Extra Particles from Extra Dimensions

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Why Extra Dimensions?

- Why not? Good source of new particles! (and make your papers look trendy)
- Theoretically well motivated
  - Can explain:
    - Stability of the EW scale
    - Flavour structure
    - Dark matter
- Useful even if ED “not real”
  - Strong EWSB
  - Design of new experimental searches

Which Extra Dimensions?

- How come we haven't seen them yet?
  - They must be small (or shielded)
  - If gauge interactions feel the EDs
    - $L \lesssim 1/\mathrm{TeV} \sim 10^{-19}\ \mathrm{m}$

Flat Extra Dimensions

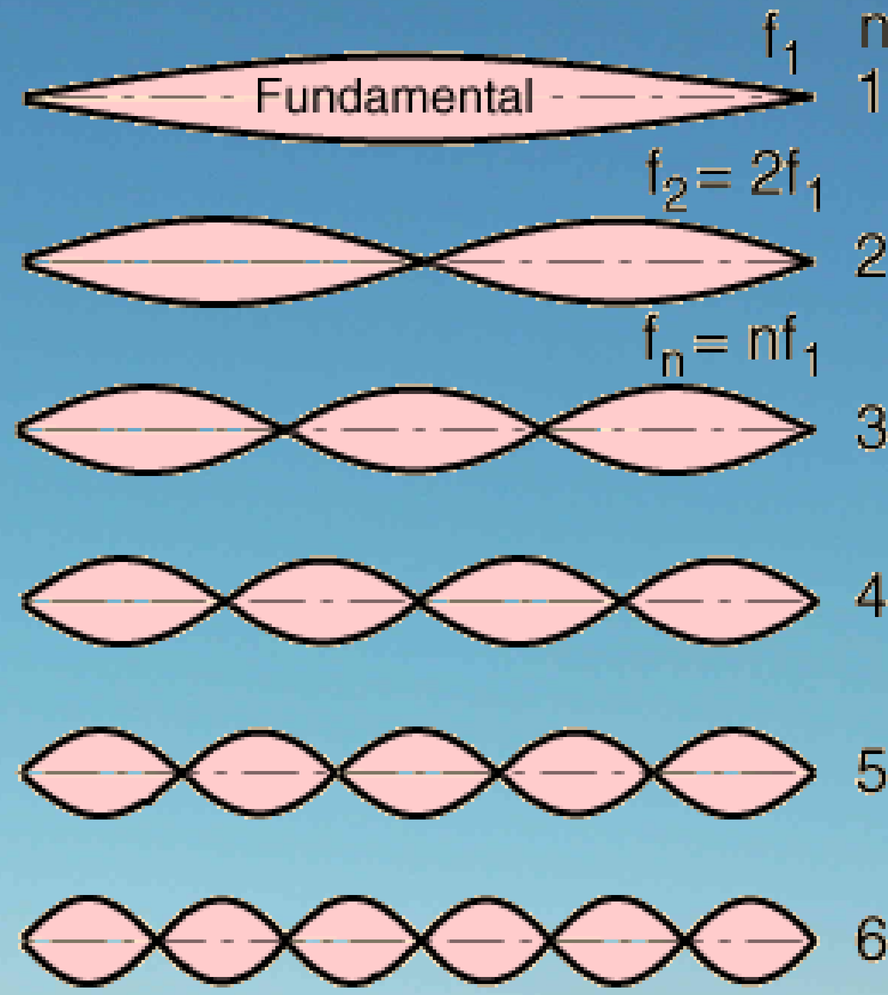
Warped Extra Dimensions

Extra particles from extra dimensions?

- We consider compact extra dimensions
- Boundary conditions: quantized momentum

$$p_5 = n/R$$

- ED particles have arbitrary momentum along 4D but discrete momentum along ED



Extra particles from extra dimensions?

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- Kaluza-Klein modes: excitations with quantized masses

$$p_\mu p^\mu - p_5^2 = M^2$$

$$m^2 = p_\mu p^\mu = M^2 + p_5^2$$

$$m_n^2 = M^2 + \left(\frac{n}{R}\right)^2$$

1 flat extra dimension

What you really care about: masses and couplings

- Fields in ED can be decomposed in KK modes (Fourier-like expansion)

$$\phi(x,y) = \sum_n f_n(y)\phi_n(x), \text{ with } \partial_\mu \partial^\mu \phi_n(x) = m_n^2 \phi_n(x)$$

- Quantized momentum in the ED: KK masses

$$[\partial_5^2 + m_n^2] f_n = 0 + \text{b.c.} \quad \Rightarrow m_n \sim 1/L$$

- Interactions given by ED couplings times wave function overlaps

$$g_5 \int dy\, \phi \bar{\psi} \psi' = \sum_{mnr} \left[g_5 \int dy\, f_m^\phi f_n^\psi f_r^{\psi'} \right] \phi_m \bar{\psi}_n \psi'_r$$

Is there anything new in ED for an experimentalist?

- Not really
  - Add a bunch of new particles:
    - Vector-like fermions, new vectors (Z',W',G', ...), new tensors, …
  - Same old constraints and phenomenology

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- Not really
  - Add a bunch of new particles:
    - Vector-like fermions, new vectors (Z',W',G', ...), new tensors, …
  - Same old constraints and phenomenology
- … but yes!
  - New methods and symmetries are naturally realised
    - Locality in ED: improved calculability
    - Natural flavour protection: top-philic new physics
    - Natural protection of certain couplings (i.e. Zbb)

How large can ED really be?

