Electroweak Radiative Corrections and Future Colliders

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Ulrich Baur
State University of New York at Buffalo

1 – Why are Electroweak Radiative Corrections important?

- Precise measurements have to be matched by precise theoretical predictions

  ☞ present and future collider experiments aim at measuring observables (cross section, mass, width,...) at the % level or better

  ☞ need to take into account higher order corrections

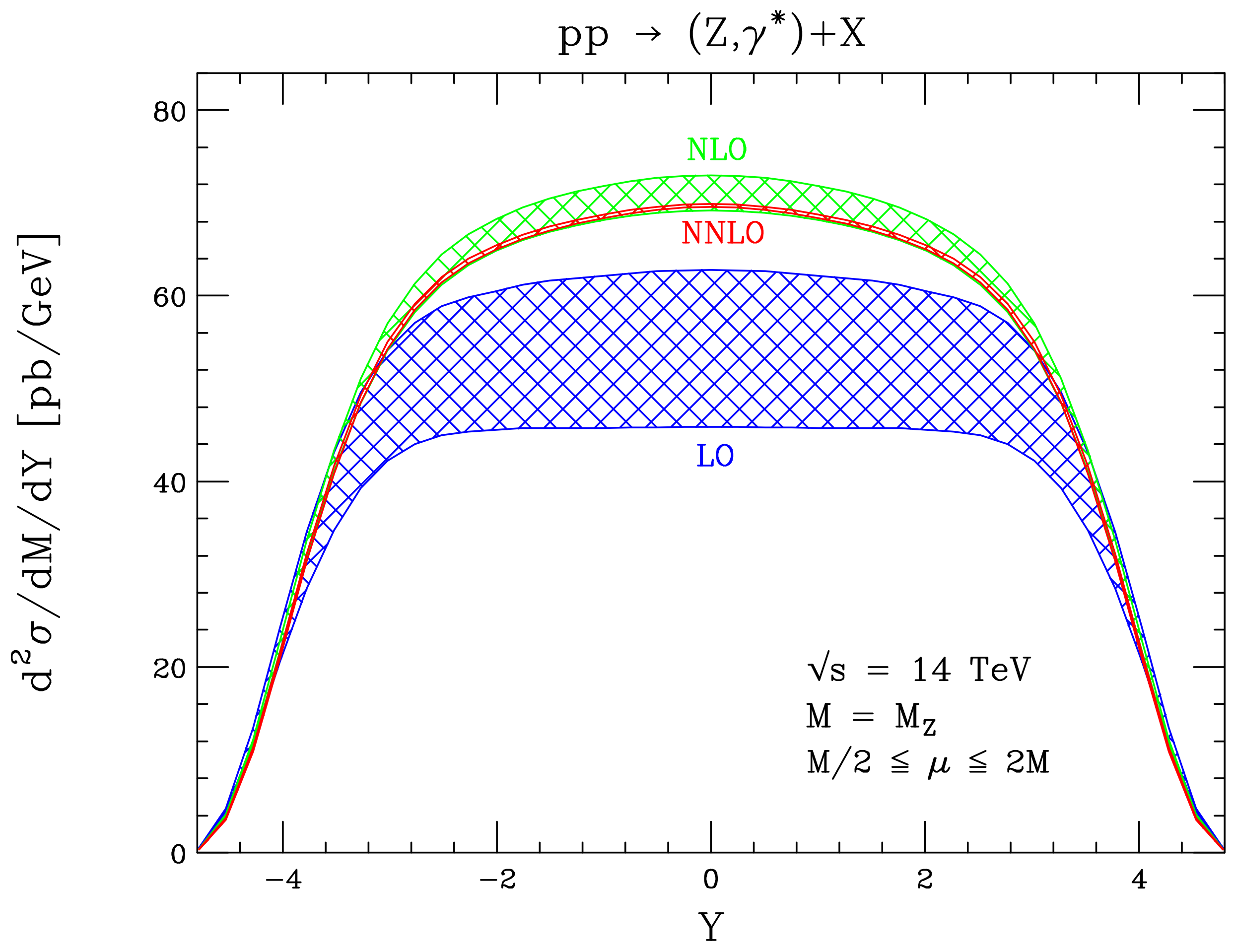
- QCD corrections:

  ☞ NLO: typically $20 - 30\%$

  ☞ NNLO: typically a few %

  ☞ taking into account QCD corrections reduces (sometimes dramatically) the renormalization and factorization scale uncertainty

