The Sherpa Monte Carlo

– automating the evaluation of QCD & EW corrections –

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Motivation & Outline

Precision phenomenology for the LHC

- accurate predictions for wide range of processes & selections
  - $\rightsquigarrow$ fully differential in event kinematics
  - $\rightsquigarrow$ multi-particle/jet final states, QCD multi-scale problems

MC generator development paradigm: automation

- propagate perturbative accuracy to particle level events
  - $\rightsquigarrow$ hard matrix elements @ QCD (N)NLO, EW NLO
  - $\rightsquigarrow$ parton shower for numerical resummation @ LL, NLL
  - $\rightsquigarrow$ sophisticated matching & merging techniques

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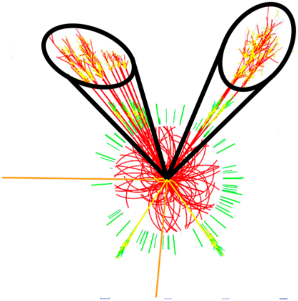
The Sherpa framework: features & news

- matrix elements for (B)SM processes
    - higher-order QCD/EW corrections
- QCD parton showers & matrix elements
    - NLO QCD parton shower
    - including EW corrections
    - fast uncertainty estimates



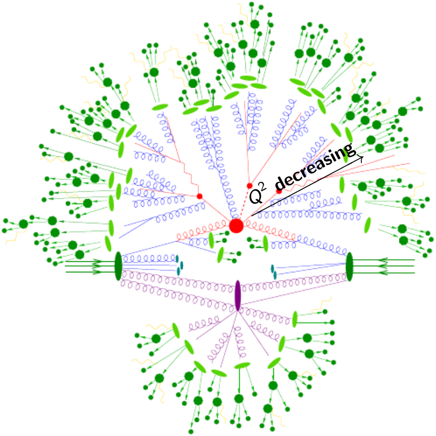
The Sherpa framework

Full simulation of collision events

[Gleisberg *et al.* JHEP **0902** (2009) 007]

↪ factorize short- & long range physics

- perturbative phases
  - **Hard interaction**
    LO,NLO,NNLO – QCD, NLO – EW, BSM
    ME generators Amegic, Comix, interfaces for HO
  - **Radiative corrections**
    resummation of soft-collinear logs: LL, NLL
    Catani–Seymour dipole shower (QCD+QED), DIRE (QCD)
- non-perturbative phases
  - **Hadronization**
    parton–hadron transition
    cluster hadronization model
  - **Hadron Decays**
    phase space or effective theories
    dedicated decay module, YFS QED corrections
  - **Underlying Event**
    beyond factorization: modelling
    multiple parton interactions model

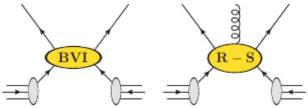


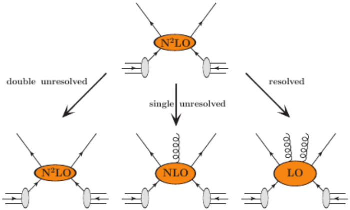
SHERPA's main focus on perturbative aspects: higher-order corrections, matching and merging with parton showers

Matrix Elements for SM processes

automating higher-order corrections

- efficient tree-level generator for Born and real-emission corrections
  AMEGIC [JHEP **0202** (2002) 044], COMIX [Gleisberg, Höche JHEP **0812** (2008) 039]
- interfaces to variety of loop-amplitude codes
- multi-channel phase space integrator
- Catani–Seymour dipole subtraction for NLO QCD & QED
  [Gleisberg, Krauss Eur. Phys. J. C **53** (2008) 501] [Schönherr to appear]
- q_T subtraction for NNLO QCD singlet production, i.e. $pp \to W/Z/H$





