Flavor and $A_{FB}^{t\bar{t}}$: Flavored Colorons and Composite t''s

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Plan

- Flavor and the top-antitop forward-backward asymmetry with B. Grinstein, M. Trott, J. Zupan, arXiv:1102.3374
  - MFV, flavor octet vectors, t-channel dominance
- New strong interaction realizations with M. Trott and J. Zupan, in progress
  - composite (u', c', t') weak singlet up quarks, composite flavor octet vectors,....
  - electroweak symmetry breaking: identification with technicolor?

Flavor and the top-antitop forward-backward asymmetry

Issues for NP explanations of $A_{FB}^{t\bar{t}}$

For $M_{t\bar{t}} > 450$ GeV CDF measures:

$$A_{FB}^{t\bar{t}} = \frac{\sigma_F^{SM} + \sigma_F^{NP} - \sigma_B^{SM} - \sigma_B^{NP}}{\sigma_F^{SM} + \sigma_F^{NP} - \sigma_B^{SM} - \sigma_B^{NP}} = 0.475 \pm 0.114$$

$$\sigma^{t\bar{t}} = 1.9 \pm 0.5 \ \ \text{pb}$$

SM theory predictions for $M_{t\bar{t}} > 450$ GeV:

$$A_{\text{NLO}}^{t\bar{t}} = 0.088 \pm 0.013 \ \ (3.4\sigma \text{ discrepancy})$$

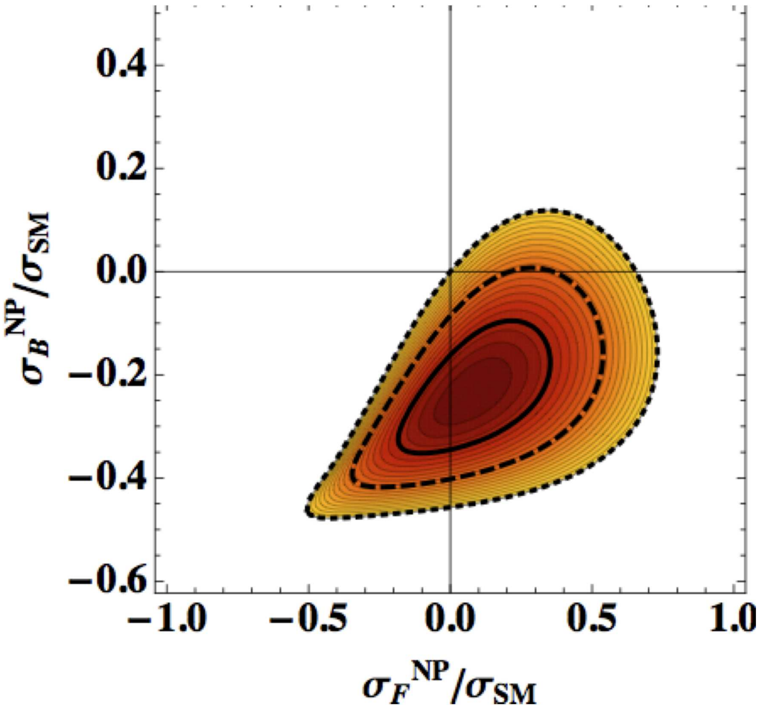
$$\sigma_{\text{NLO+NNLL}}^{t\bar{t}} = 2.26 \pm 0.18 \ \ \text{pb} \quad \text{Ahrens et al}$$

CDF inclusive $A_{FB}^{\bar{t}t}$ measurements: $A_{FB}^{\bar{t}t}$ (SM) = 0.058 ± 0.009

$$0.417 \pm 0.16 \text{ (dilepton)}, \qquad 0.158 \pm 0.074 \text{ (lepton + jet)}$$

Can study

$$\sigma_B^{NP}/\sigma^{SM} \;\; \text{vs.} \;\; \sigma_F^{NP}/\sigma^{SM} \;\; \text{for } M_{t\bar{t}} > 450 \text{ GeV}$$



$$\sigma_B^{NP} < 0 \Rightarrow \text{NP interferes with SM}$$

Therefore, s-channel explanation requires color octet vector

- $A_{FB}^{t\bar{t}} \neq 0$ requires $g_L^t \neq g_R^t$, $g_L^q \neq g_R^q$ ⇒ "Axigluon" or "Chiral gluon"
- FCNC's are an issue, e.g., $D^0 - \bar{D}^0$ mixing
- no s-channel $M_{t\bar{t}}$ bump, no excess in high $M_{t\bar{t}}$ bins, dijets ⇒ large $M_V \sim 2$ TeV -Susanne Westhoff's Slovenia talk
  - moderate $A_{FB} \lesssim 0.2$ achievable

