Introduction to the Sherpa Monte Carlo

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EIC Software Tutorial

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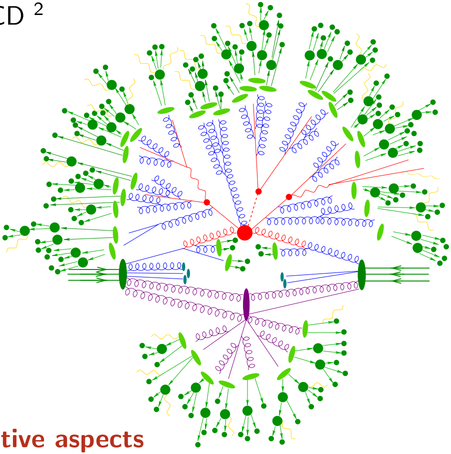
The Sherpa Framework

[Bothmann et al.] arXiv:1905.09127

- **Hard interaction**
  LO, NLO QCD/EW [1], NNLO QCD [2]
  ME generators Amegic & Comix
- **Radiative corrections**
  Catani-Seymour based PS,
  Dire, YFS QED resummation
- **Multiple interactions**
  Sjöstrand-Zijl model
- **Hadronization**
  Cluster hadronization model
- **Hadron Decays**
  Phase space or EFTs,
  YFS QED corrections



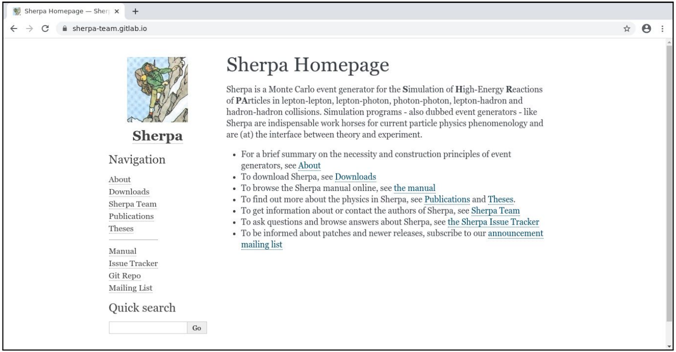
Development focused on perturbative aspects

[1] via interfaces to loop generators
[2] $pp \to Z/W^{\pm}/h/W^{\pm}W^{\mp}$, DIS

Hands on: Download and Installation

- Go to `https://sherpa-team.gitlab.io/`
- Click 'Downloads' to get download instructions:

```
git clone -b rel-2-2-10 \
    https://gitlab.com/sherpa-team/sherpa.git
```



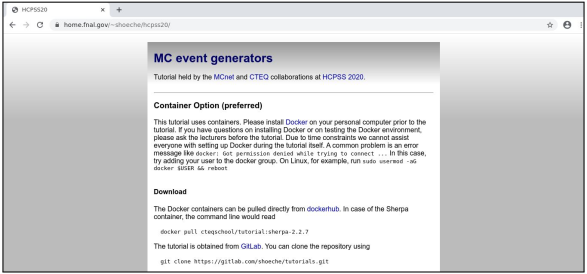
Hands on: Download and Installation

Installation steps

- autoreconf -fi
- ./configure --enable-ufo --enable-mpi \
  --enable-hepmc2=<what> --enable-rivet=<what>
- make install -j<nofcores>

For quick testing & tutorial, use container or VM

- Go to http://home.fnal.gov/~shoeche/hcpss20/
- Follow instructions on website



Short-distance cross sections

- Efficient tree-level generators for Born and real-emission corrections
  Amegic [Krauss,Kuhn,Soff] hep-ph/0109036, Comix [Gleisberg,SH] arXiv:0808.3674
- MPI-parallelized integration $\rightarrow$ good performance at high multiplicity

Process	W^-+0j	W^-+1j	W^-+2j	W^-+3j	W^-+4j	W^-+5j	W^-+6j
RAM	<1MB	<1MB	1 MB	2 MB	23 MB	81 MB	435 MB
Time[3]	8s	2m 4s	22m 8s	2h 3m	1d 5h	6d 23h	32d 19h
MC error	0.18%	0.14%	0.25%	0.44%	0.66%	0.78%	1.29%