NLO QCD accuracy

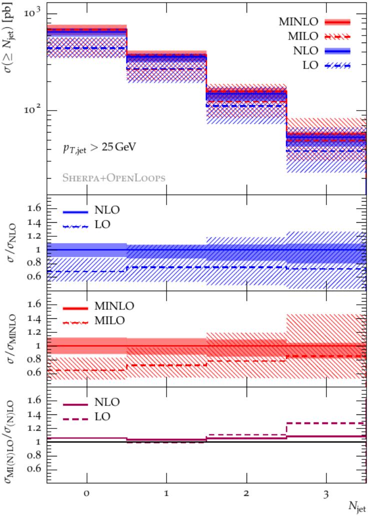
$t\bar{t}$ + 3jets at NLO QCD SHERPA +OPENLOOPS [Höche et al. Eur. Phys. J. C **77** (2017) no.3, 145]

- QCD corrections to $t\bar{t} + 0, 1, 2, 3j$ NLO/MINLO accuracy
- NLO scale choice $\mu_{R/F} = H_T/2$
- MINLO feat. nodal scale setting prescription & Sudakov weights
- 7-point scale variations
- public NTuple files

  [Bern et al. Comput. Phys. Commun. **185** (2014) 1443]

# of one-loop diagrams

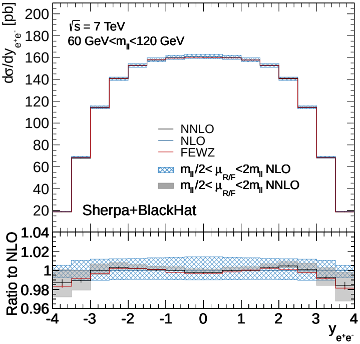
partonic channel \ N	0	1	2	3
$gg \to t\bar{t} + N\,g$	47	630	9'438	152'070
$u\bar{u} \to t\bar{t} + N\,g$	12	122	1'608	23'835
$u\bar{u} \to t\bar{t}u\bar{u} + (N-2)\,g$	–	–	506	6'642
$u\bar{u} \to t\bar{t}d\bar{d} + (N-2)\,g$	–	–	252	3'321

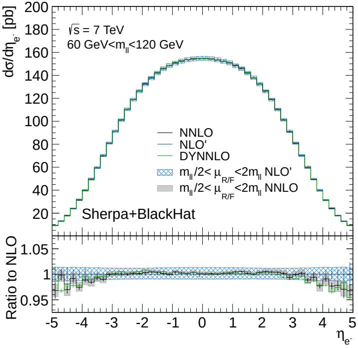


NNLO QCD accuracy

Comparison of Sherpa DY at NNLO QCD with FEWZ/DYNNLO

[Höche et al. Phys. Rev. D **91** (2015) 074015]





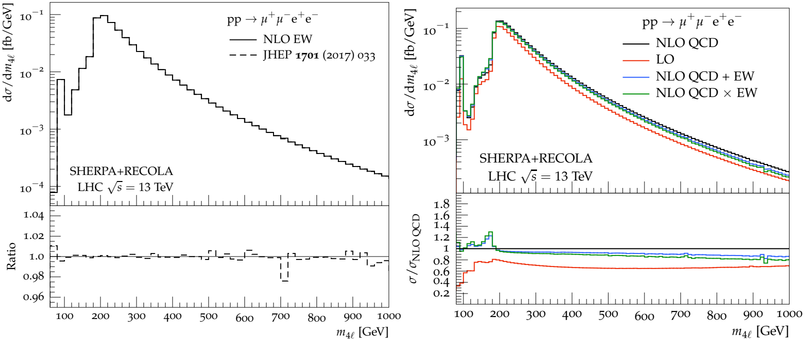
- ↪ fully differential NNLO calculation using BlackHat for one-loop amplitudes
- ↪ perfect agreement with dedicated codes FEWZ/DYNNLO

  [Gavin et al. CPC **182** (2011) 2388] & [Catani et al. Phys. Rev. Lett. **103** (2009) 082001]
- ↪ largely reduced uncertainties compared to NLO

NLO QCD & EW accuracy

NLO QCD & EW corrections to $pp \to 4l$ with SHERPA +RECOLA/COLLIER

[Biedermann et al. Eur. Phys. J. C **77** (2017) 492]



↪ RECOLA/COLLIER for QCD/EW one-loop amplitudes

[Actis et al. Comput. Phys. Commun. **214** (2017) 140] [Denner et al. Comput. Phys. Commun. **212** (2017) 220]

