Weak Boson Emission in Hadron Collider Processes

all results are preliminary

1. Introduction
2. Isolated Photon Production
3. Charged Drell-Yan Production
4. Conclusions

Ulrich Baur
State University of New York at Buffalo

1 – Introduction

- In the past few years calculations of electroweak (EW) radiative corrections at high energies ($\gg M_{W,Z}$) have been performed for a number of processes
  - ☞ $f'\bar{f} \to \ell'\ell$ (Kühn et al.)
  - ☞ $p\overset{(-)}{p} \to \ell^{\pm}\nu$, $p\overset{(-)}{p} \to \ell^{+}\ell^{-}$ (UB, D. Wackeroth, Dittmaier and Krämer)
  - ☞ isolated photon and Zj production at hadron colliders (Kühn et al.)
  - ☞ di-boson production (Accomando et al., Hollik and Meier)
  - ☞ inclusive jet production at hadron colliders (Nolten et al.)
  - ☞ $p\overset{(-)}{p} \to t\bar{t}$ (Nolten et al., Kühn et al.)
  - ☞ single top production (Comelli et al., Beccaria et al.)

- These calculations show that EW corrections become large and negative at high energies, due to the presence of Sudakov-like logarithms $((\alpha/\pi)\log(\hat{s}/M^2_{W,Z}))$.
- Where are these logarithms coming from?
  - ☞ In QED, these logarithms cancel between virtual and real corrections (KLN theorem); observables which are inclusive over soft final states (ie. photons) are infrared safe (Bloch-Nordsieck (BN) theorem)
  - ☞ In the EW case, the incoming $q'\bar{q}$ system does have a non-zero $SU(2)\times U(1)$ charge, and, due to the non-abelian character of the gauge group, the BN-theorem is violated
    (remark: In QCD the BN-theorem is also violated, but one sums/averages over colors. This effectively restores the BN-theorem (Bodwin, Brodsky, Lepage))

- ☞ In the EW case, the W and Z masses act as infrared regulators, and the virtual weak corrections are finite. There is no technical reason to take into account real emission diagrams.
- ☞ Furthermore, since the EW symmetry is broken and the massive W and Z bosons decay, the real EW radiative corrections (ie. W and Z radiation) lead to a different final state.

- Therefore, contributions from weak boson emission usually are not taken into account when calculating electroweak radiative corrections.
- This is ok if one considers exclusive final states.
- However, in experiment, analyses usually involve (semi-)inclusive final states.

- Real EW corrections (W and Z radiation) thus have to be included in the calculation.
- This results in a partial compensation of the large negative corrections originating from the Sudakov-like logarithms
- So, how large are EW radiative corrections when realistic experimental conditions are taken into account?
- I calculated weak boson emission effects for all processes for which the virtual weak corrections are known.
- In the following I discuss two interesting examples:
  → isolated photon production and
  → charged Drell-Yan production
- wherever possible consider cross section ratios: this minimizes cut, PDF and scale dependence

2 – Isolated Photon Production

- LO process: $p\overset{(-)}{p} \to \gamma j$
- typical CDF/DØ selection criteria:
  - ☞ require a hard ($p_T(\gamma) > 10$ GeV), isolated ($\Delta R > 0.4$) photon
  - ☞ some analyses also require the missing E_T in the event to be small ($\not{p}_T < 20$ GeV) to reject events with large calorimeter noise
  - ☞ there is no restriction on the number of jets or leptons in the event
- The one-loop NLL $\mathcal{O}(\alpha_s\alpha^2)$ weak corrections have a very compact form and can easily be included in a γj parton level MC program (Kühn et al.)

  they agree at the percent level with the full weak one-loop corrections

- Real EW $\mathcal{O}(\alpha_s\alpha^2)$ radiative corrections: $W\gamma j$ and $Z\gamma j$ production
  - ☞ Don't care about the jet in $V\gamma j$ ($V = W,\ Z$): it can be soft.
  - ☞ Should include $V\gamma$ production
  - ☞ better strategy: include $V\gamma$ production at NLO QCD (well known for more than a decade)
- Cuts (only on the photon!)

