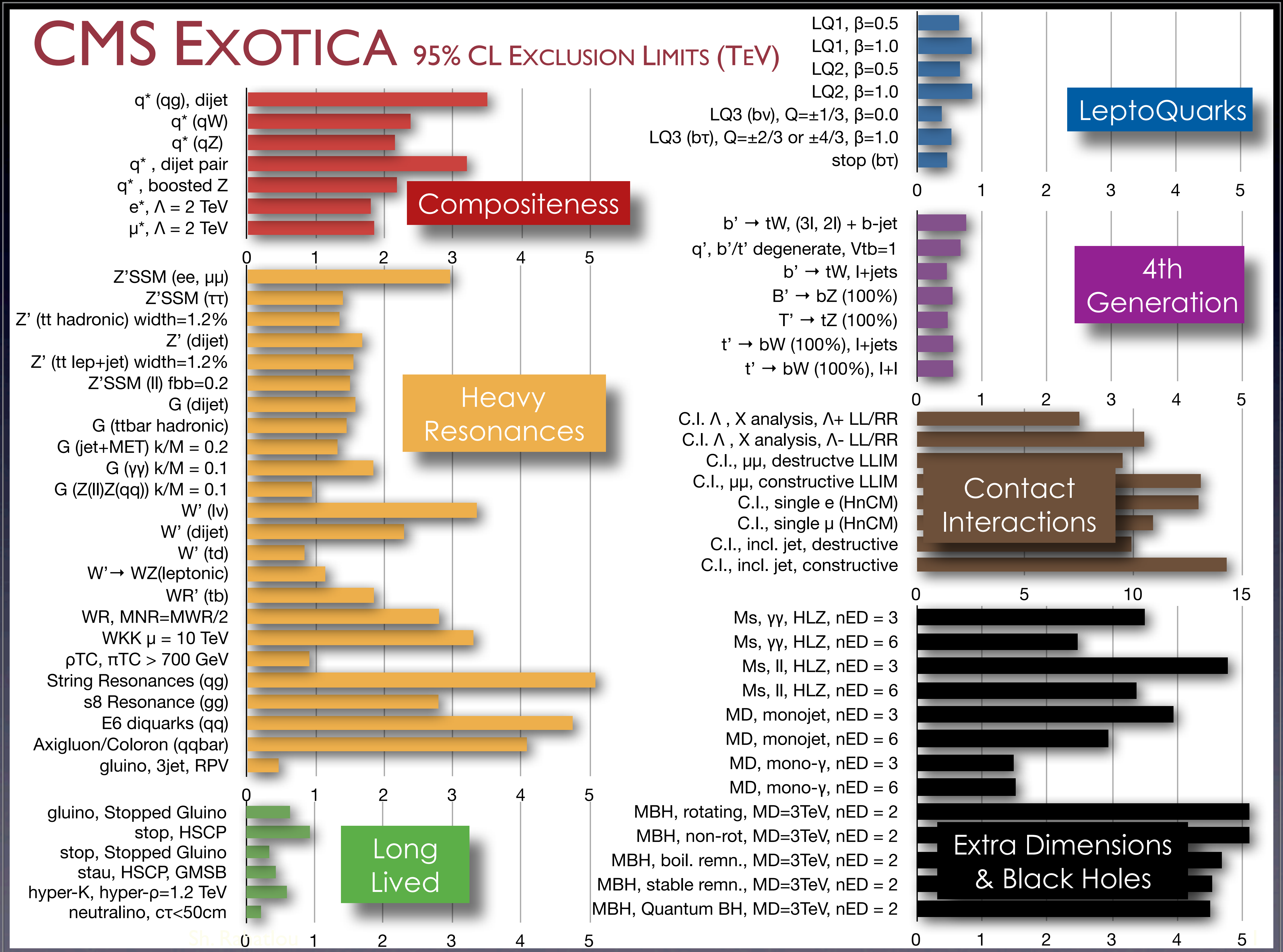
Top Quark and New Physics

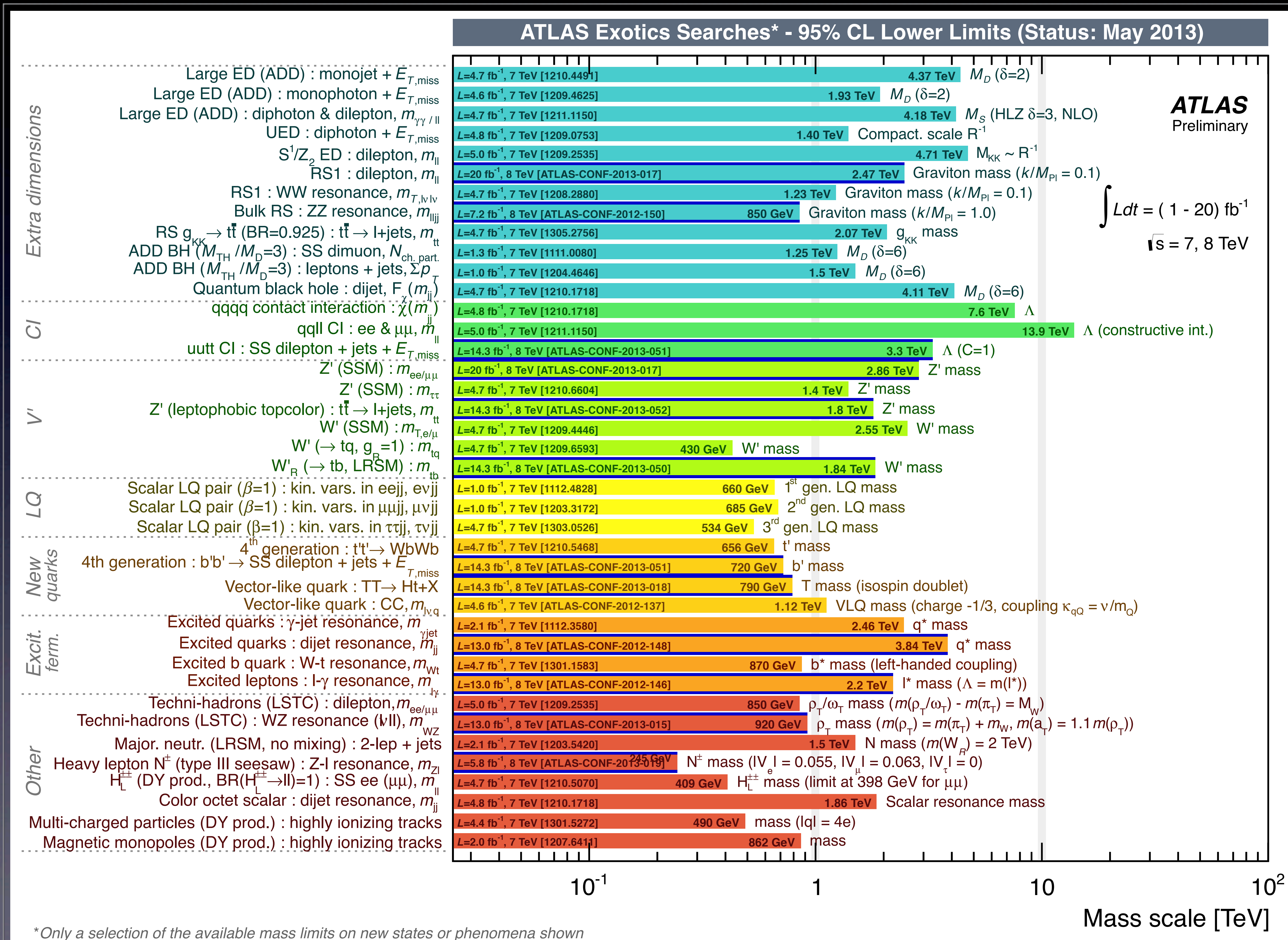
Qing-Hong Cao
Peking University

Shanghai Particle Physics and Cosmology Symposium
June 04, 2013

New Physics? Where?



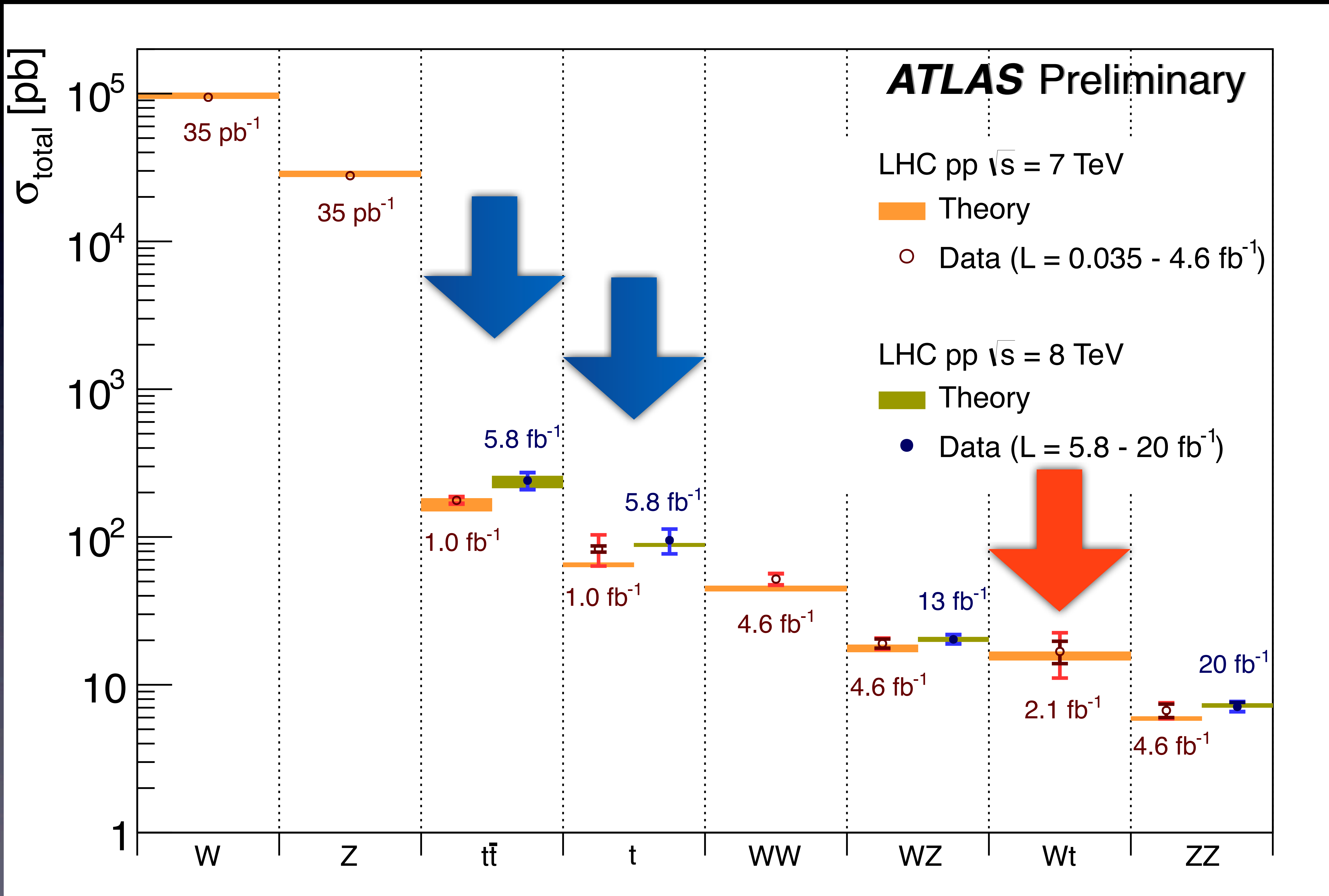
New Physics? Where?



