Electroweak Aspects of the Standard Model

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Lecture III: Weak Gauge Bosons

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Overview

1 Electroweak precision physics at $e^+e^-$ colliders

2 Cross sections at hadron colliders

3 W- and Z-boson production at hadron colliders
Electroweak precision physics

at $e^+ e^-$ colliders
1.1 Brief overview

Features of the electroweak Standard Model

• Higgs boson not yet found, particle content verified otherwise

• No really significant contradictions of GSW model with experiment

• Input parameters:
  \[ \alpha = \frac{e^2}{4\pi} \approx 1/137, \quad M_W \approx 80 \text{ GeV}, \quad M_Z \approx 91 \text{ GeV}, \quad M_H \gtrsim 100 \text{ GeV}, \quad m_f, \quad V \]

• GSW model = consistent quantum field theory
  ◦ matrix elements respect unitarity
  ◦ renormalizability
  \[ \Rightarrow \text{ evaluation of higher perturbative orders possible} \]
  \[ \text{(and phenomenologically necessary !)} \]
Important electroweak experiments

- **Muon decay:**
  \[ \mu^- \rightarrow \nu_\mu e^- \bar{\nu}_e \]
  determination of the Fermi constant
  \[ G_\mu = \frac{\pi \alpha M_Z^2}{\sqrt{2} M_W^2 (M_Z^2 - M_W^2)} + \ldots \]

- **Z production (LEP1/SLC):**
  \[ e^+ e^- \rightarrow Z \rightarrow f \bar{f} \]
  various precision measurements at the Z resonance: \( M_Z, \Gamma_Z, \sigma_\text{had}, A_{FB}, A_{LR}, \text{etc.} \)
  \[ \Rightarrow \text{good knowledge of the } Zf \bar{f} \text{ sector} \]

- **W-pair production (LEP2/ILC):**
  \[ e^+ e^- \rightarrow WW \rightarrow 4f (+\gamma) \]
  - measurement of \( M_W \)
  - \( \gamma WW/ZWW \) couplings
  - quartic couplings: \( \gamma \gamma WW, \gamma ZWW \)
    (via \( e^+ e^- \rightarrow WW + \gamma \))
Important electroweak experiments (continued)

- **W production** (Tevatron/LHC):
  \[ pp, p\bar{p} \rightarrow W \rightarrow l\nu_l(\gamma) \]
  - measurement of \( M_W \)
  - bounds on \( \gamma_{WW} \) coupling

- **top-quark production** (Tevatron/LHC):
  \[ pp, p\bar{p} \rightarrow t\bar{t} \rightarrow 6f \]
  - measurement of \( m_t \)

**Theoretical predictions**

parametrized by \( \alpha(M_Z), M_W, M_Z, m_t, m_f, \alpha_s(M_Z) \) and \( M_H \)

\[ \leftrightarrow \text{ global fit of SM to data yields bounds on } M_H \]

But: high precision necessary, since \( M_H \) sensitivity weak

\[ \sim \frac{\alpha}{\pi} \log(M_H/M_W) \]

(in contrast to top-loops where sensitivity \( \sim G_\mu m_t^2 \))
1.2 Z-boson physics at LEP1 and SLC

Precision study of the Z line shape

Unfolded resonance:

$$\sigma_{\text{res}}(s) = \sigma^0 \frac{s \Gamma^2_Z}{\left| s - M^2_Z + i M_Z \Gamma_Z \frac{s}{M^2_Z} \right|^2}$$

Resonance observables:

- **Z mass and width**: $M_Z, \Gamma_Z$
- **peak cross section**: $\sigma^0_{\text{had}}$
- **various asymmetries**: $A_{\text{FB}}, A_{\text{LR}}$, etc.
- **ratios of decay widths**: $R_l = \frac{\Gamma_{\text{had}}}{\Gamma_l}$, etc.
Number of light neutrinos

\[ \Gamma_Z = \Gamma_{\text{had}} + \Gamma_e + \Gamma_\mu + \Gamma_\tau + \Gamma_{\text{inv}} \]

