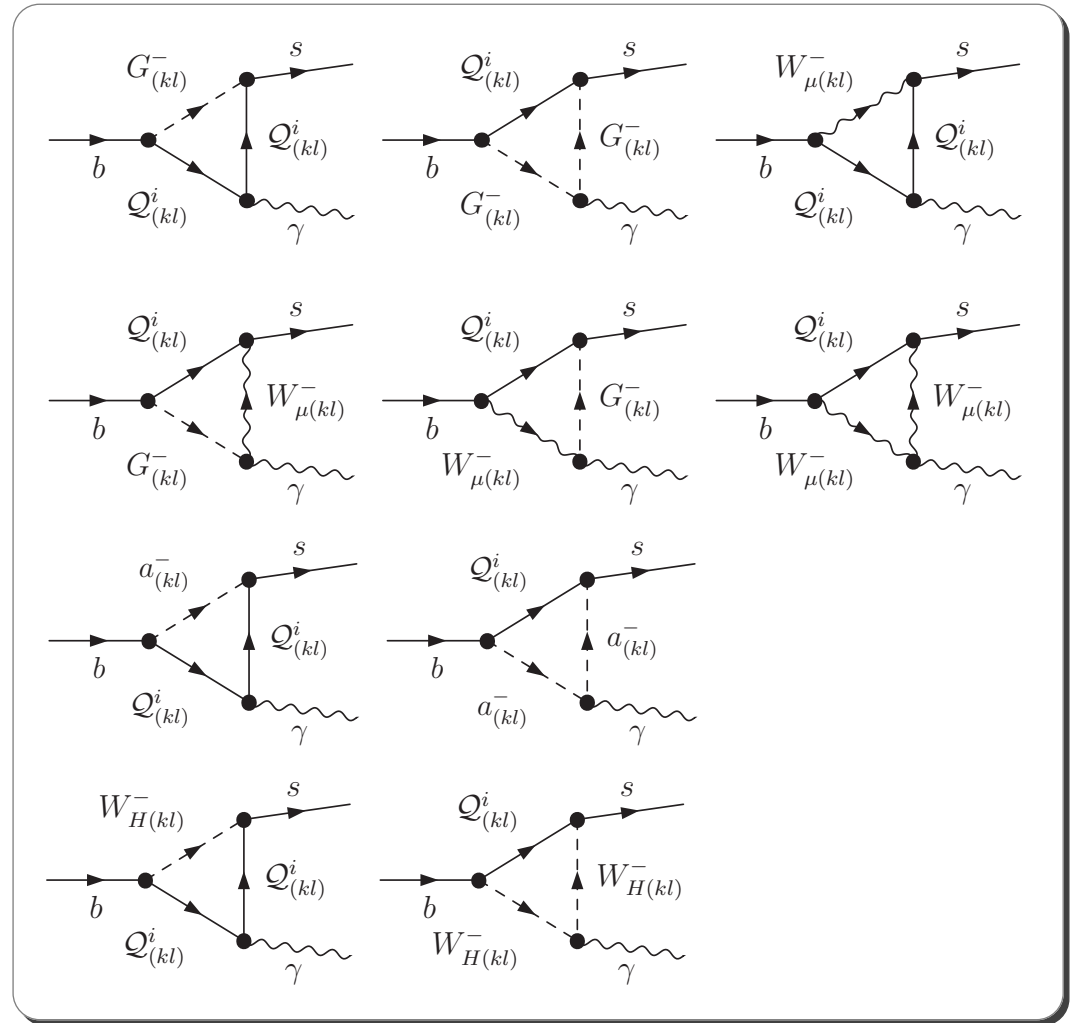
$$b \rightarrow s \gamma$$

Rare decay channel since  
b-quark changes to s-quark



Loop process in SM

→ Sensitive to new heavy particles



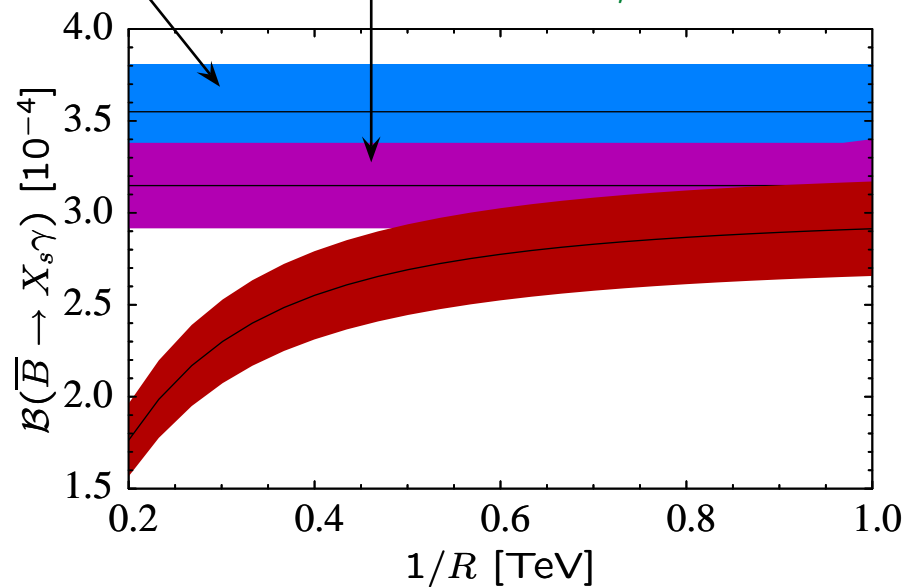
# Constraints from $B \rightarrow s\gamma$

$D = 5$ :

experimental  
result

SM prediction  
with NNLO QCD

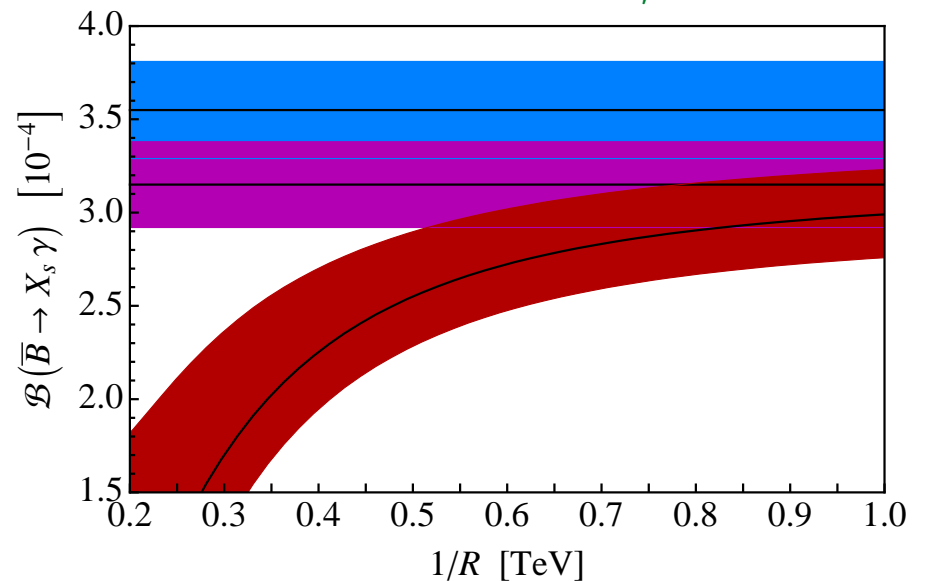
Haisch, Weiler '07



$D = 6$ :

Additional uncertainty from  
cutoff dependence

Freitas, Haisch '08



$R^{-1} > 600$  GeV at 95% CL

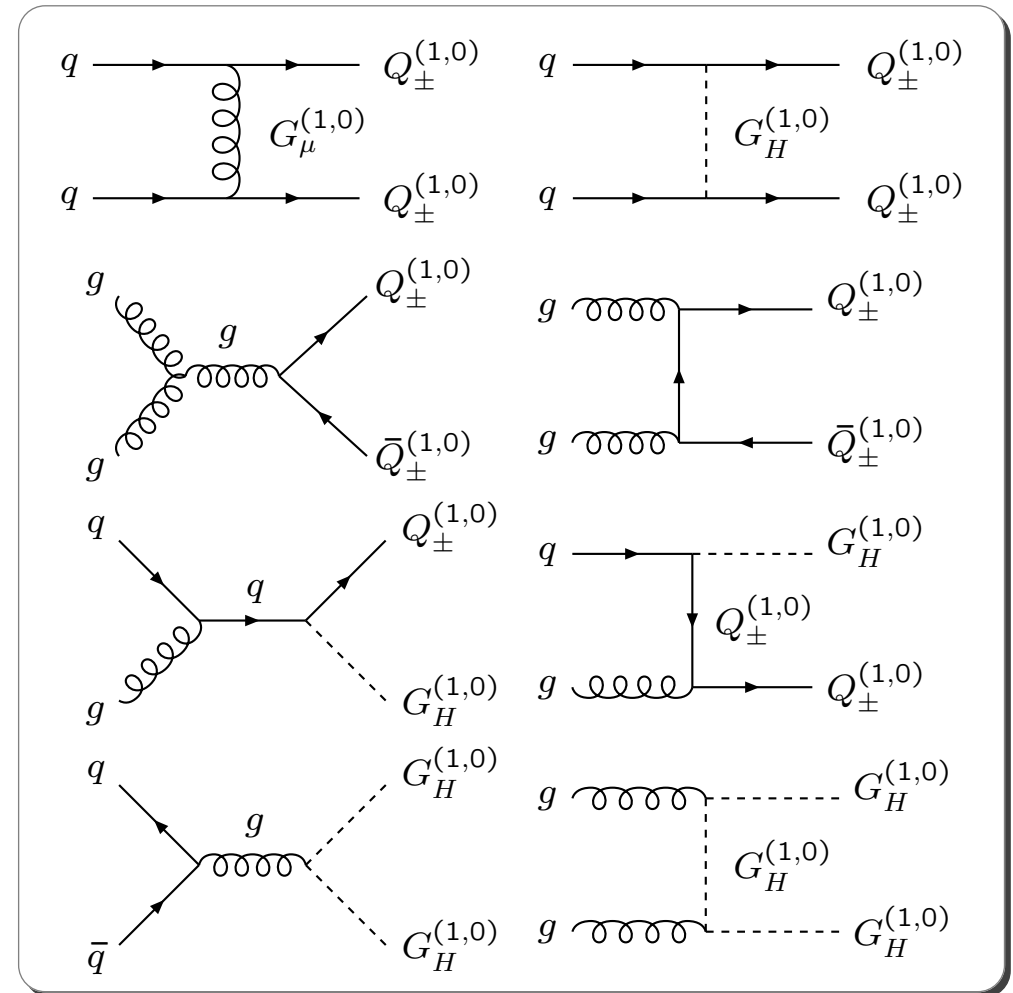
$R^{-1} > 650$  GeV at 95% CL

→ Conflict with preferred parameter region from cosmological dark matter density for  $D = 6$