☞ example: Z boson rapidity distribution (Anastasiou, Dixon, Melnikov, Petriello)

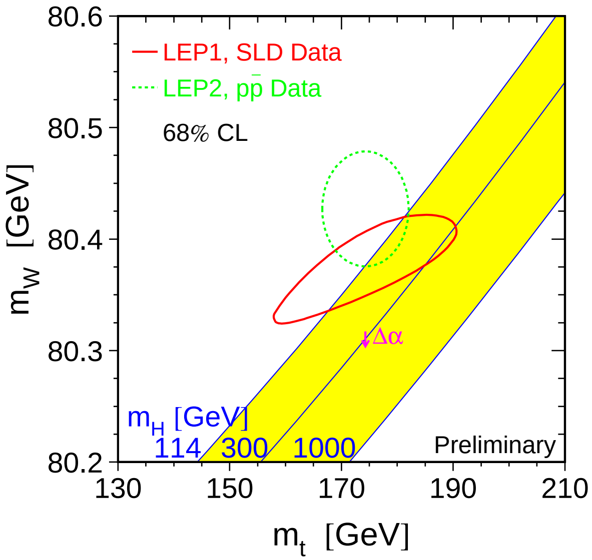


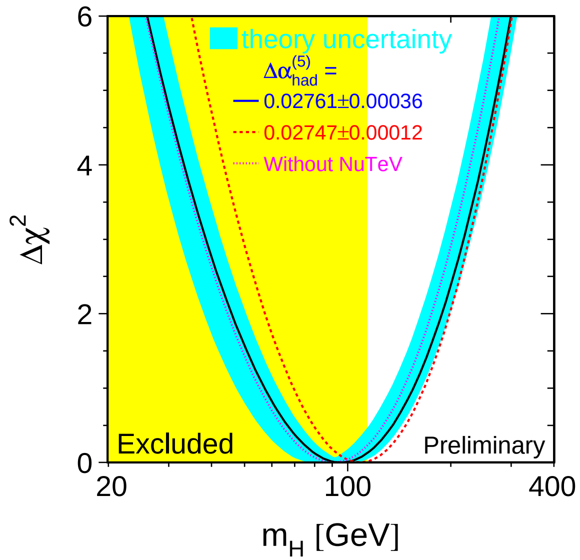
- electroweak radiative corrections:
  - ☞ 1-loop: naively of $\mathcal{O}(\alpha) \leq 1\%$
  - ☞ why bother?
- possible exceptions:
  - ☞ logarithmic enhancement factors
  - → collinear: $\log(\hat{s}/m_f^2)$,
  - → Sudakov: $\log(\hat{s}/M_{W/Z}^2)$
  - ☞ QCD corrections are small (example: W/Z cross section ratio)
  - ☞ and/or very precise measurements (M_W, $\sin^2\theta_{eff}$)
- in some cases need $\geq$ 2-loop EWK corrections
  - ☞ should be able to make use of techniques developed for NNLO QCD corrections

2 – M_W, $\sin^2\theta_{eff}$ and M_H

- 1-loop corrections to M_W and $\sin^2\theta_{eff}$ depend quadratically on the top quark mass, m_t, and logarithmically on M_H

  ☞ measuring M_W ($\sin^2\theta_{eff}$) and m_t one can extract information on M_H





- fit results depend on
  - ☞ experimental uncertainties
  - ☞ and theoretical uncertainties

  ➞ primordial theoretical uncertainties: associated with the extraction of (pseudo)observable from measured quantities

  example: M_W from transverse mass distribution

  ➞ intrinsic theoretical uncertainties: from unknown higher order corrections

  example: "blueband"

Experimental Uncertainties: Looking into the Crystal Ball

	present	Tev. run2	LHC	LC	GigaZ
$\delta \sin^2\theta_{eff}$ ($\times 10^{-5}$)	14	63	14 – 20	6	1.3
δM_W [MeV]	34	27	10 – 15	10	7
δm_t [GeV]	5.1	2.7	1.0	0.2	0.13
$\delta M_H/M_H$ (indirect)	60%	35%	20%	15%	8%

- need intrinsic theoretical uncertainties which are considerably smaller than experimental uncertainties
- estimate size of missing higher order corrections to M_W and $\sin^2\theta_{eff}$ (Erler)
  - ☞ collect all relevant enhancement and suppression factors
  - ☞ set remaining coefficient (from loop integrals) to unity
  - ☞ choose largest group theory factor

- estimate largest theoretical uncertainties come from
  ☞ $\mathcal{O}(\alpha^2\alpha_s)$ corrections for M_W (Awramik et al.)
  ☞ $\mathcal{O}(\alpha^2)$ corrections for $\sin^2\theta_{eff}$

- estimated intrinsic theoretical uncertainty

$$\delta M_W^{th} \approx 4~\text{MeV} \qquad \delta\sin^2\theta_{eff} \approx (6-7)\times 10^{-5}$$

- new results on $\mathcal{O}(\alpha^2)$ corrections for $\sin^2\theta_{eff}$ at LoopFest III?

