Multiple Top Quark Production at 100 TeV

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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

TOP

Effective Field Theory

Experimental Data

What could we see?

In this talk

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

Top

Exotic Colored States

Color Sextet

Vector Quark

4th Gen

Gluino

Heavy Quark Production via pQCD

Charged Higgs

$\cancel{CP}$

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**

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

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

- **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)

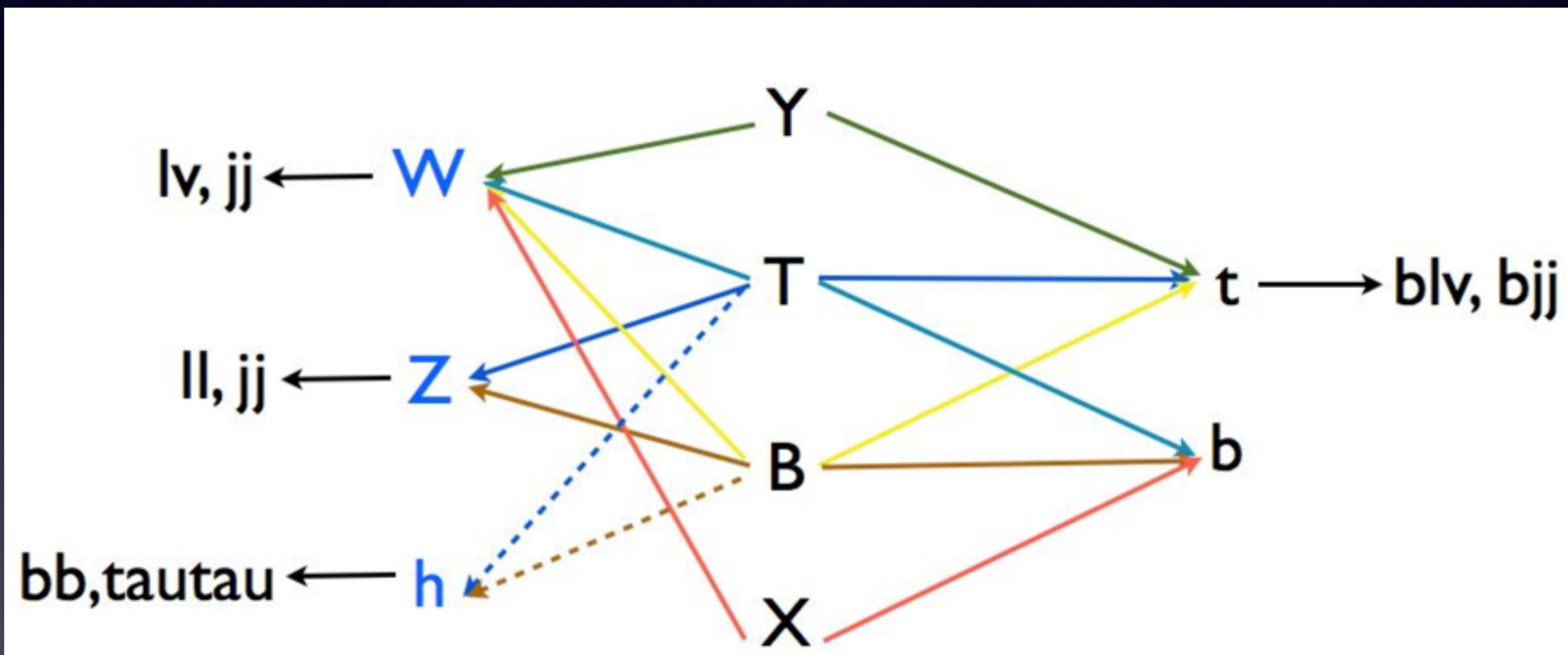
Angular-
Saavedra
(2009)

Cacciapaglia,
Deandrea,
Harada,
Okada
(2010)

Vector Quarks

$$T \to W^+b/Zt/Ht \qquad Y \to W^+t$$

$$B \to W^+t/Zb/Hb \qquad X \to W^-b$$



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

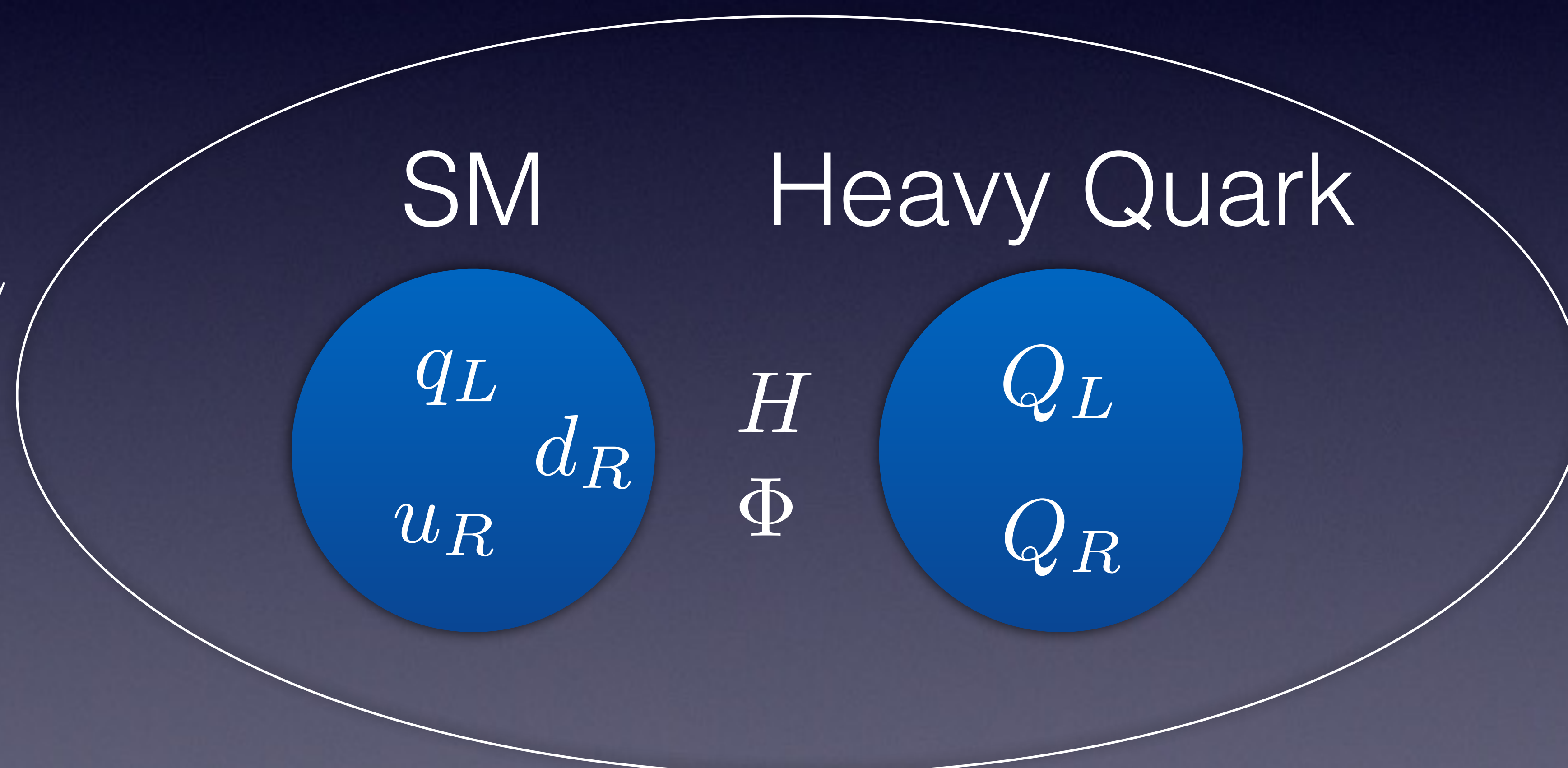
Extra Weak Boson and Quarks

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



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

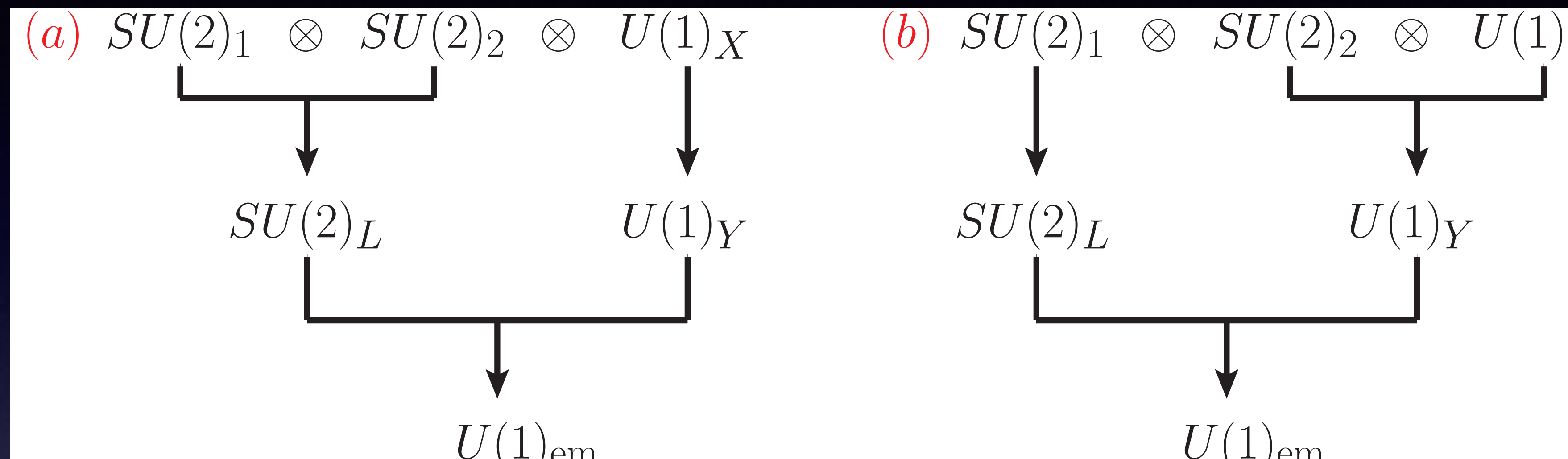
G(331) Model

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	$\begin{pmatrix} u_L \\ d_L \end{pmatrix}_{\rm 1st,2nd}, \begin{pmatrix} \nu_L \\ e_L \end{pmatrix}_{\rm 1st,2nd}$	$\begin{pmatrix} u_L \\ d_L \end{pmatrix}_{\rm 3rd}, \begin{pmatrix} \nu_L \\ e_L \end{pmatrix}_{\rm 3rd}$	$X_f = Y_{\rm SM}$
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

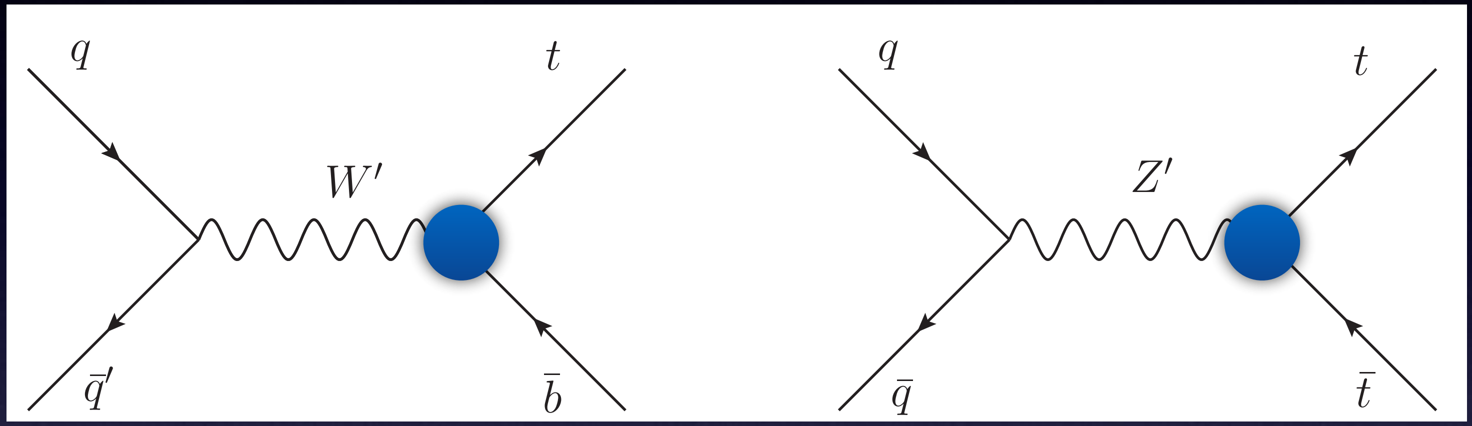
SQD: Sequential W' with doublet Higgs

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

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

$$\underset{3}{\begin{pmatrix} u \\ d \\ D \end{pmatrix}} \qquad \underset{3}{\begin{pmatrix} c \\ s \\ S \end{pmatrix}} \qquad \underset{\overline{3}}{\begin{pmatrix} b \\ -t \\ T \end{pmatrix}}$$

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

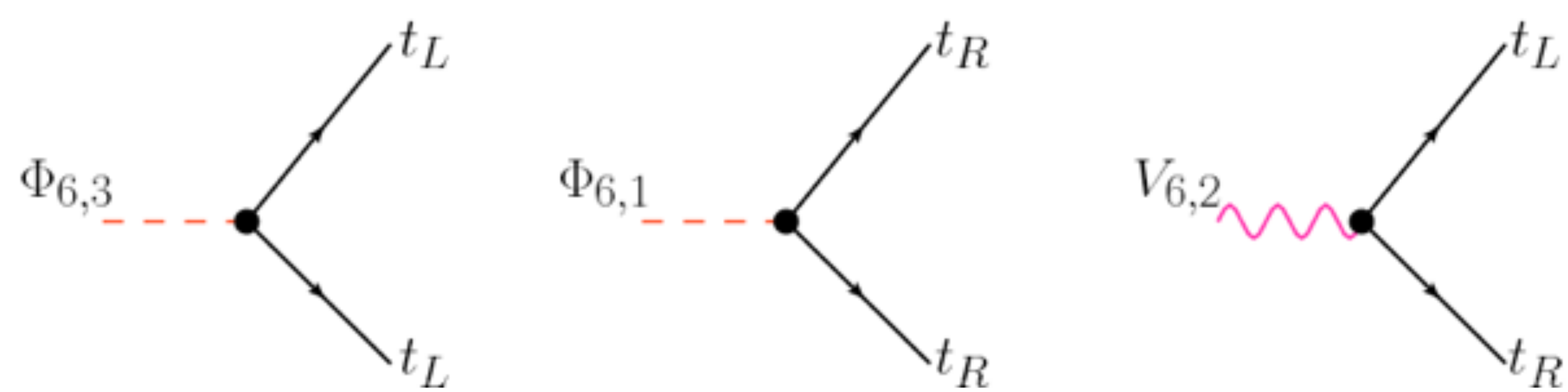
Exotic Colored Scalars/Vectors

Effective Lagrangian:

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

$$q_L = \begin{pmatrix} u_L \\ d_L \end{pmatrix}$$

$$q^c = C\bar{q}^T$$



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

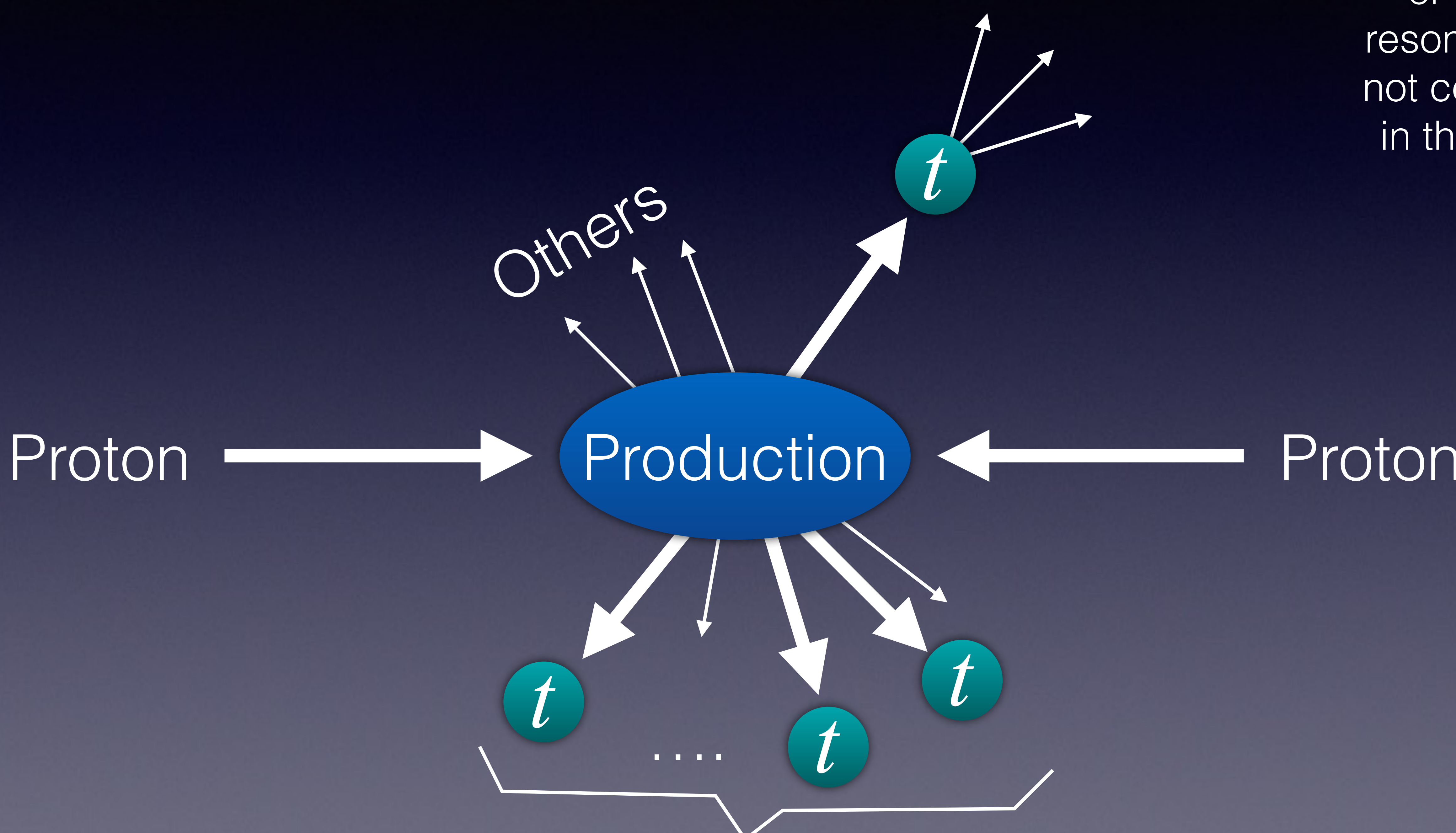
$$Q = Q_L$$

$$U = u_R$$

$$D = d_R$$

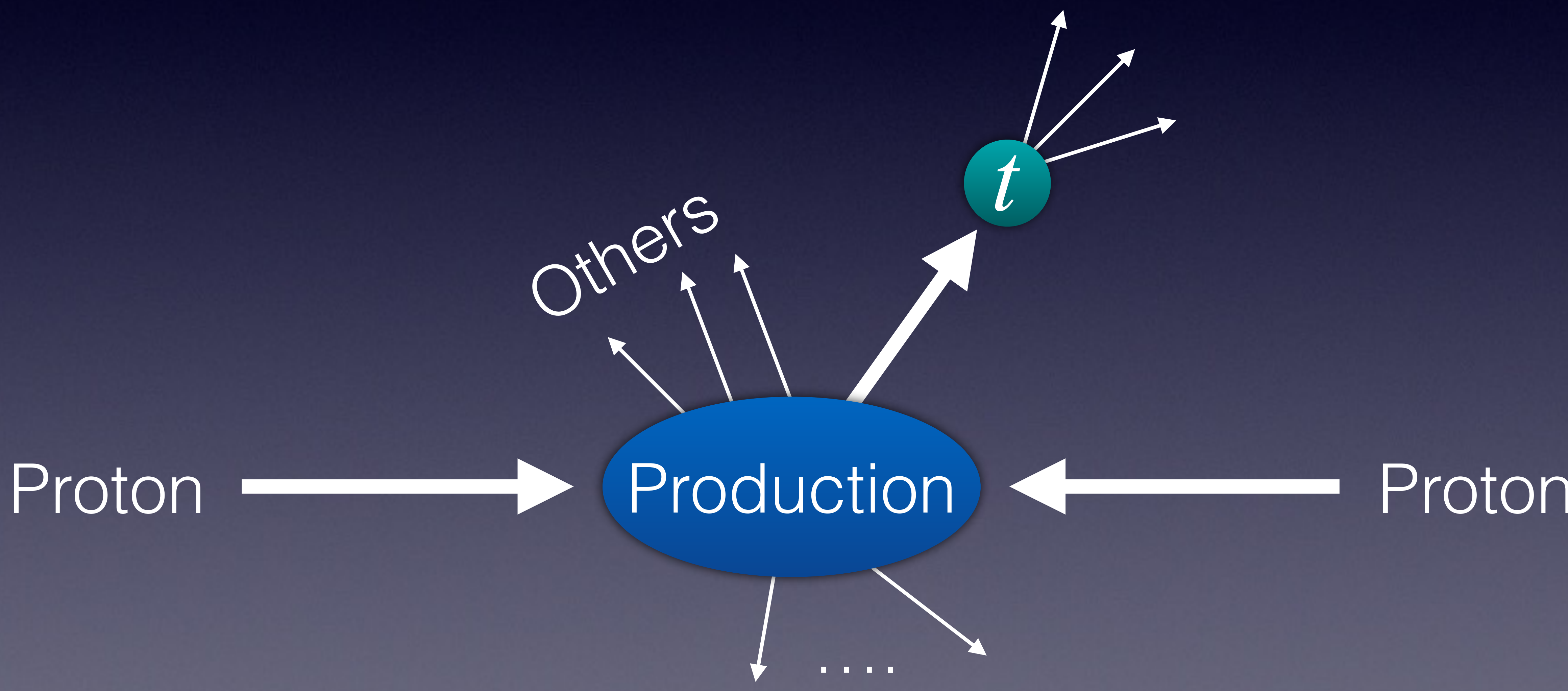
Top Quark and New Physics

Rare decays or light resonances not covered in this talk



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

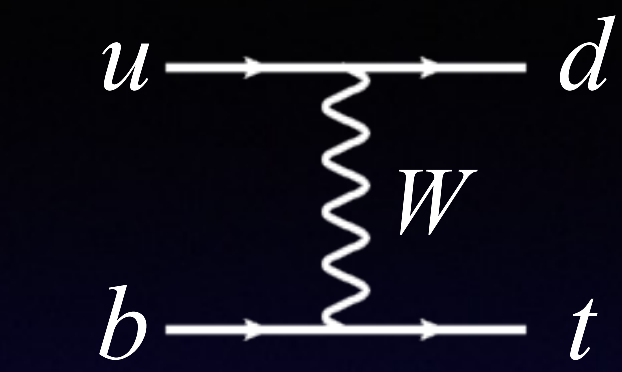
Single Top Quark Production



Single Top Quark Production

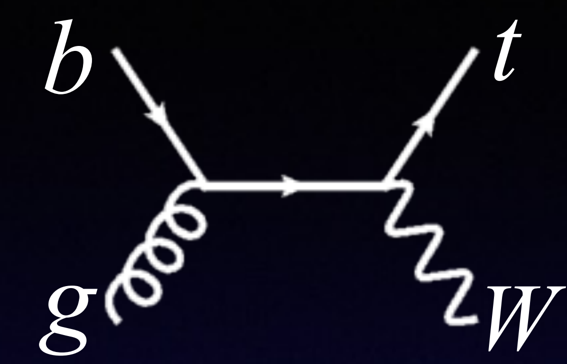
s-channel

$Q_W^2 > 0$



t-channel

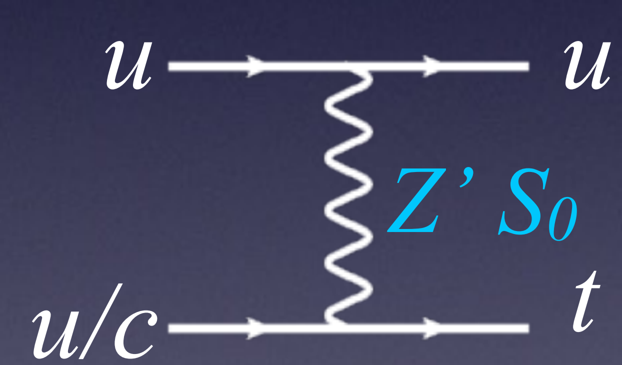
$Q_W^2 < 0$



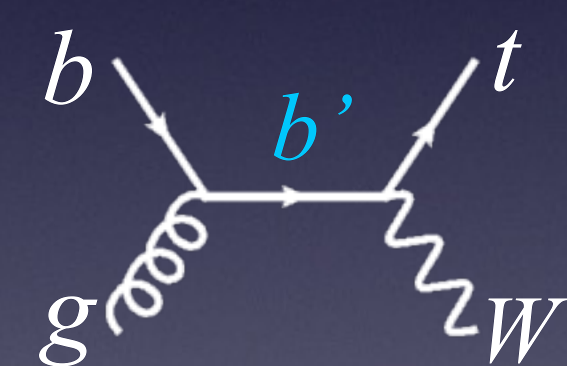
*t*W

$Q_W^2 = m_W^2$

New resonance



FCNC

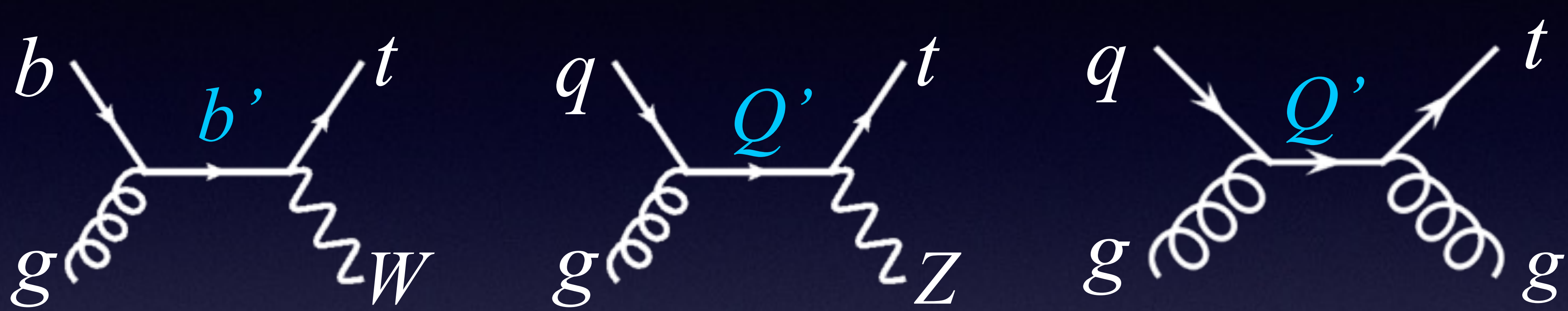


Excited quark

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

Single Top Quark Production

(s-channel excitation quark)



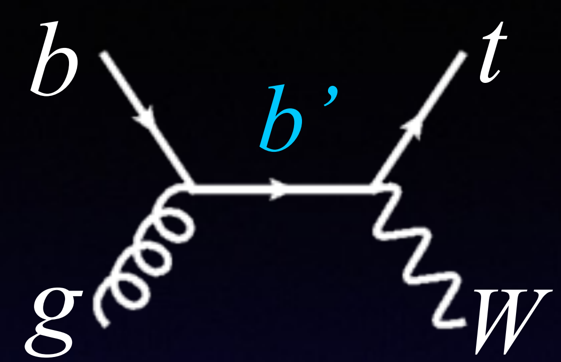
Nutter, Schwienhorst, Walker, Yu, 1207.5179

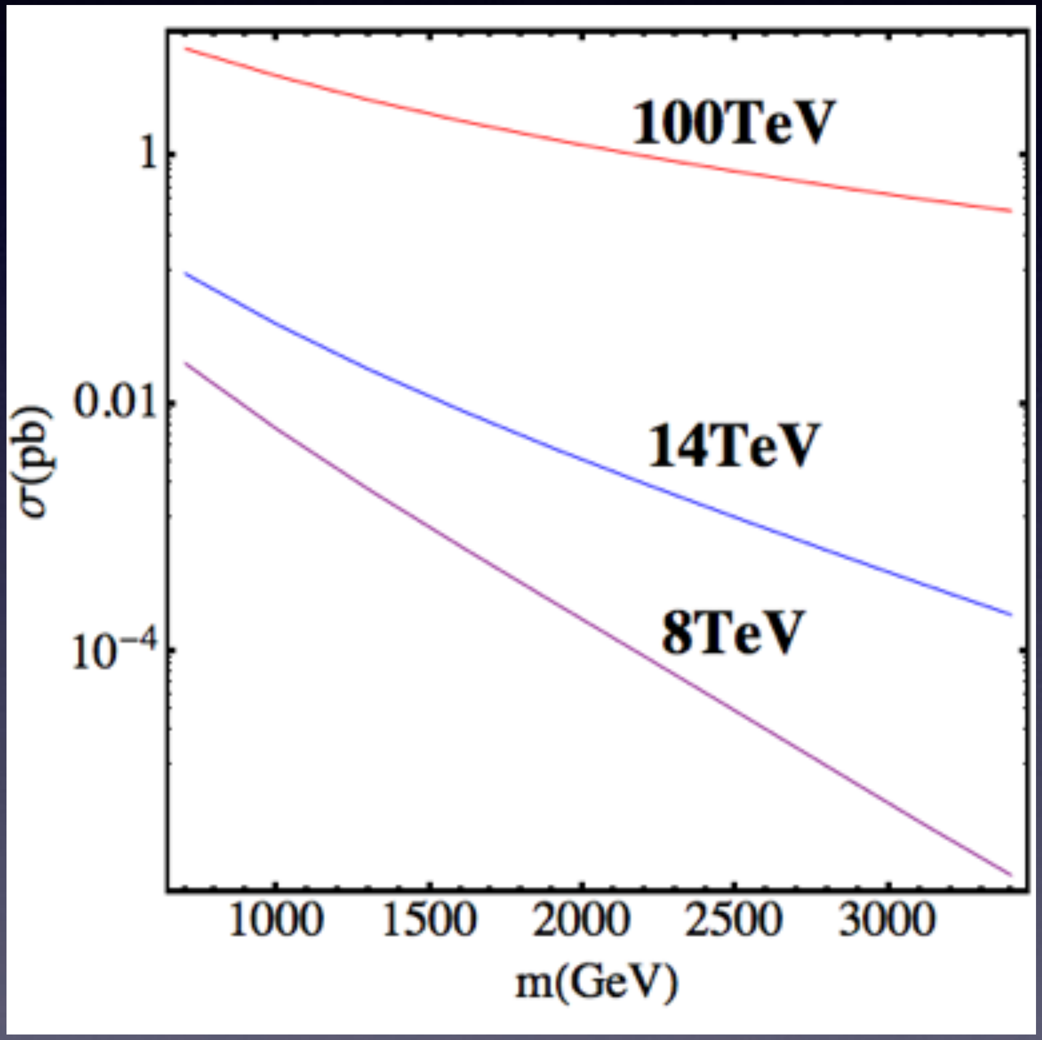
$$\mathcal{L} = g_s \bar{B}' \gamma^\mu B' + \frac{v}{\sqrt{2}\Lambda^2} G_{\mu\nu} \bar{b} \sigma^{\mu\nu} \left(\kappa_L^b P_L + \kappa_R^b P_R \right) B' + h.c.$$

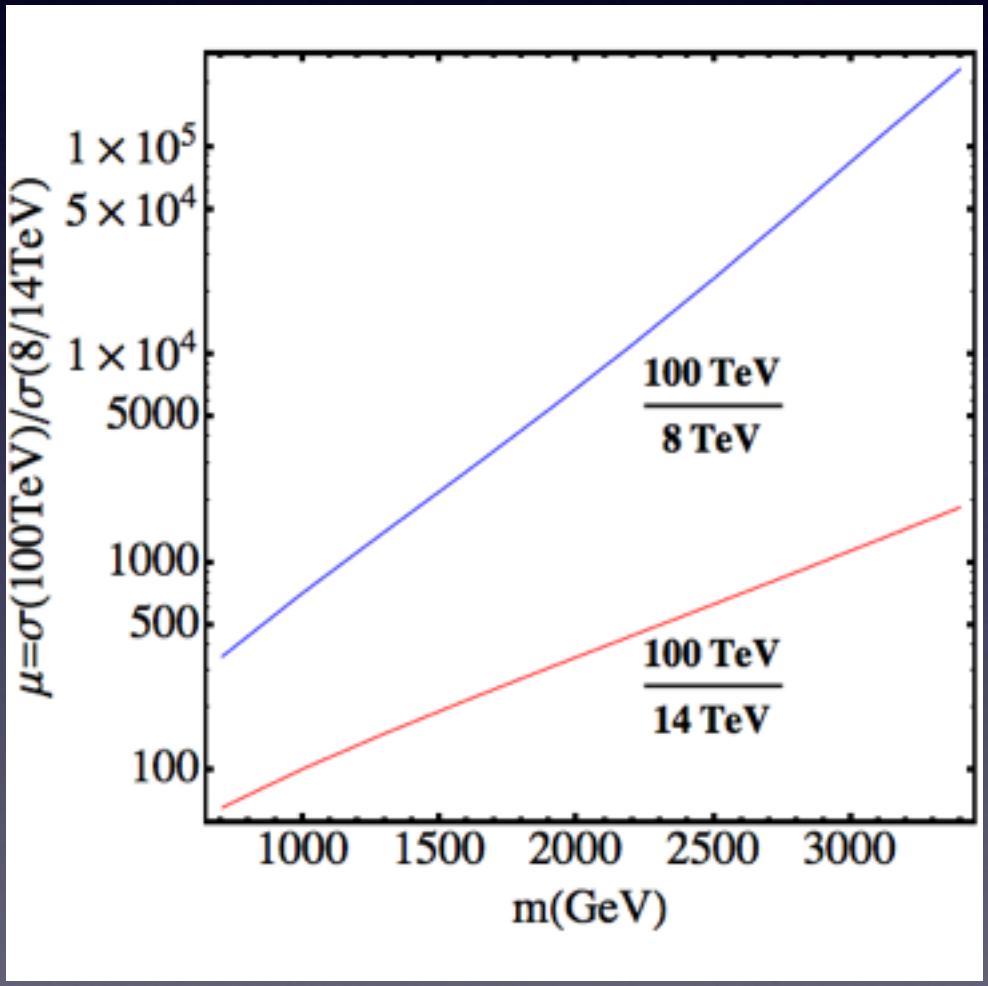
$$\mathcal{L} = \frac{g_W}{\sqrt{2}} W_\mu^+ \bar{t} \gamma^\mu (f_L P_L + f_R P_R) B' + h.c.$$

Single Top Quark Production

(s-channel excitation quark)



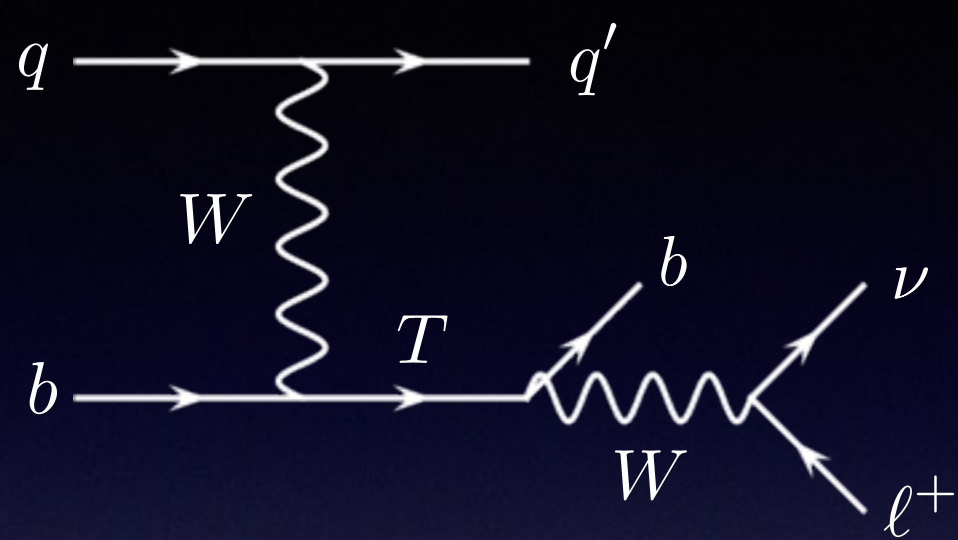




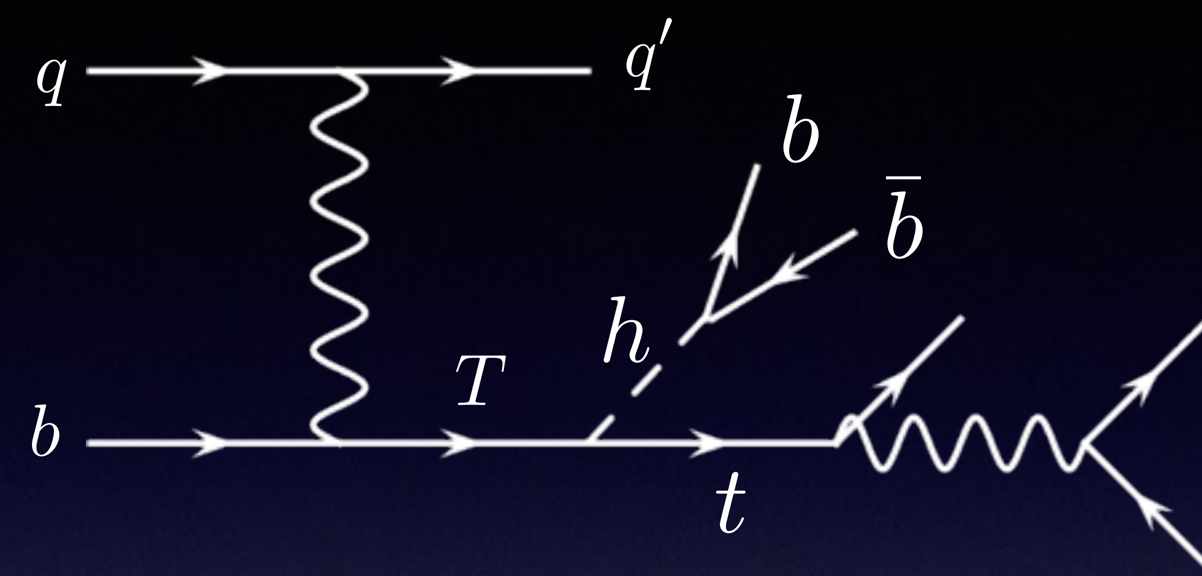
$$\mathcal{L} = g_s \bar{B}'\gamma^\mu B' + \frac{v}{\sqrt{2}\Lambda^2} G_{\mu\nu}\bar{b}\sigma^{\mu\nu}\left(\kappa_L^b P_L + \kappa_R^b P_R\right) B' + h.c.$$

