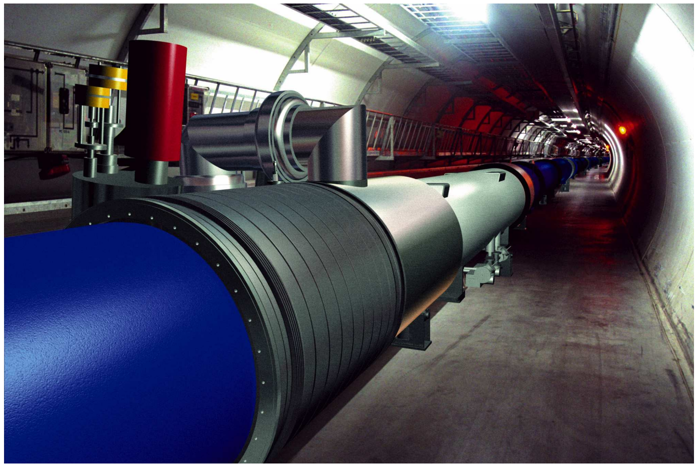
The Standard Model



1. Introduction to the Electroweak Theory
2. Introduction to Perturbative QCD and LHC Theory
3. Probing the Standard Model at the LHC I
4. Probing the Standard Model at the LHC II

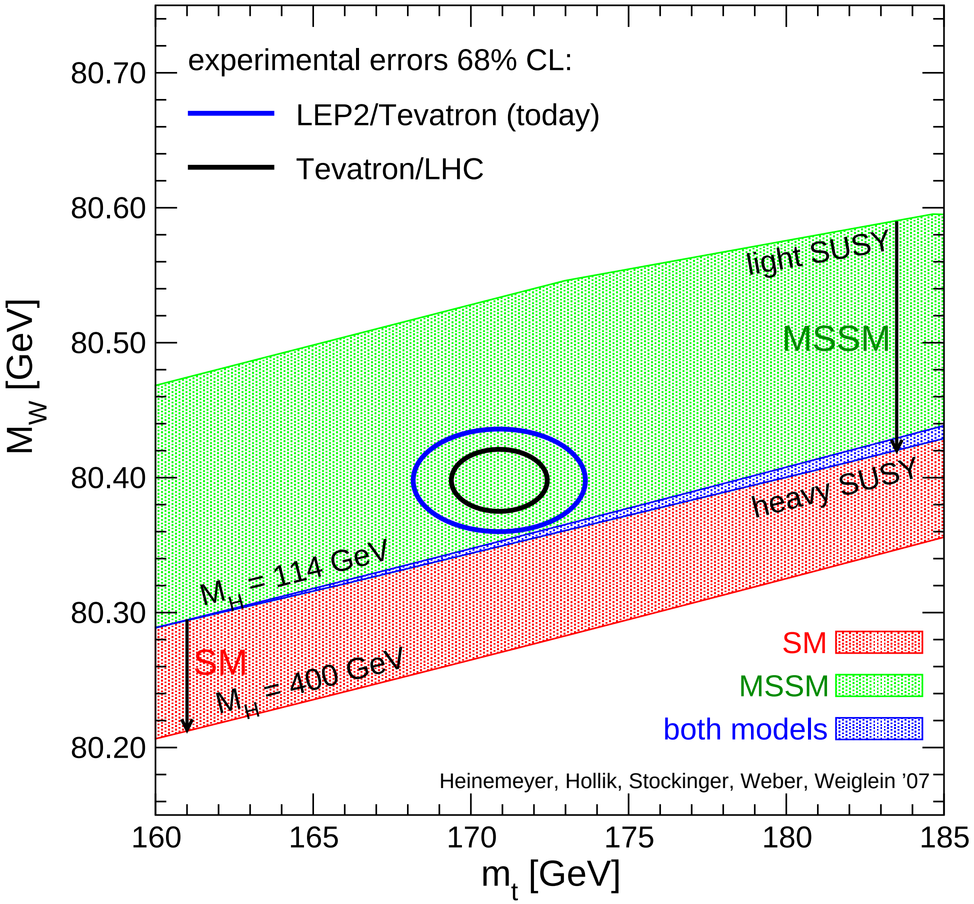
Ulrich Baur
State University of New York at Buffalo

Probing the Standard Model at the LHC I

- Plan for today:
  - ☞ W mass measurement at hadron colliders (Tevatron, LHC)
  - ☞ Electroweak radiative corrections at high energies
- good references:
  - ☞ P. Renton, hep-ph/0206231
  - ☞ CDF and DØ home pages

W Mass Measurement at Hadron Colliders

- recap: why it is important to measure M_W:
  constrain M_H, or more general, the SM



W Production at Hadron Colliders

- W decays:
  - ☞ $W \longrightarrow \ell\nu$ ($\ell = e,\ \mu$); branching ratio: $\approx 21.6\%$
  - ☞ $W \longrightarrow jj$: branching ratio: $\approx 68\%$
- $W \longrightarrow jj$ swamped by QCD jet production
- focus on $W \longrightarrow \ell\nu$

