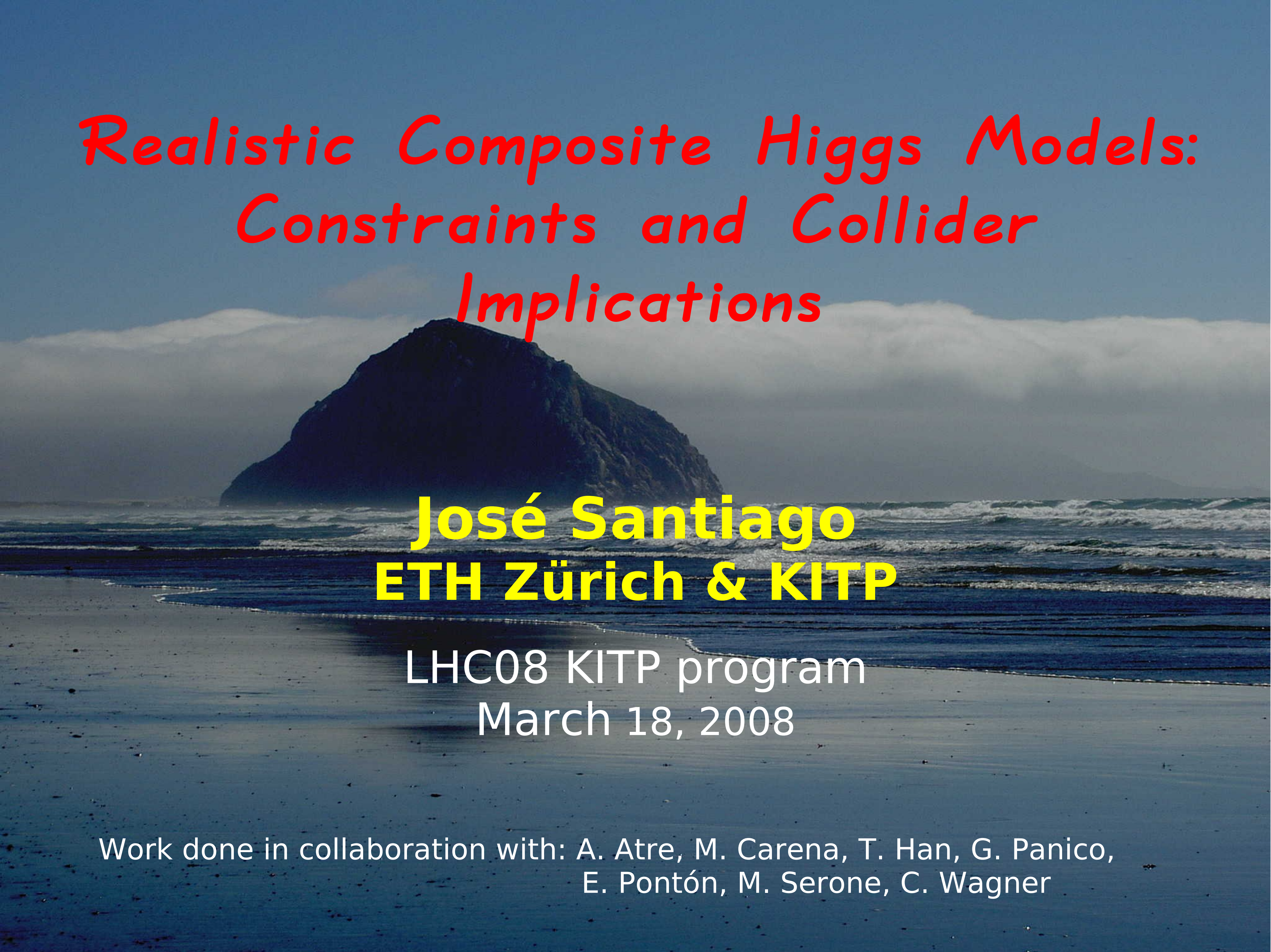


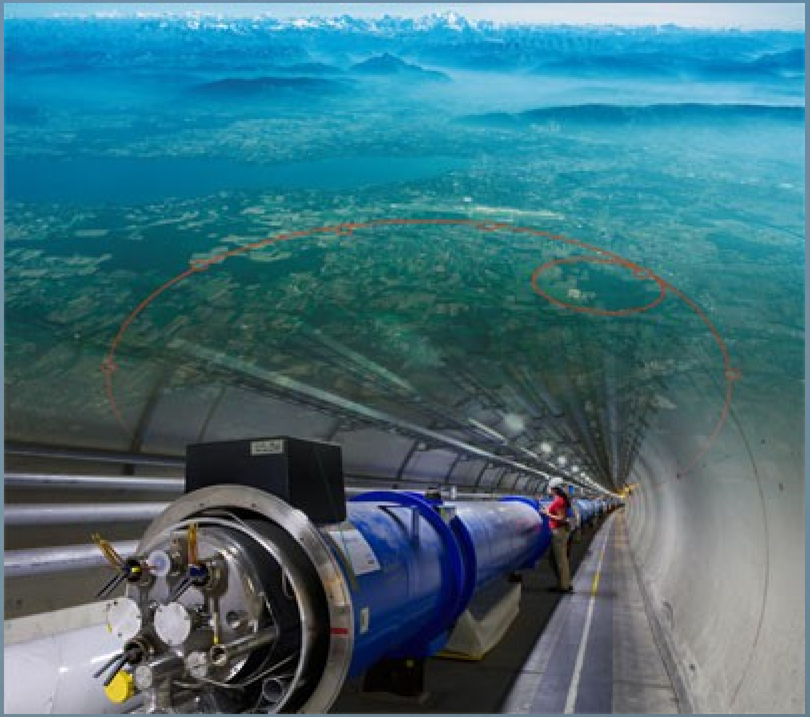
Realistic Composite Higgs Models: Constraints and Collider Implications

José Santiago
ETH Zürich & KITP

LHC08 KITP program
March 18, 2008

Work done in collaboration with: A. Atre, M. Carena, T. Han, G. Panico,
E. Pontón, M. Serone, C. Wagner

- The LHC is a unique window to Electroweak Symmetry Breaking
- V_L V_L scattering has to be unitarized at $E \lesssim TeV$
- Different realizations of EWSB lead to different phenomenology
- Some are more natural than others . . .



EWSB in the SM

- In the SM EWSB is triggered by a fundamental scalar:
  - V_L V_L scattering completely unitarized at m_H
  - Renormalizable, weakly coupled theory with custodial symmetry incorporated
  - Compatible with all experimental data
- But it's not fully satisfactory
  - Hierarchy: Higgs very sensitive to short distance physics
  - Lack of a dynamical explanation for EWSB

Alternative realizations of EWSB

- Before the LHC gives us the answer (and to better understand LHC data) we should consider all options
- There are quite a few: need a guiding principle
- Good properties of BSM realizations of EWSB
  - Natural (not sensitive to UV physics)
  - EWSB induced dynamically
  - Unitarize longitudinal gauge boson scattering
  - Not excluded experimentally

Composite Higgs Models: general idea

Georgi, Kaplan, et al, '84-'85

- Strongly coupled theory that condenses at $f \sim TeV$
- Global symmetry G broken by the condensate to a subgroup H (SM subgroup gauged)
- Higgs is a composite (pseudo)-Goldstone boson in G/H
- Higgs potential is dynamically generated at one loop

Composite Higgs Models

- Example: SO(5)/SO(4) sigma model description

Barbieri, Bellazzini, Rychkov, Varagnolo '07

$$(5) = (4, 1)$$

$$\phi = (\vec{\phi}, \phi_5) \qquad \langle \phi^2 \rangle = f^2 = \underbrace{s_h^2 f^2 + c_h^2 f^2}_{\text{Determined by dynamics}} = \langle \vec{\phi}^2 \rangle + \langle \phi_5^2 \rangle$$

H lives here (coupling to SM)

Composite Higgs Models

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H lives here (coupling to SM)

$$\langle \vec{\phi}^2 \rangle = v^2 = 2m_W^2 / g^2 = f^2 \sin\left(\frac{\langle h \rangle}{f} \right)^2$$

$s_h = 0$ No EWSB

$s_h \ll 1$ Linear EWSB (SM like)

$s_h = 1$ Maximal EWSB (effectively Higgsless)

Composite Higgs Models

- Non-linear realization → reduced couplings to SM

$$\langle \vec{\phi}^2 \rangle = v^2 = 2m_W^2/g^2 = f^2 \sin\left(\frac{\langle h \rangle}{f}\right)^2$$

$$\mathcal{L}_W = (m_W^2 + c_h g m_W \; h + \ldots) W_\mu^+ W_\mu^-$$

- Only partial unitarization of V_L V_L scattering

$$\boxed{\Lambda_{unit} = \frac{\Lambda_{unit}^{SM}}{s_h^2}}$$

- Similarly for fermions: reduced gg -> H production

Composite Higgs Models

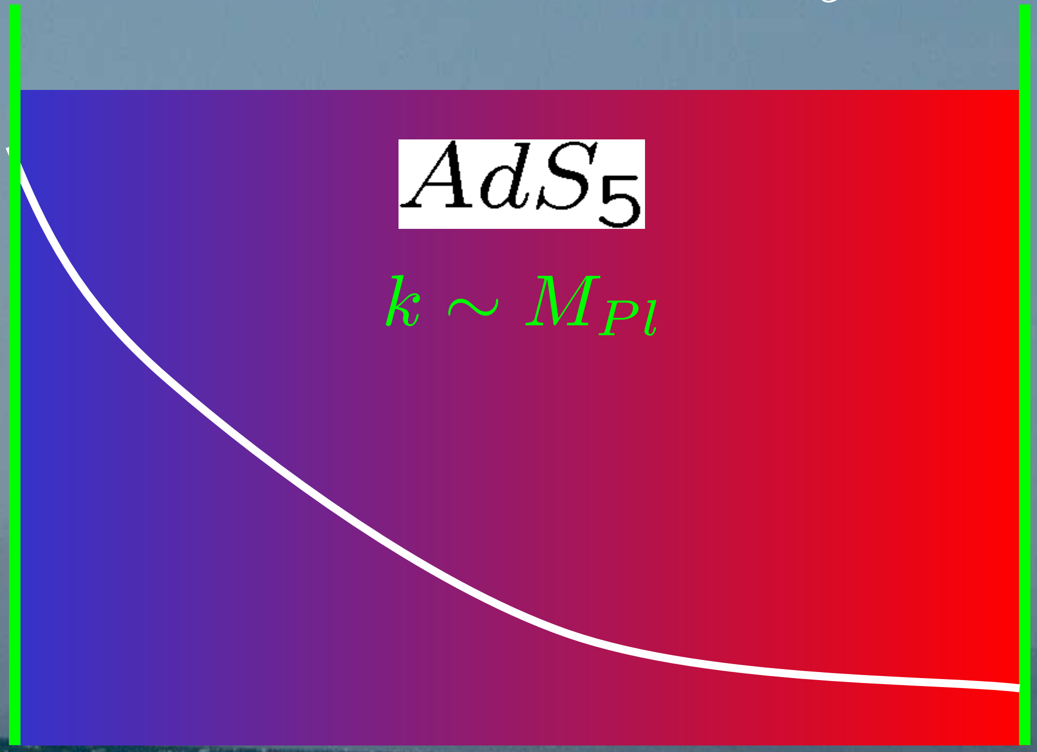
- Compositeness solves the hierarchy problem
- EWSB dynamically driven by the top
- New states with masses $m_\rho \sim g_\rho f$
- Higgs naturally lighter than f
- There is some tension $\begin{cases} s_h \ll 1 \Rightarrow \text{Fine-Tuning} \\ s_h \sim 1 \Rightarrow \text{EWPT problems} \end{cases}$
- Nice general idea but does it work?
  - Need calculability: Warped Extra Dimensions

