Dynamical EWSB in Warped Extra Dimensions

Marcela Carena
Theoretical Physics Department, Fermilab
Department of Physics and Enrico Fermi Institute, University of Chicago

2009 Aspen Winter Conference
Aspen Center for Physics, Aspen, February 13, 2009

Outline

Models of New Physics to explain:

The (dynamical) origin of EWSB, the hierarchy problem

Many interesting talks in this conference related to these ideas

EWSB Models of Strong Dynamics from Warped Extra Dimensions

** Gauge-Higgs Unification

** Top Condensation

New Heavy Quark Signatures at Colliders

Based on work done in collaboration with

E. Ponton, J. Santiago and C. Wagner,

Phys.Rev.D76:035006,2007,Nucl.Phys.B759:202-227,2006

Y. Bai and E. Ponton,

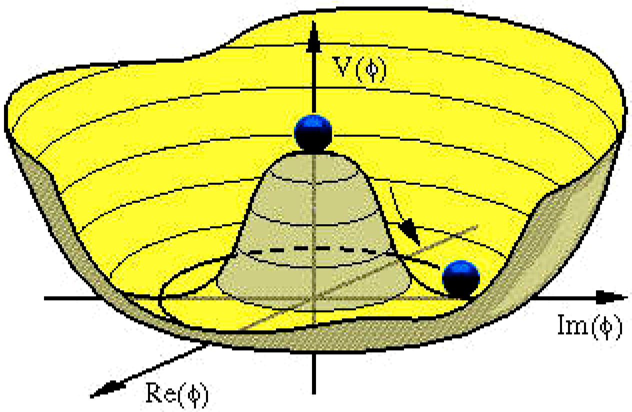
arXiv:0809.1658 [hep-ph]

A. Atre, T. Han and J. Santiago,

arXiv:0806.3966 [hep-ph] and in preparation

EWSB in the SM: The Higgs Mechanism

A self interacting complex scalar doublet with no trivial quantum numbers under $SU(2)_L \times U(1)_Y$



Higgs field acquires non-zero value to minimize its energy

$$V(\Phi) = \mu^2 \Phi^+ \Phi + \frac{\lambda}{2}\left(\Phi^+ \Phi\right)^2 \qquad \mu^2 < 0$$

Higgs vacuum condensate v ==> scale of EWSB

$SU(3)_C \times SU(2)_L \times U(1)_Y \Longrightarrow SU(3)_C \times U(1)_{em}$

The Higgs mechanism: Nambu Goldstone bosons ⟷ Longitudinally polarized W_L and Z_L

Masses to W,Z and SM fermions

- One extra physical state -- Higgs Boson -- left in the spectrum

not a real theory of EWSB, just a parameterization

Associated to the SM EWSB mechanism ==> The Hierarchy problem: Why $v \ll M_{Pl}$?

New Physics at the TeV scale is suggested

EWSB occurs at the TeV scale:

new phenomena should lie in the TeV range or below, at the reach of LHC

The Quest of EWSB is the search for the dynamics that generates the Goldstone bosons that are the source of mass for the W and Z

Two broad classes of theories have been proposed:

** weakly interacting self coupled elementary (Higgs) scalar dynamics

Standard Model, Supersymmetry ==> examples of weak EWSB

** strong interaction dynamics among new fermions (mediated perhaps by gauge interactions, in possible connection with warped extra dimension)

Technicolor, Top-condensation/Top-color, Higgsless models, Gauge-Higgs Unification, Little Higgs models,....

These mechanisms generate new particles with clear experimental signatures

precision measurements strongly constrain

the existence of new particles at the TeV scale

Weak vs Strong Dynamical EWSB

- Excellent agreement of precision measurements of EW observables with SM predictions calls for a weakly coupled New Physics Model that solves SM puzzles while minimally perturbing the SM great achievements

- On the other hand, most of the mass of matter arises dynamically from QCD, that also breaks EW symmetry and contributes to W/Z masses but, the scale (1GeV) is wrong

- In any case, EWSB from strong dynamics is rather appealing theoretically

EWSB and Strong Interaction Dynamics

New Strong Dynamics at the TeV scale:

EW symmetry broken by critically strong new interactions

Analogy with QCD: scale of EWSB is exponentially separated from M_{Planck} by running of coupling

No Higgs boson: e.g. *QCD-like Technicolor theories, Higgsless 5D models*

[talk by C. Csaki]

Composite Higgs Boson: a strong interaction postulated as an attractive four fermion interaction which forms a quark condensate (bound state boson)

e.g. *Topcolor theories* (gauging of Top condensation)

Top seesaw mechanism (top-vector-like singlet condensate)

Top condensation from Warped ED KK gluons

Pseudo-Nambu Goldstone Higgs Boson: [talks by C. Csaki and W. Skiba]

associated to a global symmetry partly broken by gauge/Yukawa interactions.

Little Higgs Models (valid up to scale of tens of TeV)

Gauge Higgs Unification Models (associated with Warped ED)

EWSB and Strong Interaction Dynamics

Flavour:

Technicolor-like models require many different flavor scales
Extended Technicolor to give masses to fermions, but induce FCNC or too small top quark mass ==> Topcolor assisted Technicolor

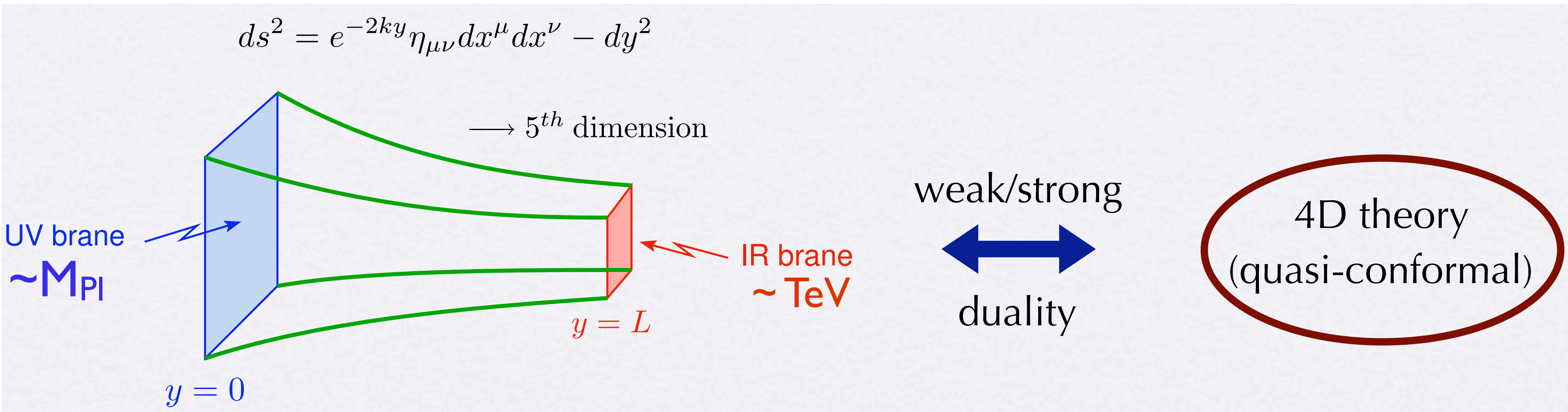
Precision electroweak bounds:
Heavier Higgs/new fermions/gauge bosons contributions strongly constrain these scenarios

These theories require a UV completion

What about the connection between theories of strong dynamics and the existence of extra dimensions of space?

Strong Dynamics from AdS_5 models of EWSB

A revival of EWSB from strong dynamics using ideas in extra dimensions

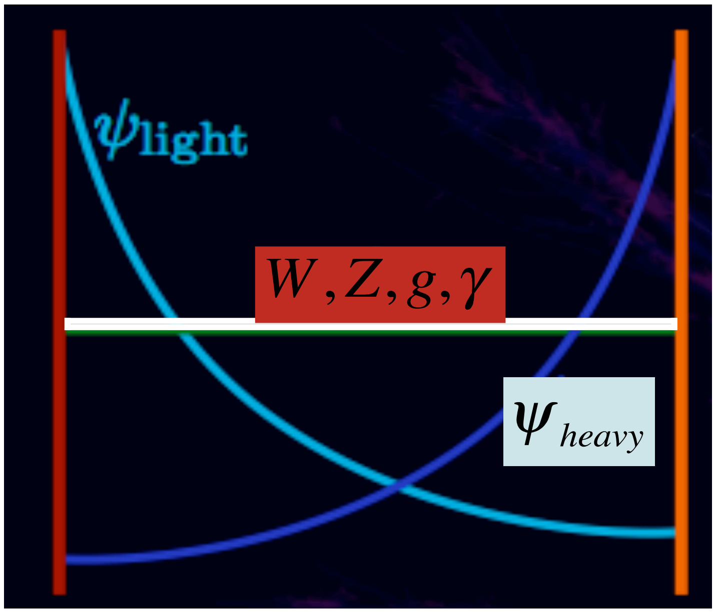


- AdS in 5D ⟷ CFT in 4D
- (Quasi) Conformal strongly coupled theory in 4D (large N) dual to weakly coupled in 5D
- Build strongly coupled theories of the TeV scales using weakly coupled AdS_5 ==> allows calculability and opens new possibilities
- Geometry of the extra dimension generates hierarchy exponentially

Higgs localized in the IR brane ==> Higgs v.e.v. naturally of order of the TeV scale

Dynamical EWSB in Warped ED with Bulk Matter Fields

- Allowing gauge fields and matter to propagate in the bulk
  $\Rightarrow$ models of EWSB, flavor, GUTs, etc.
- Bulk Randall-Sundrum models: several possibilities for model building



UV brane

IR brane
Higgs + KK modes

SM hierarchical fermion masses from localization
[masses depend on overlap with Higgs/TeV scale]

KK modes localize towards the IR for
* Weak bosons, Gluons, **Fermions**
* As well as gravitons

Flavor: talks by A. Weiler and M. Neubert

All KK modes are localized towards the IR brane
==> large corrections to SM gauge boson masses & couplings due to Higgs induced mixing
==> strong constraints on the scale of New Physics, but, if additional symmetries present:

$$\tilde{k} \geq 1.5 \text{ TeV} \ \Rightarrow \text{KK gauge boson masses} > 3\text{TeV}$$

Gauge-Higgs Unification Models

If there is a Higgs: what is its dynamical origin ?
Or why is it localized towards the TeV brane ?

- Gauge field in 5D has scalar A_5
- To extract H from A_5 need to enlarge SM gauge symmetry.

