Warped views on the LHC

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My goal for this talk

Discuss how (and when) warped extra dimensions will be found at the LHC

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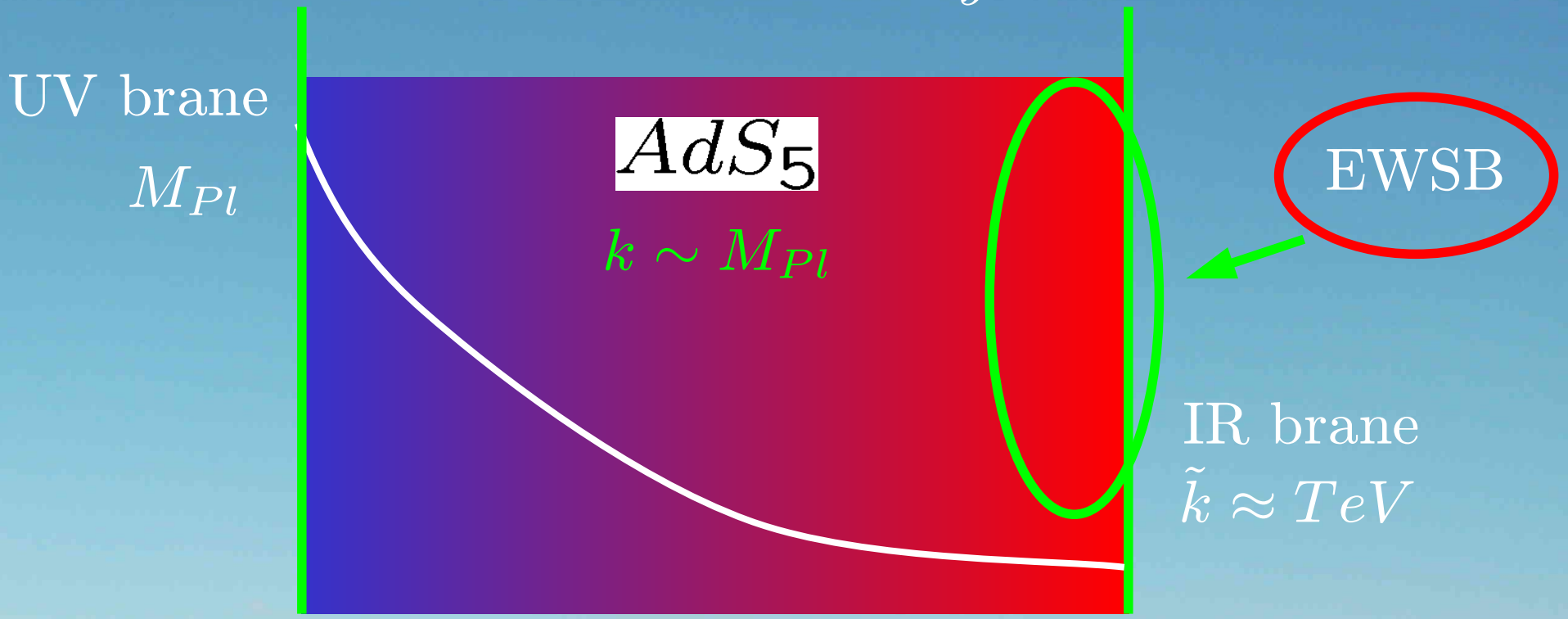
What I mean by warped extra dimensions

- A slice of AdS_5 to solve the hierarchy problem

Randall, Sundrum 99

$$ds^2 = e^{-2ky} dx^2 - dy^2$$



What I mean by warped extra dimensions

- A slice of AdS_5 to solve the hierarchy problem
- But not only actual extra dimensional models
- AdS/CFT: models with WED are weakly coupled duals to strongly coupled CFT in 4D.

