Measuring M_W at Hadron Colliders

1. M_W Measurement from the M_T Lineshape
2. Detector-specific Uncertainties
3. Theoretical Uncertainties
4. Other Methods of Determining M_W
5. Conclusions

Ulrich Baur
State University of New York at Buffalo

1 – M_W Measurement from the M_T Lineshape

- The determination of M_W makes use of the kinematics o the $W \to \ell\nu$ decay

☞ Jacobian peak with sharp edge at $M_W/2$ in $p_T(\ell)$ distribution

☞ Jacobian peak is smeared out by

→ finite W width effects

→ detector resolution effects

→ and, in particular, the effect of the p_T of the W boson

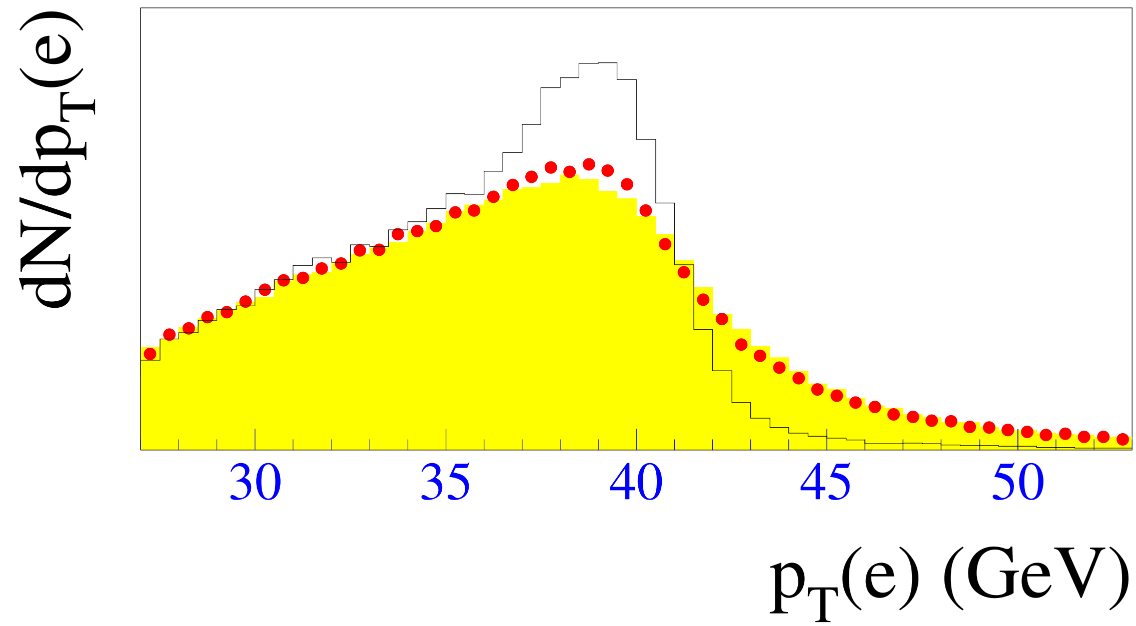
☞ historically, precise determination of p_T^W has been lacking