To avoid large corrections to EW observables impose custodial and L--R symmetry

Gauge sector enlarged to: **SO(5) x $U(1)_X$ x P_{RL} in the bulk**

broken by boundary conditions to **$SU(2)_L$ x $SU(2)_R$ x $U(1)_X$ x P_{RL} in the IR**

and to **$SU(2)_L$ x $U(1)_Y$ in the UV**

Extra Gauge Boson A_5 has a zero mode with the Higgs quantum numbers

$$SO(5)/SO(4) \longrightarrow A_\mu^{\hat{a}}(-,-) \quad A_5^{\hat{a}}(+,+)$$ ← Identify with H

Contino, Nomura, Pomarol 03
Agashe, Contino, Da Rold, Pomarol 05-06

- ❖ Higgs is a 4 of S0(4): 4 d.o.f. ⟷ complex $SU(2)_L$ doublet
- ❖ Gauge Bosons and Fermions are in complete SO(5) multiplets

Gauge-Higgs Unification Models cont'd

* No tree-level Higgs Potential

(one cannot write a potential for gauge fields due to gauge invariance)

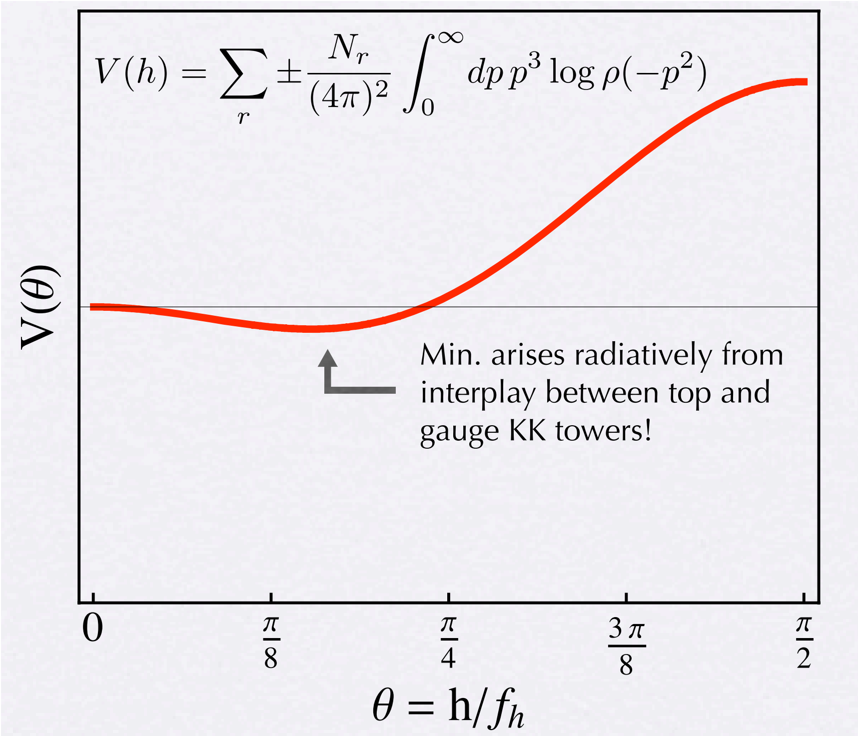
==> Induced at one-loop level Medina, Shah, Wagner 07

- The quantum vacuum prefers that $\langle h \rangle \neq 0$
  (consequence of large top mass)

↓

Dynamical EWSB:
driven by the top Yukawa

One can build models that explain EWSB, generate the SM flavor structure and be consistent with EW precision tests



❖ A fundamental scalar Higgs mainly localized in the IR (PNGB of the approx. symmetry)

❖ Yukawa couplings arrive through gauge couplings M.C, Ponton, Santiago, Wagner 07

The Heavy Quark Spectrum

- SM left-handed fermions are in bidoublets under $SU(2)_L \times SU(2)_R$ to satisfy custodial and L--R symmetries
  In general fermions can be:

$$\mathbf{5_{2/3}} = (\mathbf{2},\mathbf{2})_{2/3} \oplus (\mathbf{1},\mathbf{1})_{2/3} \qquad \mathbf{10_{2/3}} = (\mathbf{2},\mathbf{2})_{2/3} \oplus (\mathbf{1},\mathbf{3})_{2/3} \oplus (\mathbf{3},\mathbf{1})_{2/3}$$

$$\text{Hypercharge } Y = T^3_R + Q_X \qquad \text{Electric Charge } Q = T^3_L + T^3_R + Q_X \qquad Q_X = 2/3$$

- KK fermions are vector like (each has both chiralities with same quantum numbers)

- Some KK fermions have exotic charges (5/3 or -4/3)

- KK Fermion masses tend to be light:
  Lightest 1 and 2. gen. KK bidoublet/singlet quarks masses may be ~ 400 -500 GeV
  Lightest 3 gen. KK singlet or bidoublet masses must be light ~ 400 to 1500 GeV

- In realistic models of Warped ED, the new heavy doublets/singlets can couple to SM particles in ways detectable at the Tevatron and still compatible with precision and flavor data M.C., Santiago, Ponton, Wagner '07; Atre, MC, Han, Santiago'08

Heavy Quarks at the Tevatron Reach

- Due to precision measurements on light quark couplings, new vector like quarks are typically allowed to mix sizeably only mainly with the top
- However, in models of Warped Extra dimensions vector-like quarks can couple sizably to SM fermions without upsetting usual SM fermion couplings.
- Simple example: Atre, MC, Han and Santiago 08

SM fields plus two vector like quark $SU(2)_L$ doublets with Y = 1/6 and 7/6

$$Q^{(0)}_{L,R} = \begin{pmatrix} q^{(0)u}_{L,R} \\ q^{(0)d}_{L,R} \end{pmatrix}_{1/6}, \quad X^{(0)}_{L,R} = \begin{pmatrix} \chi^{(0)u}_{L,R} \\ \chi^{(0)d}_{L,R} \end{pmatrix}_{7/6}$$

Electric charges equal $2/3$ for q^u and χ^d, $1/3$ for q^d and $5/3$ for χ^u

with degenerate masses (same higher multiplet) and coupling to u_R,
Yukawa mixing only with u_R in the basis of diagonal up-type Yukawas

$$\mathcal{L} = \mathcal{L}_{\rm K} - \Big[\lambda^i_u \bar{q}^{(0)i}_L \tilde{\varphi} u^{(0)i}_R + \lambda^i_d V_{ij} \bar{q}^{(0)i}_L \varphi d^{(0)j}_R + \lambda_Q (\bar{Q}^{(0)}_L \tilde{\varphi} + \bar{X}^{(0)}_L \varphi) u^{(0)}_R + m_Q (\bar{Q}^{(0)}_L Q^{(0)}_R + \bar{X}^{(0)}_L X^{(0)}_R) + \text{h.c.}\Big]$$

In the physical basis: $D^{Q=1/3}$ and $Q^{Q=5/3}$ and $U^{Q=2/3}$ couple to u-quark via CC and NC and from 5D localization of SO(5) multiplets $\lambda_q \simeq 1$, and $\lambda_u \approx 10^{-5}$

Single production of new heavy quarks becomes an ideal discovery process, without any observable trace of their existence in SM interactions

Model-independent study of single heavy quark production at the Tevatron

Two new quarks, U (charge = 2/3) and D (charge = -1/3)
with CC and NC gauge interactions of arbitrary coupling strength

$$\frac{g}{\sqrt{2}} W_\mu^+ (\kappa_{uD}\ \overline{u}_R \gamma^\mu D_R + \kappa_{dU}\ \overline{d}_R \gamma^\mu U_R) + \frac{g}{2c_W} Z_\mu (\kappa_{uU}\ \overline{u}_R \gamma^\mu U_R + \kappa_{dD}\ \overline{d}_R \gamma^\mu D_R) + \text{h.c.}$$

$$\kappa_{qQ} = (\mathrm{v}/m_Q)\ \tilde{\kappa}_{qQ}, \qquad \mathrm{v} \equiv 174\ \mathrm{GeV}$$

$\tilde{\kappa}_{qQ}$ is a dimension parameter that encodes the model dependence

From Warped ED Gauge-Higgs Unification models we have

$$\tilde{\kappa}_{uU} \simeq -\sqrt{2}\lambda_Q \simeq \mathcal{O}(1) \ \text{ and } \ \tilde{\kappa}_{\mathrm{uD}} \simeq -\lambda_{\mathrm{Q}} \simeq \mathcal{O}(1)$$

Similarly, a Warped ED model with 2 vector-like doublets with hypercharges 1/6 and -5/6, mixing only with d_R will generate $\tilde{\kappa}_{dU}$ and $\tilde{\kappa}_{\mathrm{dD}}$

The model-independent study is flexible to include

- Extra quarks with exotic charges (5/3 or -4/3) that may couple with up and down quarks via CC can be included via enhanced production rates
- Heavy quark-Higgs couplings are not considered in the production mechanism since such contribution is negligible, but they are allowed in the heavy quarks decays $\longrightarrow$ One can reabsorb Higgs decay modes in the BR's which are treated as a free parameter
- Study does not depend relevantly on chirality of the couplings since no angular correlations are considered

