Dark Matter Complementarity: UED Review

K.C. Kong
University of Kansas

Cosmic Frontier Workshop,
SLAC National Accelerator Laboratory
March 6-8, 2013

How to illustrate complementarity?

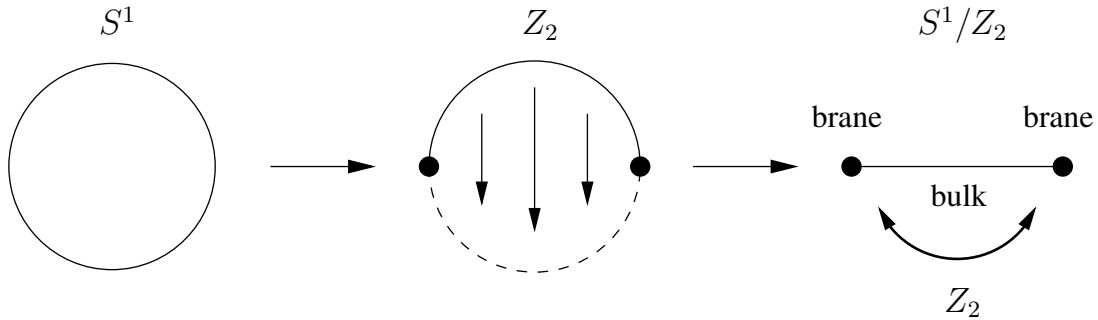
- Model-independent approaches
  - parameterize our ignorance
  - consider effective Lagrangian
  - easy to study complementarity of DM search
  - important questions to ask:
    - when does this approach make sense?
    - how do we interpret?
- Specific theory models
  - choose a complete new physics model with a dark matter candidate: SUSY is a good candidate.
  - problem: many input parameters and model-dependent assumptions
- Need both approaches
  - study different models and learn lessens

Summary I

- UED provides alternative DM candidates
  - spin-1: KK photon, KK Z
  - spin-0: spinless photon, spinless Z, KK Higgs
  - spin-2: KK graviton
  - spin-1/2: KK neutrino
- Different aspect of DM detection
- Natural set up for a model with degenerate mass spectrum
  - Importance of complementarity: LHC vs DD

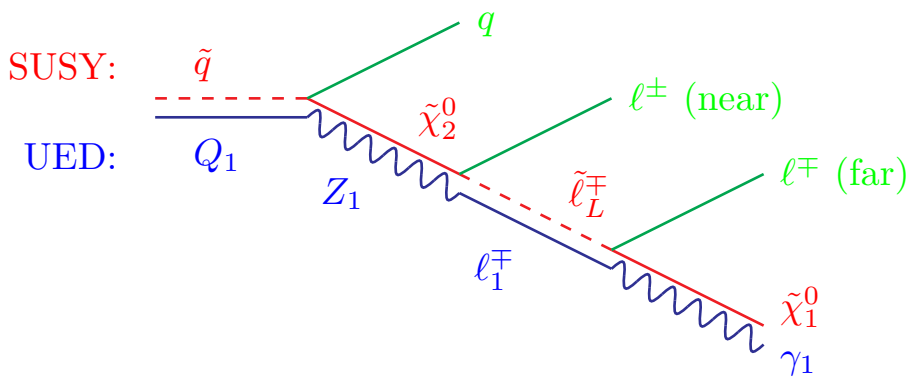
Overview on UED

- Universal: all SM particles in flat ED
- The simplest model: S1/Z2 (5D)
- KK-parity:
  - all SM particles (zero mode) are even
  - level 1 KK particles (n=1) are odd
  - level 2 KK particles (n=2) are even
  - electroweak precision constraints are avoided
    - new contributions are loop-suppressed
  - the LKP is stable and a DM candidate



More on UED

- Minimal UED: mass splitting be generated by radiative corrections (assuming no boundary terms and no bulk masses)
- Short RG running leads to compressed mass spectrum
- Larger production cross sections (compared to SUSY productions), i.e., KK gluon, KK quark productions
- SUSY-like cascade decays at the LHC



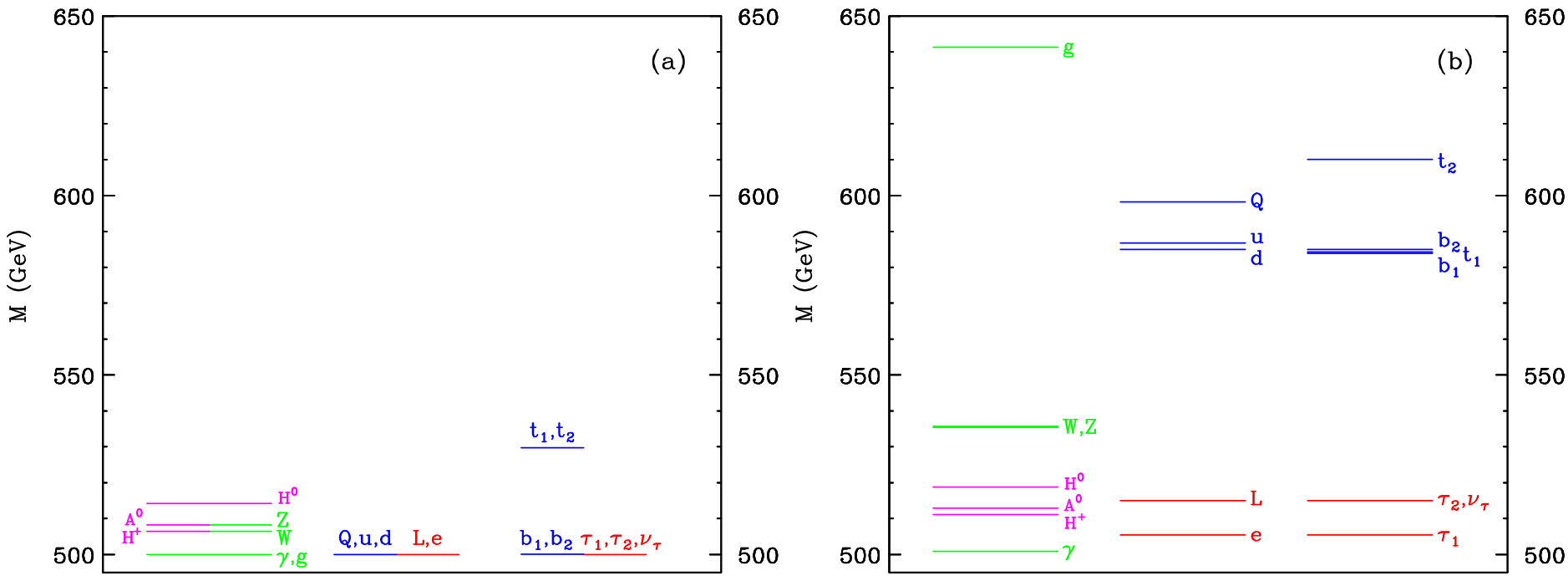
Universal Extra Dimensions

- MUED: Minimal Universal Extra Dimensions (cf. mSugra)
- 2UED: Two Universal Extra Dimensions (GMSB)
- nUED: non-minimal Universal Extra Dimensions
  - boundary terms
- SUED: Split Universal Extra Dimensions (cf. Split SUSY)
  - bulk terms
- sUED: UED with singlet extension
- NMUED: Next-to-Minimal UED
  - (with boundary and bulk terms)

Minimal UED

- Two parameters: R, Lambda (cutoff)

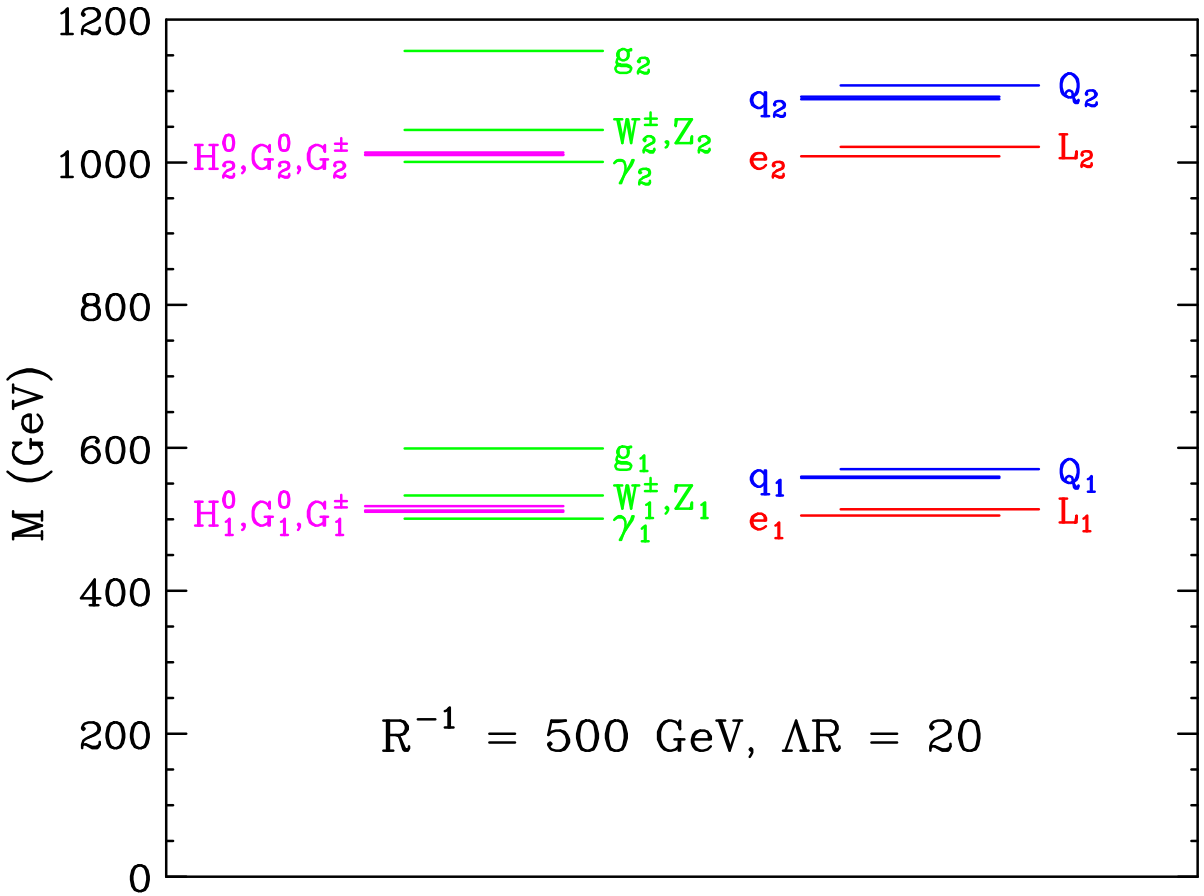
Cheng, Matchev, Schmaltz, 2002



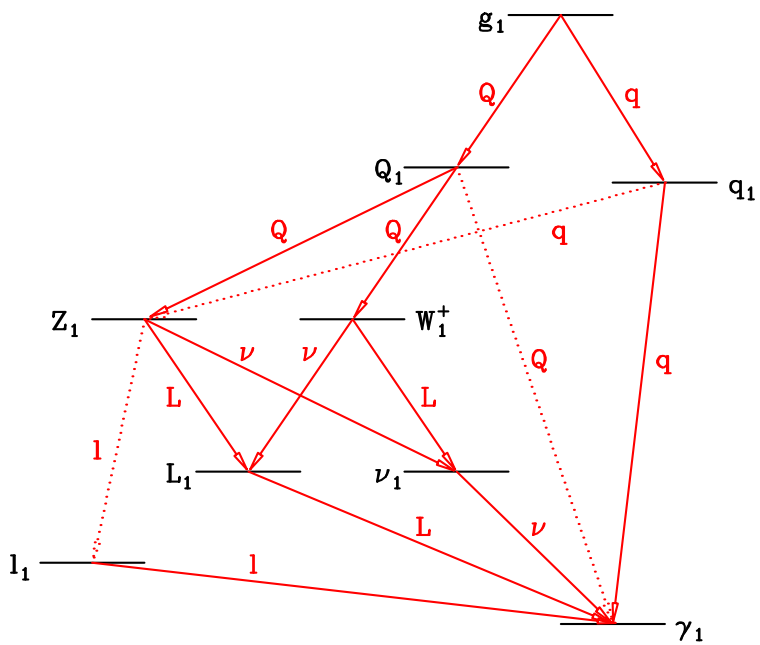
Minimal UED

- Two parameters: R, Lambda (cutoff)

