Effective Field Theory for Top and Weak Boson Physics

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Why study top and weak boson properties?

1. Measure fundamental parameters

   m_t, M_W

2. Search for physics beyond the SM

   Deviations from standard model predictions

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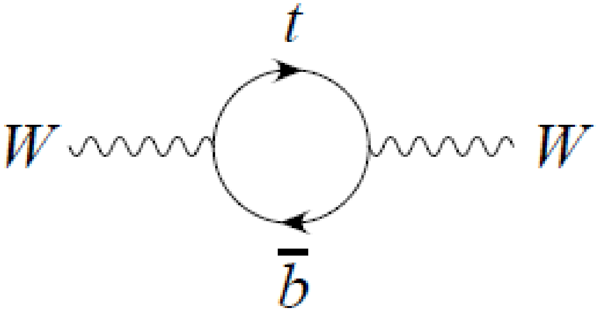

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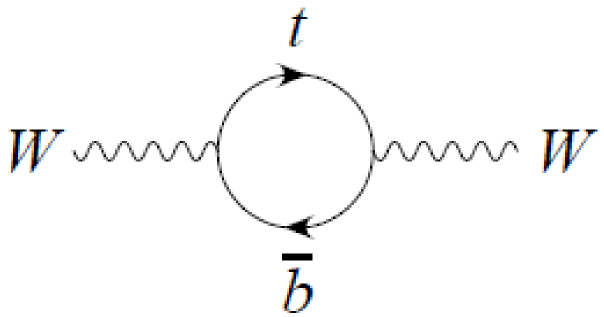

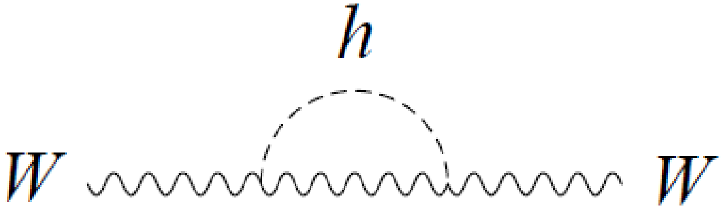

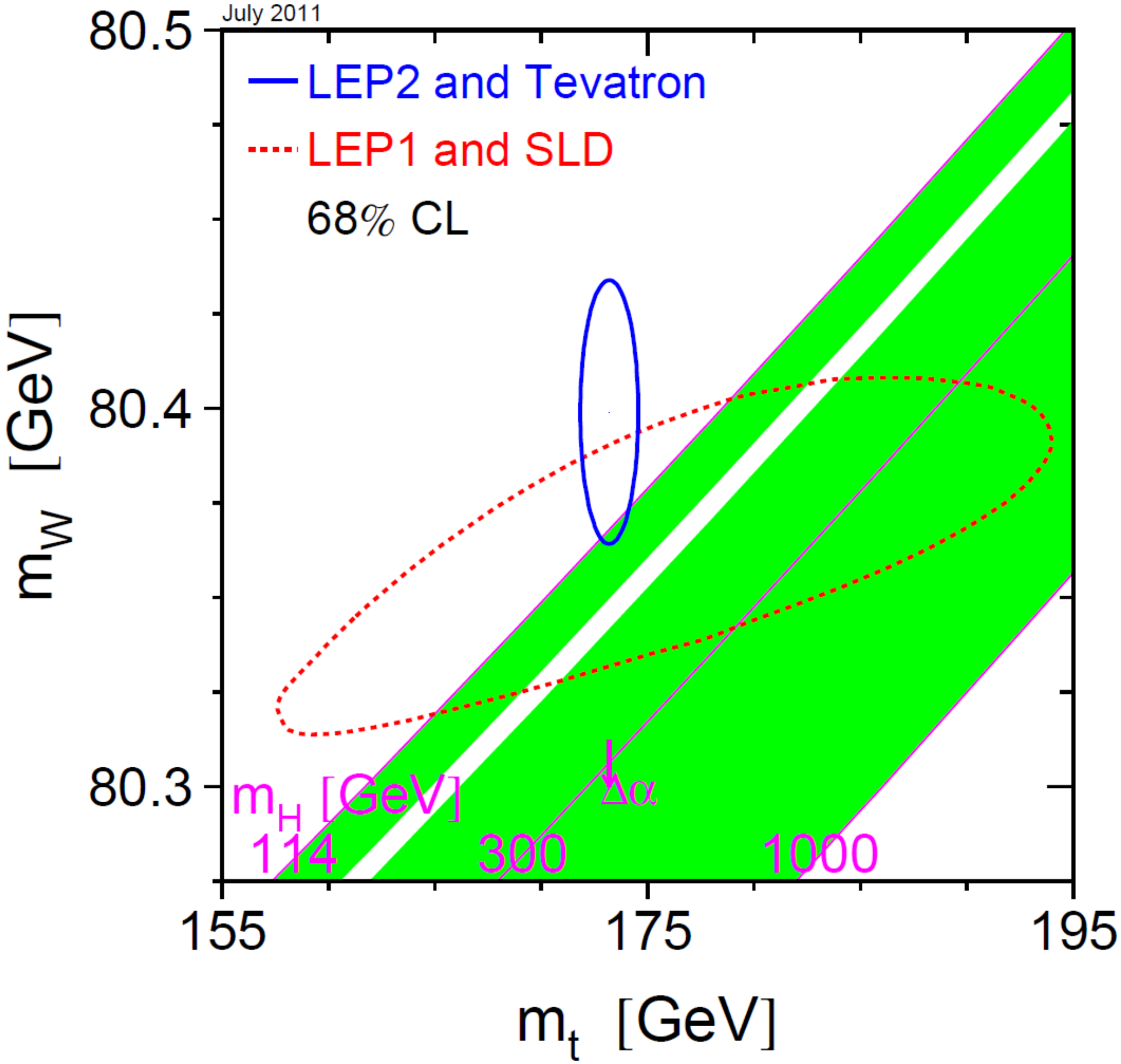
July 2011
LEP2 and Tevatron
LEP1 and SLD
68% CL
80.5
80.4
80.3
m_W [GeV]
m_H [GeV]
114
300
1000
Δα
155
175
195
m_t [GeV]

LEPEWWG

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   How should we think about this?

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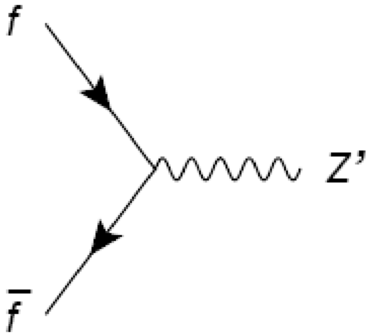
   Deviations from standard model predictions

   How should we think about this?

