Sherpa 3.0: status and updates

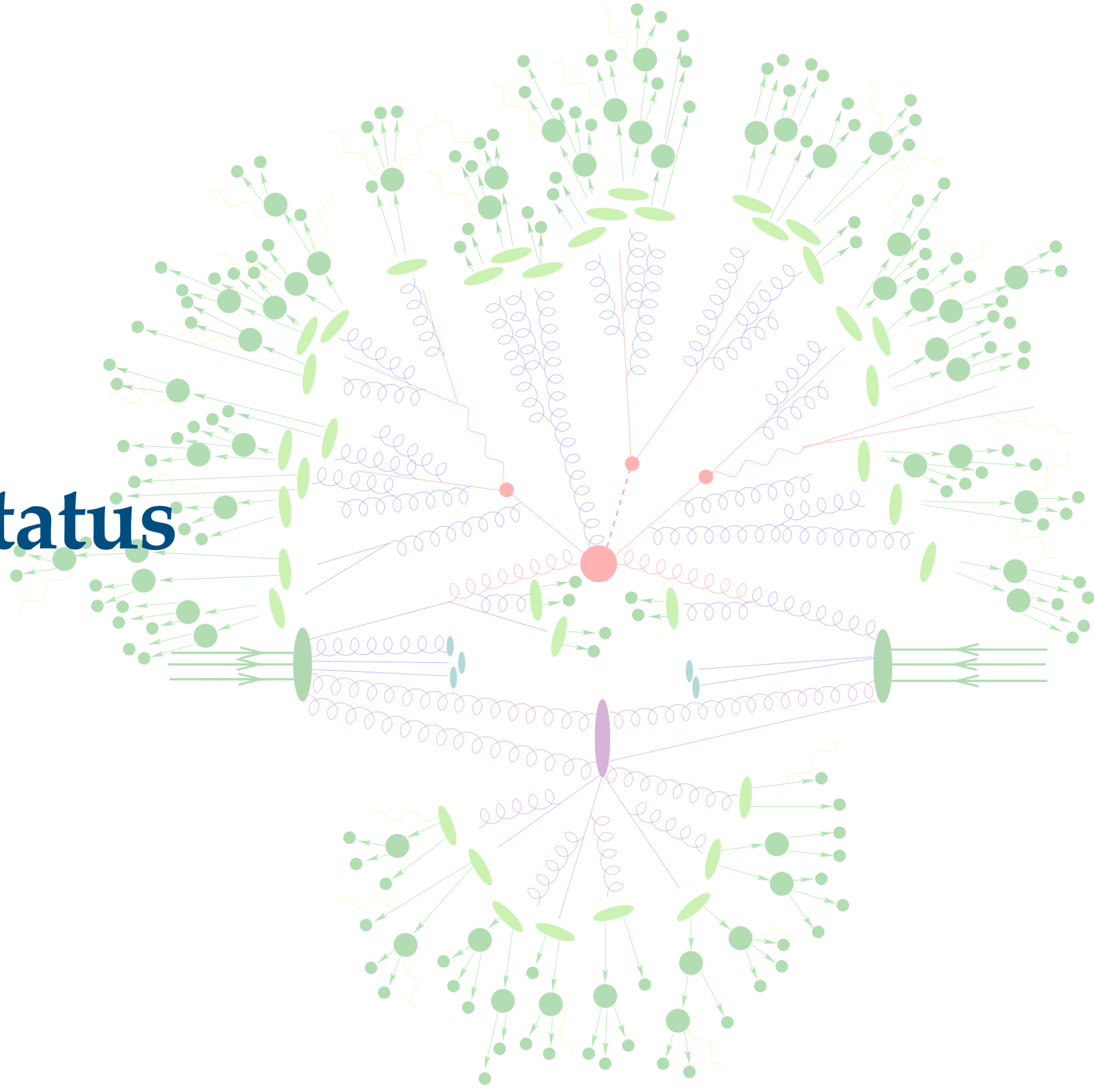
HP2, Torino, Sep. 2024

Peter Meinzinger, IPPP, Durham University, on behalf of the collaboration

Sherpa event generator

- Two tree-level build-in **matrix element generators**: COMIX, AMEGIC
- **Higher order QCD** effects:
  - **Matching** via S-MC@NLO
  - multi-jet **merging** via CKKW-L algorithm
- **Approximate NLO EW** effects: EWvirt & EW Sudakov
- Two **parton showers**: CSS, DIRE
- A **cluster fragmentation** model and interface to Pythia's string fragmentation
- A **hadron-** and **tau-decay** module
- **Multiple interaction** simulation á la PYTHIA
- **Higher-order QED** effects via YFS resummation
- Interfaces to
  - OpenLoops, Recola, GoSam, MCFM, BlackHat, MadLoop
  - RIVET 3 & 4, UFO 2, PYTHIA 8

