Revisiting Universal Extra-Dimension Model with Gravity Mediated Decays

in collaboration with Prof. Katri Huitu and Rameswar Sahu

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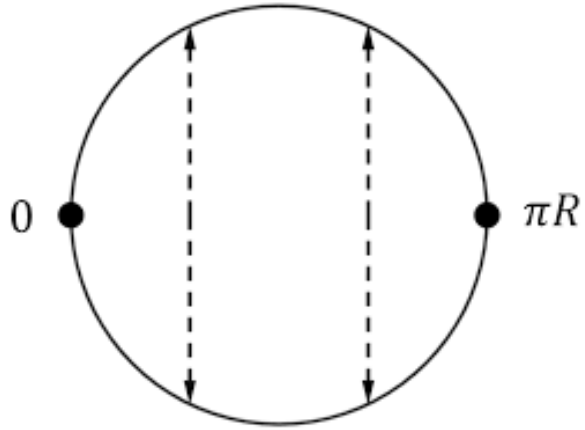
Universal Extra Dimension (UED)

UED scenarios are characterized by a single flat universal (accessible to all the SM particles) extra dimension (y), compactified on a S_1/Z_2 orbifold with radius R.

$$\mathcal{S}_{UED} = \mathcal{S}_{\text{gauge}} + \mathcal{S}_{\text{fermions}} + \mathcal{S}_{\text{scalar}}$$

$$\mathcal{S}_{\text{gauge}} = \int d^4x \int_0^{\pi R} dy \left\{ -\frac{1}{4} G^a_{MN} G^{aMN} + \left(\delta(y) + \delta(y - \pi R)\right)\left[-\frac{r_G}{4} G^a_{\mu\nu} G^{a\mu\nu} \right] \right\}$$

1. Bulk terms
2. Boundary localized terms (BLTs).

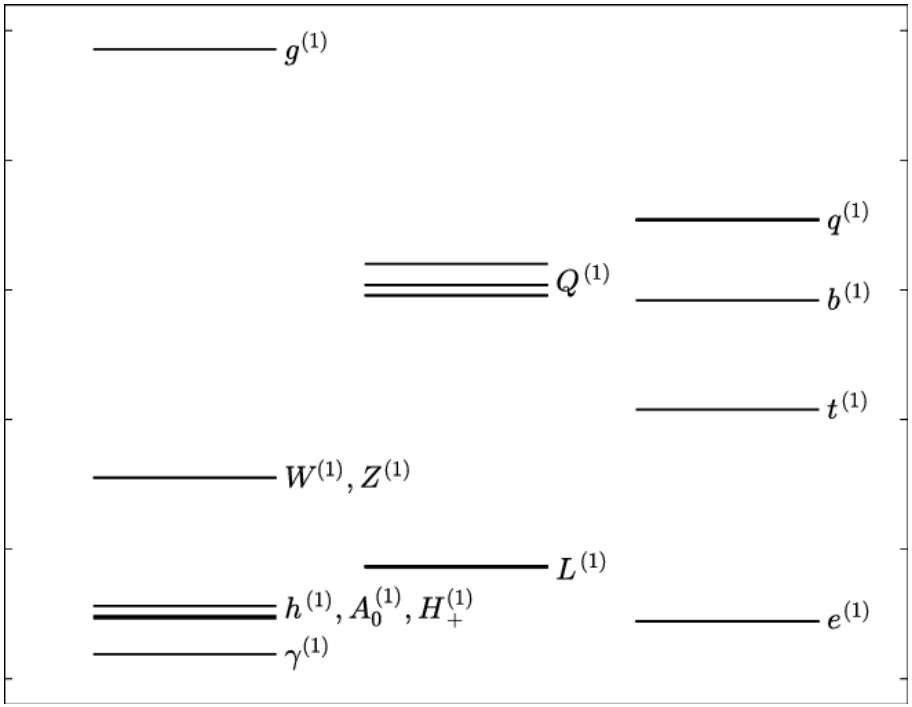


After Compactification

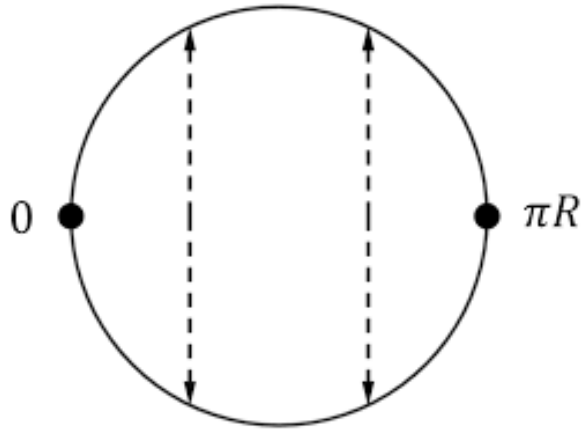
⇓

1. Kaluza-Klein modes.
2. Conserved KK-number.
3. Conserved KK-parity.
   1. A dark matter candidate

minimal Universal Extra Dimension (mUED)

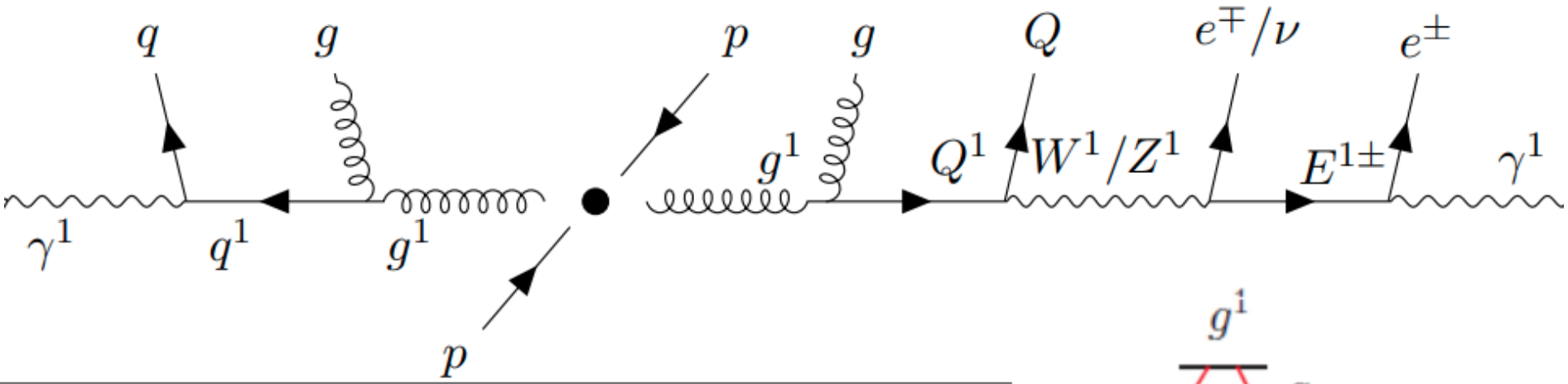


BPs	R^{-1} [TeV]	ΛR	$m_{G^{(1)}}$ [TeV]	$m_{Q^{(1)}}$ [TeV]	$m_{q^{(1)}}$ [TeV]	$m_{W^{(1)}/Z^{(1)}}$ [TeV]	$m_{L^{(1)}}$ [TeV]	$m_{B^{(1)}}$ [TeV]
BP_1^m	2.0	3	2.222	2.143	2.124	2.045	2.022	1.998
BP_2^m	1.75	40	2.341	2.171	2.122	1.877	1.814	1.748
BP_3^m	1.4	30	1.840	1.668	1.710	1.495	1.448	1.399

