Discovering Warped Extra Dimensions at the LHC

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My goal for this talk

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

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

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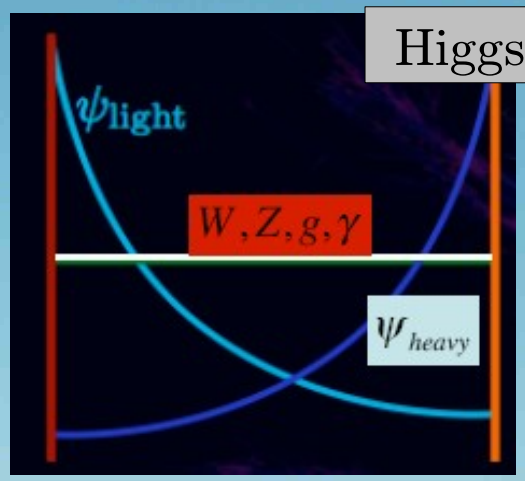
Randall, Sundrum 99

- Naturally explain the scale of electroweak symmetry breaking
- Very appealing theory of flavour



  - Natural fermion masses and mixing angles from wave function localization and/or global symmetries (leptons)
  - Flavour violation scales with masses and/or mixing

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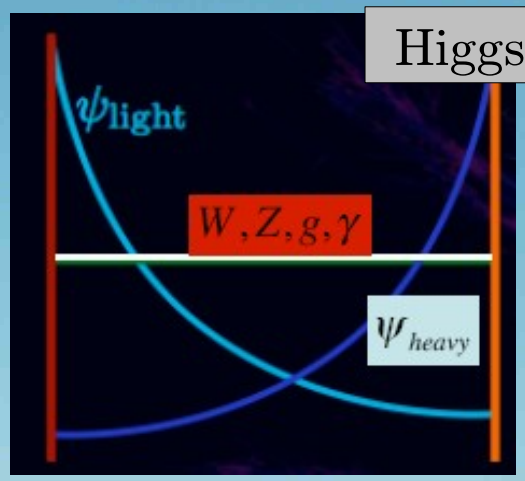


  - Natural fermion masses and mixing angles from wave function localization and/or global symmetries (leptons)
  - Flavour violation scales with masses and/or mixing

- 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 possible with custodial symmetry

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

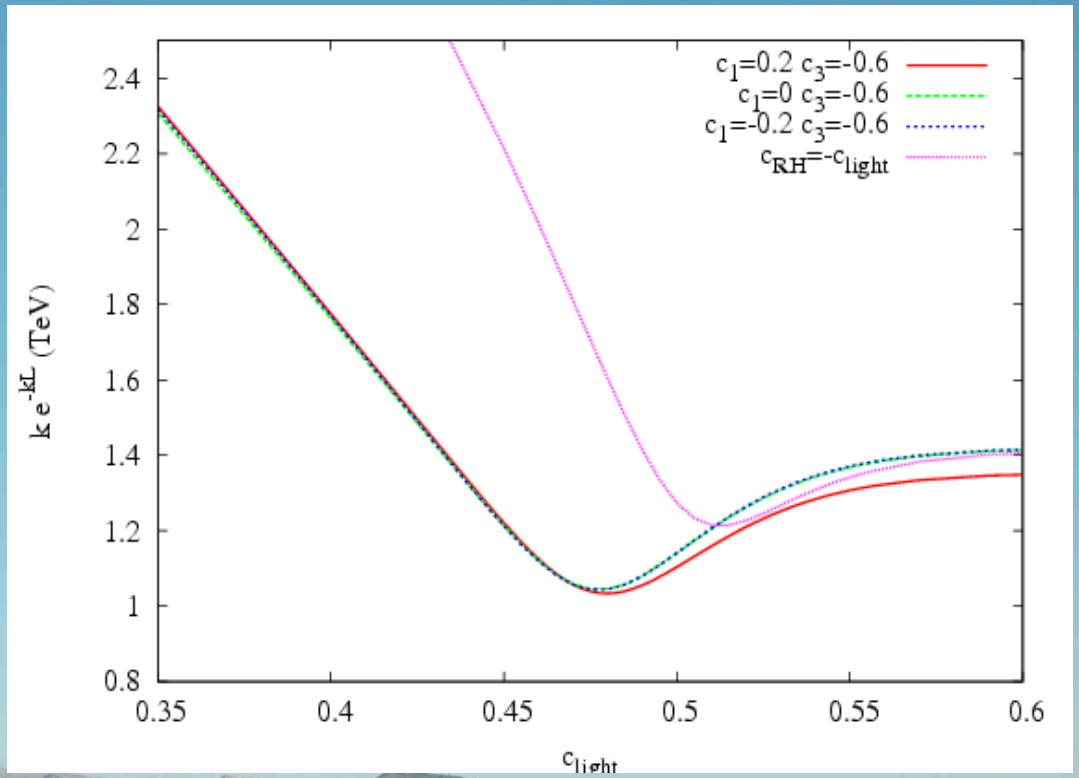
Agashe, Delgado, May, Sundrum 99; Agashe, Contino, Da Rold, Pomarol 06

- Detailed analysis of EW constraints

Carena, Pontón, Santiago, Wagner NPB (06), PRD(07)