How light can new physics be?

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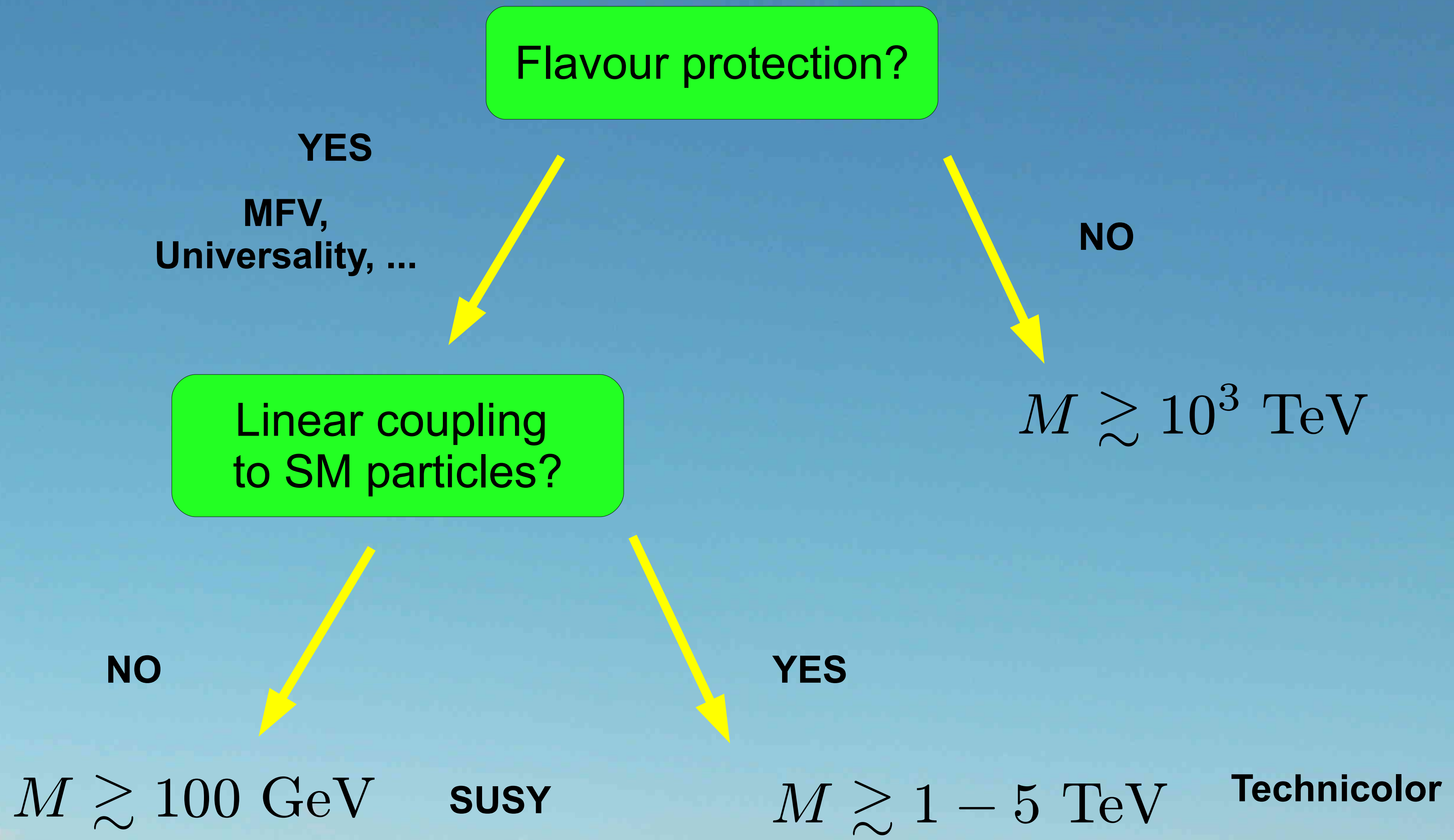
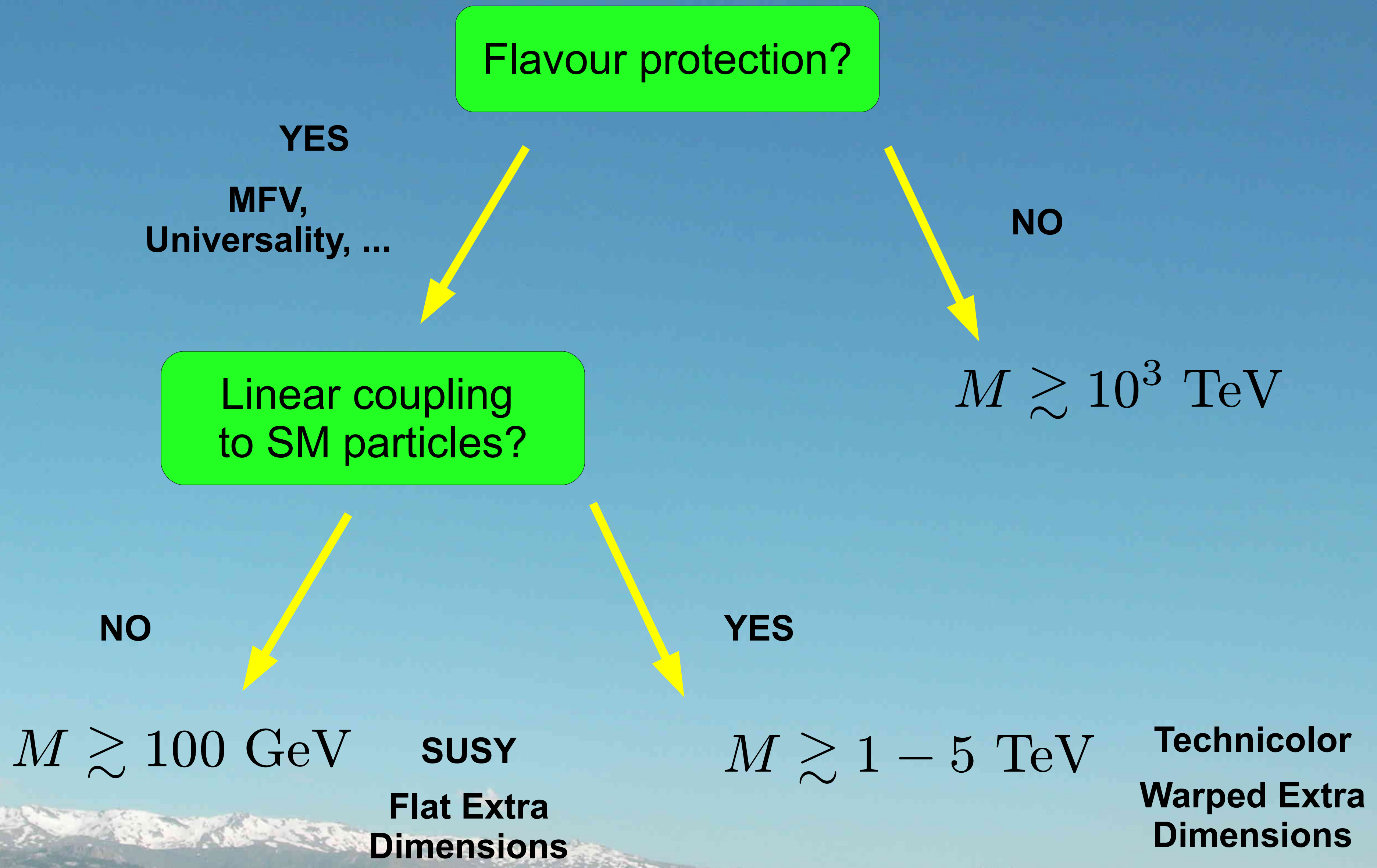


