

Effective Field Theory for Top Quark Physics

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Workshop on Heavy Particles

ETH Zurich

January 5, 2011

Effective Field Theory for Top Quark Physics

Zhang and Willenbrock

arXiv:1008.3155 (Top2010)

arXiv: 1008.3869

Degrande, Gerard, Grojean, Maltoni, Servant

arXiv:1010.6304

Two approaches to physics beyond the standard model:

1. Add new particles

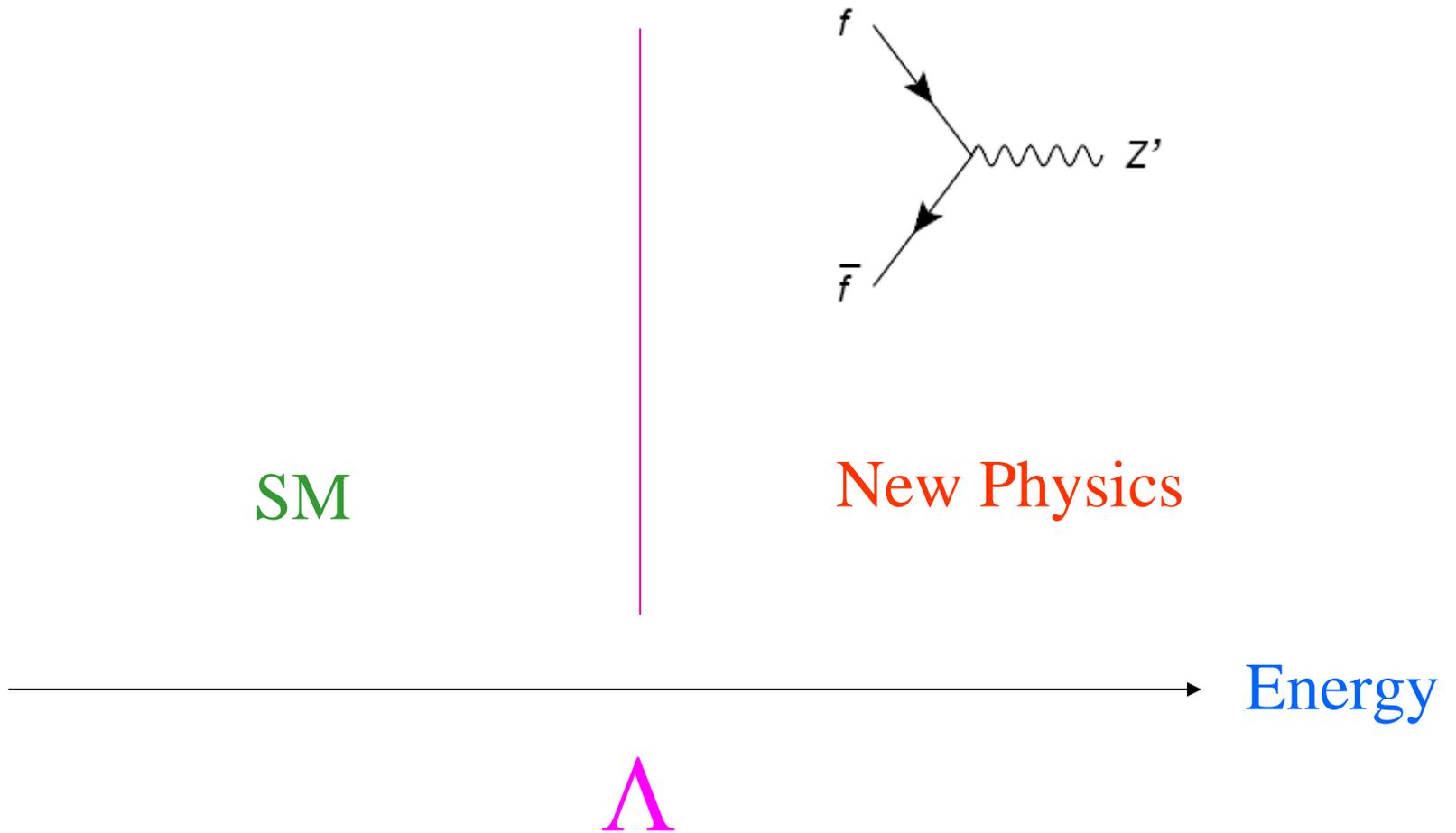
Directly observe new physics

2. Add new interactions of SM particles

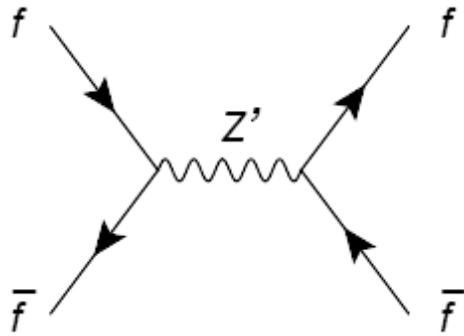
How should we do this?