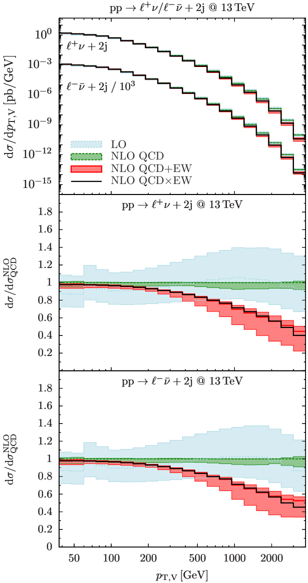
↪ Born, real-emission corrections, QED dipole subtraction etc. from SHERPA

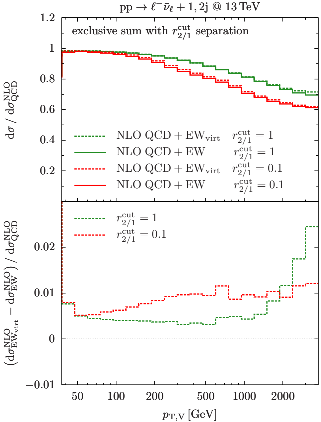
↪ perfect agreement with dedicated code [Biedermann et al. JHEP **1701** (2017) 033]

NLO QCD & EW accuracy

NLO QCD & EW corr. to $pp \to V +$jets SHERPA +OPENLOOPS/COLLIER

[Kallweit et al. JHEP **1504** (2015) 012 & JHEP **1604** (2016) 021]





↪ virtual approximation of NLO EW

$$d\sigma_{n,\mathrm{NLO\,EW_{virt}}} = \Big[\mathrm{B}_n(\Phi_n) + \mathrm{V}_{n,\mathrm{EW}}(\Phi_n) + \mathrm{I}_{n,\mathrm{EW}}(\Phi_n)\Big]\, d\Phi_n$$

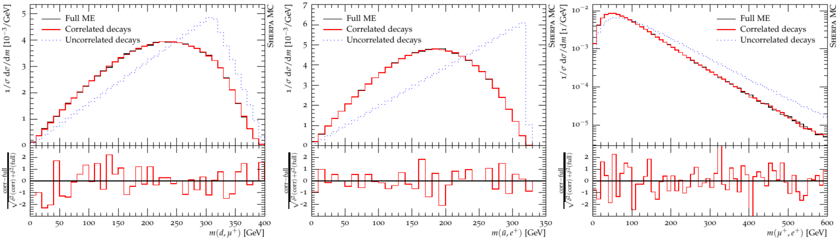
↪ applicable as mere K-factor (MEPS@NLO)

Matrix Elements for BSM processes

automating BSM physics calculations [Höche et al. Eur. Phys. J. C **75** (2015) no.3, 135]

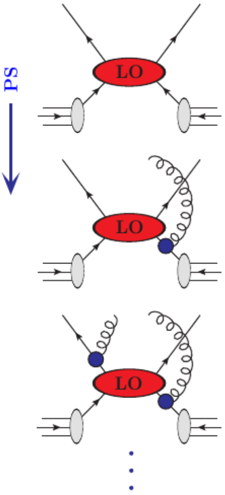
- full support of UFO model format [Degrande et al. Comput. Phys. Commun. **183** (2012) 1201]
- automatic built-up of Lorentz & color structures
  $\rightsquigarrow$ in principle arbitrary structures (EFTs) with COMIX (Spin 0,$\frac{1}{2}$,1)
- automatic identification of $1 \to 2$ and $1 \to 3$ decays
  $\rightsquigarrow$ calculation of LO decay widths
- inclusive decays or dedicated decay channels
- spin-correlated decay chains [Richardson JHEP **0111** (2001) 029]

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



QCD Parton Showers, Matching & Merging

Shower Evolution: inclusive MEs become exclusive



- probabilistic emission generation
- (N)LL approximation of jet rates
- defined through evolution variable, splitting kernels, recoil scheme etc.

