Electroweak corrections for LHC physics

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Introduction

Electroweak correction come in two variants: virtual corrections and real emission correction.

Virtual electroweak corrections often studied in the context of jet production at large transverse momentum (EW-Sudakov suppression). Usually negative and rising with $p_\perp$.

Real electroweak corrections usually constitute a separate process. However, largest BR of $W/Z$ bosons is hadronic, thus (almost) indistinguishable in jet production. Nonetheless may constitute signal in itself.

When large scale differences occur resummation is needed in either case. Practically at LHC13/14 these scale differences are moderate.

Beware of subleading orders.
Outline

1. Next-to-leading order electroweak corrections
   - Setup and subtleties
   - Selected results

2. Electroweak corrections in MCs
   - Approximate inclusion in NLO QCD merging
   - Selected results

3. Real boson radiation
   - Resummation via EW parton showers
   - Case study: Finding $W$ bosons inside jets

4. Conclusions
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4. Conclusions
Consistent setup: counting orders and defining signatures

- NLO QCD: $\alpha_s^1 = 1$ parton, only MEs from squared diagrams
- NLO EW: $\alpha^1 = 1$ photon or 1 parton, also MEs from interfering $O(\alpha_s^i\alpha_s^j\alpha^k)$ diagrams, resonances

Tree configuration:

- $pp \rightarrow W + 0 \text{ jets}$
- $pp \rightarrow W + 1 \text{ jet}$
- $pp \rightarrow W + 2 \text{ jets}$
- $pp \rightarrow W + 3 \text{ jets}$
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- NLO EW: $\alpha^1 = 1$ photon or 1 parton
  also MEs from interfering $O(\alpha_s \alpha^2)$ diagrams, resonances
Consistent setup: counting orders and defining signatures

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- NLO EW: $\alpha^1 = 1$ photon or 1 parton
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- $pp \rightarrow W + 1$ jet
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Consistent setup: counting orders and defining signatures

\[
\alpha^n \cdot \alpha^m \cdot \alpha^0 \cdot \alpha^1 \cdot \alpha^2 \cdot \alpha^3 \cdot \alpha^4
\]

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\[pp \to W + 0 \text{ jets}\]
\[pp \to W + 1 \text{ jet}\]
\[pp \to W + 2 \text{ jets}\]
\[pp \to W + 3 \text{ jets}\]
External photons

- **jet definition**: completely democratic vs. anti-tagging jets with too large photon content

- **democratic**:
  + straight forward, close to experiment for many procs
  - more subtractions (Born configs with FS photons)

- **anti-tagging jets with too large photon content**: dress quarks for collinear safety,
  discard jets if $E_\gamma > z_{\text{thr}} E_{\text{jet}}$ (e.g. $z_{\text{thr}} = 0.5$)
  + fewer contributions
  - difference to experimental jet definition (usually subpercent)
NLO EW subtraction in SHERPA

- adapt QCD subtraction (spl. fns. and colour-/spin-correlated MEs)


- replacements: $\alpha_s \rightarrow \alpha$, $C_F \rightarrow Q_f^2$, $C_A \rightarrow 0$, $T_R \rightarrow N_{c,f} Q_f^2$, $n_f T_R \rightarrow \sum_f N_{c,f} Q_f^2$,
**NLO EW subtraction in SHERPA**

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\[
\frac{T_{ij} \cdot T_k}{T_{ij}^2} \rightarrow \frac{Q_{ij} Q_k}{Q_{ij}^2}
\]

\[\sigma_{\text{RIS}} \text{ in dependence on } \alpha\text{-parameter} \]

\[\sigma_{\text{RIS}}(\alpha)/\sigma_{\text{Born}} \%\]

-Ms arXiv:1712.07975

\[\nu_e \bar{\nu}_e \rightarrow t \bar{t} @ \sqrt{s} = 2 \text{ TeV} \]

\[pp \rightarrow t \bar{t} @ \sqrt{s} = 13 \text{ TeV}, \text{ no } \gamma \text{PDF} \]
NLO EW subtraction in SHERPA

- adapt QCD subtraction (spl. fns. and colour-/spin-correlated MEs)


- replacements: 
  \[ \alpha_s \rightarrow \alpha, \quad C_F \rightarrow Q_f^2, \quad C_A \rightarrow 0, \]
  \[ T_R \rightarrow N_{c,f} Q_f^2, \quad n_f T_R \rightarrow \sum_f N_{c,f} Q_f^2, \]
  \[ \frac{T_{ij} \cdot T_k}{T_{ij}^2} \rightarrow \frac{Q_{ij} Q_k}{Q_{ij}^2}, \]

\[ \sigma_{\text{RGS}}(\alpha)/\sigma_{\text{Born}} \% \]

