QCD Loop Corrections to Top Production and Decay

(Theoretical Framework)

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Contents

1 Introduction

At LC : precision measurements of top parameters :

mass, width, couplings

Also look for

- anomalous couplings
- CP violation

Magnitude of these effects : several % of the total cross section

$\Rightarrow$ we need precise theoretical predictions for the process

QCD radiative corrections

- production : - virtual and soft gluon — Jersak, Laerman & Zerwas ('82)
  - hard gluon — Korner *et al.*, Parke *et al.*, Brandenburg *et al.*, ...
  - $\hookrightarrow e^+e^- \to t\bar{t}(g)$
- decay : virtual + hard gluons — Jezabeck & Kuhn, Lee, Oakes & Yuan, ...
  - $\hookrightarrow t \to bW(g)$

$\longrightarrow$ Top on shell — C. Schmidt

$\hookrightarrow e^+e^- \to t\bar{t}\,(g) \to bW^+\bar{b}W^-\,(g)$

Effects due to top being off-shell : naively, of order Γ_t/m_t, but : poossibly larger in differential cross-sections.

$\longrightarrow$ Top off shell :
- soft gluon radiation — Khoze, Orr & Stirling ('94)
- hard gluon — Maccsanu & Orr ('99)
- virtual corrections

2 Feynman diagrams – resonant behavior

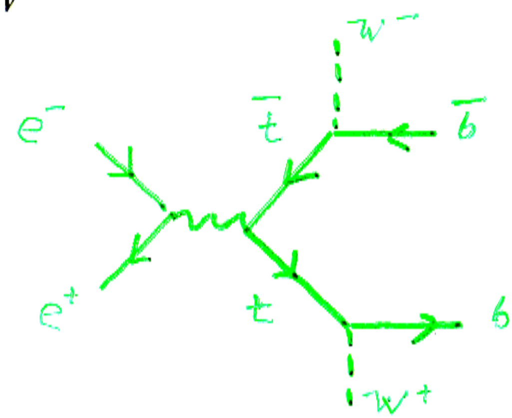
- Physical process : $e^+e^- \to \; b\, W^+ \, \bar{b}\, W^-$

TREE LEVEL

a) doubly resonant diagram :

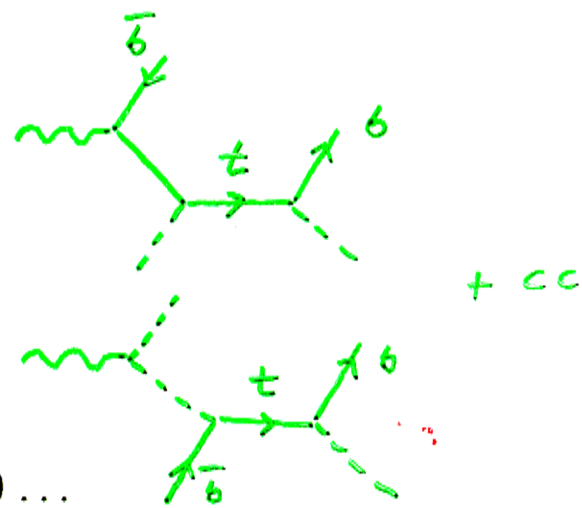
$$M_0 \sim \frac{1}{p_t^2 - \bar{m}_t^2} \, \frac{1}{p_{\bar{t}}^2 - \bar{m}_t^2}$$

$$\bar{m}_t^2 = m_t^2 - i m_t \Gamma_t$$



b) singly resonant diagrams :

$$M_0 \sim \frac{1}{p_t^2 - \bar{m}_t^2}$$



c) nonresonant diagrams : about 50 ...

- computation done in *double pole approximation* (DPA):

  – keep only the amplitudes which have a doubly resonant behavior

- Similar approach has been used in evaluating the cross section for W pair production at LEP. [1]

