# Probing the Universal Extra Dimension at the LHC

Jesús M. Moreno

Instituto de Física Teórica UAM/CSIC, Madrid

*based on work done in collaboration with A. Belyaev, M. Brown, and C. Papineau*

Planck 2012, Warsaw May 2012

# Outline

- Introduction
- The model
- Spectrum and radiative corrections
- Constraints
- Implementation
- MUED at the LHC
- Conclusion

# Introduction

## Motivation

- Many beyond the SM theories rely on the existence of Extra Dimensions (ED)

  (eg, superstring theory, the best candidate to unify gravity & gauge interactions, is only consistent in 10 D space-time)

- The presence of ED could have an impact on scales $\ll M_{Planck}$

## ⇒ New perspectives to address issues such as

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

# Introduction

## The underlying physics will depend on

- **Size and shape** of Extra Dimensions

  Compact (circle, tori ... ), ADD, warped (eg Randall Sundrum)

  Large Volume, etc

- The existence of **space-time subspaces** in which the different fields propagate

  (motivated by D-branes)

- The presence of **background fields**

  (e.g. fluxes)

## Let us concentrate on the size:

- Although present data constraint them, they could be **as large as** $\mathcal{O}$ **(1 TeV)$^{-1}$**

  ✔ In this case they would be accessible at the LHC

  ✔ Such models could be relevant for DM purposes (WIMP ~ $\mathcal{O}$ (1 TeV) )

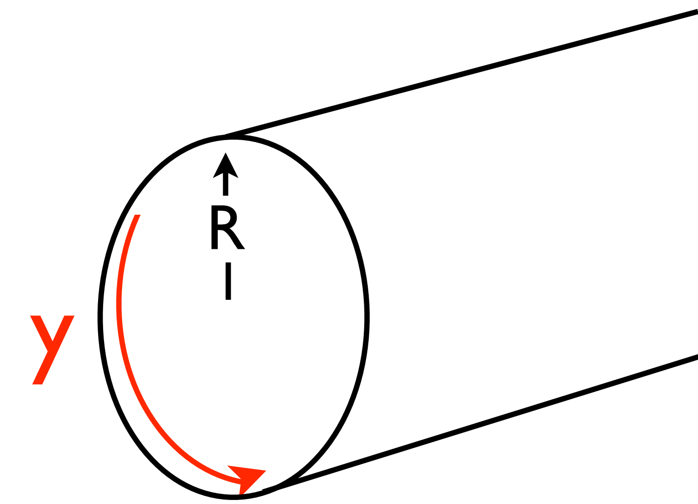
# The model

## Simplest one:

### **M**inimal **U**niversal **E**xtra **D**imension scenario

- Space-time:
  flat 4D x one single extra dimension compactified
  on a circle of radius R

*Appelquist, Cheng, Dobrescu 2001*



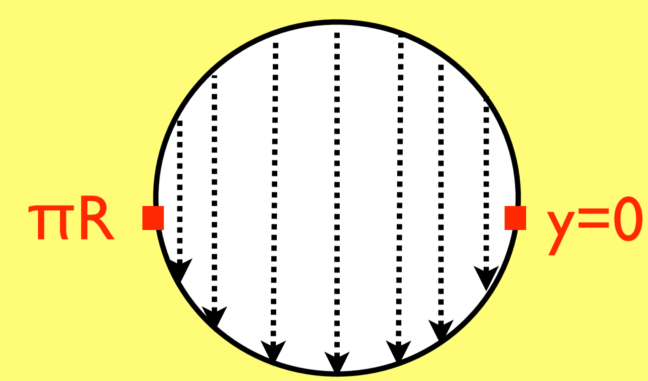

$S^1 \times \mathcal{M}_4$

- The SM particles are promoted to 5D fields that propagate in the whole space-time

- Gauge couplings are not dimensionless:
  ⇒ non-renormalizable model
  ~ an effective 5D theory valid up to some cut-off Λ

- For small radius, R, it is reduced to an effective **4D** theory whose light spectrum **contains** the SM

- The **precise** SM is obtained by imposing a $\mathbf{Z_2}$ symmetry
  - $S^1 \to S^1/Z_2$
  - It **breaks** the **translational invariance** along y
  - 1/2 of the 4D fermions are projected out **allowing** for **chirality**

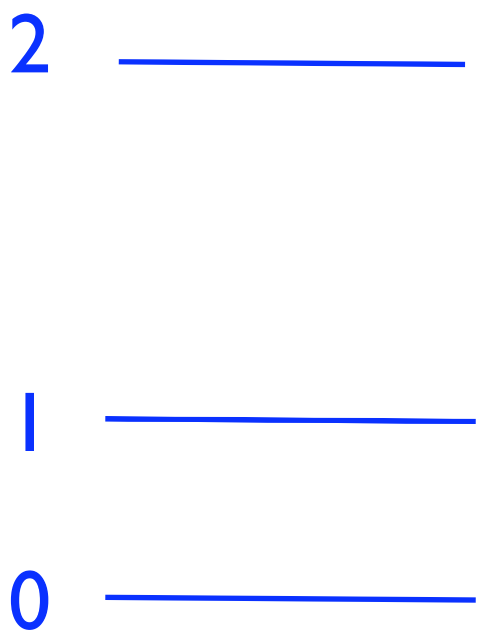



$S^1 \to S^1/Z_2$

# The model

## Spectrum

Kaluza Klein tower



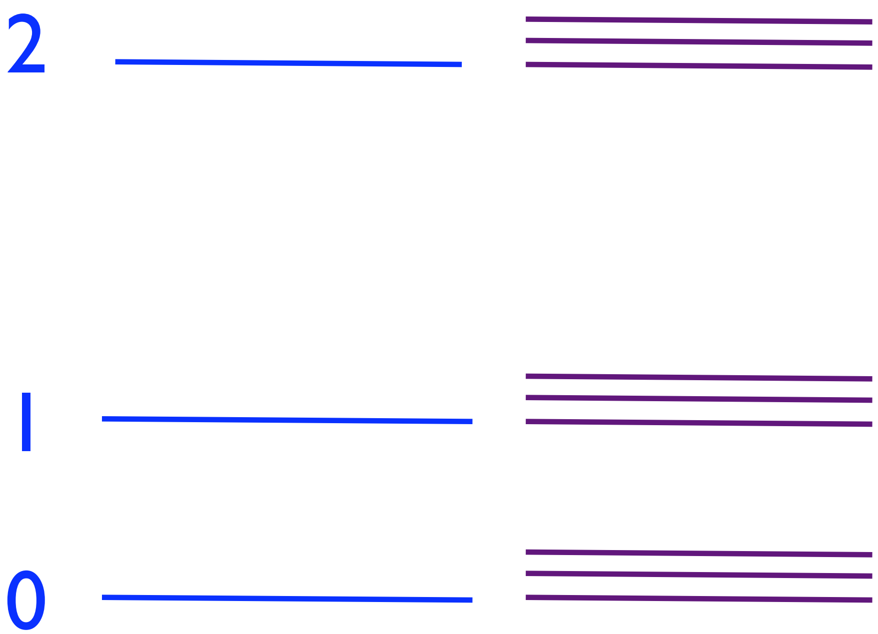

- 5D $\quad P_M P^M = 0 \qquad M = 1, 2, 3, 4, 5$
- 4D $\quad p_\mu p^\mu - \dfrac{n^2}{R^2} = 0 \qquad \mu = 1, 2, 3, 4$

$$m^2 = \frac{n^2}{R^2}$$

# The model

## Spectrum

Including <Φ>≠0



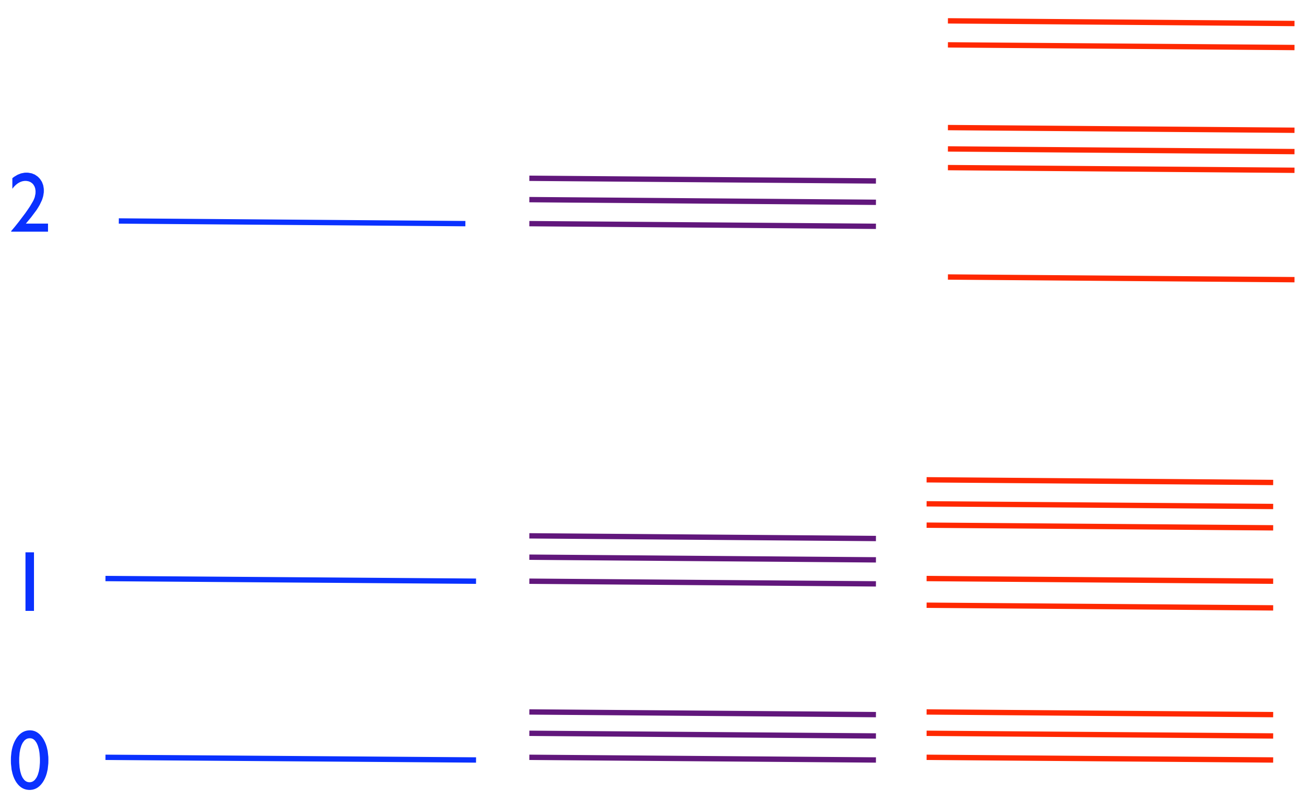

$$m^2 = \frac{n^2}{R^2}$$

$$m^2 = m_0^2 + \frac{n^2}{R^2}$$

$$m = m_0 + \frac{n}{R}$$

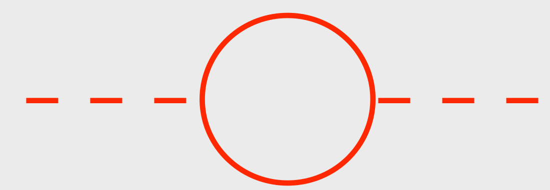
# The model

## Spectrum



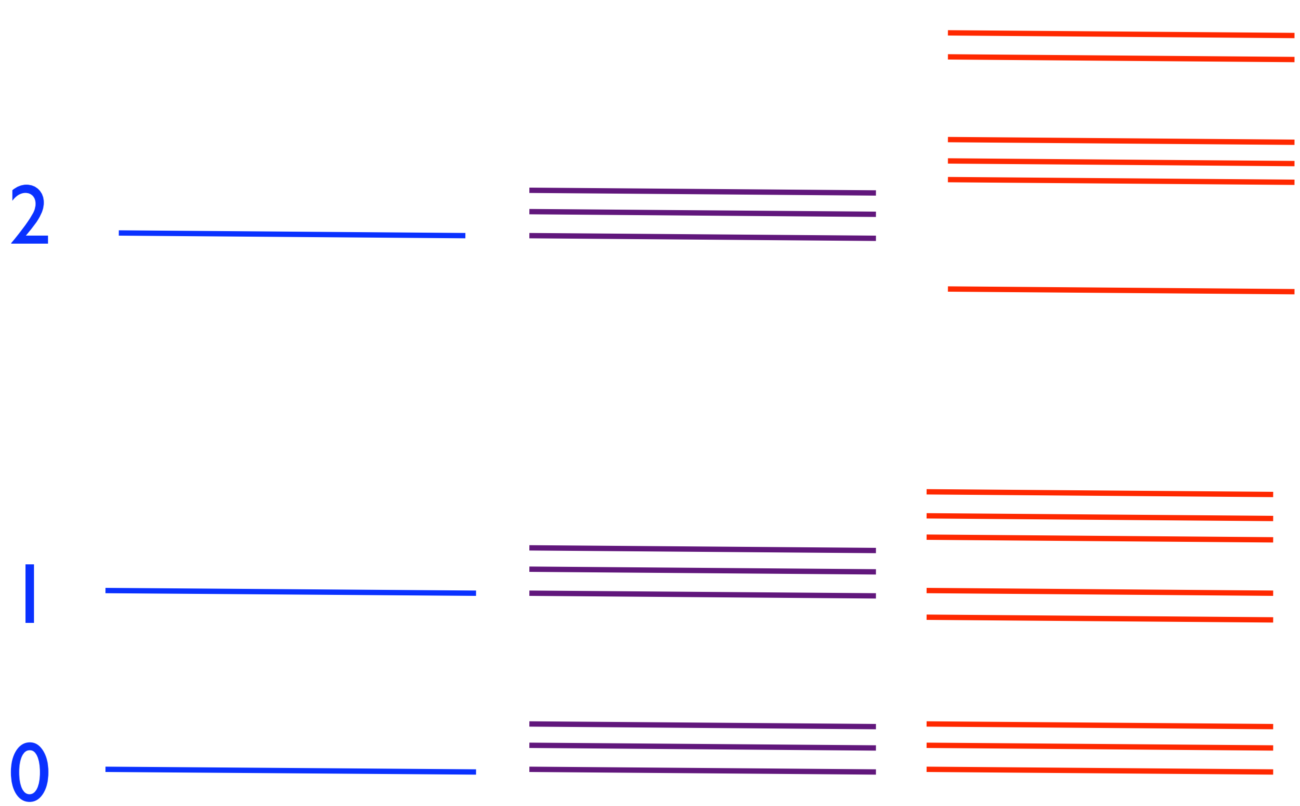

$m^2 = \frac{n^2}{R^2}$ $\qquad$ $m^2 = m_0^2 + \frac{n^2}{R^2}$ $\qquad$ $m^2 = m_0^2 + \frac{n^2}{R^2} + \Delta_{loop\ corr}$