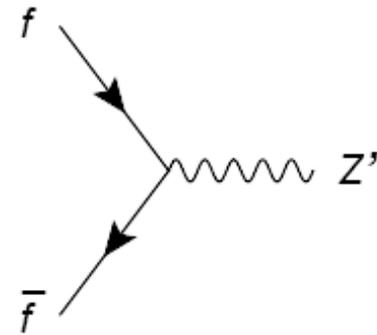
Example: Z' boson



Example: Z' boson



SM

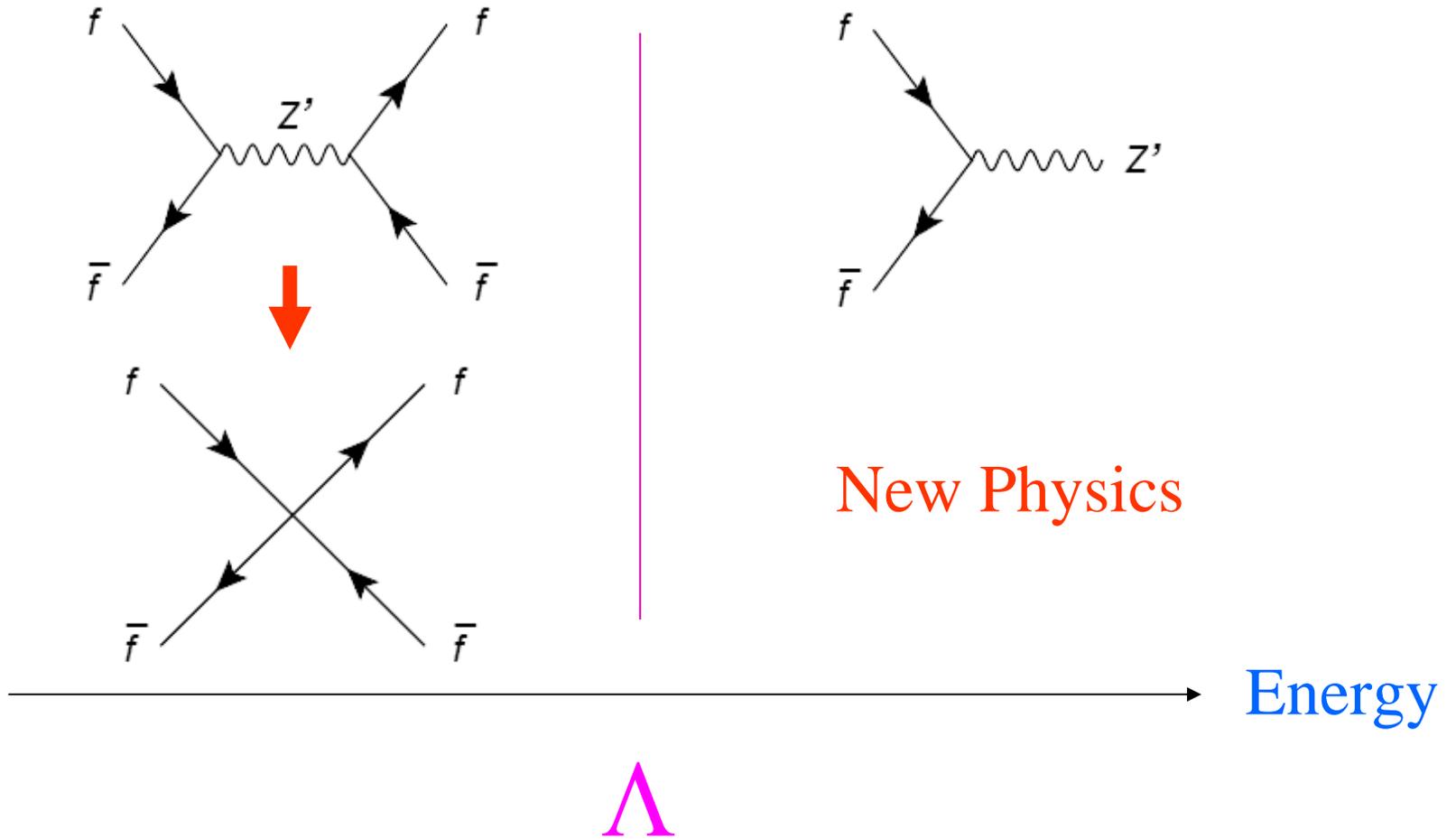


New Physics

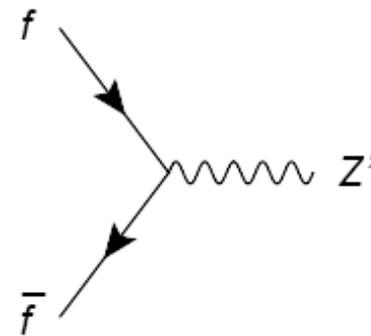
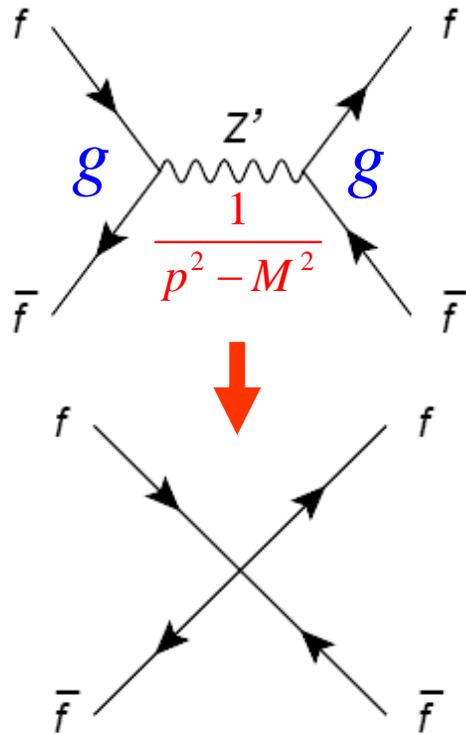
Energy \rightarrow

Λ

Example: Z' boson



Example: Z' boson

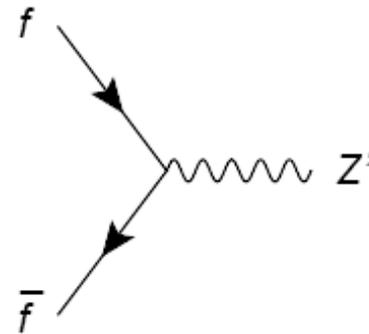
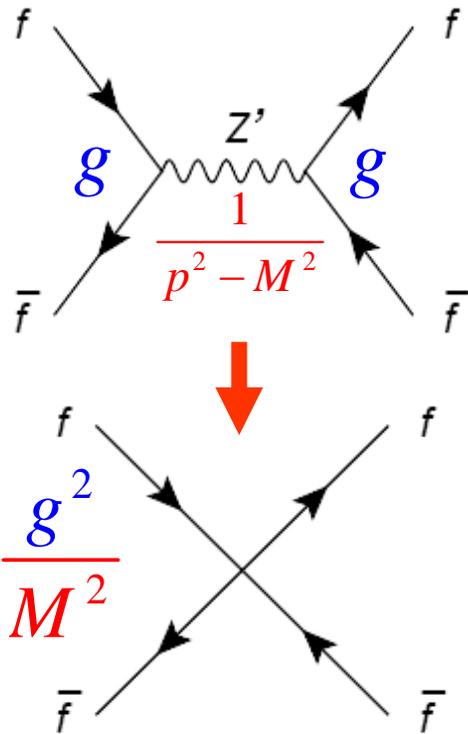


New Physics

Energy →

$$\Lambda = M$$

Example: Z' boson

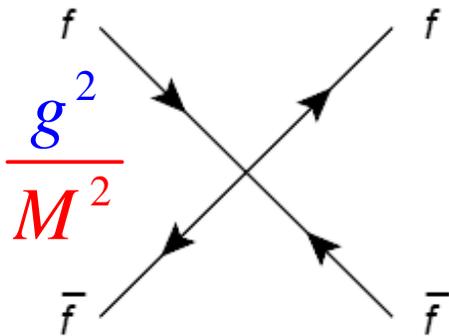


New Physics

Energy

$$\Lambda = M$$

Example: Z' boson



$$L = L_{SM} + \frac{g^2}{M^2} \bar{\psi}\psi\bar{\psi}\psi$$

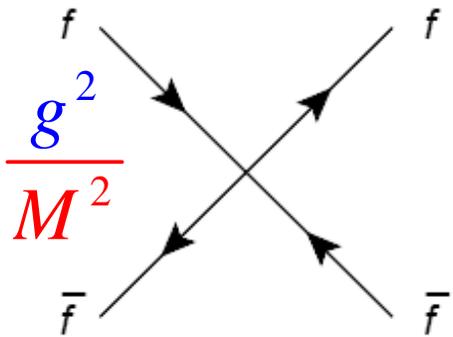
Dimensional analysis

$$\hbar = c = 1$$

$$\dim A^\mu = 1$$

$$\dim \phi = 1$$

$$\dim \psi = 3/2$$



$$L = L_{SM} + \frac{g^2}{M^2} \bar{\psi}\psi\bar{\psi}\psi$$

$\dim =$

≤ 4

6

Dimensional analysis

$$\hbar = c = 1$$

$$\dim A^\mu = 1$$

$$\dim \phi = 1$$

$$\dim \psi = 3/2$$

$$L = L_{SM} + \sum_i \frac{c_i}{\Lambda^2} O_i$$

dim =

 ≤ 4

 6

Dimensional analysis

$$\hbar = c = 1$$

$$\dim A^\mu = 1$$

$$\dim \phi = 1$$

$$\dim \psi = 3/2$$

Effective Field Theory

$$L = L_{SM} + \sum_i \frac{c_i}{\Lambda^2} \mathcal{O}_i$$

Weinberg 1979

$$\dim = \quad \begin{array}{c} \uparrow \\ \leq 4 \end{array} \quad \begin{array}{c} \uparrow \\ 6 \end{array}$$

