Searching for New Physics at the LHC with Top Quarks

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  - Most precisely measured quark mass!

$$M_{\mathrm{t}} = 173.1 \pm 0.6 \ (\mathrm{stat.}) \pm 1.1 \ (\mathrm{syst.}) \ \mathrm{GeV}/c^2.$$

(From: PDG/arXiv:0903.2503v1)

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- Sole SM decay process: $t \to W^+ b$

(Decays before hadronization; large phase space because of heavy top mass; electroweak and well understood)

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  - Top quark mass is tantalizingly close to the electroweak scale. Special role for EWSB?
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    - Top quark yukawa coupling approximately one!
  - Natural models of EWSB have top quark partners.
    - Largest SM higgs quadratic divergences come from top loops.

Why Use Top Quarks to Search for New Physics LHC?

- Top quarks @ the LHC:
  - "Top factory"
    80 million top quark pair events
    34 million single top events
    (14 TeV design luminosity; 10 inverse fb/year for 10 years)

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- Top quarks @ the LHC:
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    80 million top quark pair events
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    (14 TeV design luminosity; 10 inverse fb/year for 10 years)
  - LHC expected to start an "engineering run" by the Fall 2009. SM top properties are so well known tops are a "standard candle" for detector calibrations.

Why Use Top Quarks to Search for New Physics LHC?

- Because the SM properties of top are precisely known, copiously produced and are theoretically mandatory for natural models of new physics, they are a useful canvas to explore new physics @ the LHC.

An Overview of New Physics Signals with Top Quarks

I. Searching for Resonances with Top Quark Pairs at the LHC.

II. "Heavy Top" Decay into SM Tops with and without Large Missing Energy.

III. Signals of Exotic SM Top Decays.

IV. Signals with Same-Sign SM Tops

V. Signals from Top Compositeness.

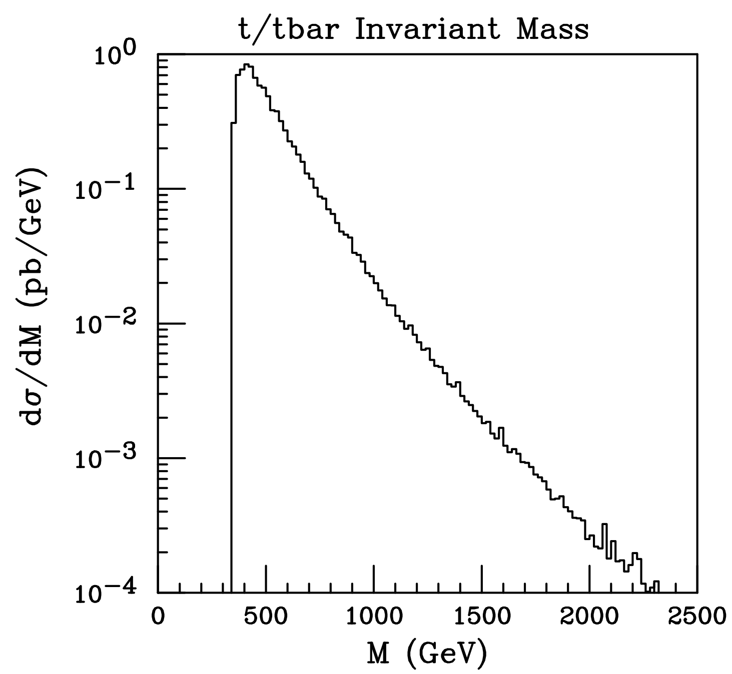
VI. Potpourri (brief listing of recent work)

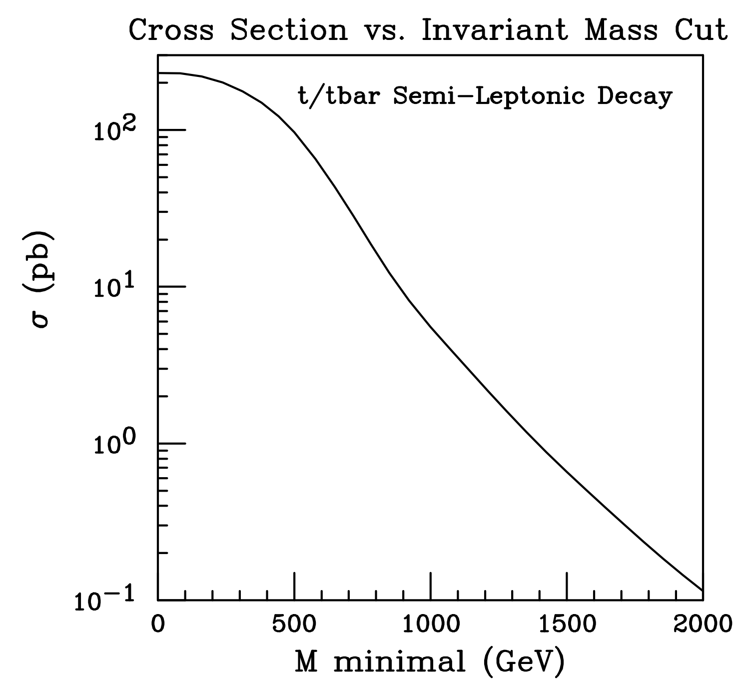
Searching for New Resonances at the LHC with Top Quark Pairs*

*Barger, Han, Walker : PRL100:031801,2008

Top Quark Pairs and Resonances

- Top quark pair production:





(Leading Order QCD Effects Only)

- Large cross section even at larger invariant masses.
- Only consider: $t\bar{t} \;\rightarrow\; bj_1j_2\,\bar{b}\ell^-\bar{\nu} + \text{c.c.} \qquad \ell = e \text{ or } \mu$
  (lepton is for tagging events)

Top Quark Pairs and Resonances

- Major Backgrounds:
  - W + jets, Z + jets, WW, WZ, ZZ
    - ALTAS: S/B = 65 (10 inverse fb)
    - CMS: S/B = 26 (1 inverse fb)

(From ATLAS and CMS TDRs; lepton tagging helps significantly)

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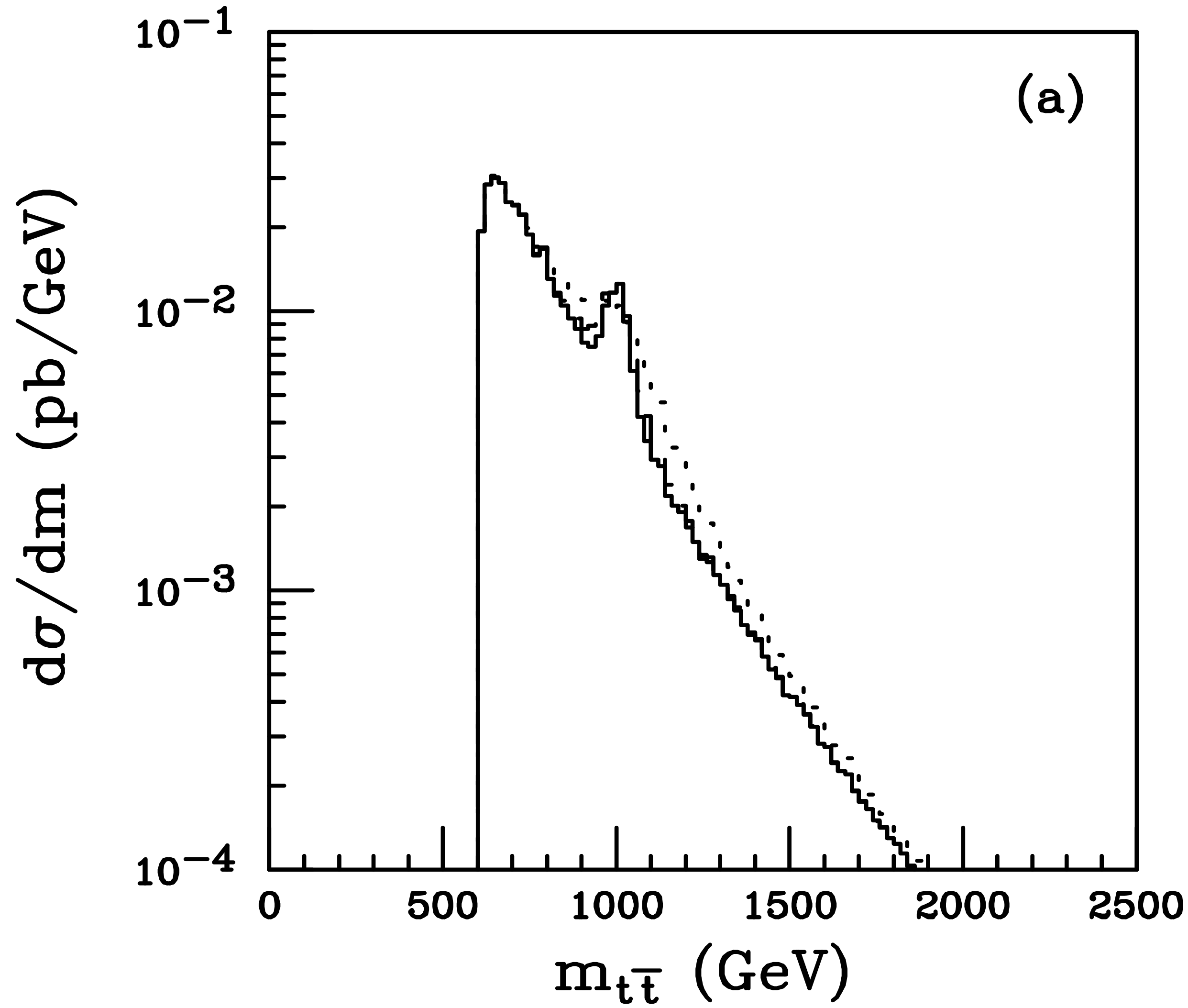
- Scalar, vector and graviton resonances considered:

$$gg \to \phi \to t\bar{t}, \quad q\bar{q} \to V \to t\bar{t}, \quad q\bar{q},\ gg \to \tilde{h} \to t\bar{t}$$

Top Quark Pairs and Resonances

- Resonances:
  1 TeV resonances width a total width of 2% (solid), 5% (dashed) and 20% (dotted).



- Reconstructed using W and top masses to eliminate two-fold ambiguity. ATLAS/CMS acceptance cuts. 600 GeV cluster transverse mass cut.

Top Quark Pairs and Resonances

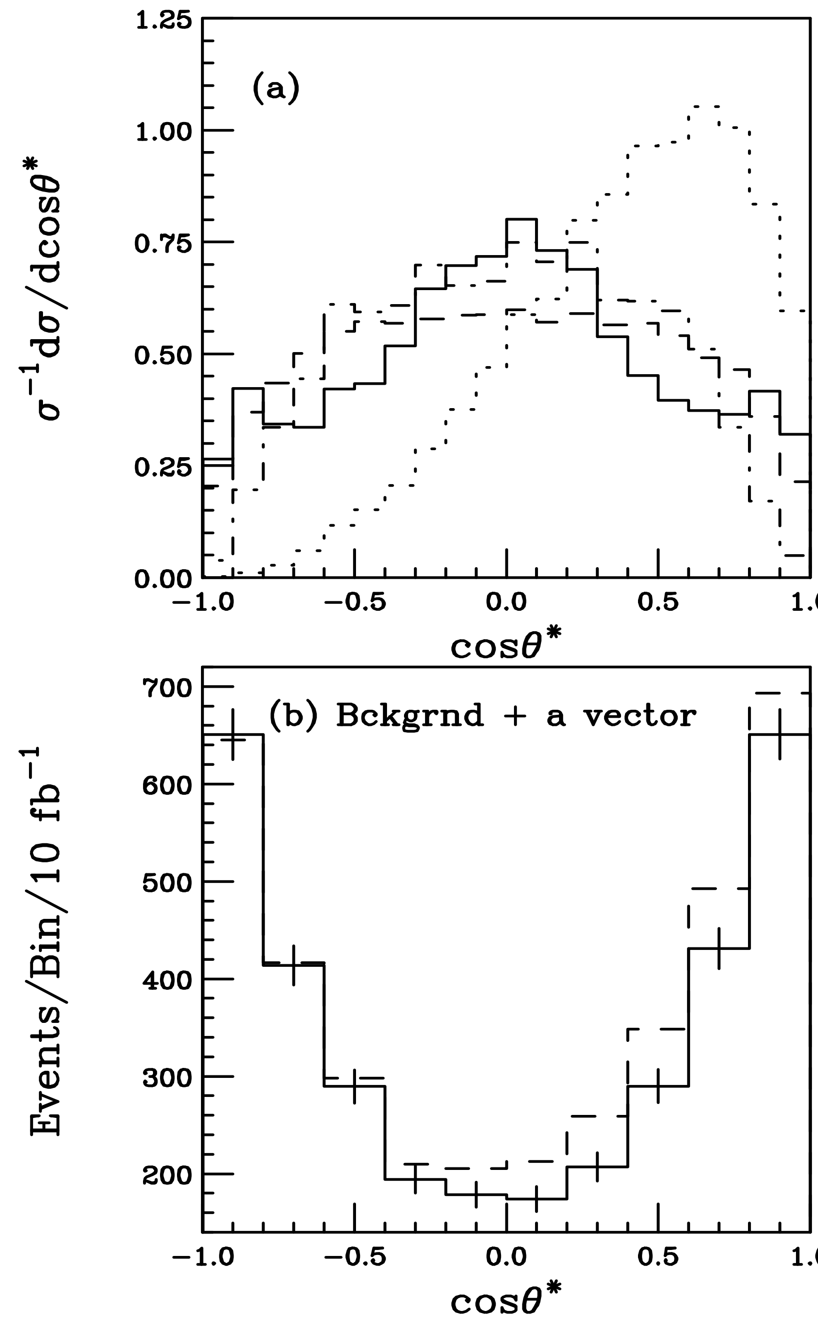
- Spin and other variables can be reconstructed:

  (ATLAS and CMS acceptance cuts)

  Signal angular distribution for
  - scalar (dashed)
  - vector (dots)
  - graviton (solid - quark initial partons)
  - graviton (dot-dashed - gluon initial partons)

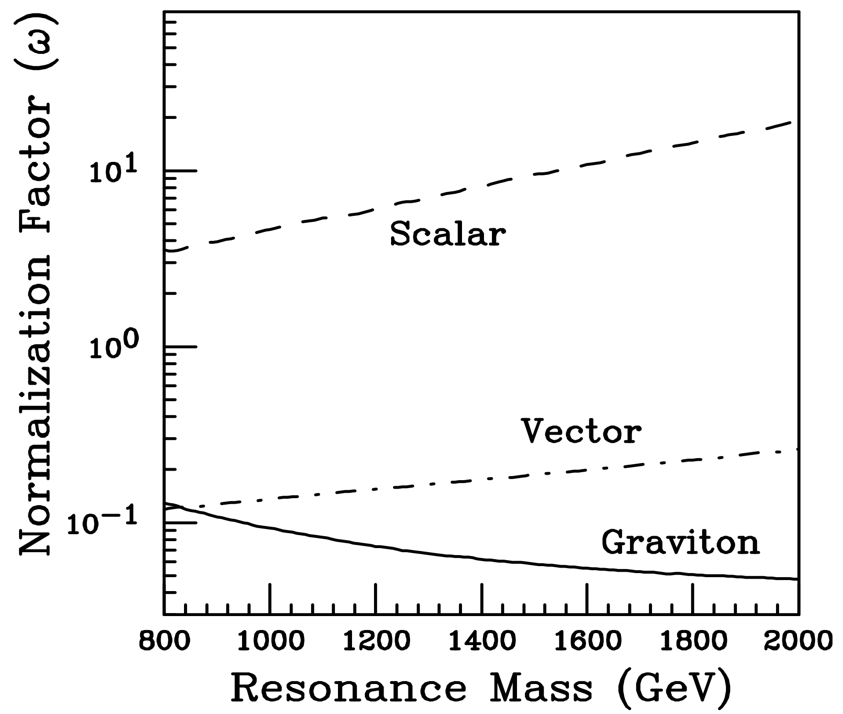
- Signal and background for a vector resonance:

  (10 inverse fb only; ATLAS and CMS cuts)



Top Quark Pairs and Resonances

- Generalize resonance couplings with a "normalization factor:"



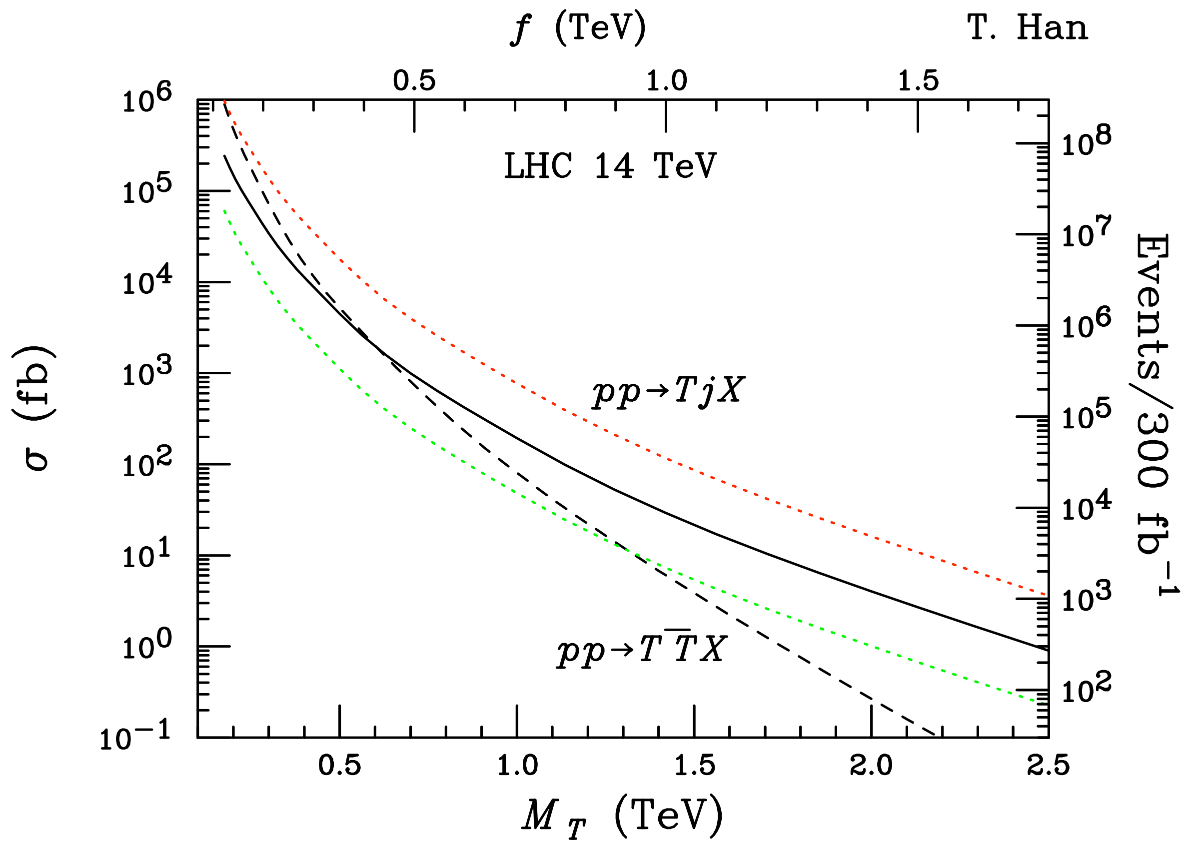
Normalization factor = 1 for
scalar - SM higgs
vector - Z prime w/electroweak strength and chiral couplings
graviton - Randall-Sundrum graviton with 2 TeV IR scale

- 10 inverse fb of luminosity

Heavy Top Quark Pairs + Missing Energy*

*Nojiri, Takeuchi: JHEP 0810:025,2008
Han, Mahbubani, Walker, Wang: JHEP 0905:117,2009

Top Quarks plus Missing Energy



- Theory: Top partners needed to naturally solve hierarchy problem.
  - Often a parity is evoked to make the new partners consistent with precision electroweak corrections.
  - Led to a general signature of top quarks in a final state with dark matter candidates (large missing transverse energy).

Top Quarks plus Missing Energy

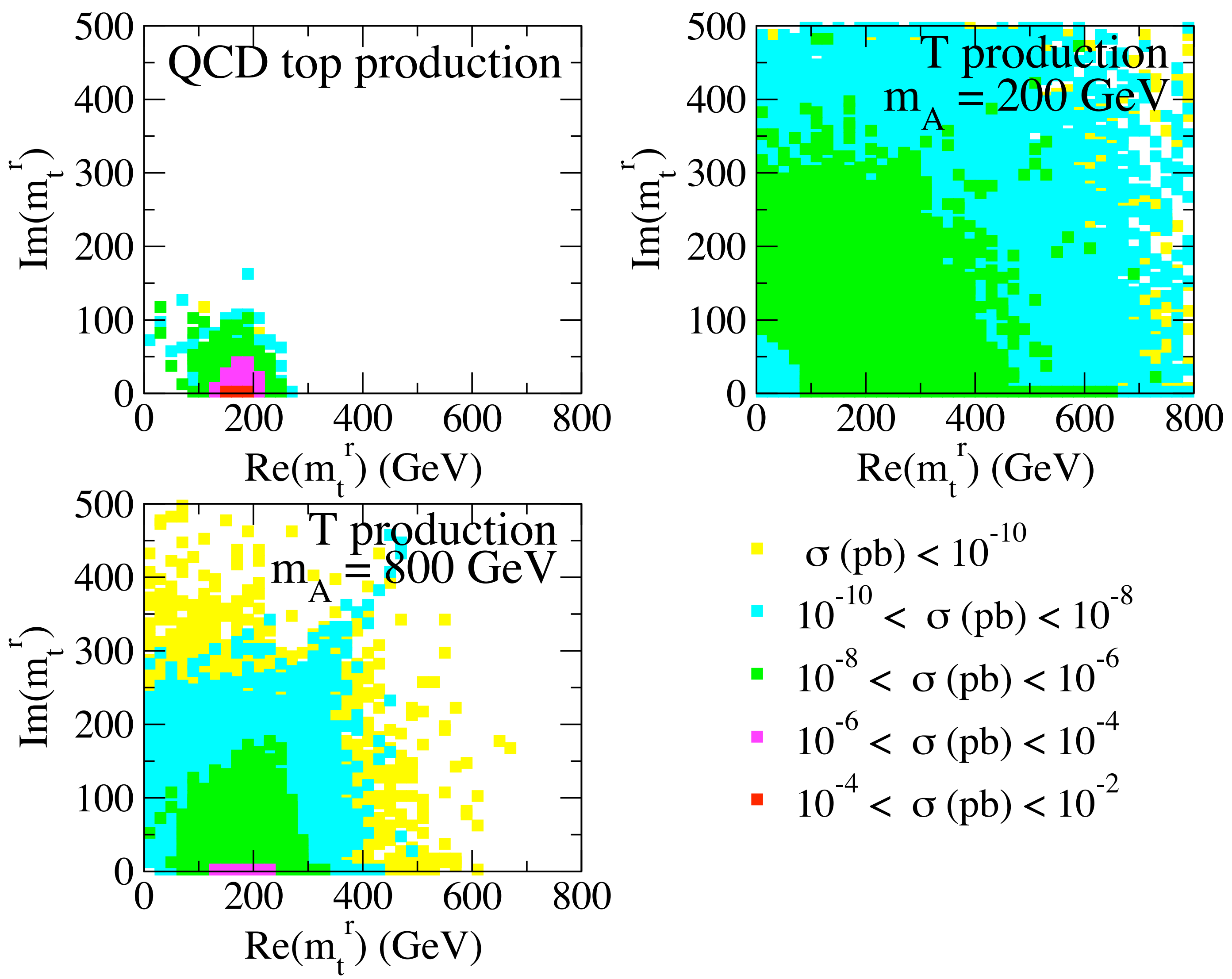
- Consider final state:

$$\bar{q}\, q,\;\; g\, g \to \bar{T}\, T \to t\, \bar{t}\, \chi\, \bar{\chi}$$

  - Similar processes in SUSY, UED, Little Higgs models w/T-parity.
  - Top pair decays into one lepton, one neutrino, two b jets and two jets.
    - Pure hadronic top pair decays are more problematic because of QCD backgrounds.

