Electroweak Radiative Corrections to Weak Boson Production at Hadron Colliders

1. Introduction
2. Outline of Calculation
3. Phenomenological Consequences
4. Conclusions

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1 – Introduction

- Precise measurements have to be matched by precise theoretical predictions
- Expectations for electroweak measurements in Run II of the Tevatron:

  ☞ $\delta M_W \approx 40$ MeV per channel and experiment for 2 fb^{-1}

  ☞ $\delta\Gamma_W \approx 50$ MeV per channel and experiment for 2 fb^{-1} from tail of transverse mass distribution

  ☞ $\delta\sin^2\theta_W \approx 6\times 10^{-4}$ per channel and experiment for 10 fb^{-1}

  ☞ W/Z cross section ratio, $\mathcal{R}$, to $\approx 0.5\%$ (extract Γ_W)

  ☞ search for W' and Z'
- use σ_W as a luminosity monitor
- For these measurements, it is necessary to fully understand QCD and EWK radiative corrections to W and Z production

- QCD corrections: in good shape
  - ☞ $O(\alpha_s^2)$ for cross section
  - ☞ resummed W and Z p_T distributions are known
- EWK corrections
  - ☞ electroweak corrections shift W and Z masses by $O(100 \text{ MeV})$
  - ☞ same for Γ_W from tail of transverse mass (M_T) distribution
  - ☞ most of the effect comes from photon radiation
- (< 1997) (Berends, Kleiss (1985))
  - ☞ only final state corrections taken into account
  - ☞ soft and virtual $O(\alpha)$ corrections are estimated indirectly from the $O(\alpha^2)$ $W \to \ell\nu\gamma$, $Z \to \ell^+\ell^-\gamma$ width and the hard photon contribution
  - ☞ CDF's and DØ's guess-timate of uncertainty from unknown EWK corrections in Run I analyses: $\delta M_W \approx 20$ MeV

- recent developments:

  ☞ full $O(\alpha)$ QED corrections to Drell-Yan (Z) production (UB, S. Keller, W.K. Sakumoto)

  ☞ full $O(\alpha)$ electroweak corrections to Drell-Yan (Z) production (UB, O. Brein, W. Hollik, C. Schappacher, D. Wackeroth)

  ☞ $O(\alpha)$ electroweak corrections to W production in the pole approximation (UB, S. Keller, D. Wackeroth)

- this talk:

  ☞ outline calculation

  ☞ summarize recent results on full $O(\alpha)$ electroweak corrections to W production and its implications (S. Dittmaier, M. Krämer and UB, D. Wackeroth, in preparation)

2 – Outline of Calculation

- use W production as an example
- first step: use pole approximation (UB, S. Keller, D. Wackeroth)

  ☞ evaluate form factors which describe radiative corrections for $\hat{s} = M_W^2$

  ☞ ignore contributions which vanish for $\hat{s} = M_W^2$
- in pole approximation, the EWK corrections can be arranged in such a way that they correspond to gauge invariant sets describing initial state, final state and interference contributions (Hollik, Wackeroth)
- employ NLO Monte Carlo technique for calculation (recent review: Harris and Owens)

  ☞ isolate soft and collinear singularities associated with real photon emission.

  ☞ partition phase space into soft, collinear and finite regions by introducing theoretical cutoffs δ_s and δ_c

☞ for

$$E_\gamma < \delta_s \frac{\sqrt{\hat{s}}}{2}$$

evaluate $2 \to 3$ diagrams in soft photon approximation ($\sqrt{\hat{s}}$: parton CM energy)

☞ soft singularities from final state radiation (FSR) cancel against those from interference of Born and virtual final state corrections

☞ the same applies to initial state radiation (ISR) and interference effects

☞ for

$$E_\gamma > \delta_s \frac{\sqrt{\hat{s}}}{2}$$

use full $2 \to 3$ matrix elements. Evaluate via Monte Carlo.

