Electroweak corrections for $W/Z(+\text{jet})$ production

Alexander Mück

in collaboration with

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W mass workshop
Milano, March 17, 2009
Outline

• single $W$ production
  • NLO EW corrections
  • multiphoton emission
  • MSSM corrections

• single $Z$ production
  • different schemes for treating the $Z$ resonance

• $W$+jet production
  • complete NLO EW corrections for
    $$ pp \rightarrow W + \text{jet} \rightarrow l\nu_l + \text{jet} $$
single W production

Dittmaier, Krämer [hep-ph/0109062]
Brensing, Dittmaier, Krämer, AM [arXiv:0710.3309]

**EW 1-loop corrections:**

- **input:** $G_\mu$ scheme

\[
\alpha = \alpha_{G_\mu} = \frac{\sqrt{2} G_\mu M_W^2 s_W^2}{\pi} = \alpha(0)(1 + \Delta r) + \mathcal{O}(\alpha^3)
\]

and $\alpha = \alpha(0)$ for collinear photon emission

⇒ higher-order universal effects due to $\Delta \alpha$ and $\Delta \rho$

absorbed in the coupling via $\Delta r$
single W production

Dittmaier, Krämer [hep-ph/0109062]
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- **resonance prescription:**
  - fixed width, correction factorizes from resonant Born
  - $\ln(\hat{s} - M_W^2 + i\epsilon) \rightarrow \ln(\hat{s} - M_W^2 + i M_W \Gamma_W)$
  to cure on-shell divergences in the correction
single W production

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  to cure on-shell divergences in the correction

• lepton-photon recombination:
  • bare muons and electron–\( \gamma \) recombination supported
  • dipole subtraction also for non-collinear safe bare muons

Dittmaier,Kabelschacht,Kasprzik [arXiv:0802.1405]
• NLO QCD corrections
• leading 2-loop Sudakov logs included
• photon-induced processes included
• MSSM corrections

and most important for the W-mass measurement:
• multi-photon emission
MSSM corrections

W production is considered a SM candle:

- contamination from physics beyond the SM, e.g. SUSY?
- calculate $O(\alpha_s)$ and $O(\alpha)$ corrections in the MSSM
MSSM corrections

W production is considered a SM candle:

- contamination from physics beyond the SM, e.g. SUSY?
- calculate $\mathcal{O}(\alpha_s)$ and $\mathcal{O}(\alpha)$ corrections in the MSSM

partonic cross section for SPS benchmark points

no impact for $M_W$ measurement

percent-level corrections only at large $\sqrt{s}$, $p_T$, $M_T$

W production is SM candle!
Multi-photon radiation

- important for **exclusive leptons** (no recombination)
- perturbative expansion in $\alpha^n \log^n \left( \frac{M_W^2}{m_l^2} \right)$
Multi-photon radiation

• two approaches in leading logarithmic accuracy:
  • QED parton shower
  • structure function approach  Kuraev, Fadin ’85; ... Abruzov ’99

\[
\sigma_{\text{LLFSR}} = \int d\sigma_0(p_u, p_d; k_{\nu_1l}, k_l) \int_0^1 dz \Gamma_{ll}^{\text{LL}}(z, Q^2) \Theta_{\text{cut}}(zk_l)
\]

where

\[
\Gamma_{ll}^{\text{LL}}(z, Q^2) = \exp\left( -\frac{1}{2} \beta_l \gamma_E + \frac{3}{8} \beta_l \right) \frac{\beta_l}{\Gamma \left(1 + \frac{1}{2} \beta_l\right)} \frac{\beta_l}{2} (1-z)^{\frac{\beta_l}{2} - 1} - \frac{\beta_l}{4} (1+z) + \mathcal{O}(\beta_l^2) + \mathcal{O}(\beta_l^3)
\]

and

\[
\beta_l = \frac{2\alpha(0)}{\pi} \left[ \log\left(\frac{Q^2}{m_l^2}\right) - 1 \right]
\]

Q: scale of the process
Multi-photon radiation

- two approaches in leading logarithmic accuracy:
  - QED parton shower
  - structure function approach

\[ p_T(\mu^+\nu_\mu) \text{[GeV]} \]
\[ M_T(\mu^+\nu_\mu) \text{[GeV]} \]

\[ \delta[\%] \]

parton shower: from Horace (Carloni Calame et al.) in arXiv:0705.3251
structure function (with scale variation): Brensing, Dittmaier, Krämer, AM
[arXiv:0710.3309]