[1] RacoonWW talk by D. Wackeroth

VIRTUAL CORRECTIONS

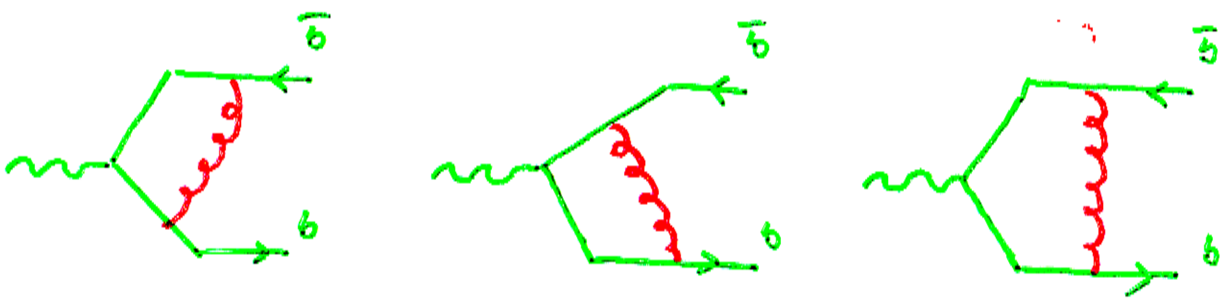
(to the doubly resonant diagram)

a) to subprocesses (factorizable-type corrections)

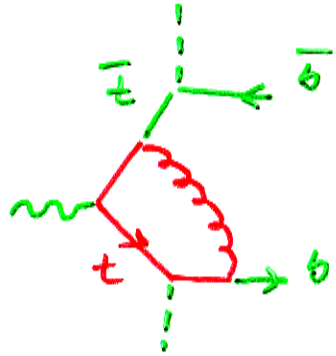
$$M \sim \frac{1}{p_t^2 - \bar{m}_t^2} \, \frac{1}{p_{\bar{t}}^2 - \bar{m}_t^2}$$

$$+ \frac{1}{p_t^2 - \bar{m}_t^2} \log(p_{\bar{t}}^2 - \bar{m}_t^2) \; + \; \log(p_t^2 - \bar{m}_t^2) \frac{1}{p_{\bar{t}}^2 - \bar{m}_t^2}$$

b) interference



$$M \sim \frac{1}{p_t^2 - \bar{m}_t^2} \log(p_{\bar{t}}^2 - \bar{m}_t^2)$$



3 Amplitudes in DPA

3.1 Production Decay Interference

$$M_{b\bar t} = \bar u(b)\Big[(-ig_s^2)\int \frac{d^4k}{2\pi^4}\,\frac{1}{k^2}\,\gamma^\mu\,\frac{\hat p_b - \hat k + m_b}{(p_b-k)^2 - m_b^2}\,\hat\epsilon_{W^+}\,\frac{\hat p_t - \hat k + m_t}{(p_t-k)^2-\bar m_t^2}\,\hat a$$

$$\frac{-\hat p_{\bar t} - \hat k + m_t}{(p_{\bar t}+k)^2 - \bar m_t^2}\,\gamma_\mu\Big]\,\frac{-\hat p_{\bar t} + m_t}{p_{\bar t}^2 - \bar m_t^2}\,\hat\epsilon_{W^-}\,v(\bar b)$$

- hard gluon : $M_{b\bar t} \sim \frac{1}{p_{\bar t}^2 - \bar m_t^2}$

  $\Rightarrow$ doubly resonant terms are entirely due to soft gluons

- employ *(extended) soft gluon approximation* (ESGA) :

Denner, Dittmaier & Roth

$$M_{b\bar t}(DPA+ESGA) = \frac{\alpha_s}{4\pi} M_0 \; * \; (-4p_b p_{\bar t})(p_{\bar t}^2 - \bar m_t^2) \; *$$

$$\int \frac{d^4k}{i\pi^2}\,\frac{1}{k^2}\,\frac{1}{k^2 - 2kp_b}\,\frac{1}{(p_t-k)^2-\bar m_t^2}\,\frac{1}{(p_{\bar t}+k)^2 - \bar m_t^2} \quad \to D^0_{b\bar t}$$

- contribution proportional to M_0

  Resonant behavior :

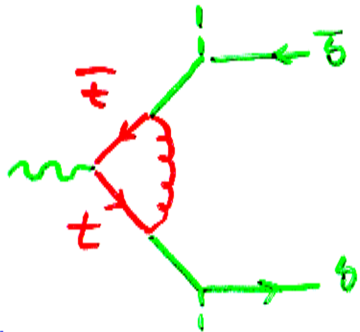
$$D^0_{b\bar t} \sim a_1 \log(p_t^2 - \bar m_t^2) + a_2 \log(p_{\bar t}^2 - \bar m_t^2)$$

$$\Rightarrow M_{b\bar t}(DPA) \sim \log(p_t^2 - \bar m_t^2)\,\frac{1}{p_{\bar t}^2 - \bar m_t^2} \qquad *$$

- similar results for the Decay-Decay Interference diagram

Also, results are identical to the ones obtained for the interference diagrams in W pair production.