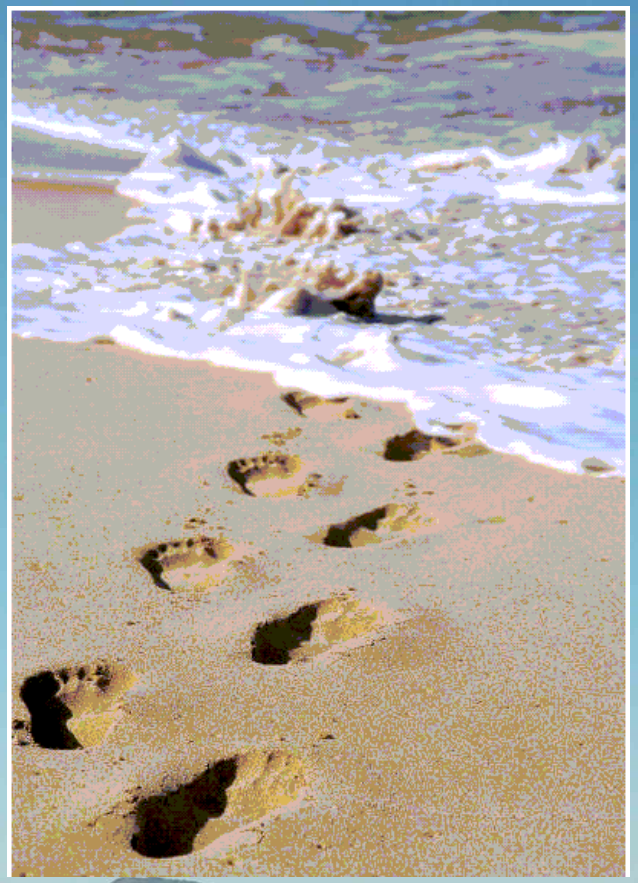
$$M_{\text{Gauge}} \gtrsim 2.5 - 3.5\,\text{TeV}$$

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



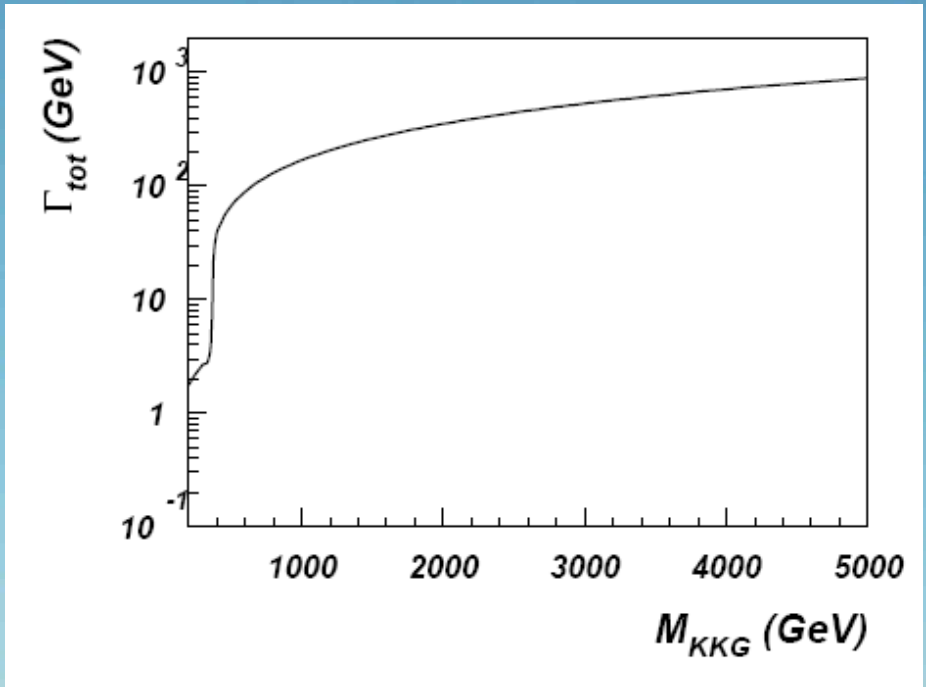
The footprint of warped extra dimensions/strong EWSB:

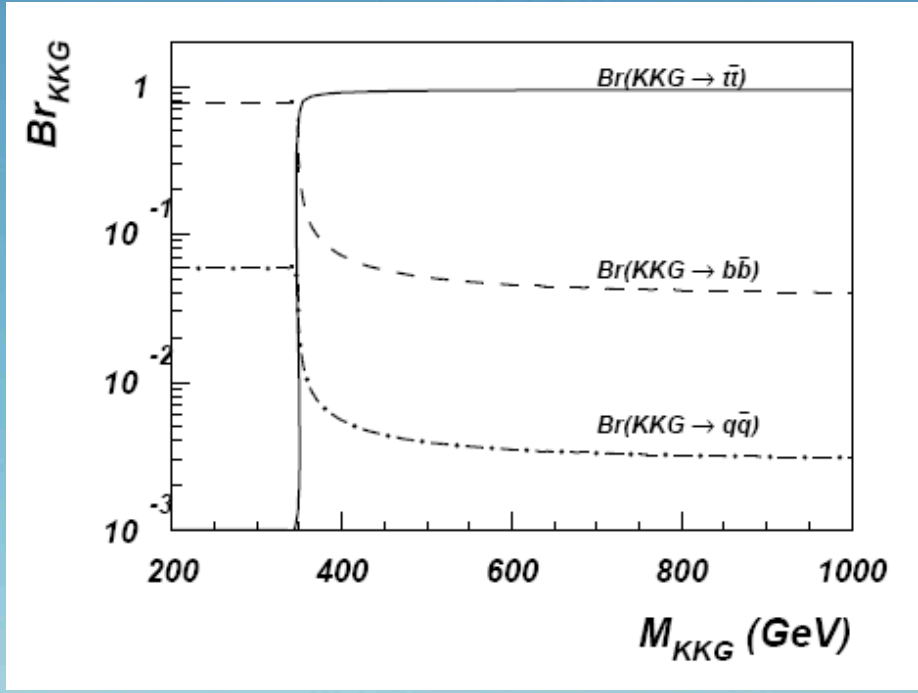
New vector resonances



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

Carena, Medina, Panes, Shah, Wagner 08

  - Require large luminosity and full machinery for boosted objects (tops, Z and W)

Vector bosons from WED (not your standard Z')

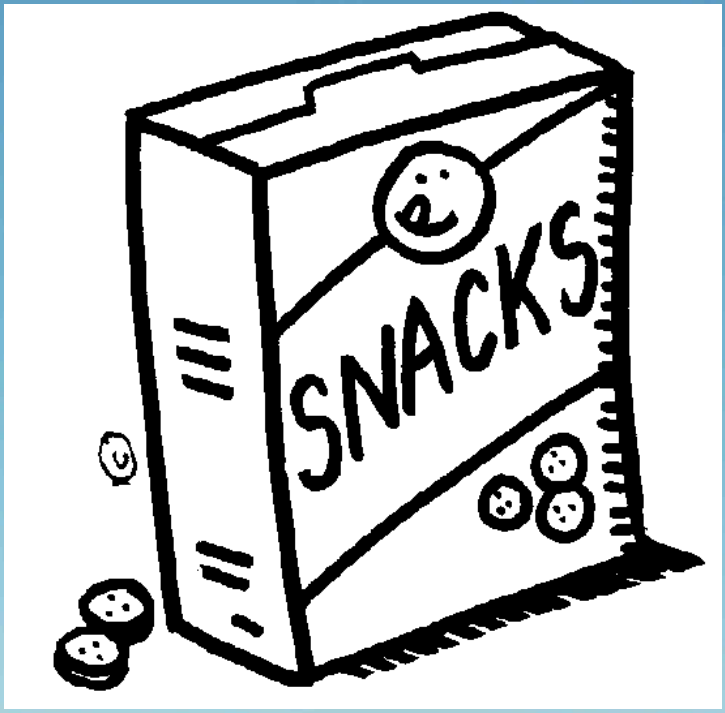
- Heavy, broad new vector bosons with reduced couplings to light SM particles and enhanced BR to tops and longitudinal gauge bosons

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

- G' $M \lesssim 4 - 4.5$ TeV — Lillie, Randall, Wang 07; Agashe, Belyaev, Krupovnickas, Perez, Virzi 07; Rehermann, Tweedie 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 can be protected by 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: <u>all SM fermions can have light custodians</u>

New fermions from WED

Custodial Symmetry

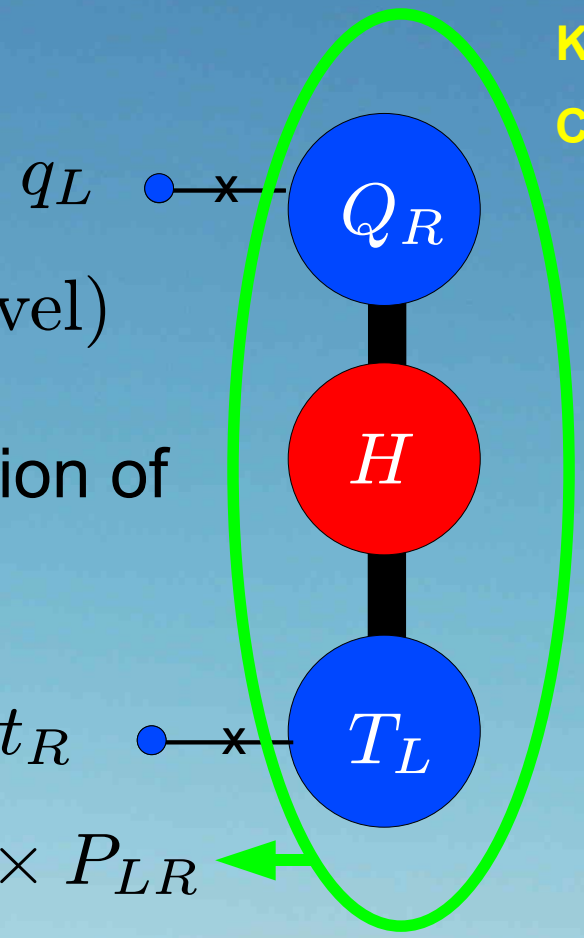
Sikivie et al 80; Agashe et al 03

$\Delta T = 0$ (tree level)

