MCnetITN and the Sherpa project

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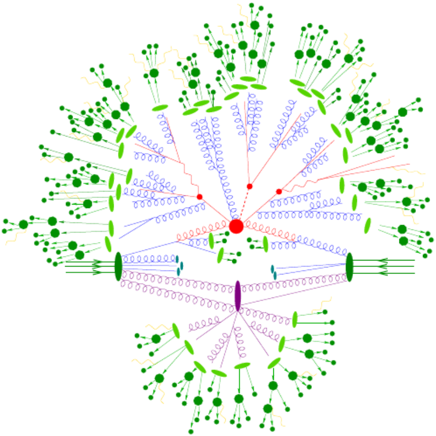
MCnetITN @ CERN

24/11/16

The SHERPA project

- perturbative QCD/EW
  - **Hard interaction**
    exact matrix elements $|\mathcal{M}|^2$
    LO,NLO,NNLO – QCD, NLO – EW
    COMIX, AMEGIC, interfaces: FEYNRULES, loop amplitudes
  - **Radiativ corrections**
    parton showers in the initial and final state
    matching/merging with LO,NLO,NNLO – QCD
    CS-shower, S-MC@NLO, DIRE
    YFS photonic corrections
    analytic soft-gluon resummation
- non-perturbative QCD
  - **Underlying Event**
    beyond factorization: modelling
    simple multiple-interactions model
  - **Hadronization**
    parton–hadron transition
    cluster-fragmentation model
  - **Hadron Decays**
    phase space or effective theories
    dedicated τ & hadron decay package



↪ SHERPA has matured to widely used standard tool
↪ focus on perturbative methods/predictions

Nodes & Personnel – MCnet perspective

Durham node

- Frank Krauss: team leader
- Silvan Kuttimalai: PhD (now PDRA SLAC)
- Sabrina Sacerdoti: Shorty
- David Bjergaard: Shorty
- Vince Croft: Shorty
- Petar Bokan: Shorty

Göttingen node

- Steffen Schumann: team leader
- Piero Ferrarese: PhD
- Jennifer Thompson: ESR
- Nathan Hartland: Shorty
- Federica Fabbri: Shorty

Heidelberg link

- Tilman Plehn: PPT chair (Higgs, BSM, Pheno)
- Michael Russell: Shorty
- Karl Nordström: Shorty

Dresden link

- Frank Siegert: Emmy Noether group (ATLAS, SHERPA, RIVET)

further core developers

- Stefan Höche: SLAC staff
- Marek Schönherr: Zurich PDRA
- Holger Schulz: Durham staff
- Korinnna Zapp: CERN

Network Activities

MCnet Summer School 2013

- 5d school in Mariaspring/Göttingen
- joint with annual Terascale HA school
- focus on NLO QCD, merging, statistics

Annual SHERPA collaboration meetings

- regular 3d get-together in January
- Munich, Zurich, Dresden, Edinburgh

Network Meeting April 2016

- Mariaspring/Göttingen

1st MCnet Scientific-Computing School

- 5d workshop Mariaspring/Göttingen
- focused lectures & hands-on projects

SHERPA development: focal points

Matrix Element calculations

- BSM: COMIX & FEYNRULES

  [Kuttimalai, Höche, S., Siegert]

- fast uncertainty estimates

  MCGRID [Hartland, Bothmann, S.]

  MEPS on-the-fly reweighting
  [Bothmann, S., Schönherr]

- NLO EW corrections [Schönherr, Thompson]

Parton Shower & Resummation

- shower improvements, e.g.

  DIRE [Höche, Prestel], NLO [Höche, Krauss]

  masses [Krauss, Napoletano, S.]

- NLO merging [Höche, Krauss, Schönherr]
- NNLO+PS [Höche, Li, Prestel]
- soft-gluon resummation [Ferrarese, Höche, S.]