- Direct interfaces to a variety of loop-amplitude providers,
  BLHA interface [Binoth et al.] arXiv:1001.1307, [Alioli et al.] arXiv:1308.3462
- Multi-channel phase-space integrators
- Catani-Seymour dipole subtraction for QCD & QED
  Amegic [Gleisberg,Krauss] arXiv:0709.2881, [Schönherr] arXiv:1712.07975, Comix (QCD) [SH]
- q_T subtraction for NNLO QCD singlet production [Li,Prestel,SH] arXiv:1405.3607
- Projection to Born for NNLO DIS [Li,Kuttimalai,SH] arXiv:1809.04192

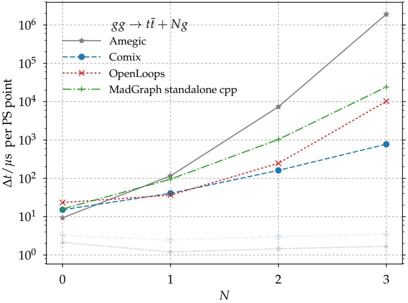
[3] Timing cumulative for all MPI ranks on dual 18-core Intel® Xeon® E5-2699 v3 2.30GHz
Divide by desired number of cores to obtain user (wallclock) time

Example: $t\bar{t}$+3jets at NLO/MINLO QCD

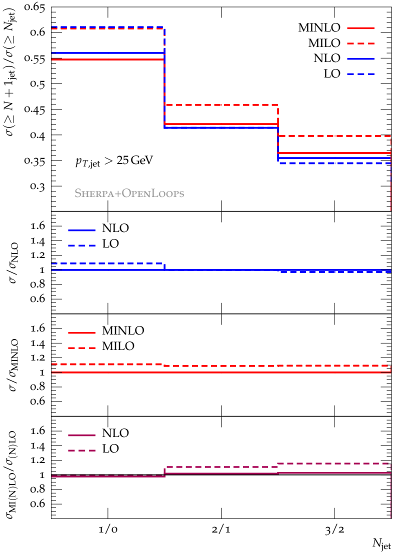
- Interesting phenomenology, e.g. behavior of Berends ratio
- Challenging number of loop graphs

Channel \ n_{light}	0	1	2	3
$gg \to t\bar{t}$	47	630	9'438	152'070
$u\bar{u} \to t\bar{t}$	12	122	1'608	23'835
$u\bar{u} \to t\bar{t}u\bar{u}$	–	–	506	6'642
$u\bar{u} \to t\bar{t}d\bar{d}$	–	–	252	3'321

- Performance impacts already at LO



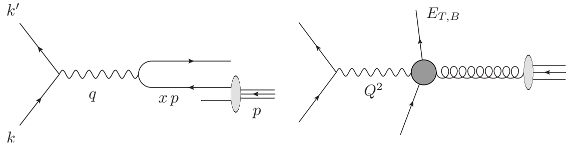
[Maierhöfer,Moretti,Pozzorini,Siegert,SH] arXiv:1607.06934



Example: DIS at NNLO QCD

[Kuttimalai,Li,SH] arXiv:1809.04192

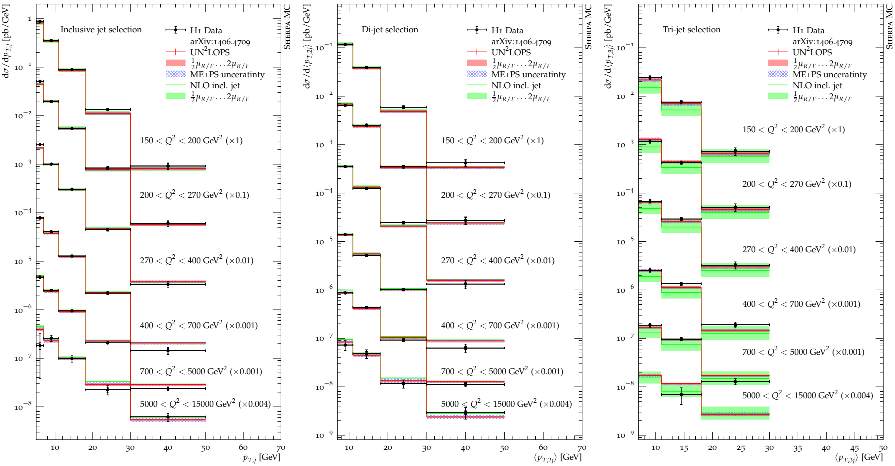
- Module for computation of inclusive DIS at NNLO QCD
- Projection-to-Born method for fully differential fixed order predictions
  [Zijlstra,vanNeerven] NPB383(1992)525, PLB297(1992)377 [Moch,Vermaseren,Vogt] hep-ph/0504242
  [Bern,Dixon,Kosower] hep-ph/9708239, [Berger et al.] arXiv:0803.4180
- UN^{2}LOPS matching to parton shower for particle-level simulations
  [Lönnblad,Prestel] arXiv:1211.7278, [Li,Prestel,SH] arXiv:1405.3607
- Scale choice appropriate for simultaneous description of inclusive DIS and inclusive jet / di-jet / tri-jet production $\rightarrow \mu^2_{R/F} = (Q^2 + (H_T/2)^2)/2$



