The Complete Phase Diagram of Minimal Universal Extra Dimensions

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Motivations

- Naturalness
  - String landscape, inflation
  - Little hierarchy – is 5% fine-tuning too much?
  - Good time to diversify
- Cosmology
  - Incontrovertible progress
  - Dark matter is the best evidence for new physics (beyond Higgs) at the weak scale. Theoretically attractive, implications for central problems
  - Room for ideas, even after 100 s
- LHC
  - Exotic signatures: are signals being lost in triggers, analyses?
  - Spectacular signals may be found in first 2 years, should be explored now

Preview

- Consider minimal Universal Extra Dimensions, a simple, 1 parameter extension of the standard model
  - Unnatural, but dark matter → weak scale
  - Diverse cosmological connections
  - Many exotic signatures for the LHC

Universal Extra Dimensions

- Following Kaluza and Klein, consider 1 extra dimension, with 5^{th} dimension compactified on circle S^1 of radius R

- Put all fields in the extra dimension, so each known particle has a KK partner with mass ~ nR^{-1} at level n

- Problem: many extra 4D fields; most are massive, but some are massless. E.g., 5D gauge field:

$$V_\mu(x^\mu, y) = \underbrace{V_\mu(x^\mu)}_{\text{good}} + \sum_n V_\mu^n(x^\mu)\cos(ny/R) + \sum_m V_\mu^m(x^\mu)\sin(my/R)$$

$$V_5(x^\mu, y) = \underbrace{V_5(x^\mu)}_{\text{bad}} + \sum_n V_5^n(x^\mu)\cos(ny/R) + \sum_m V_5^m(x^\mu)\sin(my/R)$$

- Solution: compactify on S^1/Z_2 interval (orbifold); require

$$y \to -y \ : \quad V_\mu \to V_\mu \quad V_5 \to -V_5$$

- Unwanted scalar is projected out:

$$V_\mu(x^\mu, y) = \underbrace{V_\mu(x^\mu)}_{\text{good}} + \sum_n V_\mu^n(x^\mu)\cos(ny/R) + \sum_m V_\mu^m(x^\mu)\sin(my/R)$$

$$V_5(x^\mu, y) = \underbrace{V_5(x^\mu)}_{\text{bad}} + \sum_n V_5^n(x^\mu)\cos(ny/R) + \sum_m V_5^m(x^\mu)\sin(my/R)$$

- Similar projection on fermions → 4D chiral theory at n = 0 level
- n=0 is standard model [+ gravi-scalar]
- Very simple, assuming UV completion at $\Lambda >> R^{-1}$

Appelquist, Cheng, Dobrescu (2001)

