Theoretical Challenges for a Precision Measurement of the W Mass at hadron colliders

Doreen Wackeroth

University of Rochester

in collaboration with

U. Baur, O. Brein, W. Hollik, S. Keller

and C. Schappacher

Outline

I. Introduction and Motivation
II. The $\mathcal{O}(\alpha)$ corrections to resonant W production
III. The numerical impact on W boson observables:

- precise measurement of M_W at hadron colliders !

IV. The $\mathcal{O}(\alpha)$ corrections to Z boson production:

- impact on $M(l^+l^-)$ and A_{FB} and
- the prospects for a precision measurement of $\sin^2\theta_{eff}^{lept}$ at hadron colliders !

Literature

- *Electroweak physics*, CERN report of the Workshop on Standard Model Physics (and more) at the LHC, hep-ph/0003275.
- *Report of the working group on photon and weak boson production*, Workshop on Physics at RunII at the Fermilab Tevatron, hep-ph/0005226; *Precision Physics*, Snowmass96, hep-ph/9611334.
- *Electroweak radiative corrections to W boson production in hadronic collisions*, Phys. Rev. **D59**, 013002 (1999), hep-ph/9807417.
- *Electroweak radiative corrections to resonant charged gauge boson production*, Phys. Rev. **D55**, 6788 (1997), hep-ph/9606398.
- *QED Radiative Corrections to Z Boson Production and the Forward Backward Asymmetry at Hadron Colliders*,
  Phys.Rev.**D57**, 199 (1998), hep-ph/9707301.
- *Two photon radiation in W and Z boson production at the Fermilab Tevatron collider*, Phys.Rev.**D61**, 073007 (2000), hep-ph/9910206.

I. Introduction and Motivation

Precision measurements of SM gauge boson properties

- mass, width, couplings -

at the Tevatron and the LHC require an equally precise theoretical understanding of the underlying production processes.

One of the most important measurements is a precise measurement of the W boson mass.

Prospects for a precise measurement of M_W at hadron colliders *: (assuming PDF and theoretical uncertainties can be drastically reduced)

at present: $p\bar{p}$: 62 MeV, LEP2: 46 MeV
and combined: 37 MeV

expected at LEP2: 35-40 MeV

	δM_W [MeV] (stat. and syst.)
LHC (10 fb^{-1})	15
Tevatron RUN II (1 fb^{-1})	50 (M_T)
	30 (W/Z M_T ratio)
Tevatron (10 fb^{-1})	30 (M_T)
	15 (W/Z M_T ratio)

W/Z ratios: less sensitive to PDF and QCD uncertainties, electroweak corrections important, multiple photon radiation effects ? (U.Baur and T.Stelzer, hep-ph/9910206)

*LHC: S.Keller and J.Womersley, hep-ph/9711304; S.Keller, hep-ph/9809327; Tevatron: U.Baur et al., hep-ph/9611334

For the envisioned high precision it is crucial that the predictions for W and Z boson observables are well under control:

- W boson observables:
  M_W measurement: from $M_T(W)$, $p_T(l)$ or ratios,
  Γ_W measurement: from W/Z cross section ratio, BR ratio or fit to high $M_T(W)$, and
  σ_W as a luminosity monitor

- Z boson observables:
  M_W measurement: $M_T(Z)$, $p_T(l)$ and σ_Z in ratios and M_Z for detector calibration,
  measurement of $\sin^2\theta_{eff}^{lept}$: from A_{FB}, and
  $M(ll)$ distribution at high $M(ll)$: scales of new physics, e.g. Z', extra dimensions !

Electroweak radiative corrections to the W and Z boson production processes need to be included.

Challenging precise theoretical predictions with precise measurements yields

- consistency checks:
  compare direct with indirect measurements of input parameters, e.g., the W boson mass
  from the Tevatron and LEPII measurements and from a global χ^2 fit including all electroweak precision data (LEPEWWG, Summer 99/00)

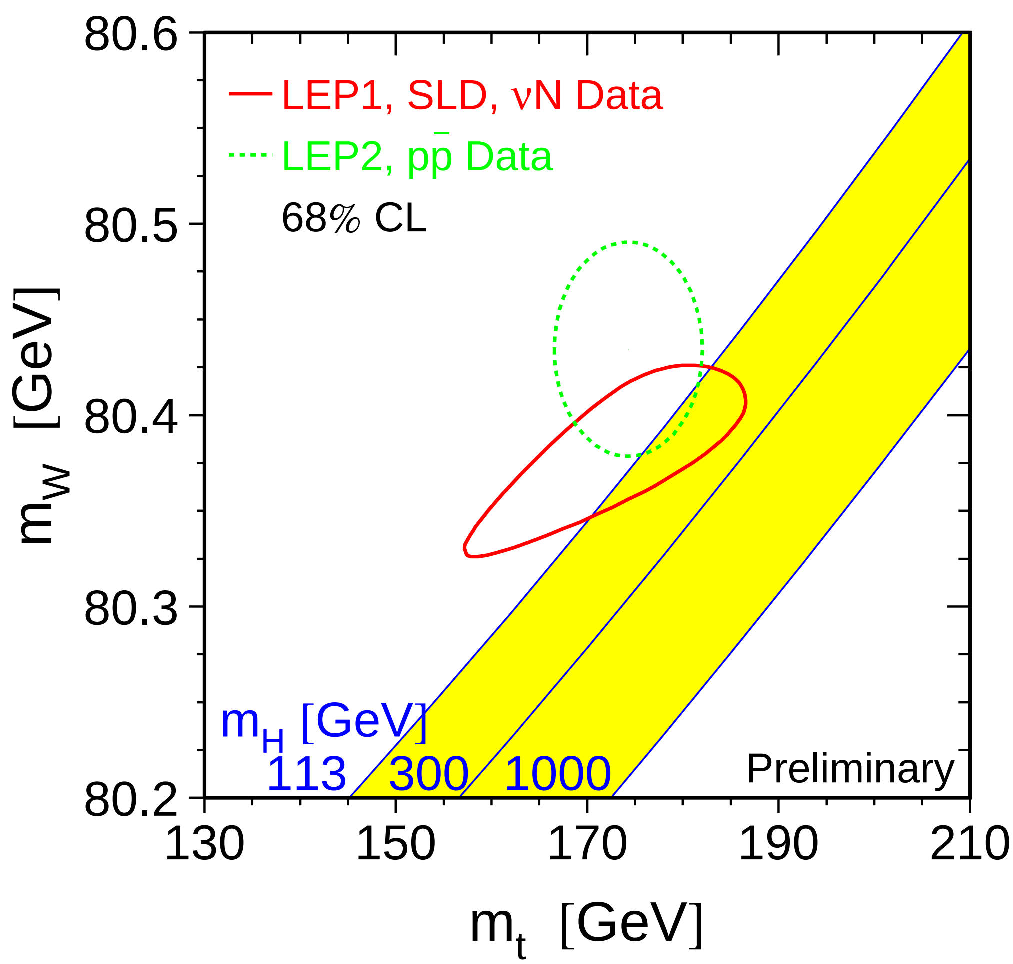
  $M_W = 80.434 \pm 0.037$GeV $M_W = 80.387 \pm 0.026$GeV