Low mass t-channel explanations have appealing features:

- vectors, e.g., Z' and W', with masses of a few hundred GeV yield large $A_{FB}^{t\bar{t}}$, increases with $M_{t\bar{t}}$, as observed -Jung, Murayama, Pierce, Wells '10
- simultaneously, good agreement with measured spectrum at large $M_{t\bar{t}}$ -Gresham, Kim, Zurek '11; Jung, Pierce, Wells '11
  - for large $M_{t\bar{t}}$, NP t-channel top production more forward
  - CDF's acceptance decreases rapidly at large rapidity
    - smaller impact on $A_{FB}^{t\bar{t}}$ due to courser $M_{t\bar{t}}$ binning

Low mass Z', W' have some problems

- Z': same sign top production
- W': single top production
- large $Z' - u - t$ or $W' - d - t$ couplings $\Rightarrow$ FCNC's are an issue

Minimal Flavor Violation: Flavor Symmetric Models

- Quark sector formally invariant under the flavor group

  $$G_F = U(3)_Q \times U(3)_u \times U(3)_d$$

  if Yukawas promoted to spurions, $Y'_{u,d} = V_Q Y_{u,d} V^\dagger_{u,d}$.

- Weak scale NP models are then in MFV class if invariant under G_F.
  - $Y'_{u,d}$, and possibly new flavor diagonal NP phases, are only source of FCNCs

- constrains possible flavor structures, e.g., for $\bar{Q}Q$ bilinears, insertions

  $$Q(Y_u^\dagger Y_u)^n Q \;\; \text{allowed}, \quad Q Y_d^\dagger (Y_u^\dagger Y_u)^n Q \;\; \text{forbidden}$$

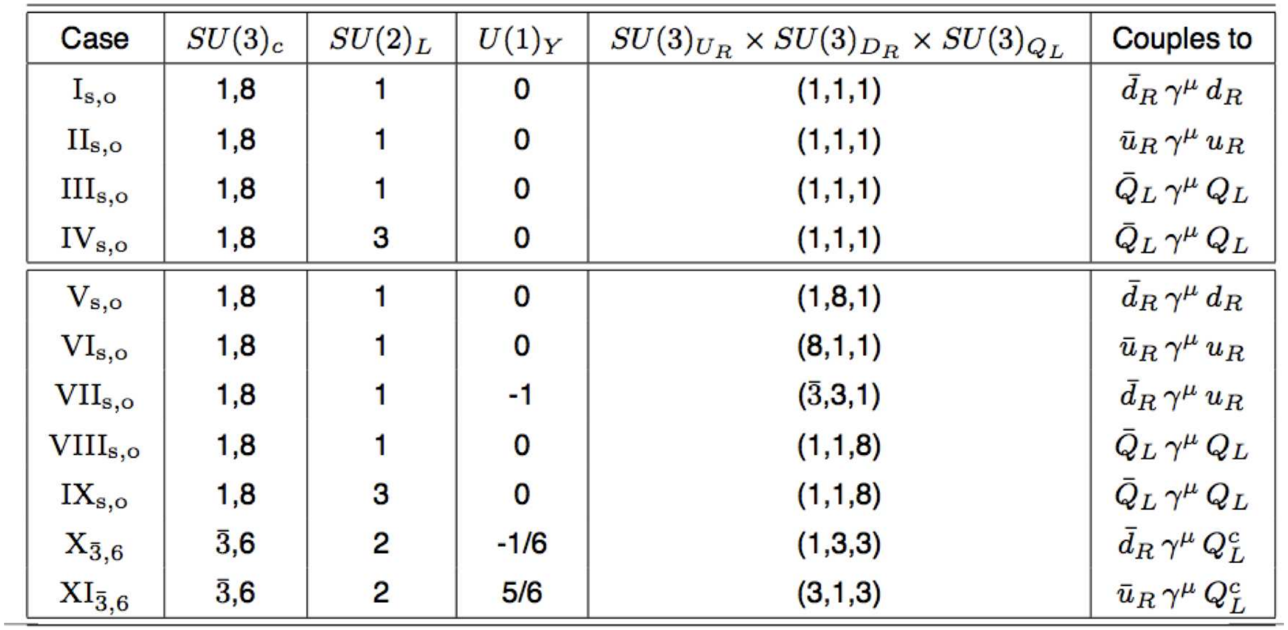
  e.g., $\bar{b}_L s_L \;\sim\; V_{tb} V_{ts}^*$
  - relaxes tensions between FCNC's and weak scale NP