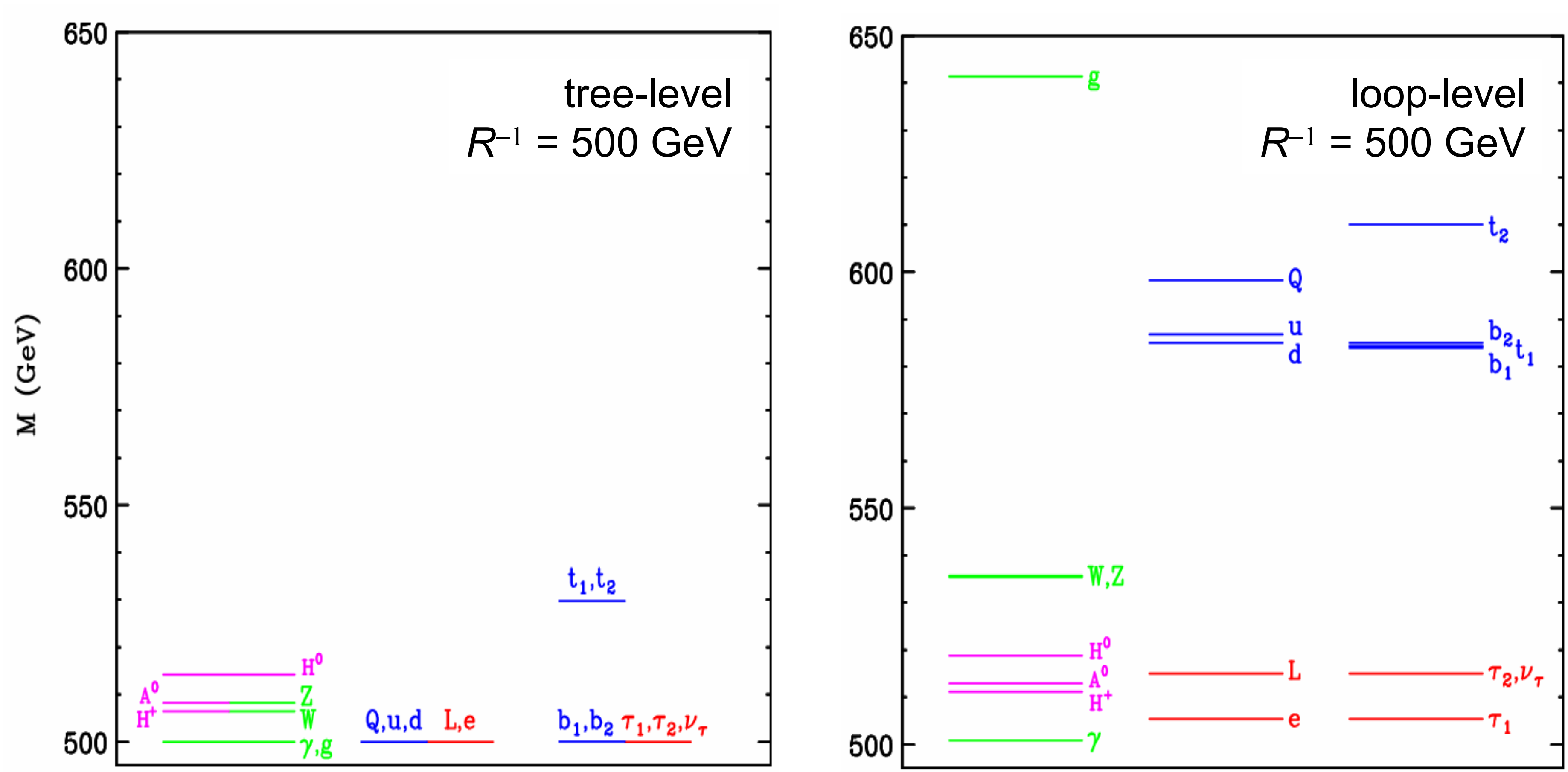
KK-Parity

- An immediate consequence: conserved KK-parity $(-1)^{KK}$ Interactions require an even number of odd KK modes
  - 1st KK modes must be pair-produced at colliders
  - Weak bounds: $R^{-1} > 250$ GeV
  - LKP (lightest KK particle) is stable – dark matter

Minimal UED

- In fact, can place mass terms on the orbifold boundaries
- These would typically break KK-parity (eliminate dark matter), or introduce flavor- and CP-violating problems
- Here assume these are absent – this defines *minimal* UED
- mUED is an extremely simple, viable extension of the SM: 1 new parameter, R

Minimal UED KK Spectrum



Cheng, Matchev, Schmaltz (2002)

mUED Common Lore

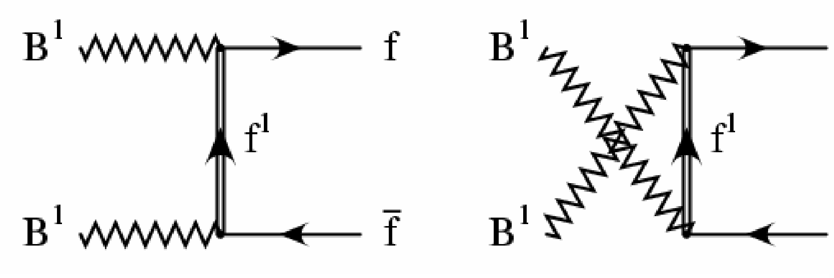
- mUED looks like SUSY
  - n=2 and higher levels typically out of reach
  - n=1 Higgses → A, H^0, $H^\pm$
  - Colored particles are heavier than uncolored ones
  - LKP is stable B^1 → missing energy at LHC
- Spectrum is more degenerate, but basically similar to SUSY

"Bosonic supersymmetry"

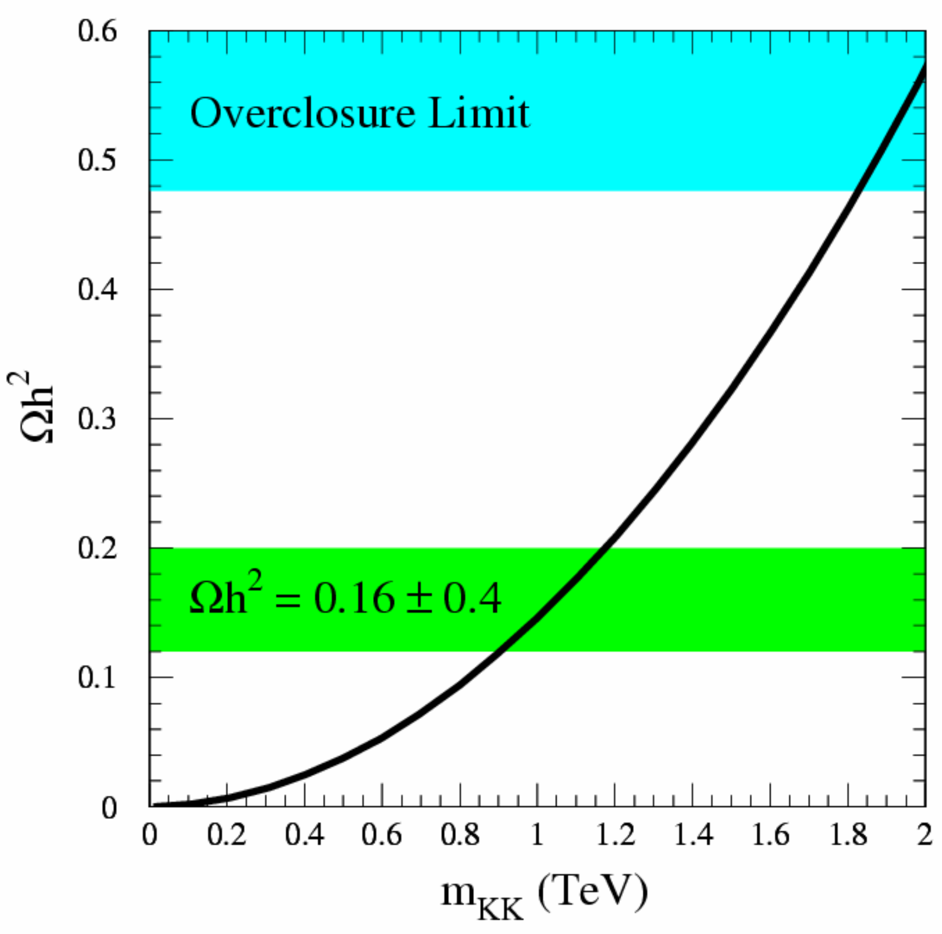
Cheng, Matchev, Schmaltz (2002)

B^1 Dark Matter

- Relic density:
  Annihilation through



Similar to neutralinos, but higher masses preferred



Servant, Tait (2002)