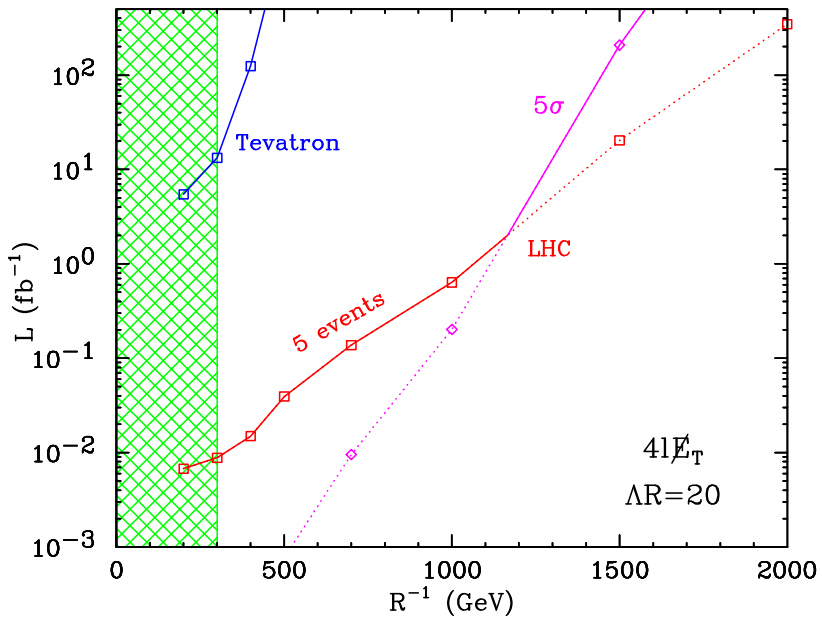
Cheng, Matchev, Schmaltz, 2002



Level 1: decays and LHC reach

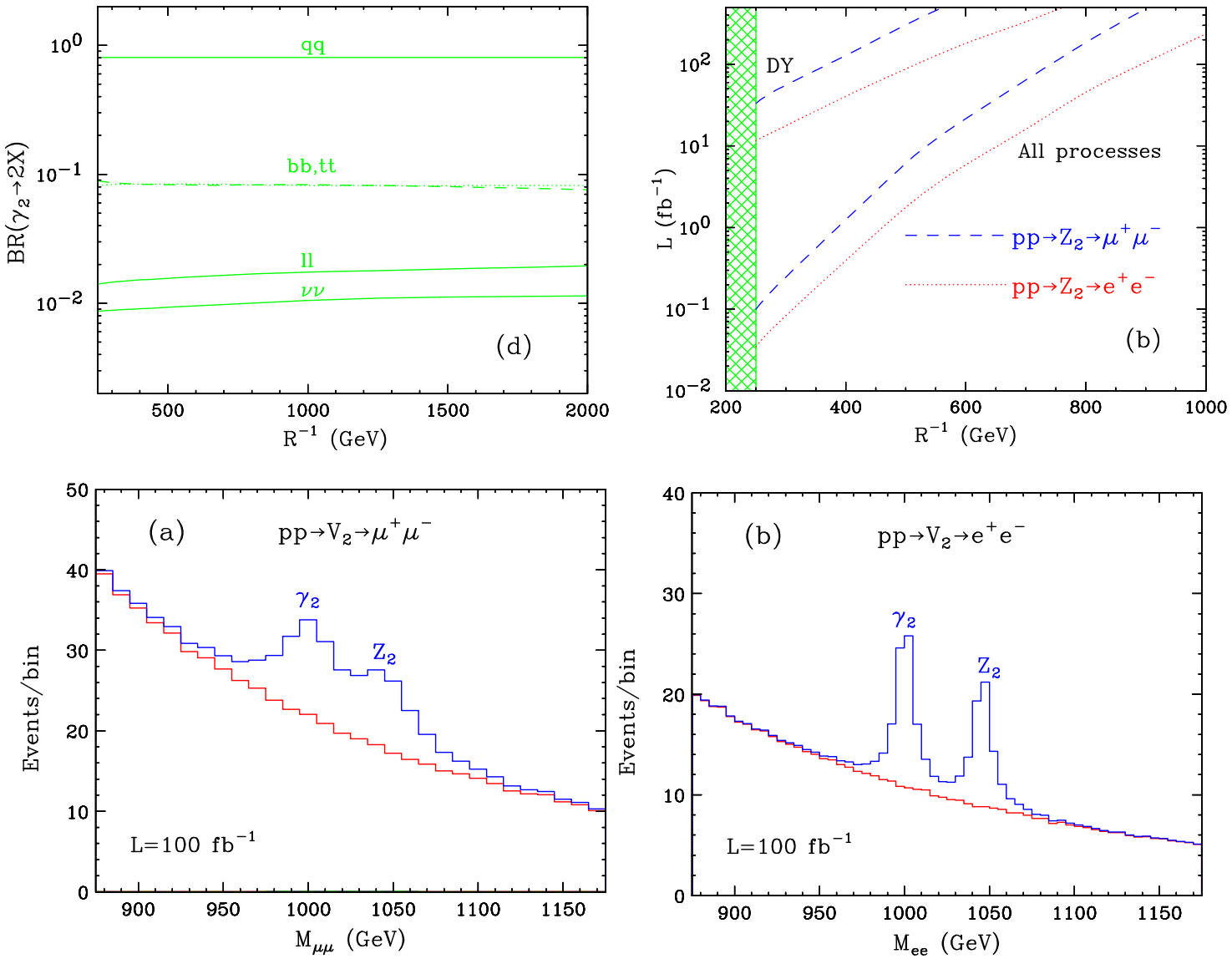


Cheng, Matchev, Schmaltz, 2002



- 4 leptons with large branching fractions

Level 2: KK resonances

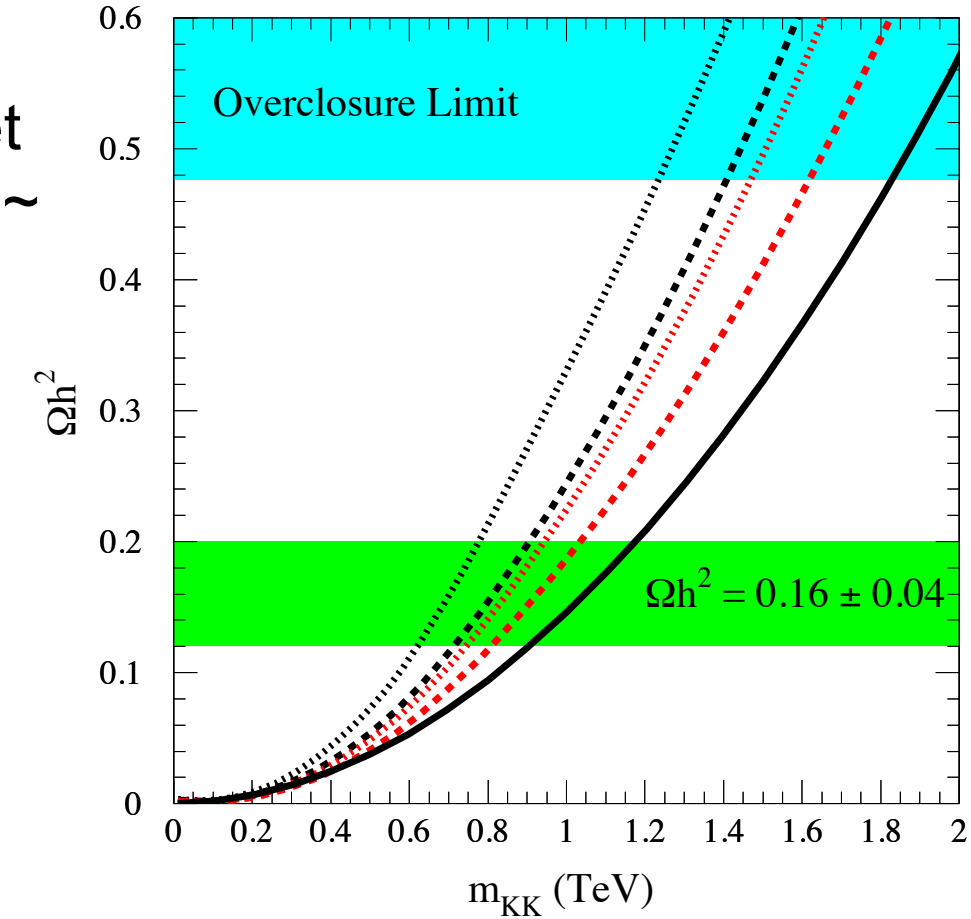


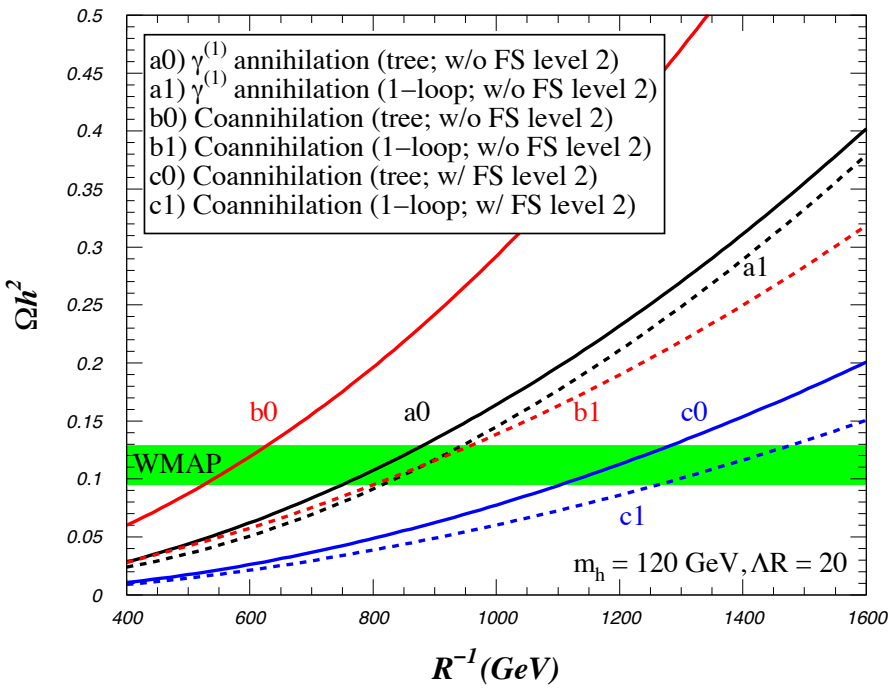
Datta, Kong, Matchev 2005

KK Dark Matter: abundance

- O(1) TeV KK photon
- Coannihilation with SU(2)-singlet KK leptons lowers LKP mass to ~ 600 GeV.

