New Physics from the Top at the Large Hadron Collider

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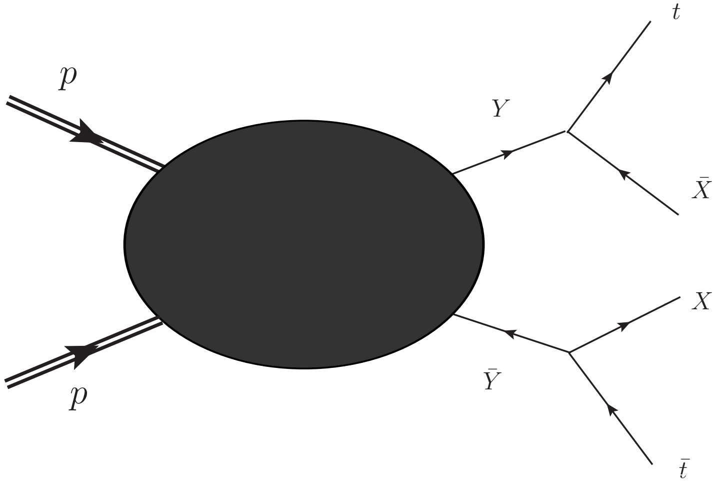
Motivations

- LHC has excluded a large part of the squark and gluino parameter space. This suggests new physics may be hiding from our probes.
- One of the possibilities is the light stop scenario:
  - Squarks of the third generation are lighter than 1st and 2nd generation squarks.
- Extend this idea to a model-independent and systematic approach by considering a color triplet of a light new particle with spin configurations (0, 1/2, 1).

Setup

$$pp \to Y\bar{Y} \to tX\bar{t}X \to bj_1j_2\bar{b}\ell^-\bar{\nu}XX + \text{h.c.}$$

where $\ell = e, \mu$ and $j_{1,2}$ are light-quark jets.



Focusing on semileptonic mode:

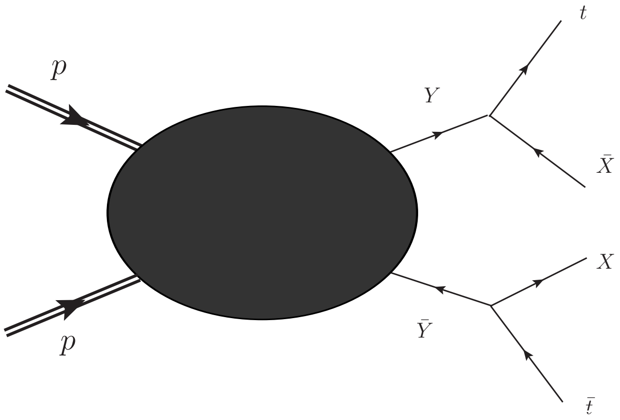
- pros: signal is clean and SM background is small
- cons: rate is not large

- Y: top partner, color triplet.
- X: Missing energy signal; electrically neutral, color singlet massive particle; possible dark matter candidate.
- Assume a discrete symmetry to ensure X is pair produced:

e.g.