- \( \Gamma_Z \) measured from Z line shape
- \( \Gamma_{\text{had}} \) and \( \Gamma_{l=e,\mu,\tau} \) from

\[ R_l = \frac{\Gamma_{\text{had}}}{\Gamma_l} \quad \text{and} \quad \sigma^0_{\text{had}} = \frac{12\pi}{M_Z^2} \frac{\Gamma_e \Gamma_{\text{had}}}{\Gamma_Z^2} \]

Fit of \( \Gamma_Z \), \( R_l \), and \( \sigma^0_{\text{had}} \) yields invisible Z-decay width:

\[ \Gamma_{\text{inv}} = N_\nu \Gamma_{Z \to \nu\bar{\nu}}^{\text{theory}} \]

\( \leftrightarrow N_\nu = 2.9840 \pm 0.0082 \)
Effective Z-boson–fermion couplings

\[ Z_\mu = i e \gamma_\mu (g_V f - g_A f \gamma_5) \]

Leptonic couplings from LEP1 asymmetry measurements, e.g.:

\[ A_{FB}^0 = \frac{\sigma_{f,F}^0 - \sigma_{f,B}^0}{\sigma_{f,F}^0 + \sigma_{f,B}^0} = \frac{3}{4} A_e A_f \]

\( (F/B = \text{For/Backward hemisphere}) \)

with

\[ A_f = \frac{2 g_V f g_A f}{g_V^2 + g_A^2} \]

Good agreement with SM

• lepton universality confirmed
• constraints on \( m_t \) and \( M_H \)
Translation of effective couplings into effective weak mixing angle

\[
\sin^2 \theta_{\text{eff}}^{\text{lept}} = \frac{1}{4} \left( 1 - \text{Re} \left\{ \frac{g_{Vl}}{g_{Al}} \right\} \right)
\]

Important features:

- high sensitivity to \( M_H \)
- combination of very different observables
- \( \sim 3\sigma \) difference between \( A^{0,b}_{FB} \) (LEP) and \( A^{0,l}_{LR} \) (SLD)

with the initial-state pol. asymmetry

\[
A^{0,l}_{LR} = \frac{\sigma^0_L - \sigma^0_R}{\sigma^0_L + \sigma^0_R} \frac{1}{\langle |P_e| \rangle}
\]

\[\begin{align*}
A^{0,l}_{fb} & = 0.23099 \pm 0.00053 \\
A^{0,c}_{fb} & = 0.23159 \pm 0.00041 \\
A^{0,c}_{l}(SLD) & = 0.23098 \pm 0.00026 \\
A^{0,b}_{fb} & = 0.23221 \pm 0.00029 \\
A^{0,b}_{l}(P_T) & = 0.23220 \pm 0.00081 \\
Q^{\text{had}}_{fb} & = 0.2324 \pm 0.0012 \\
\text{Average} & = 0.23153 \pm 0.00016
\end{align*}\]

\( \chi^2 / \text{d.o.f.}: 11.8 / 5 \)
Observables most sensitive to $m_t$ and $M_H$

**LEPEWWG ’05**

- Main sensitivity to $m_t$ via $Wtb$ and $Wt\bar{b}$
- Main sensitivity to $M_H$ via $WtH$ and $ZhZ$

### Graph

- $m_t$ vs $m_H$ plot with shaded regions indicating 68% CL
- Lines and markers representing different observables:
  - $m_W$
  - $m_{t\text{ prel.}}$
  - $R_b$
  - $\sin^2 \theta_{\text{lept}}$
  - $\sin^2 \theta_{\text{eff}}$

Stefan Dittmaier, *Electroweak Aspects of the Standard Model*
Bounds on $M_H$ (95% C.L.)