   Effective Field Theory


SM
New Physics
Energy
Λ

Example: Z’ boson



SM

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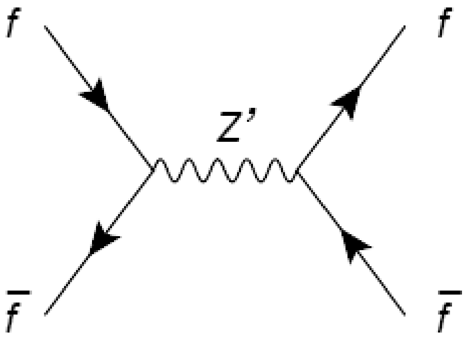

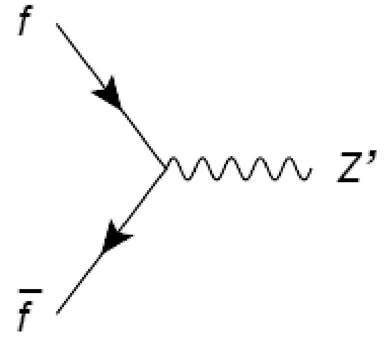

SM

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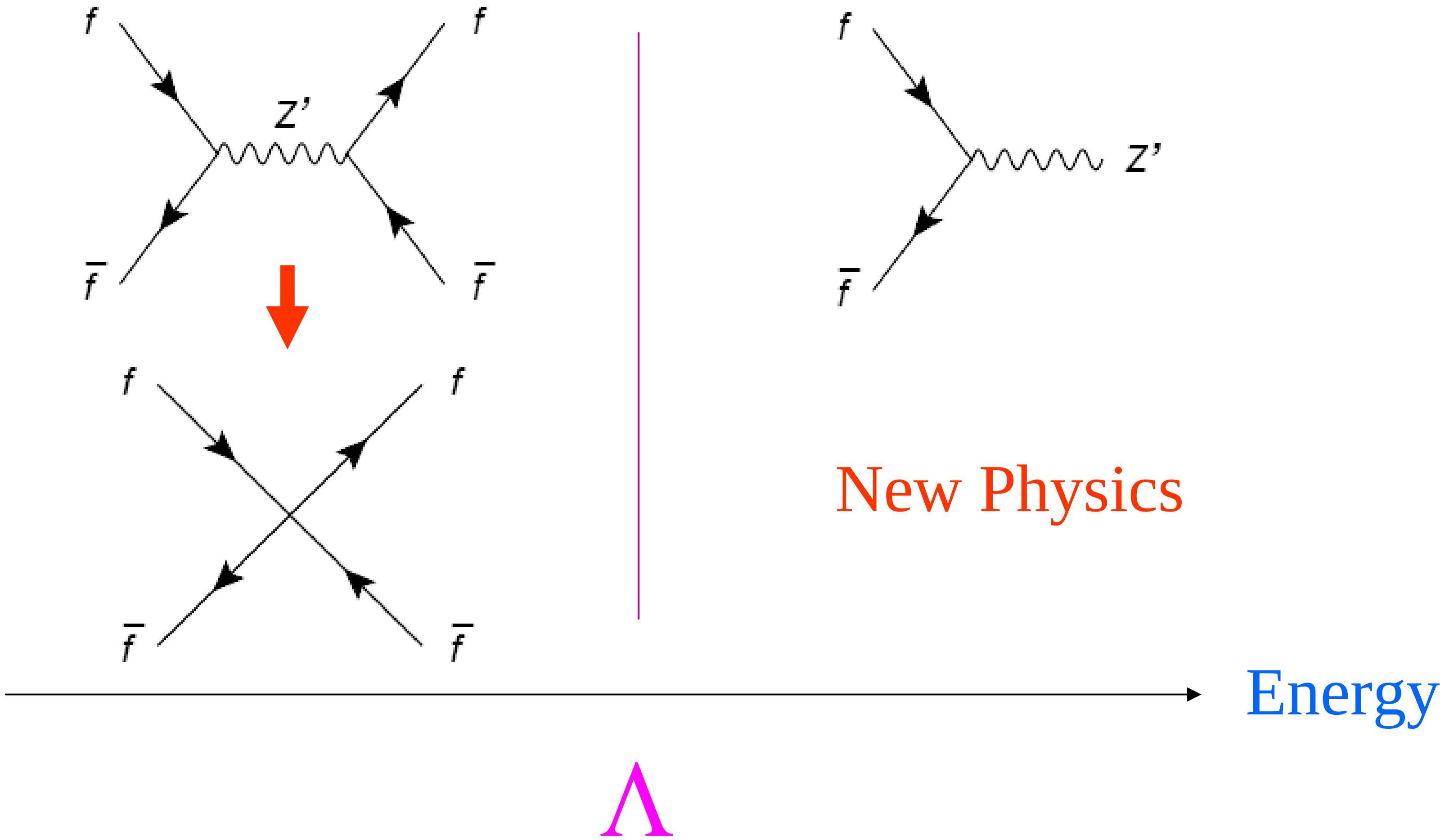

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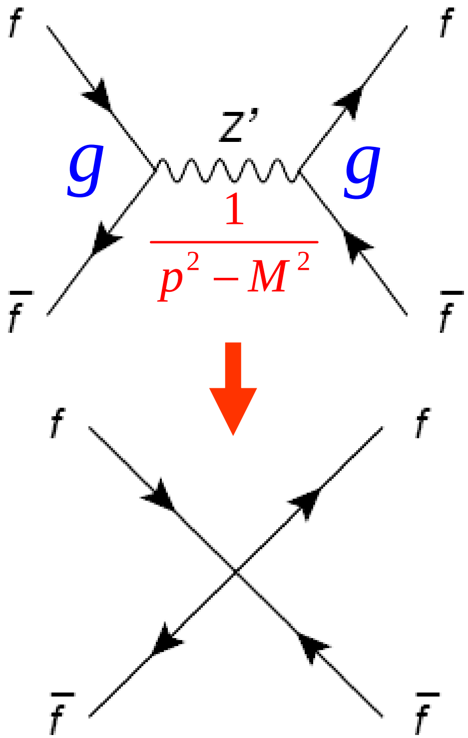
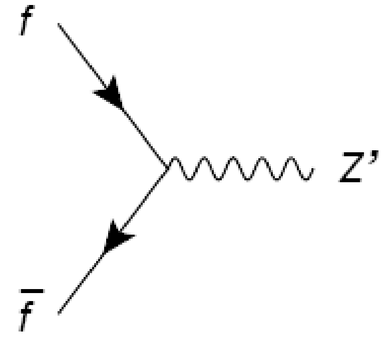