Custodial protection of $Z\bar{\psi}\psi$ coupling

Agashe, Contino, Da Rold, Pomarol 06

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



Partial Compositeness

Kaplan 91

Contino, Kramer, Son, Sundrum 06

SM: elementary states external to the strong sector

Linear coupling: degree of compositeness

FCNC suppressed by degree of compositeness

Heavy fields more composite

New fermions from WED

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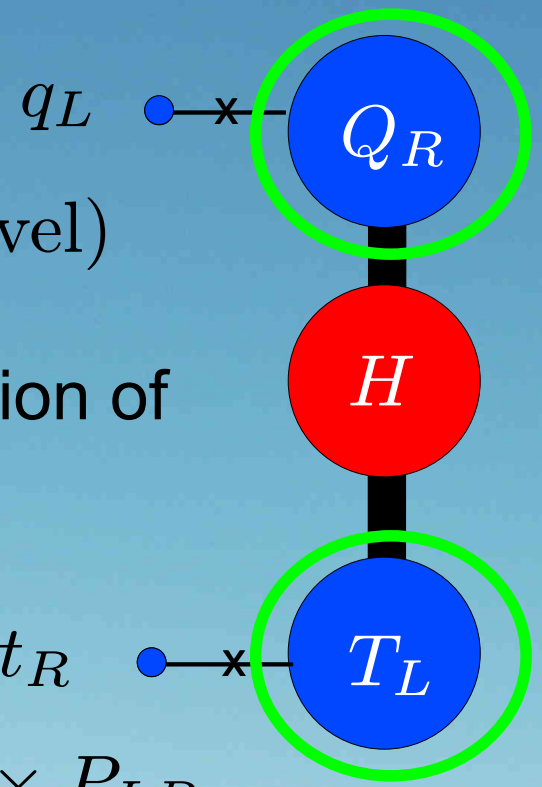


Fermion Custodians

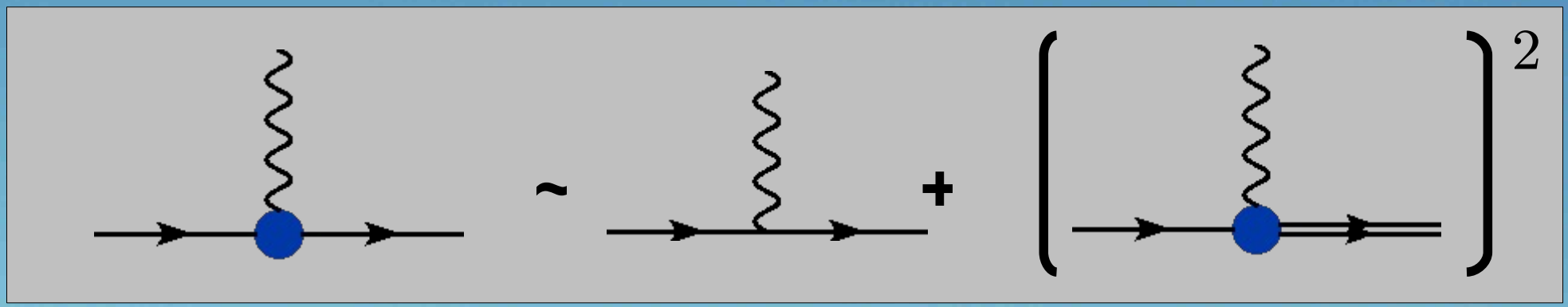
Fermion custodians: partners under custodial symmetry of composites mixing with elementary fields.

- Naturally light and strongly coupled for very composite fields

Custodial protection of couplings

- Custodians allowed even for light SM fermions

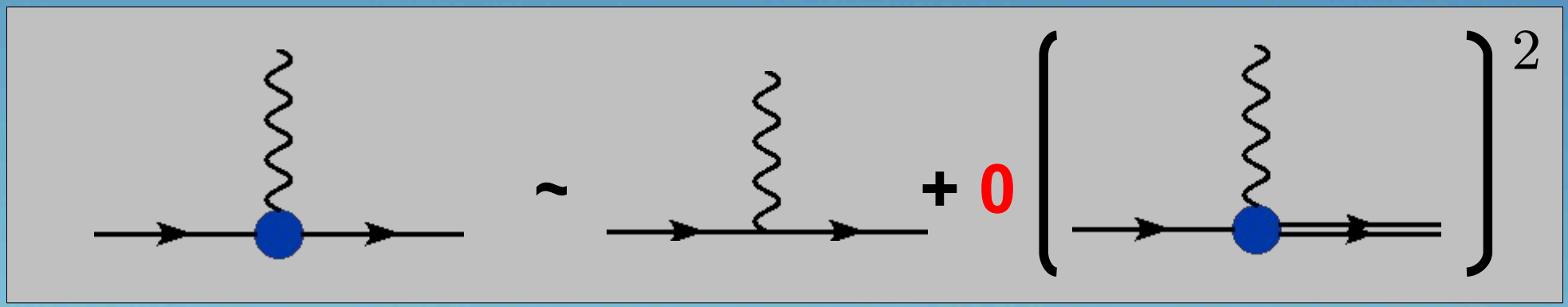
Generically



Custodial protection of couplings

- Custodians allowed even for light SM fermions

With custodial protection



- Cancellations between different contributions enforced by the custodial symmetry