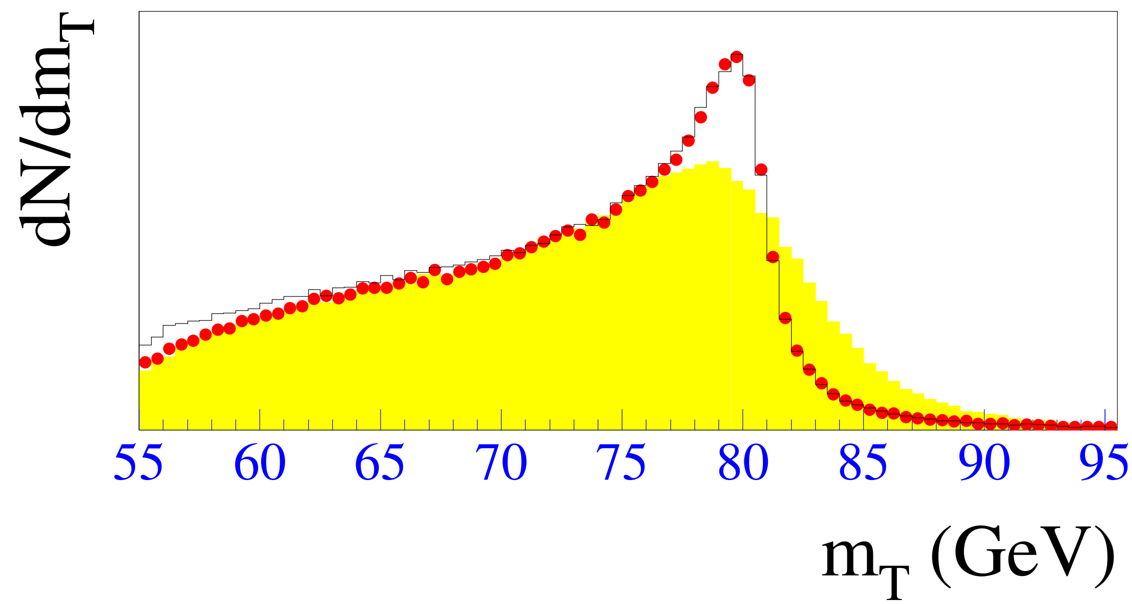
→ use transverse mass

$$M_T = \sqrt{2p_T^\ell p_T^\nu(1 - \cos(\phi_{\ell,\nu}))},$$

$\phi_{\ell,\nu}$: angle between the charged lepton and the neutrino in the transverse plane

☞ M_T is far less sensitive to p_T^W





histogram: no detector smearing, $p_T^W = 0$

dots: finite p_T^W

shaded: adds detector resolutions (here: Run 1 DØ detector)

- observables:

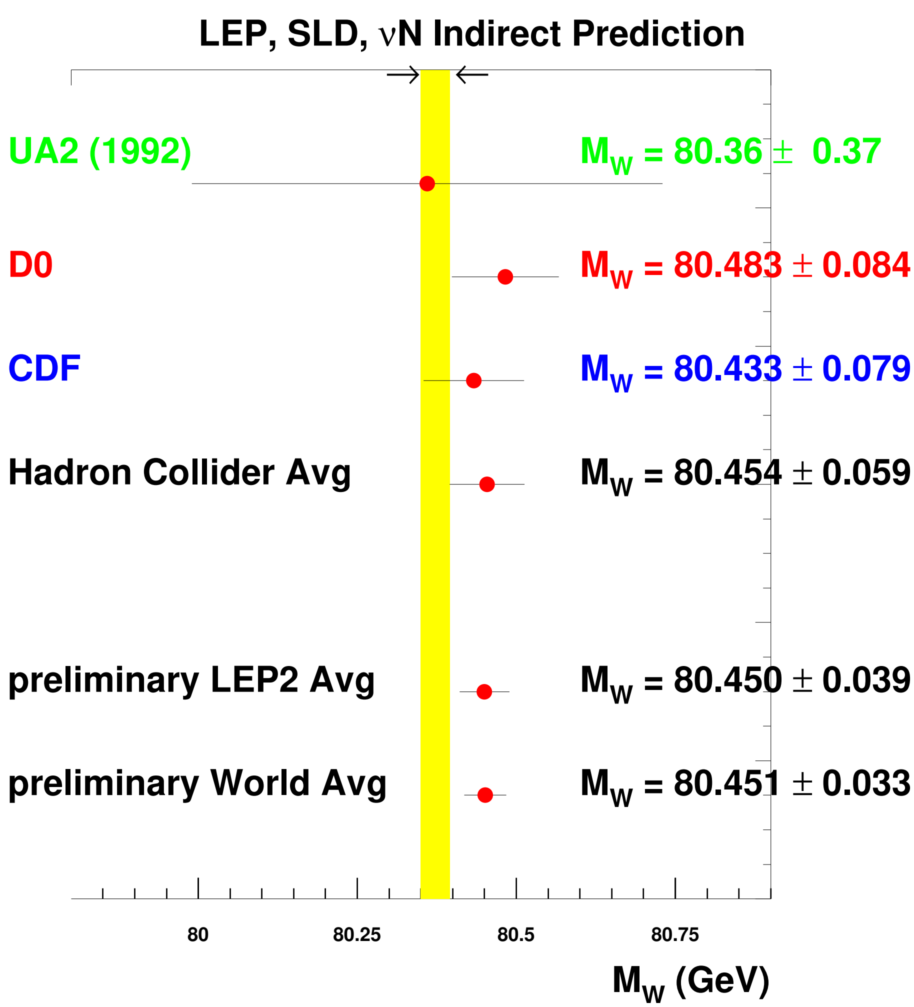
  ☞ charged lepton transverse energy/momentum