What we have discovered

July 4th , 2012

What we have discovered



The last untested gauge coupling

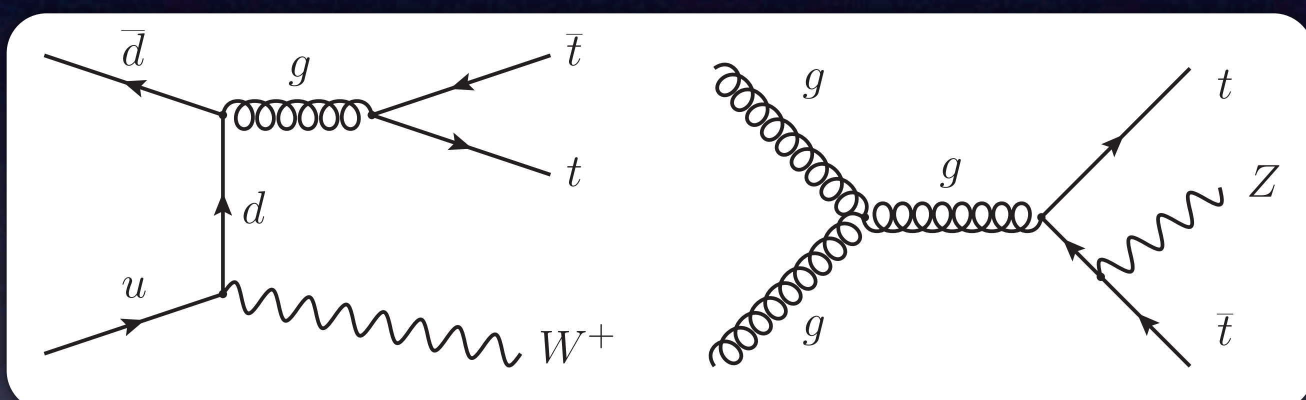
PRL **110,** 172002 (2013) PHYSICAL REVIEW LETTERS week ending 26 APRIL 2013

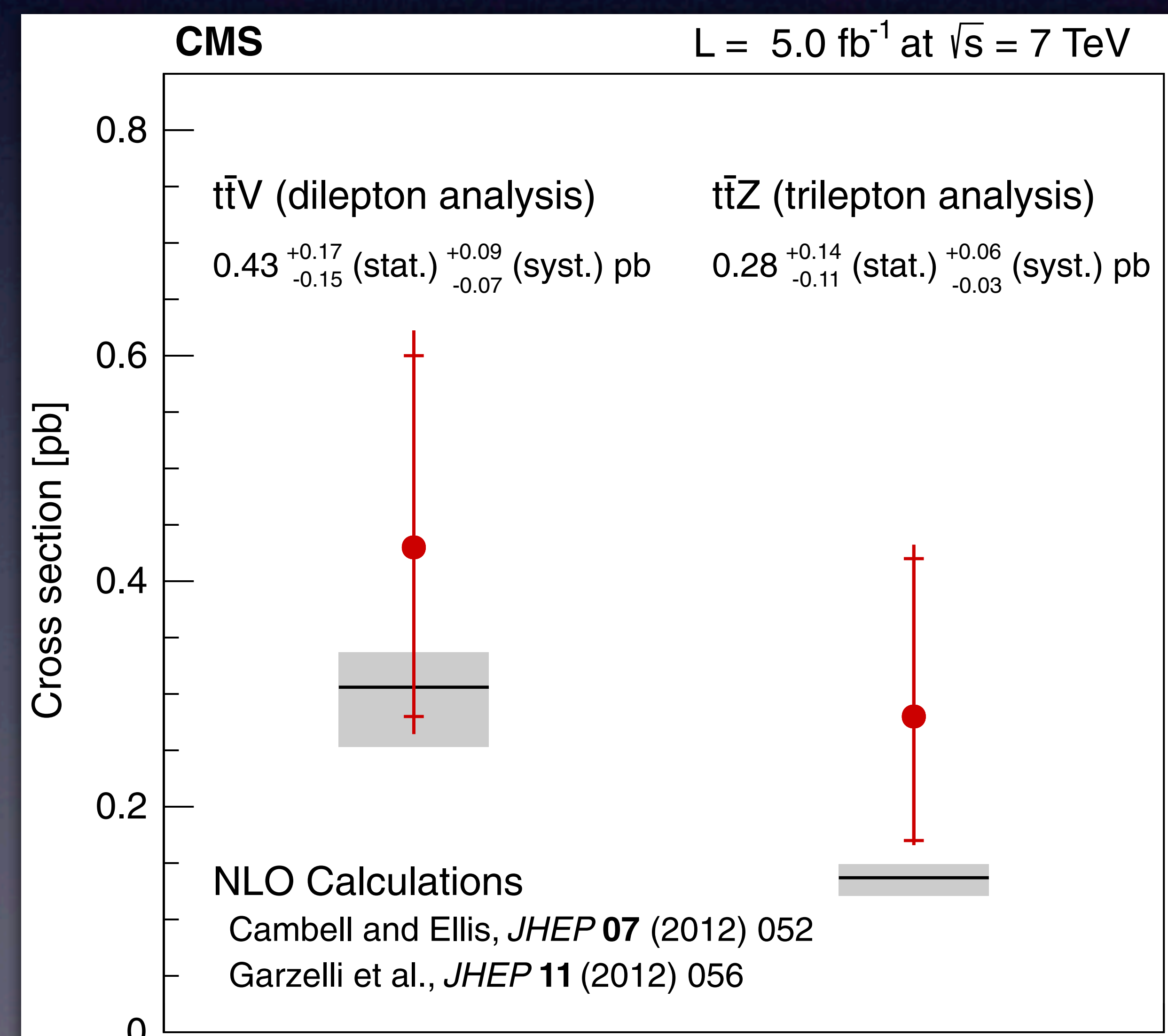
Measurement of associated production of vector bosons and top quark-antiquark pairs in *pp* collisions at $\sqrt{s} = 7$ TeV

S. Chatrchyan *et al.**
(CMS Collaboration)

(Received 13 March 2013; published 25 April 2013)

$5\ \mathrm{fb}^{-1}$





trilepton:

$$\sigma_{t\bar{t}Z} = 0.28^{+0.14}_{-0.11}(\mathrm{stat})^{+0.06}_{-0.03}(\mathrm{syst})\ \mathrm{pb}$$

$$\sigma^{\mathrm{NLO}}_{t\bar{t}Z} = 0.137^{+0.012}_{-0.016}\ \mathrm{pb}$$

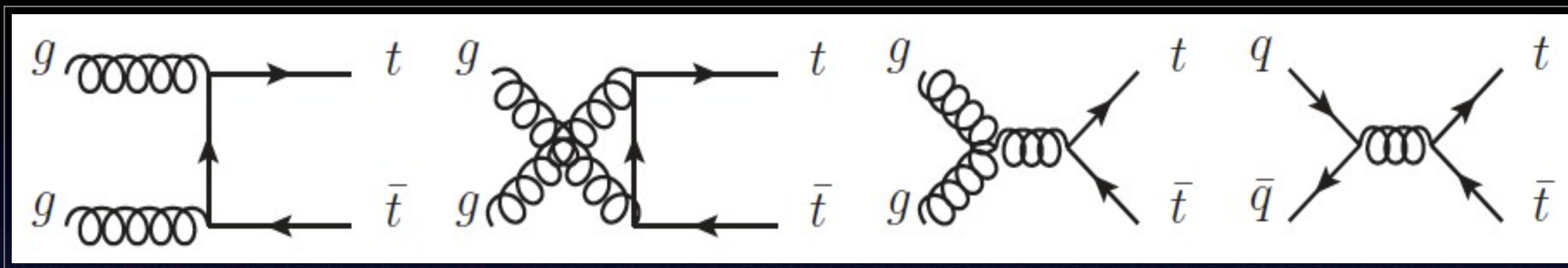
dilepton:

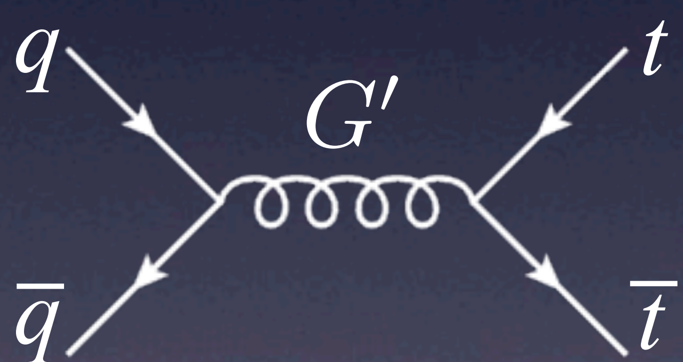
$$\sigma_{t\bar{t}V} = 0.43^{+0.17}_{-0.15}(\mathrm{stat})^{+0.09}_{-0.07}(\mathrm{syst})\ \mathrm{pb}$$

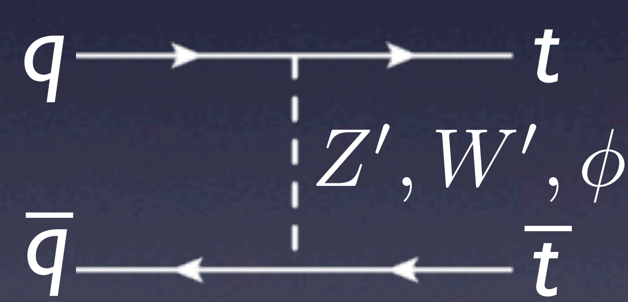
$$\sigma^{\mathrm{NLO}}_{t\bar{t}V} = 0.306^{+0.031}_{-0.053}\ \mathrm{pb}$$