- $M_H > 114.4$ GeV (LEPHIGGS '02)
  $e^+e^- \rightarrow ZH$ at LEP2

- $M_H < 158$ GeV (LEPEWWG '10)
  fit to precision data, i.e. via quantum corrections

Sensitivity via “high-precision observables”: $m_t$, $M_W$, $\sin^2 \theta_{\text{eff}}$, etc.

$\leftarrow$ precise measurement is possible at future ILC!
$\Rightarrow$ stronger bounds on $M_H$
1.3 W-boson physics at LEP2

W-pair production $e^+e^- \rightarrow WW \rightarrow 4f (+\gamma)$

Diagram dominates near W-pair threshold

Diagram contains $\gamma_{WW}/Z_{WW}$ couplings

Physics issues:

• test of non-abelian structure of triple gauge-boson couplings (TGCs)
  \[ \leftrightarrow \] constraint on non-standard $\gamma_{WW}/Z_{WW}$ couplings

• precision measurement of $W$-pair cross section

• precision measurement of $W$ mass $M_W$

• first bounds on non-standard quartic gauge-boson couplings (QGCs)

$\Rightarrow$ Theoretical requirement:
  precise understanding of $2 \rightarrow 4$ process (0.5\% level for cross section)
A typical 4-jet event observed at ALEPH
(Non-)standard TGCs

Gaemers, Gounaris ’79; Hagiwara, Hikasa, Peccei, Zeppenfeld ’87; Bilenky, Kneur, Renard, Schildknecht ’93; etc.

General parametrization (C- and P-conserving):

\[ \mathcal{L}_{VVW} = -ie g_{1}^V (W_{\mu}^{+} W_{-\mu} V_{\nu} - W_{-\mu} W_{\mu}^{+} V_{\nu}) \]

\[ + \kappa V W_{\mu}^{+} W_{\nu} V_{\mu} V_{\nu} + \lambda V \frac{M_{W}^{2}}{W_{\rho \mu}^{+} W_{-\rho \mu} V_{\nu} V_{\rho}} \]

Meaning for static \( W^+ \) bosons:

\[ Q_{W} = e g_{1}^V = \text{electric charge (}= e \text{ by charge conservation)} \]

\[ \mu_{W} = e \frac{2 M_{W}}{(g_{1}^V + \kappa_{\gamma} + \lambda_{\gamma})} = \text{magnetic dipole moment} \]

\[ q_{W} = -e \frac{M_{W}^{2}}{M_{W}} (\kappa_{\gamma} - \lambda_{\gamma}) = \text{electric quadrupole moment} \]

Standard Model values:

\[ g_{1}^V = \kappa_{V} = 1, \quad \lambda_{V} = 0 \]

Restriction to SU(2)\( \times \)U(1)-symmetric dim-6 operators:

\[ \kappa_{Z} = g_{1}^Z - (\kappa_{\gamma} - 1) \tan^2 \theta_{W}, \quad \lambda_{Z} = \lambda_{\gamma} \]
LEP2 constraints on charged TGCs

\[ \Delta g_1^Z = -0.009^{+0.022}_{-0.021} \]
\[ \Delta \kappa^\gamma = -0.016^{+0.042}_{-0.047} \]
\[ \lambda^\gamma = -0.016^{+0.021}_{-0.023} \]

Standard Model values verified at the level of 2–4%}

Note: TGC bounds \( \sim \mathcal{O}(\text{EW corrections}) \)
Total WW cross section at LEP2

Status of 1999: (LEPEWWG ’99)

Final result: (LEPEWWG ’05)

\[ \sqrt{s} \geq 189 \text{ GeV: preliminary} \]

Data
- Standard Model
- no ZWW vertex
- \( \nu_e \) exchange

\[ \sigma(e^+e^-\rightarrow W^+W^-)(\gamma) \text{ [pb]} \]

