top2014 7th International Workshop on Top Quark Physics

Top Quark and Exotic Models: Theoretical Overview

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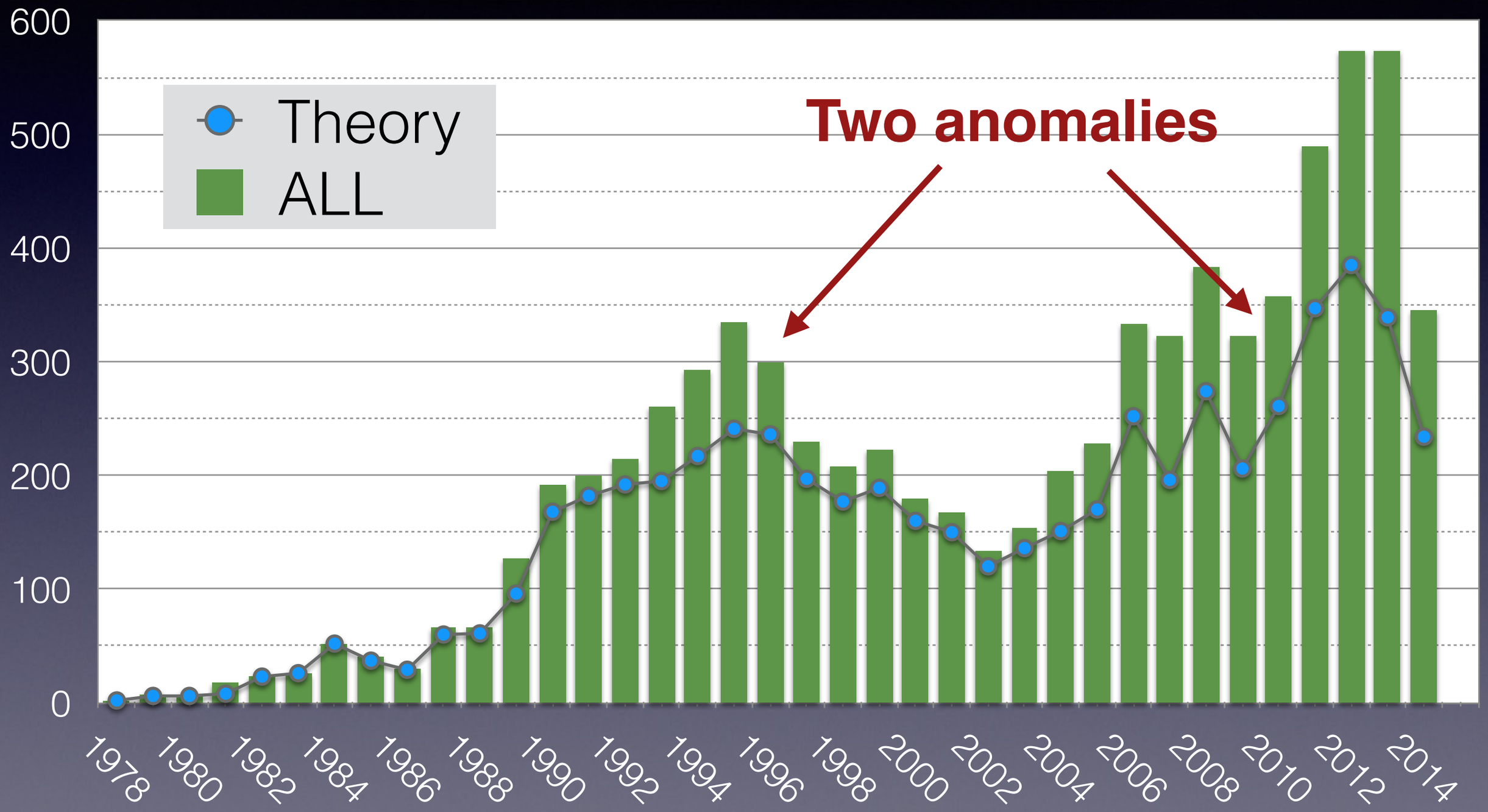
Oct. 02, 2014

TOP @ inSPIRE

Search for papers with ‘top’ in title



I will focus on the second anomaly and NP explanations

Top Quark and New Physics

SUSY, LH, Composite, RS, TC…

Weakly Interacting

Higgs (125GeV)

Strongly Interacting

What should we see?

Natural NP models always have non-trial couplings between top quark and NP particles

Effective Field Theory

Experimental Data

What could we see?

Top quark as a probe of new physics

It appears often in the decay of NP resonances

Extra Gauge Bosons

Z' W' G'

New Heavy Quarks

Vector Quark

4th Gen

Gluino

Top

Exotic Colored States

Color Sextet

Charged Higgs

Heavy Quark Production via pQCD

$\not{CP}$

FCNC

A_{FB}

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**

  SM Yukawa **FCNC Yukawa** **Explicit Dirac mass**

  - Up-type $-\mathcal{L}_T = Y_t\,\overline{q_{0L}}\,\widetilde{\Phi}\,t_{0R} + Y_T\,\overline{q_{0L}}\,\widetilde{\Phi}\,T_{0R} + M_T\,\overline{T_{0L}}T_{0R} + \text{H.c.}$
  - 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**

$$-\mathcal{L}_Q = Y_t\,\overline{q_{0L}}\,\widetilde{\Phi}\,t_{0R} + Y_T\,\overline{Q_{0L}}\,\widetilde{\Phi}\,t_{0R} + Y_B\,\overline{Q_{0L}}\,\Phi\,b_{0R} + M\,\overline{Q_{0L}}Q_{0R} + \text{H.c.}$$

$$-\mathcal{L}_{Q'} = Y_t\,\overline{q_{0L}}\,\widetilde{\Phi}\,t_{0R} + Y_T\,\overline{Q'_{0L}}\,\Phi\,t_{0R} + M\,\overline{Q'_{0L}}Q'_{0R} + \text{H.c.}$$

$$Q_{0L} = \begin{pmatrix} T_{0L} \\ B_{0L} \end{pmatrix},\ Q_{0R} = \begin{pmatrix} T_{0R} \\ B_{0R} \end{pmatrix} \quad Q'_{0L} = \begin{pmatrix} Y \\ T_{0L} \end{pmatrix},\ Q'_{0R} = \begin{pmatrix} Y \\ T_{0R} \end{pmatrix}$$

- **SU(2) triplet** — **Exotic Q=5/3 fermion**

$$-\mathcal{L}_\Sigma = Y_t\,\overline{q_{0L}}\,\widetilde{\Phi}\,t_{0R} + Y_T\,\overline{q_{0L}}\,\tau^a\,\widetilde{\Phi}\,\Sigma_{0R} + M\,\overline{\Sigma_{0L}}\Sigma_{0R} + \text{H.c.}$$

$$-\mathcal{L}_{\Sigma'} = Y_t\,\overline{q_{0L}}\,\widetilde{\Phi}\,t_{0R} + Y_T\,\overline{q_{0L}}\,\tau^a\,\Phi\,\Sigma'_{0R} + M\,\overline{\Sigma'_{0L}}\Sigma'_{0R} + \text{H.c.}$$

$$\Sigma_{0L} = \begin{pmatrix} X_{0L} \\ T_{0L} \\ B_{0L} \end{pmatrix},\ \Sigma_{0R} = \begin{pmatrix} X_{0R} \\ T_{0R} \\ B_{0R} \end{pmatrix} \quad \Sigma'_{0L} = \begin{pmatrix} T_{0L} \\ B_{0L} \\ X_{0L} \end{pmatrix},\ \Sigma'_{0R} = \begin{pmatrix} T_{0R} \\ B_{0R} \\ X_{0R} \end{pmatrix}$$

Exotic Q=-4/3 fermion

del Aguila Perez-Victoria Santiago (2000)

Angular-Saavedra (2009)

Cacciapaglia, Deandrea, Harada, Okada (2010)

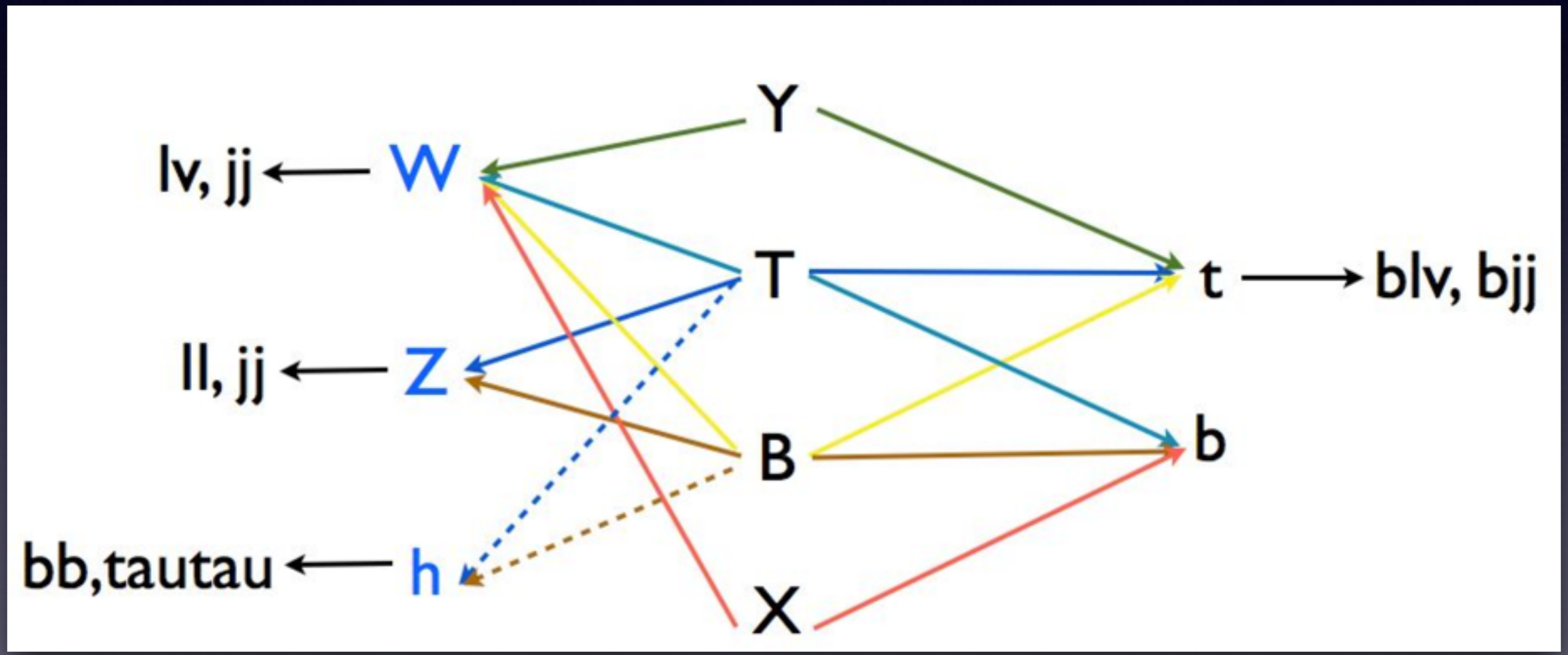
Vector Quarks

$T \to W^+ b / Zt / Ht$

$B \to W^+ t / Zb / Hb$

$Y \to W^+ t$

$X \to W^- b$



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

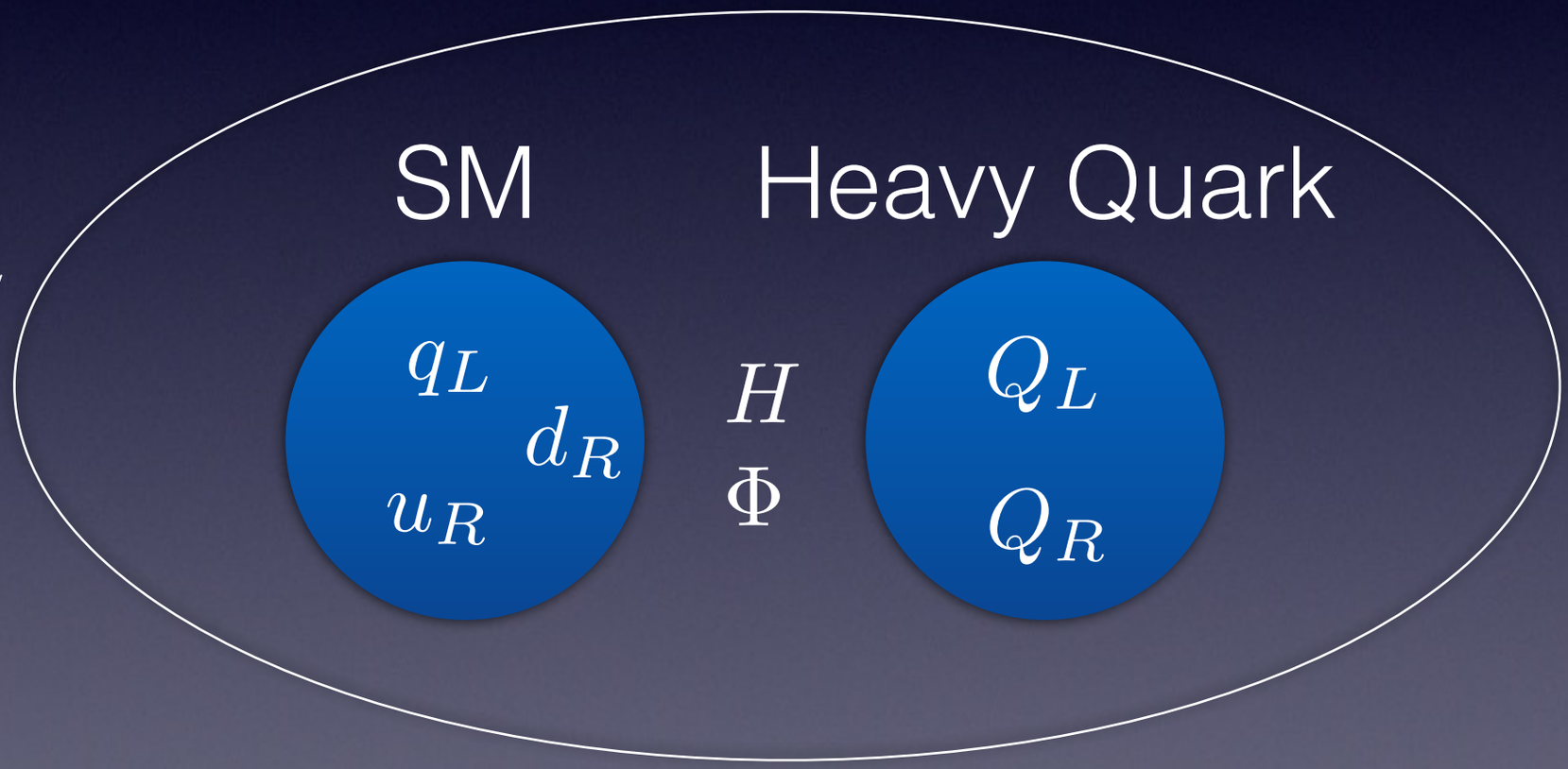
Extra Weak Boson and Quarks

G(221) Model

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

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

U’(1) model
Z-prime



$$SU(3)_C \times SU(3)_W \times U(1)_X$$

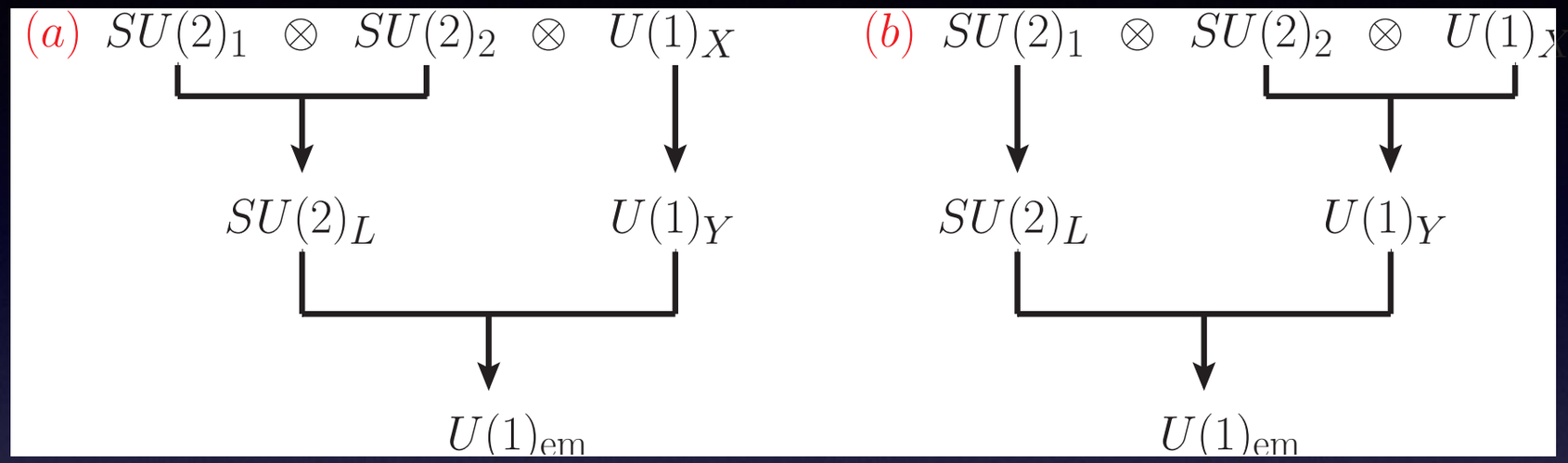
G(331) Model

Extra Weak Gauge Bosons

221 Model: $SU(2)_1 \otimes SU(2)_2 \otimes U(1)_X$

ken, Schmitz, Yu, Yuan 1003.3482

QHC, Li, Yu, Yuan 1205.3769



Models	$SU(2)_1$ (T_L, T_l)	$SU(2)_2$ (T_R, T_h)	$U(1)_X$ (X, Y)
LRD/LRT	$\begin{pmatrix} u_L \\ d_L \end{pmatrix}, \begin{pmatrix} \nu_L \\ e_L \end{pmatrix}$	$\begin{pmatrix} u_R \\ d_R \end{pmatrix}, \begin{pmatrix} \nu_R \\ e_R \end{pmatrix}$	$X_q = 1/6$ $X_l = -1/2$
LPD/LPT	$\begin{pmatrix} u_L \\ d_L \end{pmatrix}, \begin{pmatrix} \nu_L \\ e_L \end{pmatrix}$	$\begin{pmatrix} u_R \\ d_R \end{pmatrix}$	$X_q = 1/6$ $X_l = Y_{\rm SM}$
HPD/HPT	$\begin{pmatrix} u_L \\ d_L \end{pmatrix}, \begin{pmatrix} \nu_L \\ e_L \end{pmatrix}$	$\begin{pmatrix} \nu_R \\ e_R \end{pmatrix}$	$X_q = Y_{\rm SM}$ $X_l = -1/2$
FPD/FPT	$\begin{pmatrix} u_L \\ d_L \end{pmatrix}, \begin{pmatrix} \nu_L \\ e_L \end{pmatrix}$		$X_f = Y_{\rm SM}$
SQD	$\begin{pmatrix} u_L \\ d_L \end{pmatrix}, \begin{pmatrix} \nu_L \\ e_L \end{pmatrix}$		$X_f = Y_{\rm SM}$
NUD	$\begin{pmatrix} u_L \\ d_L \end{pmatrix}_{1st,2nd}, \begin{pmatrix} \nu_L \\ e_L \end{pmatrix}_{1st,2nd}$	$\begin{pmatrix} u_L \\ d_L \end{pmatrix}_{3rd}, \begin{pmatrix} \nu_L \\ e_L \end{pmatrix}_{3rd}$	$X_f = Y_{\rm SM}$
UUD	$\begin{pmatrix} u_L \\ d_L \end{pmatrix}$	$\begin{pmatrix} \nu_L \\ e_L \end{pmatrix}$	$X_f = Y_{\rm SM}$

