The SHERPA 3 event generator

3rd ECFA workshop on e^+e^- Higgs, Top & ElectroWeak Factories, Paris, 10 October 2024

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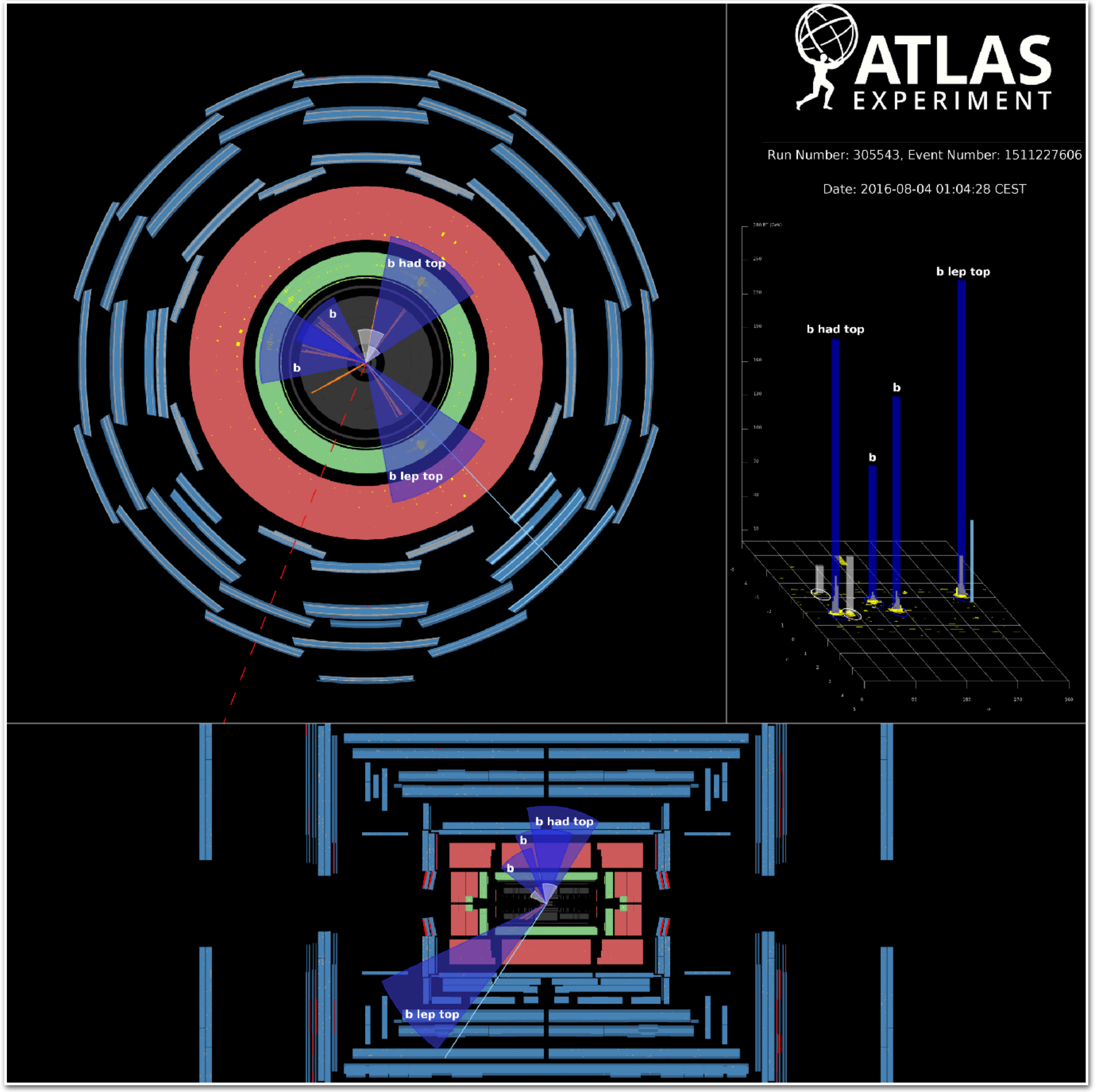
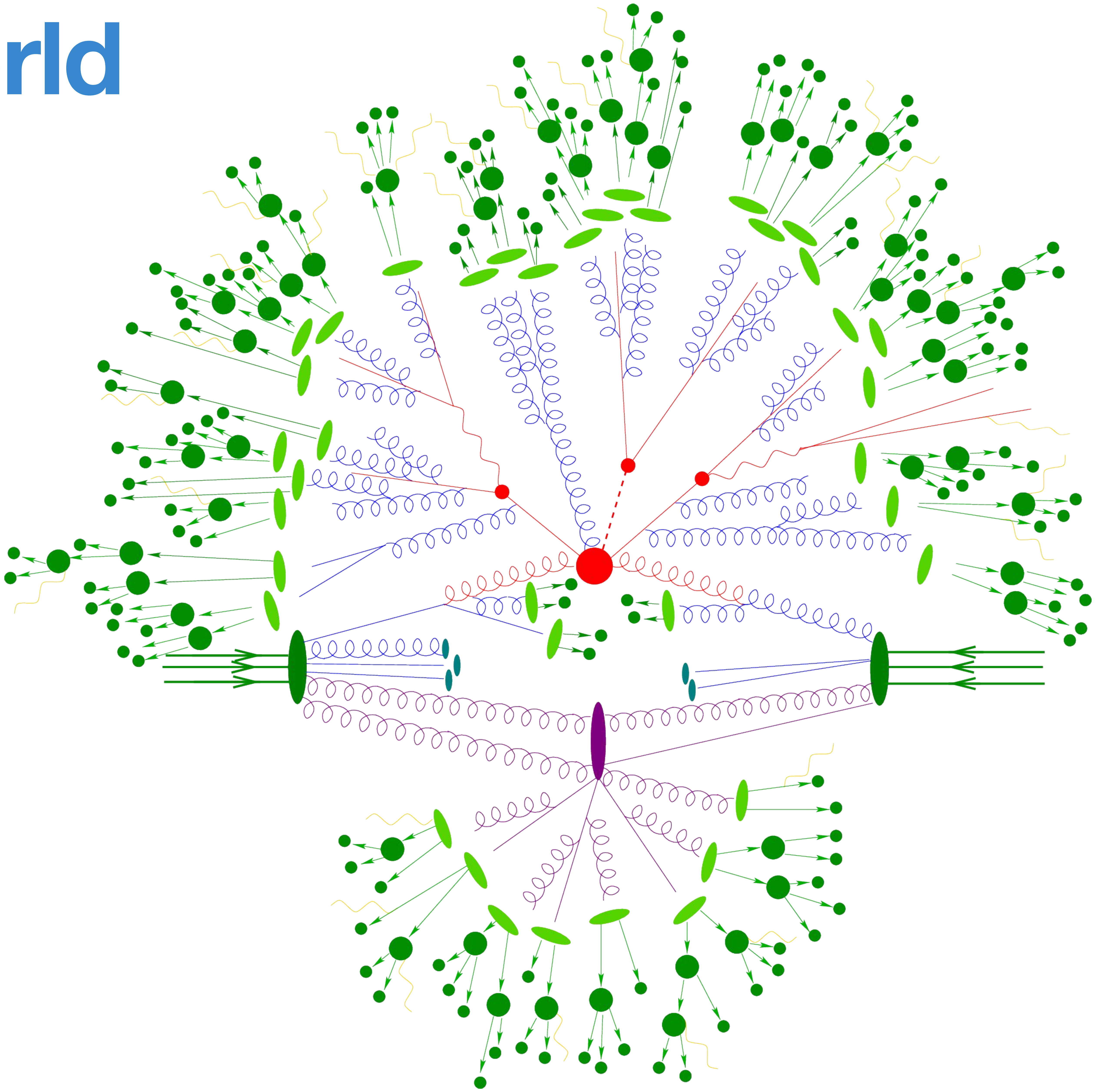
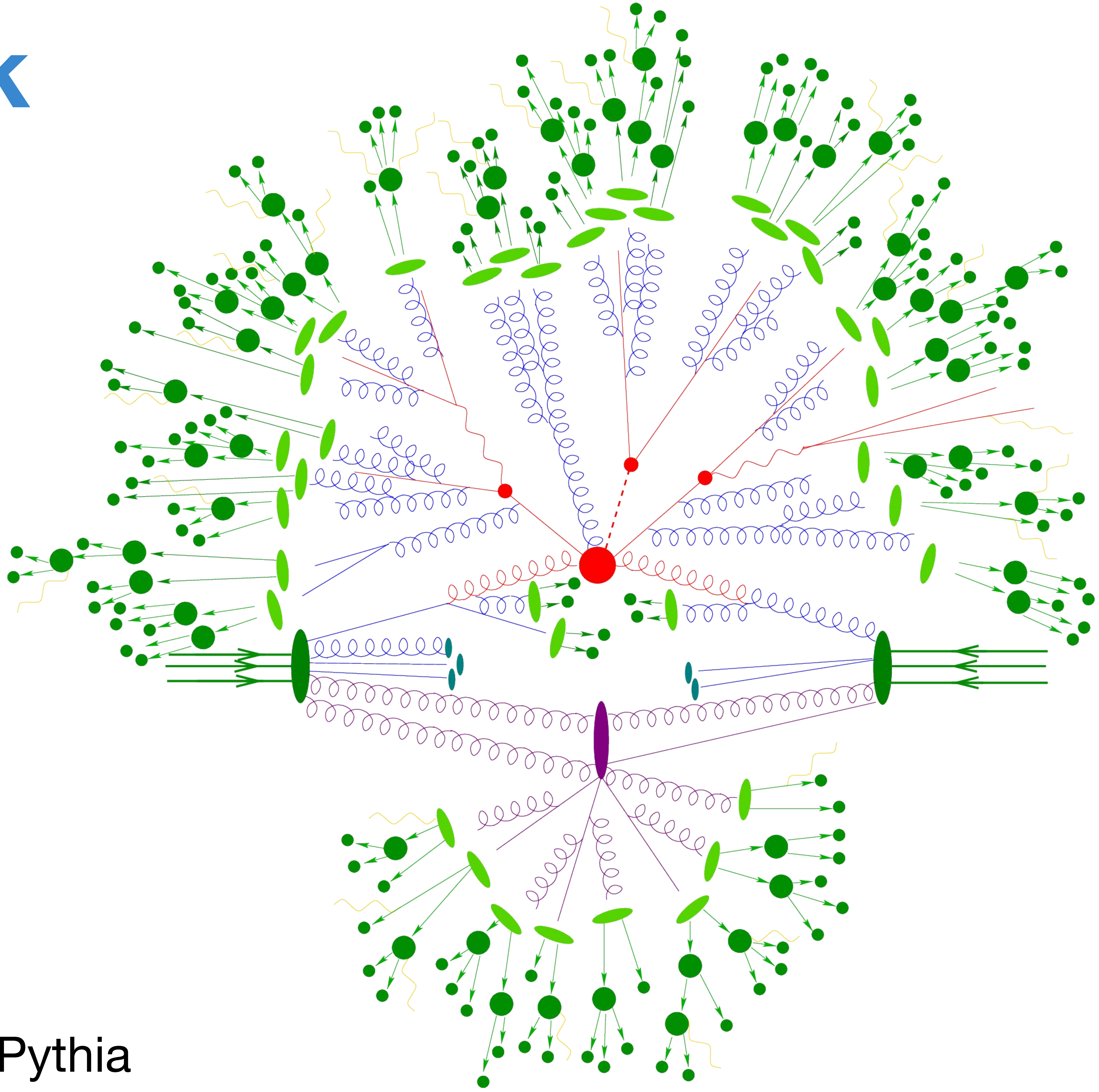
Colliders in the real world





