Report from the MC4EIC working group

EICUG meeting 2025

Ilkka Helenius
Frank Krauss

July 15, 2025

JYVÄSKYLÄN YLIOPISTO
UNIVERSITY OF JYVÄSKYLÄ

Research Council of Finland

Centre of Excellence in Quark Matter

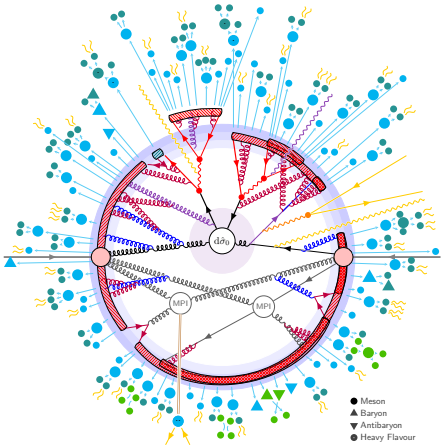
MC4EIC

Scope & Activities

- Follow up on progress of Monte Carlo Event Generators (MCEG) for EIC
- Coordinate/support validation MCEGs against relevant data
- Communicate with experimentalists on their needs

MC4EIC Workshops

- 2021: hosted by CFNS (remote)
- 2022: hosted by Fermilab (remote)
- 2024: Durham (in-person)
- 2025 July 9–11: JLab (hybrid)



[figure by P. Skands]

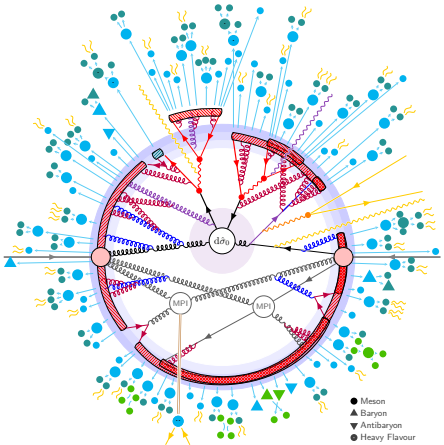
MC4EIC

Scope & Activities

- Follow up on progress of Monte Carlo Event Generators (MCEG) for EIC
- Coordinate/support validation MCEGs against relevant data
- Communicate with experimentalists on their needs

MC4EIC Workshops

- 2021: hosted by CFNS (remote)
- 2022: hosted by Fermilab (remote)
- 2024: Durham (in-person)
- 2025 July 9–11: JLab (hybrid)



[figure by P. Skands]

Event generators

General purpose event generators

- Aim to provide a full description of a collision event, ie. exclusive hadronic final states, using Monte Carlo methods
- Use perturbative QCD where applicaple, fill in with phenomenological models
- Main players:
  - Herwig (7.3.0) `https://herwig.hepforge.org` [Eur.Phys.J. C80 (2020) 452]
  - Pythia (8.315) `https://pythia.org` [SciPost Phys. Codebases 8-r8.3 (2022)]
  - Sherpa (3.0.1) `https://sherpa-team.gitlab.io` [JHEP 12 (2024) 156]

Specialized event generators

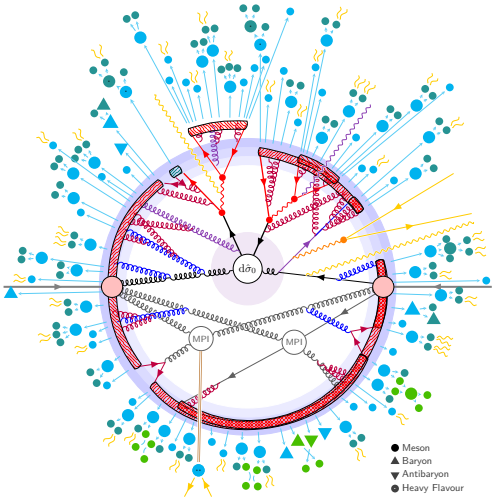
- Matrix-element (ME) (hard-process) generators for higher perturbative accuracy and multiplicities: Madgraph5(_aMC@NLO), POWHEG(-BOX)
- Fixed-order codes: MCFM, NNLOJET, ...