LRD (LRT): left-right doublet (triplet) model

LPD (LRT): Leptophobic doublet (triplet) model

HPD (LRT): Hadrophobic doublet (triplet) model

FPD (LRT): Fermio-phobic doublet (triplet) model

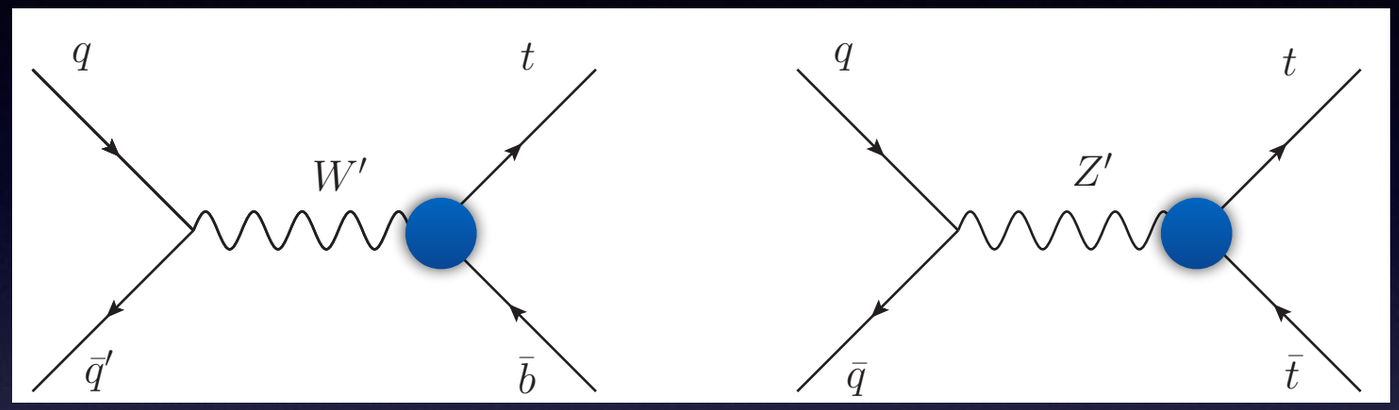
SQD: Sequential W' with doublet Higgs

NUD: Non-universal doublet model

UUD: Un-unified doublet model

Extra Weak Gauge Bosons

221 Model: $SU(2)_1 \otimes SU(2)_2 \otimes U(1)_X$



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

	$W'tb$	$Z't\bar{t}$
SSM	$\frac{g_2}{\sqrt{2}}\bar{b}\gamma_\mu P_L t W'^\mu$	$\frac{g_2}{6c_w}\bar{t}\gamma_\mu((-3+4s_w^2)P_L + 4s_w^2 P_R)tZ'^\mu$
LRM	$\frac{g_2}{\sqrt{2}}\bar{b}\gamma_\mu P_R t W'^\mu$	$\frac{g_2 t_w}{6}\bar{t}\gamma_\mu(\frac{1}{\alpha_{LR}}P_L + (\frac{1}{\alpha_{LR}} - 3\alpha_{LR})P_R)tZ'^\mu$
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: $SU(3)_C \otimes SU(3)_W \otimes U(1)_X$

$$SU(3) \times U(1)_X \xrightarrow{H_1} SU(2)_L \times U(1)_Y \xrightarrow{H_2} U(1)_{\rm em}$$

$$\begin{pmatrix} u \\ d \\ D \end{pmatrix} \quad \begin{pmatrix} c \\ s \\ S \end{pmatrix} \quad \begin{pmatrix} b \\ -t \\ T \end{pmatrix}$$

$$3 \qquad 3 \qquad \overline{3}$$

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

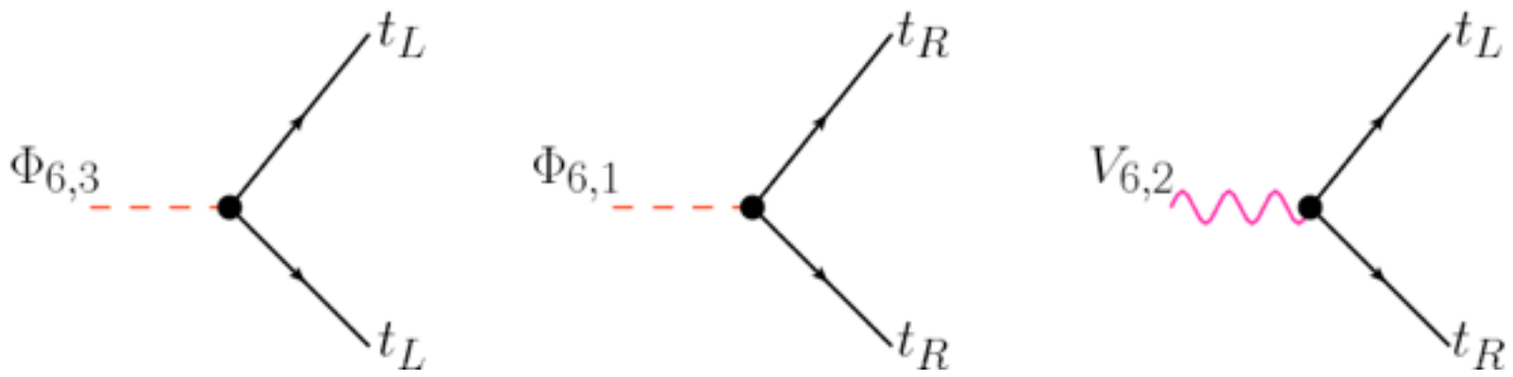
Effective Lagrangian:

$$\mathcal{L} = \left(g_{1L}\overline{q_L^c} i\tau_2 q_L + g_{1R}\overline{u_R^c} d_R\right)\Phi_{6,1,1/3}$$
$$+ g'_{1R}\overline{d_R^c} d_R \Phi_{6,1,-2/3} + g''_{1R}\overline{u_R^c} u_R \Phi_{6,1,4/3}$$
$$+ g_{3L}\overline{q_L^c} i\tau_2 \tau q_L \cdot \Phi_{6,3,1/3}$$
$$+ g_2\overline{q_L^c}\gamma_\mu d_R V^\mu_{6,2,-1/6} + g'_2\overline{q_L^c}\gamma_\mu u_R V^\mu_{6,2,5/6} + h.c.\,,$$

$$q_L = \begin{pmatrix} u_L \\ d_L \end{pmatrix}$$
$$q^c = C\bar{q}^T$$

Atag, Cakir, Sultansoy, (1999)

Arnold, Pospelov, Trott, Wise (2009)

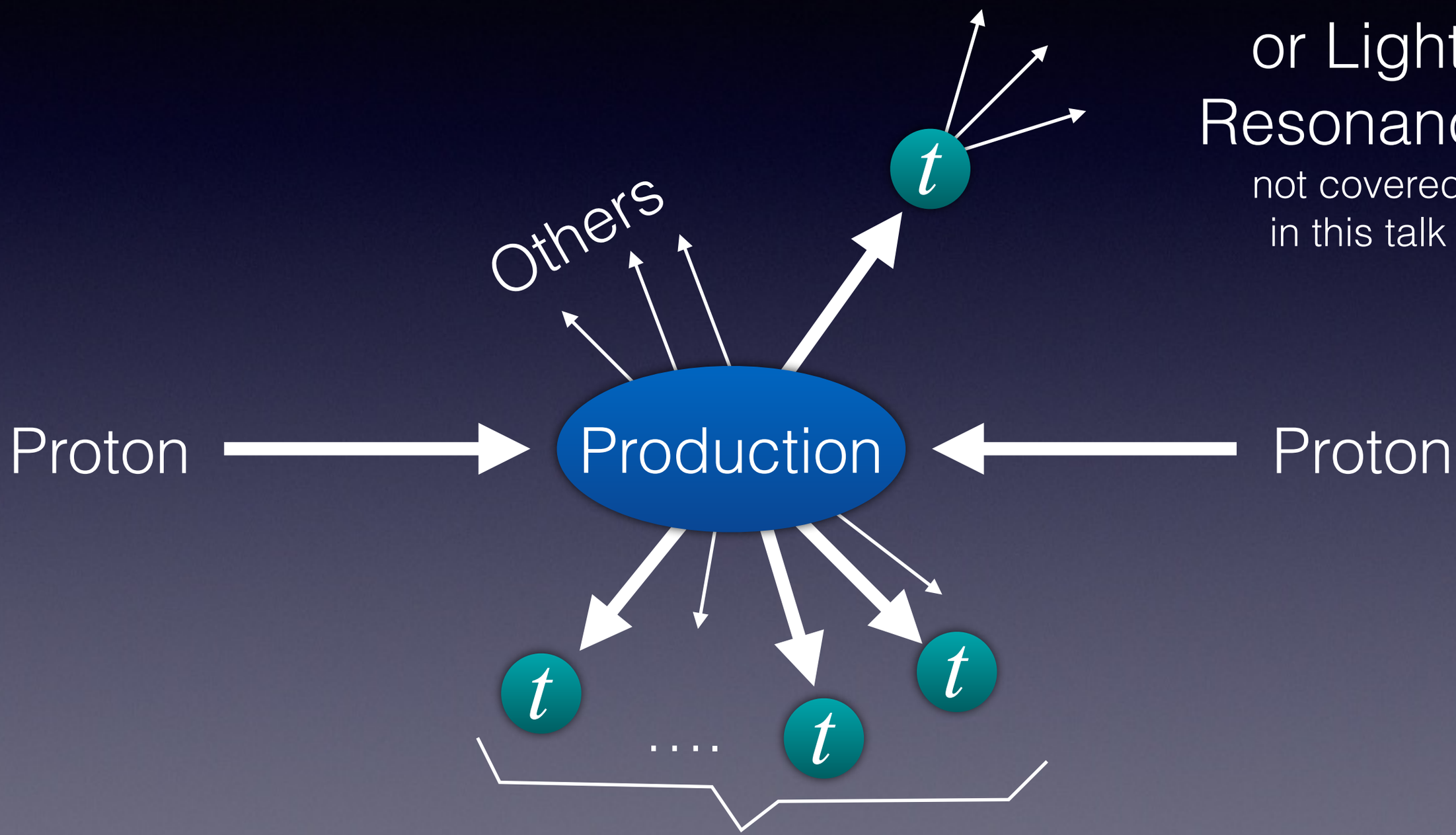


$SU(2)_L$	$U(1)_Y$	$\lvert Q\rvert = \lvert T_3 + Y\rvert$	couplings to
1	1/3	1/3	QQ, UD
3	1/3	1/3, 2/3, 4/3	QQ
1	2/3	2/3	DD
1	4/3	4/3	UU