- R-parity in supersymmetry
- KK parity in universal extra dimensions

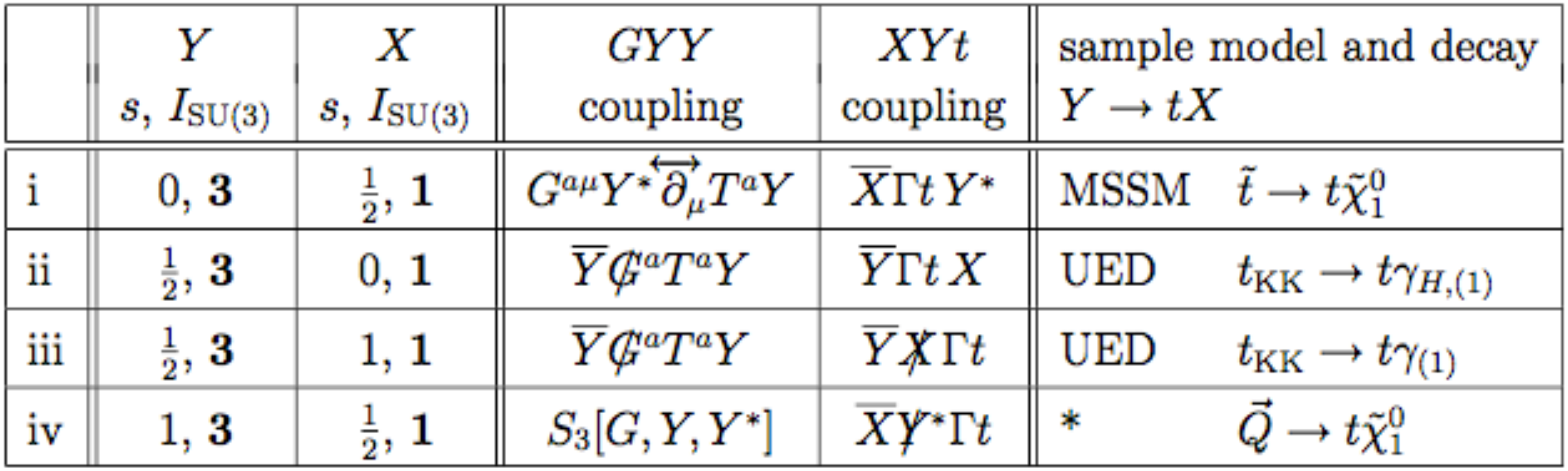
Spins of the X and Y



- Angular momentum conservation

Y	0	1/2	1
X	1/2	0 or 1	1/2
t	1/2	1/2	1/2

Combinations



	Y $s,\ I_{\mathrm{SU(3)}}$	X $s,\ I_{\mathrm{SU(3)}}$	GYY coupling	XYt coupling	sample model and decay $Y \to tX$
i	$0,\ \mathbf{3}$	$\frac{1}{2},\ \mathbf{1}$	$G^{a\mu} Y^* \overleftrightarrow{\partial}_\mu T^a Y$	$\overline{X} \Gamma t\, Y^*$	MSSM $\tilde{t} \to t\tilde{\chi}_1^0$
ii	$\frac{1}{2},\ \mathbf{3}$	$0,\ \mathbf{1}$	$\overline{Y} \not{G}^a T^a Y$	$\overline{Y} \Gamma t\, X$	UED $t_{\mathrm{KK}} \to t\gamma_{H,(1)}$
iii	$\frac{1}{2},\ \mathbf{3}$	$1,\ \mathbf{1}$	$\overline{Y} \not{G}^a T^a Y$	$\overline{Y} \not{X} \Gamma t$	UED $t_{\mathrm{KK}} \to t\gamma_{(1)}$
iv	$1,\ \mathbf{3}$	$\frac{1}{2},\ \mathbf{1}$	$S_3[G, Y, Y^*]$	$\overline{X} \not{Y}^* \Gamma t$	* $\vec{Q} \to t\tilde{\chi}_1^0$

$$\Gamma \equiv a_L P_L + a_R P_R$$

$$A \overleftrightarrow{\partial}_\mu B \equiv A(\partial_\mu B) - (\partial_\mu A)B,$$

$$S_3[G, Y, Y^*] \equiv T^a \left[G^a_\mu Y^*_\nu \overleftrightarrow{\partial}^\mu Y^\nu + G^a_\mu Y^{\mu *} \overleftarrow{\partial}^\nu Y_\nu - G^a_\mu Y^*_\rho \overrightarrow{\partial}^\rho Y^\mu \right]$$

* PRL 101, 171805 by H. Cai, H-C. Cheng, and J. Terning

- GYY coupling: fixed by QCD.
- XYt coupling: general chiral structure allowed.

Vector top partner

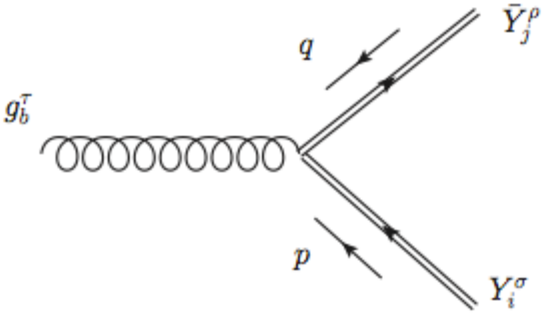
To construct a vector boson in SU(3) fundamental representation