Maldacena 97

Gubser, Klebanov, Polyakov 98; Witten 98

Arkani-Hamed, Porrati, Randall 00; Rattazzi, Zaffaroni 00; Pérez-Victoria 01

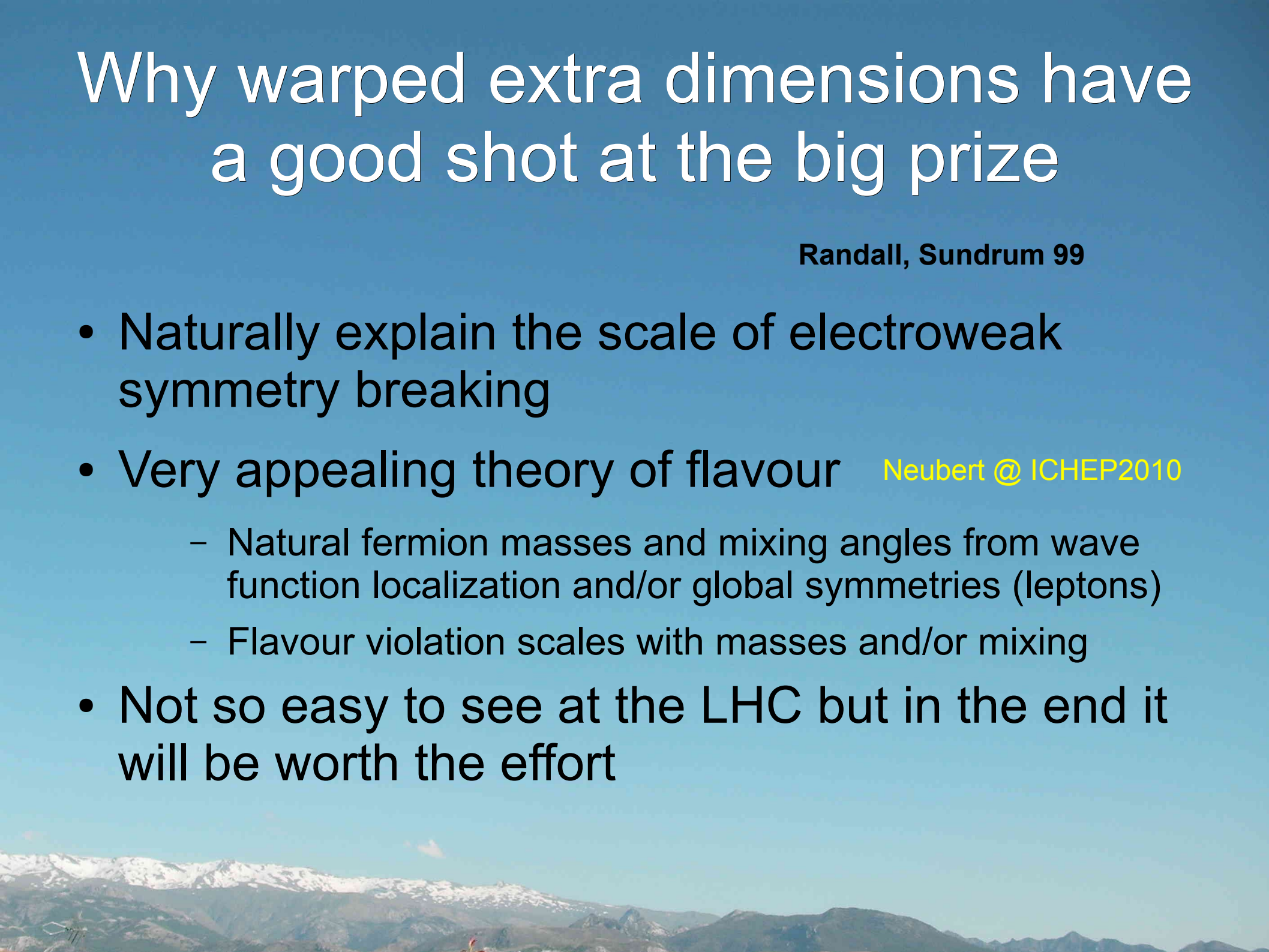
- Many models of strong EWSB share the same features

Why warped extra dimensions have a good shot at the big prize

Why warped extra dimensions have a good shot at the big prize

Randall, Sundrum 99

- Naturally explain the scale of electroweak symmetry breaking
- Very appealing theory of flavour Neubert @ ICHEP2010
  - Natural fermion masses and mixing angles from wave function localization and/or global symmetries (leptons)
  - Flavour violation scales with masses and/or mixing
- Not so easy to see at the LHC but in the end it will be worth the effort



Why not so easy?

- Many new particles with TeV-ish masses but
  - They are heavier than expected
  - They couple quite strongly to heavier SM particles (t, H, Z, W) but feebly to lighter SM particles