- Collinear singularities

  ☞ Final state collinear singularities are regulated by finite lepton masses

  ☞ Initial state collinear singularities are universal to all orders and are absorbed into the parton distribution functions (PDF's), in complete analogy to QCD

- Evaluate matrix elements for

$$|\hat{t}|\,,\;\; |\hat{u}| < \delta_c \hat{s}$$

  ($\hat{t}$, $\hat{u}$: standard Mandelstam variables) in leading pole approximation

  ☞ factorize singularities into PDF's

  ☞ Evaluate remainder as part of $2 \to 2$ contribution

  ☞ for

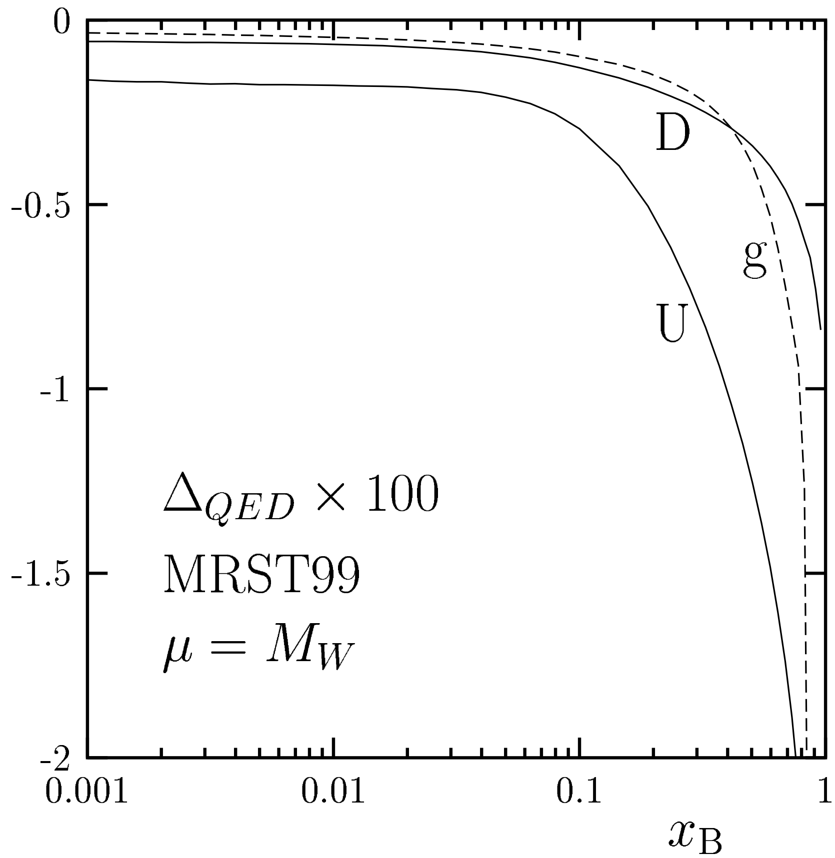
$$|\hat{t}|\,,\;\; |\hat{u}| > \delta_c \hat{s}$$

  evaluate full $2 \to 3$ matrix element

→ for a consistent treatment of the $O(\alpha)$ initial state corrections, QED corrections should be incorporated into the global fitting of PDF's.

☞ need QED corrections to PDF's

☞ QED corrections to PDF's are small except at large x (Spiesberger)



$[U = \sum_{gen}(u+\bar{u}), D = \sum_{gen}(d+\bar{d})]$

☞ also need QED corrections for all data sets used to fit PDF's

☞ Absorbing the collinear singularities into the PDF's introduces a QED factorization scheme dependence

☞ we performed our calculation in the QED $\overline{\text{MS}}$ and QED DIS schemes

☞ current global fits to the PDF's do not take into account QED corrections

→ strictly speaking our calculation is incomplete

☞ fortunately initial state corrections are small

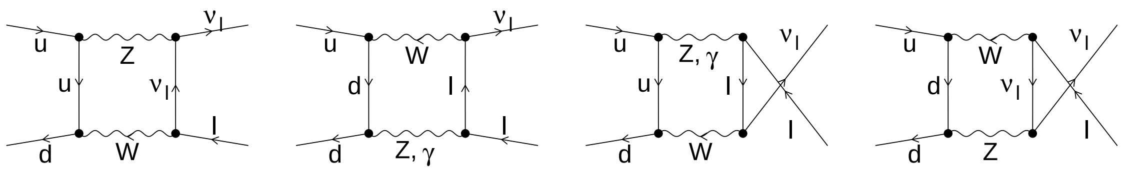
- final result

☞ two sets of weighted events corresponding to $2 \to 2$ and $2 \to 3$ contributions

☞ each set depends on δ_s and δ_c

☞ their sum must be independent of δ_s and δ_c (as long as these parameters are sufficiently small so that the soft photon and pole approximations hold)

- go beyond pole approximation
  - ☞ evaluate form factors for arbitrary $\hat{s}$
  - ☞ include leading $O(\alpha^2)$ corrections
  - ☞ include contributions which vanish at W pole (example: WZ box diagrams)



