Higher-order EW and QED in SHERPA 3.x

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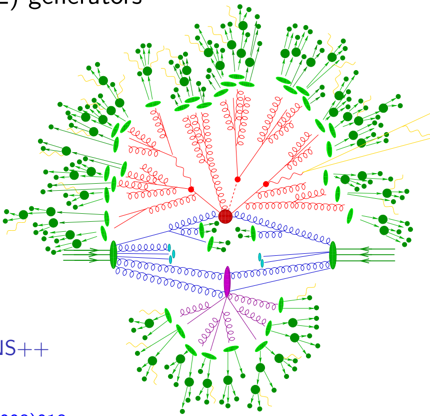
Contents

Overview

The SHERPA event generator framework

JHEP02(2009)007

- Two multi-purpose Matrix Element (ME) generators
  AMEGIC++ JHEP02(2002)044, EPJC53(2008)501
  COMIX JHEP12(2008)039, PRL109(2012)042001
- Two Parton Shower (PS) generators
  CSSHOWER JHEP03(2008)038
  DIRE EPJC75(2015)461
- A multiple interaction simulation
  à la PYTHIA AMISIC++ hep-ph/0601012
- A cluster fragmentation module
  AHADIC++ EPJC36(2004)381
- A hadron and τ decay package HADRONS++
- A higher order QED generator using
  YFS-resummation PHOTONS++ JHEP12(2008)018



Sherpa's traditional strength is the perturbative part of the event

LO, NLO, NNLO, LOPS, NLOPS, NNLOPS, MEPS, MENLOPS, MEPS@NLO

Acronyms and nomenclature

Fixed order calculations

- matrix elements only, implies fixed multiplicities
- no parton shower, no non-perturbative physics, no particle level

⇒ LO, NLO, NNLO

Parton shower matched calculations

- combination of fixed order calculation and parton shower for one multiplicity
- particle level predictions, no multijet observables

⇒ LoPs, NloPs, NnloPs

Multijet merged calculations

- combination of parton shower matched calculations for increasing final state multiplicities (mostly jets)
- particle level predictions, multijet observables

⇒ MePs(@LO), MePs@Nlo (special case MeNloPs)

SHERPA-3.0

Extensive rewrite and reorganisation (cf. SHERPA-1 → SHERPA-2)

New features:

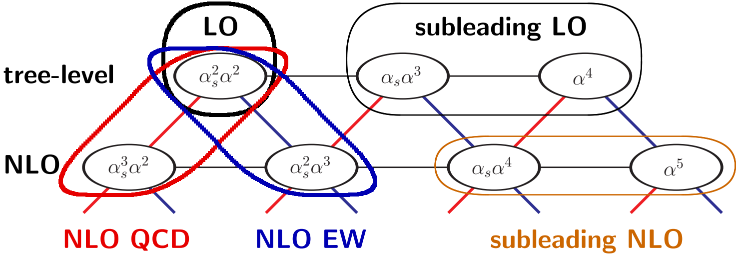
- NLO EW
- DIRE will become the default shower
- NLOPS for loop-induced processes
- **on-the-fly** variations of
  - ren. and fac. scale in ME and PS
  - PDFs
  - associated contributions (approx. EW and sub-LO)
  - merging scale Q_{cut}

  for
  - LO, NLO, NNLO
  - LOPS, NLOPS (S-MC@NLO), NNLOPS
  - MEPS, MENLOPS, MEPS@NLO
- default PDF: `NNPDF31_nnlo_as_0118_mc`
- QED corrections incl. NNLO QED and NLO EW for DY

Next-to-leading order electroweak corrections

Higher order corrections

Example: *Vjj* production



- strictly defined only through order counting
- in principle must differentiate between short-distance objects (partons) and long distance objects (observable objects):
  - well known in QCD (quarks, gluons ↔ jets)
  - introduce similar concepts in EW sector for photons and leptons

Definition of physical objects

What is a jet?