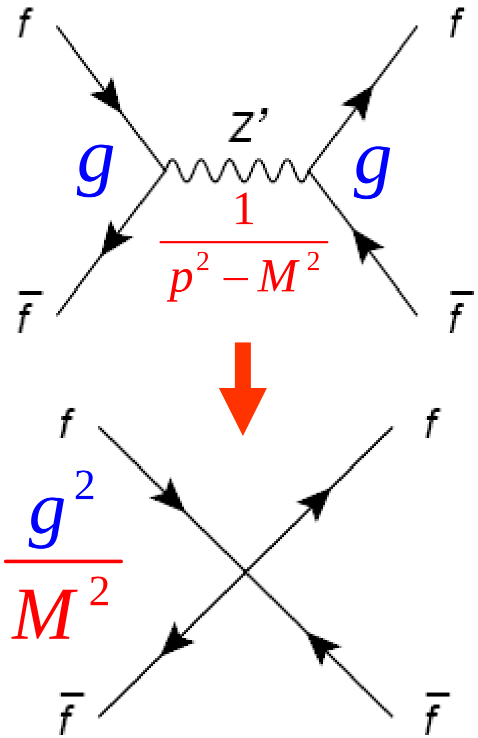


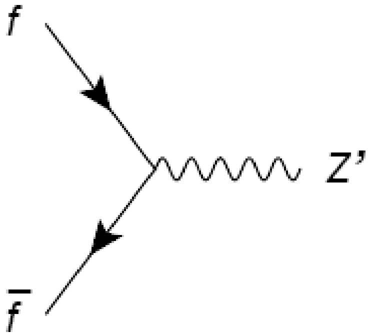
New Physics

Energy

$$\Lambda = M$$

Example: Z’ boson





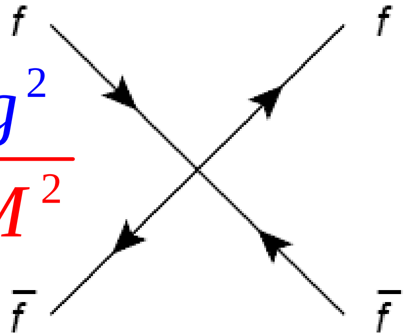
New Physics

Energy

$$\Lambda = M$$

Example: Z’ boson

$$\frac{g^2}{M^2}$$



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

Dimensional analysis

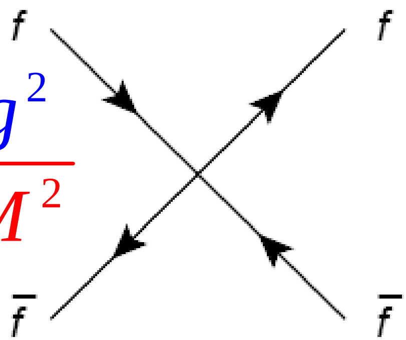
$$\hbar = c = 1$$

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

$$\dim \phi = 1$$

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

$$\frac{g^2}{M^2}$$



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

$$\dim = \quad \leq 4 \qquad\qquad 6$$

Dimensional analysis

$$\hbar = c = 1$$

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

$$\dim \phi = 1$$

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

$$\dim = \qquad \leq 4 \qquad\qquad 6$$

Dimensional analysis

$$\hbar = c = 1$$

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

Weinberg 1979

$$\dim = \quad \leq 4 \qquad\qquad 6$$

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

$$\dim = \quad \leq 4 \qquad\qquad 6$$

Good news: only a few operators contribute to top and weak boson physics

Leung, Love, Rao 1984
Buchmuller, Wyler 1986

Bad news: 59 operators

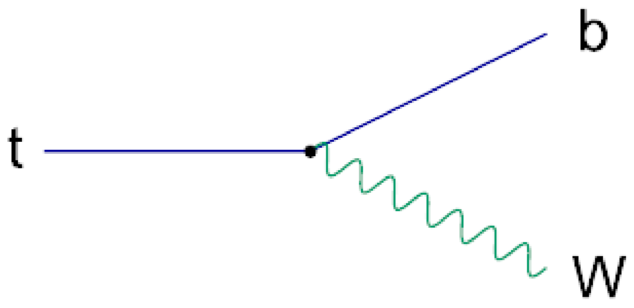
Effective Field Theory

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

Weinberg 1979

$$\text{dim} = \quad \leq 4 \quad\quad 6$$

Top decay



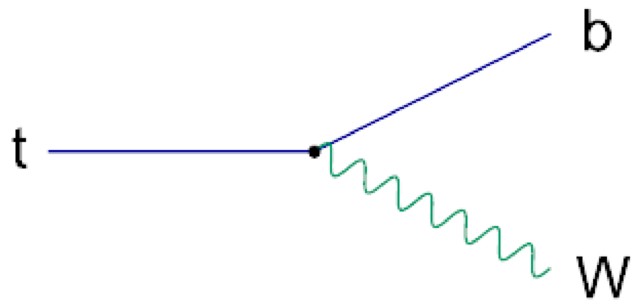
$$f_0 = \frac{m_t^2}{m_t^2 + 2M_W^2} = 0.7$$

$$f_- = \frac{m_t^2}{m_t^2 + 2M_W^2} = 0.3$$

$$f_+ = 0$$

$m_b = 0$

Top decay



$$
\begin{aligned}
O_{tW} &= (\bar{q}\sigma^{\mu\nu}\tau^I t)\tilde{\phi}W^I_{\mu\nu}
\end{aligned}
$$

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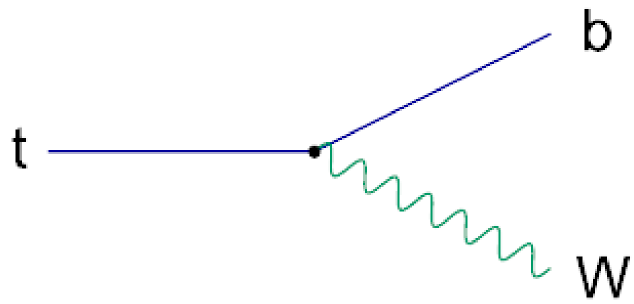
Top decay



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

$$f_0 = \frac{m_t^2}{m_t^2 + 2m_W^2}$$

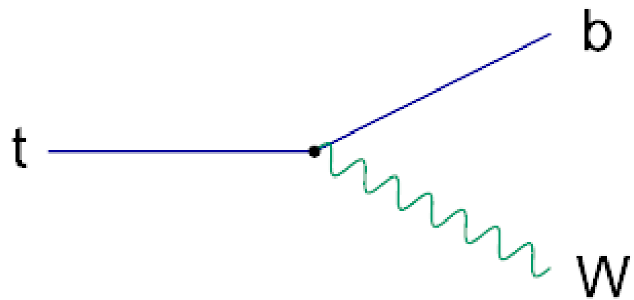
$$f_- = \frac{2m_W^2}{m_t^2 + 2m_W^2}$$

$$f_+ = 0$$

Zhang and SW

Aguilar-Saavedra et al.