SHERPA's dipole shower

[S., Krauss JHEP **0803** (2008) 038]

- transverse momentum
- Catani–Seymour dipole funcs
- mass effects included

[Krauss et al. Phys. Rev. D **95** (2017) no.3, 036012]

new DIRE shower

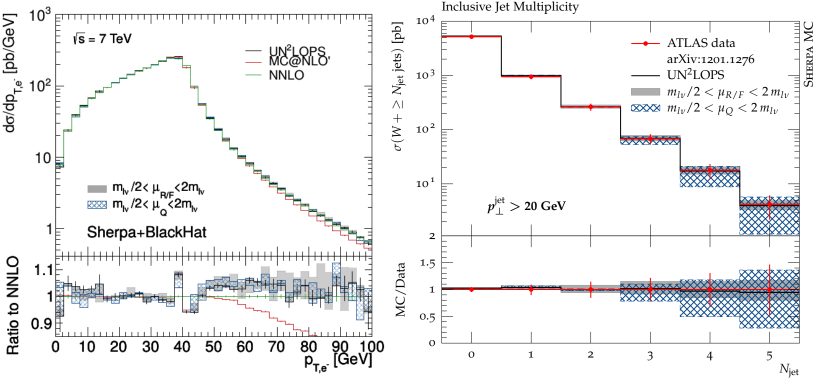
[Höche, Prestel Eur. Phys. J. C **75** (2015) no.9, 461]

- scaled transverse momentum
- DGLAP kernels (partitioned dipoles)
- avail. in PYTHIA 8 & SHERPA
- new: NLO QCD splitting funcs

[Höche, Prestel arXiv:1705.00742 [hep-ph]]

W production @ NNLO+PS with Sherpa +BlackHat

[Höche et al. arXiv:1507.05325]

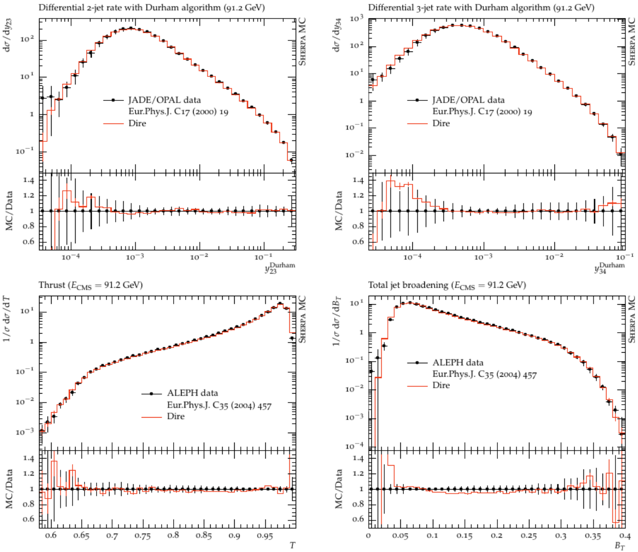


↪ fully differential hadron-level NNLO+PS simulation

- inclusive (born-like) distribution NNLO accurate
- 0-jet bin NNLO, 1-jet bin NLO, 2-jet bin LO, $\geq$ 3-jets shower accuracy

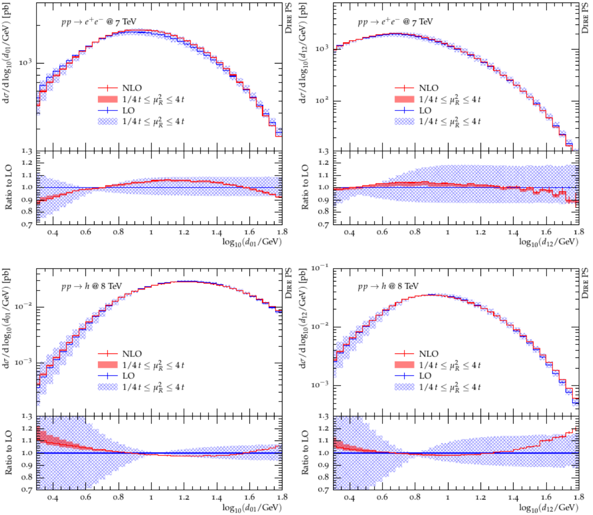
↪ small corrections away from Born kinematics