EW corrections for W/Z(+jet) production – Alexander Mück – p.6/19
Results

$M_T$ distribution for the LHC:

$$
\frac{d\sigma}{dM_{T,\nu l}}[\text{pb}/\text{GeV}]
$$

\begin{align*}
pp &\rightarrow l^+\nu_lX \\
\sqrt{s} &\;= \;14\;\text{TeV} \\
p_{T,l},p_{T} &\;> \;25\;\text{GeV} \\
|\eta_l| &\;< \;2.5
\end{align*}

$\delta_{\text{exclusive}}$ $\delta_{\text{inclusive}}$

EW corrections for W/Z(+jet) production – Alexander Mück – p.7/19
single \( Z \) production

features of the calculation:  

- full NLO EW+QCD corrections in the SM
- using complex mass scheme
  
  \( \Rightarrow \) use complex \( W \) and \( Z \) masses everywhere by means of complex renormalization (\( \Rightarrow \) complex weak mixing angle)
  
  \( \Rightarrow \) loop-integrals for complex masses needed
single Z production

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- $\gamma\gamma$ collisions included (incl. NLO EW corr.)
- $\gamma q/\gamma\bar{q}$ collisions included

Dittmaier, Huber [in preparation]
single Z production

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- **improvements beyond NLO**
  - $G_\mu$ scheme: absorb higher-order universal effects ($\Delta\alpha, \Delta\rho$)
  - two-loop Sudakov logarithms
  - multi-photon emission via structure functions

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- NLO EW+QCD corrections in the MSSM (preliminary)
  - corrections as small as for single W production

$\Rightarrow$ effects negligible near Z resonance for relevant SUSY scales
single Z production

- **status** of the calculation
  - two independent calculations for partonic results
  - results on hadronic observables in progress
single Z production

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Z boson resonance: compare different gauge invariant implementations of the Z-boson width for the weak corrections

- complex mass scheme (CMS)  
  Denner et al.’05
single Z production

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**Z boson resonance:** compare different gauge invariant implementations of the Z-boson width for the weak corrections

- **complex mass** scheme (CMS)  
  Denner et al.'05

- **pole** scheme (PS)  
  Stuart '91; Aeppli et al.'93

⇒ Laurent expand amplitude around the pole
single Z production

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**Z boson resonance:** compare different gauge invariant implementations of the $Z$-boson width for the weak corrections

• **complex mass** scheme (CMS)  
  Denner et al.’05

• **pole** scheme (PS)  
  Stuart ’91; Aeppli et al.’93

• **factorization** scheme (FS)  
  Dittmaier, Krämer ’01

\[ \sigma^{NLO} = \left(1 + \delta^{\text{weak}}|_{\Gamma_Z = 0}\right) \sigma^{LO}|_{\Gamma_Z \neq 0} \]
Partonic results

leading order:

\[
\sigma^{\text{LO}}_\text{PS} = 1 - \frac{\hat{\sigma}^{\text{LO}}|_{\text{PS/FS}}}{\hat{\sigma}^{\text{LO}}|_{\text{CMS}}}
\]

where \( r_{\text{PS/FS}} = 1 - \frac{\sigma^{\text{LO}}_\text{PS}}{\sigma^{\text{LO}}_\text{CMS}} \).
Partonic results

weak corrections:

\[
\Delta_{FS} = \delta_{q\bar{q},\text{weak}}^{\text{virt}} \bigg|_{FS} - \delta_{q\bar{q},\text{weak}}^{\text{virt}} \bigg|_{CMS}
\]

\[
\Delta_{PS} = \delta_{q\bar{q},\text{weak}}^{\text{virt}} \bigg|_{PS} - \delta_{q\bar{q},\text{weak}}^{\text{virt}} \bigg|_{CMS}
\]

⇒ relative corrections differ by about 0.1% wrt LO
How to combine QCD and EW corrections?
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- first attempt for QCD + full EW:

\[
\frac{d\sigma}{d^3p} = \frac{d\sigma}{d^3p}_{\text{MC@NLO}} + (\frac{d\sigma}{d^3p}_{\text{HORACE}} - \frac{d\sigma}{d^3p}_{\text{Born}})_{\text{HERWIG-PS}}
\]

Balossini et al. '07
How to **combine QCD and EW corrections?**

- soft-gluon resum. + final-state photon radiation (ResBos-A)  
  Cao, Yuan [hep-ph/0401026]

- first attempt for **QCD + full EW** :

  \[ d\sigma = d\sigma_{\text{MC@NLO}} + (d\sigma_{\text{HORACE}}^{\text{EW}} - d\sigma_{\text{Born}})_{\text{HERWIG–PS}} \]

Balossini et al. '07

**hard QCD radiation + EW corrections?**
**QCD + EW**

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  Balossini et al. '07

Hard QCD radiation + EW corrections?