- \( \nu_e \bar{\nu}_e \to W^+ W^- @ \sqrt{s} = 2 \text{ TeV} \)
  - Subtraction as massive Quark
  - Subtraction as massive Scalar

\[ \sigma_{\text{RGS}}(\alpha)/\sigma_{\text{Born}} \% \]

- \( pp \to W^+ W^- @ \sqrt{s} = 13 \text{ TeV}, \text{ no } \gamma\text{PDF} \)
  - Subtraction as massive Quark
  - Subtraction as massive Scalar

\[ \sigma_{\text{RGS}}(\alpha)/\sigma_{\text{Born}} \% \]
NLO EW calculations

- **SHERPA+OPENLOOPS:**
  - \( pp \rightarrow V + 0, 1, 2(, 3) \) jets
    - EW report arXiv:1606.02330
    - LH’15 arXiv:1605.04692
    - Kallweit, Lindert, Maierhöfer, Pozzorini, MS JHEP04(2015)012, JHEP04(2016)021
  - \( pp \rightarrow \gamma j \) ratio
    - LH’15 arXiv:1605.04692
    - Kallweit, Lindert, Maierhöfer, Pozzorini, MS arXiv:1505.05704
  - \( pp \rightarrow \gamma/\ell\ell/\ell\nu/\nu\nu + j \)
  - \( pp \rightarrow Vh \)
  - \( pp \rightarrow 2\ell2\nu \)
  - \( pp \rightarrow t\bar{t}/t\bar{t}j \)
  - \( pp \rightarrow t\bar{t}h \)

- **SHERPA+GOSAM**
  - \( pp \rightarrow \gamma\gamma + 0, 1, 2 \) jets
    - Chiesa et.al. arXiv:1706.09022
  - \( pp \rightarrow \gamma\gamma/\gamma\gamma\ell\nu/\gamma\gamma\ell\ell \)
  - \( pp \rightarrow \gamma\gamma bb \)

- **SHERPA+RECOLA**
  - \( pp \rightarrow V + 0, 1, 2 \) j, \( pp \rightarrow 4\ell \), \( pp \rightarrow t\bar{t}h \)
    - Biedermann et.al. arXiv:1704.05783
Tools and setup

Kallweit, Lindert, Maierhöfer, Pozzorini, MS JHEP04(2015)012, JHEP04(2016)021

- **OPENLOOPS** for virtual corrections using **COLLIER** for tensor integrals
- **SHERPA** for Born, real em., subtraction and phase space integration, **MUNICH** (MEs from OPENLOOPS) for subtraction and p. s. int.
- combine QCD and EW corrections as:
  \[ \sigma_{\text{NLO QCD+EW}} = \sigma_{\text{LO}} (1 + \delta_{\text{QCD}} + \delta_{\text{EW}}) \]
  \[ \sigma_{\text{NLO QCD\times EW}} = \sigma_{\text{LO}} (1 + \delta_{\text{QCD}}) (1 + \delta_{\text{EW}}) \]
  \[ \Rightarrow \text{use difference as indication of potential size of } \mathcal{O}(\alpha_s \alpha) \text{ corrs.} \]
- dress quarks and leptons in $\Delta R = 0.1$,
  if $\gamma$ in jet, $E_\gamma < \frac{1}{2} E_{\text{jet}}$, discard jet otherwise
Next-to-leading order electroweak corrections

Electroweak corrections in MCs

Real boson radiation

Conclusions

Selected results

\[ pp \rightarrow Wjj \ @ 13 \text{ TeV} \]

Kallweit, Lindert, Maierhöfer, Pozzorini, MS JHEP04(2016)021

\[ d\sigma/dp_{T,W} / [\text{pb/GeV}] \]

\[ pp \rightarrow e^-\bar{\nu}_e + 2j @ 13 \text{ TeV} \]

\[ d\sigma/dp_{T,j1} / [\text{pb/GeV}] \]

\[ d\sigma/dp_{T,j2} / [\text{pb/GeV}] \]
Selected results

\[ \text{pp} \to Zjj \, @ \, 13 \, \text{TeV} \]

Kallweit, Lindert, Maierhöfer, Pozzorini, MS JHEP04(2016)021
Selected results

\[ pp \rightarrow Zjj \oplus 13 \text{ TeV} \]

Kallweit, Lindert, Maierhöfer, Pozzorini, MS JHEP04(2016)021

→ EW corrections independent of the decay mode
Next-to-leading order electroweak corrections
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Selected results

