

SHERPA: overview and recent developments

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QCD@LHC 23 Aug 2016



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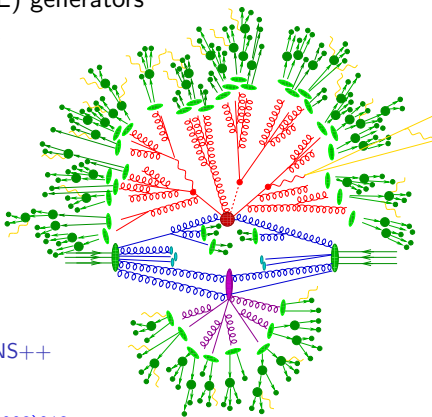


FONDS NATIONAL SUISSE
SCHWEIZERISCHER NATIONALFONDS
FONDO NAZIONALE SVIZZERO
SWISS NATIONAL SCIENCE FOUNDATION

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, MEs, MENLOs, MEs@NLO

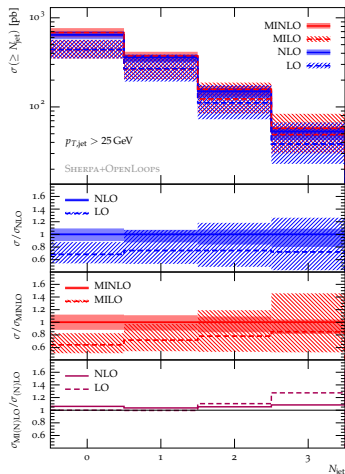
SHERPA-2.2.1

- SHERPA-2.2.1 released Jul '16
- contains bugfixes for all known bugs of SHERPA-2.2.0
- UFO support for BSM physics
- new parton shower DIRE in addition to CSSHOWER
- on-the-fly scale and PDF variations for ME part in
 - LO, NLO
 - LOPs, NLOPs (S-MC@NLO)
 - MEPS, MENLOPs, MEPS@NLO
- use named weights in HEPMC (av. since HEPMC-2.06)
- full scale & PDF variations including parton shower and for NNLO/NNLOPs in SHERPA-2.3.0
- allow to force HEPMC event record into pure tree structure, lost information available through disconnected vertices
- new default PDF: NNPDF30_nnlo_as_0118 → new tune

NLO QCD calculations – $pp \rightarrow t\bar{t} + 3\text{jets}$

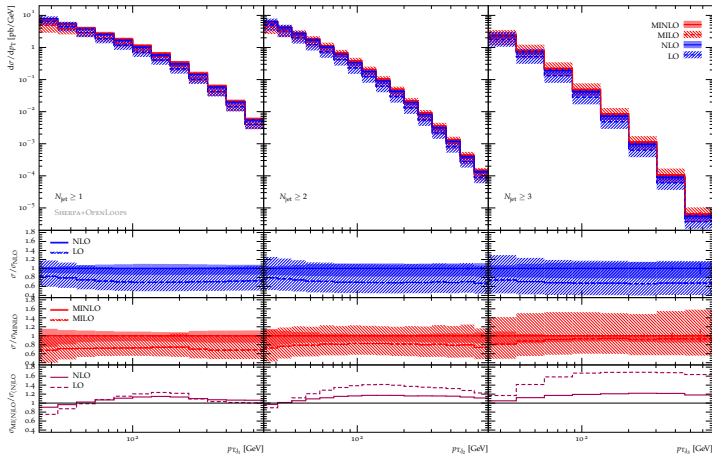
Höche, Maierhöfer, Moretti, Pozzorini, Siebert arXiv:1607.06934

- First computation of $t\bar{t} + 3$ jets at NLO / MiNLO accuracy
- Sherpa NLO MC framework using Comix [Gleisberg, Höche arXiv:0808.3674](#) combined with OpenLoops [Casoli, Maierhöfer, Pozzorini arXiv:1111.5206](#)
- Public results in NTuple format à la [BlackHat collaboration arXiv:1310.7439](#) for easy analysis & recycling available at NERSC (login req'd)
- Scale dependence studied using $H_{T,m} = \sum m_{\perp}$ and MiNLO [Hamilton, Nason, Zanderighi arXiv:1206.3572](#) extended to massive partons