- ultimate goal: bring intrinsic theoretical uncertainties down to
  ☞ $\mathcal{O}(1~\text{MeV})$ for M_W
  ☞ and $\mathcal{O}(\text{few}\times 10^{-6})$ for $\sin^2\theta_{eff}$
  → if we want GigaZ option

- probably need full 3-loop corrections to $\sin^2\theta_{eff}$ and $\mathcal{O}(\alpha^2\alpha_s)$ corrections to M_W

3 – Electroweak Radiative Corrections to W and Z Boson Production

- example for primordial theoretical uncertainties
- for W mass measurement, need radiative corrections for W and Z boson production:
  - ☞ $Z \to \ell^+\ell^-$ data constrain lepton scale and resolution
  - ☞ calibrate using using LEP data
  - ☞ need to use the same theoretical input that has been used to extract Z parameters at LEP:

    → include QED corrections (change the Z mass extracted from data)

    → include purely weak corrections

    → include $\mathcal{O}(G_F^2 m_t^2 M_W^2)$ corrections to $\sin^2\theta_{eff}$

- Treatment of 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

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

→ 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

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

☞ fortunately initial state corrections are small:

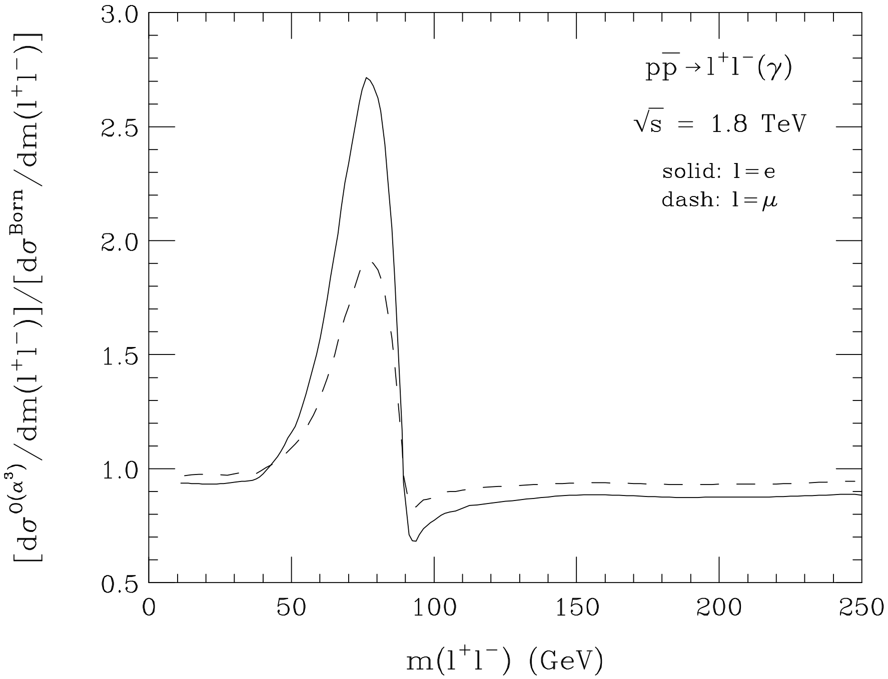
→ QED corrections to PDF's can be neglected at present stage

- 1-loop EWK corrections shift W and Z masses by $\mathcal{O}(100\text{ MeV})$
  - ☞ most of the effect comes from final state photon radiation
  - ☞ proportional to

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

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

  - ☞ taking only QED corrections into account



- 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

☞ 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

- calculations of the complete $\mathcal{O}(\alpha)$ EWK corrections to

  ☞ $p \overset{(-)}{p} \to W^{\pm} \to \ell^{\pm}\nu$ (Dittmaier+Krämer, UB+Wackeroth)