Including quantum corrections



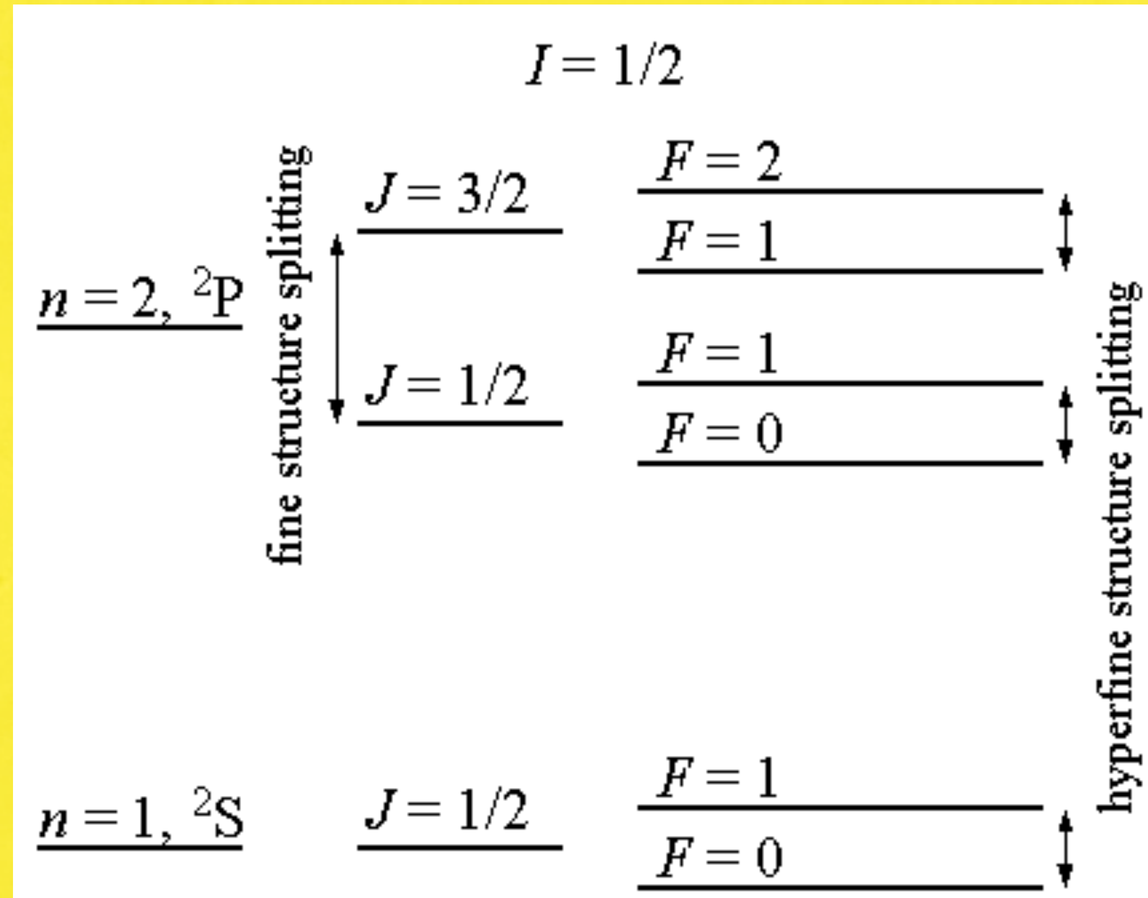
# The model

## Spectrum



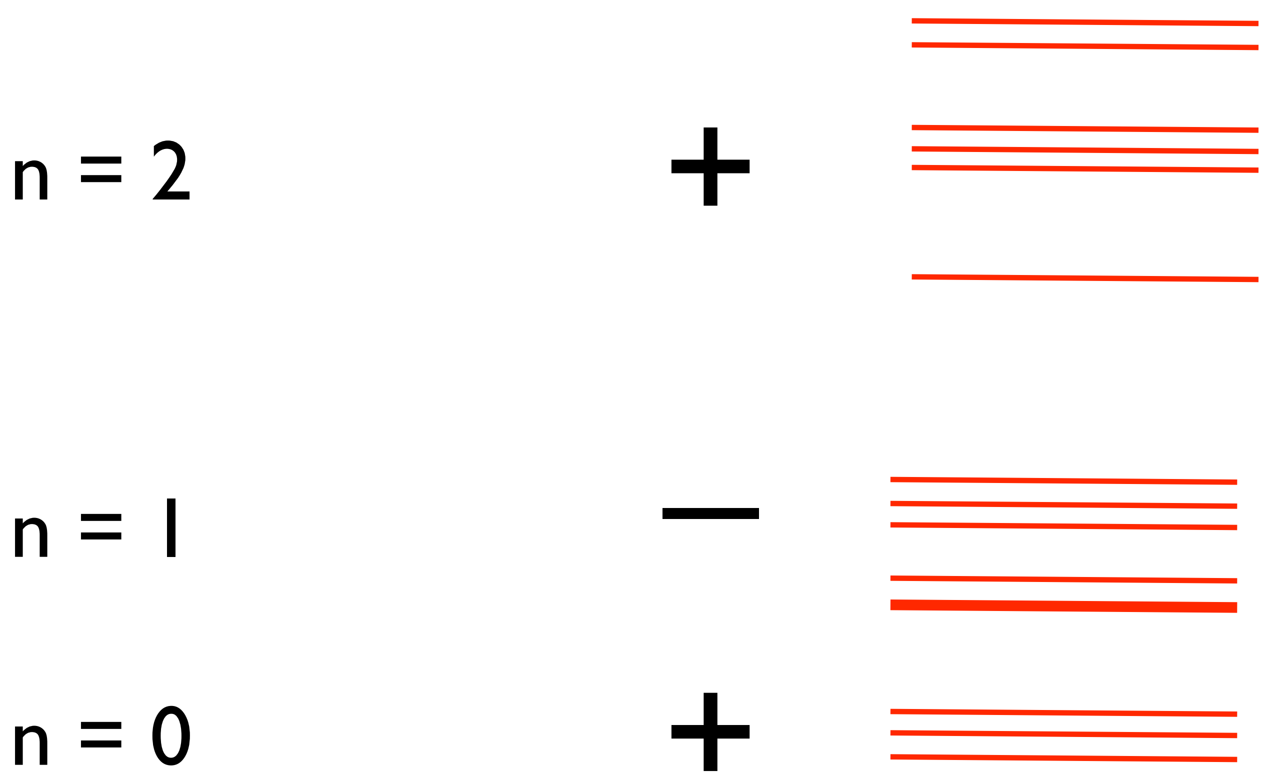

$$m^2 = \frac{n^2}{R^2} \qquad m^2 = m_0^2 + \frac{n^2}{R^2} \qquad m^2 = m_0^2 + \frac{n^2}{R^2} + \Delta_{loop\ corr}$$

Like in the Hidrogen atom



# The model

## Transitions between KK modes?




**$(-1)^n$ = KK parity conserved**

The **lightest KK** odd mode is **stable**

If neutral, the LKP could be a WIMP Dark Matter candidate

$\mathcal{O}$(1 TeV) )

...... like SUSY R-parity and LSP (neutralino DM)

# The model

## Our goal:

*A. Belyaev, M. Brown, J.M. and C. Papineau*

Provide a description of the effective 4D modes (masses and interactions)

**Consistent**

-Preserves gauge invariance (from the 5D point of view)

-Preserves unitarity

- .... or break it in a controlled way (when keeping a part of the infinity KK tower)

**Accurate**

-Include 5D quantum corrections that lift the spectrum degeneracy and fix the mass splitting

i) crucial for LHC searches (decay modes, softness of final states)
ii) crucial for DM evaluation (coanihilation effects, resonances)

- Interplay with EWSB effects (complicated mixings )

# Radiative corrections

## Dispersion relations

- Fixed by 5D Lorentz invariance of the tree level Lagrangian:

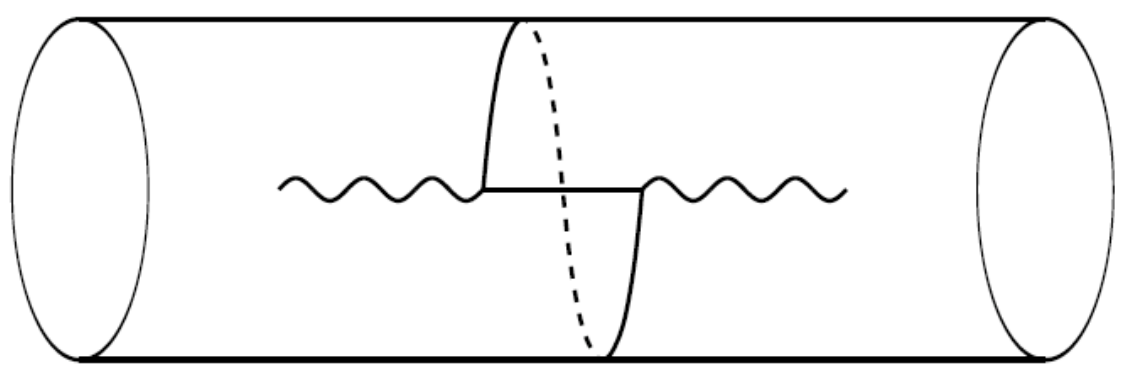
$$E^2 = \vec{p}^{\,2} + p_5^2 = \vec{p}^{\,2} + m_n^2$$

- Compactification breaks 5D Lorentz invariance: Loop diagrams will correct KK masses !

- Bulk corrections

*Cheng, Matchev, Schmaltz 2002*

*Gersdorff, Irges, Quiros 2002*



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

preserve $p_5$

- Brane corrections

$p_5$ is non-conserved ( $\Delta p_5 \neq 0$ at fixed points)

$$\delta m_n \quad = \quad \beta_i \frac{n}{R} \ln \frac{\Lambda^2}{\mu^2}$$

$$\delta m_n^2 \quad = \quad \beta_i \frac{n^2}{R^2} \ln \frac{\Lambda^2}{\mu^2}$$

# Radiative corrections

## This fixes our set-up

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

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

by the following:

$$-\frac{1}{4}F^{a\mu\nu}F^a_{\mu\nu} + \frac{1}{2}\,\mathrm{Z}_V\,F^a_{\mu 5}F^{a\mu}_5 + |D_\mu\Phi|^2 - \mathrm{Z}_\Phi\,|D_5\Phi|^2$$

Belanger, Kakizaki, Pukhov

which is gauge invariant but not Lorentz covariant.

In this way, the fields receive a KK mass

$$m_n = Z\frac{n}{R} \qquad\qquad m_n^2 = Z\frac{n^2}{R^2}$$

and fit

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

# Spectrum

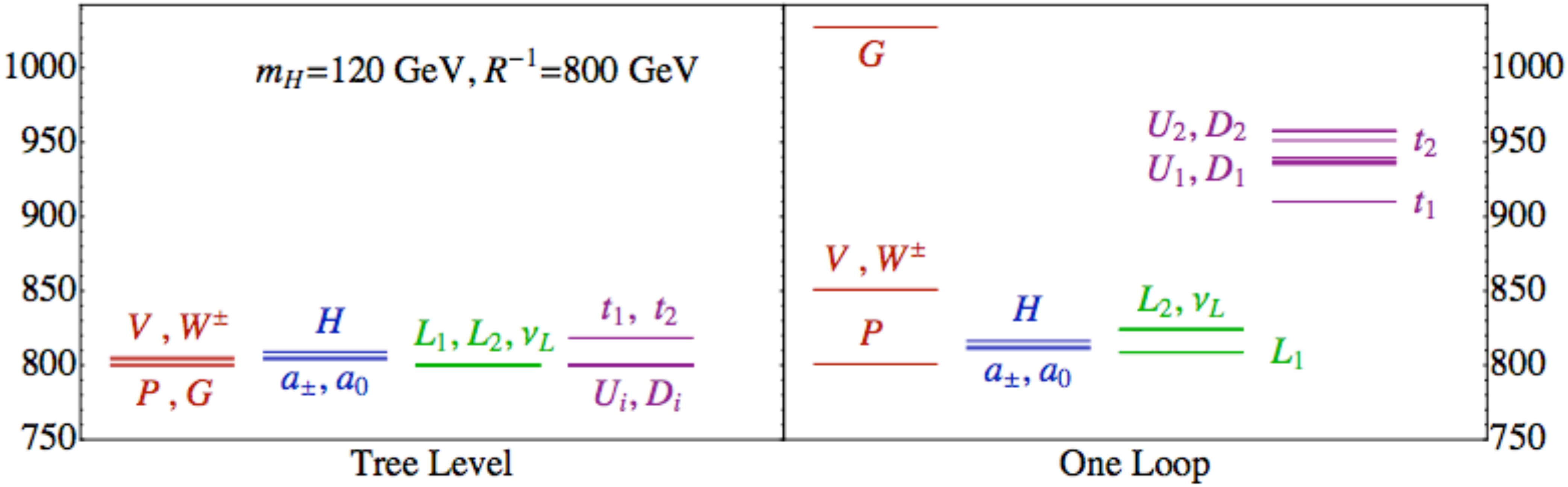



Figure 1: The first KK level of the MUED spectrum for $R^{-1} = 800$ GeV, $m_H = 120$ GeV, $\Lambda R = 20$ and $\mu R = 1$, at tree level (left) and one loop (right).