Servant, Tait 2002

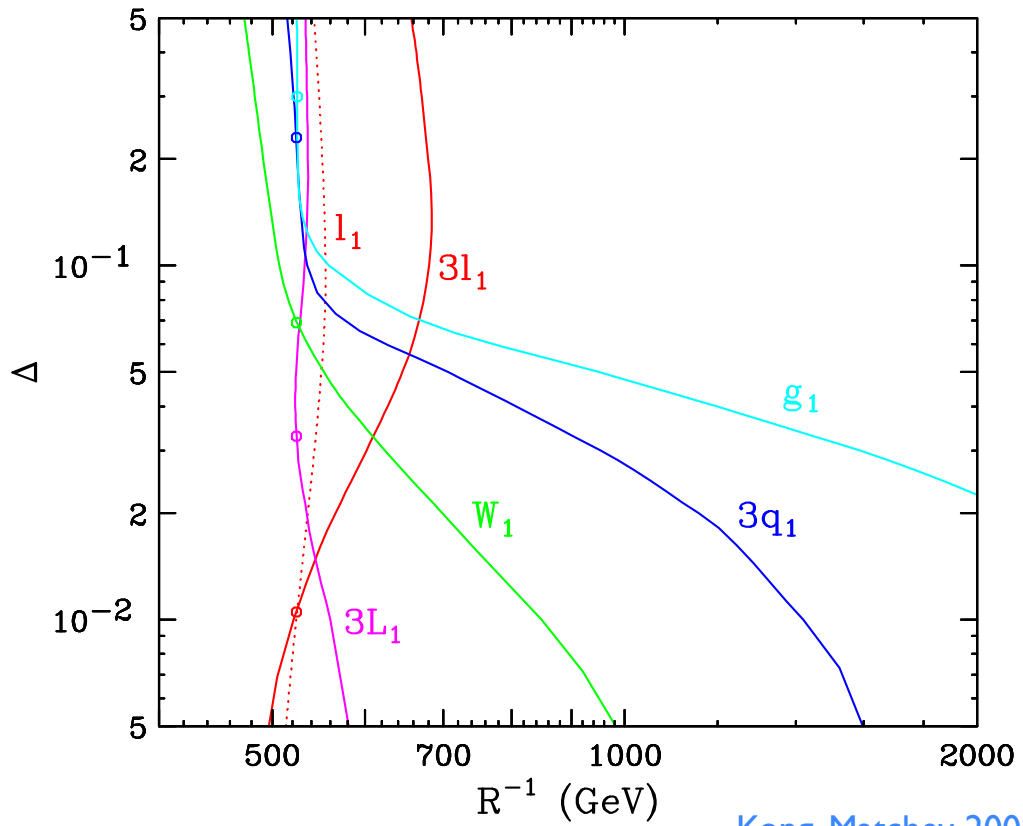




Belanger, Kakizaki, Pukhov, 2010

KK Dark Matter: abundance

- Beyond minimal model, change KK masses one at a time.

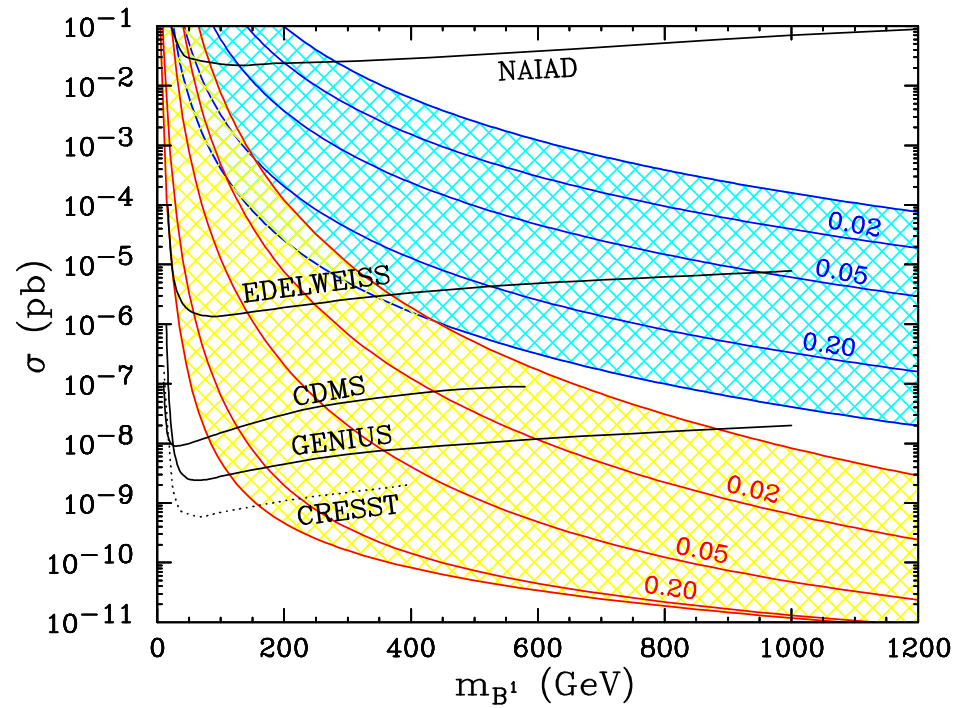


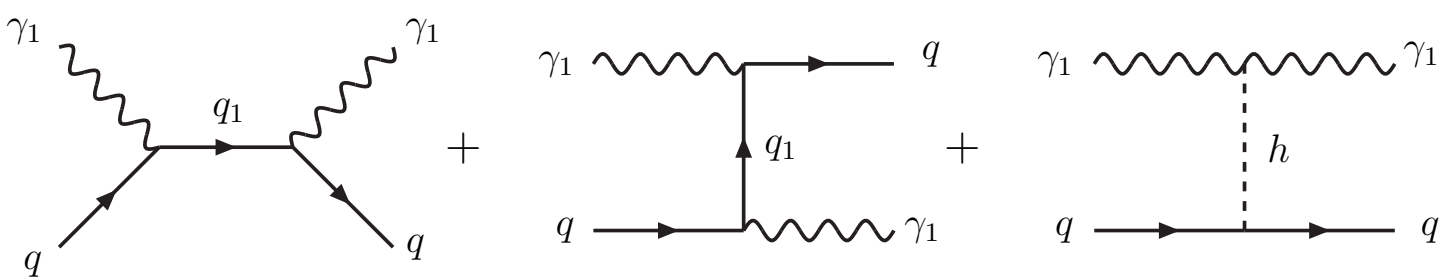
Kong, Matchev 2005

KK Dark Matter: direct detection

- Direct detection hard
- Treat mass splitting as a free parameter (better chance for direct detection)

Cheng, Feng, Matchev 2002

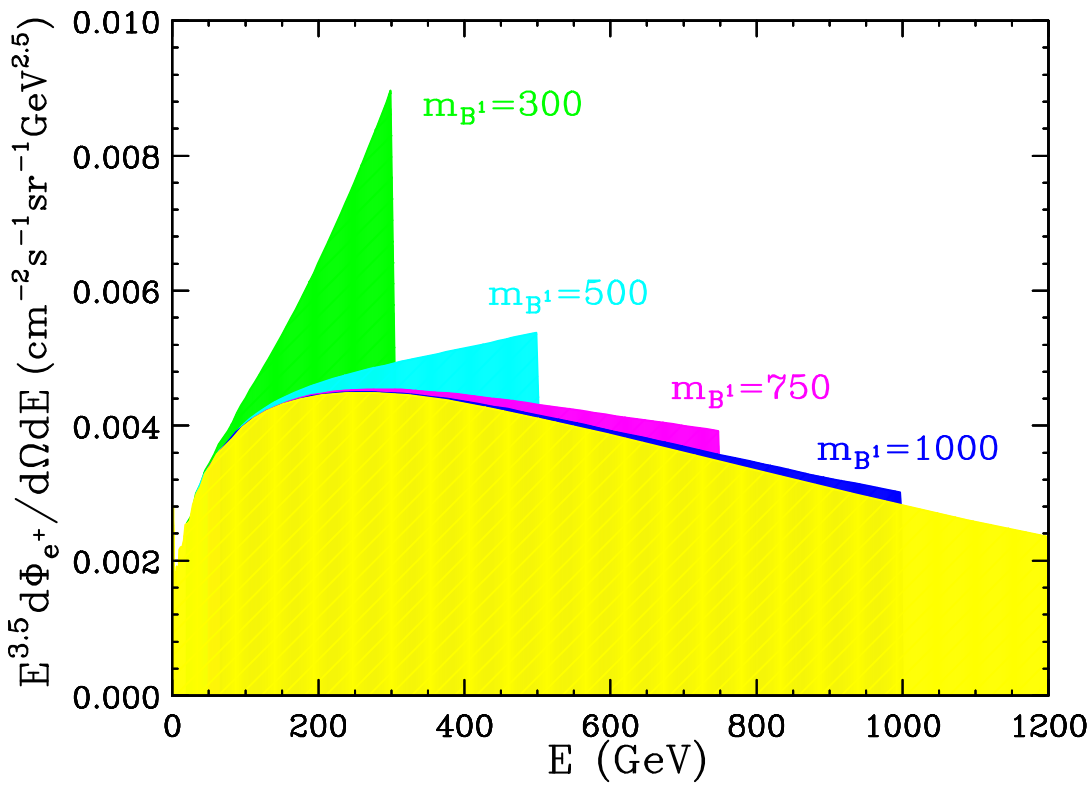




KK Dark Matter: indirect detection

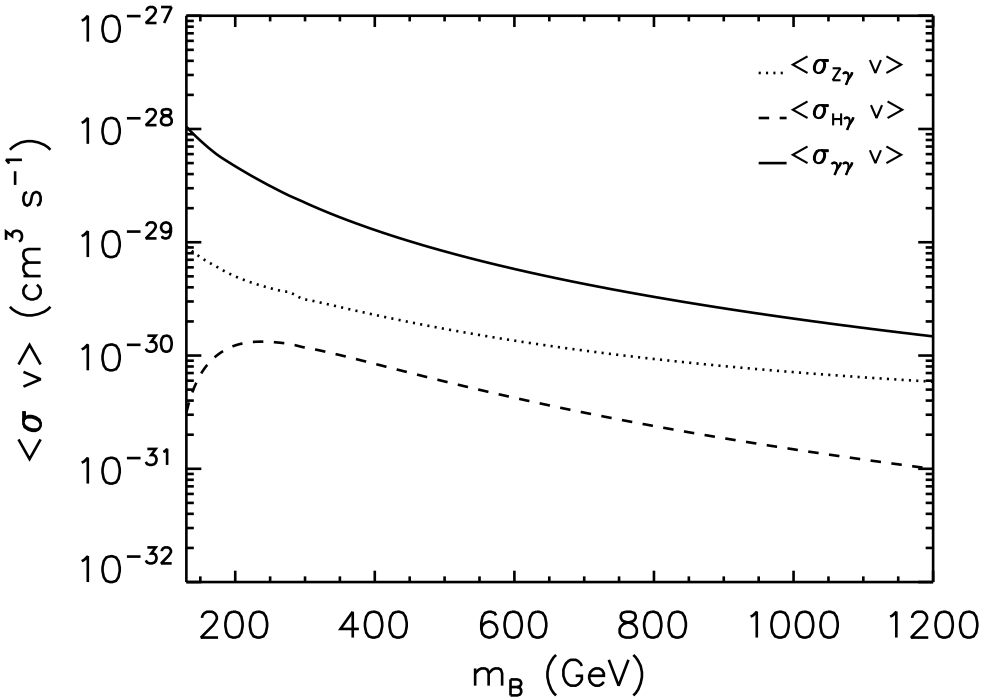
- Indirect detection: lepton final states, positron/neutrino/photon flux