- photons and leptons must be part of a jet, but to what extent?
- **democratic:**
  - + straight forward, always well defined
  - − many contributions
  - → single photons constitute a jet
  - → single leptons constitute a jet
- **anti-tagging jets with certain flavour content:**
  - + fewer contributions
  - − needs a lot of care to be well-defined at all contributing orders
  - → anti-tag jets with too large photon content
  - → anti-tag jets with net lepton content
- which approach is closer to experiment depends on analysis, general anti-tagging must proceed through fragmentation functions

Definition of physical objects

What is a photon?

- differentiate: short-distance photon (photon as parton),
  long-distance photon (identified, measurable photon)

a) treat as identified particle, renormalise on-shell ($\alpha(0)$), no $\gamma \to ff$
$\to$ renormalisation contains IR poles
$\to$ problematic if both identified and unresolved photons in Born

b) treat democratically (just another parton), renormalise in short distance scheme (G_μ, $\alpha(m_Z)$, $\overline{\text{MS}}$, ...), include $\gamma \to ff$ splittings
$\to$ pure UV renormalisation
$\to$ identify photon through frag. function $D_\gamma^p(z,\mu)$

i.e. $D_\gamma^\gamma(z,\mu) = \dfrac{\alpha(0)}{\alpha_\text{sd}}\,\delta(1-z) + \mathcal{O}(\alpha^2)$

and $D_\gamma^q(z,\mu) = \mathcal{O}(\alpha)$, $D_\gamma^g(z,\mu) = \mathcal{O}(\alpha_s\alpha)$

- identical at NLO EW, if fragmentation D_γ^q on Born is negligible

Definition of physical objects

What is a lepton?

- in principle, again differentiate between short-distance parton and long-distance identified and measurable object
- simplified as leptons not gauge bosons, thus

  $D_\ell^\ell(z,\mu) = \delta(1-z)$+QED bremsstrahlung

  $D_\ell^\gamma(z,\mu) = \mathcal{O}(\alpha)$ problematic in processes with ℓ and unresolved photons in Born

  all other $D_\ell^q(z,\mu) = \mathcal{O}(\alpha^2)$, $D_\ell^g(z,\mu) = \mathcal{O}(\alpha_s\alpha^2)$
- dressed lepton: masseless leptons must be dressed for IR safety
- bare lepton: massive leptons may be measured bare
- Born lepton: not an infrared-safe concept

Automation

⇒ emergence of automated frameworks for NLO EW computations 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
- currently generally limited to fixed-order
- a number of dedicated calculations and private codes

NLO EW calculations with SHERPA

- SHERPA+OPENLOOPS:
  - $pp \to \gamma/\ell\ell/\ell\nu/\nu\nu + 0, 1, 2(, 3)$ jets — FCC report, EW report, LH'15; Kallweit, Lindert, Maierhöfer, Pozzorini, MS arXiv:1412.5157, arXiv:1511.08692; Lindert et.al arXiv:1705.04664
  - $pp \to Vh$ — FCC report arXiv:1607.01831
  - $pp \to 2\ell2\nu$ — Kallweit, Lindert, Pozzorini, MS arXiv:1705.00598
  - $pp \to t\bar{t}/t\bar{t}j$ — 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
- SHERPA+RECOLA
  - $pp \to V + 0, 1, 2j$, $pp \to 4\ell$, $pp \to t\bar{t}h$ — Biedermann et.al. arXiv:1704.05783
  - $pp \to 3\ell3\nu$ — MS arXiv:1806.00307
  - $pp \to jj/jjj$ — Reyer, MS, Schumann arXiv:1902.01763

Triboson production – $3\ell 3\nu$ – 0, 1, 2 SFOS

MS arXiv:1806.00307

- contribs from 0 SFOS ($e^-\mu^+\mu^+\bar{\nu}\nu\nu$), 1 SFOS ($e^-e^+\mu^+\bar{\nu}\nu\nu$) and 2 SFOS ($e^-e^+e^+\bar{\nu}\nu\nu$) processes, and $e \leftrightarrow \mu$