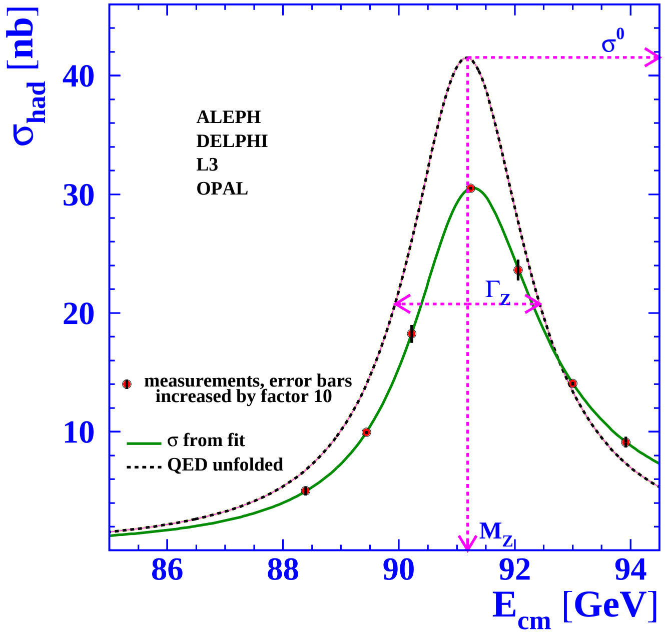
Sidebar: Z resonance in $e^+e^- \to \mu^+\mu^-$

- cross section sharply peaks at $\sqrt{s} = M_Z$:

$$\sigma_Z = \frac{12\pi\Gamma_{ee}\Gamma_{\mu\mu}}{(s - M_Z^2)^2 + M_Z^2\Gamma_Z^2}\,\frac{s}{M_Z^2}$$

s: squared CM energy

$\Gamma_{\ell\ell}$: $Z \to \ell^+\ell^-$ decay width



- alternative expression for s: squared invariant mass of final state μ pair

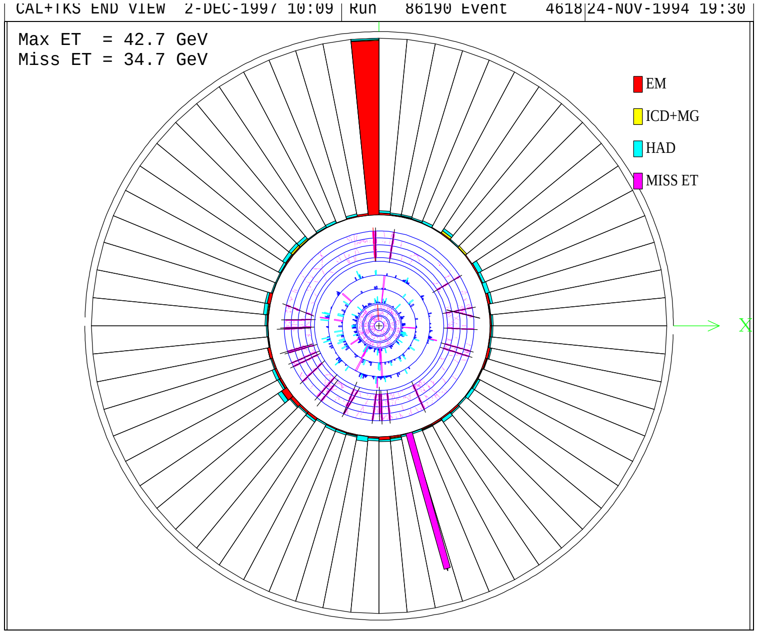
$$s = m^2(\mu^+\mu^-) = (E(\mu^+) + E(\mu^-))^2 - (\vec{p}(\mu^+) + \vec{p}(\mu^-))^2$$

→ reconstruct M_Z from inv. mass of final state particles

…back to measuring M_W

- trying to use the same trick to measure M_W is impossible
- reason: the neutrino from $W \to \ell\nu$ is not detected; only its transverse momentum, p_T, can be determined from apparent momentum imbalance (parton center of mass energy $\sqrt{\hat{s}}$ can vary)

  transverse momentum: momentum components transverse to beam direction



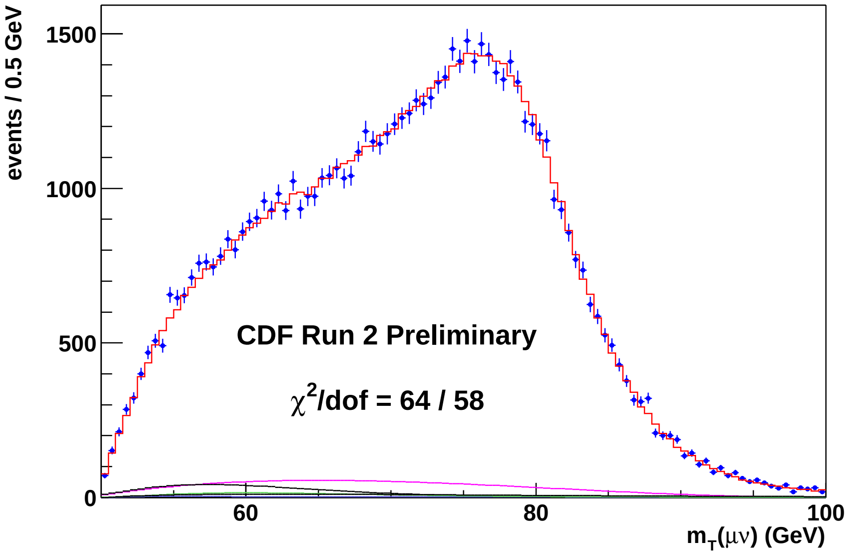
The Transverse Mass

- Define transverse mass variable:

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

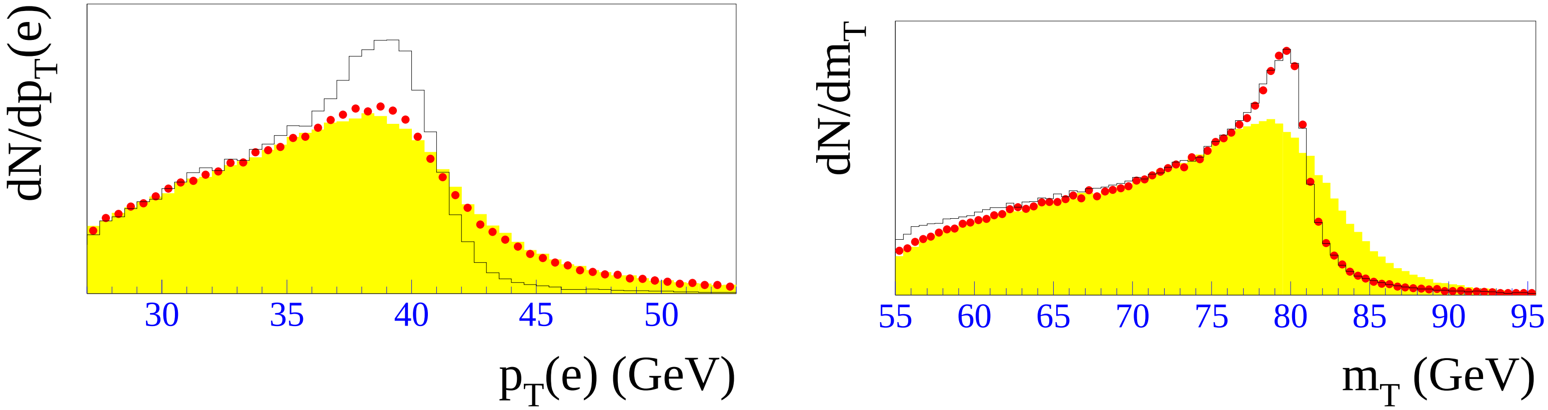
$p_T(\nu) = \not{p}_T$: missing transverse momentum $\phi^{\ell\nu}$: angle between charged lepton and missing transverse momentum in transverse plane

- M_T distribution sharply peaks at M_W (so-called Jacobian peak)



Alternative: the lepton p_T distribution

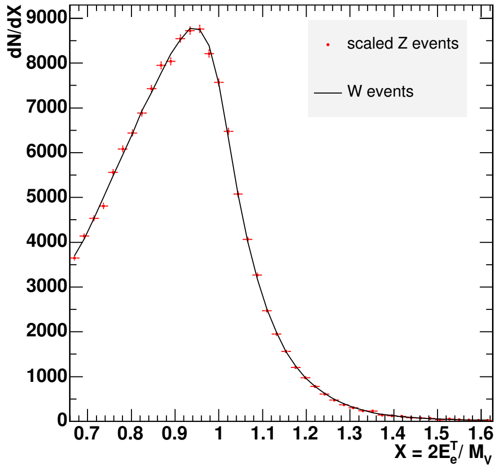
- the $p_T(\ell)$ distribution also has a Jacobian peak, but at $M_W/2$
- what determines the shape of the Jacobian peak:
  - ☞ the W width, Γ_W
  - ☞ detector resolution effects
  - ☞ and the transverse momentum of the W boson, $p_T(W)$
- $p_T(W)$: caused by initial state gluon radiation
- M_T is far less sensitive to $p_T(W)$ than $p_T(\ell)$

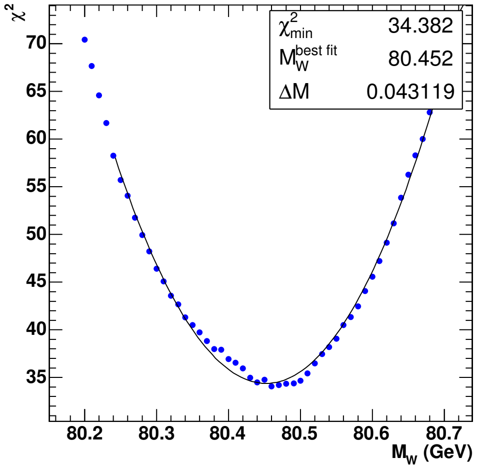


- histogram: no detector smearing, $p_T^W = 0$
  dots: finite p_T^W
  shaded: adds detector resolutions (here: Run 1 DØ detector)
- disadvantage of M_T distribution: have to reconstruct $\not{p}_T$
- observables:
  - ☞ charged lepton transverse energy/momentum
  - ☞ non-leptonic transverse energy (hadronic recoil) $\vec{u}$
  - ☞ derive ν transverse momentum and M_T from $\vec{p}_T(\ell)$ and $\vec{u}$

The ratio method (CMS Physics TDR Vol. 2)

- use ratio of W to Z lepton transverse momenta or ratio of transverse mass distributions
- 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)





Uncertainties

- main experimental systematic uncertainties:
  - ☞ lepton energy and momentum scales
  - ☞ modeling W recoil
- $Z \to \ell^+\ell^-$ data constrain lepton scale and resolution
  - ☞ calibrate 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

- $p_T(W)$ distribution: extract $p_T(W)$ distribution from
  - ☞ ratio of W and Z differential cross sections obtained from QCD calculations
  - ☞ and measured $p_T(Z)$ distribution
  - ☞ experimental uncertainties dominated by Z statistics
- M_T line-shape simulation requires a theoretical model of differential cross section as a function of M_W and the W width, Γ_W
- theoretical uncertainties
  - ☞ parton distribution functions
  - ☞ higher order electroweak and QCD corrections
  - ☞ final state radiation affects M_W value extracted from data

M_W: Present and Future

- recall current value:

$$M_W = 80.398 \pm 0.025 \text{ GeV}$$

combined Tevatron Run I, Run II and LEP2 value

- Tevatron Run II: from first 200 pb^{-1} (CDF):

$$\delta M_W \approx 48 \text{ MeV}$$

Estimated precision for 2 fb^{-1}:

$$\delta M_W \approx 25 \text{ MeV}$$

combining e and μ final states and CDF and DØ results

- LHC: using the ratio method, CMS estimates for 10 fb^{-1}

$$\delta M_W \approx 20 \text{ MeV}$$

combining e and μ final states

- remarks:
  - ☞ measuring M_W at a hadron collider is very challenging
  - ☞ it requires a detailed understanding of the detector
  - ☞ it will probably take years before this has been achieved (recall: we are 5 years into Run II of the Tevatron and the first M_W measurement was released in January 2007)
  - ☞ it also requires a very detailed understanding of the the theoretical production model:
    - → QCD corrections
    - → electroweak radiative corrections