  ☞ and $p \overset{(-)}{p} \to \gamma, Z \to \ell^{+}\ell^{-}$, including $\mathcal{O}(G_F^2 m_t^2 M_W^2)$ corrections to $\sin^2\theta_{eff}$ (UB et al.) exist now

- if 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 taking multi-photon radiation into account: 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

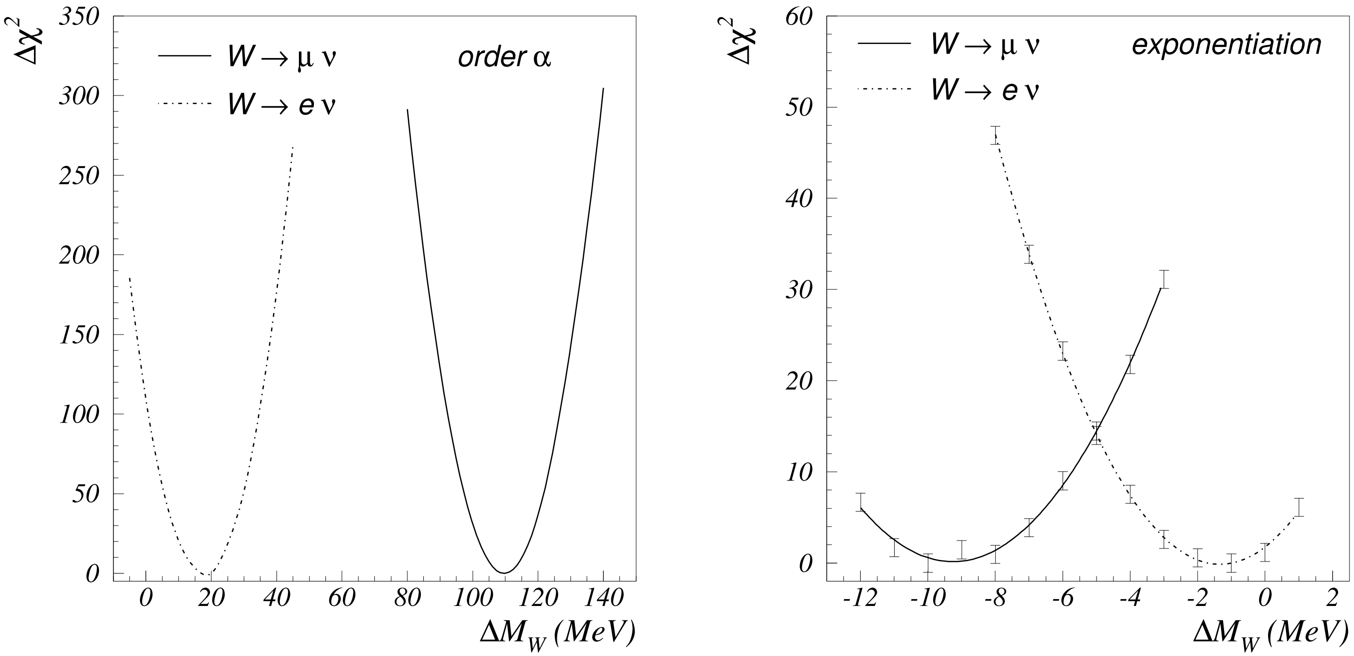
  ➞ however, terms violating gauge invariance are numerically small ($< 0.1\%$)

- 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)

- for W mass analysis need calculation of W and Z production including electroweak and resummed QCD corrections

  ☞ need accurate knowledge of W p_T distribution to determine $\not{p}_T$ resolution

  ☞ $\not{p}_T$ resolution determines how “sharp” the edge in the M_T distribution at $M_T \approx M_W$ is