→ information about (not yet) accessible sectors of the MSM, e.g. the Higgs-sector through the virtual presence of Higgs-bosons in loop diagrams (A.Gurtu, ICHEP2000)

$$M_H < 210\,\text{GeV}(95\%\text{CL})\ ;\ M_H = 62^{+53}_{-30}\,\text{GeV}$$

M_W - M_Z correlation: $M_W^2(1-\frac{M_W^2}{M_Z^2}) = \frac{\pi\alpha(0)}{\sqrt{2}G_\mu(1-\Delta r(M_W,m_t,M_H,\ldots))}$

LEPEWWG Summer 2000 (preliminary)



$$\delta m_{top} = 2\text{GeV and } \delta M_W = 20\text{MeV} \Rightarrow \frac{\delta M_H}{M_H} \approx 30\%$$

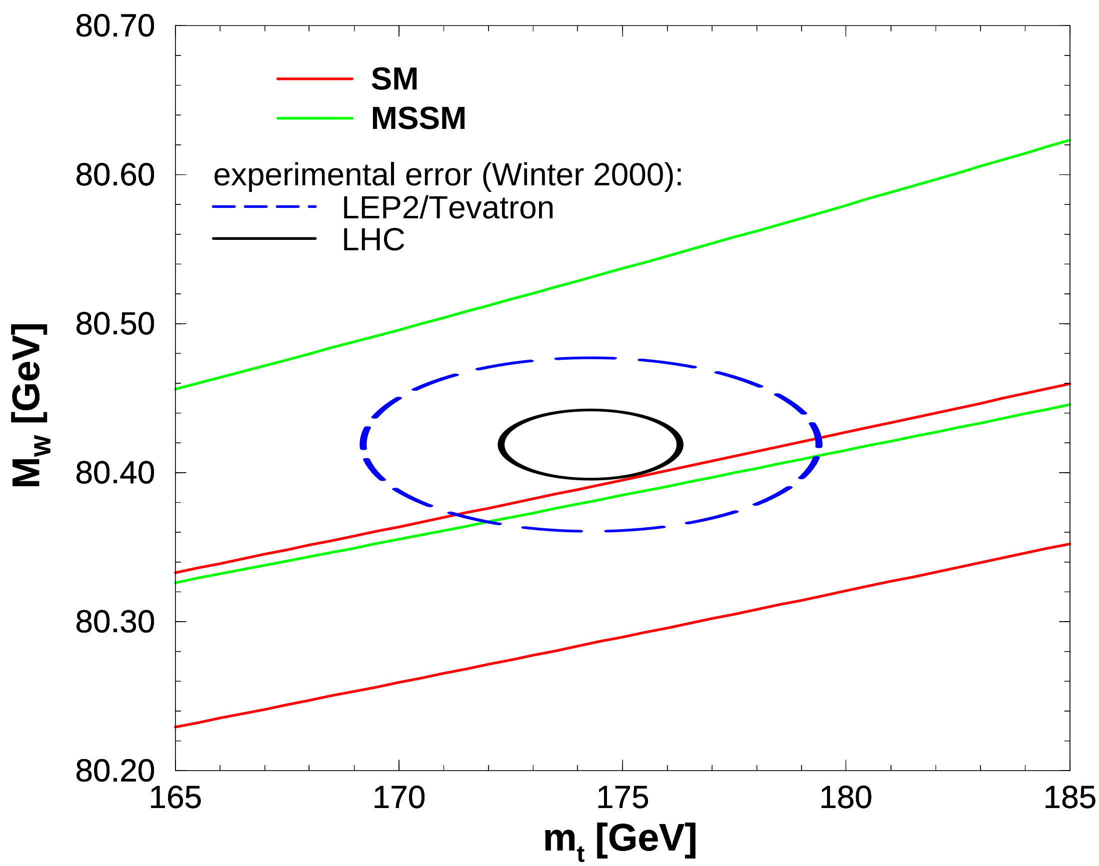
and even better from global fits to all EWK data !

from G.Weiglein, LHC report, hep-ph/0003275

MSSM predictions:

P.H. Chankowski, A.Dabelstein, W.Hollik, W.M. Mösle, S.Pokorski, J.Rosiek, Nucl. Phys. B417, 101 (1994)

A.Djouadi et al., Phys.Rev. D57, 4179 (1998)



II. EWK $\mathcal{O}(\alpha)$ corrections to resonant W production

The complete $\mathcal{O}(\alpha^3)$ parton level cross section of resonant W production via the Drell-Yan mechanism

$$q_i\overline{q}_{i'} \to W \to f\overline{f}'(\gamma)$$

can be written as (W.Hollik and D.W, hep-ph/9606398)

$$d\hat{\sigma}^{(0+1)} = d\hat{\sigma}^{(0)}\,[1 + 2\mathcal{R}e(\tilde{F}^{initial}_{weak} + \tilde{F}^{final}_{weak})(M_W^2)]$$
$$+ \sum_{\substack{a=initial,final,\\ interf.}} [d\hat{\sigma}^{(0)}\,F^a_{QED}(\hat{s},\hat{t}) + d\hat{\sigma}^a_{2\to 3}]$$

- $\tilde{F}^{initial,final}_{weak}(\hat{s} = M_W^2)$:
  gauge invariant modified weak form factors. They comprise the pure weak 1-loop contribution and the IR finite parts of the virtual photon corrections. W/Z box diagrams and terms $\propto s - M_W^2$ are neglected as non-resonant contributions.