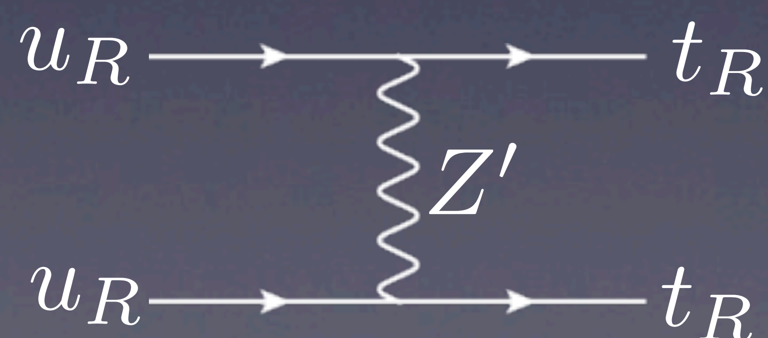
The Era of Top Quark Precision

Top pair production in the SM





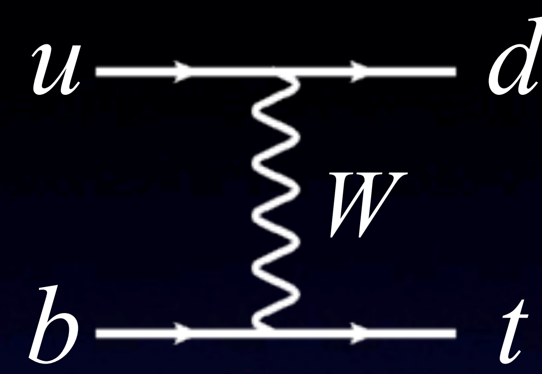




Single top production in the SM

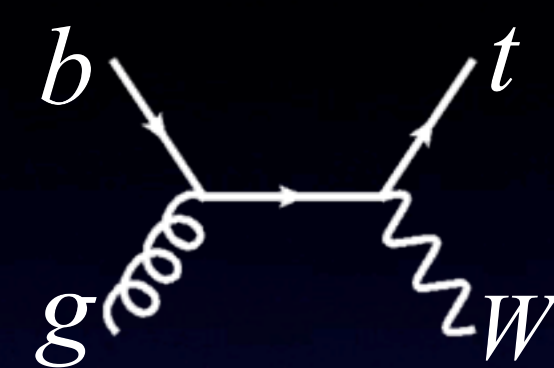
s-channel

$Q_W^2 > 0$



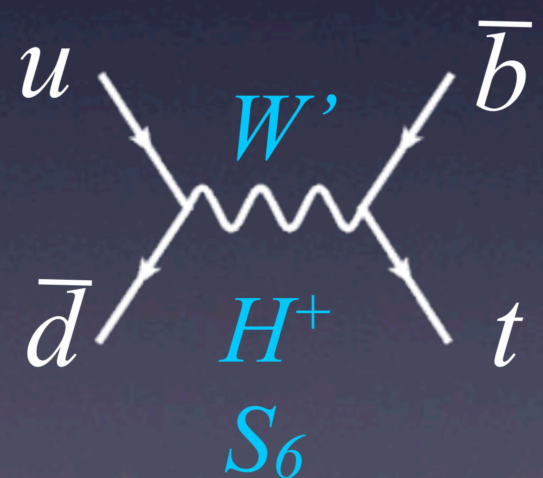
t-channel

$Q_W^2 < 0$

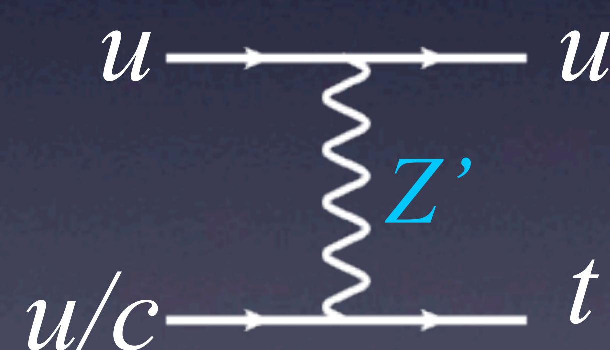


*t*W

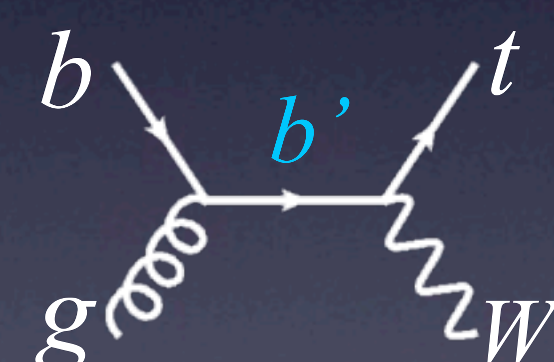
$Q_W^2 = m_W^2$



New resonance



FCNC

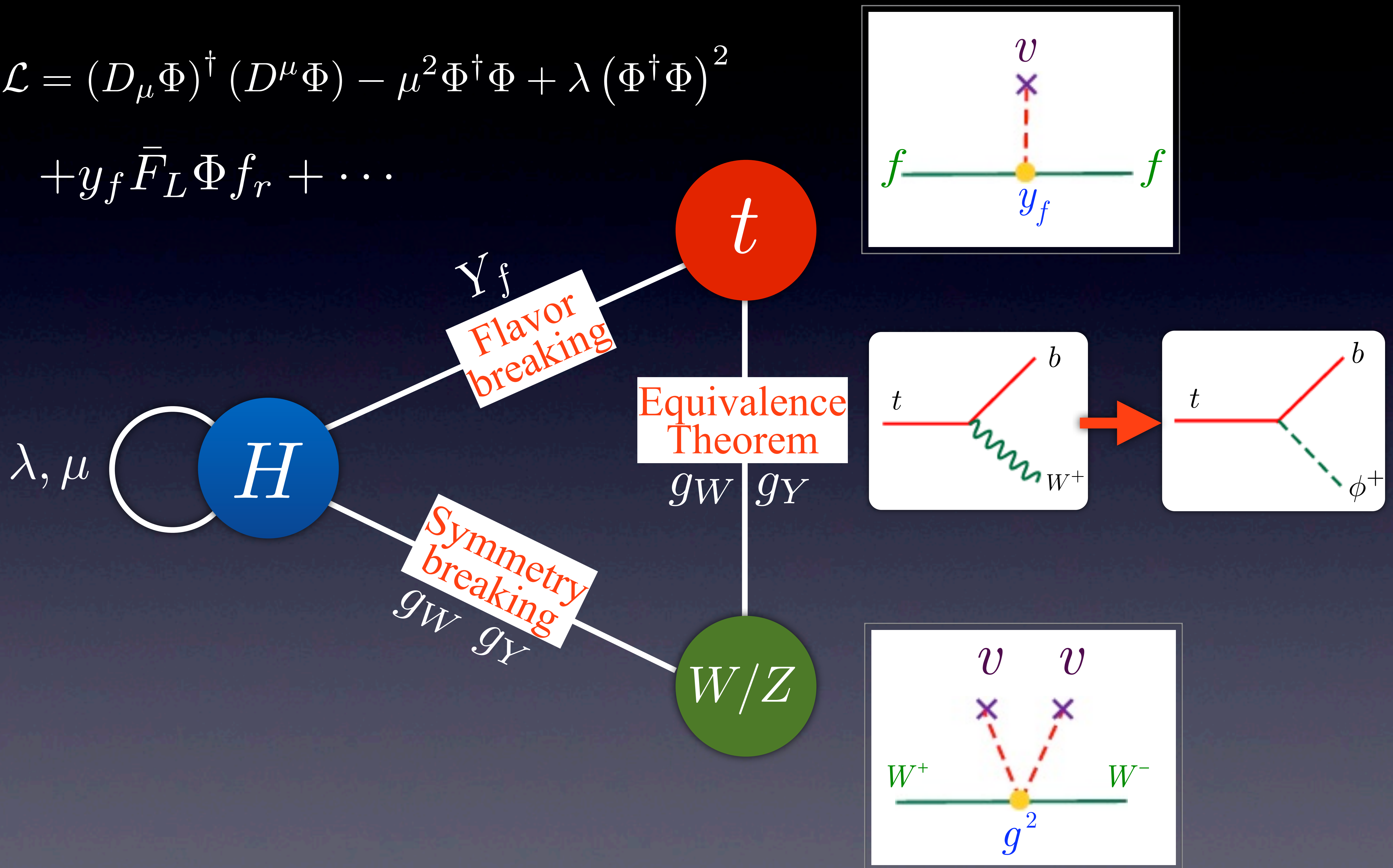


Excited quark

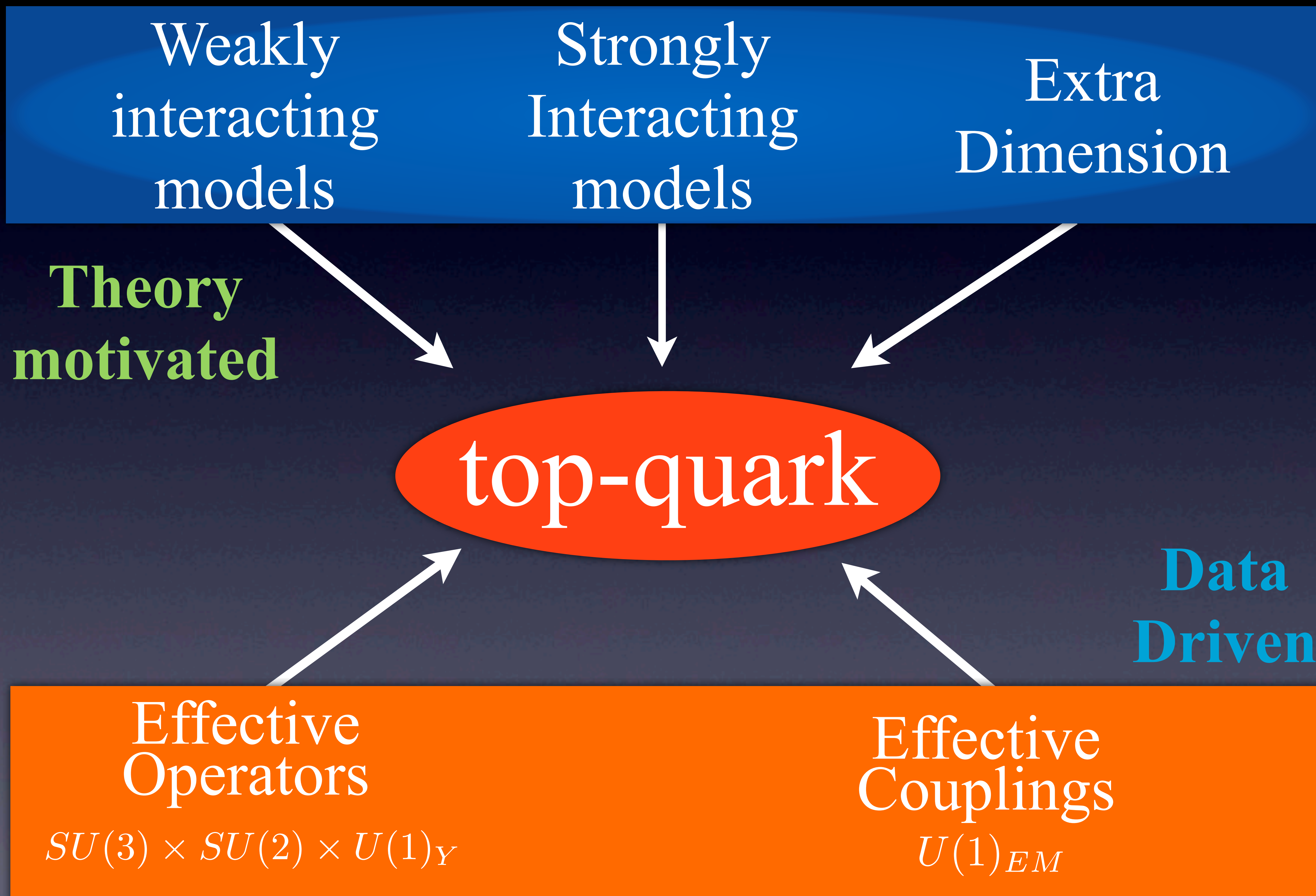
Electroweak triangle

$$\mathcal{L} = \left(D_\mu \Phi\right)^\dagger \left(D^\mu \Phi\right) - \mu^2 \Phi^\dagger \Phi + \lambda \left(\Phi^\dagger \Phi\right)^2$$

$$+ y_f \bar{F}_L \Phi f_r + \cdots$$



Top-quark as a link to NP



Model Independent Analysis of
(1) Single-top Production
(2) Wtb, Ztt and Zbb Couplings

(Indirect probe to new physics)

Top quark anomalous couplings

- NP effects can be summarized in effective Lagrangian:

$$
\begin{aligned}
\mathcal{L} = & \frac{g}{\sqrt{2}} W_\mu^- \bar{b} \gamma^\mu (f_1^L P_L + f_1^R P_R) t \\
& - \frac{g}{\sqrt{2} m_W} \partial_\nu W_\mu^- \bar{b} \sigma^{\mu\nu} (f_2^L P_L + f_2^R P_R) t \\
& + \frac{g}{\sqrt{2} m_W} \bar{b} (f_3^L P_L + f_3^R P_R) \partial_\mu t W^{-\mu} \\
& + \frac{g}{\sqrt{2} m_W} \bar{b} (f_4^L P_L + f_4^R P_R) t \partial_\mu W^{-\mu} + h.c.
\end{aligned}
$$

$\Longrightarrow$ 8 different form factors

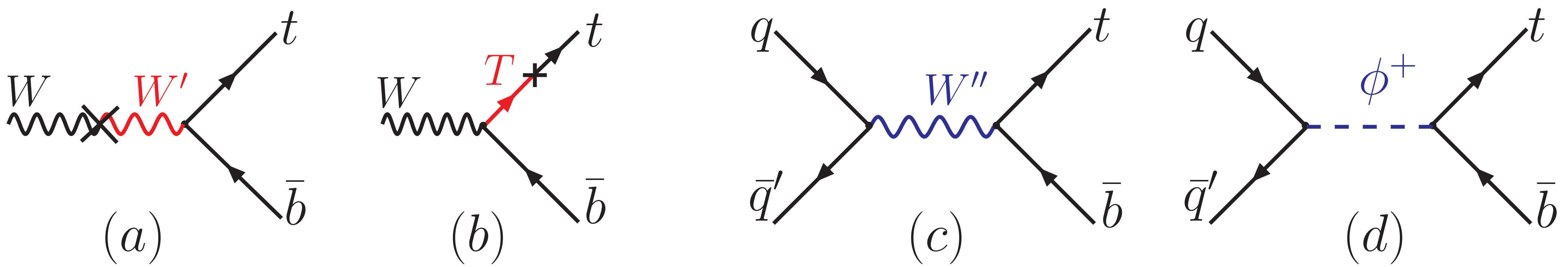
- We adopt a new approach of effective field theory to study top coupling.

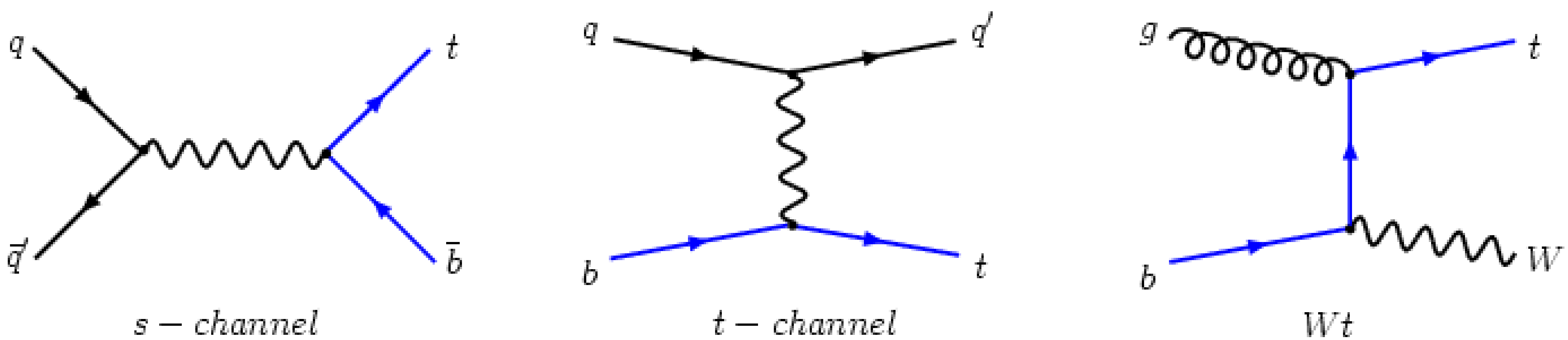
➡ We consider only tree-level induced operators.

