The $t\bar{t}$ forward-backward asymmetry, flavor symmetries, and new strong interactions

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Roma, June 2013

Plan

- Flavor and $A_{\rm FB}^{t\bar{t}}$
  - flavor symmetric vectors B. Grinstein, A.K., M. Trott, J. Zupan
  - A_C (LHC) vs. A_{FB} (Tevatron) J. Drobnak, A.K., J. Kamenik, G. Perez, J. Zupan
- Strong interaction realizations with J. Brod, J. Drobnak, E. Stamou, J. Zupan, in progress

Flavor symmetry and $A_{\rm FB}^{t\bar{t}}$

The situation

For $M_{t\bar{t}} > 450$ GeV CDF measures (lepton+jets):

$$A_{FB}^{t\bar{t}} = \frac{\sigma_F^{SM} + \sigma_F^{NP} - \sigma_B^{SM} - \sigma_B^{NP}}{\sigma_F^{SM} + \sigma_F^{NP} + \sigma_B^{SM} + \sigma_B^{NP}} = 0.295 \pm 0.066$$

SM NLO prediction for $M_{t\bar{t}} > 450$ GeV:

$$A_{FB}^{t\bar{t}}\,(\mathrm{NLO}) = 0.129^{+0.008}_{-0.006} \qquad 2.4\sigma \text{ discrepancy} \quad \text{Bernreuther, Si}$$

SM prediction decreases by $\sim 30\%$ for $\sigma^{t\bar{t}}_{\mathrm{NLO}}$ in the denominator

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

$$A_{FB}^{t\bar{t}} = 0.084 \pm 0.053 \ \text{ consistent with SM}$$

D0 does not see a significant $M_{t\bar{t}}$ dependence (not unfolded)

Inclusive $A_{FB}^{\bar{t}t}$ measurements (lepton + jets):

CDF:

$$A_{FB}^{\bar{t}t} = 0.196 \pm 0.065 \text{ (D0)}, \quad 0.164 \pm 0.045 \text{ (CDF)}$$

$$A_{FB}^{\bar{t}t} \text{ (exp avg)} = 0.174 \pm 0.037 \text{ vs. } A_{FB}^{\bar{t}t}(\text{NLO SM}) = 0.088 \pm 0.006$$

inclusive leptonic asymmetry (ℓ+jets:

$$A_{FB}^{\ell} = 0.094 \pm 0.032 \text{ (CDF)}, \quad 0.152 \pm 0.04? \text{ (D0)}$$

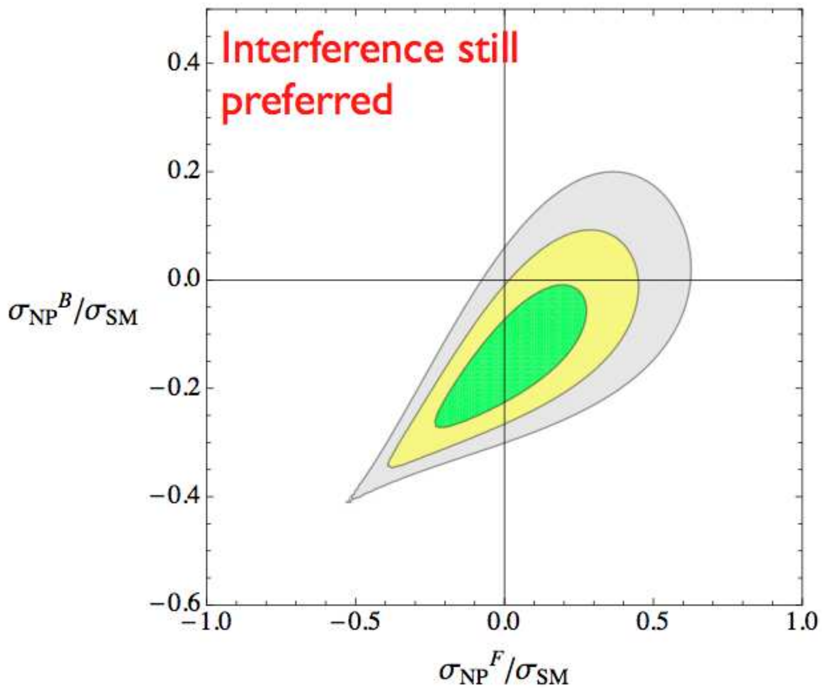
$$\text{vs. } A_{FB}^{\ell}(\text{NLO SM}) = 0.038 \pm 0.003$$

above SM predictions decrease by $\approx 30\%$ for $\sigma_{\text{NLO}}^{t\bar{t}}$ in the denominator

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

use $\sigma^{t\bar{t}}\,(\mathrm{CDF}) = 1.9 \pm 0.5$ pb, $\sigma^{t\bar{t}}_{\mathrm{NLO+NNLL}} = 2.26 \pm 0.18$ pb (Ahrens et al)

update courtesy of M. Trott



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

For NP interference with the SM have two options:

- s-channel: color octet vector
- t-channel: color singlet, or colored resonances

Low mass t-channel explanations have appealing features:

- vectors, e.g., Z' or W' with masses of a few hundred GeV yield large $A^{t\bar{t}}_{FB}$, 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
  - but CDF's acceptance decreases rapidly at large rapidity

Low mass Z', W' have some problems

- Z': same sign top production $uu \to tt$
- W': single top production
- large $Z' - u - t$ or $W' - d - t$ couplings $\Rightarrow$ FCNC's are an issue
  - why are other couplings, e.g., $Z' - u - c$ (danger for $D - \bar{D}$ mixing), much smaller?
- contribution to $\sigma_{t\bar{t}}$ at LHC via single light mediator decay, e.g. Gresham, Kim, Zurek

$$gq \to t + (Z' \to \bar{t}q)$$

  - but depends on $\mathrm{Br}(Z' \to \bar{t}q)$

Flavor Symmetric Models

- Weak scale NP models are in MFV class if invariant under

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

  - Yukawas and new flavor diagonal phases only source of FCNCs
  - relaxes tensions between FCNC's and weak scale NP

- NP that is invariant under the flavor subgroup

$$H_F = U(2)_Q \times U(2)_u \times U(2)_d \times U(1)_3$$

is also appealing for relaxation of FCNC constraints

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

- do not contain additional breaking of G_F or the alternative H_F, beyond the SM Yukawas

- contain new fields in non-trivial representations of G_F or H_F

- have $O(1)$ couplings to the top and light quarks

Flavor symmetry $\Rightarrow$ no like sign top or single top production;
negligible FCNC's, e.g., $D^0 - \bar{D}^0$ mixing

- impact of single mediator decay on $\sigma_{t\bar{t}}$ (LHC) suppressed if its branching ratio to quark pairs is suppressed
    - suppressed BR's to quark pairs also favored by dijet constraints

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
$\mathrm{I}_{\mathrm{s,o}}$	1,8	1	0	(1,1,1)	$\bar{d}_R\,\gamma^\mu\,d_R$
$\mathrm{II}_{\mathrm{s,o}}$	1,8	1	0	(1,1,1)	$\bar{u}_R\,\gamma^\mu\,u_R$
$\mathrm{III}_{\mathrm{s,o}}$	1,8	1	0	(1,1,1)	$\bar{Q}_L\,\gamma^\mu\,Q_L$
$\mathrm{IV}_{\mathrm{s,o}}$	1,8	3	0	(1,1,1)	$\bar{Q}_L\,\gamma^\mu\,Q_L$
$\mathrm{V}_{\mathrm{s,o}}$	1,8	1	0	(1,8,1)	$\bar{d}_R\,\gamma^\mu\,d_R$
$\mathrm{VI}_{\mathrm{s,o}}$	1,8	1	0	(8,1,1)	$\bar{u}_R\,\gamma^\mu\,u_R$
$\mathrm{VII}_{\mathrm{s,o}}$	1,8	1	-1	($\bar{3}$,3,1)	$\bar{d}_R\,\gamma^\mu\,u_R$
$\mathrm{VIII}_{\mathrm{s,o}}$	1,8	1	0	(1,1,8)	$\bar{Q}_L\,\gamma^\mu\,Q_L$
$\mathrm{IX}_{\mathrm{s,o}}$	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)	$\bar{u}_R\,\gamma^\mu\,Q^c_L$

Flavor symmetric vector models

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

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

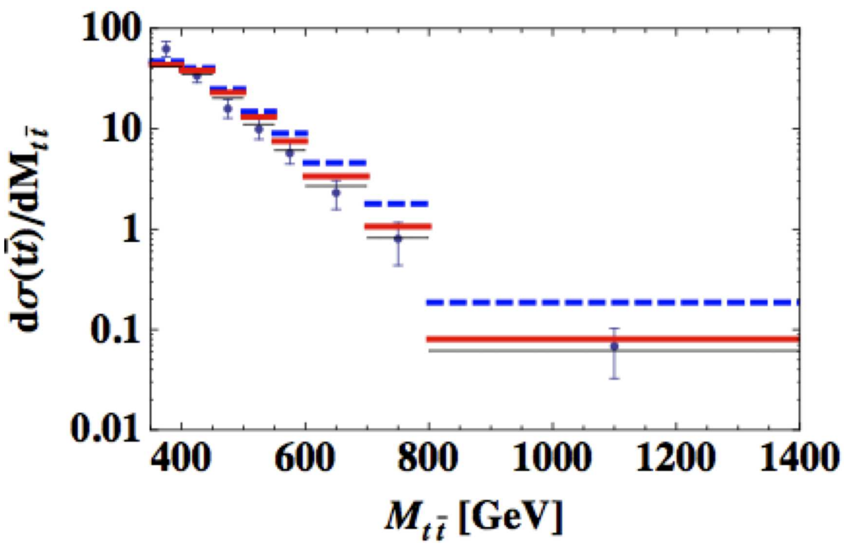
  - color octet: $V_\mu^o = V_\mu^{A,B} \mathcal{T}^A T^B$
  - color singlet: $V_\mu^s = V_\mu^A T^A$