LEP-I observables from DIRE+SHERPA



QCD Parton Showers, Matching & Merging: DIRE

DIRE NLO QCD DGLAP kernels [Höche, Prestel arXiv:1705.00742 & Höche et al. arXiv:1705.00982 [hep-ph]]

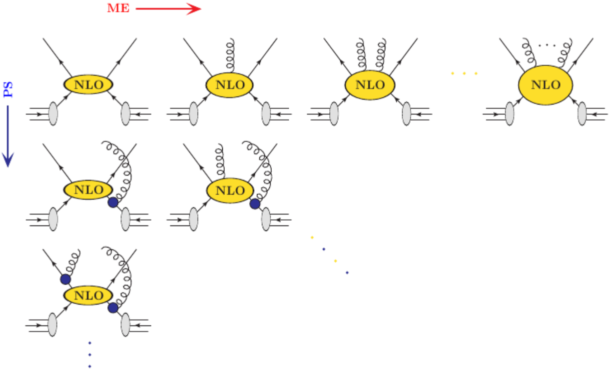


$\hookrightarrow$ largely reduced renormalization-scale dependence at NLO QCD

Merging NLO QCD matrix elements & showers: aka MEPS@NLO

- combine different NLO+PS multiplicities (optionally further LO+PS)
- reconstructed core process & CKKW-style nodal scale setting prescription
- notion of exclusive NLO+PS sample: truncated dipole shower

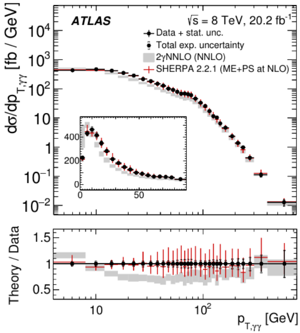
[Höche et al. JHEP **0905** (2009) 053 & JHEP **1304** (2013) 027]

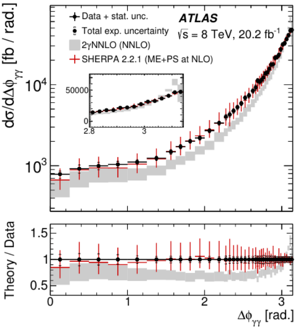


QCD Parton Showers, Matching & Merging: application

Diphoton production in ATLAS @ 8 TeV [ATLAS arXiv:1704.03839 [hep-ex]]

- $\gamma\gamma + 0, 1$j at NLO QCD matched MC@NLO style
- $\gamma\gamma + 2, 3$j at LO matched using truncated shower
- factorization & renormalization scale variations – $\mu/2$ & 2μ



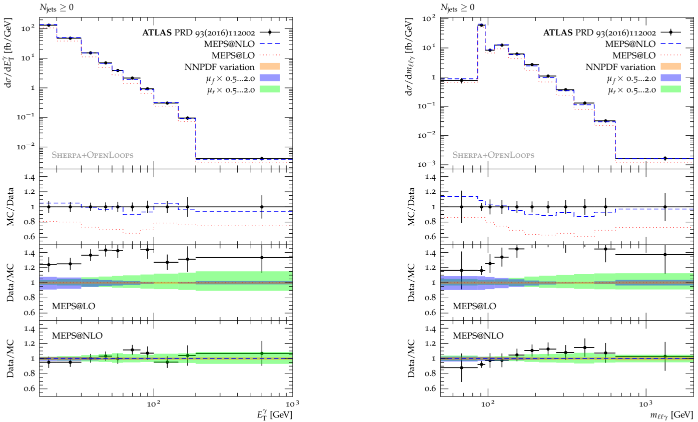


↪ rate comparison: MEPS@NLO $\sigma_{\rm fid}^{SH} = 16.4^{+3.1}_{-2.2}\,\text{pb}$ vs. $\sigma_{\rm fid}^{data} = 16.8 \pm 0.8\,\text{pb}$