Top Quarks plus Missing Energy

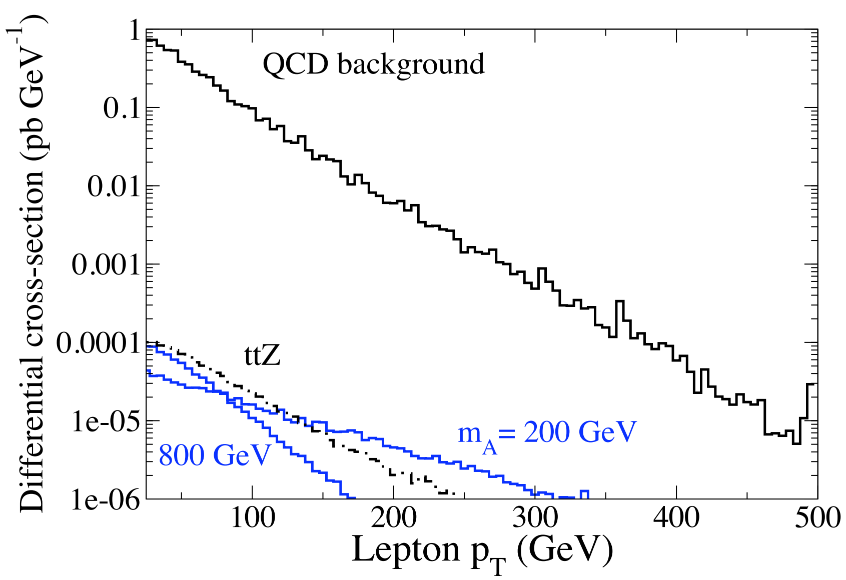
- A first signal of new physics?
  (Large fraction of events with poor top quark pair reconstruction with large missing transverse energy.)

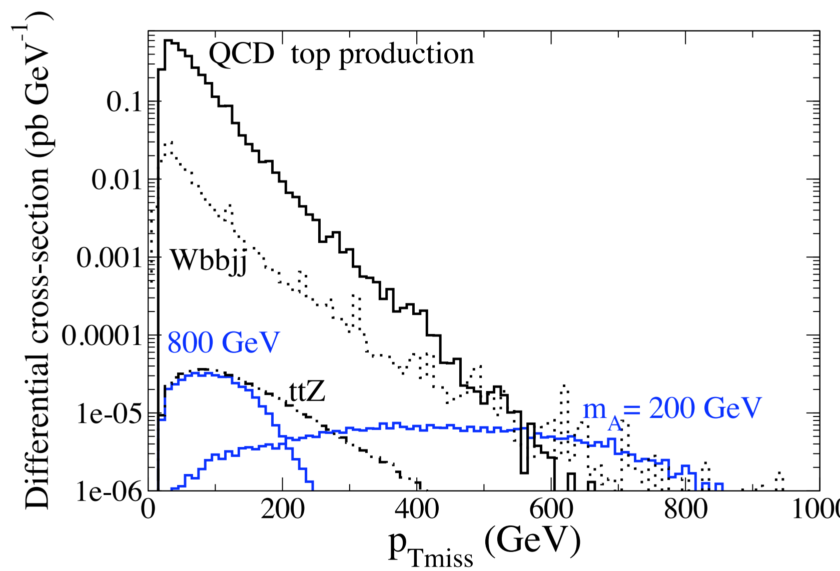


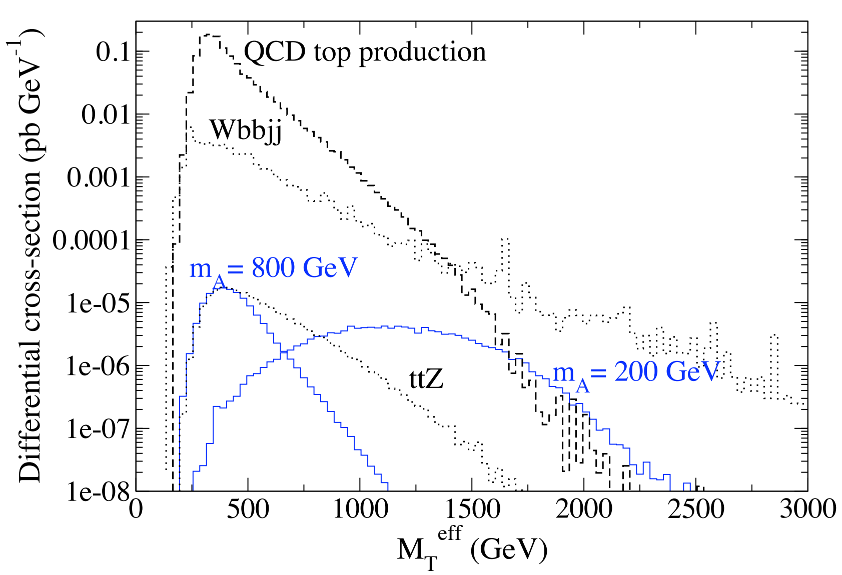
Top Quarks plus Missing Energy

- Backgrounds: W+jets, Z+jets, ttbar+Z, QCD

(1 TeV Heavy Top; Signal in blue; Backgrounds in black)







Top Quarks plus Missing Energy

- Crucial variable:

  (Notation: "A" = DM; "T" = heavy top)