The SHERPA framework

- ME generators for hard process
  - Comix, Amegic
  - + interfaces to loop libraries (OpenLoops, Recola, MCFM)
- Parton Showers
  - CSShower, Dire
- Underlying Event/MPI model
- Hadronisation
  - Cluster Fragmentation, + interface to Pythia
- QED radiation via YFS resummation



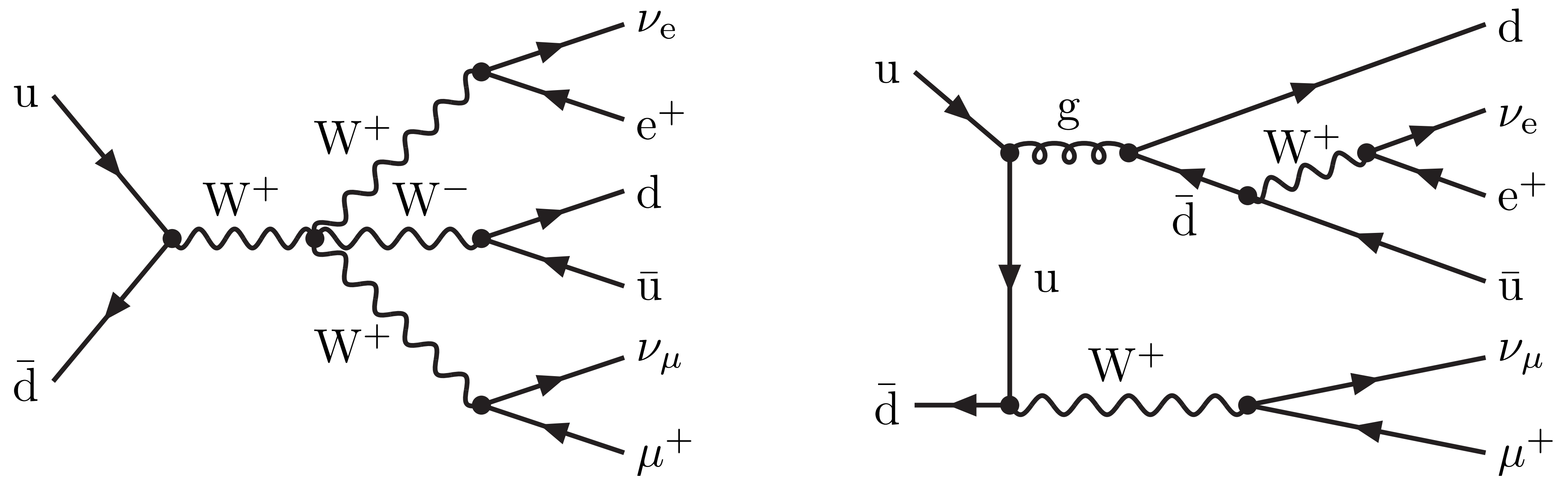
SHERPA 3 — multi-purpose event generation

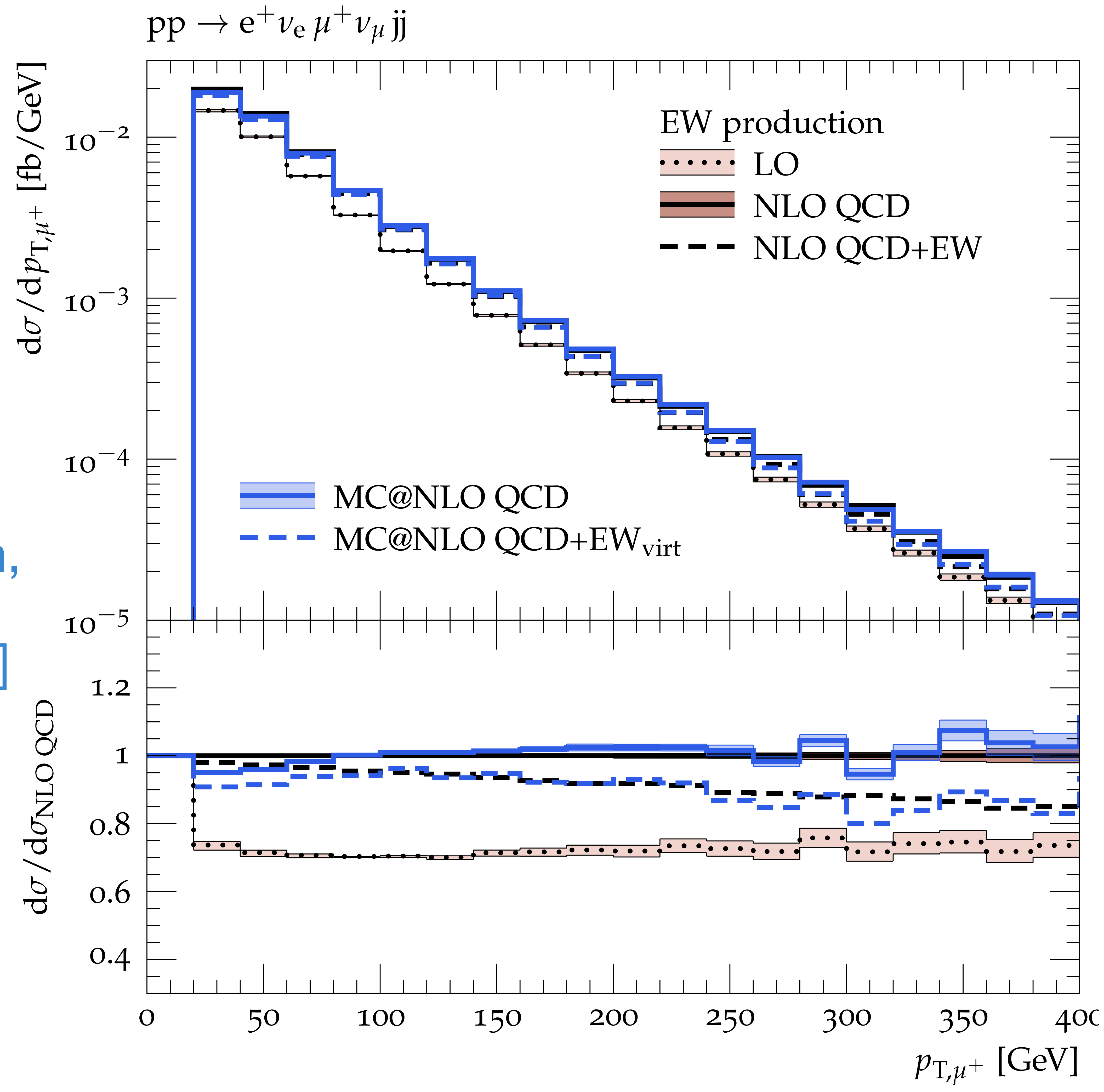
- (Selected) Features:
  - Fixed Order
    - NLO QCD+**EW**,
    - **NNLO** QCD (selected processes)
  - Automated NLO (QCD) matching in S-MC@NLO
  - **UN2LOPS** matching to NNLO QCD
  - multi-jet merging in CKKW-L
  - Approximate **EW-corrections in matching & merging** (EWvirt/EWSud)
  - **Photoproduction @ NLO QCD + PS**
- YFS resummation of photon radiation
  - radiation from final state leptons
  - **initial state radiation** at e^+e^- colliders
  - extended by $\gamma \to f\bar{f}$ **splittings**
- Polarised
  - beams
  - **intermediate particles**
- MPI/MinBias and **fragmentation modelling, including color reconnection**
- External Interfaces:
  - HepMC 3
  - UFO 2 (including **form factors**)
  - RIVET 3/4
  - LHAPDF + several explicit pdf interfaces including various **photon pdfs**
  - OpenLoops/ Recola/MCFM/ MadLoops/ BlackHat
  - **Pythia 8** (string fragmentation)

bold - added/significantly updated in Sherpa 3 development, some back-ported to Sherpa 2

NLO EW corrections and MC@NLO

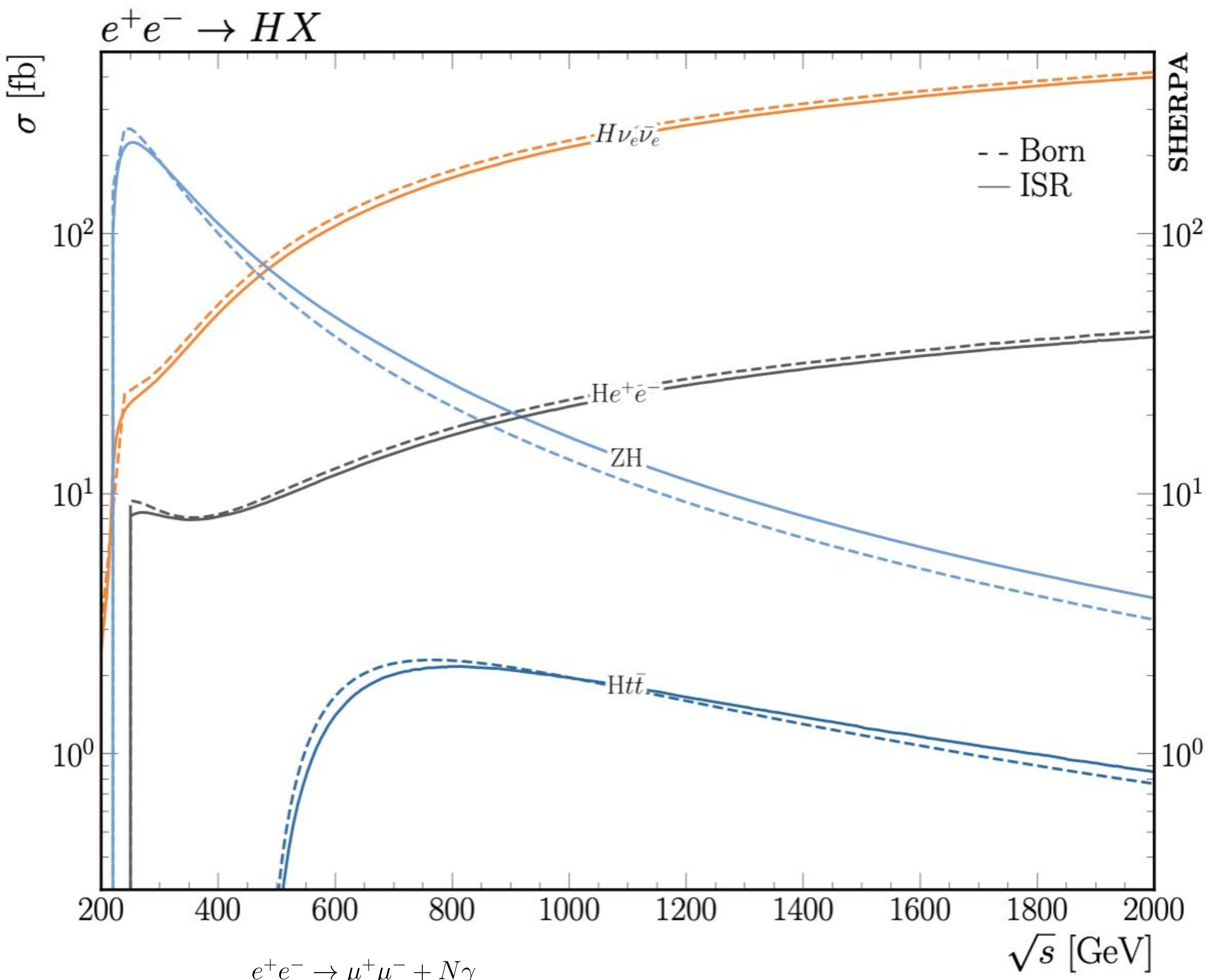
- NLO and MC@NLO crucial for current theory successes at LHC, traditional focus of SHERPA
- **New:** NLO EW calculations [Schönherr '17]
- Example: Full NLO calculation for tri-bosons $pp \to e^+\mu^+\nu_e\nu_\mu jj$ [Denner, Pellen, Schönherr, Schumann '24]
- Combined with MC@NLO in $\mathrm{EW_{virt}}$ approximation