EW Radiative Corrections to W (and Z) Production

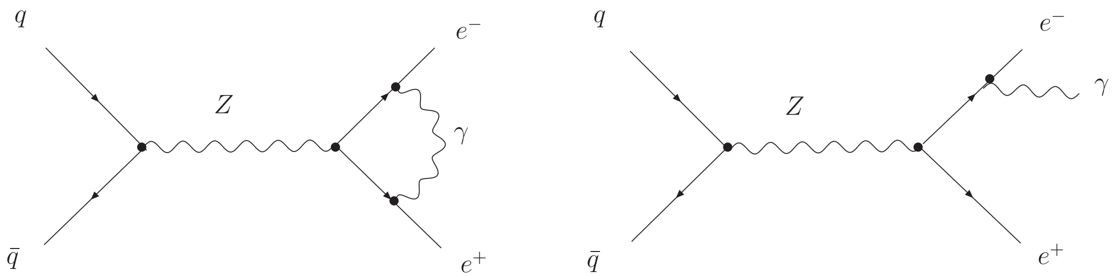
- electroweak radiative corrections distort the Breit-Wigner resonance shape, and have an impact on the W/Z mass extracted from data.
  - ☞ Tevatron Run I experience: shift in M_W due to EW corrections: $\Delta M_W \approx -50$ MeV for $W \to e\nu$ and $\Delta M_W \approx -150$ MeV for $W \to \mu\nu$
- determine M_W by comparing experimental M_T distribution with templates for different values of M_W (similar procedure for M_Z)
- do step by step with increasing complexity:
  1. QED corrections to Z production (separately gauge invariant)
  2. EW corrections to W production in the pole region
  3. full EW corrections to W and Z production

References for this section

- UB, hep-ph/0304266 (review)
- UB, S. Keller, and W.K. Sakumoto, PRD57, 199 (1998)
- UB, S. Keller, and D. Wackeroth, PRD59, 013002 (1999)
- UB et al. PRD65, 033007 (2002)
- S. Dittmaier and M. Krämer, PRD65, 073007 (2002);
  UB and D. Wackeroth PRD70, 073015 (2004)

QED Corrections to Z Production

- have to calculate virtual and real corrections
- soft singularities from final state radiation (FSR) cancel against those from interference of Born and virtual final state corrections

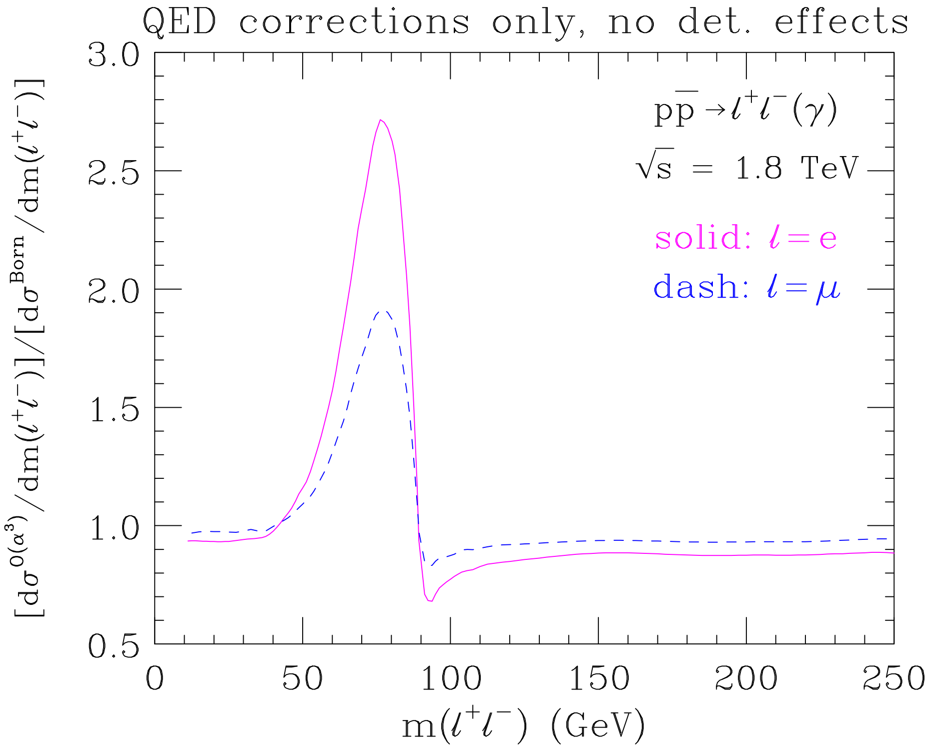


- the same applies to initial state radiation (ISR) and IS-FS interference effects

- there are also collinear singularities
  - ☞ Final state collinear singularities are regulated by finite lepton masses
  - ☞ Initial state collinear singularities are universal to all orders and can be 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
  - ☞ PDF's which include QED corrections now exist (MRST2004QED)
- final state radiative corrections are proportional to