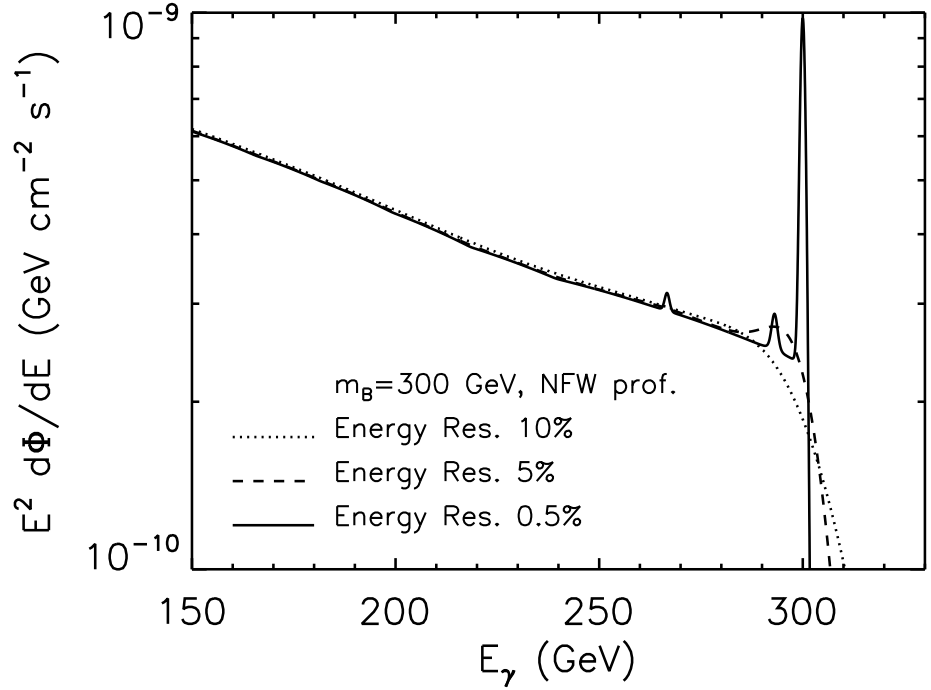
Cheng, Feng, Matchev 2002



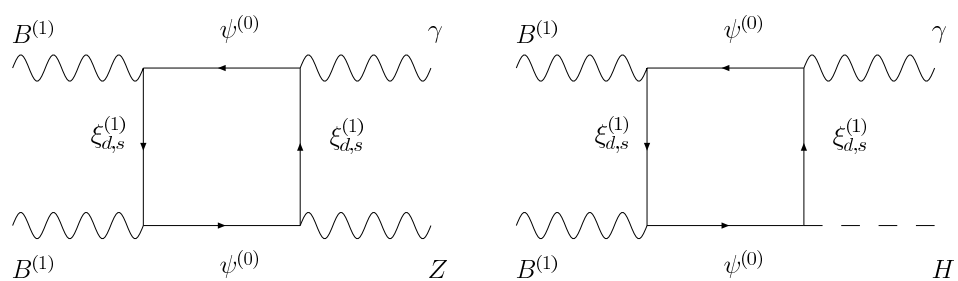
KK Dark Matter: indirect detection

- Indirect detection: lepton final states, positron/neutrino/photon flux





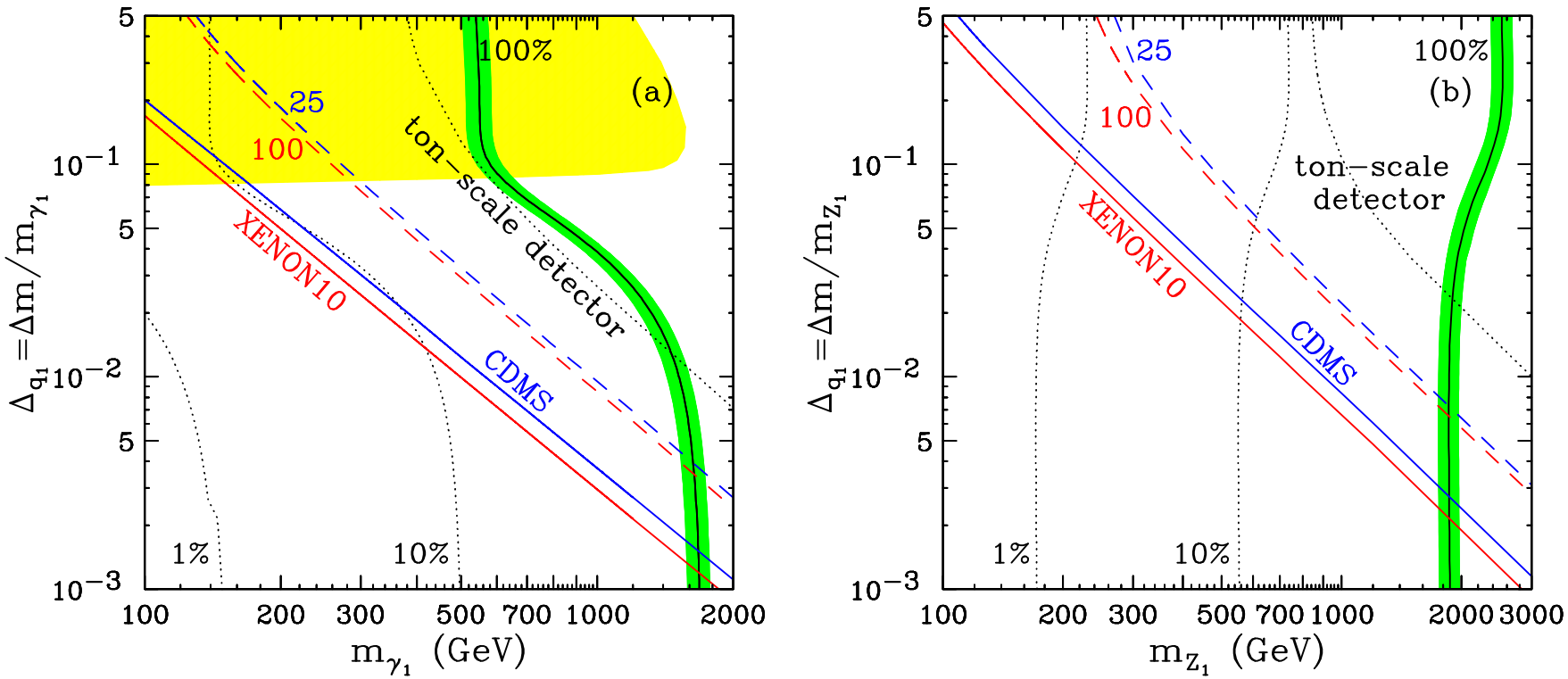
$$E_\gamma = M_{WIMP}\left(1 - \frac{M_X^2}{4M_{WIMP}^2}\right)$$



Bertone, Jackson, Shaughnessy, Tait, Vallinotto 2010

KK Dark Matter: complementarity

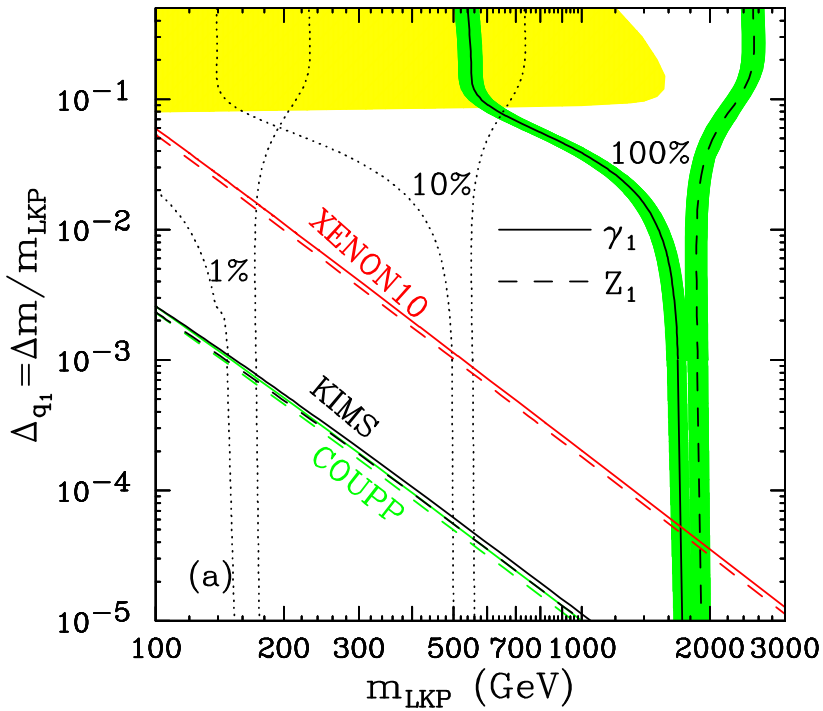
- Treat the LKP mass and mass splitting as free parameters.
- Gives a better chance for the LHC, and direct detection.



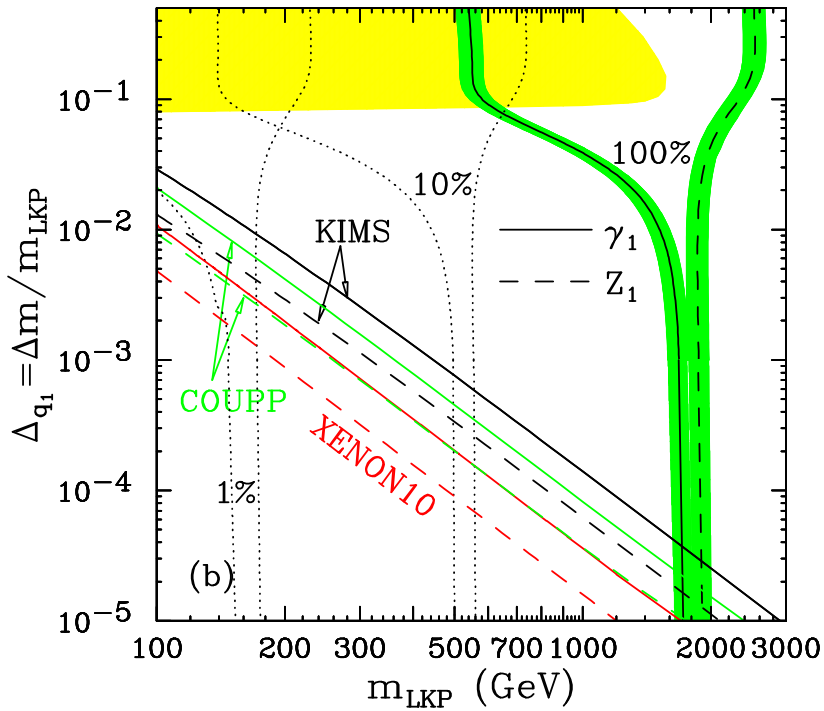
- Yellow: 4 leptons plus MET at 14 TeV LHC with 100 fb-1
- Green: relic abundance

