

2014 7<sup>th</sup> International Workshop on Top Quark Physics

## Top Quark and Exotic Models: Theoretical Overview

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## Top Quark and New Physics



### Top quark as a probe of new physics It appears often in the decay of NP resonances



## Vector Quarks

Common in many NP models, Economics for model building

#### Mass Mixing and Heavy Quark Couplings to Higgs

Chiral Doublet

 $-\mathcal{L}_Q = Y_U^{ij} \bar{Q}_L \tilde{\Phi} U_R + Y_D^{ij} \bar{Q}_L \Phi D_R + h.c.$ 

□ SU(2) singlet

 $\square \text{ Up-type} \qquad \qquad \text{SM Yukawa FCNC Yukawa Explicit Dirac mass} \\ \square \text{ Up-type} \qquad \qquad -\mathcal{L}_T = Y_t \overline{q_{0L}} \,\widetilde{\Phi} \, t_{0R} + Y_T \, \overline{q_{0L}} \,\widetilde{\Phi} \, T_{0R} + M_T \, \overline{T_{0L}} T_{0R} + \text{H.c.}$ 

**Down-type**  $-\mathcal{L}_B = Y_b \overline{q_{0L}} \Phi b_{0R} + Y_B \overline{q_{0L}} \Phi B_{0R} + M_B \overline{B_{0L}} B_{0R} + \text{H.c.}$ 

SU(2) doublet

 $-\mathcal{L}_{Q} = Y_{t} \overline{q_{0L}} \widetilde{\Phi} t_{0R} + Y_{T} \overline{Q_{0L}} \widetilde{\Phi} t_{0R} + Y_{B} \overline{Q_{0L}} \Phi b_{0R} + M \overline{Q_{0L}} Q_{0R} + \text{H.c.}$  $-\mathcal{L}_{Q'} = Y_{t} \overline{q_{0L}} \widetilde{\Phi} t_{0R} + Y_{T} \overline{Q'_{0L}} \Phi t_{0R} + M \overline{Q'_{0L}} Q'_{0R} + \text{H.c.}$  $Q_{0L} = \begin{pmatrix} T_{0L} \\ B_{0L} \end{pmatrix}, \ Q_{0R} = \begin{pmatrix} T_{0R} \\ B_{0R} \end{pmatrix}, \ Q'_{0L} = \begin{pmatrix} \mathbf{Y} \\ T_{0L} \end{pmatrix}, \ Q'_{0R} = \begin{pmatrix} \mathbf{Y} \\ T_{0R} \end{pmatrix}$ 

#### SU(2) triplet

Exotic Q=5/3 fermion

 $\begin{aligned} -\mathcal{L}_{\Sigma} &= Y_t \,\overline{q_{0L}} \,\widetilde{\Phi} \, t_{0R} + Y_T \,\overline{q_{0L}} \,\tau^a \,\widetilde{\Phi} \, \Sigma_{0R} + M \,\overline{\Sigma_{0L}} \Sigma_{0R} + \text{H.c.} \\ -\mathcal{L}_{\Sigma'} &= Y_t \,\overline{q_{0L}} \,\widetilde{\Phi} \, t_{0R} + Y_T \,\overline{q_{0L}} \,\tau^a \,\Phi \, \Sigma'_{0R} + M \,\overline{\Sigma'_{0L}} \Sigma'_{0R} + \text{H.c.} \\ \Sigma_{0L} &= \begin{pmatrix} X_{0L} \\ T_{0L} \\ B_{0L} \end{pmatrix}, \, \Sigma_{0R} &= \begin{pmatrix} X_{0R} \\ T_{0R} \\ B_{0R} \end{pmatrix} \, \Sigma'_{0L} = \begin{pmatrix} T_{0L} \\ B_{0L} \\ X_{0L} \end{pmatrix}, \, \Sigma'_{0R} &= \begin{pmatrix} T_{0R} \\ B_{0R} \\ X_{0R} \end{pmatrix} \end{aligned}$ 