signature		on-shell channels		
0 SFOS	$e^-\mu^+\mu^+\bar{\nu}_e\nu_\mu\nu_\mu$	WWW	$WZ[\to 2\ell 2\nu]$	Wh
1 SFOS	$e^-e^+\mu^+\bar{\nu}_e\nu_e\nu_\mu$	$WWW + WZZ$	$WZ[\to 2\ell 2\nu]$	Wh
	$e^-e^+\mu^+\bar{\nu}_\mu\nu_\mu\nu_\mu$	WZZ	$WZ[\to 2\ell 2\nu]$	Wh
	$e^-e^+\mu^+\bar{\nu}_\tau\nu_\tau\nu_\mu$	WZZ	$WZ[\to 2\ell 2\nu]$	Wh
2 SFOS	$e^-e^+e^+\bar{\nu}_e\nu_e\nu_e$	$WWW + WZZ$	$WZ[\to 2\ell 2\nu]$	Wh
	$e^-e^+e^+\bar{\nu}_{\mu/\tau}\nu_{\mu/\tau}\nu_e$	WZZ	$WZ[\to 2\ell 2\nu]$	Wh

- standard lepton acceptance cuts, idealised from ATLAS arXiv:1610.05088

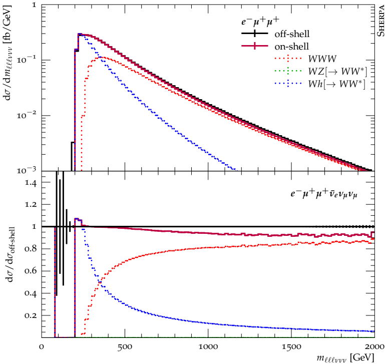
NLO EW corrections in off-shell trilepton production

MS arXiv:1806.00307

Selection	Cut	Value	
general	$p_{\mathrm{T}}(\ell)$	$[20\,\text{GeV},\infty)$	lepton acceptance
	$y(\ell)$	$[-2.5,2.5]$	
	$\Delta R(\ell,\ell)$	$[0.2,\infty)$	
$\not{p}_{\mathrm{T}} > 20\,\text{GeV}$	$\Delta\phi(\not{p}_{\mathrm{T}},\ell\ell\ell)$	$[\frac{5}{6}\pi,\pi]$	jet veto
1, 2 SFOS	$\not{p}_{\mathrm{T}}$	$[50\,\text{GeV},\infty)$	WZ veto
	$m_{\ell\ell}^{\text{SFOS}}$	$[0,70\,\text{GeV}]\wedge[100\,\text{GeV},\infty)$	

- minimise $t\bar{t}W$, tWW, WZ backgrounds
- scale choice: $\mu=\sum m_{\mathrm{T},i}^{W}$ ambiguous in all channels, EW corrections largely scale independent: choose $\mu_R=\mu_F=3\,m_W$
- use `NNPDF31_nlo_as_0118_luxqed` for reliable γPDF

On-shell vs. off-shell triboson production

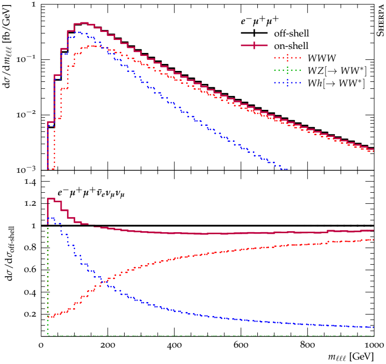


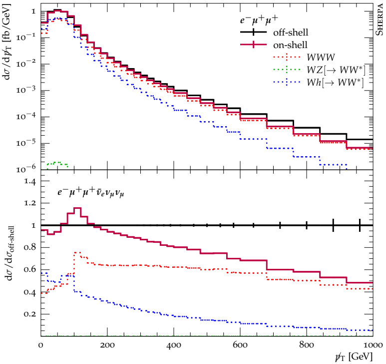
$$m_{\ell\ell\ell\nu\nu\nu} = m_{WWW}$$

- no unique W identifaction possible in off-shell calculation, even in MC truth, due to occurrence of SF pairs
- on-shell WWW not dominating for incl. xsec
- large cross section from Wh, WZ negligible
- at larger m_{WWW} contribs from double (single) resonant

→ cross checked with off-shell calculation projected on triple W resonant subset of diagrams