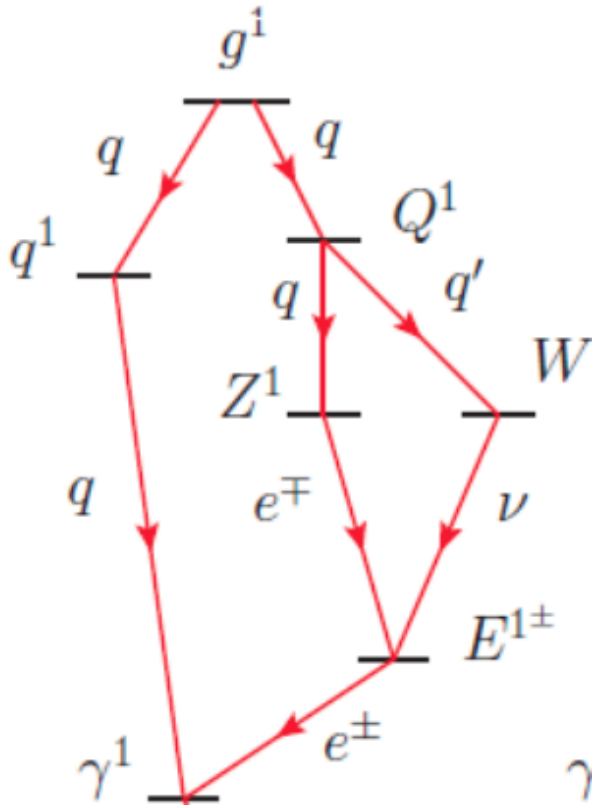


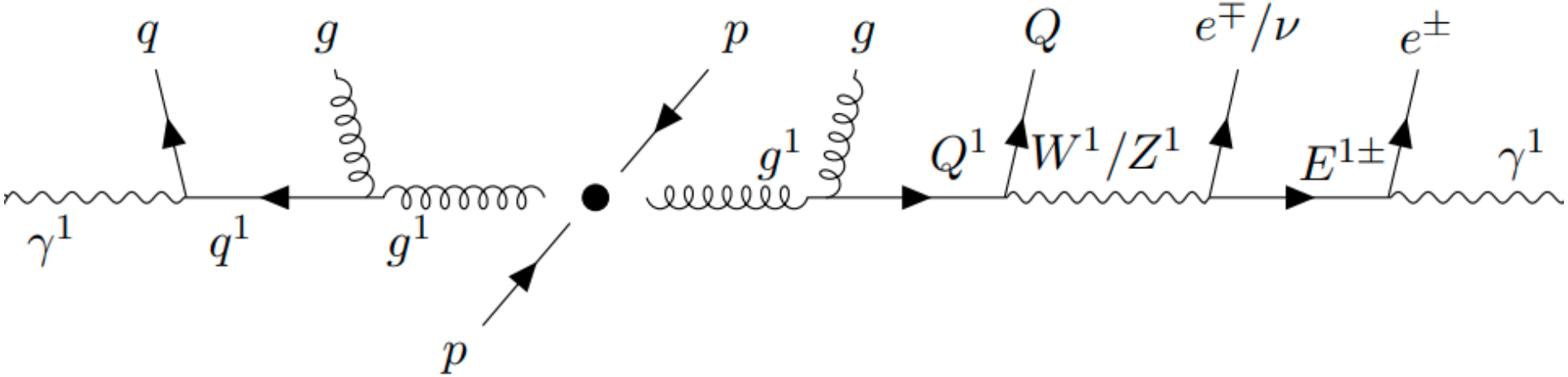
1. In the *minimal* version of *UED* (mUED), all BLTs are assumed to vanish at the cut-off scale (Λ).
2. The phenomenology of *mUED* is determined by only two additional parameters:
   1. The radius of compactification, R
   2. The cut-off scale, Λ

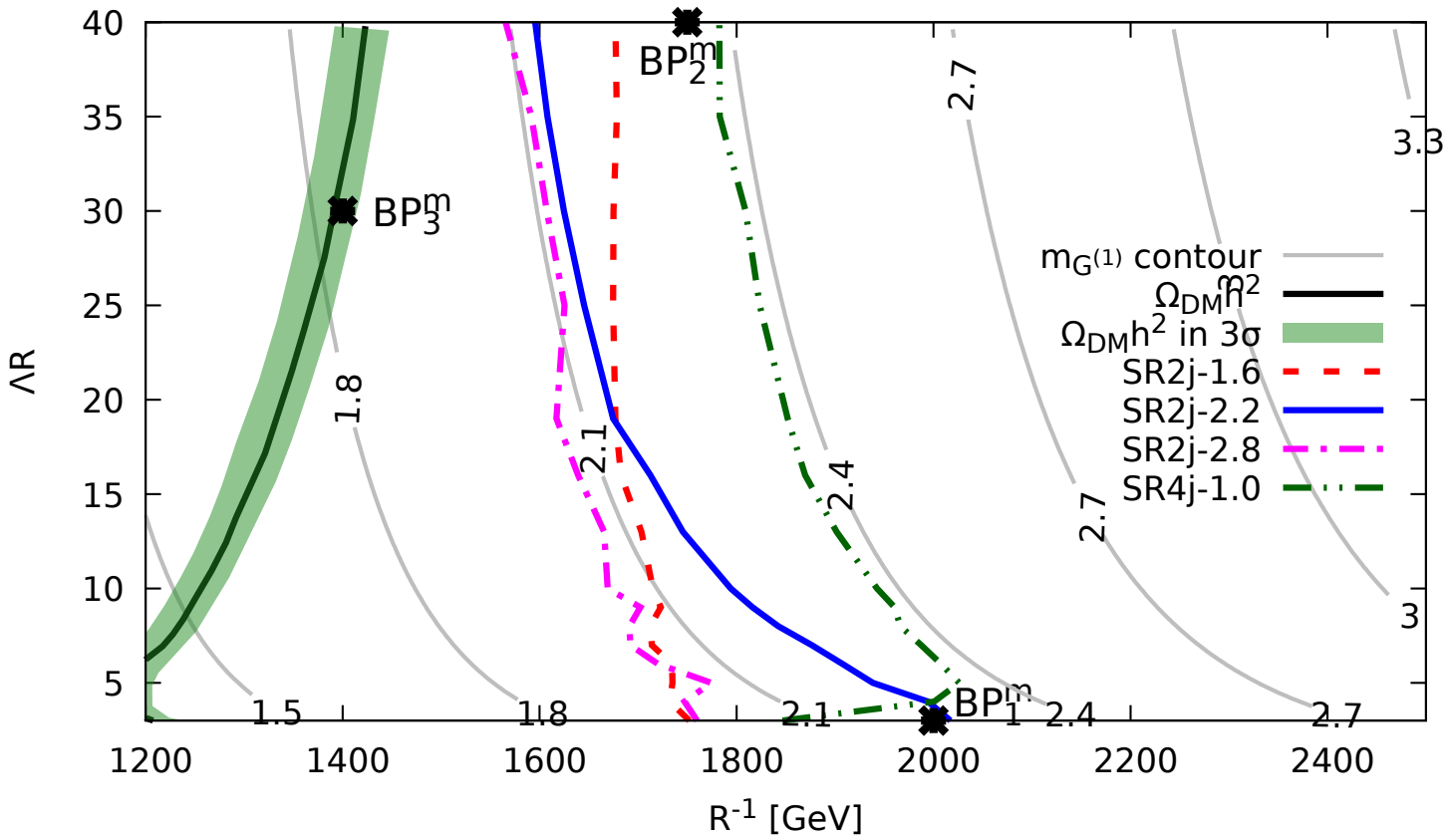
mUED after ATLAS search (ATLAS-CONF-2019-040) for multijets $+\not{E}_T$ with $\mathcal{L}$ =139 fb^{-1}



