# Electroweak Sudakov logarithms and 100TeV Colliders

Christian Bauer, LBNL

2015 workshop at CERN
Oct 8 2015

## In this talk I will discuss the appearance of EW Sudakov logarithms and the necessity to resum them

General introduction
to EW Sudakovs

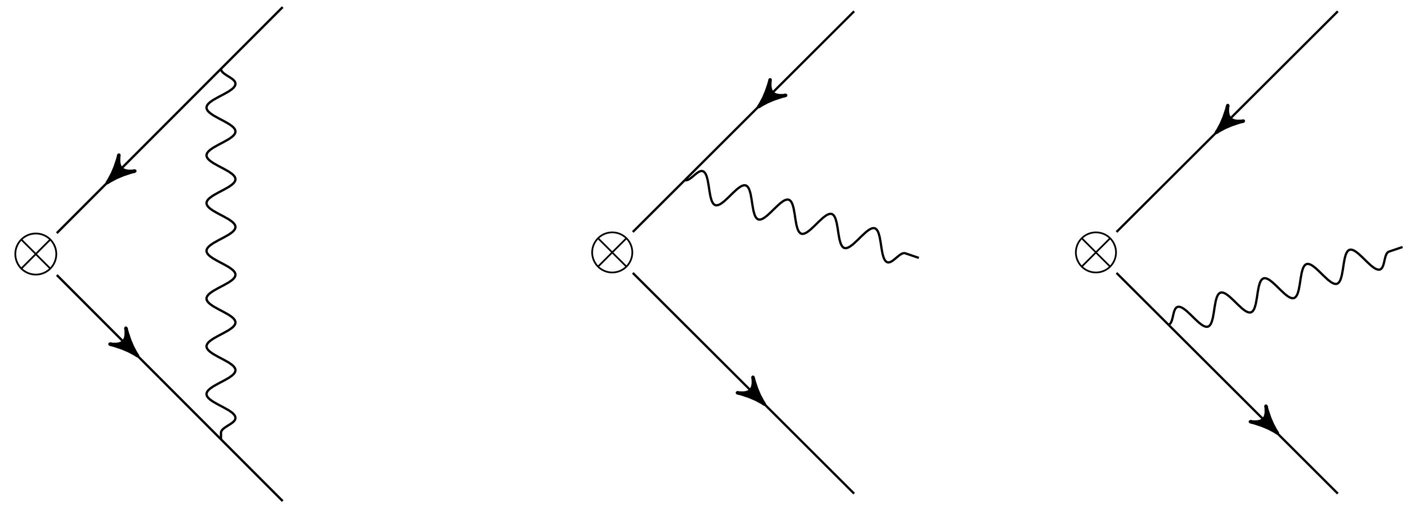
Resummation for virtual
corrections

Adding real radiation at
to the process

Note that I am not giving definite results for 100TeV, but rather raise some issues we need to think about