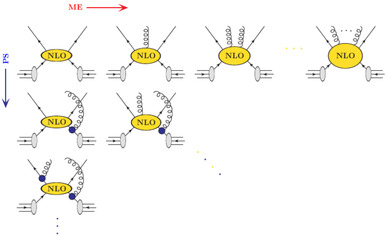
Matrix Elements

&

Parton Showers

NLO QCD with parton showers

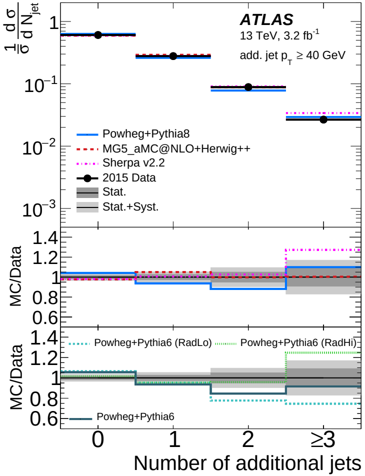
Merging NLO matrix elements & showers: aka MEPS@NLO



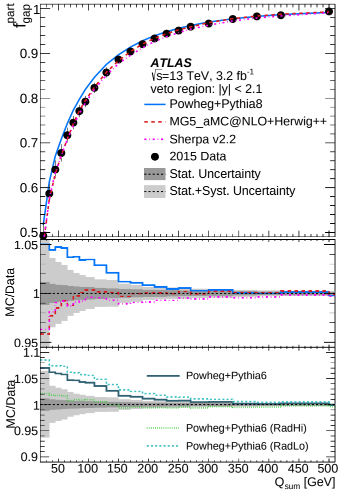
- combine different NLO+PS multiplicities
  (optional further LO+PS)
- notion of exclusive NLO+PS sample
  Sudakov weight, vetoed/truncated shower
  SHERPA [Höche et al. JHEP **1304** (2013) 027]
  truncated dipole shower

Application: jet activity in leptonic top-pair events [ATLAS arXiv:1610.09978 [hep-ex]]

extra-jet multiplicity

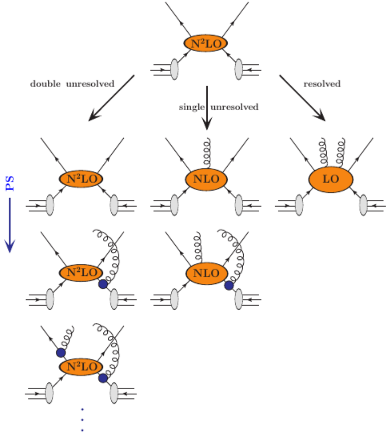


jet veto in between *b*-jets



NNLO QCD with parton showers

NNLO QCD production of color singlets, dressed with shower



- SHERPA UN^{2}LOPS

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

  based on q_T subtraction, genuine implementation of two-loop part, generalisation of the UNLOPS method

- implemented for color-singlets

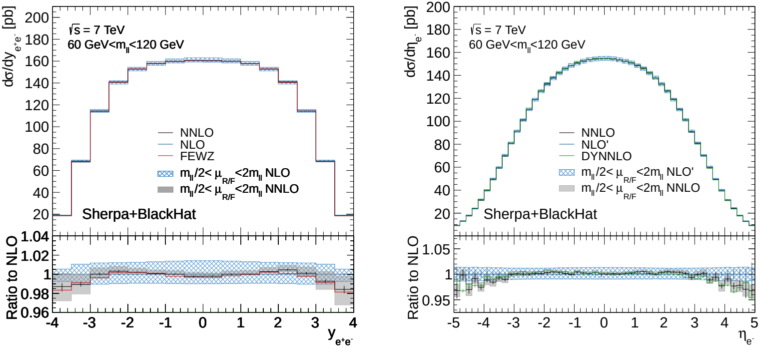
  $pp \to W/Z/H$ (HEFT)

  more to come ...