Warped Extra Dimensions 101

- 5D model in a slice of AdS_5

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

Randall, Sundrum '99



UV brane

AdS_5

$k \sim M_{Pl}$

IR brane

$y = 0$

$E_{\text{eff}}(y) \sim k\, e^{-ky}$

$y = L$

Warped Extra Dimensions 101

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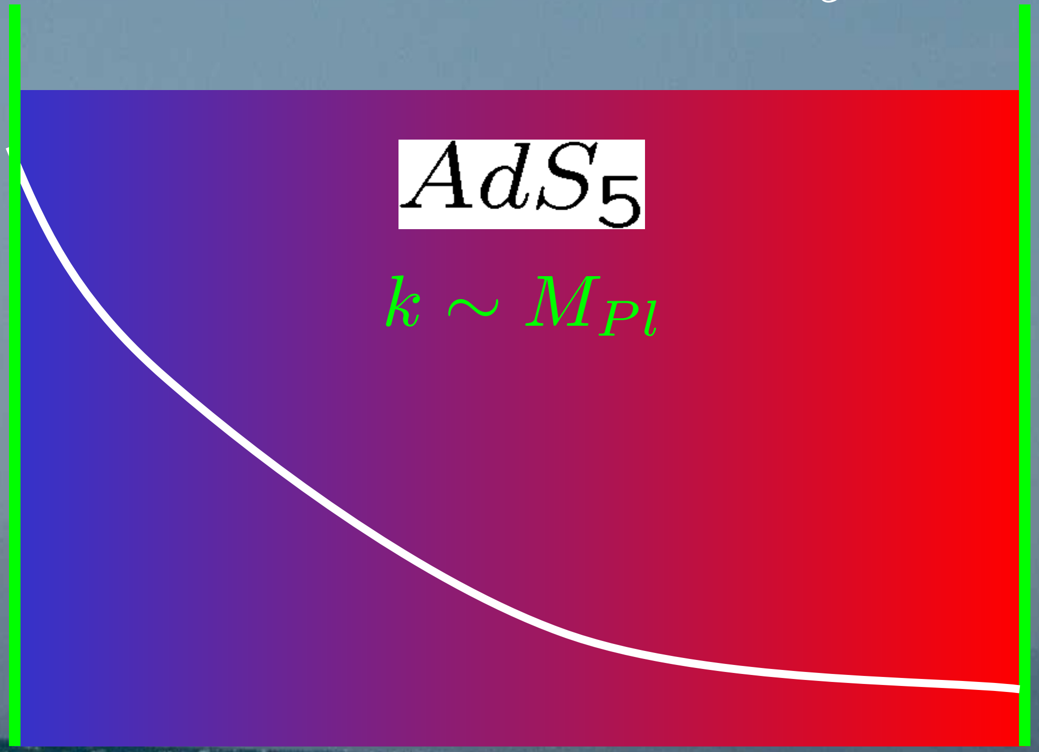
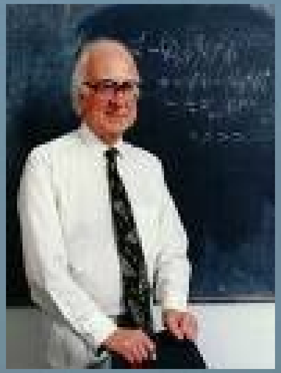


UV brane

M_{Pl}

AdS_5

$k \sim M_{Pl}$



IR brane

TeV

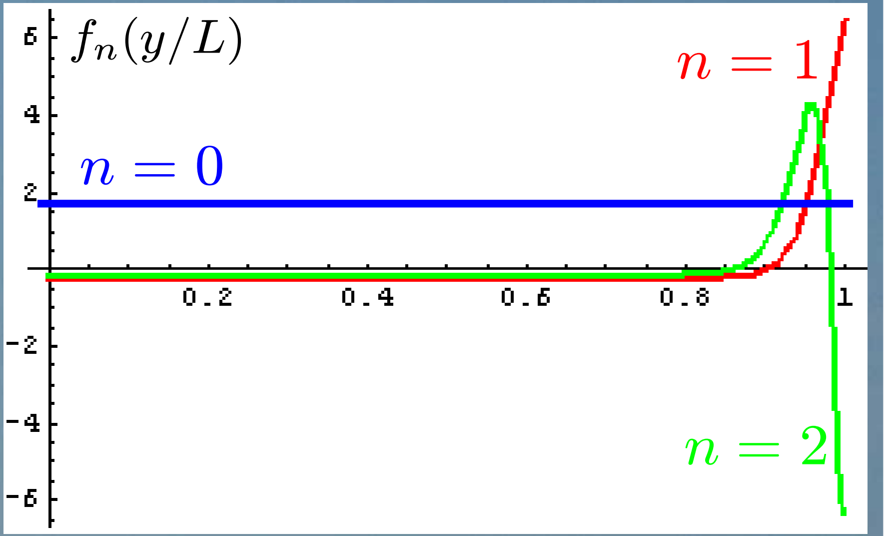
$y = 0$ $\quad E_{\text{eff}}(y) \sim k\, e^{-ky}$ $\quad y = L$

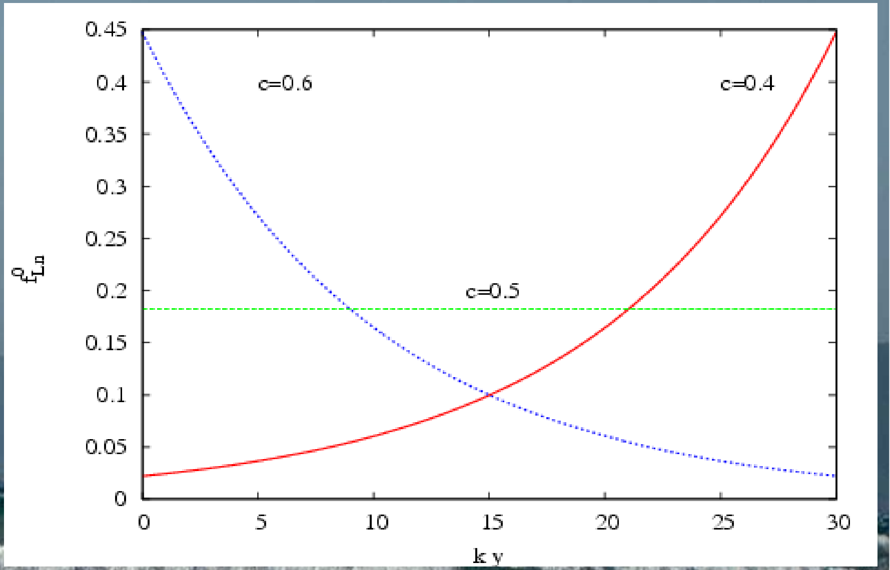
Warped Extra Dimensions 101

- KK modes have masses ~TeV: localized near the IR brane (flat towards UV brane)

- Fermion zero modes: exponential localization

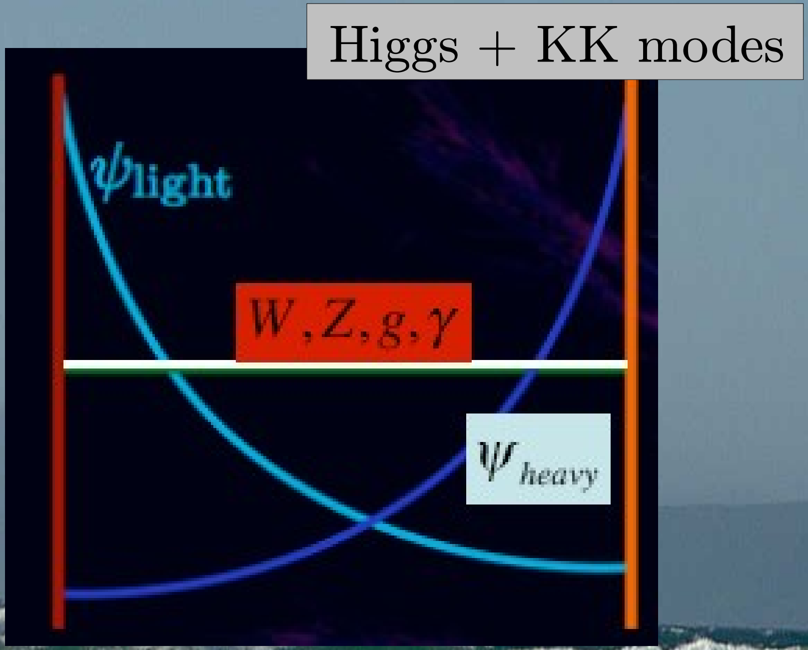
$$\mathcal{L}_5 = \bar{\Psi}[\gamma^M \partial_M + c\kappa]\Psi$$





