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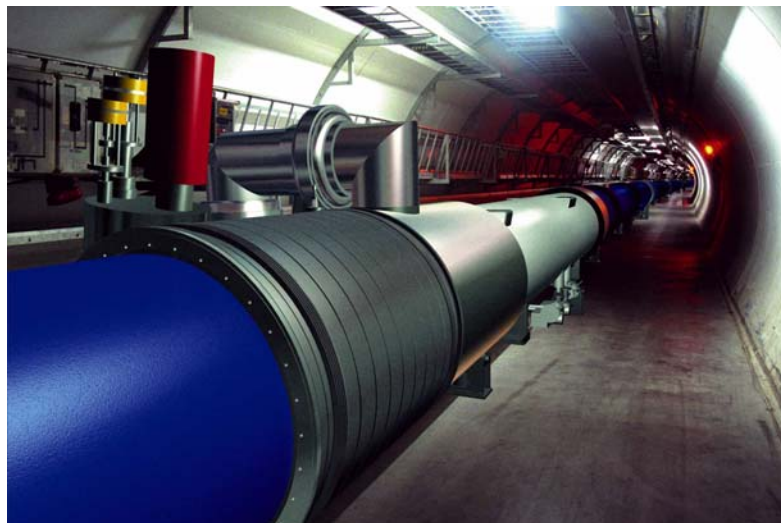
SCHOOL ON PHYSICS AT LHC: "EXPECTING LHC"
11 - 16 September 2006

ELECTROWEAK PHYSICS AT LHC
Part II

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These are preliminary lecture notes, intended only for distribution to participants.