On-shell vs. off-shell triboson production



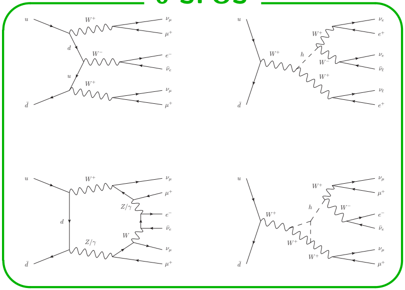


- on-shell approximation reasonable for $m_{\ell\ell\ell}$
- large single and double resonant contribs for MET

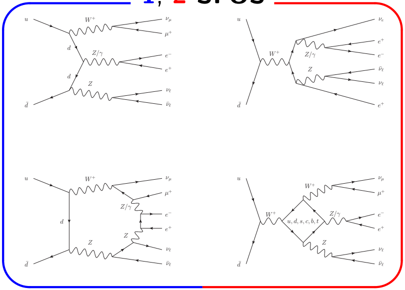
NLO EW corrections in off-shell trilepton production

MS arXiv:1806.00307

0 SFOS



1, 2 SFOS



- at LO: triple and quartic gauge boson self-interactions
- at NLO EW: appearance of octagons, closed fermion loops, Higgs self-interactions, Yukawa couplings, etc
- genuine NLO EW $2 \to 6$ calculation with 3 resonances

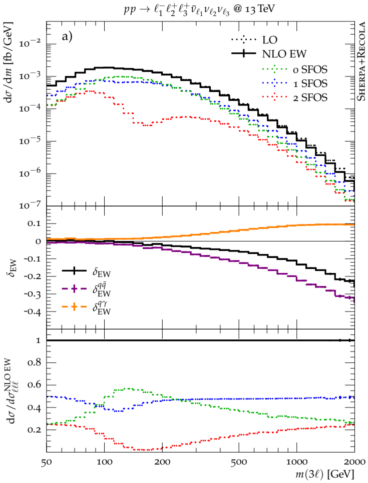
Triboson production

MS arXiv:1806.00307

- off-shell $W^+W^+W^-$ production
- includes 0, 1, 2 SFOS processes (WWW and WZZ structures)
- EW correction (incl. γ-induced) important
- accidental cancellations of EW corr. in $q\bar{q}$ and $q\gamma/\bar{q}\gamma$ channels

  Dittmaier, Huss, Knippen arXiv:1705.03722

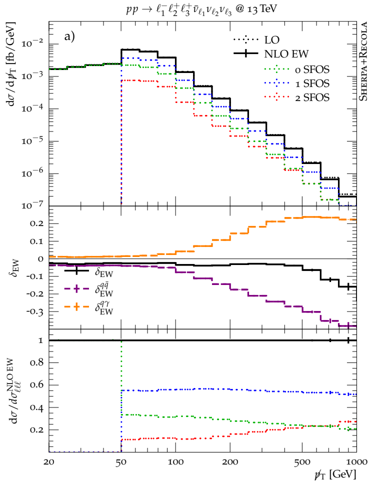
  but highly obs. dependent



Triboson production

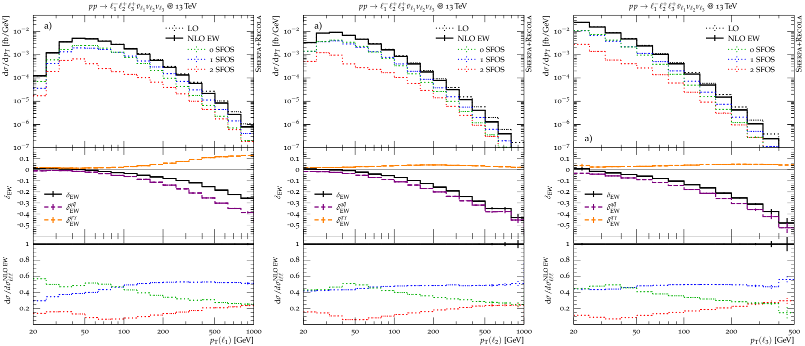
MS arXiv:1806.00307

- 1, 2 SFOS: req. $\not{p}_T > 50\,\text{GeV}$ to suppress WZ background
- substantial γ-induced contributions
- accidental cancellations