C. Arzt, M.B. Einhorn, J. Wudka, Nucl.Phys.B433:41 (1995)

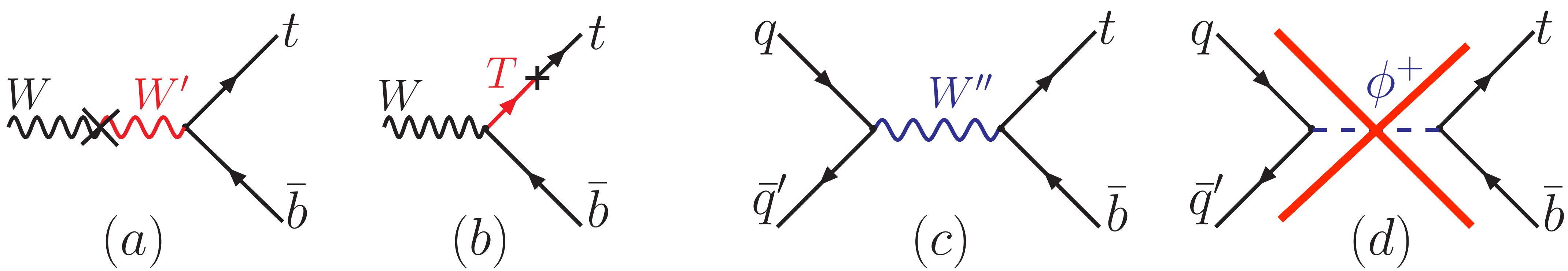
Tree-level induced dim-6 operators contributing to single-top productions

QHC, J. Wudka, C.-P. Yuan, Phys.Lett.B658:50(2007)





Effective couplings



Does not interfere with the SM channel

Upon symmetry breaking

$$\phi = \frac{v+h}{\sqrt{2}} \begin{pmatrix} 1 \\ 0 \end{pmatrix}$$

$b \to s\gamma$

$-0.0007 < \mathcal{F}_R < 0.0025$

$$\mathcal{O}_{Wtb} = \frac{g}{\sqrt{2}} \{ \bar{t}\gamma^\mu \left(\mathcal{F}_L P_L + \mathcal{F}_R P_R \right) b W^+_\mu + h.c. \}$$

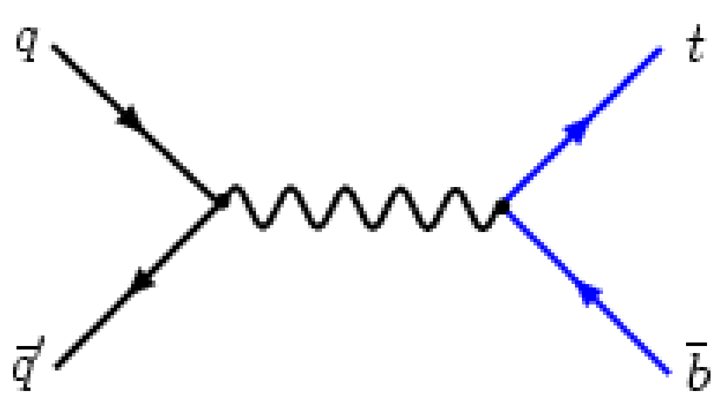
$$\mathcal{O}_{4f} = \mathcal{G}_{4f} \frac{1}{v^2} \left(\bar{Q}' \gamma^\mu P_L Q \right) \left(\bar{b} \gamma_\mu P_L t \right) + h.c.$$

$$\mathcal{F}_L = \frac{C^{(3)}_{\phi q} v^2}{\Lambda^2} \qquad \mathcal{F}_R = \frac{C_{\phi\phi} v^2}{2\Lambda^2} \qquad \mathcal{G}_{4f} = \frac{C^{(3)}_{\phi q} v^2}{2\Lambda^2}$$

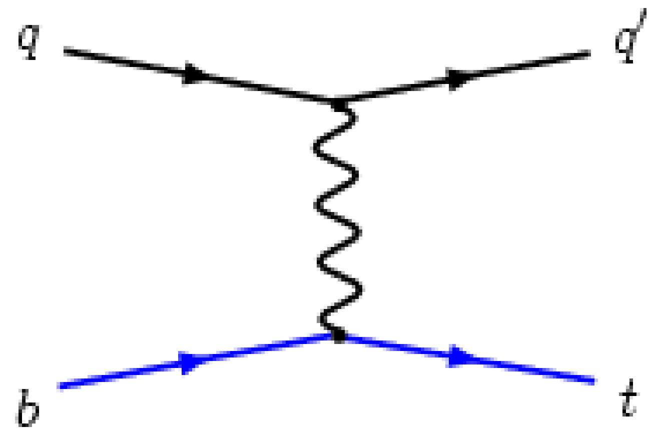
Single top productions

- Inclusive cross sections:

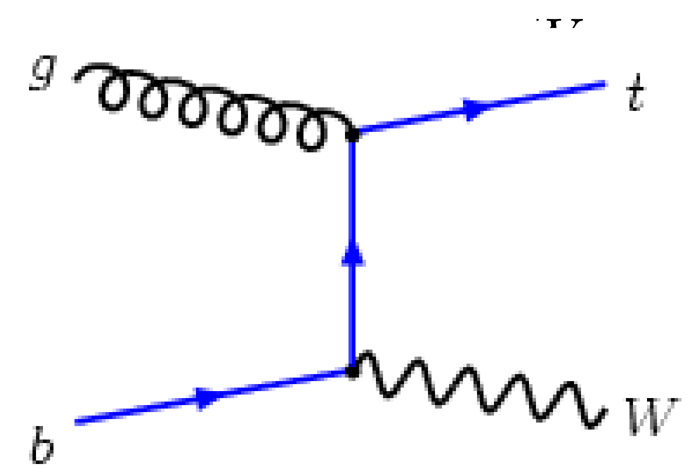
$$
\begin{aligned}
\sigma_{tW} &= \sigma^0_{tW}\left(1 + 4\mathcal{F}_L\right), \\
\sigma_s &= \sigma^0_s\left(1 + 4\mathcal{F}_L + 19.69\mathcal{G}_{4f}\right), \\
\sigma_t &= \sigma^0_t\left(1 + 4\mathcal{F}_L - 3.06\mathcal{G}_{4f}\right),
\end{aligned}
$$



$s - channel$

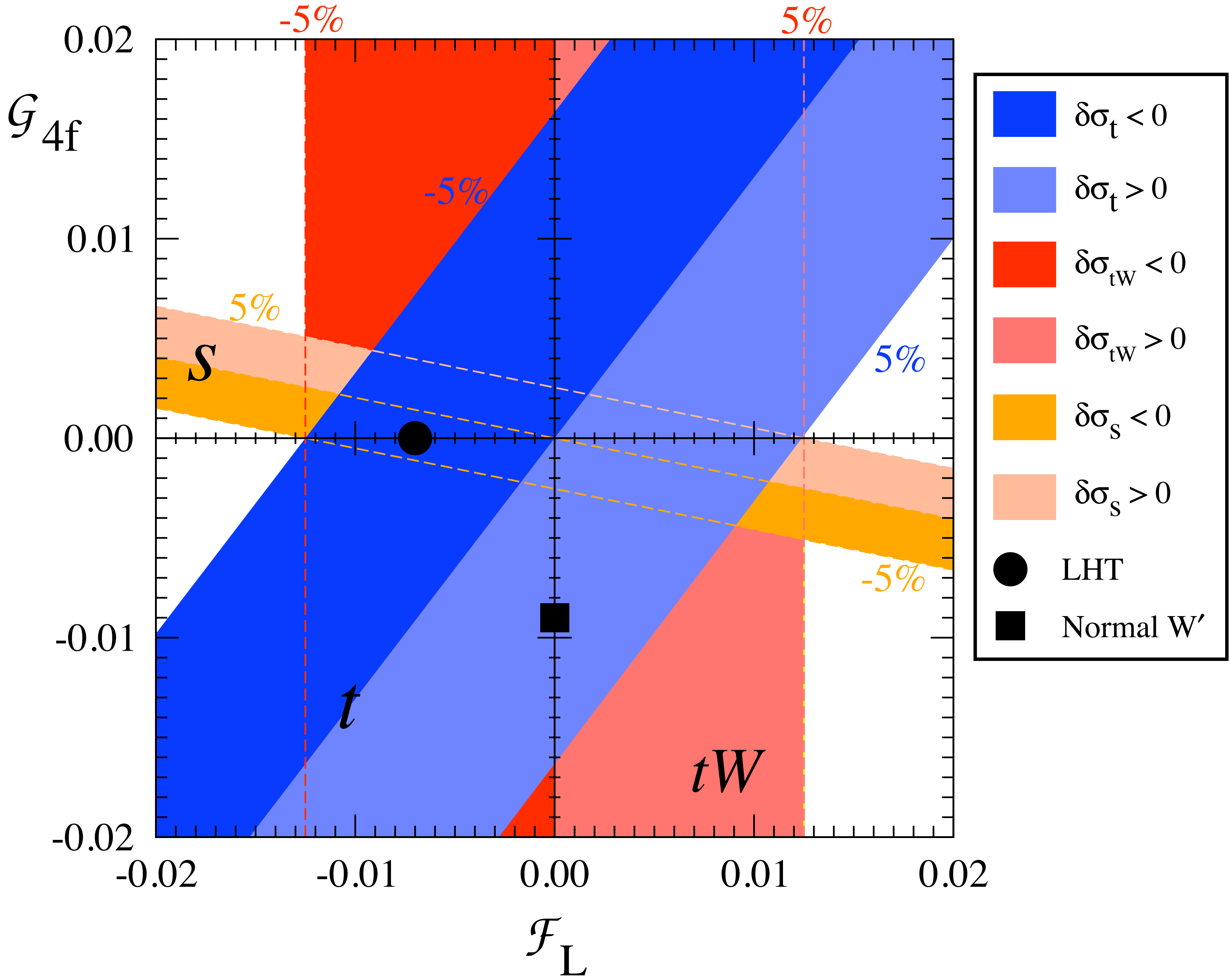


$t - channel$



Wt

Single top productions

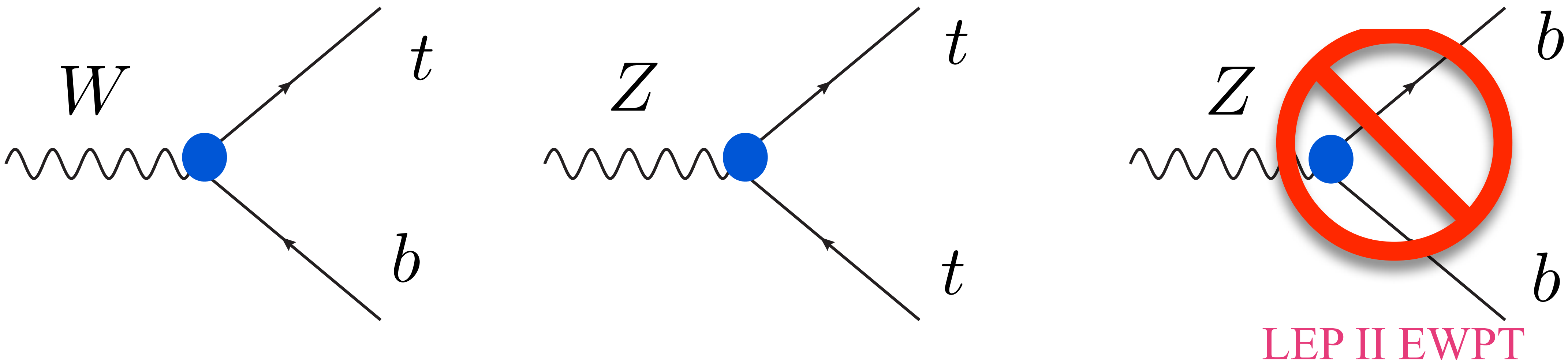


But wait ...

- The operator

$$\mathcal{O}_{\phi q}^{(3)} = i\left(\phi^\dagger \tau^I D_\mu \phi\right)\left(\bar{q}_h \gamma^\mu \tau^I q_h\right) + h.c.$$

induces not only effective Wt_Lb_L but also Zb_Lb_L coupling.



- We need other operators to protect the Zb_Lb_L couplings.

