Beyond Neutralino Dark Matter: Recent results on Kaluza-Klein Photons and Gravitinos

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Based on:
<u>*KK Photons:*</u> JC, Stefano Profumo, and William Shepherd, Phys. Rev. D89 (2014) 056005 (arXiv: 1401.7050)
<u>*Gravitinos:*</u> Angelo Monteux, Eric Carlson, JC. (arXiv:1404.5952)

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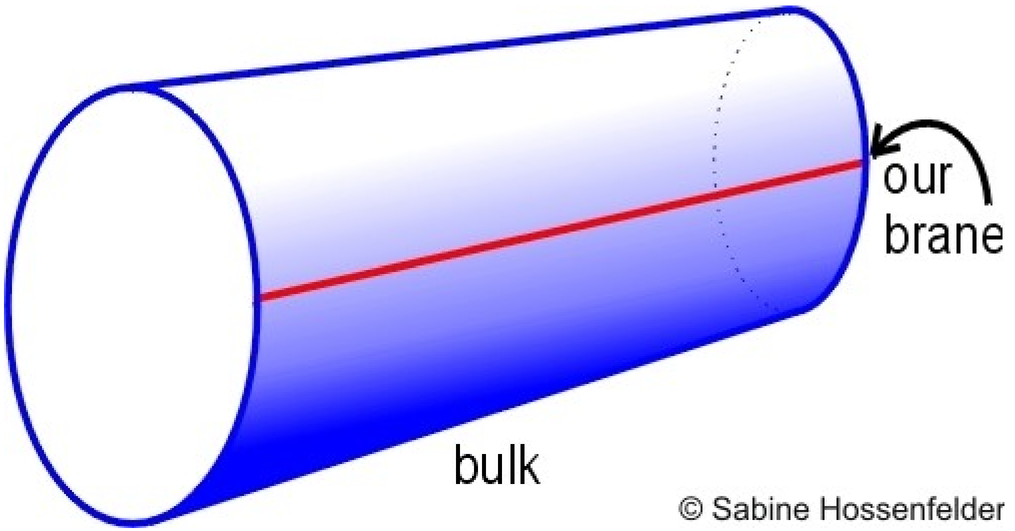
Dark Matter Candidate #1: Kaluza Klein Photons in minimal Universal Extra Dimensions



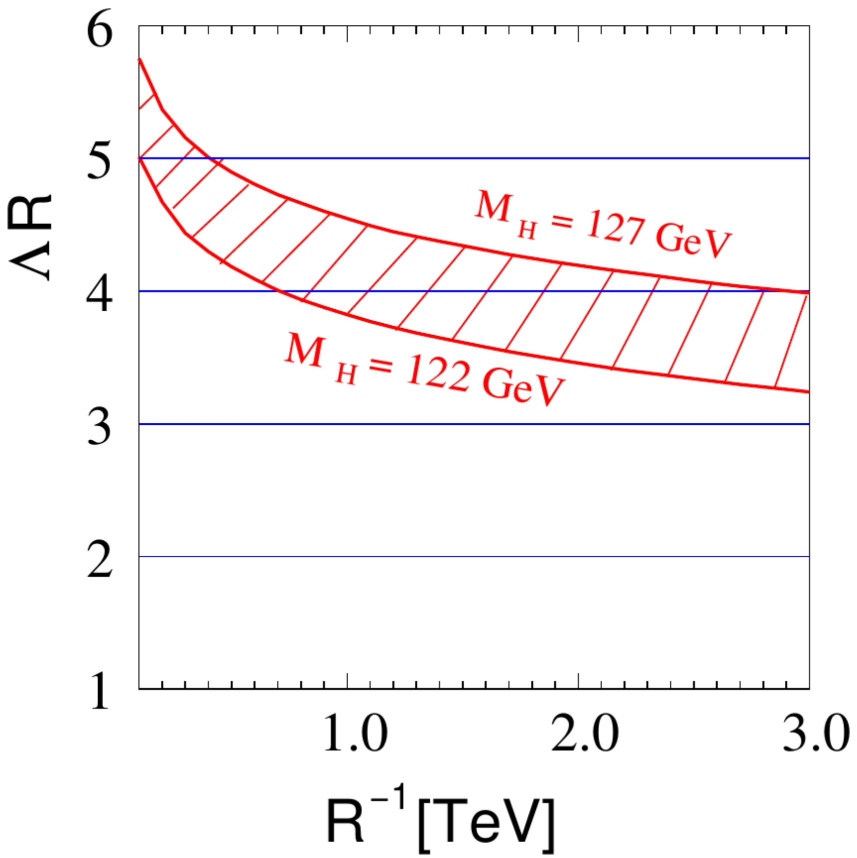
Minimal Universal Extra Dimensions

- 5 dimensional theory with the fifth dimension compactified
- Kaluza-Klein Parity imposed to stabilize the Lightest Kaluza-Klein Particle
- No bulk mass terms

Three Parameters in the Theory:

R^{-1}	$\cancel{m_h}$	ΛR
Compactification Scale	Higgs Mass	Cutoff Scale

Vacuum Stability in UED



- Higgs self coupling λ driven to zero by addition of additional degrees of freedom.

$$V_{\text{Higgs}} = \frac{1}{2}\mu^2\Phi^2 + \frac{1}{4}\lambda\Phi^4$$

- This leads to unstable vacuum and much lower cutoff on ΛR than previously considered.