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

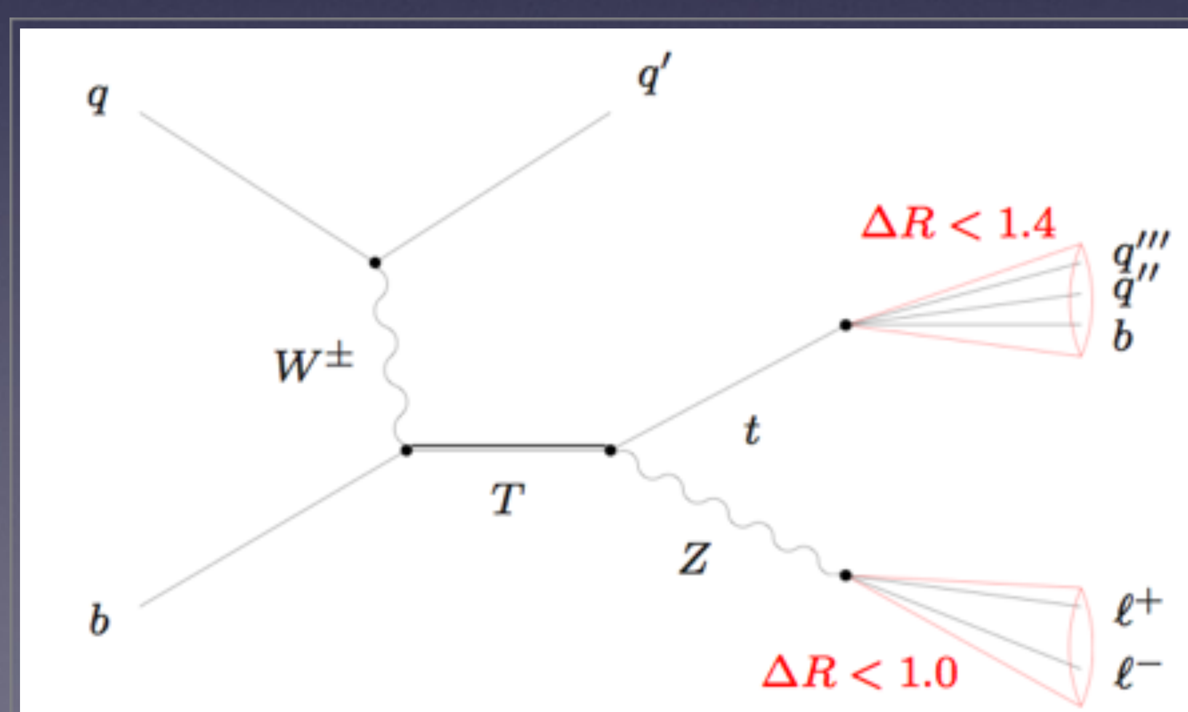
Single Heavy Quark Production



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

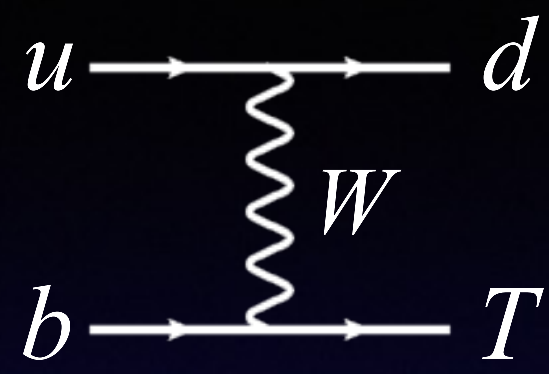


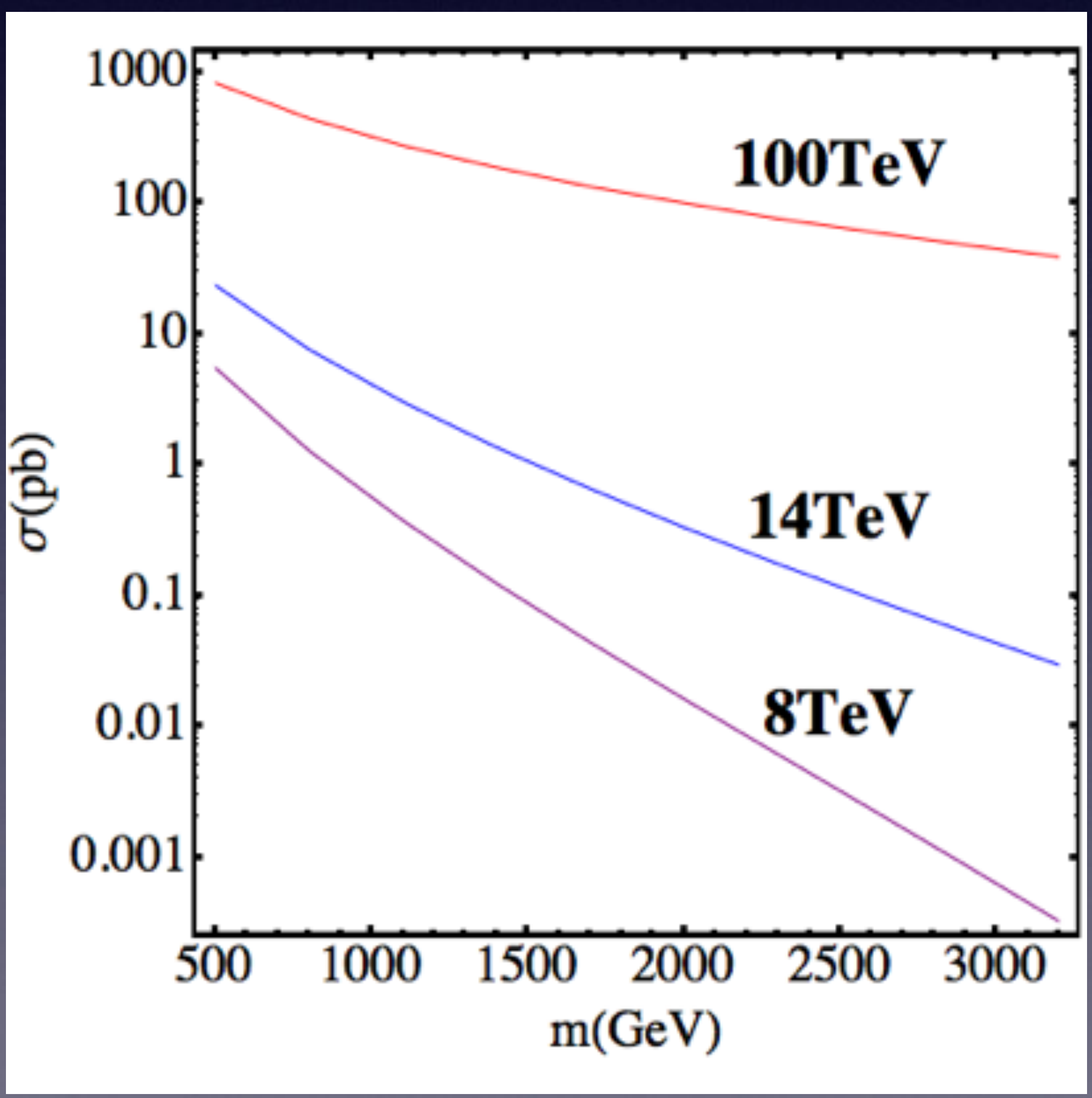
Composite Higgs
Li, Liu, Shu, 1306.5841
Boosted jet-substructure

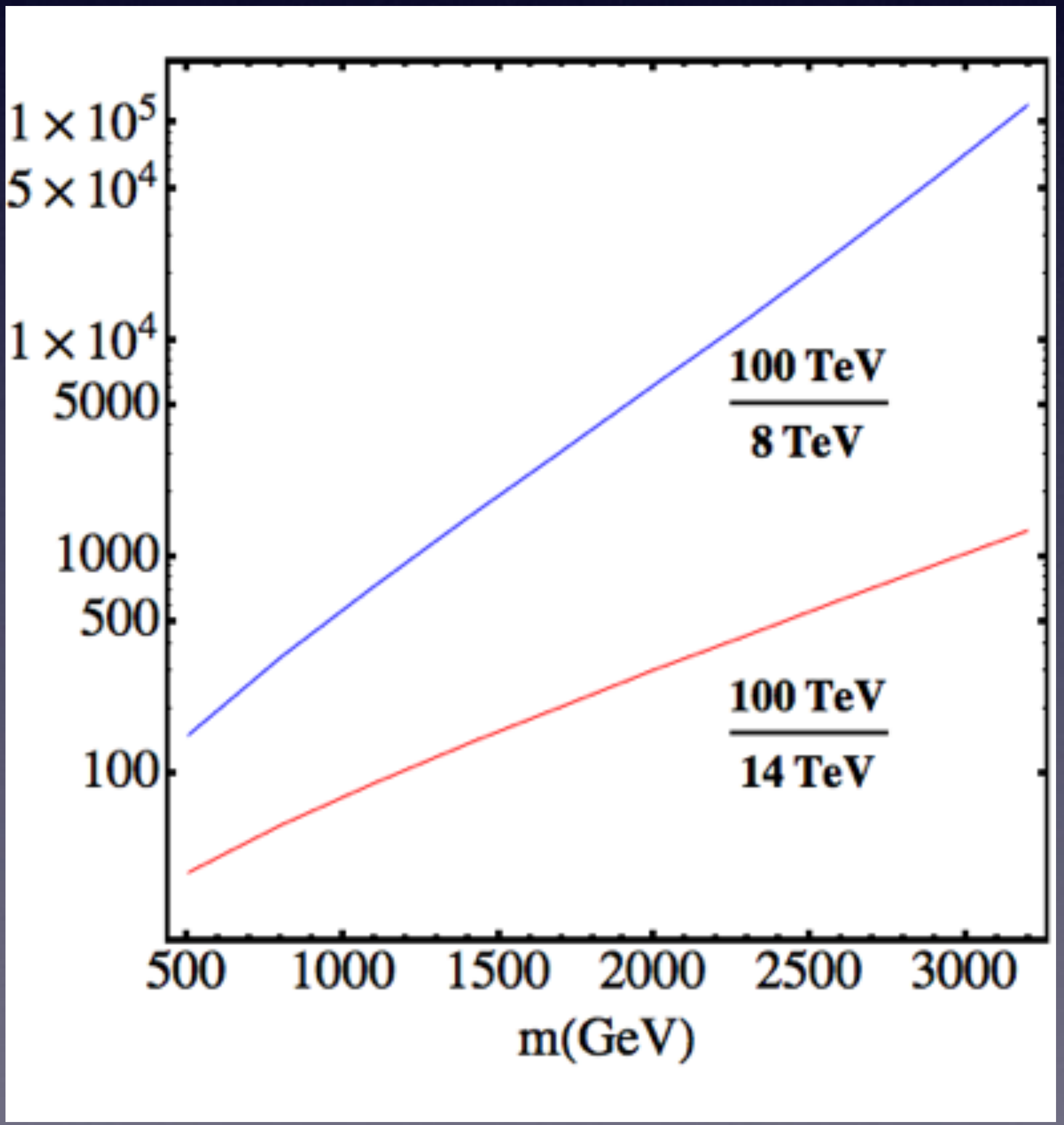


Reuter, Tonini,
1409.6962

Single Heavy Quark Production





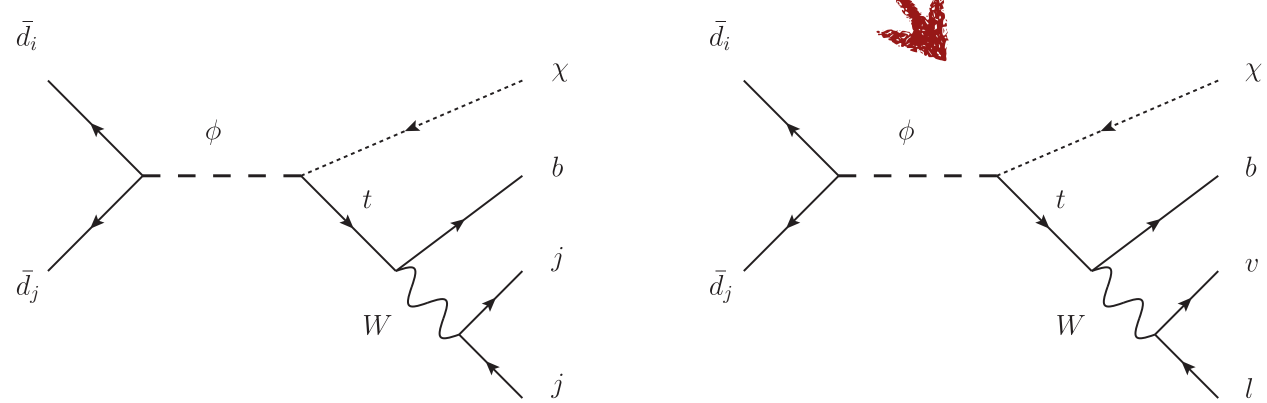


Mono Top Quark Production

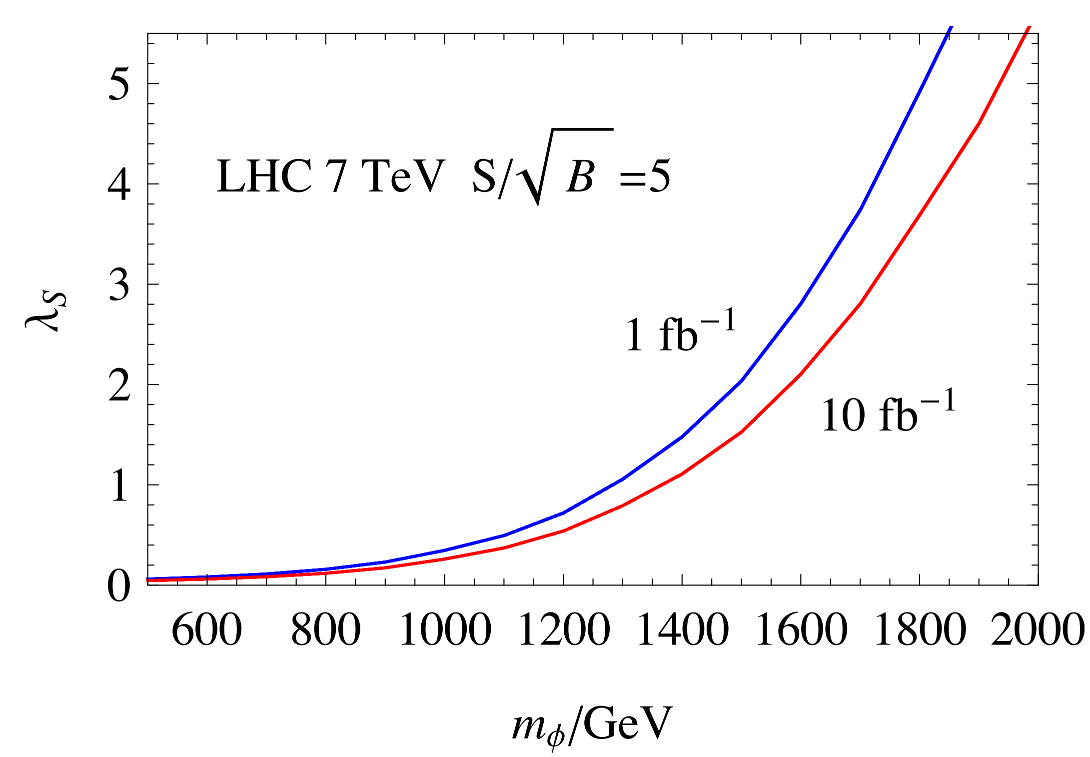
(R-parity violating SUSY inspired)