- Good agreement with H1 measurements in both high-Q^2 and low-Q^2 region [Andreev et al.] arXiv:1406.4709, arXiv:1611.03421

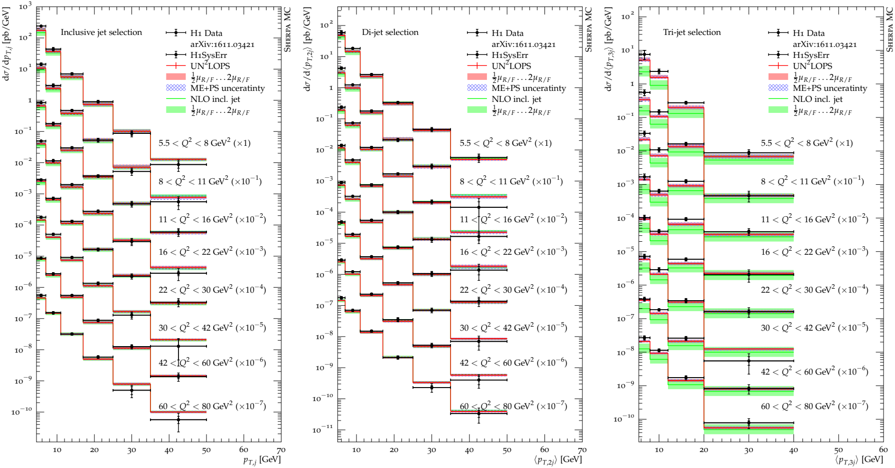
Example: DIS at NNLO QCD

[Kuttimalai,Li,SH] arXiv:1809.04192



Example: DIS at NNLO QCD

[Kuttimalai,Li,SH] arXiv:1809.04192



BSM simulations

[Kuttimalai,Schumann,Siegert,SH] arXiv:1412.6478

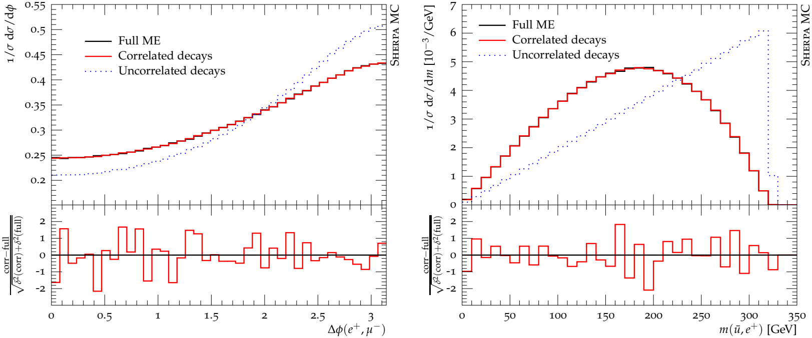
- Model information from Feynrules [Christensen,Duhr] arXiv:0806.4194 [Alloul et al.] arXiv:1310.1921 via UFO [Degrande at al.] arXiv:1108.2040
- Automatic construction of Lorentz & color calculators
- Limited by external wave functions in Comix (Spin 0,1/2,1) but extension to other spins possible (any volunteers?)
- Tested on a large set of processes, including [Hagiwara et al.] hep-ph/0512260, [Christensen et al.] arXiv:0906.2474

