Electroweak corrections and parton showers

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Introduction

Electroweak sector of the Standard Model is descibed by a broken $SU(2)_{\mathrm{L}} \times U(1)_{\mathrm{Y}}$ gauge group resulting in $U(1)_{\mathrm{QED}}$ and massive weak gauge bosons ($W^{\pm}$, Z).

Inclusive observables
Electroweak corrections are of $\mathcal{O}(\alpha)$, thus generally of $\mathcal{O}(1\%)$. Roughly, their size can be gauged by $\mathcal{O}(\alpha) \approx \mathcal{O}(\alpha_s^2)$. Important to take into account in precision measurements.

TeV scale observables
Incomplete infrared cancellation due to broken structure of the gauge group introduces logarithms of the scale of the process and that of the EW bosons. This introduces EW Sudakov logarithms which are negative and grow with the size of the kinematic invariants, e.g. p_{T}. Thus, $\mathcal{O}(20\%)$ corrections possible already for LHC range.

Introduction

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

Virtual electroweak corrections often studied in the context of gauge boson and jet production at large transverse momentum (EW-Sudakov suppression). Usually negative and increasing 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.

Beware of subleading orders.

Electroweak corrections in Event Generators

NLO EW well automated

⇒ along the principles of NLO QCD automation

- Monte-Carlo frameworks (Born and real emission matrix elements, infrared subtraction, phase space generation, process coordination)
  - SHERPA — MS arXiv:1712.07975
  - MADGRAPH — Frederix et.al. arXiv:1804.10017
- virtual corrections (EW one-loop matrix elements, renormalisation)
  - GOSAM — Chiesa et.al. arXiv:1507.08579
  - MADLOOP — Frixione et.al. arXiv:1407.0823
  - OPENLOOPS — Kallweit et.al. arXiv:1412.5157
  - RECOLA — Actis et.al. arXiv:1211.6316

Matched NLO EW (QED)

- QED parton showers in existence for 30 years now
- internal resonance for almost all process — Mück, Oymanns arXiv:1612.04292

- SHERPA+OPENLOOPS:
  - $pp \to V + 0, 1, 2(, 3)$ jets — FCC report, arXiv:1607.01831; EW report arXiv:1606.02330; LH'15 arXiv:1605.04692; Kallweit,Lindert,Maierhöfer,Pozzorini,MS arXiv:1412.5157, arXiv:1511.08692
  - $pp \to Zj/pp \to \gamma j$ ratio — LH'15 arXiv:1605.04692; Kallweit,Lindert,Maierhöfer,Pozzorini,MS arXiv:1505.05704
  - $pp \to \gamma/\ell\ell/\ell\nu/\nu\nu + j$ — Lindert et.al arXiv:1705.04664
  - $pp \to Vh$ — FCC report, arXiv:1607.01831
  - $pp \to 2\ell 2\nu$ — Kallweit,Lindert,Pozzorini,MS, arXiv:1705.00598
  - $pp \to 4\ell$ — Gütschow,MS, arXiv:1906.xxxxx
  - $pp \to t\bar{t}/t\bar{t}j$ — Gütschow, Lindert, MS arXiv:1803.00950
  - $pp \to t\bar{t}h$ — LH'15 arXiv:1605.04692
- SHERPA+GOSAM
  - $pp \to \gamma\gamma + 0, 1, 2$ jets — Chiesa et.al. arXiv:1706.09022
  - $pp \to \gamma\gamma\gamma \,/\, \gamma\gamma\ell\nu \,/\, \gamma\gamma\ell\ell$ — Greiner, MS arXiv:1710.11514
  - $pp \to \gamma\gamma b\bar{b}$ — Greiner, MS in prep.
- SHERPA+RECOLA
  - $pp \to V + 0, 1, 2$ j, $pp \to 4\ell$, $pp \to t\bar{t}h$ — Biedermann et.al. arXiv:1704.05783
  - $pp \to 3\ell 3\nu$ — MS arXiv:1806.00307

Electroweak corrections in event generation

How to incorporate (approx.) NLO EW corrections into existing event generators

- analogously to EW Sudakov approximation replace

$$\mathrm{B}(\Phi_B) \to \mathrm{B}(\Phi_B)\left(1+\frac{\mathrm{V}_{\mathsf{EW}}(\Phi_B)+\mathrm{I}_{\mathsf{EW}}(\Phi_B)}{\mathrm{B}(\Phi_B)}\right)$$

- real emission correctiosn “unfolded by” QED FSR (YFS soft photon resummation / QED parton shower)
- formally no better than EW Sudakov approximation (in practice, NLO EW can recovered at the percent level)

How well does the approx. work in various regimes and processes?