# UED collider phenomenology

## Production at hadron colliders

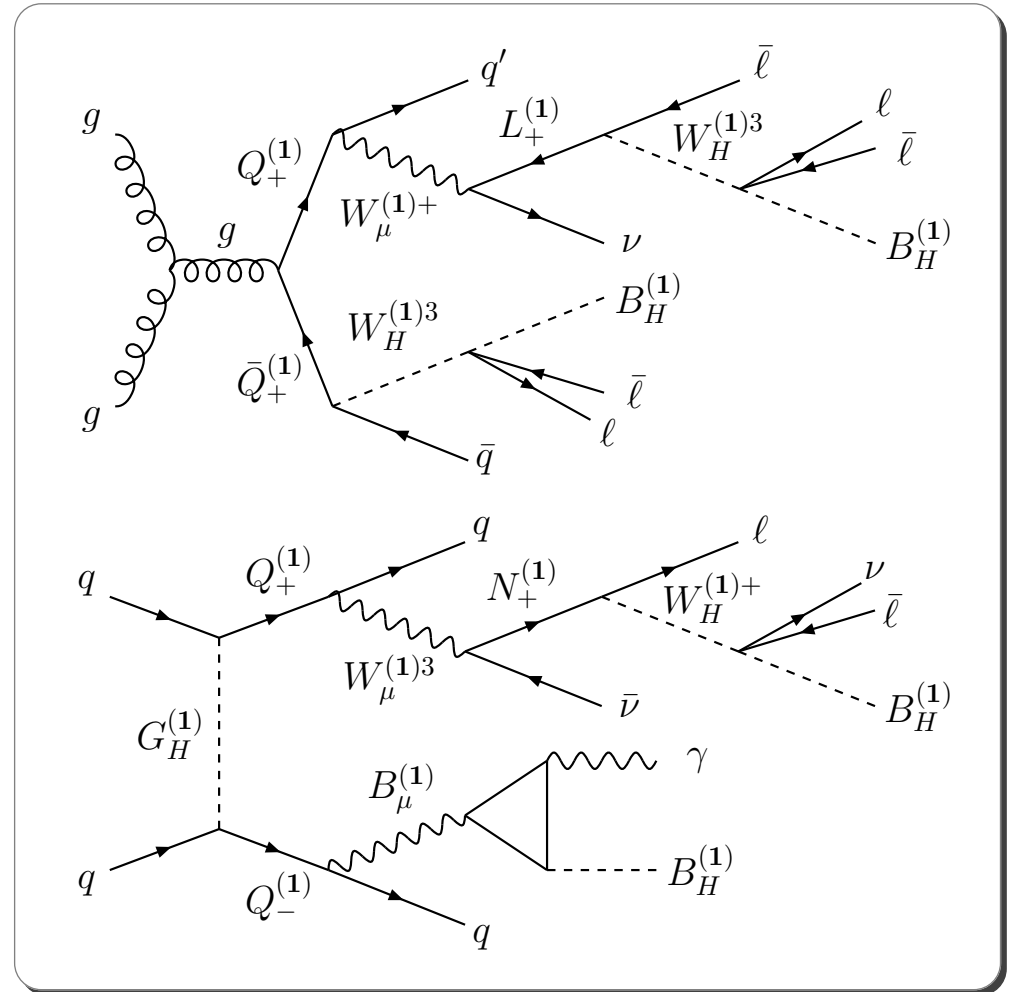
- Large rates for KK-quark and KK-gluon production
- For  $D = 6$  also scalar KK-gluon production
- Cascade decays via KK- $W$ -bosons and KK-Leptons
- LKP is stable and weakly interacting:  
escapes detector undetected  
as missing momentum
- Phenomenology similar to SUSY



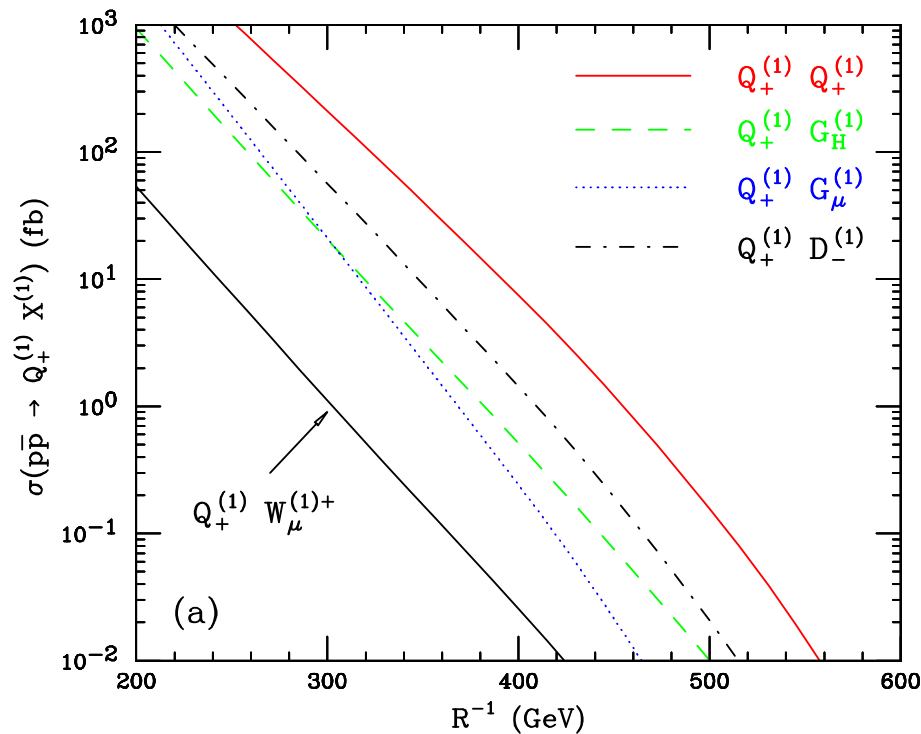
# UED collider phenomenology

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escapes detector undetected as missing momentum
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Production rates of up to  $\mathcal{O}(100 \text{ fb})$ , comparable to SUSY



Searches in  $\text{jets} + \cancel{E}$  and  $3l$  channels  
give constraint  $R^{-1} \gtrsim 250\text{--}300 \text{ GeV}$

CDF, D0 collaborations '07–09

(but no experimental analysis available)

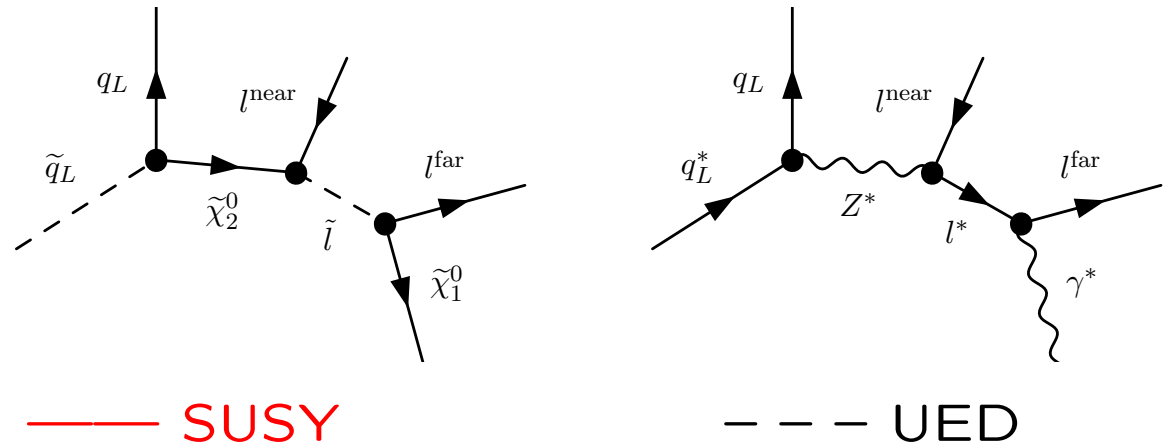
## Signals at LHC

- Large production rates of 1–100 pb for  $R^{-1} \lesssim 800$  GeV
- Can determine particle properties from differential distributions
- Spin determination important for distinguishing SUSY and UED

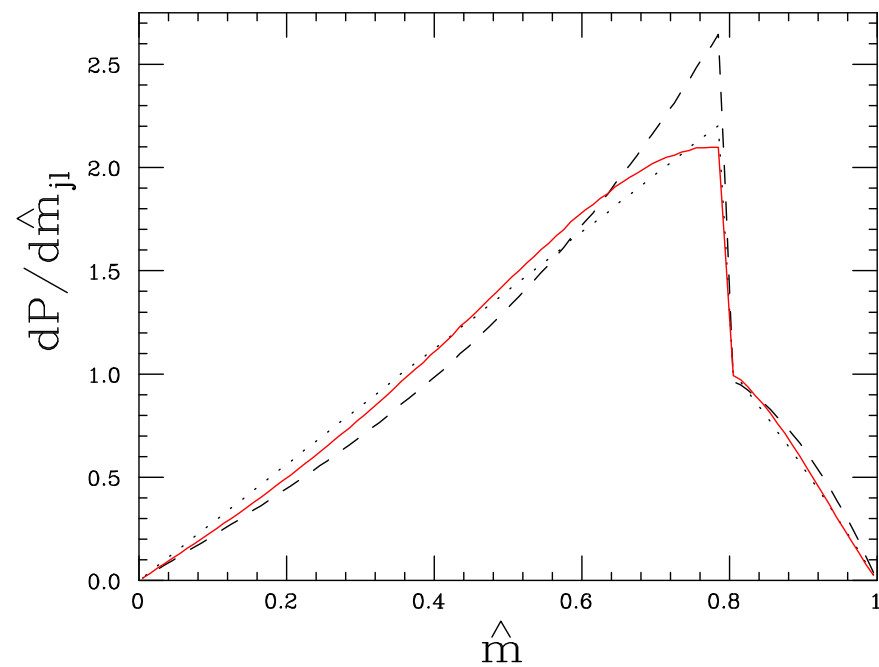
SUSY		UED		
gluino	1/2	KK-gluon	1	Alves, Eboli, Plehn '06 Csaki, Heinonen, Perelstein '07
chargino	1/2	KK- $W$ -boson	1	Wang, Yavin '07, Smillie '07
slepton	0	KK-lepton	1/2	Barr '04, Smillie, Webber '05
neutralino	1/2	KK- $Z$ -boson	1	Datta, Kong, Matchev '05 Kilic, Wang, Yavin '07
squark	0	KK-quark	1/2	Smillie, Webber '05
gravitino	3/2	scal. adjoint	0	Ehrenfeld, Freitas, Landwehr, Wyler '09

# Signals at LHC

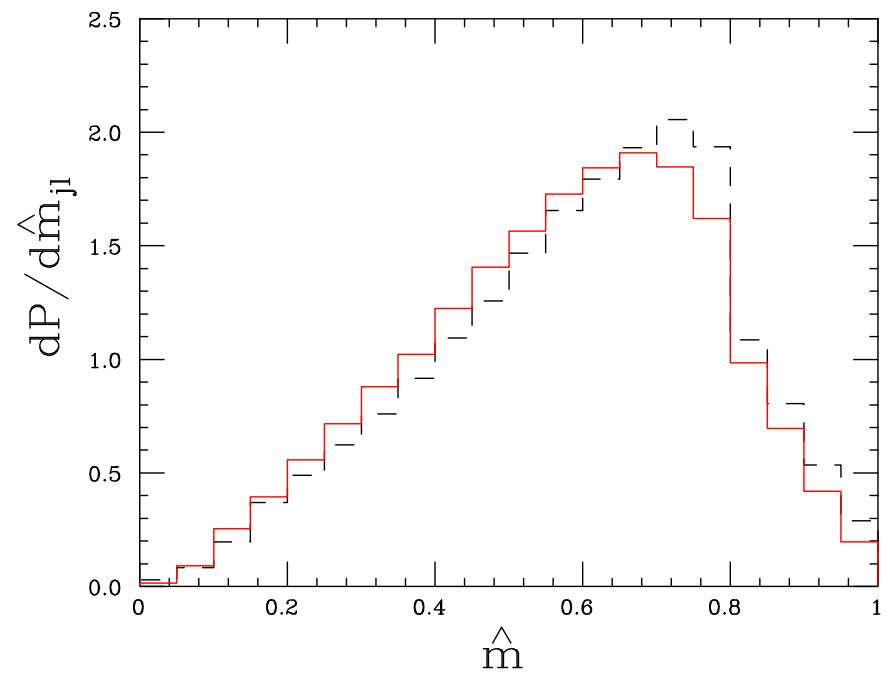
Example:  $jll$  distributions



Analytic shape formulas:



Simulation with detector effects:



Smillie, Webber '05

## Spin determination of stable WIMP

Spin of dark matter particle is characteristic feature of model:

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

UED  $D = 5$ :  $B_\mu^{(1)}$  (**vector**)

UED  $D = 6$ :  $B_H^{(1,0)}$  (**scalar**)

# Spin determination at an $e^+e^-$ collider

Freitas, Kong '07

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

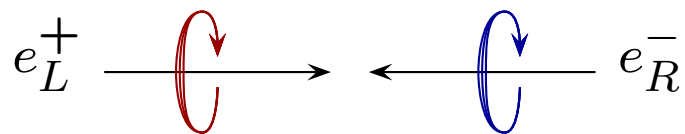
For comparison:

$$\text{6DSM: } e^+e^- \rightarrow e_R^{(1,0)+} e_R^{(1,0)-} \quad e_R^{(1,0)\pm} \rightarrow e^\pm B_H^{(1,0)}$$

$$\text{5DSM: } e^+e^- \rightarrow e_R^{1+} e_R^{1-} \quad e_R^{1\pm} \rightarrow e^\pm B_\mu^1$$

$$\text{SUSY: } e^+e^- \rightarrow \tilde{e}_R^+ \tilde{e}_R^- \quad \tilde{e}_R^\pm \rightarrow e^\pm \tilde{\chi}_1^0$$

Make use of polarized beams: create spin-1 state



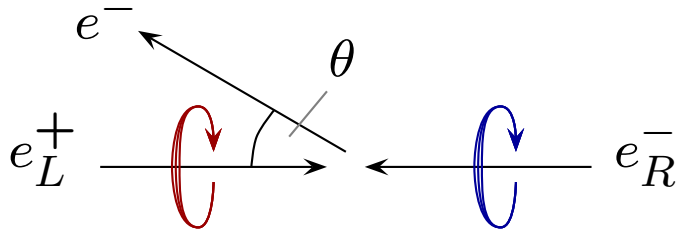
Coupling structure:

6DSM:  $e_R^{(1,0)-} \rightarrow e^- B_H^{(1,0)}$  produces **right-handed**  $e^-$   
 $\Rightarrow e^-$  go in **forward** direction

5DSM:  $e_R^{(1,0)-} \rightarrow e^- B_\mu^1$  produces **left-handed**  $e^-$   
 $\Rightarrow e^-$  go in **backward** direction

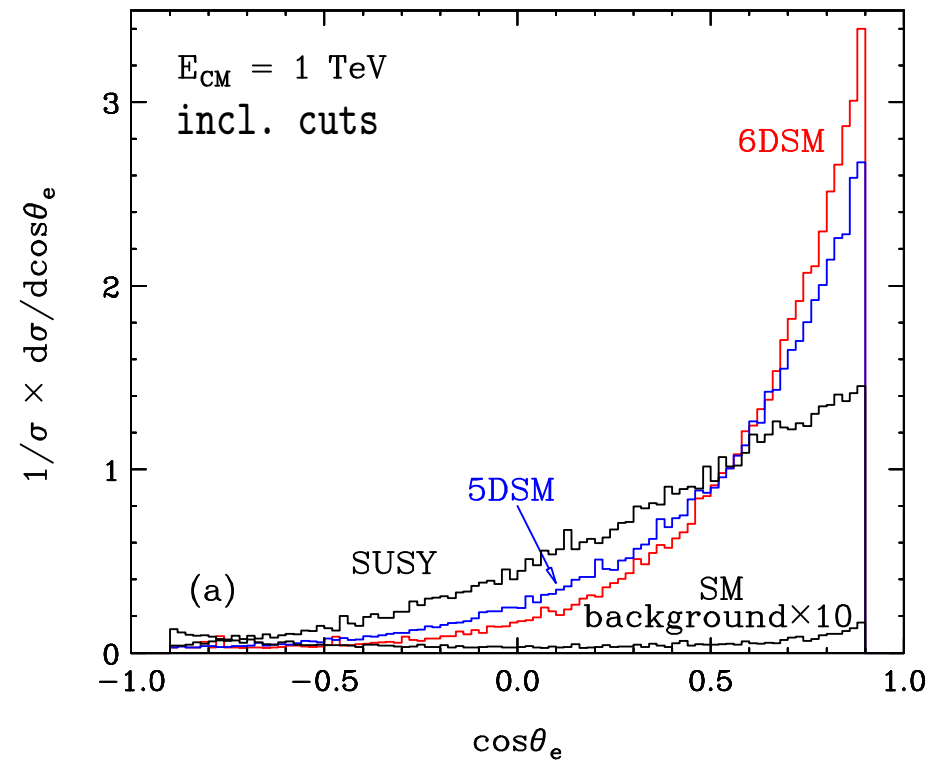
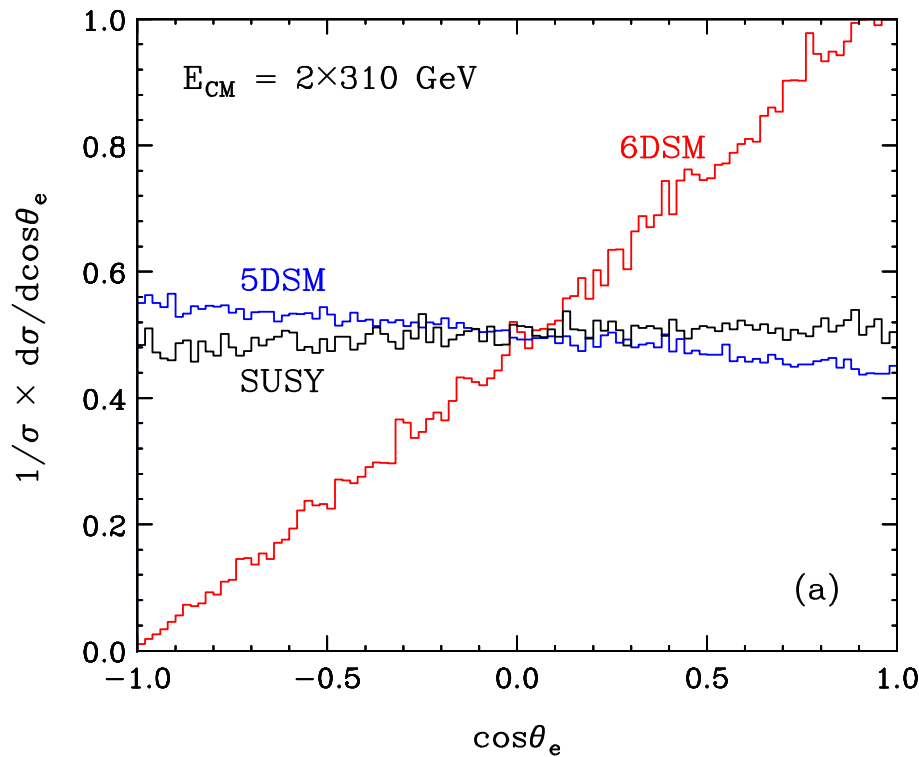
# Spin determination at an $e^+e^-$ collider

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  $2\text{--}20 \text{ fb}^{-1}$  of luminosity sufficient to distinguish spins (depending on cross-section)

# Spin determination at the LHC

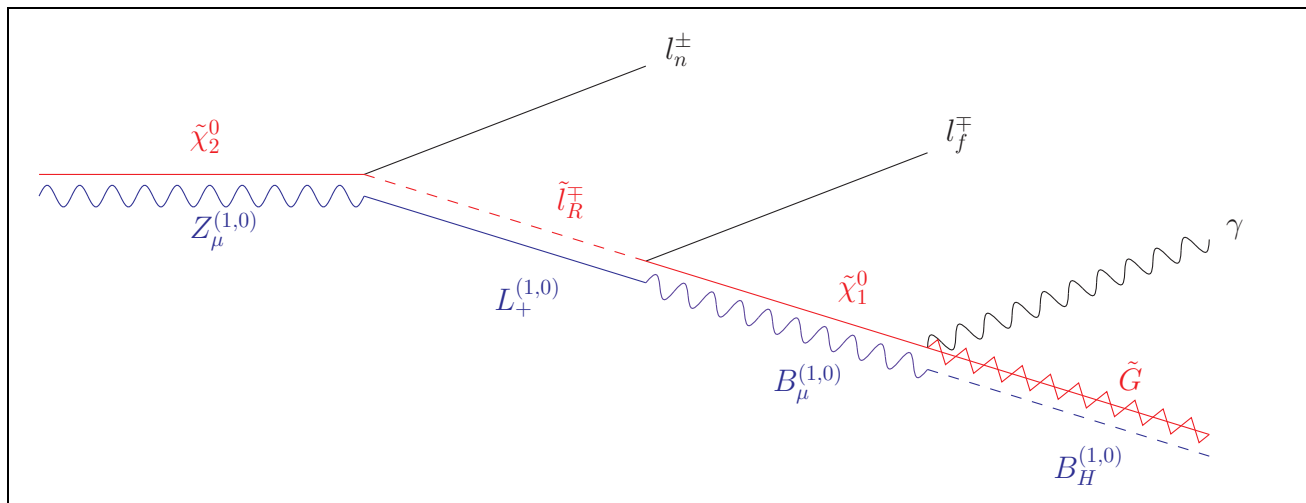
Focus on characteristic decay chains with photons:

- **GMSB**: typical decay  $\tilde{\chi}_1^0 \rightarrow \gamma \tilde{G}$
- **UED  $D = 6$** : typical decay  $B_\mu^{(1,0)} \rightarrow \gamma B_H^{(1,0)}$

As part of longer decay chains:

$$\tilde{\chi}_2^0 \rightarrow l^\pm \tilde{l}_R^\mp \rightarrow l^+ l^- \tilde{\chi}_1^0 \rightarrow l^+ l^- \gamma \tilde{G}$$

$$Z_\mu^{(1,0)} \rightarrow l^\pm L_+^{(1,0)} \rightarrow l^+ l^- B_\mu^{(1,0)} \rightarrow l^+ l^- \gamma B_H^{(1,0)}$$



## Analytical treatment of spin correlations

Determine spin from distributions of visible decay products of

$$D \rightarrow l_n^\pm C \rightarrow l_n^\pm l_f^\mp B \rightarrow l_n^\pm l_f^\mp \gamma A$$

Barr '04

Smillie, Webber '05

Miller, Osland, Raklev '06

Can construct four invariant mass distributions

$$m_{n\gamma}^2 \equiv (p_{l_n} + p_\gamma)^2 = (m_{n\gamma}^{\max})^2 \frac{1}{4} \left[ 2 - \left( 1 - \frac{m_B^2}{m_C^2} \right) (1 - \cos \theta_{nf}^{(C)}) \right] (1 - \cos \theta_{n\gamma}^{(B)})$$

$$m_{f\gamma}^2 \equiv (p_{l_f} + p_\gamma)^2 = (m_{f\gamma}^{\max})^2 \frac{1}{2} (1 - \cos \theta_{f\gamma}^{(B)})$$

$$m_{nf}^2 \equiv (p_{l_n} + p_{l_f})^2 = (m_{nf}^{\max})^2 \frac{1}{2} (1 - \cos \theta_{nf}^{(C)})$$