Datta, Patra, Raychaudhuri, 2013
Blennow et al, 2012

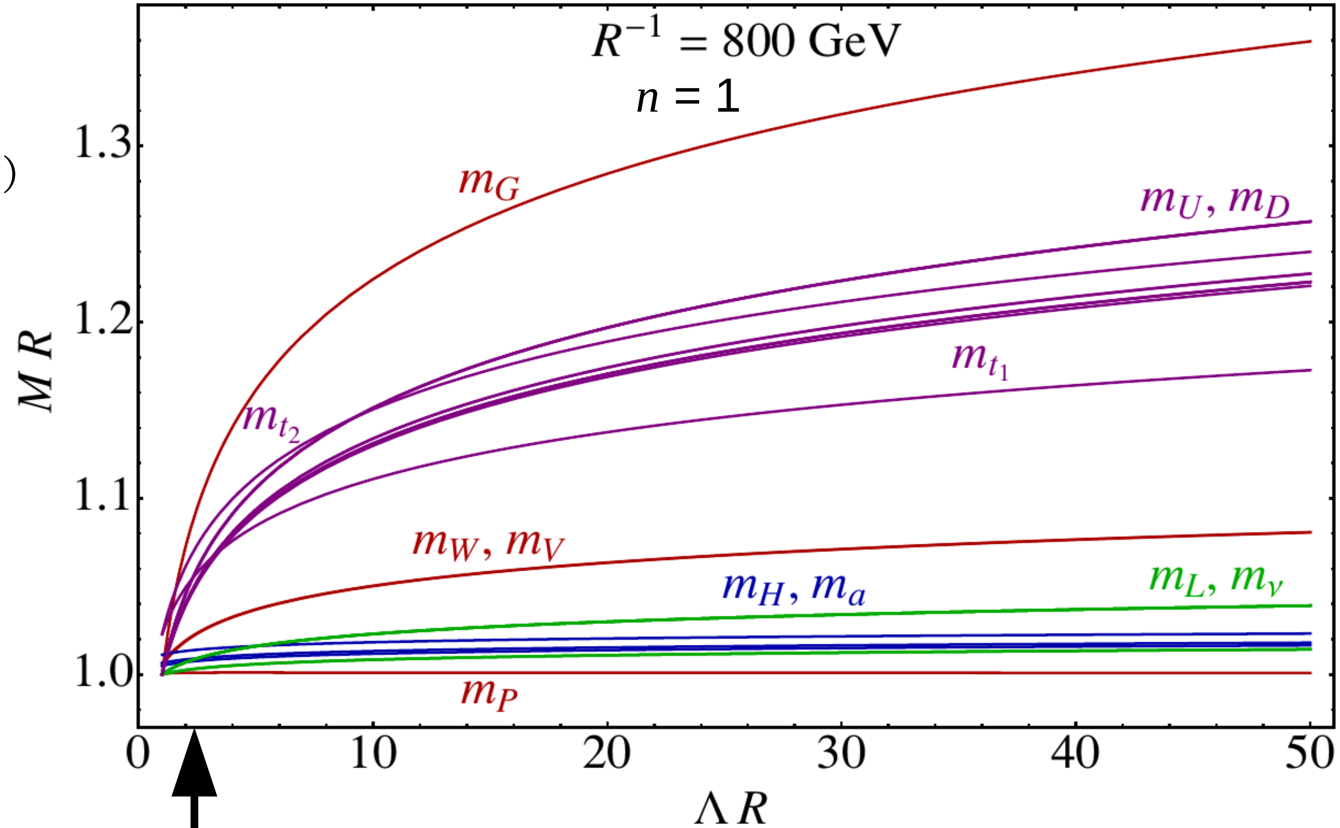
Mass Spectrum of KK excitations

At tree level:

$$m^2_{X^{(n)}} = \frac{n^2}{R^2} + m^2_{X^{(0)}}$$

1 Loop Corrections:

$$\delta m \propto \ln \Lambda R$$

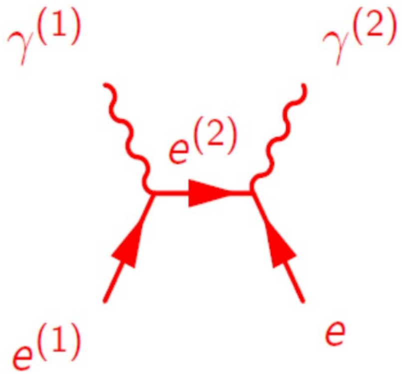


Belyaev, et. al. 2013

At low ΛR, masses are essentially degenerate.

Dominant Relic Density Processes

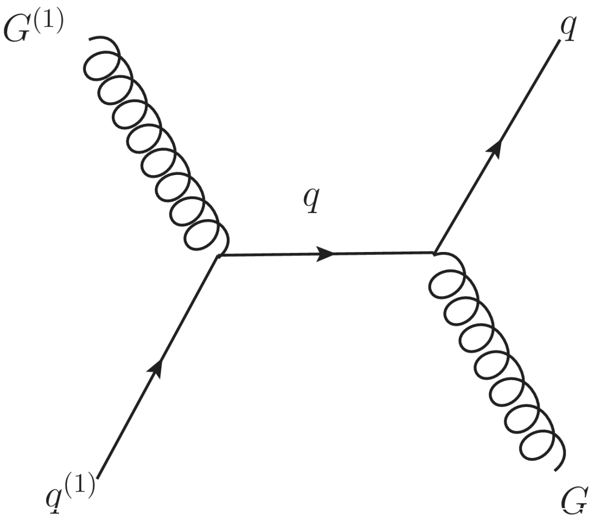
At high ΛR:



- Resonant enhancement
- KK2 Photon can only decay to SM states

Bélanger,Kakizaki,Pukov, 2011

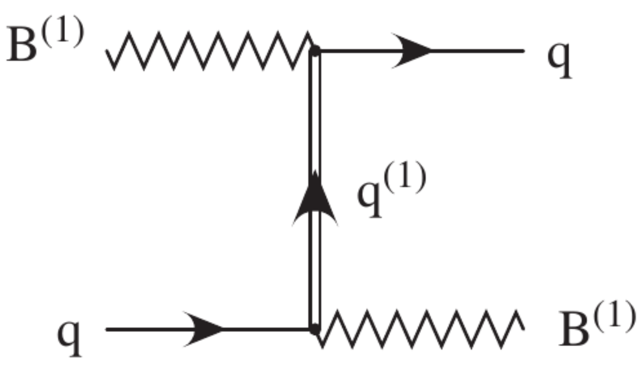
At low ΛR:

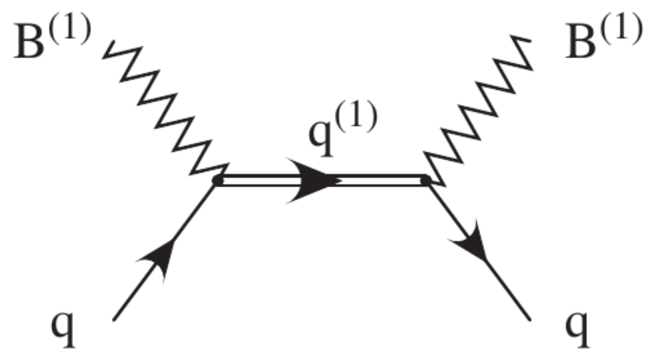


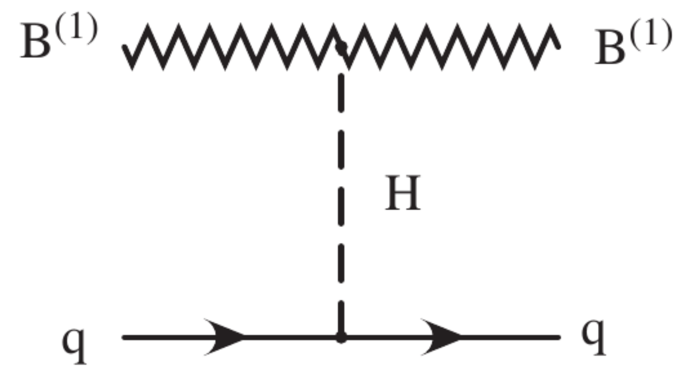
- Small mass splittings make this strong process dominant.

Spin Independent Direct Detection

Servant, Tait 2002



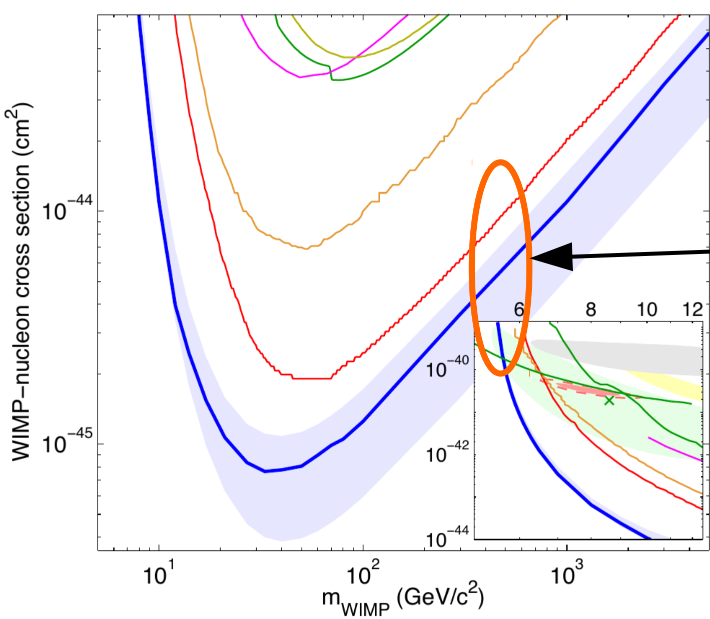




Resonantly enhanced at low ΛR

Dominant process

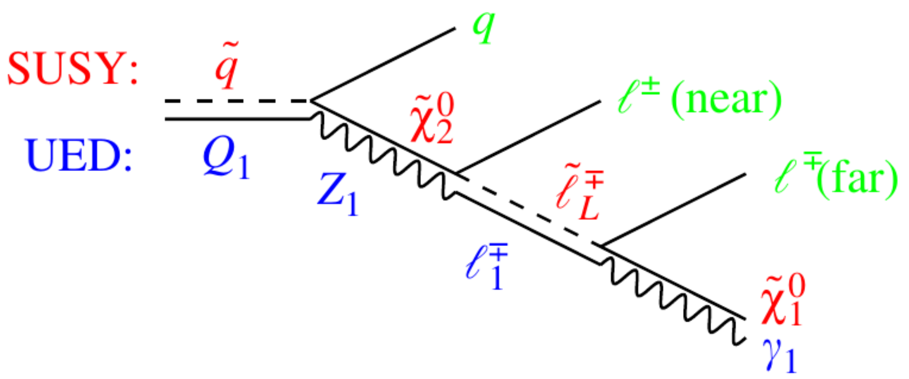
LUX 2013 SI Results



Relevant mass/cross section for this model.

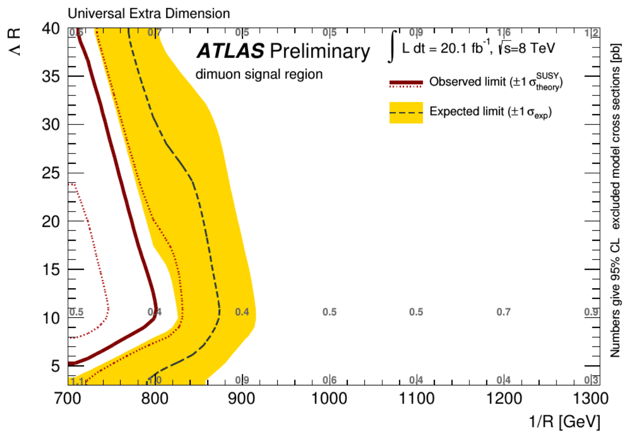
LHC Limits

- Repurposed SUSY searches with leptons, jets and missing tranverse energy as mUED searches



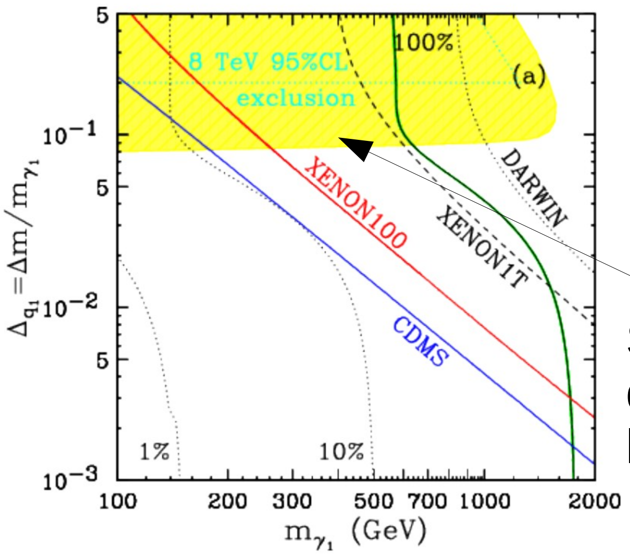
Datta, Kong, Matchev. 2005

Current di-lepton limits (20 fb^{-1})



