Exploring Universal Extra-Dimensions at the LHC

Alexander Belyaev

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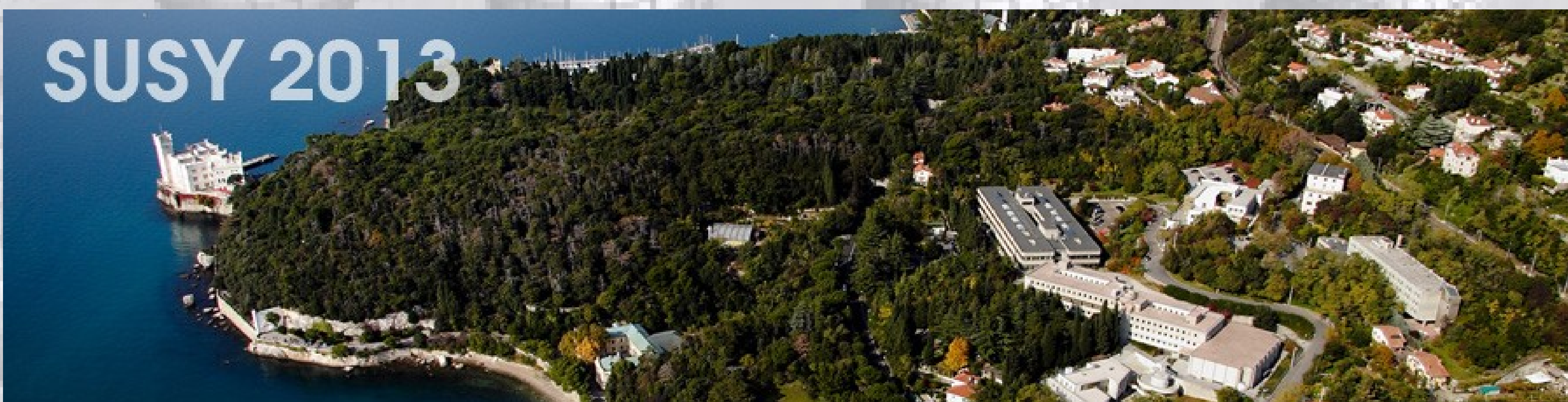
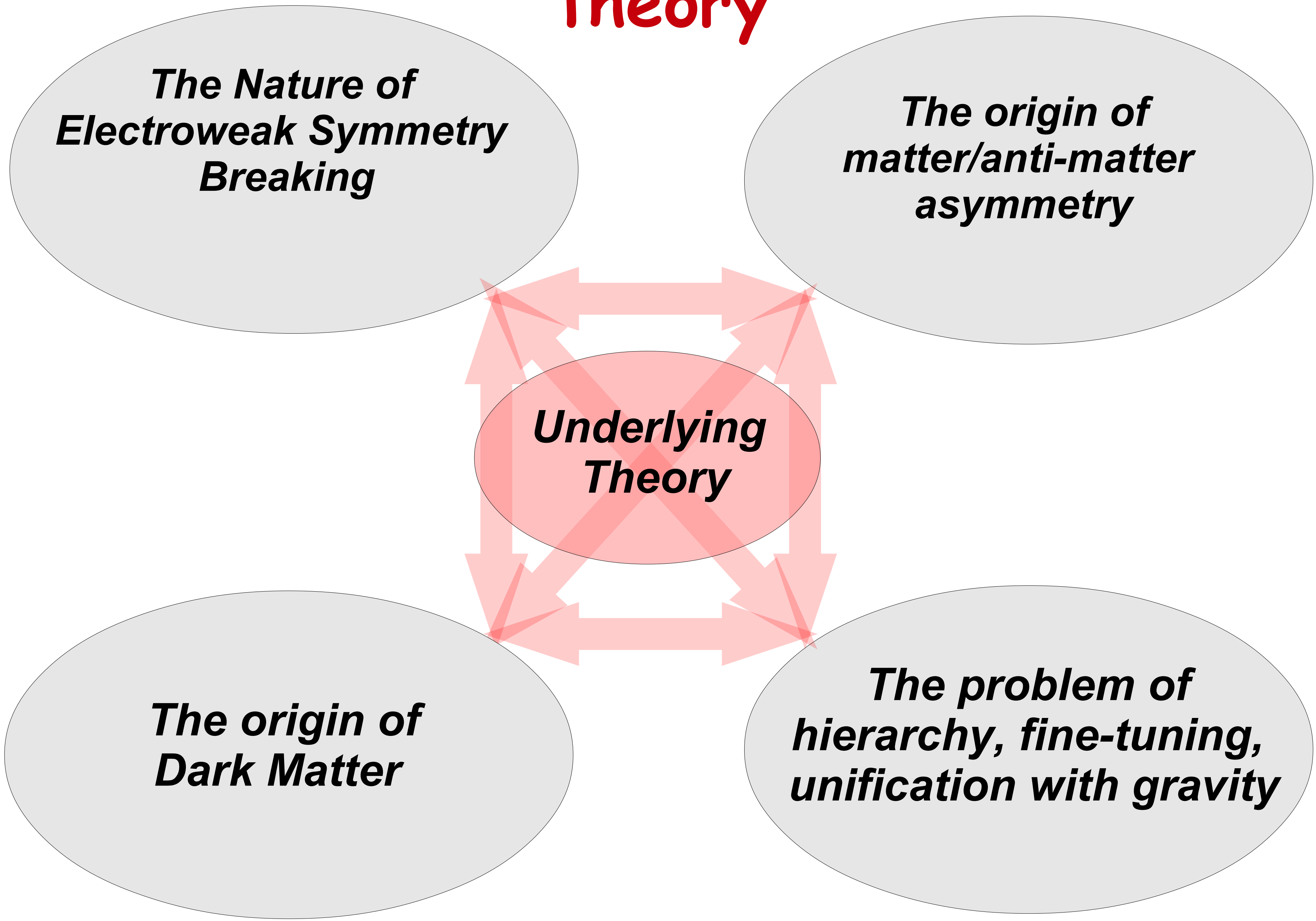
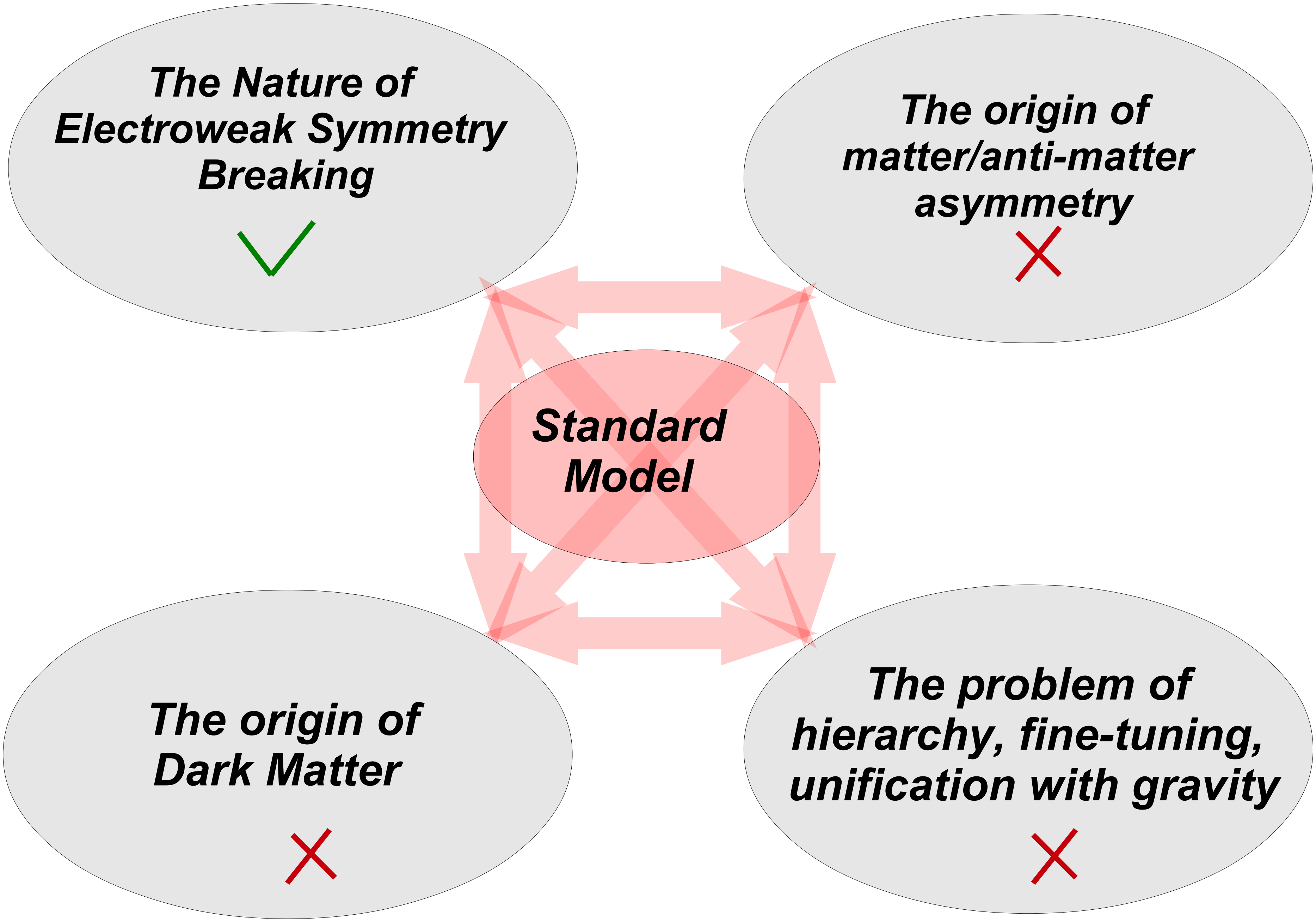


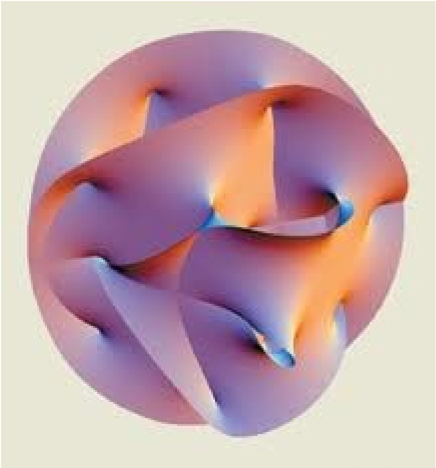
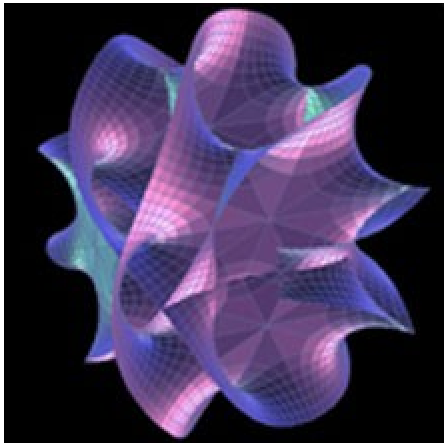
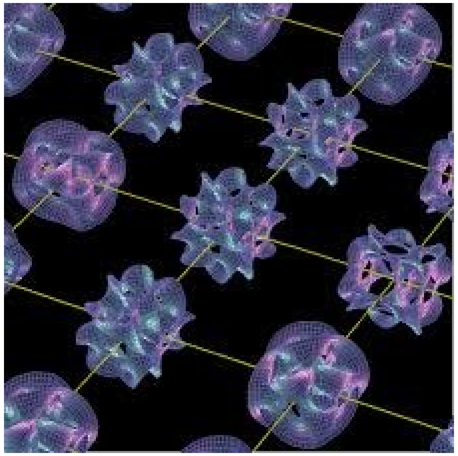
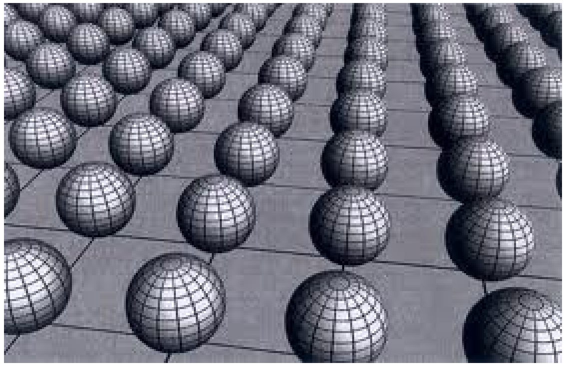
Problems to be addressed by the underlying theory




The Nature of Electroweak Symmetry Breaking
The origin of matter/anti-matter asymmetry
Standard Model
The origin of Dark Matter
The problem of hierarchy, fine-tuning, unification with gravity

What could lie below the 10^{-19}m scale?

Extra Dimensions! (ED)

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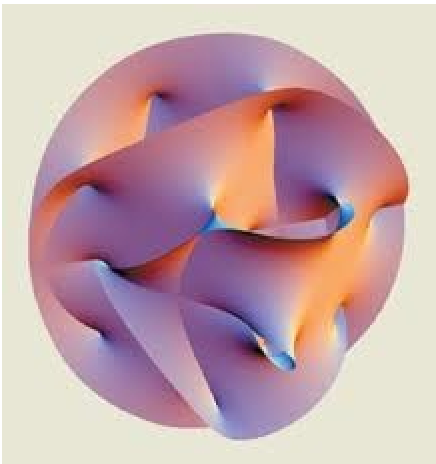
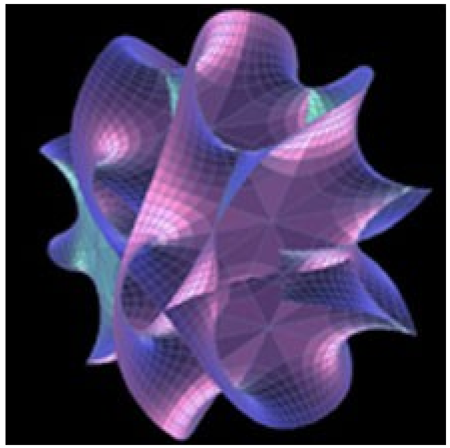
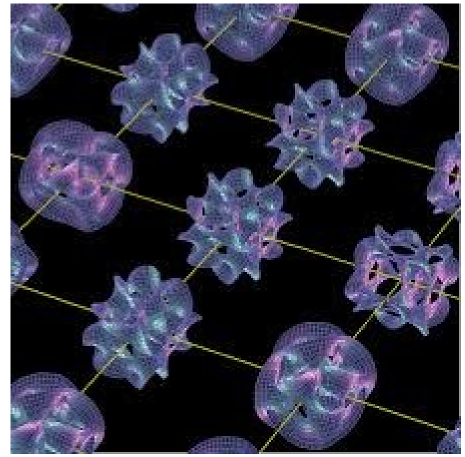
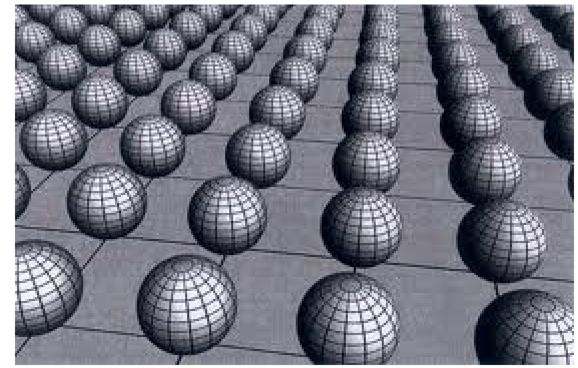





Motivations

- String theory, the best candidate to unify gravity & gauge interactions, is only consistent in 10 D space-time
- Extending symmetries:
  Internal symmetries - GUTs, technicolour...; Fermionic spacetime- SUSY
  Bosonic spacetime - Extra dimensions
- The presence of XD could have an impact on scales << M_{planck} (started with ADD)

The question is what is the size and the shape of ED ?!

New perspectives of XD

- The nature of electroweak symmetry breaking
- The origin of fermion mass hierarchies
- The supersymmetry breaking mechanism
- The description of strongly interacting sectors (provide a way to model them)
- ....

Brief History

- 1914: Nordstrom tried to unify gravity and electromagnetism in 5D
  (A_μ -> A_M, where $M = 0,1,2,3,4$)

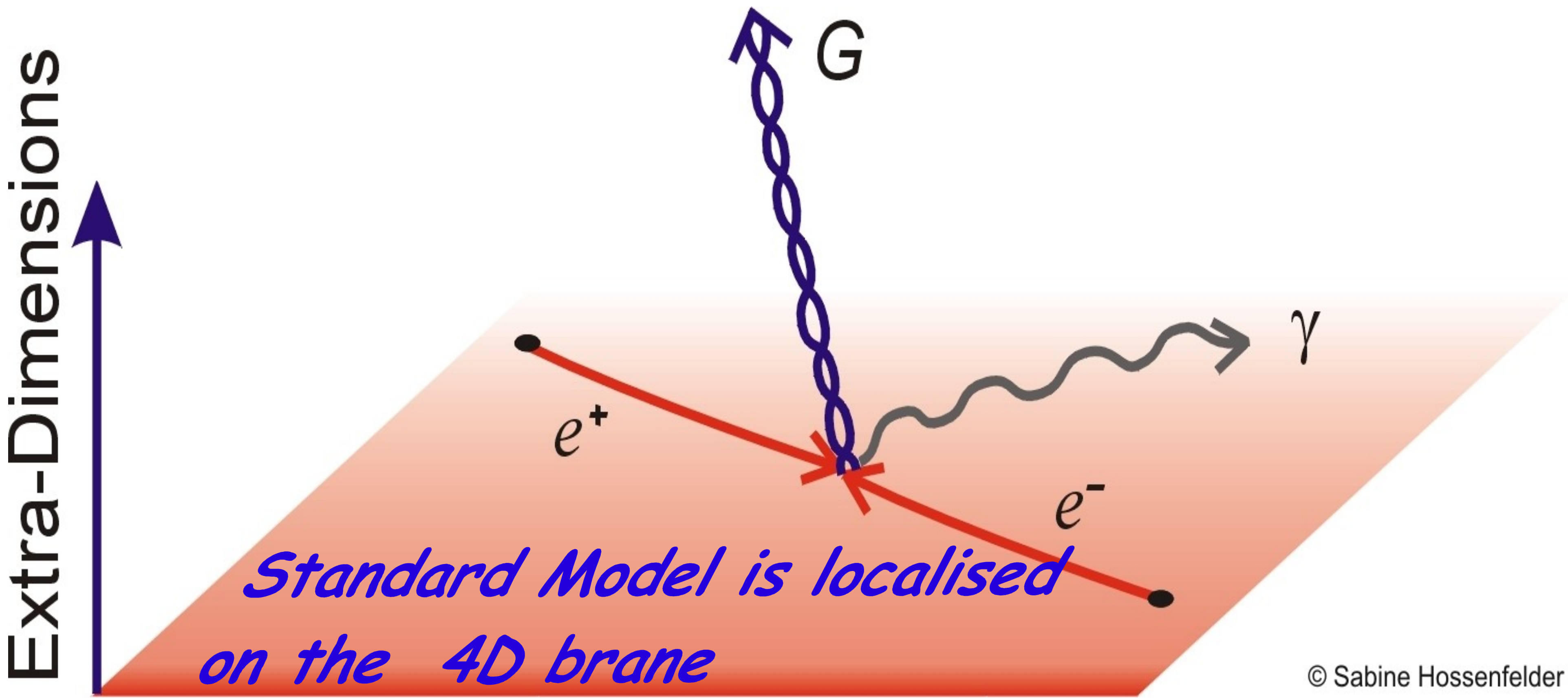
- 1920's: Kaluza and Klein tried using Einstein's equations in 5D ($g^{\mu\nu}$ -> $g^{MN} \sim g^{\mu\nu}, g^{\mu 4}, g^{44}$)

- 1970's: Development of superstring theory and supergravity required extra dimensions

- 1998: Arkani-Hamed, Dimopoulos, and Dvali propose Large Extra Dimensions (ADD) as a solution to the Hierarchy /Fine tuning problem of the Standard Model

The idea of ADD

- The Standard Model has been tested to r ~ 10^{-16} mm, Gravity has been tested to r ~ 1 mm only



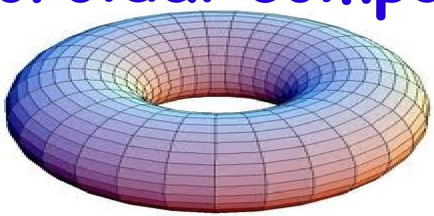
The idea of ADD

- The Standard Model has been tested to r ~ 10^{-16} mm,
  Gravity has been tested to r ~ 1 mm only
- 4D –> (4 + n)D
  The effective D = 4 action is

$$\frac{M_{\rm f}^{2+n}}{2}\int d^4x \int_0^{2\pi R} d^n Z \sqrt{G}\, R_{4+n} \longrightarrow \frac{1}{2} M_{\rm f}^{2+n} V_n \int d^4x \sqrt{g}\, R$$