$$p_T(\gamma) > 25\,(50)~\text{GeV} \quad \text{at Tevatron (LHC)},$$
$$|\eta(\gamma)| < 2.5 \qquad \Delta R(\gamma, X) > 0.4$$

$X = j,\ \ell$

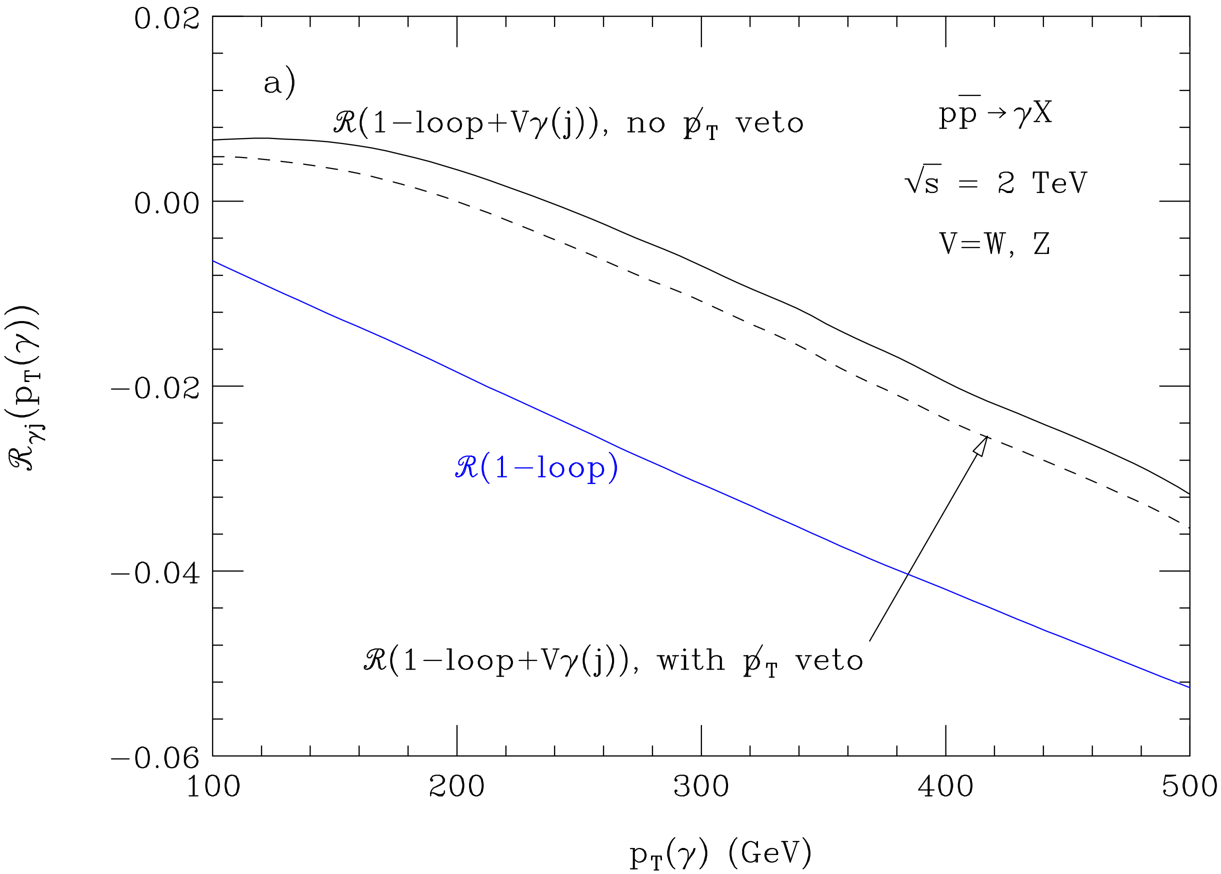
- Sometimes one also imposes a $\not{p}_T$ veto: require