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

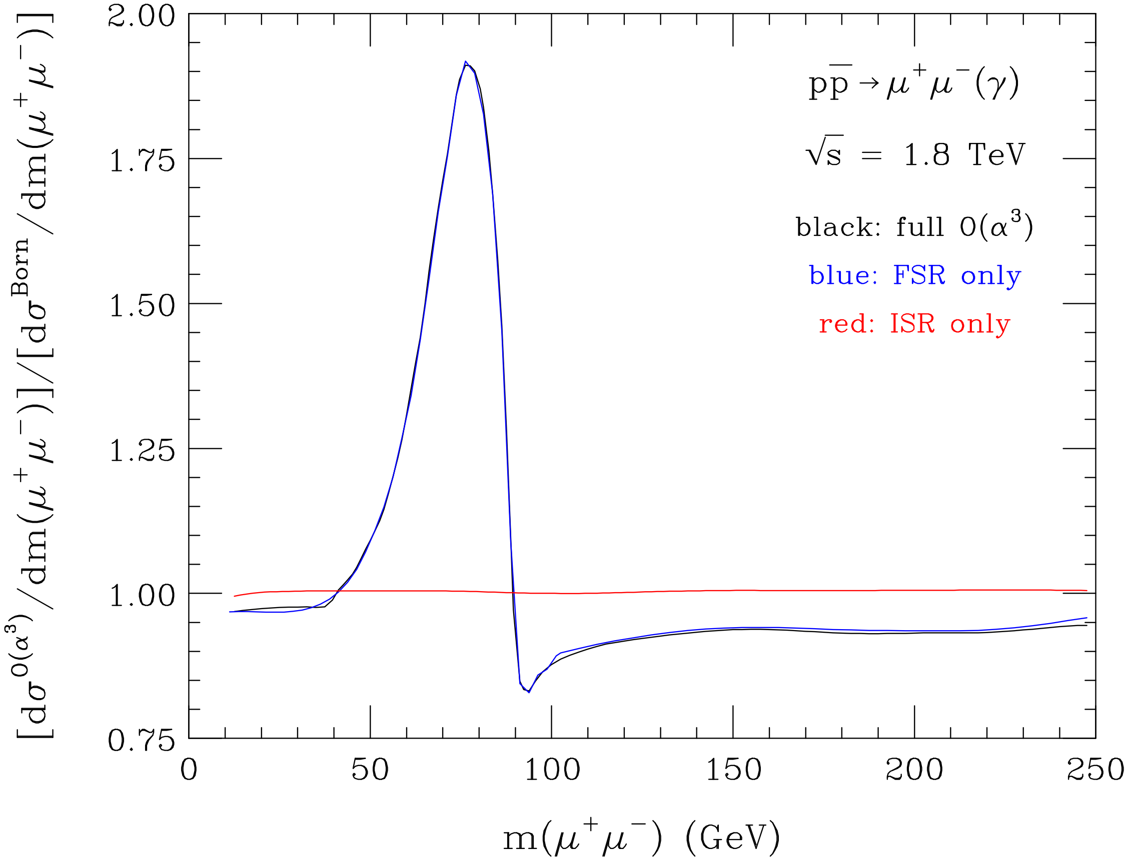
- near the Z peak: $\hat{s} = m^2(\ell\ell) \approx M_Z^2$
  - ☞ since the e and μ masses are small ($m_e = 0.511$ MeV, $m_\mu = 105.6$ MeV), the log becomes very large
  - ☞ FSR corrections significantly influence the $\ell^+\ell^-$ invariant mass distribution



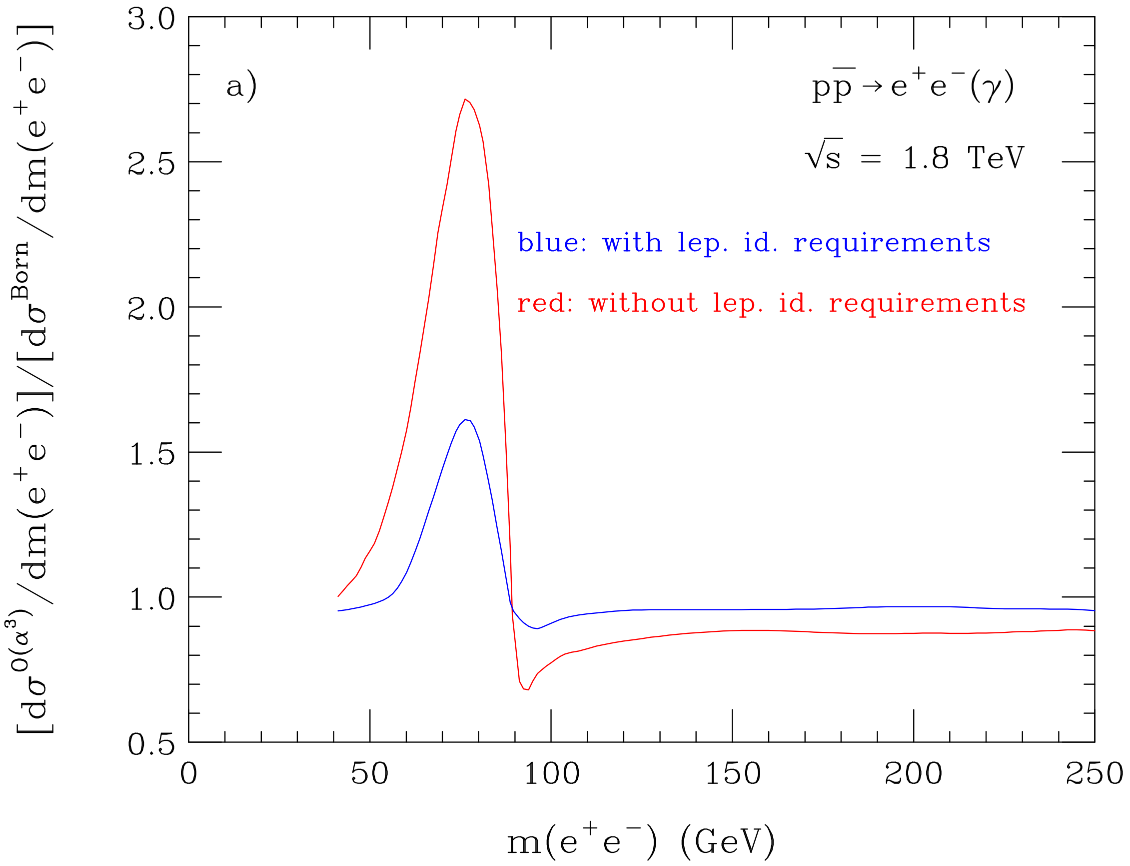
- big enhancement below the peak (due to Breit Wigner peak)
- at the peak the cross section is reduced by about 30% for electrons and 20% for muons
- for $m(\ell\ell) > 120$ GeV, the cross section is reduced by about $\sim 12\%$ ($\sim 7\%$) for e (μ)
- integrating over $m(\ell\ell)$, the large positive and negative corrections cancel