## Electroweak Sudakov logarithms arise from exchanges of electroweak gauge bosons

Consider example of qq production

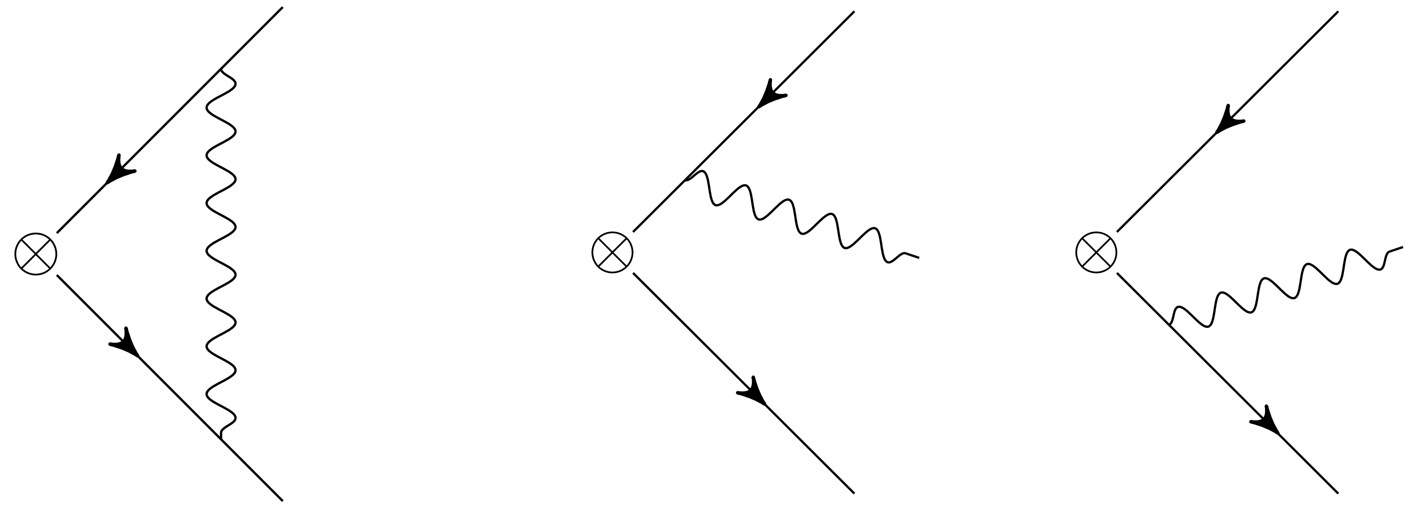


Have contributions from virtual and real emission

For massless gauge boson, get IR divergences in both virtual and real that cancel by KLN