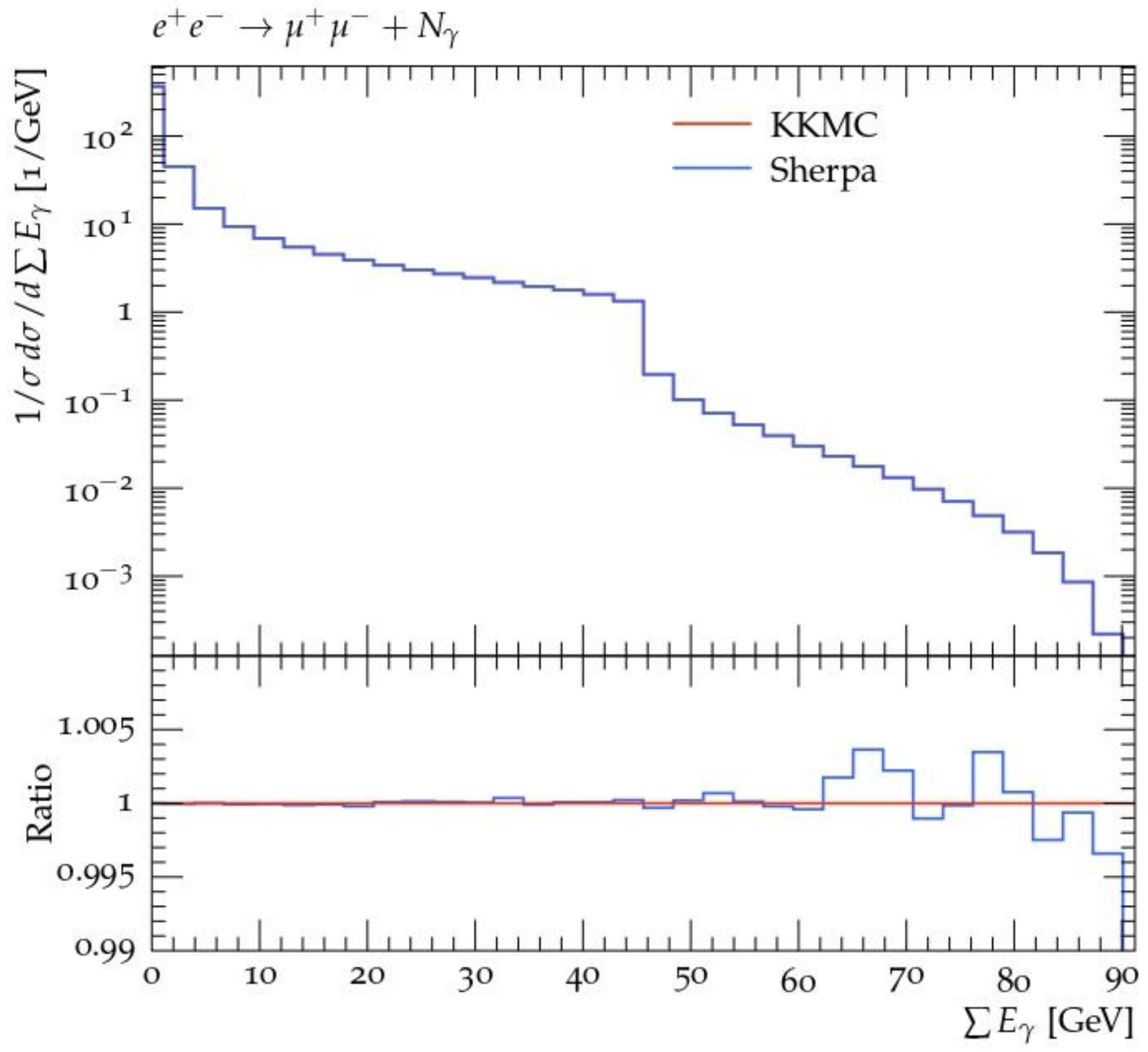


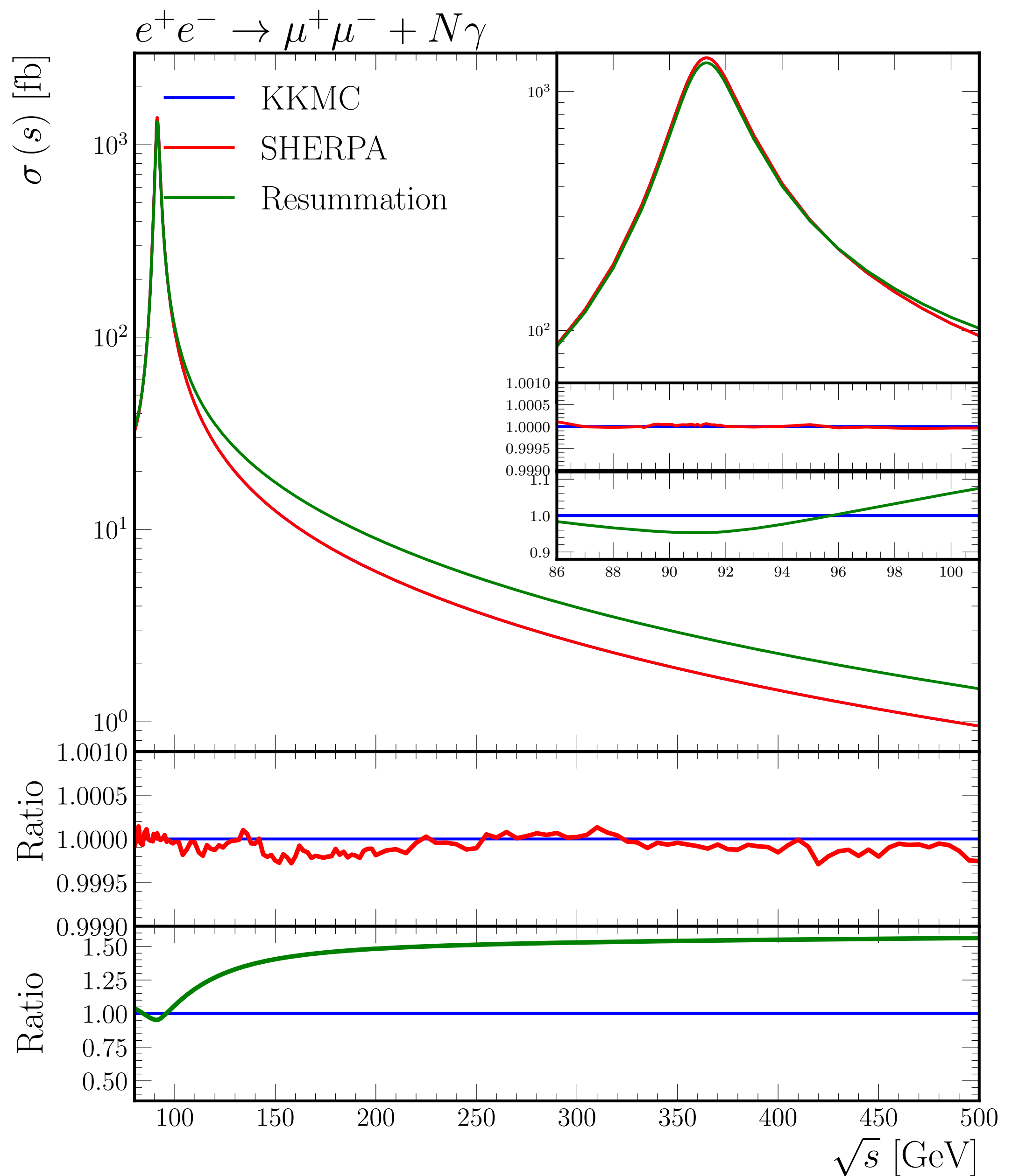


QED initial state radiation

- Soft photon resummation in Sherpa via YFS module [Krauss, Schönherr '08]
- **New**: real photon emission from initial state [Krauss, Schönherr, Price '22]
- replace simple electron pdf with explicit multi-photon emissions
- validated agains KKMC [Jadach, War, Was '99]