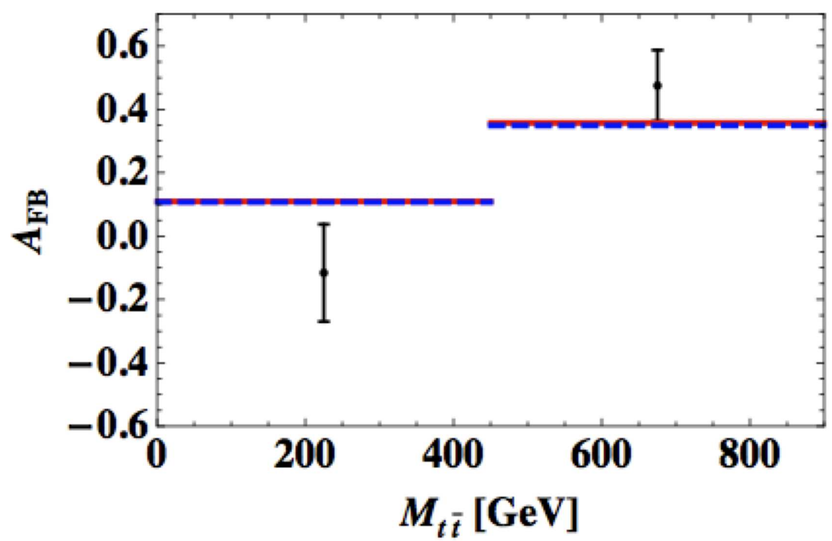
$$\text{t} - \text{channel} \qquad (V_\mu^4 - iV_\mu^5)(\bar{t}_R \gamma^\mu u_R) + ...$$

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

- $t\bar{t}$ production t-channel dominated
- MFV corrections split $\bar{t}t$, $\bar{t}q$, and $\bar{q}q$ couplings, preserve $SU(2)_{U_R}$ symmetry
- or could have $[SU(2) \times U(1)]_{U_R}$ symmetry from the start

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

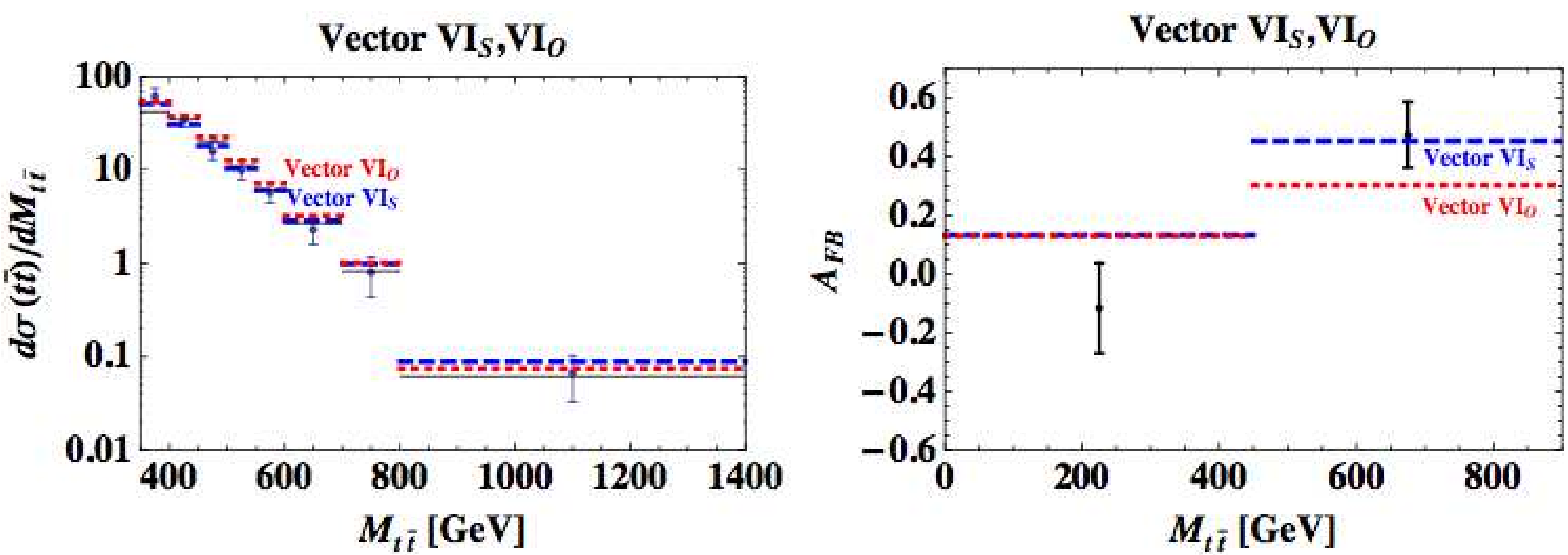




- $\mathrm{A}_{\mathrm{FB}}^{\mathrm{t\bar{t}}}$ and $d\sigma(t\,\bar{t})/dM_{t\bar{t}}$, for two different values of $(m_V, \sqrt{\lambda_{qq}\lambda_{tt}}, \lambda_{qt}, \Gamma_V/m_V)$: solid red $(300\,\mathrm{GeV}, 1, 1.33, 0.08)$; dashed blue $(1200\,\mathrm{GeV}, 2.2, 4.88, 0.5)$. Inclusive $\mathrm{A}_{\mathrm{FB}}^{\mathrm{t\bar{t}}} = 0.17$ in both cases
  - CDF rapidity acceptance corrections included
- For light vectors with O(10%) widths due to additional unspecified decay channel, Tevatron and LHC dijet constraints on s-channel exchange contributions can be satisfied with little or no G_F flavor symmetry breaking in the quark couplings, $\lambda_{ij} \approx \lambda_{33} \approx \lambda_{i3}$

$A_{FB}^{t\bar{t}}$ and $d\sigma/dM_{t\bar{t}}$ for narrow flavor octet, color singlet and octet

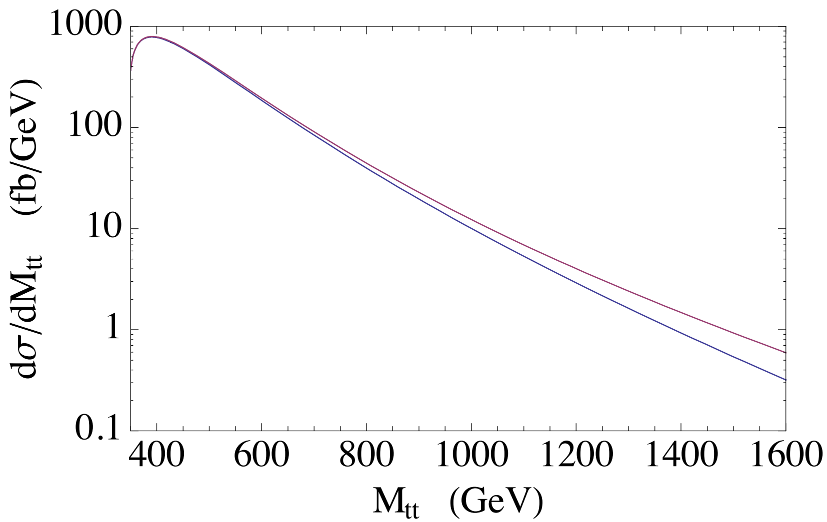
For $\mathrm{Br}(V \to u_i \bar{u}_j) = 100\%$ (narrow), evade $t\bar{t}$ and dijet bump hunting constraints via large G_F flavor symmetry breaking in the quark couplings:



- $\mathrm{A}_{\mathrm{FB}}^{\mathrm{t\bar{t}}}$ and $d\sigma(t\,\bar{t})/dM_{t\bar{t}}$, for color singlet flavor octet ($\mathrm{VI_s}$), and color octet flavor octet ($\mathrm{VI_o}$), for $m_V = 350$ GeV, and $\sqrt{\lambda_{qq}\lambda_{tt}} = 0.55$, $\lambda_{qt} = 1.3$

LHC $M_{t\bar{t}}$ spectrum

The $M_V = 300$ GeV color octet example:



$$\text{e.g., for } M_{t\bar{t}} \in [1400, 1600] \text{ GeV}, \quad \frac{\sigma_{NP}}{\sigma_{SM}} \approx 1.7\,, \quad \sigma_{NP} \approx 80 \text{ fb}$$

- below the $O(200)$ fb sensitivity of a CMS “bump hunting" search at 4.6 fb^{-1}

CMS PAS-EXO-11-006

The charge asymmetry A_C at the LHC

- the LHC is a symmetric collider (P-invariant) therefore $A^{\bar{t}t}_{FB} = 0$.