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

$$g_{W,Z,H} \sim 5\, g_{SM}$$

$$g_{t_L,b_L} \sim g_{SM}$$

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

EW Constraints on Warped Extra Dimensions

- Strong coupling to top and gauge bosons requires custodial symmetry

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

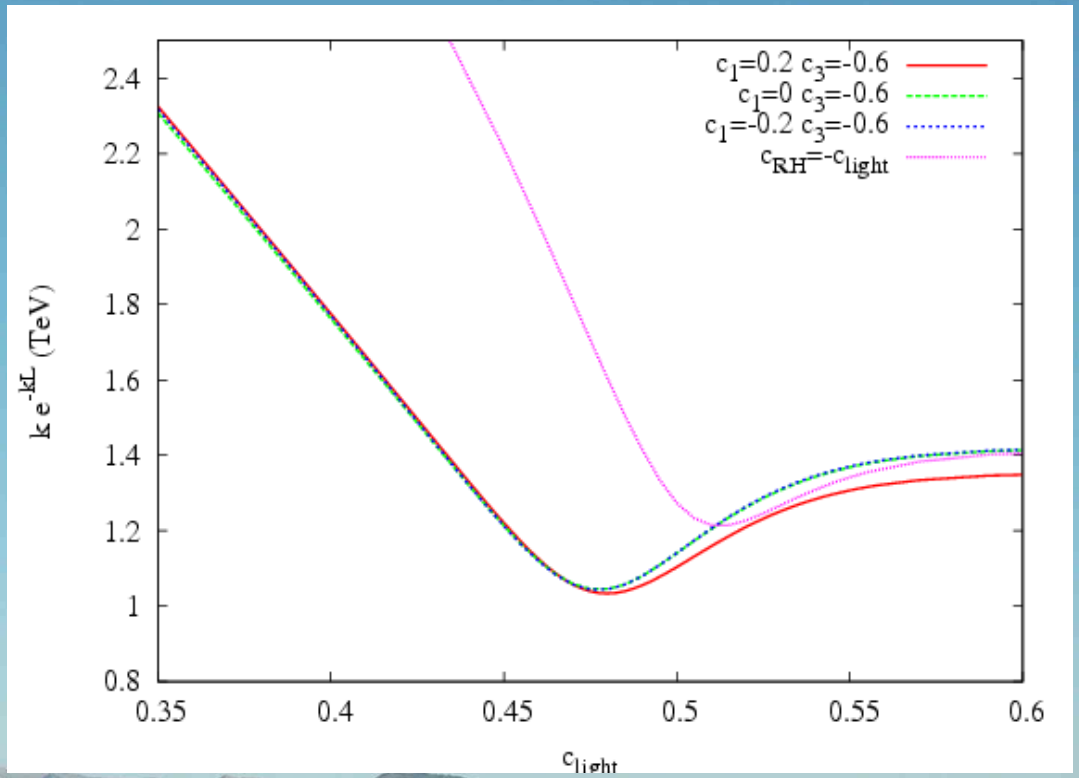
Agashe, Delgado, May, Sundrum 99; Agashe, Contino, Da Rold, Pomarol 06

- Detailed analysis of EW constraints

Carena, Pontón, Santiago, Wagner 06-07

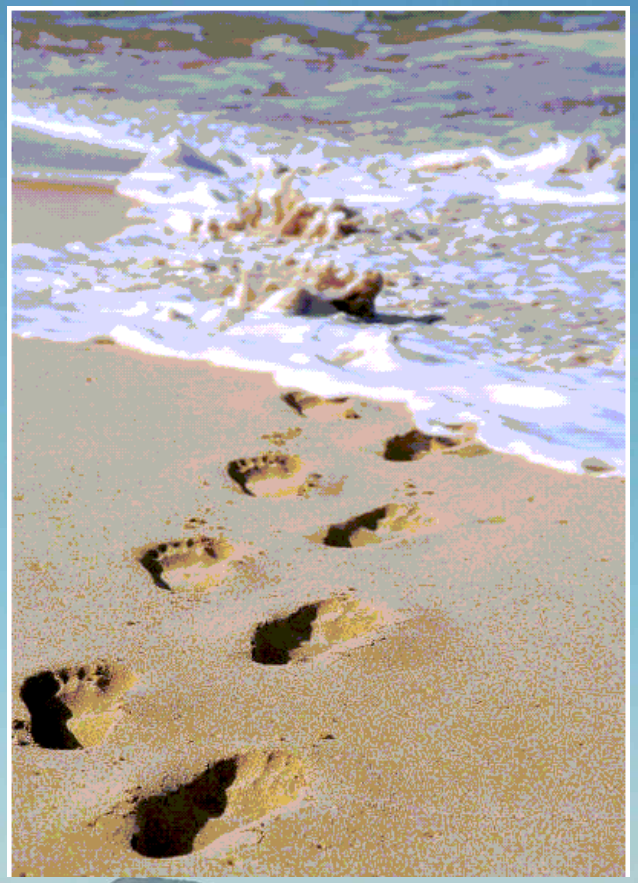
$$M_{\text{Gauge}} \gtrsim 2.5 - 3.5\text{TeV}$$

$$M_{\text{Fermions}} \gtrsim 300\text{GeV}$$



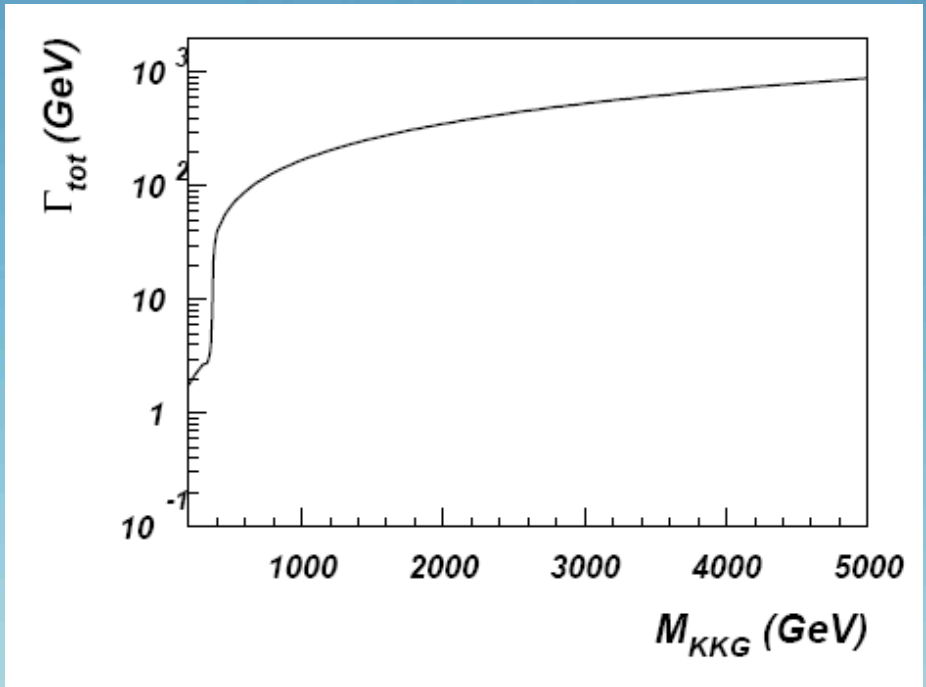
The footprint of warped extra dimensions/strong EWSB:

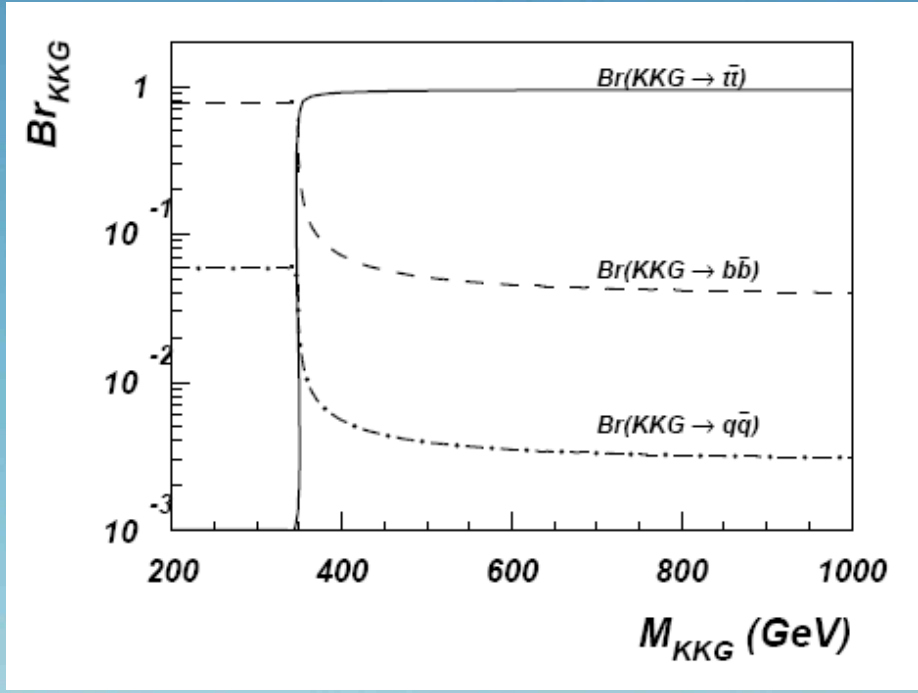
New vector resonances



Vector bosons from WED (not your standard Z')

- Heavy, broad new vector bosons with reduced couplings to light SM particles and enhanced BR to tops and longitudinal gauge bosons





Taken from Agashe, Belyaev, Krupovnickas, Perez, Virzi 07

Vector bosons from WED (not your standard Z')

- 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
  - Can decay to new fermions
    - Reduced BR to tops
    - Even larger widths
  - Require large luminosity and full machinery for boosted objects (tops, Z and W)

Carena, Medina, Panes, Shah, Wagner 08

Vector bosons from WED (not your standard Z')

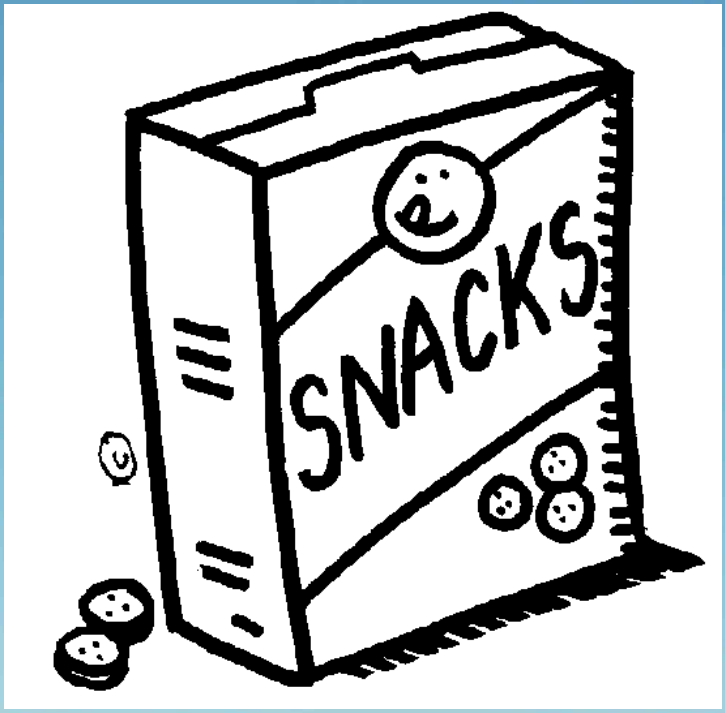
- Heavy, broad new vector bosons with reduced couplings to light SM particles and enhanced BR to tops and longitudinal gauge bosons