NNLO QCD validation

Comparison of SHERPA DY at NNLO QCD with FEWZ/DYNNLO

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

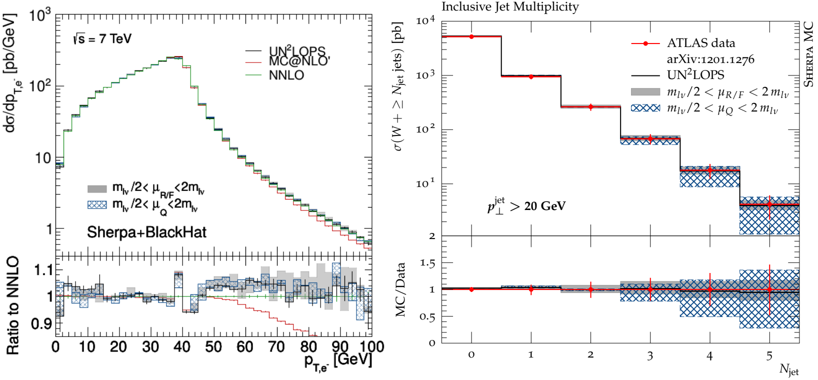


- ↪ fully differential NNLO calculation using BLACKHAT for one-loop amplitudes
- ↪ perfect agreement with dedicated codes FEWZ/DYNNLO

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

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

Fast uncertainty estimates

Fast uncertainty evaluation

theoretical uncertainties in pQCD calculations

- QCD input parameters & scale choices: $\alpha_S(M_Z)$, PDFs, μ_R, μ_F
  $\hookrightarrow$ appear both in MEs & parton showers: traceable
- shower-inherent choices: evolution variable, recoil scheme, cut-off, ...
  $\hookrightarrow$ defines shower model, partially subject to tuning
- dedicated re-simulation often too expensive/time consuming

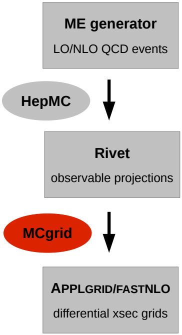
various (complementary) solutions exist

- projecting fixed-order QCD calculations on interpolation grids
  APPLGRID [Carli et al. Eur. Phys. J. C **66** (2010) 503] or FASTNLO [Kluge et al. hep-ph/0609285]
- extented event files for reweighting of NLO QCD events
  BLACKHAT/SHERPA Ntuple format [Bern et al. Comput. Phys. Commun. **185** (2014) 1443]
- on-the-fly reweighting of NLO matrix elements
  MG5_AMC@NLO [Alwall et al. JHEP **1407** (2014) 079] & POWHEGBOX [Alioli et al. JHEP **1006** (2010) 043]
  MEPS@(N)LO with SHERPA [Bothmann et al. Eur. Phys. J. C **76** (2016) 590]

Fast uncertainty evaluation – interpolation grids

automated projection of observable calculation on grids

- trace parameter/scale dependence eventwise
  ↪ isolate perturbative coefficients of hard matrix element
  ↪ calculate observable value and fill APPLGRID or FASTNLO grid
- recompute observable with modified input parameters/scales
  ↪ reconvolution within ms, applicable for PDF, α_S fits



- AMCFAST [Bertone et al. JHEP **1408** (2014) 166]

  projection of NLO MG5_aMC@NLO events on APPLGRID, based on user analysis code

- MCgrid [Del Debbio et al. CPC **185** (2014) 2115]

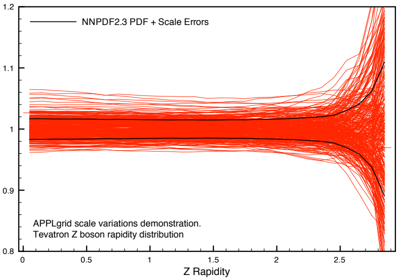
  plugin to RIVET, projects extented HepMC events on APPLGRID/FASTNLO

  used to project SHERPA LO, NLO & $\mathcal{O}(\alpha_S)$ SHERPA-MC@NLO

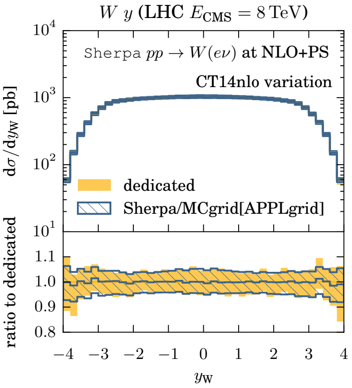
Fast uncertainty evaluation – interpolation grids

scale/PDF variations through interpolating grids

DY production @ NLO
(scale & PDF variations)



W production @ NLO
(CT14 PDF variations)