- can define a charge asymmetry using rapidity differences, which can access the physics responsible for $A^{\bar{t}t}_{FB}$ at the Tevatron:

$$A_C = \frac{N(\Delta|y| > 0) - N(\Delta|y| < 0)}{N(\Delta|y| > 0) - N(\Delta|y| < 0)}$$

where $\Delta|y| = |y_t| - |y_{\bar{t}}|$ and similarly with $y\ \text{(rapidity)} \to \eta\ \text{(pseudorapidity)}$

- dilution due to large $gg \to t\bar{t}$ means A_C is much smaller than $A^{\bar{t}t}_{FB}$.

- good agreement between experiment and SM theory for A_C

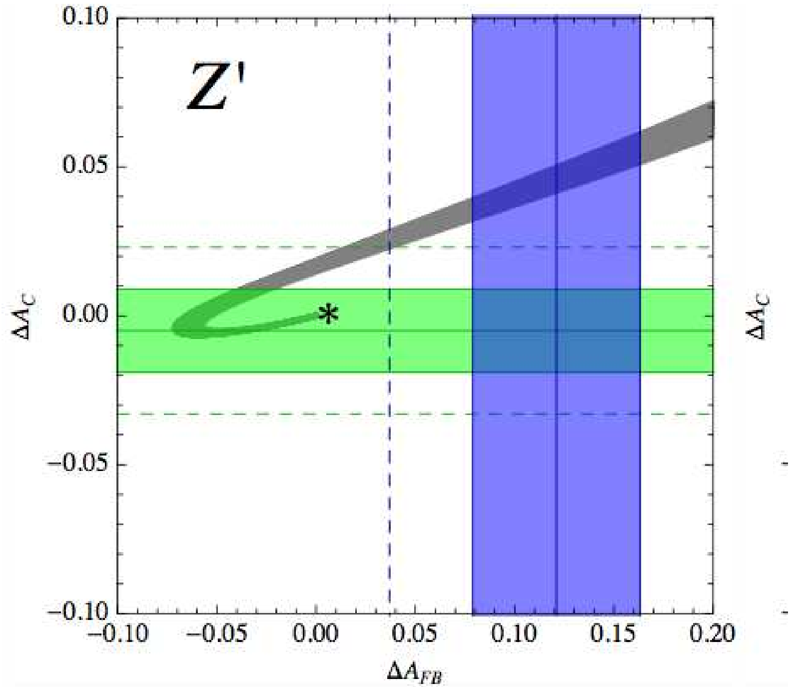
$$A_C = 1.4 \pm 0.7\% \ \ \text{(CMS)}, \quad 2.9 \pm 2.3\% \ \ \text{(ATLAS)}$$

$$A_C = 1.3 \pm 1.2\% \ \ \text{(exp avg)} \ \ \text{vs.} \ \ A_C = 1.23 \pm 0.05 \ \text{(NLO SM)}$$

again $\sim 30\%$ reduction in SM prediction from taking $\sigma^{t\bar{t}}_{\text{NLO}}$ in the denominator

A_C for $Z' - t_R - u_R$ t-channel models

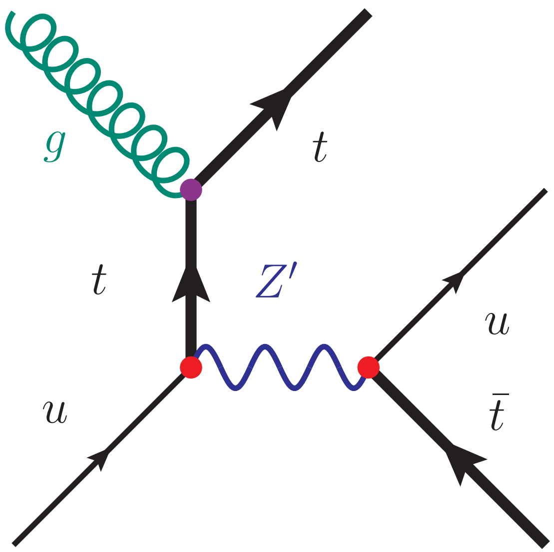
- correlation between NP shifts in $\Delta A^{t\bar{t}}_{FB}$ and A_C for t-channel $q\bar{q} \to t\bar{t}$ Fajfer, Kamenik, Melic

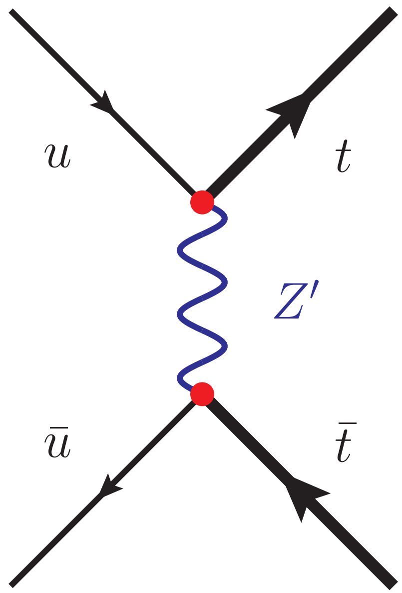


Contribution to A_C from single mediator production

J. Drobniak, A.K., J. Kamenik, G. Perez, J. Zupan; Alvarez, Leskow

$$ug \to Z'\,\bar{t}\,u + t, \quad \bar{u}g \to Z'\bar{t} \to t\bar{u} + \bar{t}$$



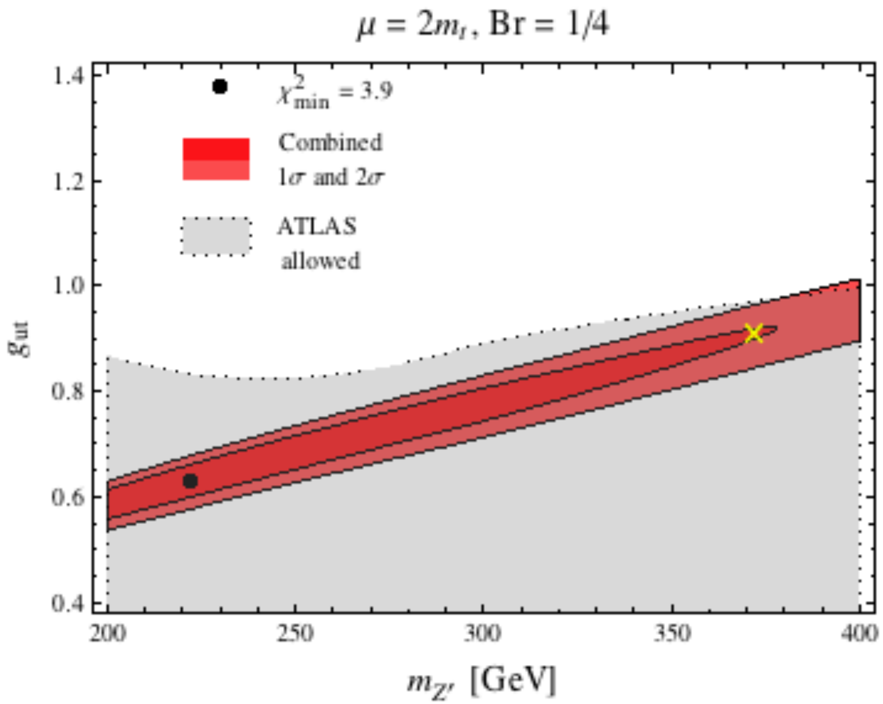


- for ug process Z' gets a boost due to larger momentum of u than g,
  $\Rightarrow$ boosted $\bar{t}$ relative to t, opposite to what happens in $u\bar{u} \to t\bar{t}$

Z' model continued J. Drobniak, A.K., J. Kamenik, G. Perez, J. Zupan

$$\mathcal{L} = g_{ut}\, Z'_\mu\, \bar{u}_R\, \gamma^\mu\, t_R \,+\, \text{h.c.} \,+\, M^2_{Z'}\, Z'^{\dagger}_\mu\, Z'^{\,\mu}$$

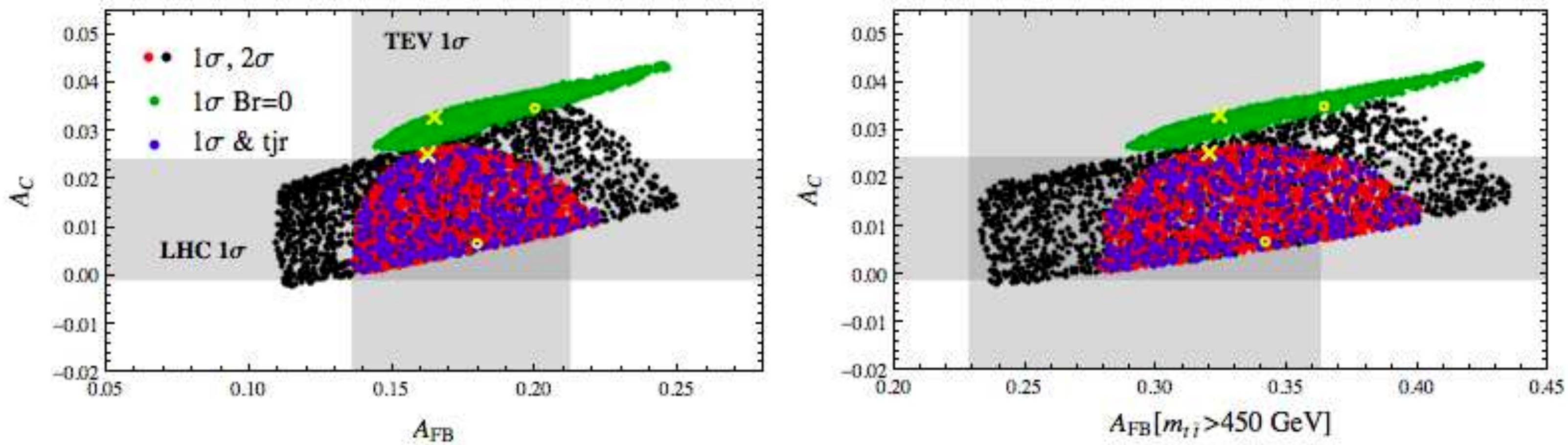
- non self-conjugate Z' (due to flavor symmetry) $\Rightarrow$ no same sign top problem
- Employ χ^2 to search for optimal ranges of g_{ut}, $M_{Z'}$, $rmBr(Z' \to t\bar{u})$ for three renormalization/factorization scale $\mu = m_t/2,\ m_t,\ 2m_t$.
- Six $t\bar{t}$ observables in fit: σ_{total} at Tevatron and LHC, $A_{FB}\ (\text{inclusive})$, $A_{FB}(m_{t\bar{t}} > 450)$, $A_{FB}(m_{t\bar{t}} < 450)$, A_C
- Best fit points tend to lie near $M'_Z \approx 200$ GeV, $\text{Br}(Z' \to t\bar{u}) \approx 1/4$, and larger μ.