- matrix elements and cross sections for the full $O(\alpha)$ corrections to W production were published recently by Dittmaier and Krämer, PRD65, 073007 (April 2002).
  - ☞ DK vs BW comparison for Tevatron:

$p\bar{p} \to \nu_l l^+(+\gamma)$ at $\sqrt{s} = 2\,\text{TeV}$						
$p_{\text{T},l}/\text{GeV}$	25–∞	50–∞	75–∞	100–∞	200–∞	300–∞
σ_0/pb	407.03(5)	2.481(1)	0.3991(1)	0.1305(1)	0.006020(2)	0.0004821(1)
our result	407.02(7)	2.4817(6)	0.39926(9)	0.13058(3)	0.006017(2)	0.0004821(3)
$\delta_{\text{rec}}/\%$	−1.8(1)	−2.7(1)	−4.8(1)	−6.3(1)	−10.4(1)	−13.6(1)
our result	−1.70(6)	−2.56(8)	−4.75(8)	−6.14(8)	−10.17(14)	−13.44(22)
$\delta_{\text{rec,PA}}/\%$	−1.7(1)	−1.6(1)	−2.3(1)	−2.5(1)	−3.3(1)	−3.9(1)
our result	−1.71(6)	−1.60(8)	−2.24(8)	−2.42(8)	−3.24(14)	−3.96(22)

excellent agreement

- Drell-Yan production:

  ☞ use same phase space slicing method and treat collinear singularities as in W case

  ☞ perform calculation in ’t Hooft-Feynman gauge

  ☞ use dimensional regularization

  ☞ and the `ON-SHELL` renormalization scheme

3 – Phenomenological Consequences

- photonic effects:

☞ use Drell-Yan production as example

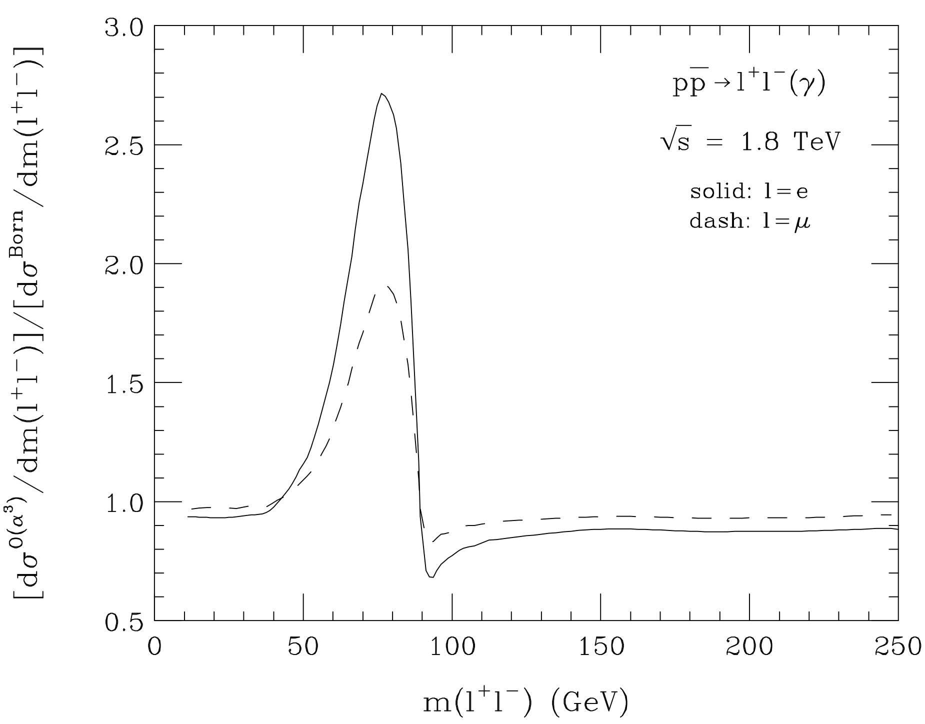
☞ for simplicity, only take QED corrections into account for the moment

☞ FSR terms dominate: they are proportional to

$$\frac{\alpha}{\pi} \log\left(\frac{\hat{s}}{m_\ell^2}\right)$$

→ these terms significantly influence the $\ell^+\ell^-$ invariant mass distribution

☞ Tevatron:



- integrating over $m(\ell\ell)$, the large positive and negative corrections cancel (KLN theorem)
- Detector effects may significantly influence the QED corrections:

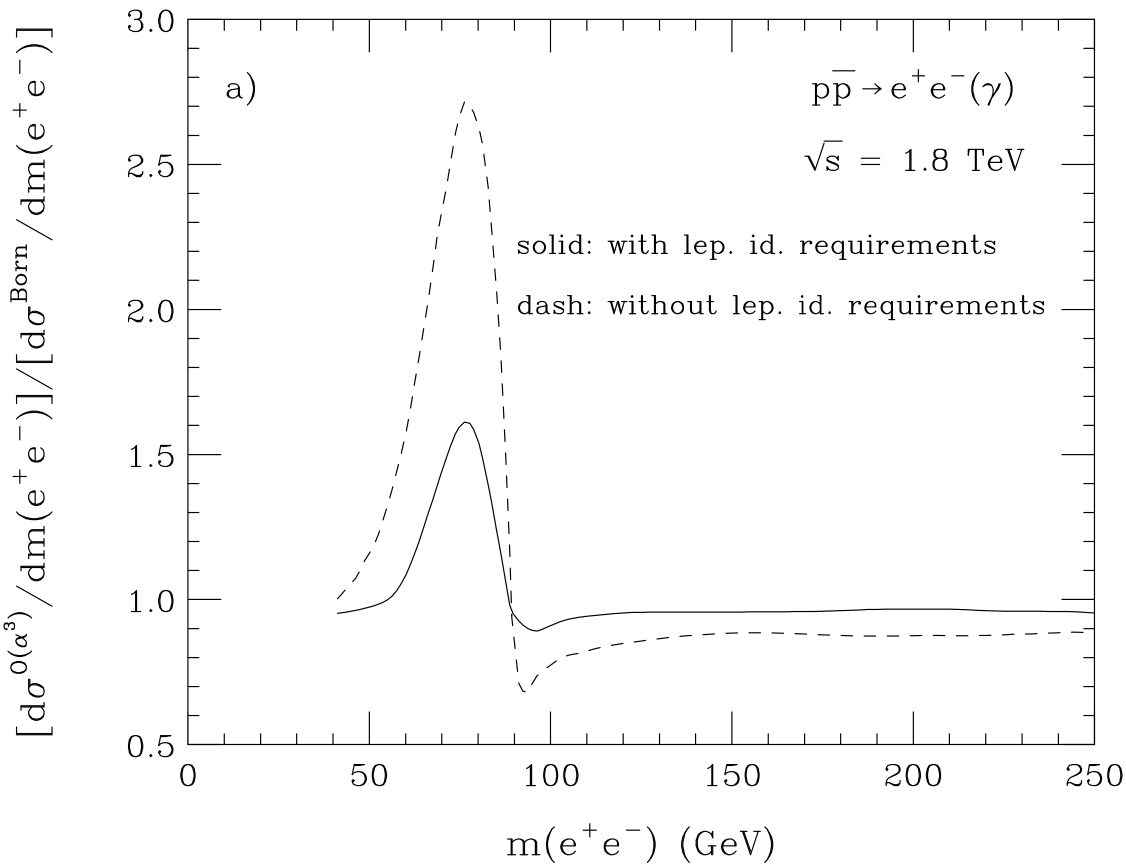
☞ It is difficult to discriminate electrons and photons which hit the same calorimeter cell

→ recombine e and γ momenta to an effective electron momentum in that case

→ an inclusive quantity is formed

→ the mass singular terms ($(\alpha/\pi)\log(\hat{s}/m_\ell^2)$) disappear (KLN again ...)