$$Q = Q_L$$
$$U = u_R$$
$$D = d_R$$

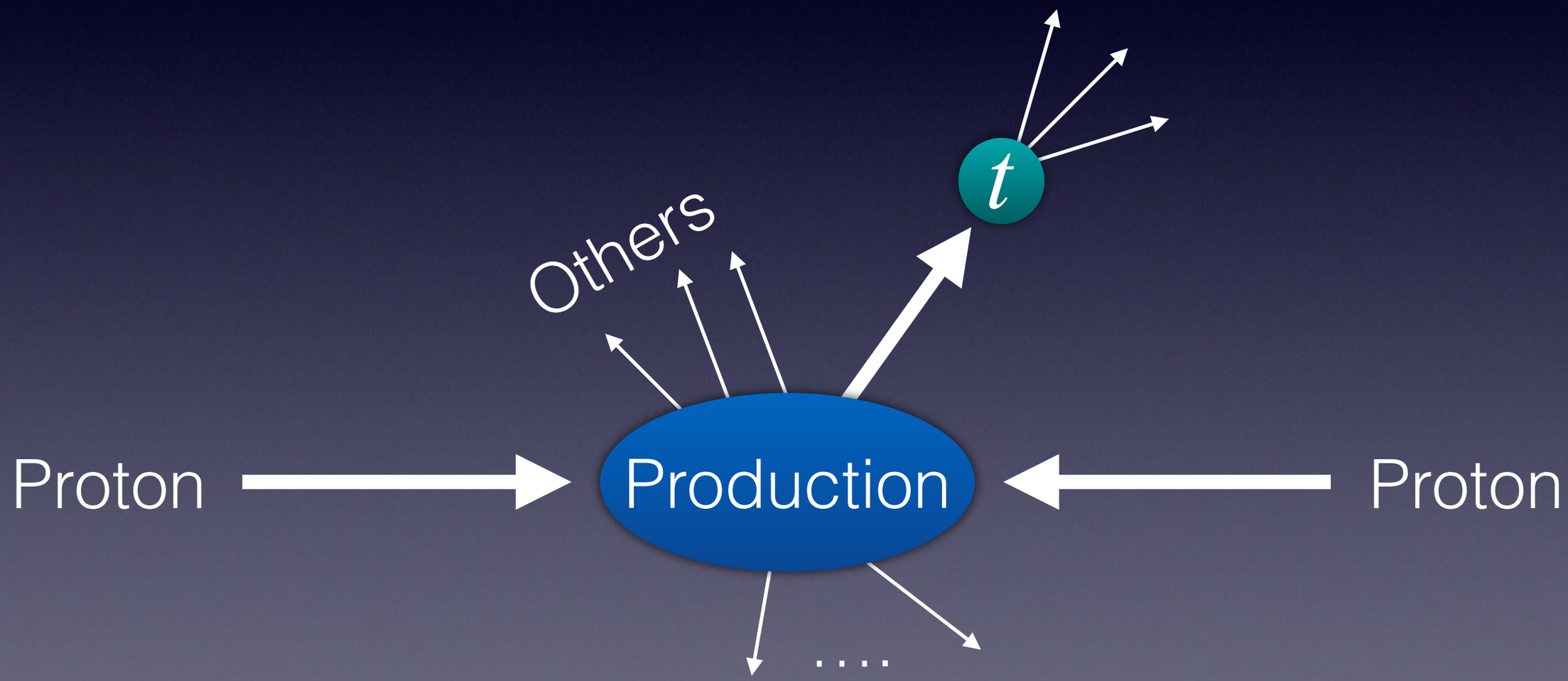
Top Quark and New Physics

Rare Decay
or Light
Resonance
not covered
in this talk



$T, B, G', W', Z', \phi^0, \phi^+, \phi_8, \phi_3, \phi_6,$ DM

Single Top Quark Production



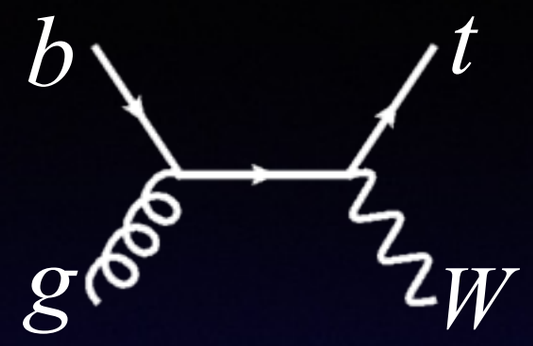
Single Top Quark Production

s-channel

$Q_W^2 > 0$

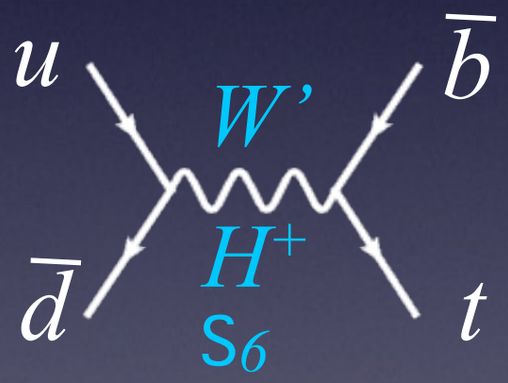
***t*-channel**

$Q_W^2 < 0$



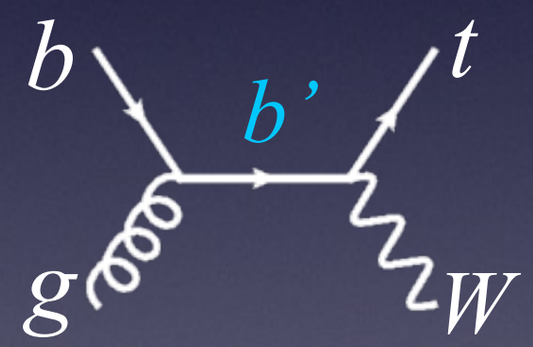
tW

$Q_W^2 = m_W^2$



New resonance

FCNC

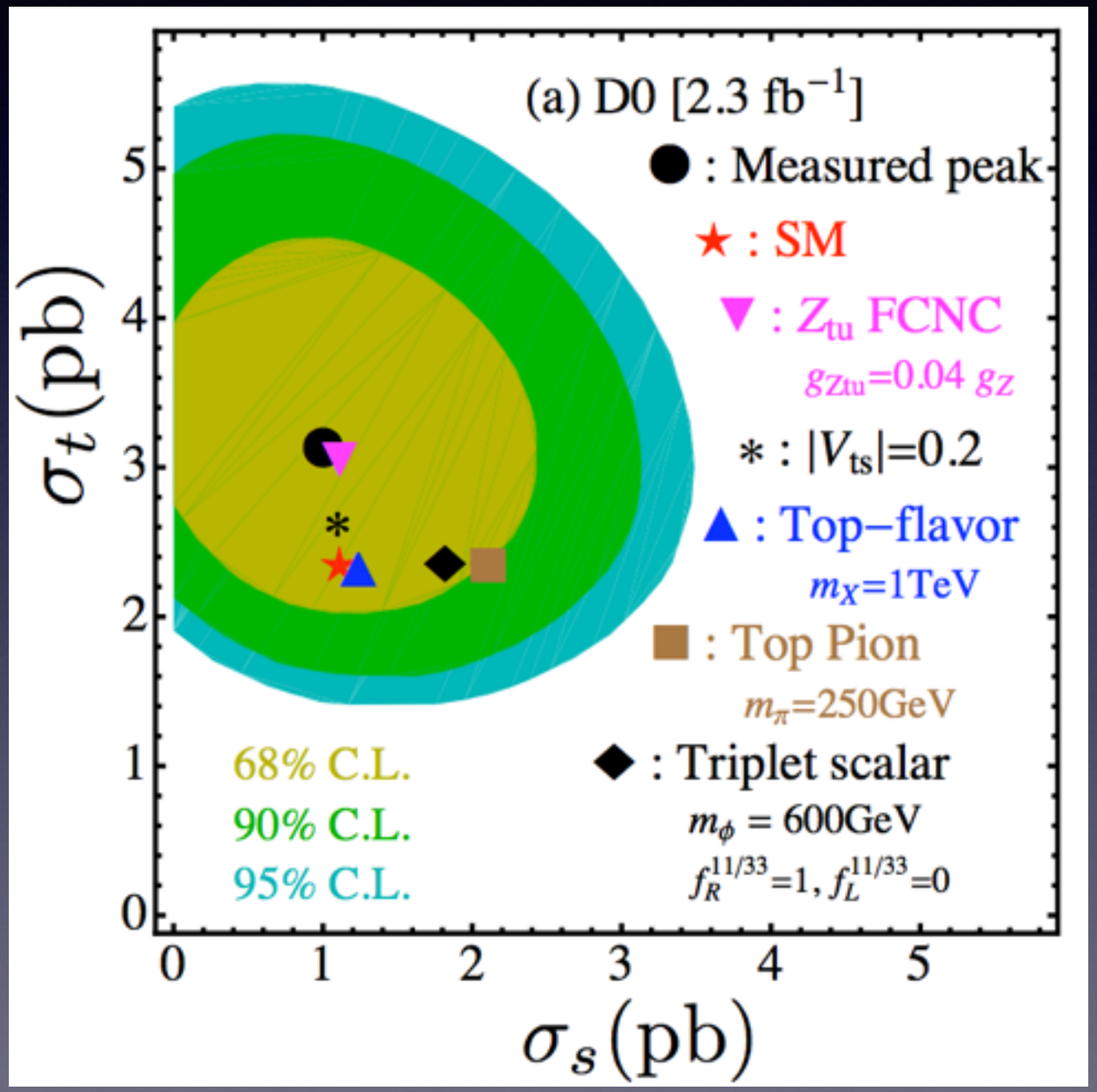


Excited quark

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

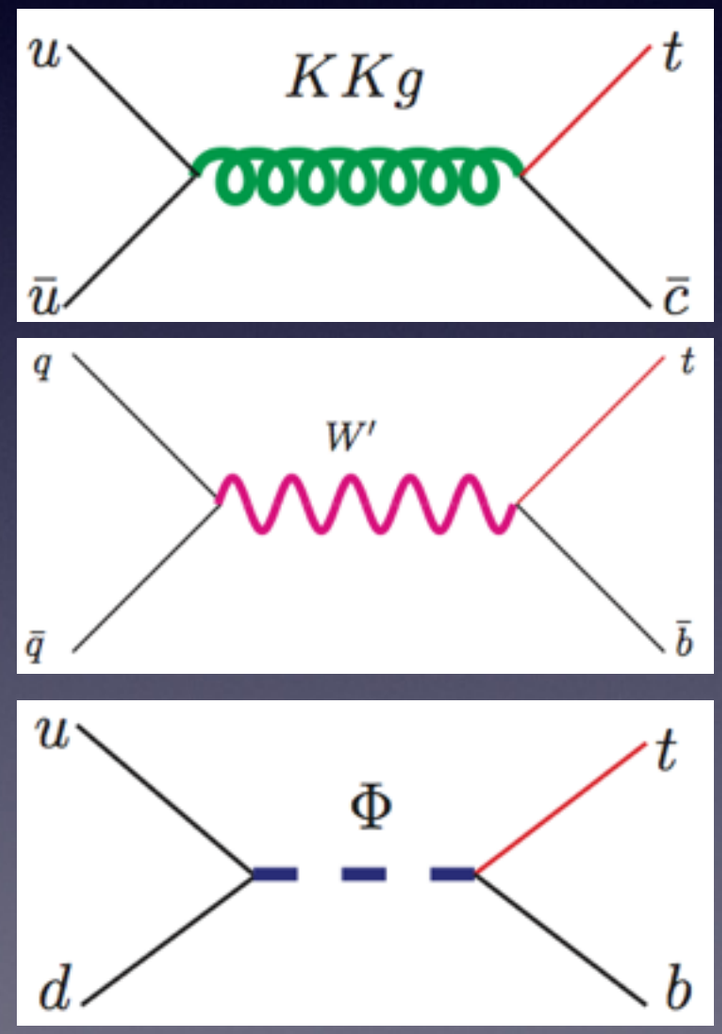
Single Top Quark Production

(s-channel resonance and t-channel FCNC)



Tait, Yuan, hep-ph/0007298

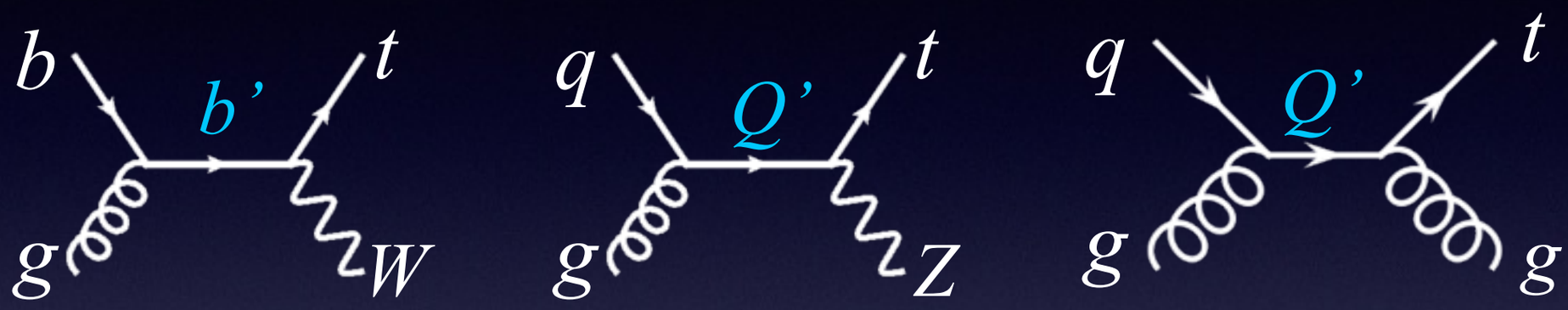
Drueke, Schwienhorst, Vignaroli
Walker, Yu, 1409.7607



Gogoladze et al, 1001.5260

Single Top Quark Production

(s-channel excitation quark)

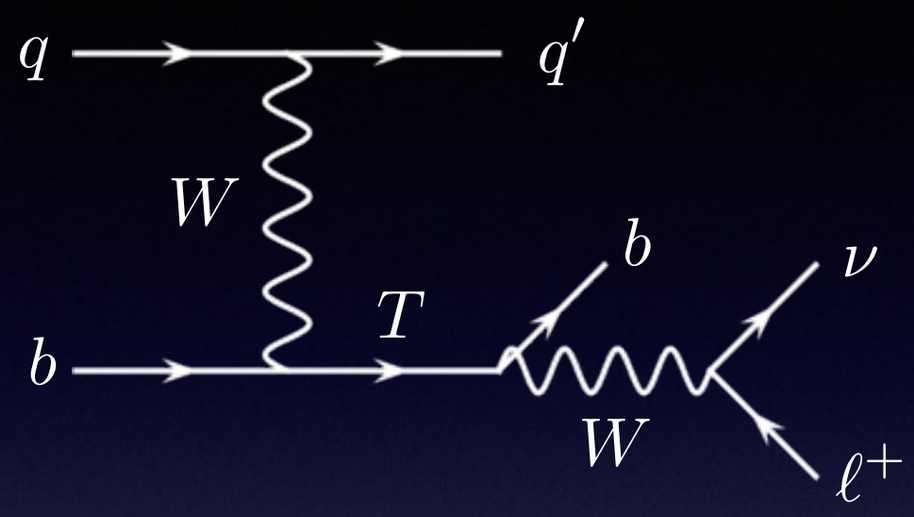


Nutter, Schwienhorst, Walker, Yu, 1207.5179

$$\mathcal{L} = g_s \bar{B}' \gamma^\mu B' + \frac{g_s \lambda}{2\Lambda} G_{\mu\nu} \bar{b} \sigma^{\mu\nu} \left(\kappa_L^b P_L + \kappa_R^b P_R \right) B' + h.c.$$

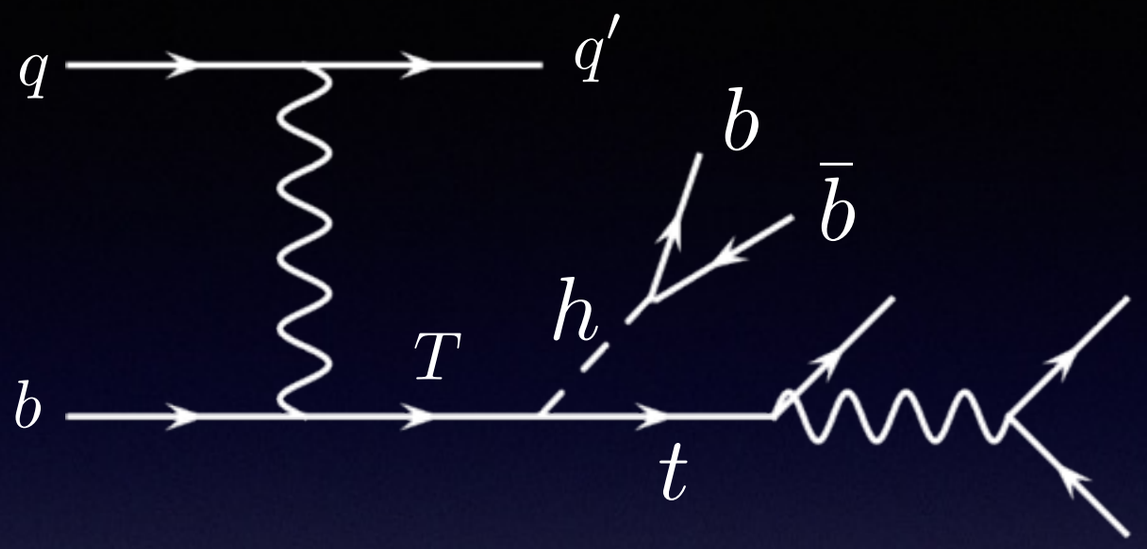
$$\mathcal{L} = \frac{g_W}{\sqrt{2}} W_\mu^+ \bar{t} \gamma^\mu (f_L P_L + f_R P_R) B' + h.c.$$

Single Heavy Quark Production



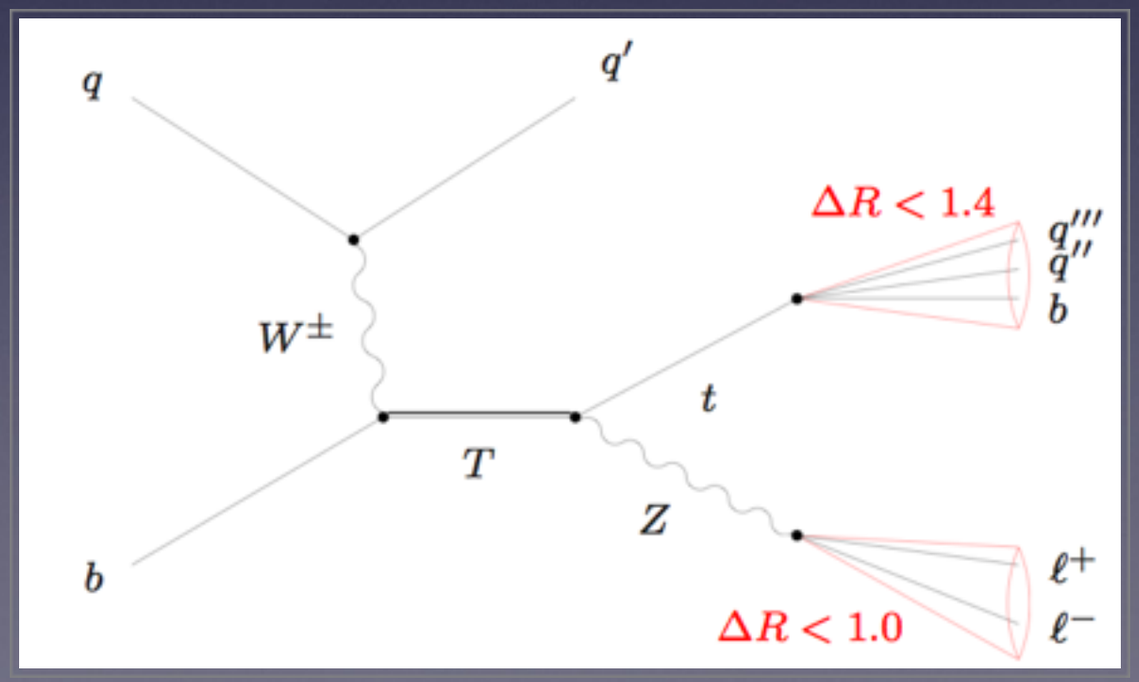
Little Higgs

Perelstein, Peskin, Pierce
hep-ph/0310039



Composite Higgs

Li, Liu, Shu, 1306.5841
Boosted jet-substructure



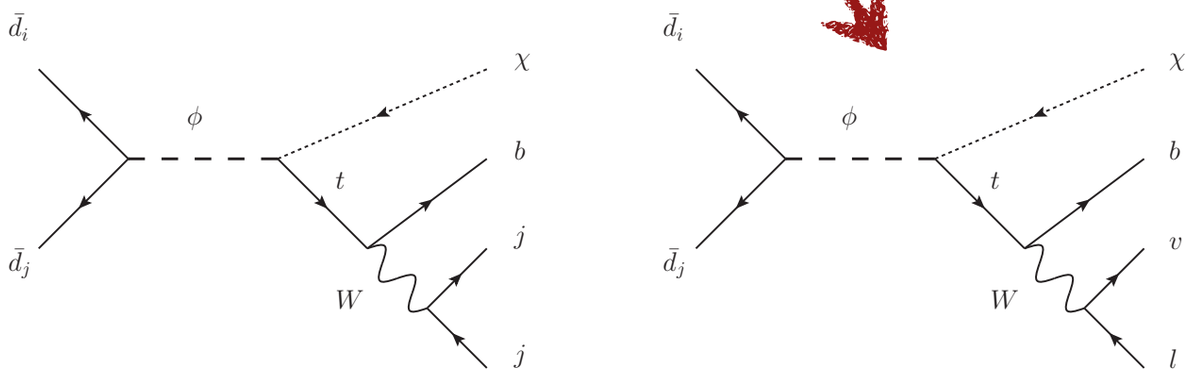
Reuter, Tonini,
1409.6962

Mono Top Quark Production

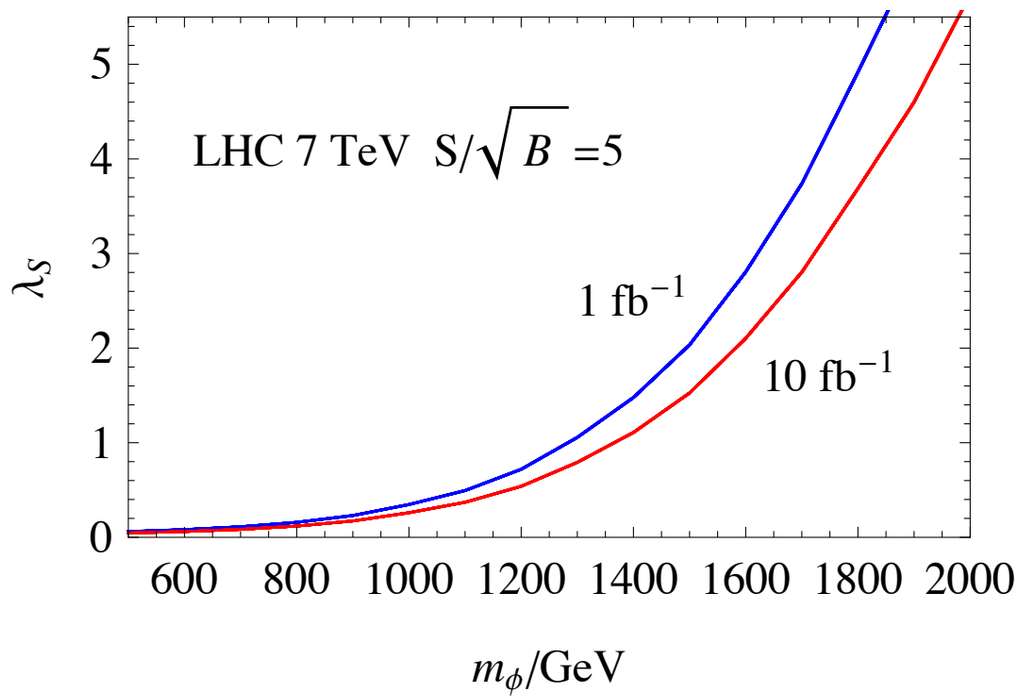
(R-parity violating SUSY inspired)

