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

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KITP, July 2013

Plan

- Flavor and $A_{\rm FB}^{t\bar{t}}$
  - flavor symmetric vectors B. Grinstein, A.K., M. Trott, J. Zupan
- The $(\bar{u}t)$ flavor-changing Z'
  - A_C vs. A_{FB} and other constraints
    J. Drobnak, A.K., J. Kamenik, G. Perez, J. Zupan
- A strong interaction realization
  J. Brod, J. Drobnak, A.K., E. Stamou, J. Zupan, in preparation

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

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:

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

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 $\sim 30\%$ for $\sigma_{\rm NLO}^{t\bar{t}}$ in the denominator

The charge asymmetry A_C at the LHC

- the LHC is a symmetric collider (P-invariant) therefore $A_{FB}^{\bar{t}t} = 0$.
- can define a charge asymmetry using rapidity differences, which can access the physics responsible for $A_{FB}^{\bar{t}t}$ at the Tevatron:

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

where $\Delta|y| = |y_t| - |y_{\bar{t}}|$

- dilution due to large $gg \to t\bar{t}$ means A_C is much smaller than $A_{FB}^{\bar{t}t}$.
- Experiment and SM theory are consistent

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

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

($\sim 30\%$ reduction in SM prediction with $\sigma_{\text{NLO}}^{t\bar{t}}$ in denominator)

Low mass t-channel explanations

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

Issues

- 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

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

  - and bounds from top+jet resonance searches
  - both evaded if $\mathrm{Br}(Z' \to \bar{t}q)$ is suppressed

Flavor Symmetric Models

Consider

- NP in MFV class, i.e., 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

- or NP invariant under the flavor subgroup

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

  - also appealing for relaxation of FCNC constraints

- new fields in non-trivial representations of G_F or H_F with $O(1)$ 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

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

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

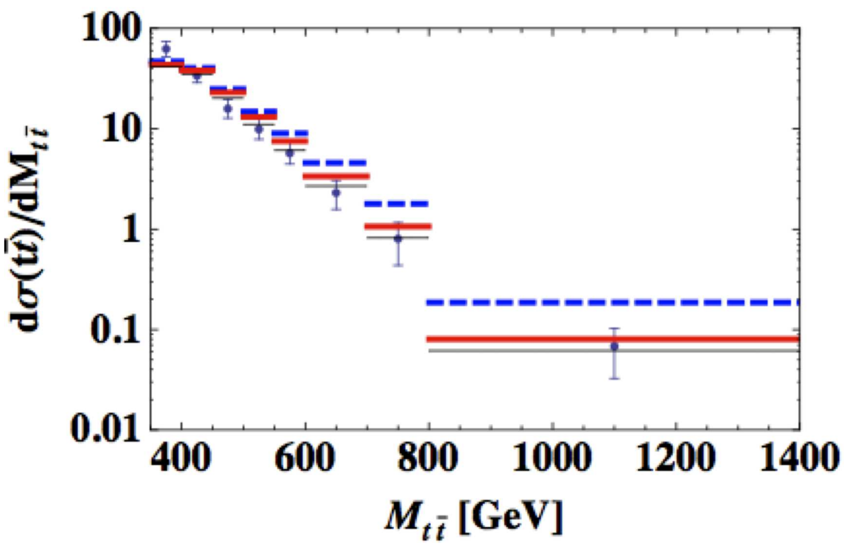
  - color octet: $V_\mu^o = V_\mu^{A,B} \mathcal{T}^A T^B$
  - color singlet: $V_\mu^s = V_\mu^A T^A$

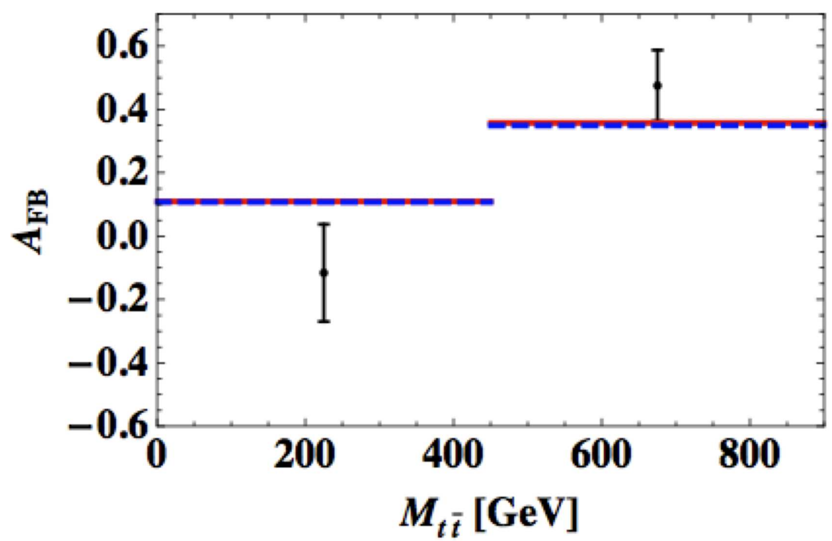
$$\text{t}-\text{channel} \quad (V_\mu^4 - iV_\mu^5)(\bar{t}_R \gamma^\mu u_R) + ... \quad \Rightarrow \quad K^*$$

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

- $t\bar{t}$ production t-channel dominated
- or could have $[SU(2) \times U(1)]_{U_R}$ symmetry

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

- light vectors with O(10%) widths, due to additional decay channel, can evade constraints on s-channel dijet contributions, with approximately flavor symmetric couplings

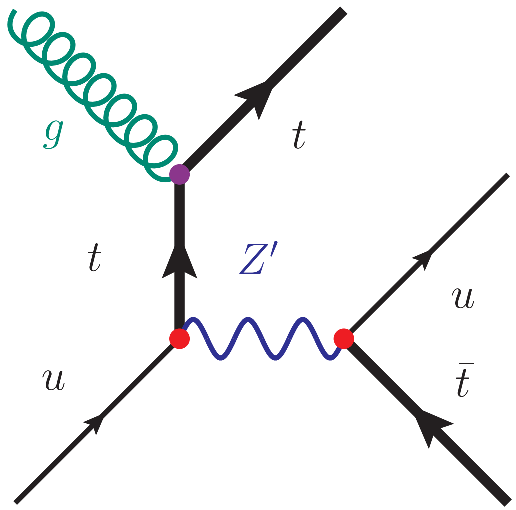
$$\lambda_{qq} \approx \lambda_{33} \approx \lambda_{i3}$$