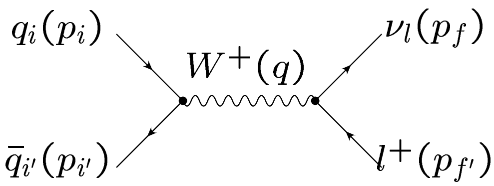
- $F^{initial,final,interf}_{QED}(\hat{s},\hat{t})$:
  IR finite, gauge invariant QED-like form factors describing initial and final-state radiation and their interference. They comprise the IR singular parts of the virtual photon contribution and the soft and collinear limits of real photon radiation.

- $d\hat{\sigma}^{initial,final,interf.}_{2\to 3}$:
  real hard photon radiation away from soft and collinear singularities.

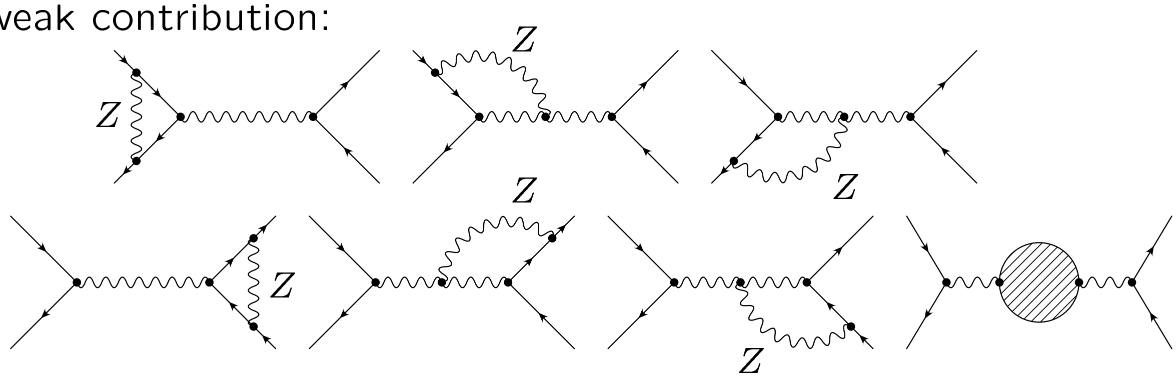
The Feynman diagrams contributing to W production at $\mathcal{O}(\alpha^3)$

(shaded loop: non-photonic contributions (i.e. f,H,Z,W in loop))

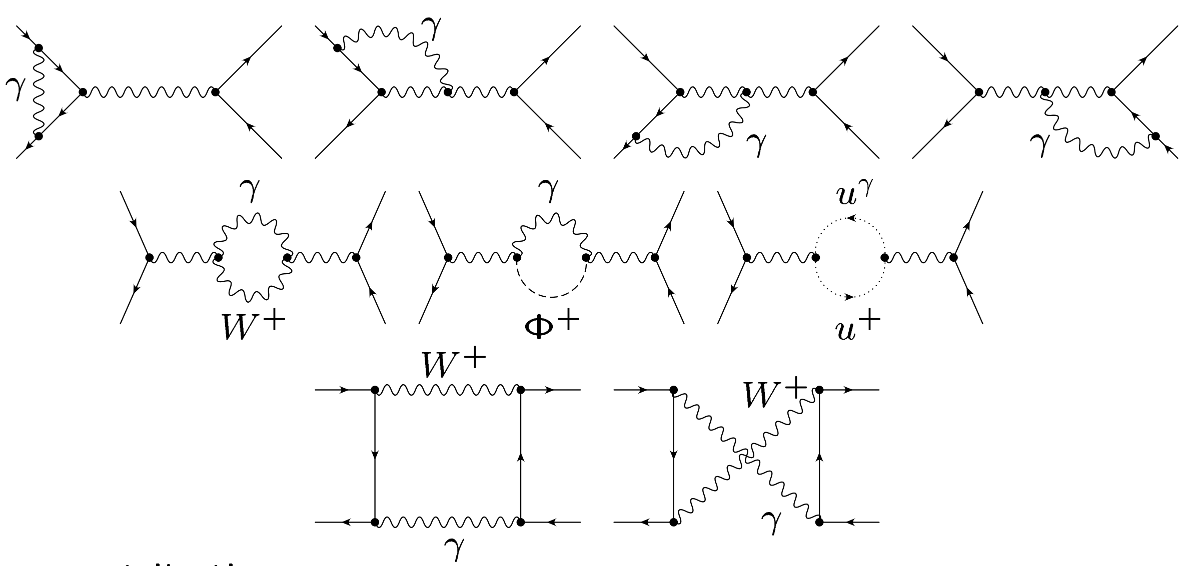
Born-diagram:



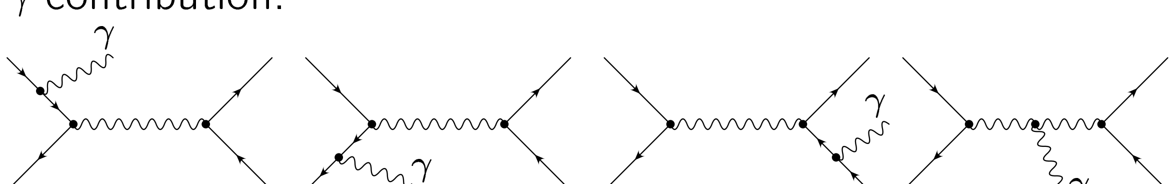
pure weak contribution:



virtual γ contribution:



real γ contribution:



Treatment of mass singularities
(same for Z boson production)

$F_{QED}^{initial,final}$ and $d\hat{\sigma}_{2\to3}^{initial,final}$ contain large mass singular logarithms: the photon is emitted collinear with a charged fermion and the resulting singularity is regularized by retaining finite fermion masses.
We extract the collinear singularities from $d\hat{\sigma}_{2\to3}^{initial,final}$ by defining a collinear region with $\cos\theta > 1-\delta_\theta$ and perform the cancellation of the mass singularities analytically:

- Final-state radiation (FSR):
  in sufficiently inclusive observables the mass singularities completely cancel.