→ the effect of the QED corrections is reduced

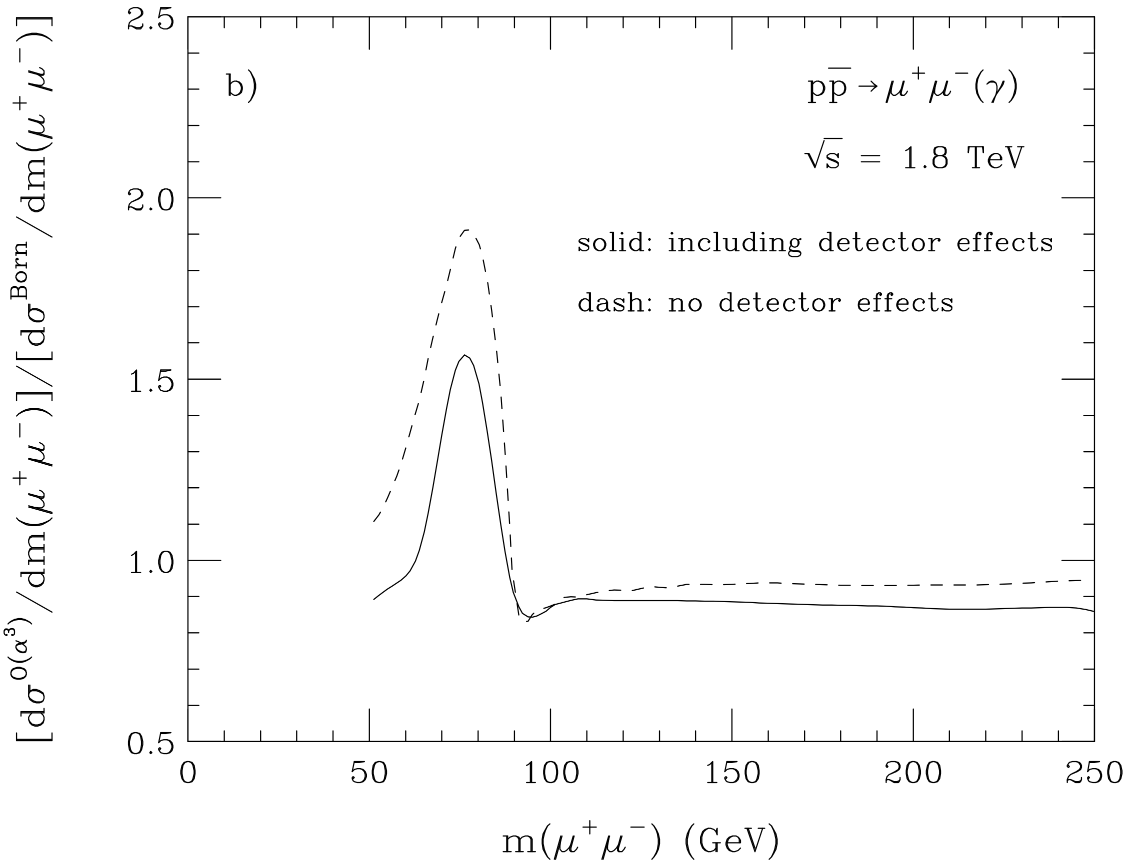

a)
$p\bar{p} \to e^+e^-(\gamma)$
$\sqrt{s}$ = 1.8 TeV
solid: with lep. id. requirements
dash: without lep. id. requirements
$[d\sigma^{O(\alpha^3)}/dm(e^+e^-)]/[d\sigma^{Born}/dm(e^+e^-)]$
$m(e^+e^-)$ (GeV)
0.5
1.0
1.5
2.0
2.5
3.0
0
50
100
150
200
250

☞ Muons must be consistent with a minimum ionizing particle

→ require $E_\gamma < 2$ GeV in cell traversed by muon

→ this reduces the hard photon part

→ the mass singular terms survive



- non-photonic effects: use corrections ignored in pole approximation of W production as an example:

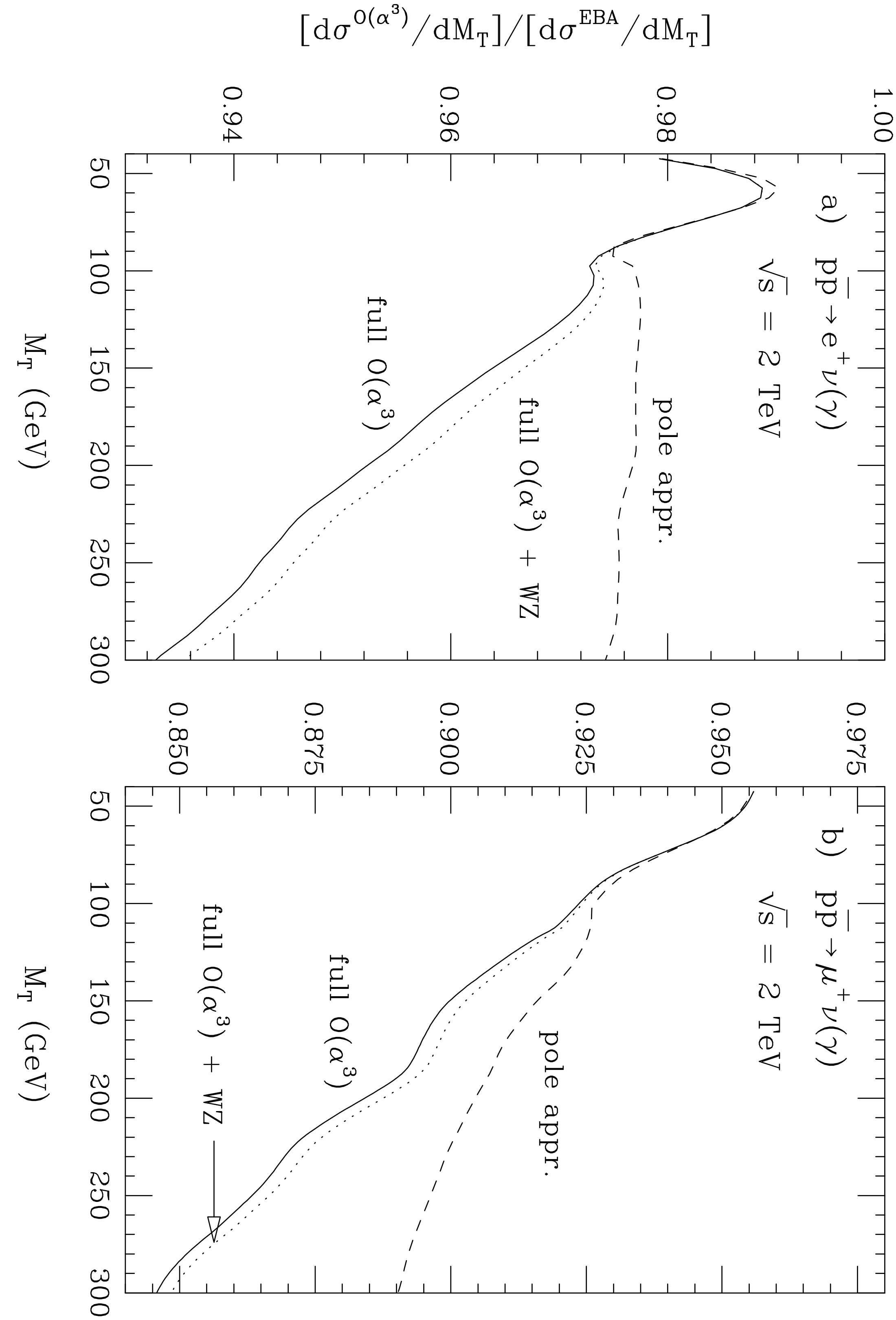
  ☞ change W cross section by $< 0.1\%$

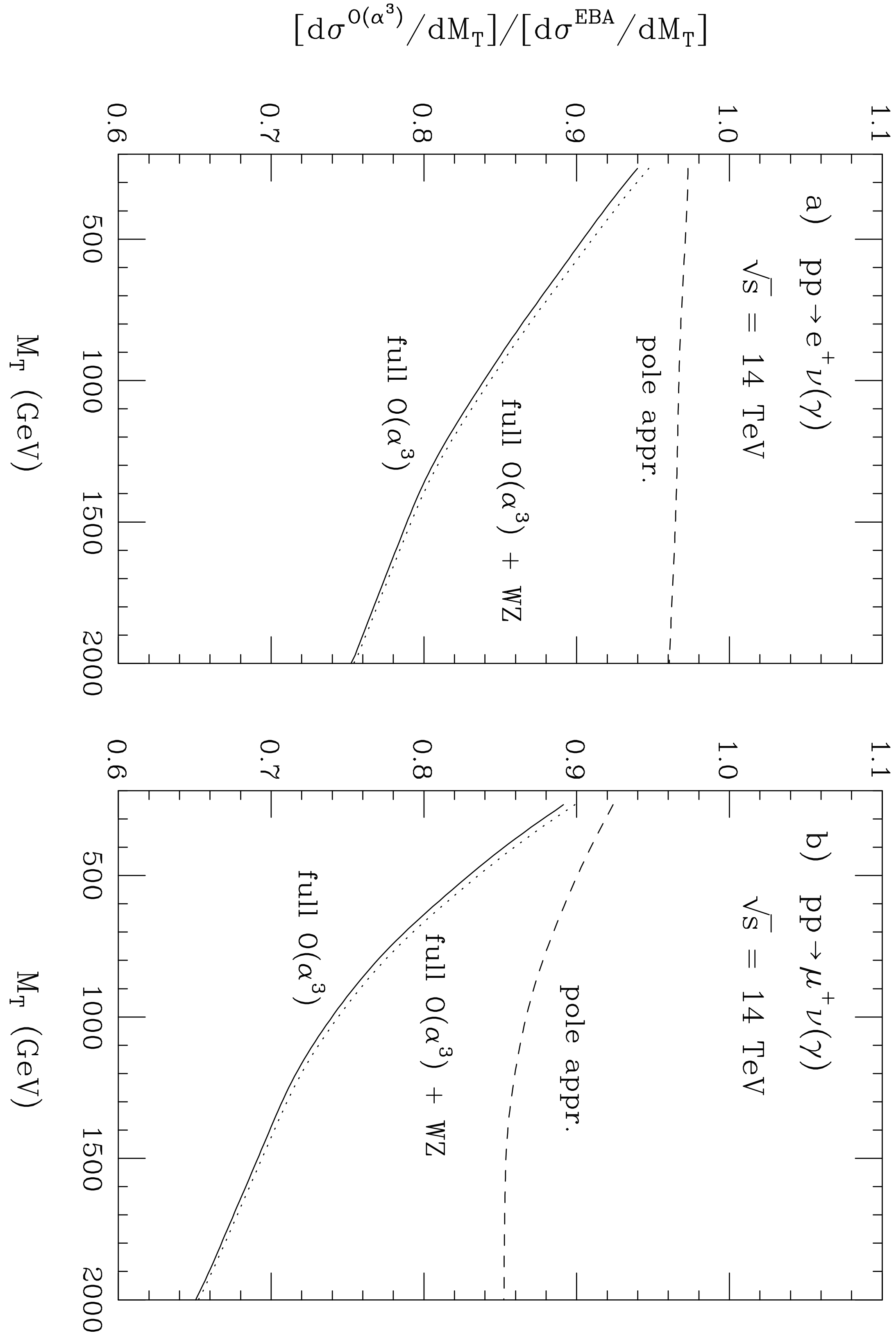
  ☞ become large and negative in high M_T tail