SM in warped ED

- Higgs + heavy fermions (t/b) at IR brane
- Light fermions: UV brane



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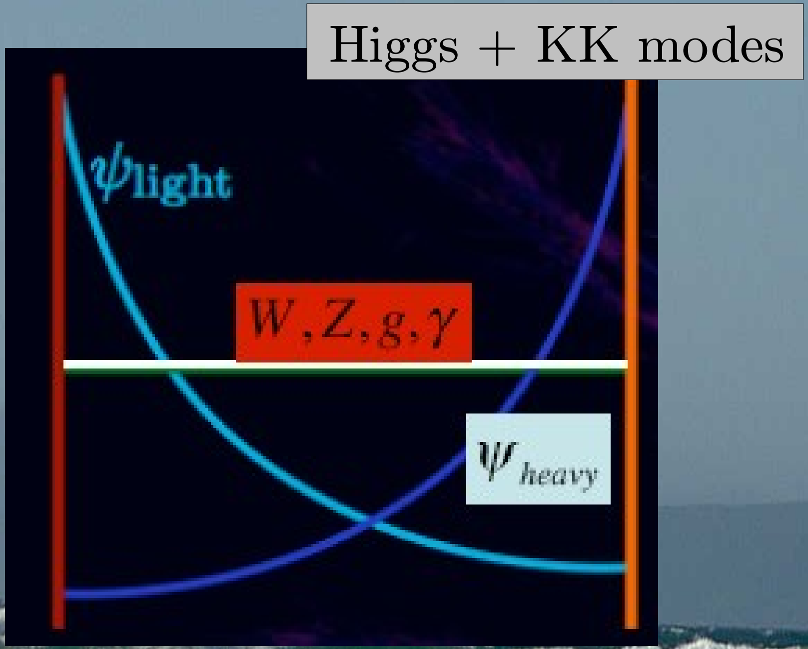
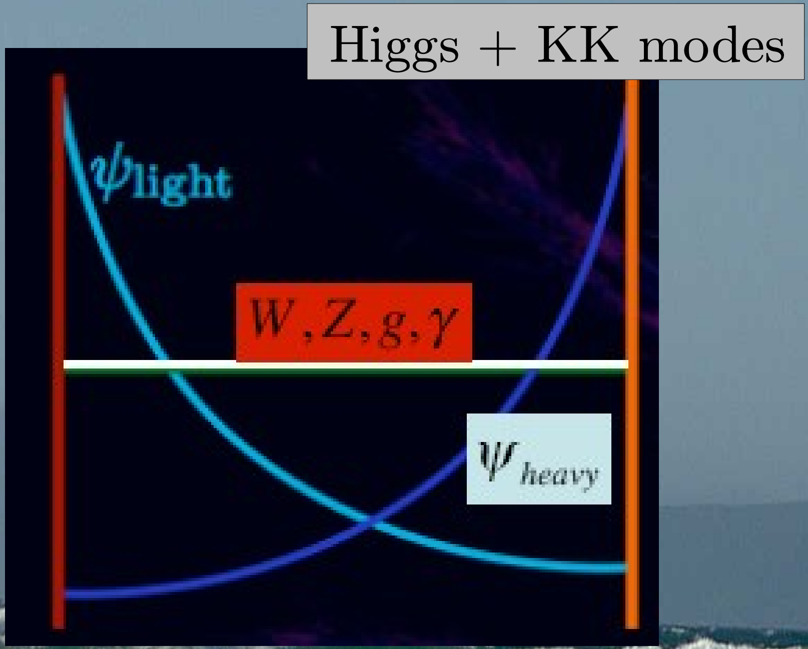


- Solves hierarchy problem
- Natural realization of flavour
- FCNC and higher-dimensional operators suppressed for light fermions
- Large effects on top/bottom
- Wealth of new particles at TeV scale

SM in warped ED

- Higgs + heavy fermions (t/b) at IR brane
- Light fermions: UV brane



- Might need some additional flavor structure
- Natural realization of flavour
- FCNC and higher-dimensional operators suppressed for light fermions
- Large effects on top/bottom

Agashe, Contino, Da Rold, Pomarol '06
Cacciapaglia et al. '07
Fitzpatrick, Perez, Randall '07

Wait, wait … why warped ED?

AdS/CFT

Maldacena '97

Gubser, Klebanov, Polyakov '98

Witten '98

Arkani-Hamed, Porrati, Randall '00

Rattazzi, Zaffaroni '00

Pérez-Victoria '01

5D model in warped ED with gauge group G, broken to H_{UV} in the UV and H_{IR} in the IR ⟺ 4D strongly coupled CFT with global symmetry G, spontaneously broken to H_{IR} weakly coupled to gravity and fundamental fields (including H_{UV})

KK modes ⟺ Composite states

Wait, wait … why warped ED?

AdS/CFT

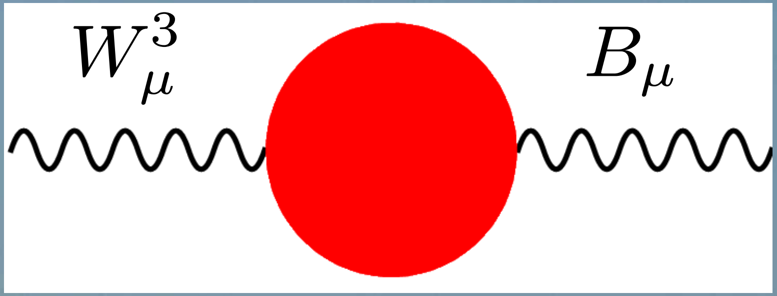
CALCULABLE!

5D model in warped ED with gauge group G, broken to H_{UV} in the UV and H_{IR} in the IR ⟺ 4D strongly coupled CFT with global symmetry G, spontaneously broken to H_{IR} weakly coupled to gravity and fundamental fields (including H_{UV})

KK modes ⟺ Composite states

The problems with WED...

- The usual suspect: S parameter



$$S \approx +0.3 \left(\frac{2.5}{M_{KK}^{\text{gauge}}} \right)^2$$

- For natural realization of flavor
- Difficult to change sign

Agashe, Csaki, Grojean, Reece '07

- Can be reduced with ideal delocalization

Cacciapaglia, Csaki, Grojean, Terning '04

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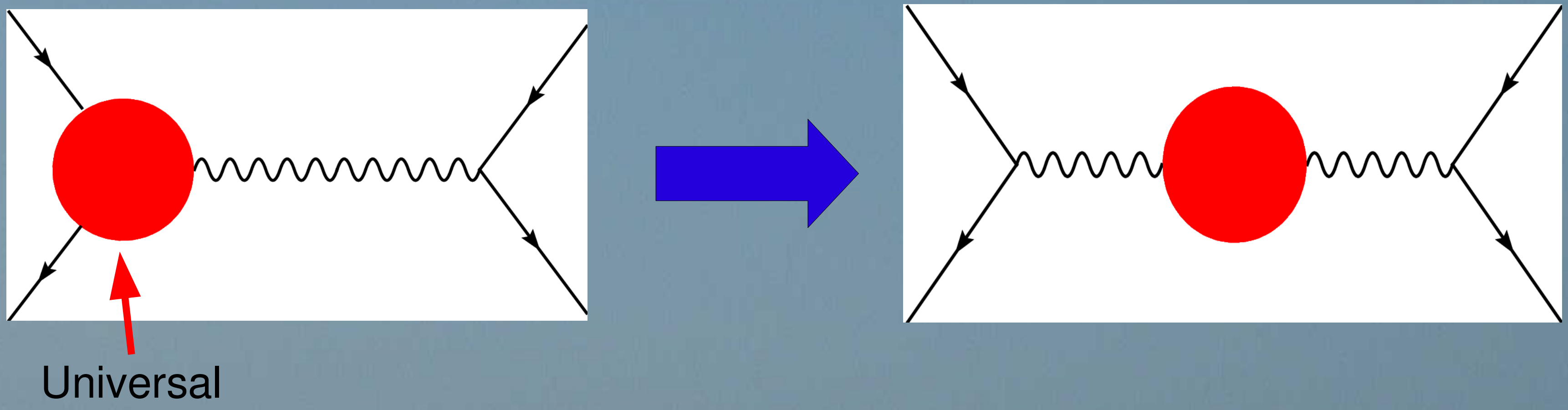

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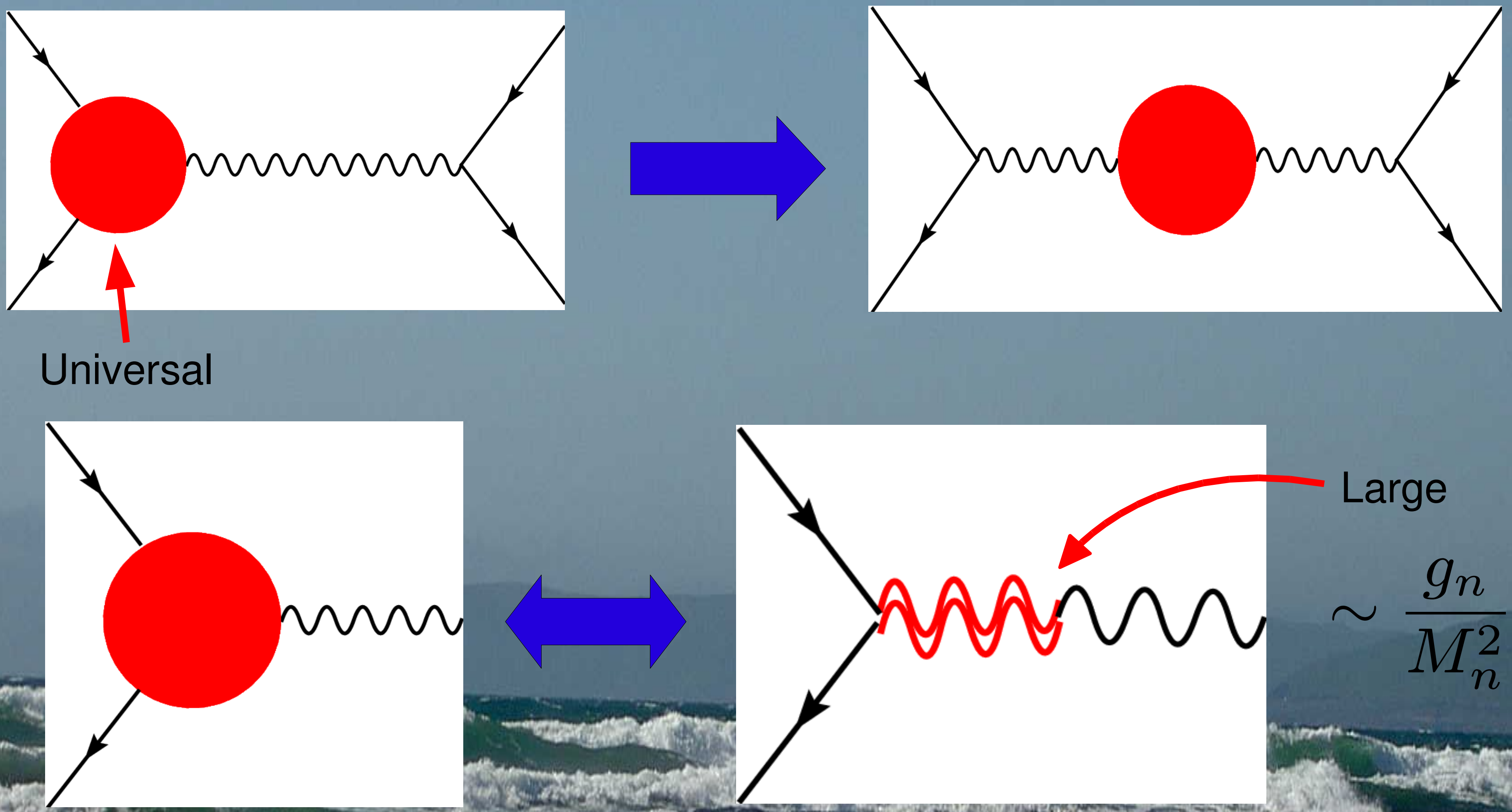


Universal

Large

$$\sim \frac{g_n}{M_n^2}$$

The problems with WED...