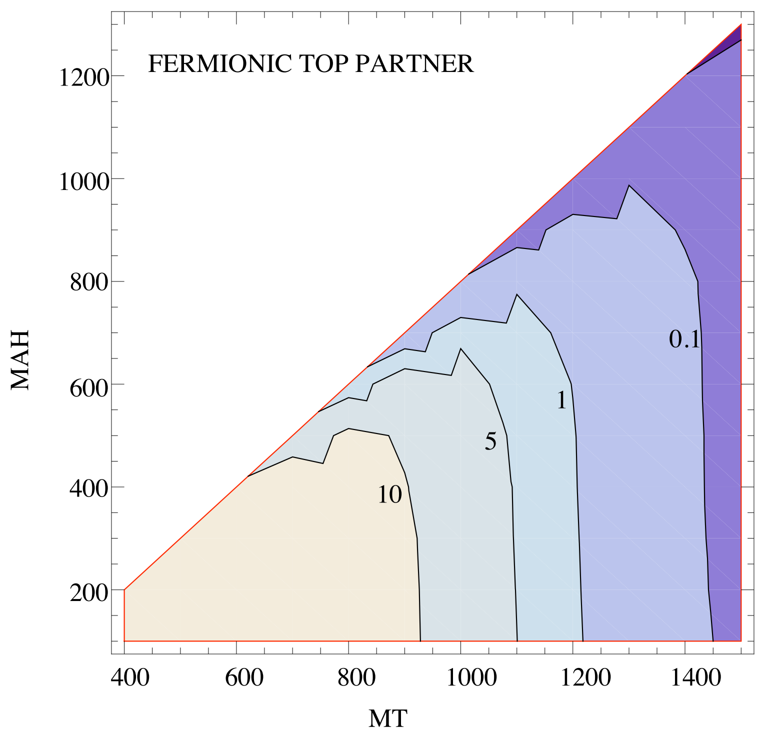
$$\Delta M_{TA} = \ m_T - m_A$$

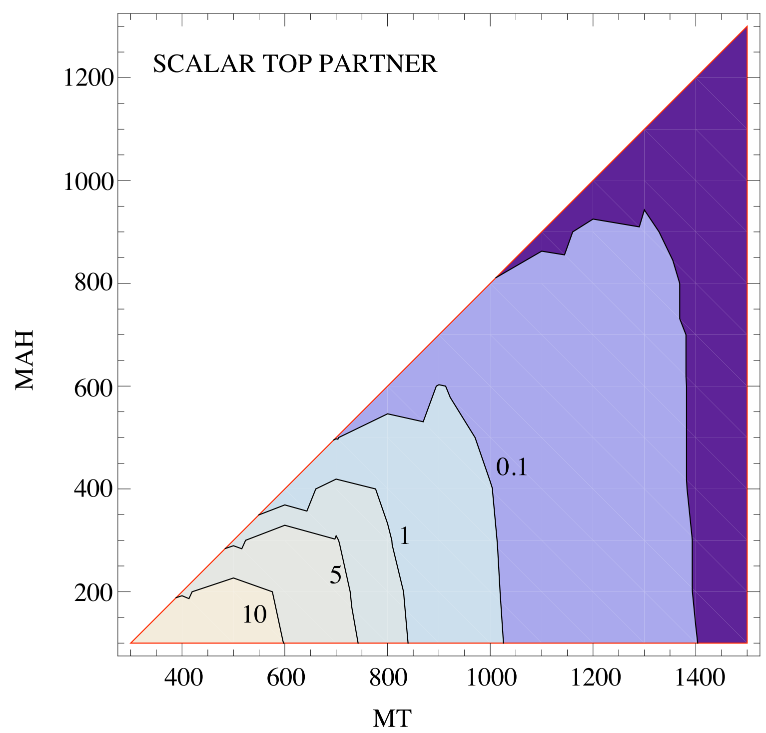
  - Large difference: Missing energy cut may suppress background
  - Small difference: Hard; Additionally impose

$$|m_t - m_t^r| > 110 \text{ GeV}$$

to optimize signal.

Top Quarks plus Missing Energy





- Signal Significance in terms of the dark matter, mAH, and heavy top partner mass, mT for 100 inverse fb.

Heavy Top Quark Decay with no Missing Energy*

* Azuelos, et al. [ATLAS Collaboration]: hep-ph/0402037

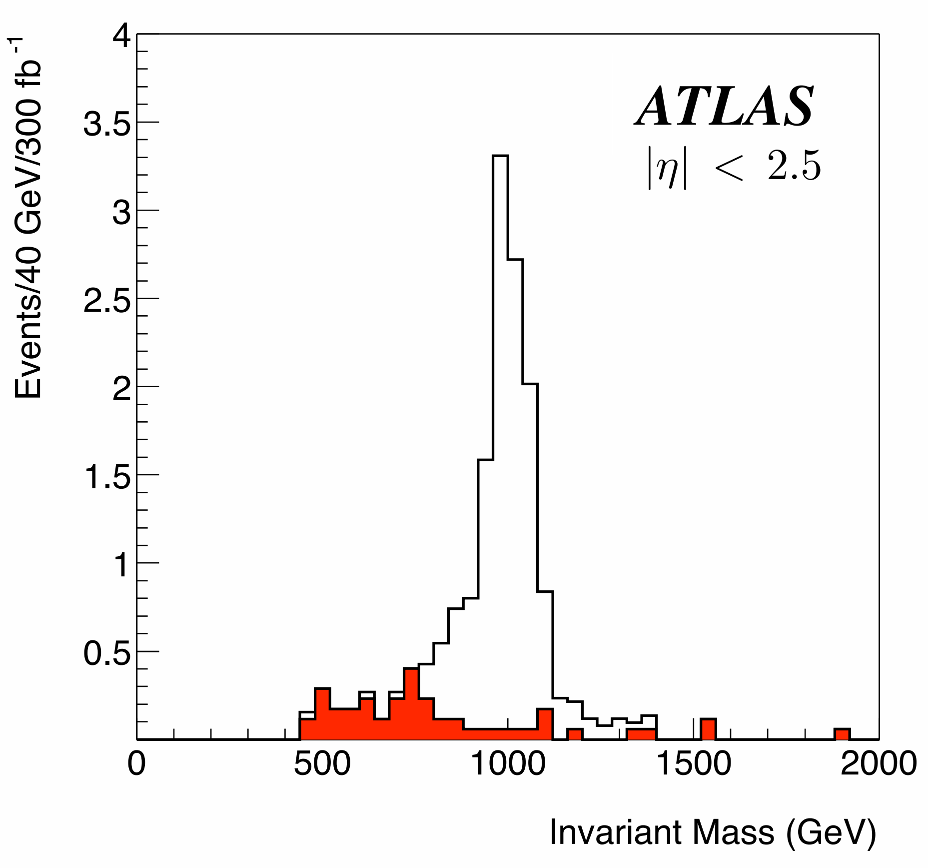
Heavy Top Decays into the SM

Theories with no stabilizing parity and heavy tops can decay to tops to generate exotic signals.

Little Higgs (no parity) with the decay $T \to Zt$

Cuts/Requirements:

1. Three isolated leptons with pT > 40 GeV with one with pT > 100 GeV.
2. No other leptons with pT > 15 GeV.
3. $\not{E}_T > 100 \text{ GeV}$
4. At least one tagged b-jet with pT > 30 GeV.



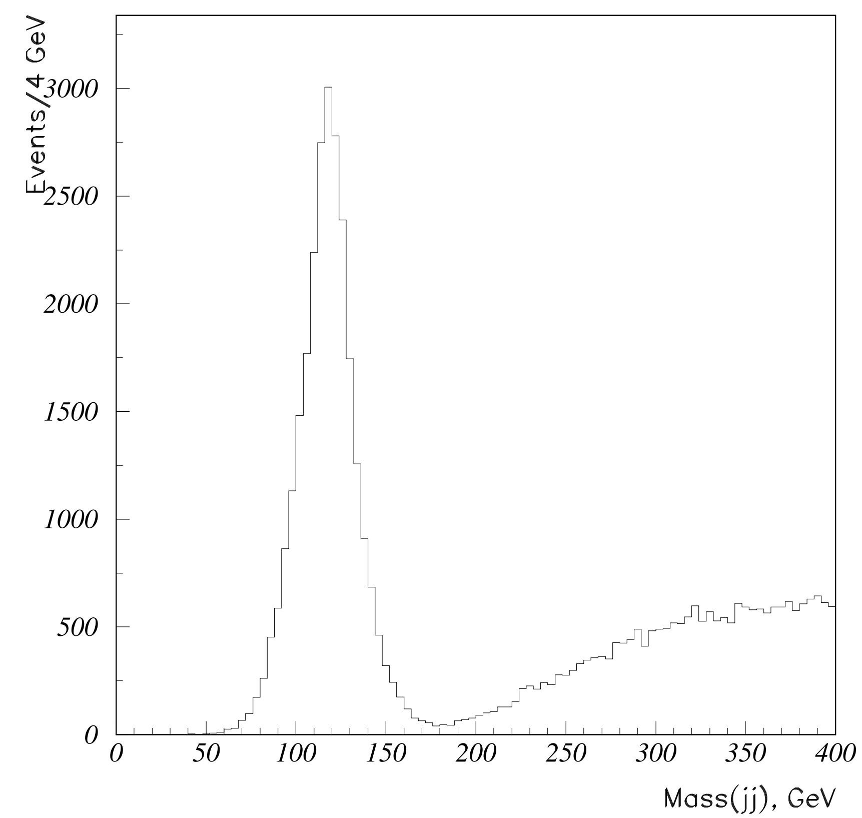
Heavy Top Decays into the SM

Little Higgs (no parity) with the decay $T \to ht$

Top decays to one lepton, one b-jet and one neutrino.