For vector fields: $\partial_\mu V^\mu = 0$

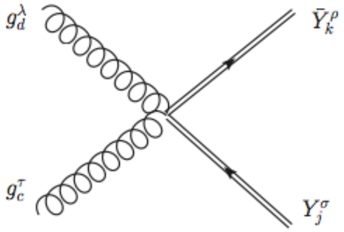
$$\mathcal{L}_{\text{kin}} = -\frac{1}{2}(F_{\mu\nu})^\dagger F^{\mu\nu}$$

$$F_{\mu\nu} = D_\mu Y_\nu - D_\nu Y_\mu$$

where $D_\mu = \partial_\mu - igT_a G^a_\mu$

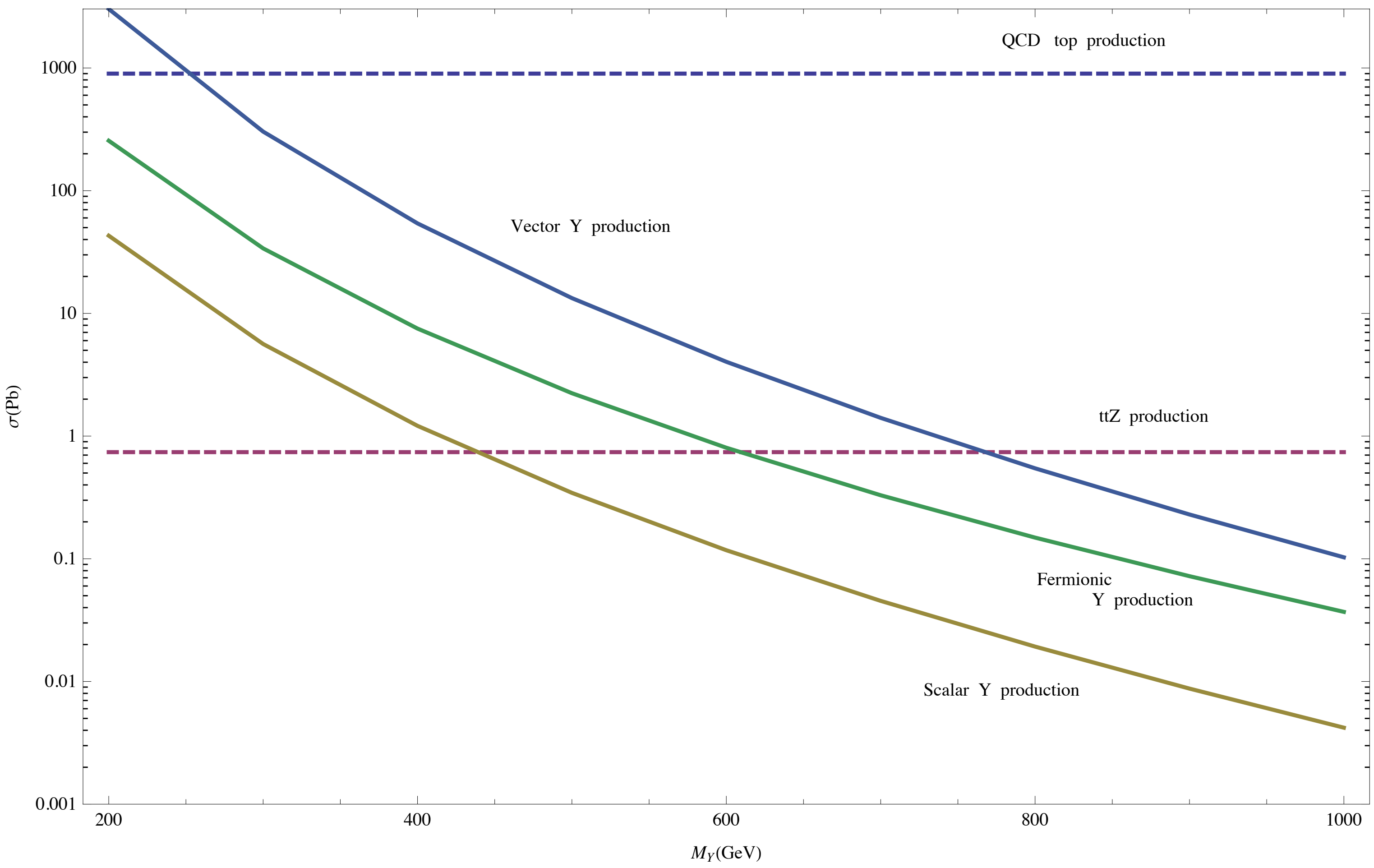


$$= ig(T_b)_{ji}\left((q-p)^\tau g^{\sigma\rho} + p^\rho g^{\sigma\tau} - q^\sigma g^{\rho\tau}\right)$$



$$= -ig^2\left((T_cT_d + T_dT_c)_{kj} g^{\tau\lambda} g^{\rho\sigma} - (T_cT_d)_{kj} g^{\tau\sigma} g^{\lambda\rho} - (T_dT_c)_{kj} g^{\tau\rho} g^{\lambda\sigma}\right)$$

Production



- QCD production cross section for top partners at $\sqrt{s}$ = 14 TeV.
  - Spin state counting: $\sigma(\mathrm{scalar}) < \sigma(\mathrm{fermion}) < \sigma(\mathrm{vector})$