- Initial-state radiation (ISR):
  mass singularities always survive but can be absorbed by universal collinear counterterms to the parton distribution functions (in complete analogy to QCD).
  - introduces dependence on QED factorization scheme (in analogy to QCD, a DIS and $\overline{MS}$ scheme has been introduced)
  - currently no PDFs available which include QED corrections but the effects of QED on the PDFs are expected to be small (H. Spiesberger, LHC report).

III. The numerical impact on W boson observables

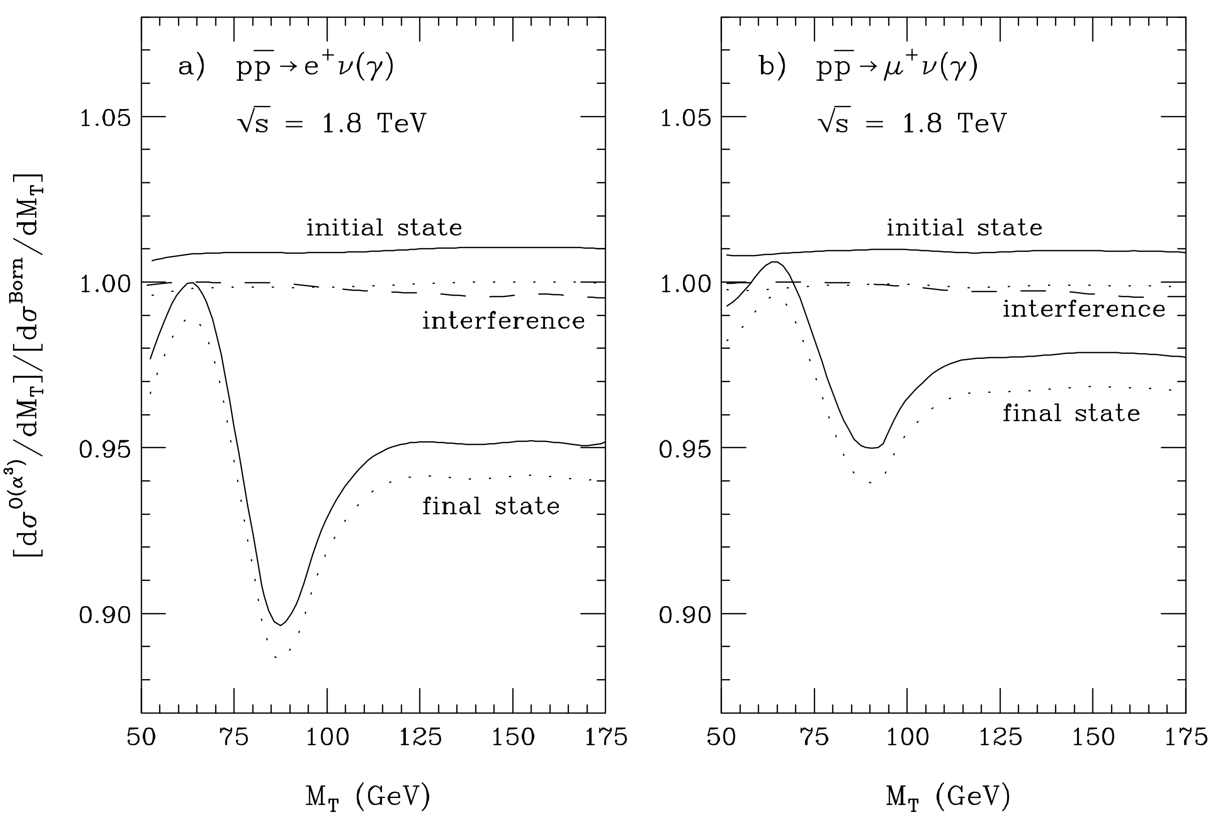
The electroweak $\mathcal{O}(\alpha)$ corrections are implemented in the Monte Carlo program WGRAD (U.Baur, S.Keller, D.W., hep-ph/9807417).

We studied the impact of the electroweak radiative corrections in the W resonance region on the W transverse mass distribution, the W to Z transverse mass ratio, the charge asymmetry of leptons in $W \to l\nu$, the W production cross section and the W to Z cross section ratio.

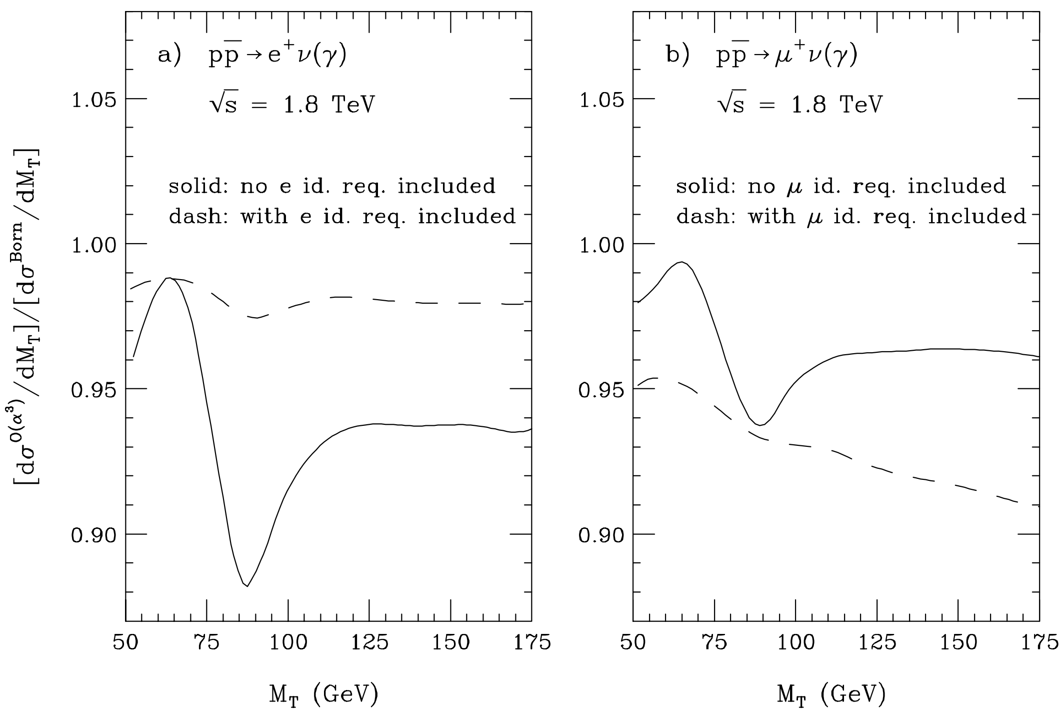
The transverse mass M_T distribution of the final state $l\nu$ pair is used to extract M_W at the Tevatron

