Next-to-Minimal Universal Extra Dimensions

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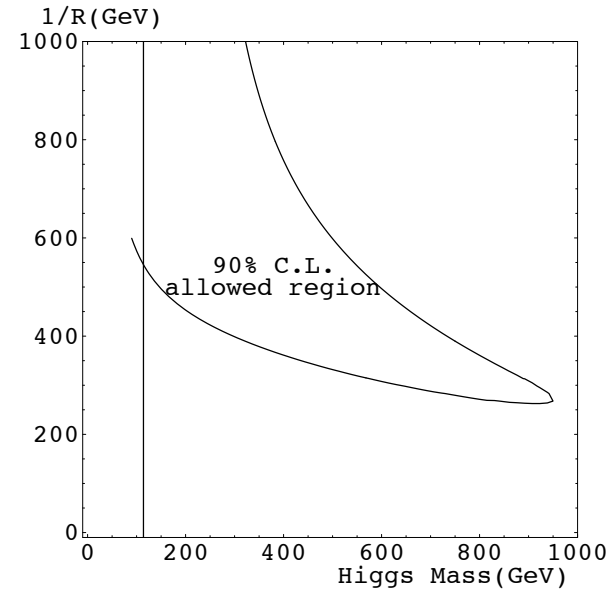
Outline

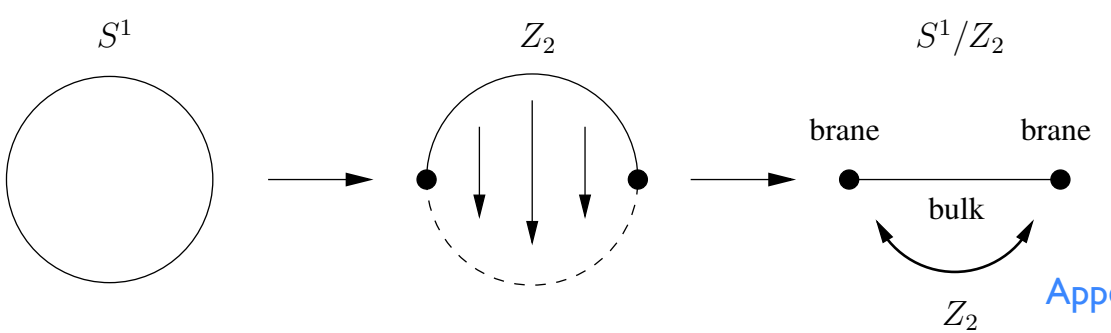
- Review on UED (back in 2001)
  - collider and dark matter
  - 5D and 6D
  - current LHC bounds (2012)
- Discrimination between “UED” and “SUSY”
  - spins and level-2 resonances
- Beyond minimal UED (2013)
  - more parameters

Overview on UED

- Universal: all SM particles in flat ED (no gravity)
- The simplest model: S1/Z2 (5D)
- KK tower after compactification with n/R
- KK-parity: $(-1)^n$
  - 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



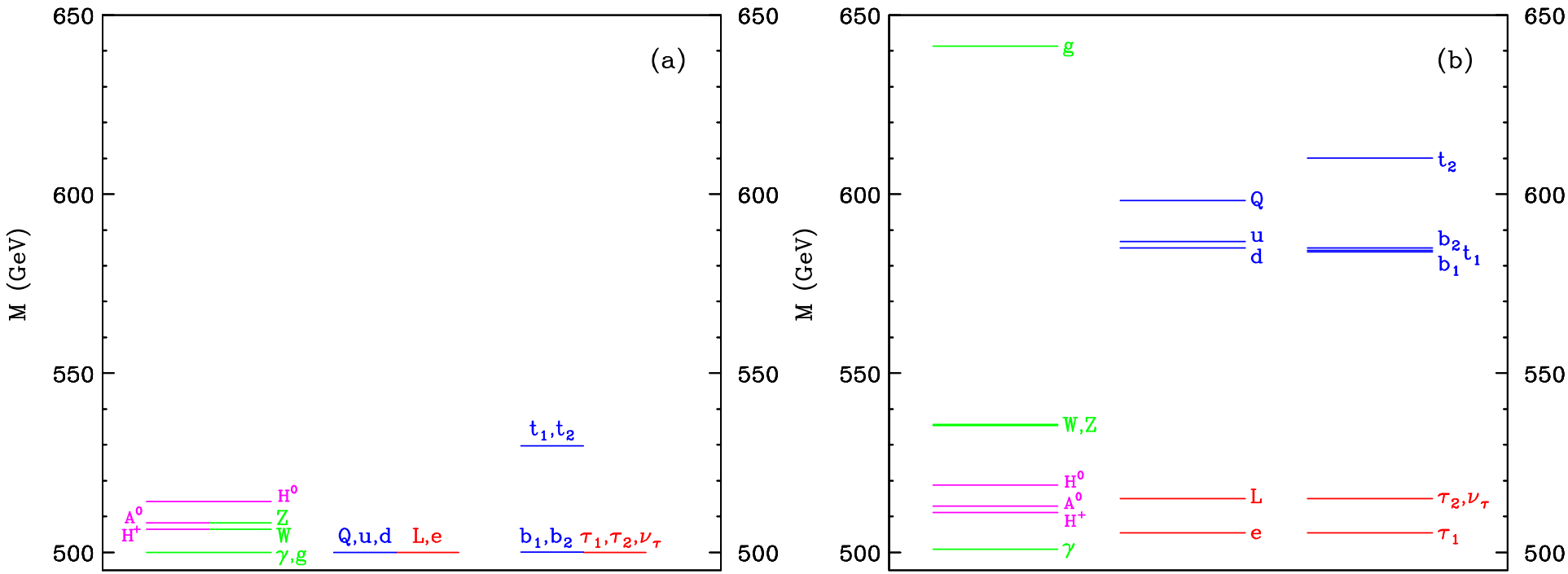
Appelquist, Yee 2002



Appelquist, Cheng, Dobrescu 2001

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
- Two parameters: R, Lambda (cutoff)



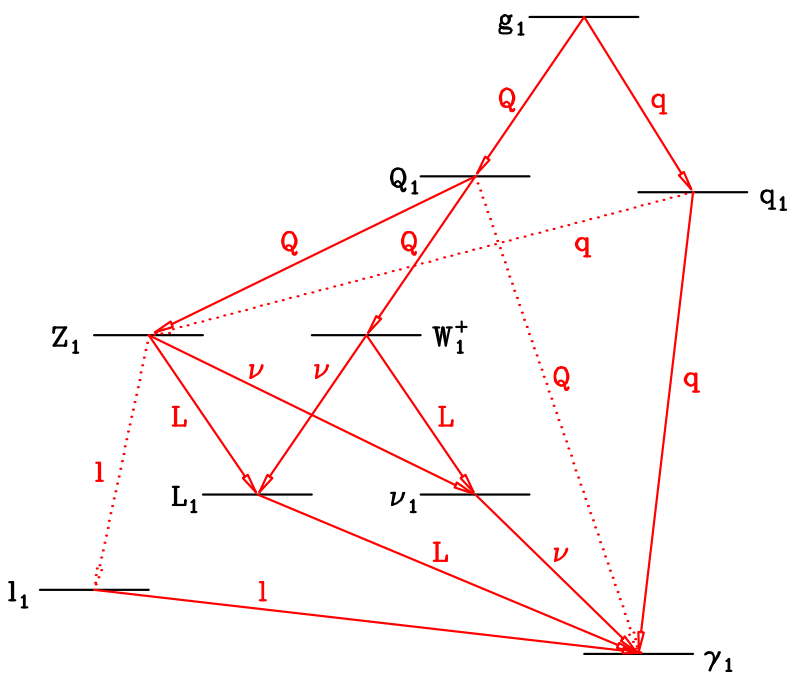
1/R = 500 GeV

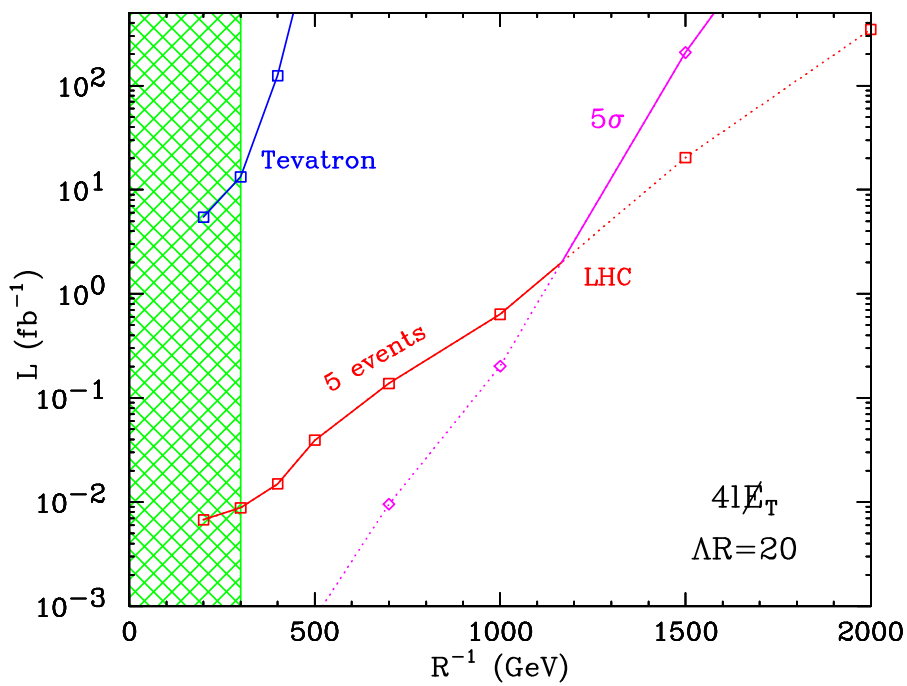
Cheng, Matchev, Schmaltz, 2002

More on UED

- Two parameters: R, Lambda (cutoff)
- The same spin: SM and KK partners
- Larger production cross sections (compared to SUSY productions), i.e., KK gluon, KK quark productions
- Decay products are softer
- 4 leptons with large branching fractions

0205314, Cheng, Matchev, Schmaltz





KK Photon Dark Matter

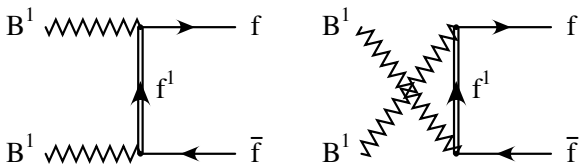


Figure 4: Feynman diagrams for $B^{(1)}B^{(1)}$ annihilation into fermions.

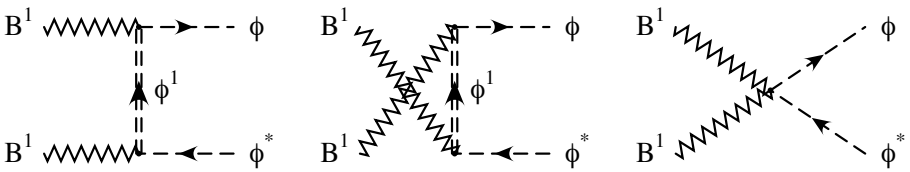
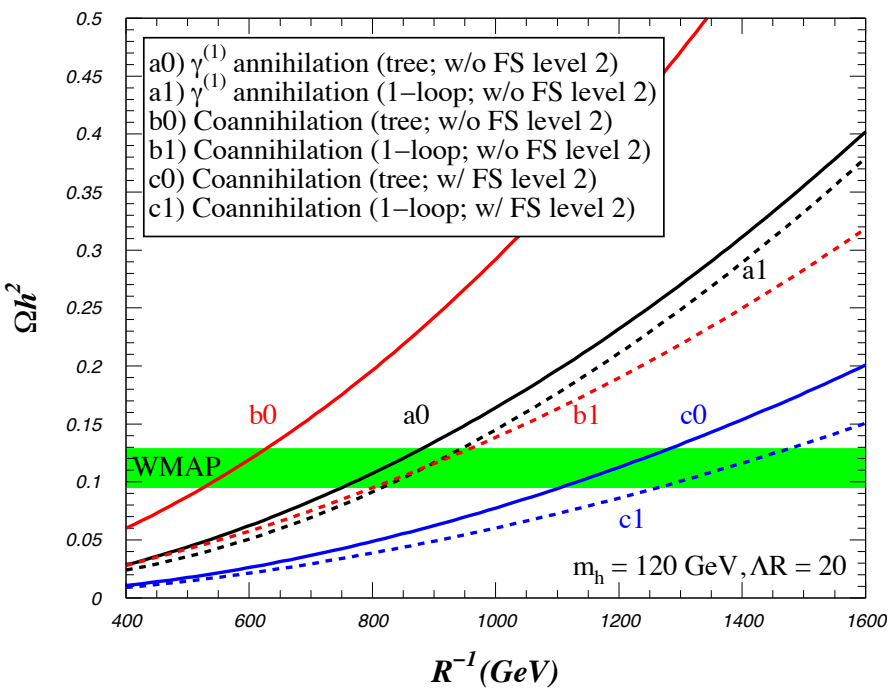
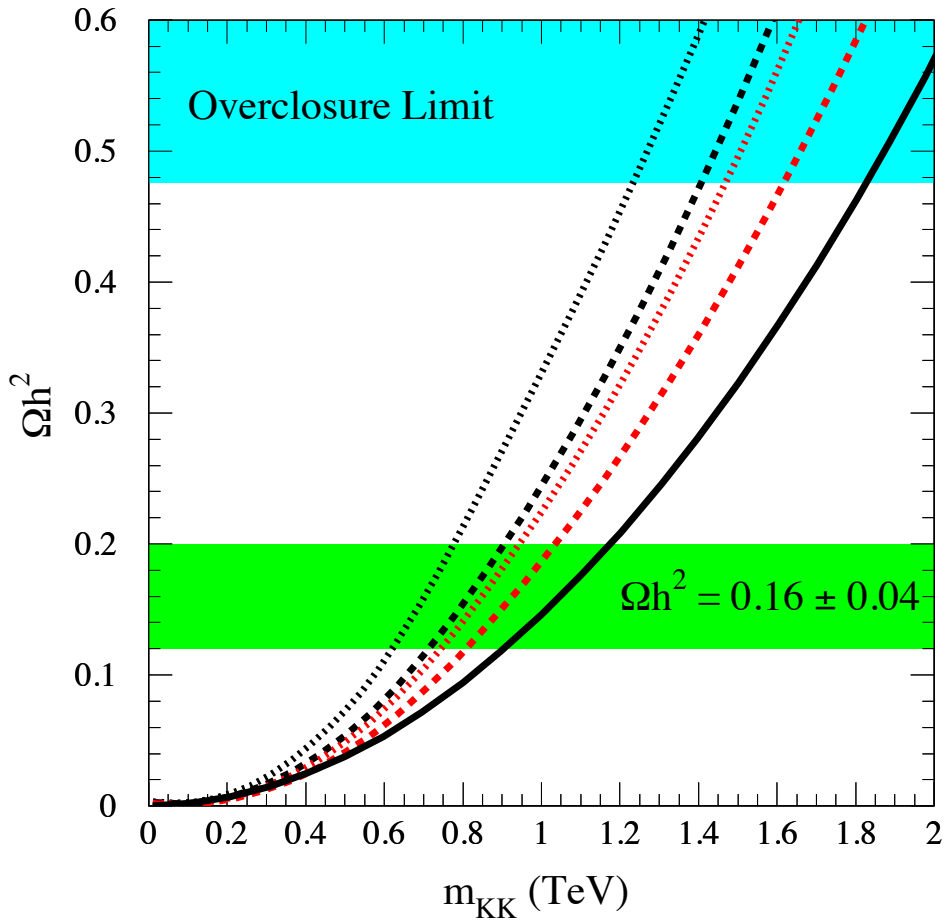


Figure 5: Feynman diagrams for $B^{(1)}B^{(1)}$ annihilation into Higgs scalar bosons.