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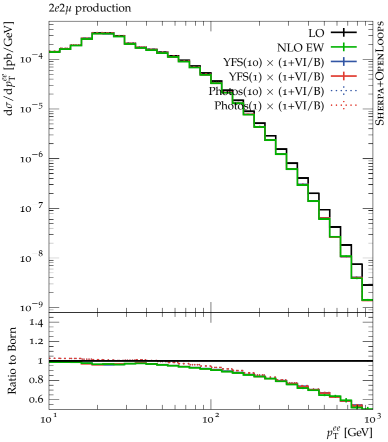
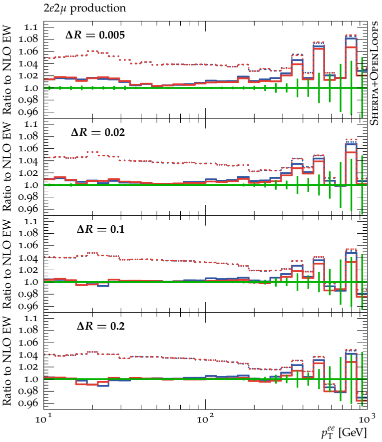
Four lepton production – preliminary





Observation: NLO EW very well reproduced by EW_{virt} in TeV regime

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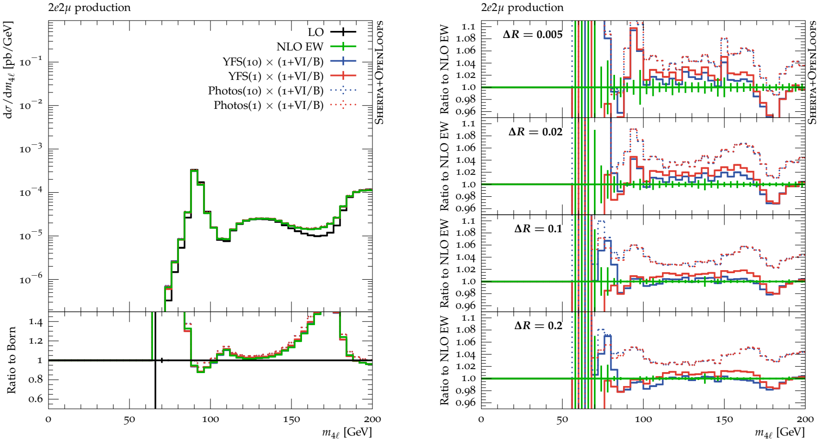
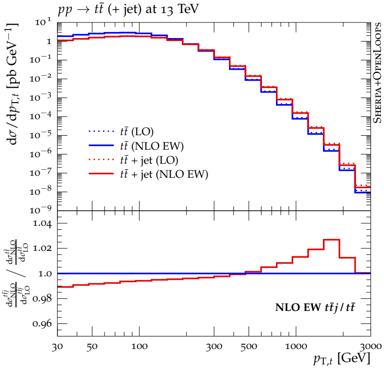
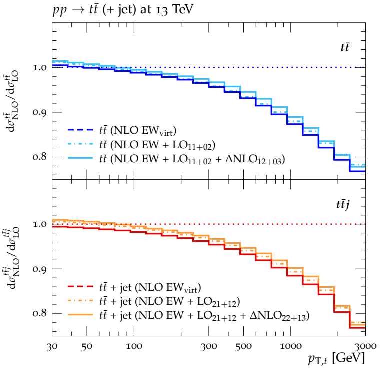


Observation: FSR sensitive obs. w/ larger $\mathcal{O}(\alpha^2)$ effects

Top pair production in association with jets

Gütschow, Lindert, MS in arXiv:1803.00950





Observation: NLO EW factorises from additional jet activity when rather inclusive on jet definition