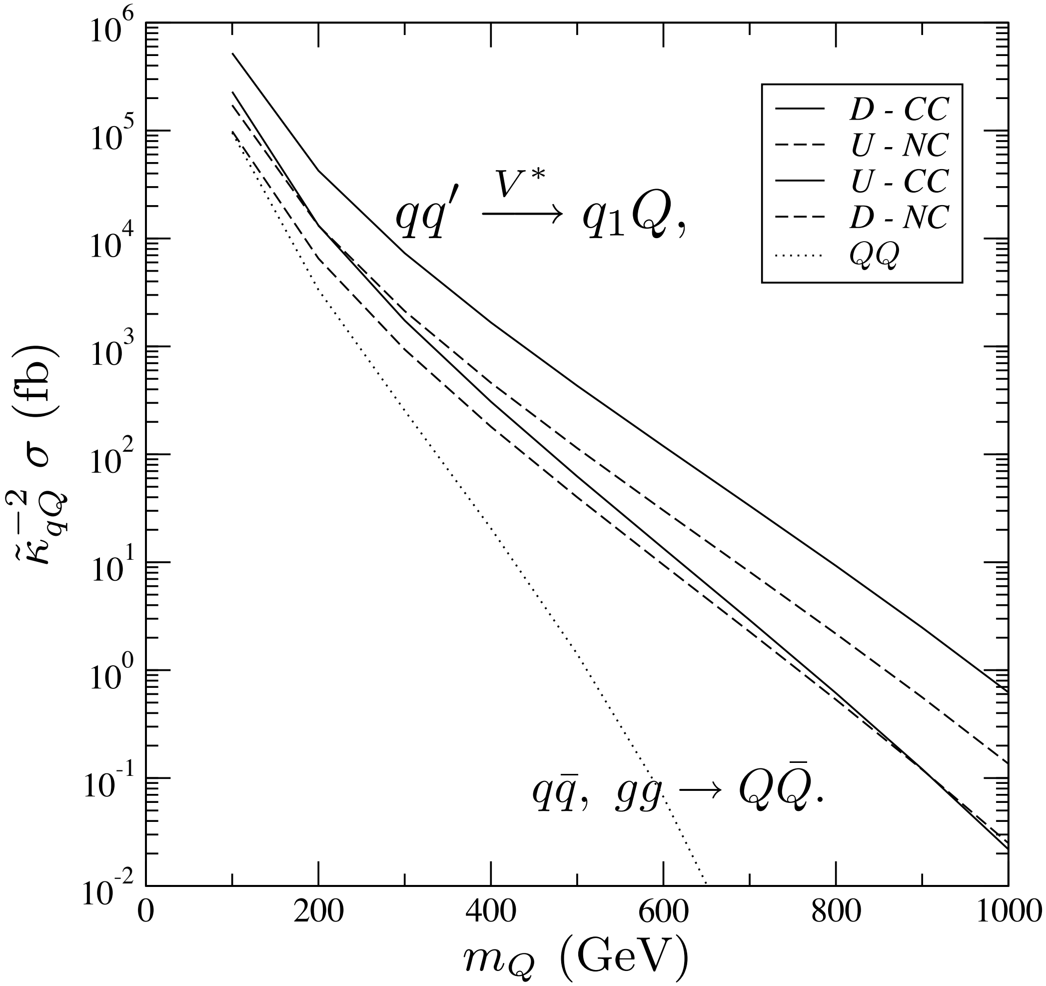
  -- Right-handed CC and NC gauge interactions appear in the case of vector like doublets

  -- Left-handed CC and NC gauge interactions appear in the case of vector like singlets

  both type of New quarks can be present in Warped ED models

Heavy Quark Production at the Tevatron
QCD pair production vs electroweak single quark Production

Atre, M.C., Han, Santiago



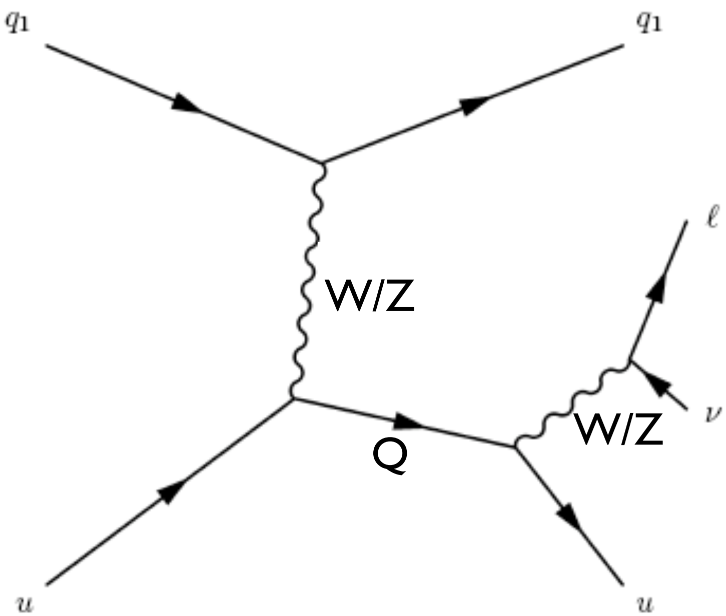
- NLO corrections included via K factors:
  K ~ 1.5 (pair prod.)
  K ~ 0.96 (single prod.)
- Present Tevatron bound: m_Q > about 300 GeV at 95%C.L. for heavy up/down type quarks
- Single Quark production becomes dominant for large m_Q, if $\tilde{\kappa} \approx \mathcal{O}(1)$

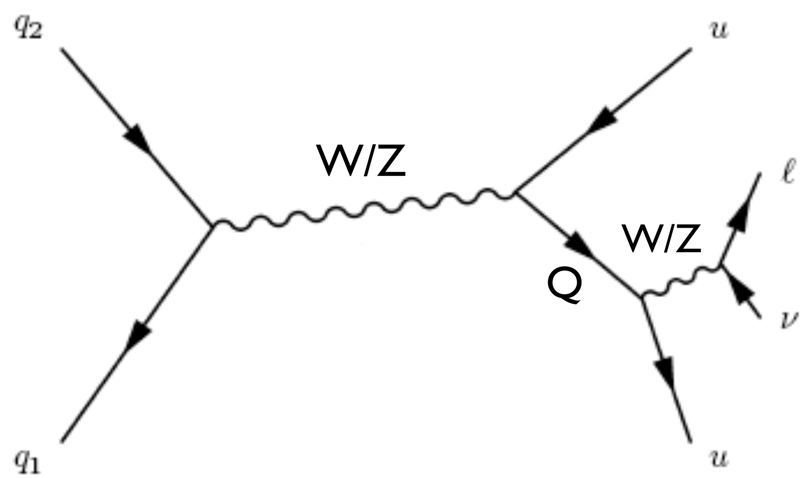
Single production via CC and NC currents involve $D + \bar{D}$ or $U + \bar{U}$

Heavy Quark Signals:

via Charged Current or Neutral Current Interactions

$$D \to W^- u,\ Zd,\ hd, \quad U \to W^+ d,\ Zu,\ hu.$$





$pp(p\bar{p}) \to qQ \to quW \to qul\nu \quad \Rightarrow \text{Signal}:\ 2j + l + \not{E}_T$

$pp(p\bar{p}) \to qQ \to quZ \to qul^+l^- \quad \Rightarrow \text{Signal}:\ 2j + l^+l^-$

$pp(p\bar{p}) \to qQ \to quZ \to qu\nu\bar{\nu} \quad \Rightarrow \text{Signal}:\ 2j + \not{E}_T$

Both D and $\bar{\text{D}}$ or U and $\bar{\text{U}}$ considered

Single Quark Production Cross Section

define production cross section with heavy quark BR's as free parameters

$$\sigma(pp \to q_1 q_2 f\overline{f}) \equiv S_Q^{CC(NC)}\ \sigma_{prodn}^{CC(NC)}\ Br(V \to f\bar{f}),$$

under narrow width approximation

$\sigma_{prodn}^{CC(NC)}$ is only dependent on the mass of the heavy quark

$S_Q^{CC(NC)}$ encode model-dependent mixing terms

Model-dependent mixing terms are defined as

$$\begin{aligned}
S_D^{CC} &\equiv (\tilde{\kappa}_{uD}^2 + \alpha_D^{CC}\ \tilde{\kappa}_{dD}^2)\ Br(D \to qW),\\
S_U^{CC} &\equiv (\tilde{\kappa}_{dU}^2 + \alpha_U^{CC}\ \tilde{\kappa}_{uU}^2)\ Br(U \to qW),\\
S_D^{NC} &\equiv (\tilde{\kappa}_{dD}^2 + \alpha_D^{NC}\ \tilde{\kappa}_{uD}^2)\ Br(D \to qZ),\\
S_U^{NC} &\equiv (\tilde{\kappa}_{uU}^2 + \alpha_U^{NC}\ \tilde{\kappa}_{dU}^2)\ Br(U \to qZ),
\end{aligned}$$

$\alpha_Q^{CC} \equiv \sigma_{prodn}^{NC}/\sigma_{prodn}^{CC}$ and $\alpha_Q^{NC} \equiv \sigma_{prodn}^{CC}/\sigma_{prodn}^{NC}$

are the ratios of the production cross section of the heavy quarks via CC and NC

In the case of degenerate bidoublets only one gauge boson decay mode is available for each new quark

$Br[Q \to qW(Z)]$ is 100% $\quad S_D^{CC} = \tilde{\kappa}_{uD}^2$ and $S_U^{NC} = \tilde{\kappa}_{uU}^2$

Background Processes

- $W + 2$ jets, $Z + 2$ jets with W, Z leptonic decays; (dominant background)
- $W^+W^-, W^\pm Z$, and ZZ with semi-leptonic decays;
- single top production leading to $W^\pm b\ q$.

Basic Cuts

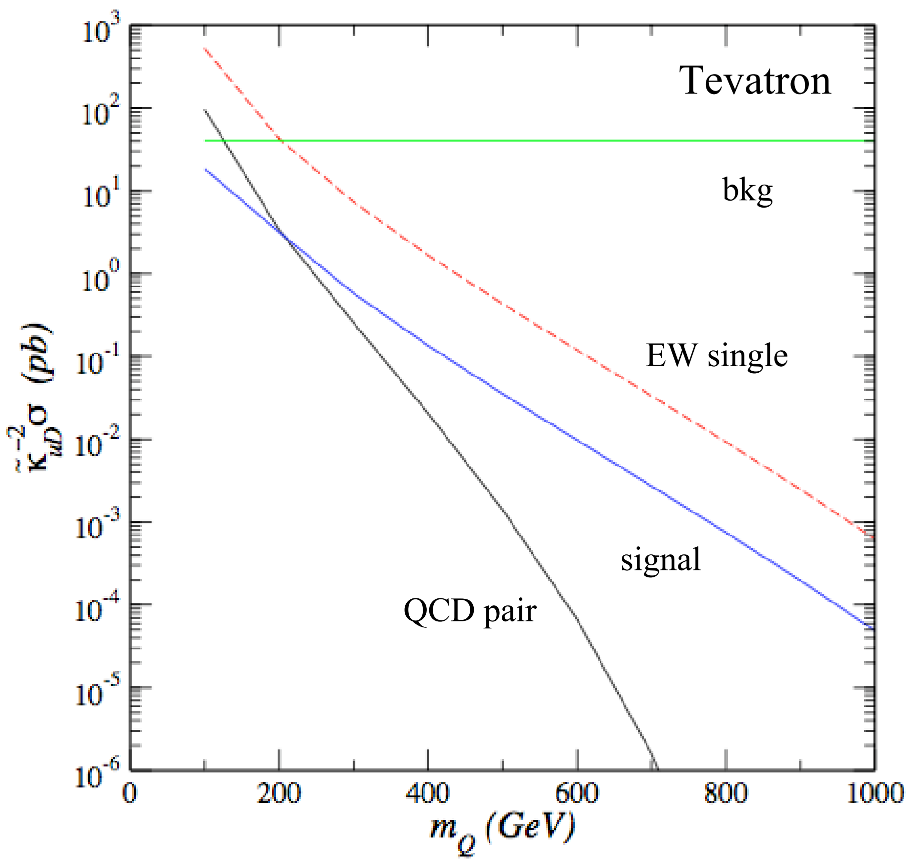
$p_T(jet) > 15\ GeV$	$\lvert\eta_{jet}\rvert < 3$	$\Delta R_{jj} > 0.7$
$p_T(lep) > 15\ GeV$	$\lvert\eta_{lep}\rvert < 2$	$\Delta R_{j\ell} > 0.5$
$p_T(miss) > 15\ GeV$		$\Delta R_{\ell\ell} > 0.3$

