"Top Tools" for New Physics

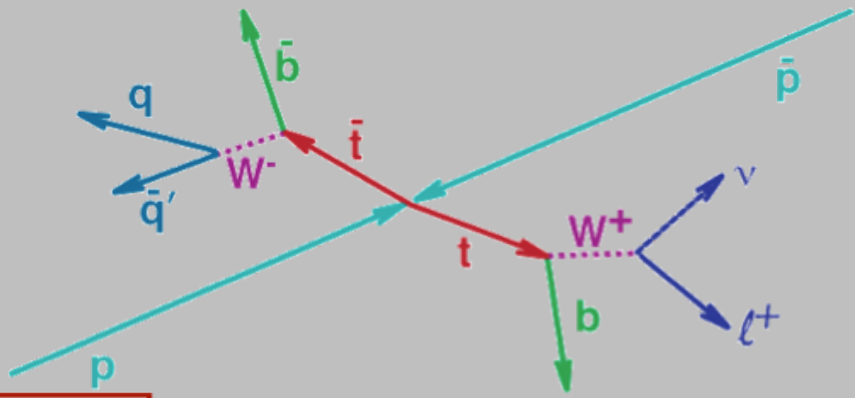
The 3rd Annual Conference on Large Hadron Collider Physics

St. Petersburg, Sept. 2, 2015

Tao Han
University of Pittsburgh

Celebration!

Top Turns to 20 !



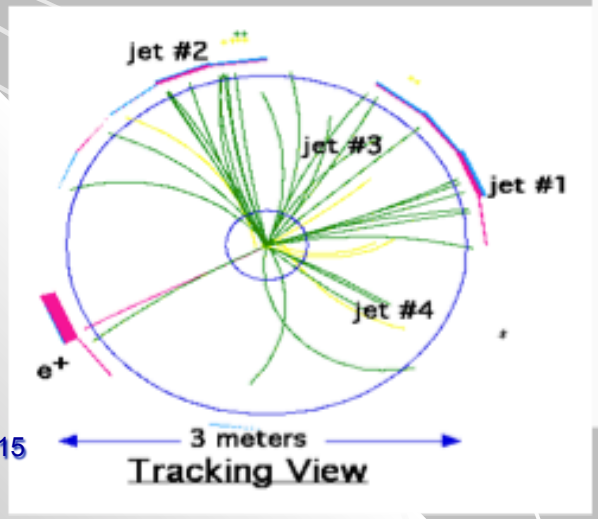
Tevatron: Schwienhorst; Yao

Physicists Discover Top Quark

News Release - March 2, 1995

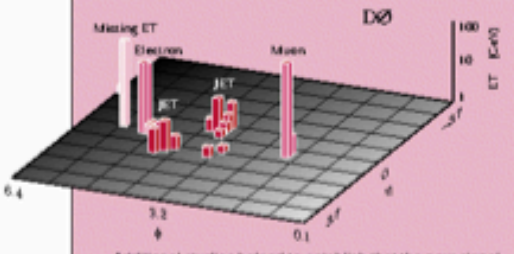
PHYSICISTS DISCOVER TOP QUARK

Batavia, IL--Physicists at the Department of Energy's Fermi Natio
subatomic particle called the top quark, the last undiscovered quar
sought the top quark since the discovery of the bottom quark at Fe
of the structure of matter.

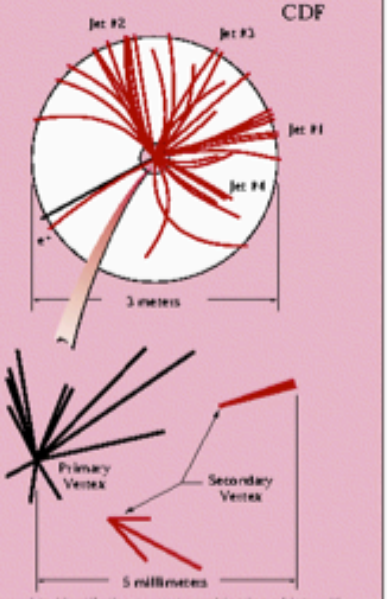


CDF AND DØ RESULTS

THE RESULTS FROM THE TWO COLLABORATIONS were remarkably similar. CDF found 8 dilepton events with a background of 1.3; 21 single-lepton events in which 27 cases of a *b* quark tag by the vertex detector (with 6.7 background tags expected); and 22 single-lepton events with 23 cases of a *b* tag through leptonic decay (with 15.4 background tags expected). DØ found 3 dilepton events (0.65 background events); 8 single-lepton events with topological tagging (1.9 background events); and 8 single-lepton events with *b*-to-lepton tags (1.2 background events). A particularly striking example of a dilepton event with very energetic electron, muon, and missing E_T (due to the neutrinos), plus two jets, is shown below from the DØ data. The plot shows the detector unfolded on to a plane, with the energy of the various objects indicated by the height of the bars. This event has a very low probability to be explained by any known background. The probability that background fluctuations could explain the observed signal was one-in-a-million for CDF and two-in-a-million for DØ—sufficiently solid that each experiment was able to claim the observation of the top independently.



Additional studies helped to establish that the new signal



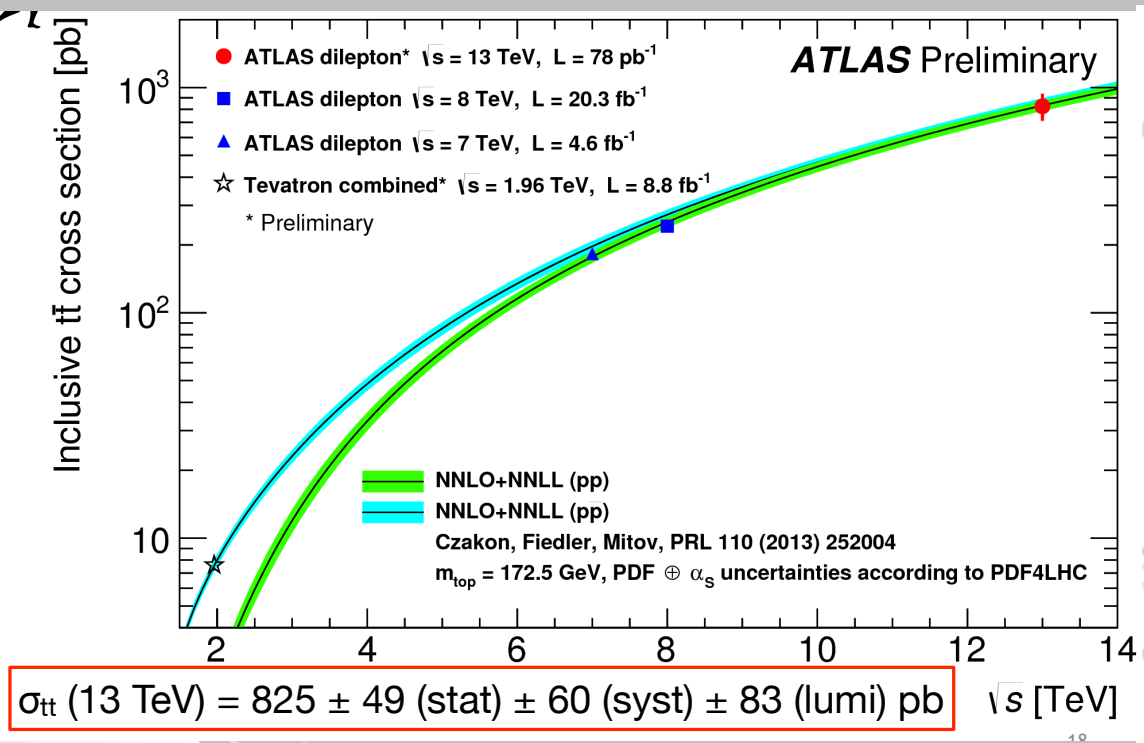
by the need to identify the correct combination of jets with parent quarks in the decay and to accommodate the tendency of the strong interaction to generate additional jets. The two experiments obtained consistent results for this

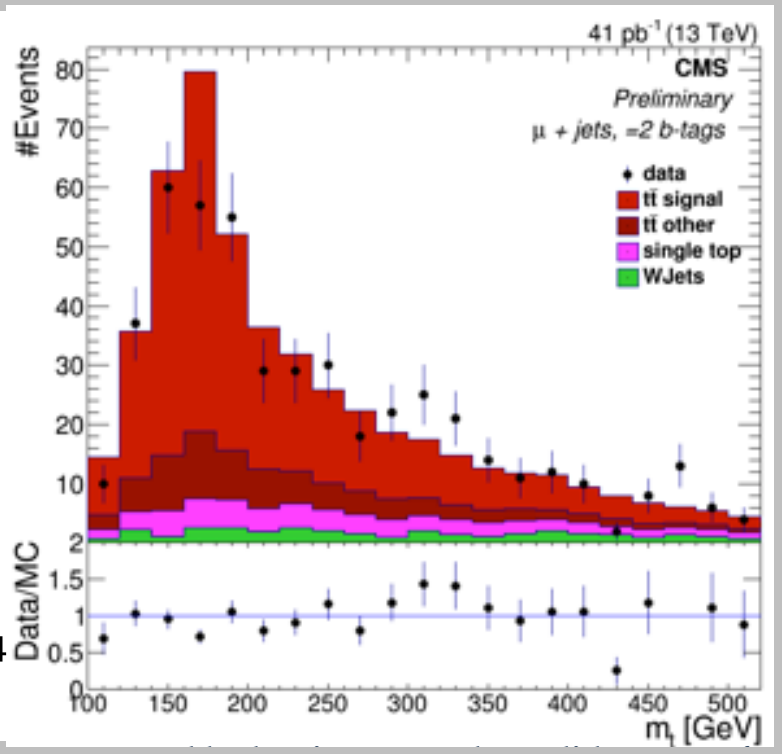
Top Rediscovered @ the LHC13

See, the next three talks

ATLAS: E. Torrence + others

CMS: P. Spagnolo + others





280 million tt pairs + 100 million single t's @14 TeV, 300 fb^{-1}

New era for top quark physics has just begun !