Leung, Love, Rao 1984
Buchmuller, Wyler 1986

Bad news: 59 operators



Effective Field Theory

$$L = L_{SM} + \sum_i \frac{c_i}{\Lambda^2} O_i$$

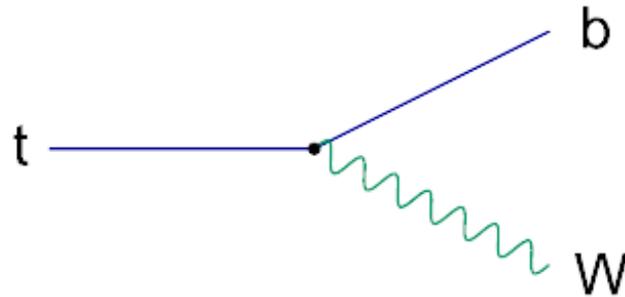
Weinberg 1979

dim =

↑
≤ 4

↑
6

Top decay



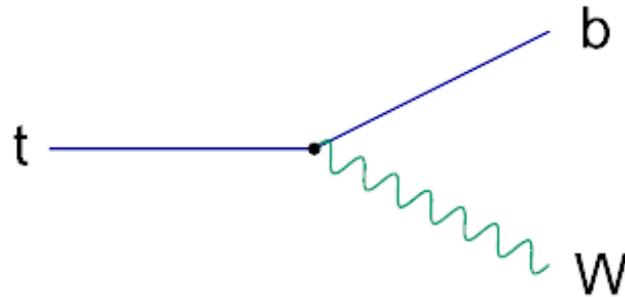
$$F_0 = \frac{m_t^2}{m_t^2 + 2m_W^2} = 0.7$$

$$F_L = \frac{2m_W^2}{m_t^2 + 2m_W^2} = 0.3$$

$$F_R = 0$$

$$m_b = 0$$

Top decay



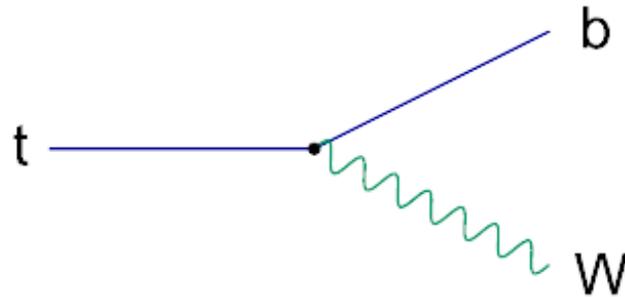
$$O_{tW} = (\bar{q}\sigma^{\mu\nu}\tau^I t)\tilde{\phi}W_{\mu\nu}^I$$

$$F_0 = \frac{m_t^2}{m_t^2 + 2m_W^2}$$

$$F_L = \frac{2m_W^2}{m_t^2 + 2m_W^2}$$

$$F_R = 0$$

Top decay



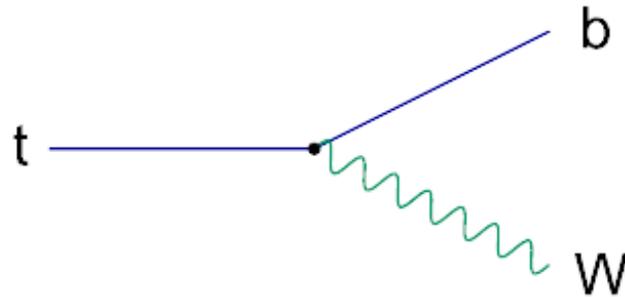
$$O_{tW} = (\bar{q}\sigma^{\mu\nu}\tau^I t)\tilde{\phi}W_{\mu\nu}^I \longrightarrow L_{eff} = i\frac{C_{tW}}{\Lambda^2}v(\bar{b}\sigma^{\mu\nu}(1+\gamma_5)t)\partial_\nu W_\mu^-$$

$$F_0 = \frac{m_t^2}{m_t^2 + 2m_W^2}$$

$$F_L = \frac{2m_W^2}{m_t^2 + 2m_W^2}$$

$$F_R = 0$$

Top decay



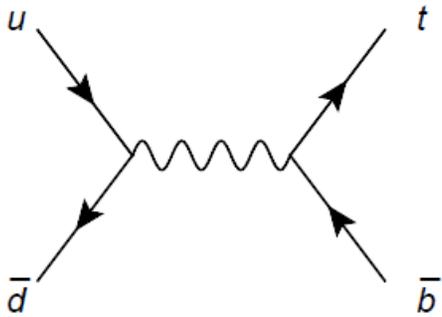
$$O_{tW} = (\bar{q}\sigma^{\mu\nu}\tau^I t)\tilde{\phi}W_{\mu\nu}^I \longrightarrow L_{eff} = i\frac{C_{tW}}{\Lambda^2}v(\bar{b}\sigma^{\mu\nu}(1+\gamma_5)t)\partial_\nu W_\mu^-$$

$$F_0 = \frac{m_t^2}{m_t^2 + 2m_W^2} - \frac{4\sqrt{2}C_{tW}v^2}{\Lambda^2} \frac{m_t m_W (m_t^2 - m_W^2)}{(m_t^2 + 2m_W^2)^2}$$

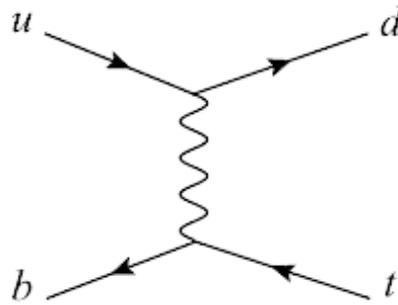
$$F_L = \frac{2m_W^2}{m_t^2 + 2m_W^2} + \frac{4\sqrt{2}C_{tW}v^2}{\Lambda^2} \frac{m_t m_W (m_t^2 - m_W^2)}{(m_t^2 + 2m_W^2)^2}$$