  ☞ non-leptonic transverse energy (hadronic recoil) $\vec{u}$

  ☞ derive ν transverse momentum and M_T from $\vec{p}_T(\ell)$ and $\vec{u}$

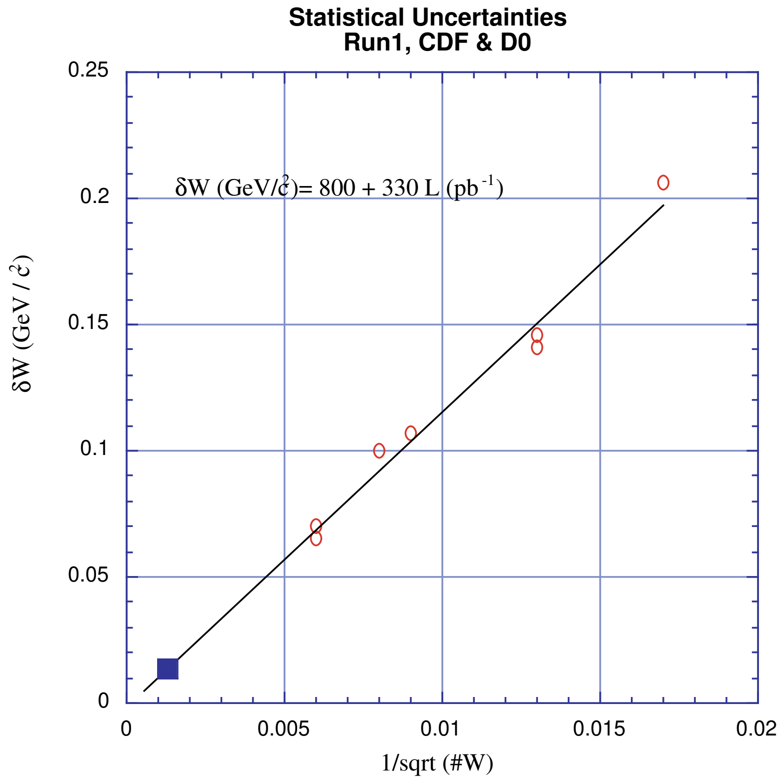
  ☞ disadvantage of using M_T:
  need to precisely determine ν direction (difficult)

- present results:



- Run II expectation/goal (1999 Run II workshop):

☞ statistical uncertainty: $\delta M_W = 13$ MeV per channel and experiment for 2 fb^{-1}



☞ overall uncertainty of $\delta M_W = 30$ MeV per channel and experiment for 2 fb^{-1}

- current Run II situation:

both CDF and DØ have accumulated ≈ 70 pb^{-1}

→ ie. about 40,000 W candidates

☞ serious analysis is beginning

☞ experiments look into simulation issues (more later)

- beyond Run II:

  ☞ Run IIb (15 fb^{-1}): overall uncertainty of $\delta M_W = 17$ MeV per channel and experiment

  ☞ for even higher integrated luminosities the determination of the energy resolution is systematically limited by the uncertainty in the Z width

  → δM_W limited to 15 MeV with M_T distribution

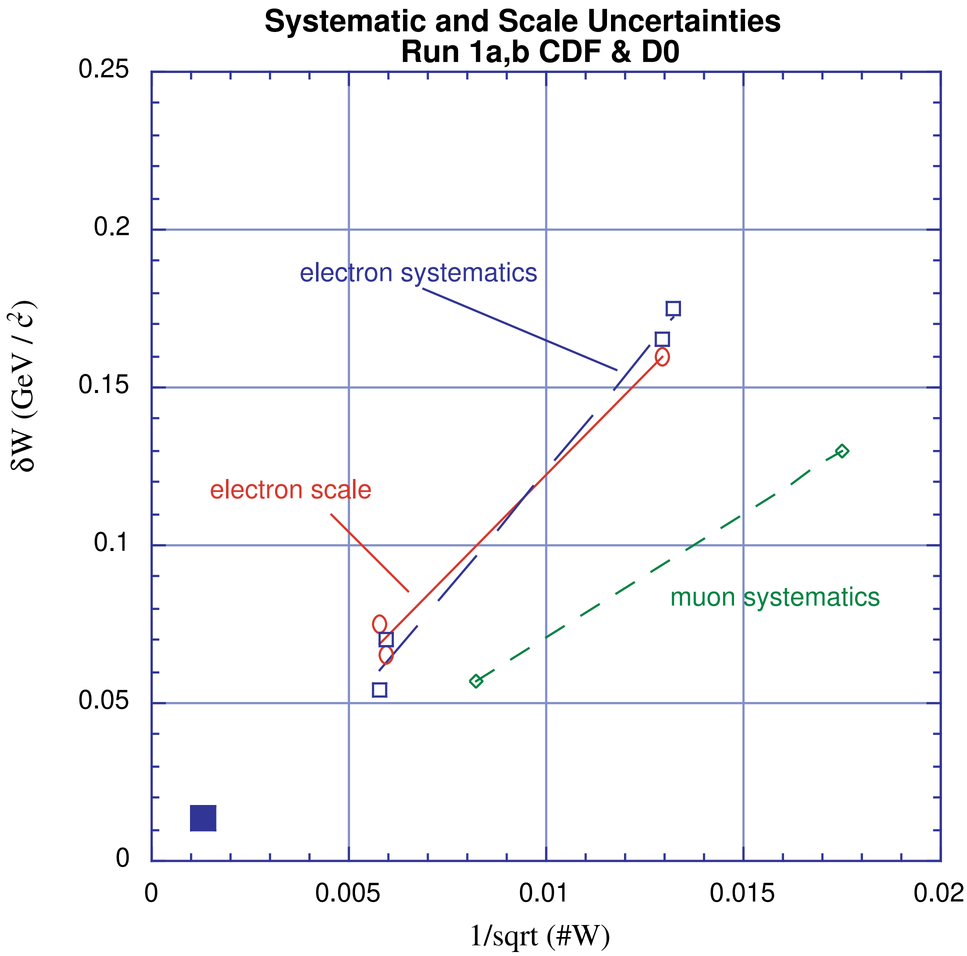
- LHC:

  ☞ for 10 fb^{-1} $\delta M_W(stat) < 2$ MeV

  ☞ can reach overall uncertainty of $\delta M_W = 15$ MeV if lepton energy and momentum scales are known to 0.02%

2 – Detector-specific Uncertainties

- main systematic uncertainties:
  - ☞ lepton energy and momentum scales
  - ☞ modeling W recoil
- uncertainty from W recoil dominated by Z boson statistics
  - ☞ should be significantly reduced in Run II
  - ☞ non-Z related recoil systematics is estimated to be at 10 MeV level
- other uncertainties related to Z boson statistics:
  - ☞ background determination
  - ☞ underlying event studies
  - ☞ selection bias
  - ☞ lepton energy and momentum scales



- calorimeter scale uncertainty:

☞ tied to determination of fiducial di-lepton decay resonances (Z, J/ψ, Υ)

☞ and the E/p dependence

☞ Run II: expect 15 MeV for calorimeter scale and muon momentum scale uncertainty

☞ there are also non-scale systematic uncertainties

- $Z \to \ell^+\ell^-$ 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 $\sin^2\theta_{eff}$

  ☞ these corrections are included in `ZGRAD2` (UB, O. Brein, W. Hollik, C. Schappacher, D. Wackeroth)

3 – Theoretical Uncertainties

- M_T lineshape simulation requires a theoretical model of differential cross section as a function of M_W and the W width, Γ_W
- determine M_W by comparing data with templates for different values of M_W
- theoretical model must take into account

  ☞ QCD corrections

  → resummation needed to describe W and Z p_T distributions

  → augmented by a non-perturbative contribution which depends on three parameters which are tuned to fit p_T^Z data

  ☞ electroweak radiative corrections

  → final state radiation affects M_W value extracted from data

  → and isolation variables needed to select clean W sample

- generators:

  ☞ QCD corrections: `RESBOS` (Balazs et al.); does not include electroweak corrections

  ☞ electroweak corrections: `WGRAD` (UB, S. Keller, D. Wackeroth) does not include QCD corrections

- both programs are standard tools for CDF/DØ analyses and have been interfaced with detector simulation software

- urgent need to unify/merge the two generators

Uncertainties in current W production model

- Parton distribution functions

  ☞ M_T distribution is invariant under longitudinal boosts

  ☞ incomplete angular coverage of detector introduces dependence on longitudinal momentum distribution of the produced W, which are determined by PDF's

  ☞ since angular coverage better than in Run I, the PDF uncertainty should be reduced in Run II

  ☞ can partially constrain PDF's using the W lepton charge asymmetry

  → this is part of a global effort to map out PDF uncertainties

  → first global fit of PDF's with uncertainties: CTEQ6 (CTEQ Collaboration)

  → warning: it is quite possible that uncertainties from PDF's have been underestimated in the past