	SR2j-1.6	SR2j-2.2	SR2j-2.8	SR4j-1.0	SR4j-2.2
n_j	≥ 2	≥ 2	≥ 2	≥ 4	≥ 4
$p_T(j_1)$[GeV]	> 250	> 600	> 250	> 200	> 200
$p_T(j_{i=2,..,n_{\min}})$[GeV]	> 250	> 50	> 250	> 100	> 100
$\lvert\eta(j_{1,..,n_{min}})\rvert$	< 2.0	< 2.8	< 1.2	< 2.0	< 2.0
$\Delta\phi(j_{1,2,(3)}, p_T^{\text{mis}})_{\min}$	> 0.8	> 0.4	> 0.8	> 0.4	> 0.4
$\Delta\phi(j_{i>3}, p_T^{\text{mis}})_{\min}$	> 0.4	> 0.2	> 0.4	> 0.4	> 0.4
Aplanarity	-	-	-	> 0.04	> 0.04
$\frac{E_T'}{\sqrt{H_T}}[\sqrt{\text{GeV}}]$	> 16	> 16	> 16	> 16	> 16
m_{eff}[TeV]	> 1.6	> 2.2	> 2.8	> 1.0	> 2.2
$\langle\epsilon\sigma\rangle_{obs}^{95}$ [fb]	1.46	0.78	0.13	0.54	0.14
mUED predictions [fb]					
BP_1^m	0.35	0.92	0.03	0.28	0.03
BP_2^m	0.96	0.29	0.05	0.58	0.11
BP_3^m	5.25	2.96	0.33	6.41	0.75





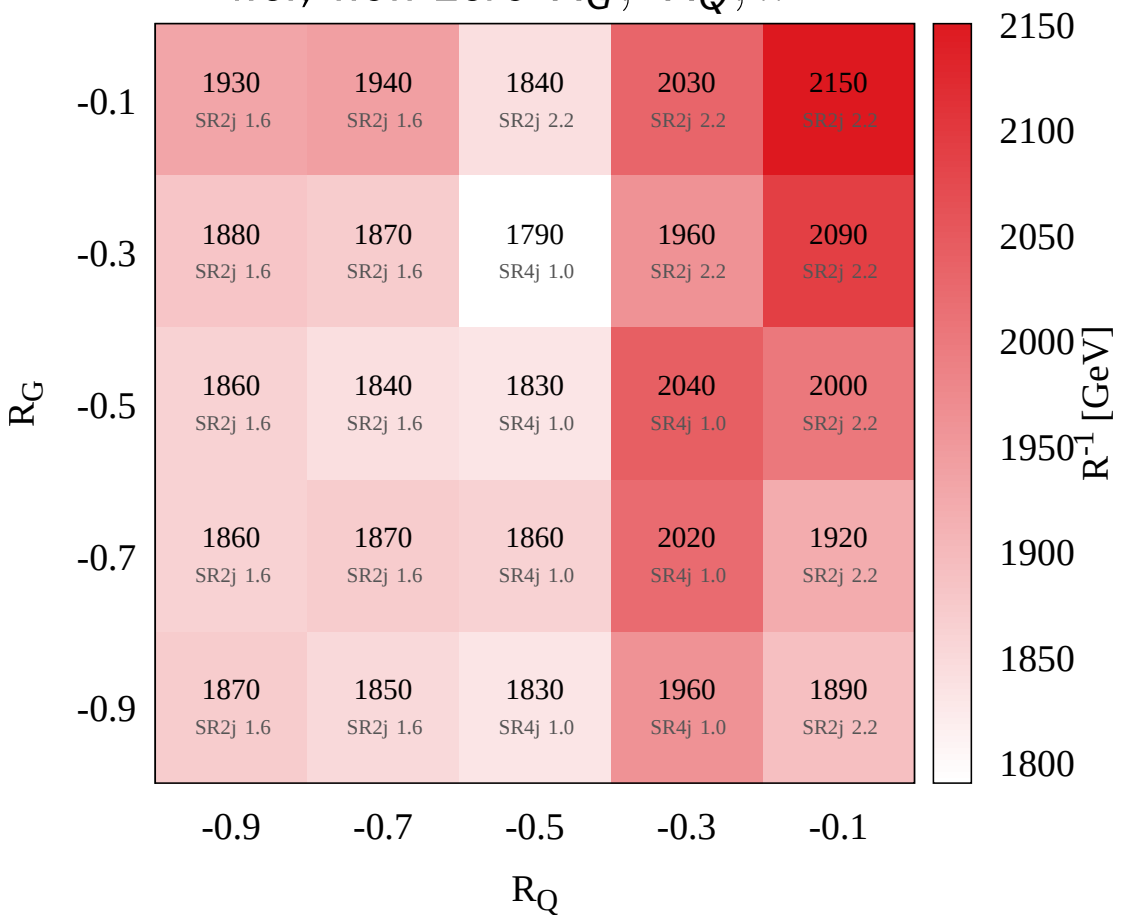


mUED is *Ruled Out* !!

[Avnish, Ghosh, Jha, Niyogi PRD 2021; PDG 2023]

Options beyond mUED

1. Non-minimal UED:
   - Non-vanishing BLTs
     i.e., non-zero R_G, R_Q, ..



[Avnish, Ghosh, Jha, Niyogi PRD 2021]

Next-to-minimal UED:
e.g., 'Fat-brane' realization of mUED

$\Downarrow$

mUED is embedded in a $(4+N)$-dimensional bulk.