Current Bounds

- ATLAS* : Based on 1/fb data: exclude a fermionic Y with mass below 420 GeV (for $m_x << m_Y$). This can be translated into a bound $m_Y \gtrsim 500\ \mathrm{GeV}$ for vector Y particles. ***Phys.Rev.Lett. 108 (2012) 041805 by G. Aad et al.**
    - For any Y spin, there is no limit for very small mass difference,

$$m_Y - m_x \lesssim m_t + 10\ \mathrm{GeV}$$

- Signals: $pp \to Y\bar{Y} \to tX\bar{t}X \to bj_1j_2\bar{b}\ell^-\bar{\nu}XX + \text{h.c.}$
  - Use CalcHEP to simulate the signals at the parton level and then pass them into PYTHIA for detector effects.

- Standard Model background:
  - t tbar production (large cross section): semileptonic mode

    $$pp \to t\bar{t} \to bj_1j_2\bar{b}\ell^-\bar{\nu} + \text{h.c.}$$

    where $\ell = e, \mu$ and $j_{1,2}$ are light-quark jets.

  - t tbar Z: the cross section is smaller than t tbar production, but its kinematics are more similar to the signals

    $$pp \to t\bar{t}Z \to bj_1j_2\bar{b}\ell^-\bar{\nu}\nu\bar{\nu} + \text{h.c.} \quad \text{with } Z \to \nu\bar{\nu}.$$

  - W b b j j: $pp \to Wb\bar{b}\ j_1j_2 \to \ell^-\bar{\nu}\ b\bar{b}\ j_1j_2\ X + c.c.$

    Can be cut out by applying :

    $$70\ \text{GeV} < m_{jj} < 90\ \text{GeV},$$
    $$120\ \text{GeV} < m_t^r|_{\text{had}} = m(b_1jj) < 180\ \text{GeV}$$

  - Using PYTHIA to simulate the SM background with initial and final state radiations.

    jet smearing: $\frac{\Delta E_j}{E_j} = \frac{50\%}{\sqrt{E_j(\text{GeV})}}$ b-tagging efficiency $\epsilon_b = 60\%$

Signal observability

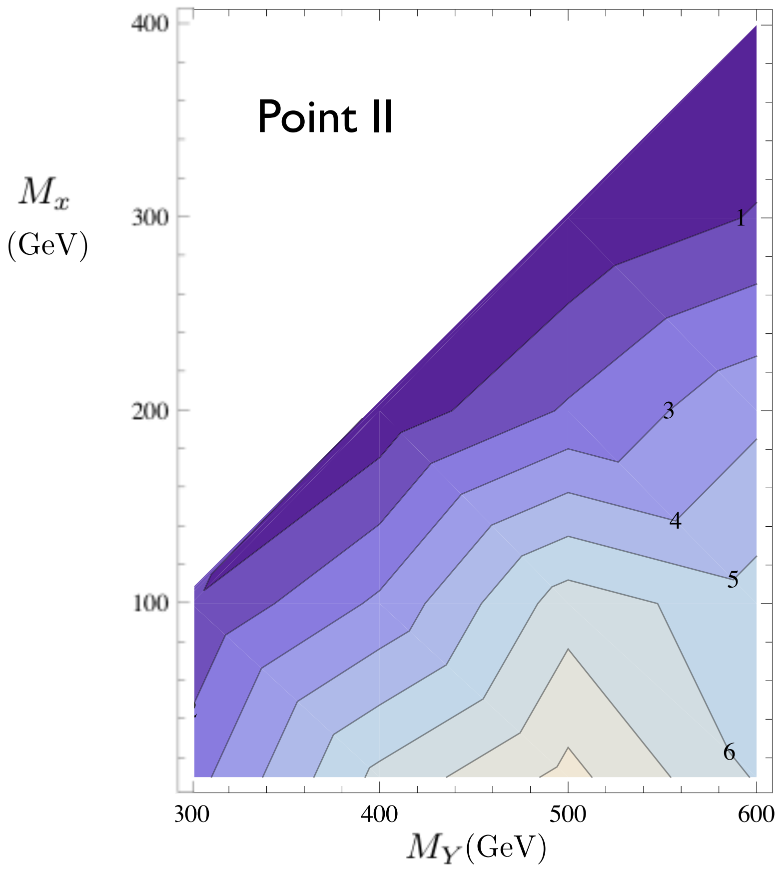
- Using comb 1 (Scalar Y) as an example at 14 TeV with integrated luminosity 100 /fb

$$\text{Statistical significance} = \frac{S}{\sqrt{B}}$$

- Choose two points to optimize
- Point 1: $(M_Y, M_x) = (300, 10)$ GeV
  - Large cross section but small missing energy
  - no additional cuts are applied
  - independent of M_x
- Pioint II: $(M_Y, M_x) = (600, 10)$ GeV
  - Small cross section but large missing energy
  - (MET, MT) > (350, 90) GeV is applied