- p_T^W distribution

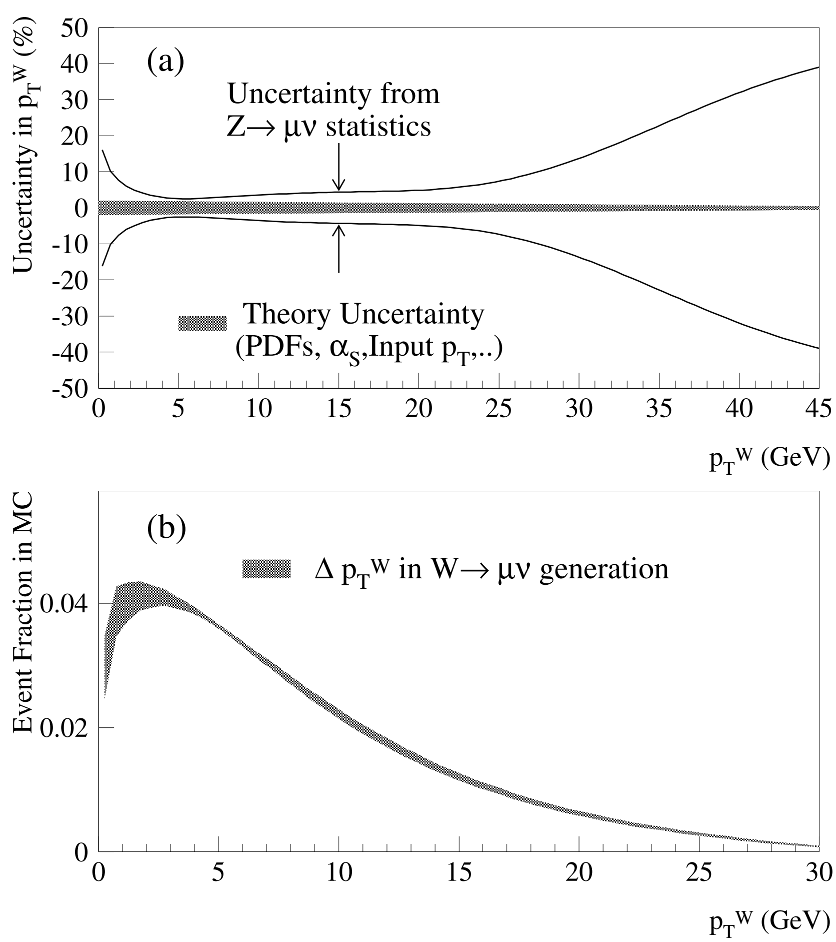
  ☞ extract p_T^W distribution from

  → ratio of W and Z differential cross sections obtained from resummation calculations

  → and measured p_T^Z distribution

  ☞ experimental uncertainties dominated by Z statistics (should scale in Run II)

  ☞ theoretical uncertainties in the ratio of W to Z p_T distributions: $\mathcal{O}(5\text{ MeV})$



- higher order QCD corrections

  ☞ QCD corrections are initial state corrections

  → impact on M_W is small

  ☞

$$\frac{d\sigma}{d\cos\theta_{CS}} \propto 1 + a_1(p_T^W)\cos\theta_{CS} + a_2(p_T^W)\cos^2\theta_{CS}$$

  θ_{CS}: polar angle of charged lepton w/r to proton direction in Collins-Soper frame

  LO: $a_1 = 2$, $a_2 = 1$, NLO corrections modify this

  ☞ expect that QCD corrections to a_i change M_W by a few MeV only, but no detailed simulations exist yet

- electroweak corrections

☞ dominant effect from final state photon radiation (FSPR):

➞ strongly depends on lepton id criteria

☞ in Run Ib CDF W mass measurement, shifts in M_W due to FSPR:

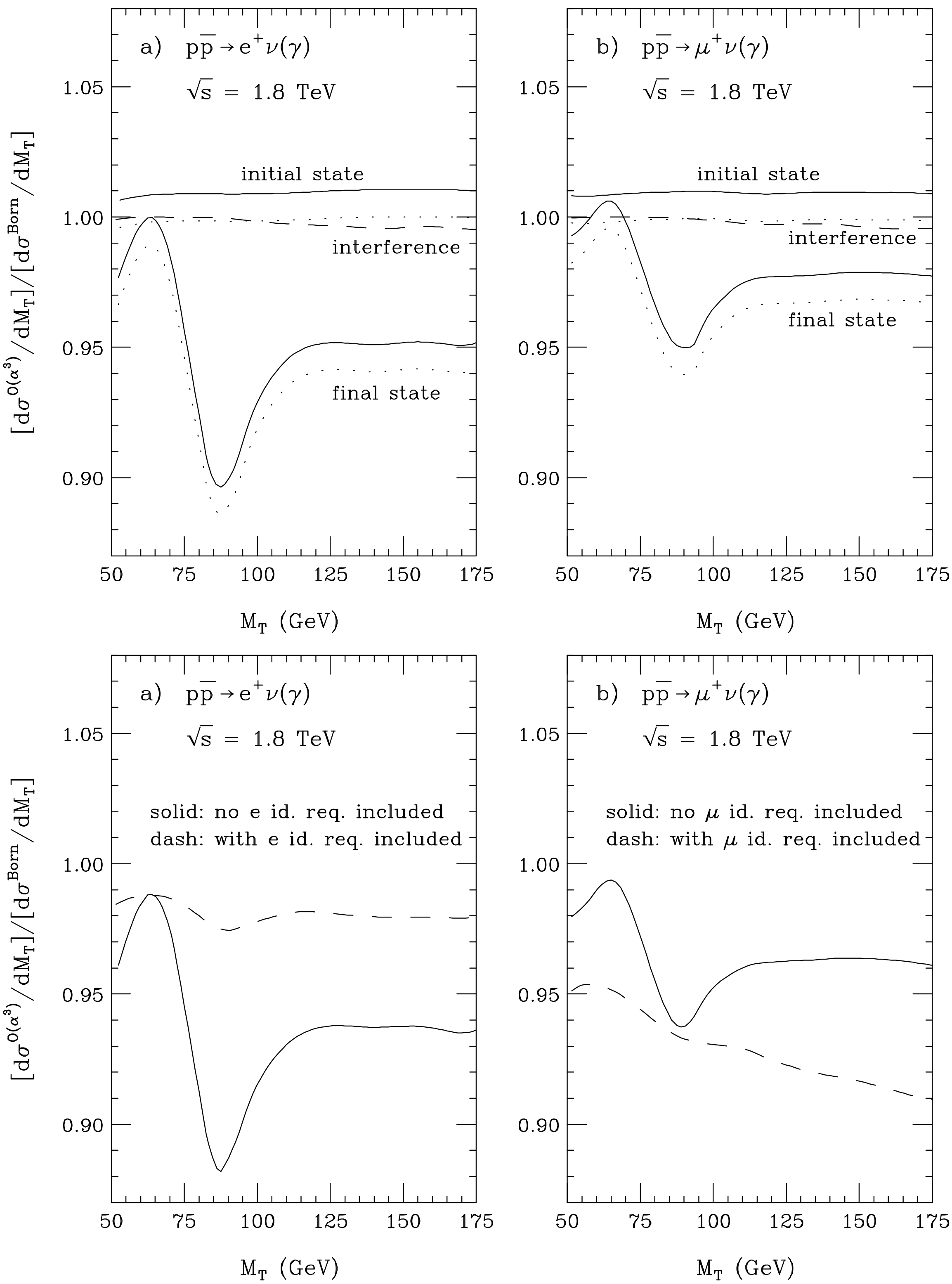
$$\begin{aligned} \text{electron channel :} &\quad -65 \pm 20 \text{ MeV} \\ \text{muon channel :} &\quad -168 \pm 10 \text{ MeV} \end{aligned}$$

☞ MC program used in Run I does not include initial state corrections or any virtual or soft corrections

➞ systematic uncertainty of $10 \ldots 20$ MeV in Run I from un-calculated radiative corrections

☞ calculations of the full $\mathcal{O}(\alpha)$ electroweak corrections now exist in Monte Carlo form (UB, D. Wackeroth, S. Dittmaier, M. Krämer)

➞ how big are the remaining uncertainties?


a) $p\bar{p} \to e^+\nu(\gamma)$
$\sqrt{s}$ = 1.8 TeV
initial state
interference
final state
b) $p\bar{p} \to \mu^+\nu(\gamma)$
$\sqrt{s}$ = 1.8 TeV
initial state
interference
final state
a) $p\bar{p} \to e^+\nu(\gamma)$
$\sqrt{s}$ = 1.8 TeV
solid: no e id. req. included
dash: with e id. req. included
b) $p\bar{p} \to \mu^+\nu(\gamma)$
$\sqrt{s}$ = 1.8 TeV
solid: no μ id. req. included
dash: with μ id. req. included
$[d\sigma^{O(\alpha^3)}/dM_T]/[d\sigma^{Born}/dM_T]$
M_T (GeV)

- important question: what is the shift due to multi-photon radiation effects?