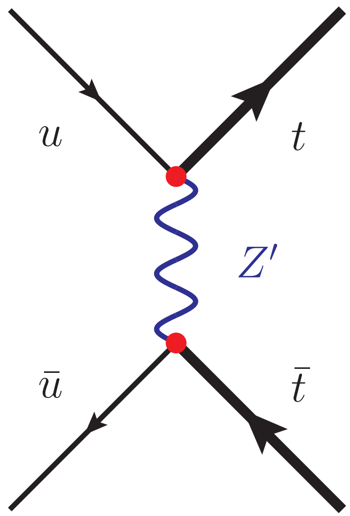
Focus on the flavor changing Z'

Contribution to A_C from single mediator production

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

$ug \to Z't \to \bar{t}\,u + t, \quad \bar{u}g \to Z'\bar{t} \to t\bar{u} + \bar{t}$ (Z' is the K*)



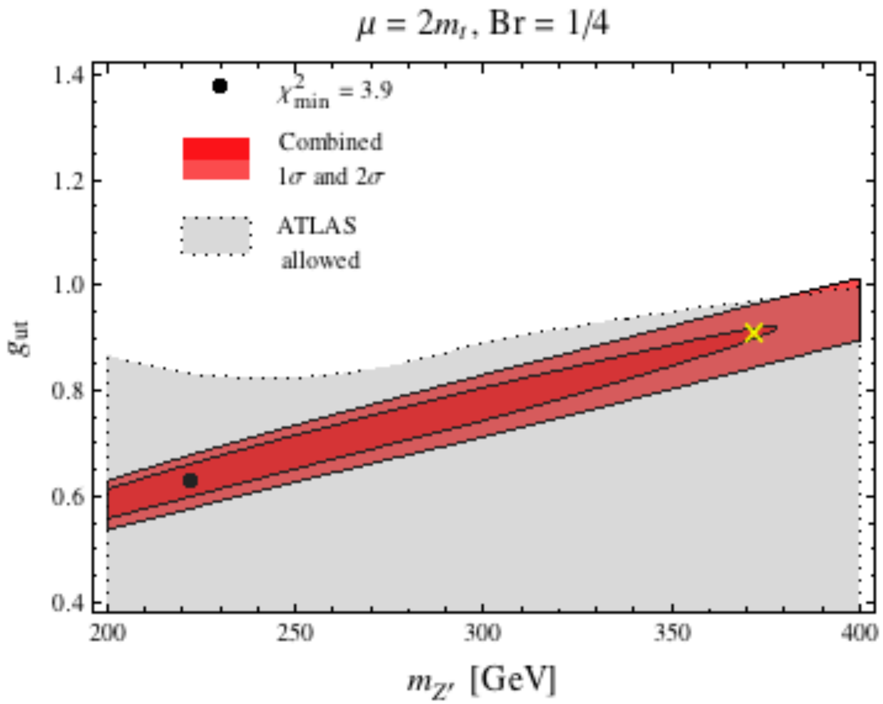


- for ug process Z' gets a boost due to larger momentum of u than g,
  $\Rightarrow$ boosted $\bar{t}$ relative to t, opposite to what happens in $u\bar{u} \to t\bar{t}$
  $\Rightarrow$ negative contribution to A_C
- breaks the correlation between A_C and A_{FB}

Z' continued

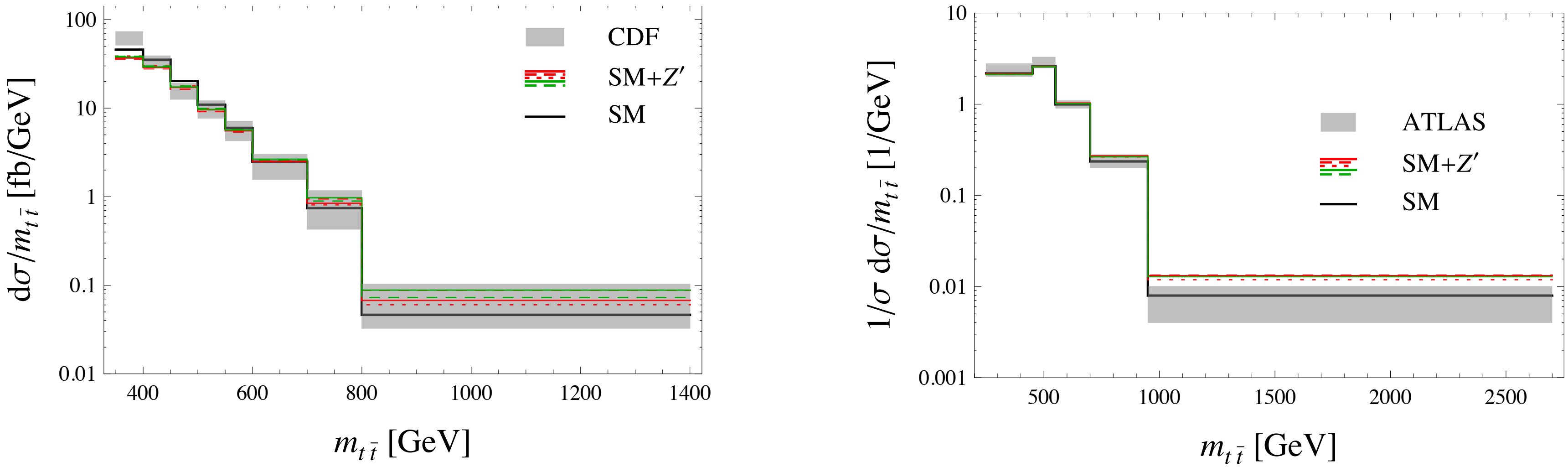
$$\mathcal{L} = g_{ut}\, Z'_\mu\, \bar{u}_R\, \gamma^\mu\, t_R \,+\, \text{h.c.} \,+\, M^2_{Z'}\, Z'^\dagger_\mu\, Z'^\mu$$