Arrenberg, Baudis, Kong, Matchev, Yoo 2008

- Spin-dependent case



neutron



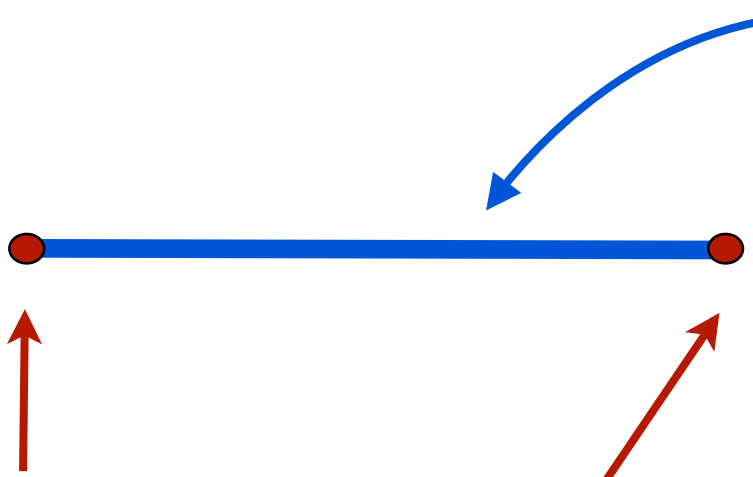
proton

Arrenberg, Baudis, Kong, Matchev, Yoo 2008

NMUED

Flacke, Kong, Park 2013

$$S_5 = \int d^4x \int_{-L}^{L} dy \, [\mathcal{L}_V + \mathcal{L}_\Psi + \mathcal{L}_H + \mathcal{L}_{Yuk}]$$



$$\mathcal{L}_V = \sum_{\mathcal{A}}^{G,W,B} -\frac{1}{4}\mathcal{A}^{MN} \cdot \mathcal{A}_{MN}$$

$$\mathcal{L}_\Psi = \sum_{\Psi}^{Q,U,D,L,E} i\overline{\Psi}\overleftrightarrow{D}_M \Gamma^M \Psi - M_\Psi \overline{\Psi}\Psi$$

$$\mu\theta(y) = M_{Q,L} = -M_{U,D,E}$$

$$M_\Psi(y) = -M_\Psi(-y).$$

$$\mathcal{L}_{\partial V} = \sum_{\mathcal{A}}^{G,W,B} -\frac{r_{\mathcal{A}}}{4}\mathcal{A}_{\mu\nu} \cdot \mathcal{A}^{\mu\nu},$$

$$\mathcal{L}_{\partial\Psi} = \sum_{\Psi=Q,L} i r_\Psi \overline{\Psi}_L D_\mu \gamma^\mu \Psi_L + \sum_{\Psi=U,D,E} i r_\Psi \overline{\Psi}_R D_\mu \gamma^\mu \Psi_R,$$

$$\mathcal{L}_{\partial H} = r_H \left(D_\mu H\right)^\dagger D^\mu H + r_\mu \mu_5^2 |H|^2 - r_\lambda \lambda_5 |H|^4 \,,$$

$$\mathcal{L}_{\partial Yuk} = r_{\lambda^E} \lambda_5^E \overline{L} H E + r_{\lambda^D} \lambda_5^D \overline{Q} H D + r_{\lambda^U} \lambda_5^U \overline{Q} \tilde{H} D + \text{h.c.}$$

$$\mathcal{L}_H = \left(D_M H\right)^\dagger D^M H - V(H),$$

$$V(H) = -\mu_5^2 |H|^2 + \lambda_5 |H|^4 \,,$$

$$\mathcal{L}_{Yuk} = \lambda_5^E \overline{L} H E + \lambda_5^D \overline{Q} H D + \lambda_5^U \overline{Q} \tilde{H} D + \text{h.c.}$$

$$S_{bdy} = \int d^4x \int_{-L}^{L} dy \, \left(\mathcal{L}_{\partial V} + \mathcal{L}_{\partial\Psi} + \mathcal{L}_{\partial H} + \mathcal{L}_{\partial Yuk}\right) \left[\delta(y-L) + \delta(y+L)\right]$$

NMUED

Flacke, Kong, Park 2013

fermion bulk masses $M_{Q,U,D,L,E}$

boundary gauge parameters r_G, r_W, r_B

boundary Higgs parameters r_H, r_μ, r_λ

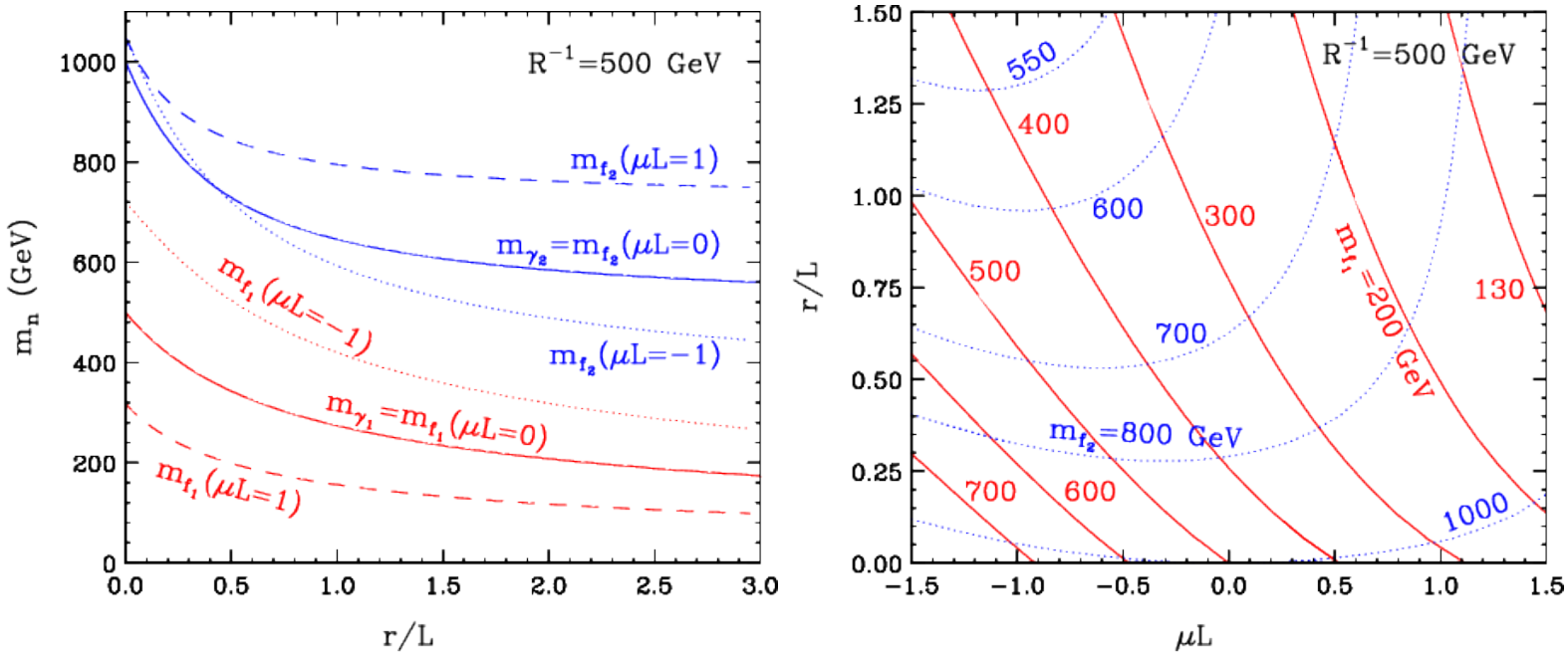
boundary fermion parameters $r_{Q,U,D,L,E}$

boundary Yukawa couplings $r_{\lambda^{U,D,E}}$

- To avoid tree-level FCNC, set all M and r flavor blind -> 19.
- For $r_\mu \neq r_\lambda$, bulk VEV and boundary VEV different.
- To avoid KK mode mixing, set all r's the same.
- Assume universal bulk masses.

NMUED: mass spectrum

Flacke, Kong, Park 2013



NMUED: couplings

Flacke, Kong, Park 2013

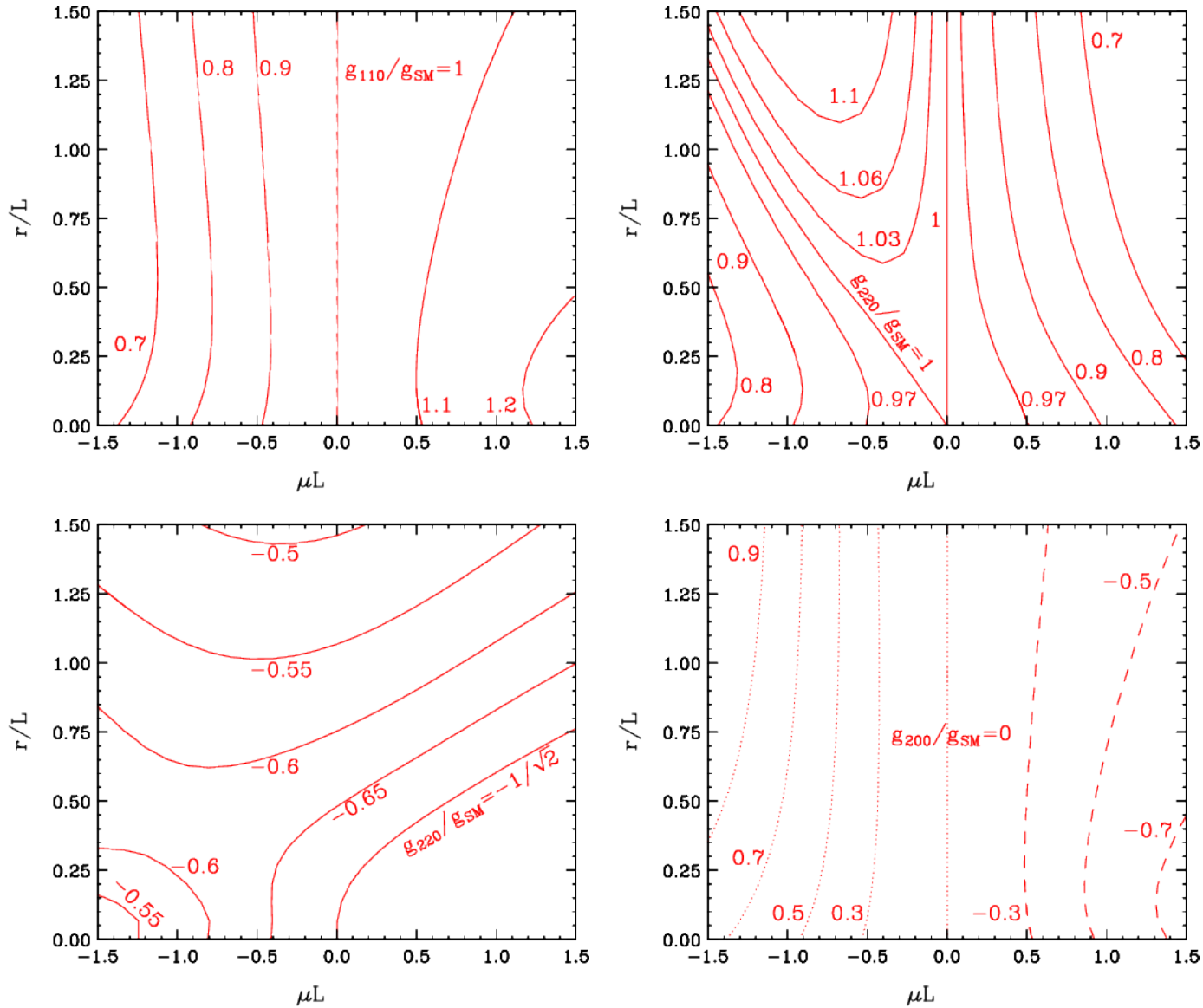
$$g^{\mathcal{A}}_{211} = g^5_{\mathcal{A}} \int dy \left[1 + r\left(\delta(y+L) + \delta(y-L)\right]\right. f^{\mathcal{A}}_2 f^{\Psi_L}_1 f^{\Psi_L}_1 \equiv g^{\mathcal{A}} \mathcal{F}_{211}$$

$$g^{\mathcal{A}}_{200} = g^5_{\mathcal{A}} \int dy \left[1 + r\left(\delta(y+L) + \delta(y-L)\right]\right. f^{\mathcal{A}}_2 f^{\Psi_L}_0 f^{\Psi_L}_0 \equiv g^{\mathcal{A}} \mathcal{F}_{200}$$

$$g^{\mathcal{A}}_{220} = g^5_{\mathcal{A}} \int dy \left[1 + r\left(\delta(y+L) + \delta(y-L)\right]\right. f^{\mathcal{A}}_2 f^{\Psi_L}_2 f^{\Psi_L}_0 \equiv g^{\mathcal{A}} \mathcal{F}_{220}$$

$$g^{\mathcal{A}}_{110} = g^5_{\mathcal{A}} \int dy \left[1 + r\left(\delta(y+L) + \delta(y-L)\right]\right. f^{\mathcal{A}}_1 f^{\Psi_L}_1 f^{\Psi_L}_0 \equiv g^{\mathcal{A}} \mathcal{F}_{110}$$