Electroweak Physics at the LHC



1. Introduction to the Standard Model
2. Electroweak Measurements at the LHC I
3. Electroweak Measurements at the LHC II

Ulrich Baur

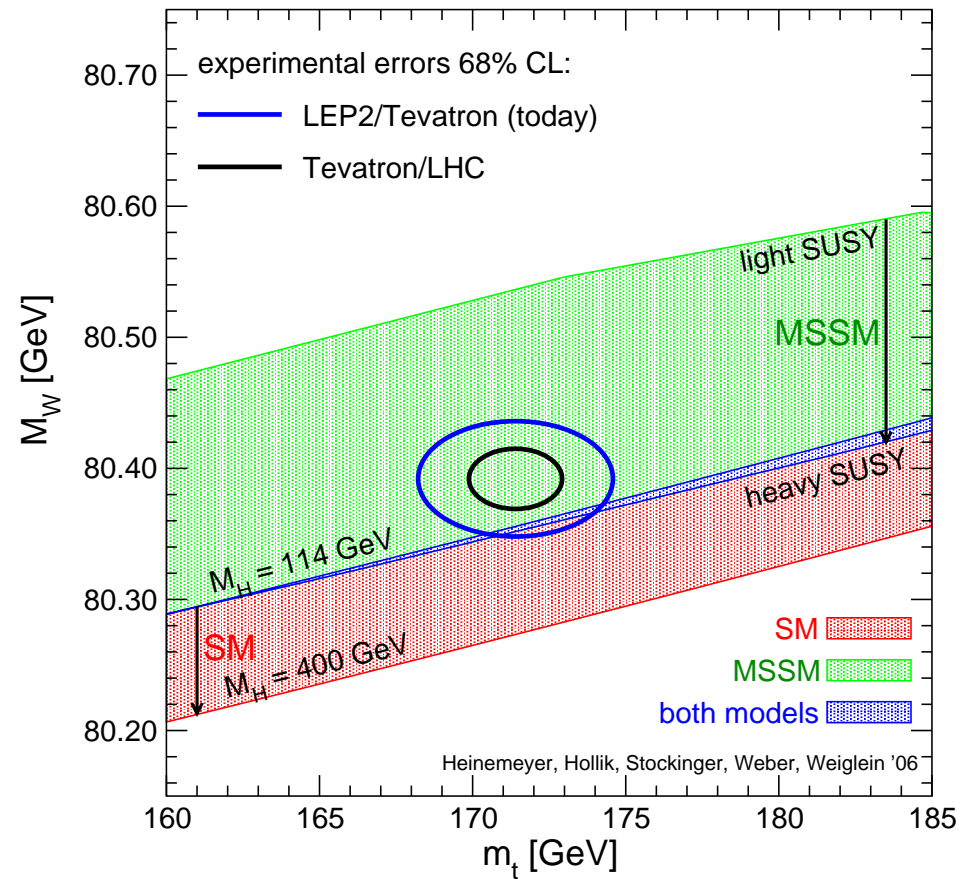
State University of New York at Buffalo

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

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

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

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

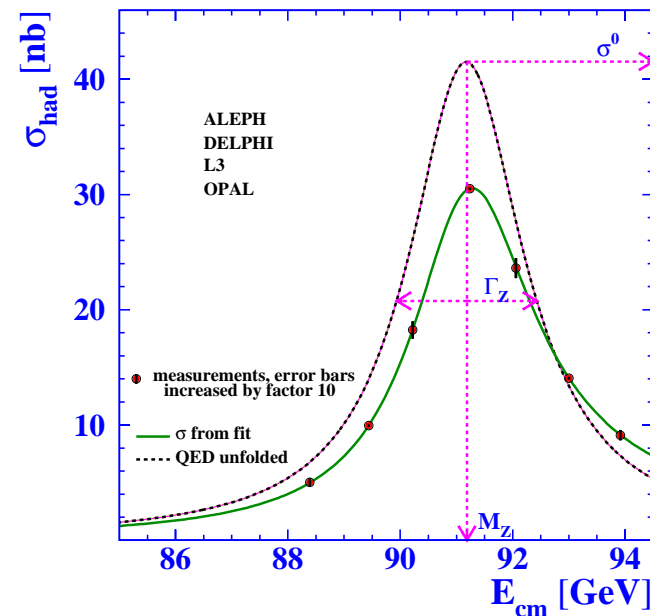
s : squared CM energy

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

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

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

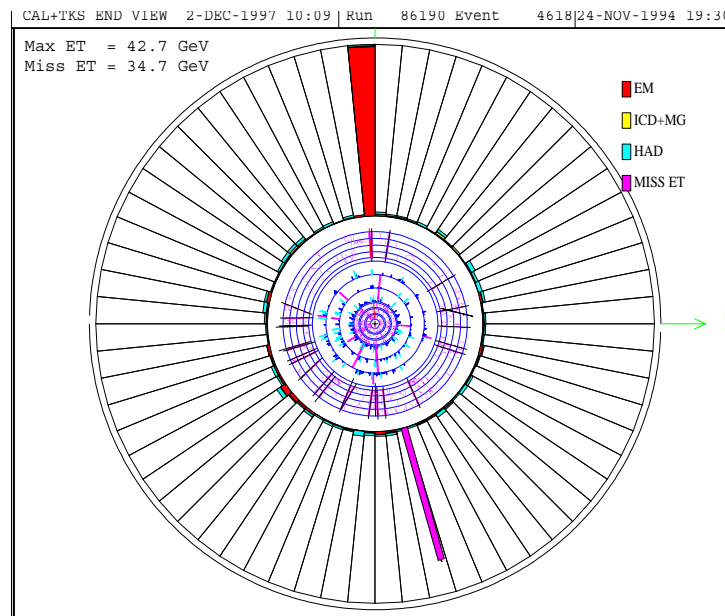
→ reconstruct M_Z from inv. mass of final state particles



... back to measuring M_W

- trying to use the same trick to measure M_W is impossible
- reason: the neutrino from $W \rightarrow \ell\nu$ 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



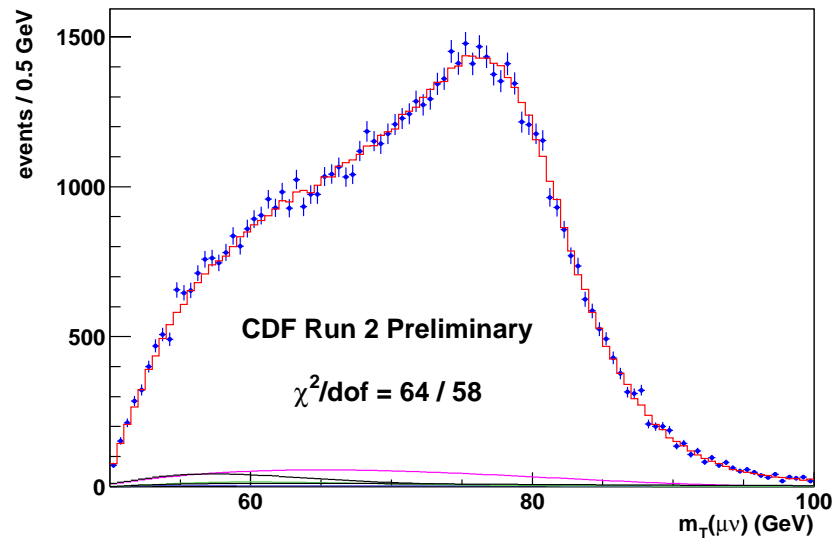
The Transverse Mass

- Define **transverse mass** variable:

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

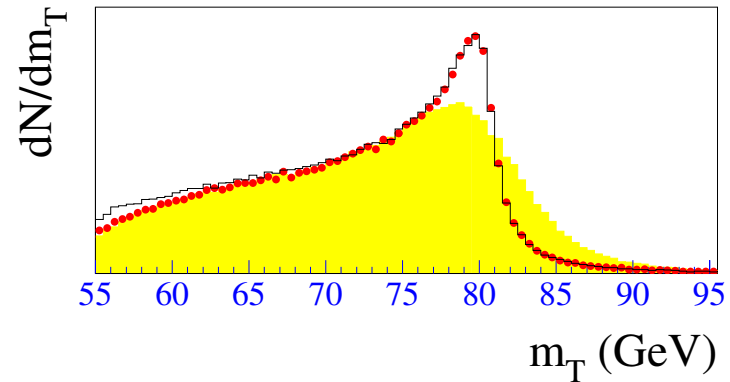
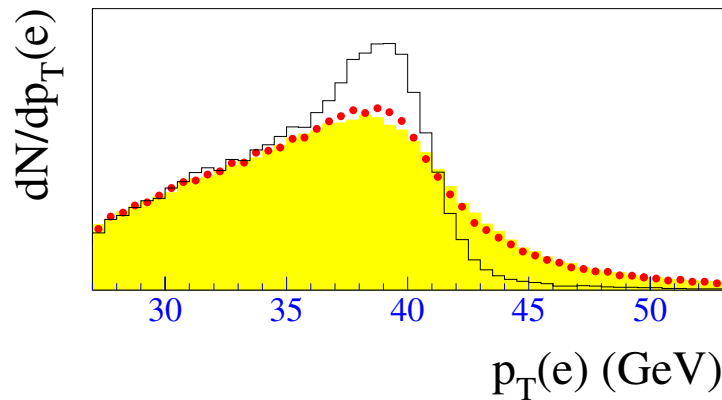
$p_T(\nu) = \cancel{p}_T$: missing transverse momentum $\phi^{\ell\nu}$: angle between charged lepton and missing transverse momentum in transverse plane

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



Alternative: the lepton p_T distribution

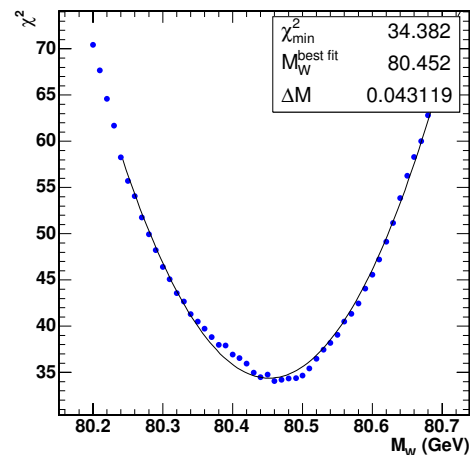
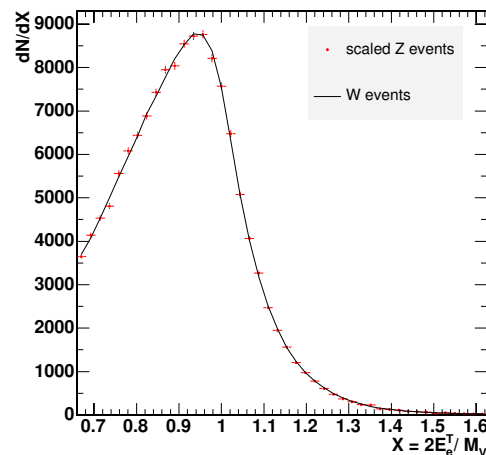
- the $p_T(\ell)$ distribution also has a Jacobian peak, but at $M_W/2$
- what determines the shape of the Jacobian peak:
 - ➡ the W width, Γ_W
 - ➡ detector resolution effects
 - ➡ and the transverse momentum of the W boson, $p_T(W)$
- $p_T(W)$: caused by initial state gluon radiation
- M_T is far less 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 \cancel{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
- $Z \rightarrow \ell^+ \ell^-$ 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 (see QCD lectures)
 - ➡ higher order electroweak and QCD corrections
 - ➡ final state radiation affects M_W value extracted from data

M_W : Present and Future

- recall current value:

$$M_W = 80.392 \pm 0.029 \text{ GeV}$$

combined Tevatron Run I and LEP2 value

- Tevatron Run II: no results yet. 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 several years into Run II of the Tevatron and still waiting for M_W ...)