How light can new physics be?

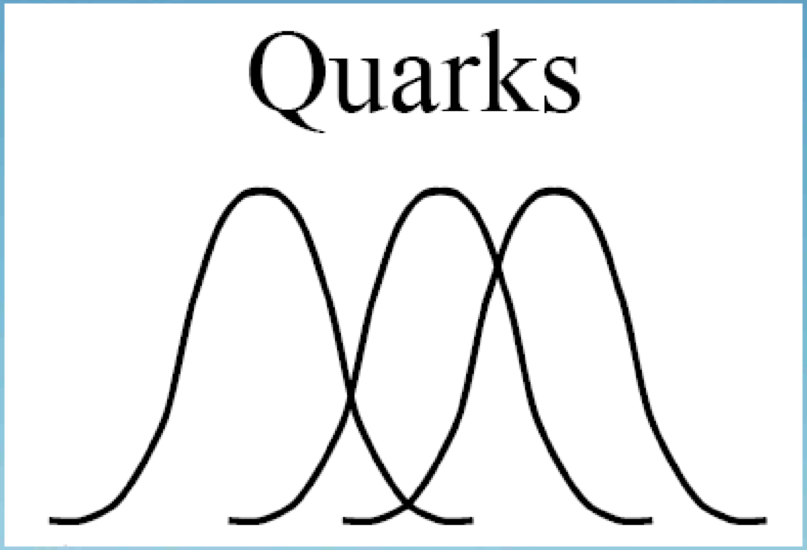


Flat Extra Dimensions

TeV^{-1} Flat Extra Dimensions

- Give up explanation of the v/M_P hierarchy
- Fermion masses could be naturally explained

Arkani-Hamed, Schmaltz 00



TeV^{-1} Flat Extra Dimensions

- Give up explanation of the v/M_P hierarchy
- Fermion masses could be naturally explained
- But then flavour and CP maximally violated

Delgado, Pomarol, Quiros 00

- Could still have implications for top physics

Aguila, Santiago 01

TeV^{-1} Flat Extra Dimensions

- Give up explanation of the v/M_P hierarchy
- Fermion masses could be naturally explained
- But then flavour and CP maximally violated
- Impose Universality: all fields are identical
  - Give up explanation of flavour **Appelquist, Cheng, Dobrescu 01**
  - Geometric discrete symmetry: KK parity
    - (Lightest) new physics only pair produced $M \gtrsim 0.5\ \mathrm{TeV}$
    - Natural dark matter candidate **Servant, Tait 03**
    - SUSY look-alike!! **Cheng, Matchev, Schmaltz 02**

Universal Extra Dimensions

PHYSICAL REVIEW D **66**, 056006 (2002)

Bosonic supersymmetry? Getting fooled at the CERN LHC

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Martin Schmaltz
Department of Physics, Boston University, Boston, Massachusetts 02215
(Received 3 June 2002; published 23 September 2002)

We define a minimal model with universal extra dimensions, and begin to study its phenomenology. The collider signals of the first Kaluza-Klein (KK) level are surprisingly similar to those of a supersymmetric model with a nearly degenerate superpartner spectrum. The lightest KK particle (LKP) is neutral and stable because of KK parity. KK excitations cascade decay to the LKP yielding missing energy signatures with relatively soft jets and leptons. Level 2 KK modes may also be probed via their KK number violating decays to standard model particles. In either case we provide initial estimates for the discovery potential of the Fermilab Tevatron and the CERN Large Hadron Collider.