$$F_R = 0$$

Single top

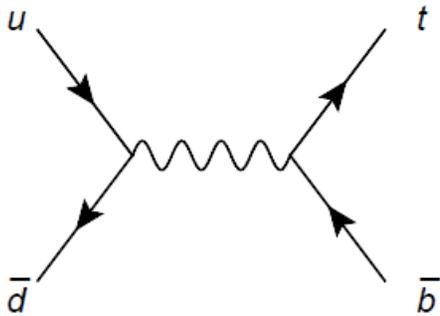


s channel



t channel

Single top

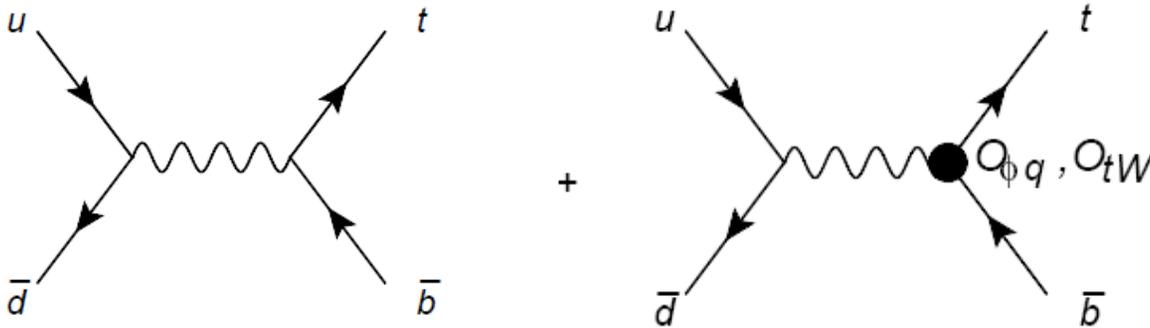


$$O_{tW} = (\bar{q}\sigma^{\mu\nu}\tau^I t)\tilde{\phi}W_{\mu\nu}^I \longrightarrow L_{eff} = i\frac{C_{tW}}{\Lambda^2}v(\bar{b}\sigma^{\mu\nu}(1+\gamma_5)t)\partial_\nu W_\mu^-$$

Cao, Wudka 2006

Cao, Wudka, Yuan 2007

Single top



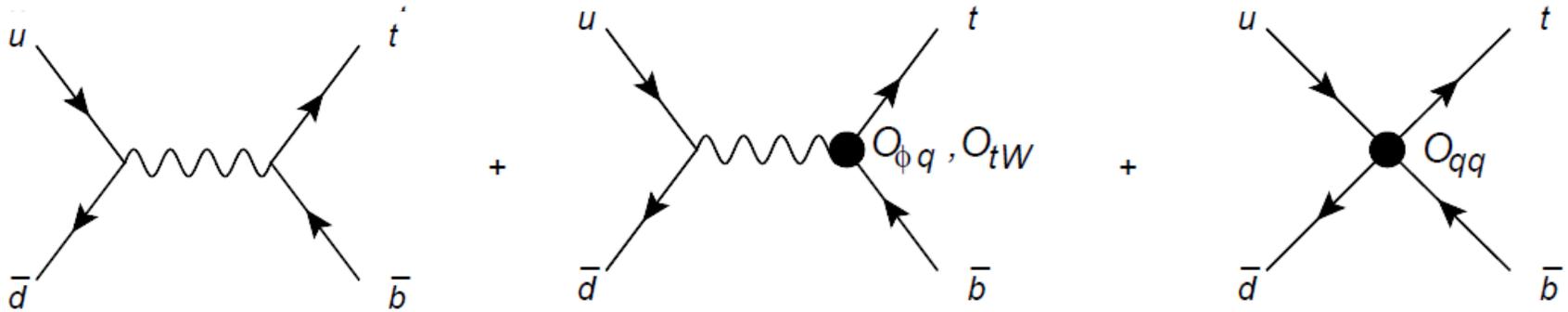
$$O_{tW} = (\bar{q}\sigma^{\mu\nu}\tau^I t)\tilde{\phi}W_{\mu\nu}^I \longrightarrow L_{eff} = i\frac{C_{tW}}{\Lambda^2}v(\bar{b}\sigma^{\mu\nu}(1+\gamma_5)t)\partial_\nu W_\mu^-$$

$$O_{\phi q} = i(\phi^+\tau^I D_\mu\phi)(\bar{q}\gamma^\mu\tau^I q) \longrightarrow L_{eff} = \frac{C_{\phi q}}{\Lambda^2}\frac{gv^2}{2\sqrt{2}}(\bar{b}\gamma^\mu(1-\gamma_5)t)W_\mu^-$$

Cao, Wudka 2006

Cao, Wudka, Yuan 2007

Single top



$$O_{tW} = (\bar{q}\sigma^{\mu\nu}\tau^I t)\tilde{\phi}W_{\mu\nu}^I \longrightarrow L_{eff} = i\frac{C_{tW}}{\Lambda^2}v(\bar{b}\sigma^{\mu\nu}(1+\gamma_5)t)\partial_\nu W_\mu^-$$

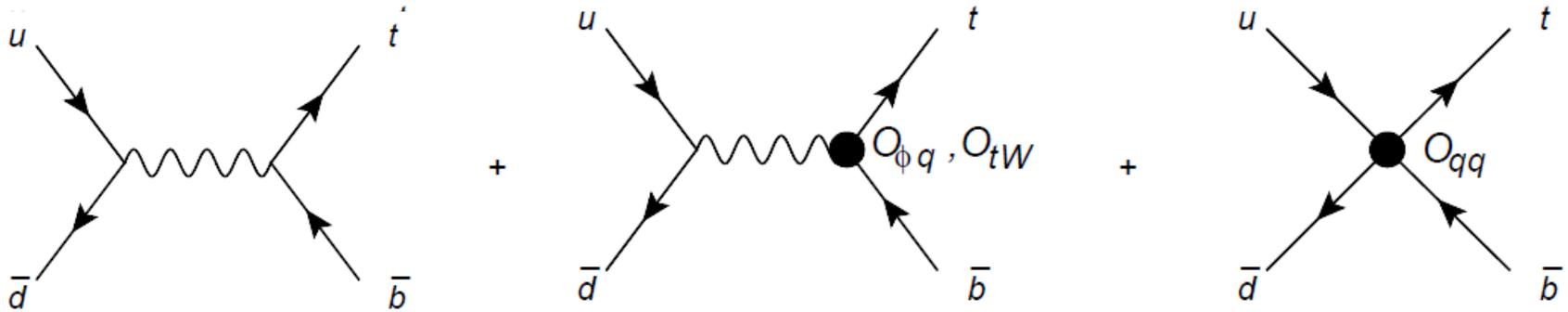
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$$O_{qq} = (\bar{q}^i\gamma_\mu\tau^I q^j)(\bar{q}\gamma^\mu\tau^I q)$$

Cao, Wudka 2006

Cao, Wudka, Yuan 2007

Single top



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$$O_{qq} = (\bar{q}^i\gamma_\mu\tau^I q^j)(\bar{q}\gamma^\mu\tau^I q)$$

Strategy:

O_{tW} from t decay

$O_{\phi q}$ O_{qq} from s-, t-channel single top:

Vertex function approach

Kane, Ladinsky, Yuan 1992

Aguilar-Saavedra 2008, 2009

Vertex function approach

Kane, Ladinsky, Yuan 1992

Aguilar-Saavedra 2008, 2009

- **General form of Wtb vertex:**

$$\Gamma_{Wtb}^\mu = -\frac{g}{\sqrt{2}} V_{tb} \left\{ \gamma^\mu [f_1^L P_L + f_1^R P_R] - \frac{i\sigma^{\mu\nu}}{M_W} (p_t - p_b)_\nu [f_2^L P_L + f_2^R P_R] \right\}$$