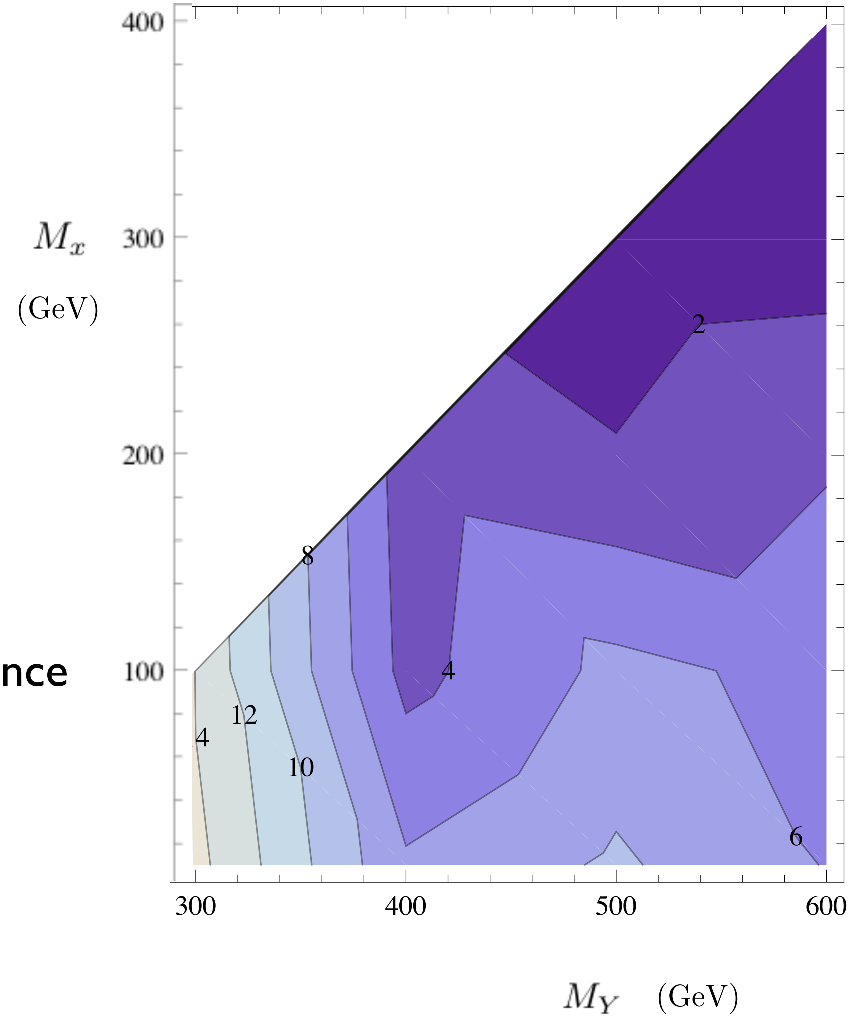
$$M_T^2(W) = (E_{\ell T} + E_{\nu T})^2 - (\vec{p}_{\ell T} + \vec{p}_{\nu T})^2$$

Contours of the statistical significance



Signal observability

- Combine point I & II:
    - Small mass splitting $m_Y - m_X \approx m_t$
    - M_Y < 400 GeV
    - Possible to achieve 5 statistical significance
    - Larger mass splitting
    - M_x < 100 GeV
    - Possible to achieve 5 statistical significance



Spin determination

- $\tanh(\frac{\Delta y_{t\bar{t}}}{2}) = \tanh(\frac{|y_t - y_{\bar{t}}|}{2}) = \cos\theta^*$
  - θ^* is the production angle.
  - y : The rapidity of the top $y = \frac{1}{2}\log\left[\frac{E+p_z}{E-p_z}\right]$
- P_T^{bl} : Transverse momentum of the leptonically decaying top quark

$pp \to t\bar{t} \to bj_1j_2\bar{b}\ell^-\bar{\nu} + \text{h.c.}$

where $\ell = e, \mu$ and $j_{1,2}$ are light-quark jets.

- They are all Lorentz invariant along the boost direction.