  ☞ guidance from LEP: multi-photon radiation effects reduce the shift of M_Z induced by $\mathcal{O}(\alpha)$ corrections by about a factor 2

  ☞ expect smaller effect for W, since only one of the final state particles radiates photons

- first steps to address this question:

  ☞ explicit matrix element calculation of $\ell\nu\gamma\gamma$ and $\ell^+\ell^-\gamma\gamma$ production (UB, T. Stelzer)

  ➞ valid for small and large angle brem

  ➞ and photon p_T's as small as 100 MeV

  ☞ calculation of multi-photon radiation effects in the YFS exclusive exponentiation (`WINHAC`) (W. Placzek, S. Jadach)

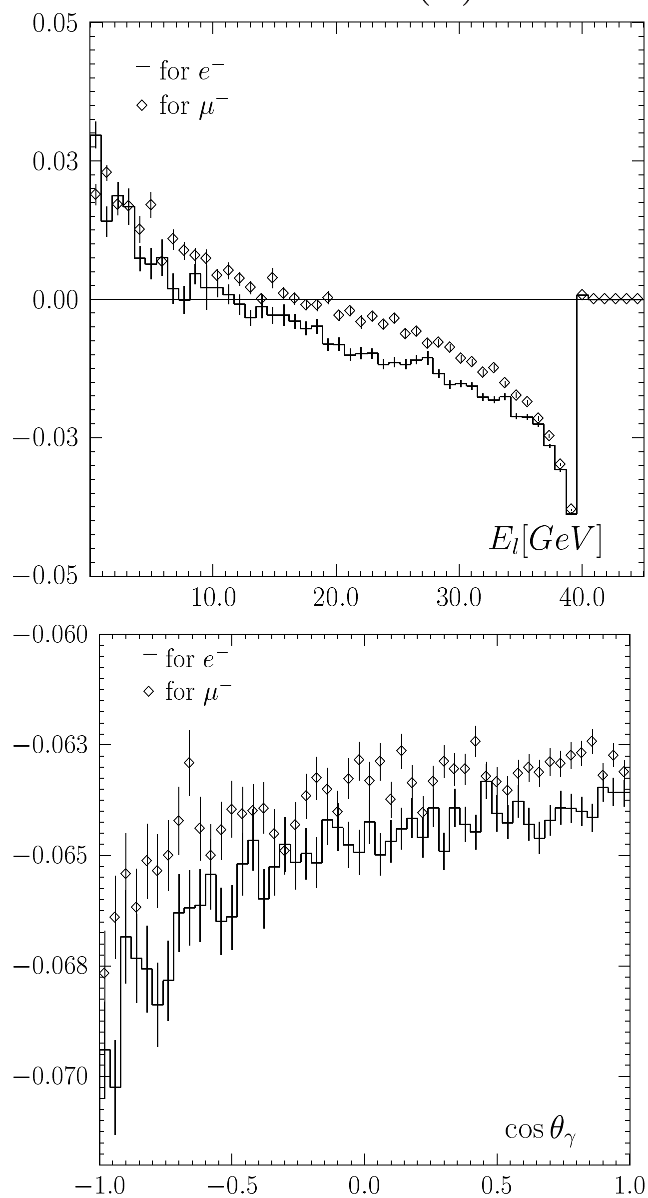
  ➞ currently only at parton level

☞ parton level examples (W. Placzek, S. Jadach)

→ correction to lepton energy distribution and distribution of angle of hardest photon

→ lepton id requirements are included

$$\delta = (d\sigma_{YFS} - d\sigma_{\mathcal{O}(\alpha)})/d\sigma_{YFS}$$



→ corrections are sizeable

- remarks:

  ☞ we also need to know the multi-photon corrections in the Z case

  ☞ since the experimental community has already invested a substantial amount of work in interfacing `WGRAD` and `RESBOS` with CDF/DØ detector simulation tools, it would make sense to collaborate and merge `RESBOS`, `WGRAD` and `WINHAC`, to provide one unified generator for W production (ditto for the Z case . . .)

4 – Other Methods of Determining M_W

possibilities:

- fit of the Jacobian kinematical edge from the p_T of the charged lepton

  → advantage: better electron and hadron response than for M_T lineshape

  → disadvantage: larger uncertainty from p_T^W

  → net effect: slightly larger uncertainties than using M_T lineshape

- ratio method (W. Giele, S. Keller, M. Rijssenbeek, S. Rajagopalan):