Top decay



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$$f_0 = \frac{m_t^2}{m_t^2+2m_W^2} - \frac{4\sqrt{2}C_{tW}v^2}{\Lambda^2}\frac{m_t m_W(m_t^2-m_W^2)}{(m_t^2+2m_W^2)^2}$$

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

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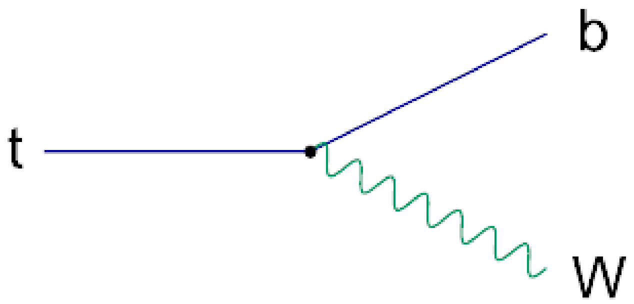

CDF + D0

$$f_0 = 0.685 \pm 0.035\,(\mathrm{stat}) \pm 0.045\,(\mathrm{syst})$$

$$f_0 = \frac{m_t^2}{m_t^2 + 2m_W^2} - \frac{4\sqrt{2}C_{tW}v^2}{\Lambda^2}\frac{m_t m_W (m_t^2 - m_W^2)}{(m_t^2 + 2m_W^2)^2}$$

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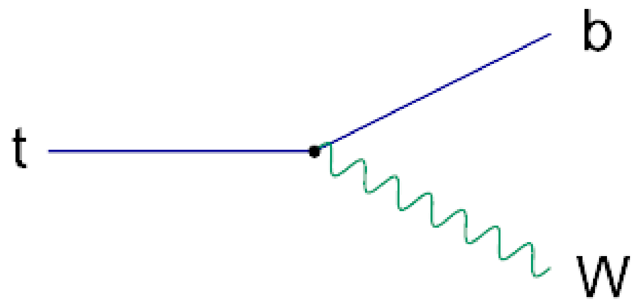

CDF + D0

$$f_0 = 0.685 \pm 0.035\,(\mathrm{stat}) \pm 0.045\,(\mathrm{syst}) \longrightarrow \frac{C_{tW}}{\Lambda^2} = 0.03 \pm 0.94\ \mathrm{TeV}^{-2}$$

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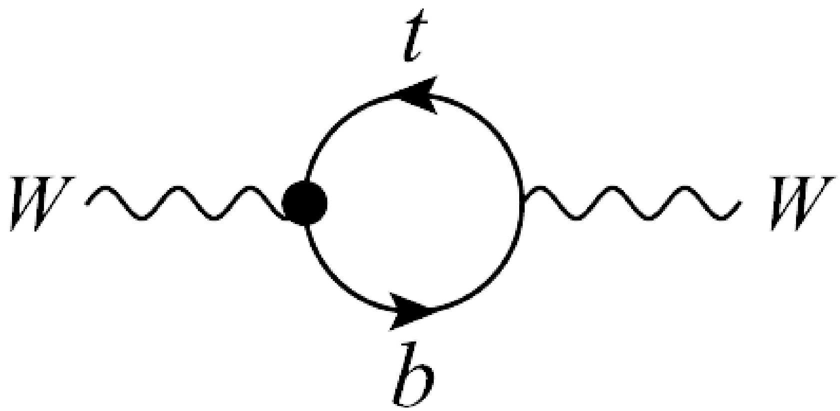
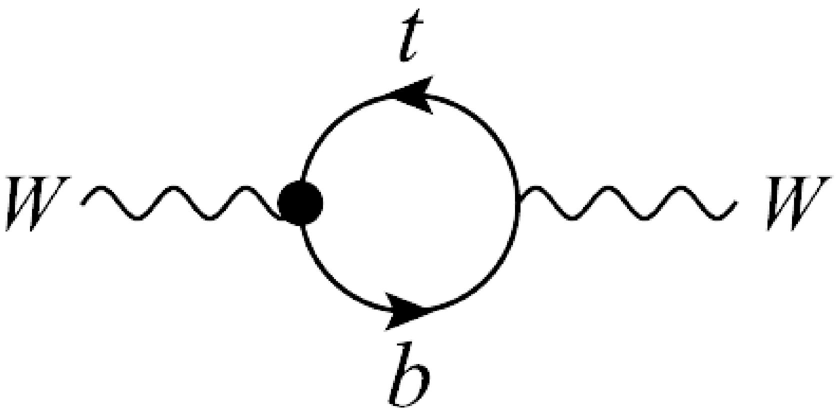
Virtual Top



Greiner, Zhang, SW

Virtual Top

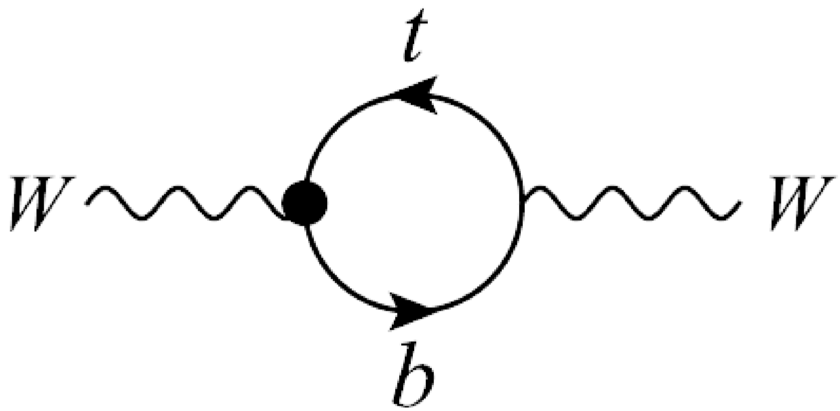


$$\hat{U} = N_c \frac{g C_{tW}}{4\pi^2} \frac{\sqrt{2} v m_t}{4\Lambda^2}$$

Barbieri, Pomarol, Rattazzi, Strumia

Greiner, Zhang, SW

Virtual Top



$$\hat{U} = N_c \frac{g C_{tW}}{4\pi^2} \frac{\sqrt{2} v m_t}{4\Lambda^2}$$

$$\hat{U} = (-5.0 \pm 8.4) \times 10^{-4} \longrightarrow \frac{C_{tW}}{\Lambda^2} = -0.7 \pm 1.1 \text{ TeV}^{-2}$$

Barbieri, Pomarol, Rattazzi, Strumia

Top dim 6 operators

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

Zhang and SW

$$O_{\phi q} = i(\phi^+\tau^I D_\mu\phi)(\bar{q}\gamma^\mu\tau^I q)$$

Degrande, Gerard, Grojean, Maltoni, Servant

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

Aguilar-Saavedra et al.

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

Cao, Wudka, Yuan

Grzadkowski et al.