$$\not{p}_T < 5~\text{GeV}^{1/2}\sqrt{\sum p_T}$$

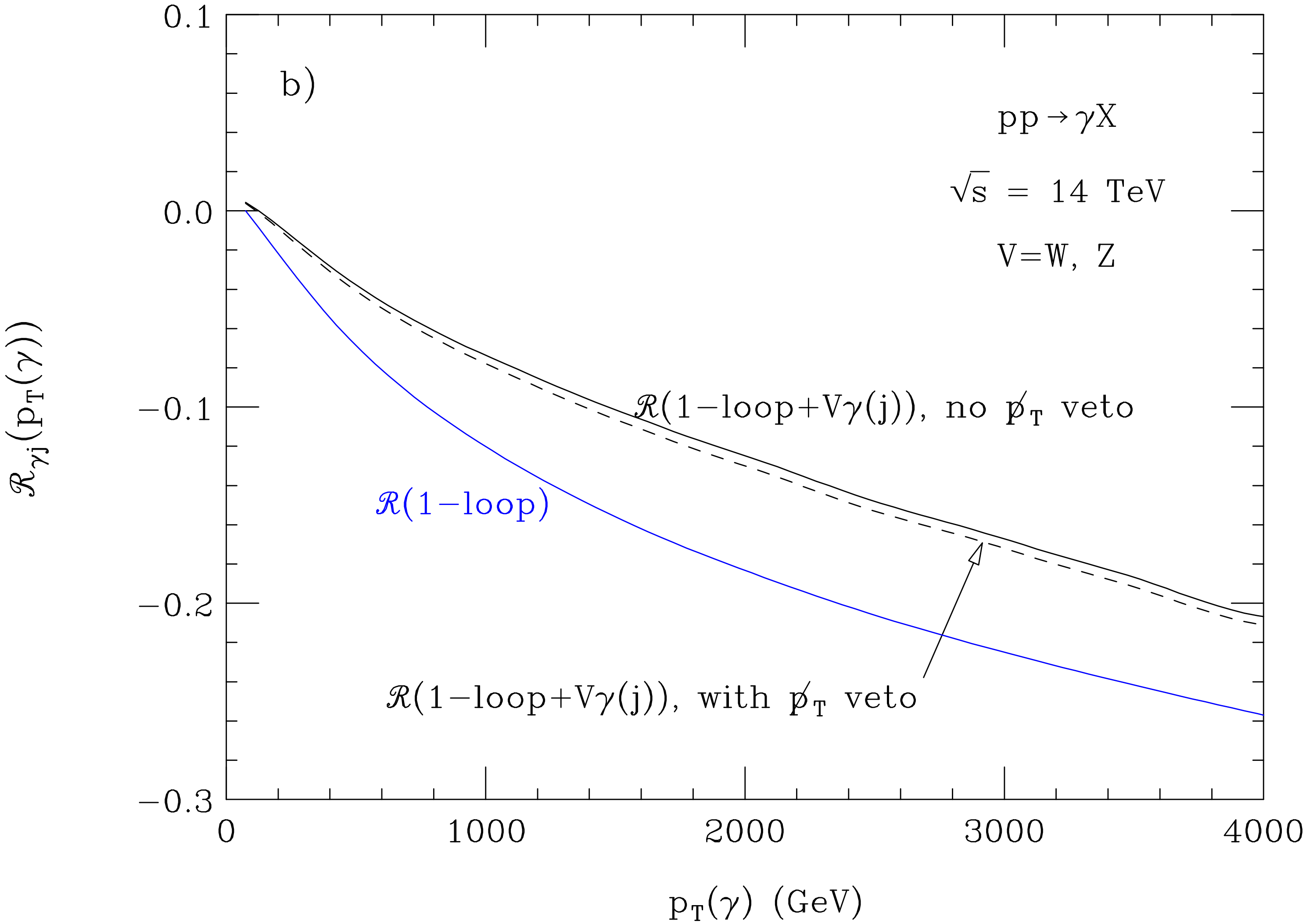
- consider relative correction w/r to LO cross section:

$$\mathcal{R}_Y(X) = \frac{d\sigma/dX}{d\sigma^{LO}(Y)/dX} - 1$$

with $Y = \gamma j$, $X = p_T(\gamma)$. Tevatron:



. . . and LHC:



0.1
0.0
−0.1
−0.2
−0.3
0
1000
2000
3000
4000
b)
pp → γX
√s = 14 TeV
V=W, Z
$\mathcal{R}_{\gamma j}(p_T(\gamma))$
$\mathcal{R}$(1−loop+Vγ(j)), no $\not{p}_T$ veto
$\mathcal{R}$(1−loop)
$\mathcal{R}$(1−loop+Vγ(j)), with $\not{p}_T$ veto
$p_T(\gamma)$ (GeV)