  ☞ use ratio of W to Z transverse masses

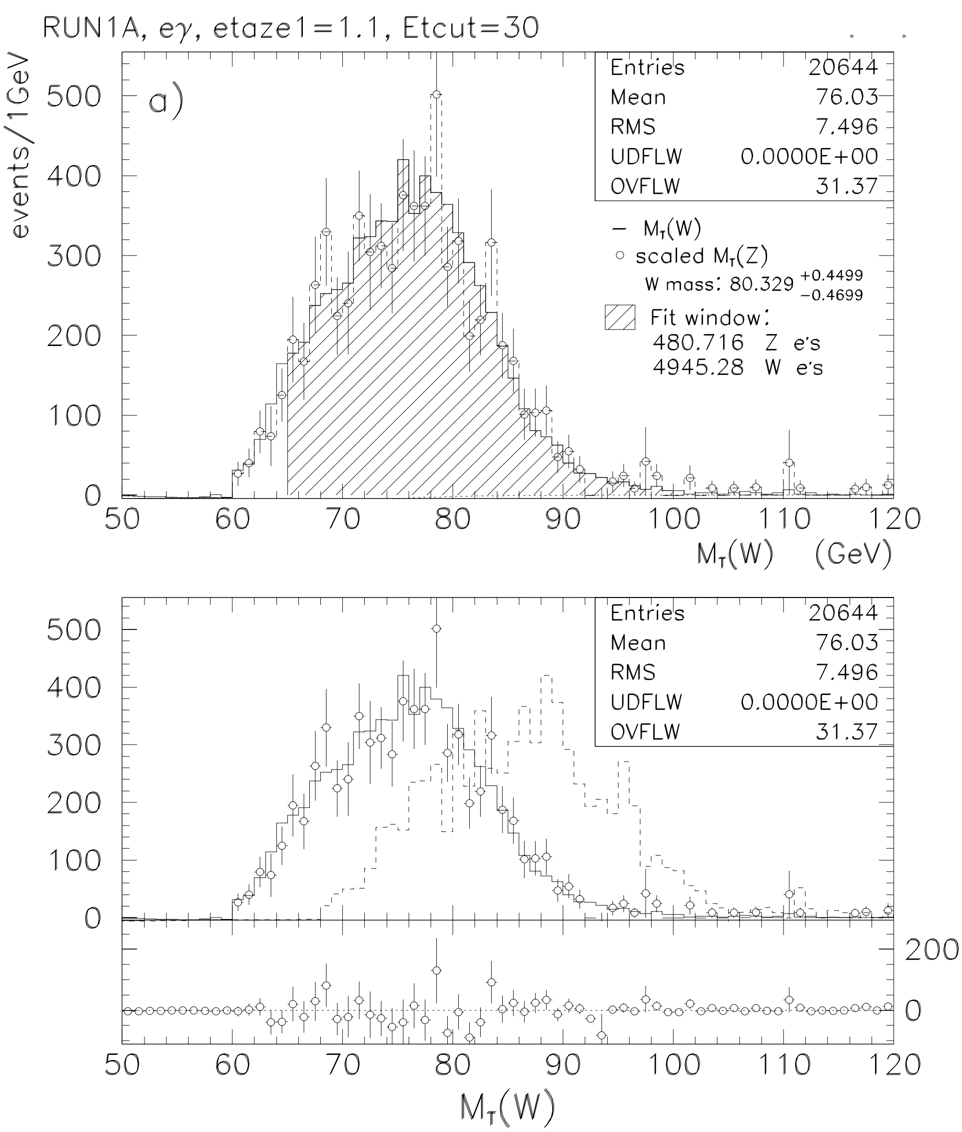
  ☞ advantage: many systematic effects cancel in ratio

  ☞ disadvantage: statistical uncertainty dominated by Z statistics

  ☞ must scale Z mass down to M_W

☞ 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:

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

→ larger statistical, but much smaller systematic uncertainties

- when will the ratio method become competitive?

$\int \mathcal{L}dt$ (fb^{-1})	2	15	30
M_T fit			
stat. uncert. (MeV)	19	7	5
syst. uncert. (MeV)	19	16	15
total uncert. (MeV)	27	17	16
ratio method			
stat. uncert. (MeV)	44	16	11
syst. uncert. (MeV)	10	4	3
total uncert. (MeV)	45	16	11

☞ ratio method competitive for ≥ 15 fb^{-1}

5 – Conclusions

- Measuring M_W at a hadron collider is difficult
- most detector related uncertainties scale with luminosity
- the M_T lineshape fit hits a brick wall at $15~\text{fb}^{-1}$. For higher luminosities the W/Z transverse mass ratio method promises better results
- the main remaining theoretical uncertainties originate from PDF's and multi-photon radiation effects
- there is an urgent need for a unified W event generator which includes

  ☞ QCD corrections together with soft gluon resummation

  ☞ electroweak radiative corrections, including multi-photon radiation