Additional lepton/$\not{E}_T$ veto to reduce $t\bar{t}$ background

CC: veto 2nd lepton:

$p_T(\ell) > 15$ GeV, $|\eta_\ell| < 2$ and $\Delta R(j\ell) > 0.5$

NC: veto events with any lepton or w/ $\not{E}_T > 15$ GeV



Energy Smearing:

$$\Delta E_\ell/E_\ell = 0.135/\sqrt{E_\ell/\mathrm{GeV}} \oplus 0.02$$

$$\Delta E_j/E_j = 0.75/\sqrt{E_j/\mathrm{GeV}} \oplus 0.03$$

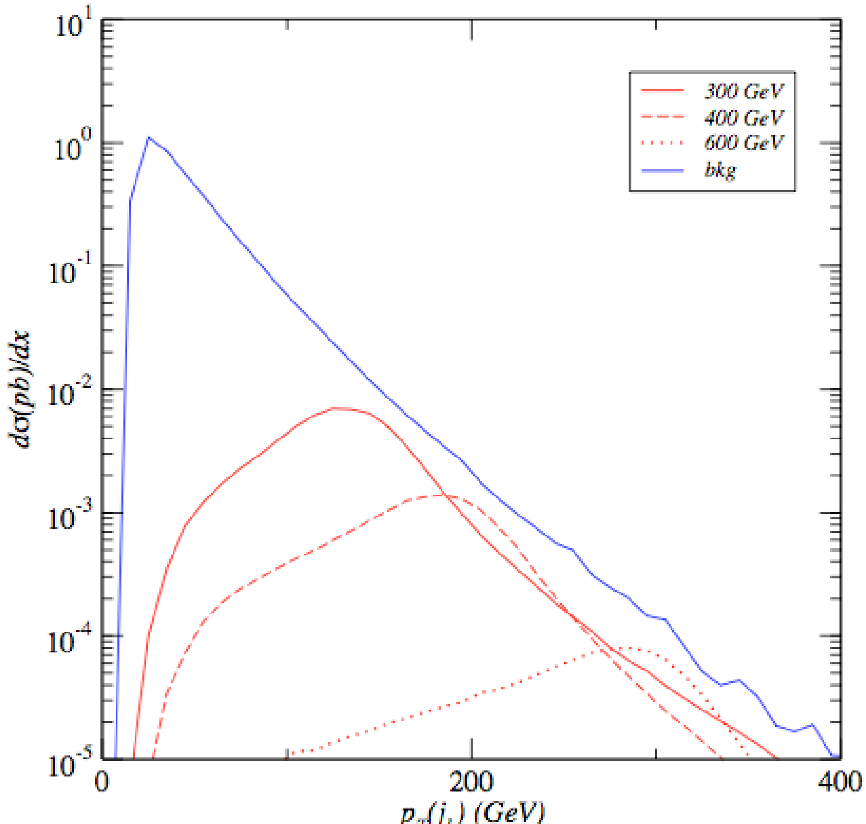
Signal vs Background Distributions

Improved Cuts I

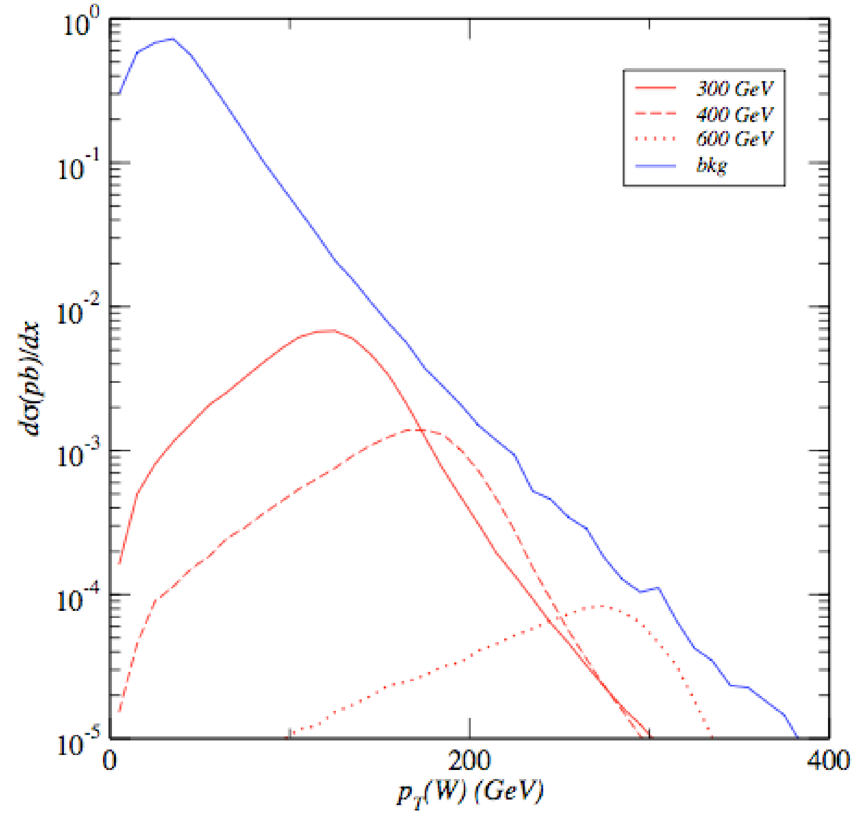
Jet associated with W/Z channel exchange is soft,

jet from heavy quark decay is very energetic

Similarly, W/Z from heavy quark decays are energetic



$$p_T(j_h) > \frac{1}{4} m_Q$$

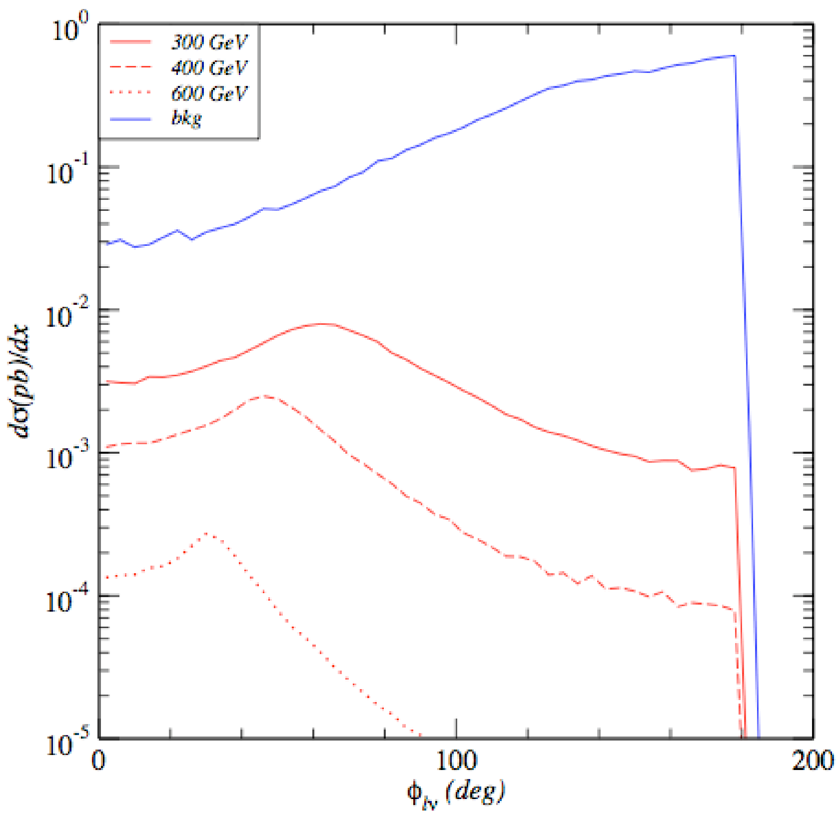


$$p_T(W/Z) > \frac{1}{5} m_Q$$

Improved Cuts 2

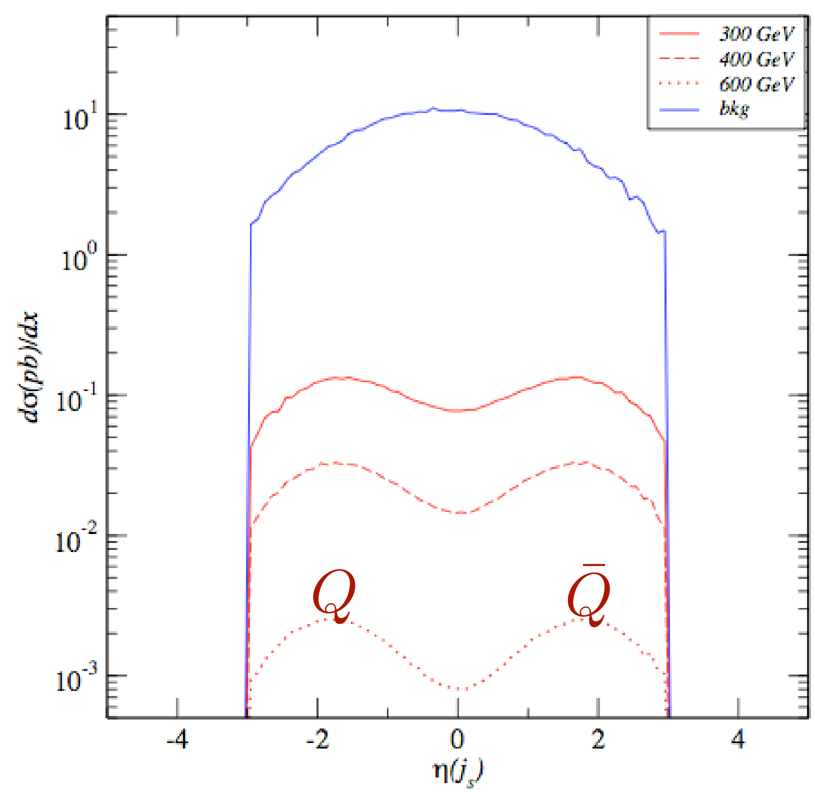
Decay products of W/Z very energetic, tend to be more collimated than the background.