see Theveneaux-Pelzer's poster

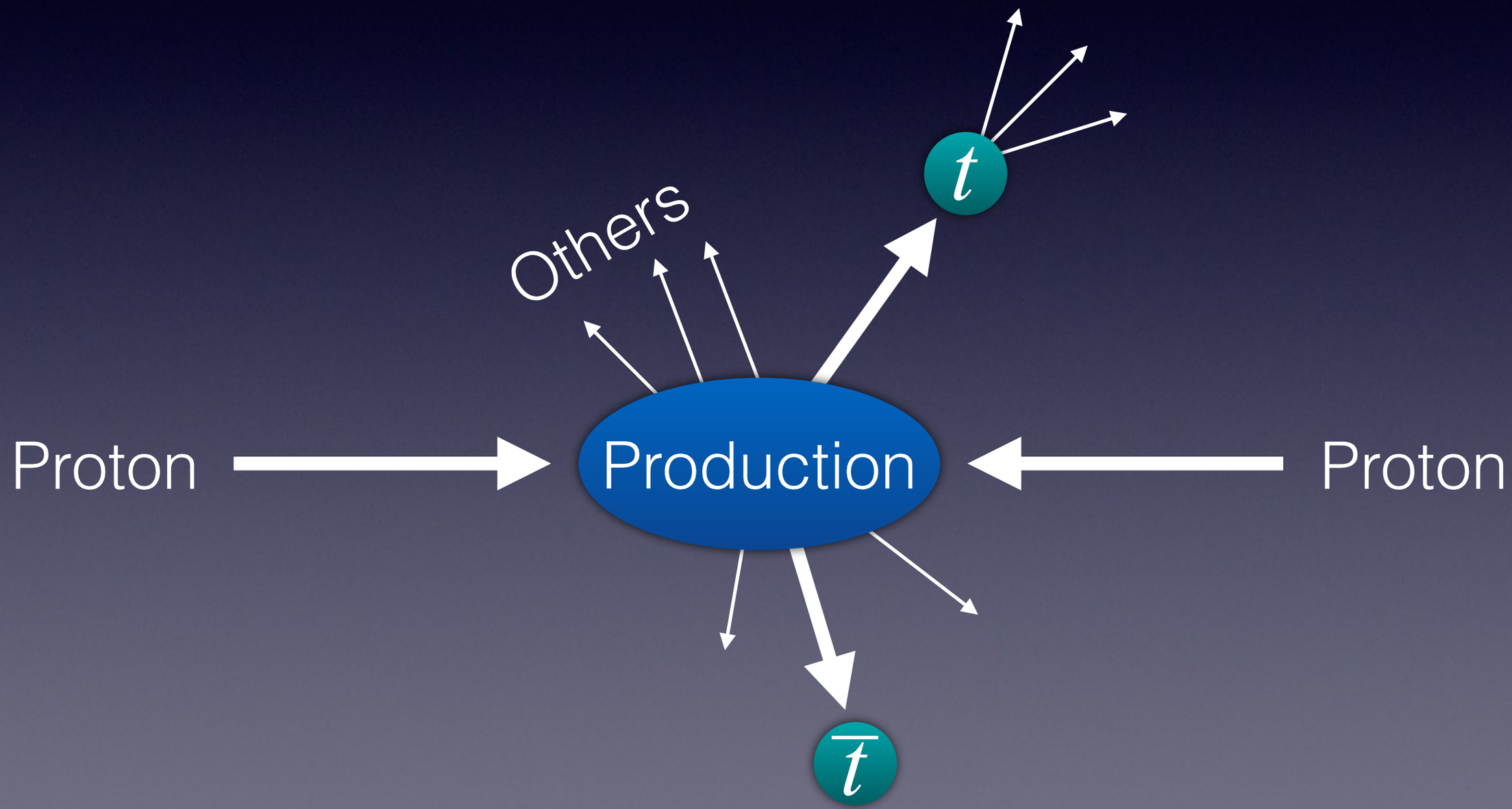
Andrea, Fuks, Maltoni, 1106.6199
Wang, Li, Shao, Zhang, 1109.5963



$$
\begin{aligned}
\mathcal{L} = \; & \mathcal{L}_{SM} \\
& + \phi\bar{u}\left[a^0_{FC}+b^0_{FC}\gamma_5\right]u + V_\mu\bar{u}\left[a^1_{FC}\gamma^\mu+b^1_{FC}\gamma^\mu\gamma_5\right]u \\
& + \epsilon^{ijk}\varphi_i\bar{d}^c_j\left[a^q_{SR}+b^q_{SR}\gamma_5\right]d_k + \varphi_i\bar{u}^i\left[a^{1/2}_{SR}+b^{1/2}_{SR}\gamma_5\right]\chi \\
& + \epsilon^{ijk}\tilde{\varphi}_i\bar{d}^c_j\left[\tilde{a}^q_{SR}+\tilde{b}^q_{SR}\gamma_5\right]u_k + \tilde{\varphi}_i\bar{d}^i\left[\tilde{a}^{1/2}_{SR}+\tilde{b}^{1/2}_{SR}\gamma_5\right]\chi \\
& + \epsilon^{ijk}X_{\mu,i}\;\bar{d}^c_j\left[a^q_{VR}\gamma^\mu + b^q_{VR}\gamma^\mu\gamma_5\right]d_k \\
& + X_{\mu,i}\;\bar{u}^i\left[a^{1/2}_{VR}\gamma^\mu + b^{1/2}_{VR}\gamma^\mu\gamma_5\right]\chi + \text{h.c.},
\end{aligned}
$$

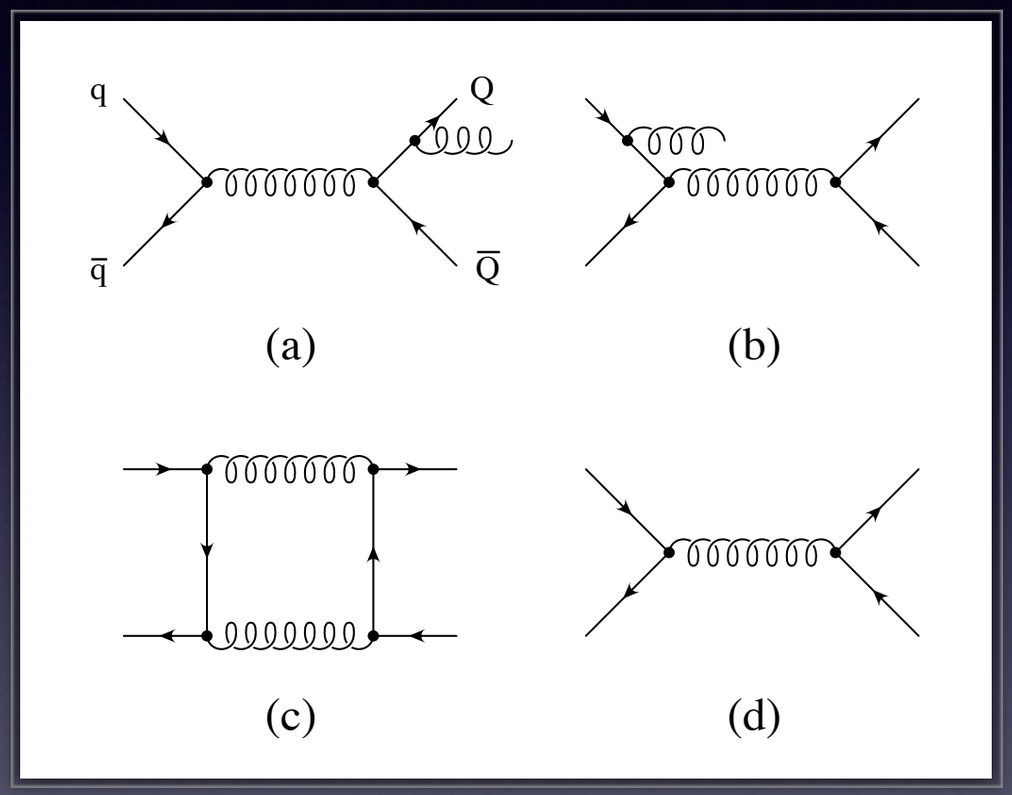


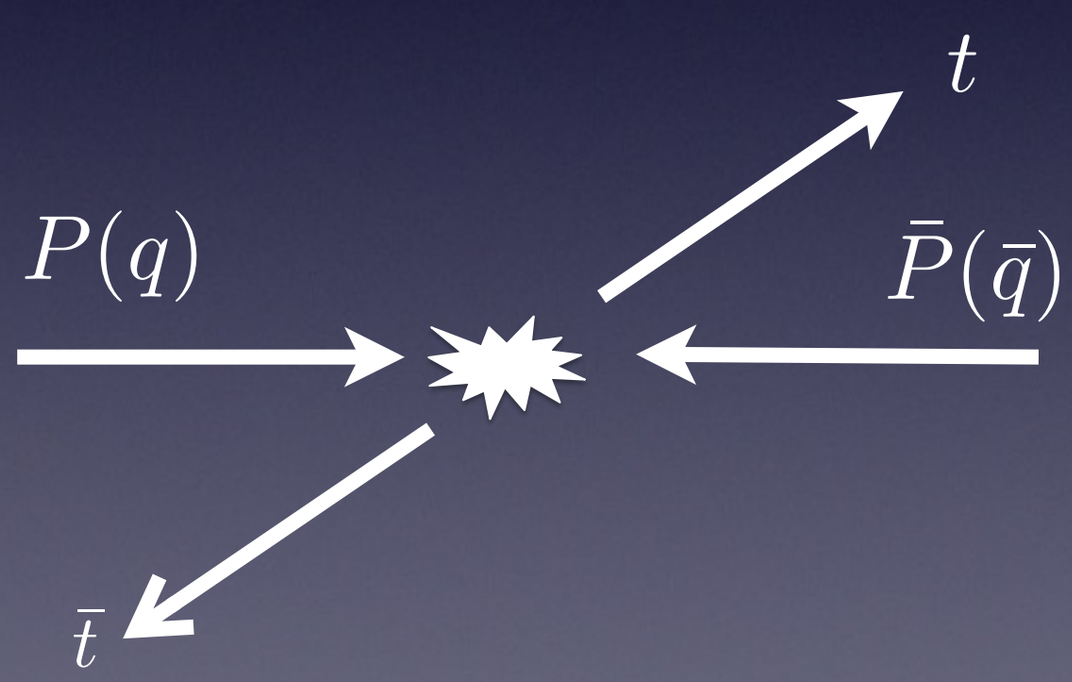
Top-Antitop or Top-Top Quark Pair Production



Top-quark F-B asymmetry in the SM

(A charge asymmetry arises at NLO)





Timeline of top-quark A_{FB}

SM theo. Prediction

Brown, Ellis, Rainwater
hep-ph/0509267
Collider simulation of *tt+0(1)j*
Measuring AFB is
very challenging

Almeida, Sterman, Vogalsang
0805.1885
NLL Threshold resum.
Asymmetry is robust

Melnikov, Schulze
1004.3284
Confirm Dittmaier et al

Kuhn, Rodrigo
hep-ph/9802268
SM NLO QCD
$A^t_{FB} = 5\%$

Dittmaier, Uwer, Weinzierl
hep-ph/0703120
NLO QCD corr. to ttbar+j

Ahrens, Ferroglia, Neubert,
Pecjak, Li Lin Yang,
1003.5827
SCET NNLL

1998 2005 2007 2008 2010 2011

EXP. Measurements

D0 (1.9 fb^{-1})
0712.0851
uncorrected
$A_{FB} = [12 \pm 8 \pm 1]\%$

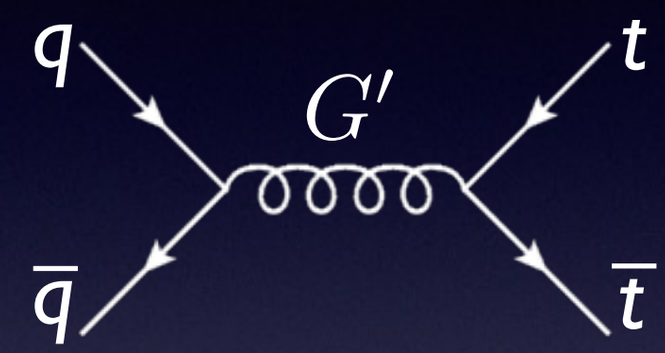
CDF (1.9 fb^{-1})
0806.2472
$A_{FB} = [24 \pm 14]\%$
Consistent with SM

CDF (5.3fb^{-1})
1101.0034
$A_{FB} = 0.475 \pm 0.114$
for $m_{t\bar{t}} \geq 450$ GeV

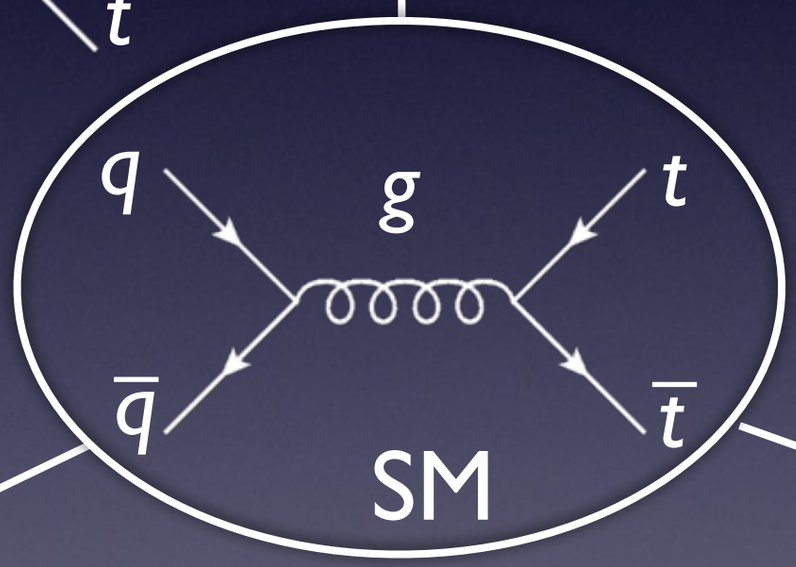
D0 (5.4fb^{-1})
1107.4995
$A^t_{FB} = [19.6 \pm 6.5]\%$
$A^\ell_{FB} = [15.2 \pm 4.0]\%$

Top Quark A_{FB} and NP

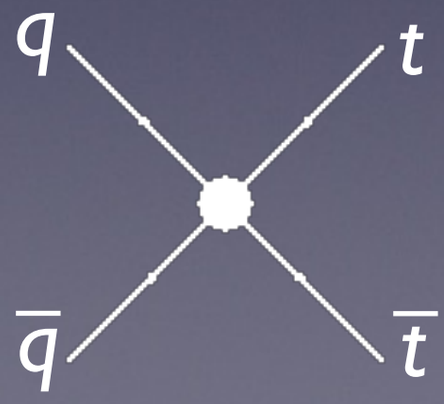
<u>*s-channel*</u>



<u>*t-channel*</u> *(Flavor changing)*



<u>*Effective theory*</u>



Timeline of A_{FB}^t and NP models

s-channel

Ferrario, Rodrigo
Axigluon
0809.3353

Antunan, Kuhn, Rodrigo
Axigluon
0709.1652

Ferrario, Rodrigo
chiral G'
0906.5541

Djouadi, Moreau, Richard, singh
KK Gluon
0906.0604

Chivukula, Simmons, Yuan
Axigluon
1007.0260

Frampton, Shu, Wang
Axigluon
0911.2955

EFT

Degrande, Gerard,
Grojean, Maltoni,
Servant, 1010.6304

QHC et al
Effective coupling
(G', Z', W', H^0, H^+)
1003.3461

Jung, Ko, Lee, Nam
EFT
0912.1105

Aguilar-Saavedra
Perez-Victoria
1103.2765

2007, 2008 | 2009 | 2010, 2011

t-channel

Jung, Murayama, Pierce, Wells
FCNC Z-prime
0907.4112

Cheung, Keung, Yuan
FC W-prime
0908.2589

Dorsner, Fajfer, Kamenik, Kosnik,
Colored scalar
0912.0972

Shu, Tait, Wang
Color Sextet/triplet scalar
0911.3237

Arhrib, Benbrik, Chen
Color Sextet/triplet scalar
0911.4875

J. Cao, Heng, Wu, Yang
$\not{R}$-SUSY and TC2
0912.1447

NLO QCD

Xiao, Wang, Zhu,
NLO QCD to Z-prime
1006.2510

Bauer et al,
NLO RS
1008.0742

Shao, Li, et al
NLO QCD to EFT
1107.4012

Yan, Wang, Shao, Li
NLO QCD to W-prime
1110.6684

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: 10.1103/PhysRevLett.101.202001
e-Print: **arXiv:0806.2472** [hep-ex] | PDF

References | BibTeX | LaTeX(US) | LaTeX(EU) | Harvmac | EndNote
CERN Document Server ; ADS Abstract Service; Fermilab Library Server (fulltext available)

Detailed record - Cited by 229 records 100+

. **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: 10.1103/PhysRevD.83.112003
e-Print: **arXiv:1101.0034** [hep-ex] | PDF

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

Detailed record - Cited by 425 records 250+

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: 10.1103/PhysRevD.84.112005
e-Print: **arXiv:1107.4995** [hep-ex] | PDF

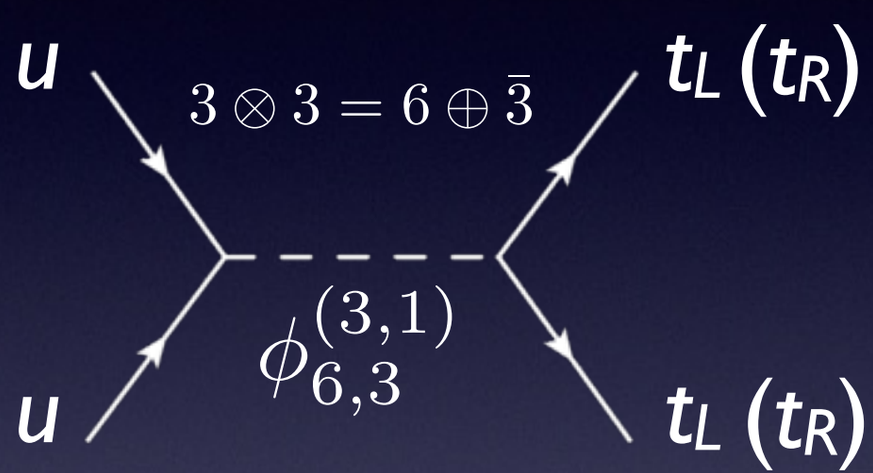
References | BibTeX | LaTeX(US) | LaTeX(EU) | Harvmac | EndNote
CERN Document Server ; ADS Abstract Service; Fermilab Library Server (fulltext available); Fermilab Today Result of the Week