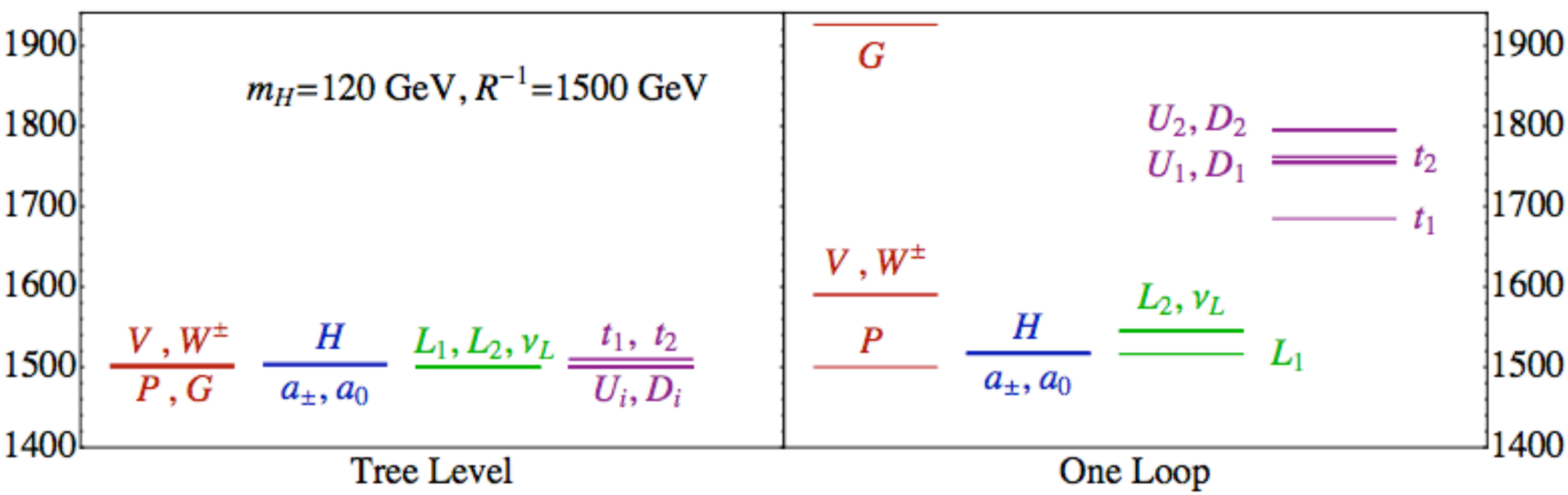
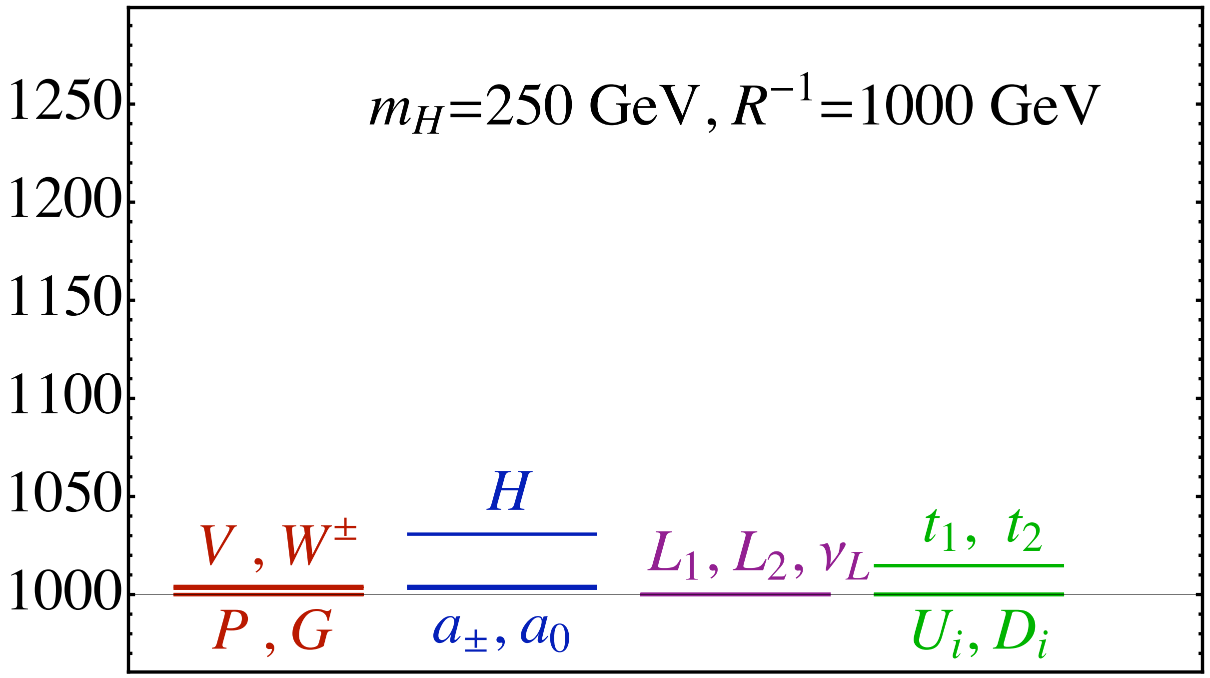
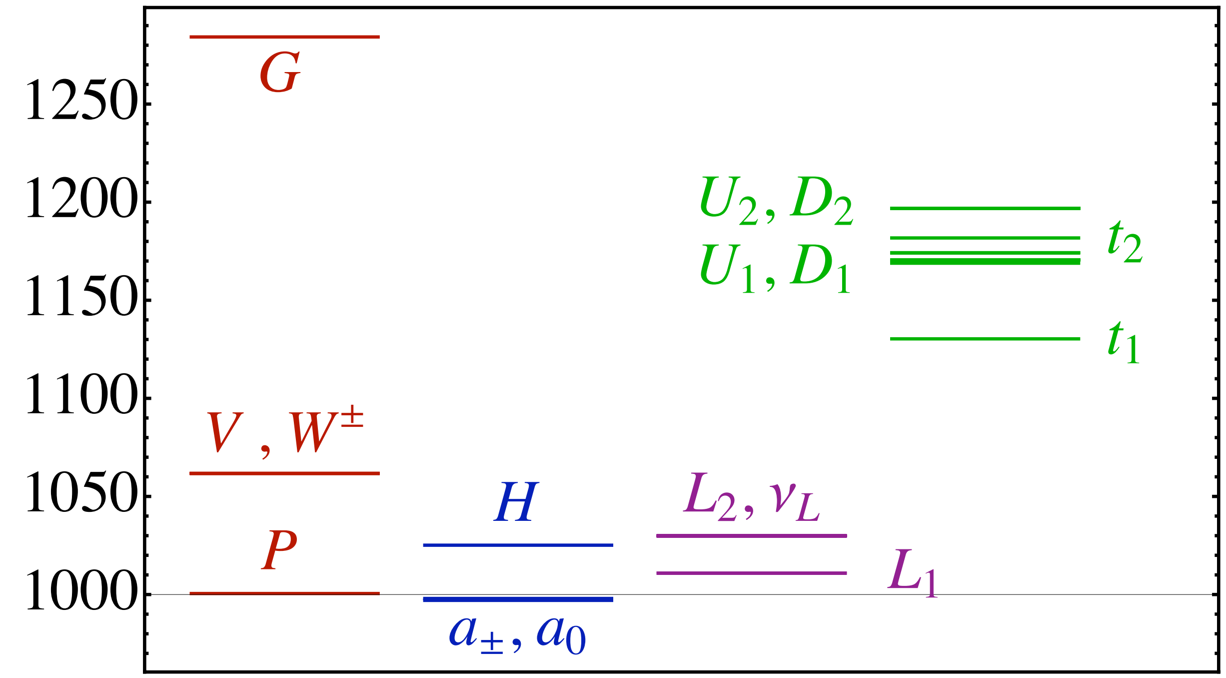



Figure 2: The first KK level of the MUED spectrum for $R^{-1} = 1500$ GeV, $m_H = 120$ GeV,

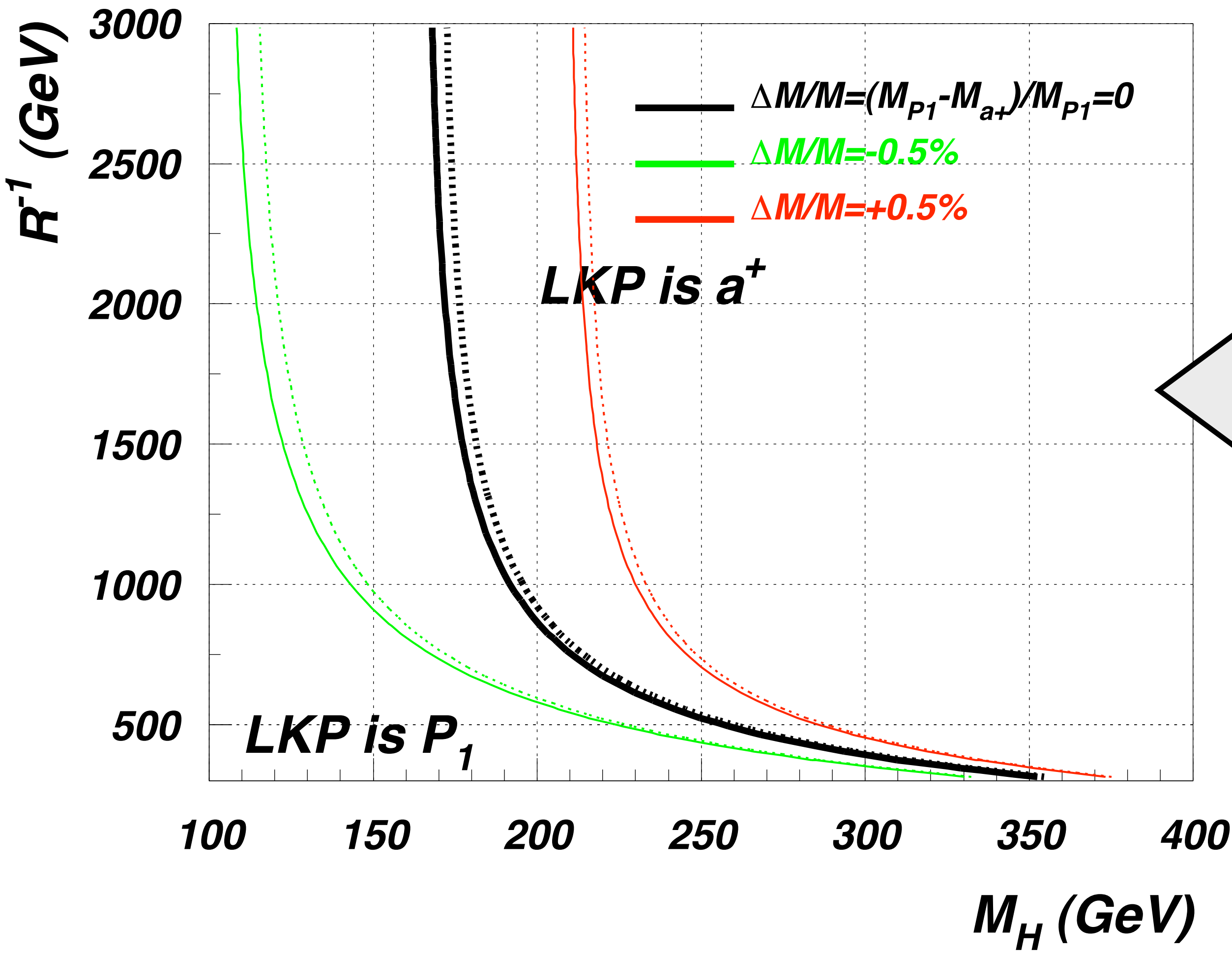
# Spectrum




Tree Level




One Loop




For large 1/R, $m_H$ values, the LKP is charged

# Model Implementation

Semenov, 2010

- In LanHEP :

LanHEP is a package that generates the Feynman rules out of a Lagrangian. We have implemented MUED@1Loop in Feynman and unitary gauges. We discart the bulk corrections.

Pukhov, 1999

- 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. The procedure is entirely automated.

We are cross-checking our implementation with the Annecy group. It agrees in the unitary gauge.