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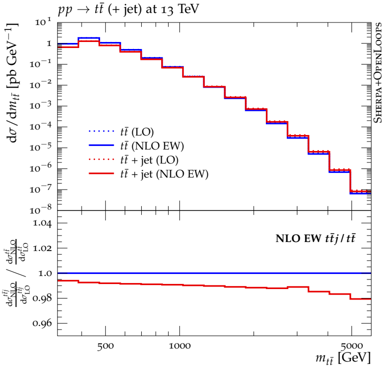

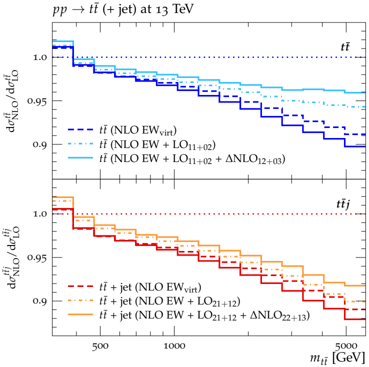

Observation: subleading orders important

Electroweak corrections in particle-level event generation

- incorporate approximate electroweak corrections in SHERPA's NLO QCD multijet merging (MEPS@NLO)
- taylored to large-p_T regions where EW corrections dominated by virtual W/Z exchange and RG running
- modify MC@NLO $\overline{\mathrm{B}}$-function to include NLO EW virtual corrections and integrated approx. real corrections

$$\overline{\mathrm{B}}_{n,\mathrm{QCD+EW_{virt}}}(\Phi_n) = \overline{\mathrm{B}}_{n,\mathrm{QCD}}(\Phi_n) + \mathrm{V}_{n,\mathrm{EW}}(\Phi_n) + \mathrm{I}_{n,\mathrm{EW}}(\Phi_n) + \mathrm{B}_{n,\mathrm{mix}}(\Phi_n)$$

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- simple stand-in for proper QCD+EW matching and merging

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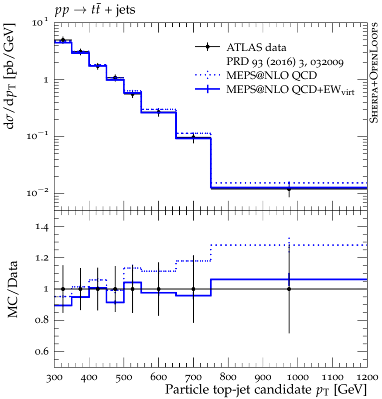
Results: $pp \to t\bar{t} + \text{jets}$



Gütschow, Lindert, MS in arXiv:1803.00950

- $pp \to t\bar{t} + 0, 1j$@NLO $+ 2, 3, 4j$@LO
- additional LO multiplicities inherit electroweak corrections through MENLOPS differential K-factor

  Höche, Krauss, MS, Siegert arXiv:1009.1127
- improved description of data

Electroweak corrections in parton showers

QED parton showers

Well-understood abelian limit of QCD parton showers which suffer from non-existing $N_c \to \infty$ limit. QED is U(1), and $\frac{1}{1}$ is not so small.
$\Rightarrow$ all charge partners of equal importance, but contrib. with diff. signs.

Parton showers:

- coll. emission pattern trivial, soft coherence tricky

Dipole showers:

- without inclusion of neg. dipoles get both soft and coll. limits wrong

Multipole showers:

- trivially pos. definite, coherence by default, used in soft-photon resummation

Additional complication: QED result of a broken gauge group
$SU(2)_L \times U(1)_Y \to U(1)_{\text{QED}}$
in addition to massive fermions
$\Rightarrow$ resonances everywhere

QED dipoles

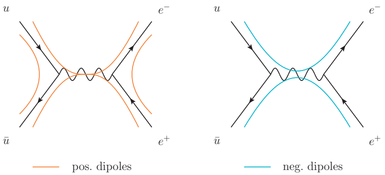
Main issue: QED is U(1)

equivalent of large-N_c expansion not very meaningful

need full multipole picture for soft-photon coherence

Example: $u\bar{u} \to e^+e^-$

quadrupole, or 6 dipoles (4 opposite sign, 2 same sign)



need all dipoles for correct soft-collinear structure,
all dipoles contribute on equal footing