Status



New version 3.0

Published in July 2024

New features in Sherpa 3.0:

- NLO EW at Fixed Order *[arxiv:1712.07975]*
- New MPI/MinBias modelling
- Improved cluster fragmentation incl. Colour Reconnection module *[arxiv:2310.14803]*
- Photon splittings in YFS resummation *[arxiv:2210.07007]*
- Dedicated scale setter for VBF and VBS
- Polarized XS for vector bosons *[arxiv:2310.14803]*
- EW Sudakovs *[arxiv:2006.14635], [arxiv:2111.13453]*
- Photoproduction and Diffraction at HERA and EIC *[arxiv:2310.18674], [arxiv:2311.14571], [arxiv:2407.02133]*
- New YAML-based input
- Rivet 4.0 support incl. MPI parallelisation
- UFO 2.0 support

Release paper in preparation

Sherpa 3.0

Technical improvements

Big structural changes to the architecture

- New format based on YAML standard
- Automated settings reporting, informing of, e.g., unused settings
- New CMake build system
- New Sphinx-based manual

```
(run){
  % collider setup
  BEAM_1 2212; BEAM_ENERGY_1 = 6500.;
  BEAM_2 2212; BEAM_ENERGY_2 = 6500.;

  % me generator settings
  ME_SIGNAL_GENERATOR Comix Amegic OpenLoops;

  % scales, tags for scale variations
  FSF:=1.; RSF:=1.; QSF:=1.;
  SCALES METS{FSF*MU_F2}{RSF*MU_R2}{QSF*MU_Q2};

  % tags for process setup
  LJET:=2,3,4;

  ## % optional: extra tags for custom jet criterion
  ## SHERPA_LDADD MyJetCriterion;
  ## JET_CRITERION FASTJET[A:antikt,R:0.4,y:5];

  % exclude tau from lepton container
  MASSIVE[15] 1;
}(run)

(processes){
  Process 93 93 -> 90 91 93{4};
  Order (*,2); CKKW sqr(20/E_CMS);
  NLO_QCD_Mode MC@NLO {LJET};
  ME_Generator Amegic {LJET};
  RS_ME_Generator Comix {LJET};
  Loop_Generator OpenLoops {LJET};
  Integration_Error 0.02 {4};
  Integration_Error 0.02 {5};
  Integration_Error 0.05 {6};
  Integration_Error 0.08 {7};
  Integration_Error 0.10 {8};
  Scales LOOSE_METS{FSF*MU_F2}{RSF*MU_R2}{QSF*MU_Q2} {7,8};
  End process;
}(processes)

(selector){
  Mass 11 -12 1. E_CMS
  Mass 13 -14 1. E_CMS
  Mass -11 12 1. E_CMS
  Mass -13 14 1. E_CMS
}(selector)
```

W+2j@NLO,
3-4j@LO

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

# matrix-element calculation
ME_GENERATORS:
- Comix
- Amegic
- OpenLoops

# optional: use a custom jet criterion
#SHERPA_LDADD: MyJetCriterion
#JET_CRITERION: FASTJET[A:antikt,R:0.4,y:5]

# exclude tau (15) from (massless) lepton container (90)
PARTICLE_DATA:
  15:
    Massive: 1

# pp -> W[lv]+jets
PROCESSES:
- 93 93 -> 90 91 93{4}:
    Order: {QCD: 0, EW: 2}
    CKKW: 20
    # set up NLO+PS final-state multiplicities
    2->2-4:
      NLO_Mode: MC@NLO
      NLO_Order: {QCD: 1, EW: 0}
      ME_Generator: Amegic
      RS_ME_Generator: Comix
      Loop_Generator: OpenLoops
    # make integration of higher final-state multiplicities faster
    2->4-6:
      Integration_Error: 0.05