ATLAS-CONF-2013-062

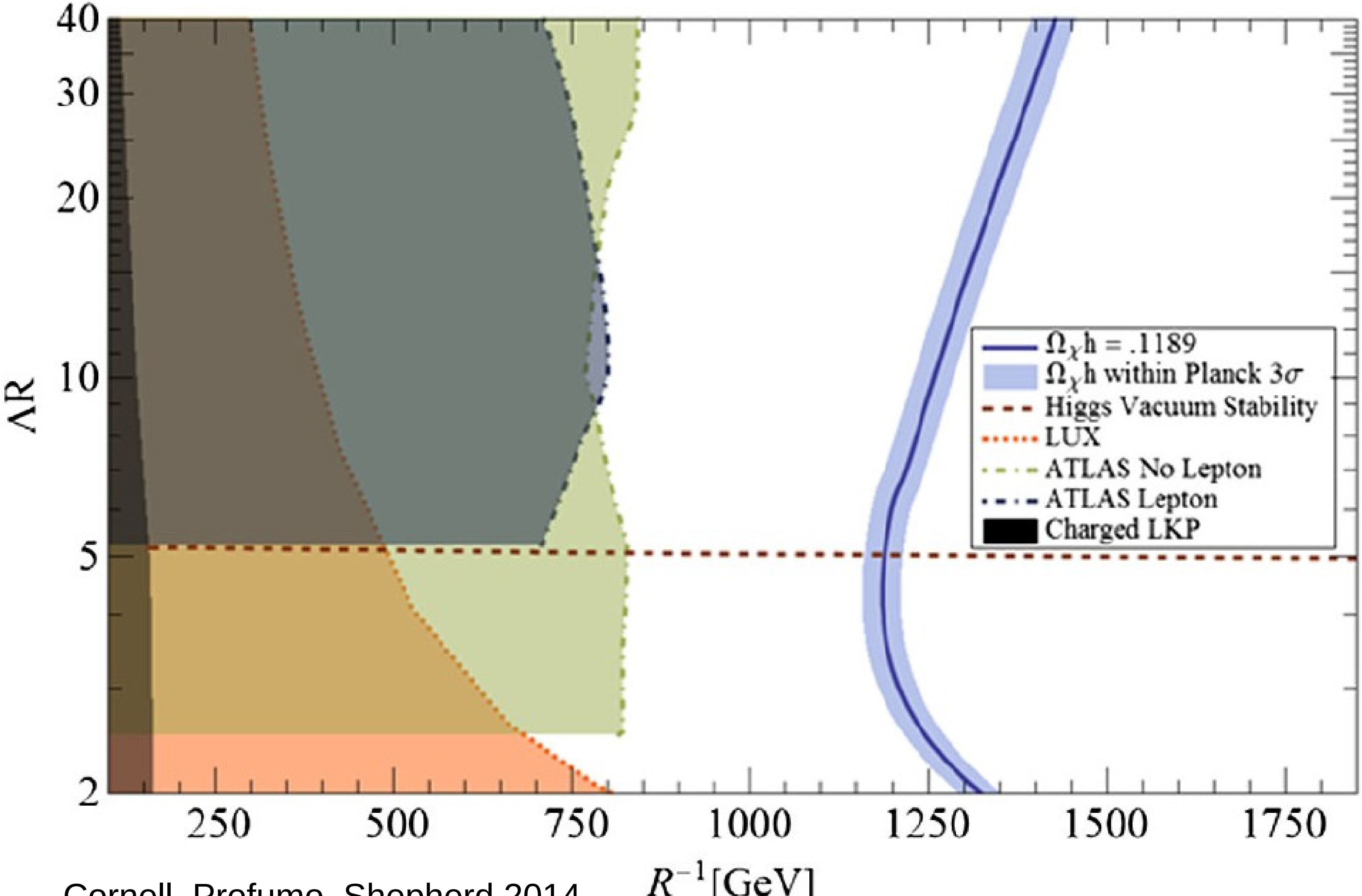
Projected 8 TeV 4 lepton limits (100 fb^{-1})



Sensitivity cutoff due to softness of leptons.