Servant, Tait 2002

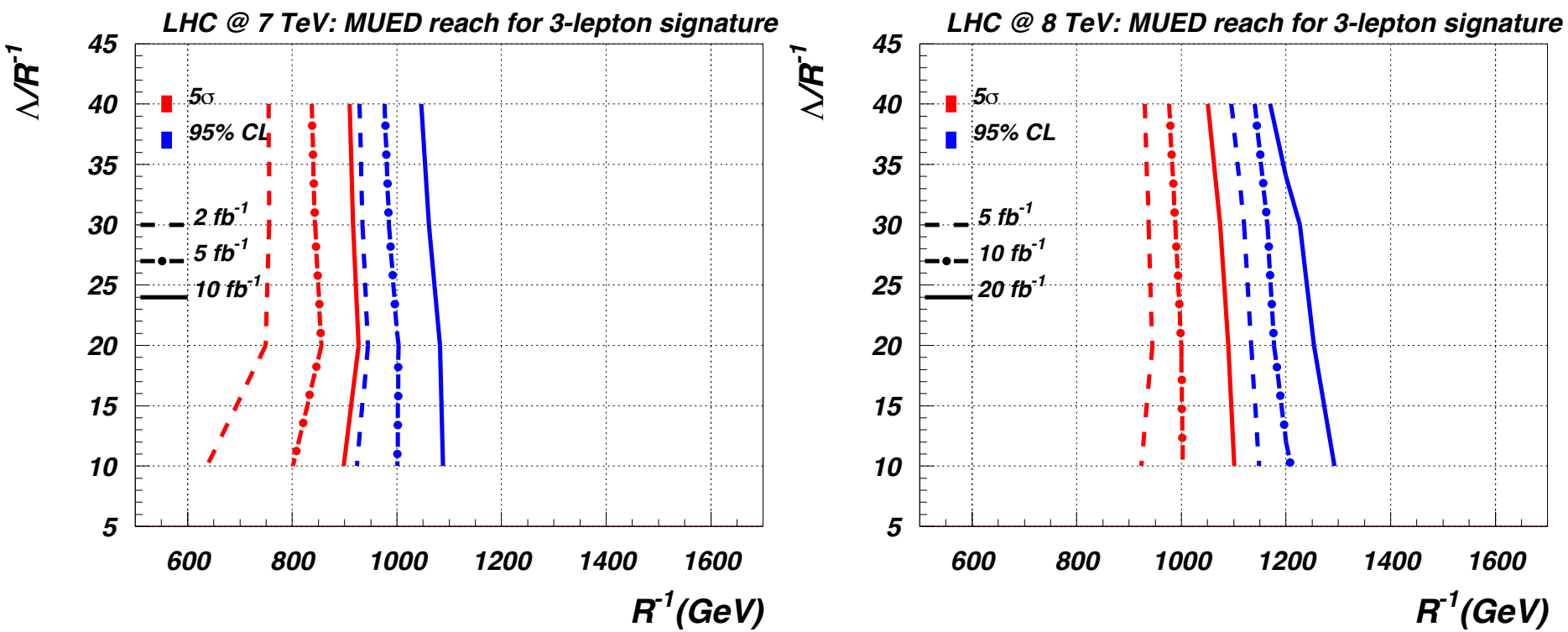


Belanger, Kakizaki, Pukhov, 2010

Kong, Matchev, 2005

Current bounds from LHC

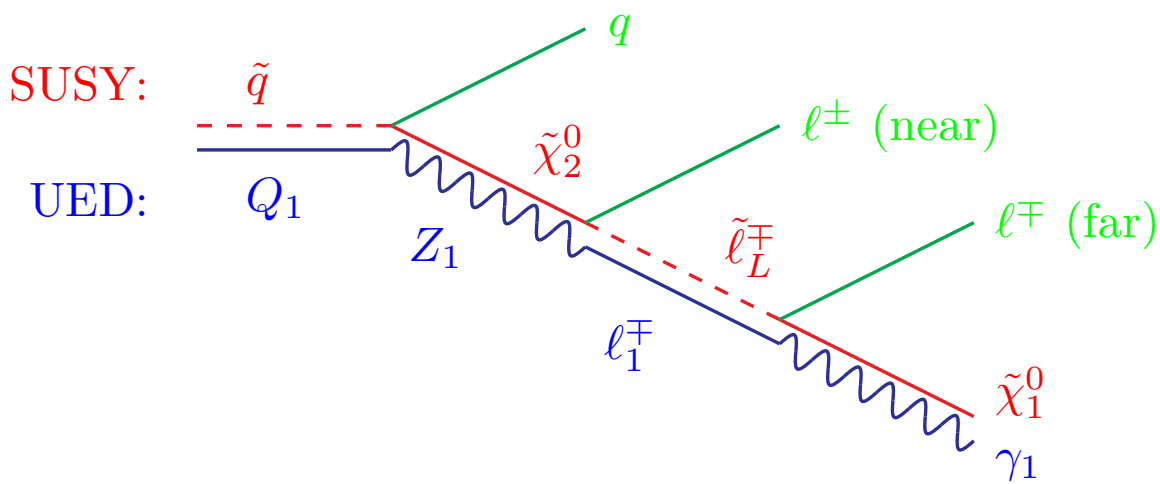
Belyaev, Brown, Moreno, Papineau 2012



- Collider and low energy experiments provide lower bound on KK scale (1/R)
- Minimal UED (2 parameters) is very constrained
- Cutoff dependence is logarithmic

SUSY vs UED

- SUSY-like cascade decays at the LHC from the first KK modes.



- Distinct feature: 2nd KK modes.

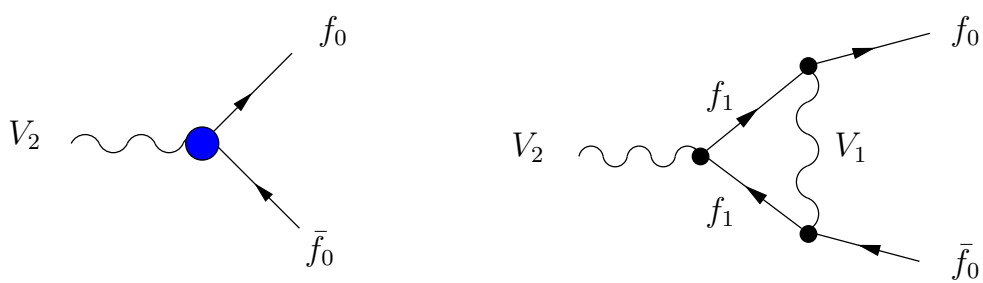
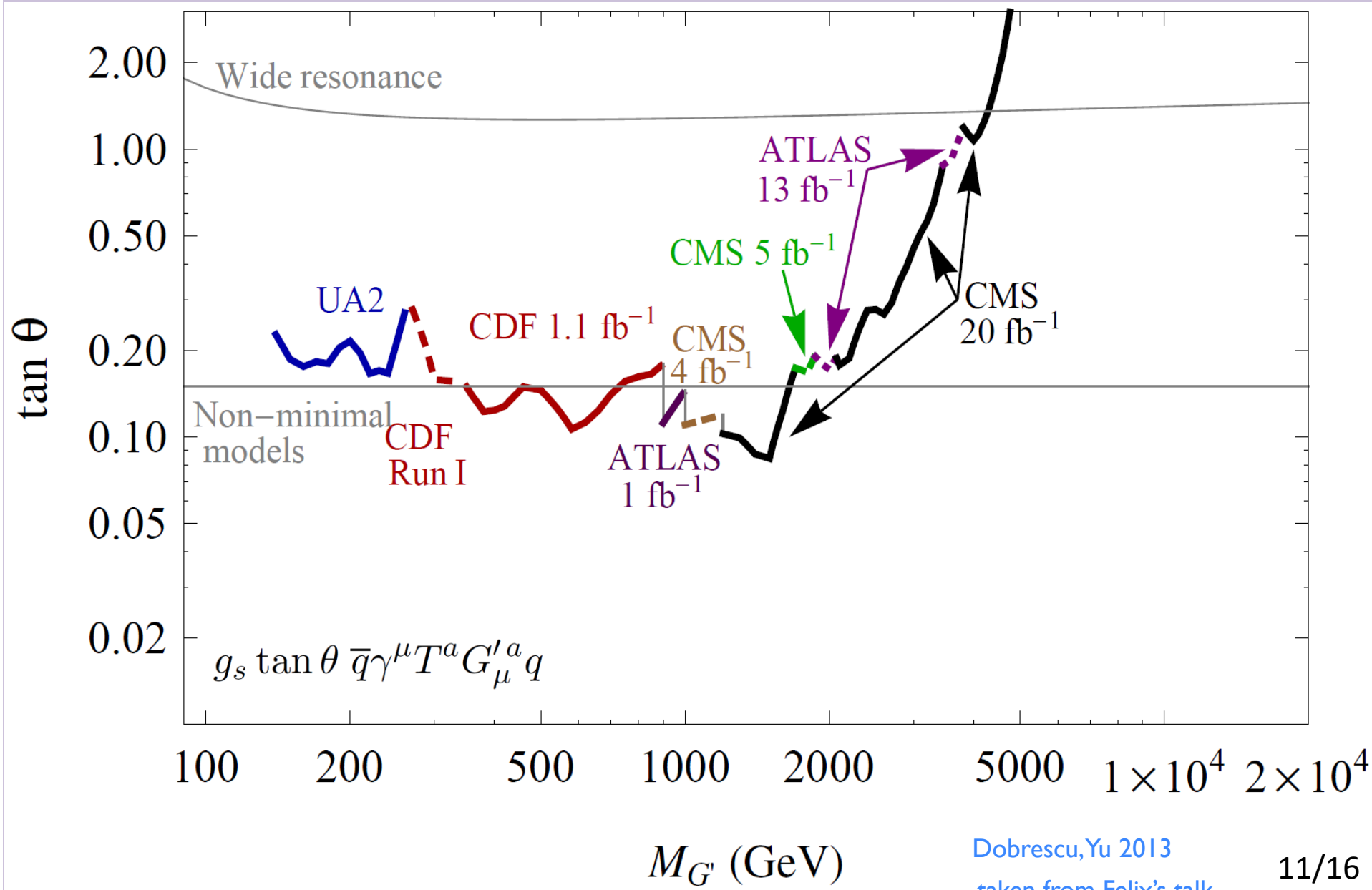


Figure 3. The effective $\bar{f}_0 V_2^\mu f_0$ KK-number violating coupling on the left is generated at one loop order from the one loop diagram on the right.

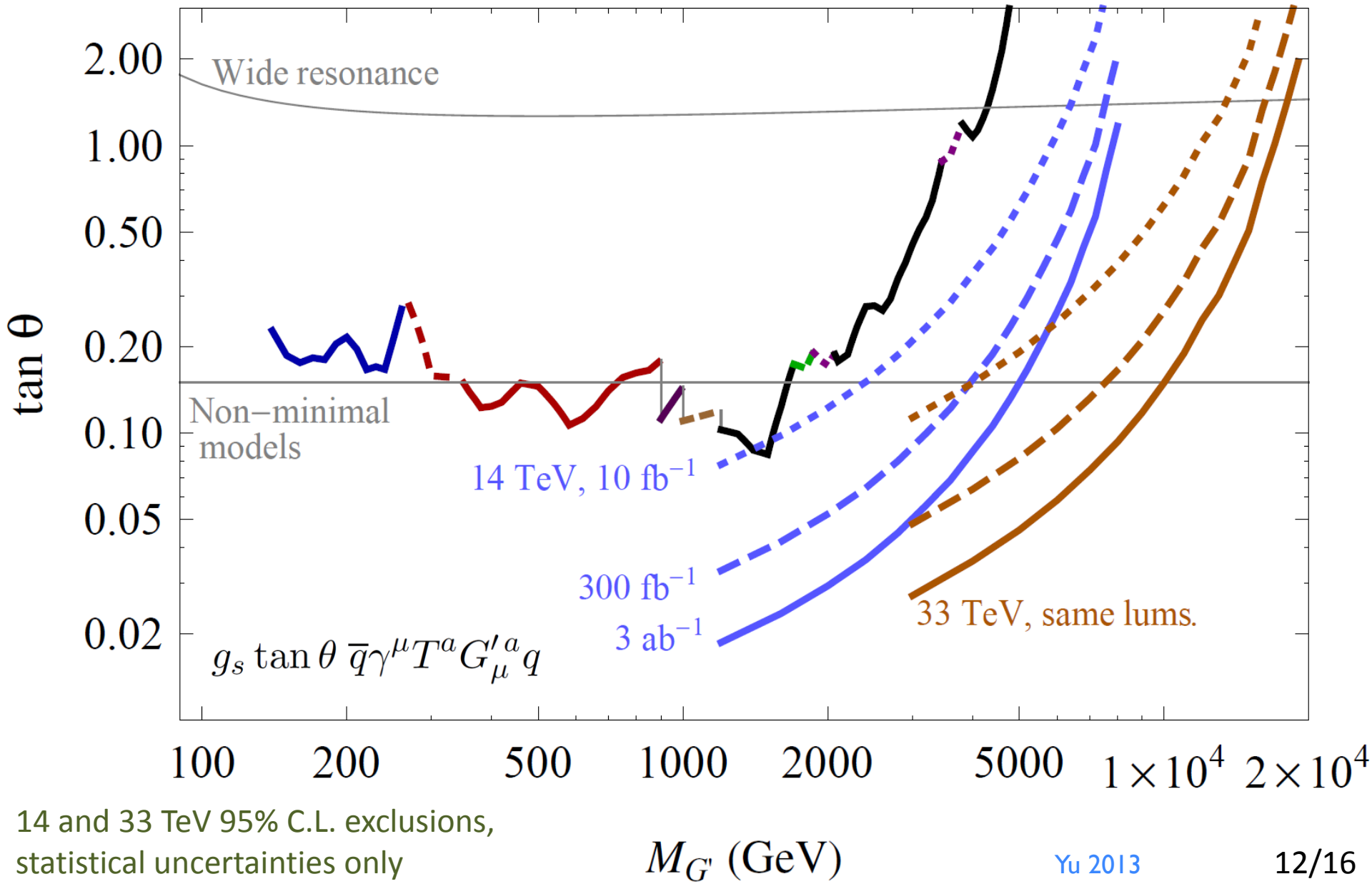
Coupling vs. mass **current limits: G'**



Dobrescu, Yu 2013

taken from Felix's talk

Coupling vs. mass **projections:** G'



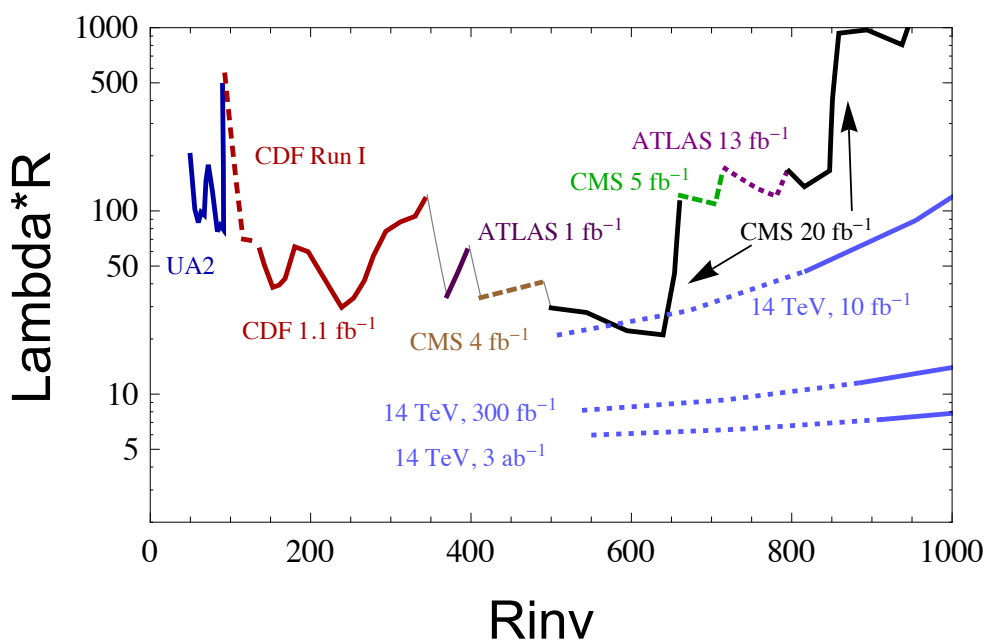
14 and 33 TeV 95% C.L. exclusions, statistical uncertainties only

