Theoretical Challenges (not just) for a Measurement of M_W at the Tevatron and LHC

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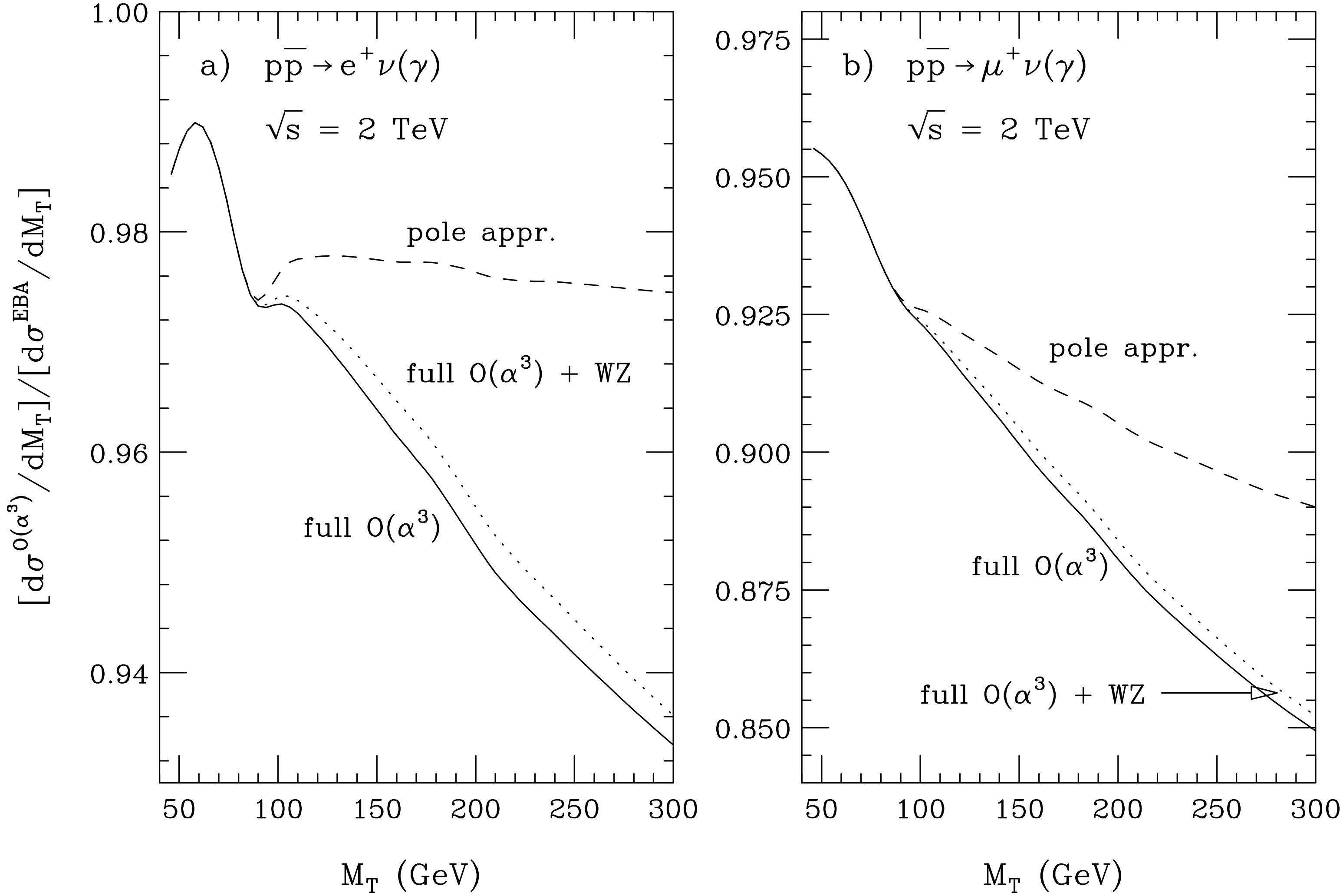
1 – Introduction

- 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)
- use σ_W as a luminosity monitor
- most important of these measurements: M_W
  ☞ together with m_{top} determines indirect bounds on Higgs boson mass