see Theveneaux-Pelzer's poster

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

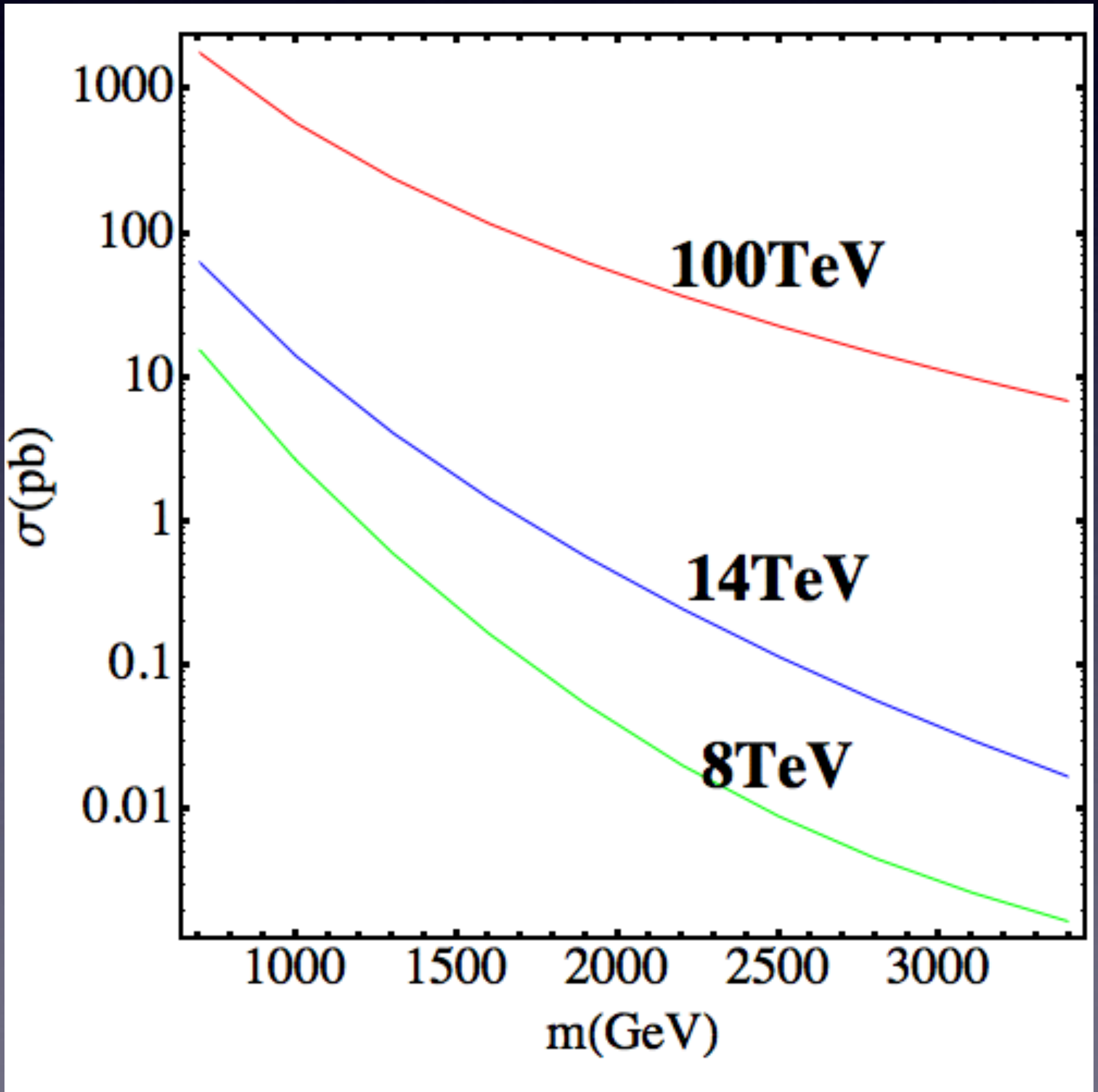


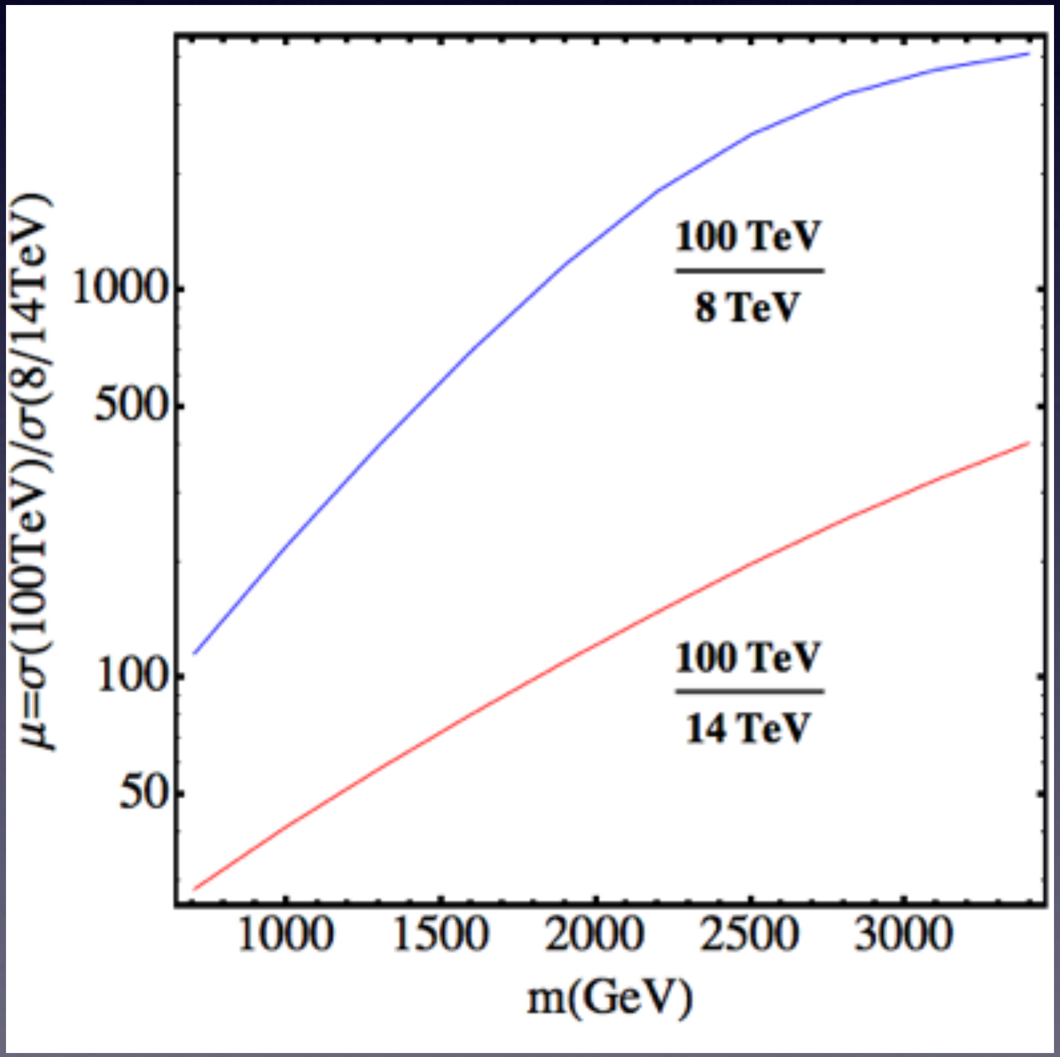
$$\begin{aligned}
\mathcal{L} = \; & \mathcal{L}_{SM} \\
& + \phi \bar{u} \left[a^0_{FC} + b^0_{FC}\gamma_5 \right] u + V_\mu \bar{u} \left[a^1_{FC}\gamma^\mu + b^1_{FC}\gamma^\mu\gamma_5 \right] u \\
& + \epsilon^{ijk} \varphi_i \bar{d}^c_j \left[a^q_{SR} + b^q_{SR}\gamma_5 \right] d_k + \varphi_i \bar{u}^i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



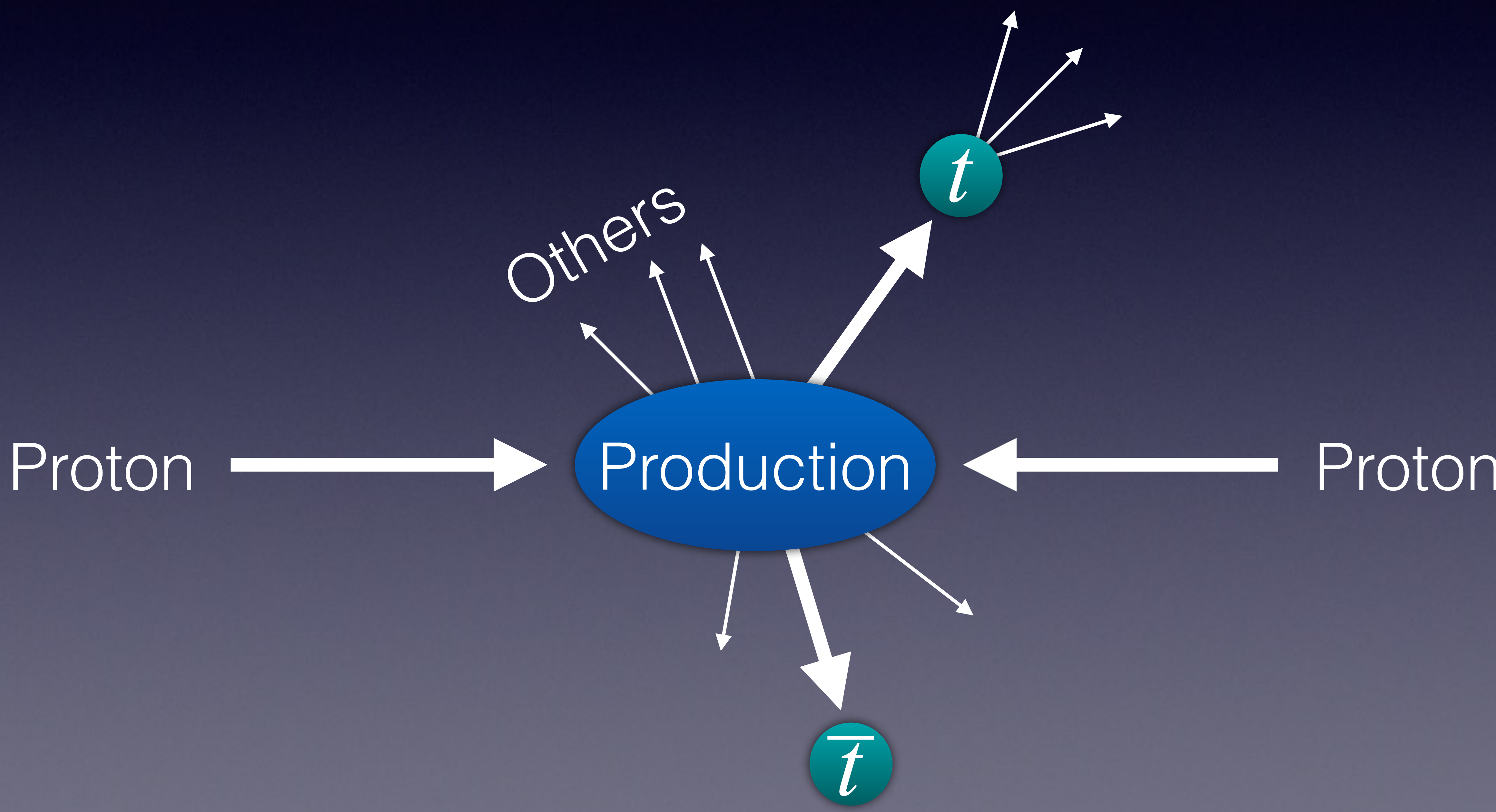
Mono Top Quark Production

(R-parity violating SUSY inspired)





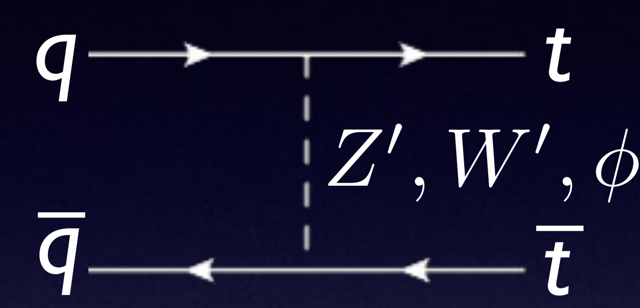
Top-Antitop or Top-Top Quark Pair Production

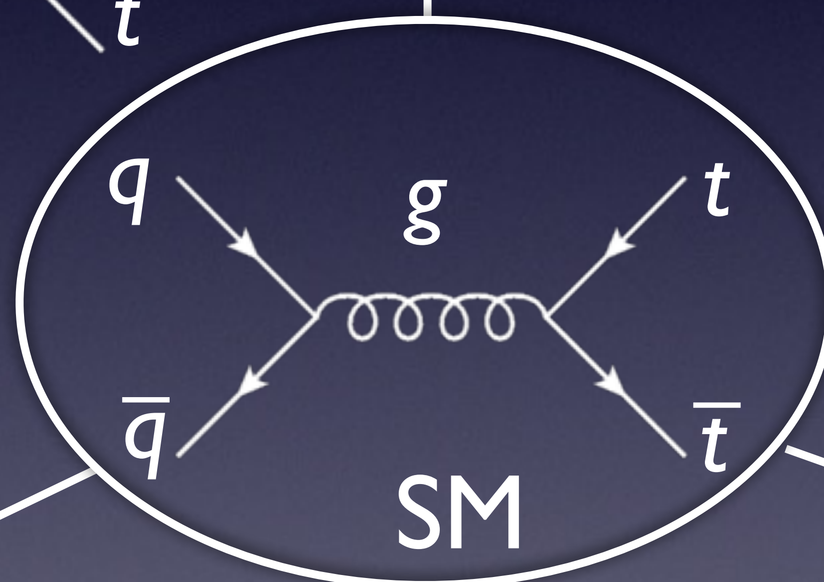


Top Quark A_{FB} and NP

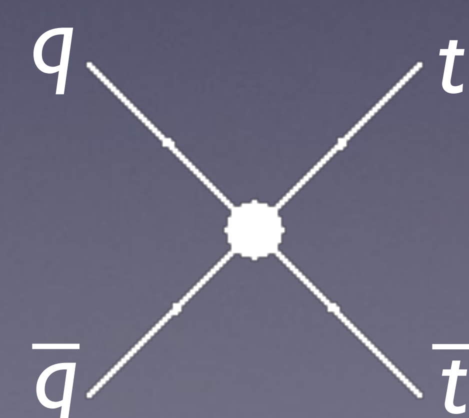
s-channel

t-channel *(Flavor changing)*





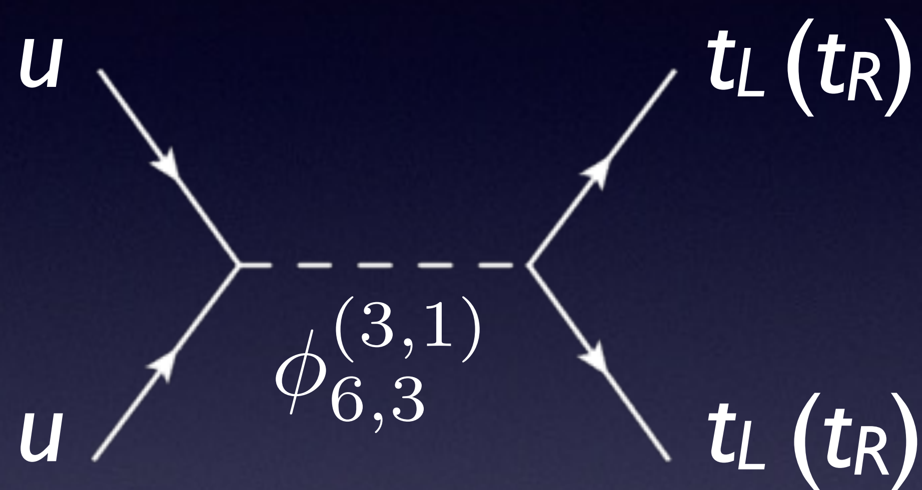
Effective theory



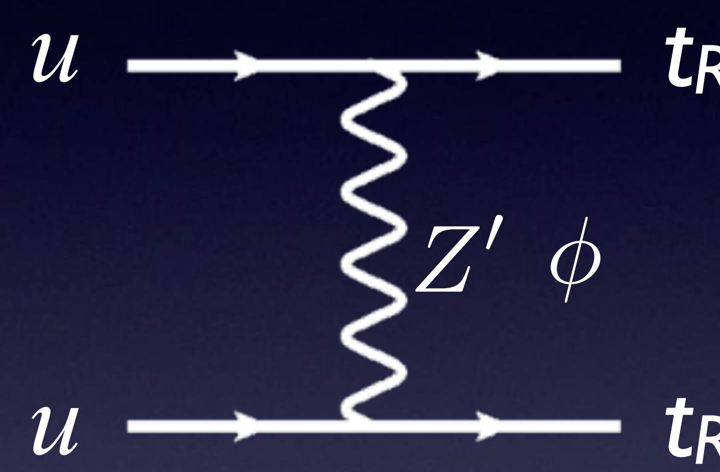
1) Same Sign Top Quark Pair

s-channel

$$3 \otimes 3 = 6 \oplus \bar{3}$$



t-channel



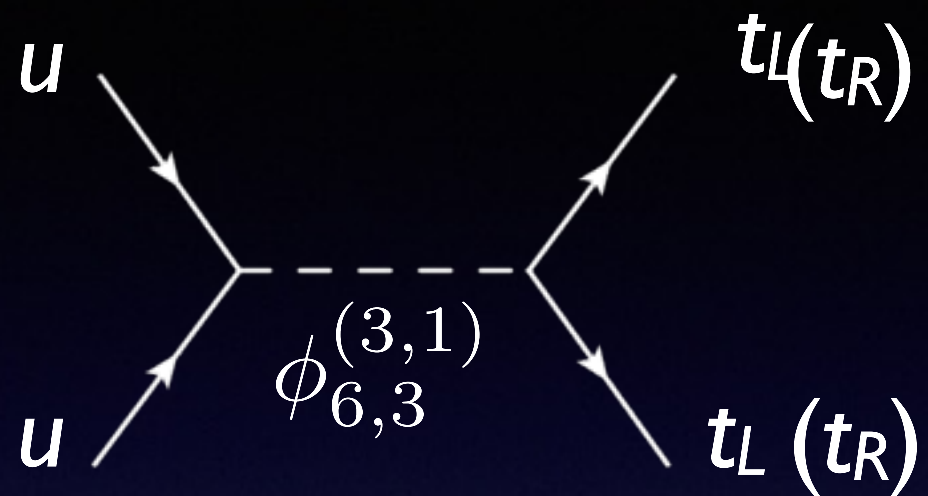
Mohapatra, Okada, Hai-Bo Yu, 0709.1486
Berger, QHC, Chen, Shaughnessy, Zhang,
1005.2622, 1009.5379
Aguilar-Saavedra, Perez-Victoria, 1104.1385
Atwood, Gupta, Soni, 1301.2250

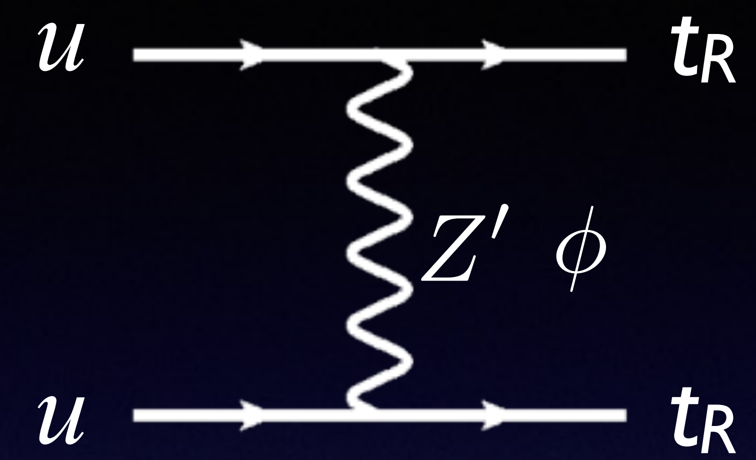
Flavor changing Z-prime
Berger, QHC, Chen, Li, Zhang
1101.5625

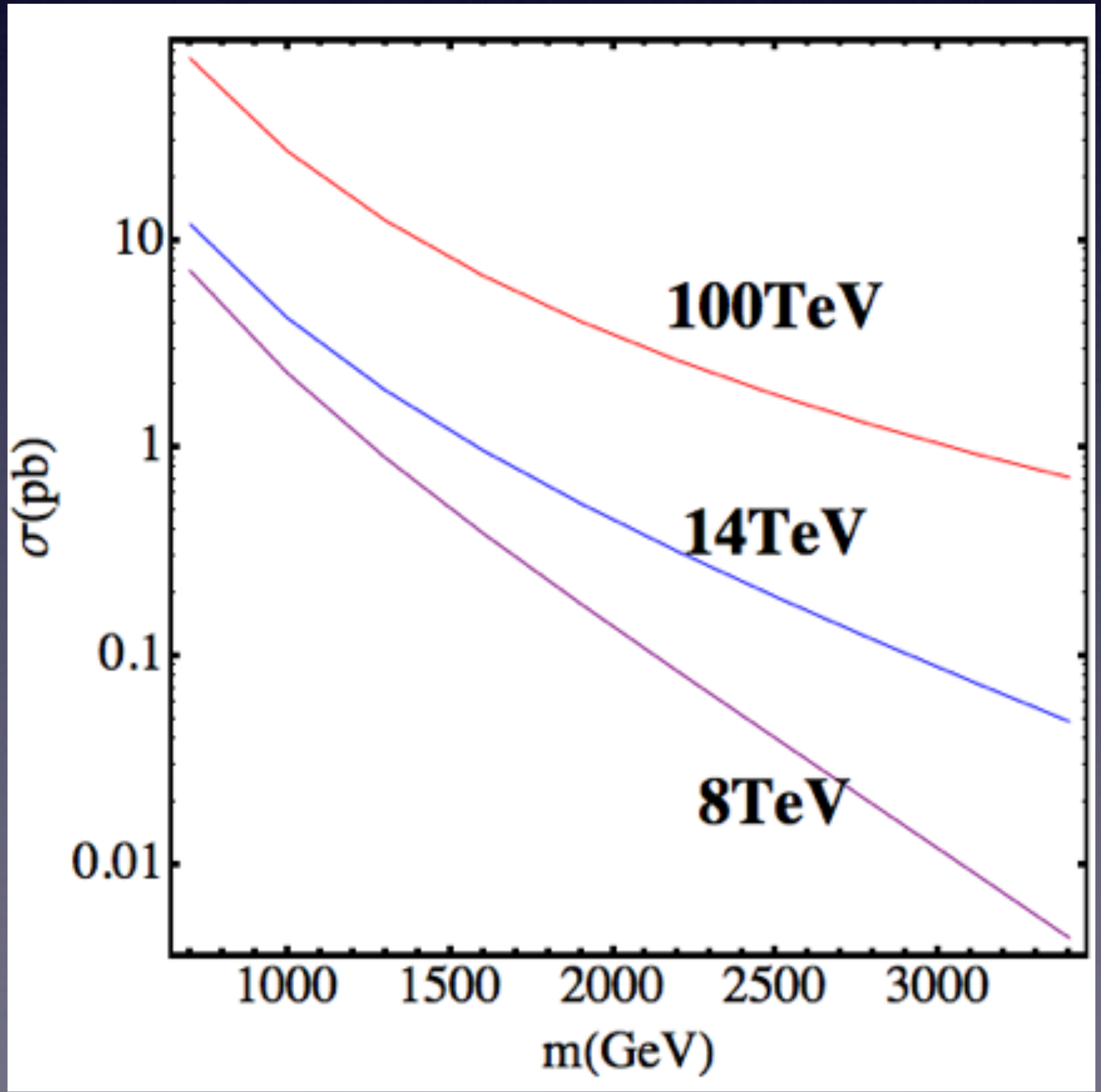
Maximal flavor violation
Bar-Shalom, Rajaraman,
Whiteson, Yu, 0803.3795