- ☞ it also requires a very detailed understanding of the theoretical production model:

- QCD corrections

- electroweak radiative corrections

EW Radiative Corrections to W (and Z) Production

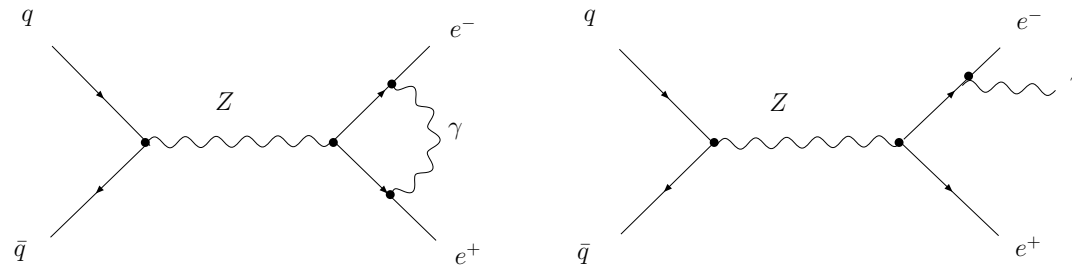
- electroweak radiative corrections distort the Breit-Wigner resonance shape, and have an impact on the W/Z mass extracted from data.
 - ☞ Tevatron Run I experience: shift in M_W due to EW corrections:
 $\Delta M_W \approx -50 \text{ MeV}$ for $W \rightarrow e\nu$ and $\Delta M_W \approx -150 \text{ MeV}$ for $W \rightarrow \mu\nu$
- 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. Wackerath, PRD59, 013002 (1999)
- UB et al. PRD65, 033007 (2002)
- S. Dittmaier and M. Krämer, PRD65, 073007 (2002);
UB and D. Wackerath 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

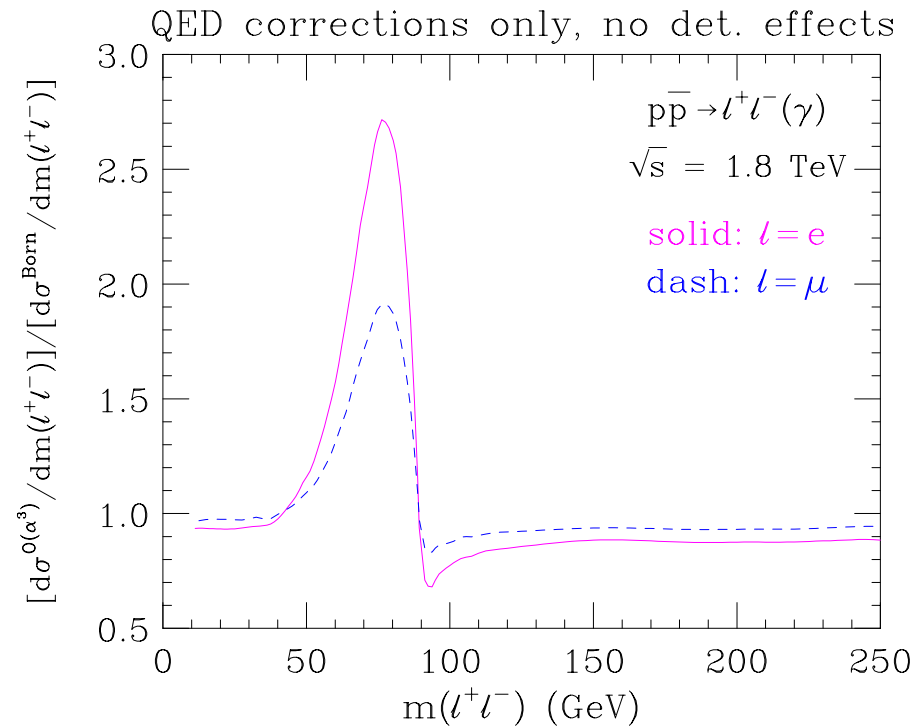


- the same applies to initial state radiation (ISR) and IS-FS interference effects