Triboson production

MS arXiv:1806.00307



1st lepton | 2nd lepton | 3rd lepton

Three-jet production

Dijet production

- NLO QCD — Ellis, Kunszt, Soper PRL 69 (1992) 1496-1499; Giele, Glover, Kosower hep-ph/9302225
- NLO EW and all subl. corrections — Moretti, Nolten, Ross hep-ph/0606201; Dittmaier, Huss, Speckner arXiv:1210.0438; Frederix et.al. arXiv:1612.06548

Three-jet production

- NLO QCD — Nagy hep-ph/0110315
- NLO EW and all subl. corrections — Reyer, MS, Schumann arXiv:1902.01763

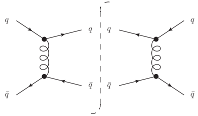
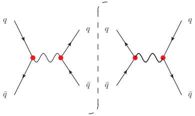
N-jet production

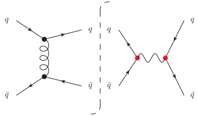
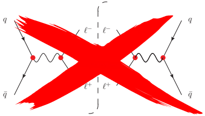
- NLO QCD known for 4- and 5-jet production

Bern et.al. arXiv:1112.3940
Badger et.al. arXiv:1309.6585

Contributions

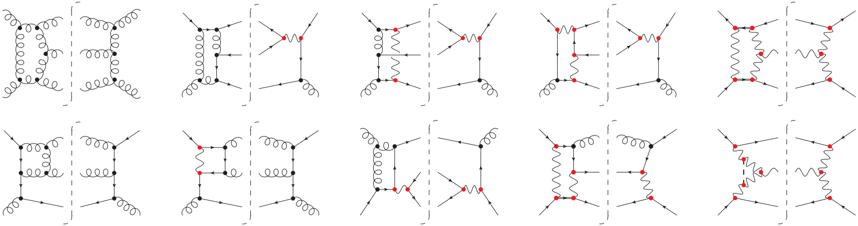
- **define jets completely democratically**,
  incl. all massless visible particles of the SM (q, g, γ, ℓ)
  $p_\mathrm{T}(j_1) > 80\,\mathrm{GeV}$, $p_\mathrm{T}(j_i) > 60\,\mathrm{GeV}$ ($i > 1$)

$\mathcal{O}(\alpha_s^2)$  $\mathcal{O}(\alpha^2)$  hadronic DY

$\mathcal{O}(\alpha_s\alpha)$  $\mathcal{O}(\alpha^2)$  leptonic DY

- **anti-tag jets against leptons**
  exclude jets with net lepton number within lepton acceptance
  care: jet acceptance and lepton acceptance may differ
  here: $|\eta(j)| < 2.8$, $|\eta(\ell)| < 2.5$

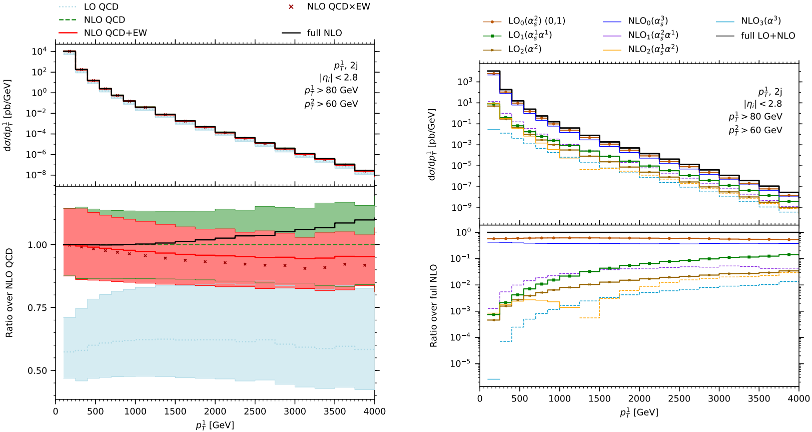
Contributions at NLO



$\mathcal{O}(\alpha_s^4)$ $\mathcal{O}(\alpha_s^3\alpha)$ $\mathcal{O}(\alpha_s^2\alpha^2)$ $\mathcal{O}(\alpha_s\alpha^3)$ $\mathcal{O}(\alpha^4)$