Tree-level induced dim-6 operators

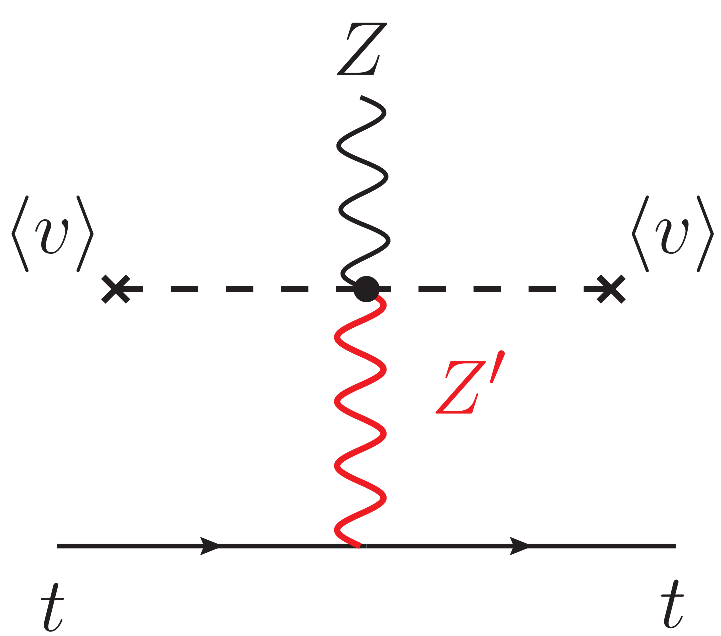
Ed L. Berger, QHC, Ian Low, Phys.Rev.D80:074020(2009)

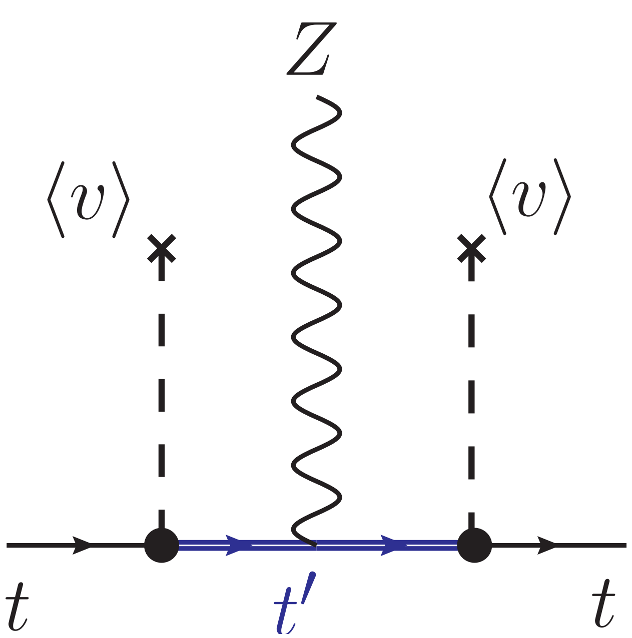
$$
\begin{aligned}
\mathcal{O}^{(1)}_{\phi q} &= i\left(\phi^\dagger D_\mu \phi\right)\left(\bar{q}\gamma^\mu q\right), \\
\mathcal{O}^{(3)}_{\phi q} &= i\left(\phi^\dagger \tau^I D_\mu \phi\right)\left(\bar{q}\gamma^\mu \tau^I q\right), \\
\mathcal{O}_{\phi t} &= i\left(\phi^\dagger D_\mu \phi\right)\left(\bar{t}_R\gamma^\mu t_R\right), \\
\mathcal{O}_{\phi b} &= i\left(\phi^\dagger D_\mu \phi\right)\left(\bar{b}_R\gamma^\mu b_R\right), \\
\mathcal{O}_{\phi \phi} &= \left(\phi^\dagger \epsilon D_\mu \phi\right)\left(\bar{t}_R\gamma^\mu b_R\right),
\end{aligned}
$$

$$q = \begin{pmatrix} t \\ b \end{pmatrix}_L$$

$t_R \quad b_R$

ϕ : Higgs doublet





Effective Wtb, Ztt, Zbb couplings

$b \to s\gamma$

$-0.0007 < \frac{c_{\phi\phi} v^2}{2\Lambda^2} < 0.0025$

B. Grzadkowski and M. Misiak, Phys. rev. D78, 077501 (2008)

$$\mathcal{O}_{Wtb} = \frac{c_{\phi q}^{(3)} v^2}{\Lambda^2} \frac{g_2}{\sqrt{2}} W_\mu^+ \bar{t}_L \gamma^\mu b_L - \frac{c_{\phi\phi} v^2}{2\Lambda^2} \frac{g_2}{\sqrt{2}} W_\mu^+ \bar{t}_R \gamma^\mu b_R + h.c.$$

$$\mathcal{O}_{Zt\bar{t}} = \frac{\left(c_{\phi q}^{(3)} - c_{\phi q}^{(1)}\right) v^2}{\Lambda^2} \frac{\sqrt{g_1^2 + g_2^2}}{2} Z_\mu \bar{t}_L \gamma^\mu t_L - \frac{c_{\phi t} v^2}{\Lambda^2} \frac{\sqrt{g_1^2 + g_2^2}}{2} Z_\mu \bar{t}_R \gamma^\mu t_R$$

$$\mathcal{O}_{Zb\bar{b}} = -\frac{\left(c_{\phi q}^{(1)} + c_{\phi q}^{(3)}\right) v^2}{\Lambda^2} \frac{\sqrt{g_1^2 + g_2^2}}{2} Z_\mu \bar{b}_L \gamma^\mu b_L - \frac{c_{\phi b} v^2}{\Lambda^2} \frac{\sqrt{g_1^2 + g_2^2}}{2} Z_\mu \bar{b}_R \gamma^\mu b_R$$

R_b and $A_{FB}^{(b)}$

$\frac{\delta g_{Zb_L b_L}}{g_{Zb_L b_L}^{\mathrm{SM}}} \leq 0.25\%$

$\rightarrow$ $c_{\phi q}^{(3)} + c_{\phi q}^{(1)} \simeq 0$

J. Alcaraz et al, arXiv:hep-ex/0511027

Effective Wtb, Ztt, Zbb couplings

- New parameterization of couplings

$$\mathcal{O}_{Wtb} = \frac{g}{\sqrt{2}} \mathcal{F}_L W_\mu^+ \bar{t}_L \gamma^\mu b_L + h.c. \ ,$$

$$\mathcal{O}_{Zt\bar{t}} = \frac{g}{2c_w} Z_\mu \left(2\mathcal{F}_L \bar{t}_L \gamma^\mu t_L + \mathcal{F}_R \bar{t}_R \gamma^\mu t_R\right)$$

- The coefficients of the left-handed neutral and charged currents are related,

$$g^L_{Zt\bar{t}} = 2 g^L_{Wtb} = 2\mathcal{F}_L$$

which is predicted by the EW gauge symmetry after the stringent constraint on Zb_Lb_L imposed.

How to probe such correlations?

$$\mathcal{O}_{Wtb} = \frac{g}{\sqrt{2}} \mathcal{F}_L W_\mu^+ \bar{t}_L \gamma^\mu b_L + h.c. \;,$$

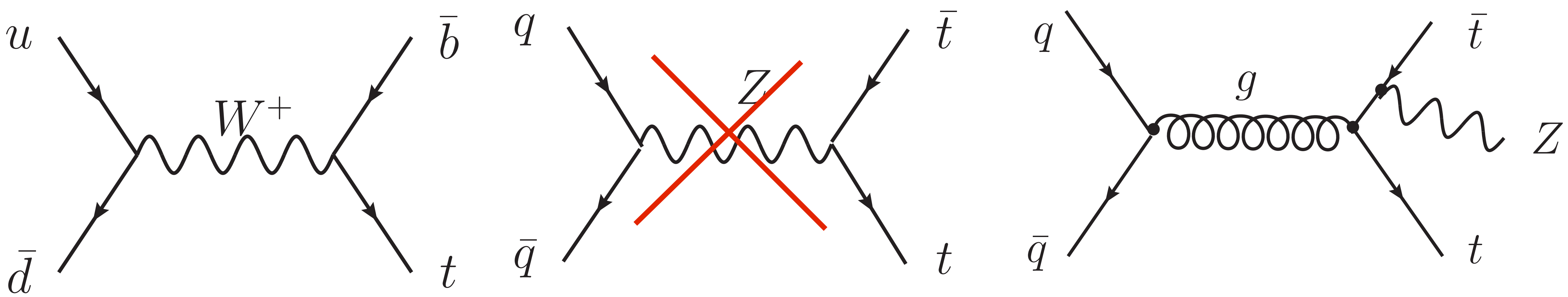
$$\mathcal{O}_{Zt\bar{t}} = \frac{g}{2c_w} Z_\mu \left(2\mathcal{F}_L \bar{t}_L \gamma^\mu t_L + \mathcal{F}_R \bar{t}_R \gamma^\mu t_R \right)$$

- At the LHC

U. Baur, A. Juste, L.H. Orr, D. Rainwater

Phys.Rev.D71:054013,2005;

Phys. Rev.D73:034016,2006



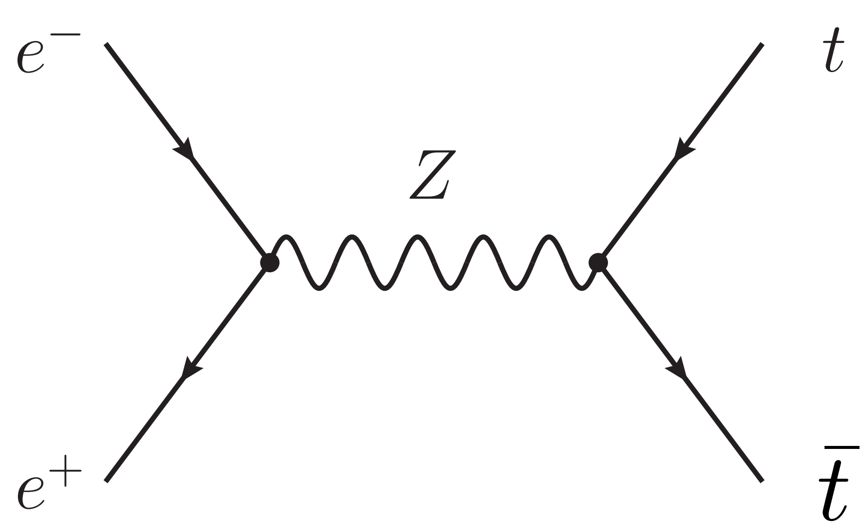
How to probe such correlations?

$$\mathcal{O}_{Wtb} = \frac{g}{\sqrt{2}} \mathcal{F}_L W_\mu^+ \bar{t}_L \gamma^\mu b_L + h.c. \ ,$$

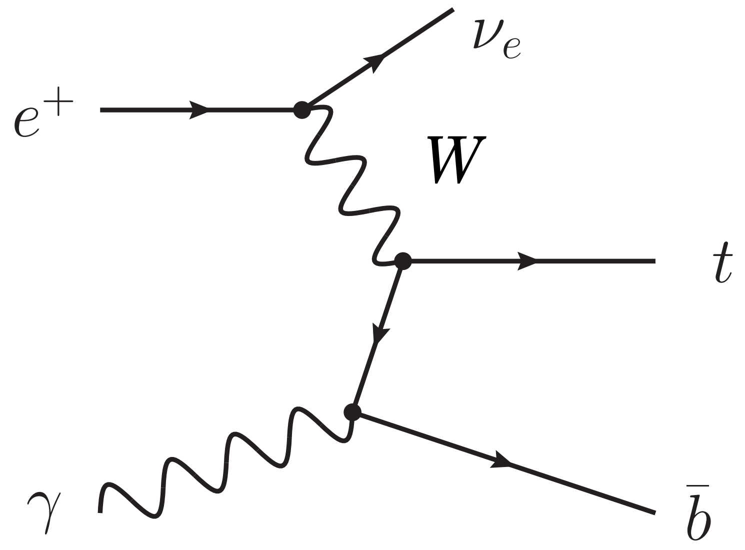
$$\mathcal{O}_{Zt\bar{t}} = \frac{g}{2c_w} Z_\mu \left(2\mathcal{F}_L \bar{t}_L \gamma^\mu t_L + \mathcal{F}_R \bar{t}_R \gamma^\mu t_R\right)$$

- At the Linear Collider

P. Batra, T. Tait,
Phys.Rev.D74:054021,2006



QHC, J. Wudka,
Phys.Rev.D74:094015,2006



Impact on $\sigma(t)$ and $\sigma(Ztt)$

- Inclusive cross sections of single-t and Ztt productions:

$$\sigma_t = \sigma_t^0 \left[1 + 2\mathcal{F}_L + 2\delta V_{tb} + \mathcal{O}\left(\mathcal{F}_L^2, \delta V_{tb}^2\right)\right],$$

$$\sigma_{Zt\bar{t}} = \sigma_{Zt\bar{t}}^0 \left[1 + 4.4\mathcal{F}_L - 1.5\mathcal{F}_R + \mathcal{O}\left(\mathcal{F}_L^2,\ \mathcal{F}_R^2,\ \mathcal{F}_L\mathcal{F}_R\right)\right]$$

$$\delta\sigma = (\sigma - \sigma^0)/\sigma^0 \qquad \delta V_{tb} = |V_{tb}|^{(\mathrm{exp})} - |V_{tb}|^{(\mathrm{SM})}$$