Weak showers: Collinear limit with $E \gg m$

Krauss, Petrov, MS, Spannowsky arXiv:1403.4788

- approximation to collinear (vector) boson emission in limit $E \gg m$, in dipole language (splitter-spectator pairs): $f(s) \to f^{(\prime)}V(s)$

$$\mathrm{d}\sigma_{n+V} = \mathrm{d}\sigma_n \sum_f \sum_s^{n_{\text{spec}}} \mathrm{d}t\,\mathrm{d}z\,\frac{\mathrm{d}\phi}{2\pi}\,\frac{1}{n_{\text{spec}}}\,J(t,z)\,\mathcal{K}_{f(s)\to f^{(\prime)}V(s)}(t,z)$$

- emitter fermion f, suitable spectator s
- flavour change $f \to f'$ in case of W emissions
- IS kernels contain ratio of PDFs (change in x,Q,flavour)
- immediately decay freshly produced boson
- similar ansatz with diff. kernels in — Christiansen, Sjöstrand arXiv:1401.5238
- new developments — Chen, Han, Tweedie arXiv:1611.00788; Bauer, Ferland, Webber arXiv:1703.08562

Denner, Hebenstreit unpublished

- use Denner-Hebenstreit expressions modified into CDST form

$$\mathcal{K}_{f(s)\to f'W(s)}(t,z) = \frac{\alpha}{2\pi t}\left[f_W\, c_\perp^W\, \tilde{\mathrm{V}}^{\mathrm{CDST}}_{f(s)\to f'b(s)}(t,z) + f_h\, c_L^W\, \tfrac{1}{2}\,(1-z)\right]$$
$$\mathcal{K}_{f(s)\to fZ(s)}(t,z) = \frac{\alpha}{2\pi t}\left[f_Z\, c_\perp^Z\, \tilde{\mathrm{V}}^{\mathrm{CDST}}_{f(s)\to fb(s)}(t,z) + f_h\, c_L^Z\, \tfrac{1}{2}\,(1-z)\right]$$

with

$$c_\perp^W = s_{\mathrm{eff}}\,\tfrac{1}{2s_W^2}\,|V_{ff'}|^2\,, \qquad c_\perp^Z = s_{\mathrm{eff}}\,\tfrac{s_W^2}{c_W^2}\,Q_f^2 + (1-s_{\mathrm{eff}})\,\tfrac{(I_f^3-s_W^2Q_f)^2}{s_W^2c_W^2}\,,$$
$$c_L^W = \tfrac{1}{2s_W^2}\,|V_{ff'}|^2\left[s_{\mathrm{eff}}\,\tfrac{m_{f'}^2}{m_W^2} + (1-s_{\mathrm{eff}})\,\tfrac{m_f^2}{m_W^2}\right]\,, \qquad c_L^Z = \tfrac{I_f^3}{s_W^2}\,\tfrac{m_f^2}{m_W^2}\,,$$

- couplings $ff^{(\prime)}V$ depend on spin of f, but standard parton showers are spin avaraged (no spin information)
- process dependent avarage spin of fermion line s_{eff}
  $\Rightarrow$ $pp\to jj$: $s_{\mathrm{eff}}=\frac{1}{2}$, $pp\to W$: $s_{\mathrm{eff}}=1$, undefined in general
- factors f_W, f_Z, f_h modify couplings to test sensitivity

Weak showers: Collinear limit with $E \gg m$

What is missing?

1) spin-correlations
   $O(1)$ effect in EW splittings,
   in principle no different than colour-correlations in QCD PS
2) secondary splittings
   $W \to W\gamma$, $W \to WZ$, $W \to Wh$, $Z \to WW$, ...
3) simultaneous treatment of secondary scattering and decays
   $W \to q\bar{q}'$, $Z \to q\bar{q}$, $h \to 4f$, ...