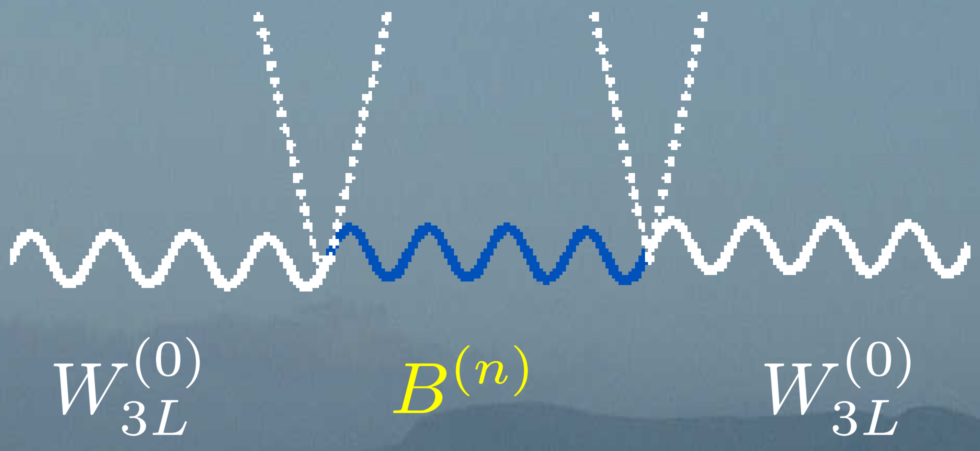
- KK states (composites of the 4D strongly coupled theory) difficult to produce at LHC
  - Heavy and weakly coupled to light fermions (and gluons)
- It might be that in composite Higgs models, all resonances but the Higgs are close to or even beyond the LHC threshold
- An effective Lagrangian approach is possible and useful as a complementary probe

Giudice, Grojean, Pomarol, Rattazzi '07

- Size of effective operators given in terms of g_ρ, m_ρ

The problems with WED...

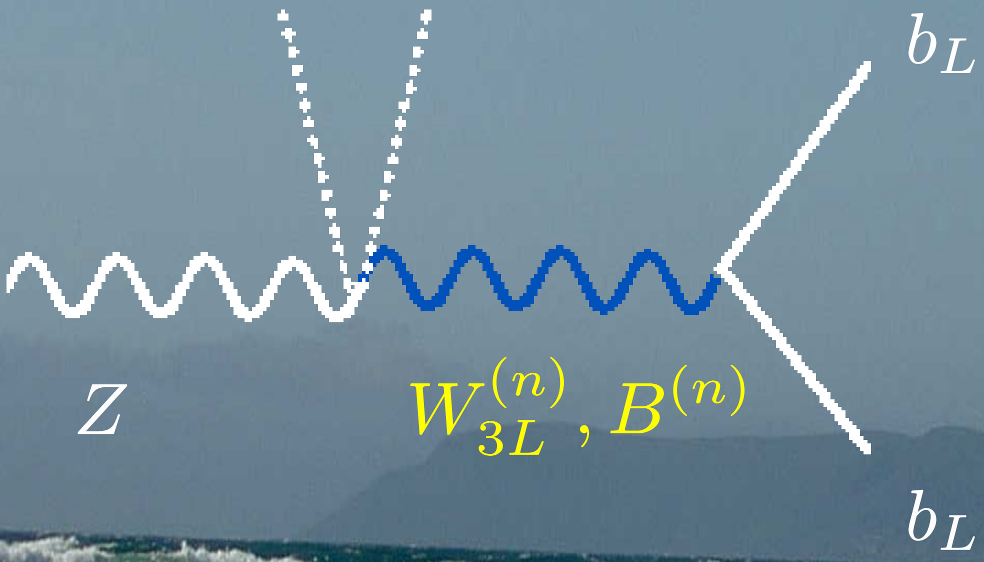
- Gauge boson KK modes are localized towards IR brane: strong mixing through the Higgs induces large contribution to the T parameter



$$\Rightarrow \quad M_{KK} \gtrsim 5-10 \text{ TeV}$$

The problems with WED...

- Top (bottom) zero modes are localized near IR brane: large corrections to their couplings, in particular anomalous Zb_Lb_L coupling

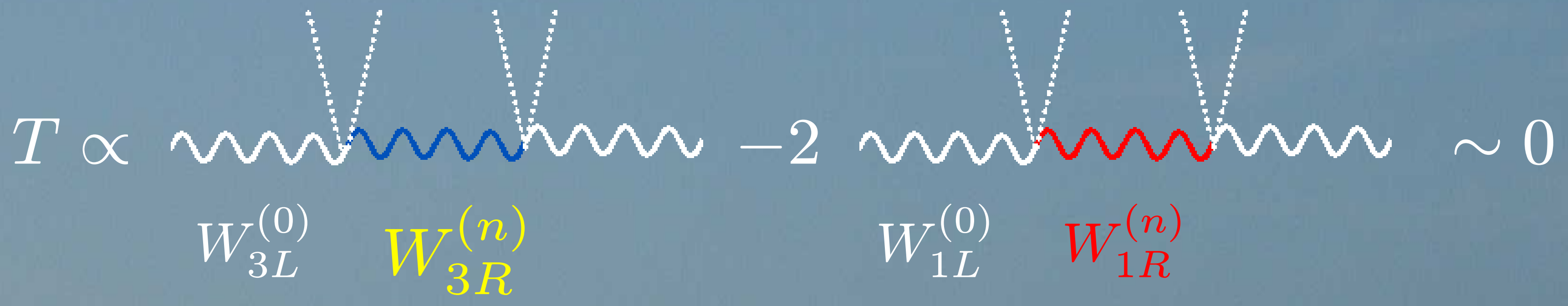


$\Rightarrow \quad M_{KK} \gtrsim 7 - 8 \text{ TeV}$

…and the solution: Custodial protection of T and Zbb

Agashe, Delgado, May, Sundrum '03

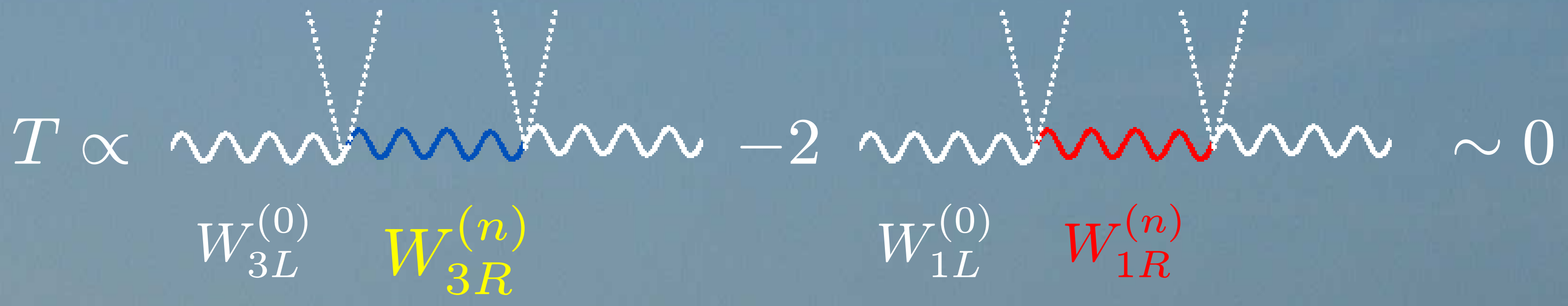
- Bulk gauge symmetry: $\underline{SU(2)_L \times SU(2)_R} \times U(1) \times P_{LR}$



...and the solution: Custodial protection of T and Zbb

Agashe, Contino, Da Rold, Pomarol '06

- Bulk gauge symmetry: $\underline{SU(2)_L \times SU(2)_R} \times U(1) \times \underline{P_{LR}}$



Recipe for a Realistic Composite Higgs Model

- SO(5)xU(1) gauge symmetry broken to O(4)xU(1) at IR brane and $SU(2)_L \times U(1)_Y$ at UV brane
- SO(5)/SO(4) broken on both branes

$A_\mu^{\hat{a}} \sim (-,-)$ Zero mode: scalar in a (4) of SO(4) HIGGS

$A_5^{\hat{a}} \sim (+,+)$ Massive modes: eaten Goldstone bosons

- b_L needs to have $T_L^3 = T_R^3$
  - Can be accommodated in a fundamental (5) or adjoint (10) of SO(5)

Recipe for a Realistic Composite Higgs Model

- The Higgs potential is zero at tree level and given by the Coleman-Weinberg potential at one loop

$$V(h) = \sum_r \pm \frac{N_r}{(4\pi)^2} \int dp\, p^3 \log[\rho(-p)]$$

Spectral function

Hosotani '83-'07
Agashe, Contino, Pomarol '05
Falkowski '07
Medina, Shah, Wagner '07

Panico, Pontón, J.S., Serone, '08

$$V(h) \approx \alpha \cos(h/f) - \beta \sin^2(h/f)$$

t

A_μ, ξ_{u_-}

EWSB $\sin\left(\frac{<h>}{f}\right) \approx \sqrt{1-\left(\frac{\alpha}{2\beta}\right)^2}$

Fermion Quantum Numbers

- *Fundamental* $(5) = (2,2) \oplus (1)$

$$Y = \frac{7}{6} \qquad \frac{1}{6} \qquad\qquad \frac{2}{3}$$

$$\begin{pmatrix} \chi^u_{\frac{5}{3}} & q^u_{\frac{2}{3}} \\ \chi^d_{\frac{2}{3}} & q^d_{-\frac{1}{3}} \end{pmatrix} \oplus (t_{\frac{2}{3}})$$