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

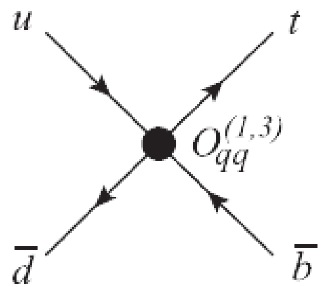
Cho and Simmons

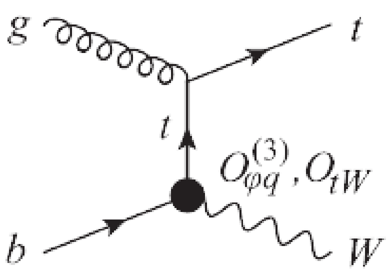
Strategy:

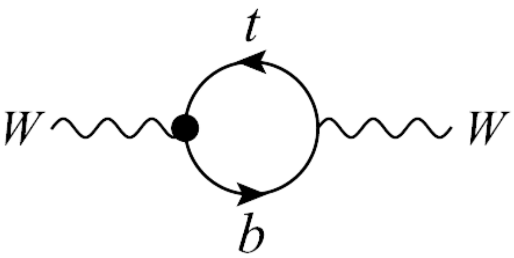
O_{tW}	from t decay
$O_{\phi q}$ O_{qq}	from s-, t-channel single top
O_{tG}	from Wt
O_G	from tt

Effective field theory

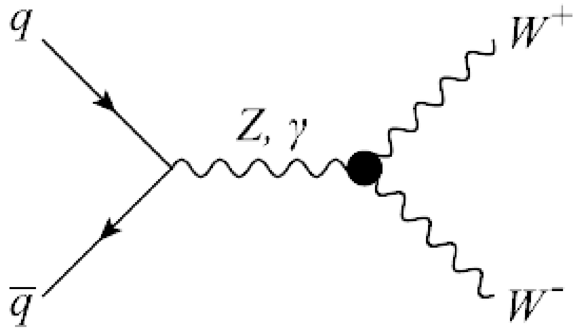
- Well motivated and provides guidance
- SU(3)xSU(2)xU(1) gauge invariant
- Includes contact interactions
- Valid for top and bottom off shell
- Can calculate radiative corrections



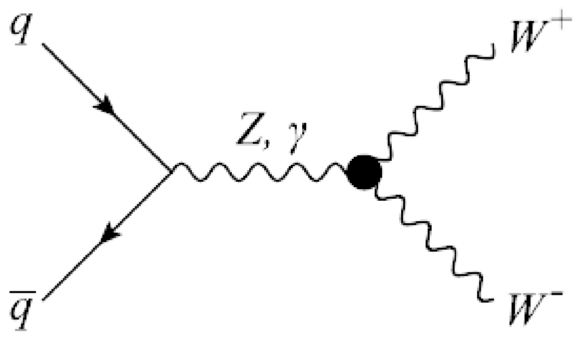




Weak boson pair production



Weak boson pair production



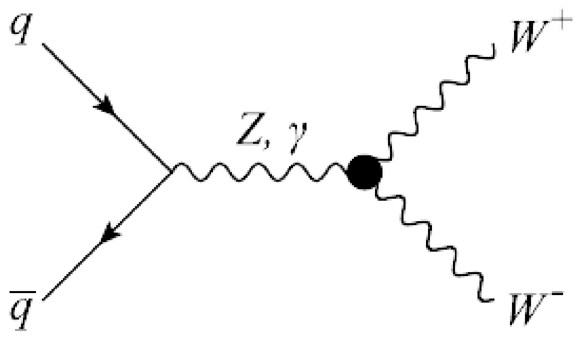
Hagiwara, Isihara, Szalapski, Zeppenfeld

Wudka

$$
\begin{aligned}
\mathcal{O}_{WWW} &= \mathrm{Tr}[W_{\mu\nu}W^{\nu\rho}W_{\rho}^{\mu}] \\
\mathcal{O}_{W} &= (D_\mu\Phi)^\dagger W^{\mu\nu}(D_\nu\Phi) \\
\mathcal{O}_{B} &= (D_\mu\Phi)^\dagger B^{\mu\nu}(D_\nu\Phi)
\end{aligned}
$$

C and P conserving

Weak boson pair production



Hagiwara, Isihara, Szalapski, Zeppenfeld

Wudka

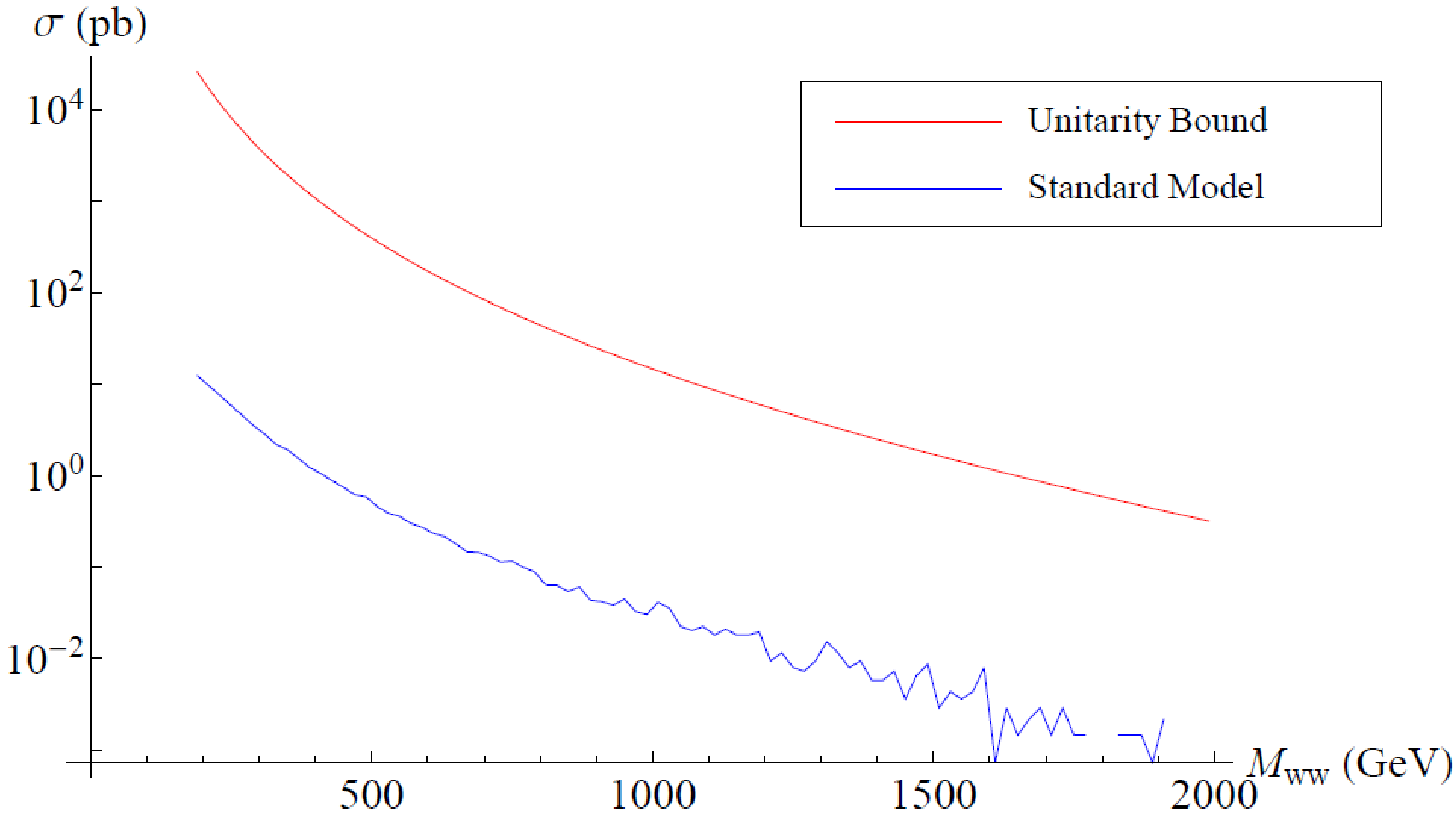
$$\begin{aligned}\mathcal{O}_{WWW} &= \mathrm{Tr}[W_{\mu\nu}W^{\nu\rho}W_{\rho}^{\mu}] \\ \mathcal{O}_{W} &= (D_\mu\Phi)^\dagger W^{\mu\nu}(D_\nu\Phi) \\ \mathcal{O}_{B} &= (D_\mu\Phi)^\dagger B^{\mu\nu}(D_\nu\Phi)\end{aligned}$$