NLO QCD calculations – $pp \rightarrow t\bar{t} + 3\text{jets}$

Höche, Maierhöfer, Moretti, Pozzorini, Siebert arXiv:1607.06934



- Inclusive jet- p_T spectra

Parton showers – DIRE

Höche, Prestel EPJC75(2015)461

- combination of parton and dipole shower picture
 → partial fractioning soft eikonal [Catani, Seymour Nucl.Phys.B485\(1997\)291](#)

$$\frac{p_i p_k}{(p_i p_j)(p_j p_k)} \rightarrow \frac{1}{p_i p_j} \frac{p_i p_k}{(p_i + p_k) p_j} + \frac{1}{p_k p_j} \frac{p_i p_k}{(p_i + p_k) p_j}$$

- capture dominant coherence effects (3-parton correlations)

$$\frac{1}{1-z} \rightarrow \frac{1-z}{(1-z)^2 + \kappa^2} \quad \kappa^2 = \frac{k_{\perp}^2}{Q^2}$$

- preserve collinear anomalous dimensions & sum rules
 → splitting functions fixed

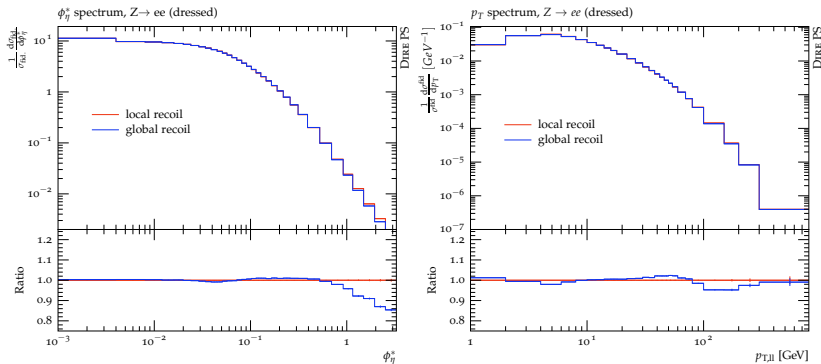
$$P_{qq}(z, \kappa^2) = 2 C_F \left[\left(\frac{1-z}{(1-z)^2 + \kappa^2} \right)_+ - \frac{1+z}{2} \right] + \gamma_q \delta(1-z)$$

$$P_{gg}(z, \kappa^2) = 2 C_A \left[\left(\frac{1-z}{(1-z)^2 + \kappa^2} \right)_+ + \frac{z}{z^2 + \kappa^2} - 2 + z(1-z) \right] + \gamma_g \delta(1-z)$$

$$P_{qg}(z, \kappa^2) = 2 C_F \left[\frac{z}{z^2 + \kappa^2} - \frac{2-z}{2} \right] \quad P_{gq}(z, \kappa^2) = T_R \left[z^2 + (1-z)^2 \right]$$

Parton showers – DIRE

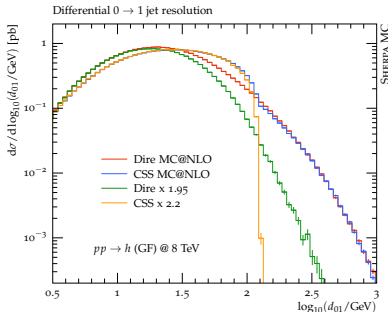
Höche, Prestel EPJC75(2015)461



- Two mapping schemes for IF dipoles
 - local [Catani, Seymour Nucl.Phys.B485\(1997\)291](#)
 - global [Plätzer, Gieseke JHEP01\(2011\)024](#), [Höche, Schumann, Siebert PRD81\(2010\)034026](#)
- Negligible impact on q_T -spectrum in low- q_T range (spectrum dominated by singlet evolution at LHC energies)