- $\rightsquigarrow$ easy generation of grids for arbitrary processes
- $\rightsquigarrow$ fast and efficient evaluation of fixed-order scale & parameter uncertainties

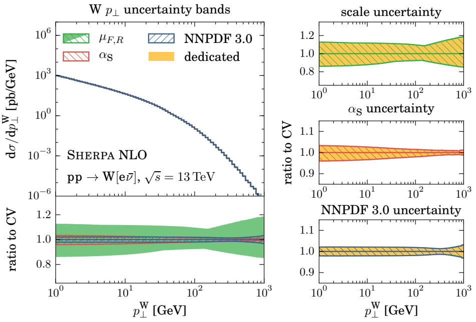
Fast uncertainty evaluation – reweighting

reweighting pQCD calculations on-the-fly [Bothmann et al. Eur. Phys. J. C **76** (2016) 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



Fast uncertainty evaluation – reweighting

reweighting the parton showers: α_S & PDF variations

[Bothmann et al. Eur. Phys. J. C **76** (2016) 590]

- shower Sudakov depends on α_S & PDFs

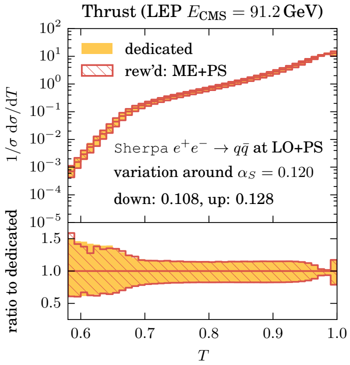
$\rightsquigarrow$ accept/reject probability

- 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

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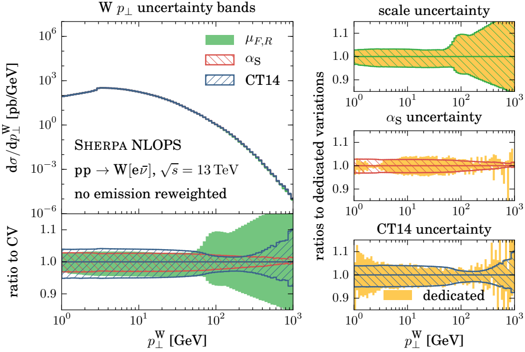
$$\text{with } q \equiv \frac{\alpha_S'}{\alpha_S} \cdot \frac{f_a'(x/z)/f_b'(x)}{f_a(x/z)/f_b(x)}$$

no shower emission reweighted



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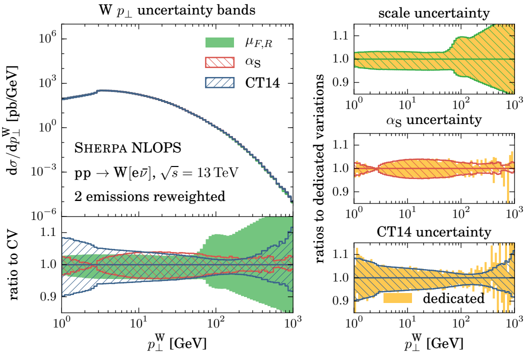
with $q \equiv \frac{\alpha_S'}{\alpha_S} \cdot \frac{f_a'(x/z)/f_b'(x)}{f_a(x/z)/f_b(x)}$

two shower emissions reweighted



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NLO EW corrections

Automation of NLO QCD+EW corrections

importance of EW corrections

- generic size of EW corr. $\mathcal{O}(\alpha) \sim \mathcal{O}(\alpha_S^2)$, i.e. NLO EW $\sim$ NNLO QCD
- enhanced in high-p_T tails – Sudakov logarithms $\alpha \log^2(M_V/p_T)$

$\hookrightarrow$ automated evaluation of NLO EW contributions demands

  - generalisation of loop providers
  - generalisation of subtraction method implementations in MCs
  - evaluation of photon-induced processes, QED-corrected PDFs

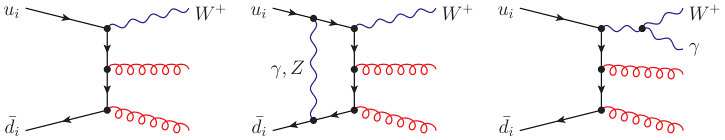
$\hookrightarrow$ several tools in preparation: aMC@NLO, GoSam, Recola, OpenLoops, Sherpa, ...