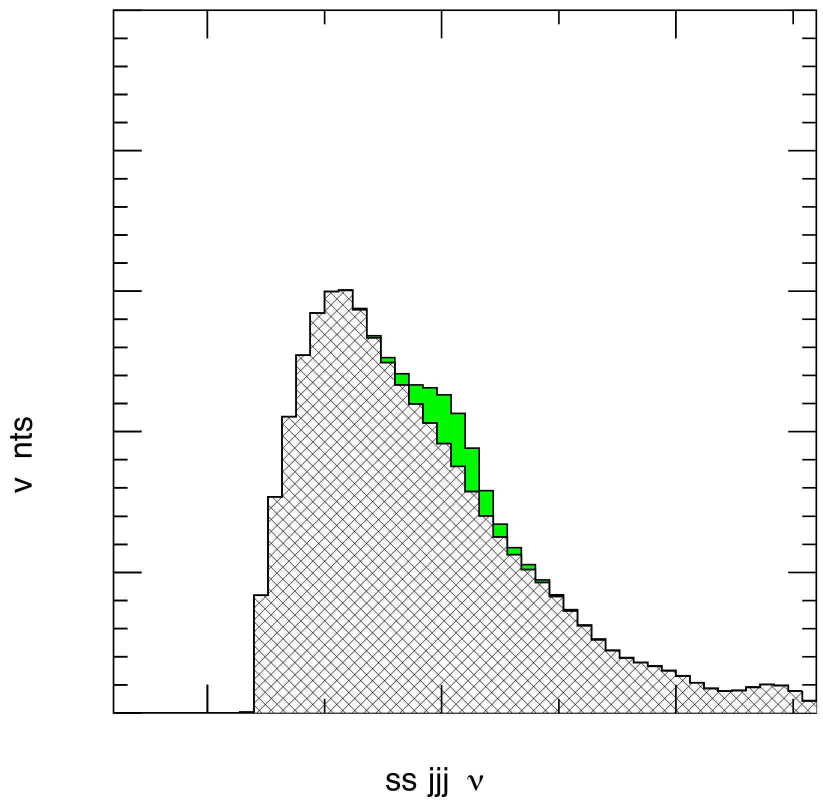
Cuts/Requirements:

1. One isolated leptons with pT > 100 GeV.
2. Three jets with pT > 130 GeV.
3. At least one tagged b-jet.

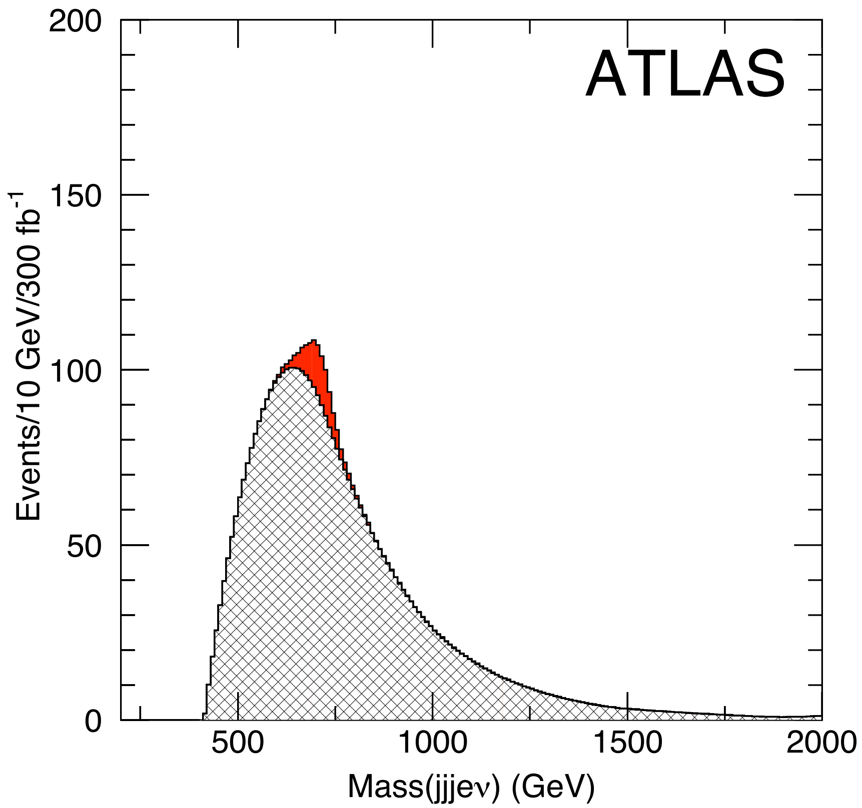


Reconstructed daughter dijet from 120 GeV SM higgs; assume BR(T ➔ ht) = 25%

Heavy Top Decays into the SM



(1 TeV Heavy Top)



(700 GeV Heavy Top)

Exotic Top Decays*

*See for example Charkraborty, Konigsberg, Rainwater:Ann.Rev.Nucl.Part.Sci.53,301,
Abazov, et al.[D0 Collaboration]:PRL88,151803,
Hshemi,arXiv:hep-ph/06912104,
Tait,Yuan:Phys.Rev.D63,014018,
Chen,Larios,Yuan:PRB631,126,
Diaz-Cruz,He,Yuan:Phys.Lett.B530,179,
Aguilar-Saavedra,Acta Phys.Polon.B35,2695,
Eilam,Gemintern,Han,Yang,Zhang,Phys.Lett.B510,227,
Larios,Martinez,Perez,Int.J.Mod.Phys.A21,3473,
Agashe,Perez,Soni,Phys.Rev.D75,015002,
Neutral current review:Yang,arXiv:0801.0210[hep-ph],
Atwood,Reina,Soni,Phys.Rev.D53,1199.

Exotic Top Decays*

- Decays possible in SUSY, Technicolor models or simply models with extended higgs sectors
  - Example Charged Current Decays

$$t \longrightarrow H^+ b$$

(Extended Higgs/SUSY Sector)

$$t \longrightarrow \pi^+ b$$

(Technicolor)

  - Example Neutral Current Decays

$$t \longrightarrow Z\, c \qquad t \longrightarrow H\, c$$

$$t \longrightarrow \gamma\, c \qquad t \longrightarrow g\, c$$

(SUSY/Technicolor/Extra-Dimensional Scenarios)

Exotic Top Decays*

- Consider charged higgs: $t \to H^+ b$

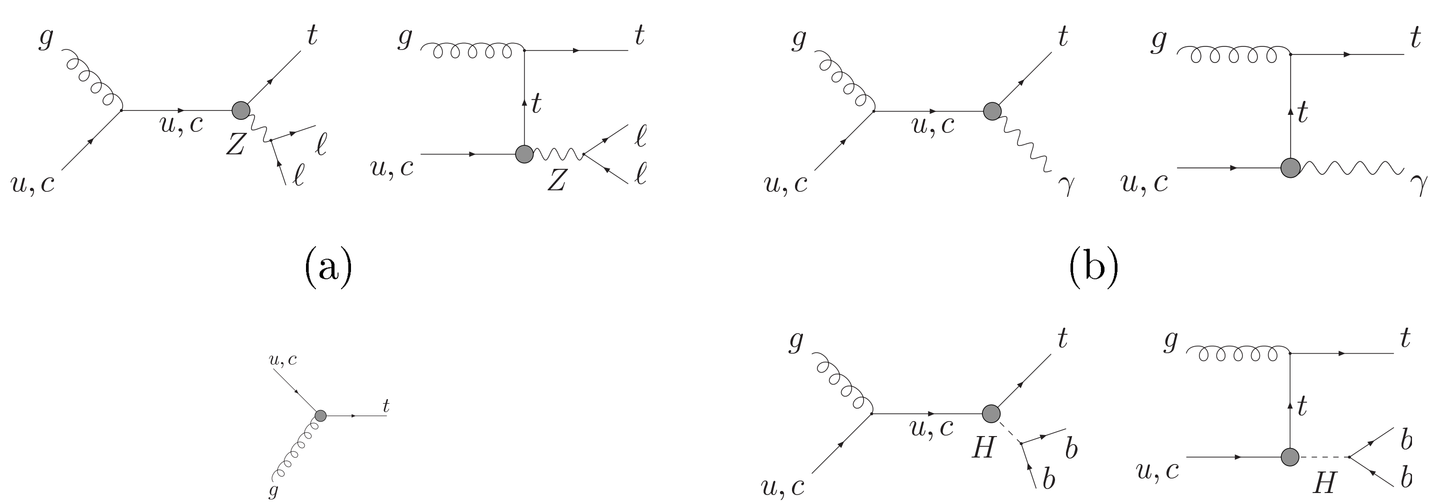
(From Hashemi, arXiv:hep-ph/0612104; tan beta = 20)