Parton showers – DIRE

- New shower kernels can be used as modified CS subtraction
- Sherpa S-MC@NLO based on exponentiation of CS dipole subtraction terms
 Höche, Krauss, Siebert, MS
 JHEP09(2012)049, PRD86(2012)094042
- Dire modified CS subtraction automatically available for S-MC@NLO matching
- Interesting differences due to evolution variables and kernels



Higgs physics I

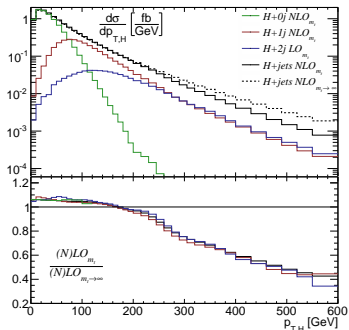
Buschmann, Goncalves, Kuttimalai, MS, Krauss, Plehn JHEP02(2015)038

$pp \rightarrow H + \text{jets}$ production (ggF)

- correction factor/weight

$$r_t^{(n)} = \frac{|\mathcal{M}^{(n)}(m_t)|^2}{|\mathcal{M}^{(n)}(m_t \rightarrow \infty)|^2}$$

- loops from OPENLOOPS
- construct MEPS@NLO from reweighted S-MC@NLO
- factorised approach for unknown top mass dependence in V_n , otherwise exact NLO mass dependence



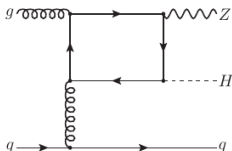
$$d\sigma_n = d\Phi_n r_t^{(n)} \left[B_n + V_n + \int d\Phi_1 D_n \right] \widetilde{\text{PS}}_n + d\Phi_{n+1} \left[r_t^{(n+1)} R_n - r_t^{(n)} D_n \right]$$

Higgs physics II

Goncalves, Krauss, Kuttimalai, Maierhöfer PRD92(2015)7,073006

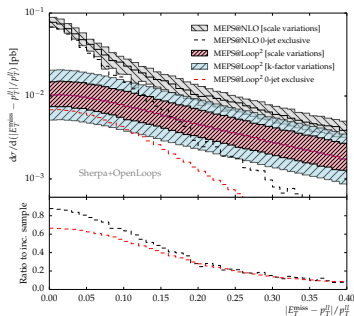
$pp \rightarrow ZH + \text{jets production}$

- MEPS@NLO for $q\bar{q}$
MEPS@LOOP² for gg
- care for $qg \rightarrow ZHq$:



→ part of NLO ZHj
→ in loop-induced as gauge
inv. subset of NNLO ZHj

- loops from OPENLOOPS



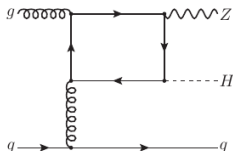
$pp \rightarrow Z[\rightarrow \ell\ell]H[\rightarrow \text{inv}] + \text{jets}$

Higgs physics II

Goncalves, Krauss, Kuttimalai, Maierhöfer PRD92(2015)7,073006

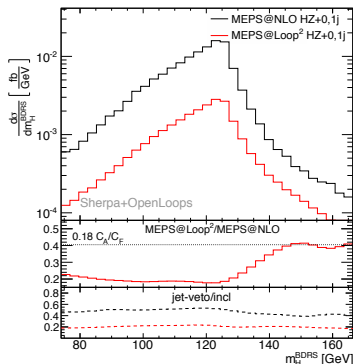
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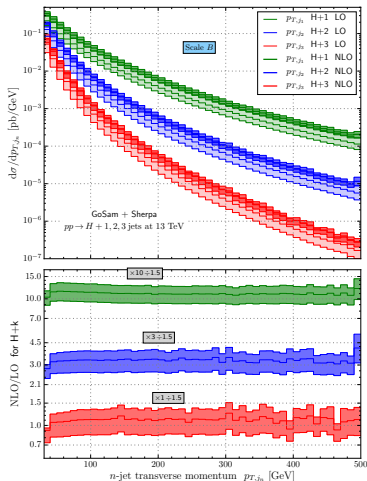
$pp \rightarrow Z[\rightarrow \ell\ell] H[\rightarrow b\bar{b}] + \text{jets}$