SELECTORS:
# Safety cuts to avoid PDF calls with muF < 1 GeV
- [Mass, 11, -12, 1.0, E_CMS]
- [Mass, 13, -14, 1.0, E_CMS]
- [Mass, -11, 12, 1.0, E_CMS]
- [Mass, -13, 14, 1.0, E_CMS]
```

Much more user-friendly!

Polarised vector bosons

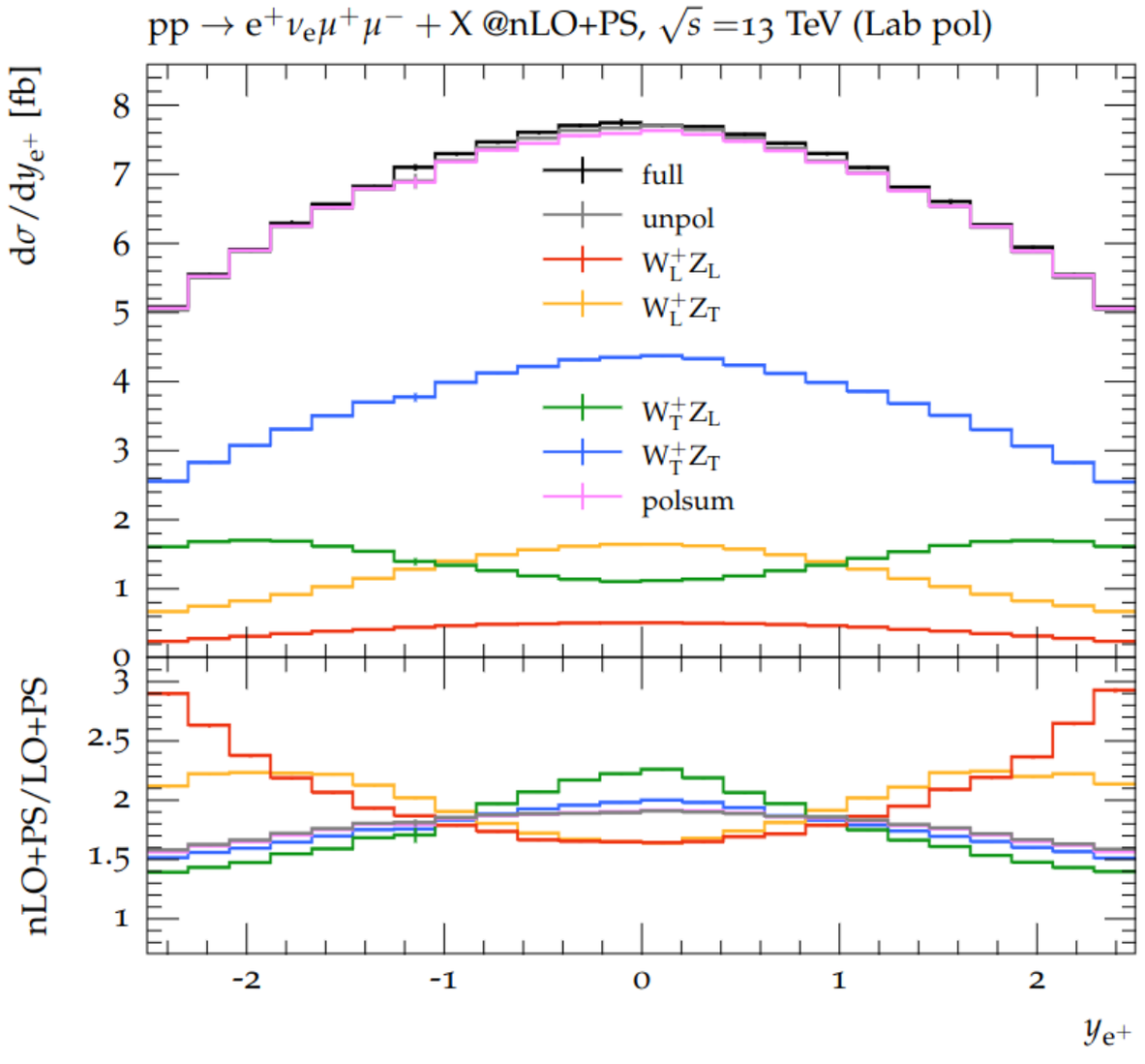
[arxiv:2310.14803]

Probe for electroweak gauge sector & electroweak symmetry breaking

Measurement strategy: fully exclusive polarized XS from MC as fitting templates

Methodology in Sherpa:

- Unpolarized simulation run, polarized XS as event weights