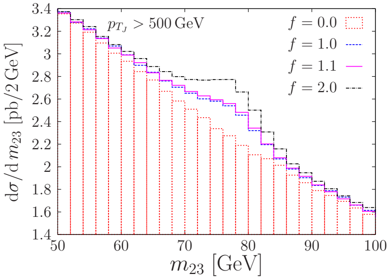
⇒ **though important, should be small effect in the following case study (after fixing s_{eff})**

Case study: Finding W bosons inside jets

Krauss, Petrov, MS, Spannowsky arXiv:1403.4788

Boosted analysis:

- high-$p_\perp$ fat jet, recluster into C/A microjets
- discard leading microjet as likely from leading quark
- use m_{23} as gluon em. tends to be softer then decay prod. of W em.
- accept candidate if $m_{23} \in [70, 86]$ GeV



$\Rightarrow$ large, but continuous QCD background, clear signal shape

$\Rightarrow$ more W emissions with high $p_\perp$, but peak shifts

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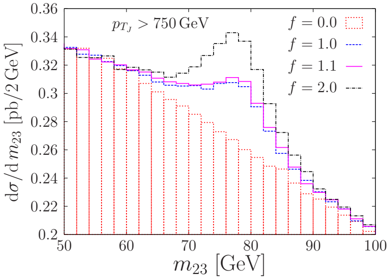

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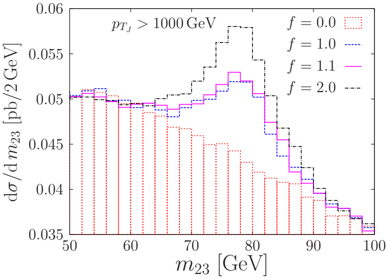

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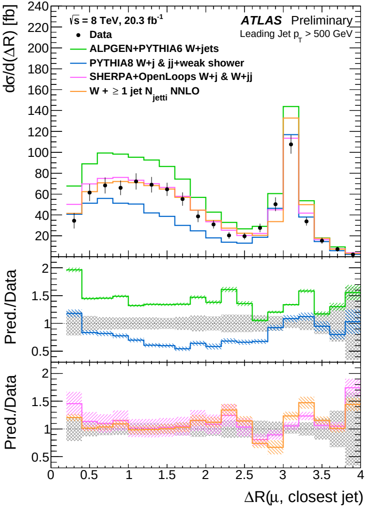
NLO EW predictions for $\Delta R(\mu, j_1)$



Measure coll. W em., simplified from Krauss et.al. arXiv:1403.4788

LHC@8TeV, central μ and jet, $p_\perp^{j_1} > 500\,\mathrm{GeV}$ ATLAS arXiv:1609.07045

- ALPGEN+PYTHIA
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  Mangano et.al. hep-ph/0206293
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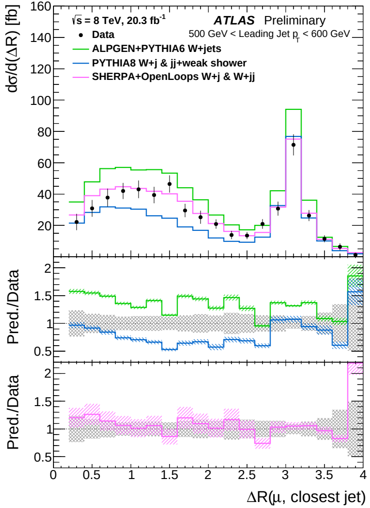

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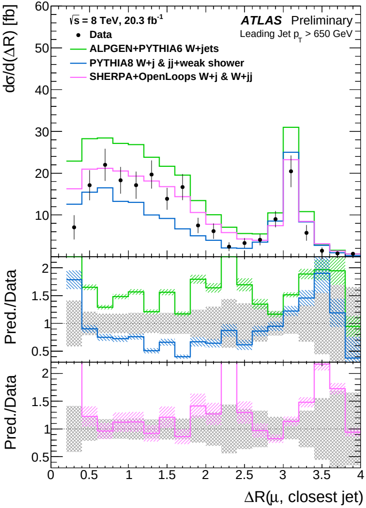

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Conclusions

- electroweak effects are important at LHC, HE–LHC, FCC, etc.
- become large whenever the scale is large compared the EW scale
- can be incorporated in multijet-merged particle-level calculations to improve description in those regions
  $\rightarrow$ currently tailored to TeV-scale physics and FSR dominated obs.
- NLO EW matched predictions available for few processes,
  though resonances rarely treated properly
- weak showers in their infancy,
  some very interesting developments in recent years

Thank you for your attention!

Backup