On top, where we stand

Top in the SM:

$$-\mathcal{L}_{SM} = m_t \bar{t}t + \frac{m_t}{v} H\bar{t}t + g_s \bar{t}\gamma^\mu T^a t G^a_\mu + eQ_t \bar{t}\gamma^\mu t A_\mu$$

$$+ \frac{g}{\cos\theta_w} \bar{t}\gamma^\mu (g_V + g_A\gamma^5) t Z_\mu + \frac{g}{\sqrt{2}} \sum_q^{d,s,b} V_{tq} \bar{t}\gamma^\mu P_L q W^-_\mu + h.c.$$

On top, where we stand

Top in the SM:

0.5% by kinematics

30% fitted

a few%

30-40% via direct production

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$|V_{tb}| > 0.92$; $\Gamma_t^{D0} \approx 2.00 \pm 0.47$ GeV

Snowmass top report: arXiv:1311.2028;
Other ATLAS/CMS papers/talks.

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Top Precision @ LHC 14

$\Delta m_t < 600$ MeV! Connection to well-defined MS-bar mass?

Δ(ttZ, tbW, ttH) ~ 10% New scale: ***$(v/\Lambda)^2 \rightarrow \Lambda \sim 1$ TeV***

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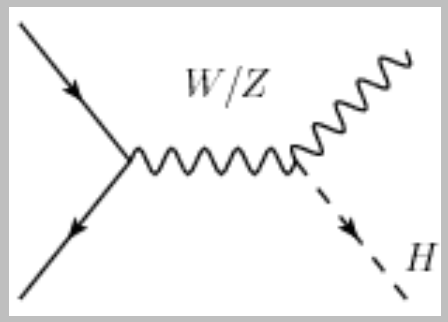
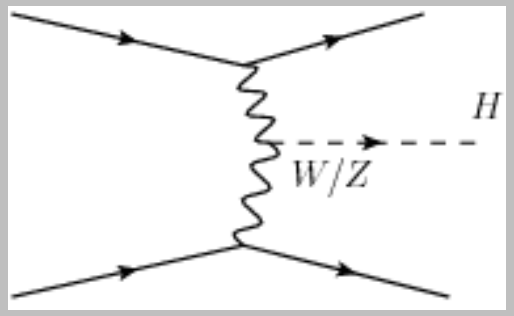
New Physics: Top Credits!

The "Higgs mechanism" was designed to give W/Z masses. Thus:





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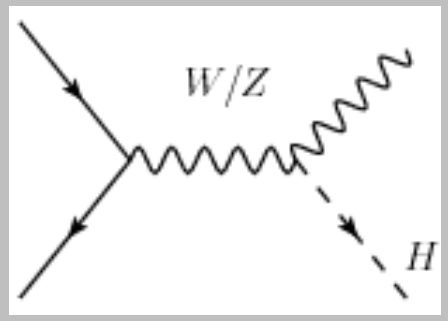
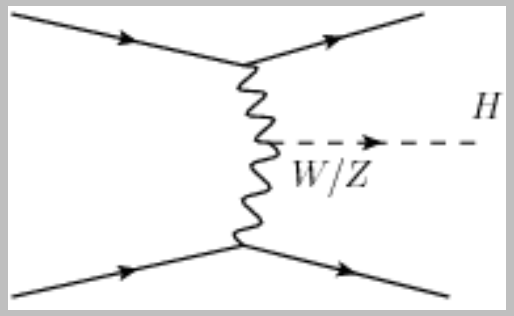
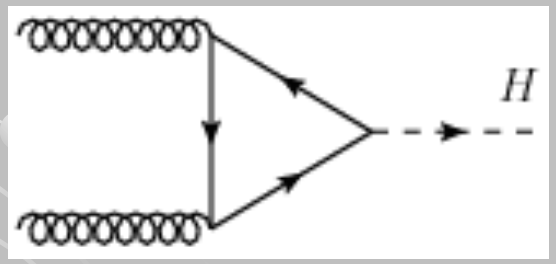
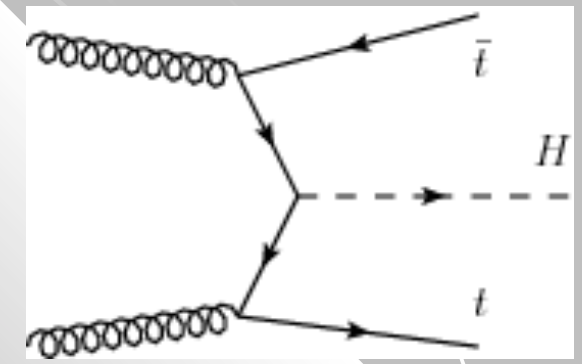
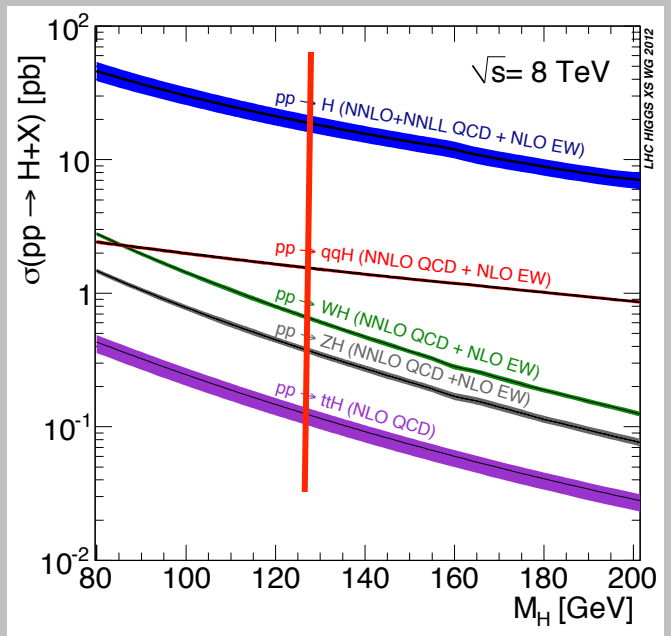




Yet, the top quark already stole the show, and will continue to be on the "center stage"!



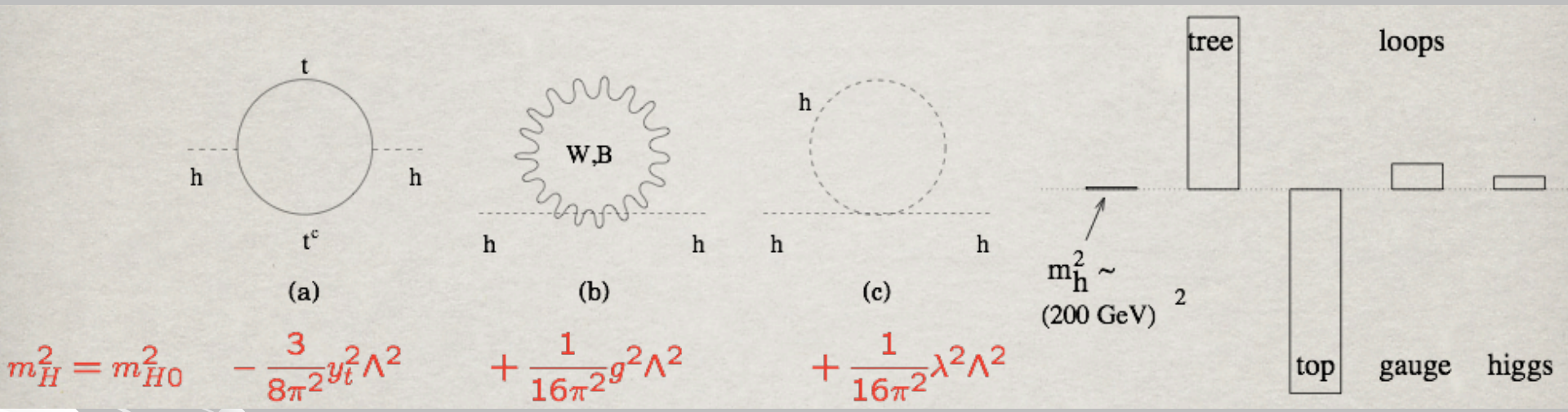




New Physics: Top Rules!

Due to the large Yukawa coupling: $y_t \approx 1$,

- Higgs mass quadratically sensitive to quantum-corrections, mostly from top-loop:



"Naturalness" argument:

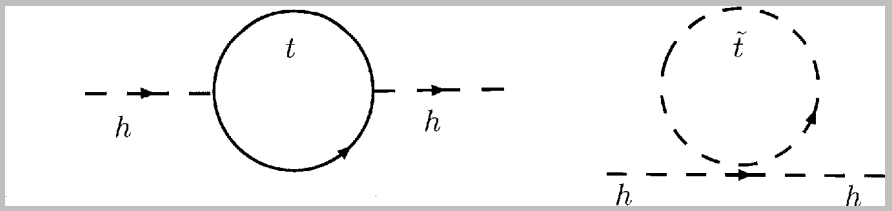
~ 90% cancellation → Λ_t (top partners) < 3 TeV

- The large y_t might determine the fate of our vacuum.