Model	number of processes tested	max. rel. deviation Comix $\leftrightarrow$ MadGraph5
Standard Model	60	$2.3 \cdot 10^{-10}$
Higgs Effective Field Theory	13	$4.3 \cdot 10^{-13}$
MSSM	401	$1.0 \cdot 10^{-10}$
Minimal Universal Extra Dimensions	51	$2.8 \cdot 10^{-12}$
Anomalous Quartic Gauge Couplings	16	$5.9 \cdot 10^{-12}$

BSM simulations

[Kuttimalai,Schumann,Siegert,SH] arXiv:1412.6478

- Automatic construction & LO calculation of all $1 \to 2$ and $1 \to 3$ decays
- Inclusive decays or dedicated channels, branching ratios can be manipulated
- Spin correlation algorithm for decay chains [Richardson] hep-ph/0110108
- Examples: $pp \to t\bar{t} \to be^+\nu_e\bar{b}\mu^-\bar{\nu}_\mu$ in SM,
  $pp \to \tilde{u}\tilde{u}^* \to d\,\chi_1^0\,\mu^+\,\nu_\mu\,\bar{u}\,e^+\,e^-\,\chi_1^0$ in MSSM



Uncertainty estimates

Explicit variations

- Can be done for any scale or PDF dependence
- Functional form can be changed
- Separate runs with changed input

On-the-fly variations

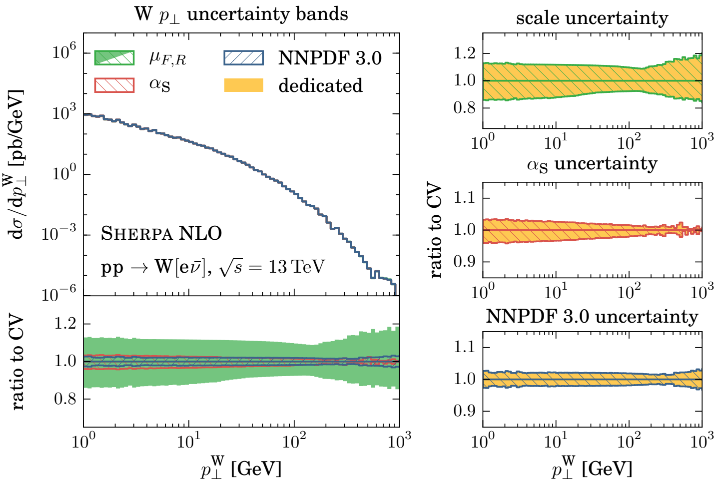
- Can be done for $\mu_{R/F}$ and PDF dependence of matrix elements
- Functional form of scale can currently not be changed
- Full syntax cf. Manual, simplified syntax:

```
SCALE_VARIATIONS 0.25,0.25 4.,4.;
PDF_VARIATIONS NNPDF30_nnlo_as_0118[all];
```

- Stored in HepMC::WeightContainer
  using LH naming convention [LesHouches SM WG] arXiv:1405.1067

Uncertainty estimates – NLO

[Bothmann,Schönherr,Schumann] arXiv:1606.08753



Hands on: Fixed-order calculation of $e^+p \to e^+p$

- Open file '`Run.dat`', add

```
(run){
  BEAM_1 -11 26.7; BEAM_2 2212 820
  RESPECT_MASSIVE_FLAG 1; PDF_SET_1 None;
  SCALES VAR{-Abs2(p[0]-p[2])}
}(run)
(processes){
  Process -11 93 -> -11 93
  End process
}(processes)
(selector){
  Q2 -11 -11 4 1e12
}(selector)
```

- Run Sherpa using '`Sherpa -e0`' (no events for now)
- Draw Feynman graphs by adding '`Print_Graphs graphs`' to `(processes)` section and running '`plot_graphs.sh graphs`'

Hands on: Fixed-order calculation of $pp \to e^+e^-$

- Perform calculation at NLO by modifying runcard like this

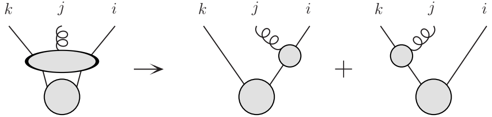
```
(processes){
  Process -11 93 -> -11 93
  NLO_QCD_Mode Fixed_Order
  Loop_Generator OpenLoops
  End process
}(processes)
```