- Employ χ^2 to search for optimal ranges of g_{ut}, $M_{Z'}$, $\mathrm{Br}(Z' \to t\bar{u})$ for three renormalization/factorization scales $\mu = m_t/2,\ m_t,\ 2m_t$.
- Six $t\bar{t}$ observables in fit: σ_{total} at Tevatron and LHC, A_{FB} (inclusive), $A_{FB}(m_{t\bar{t}} > 450)$, $A_{FB}(m_{t\bar{t}} < 450)$, A_C
- Best fit points lie near $M'_Z \approx 200$ GeV, $\mathrm{Br}(Z' \to t\bar{u}) \approx 1/4$
- $\mathrm{Br}(Z' \to t\bar{u})$ suppression is due to LHC $(t\bar{t})$ xsec constraint
  - Suppressed $\mathrm{Br}(Z' \to t\bar{u}) \Rightarrow$ satisfy LHC top+jet resonance production bounds
- require an additional dominant Z' decay mode



1σ and 2σ preferred regions (red). Blackdot is best fit point.

- $\chi^2_{\rm min} = 3.9$; for comparison, the best SM $\chi^2 = 12.1$ at $\mu = m_t/2$
- Grey area is region not excluded by ATLAS search for top+jet resonances
- best fit point features dramatic reduction of A_C due to associated $Z'\bar{t}$ production: from $A_C \approx 0.032 \to A_C \approx 0.07$

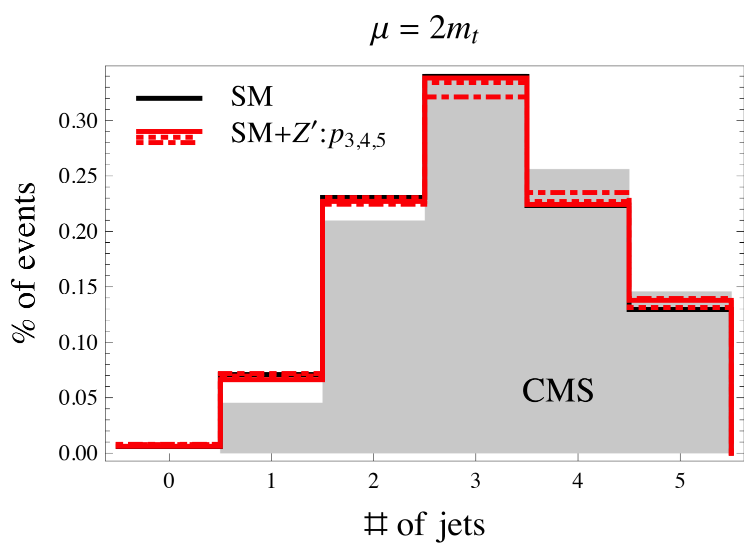


- Comparison of measured CDF and (normalized) ATLAS $m_{t\bar{t}}$ spectra (1σ grey bands) to SM prediction, and a few BM's. Best fit point in previous plot corresponds to the red dotted curves

- small tail at large $m_{t\bar{t}}$ in the LHC spectrum is 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 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

J. Brod, J. Drobnak, A.K., E. Stamou, J. Zupan

Motivation

- phenomenological models with massive flavor symmetric vectors not renormalizable
- two options for UV completions
  - local horizontal symmetry flavor gauge bosons (FGB's)
  - composite vector meson flavor multiplets
- FGB's are a problematic framework for low scale models
  - a sub-TeV flavor gauge symmetry breaking scale is dangerous for FCNC's
- composite vector mesons naturally have new dominant channels for decay: $V \to PP$, e.g. $\rho \to \pi\pi$, $K^* \to K\pi$
  - required in low scale t-channel models: LHC $t\bar{t}$ xsec,...
  - favored by dijet constraints

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 $SU(2)_L$ singlets:
  - a vectorlike $[SU(2) \times U(1)]_{U_R}$ "flavor triplet" of hypercolor quarks $(\omega_{L_i}, \omega_{R_i}),\; i = 1, 2, 3$
  - a "flavor singlet" hypercolor scalar $\mathcal{S}$

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

$$\omega_{L_i,R_i}(3,1,1,0), \quad \mathcal{S}(\bar{3},3,1,2/3b)$$

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

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 $[SU(2) \times U(1)]_{U_R} \Rightarrow$ $\mathbf{h} = \mathrm{diag}(h_1, h_1, h_3), \quad \mathbf{m}_\omega = \mathrm{diag}(\mu_1, \mu_1, \mu_3)$
- 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, $\mathcal{N}$,

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

  - 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

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

- the hypercolor sector only couples to the right-handed up quarks
  - due to choice of hypercharge assignments for ω, $\mathcal{S}$
- Therefore, do not have to single out the right-handed quarks for special treatment in the UV
  - the NP $[SU(2) \times U(1)]_{U_R}$ symmetry 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 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 + a new flavor symmetric hypercolor sector

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

  - for simplicity, did 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 considered η_8 (ignored η', and $\eta - \eta'$ mixing)

- 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 $A_{FB}^{t\bar{t}}$

- $m_\rho^{HC} \sim 200$ GeV $\Rightarrow$ $f_\pi^{HC} \sim 20 - 30$ GeV
- $\Lambda_{HC}^{\chi SB} \sim 4\pi f_\pi^{HC} \sim 200 - 300$ GeV
- $m_\pi^2 \sim 8\pi\, f_\pi^{HC}\, m_\omega$