Z/γ ratio @ 8 TeV

Kallweit, Lindert, Maierhöfer, Pozzorini, MS arXiv:1505.05704

→ EW corrections different for Z and γ
**Z/γ** ratio @ 8 TeV

Kallweit, Lindert, Pozzorini, MS for LH’15

- use this ratio to get handle on $p_T^{Z}$ in $Z \rightarrow \nu \bar{\nu}$ for NP searches
- test how well data is described in $Z \rightarrow \ell \ell$
  ⇒ NLO EW improves data description
**Z/γ ratio @ 8 TeV**

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⇒ NLO EW improves data description
Diboson production – DF and SF

Combination of QCD and EW correction

- additive – strict fixed order expansion

\[ d\sigma_{\text{QCD+EW}}^{\text{NLO}} = d\sigma_{\text{LO}} (1 + \delta_{\text{QCD}} + \delta_{\text{EW}}) \]

- multiplicative – contains terms of \( \mathcal{O}(\alpha_s\alpha) \)

\[ d\sigma_{\text{QCD}\times\text{EW}}^{\text{NLO}} = d\sigma_{\text{LO}} (1 + \delta_{\text{QCD}}) (1 + \delta_{\text{EW}}) \]

NLO EW for photon initiated processes

- resolved final state photons should be renormalised on-shell (\( \alpha(0) \))
  \( \rightarrow \) absorbs IR divergences from \( \gamma \rightarrow f \bar{f} \) splittings not included

- initial state (and unresolved final state) photons should be renormalised at the hard scale (\( \alpha(m_Z), G_\mu, \overline{\text{MS}}, \text{etc.} \))
  \( \rightarrow \) match IR divergences in PDF evolution and collinear counter term

Kallweit, Lindert, Pozzorini, MS arXiv:1705.00598
Diboson production – DF

$\text{pp} \rightarrow e^+ \mu^- \nu_e \bar{\nu}_\mu$

Kallweit, Lindert, Pozzorini, MS arXiv:1705.00598

- absolute prediction
- relative correction wrt. LO
- NLO QCD (w/ moderate jet veto)
- LO
- NLO QCD+EW
- NLO QCD $\times$ EW
- NLO EW

- large pos. NLO QCD, large neg. NLO EW
  $\rightarrow$ NLO QCD+EW and NLO QCD $\times$ EW differ significantly
**Diboson production – DF**

relative importance of $\gamma$-induced channels wrt. NLO QCD $\times$ EW

- CT14qed (baseline) no $\gamma$PDF
- LUXqed

- all $\gamma$PDF agree that $\gamma$-ind. > 10% for $p_T > 500$ GeV
- very good agreement between CT14qed and LUXqed
Diboson production – DF

\[ \text{pp} \to e^+ \mu^- \nu_e \bar{\nu}_\mu \]

- ZZ dominant at very large \( p_T \)
  \( \rightarrow \) different EW corrections, take care when extrapolating

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Electroweak corrections for LHC physics

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Diboson production – SF

\[ pp \to e^+ e^- \nu \bar{\nu} \]

- **ZZ** dominant at very large \( p_T \)
  - \( \to \) different EW corrections, take care when extrapolating

\[ pp \to W^+ [\to e^+ \nu] W^- [\to e^- \bar{\nu}] \]
\[ pp \to Z/\gamma [\to e^+ e^-] Z [\to \nu \bar{\nu}] \]
\[ \text{incoherent sum} \]

\[ d\sigma/dp_T,\ell^2 \ [\text{GeV}] \]
\[ d\sigma/d\sigma_{NLO} \times \text{EW} \]

\[ LHC \ 13 \ TeV \]
\[ \mu_R = \mu_F = \frac{1}{2} \mu_F^{lep} \]
\[ \text{CT14 QED}_{0.05\%} \]
Diboson production – DF

\[ pp \rightarrow e^+ \mu^- \nu_e \bar{\nu}_\mu \]

- kinematic suppression for \( p_T^{\nu\nu} \) at LO, unlocked at NLO QCD
- not present in \( \gamma \)-induced \( \Rightarrow \) large contrib
Diboson production – SF

\[ pp \rightarrow e^+ e^- \nu \bar{\nu} \]

- kinematic suppression for \( p_T^{\nu\nu} \) for \( WW \), but not \( ZZ \)
- \( ZZ \) dominates for \( \text{MET} > 100 \text{ GeV} \) with large EW corr.

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Electroweak corrections for LHC physics

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Top pair production in association with jets

Gütschow, Lindert, MS in prep.