Detailed record - Cited by 314 records 250+

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

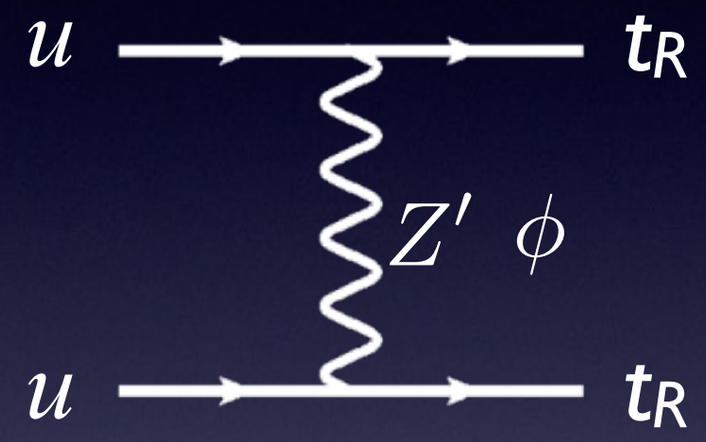
1) Same Sign Top Quark Pair

s-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

t-channel



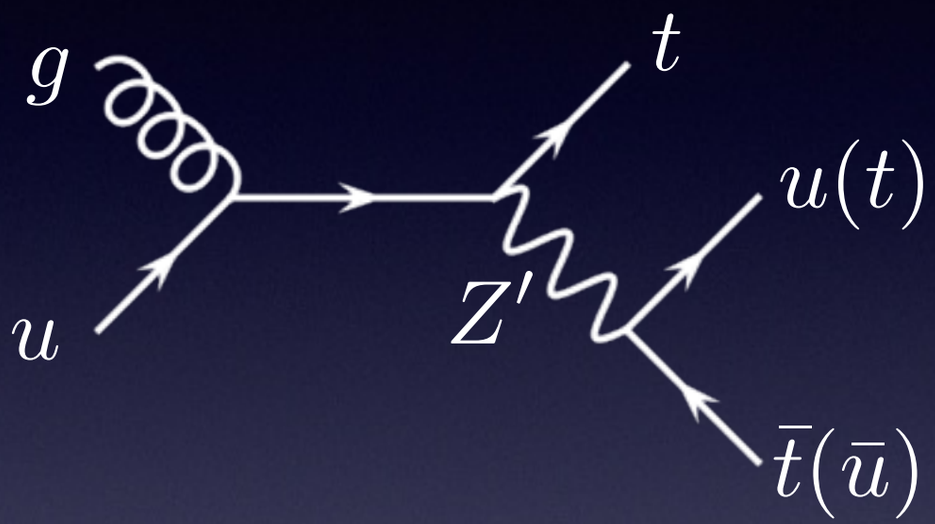
Flavor changing Z-prime
Berger, QHC, Chen, Li, Zhang
1101.5625

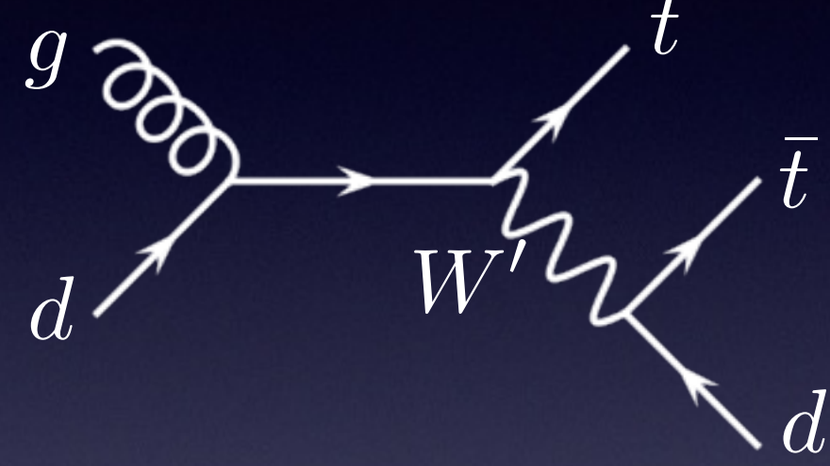
Maximal flavor violation
Bar-Shalom, Rajaraman,
Whiteson, Yu, 0803.3795

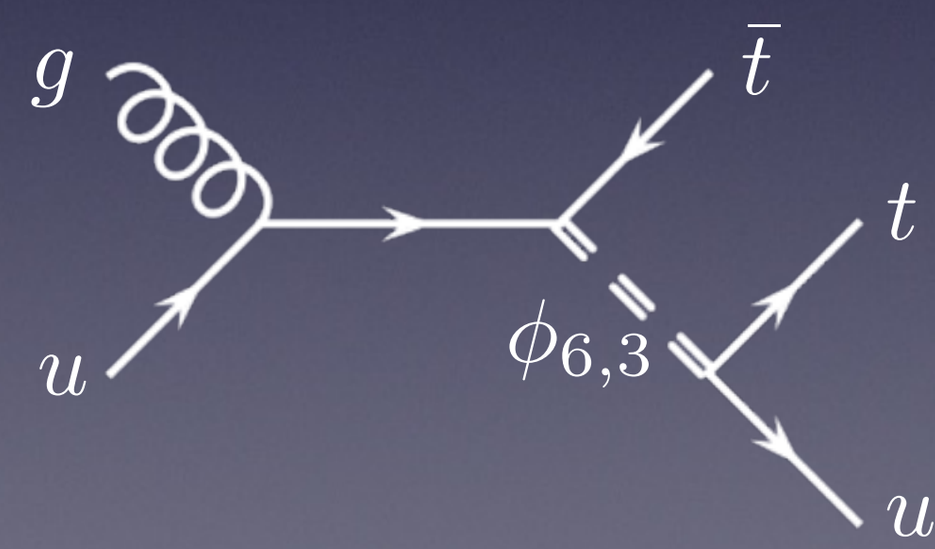
FCNC effective coupling
see Goldouzian's talk, 1408.0493

2) Top Quark Pair Plus one Jet

(Flavor Changing Interaction)





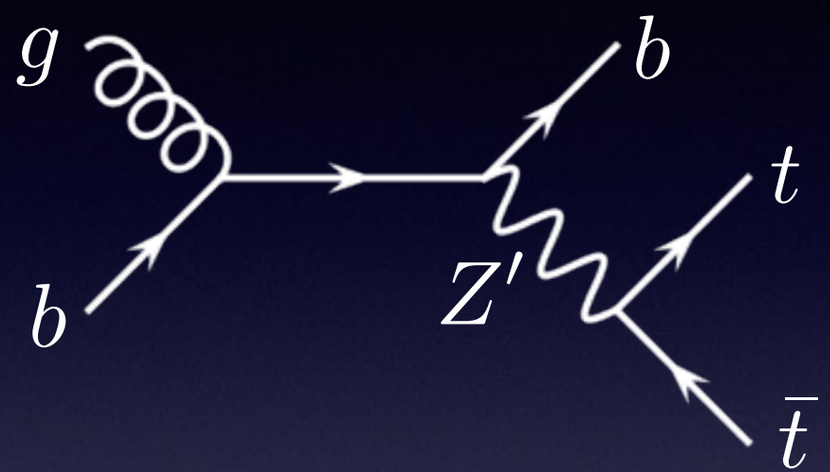


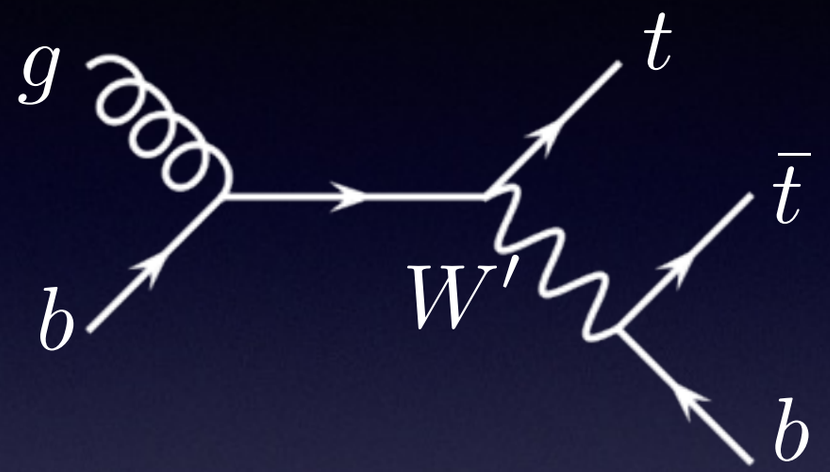
Berger, QHC, Chen, Li, Zhang, 1101.5625

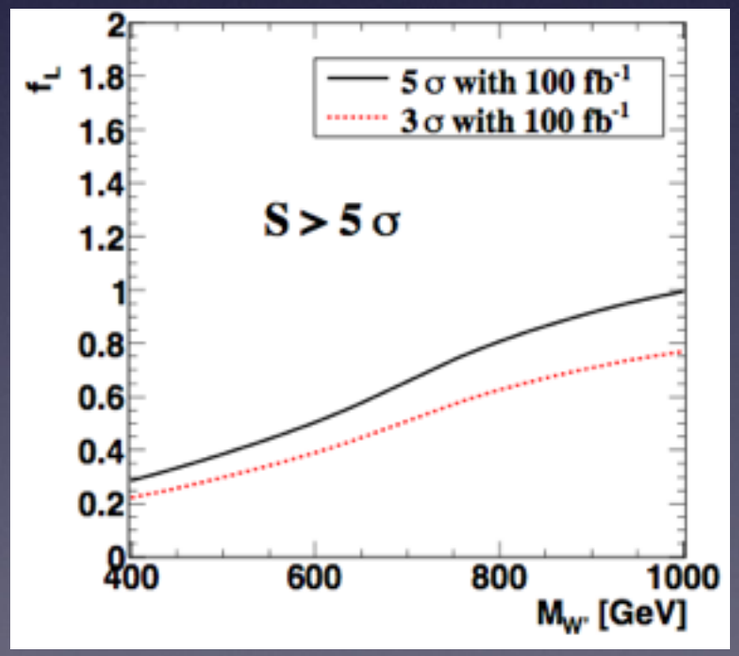
Gresham, Kim, Zurek, 1102.0018

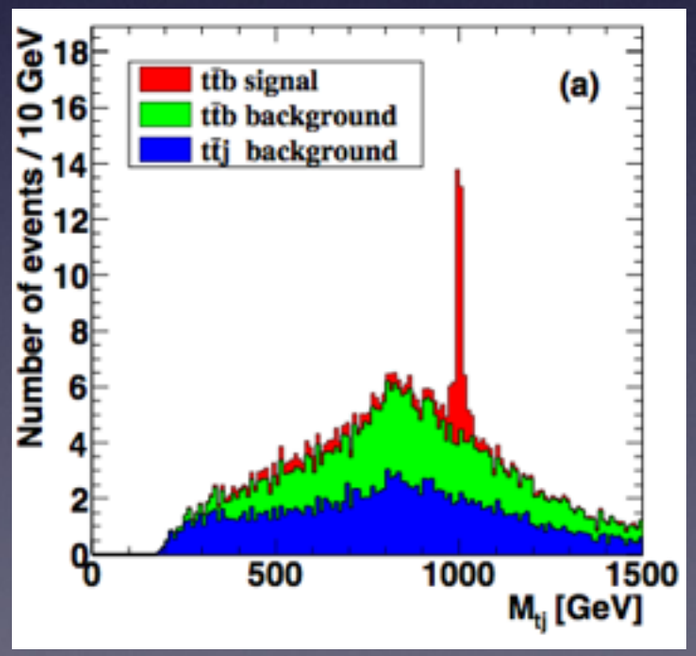
3) Top Quark Pair Plus One Jet

(Third Generation Favored W-prime and Z-prime)







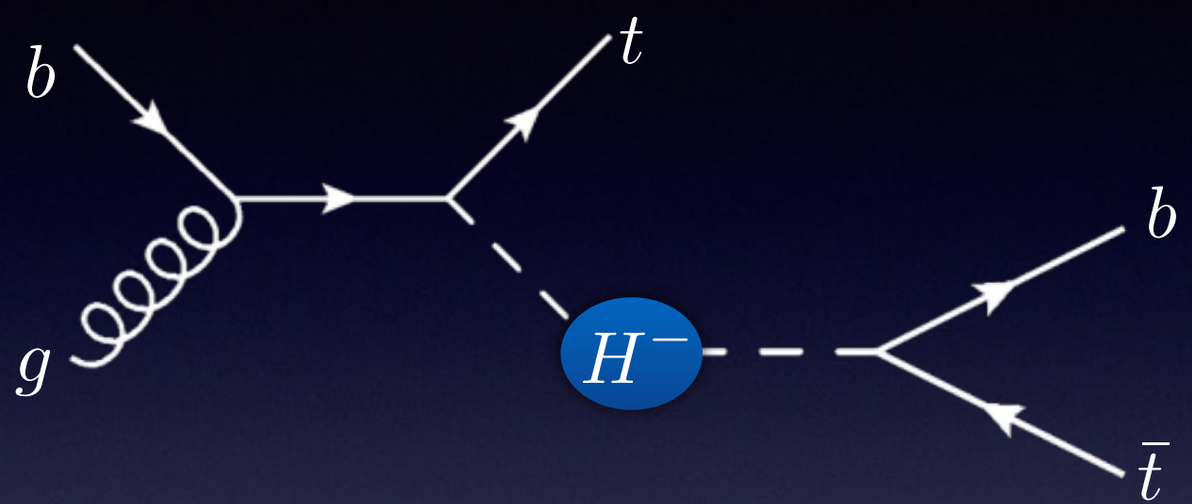


Berger, Cao, Yu, Yuan, 1108.3613

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

4) Top Quark Pair Plus One Jet

(Charged Higgs Boson)



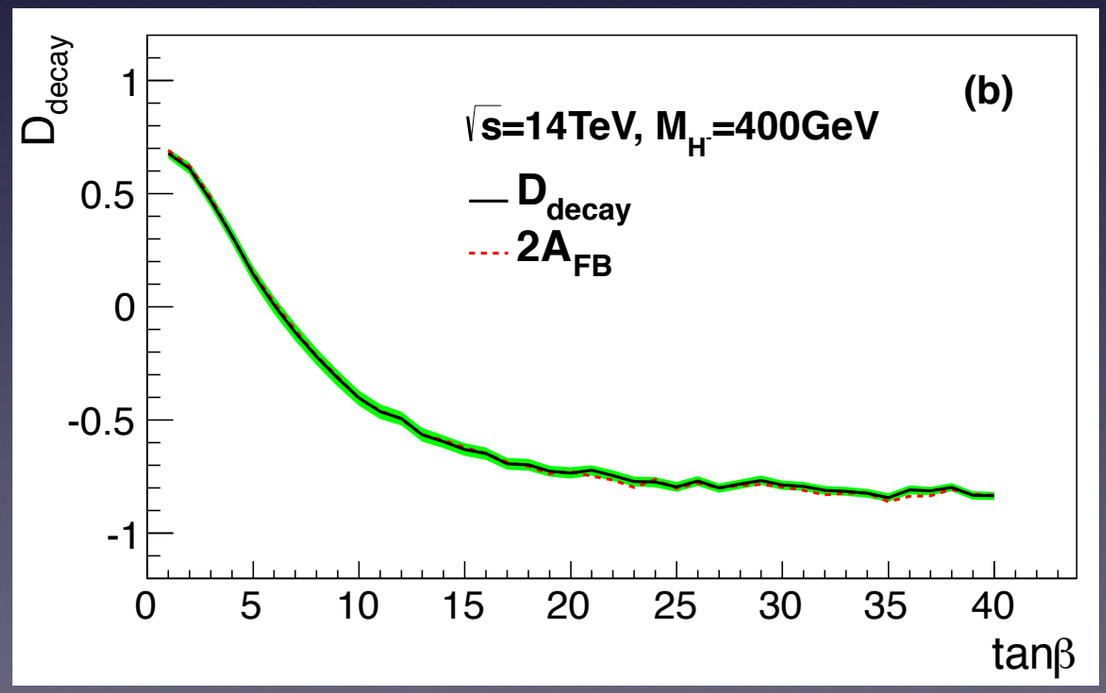
X-section is large for large tanb in MSSM or Type II 2HDB.