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

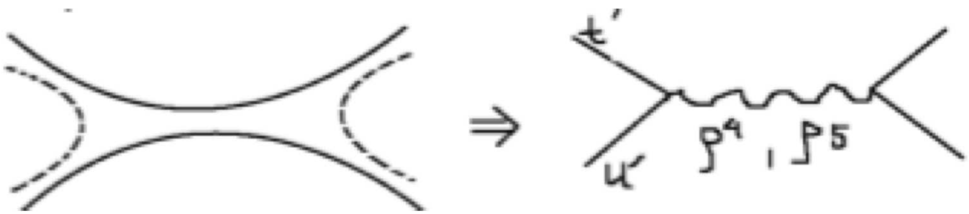
$$\text{VMD} \Rightarrow \frac{\Gamma(\rho_{HC} \to \pi_{HC}\, \pi_{HC})}{m_\rho^{HC}} = O(10\%)$$

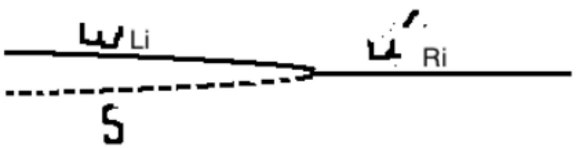
new composite quarks and partial compositeness

- 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 - partial compositeness





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

$\rho^a - u_i - u_j, a_1^a - u_i - u_j$ couplings via partial compositeness

up quark mass matrix of form:

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

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

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

- $\rho^a - u_i - u_j$ 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 $\sin\theta^t_L \sim 1/3 \times m_t/M_{t'}$

- pion couplings to composite quarks

$$\frac{\tilde{g}_A}{f_\pi} \left(\bar{u}'_R \, T^a \, \not{\partial}\pi^a \, u'_R - \bar{u}'_L \, T^a \, \not{\partial}\pi^a \, u'_L \right)$$

coupling to ordinary quarks via partial compositeness

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

- include s-channel exchanges of P-wave vector meson bound states of the scalars, $V^{\mu}\left[\mathcal{S}^* \mathcal{S}\right]$,
  - 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 suggests $f_V / M_V \sim 0.1$ (K.C. Yang)
  - “VMD" suggests coupling to composite quarks $g_V \sim m_V / f_V$
  - NDA yields similar estimates

- want $m_{V_o} \gtrsim 1$ TeV to avoid $t\bar{t}$ peak in Tevatron data due to V_o s-channel exchange
  $\Rightarrow m_{\mathcal{S}} \gtrsim 1/2$ TeV or $m_{\mathcal{S}} \sim (2-3) \times \Lambda$

- therefore composite quarks probably “lie between" D^* and B^* in terms of mass

  - the u', c', t' are “heavy-light mesons", with heavy scalar quark $\mathcal{S}$, light quarks ω_i

  - to leading order, identify u'_i decay width with partonic $\mathcal{S} \to \omega u_i$ width

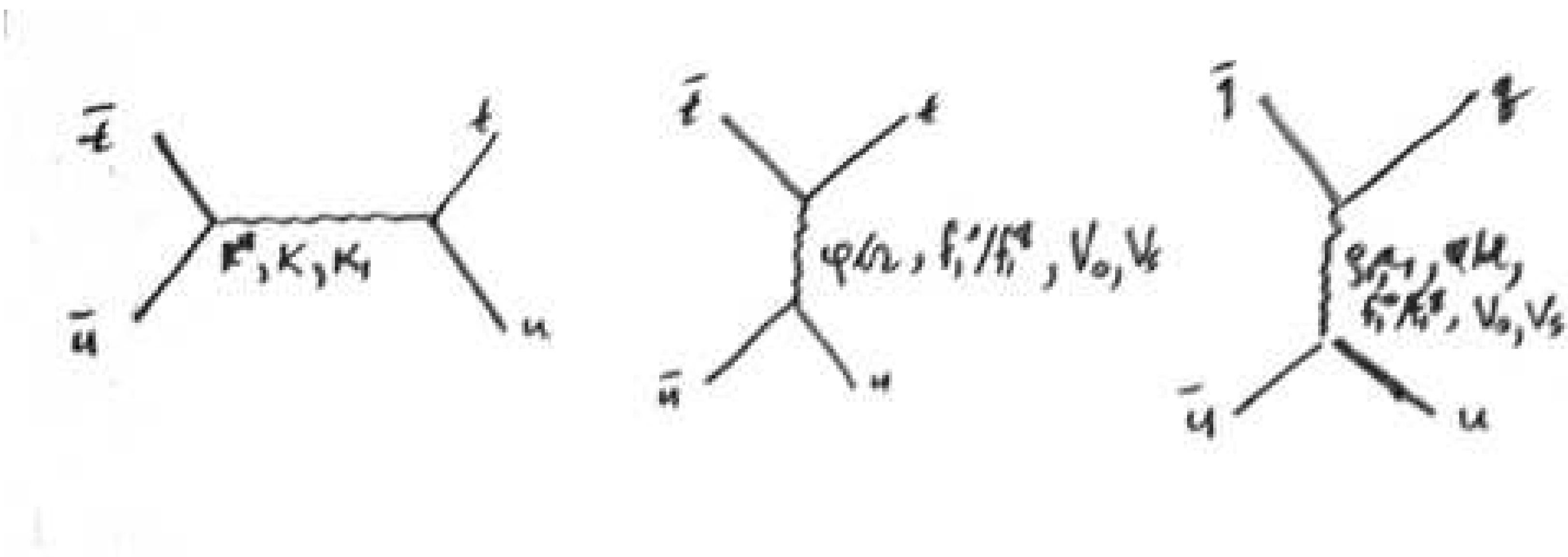
  - bound pion-composite quark coupling $\tilde{g}_A$ by requiring

