An effective Lagrangian Approach to Like Sign Top Pair Production at the LHC

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Outline

- Motivation
- The Signal
- Operator Basis
- Distributions
- Connection to fb top asymmetry
- New Physics Models
- Conclusion

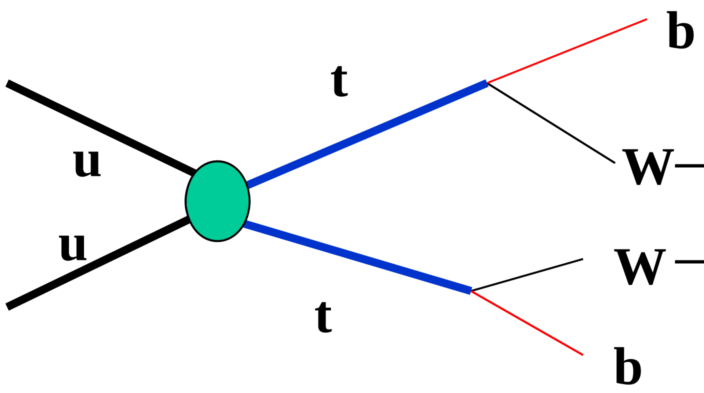
Motivation

- The LHC provides an opportunity to Find new physics at the TEV scale.
- Signals which have little or now SM background can provide the most striking evidence of new physics.
- Production of same sign top pairs is such a signal.
- This final state has the added benefit that the self analyzing nature of the top decays can fully characterize the nature of the new physics.
- Many of the NP models that give rise to same sign top pairs may also explain the Tevatron FB asymmetry.

The Signal

- To produce a like sign top pair, the initial parton state must be uu, so over all we are looking for Δtop=2 operators.
- The final state will only be evident if both tops decay semileptonically.
- When a top undergoes semileptonic decay, in the rest frame of the top it is 100% polarized in the direction of the lepton momentum.

Parton Level Event



$W \to \ell\nu$

$W \to \ell\nu$

Final State

$\ell^+\ell^+ + p_{Tmiss} + 2\,jets$

Kinematics

8 Unknowns

$p_{\nu 1} \to 4?$

$p_{\nu 2} \to 4?$

8 Constraints

$$p_{\nu 1x} + p_{\nu 2x} = \not{p}_x \qquad p_{\nu 1y} + p_{\nu 2y} = \not{p}_y$$

$$(p_{\nu 1})^2 = 0 \qquad (p_{\nu 2})^2 = 0$$

$$(p_{\nu 1} + p_{\ell 1})^2 = m_W^2 \qquad (p_{\nu 2} + p_{\ell 2})^2 = m_W^2$$

$$(p_{\nu 1} + p_{\ell 1} + j_1)^2 = m_t^2 \qquad (p_{\nu 2} + p_{\ell 2} + j_2)^2 = m_t^2$$

Solving the Kinematics

- Since we have 8 eqns in 8 unknowns, we can solve for the neutron momenta and so the complete kinematics however there are combinatorial backgrounds
- There is a 2-fold ambiguity for matching the jet with the lepton.
  - The wrong match generally does not produce a physical solution
- There is up to a 4-fold ambiguity in the algebra (quartic equation)
  - Picking the solution with the largest parton luminosity will statistically select the correct solution

Effective Lagrangian

- At Dimension 6 there are 8 effective lagrangian terms.
- Combining the identical tops into triplet and sextet color states produces a basis where there are few interference terms.
- This leads to a cleaner connection between the angular distributions of the final state and the operator coefficients.

Operator Basis

$$O_1 = g^i_{ab}(\overline{u}_a L u^c_b) g^i_{cd}(\overline{t}^c_c L t_d)$$
$$O_2 = g^i_{ab}(\overline{u}_a R u^c_b) g^i_{cd}(\overline{t}^c_c R t_d)$$
$$O_3 = g^i_{ab}(\overline{u}_a L u^c_b) g^i_{cd}(\overline{t}^c_c R t_d)$$
$$O_4 = g^i_{ab}(\overline{u}_a R u^c_b) g^i_{cd}(\overline{t}^c_c L t_d)$$
$$O_5 = h^j_{ab}(\overline{u}_a \gamma^\mu u^c_b) h^j_{cd}(\overline{t}^c_c \gamma_\mu t_d)$$
$$O_6 = g^i_{ab}(\overline{u}_a \gamma^\mu \gamma^5 u^c_b) g^i_{cd}(\overline{t}^c_c \gamma_\mu \gamma^5 t_d)$$
$$O_7 = h^j_{ab}(\overline{u}_a \sigma^{\mu\nu} L u^c_b) h^j_{cd}(\overline{t}^c_c \sigma_{\mu\nu} L t_d)$$
$$O_8 = h^j_{ab}(\overline{u}_a \sigma^{\mu\nu} R u^c_b) h^j_{cd}(\overline{t}^c_c \sigma_{\mu\nu} R t_d)$$