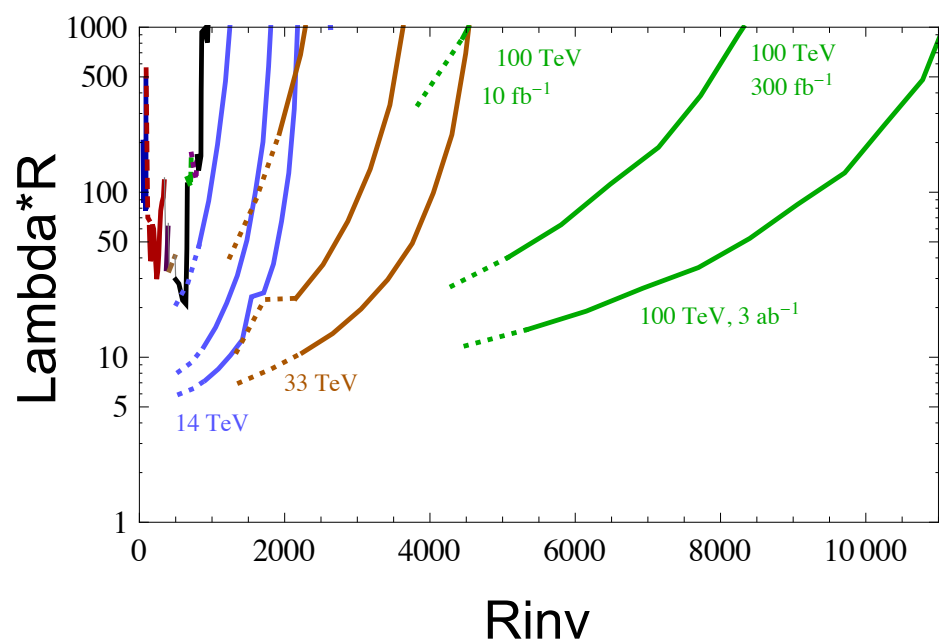
Yu 2013
taken from Felix's talk

Current/projected bounds on level-2 KK gluon

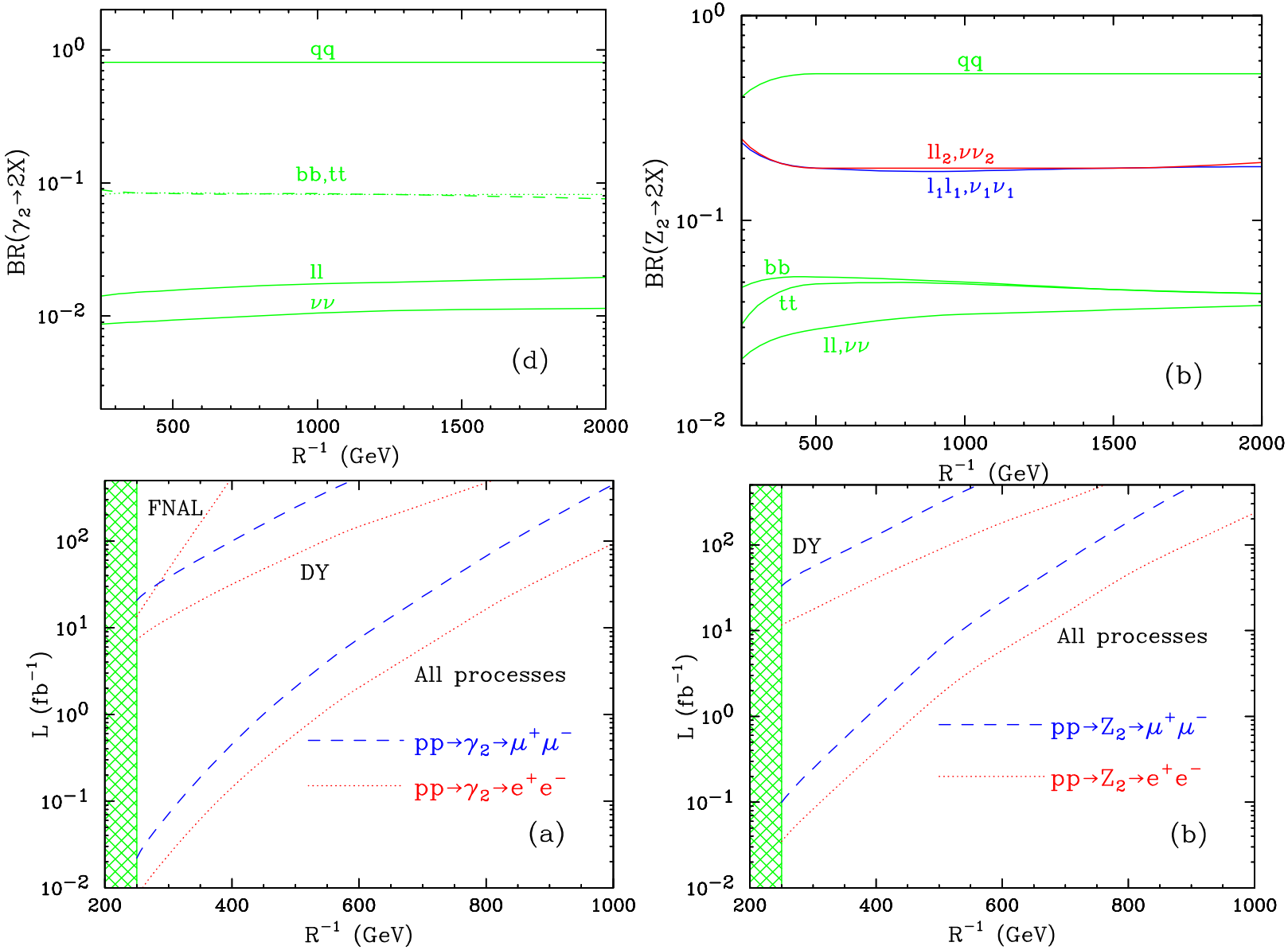
Kong, Yu for snowmass2013

$SU(3)_c$ gauge boson	Quark (up)	$ig_3 \frac{\lambda^A}{2}\gamma^\mu \frac{1}{\sqrt{2}}\frac{1}{16\pi^2}\ln\left(\frac{\Lambda}{\mu}\right)^2 \left[P_L\left(\frac{1}{8}g_1^2+\frac{27}{8}g_2^2-\frac{11}{2}g_3^2\right) +P_R\left(2g_1^2-\frac{11}{2}g_3^2\right)\right]$
G_2	Quark (down)	$ig_3 \frac{\lambda^A}{2}\gamma^\mu \frac{1}{\sqrt{2}}\frac{1}{16\pi^2}\ln\left(\frac{\Lambda}{\mu}\right)^2 \left[P_L\left(\frac{1}{8}g_1^2+\frac{27}{8}g_2^2-\frac{11}{2}g_3^2\right) +P_R\left(\frac{1}{2}g_1^2-\frac{11}{2}g_3^2\right)\right]$





Level 2: KK (dilepton) resonances



Datta, Kong, Matchev 2005

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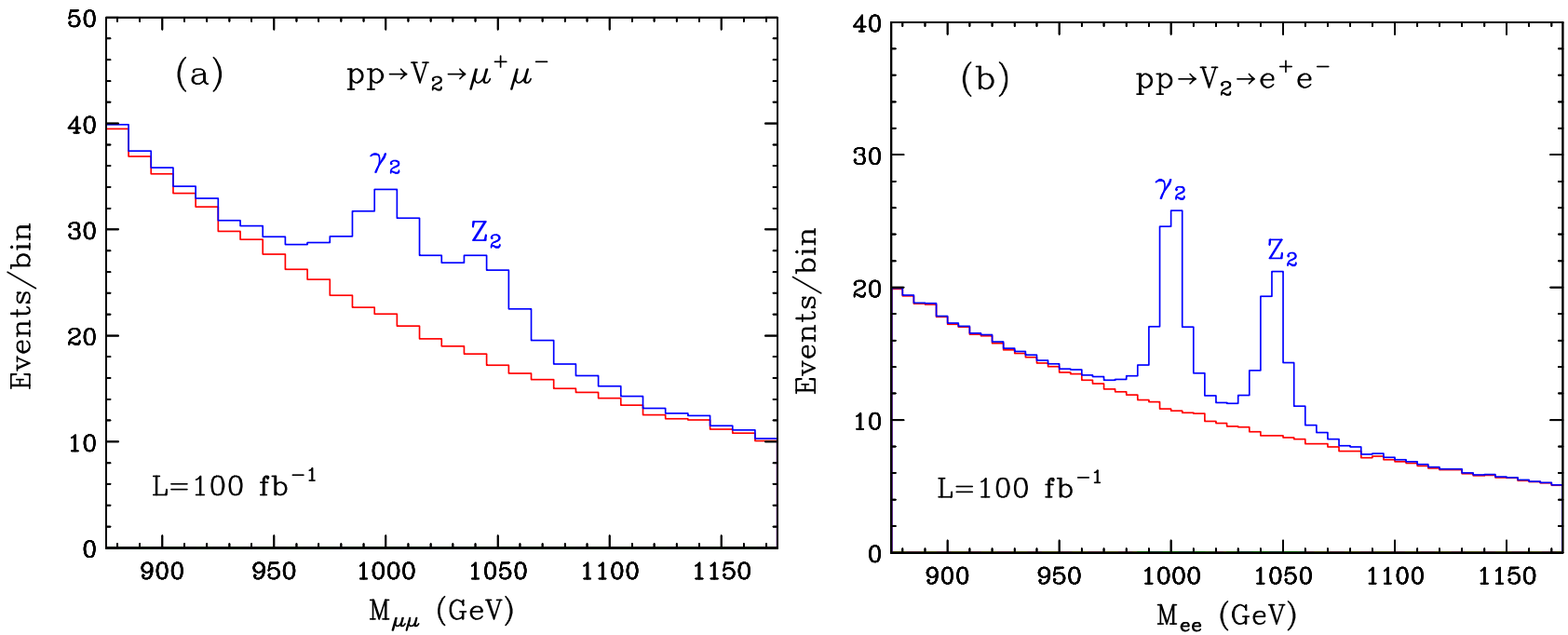
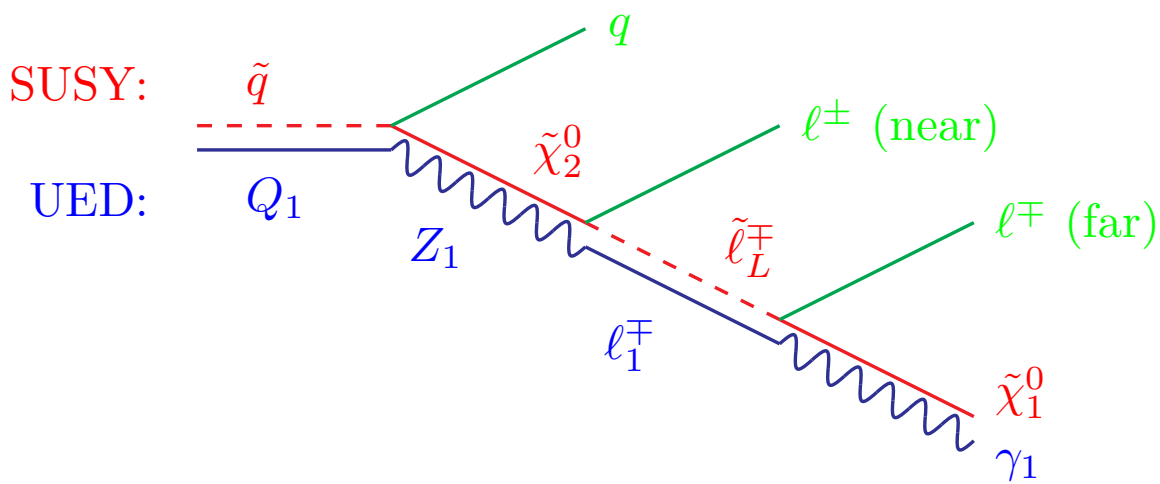


Datta, Kong, Matchev 2005

SUSY vs UED

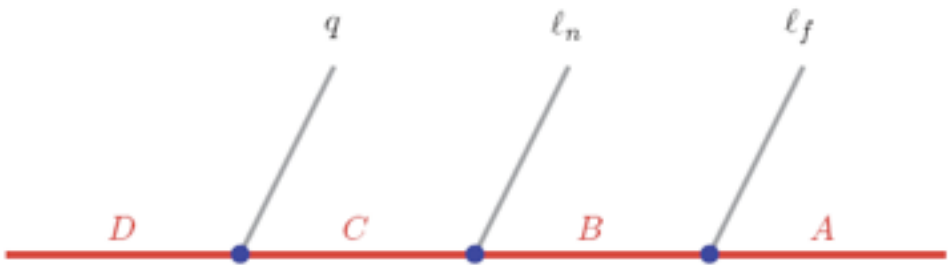
- SUSY-like cascade decays at the LHC from the first KK modes.



- Distinct feature: 2nd KK modes...

Spin and Couplings of Dark Matter: Why is it difficult to measure them?

- Missing energy signatures arise from something like:



- Several alternative explanations:

S	Spins	D	C	B	A	Example
1	SFSF	Scalar	Fermion	Scalar	Fermion	$\tilde{q} \to \tilde{\chi}_2^0 \to \tilde{\ell} \to \tilde{\chi}_1^0$
2	FSFS	Fermion	Scalar	Fermion	Scalar	$q_1 \to Z_H \to \ell_1 \to \gamma_H$
3	FSFV	Fermion	Scalar	Fermion	Vector	$q_1 \to Z_H \to \ell_1 \to \gamma_1$
4	FVFS	Fermion	Vector	Fermion	Scalar	$q_1 \to Z_1 \to \ell_1 \to \gamma_H$
5	FVFV	Fermion	Vector	Fermion	Vector	$q_1 \to Z_1 \to \ell_1 \to \gamma_1$
6	SFVF	Scalar	Fermion	Vector	Fermion	—

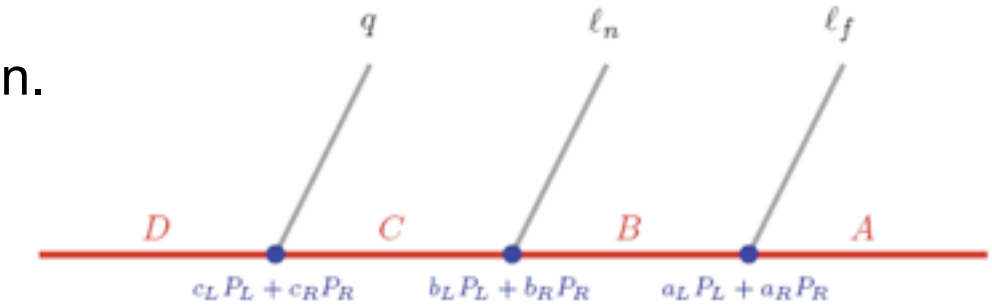
Burns, Kong, Matchev, Park 2008

What is a good distribution to look at?

- Invariant mass distributions!
- Advantages: well studied, know about spin. For adjacent SM particles

$$\frac{dN}{dm^2} = a_0 + a_2 m^2 + a_4 m^4 + \ldots$$

  - Plot versus m^2!
  - For an intermediate BSM particle of spin s, the highest order term is m^{4s}
  - For non-adjacent BSM particles, there are log terms as well.
- Disadvantage: know about many other things (hidden in the coefficients a), not all of which are measured!
  - Masses M_A, M_B, M_C, M_D (x,y,z)
  - Couplings and mixing angles (g_L and g_R)
  - Particle-antiparticle (D/D*) fraction (f/f*) (f +f*=1)



$$x = \frac{m_C^2}{m_D^2} \qquad y = \frac{m_B^2}{m_C^2} \qquad z = \frac{m_A^2}{m_B^2}$$

$$\tan\varphi_a = \frac{|a_R|}{|a_L|}, \qquad \tan\varphi_b = \frac{|b_R|}{|b_L|}, \qquad \tan\varphi_c = \frac{|c_R|}{|c_L|}$$

S	Spins	D	C	B	A
1	SFSF	Scalar	Fermion	Scalar	Fermion
2	FSFS	Fermion	Scalar	Fermion	Scalar
3	FSFV	Fermion	Scalar	Fermion	Vector
4	FVFS	Fermion	Vector	Fermion	Scalar
5	FVFV	Fermion	Vector	Fermion	Vector
6	SFVF	Scalar	Fermion	Vector	Fermion

What is the relevant question?

- Given the data, which spin configuration gives a good fit for arbitrary values of the yet unknown parameters?
  - fix mass spectrum
  - let spins, couplings, mixing angles, particle/antiparticle fraction f, etc. to float
- Previously people had asked: Given the data, which spin configuration gives a good fit for fixed values (the true ones) of the yet unknown parameters?
  - They fix: everything but the spins
  - Then let spins to float
- What is wrong with the latter approach?
  - It's the wrong chronological order
  - To measure the chirality of the couplings, we will probably need to measure the spins first
  - It's not a pure spin measurement, i.e. it is a spin measurement under certain model assumptions which still need to be verified experimentally

How do we do it?

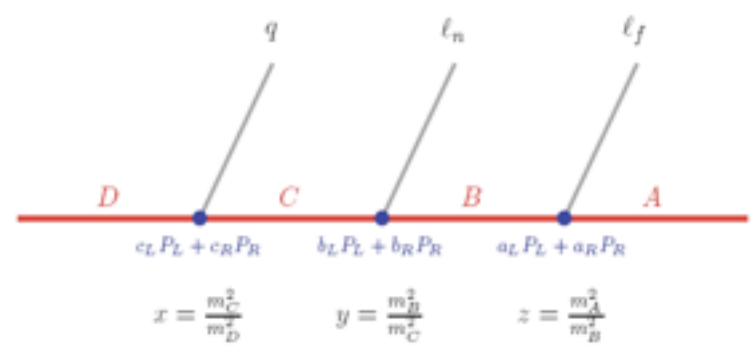
- Separate the spin dependence from all the rest
  - Parameterize conveniently the effect from “all the rest”

$$\left(\frac{dN}{dm^2}\right)_S = F_{S;\delta}(m^2) + \alpha F_{S;\alpha}(m^2) + \beta F_{S;\beta}(m^2) + \gamma F_{S;\gamma}(m^2)$$

- Measure both the spin (S) as well as all the rest: α, β, γ

$$\alpha(\varphi_b, \varphi_a) = \cos 2\varphi_b \cos 2\varphi_a \ ,$$
$$\beta(\tilde{\varphi}_c, \varphi_b) = \cos 2\tilde{\varphi}_c \cos 2\varphi_b = (f - \bar{f}) \cos 2\varphi_c \cos 2\varphi_b$$
$$\gamma(\varphi_a, \tilde{\varphi}_c) = \cos 2\varphi_a \cos 2\tilde{\varphi}_c = (f - \bar{f}) \cos 2\varphi_a \cos 2\varphi_c$$

$$\tan\varphi_a = \frac{|a_R|}{|a_L|} \ , \qquad \tan\varphi_b = \frac{|b_R|}{|b_L|} \ , \qquad \tan\varphi_c = \frac{|c_R|}{|c_L|}$$



What is the method?