- $pp \to t\bar{t}$
  NNLO QCD + NLO EW
  Czakon et.al. arXiv:1705.04105
  - include NLO corrections to subleading orders
- $pp \to t\bar{t}j$
  NLO QCD + NLO EW
  - include NLO corrections to subleading orders
Top pair production in association with jets

Gütschow, Lindert, MS in prep.

NLO EW factorises from additional jet activity
Top pair production in association with jets

Gütschow, Lindert, MS in prep.

subleading orders important
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4. Conclusions
Electroweak corrections in particle-level event generation

- incorporate approximate electroweak corrections in SHERPA’s NLO QCD multijet merging (MEPS@NLO)
- modify MC@NLO $\overline{B}$-function to include NLO EW virtual corrections and integrated approx. real corrections

$$\overline{B}_{n,QCD+EW_{virt}}(\Phi_n) = \overline{B}_{n,QCD}(\Phi_n) + V_{n,EW}(\Phi_n) + I_{n,EW}(\Phi_n) + B_{n,mix}(\Phi_n)$$

- real QED radiation can be recovered through standard tools (parton shower, YFS resummation)
- simple stand-in for proper QCD+EW matching and merging → validated at fixed order, found to be reliable, diff. $\lesssim 5\%$ for observables not driven by real radiation
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exact virtual contribution

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  \[
  \overline{B}_{n,\text{QCD+EW virt}}(\Phi_n) = \overline{B}_{n,\text{QCD}}(\Phi_n) + V_{n,\text{EW}}(\Phi_n) + I_{n,\text{EW}}(\Phi_n) + B_{n,\text{mix}}(\Phi_n)
  \]

  optionally include subleading Born

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  - optionally include subleading Born
  - exact virtual contribution
  - approximate integrated real contribution
- real QED radiation can be recovered through standard tools (parton shower, YFS resummation)
- simple stand-in for proper QCD+EW matching and merging
  \[ \rightarrow \text{validated at fixed order, found to be reliable, diff. } \lesssim 5\% \text{ for observables not driven by real radiation} \]
Results: \( pp \rightarrow \ell^- \bar{\nu} + \text{jets} \)

Kallweit, Lindert, Maierhöfer, Pozzorini, MS JHEP04(2016)021

⇒ particle level events including dominant EW corrections
Results: $pp \rightarrow t\bar{t} + \text{jets}$

Gütschow, Lindert, MS in prep.

- $pp \rightarrow t\bar{t} + 0, 1j@\text{NLO}$
  $+ 2, 3, 4j@\text{LO}$

- additional LO multiplicities inherit electroweak corrections through MENLOPS differential $K$-factor
  Höche, Krauss, MS, Siegert
  \text{arXiv:1009.1127}

- improved description of data
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4. Conclusions
Collinear limit with $E \gg m$

- QED parton showers well known and available in every major shower
- approximation to collinear (vector) boson emission in limit $E \gg m$, in dipole language (splitter-spectator pairs): $f(s) \rightarrow f'(t)V(s)$

$$d\sigma_{n+V} = d\sigma_n \sum_f \sum_s n_{\text{spec}} dt\, dz\, d\phi\, \frac{1}{n_{\text{spec}}} \, J(t, z) \, K_{f(s)\rightarrow f'(t)V(s)}(t, z)$$

- emitter fermion $f$, suitable spectator $s$
- flavour change $f \rightarrow f'$ in case of $W$ emissions
- IS kernels contain ratio of PDFs (change in $x, Q, \text{flavour}$)
- similar ansatz with diff. kernels in Christiansen, Sjöstrand JHEP04(2014)115
- new developments Chen, Han, Tweedie arXiv:1611.00788 Bauer, Ferland, Webber JHEP08(2017)036
Splitting kernels

- use Denner-Hebenstreit expressions modified into CDST form

\[ \mathcal{K}_{f(s)\rightarrow f'W(s)}(t, z) = \frac{\alpha}{2\pi t} \left[ f_W c^W_{\perp} \tilde{V}_{f(s)\rightarrow f'W(s)}(t, z) + f_h c^W_{L} \frac{1}{2} (1 - z) \right] \]

\[ \mathcal{K}_{f(s)\rightarrow fZ(s)}(t, z) = \frac{\alpha}{2\pi t} \left[ f_Z c^Z_{\perp} \tilde{V}_{f(s)\rightarrow fZ(s)}(t, z) + f_h c^Z_{L} \frac{1}{2} (1 - z) \right] \]

with

\[ c^W_{\perp} = s_{\text{eff}} \frac{1}{2s^2_W} |V_{ff'}|^2, \quad c^Z_{\perp} = s_{\text{eff}} s^2_W Q_f^2 + (1 - s_{\text{eff}}) \frac{(l_f^3 - s^2_W Q_f^2)}{s^2_W c^2_W}, \]

\[ c^W_{L} = \frac{1}{2s^2_W} |V_{ff'}|^2 \left[ s_{\text{eff}} \frac{m^2_{f'}}{m^2_W} + (1 - s_{\text{eff}}) \frac{m^2_f}{m^2_W} \right], \quad c^Z_{L} = \frac{l^3_f}{s^2_W} \frac{m^2_{f'}}{m^2_W}, \]