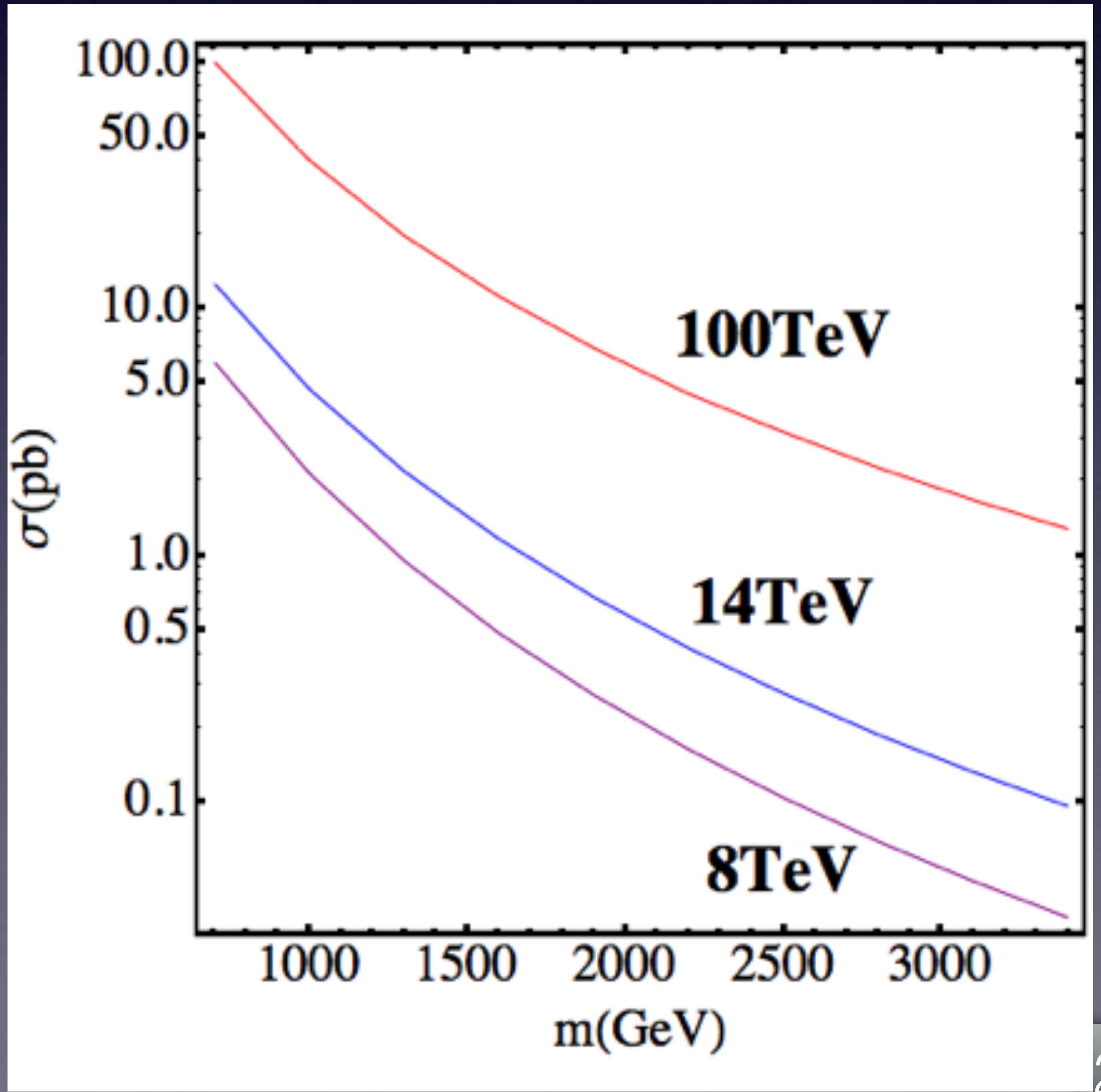
FCNC effective coupling
see Goldouzian's talk, 1408.0493

1) Same Sign Top Quark Pair



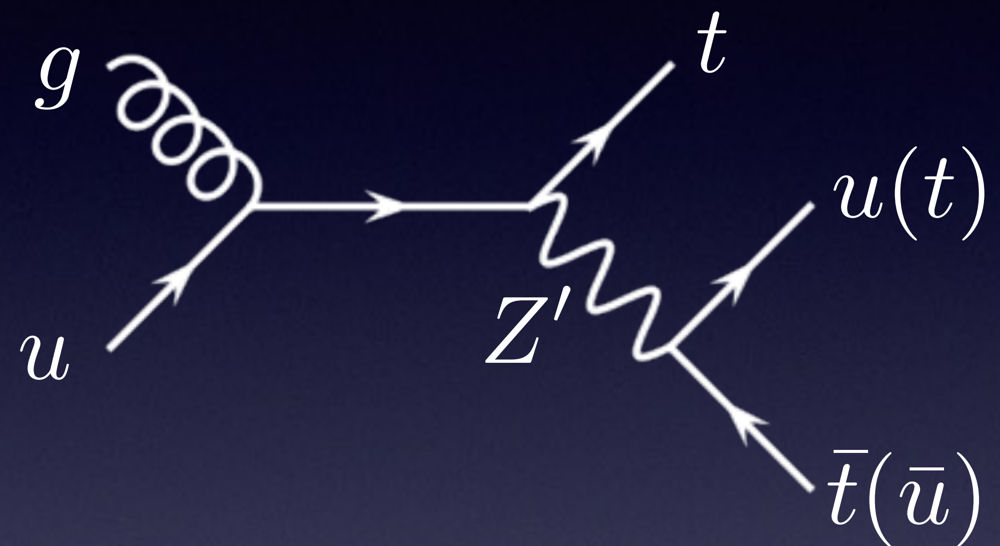


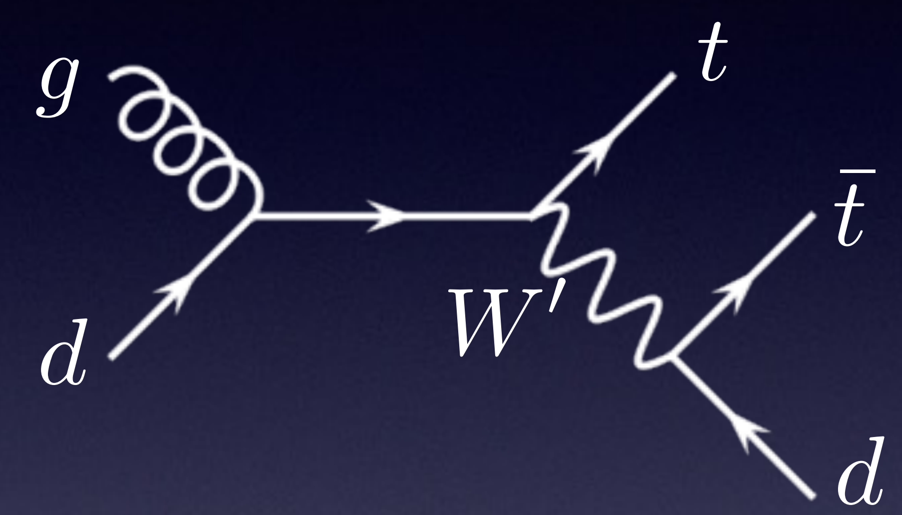


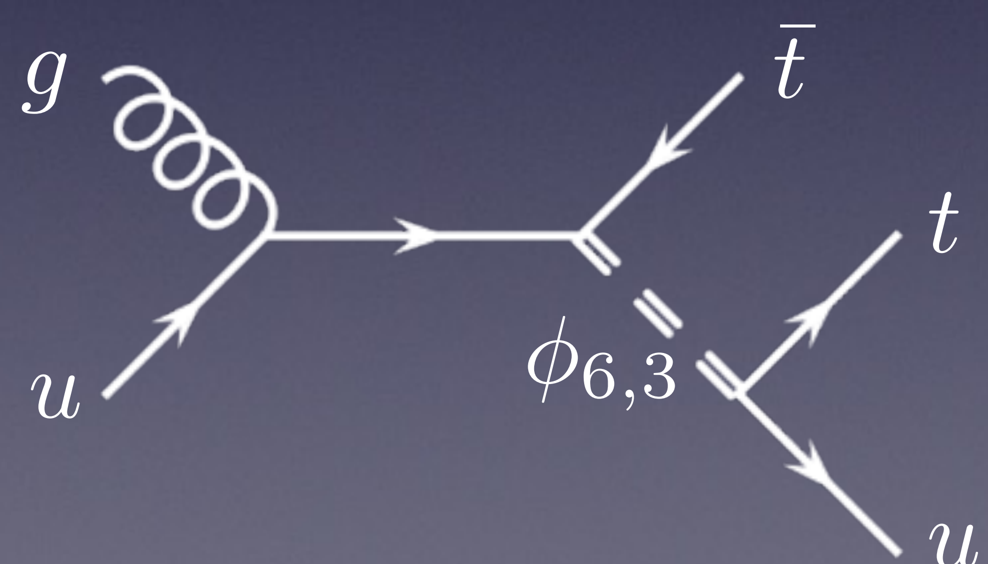


2) Top Quark Pair Plus one Jet

(Flavor Changing Interaction)





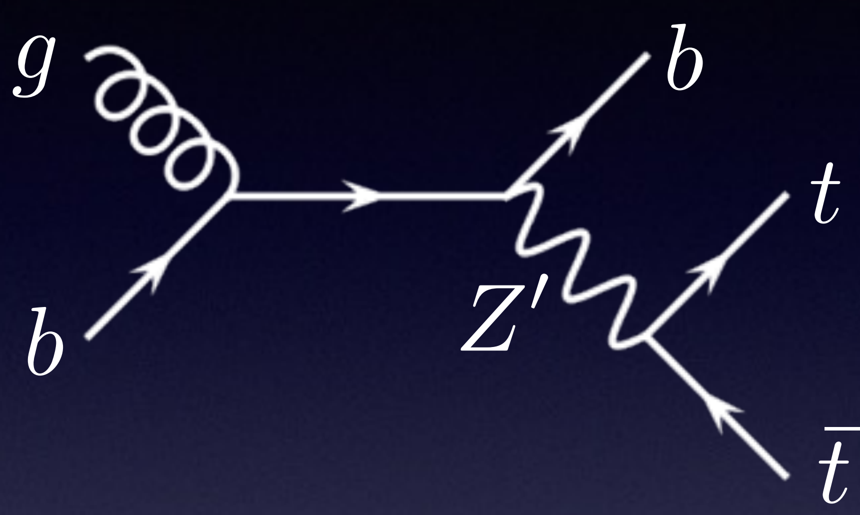


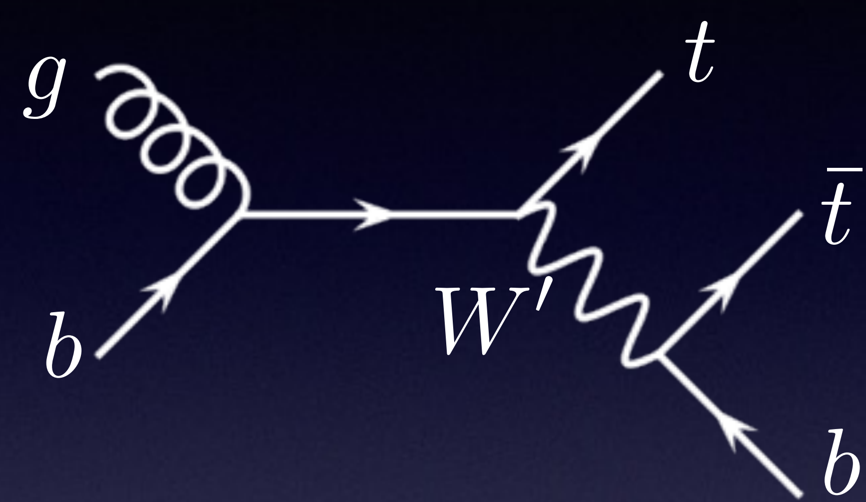
Berger, QHC, Chen, Li, Zhang, 1101.5625

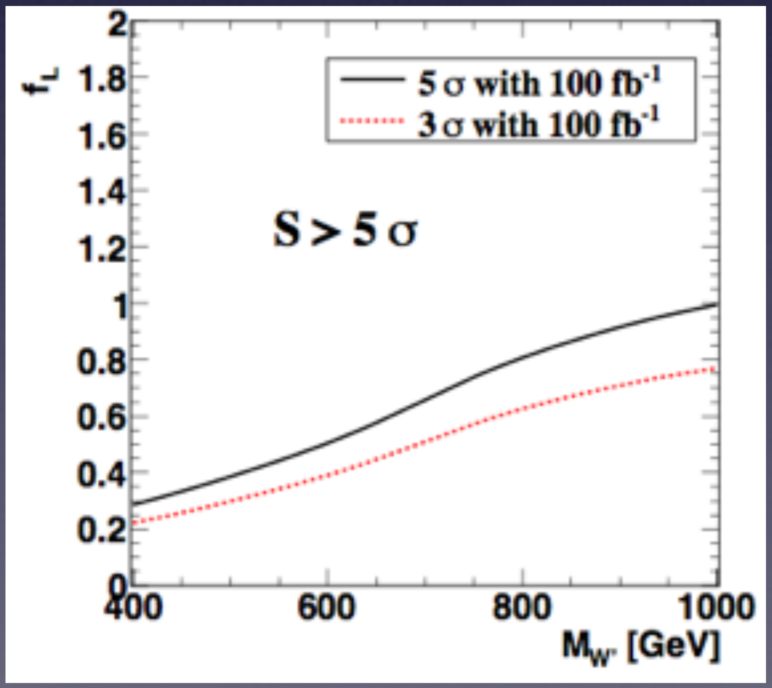
Gresham, Kim, Zurek, 1102.0018

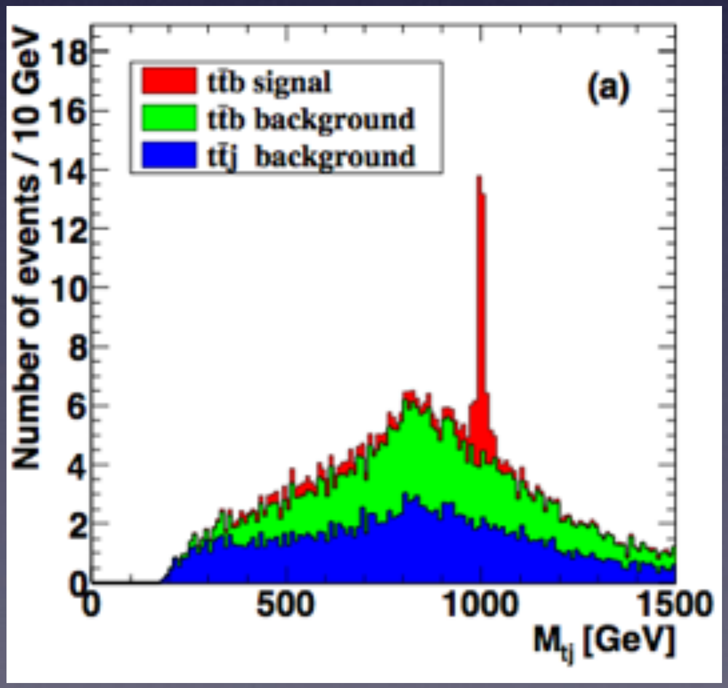
3) Top Quark Pair Plus One Jet

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







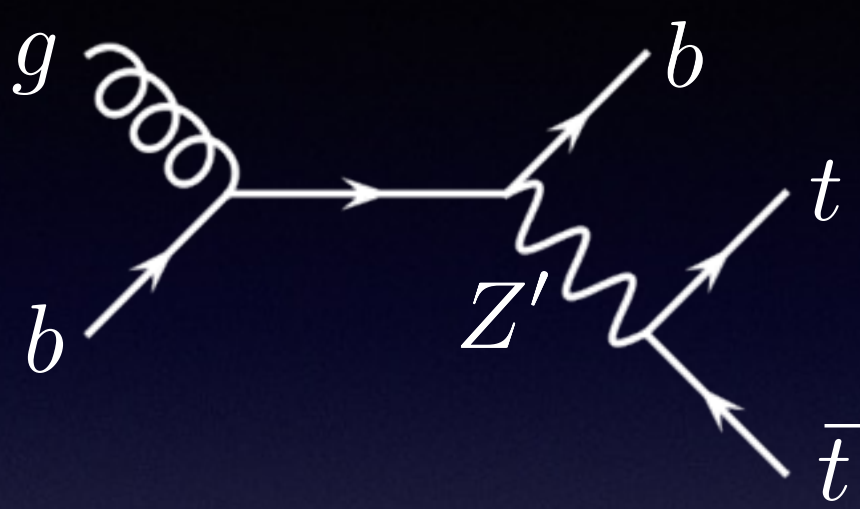


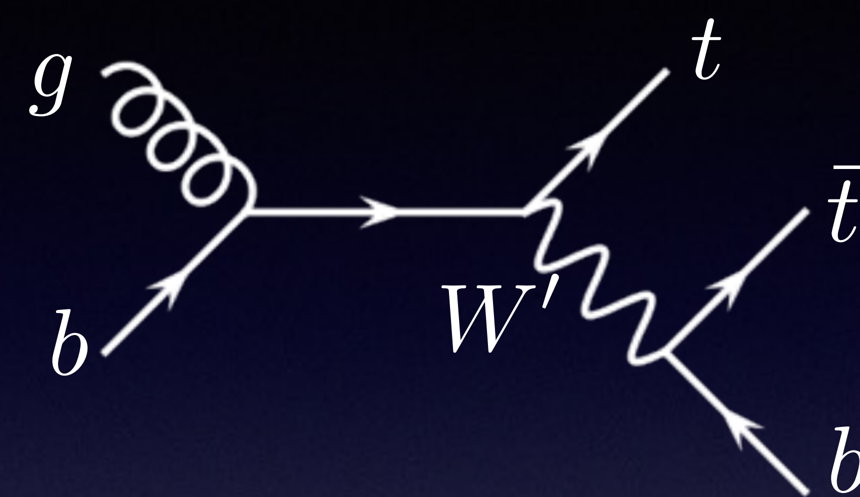
Berger, Cao, Yu, Yuan, 1108.3613

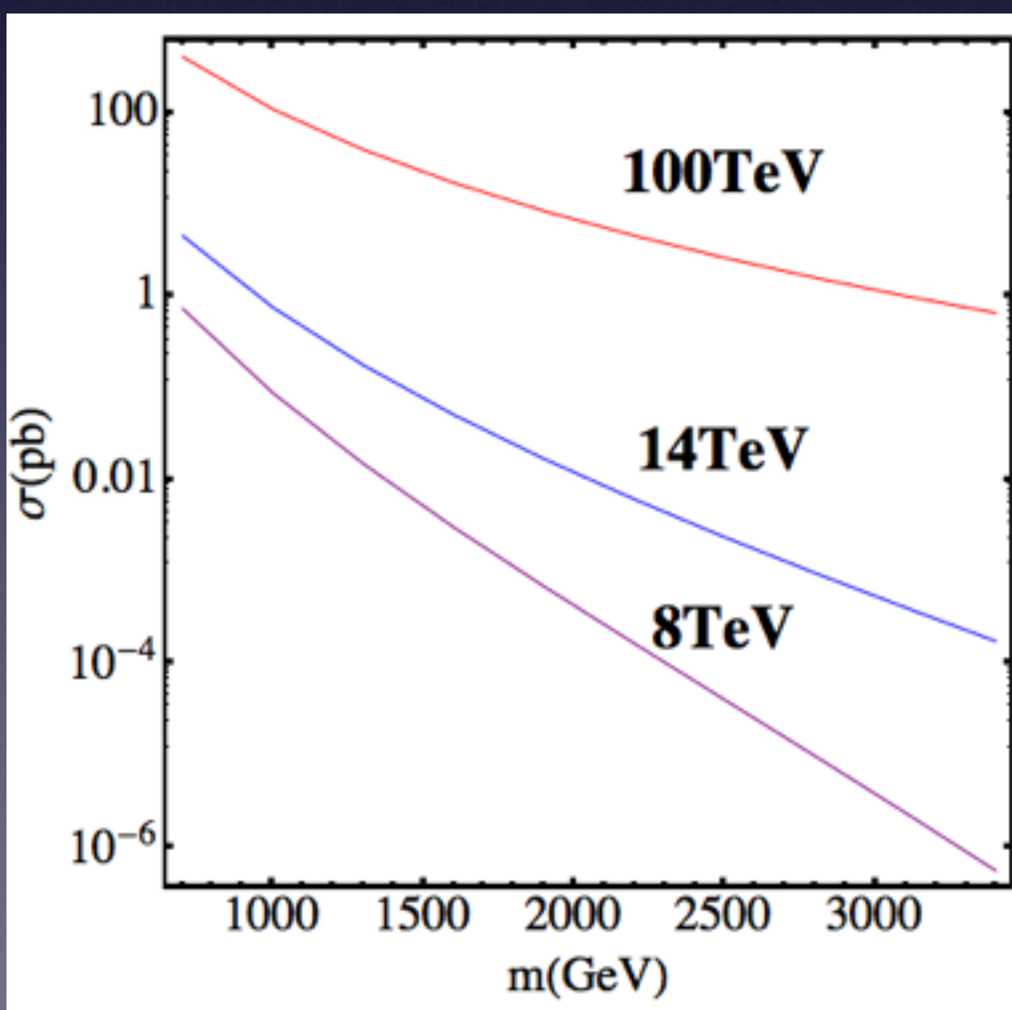
Topflavor Seesaw Model
He, Tait, Yuan (2000), Wang, Du, He (2013)