Top custodians

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

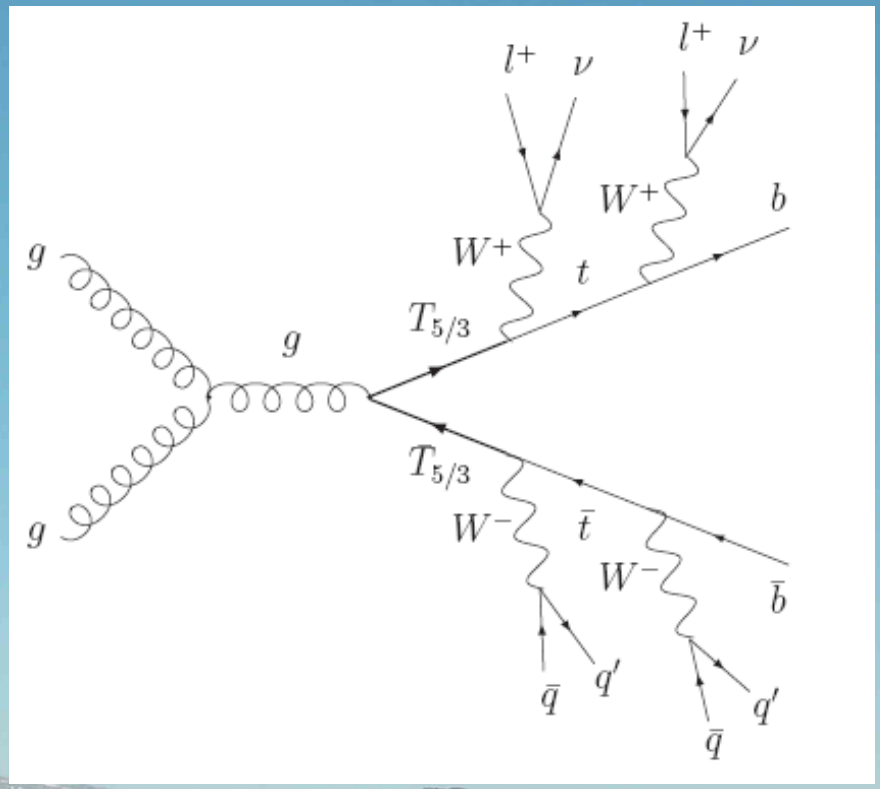
  Carena, Pontón, Santiago, Wagner 06-07; Cacciapaglia, Csaki, Marandella, Terning 06; Contino, Da Rold, Pomarol 06

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

$$\left.\begin{pmatrix} T \\ B \end{pmatrix}\right\} \rightarrow Z_L t, Ht$$

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

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 (@ 14 TeV)

    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

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

Tau custodians

- Can also happen for the tau lepton

Aguila, Carmona, Santiago JHEP(10)

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

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

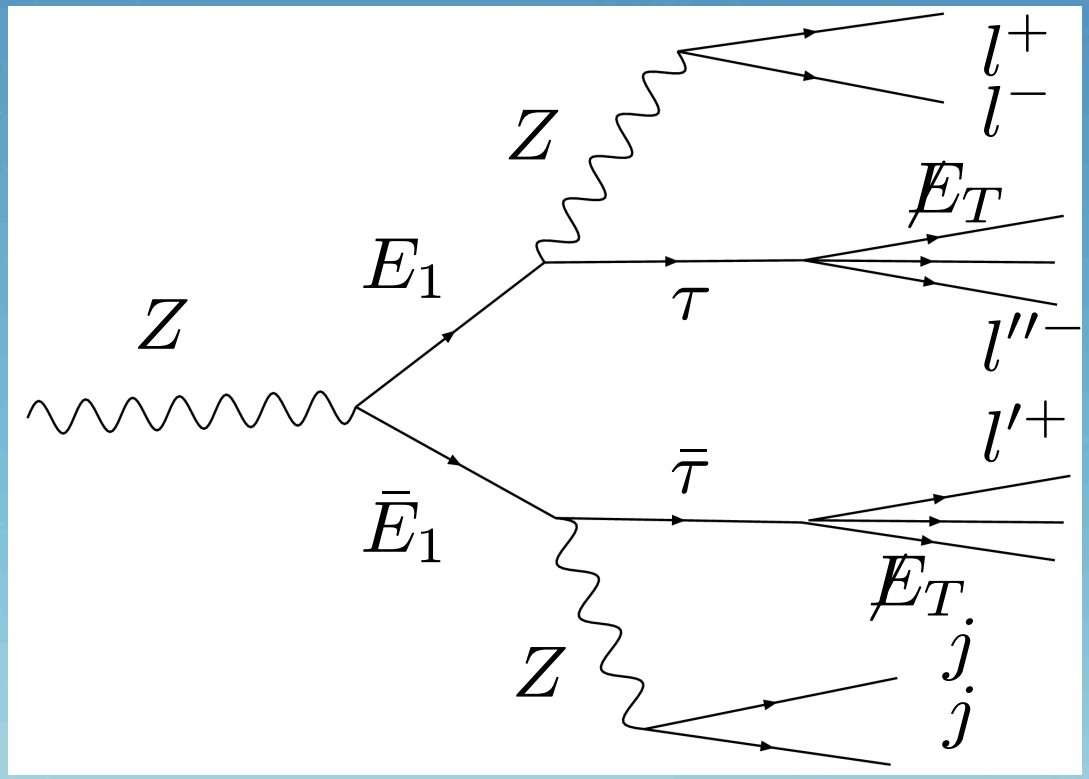
$$\begin{pmatrix} E_2 \\ Y \end{pmatrix} \rightarrow W_L\tau$$

- 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 couplings protected, large mixing allowed.