- Construct and then fit the three invariant mass distributions to

$$L_S^{+-}(\hat{m}^2_{\ell\ell}; x, y, z, \alpha) \equiv \left(\frac{dN}{d\hat{m}^2_{\ell\ell}}\right)_S = \mathcal{F}^{(\ell\ell)}_{S;\delta}(\hat{m}^2_{\ell\ell}; x, y, z) + \alpha\, \mathcal{F}^{(\ell\ell)}_{S;\alpha}(\hat{m}^2_{\ell\ell}; x, y, z) \ ,$$

$$S_S^{+-}(\hat{m}^2_{j\ell}; x, y, z, \alpha) \equiv \left(\frac{dN}{d\hat{m}^2_{j\ell+}}\right)_S + \left(\frac{dN}{d\hat{m}^2_{j\ell-}}\right)_S$$

$$= r_n^2\, \mathcal{F}^{(j\ell_n)}_{S;\delta}(r_n^2 \hat{m}^2_{j\ell}; x, y, z) + r_f^2\, \mathcal{F}^{(j\ell_f)}_{S;\delta}(r_f^2 \hat{m}^2_{j\ell}; x, y, z) + \alpha\, r_f^2\, \mathcal{F}^{(j\ell_f)}_{S;\alpha}(r_f^2 \hat{m}^2_{j\ell}; x, y, z) \ ,$$

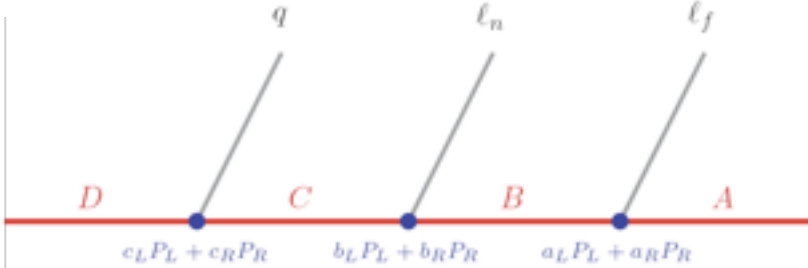
$$D_S^{+-}(\hat{m}^2_{j\ell}; x, y, z, \beta, \gamma) \equiv \left(\frac{dN}{d\hat{m}^2_{j\ell+}}\right)_S - \left(\frac{dN}{d\hat{m}^2_{j\ell-}}\right)_S$$

$$= \gamma\, r_f^2\, \mathcal{F}^{(j\ell_f)}_{S;\gamma}(r_f^2 \hat{m}^2_{j\ell}; x, y, z) + \beta\, r_f^2\, \mathcal{F}^{(j\ell_f)}_{S;\beta}(r_f^2 \hat{m}^2_{j\ell}; x, y, z) - \beta\, r_n^2\, \mathcal{F}^{(j\ell_n)}_{S;\beta}(r_n^2 \hat{m}^2_{j\ell}; x, y, z)$$

$$\alpha(\varphi_b, \varphi_a) = \cos 2\varphi_b \cos 2\varphi_a \ ,$$

$$\beta(\tilde{\varphi}_c, \varphi_b) = \cos 2\tilde{\varphi}_c \cos 2\varphi_b = (f - \bar{f}) \cos 2\varphi_c \cos 2\varphi_b$$

$$\gamma(\varphi_a, \tilde{\varphi}_c) = \cos 2\varphi_a \cos 2\tilde{\varphi}_c = (f - \bar{f}) \cos 2\varphi_a \cos 2\varphi_c$$



Coupling measurements

- The fitted values of alpha, beta, gamma represent measurements of certain combinations of couplings and mixing angles
- The sign ambiguity corresponds to the chirality exchange

$$|a_L| \leftrightarrow |a_R|\,,$$

$$|b_L| \leftrightarrow |b_R|\,,$$

$$|c_L| \leftrightarrow |c_R|\,.$$

$$|a_L| = \frac{1}{\sqrt{2}}\left(1 \pm \frac{1}{\beta}\sqrt{\alpha\beta\gamma}\right)^{\frac{1}{2}},$$

$$|a_R| = \frac{1}{\sqrt{2}}\left(1 \mp \frac{1}{\beta}\sqrt{\alpha\beta\gamma}\right)^{\frac{1}{2}},$$

$$|b_L| = \frac{1}{\sqrt{2}}\left(1 \pm \frac{1}{\gamma}\sqrt{\alpha\beta\gamma}\right)^{\frac{1}{2}},$$

$$|b_R| = \frac{1}{\sqrt{2}}\left(1 \mp \frac{1}{\gamma}\sqrt{\alpha\beta\gamma}\right)^{\frac{1}{2}},$$

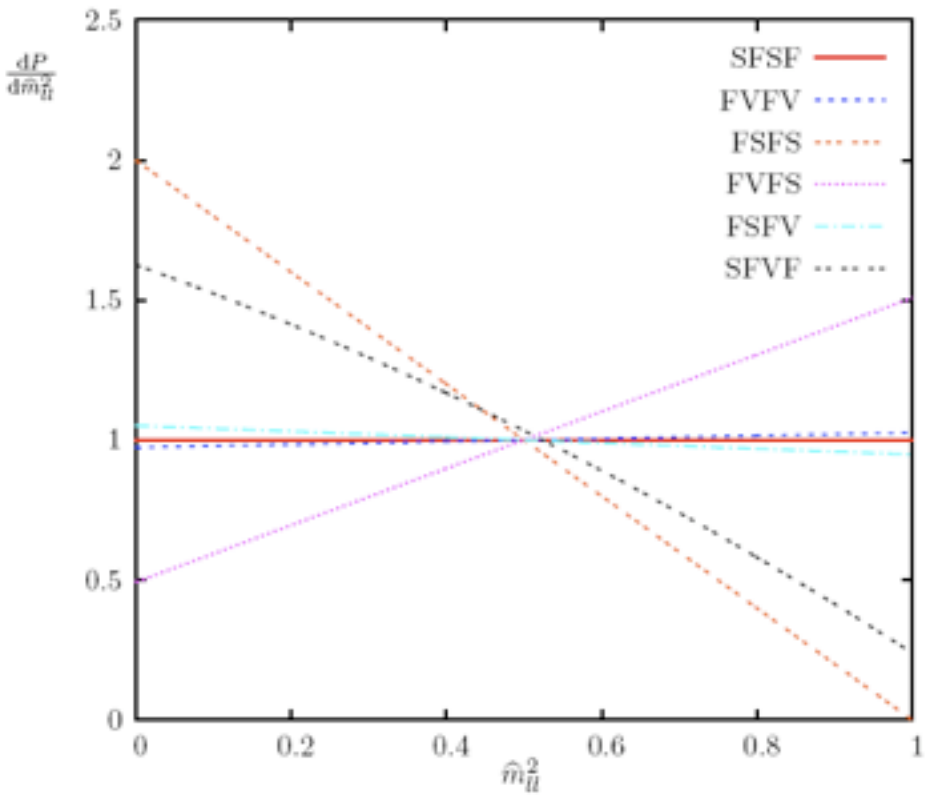
$$|c_L| = \frac{1}{\sqrt{2}}\left(1 \pm \frac{1}{f-\bar{f}}\frac{1}{\alpha}\sqrt{\alpha\beta\gamma}\right)^{\frac{1}{2}},$$

$$|c_R| = \frac{1}{\sqrt{2}}\left(1 \mp \frac{1}{f-\bar{f}}\frac{1}{\alpha}\sqrt{\alpha\beta\gamma}\right)^{\frac{1}{2}},$$

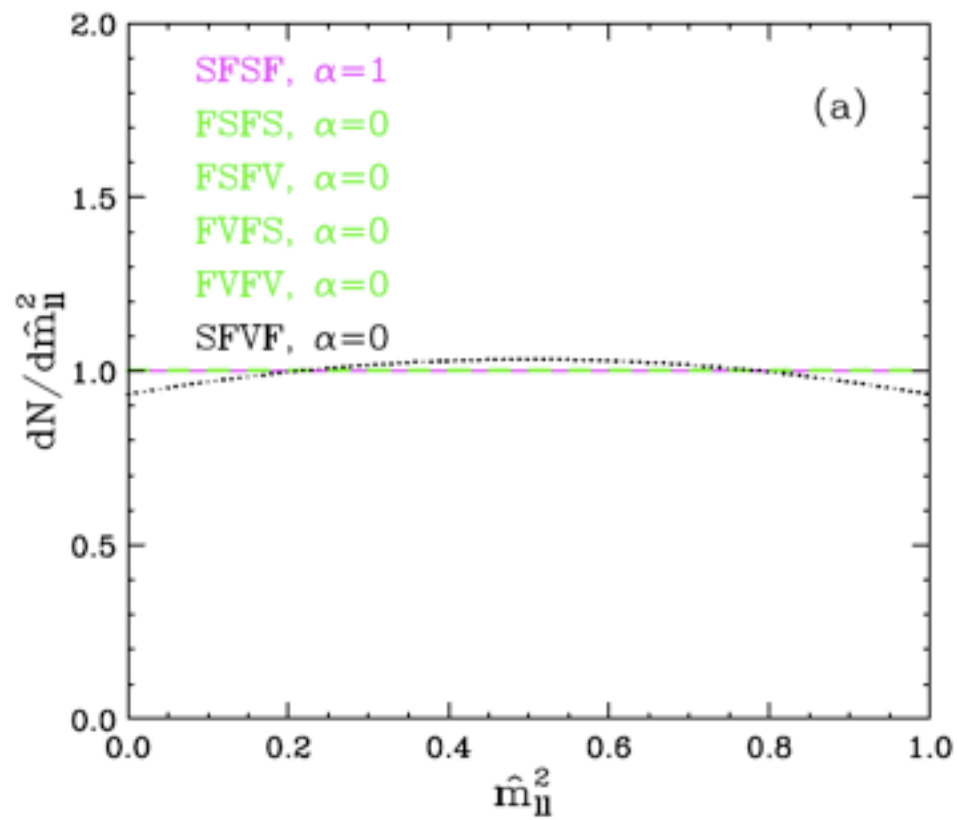
Does this really make any difference?

- Yes! Dilepton invariant mass distribution. Data from SPS1a.

Athanasiou, Lester, Smillie, Webber 06



Burns, Kong, Matchev, Park 08



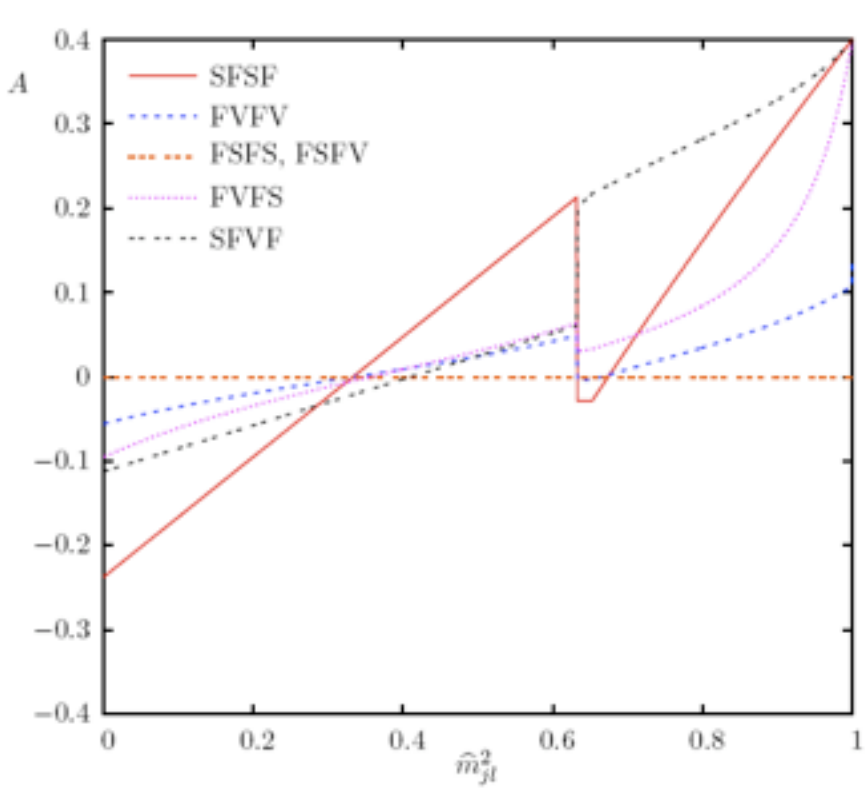
- Spins vary
- Everything else fixed to SPS1a values
- Easy to distinguish!

- Mass spectrum fixed to SPS1a values
- Everything else varies
- Difficult to distinguish!

Does this really make any difference?

- Yes! Lepton charge (Barr) asymmetry. Data: “UED” with SPS1a mass spectrum.

Athanasiou, Lester, Smillie, Webber 06



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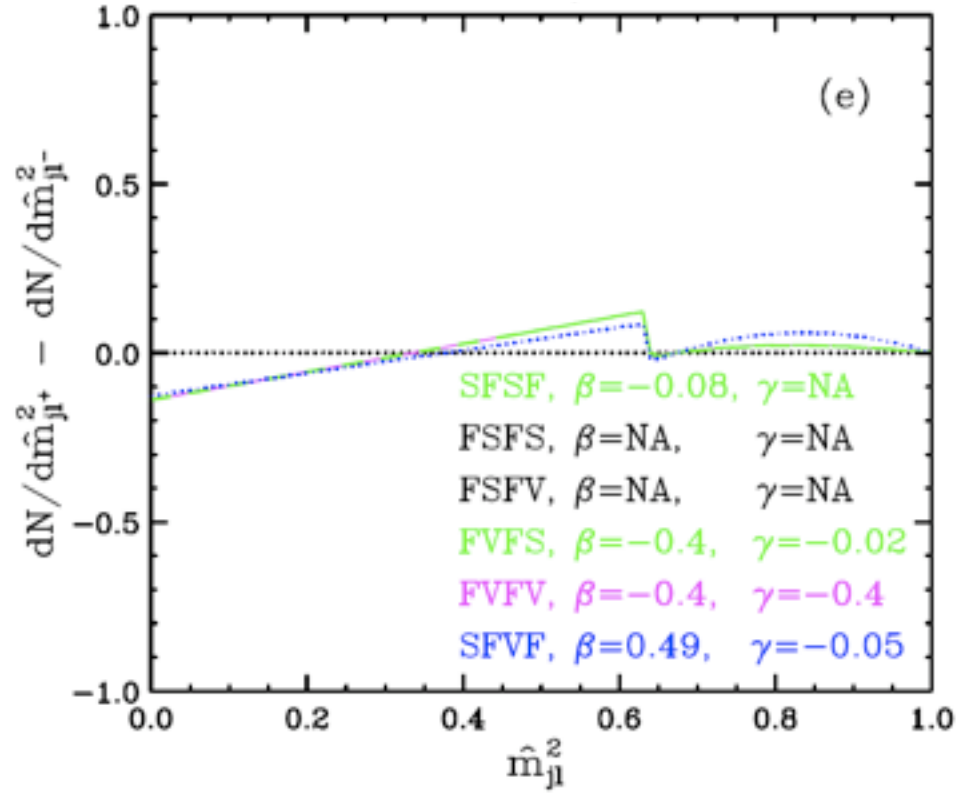

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With Infinite Statistics

Burns, Kong, Matchev, Park 08

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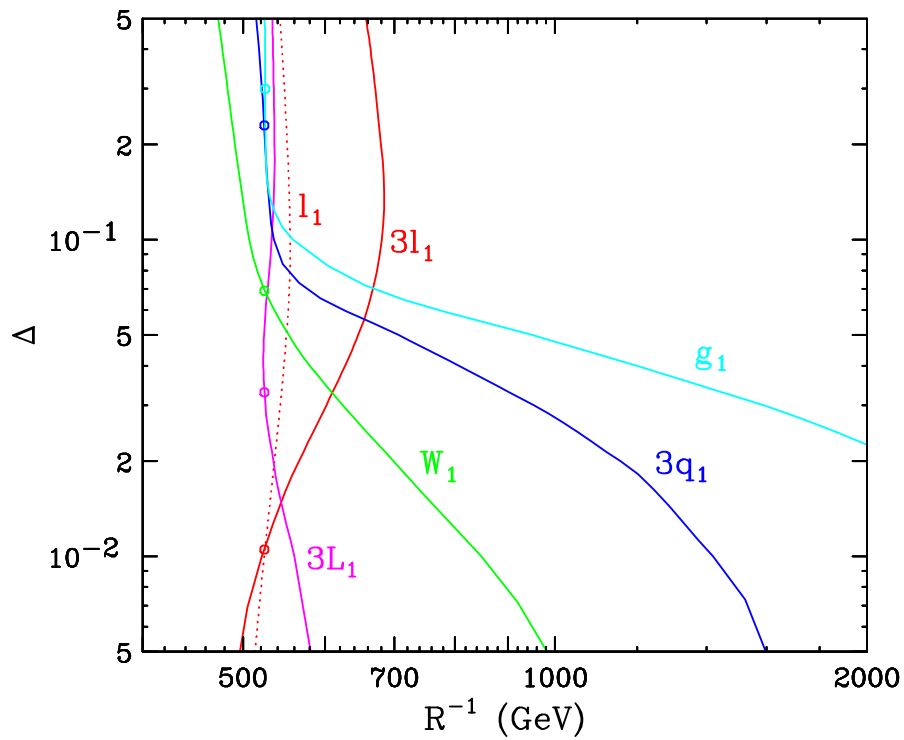
- Measure both the spin (S) as well as all the rest: α, β, γ

Data from	Can this data be fitted by model					
	SFSF	FSFS	FSFV	FVFS	FVFV	SFVF
SFSF	yes	no	no	no	no	no
FSFS	no	yes	maybe	no	no	no
FSFV	no	yes	yes	no	no	no
FVFS	no	no	no	yes	maybe	no
FVFV	no	no	no	yes	yes	no
SFVF	no	no	no	no	no	yes

KKDM in non-minimal model

- The change in the cosmologically preferred value for R^{-1} as a result of varying the different KK masses away from their nominal MUED values (along each line, $\Omega h^2 = 0.1$)

(Kong, Matchev, hep-ph/0509119)



- In nonminimal UED, Cosmologically allowed LKP mass range can be larger
  - If $\Delta = \frac{m_1 - m_{\gamma_1}}{m_{\gamma_1}}$ is small, m_{LKP} is large, UED escapes collider searches
    $\longrightarrow$ But, good news for dark matter searches