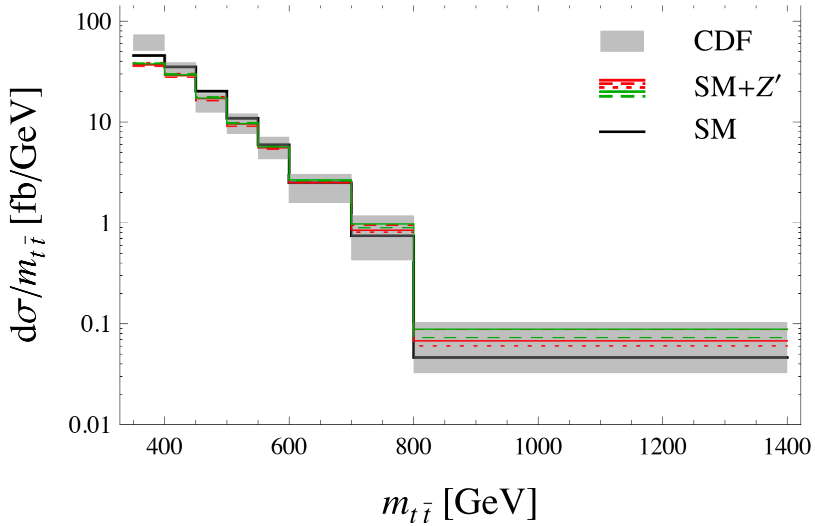
1σ and 2σ preferred regions (red). Grey area is region not excluded by ATLAS search for top+jet resonances. Blackdot is best fit point.

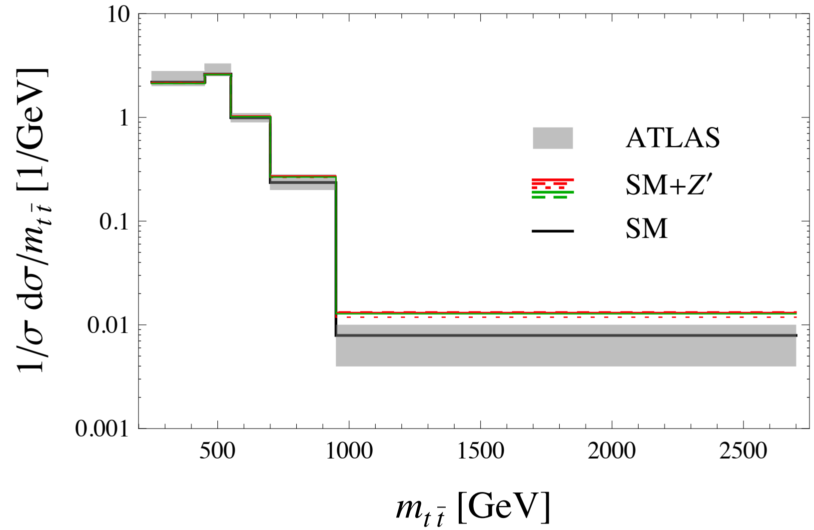
- $\chi^2_{\min} = 3.9$; for comparison, the best SM $\chi^2 = 12.1$ at $\mu = m_t/2$

$\mu = 2m_t$, Br = 1/4



Scatter points corresponding to 1σ region (red), 2σ region (black). The 1σ points compatible with ATLAS top+jet resonance search are in blue. Green points obtained from 1σ red points by setting $\mathrm{Br}(Z' \to t\bar{u}) = 0$. Yellow circles are the $\chi^2_{\min}$ point and its shift for $\mathrm{Br} = 0$

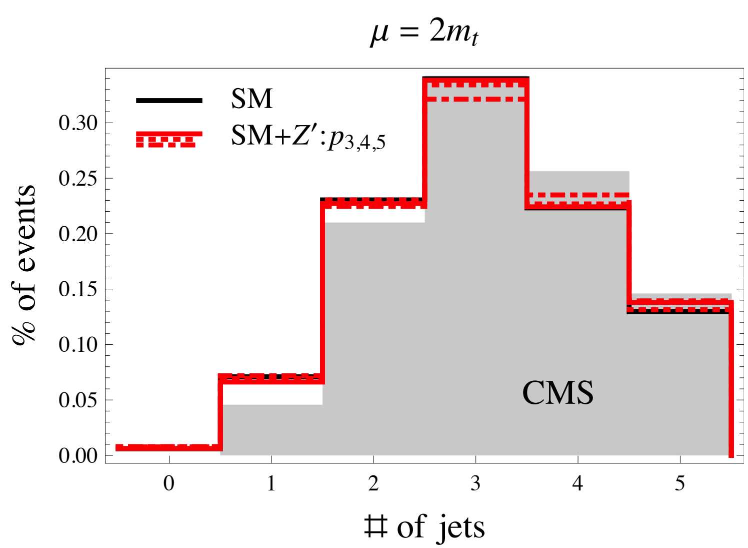




- The measured CDF and (normalized) ATLAS $m_{t\bar{t}}$ spectra (1σ grey bands), SM prediction (black), and a few BM's. The best fit point in previous plots corresponds to the red dotted curves
  - can see a small tail at large $m_{t\bar{t}}$ in the LHC spectrum, characteristic of low scale t-channel models

Jet multiplicities

- one might worry that $t + Z' \to t\bar{t}j$ production could observably modify the jet multiplicity distribution in $t\bar{t}$ events, relative to SM prediction. For our benchmarks we have checked that the distributions are consistent with a CMS study of the jet multiplicity in semileptonic $t\bar{t}$ events, in particular, in the cleanest double b-tagged sample.
  - using MadGraph5, Pythia6.425, and FastJet, we compared the jet multiplicities with and without new physics to the data. The differences in the percentage of events with n=1,..,5 jets is always smaller than a few percent



Strong interaction realization

with J. Brod, J. Drobnak, E. Stamou, J. Zupan

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 the prototype for flavor octet (nonet) composite vector mesons
- add asymtpotically free $SU(3)_{HC}$ "hypercolor" gauge interaction, with strong interaction scale $\Lambda_{HC} \sim 1/2$ TeV
- Minimal model: add $SU(2)_L$ singlet, vectorlike $SU(3)_{U_R}$ or $[SU(2) \times U(1)]_{U_R}$ "flavor triplet" of hypercolor quarks $(\omega_{L_i}, \omega_{R_i})$ ($i = 1, 2, 3$);
  and a new "flavor singlet" hypercolor scalar $\mathcal{S}$

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

$$\omega_{L_i,R_i}(N,1,1,a), \quad \mathcal{S}(\bar{N},3,1,b), \quad a+b=2/3$$

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

u_R is the usual flavor triplet of RH up quarks (u_R, c_R, t_R),
the ω_i are in a flavor triplet of up quark flavors $(\omega_u, \omega_c, \omega_t)$

- imposing MFV $\Rightarrow$ $\mathbf{h}_{ij} = h\,\delta_{ij}, \quad \mathbf{m}_{\omega\,ij} = m_\omega\,\delta_{ij}$
- imposing $[SU(2)\times U(1)]_{U_R}$, or taking into account MFV corrections
  $\Rightarrow$ $\mathbf{h} = \mathrm{diag}(h_1, h_1, h_3), \quad \mathbf{m}_\omega = \mathrm{diag}(\mu_1, \mu_1, \mu_3)$
- will take $m_\omega << \Lambda$, like u, d, s in QCD
- could "supersymmetrize" in order to protect scalar mass; or could imagine that the scalar is composite

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

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

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

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

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

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

- hypercolor sector only couples to the right-handed up quarks
  - due to choice of representations for ω, $\mathcal{S}$ (hypercharge assignments)
  - Therefore, $SU(3)_{U_R}$ or $[SU(2) \times U(1)]_{U_R}$ symmetry of $\mathcal{L}_{NP}$ could be an accidental consequence of an $SU(3)_H$ or $[SU(2) \times U(1)]_H$ horizontal gauge symmetry, under which all quarks transform
  - Spontaneous breaking of $SU(3)_H$ or $[SU(2) \times U(1)]_H$ 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) + a new flavor symmetric hypercolor sector
- Flavor structure of the resonances would hint at a horizontal symmetry solution to the quark mass hierarchy problem