To address problems mentioned above consider models for $A^{t\bar{t}}_{FB}$ that

- do not contain additional breaking of the SM flavor group G_F beyond the Yukawa spurions
- contain new fields in non-trivial representations of G_F
- have $O(1)$ couplings to the top and light quarks

Vectors in MFV

- Motivated by nice features of vector t-channel models
- There are 22 vector representations satisfying the MFV hypothesis (not all relevant to $A^{t\bar{t}}_{FB}$)



Case	$SU(3)_c$	$SU(2)_L$	$U(1)_Y$	$SU(3)_{U_R} \times SU(3)_{D_R} \times SU(3)_{Q_L}$	Couples to
$\mathrm{I}_{s,o}$	1,8	1	0	(1,1,1)	$\bar{d}_R\,\gamma^\mu\,d_R$
$\mathrm{II}_{s,o}$	1,8	1	0	(1,1,1)	$\bar{u}_R\,\gamma^\mu\,u_R$
$\mathrm{III}_{s,o}$	1,8	1	0	(1,1,1)	$\bar{Q}_L\,\gamma^\mu\,Q_L$
$\mathrm{IV}_{s,o}$	1,8	3	0	(1,1,1)	$\bar{Q}_L\,\gamma^\mu\,Q_L$
$\mathrm{V}_{s,o}$	1,8	1	0	(1,8,1)	$\bar{d}_R\,\gamma^\mu\,d_R$
$\mathrm{VI}_{s,o}$	1,8	1	0	(8,1,1)	$\bar{u}_R\,\gamma^\mu\,u_R$
$\mathrm{VII}_{s,o}$	1,8	1	-1	($\bar{3}$,3,1)	$\bar{d}_R\,\gamma^\mu\,u_R$
$\mathrm{VIII}_{s,o}$	1,8	1	0	(1,1,8)	$\bar{Q}_L\,\gamma^\mu\,Q_L$
$\mathrm{IX}_{s,o}$	1,8	3	0	(1,1,8)	$\bar{Q}_L\,\gamma^\mu\,Q_L$
$\mathrm{X}_{\bar{3},6}$	$\bar{3}$,6	2	-1/6	(1,3,3)	$\bar{d}_R\,\gamma^\mu\,Q^c_L$
$\mathrm{XI}_{\bar{3},6}$	$\bar{3}$,6	2	5/6	(3,1,3)	$\bar{u}_R\,\gamma^\mu\,Q^c_L$

- Simplest possibilities are the $SU(3)_{U_R}$ flavor octet color octet or color singlet vectors coupling only to RH up quarks

$$\mathcal{L} = \lambda \bar{u}_R \gamma^\mu V_\mu^{o,s} u_R + \text{MFV corrections}$$

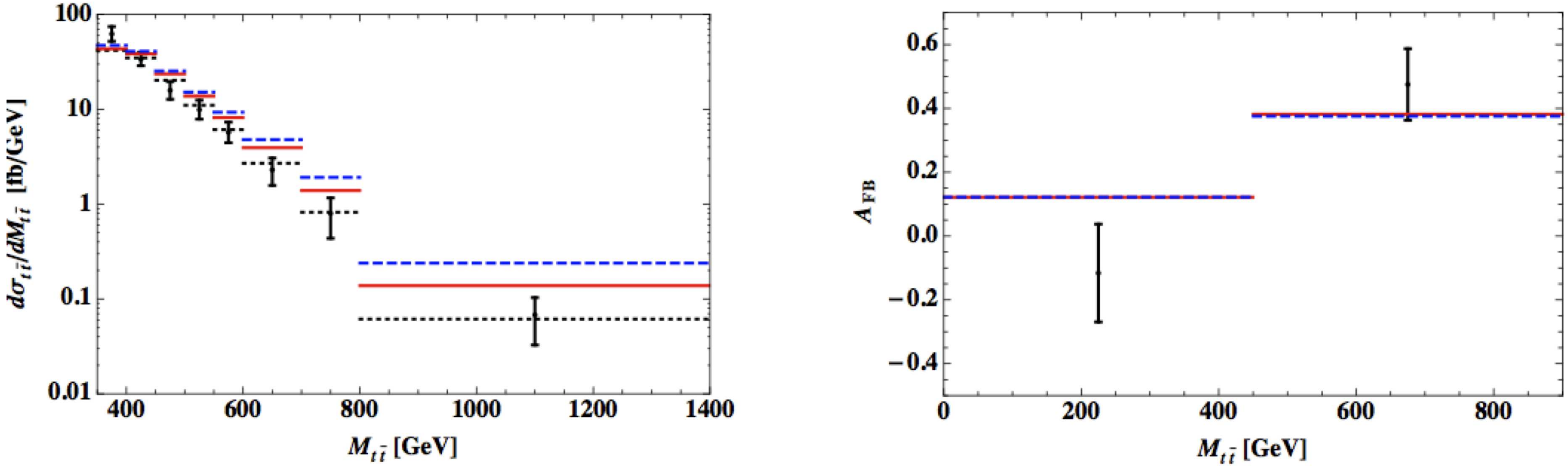
  - color octet: $V_\mu^o = V_\mu^{A,B} \mathcal{T}^A T^B$
  - color singlet: $V_\mu^s = V_\mu^A T^A$