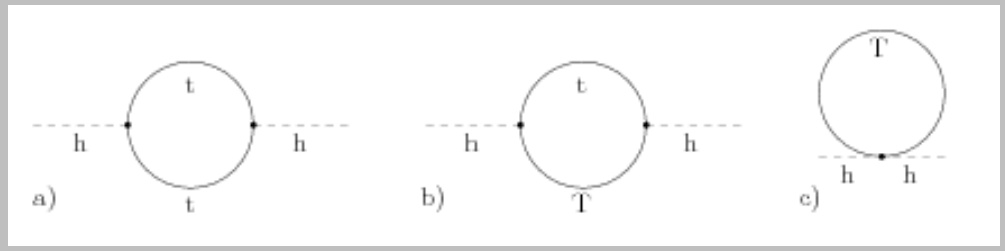
Stefania Gori's talk

Top Partners: "Natural" Demand

In SUSY:
scalar top: $\tilde{t}$ David Shih's talk
Partner's partners: $\tilde{b}$, $\tilde{g}$



In Composite (or Little) Higgs:
Fermionic partner: T …



There are also other incarnations for a "natural" theory:
Twin Higgs etc., all with "top partners".

Top Connections

And far reaching:

- top needs partners for naturalness in EWSB.
- light stop may help with EW baryon-genesis.
- top + partner may reveal dark matter signal.

Theory	Top role	Top imprints
EWSB	$t\bar{t}H$	$gg \to H,\ t\bar{t}H;\quad H \to t\bar{t},\ ...$
2HDM	$t\bar{t}A,\ t\bar{b}H^{\pm}$	$t \to bH^{\pm};\ gg \to A,\ b\bar{b}H(A);\ gb \to tH^{\pm},\ ...$
SUSY	$\tilde{t}_R$ light	$t \to \tilde{t}\chi;\ \tilde{t} \to t\chi,\ ...$
	radiative EWSB	m_h light, $\tan\beta$ large
Strong dynamics/	enhanced couplings $\rho_{TC}^{0,\pm}$	$WW \to t\bar{t}, ...$
Extra Dim	$G_{KK}, g_{KK}, Z', W'^{\pm}$ ...	$\to t\bar{t},\ t\bar{b}$
4^{th} family/	$t',\ b'$	$t',\ b' \to tX^0,\ bX^{\pm},\ cX$
Little Higgs	naturalness TtH	$T \to tA^0$

Pretty much in any new physics scenarios related to the EWSB, top quark will play a significant role.

New Physics: Top Tools

- Large mass →
  Access to new decay channels
- Short life-time →
  Direct probe for spin correlation &
  other (bare-quark) quantum numbers (Q_t, B_t …)
- Reconstructable →
  leptonic, hadronic, top-tag …
- Large Yukawa coupling →
  Portal to Higgs & EWSB sector

Now some (incomplete) illustrative examples …

Franceschini's talk

Top Decays

-- Anything not "well-done" is "rare".

SM:

BR(t → s W) ~ 0.16%

BR(t → d W) ~ 6.4×10^{-5}

BR(t → b W*h) ~ 1.8×10^{-9}

BR(t → c g) ~ 5×10^{-12}

BR(t → c γ) ~ 5×10^{-14}

BR(t → c Z) ~ 10^{-14}

BR(t → c h) ~ 3×10^{-15}

SM unobservable!

Discovery for flavor-violations; new light particles in loops …

arXiv:1311.2028

B. Lemmer's talk

Probes:

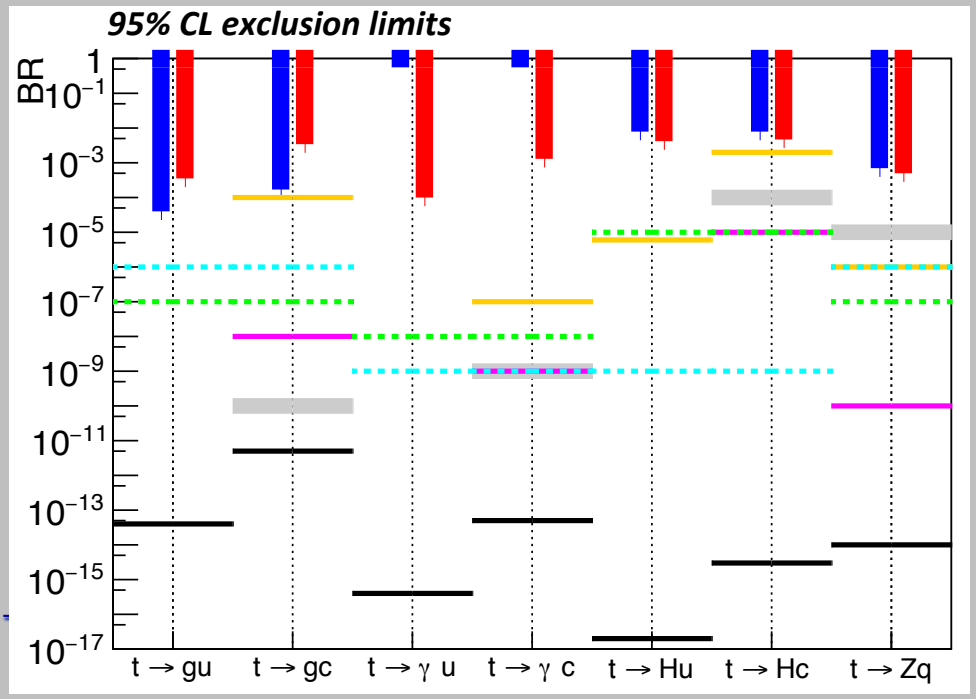
LHC: only a loose bound.

uhm …

Aguilar–Saavedraa, Onofre: arXiv:1002.4718

Higgs! Important to verify!

TH, R. Ruiz: arXiv:1312.3324



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BSM:

$BR(t \to b\, H^{\pm}) < 0.3\%$

$BR(t \to \tilde{t}\, \chi^0)$?

$BR(t \to \bar{b}\, \bar{u}\, e^+) < 0.15\%$ (CMS)

NP Probes:

Important to push forward!

Not much room, but watch out.

B-L reconstructable:

$m(jje) = m_t$; $m(jj) \neq M_W$

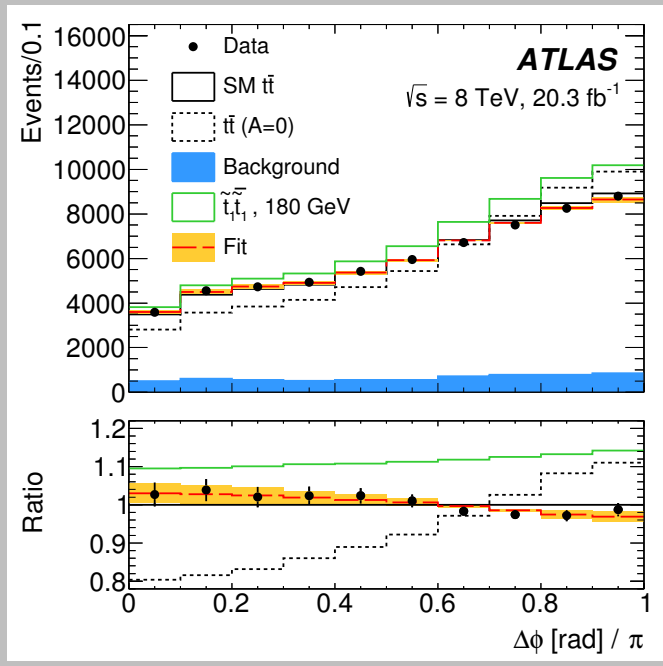
Z. Dong et el.: arXiv:1107.3805

Spin Correlations, Asymmetries in Top Production

ATLAS: arXiv:1412.4742
CMS-PAS-TOP-13-001
C. Gerber's talk

Top pair spin correlation via l^+l^- observed by D0, ATLAS, CMS.

Good agreement with SM excludes the stop pair contribution in m_t – 190 GeV



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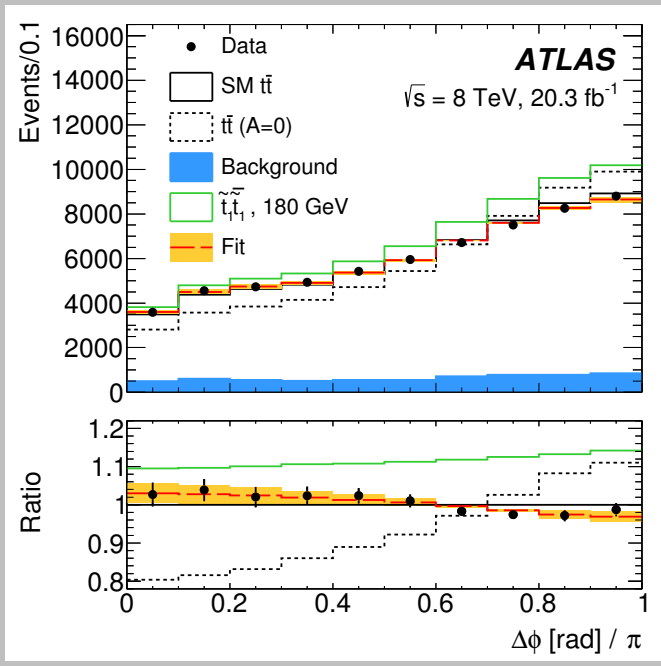

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A set of spin correlation observables may be sensitive to NP.

Bernreuther, Heisler, Si: arXiv:1508.0527

A set of charge asymmetries may be sensitive to NP.