Higgs physics III

Greiner, Höche,

$pp \rightarrow H + \text{jets}$ in ggF (HEFT)

- public NTuples for $h1j, h2j, h3j$ @ NLO
→ fixed-order analysis
GoSAM interfaced for virtuals
- MEPs@NLO preliminary
 $pp \rightarrow h + 0, 1, 2, 3j$ @ NLO,
4, 5j @ LO
produced for Les Houches '15
detailed comparison

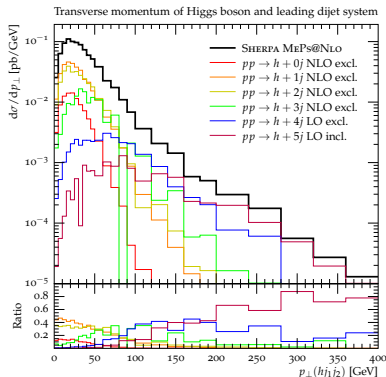


Higgs physics III

Greiner,Höche,Luisoni,MS,Winter,Yundin JHEP01(2016)169

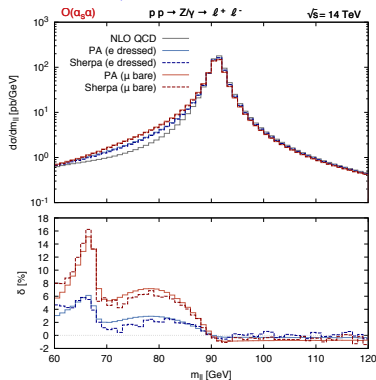
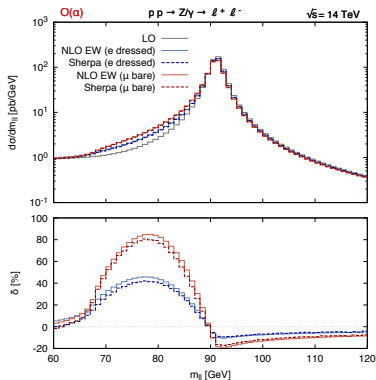
$pp \rightarrow H + \text{jets}$ in ggF (HEFT)

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detailed comparison



YFS – comparison against dedicated calculations

Huss,MS for LH'15 arXiv:1605.04692



- compare against pole approximation NNLO $O(\alpha_s\alpha)$
Dittmaier,Huss,Schwinn Nucl.Phys.B904(2016)216
- very good reproduction of $O(\alpha)$ and $O(\alpha_s\alpha)$
- major differences traced to multi-photon emissions in YFS

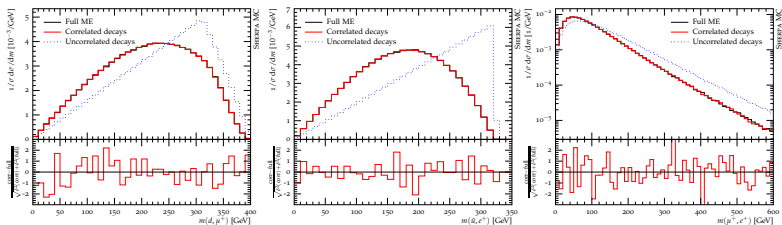
BSM physics

[Höche, Kuttimalai, Schumann, Siebert EPJC75\(2015\)3,135](#)

- full support for UFO model [Degrande et.al. CPC183\(2012\)1201](#)
- Lorentz structures automatically built, colour structures mapped on SM/MSSM-like
- automatic identification of all $1 \rightarrow 2$ and $1 \rightarrow 3$ decay channels of every unstable particle in the model
→ calculation of all decay widths (LO)
- per default all decay channel used
→ inclusive production
→ mechanism to select individual channels, cross section optionally adjusted accordingly
- spin-correlated decay chains of arbitrary length using spin density matrices [Richardson JHEP11\(2001\)029](#),
[Knowles CPC58\(1990\)271](#)