⇒ look at EW corrections for W+jet production
$pp \rightarrow l\nu_l + \text{jet}$:

- **large cross section**
  ($\sim 1\text{nb after basic cuts}$)
- **dominant channel for high $p_T$ leptons**
- **$W$+jet(s) important background for**
  many (new physics) searches
$pp \rightarrow l\nu_l + \text{jet}$:

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  many (new physics) searches

**Theoretical status:**

- **NLO QCD** corrections known and available
  
  DYRAD: Giele et al. [hep-ph/9302225]  
  MCFM: Campbell,Ellis [hep-ph/0202176]  
  and as part of NNLO single $W$: Melnikov, Petriello [hep-ph/0609070]  
  Catani et al. [arXiv:0903.2120]
W+jet production

\[ pp \rightarrow l\nu_l + \text{jet}: \]

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- dominant channel for **high** \( p_T \) leptons
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  many (new physics) searches

Theoretical status:

- **NLO QCD** corrections known and available
- **EW** corrections for stable W bosons
  - Hollik, Kasprzik, Kniehl [arXiv:0707.2553]
Complete EW corrections for off-shell W bosons calculated
Denner, Dittmaier, Kasprzik, AM [in preparation]

95 diagrams per partonic channel
Complete EW corrections for off-shell W bosons calculated
Denner, Dittmaier, Kasprzik, AM [in preparation]

- stable reduction scheme for tensor integrals
  Denner, Dittmaier [hep-ph/0509141]
  - avoid inverse Gram determinants for pentagon reduction
  - expand around vanishing determinants in critical phase-space regions
Complete EW corrections for off-shell W bosons calculated
Denner, Dittmaier, Kasprzik, AM [in preparation]

- **stable reduction** scheme for tensor integrals
  Denner, Dittmaier [hep-ph/0509141]

- **complex mass scheme** for resonances
  Denner, Dittmaier, Roth, Wieders [hep-ph/0505042]
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• **dipole subtraction** for infrared divergences
  Catani, Seymour [hep-ph/9605323]
  Dittmaier [hep-ph/9904440]
  Dittmaier, Kabelschacht, Kasprzik [arXiv:0802.1405]

• subtraction formalism also for non-collinear safe observables

• slicing used as a check
Complete **EW corrections for off-shell W bosons** calculated
Denner, Dittmaier, Kasprzik, AM [in preparation]

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- **multi-channel** phase space integration
  Berends, Kleiss, Pittau [hep-ph/9904440]
  adaptive realization using **Vegas** (e.g. like in Whizard, Sherpa)
some details

- consistent photon–jet recombination
  - $W^{+}\text{jet}$ and $W^{+}\gamma$ production separated by means of photon fragmentation function
some details

- consistent photon–jet recombination
- also full NLO QCD corrections
  - variable (phase-space dependent) scale choice supported
  - for photon induced processes
some details

- consistent photon–jet recombination
- also full NLO QCD corrections
- two completely independent calculations
  - in mutual agreement
some details

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- also full NLO QCD corrections
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- MPI: FeynArts 1.0 [Böhm, Denner, Küblbeck]
  - in-house Mathematica Routines
  - loop integral library: DD [Dittmaier]
  - Vegas integration
- PSI: FeynArts 3.2, FormCalc 3.1 [Hahn]
  - loop integral library: Coli [Denner]
  - Pole [Meier, AM]
    - using Weyl-van der Waerden formalism
    - automatic generation of subtraction/slicing terms
    - automatic multi-channeling using Lusifer
  Dittmaier, Roth [hep-ph/0206070]
Results for W+jet

$M_T$ distribution for the LHC:

**Basic cuts:**

- $p_T,l/miss\/jet > 25$ GeV, $|y_{l/jet}| < 2.5$
- Lepton isolation: $R_{l,\text{jet}} > 0.5$
- Recomb. for $R_{\gamma,l} < 0.1$, $R_{\gamma,\text{jet}} < 0.5$

$$pp \rightarrow l^+\nu_l + \text{jet (+}\gamma\text{)}$$

$\sqrt{s} = 14$ TeV
**Results for W+jet**

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- $\sqrt{s} = 14 \text{ TeV}$