# Code validation

| Process | DKM | BBMP | |
|---|---|---|---|
| $G^{(1)}\,G^{(1)} \to G\,G$ | 3.135E+1 | 3.135E+1 | |
| $G^{(1)}\,G \to G^{(1)}\,G$ | 3.183E+3 | 3.183E+3 | |
| $G^{(1)}\,G^{(1)} \to G^{(1)}\,G^{(1)}$ | 3.170E+3 | 3.157E+3 | |
| $G^{(1)}\,Z^{(1)} \to c\,\bar{c}$ | 3.952E−2 | 3.888E−2 | |
| $G^{(1)}\,\gamma^{(1)} \to b\,\bar{b}$ | 6.761E−3 | 6.195E−3 | |
| $\gamma^{(1)}\,\gamma^{(1)} \to t\,\bar{t}$ | 6.837E−3 | 5.530E−3 | |
| $Z^{(1)}\,Z^{(1)} \to d\,\bar{d}$ | 1.830E−2 | 1.880E−2 | |
| $Z^{(1)}\,Z^{(1)} \to W^+\,W^-$ | 6.910E+0 | 6.878E+0 | |
| $W^{+\,(1)}\,W^{-\,(1)} \to Z\,Z$ | 2.040E+0 | 2.041E+0 | |
| $W^{+\,(1)}\,W^{-\,(1)} \to Z\,\gamma$ | 1.226E+0 | 1.226E+0 | |
| $W^{+\,(1)}\,W^{-\,(1)} \to W^+\,W^-$ | 3.507E+0 | 3.114E+0 | |
| $W^{+\,(1)}\,W^{-\,(1)} \to \gamma\,\gamma$ | 1.842E−1 | 1.842E−1 | |
| $Z\,\gamma \to W^{+\,(1)}\,W^{-\,(1)}$ | 1.738E+0 | 1.738E+0 | |
| $Z^{(1)}\,Z^{(1)} \to W^{+\,(1)}\,W^{-\,(1)}$ | 3.635E+2 | 3.615E+2 | |
| $Z\,Z^{(1)} \to W^+\,W^{-\,(1)}$ | 1.134E+2 | 1.097E+2 | |
| $W^{+\,(1)}\,W^{-\,(1)} \to W^{+\,(1)}\,W^{-\,(1)}$ | 1.820E+2 | 1.816E+2 | |
| $W^+\,W^{-\,(1)} \to Z^{(1)}\,\gamma$ | 2.858E+1 | $P^{(1)}$ | 5.194E−2 |
| | | $V^{(1)}$ | 2.853E+1 |
| | | *total* | 2.858E+1 |
| $W^+\,W^{-\,(1)} \to Z^{(1)}\,Z$ | 1.134E+2 | $P^{(1)}$ | 2.015E−1 |
| | | $V^{(1)}$ | 1.097E+2 |
| | | *total* | 1.099E+2 |

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

# Experimental Bounds

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

$$S = \frac{4\sin^2\theta_W}{\alpha}\left[\frac{3g^2}{4(4\pi)^2}\left(\frac{2}{9}\frac{m_t^2}{M_{KK}^2}\right)\zeta(2) + \frac{g^2}{4(4\pi)^2}\left(\frac{1}{6}\frac{M_H^2}{M_{KK}^2}\right)\zeta(2)\right],$$

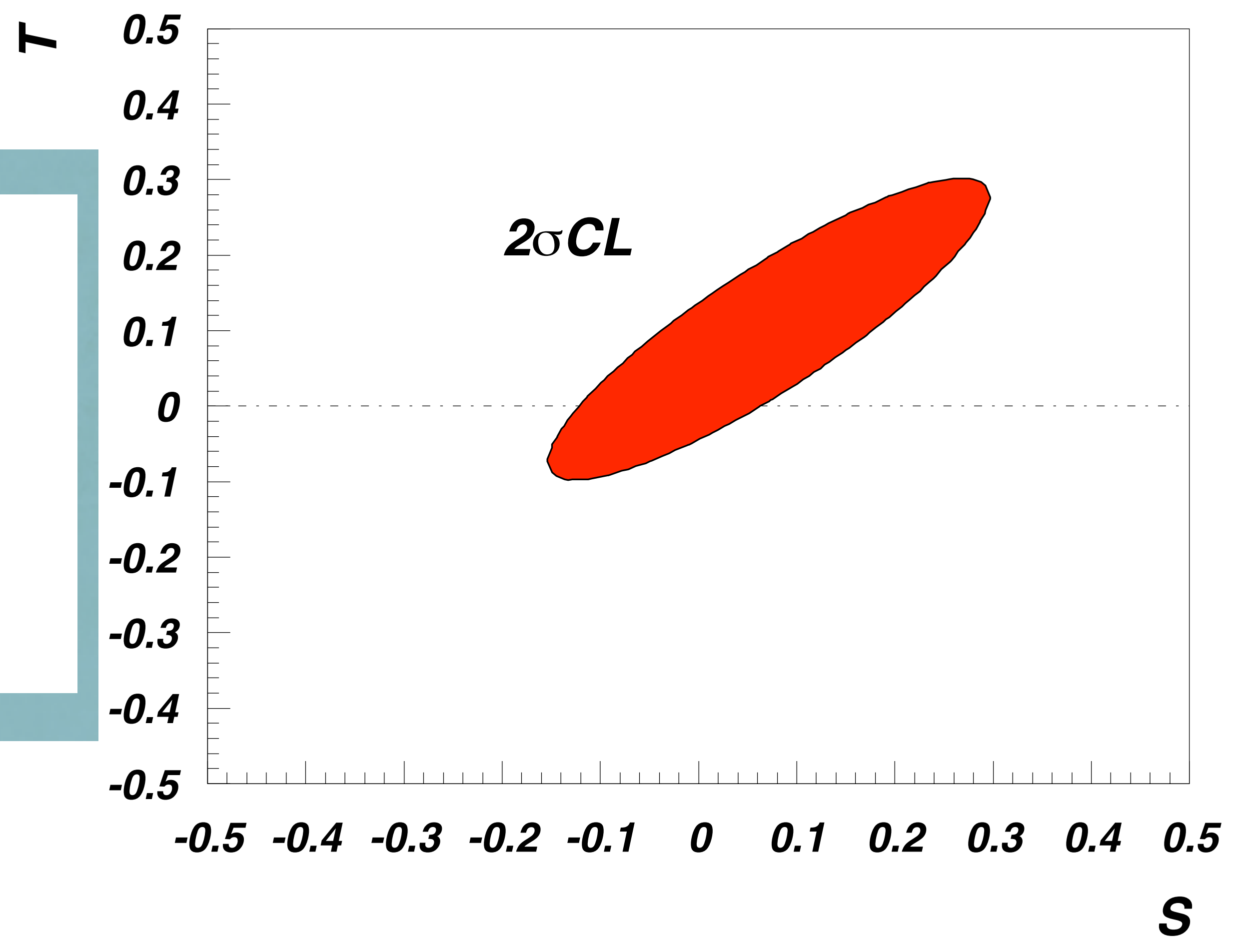
$$T = \frac{1}{\alpha}\left[\frac{3g^2}{2(4\pi)^2}\frac{m_t^2}{M_W^2}\left(\frac{2}{3}\frac{m_t^2}{M_{KK}^2}\right)\zeta(2) + \frac{g^2\sin^2\theta_W}{(4\pi)^2\cos^2\theta_W}\left(-\frac{5}{12}\frac{M_H^2}{M_{KK}^2}\right)\zeta(2)\right],$$

$$U = -\frac{4\sin^2\theta_W}{\alpha}\left[\frac{g^2\sin^2\theta_W}{(4\pi)^2}\frac{M_W^2}{M_{KK}^2}\left(\frac{1}{6}\zeta(2) - \frac{1}{15}\frac{M_H^2}{M_{KK}^2}\zeta(4)\right)\right],$$

$$S \approx \frac{1}{12\pi}\ln\frac{M_H^2}{M_{H,\mathrm{ref}}^2} + \frac{1}{6\pi}\ln\frac{m_t^2}{m_{t,\mathrm{ref}}^2},$$

$$T \approx -\frac{3}{16\pi\cos^2\theta_W}\ln\frac{M_H^2}{M_{H,\mathrm{ref}}^2} + \frac{3}{16\pi\sin^2\theta_W\cos^2\theta_W}\ln\frac{m_t^2 - m_{t,\mathrm{ref}}^2}{m_Z^2},$$

$$U \approx \frac{1}{2\pi}\ln\frac{m_t^2}{m_{t,\mathrm{ref}}^2}.$$




S = 0.04 ± 0.10
T = 0.05 ± 0.11
U = 0.08 ± 0.11

# Experimental Bounds

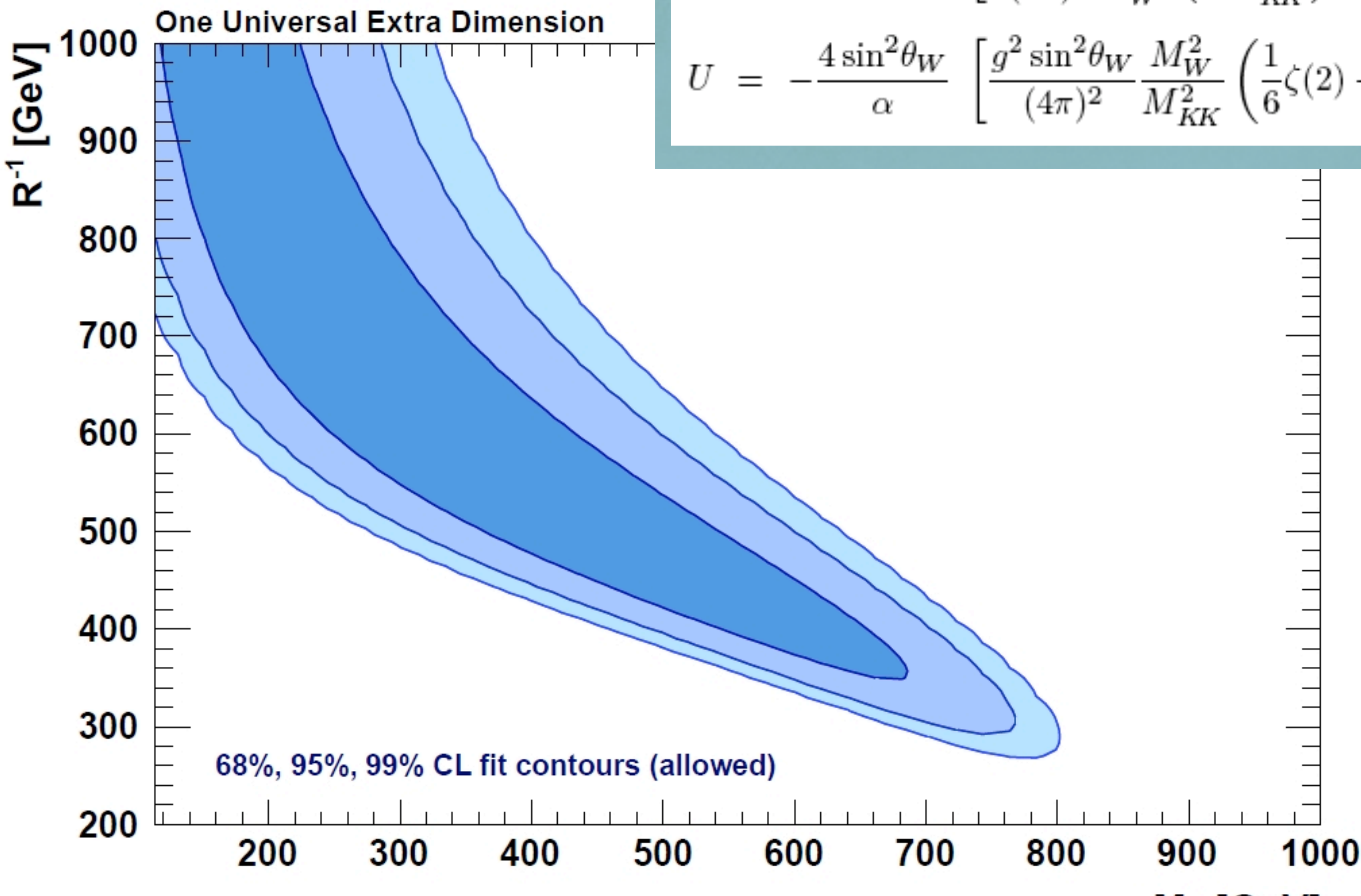
The tower of KK particles modify the gauge bosons self-energies, contributing to the S,T, and U electroweak parameters:

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

$$S = \frac{4\sin^2\theta_W}{\alpha}\left[\frac{3g^2}{4(4\pi)^2}\left(\frac{2}{9}\frac{m_t^2}{M_{KK}^2}\right)\zeta(2) + \frac{g^2}{4(4\pi)^2}\left(\frac{1}{6}\frac{M_H^2}{M_{KK}^2}\right)\zeta(2)\right],$$

$$T = \frac{1}{\alpha}\left[\frac{3g^2}{2(4\pi)^2}\frac{m_t^2}{M_W^2}\left(\frac{2}{3}\frac{m_t^2}{M_{KK}^2}\right)\zeta(2) + \frac{g^2\sin^2\theta_W}{(4\pi)^2\cos^2\theta_W}\left(-\frac{5}{12}\frac{M_H^2}{M_{KK}^2}\right)\zeta(2)\right],$$

$$U = -\frac{4\sin^2\theta_W}{\alpha}\left[\frac{g^2\sin^2\theta_W}{(4\pi)^2}\frac{M_W^2}{M_{KK}^2}\left(\frac{1}{6}\zeta(2) - \frac{1}{15}\frac{M_H^2}{M_{KK}^2}\zeta(4)\right)\right],$$