BSM physics

Höche, Kuttimalai, Schumann, Siebert EPJC75(2015)3,135



- simple three-step example:

$$pp \rightarrow \tilde{u}[\rightarrow d\chi_1^+[\rightarrow \chi_1^0 W^+[\rightarrow \mu^+ \nu_\mu]]] \tilde{u}^*[\rightarrow \bar{u}\chi_2^0[\rightarrow e^+ \tilde{e}^-[\rightarrow e^- \chi_1^0]]]$$

- use truncated showers for QCD radiation off intermediate particles
- QED correction for each decay in YFS soft-photon resummation

Reweighting

Parameters

parametric e.g. $\alpha_s(m_Z)$, m_t , PDF

perturbative e.g. NLO, NLL, leading- $N_c \rightarrow \mu_R, \mu_F$

algorithmic e.g. evolution variable, recoil schemes, matching scheme

Explicit variations

- can be done for any scale or PDF dependence
- functional form can be changed
- separate run (independent calculation) for every variation

On-the-fly variations

[Bothmann,MS,Schumann arXiv:1606.08753](#)

- can be done for μ_R, μ_F, α_s & PDF dependence of ME & PS
- functional form can currently not be changed
- full syntax, cf. Manual

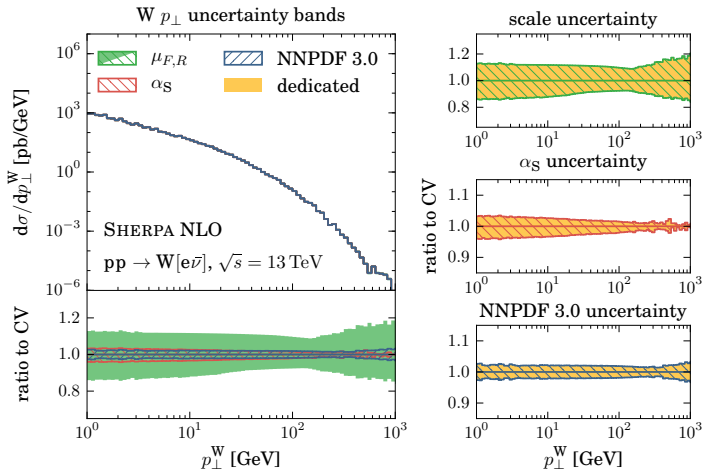
VARIATIONS 0.25,0.25 4.,4.

VARIATIONS NNPFD30_nnlo_as_0118[all]