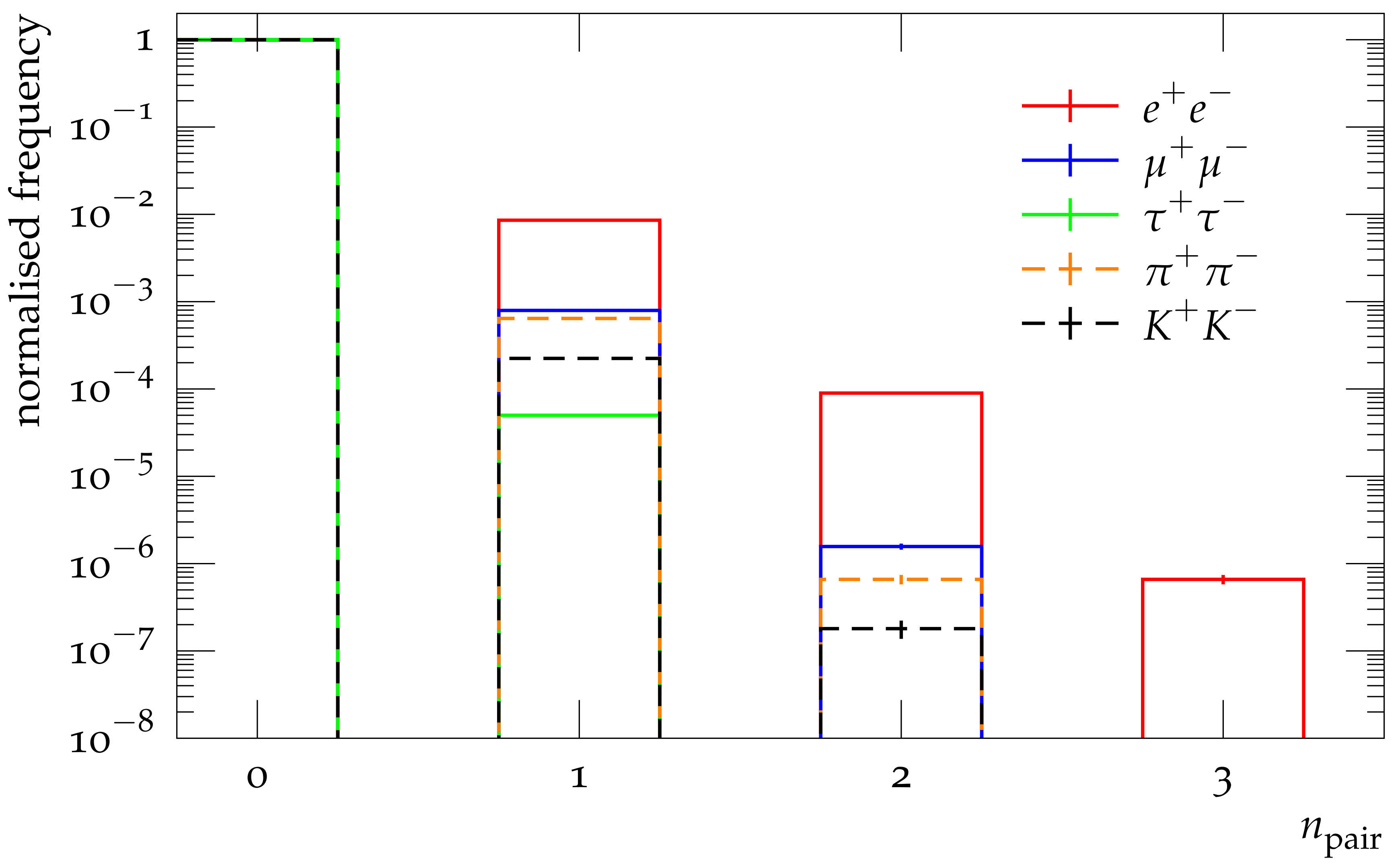


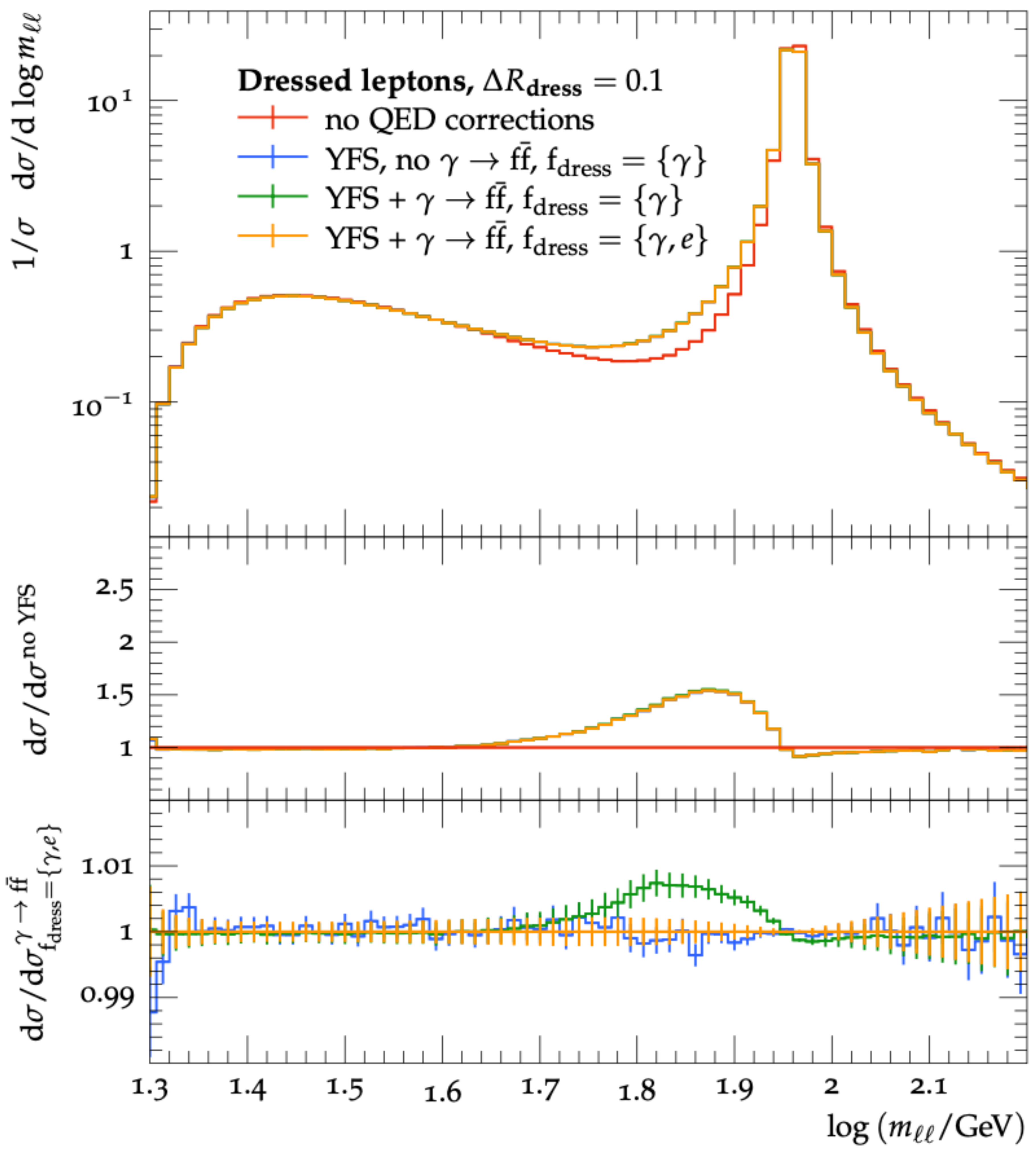




QED radiation with $\gamma \to e^+e^-$

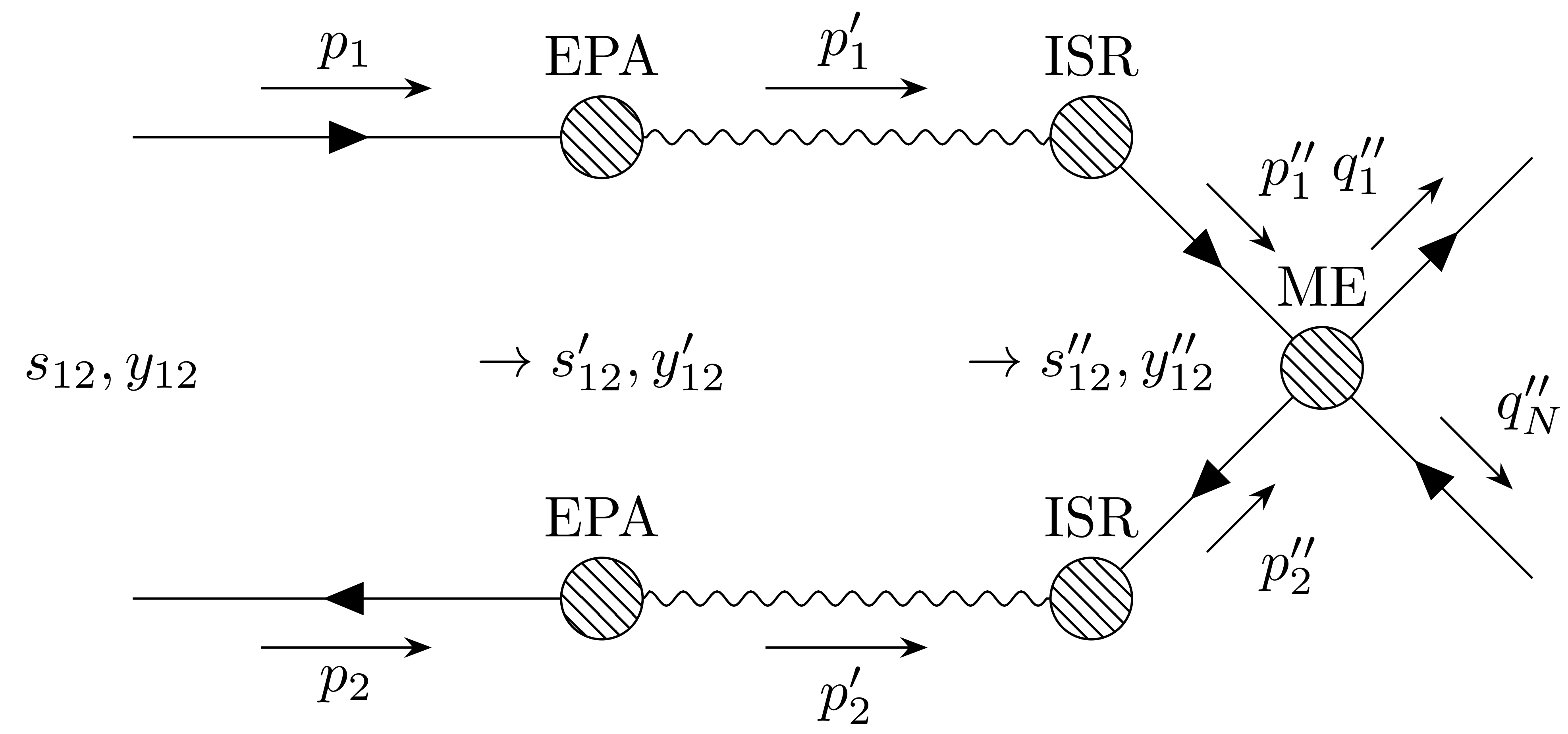
- Final state QED radiation, i.e. photon radiation from final state leptons [Krauss, Schönherr '08]
- **New**: supplemented with $\gamma \to e^+e^-$ splittings [Flower, Schönherr '22]
- Example: dilepton invariant mass in $pp \to e^+e^-$