DOI: 10.1103/PhysRevD.66.056006 PACS number(s): 11.10.Kk, 14.80.−j, 04.50.+h

Universal Extra Dimensions

- Discrimination from SUSY difficult at LHC
- Relevant scales probed with $\mathcal{L} \sim 1\mathrm{fb}^{-1}(14\ \mathrm{TeV})$
- Second level accessible for high luminosity
  - Double peak for EW bosons to dileptons
  - G_2 decay to boosted tops competitive!
- More sophisticated models possible: worth looking for them!
- First example (but not the only one) that we shouldn't call it SUSY too early!

Warped Extra Dimensions

Warped Extra Dimensions

Randall, Sundrum 99

- Extra dimension strongly curved $\kappa \sim M_P$
- EWSB scale natural from gravitational redshift
- Built-in flavour protection: RS-GIM mechanism
  - Hierarchical fermion masses and mixing angles from wave function localization
  - Flavour violation scales with masses and/or mixing
- New physics couples linearly with stronger coupling to heavier SM particles (Top, H, V_L)

$$g_{q,l} \sim g_{SM}/5 \qquad g_{t_L,b_L} \sim g_{SM}$$

$$g_H \sim 5\,g_{SM} \qquad g_{t_R} \sim 5\,g_{SM}$$

How large can ED be?

Flavour protection?

YES

MFV,
Universality, ...

NO

$M \gtrsim 10^3$ TeV

Linear coupling
to SM particles?

NO

YES

$M \gtrsim 100$ GeV

SUSY

Flat Extra
Dimensions

$M \gtrsim 1-5$ TeV

Technicolor

Warped Extra
Dimensions

Warped Extra Dimensions

Randall, Sundrum 99

- Strong coupling to top and gauge bosons

$$M \gtrsim 3.5\ \text{TeV}$$

Carena, Ponton, Santiago, Wagner 06-07

- Requires custodial symmetry (or $M \gtrsim 5\ \text{TeV}$)

$$SU(2)_L \to SU(2)_L \times SU(2)_R \times P_{LR}$$

Agashe, Delgado, May, Sundrum 99; Agashe, Contino, Da Rold, Pomarol 06

- New fermions (Custodians) are naturally lighter and can have exotic quantum numbers

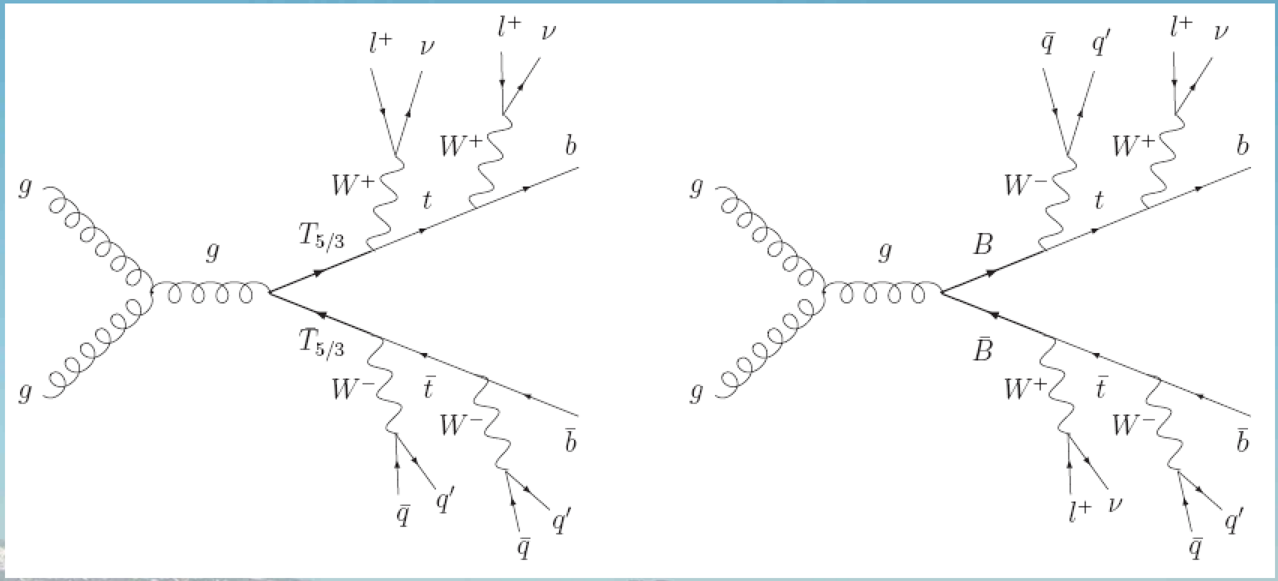
$$M_\Psi \gtrsim 0.5\ \text{TeV} \qquad \begin{pmatrix} T \\ B \end{pmatrix} \quad \begin{pmatrix} X \\ T \end{pmatrix} \qquad Q = \frac{5}{3}$$