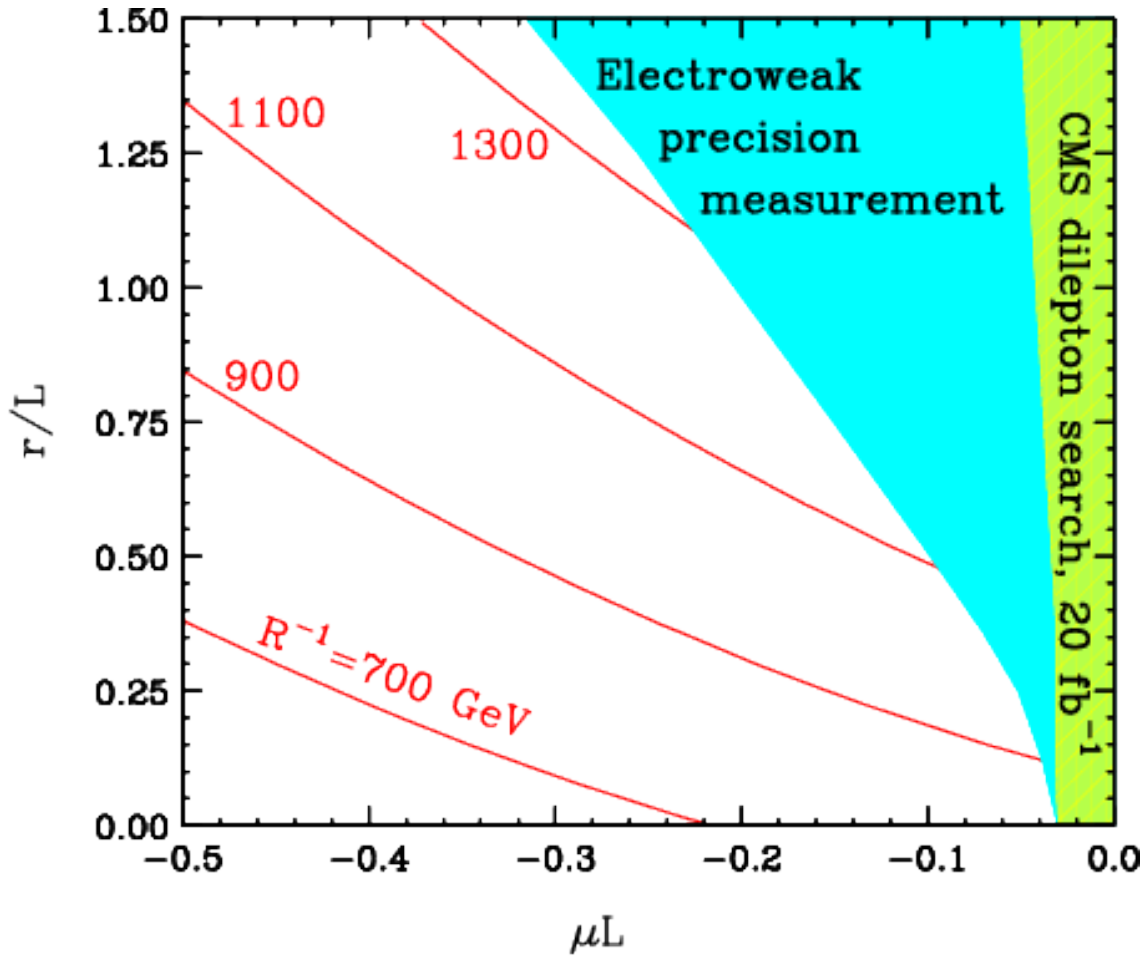
NMUED: couplings



Flacke, Kong, Park 2013

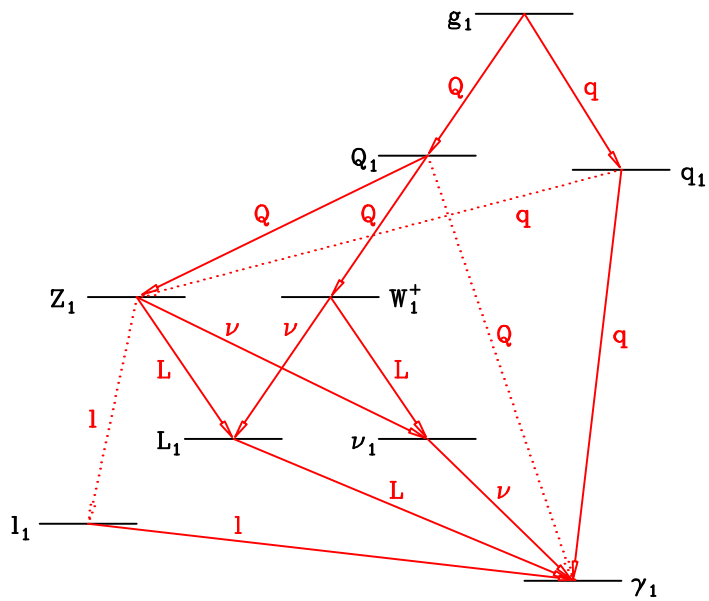
NMUED

Flacke, Kong, Park 2013

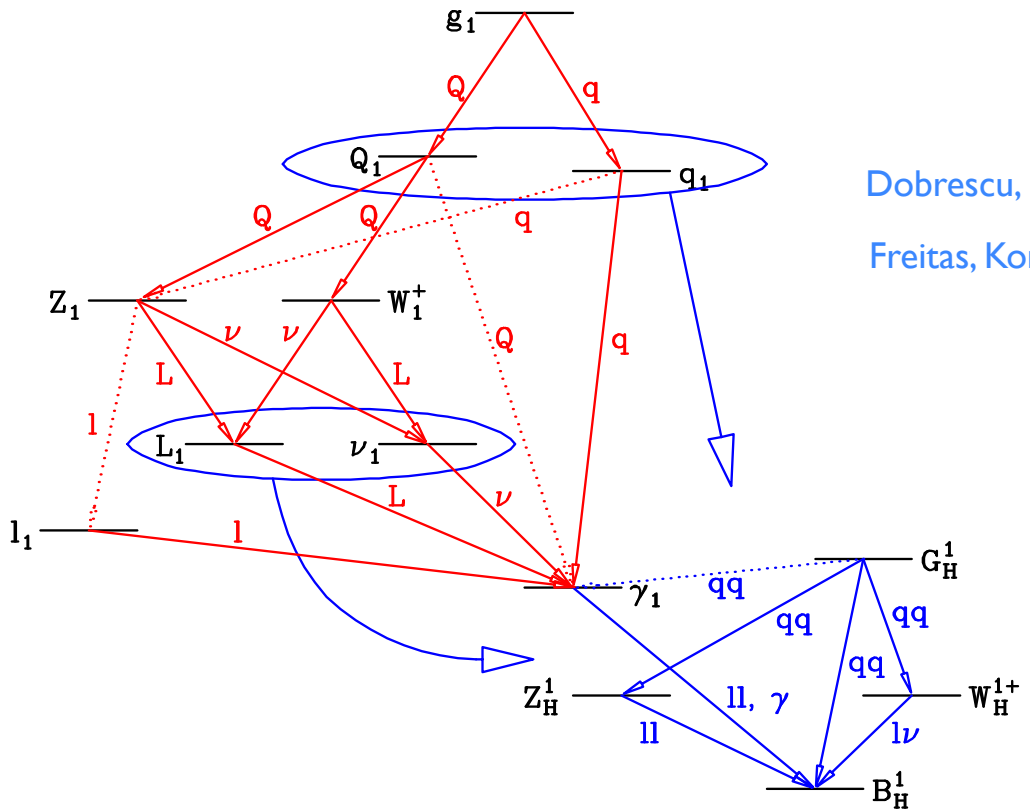


- For universal boundary and universal bulk mass

Two Universal Extra Dimensions



Two Universal Extra Dimensions



Dobrescu, Kong, Mahbubani, 2007

Freitas, Kong 2007

- Extra “spinless” states: GH, ZH, WH, BH
- KK photon is NOT DM and decays to spinless photon via 1-loop or 3 body decay
- Spinless (1,1) decays to top pair

HF4: UED Benchmarks

- We propose the following:
  - Consider 5D UED only
    - 6D model needs to address an issue with DM (too low KK scale)
  - Minimal UED
    - two parameters: R and Lambda (cutoff)
    - cutoff dependence is only logarithmic
    - mass spectrum from radiative correction (no boundary terms)
    - compressed mass spectrum
  - Non-minimal UED with brane terms for strong sector
    - two additional parameters: rG and rQ (for universal brane terms)
  - Signatures (standard SUSY search + resonances)
    - level 1: jets + n-leptons + met, n=0,1,2,3,4
    - level 2: dijet, dilepton and lepton-neutrino final states

Summary I

- UED provides alternative DM candidates
  - spin-1: KK photon, KK Z
  - spin-0: spinless photon, spinless Z, KK Higgs
  - spin-2: KK graviton
  - spin-1/2: KK neutrino
- Different aspect of DM detection
- Natural set up for a model with degenerate mass spectrum
  - Importance of complementarity: LHC vs DD

Summary II

- MUED (5D): two parameters (cutoff, radius of ED)
  - interesting indirect detection: leptons/photons
  - direct detection hard
  - collider: level 1 vs SUSY, level 2 resonances
- 2UED (chiral squre)
  - resembles SUSY DM
  - has an issue with low mass DM and LHC constraints
- Next-to-Minimal UED: bulk-masses, brane kinetic terms
  - detection needs more study

more slides

NMUED

Flacke, Kong, Park 2013

$$S_5 = \int d^4x \int_{-L}^{L} dy \, [\mathcal{L}_V + \mathcal{L}_\Psi + \mathcal{L}_H + \mathcal{L}_{Yuk}]$$

$$\mu\theta(y) = M_{Q,L} = -M_{U,D,E}$$

$$M_\Psi(y) = -M_\Psi(-y).$$

$$\mathcal{L}_V = \sum_{\mathcal{A}}^{G,W,B} -\frac{1}{4}\mathcal{A}^{MN} \cdot \mathcal{A}_{MN}$$

$$\mathcal{L}_\Psi = \sum_{\Psi}^{Q,U,D,L,E} i\overline{\Psi}\overleftrightarrow{D}_M \Gamma^M \Psi - M_\Psi \overline{\Psi}\Psi$$

$$\begin{aligned}
\mathcal{L}_H &= (D_M H)^\dagger D^M H - V(H), \\
V(H) &= -\mu_5^2 |H|^2 + \lambda_5 |H|^4 , \\
\mathcal{L}_{Yuk} &= \lambda_5^E \overline{L} H E + \lambda_5^D \overline{Q} H D + \lambda_5^U \overline{Q} \tilde{H} D + \text{h.c.}
\end{aligned}$$

$$S_{bdy} = \int d^4x \int_{-L}^{L} dy \, (\mathcal{L}_{\partial V} + \mathcal{L}_{\partial\Psi} + \mathcal{L}_{\partial H} + \mathcal{L}_{\partial Yuk}) \, [\delta(y-L) + \delta(y+L)]$$

$$\begin{aligned}
\mathcal{L}_{\partial V} &= \sum_{\mathcal{A}}^{G,W,B} -\frac{r_{\mathcal{A}}}{4}\mathcal{A}_{\mu\nu} \cdot \mathcal{A}^{\mu\nu}, \\
\mathcal{L}_{\partial\Psi} &= \sum_{\Psi=Q,L} i r_\Psi \overline{\Psi}_L D_\mu \gamma^\mu \Psi_L + \sum_{\Psi=U,D,E} i r_\Psi \overline{\Psi}_R D_\mu \gamma^\mu \Psi_R, \\
\mathcal{L}_{\partial H} &= r_H \, (D_\mu H)^\dagger D^\mu H + r_\mu \mu_5^2 |H|^2 - r_\lambda \lambda_5 |H|^4 , \\
\mathcal{L}_{\partial Yuk} &= r_{\lambda^E} \lambda_5^E \overline{L} H E + r_{\lambda^D} \lambda_5^D \overline{Q} H D + r_{\lambda^U} \lambda_5^U \overline{Q} \tilde{H} D + \text{h.c.}
\end{aligned}$$

NMUED

Flacke, Kong, Park 2013

fermion bulk masses $M_{Q,U,D,L,E}$

boundary gauge parameters r_G, r_W, r_B

boundary Higgs parameters r_H, r_μ, r_λ

boundary fermion parameters $r_{Q,U,D,L,E}$

boundary Yukawa couplings $r_{\lambda^{U,D,E}}$

- To avoid tree-level FCNC, set all M and r flavor blind -> 19.
- For $r_\mu \neq r_\lambda$, bulk VEV and boundary VEV different.
- To avoid KK mode mixing, set all r's the same.
- Assume universal bulk masses.

