Monte Carlo Generators for
Lepton-Hadron Colliders

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disclaimer: will focus on multi-purpose inclusive Monte Carlos only

(my apologies if I miss something dear to your heart)

- why lepton-hadron physics?

- Monte Carlos for DIS

- Monte Carlos for photo-production

- Including heavy ions

- Summary

why lepton-hadron physics?

simple answer(s)

1. next large experiment: EIC, but also LHeC

   EIC science case (reminder):
   1. extract the Wigner function (3D-structure)
   2. free nucleons vs. nucleons in nuclear matter
   3. saturation physics

2. traditional test frame for QCD/strong interactions:
   - QCD scaling & strong coupling
   - nucleon/nuclear structure

3. interface of particle & nuclear physics

4. important inputs for future neutrino programme (nuclear structure)

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Monte Carlos for DIS:
the next generation is here

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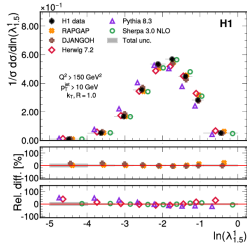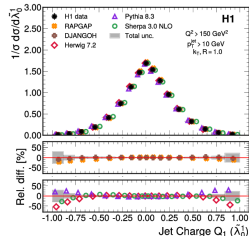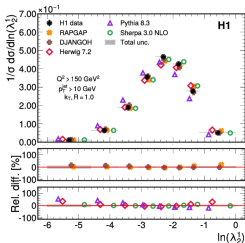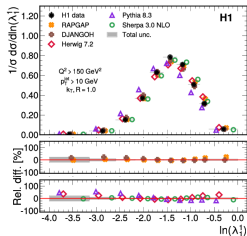# Monte Carlos for DIS, past & present - bird's eye view

- DJANGOH, RAPGAP, LEPTO, . . .
- LO matrix elements + parton showers
  (usually PYTHIA or ARIADNE)
- interface to Lund fragmentation
- QED ISR mainly through interfaces
  (usually HERACLES)
- diffraction with pomeron flux and pomeron PDF

- HERWIG, PYTHIA, SHERPA, and POWHEG +PYTHIA
  (certainly more to come!)
- NLO matched and/or merged
- various (internal) parton showers for systematic studies
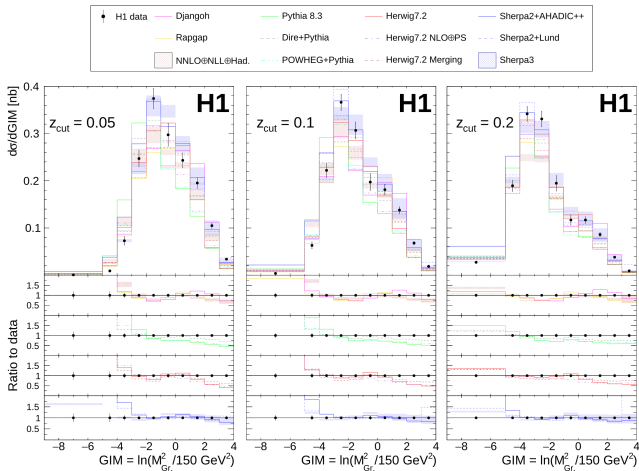- "complete" frameworks, including fragmentation, QED, . . .

recent example results: jet sub-structures at H1
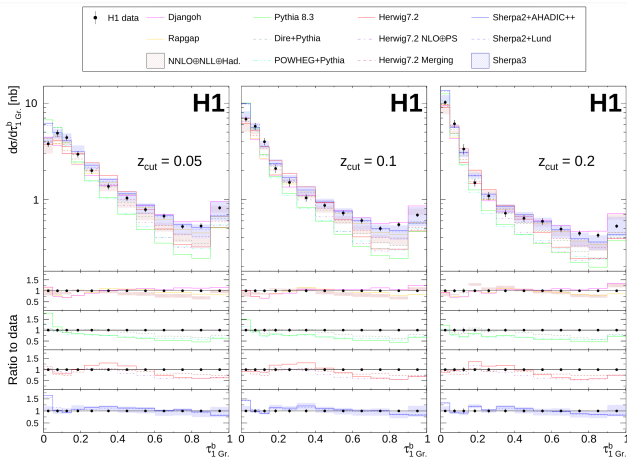
(Phys.Lett.B 844 (2023) 138101)

recent example results: groomed event shapes at H1

(2403.10134 [hep-ex])