X-section depends on m_{H^-} and tanb

Top-quark polarization depends on tanb

$$D_{\rm decay} \sim \frac{(m_t \cot\beta)^2 - (m_b \tan\beta)^2)}{(m_t \cot\beta)^2 + (m_b \tan\beta)^2)}$$

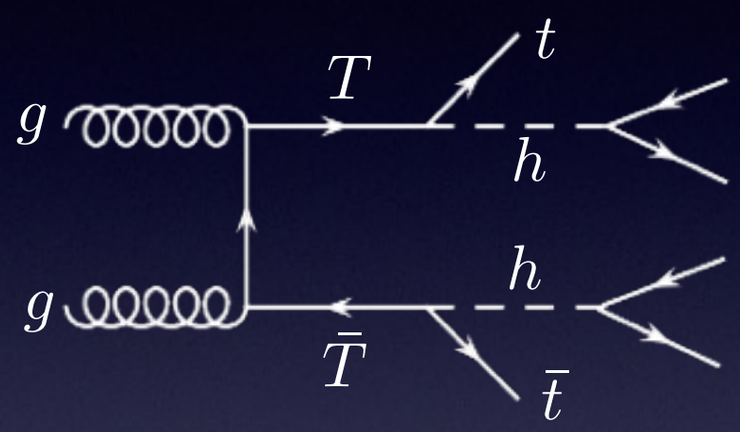
Huitu, Rai, Rao, Rindani, Sharma, 1012.0527
Godbole, Hartgring, Niessen, White, 1111.0759
Gong, Si, Yang, Zheng,1210.7822

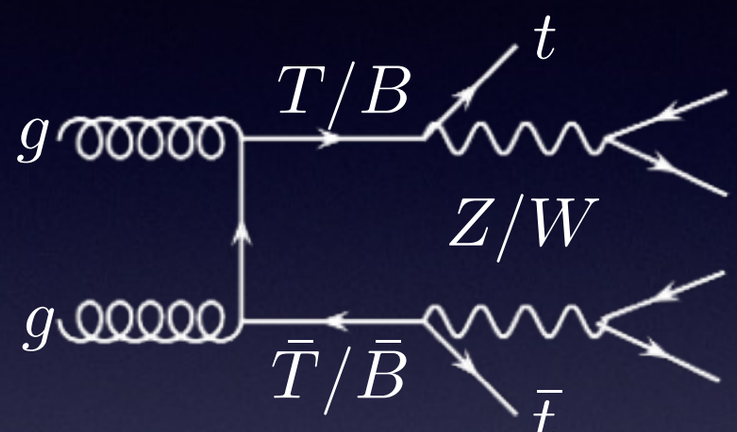


QHC, Wan, Wang, Zhu, 1301.6608

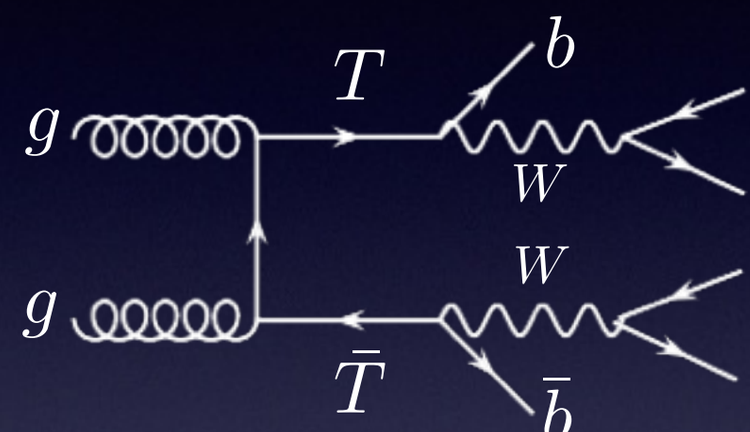
5) Top Quark Pair Plus Jets

Heavy Quark Pair Production

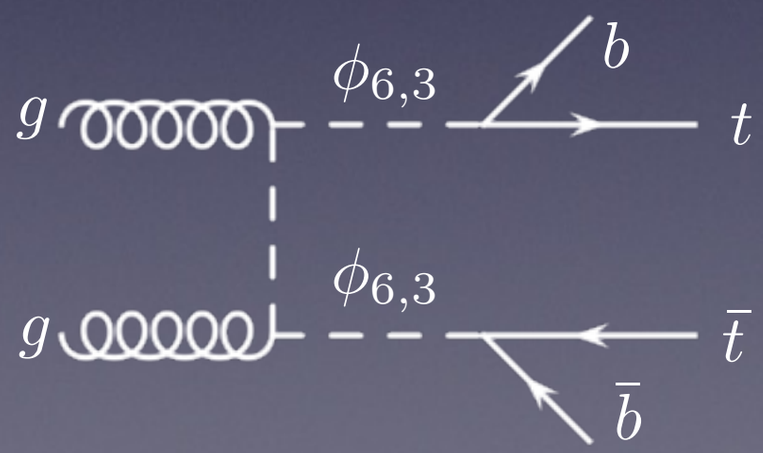




(Faked Top Quark Pair)

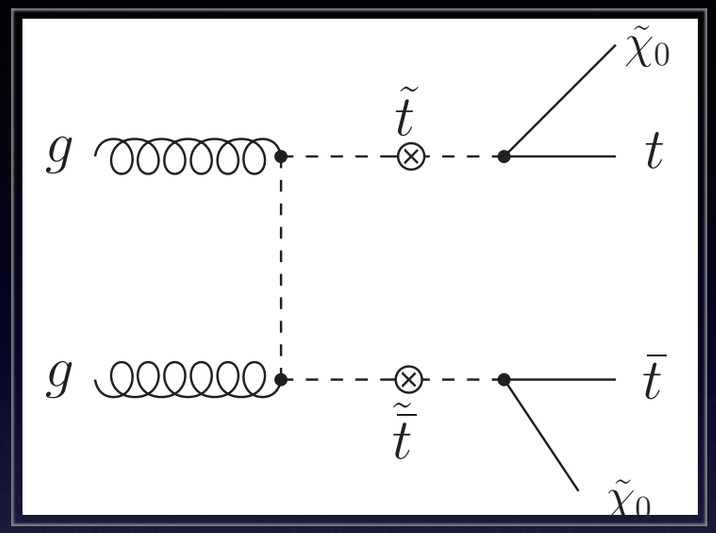


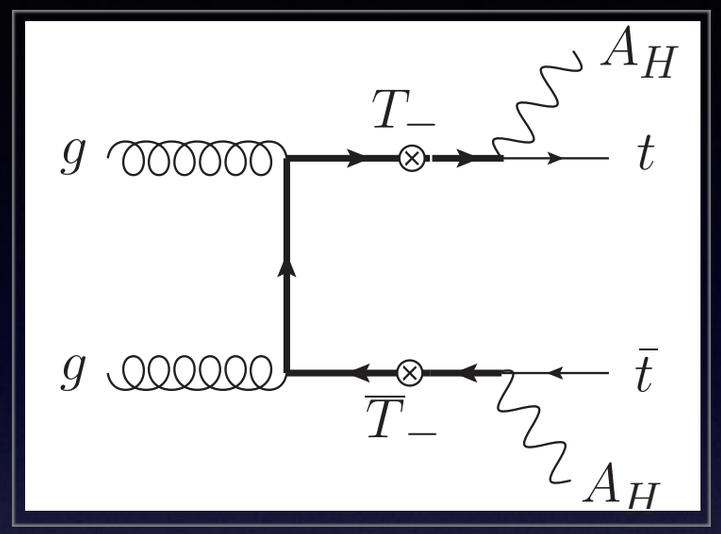
Color Sextet/Triplet Scalar Pair Production



6) Top Quark Pair + Invisibles

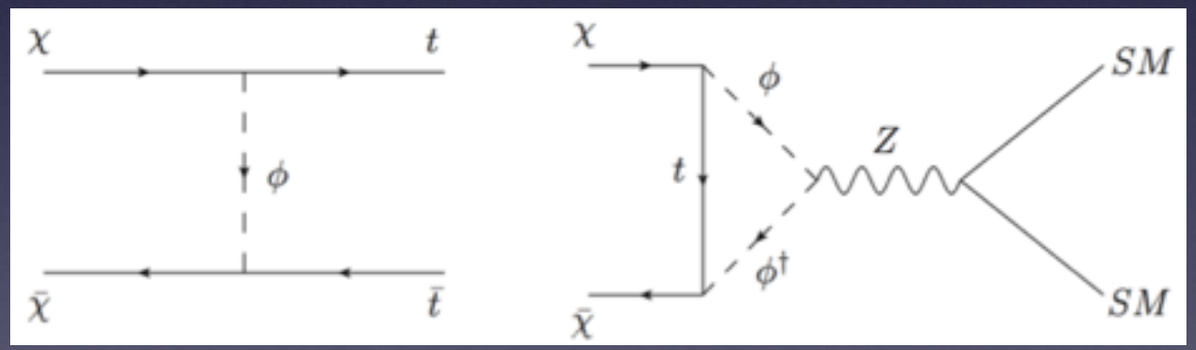
SUSY

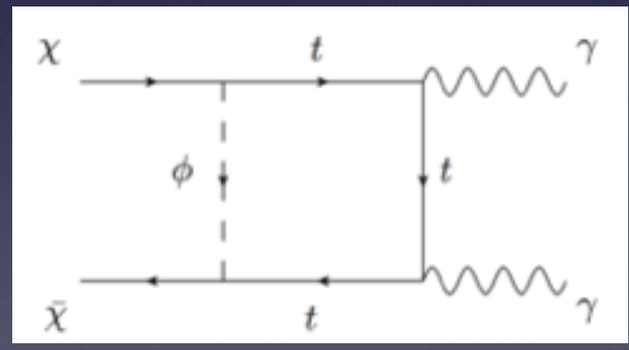




LHT, UED

Top-Quark Mediated Dark Matter Models





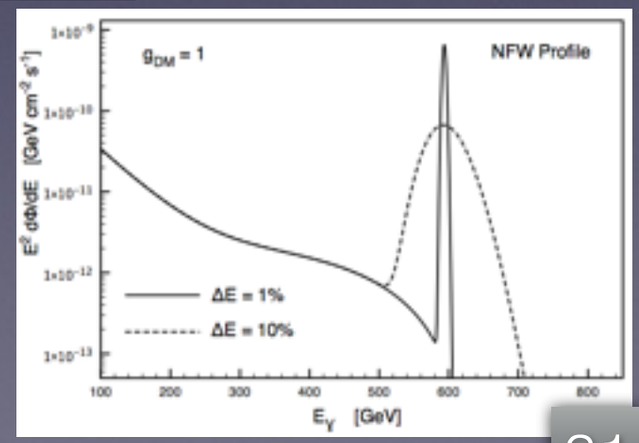
Dark Matter Effective Theory:

Cheung, Mawatari, Senaha, Tseng, Yuan, 1009.0618

Gomez, Jackson, Shaughnessy, 1404.1918

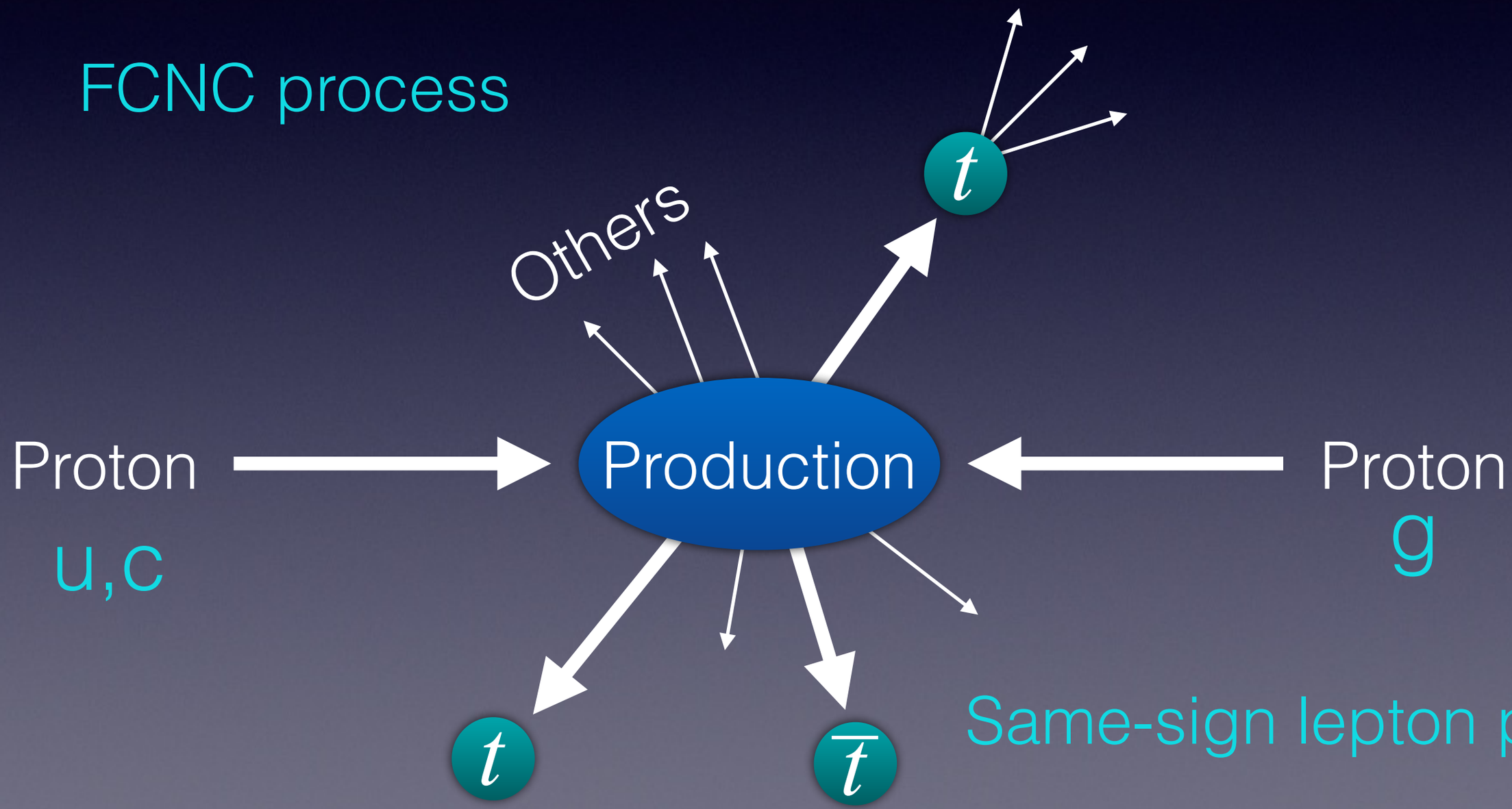
UV Completion Theory:

Jackson, Servant, Shaughnessy, Tait, Taoso,1303.4717

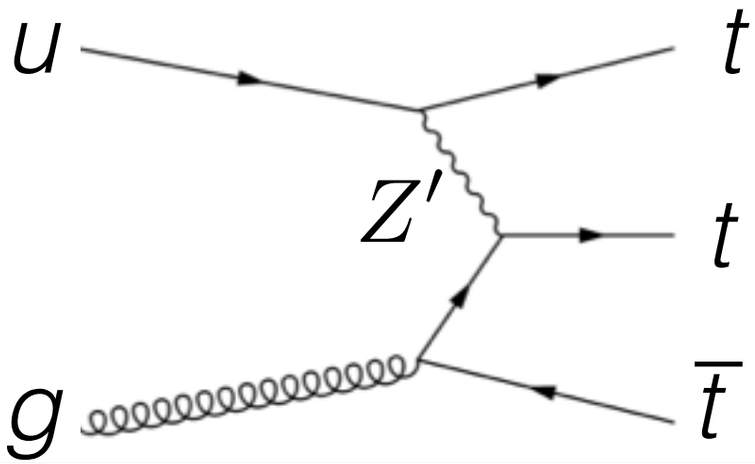


Triple Top Quark Production

FCNC process

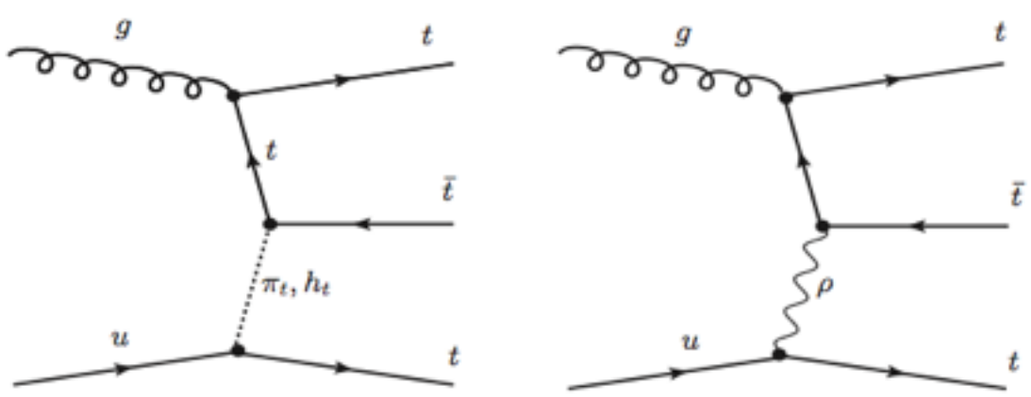


Triple Top Quark Production



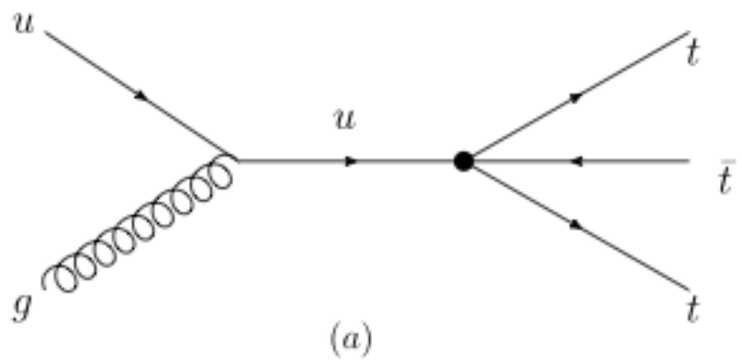
Leptophobic Z' from U'(1) directly couples top-quark to u-quark to explain AFB(t)

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)