Tau custodians

- Can also happen for the tau lepton

Aguila, Carmona, Santiago PLB (in press)



Very collimated

Very collimated

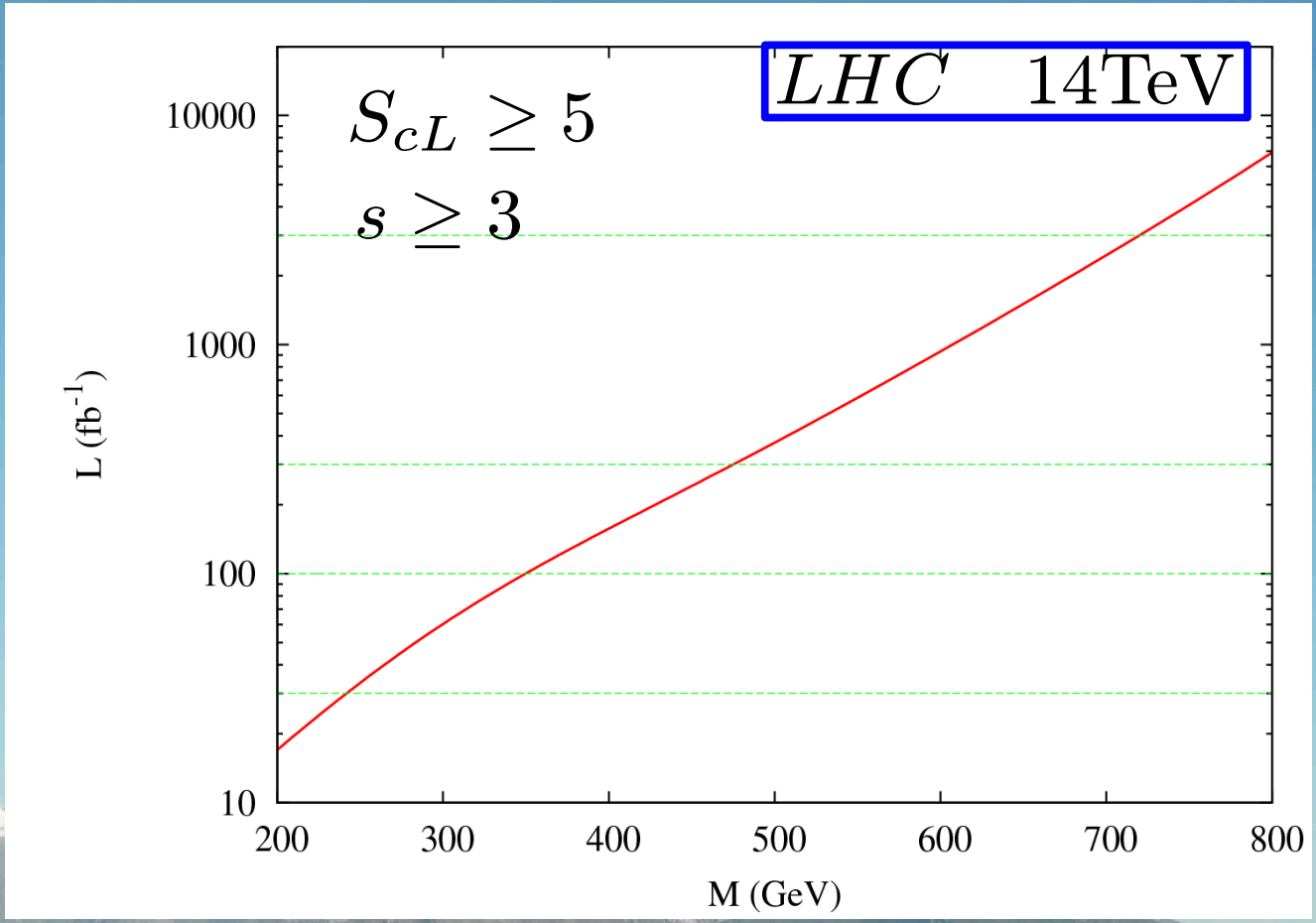
Assuming full collimation, two leptonic taus can be fully reconstructed

Tau custodians

- Discovery reach

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

Aguila, Carmona, Santiago PLB (in press)