$$\text{t} - \text{channel} \qquad (V_\mu^4 - iV_\mu^5)(\bar{t}_R \gamma^\mu u_R) + ...$$

$$\text{s} - \text{channel} \qquad V_\mu^8 (\bar{u}_R \gamma^\mu u_R + \bar{c}_R \gamma^\mu c_R - 2\bar{t}_R \gamma^\mu t_R)$$

- color octet: $t\bar{t}$ production t-channel dominated
- color singlet: s-channel larger than for color octet ⇒ problematic for $M_{t\bar{t}}$ bump and dijets at Tevatron
- MFV corrections split $\bar{t}t$, $\bar{t}q$, and $\bar{q}q$ couplings, preserve $SU(2)_{U_R}$ symmetry
- Flavor symmetry ⇒ no like sign top or single top production;
  negligible FCNC's: $D^0 - \bar{D}^0$ mixing

$A_{FB}^{t\bar{t}}$ and $d\sigma/dM_{t\bar{t}}$ for the octet of color and flavor



$\mathrm{A_{FB}^{t\bar{t}}}$ and $d\sigma(t\,\bar{t})/dM_{t\bar{t}}$, for two different values of $(m_V\,, \sqrt{\lambda_{qq}\lambda_{33}}, \lambda_{q3}, \Gamma_V/m_V)$: solid red $(300\,\mathrm{GeV}, 1, 1.33, 0.08)$; dashed blue $(1200\,\mathrm{GeV}, 2.2, 4.88, 0.5)$. Inclusive $\mathrm{A_{FB}^{t\bar{t}}} = 0.17$ in both cases

- CDF rapidity acceptance corrections (in progress) should eliminate $M_{t\bar{t}} > 600$ GeV spectrum excesses for light vector example
- Tevarton, LHC dijet constraints: do not require flavor symmetry breaking for light vectors; large breaking ($\lambda_{qq} < \lambda_{q3}$) for heavy vectors

Strong interaction realizations:
composite t''s, flavored colorons

The set-up

- can we build models with composite flavor octet vector mesons?
- can they naturally only couple to right-handed up quarks?
- QCD provides a beautiful example of flavor octet composite vector mesons
- add asymtpotically free $SU(N)_{HC}$ "hypercolor" gauge interaction, with strong interaction scale $\Lambda_{HC} \sim 1/2$ TeV
- add $SU(2)_L$ singlet, vectorlike, $SU(3)_{U_R}$ "flavor triplet" of hypercolored quarks $(\omega_{L_i}, \omega_{R_i})$ $(i = 1, 2, 3)$, and new hypercolored "flavor singlet" scalar $\mathcal{S}$.

They transform under $SU(N)_{HC} \times SU(3)_C \times SU(2)_L \times U(1)_Y$ as

$$\text{model A}: \quad \omega_{L_i, R_i}(N, 1, 1, 2/3), \quad \mathcal{S}(\bar{N}, 3, 1, 0)$$

$$\text{model B}: \quad \omega_{L_i, R_i}(N, 3, 1, 2/3), \quad \mathcal{S}(N, 1, 1, 0)$$

$$\text{with} \quad \mathcal{L}_{NP} = \mathbf{h}_{ij}\, \bar{u}_{Ri} \omega_{Li} \mathcal{S} + h.c. + \mu_{\omega\, ij}\, \bar{\omega}_i \omega_j + m_s^2 |\mathcal{S}|^2$$

u_R is the usual flavor triplet of RH up quarks (u_R, c_R, t_R)

$$\mathcal{L}_{NP} = \mathbf{h}_{ij}\,\bar{u}_{Ri}\,\omega_{Li}\,\mathcal{S} + h.c. + \mu_{\omega\,ij}\,\bar{\omega}_i\,\omega_j + m_s^2|\mathcal{S}|^2$$