- *Adjoint* $(10) = (2,2) \oplus (3,1) \oplus (1,3)$

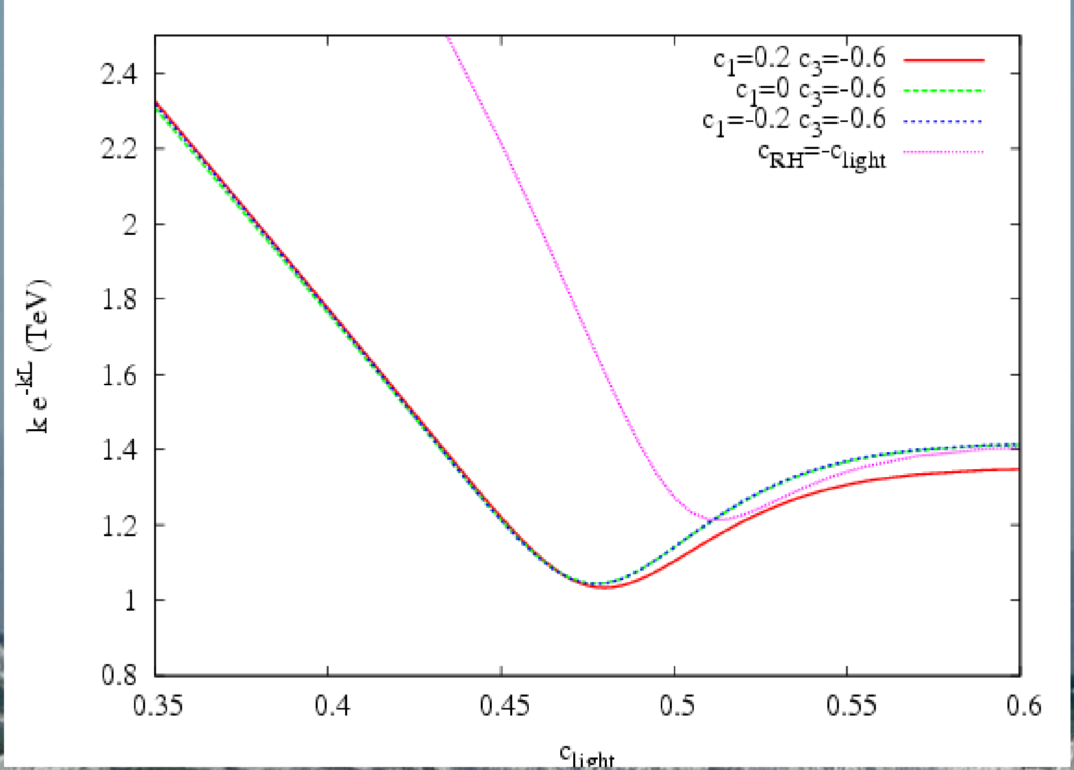
$$\begin{pmatrix} \chi^u_{\frac{5}{3}} & q^u_{\frac{2}{3}} \\ \chi^d_{\frac{2}{3}} & q^d_{-\frac{1}{3}} \end{pmatrix} \oplus \begin{pmatrix} \psi'_{\frac{5}{3}} \\ t'_{\frac{2}{3}} \\ b'_{-\frac{1}{3}} \end{pmatrix}_{2/3} \oplus \begin{pmatrix} \psi''_{\frac{5}{3}} \\ t''_{\frac{2}{3}} \\ b''_{-\frac{1}{3}} \end{pmatrix}_{2/3}$$

Fermion Quantum Numbers

- Non-standard new quarks are a common prediction:
  - Hypercharge 7/6 doublets + hypercharge 1/6 doublets
  - Hypercharge 2/3 triplets
- Typically lighter than vector resonances:
  - Have to cut-off the large top contribution to V(h)
  - Associated to heavy top
  - Could be light for light generations (highly degenerate)
- Important footprint even if m_ρ at LHC threshold

Constraints from EWPT

- New particles at the TeV scale are quite constrained by experimental data
- Global fit to EW precision data required



Carena, Pontón, J.S., Wagner '06

Carena, Pontón, J.S., Wagner '07

$$M_{KK}^{\text{gauge}} \gtrsim 2.5 - 3.5 \text{ TeV}$$

$$M_{KK}^{\text{ferm.}} \gtrsim 0.3 - 1 \text{ TeV}$$

Constraints from EWPT

- One loop (calculable) corrections to T and Zbb are crucial

Carena, Pontón, J.S., Wagner '07
Barbieri, Bellazzini, Rychkov, Varagnolo '07

  - Light singlets contribute positively to T and to Zbb
  - Light Y=7/6 doublets contribute negatively to T
- Reduced Higgs couplings affect the fit (heavier h)

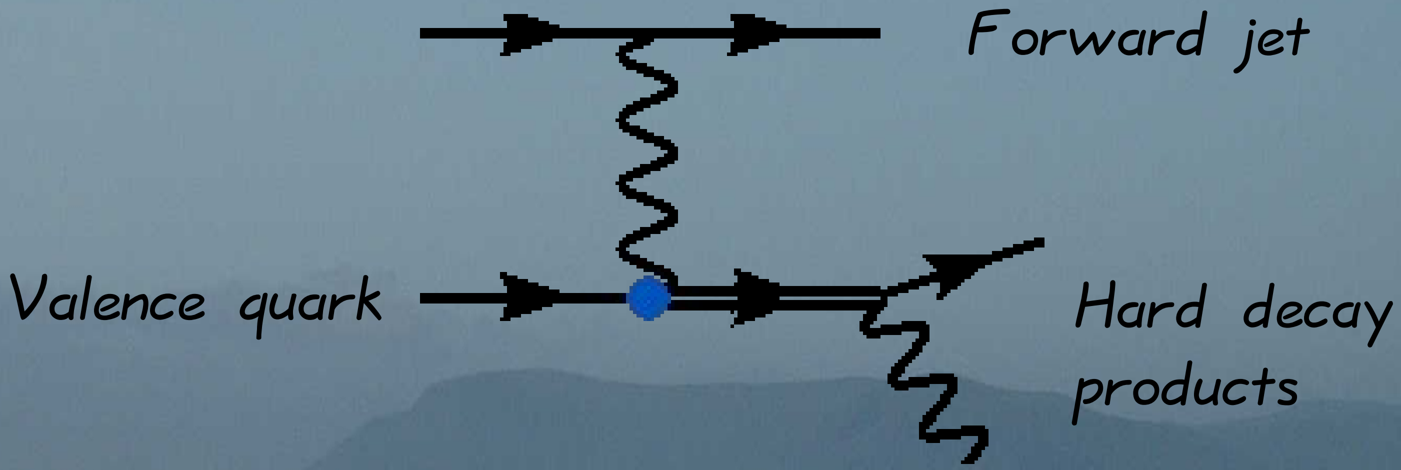
$$m_{EWPT,eff} \approx m_h (\Lambda/m_h)^{s_h^2}$$

- Large s_h → large m_h → large negative T
- Large T from singlet required → large δg_{b_L}

Novel Vector-like Quark Phenomenology

- Degenerate bidoublets can be light and mix strongly with valence quarks without phenomenological problems
- Large single production at Tevatron and LHC with singular kinematics

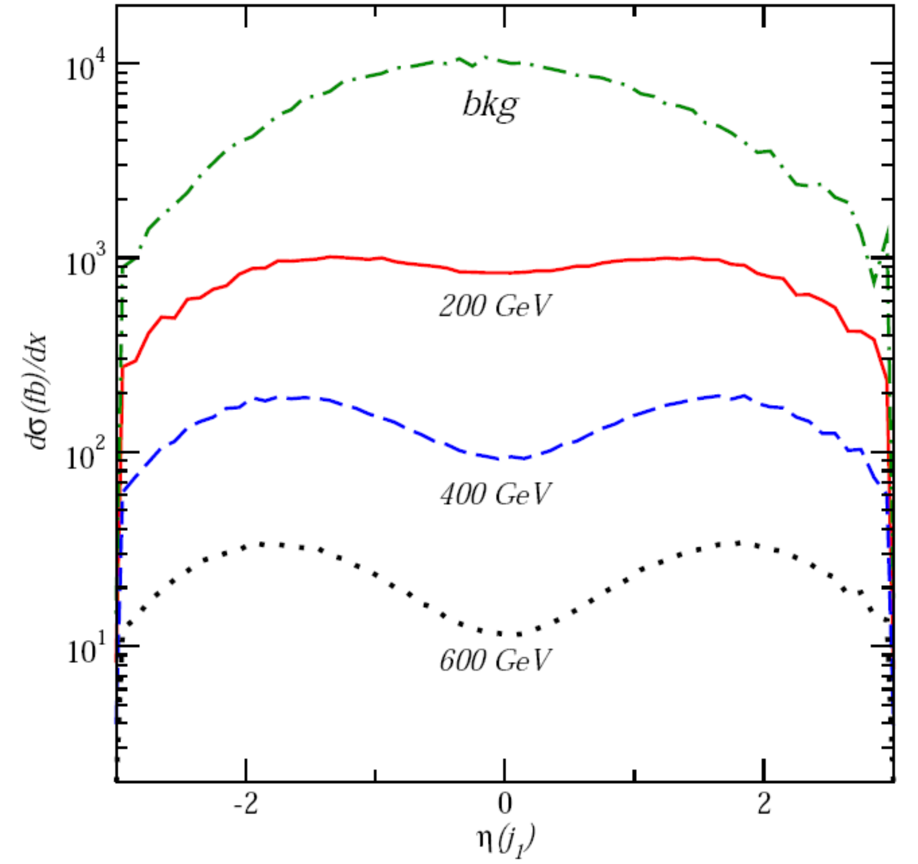
Atre, Carena, Han, J.S.

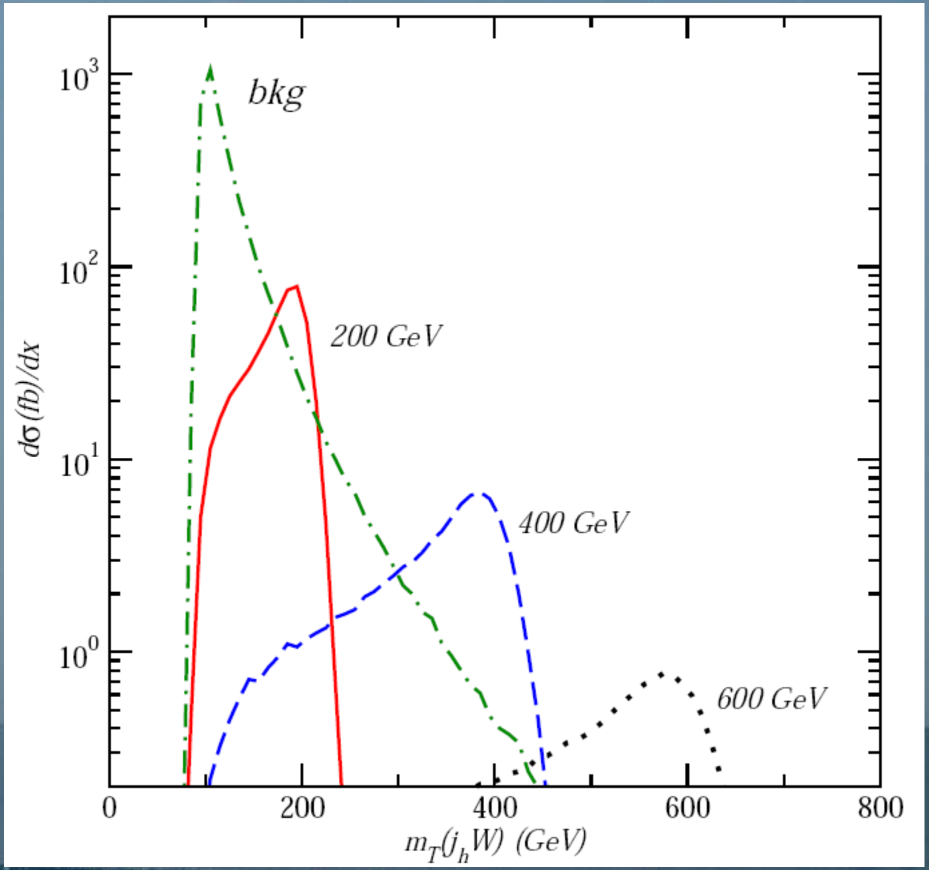


Novel Vector-like Quark Phenomenology

- Single production at Tevatron

Atre, Carena, Han, J.S.