B1 Dark Matter Detection

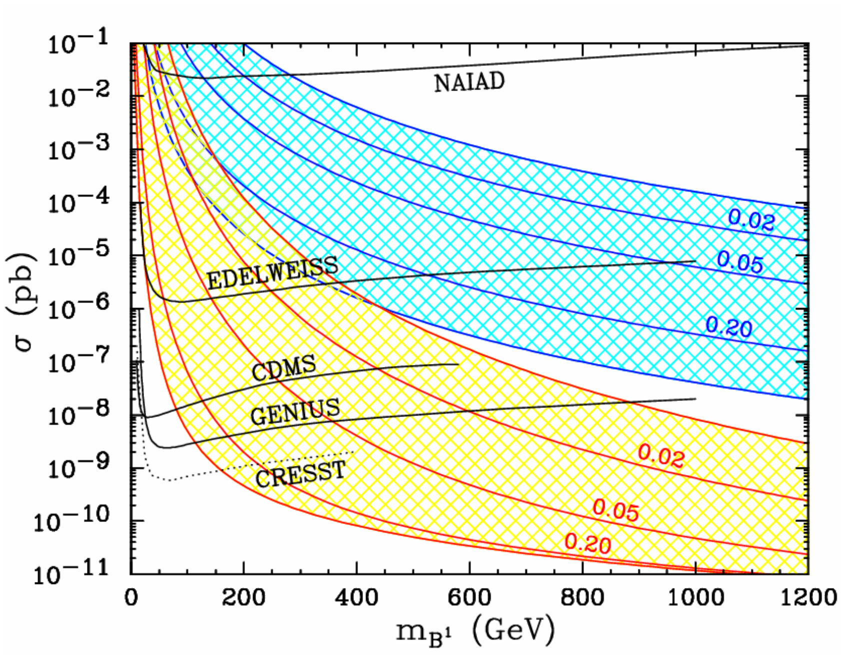
Cheng, Feng, Matchev (2002)

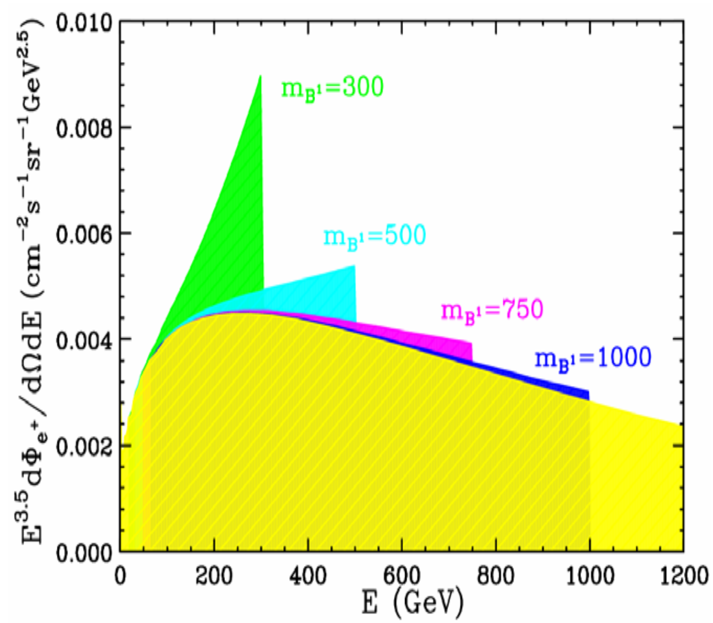
- Direct Detection

  e.g., $B^1 q \rightarrow q^1 \rightarrow B^1 q$

- Indirect Detection

  e.g., $B^1 B^1 \rightarrow e^+ e^-$





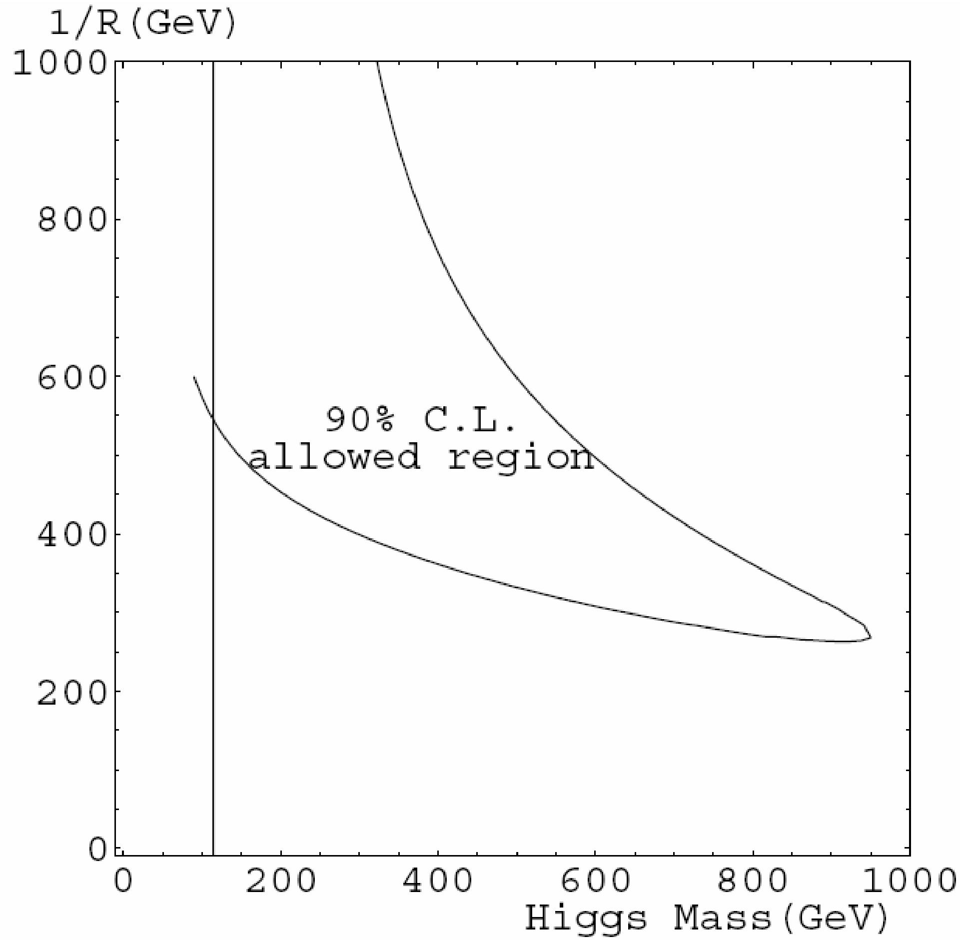
Some interesting differences relative to neutralinos, but basically WIMP-like