Hypercolor resonances

- the lowest lying $[\bar{\omega}\omega]$ vector meson flavor 8+1 "nonets" (a=1,..,9):

  ρ^a_{HC} vectors; $a^a_{1\,HC}$ axial-vectors

  - do not include ${}^1P_1$ vector multiplet (ignored “$K_1^A - K_1^B$" mixing)

- $\langle\bar{\omega}\omega\rangle \neq 0$ 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}

  - for now only considered η_8 (ignored η' and $\eta - \eta'$ mixing)

- $t\bar{t}$ production in t-channel via K^* (the “Z'"), K_1, K exchange

- s-channel $t\bar{t}$ production via ϕ, ω exchange highly suppressed by ϕ/ω mixing

  - check s-channel ρ, ϕ, ω exchange contributions to dijets

- mass scales from naive scaling from QCD

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

Motivated by Z' analysis of $A_{FB}^{t\bar{t}}$

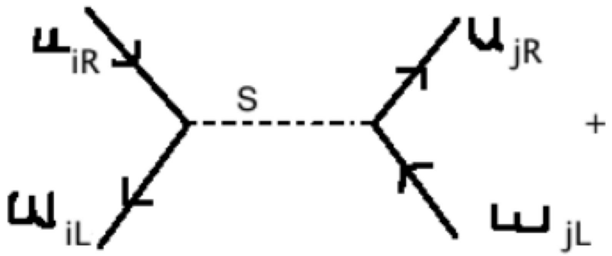
  - $m_\rho^{HC} \sim 200 - 400$ GeV $\Rightarrow$ $f_\pi^{HC} \sim 20 - 50$ GeV
  - $\Lambda_{HC}^{\chi SB} \sim 4\pi f_\pi^{HC} \sim 1/2$ TeV
  - $m_\pi^2 \sim 8\pi\, f_\pi^{HC}\, m_\omega$

$$m_\omega \sim 10 \text{ GeV} \;\Rightarrow\; m_\pi^{HC} = O(100) \text{ GeV}$$

$$\text{VMD or scaling from QCD} \;\Rightarrow\; \frac{\Gamma(\rho_{HC} \to \pi_{HC}\,\pi_{HC})}{m_\rho^{HC}} = O(10\%)$$

- employed naive quark model based treatment for dependence on “quark masses" $m_{\omega_1}, m_{\omega_3}$ of $\rho, K*, ..$ and $a_1, K_1, ...$ masses, as well as ω/ϕ and f_0/f_8 mixing
  Cheng, Shrock

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: $\lambda^V \, \rho^a_\mu \, \bar{u} \, T^a \, \gamma^\mu \, u \, + \, \lambda^A \, a^a_1 \, \bar{u} \, T^a \, \gamma^\mu \, \gamma_5 \, u \, ,$

$$m_{\mathcal{S}} >> \Lambda \;\Rightarrow\; \lambda^V \sim h^2 \, \frac{f_\rho m_\rho}{m^2_{\mathcal{S}}}, \quad \lambda^A \sim h^2 \, \frac{f_{a_1} m_{a_1}}{m^2_{\mathcal{S}}}$$

- observed $A^{t\bar{t}}_{FB} \Rightarrow \rho - u - t$ coupling $\lambda = O(1)$
  - for $m_{\mathcal{S}} \sim \Lambda$ naive dimensional analysis (NDA) $\Rightarrow$

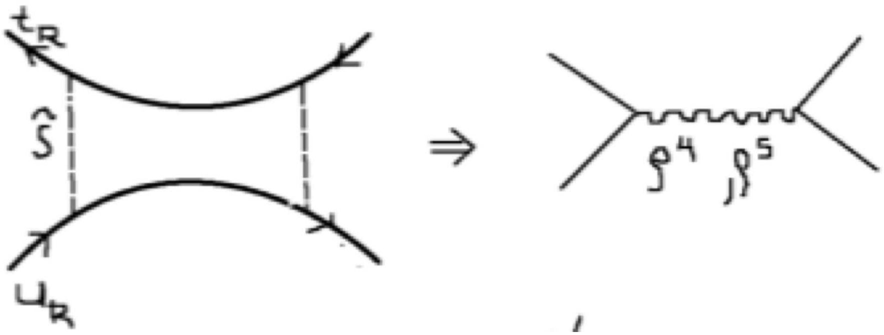
$$\lambda \sim h^2 \, \frac{f_\rho}{\Lambda} \quad \text{or} \quad h = O(\text{few})$$

composite quarks

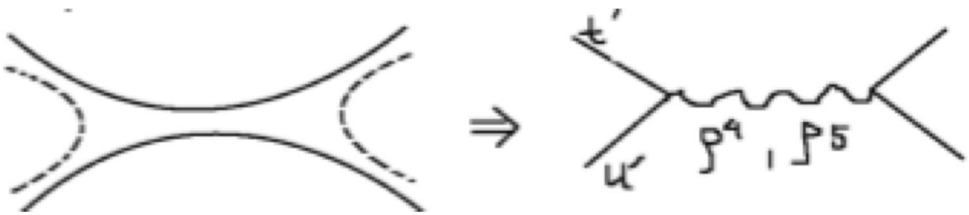
- resonances include $SU(3)_{U_R}$ flavor triplet of weak singlet vectorlike up quarks, with masses of $O(1/2\ \mathrm{TeV})$

$$u'[\mathcal{S}\,\omega_u],\quad c'[\mathcal{S}\,\omega_c],\quad t'[\mathcal{S}\,\omega_t]$$

- $t\bar{t}$ production via exchange of K^*, K_1,.... and large $u'_{R_i} - u_{R_i}$ mixing



$$m_{\mathcal{S}} >> \Lambda$$



$$m_{\mathcal{S}} \sim \Lambda,$$

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

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

up quark mass matrix of form:

$$M_{RL} = \begin{pmatrix} m_u & \sqrt{2} h f_{u'} \\ 0 & M_{u'} \end{pmatrix}$$

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

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

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

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

- use kinetic mixing (e.g. $\rho^{\mu\nu} F_{\mu\nu}$) and Vector Meson Dominance (VMD) to estimate the $\rho^a - u'_i - u'_j$ and $a_1^a - u'_i - u'_j$ couplings

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

- $\rho^a - u_i - u_j$ and $a_1^a - u_i - u_j$ couplings follow from $u' - u$ mixing:

$$\lambda^V \approx g_V \sin^2\theta_R, \quad \lambda^A \approx g_A \sin^2\theta_R$$

$$\lambda^V \sim 1 \;\Rightarrow\; h \sim 2$$

- obtain partially composite RH up quarks with $\sin\theta_{R_i} \sim 1/3$, and LH top with $\sin\theta^t_L \sim 1/3 \times m_t/M_{t'}$

P-wave $[S^* S]$ vectors

- include s-channel exchanges of P-wave vector meson bound states of the scalars, $V^\mu\,[\mathcal{S}^*\mathcal{S}]$,
  - a flavor singlet color octet V_o, and flavor singlet color singlet V_s,

$$\langle V_o^a | \mathcal{S}^* T^a \partial_\mu \mathcal{S} - (\partial_\mu \mathcal{S}^*) T^a \mathcal{S} | 0 \rangle \sim f_V m_V \epsilon_\mu$$

- gain insight on masses, decay constants from QCD tensor mesons $f_2(1270)$, $f_2'(1525)$, which also have derivative couplings
  - QCD sum-rule study of the tensors K.C. Yang suggests $f_V/M_V \sim 0.1$
  - “VMD" suggests coupling to composite quarks $g_V \sim m_V/f_V$
    - couplings to ordinary RH up quarks via $u' - u$ mixing
  - NDA yields similar estimates
- V expected to be very broad , e.g. $\Gamma/M = O(30 - 50\%)$, due to $V \to \bar{u}_i' u_i$

Numerics

- vector and axial-vector masses: scale from quark model based treatment of QCD Cheng, Shrock

$$\left(M^{HC}_{\rho^{1,2,3}}\right)^2 = \mu^{HC}\left(E^{HC}_V + 2m_{\omega_1}\right), \quad (1)$$

$$\left(M^{HC}_{K^{*1,2,3,4}}\right)^2 = \mu^{HC}\left(E^{HC}_V + m_{\omega_3} + m_{\omega_1}\right), \quad (2)$$

$\omega - \phi$, $f_0 - f_8$ systems require additional massive parameters, $x^{HC}_{V,A}$, to account for flavor singlet mass contribution from annihilation to gluons