- imposing MFV ⇒ $\mathbf{h}_{ij} = h\,\delta_{ij}\,,\quad \mu_{\omega\,ij} = \mu_\omega\,\delta_{ij}$
- MFV corrections ⇒ $\mathbf{h} = \mathrm{diag}(h_1, h_1, h_3),\quad \mu_\omega = \mathrm{diag}(\mu_1, \mu_1, \mu_3)$
  - $\mu_\omega << \Lambda,$ like u, d, s in QCD
- hypercolor sector only couples to the right-handed up quarks
  - due to choice of representations for ω, $\mathcal{S}$ (hypercharge assignments)
  - Therefore, $SU(3)_{U_R}$ symmetry of $\mathcal{L}_{NP}$ could be an accidental consequence of an $SU(3)_H$ horizontal gauge symmetry, under which all quarks are triplets
  - Spontaneous breaking of $SU(3)_H$ (flavons) in the UV could generate the quark mass and mixing hierarchies via a Frogatt-Nielsen type mechanism
  - At the weak scale could have the SM (or MSSM) + new hypercolor sector ⇒ MFV
- Flavor structure of the resonances would hint at horizontal symmetry solution to the quark mass hierarchy problem!

- variation on $\mathcal{L}_{NP}$: add gauge singlet scalar, $\mathcal{N}$,

$$\mathcal{L}_{NP} = \mathbf{h}\,\bar{u}_R\,\omega_L\,\mathcal{S} + h.c. + \eta\,\mathcal{N}\,\bar{\omega}\omega + +\mu_s\,\mathcal{N}\mathcal{S}^*\mathcal{S} + m_s^2\,|\mathcal{S}|^2 + m_N^2|\mathcal{N}|^2 + ...$$

  - dynamically generate ω current masses via $SU(N)_{HC}$ condensates,

$$\langle\bar{\omega}\omega\rangle,\ \langle\mathcal{S}^*\mathcal{S}\rangle \neq 0 \ \Rightarrow\ \langle\mathcal{N}\rangle \neq 0 \ \Rightarrow\ \mu_\omega \neq 0$$

  - $SU(3)_c$ breaking alignment of condensates can be avoided via the new terms

$$\eta\,\mathcal{N}\,\bar{\omega}\omega + +\mu_s\,\mathcal{N}\mathcal{S}^*\mathcal{S}$$

- could "supersymmetrize" in order to protect scalar masses; or could imagine that the scalars are themselves composites

Hypercolor resonances and $A_{FB}^{t\bar{t}}$

consider model A: $\omega_{L_i}, \omega_{R_i}(N,1,1,2/3), \quad \mathcal{S}(\bar{N},3,1,0)$

- the lowest vector meson flavor 8+1 "nonets" (a=1,..,9):
  $\rho^a_{HC}[\bar{\omega}\omega]$ vectors; $a^a_{1\,HC}[\bar{\omega}\omega]$ axial-vectors

- $\langle\bar{\omega}\omega\rangle \neq 0$ breaks global chiral symmetry

$$SU(3)_L \times SU(3)_R \to SU(3)_V$$

$\Rightarrow$ flavor octet of pions π^a_{HC}, heavier η'_{HC}

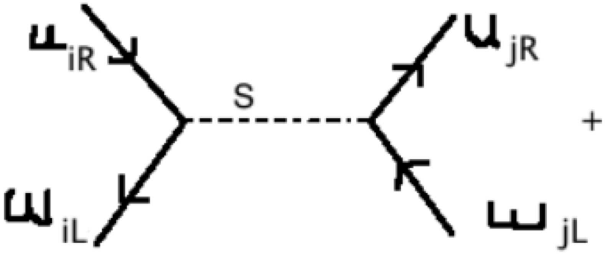
- mass scales: scale up from QCD

$$\frac{f_\pi^{HC}}{f_\pi} \sim \frac{f_\rho^{HC}}{f_\rho} \sim \frac{m_{\rho_{HC}}}{m_\rho}\sqrt{\frac{N_{HC}}{3}}, \qquad \frac{f_\rho^{HC}}{m_\rho^{HC}} \approx 0.2\sqrt{\frac{N_{HC}}{3}}$$