- couplings \( ff'V \) depend on spin of \( f \), but standard parton showers are spin averaged (no spin information)
- process dependent average spin of fermion line \( s_{\text{eff}} \)
  \( \Rightarrow pp \rightarrow jj: s_{\text{eff}} = \frac{1}{2}, pp \rightarrow W: s_{\text{eff}} = 1, \) undefined in general
- factors \( f_W, f_Z, f_h \) modify couplings to test sensitivity
**Can we see radiated $W$ bosons inside jets at the LHC (14 TeV)?**

- need high-$p_{\perp}$ jets to produce real $W$ bosons at sufficient rate
- need high-$p_{\perp}$ jets to satisfy assumption $E \gg m$

**Boosted analysis:**

- isolated leptons ($p_{\perp} > 25$ GeV, $|\eta| < 2.5$, max. 10% in $\Delta R = 0.2$)
- find jets (anti-$k_{\perp}$, $R = 1.5$, $p_{\perp} > 200$ GeV) on remainder
- two cases: no isolated leptons $\Rightarrow$ hadronic analysis
  
  one isolated lepton $\Rightarrow$ leptonic analysis
- require further two jets with $p_{\perp} > 500, 750, 1000$ GeV to drive $W$ radiation into collinear region
Case study: Finding $W$ bosons inside jets

### Hadronic analysis

- recluster fat jets into C/A ($R = 0.3, \ p_\perp > 20 \ \text{GeV}$) microjets
- discard leading microjet as likely from leading quark
- use $m_{23}$ as em. gluons tend to be softer than decay prod. of em. $W$
- accept candidate if $m_{23} \in [70, 86] \ \text{GeV}$

$\Rightarrow$ large, but continuous QCD background, clear signal shape
$\Rightarrow$ more $W$ emissions with hight $p_\perp$, but peak shifts
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NLO EW predictions for $\Delta R(\mu, j_1)$

Measure coll. W emissions, simplified from Krauss, Petrov, MS, Spannowsky PRD89(2014)114006

LHC@8TeV, $p_T^{j_1} > 500$ GeV, central $\mu$ and jet

- LO $pp \to Wj$ with $\Delta \phi(\mu, j) \approx \pi$
- NLO corrections neg. in peak
- large $pp \to Wjj$ component opening PS
- subleading Born ($\gamma$PDF) imp. at large $\Delta R$
- restrict to exactly 1j, no $p_T^{j_2} > 100$ GeV
- describe $pp \to Wjj$ @ NLO, $p_T^{j_2} > 100$ GeV
- pos. NLO QCD, neg. NLO EW, $\sim$ flat
- subleading Born contribs positive
- sub$^2$leading Born (diboson etc) conts. pos.
- $\to$ possible double counting with BG
- merge using exclusive sums
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Case study: Finding $W$ bosons inside jets

**NLO EW predictions for $\Delta R(\mu, j_1)$**

Measure coll. $W$ emissions, simplified from Krauss, Petrov, MS, Spannowsky PRD89(2014)114006

LHC@8TeV, $p_T^{j_1} > 500$ GeV, central $\mu$ and jet

- LO $pp \rightarrow Wj$ with $\Delta \phi(\mu, j) \approx \pi$
- NLO corrections neg. in peak large $pp \rightarrow Wjj$ component opening PS
  - subleading Born ($\gamma$PDF) imp. at large $\Delta R$
  - restrict to exactly 1$j$, no $p_T^{j_2} > 100$ GeV
  - describe $pp \rightarrow Wjj$ @ NLO, $p_T^{j_2} > 100$ GeV
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$$\Delta R(\mu, j_1)$$

**Angular separation of leading jet and muon**

<table>
<thead>
<tr>
<th>LO</th>
<th>NLO QCD</th>
<th>NLO QCD+EW</th>
<th>NLO QCD+EW+subLO</th>
<th>NLO QCD+EW+subLO+subLO</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.25</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
</tbody>
</table>