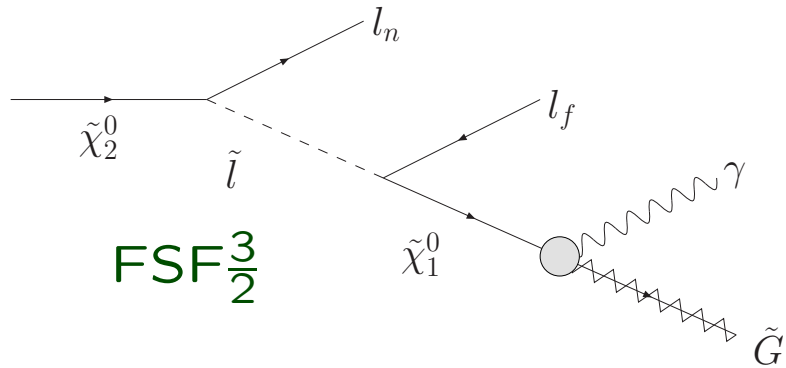
$$m_{nf\gamma}^2 \equiv (p_{l_n} + p_{l_f} + p_\gamma)^2 = m_{n\gamma}^2 + m_{f\gamma}^2 + m_{nf}^2$$

Cannot distinguish “near” lepton  $l_n$  and “far” lepton  $l_f$  experimentally

→ Use instead  $m_{h\gamma}^2 = \max\{m_{n\gamma}^2, m_{f\gamma}^2\}$   $m_{l\gamma}^2 = \min\{m_{n\gamma}^2, m_{f\gamma}^2\}$

# Spin structures

GMSB:



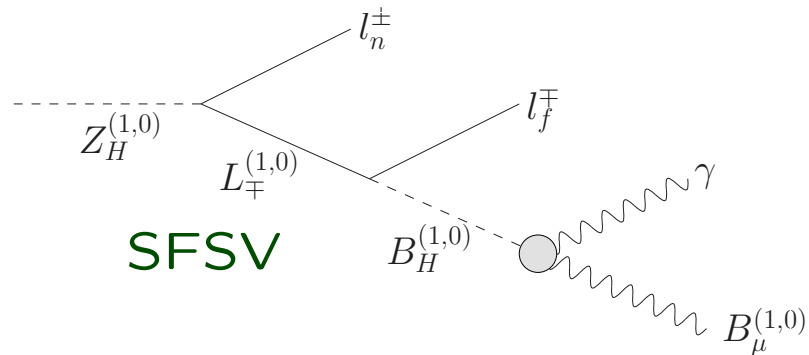
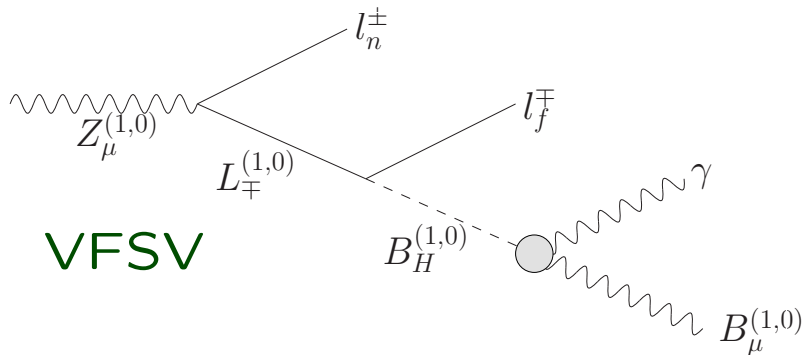
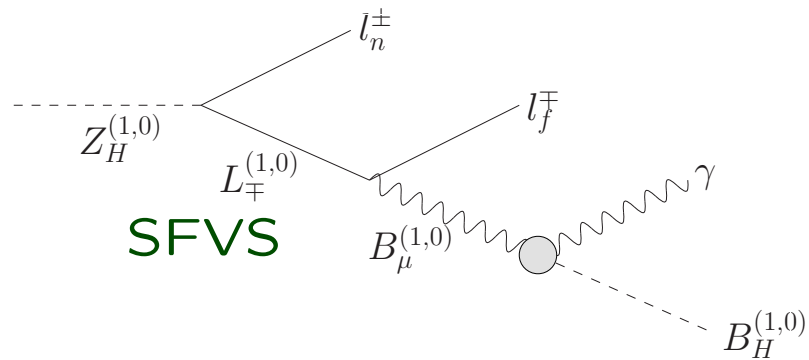
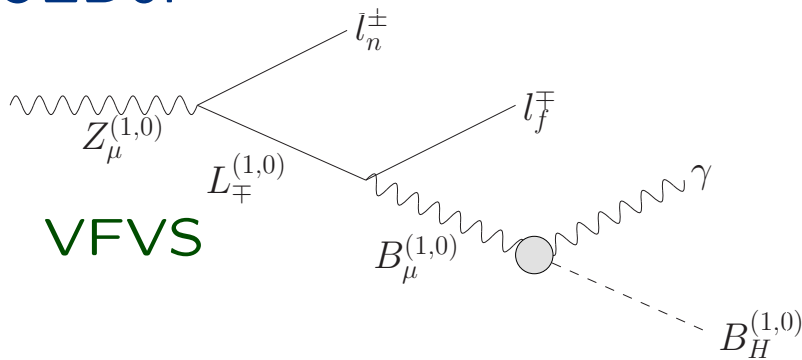
Visible spin correlations for **chiral** fermion vertices only Wang, Yavin '07

$\tilde{\chi}_1^0$ - $\gamma$ - $\tilde{G}$  vertex has the form

$$[\not{p}_\gamma, \gamma_\mu] \gamma_\alpha$$

→ No spin effects for GMSB

UED6:



# Mass spectra

G1a		U1	
Particle	Mass	Particle	Mass
$\tilde{g}$	747	$G_{\mu}^{(1,0)}$	696
$\tilde{u}_L$	986	$Q_+^{(1,0)}$	662
$\tilde{d}_L$	989	$U_-^{(1,0)}$	608
$\tilde{u}_R$	942	$D_-^{(1,0)}$	606
$\tilde{d}_R$	939	$Z_{\mu}^{(1,0)}$	538
$\tilde{\chi}_2^0$	224	$B_{\mu}^{(1,0)}$	487
$\tilde{\chi}_1^0$	119	$L_+^{(1,0)}$	521
$\tilde{e}_L$	326	$E_-^{(1,0)}$	508
$\tilde{e}_R$	164	$B_H^{(1,0)}$	427
$\tilde{G}$	0		

**Minimal GMSB** has hierarchical mass spectrum

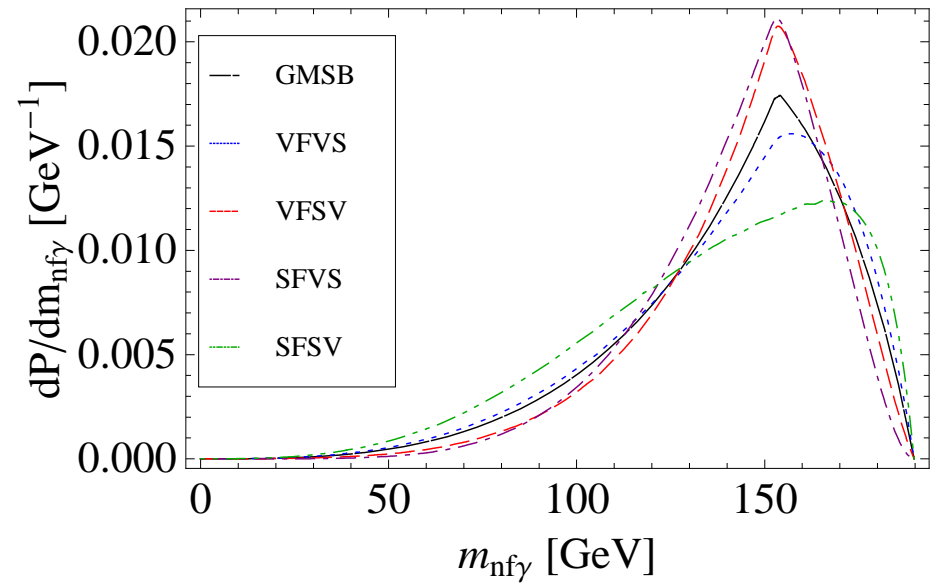
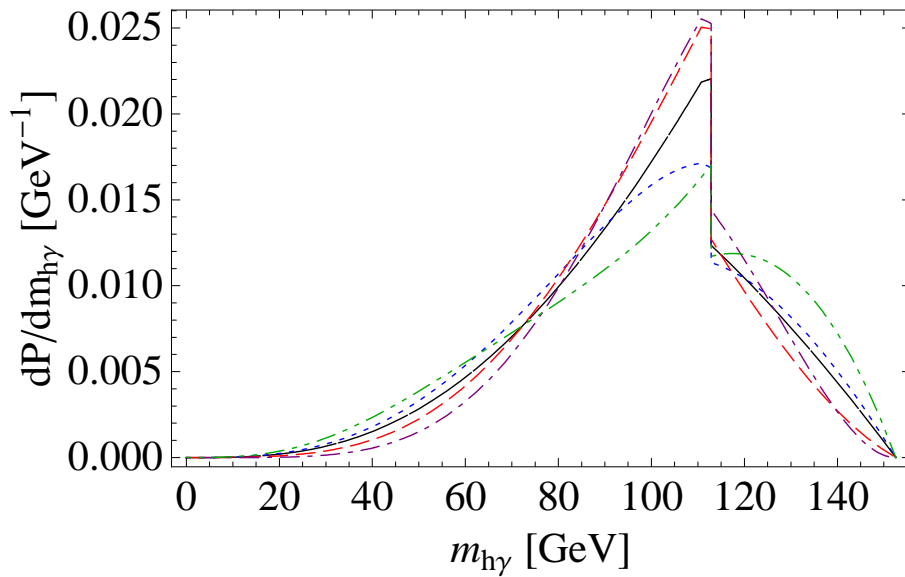
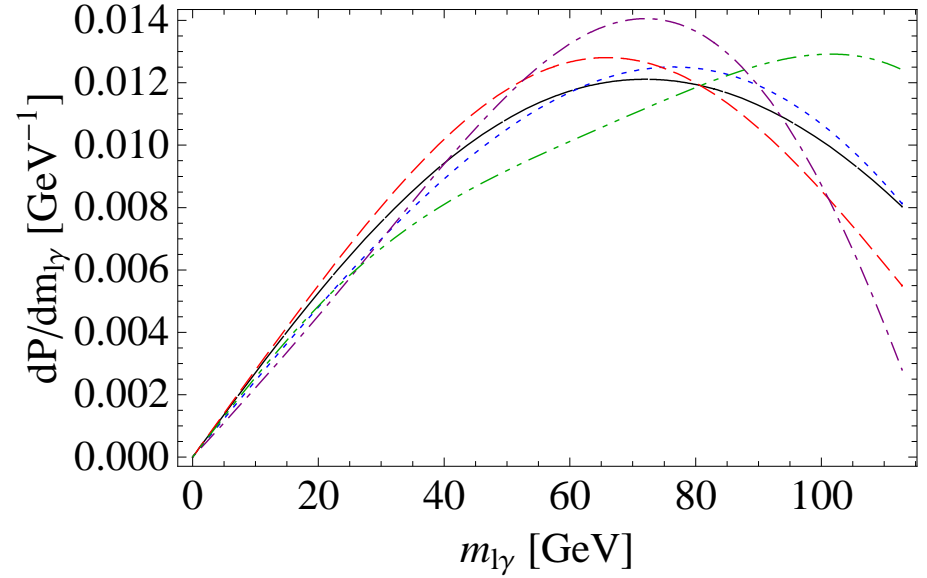
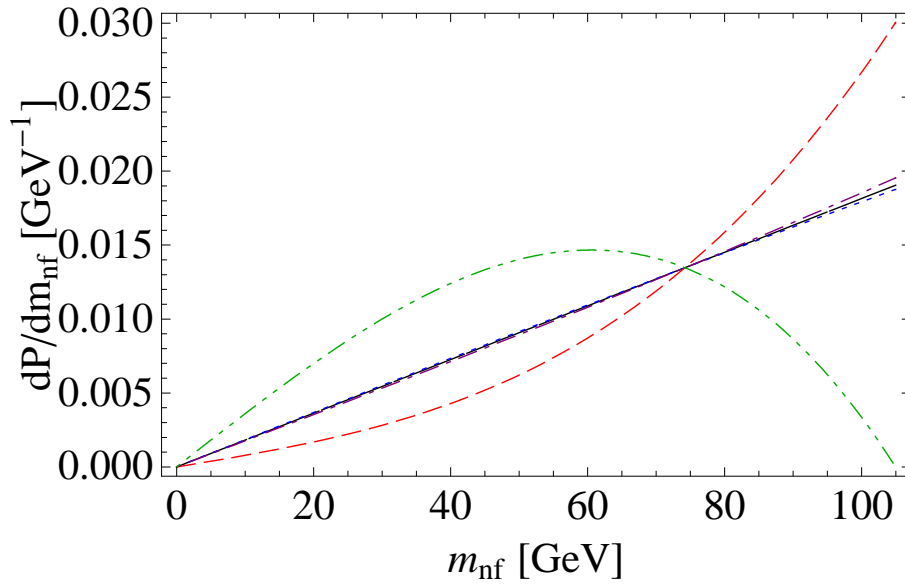
UED6 **without UV operators** has more degenerate spectrum