Aguilar-Saavedra et al., arXiv:1406.1798

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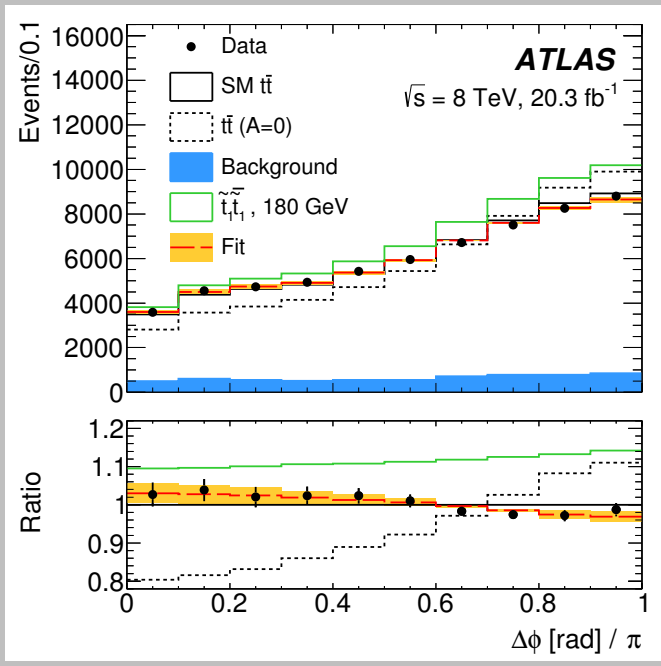

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Also important! Understand individual channels:
t t-bar, t-channel t, s-channel t, and tW

New Resonances to Tops

$q\bar{q}, gg \rightarrow R^* \rightarrow t\,\bar{t}$

Frederix and Maltoni, 0712.2355
Barger, Han, Walker, hep-ph/0612016

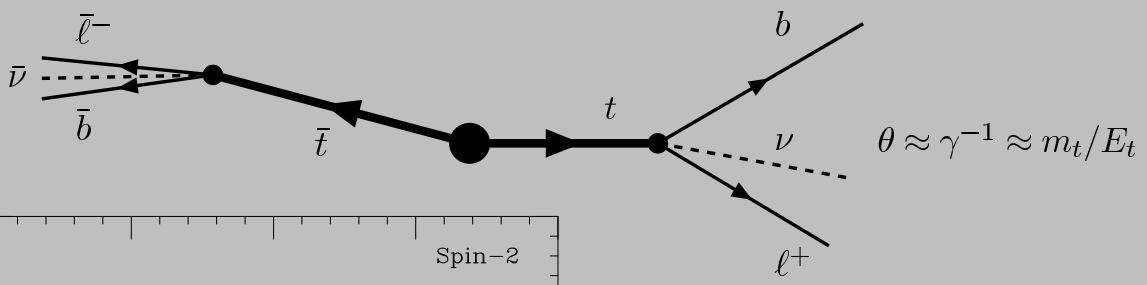
Spin	color	parity $(1, \gamma_5)$	some examples/Ref.
0	0	(1,0)	SM/MSSM/2HDM, Ref. [51, 52, 53]
0	0	(0,1)	MSSM/2HDM, Ref. [52, 53]
0	8	(1,0)	Ref. [54, 55]
0	8	(0,1)	Ref. [54, 55]
1	0	(SM,SM)	Z'
1	0	(1,0)	vector
1	0	(0,1)	axial vector
1	0	(1,1)	vector-left
1	0	(1,-1)	vector-right
1	8	(1,0)	coloron/KK gluon, Ref. [56, 57, 58]
1	8	(0,1)	axigluon, Ref. [57]
2	0	–	graviton "continuum", Ref. [17]
2	0	–	graviton resonances, Ref. [18]

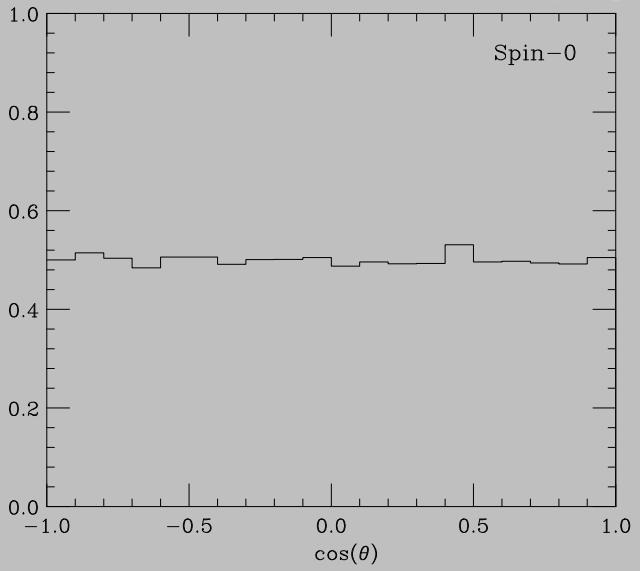
Table 1: The BSM particles included in the `topBSM` "model".

Current 95% CL exclusion on color resonance: 2-3 TeV

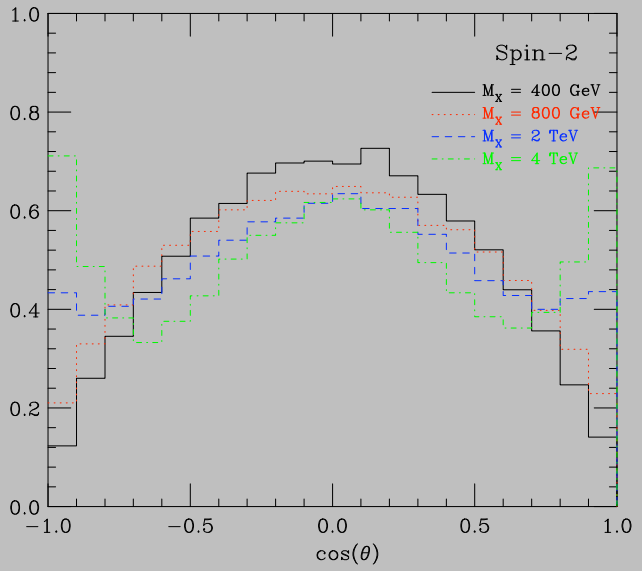
Features:

Boosted top jet





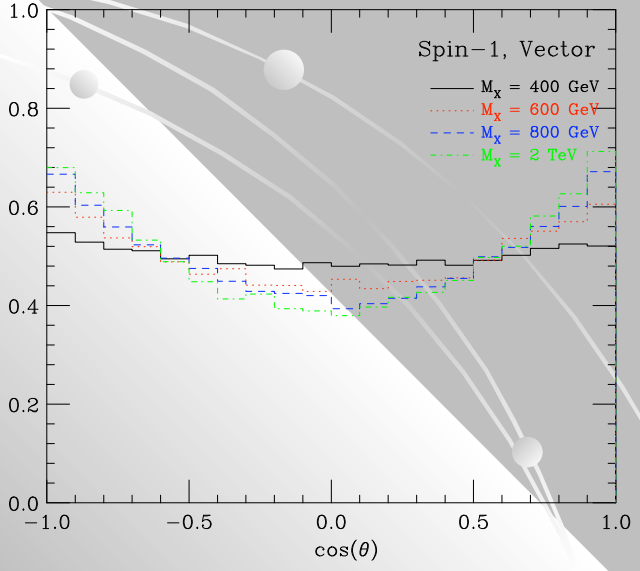
(a)

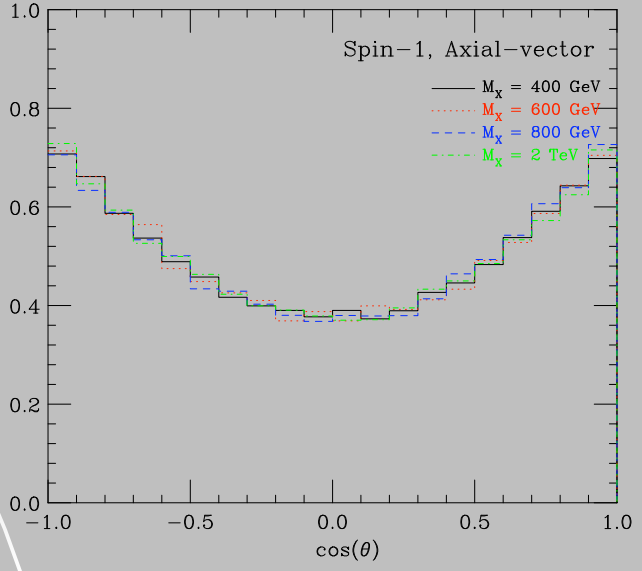


(b)

Diagnostic studies for spin / chiral couplings:

in polar angle distributions

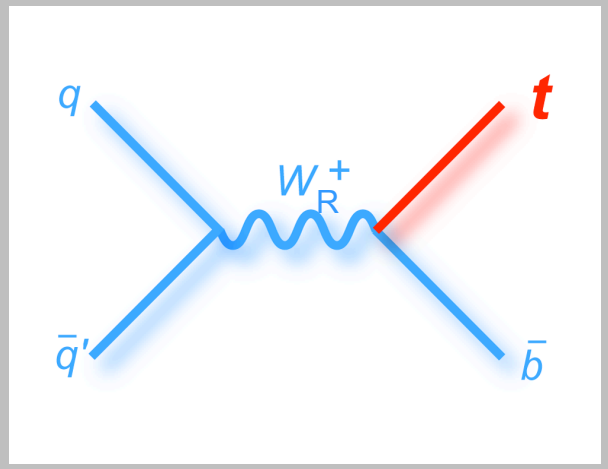




T. Han, 0804.3718

Charged Resonance:

$W_R^{\pm}$ remains to be a top contender for the LHC "di-boson" anomalies*, this tb channel should serve as a crucial test !