In case of toroidal compactification of equal radii, R

$$V_n = (2\pi R)^n$$



$$M_P^2 = M_f^{2+n} V_n$$

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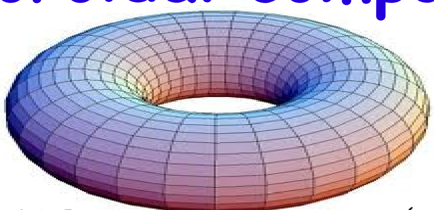

$$M_P^2=M_f^{2+n}V_n$$

r>>R ⇒ the torus effectively disappear

$$V(r)=-G_N\frac{m_1m_2}{r}=-\frac{m_1m_2}{M_P^2 r}$$

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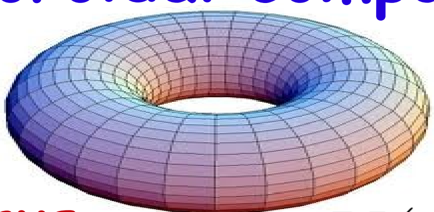

$$M_P^2 = M_f^{2+n} V_n$$

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$$V(r) = -G_N \frac{m_1 m_2}{r} = -\frac{m_1 m_2}{M_P^2 r}$$

r<<R ⇒ observer is able to feel the bulk

$$V(r) = -G_* \frac{m_1 m_2}{r} = -\frac{m_1 m_2}{M_f^{2+n} r^{1+n}}$$

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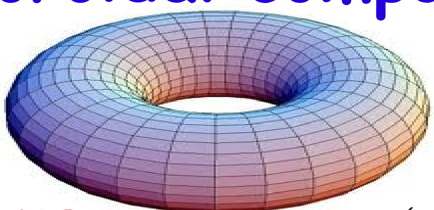

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$$V(r) = -G_*\frac{m_1 m_2}{r} = -\frac{m_1 m_2}{M_f^{2+n} r^{1+n}}$$

Fundamental quantum gravity scale

The current status of ADD

So, $M_P^2 = M_f^{n+2}(2\pi R)^n$ and respectively,

$$R = \frac{1}{2\pi}\frac{1}{M_f}\left(\frac{M_P}{M_f}\right)^{\frac{2}{n}} [\mathrm{GeV}^{-1}] \times 0.197[\ \mathrm{GeV\ \ m}]$$

The current status of ADD

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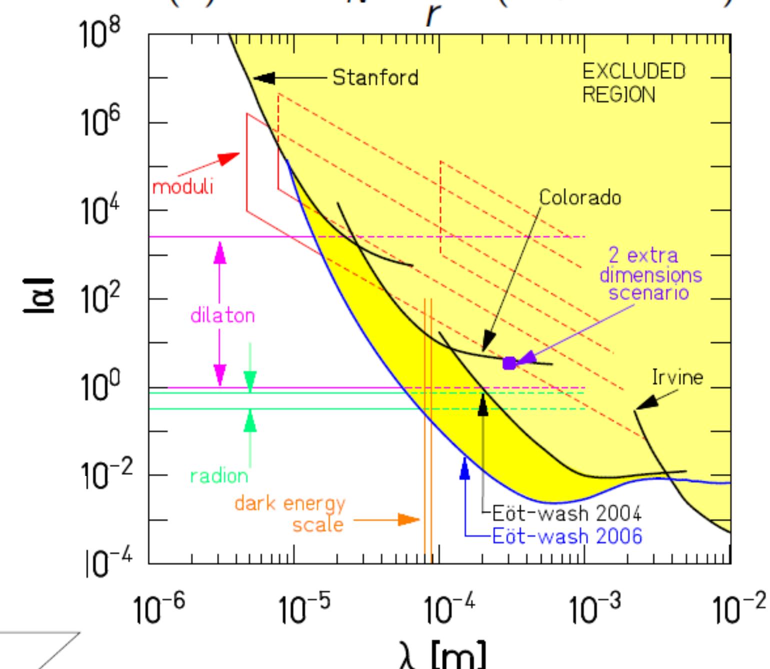
How big are these dimensions are?

Let us assume $M_f \sim 1$ TeV, then

$$R \sim \begin{cases} 10^{15}\ \mathrm{mm} & n = 1 \\ 1\ \mathrm{mm} & n = 2 \\ 10^{-6}\ \mathrm{mm} & n = 3 \\ \vdots & \end{cases}$$

× Already
× ruled out

$$V(r) = -G_N \frac{m_1 m_2}{r}(1 + \alpha e^{-r/\lambda})$$

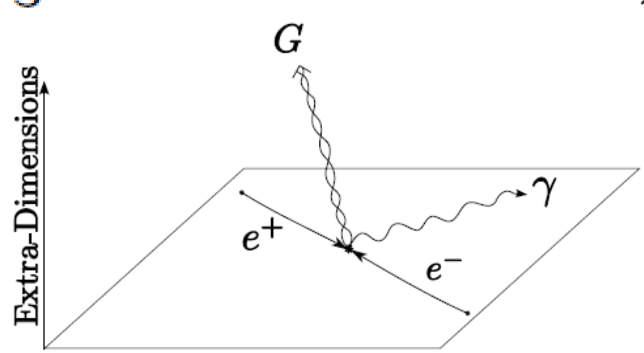


The current bound is $R < 37\ \mu\mathrm{m}$

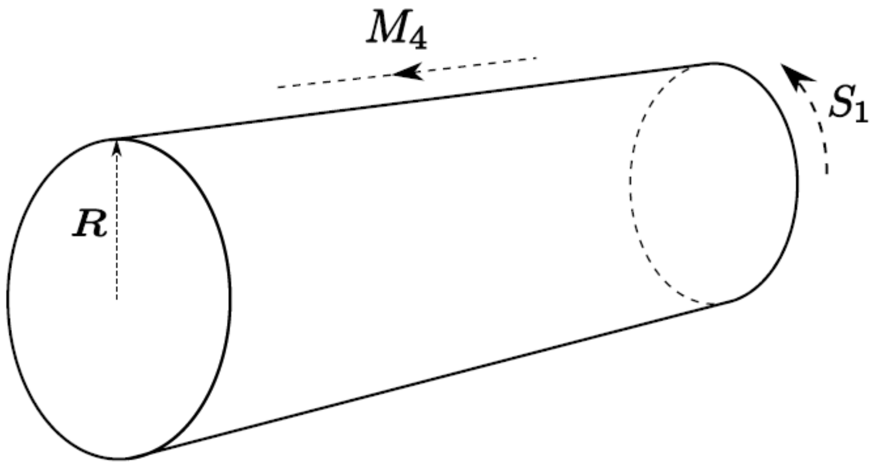
For $n = 2$ this means that $M > 1.4$ TeV

Collider signature:

$$pp \to jet + \not{E}_T$$



KK-towers from XD

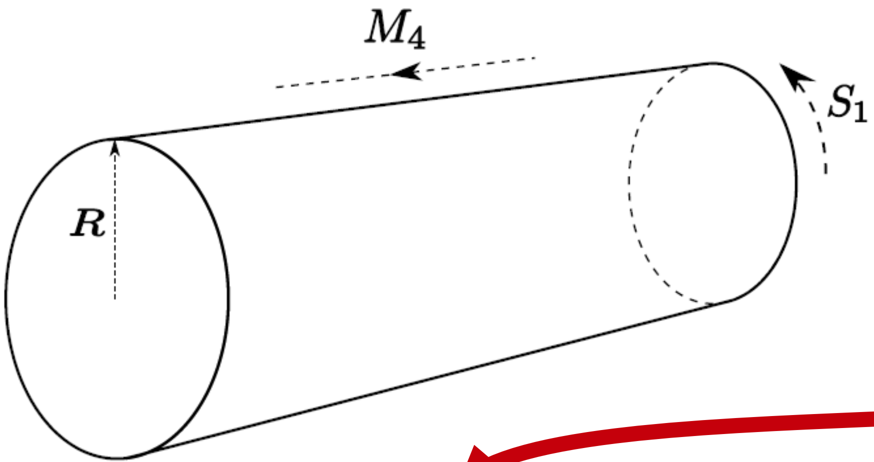


$$\Phi(x_\mu,\ Z) = \Phi(x_\mu,\ Z + 2\pi R)$$

$\mu = 0, 1, 2, 3$

Periodicity in Z

KK-towers from XD



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Periodicity in Z

Fourier series

$$\Phi(x_\mu,\ Z) = \sum_{k=0,\pm1,\dots} \phi_k(x_\mu) e^{ikZ/R}$$

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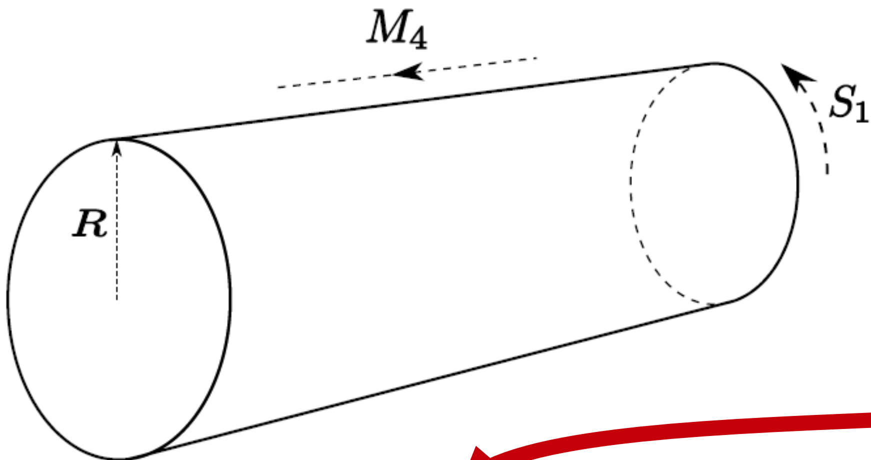

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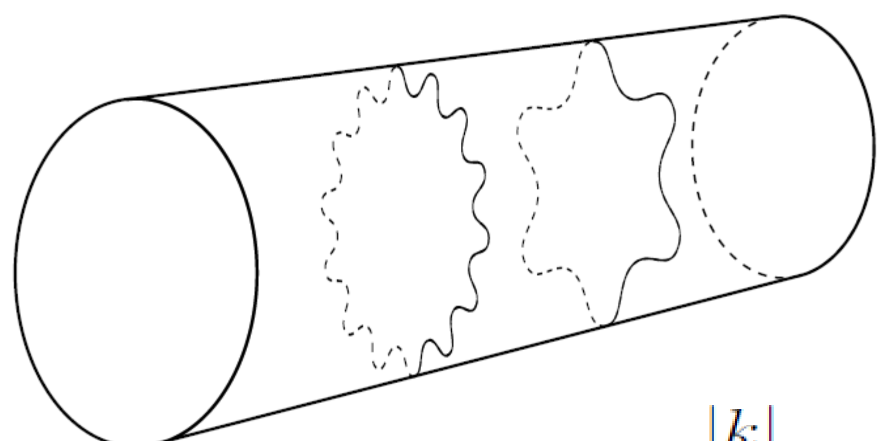
The non-zero modes in the KK decomposition

$$\Box_5\, \Phi(x_\mu,\ Z) \equiv \left(\partial_\mu^2 - \frac{\partial^2}{\partial Z^2}\right) \Phi(x_\mu,\ Z) = 0$$

$$\left(\Box_4 + \frac{k^2}{R^2}\right) \phi_k(x_\mu) \equiv \left(\partial_\mu^2 + \frac{k^2}{R^2}\right) \phi_k(x_\mu) = 0$$



$$m_k = \frac{|k|}{R}$$

From Brane – to Bulk: Universal Extra Dimensions (UED)

[Appelquist, Cheng, Dobrescu '01]

- all fields propagate in the extra dimensions, so $1/R > 1$ TeV to obey experimental data

- for D=5 (minimal UED = MUED) we immediately find that $M_f = 10^{15}$ GeV for $1/R = 1$TeV
- hierarchy problem is not addressed

  but MUED has interesting features ...

Minimal Universal Extra Dimensions

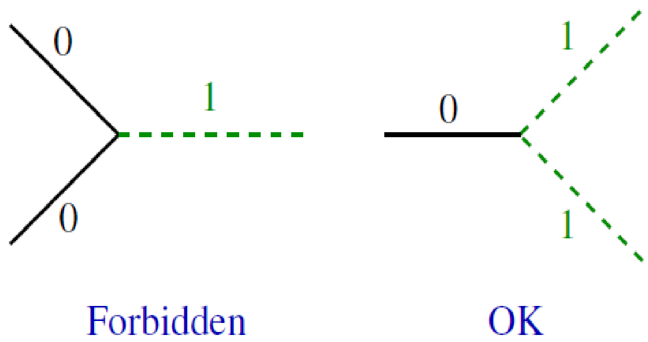
compactifying on the circle

$$\phi(x,y) = \frac{1}{\sqrt{2\pi R}}\phi_0(x) + \sqrt{\frac{\pi}{R}}\sum_{n=1}^{\infty}\left[\phi_n^+(x)\cos\frac{ny}{R} + \phi_n^-(x)\sin\frac{ny}{R}\right]$$

$$S = \int d^4x \overbrace{\int_0^{2\pi R} dy \underbrace{\frac{1}{2}\left[\partial_M\phi\partial^M\phi - m^2\phi(x,y)^2\right]}_{\mathcal{L}_5}}^{\mathcal{L}_4}$$

$$\mathcal{L}_4 = \frac{1}{2}\left[\partial_\mu\phi_0\partial^\mu\phi_0 - m^2\phi_0^2\right] + \sum_{n=1}^{\infty}\frac{1}{2}\left[\partial_\mu\phi_n^\pm\partial^\mu\phi_n^\pm - \overbrace{\left(m^2 + \frac{n^2}{R^2}\right)}^{m_n^2}\phi_n^{\pm\,2}\right]$$

- all fields propagate in the bulk – 5D momentum conservation
- This leads to the KK-number conservation at this point: $\pm n_1 \pm n_2 = \pm n_3$

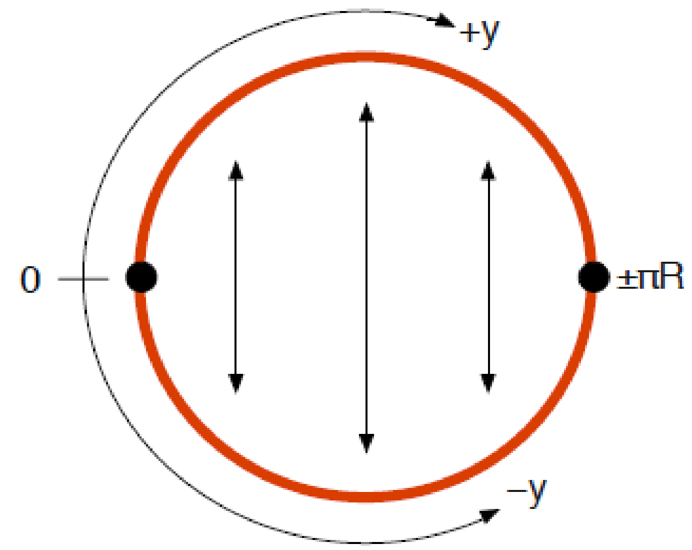


Universal Extra Dimensions (UED)

compactifying on the orbifold

- **Choose action of Z_2 symmetry on Dirac Fermions to project out ½ of them and arranges chirality:**

$$\psi_\pm(y) \mapsto \psi'_\pm(-y) = \pm\gamma^5\psi_\pm(y)$$



If we identify $y \sim -y$ then we require $\psi'_\pm(y) = \psi_\pm(y)$, so

$$\psi_\pm(y) = \psi_0^{R,L} + \sum_n \left(\psi_n^{R,L}\cos_n + \psi_n^{L,R}\sin_n\right)$$

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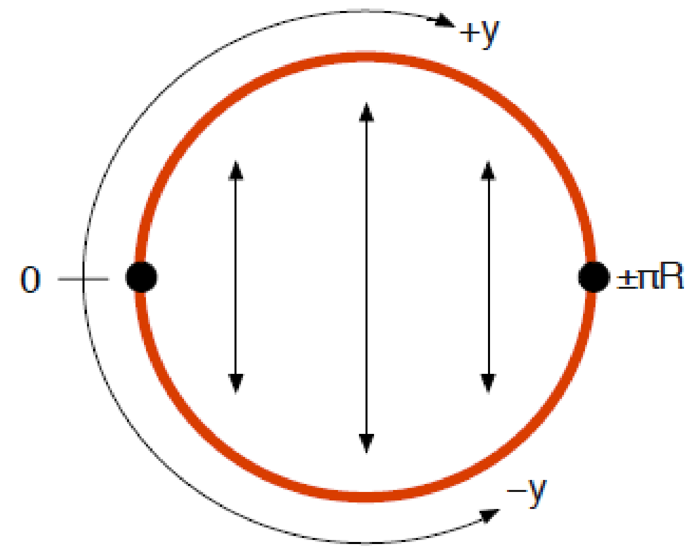

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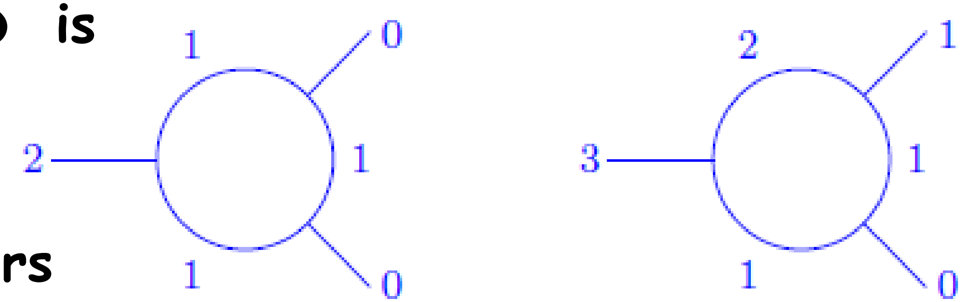
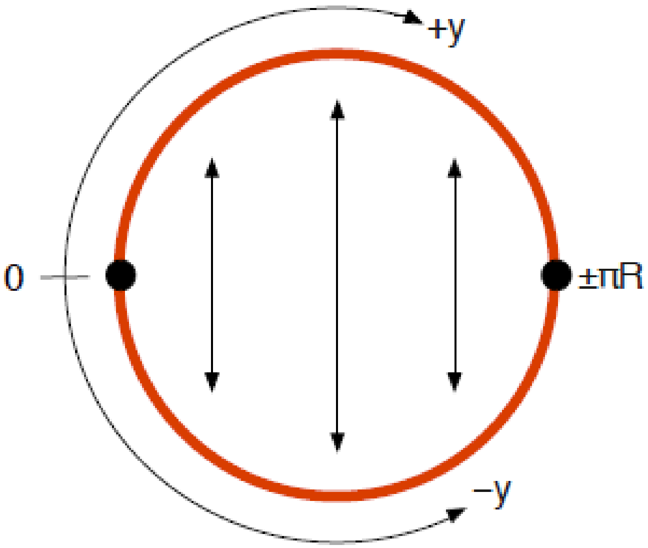
- Translational invariance along the 5th D is broken, but KK parity is preserved!
- KK number n broken down to the KK parity, $(-1)^n$: KK excitations must be produced in pairs



These vertices are allowed and can be generated at loop-level

- LKP is stable DM candidate!

Minimal Universal Extra Dimensions



$$\boxed{SU(3) \times SU(2) \times U(1)}$$

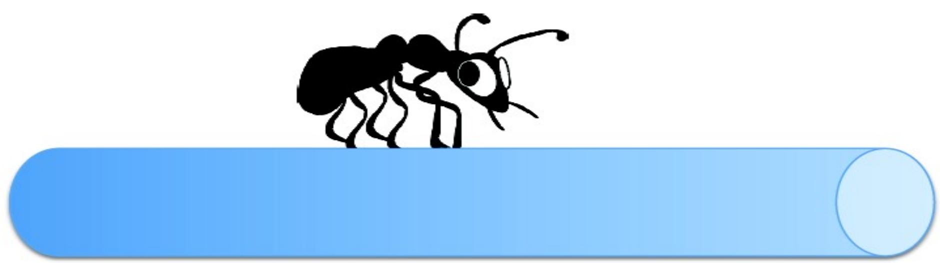
$$\psi^{R,L}(x) \to \psi^{\pm}(x,y)$$
$$A_\mu(x) \to A_M(x,y)$$
$$\phi(x) \to \phi(x,y)$$

$S^1/\mathcal{Z}_2$ orbifold

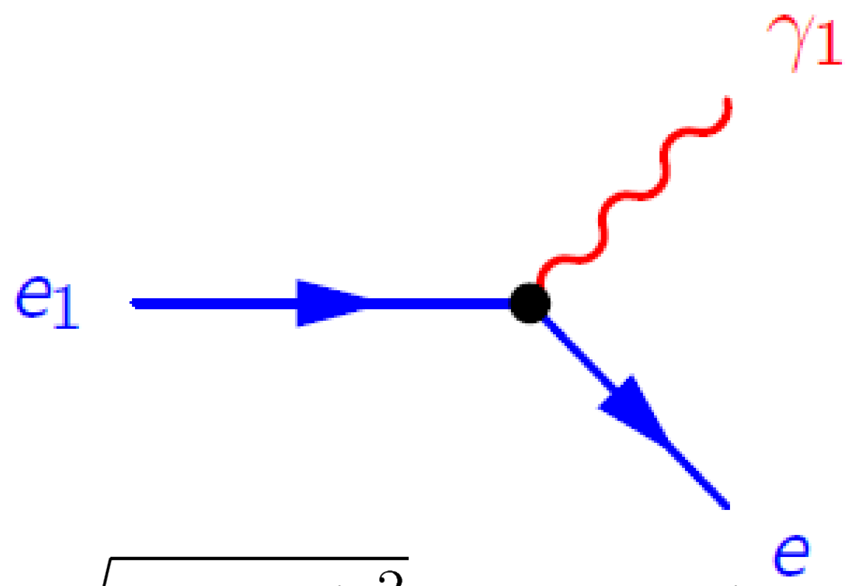
SM Gauge group

SM field content

brane localised terms are zero at the cutoff scale



The role of radiative corrections



$$\sqrt{m_e^2 + \frac{1}{R}^2} < m_e + \frac{1}{R} (!!!)$$

e.g. the 1st KK excitation of the electron is stable at tree-level!