C and P conserving

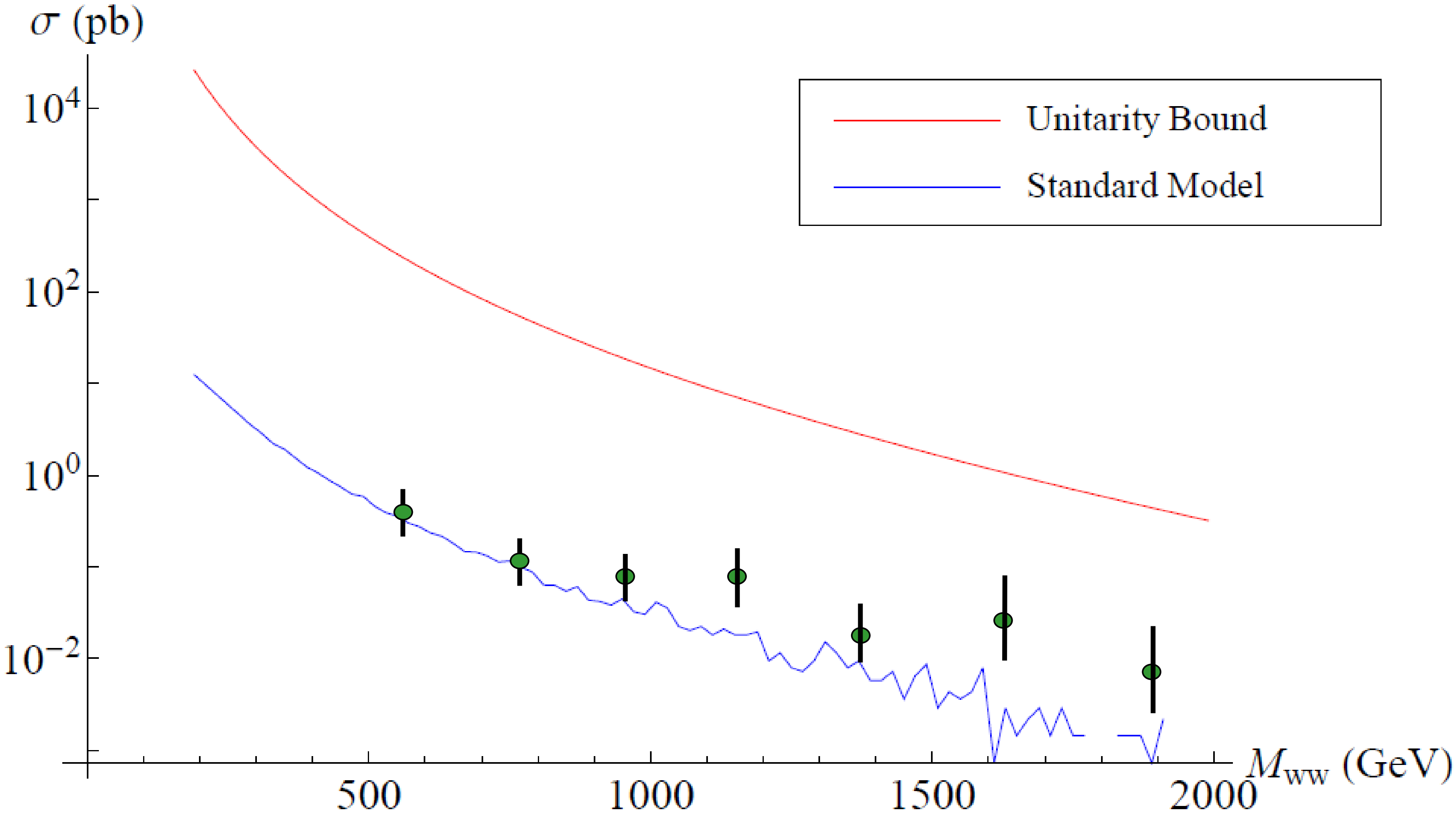
$$\begin{aligned}\mathcal{O}_{\tilde{W}WW} &= \mathrm{Tr}[\tilde{W}_{\mu\nu}W^{\nu\rho}W_{\rho}^{\mu}] \\ \mathcal{O}_{\tilde{W}} &= (D_\mu\Phi)^\dagger \tilde{W}^{\mu\nu}(D_\nu\Phi)\end{aligned}$$