- obtain μ^{HC}, E^{HC}, x^{HC} by scaling from fit results in QCD (in GeV):

$$\mu^{QCD}_{V,A} = 2.2$$

$$E^{QCD}_V = 0.26GeV \qquad x^{QCD}_V = 0.015$$

$$E^{QCD}_A = 0.70 \qquad x^{QCD}_A = 0.064$$

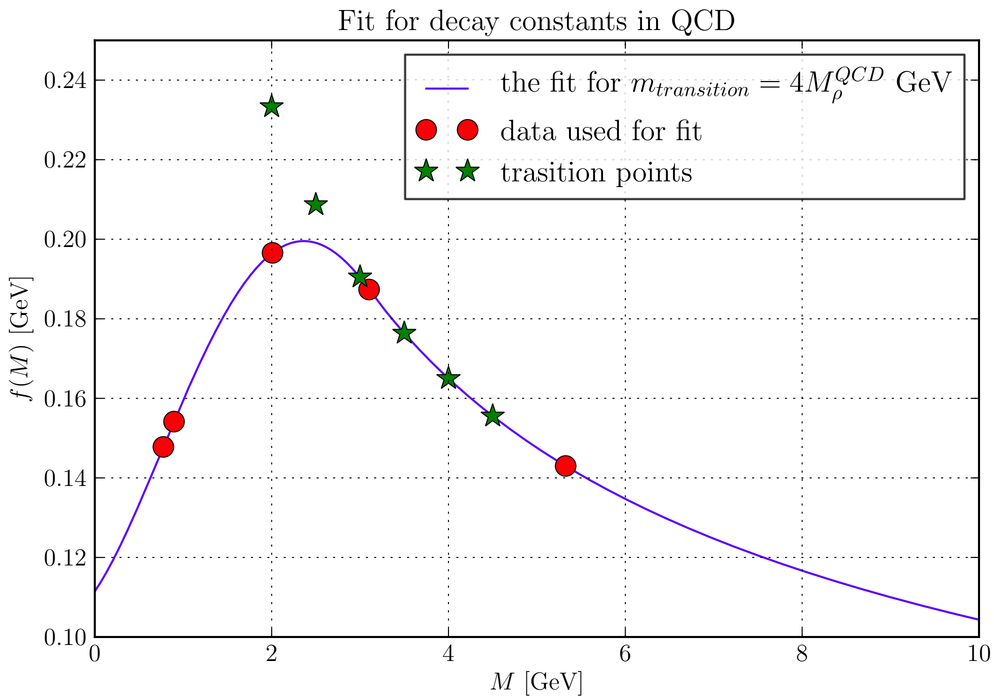
$$\mu^{HC} = \mu^{QCD}\frac{M^{HC}}{M^{QCD}_\rho}, \ldots\ldots$$

where M^{HC} is the would-be HC vector mass in chiral limit

- decay constants of π^a, ρ^a, a_1^a scaled from QCD

$$f_\pi^{HC} = f_\pi^{QCD} \frac{M^{HC}}{M_\rho^{QCD}}, \qquad f_{\rho\,(a_1)}^{HC} = f_{\rho\,(a_1)}^{QCD} \frac{M^{HC}}{M_\rho^{QCD}}$$

- decay constants of composite quarks $f_{t'}, \ldots$
  - ignore different spin structure of composite quark constituents
  - require large scalar mass $m_{\mathcal{S}} \sim 1/2$ TeV to avoid $t\bar{t}$ peak in Tevatron data due to V_o s-channel exchange, i.e., want $m_{V_o} > 1$ TeV.
  - therefore composite quarks probably “lie between" D^* and B^* in terms of mass
  - use information on light and heavy-light vector mesons in QCD, f_ρ, f_{K^*}, f_{D^*}, f_{B^*} (HQET + f_B) vs. meson masses, to interpolate.
  - assume transition to heavy quark limit $f \propto 1/\sqrt{M}$ at $M \approx (4-5)M_\rho$



scale to HC to obtain $f_{t'}$ vs $M_{t'}/M_{\mathrm{chiral}}$

- pseudoscalar masses

$$\left(M^{HC}_{\pi^{1,2,3}}\right)^2 = \frac{M^{HC}}{M^{QCD}_\rho}\, 2B\, m_{\omega_1}\,, \tag{3}$$

$$\left(M^{HC}_{K^{1,2,3,4}}\right)^2 = \frac{M^{HC}}{M^{QCD}_\rho}\, B\,(m_{\omega_1} + m_{\omega_3}), \tag{4}$$

$$\left(M^{HC}_{\eta}\right)^2 = \frac{M^{HC}}{M^{QCD}_\rho}\, B\, \frac{2}{3}(m_{\omega_1} + 2m_{\omega_3}), \tag{5}$$

$$\tag{6}$$

use $B \approx 2.7$ GeV (UKQCD)

- heavier masses (heavy quark - like relations)

$$M^{HC}_{V_{o,s}s} = M^{HC} + 2m_S$$

$$M^{HC}_{u'_i} = M^{HC} + m_{\omega_i} + m_S$$

A light K^* (Z') benchmark

- from χ^2 scans in the 6 observables: $\sigma_{\rm total}$ at Tevatron and LHC, A_{FB} (inclusive), $A_{FB}(m_{t\bar{t}} > 450)$, $A_{FB}(m_{t\bar{t}} < 450)$, A_C

- input parameters, renormalization scale $\mu = 2m_t$ for cross sections etc :

$$M^{HC} = 176\,\text{GeV},\ m_{\omega_1} = 2.5\,\text{GeV},\ m_{\omega_3} = 2.5\,\text{GeV},\ m_{\mathcal{S}} = 520\ \text{GeV},\ h_1 = 2,\ h_3 = 4$$

- IR outputs:

$$M_\pi = 56\text{ GeV},\ \ M_K = 147\text{ GeV},\ M_\rho = 180\text{ GeV},\ \ M_{K*} = 217\text{ GeV}, ...$$

$$M_{a_1} = 371\text{ GeV},\ \ M_{K_1} = 404\ \text{ GeV},\ \ M_{V_{o,s}} = 1300\text{ GeV}$$

$$M_{u'} = M_{c'} = 695\text{ GeV},\ \ M_{t'} = 724\ \text{ GeV}$$

- for the 6 scan observables obtain $\chi^2 = 3.3$!

Madgraph Results for Benchmark:

bmCHI2_Siveter_Brandey_eOHM_mod_interchanged

Scale : 346.6 GeV **tuning** = 4.0
PDF-set : $\texttt{cteq6}_\texttt{m}$ $\text{PS}[\ldots]^3$ = 0.031

Tevatron results

$\sigma^{\text{TEV,inc}}_{F,t\bar{t}} = 2.194$ pb $\sigma^{\text{TEV,low}}_{F,t\bar{t}} = 1.088$ pb $\sigma^{\text{TEV,high}}_{F,t\bar{t}} = 1.044$ pb
$\sigma^{\text{TEV,inc}}_{B,t\bar{t}} = 1.468$ pb $\sigma^{\text{TEV,low}}_{B,t\bar{t}} = 0.91$ pb $\sigma^{\text{TEV,high}}_{B,t\bar{t}} = 0.525$ pb
$\sigma^{\text{TEV,inc}}_{F,\text{asc}} = 0.019$ pb $\sigma^{\text{TEV,low}}_{F,\text{asc}} = 0.013$ pb $\sigma^{\text{TEV,high}}_{F,\text{asc}} = 0.005$ pb
$\sigma^{\text{TEV,inc}}_{B,\text{asc}} = 0.028$ pb $\sigma^{\text{TEV,low}}_{B,\text{asc}} = 0.018$ pb $\sigma^{\text{TEV,high}}_{B,\text{asc}} = 0.009$ pb

$\sigma^{\text{TEV,inc}} = 6.684$ pb
$\sigma^{\text{TEV,inc}}_{\text{no asc}} = 6.637$ pb

$A^{\text{inc}}_{FB,lo} = 0.284$ $A^{\text{low}}_{FB,lo} = 0.159$ $A^{\text{high}}_{FB,lo} = 0.443$
$A^{\text{inc,no asc}}_{FB,lo} = 0.29$ $A^{\text{low,no asc}}_{FB,lo} = 0.164$ $A^{\text{high,no asc}}_{FB,lo} = 0.449$

$\boldsymbol{\chi^2_{\text{TEV,lo}} = 17.591}$
$\chi^2_{\text{TEV,lo,no asc}} = 19.552$

$A^{\text{inc}}_{FB,mc@nlo} = 0.188$ $A^{\text{low}}_{FB,mc@nlo} = 0.097$ $A^{\text{high}}_{FB,mc@nlo} = 0.316$
$A^{\text{inc,no asc}}_{FB,mc@nlo} = 0.192$ $A^{\text{low,no asc}}_{FB,mc@nlo} = 0.099$ $A^{\text{high,no asc}}_{FB,mc@nlo} = 0.32$

$\boldsymbol{\chi^2_{\text{TEV,mc@nlo}} = 2.588}$
$\chi^2_{\text{TEV,mc@nlo,no asc}} = 2.996$

LHC results

$\sigma^{\text{LHC,inc}}_{F,t\bar{t}} = 41.98$ pb
$\sigma^{\text{LHC,inc}}_{B,t\bar{t}} = 39.063$ pb
$\sigma^{\text{LHC,inc}}_{F,\text{asc}} = 1.708$ pb
$\sigma^{\text{LHC,inc}}_{B,\text{asc}} = 2.228$ pb
$\sigma^{\text{LHC,inc}} = 169.409$ pb
$\sigma^{\text{LHC,inc}}_{\text{no asc}} = 165.473$ pb

$A^{\text{inc}}_{C,lo} = 0.039$ $\boldsymbol{\chi^2_{\text{LHC,lo}} = 4.593}$
$A^{\text{inc,no asc}}_{C,lo} = 0.047$ $\chi^2_{\text{LHC,lo,no asc}} = 8.105$

$A^{\text{inc}}_{C,mc@nlo} = 0.023$ $\boldsymbol{\chi^2_{\text{LHC,mc@nlo}} = 0.675}$
$A^{\text{inc,no asc}}_{C,mc@nlo} = 0.027$ $\chi^2_{\text{LHC,mc@nlo,no asc}} = 1.489$