Dark Matter would be charged – which is not acceptable

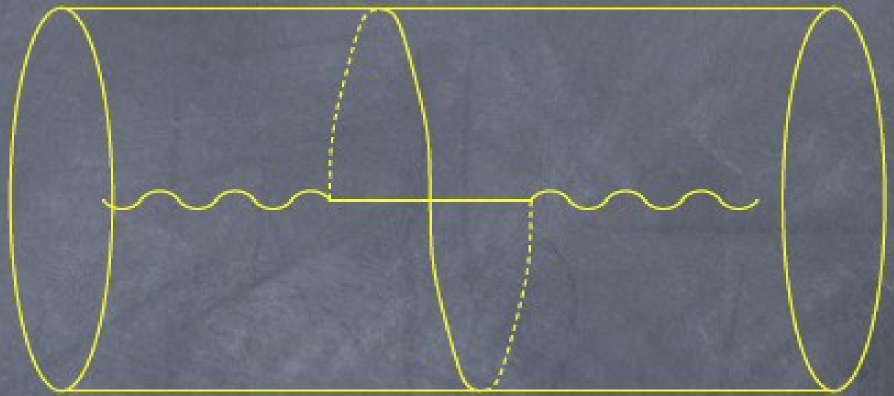
MUED at one loop

Cheng, Matchev, Schmaltz
2002

Loop corrections come from 5D Lorentz violating processes. They appear as tree-level mass corrections in 4D.

- Bulk corrections :

the gauge bosons receive an extra mass which is KK-independent



$$\delta m_n^2 = \alpha_i \frac{1}{R^2}$$

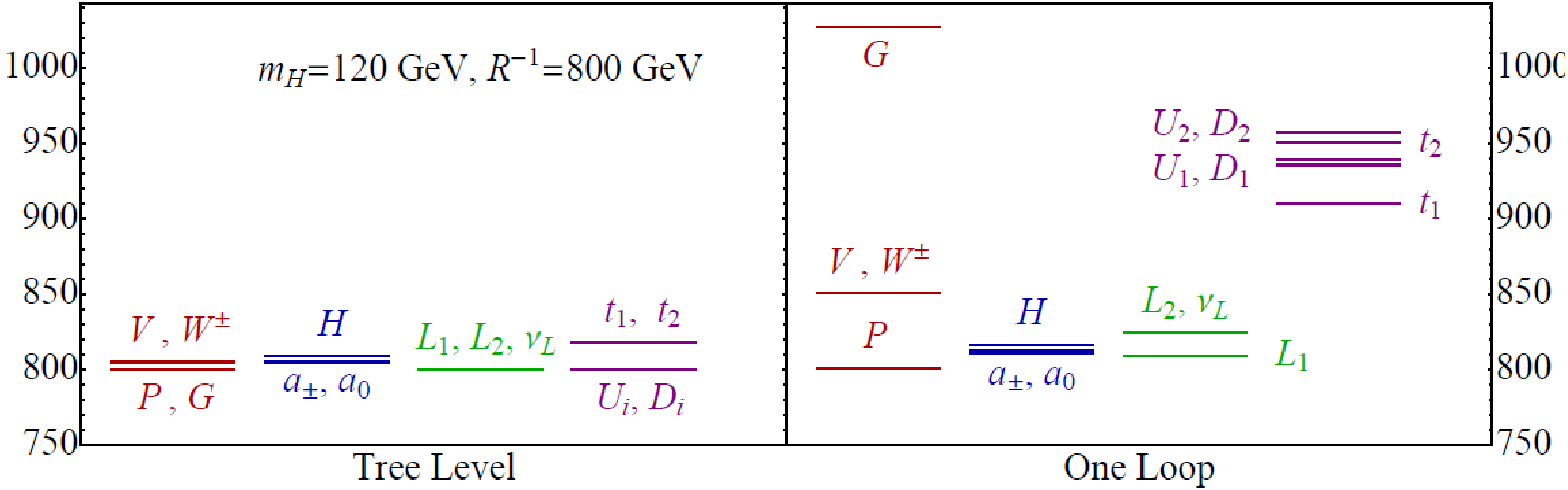
- Brane corrections : p_5 is not conserved, all particles receive a mass correction

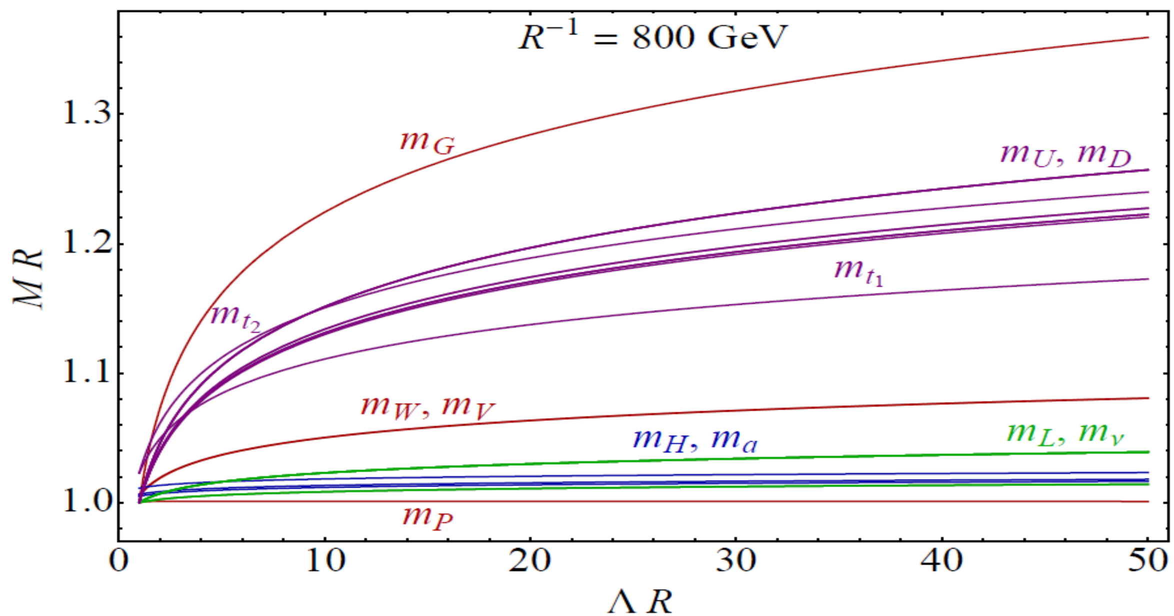
$$\delta m_n = \beta_i \frac{n}{R} \ln \frac{\Lambda^2}{\mu^2} \qquad \text{for fermions}$$

$$\delta m_n^2 = \beta_i \frac{n^2}{R^2} \ln \frac{\Lambda^2}{\mu^2} \qquad \text{for bosons}$$

Problem : Electroweak symmetry breaking was not included

MUED spectrum at 1loop vs tree-level





Our setup

We model the corrections to the self-energy by wave-function normalisations. We replace a 5D-Lorentz conserving action

$$-\frac{1}{4}F^a_{MN}F^{a\,MN} + |D_M\Phi|^2$$

by the following

$$-\frac{1}{4}F^{a\,\mu\nu}F^a_{\mu\nu} + \frac{1}{2}Z_v F^a_{\mu 5}F^{a\,\mu}_{\ \ 5} + |D_\mu\Phi|^2 - Z_\Phi|D_5\Phi|^2$$

which is gauge invariant but not Lorentz covariant.
In this way, the fields receive a KK mass

$$m_n = Z\,\frac{n}{R} \quad \text{for fermions ,} \quad m_n^2 = Z\,\frac{n^2}{R^2} \quad \text{for bosons}$$

We are free to match our normalisations with the previous results

$$Z_i = 1 + \beta_i \ln\frac{\Lambda^2}{\mu^2}$$

Model implementation

Semenov

• In LanHEP :

LanHEP is a package that generates the Feynman rules out of a Lagrangian.

We have implemented MUED@1L in Feynman and unitary gauges. We discart the bulk corrections.

Pukhov, AB, Christensen

• In CalcHEP/CompHEP :

CalcHEP calculates cross-sections out of Feynman rules of a theory.
The vertices generated by LanHEP are included into CalcHEP.
We have taken particular care of the splitting of 4-gluon vertices.

Model is available at High Energy Physcs Model Database (HEPMDB)
http://hepmdb.soton.ac.uk/hepmdb:1212.0121

Model Validation

Sample of processes with two-gauge bosons for cross-section comparison (in pb) between previous implementation by Datta,Kong, Matchev (DKM) and our implementation (BBMP) arXiv:1212.4858

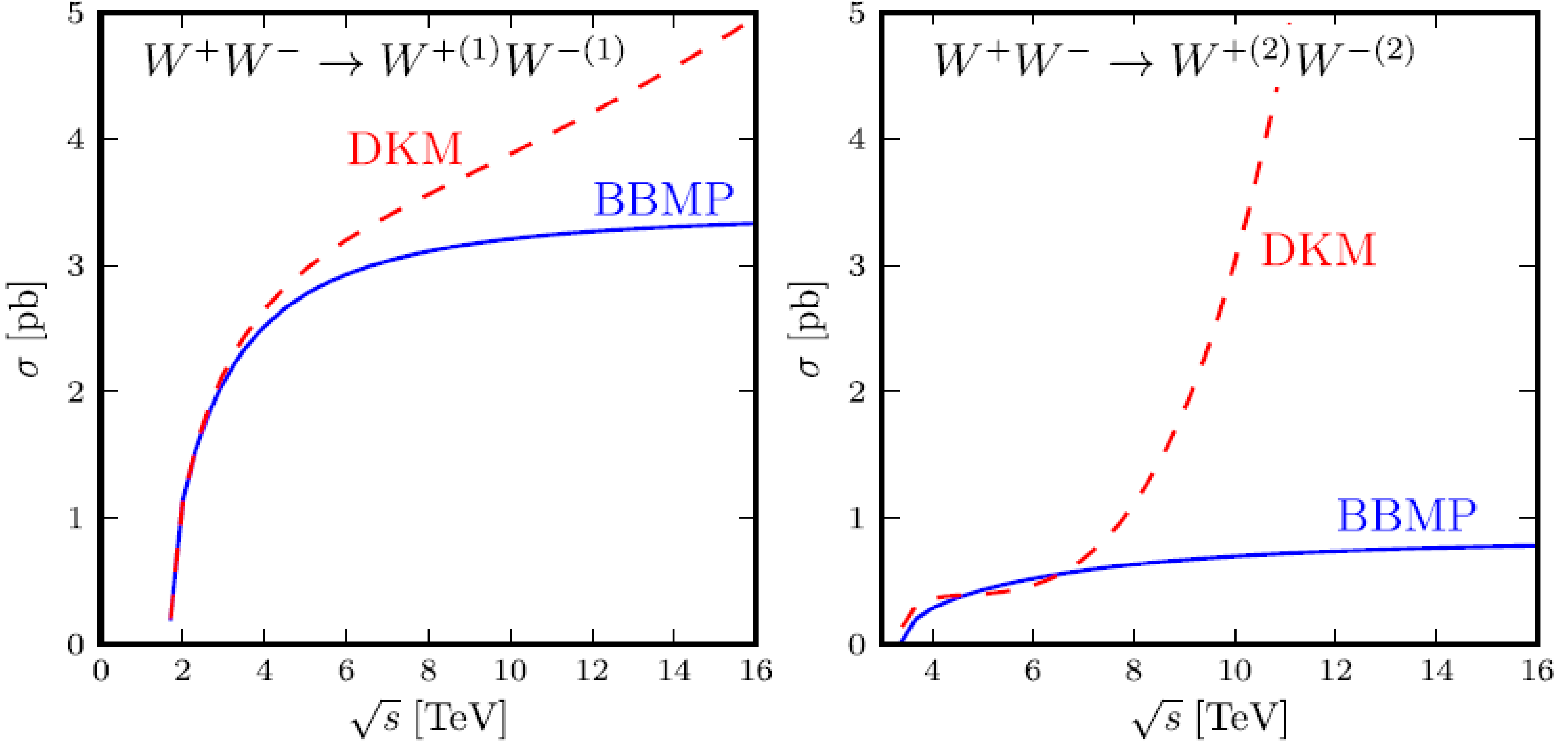
	Process	DKM σ [pb]	BBMP σ [pb]
1	$G^{(1)}\,G^{(1)} \to G\,G$	3.952×10^{1}	3.952×10^{1}
2	$G^{(1)}\,G \to G^{(1)}\,G$	7.600×10^{3}	7.600×10^{3}
* 3	$G^{(1)}\,G^{(1)} \to G^{(1)}\,G^{(1)}$	8.619×10^{3}	8.600×10^{3}
* 4	$G^{(1)}\,Z^{(1)} \to c\,\bar{c}$	2.132×10^{-1}	2.037×10^{-1}
* 5	$G^{(1)}\,\gamma^{(1)} \to b\,\bar{b}$	3.651×10^{-2}	3.249×10^{-2}
* 6	$\gamma^{(1)}\,\gamma^{(1)} \to t\,\bar{t}$	2.641×10^{-2}	2.758×10^{-2}
* 7	$Z^{(1)}\,Z^{(1)} \to d\,\bar{d}$	9.098×10^{-2}	9.165×10^{-2}
* 8	$Z^{(1)}\,Z^{(1)} \to W^{+}\,W^{-}$	9.293×10^{0}	9.288×10^{0}
* 9	$W^{+\,(1)}\,W^{-\,(1)} \to Z\,Z$	2.744×10^{0}	2.761×10^{0}
10	$W^{+\,(1)}\,W^{-\,(1)} \to Z\,\gamma$	1.653×10^{0}	1.653×10^{0}
*11	$W^{+\,(1)}\,W^{-\,(1)} \to W^{+}\,W^{-}$	3.152×10^{0}	3.081×10^{0}

$\sqrt{s}$=2 TeV

$P_T > 100$ GeV

KK up to n=2: if KK numbers of the external particles is 5 or less [<2*(n+1) in general] gauge invariance is ensured

Model Validation



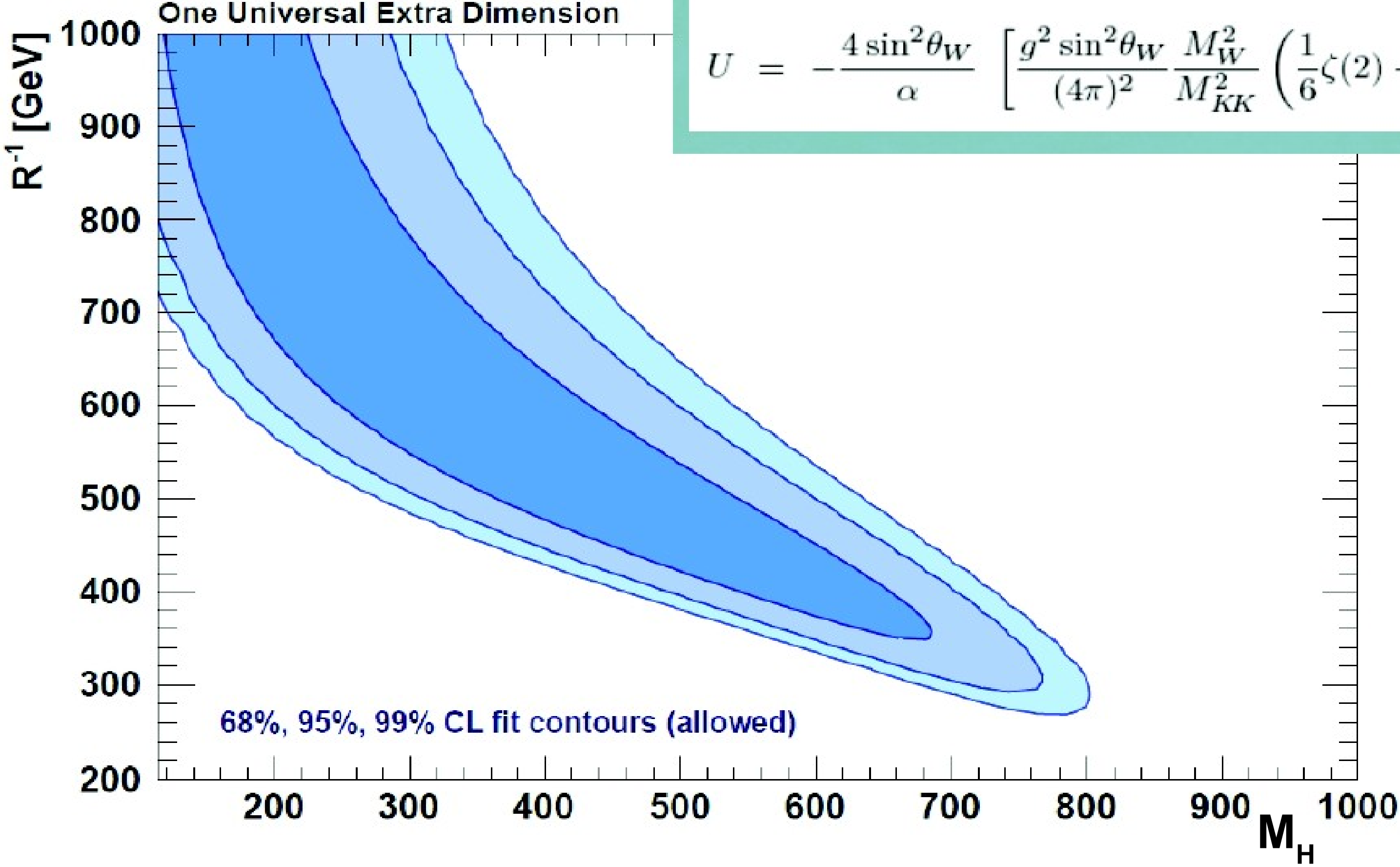
Proper implementation of the Higgs sector lead to the correct High Energy asymptotic which respects Unitarity

EW precision constraints

The tower of KK particles modify the gauge bosons self-energies, contributing to the S,T, and U electroweak parameters:

T. Appelquist H.-U. Yee 2001
I. Gogoladze and C. Macesanu, 2006

$$
\begin{aligned}
S &= \frac{4\sin^2\theta_W}{\alpha}\left[\frac{3g^2}{4(4\pi)^2}\left(\frac{2}{9}\frac{m_t^2}{M_{KK}^2}\right)\zeta(2) + \frac{g^2}{4(4\pi)^2}\left(\frac{1}{6}\frac{M_H^2}{M_{KK}^2}\right)\zeta(2)\right], \\
T &= \frac{1}{\alpha}\left[\frac{3g^2}{2(4\pi)^2}\frac{m_t^2}{M_W^2}\left(\frac{2}{3}\frac{m_t^2}{M_{KK}^2}\right)\zeta(2) + \frac{g^2\sin^2\theta_W}{(4\pi)^2\cos^2\theta_W}\left(-\frac{5}{12}\frac{M_H^2}{M_{KK}^2}\right)\zeta(2)\right], \\
U &= -\frac{4\sin^2\theta_W}{\alpha}\left[\frac{g^2\sin^2\theta_W}{(4\pi)^2}\frac{M_W^2}{M_{KK}^2}\left(\frac{1}{6}\zeta(2) - \frac{1}{15}\frac{M_H^2}{M_{KK}^2}\zeta(4)\right)\right],
\end{aligned}
$$



arXiv: 1107.0975

FCNC and DM constraints

FCNC

K. Agashe, N.G. Deshpande, G.-H. Wu
L. A. J. Buras, A. Poschenrieder, M. Spranger, A. Weiler

KK modes will give contributions to FCNC processes . From $b \to s\gamma$

$1/R > 600$ GeV

Cosmology (DM)

Belanger, Kakizaki, Pukhov

The evaluation of the LKP relic abundance depends on the spectrum details and on the number of KK levels included in the calculation (eg level 2 resonances, level 2 particles in the final state, etc) Electroweak symmetry breaking effects are also important.