$$M_T = \sqrt{2p_t(l)p_T(\nu)(1-\cos\Phi^{l\nu})}$$

The $M_T(l^+\nu)$ distributions at the Tevatron with WGRAD:



The NLO/LO ratio (only FSR is included) at the Tevatron with WGRAD taking into account lepton identification requirements:



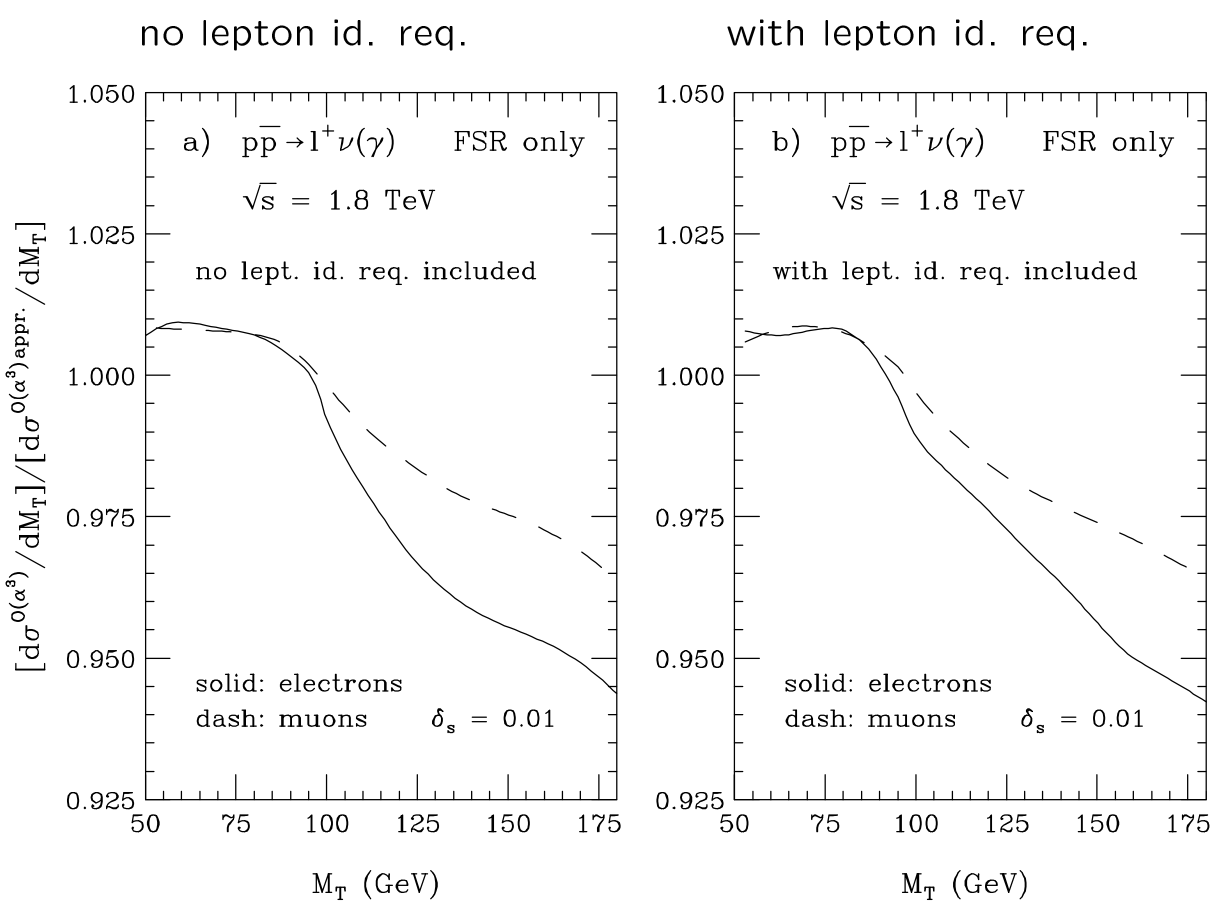
⇒ The effects of FSR are largely reduced in the electron case when lepton id. req. are taken into account.

To simulate the detector responds we apply

- Gaussian smearing of the lepton momenta
- lepton id. req.: charged leptons and photons with small opening angles cannot be discriminated:
  electron and photon momenta are combined when $\Delta R_{e\gamma} < R_c$
  muons: events are rejected
- separation cuts:

$$p_T(l) > 25\,\text{GeV}\,,\ |\eta(l)| < 1.2\,,\ \not{p}_T > 25\,\text{GeV}$$

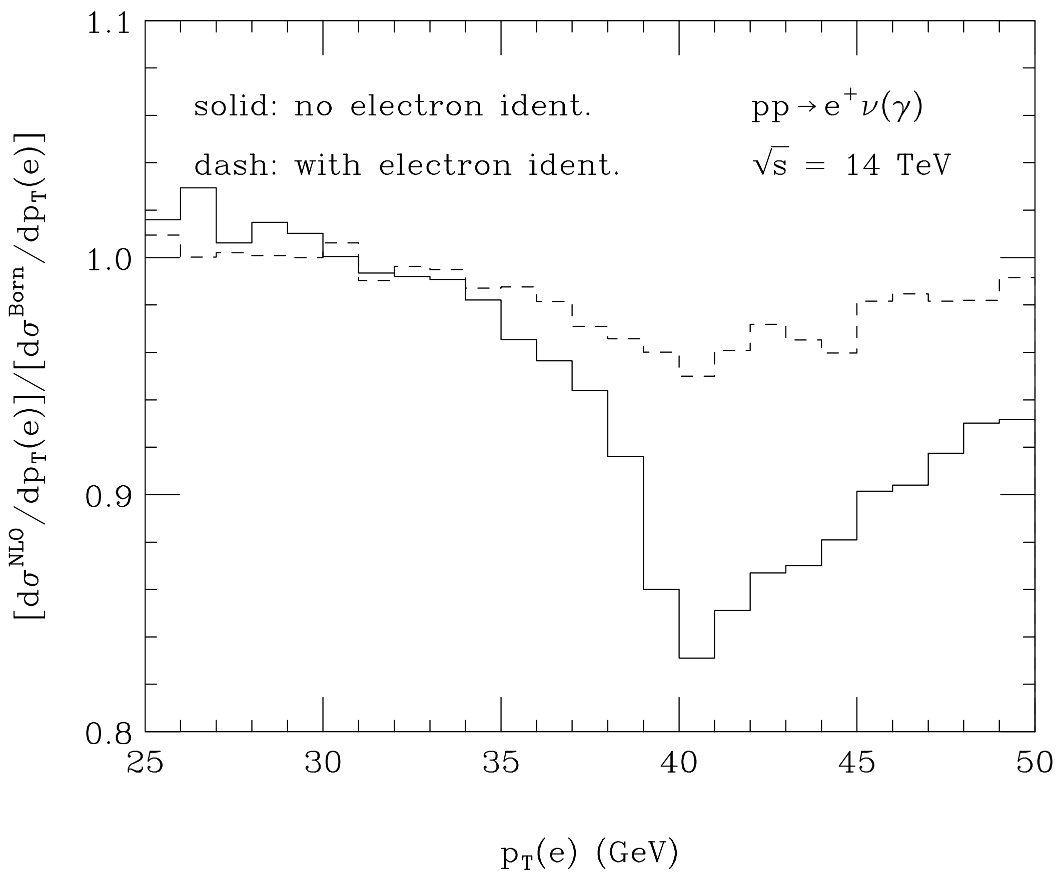
The comparison of the full calculation with WGRAD with the approximation a la Berends et al. (Z. Phys. C 27, 365 (1985)):



⇒ approximation → full calculation: additional shift in M_W of $\mathcal{O}(10)$ MeV !

The impact of the electroweak corrections on the $p_T(e)$ distribution at the LHC with WGRAD:

(from the LHC workshop report, hep-ph/0003275)



See also results of a new calculation of electroweak radiative corrections to W production at the resonance and beyond at hadron colliders by S.Dittmaier and M.Krämer (LHC workshop report, hep-ph/0003275).

IV. The $\mathcal{O}(\alpha)$ corrections to Z boson production

The QED $\mathcal{O}(\alpha)$ corrections to

$$p \overset{(-)}{p} \to Z, \gamma* \to l^+ l^- (l = e, \mu)$$

have been calculated and implemented in the MC program ZGRAD (U.Baur, S.Keller, W.Sakumoto, hep-ph/9707301).

Recently, also the (non-universal) weak one-loop corrections have been calculated and implemented in ZGRAD2 (U.Baur, O.Brein, W.Hollik, C.Schappacher, D.W.).

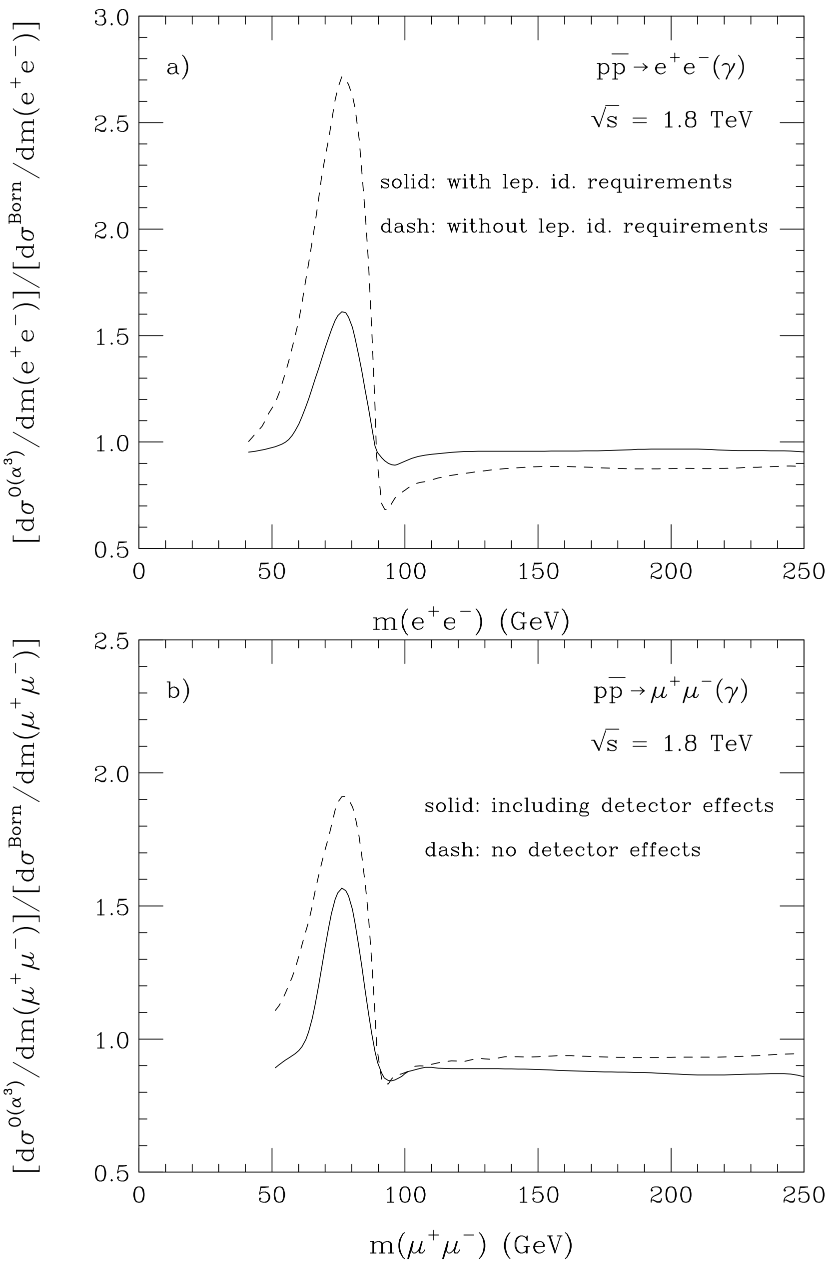
While (non-universal) weak corrections are small in the Z peak region, they become increasingly important for high parton CM energies $\hat{s}$ due to large Sudakov-like logarithms $\ln(\hat{s}/M_V^2)$.