↪ very satisfactory description of rates & shapes

Z($\to e^+e^-$)γ production [Krause, Siegert arXiv:1708.06283 [hep-ph]]

- MEPS@NLO: $e^+e^-\gamma + 0, 1j$ @ NLO, $e^+e^-\gamma + 2, 3$ @ LO
- MEPS@LO: $e^+e^-\gamma + 0, 1, 2, 3j$ @ LO



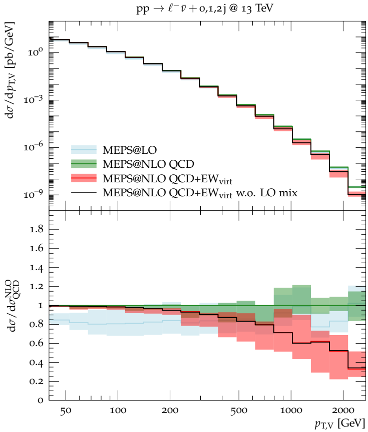
$\hookrightarrow$ core process types: $jj \to e^+e^-$, $Z\gamma$, $Z/\gamma j$, jj or unordered $Z\gamma$+jets

$\hookrightarrow$ elaborate study on theory uncertainties & photon isolation criteria

MEPS@NLO QCD+EW$_{\text{virt}}$ for W+jets with OPENLOOPS +SHERPA

[Kallweit et al. JHEP **1604** (2016) 021]

- $\hookrightarrow$ NLO EW often suffers from large higher-order QCD corrections
- $\hookrightarrow$ MEPS@NLO of $W(\to l\nu) + 0, 1, 2$j incl. virtual EW & Born interference
- $\hookrightarrow$ captures full QCD corrections & dominant EW effects of Sudakov-type

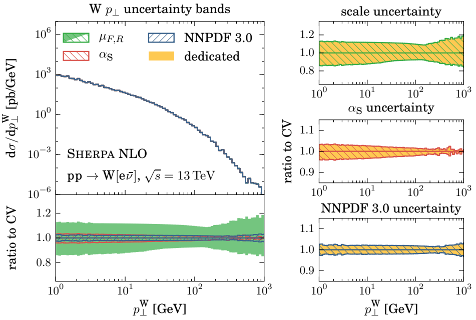


reweighting pQCD calculations on-the-fly [Bothmann et al. Eur. Phys. J. C **76** (2016) no.11, 590]

- trace full parameter & scale dependence of ME+PS events
  - ↪ perturbative coefficients of hard matrix element ($\mu_{R/F}$, α_S, PDFs)
  - ↪ book-keeping of accepted & rejected shower emissions (α_S, PDFs)
- recompute full event weight with modified input parameters/scales
  - ↪ store multiple event weights in event record (`HepMC::WeightContainer`)

Example: $pp \to e\bar{\nu}_e$ **@ NLO**

- NLO QCD and MC@NLO $\mathcal{O}(\alpha_S)$ public as of SHERPA-2.2.0
- full shower & MEPS@(N)LO with SHERPA-2.3.0



reweighting the parton showers: α_S & PDF variations

[Bothmann et al. Eur. Phys. J. C **76** (2016) no.11, 590]

- shower Sudakov depends on α_S & PDFs

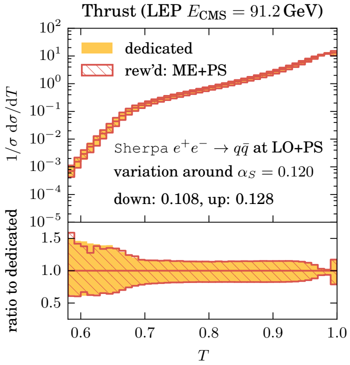
$\rightsquigarrow$ accept/reject probability

- need to reweight all acceptances/rejections

  $P_{\rm acc} \to q\, P_{\rm acc}$

  $P_{\rm rej} = 1 - P_{\rm acc} \to 1 - qP_{\rm acc}$

  with $q \equiv \frac{\alpha_S'}{\alpha_S} \cdot \frac{f_a'(x/z)/f_b'(x)}{f_a(x/z)/f_b(x)}$