- All polarization combinations, interferences, reference frames in one simulation run
- Accuracy up to nLO QCD (via MC@NLO) , multi-leg merging
  - nLO: approximation for calculation of polarization fractions



Photon splittings in YFS

[arxiv:2210.07007]

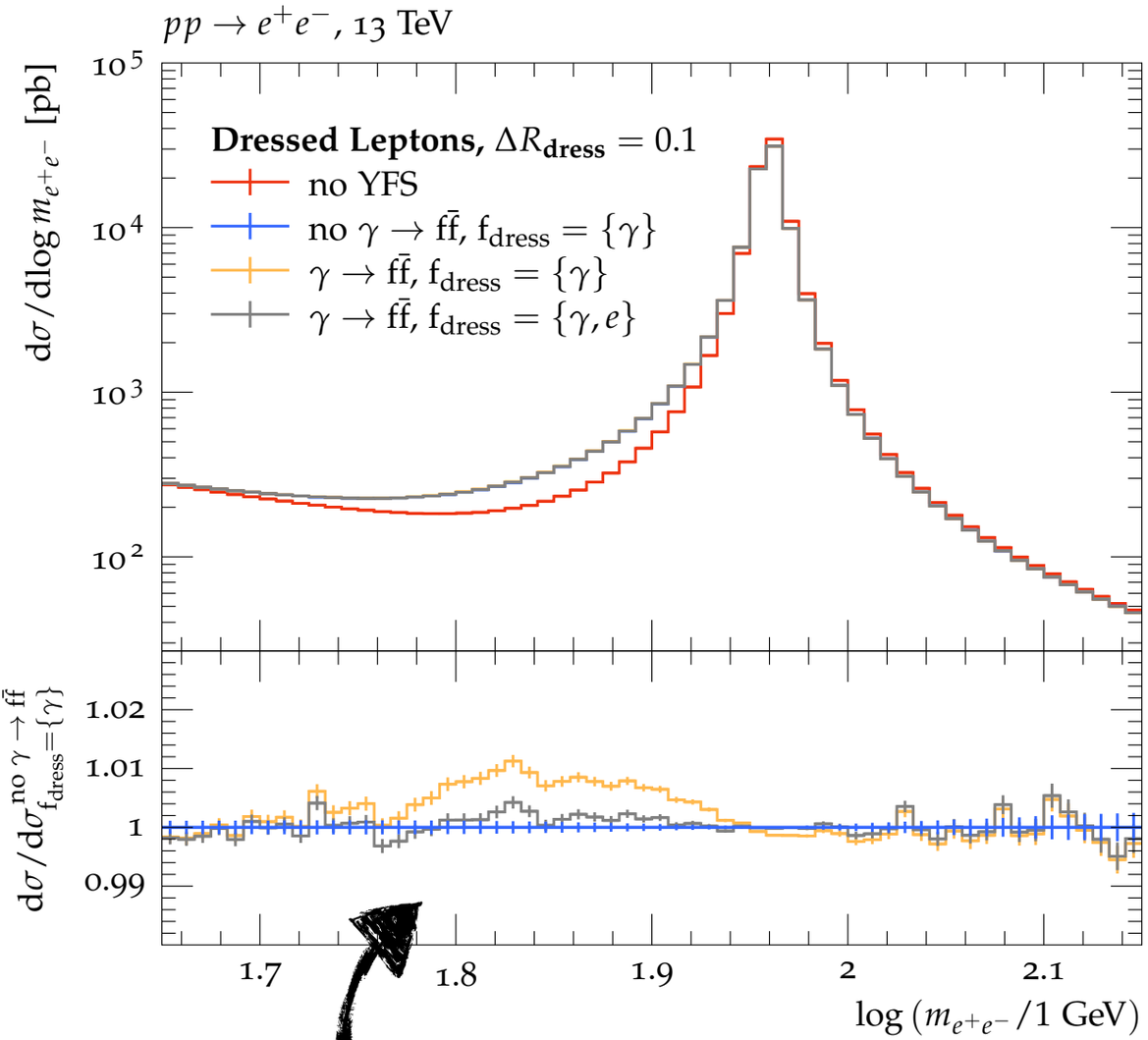
Decay of vector bosons important part of precision measurements

Soft photon resummation in YFS but no further splitting of photons after emission:

- splitting in light flavours significant