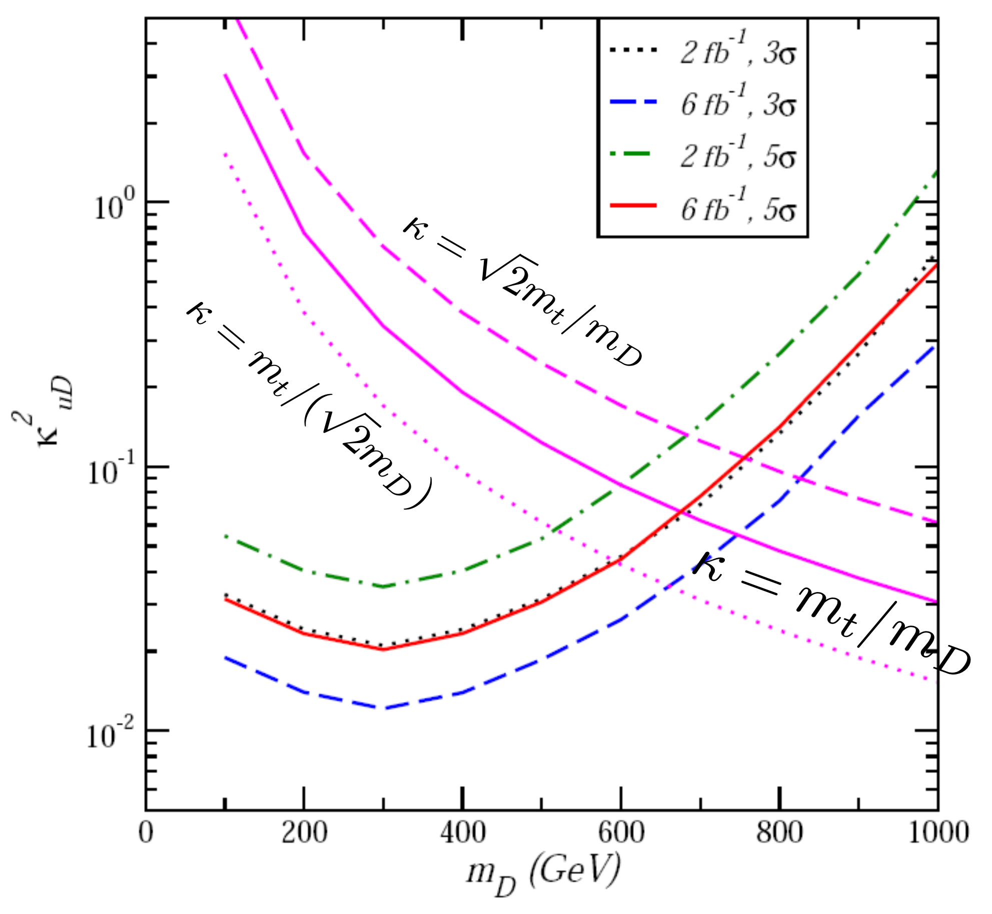




Novel Vector-like Quark Phenomenology

- Single production at Tevatron

Atre, Carena, Han, J.S.



$$\mathcal{L} = \frac{g\kappa}{\sqrt{2}} W_\mu^+ \bar{u}_R \gamma^\mu D_R + \text{h.c.}$$

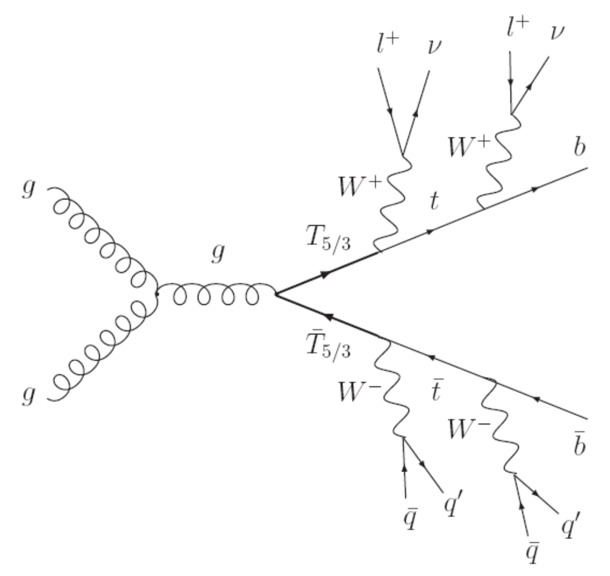
$$\kappa \lesssim \frac{v}{m_D} \sim \frac{m_t}{m_D}$$

$$m_D \sim 600 - 800 \text{ GeV}$$

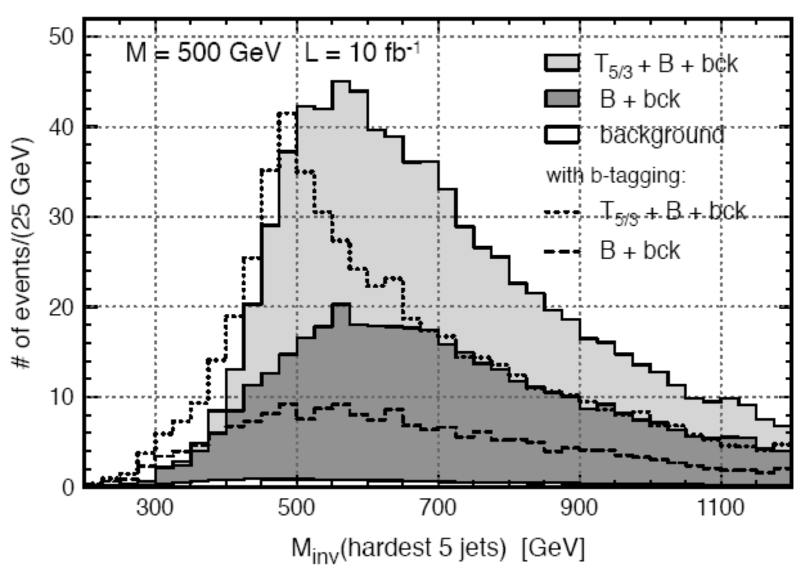
Novel Vector-like Quark Phenomenology

- Signature quark: charge 5/3 quark mixing with top

Contino, Servant ’08



- Very early discovery with same-sign leptons
- 100 pb^{-1} for Mq=500 GeV



- Full reconstruction of the hadronic decays

Novel Vector-like Quark Phenomenology

- Strong indication but need full reconstruction
- Charge 5/3 come in bidoublets or triplets
  - Both have charge -1/3 and charge 2/3 quarks
- Charge 2/3 have different decays depending on the quantum numbers:
  - Bidoublet: mainly neutral decays, Zt and Ht
  - Triplet: similar to singlet Wb, Zt, Ht in 2:1:1 ratio
- Study charge 2/3 quarks to discriminate quantum numbers

Novel Vector-like Quark Phenomenology

- Pair production:

$$pp \to T\bar{T} \to ZZt\bar{t} \to ZZW^+W^-b\bar{b}$$

- Optimal discovery channel depends on the mass but trilepton analysis (similar to SUSY) looks promising

- Single production:

$$t\bar{t}Z + \text{forward jet}$$

- Singular kinematics can help beat the background

Gauge resonances

- Not your standard Z'
  - Reduced couplings to light quarks
  - Enhanced couplings to top
- Assuming decay only to t_R

  Agashe et al '06
  Lillie, Randall, Wang '07
  - High p_T tops, difficult to reconstruct (top jets)

$$m_{G^{(1)}} \sim 4 \text{ TeV, } 100 \text{ fb}^{-1}$$

- Decay also to T_R in realistic models

  Carena, Medina, Panes, Shah, Wagner '07
  - Improved reach for T_R and $G^{(1)}$

  Lillie, Shu, Tait '07
- Larger decay to light quarks with IR BKTs

Dark Matter in Warped ED

- Introduce a discrete symmetry: stable WIMP
  - Geometrical: technically difficult due to warping

Agashe, Falkowski, Low, Servant '07

  - Non-geometrical: can involve a subset of particles

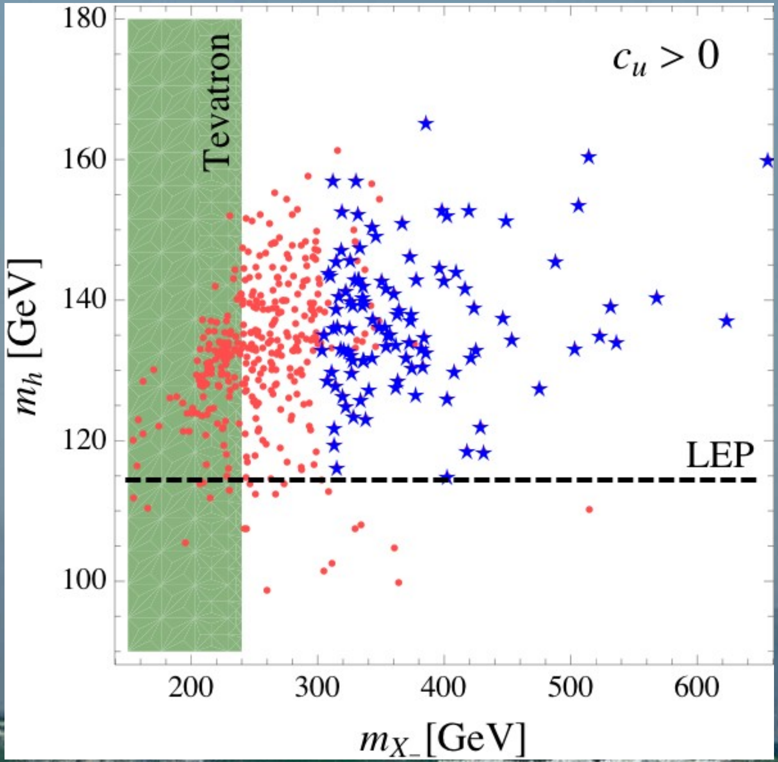
Panico, Pontón, J.S., Serone, '08

- Partial T-parity
  - Double a subset of fields and impose discrete symmetry
  - Lightest odd particle is stable, can be a U(1) gauge boson
  - Improved agreement with EWPT
  - Large overlap of regions with right EWSB, EWPT, m_t and m_h and correct Ω_{DM}