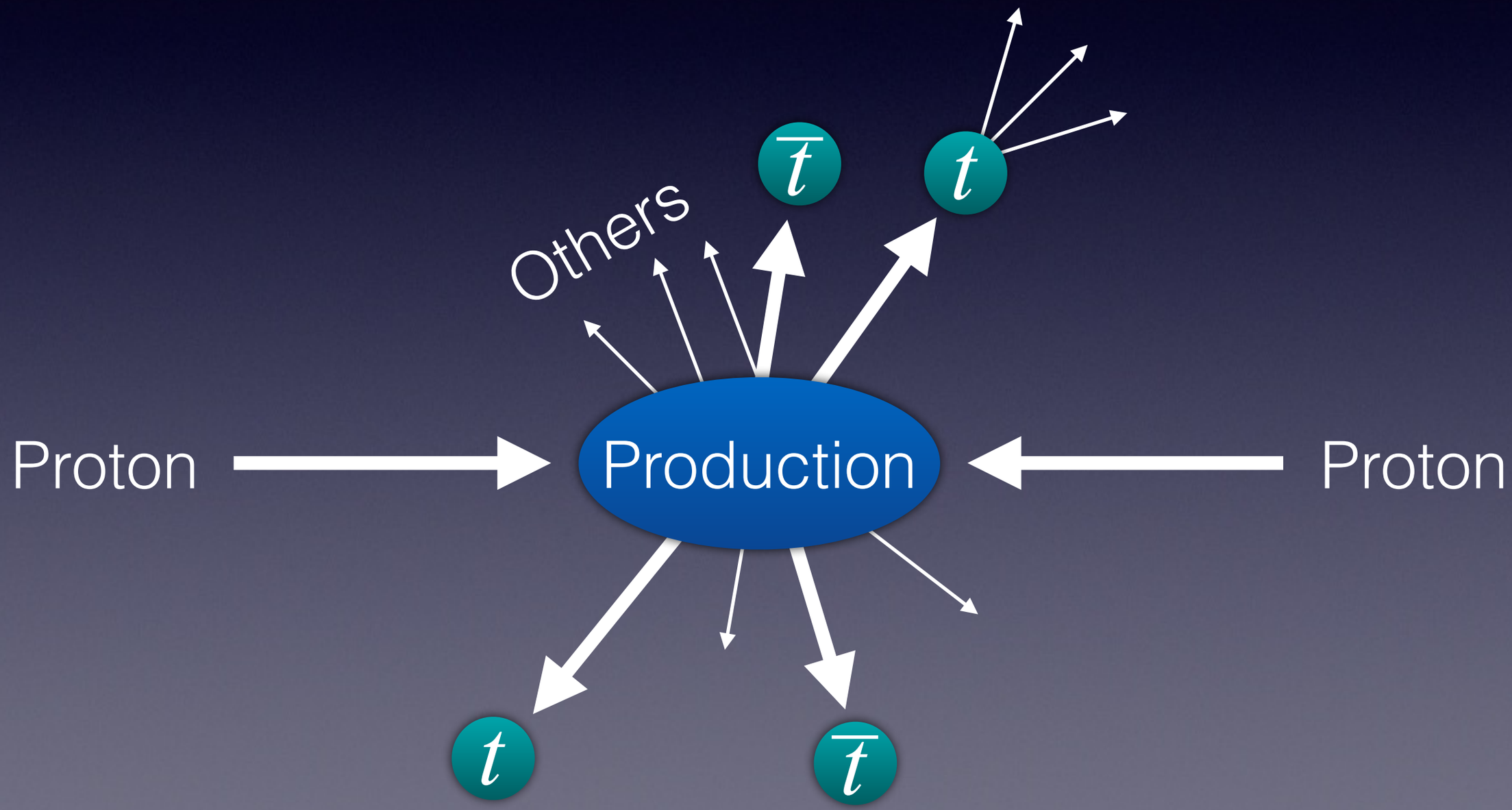


$$O^{LL}_{uttt} = \frac{1}{2}(\bar{u}_{Li}\gamma^{\mu}t_L)(\bar{t}_L\gamma_{\mu}t_L); \qquad O^{RR}_{uttt} = \frac{1}{2}(\bar{u}_{Ri}\gamma^{\mu}t_R)(\bar{t}_R\gamma_{\mu}t_R)$$

$$O^{LR}_{uttt} = (\bar{u}_{Li}t_R)(\bar{t}_Rt_L); \qquad O'^{LR}_{uttt} = (\bar{t}_Lu_{iR})(\bar{t}_Rt_L), \qquad (2$$

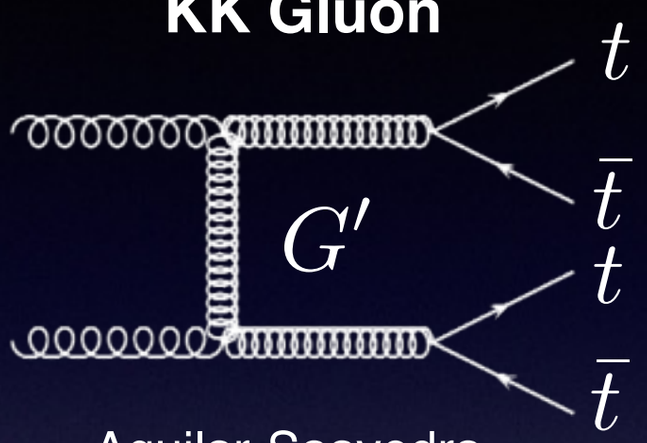
Chuan-Ren Chen (2014)

Four Top Quark Production



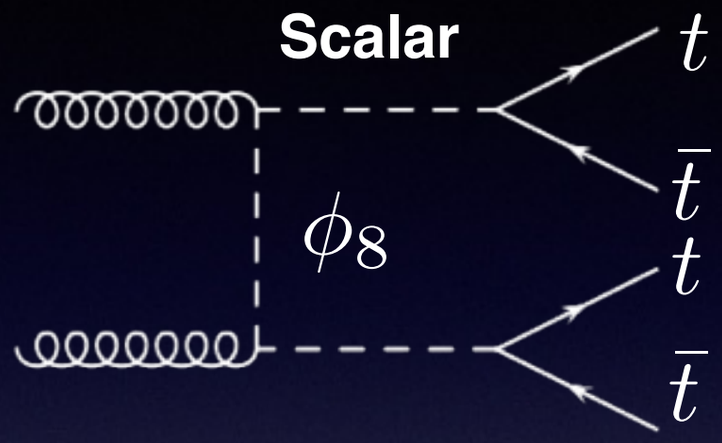
Four Top Quark Production

Axigluon
KK Gluon



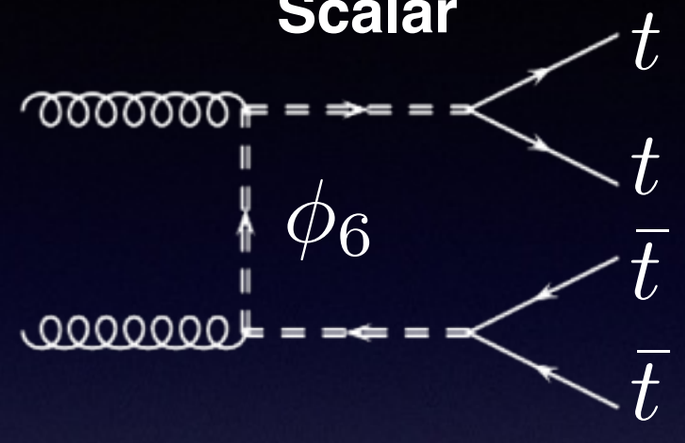
Aguilar-Saavedra, Santiago (2012)

Color Octet
Scalar



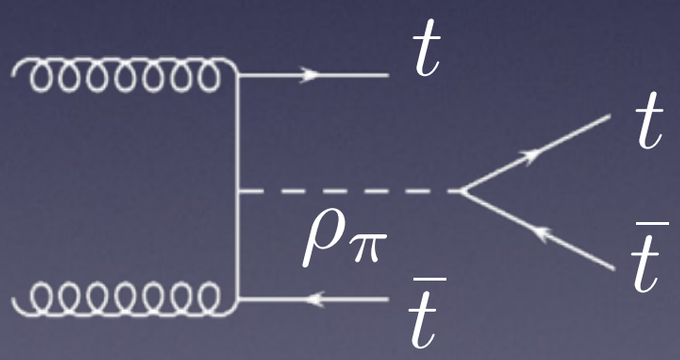
Plehn, Tait (2008)

Color Sextet
Scalar



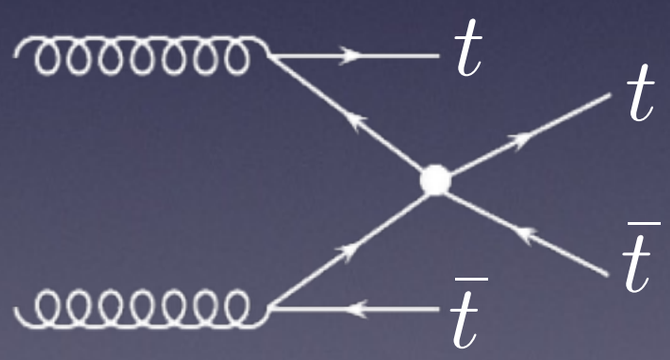
Chen, Klemm, Rentala, Wang (2008)

TC2



Han, Liu, Wu, Yang (2012)

Top Compositeness

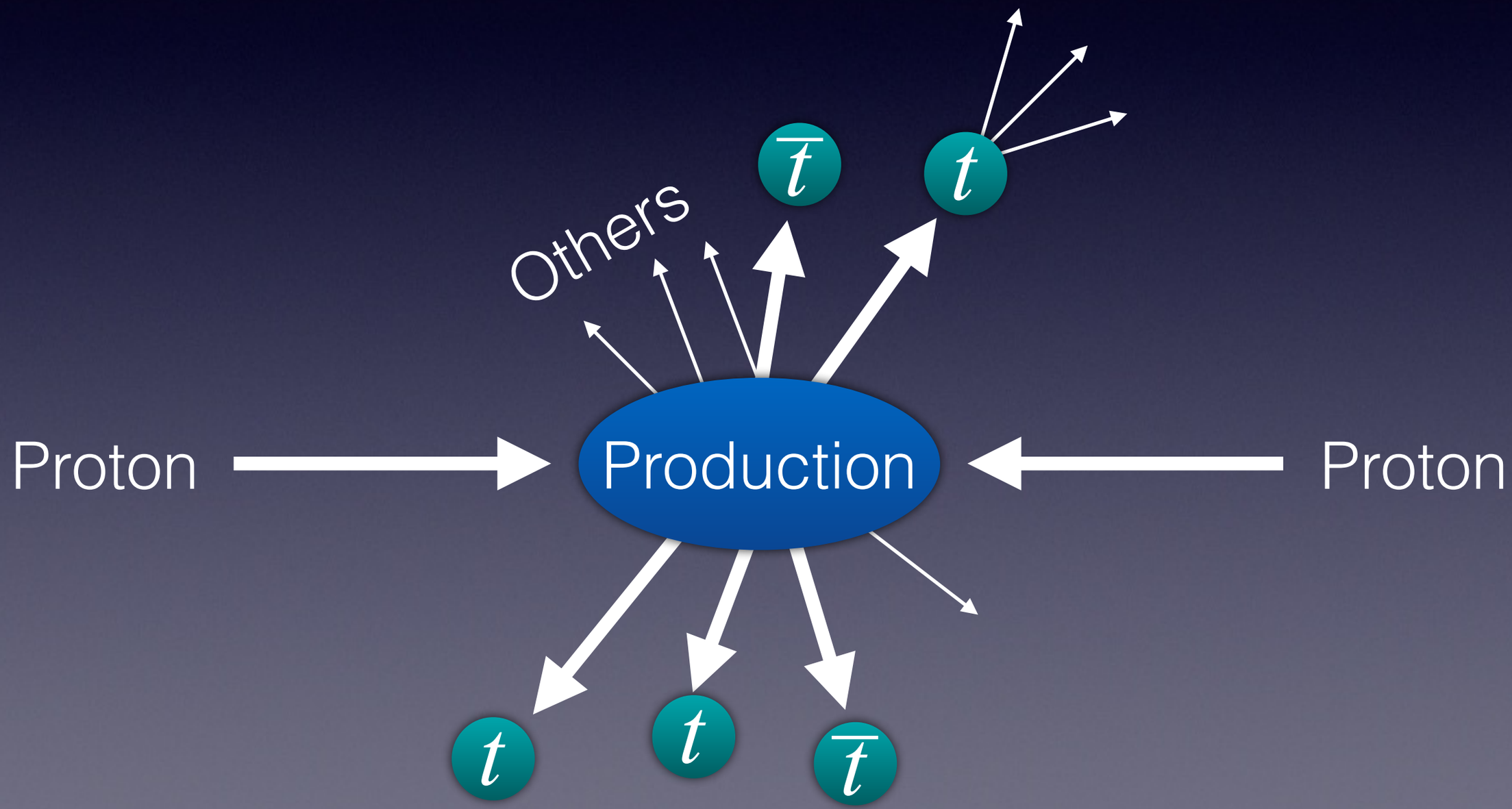


Lillie, Shu, Tait (2007)
Kumar, Tait, Veg-Morale (2009)

SM QCD production @ NLO,
Bevilacqua and Worek, 1206.3064

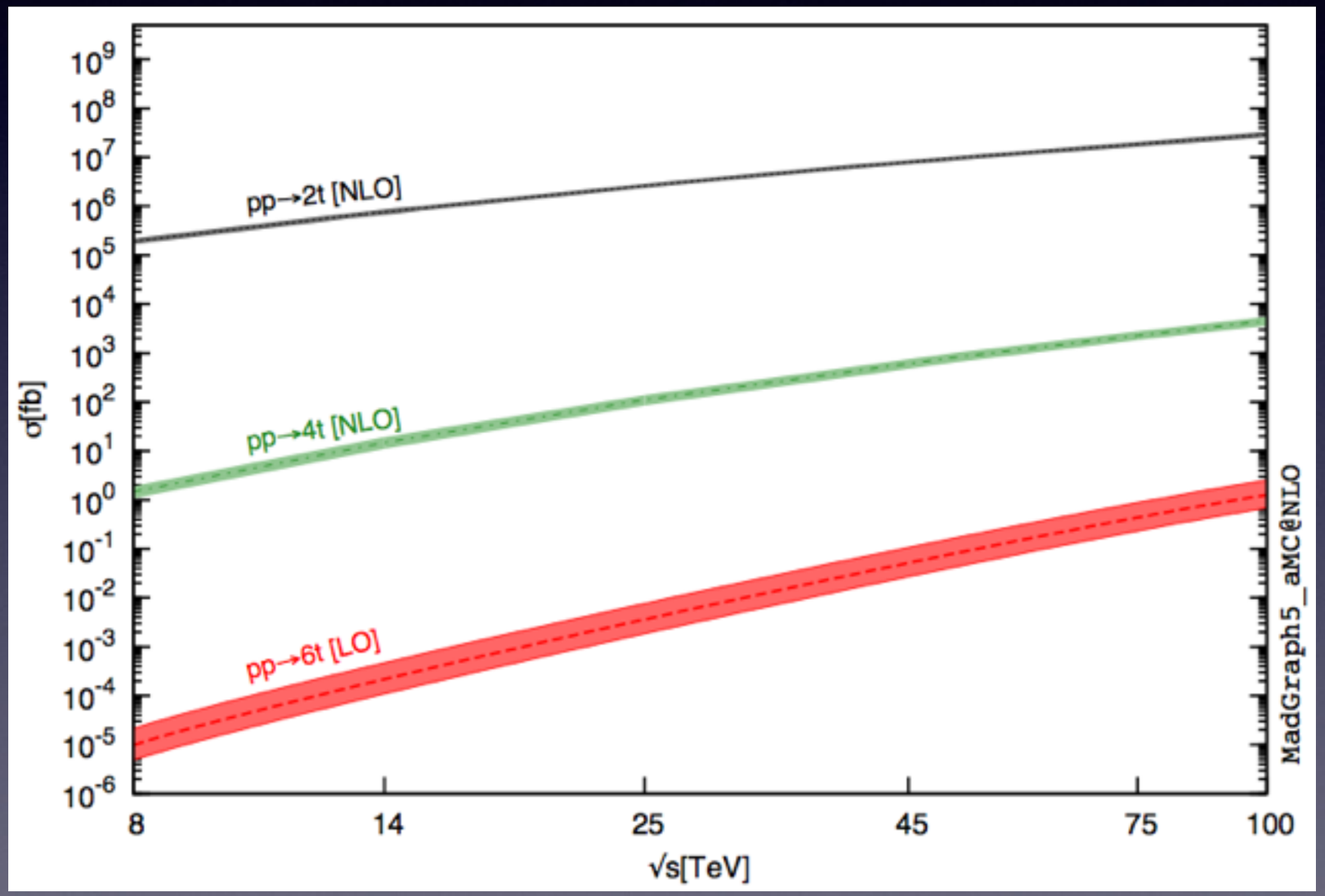
See Keaveney's poster

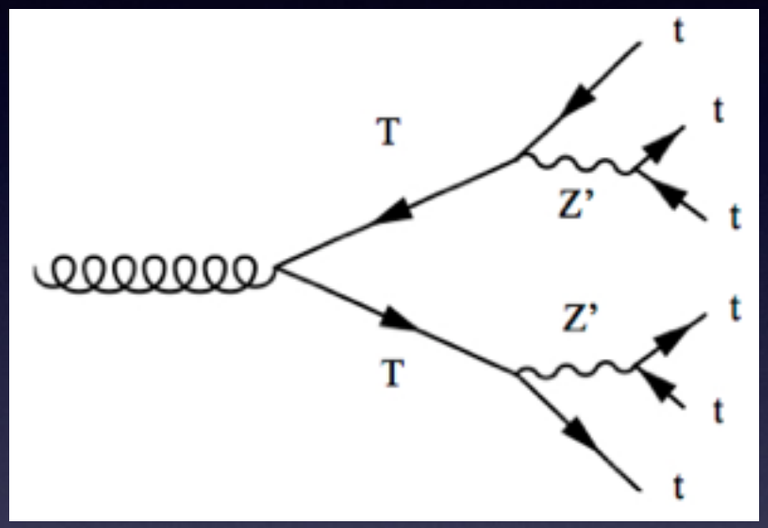
Six or More Top Quark Production



Six or More Top Quark Production

Deandrea, Deutschmann, 1405.6119





Color quantum #

	$R_{Z'}$	R_T
R_1	**1**	**3**
R_2	**8**	**3**
R_3	**8**	$\bar{\mathbf{6}}$
R_4	**8**	**15**

Summary

Top quark as a probe of new physics

It appears often in the decay of NP resonances

Extra Gauge Bosons

Z' W' G'