- Speed up calculation by running '`mpirun -n <nofcores> Sherpa`'
- Run '`Sherpa -wW -e10k EVENT_OUTPUT=HepMC_Short[events]`' to produce 10k weighted events & store them in `events.hepmc`
- Have a look with '`zless events.hepmc`'
- Add '`SCALE_VARIATIONS 0.25,0.25 4.,4.`' to `(run)` section and repeat analysis to learn about variations

Parton showers

- Probabilistic emission generation based on dipole-like factorization
  $\leftrightarrow$ Partial fractioned & coll. matched eikonal [Catani,Seymour] hep-ph/9605323

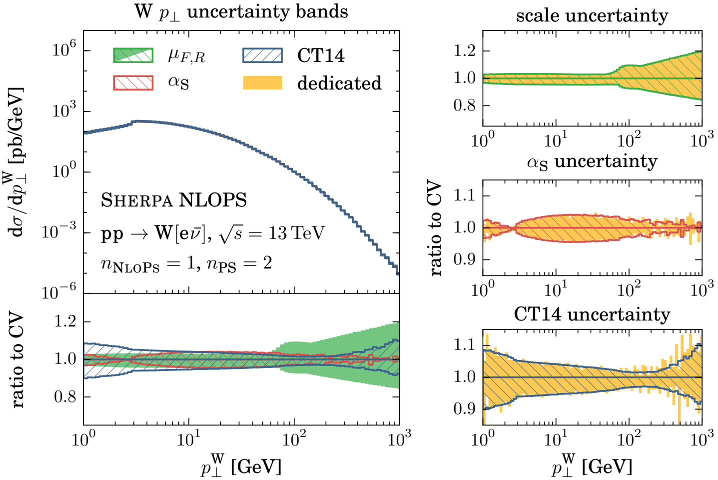
$$\frac{p_i p_k}{(p_i p_j)(p_j p_k)} \to \frac{1}{p_i p_j}\frac{p_i p_k}{(p_i+p_k)p_j} + \frac{1}{p_k p_j}\frac{p_i p_k}{(p_i+p_k)p_j}$$



- Two implementations:
  - CSS [Schumann,Krauss] arXiv:0709.1027
    Collinear-k_T ordered, pure Catani-Seymour dipoles
  - Dire [Prestel,SH] arXiv:1506.05057
    Dipole-k_T ordered, modified Catani-Seymour dipoles
    $\leftrightarrow$ DGLAP kernels where $\frac{1}{1-z} \to \frac{1-z}{(1-z)^2+k_T^2/Q^2}$
- Dire also implemented in Pythia, allowing various cross-checks

Uncertainty estimates – NLO+PS

[Bothmann,Schönherr,Schumann] arXiv:1606.08753



Hands on: Parton shower simulation

- Use previous runcard & remove 'NLO_QCD_Mode Fixed_Order'
- Add an analysis section to '`Run.dat`'

  ```
  (analysis){
    BEGIN_RIVET
      -a H1_1994_S2919893_
      USE_HEPMC_SHORT 1
    END_RIVET
  }(analysis)
  ```

  For this tutorial: Hacked version of Rivet routine (allow swap of beams)

  ```
  wget https://home.fnal.gov/~shoeche/hcpss20/H1.tar.gz
  tar -xzf H1.tar.gz
  docker-run-sherpa rivet-buildplugin *.cc
  ```
- Run Sherpa using '`Sherpa -aRivet -e10k`'
  to produce 10k unweighted events & analyze directly
- Run '`rivet-mkhtml Analysis.yoda`' to plot
  '`firefox rivet-plots/index.html`' to view results

Hands on: PS & MC@NLO simulations

- For MC@NLO, modify runcard like this

```
(processes){
  Process -11 93 -> -11 93
  NLO_QCD_Mode MC@NLO
  ME_Generator Amegic
  RS_ME_Generator Comix
  End process
}(processes)
```

- Run '`Sherpa`' to produce ME code and compile using '`./makelibs -j<nofcores>`'
- Run '`Sherpa -aRivet -e10k -AMCNLO`' to integrate and analyze 10k unweighted NLO events with output file `MCNLO.yoda`
- Compare to parton shower results from previous run '`rivet-mkhtml Analysis.yoda MCNLO.yoda`'

Hands on: PS, MC@NLO & POWHEG simulation

- Great resource for PS & matching: “Hackathons” at CTEQ schools
  `https://home.fnal.gov/~shoeche/hcpss20/ws`

Tutorial on MC event generators

Held by the MCnet collaboration at CTEQ 2017.