$$\Gamma(u'_i \to \pi^a u_j) < \Gamma(\mathcal{S} \to \omega u_i)$$

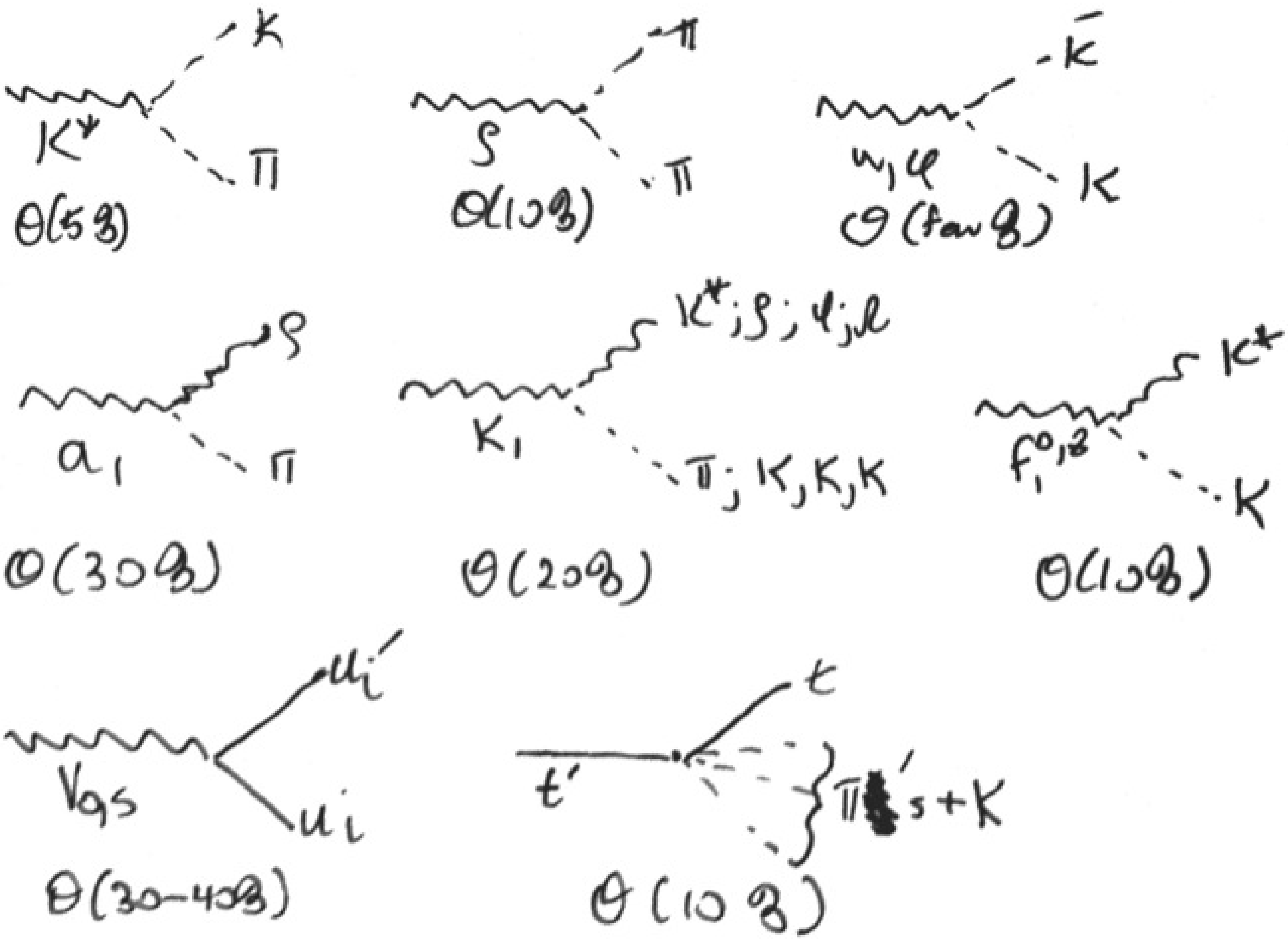
- $V_{o,s}$ are very broad , e.g. $\Gamma/M = O(30-50\%)$, due to $V_{o,s} \to \bar{u}'_i\, u_i$

new $t\bar{t}$ production modes

- t-channel $t\bar{t}$ production via K^*, K_1, K exchange
- s-channel $t\bar{t}$ production via
  - ϕ, ω: highly suppressed by ϕ/ω mixing
  - similarly for f_1^0/f_1^8 exchange
  - V_o, V_s exchange
- s-channel dijet production via ρ, a_1, ϕ/ω, f_1^0/f_1^8, $V_{o,s}$ exchange



Decay Widths



Numerics

- dependence of $\rho, K*, .., a_1, K_1, ...$ masses, ω/ϕ and f_1^0/f_1^8 mixing on “quark masses" m_{ω_1}, m_{ω_3} obtained by scaling massive parameters from naive QCD quark model treatment Cheng, Shrock

$$\text{scale factor} \quad \frac{M^{HC}}{M_\rho^{QCD}},$$

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

- pseudoscalar masses

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

  use $B \approx 2.7$ GeV (UKQCD)

- heavier masses (heavy quark - like relations)

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

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

- 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 $f_{t'}, \ldots$
  - 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 between light and heavy-light vector meson limits in QCD.
  - scale up via M^{HC}/M_ρ^{QCD}

A light K^* benchmark

- 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.
  renormalization scale $\mu = 2m_t$ for cross sections, asymmetries
- UV inputs :

$$M^{HC} = 176\,\text{GeV},\;\; m_{\omega_1} = 2.5\,\text{GeV},\;\; m_{\omega_3} = 2.5\,\text{GeV},\;\; m_{\mathcal{S}} = 520\;\;\text{GeV},\;\; h_1, h_3 = 2.9$$

- IR outputs:

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

$$M_{a_1} = 371\ \text{GeV},\;\; M_{K_1} = 404\;\;\text{GeV}, ...$$

$$M_{V_{o,s}} = 1300\ \text{GeV};\quad M_{u'} = M_{c'} = 695\ \text{GeV},\;\; M_{t'} = 724\;\;\text{GeV}, ...$$