/ Quarks, 20-21 Dec 2011

Koji Tsumura (ntu)

Exotic Q=-4/3 fermion  $_4$ 

del Aguila Perez-Victoria Santiago (2000)

> Angular-Saavedra (2009)

Cacciapaglia, Deandrea, Harada, Okada (2010)

### Vector Quarks

 $T \to W^+ b/Zt/Ht$  $B \to W^+ t/Zb/Hb$ 

 $Y \to W^+ t$  $X \to W^- b$ 



#### Very Rich Collider Signatures

Extra Color Gauge Boson				
$SU(3)_1 \times SU(3)_2 \to SU(3)_C$			q=u,d,c,s	
Model	$SU(3)_1$	$SU(3)_2$		
Classic Axigluon Frampton, Glashow (1987)	$t_R \ b_R \ q_R$	$q_L \ (t,b)_L$	dijet, AFB(t)	
New Axigluon Frampton, Shu, Wang (2010)	$q_L t_R b_R$	$(t,b)_L q_R$	dijet, AFB(t)	
Topgluon Hill (1991)	$q_L q_R$	$(t,b)_L t_R b_R$	dijet, FCNC	
+ Extra color scalars				

## Extra Weak Boson and Quarks

G(221) Model

 $SU(3)_C \times SU(2)_1 \times SU(2)_2 \times U(1)_X$ 



## $\frac{SU(3)_C \times SU(3)_W \times U(1)_X}{G(331) \text{ Model}}$

### Extra Weak Gauge Bosons 221 Model: $SU(2)_1 \otimes SU(2)_2 \otimes U(1)_X$



### Extra Weak Gauge Bosons 221 Model: $SU(2)_1 \otimes SU(2)_2 \otimes U(1)_X$



 $\mathcal{L} = \bar{q}\gamma^{\mu}(g_L^{Z'}P_L + g_R^{Z'}P_R)q\ Z'_{\mu} + +\bar{q}\gamma^{\mu}(g_L^{W'}P_L + g_R^{W'}P_R)q'\ W'_{\mu} + h.c.$ 

	W'tb	$Z'tar{t}$
SSM	$\frac{g_2}{\sqrt{2}}\bar{b}\gamma_{\mu}P_L tW'^{\mu}$	$\frac{g_2}{6c_w}\bar{t}\gamma_\mu((-3+4s_w^2)P_L+4s_w^2P_R)tZ'^\mu$
LRM	$\frac{g_2}{\sqrt{2}}\bar{b}\gamma_{\mu}P_R tW'^{\mu}$	$\frac{g_2 t_w}{6} \bar{t} \gamma_\mu \left(\frac{1}{\alpha_{LR}} P_L + \left(\frac{1}{\alpha_{LR}} - 3\alpha_{LR}\right) P_R\right) t Z'^\mu$
Top-Flavor	$\frac{g_2 \sin \tilde{\phi}}{\sqrt{2}} \bar{b} \gamma_\mu P_L t W'^\mu$	$\frac{g_2 \sin \tilde{\phi}}{\sqrt{2}} \bar{t} \gamma_\mu P_L t Z'^\mu$

Extra Weak Gauge Bosons 331 Model:  $SU(3)_C \otimes \overline{SU(3)_W} \otimes U(\overline{1})_X$  $SU(3) \times U(1)_X \xrightarrow{H_1} SU(2)_L \times U(1)_Y \xrightarrow{H_2} U(1)_{em}$  $\begin{pmatrix} u \\ d \\ D \end{pmatrix} \begin{pmatrix} c \\ s \\ S \end{pmatrix} \begin{pmatrix} b \\ -t \\ T \end{pmatrix}$  $3 \quad 3 \quad \overline{3}$ 

Z-prime: flavor changing coupling to u- and top-quark also the chiral coupling to light-quarks and top-quarks

> Diaz, Martinez, Ochoa, hep-ph/0309280 Barreto, Coutinho, Sa Borges, 1103.1266 Buras, Fazio, Girrbach, Carlucci, 1211.1237