- **The operators are like s-channel triplet or sextet diquark channels.**
- **The only interference terms are 1×3 and 2×4 (in massless u-quark limit)**
- **Also $O_{1\text{-}4}$ are scalar, thus isotropic.**

$$L^{\dim=6}_{eff} = \sum_{i=1-8} C_i O_i$$

<u>Notation</u>

***abcd*= color 3 indices**

i=color sextet index

j=color $\overline{3}$ index

g: 3×3→6 cg coefs

h: 3×3 →$\overline{3}$ cg coefs

Distributions

- Total Cross section

$$\sigma = \frac{\beta s}{288\pi}\left[3(1+\beta^2)\sum_{i=1-4}|C_i|^2 - 6(1-\beta^2)\,\mathrm{Re}(C_1C_3^* + C_2C_4^*) + 8(3-\beta^2)\sum_{i=5,7,8}|C_i|^2 + 32\beta^2|C_6|^2\right]$$

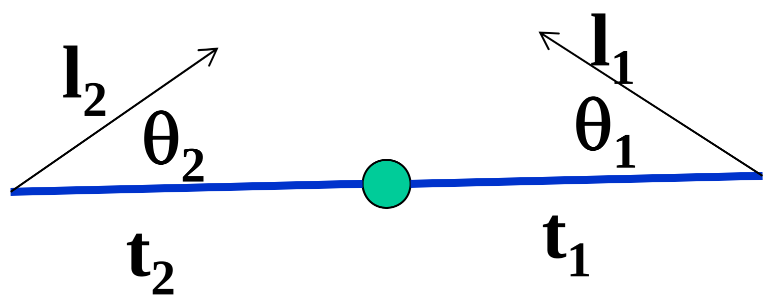
- Top Angular Distribution
  - Define θ_t to be the angle between a u-quark and a t-quark in parton rest frame
  - Define $z=\cos\theta_t$

$$\frac{d\sigma}{dz} \propto 3(1+\beta^2)\sum_{i=1-4}|C_i|^2 - 6(1-\beta^2)\,\mathrm{Re}(C_1C_3^* + C_2C_4^*)$$
$$+12(2-\beta^2+\beta^2 z^2)|C_5|^2 + 24(1+z^2)\beta^2|C_6|^2$$
$$+24(1-\beta^2+2\beta^2 z^2)(|C_7|^2+|C_8|^2)$$

- Conclusion: $O_{1\text{-}4}$ are isotropic
- z^2 term is a linear combination of $O_{5\text{-}8}$
  - This term must be positive

Lepton Distributions

- Define θ_1 as the angle between lepton 1 and top 2 in the top 1 rest frame
- Define θ_2 Likewise.



- Let $c_i = \cos\theta_i$.
- In general the distribution in these variables will have the form

$$\frac{d\sigma}{dc_1 dc_2} = A + B(c_1 + c_2) + C c_1 c_2$$

Lepton Distributions cont.

$$\frac{d\sigma}{dc_1 dc_2} = A + B(c_1 + c_2) + C c_1 c_2$$

$$A \propto 3(1+\beta^2)\sum_{i=1-4} |C_i|^2 - 6(1-\beta^2)\,\mathrm{Re}(C_1 C_3^* + C_2 C_4^*) + 8(3-\beta^2)\sum_{i=5,7,8} |C_i|^2 + 32\beta^2 |C_6|^2$$