But Wait, There's More

- R is the only new parameter, but it is not the only free parameter: the Higgs boson mass is unknown

- These studies set m_h=120 GeV, but it can be larger

- H^0, A, $H^\pm$ masses depend on m_h



Appelquist, Yee (2002)

The KK Graviton

- The KK graviton G^1 exists with mass R^{-1} and can be lighter than the B^1

- (B^1, W^1) mass matrix:

$$\begin{pmatrix} R^{-2} + \frac{1}{4}g'^2v^2 + \delta m_{B^1}^2 & \frac{1}{4}g'gv^2 \\ \frac{1}{4}g'gv^2 & R^{-2} + \frac{1}{4}g^2v^2 + \delta m_{W^1}^2 \end{pmatrix}$$

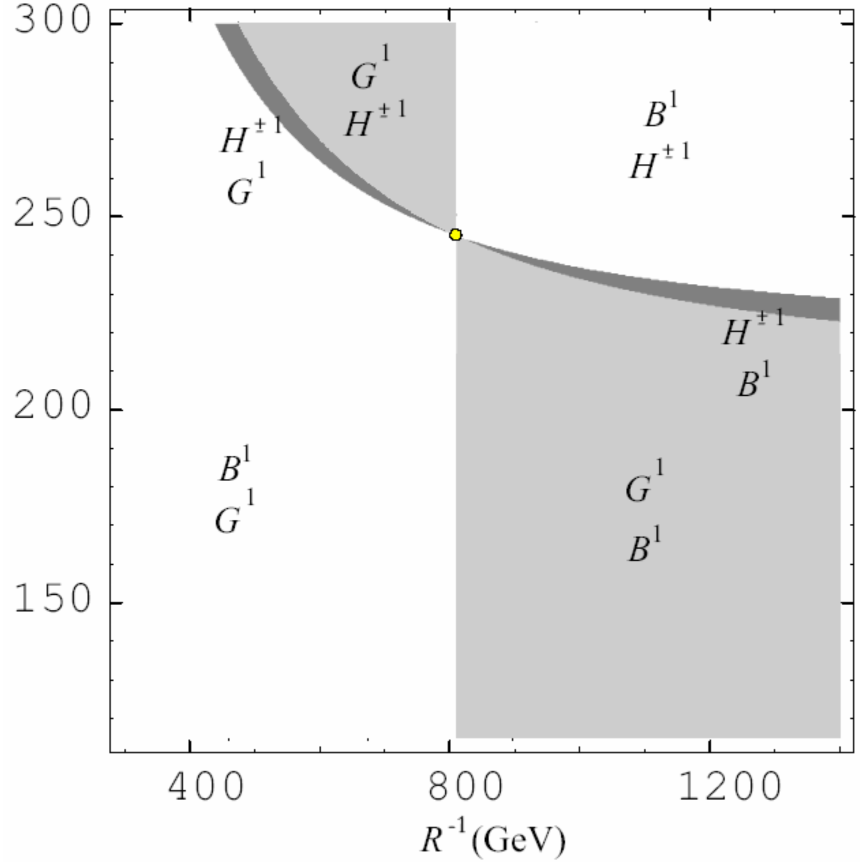
$$\delta m_{B^1}^2 = \left(-\frac{39}{2}\frac{g'^2\zeta(3)}{16\pi^4} - \frac{g'^2}{6}\frac{\ln(\Lambda^2R^2)}{16\pi^2}\right)R^{-2}$$

$$\delta m_{W^1}^2 = \left(-\frac{5}{2}\frac{g^2\zeta(3)}{16\pi^4} + \frac{15g^2}{2}\frac{\ln(\Lambda^2R^2)}{16\pi^2}\right)R^{-2}$$

Complete Phase Diagram

- Including the graviton, there are 6 (NLKP, LKP) phases

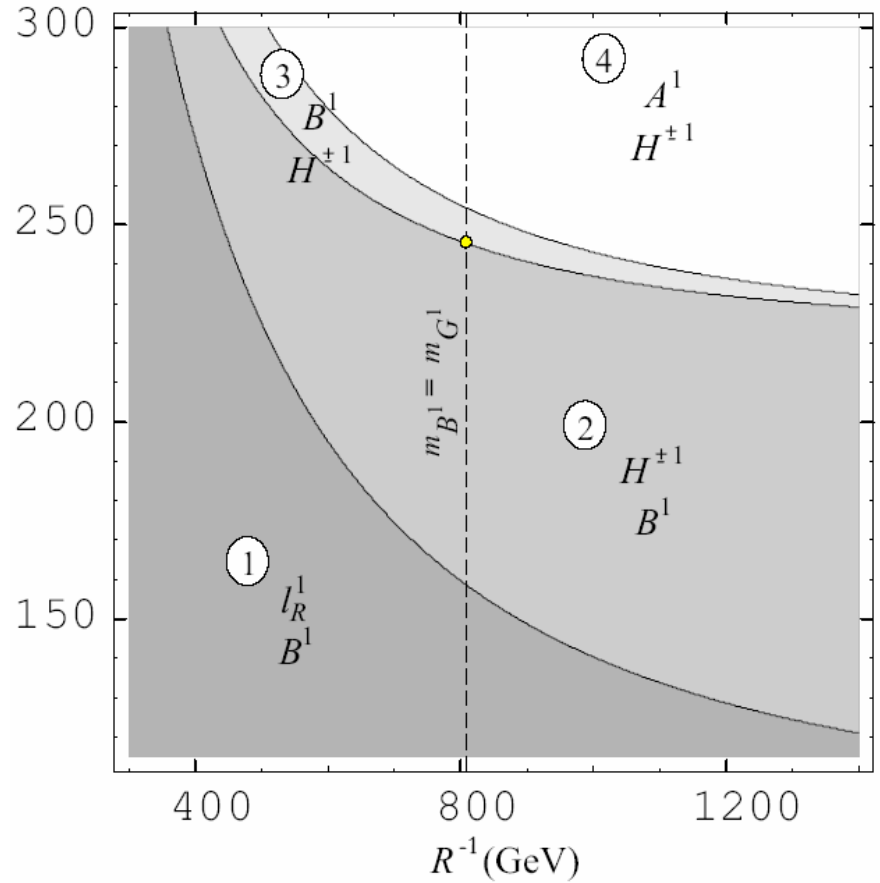
- The triple point with
  G^1, B^1, $H^\pm$
  all degenerate lies in the heart of parameter space