LEP

YFSWW (Jadach et al.) / RacoonWW (Denner et al.)
- non-universal corrections included
- theoretical uncertainty \( \sim \pm 0.5\% \) for \( \sqrt{s} > 170 \text{ GeV} \)

GENTLE (Bardin et al.)
- only universal EW corrections
- theoretical uncertainty \( \sim \pm 2\% \)
Cross sections at hadron colliders
Inelastic hadronic collisions:

Parton content of the proton:
- valence quarks $uud$,
- sea quarks $u, d, c, s, (+b, )$
- gluons $g (+\text{photons } \gamma)$

“Parton distribution functions” (PDF) $f_{i/p}(x, Q)$ determine fraction $x$ of the $p$ momentum carried by parton $i$ at “factorization scale” $Q$
- non-perturbative input (from exp.),
- but process independent

Hard interaction of partons
- $\leftrightarrow$ perturbative QCD applicable,
- model for hard interactions
- (apart from QCD/QED) enters only here
Parton model description of hadronic collisions

\[ \hat{\sigma}_{ab \rightarrow C} \rightarrow \left( \hat{s}, Q \right) \]

hadronic momenta: \( p_A, p_B \)

hadronic CM energy: \( \sqrt{s} = E_A + E_B \)

partonic momenta: \( p_a = x_A p_A, p_b = x_B p_B \)

partonic CM energy: \( \sqrt{\hat{s}} = \sqrt{x_A x_B s} \)

Hadronic cross section for \( AB \rightarrow C + X \):  
\( (X = \text{any hadronic remnant/activity}) \)

\[
\sigma_{AB \rightarrow C + X} (s) = \int_0^1 dx_A \int_0^1 dx_B \sum_{a,b} f_{a/A}(x_A, Q) f_{b/B}(x_B, Q) \hat{\sigma}_{ab \rightarrow C}(\hat{s}, Q)
\]

Factorization scale \( Q \) separates soft from hard contributions.

- \( Q \) dependence of PDFs \( f_{a/A}(x_A, Q) \) ruled by DGLAP evolution equations
- \( Q \) dependence of hard scattering cross section \( \hat{\sigma}_{ab \rightarrow C}(\hat{s}, Q) \) universal
- \( Q \) drops out in “all-order” calculations for \( \sigma_{AB \rightarrow C + X} (s) \)

\( \rightarrow \) residual \( Q \) dependence in finite-order predictions reflects theoretical uncertainty
Parton distribution functions

- DGLAP evolution to larger $Q$ shifts PDFs to lower $x$
  $\rightarrow$ enhancement of sea-quark and gluon PDFs
- Processes with both $gg$ and $q\bar{q}$ channels (e.g. $t\bar{t}$ production)
  Tevatron: $q\bar{q}$ often dominates by $\sim 90\%$
  LHC: $gg$ often much more important than $q\bar{q}$
Some Standard Model cross sections at the Tevatron (p¯p) and the LHC (pp)

# events = \sigma \times \text{luminosity}

design luminosity: \(100 \text{ fb}^{-1} \text{a}^{-1}/\text{exp.}\)

2 experiments in 5 years:

\(\sigma \sim 1 \text{ pb} \rightarrow \sim 10^6 \text{ events}\)
   \(\rightarrow\) precision physics
   (systematics dominates uncertainty)

\(\sigma \sim 1 \text{ fb} \rightarrow \sim 10^3 \text{ events}\)
   \(\rightarrow\) good prospects for searches
   (statistics dominates uncertainty)

BUT:

inclusive cross sections reduced by branching ratios, event selection, experimental efficiencies, etc.
W- and Z-boson production at hadron colliders
W- and Z-boson production at hadron colliders

\[ p \rightarrow q' \rightarrow W, Z \rightarrow q, \bar{q}, l^-, l^+ \]

Physics goals:

- \( M_Z \rightarrow \) detector calibration by comparing with LEP1 result
- \( \sin^2 \theta_{\text{eff}}^{\text{lep}} \rightarrow \) comparison with results of LEP1 and SLC
- \( M_W \rightarrow \) improvement to \( \Delta M_W \sim 15 \text{ MeV} \), strengthen EW precision tests
  \( (W/Z\) shape comparisons even sensitive to \( \Delta M_W \sim 7 \text{ MeV} \) at LHC) \cite{Besson}
- decay widths \( \Gamma_Z \) and \( \Gamma_W \) from \( M_{ll} \) or \( M_{T,l\nu_l} \) tails
- search for \( Z' \) and \( W' \) at high \( M_{ll} \) or \( M_{T,l\nu_l} \)
- information on PDFs or parton–parton luminosities

\cite{Stefan Dittmaier, Electroweak Aspects of the Standard Model}
A W-boson event at the LHC

\[ W \rightarrow ev \text{ candidate in } 7 \text{ TeV collisions} \]

\[ p_T(e^+) = 34 \text{ GeV} \]
\[ \eta(e^+) = -0.42 \]
\[ E_T^{\text{miss}} = 26 \text{ GeV} \]
\[ M_T = 57 \text{ GeV} \]
W/Z production in the QCD-improved parton model

\[ \leftrightarrow \] inclusion of higher-order corrections in \( \alpha_s \):

- **virtual corrections:** diagrams with loops

  - UV divergences
    \[ \rightarrow \] absorbed by renormalization \( (\alpha_s(\mu_{\text{ren}}), \text{etc.}) \)
  - soft IR divergences
  - collinear divergences

- **real corrections:** diagrams with additional external partons

  - soft IR divergences  \[ \rightarrow \] compensate soft IR divergences of virtual corrections
  - collinear divergences  \[ \rightarrow \] not completely compensated
Collinear divergences in initial state and factorization

\[ \begin{array}{c}
p \quad \{q, g\} \quad X \\
p \quad g \quad \{q, \bar{q}\} \quad X \\
g, \bar{q} \text{ have transverse momenta } k_T \to 0
\end{array} \]

- process-independent divergence in \( \int d k_T^2 \)
- \( g, \bar{q} \) are part of proton remnant \( X \)

\[ q(x, Q) = q(x) + \left\{ \text{divergent part from } \int_0^{Q^2} d k_T^2 \right\}, \text{ etc.} \]

\[ Q = \text{“factorization scale”; } Q \text{ dependence ruled by DGLAP evolution} \]

\[ \sigma_{pp} = \sum_{f_1 f_2} \int_0^1 dx_1 \, f_1(x_1, Q) \int_0^1 dx_2 \, f_2(x_2, Q) \, \hat{\sigma}_{f_1 f_2}(x_1 x_2 s, Q) \]

\[ (f_1 f_2 = \bar{q} q, q \bar{q}, g q, g \bar{q}, \bar{q} g, q g, g g) \]

Note: incomplete compensation of \( Q \) dependence in finite perturbative orders

\[ \leftarrow \text{ measure of missing corrections} \]
QCD corrections to W/Z production:

- **NNLO QCD corrections**
  - total cross sections
    - Harlander, Kilgore ’02
  - W/Z rapidity distributions
    - Anastasiou et al. ’03
  - fully differential
    - Melnikov, Petriello ’06; Catani et al. ’09

- **soft-gluon resummation** (partially combined with γ emission)
  - Balazs, Yuan ’97; Landry et al. ’02
  - Cao, Yuan ’04

EW corrections to W/Z production:

- **NLO EW correction to W production**
  - Baur, Keller, Wackeroth ’98; S.D., Krämer ’02
  - Baur, Wackeroth ’04; Arbuzov et al. ’05
  - Carloni Calame et al. ’06

- **NLO EW correction to Z production**
  - Baur, Keller, Sakumoto ’97; Baur, Wackeroth ’99
  - Brein, Hollik, Schappacher ’99; Arbuzov et al. ’06
  - S.D., Huber ’09