Gfitter

arXiv: 1107.0975

# Experimental Bounds

## 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 $b \rightarrow s\gamma$

**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.

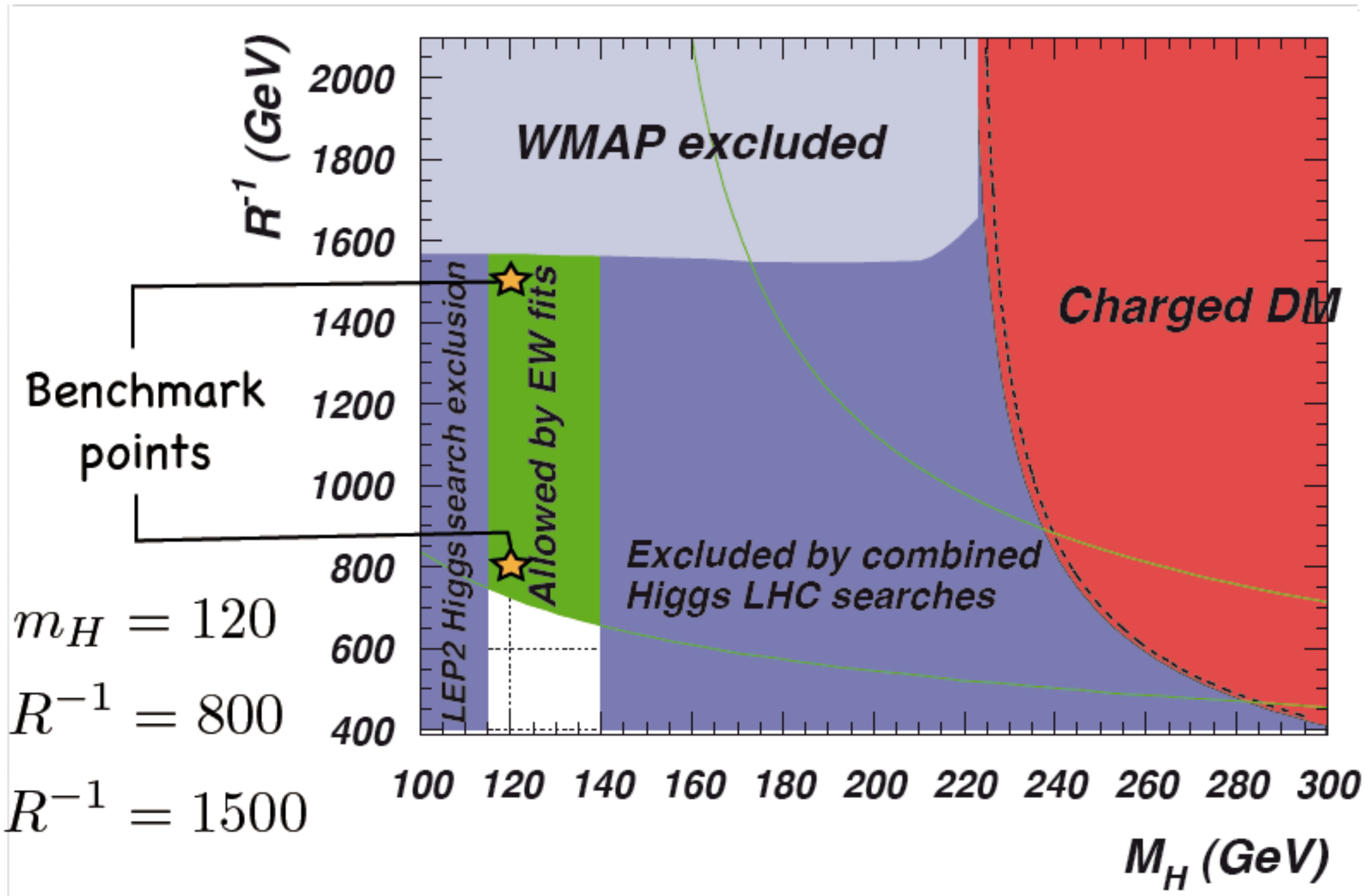
1/R as high as1.3 TeV

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**

# Experimental Bounds

See also T. Flacke and M. Brown  talks



# MUED at the LHC

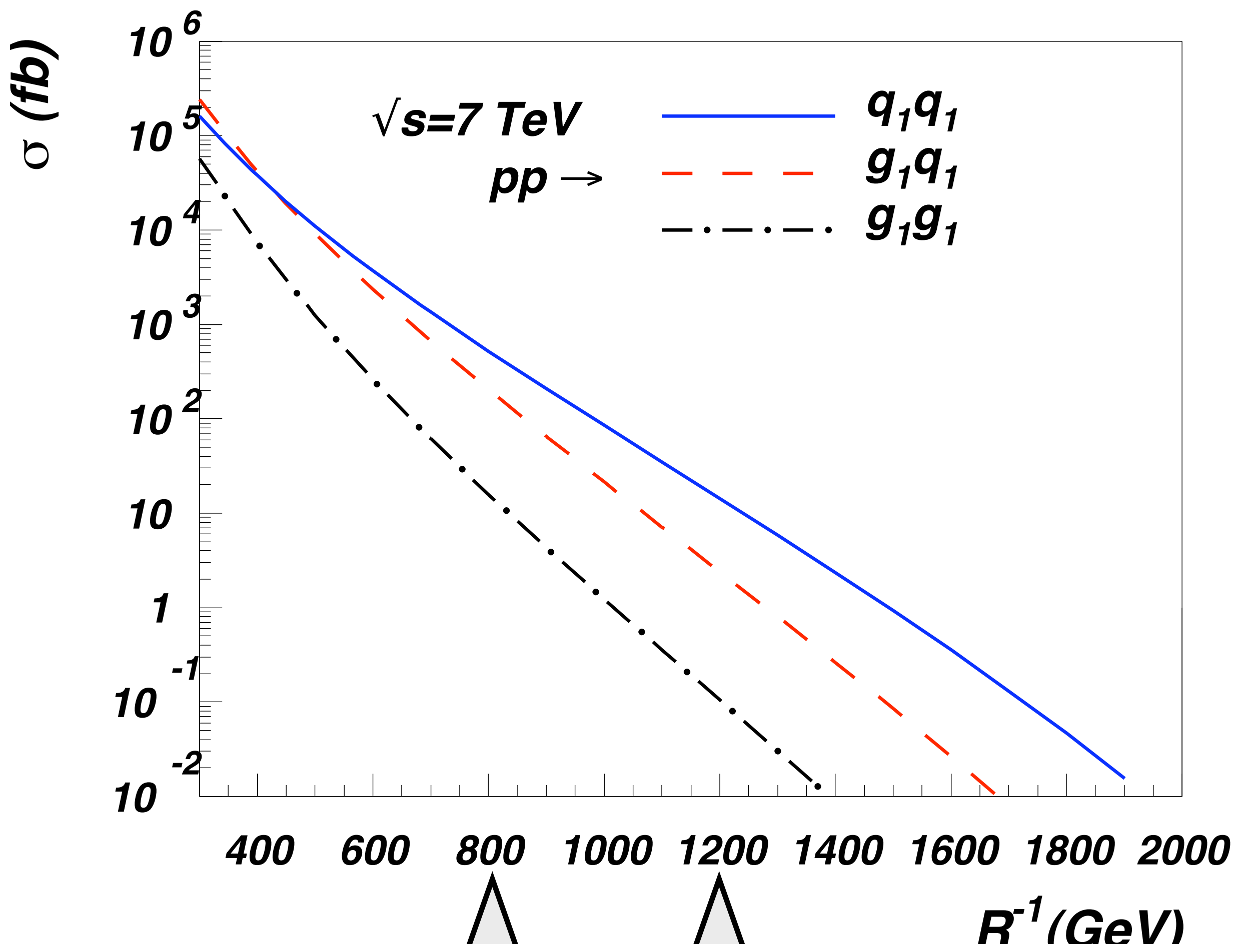
*B. Bhattacherjee, K. Ghosh*

*H. Murayama, M. Nojiri, K.Tobioka*

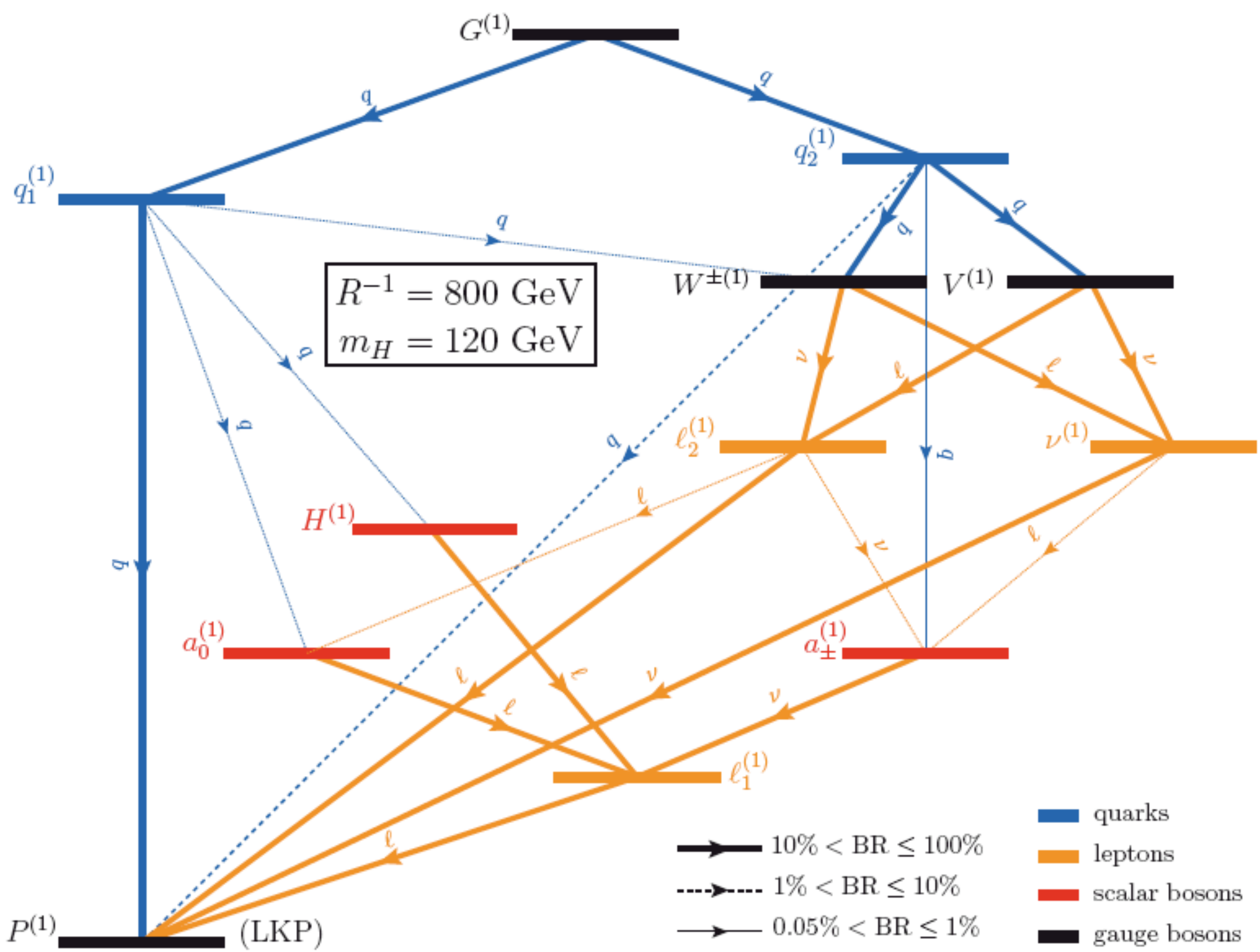
A. *Belyaev, M. Brown, J.M. M. and C. Papineau*

- KK-gluon and KK-quarks are the particles with largest production cross section at the LHC.

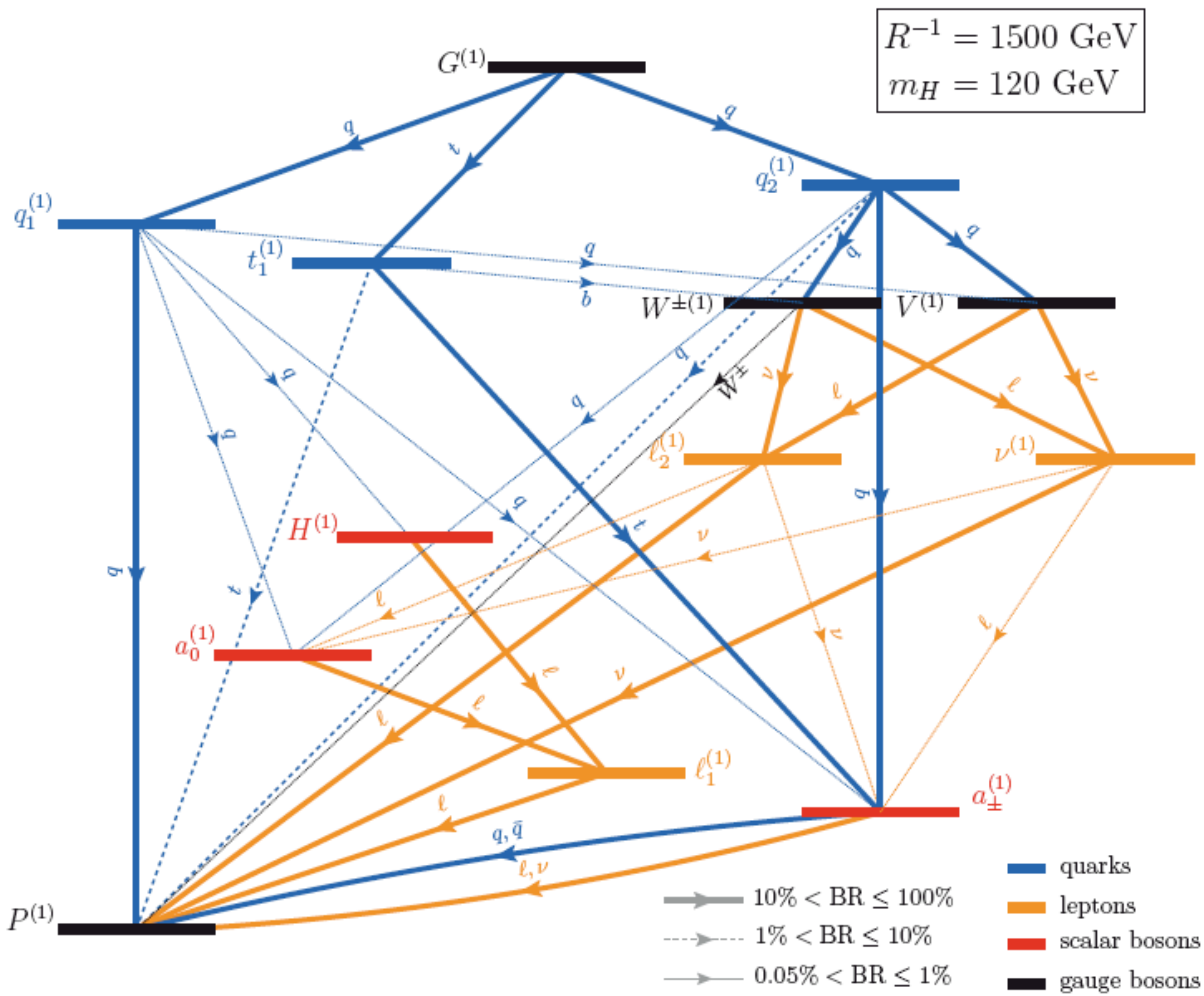
- For $R^{-1} > 500$ GeV , $q_1 q_1$ production dominates.