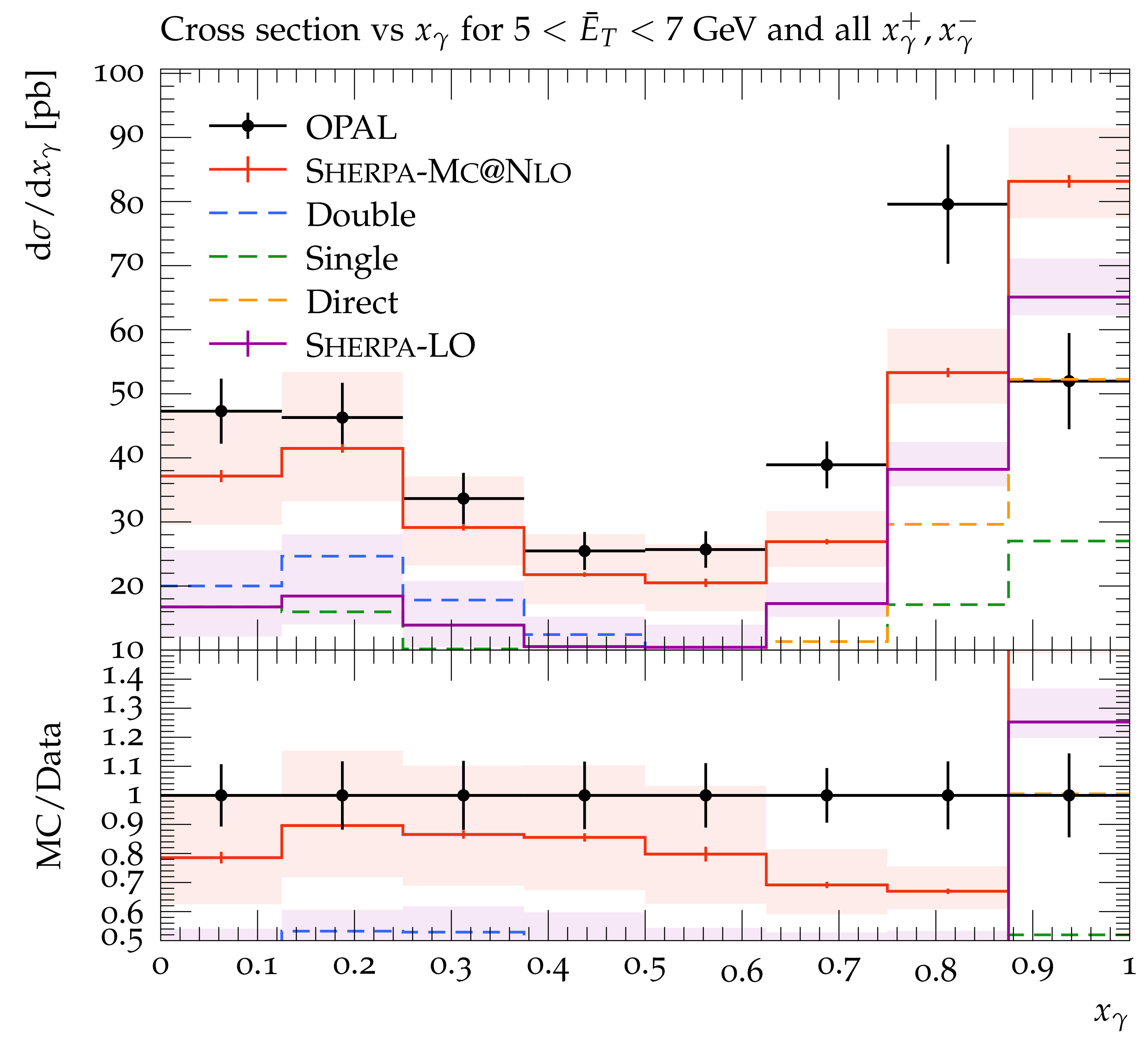


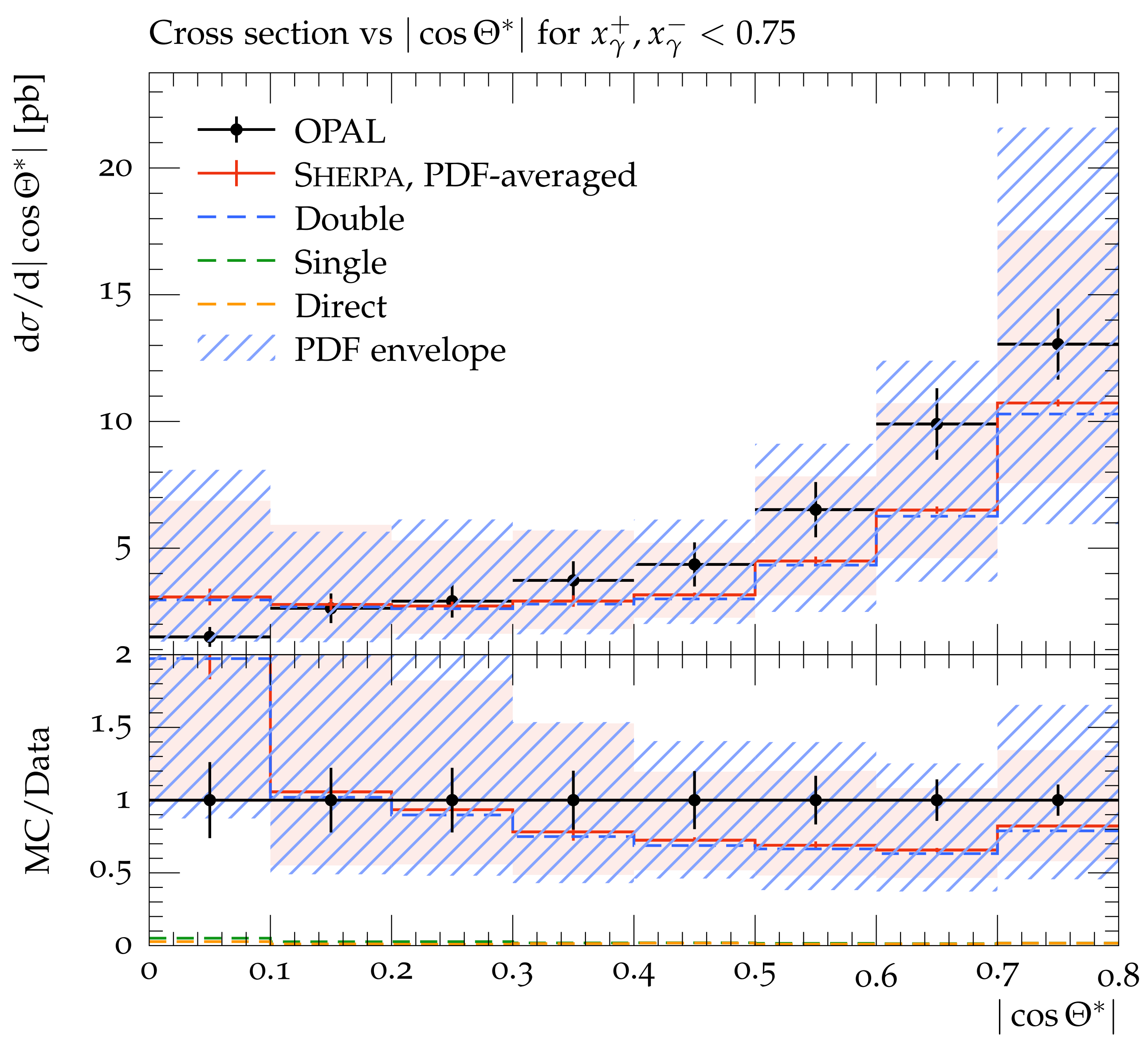


Photoproduction

- **New:** Photoproduction processes including MC@NLO matching
  [Höche, Krauss, Meinzinger ’23]
- photon spectrum in effective photon approximation
- photon either directly takes part in hard process or is “resolved” into quarks/hadrons
- photon pdf (i.e. partons in the photon) limit precision