- For these measurements, it is necessary to fully understand QCD and EWK radiative corrections to W and Z production
- QCD corrections: in good shape
  - ☞ $\mathcal{O}(\alpha_s^2)$ for cross section
  - ☞ resummed W and Z p_T distributions are known (RESBOS)
- EWK corrections
  - ☞ electroweak corrections shift W and Z masses by $\mathcal{O}(100\text{ MeV})$
  - ☞ same for Γ_W from tail of transverse mass (M_T) distribution
  - ☞ most of the effect comes from final state photon radiation
  - ☞ however, for anticipated precision it is important to understand the complete $\mathcal{O}(\alpha)$ corrections
  - ☞ need to understand EWK corrections for W and Z production:
  - → Measuring M_Z and Γ_Z helps to calibrate detector

2 – Status of Theoretical Calculations

- The complete $\mathcal{O}(\alpha)$ corrections to W and Z boson production are now known (Dittmaier, Krämer, UB, Wackeroth et al.) and available in form of parton level MC programs (`WGRAD` and `ZGRAD`)
- highlights:
  - ☞ EW radiative corrections significantly change the shape of the W transverse mass M_T distribution
  - ☞ this leads to a shift in the W mass extracted from data
  - ☞ for $M_T < M_W$, the contributions from non-resonant diagrams, such as the WZ box diagrams is negligible
  - ☞ the non-resonant contributions become large and negative above the W resonance region (proportional to $\alpha \log^2(\hat{s}/M_W^2)$, Sudakov logs)



dashed: evaluate weak form factors for $\hat{s} = M_W^2$

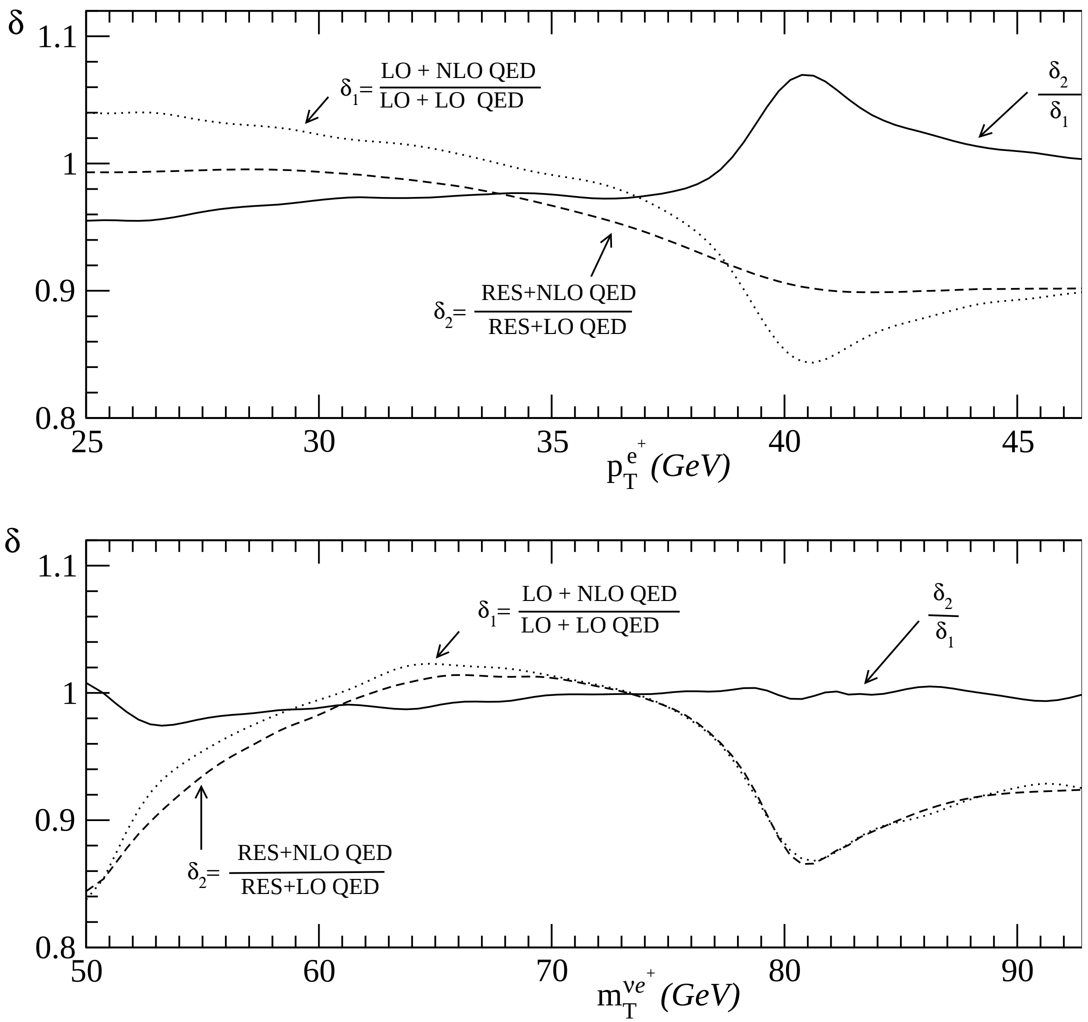
- the non-resonant radiative corrections shift the W width extracted from the high M_T tail by