$\Downarrow$

Gravity spans across N large extra dimensions $\sim \text{eV}^{-1}$, while the propagation of matter is confined to a length scale $\sim \text{TeV}^{-1}$

1. $M_{\text{Pl}}^2 = M_D^{N+2} \left(\frac{r}{2\pi}\right)^N$
2. Gravity-Matter interaction
3. Gravity mediated decay of LKP

'Fat-brane' realization of mUED: Matter-Gravity Interaction

$(4+N)$-D Action

$$S = \int dx^{4+N}\, \delta(x^5)\ldots\delta(x^{4+N})\sqrt{-\hat{g}}\,\mathcal{L}_m$$

$$\Downarrow$$

$(4+N)$-D Gravity-Matter Interaction Action

$$S_{\text{int}} = -\frac{\hat{k}}{2}\int d^{N+4}x\,\delta(x^5)\ldots\delta(x^N)\,\hat{h}^{\hat{\mu}\hat{\nu}}\,T_{\hat{\mu}\hat{\nu}}$$

$$\Downarrow$$

4-D Gravity-Matter Interaction Action

$$S_{\text{int}} = -\frac{k}{2}\int d^4x \sum_n \left\{\left[\tilde{h}^{\vec{n}}_{\mu\nu} + \omega\left(\eta_{\mu\nu} + \frac{\partial_\mu\partial_\nu}{m^2_{\vec{n}}}\right)\tilde{\phi}^{\vec{n}}\right] T^{\mu\nu}_{n_5} - 2\tilde{A}^{\vec{n}}_{\mu 5}\,T^{\mu}_{n_5 5} + \left(\sqrt{2}\tilde{\phi}^{\vec{n}}_{55} - 3\omega a\left(1-\frac{n_5^2}{\vec{n}^2}\right)\tilde{\phi}^{\vec{n}}\right) T^{n_5}_{55}\right\}$$

where, $T^{n_5}_{MN}(x) = \int_0^{\pi R} dy\; T_{MN}(x,y)\, e^{\frac{2\pi i n_5 y}{r}}$

$$\hat{g}_{\hat{\mu}\hat{\nu}} = \eta_{\hat{\mu}\hat{\nu}} + \hat{k}\hat{h}_{\hat{\mu}\hat{\nu}},\ \hat{k}^2 = 16\pi G^{4+N}$$

$$\hat{h}_{\hat{\mu}\hat{\nu}}(x,y) = \sum_{\vec{n}} \hat{h}^{\vec{n}}_{\hat{\mu}\hat{\nu}}(x)\exp\left(i\frac{2\pi\vec{n}\cdot\vec{y}}{r}\right)$$

$$\hat{h}^{\vec{n}}_{\hat{\mu}\hat{\nu}} = V_N^{-1/2}\begin{pmatrix} h^{\vec{n}}_{\mu\nu} + \eta_{\mu\nu}\phi^{\vec{n}} & A^{\vec{n}}_{\mu i} \\ A^{\vec{n}}_{\nu j} & 2\phi^{\vec{n}}_{i,j}\end{pmatrix}$$

The KK-gravity excitations:

1. Gravitons:
$$\tilde{h}^{\vec{n}}_{\mu\nu} = h^{\vec{n}}_{\mu\nu} - \omega\left(\frac{\partial_\mu\partial_\nu}{m^2_{\vec{n}}} - \frac{1}{2}\eta_{\mu\nu}\right)\tilde{\phi}^{\vec{n}}$$
2. Graviphotons:
$$\tilde{A}^{\vec{n}}_{\mu i} = A^{\vec{n}}_{\mu i}$$
3. Graviscalars:
$$\frac{1}{\sqrt{2}}\tilde{\phi}^{\vec{n}}_{ij} = \phi^{\vec{n}}_{ij} + \frac{3\omega a}{2}\left(\delta_{ij} - \frac{n_i n_j}{\vec{n}^2}\right)\tilde{\phi}^{\vec{n}}$$

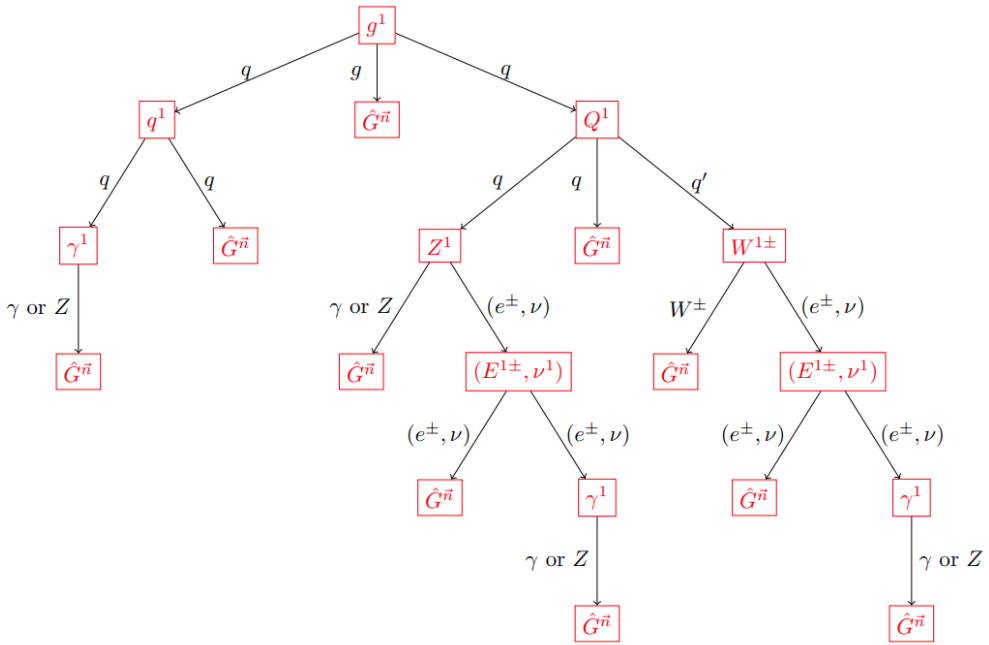
where, $\omega = \sqrt{2/(3N+6)}$ and a satisfies $3(N-1)a^2 + 6a - 1 = 0$

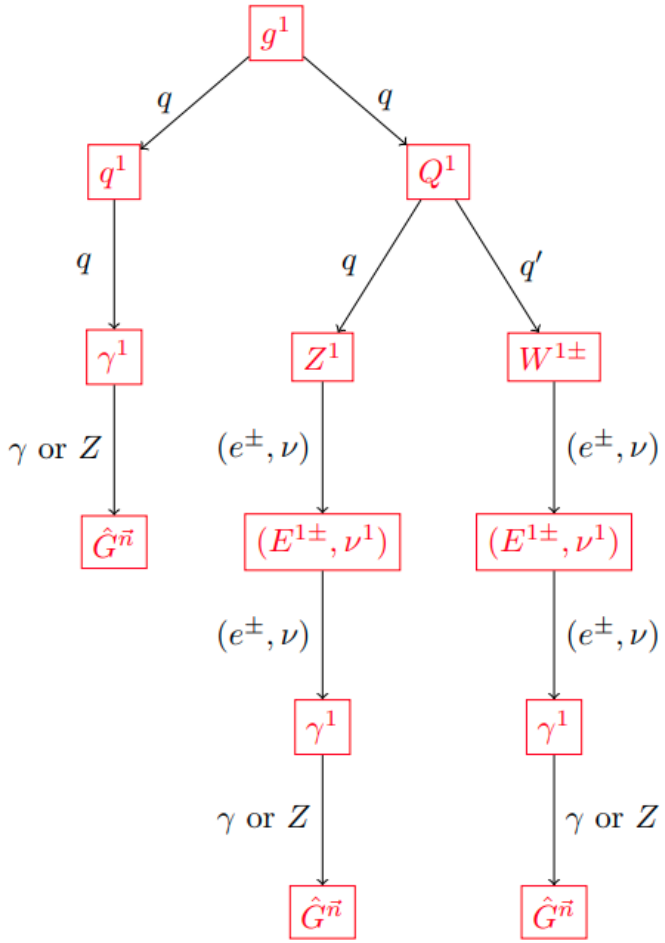
Matter field can decay into any kinematically allowed gravity excitations.