  → may have significant impact on Γ_W measured from tail of M_T distribution

- $O(\alpha^3)$ M_T distribution normalized to M_T distribution in enhanced Born approximation (EBA) at Tevatron and LHC

  ☞ slight bump in μ case at the Tevatron is due to WZ box threshold effects


[dσ^O(α³)/dM_T]/[dσ^EBA/dM_T]
a) pp̄→e⁺ν(γ)
√s = 2 TeV
pole appr.
full O(α³) + WZ
full O(α³)
M_T (GeV)
b) pp̄→μ⁺ν(γ)
√s = 2 TeV
pole appr.
full O(α³)
full O(α³) + WZ
M_T (GeV)



$[d\sigma^{O(\alpha^3)}/dM_T]/[d\sigma^{EBA}/dM_T]$
a) $pp \to e^+\nu(\gamma)$
$\sqrt{s}$ = 14 TeV
pole appr.
full $O(\alpha^3)$ + WZ
full $O(\alpha^3)$
b) $pp \to \mu^+\nu(\gamma)$
$\sqrt{s}$ = 14 TeV
pole appr.
full $O(\alpha^3)$ + WZ
full $O(\alpha^3)$
M_T (GeV)
M_T (GeV)
0.6
0.7
0.8
0.9
1.0
1.1
500
1000
1500
2000

- reason: terms $\sim \alpha \log^2(\hat{s}/M_W^2)$ from vertex and box corrections
  ☞ need to resum?
  ☞ certainly for the LHC this is necessary

- the large invariant mass region is interesting to probe for deviations from the SM (large extra dimensions, compositeness, etc.)

- impact on W width measurement
  ☞ recall form of Breit-Wigner:

$$\frac{1}{(\hat{s} - M_W^2)^2 + \Gamma_W^2 \hat{s}^2/M_W^2}$$

  ☞ sensitivity to Γ_W comes from region where $\sqrt{\hat{s}} - M_W \sim \Gamma_W$
  ☞ cross section at peak scales like $1/\Gamma_W^2$ but this is washed out by detector resolution effects
  ☞ σ_W scales like $1/\Gamma_W$

☞ ratio

$$\frac{\{[d\sigma/dM_T]/\sigma_W\}_{\Gamma_W}}{\{[d\sigma/dM_T]/\sigma_W\}_{\Gamma_W^{SM}}} \sim \frac{\Gamma_W}{\Gamma_W^{SM}}$$