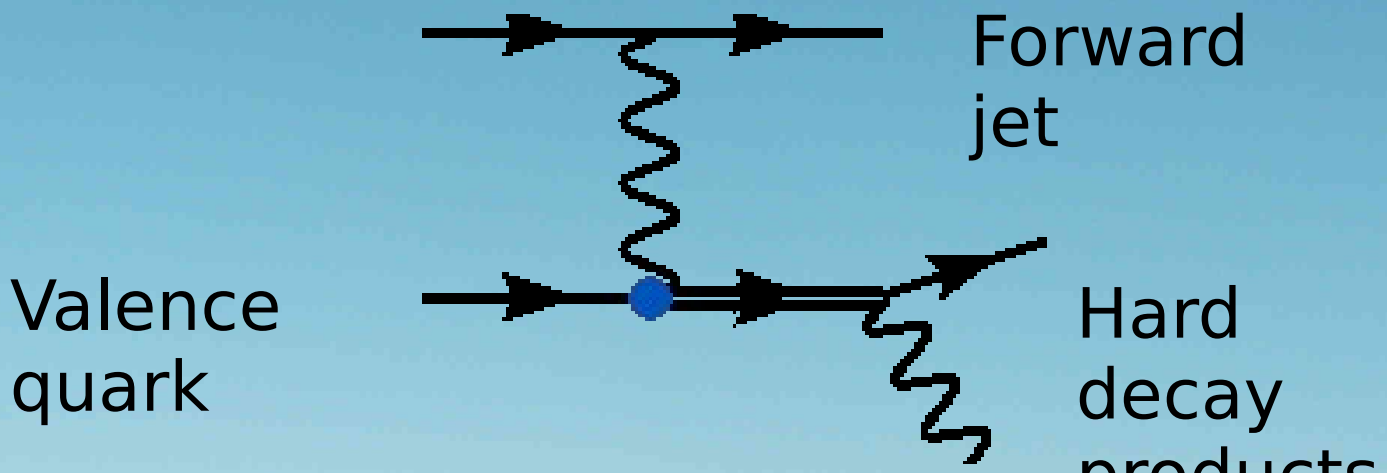


Valence quark custodians

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

Atre, Carena, Han, Santiago PRD(09)

  - Large coupling to valence quarks
  - Distinctive kinematics

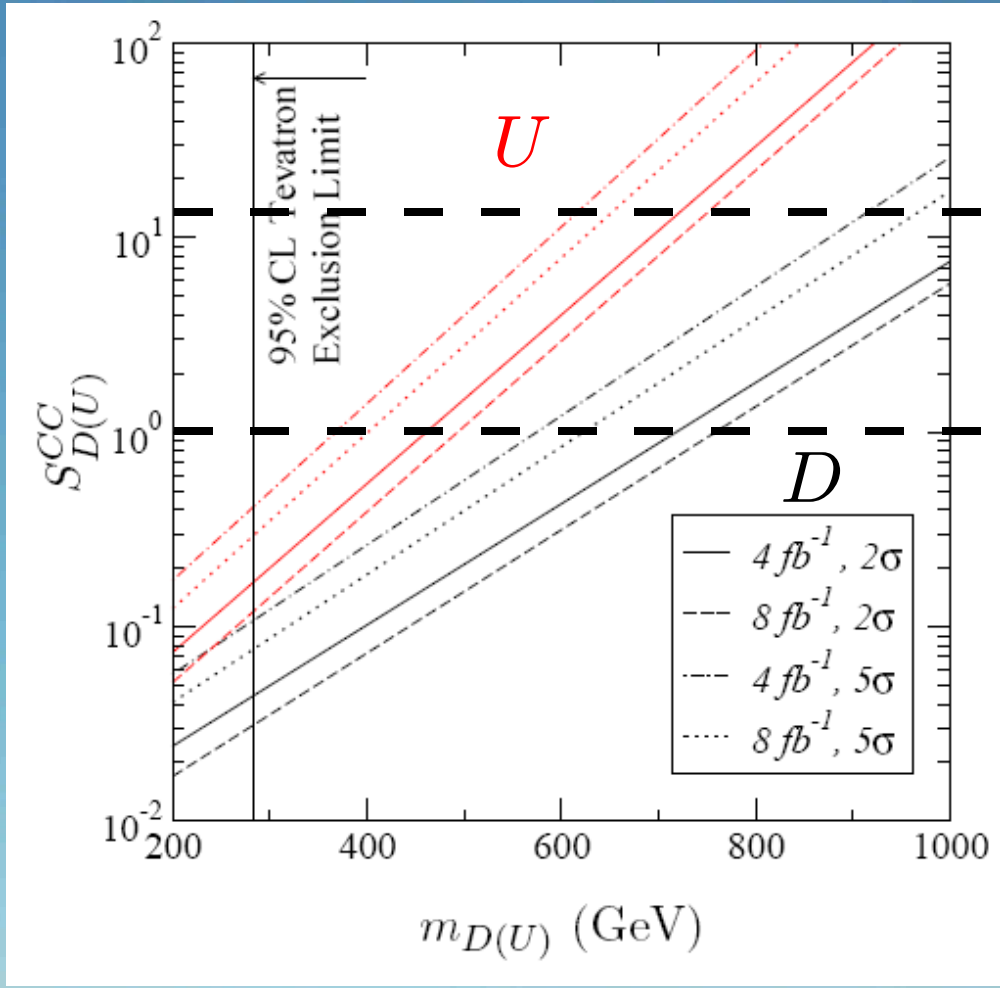


Valence quark custodians

- Tevatron analysis

Atre, Carena, Han, Santiago PRD(09)