General-purpose event generators

Classify event generation in terms of "hardness"

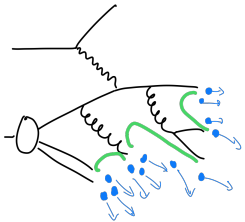
1. Hard Process (here $t\bar{t}$)
2. Resonance decays ($t, Z, \ldots$)
3. Matching, Merging and matrix-element corrections
4. Multiparton interactions
5. Parton showers: ISR, FSR, QED, Weak
6. Hadronization, Beam remnants
7. Decays, Rescattering

[figure credit: P. Skands]

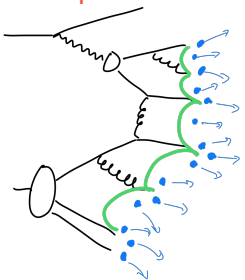


- EIC measurenemts will cover both photoproduction and electroproduction (DIS)
  - ⇒ Need also smooth interpolation between these regions
- Precise knowledge of kinematics (x, Q^2, ...)
  - ⇒ QED radiation effects
- Multi-dimensional nucleon structure
  - ⇒ Incorporate polarization into all stages
  - ⇒ Transverse-momentum dependent evolution for TMDs
  - ⇒ Exclusive processes for GPDs
- Nuclear targets
  - ⇒ Hadronization, saturation, nuclear breakup,

Electroproduction: $Q^2 \gg 1$ GeV



Photoproduction: $Q^2 \approx 0$



Herwig 7

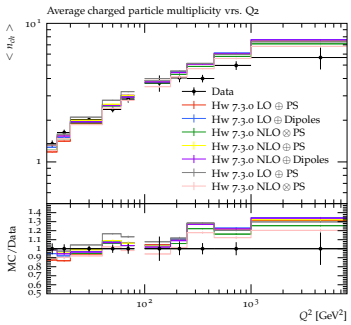
- Internal MEs at LO and NLO (matchbox)
- Various Matching and Merging options
- Angular-ordered (QTilde) and Dipole shower
- Cluster and string hadronization

Electro- and photoproduction

- LO DIS for NC and CC, jet merging
- Diffractive jets and soft diffraction in DIS
- Inclusive photoproduction at LO

Ongoing efforts

- Include higher-order corrections, EW radiation
- Diffractive photoproduction



Herwig 7

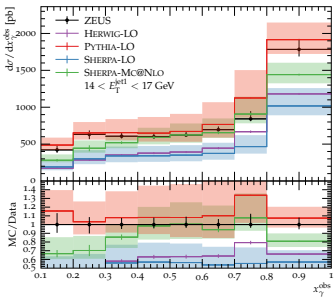
- Internal MEs at LO and NLO (matchbox)
- Various Matching and Merging options
- Angular-ordered (QTilde) and Dipole shower
- Cluster and string hadronization

Electro- and photoproduction

- LO DIS for NC and CC, jet merging
- Diffractive jets and soft diffraction in DIS
- Inclusive photoproduction at LO

Ongoing efforts

- Include higher-order corrections, EW radiation
- Diffractive photoproduction



[I. Helenius, P. Meinzinger, S. Plätzer, P. Richardson, arXiv:2406.08026]

Electroproduction

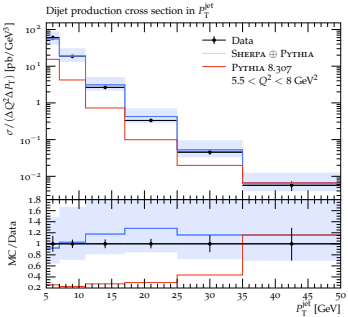
- Dipole recoil variant of the default PS
- Vincia sector shower
- Multi-jet merging for DIS

Photoproduction

- Soft and hard QCD processes with MPIs
- Diffraction, hard with MPI rejection
- Nuclear targets with VMD model

Ongoing efforts

- Further tuning for DIS and photoproduction
- Improved DIS kinematics
- Extend γA capabilities, validate in UPCs



[H1: EPJC 77 (2017) 215]

[I. Helenius, J. Laulainen, C.T. Preuss: JHEP 05 (2025) 153]

Electroproduction

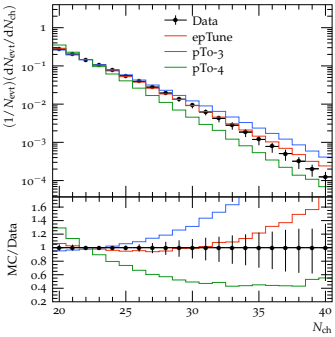
- Dipole recoil variant of the default PS
- Vincia sector shower
- Multi-jet merging for DIS

Photoproduction

- Soft and hard QCD processes with MPIs
- Diffraction, hard with MPI rejection
- Nuclear targets with VMD model

Ongoing efforts

- Further tuning for DIS and photoproduction
- Improved DIS kinematics
- Extend γA capabilities, validate in UPCs



[ZEUS: JHEP 12 (2021) 102]