Instructions

PS coding tutorial
MC running tutorial

TASI Lectures

arXiv:1411.4085

Tutorial on Parton Showers and Matching

CTEQ School 2017

1 Introduction

In this tutorial we will discuss the construction of a parton shower, the implementation of on-the-fly uncertainty estimates, and of matrix-element corrections, and matching at next-to-leading order. At the end, you will be able to run your own parton shower for $e^+e^- \to$hadrons at LEP energies and compare its predictions to results from the event generator Sherpa (using a simplified setup). You will also have constructed your first MC@NLO and POWHEG generator.

2 Getting started

On the CTEQ 2017 VM change to the tutorial directory

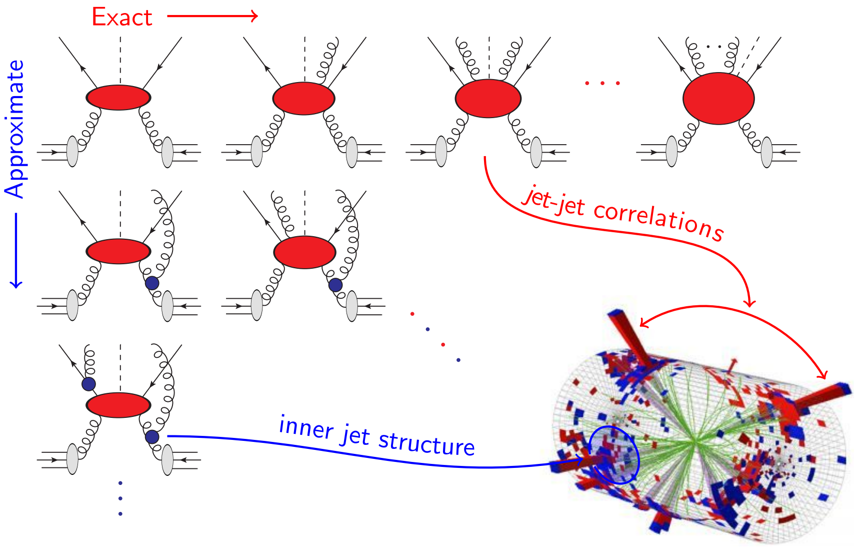
```
cd ~/tutorials/ps/
```

You can also use your own PC (In this case you should have PyPy and Rivet installed)

```
svn co svn://svn.slac.stanford.edu/mc/ps && cd ps/
```

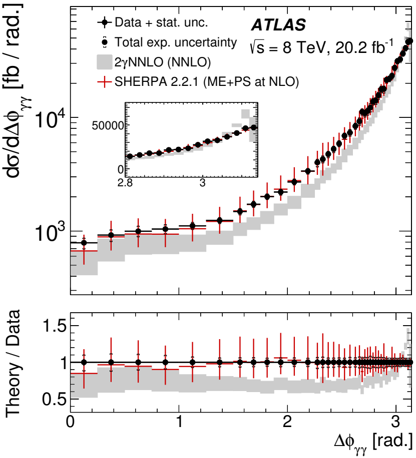
For simplicity, this tutorial uses PyPy, a just-in-time compiled variant of Python. If you are unfamiliar with Python, think of it as yet another scripting language, such as bash, but way more powerful. A peculiar feature of Python, and indeed its biggest weakness, is that code is structured by indentation. That means you need to pay careful attention to all the spaces in this worksheet. Missing spaces, or additional ones may render your code entirely useless at best. The worst case scenario is that it will still