## Electroweak Sudakov logarithms arise from exchanges of electroweak gauge bosons

Consider example of qq production

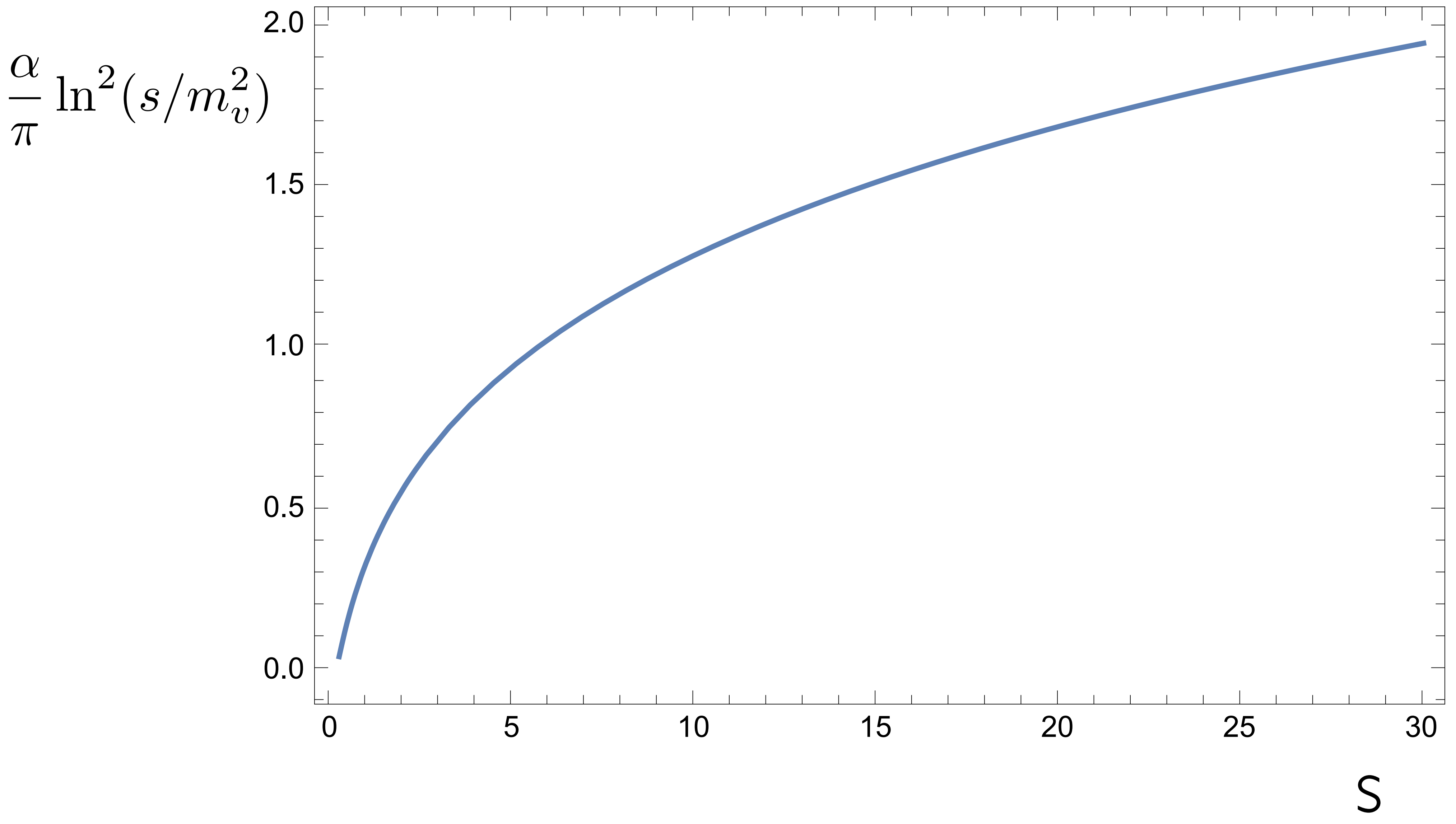


Have contributions from virtual and real emission

For massive W, IR divergences turn into $\log(m_W^2/s)$, and generally have two powers per power of alpha

**Both virtual and real sensitive to $\log(m_W^2/s)$**

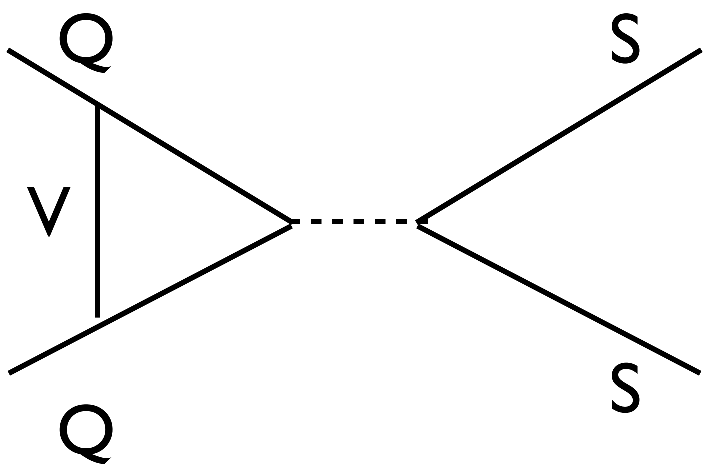
# The numerical effect of EW Sudakov logarithms becomes large at high energies

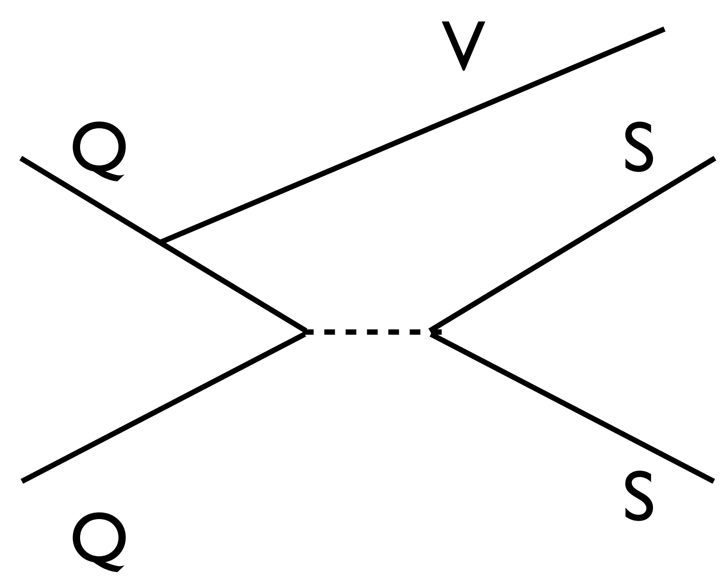



No sense in which electroweak corrections are small

## The cancellation between virtual and real corrections is very different from the usual story in QCD

Look at "Drell-Yan" production of a SU(2) singlet state




$\sigma^{V}{}_{uu+dd} = \sigma_B\ (\ 1 - 3/2\ \alpha\ L^2)$ $\qquad$ $\sigma^{R}{}_{uu+dd} = \sigma_B\ 1/2\ \alpha\ L^2$