Cembranos, Feng, Strigari (2006)

Collider Phase Diagram

- To make progress, first exclude G^1
  - Decouples cosmology
  - Reduces complexity
- Then there are 4 (NLKP, LKP) phases
- Note: m_h=120 GeV lies entirely in Phase 1

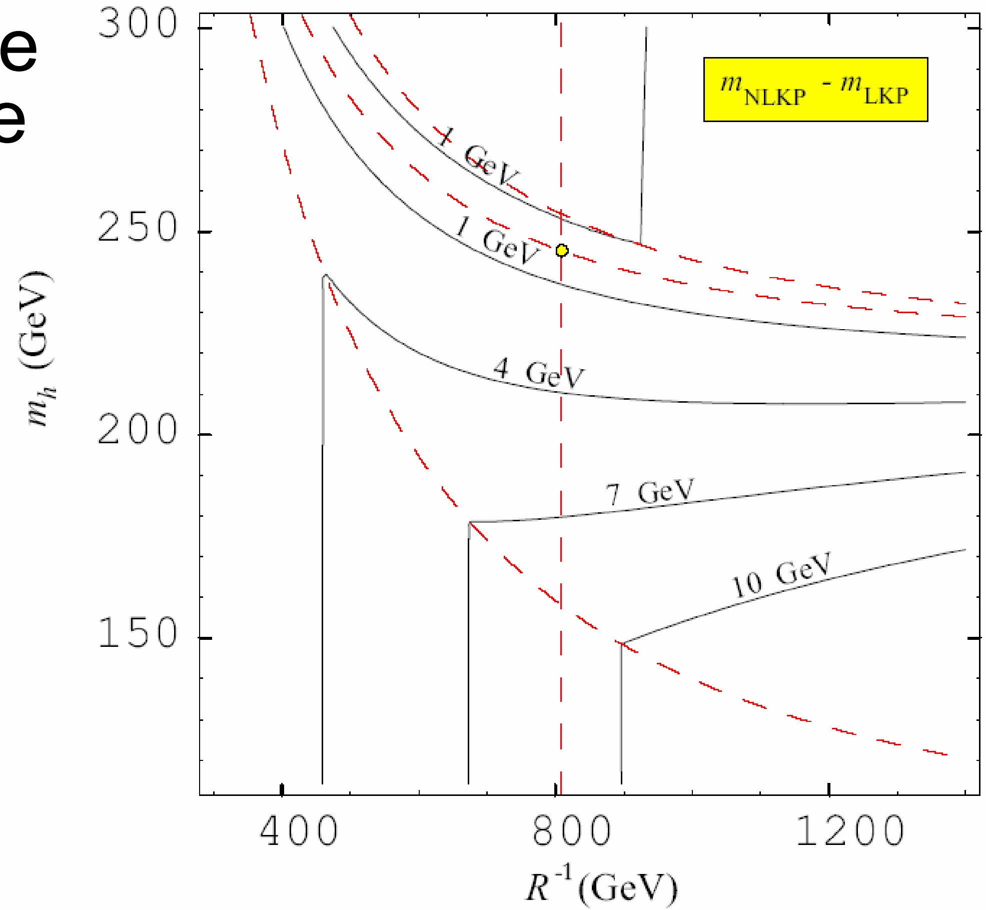


Cembranos, Feng, Strigari (2006)

Degeneracies

- The lightest states are extremely degenerate
- One might expect degeneracies of

  $m_W^2 R^{-1} \sim 10$ GeV
- Modest accidental cancelations tighten the degeneracies