Junjie Zhu's talk;
Dobrescu & Liu, arXiv:1506.06736

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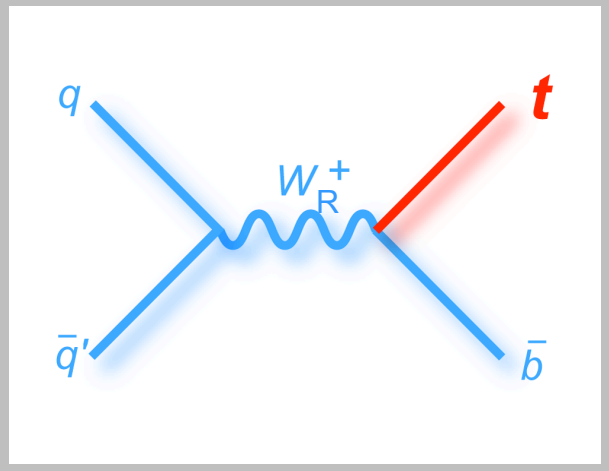

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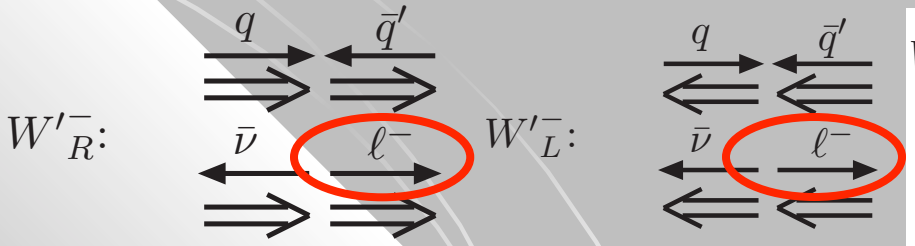
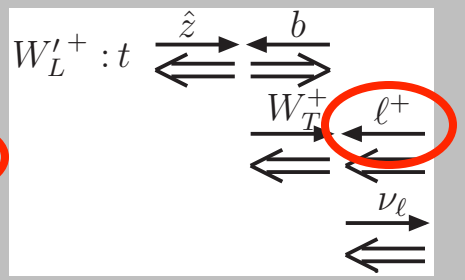
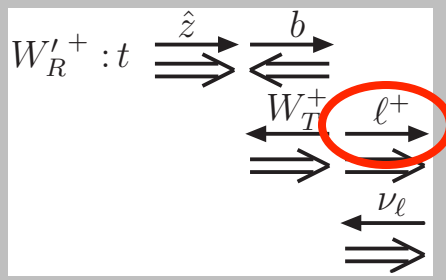
Top spin as a discriminator for $W'_{L,R}$ chirality:

$d\,\bar{u} \to W^- \to e^-\,\nu$



$d\,\bar{u} \to W_{L,R}^- \to \bar{t}b \to e^-\nu\,bb$

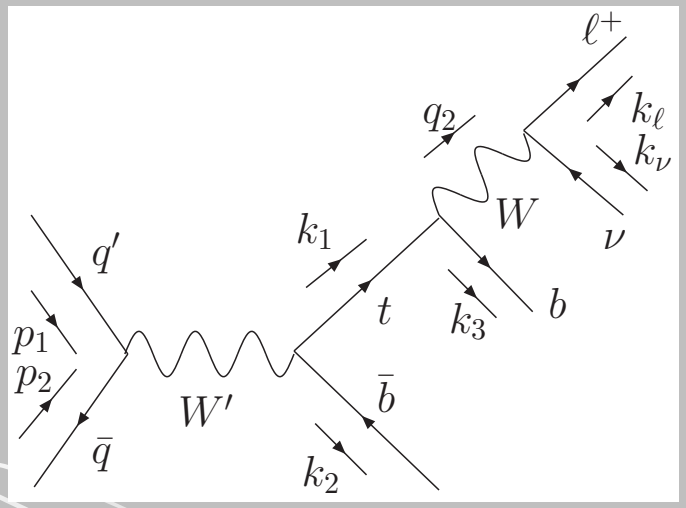




Repko, Frere; Si et al.

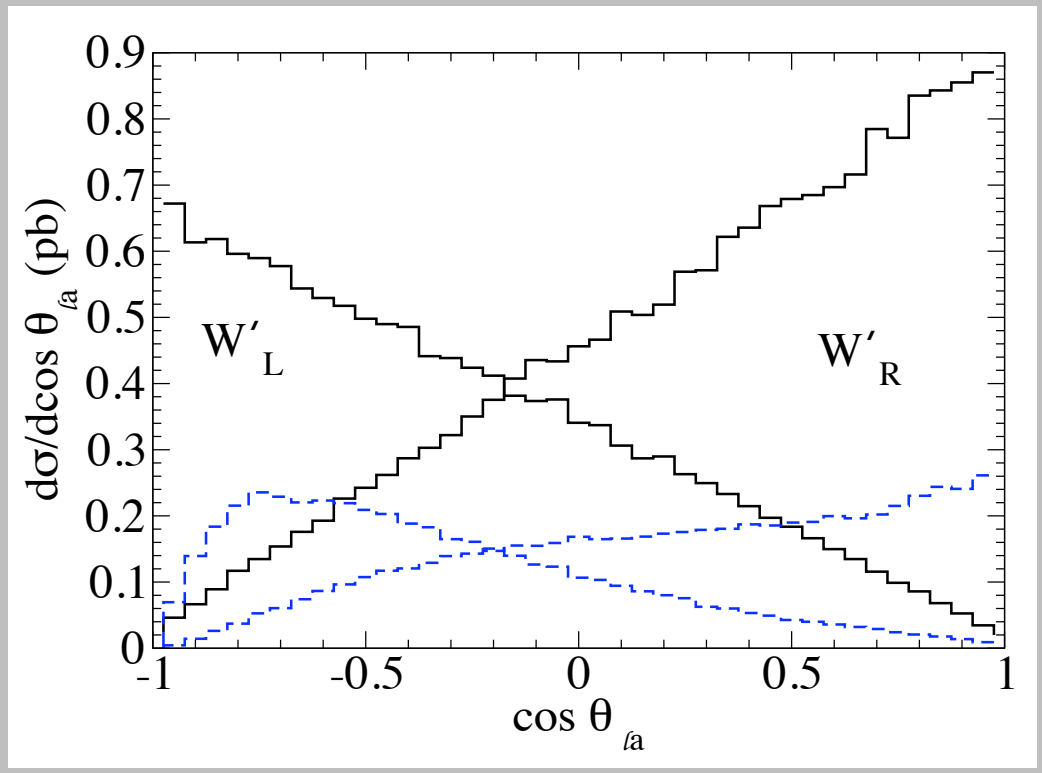
Top as a "Polarizer"

Define a polar angle of a charge lepton in the top-rest frame, w.r.t the top momentum direction:



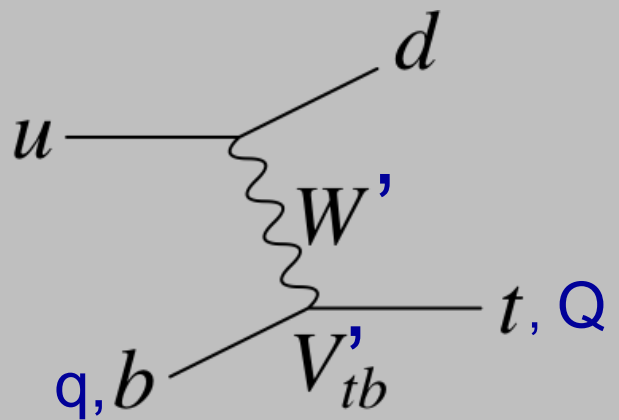
$$\frac{d\hat{\sigma}}{d\cos\theta_\ell} \propto 1 + A \cos\theta_\ell,$$

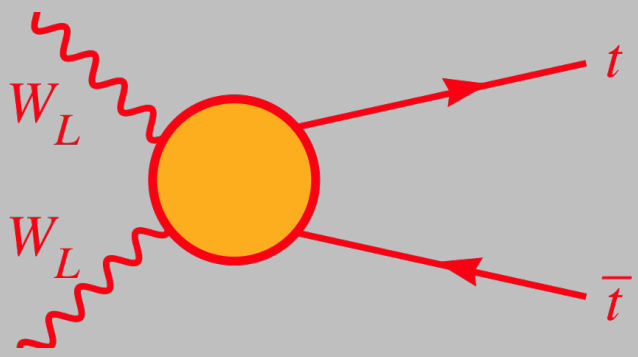
$$A = \frac{g_R^{tb\,2} - g_L^{tb\,2}}{g_R^{tb\,2} + g_L^{tb\,2}}.$$



I. Lewis et al., arXiv:1008.3508

Non-Resonance t-channel Enhancement

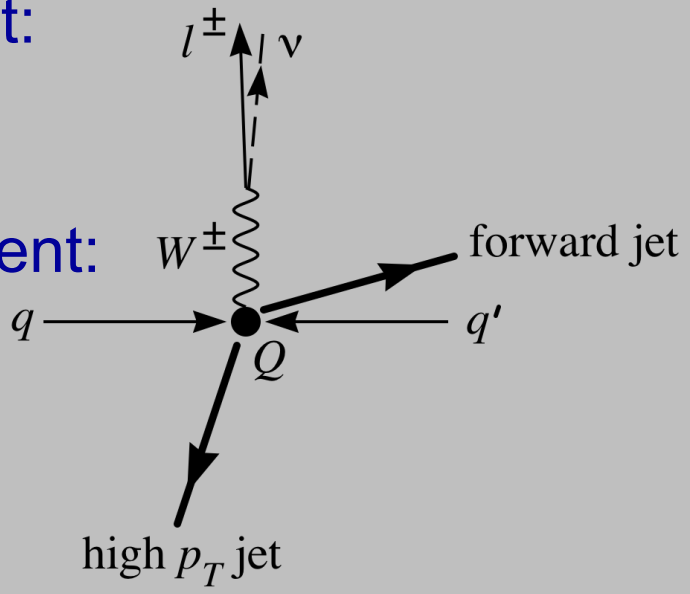




Forward jet tagging: VBF kinematics

- t-channel vector boson enhancement:
  $\ln(s/M^2_W)$
- longitudinal gauge boson enhancement:
  M_Q/M_W