- store in HEPMC weight container using LH'13 naming convention

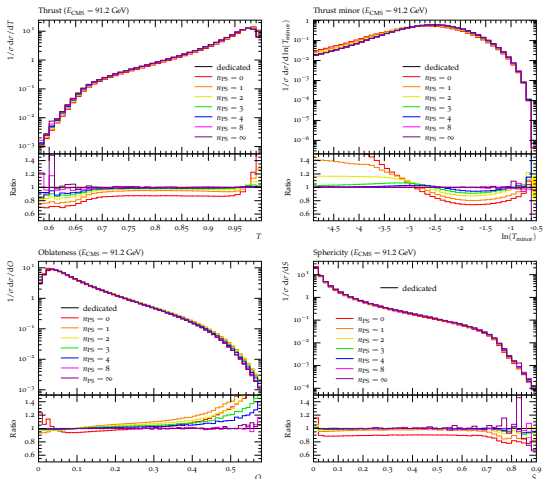
Reweighting – closure test – NLO

Bothmann,MS,Schumann arXiv:1606.08753



Reweighting – closure test – LOPs

Bothmann,MS,Schumann arXiv:1606.08753



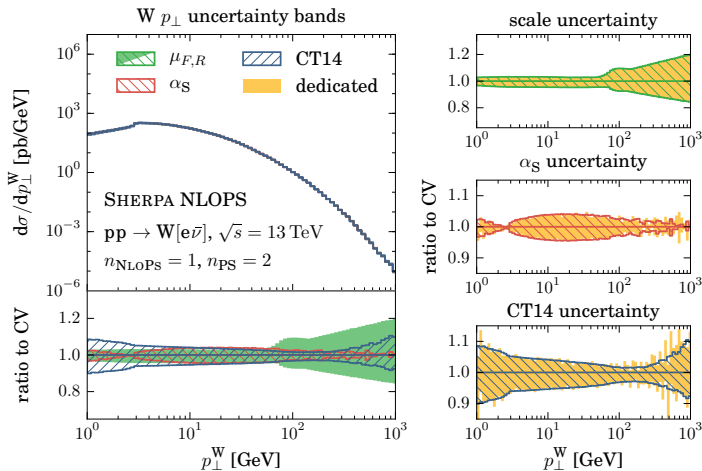
$e^+e^- \rightarrow \text{hadrons}$

closure test with
 $n_{\text{PS}} = 0, 1, 2, 3, 4, 8, \infty$

- $\alpha_s(m_Z) = 0.120$
↓
 $\tilde{\alpha}_s(m_Z) = 0.128$
- n_{PS} needed obs. dependent

Reweighting – closure test – NLOs

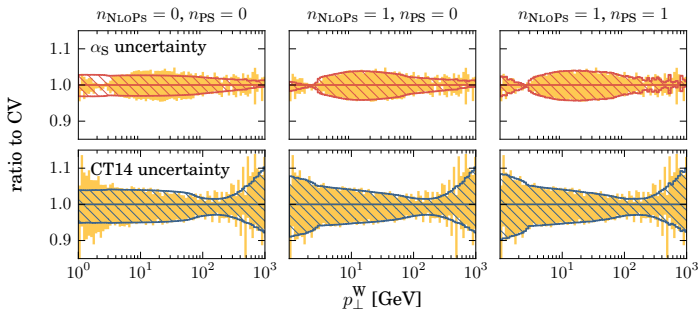
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Reweighting – closure test – NLOs

Bothmann,MS,Schumann arXiv:1606.08753

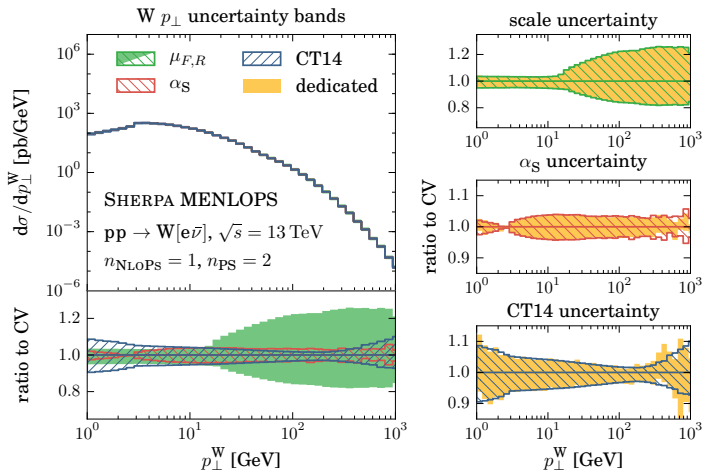
other maximum numbers of reweighted emissions $n_{\text{NLOs}}, n_{\text{PS}}$



→ reweighting two emission sufficient for this observable

Reweighting – closure test – MEPS@NLO

Bothmann,MS,Schumann arXiv:1606.08753



NLO EW corrections

[Kallweit,Lindert,Maierhöfer,Pozzorini, MS JHEP04\(2015\)012, JHEP04\(2016\)021](#)

- fixed-order next-to-leading order electroweak corrections
- use one-loop matrix element from OPENLOOPS
- already studied a range of processes:
 - $pp \rightarrow V + 0, 1, 2(, 3)$ jets

[Kallweit,Lindert,Maierhöfer,Pozzorini,MS JHEP04\(2015\)012, JHEP04\(2016\)021](#)

[EW report arXiv:1606.02330](#)

- $pp \rightarrow t\bar{t}h$

[LH'15 arXiv:1605.04692](#)