Matsumoto, Senami '05; Kong, Matchev '05
Brunel, Kribs '05; Belanger, Kakizaki, Pukhov '10
....

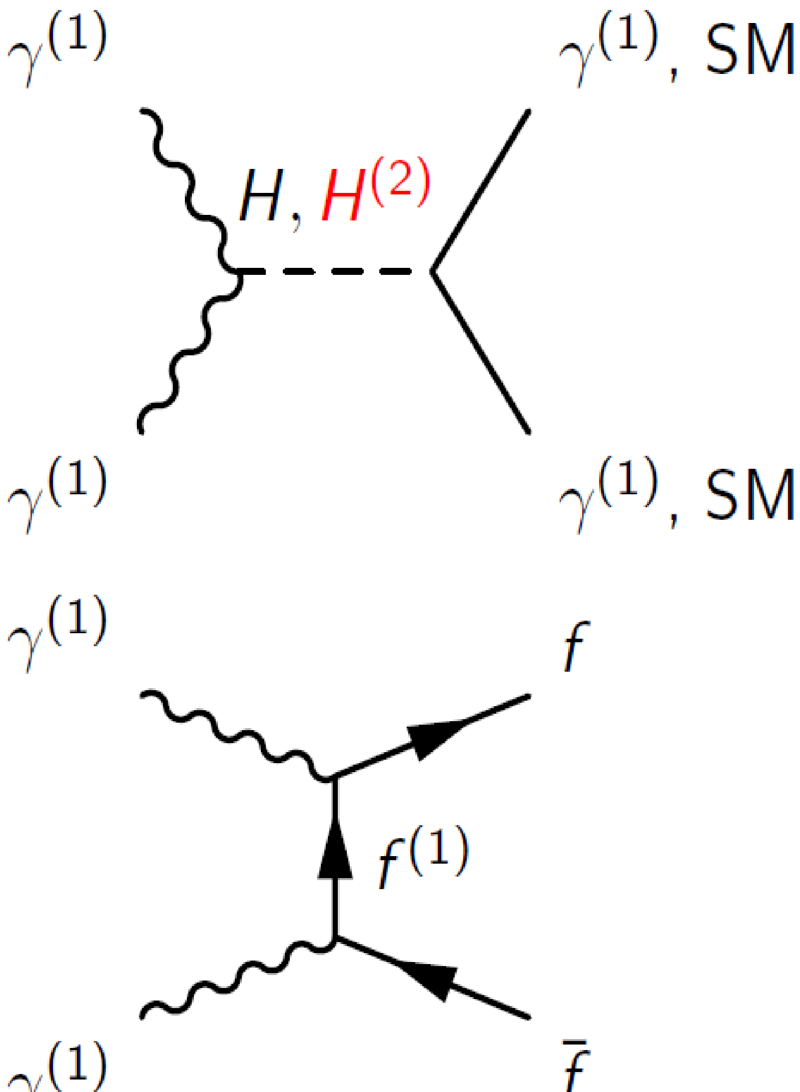
WMAP imposes a bound from above to DM scale: if DM were heavier it would lead to the Universe having a measurable positive curvature

$1/R < 1.6$ TeV

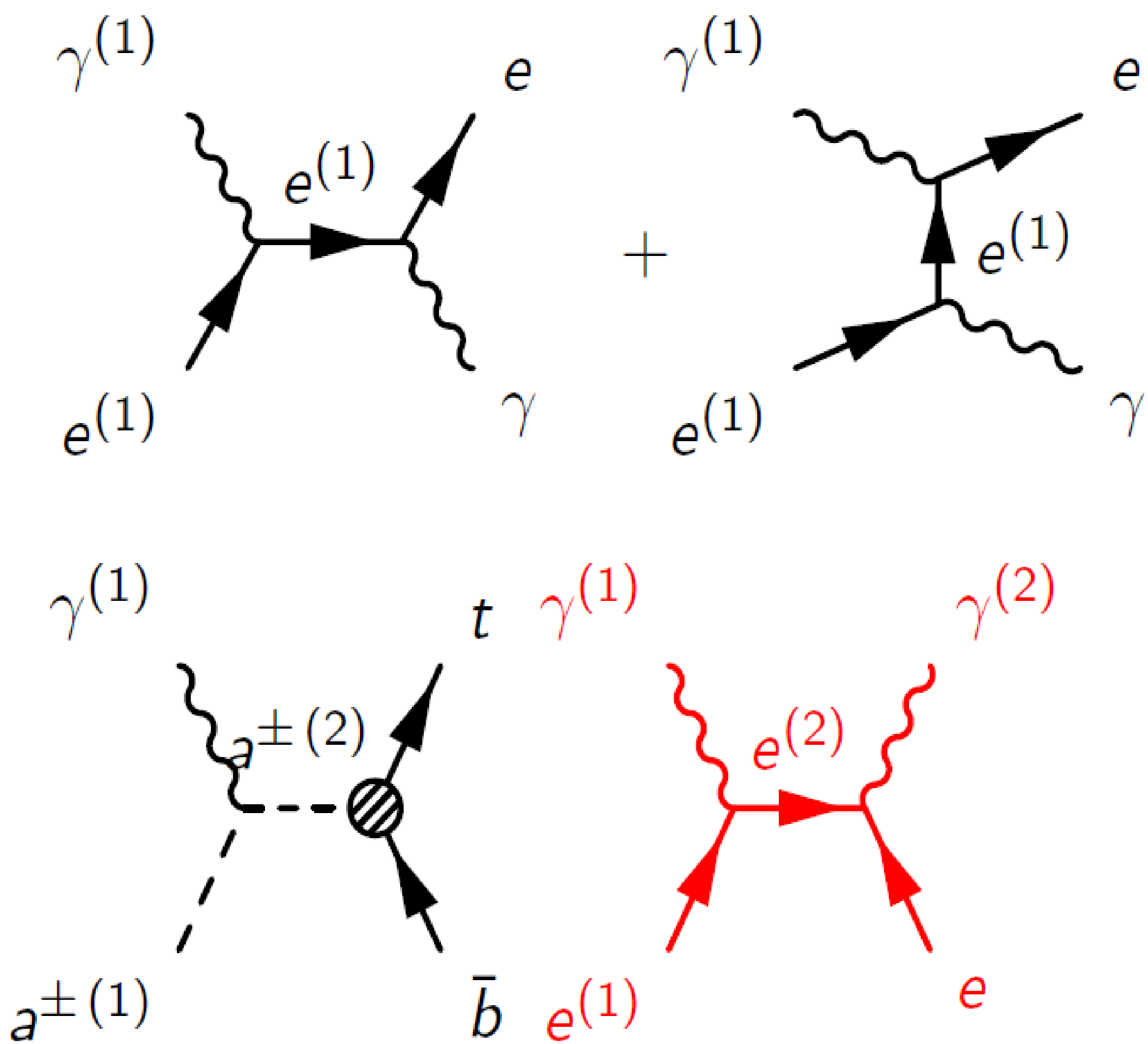
The role of the 2nd level of KK excitation

Processes important for calculating DM relic abundance. . .

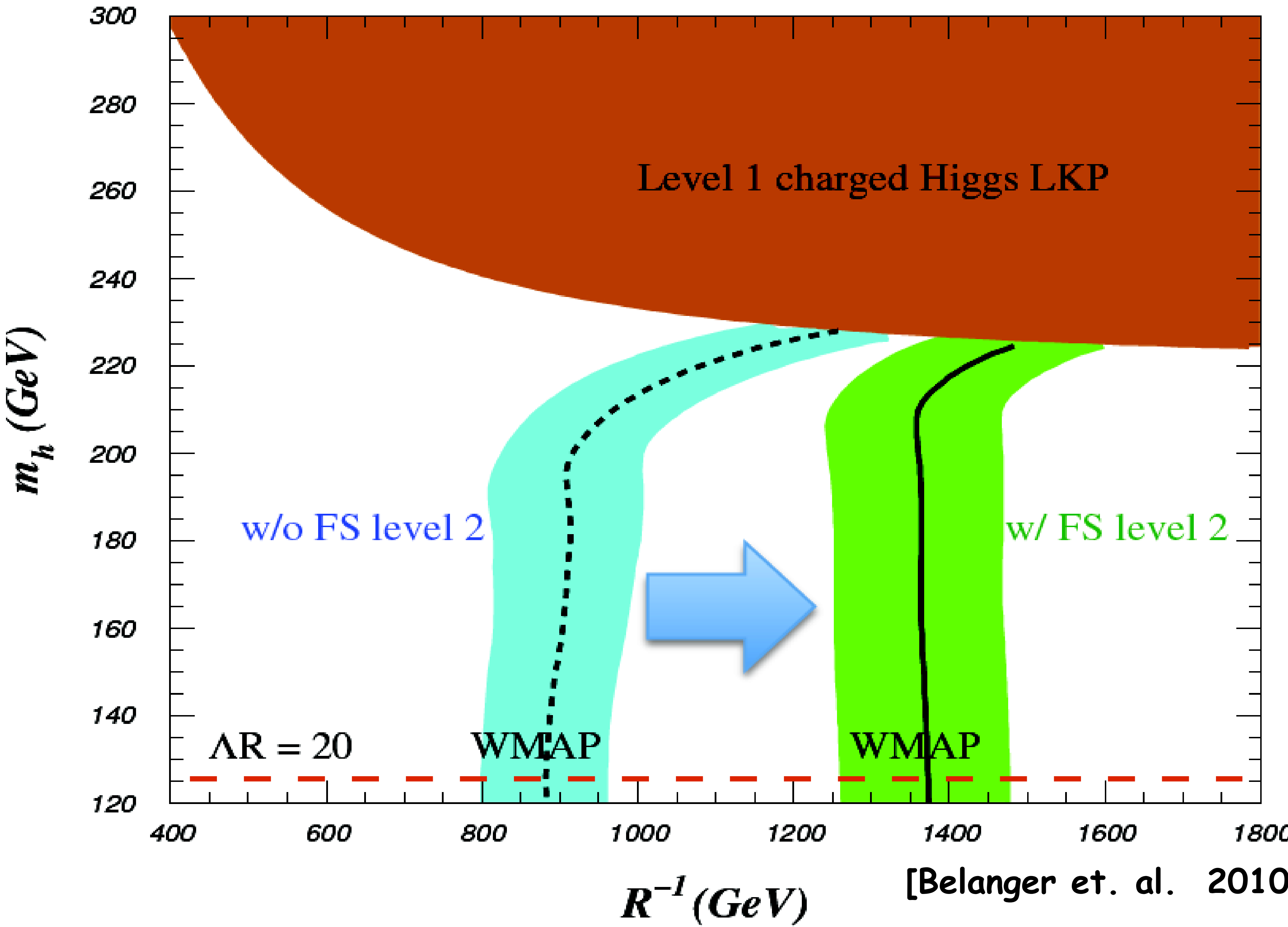
Self-annihilation



Co-annihilation

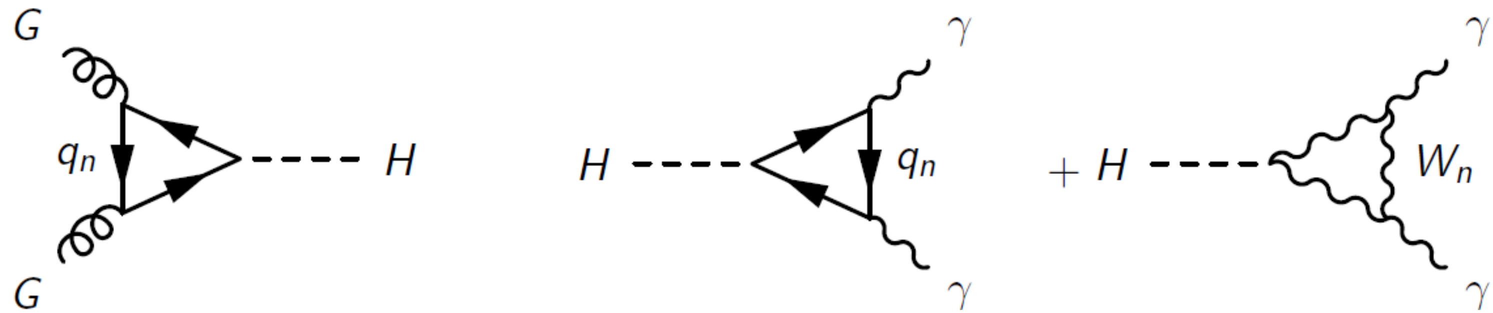


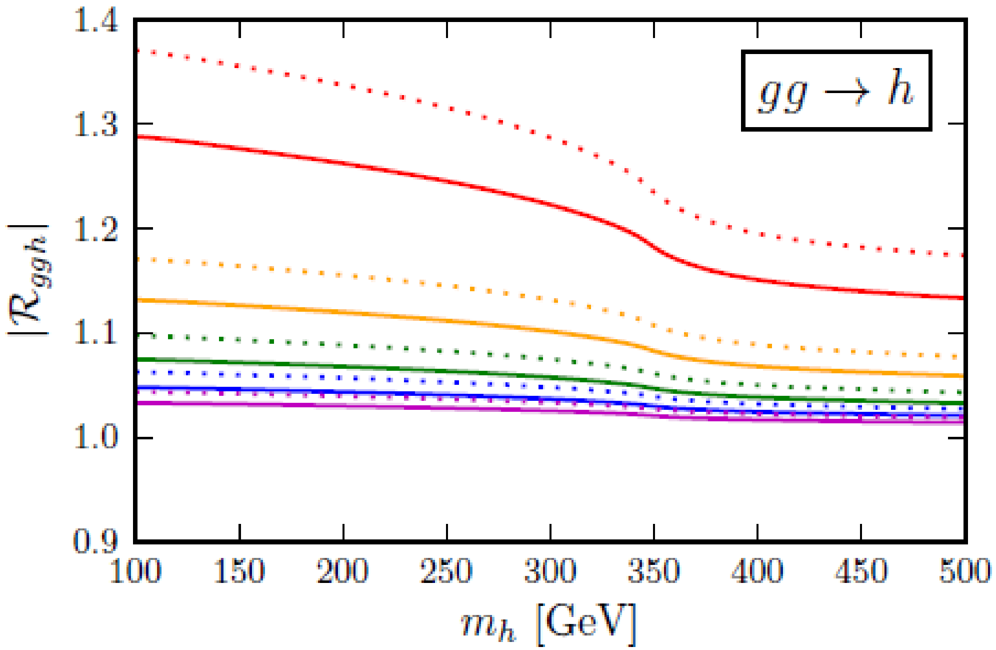
The role of the 2nd level of KK excitation

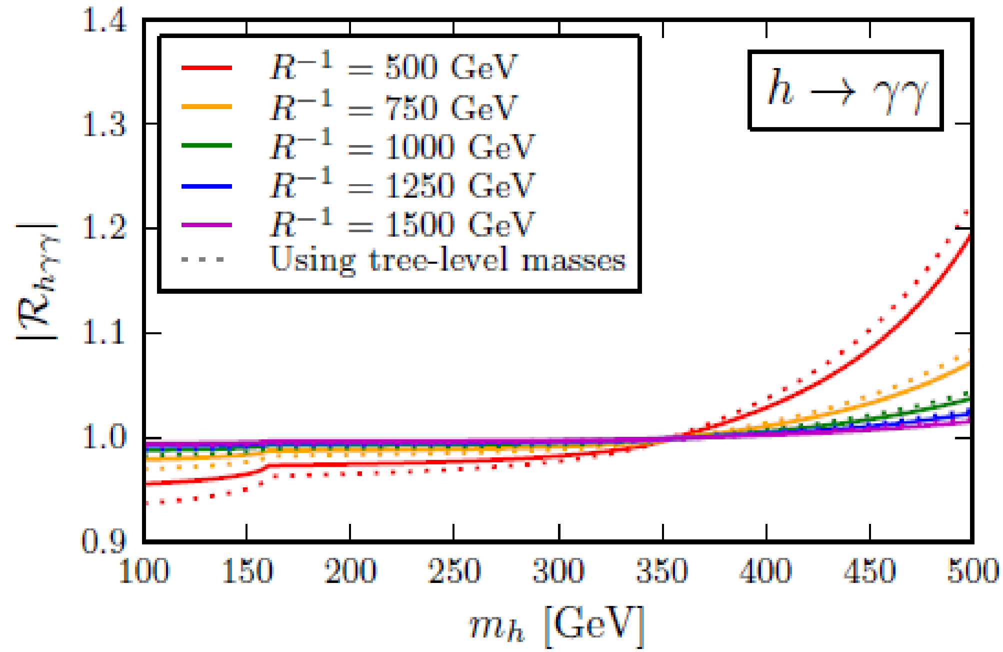


[Belanger et. al. 2010]

The role of the Higgs searches in constraining of the mUED model



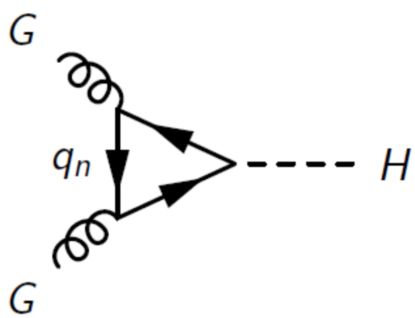


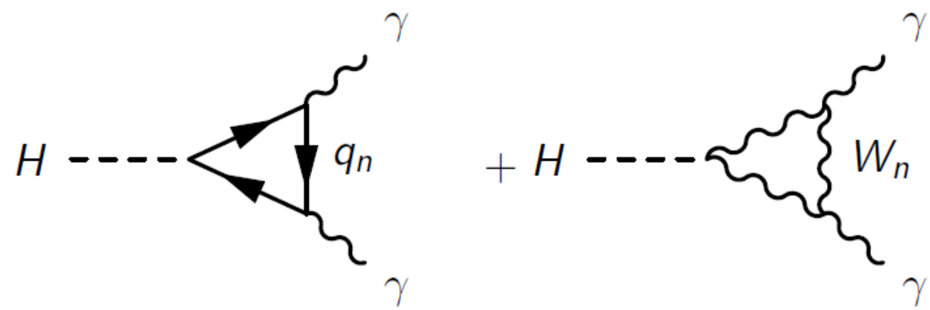


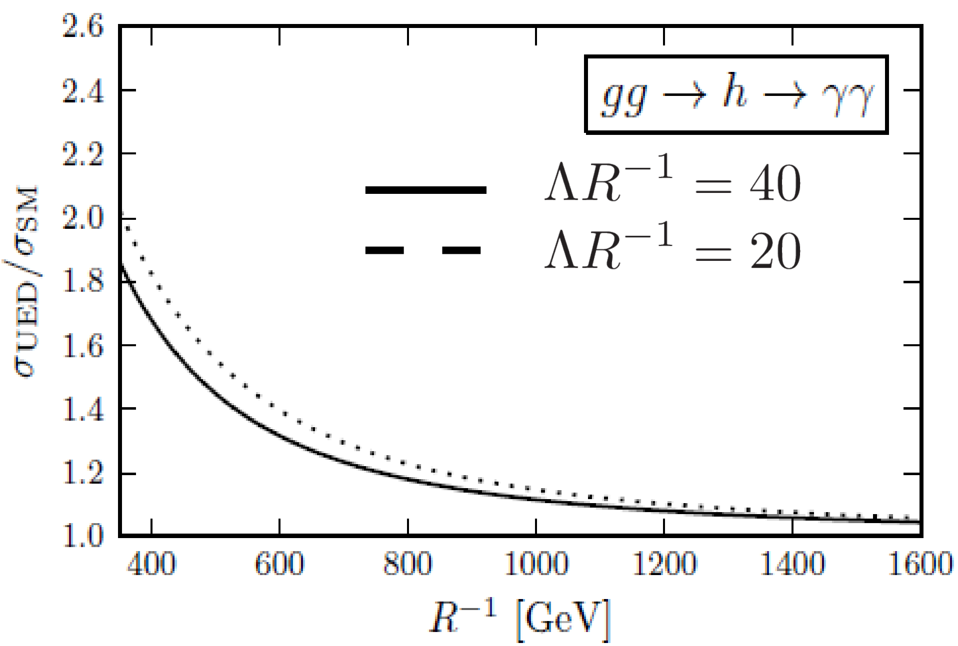
- **Production is enchanced**
- **Decay is slightly suppressed**