  This is an example of how the Kinoshita-Lee-Nauenberg (KLN) theorem works
- KLN theorem: large logarithmic QED corrections cancel in sufficiently inclusive observables
- the peak is distorted, and the Z mass extracted from experiment is shifted

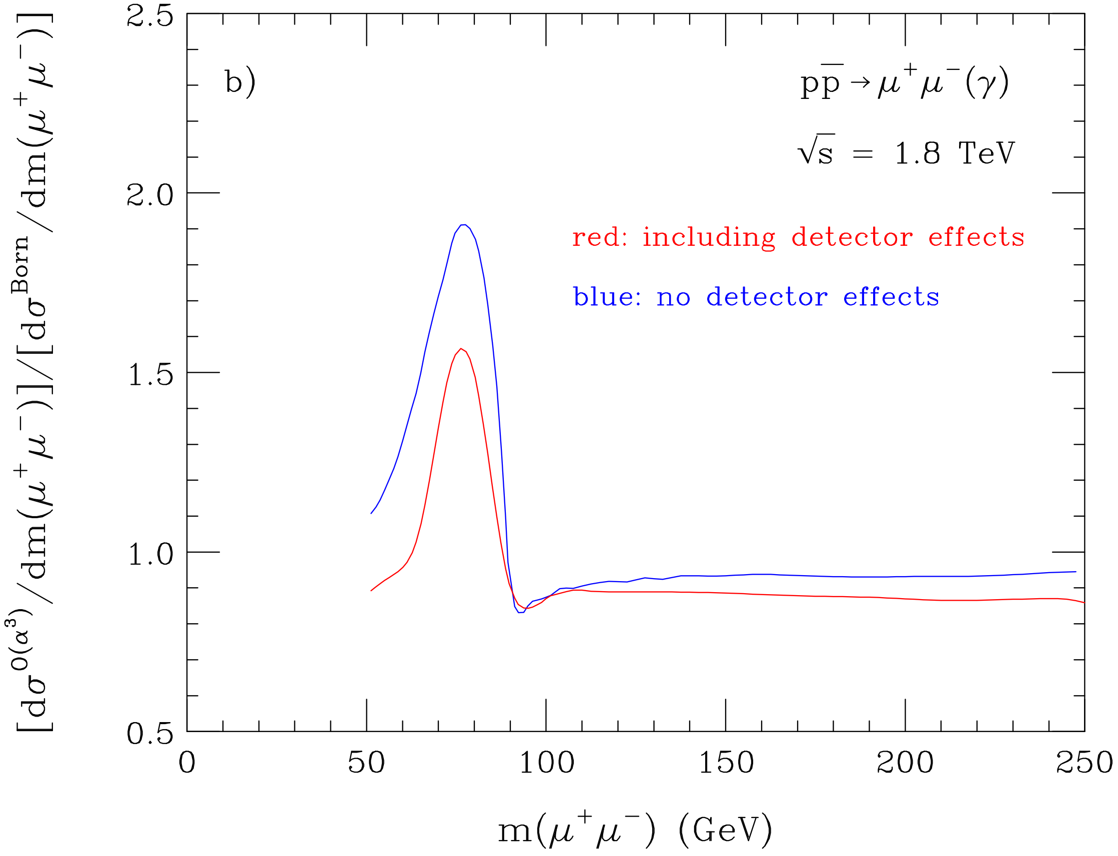
- final state corrections dominate everywhere
- Initial state corrections are small and uniform



- so, theory predicts that the QED for $W \to e\nu$ are larger than for $W \to \mu\nu$
- but, in experiment, the opposite is true
- Experimental lepton ID and QED corrections
  - ☞ 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 for small e, γ opening angle
  - ☞ an inclusive quantity is formed
  - ☞ the lepton mass m_ℓ in $(\alpha/\pi)\log(\hat{s}/m_\ell^2)$ is replaced by the $e\gamma$ invariant mass at the recombination threshold (KLN again…)
  - ☞ the effect of the QED corrections is reduced