1. The decay width into individual graviton modes is suppressed by $1/M_{\rm Pl}^2$
2. Since the mass difference between individual gravity excitations is of the order eV^{-1}, the number of allowed gravity-mediated decay modes is large.
   - Ensure prompt decay of LKP

$$\Gamma = \sum_{\vec{n}} \Gamma_{\vec{n}} = \sum \Gamma_{h^{\vec{n}}} + \Gamma_{A^{\vec{n}}} + \Gamma_{\phi^{\vec{n}}}$$

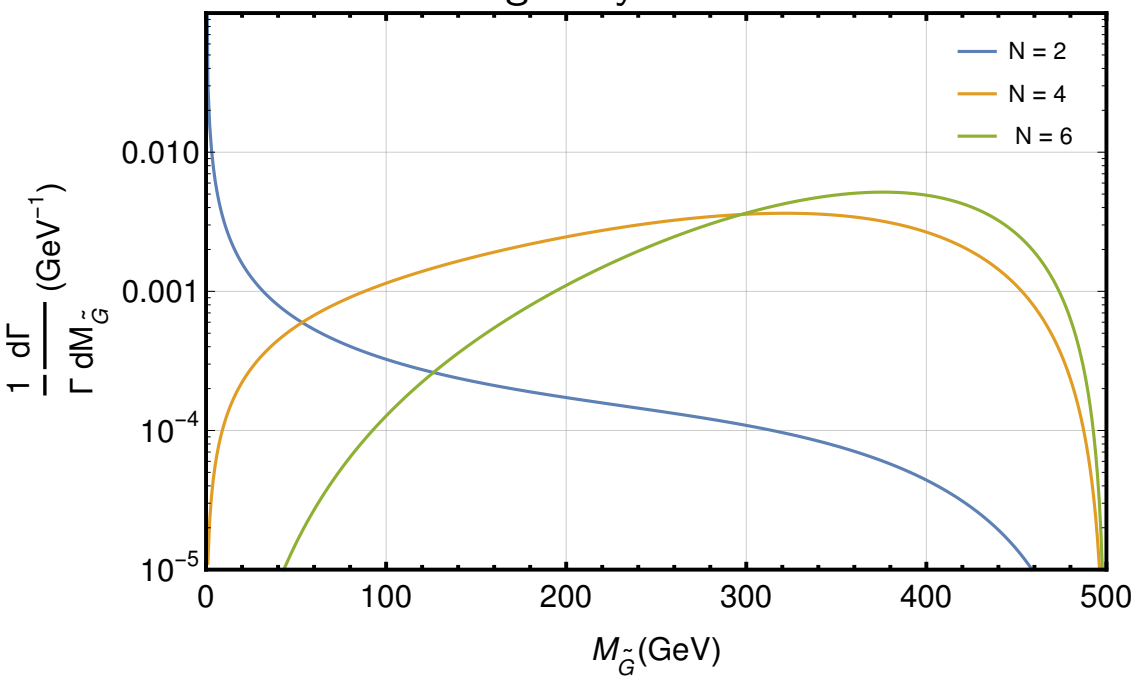
$$\Gamma = \frac{M_{\rm Pl}^2}{M_D^{N+2}} \int dm\, d\Omega\, \Gamma_{\vec{n}} m_{\vec{n}}^{N-1}$$





Event Simulation

The normalized partial decay width for level-1 KK-gluon into a gluon and gravity excitations as a function of the mass of the gravity excitations.

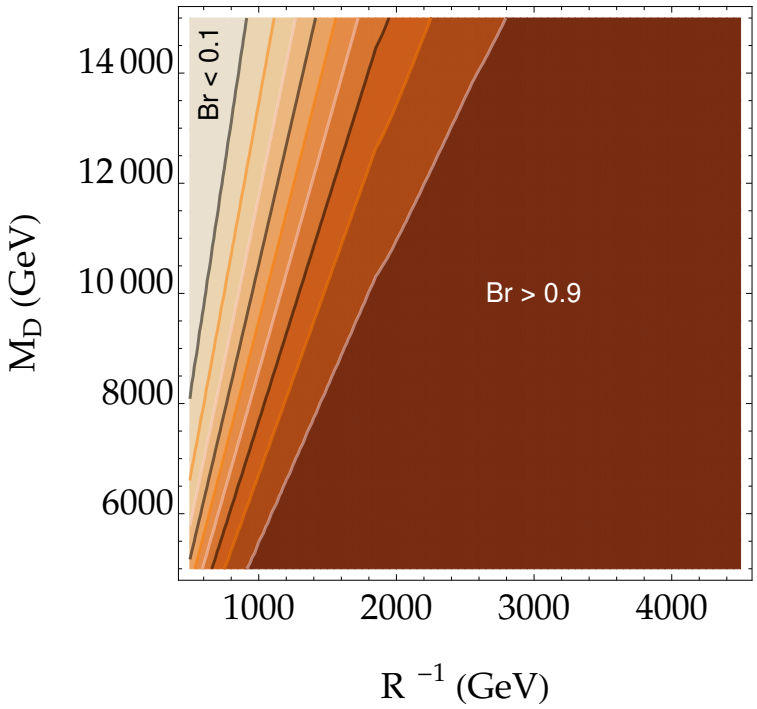


1. Production: MG5_AMC@NLO
2. Decays: PYTHIA8
   1. PYTHIA8 does not consider gravity-mediated decay (GMD)
   2. GMDs cannot be trivially incorporated by modifying the decay table in the SLHA file.
   3. Modified the PYTHIA PYWIDTH subroutine according to our requirements.
3. Showering/hadronization: PYTHIA8