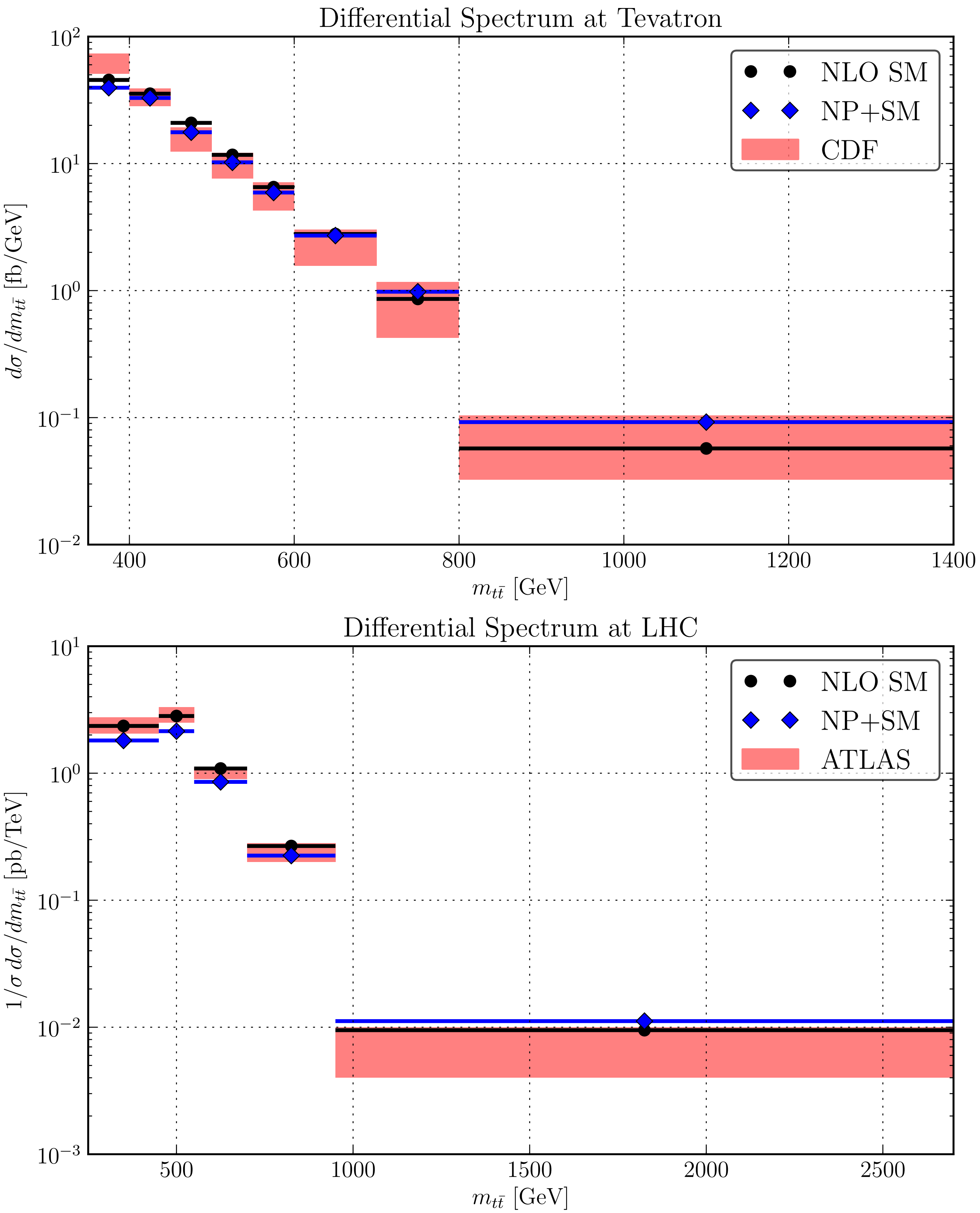
- for the 6 scan observables obtain $\chi^2 \approx 1.9$

differential spectra

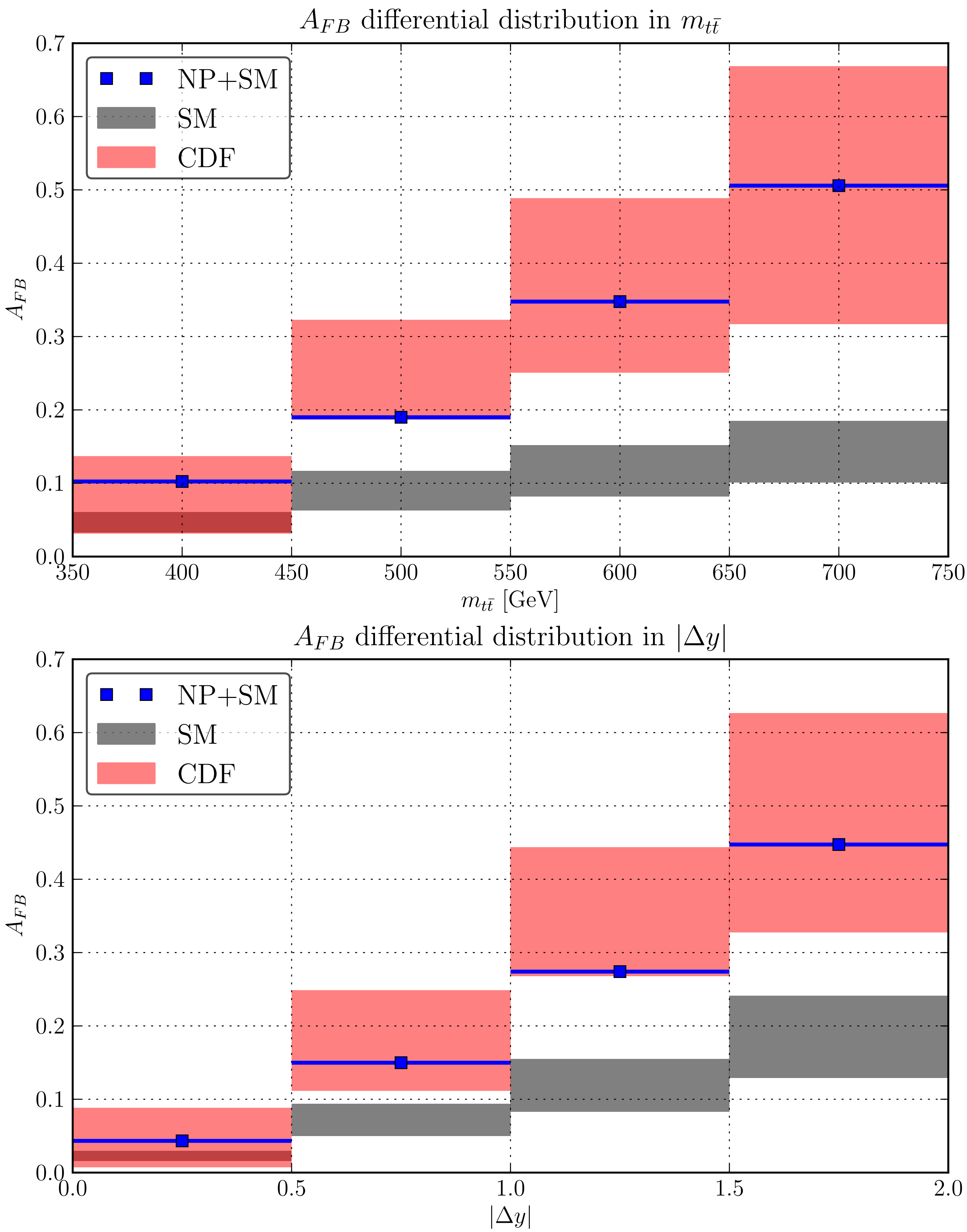
- obtained partonically in MG
- xsecs: $d\sigma/dm_{t\bar{t}}$ at Tevatron, LHC
- comparison of A_{FB} vs. $m_{t\bar{t}}$, and A_{FB} vs. $|\Delta y|$
- dijet spectra
  - comparison of $d\sigma/dm_{jj}$ with CDF; LHC spectra in progress
  - comparison of dijet angular distributions with $D0$; LHC spectra in progress
    - $1/\sigma_{\rm dijet} d\sigma/d\chi$ in intervals of m_{jj}