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 2013

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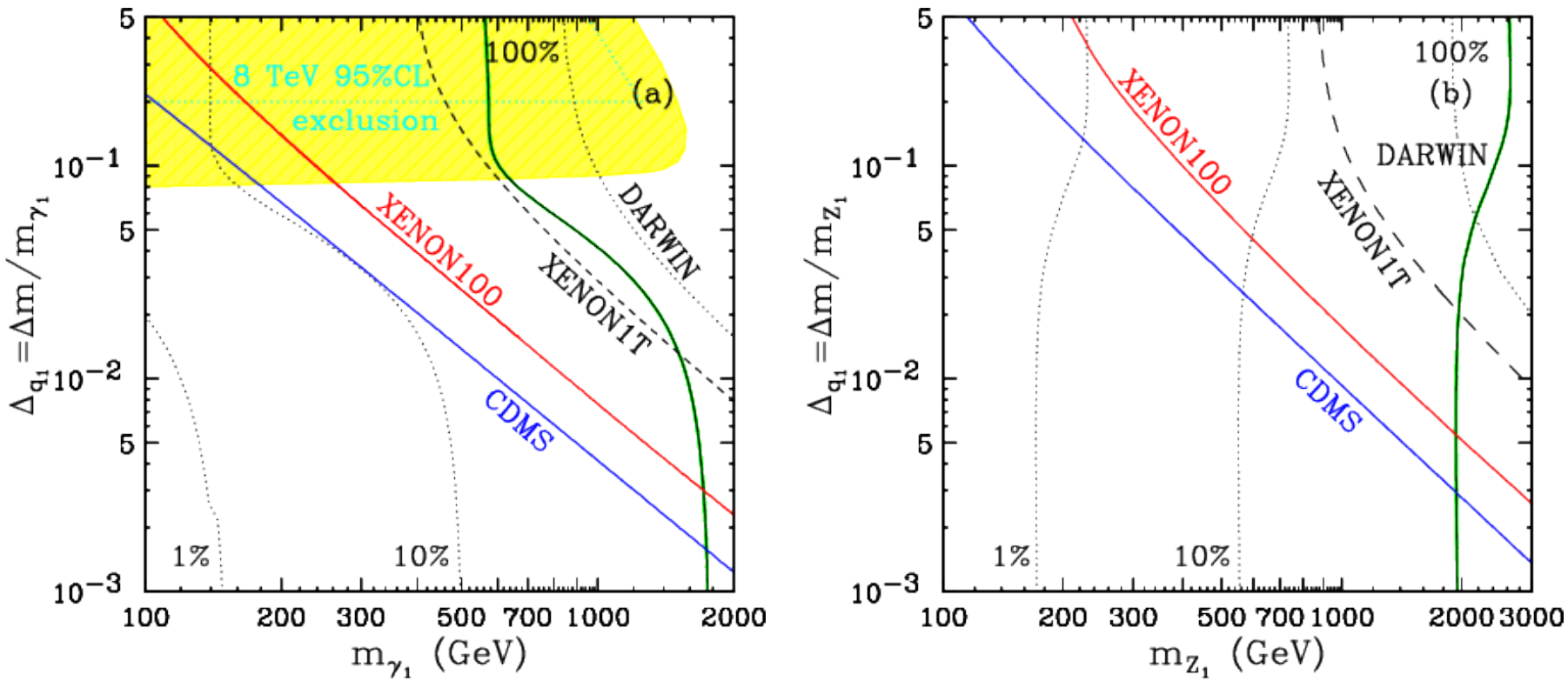

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Arrenberg, Baudis, Kong, Matchev, Yoo 2013

How Many Extra Dimensions ?

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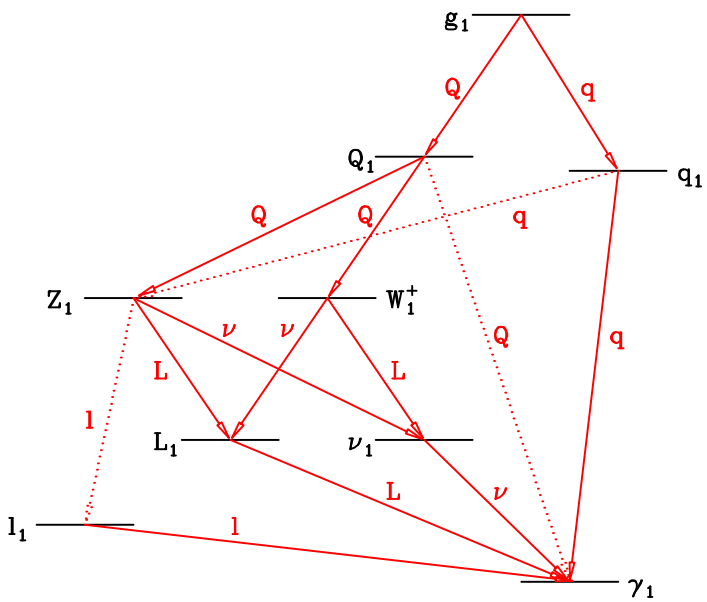

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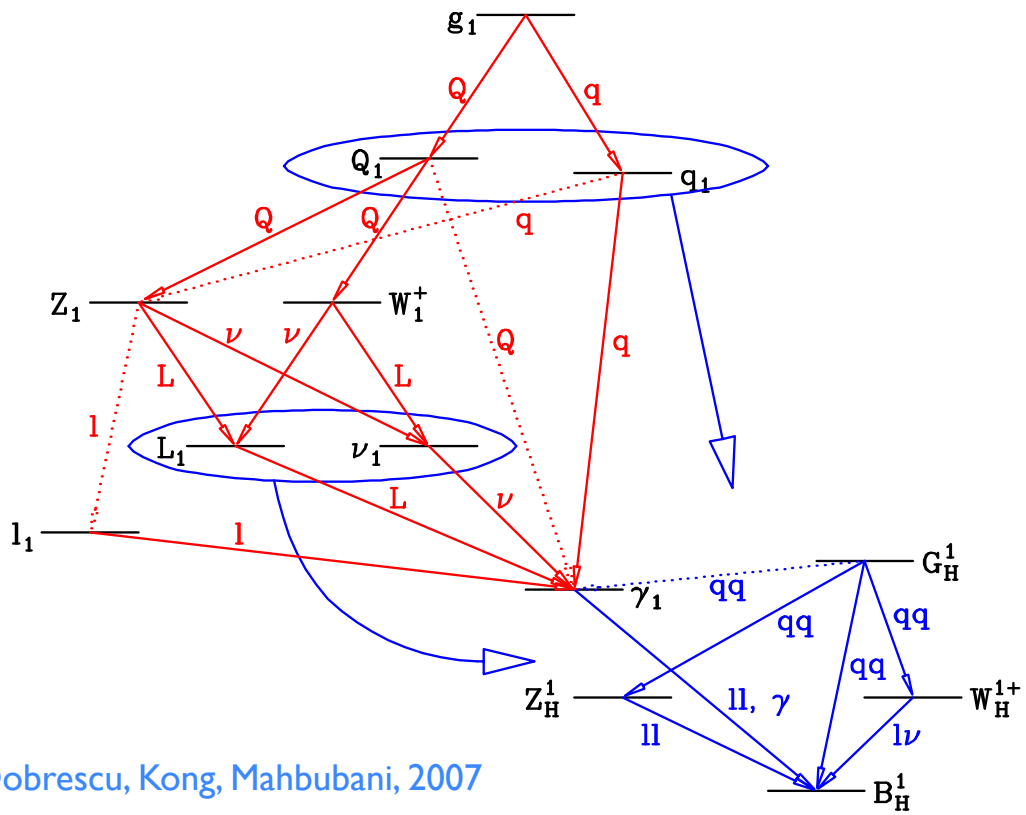
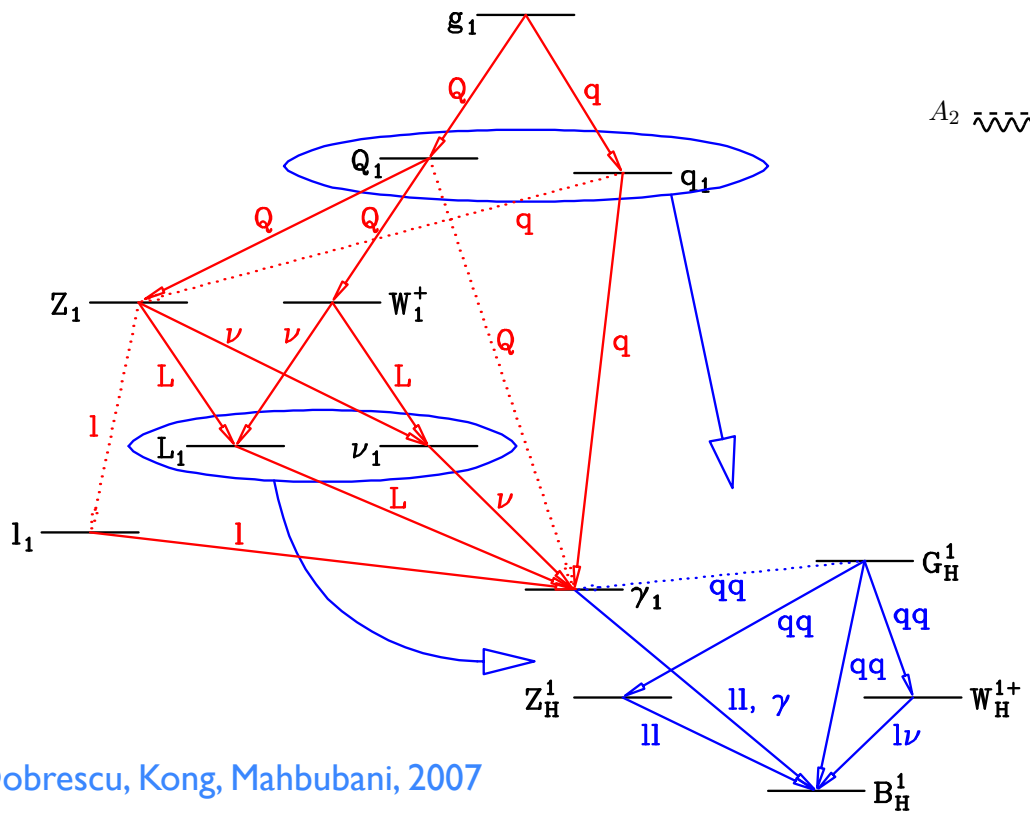


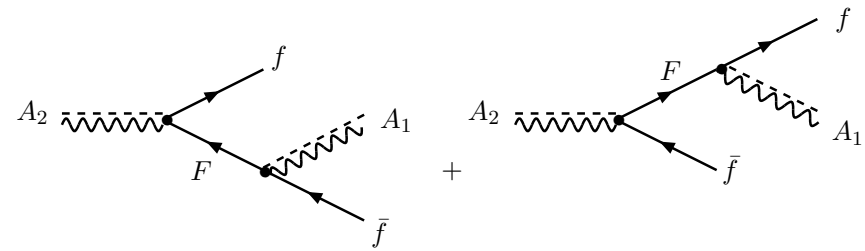
Dobrescu, Kong, Mahbubani, 2007

- Extra “spinless” states: GH, ZH, WH, BH

How Many Extra Dimensions ?

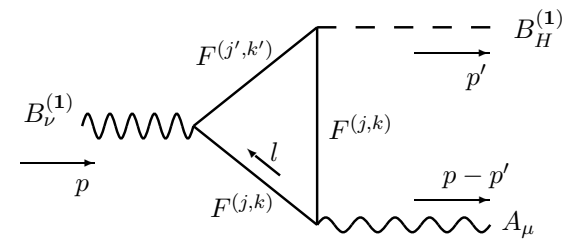


Dobrescu, Kong, Mahbubani, 2007



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

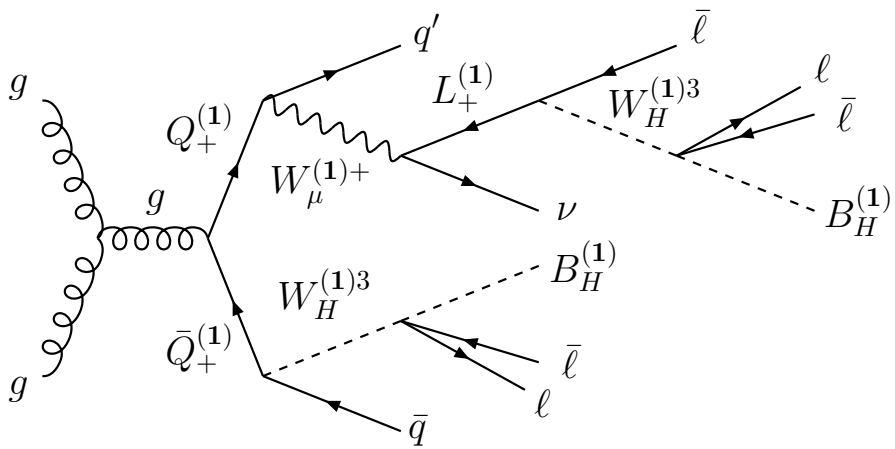
$$\mathrm{Br}\left(B_\mu^{(1)} \to B_H^{(1)}e^+e^-\right) \equiv b_{Be} \approx 21.3\%$$

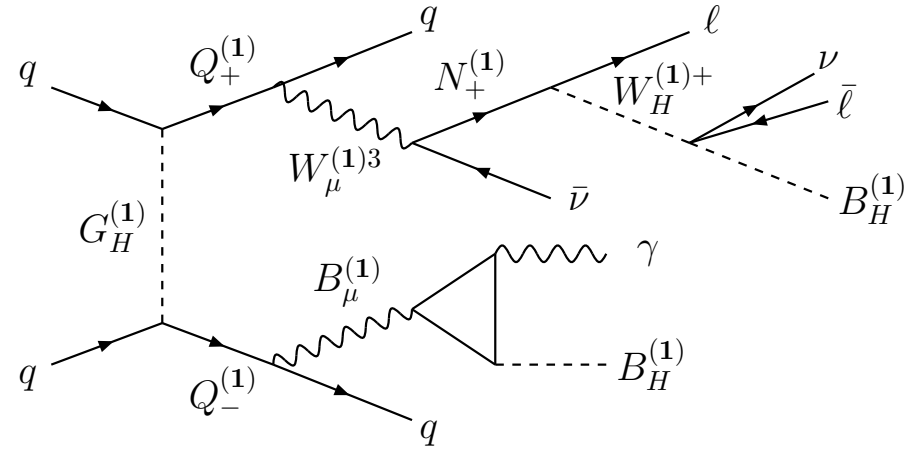


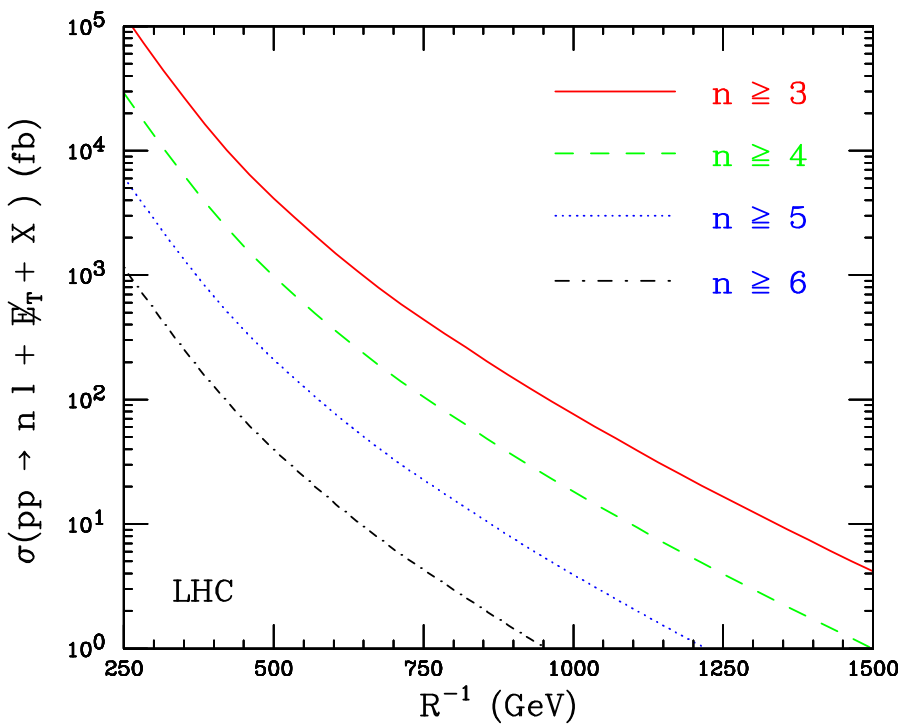
$$-\frac{R}{4}\left(\mathcal{C}_B\epsilon^{\mu\nu\alpha\beta}F_{\mu\nu}B_{\alpha\beta}^{(1)}B_H^{(1)} + \mathcal{C}_G\epsilon^{\mu\nu\alpha\beta}G_{\mu\nu}B_{\alpha\beta}^{(1)}G_H^{(1)}\right)$$

- Extra “spinless” states: GH, ZH, WH, BH
- KK photon is a not DM and decays to spinless photon via 1-loop 2 body or tree-level 3 body decay (with vanishing BC at cutoff scale)