# Exotic Colored Scalars/Vectors

$$\begin{aligned} \mathcal{L} &= \left(g_{1L}\overline{q_{L}^{c}}i\tau_{2}q_{L} + g_{1R}\overline{u_{R}^{c}}d_{R}\right)\Phi_{6,1,1/3} & q_{L} = \left(\begin{smallmatrix} u_{L} \\ d_{L} \end{smallmatrix} \right) \\ &+ g_{1R}\overline{d_{R}^{c}}d_{R}\Phi_{6,1,-2/3} + g_{1R}''\overline{u_{R}^{c}}u_{R}\Phi_{6,1,4/3} & q_{L} = \left(\begin{smallmatrix} u_{L} \\ d_{L} \end{smallmatrix} \right) \\ &+ g_{3L}\overline{q_{L}^{c}}i\tau_{2}\tau q_{L} \cdot \Phi_{6,3,1/3} & q^{c} = C\bar{q}^{T} \\ &+ g_{2}\overline{q_{L}^{c}}\gamma_{\mu}d_{R}V_{6,2,-1/6}^{\mu} + g_{2}'\overline{q_{L}^{c}}\gamma_{\mu}u_{R}V_{6,2,5/6}^{\mu} + h.c. , \\ &\Phi_{6,3} & \downarrow^{t_{L}} & \Phi_{6,1} & \downarrow^{t_{R}} & \bigvee_{6,2} \\ &\downarrow^{t_{L}} & \downarrow^{t_{L}} & \downarrow^{t_{R}} & \bigvee_{6,2} \\ &\downarrow^{t_{L}} & \downarrow^{t_{R}} & \bigvee_{6,2} \\ &\downarrow^{t_{R}} & \downarrow^{t_{R}} & \downarrow^{t_{R}} & \downarrow^{t_{R}} \\ &\downarrow^{t_{R}} & \downarrow^{t_{R}} & \downarrow^{t_{R}} \\ &\downarrow^{t_{R}} & \downarrow^{t_{R}} & \downarrow^{t_{R}} & \downarrow^{t_{R}} \\ &\downarrow^{t_{R}} & \downarrow^{t_{R}} & \downarrow^{t_{R}} & \downarrow^{t_{R}} & \downarrow^{t_{R}} \\ &\downarrow^{t_{R}} & \downarrow^{t_{R}} & \downarrow^{t_{R}} & \downarrow^{t_{R}} \\ &\downarrow^{t_{R}} & \downarrow^{t_{R}} & \downarrow^{t_{R}} & \downarrow^{t_{R}} & \downarrow^{t_{R}} & \downarrow^{t_{R}} & \downarrow^{t_{R}} \\ &\downarrow^{t_{R}} & \downarrow^{t_{R}} & \downarrow^{t_$$

UU

4/3

4/3

## Top Quark and New Physics



## Single Top Quark Production

Production

Others

Proton



Proton

## Single Top Quark Production

 $\mathcal{U}$ b Ws-channel  $Q_W^2 > 0$ 



New resonance

t-channel

 $Q_W^2 < 0$ 

 $\begin{array}{c} u \longrightarrow u \\ \overbrace{S}Z'S_0 \\ u/c \longrightarrow t \end{array}$ 

FCNC



 $Q_W^2 = m_W^2$ 



Excited quark

Tait, Yuan, hep-ph/0007298 QHC, Wudka, Yuan, 0704.2809 Drueke, Schwienhorst, Vignaroli, Walker, Yu, 1409.7607

### Single Top Quark Production (s-channel resonance and t-channel FCNC)



Tait, Yuan, hep-ph/0007298

Drueke, Schwienhorst, Vignaroli Walker, Yu, 1409.7607



Gogoladze et al, 1001.5260

## Single Top Quark Production

(s-channel excitation quark)