Design mass based cut on $\phi_{\ell\nu}, \phi_{\ell\ell}$



Pseudo-rapidity of the soft jet associated to W/Z t-channel exchange peaks at $|\eta_{j_s}| \sim 2$

$$0.5 < |\eta_{j_s}| < 3.0.$$



Also tigthen the cut on ΔR

$$\Delta R_{jj} > 1.5 \quad \Delta R_{j\ell} > 0.8$$

Identify Q vs anti-Q from lepton em charge

Soft jet forward (backward) imply anti-Q (Q) production

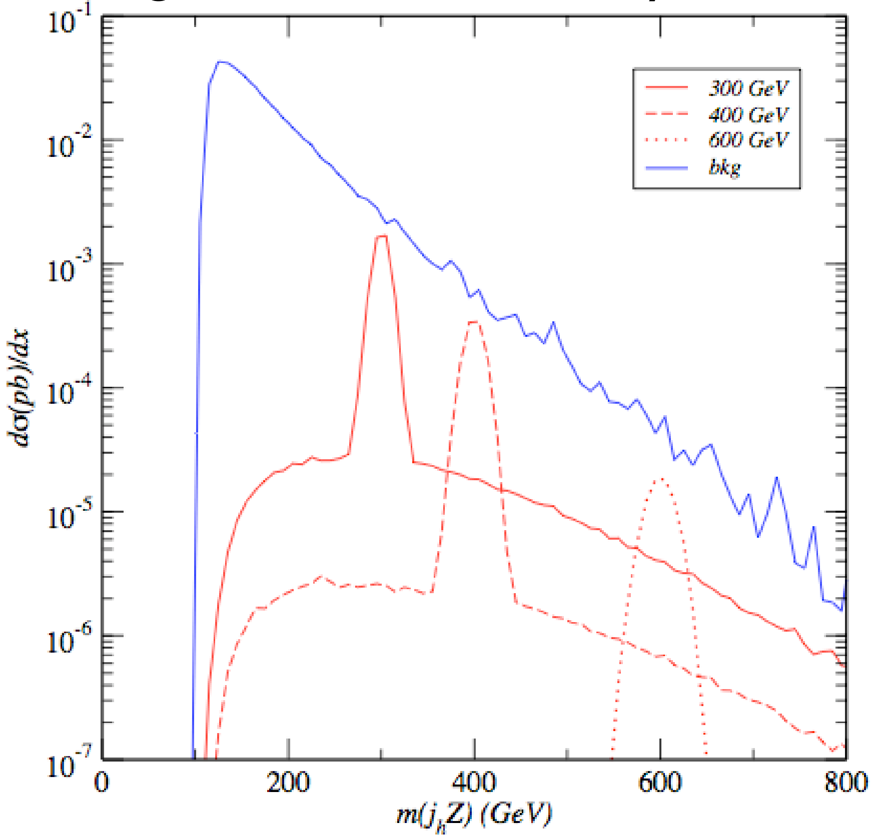
Backward soft jet and l^+ (l^-) indicate U (D) production

Forward soft jet and l^+ (l^-) indicate anti-D (anti-U) instead

Improved Cuts 3

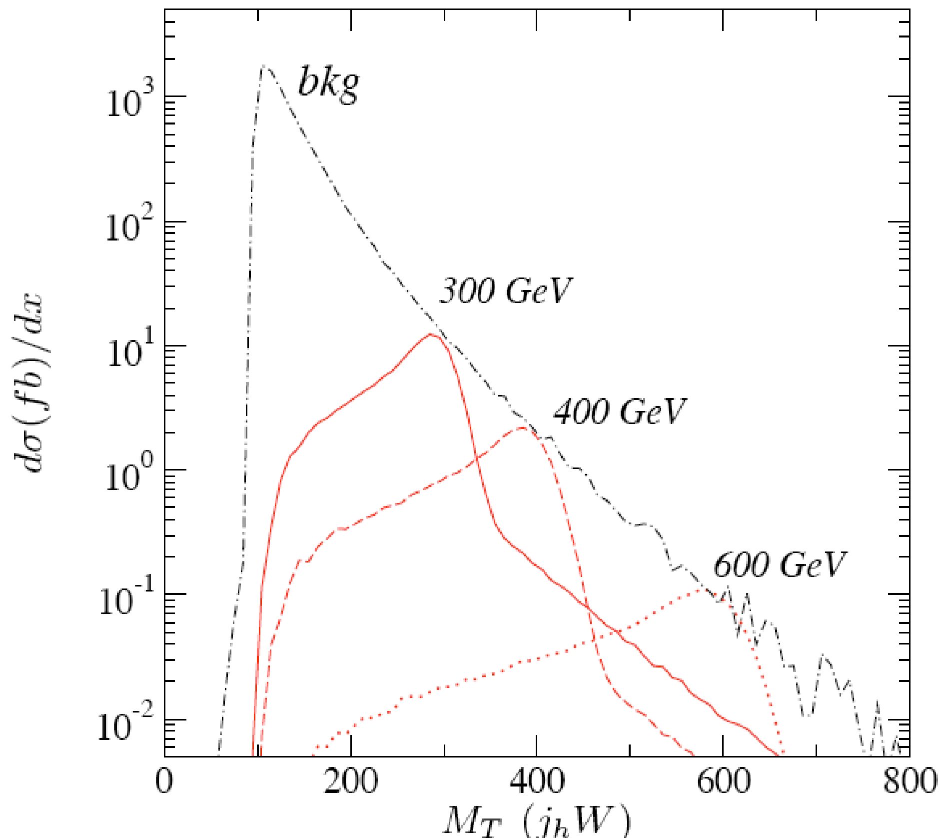
Mass peak reconstruction of the heavy quark

Straightforward for the decay of Z to l^+l^-.



For the decays $W \to \ell\nu$ and $Z \to \nu\bar{\nu}$.

$$M_T^2 = \left(\sqrt{p_{TW,Z}^2 + M_{W,Z}^2} + p_{Tj_h}\right)^2 - (\vec{p}_{TW,Z} + \vec{p}_{Tj_h})^2$$



Suggest Mass Cuts:

$$m_Q - \frac{1}{4} m_Q \ < \ M_T(j_h W/Z) < m_Q + 50\ \text{GeV}$$

$$m_Q - 30\ \text{GeV} \ < \ M(j_h Z) < m_Q + 30\ \text{GeV}$$

Real analysis must consider several window cuts and include statistical dilution factor

Total cross-sections (in fb) for the signal with $m_Q = 400$ GeV and the leading SM backgrounds

CC current, with $S_Q^{CC}=1$

channels	Basic cuts (10)	High p_T (11)	m_Q (12)
$D \to W^\pm q$	270	190	160
$U \to W^\pm q$	49	35	29
$W^\pm + 2j$	79000	1200	280
$W^\pm W^\mp(\to 2j)$	1500	15	1.4
$W^\pm Z(\to 2j)$	230	4.7	0.52
single top: $W^\pm b\ j$	330	10	2.9
$t\bar{t}$: fully leptonic	170 (79)	2.0	0.40
$t\bar{t}$: semi-leptonic	600	0.19	-

$D + \overline{D}$ and $U + \overline{U}$ and the leptons $\ell = e, \mu$

For $t\bar{t}$
a veto on events with two isolated leptons.

NC current, with $S_Q^{NC}=1$

channels	Basic cuts (9)	High p_T (10)	m_Q (11)
$D \to Z(\to \ell\ell)q$	8.8	6.0	5.7
$U \to Z(\to \ell\ell)q$	22	15	15
$Z(\to \ell\ell) + 2j$	6962	118	14
$Z(\to \ell\ell)W^\pm(\to 2j)$	60	0.65	0.08
$Z(\to \ell\ell)Z(\to 2j)$	55	1.1	0.11
$t\bar{t}$: fully leptonic	162 (1.70)	-	-

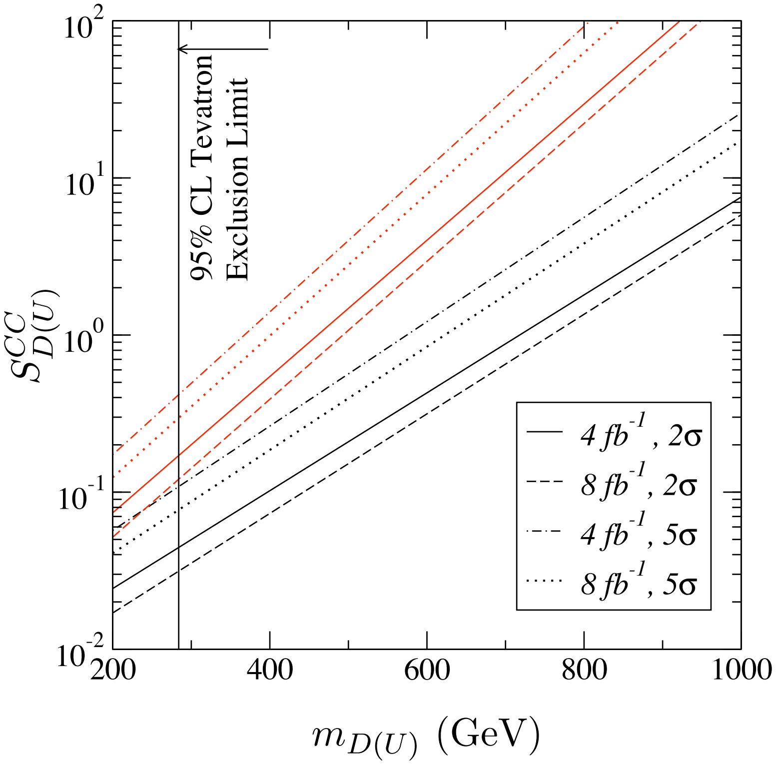
$\ell = e, \mu$ For $t\bar{t}$ a veto on events with $\not{E}_T$

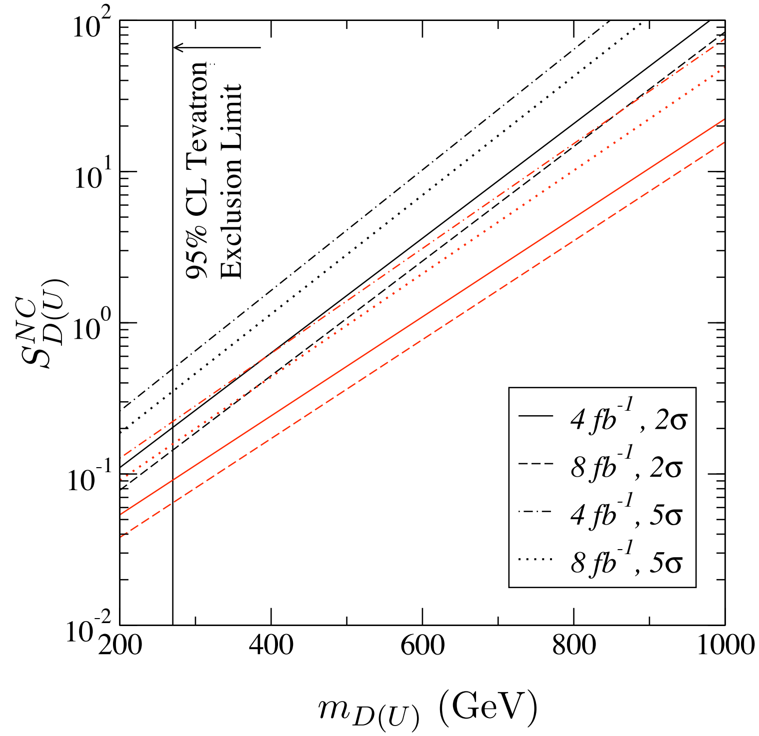
channels	Basic cuts (10)	High p_T (11)	m_Q (12)
$D \to Z(\to \nu\nu)q$	31	22	18
$U \to Z(\to \nu\nu)q$	79	56	46
$Z(\to \nu\nu) + 2j$	28000	630	160
$Z(\to \nu\nu)W^\pm(\to 2j)$	240	3.4	0.30
$Z(\to \nu\nu)Z(\to 2j)$	220	6.1	0.76
$t\bar{t}$: fully leptonic	260 (12)	1.5	0.89
$t\bar{t}$: semi-leptonic	880 (290)	2.3	1.1

$\nu = \nu_e, \nu_\mu, \nu_\tau$.