at high values of M_T

- now suppose one compares data with pole approximation

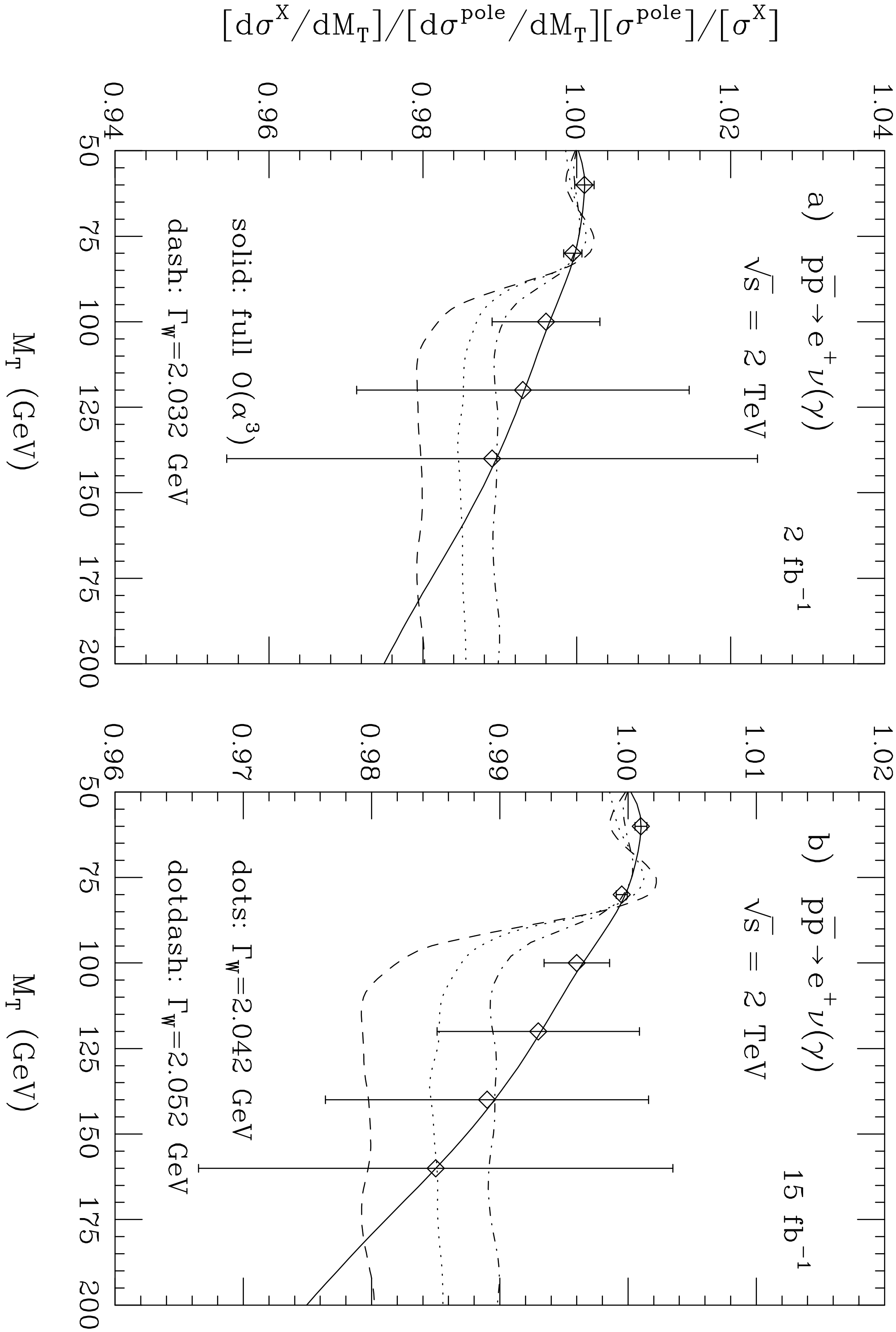
  ☞ compare shapes of M_T distributions by using normalized distributions

  ☞ for input parameters chosen, $\Gamma_W^{SM} = 2.072$ GeV

  ☞ size of corrections ignored in pole approximation is of the same order as effects caused by non-SM values of Γ_W in the range accessible in Run II

- ignoring these corrections shifts Γ_W by about -0.5% $(-10$ MeV$)$

  ☞ this is not negligible compared with the expected precision in Run II (40 MeV/channel/exp.)



[dσ^X/dM_T]/[dσ^pole/dM_T][σ^pole]/[σ^X]
a) pp̄→e⁺ν(γ)
√s = 2 TeV
2 fb⁻¹
solid: full O(α³)
dash: Γ_W=2.032 GeV
b) pp̄→e⁺ν(γ)
√s = 2 TeV
15 fb⁻¹
dots: Γ_W=2.042 GeV
dotdash: Γ_W=2.052 GeV
M_T (GeV)

4 – Conclusions

- Calculations of the full $O(\alpha)$ corrections to Z and W production now exist
- These calculations are essential ingredients for Run II and LHC precision electroweak measurements
- the electroweak corrections become large at high energies
- in the W case they will play a role in the determination of the W width from the tail of the transverse mass distribution