Nutter, Schwienhorst, Walker, Yu, 1207.5179

$$\mathcal{L} = g_s \bar{B}' \gamma^{\mu} B' + \frac{g_s \lambda}{2\Lambda} G_{\mu\nu} \bar{b} \sigma^{\mu\nu} \left(\kappa_L^b P_L + \kappa_R^b P_R\right) B' + h.c.$$
$$\mathcal{L} = \frac{g_W}{\sqrt{2}} W^+_{\mu} \bar{t} \gamma^{\mu} (f_L P_L + f_R P_R) B' + h.c.$$

## Single Heavy Quark Production



Little Higgs Perelstein, Peskin, Pierce hep-ph/0310039



Composite Higgs Li, Liu, Shu, 1306.5841 Boosted jet-substructure



Reuter, Tonini, 1409.6962

## Mono Top Quark Production (R-parity violating SUSY inspired)

see Theveneaux-Pelzer's poster

Andrea, Fuks, Maltoni, 1106.6199 Wang, Li, Shao, Zhang, 1109.5963



## Top-Antitop or Top-Top Quark Pair Production

Production

Others

Proton

19

Proton

## TOP @ inSPIRE

#### Search for papers with 'top' in title



## Top-quark F-B asymmetry in the SM (A charge asymmetry arises at NLO)





## Timeline of top-quark AFB



## Timeline of $A_{FB}^t$ and NP models



Forward-Backward Asymmetry in Top Quark Production in  $p\bar{p}$  Collisions at sqrts = 1.96 TeV CDF Collaboration (T. Aaltonen (Helsinki Inst. of Phys.) *et al.*). Jun 2008. 8 pp. Published in Phys.Rev.Lett. 101 (2008) 202001 FERMILAB-PUB-08-171-E DOI: <u>10.1103/PhysRevLett.101.202001</u> e-Print: <u>arXiv:0806.2472 [hep-ex] | PDF</u> <u>References | BibTeX | LaTeX(US) | LaTeX(EU) | Harvmac | EndNote</u> <u>CERN Document Server ; ADS Abstract Service; Fermilab Library Server (fulltext available)</u> Detailed record - Cited by 229 records

Evidence for a Mass Dependent Forward-Backward Asymmetry in Top Quark Pair Production CDF Collaboration (T. Aaltonen (Helsinki Inst. of Phys.) *et al.*). Jan 2011. 23 pp. Published in Phys.Rev. D83 (2011) 112003

FERMILAB-PUB-10-525-E

DOI: <u>10.1103/PhysRevD.83.112003</u>

e-Print: arXiv:1101.0034 [hep-ex] | PDF

<u>References</u> | <u>BibTeX</u> | <u>LaTeX(US)</u> | <u>LaTeX(EU)</u> | <u>Harvmac</u> | <u>EndNote</u> <u>CERN Document Server</u> ; <u>ADS Abstract Service</u>; <u>Fermilab Library Server (fulltext available</u>); <u>Link to</u> <u>SYMMETRYBREAKING</u>; <u>Fermilab Today Result of the Week</u>

Detailed record - Cited by 425 records 25

#### Forward-backward asymmetry in top quark-antiquark production

D0 Collaboration (Victor Mukhamedovich Abazov (Dubna, JINR) *et al.*). Jul 2011. Published in Phys.Rev. D84 (2011) 112005 FERMILAB-PUB-11-347-E DOI: <u>10.1103/PhysRevD.84.112005</u> e-Print: <u>arXiv:1107.4995</u> [hep-ex] | PDF

<u>References | BibTeX | LaTeX(US) | LaTeX(EU) | Harvmac | EndNote</u> <u>CERN Document Server ; ADS Abstract Service; Fermilab Library Server (fulltext available); Fermilab Today Result of the Week</u>