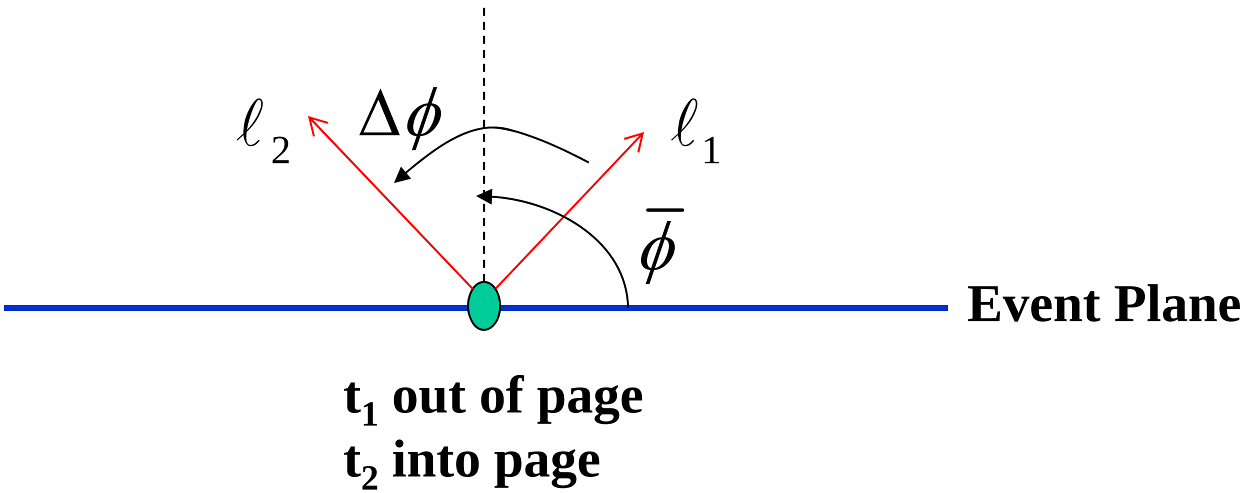
$$B \propto 6(|C_1|^2 + |C_4|^2 - |C_2|^2 - |C_3|^2) + 16(|C_7|^2 - |C_8|^2)$$

$$C \propto 3(1+\beta^2)\sum_{i=1-4} |C_i|^2 - 6(1-\beta^2)\,\mathrm{Re}(C_1 C_3^* + C_2 C_4^*) + 8(3-\beta^2)\sum_{i=5,7,8} |C_i|^2 + 32\beta^2 |C_6|^2$$

Note that B is proportional to the helicity of the top pairs produced by the scalar and tensor operators but gets no contribution from the vector operators.

Azimuthal Angular Distribution

Let us define $\Delta\phi$ to be the difference between the azimuthal angle of the Leptons and $\bar{\phi}$ to be the average angle.



In General, this angular distribution has the form

$$\frac{d\sigma}{d(\Delta\phi)d\bar{\phi}} \propto \sigma + s^2\beta^2\pi^2\left(U\cos\Delta\phi + V\cos 2\bar{\phi} + W\sin\Delta\phi\right)$$

Azimuthal Angular Distribution cont.

$$\frac{d\sigma}{d(\Delta\phi)d\overline{\phi}} \propto \sigma + s^2\beta^2\pi^2\left(U\cos\Delta\phi + V\cos 2\overline{\phi} + \beta W\sin\Delta\phi\right)$$

$$U = (1-\beta^2)(-\tfrac{3}{16}|C_1|^2 - \tfrac{3}{16}|C_2|^2 - \tfrac{3}{16}|C_3|^2 - \tfrac{3}{16}|C_4|^2 + \tfrac{1}{2}|C_5|^2 + \tfrac{1}{2}|C_7|^2 + \tfrac{1}{2}|C_8|^2) - \tfrac{3}{8}(1+\beta^2)\,\mathrm{Re}(C_1C_3^* + C_2C_4^*)$$

$$V = -\tfrac{1}{2}|C_5|^2 + |C_6|^2 + (1-\beta^2)(|C_7|^2 + |C_8|^2)$$

$$W = \tfrac{3}{4}\,\mathrm{Im}(C_1C_3^* - C_2C_4^*)$$

CP odd

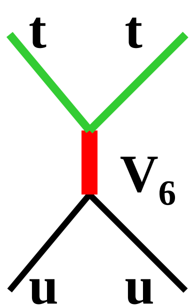
What do we learn from Angular Distributions

- The $\cos(\theta_t)$ distribution is flat for $O_{1\text{-}4}$ and concave for the others.
- The $c_1\ c_2$ distribution tells us about the helicity of the final state in particular for $O_{1\text{-}4}$ and $O_{7,8}$. In β=1 limit:
  - LL $\rightarrow$ A:B:C ~ +1:-1:+1 $O_1\ O_4\ O_7$
  - RR $\rightarrow$ A:B:C ~ +1:+1:+1 $O_2\ O_3\ O_8$
  - RL+RL$\rightarrow$ A:B:C ~ +1:0:-1 $O_5\ O_6$
- The azimuthal angle distribution gives information about the phase between the LL and RR scalar operators.
- The sin $\Delta\phi$ term is P-odd T_N-odd and may be CP odd.
- We can't full solve for $C_{1\text{-}4}$ because we don't have information about the helicity of the initial state.