$\chi^2_{\text{SM,lo}} = 13.561$ $\chi^2_{\text{lo,no asc}} = 27.657$ $\boldsymbol{\chi^2_{\text{lo}} = 22.184}$
$\chi^2_{\text{SM,mc@nlo}} = 21.072$ $\chi^2_{\text{mc@nlo,no asc}} = 4.485$ $\boldsymbol{\chi^2_{\text{mc@nlo}} = 3.263}$

UV parameters

$M^{\rm HC} = 175.8$ GeV
$m_{\omega_1} = 2.5$ GeV
$m_{\omega_3} = 32.0$ GeV
$m_S = 520.0$ GeV
$h_1 = 2.0$
$h_3 = 4.1$

Mixings

$\sin^R_1 = 0.2204$
$\sin^R_2 = 0.2204$
$\sin^R_3 = 0.4177$
$\sin^L_1 = 0.0$
$\sin^L_2 = 0.0004$
$\sin^L_3 = 0.0911$

Fudge factors

$\texttt{fud}_{\texttt{g}_\texttt{A}} = 1.0$
$\texttt{fud}_{\texttt{g}_\rho} = 1.0$
$\texttt{fud}_{\texttt{g}_{\texttt{a}_1}} = 1.0$
$\texttt{fud}_{\texttt{f}_{\texttt{u}'}} = 1.3$
$\texttt{fud}_{\texttt{p/s-wave V}_\texttt{o}} = 1.5$
$\texttt{fud}_{\texttt{gV}_\texttt{o}} = 1.0$
$\texttt{fud}_{\texttt{GV}_\texttt{o}} = 0.0$
$\texttt{fud}_{\texttt{p/s-wave V}_\texttt{s}} = 1.5$
$\texttt{fud}_{\texttt{gV}_\texttt{s}} = 1.0$
$\texttt{fud}_{\texttt{GV}_\texttt{s}} = 0.0$

IR parameters

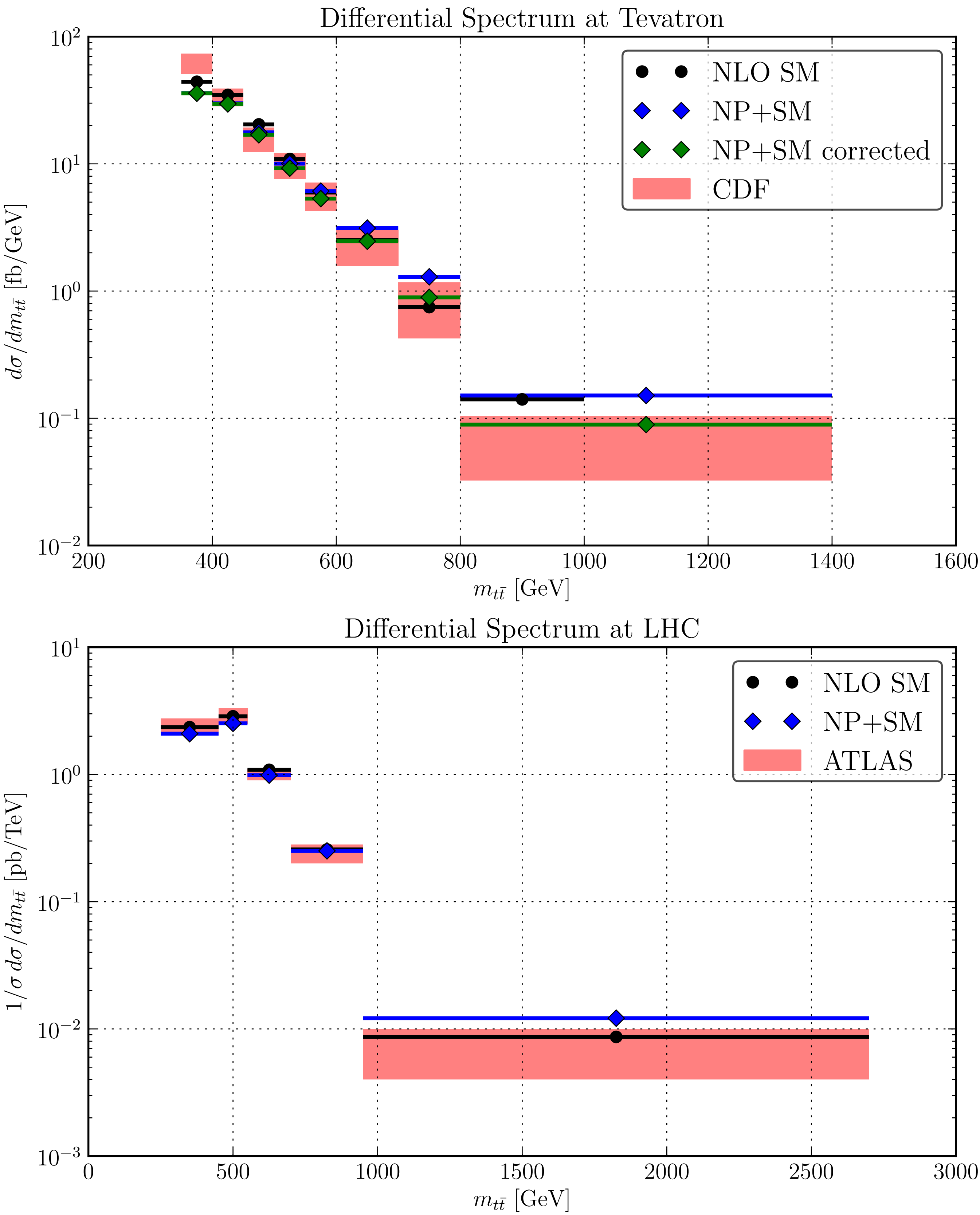
$G_{a_1}/M_{a_1} = 0.1$
$G_{K_1}/M_{K_1} = 0.1$
$G_{A_L}/M_{A_L} = 0.159$
$G_{A_H}/M_{A_H} = 0.209$