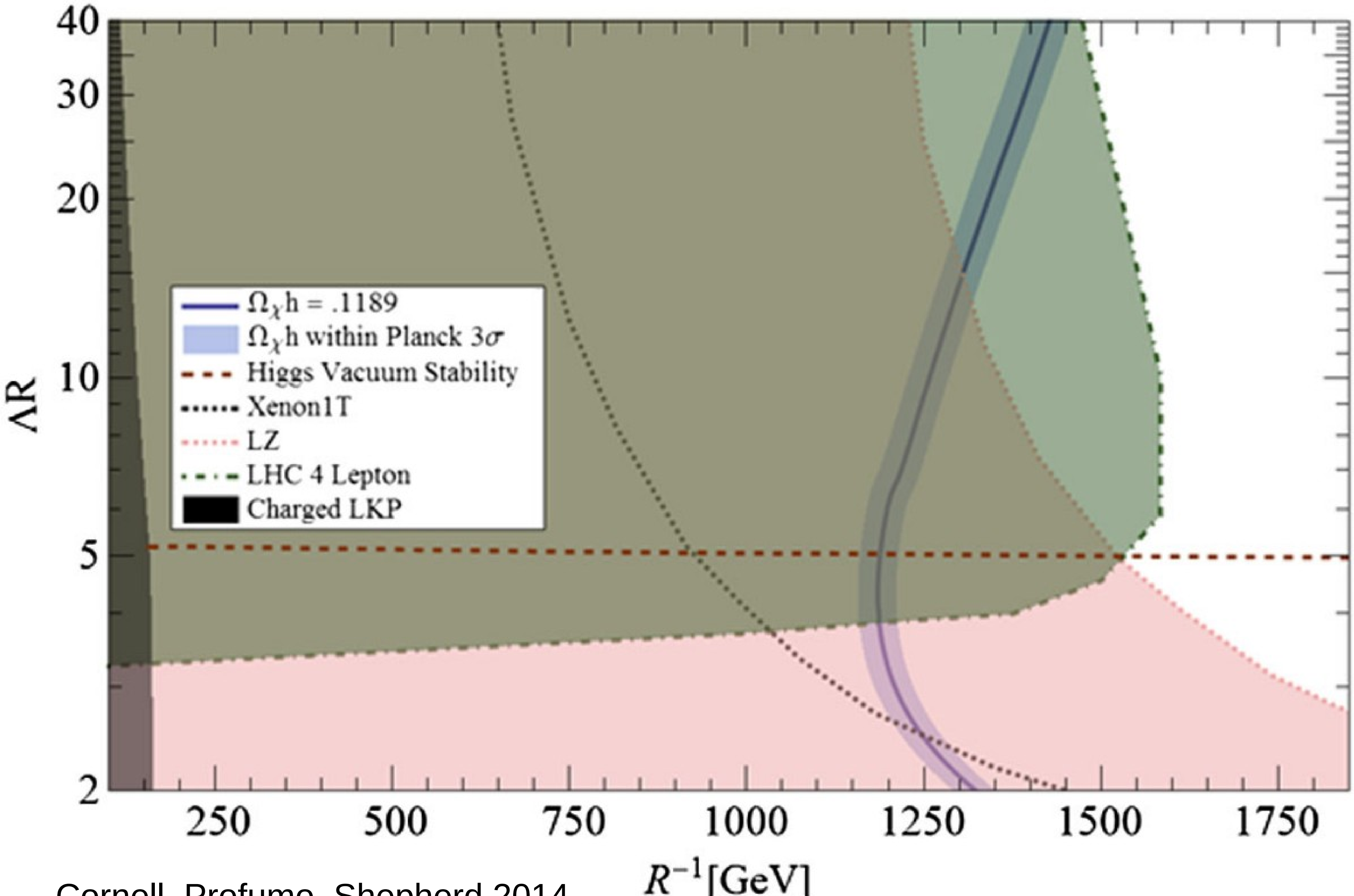
Arrenberg et. al., 2013

Current Limits



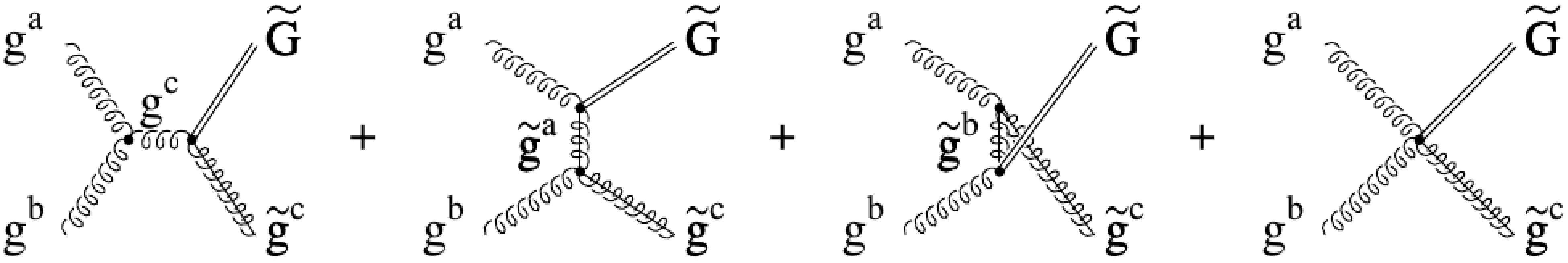
Cornell, Profumo, Shepherd 2014

Projected Sensitivity



Cornell, Profumo, Shepherd 2014

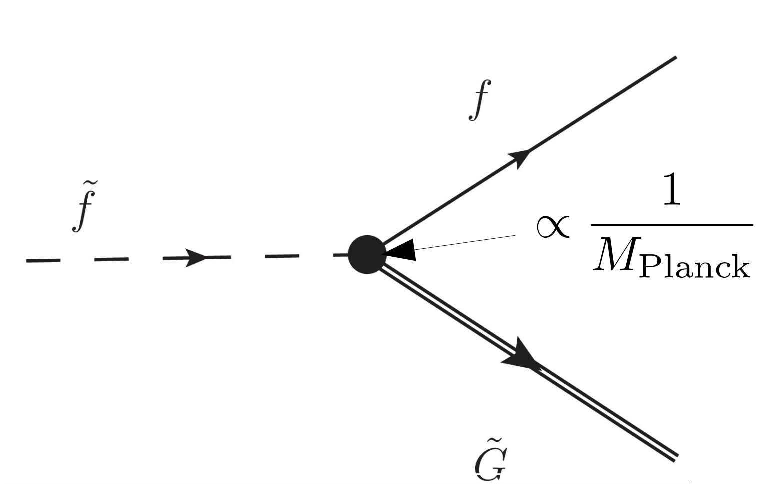
Dark Matter Candidate #2: Gravitino with R-parity Violation and Flavor Symmetry



The Gravitino Dark Matter Problem

The Gravitino $\tilde{G}$:

- Spin 3/2 partner of graviton
- Can be LSP, and with R-parity, it can be the DM



Caveats:

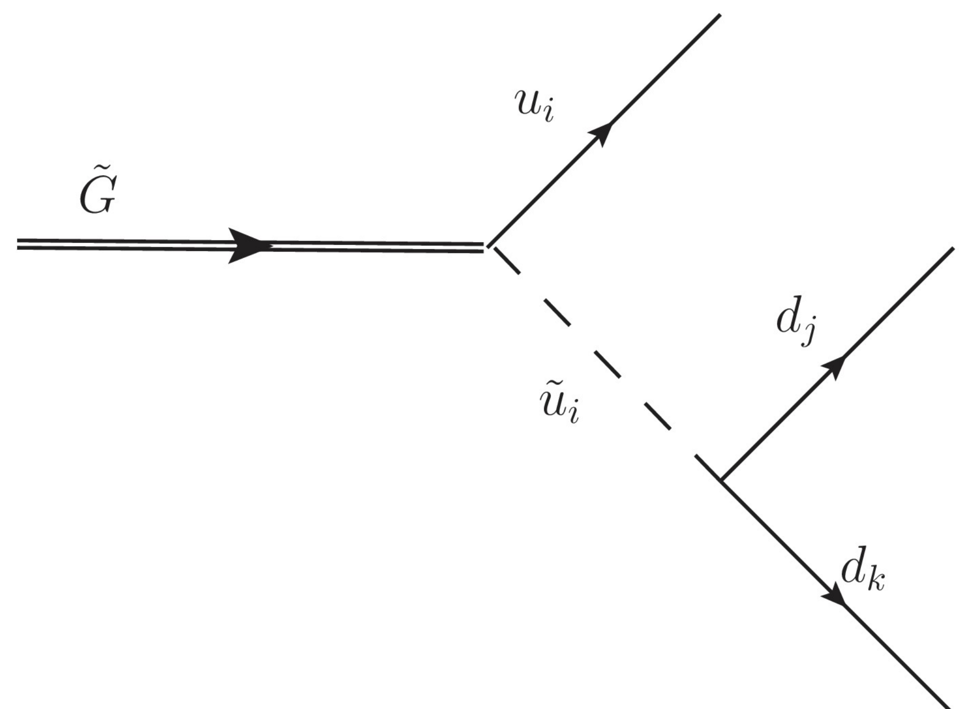
- Late time decays of NLSP to gravitino can cause problems with BBN
- Does not annihilate, so not astrophysically observable.

Moroi, 1995

A Solution: R-Parity Violation

$$W_{RPV} = \underbrace{\mu_i L_i \phi_u + \lambda_{ijk} L_i L_j \bar{\ell}_k + \lambda'_{ijk} L_i Q_j \bar{d}_k}_{\text{Lepton Number Violating}} + \underbrace{\lambda''_{ijk} \bar{u}_i \bar{d}_j \bar{d}_k}_{\text{Baryon Number Violating}}$$

- NLSP can quickly decay directly to SM particles
- To avoid proton decay and LHC constraints, we consider only the baryon number violating operator
- Gravitino decays as shown on right, producing cosmic ray and gamma ray astrophysical signatures



Flavor Symmetries

- To avoid flavor changing neutral currents, flavor symmetries are posited.
- Reduces parameter space from 9 independent λ''_{ijk} couplings to one or two parameters
- We consider two symmetries:

Horizontal U(1) Symmetry – Relative structure of couplings determined by SM fermion masses and mixings

Joshipura, Vaidya, Vempati, 2000 Monteux, 2013

Minimal Flavor Violation – Higgs sector parameters enter as well

Nikolidakis, Smith, 2008 Csaki, Grossman, Heidenreich, 2012

Horizontal Symmetry	Minimal Flavor Violation
$$\lambda''_{ijk} = \lambda''_{323}\varepsilon^{u_{i3}+d_{j2}+d_{k3}}$$	$$\lambda''_{ijk} = w'' V^*_{il}\epsilon_{jkl}\frac{m_i^{(u)}m_j^{(u)}m_k^{(d)}}{v^3}\frac{1}{\sin(\beta)\cos^2(\beta)}$$
$$\varepsilon \equiv V_{12}^{CKM} \simeq \sin\theta_C$$	$$\omega'' \approx 1$$

$$\begin{pmatrix} \lambda''_{112} & \lambda''_{212} & \lambda''_{312} \\ \lambda''_{113} & \lambda''_{213} & \lambda''_{313} \\ \lambda''_{123} & \lambda''_{223} & \lambda''_{323} \end{pmatrix} = \lambda''_{323}\begin{pmatrix} 3\times10^{-5} & 3\times10^{-3} & 5\times10^{-2} \\ 1\times10^{-4} & 1\times10^{-2} & 2\times10^{-1} \\ 6\times10^{-4} & 5\times10^{-2} & 1 \end{pmatrix}$$

$$w''\tan^2\beta\begin{pmatrix} 3\times10^{-12} & 1\times10^{-8} & 4\times10^{-5} \\ 6\times10^{-9} & 1\times10^{-5} & 6\times10^{-5} \\ 5\times10^{-7} & 4\times10^{-5} & 2\times10^{-4} \end{pmatrix}$$

Dominant decay process when top is not kinematically accessible. $\tilde{G} \to \bar{c}\bar{b}\bar{s}$

Dominant decay process when top is kinematically accessible. $\tilde{G} \to \bar{t}\bar{b}\bar{s}$

Our signal of interest: Anti-Deuterons

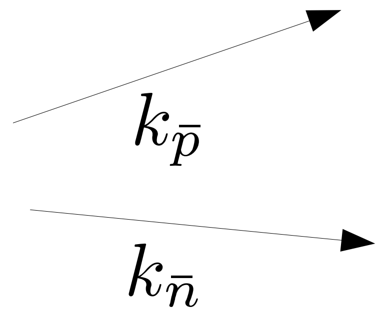
Have a very low astrophysical background at low energies where the DM signal is peaked.

Three reasons for this:

1. High production threshold ($\sim 17\ m_p$).
2. Astrophysical production occurs in boosted frame, while dark matter decays occur at rest.
3. Anti-deuterons have low binding energy, so they disintegrate rather than scatter down to lower kinetic energies.

Donato, Fornengo, Salati, 2000.