Motivated by vector flavor/color octet analysis of $A_{FB}^{t\bar{t}}$

- $m_\rho^{HC} \sim 300 - 500$ GeV $\Rightarrow$ $f_\pi^{HC} \sim 35 - 60$ GeV ($N_{HC} = 3$)
- $\Lambda_{HC}^{\chi SB} \sim 4\pi f_\pi^{HC} \sim 450 - 750$ GeV

vector meson - quark couplings



$\langle \rho^a | \bar{\omega} \gamma^\mu \, T^a \, \omega | 0 \rangle \sim f_\rho m_\rho \epsilon^\mu \;\; \Rightarrow$

ρ, a_1 couplings to up quarks: $\lambda^V \, \rho^a_\mu \, \bar{u} \, T^a \, \gamma^\mu \, u \, + \, \lambda^A \, a^a_1 \, \bar{u} \, T^a \, \gamma^\mu \, \gamma_5 \, u \,,$ with

$$\lambda^V \sim h^2 \, \frac{f_\rho m_\rho}{m_s^2}, \quad \lambda^A \sim h^2 \, \frac{f_{a_1} m_{a_1}}{m_s^2} \quad \text{for } m_s >> \Lambda$$

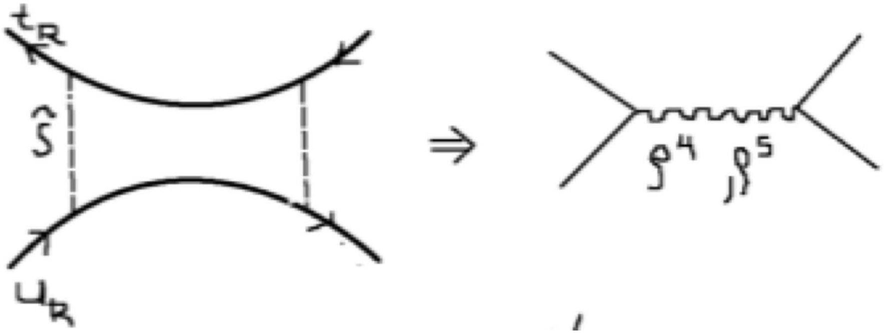
- observed $A^{t\bar{t}}_{FB} \;\Rightarrow\; \rho - u - t$ coupling $\lambda = O(1)$
  - h perturbative $\Rightarrow m^2_S << \Lambda^2$ Naive dimensional analysis (NDA) implies

$$\lambda \sim h^2 \, \frac{f_\rho}{\Lambda} \quad \text{or} \quad h = O(\text{few})$$

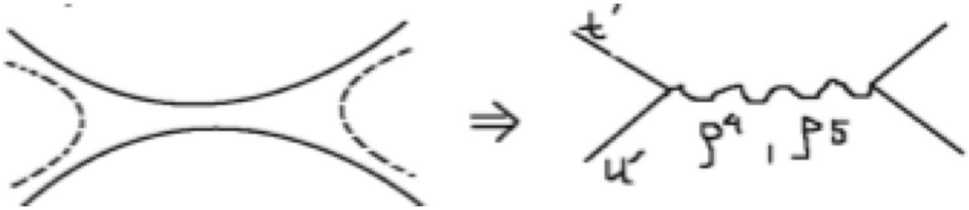
- $m_s << \Lambda \Rightarrow$ modified resonance picture, includes $SU(3)_{U_R}$ flavor triplet of weak singlet vectorlike up quarks, with masses of $O(m_\rho)$ or $O(1/2\ \mathrm{TeV})$

$$u'[\mathcal{S}\,\omega_1], \quad c'[\mathcal{S}\,\omega_2], \quad t'[\mathcal{S}\,\omega_3]$$

- $t\bar{t}$ production via exchange of ρ^a, a_1^a and large $u'_{R_i} - u_{R_i}$ mixing



$m_s^2 >> \Lambda^2$



$m_s^2 << \Lambda^2$,

$\Rightarrow \quad m\,\bar{u}_{R_i} u'_{L_i}$ via $\langle u'_i | \bar{\omega}_i\, \mathcal{S}^* | 0 \rangle = \sqrt{2} f'_u \bar{u}'_i$