The impact of QED corrections on the $M(l^+l^-)$ invariant mass distribution and on the $p_T(l)$ spectrum at the Tevatron has been studied with ZGRAD:

- initial-final state interference and ISR contributions are small (after factorizing the collinear singularities into the PDFs)

- FSR dominates and strongly affects the $M(l^+l^-)$ distribution.

The impact of QED corrections on $d\sigma/dM(l^+l^-)$ at the Tevatron with ZGRAD: (from U.Baur et al., Phys. Rev. D57, 199 (1998))



Difference in M_Z when comparing approximate (Berends et al.) with full calculation: $\approx$ 10 MeV

$\rightarrow$ also affects M_W measurement !

A precise measurement of the weak mixing angle $\sin^2\theta_{eff}^{lept}$ at hadron colliders from the forward-backward asymmetry A_{FB} might be possible.

Prospects for the precision on $\sin^2\theta_{eff}^{lept}$ extracted from A_{FB} (Z peak): (from LHC report, hep-ph/9611334; J.Rha and E.Ellison, Run II workshop; U.Baur et al., Phys. Rev. D57, 199 (1998); Snowmass 96)

LEP/SLC: 0.00017 (LEPEWWG2000); planned: 0.00012

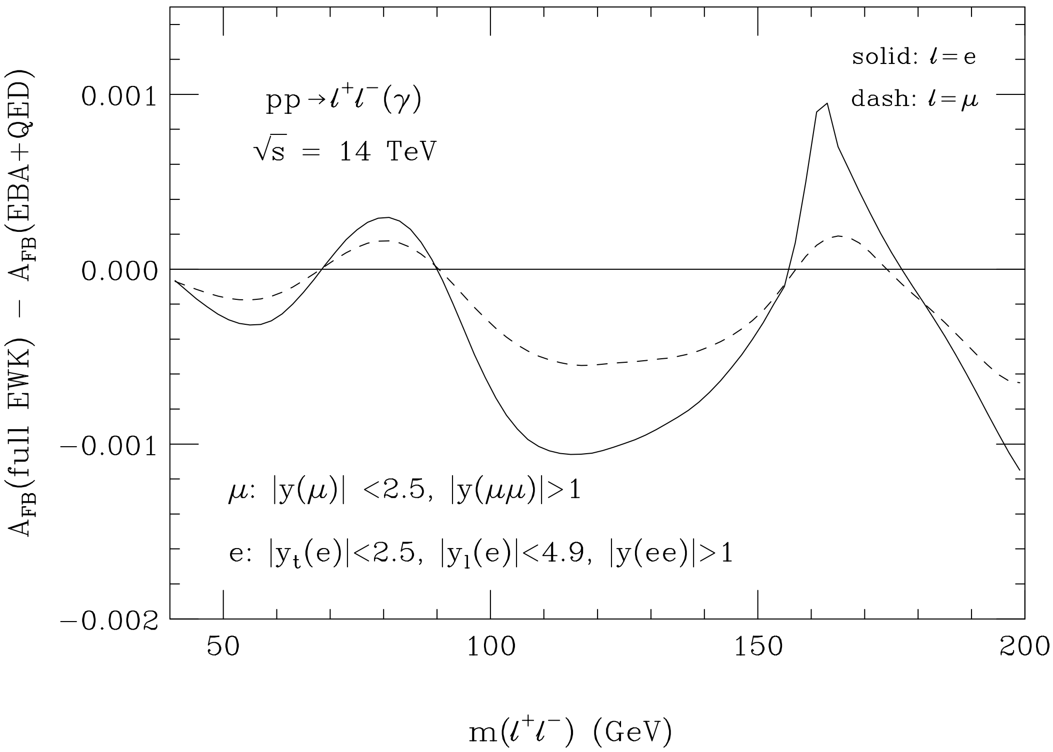
	$\delta\sin^2\theta_{eff}^{lept}$ (statistical)
LHC with 100 fb^{-1}	0.0002 for $\lvert\eta\rvert < 2.5, y(l^+l^-) > 1$
	0.00014 for $\lvert\eta(e^\pm)\rvert < 2.5, 4.9$
	0.000039 for full η coverage
Tevatron with 10 fb^{-1}	0.00028
TEV33 (30 fb^{-1})	0.00013 per experiment

The effects of QED (and QCD) corrections on $A_{FB}(M(ll))$ at the Tevatron and the LHC have been studied with ZGRAD (from U.Baur et al., hep-ph/9707301):

- QED (+QCD) corrections are considerably larger than the expected statistical errors of $\sin^2\theta_{eff}^{lept}$!
- weak corrections should be included and the effects of higher-order QED need to be studied (U.Baur and T.Stelzer, hep-ph/9910206)

ZGRAD2 predictions for A_{FB} including electroweak corrections at the LHC: (U.Baur et al., in preparation)

preliminary



→ interesting effects from non-universal electroweak corrections at $M(ll) \sim M_W, 2M_W$ which are the more pronounced the larger the rapidity coverage !