Dark Matter in Warped ED

- Partial T-parity
  - New collider signatures with large amounts of missing E_T

Panico, Pontón, J.S., Serone, '08



● DM + m_t

★ DM + m_t + EWPT

Dark matter in RS

- $A \Leftrightarrow B$ symmetry

$$SU(2)_L \times SU(2)_R \times U(1)_A \times U(1)_B$$

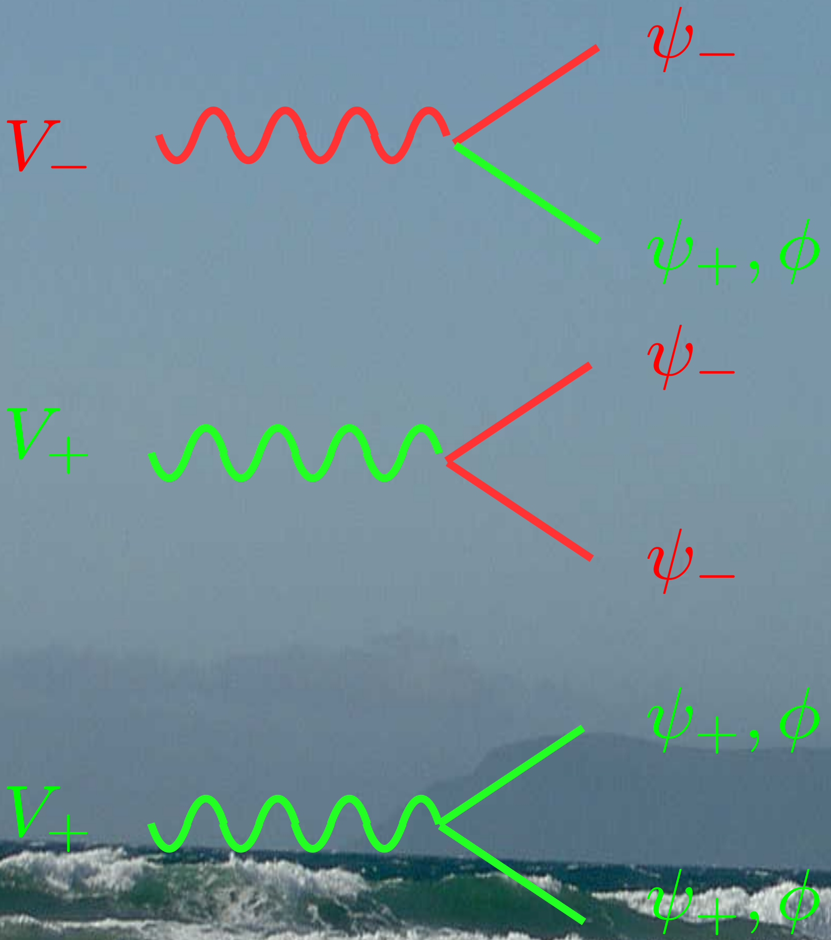
- Two kinds of fields:
  - (Equally) Charged under both groups ϕ
  - Charged under one group (need a mirror partner charged under the other) $\psi_{A,B}$
- Can be classified according to the symmetry

$$V_- \propto V_A - V_B \qquad \left.\begin{matrix} V_+ \propto V_A + V_B \\ \psi_+ \propto \psi_A + \psi_B \\ \phi \end{matrix}\right\} \text{SM and new particles}$$

$$\underbrace{\psi_- \propto \psi_A - \psi_B}_{\text{New particles}}$$

Dark matter in RS

- Couplings have to be globally even



- The lightest odd particle is stable: good dark matter candidate
- Relic abundance in the right range for the simplest model with V- as dark matter

Panico, Pontón, J.S., Serone, '08

A full model: Z_2 $MCHM_5$

- Gauge-Higgs unification model based on bulk gauge group

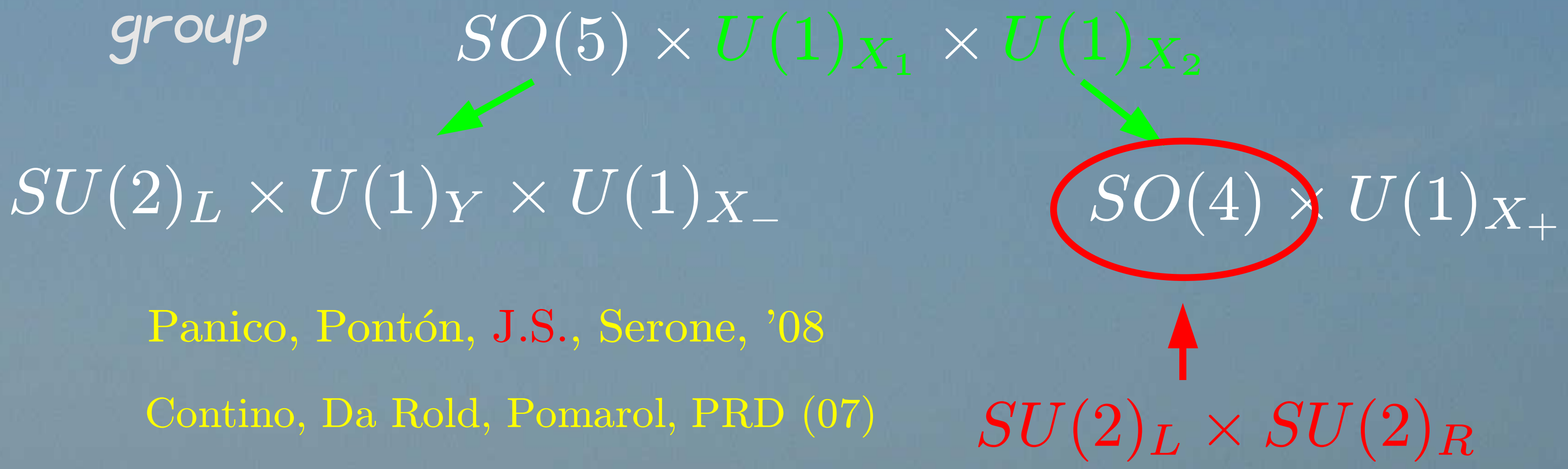
$$\begin{tikzcd}
 & SO(5) \times U(1)_{X_1} \times U(1)_{X_2} \arrow[dl] \arrow[dr] & \\
SU(2)_L \times U(1)_Y \times U(1)_{X_-} & & SO(4) \times U(1)_{X_+}
\end{tikzcd}$$

Panico, Pontón, J.S., Serone, '08

Contino, Da Rold, Pomarol, PRD (07)

A full model: Z_2 MCHM$_5$

- *Gauge-Higgs unification* model based on bulk gauge group



$SO(5) \times U(1)_{X_1} \times U(1)_{X_2}$

$SU(2)_L \times U(1)_Y \times U(1)_{X_-}$

$SO(4) \times U(1)_{X_+}$

$SU(2)_L \times SU(2)_R$

Panico, Pontón, J.S., Serone, '08

Contino, Da Rold, Pomarol, PRD (07)

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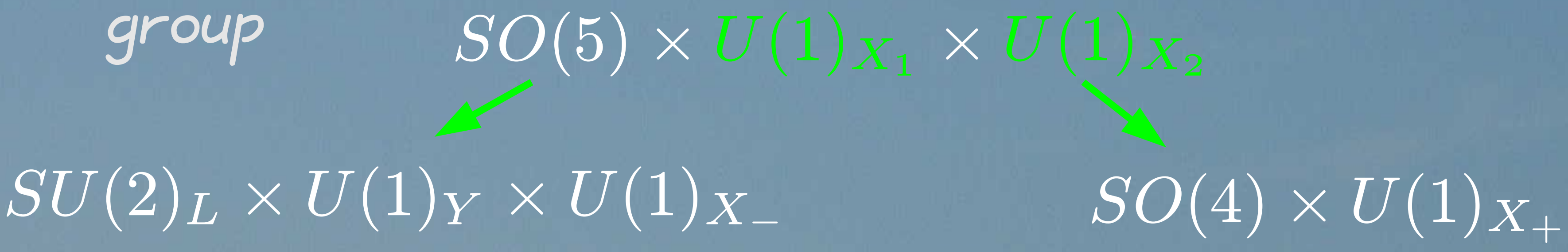


$$SO(5) \times U(1)_{X_1} \times U(1)_{X_2}$$

$$SU(2)_L \times U(1)_Y \times U(1)_{X_-} \qquad SO(4) \times U(1)_{X_+}$$

- $A_5^{\hat{a}}$ along the $SO(5)/SO(4)$ direction has the quantum numbers of the Higgs

- Quarks can be embedded in the vectorial (5) representation of SO(5) to ensure P_{LR} is a good symmetry for b_L

A full model: Z_2 $MCHM_5$

- Top sector contains three multiplets:

$$\xi^L_{q_1} = \left[\begin{pmatrix} \chi^u_L(-+) & q^u_L(++) \\ \chi^d_L(-+) & q^d_L(++) \end{pmatrix} \oplus u_L(--) \right]_{(\frac{\sqrt{2}}{3},\frac{\sqrt{2}}{3})}$$

Z2 neutral

$$\left.\begin{aligned} \xi^L_{u_1} &= \left[\begin{pmatrix} (+-) & (+-) \\ (+-) & (+-) \end{pmatrix} \oplus (-+) \right]_{(\frac{2\sqrt{2}}{3},0)} \\ \xi^L_{u_2} &= \left[\begin{pmatrix} (+-) & (+-) \\ (+-) & (+-) \end{pmatrix} \oplus (-+) \right]_{(0,\frac{2\sqrt{2}}{3})} \end{aligned}\right\}$$