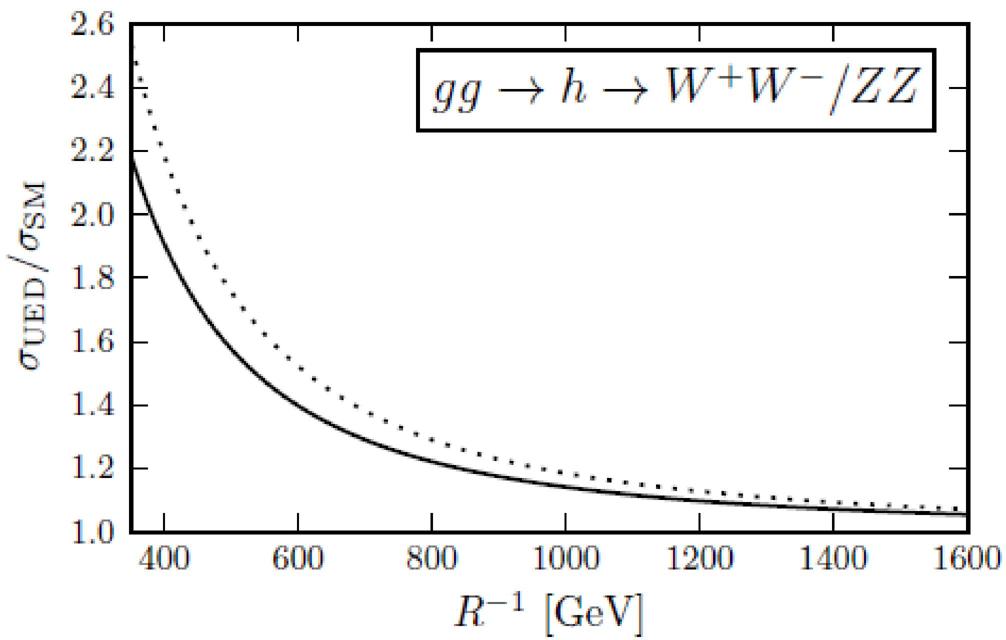
AB, Belanger, Brown, Kakizaki, Pukhov '12

Constraints from the Higgs data





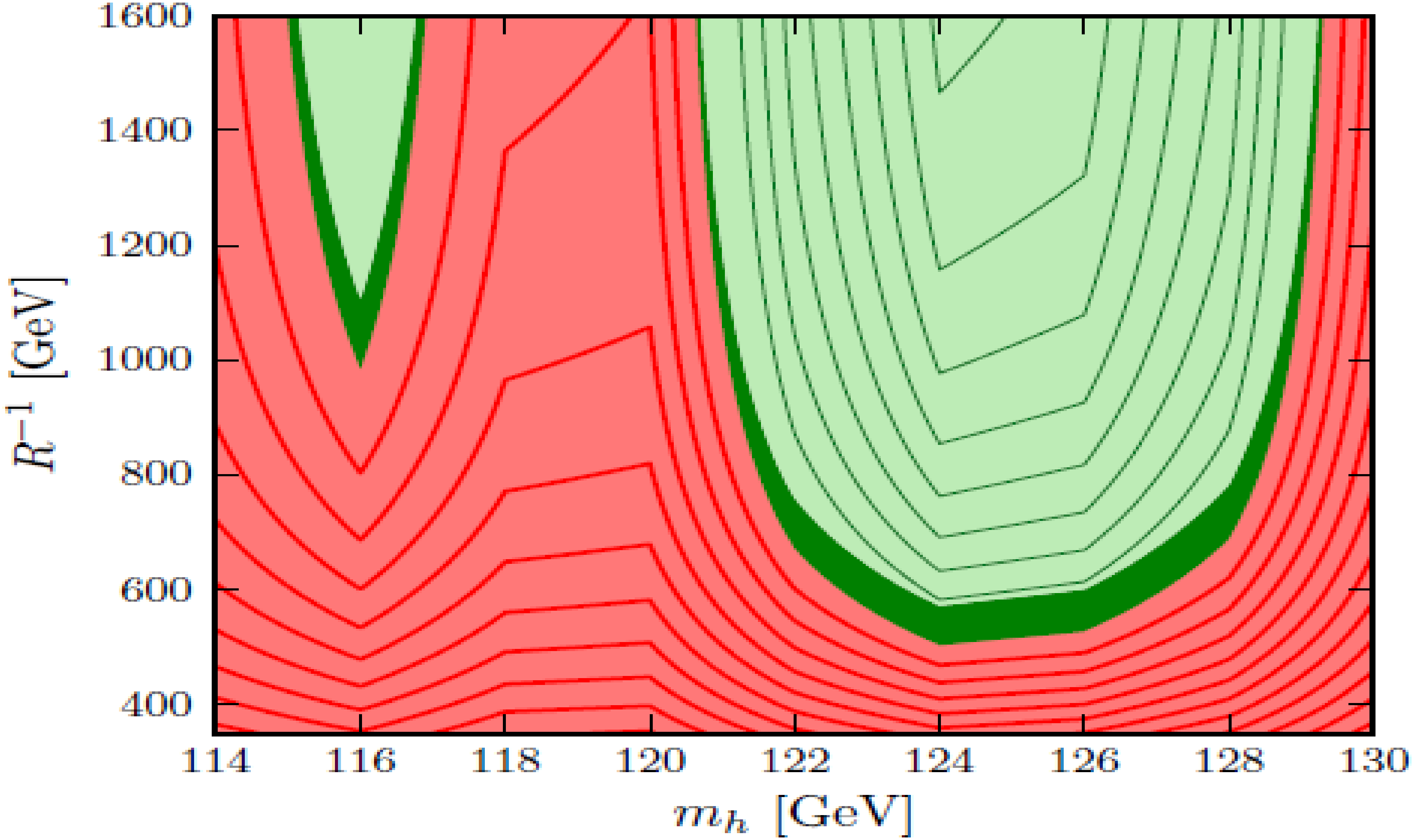




- **Production is enchanced**
- **Decay is slightly suppressed**
- **Overall, the GG->H->γγ is enhanced**

AB, Belanger, Brown, Kakizaki, Pukhov '12

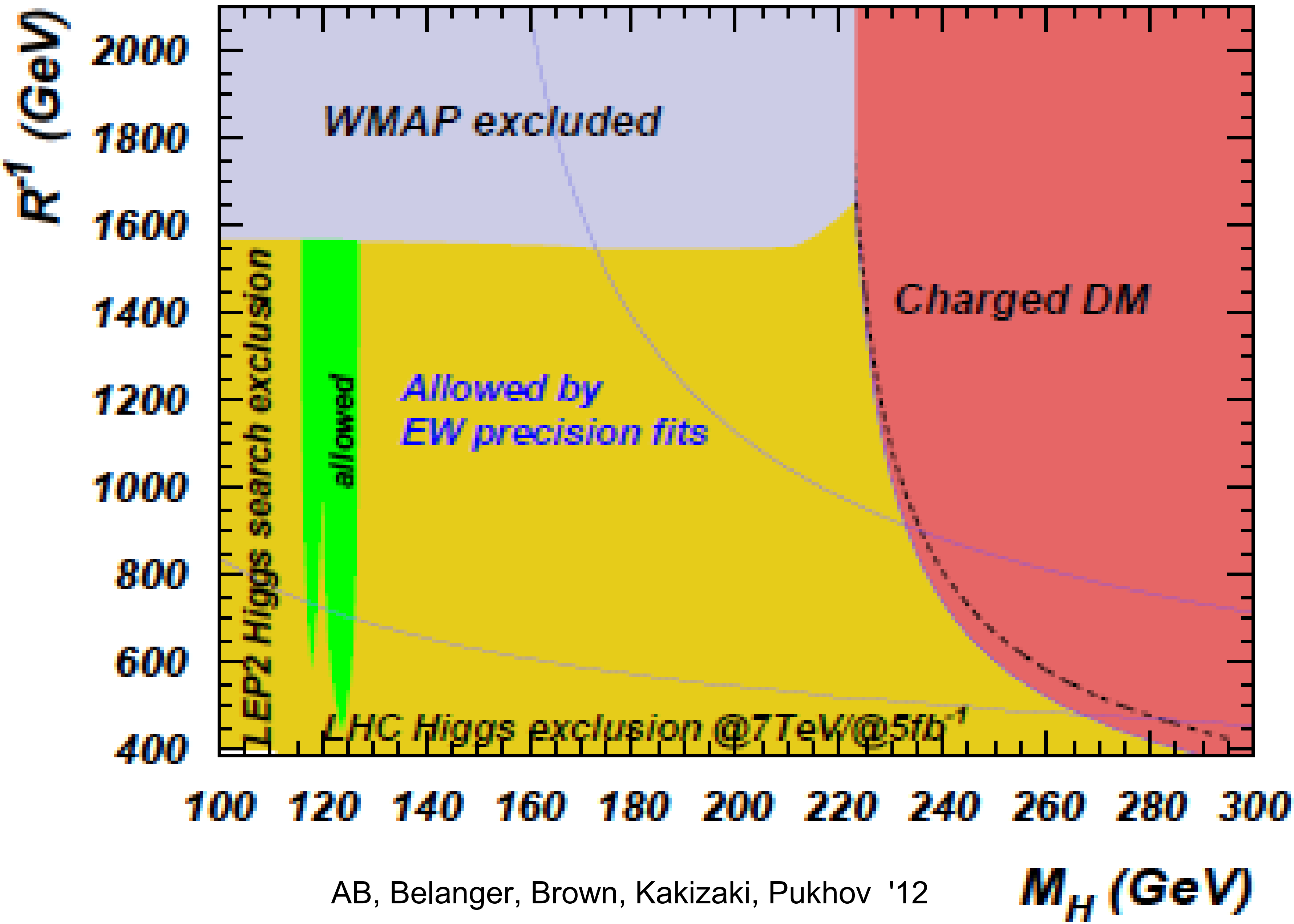
Constraints from the Higgs data



- Same channels ($\gamma\gamma$ and WW) from CMS/ATLAS are combined
- R^{-1}<500 is excluded at 95% CL
- overall, the GG->H->$\gamma\gamma$ is enhanced
- Narrow window around 125 GeV is left

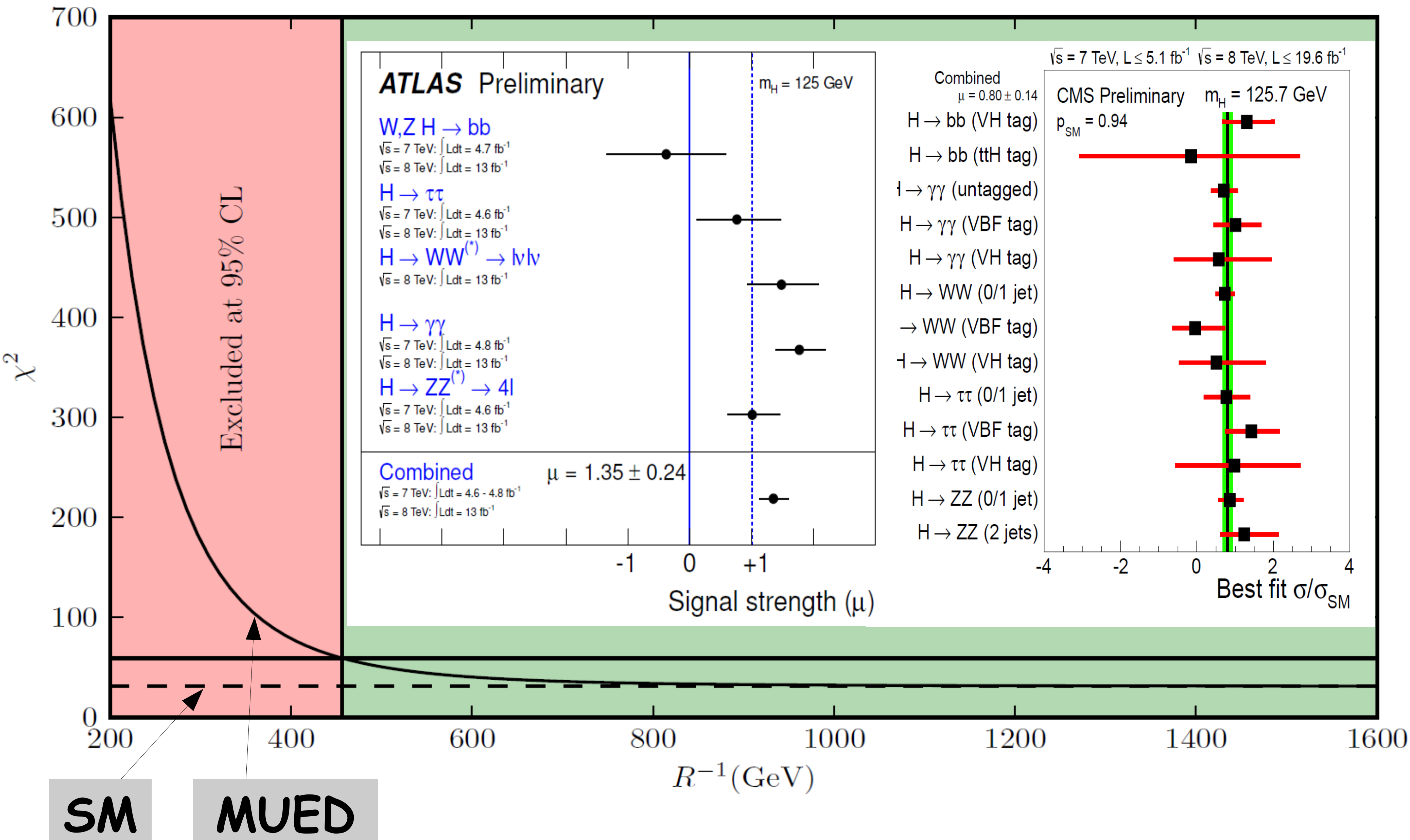
AB, Belanger, Brown, Kakizaki, Pukhov '12

The Status of MUED (with LHC@7 TeV Higgs data)