Fermion Custodians in WED

- New light vector-like quarks that decay to top and longitudinal vector bosons or Higgs

$$\left.\begin{matrix}\begin{pmatrix} X \\ T \end{pmatrix} \\ \\ \begin{pmatrix} T \\ B \end{pmatrix}\end{matrix}\right\} \begin{matrix} \to W_L t \\ \to Z_L t, Ht \\ \to W_L t \end{matrix}$$

Dennis, Karagoz, Servant, Tseng 07
Contino, Servant 08
Aguilar-Saavedra 09
Mrazek, Wulzer 09



Fermion Custodians in WED

- New light vector-like quarks that decay to top and longitudinal vector bosons or Higgs
- Very early discovery at the LHC
    - $\mathcal{L} \sim 0.16 - 1.9\ \mathrm{fb}^{-1}$ for $M = 500\ \mathrm{GeV}$

Aguilar-Saavedra 09

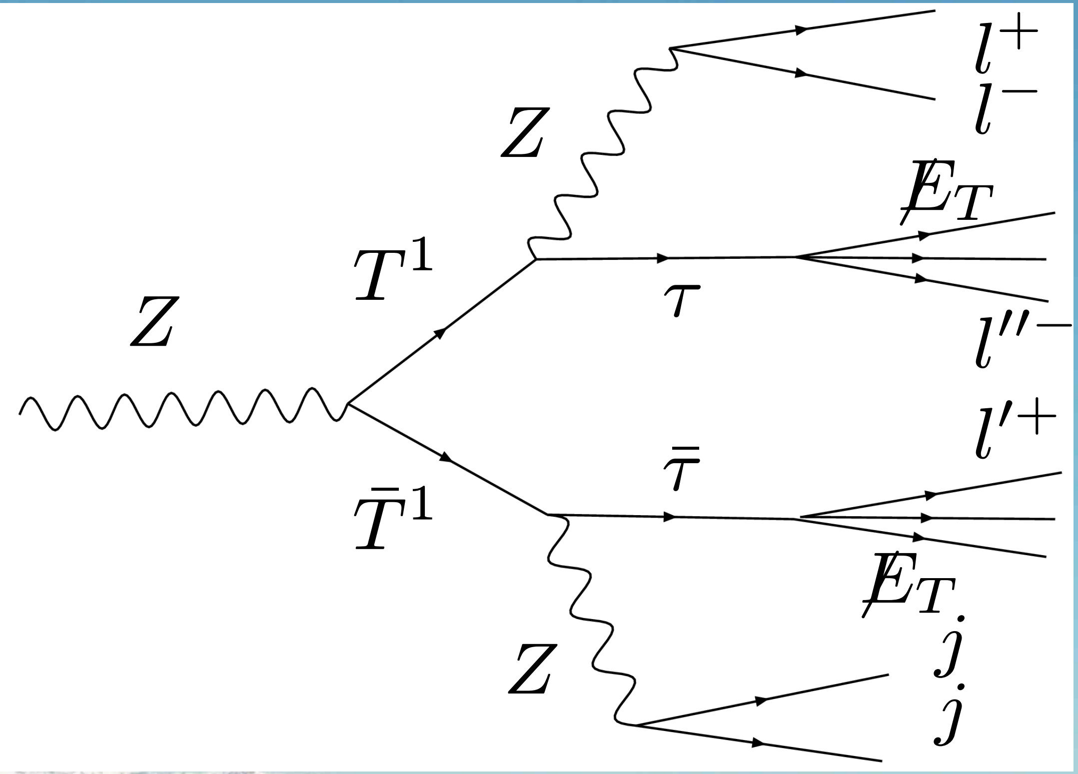
- Single production useful for heavier masses
    - $M = 1.5\ \mathrm{TeV}$
    - Boosted tops/W/Z can be an issue/advantege