NMUED: Fermions

$$\Psi(x,y) = \sum_{n=0}^{\infty} \left(\psi_L^{(n)}(x) f_n^{\Psi_L}(y) + \psi_R^{(n)}(x) f_n^{\Psi_R}(y) \right) \qquad m_{\Psi_n} = \sqrt{m_{f_n}^2 + m_\Psi^2}, \qquad m_{f_n} = \sqrt{k_n^2 + \mu^2},$$

$$\int_{-L}^{L} dy\, f_m^{\Psi_L} f_n^{\Psi_L} [1 + r\,(\delta(y+L) + \delta(y-L)] = \delta_{mn},$$

$$\int_{-L}^{L} dy\, f_m^{\Psi_R} f_n^{\Psi_R} = \delta_{mn}.$$

$$\begin{aligned} k_n \cos(k_n L) &= (r\,(m_{f_n})^2 + \mu) \sin(k_n L) && \text{for odd n}\,, \\ r k_n \cos(k_n L) &= -(1 + r\mu) \sin(k_n L) && \text{for even n}\,, \end{aligned}$$

$$n = 0: \quad f_0^{\Psi_L} = \mathcal{N}_0^\Psi e^{\mu|y|},$$

$$\text{odd } n: \quad \begin{cases} f_n^{\Psi_L} = \mathcal{N}_n^\Psi \sin(k_n y)\,, \\ f_n^{\Psi_R} = \mathcal{N}_n^\Psi \left(-\frac{k_n}{m_{f_n}} \cos(k_n y) + \frac{\mu}{m_{f_n}} \theta(y) \sin(k_n y) \right)\,, \end{cases}$$

$$\text{even } n: \quad \begin{cases} f_n^{\Psi_L} = \mathcal{N}_n^\Psi \left(\frac{k_n}{m_{f_n}} \cos(k_n y) + \frac{\mu}{m_{f_n}} \theta(y) \sin(k_n y) \right)\,, \\ f_n^{\Psi_R} = \mathcal{N}_n^\Psi \sin(k_n y)\,. \end{cases}$$

Flacke, Kong, Park 2013

NMUED: Bosons

Flacke, Kong, Park 2013

$$\mathcal{A}_\mu(x,y) = \sum_{n=0}^{\infty} \mathcal{A}_\mu^{(n)}(x) f_n^{\mathcal{A}}(y)\,,$$

$$H(x,y) = \sum_{n=0}^{\infty} H^{(n)}(x) f_n^{\mathcal{A}}(y)\,.$$

$$m_{\mathcal{A}_n} = \sqrt{k_n^2 + m_{\mathcal{A}_0}^2},$$

$$\begin{aligned} \cot(k_n L) &= r k_n \quad \text{for odd n,} \\ \tan(k_n L) &= -r k_n \quad \text{for even n}\,, \end{aligned}$$

$$n = 0: \quad f_0^{\mathcal{A}}(y) = \frac{1}{\sqrt{2L(1+\frac{r}{L})}}$$

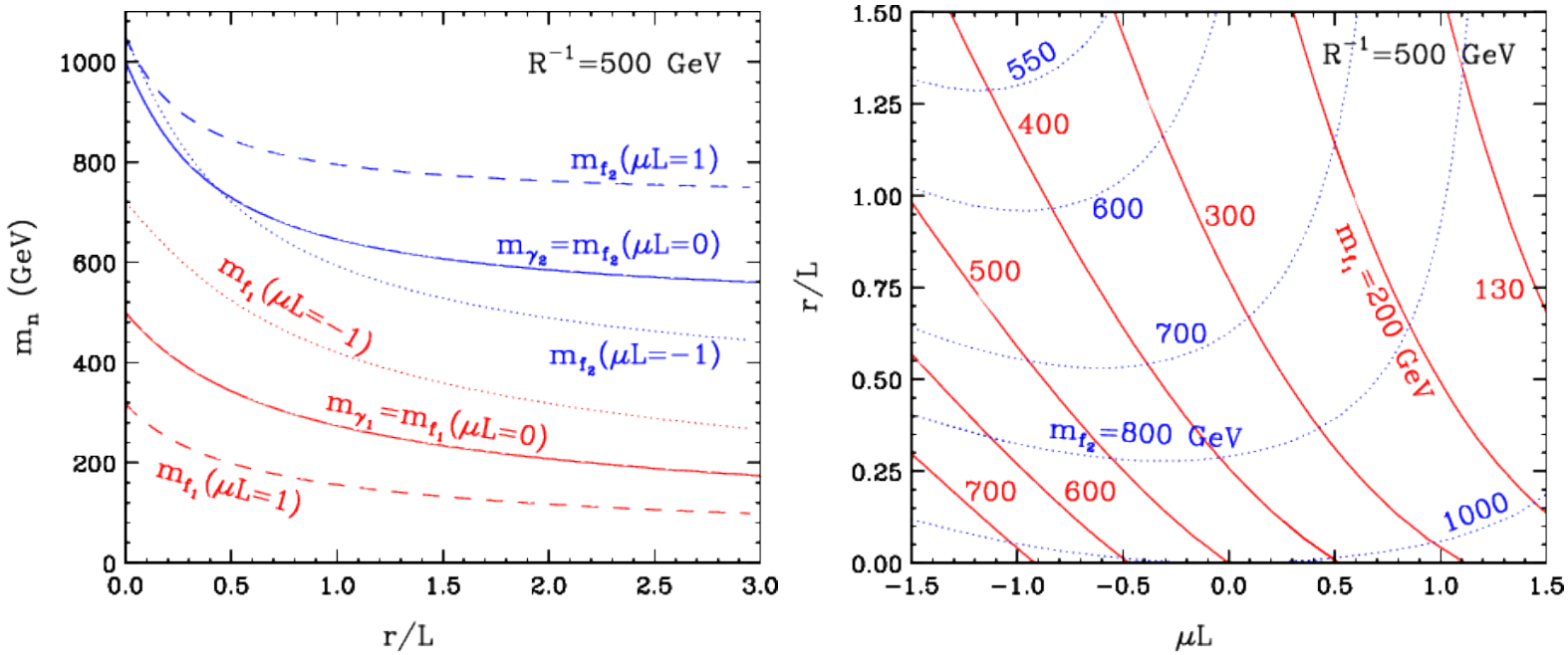
$$\text{odd } n: \quad f_n^{\mathcal{A}}(y) = \sqrt{\frac{1}{L + r\sin^2(k_n L)}}\sin(k_n y)\,,$$

$$\text{even } n: \quad f_n^{\mathcal{A}}(y) = \sqrt{\frac{1}{L + r\cos^2(k_n L)}}\cos(k_n y)\,,$$

$$\int_{-L}^{L} dy\, f_m^{\mathcal{A}} f_n^{\mathcal{A}} \left[1 + r\left(\delta(y+L) + \delta(y-L)\right)\right] = \delta_{mn}.$$

NMUED: mass spectrum

Flacke, Kong, Park 2013



NMUED: couplings

Flacke, Kong, Park 2013

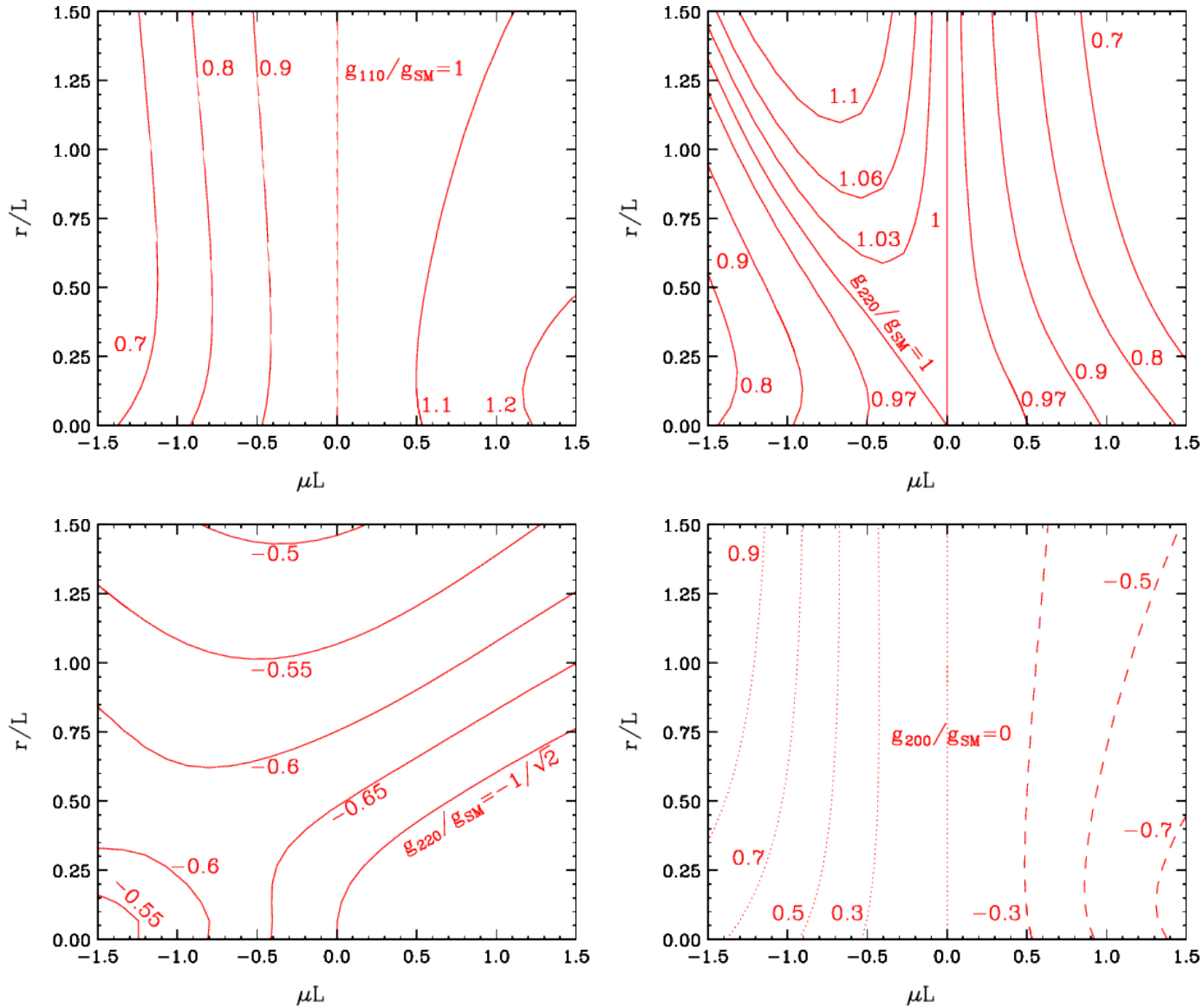
$$g^{\mathcal{A}}_{211} = g^5_{\mathcal{A}} \int dy \left[1 + r\left(\delta(y+L) + \delta(y-L)\right]\right. f^{\mathcal{A}}_2 f^{\Psi_L}_1 f^{\Psi_L}_1 \equiv g^{\mathcal{A}} \mathcal{F}_{211}$$

$$g^{\mathcal{A}}_{200} = g^5_{\mathcal{A}} \int dy \left[1 + r\left(\delta(y+L) + \delta(y-L)\right]\right. f^{\mathcal{A}}_2 f^{\Psi_L}_0 f^{\Psi_L}_0 \equiv g^{\mathcal{A}} \mathcal{F}_{200}$$

$$g^{\mathcal{A}}_{220} = g^5_{\mathcal{A}} \int dy \left[1 + r\left(\delta(y+L) + \delta(y-L)\right]\right. f^{\mathcal{A}}_2 f^{\Psi_L}_2 f^{\Psi_L}_0 \equiv g^{\mathcal{A}} \mathcal{F}_{220}$$