# MUED at the LHC

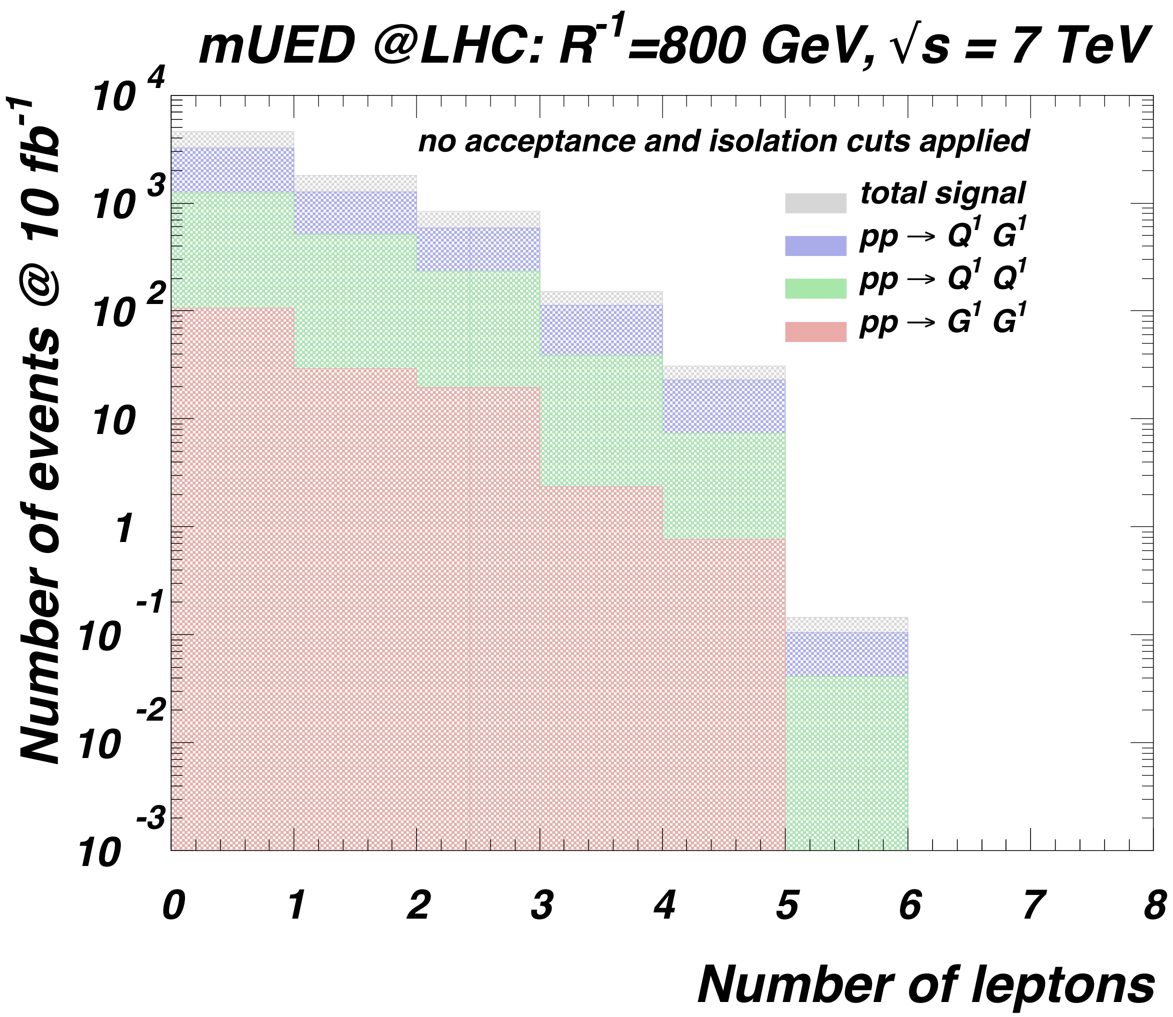


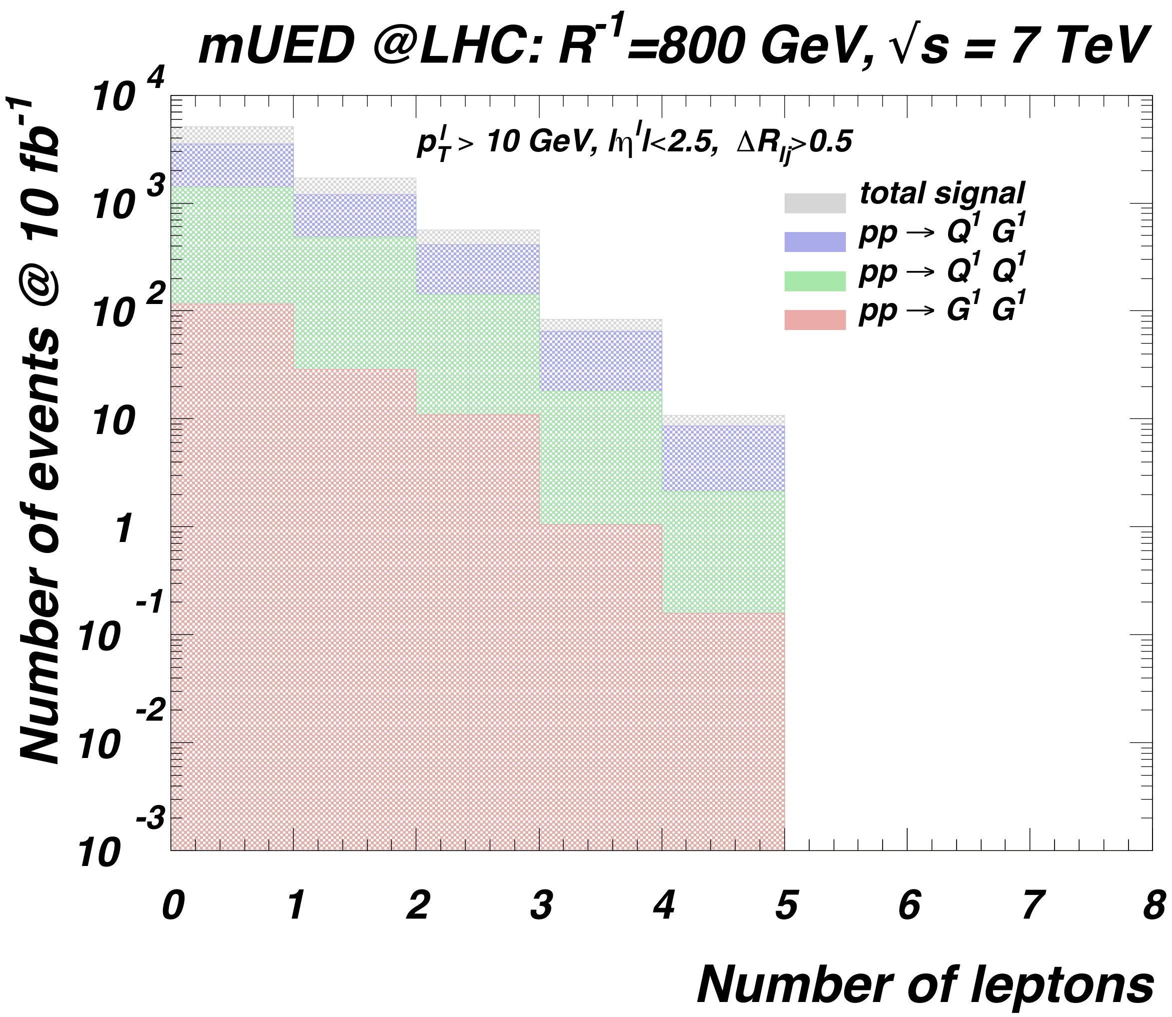
# MUED at the LHC



# MUED at the LHC

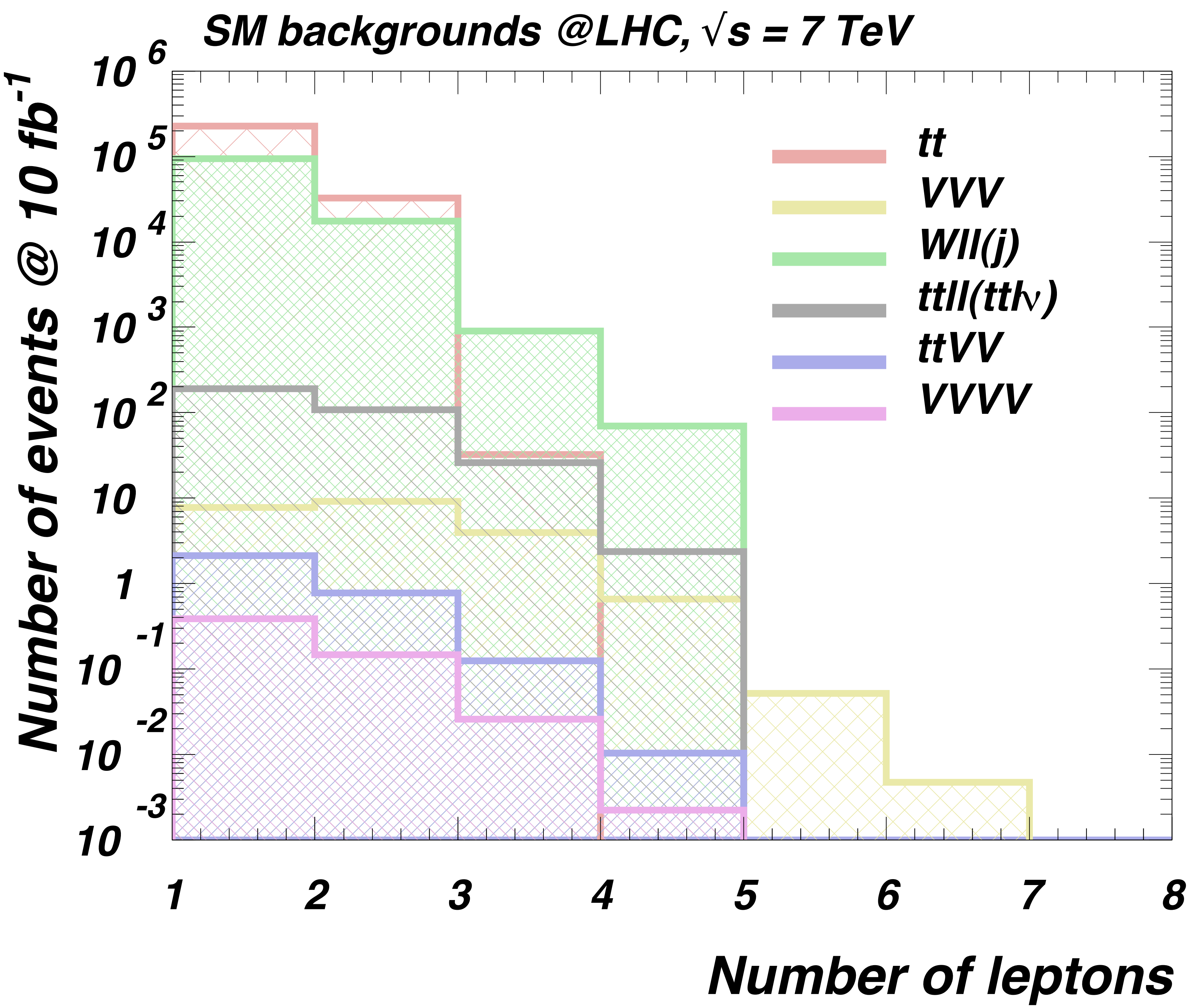
- We use lepton multiplicity to clasify the # of events