- 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

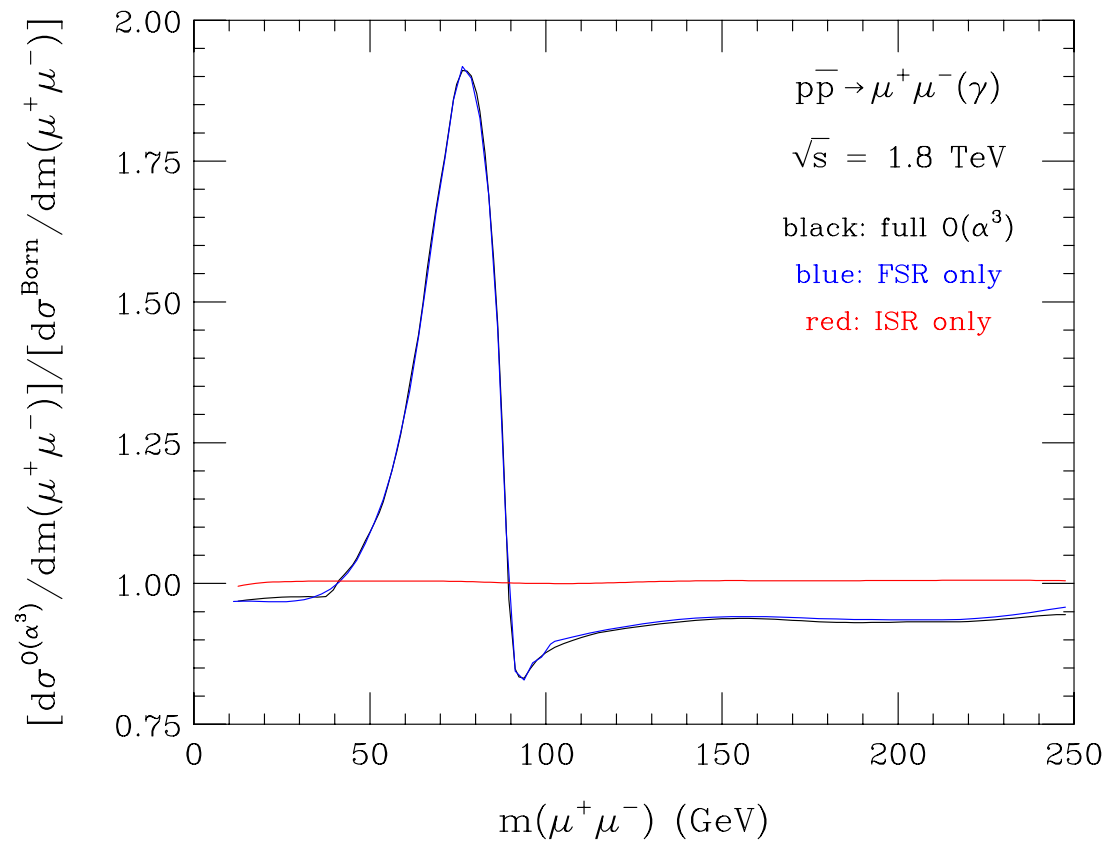


- big enhancement below the peak (due to Breit Wigner peak)
- at the peak the cross section is reduced by about 30% for electrons and 20% for muons
- for $m(\ell\ell) > 120$ GeV, the cross section is reduced by about $\sim 12\%$ ($\sim 7\%$) for e (μ)
- integrating over $m(\ell\ell)$, the large positive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

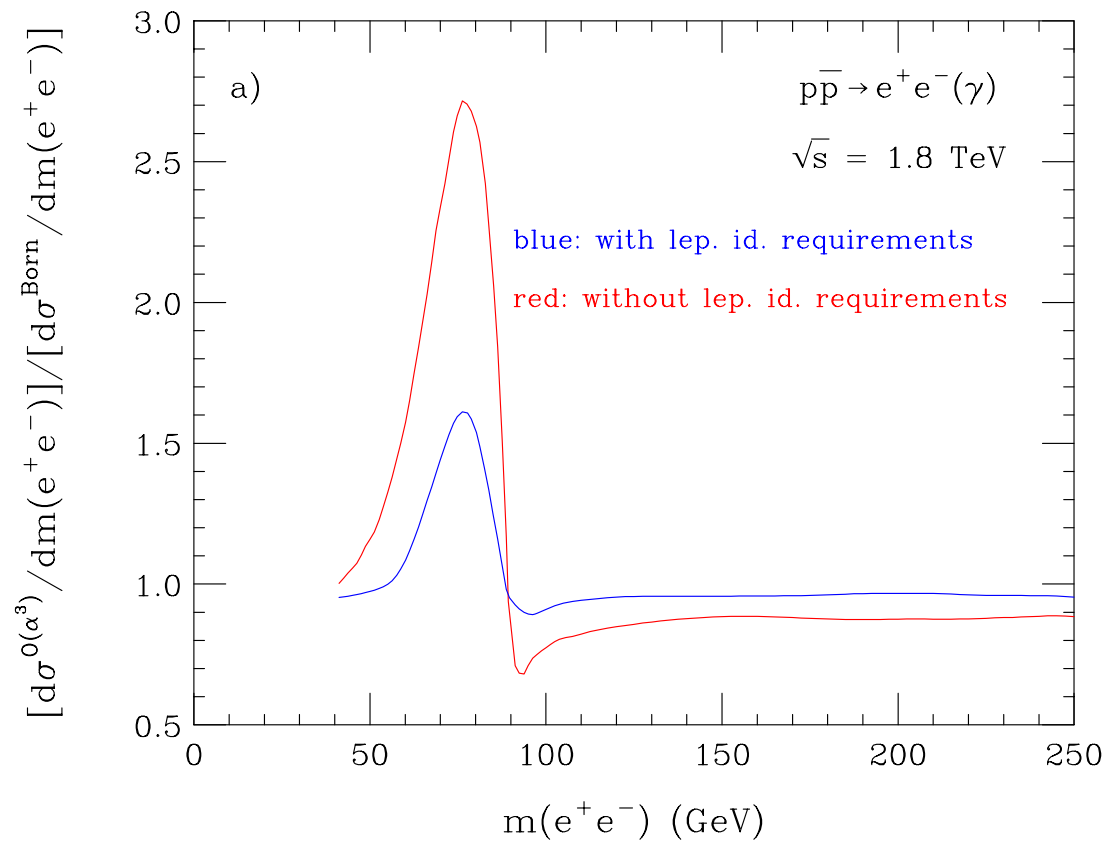
This is an example of how the Kinoshita-Lee-Nauenberg (KLN) theorem works