Vertex function approach

Kane, Ladinsky, Yuan 1992

Aguilar-Saavedra 2008, 2009

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Form factors: functions of Q^2

Vertex function approach

Kane, Ladinsky, Yuan 1992

Aguilar-Saavedra 2008, 2009

■ General form of Wtb vertex:

$$\Gamma_{Wtb}^\mu = -\frac{g}{\sqrt{2}} \cancel{V_{tb}} \left\{ \gamma^\mu [f_1^L P_L + f_1^R P_R] - \frac{i\sigma^{\mu\nu}}{M_W} (p_t - p_b)_\nu [f_2^L P_L + f_2^R P_R] \right\}$$

Effective field theory $V_{tb} + C_{\phi q} \frac{v^2}{\Lambda^2}$

$\sqrt{2}C_{tW} \frac{v^2}{\Lambda^2}$

Vertex function approach

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Effective field theory $V_{tb} + C_{\phi q} \frac{v^2}{\Lambda^2}$

$\sqrt{2}C_{tW} \frac{v^2}{\Lambda^2}$

contribute only at $\mathcal{O}(m_b)$ and $\mathcal{O}(1/\Lambda^4)$

Vertex function approach

Kane, Ladinsky, Yuan 1992

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Effective field theory $V_{tb} + C_{\phi q} \frac{v^2}{\Lambda^2}$

$\sqrt{2}C_{tW} \frac{v^2}{\Lambda^2}$

contribute only at $\mathcal{O}(m_b)$ and $\mathcal{O}(1/\Lambda^4)$

Effective field theory approach provides rationale for neglecting some f 's, setting others to constants

Effective field theory

Vertex function approach

- Well motivated and provides guidance
- $SU(3) \times SU(2) \times U(1)$ gauge invariant
- Includes contact interactions
- Valid for top and bottom off shell
- Can calculate radiative corrections