C and/or P violating

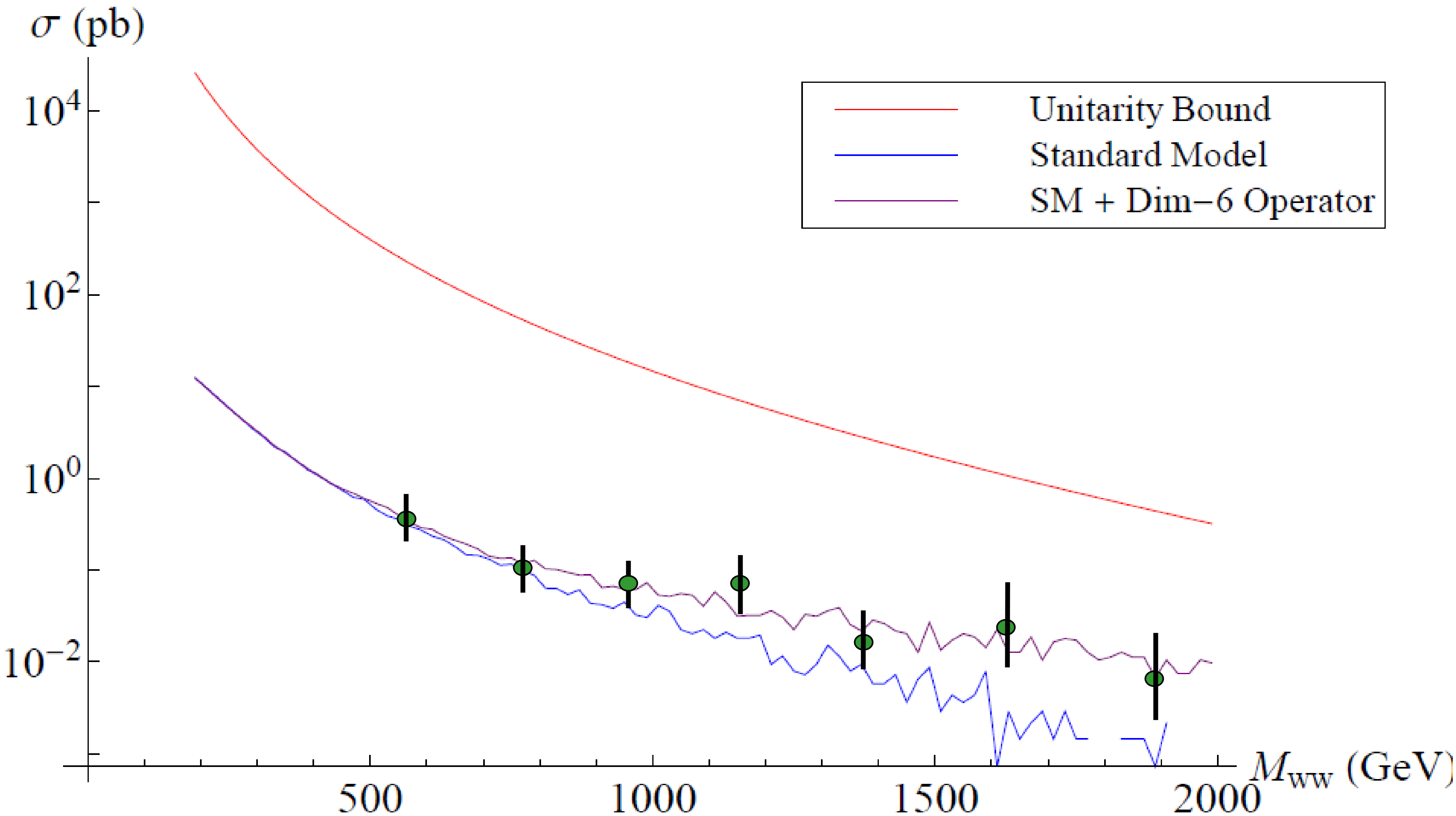
$pp \rightarrow WW$



pp ⟶ WW


σ (pb)
10^4
10^2
10^0
10^{-2}
Unitarity Bound
Standard Model
500
1000
1500
2000
M_{WW} (GeV)

pp → WW



σ (pb)
10^4
10^2
10^0
10^{-2}
Unitarity Bound
Standard Model
SM + Dim−6 Operator
500
1000
1500
2000
M_{WW} (GeV)

Relationship to anomalous couplings

$$
\begin{aligned}
g_1^Z &= 1 + c_W \frac{m_Z^2}{2\Lambda^2} \\
\kappa_\gamma &= 1 + (c_W + c_B)\frac{m_W^2}{2\Lambda^2} \\
\kappa_Z &= 1 + (c_W - c_B \tan^2\theta_W)\frac{m_W^2}{2\Lambda^2} \\
\lambda_\gamma &= \lambda_Z = c_{WWW}\frac{3g^2 m_W^2}{2\Lambda^2}
\end{aligned}
$$

Hagiwara, Isihara, Szalapski, Zeppenfeld

Wudka

1. Three parameters instead of five

   c_W, c_B, c_{WWW} (C and P conserving)

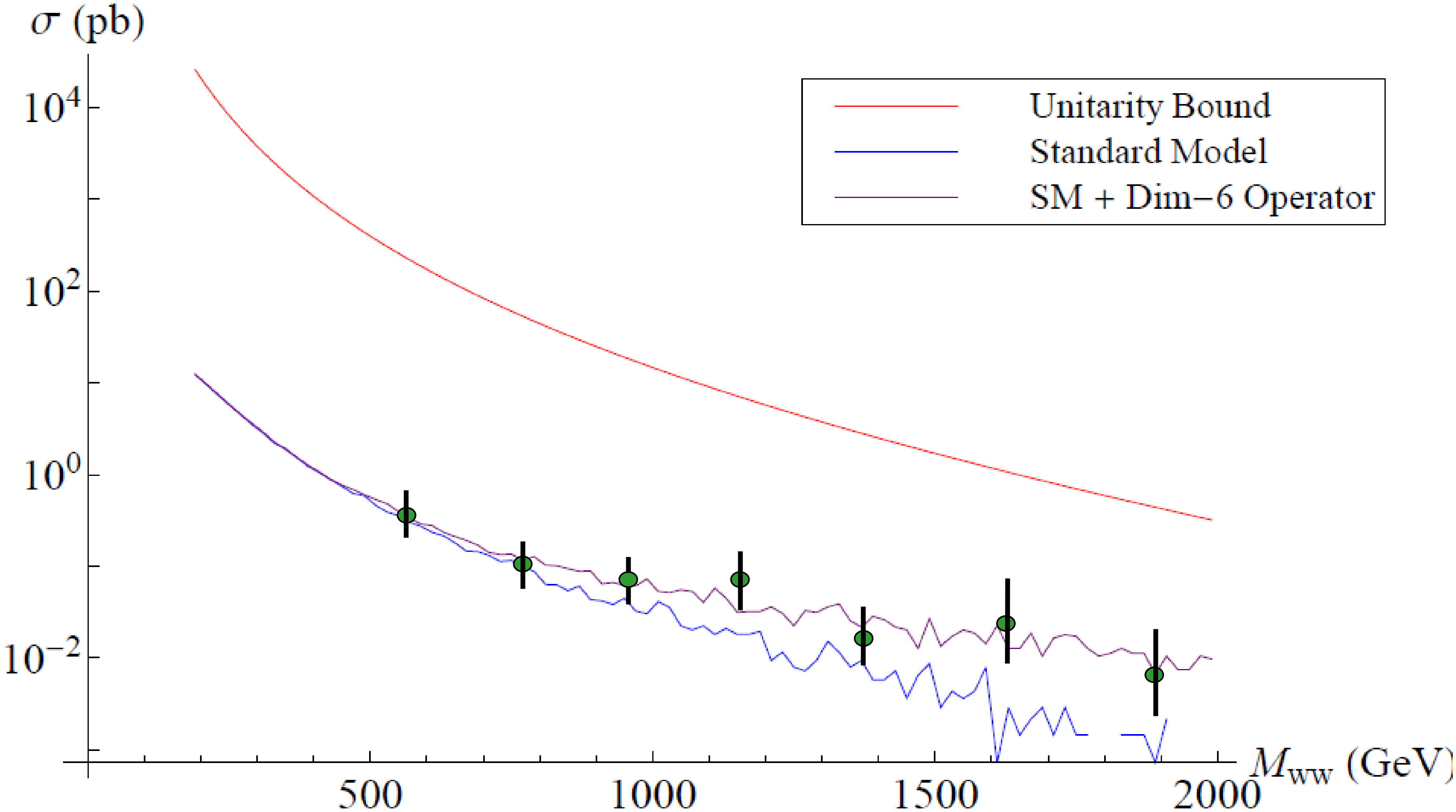
2. All parameters are constants

   Independent of energy

What about unitarity bounds?