**But:** Variations possible

Robust distinction only through spin analysis

# Results for scenario G1a

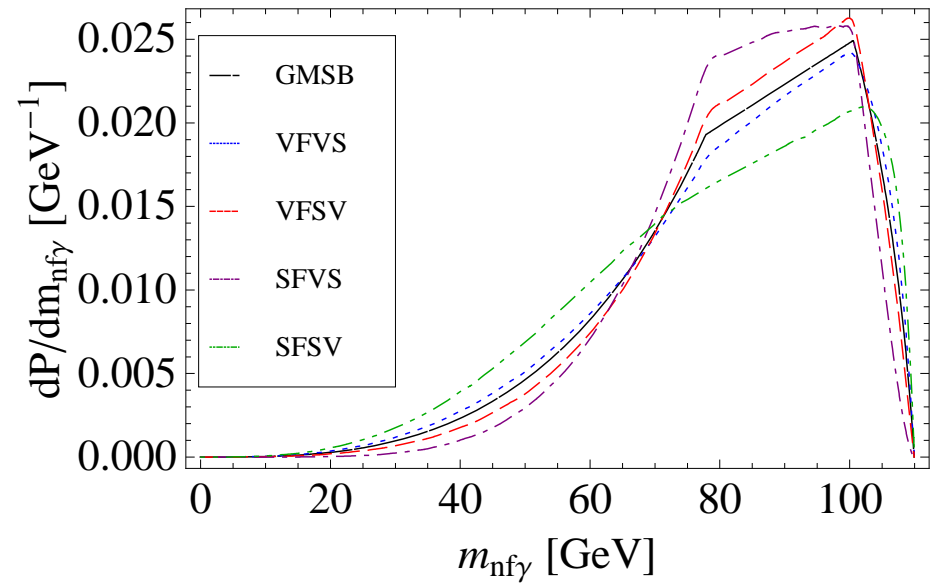
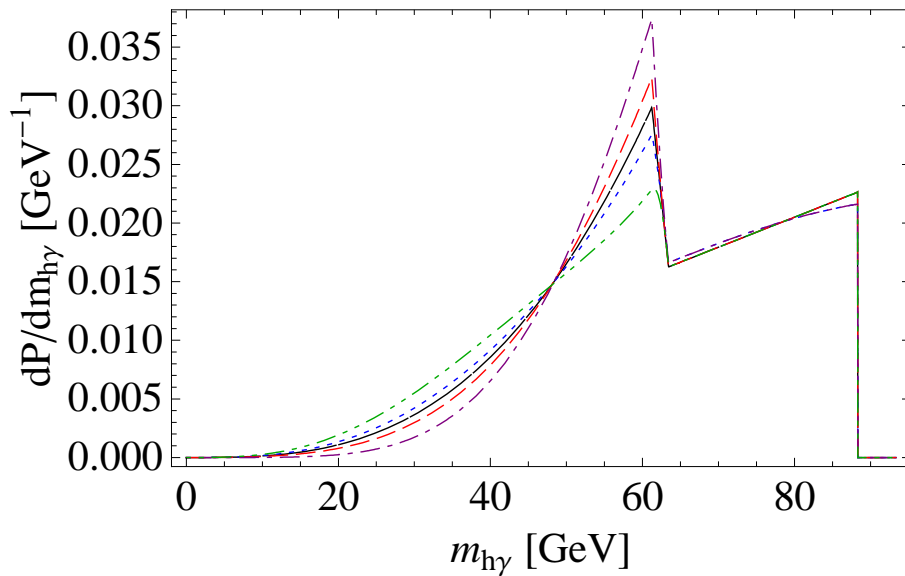
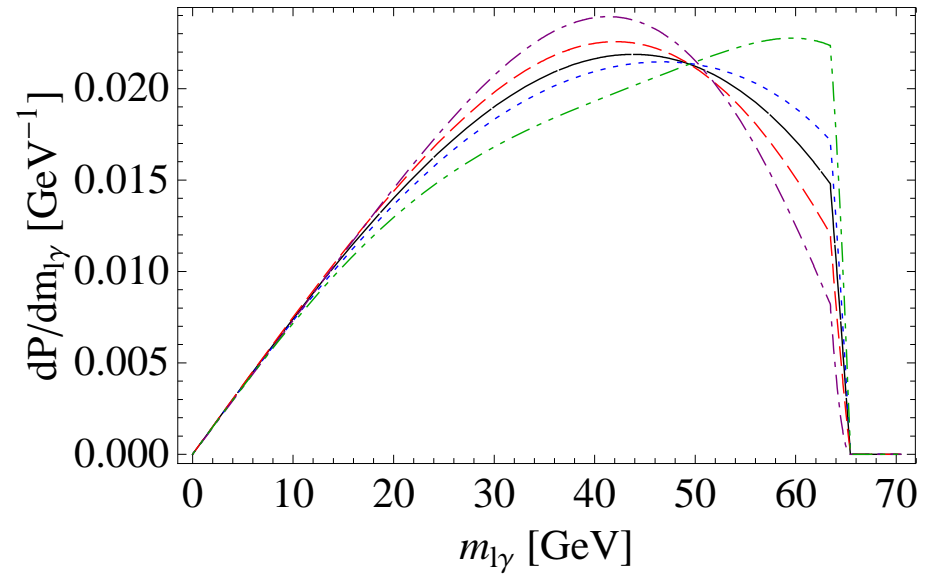
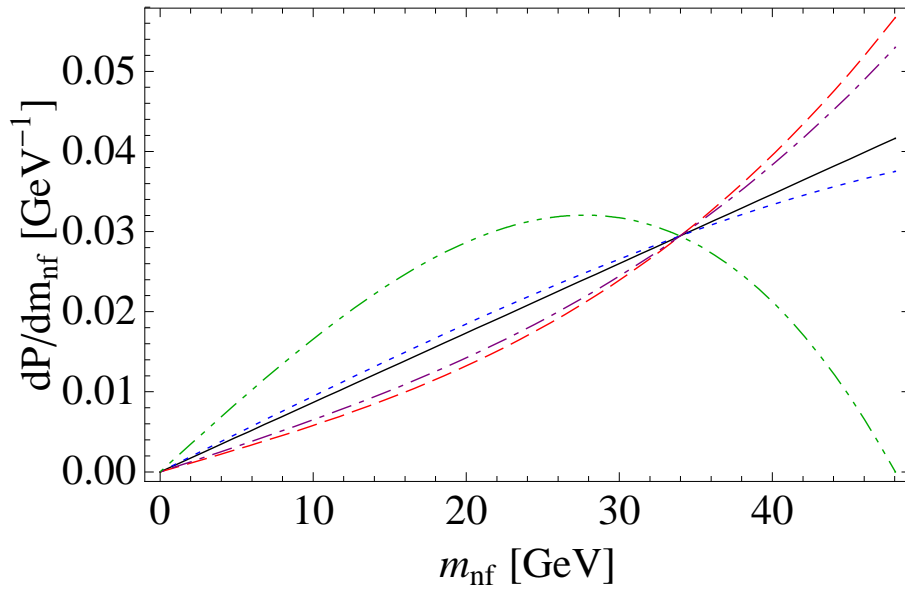
Ehrenfeld, Freitas, Landwehr, Wyler '09



(Distributions are normalized to 1)

# Results for scenario U1

Ehrenfeld, Freitas, Landwehr, Wyler '09



(Distributions are normalized to 1)

## Monte-Carlo simulation

- Event generation: **CompHEP 4.4 + Pythia 6.4.12**
- SUSY and KK particles are produced in pairs  
→ include second decay chain (with Pythia)
- Detector effects: **AtIFast**

### ■ Cuts for SM reduction:

Hinchliffe, Paige '99

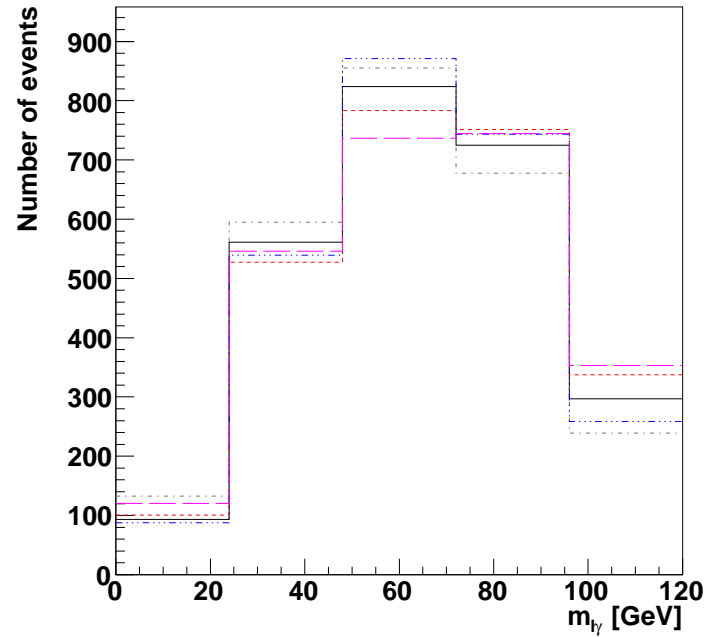
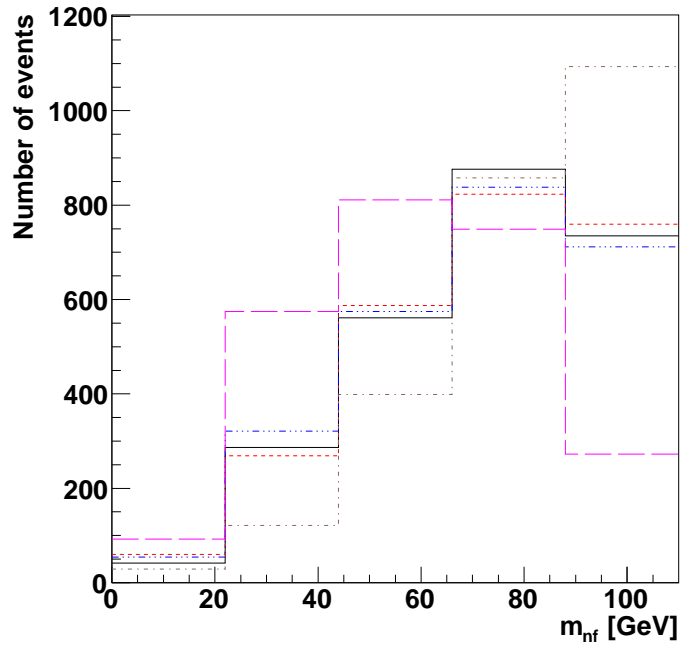
- 4 jets with  $p_T > 25$  GeV
  - $M_{\text{eff}} = \cancel{E}_T + p_{T,1} + p_{T,2} + p_{T,3} + p_{T,4} > 400$  GeV
  - $\cancel{E}_T > 0.1 M_{\text{eff}}$
  - 2 photons with  $p_T > 20$  GeV
  - 2 electrons or muons with  $p_T > 20$  GeV
- Negligible SM background, 20% signal efficiency