Electroproduction

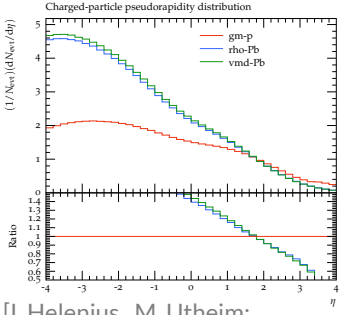
- Dipole recoil variant of the default PS
- Vincia sector shower
- Multi-jet merging for DIS

Photoproduction

- Soft and hard QCD processes with MPIs
- Diffraction, hard with MPI rejection
- Nuclear targets with VMD model

Ongoing efforts

- Further tuning for DIS and photoproduction
- Improved DIS kinematics
- Extend γA capabilities, validate in UPCs



[I. Helenius., M. Utheim: EPJC 84 (2024) 11, 1155]

New in Sherpa 3

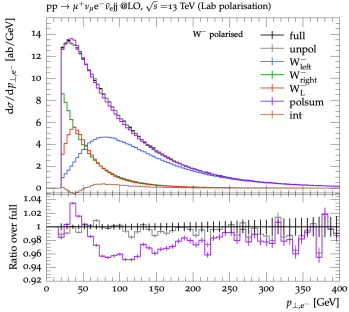
- NLL accurate parton shower Alaric
- Automatic electroweak corrections
- Polarized cross sections

Electroproduction

- Inclusive NC-DIS at NNLO
- NC- and CC-DIS with MEPS@NLO
- Tuning with uncertainties

Photoproduction

- NLO+PS available for jets
- Hard diffraction at LO and NLO



[Hoppe, Schönherr, Siegert, JHEP 04 (2024) 001]

New in Sherpa 3

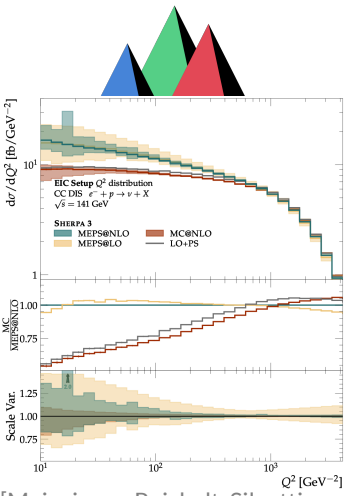
- NLL accurate parton shower Alaric
- Automatic electroweak corrections
- Polarized cross sections

Electroproduction

- Inclusive NC-DIS at NNLO
- NC- and CC-DIS with MEPS@NLO
- Tuning with uncertainties

Photoproduction

- NLO+PS available for jets
- Hard diffraction at LO and NLO



[Meinzinger, Reichelt, Silvetti, 2506.08994]

New in Sherpa 3

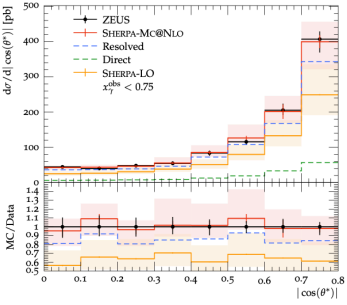
- NLL accurate parton shower Alaric
- Automatic electroweak corrections
- Polarized cross sections

Electroproduction

- Inclusive NC-DIS at NNLO
- NC- and CC-DIS with MEPS@NLO
- Tuning with uncertainties

Photoproduction

- NLO+PS available for jets
- Hard diffraction at LO and NLO



[Krauss, Meinzinger, PRD 109 (2024) 3, 034037]

Theoretical descriptions

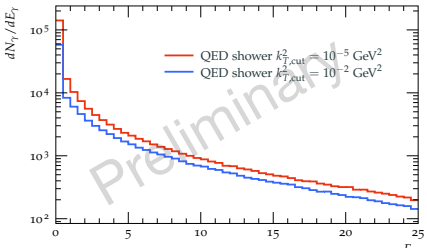
- Classical YFS resummation
- Structure functions with resummation
- QED showers

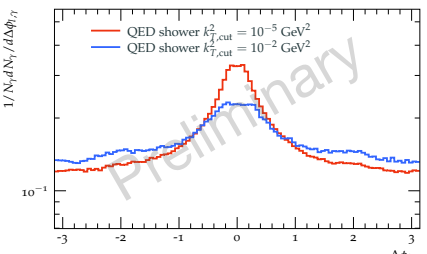
Implementations

- Sherpa: ISR with structure functions, FSR with collinear splitting functions
- Pythia: QED shower, not tested for DIS

Validation

- What are relevant benchmarks?
- Which observables would be relevant?
  $\Rightarrow$ Follow-up meeting on early Autumn