$$\chi = \frac{1 + |\cos\theta|}{1 - |\cos\theta|}$$

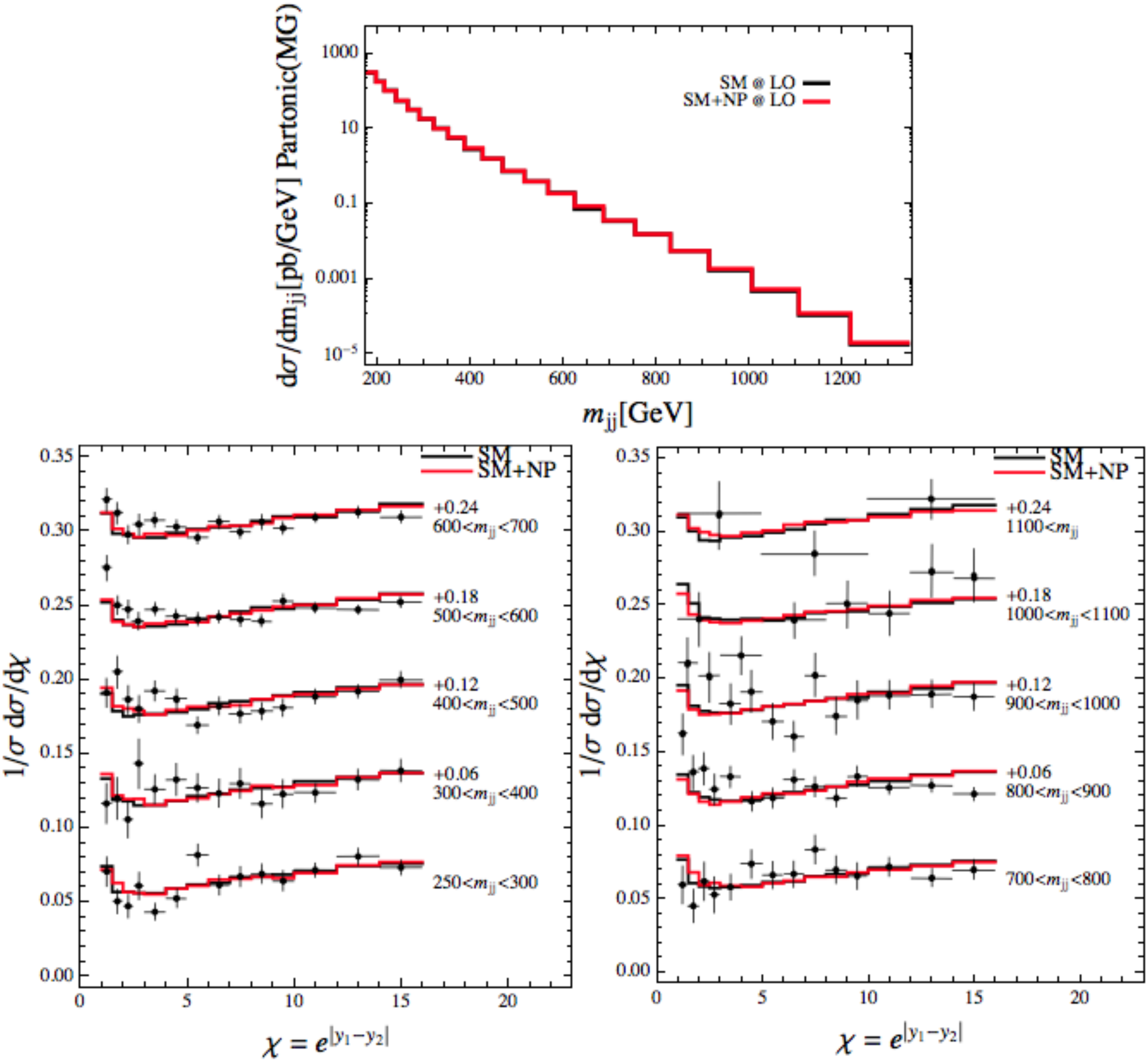
θ is scattering angle for $2 \to 2$ parton scattering process in parton CM frame