$\rho^a - u_i - u_j$ couplings via exchange of composite u''s

- $\langle u'_i | \bar{\omega}_i \, \mathcal{S}^* | 0 \rangle = \sqrt{2} f_{u_i} \bar{u}'_i$, with $f'_u \sim f_\rho$ $\Rightarrow$

$$|u_{R_i\,(L_i)}\rangle^{\rm phys} = \cos\theta_{R_i\,(L_i)}\,|u_{R_i\,(L_i)}\rangle - \sin\theta_{R_i\,(L_i)}\,|u'_{R_i\,(L_i)}\rangle$$

$$\sin\theta_{R_i} \approx \sqrt{2}\,h_i\,\frac{f'_{u_i}}{M_{u'_i}}\,, \qquad \sin\theta_{L_i} \approx \sqrt{2}\,h_i\,\frac{f'_{u_i} m_{u_i}}{M^2_{u'_i}}$$

  m_{u_i} are ordinary up quark masses, $M_{u'_i}$ are composite up quark masses

- using Vector Meson Dominance (VMD) to estimate the $\rho^a - u'_i - u'_j$ and $a_1^a - u'_i - u'_j$ couplings

$$g_V\,\rho^a_\mu\;\bar{u}'\,T^a\,\gamma^\mu\,u' \;+\; g_A\;a^a_{1\,\mu}\;\bar{u}'\,T^a\,\gamma^\mu\,\gamma_5\,u' \;\Rightarrow\; g_V \approx \frac{m_\rho}{\sqrt{3}\,f_\rho}\,, \quad g_A \approx \frac{m_{a_1}}{\sqrt{3}\,f_{a_1}}$$

- $\rho^a - u_i - u_j$ and $a_1^a - u_i - u_j$ couplings follow from $u' - u$ mixing ($c_v \sim 1$):

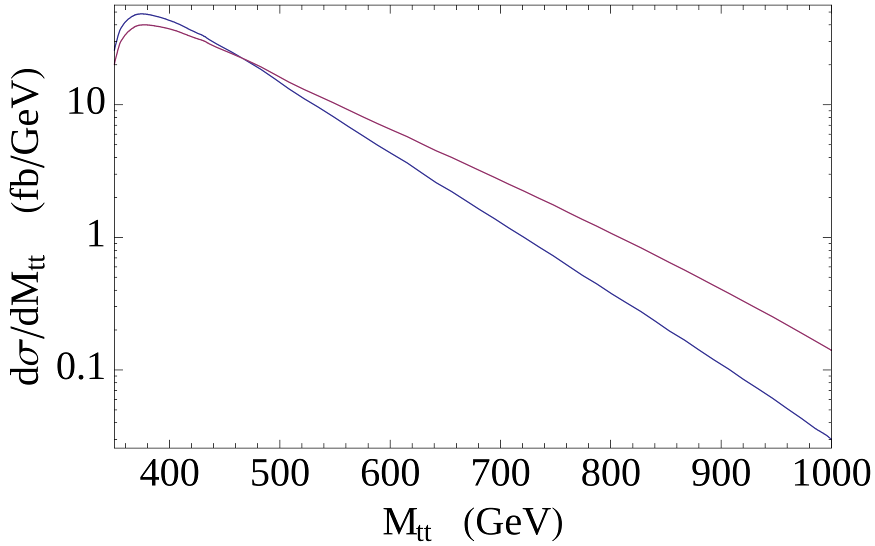
$$\lambda^{V_a}_{ij} = c_{v_a}\,h_i h_j\,\frac{m_{\rho^a}}{f_{\rho^a}}\,\frac{f'_{u_i} f'_{u_j}}{M_{u'_i} M_{u'_j}} = \mathcal{O}\left(h^2\,\frac{f_\rho}{m_\rho}\right) \sim 0.2\,h^2\,, \qquad \frac{\lambda^A}{\lambda^V} \approx \frac{m_{a_1} f_\rho}{m_\rho f_\rho}$$

$\lambda^V \approx 1$ $\Rightarrow$ $h = O(\text{few})$, as expected from NDA

$A_{FB}^{t\bar{t}}$ and $d\sigma/dM_{t\bar{t}}$ from the flavor nonets ρ^a, a_1^a

- for simplicity, consider $SU(3)_{U_R}$ limit (rather than $SU(2) \times U(1)$) :
  - degenerate nonets $m_{\rho^a} = m_\rho, \;\; m_{a_1^a} = m_{a_1}$
  - degenerate couplings for λ^V and λ^A
  - in $SU(3)_{U_R}$ limit no s-channel contribution: no "$\omega - \phi$" mixing
  - our results do not yet include exchange of the P-wave vector meson bound states of the scalars, $V^\mu\,[S^*S]$ (work in progress)
    - a flavor singlet color octet, and a flavor singlet color singlet
    - expected to be very broad, e.g. $\Gamma/M \sim 50\%$, due to $V \to \bar{u}_i' u_i$
- analysis of Model B is also in progress: exchange of
  - vector meson flavor nonets which are color octets $\rho^{a,b}$, and color singlets ρ^a, and their axial vector partners
  - a very broad P-wave color and flavor singlet vector meson bound state