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Yes

No

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Yes

No

Yes

No

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Yes

No

Yes

No

Yes

No

Yes

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No

Effective field theory

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Yes

No

Yes

No

Yes

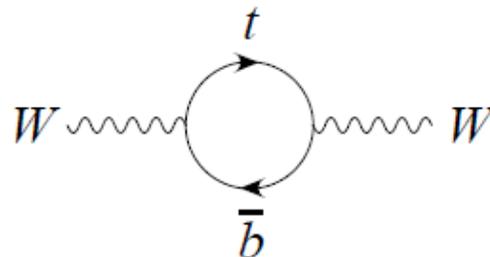
No

Yes

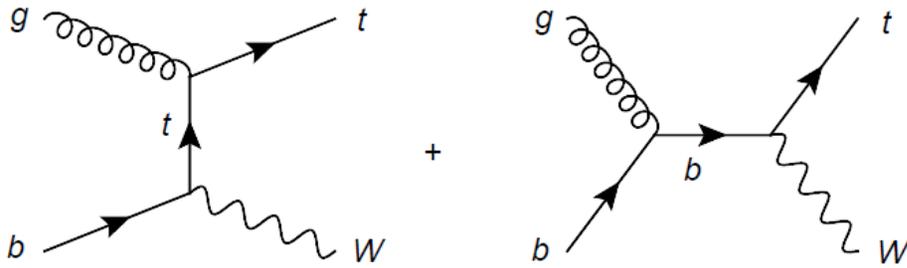
No

Yes

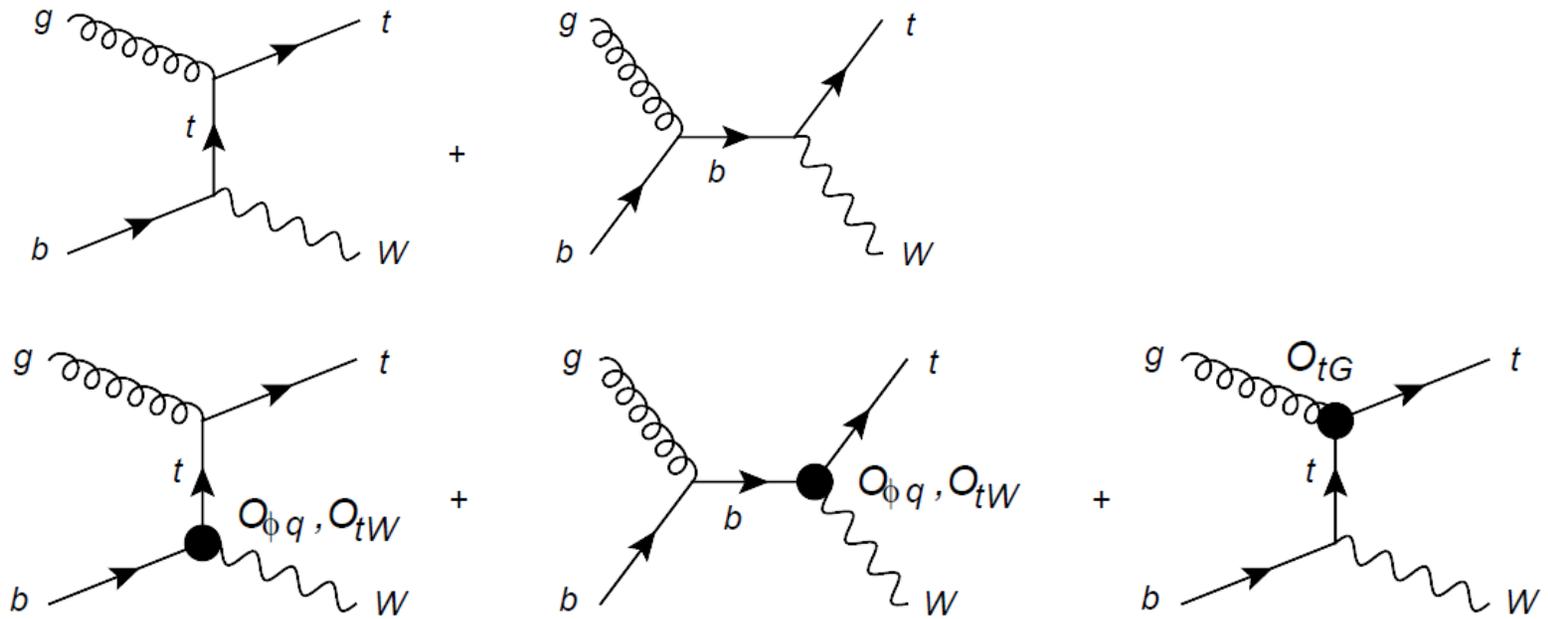
No



Wt production

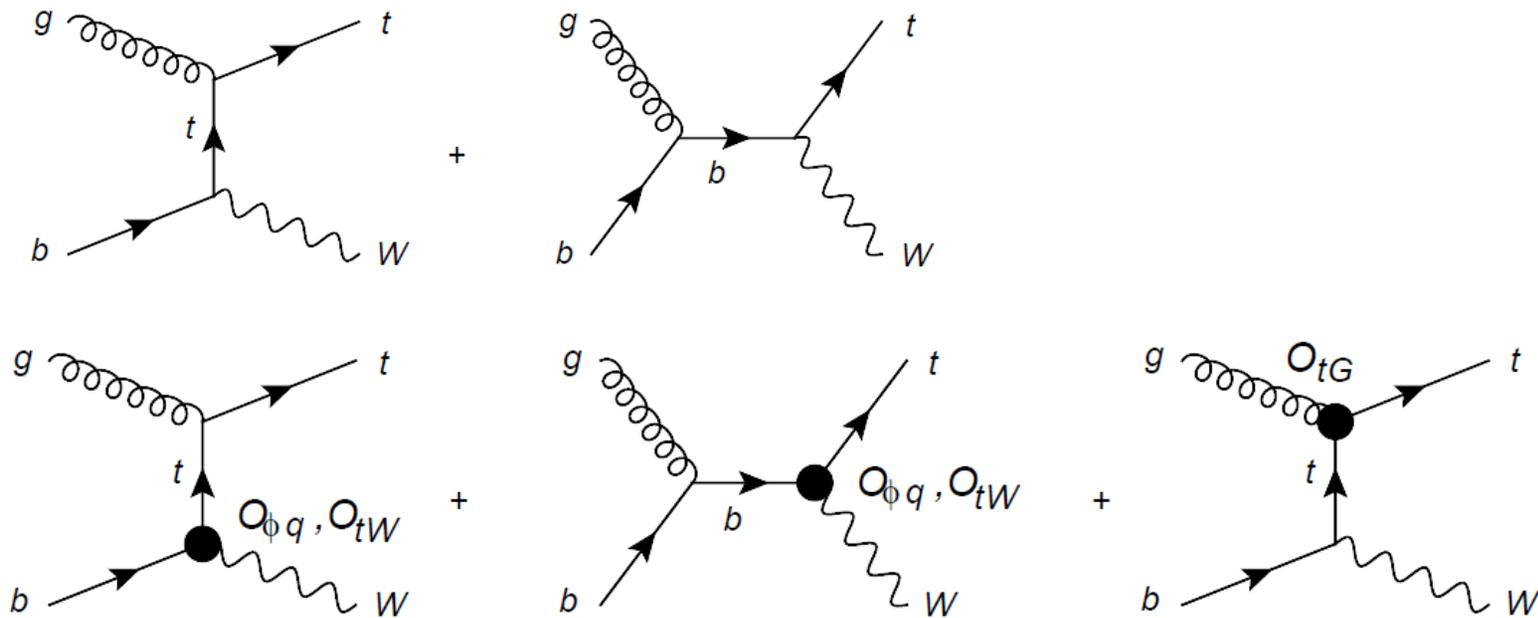


Wt production



$$O_{tG} = (\bar{q}\sigma^{\mu\nu}\lambda^A t)\tilde{\phi}G_{\mu\nu}^A + h.c.$$

Wt production



Strategy:

O_{tW}

from t decay

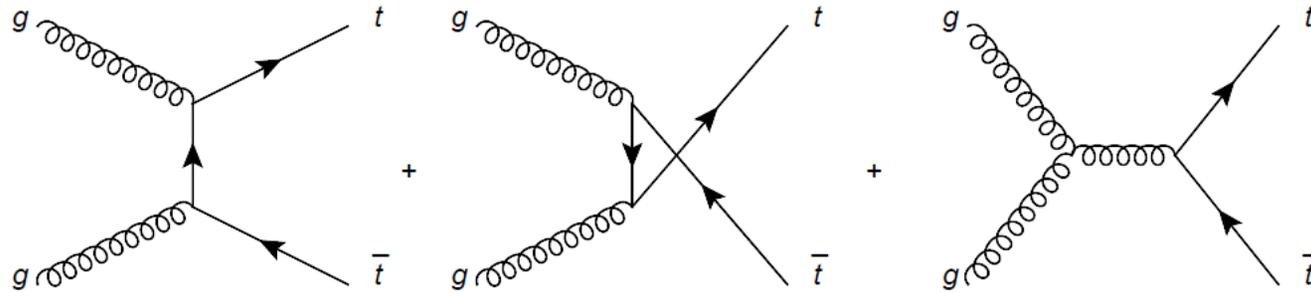
$O_{\phi q}$ O_{qq}

from s-, t-channel single top

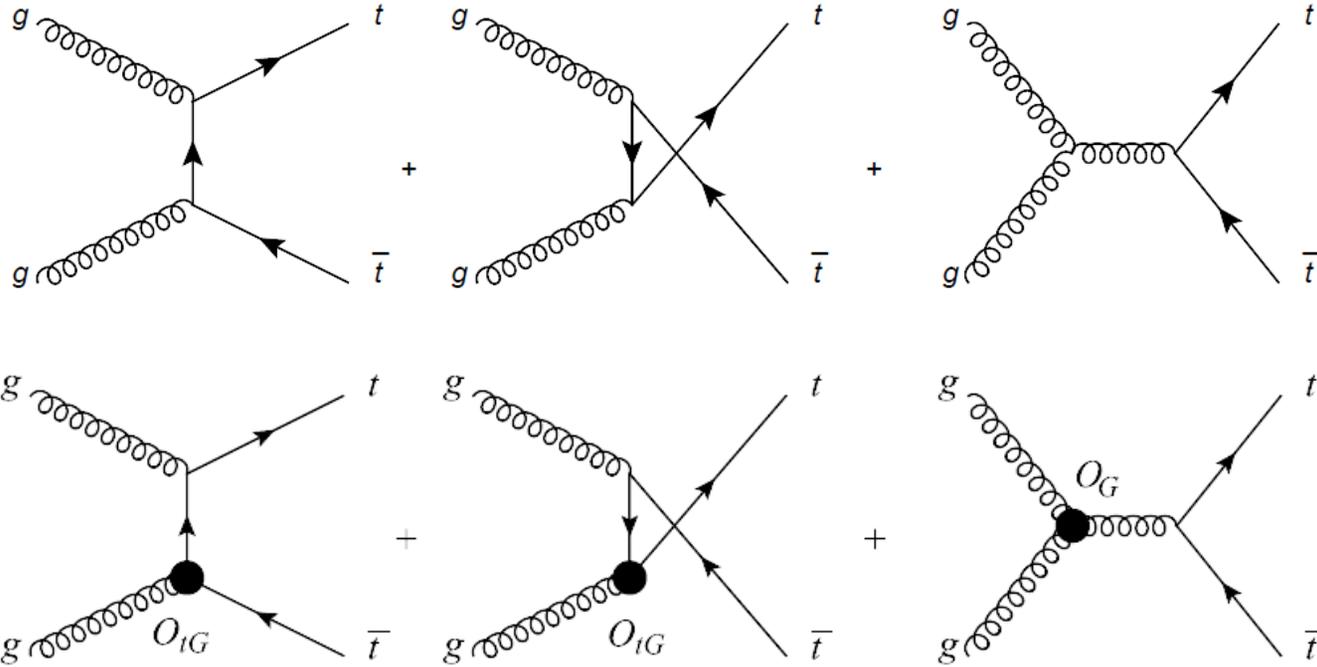
O_{tG}

from Wt

Top pair production

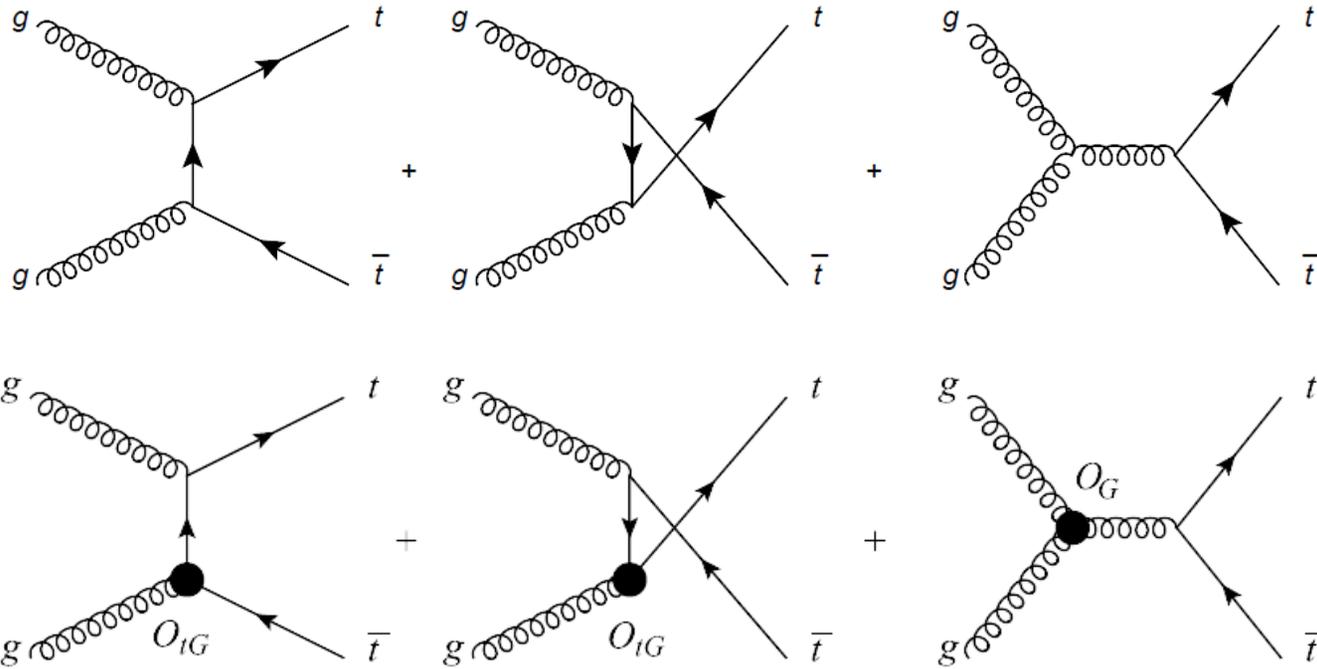


Top pair production



$$O_G = f_{ABC} G_{\mu}^{A\nu} G_{\nu}^{B\rho} G_{\rho}^{C\mu}$$

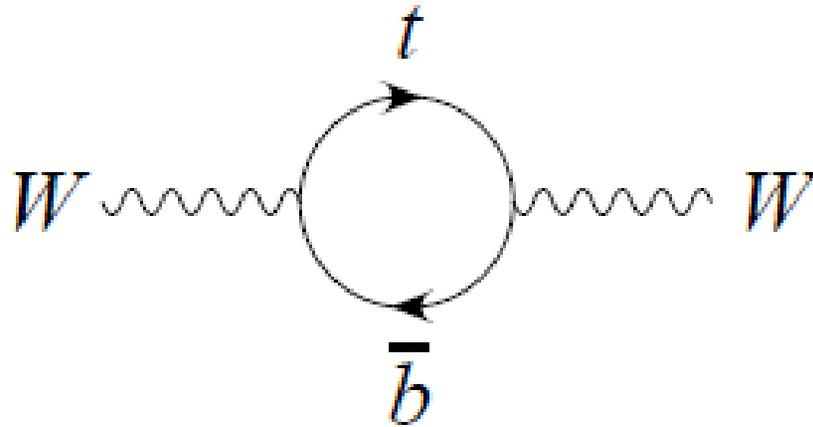
Top pair production



Strategy:

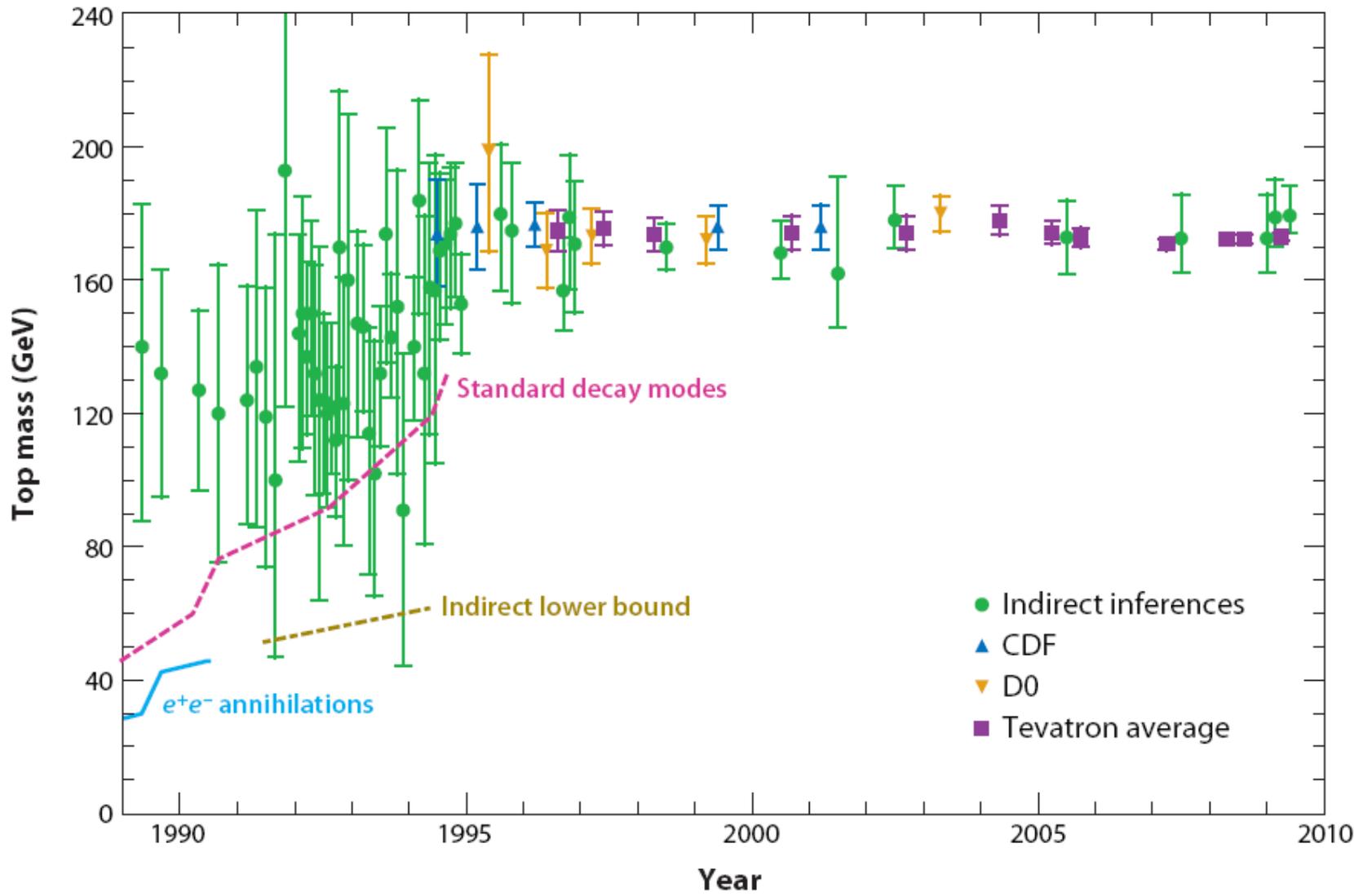
O_{tW} from t decay
 $O_{\phi q}$ O_{qq} from s-, t-channel single top
 O_{tG} from Wt
 O_G from $t\bar{t}$