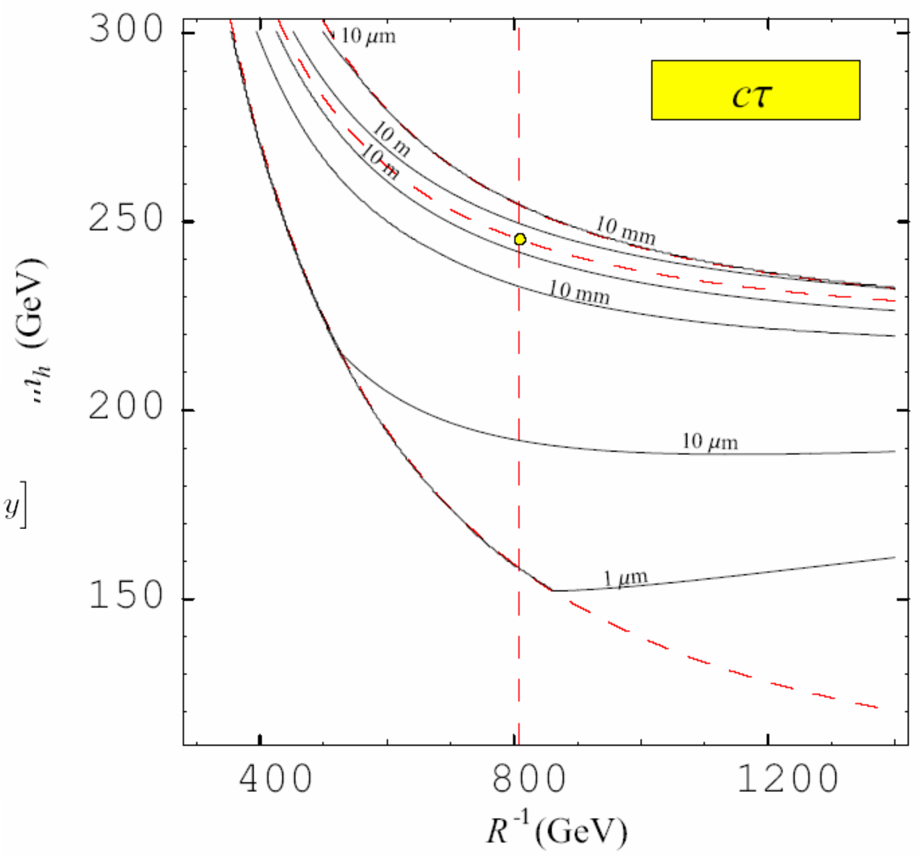


Cembranos, Feng, Strigari (2006)

NLKP Decays

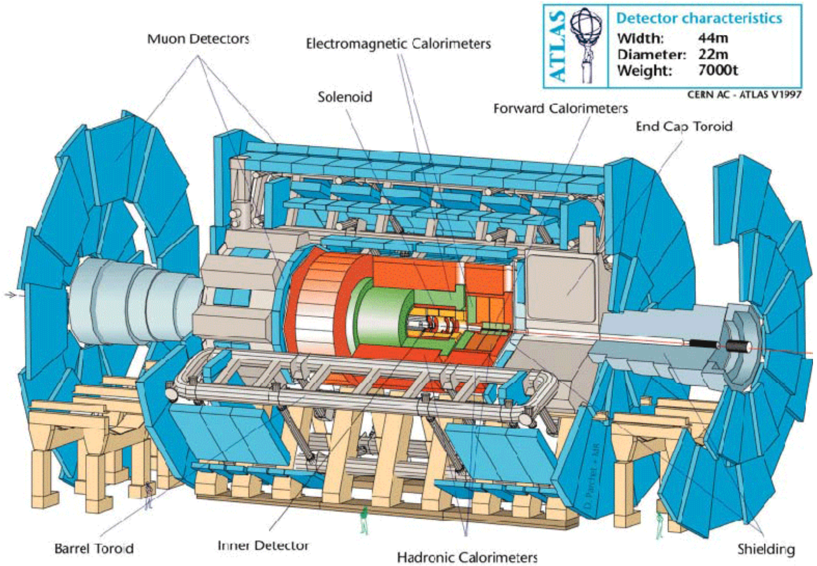
- This leads to long decay lengths: microns to 10 m

$$
\begin{aligned}
\Gamma(H^{\pm 1} \to B^1 f \bar{f}') &= \frac{N_C g^2 g'^2}{49152\pi^3} \frac{M^5}{m_W^2 m_1^2} \times \\
& \Big[(1-y)(1+y+73y^2+9y^3) + 12y^2(3+4y)\ln y\Big] \\
&\approx \frac{N_C \alpha^2}{80\pi \sin^2\theta_W \cos^2\theta_W} \frac{(\Delta m)^5}{m_W^2 M^2} \\
&\simeq 1.96 \times 10^{-16}\ \mathrm{GeV}\ N_C \left[\frac{\Delta m}{\mathrm{GeV}}\right]^5 \left[\frac{\mathrm{TeV}}{M}\right]^2 \\
&\simeq \left[1.01\ \mathrm{m}\ \frac{1}{N_C} \left[\frac{\mathrm{GeV}}{\Delta m}\right]^5 \left[\frac{M}{\mathrm{TeV}}\right]^2\right]^{-1} ,
\end{aligned}
$$