Z2 mirror

A full model: Z_2 $MCHM_5$

- Top sector contains three multiplets:

$$\xi^L_{q_1} = \left[\begin{pmatrix} \chi^u_L(-+) & q^u_L(++) \\ \chi^d_L(-+) & q^d_L(++) \end{pmatrix} \oplus u_L(--)\right]_{\left(\frac{\sqrt{2}}{3},\frac{\sqrt{2}}{3}\right)} \qquad c_{q_1}$$

$$\left.\begin{aligned} \xi^L_{u_1} &= \left[\begin{pmatrix} (+-) & (+-) \\ (+-) & (+-) \end{pmatrix} \oplus (-+)\right]_{\left(\frac{\sqrt{2}}{3},0\right)} \\ \xi^L_{u_2} &= \left[\begin{pmatrix} (+-) & (+-) \\ (+-) & (+-) \end{pmatrix} \oplus (-+)\right]_{\left(0,\frac{\sqrt{2}}{3}\right)} \end{aligned}\right\} \qquad c_u$$

$$\boxed{\mathcal{L}_M = \delta(y-L)\left[\underline{m_u}\,\overline{(2,2)}^{q_1}_L\,(2,2)^{u_i}_R + \underline{M_u}\,\overline{(1,1)}^{q_1}_R\,(1,1)^{u_i}_L + \text{h.c.}\right]}$$

A full model: Z_2 $MCHM_5$

- The Higgs potential is zero at tree level and given by the Coleman-Weinberg potential at one loop

$$V(h) = \sum_r \pm \frac{N_r}{(4\pi)^2} \int dp\, p^3 \log[\rho(-p)]$$

Spectral function

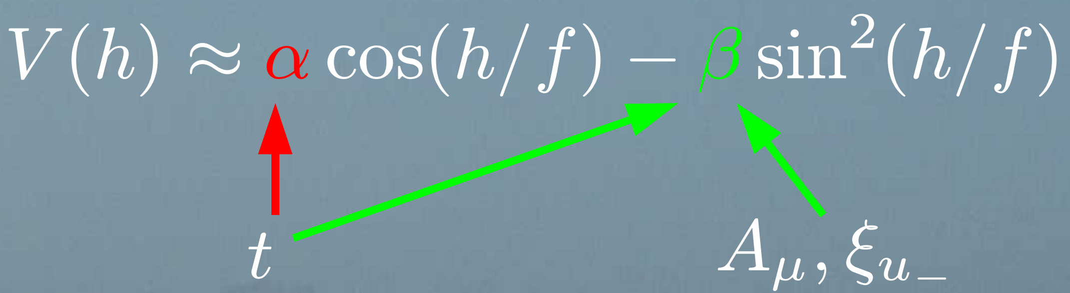
Hosotani '83-'07

Agashe, Contino, Pomarol '05

Falkowski '07

Medina, Shah, Wagner '07

Panico, Pontón, J.S., Serone, '08

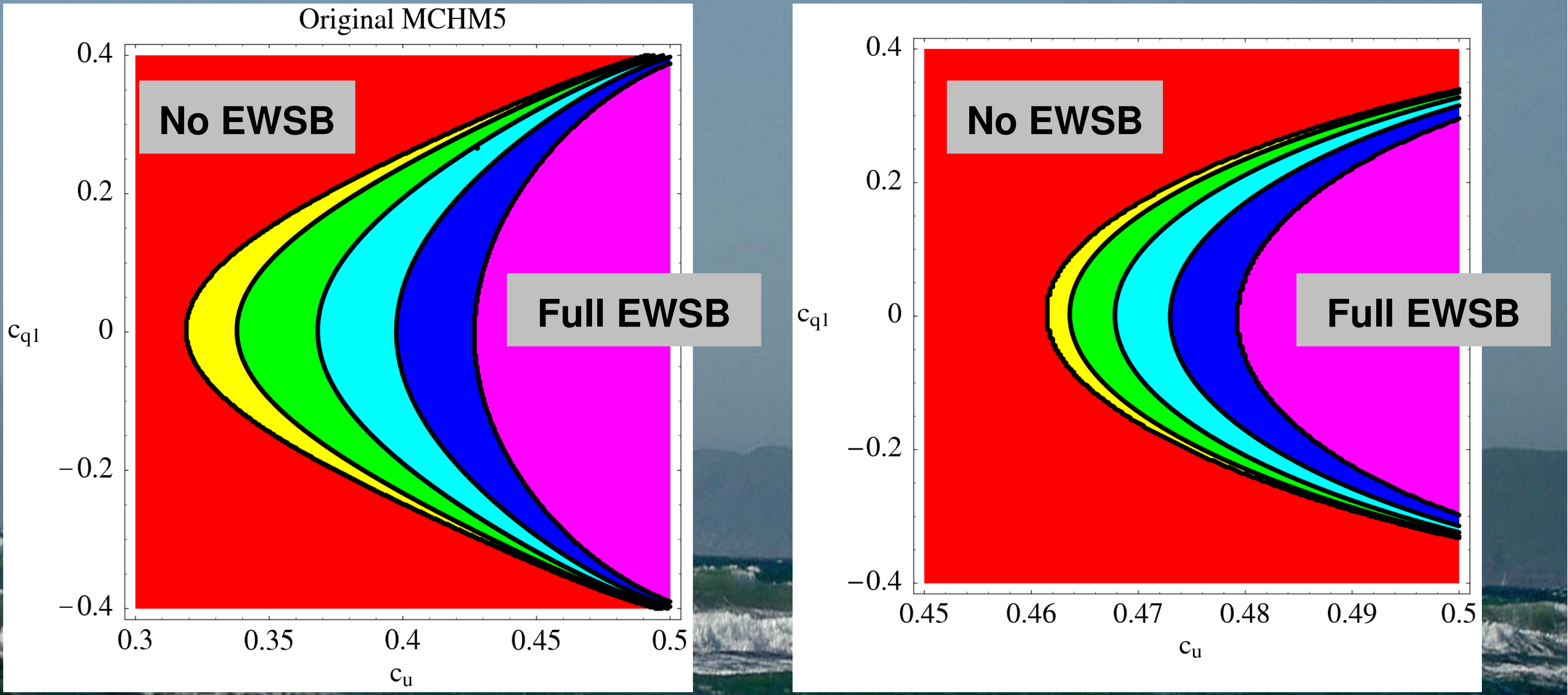


$$V(h) \approx \alpha \cos(h/f) - \beta \sin^2(h/f)$$

EWSB $\sin\left(\frac{<h>}{f}\right) \approx \sqrt{1-\left(\frac{\alpha}{2\beta}\right)^2}$

A full model: Z_2 $MCHM_5$

- Good region of parameter space: right EWSB pattern, top and Higgs masses, EW precision observables

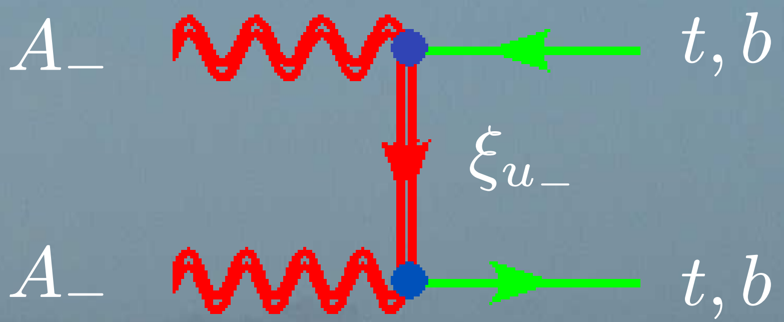


A full model: Z_2 $MCHM_5$

- Contribution to the relic abundance

$$0.094 \leq \Omega^{\mathrm{WMAP}} h^2 \leq 0.129$$

  - A- annihilation



$$\Omega h^2 \propto \frac{m_{A_-}^2}{g^4} \gtrsim 0.2 - 0.4$$

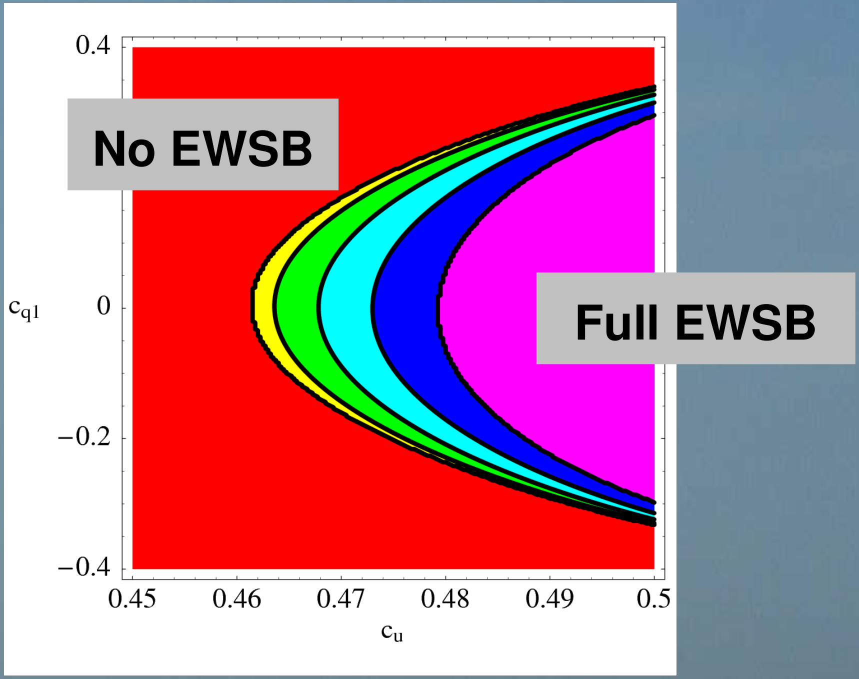
  - Coannihilations seem necessary!!

A full model: Z_2 $MCHM_5$

- EWSB prefers the region where coannihilations are relevant

$$m_{q_-} \sim m_{A_-} \text{ for } c_u \to 1/2$$

  - Good agreement with the observed relic abundance in the region with EWSB



- Also positive contribution to T (improved fit to EW precision data)

A full model: Z_2 $MCHM_5$

- New light (Z2 even and odd) vector-light quarks, accessible during the early phase of the LHC
  - Massive production of WWtt and WWbb events
  - Strong production of MET+ tt, bb, jj events
  - Large modifications of top couplings to H, W and Z
- Direct detection of WIMP difficult: full reconstruction of the model at colliders is crucial

Conclusions

- Composite Higgs models are an atractive alternative for a natural theory of EWSB
- Full calculability in models with warped EDs
- Completely novel collider phenomenology (large class of warped models, not necessarily Composite Higgs)
- Study at LHC of vector-like quarks promising and crucial to unfold these models
- Possible to implement dark matter with new collider signatures

Enjoy the rest of the workshop

- And the weather . . . while you can!