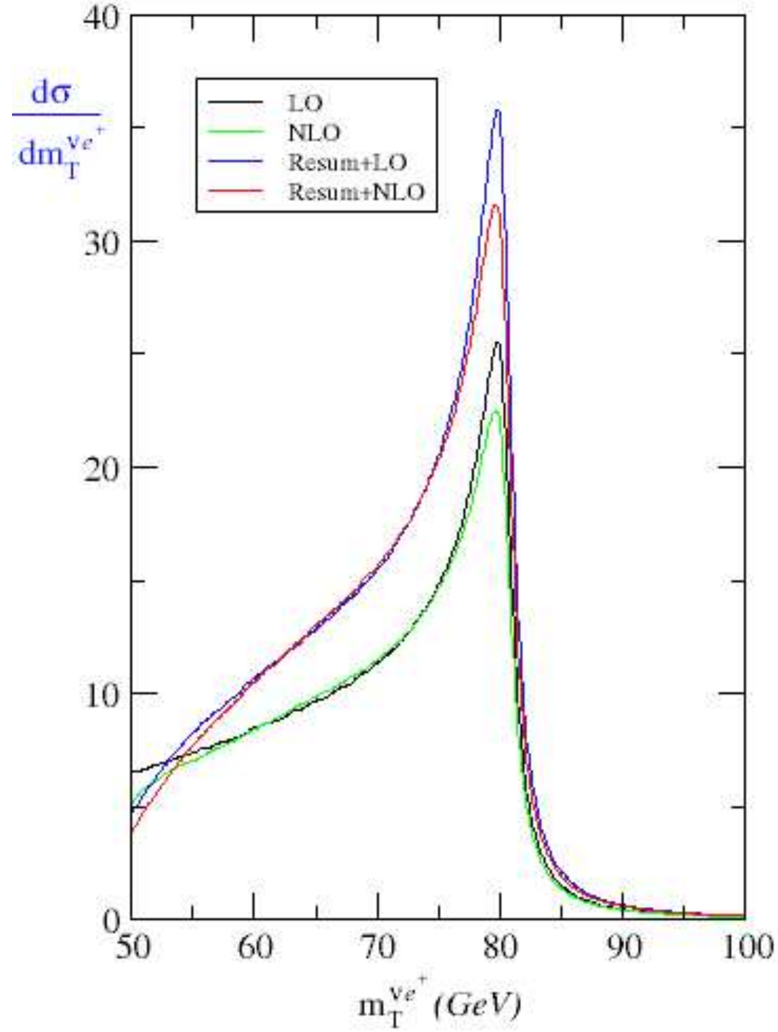
  ☞ which in turn determines how well M_W can be measured

- first step towards this lofty goal:

  ☞ incorporate final state photon radiation effects into RESBOS calculation (Cao, Yuan)

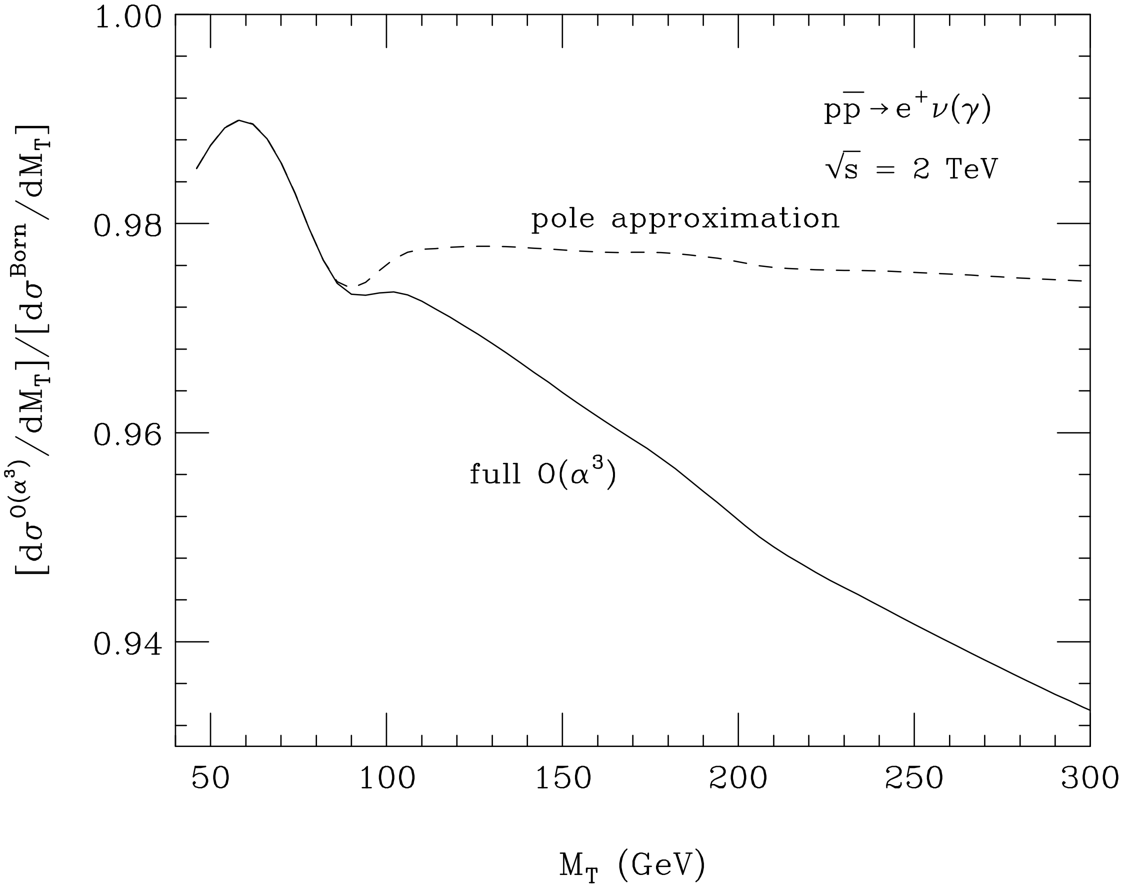
NLO: $\mathcal{O}(\alpha)$ QED final state radiation