Detailed record - Cited by 314 records 2504

#### See review: kamenik, Shu, Zupan, 1107.5257 Aguilar-Saavedra, Amidei, Juste, Perez-Victoria, 1406.1798



## Top Quark AFB and NP



## 1) Same Sign Top Quark Pair

s-channel

t-channel



Mohapatra, Okada, Hai-Bo Yu, 0709.1486 Berger, QHC, Chen, Shaughnessy, Zhang, 1005.2622, 1009.5379 Aguilar-Saavedra, Perez-Victoria, 1104.1385 Atwood, Gupta, Soni, 1301.2250



Flavor changing Z-prime Berger, QHC, Chen, Li, Zhang 1101.5625

Maximal flavor violation Bar-Shalom, Rajaraman, Whiteson, Yu, 0803.3795

FCNC effective coupling see Goldouzian's talk, 1408.0493



## 2) Top Quark Pair Plus one Jet

(Flavor Changing Interaction)







Berger, QHC, Chen, Li, Zhang, 1101.5625 Gresham, Kim, Zurek, 1102.0018

### 3) Top Quark Pair Plus One Jet (Third Generation Favored W-prime and Z-prime)



1108.3613

Berger, Cao, Yu, Yuan, Topflavor Seesaw Model He, Tait, Yuan (2000), Wang, Du, He (2013)

### 4) Top Quark Pair Plus One Jet (Charged Higgs Boson)



X-section is large for large tanb in MSSM or Type II 2HDB.

X-section depends on m<sub>H</sub>- and tanb

Top-quark polarization depends on tanb  $D_{\text{decay}} \sim \frac{(m_t \cot \beta)^2 - (m_b \tan \beta)^2)}{(m_t \cot \beta)^2 + (m_b \tan \beta)^2)}$ 

Huitu, Rai, Rao, Rindani, Sharma, 1012.0527 Godbole, Hartgring, Niessen, White, 1111.0759 Gong, Si, Yang, Zheng,1210.7822



QHC, Wan, Wang, Zhu, 1301.6608

## 5) Top Quark Pair Plus Jets

Heavy Quark Pair Production



Color Sextet/Triplet Scalar Pair Production

## 6) Top Quark Pair + Invisibles



#### Top-Quark Mediated Dark Matter Models





Dark Matter Effective Theory:
Cheung, Mawatari, Senaha, Tseng, Yuan, 1009.0618
Gomez, Jackson, Shaughnessy, 1404.1918
UV Completion Theory:
Jackson, Servant, Shaughnessy, Tait, Taoso, 1303.4717



## Triple Top Quark Production



## Triple Top Quark Production



Leptophobic Z' from U'(1) directly couples top-quark to u-quark to explain AFB(t)

Barger, Keung, Yencho, 1001.0211



Topcolor-assisted technicolor model with large FCNC top-coupling to explain AFB(t)

> Cui, Han, Schwartz (2011) Han, Liu, Wu, Yang (2012)



$$O_{uttt}^{LL} = \frac{1}{2} (\bar{u}_{Li} \gamma^{\mu} t_L) (\bar{t}_L \gamma_{\mu} t_L); \qquad O_{uttt}^{RR} = \frac{1}{2} (\bar{u}_{Ri} \gamma^{\mu} t_R) (\bar{t}_R \gamma_{\mu} t_R) O_{uttt}^{LR} = (\bar{u}_{Li} t_R) (\bar{t}_R t_L); \qquad O_{uttt}'^{LR} = (\bar{t}_L u_{iR}) (\bar{t}_R t_L), \qquad (2)$$

Chuan-Ren Chen (2014)



## Four Top Quark Production



TC2



**Top Compositeness** 



Lillie, Shu, Tait (2007) Kumar, Tait, Veg-Morale (2009)

SM QCD production @ NLO, Bevilacqua and Worek, 1206.3064 See Keaveney's poster

## Six or More Top Quark Production

Proton

Production

Others

Proton

## Six or More Top Quark Production

#### Deandrea, Deutschmann, 1405.6119



## Summary

### Top quark as a probe of new physics It appears often in the decay of NP resonances



# Top Quark Production: rich signatures Single Top **Top Pair** (Top)

#### Four Tops

Triple Tops