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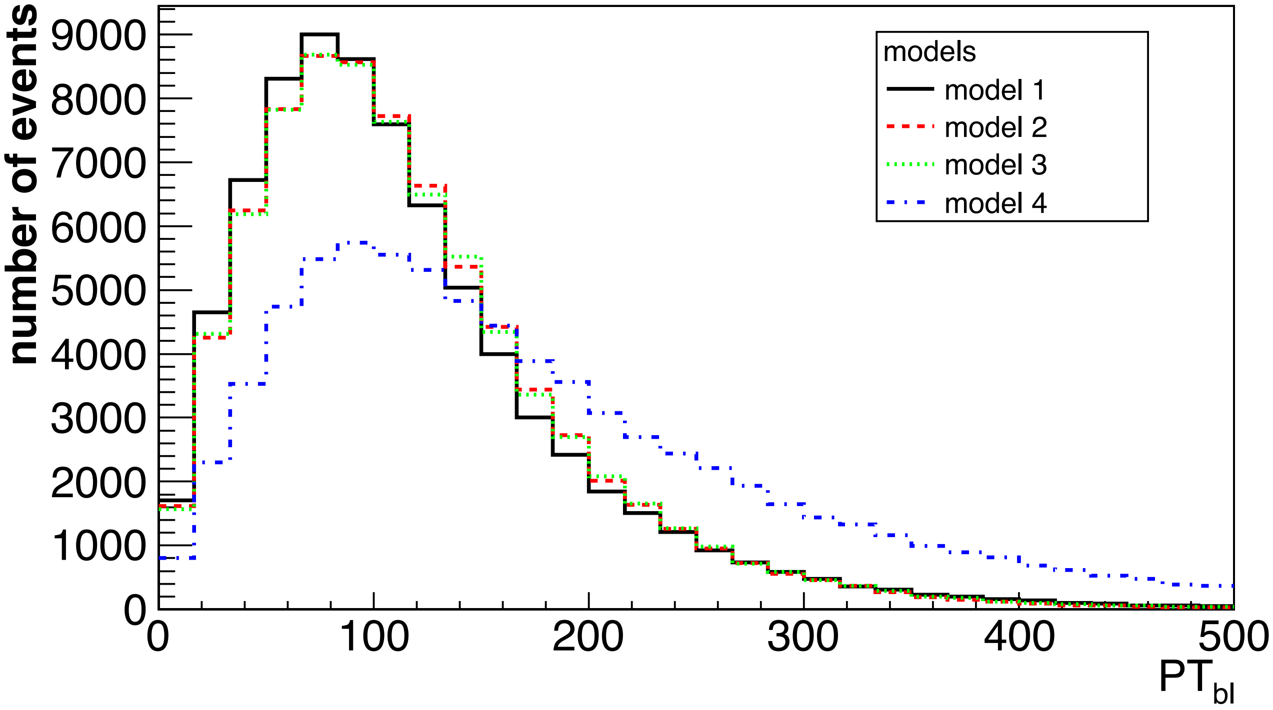
- They are all Lorentz invariant along the boost direction.

Numerical results

$m_Y = 300 \text{ GeV and } m_X = 100 \text{ GeV.}$

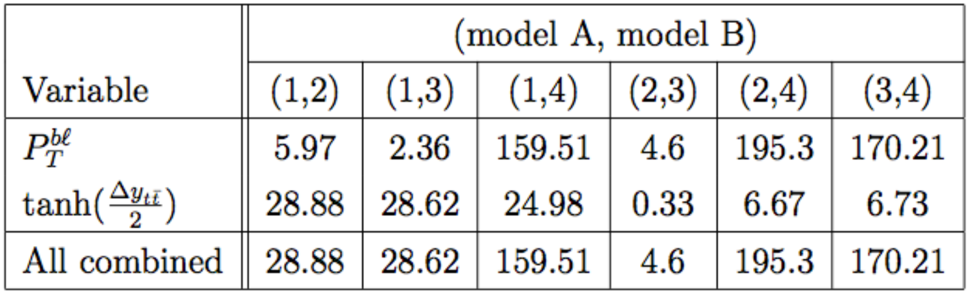
- Coupling aL=1 and aR=0
- # of events of all models are normalized to that of model 1 at 14 TeV with integrated luminosity 100 /fb
- Detector effects are considered by passing parton-level events into PYTHIA.

χ^2 analysis



A good variable for discriminating model 4 from models 1,2 and 3.