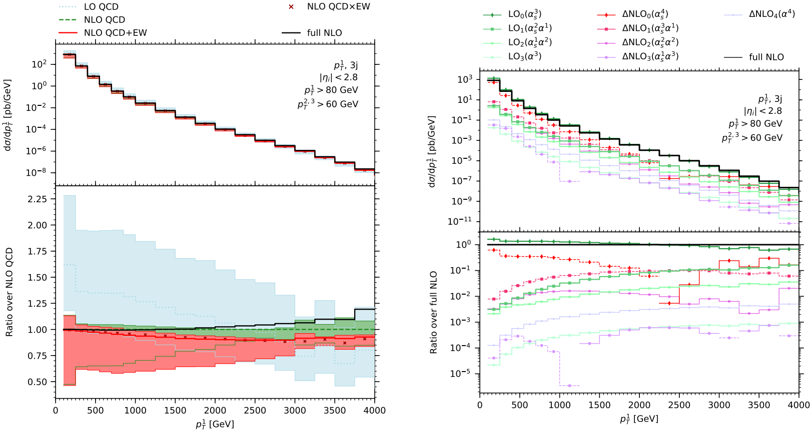
- sensitive to the full SM spectrum, incl. top quark, Higgs boson, all lepton and neutrino flavours
- real emission corrections include: $\ell\nu qg$, $\ell\ell qg$, $\ell\ell\ell\ell$, $\ell\ell\ell\nu$ final states

Leading jet transverse momenta in dijet production



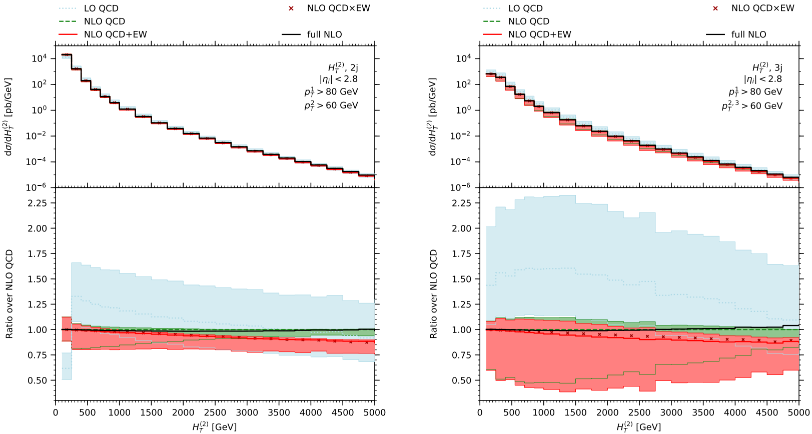
- moderate EW corrections
- overcompensated by subleading orders

Leading jet transverse momenta in 3-jet production



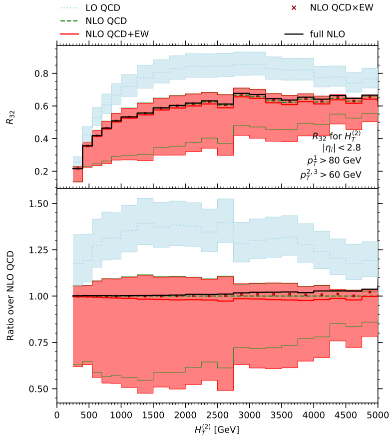
- moderate EW corrections
- overcompensated by subleading orders, can be as large as QCD corr.

$H_{\mathrm{T}}^{(2)}$



- NLO EW reduces x-sec. by ≈ 15% at $H_{\mathrm{T}}^{(2)} = 2\,\mathrm{TeV}$
- again, large accidental compensations between NLO EW and subleading orders