For $t\bar{t}$ a veto on events with isolated leptons.

Sensitivity plots in the model-independent parameter S_Q^{CC} or S_Q^{NC} vs. the heavy quark mass $m_Q = m_U$ or m_D.





$\int \mathcal{L}dt$	$4\ \text{fb}^{-1}$		$8\ \text{fb}^{-1}$	
Sensitivity	2σ	5σ	2σ	5σ
m_D for $S_D^{CC} = 1$ (2)	720 (820)	580 (670)	760 (860)	630 (710)
m_U for $S_U^{CC} = 1$ (2)	470 (530)	370 (440)	490 (560)	400 (470)
m_D for $S_D^{NC} = 1$ (2)	450 (530)	350 (420)	490 (570)	380 (470)
m_U for $S_U^{NC} = 1$ (2)	590 (680)	460 (540)	640 (730)	510 (590)

Tevatron reach for $m_{U,D}$ [GeV]
via
single heavy quark production

$m_Q \sim$ 400 - 850 GeV range

The Planck Scale from Top Condensation

Top-condensation models (Nambu; Bardeen, Hill, Lindner):
EWS broken by $\langle \bar{t}t \rangle \neq 0$

- Top quark is too light: $m_t \sim 600$ GeV if $\Lambda \sim O(1)$ TeV.
  Or $\Lambda \sim 10^{15}$ GeV if $m_t \sim 200$ GeV.

- What is the underlying interaction that produces the condensate?

However, if you are willing to buy one extra dimension... many things follow:

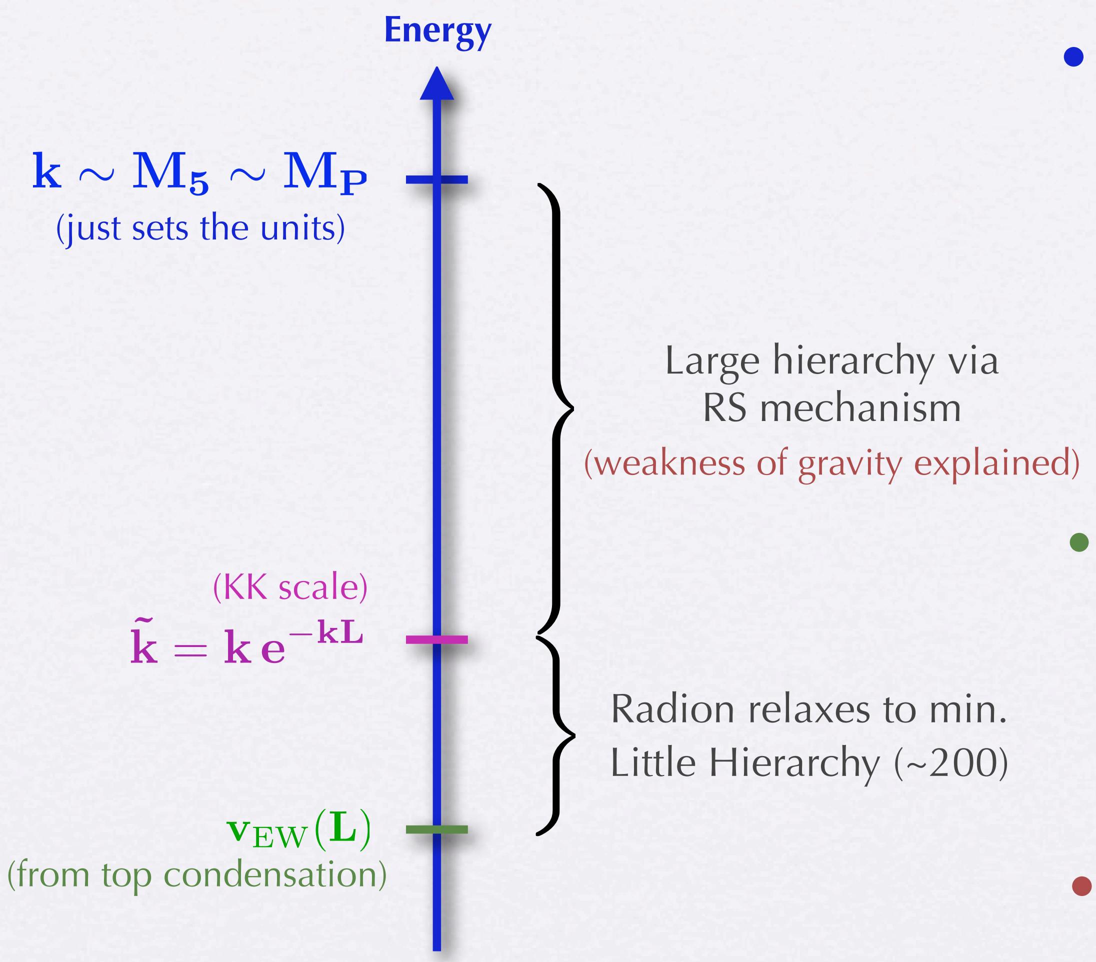
- 4-fermion interactions induced by KK gluon exchange

- the EW symmetry is broken dynamically
- the Planck/EW scale hierarchy is natural

Given by Top Condensation via Radion Stabilization

Bai, M.C, Ponton '08

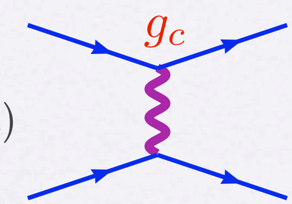
The scales of the Model



- A single dimensionful scale: k
  - OK. 5D theory also has cutoff Λ , but not too different
  - Other dimensionless parameters:
    c_f : fermion localization
    $g_5\sqrt{k}$: KK gauge interactions
- Other scales generated dynamically
  - $\langle \bar{t}_L t_R \rangle \neq 0 \quad \longrightarrow \quad v_{\rm EW}$
  - Radion field: $\langle \phi \rangle = L$
    (potential results from EWSB!)
- Upshot: model induces two ratios
  - Planck/EW (already measured)
  - KK/EW (prediction)

The Mechanism: a toy model

Consider a $SU(N_c)$ theory with two flavors: $\Psi_{1,2}$ (fundamental rep.)



- KK gluon exchange $\longrightarrow$ attractive interaction (among fermion 0-modes)
- If attraction sufficiently strong $\langle\overline{\Psi}\Psi\rangle \neq 0$
- But strength (g_c) and range $(M_{\rm KK})$ are L-dependent:

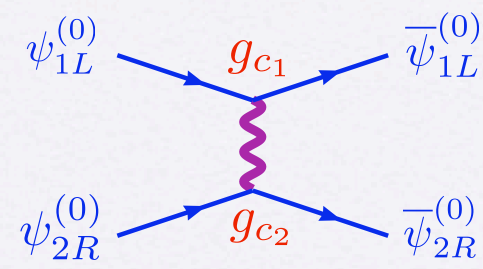
radion potential $\longleftrightarrow$ fermion condensation ➡ $\underbrace{V(\langle\overline{\Psi}\Psi\rangle, L)}_{\text{minimize simultaneously}}$

Will show that

- Only 0-modes near IR brane condense (can understand in 4D effective theory)
- Potential has well-defined minimum
- Easily $kL_{\rm min} = \mathcal{O}(10)$
- Hierarchy of scales $v_{\rm EW} \ll M_{\rm KK} \ll M_P$

The Mechanism: a toy model (cont'd)

Assume Ψ_1 has LH 0-mode and Ψ_2 has RH 0-mode.



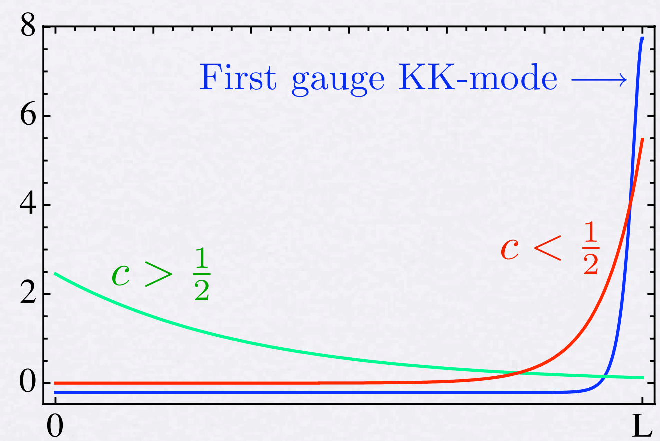
Can understand analytically in large N_c limit...