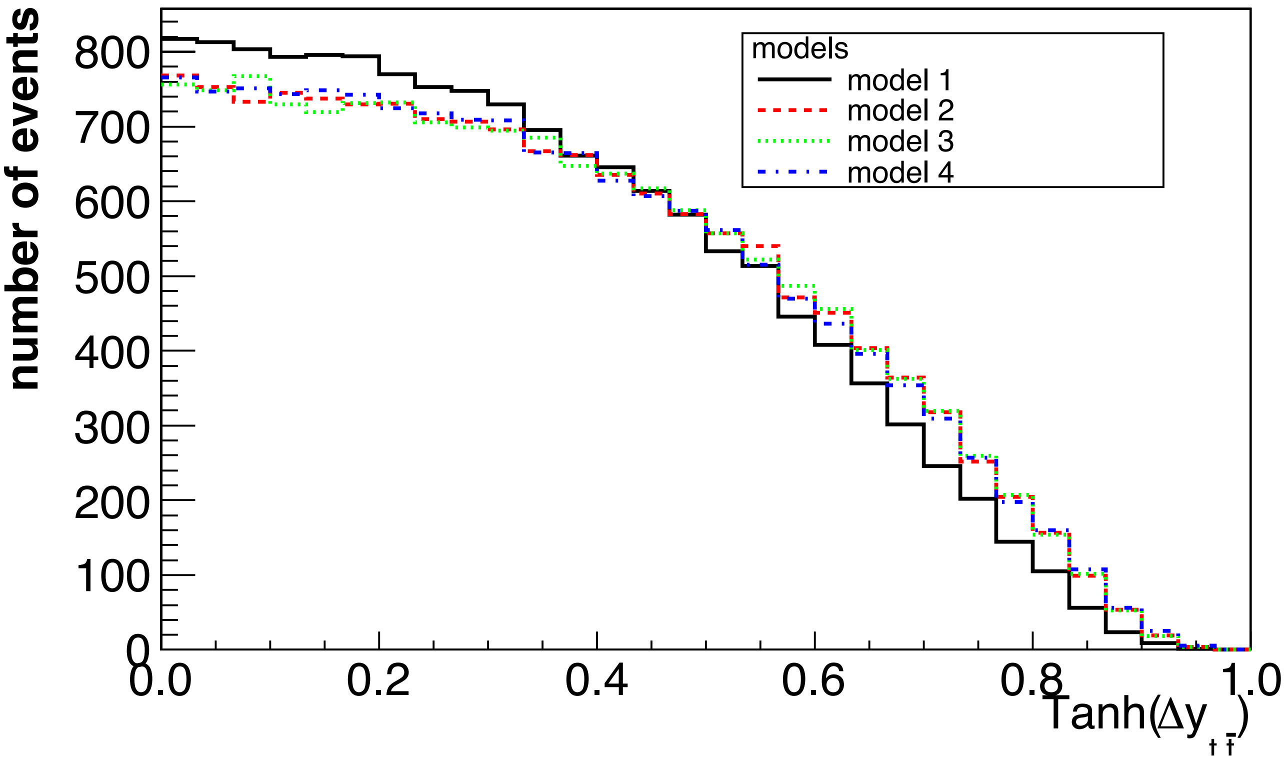
3-bin results



	(model A, model B)					
Variable	(1,2)	(1,3)	(1,4)	(2,3)	(2,4)	(3,4)
$P_T^{b\ell}$	5.97	2.36	159.51	4.6	195.3	170.21
$\tanh(\frac{\Delta y_{t\bar{t}}}{2})$	28.88	28.62	24.98	0.33	6.67	6.73
All combined	28.88	28.62	159.51	4.6	195.3	170.21

in units of standard deviations

χ^2 analysis



A good variable for discriminating model 1 from models 2 and 3.

$$\text{scalar } Y \text{ (spin 0)}: \qquad \frac{d\sigma}{d\cos\theta^*} \propto 1 - \cos^2\theta^*,$$

$$\text{fermion } Y \text{ (spin } \tfrac{1}{2}\text{)}: \qquad \frac{d\sigma}{d\cos\theta^*} \propto 2 + \beta_Y^2(\cos^2\theta^* - 1)$$

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Conclusion

- A model-independent and systematic analysis of the top partners with spin 0, 1/2 and 1 is performed. In particular, the systematic analysis of the spin 1 top partner is of the first time.
- At 14 TeV if the scalar top partner is lighter than 400 GeV for small mass splitting or Mx < 100 GeV and My < 600 GeV for large mass splitting it is possible to observe the scalar top partner.
- Two variables are considered for spin determination. Discrimination between combinations 2 and 3 is still difficult and one cannot achieve a 5 sigma standard deviation.

Thank you!