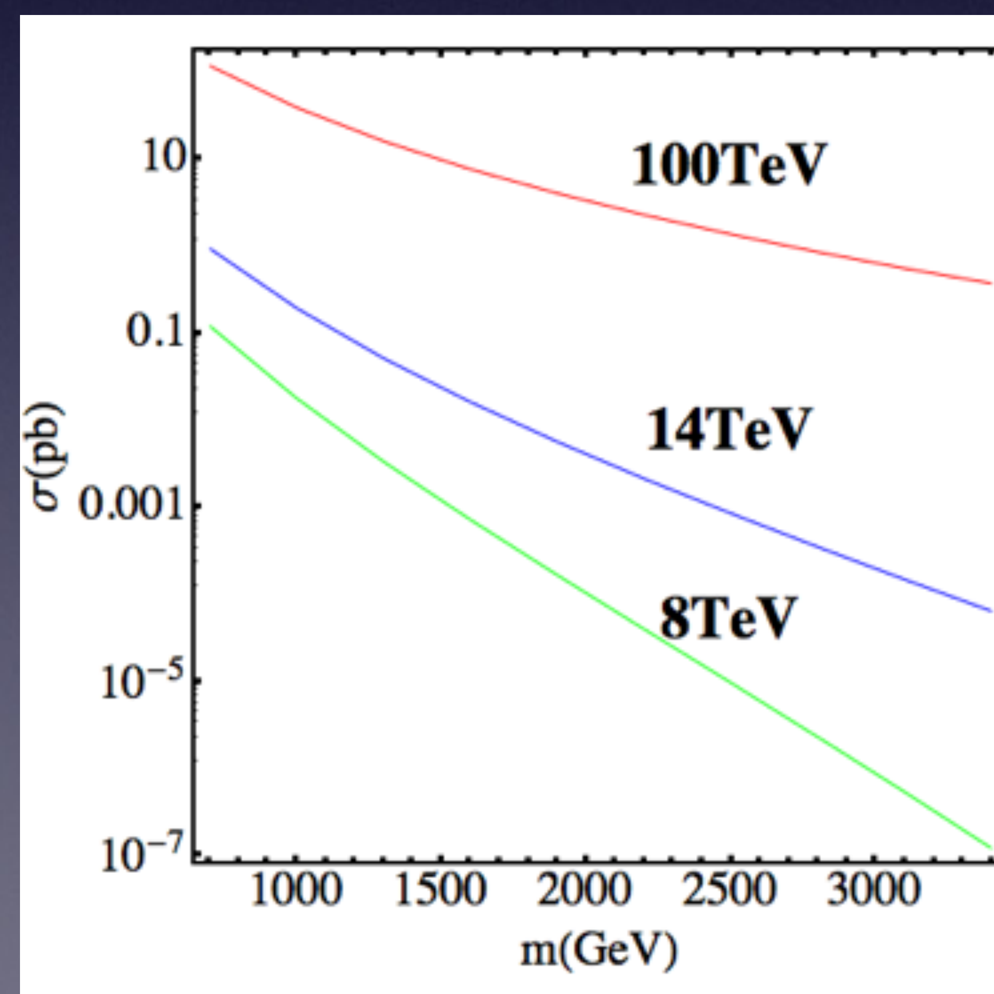
3) Top Quark Pair Plus One Jet

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



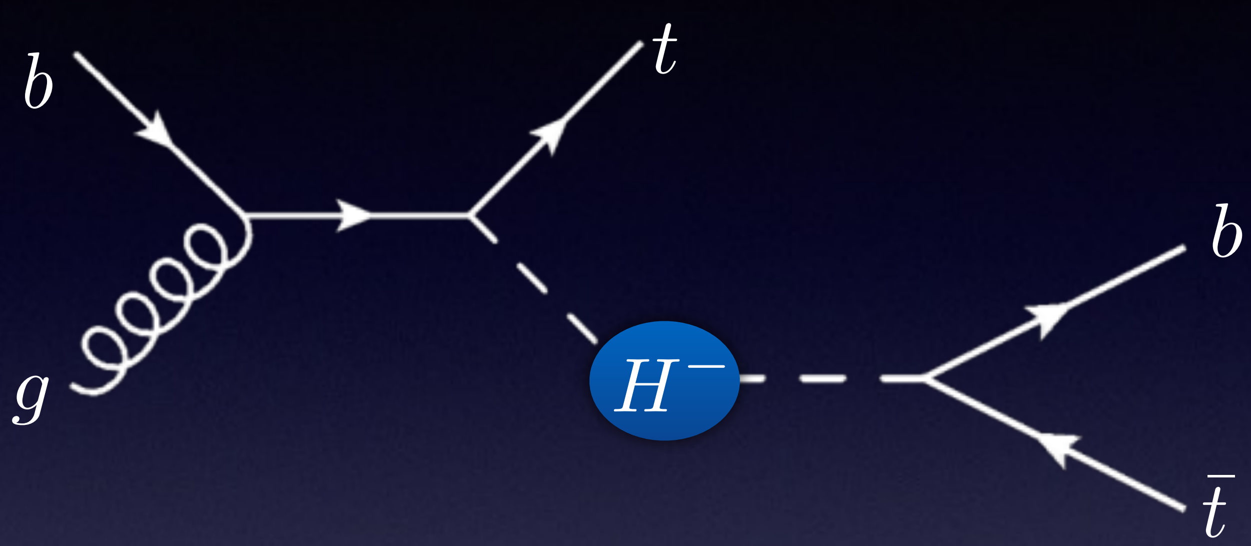






4) Top Quark Pair Plus One Jet

(Charged Higgs Boson)

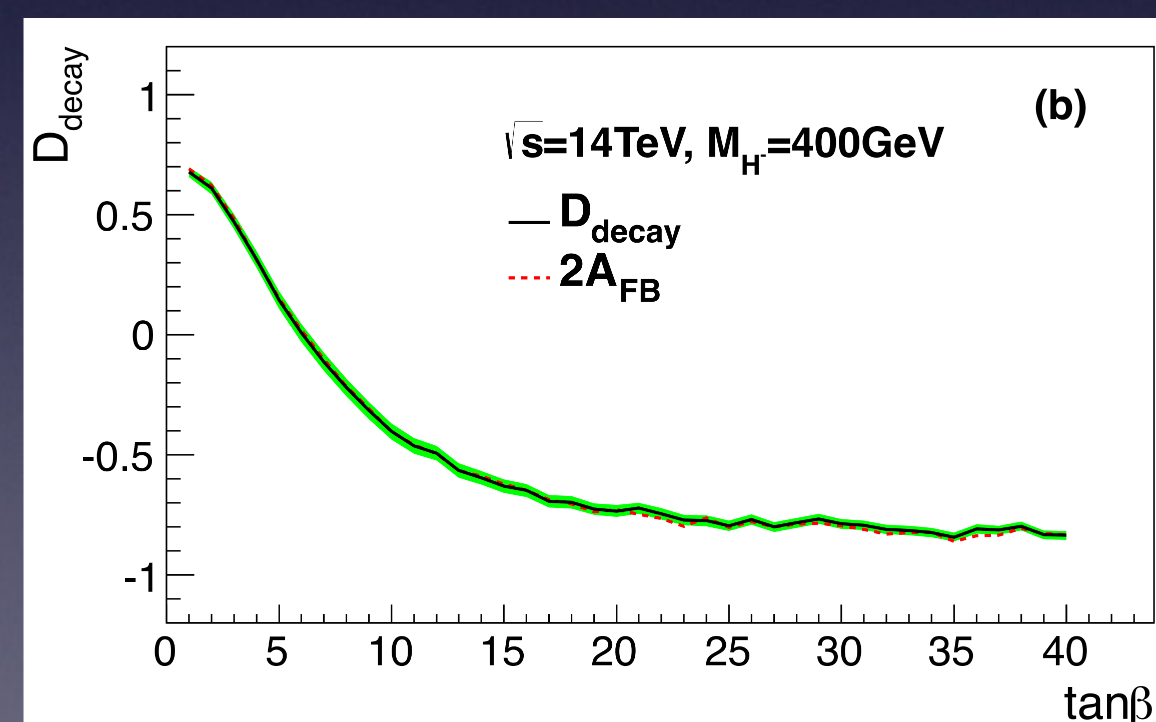


X-section is large for large tanb in MSSM or Type II 2HDB.

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

Top-quark polarization depends on tanb

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

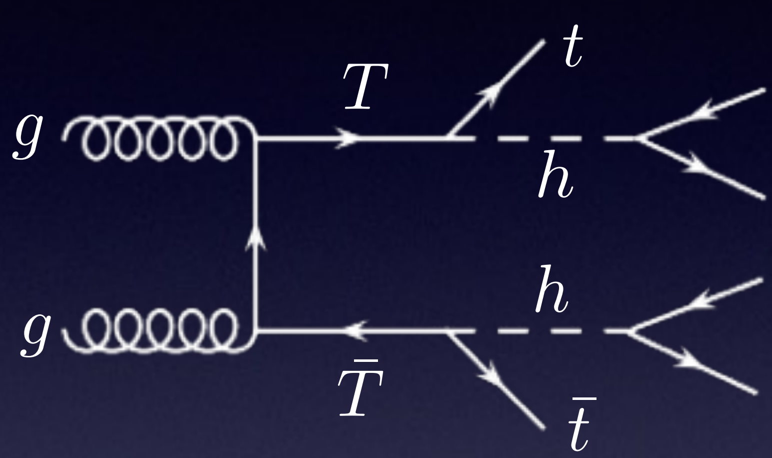


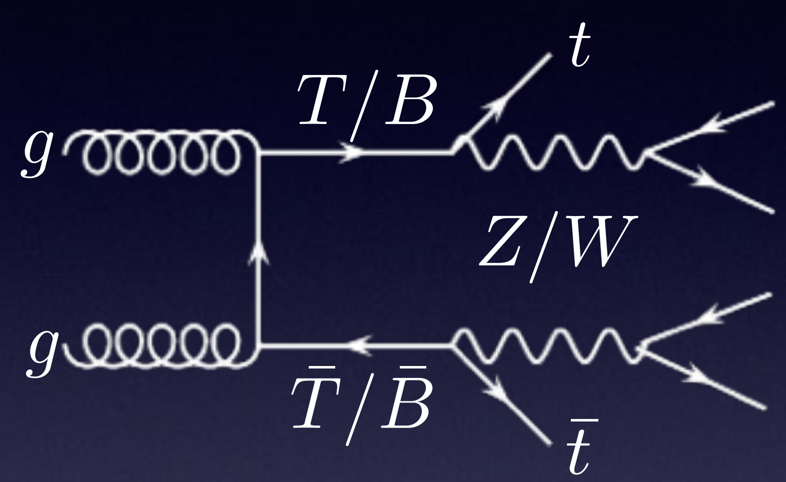
Huitu, Rai, Rao, Rindani, Sharma, 1012.0527
Godbole, Hartgring, Niessen, White, 1111.0759
Gong, Si, Yang, Zheng,1210.7822

QHC, Wan, Wang, Zhu, 1301.6608

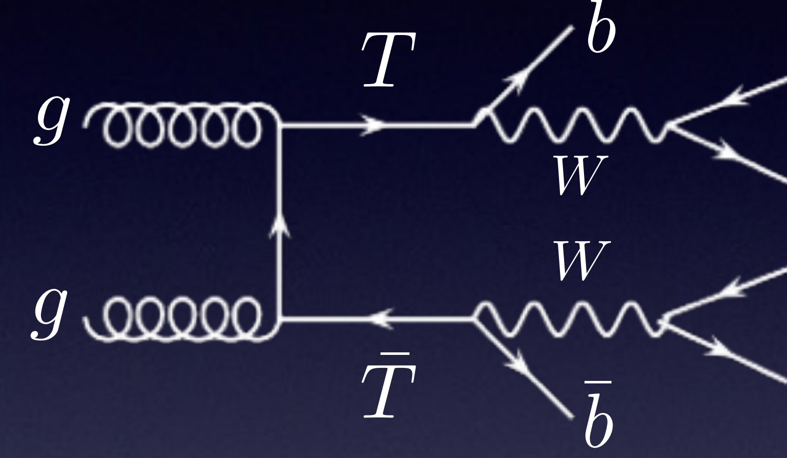
5) Top Quark Pair Plus Jets

Heavy Quark Pair Production

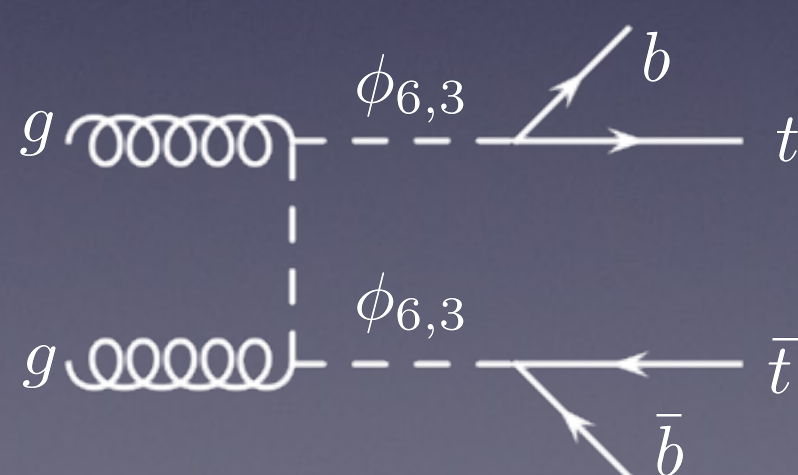




(Faked Top Quark Pair)

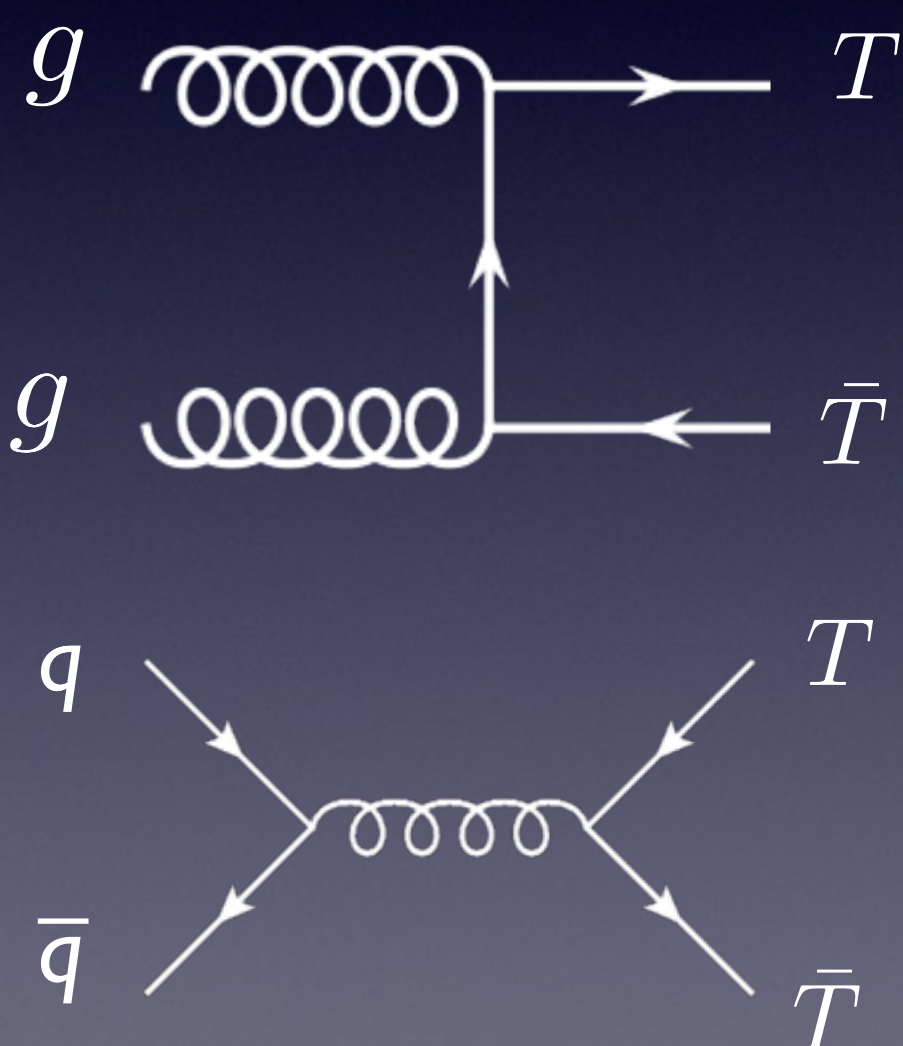


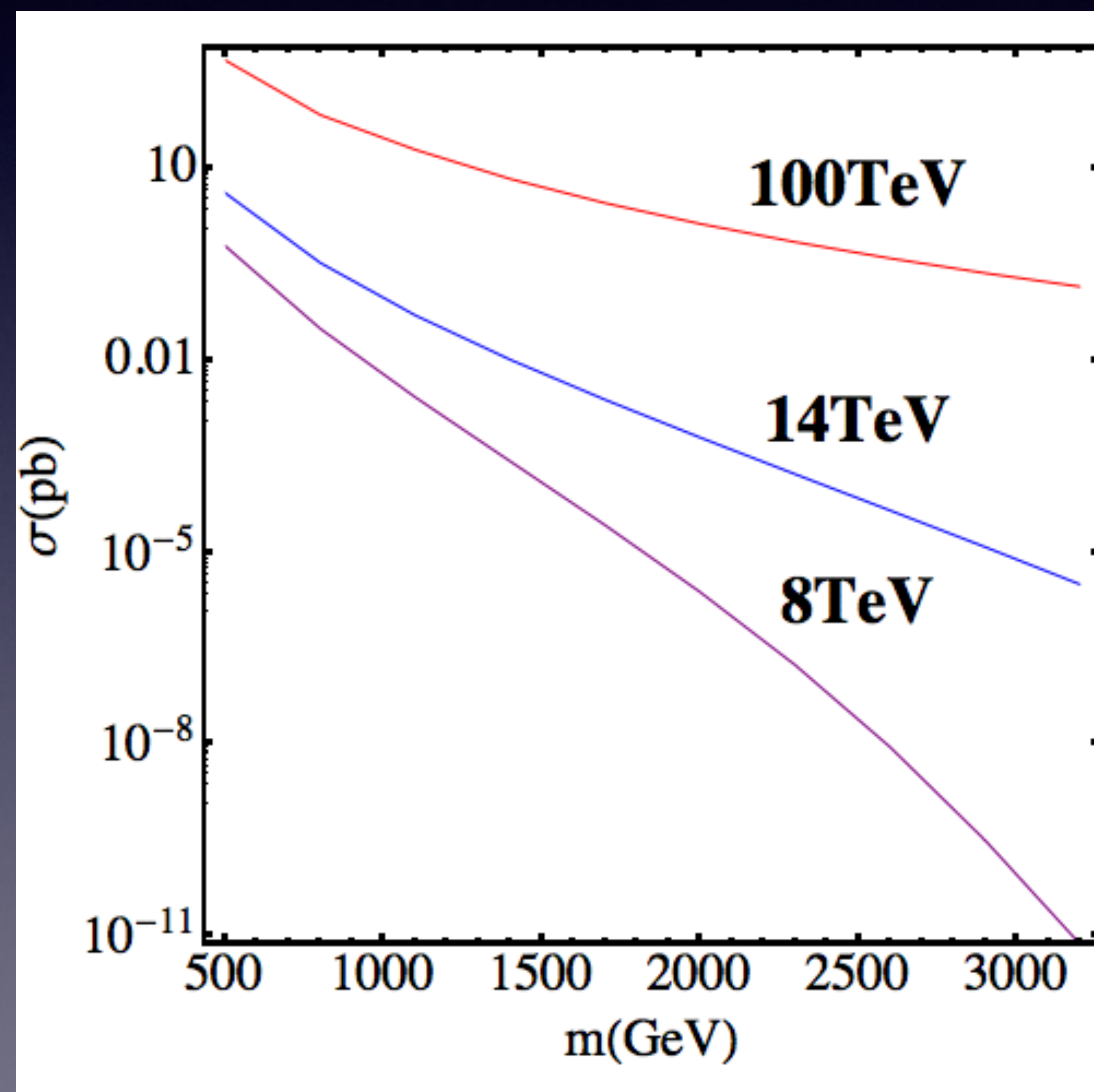
Color Sextet/Triplet Scalar Pair Production