Anti-deuteron production



$$(k_{\bar{p}} - k_{\bar{n}})^2 = (\Delta\vec{k})^2 - (\Delta E)^2 \leq p_0^2$$

Anti-protons and anti-neutrons form an anti-deuteron if the difference in their momenta is less than p_0, the *coalescence momentum*

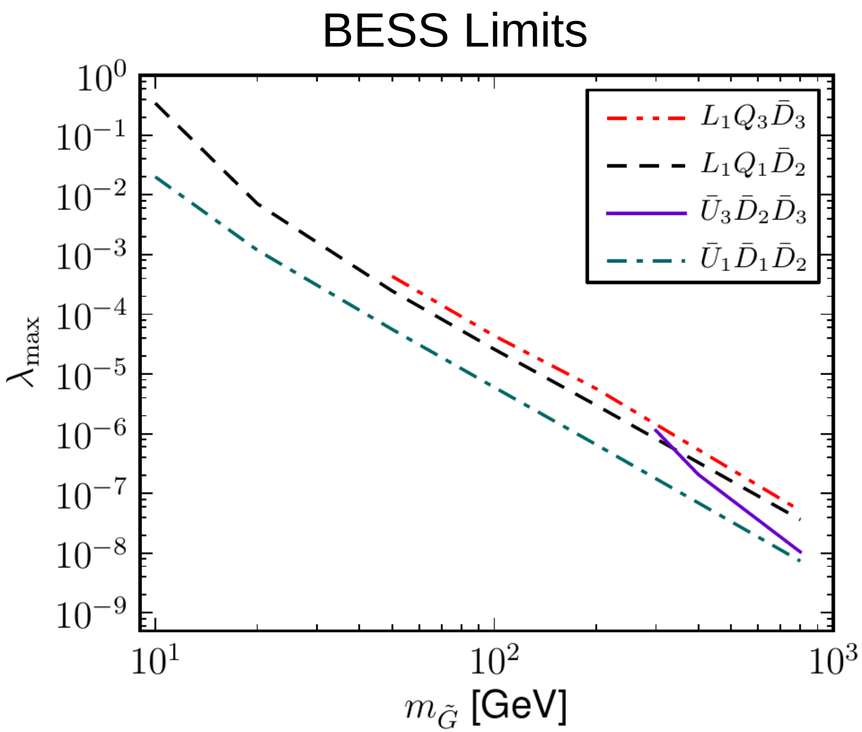
- Usually coalescence momentum is tuned to reproduce anti-deuteron results from ALEPH, leading to p_0=.192 GeV when Pythia is used to simulate anti-proton and anti-neutron production.
- Significant difference when Herwig++ is used (p_0=.159 GeV), or if tuned to something other than ALEPH data.

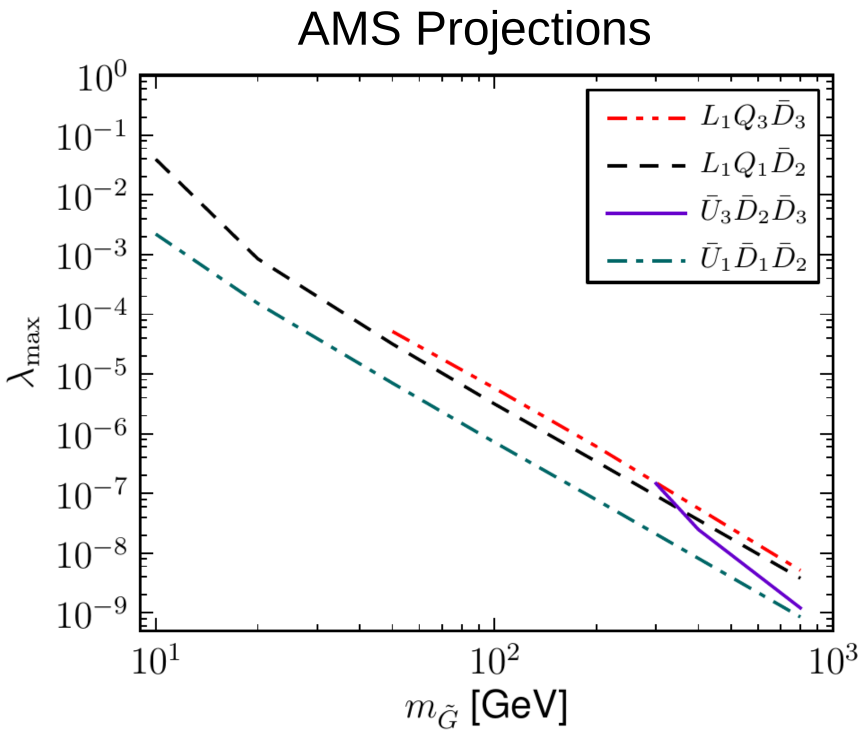
Kadastik, Raidal, Strumia 2009
Dal, Kachelriess 2012

Ibarra, Wild 2013
Dal, Raklev 2014

Limits on λ''_{ijk}

Dal, Raklev 2014

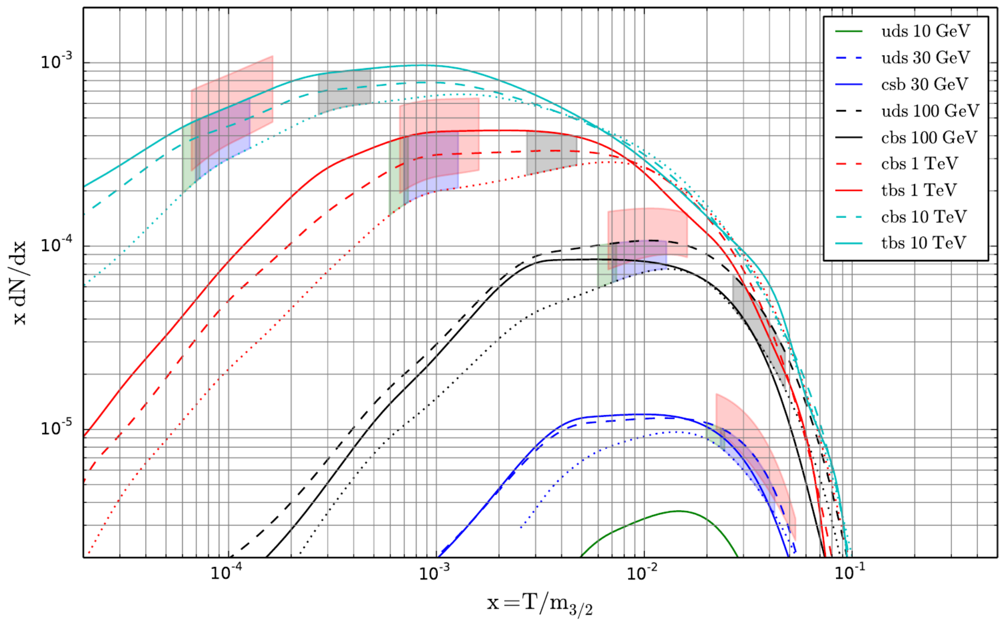




- Two-Zone Diffusion Model – a simple, semi-analytic model in which non-annihilating elastic scattering is neglected.
- Solar modulation of kinetic energies included
- SUSY scale (mass of mediator) set at 1 TeV

Rescaling Fluxes

- Simple diffusion model allows injection spectrum to be factored out of the propagation, and therefore expected fluxes (and limits on λ''_{ijk}) can be approximately rescaled from one channel to another based on different injection spectra.
- Decay rate calculation allows rescaling of limits based on SUSY scale.