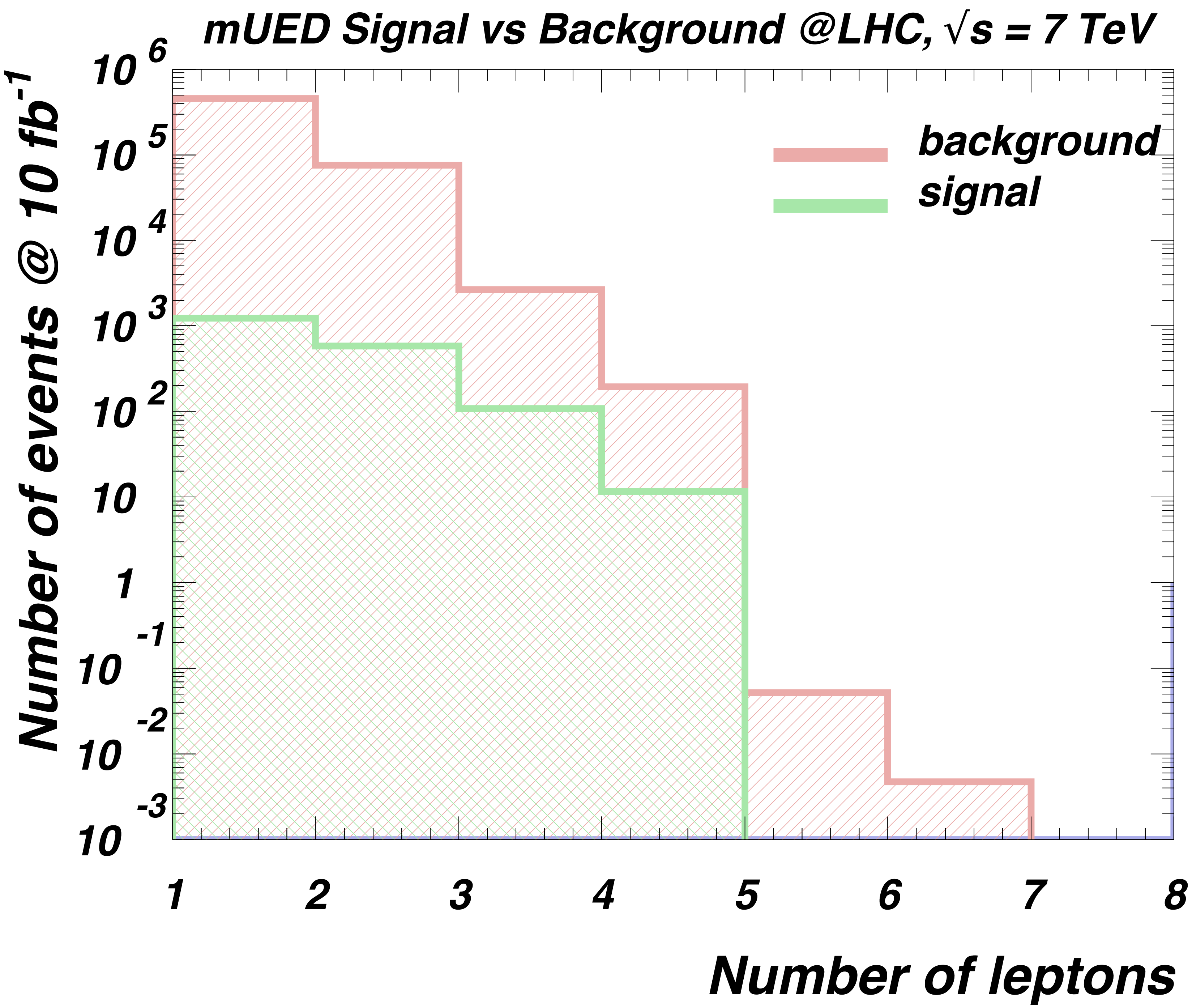



# MUED at the LHC

- Main backgrounds for multilepton processes

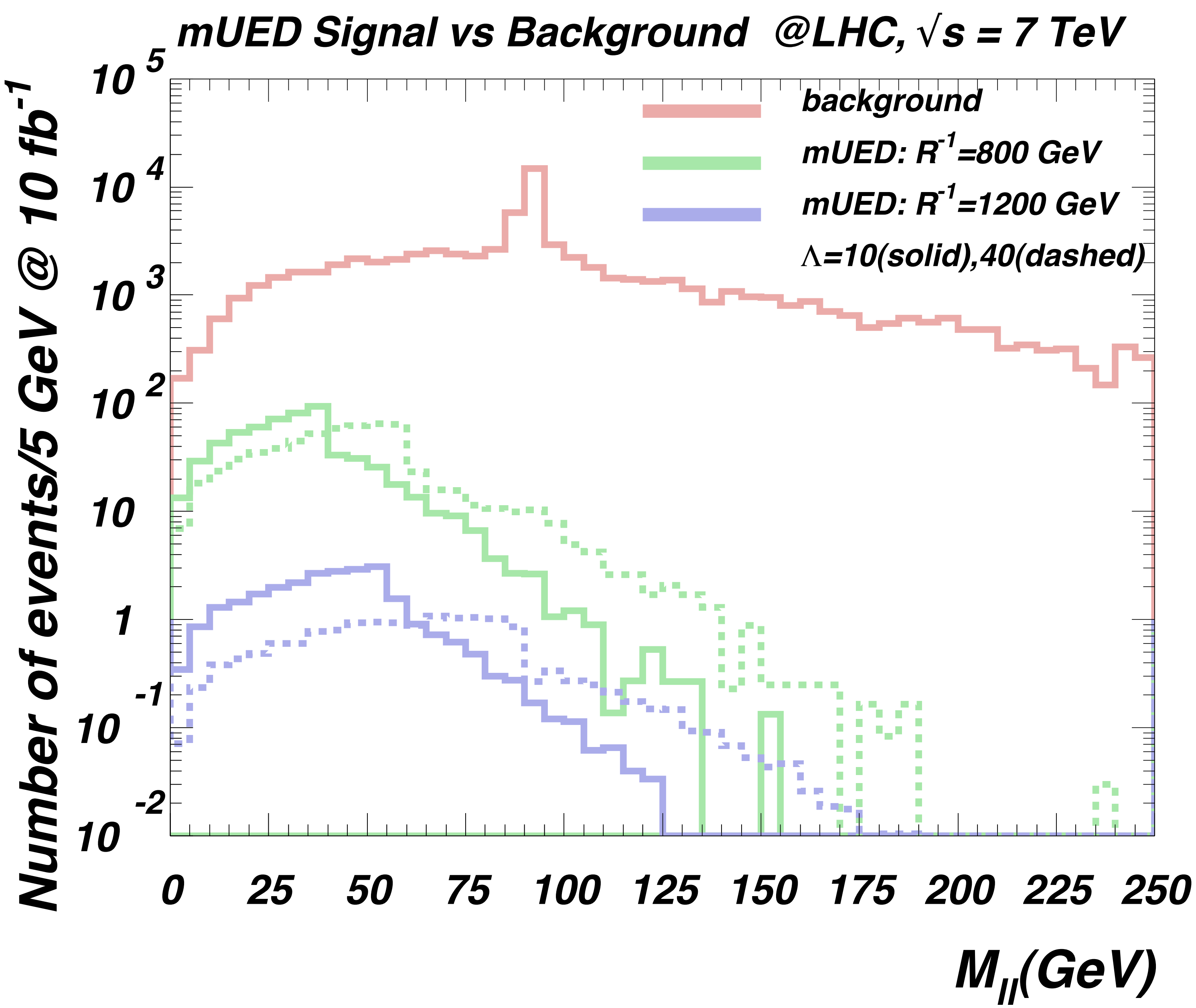


# MUED at the LHC

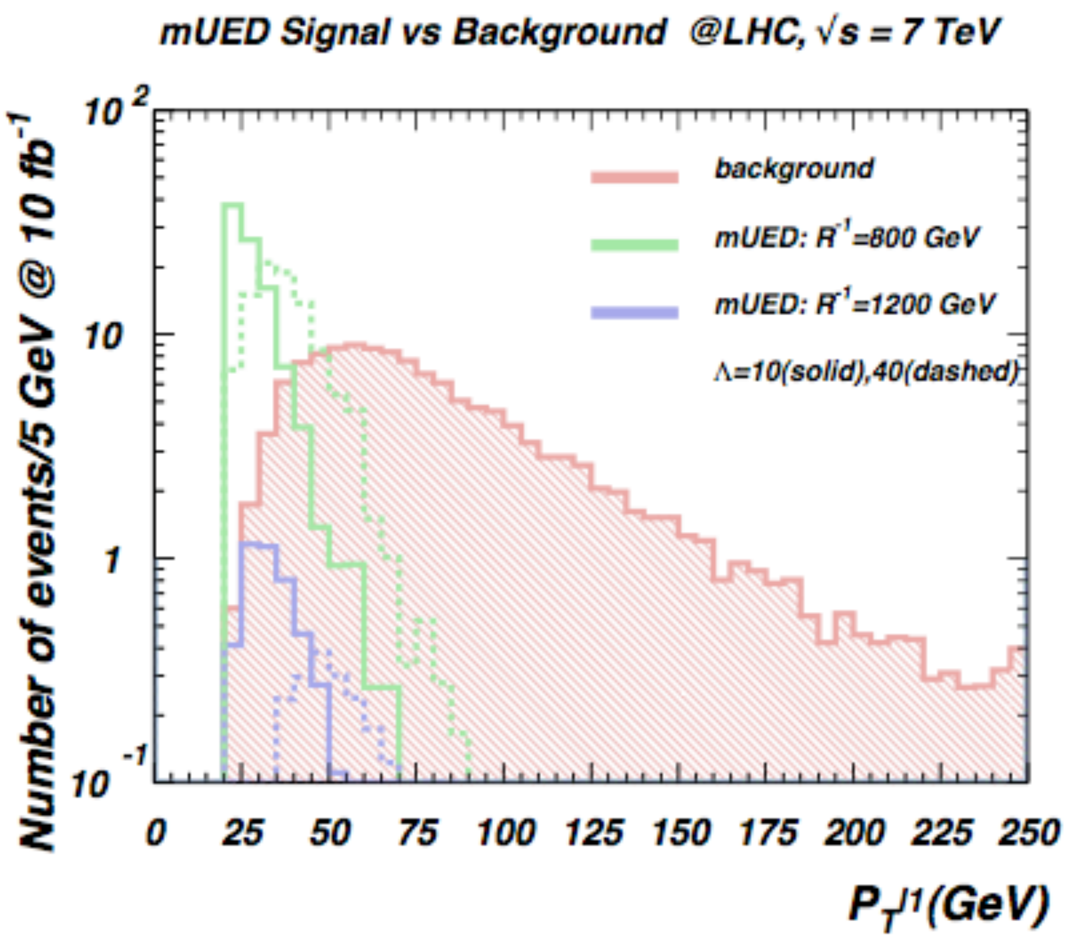


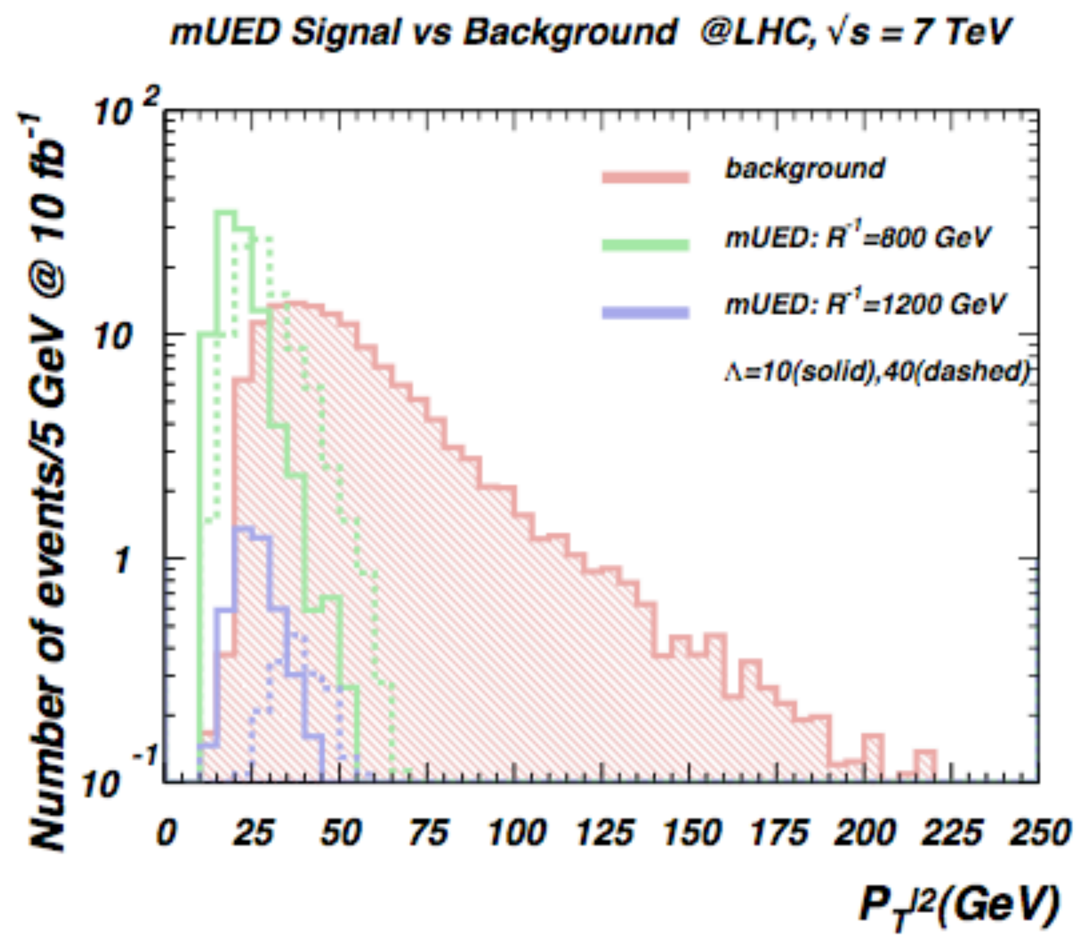

Lepton multiplicity distribution for background versus signal after the acceptance cuts

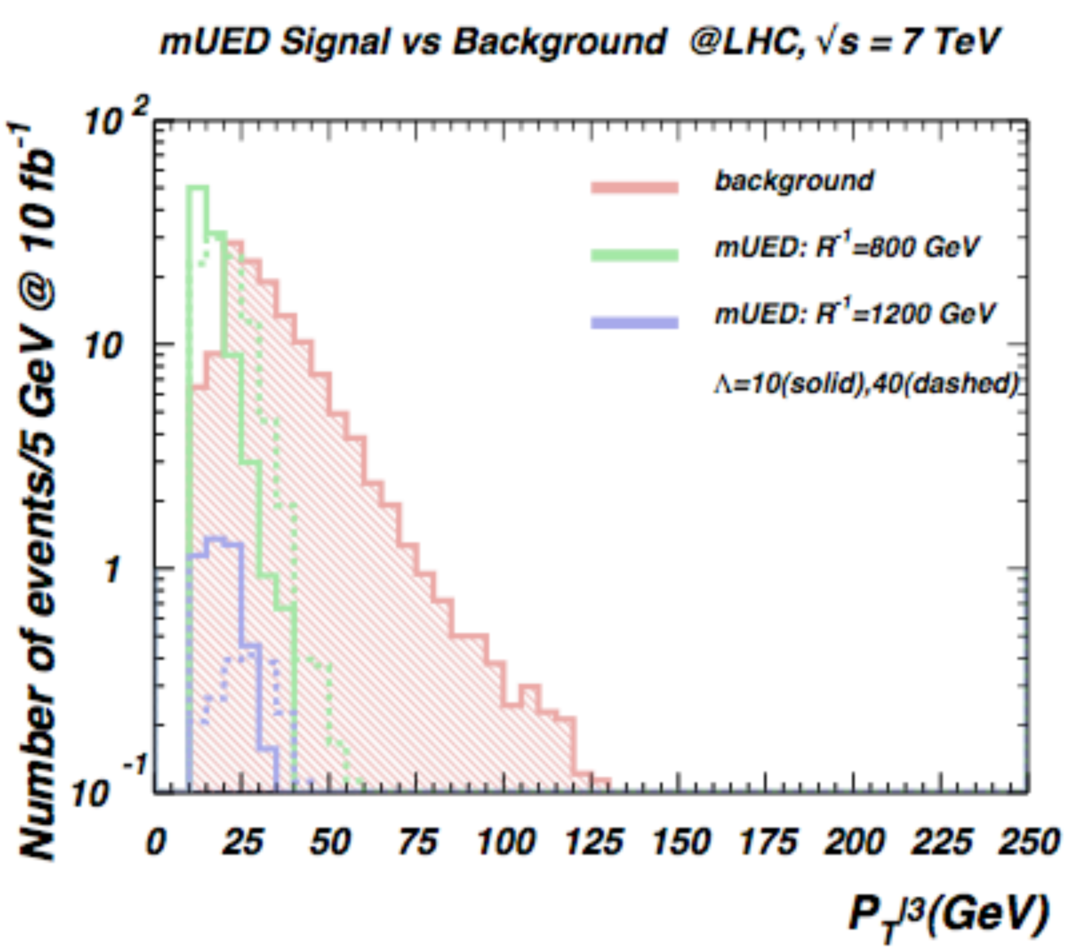
# MUED at the LHC




Invariant mass of the two leptons with the highest $P_T$ for the background versus the signal after the acceptance cuts