$$\text{with } 100 \text{ fb}^{-1}$$

- G'	$M \lesssim 4 - 4.5$ TeV	**Lillie, Randall, Wang 07; Agashe, Belyaev, Krupovnickas, Perez, Virzi 07; Rehermann, Tweedied 10**
- Z'	$M \lesssim 2$ TeV	**Agashe, Davoudiasl, Gopalakrishna, Han, Huang, Perez, Si, Soni 07**
- W'	$M \lesssim 2 - 3$ TeV	**Agashe, Gopalakrishna, Han, Huang, Soni 09**

OK, it's a long-distance race.

Do we get any snacks along the way?



New fermions from WED

- EW precision observables require a new structure: custodial symmetry
  - New fermions come in multiplets of a larger symmetry $SU(2)_L \to SU(2)_L \times SU(2)_R \times P_{LR}$
  - These fermion custodians can be light and couple strongly to SM fermions
    - More natural for heavier SM fermions
    - Custodial symmetry protects some of their couplings: all SM fermions can have light custodians

Top custodians

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

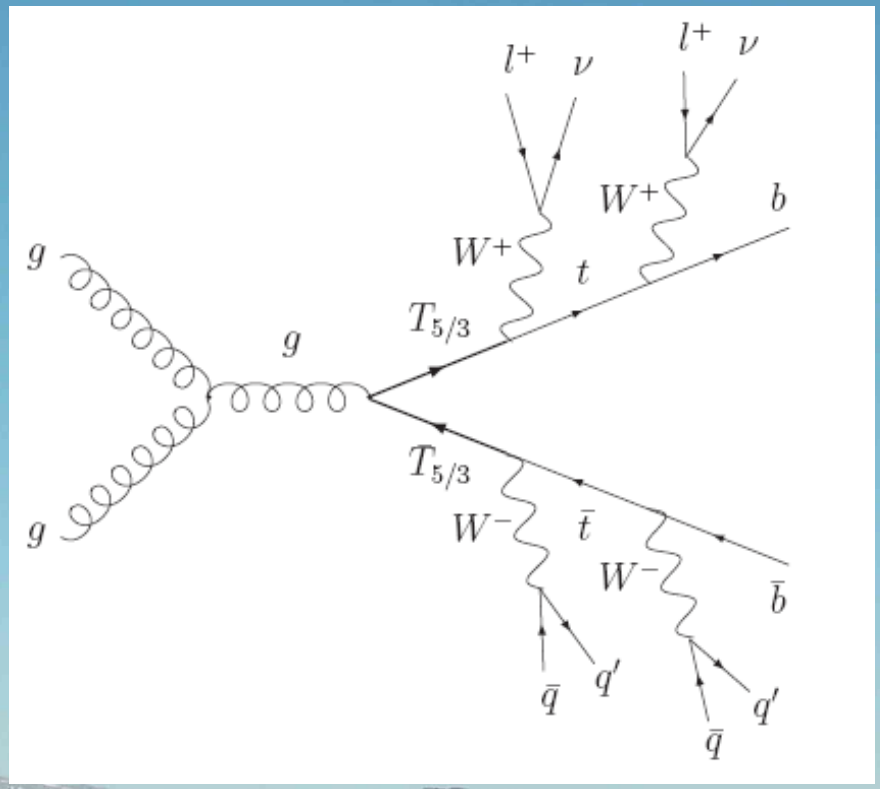
Carena, Pontón, Santiago, Wagner 06-07; Cacciapaglia, Csaki, Marandella, Terning 06; Contino, Da Rold, Pomarol 06

$$\begin{pmatrix} X \\ T \end{pmatrix} \rightarrow W_L t$$

$$\rightarrow Z_L t, Ht$$

$$\begin{pmatrix} T \\ B \end{pmatrix} \rightarrow W_L t$$

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



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Dennis, Karagoz, Servant, Tseng 07
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  - Very early discovery