Mrazek, Wulzer 09

Fermion Custodians in WED

Aguila, Carmona, Santiago 10

- Can also happen for the tau lepton



Very collimated

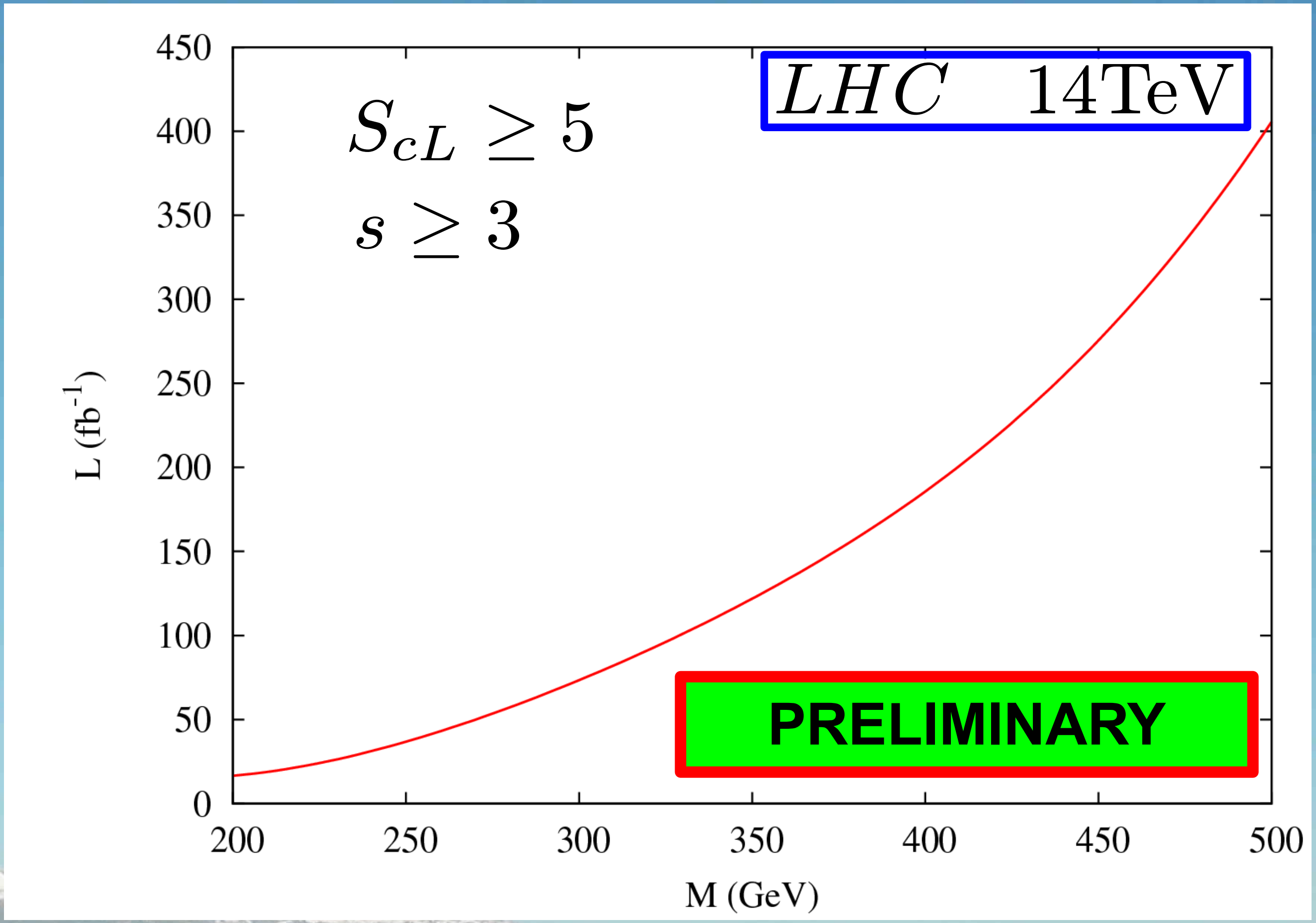
Very collimated

Fermion Custodians in WED

Aguila, Carmona, Santiago 10

- Discovery reach

$$S_{cL} \equiv \sqrt{2\left[(s+b)\ln\left(1-\frac{s}{b}\right)-s\right]}$$



Vector bosons from WED

- Heavy, broad new vector bosons with reduced couplings to light SM particles and enhanced BR to tops and longitudinal gauge bosons
  - KK gluon $M \lesssim 4\ \mathrm{TeV}$ — **Lillie, Randall, Wang 07; Agashe, Belyaev, Krupovnickas, Perez, Virzi 07; ...**
  - KK Z/A $M \lesssim 2\ \mathrm{TeV}$ — **Agashe, Davoudiasl, Gopalakrishna, Han, Huang, Perez, Si, Soni 07**
  - KK W $M \lesssim 3\ \mathrm{TeV}$ — **Agashe, Gopalakrishna, Han, Huang, Soni 09**

Vector bosons from WED

- Heavy, broad new vector bosons with reduced couplings to light SM particles and enhanced BR to tops and longitudinal gauge bosons
- Difficult at the LHC
  - Reduced cross section (small coupling to valence quarks)
  - Wide resonances
  - Require full machinery for boosted objects:
    - Boosted tops for KK gluons, Z and W
    - Boosted W, Z (including leptons) from KK Z and W
  - Can decay to KK fermions
    - Reduced BR to tops

Carena, Medina, Panes, Shah, Wagner 08

Other signatures

- KK gravitons: similar to KK Z
- Radion:
  - Non-standard Higgs type phenomenology
- Many more possibilities:
  - Discrete symmetry: dark matter+lighter resonances
  - Higgsless models $M \gtrsim 0.7\ \mathrm{TeV}$ (with tuning)
  - Soft-wall: deviations from RS on the IR
    - KK modes closer together (can discover several levels)
    - $M \gtrsim 1.5\ \mathrm{TeV}$
  - Unhiggs: continuum with a mass gap

LHC timeline for warped extra dimensions (personal view)

- Early discovery of new vector-like quarks with large couplings to the top $\mathcal{L} \sim 1\ \mathrm{fb}^{-1}$
- Nothing else for a while
- Discovery of new vector-like leptons with large couplings to the tau for $\mathcal{L} \sim 10 - 100\ \mathrm{fb}^{-1}$
- High luminosity discovery of new wide vector resonances with large BR into tops $\mathcal{L} \sim 300\ \mathrm{fb}^{-1}$
- Non standard Higgs phenomenology due to radion