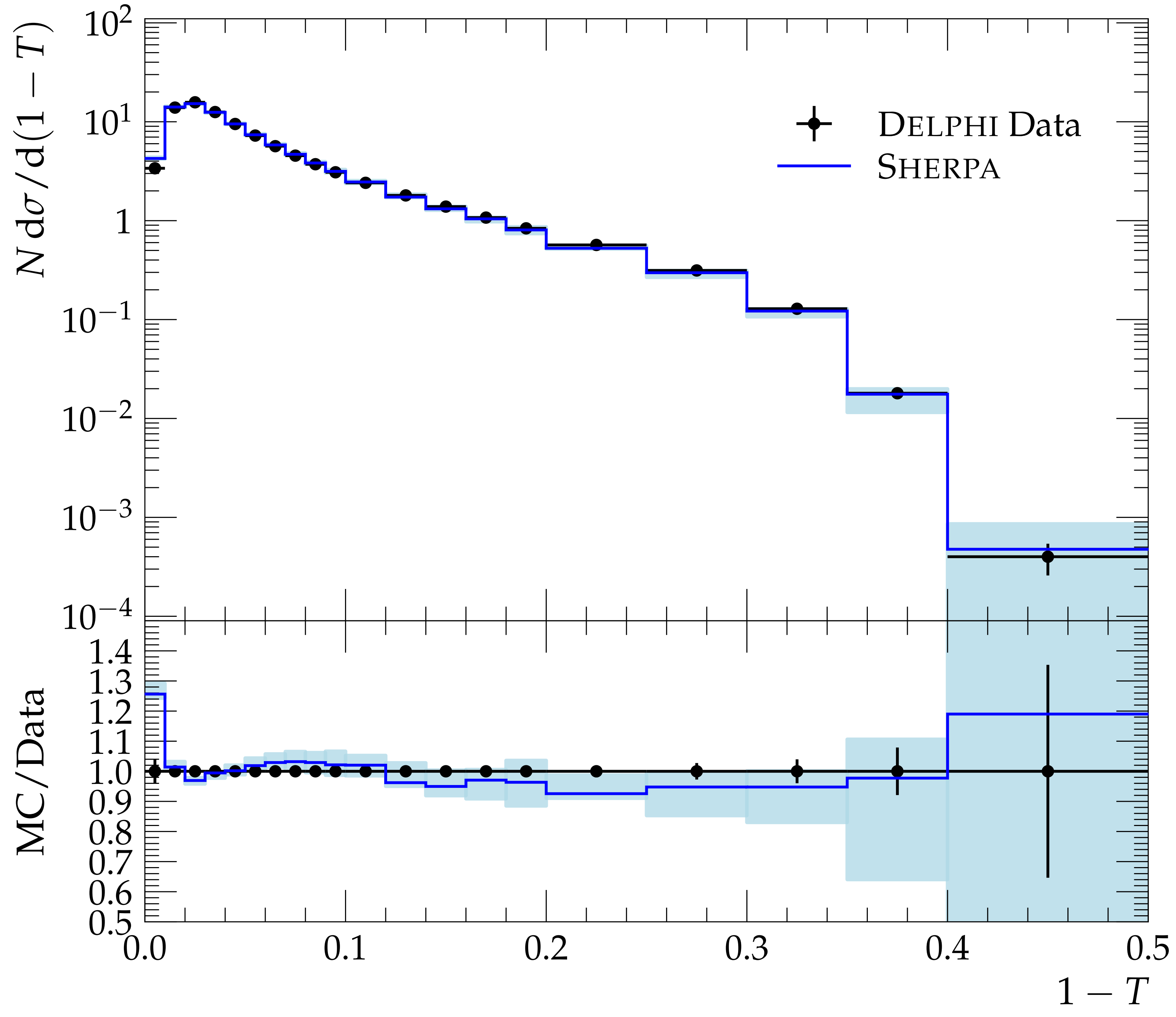


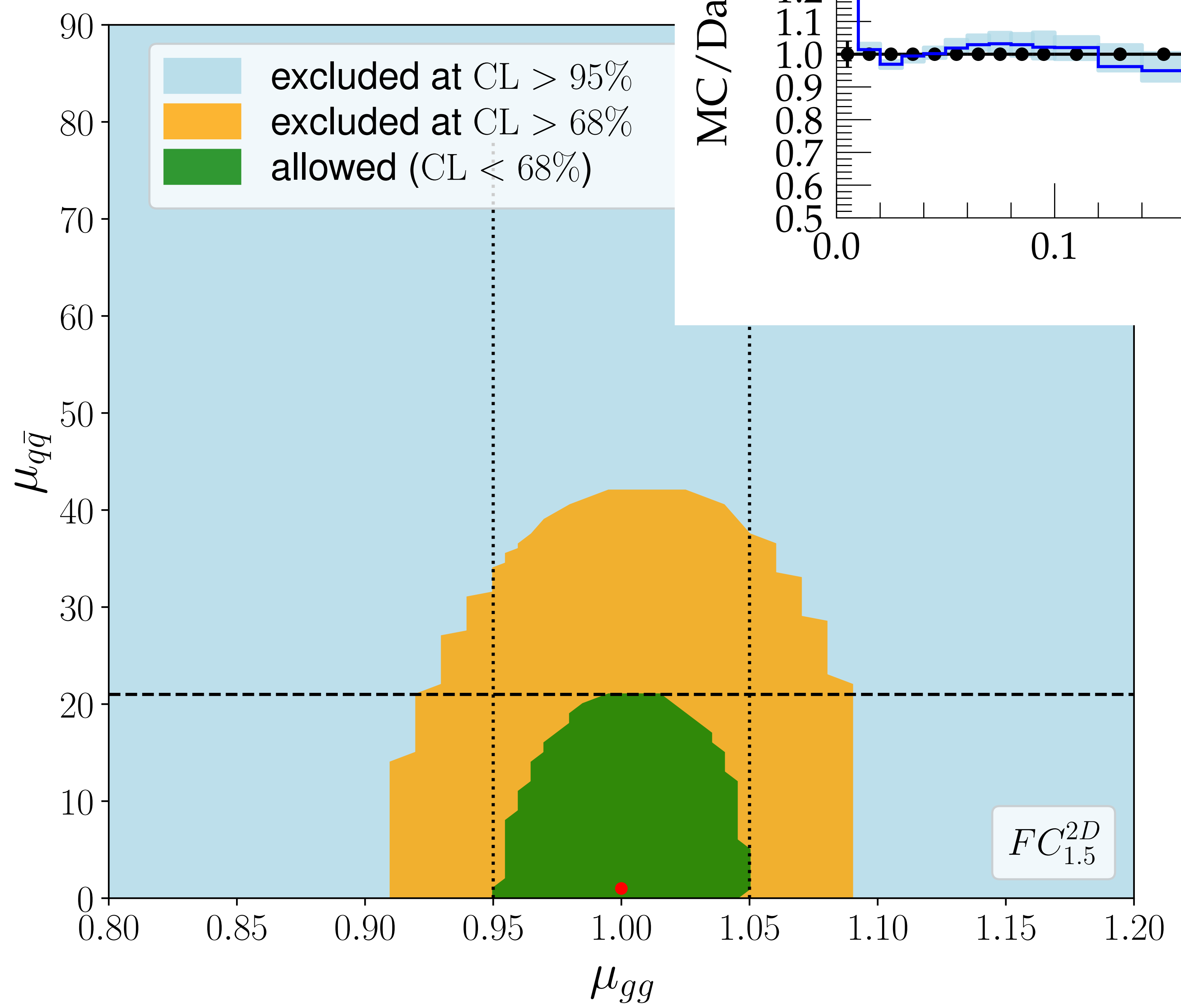




QCD at lepton colliders

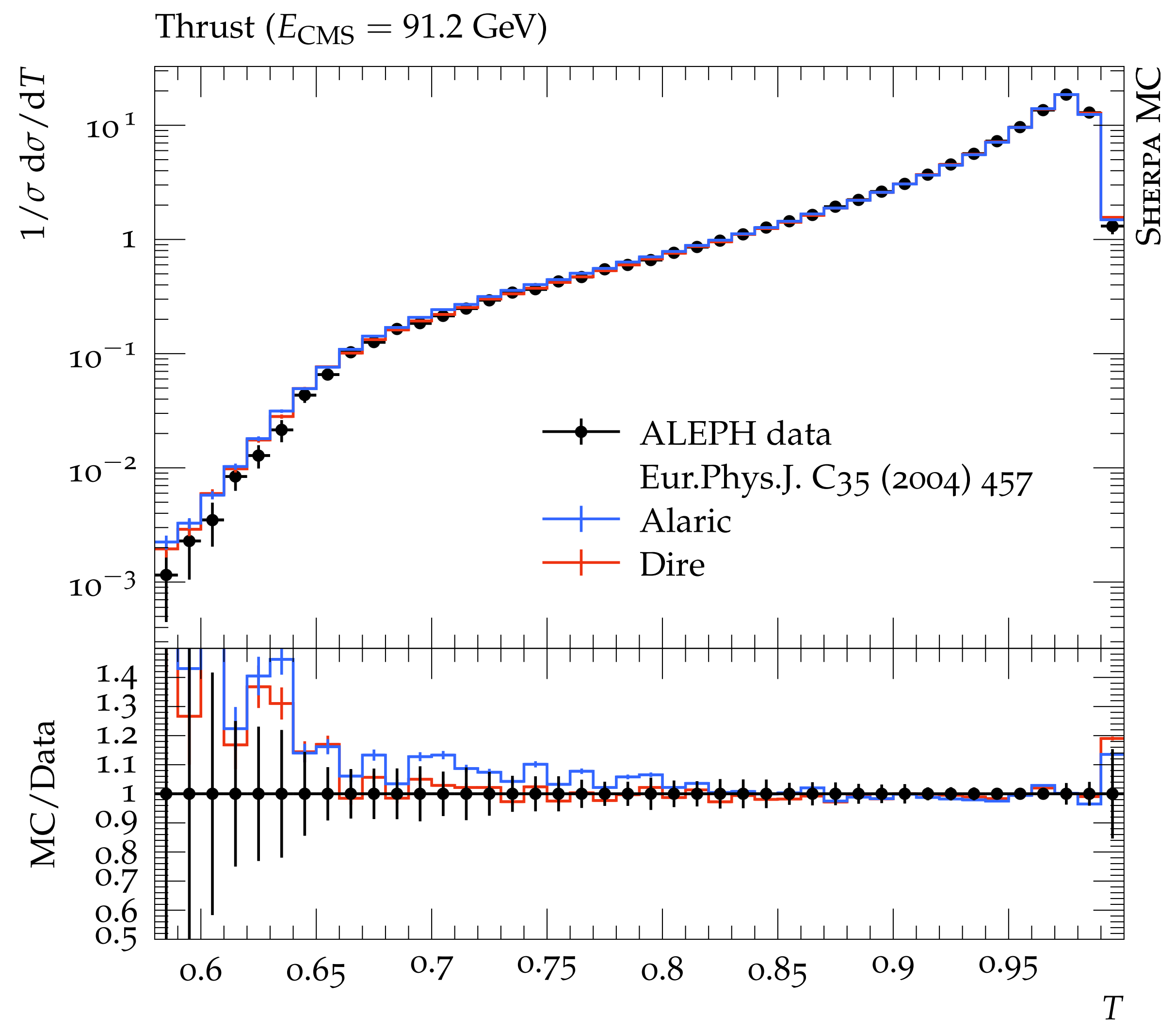
- not only important as probe of QCD
- understand jet/event (sub)structure
  e.g. in $H \rightarrow \text{hadrons}$
- example strategy: [Knobbe, Krauss, DR, Schumann ’22]
  - tune Sherpa 3(α/β) to LEP data at $\sqrt{s} \approx M_Z$
    - replica tunes to gauge internal uncertainty of cluster fragmentation tune
  - analyse Higgs decays in $e^+e^- \rightarrow ZH$ at $\sqrt{s} = 240\ \text{GeV}$