Many event contain **two photons**

→ For computing distributions pick the one which gives smaller  $m_{ll\gamma}^2$

# Results

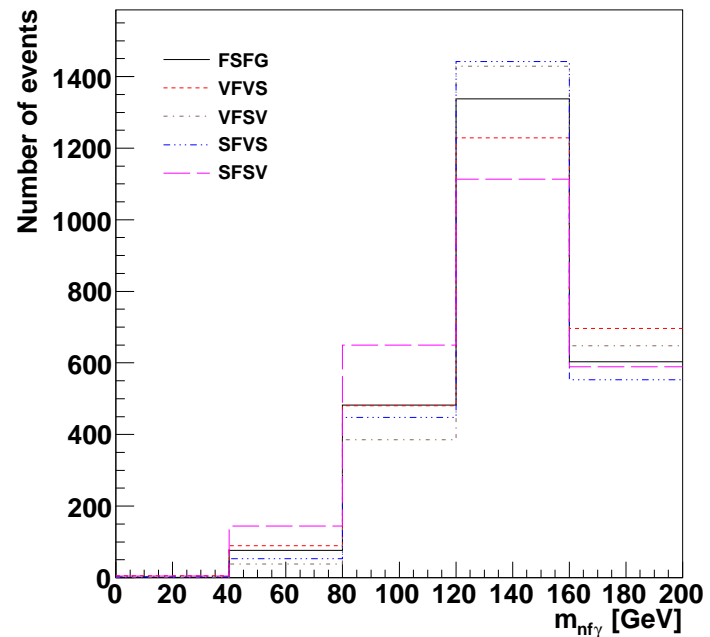
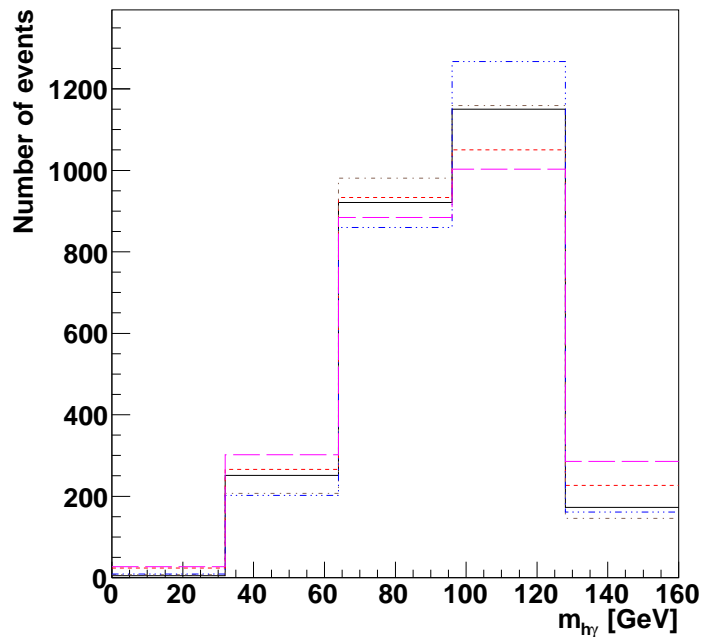
Ehrenfeld, Freitas, Landwehr, Wyler '09



G1a

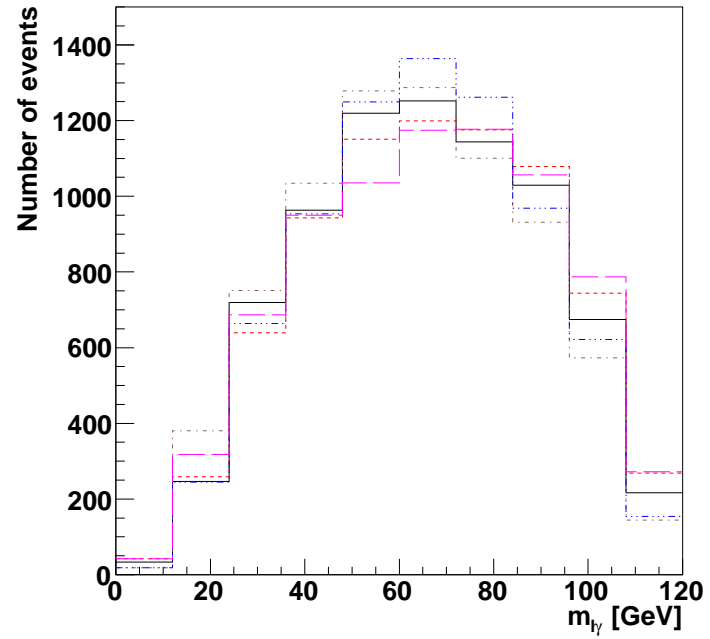
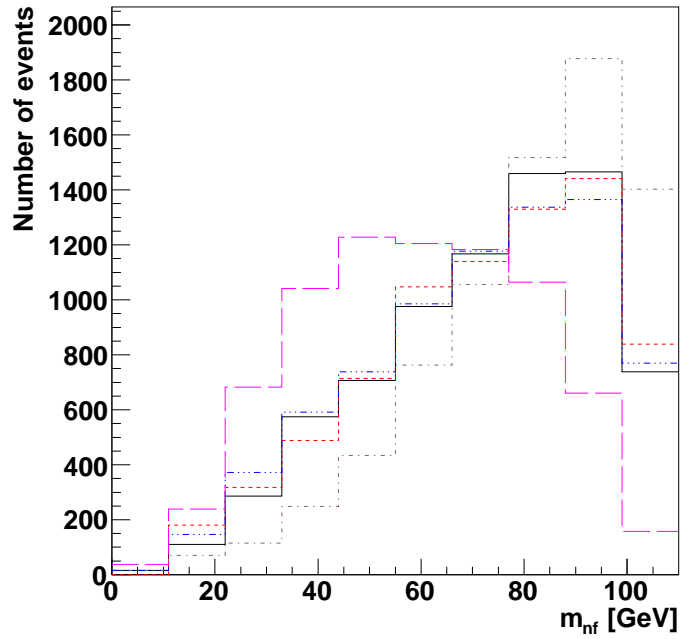
masses and  
cross  
sections

$10 \text{ fb}^{-1}$



# Results

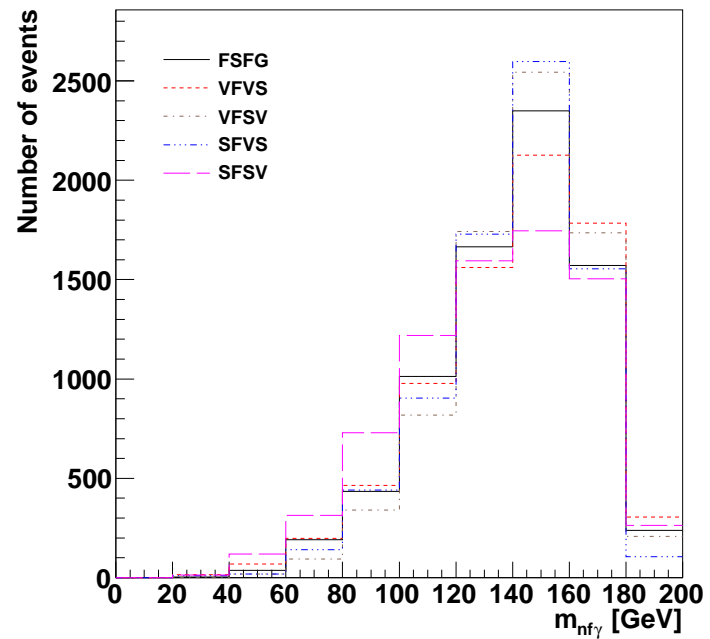
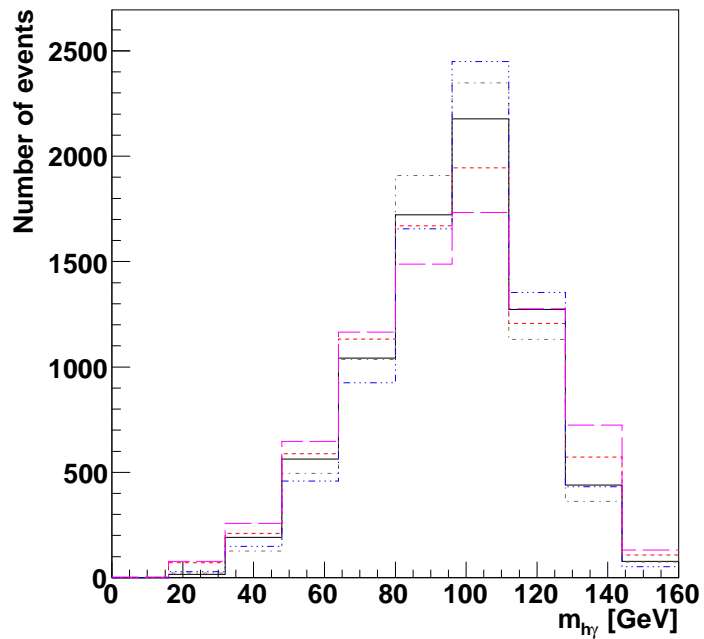
Ehrenfeld, Freitas, Landwehr, Wyler '09