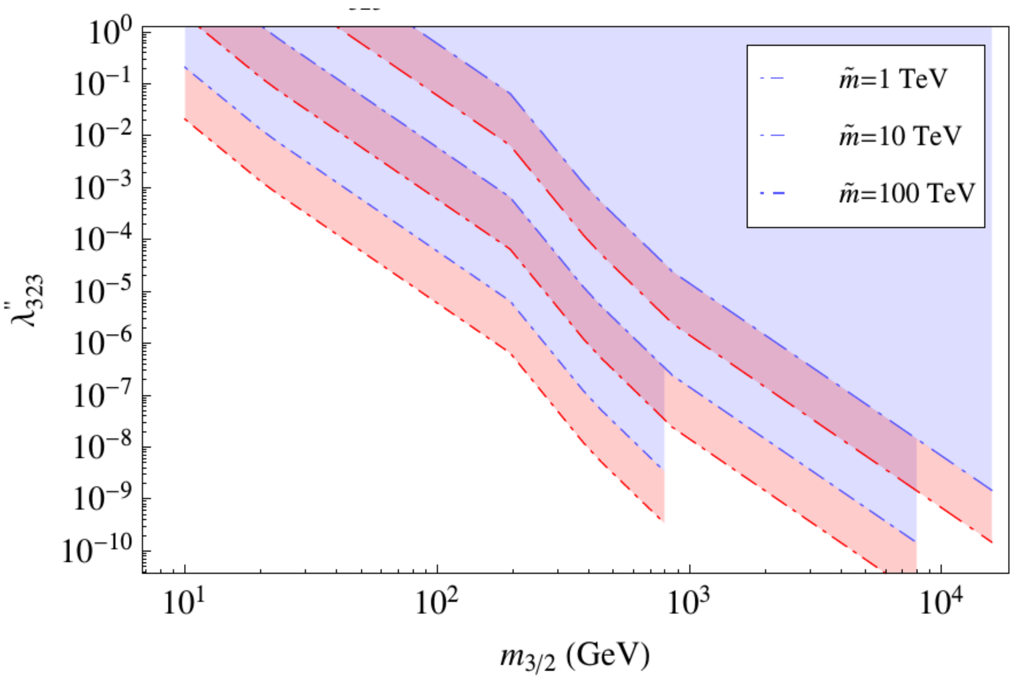
Monteux, Carlson, Cornell 2014

$$\tau_{\tilde{G}\to u_i d_j d_k} = 2.9 \times 10^{14}\text{sec}\left(\frac{10\ \text{GeV}}{m_{3/2}}\right)^3 \frac{1}{\lambda''^2_{ijk}}\left(\frac{\tilde{m}}{m_{3/2}}\right)^4$$

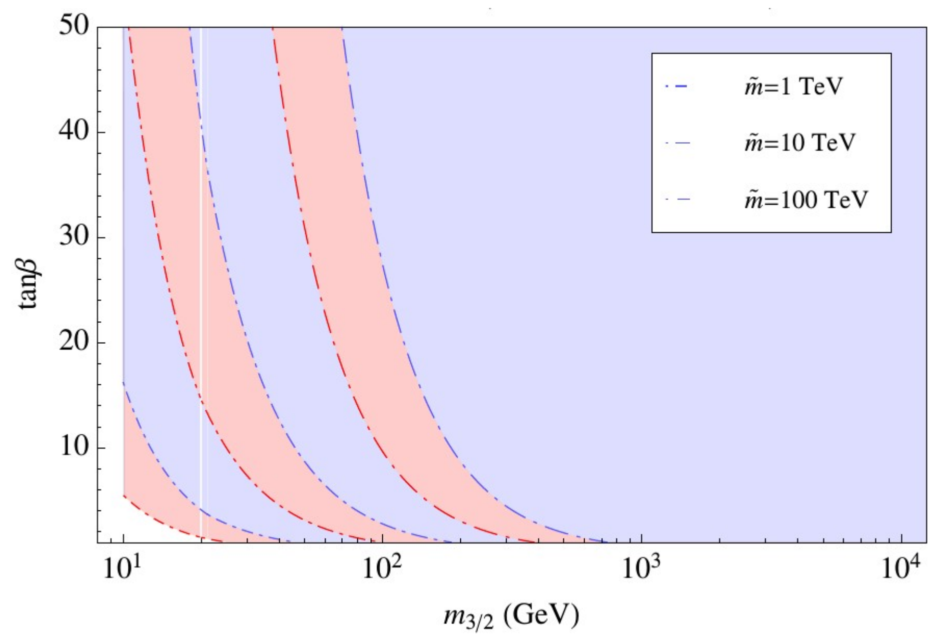
Moreau, Chemtob, 2002

Limits and Sensitivities

Horizontal Symmetry



Minimal Flavor Violation



Blue – BESS Limits

Red – AMS-02 Sensitivities

Monteux, Carlson, Cornell 2014

Conclusions

KK Photons:

- The measurement of the Higgs mass and constraints on the stability of the electroweak vacuum lead to stringent constraints on the cutoff scale of mUED
- This leads to significantly different direct detection, relic density, and LHC phenomenology than previously considered.
- Future LHC searches combined with the next generation of direct detection experiments should exclude all of the mUED parameter space.

Gravitinos:

- Anti-deuterons proved a promising channel for constraining R-parity violating gravitino dark matter.
- In the minimal flavor violating scenario, the gravitino mass is forced to less than 20 GeV for TeV scale SUSY
- With horizontal flavor symmetries, the gravitino mass is much less constrained, but anti-deuteron searches do place substantial limits on the allowed parameter space.