    Aguilar-Saavedra 09

$$\mathcal{L} \sim 0.16 - 1.9 \text{ fb}^{-1} \quad (M = 500 \text{ GeV})$$

  - Single production useful for heavier masses

    Mrazek, Wulzer 09

$$M \gtrsim 1.5 \text{ TeV}$$

Tau custodians

- Can also happen for the tau lepton

Aguila, Carmona, Santiago 10

$$\begin{pmatrix} N \\ E_1 \end{pmatrix} \rightarrow W_L\tau$$

$$\rightarrow Z_L\tau, H\tau$$

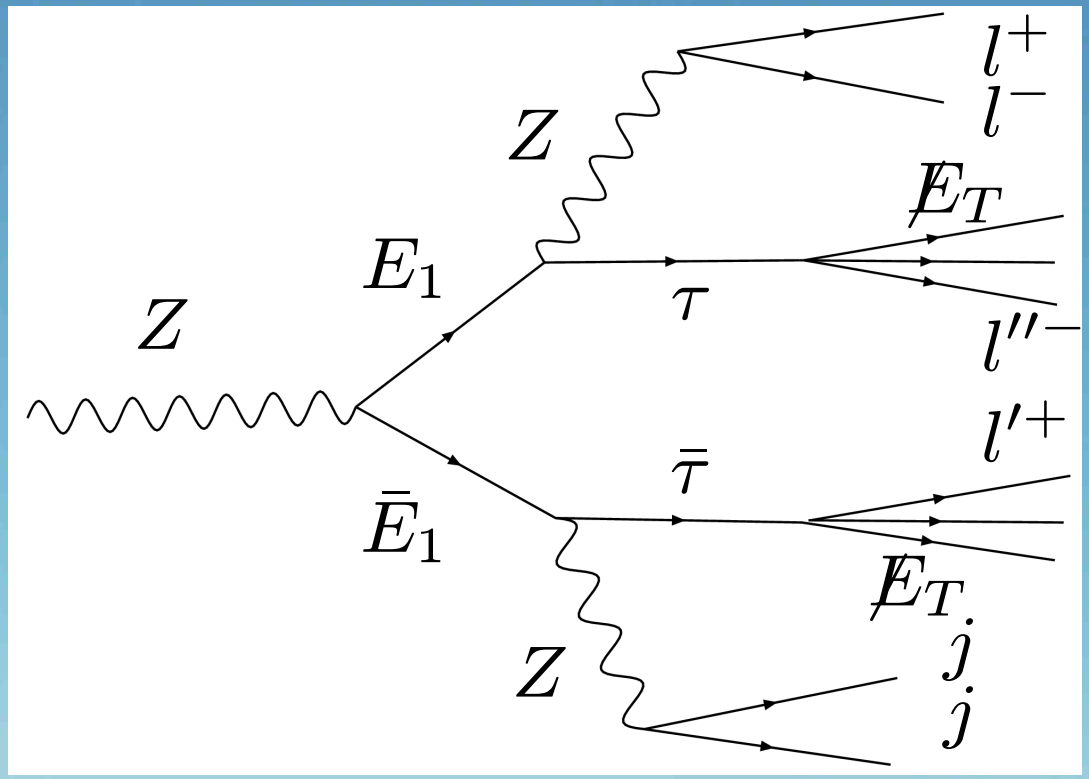
$$\begin{pmatrix} E_2 \\ Y \end{pmatrix} \rightarrow W_L\tau$$