5) Top Quark Pair Plus Jets

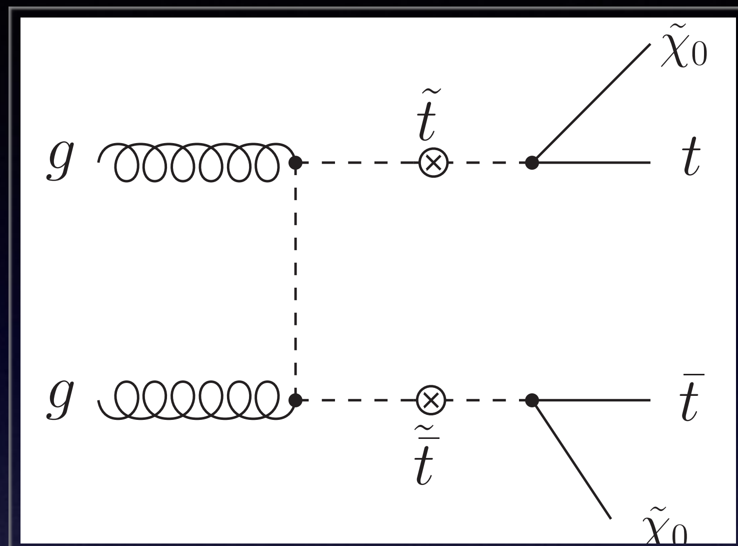
Heavy Quark Pair Production

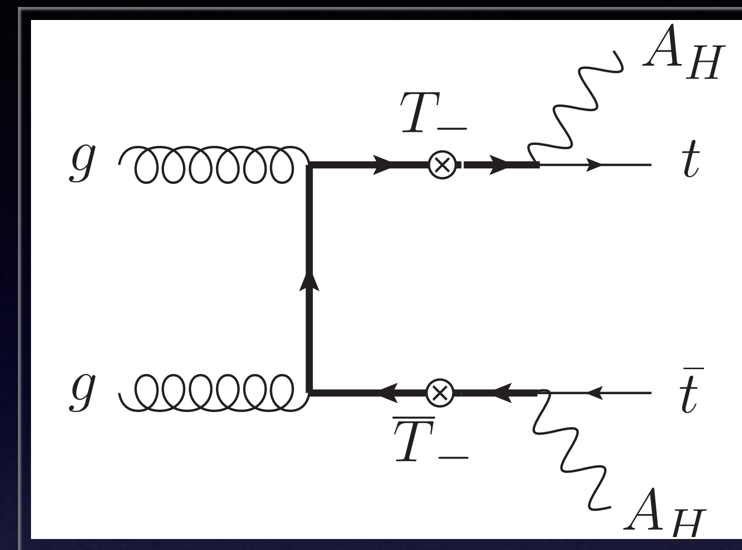




6) Top Quark Pair + Invisibles

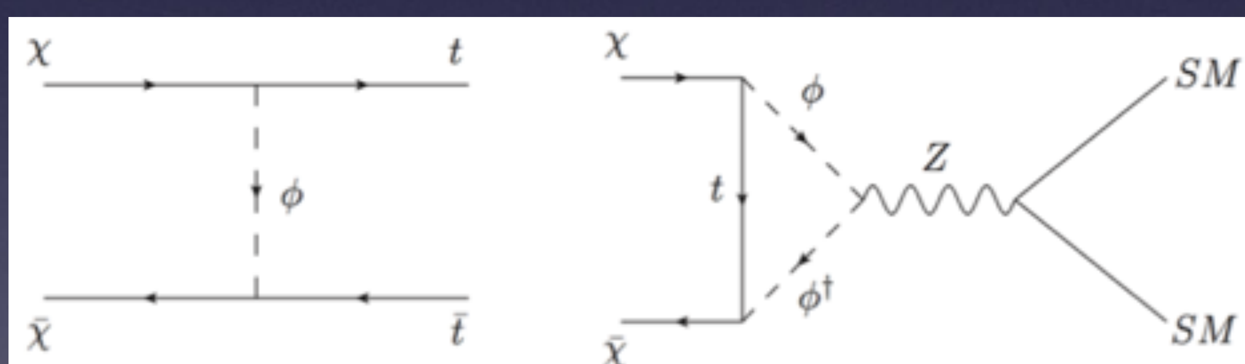
SUSY

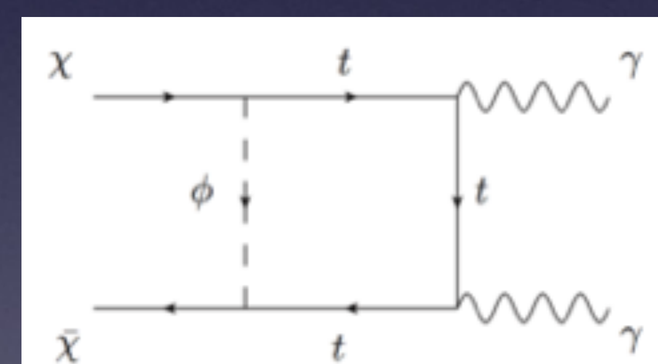




LHT, UED

Top-Quark Mediated Dark Matter Models





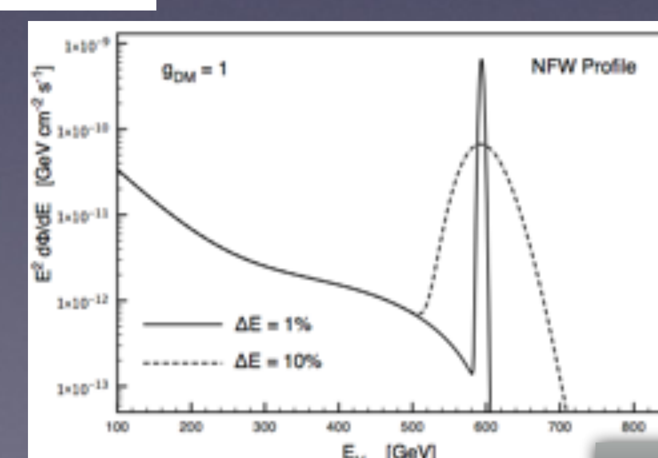
Dark Matter Effective Theory:

Cheung, Mawatari, Senaha, Tseng, Yuan, 1009.0618

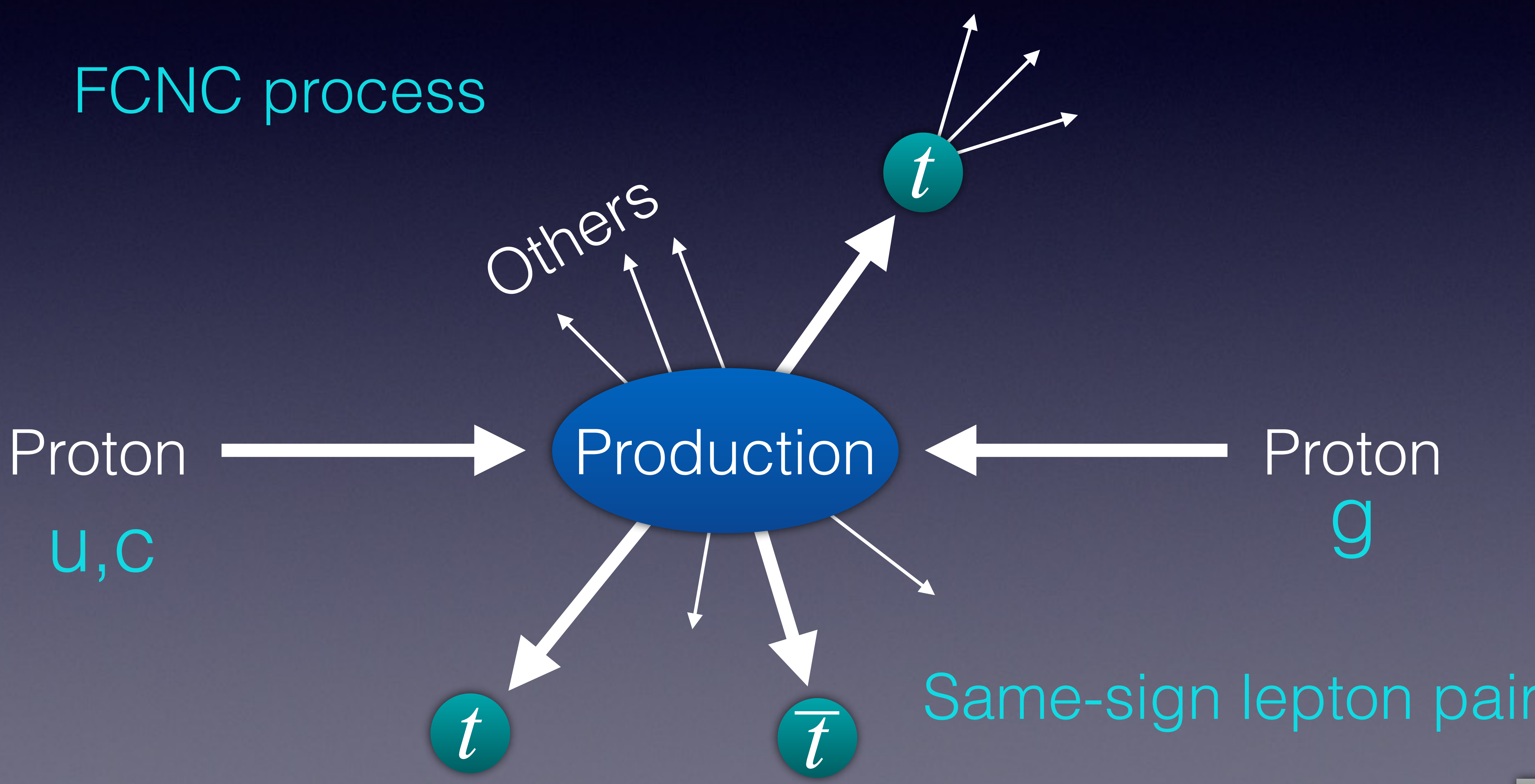
Gomez, Jackson, Shaughnessy, 1404.1918

UV Completion Theory:

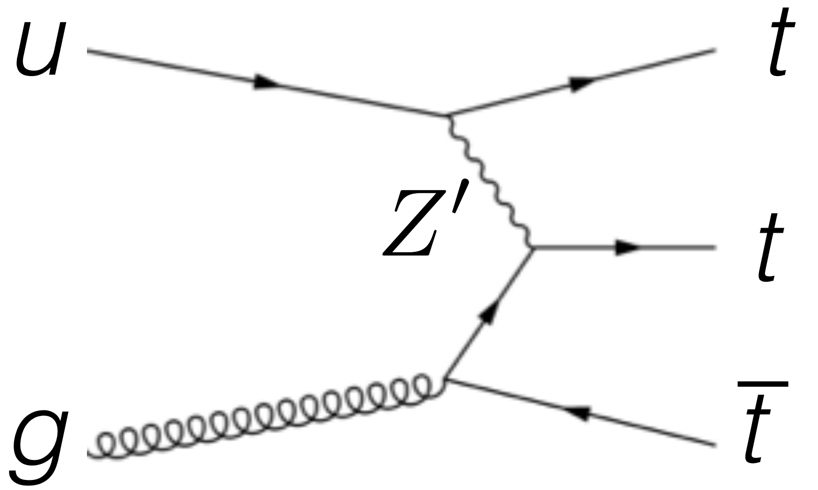
Jackson, Servant, Shaughnessy, Tait, Taoso,1303.4717



Triple Top Quark Production

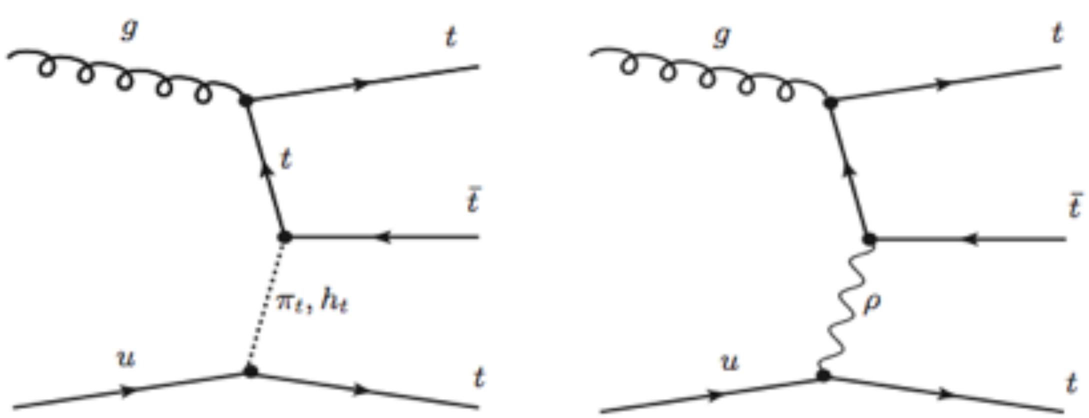


Triple Top Quark Production



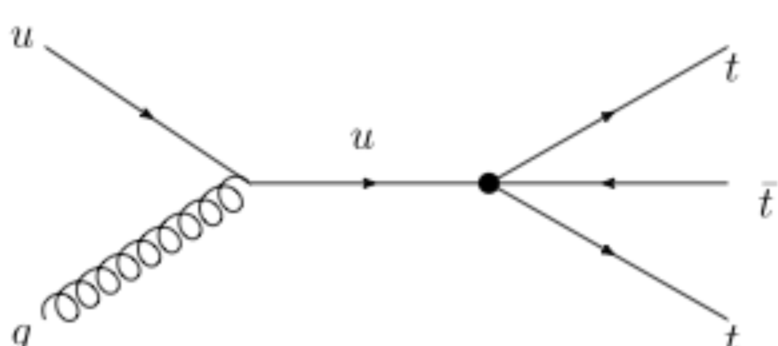
Leptophobic Z' from U'(1) directly couples top-quark to u-quark to explain AFB(t)

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)



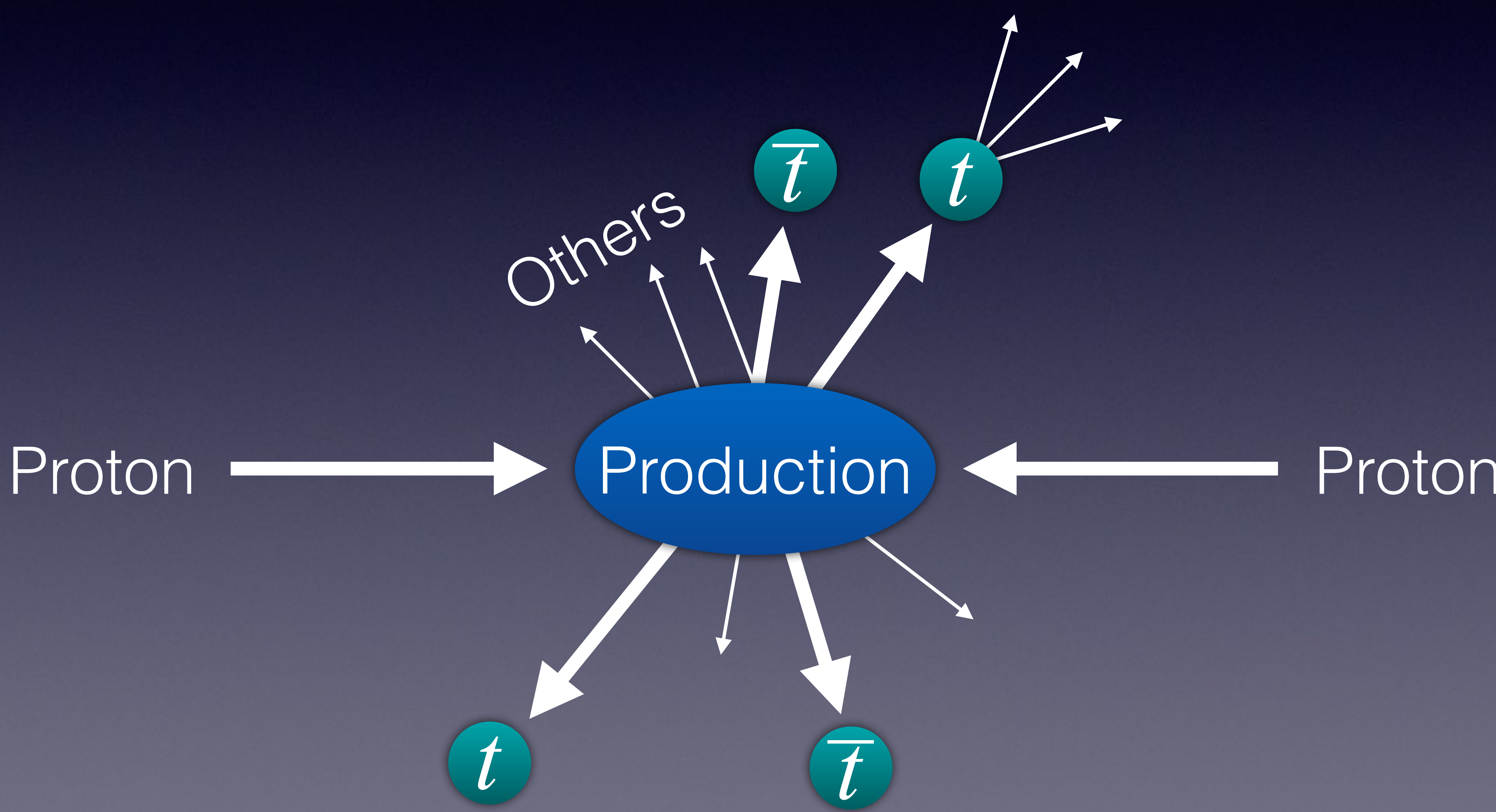
(a)