G1a

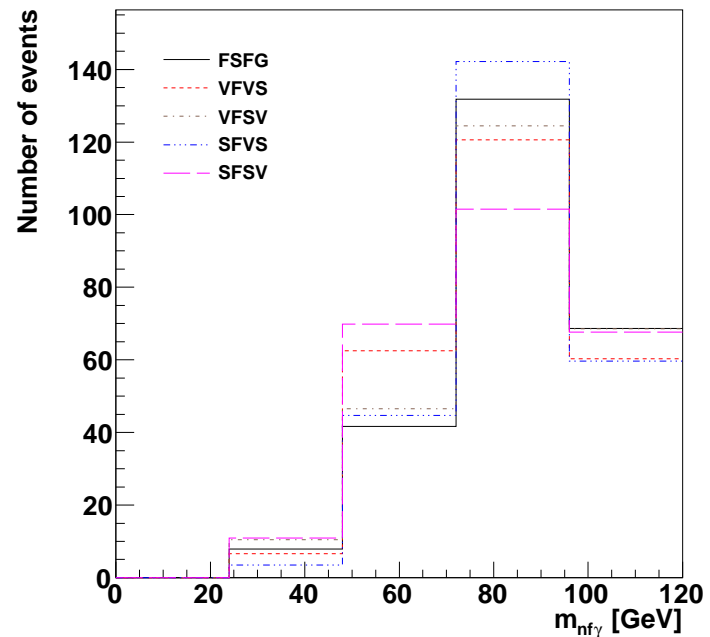
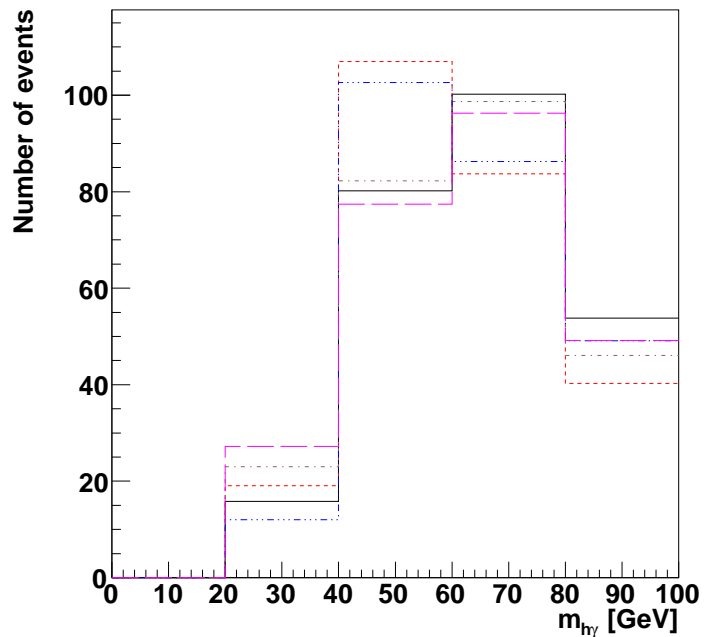
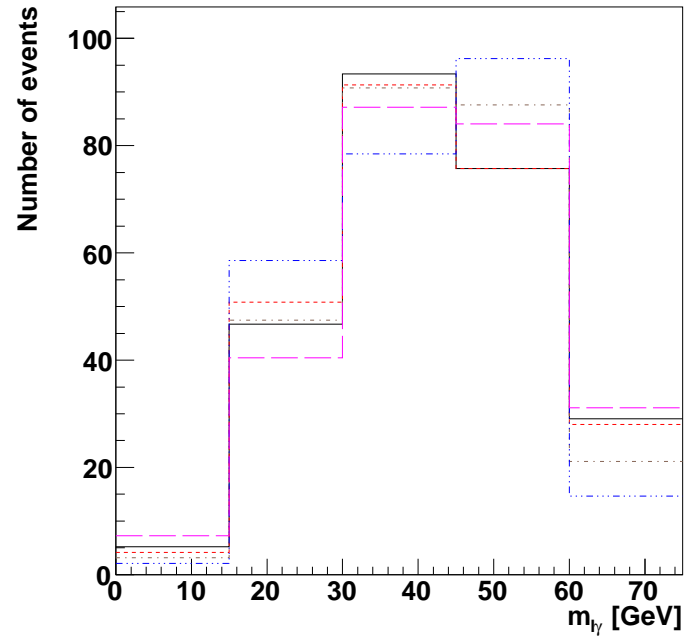
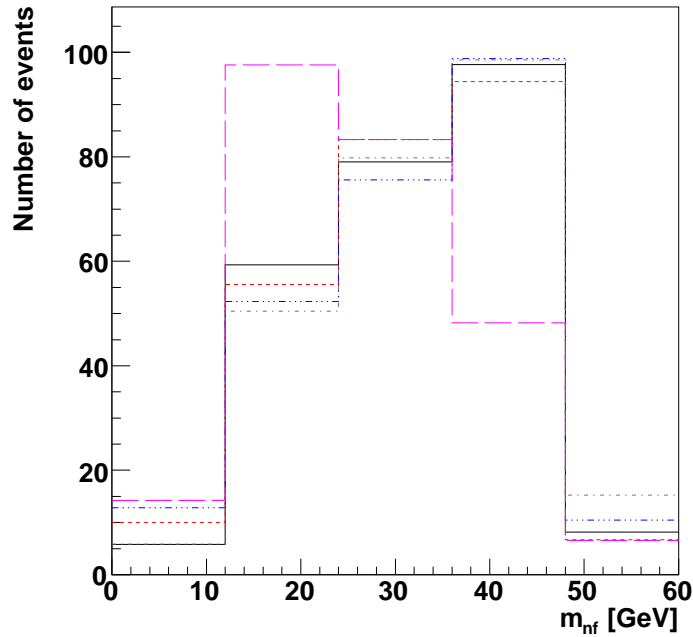
masses and  
cross  
sections

$30 \text{ fb}^{-1}$



# Results

Ehrenfeld, Freitas, Landwehr, Wyler '09



U1

masses and  
cross  
sections

$10 \text{ fb}^{-1}$

# Results

Ehrenfeld, Freitas, Landwehr, Wyler '09

- GMSB and UED6 can be distinguished from spin correlations in decay chains
- $\chi^2$  analysis with  $10 \text{ fb}^{-1}$ :

	GMSB	VFVS	VFSV	SFVS	SFSV
GMSB		0.000 ( $m_{h\gamma}$ )	0.000 ( $m_{n,f}$ )	0.006 ( $m_{h\gamma}$ )	0.000 ( $m_{n,f}$ )
VFVS	0.056 ( $m_{h\gamma}$ )		0.000 ( $m_{n,f}$ )	0.000 ( $m_{h\gamma}$ )	0.000 ( $m_{n,f}$ )
VFSV	0.577 ( $m_{n,f}$ )	0.155 ( $m_{h\gamma}$ )		0.000 ( $m_{n,f}$ )	0.000 ( $m_{n,f}$ )
SFVS	0.025 ( $m_{l\gamma}$ )	0.065 ( $m_{l\gamma}$ )	0.084 ( $m_{h\gamma}$ )		0.000 ( $m_{n,f}$ )
SFSV	0.000 ( $m_{n,f}$ )	0.000 ( $m_{n,f}$ )	0.000 ( $m_{n,f}$ )	0.000 ( $m_{n,f}$ )	

U1 masses and cross sec.

G1a masses and cross sec.

(numbers are probability that two distributions originate from same underlying physics)

## Summary

- Universal extra dimensions are in agreement with **electroweak precision data** and can explain **dark matter** for  $R^{-1} \sim O(\text{few } 100 \text{ GeV})$
- **Flavor observables** lead to a stricter bound  $R^{-1} \gtrsim 600 \text{ GeV}$ , but there is some loss of predictivity from UV physics, in particular for  $D > 5$ .
- TeV-scale universal extra dimensions will be **discovered at LHC**.
- Detailed measurements at LHC and ILC will allow to determine the **spins of the KK-level-1 particles** and thus distinguish SUSY and UED with  $D = 5$  or  $D = 6$ .

**Backup slides**

# Radiative corrections

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

One-loop corrections play important role for phenomenology:

- Mass corrections
- KK-number violating interactions (forbidden at tree-level)

Summation over KK-modes in loop

→ Integration over momenta in extra dimensions

→ Fourier transform:

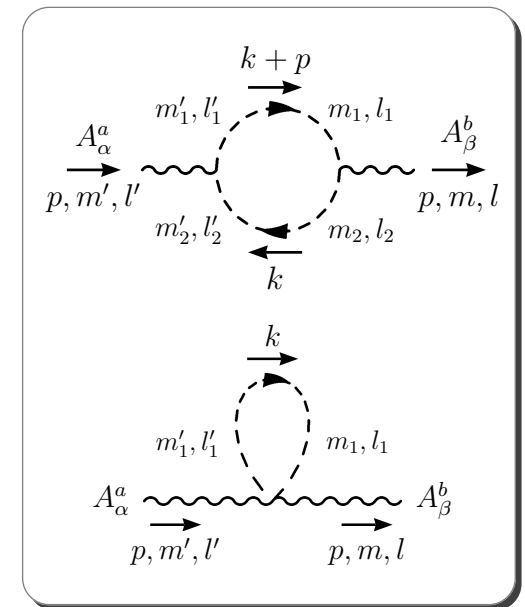
operators localized at corners of boundaries

$$\mathcal{L}_{\text{one-loop}} = \left[ \delta(x_4) + \delta(\pi R - x_4) \right] \mathcal{L}_1$$

→ **breaks** 6D Lorentz invariance,  
and thus **KK-number**

→ preserves **KK-parity**:  $j + k$  even/odd

Get (loop-suppressed) interactions between  
even KK excitations and zero modes



## UV operators

Models with extra dimensions break down at a high scale:

- Loop corrections to masses and couplings are generally divergent (not renormalizable)
- Sum over KK modes is divergent for  $D \geq 6$
- 6D gauge couplings become strong for large energies

Theory only valid up to some cutoff scale  $\Lambda$

→ Unknown new physics enters

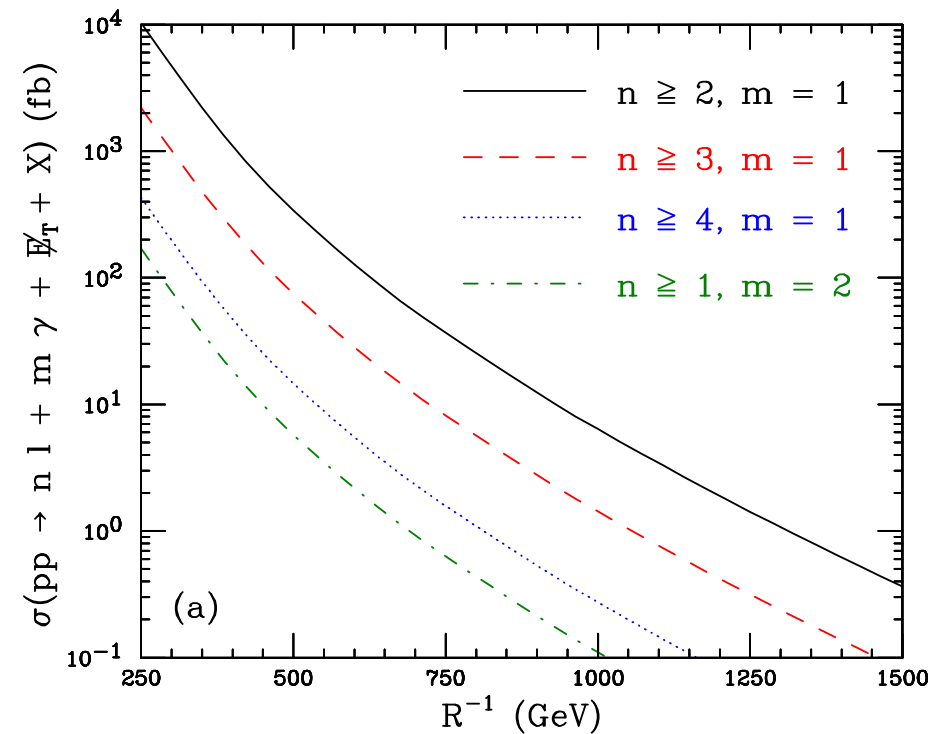
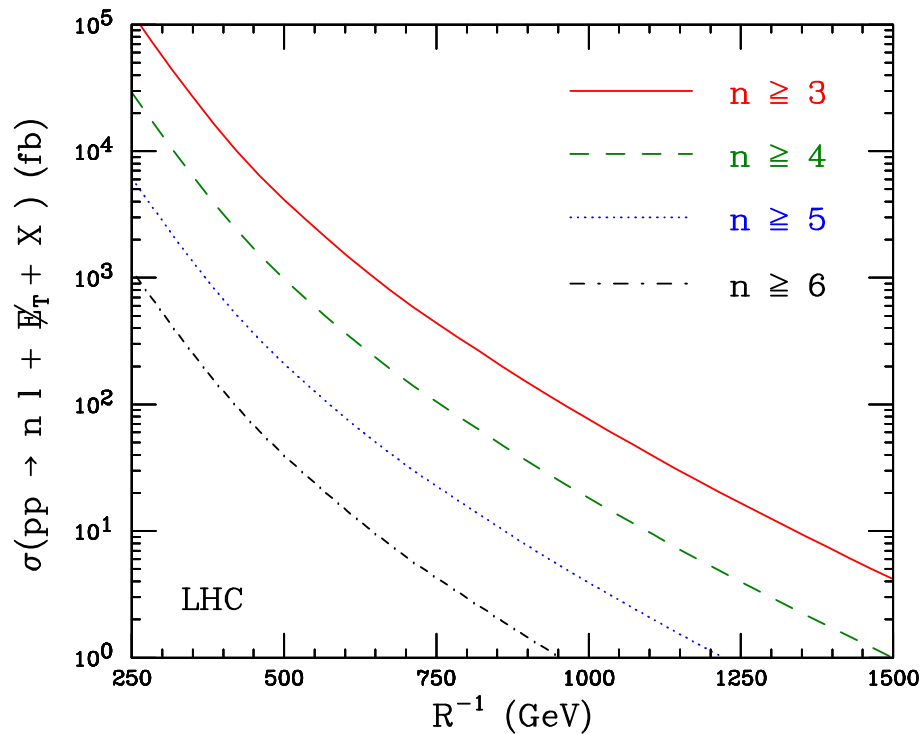
New physics could generate additional operators at low energies, suppressed by  $\Lambda$ , but still important:

→ Problem for flavor changing effects, e.g. to  $B \rightarrow s\gamma$

→ Would overwhelm SM contribution by factor  $\sim 50$

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

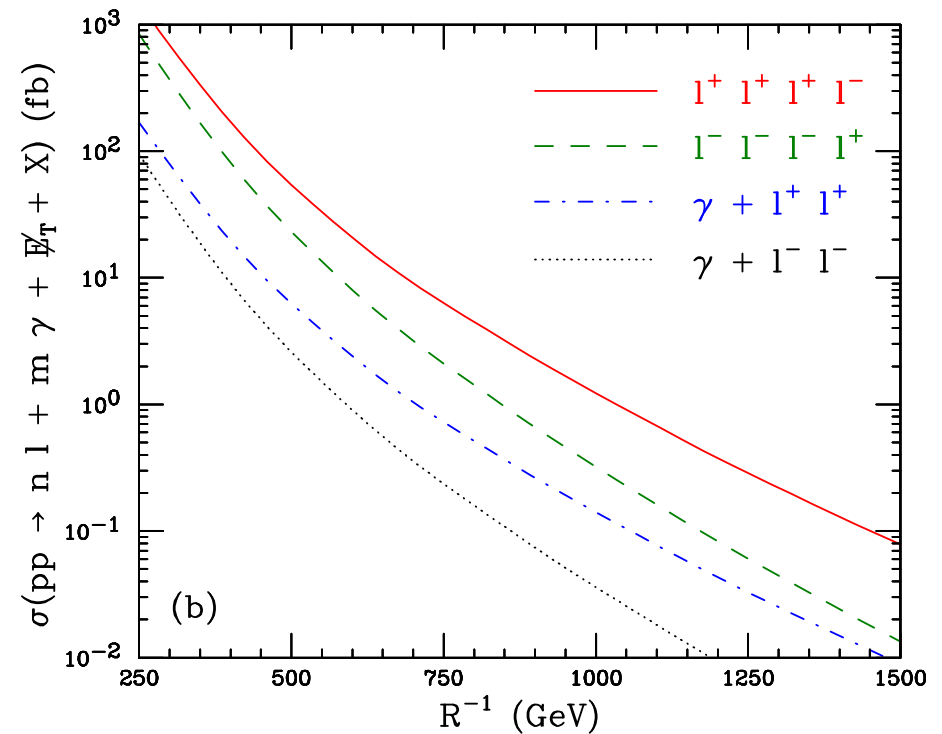
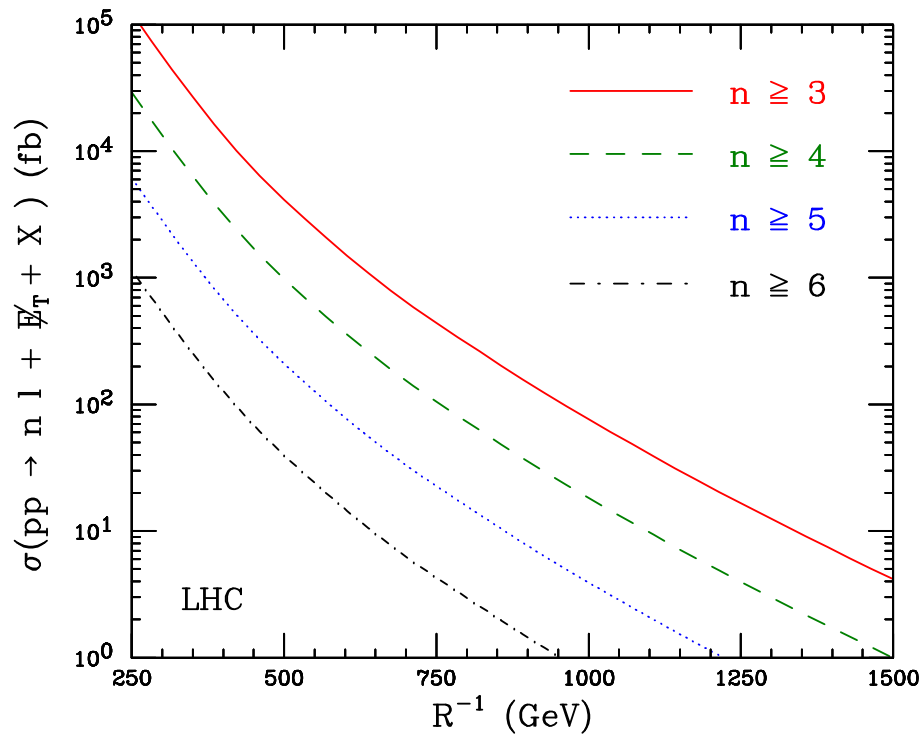
$$pp \rightarrow n l + m \gamma + \cancel{E}_T + X, \quad X = \text{hadrons (jets)}$$



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

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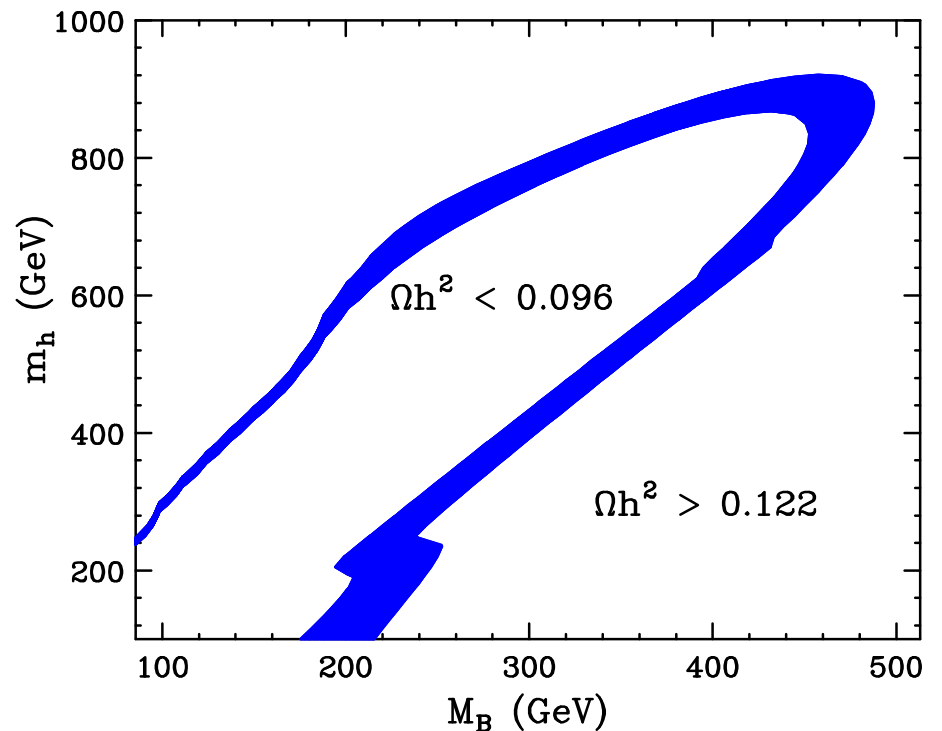
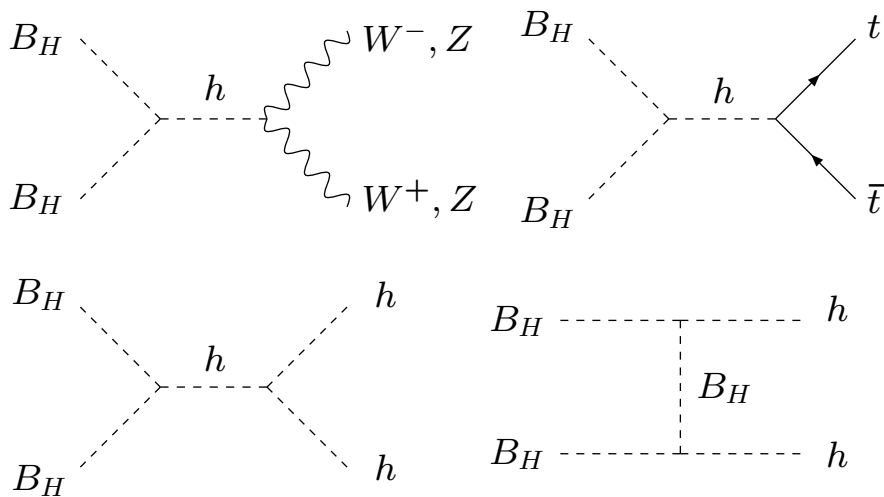
# Dark matter

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



# Spin determination at the LHC

Focus on characteristic decay chains with photons:

- **GMSB**: typical decay  $\tilde{\chi}_1^0 \rightarrow \gamma \tilde{G}$
- **UED  $D = 6$** : typical decay  $B_\mu^{(1,0)} \rightarrow \gamma B_H^{(1,0)}$

As part of longer decay chains:

$$\begin{aligned} \tilde{\chi}_2^0 &\rightarrow l^\pm \tilde{l}_R^\mp \rightarrow l^+ l^- \tilde{\chi}_1^0 \rightarrow l^+ l^- \gamma \tilde{G} \\ Z_\mu^{(1,0)} &\rightarrow l^\pm L_+^{(1,0)} \rightarrow l^+ l^- B_\mu^{(1,0)} \rightarrow l^+ l^- \gamma B_H^{(1,0)} \end{aligned}$$

Differences between GMSB and UED with  $D = 6$ :

- Hierarchical vs. condensed mass spectrum (in “minimal” models)
- BR for this decay chain is low for UED [ $\mathcal{O}(1\%)$ ]
- **Spins**