- Close to TeV masses can be probed if coupling is strong enough

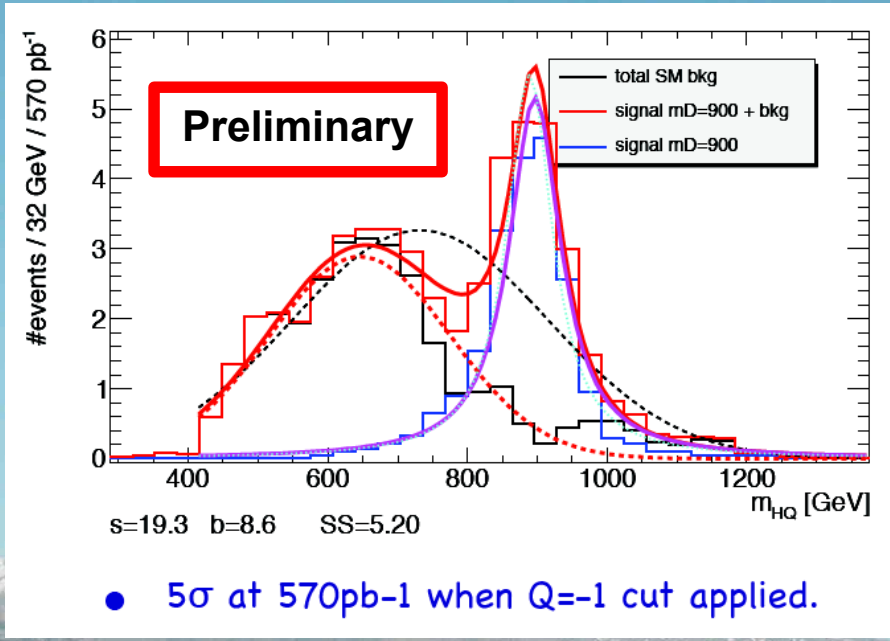


Valence quark custodians

- LHC analysis currently under way

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

- Even the first run with 1 fb^{-1} at 7 TeV will improve the Tevatron result



(CC analysis)

$m_D \sim 1$ TeV at 5 σ

$m_D \sim 1.7$ TeV at 5 σ

$(\lambda_{\max} \approx 2.9)$

Valence quark custodians

- LHC analysis currently under way

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

- Even the first run with 1 fb^{-1} at 7 TeV will improve the Tevatron result

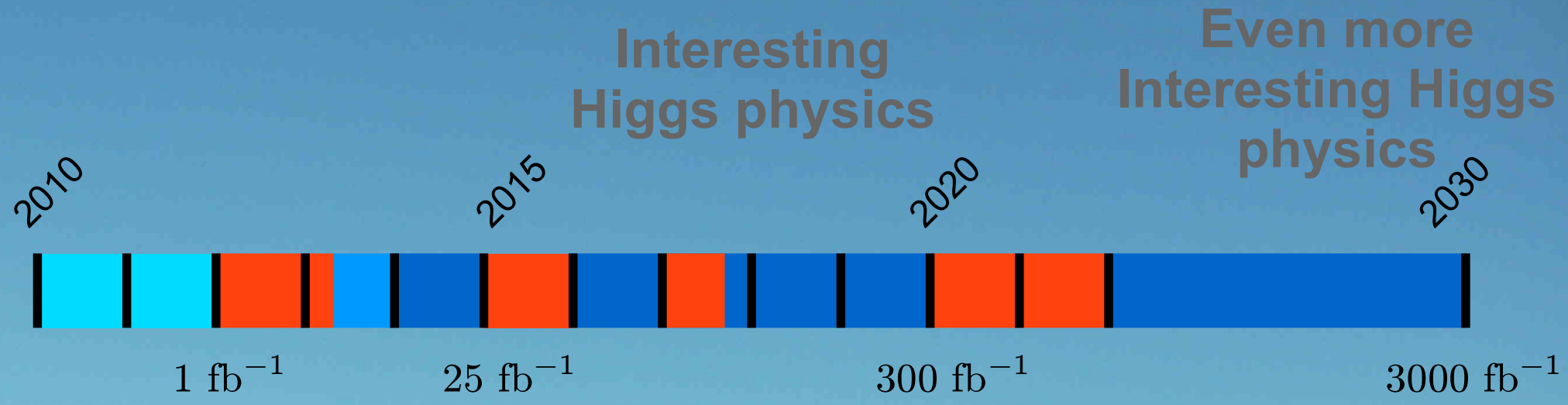
- Up to 3-4 TeV could be reached with 100 fb^{-1} at 14 TeV, depending on the model and parameters

Other signatures

- KK gravitons: similar to KK Z
- Higgs physics:
  - Modified couplings: new fermions, composite Higgs
  - Radion/Higgs mixing
- Many more possibilities:
  - Discrete symmetry: dark matter+lighter resonances
  - Higgsless models $M \gtrsim 0.7\ \mathrm{TeV}$ (give up flavour)
  - Little RS: weaker constraints, new LHC pheno
  - 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

Warped Extra Dimensions at the LHC

- Discovering Warped Extra Dimensions will require ingenuity both from the experimental and theoretical community
  - Development of new tools and techniques
  - Good knowledge of backgrounds (tails important)