Multi-leptons from 2UED







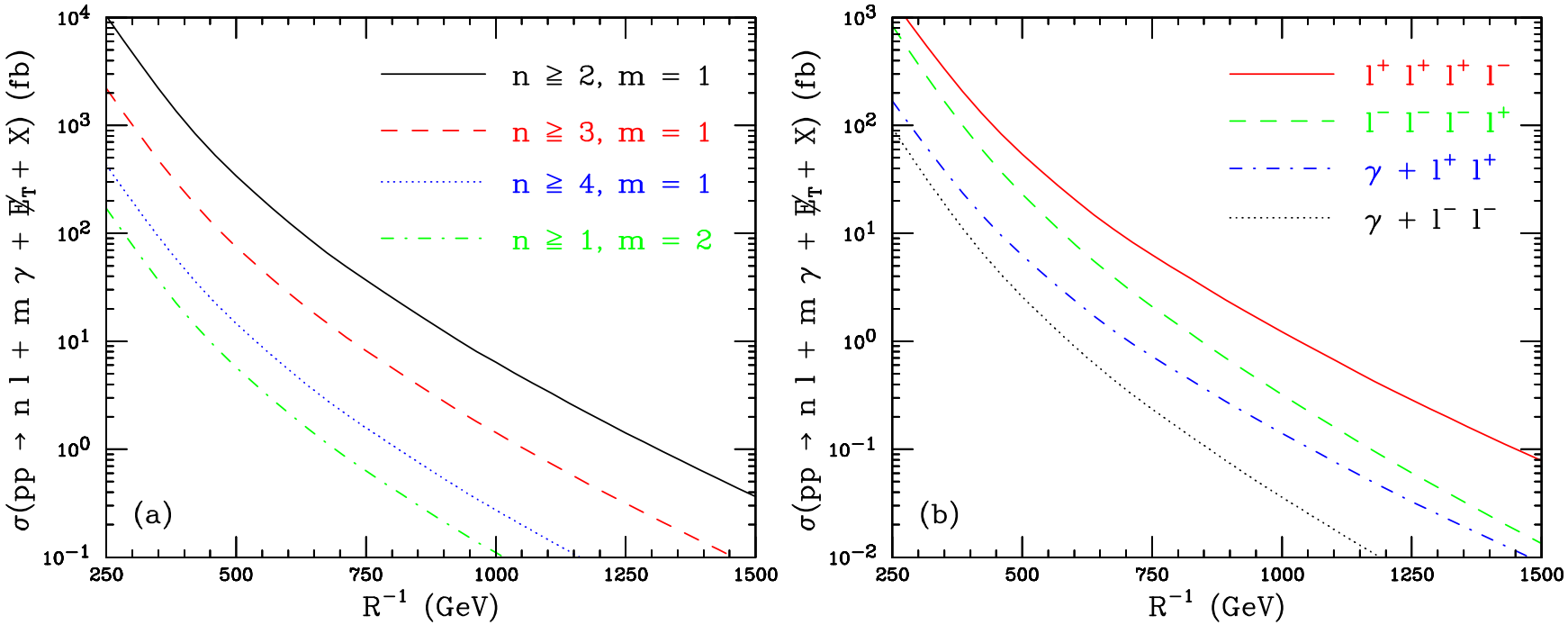
$$\sigma(pp \to n\ell + m\gamma + \not{E}_T\ , n \geq n_{min}) = \sum_{i=1}^{11}\sum_{j\geq i}^{11} \sigma(pp \to A_i^{(1)} A_j^{(1)}) B_{ij}$$

$$B_{ij} = \sum_{\substack{a,b=0 \\ a+b\geq n_{min}}}^{4} \sum_{\substack{a',b'=0 \\ a'+b'=m}}^{1} \mathrm{Br}(i,a,a')\mathrm{Br}(j,b,b')$$

$$0 \leq n + 2m \leq 8$$

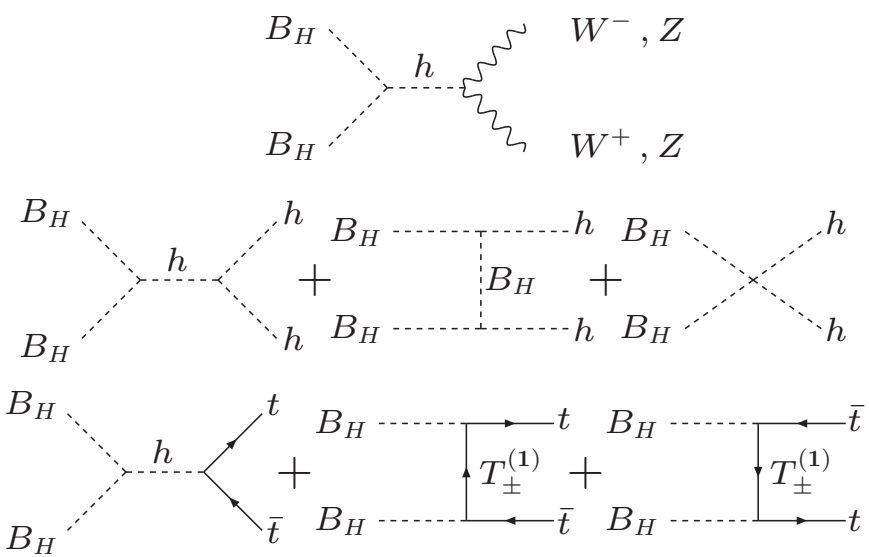
- The number of multi-lepton events at 14 TeV LHC
- No acceptance cuts

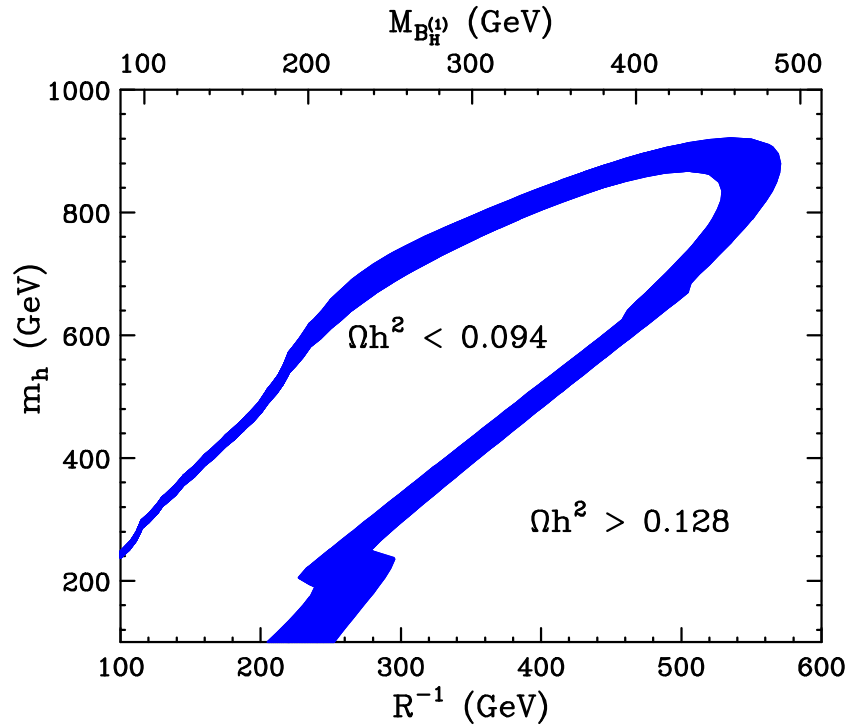
Leptons and Photons from 2UED



- The number of lepton + photon events (14 TeV)

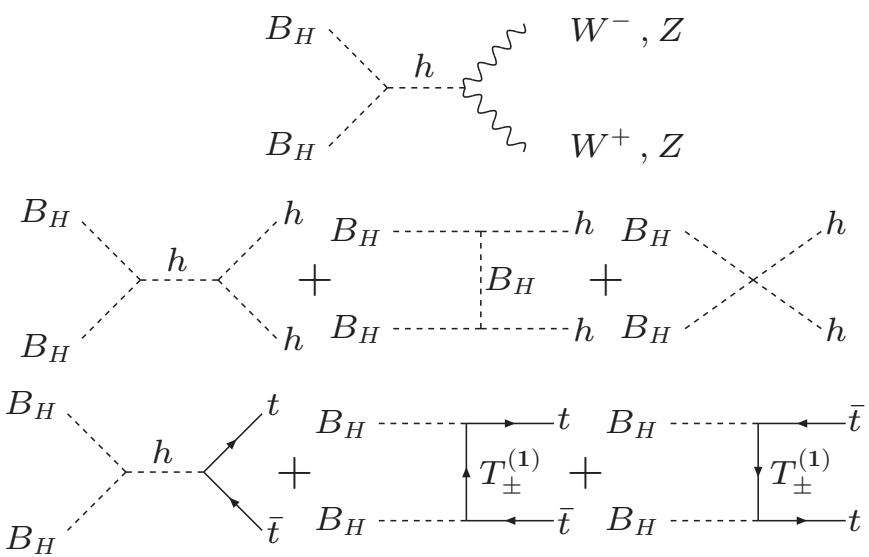
Spinless Photon Dark Matter

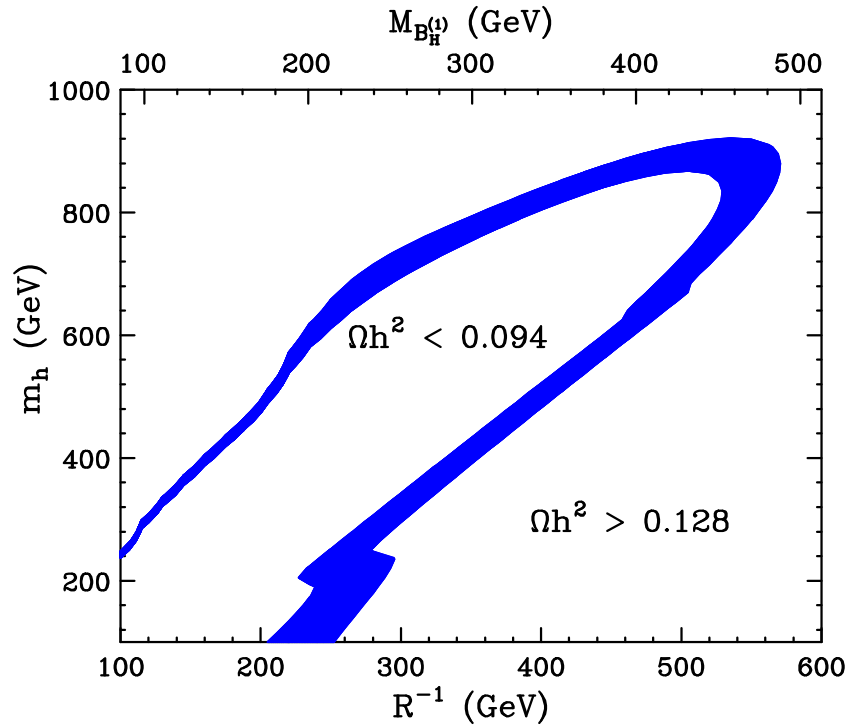




- $R^{-1} < 600$ GeV
- Light higgs requires light KK particles
  $\longrightarrow$ large production cross-sections at the LHC/Tevatron

Spinless Photon Dark Matter





Dobrescu, Hooper, Kong, Mahbubani, 2007

- $R^{-1} < 600$ GeV
- Light higgs requires light KK particles
  $\longrightarrow$ large production cross-sections at the LHC/Tevatron

Many Variations

- MUED: Minimal Universal Extra Dimensions (cf. mSugra)
- 2UED: Two Universal Extra Dimensions (cf. 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)
- Many others with larger gauge groups (cf. SU(2)L x SU(2)R)

Next-to-Minimal UED

Flacke, Kong, Park 2013

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

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

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

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

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

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

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

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

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

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

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

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

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

Carena, Tait, Wagner 2002

Flacke, Menon, Phalen 2008

L=pi*R/2

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 --> two extra parameters in addition to R and Lambda (cutoff)

Fermions

$$\Psi(x,y) = \sum_{n=0}^{\infty} \left(\psi_L^{(n)}(x) f_n^{\Psi_L}(y) + \psi_R^{(n)}(x) f_n^{\Psi_R}(y) \right)$$

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

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

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

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

$$m_{f_n} = \sqrt{k_n^2 + \mu^2},$$

$$\mathcal{N}_n^{\Psi} = \begin{cases} \sqrt{\frac{\mu}{(1+2r\,\mu)\exp(2\mu L) - 1}} & \text{for } n = 0\,, \\ \frac{1}{\sqrt{L - \frac{\cos(k_n L)\sin(k_n L)}{k_n} + 2r \sin^2(k_n L)}} & \text{for odd } n\,, \\ \frac{1}{\sqrt{L - \frac{\cos(k_n L)\sin(k_n L)}{k_n}}} & \text{for even } n\,, \end{cases}$$

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

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

Bosons

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

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

$$\cot(k_n L) = r k_n \qquad \text{for odd n,}$$

$$\tan(k_n L) = -r k_n \qquad \text{for even n}\,,$$

$$m_{\gamma_n} = k_n\,.$$

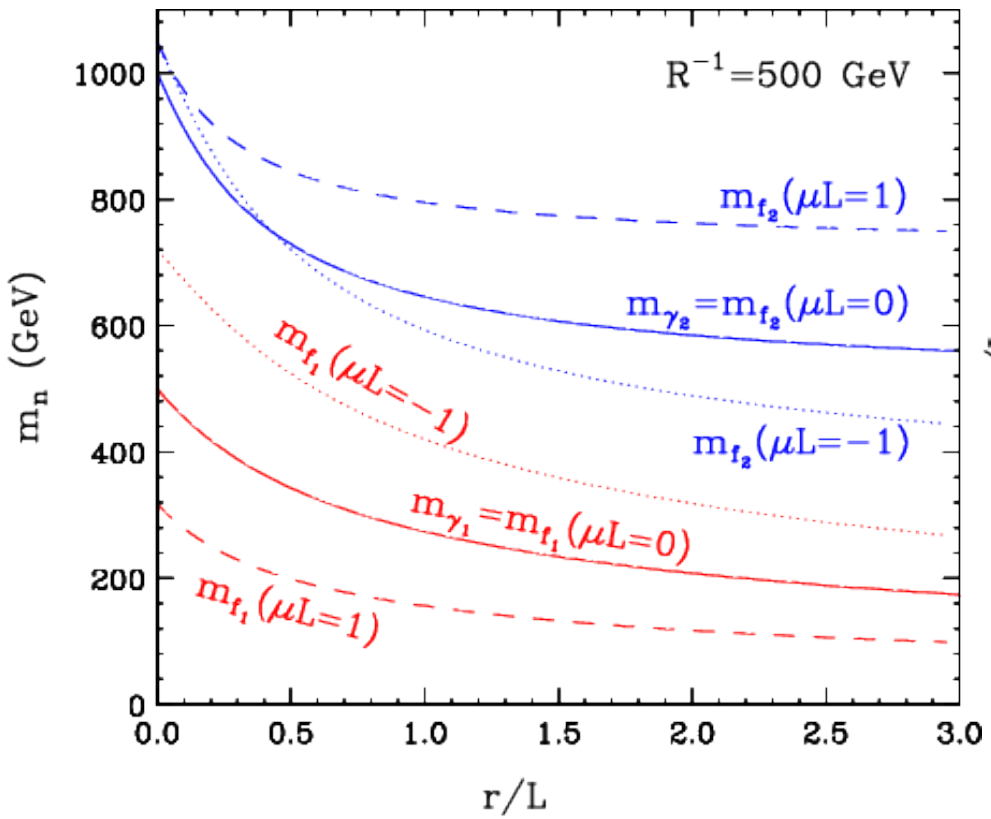
$$n=0: \quad f_0^{\mathcal{A}}(y) = \frac{1}{\sqrt{2L(1+\frac{r}{L})}}$$

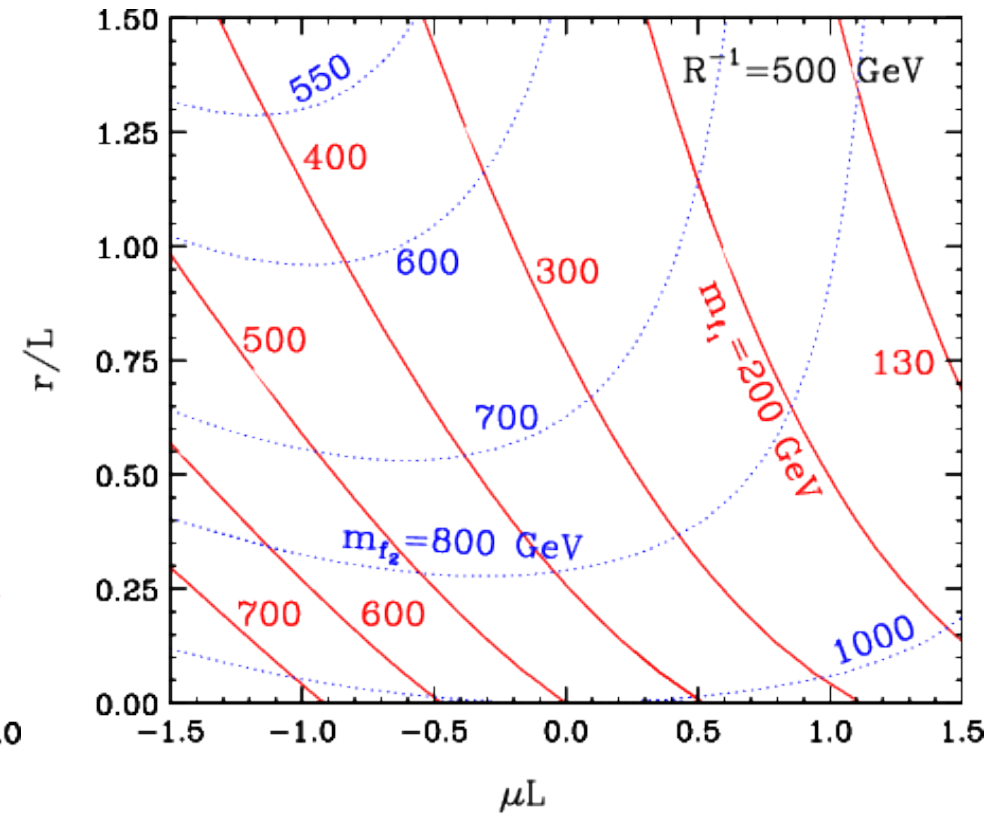
$$\text{odd } n: \quad f_n^{\mathcal{A}}(y) = \sqrt{\frac{1}{L + r\sin^2(k_n L)}}\,\sin(k_n y)\,,$$