- leptons & photons experimentally distinguishable

Sherpa 3.0: implementation of photon splitting into light flavours (e, μ, τ, π, K) based on one-step parton shower for YFS-photons

- Photon dressing: correction at per-cent level
- depending on dressing algorithm, more or less energy may be recombined into dressed lepton



off-shell Z production;
used recombination flavours make a difference

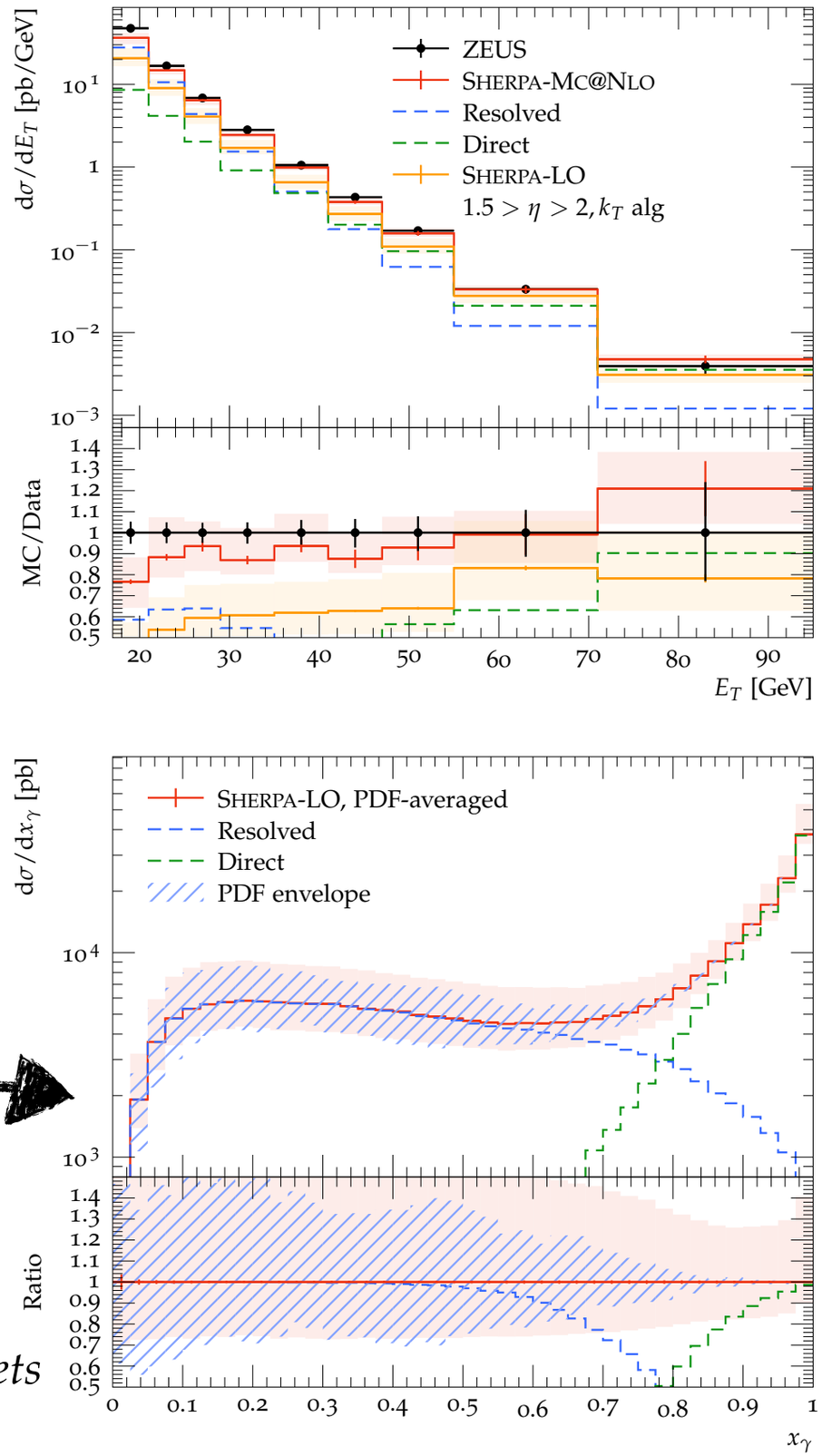
EIC physics

Photoproduction *[arxiv:2310.18674], [arxiv:2311.14571]*