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

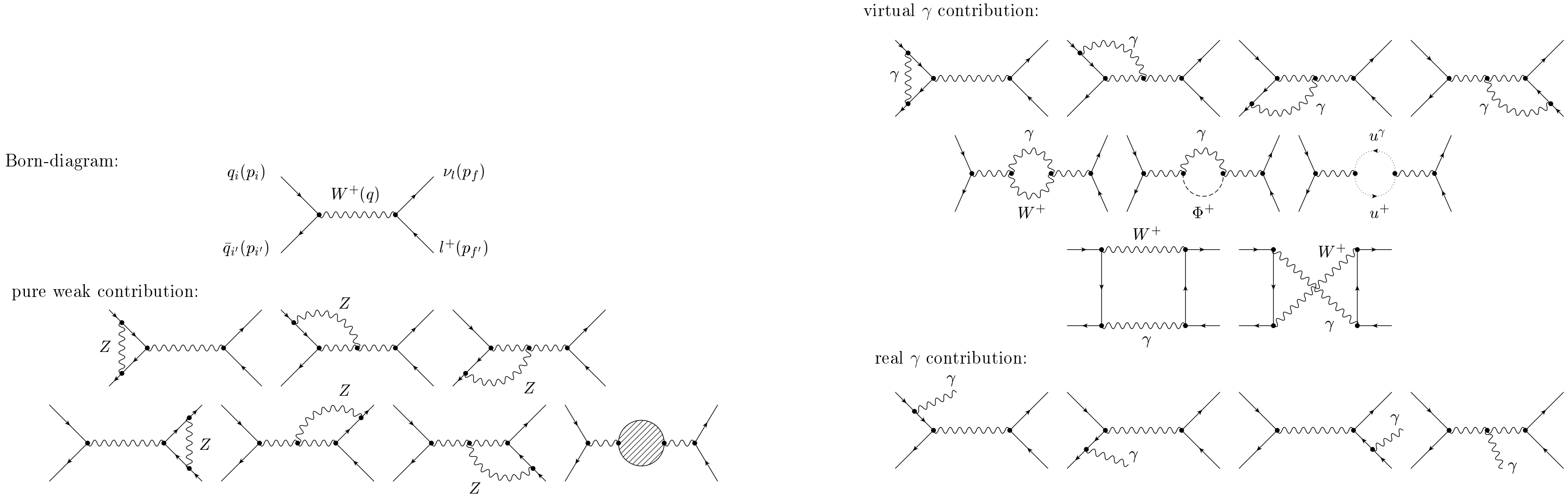
- Muons must be consistent with a minimum ionizing particle
  - → require $E_\gamma <$ a few GeV in cell traversed by muon
  - → this reduces the hard photon part
  - → the mass singular terms survive



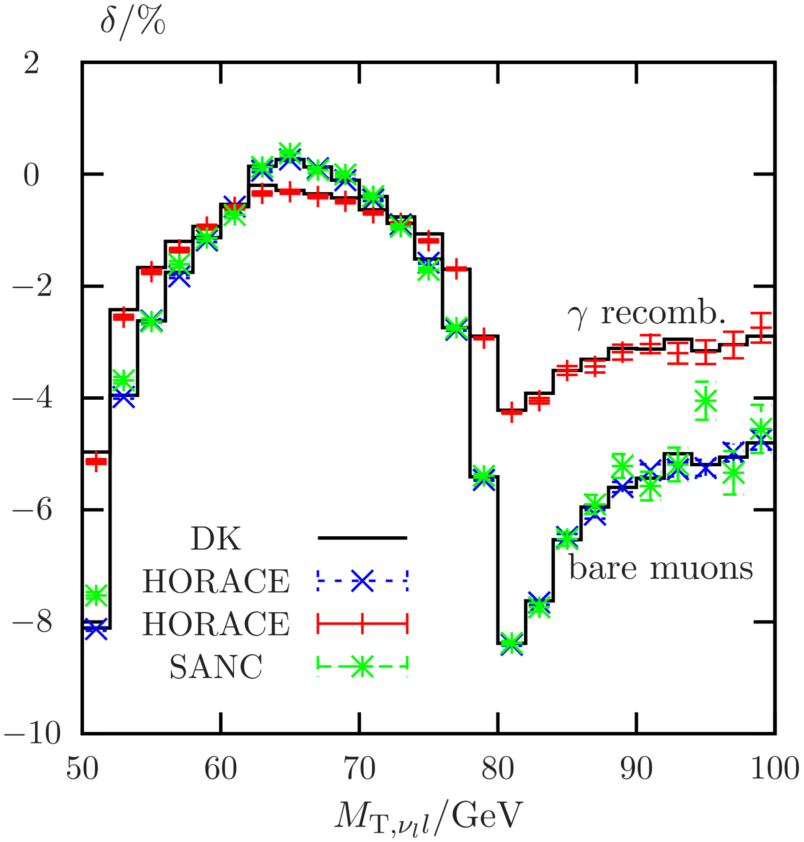
EW Corrections to W Production

- Since the W is charged, the EWK corrections to W production cannot be separated into gauge invariant QED and purely weak corrections

  → need to take weak corrections into account

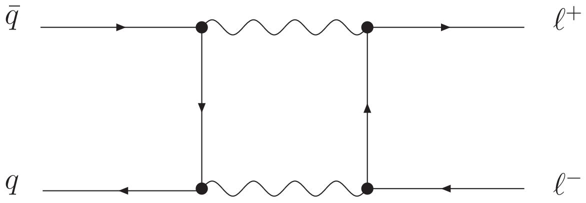


- ignore contributions which vanish for $\hat{s} = M_W^2$ (pole approximation)
- technical details very similar to Z case
- observe significant corrections to M_T distribution in Jacobian peak region