$\sigma^{V}{}_{ud+du} = 0$ $\qquad$ $\sigma^{R}{}_{ud+du} = \sigma_B\ \alpha\ L^2$

$$\alpha = \alpha_{EW}/2\pi \qquad L = \log(m^2/s)$$

**The cancellation between virtual and real corrections is very different from the usual story in QCD**

## Look at "Drell-Yan" production

| | V | R | V+R |
|---|---|---|---|
| uu+dd | $(1 - 3/2\, \alpha\, L^2)$ | $1/2\, \alpha\, L^2$ | $(1 - \alpha\, L^2)$ |
| ud+du | 0 | $\alpha\, L^2$ | $\alpha\, L^2$ |
| uu+dd +ud+du | $(1 - 3/2\, \alpha\, L^2)$ | $3/2\, \alpha\, L^2$ | 0 |

Cancellation for completely inclusive observables (KLN)

## The cancellation between virtual and real corrections is very different from the usual story in QCD

# Look at "Drell-Yan" production

| | V | R | V+R |
|---|---|---|---|
| uu+dd | $(1 - 3/2\,\alpha\,L^2)$ | $1/2\,\alpha\,L^2$ | $(1 - \alpha\,L^2)$ |
| ud+du | 0 | $\alpha\,L^2$ | $\alpha\,L^2$ |
| uu+dd +ud+du | $(1 - 3/2\,\alpha\,L^2)$ | $3/2\,\alpha\,L^2$ | 0 |

Cancellation only happens if we include both real and virtual corrections, and average over initial states

1. Most experimental analyses are not inclusive over initial states
2. Averaging over initial states is impossible, since beams are not SU(2) symmetric

# Resummation of EW Sudakov logarithms for virtual corrections

## Sudakov logarithms in EW processes have been studied for a while, and resummation techniques are available

The existence of large Sudakov style logarithms of the ration m^2/s has been known for quite some time …

Fadin et al ('99)

Ciafaloni, Comelli ('99, '00)

Melles et al ('99, '00)

… and the leading logs were known to exponentiate

Using IR evolution equations, higher logarithms have been resummed as well

Kühn et al ('01)

# Effective field theories are a great tool to derive resummed expression to arbitrary order in the logarithmic resummation

Full theory

$\mu \simeq Q$

Match onto SCET
no logarithms

SCET with $m_V \ll Q$
Unbroken SU(2)
$A_3$ $A_+$ $A_-$ $A_0$

Renormalization group
between Q and $m_V$
resums Sudakov logs

$\mu \simeq m_V$

Integrate out W, Z
(almost) no logarithms

SCET with $\mu \ll m_V$
Broken SU(2)
Only $\gamma$

## The advantage of using effective field theories is that the calculations are considerably easier

Full theory

$\mu \simeq Q$

SCET

$\mu \simeq m_V$

SCET$_\gamma$

- For the calculation in SCET can use unbroken SU(2)
- Can set all masses to zero, which makes life much easier
- Factorization of amplitudes allows to write completely generic result in terms of collinear and soft functions
- Completely general results available

# Adding real radiation at fixed order

# Most observables are not fully inclusive, such that EW Sudakov logarithms remain

$$\sigma_T = \frac{\alpha_W}{2\pi} (G_R - G_V)\, \widehat{\sigma}_0 \left\{ \ln^2 r + 3 \ln r + \ldots \right\}$$

| Process | $G_V$ | $G_R$ | $G_R$ - $G_V$ |
|---|---|---|---|
| Inclusive **ff(V)** | N CF | N $C_F$ | **0** |
| Any fermion **ff** | N $C_F$ | 0 | **-N $C_F$** |
| Specified f's **$f_i f_j$(V)** | 1/2(1 - $\delta_{ij}$/N) | $C_F \delta_{ij}$ | **1/2(1 - N $\delta_{ij}$)** |