- $pp \rightarrow Zj/pp \rightarrow \gamma j$ ratio

[Kallweit,Lindert,Maierhöfer,Pozzorini,MS arXiv:1505.05704](#)

[LH'15 arXiv:1605.04692](#)

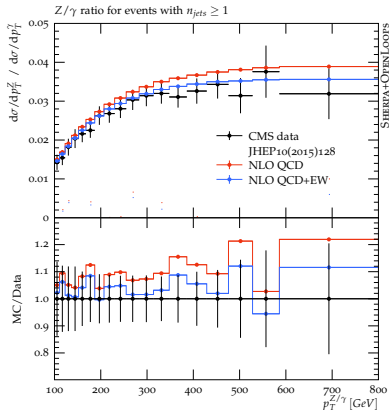
- $pp \rightarrow Vh$

[FCC report, arXiv:1607.01831](#)

- dedicated comparisons in LH'15 against RECOLA ($Z + 2j$) and MADGRAPH (tth) showed agreement

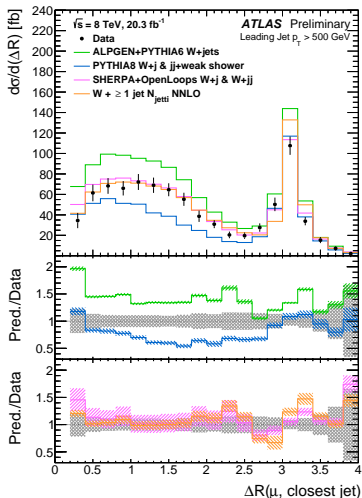
NLO EW corrections

LH'15 arXiv:1605.04692



important to describe Z/γ ratio

Wu ICHEP'16



Electroweak corrections in particle-level event generation

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

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

- 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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optionally include subleading Born

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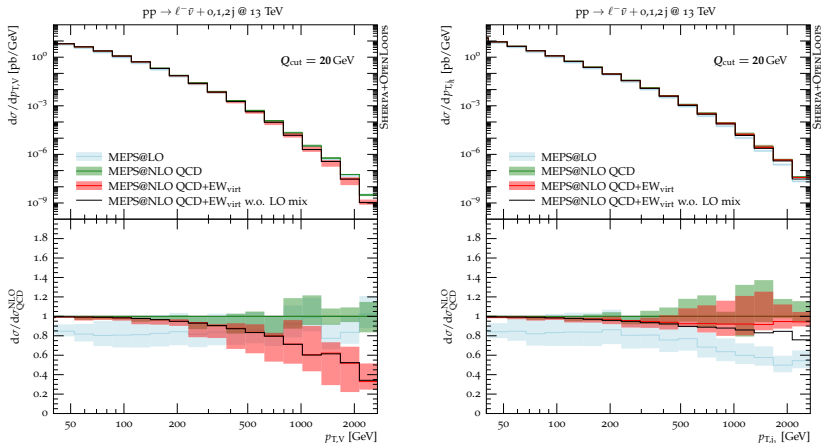
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Results: $pp \rightarrow \ell^- \bar{\nu} + \text{jets}$

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



⇒ particle level events including dominant EW corrections

SHERPA-2.2.1

- a new parton shower DIRE
- vastly extended support for UFO BSM format
- multijet merging for loop induced processes further tested, use as:
 - MEPS@LOOP²
 - reweight MEPS@NLO Higgs production in HEFT with top mass dependence (approximate in virtual corrections only)
- on-the-fly variations of μ_R , μ_F , α_s and PDF for
 - LO, NLO
 - LOPs, NLOPs (S-MC@NLO)
 - MEPS, MENLOPs, MEPS@NLO
- incorporation of approx. NLO EW corrs in existing NLO QCD MEPS@NLO
- default PDF: NNPDF30_nnlo_as_0118 including tune of non-perturbative parameters
- **coming in SHERPA-2.3.0:** PS reweighting, full NLO EW

<http://sherpa.hepforge.org>

Thank you for your attention!