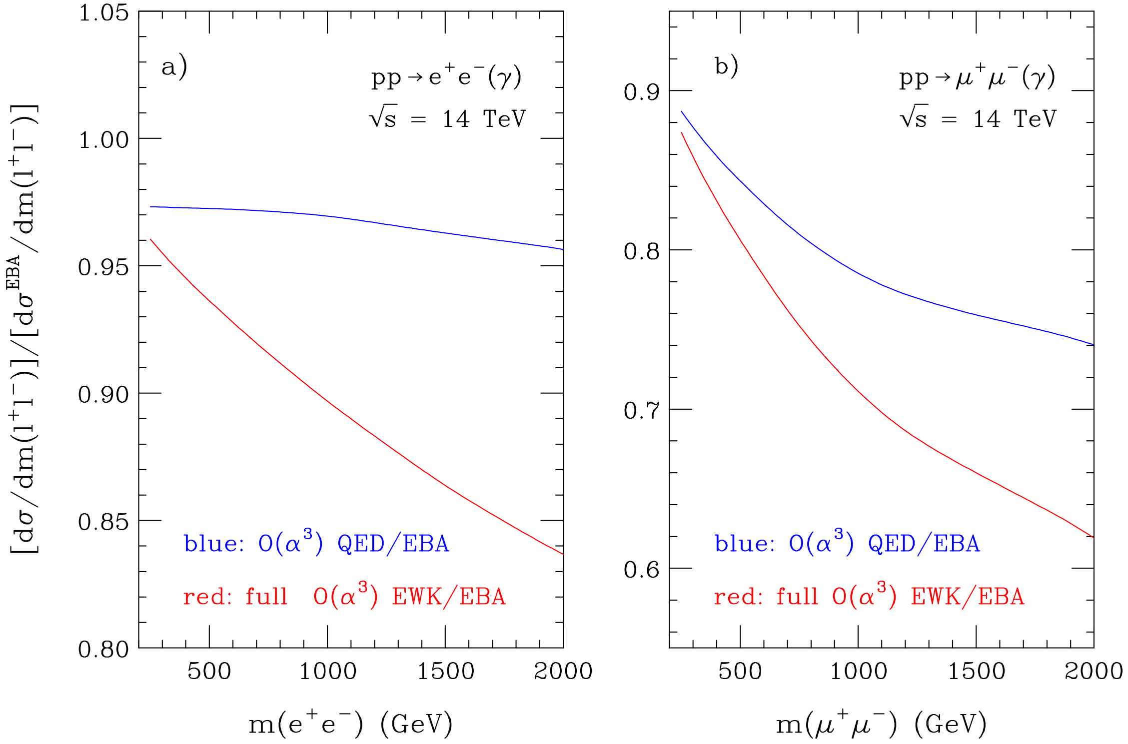
…on to the full EW corrections

- now we include EW corrections which are small in the W/Z pole region



- they are important for $m(\ell^+\ell^-) > M_Z$ and $M_T > M_W$
- why is the high (transverse) mass region of interest?
  - ☞ Search for new heavy gauge bosons (charged and neutral), Kaluza-Klein (KK) excitations of W and Z, KK gravitons, …

- the electroweak corrections become large and negative at high energies. Z case:

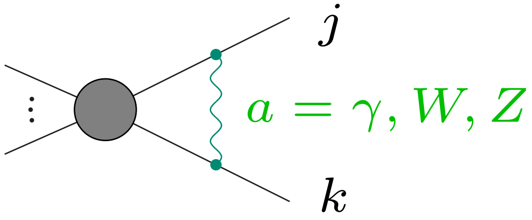


EBA: enhanced Born approximation (some radiative corrections have been taken into account by using running coupling constants, the physical W and Z masses, etc.)

- the EW corrections to $\ell^+\ell^-$ production rival QCD corrections in the TeV region
- the same thing happens in the W case
- …and for many other processes:
  - ☞ inclusive jet production
  - ☞ isolated photon and $Z + 1$ jet production
  - ☞ $\bar{t}t$ and single top production
  - ☞ di-boson ($W\gamma$, $Z\gamma$, WZ, ZZ, WW) production
- what is going on here?

Logarithms, again!

- so-called Sudakov logarithms induced by soft W, Z exchange



- relative correction to cross section for $2 \longrightarrow 2$ reactions at $\sqrt{\hat{s}} = 1$ TeV:

$$\delta_{1-loop} \sim -\frac{\alpha}{\pi \sin^2\theta_W} \log^2\left(\frac{\hat{s}}{M_W^2}\right) \approx -26\%$$

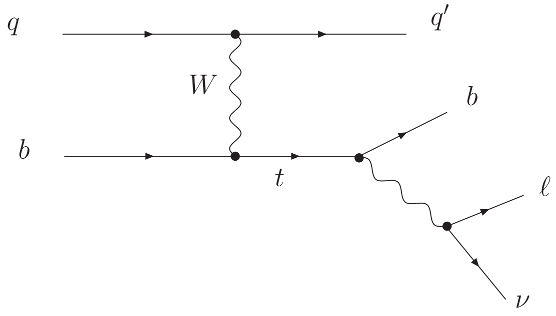
- origin of Sudakov logs:
  - ☞ corresponding logs in QED/QCD cancel between virtual and real corrections
  - ☞ massive W and Z bosons are infrared regulators for loops
  - ☞ no technical reason to include real W and Z radiation
- but W and Z radiation can still be important
  - ☞ since W's and Z's decay
  - ☞ it depends on whether one considers an inclusive or exclusive final state
  - ☞ since W's and Z's decay, W/Z radiation lead to a different final state
  - ☞ for inclusive processes W/Z radiation may be important
  - ☞ example for inclusive process: inclusive jet or isolated photon production

☞ exclusive: t-channel single top production:

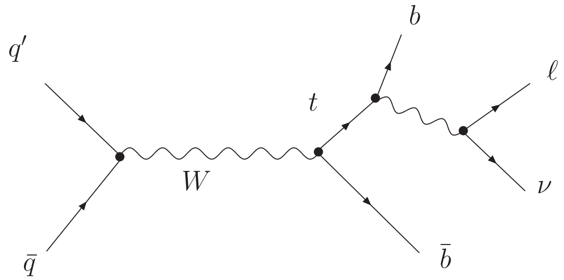
→ require exactly one jet

→ and one tagged b-quark

to suppress s-channel single top and $\bar{t}t$ backgrounds



t-channel



s-channel

- references for this part:

  M. Melles, Phys. Rept. 375, 219 (2003)