$\texttt{fud}_{\texttt{M}_{\texttt{K}_1}/\texttt{M}_{\texttt{K}^*}} = 1.3$

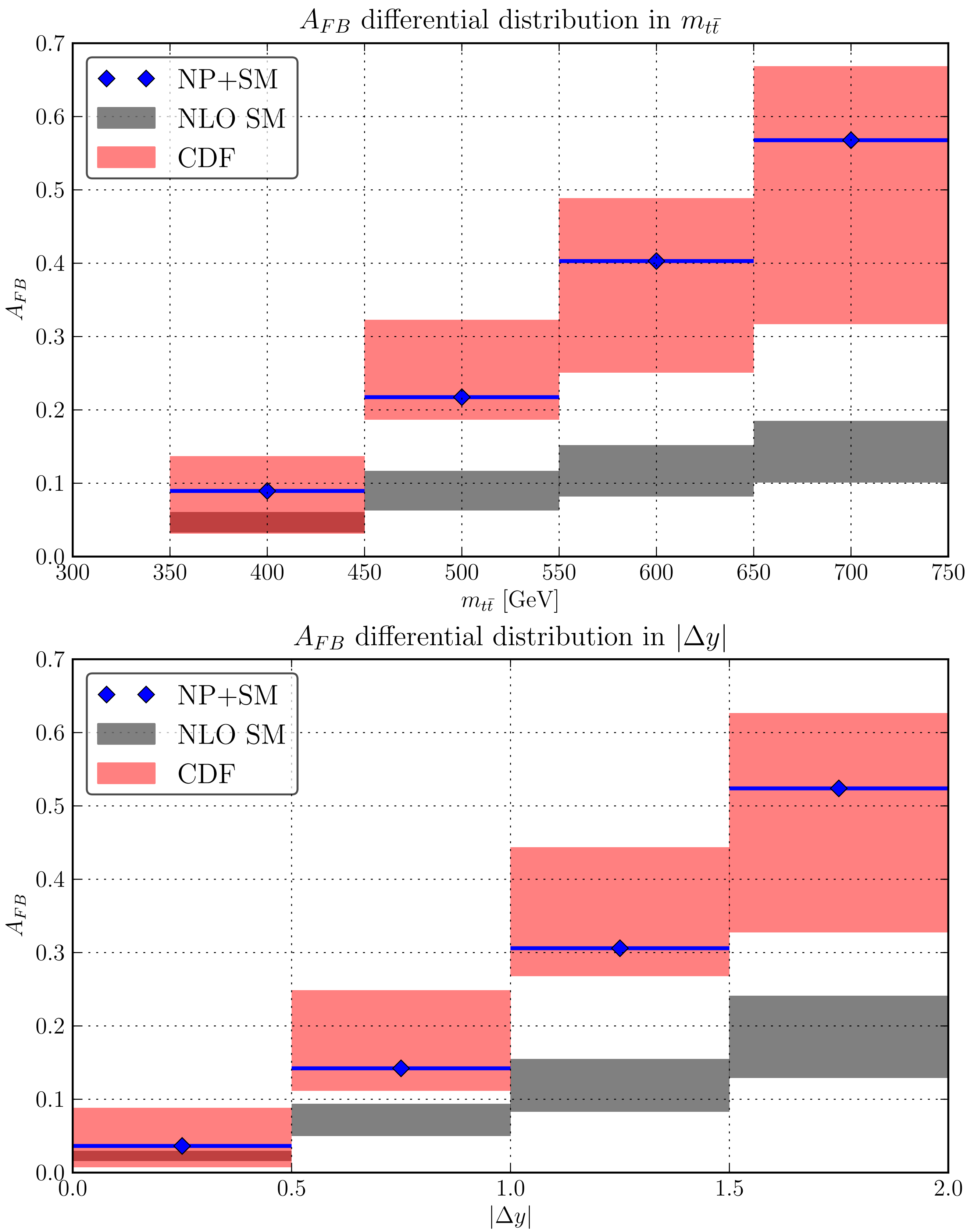
Couplings

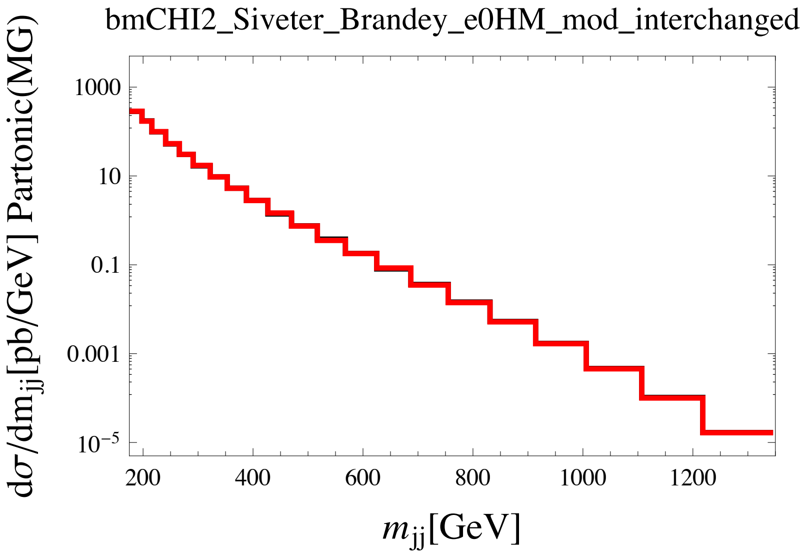
$g_\rho = 5.247$
$g_{\rho\pi\pi} = 5.247$
$g_a = 9.713$
$g_{V_o} = 12.5$
$g_{V_s} = 5.103$
$g_A = 1.308$

Masses	**Widths**	**Decay constants**
$M_\pi^{HC} = 56.4$ GeV	$\Gamma^{HC}_{\pi^{1,2}}/M^{HC}_{\pi^{1,2}} = 0.0$	$f_\pi^{HC} = 21.0$ GeV
	$\Gamma^{HC}_{\pi^3}/M^{HC}_{\pi^3} = 0.0$	
$M_K^{HC} = 147.0$ GeV	$\Gamma^{HC}_{K^{1,2}}/M^{HC}_{K^{1,2}} = 0.0$	
	$\Gamma^{HC}_{K^{3,4}}/M^{HC}_{K^{3,4}} = 0.0$	
$M_\eta^{HC} = 166.6$ GeV	$\Gamma^{HC}_\eta/M^{HC}_\eta = 0.0$	
$M_\rho^{HC} = 179.6$ GeV	$\Gamma^{HC}_\rho/M^{HC}_\rho = 0.087$	$f_\rho^{HC} = 33.5$ GeV
$M_{K^*}^{HC} = 216.8$ GeV	$\Gamma^{HC}_{K^*_{1,2}}/M^{HC}_{K^*_{1,2}} = 0.005$	
	$\Gamma^{HC}_{K^*_{3,4}}/M^{HC}_{K^*_{3,4}} = 0.005$	
$M_{V_L}^{HC} = 182.6$ GeV	$\Gamma^{HC}_{V_L}/M^{HC}_{V_L} = 0.001$	
$M_{V_H}^{HC} = 249.7$ GeV	$\Gamma^{HC}_{V_H}/M^{HC}_{V_H} = 0.0$	
$M_{a_1}^{HC} = 371.3$ GeV	$\Gamma^{HC}_{a_1}/M^{HC}_{a_1} = 0.1$	$f_{a_1}^{HC} = 38.1$ GeV
$M_{K_1}^{HC} = 403.5$ GeV	$\Gamma^{HC}_{K_1}/M^{HC}_{K_1} = 0.1$	
$M_{A_L}^{HC} = 381.3$ GeV	$\Gamma^{HC}_{A_L}/M^{HC}_{A_L} = 0.159$	
$M_{A_H}^{HC} = 438.9$ GeV	$\Gamma^{HC}_{A_H}/M^{HC}_{A_H} = 0.209$	
$M_{V_s}^{HC} = 1298.5$ GeV	$\Gamma^{HC}_{V_s}/M^{HC}_{V_s} = 0.331$	
$M_{V_o}^{HC} = 1298.5$ GeV	$\Gamma^{HC}_{V_o}/M^{HC}_{V_o} = 0.332$	
$M_{u'}^{HC} = 694.9$ GeV	$\Gamma^{HC}_{u'}/M^{HC}_{u'} = 0.06$	$f_{u'}^{HC} = 55.5$ GeV
$M_{c'}^{HC} = 694.9$ GeV	$\Gamma^{HC}_{c'}/M^{HC}_{c'} = 0.06$	$f_{c'}^{HC} = 55.5$ GeV
$M_{t'}^{HC} = 724.3$ GeV	$\Gamma^{HC}_{t'}/M^{HC}_{t'} = 0.19$	$f_{t'}^{HC} = 54.4$ GeV

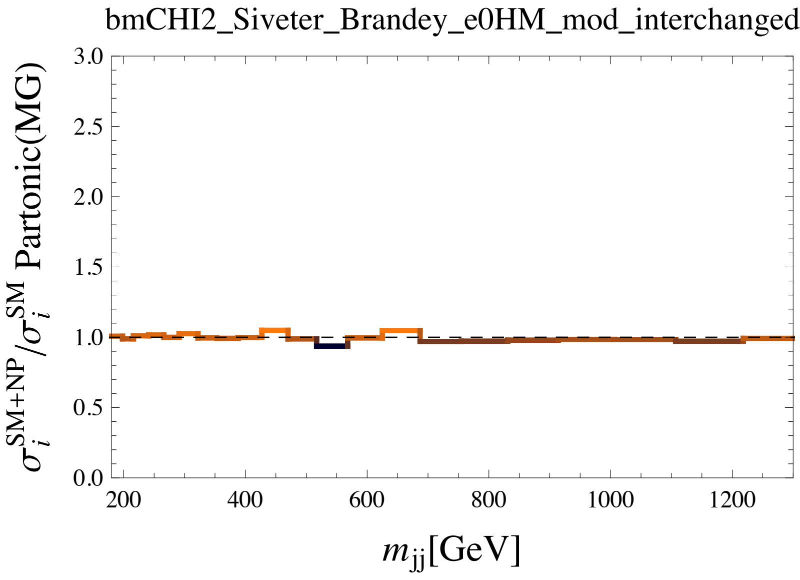


Differential Spectrum at Tevatron
NLO SM
NP+SM
NP+SM corrected
CDF
$d\sigma/dm_{t\bar{t}}$ [fb/GeV]
10^{2}
10^{1}
10^{0}
10^{-1}
10^{-2}
200
400
600
800
1000
1200
1400
1600
$m_{t\bar{t}}$ [GeV]
Differential Spectrum at LHC
NLO SM
NP+SM
ATLAS
$1/\sigma\, d\sigma/dm_{t\bar{t}}$ [pb/TeV]
10^{1}
10^{0}
10^{-1}
10^{-2}
10^{-3}
0
500
1000
1500
2000
2500
3000
$m_{t\bar{t}}$ [GeV]


A_{FB} differential distribution in $m_{t\bar{t}}$
NP+SM
NLO SM
CDF
A_{FB}
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
300
350
400
450
500
550
600
650
700
750
$m_{t\bar{t}}$ [GeV]
A_{FB} differential distribution in $|\Delta y|$
NP+SM
NLO SM
CDF
A_{FB}
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.0
0.5
1.0
1.5
2.0
$|\Delta y|$



bmCHI2_Siveter_Brandey_e0HM_mod_interchanged
dσ/dm_jj[pb/GeV] Partonic(MG)
1000
10
0.1
0.001
10^-5
200
400
600
800
1000
1200
m_jj[GeV]


bmCHI2_Siveter_Brandey_e0HM_mod_interchanged
$\sigma_i^{SM+NP}/\sigma_i^{SM}$ Partonic(MG)
3.0
2.5
2.0
1.5
1.0
0.5
0.0
200
400
600
800
1000
1200
m_{jj}[GeV]

On the composite u''s

- unfortunately, detection at LHC via could be quite difficult $u'_i \to t + \pi' s$
- π^a are color singlets, decay via $\pi^a \to \bar{u}u,\ \bar{c}c$, or $\pi^a \to \bar{t}^{(*)}u,\ \bar{t}^{(*)}c$
- final states with two tops: $\bar{u}'_i u'_i \to \bar{t}\, t\, \bar{q}\, q\, \bar{q}\, q$,
  $\bar{u}'_i u_i \to \bar{t}\, t\, \bar{u}_i\, u_i$ (suppressed)
- final states with 4 tops?: $\bar{u}' u' \to \bar{t}\, t\, \bar{t}\, t\, \bar{q}\, q$
- Production mechanism:
  - $\bar{u}'_i\ u'_i$: via QCD and $\rho^a,\ a_1^a$, $V_{o,s}$ exchange
  - $\bar{u}'_i\, u_i$ (single u' production): via $\rho^a,\ a_1,\ \ V_{o,s}$ exchange