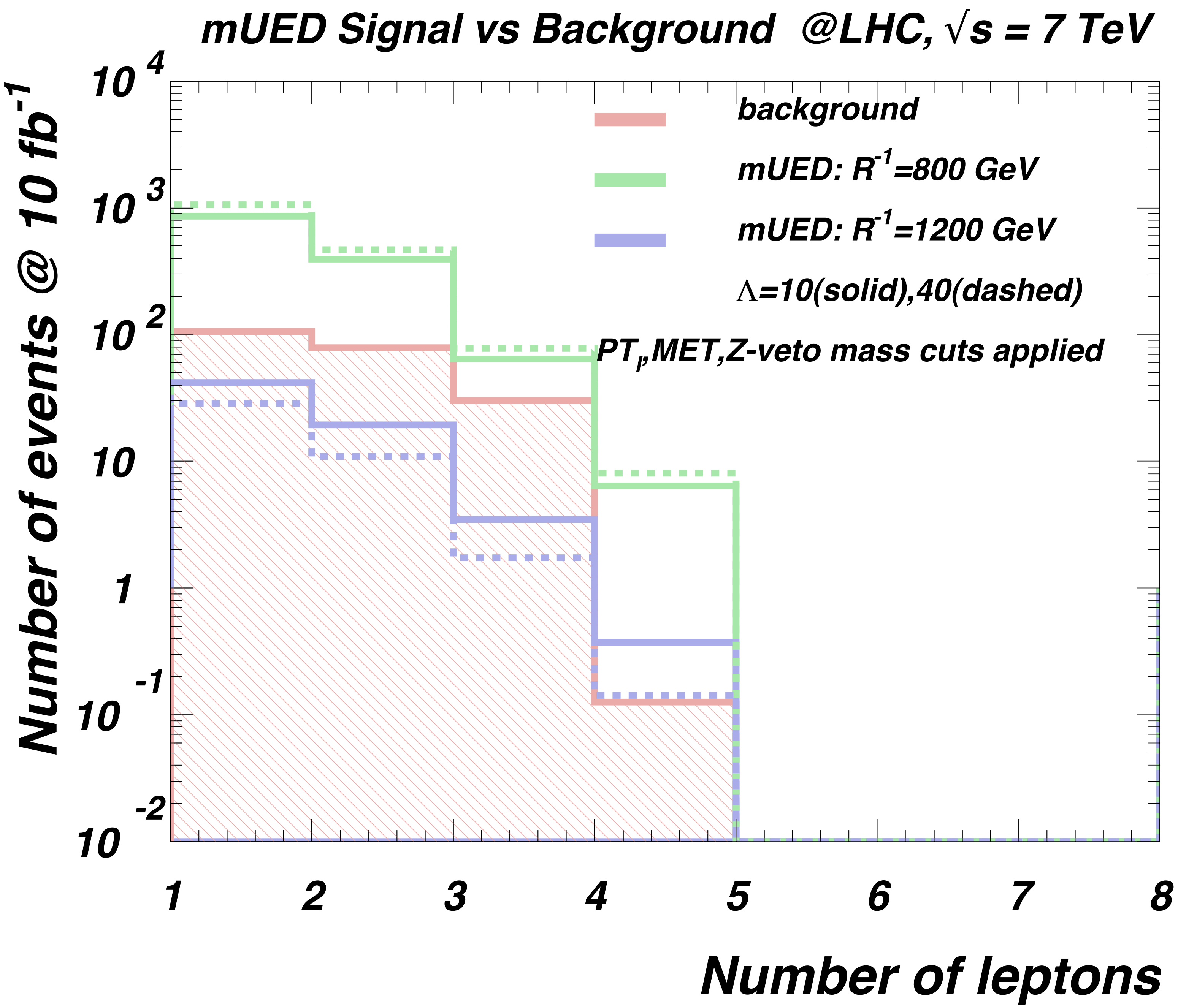


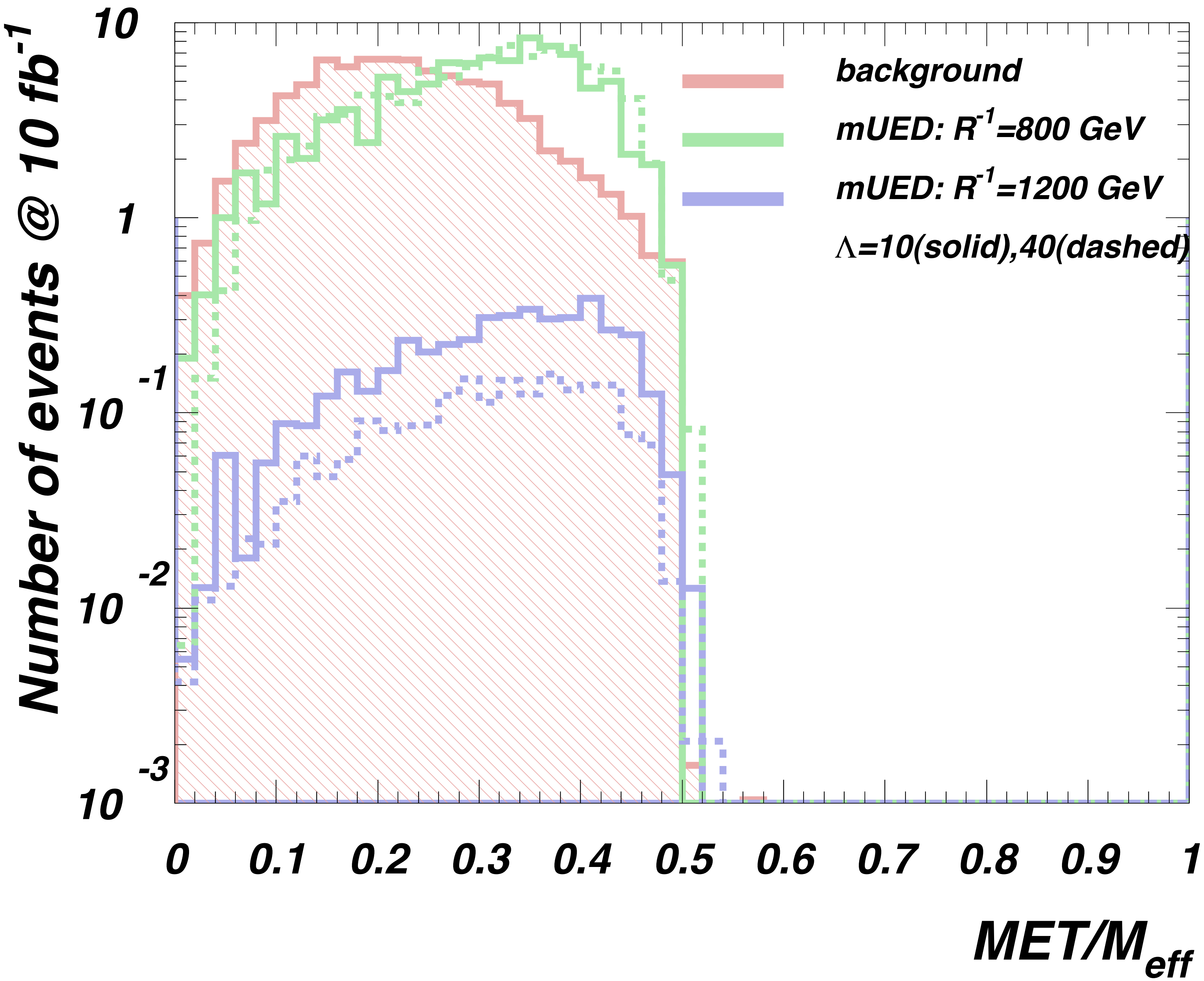

Transverse momentum of the 1st, 2nd and 3rd highest $P_T$ leptons after the acceptance and $|M_Z - M_{ll}| > 10$ GeV mass window cuts for backgrounds versus signal

# MUED at the LHC




Lepton multiplicity distribution for background versus signal after all cuts (acceptance, mass windows cut, $P_T^{l1} < 100$ GeV, $P_T^{l2} < 70$ GeV, $P_T^{l3} < 50$ GeV, MET > 50 GeV, $M_{eff} > R^{-1}/5$) applied,

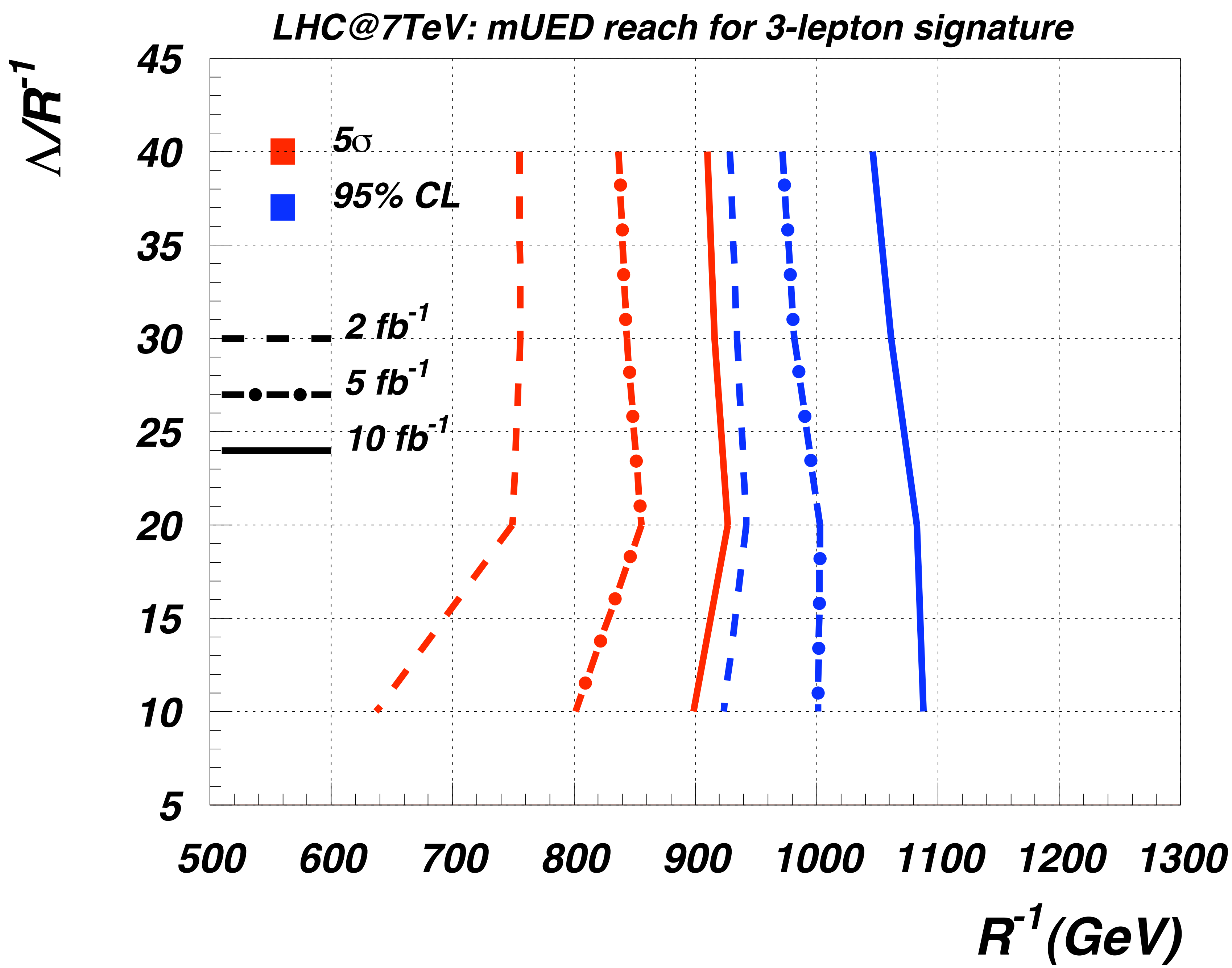
# MUED at the LHC




MET / $M_{eff}$ distribution for background versus signal after acceptance, mass window cut, $P_T^{l1} < 100$ GeV, $P_T^{l2} < 70$ GeV, $P_T^{l3} < 50$ GeV cuts

# MUED at the LHC

LHC @ 7 TeV exclusion and discovery potential for mUED for different luminosities.



# Conclusion

- We have developed the effective 4D MUED@1L model by including EWSB and loop-corrections in a gauge invariant manner.
- We have implemented it in LanHeP + CalcHEP code that will make public soon.
- Present data provide strong constraints on the ($R^{-1}$, $m_H$) model parameters.
- KK vs SUSY: decay produced particles are softer.
- 3-lepton signal seems the more promising channel to look for MUED at the LHC
  - New techniques: (same / different sign leptons, $m_{T2}$, etc)
  - Devoted analysis, new LHC data