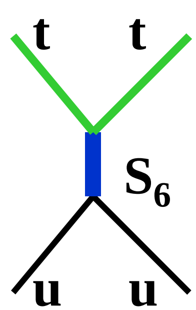
NP Models

Various NP models can contribute to different combinations of the operators:

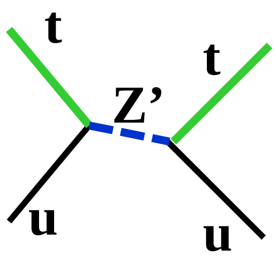
- Color sextet vector bosons [Zhang et. al PLB (2011)]
  - Only O_6



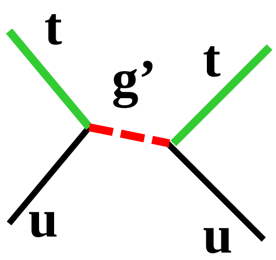
- Sextet Scalars: $O_{1\text{-}4}$
  - This is the only model that could give the P-odd distribution



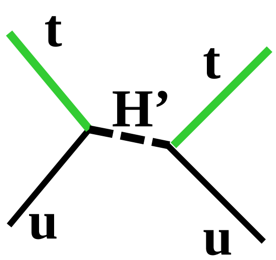
- Flavor changing Z':
  - Only O_3 O_4 and O_5 - O_6



- Flavor changing g*, for example from RS extra-dimension models:
  - Only O_3 or O_4



- Flavor changing neutral scalar:
  - Only O_1 - O_7/4 or O_2 - O_8/4 or O_5 +O_6



FB top asymmetry

- SM 7-9% Tevatron results ~20% (see previous talks)
- Some of the NP models which could produce same sign top pairs at the LHC could also contribute to the observed FB top asymmetry at the Tevatron.
- The effective Lagrangian approach we can provide a somewhat model independent mapping between these two signals.
- First, we need to write an effective Lagrangian for $u\bar{u} \to t\bar{t}$

Effective Lagrangian for $u\bar{u} \to t\bar{t}$

$$P_1 = \delta_{ab}(\bar{u}_a L t_b)\ \delta_{cd}(\bar{t}_c L u_d) \qquad P_2 = T^i_{ab}(\bar{u}_a L t_b)\ \mathrm{T}^i_{cd}(\bar{t}_c L u_d)$$

$$P_3 = \delta_{ab}(\bar{u}_a L t_b)\ \delta_{cd}(\bar{t}_c R u_d) \qquad P_4 = T^i_{ab}(\bar{u}_a L t_b)\ \mathrm{T}^i_{cd}(\bar{t}_c R u_d)$$

$$P_5 = \delta_{ab}(\bar{u}_a R t_b)\ \delta_{cd}(\bar{t}_c L u_d) \qquad P_6 = T^i_{ab}(\bar{u}_a R t_b)\ \mathrm{T}^i_{cd}(\bar{t}_c L u_d)$$

$$P_7 = \delta_{ab}(\bar{u}_a \gamma^\mu L t_b)\ \delta_{cd}(\bar{t}_c \gamma_\mu L u_d) \qquad P_8 = T^i_{ab}(\bar{u}_a \gamma^\mu L t_b)\ \mathrm{T}^i_{cd}(\bar{t}_c \gamma_\mu L u_d)$$

$$P_9 = \delta_{ab}(\bar{u}_a \gamma^\mu R t_b)\ \delta_{cd}(\bar{t}_c \gamma_\mu R u_d) \qquad P_{10} = T^i_{ab}(\bar{u}_a \gamma^\mu R t_b)\ \mathrm{T}^i_{cd}(\bar{t}_c \gamma_\mu R u_d)$$

$$P_{11} = \delta_{ab}(\bar{u}_a \gamma^\mu L t_b)\ \delta_{cd}(\bar{t}_c \gamma_\mu R u_d) \qquad P_{12} = T^i_{ab}(\bar{u}_a \gamma^\mu L t_b)\ \mathrm{T}^i_{cd}(\bar{t}_c \gamma_\mu R u_d)$$

$$P_{13} = \delta_{ab}(\bar{u}_a \sigma^{\mu\nu} L t_b)\ \delta_{cd}(\bar{t}_c \sigma_{\mu\nu} L u_d) \qquad P_{14} = T^i_{ab}(\bar{u}_a \sigma^{\mu\nu} L t_b)\ \mathrm{T}^i_{cd}(\bar{t}_c \sigma_{\mu\nu} L u_d)$$

$$L^{\mathrm{dim}=6}_{eff} = \sum_{i=1-14} D_i P_i + \mathrm{h.c.} \qquad \text{where } D_{3-10} \text{ are real}$$