LHC Signals

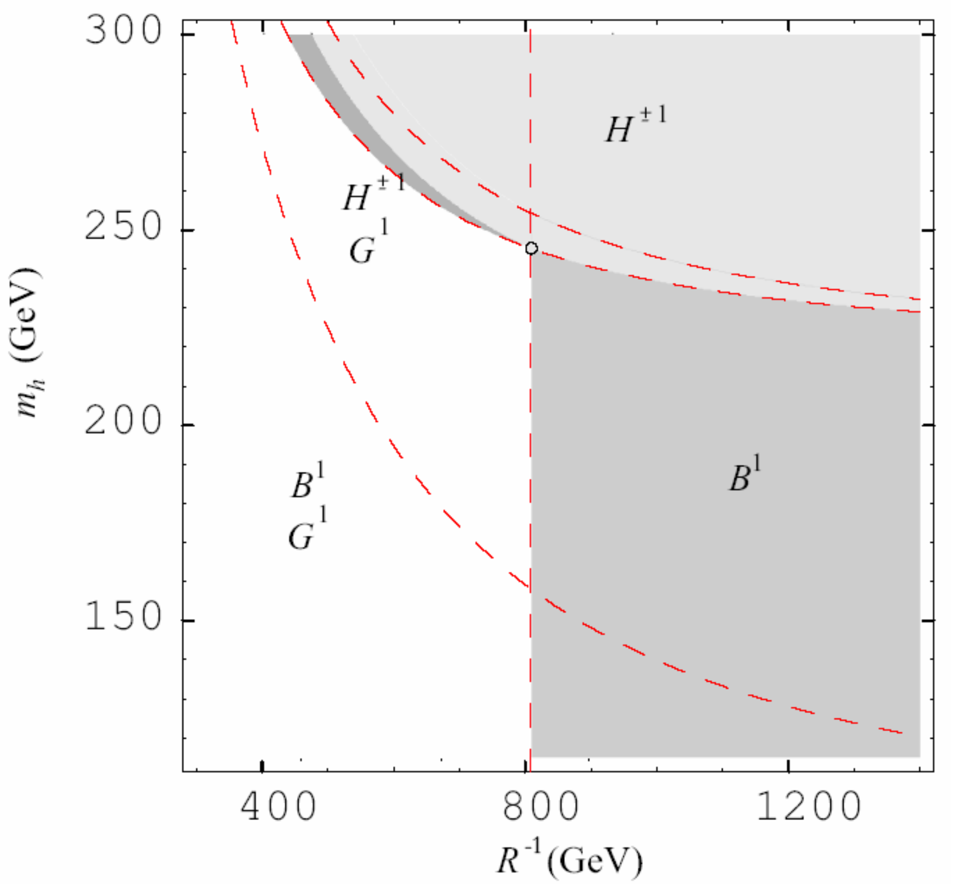
- Kinks: $H^{\pm} \rightarrow B^1\, e\, \nu$
- Displaced vertices: $H^{\pm} \rightarrow B^1\, u\, d$
- Vanishing tracks: $H^{\pm} \rightarrow B^1\, (e)\, \nu$
- Highly-ionizing tracks : $H^{\pm}$
- Time-of-flight anomalies: $H^{\pm}$
- Appearing tracks: $A \rightarrow H^{\pm}\, e\, \nu$
- Appearing tracks: $A \rightarrow H^{\pm}\, (e^{\pm})\, \nu$
- Impact parameter: $A \rightarrow H^{\pm}\, (e^{\pm})\, \nu$
- …
- Decays in vertex detectors, trackers, calorimeters, muon chambers, outside detector are all possible.



Cosmological Phase Diagram

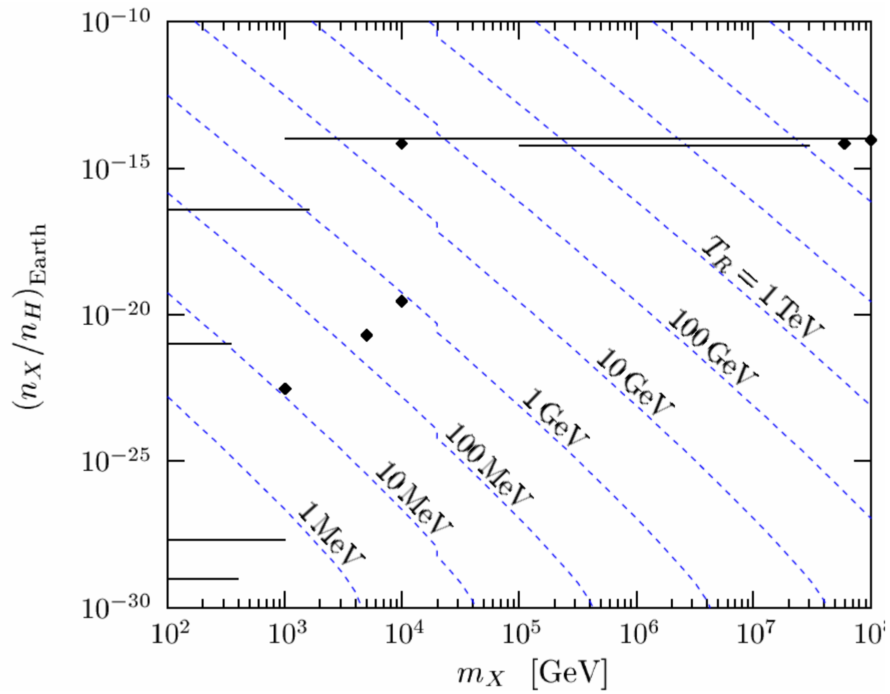
- Can cosmological constraints restore order?
- Include G^1 – cosmologically relevant when it's the LKP

[$H^{\pm} \rightarrow G^1$ takes 10^{26} s]



Charged Stable Relics

- Charged stable relics create anomalously heavy isotopes
- Severe bounds from sea water searches
- But inflation can dilute this away
- What is the maximal reheat temperature?