Backup slides

Current Bounds

- CDF[†] : 4.8 /fb data, exclude fermionic Y particles below 360 GeV assuming a large hierarchy $m_x << m_Y$. This can be translated into a limit $m_Y > 260$ for scalar Y. [†]Phys.Rev.Lett. 106 (2011) 191801 by T. Aaltonen et al.
  - $m_Y \gtrsim 240$ GeV if $m_Y - m_X \approx m_t$

- ATLAS* : Based on 1/fb data: exclude a fermionic Y with mass below 420 GeV (for $m_x << m_Y$). This can be translated into a bound $m_Y \gtrsim 500$ GeV for vector Y particles. ***Phys.Rev.Lett. 108 (2012) 041805 by G. Aad et al.**
  - For any Y spin, there is no limit for very small mass difference, $m_Y - m_x \lesssim m_t + 10$ GeV

Simulations

- To simulate the detector acceptance:

JHEP 117, 0905 by T. Han et. al.

$$
\begin{array}{lll}
p_T^\ell > 20 \text{ GeV}, & |\eta_\ell| < 2.5, & \Delta R_\ell > 0.3, \\
E_T^j > 25 \text{ GeV}, & |\eta_j| < 2.5, & \not{E}_T > 25 \text{ GeV}, \\
E_T^b > 30 \text{ GeV}, & |\eta_b| < 2.5, & \Delta R_j,\ \Delta R_b > 0.4,
\end{array}
$$

jet smearing: $\frac{\Delta E_j}{E_j} = \frac{50\%}{\sqrt{E_j(\text{GeV})}}$ b-tagging efficiency $\epsilon_b = 60\%$

- For signals:

$$pp \to Y\bar{Y} \to tX\bar{t}X \to bj_1j_2\bar{b}\ell^-\bar{\nu}XX + \text{h.c.}$$

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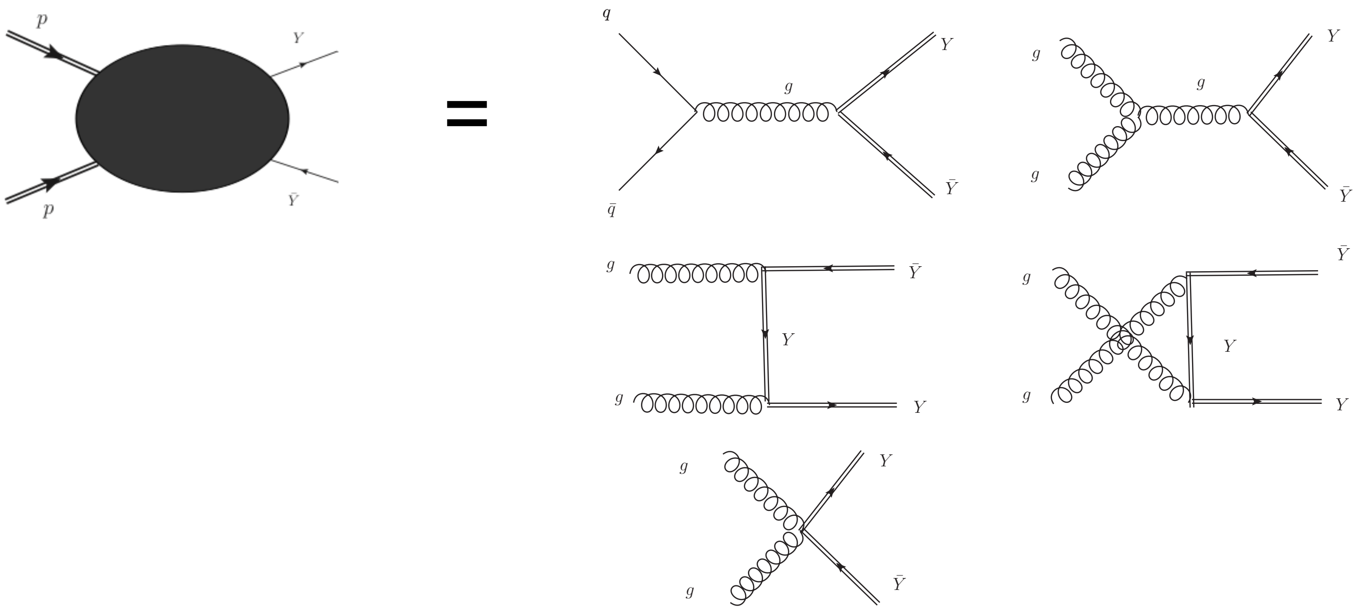

- Diagrams with gluon gluon initial state dominate at the LHC
- Models 2 and 3 do not have four-field interaction (renormalizability).