$$\delta\Gamma_W \approx -7.2 \text{ MeV}$$

- $\mathcal{O}(\alpha)$ correction to Z production qualitatively similar to W case:
  - ☞ affect the Breit-Wigner shape of Z resonance
  - ☞ shift the Z mass; the effect is about a factor 2 larger than in W case (both leptons can radiate photons)
  - ☞ the purely weak corrections become large and negative for large di-lepton invariant masses
  - ☞ include $\mathcal{O}(G_F^2 m_t^2 M_W^2)$ corrections to $\sin^2\theta_{eff}$ to ensure that same theoretical input as in LEP analysis is used

- WGRAD/ZGRAD do not include QCD corrections
- RESBOS does not include electroweak radiative corrections
- for W mass analysis one needs a calculation which includes both
- first step in that direction: RESBOS-A (Cao, Yuan)
  - ☞ RESBOS + final state photon radiation from W decay lepton (dominant contribution to W mass shift)

- impact on transverse momentum distribution of lepton and M_T distribution

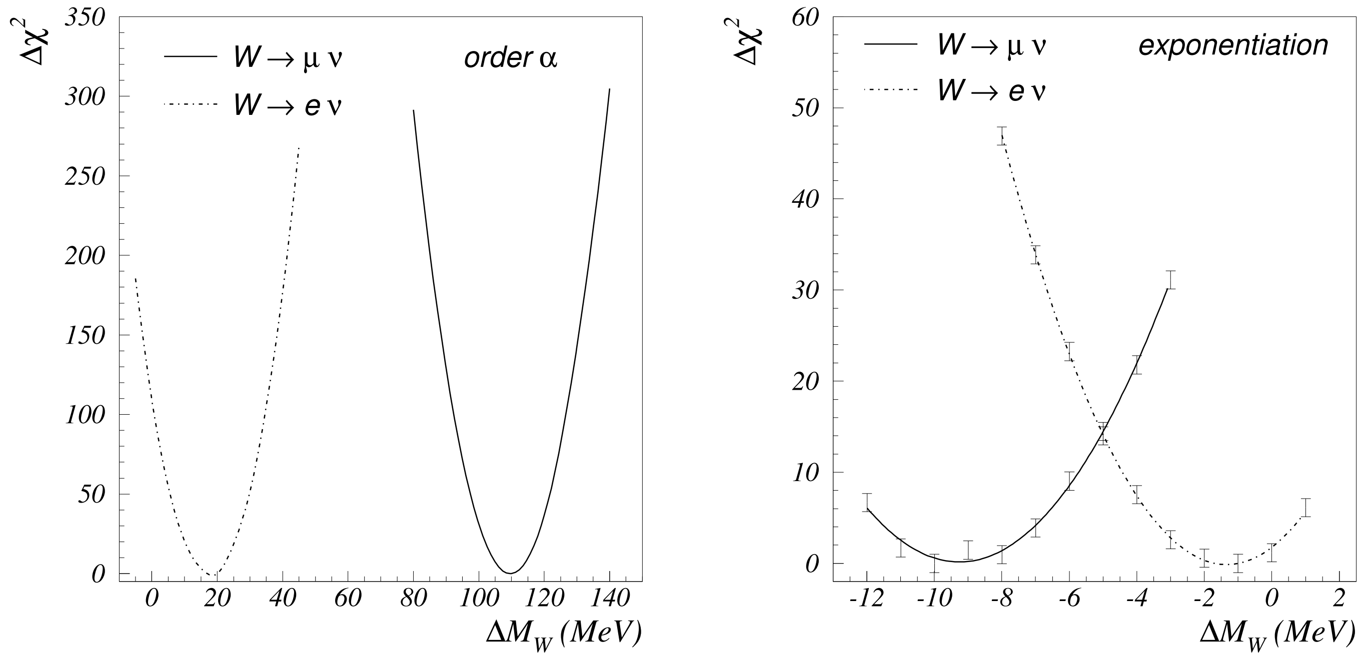


- effect of combined QCD$\oplus$EWK corrections on lepton p_T distribution is $\neq$LO + QCD corr. + EWK corr
- but effect of combined QCD$\oplus$EWK corrections on M_T distribution is $\approx$LO + QCD corr. + EWK corr:
  reason: M_T distribution is invariant under transverse boosts to first order in velocity

- since final state photon radiation shifts W mass by $\mathcal{O}(100)$ MeV:
  - ☞ need to worry about multiple (final) state photon radiation in W *and* Z production
  - ☞ effect should be more pronounced in Z case since both final state leptons radiate
  - ☞ two photon radiation is known to significantly change the shape of the $m(\ell\ell)$ and M_T distributions (UB, Stelzer)

- recent progress in incorporating multi-photon radiation: two approaches
  - ☞ YFS exclusive exponentiation (Jadach, Placzek)
    - → currently only at parton level and for W decay
    - → procedure used is gauge invariant
  - ☞ QED structure function approach (Montagna et al.)
    - → only final state corrections are presently incorporated
    - → procedure used is not gauge invariant
    - → however, terms violating gauge invariance are (probably) numerically small ($< 0.1\%$)
- Montagna et al. calculate shift in M_W using simplified detector model:
  - → combine e and γ momenta for $\Delta R(e,\gamma) < 0.2$
  - → reject μ events if $E_\gamma > 2$ GeV and $\Delta R(\mu,\gamma) < 0.2$

☞ result:



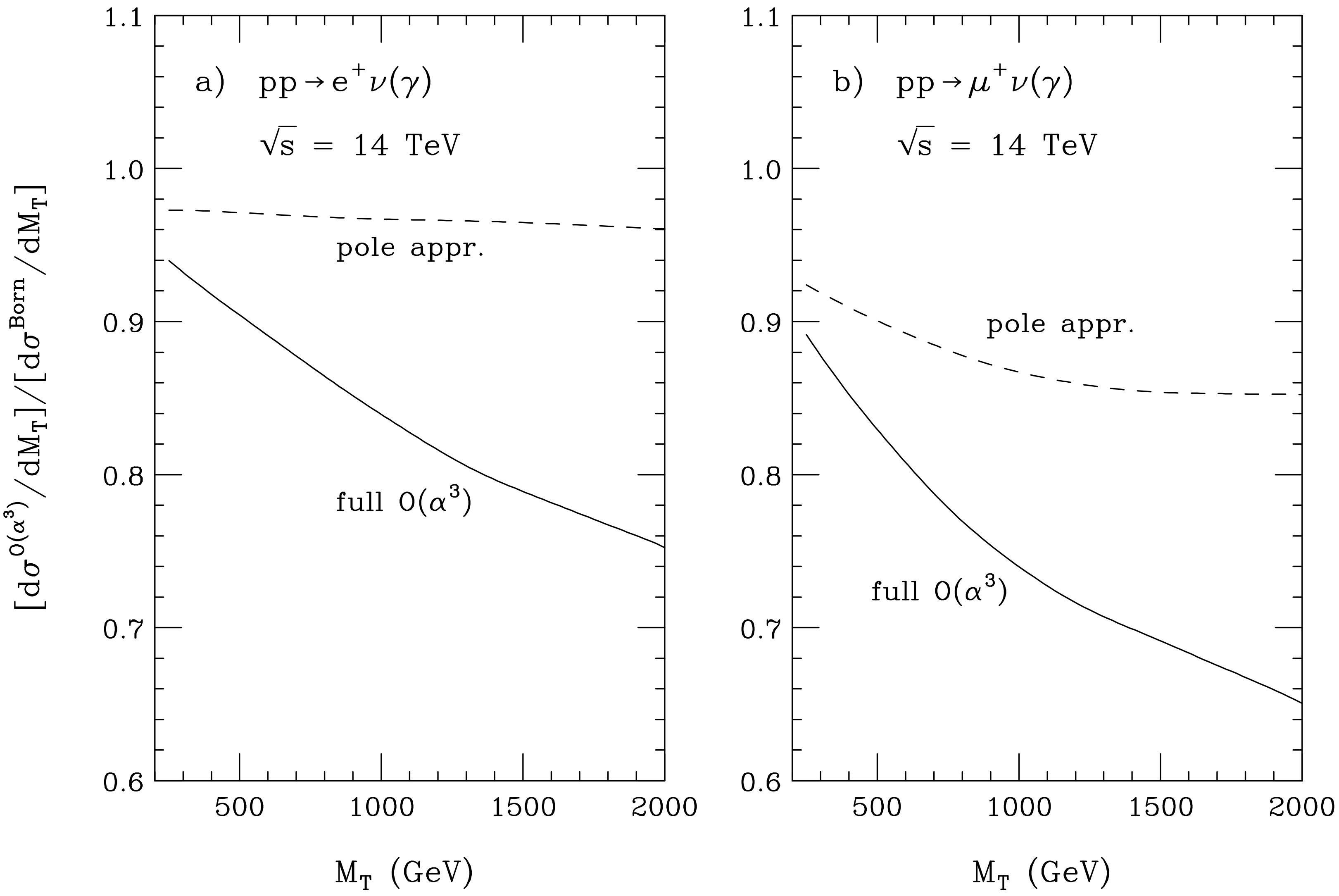
☞ shift of M_W caused by multi-photon radiation is about 10% of that caused by one photon radiation

☞ Note: absolute value of shift caused by $\mathcal{O}(\alpha)$ corrections smaller than value observed by CDF/DØ, due to simplified detector model

☞ expect larger shifts in Z case (two final state radiators)