- 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

Tau custodians

- Can also happen for the tau lepton

Aguila, Carmona, Santiago 10



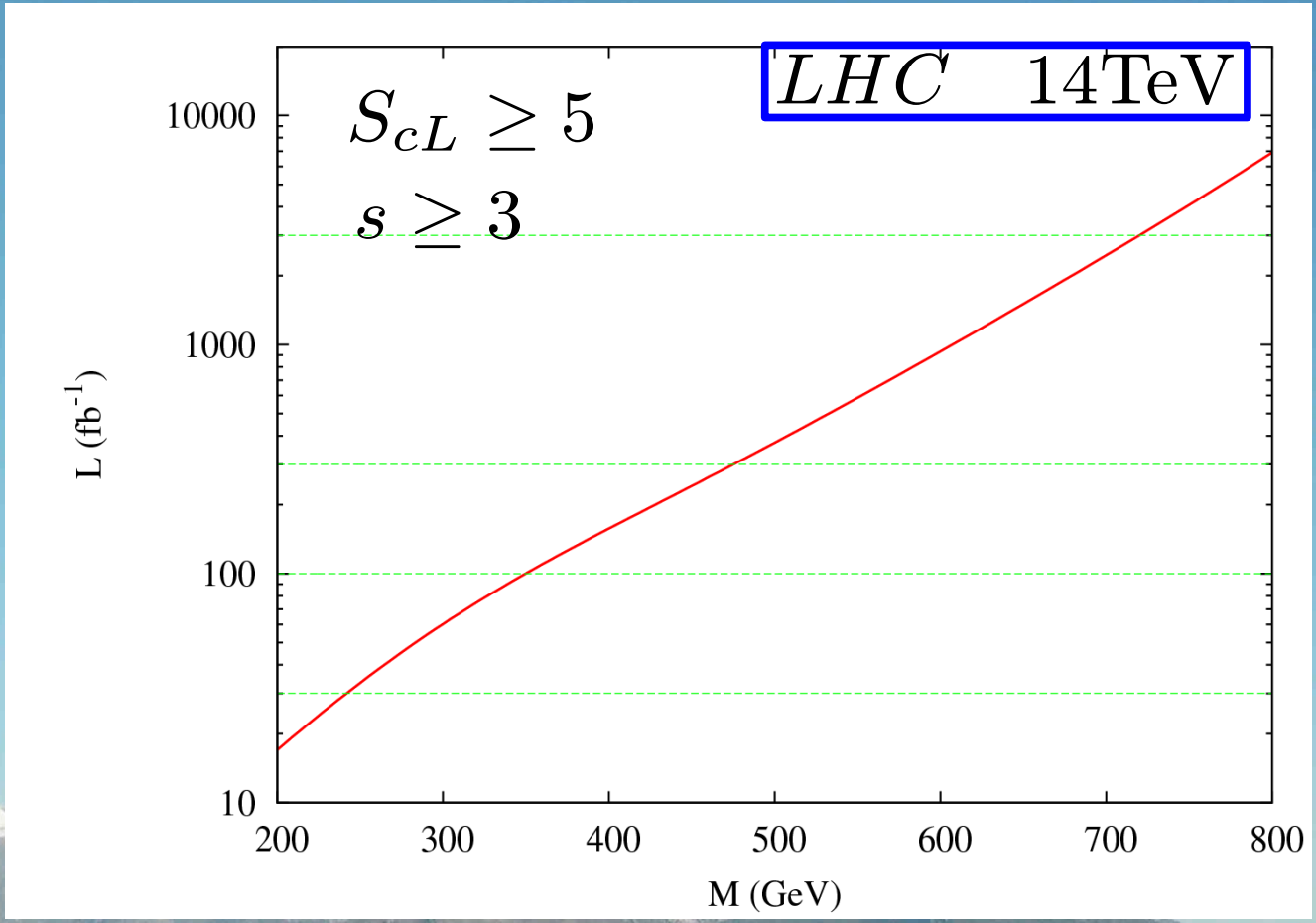
Very collimated

Very collimated

Tau custodians

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

Aguila, Carmona, Santiago 10

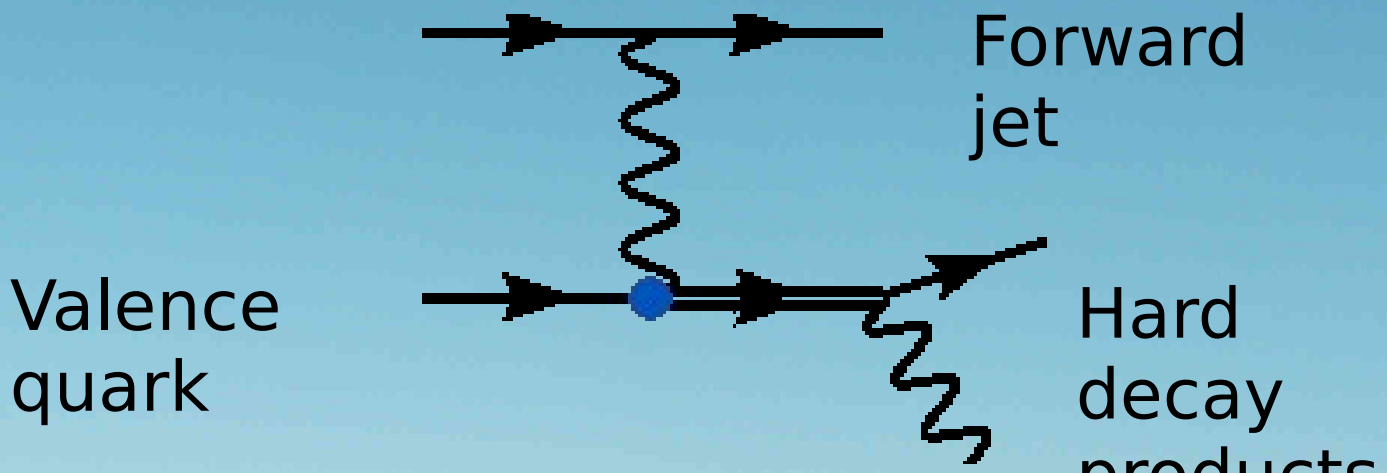


u, d custodians

- New quarks with large couplings to u,d
- Single production

Atre, Carena, Han, Santiago 08

  - Large coupling to valence quarks
  - Distinctive kinematics



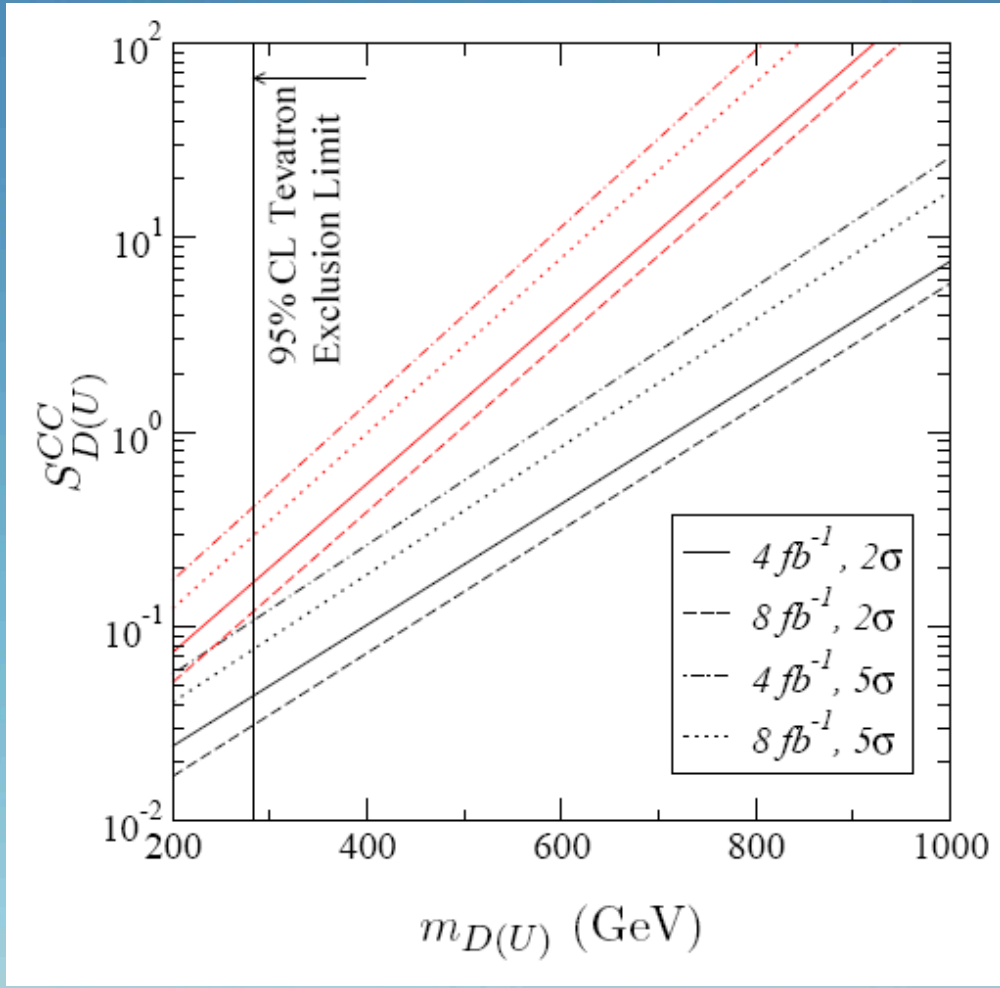
u, d custodians

- Tevatron analysis

  Atre, Carena, Han, Santiago 08

- First LHC run can be competitive

  Atre, Azuelos, Carena, Han, Ozcan, Santiago, Unel (in progress)