MC implementation

- Several ED models implemented in MC:
  - Minimal UED:
    - FeynRules **Christensen et al., 08-09**
    - Comphep **Datta, Kong, Matchev 10**
  - RS:
    - Pythia
    - Some private codes (Madgraph)

MC implementation

- Several ED models implemented in MC:
  - FeynRules **Christensen et al., 08-09**

Model	Contact	Status
Standard Model	N. Christensen, C. Duhr	Available
Mimimal Higgsless Model (3-Site Model)	N. Christensen	Available
Standard model + Scalars	C. Duhr	Available
Higgs effective theory	C. Duhr	Available
Hidden Abelian Higgs Model	C. Duhr	Available
Hill Model	P. de Aquino, C. Duhr	Available
The general 2HDM	C. Duhr, M. Herquet	Available
MSSM	B. Fuks	Available
Minimal UED	P. de Aquino	Available
Large Extra Dimensions	P. de Aquino	Available
Chiral perturbation theory	C. Degrande	Available
Strongly Interacting Light Higgs	C. Degrande	Available

- Interfaces to:
  - Calchep/Comphep
  - Feynarts
  - Madgraph
  - Sherpa
  - ...

Conclusions

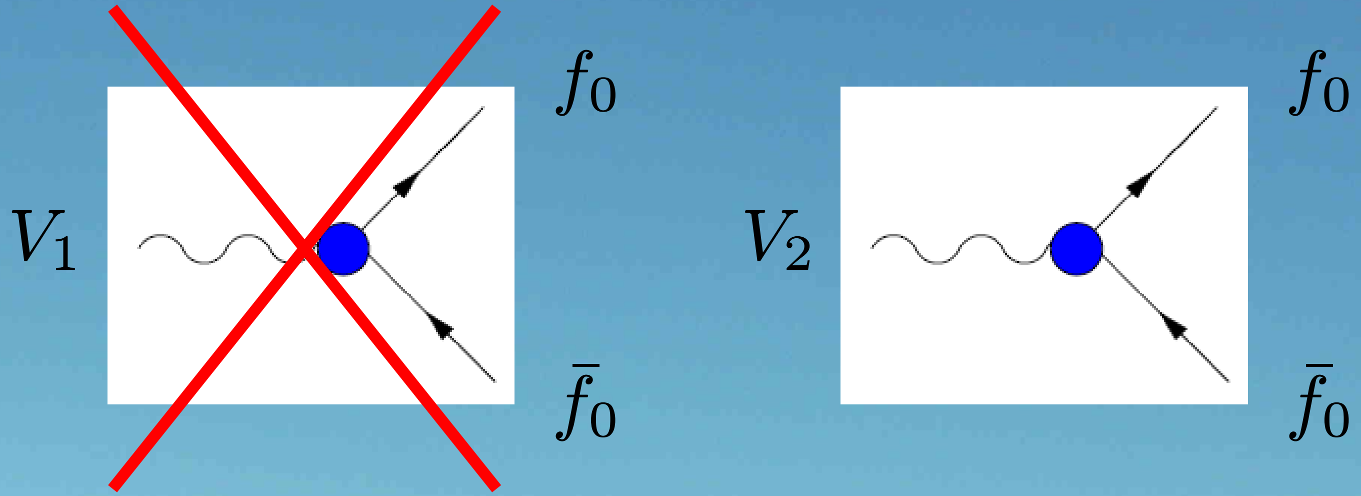
- Extra dimensions: well motivated BSM physics
- Will we (ever) know there are extra dimensions?
  - … not likely (in the near future)
  - It is difficult to get the full picture at the LHC
    - UED (Bosonic SUSY) ⟺ SUSY
    - WED/New strong interactions: too close to LHC threshold?
- Heavy new physics results in boosted final states
  - Dedicated analysis for boosted objects are necessary
  - Crucial to disentangle top jets, W or Z jets, b jets, etc.