* Unique kinematics Q → W q



Top + Missing Particles

In SUSY:

scalar top: $\tilde{t} \rightarrow t\,\chi^0,\ t\,\chi_{2,3}^0\,(W\chi^{\pm},\ Z/h\chi^0),\ b\,\chi^{\pm}\,(W\chi^0)$

Partner's partners: $\tilde{b} \rightarrow t\,\chi^{\pm}\,(W\chi^0),\ b\,\chi^0,\ b\,\chi_{2,3}^0\,(W\chi^{\pm},\ Z/h\chi^0)$

$\tilde{g} \rightarrow tt,\ bb\ \ldots$

Final state signals: Missing ET + top-rich events

(n) tt + (m)V's/h's + MET (dark matter connection)

Current search: No bounds for $m_{\chi 0} > 250\ GeV.$

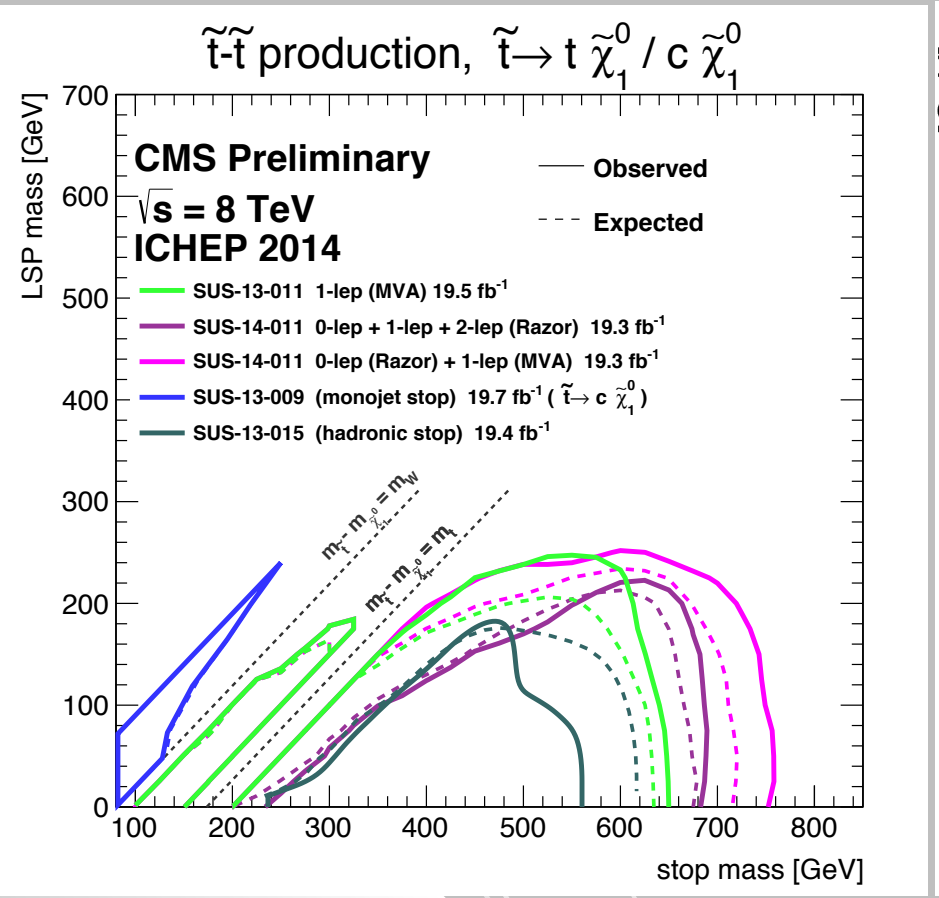
"Compressed/stealthy SUSY" even more challenging !

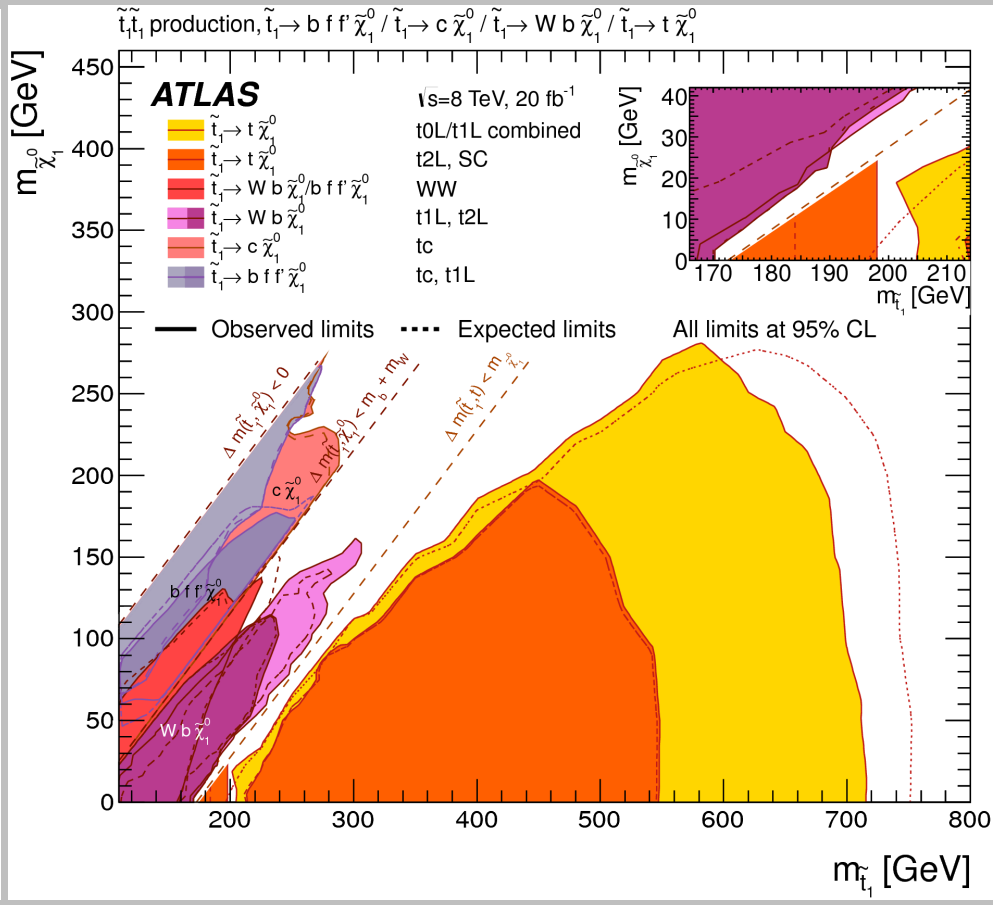
In Composite (or Little) Higgs:

Fermionic partner: $T \rightarrow t\,A^0,\ b\,W_H^{\pm},\ t\,Z_H/h$

Color-octet partner: $G_{KK} \rightarrow t_{kk}\,t$

Well-known searches and results:
m(stop) > 700-800 GeV,
but m(stop) ~ m_t+m_χ difficult !





Top Partner → Top + Missing Particles: $Y \to t\,X$

C. Chen et al., arXiv:1207.4794

	Y $J_Y,\ I_{\mathrm{SU}(3)}$	X $J_X,\ I_{\mathrm{SU}(3)}$	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 $t_{\mathrm{KK}} \to t\gamma_{H,\mathrm{KK}}$
iii	$\frac{1}{2},\ \mathbf{3}$	$1,\ \mathbf{1}$	$\overline{Y}\not{G}^a T^a Y$	$\overline{Y}\not{X}\Gamma t$	UED $t_{\mathrm{KK}} \to t\gamma_{\mathrm{KK}}$
iv	$1,\ \mathbf{3}$	$\frac{1}{2},\ \mathbf{1}$	$S_3[G, Y, Y^*]$	$\overline{X}\not{Y}^*\Gamma t$	[12] $\vec{Q} \to t\tilde{\chi}_1^0$

Current ATLAS Bounds:

J_Y	Limit on m_Y
0	$\gtrsim 500$ GeV
1/2	$\gtrsim 650$ GeV
1	$\gtrsim 730$ GeV

Top Partner → Top + Missing Particles:

$Y \to t\,X$

C. Chen et al., arXiv:1207.4794

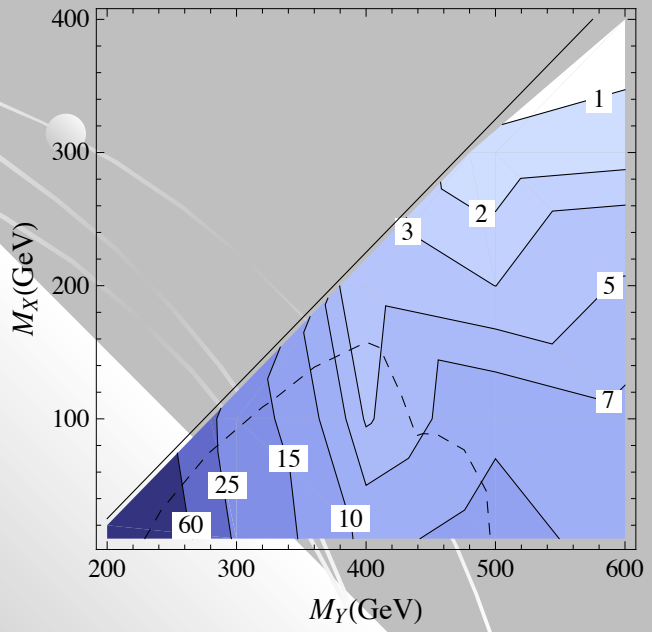
	Y $J_Y,\ I_{SU(3)}$	X $J_X,\ I_{SU(3)}$	GYY coupling	XYt coupling	sample model and decay $Y \to tX$
i	$0,\ \mathbf{3}$	$\frac{1}{2},\ \mathbf{1}$	$G^{a\mu}Y^*\overleftrightarrow{\partial_\mu}T^aY$	$\overline{X}\Gamma t\,Y^*$	MSSM $\tilde{t} \to t\tilde{\chi}_1^0$
ii	$\frac{1}{2},\ \mathbf{3}$	$0,\ \mathbf{1}$	$\overline{Y}\not{G}^aT^aY$	$\overline{Y}\Gamma t\,X$	UED $t_{KK} \to t\gamma_{H,KK}$
iii	$\frac{1}{2},\ \mathbf{3}$	$1,\ \mathbf{1}$	$\overline{Y}\not{G}^aT^aY$	$\overline{Y}\not{X}\Gamma t$	UED $t_{KK} \to t\gamma_{KK}$
iv	$1,\ \mathbf{3}$	$\frac{1}{2},\ \mathbf{1}$	$S_3[G,Y,Y^*]$	$\overline{X}\not{Y}^*\Gamma t$	[12] $\vec{Q} \to t\tilde{\chi}_1^0$