- There are large logarithms present in $V\gamma j$ production:

$$d\hat{\sigma}(q_1 g \to V\gamma q_{1,2}) = d\hat{\sigma}(q_1 g \to \gamma q_1)\, \frac{\alpha}{4\pi \sin^2\theta_W}\, \log^2\left(\frac{p_T^2(\gamma)}{M_V^2}\right)$$

- there are no large logarithms in $V\gamma$ production:
  it contributes significantly only for $p_T(\gamma) < 200$ GeV
- the one-loop EW corrections are a few percent at most at the Tevatron
  weak boson emission considerably reduces the effect of the virtual weak corrections
- At the LHC one can measure the $p_T(\gamma)$ distribution out to 1.5 TeV with 10 fb^{-1}:
  - ☞ without weak boson emission: $\mathcal{R}_{\gamma j} = -0.15$
  - ☞ including weak boson emission: $\mathcal{R}_{\gamma j} = -0.11$
  - ☞ moderate reduction

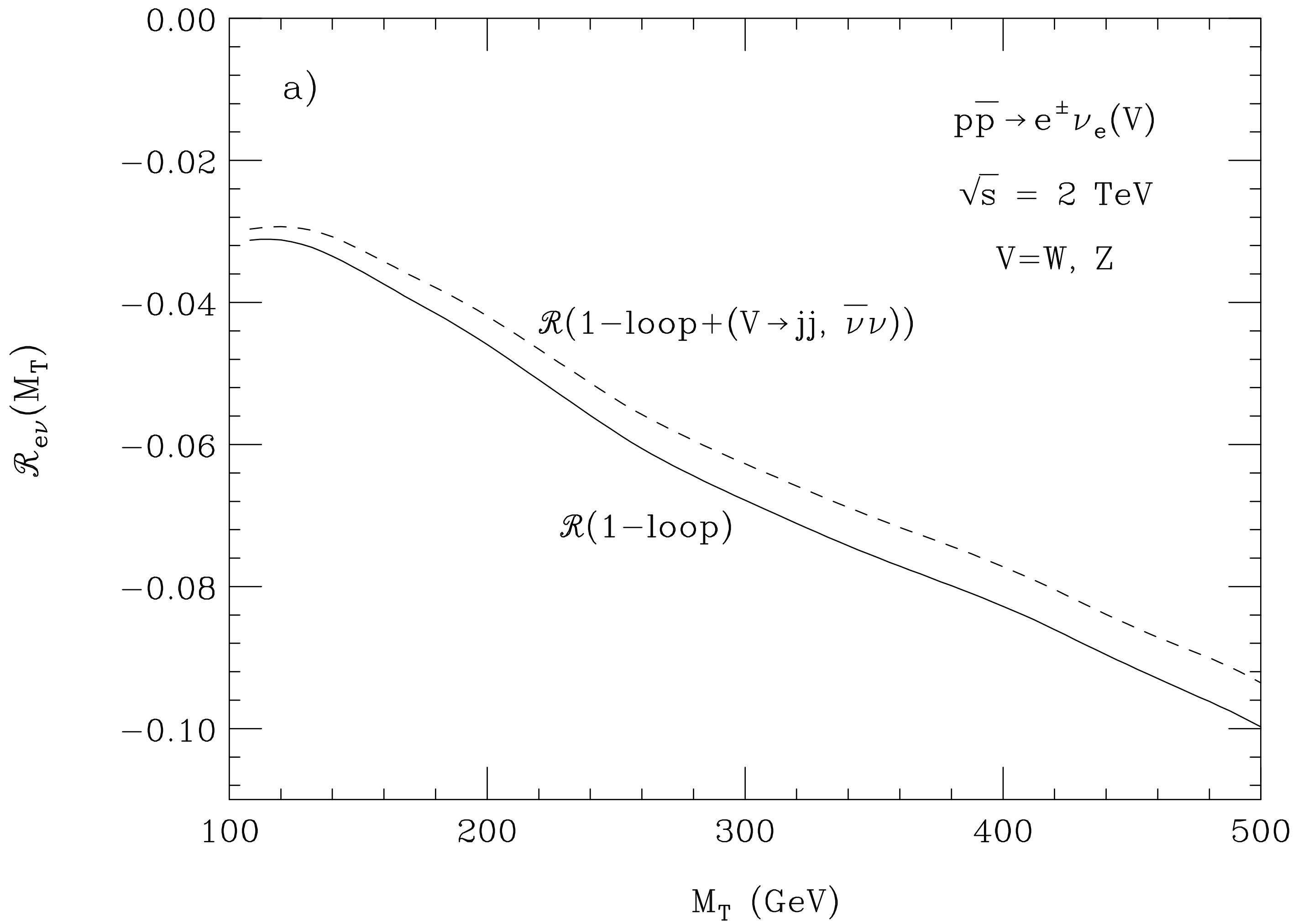
- weak boson emission effects are of the same size as the leading two-loop electroweak corrections (Kühn et al.)
- are the combined real + virtual weak corrections important?
  - ☞ compare with statistical and systematic uncertainties
  - ☞ Tevatron: systematic uncertainties dominate over statistical, except for the highest values of $p_T(\gamma)$ one can access
  - ☞ Tevatron: systematic uncertainties are $10-20\%$
  - ☞ expect similar uncertainties at the LHC
  - ☞ real + virtual EW corrections are important at the LHC, but probably not at the Tevatron