**Ratio wrt. NLO QCD**

- 0.5
- 1
- 1.5

$p_{T}^{j_1,2}$
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Data comparison
M. Wu ICHEP’16, ATLAS arXiv:1609.07045
- **ALPGEN+PYTHIA**
  
  $pp \rightarrow W + \text{jets MLM merged}$
  Mangano et.al. JHEP07(2003)001

- **PYTHIA 8**
  
  $pp \rightarrow Wj + \text{QCD shower}$

  $pp \rightarrow jj + \text{QCD+EW shower}$
  Christiansen, Prestel EPJC76(2016)39

- **SHERPA+OPENLOOPS**

  NLO QCD+EW+subLO

  $pp \rightarrow Wj / Wjj$ excl. sum
  Kallweit, Lindert, Maierhöfer, Pozzorini, MS JHEP04(2016)021

- **NNLO QCD**

  $pp \rightarrow Wj$
  Boughezal, Liu, Petriello arXiv:1602.06965
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Conclusions

- Electroweak effects are important at LHC, HE–LHC, FCC, etc.
- Become large whenever the scale is large compared to the EW scale
- Can be incorporated in multijet merging to improve description in those regions
  ⇒ included since SHERPA-2.2.1 (now SHERPA-2.2.4)
- Automation of NLO EW follows on the heels of NLO QCD
  → much more care with consistent schemes and order counting
  → very rich phenomenology
  → includes many more pitfalls than NLO QCD
  ⇒ included in next major SHERPA release
- EW parton showers suffer from strong spin dependence of $W/Z$ emission as parton showers are usually do not have spin information
  ⇒ not included in SHERPA public release
Thank you for your attention!
Backup
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\[ pp \rightarrow Wj \ @ 13 \text{ TeV} \]

Kallweit, Lindert, Maierhöfer, Pozzorini, MS JHEP04(2016)021

- NLO QCD to \( p_T^j \) dominated by hard dijet topologies
  \( \rightarrow \) LO, no EW corr.
  Rubin, Salam, Sapeta
  JHEP09(2010)084

- need merging

- remove dijet configs through \( \Delta \phi_{j_1 j_2} < \frac{3}{4} \pi \)
  \( \rightarrow \) EW Sudakov recovered
**pp → Wj @ 13 TeV**

Kallweit, Lindert, Maierhöfer, Pozzorini, MS JHEP04(2016)021

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  → EW Sudakov recovered
Example: Forward-backward asymmetry @ Tevatron

Höche, Huang, Luisoni, MS, Winter Phys.Rev.D88(2013)1,014040

Chose two different $\mu_\text{core} \rightarrow$ largest impact
Electroweak histories not an issue, but merging works nicely
Recent NNLO+NNLL results:
Forward-backward asymmetry @ Tevatron

Czakon, Fiedler, Mitov arXiv:1411.3007

MEPS@NLO result very well reproduced by higher order calculation
Merging systematics: \( pp \to \ell^- \bar{\nu} + \text{jets} \)

Kallweit, Lindert, Maierhöfer, Pozzorini, MS JHEP04(2016)021

\[ \text{pp} \to \ell^- \bar{\nu} + 0,1,2 \text{j} \oplus 13 \text{TeV} \]

\[ \text{MEPS@LO} \]

⇒ dead zones in incl. obs. if \( Q_{\text{cut}} \) too high
Merging systematics: \( pp \rightarrow \ell^- \bar{\nu} + \text{jets} \)

Kallweit, Lindert, Maierhöfer, Pozzorini, MS JHEP04(2016)021

\[
\frac{d\sigma}{d\vec{d}_{12}} [\text{pb/GeV}] \\
\text{SHERPA+OPENLOOPS} \\
\text{Q}_{\text{cut}} = 10 \text{ GeV} \\
\text{Q}_{\text{cut}} = 15 \text{ GeV} \\
\text{Q}_{\text{cut}} = 20 \text{ GeV} \\
\text{Q}_{\text{cut}} = 30 \text{ GeV} \\
\text{Q}_{\text{cut}} = 40 \text{ GeV} \\
\text{Q}_{\text{cut}} = 60 \text{ GeV} \\
\text{Q}_{\text{cut}} = 100 \text{ GeV} \\
\text{Q}_{\text{cut}} = 200 \text{ GeV} \\
\]

\[ p_{T}^{W} > 1 \text{ TeV} \]

\[ p_{T}^{j} > 1 \text{ TeV} \]

\[
\Rightarrow \text{dead zones in incl. obs. if } Q_{\text{cut}} \text{ too high}
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Kallweit, Lindert, Maierhöfer, Pozzorini, MS JHEP04(2016)021