NLO QCD+EW corrections with OpenLoops+Sherpa/Munich

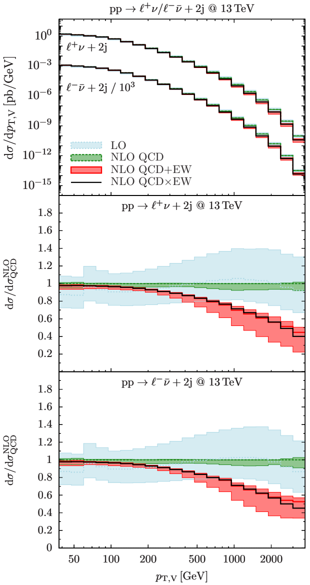
[Kallweit et al. JHEP **1504** (2015) 012 & arXiv:1511.08692]

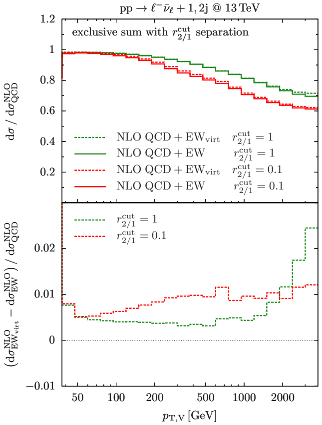
- consider $V(\to ll/l\nu)$+jets at 13 TeV LHC
- on-shell/off-shell gauge bosons considered
- first steps towards MEPs@Nlo with EW corrections included

sample diagrams for $u\bar{d} \to W^+gg$



$W(\to l\nu) + 1, 2$ jets @ NLO QCD+EW





$\hookrightarrow$ virtual approximation of NLO EW

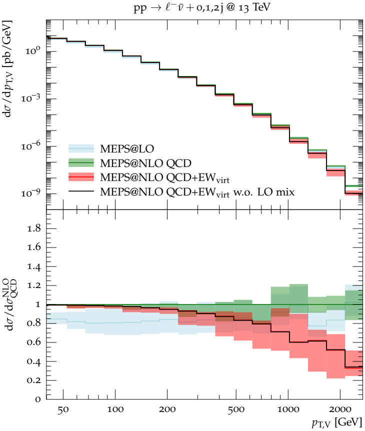
$$d\sigma_{n,\text{NLO EW}_\text{virt}} = \left[\text{B}_n(\Phi_n) + \text{V}_{n,\text{EW}}(\Phi_n) + \text{I}_{n,\text{EW}}(\Phi_n)\right] d\Phi_n$$

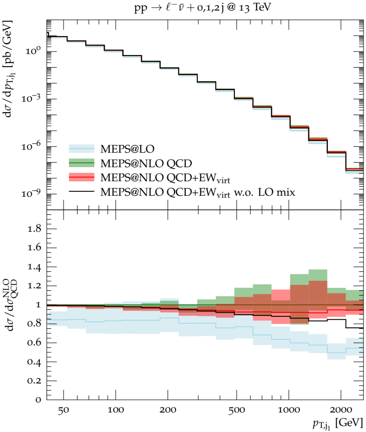
$\hookrightarrow$ applicable as mere K-factor

MEPS@NLO QCD+EW$_{\rm virt}$ for W+jets with OpenLoops +Sherpa

[Kallweit et al. arXiv:1511.08692]

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





Summary & Outlook

MCnetITN2 achievements

- established NLO QCD automation, matched & merged with showers
- first NNLO+PS accurate predictions for $Z/W/H$ production
- generalised BSM modelling by interfacing COMIX to FEYNRULES/UFO
- fast & efficient uncertainty evaluations
- towards automation of NLO EW

plans for MCnetITN3

- automation of NLO EW plus parton showers
- NNLO subtraction schemes
- NNLO+PS for colourful processes
- PDFs and shower resummation
- continuous shower improvements
- automatised soft-gluon resummation

  ↪ established formal link to SLAC: option for secondments