3 – Charged Drell-Yan Production

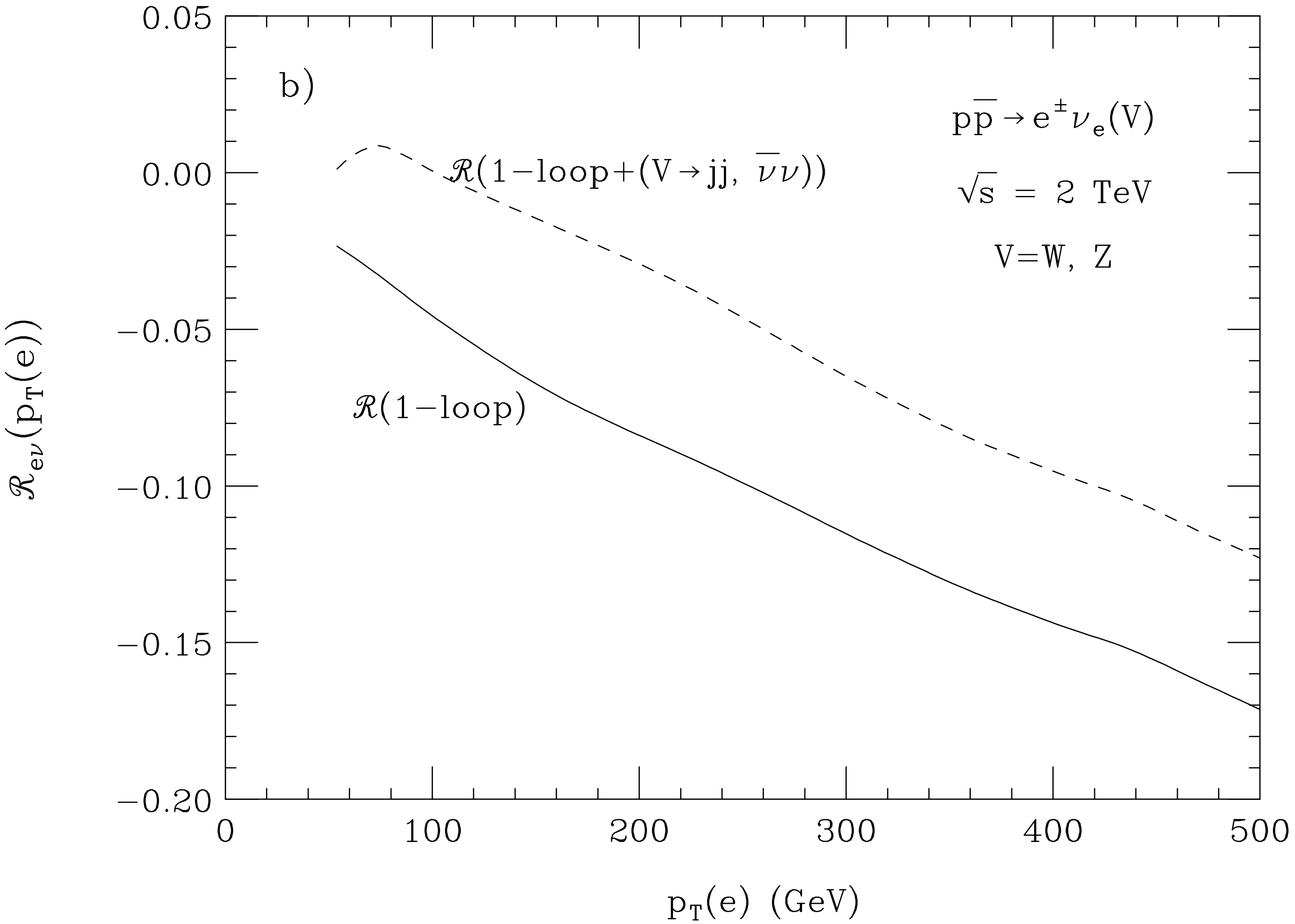
- LO: $p \overset{(-)}{p} \to \ell\nu$
- used to search for new heavy charged vector bosons
- selection criteria:
  - ☞ one high p_T charged lepton ($p_T(\ell) > 25$ GeV): events with two or more charged leptons are classified as di-boson events
  - ☞ missing transverse momentum $\not{p}_T > 25$ GeV
  - ☞ any number of jets
- real EW radiative corrections: $W^{\pm}\ell\nu$ and $Z\ell\nu$ production (WW, WZ production, and W, Z bremsstrahlung diagrams)