Furthermore, since initial pp state not SU(2) singlet, EW Sudakov logs don't cancel even in fully inclusive case

## Most of the literature has focussed on Sudakov logarithms from virtual corrections

No IR divergences arise, so exclusive cross-section are physical observables

Additional radiation of EW gauge bosons leads to mostly distinct experimental signatures (extra high $p_T$ leptons, extra jets etc)

Improving techniques for loop calculations have allowed many advances

## However, most experimental signatures are in fact not fully exclusive over extra real radiation of W and Z bosons

Extra Z bosons decaying to neutrinos are very hard to reject

Often, measurements are inclusive over the number of leptons or jets, such that additional vector bosons are included in the event samples

So we need to include real radiation in any sensible study of EW Sudakov logarithms

## One should study the effect of real radiation on the size of EW corrections

To get a feeling of the size of these effects, we have considered a toy model, which should closely resemble the real situation

- Consider gg→tt in a theory with only a broken SU(2)
  - This gets rid of complications of adding the U(1)
  - gg initial state is SU(2) singlet
- Let's only look at partonic scattering
  - Allows us to see directly dependence on s

CWB, Manohar, Shotwell, Turcyk ('14)

# One should study the effect of real radiation on the size of EW corrections

$$\sigma(t\bar{b}W^-) \to \sigma(u\bar{d}W^-) + 2(y_t^2 + y_b^2)\sigma_S$$

$$\sigma(t\bar{t}Z) \to \frac{1}{2}\sigma(u\bar{d}W^-) + 2y_t^2\sigma_S$$

$$\sigma(b\bar{b}Z) \to \frac{1}{2}\sigma(u\bar{d}W^-) + 2y_b^2\sigma_S$$

$$\sigma(t\bar{t}H) \to 2y_t^2\sigma_S$$

$$\sigma(b\bar{b}H) \to 2y_b^2\sigma_S$$

$$\sigma_V(t\bar{t}) \to (v_W + 3v_t + v_b)\,\sigma(u\bar{u})$$

$$\sigma_V(b\bar{b}) \to (v_W + v_t + 3v_b)\,\sigma(u\bar{u})$$

$$v_W = \frac{C_F\alpha_W}{4\pi}\left[-\mathsf{L}^2 + 3\mathsf{L}\right]$$

$$v_t = -\frac{y_t^2}{32\pi^2}\mathsf{L}$$

$$v_b = -\frac{y_b^2}{32\pi^2}\mathsf{L}$$

$$3\sigma(u\bar{d}W^-) + 8(y_t^2 + y_b^2)\sigma_S + (2v_W + 4v_t + 4v_b)\,\sigma(u\bar{u}) \to 0$$