New Heavy Quarks

Vector Quark

4th Gen

Gluino

Top

Exotic Colored States

Color Sextet

Charged Higgs

Heavy Quark Production via pQCD

$\not{CP}$

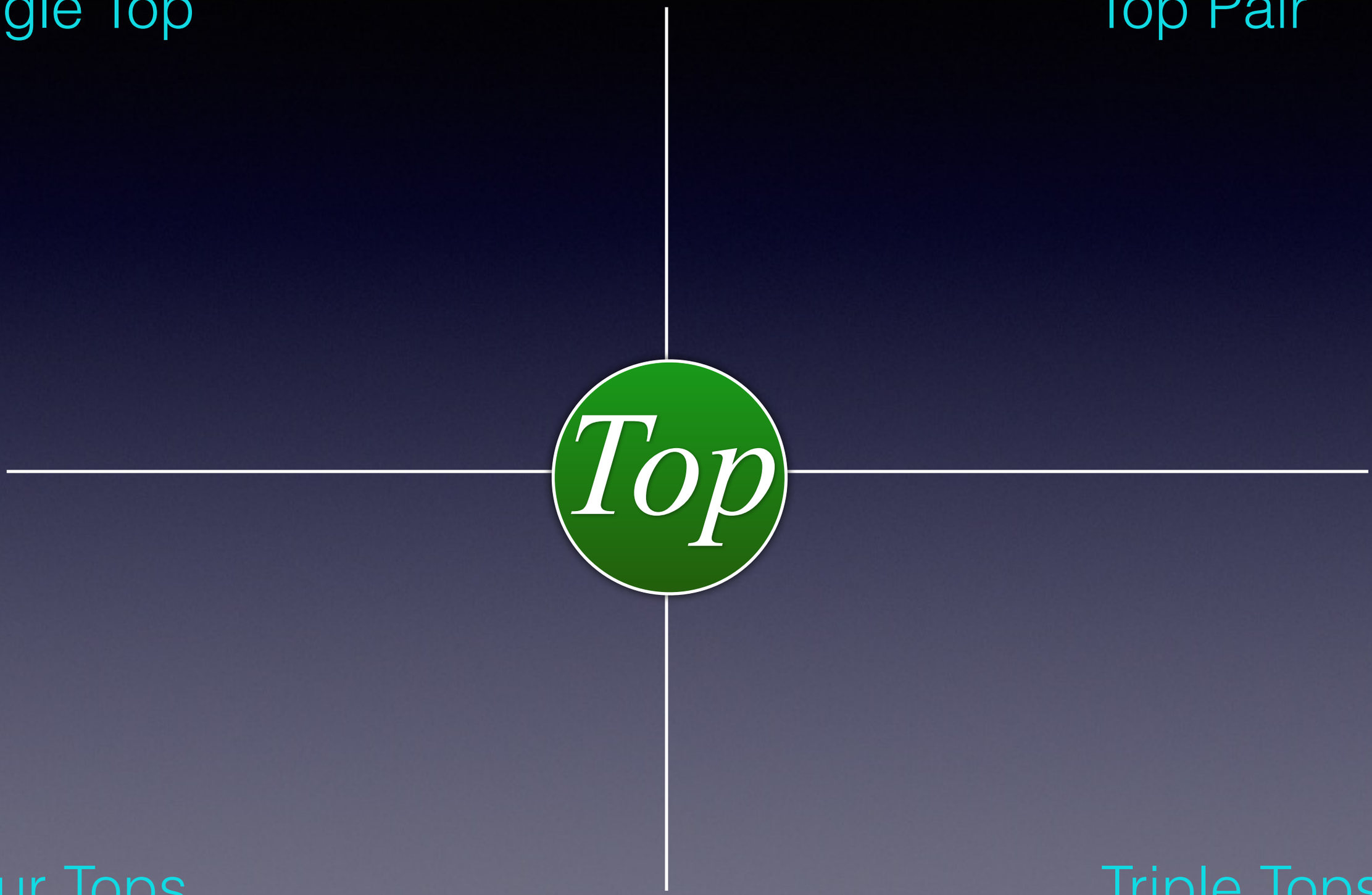
FCNC

A_{FB}

Top Quark Production: rich signatures

Single Top

Top Pair



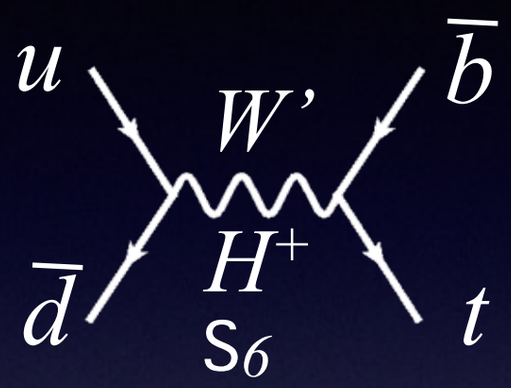
Four Tops

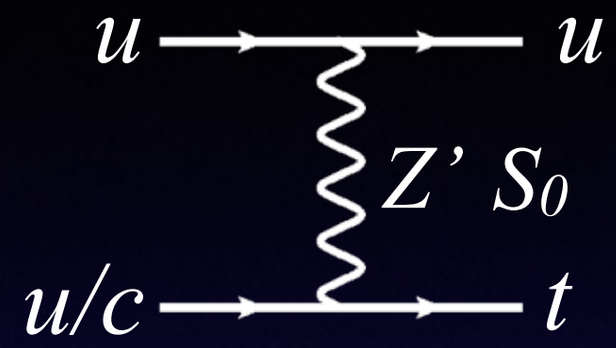
Triple Tops

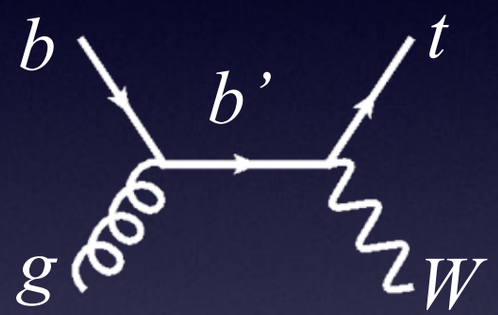
Flavor changing+Flavor conserving

Top Quark Production: rich signatures

Single Top







Top Pair

Top

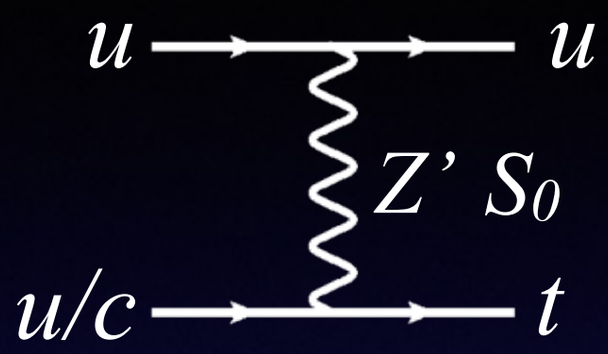
Four Tops

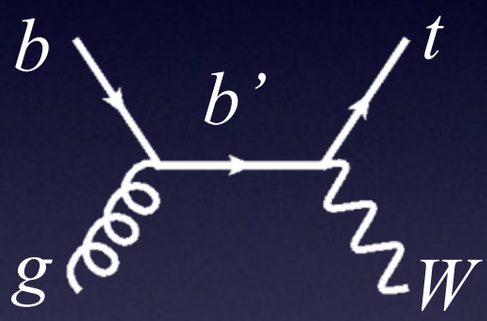
Triple Tops

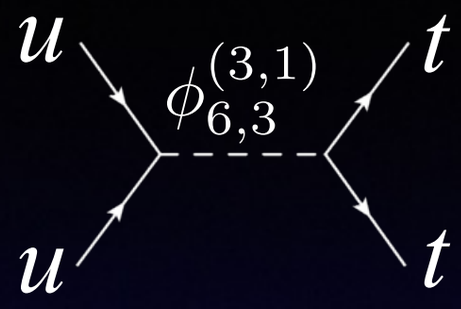
Flavor changing+Flavor conserving

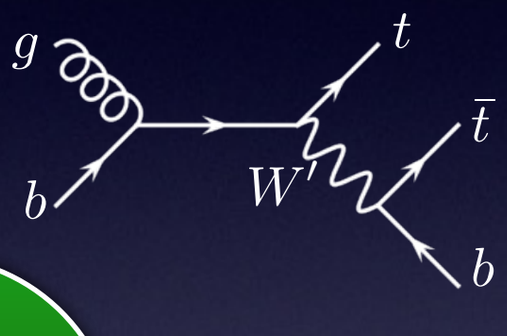
Top Quark Production: rich signatures

Single Top

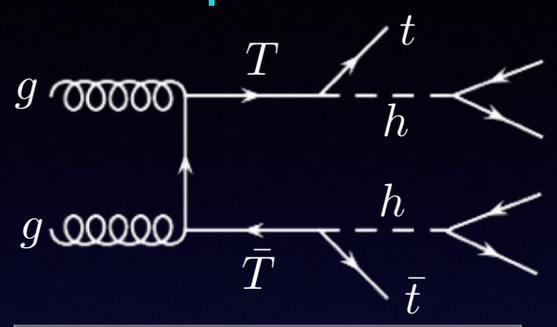


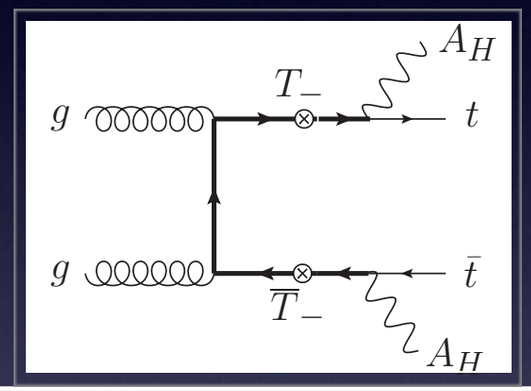






Top Pair





Top

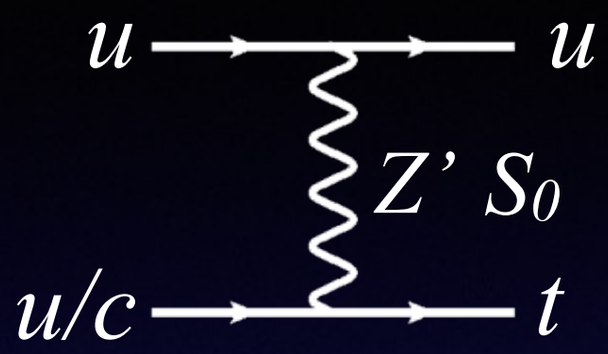
Four Tops

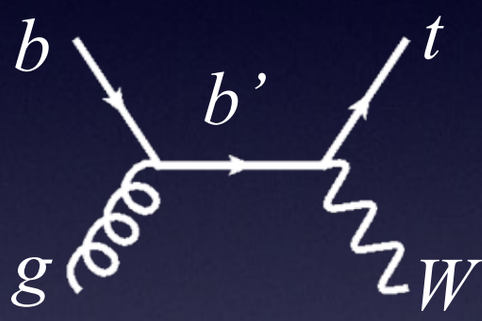
Triple Tops

Flavor changing+Flavor conserving

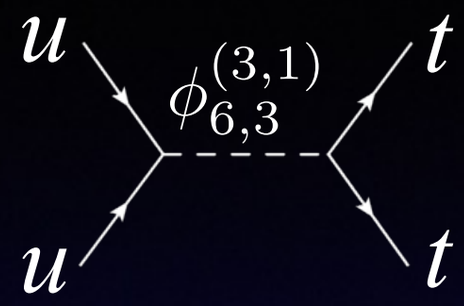
Top Quark Production: rich signatures

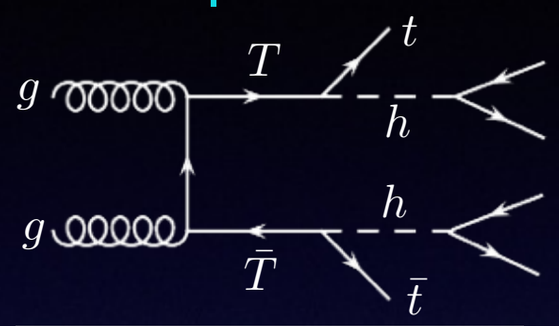
Single Top

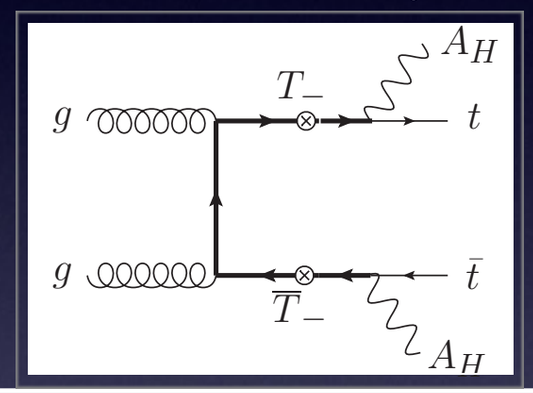




Top Pair







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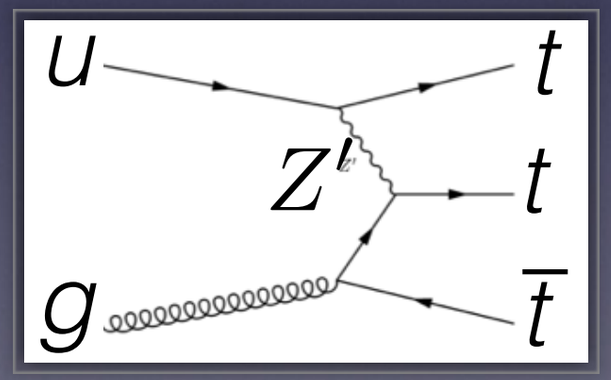

Four Tops

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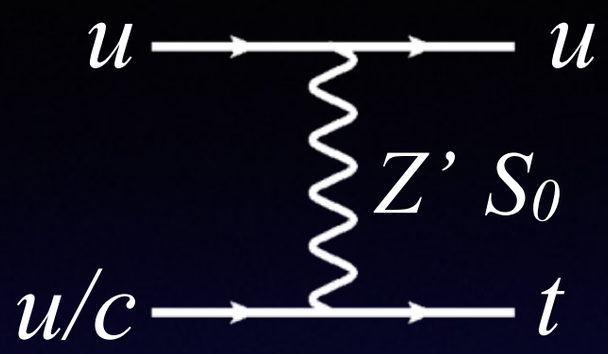
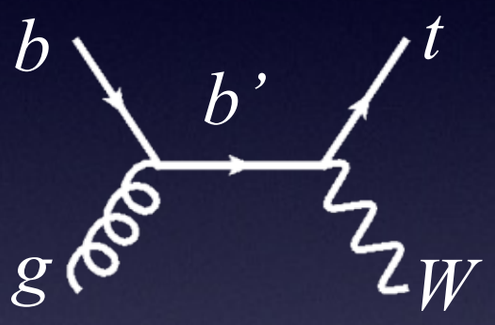
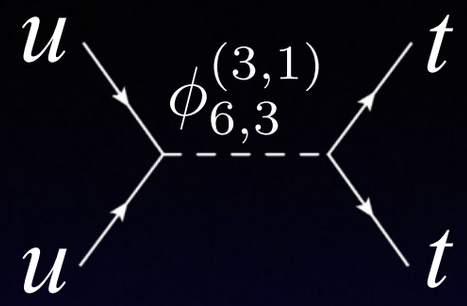
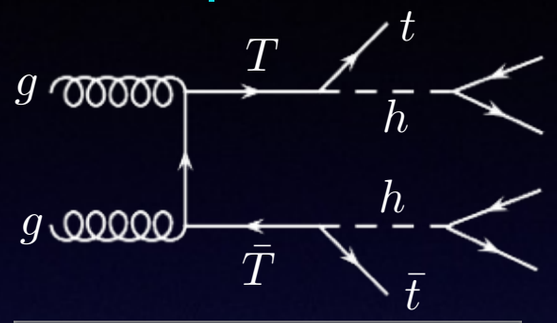
Single Top

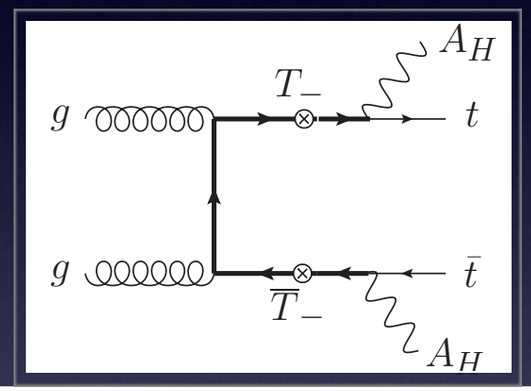






Top Pair





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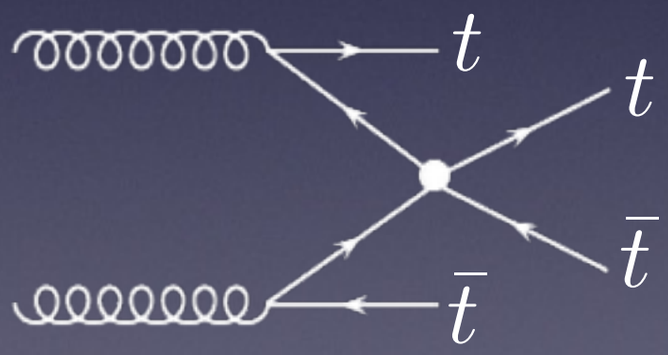
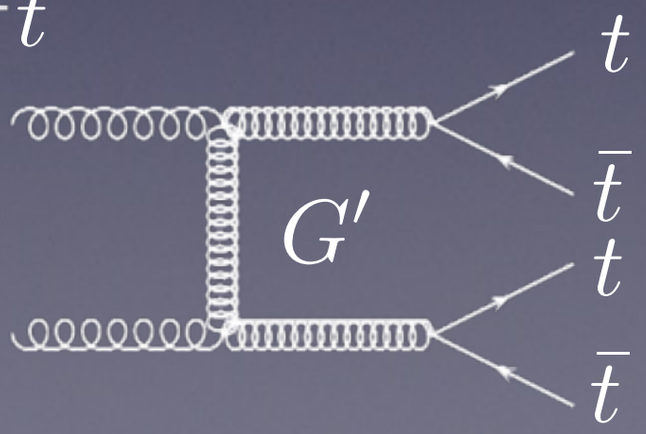
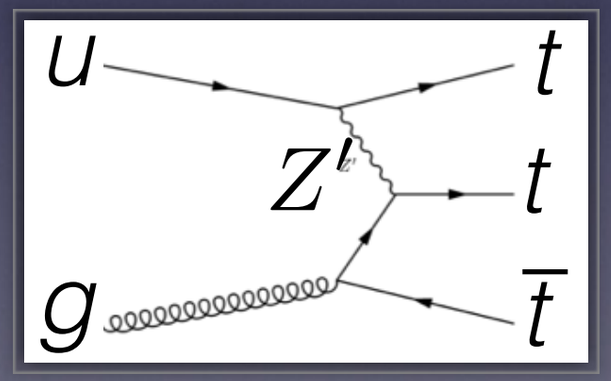




Four Tops



Triple Tops

Flavor changing+Flavor conserving