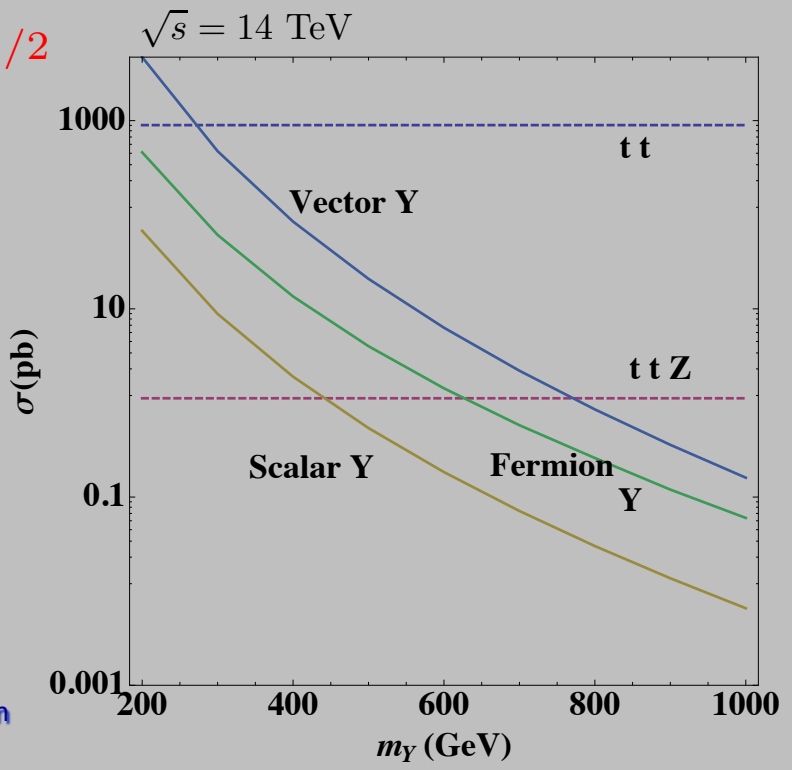
Current ATLAS Bounds:

J_Y	Limit on m_Y
0	$\gtrsim 500$ GeV
1/2	$\gtrsim 650$ GeV
1	$\gtrsim 730$ GeV

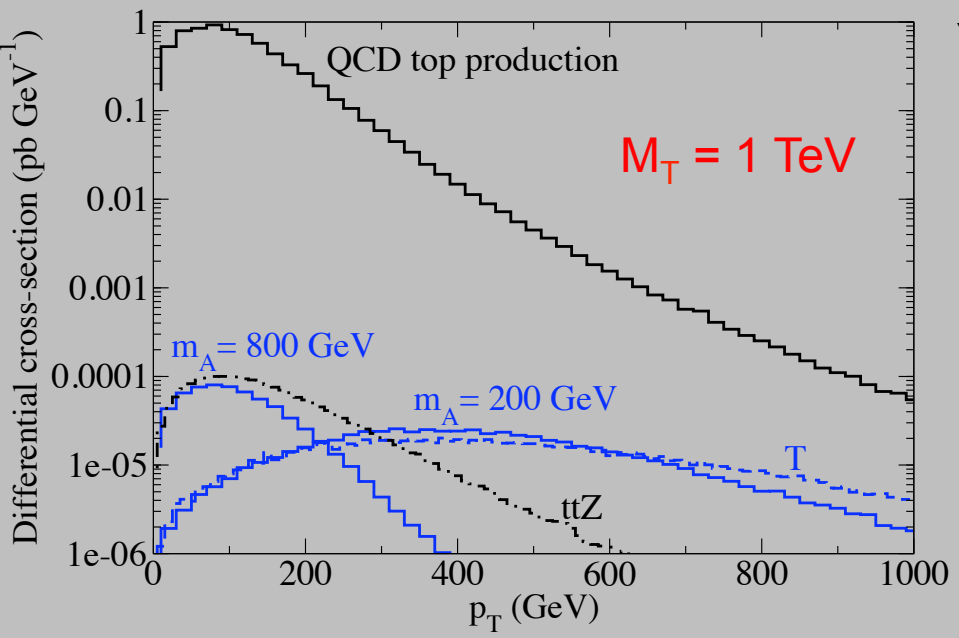
$$\sigma(YY)_{J=1} \approx (2-3)\ \sigma(T\bar{T})_{1/2}$$

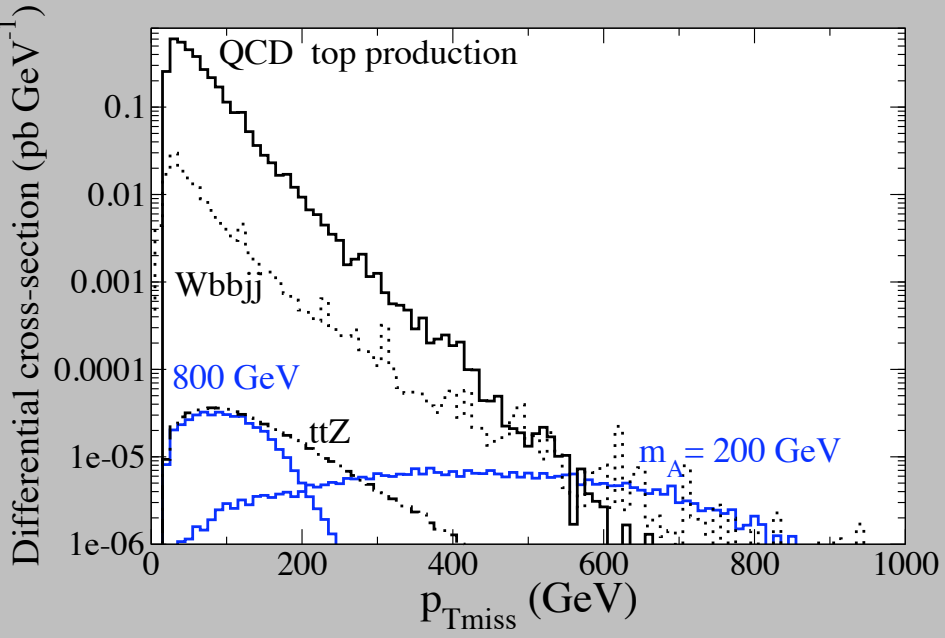
$$\sigma(T\bar{T})_{1/2} \approx 8\ \sigma(\tilde{t}\tilde{t})_0$$





$$pp \to T\bar{T}\ X \to tA^0\ \bar{t}A^0\ X \to t\bar{t} + \not{E}_T + X,$$





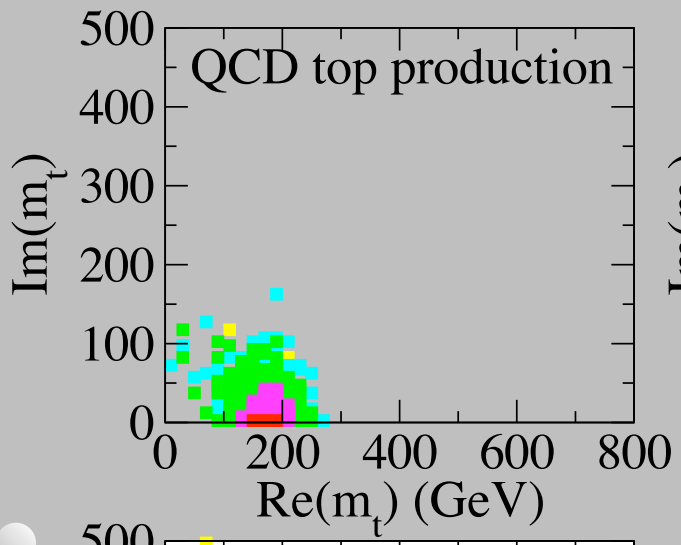
How to dig the tops out in the (nearly) degenerate region?