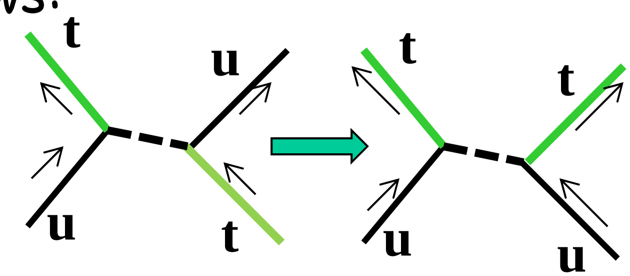
Relation between Lagrangians

- A priori there is no relation between these two effective lagrangians.
- However, we can consider a class of theories where the flavor matrix has symmetry.
- This idea can be implemented as follows:

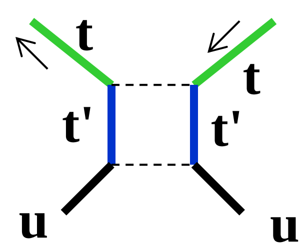
$$D(\bar{u}\Gamma t)(\bar{t}\Gamma u) \rightarrow C(\bar{u}\Gamma t)(\bar{u}\Gamma t)$$

where

$$|D| \approx |C|$$



- This will be a good approximation in theories involving t-channel exchange (for example Jung et. al. PRD (2010))
- This will also apply in theories where box diagrams such as the scalar exchange model in Davoudiasl et. al. (2011)



Relation between effective Lagrangians

$$P_1 \to -\tfrac{1}{2} O_1 + \tfrac{1}{8} O_7 \qquad P_1^\dagger \to -\tfrac{1}{2} O_2 + \tfrac{1}{8} O_8$$

$$P_2 \to -\tfrac{1}{6} O_1 - \tfrac{1}{12} O_7 \qquad P_2^\dagger \to -\tfrac{1}{6} O_2 - \tfrac{1}{12} O_8$$

$$P_3 \to \tfrac{1}{2} O_5 + \tfrac{1}{2} O_6 \qquad P_4 \to -\tfrac{1}{3} O_5 + \tfrac{1}{6} O_6$$

$$P_5 \to \tfrac{1}{2} O_5 + \tfrac{1}{2} O_6 \qquad P_5 \to -\tfrac{1}{3} O_5 + \tfrac{1}{6} O_6$$

$$P_7 \to 2 O_4 \qquad P_8 \to \tfrac{3}{2} O_4$$

$$P_9 \to 2 O_3 \qquad P_{10} \to \tfrac{3}{2} O_3$$

$$P_{11} \to O_5 - O_6 \qquad P_{12} \to -\tfrac{2}{3} O_5 - \tfrac{1}{3} O_6$$

$$P_{13} \to 6 O_1 + \tfrac{1}{2} O_7 \qquad P_{14} \to 2 O_1 - \tfrac{1}{3} O_7$$

$$P_{13}^\dagger \to 6 O_2 + \tfrac{1}{2} O_8 \qquad P_{14}^\dagger \to 2 O_2 - \tfrac{1}{3} O_8$$

Other NP Which Doesn't Work

- For other NP models this symmetry will not apply, for example
- If flavor is conserved NP can contribute to FB asymmetry but not same sign top pairs
  - e.g. flavor diagonal Z'
- The symmetry may not apply to diquark models such as the sextet vector. This gives same sign top pairs but may not contribute to FB asymmetry.

Conclusion

- Same sign top pairs (with leptonic decays) at the LHC would be an unmistakable signal for NP
- An effective Lagrangian model for this signal has 8 terms
- The angular distribution of the leptons will constrain the operator coefficients. In particular
  - $\cos\theta_t$ checks if operators are scalar.
  - c_1-c_2 distribution gives the helicity structure of the final state.
  - Azimuthal distribution checks for CP violation and gives more info.
- In a wide class of models, there will be a symmetry with terms operators that can contribute to FB asymmetry at the Tevatron.