- Corrections very similar to single W production

EW corrections for W/Z(+jet) production – Alexander Mück – p.16/19
Results for W+jet

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- recomb. for $R_{\gamma,l} < 0.1$, $R_{\gamma,jet} < 0.5$

$\sqrt{s} = 14 \text{ TeV}$

- Born
- $\gamma \text{ rec.}$
- bare $\mu^+$
Results for W+jet

$p_T$ distribution for the LHC:

$$\frac{d\sigma}{dp_{T,l}} [\text{pb/GeV}]$$

pp $\rightarrow l^+ \nu_l + \text{jet (+\gamma)}$

$\sqrt{s} = 14 \text{ TeV}$

basic cuts:

- $p_{T,l/\text{miss/jet}} > 25 \text{ GeV}$, $|y_{l/jet}| < 2.5$
- lepton isolation: $R_{l,jet} > 0.5$
- recomb. for $R_{\gamma,l} < 0.1$, $R_{\gamma,jet} < 0.5$

no similarity to single W production
Results for W+jet

$p_{T,\text{jet}}$ distribution for the LHC:

- Basic cuts:
  - $p_{T,l/\text{miss}/\text{jet}} > 25$ GeV, $|y_{l/\text{jet}}| < 2.5$
  - Lepton isolation: $R_{l,\text{jet}} > 0.5$
  - Recombination: $R_{\gamma,l} < 0.1$, $R_{\gamma,\text{jet}} < 0.5$

- Born + $\gamma$ recoiled $\mu^+$
- $\sqrt{s} = 14$ TeV

Large corrections at large energies
Summary

- **single W production**
  - complete NLO EW+QCD corrections
  - plus higher-order improvements

- **single Z production**
  - complete NLO EW+QCD corrections
  - plus higher-order improvements
  - finalizing checks for hadronic observables

- **W+jet production**
  - complete NLO EW+QCD corrections

- **What comes next?**
  - **Z+jet production**
  - improved QCD predictions: resummation
Back-up slides
Photon-induced processes

There are photons inside the proton: $\gamma$ as a parton
There are photons inside the proton: $\gamma$ as a parton

- initial state photon emission $\Rightarrow$ collinear singularity
There are photons inside the proton: $\gamma$ as a parton

- initial state photon emission $\Rightarrow$ collinear singularity
- absorb singularity into PDF
- include QED in DGLAP evolution

$\Rightarrow$ photon density inside the proton: MRSTQED2004 PDF

Martin, Roberts, Stirling, Thorne [hep-ph/0411040]
Photon-induced processes

- Genuine contribution at $\mathcal{O}(\alpha)$:

- Usually percent level correction

- Not relevant for $M_W$ measurement in $M_T$

- Can be enhanced:
  - Up to $\sim 15\%$ at large $p_T,l \sim 500$ GeV
  - But overwhelmed by QCD uncertainties
  - Below 1% in $M_T$
EW corrections for $W/Z(+\text{jet})$ production – Alexander Mück – p.23/19

EW corr.: $M_T @ \text{LHC}$

Brensing, Dittmaier, Krämer, AM [arXiv:0710.3309]

$\frac{d\sigma}{dM_{T,\nu l}}[\text{pb/GeV}]$

$pp \rightarrow l^+\nu_lX$
$\sqrt{s} = 14$ TeV
$p_{T,l}, p_{T} > 25$ GeV
$|\eta_l| < 2.5$

$\sigma_0$

$|\eta| < 2.5$

$\delta_{\text{inclusive}}$
$\delta_{\text{exclusive}}$

EW corrections for $W/Z(+\text{jet})$ production – Alexander Mück – p.23/19
$\sigma$ vs $p_T$ at LHC

**EW corrections for W/Z(+jet) production**

**Brensing, Dittmaier, Krämer, AM [arXiv:0710.3309]**

**Graphs:**
- **Left:** $d\sigma/dp_{T,l}[pb/GeV]$ for $pp \rightarrow l^+\nu_l X$ with $\sqrt{s} = 14$ TeV, $p_{T,l}, p_T > 25$ GeV, $|\eta_l| < 2.5$.
- **Right:** Plot shows variations in $\delta[\%]$ with respect to $p_{T,l}$[GeV], inclusive and exclusive.
EW corrections for W/Z(+jet) production

\[ p\bar{p} \rightarrow l^+ \nu_l X \]