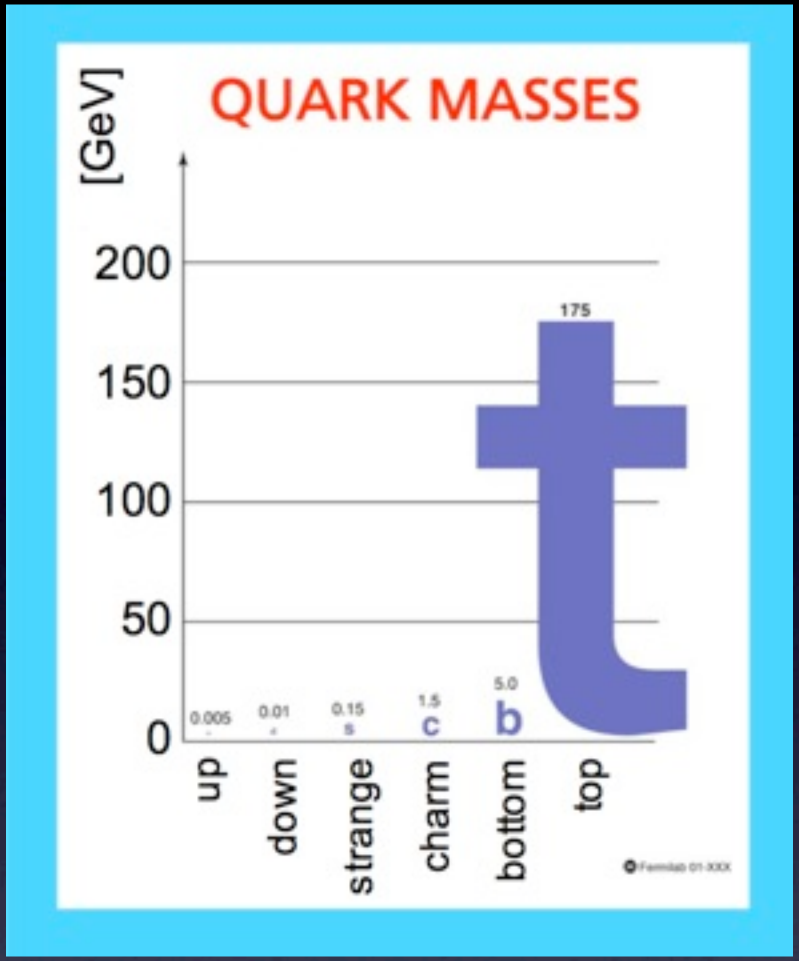
$$\delta V_{tb} = -0.23\delta\sigma_{Zt\bar{t}} + 0.5\delta\sigma_t - 0.34\mathcal{F}_R$$

Note: Vtb cannot be extracted out from single top production alone.

Top quark polarization

Top-quark: king of the SM

- Large mass： 172GeV ($y_t \sim O(1)$)

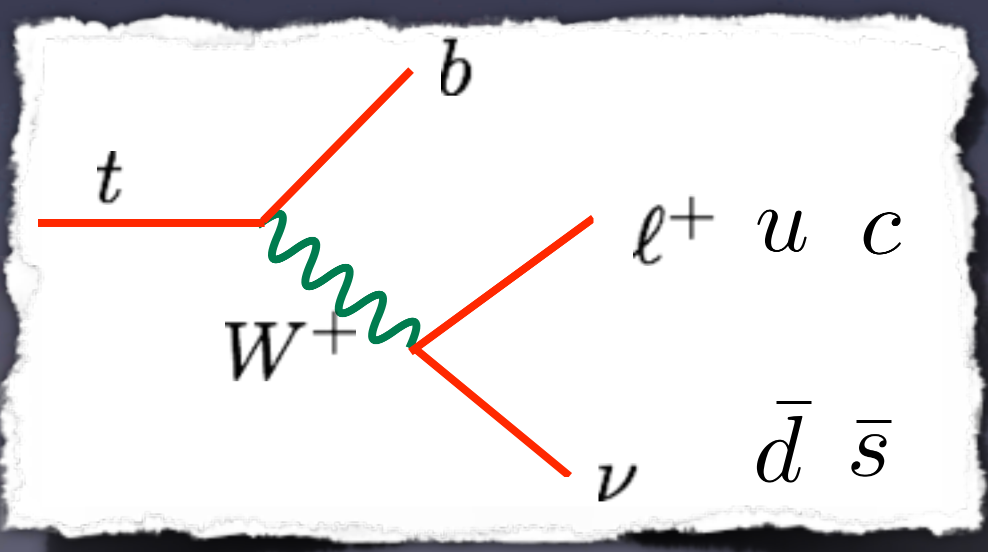


- Short lifetime:

$\frac{1}{m_t}$	$\frac{1}{\Gamma_t}$	$\frac{1}{\Lambda_{QCD}}$
5×10^{-27} s	5×10^{-25} s	3×10^{-24} s
pQCD	WEAK	

- "bare" quark:

  spin info well kept among its decay products

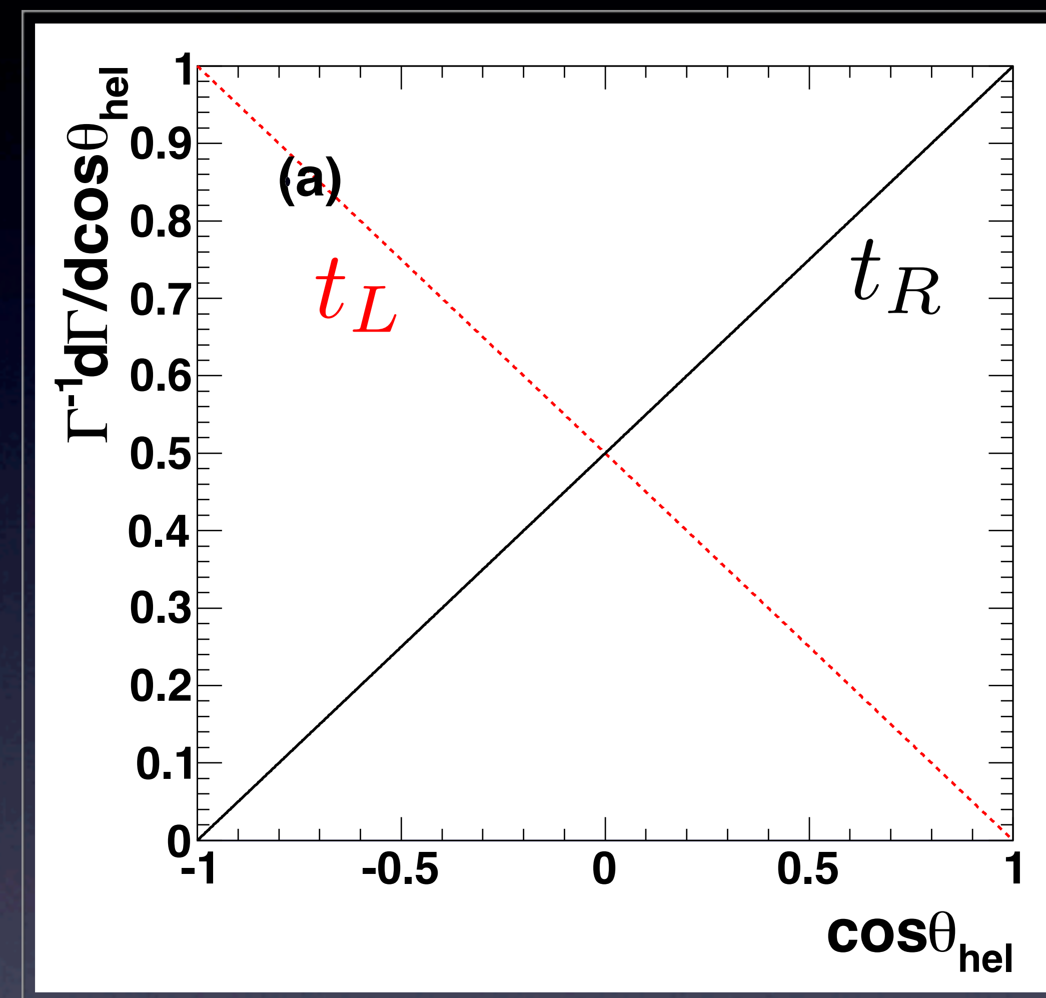


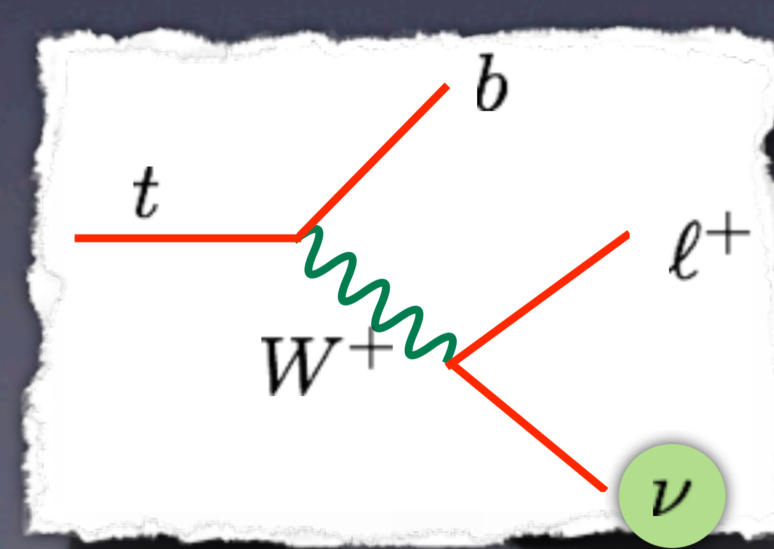
Charged lepton distribution

- The charged-lepton tends to *follow* the top-quark spin direction.
- In top-quark rest frame

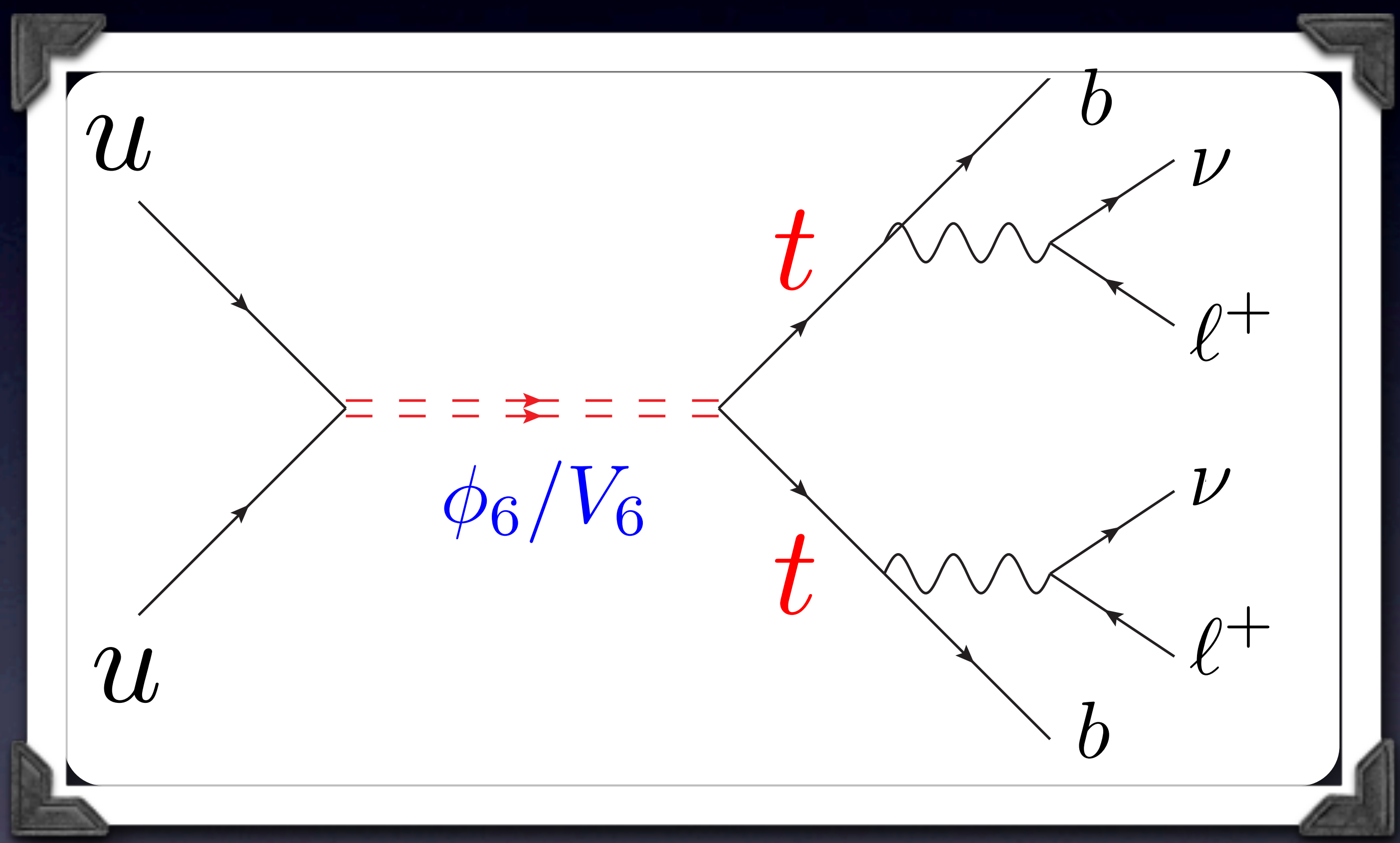
$$\frac{1}{\Gamma}\frac{d\Gamma}{d\cos\theta_{\rm hel}} = \frac{1+\lambda_t\cos\theta_{\rm hel}}{2}$$

$$\begin{array}{ll} \lambda_t = + & \text{right-handed} \\ \lambda_t = - & \text{left-handed} \end{array}$$