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(2403.10134 [hep-ex])
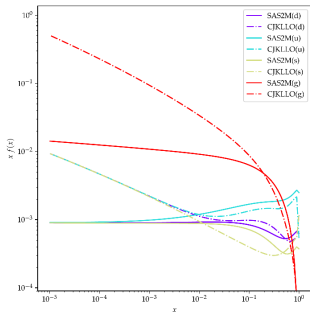
Monte Carlos for photo-production

theory framework

- assume: $Q^2 \overset{<}{\sim} 4$ GeV^2 $\longrightarrow$ photons are quasi-real

  (model with equivalent photon approximation: photons collinear and $Q^2 = 0$)

- two components:
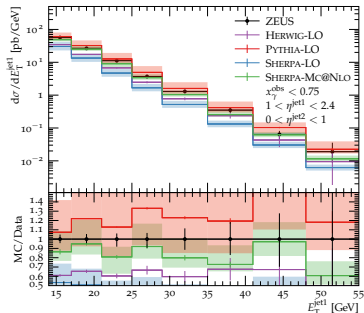
  (kinematically identified in experiment)
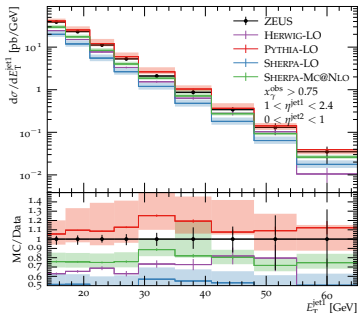
  - direct: photon = point-particle
  - resolved: photon has internal
    structure, like a hadron
    mixture of non-perturbative photon=vector meson and perturbative $\gamma \rightarrow q\bar{q}$ splittings + QCD evolution components
  - last fit of resolved component:
    about 2 decades ago
    (maybe an interesting place for UK PDF groups?)
  - large $\sigma_{\gamma p}$ at low Q^2: critical input for
    EIC!

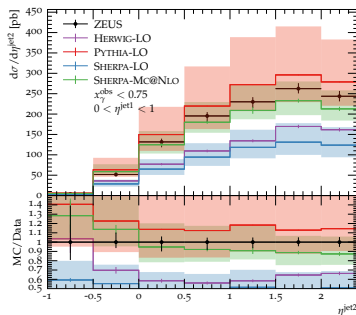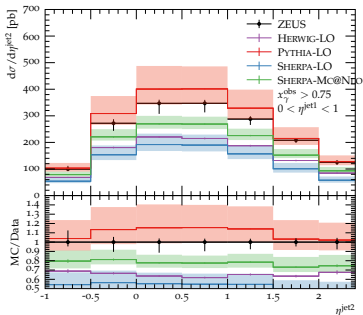# recent MC comparison

(2406.08026 [hep-ph])