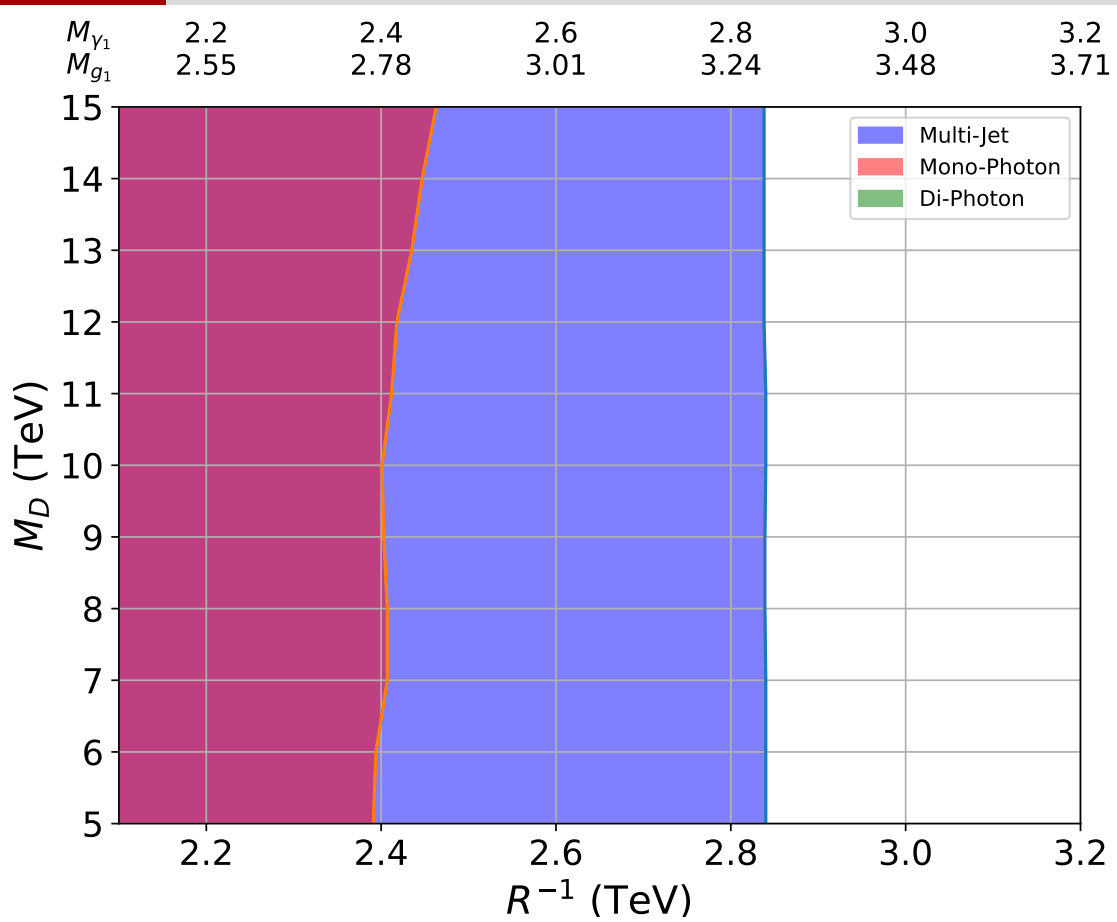
(Re)interpretation of existing LHC searches

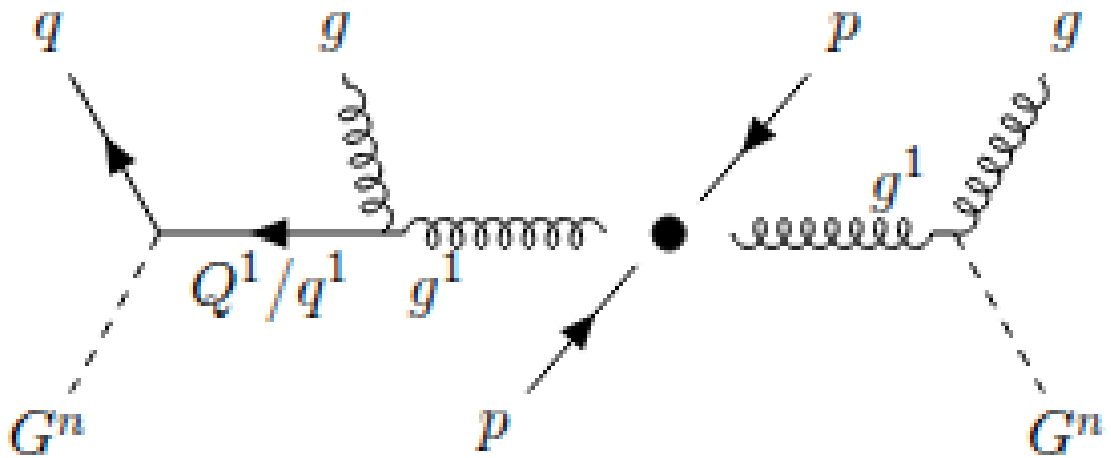
1. ATLAS mono-photon plus missing transverse energy search
   "Search for new phenomena in final states with photons, jets and missing transverse momentum in pp collisions at $\sqrt{s}$ = 13 TeV with the ATLAS detector", 2206.06012
2. ATLAS multi-jet plus missing transverse energy search
   "Search for squarks and gluinos in final states with jets and missing transverse momentum using 139 fb^{-1} of $\sqrt{s}$ =13 TeV pp collision data with the ATLAS detector", ATLAS-CONF-2019-040
3. ATLAS di-Photon plus missing transverse energy search
   "Search for photonic signatures of gauge-mediated supersymmetry in 13 TeV pp collisions with the ATLAS detector", 1802.03158