At low-energies $E \ll M_{\rm KK}$, 4-fermion interactions induced:

$$-\frac{g_{c_1} g_{c_2}}{M_{\rm KK}^2}(\overline{\psi}_{1L} T^A \gamma^\mu \psi_{1L})(\overline{\psi}_{2R} T^A \gamma^\mu \psi_{2R}) \quad = \quad \frac{g_{c_1} g_{c_2}}{M_{\rm KK}^2}(\overline{\psi}_{1L} \psi_{2R})(\overline{\psi}_{2R} \psi_{1L}) + \mathcal{O}(1/N_c)$$

Couplings arise from overlap of wavefunctions

$$g_c = \frac{g_5}{L^{3/2}} \int_0^L dy |f_c(y)|^2 f_G^{(1)}(y) \sim g_4 \times \begin{cases} \sqrt{(\frac{1}{2} - c)kL} \\ -1/\sqrt{kL} \end{cases}$$



- Other KK modes have more nodes: destructive interference (more weakly coupled)
- Only most IR localized fermion 0-modes condense (attraction from exchange of first KK gluon)

Recall: NJL and fermion condensate

Well below the KK scale, condensate and scalar bound state. Simplest way to see this:

$$\mathcal{L}_4 = i\overline{\psi}_{1L}\not{D}\psi_{1L} + i\overline{\psi}_{2R}\not{D}\psi_{2R} \underbrace{- M_{\rm KK}^2 H^\dagger H + (g_\psi H\overline{\psi}_{1L}\psi_{2R} + \text{h.c.})}$$

Integrate auxiliary H out to recover $\dfrac{g_\psi^2}{M_{\rm KK}^2}(\overline{\psi}_{1L}\psi_{2R})(\overline{\psi}_{2R}\psi_{1L})$

$g_\psi^2 = g_{c_1}g_{c_2} > 0$

But at low scales H becomes dynamical:

$$Z_H\partial_\mu H^\dagger\partial^\mu H - m_H^2 H^\dagger H - \frac{\lambda}{2}(H^\dagger H)^2$$

Largest effect from Yukawa interactions (include gauge and quartic interactions later...)

$$m_H^2 \approx M_{\rm KK}^2\left[1 - \frac{g_\psi^2 N_c}{8\pi^2}\left(1 - \frac{\mu^2}{M_{\rm KK}^2}\right)\right] \qquad \lambda \approx \frac{g_\psi^4 N_c}{8\pi^2}\ln\left(\frac{M_{\rm KK}^2}{\mu^2}\right)$$

If $g_\psi^2 > G_c^2 \equiv \dfrac{8\pi^2}{N_c}$ then $m_H^2 < 0$ for $\mu \ll M_{\rm KK}$

≈ 26 for $N_c = 3$

The Radion Potential

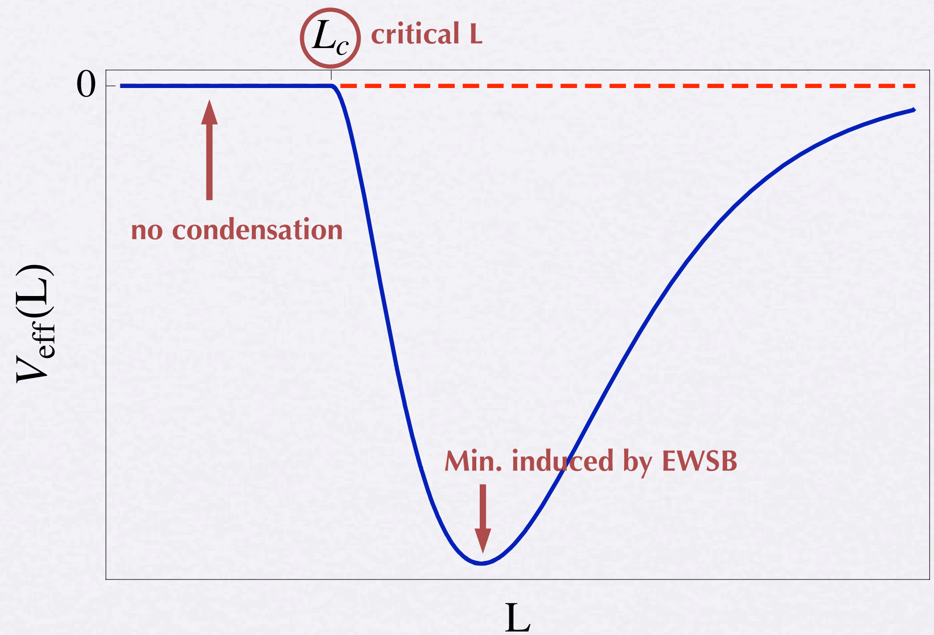
Only fields getting VEV's contribute to the radion potential:

$$V(H,L) = \overline{m}_H^2\, H^\dagger H + \frac{\bar\lambda}{2}(H^\dagger H)^2 = \frac{\bar\lambda}{2}\left[H^\dagger H - v^2\right]^2 - \frac{\overline{m}_H^4}{2\bar\lambda} \qquad v^2 = -\frac{\overline{m}_H^2}{2\bar\lambda}$$

Effective radion potential:

$$V_{\text{eff}}(L) = -\frac{\overline{m}_H^4}{2\bar\lambda}\,\theta(L-L_c)$$

$$\approx -\frac{M_{\text{KK}}^4\left(\frac{1}{G_c^2}-\frac{1}{g_\psi^2}\right)^2}{\frac{N_c}{4\pi^2}\log\frac{M_{\text{KK}}^2}{\mu^2}}\,\theta(L-L_c)$$



L-dependence from:

$$M_{\text{KK}} = x_1 k\, e^{-kL} \qquad x_1 \approx 2.45$$

$$g_\psi^2 = g_{c_1} g_{c_2} = \bar f_1(c_1,c_2) - \frac{\bar f_2(c_1,c_2)}{kL} + \frac{1}{4k^2L^2} \qquad \bar f_1, \bar f_2 > 0 \qquad \bar f_i = \mathcal{O}(6 g_5^2 k)$$

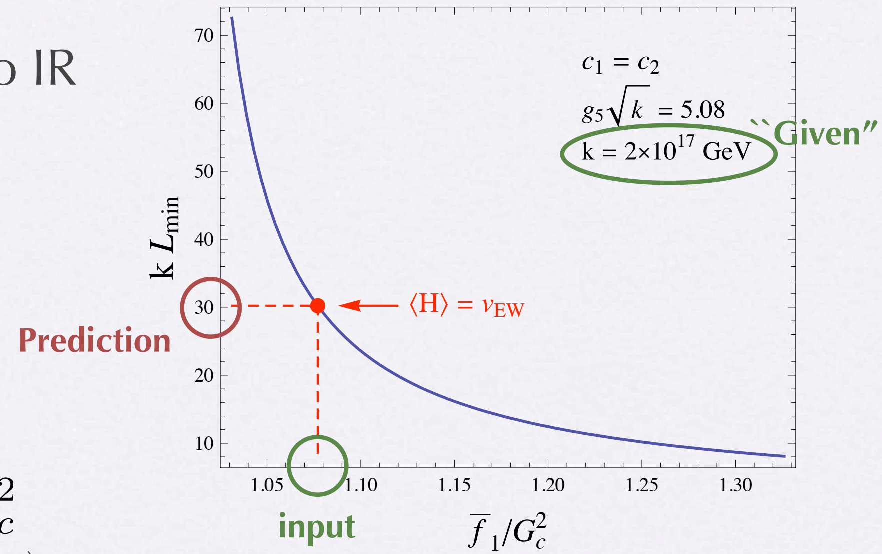
Hierarchies without Tuning

Fix gauge coupling ($g_5\sqrt{k} \sim 5$ if QCD) and localize fermions near IR brane: $\langle \bar{\psi}_{1L}\psi_{2R}\rangle \neq 0$

- M_P/v_{EW} determined by how close fermions to IR

$$g_\psi^2 = \bar{f}_1(c_1,c_2) - \frac{\bar{f}_2(c_1,c_2)}{kL} + \frac{1}{4k^2L^2} \qquad \bar{f}_1, \bar{f}_2 > 0$$

Choose 10% above G_c^2 $(= 8\pi^2/N_c)$ to get observed M_P/v_{EW}

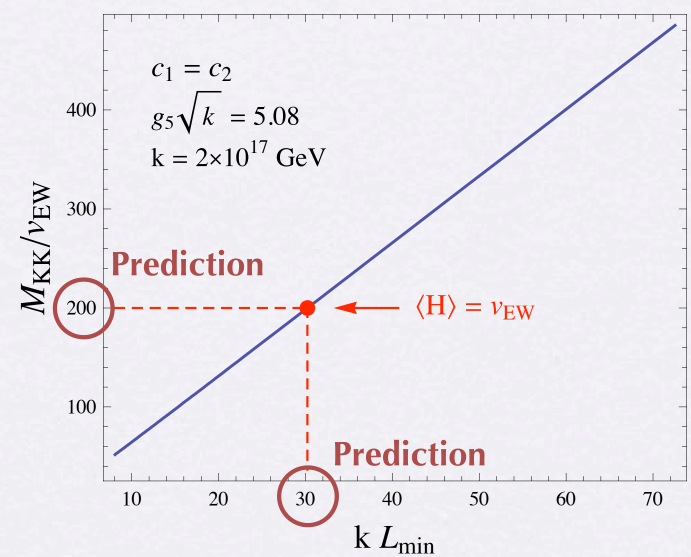


- As L slides to min, g_ψ^2 brought very close to G_c^2 (from above)

$$v_{EW} \approx M_{KK}\left(\frac{\bar{f}_1 - G_c^2}{2G_c^2}\right)\sqrt{\frac{1}{\bar{f}_2}} = M_{KK} \times \mathcal{O}(1/G_c^3)$$

Numerically: $M_{KK} \sim 200\, v_{EW} \sim 35$ TeV

Also: $\alpha_s(\mu = M_{KK}) = \dfrac{g_5^2}{4\pi L_{min}} \approx 0.068$



A new way of dealing with the Hierarchy Problem

4D toy Model contains:

- a scalar (~500 GeV) that gets a VEV $\langle H \rangle = 174 \text{ GeV}$
- a fermion with a dynamically induced mass (~400 GeV)
- a cutoff at 35 TeV

There is no light ``new physics" to cut off fermion loop contribution to H mass

From 4D point of view: $$m_H^2 \approx \underbrace{M_{\rm KK}^2}_{\text{bare}} - \underbrace{\frac{N_c g_\psi^2}{8\pi^2} M_{\rm KK}^2}_{\text{loop}}$$

Appears like fine-tuned cancellation

However, the two terms are close for a dynamical reason (radion seeks minimum)!

Note: radion field is light (few GeV) but couples weakly to matter...