$$8(y_t^2 + y_b^2)\sigma_S + (4v_t + 4v_b)\,\sigma(u\bar{u}) \to 0$$

## For true understanding of EW Sudakov effects, need to understand exactly what event selection is

Consider gg → t tbar production

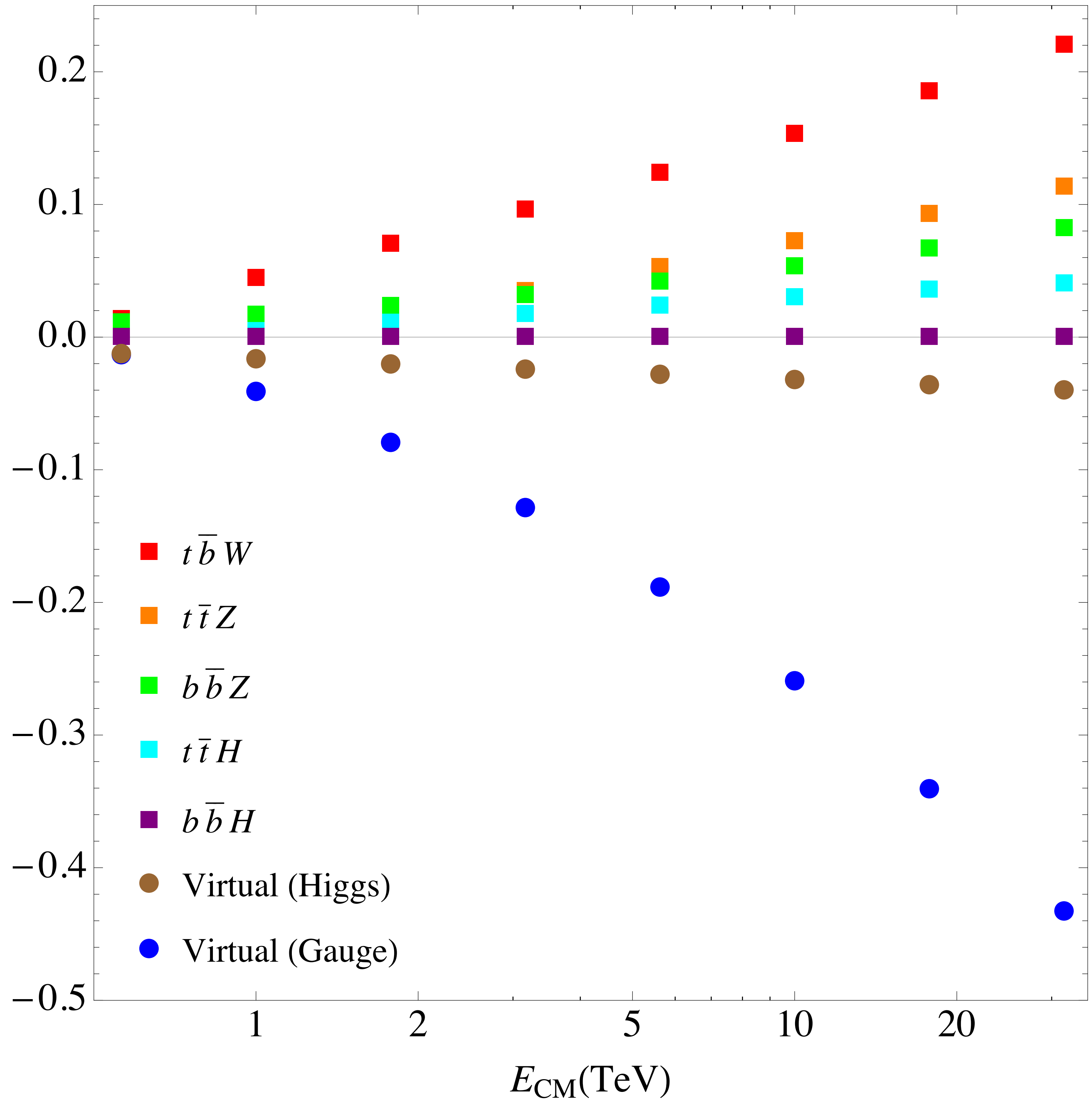
Important question that needs to be asked:

What is the actual experimental signature?
Is extra radiation of gauge bosons included?

| | | | |
|---|---|---|---|
| Most likely: | $tt+(Z\to\nu\nu)$ | $tb+(W\to l\nu)$ | |
| Maybe: | $tt+(Z\to qq?)$ | | |
| Likely not: | $tt+(Z\to\ell\ell)$ | bb | bbZ |