$N = 2$

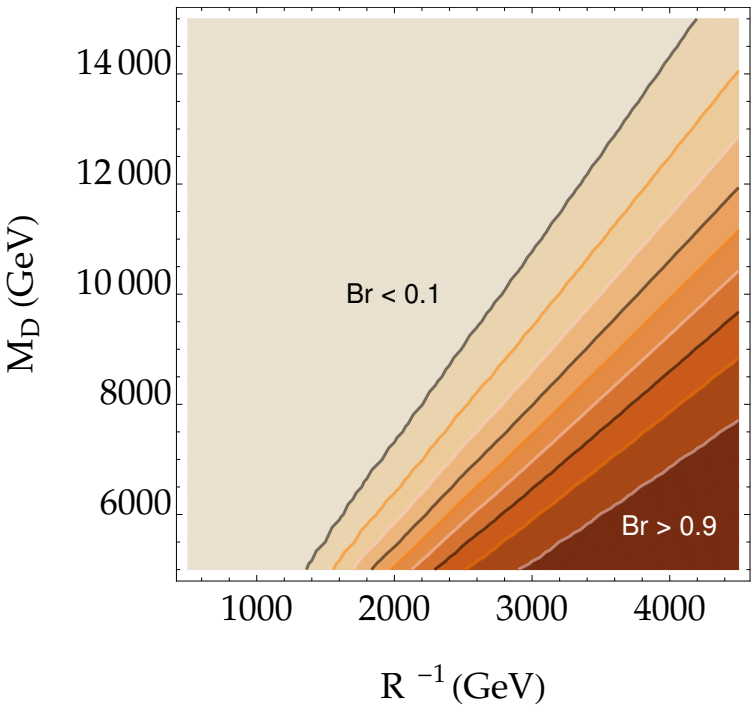


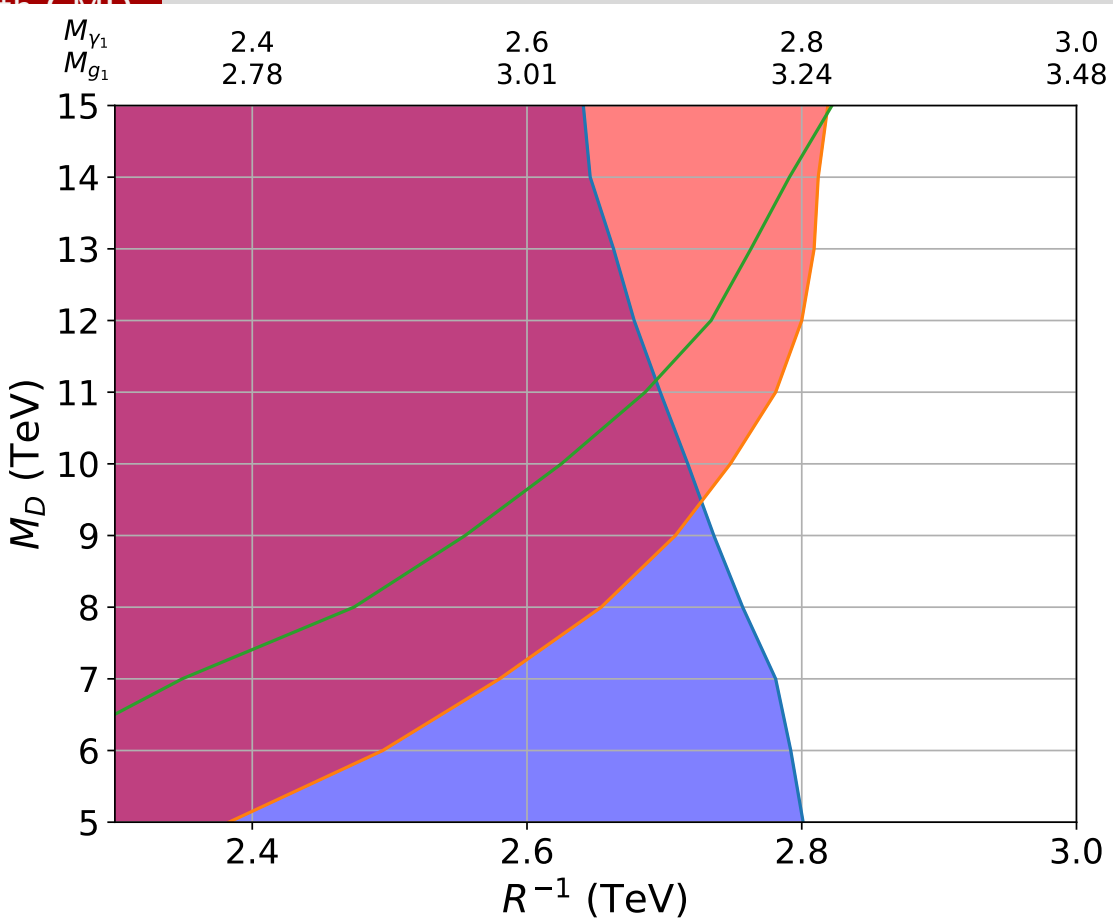
Br= $Br(g^1 \rightarrow GMD)$

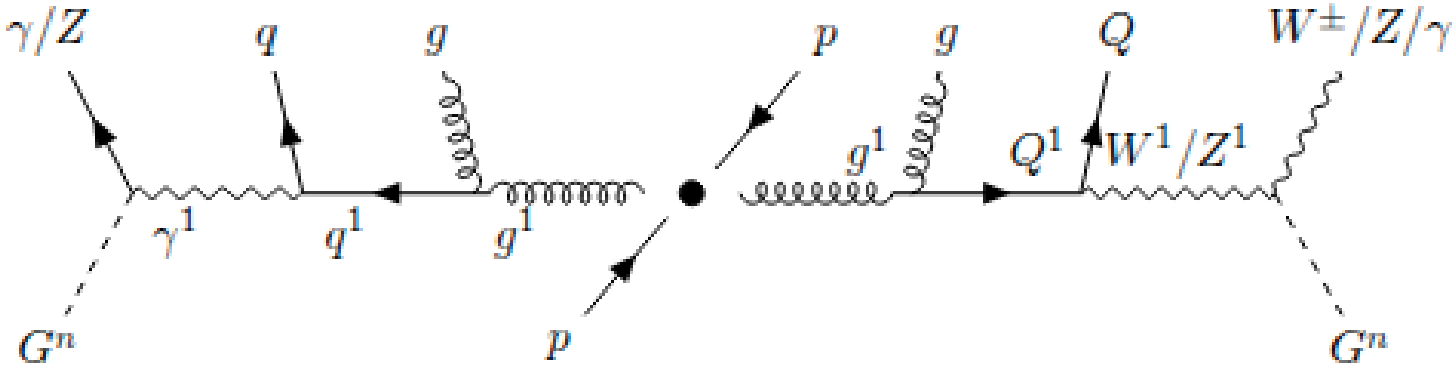




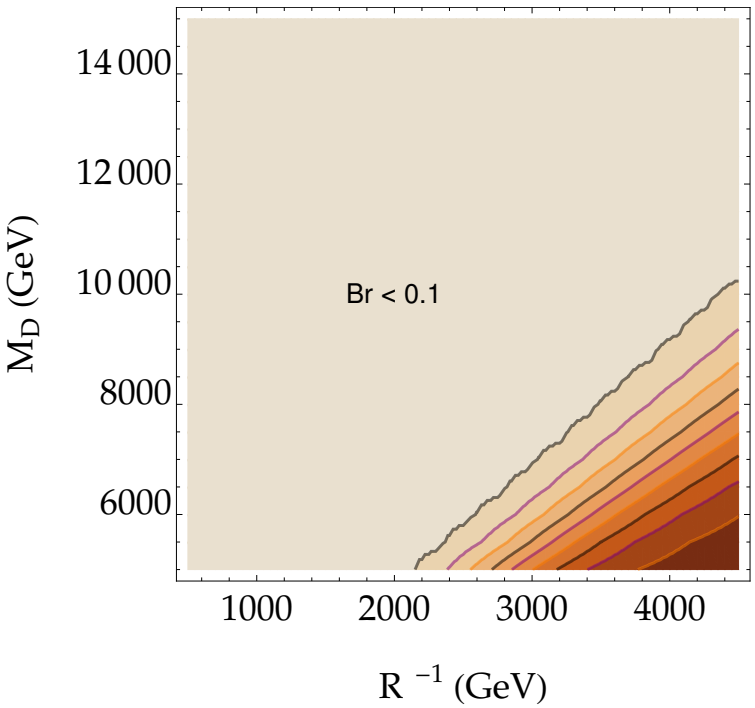
$N = 4$

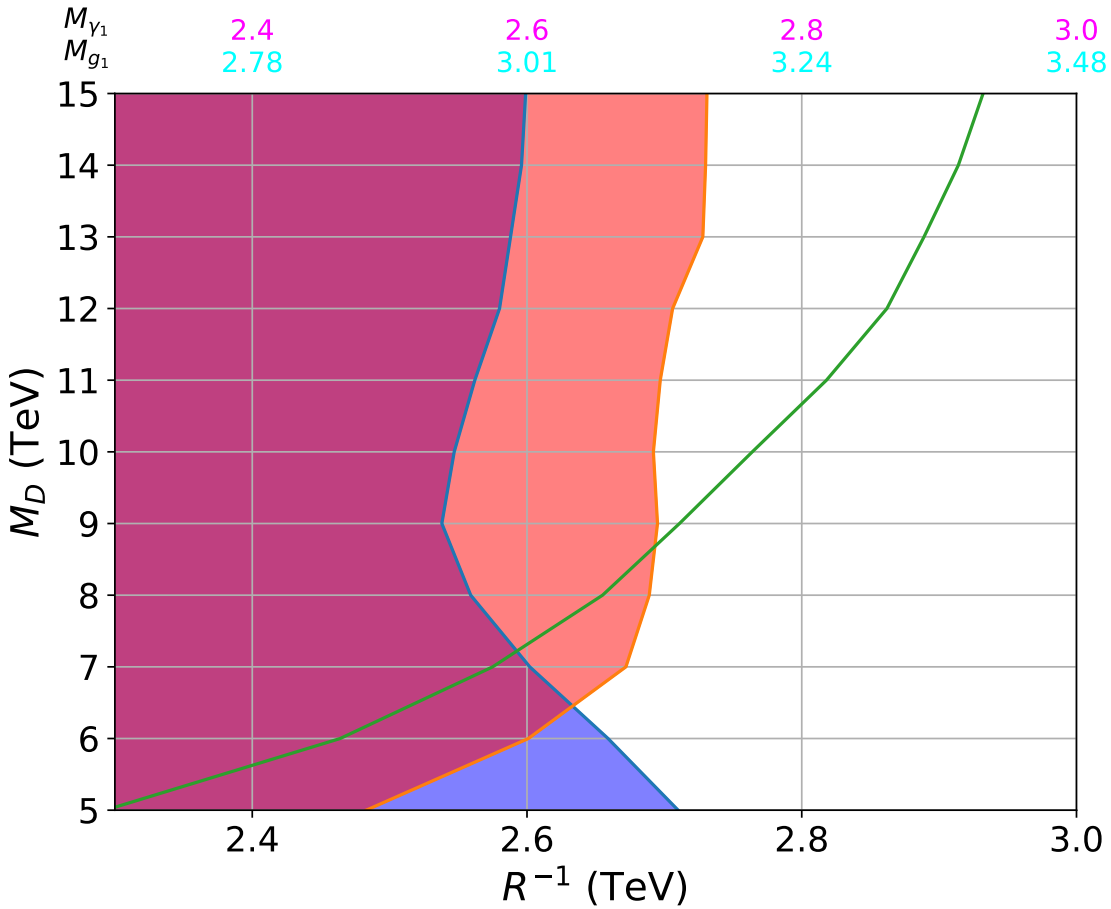

14 000
12 000
10 000
8000
6000
M_D (GeV)
Br < 0.1
Br > 0.9
1000
2000
3000
4000
R^{-1} (GeV)


M_{γ1}
M_{g1}
2.4
2.78
2.6
3.01
2.8
3.24
3.0
3.48
15
14
13
12
11
10
9
8
7
6
5
M_D (TeV)
2.4
2.6
2.8
3.0
R^{-1} (TeV)


γ/Z
q
g
p
g
Q
W^±/Z/γ
γ^1
q^1
g^1
g^1
Q^1
W^1/Z^1
G^n
p
G^n

$N = 6$


14 000
12 000
10 000
8000
6000
M_D (GeV)
Br < 0.1
1000
2000
3000
4000
R^{-1} (GeV)


M_{γ1}
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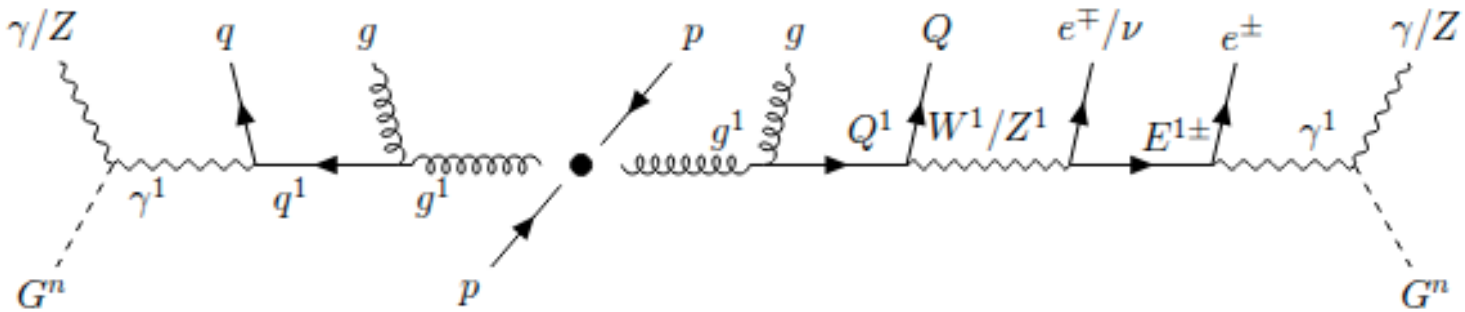
14
13
12
11
10
9
8
7
6
5
M_D (TeV)
2.4
2.6
2.8
3.0
R^{-1} (TeV)


γ/Z
q
g
p
g
Q
e^∓/ν
e^±
γ/Z
γ^1
q^1
g^1
g^1
Q^1
W^1/Z^1
E^{1±}
γ^1
G^n
p
G^n

Summary

1. We studied the fat-brane Minimal Universal Extra Dimensions (MUED) scenario, extending MUED with additional dimensions (eV^{-1} to KeV^{-1}) accessible only via gravity.
2. Studied the signatures of the level-1 particles at the LHC, leading to three distinct final states:
   - Multijet + missing transverse energy
   - Mono-photon + missing transverse energy
   - Di-photon + missing transverse energy
3. ATLAS has already conducted searches for these final states in MSSM and Gauge Mediated Supersymmetry Breaking (GMSB) models.
4. We utilized three ATLAS searches to constrain the fat-brane MUED parameter space.
5. Key results for different values of N (number of extra dimensions):
   - $N = 2$: Multijet search provides the best sensitivity, excluding $R^{-1} < 2975$ GeV, independent of M_D.
   - $N = 4$: Multijet and mono-photon searches probe complementary regions:
     - Multijet excludes $R^{-1} < 2898$ GeV for $M_D = 500$ GeV.
     - Mono-photon excludes $R^{-1} < 2958$ GeV for $M_D = 15000$ GeV.
   - $N = 6$: The di-photon search is most effective, setting a lower limit of $R^{-1} > 3002$ GeV for $M_D = 15000$ GeV.

Thank You