A fully realistic model based on top condensation with top seesaw:

Add *one* new 5D *quark*, singlet under SU(2) and Y = 4/3 (quantum numbers like t_R)

EWSB from Top Condensation via Radion Stabilization

Bai, M.C, Ponton

- Strong interactions responsible for fermion condensation related to the 5D SU(3)c QCD interactions: Gluon KK modes

- Relaxation of the radion field to the minimum of the potential energy ensures that the fermion closest to the IR brane condenses ($g_{4F} > g_{4F}^{c}$)
  * strength of the fermion KK gluon coupling depends on fermion localization

- Condensation involves the top quark ==> Topcolor
  To reproduce the top quark mass, a TopSeesaw mechanism is necessary,
  ==> condensate: $< \bar{t}_L \chi_R >$
  With χ_R a linear combination of the top quark and a new vector-like fermion singlet

- Physics that leads to top condensation automatically induces a potential that stabilizes the distance between the UV and IR branes
  ==> the electroweak-Planck hierarchy determined dynamically and the KK scale predicted to be about 35 TeV

Spectrum:

A heavy (composite) SM-like Higgs with mass of about 500 GeV

A vector-like "singlet" quark with mass ~1.6 - 3 TeV,
and large mixing with the left top quark via condensation mechanism

Single heavy quark production at LHC with decays into Higgs and gauge bosons plus third generation quarks
Previous studies show sensitivity in the 2 TeV range

A radion with mass a few GeV very weakly coupled to SM particles

KK scale is in the 30 TeV range (No KK excitations accessible at LHC)

Outlook

Warped ED inspired, strong dynamics models

-- Gauge-Higgs Unification and Top Condensation via Radion Stabilization Models --

may offer elegant solutions to SM unsolved mysteries :

The hierarchy problem and the Dynamical Generation of EWSB

To provide such solutions at least some new particles are expected at the Tevatron/LHC reach, and a SM-like Higgs is expected to be there as well.

Gauge -Higgs Unification models may contain heavy quarks with masses below one TeV and production cross sections at the Tevatron reach

We are entering a new era with the LHC

BUT

In the next couple of years the Tevatron may still make discoveries to answer one of the essential puzzles in particle physics

EXTRAS

KK Fermion Signatures from Warped Space at the LHC

3rd. generation KK fermions with masses ~1TeV accessible at the LHC with ~ 100 fb^{-1}

$$pp \to t\bar{t}' \to W^+ b W^- \bar{b} \text{ with one W decaying leptonically}$$

Aguilar-Saavedra '05; Skiba, Tucker-Smith'07; Holdom'07

For smaller masses ~500 GeV < 10 fb^{-1} suffice + observation in Higgs decays viable

Exotic quantum numbers of the KK fermions ==> spectacular new signatures

Quarks with charge 5/3 and -1/3 have similar decay channels:

$$pp \to q'\bar{q}' \to W^+ W^- t\bar{t} \to W^+ W^+ W^- W^- b\bar{b}$$

Servant, Contino '08

Non-negligible BR of KK fermion of Q= 2/3 decaying into KK fermion of Q= -1/3

==> $$pp \to u_{2/3}\bar{u}_{2/3} \to W^+ d_{-1/3} W^- \bar{d}_{1/3} \to 4W + t\bar{t} \to 6W + b\bar{b}$$

Channels with 4 or even 6 W's may allow early discovery of q'

MC, Ponton, Santiago, Wagner '07

Dennis, Ünel, Servant, Tseng '07

KK fermions in the decay of KK gluons

- In simple Gauge-Higgs unification models, consistency with precision measurements demands the presence of light KK right handed top quark states.

M.C., E. Ponton, J. Santiago and C. Wagner

- The KK gluon may decay into these additional KK modes, which are strongly coupled to it and decay mostly into weak gauge bosons and third generation quarks,

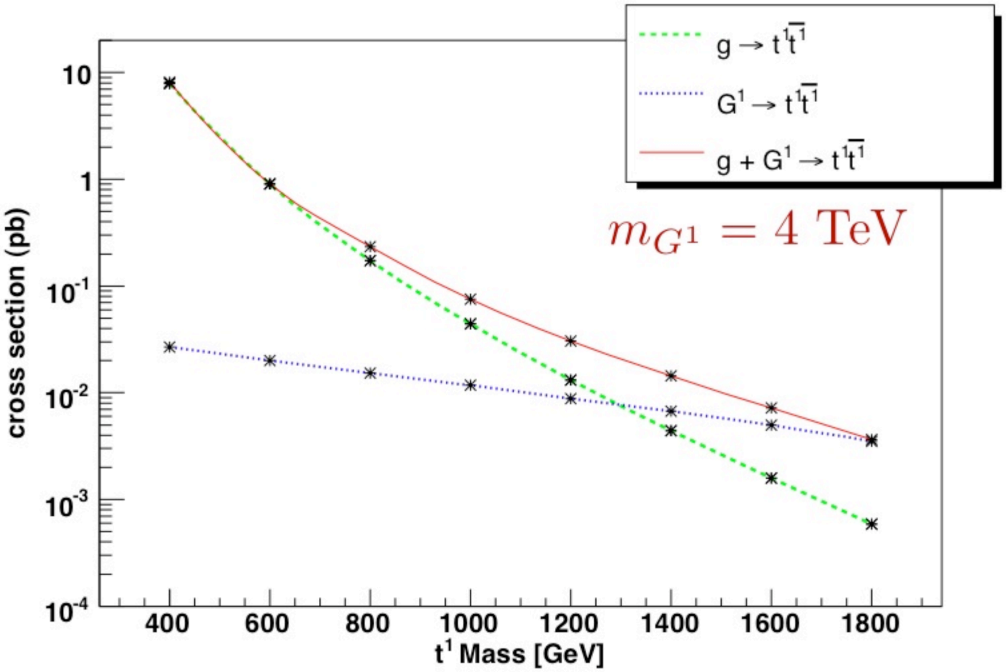
$$\Gamma(t^1 \to Wb) = 2\,\Gamma(t^1 \to tZ) = 2\,\Gamma(t^1 \to Ht)$$

- Fermion KK modes enhance the width of KK gluon and reduces the branching ratio of its decay into top quarks

Gluon KK search becomes very difficult, but search for fermion KK modes still possible, due to constructive interference of contributions to the gluon and KK gluon induced production cross section.

Reach of t^1 up to masses of about 1.5 TeV may be achieved.

Single t^1 production may be used as a complementary channel.



M.C., A. Medina, B. Panes, N. Shah and C. Wagner

The search for the SM Higgs from Warped Space at the LHC

New possibilities for early discoveries:

Recent results: $pp \to T\bar{T} \to W^+ bH\bar{t}/HtW^-\bar{b} \to W^+ bW^-\bar{b}H$

$pp \to T\bar{T} \to HtH\bar{t} \to W^+ bW^-\bar{b}HH$ Aguilar-Saavedra'06

T is a vector-like "singlet" $\Rightarrow BR(T \to Ht) \approx 25\%$

as the SM $t\bar{t}H$ process ==> only channel to search for H to bb at LHC
shown recently to need at least 60 fb^{-1}

Kinematics and high b jet multiplicity, plus m_T mass reconstruction help against tt+nj background

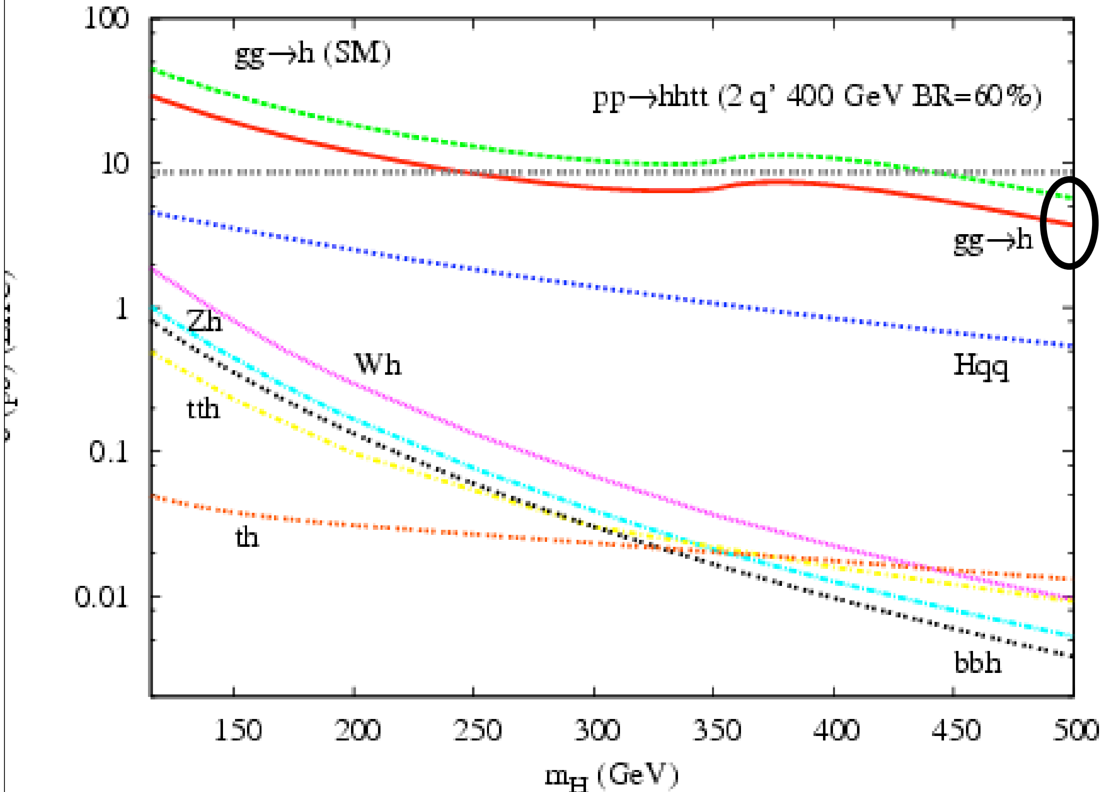
5σ discovery for m_T=500 GeV and m_H=115 GeV with 8 fb^{-1}

Gauge-Higgs Unification models:

multiplicity of KK 3.generation fermion doublets with same mass
+ enhanced BR(t'--> Ht) ~ 40 --70 % ==> Very promising! →

Interesting new possibilities for Higgs searches at the LHC

New Higgs production mechanism mediated by q' pair production



Gluon fusion production reduced up to a factor 0.65

Top mixing with KK modes ==> reduced top Yukawa

Major enhancement of Higgs production by new mechanism associated with q'

(for Mq' ~ 400 - 500 GeV)

$$\sigma(p\bar{p} \to q'\bar{q}' \to 2H2j) \sim \sigma(gg \to H)$$

light 3. generation KK fermions are a solid prediction of the model tied to the mechanism of top quark mass generation

Sizeable enhancement of inclusive Higgs signal. Some backgrounds (WW/ZZ +jets) enhanced

New channels may allow to explore different mass regions

$$p\bar{p} \to q'\bar{q}' \to 2H + 2j \to 4b + 2j$$
$$p\bar{p} \to q'\bar{q}' \to 2H + 2j \to 2b + 2W + 2j$$
$$p\bar{p} \to q'\bar{q}' \to 2H + 2j \to 4W + 2j$$