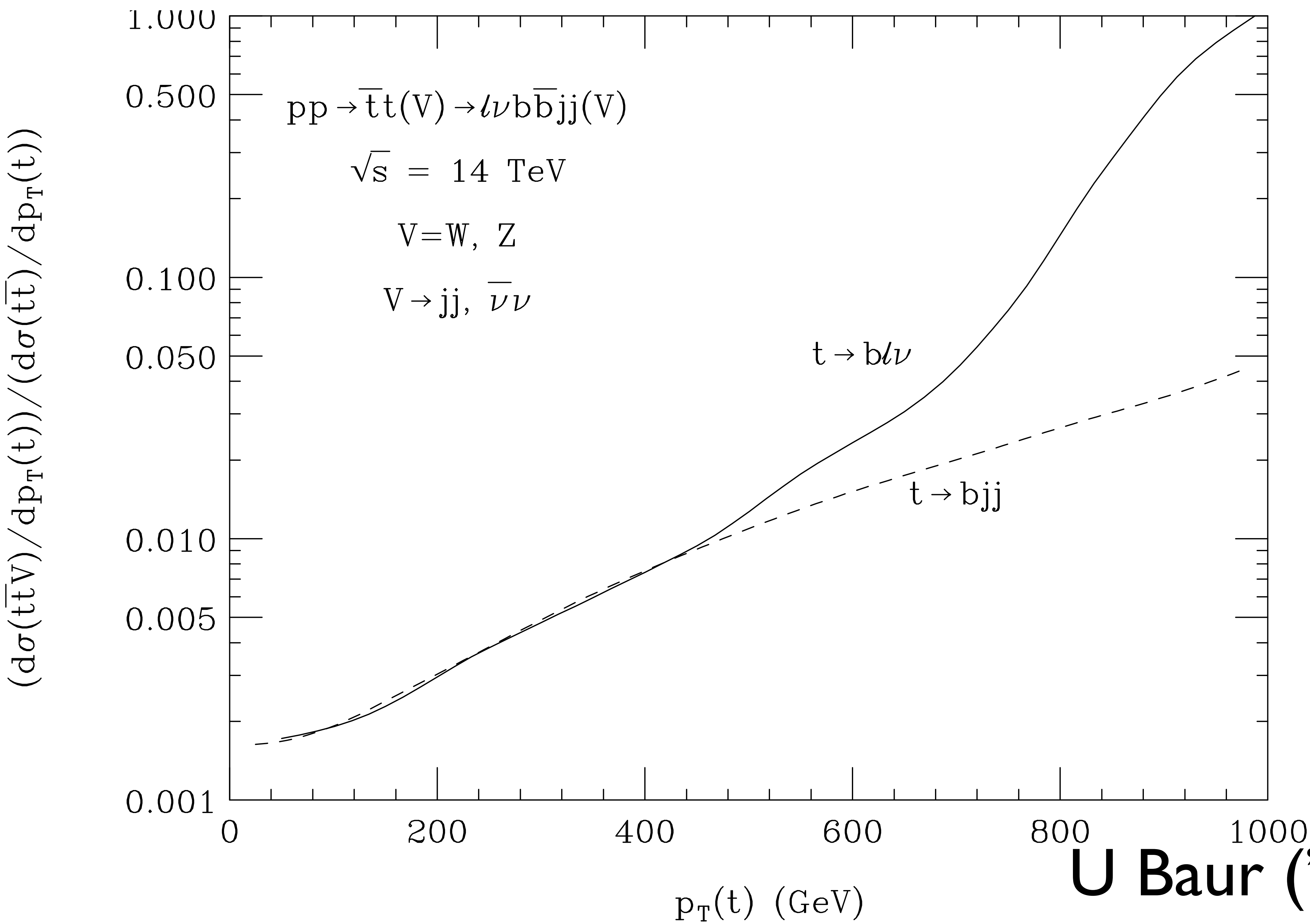
**Most of the time, real radiation is partially included**