	$t\bar{t} \to H^{\pm}W^{\mp}b\bar{b} \to \ell\nu_\ell\tau\nu_\tau b\bar{b}$ $m_{H^\pm} = 140$ GeV/c^2	$t\bar{t} \to H^{\pm}W^{\mp}b\bar{b} \to \ell\nu_\ell\tau\nu_\tau b\bar{b}$ $m_{H^\pm} = 150$ GeV/c^2	$t\bar{t} \to H^{\pm}W^{\mp}b\bar{b} \to \ell\nu_\ell\tau\nu_\tau b\bar{b}$ $m_{H^\pm} = 160$ GeV/c^2
$\sigma \times$ BR[fb]	10.7 $\times 10^3$	5060.	1830.
L1 + HLT	5170.5(48.3)	2456.3(48.5)	888.9(48.6)
>= 3 jets	1889.7(36.5)	795.0(32.4)	264.3(29.7)
$\geq$ 1 b jet	1103.5(58.4)	427.4(53.8)	131.4(49.7)
$<$ 2 b jets	883.0(80.0)	358.7(83.9)	119.2(90.7)
Having L1 τ	878.4(99.5)	357.4(99.6)	119.0(99.8)
τ-jet reconstruction	875.0(99.6)	356.5(99.7)	118.8(99.8)
Hottest HCAL tower $E_T > 2$ GeV	778.0(88.9)	316.1(88.6)	105.9(89.1)
Tracker isolation	378.2(48.6)	163.5(51.7)	52.7(49.8)
Ecal isolation	292.9(77.4)	134.2(82.1)	43.1(81.8)
τ $E_T > 40$ GeV	244.3(83.4)	113.0(84.2)	36.5(84.7)
$p_{\text{leading track}}/E_\tau > 0.8$	102.3(41.9)	50.7(44.8)	16.8(45.9)
$Q(\ell) + Q(\tau) = 0$	88.0(86.0)	42.4(83.6)	14.6(87.0)
$E_T^{\text{miss}} > 70$ GeV	51.0(58.0)	25.4(59.9)	9.2(63.3)
Expected Number of events after 10 fb^{-1}	510	254	92

Exotic Top Decays*

- Consider neutral current decays.

(From Aguilar-Saavedra, arXiv:hep-ph/0409342v4)



Process	Cross section	Process	Cross section
$gu \to Zt\ (\gamma_\mu)$	$(260 + 50)\,\lvert X_{ut}\rvert^2$	$gc \to Zt\ (\gamma_\mu)$	$(26 + 26)\,\lvert X_{ct}\rvert^2$
$gu \to Zt\ (\sigma_{\mu\nu})$	$(540 + 87)\,\lvert \kappa_{ut}\rvert^2$	$gc \to Zt\ (\sigma_{\mu\nu})$	$(45 + 45)\,\lvert \kappa_{ct}\rvert^2$
$gu \to \gamma t$	$(440 + 76)\,\lvert \lambda_{ut}\rvert^2$	$gc \to \gamma t$	$(39 + 39)\,\lvert \lambda_{ct}\rvert^2$
$gu \to t$	$(9.0 + 2.6) \times 10^5\,\lvert \zeta_{ut}\rvert^2$	$gc \to t$	$(1.5 + 1.5) \times 10^5\,\lvert \zeta_{ct}\rvert^2$
$gu \to Ht$	$(16 + 2.8)\,\lvert g_{ut}\rvert^2$	$gc \to Ht$	$(1.5 + 1.5)\,\lvert g_{ct}\rvert^2$

(Processes in pb; term after sum is the charge conjugate process)

Same-Sign Tops*

*See for example Kraml,Raklev:hep-ph/0512284.

Same-Sign Tops

- Signature possible from sign tops from pair produced gluinos in SUSY scenarios:

$$\tilde{g}\,\tilde{g} \rightarrow t\,t\,\tilde{t}^*\,\tilde{t} \rightarrow b\,b\,l^+\,l^+\ (\mathrm{or}\,\bar{b}\,\bar{b}\,l^-\,l^-) + \mathrm{jets} + E_T^{\mathrm{miss}}$$

Same-Sign Tops*

Cut	2lep 4jet	p_T^{lep}	p_T^{jet}	$2b$	E_T^{miss}	$2t$	SS
Signal							
$\tilde{g}\tilde{g}$	10839	6317	4158	960	806	628	330
Background							
SUSY	1406	778	236	40	33	16	5
SM	25.3M	1.3M	35977	4809	1787	1653	12

- Signal (30 inverse fb) with cuts:

  1. Two same sign leptons
  2. Four jets w/ pT > 50 GeV
  3. ETmiss > 100 GeV
  4. b-lepton invariant mass > 160 GeV

- *More see Kraml,Raklev:hep-ph/0512284

Top Compositness*

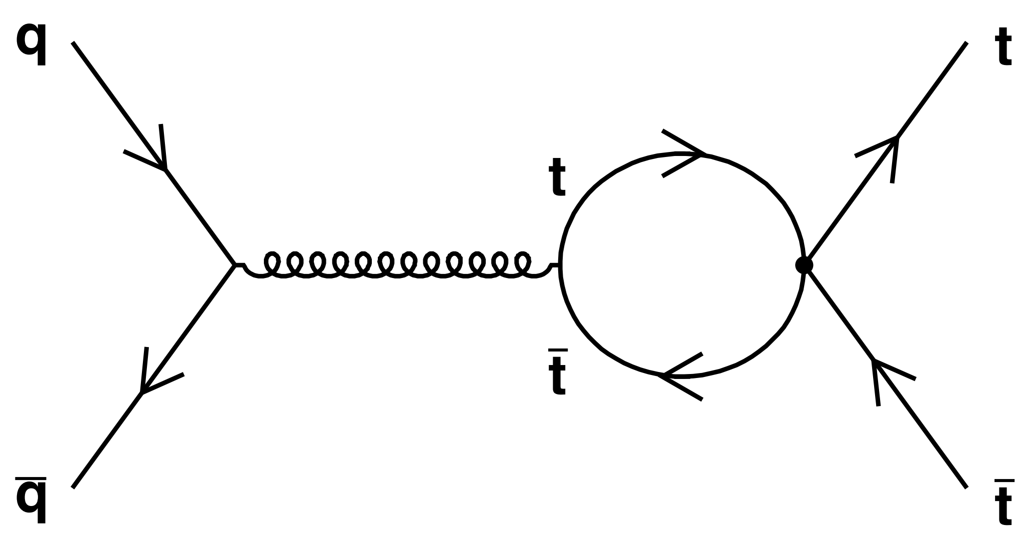
*Lillie,Shu,Tait:arXiv:0712.3057.

Models with Right-Handed Top Compositeness

- Consider the composite effective operator for right-handed tops:

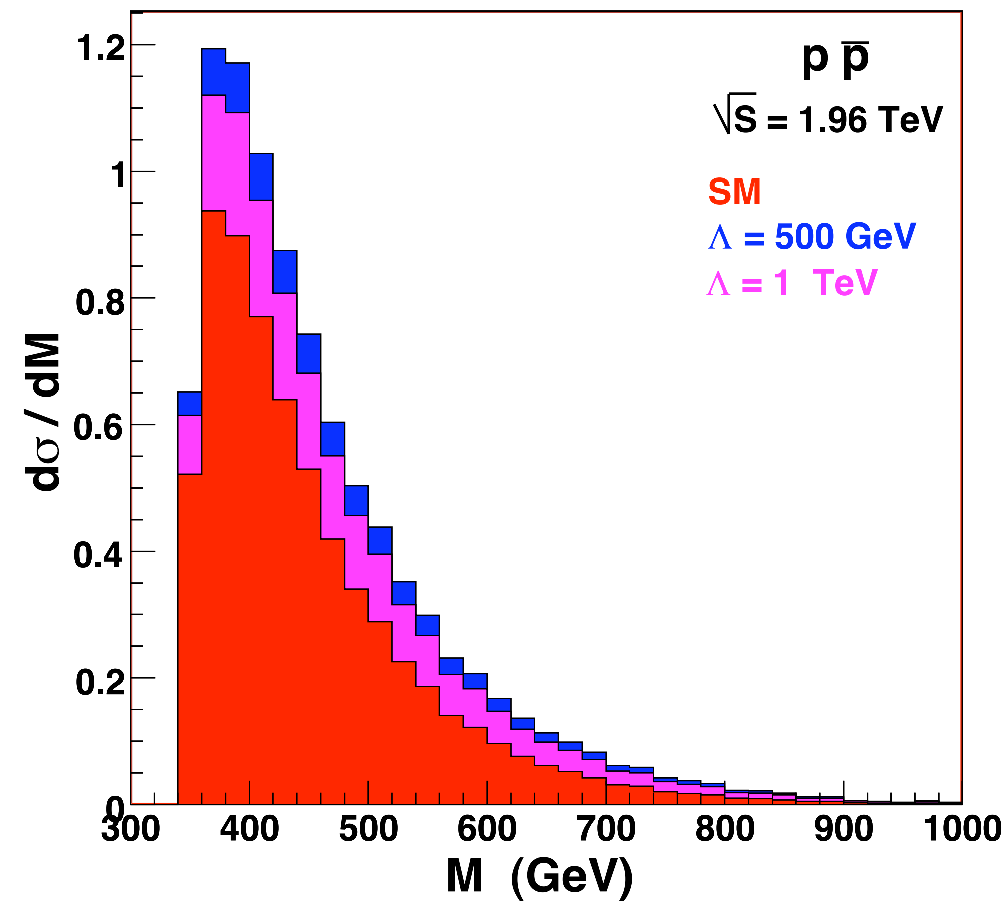
$$\frac{g^2}{\Lambda^2}\left[\bar{t}^i\gamma^\mu P_R t_j\right]\left[\bar{t}^k\gamma_\mu P_R t_l\right]$$