$pp \rightarrow \ell^- \bar{\nu} + 0,1,2 \text{j} @ 13 \text{TeV}$

- **MEPS@NLO QCD**
  - $d\sigma^{\text{NLO}}(Q_{\text{cut}})/d\sigma^{\text{NLO}}(20 \text{ GeV})$
  - $Q_{\text{cut}} = 10 \text{ GeV}$
  - $Q_{\text{cut}} = 15 \text{ GeV}$
  - $Q_{\text{cut}} = 20 \text{ GeV}$
  - $Q_{\text{cut}} = 30 \text{ GeV}$
  - $Q_{\text{cut}} = 40 \text{ GeV}$

- **MEPS@LO**
  - $Q_{\text{cut}} = 60 \text{ GeV}$
  - $Q_{\text{cut}} = 100 \text{ GeV}$
  - $Q_{\text{cut}} = 200 \text{ GeV}$

$\Rightarrow$ TeV region stable ($\lesssim 5\%$), $Q_{\text{cut}} = 20 \text{ GeV}$ suitable for whole range
QCD multijet merging – LO case

Parton showers
resummation of (soft-)collinear limit
→ intrajet evolution

- matrix elements (ME) and parton showers (PS) are approximations in different regions of phase space
- MEPS combines multiple LOPs – keeping either accuracy
- NLOPS elevate LOPS to NLO accuracy
- MENLOPS supplements core NLOPS with higher multiplicities LOPS
**QCD multijet merging – LO case**

- **Matrix elements**
  - fixed-order in $\alpha_s$
  - \(\rightarrow\) hard wide-angle emissions
  - \(\rightarrow\) interference terms

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**MEPS** (CKKW, MLM)

Catani, Krauss, Kuhn, Webber JHEP11(2001)063
Lönnblad JHEP05(2002)046
Höche, Krauss, Schumann, Siegert JHEP05(2009)053

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Hamilton, Nason JHEP06(2010)039
Höche, Krauss, MS, Siegert JHEP08(2011)123
Gehrmann, Höche, Krauss, MS, Siegert JHEP01(2013)144
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Lavesson, Lönnblad JHEP12(2008)070
Höche, Krauss, MS, Siegert JHEP04(2013)027
Gehrmann, Höche, Krauss, MS, Siegert JHEP01(2013)144
Lönnblad, Prestel JHEP03(2013)166
Plätzer JHEP08(2013)114
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Plätzer JHEP08(2013)114
**M@NLO**

Transverse momentum of the Higgs boson

\[ \frac{d\sigma}{dp_{\perp}} \text{ [pb/GeV]} \]

- *first emission by N@LOs*, restrict to \( Q_1 < Q_{\text{cut}} \)
- *N@LOs* \( pp \rightarrow h \text{ + jet} \) for \( Q_1 > Q_{\text{cut}} \)
- restrict emission off \( pp \rightarrow h \text{ + jet} \) to \( Q_2 < Q_{\text{cut}} \)
- *N@LOs* \( pp \rightarrow h \text{ + 2jets} \) for \( Q_2 > Q_{\text{cut}} \)
- iterate
- sum all contribs
**MEPs@NLO**

Transverse momentum of the Higgs boson

\[ \frac{d\sigma}{dp_T} \text{ [pb/GeV]} \]

- first emission by NLOPS, restrict to \( Q_1 < Q_{\text{cut}} \)
  - NLOPS
    - \( pp \to h + \text{jet for } Q_1 > Q_{\text{cut}} \)
  - restrict emission off
    - \( pp \to h + \text{jet to } Q_2 < Q_{\text{cut}} \)
  - NLOPS
    - \( pp \to h + 2\text{jets for } Q_2 > Q_{\text{cut}} \)
  - iterate
  - sum all contribs


**MEPs@NLO**

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Transverse momentum of the Higgs boson

\[
p_{\perp}(h) \ [\text{GeV}]
\]

\[
d\sigma/dp_{\perp} \ [\text{pb/GeV}]
\]
MEPS@NLO

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NLOPS

$pp \rightarrow h + \text{jet}$ for $Q_1 > Q_{cut}$

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NLOPS

$pp \rightarrow h + 2\text{jets}$ for $Q_2 > Q_{cut}$

iterate

sum all contribs
QCD multijet merging – identifying a history

Example: Drell-Yan production in association with jets

- cluster external particles using inverse parton shower → flavour conscious, initial state aware, probability determined through splitting kernels
- identify a shower history (probabilistically), determine scale $t_i$ up to predefined $t_I$