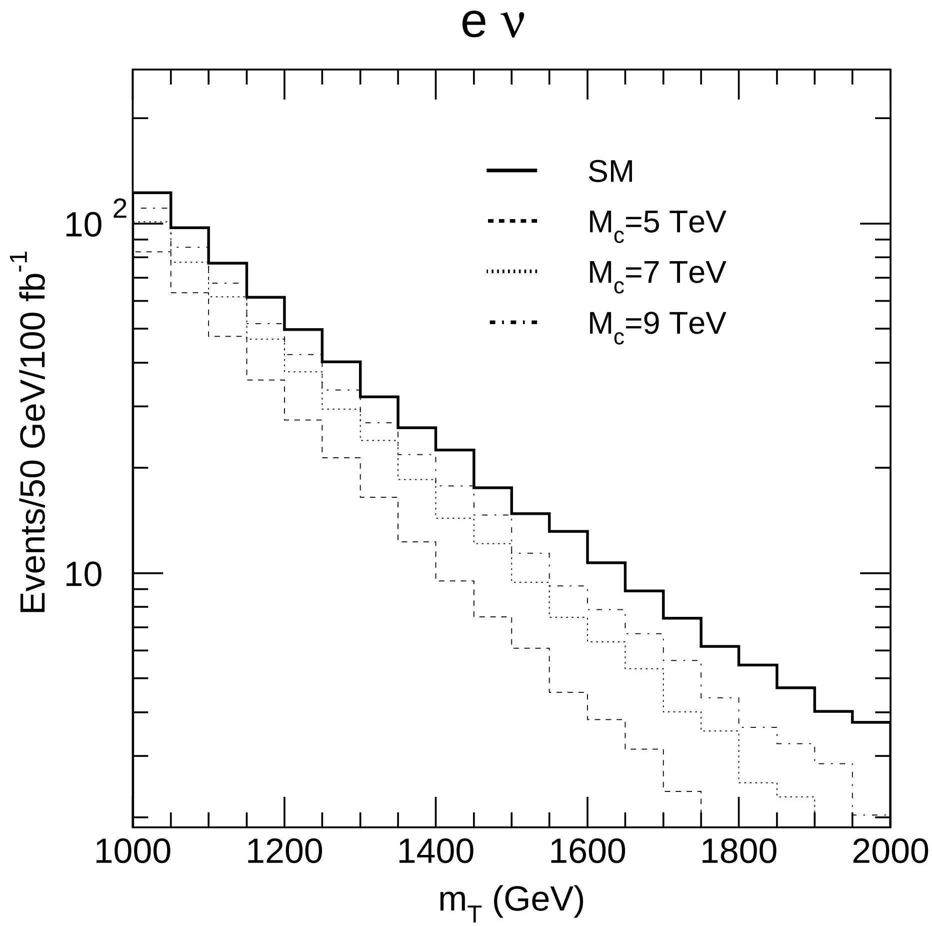
3 – What remains to be done

- we plan to incorporate multi-photon effects in `WGRAD` and `ZGRAD` using a YFS approach similar to that used by Jadach et al.
- need more complete calculation of QCD$\oplus$EWK corrections; `RESBOS-A` is only the first step
- weak corrections become large and negative at large transverse masses (W) or di-lepton masses (Z) (Sudakov logs prop. to $\alpha \log(\hat{s}/M^2_{W,Z})$)
  ☞ at LHC energies, these terms have to be resummed (not done yet)



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

- important for new physics searches:
  - ☞ example: KK excitations of W boson: a slight reduction in cross section could signal a heavy KK excitation beyond reach for direct production (Polesello, Prata)