- Model A example: exchange of ρ^a flavor nonet vector mesons ($m_\rho = 300$ GeV; $m_{a_1} = 450$ GeV; $\lambda^V = 1.04$; $\lambda^A = \lambda^V m_{a_1}/m_\rho$, $\Gamma_\rho/m_\rho = \Gamma_{a_1}/m_{a_1} = 10\%$):
  - $M_{\bar{t}t}$ spectrum:



blue $= SM$

  - $A^{\bar{t}t}_{FB}(M > 450 \text{ GeV}) = 0.40, \quad A^{\bar{t}t}_{FB}(M < 450 \text{ GeV}) = 0.02$
    $A^{\bar{t}t}_{FB}(\text{inclusive}) = 0.21$
- expect the CDF rapidity acceptance correction to bring the true excess at large $M_{\bar{t}t}$ into agreement with the measured spectrum
- checked that Tevatron and LHC dijet contsraints satisfied

On the composite u''s

- The new composite quarks can be quite broad! Due to decays to ordinary RH up quarks and HC pions, π^a, e.g.,

$$u'_i \longrightarrow \pi^a + t$$

- using NDA for the couplings of the π^a to the u''s

$$O(4\pi)\,\bar{u}'_{R_i} T^b_{ij} \pi^b u'_{Lj} \;\Rightarrow\; \Gamma_{u'}/M_{u'} = \mathcal{O}(10\%),$$

  compared with $\approx 1\%$ for the top quark

- quark masses $\sim 1/2$ TeV

- detection at LHC via $u'_i \longrightarrow t + \pi^a$
  - Model A: the π^a are color singlets, decay to light quarks $\pi^a \longrightarrow \bar{u}_i\, u_j$
  - Model B: the π^a are color octets, flavor singlets also decay to two gluons

- Production mechanism:
  - $\bar{u}'_i\ u'_i$: via QCD + $\rho^a,\ a^a_1$ exchange
  - $\bar{u}'_i\ u_i$: via $\rho^a,\ a^a_1$ exchange

Electroweak Symmetry Breaking

- can identify the new strong interaction with technicolor (TC): $SU(N)_{HC} = SU(N)_{TC}$
- the low mass scale $m_\rho^{HC} \sim 300 - 500$ GeV favored by $A_{FB}^{t\bar{t}}$, or the correspondingly low hypercolor decay constant $f_\pi^{HC} \sim 30 - 50$ GeV, is suggestive of a low scale technicolor scenario - Eichten, Lane
- Example: Bosonic Technicolor - Simmons (non-susy); Dine, A.K., Samuel (supersymmetric)
  - supersymmetry stabilizes the masses of fundamental scalars, e.g., higgs doublets, or the scalars S introduced earlier
  - Technicolor triggers electroweak symmetry breaking, induces VEV's for fundamental MSSM Higgs doublets, H^u, H^d via Yukawas to $SU(2)_L$ breaking technifermion condensates (techniscalar condensates also possible)

$$L = h_u H^u TU + h_d H^d TD + \ldots$$

$$\langle TU \rangle = \langle TD \rangle \approx 4\pi F_{\mathrm{TC}}^3 \Rightarrow \langle H^u \rangle \approx h_u \langle TU \rangle / m_{H^u}^2 , \;\; \langle H^d \rangle \approx h_d \langle TD \rangle / m_{H^d}^2$$

Higgs masses $m_{H^u}^2, m_{H^d}^2 > 0$!

Bosonic Technicolor continued:

- ordinary fermions receive masses via MSSM Yukawas to the Higgs VEVs: $y^t \langle H^u \rangle \bar{t}t + \ldots.$
- W, Z receive masses both from technicolor condensates, HIggs VEV's

$$v^2 = (246\ \mathrm{GeV})^2 = F_{\mathrm{TC}}^2 + \langle H^u \rangle^2 + \langle H^d \rangle^2$$

- require perturbative yukawa couplings ($y^t, h_u \lesssim 1$), and a light higgs doublet (precision electroweak data)
  - Top mass favors a small TC pion decay constant, e.g., $F_\pi^{TC} \sim 30 - 70$ GeV, and $\langle H^u \rangle \approx v$
  - no susy little hierarchy problem
- low TC scale fits nicely with strong interaction scale for $A_{FB}^{t\bar{t}}$
- bulk of W, Z masses come from Higgs VEV's
- models combining TC and a strong interaction explanation for $A_{FB}^{t\bar{t}}$ are currently under investigation, including alternative realizations in which quark masses are generated via mixing with composite quarks , with a direct connection to $A_{FB}^{t\bar{t}}$