- KLN theorem: large logarithmic QED corrections cancel in sufficiently inclusive observables
- the peak is distorted, and the Z mass extracted from experiment is shifted

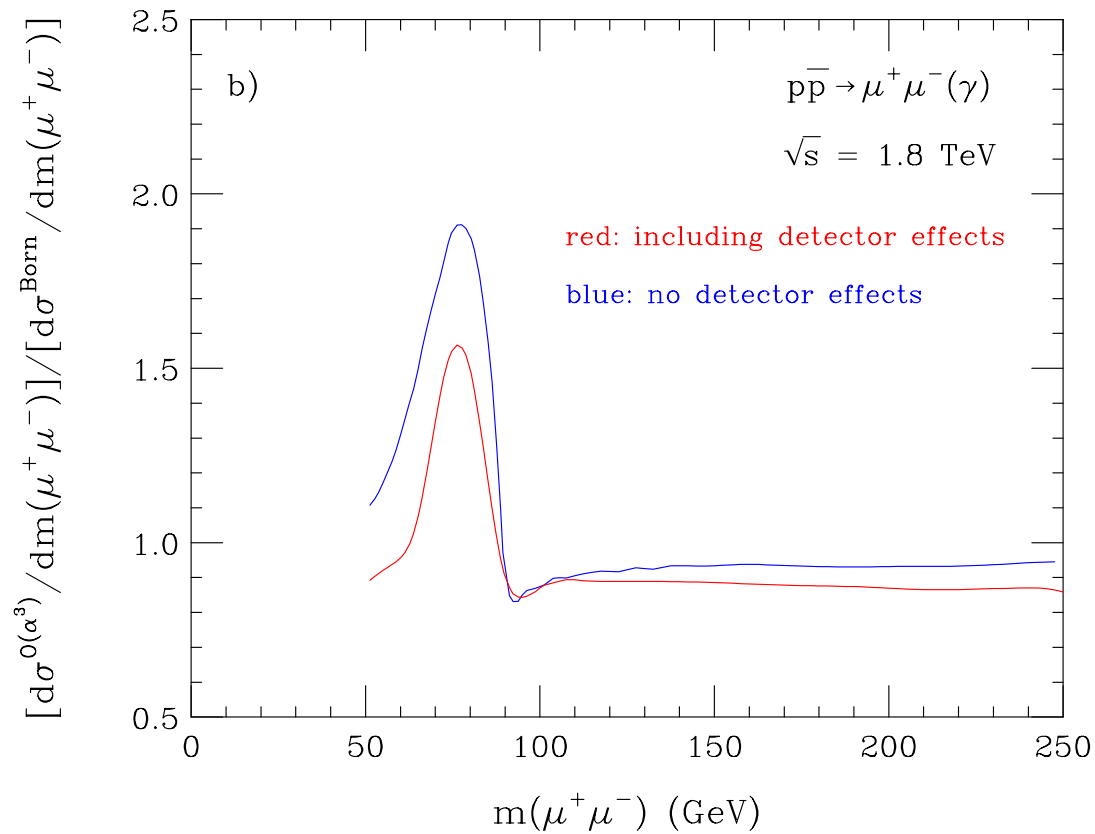
- final state corrections dominate everywhere
- Initial state corrections are small and uniform



- so, theory predicts that the QED for $W \rightarrow e\nu$ are larger than for $W \rightarrow \mu\nu$
- 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



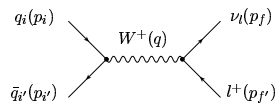
- Muons must be consistent with a minimum ionizing particle
 - require $E_\gamma < \text{a few GeV}$ in cell traversed by muon
 - this reduces the hard photon part
 - the mass singular terms survive