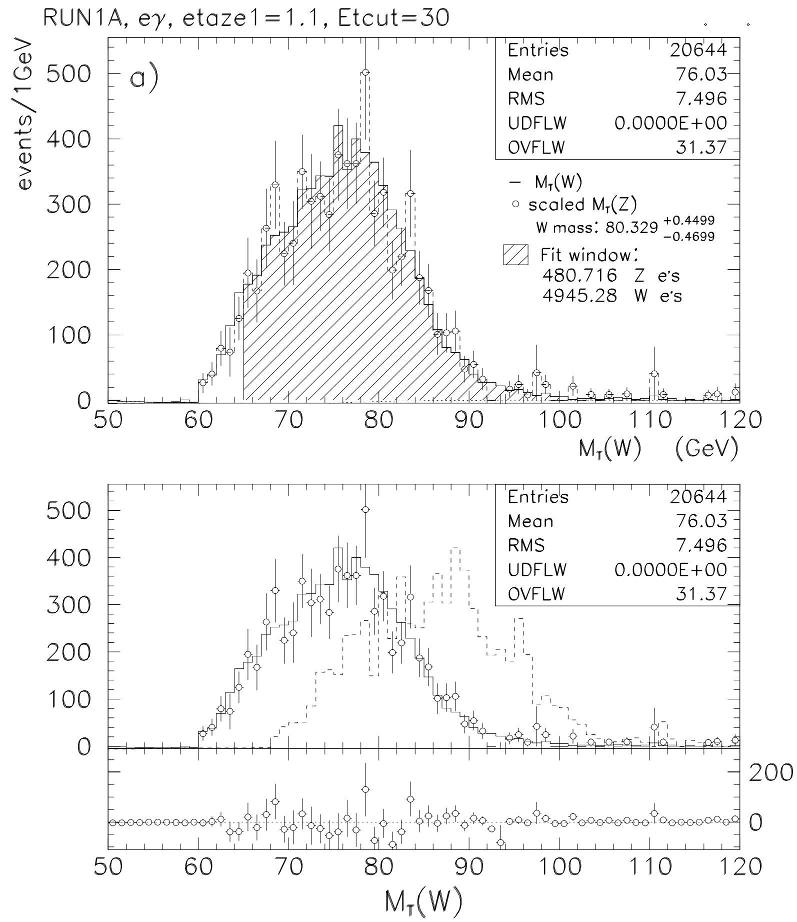


4 – Reviving the M_T^W/M_T^Z Ratio Method for the LHC

- method goes back to W. Giele, S. Keller, M. Rijssenbeek, and S. Rajagopalan; recently reconsidered for LHC by Alexander Schmidt (Karlsruhe) (for μ final state only)
- basic idea:
  - ☞ use ratio of W to Z transverse masses
  - ☞ advantage: many systematic effects cancel in ratio
  - ☞ interesting for LHC: don't need to know detailed detector response → can do M_W measurement more quickly?
  - ☞ disadvantage: statistical uncertainty dominated by Z statistics
  - ☞ must scale Z mass down to M_W
  - ☞ extract M_W/M_Z and take M_Z from LEP measurement

- need to correct for different resolutions, efficiencies and acceptances in W (ν in final state) and Z case (2nd charged lepton in final state)

- proof of principle: DØ Run I analysis



- ratio method:

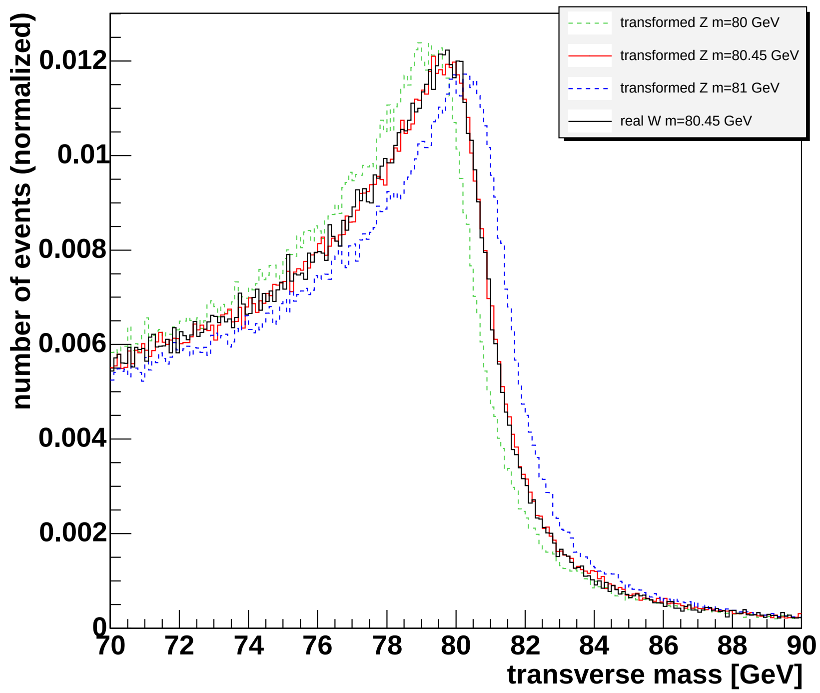
$$M_W = 80.115 \pm 0.211\ (\text{stat.}) \pm 0.050\ (\text{syst.})\ \text{MeV}$$

- M_T line fit (DØ only):

$$M_W = 80.440 \pm 0.070\ (\text{stat.}) \pm 0.096\ (\text{syst.})\ \text{MeV}$$

- larger statistical, but much smaller systematic uncertainties
- ratio method competitive for $\geq 15\ \text{fb}^{-1}$ at Tevatron (Snowmass 2001)
  ☞ not so interesting

- LHC (A. Schmidt):



- expected uncertainty: $\delta M_W \approx 10$ MeV for 10 fb^{-1}
- from M_T distribution: $\delta M_W \approx 15$ MeV for 10 fb^{-1}. To achieve this: must know lepton energy scale to 0.02%, ie. solenoid field to $\sim 0.1\%$ and alignment locally to $\sim 1\mu m$

☞ ratio method shows clear advantage

5 – Conclusions

- Calculations of the full $\mathcal{O}(\alpha)$ 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
- need unified generator which includes resummed QCD corrections, $\mathcal{O}(\alpha)$ EWK corrections and resummed final state photon radiation effects
- the M_T^W/M_T^Z ratio method looks promising for the LHC
  ☞ reconsider for Run II?