- \( \sqrt{s} = 1.96 \text{ TeV} \)
- \( p_{T,l}, p_T > 25 \text{ GeV} \)
- \( |\eta_l| < 2.5 \)

\[ \sigma_0 \]

\[ \frac{d\sigma}{dM_{T,\nu_l}} \text{[pb/GeV]} \]

\[ M_{T,\nu_l} \text{[GeV]} \]

Brensing, Dittmaier, Krämer, AM [arXiv:0710.3309]
EW corrections for $W/Z(+\text{jet})$ production – Alexander Mück – p.26/19

$\sqrt{s} = 1.96$ TeV

$\rho_T, \rho_T > 25$ GeV

$|\eta_l| < 2.5$

Brensing, Dittmaier, Krämer, AM [arXiv:0710.3309]
EW corrections distort shapes:
- in particular due to final state photon radiation
- also for $M_T$ distribution
- strong dependence on lepton-photon recombination
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exclusive (bare) leptons (muons): $\alpha \log(M_W^2/M_l^2)$ corrections
inclusive leptons (electrons): no large logs (KLN theorem)
EW corrections distort shapes:

- in particular due to final state photon radiation
- also for $M_T$ distribution
- strong dependence on lepton-photon recombination

$\delta q\gamma$

$\delta_{qq}$

$\delta_{\mu^+\nu_\mu}$

$\delta_{\text{multi-}\gamma}$

$\delta_{q\gamma}$

Brensing, Dittmaier, Krämer, AM [arXiv:0710.3309]
EW corrections

• $O(\alpha)$ corrections to resonant W production
  Hollik, Wackeroth [hep-ph/9606398]
  Baur, Keller, Wackeroth [hep-ph/9807417]
EW corrections

- $\mathcal{O}(\alpha)$ corrections to resonant W production
  $\Rightarrow \sim 170 \ (65) \ \text{MeV shift for } M_W \ \text{for } \mu^{\pm} \ (e^{\pm}) \ \text{channel}$
  from final state radiation
  $\Rightarrow \sim 10 \ \text{MeV shift for } M_W \ \text{beyond final state radiation}$

CDF [hep-ex/0007044]
**EW corrections**

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- multi-photon final-state radiation
  
  Baur, Stelzer [hep-ph/9910206]
  Placzek, Jadach [hep-ph/0302065]
  Carloni Calame et al. [hep-ph/0303102]
  Brensing, Dittmaier, Krämer, AM [arXiv:0710.3309]
EW corrections

- $\mathcal{O}(\alpha)$ corrections to resonant W production
  - $\Rightarrow \sim 170\ (65)\ \text{MeV shift}$ for $M_W$ for $\mu^\pm\ (e^\pm)$ channel from final state radiation
  - $\Rightarrow \sim 10\ \text{MeV shift}$ for $M_W$ beyond final state radiation

- multi-photon final-state radiation
  - $\Rightarrow$ additional $\sim 10\ \text{MeV shift}$ in $M_W$

Carloni Calame et al. [hep-ph/0303102]
EW corrections

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- complete $\mathcal{O}(\alpha)$ corrections
  Dittmaier, Krämer [hep-ph/0109062]
  Zykunov [hep-ph/0107059]
  Baur, Wackeroth [hep-ph/0405191]
  Arbuzov et. al [hep-ph/0506110]
  Carloni Calame et. al [hep-ph/0609170]
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  \[ \Rightarrow \text{additional } \sim 10 \text{ MeV shift in } M_W \]

• complete $\mathcal{O}(\alpha)$ corrections
  • negligible additional shift for $M_W$
EW corrections

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- complete $\mathcal{O}(\alpha)$ corrections
  - negligible additional shift for $M_W$
  - incl. photon-induced processes (using MRSTQED2004 PDF)

  Dittmaier, Krämer [hep-ph/0604120]
  Arbuzov, Sadykov [arXiv:0707.0423]
  Brensing, Dittmaier, Krämer, AM [arXiv:0710.3309]
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  $\Rightarrow \sim 10 \text{ MeV shift for } M_W \text{ beyond final state radiation}$

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• complete $\mathcal{O}(\alpha)$ corrections
  • negligible additional shift for $M_W$
  • incl. photon-induced processes (using MRSTQED2004 PDF)
  • important at high $p_{T,l}, M_T$
Corrections at high energies

at LHC: $\sqrt{s} \gg M_W$ available: $W'$ searches
Corrections at high energies

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effect of real massive vector boson emission:

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