Example 1:
Color sextet scalar/vector



The Models

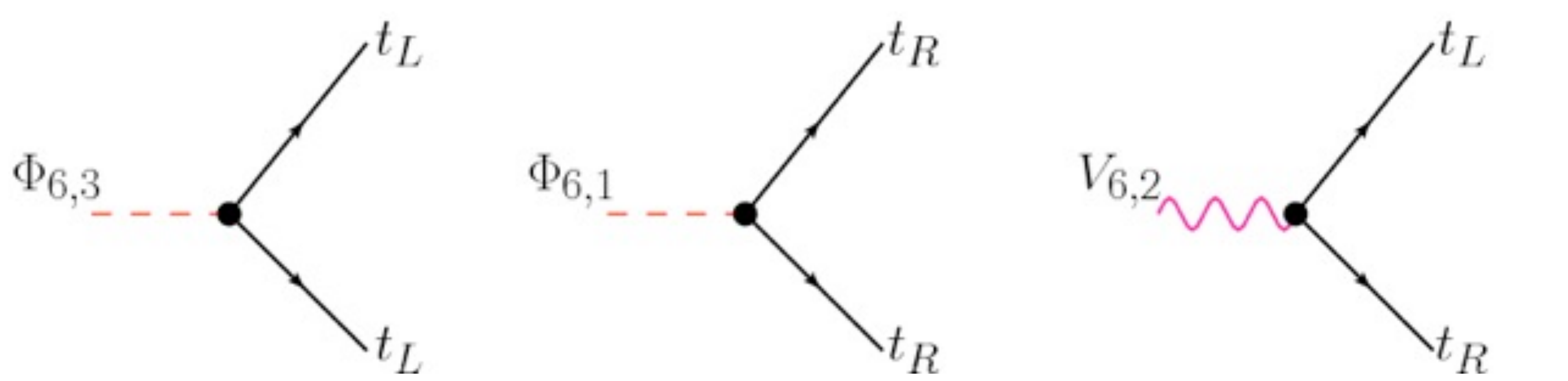
- Effective Lagrangian ($SU(3)_C$ x $SU(2)_L$ x $U(1)_Y$)

Atag, Cakir, Sultansoy, PRD59 (1999) 015008

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

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

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



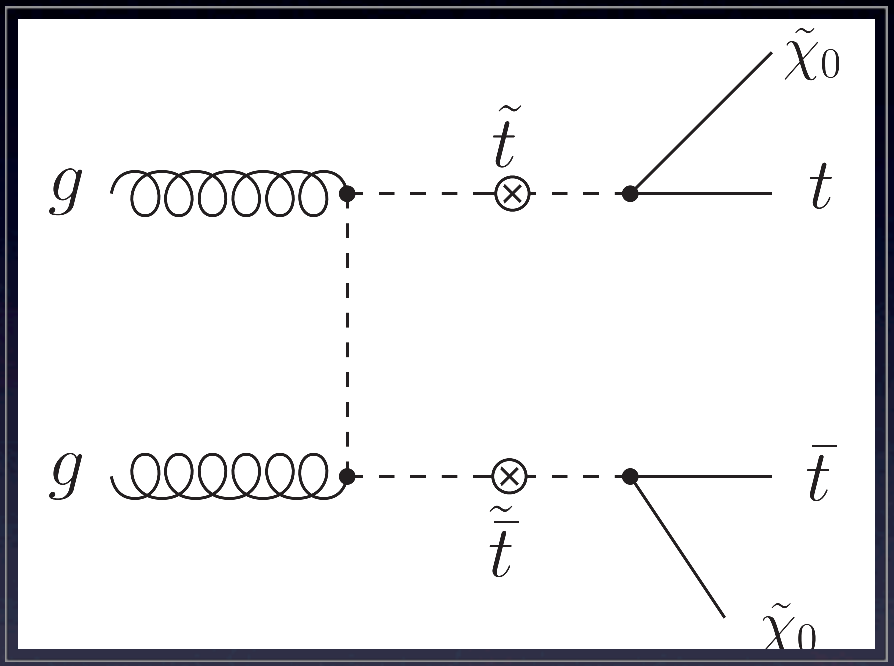
Measuring polarizations of ***both*** top quarks → Spin and gauge quantum numbers of heavy resonances

Berger, QHC, Chen, Shaughnessy, Zhang, Phys Rev Lett **105** (2010) 181802

Zhang, Berger, QHC, Chen, Shaughnessy, Phys Lett B **696** (2001) 68

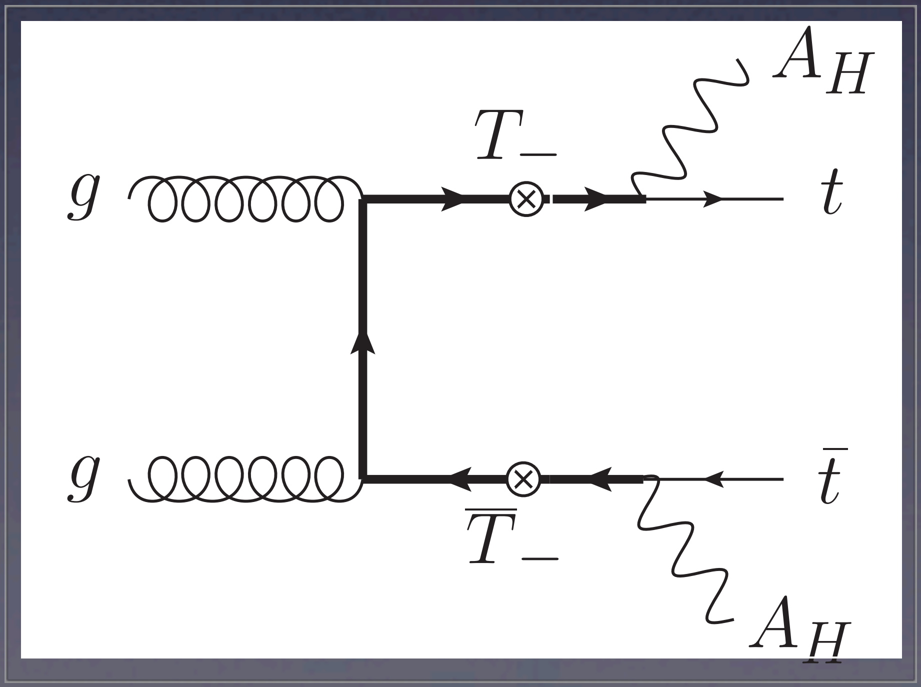
Example 2: Top-quark pair plus missing energy

- Typical collider signature in several NP models
  - Minimal Supersymmetric extension of the Standard Model (MSSM)



spin 0

  - Little Higgs Model with T-parity (LHT)
  - Universal Extra Dimension Model (UED)

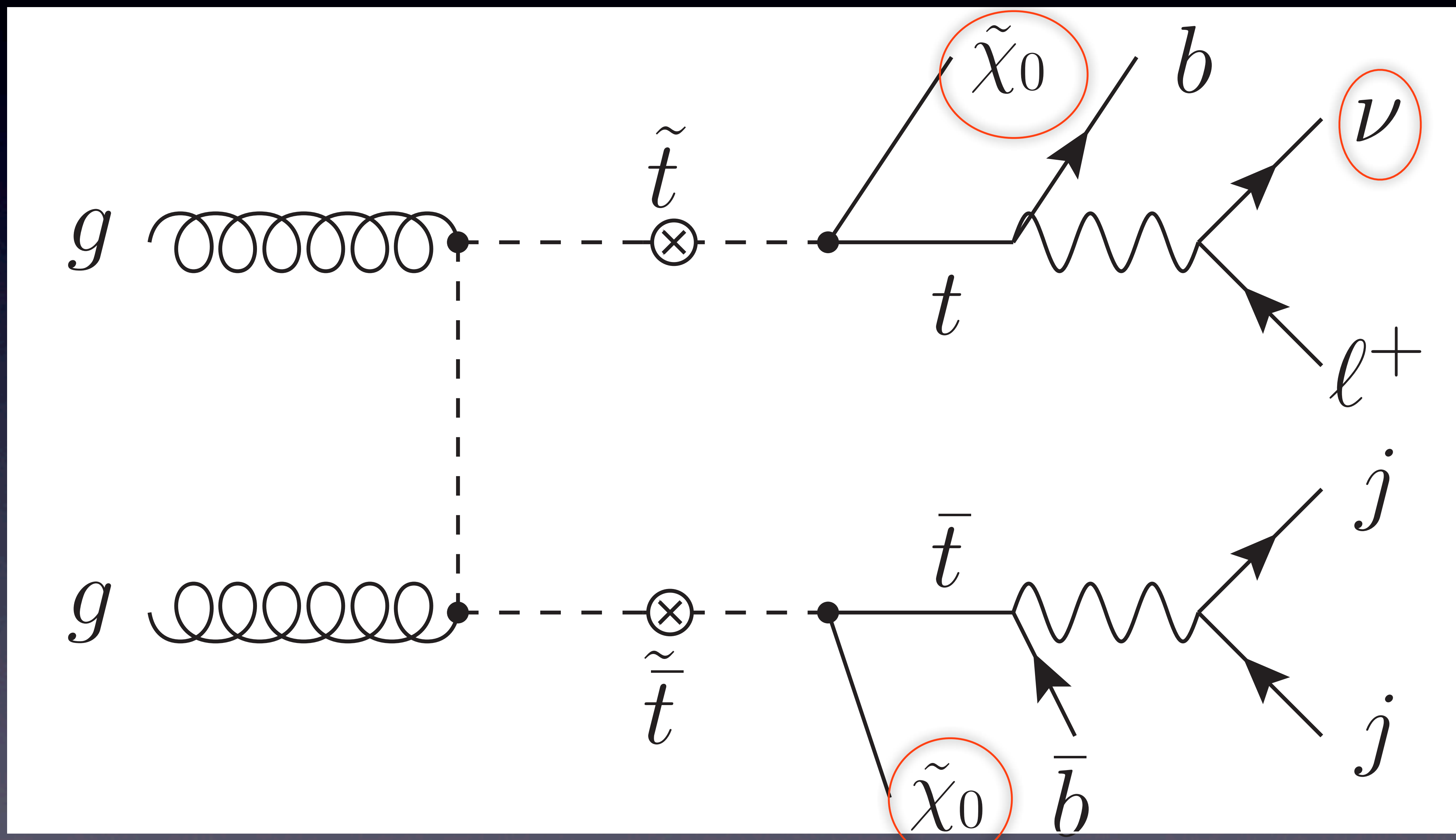


spin 1/2

Difficulty in $t\bar{t} + \not{E}_T$ events

- It is impossible to reconstruct a top-quark in the leptonic-decay mode.

Angular distribution of the charged-lepton cannot be used.



Masses and spins of $\tilde{t}$ and $\tilde{\chi}_0$ are not known.

Lepton energy and top-quark polarization

Berger, QHC, Zhang, Yu, Phys. Rev. Lett. 109 (2012) 152004

★ Lepton energy distribution is sensitive to top quark polarization.