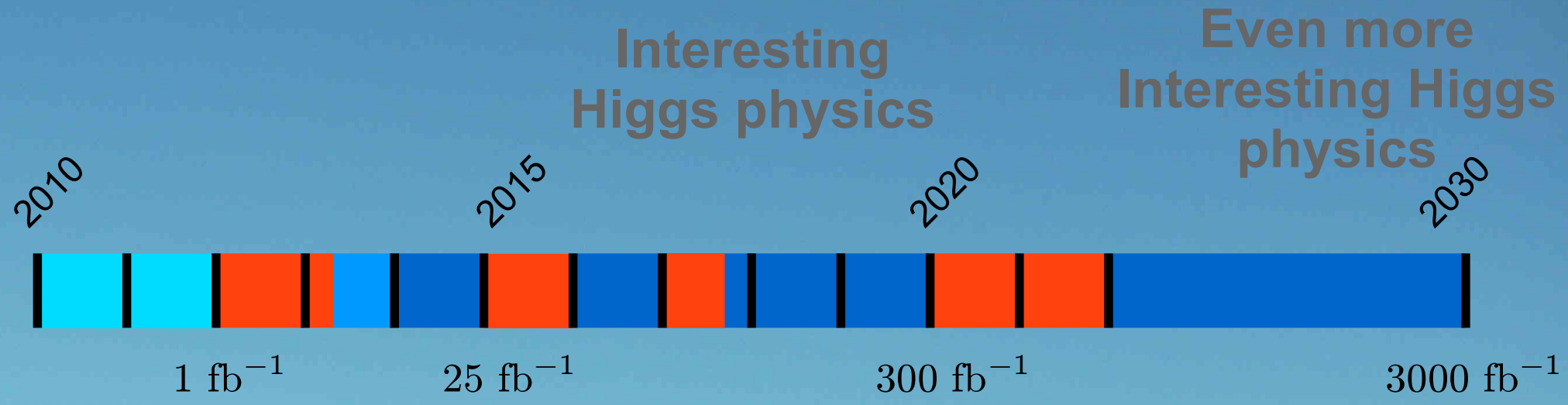


Other signatures

- KK gravitons: similar to KK Z
- Radion:
  - Non-standard Higgs type phenomenology
- Many more possibilities: Csaki @ ICHEP2010
  - Discrete symmetry: dark matter+lighter resonances
  - Higgsless models $M \gtrsim 0.7\ \mathrm{TeV}$ (give up flavour)
  - Little RS: weaker constraints, new LHC pheno Soni @ ICHEP2010
  - Soft-wall: deviations from AdS on the IR
  - Unhiggs: continuum with a mass gap

Warped Extra Dimensions at the LHC

LHC schedule taken from talks by M. Lamont (pLHC2010) and F. Zimmermann (KEK)



top custodians

u, d custodians

tau custodians

Heavy gluons

Heavy Z, W

New physics under the lamppost?

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Thank you for your attention!