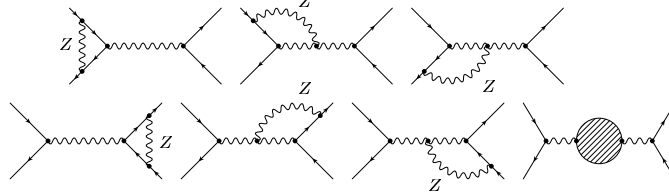
EW Corrections to W Production

- 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

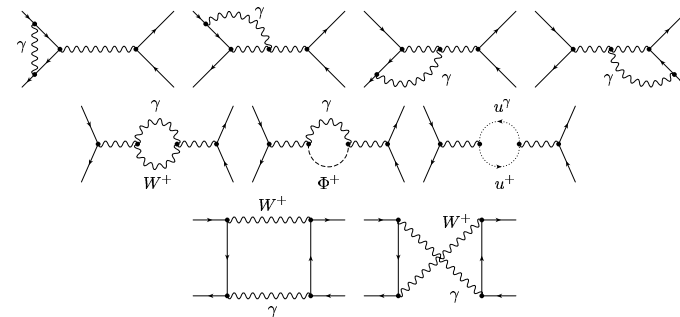
Born-diagram:



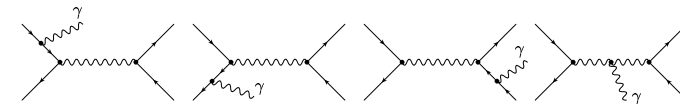
pure weak contribution:



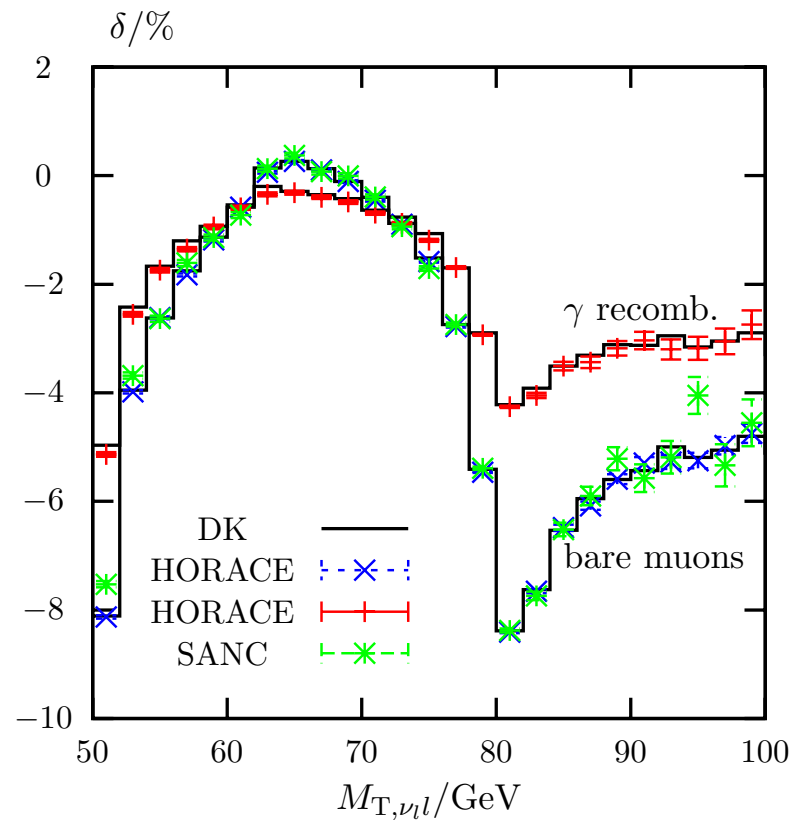
virtual γ contribution:



real γ contribution:

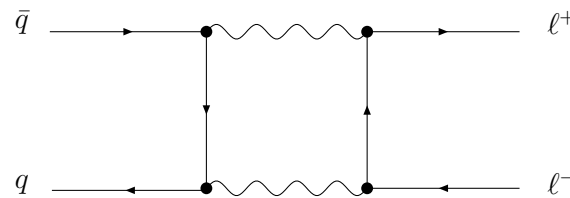


- ignore contributions which vanish for $\hat{s} = M_W^2$ (pole approximation)
- technical details very similar to Z case
- observe significant corrections to M_T distribution in Jacobian peak region