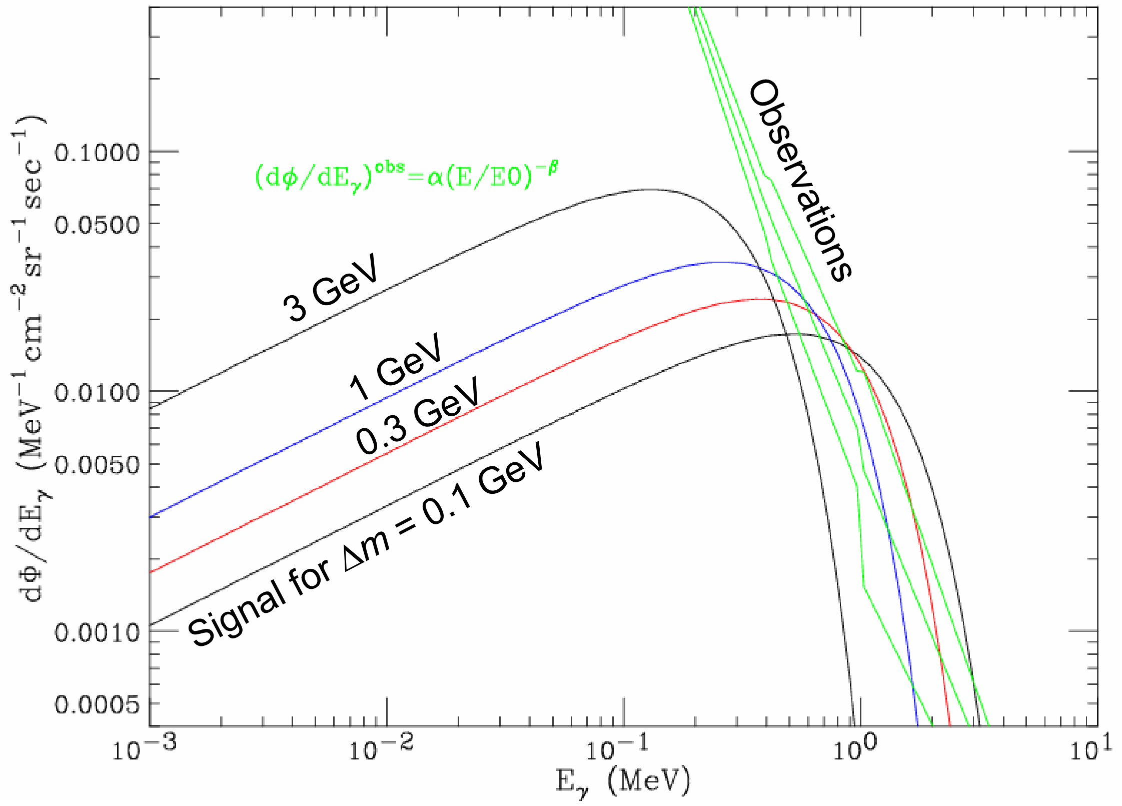


Kudo, Yamaguchi (2001)

Masses < TeV are excluded by T_{RH} > 1 MeV, but masses > TeV are allowed

Diffuse Photon Flux

- Late $B^1 \rightarrow \gamma\, G^1$ contributes to diffuse photon flux
- Small Δm implies smaller initial energy, but also less red shifting; latter effect dominates
- Excludes lifetimes < 10 Gyr, but again evaded for low T_{RH}



Feng, Rajaraman, Takayama (2003)

Overproduction of B^1 WIMPs

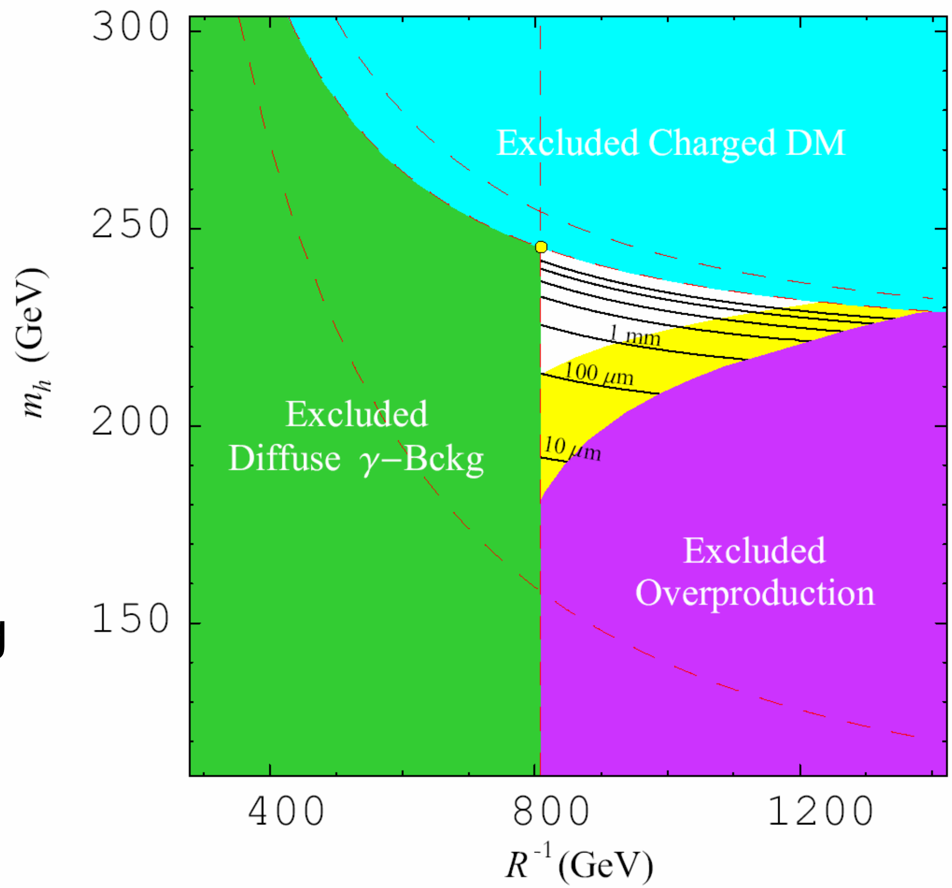
- The original calculation of thermal relic densities has now been greatly refined
  - Radiative contributions to masses included
  - n=2 resonances included
  - All co-annihilations included

Kakizaki, Matsumoto, Sato, Senami (2005); Burnell, Kribs (2005)
Kong, Matchev (2005); Kakizaki, Matsumoto, Senami (2006)

- The requirement that B^1's not overclose the universe also restricts the parameter space (but is again avoided for low T_{RH})

Complete Cosmologically Constrained Phase Diagram

- Assuming T_{RH} > 10 GeV, get triangle region, predict
  - Long-lived tracks at colliders
  - 180 GeV < m_h < 245 GeV
  - R^{-1} > 800 GeV
  - All KK masses degenerate to 330 GeV
  - $B^1 \rightarrow G^1$ may be happening right now



Cembranos, Feng, Strigari (2006)

- This is not like SUSY

CONCLUSIONS

- mUED is a simple, 1 parameter extension of the SM
- Nevertheless it has extremely rich implications for particle physics and cosmology
- "Exotic" signatures may produce spectacluar signals *soon* if we are prepared; much work to be done