- virtual corrections: full one-loop $\mathcal{O}(\alpha)$ (including photonic corrections)
- focus on $\ell = e$; recombine photons and electrons for small opening angles
  - ☞ necessary because photons and electrons which are collinear cannot be discriminated
  - ☞ minimizes the effect of the photonic corrections (we are not interested in them)
- for μ final state relative effects are smaller because photonic corrections play a larger role (no recombination with photon; hard photons close to μ are vetoed)
- consider $e\nu$ transverse mass (M_T) and $p_T(e)$ distributions

Tevatron: M_T distribution

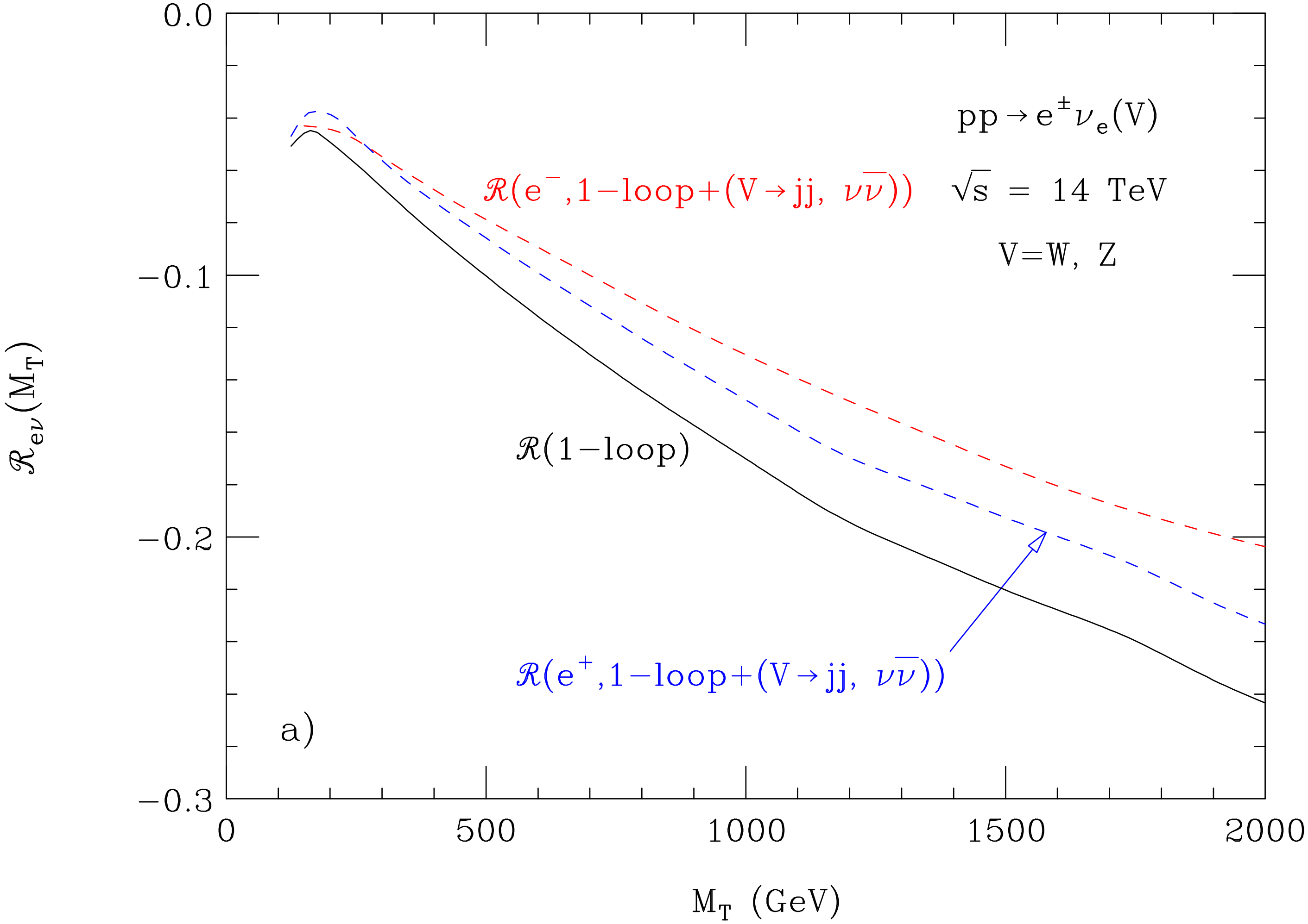


... and $p_T(e)$ distribution

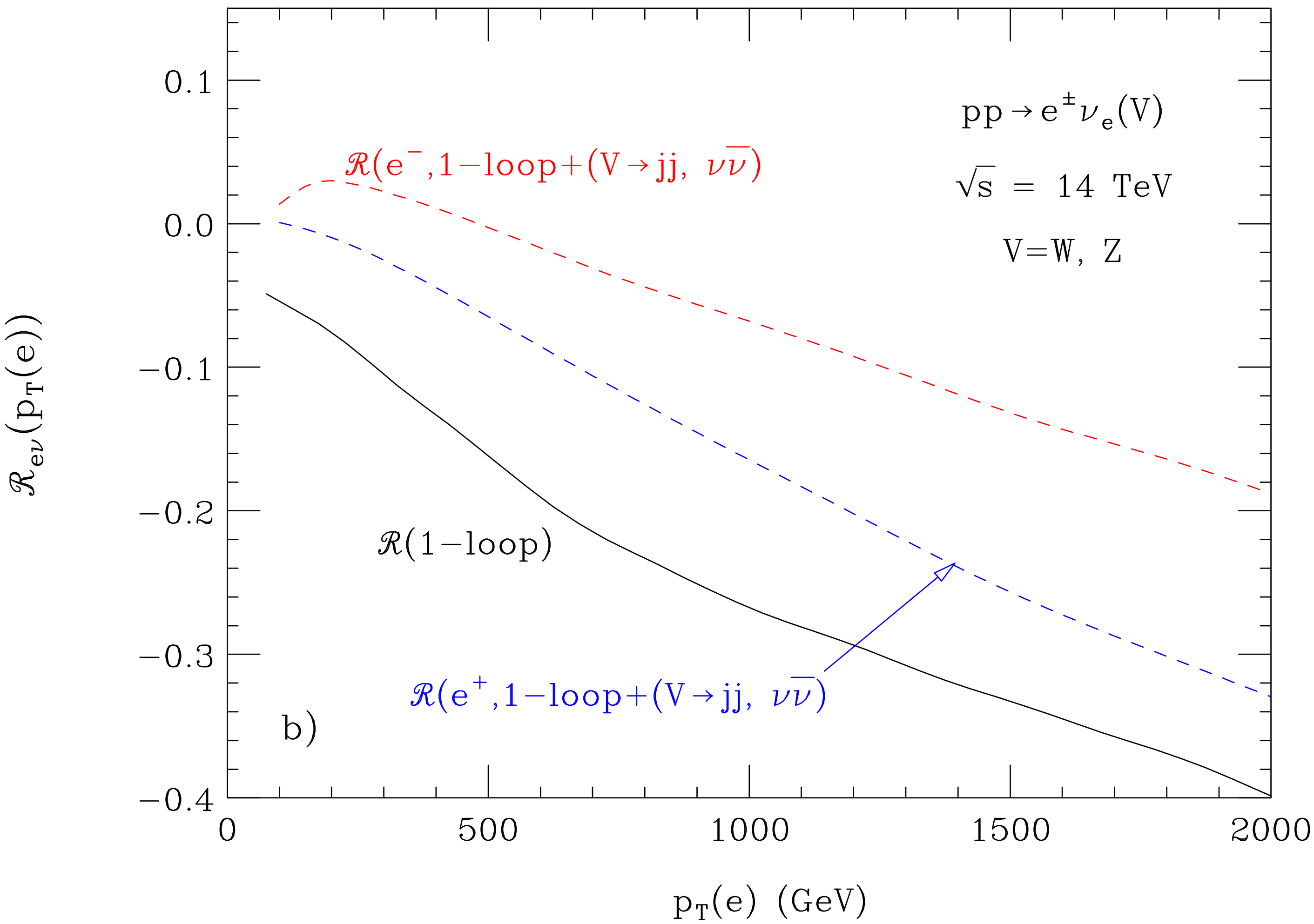


- virtual weak corrections become $\mathcal{O}(10\%)$ at very large M_T or p_T