# One should study the effect of real radiation on the size of EW corrections



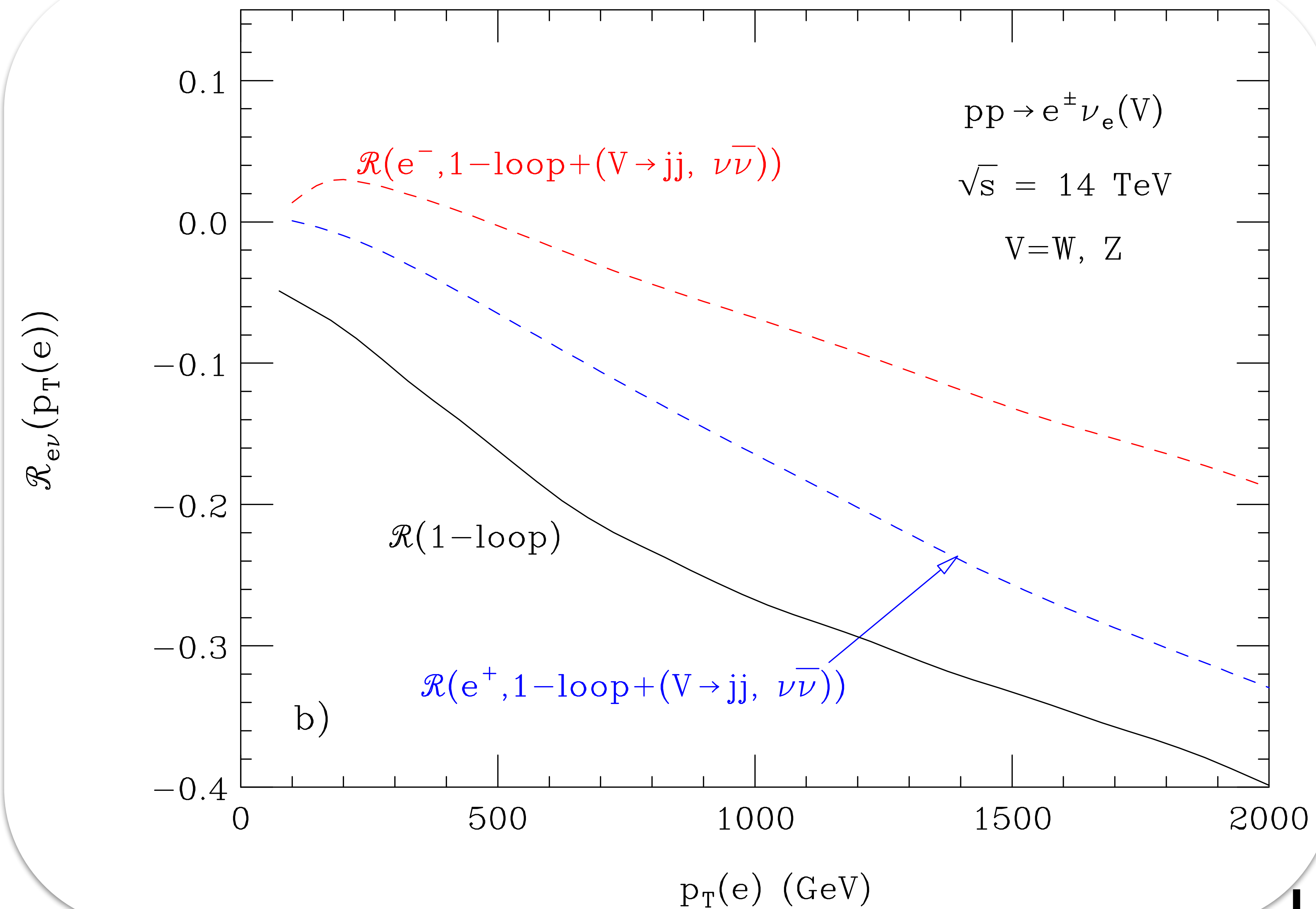

CWB, Manohar, Shotwell, Turcyk ('14)

# One should study the effect of real radiation on the size of EW corrections




U Baur ('06)

# These effects can be quite large, and it is very important to get this correct




U Baur ('06)

# Adding real radiation at fixed order

## How can we resum logarithms that arise from integrations over phase space?

Logarithms from virtual corrections are related to the UV divergences in factorized cross-sections

$$\frac{1}{\epsilon}\left(\frac{\mu^2}{m_V^2}\right)^{\epsilon} = \frac{1}{\epsilon} + \ln\frac{\mu^2}{m_V^2}$$

But naively there are no UV divergences in real emission diagram, such that it is not clear how the renormalization group can be used to resum logarithms

## Should be able to resum real Sudakovs using effective theories, but I am still working out the details

In fully inclusive event samples, only logs from initial state remain

Since we are inclusive over final state, can perform OPE for forward scattering

Renormalizing the resulting operators should resum the leftover logs from initial state

Need to figure out how to deal with partially inclusive quantities next

**CWB, N Ferland, in preparation**

Electroweak corrections can become very large at 100TeV collider. Might have to rethink EW perturbation theory