Resum: resummed QCD corrections (RESBOS)



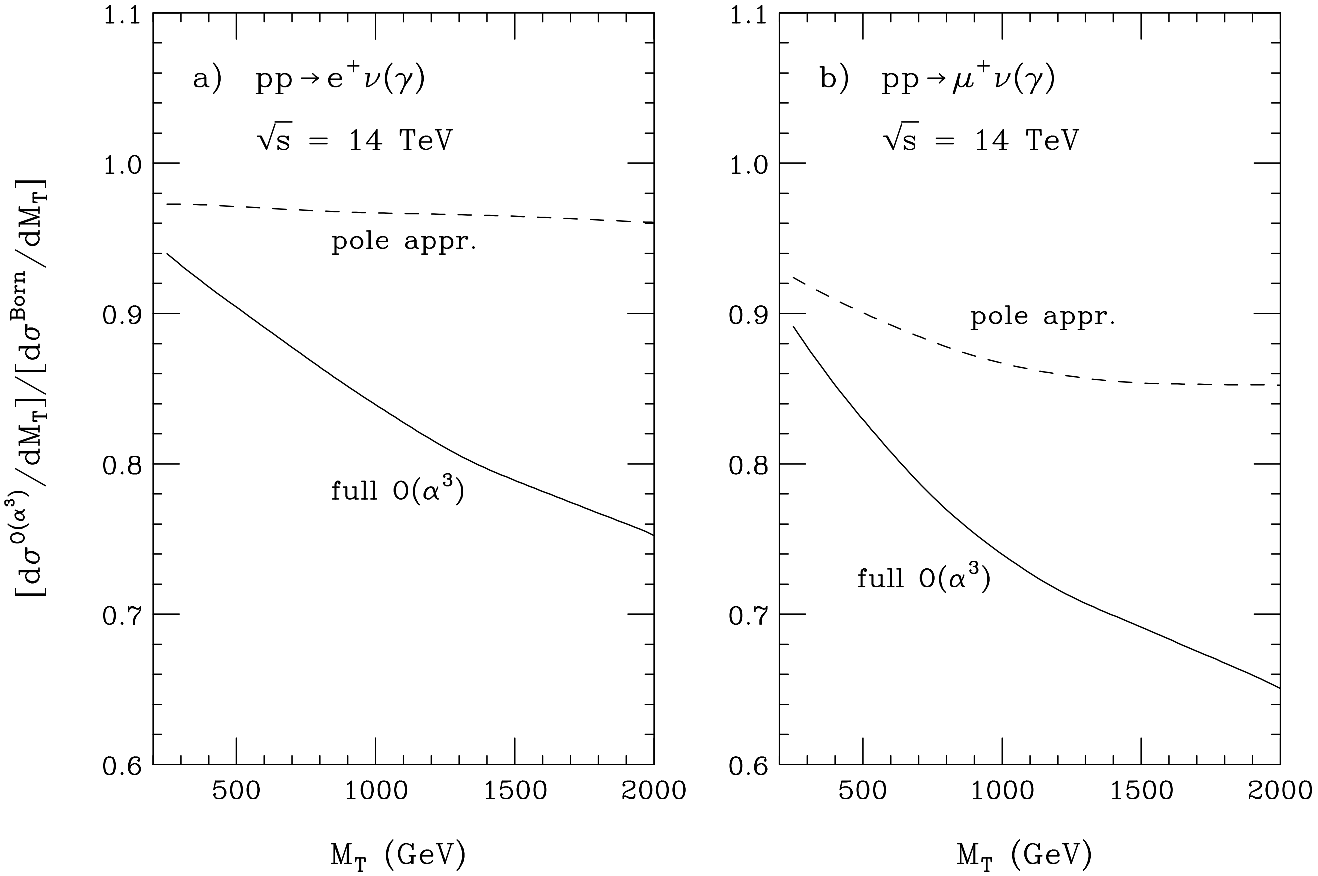
Elctroweak Sudakov Logs

- for $\hat{s} \gg M_{W/Z}^2$, the weak corrections become large and negative



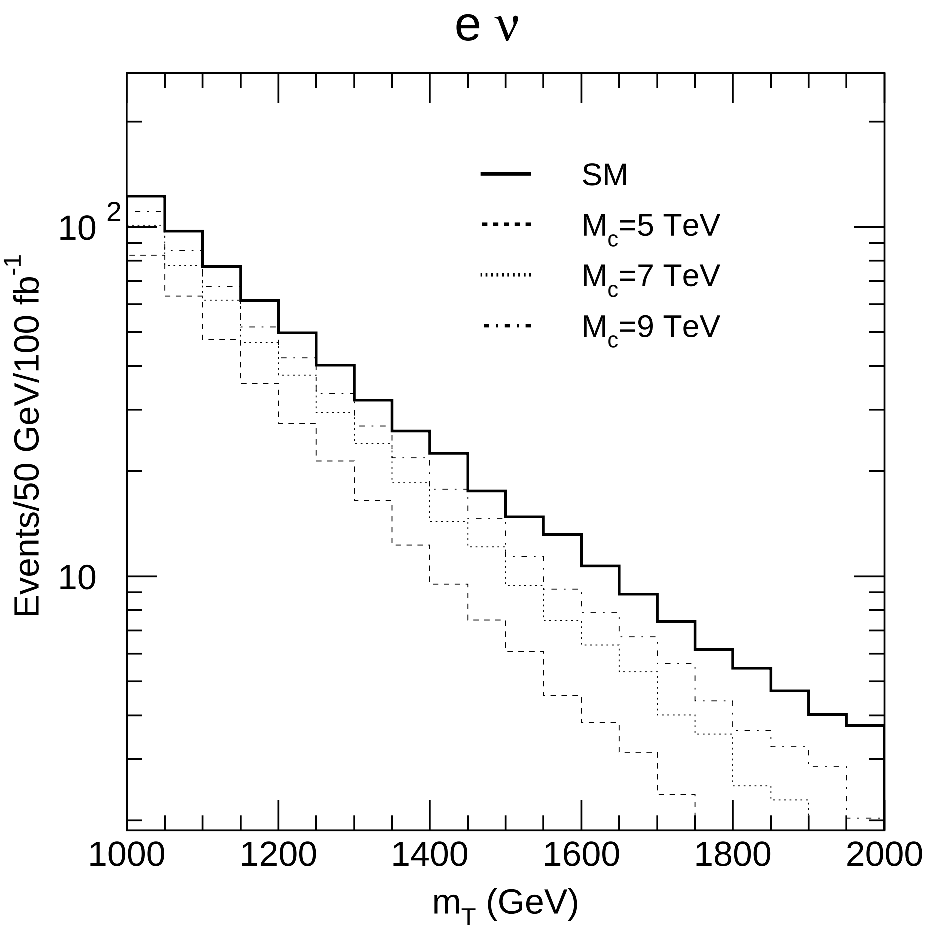
dashed: evaluate weak form factors for $\hat{s} = M_W^2$

- 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 (not done yet)



- 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)



- effect on W width extracted from high M_T tail

☞ the non-resonant weak corrections which contain the Sudakov logs have not been taken into account in previous exp. analyses

☞ they change the shape of the M_T distribution

☞ performing a χ^2 analysis:
non-resonant weak corrections shift W width by

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

☞ expected exp. precision in Tevatron run2 (2 fb^{-1}, $e+\mu$, CDF+DØ combined):

$$\Delta\Gamma_W \approx 25 - 30 \text{ MeV}$$

not negligible!

4 – Radiative Corrections to $e^+e^- \to 4f$ and Bhabha Scattering

- Measuring M_W at Linear Collider (LC):

☞ continuum measurement ($\sqrt{s} > 2M_W$):

➞ reconstruct W's from decay products (similar to method employed by LEP II exps.)