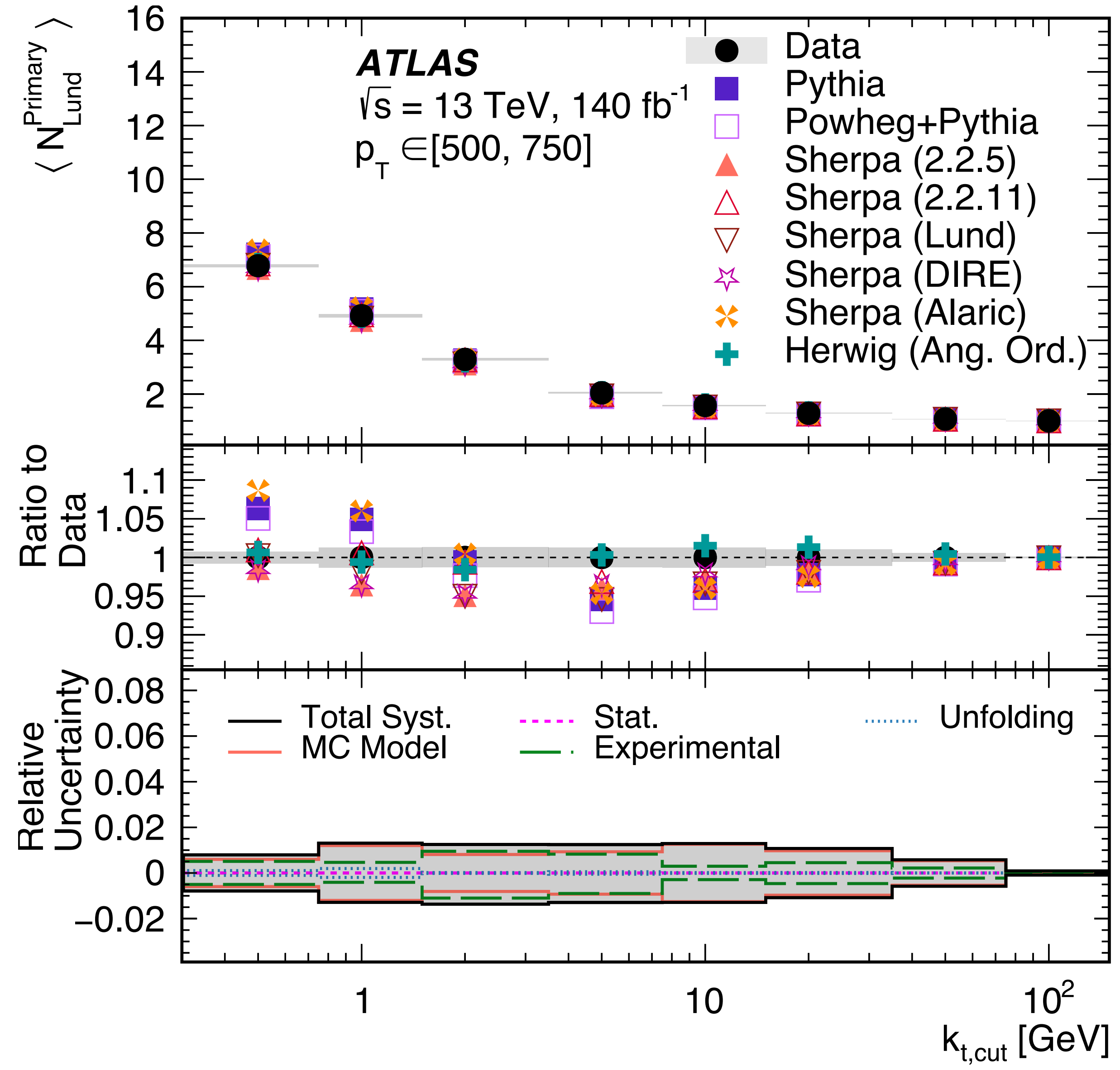


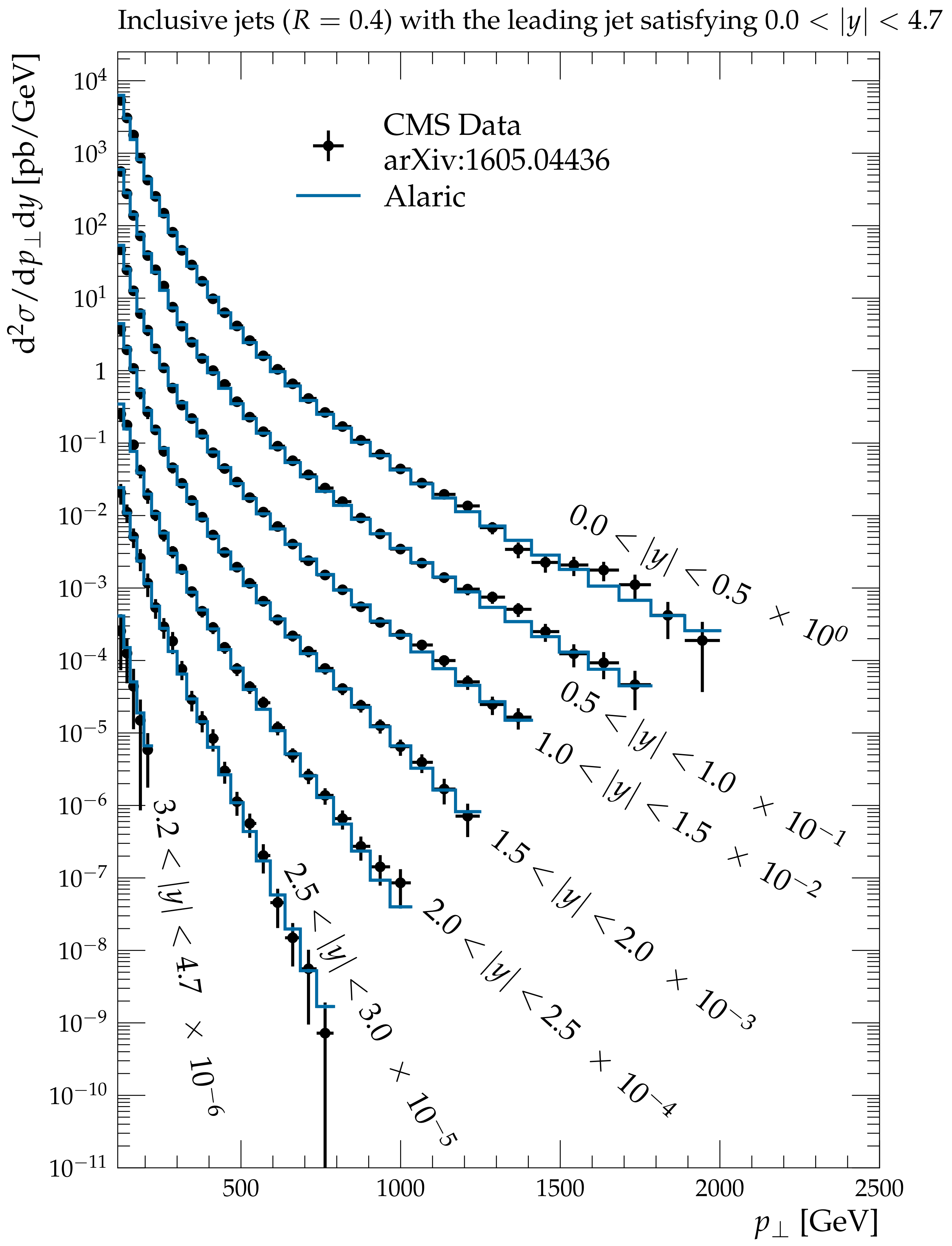


Outlook: more accurate parton showers

- **New:** Parton shower module ALARIC
  [Herren, Höche, Krauss, DR, Schönherr,’22]
  - explore connection between angular ordering and dipole showers
  - address NLL deficiencies found in recoil schemes of current dipole showers
- Multi-jet merging available now
  [Höche, Krauss, DR ‘24]
  - + first LHC phenomenology
- full NLO matching still WIP
- Basis for development towards higher accuracy showers

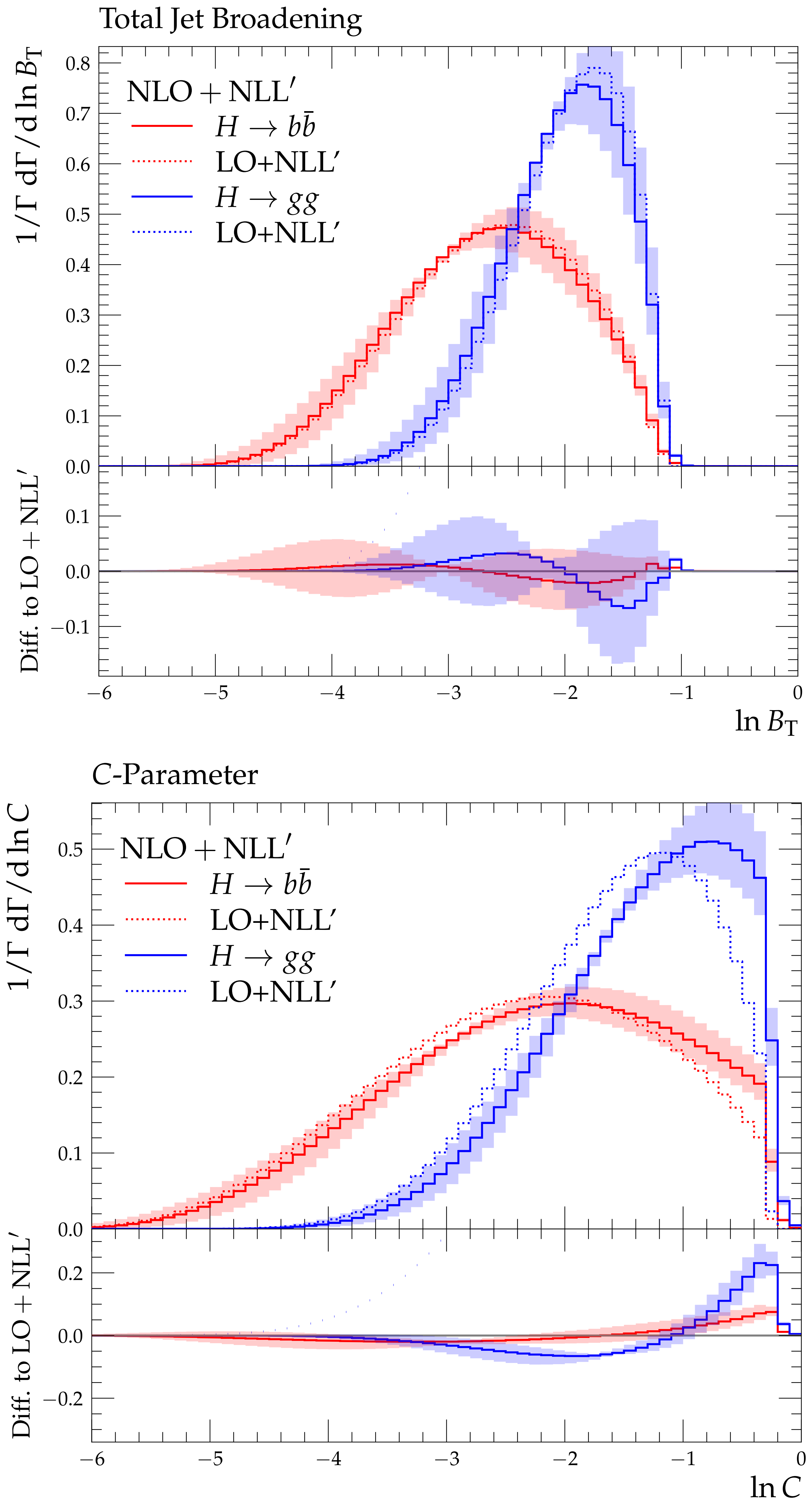






Outlook: automated resummation

- accesible precise resummed calculations important
  - predictions for experiments
  - references for parton showers
- CAESAR formalism provides convenient framework event/jet shape-type observables [Banfi, Salam, Zanderighi ’04]
- CAESAR implementation in Sherpa [Gerwick, Höche, Marzani, Schumann ’15] [Baberuxki, Preuss, DR, Schumann ’19]
  - several studies already for LEP/ LHC/RHIC/FCC-ee (future lepton collider)



Example: event shapes in $H \to gg$ and and $H \to q\bar{q}$ decays using EERad in conjunction with Sherpa+CAESAR [Gehrmann-de Ridder, Preuss, DR, Schumann ’24]