- Effects SM top pair production at 1 loop.



Models with Right-Handed Top Compositeness

- Top compositeness search at the TeVatron. Excesses due to the 1-loop correction.



Models with Right-Handed Top Compositeness

- Operator

$$\frac{g^2}{\Lambda^2}\left[\bar{t}^i\gamma^\mu P_R t_j\right]\left[\bar{t}^k\gamma_\mu P_R t_l\right]$$

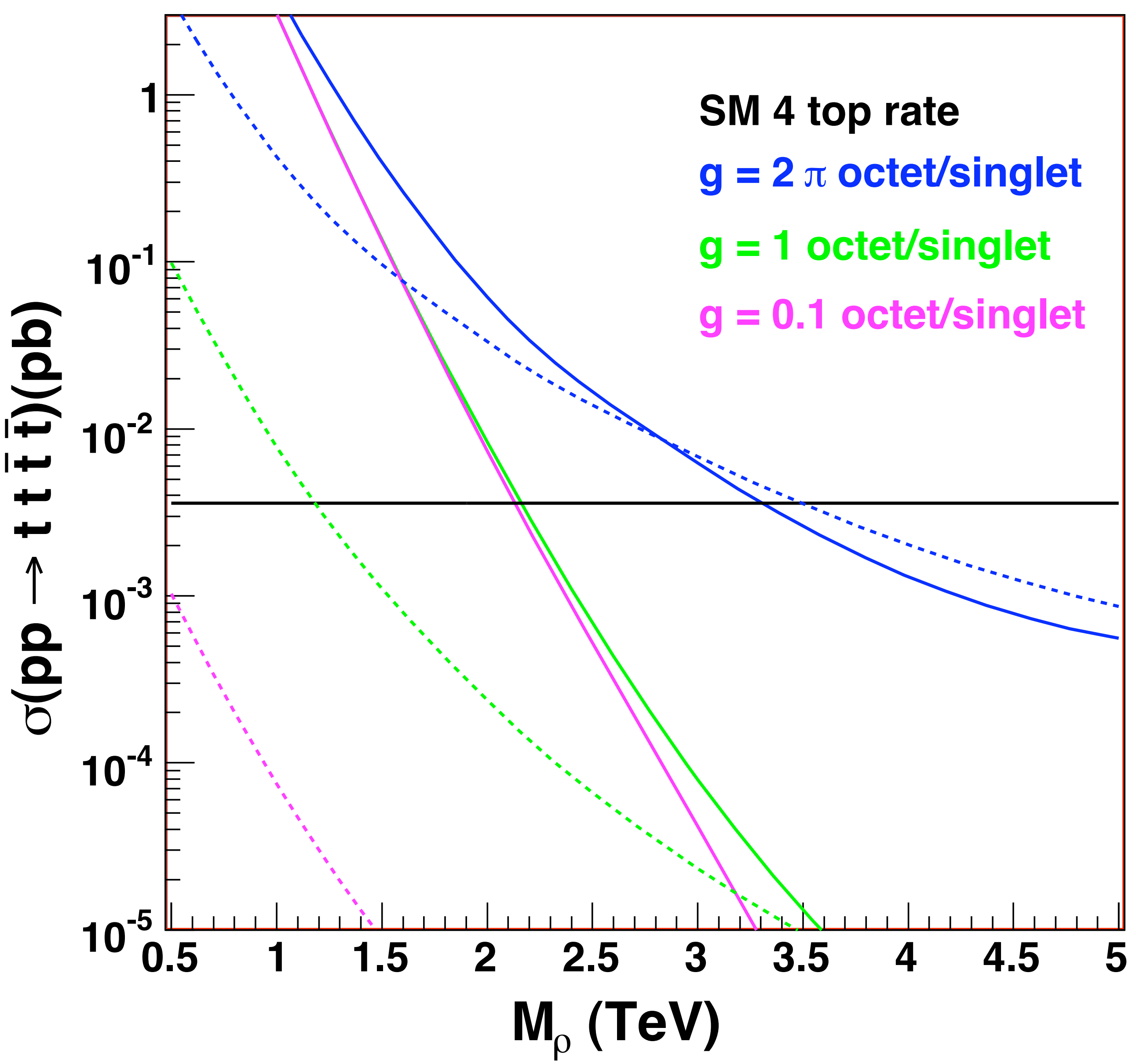
generates four top signal at the LHC.

- Processes:

$$pp \rightarrow t\bar{t}^* \ \bar{t}^* \rightarrow \bar{t}t\bar{t}$$

$$gg \rightarrow \rho\rho \qquad \rho \rightarrow t\bar{t}$$

$$pp \rightarrow t\bar{t}\rho$$



(rho is an integrated out color octet that generates the effective operator)

Potpourri

Potpourri

- 2009 Search on the arXiv:

  86+ new papers on aspects of new physics from top quarks
  (Including top production from black holes and string balls.)

- 2008 Search on the arXiv:

  240+ paper on new physics.

  Active and fruitful research area!

(Processes in pb; term after sum is the charge conjugate process)

Looking Forward

- More to do!
  - Tops are an excellent probe of new electroweak physics. Relatively easy to tag, produce and theoretically compelling.
- Looking forward to a LHC era of discovery and wonder!

(Apologies for unintentional omission of someone's personal (or favorite) work.)

Additional Slides

Rare top quark decays are parametrized as

(Yuan,Tait,Larios,Chen,Han,Peccei,Zhang,Hosch,Whisnant,Young,Zhang)

$$\mathcal{L}_{CC} = \frac{g}{\sqrt{2}} \left(\bar{t}(1+\delta_L)\gamma^\mu P_L q W^-_\mu + \bar{t}\delta_R \gamma^\mu P_R q W^-_\mu \right) + h.c.$$

$$\begin{aligned} \mathcal{L}_{NC} \ &= \ \frac{g}{2\cos\theta_w} \sum_{\tau=\pm, q=c,u} \kappa_\tau \bar{t}\gamma^\mu P_\tau q Z_\mu + h.c. \\ &+ \ g_s \sum_{q=c,u} \frac{\kappa_q^g}{\Lambda} \bar{t}\sigma^{\mu\nu} T^a t G^a_{\mu\nu} + eQ_t \sum_{q=c,u} \frac{\kappa_q^\gamma}{\Lambda} \bar{t}\sigma^{\mu\nu} t A_{\mu\nu} + h.c. \end{aligned}$$

Sensitivity of the LHC to FCNC

(ATLAS Collaboration)

Channel	10 fb^{-1}	100 fb^{-1}
$t \to Zq$	3.1×10^{-4}	6.1×10^{-5}
$t \to \gamma q$	4.1×10^{-5}	1.2×10^{-5}
$t \to gq$	1.3×10^{-3}	4.2×10^{-4}