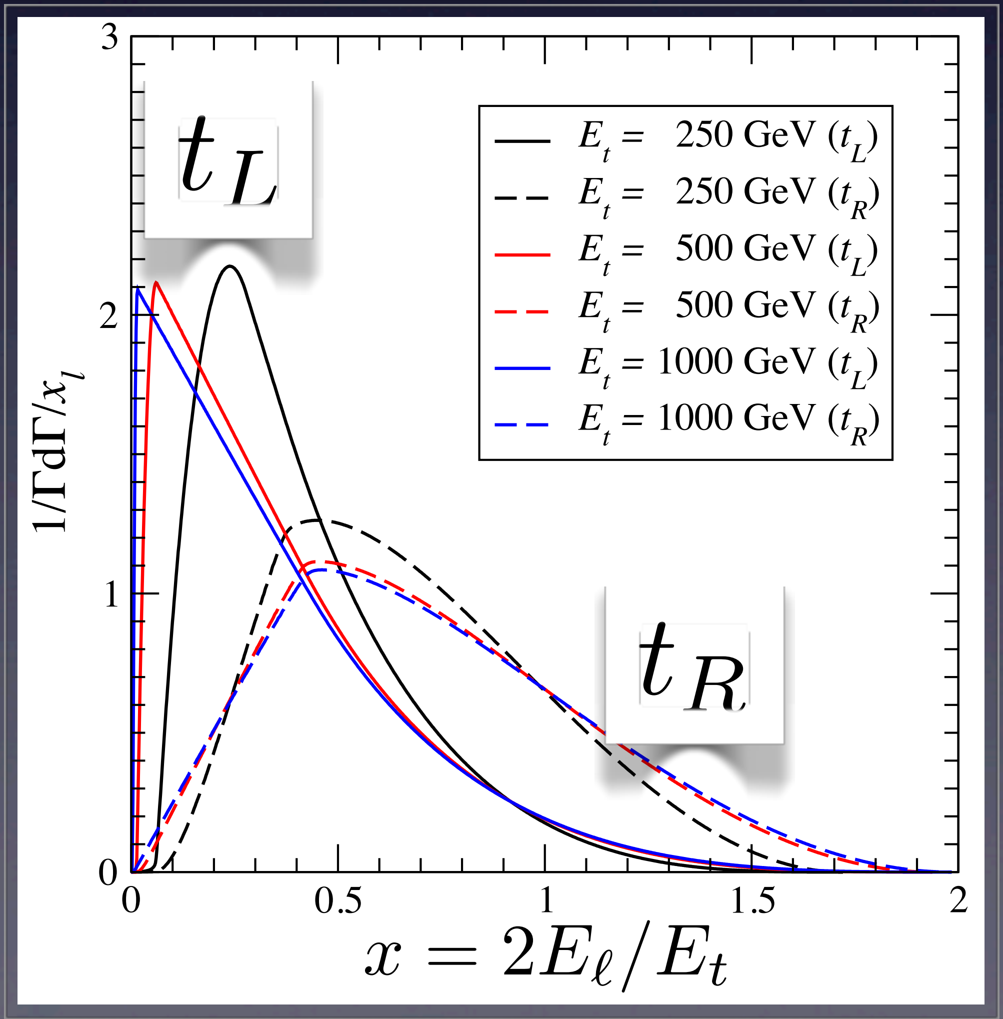
$$\frac{d\Gamma(\hat{s}_t)}{dx} = \frac{\alpha_W^2 m_t}{64\pi AB}\int_{z_{\min}}^{z_{\max}} x\gamma^2[1 - x\gamma^2(1-z\beta)] \times \left(1 + \hat{s}_t\frac{z-\beta}{1-z\beta}\right)\text{Arctan}\left[\frac{Ax\gamma^2(1-z\beta)}{B - x\gamma^2(1-z\beta)}\right]dz$$

$$A = \frac{\Gamma_W}{m_W} \qquad B = \frac{m_W^2}{m_t^2} \approx 0.216$$

$$\gamma = \frac{E_t}{m_t} \qquad \beta = \sqrt{1 - 1/\gamma^2}$$

$$z_{\min} = \max[(1 - 1/\gamma^2 x)/\beta, -1]$$

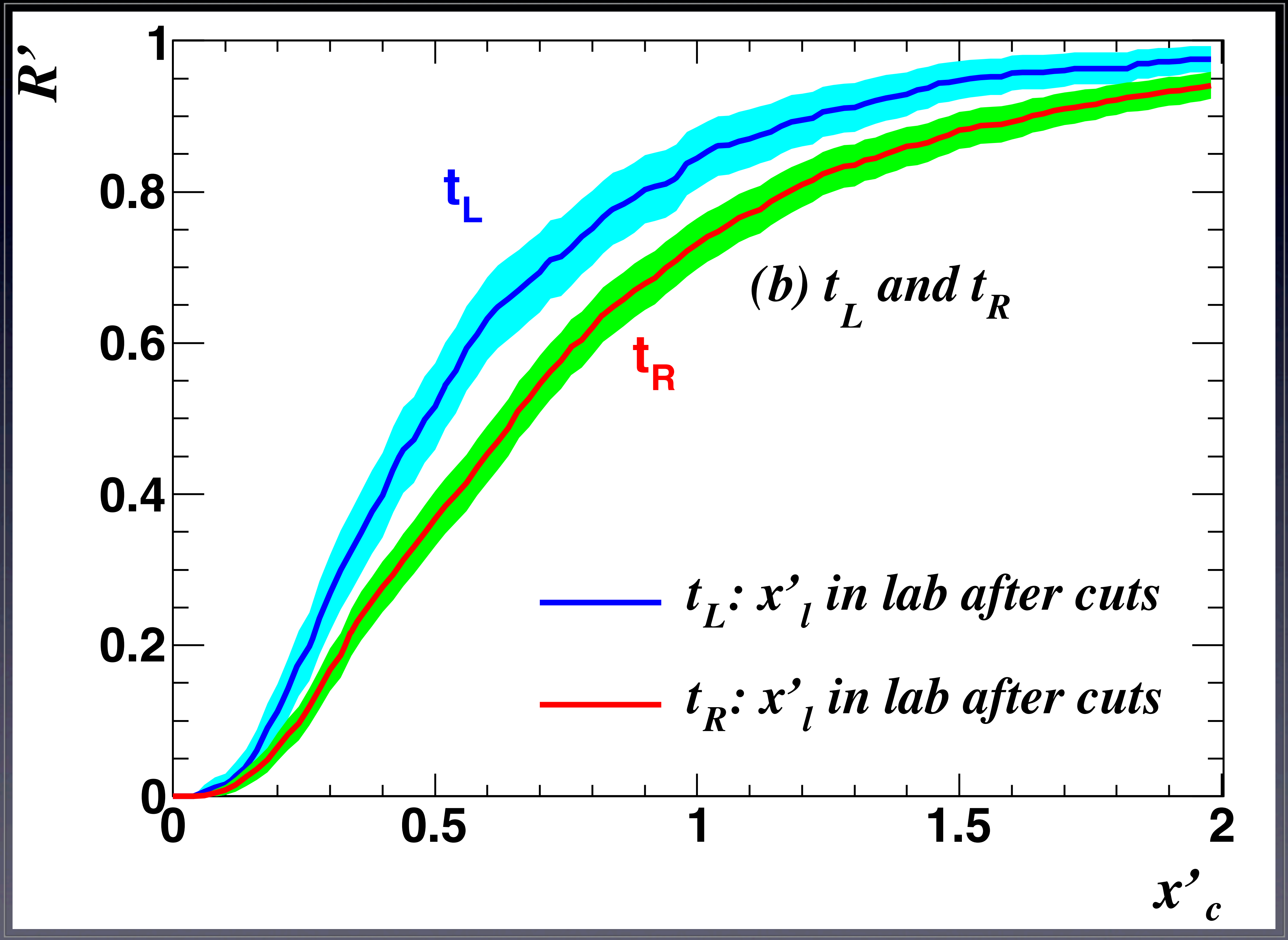
$$z_{\max} = \min[(1 - B/\gamma^2 x)/\beta, 1]$$



$\mathcal{R}'$ distribution

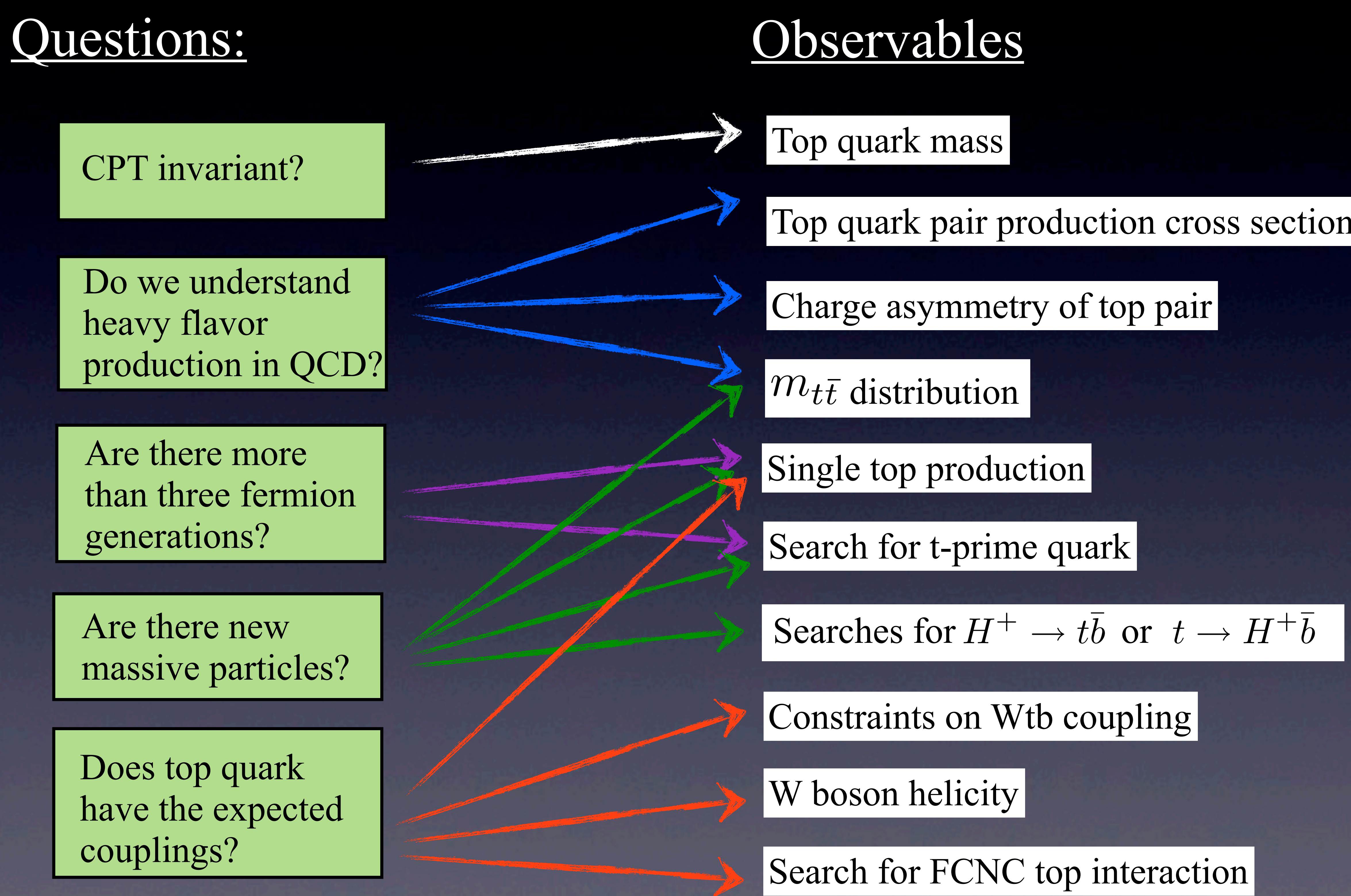
- t_L and t_R are separated

LHC: 14 TeV, 100fb^{-1}



Berger, QHC, Zhang, Yu, Phys. Rev. Lett. 109 (2012) 152004

Summary


Questions:
Observables
CPT invariant?
Do we understand heavy flavor production in QCD?
Are there more than three fermion generations?
Are there new massive particles?
Does top quark have the expected couplings?
Top quark mass
Top quark pair production cross section
Charge asymmetry of top pair
$m_{t\bar{t}}$ distribution
Single top production
Search for t-prime quark
Searches for $H^+ \to t\bar{b}$ or $t \to H^+\bar{b}$
Constraints on Wtb coupling
W boson helicity
Search for FCNC top interaction

THANK YOU!