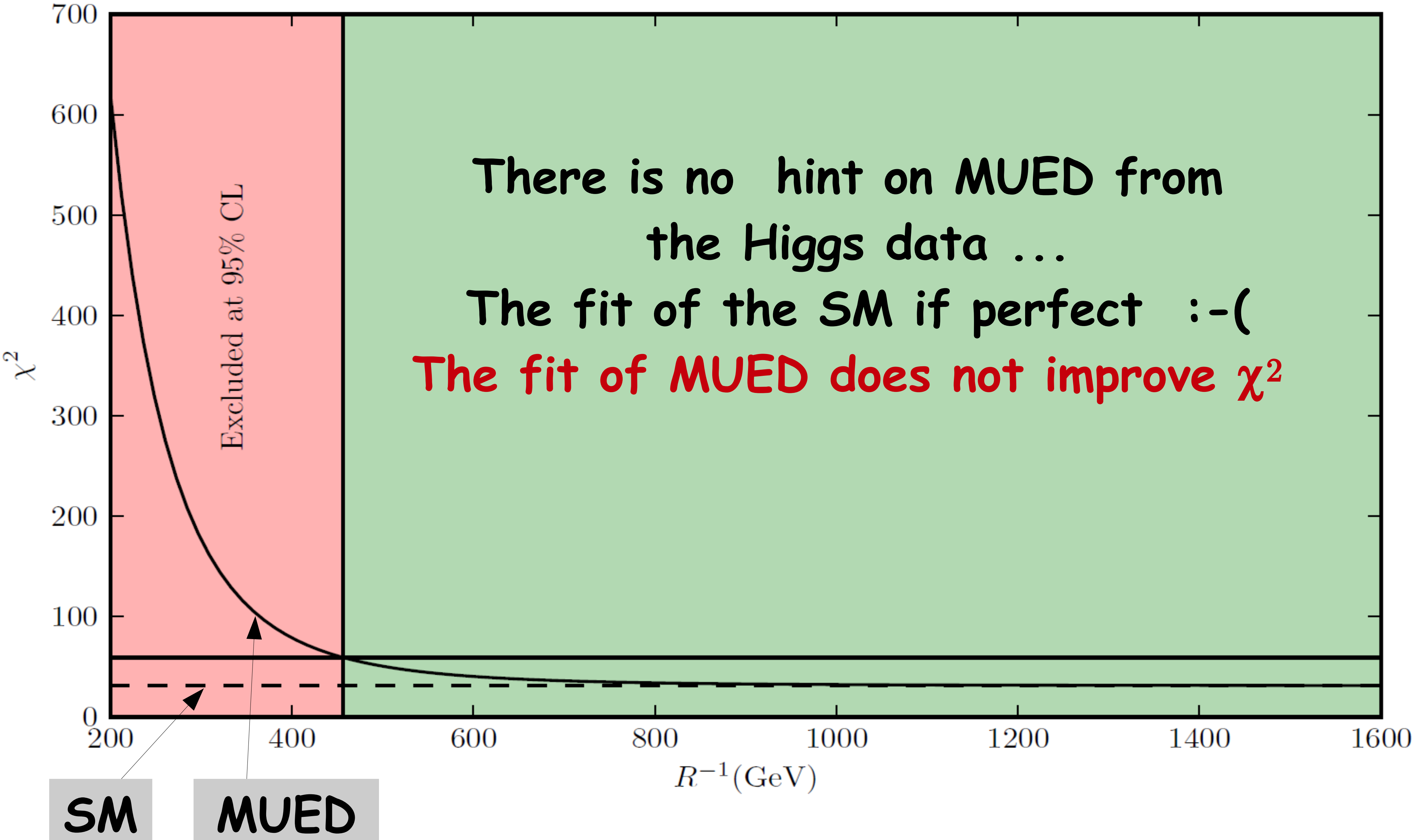


AB, Belanger, Brown, Kakizaki, Pukhov '12

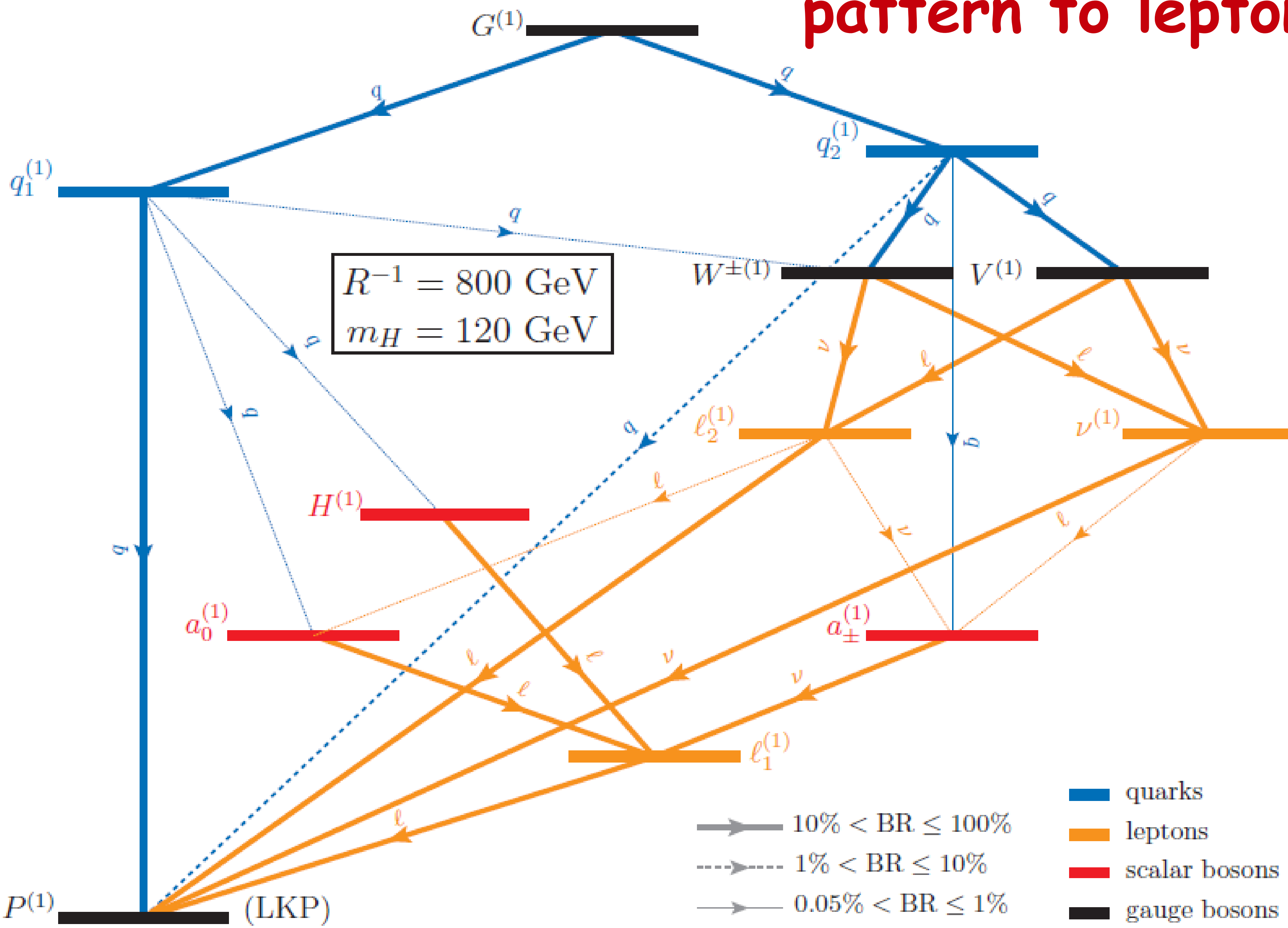
Data Fit with MUED vs SM



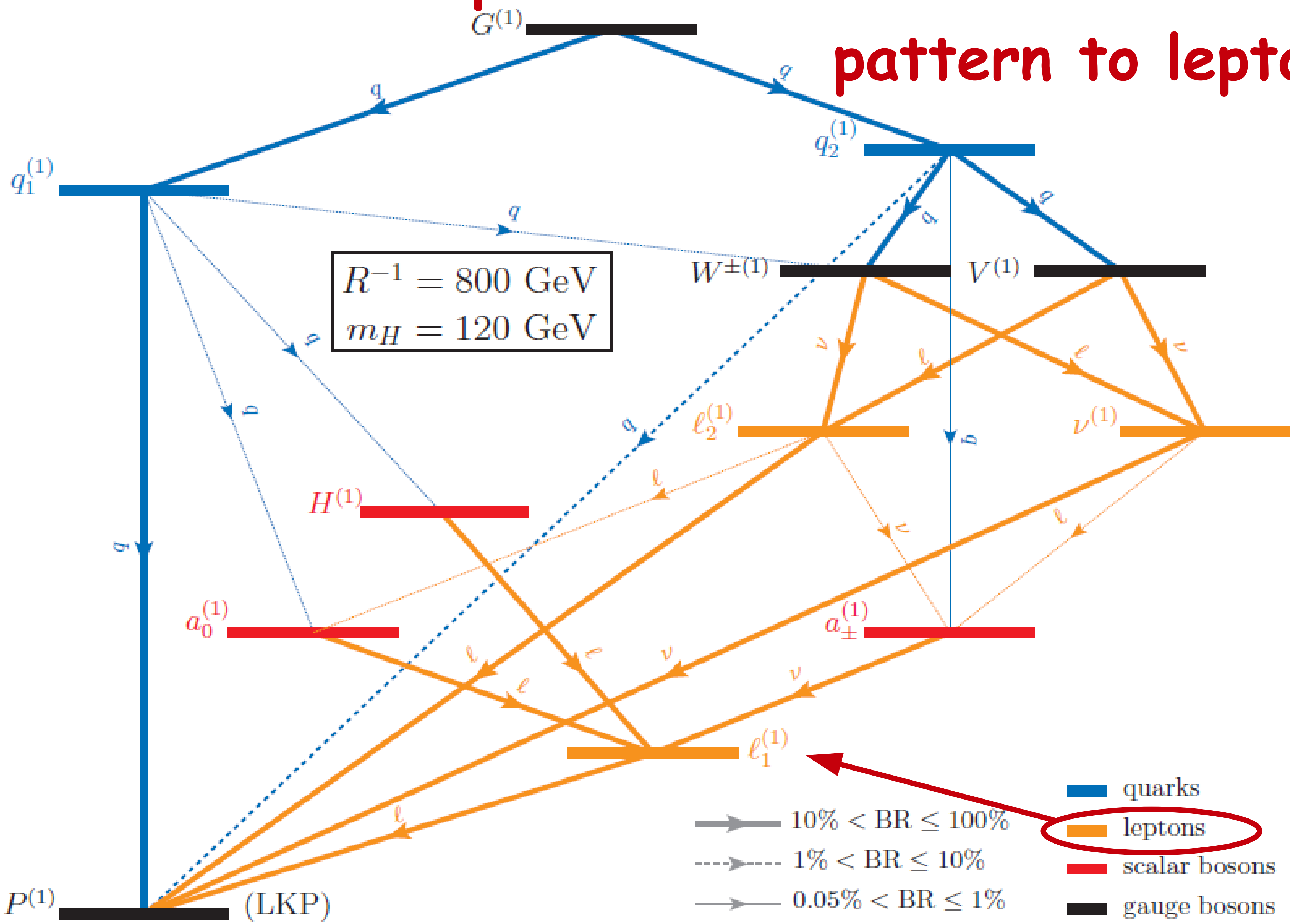
Data Fit with MUED vs SM



mUED: the mass spectrum defines dominant decay pattern to leptons!!!



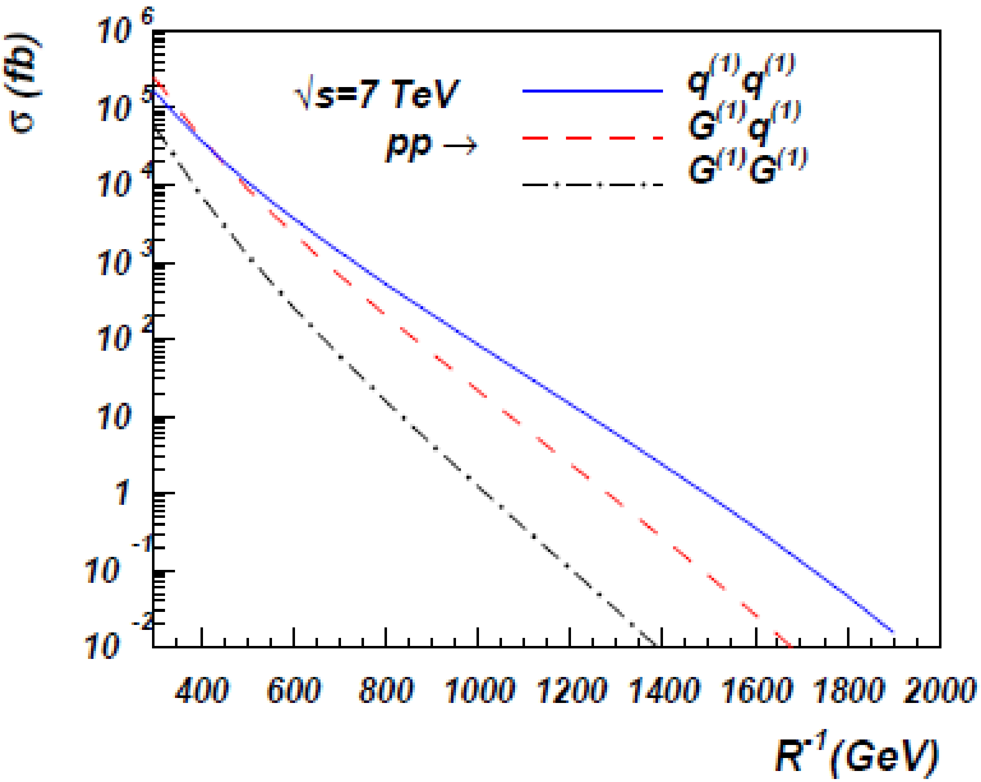
mUED: the mass spectrum defines dominant decay pattern to leptons!!!

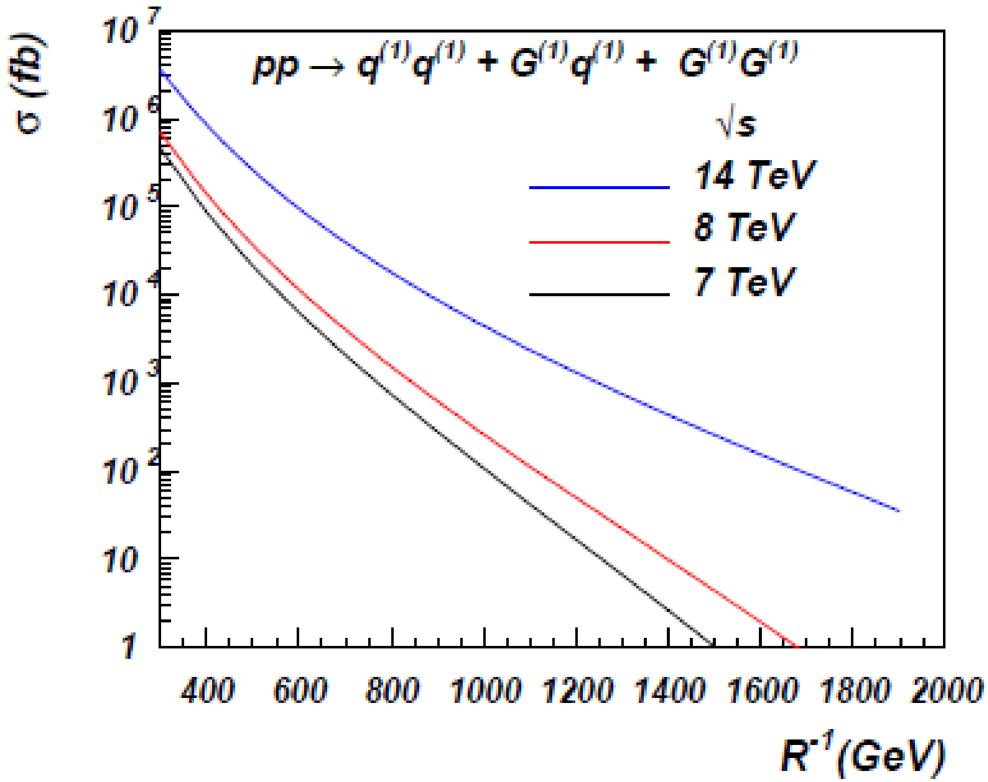


Can SUSY have this pattern?! $M_{G^{(1)}} > M_{q^{(1)}} > M_{W^{(1)}}, M_{Z^{(1)}} > M_{l^{(1)}} > M_{\gamma^{(1)}}$

mUED collider phenomenology with leptons

AB, Brown, Moreno, Papineau'12





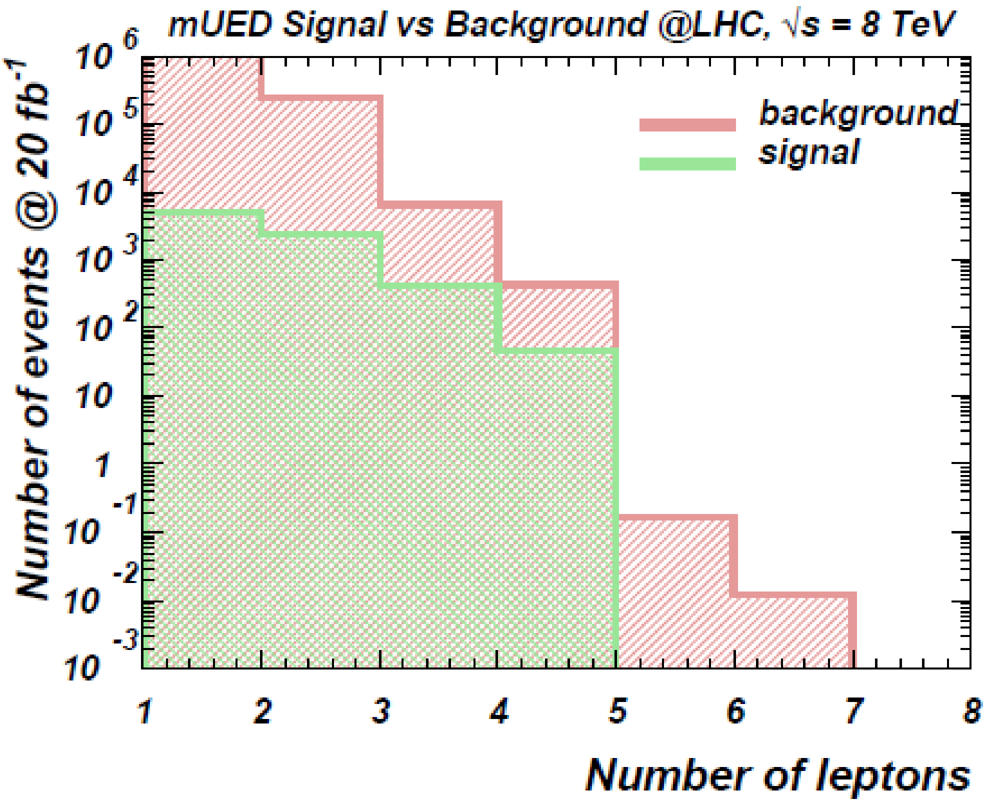
Q^1 Q^1 production rate is the highest

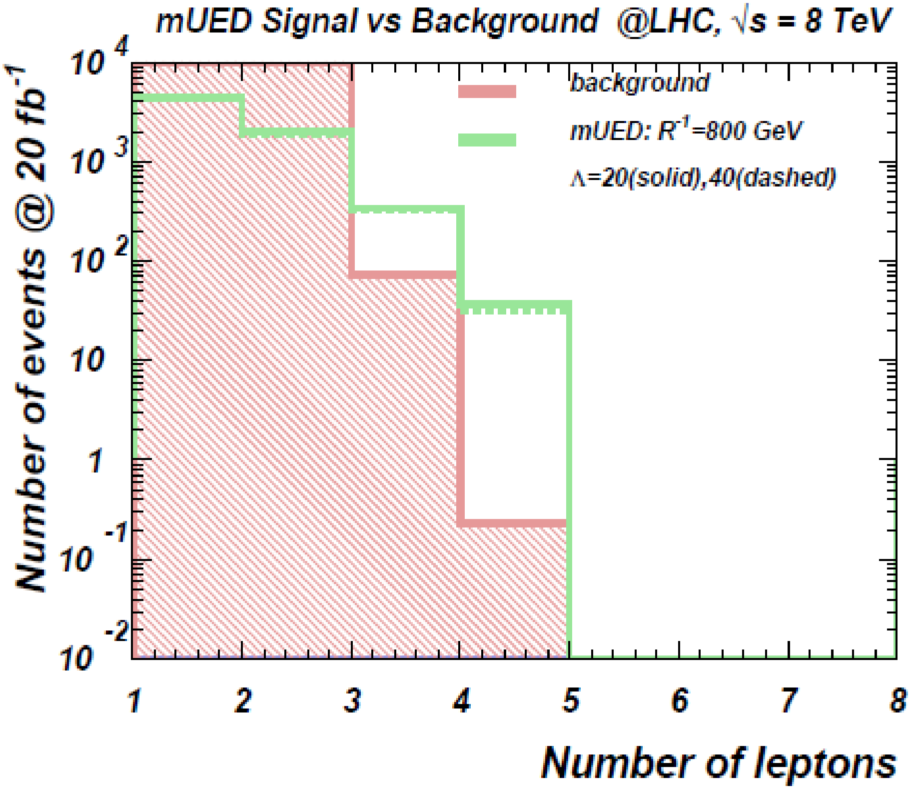
mUED collider phenomenology with leptons

Lepton multiplicity:

AB, Brown, Moreno, Papineau'12

Signal vs BG before (left) and after(right) selection cuts





$P_T^{\ell_1} > 20$ GeV, $P_T^{\ell}(\text{all}) > 10$ GeV, $|\eta_\ell| < 2.5$, $\Delta R_{\ell j} = \sqrt{\Delta\phi_{\ell j}^2 + \Delta\eta_{\ell j}^2} > 0.5$

$|m_Z - M_{\ell\bar{\ell}}| > 10\,\text{GeV}$

$\not{P}_T > 50\,\text{GeV}$

$P_T^{\ell_1} < 100\,\text{GeV}$; $P_T^{\ell_2} < 70\,\text{GeV}$; $P_T^{\ell_3} < 50\,\text{GeV}$

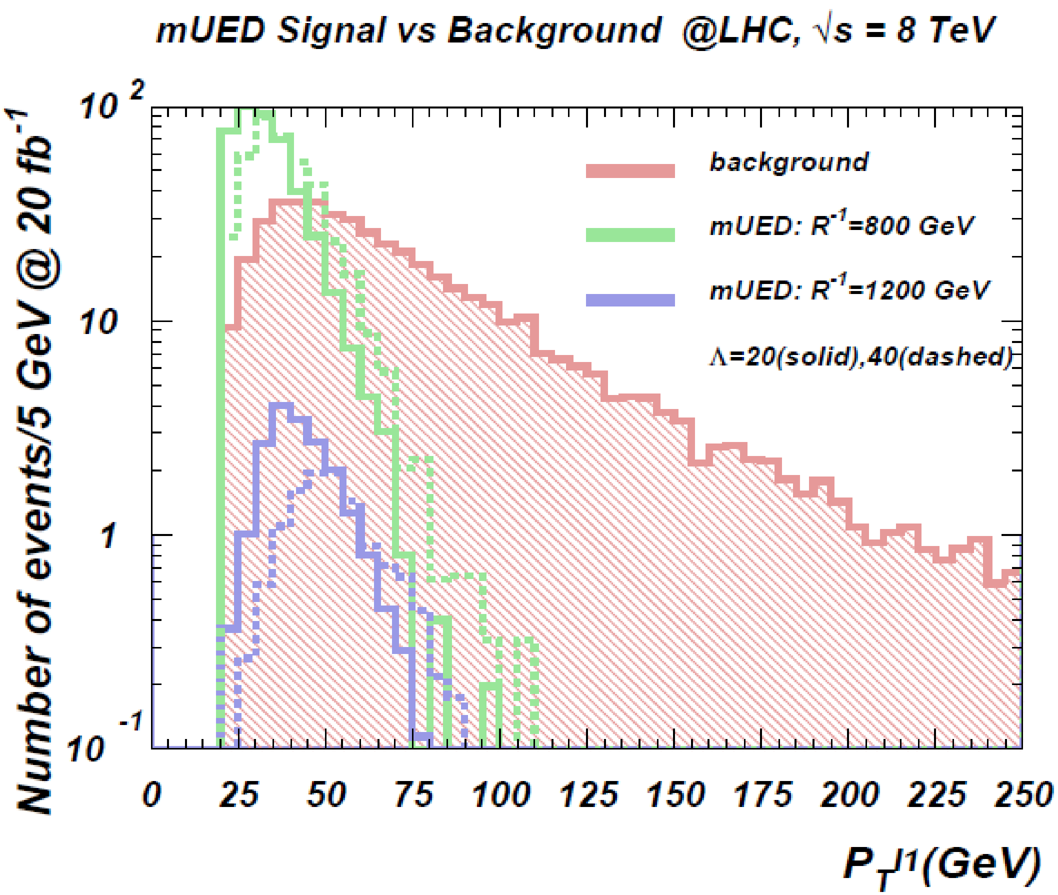
$M_{\text{eff}} > R^{-1}/5 \qquad M_{\text{eff}} = \not{P}_T + \sum_{\ell,j} P_T$

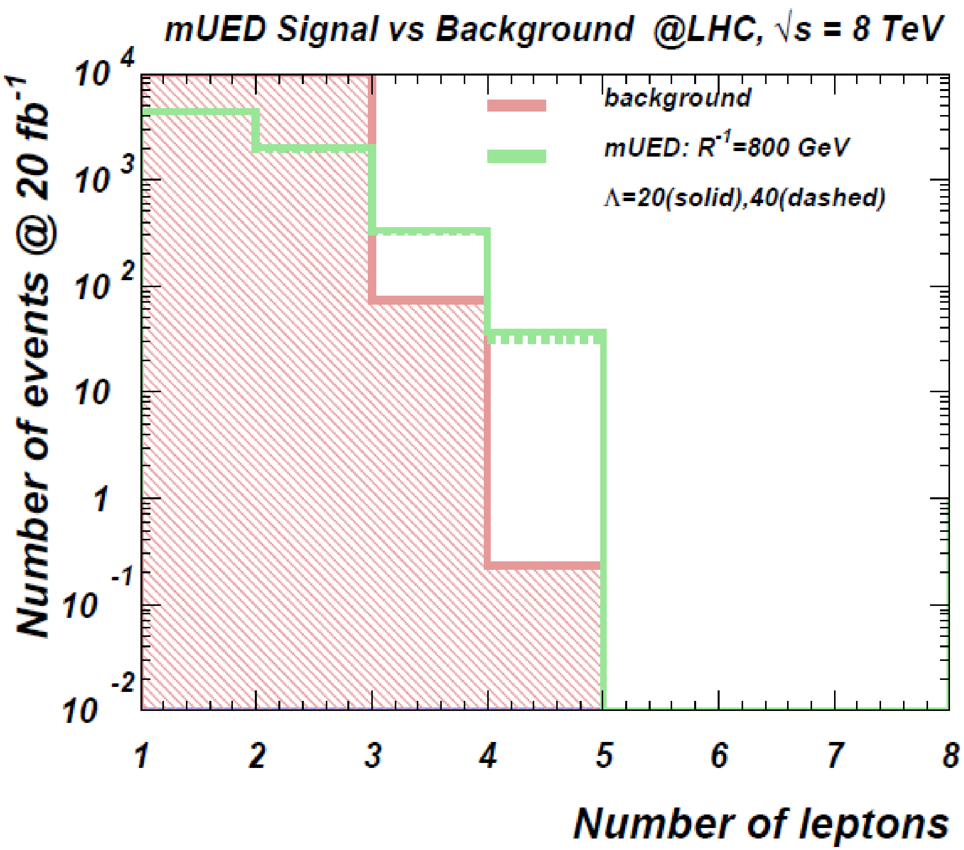
Selection cuts

mUED collider phenomenology with leptons

AB, Brown, Moreno, Papineau'12

Cut on the maximum P_T of the lepton is important!