- weak boson emission contribution small (about 1%) in the M_T distribution
- they are much larger (about 5%) in the $p_T(e)$ distribution
  reason: $e\nu$ necessarily off-shell in M_T distribution, but can be on-shell in p_T distribution

now the LHC...



0.0
−0.1
−0.2
−0.3
0
500
1000
1500
2000
$\mathcal{R}_{e\nu}(M_T)$
M_T (GeV)
$pp \to e^{\pm}\nu_e(V)$
$\sqrt{s}$ = 14 TeV
V=W, Z
$\mathcal{R}(e^-,1-loop+(V\to jj,\ \nu\bar{\nu}))$
$\mathcal{R}(1-loop)$
$\mathcal{R}(e^+,1-loop+(V\to jj,\ \nu\bar{\nu}))$
a)



$pp \to e^{\pm}\nu_e(V)$
$\sqrt{s}$ = 14 TeV
V=W, Z
$\mathcal{R}(e^-,1-loop+(V\to jj,\ \nu\bar{\nu})$
$\mathcal{R}(1-loop)$
$\mathcal{R}(e^+,1-loop+(V\to jj,\ \nu\bar{\nu})$
b)
$\mathcal{R}_{e\nu}(p_T(e))$
$p_T(e)$ (GeV)
0.1
0.0
−0.1
−0.2
−0.3
−0.4
0
500
1000
1500
2000

- At the LHC, the $e^+\nu$ and $e^-\nu$ cross sections are different ($\sigma(e^+\nu) \gg \sigma(e^-\nu)$ at high energies)
- The virtual corrections are proportional to the Born amplitude
  $\rightarrow$ relative corrections are equal for $e^+\nu$ and $e^-\nu$
- Since $e\nu W$ production dominates the weak boson emission processes, the relative corrections for $e^+\nu$ and $e^-\nu$ are different
- Weak boson emission effects for $e^-\nu$ are substantially larger
- Taking into account weak boson emission is clearly important

4 – Conclusions

- The size of the EW radiative corrections at hadron colliders depends on the experimental selection criteria
- In (partially) inclusive reactions, real EW radiative corrections may significantly reduce the effect of the $\mathcal{O}(\alpha)$ one-loop corrections
- Details depend on the process considered, and the distribution which is studied.