Back-up slides

Universal Extra Dimensions

Appelquist, Cheng, Dobrescu 01

- KK parity: $(-1)^n$ preserved at interactions

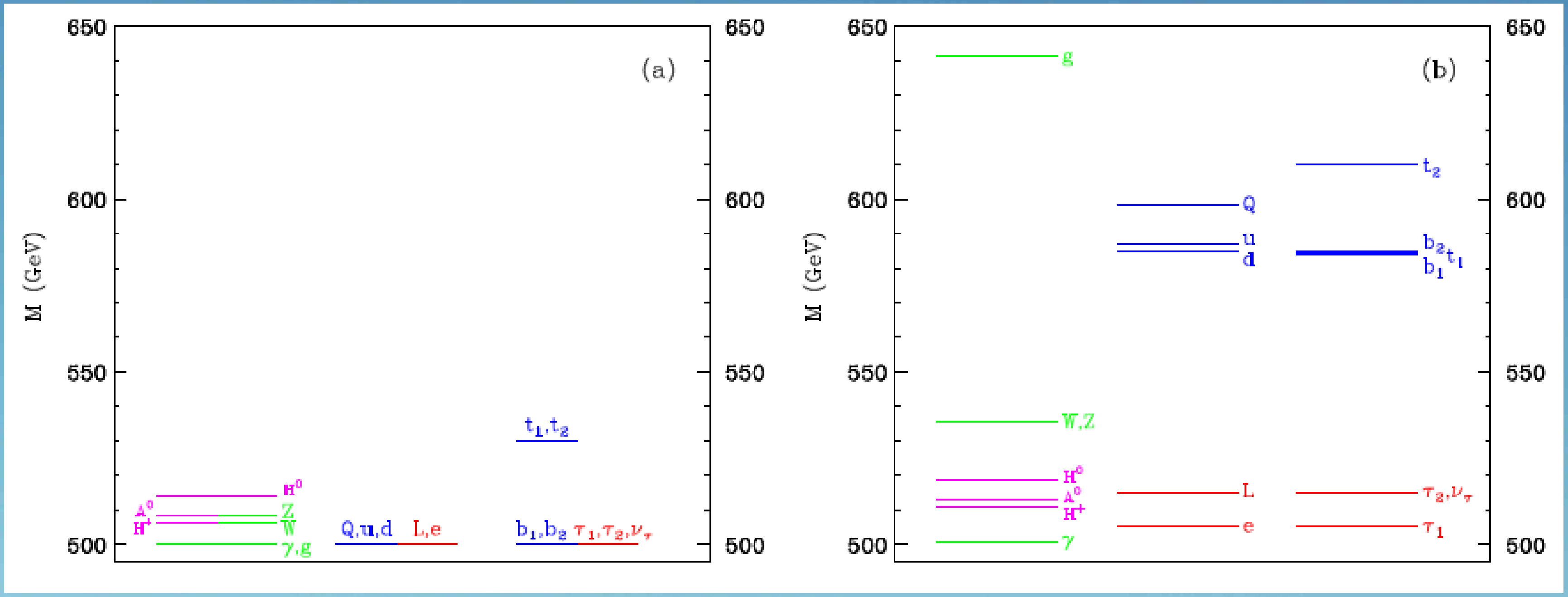


- Below 1 TeV (only first KK level) every SM particle has a (same spin) partner, which is odd under KK parity

Universal Extra Dimensions

Cheng, Matchev, Schmaltz 02

- The KK spectrum is strongly degenerate



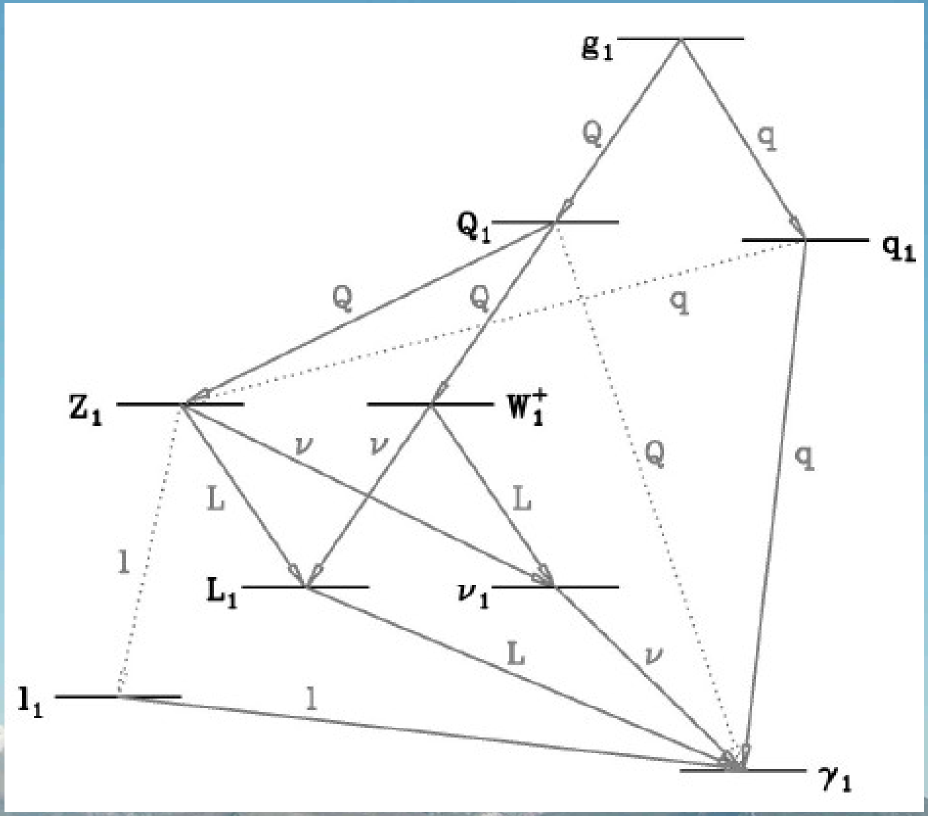
Tree level spectrum

One loop spectrum

- New physics is quite soft

Universal Extra Dimensions

- Collider Phenomenology
  - Pair production of new particles
  - Cascade decays into soft particles and missing energy



Fermion Custodians in WED

Aguila, Carmona, Santiago 10

- Can also happen for the tau lepton

$$\left.\begin{matrix}\begin{pmatrix} N \\ T \end{pmatrix} \\ \\ \begin{pmatrix} T \\ Y \end{pmatrix}\end{matrix}\right\} \quad \begin{matrix} \to W_L \tau \\ \\ \to Z_L \tau, H\tau \\ \\ \to W_L \tau \end{matrix}$$

- Lepton mixing from A4 symmetry
  - LFV and lepton masses suppressed by A4 breaking
  - Tau is naturally more composite than expected from its mass
  - Tau custodians (light lepton resonances with strong coupling to the tau) natural in these models