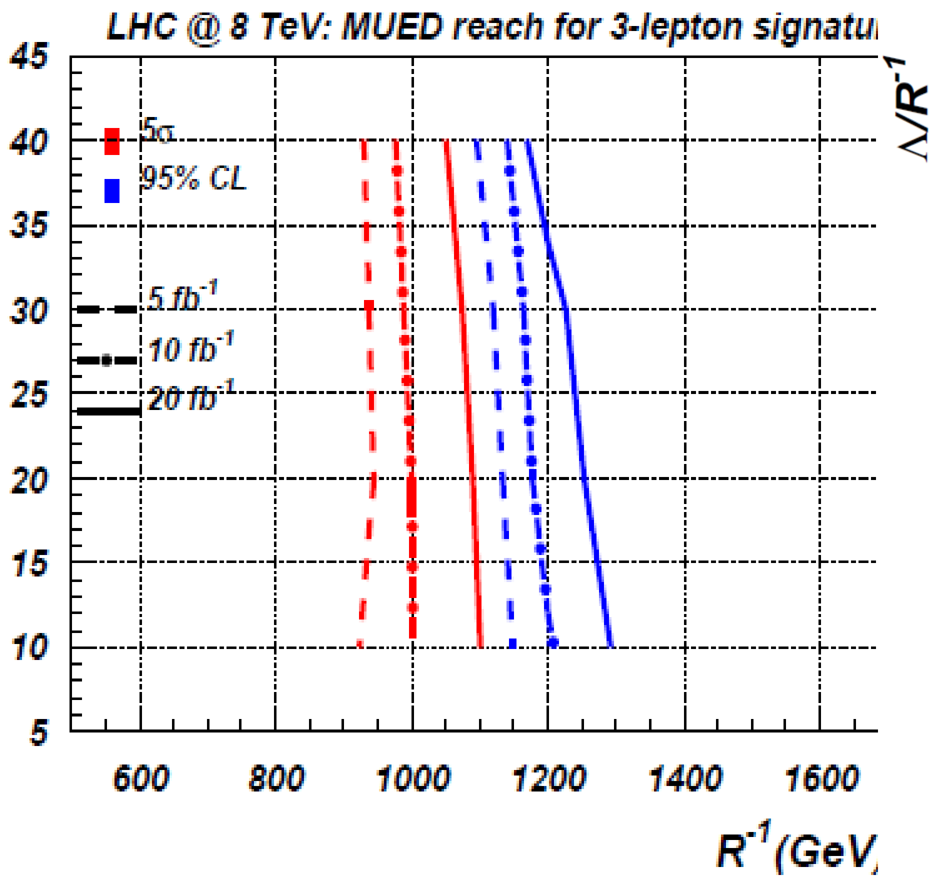


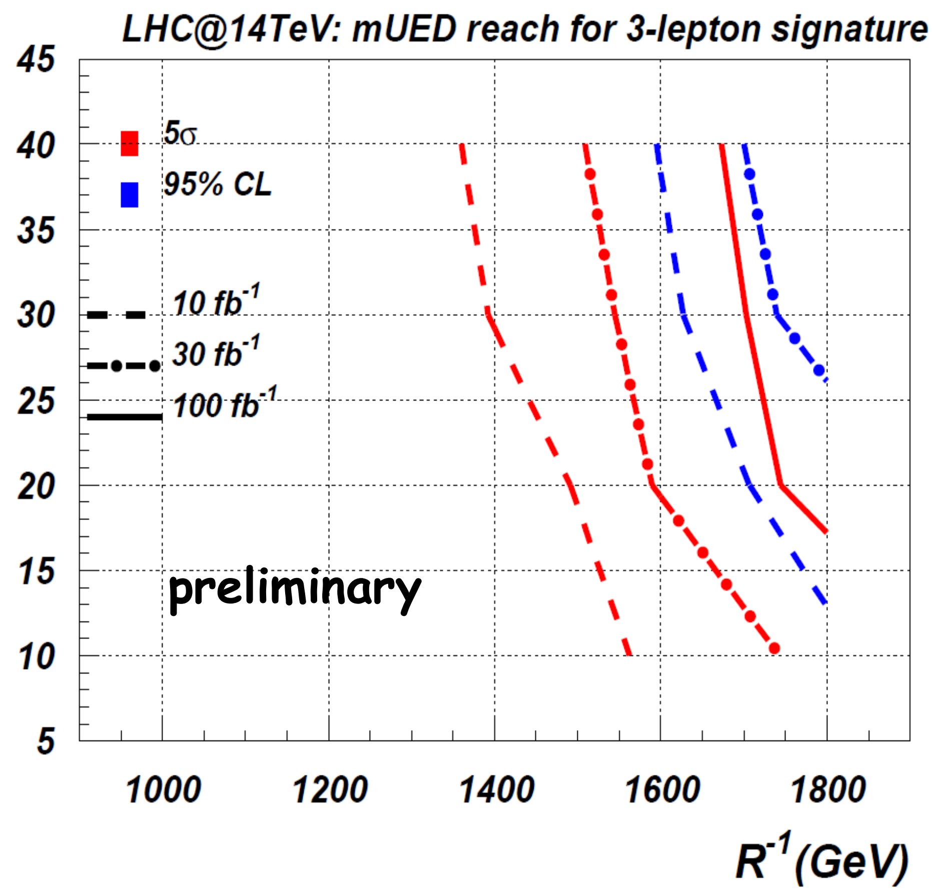


3-lepton signature has the highest significance in comparison with 4-lepton signature

mUED collider phenomenology with leptons

AB, Brown, Moreno, Papineau'12





- Small mass gap (as compared to MSSM) – much lower missing PT
- Quite a few PHENO papers, but there are no experimental limits!!!

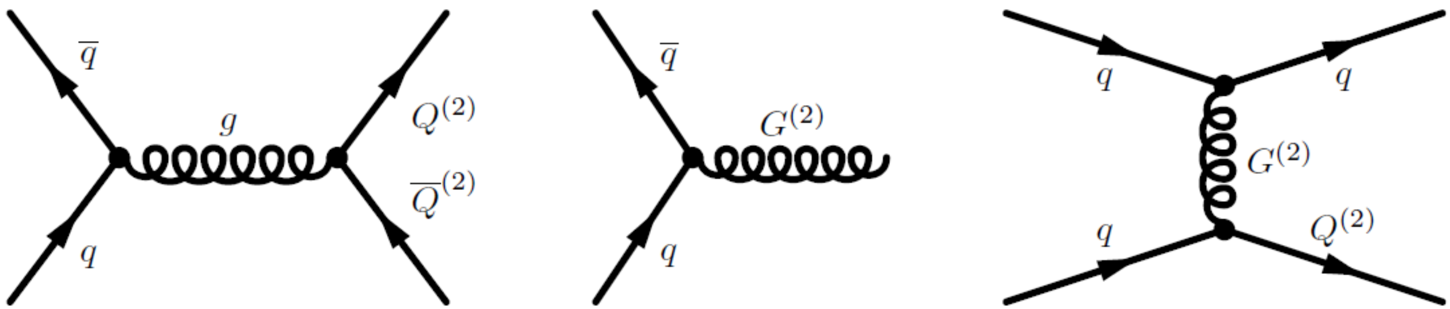
  the projected limit from this study: R^{-1} > 1.2—1.3 TeV
- 3-lepton signature – is very promising:

  LHC@14 will eventually discover or close MUED!

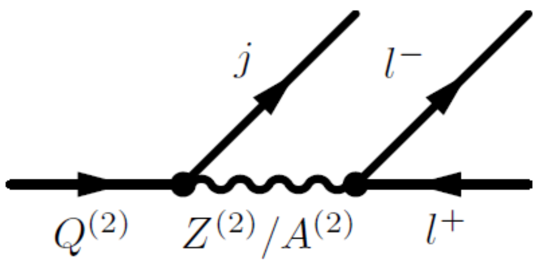
Constraints from di-lepton searches

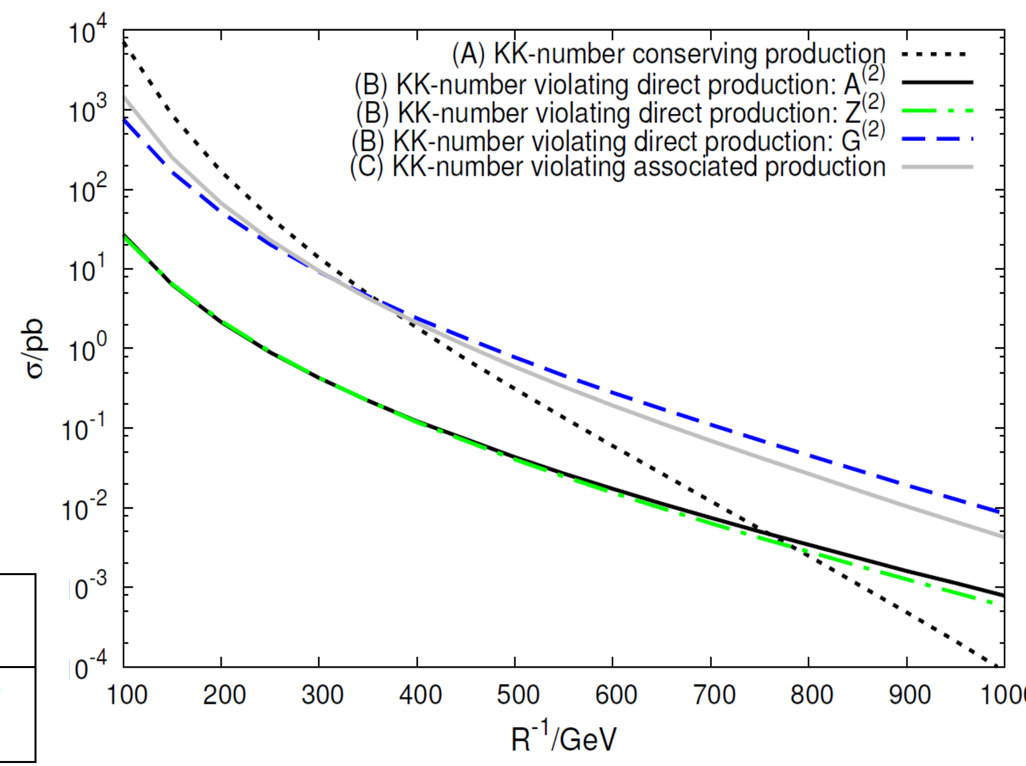
Edelhäuser,Flacke,Kramer, '13

- **production**



- **decay**



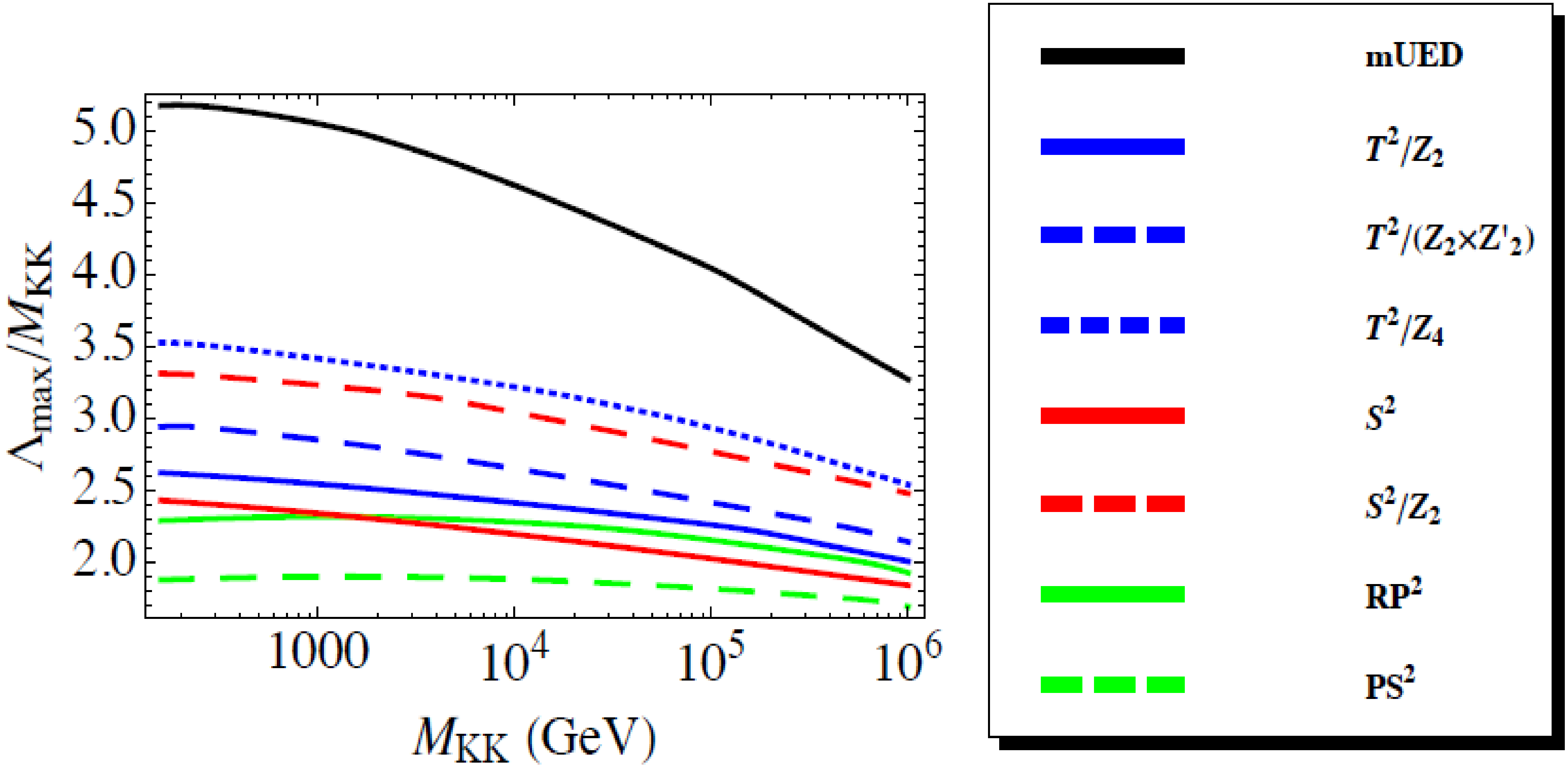


- **Lower bounds**

ΛR	5	10	20	50
$R^{-1}/[\,\mathrm{GeV}]$	623	613	601	627

Vacuum stability bounds

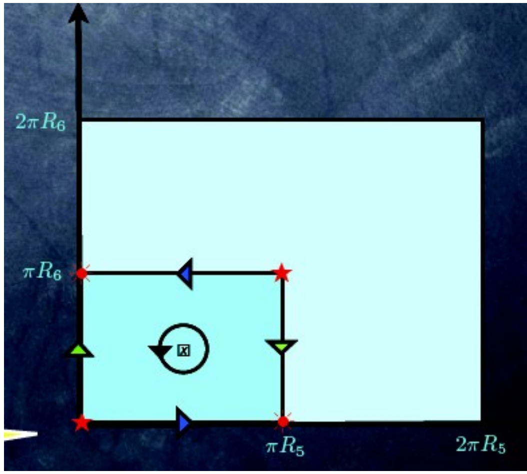
Kakuda, Nishiwaki, Oda, Watanabe, '13



Model	mUED	T^2/Z_2	$T^2/(Z_2\times Z_2')$	T^2/Z_4	S^2	S^2/Z_2	RP^2	PS
$\tilde{\Lambda}_{\max}$	5.0	2.5	2.9	3.4	2.3	3.2	2.3	1.9

6D UED
(Dark Matter in a twisted bottle)

Arbey,Cacciapaglia,Deandrea,Kubik'12



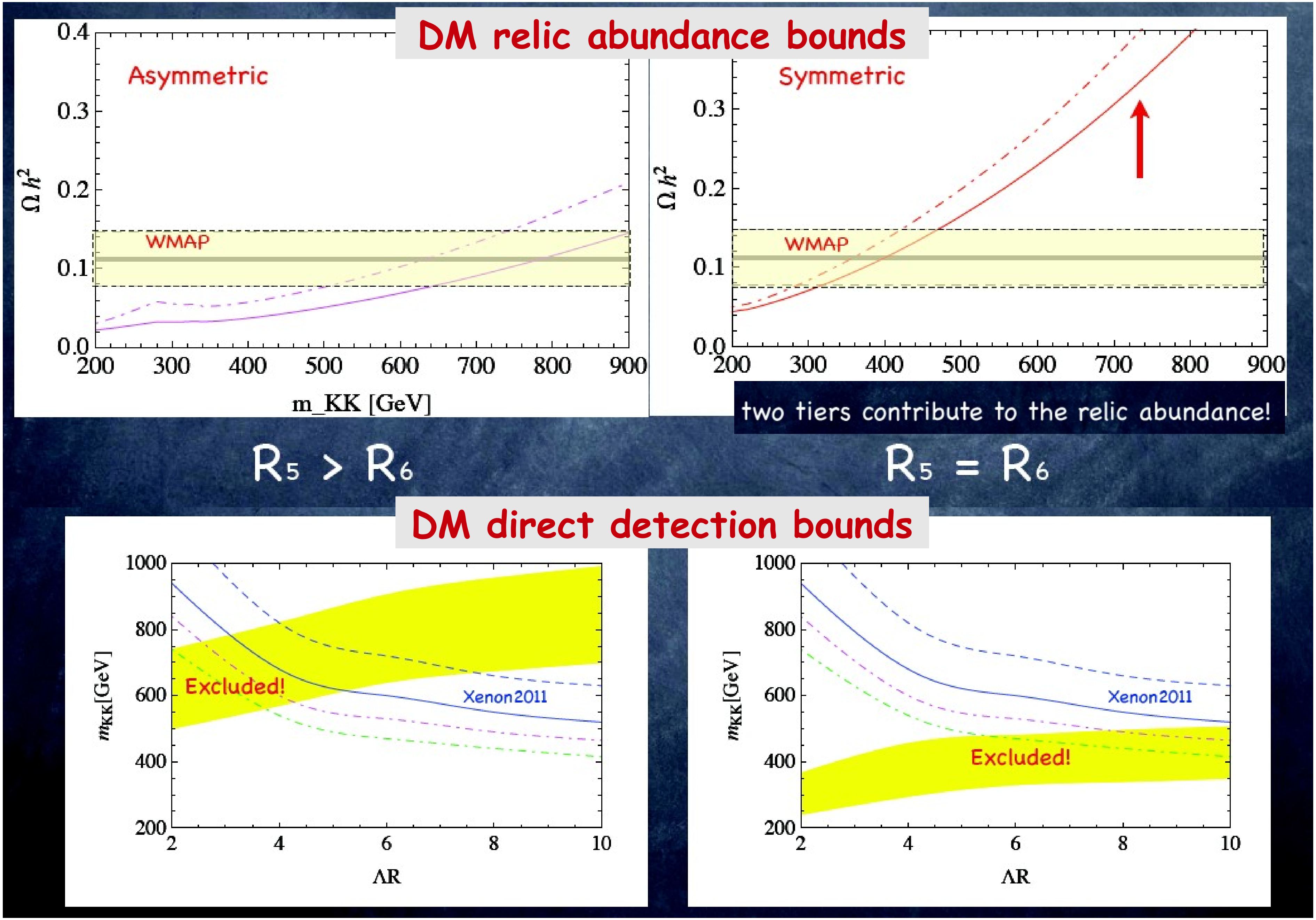
Spectrum of the SM

	+	−	+	+	−
$p_{KK} = (-1)^{k+l}$	(0,0) m = 0	(1,0) & (0,1) m = 1	(1,1) m = 1.41	(2,0) & (0,2) m = 2	(2,1) & (1,2) m = 2.24
Gauge bosons G, A, Z, W	✓		✓	✓	✓
Gauge scalars G, A, Z, W		✓	✓		✓
Higgs boson(s)	✓		✓	✓	✓
Fermions	✓	✓	✓ (x2)	✓	✓ (x2)

DM candidate here!