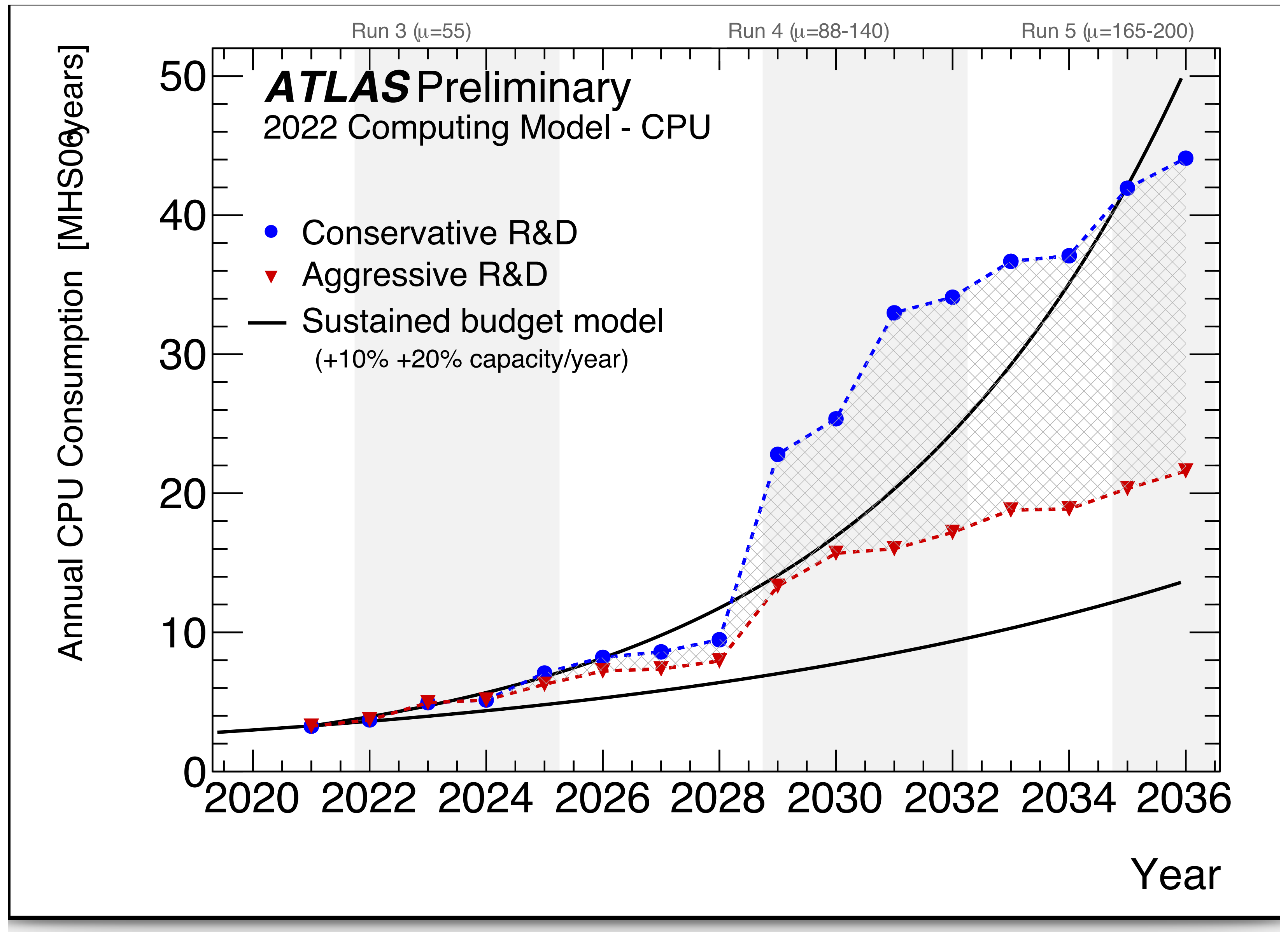
Outlook: performance updates/HPC

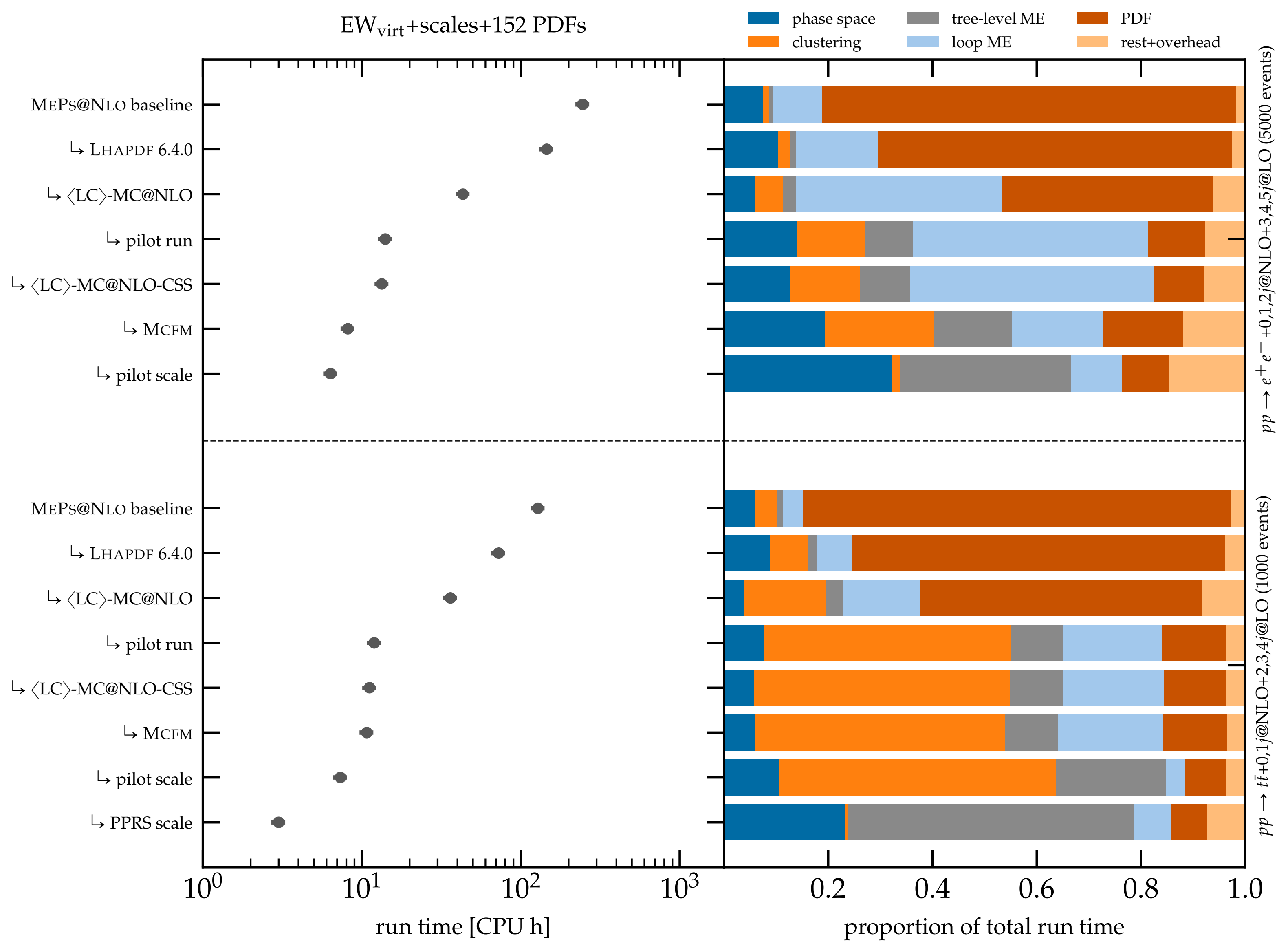
[arXiv:2209.00843]
slide by E. Bothmann

- MC event generation uses significant+increasing resources
- (HL-)LHC measurements in danger of being limited by MC statistics
- Explore reduction of CPU footprint for heaviest use cases, e.g. ATLAS default setup $Z + 0{,}1{,}2j\,@\mathrm{NLO} + 3{,}4{,}5j\,@\mathrm{LO}$

  1. LHAPDF improvement
  2. ⟨LC⟩-MC@NLO: reduce matching accuracy to leading colour, neglect spin correlations, i.e. S-MC@NLO → MC@NLO
     also useful to reduce negative event fractions [Danziger, Höche, Siegert 2110.15211]
  3. pilot run: minimal setup until PS point accepted, then rerun full setup
  4. ⟨LC⟩-MC@NLO-CSS: defer MC@NLO emission until after unweighting
  5. use analytical loop library where available
     here: OpenLoops → MCFM via interface [Campbell, Höche, Preuss 2107.04472]
  6. pilot scale definition in pilot run that requires no clustering
     small weight spread by correction to correct scale

- all new developments part of Sherpa 2.2.13 or later





SHERPA 3

- SHERPA 3 available https://sherpa-team.gitlab.io/
  - NB: several technical improvements:

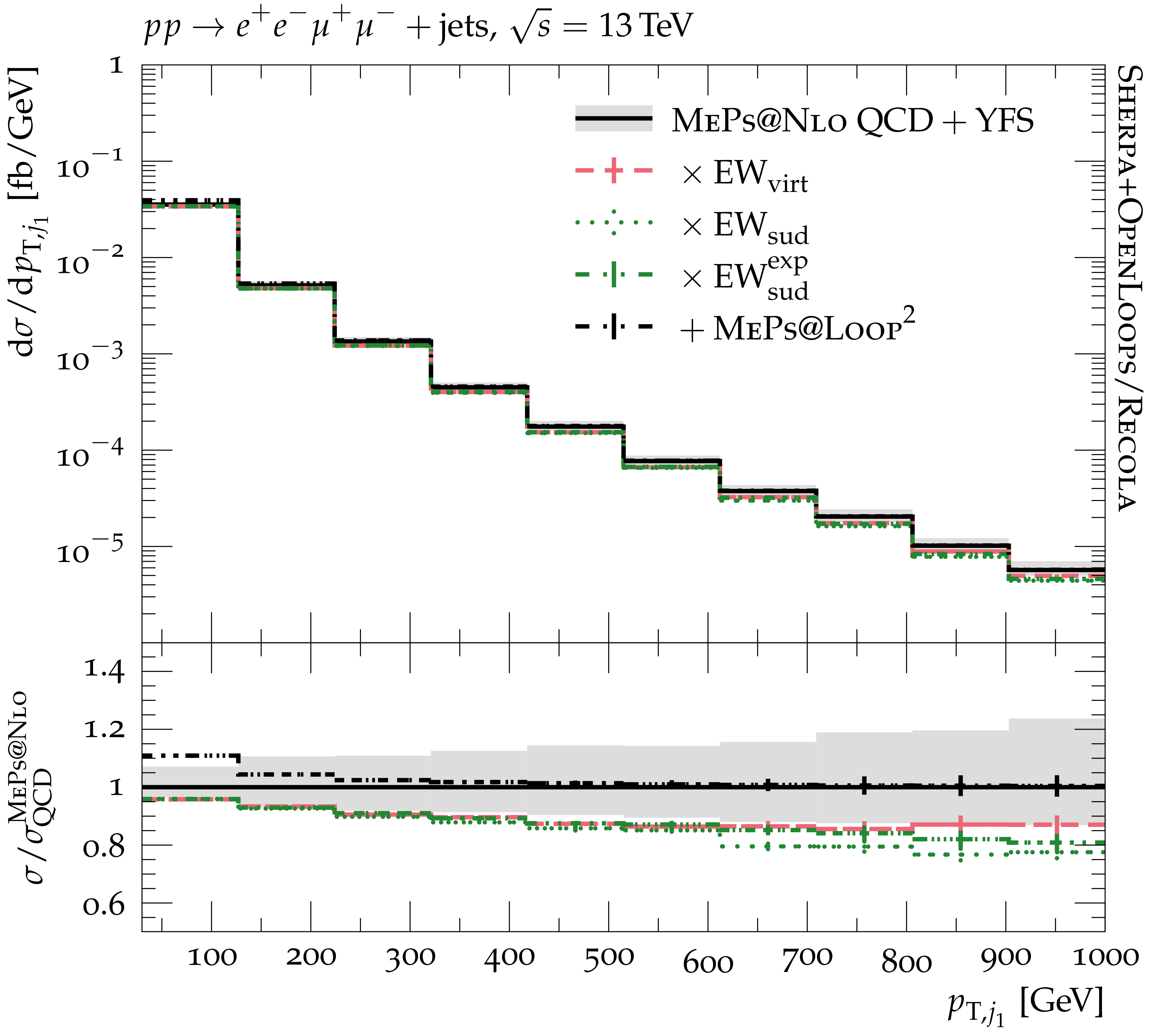
```
# set up beams for LHC run 2
BEAMS: 2212
BEAM_ENERGIES: 6500

# matrix-element calculation
ME_GENERATORS: [Comix]

## 7-point variations
SCALE_VARIATIONS: 4.0*

# pp -> Z[ee]
PROCESSES:
- 93 93 -> 11 -11:
    Order: {QCD: 0, EW: 2}

SELECTORS:
- [Mass, 11, -11, 66, E_CMS]
```

- Input based on standardised YAML format
- Improved input error handling with settings report and flagging of unused settings
- Build system based on CMake
- New manual based on sphinx

```
$ cd sherpa-<VERSION>/
$ cmake -S . -B <builddir>
$ cmake --build <builddir>
$ cmake --install <builddir>
```

- many topics not covered (in detail) here, see forthcoming publication

EW Sudakov logarithms



- Corrections due to soft/coll. EW gauge bosons coupled to external legs in high-energy limit
  (e.g. $p_T \gtrsim 1\,\text{TeV} \to \mathcal{O}(10\,\%)$ corrections)
- Corrections worked out in full generality
  [Denner, Pozzorini (2001) hep-ph/0010201]
- partial implementation in ALPGEN
  [Chiesa et al 1305.6837]
- In SHERPA fully automated as universal ME-level corrections applicable in all setups for any process, including MEPS@NLO predictions
  [EB, Napoletano 2006.14635], [EB et al. 2111.13453]
  - EW$_{\text{virt}}$ for $\mathcal{S}$ events, EW$_{\text{sud}}$ for $\mathcal{H}$ and LO events
  - YFS resummation for QED FSR
- Example: application to MEPS@NLO diboson production
  $pp \to 0{,}1j\,@\,\text{NLO} + 2{,}3j\,@\,\text{LO}$ [EB et al. 2111.13453]
- similar implementations in development for MadGraph5_aMC@NLO and OpenLoops [Pagani, Vitos, Zaro 2309.00452], [Recent talks by OpenLoops]