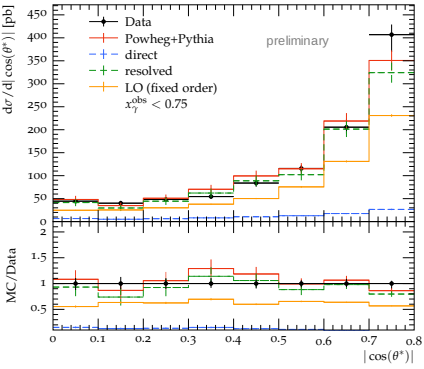


The POWHEG method

- Multiplicative matching of fixed-order NLO hard processes with parton shower
- Available also for DIS

Photoproduction

- Implementation for dijet production
- Avoid double-counting of direct and resolved processes
- Mathced to FSR in Pythia



[A. Feike, T. Ježo and M. Klasen, *in progress*]

Rivet

- Framework to encode experimental analysis and perform these on simulated events
- Consistent and robust comparison of theory predictions and experimental measurement
- Essential for MCEG validation and tuning
- Standard tool for LHC experimentalists, almost 2000 analysis available

Tutorial for EIC

- Self-guided tutorial for EIC-related features and analysis writing
- https://gitlab.com/hepcedar/tutorials/mc4eic25

MC4EIC Tutorial: Rivet for EIC

Useful links: Workshop website | HepMC event files

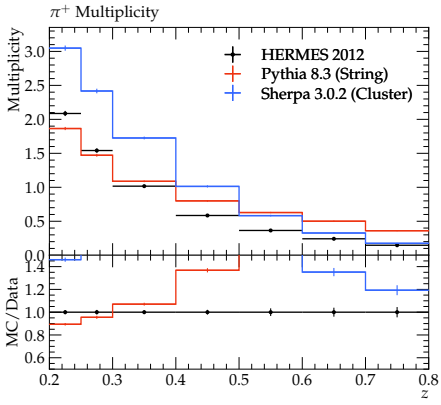
MCEG validation for EIC

- A limited selection (41/514) of analyses available from H1 and ZEUS, none from fixed-target e-p/A (HERMES, COMPASS)
- Not enough for EIC requirements

⇒ An afternoon for writing new analyses

An example outcome (Max Knobbe)

- `HERMES_2012_I1208547`
- Multiplicities of charged Pions and Kaons in SIDIS at 27.6 GeV electrons
- Comparisons with Pythia and Sherpa



[HERMES: PRD 87 (2013) 074029]

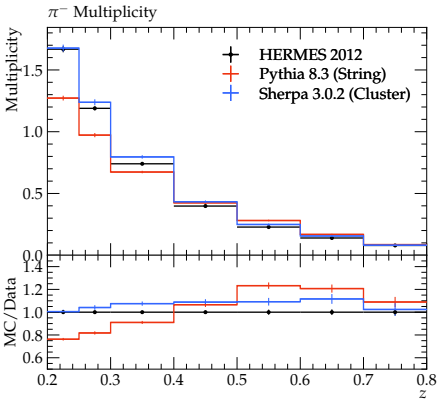
MCEG validation for EIC

- A limited selection (41/514) of analyses available from H1 and ZEUS, none from fixed-target e-p/A (HERMES, COMPASS)
- Not enough for EIC requirements

⇒ An afternoon for writing new analyses

An example outcome (Max Knobbe)

- `HERMES_2012_I1208547`
- Multiplicities of charged Pions and Kaons in SIDIS at 27.6 GeV electrons
- Comparisons with Pythia and Sherpa



[HERMES: PRD 87 (2013) 074029]

Future MC4EIC plans

QED radiation effects

- A follow-up meeting to discuss implementations and validation

A write-up of the MC4EIC meetings

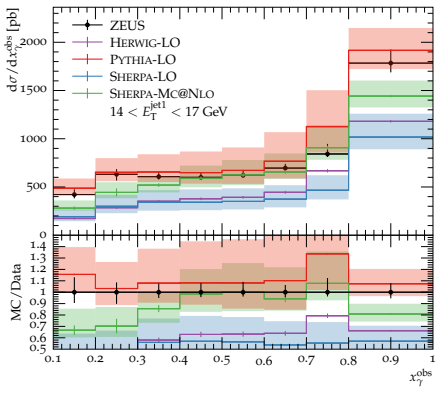
Markus Diefenthaler, Frank Krauss, I.H.

- Discussion on physics requirements and generator status review
- MCEG validation with selected HERA analyses

Further validation with Rivet

- Tutorial in place for EIC, several examples available

  $\Rightarrow$ Code up your own analysis!



[I. Helenius, P. Meinzinger, S. Plätzer, P. Richardson, arXiv:2406.08026]