➞ expect to achieve $\delta M_W \approx 10$ MeV for $\int \mathcal{L} dt = 500$ fb^{-1} (uncertainty dominated by systematic uncertainty)

☞ threshold scan: $\sqrt{s} \approx 161$ GeV (Wilson, Sitges Workshop)

$e^+e^- \to 4$ fermion cross section is sensitive to M_W in threshold region

- the threshold scan under the magnifying glass:
  - ☞ statistical uncertainty: (Stirling)

$$\delta M_W^{stat} = 90\ \mathrm{MeV} \left[\frac{\epsilon \int \mathcal{L} dt}{100\ \mathrm{pb}^{-1}} \right]^{-1/2}$$

for $\epsilon = 0.67$ (efficiency) and $\int \mathcal{L} dt = 100\ \mathrm{fb}^{-1}$:

$$\delta M_W^{stat} \approx 3.5\ \mathrm{MeV}$$

  - ☞ add systematic errors

For a multiplicative factor C:

$$\delta M_W^{sys} = 17\ \mathrm{MeV} \left[\frac{\Delta C}{C} \times 100\% \right]$$

assume $\Delta\epsilon \approx 0.25\%$, $\Delta\mathcal{L} \approx 0.1\%$:

$$\delta M_W \approx 6\ \mathrm{MeV}$$

  - ☞ detailed simulations yield $\delta M_W \approx 7$ MeV (Mönig)

- theoretical uncertainties:

☞ if one wishes to achieve $\delta M_W \approx 7$ MeV, one needs $\delta M_W^{theor} \sim 1$ MeV

☞ need to know cross section in threshold region with

$$\frac{\Delta\sigma}{\sigma} \approx 0.05\%$$

☞ present situation: only calculation valid in threshold region: GENTLE, includes full (improved) Born $e^+e^- \to 4$ fermion cross section, including non-resonant graphs, finite W width, Coulomb corrections and ISR effects

☞ uncertainty of GENTLE cross section in threshold region (CERN LEP2 Yellow Report):

$$\frac{\Delta\sigma}{\sigma} \approx 1.4\%$$

☞ need full $\mathcal{O}(\alpha)$ corrections in threshold region

☞ finite W width effects are important in threshold region:

→ must go beyond double pole approximation

☞ current status: $\mathcal{O}(\alpha)$ corrections to $e^+e^- \to 4$ fermions known in double pole approximation (`RACOONWW` and `YFSWW3`)

☞ full $\mathcal{O}(\alpha)$ calculation extremely problematic, results out of sight

→ many channels contribute

→ $\mathcal{O}(1000-10000)$ Feynman diagrams per channel (Vicini, Jegerlehner)

→ technical problems with 4, 5 and 6-point functions and phase space (lots of peaks)

→ no practicable solution of gauge invariance problem associated with finite width and radiative corrections

☞ If theoretical uncertainties of cross section do not improve:

$$\delta M_W \approx \delta M_W^{theor} \approx 24\ \mathrm{MeV}$$

sic transit gloria mundi...

- recall: need to measure luminosity to 0.1% to be able to achieve $\delta M_W = 7$ MeV at GigaZ

  ☞ an accurate determination of the luminosity is important for many measurements at a LC

- LEP and SLC: used small angle Bhabha scattering, $e^+e^- \to e^+e^-$, to measure luminosity

  ☞ has large cross section

  ☞ accurately calculable (QED + contributions from hadronic vacuum polarization)

- due to beamstrahlung, resulting in variable e^+e^- energy, small angle Bhabha scattering cannot be used to determine luminosity at a LC

  ☞ use large angle Bhabha scattering

  ☞ measure acollinearity angle, caused by the asymmetric collision of electrons and positrons (Frary, Miller)

- to achieve desired precision need

  ☞ 2-loop QED corrections

  ☞ need to include Z exchange diagrams (log enhanced: $\log(s/m_e^2)$ and $\log(s/m_Z^2)$)

- 2-loop QED matrix elements for Bhabha scattering exist (Bern, Ghinkulov, Dixon)

- still need to construct numerically stable code for performing singular phase space integrations

  ☞ similar to NNLO QCD predictions

5 – Conclusions

- controlling electroweak radiative corrections is essential for future high precision tests of the SM
- significant progress has been made over the last few years
- a long shopping list of things to do remains:
  - ☞ higher order corrections to M_W and $\sin^2\theta_{eff}$
  - ☞ higher order EWK corrections to W and Z production in the pole region
  - ☞ resummation of EWK Sudakov logs
  - ☞ full 1-loop corrections to $e^+e^- \to 4$ fermions
  - ☞ ....