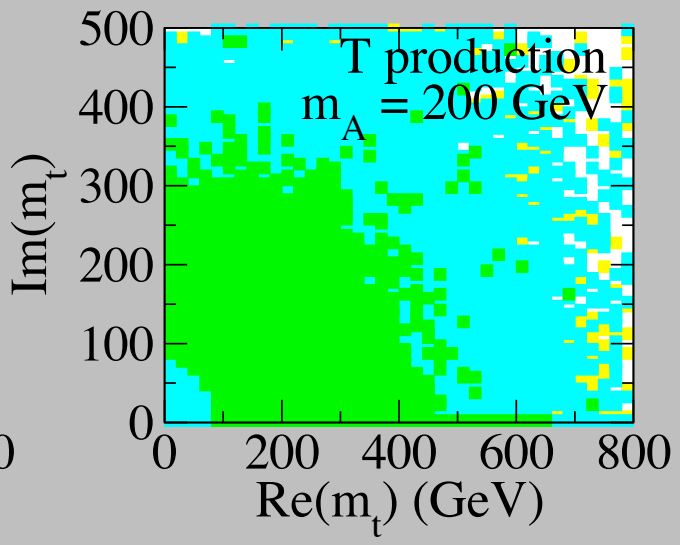
TH et al., arXiv:0803.3820

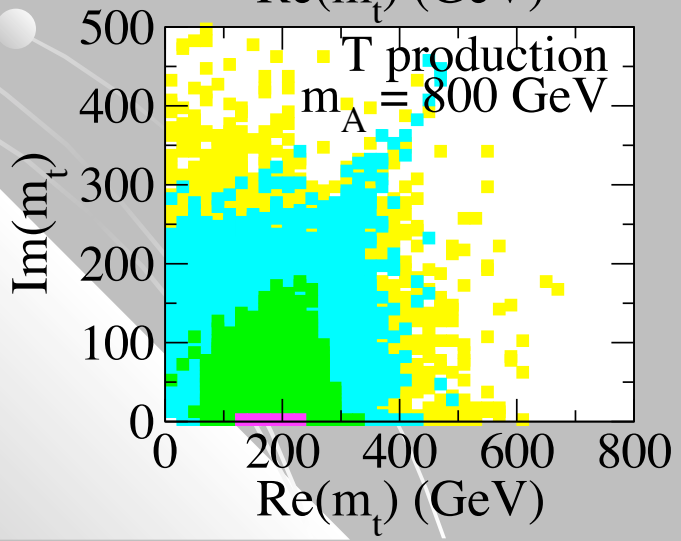
Top mass reconstruction ?

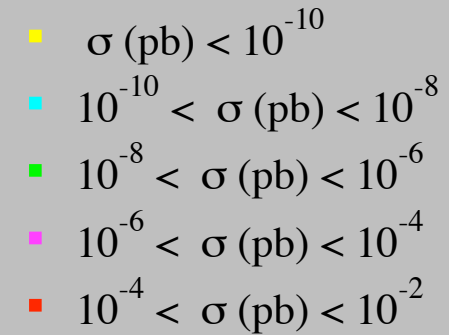
$(p_l + p_n)^2 = M_W^2$, $(p_l + p_n + p_b)^2 = m_t^2$

If $p_n \neq p_\nu$, then M_W^{rec}, m_t^{rec} unphysical, thus separate from the SM tops









TH et al., arXiv:0803.3820

Top-rich Events: From Partner's Partner

Color-Octet: $Z \to Y t \to tX, t$

C. Chen et al., arXiv:1410.8113

	$\mathcal{Z}$ s, $I_{\mathrm{SU}(3)}$	Y s, $I_{\mathrm{SU}(3)}$	$G\mathcal{Z}\mathcal{Z}$ coupling	$\mathcal{Z}Yt$ coupling	sample model and decay $\mathcal{Z} \to Y\bar{t}$	
v	0, **8**	$\frac{1}{2}$, **3**	$G^{a\mu}\mathcal{Z}^c \overleftrightarrow{\partial_\mu} \mathcal{Z}^b f^{abc}$	$\overline{Y} T^a \Gamma' t \mathcal{Z}^a$	UED	$g_H \to t_{\mathrm{KK}}\bar{t}$
vi(a)	$\frac{1}{2}$, **8**	0, **3**	$\overline{\mathcal{Z}}^c \not{G}^a \mathcal{Z}^b f^{abc}$	$\overline{\mathcal{Z}}^a Y^* T^a \Gamma' t$	MSSM	$\tilde{g} \to \tilde{t}\bar{t}$
vi(b)	$\frac{1}{2}$, **8**	0, **3**	$\overline{\mathcal{Z}}^c_D \not{G}^a \mathcal{Z}^b_D f^{abc}$	$(\overline{\mathcal{Z}}^a_D)^* Y^* T^a b_L t_L$ $+ \overline{\mathcal{Z}}^a_D Y^* T^a b_R t_R$	$\mathcal{N} = 2$ SUSY	$\tilde{g}_D \to \tilde{t}\bar{t}$
vii	$\frac{1}{2}$, **8**	1, **3**	$\overline{\mathcal{Z}}^c \not{G}^a \mathcal{Z}^b f^{abc}$	$\overline{\mathcal{Z}}^a \not{Y}^* T^a \Gamma' t$	[34]	$\tilde{g} \to \vec{Q}\bar{t}$
viii	1, **8**	$\frac{1}{2}$, **3**	$S_8[G, \mathcal{Z}, \mathcal{Z}]$	$\overline{Y} \not{\mathcal{Z}}^a T^a \Gamma' t$	UED	$g_{\mathrm{KK}} \to t_{\mathrm{KK}}\bar{t}$

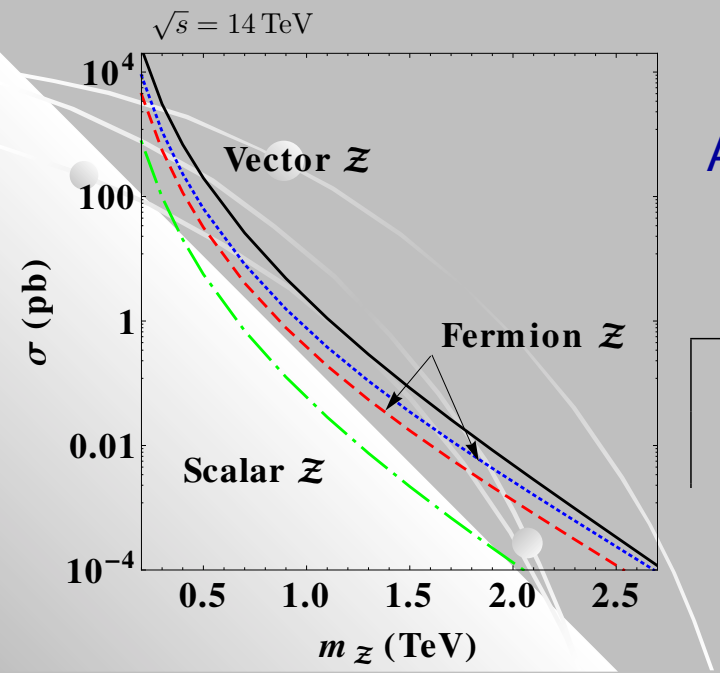
$$pp \to \mathcal{Z}\bar{\mathcal{Z}} \to t\bar{t}\,Y\bar{Y} \to t\bar{t}t\bar{t}X\bar{X}$$

Top-rich Events: From Partner's Partner

Color-Octet: $Z \to Y t \to tX, t$

C. Chen et al., arXiv:1410.8113

	$\mathcal{Z}$ $s,\ I_{\mathrm{SU}(3)}$	Y $s,\ I_{\mathrm{SU}(3)}$	$G\mathcal{Z}\mathcal{Z}$ coupling	$\mathcal{Z}Yt$ coupling	sample model and decay $\mathcal{Z} \to Y\bar{t}$	
v	$0,\ \mathbf{8}$	$\frac{1}{2},\ \mathbf{3}$	$G^{a\mu}\mathcal{Z}^c \overleftrightarrow{\partial_\mu} \mathcal{Z}^b f^{abc}$	$\overline{Y} T^a \Gamma' t \mathcal{Z}^a$	UED	$g_H \to t_{\mathrm{KK}}\bar{t}$
vi(a)	$\frac{1}{2},\ \mathbf{8}$	$0,\ \mathbf{3}$	$\overline{\mathcal{Z}}^c \not{G}^a \mathcal{Z}^b f^{abc}$	$\overline{\mathcal{Z}}^a Y^* T^a \Gamma' t$	MSSM	$\tilde{g} \to \tilde{t}\bar{t}$
vi(b)	$\frac{1}{2},\ \mathbf{8}$	$0,\ \mathbf{3}$	$\overline{\mathcal{Z}}^c_D \not{G}^a \mathcal{Z}^b_D f^{abc}$	$(\overline{\mathcal{Z}}^a_D)^* Y^* T^a b_L t_L$ $+ \overline{\mathcal{Z}}^a_D Y^* T^a b_R t_R$	$\mathcal{N} = 2$ SUSY	$\tilde{g}_D \to \tilde{t}\bar{t}$
vii	$\frac{1}{2},\ \mathbf{8}$	$1,\ \mathbf{3}$	$\overline{\mathcal{Z}}^c \not{G}^a \mathcal{Z}^b f^{abc}$	$\overline{\mathcal{Z}}^a \not{Y}^* T^a \Gamma' t$	[34]	$\tilde{g} \to \vec{Q}\bar{t}$
viii	$1,\ \mathbf{8}$	$\frac{1}{2},\ \mathbf{3}$	$S_8[G, \mathcal{Z}, \mathcal{Z}]$	$\overline{Y} \not{\mathcal{Z}}^a T^a \Gamma' t$	UED	$g_{\mathrm{KK}} \to t_{\mathrm{KK}}\bar{t}$



$$pp \to \mathcal{Z}\bar{\mathcal{Z}} \to t\bar{t}\,Y\bar{Y} \to t\bar{t}t\bar{t}X\bar{X}$$

About a factor of 10 larger than the triplet

LHC reach :

	spin-0 $\mathcal{Z}$	spin-1/2	spin-1
8 TeV (2σ with 21 fb^{-1})	900 GeV	1160 GeV	1290 GeV
14 TeV (5σ with 300 fb^{-1})	1280 GeV	1650 GeV	1900 GeV

T. Han

Top Remarks

Top physics has entered a new exciting era!

- Hard to imagine that top won't play a significant role in the new physics discovery!

- Precision top physics:
  σ(tt), σ(t), m_t, spin correlation/asymmetries, ttH…

- Boosted tops for new heavy resonances:
  jets, b-tagging at high pT, top-taggers …

- Pursue the extreme kinematics:
  tt + low *MET*, high m_{tt}

It is the "Top priority"!