- Photoproduction is the low-Q^2 complementary to DIS
- Photon has to be treated like a hadron due to $\gamma \to q\bar{q}$ splittings

Sherpa 3.0: First MC@NLO calculation

- validated against LEP and HERA
- predictions for EIC
- Photon PDFs (i.e. partons in photon) are bottleneck for precision requirements



LO study for EIC, averaging over 11 PDF sets

EIC physics

Diffraction *[arxiv:2407.02133]*

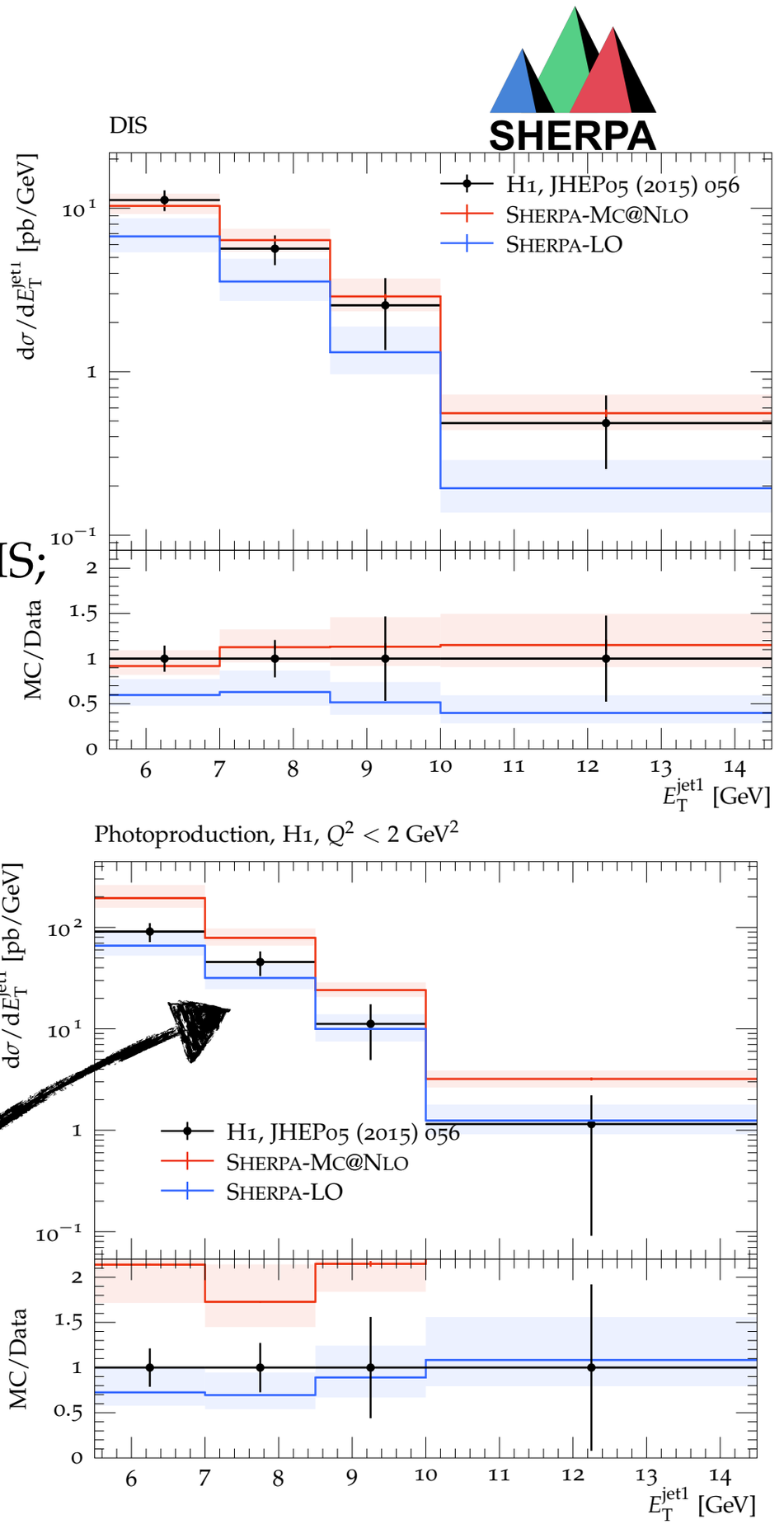
- Diffraction was 10% of total cross-section at HERA; important for precision measurements at EIC