- on-going validation effort: impact of
  LO vs. NLO, different PDFs, values of α_S, MPIs etc.
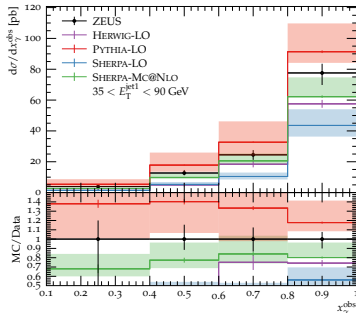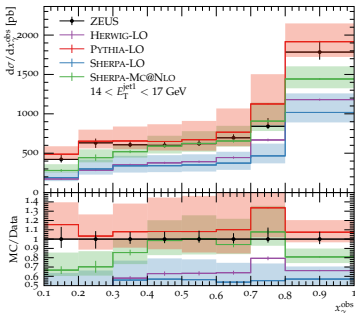
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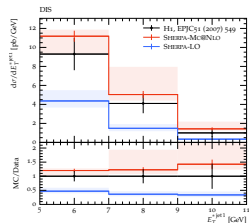
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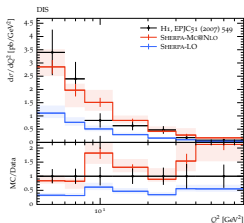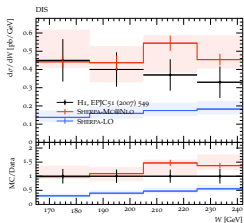
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recent SHERPA results: hard diffraction

(2407.02133 [hep-ph])

- DIS: ✓

recent SHERPA results: hard diffraction

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- DIS: ✓

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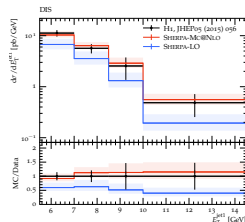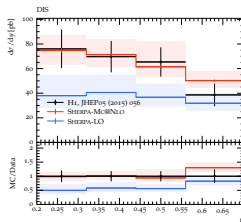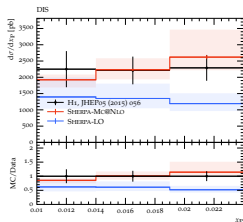
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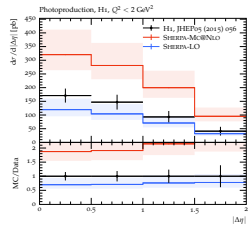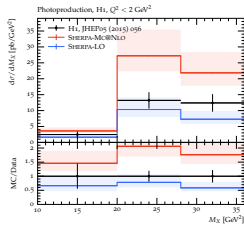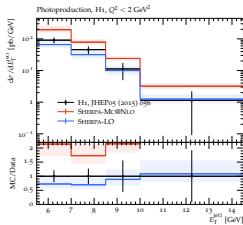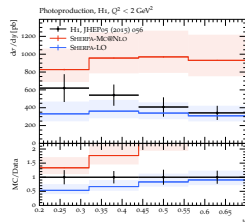- photo-production: ✗ (interpreted as factorization breaking)

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including heavy ions

modelling lepton-nucleus collisions

- currently (and traditionally) a bit of a mess:
  - often just "superposition+X" of PYTHIA etc.
  - great new approaches, mainly for (inclusive) LHC: DIPSY, ANGANTYR
  - plus a multitude of codes for jet quenching
- but: no real integrated picture
  (personal: the approach/framework is maybe a bit too fragmented)
- efforts mandatory!

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summary & future attractions

- summary:
  - new event generators incorporate a lot of "new" technology

    (transfer from LHC, at least as good as or better than previous)
  - "(re-)discovery" of photo-production as important arena
  - diffraction with pomeron PDFs: DIS ✓, photo-production ✗

- ongoing work (within existing frameworks):
  - matrix elements and parton showers: NNLO/N^{3}LO $\otimes$ N^{n}LL

    showers: see PANSCALES & ALARIC
  - seamless combination of DIS & photo-production
  - more/better soft physics: hadronization, MPI, diffraction, . . .

further needs

- to fully support Eic's science programme:
  1. importance of photo-production: new fits of photon PDF

     (no, **not** photon as parton of proton, but **parton content of photon**)
  2. saturation physics: add non-linear kernels to parton showers

     (recombination and space-time picture – conceptually challenging)
  3. analysis of 3D structure: new parton showers based on TMD's

     (at least unpolarised TMD's – conceptually new)
  4. nuclear targets: new integrated simulation frameworks

     (rescattering of hadrons/partons in medium, fragementation, . . . – lots of new concepts)