Multi-jet merging



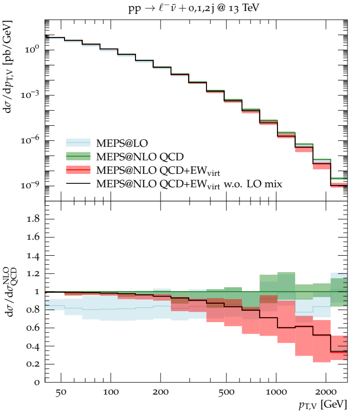
Multi-jet merging at LO and NLO

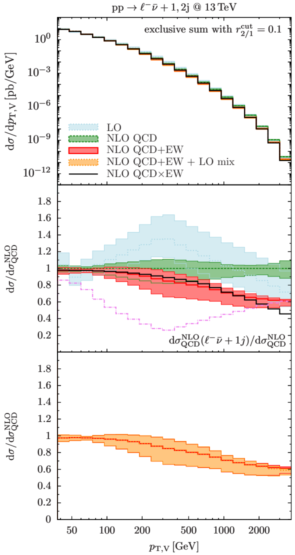
- S-MC@NLO matching to PS
  [Krauss,Siegert,Schönherr,SH]
  arXiv:1111.1220, arXiv:1201.5882
  - Full-color PS in matching step
  - $\mathbb{S}$-events restricted to Amegic
- MEPS@(N)LO merging
  [Krauss,Siegert,Schumann,SH] arXiv:0903.1219
  [Krauss,Siegert,Schönherr,SH] arXiv:1207.5030
  - Non-unitarized, truncated PS
  - See TASI lecture arXiv:1411.4085
- Works for non-trivial processes
  Example: $pp \to \gamma\gamma$+jets
  [ATLAS] arXiv:1704.03839



Electroweak merging

[Kallweit,Lindert,Maierhöfer,Pozzorini,Schönherr] arXiv:1511.08692

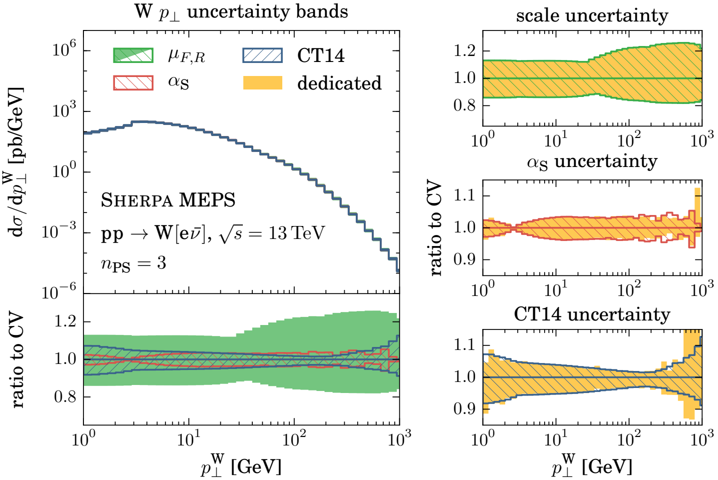




- QCD merging extended to QCD+EW matrix elements

Uncertainty estimates – ME+PS

[Bothmann,Schönherr,Schumann] arXiv:1606.08753



Hands on: MEPS merging at (N)LO

- Use previous runcard, remove '`SCALES`' definition
- Change process declaration as

```
(processes){
  Process -11 93 -> -11 93 93{1} # up to 1 light jet added
  NLO_QCD_Mode MC@NLO {2} # only 2-particle final state
  ME_Generator Amegic {2} # same here
  RS_ME_Generator Comix {2} # and here
  Order (*,2) # QCD corrections only
  CKKW sqr(5/E_CMS)/(1.0+sqr(5)/Abs2(p[2]-p[0]))
  End process
}(processes)
```

- Run '`Sherpa -aRivet -e10k -AMENLOPS`' to integrate and analyze 10k unweighted (N)LO events with output file `MENLOPS.yoda`
- Compare to parton shower and MC@NLO results from previous runs '`rivet-mkhtml Analysis.yoda MCNLO.yoda MENLOPS.yoda`'

Summary

- Current capabilities of Sherpa
  - Fixed-order calculations at LO & NLO
    NLO via interfaces to loop providers
  - NNLO for standard candles at the LHC
  - LO & partially NLO parton shower
  - MC@NLO matching and MEPS@(N)LO merging
  - BSM models via UFO interface
  - On-the-fly evaluation of uncertainties
- Future additions
  - Automation of NLO QCD+EW corrections
  - Resummation of EW Sudakov logarithms