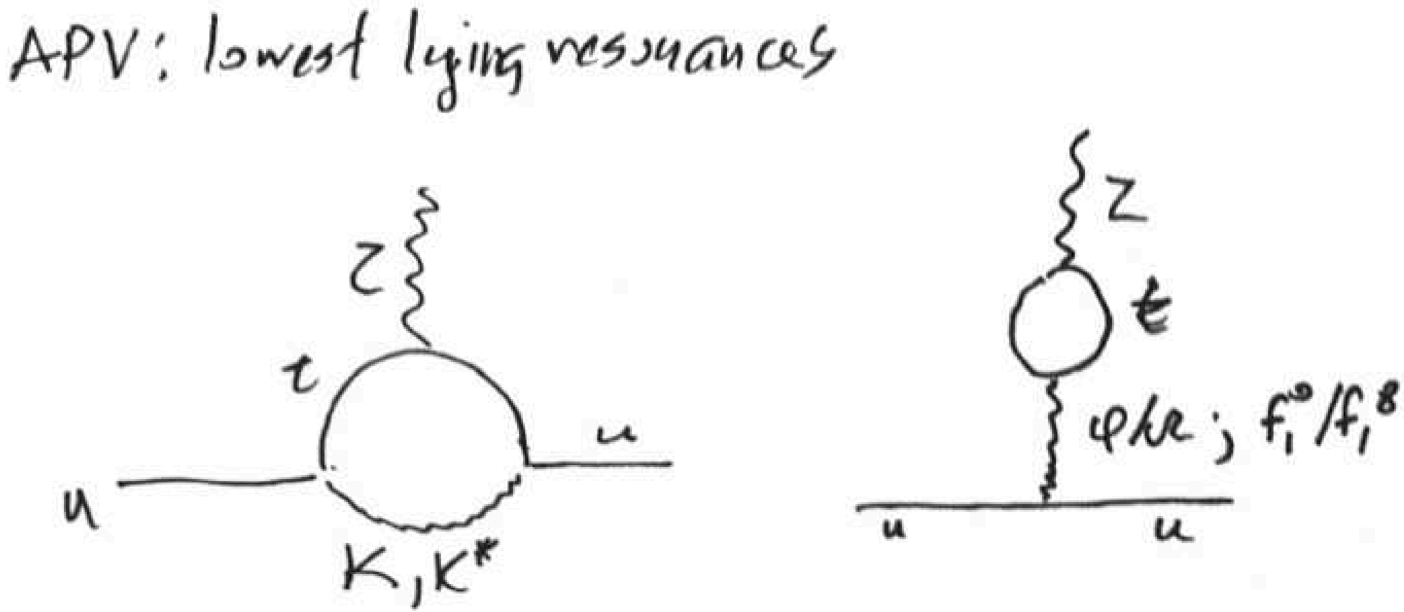
Differential Spectrum at Tevatron
NLO SM
NP+SM
CDF
$d\sigma/dm_{t\bar{t}}$ [fb/GeV]
$m_{t\bar{t}}$ [GeV]
Differential Spectrum at LHC
NLO SM
NP+SM
ATLAS
$1/\sigma\, d\sigma/dm_{t\bar{t}}$ [pb/TeV]
$m_{t\bar{t}}$ [GeV]



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


dσ/dm_jj [pb/GeV] Partonic(MG)
SM @ LO
SM+NP @ LO
m_jj [GeV]
SM
SM+NP
+0.24
600<m_jj<700
+0.18
500<m_jj<600
+0.12
400<m_jj<500
+0.06
300<m_jj<400
250<m_jj<300
1/σ dσ/dχ
χ = e^|y1−y2|
+0.24
1100<m_jj
+0.18
1000<m_jj<1100
+0.12
900<m_jj<1000
+0.06
800<m_jj<900
700<m_jj<800

Atomic parity violation bounds Gresham, Kim, Tulin, Zurek



contributions of lowest lying resonances, K, K^*, ϕ/Ω, f_1^0/f_1^8 to $a_R(u)$

$$-\frac{g_2}{c_W} Z^\mu a_R^u \bar{u}_R \gamma_\mu u_R$$

are at $O(10^{-3})$, a factor of a few below current bounds

On the composite u''s

- widths $\approx 10\%$
- detection at LHC is challenging $u'_i \to t + \pi^{a}\,'s$
- π^a are color singlets, decay via $\pi \to \bar{u}u,\ \bar{c}c,\ \bar{u}c$, or $K \to \bar{t}^{(*)}u,\ \bar{t}^{(*)}c$
- final states with two tops, e.g., $\bar{t}'t' \to \bar{t}\,t$ + n jets,
- 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 $\rho^a,\ a_1^a,\ \ V_{o,s}$ exchange

associated K^* production at LHC

- For this BM, $\sigma(pp \to K^* t) \approx 15$ [pb]; $\mathrm{Br}(K^* \to u\bar{t}) = \mathrm{Br}(K^* \to c\bar{t}) \approx 16\%$
  - modest reduction in A_C from 0.028 to 0.023 via $K^* \to \bar{u}t, \bar{c}t$
- ATLAS top + jet resonance search:

$$\sigma(pp \to K^* t) \times \mathrm{Br}(K^* \to u\bar{t} + c\bar{t}) \approx 20\% \times \text{ATLAS bound}$$

- signal in single top production? $pp \to K^* t \to (K\pi)t \to (\bar{t}^* \pi\pi)t$ with xsec ≈ 15 [pb]
  - cross section $\approx 25\%$ of SM t-channel single top xsec
  - problem: single top searches not optimized for $t + n$ jets final state
- for t' and K^* production signals need to refine inclusive multi jet searches

conclusion

- There exists a viable strong interaction realization of the low scale flavor symmetric t-channel idea
- in the UV it is a copy of QCD with 3 light HC quarks and an additional HC scalar
- in the IR leads to an even bigger zoo of resonances than low scale QCD, e.g., additional composite quarks,...
- nevertheless it is appears challenging at the LHC
  - the lowest lying resonances are color singlets
  - the colored resonances are broad, decay to exotic multi jet final states
- the lightest HC baryon, e.g., $[\omega_u \omega_u \omega_c]$, may provide an example of flavorful DM