1. Data respect unitarity bounds
   - Physical requirement
2. A theory that fits the data will also respect unitarity bounds
   - Effective theory is intended to describe data

pp → WW



σ (pb)
10^4
10^2
10^0
10^−2
Unitarity Bound
Standard Model
SM + Dim−6 Operator
500
1000
1500
2000
M_WW (GeV)

What about unitarity bounds?

1. Data respect unitarity bounds

   Physical requirement

2. A theory that fits the data will also respect unitarity bounds

   Effective theory is intended to describe data

Unitarity is irrelevant

Degrande et al.

Wudka

No need for form factors

Conclusion

- Effective field theory is the ideal way to parameterize unknown physics at “low” energy
  - Well motivated, provides guidance, systematic
  - Incorporates gauge symmetry
  - Includes contact interactions
  - Valid for real or virtual particles
  - Allows for unambiguous loop calculations
- No need for form factors in WW physics
  - Unitarity bound is automatically satisfied

Conclusion

- We are putting all 59 dim 6 operators into Madgraph 5.
  - Top physics
  - WW physics
  - Higgs physics
  - …
- Contact Celine Degrande

  cdegrand@illinois.edu

Vertex function approach

Kane, Ladinsky, Yuan 1992

- **General form of *Wtb* vertex:**

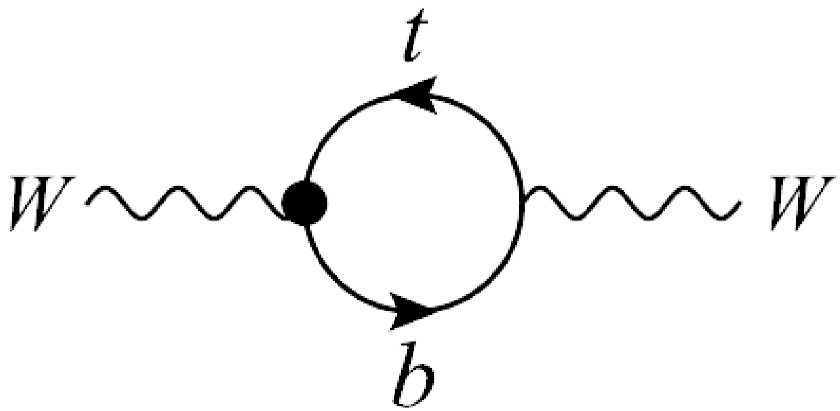
$$\Gamma^{\mu}_{Wtb} = -\frac{g}{\sqrt{2}} V_{tb} \left\{ \gamma^{\mu} \left[f_1^L P_L + f_1^R P_R \right] - \frac{i\sigma^{\mu\nu}}{M_W} (p_t - p_b)_{\nu} \left[f_2^L P_L + f_2^R P_R \right] \right\}$$

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 $\mathcal{O}(1/\Lambda^4)$

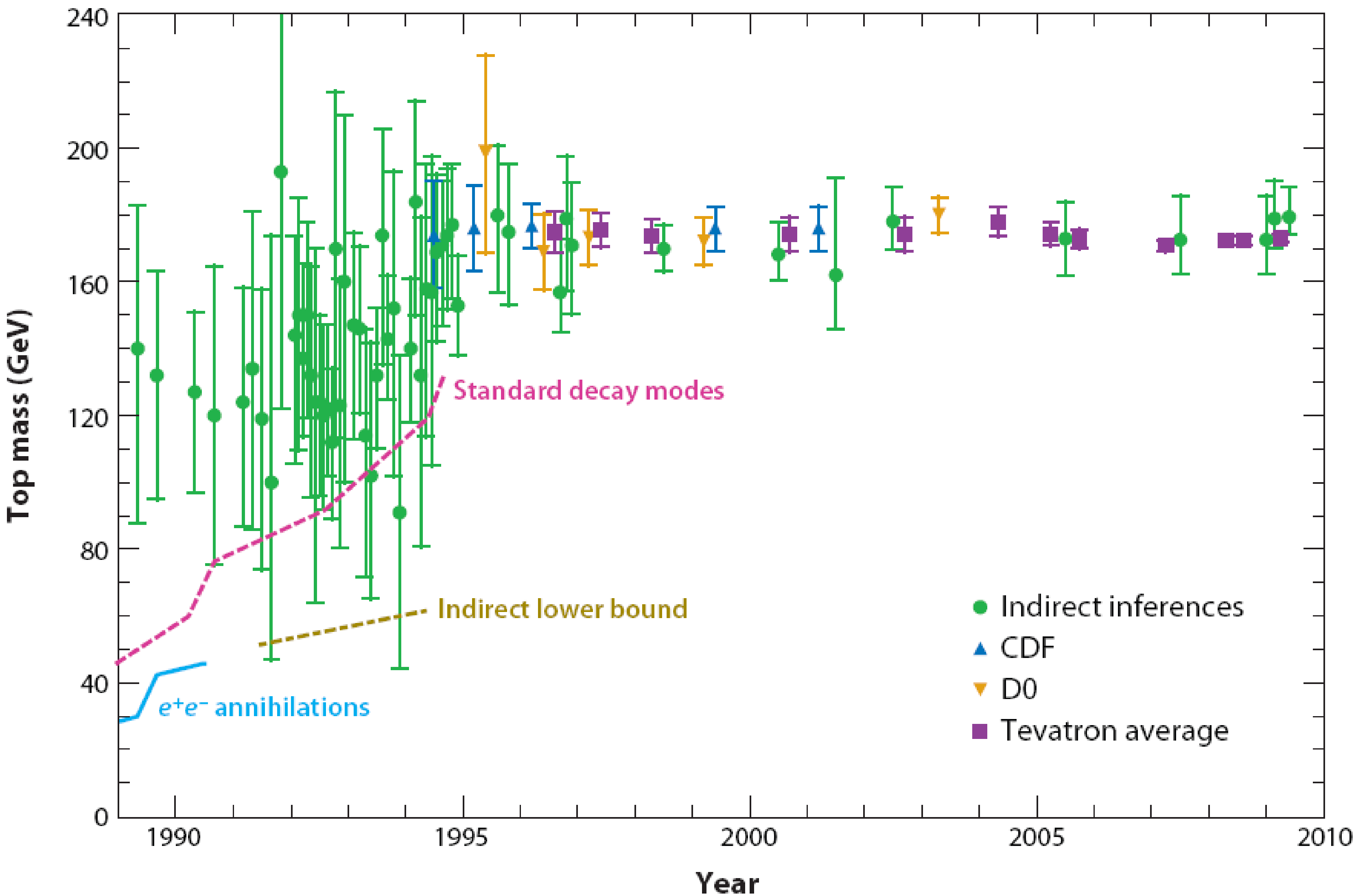
Effective field theory approach provides rationale for neglecting some f's, setting others to constants

Virtual Top



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

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



240
200
160
120
80
40
0
Top mass (GeV)
1990
1995
2000
2005
2010
Year
Standard decay modes
Indirect lower bound
e+e− annihilations
Indirect inferences
CDF
D0
Tevatron average

Quigg