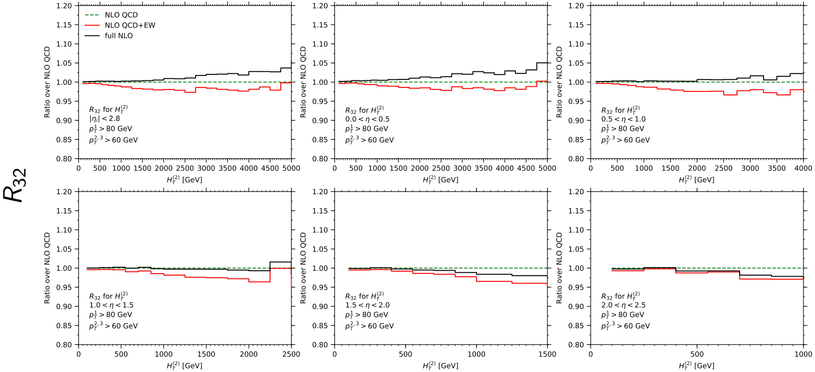
R_{32}



- NLO EW and subleading order contribs very similar between $2j$ and $3j$
  $\Rightarrow$ R_{32} largely uneffected
- supports factorisation of NLO QCD and NLO EW correction at large $H_{\mathrm{T}}^{(2)}$
- scale uncertainty by synchronous scale variation

$\Rightarrow$ safe to use R_{32} with NLO QCD MCs for α_s extraction

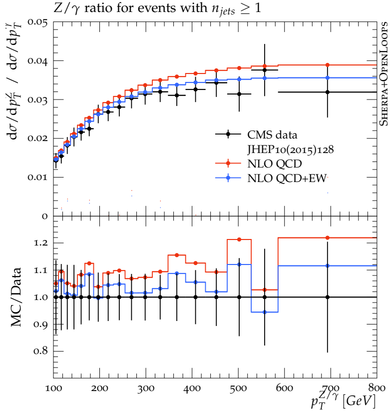
R_{32} in different Δy-slices



- different net effects in different rapidity slices

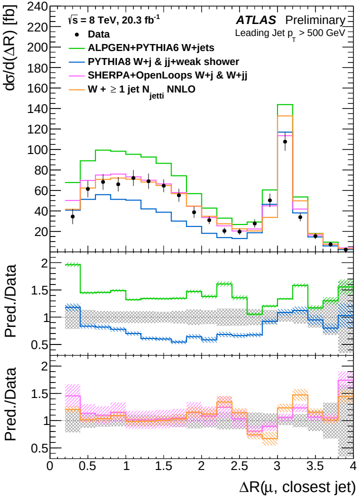
NLO EW corrections

LH'15 arXiv:1605.04692



important to describt Z/γ ratio

ATLAS arXiv:1609.0745



Approximate electroweak corrections for high p_T physics

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

optionally include subleading Born

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

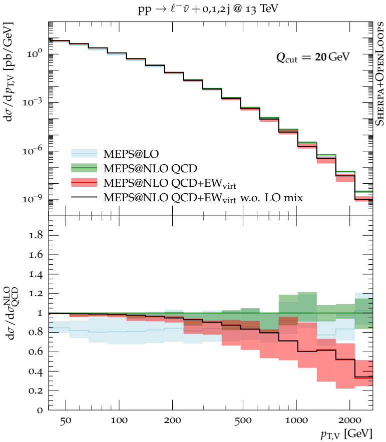
exact virtual contribution

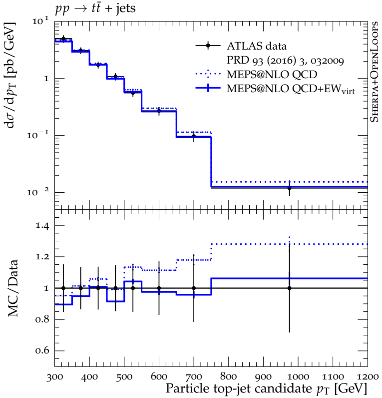
approximate integrated real contribution

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

Approximate electroweak corrections for high p_T physics

Lindert, Kallweit, Maierhöfer, Pozzorini, MS arXiv:1511.08692
Gütschow, Lindert, MS arXiv:1803.00950





NNLO QED + NLO EW + YFS

Soft-photon resummation

- SHERPA uses the Yennie-Frautschi-Suura soft-photon resummation to account for higher-order QED effets
  $\rightarrow$ correctly describes coherence effects and wide-angle emissions
  $\rightarrow$ energy loss dominated by wide-angle emissions (not recombined)