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

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

NMUED: tree-level spectrum





L=pi*R/2

- "r" decreases masses of KK bosons and KK fermions
- "mu" increases masses of KK fermions (demand: mu < 0)
- No loop corrections --> no dependence on cutoff

Flacke, Kong, Park 2013

Carena, Tait, Wagner 2002

Couplings

$$S_{eff} \supset \int d^4x\, i g^5_{\mathcal{A}} \overline{\psi}^{(0)}_{L/R} \not{\mathcal{A}}^{(0)} \psi^{(0)}_{L/R} \int_{-L}^{L} dy f_0^{\mathcal{A}} f_0^{\Psi_{L/R}} f_0^{\Psi_{L/R}} \left[1 + r\left(\delta(y+L) + \delta(y-L)\right)\right]$$
$$= \int d^4x\, i \frac{g^5_{\mathcal{A}}}{\sqrt{2L(1+r/L)}} \overline{\psi}^{(0)}_{L/R} \not{\mathcal{A}}^{(0)} \psi^{(0)}_{L/R}\,,$$

$$g^{\mathcal{A}}_{110} = g^5_{\mathcal{A}} \int dy \left[1 + r\left(\delta(y+L) + \delta(y-L)\right)\right] f_1^{\mathcal{A}} f_1^{\Psi_L} f_0^{\Psi_L} \equiv g^{\mathcal{A}} \mathcal{F}_{110}$$

$$g^{\mathcal{A}}_{220} = g^5_{\mathcal{A}} \int dy \left[1 + r\left(\delta(y+L) + \delta(y-L)\right)\right] f_2^{\mathcal{A}} f_2^{\Psi_L} f_0^{\Psi_L} \equiv g^{\mathcal{A}} \mathcal{F}_{220}$$

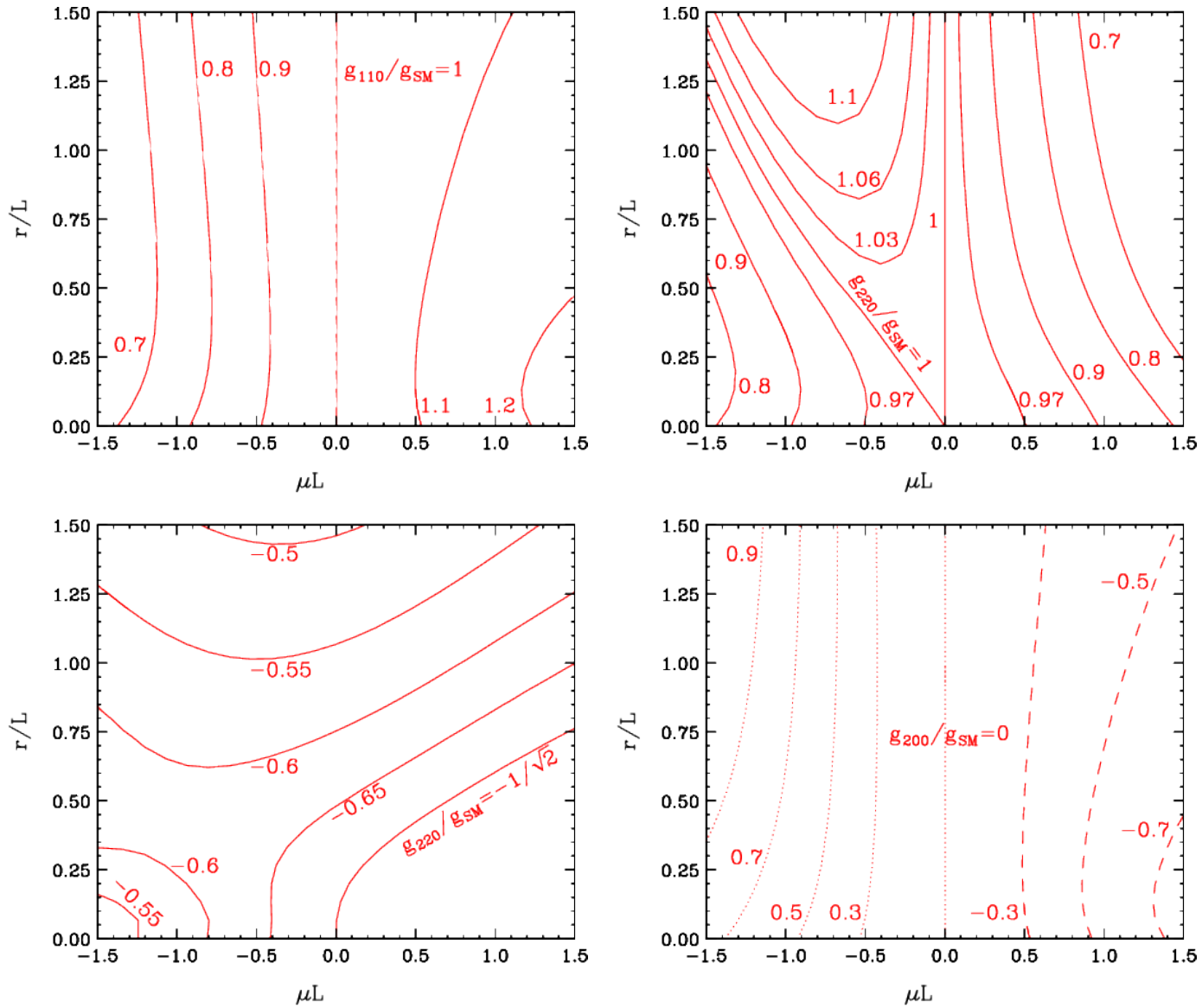
$$g^{\mathcal{A}}_{211} = g^5_{\mathcal{A}} \int dy \left[1 + r\left(\delta(y+L) + \delta(y-L)\right)\right] f_2^{\mathcal{A}} f_1^{\Psi_L} f_1^{\Psi_L} \equiv g^{\mathcal{A}} \mathcal{F}_{211}$$

$$g^{\mathcal{A}}_{200} = g^5_{\mathcal{A}} \int dy \left[1 + r\left(\delta(y+L) + \delta(y-L)\right)\right] f_2^{\mathcal{A}} f_0^{\Psi_L} f_0^{\Psi_L} \equiv g^{\mathcal{A}} \mathcal{F}_{200}$$

$$g^5_{\mathcal{A}} = g_{\mathcal{A}} \sqrt{2L\left(1 + \frac{r}{L}\right)}$$

$$\mu_5 = \mu_H\,,$$
$$\lambda_5 = \lambda_H \left(2L\left(1 + \frac{r}{L}\right)\right)\,,$$
$$\lambda_5^{U,D,E} = \lambda^{U,D,E} \sqrt{2L\left(1 + \frac{r}{L}\right)}\,.$$

NMUED: couplings (mu<0)

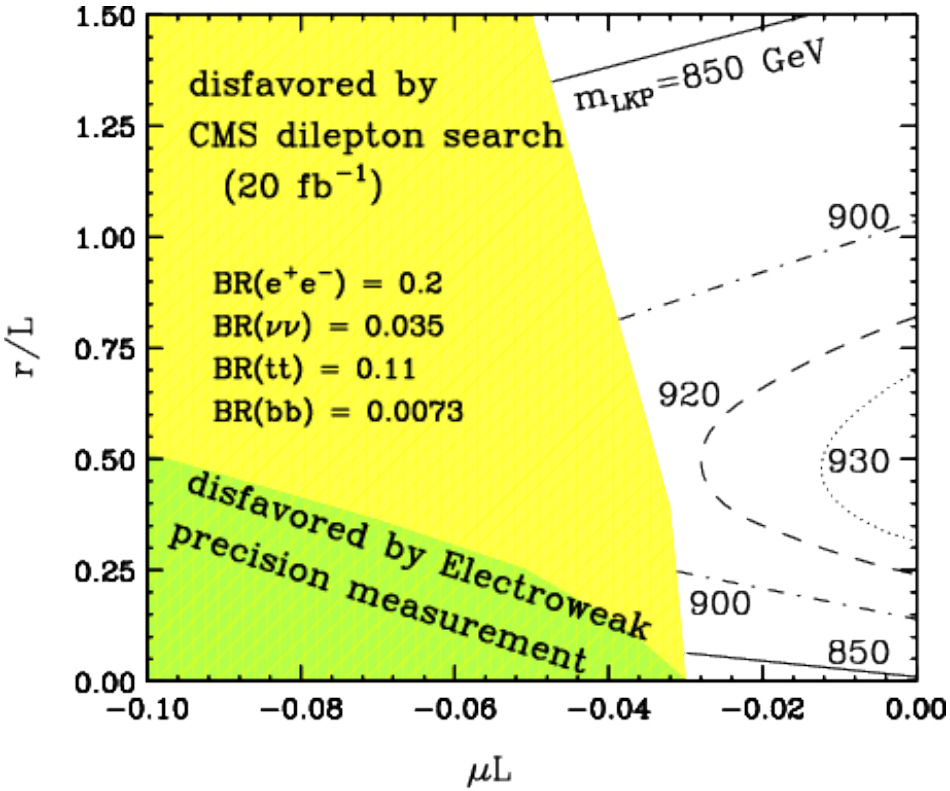


Flacke, Kong, Park 2013

Carena, Tait, Wagner 2002, without bulk masses

NMUED

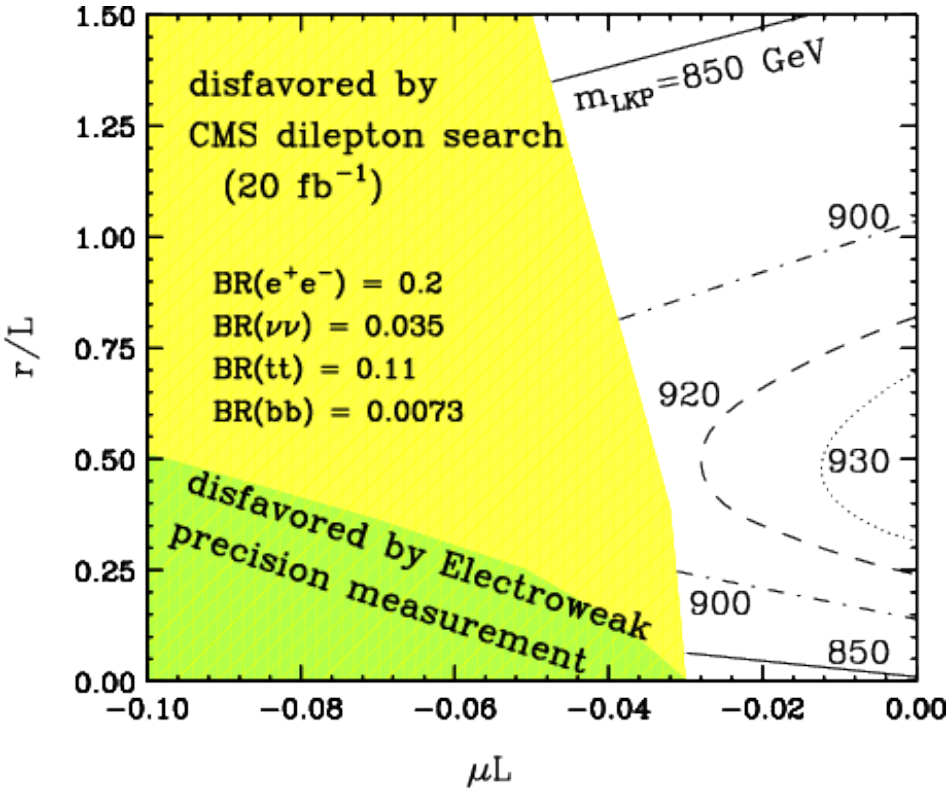
Kong, Marfatia, Gao, preliminary



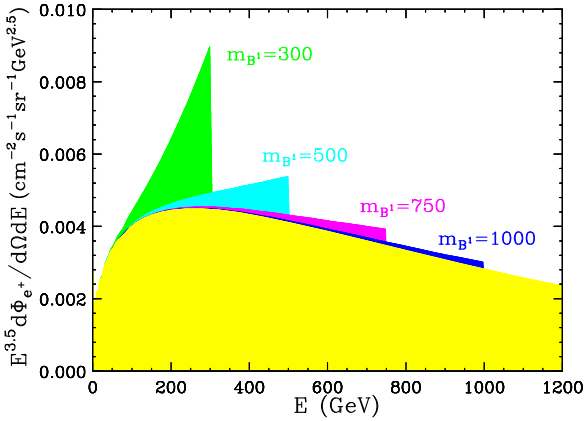
- For universal boundary and universal bulk mass

NMUED

Kong, Marfatia, Gao, preliminary



Cheng, Feng, Matchev 2002



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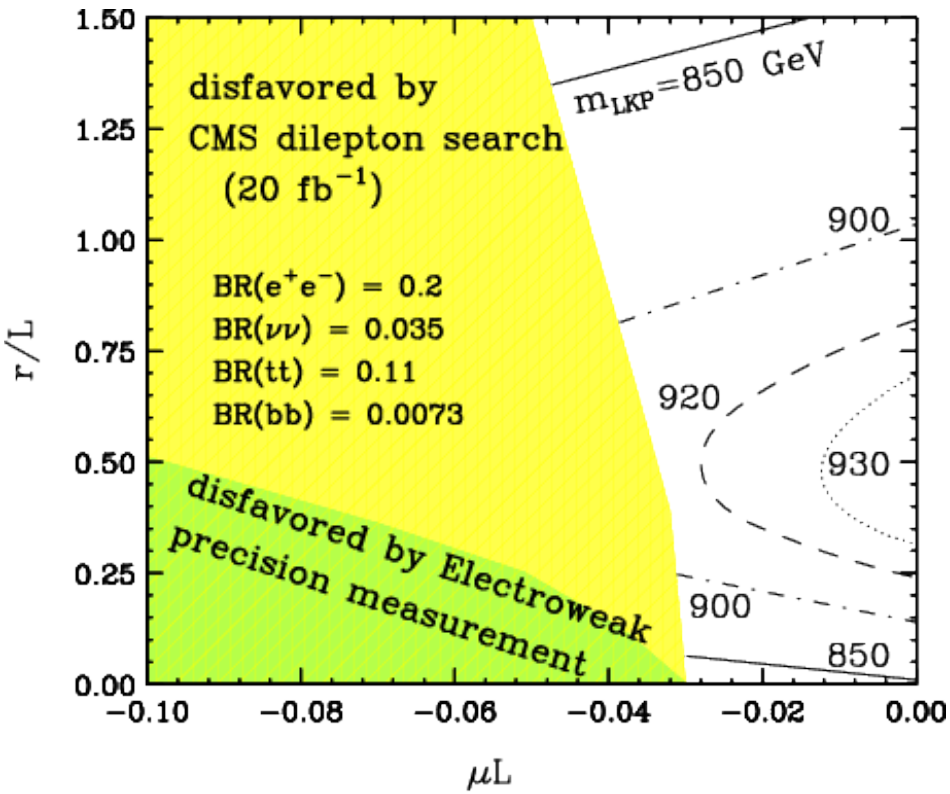
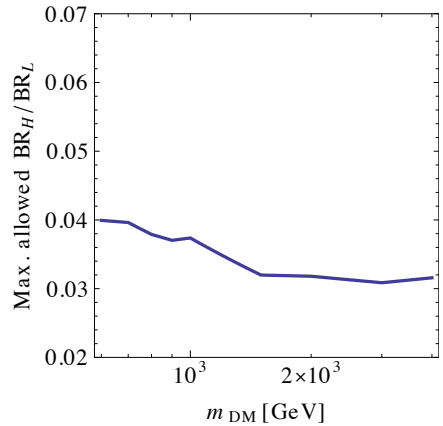
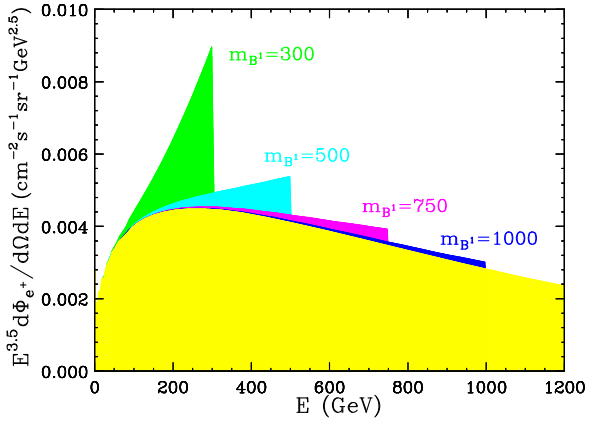
Kong, Marfatia, Gao, preliminary