6D UED DM bounds

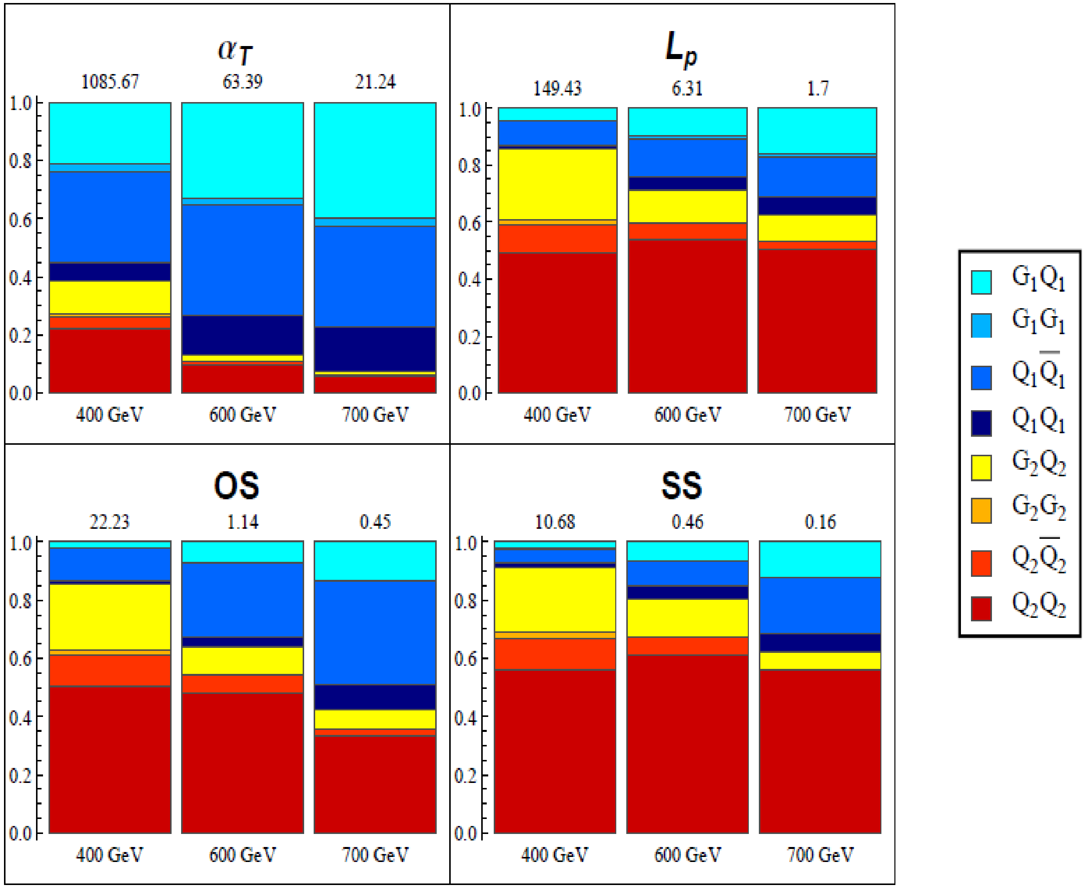
Arbey,Cacciapaglia,Deandrea,Kubik'12



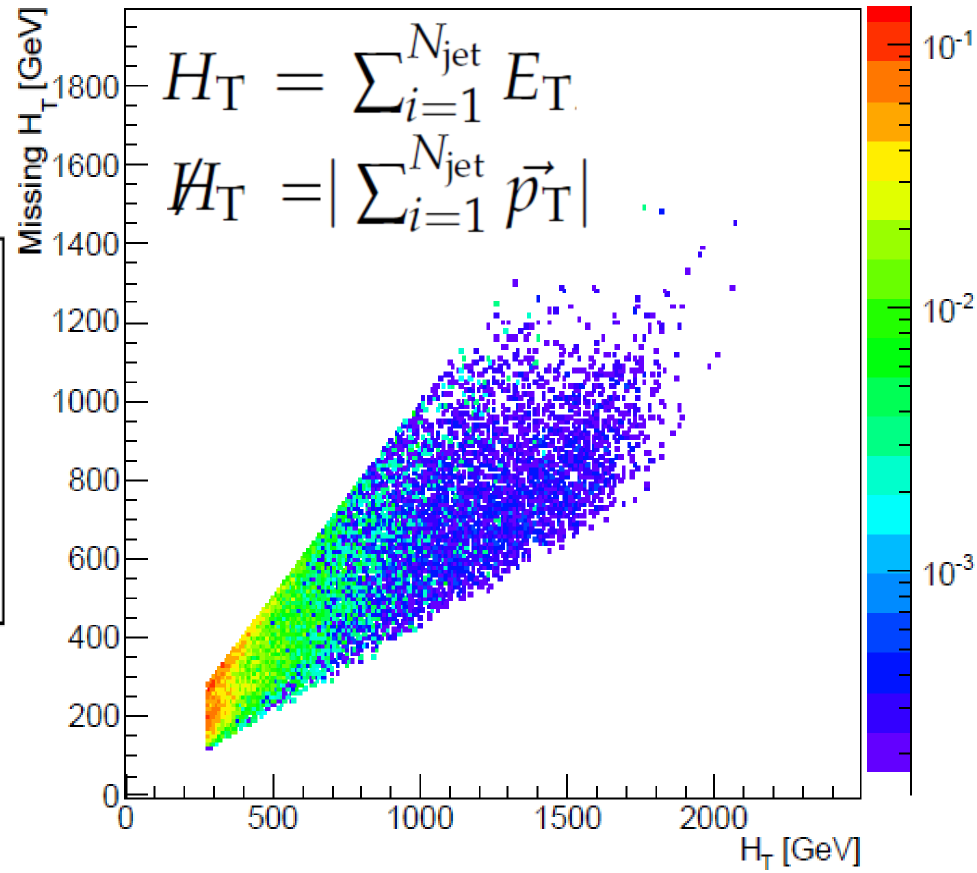
6D UED LHC bounds

Cacciapaglia, Deandrea, Ellis, Marrouche, Panizzi '13

"composition " of signal signatures



MHT-HT analysis plane



$$\alpha_T = \frac{p_T(j_2)}{M_{jj}} = \frac{p_T(j_2)}{\sqrt{H_T^2 - MH_T^2}}$$

Exclusion limit: M_{KK}>600-700 GeV
Almost all parameter space is excluded

Conclusions

- UED are limited from above by DM relic abundance and from below by the LHC searches
  LHC and DM search experiments provide an important test: LHC@14 TeV will discover or exclude the complete parameter space for 5 & 6D UED (no boundary localised terms).

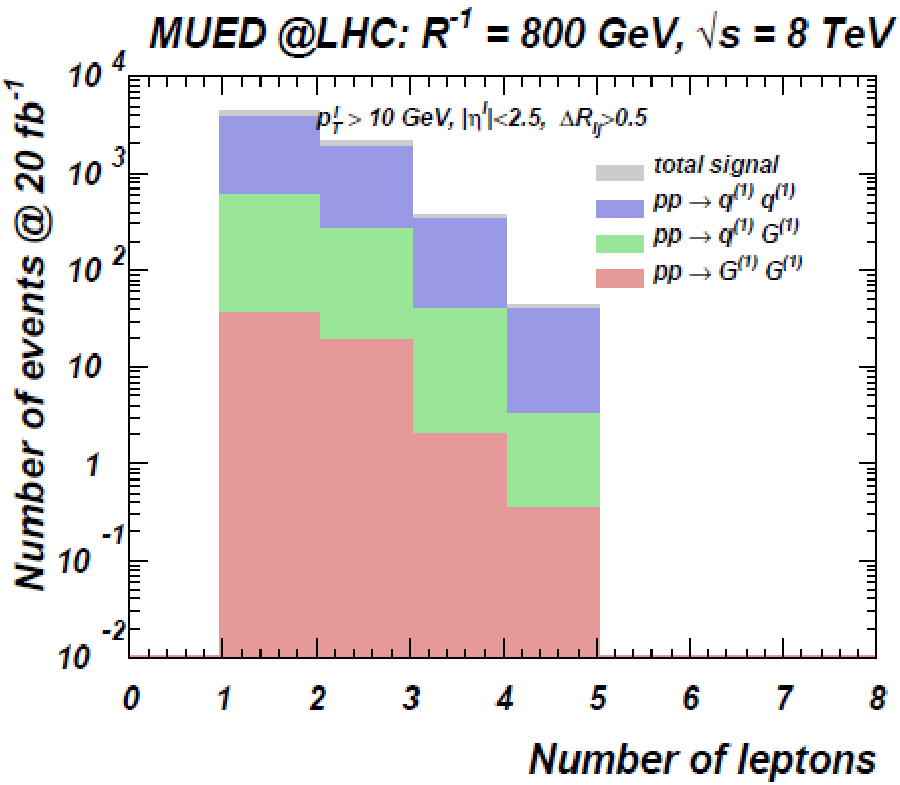
- There are still no dedicated experimental searches for MUED signals which could be in data! It is time to check them!
  3-lepton signal is very promising for MUED at the LHC.

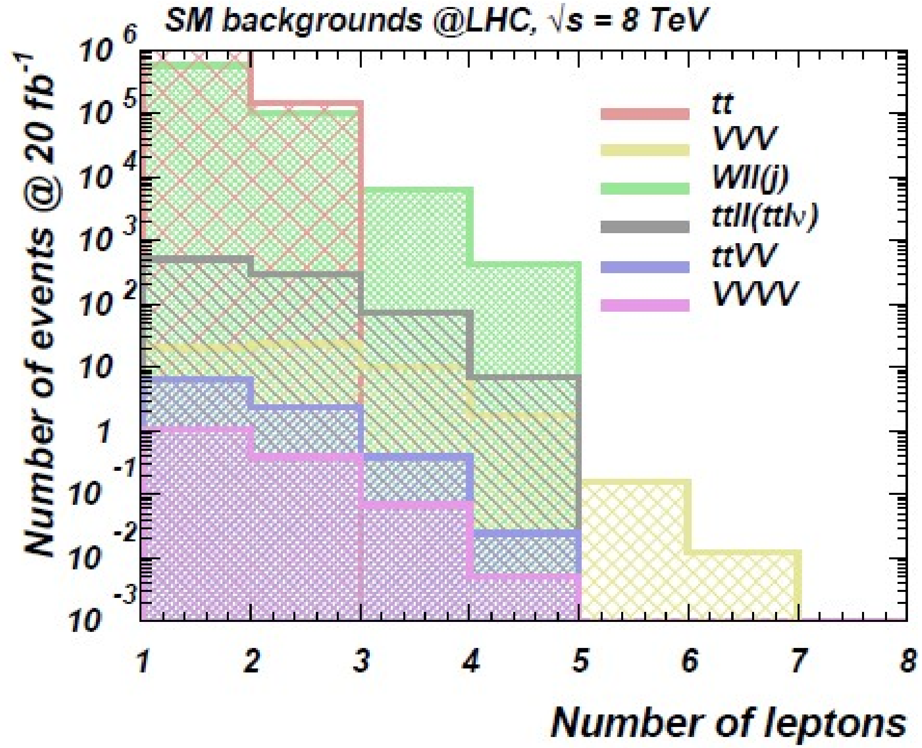
- Consistent MUED with EWSB and loop-corrections is implemented into LanHEP and publicly available at HEPMDB [CalcHEP and UFO(Madgraph5) formats are available].
  It is ready to be used by experimentalists and theorists!

THANK YOU !

mUED collider phenomenology with leptons

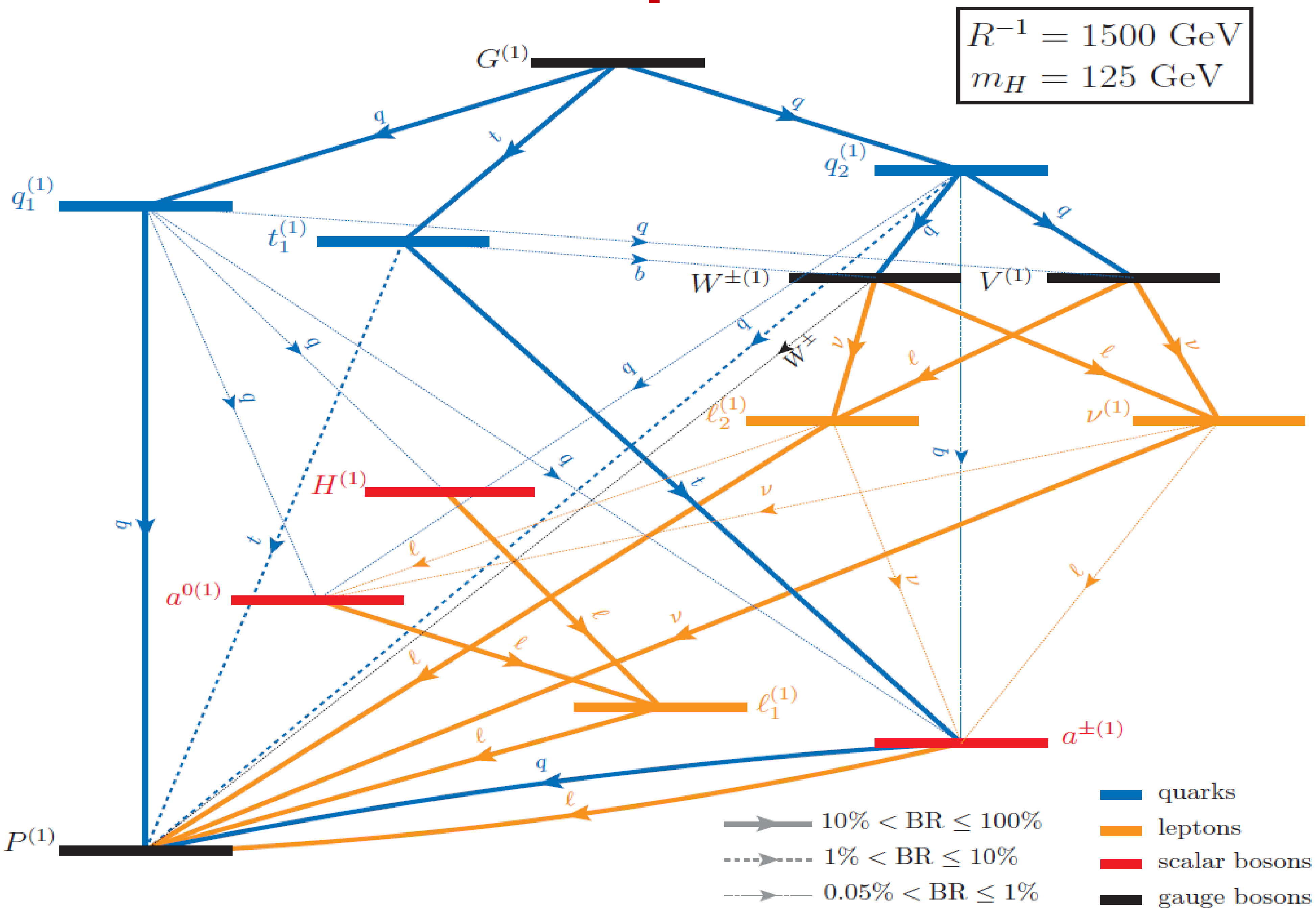
AB, Brown, Moreno, Papineau'12





Signal vs BG in lepton multiplicity

Backup slides



MUED; Direct DM detection rates

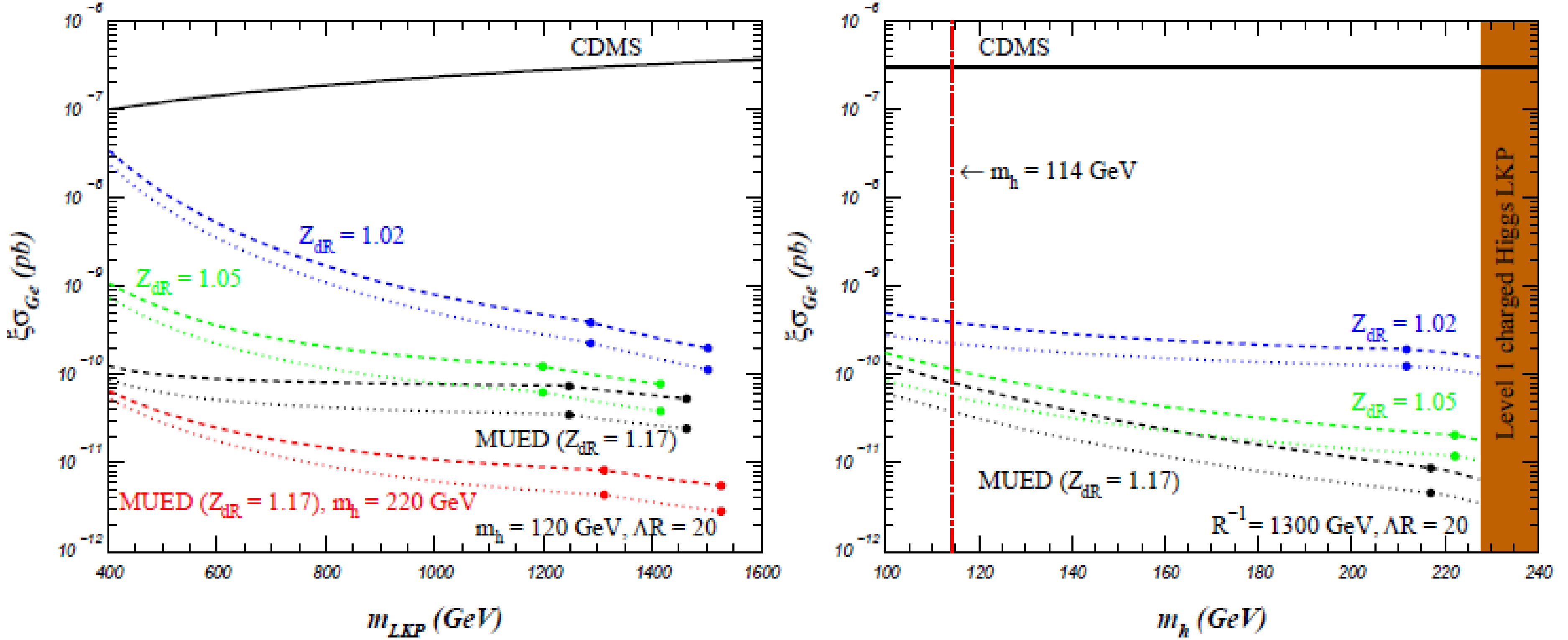


Figure 5: Rescaled LKP-nucleon cross section on Ge^{76} vs m_{LKP} for $m_h = 120$ GeV, $\Lambda R = 20$ and 2 sets of quark coefficients ($(\sigma_{\pi N}, \sigma_0) = (56$ MeV, 35 MeV$)$ (dash) or (47 MeV, 42.9 MeV) (dot)) and for different values of the mass splitting between the KK singlet d-quarks and the LKP including the MUED case (left panel). The MUED results for $m_h = 220$ GeV are also shown. In each line the region between the blobs is consistent with the 3σ WMAP range. Rescaled LKP-nucleon cross section on Ge^{76} vs m_h for $R^{-1} = 1300$ GeV, $\Lambda R = 20$ (right). In each line the region left of the blob is consistent with the 3σ WMAP range.

The spectrum

Because of the loop-corrections, the B and W^3 do not mix with the Weinberg angle

$$\begin{pmatrix} Z_B \frac{n^2}{R^2} + \frac{1}{4} g_1^2 v^2 & -\frac{1}{4} g_1 g_2 v^2 \\ -\frac{1}{4} g_1 g_2 v^2 & Z_W \frac{n^2}{R^2} + \frac{1}{4} g_2^2 v^2 \end{pmatrix}$$

Consequently, the mass eigenstates are not the KK photon or KK Z-boson. We call them $P^{(n)}$ and $Q^{(n)}$.

There is a tree-level $H^{(k)} P^{(l)} P^{(m)}$ vertex.

Associated with the KK vectors $A_\mu^{(n)}$, the Goldstone bosons are combinations of the fifth components $A_5^{(n)}$ and the Higgses $\chi^{(n)}$.

Finally, there are two KK fermions per SM one, and they mix with angles related to the Z_i .

The spectrum

Spin	Name	Particle	Mass
1	Gluon	$G^{(n)}$	$m^2_{G(n)} = Z_G \frac{n^2}{R^2}$
	P boson	$P^{(n)}$	$m^2_{P(n)}$
	Q boson	$Q^{(n)}$	$m^2_{Q(n)}$
	W boson	$W^{\pm\,(n)}$	$m^2_{W(n)} = Z_W \frac{n^2}{R^2} + M_W^2$
1/2	Neutrinos	$\nu_{i\,L}^{(n)}$	$m_{\nu_i(n)} = Z_{eL} \frac{n}{R}$
	Charged leptons 1	$e_1^{(n)}, \mu_1^{(n)}, \tau_1^{(n)}$	$m_{e\,1(n)}, m_{\mu\,1(n)}, m_{\tau\,1(n)}$
	Charged leptons 2	$e_2^{(n)}, \mu_2^{(n)}, \tau_2^{(n)}$	$m_{e\,2(n)}, m_{\mu\,2(n)}, m_{\tau\,2(n)}$
	Up-quarks 1	$u_1^{(n)}, c_1^{(n)}, t_1^{(n)}$	$m_{u\,1(n)}, m_{c\,1(n)}, m_{t\,1(n)}$
	Up-quarks 2	$u_2^{(n)}, c_2^{(n)}, t_2^{(n)}$	$m_{u\,2(n)}, m_{c\,2(n)}, m_{t\,2(n)}$
	Down-quarks 1	$d_1^{(n)}, s_1^{(n)}, b_1^{(n)}$	$m_{d\,1(n)}, m_{s\,1(n)}, m_{b\,1(n)}$
	Down-quarks 2	$d_2^{(n)}, s_2^{(n)}, b_2^{(n)}$	$m_{d\,2(n)}, m_{s\,2(n)}, m_{b\,2(n)}$
0	Higgs scalar	$h^{(n)}$	$m^2_{h(n)} = Z_H \frac{n^2}{R^2}$
	neutral scalar	$a_0^{(n)}$	$m^2_{a0(n)} = Z_H \left[\frac{n}{R} + \frac{v^2}{4}\left(\frac{g_1^2}{Z_B} + \frac{g_2^2}{Z_W}\right)\right]$
	charged scalar	$a_\pm^{(n)}$	$m^2_{a(n)} = \frac{Z_H}{Z_W}\left[Z_W \frac{n^2}{R^2} + M_W^2\right]$