$\hookrightarrow$ on-the-fly evaluation of ME & PS α_S, PDF and scale uncertainties

$\hookrightarrow$ takes only factor of $\mathcal{O}(1)$ more time wrt to standard single run

QCD Parton Showers, Matching & Merging: uncertainties

reweighting the parton showers: α_S & PDF variations

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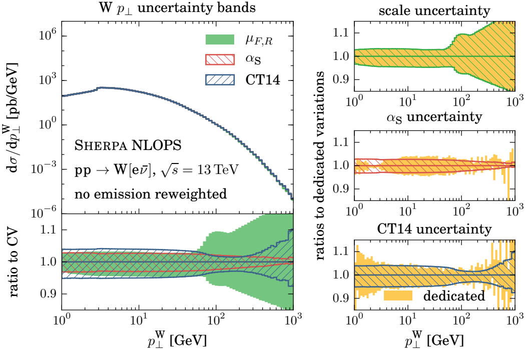
no shower emission reweighted



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reweighting the parton showers: α_S & PDF variations

[Bothmann et al. Eur. Phys. J. C **76** (2016) no.11, 590]

two shower emissions reweighted

- shower Sudakov depends on α_S & PDFs

$\rightsquigarrow$ accept/reject probability

- need to reweight all acceptances/rejections

  $P_{\rm acc} \to q\, P_{\rm acc}$

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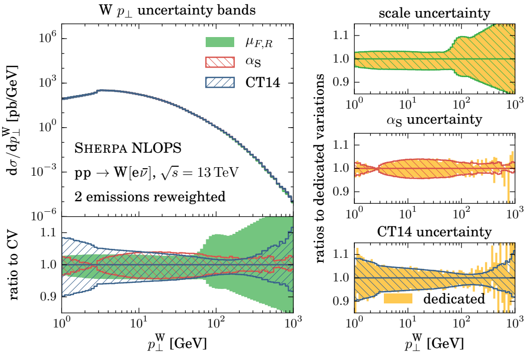

$\hookrightarrow$ on-the-fly evaluation of ME & PS α_S, PDF and scale uncertainties

$\hookrightarrow$ takes only factor of $\mathcal{O}(1)$ more time wrt to standard single run

Summary

- MEPS@NLO precise predictions for the Standard Model
  - multileg tree-level & one-loop matrix elements
  - sophisticated parton-shower & matching algorithms
- NNLO+PS for standard candles
- general BSM models via UFO inputs
- on-the-fly evaluation of QCD ME & PS uncertainties

- further improving our Standard Model predictions
  - automation of NLO QCD+EW corrections, matching with showers
    $\hookrightarrow$ needs full QED MC@NLO, QCD+EW shower/clustering
  - improving accuracy of parton showers
    $\hookrightarrow$ DIRE algorithm [Höche, Prestel Eur. Phys. J. C **75** (2015) no.9, 461]
    $\hookrightarrow$ implemented in PYTHIA 8 & SHERPA
    $\hookrightarrow$ QCD one-loop splitting functions, sub-leading color

The current Sherpa release

The current SHERPA-2.2.3 release (available since 04/2017)

- fixes for all known bugs up to SHERPA-2.2.2
- full UFO support for BSM models
- introduced new DIRE QCD parton shower
- QCD one-loop matrix elements through interfaces to:
  BLACKHAT, OPENLOOPS, GOSAM, RECOLA, ...
- on-the-fly scale, PDF and α_S variations for matrix elements
  LO & NLO QCD, MEPS@LO & MEPS@NLO

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  LO & NLO QCD, MEPS@LO & MEPS@NLO

The upcoming SHERPA-2.3.0 release (available soon)

- Catani–Seymour subtraction for NLO QED corrections
- automated NLO EW corrections for SM processes
  SHERPA+OPENLOOPS, SHERPA+RECOLA/COLLIER
- full scale, PDF and α_S variations in ME+PS calculations
  MEPS@LO, MEPS@NLO, NNLO+PS
- DIRE NLO DGLAP shower evolution