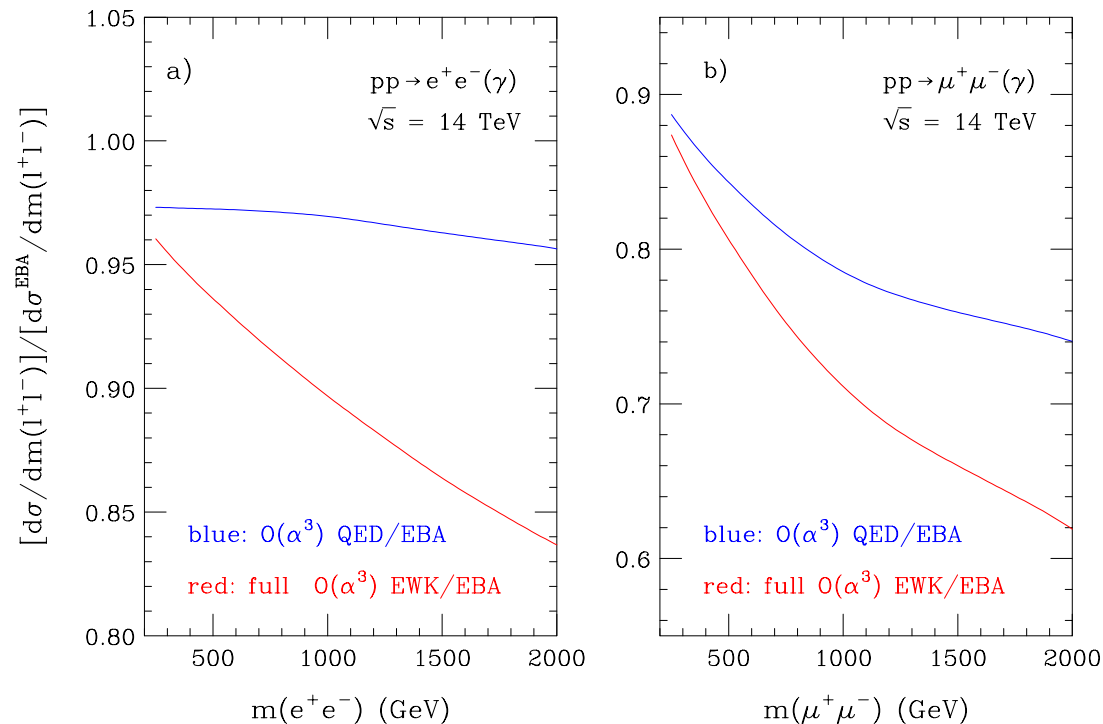
... on to the full EW corrections

- 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:**

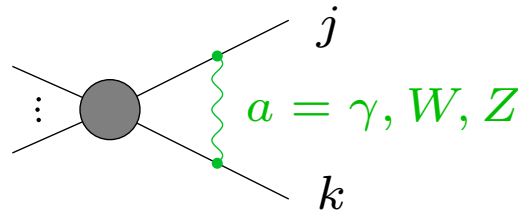


EBA: enhanced Born approximation (some radiative corrections have been taken into account by using running coupling constants, the physical W and Z masses, etc.)

- 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
 - ☞ $t\bar{t}$ 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

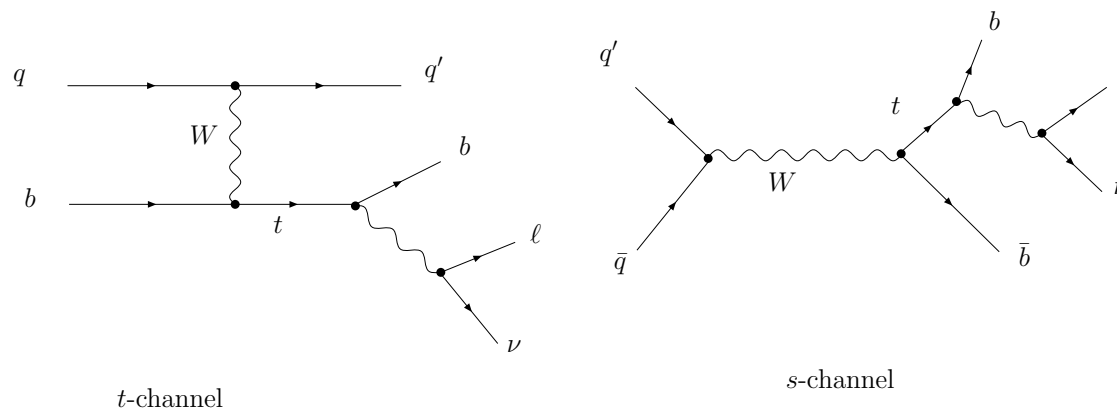


- relative correction to cross section for $2 \rightarrow 2$ reactions at $\sqrt{\hat{s}} = 1$ TeV:

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

- 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 $t\bar{t}$ backgrounds



- references for this part:
 - M. Melles, Phys. Rept. 375, 219 (2003)