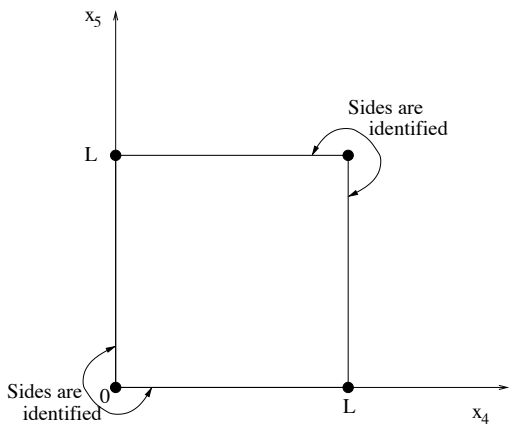
$$g^{\mathcal{A}}_{110} = g^5_{\mathcal{A}} \int dy \left[1 + r\left(\delta(y+L) + \delta(y-L)\right]\right. f^{\mathcal{A}}_1 f^{\Psi_L}_1 f^{\Psi_L}_0 \equiv g^{\mathcal{A}} \mathcal{F}_{110}$$

NMUED: couplings

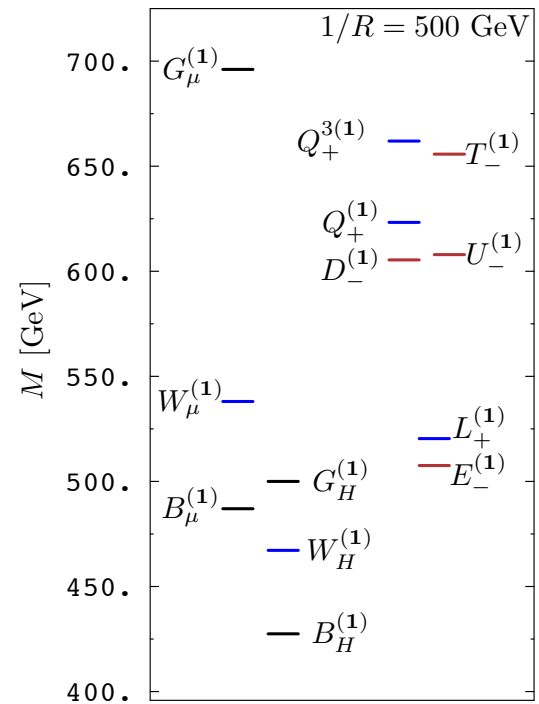


Flacke, Kong, Park 2013

Two Universal Extra Dimensions

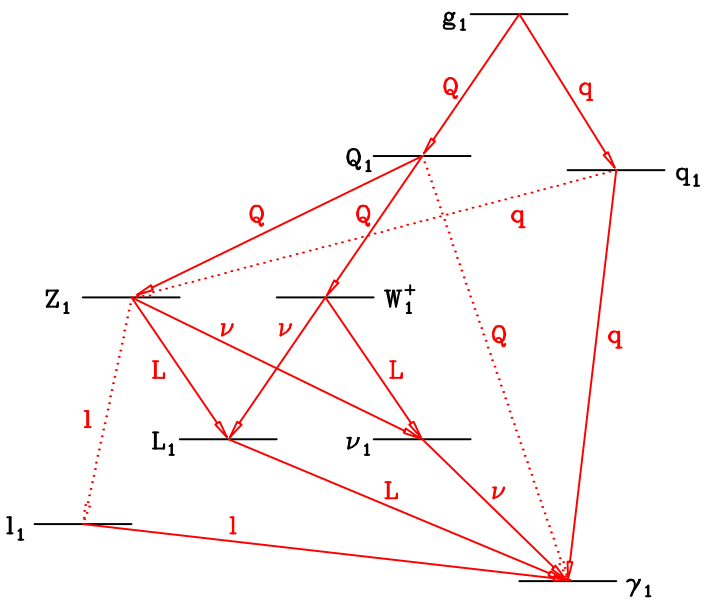


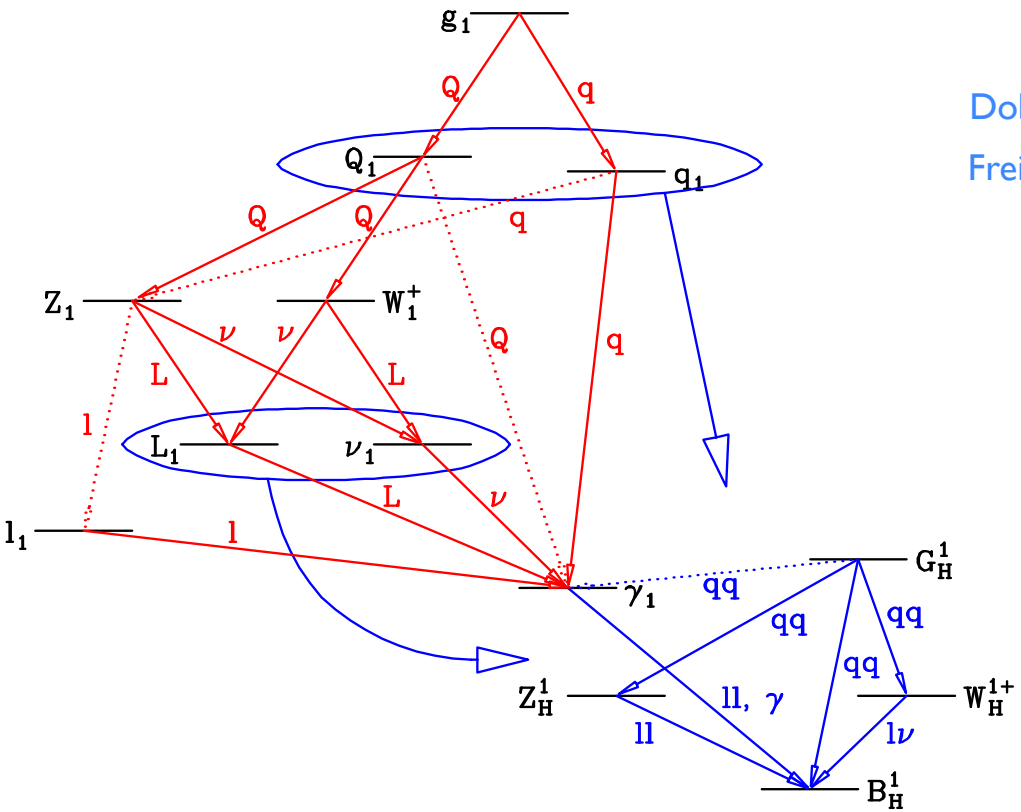
boson	MR	fermion	MR
$G_\mu^{(\mathbf{1})}$	1.392	$Q_+^{(\mathbf{1})3}$	$1.265 + \frac{1}{2}(m_t R)^2$
$W_\mu^{(\mathbf{1})}$	$1.063 + \frac{1}{2}(M_W R)^2$	$T_-^{(\mathbf{1})}$	$1.252 + \frac{1}{2}(m_t R)^2$
$G_H^{(\mathbf{1})}$	1.0	$Q_+^{(\mathbf{1})}$	1.247
$B_\mu^{(\mathbf{1})}$	0.974	$U_-^{(\mathbf{1})}$	1.216
$W_H^{(\mathbf{1})}$	$0.921 + \frac{1}{2}(m_W R)^2$	$D_-^{(\mathbf{1})}$	1.211
$B_H^{(\mathbf{1})}$	0.855	$L_+^{(\mathbf{1})}$	1.041
		$E_-^{(\mathbf{1})}$	1.015



Dobrescu, Kong, Mahbubani, 2007

Burdman, Dobrescu, Ponton, 2006


g_1
Q
q
Q_1
q_1
Q
Q
q
Z_1
W_1^+
ν
ν
Q
q
L
L
l
L_1
ν_1
L
ν
l_1
l
γ_1



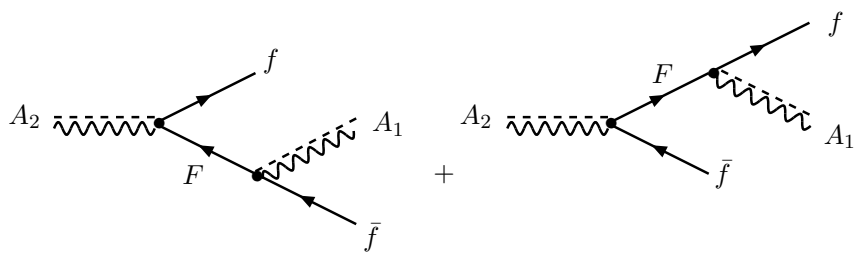
Dobrescu, Kong, Mahbubani, 2007

Freitas, Kong 2007

- Extra “spinless” states: GH, ZH, WH, BH
- KK photon is NOT DM and decays to spinless photon via 1-loop or 3 body decay
- Spinless (1,1) decays to top pair

Decay of KK photon

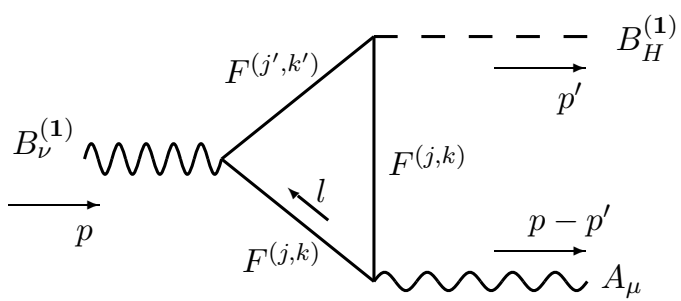
- 3 body decay



$$\mathrm{Br}\left(B_\mu^{(\mathbf{1})} \to B_H^{(\mathbf{1})}\gamma\right) \equiv b_{B\gamma} \approx 34.0\%$$

$$\mathrm{Br}\left(B_\mu^{(\mathbf{1})} \to B_H^{(\mathbf{1})}e^+e^-\right) \equiv b_{Be} \approx 21.3\%$$

- 1-loop 2-body decay



$$-\frac{R}{4}\left(\mathcal{C}_B\epsilon^{\mu\nu\alpha\beta}F_{\mu\nu}B_{\alpha\beta}^{(\mathbf{1})}B_H^{(\mathbf{1})} + \mathcal{C}_G\epsilon^{\mu\nu\alpha\beta}G_{\mu\nu}B_{\alpha\beta}^{(\mathbf{1})}G_H^{(\mathbf{1})}\right)$$

Dobrescu, Kong, Mahbubani, 2007