Cheng, Feng, Matchev 2002



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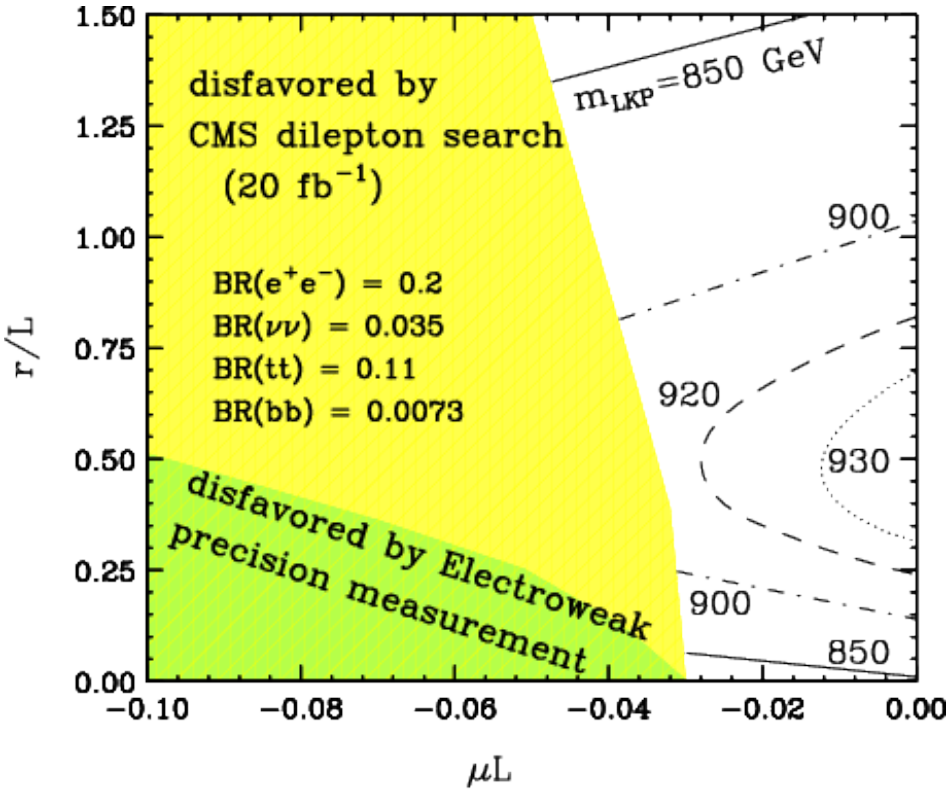
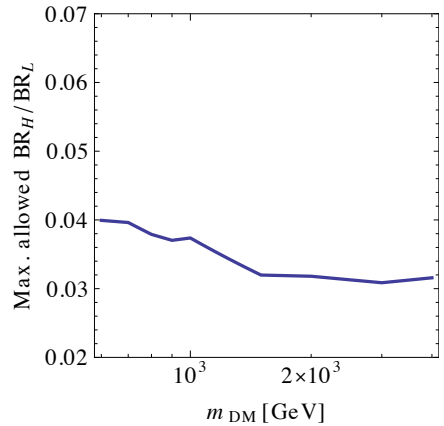
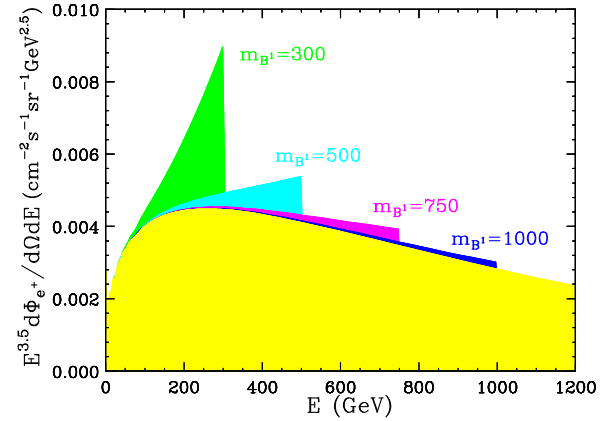
NMUED

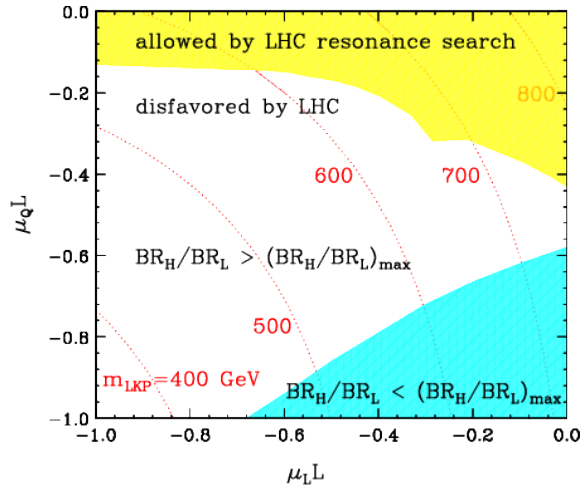
Kong, Marfatia, Gao, preliminary

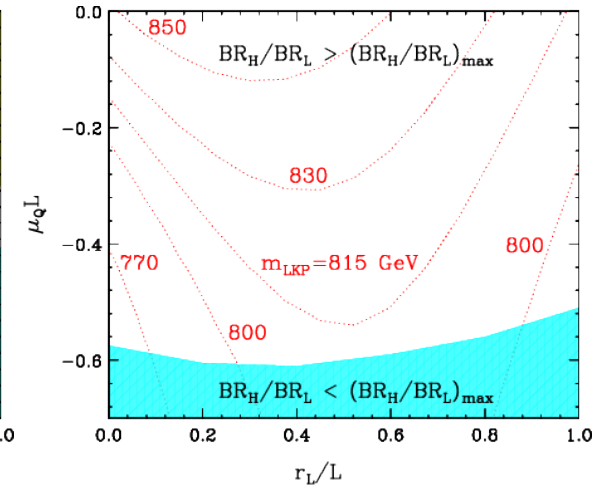


Cheng, Feng, Matchev 2002





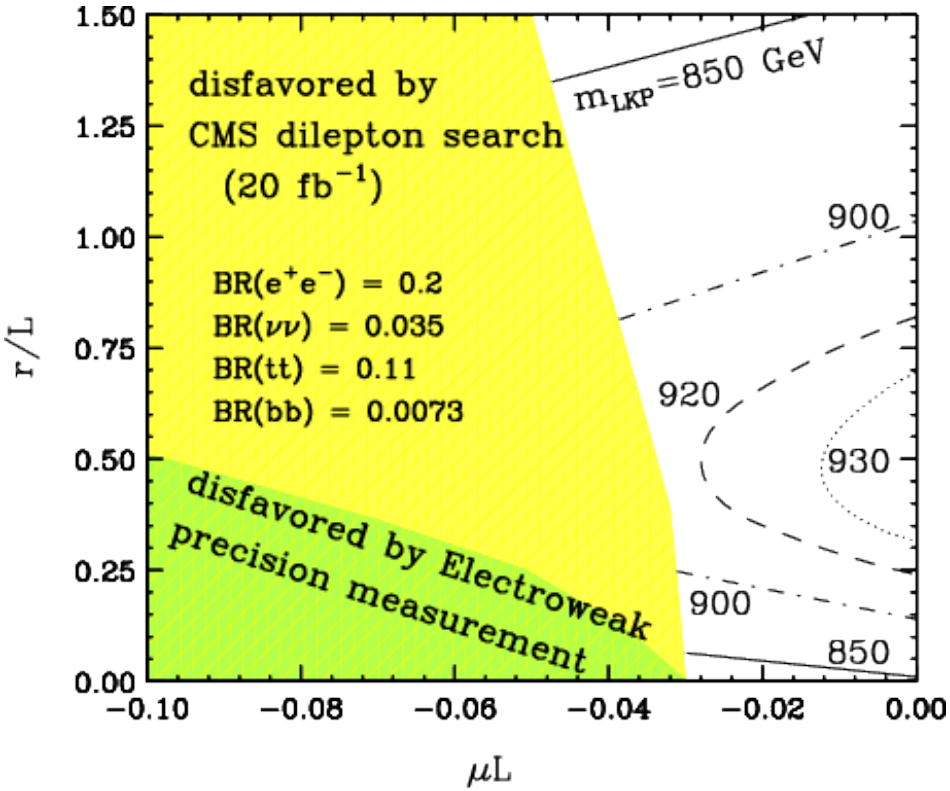




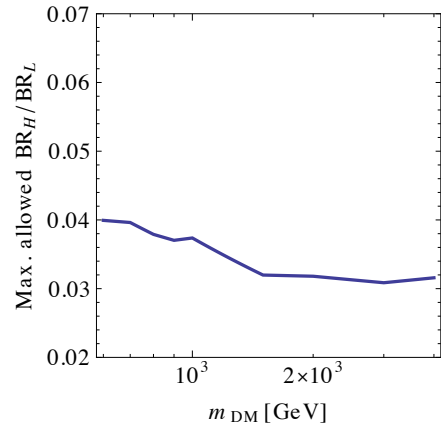
- For universal boundary and universal bulk mass

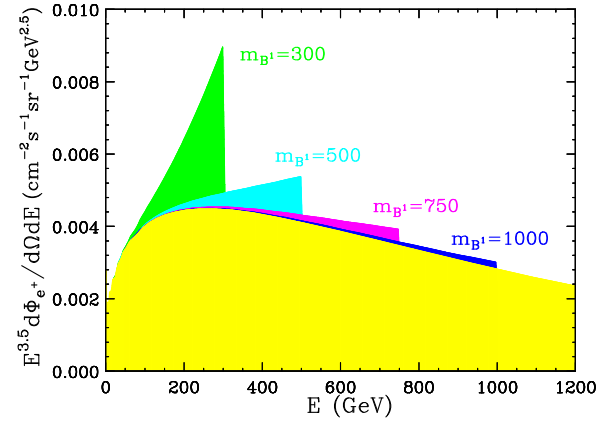
NMUED

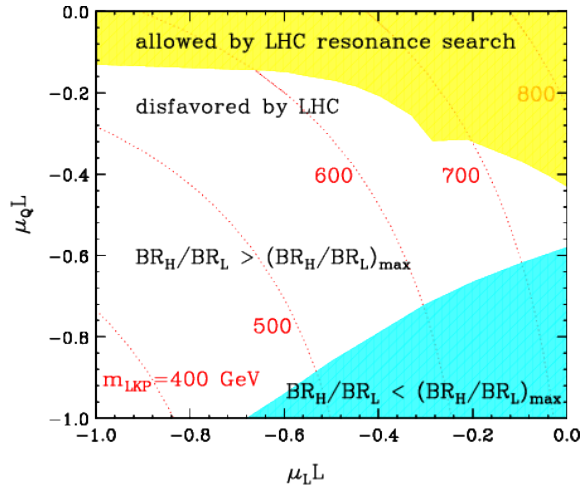
Kong, Marfatia, Gao, preliminary

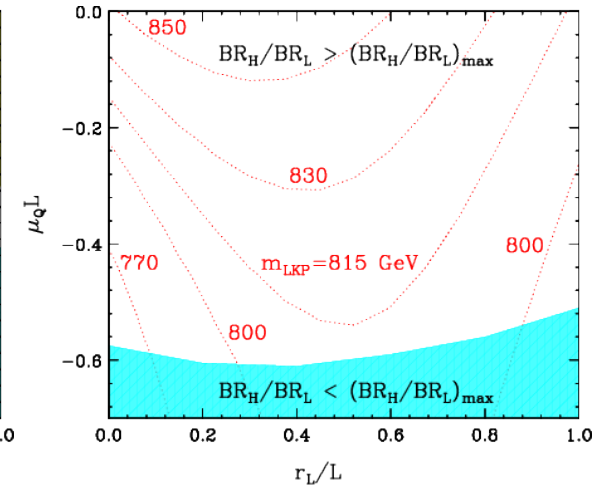


Cheng, Feng, Matchev 2002





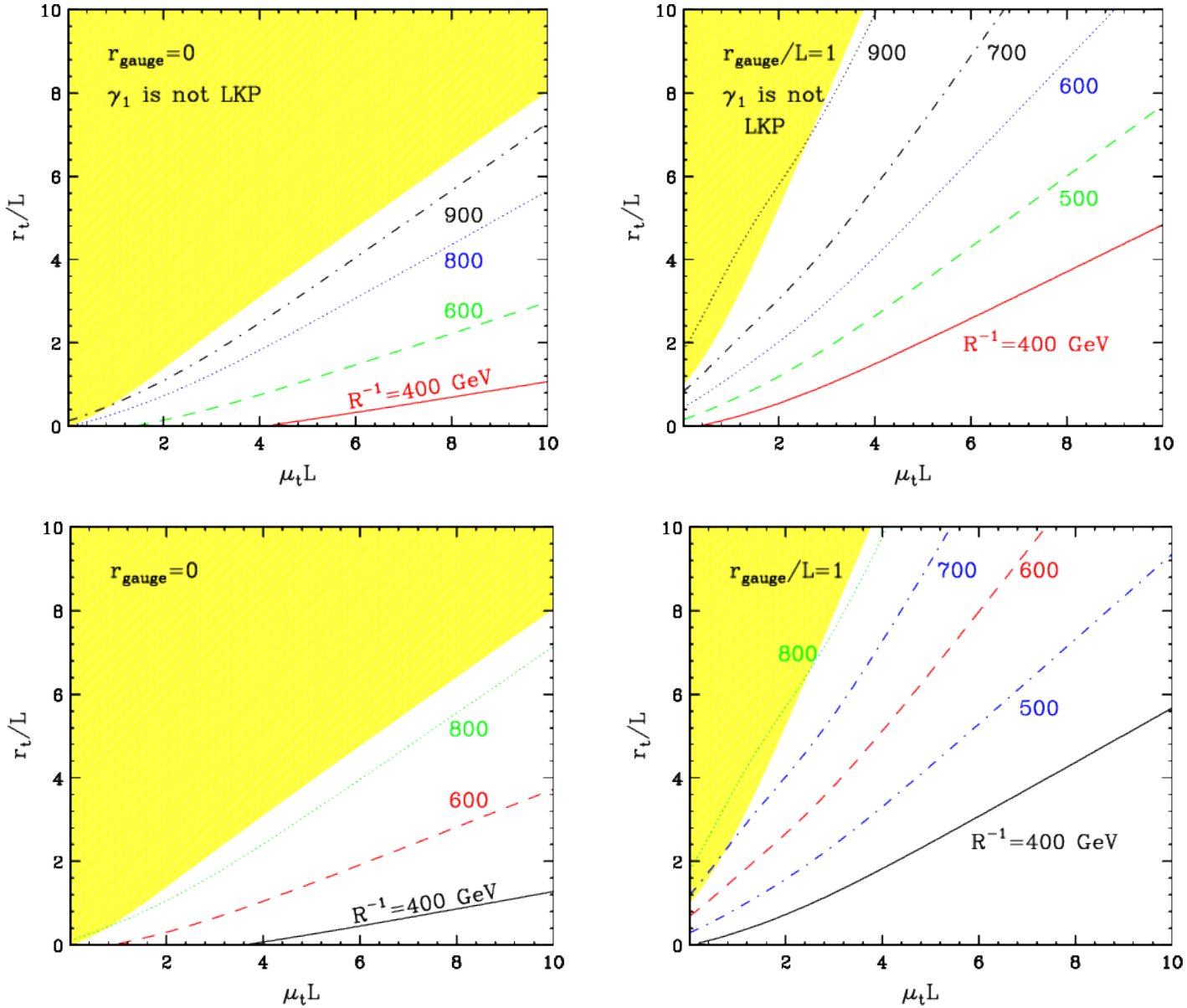




- For universal boundary and universal bulk mass
- dijet constraints and indirect detection indicates more complicated structure

MH=126 GeV in UED

Flacke, Kong, Park, preliminary



Summary

- MH=126 GeV and relic abundance disfavors 2UED with minimal mass spectrum
- MUED is very constrained
  - Rinv > 1.2 TeV from tri-lepton search (8 TeV)
  - Rinv < 1.5 TeV from relic abundance
- NMUED introduces brane terms and bulk masses
  - More parameter space, and hence tension reduced
  - Can accommodate Higgs in broad parameter space
  - Positron/antiproton data disfavors universal parametrization
  - dijet+positron data indicates more complicated structure
  - MUED exists in various event generators: CalcHEP, PYTHIA, MG/ME, Herwig, Sherpa, etc
  - For NMUED, coupling and mass spectrum can be modified easily

Why Consider Exotica?

- Some exotica aren't really all that exotic
- Urgent – real possibilities for 2009-10
- You have the potential to advance science

Would experimentalists have thought of this if you didn't do this work?

– *Witten*

- …and you might actually advance science

Never start a project unless you have an unfair advantage.

– *Seiberg*

stolen from Joe's talk

Why Consider Exotica?

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- It’s fun

If every individual student follows the same current fashion …, then the variety of hypotheses being generated…is limited. Perhaps rightly so, for possibly the chance is high that the truth lies in the fashionable direction. But, on the off-chance that it is in another direction - a direction obvious from an unfashionable view … -- who will find it? Only someone who has sacrificed himself…I say sacrificed himself because he most likely will get nothing from it…But, if my own experience is any guide, the sacrifice is really not great because…you always have the psychological excitement of feeling that possibly nobody has yet thought of the crazy possibility you are looking at right now.

– *Richard Feynman, Nobel Lecture*

stolen from Joe’s talk