- **multi-photon radiation via leading logs**
  - Baur, Stelzer ’99; Carloni Calame et al. ’03
  - Placzek, Jadach ’04; Brensing et al. ’07

Corrections beyond the SM:

- **NLO SUSY corrections in the MSSM**
  - Brensing et al. ’07; S.D., Huber ’09

  → negligible near W/Z resonances ⇒ standard candles!
Structure of EW corrections: example of W production

Born amplitude:

\[ \mathcal{M}_0 = \frac{e^2}{2s_w^2} \left[ \bar{u}_d \gamma^{\mu} \frac{1}{2} (1 - \gamma_5) u_u \right] \frac{1}{\hat{s} - M_W^2 + iM_W \Gamma_W} \left[ \bar{u}_\nu_l \gamma^{\mu} \frac{1}{2} (1 - \gamma_5) v_l \right] \]

results from (partial) Dyson summation of W self-energy

Virtual corrections:

consistent gauge-invariant treatment of W resonance required

\[ \sim \textbf{solutions: pole scheme, factorization schemes, complex-mass scheme} \]

see S.D., Huber '09 and refs. therein

\[ \mathcal{M}_1 = \delta^{\text{virt}} \mathcal{M}_0 \]

\[ \delta^{\text{virt}} = \delta_{WW}(\hat{s}) + \delta_{Wud}(\hat{s}) + \delta_{W\nu_l}(\hat{s}) + \delta_{\text{box}}(\hat{s}, \hat{t}) \]

Note: \( \delta^{\text{virt}} \) is not analytic at \( \hat{s} \rightarrow M_W^2 \), but contains terms \( \propto \alpha \ln(\hat{s} - M_W^2 + iM_W \Gamma_W) \)
Real photon corrections:
consistent treatment of W resonance with correct IR (soft and collinear) limits

• final-state radiation:

\[
\sigma_{\text{FSR}} = \sigma_0 \int_0^1 dz \frac{Q_l^2 \alpha}{2\pi} \ln \left( \frac{M^2}{m_l^2} \right) \left( \frac{1 + z^2}{1 - z} \right) + \Theta_{\text{cut}}(k_l = \hat{k}_l) + \ldots
\]

→ large mass-singular correction if \( \int dz \) restricted

Note: singularity vanishes after “photon recombination” due to full \( z \) integration (inclusiveness \( \rightarrow \) KLN theorem)

• initial-state radiation:

Mass singularity absorbed via PDF redefinition as in QCD

\( \leftarrow \text{remaining ISR corrections not enhanced and depend on factorization scale } Q \)

But: QED-corrected PDFs required (corrections \( \sim 1\% \))

only old set MRST2004qed available \( \rightarrow \) update necessary

• photon-induced processes:

PDF redefinition necessarily includes photon PDF

\( \leftarrow \gamma q \text{ processes deliver real corrections, effects typically } \lesssim 1\% \)

\( \gamma \text{ PDF measurable via } \gamma\gamma \rightarrow l^+ l^- \text{ via special cuts ?} \)
Observables for W/Z production at hadron colliders

Momentum/energy measurements:

• \( p_{T,l} \) = lepton transverse momenta
• \( p_{T,\text{miss}} \) = missing transverse momentum (or energy)
• \( y_l = \frac{1}{2} \ln \left( \frac{p^0_l + p^3_l}{p^0_l - p^3_l} \right) \) = lepton rapidities

“Derived” observables:

• \( M_{ll} = (p_{l+} + p_{l-})^2 \) = dilepton invariant mass for Z production
  \( \leftrightarrow \) important for calibration
• \( M_{T,\nu l} = \sqrt{2p_{T,\nu l}} p_{T,\text{miss}} (1 - \cos \phi_{\nu l}) \) = transverse invariant mass for W production
  \( \leftrightarrow \) measurement of \( M_W \)
• \( p_{T,W/Z} = p_{T,\nu l} + p_{T,\nu} \) = transverse W/Z momenta
  \( \leftrightarrow \) induced by QCD radiation (jets)
• various asymmetries
• LHC:  ◇ all rapidity distributions are forward–backward (FB) symmetric (see plot)
  ◇ FB asymmetry defined wrt boost direction of Z boson
  \[
  \sin^2 \theta_{\text{eff}}^{\text{lept}} \quad \text{measurable with precision competitive to LEP/SLC}
  \]

• Tevatron:  ◇ FB asymmetry defined wrt p direction \( \rightarrow \sin^2 \theta_{\text{eff}}^{\text{lept}} \) in progress
  ◇ W (charged lepton) rapidity constrains PDF ratio \( u(x)/d(x) \)

• QCD predictions show nice convergence in \( \text{LO} \rightarrow \text{NLO} \rightarrow \text{NNLO} \)

• EW corrections at the level of few % (not shown)
Dilepton invariant-mass distribution (at intermediate $M_{ll}$ values)

\[ \frac{d\sigma}{dM_{ll}[\text{pb}]} \]

\[ M_{ll} [\text{GeV}] \]

- QCD corrections of $\mathcal{O}(20\%)$, but very little resonance distortion
  - photonic corrections very large due to FSR ("inverse radiative tail")
    - resonance distortion
      - "bare muons": enhanced by mass sing. $\propto \alpha \ln m_\mu$
      - "photon recombination" ($e^\pm$ case): mass sing. canceled due to KLN
- weak corrections (loops with $W$'s, $Z$'s, fermions) at the order of $\lesssim 5\%$
Lepton transverse-momentum distribution for Z-boson production

![Graph showing distribution]

S.D., Huber ’09

- “Jacobian peak” near $p_{T,l} \approx M_Z/2$; resonant Z’s contribute only to $p_{T,l} \lesssim M_Z/2$

- patterns of corrections similar for Z and W production

- size of photonic and weak corrections qualitatively similar to $M_{ll}$ distribution

- QCD corrections extremely huge for $p_{T,l} \gtrsim M_Z/2$ because of jet ISR: LO process becomes Z+jet prod.

$\Rightarrow$ no good perturbative control of QCD

$\Rightarrow M_W$ measured better from $M_{T,\nu l}$
Transverse-mass distribution for W production

Balossini et al. ’09

- QCD corrections moderate and flat near the peak
- EW corrections (mainly FSR) shift peak by about $\mathcal{O}(100 \text{ MeV})$
- different ways of combining QCD and EW corrections
  $$(1+\delta_{\text{QCD}}+\delta_{\text{EW}}) \text{ vs. } (1+\delta_{\text{QCD}})\times(1+\delta_{\text{EW}})$$
  differ at %-level
  $\rightarrow \mathcal{O}(\alpha\alpha_s)$ calculation needed . . .

W-mass reconstruction from “Jacobian peak” near $M_W^\perp \equiv M_{T,\nu l} \approx M_W$:

- resonant W bosons contribute only for $M_{T,\nu l} < M_{\nu l} \approx M_W$
- the tail $M_{T,\nu l} \gtrsim M_W$ can be used to fit the W width $\Gamma_W$
Fits of $M_W$ to W transverse mass at the Tevatron

Theory prediction based on QCD resummations (improved by some EW corrections)

Result from CDF Run II: \[ M_W = 80.413 \pm 0.048 \text{ GeV} \]

Result from D0 Run II: \[ M_W = 80.402 \pm 0.043 \text{ GeV} \]

CDF/D0 combination 2009: \[ M_W = 80.420 \pm 0.031 \text{ GeV} \] (from Fermilab homepage)

Result from LEP: \[ M_W = 80.376 \pm 0.033 \text{ GeV} \]

World average 2009: \[ M_W = 80.399 \pm 0.023 \text{ GeV} \]