Virtual Top



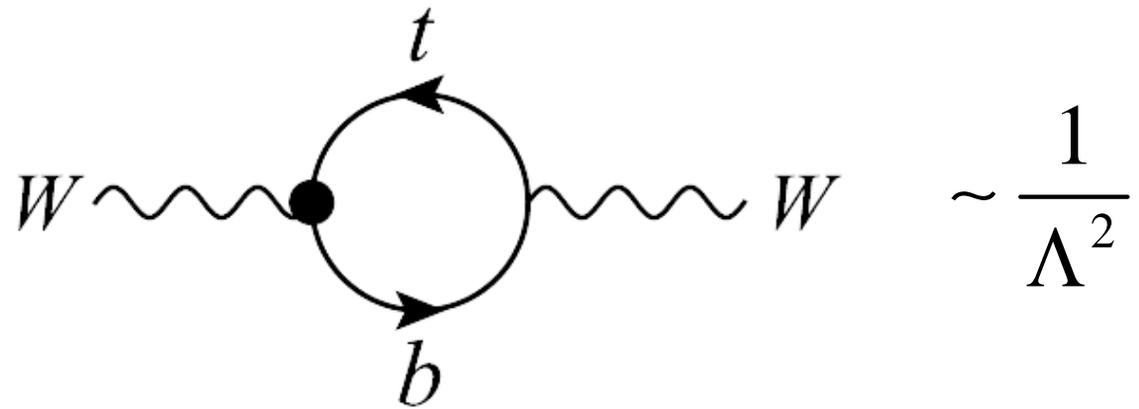
Nick Greiner, Cen Zhang, and SW

in progress

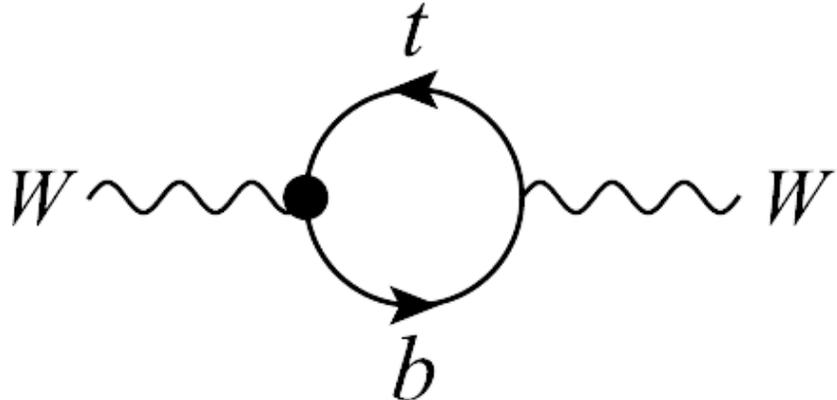


Quigg

Virtual Top

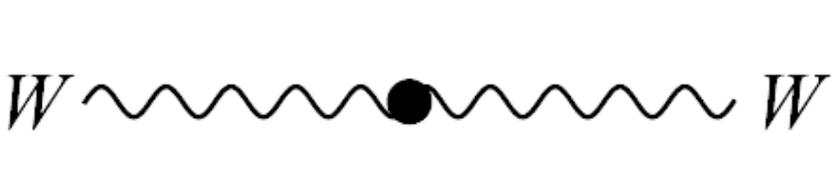


Virtual Top



A Feynman diagram showing two external wavy lines labeled W connected by a circular loop. The top arc of the loop is labeled t with an arrow pointing clockwise, and the bottom arc is labeled b with an arrow pointing clockwise. A black dot is located on the left W line where it meets the loop.

$$\sim \frac{1}{\Lambda^2}$$



A Feynman diagram showing two external wavy lines labeled W connected by a single black dot, representing a contact interaction.

$$\sim \frac{1}{\Lambda^2}$$

Conclusion

- Effective field theory is the ideal way to parameterize unknown physics at “low” energy
 - Well motivated, provides guidance
 - Incorporates gauge invariance
 - Includes contact interactions
 - Valid for real or virtual top
 - Allows for unambiguous loop calculations

Conclusion

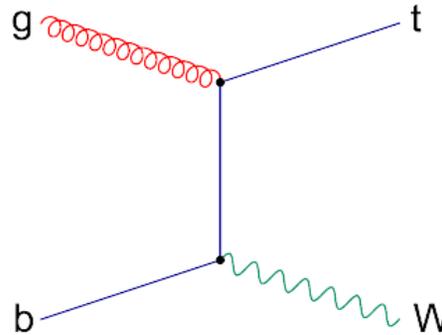
- We intend to add all 59 dim 6 operators to Madgraph.
 - Top physics
 - WW physics
 - Higgs physics
 - ...

Single top production

Tevatron

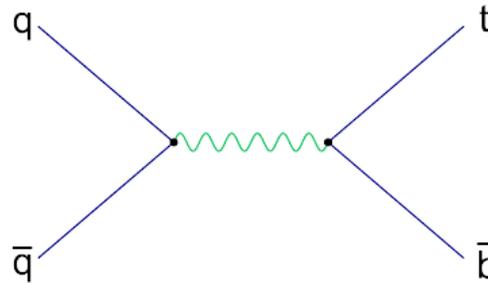
LHC

Wt associated



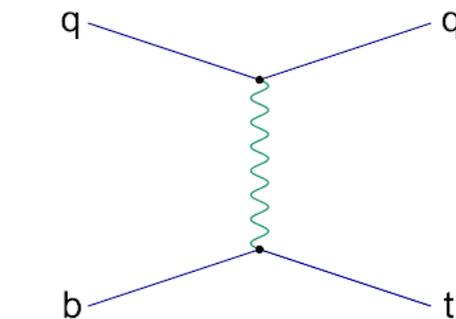
0.15 pb 70 pb

s-channel single top



0.9 pb 10.6 pb

t-channel single top



2.0 pb 240 pb