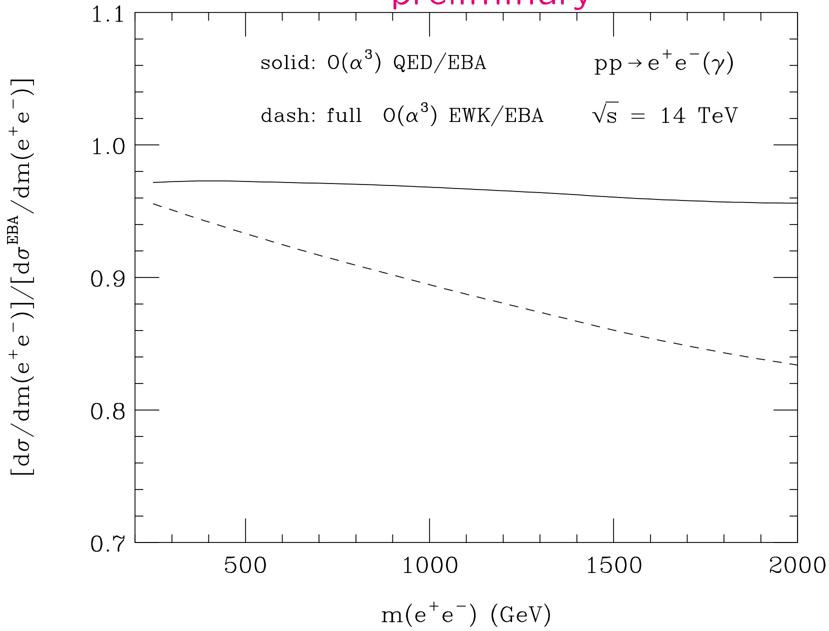
$\Delta A_{FB} =$ (3-4) 10^{-3} (per experiment) could be observable at the LHC (100 fb^{-1}). In the electron case for large rapidity coverage for one of the electrons the effect is of $\mathcal{O}(10^{-3})$.

A detailed study of electroweak $\mathcal{O}(\alpha)$ corrections to $p \overset{(-)}{p} \to l^+l^-(l = e, \mu)$ with ZGRAD2 is work in progress !

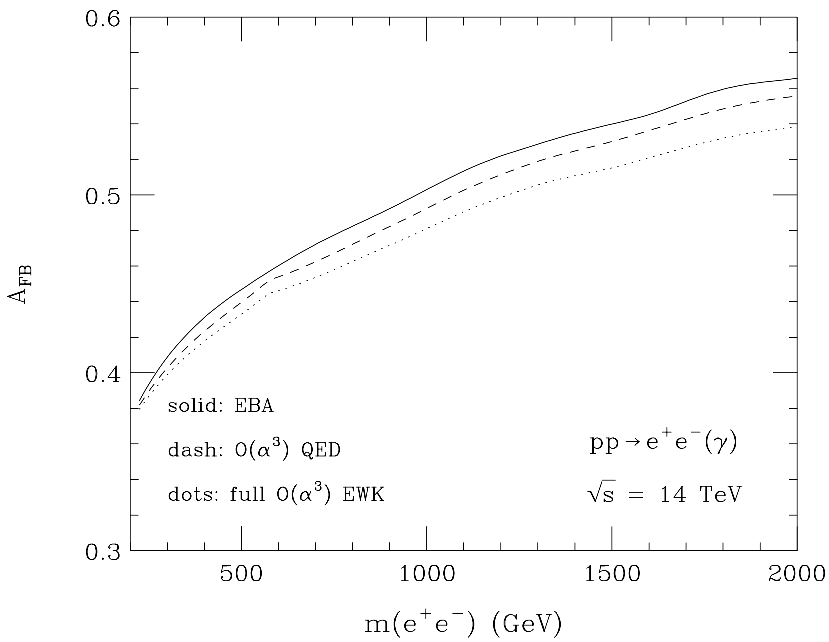
The impact of electroweak corrections on $d\sigma/dM(e^+e^-)$ and $A_{FB}(M(e^+e^-))$ at high invariant masses at the LHC with ZGRAD2: (U.Baur et al., in preparation)

with separation cuts and lepton identification requirements (ATLAS inspired):

preliminary



with cuts and el. id, MRSR2



Summary and Conclusions

In view of future precise measurements at the Tevatron and the LHC it is crucial to fully control QCD and electroweak (EWK) radiative corrections.

As a first step the QED $\mathcal{O}(\alpha)$ corrections to Z boson production and the EWK corrections to resonant W boson production in hadronic collisions have been calculated and implemented in Monte Carlo generators which are publicly available:

ZGRAD: QED $\mathcal{O}(\alpha)$ corrections to Z boson production
WGRAD: EWK $\mathcal{O}(\alpha)$ corrections to resonant W boson production

The impact on interesting observables has been studied, esp. on those which are relevant for the extraction of M_W, M_Z and $\sin^2\theta^{lept}_{eff.}$ (A_{FB}).

In particular, it has been investigated how experimental lepton identification requirements affect the EWK corrections.

However, for the envisioned precision

- the complete $\mathcal{O}(\alpha^3)$ corrections should be included

  Done ! (up to QED effects in PDFs)

  The updated versions of WGRAD and ZGRAD include all the improvements necessary to be ready for Run II:

  ZGRAD2: QED+complete EWK one-loop corrections to Z boson production with proper treatment of higher-order terms around the Z resonance.

  WGRAD2: complete EWK $\mathcal{O}(\alpha)$ corrections (photonic and non-photonic) to W boson production (non-resonant contribution and tuned comparison with the calculation by S.Dittmaier and M.Krämer is work in progress).

- the impact of higher-order corrections needs to be studied and eventually taken into account:

  → two-photon radiation in W and Z boson production ?
  First step: real photons (U.Baur, T.Stelzer, hep-ph/9910206), complete calculation needs two-loop virtual corrections.

  → resummation of large logs (QED and EWK Sudakov-like) ?

There is still work to be done !