\[
\alpha_s^{n+k}(\mu_R^2) = \alpha_s^k(\mu_{\text{core}}^2) \prod_{i=1}^{n} \alpha_s(t_i) \]

\[\text{Marek Schönherr} \quad \text{Electroweak corrections for LHC physics} \quad 50/37\]
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- choose

$$
\alpha_s^{n+k}(\mu^2_R) = \alpha_s^k(\mu^2_{core}) \prod_{i=1}^{n} \alpha_s(t_i)
$$
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- identify a shower history (probabilistically), determine scale $t_i$ up to predefined $t_I$
- choose

$$\alpha_s^{n+k}(\mu_R^2) = \alpha_s^k(\mu_{\text{core}}^2) \prod_{i=1}^n \alpha_s(t_i)$$
QCD multijet merging – identifying a history

ME also provides expression beyond $t_I$

two types of configuration: $pp \rightarrow Z + \text{jets}$ and $pp \rightarrow \text{jets} + Z$

- different core process, naively not part of $pp \rightarrow Z + \text{jets}$ but indistinguishable
- configuration that would have arisen from dijets plus QCD+EW showering
- necessitates EW splitting kernels to calculate splitting probability
- leads to different scale choices and Sudakov factors
QCD multijet merging – identifying a history

ME also provides expression beyond $t_l$

two types of configuration: $pp \rightarrow Z+\text{jets}$ and $pp \rightarrow \text{jets}+Z$

- different core process, naively not part of $pp \rightarrow Z+\text{jets}$ but indistinguishable
- configuration that would have arisen from dijets plus QCD+EW showering
- necessitates EW splitting kernels to calculate splitting probability
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QCD multijet merging – identifying a history

ME also provides expression beyond $t_1$

Two types of configuration: $pp \rightarrow Z+$jets and $pp \rightarrow$jets+$Z$

- different core process, naively not part of $pp \rightarrow Z+$jets but indistinguishable
- configuration that would have arisen from dijets plus QCD+EW showering
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QCD multijet merging – identifying a history

VS.
Importance of electroweak clustering

$$\Rightarrow$$ large impact at high $p_{\perp}$ and multiplicity
Importance of electroweak clustering

ATLAS

\[ L \, dt = 4.6 \, fb^{-1} \]

anti-\( k_T \) jets, \( R = 0.4 \)

\( p_T^{\text{jet}} > 30 \, \text{GeV}, |y^{\text{jet}}| < 4.4 \)

\( \sigma(Z/\gamma^* \to \ell^+ \ell^- + \text{jets}) \) [pb]

Data 2011 (\( \sqrt{s} = 7 \, \text{TeV} \))

ALPGEN

SHERPA

MC@NLO

BLACKHAT + SHERPA

MC / Data

0.6

0.8

1

1.2

1.4

NLO / Data

0.6

0.8

1

1.2

1.4

ATLAS

\[ L \, dt = 4.6 \, fb^{-1} \]

anti-\( k_T \) jets, \( R = 0.4 \)

\( p_T^{\text{jet}} > 30 \, \text{GeV}, |y^{\text{jet}}| < 4.4 \)

\( \frac{1}{\sigma(Z/\gamma^* \to \ell^+ \ell^- + \text{jets})} \, \frac{d\sigma}{dp_T} \) [1/GeV]

Data 2011 (\( \sqrt{s} = 7 \, \text{TeV} \))

ALPGEN

SHERPA

MC@NLO

BLACKHAT + SHERPA

MC / Data

0.6

0.8

1

1.2

1.4

p_T (leading jet) [GeV]
Hadronic analysis

- use event shape variables on microjets of reconstructed $W$ candidate to enhance S/B, e.g. ellipticity

\[ \hat{t} = \frac{T_{\text{min}}}{T_{\text{maj}}} \]

→ small when radiation pattern is 1D ($W \rightarrow q\bar{q}$)

- fat jet $p_{T} > 750$ GeV optimal best balance between cross section and emission rate

⇒ additional discrimination
Hadronic analysis

Can we distinguish between \( f = 1 \) and \( f = 2 \)?
(simplified version of: How accurate can we measure the coupling?)

- signal: \( f = 2 \), background: \( f = 1 \) (SM)
- moderate sensitivity even under ideal conditions
  benefits from larger emission at large \( p_T \) despite smaller cross section
Leptonic analysis

Can we distinguish between $f = 1$ and $f = 1.1$? (simplified version of: How accurate can we measure the coupling?)

- signal: $f = 1.1$, background: $f = 1.0$ (SM)
- improved sensitivity, despite small cross sections, benefits from ideal background rejection