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

$$O_{uttt}^{LR} = (\bar{u}_{Li}t_R)(\bar{t}_R t_L); \qquad O_{uttt}^{\prime LR} = (\bar{t}_L u_{iR})(\bar{t}_R t_L), \qquad (2$$

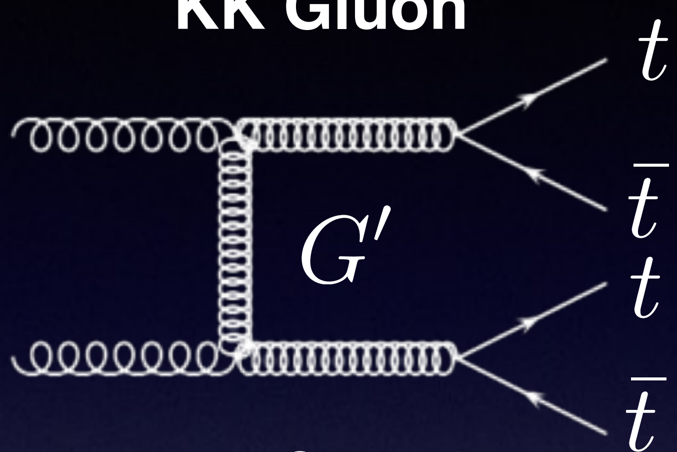
Chuan-Ren Chen (2014)

Four Top Quark Production



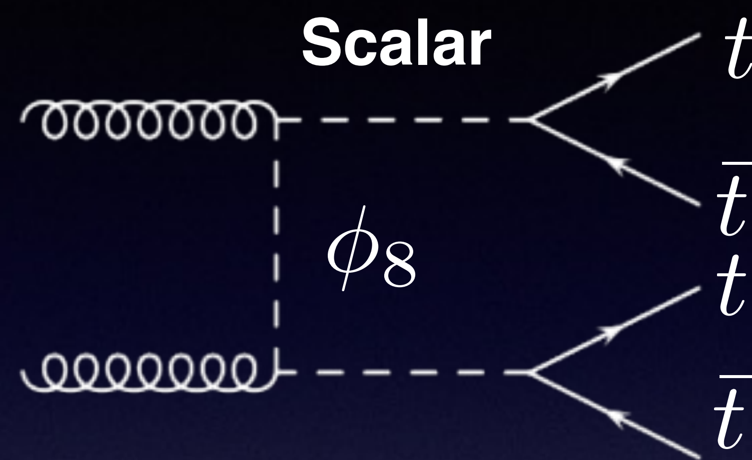
Four Top Quark Production

Axigluon
KK Gluon



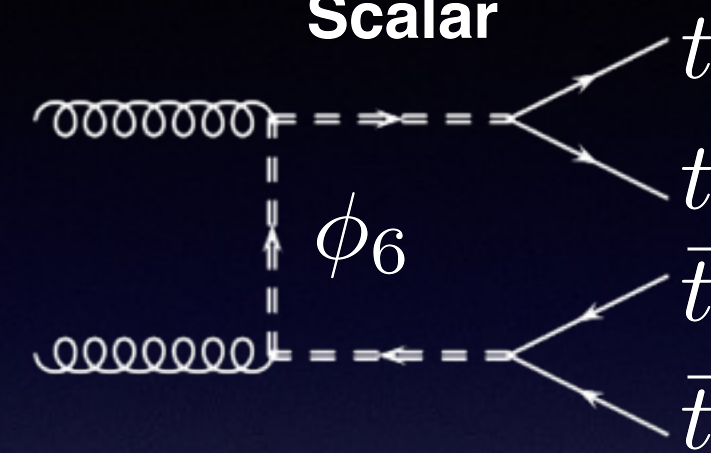
Aguilar-Saavedra, Santiago (2012)

Color Octet Scalar



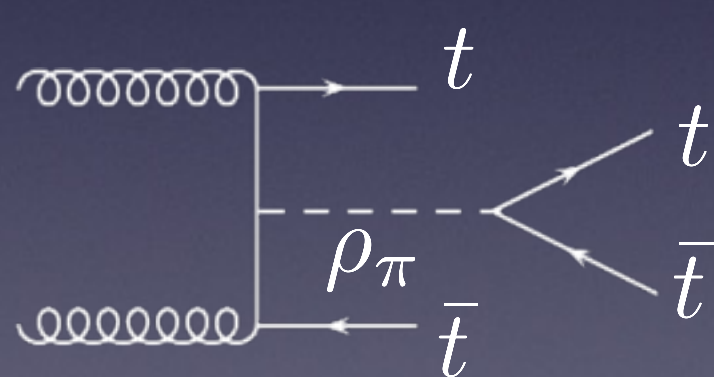
Plehn, Tait (2008)

Color Sextet Scalar



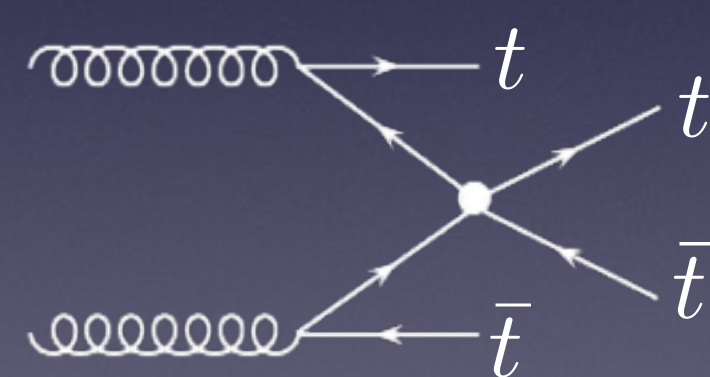
Chen, Klemm, Rentala, Wang (2008)

TC2



Han, Liu, Wu, Yang (2012)

Top Compositeness



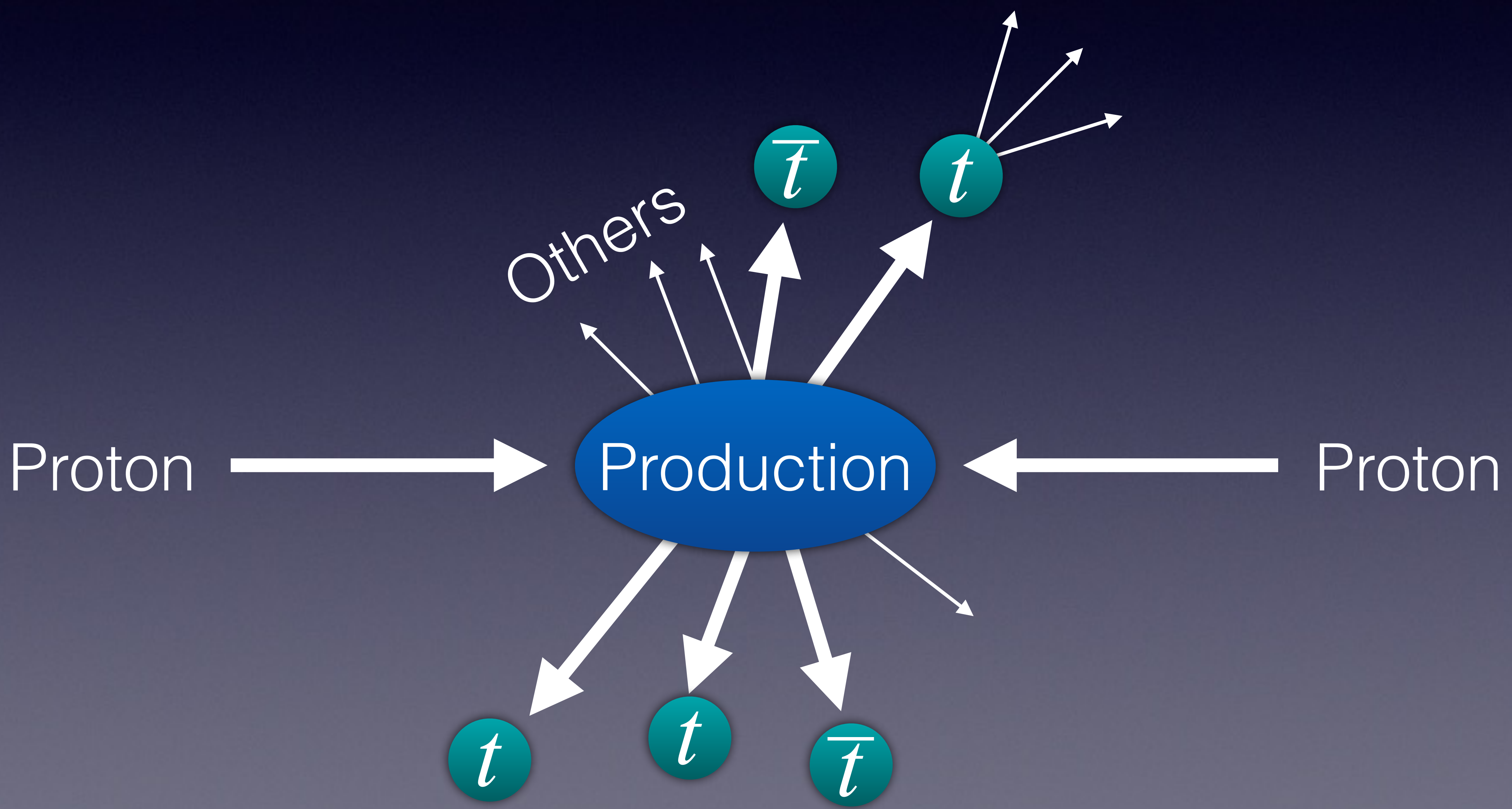
Lillie, Shu, Tait (2007)

Kumar, Tait, Veg-Morale (2009)

SM QCD production @ NLO,
Bevilacqua and Worek, 1206.3064

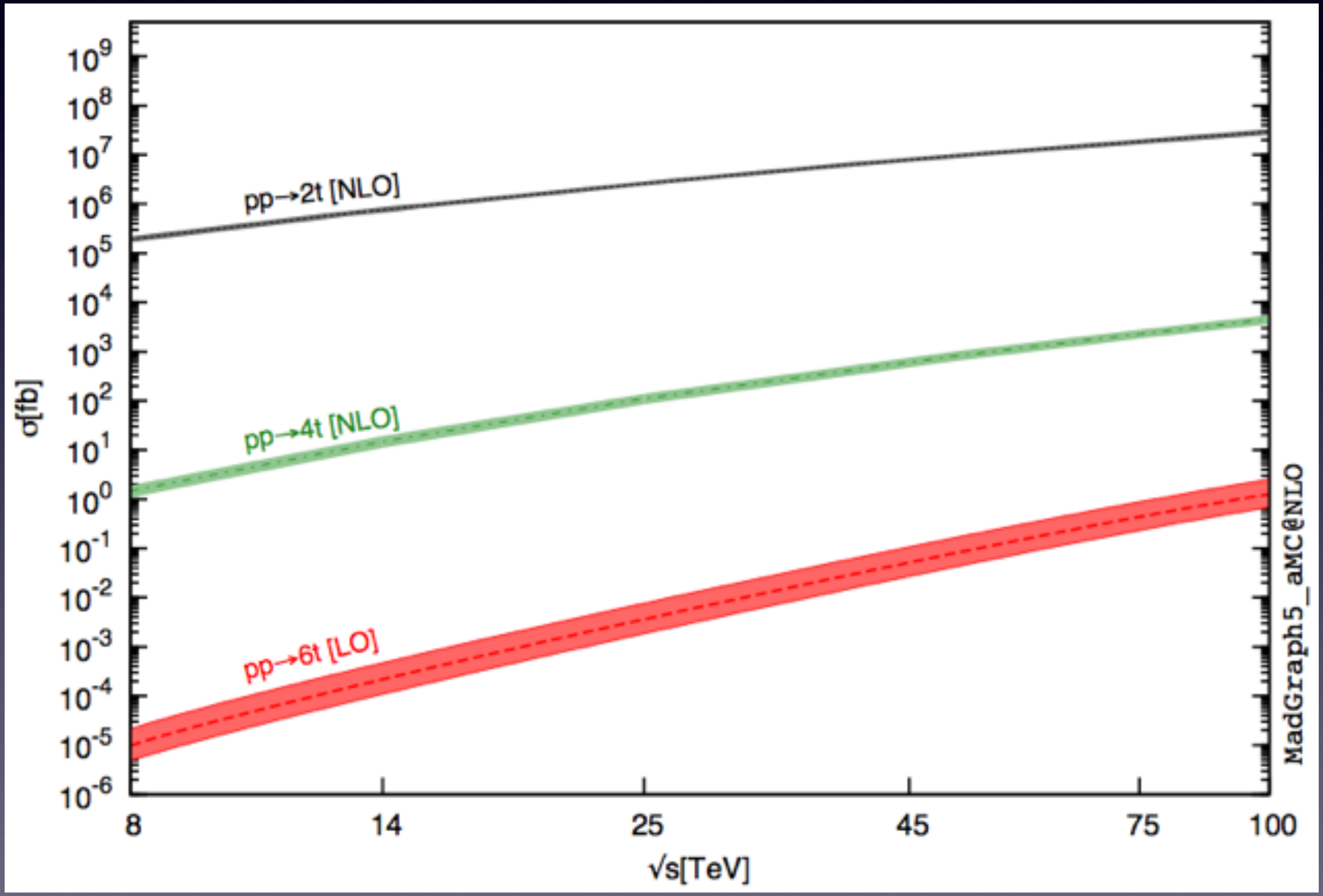
See Keaveney's poster

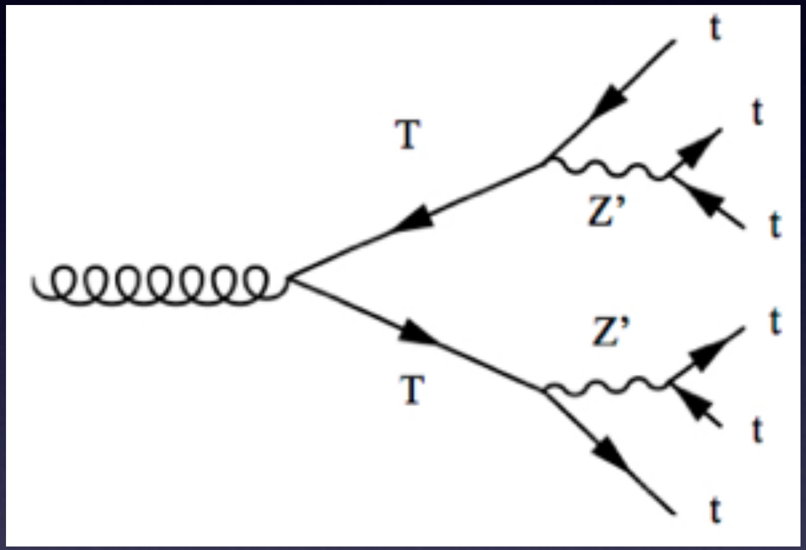
Six or More Top Quark Production



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'

Exotic Colored States

Color Sextet

New Heavy Quarks

Top

Vector Quark

4th Gen

Gluino

Charged Higgs

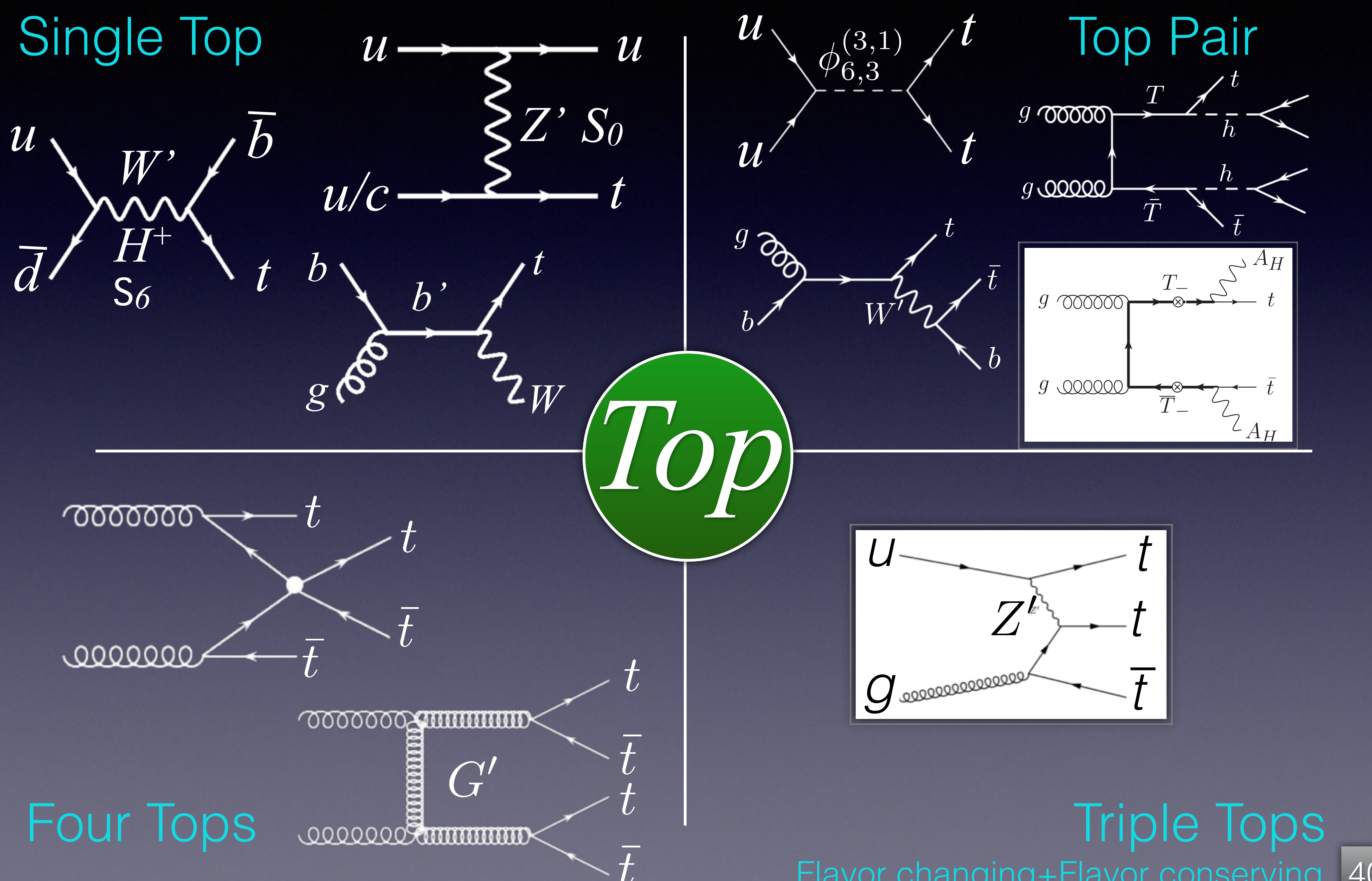
Heavy Quark Production via pQCD

$\cancel{CP}$

FCNC

A_{FB}

Top Quark Production: rich signatures



Flavor changing+Flavor conserving

TOP @ inSPIRE

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