3.2 Vertex Correction



$$M_{t\bar{t}} = \bar{u}(b)\ \hat{\epsilon}_{W^+}\ \frac{\hat{p}_t + m_t}{p_t^2 - \bar{m}_t^2}\ \delta\Gamma^\mu\ \frac{-\hat{p}_{\bar{t}} + m_t}{p_{\bar{t}}^2 - \bar{m}_t^2}\ \hat{\epsilon}_{W^-}\ v(\bar{b})$$

The vertex correction can be written :

$$\delta\Gamma^\mu = \frac{\alpha_s}{4\pi} *$$

$$\begin{array}{llllllll}
[& & p_t^\mu & F_1 & + & & \gamma^\mu & F_2 \\
+ & (\hat{p}_t - m_t) & p_t^\mu & F_3 & + & (\hat{p}_t - m_t) & \gamma^\mu & F_4 \\
+ & & p_t^\mu & (\hat{p}_{\bar{t}} + m_t)\ F_5 & + & & \gamma^\mu & (\hat{p}_{\bar{t}} + m_t)\ F_6 \\
+ & (\hat{p}_t - m_t) & p_t^\mu & (\hat{p}_{\bar{t}} + m_t)\ F_7 & + & (\hat{p}_t - m_t) & \gamma^\mu & (\hat{p}_{\bar{t}} + m_t)\ F_8\ ]
\end{array}$$

- 8 form factors in the general case; on-shell, only F_1 and F_2 contribute
- $F_i \sim f_i C_{t\bar{t}}^0 + \ldots \qquad i = 1, ..., 8,$

$$C_{t\bar{t}}^0 \sim \log(a(p_t^2, p_{\bar{t}}^2))$$

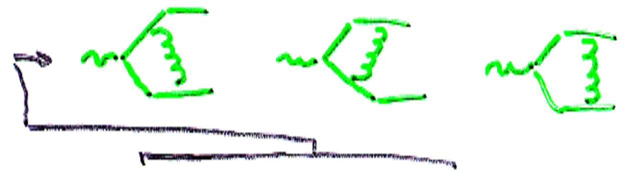
where $a(p_t^2, p_{\bar{t}}^2) \to 0$ when $p_t^2, p_{\bar{t}}^2 \to 0$

$\Rightarrow$ in DPA, keep $F_1, \ldots, F_6$

- beside terms similar to on-shell computation (F_1, F_2), we aquire extra terms $(F_3, \ldots, F_6)$. This is due to the fact that our off-shell particle is a fermion.

3.3 Total Amplitude

Virtual corrections in DPA :



$$M_1 = M_{t\bar{t}} + M_{tb} + M_{\bar{t}\bar{b}} + M_0(f_{b\bar{t}} + f_{\bar{t}b} + f_{b\bar{b}})$$

- Evaluation :
  - loop integrals : routines for evaluating 4-point functions for complex masses
  - matrix elements : use spinor techniques (Kleiss & Stirling)

Gauge Invariance

- for W pair production computation, gauge invariance in DPA is guaranteed by the fact that the off shell corrections are proportional to the on-shell result.
- for t pair production, this is no longer true; but we have checked – analytically – that our results are gauge invariant in the approximation used (that is, up to singly resonant terms).

Infrared gluon radiation

- we take into account only radiation from the on-shell particles (final state b's).
- radiation from the off-shell particles ($t\bar{t}$) is an infrared safe quantity - compute it using real gluons
- maximum energy of infrared gluons (analytically integrated) is much smaller that the top width ($\sim$ 0.1 GeV).

4 Status

• We have constructed a Monte Carlo program which implements the DPA computation for virtual corrections presented here.

This, together with a real gluon radiation MC , gives us the necessary tools for a full analysis of the top production and decay at an e^+e^- collider.

– Checks on the results going on right now.

• comparision with the on-shell computation

– in this approximation, we have been able to recreate the results first obtained by C. Schmidt

• In the near future : anticipate results for total cross section for $t\bar{t}$ production, top mass reconstruction analysis.