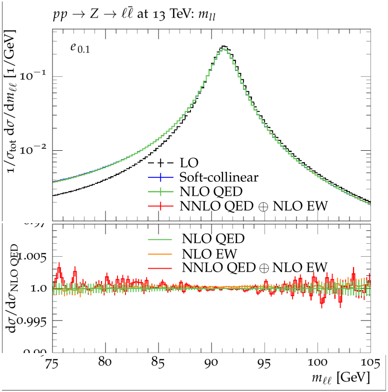
  Yennie, Frautschi, Suura Ann. Phys. 13 (1961) 379452
  MS, Krauss arXiv:0810.5071

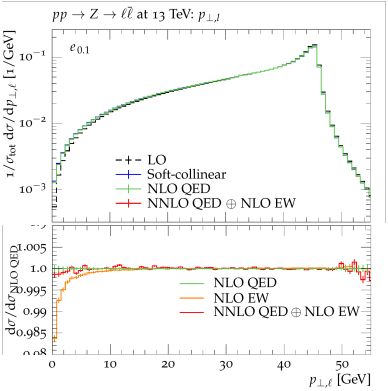
- YFS resummation systematically corrected by exact higher-order MEs to correctly describe hard photon emission
  - SHERPA-1.0–2.2: use NLO QED for W and Z decays,
    coll. approx. otherwise
  - SHERPA-3: NNLO QED + NLO EW for Z, NLO EW for W decays

    Krauss, Lindert, Linten, MS arXiv:1809.10650
  - **every** emission is corrected, not only hardest one
    (matching works differently, not POWHEG/MC@NLO-style)
    $\rightarrow$ subleading photons never pure resummation
    $\rightarrow$ new at NNLO: hard $\ell \rightarrow \ell\gamma\gamma$ splitting corrections etc.
- FSR only, no ISR, no initial-final-interference

Z decays

Krauss, Lindert, Linten, MS arXiv:1809.10650

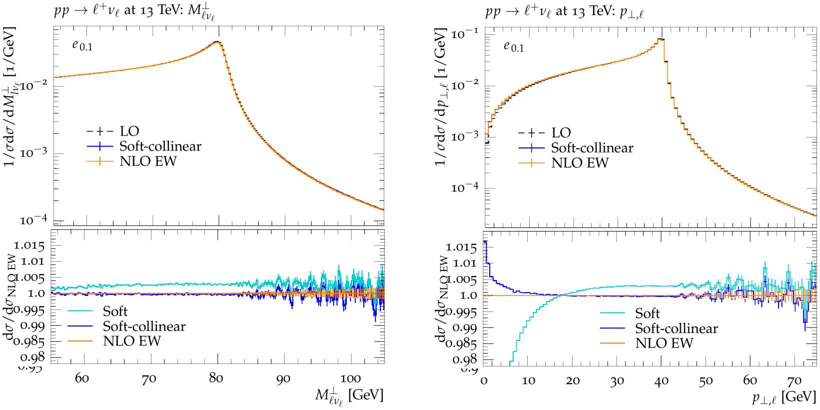




- **2.2:** NLO QED, **3.0:** NNLO QED + NLO EW
- larger effect only in corners of phase space

W decays

Krauss, Lindert, Linten, MS arXiv:1809.10650



- **2.2:** NLO QED, **3.0:** NLO EW
- larger effect only in corners of phase space

SHERPA-3.x

- automated NLO electroweak calculations
- new default shower: DIRE
- NLOPS for loop-induced processes
- on-the-fly variations of
  - ren. and fac. scale in ME and PS
  - PDFs
  - associated contributions (approx. EW and sub-LO)
  - merging scale Q_{cut}

  for
  - LO, NLO, NNLO
  - LOPS, NLOPS (S-MC@NLO), NNLOPS
  - MEPS, MENLOPS, MEPS@NLO
- default PDF: `NNPDF31_nnlo_as_0118_mc`
- QED corrections incl. NNLO QED and NLO EW for DY
- DIRE@NLO, ...

http://sherpa.hepforge.org

Thank you!

Backup