- Factorisation into DPDFs and MEs for Diffractive DIS; does not hold for Diffractive Photoproduction

Sherpa 3.0: First MC@NLO calculation for both Diffractive DIS and Diffractive Photoproduction

- Validation against HERA data
  - excellent agreement for DDIS
  - study of factorisation breakdown in DPHO
- predictions for EIC

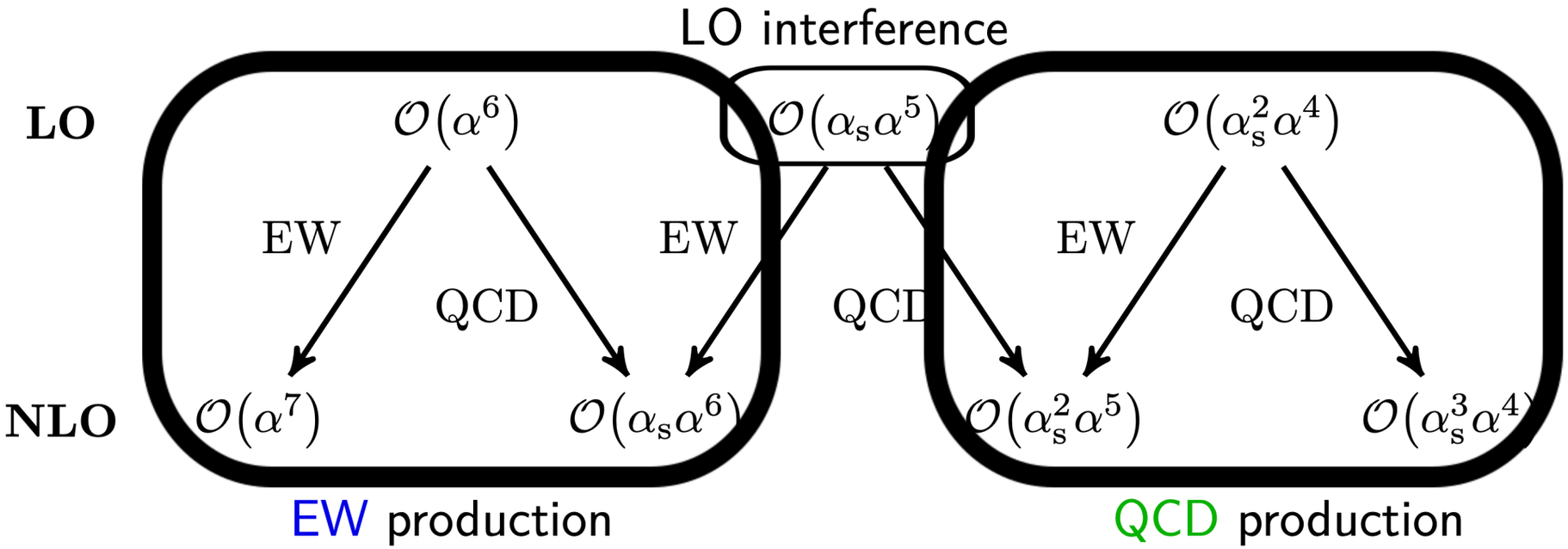
factorisation breaking leads to overshooting of the calculation; mechanism not yet understood



Off-shell tri-bosons @ MC@NLO

SHERPA

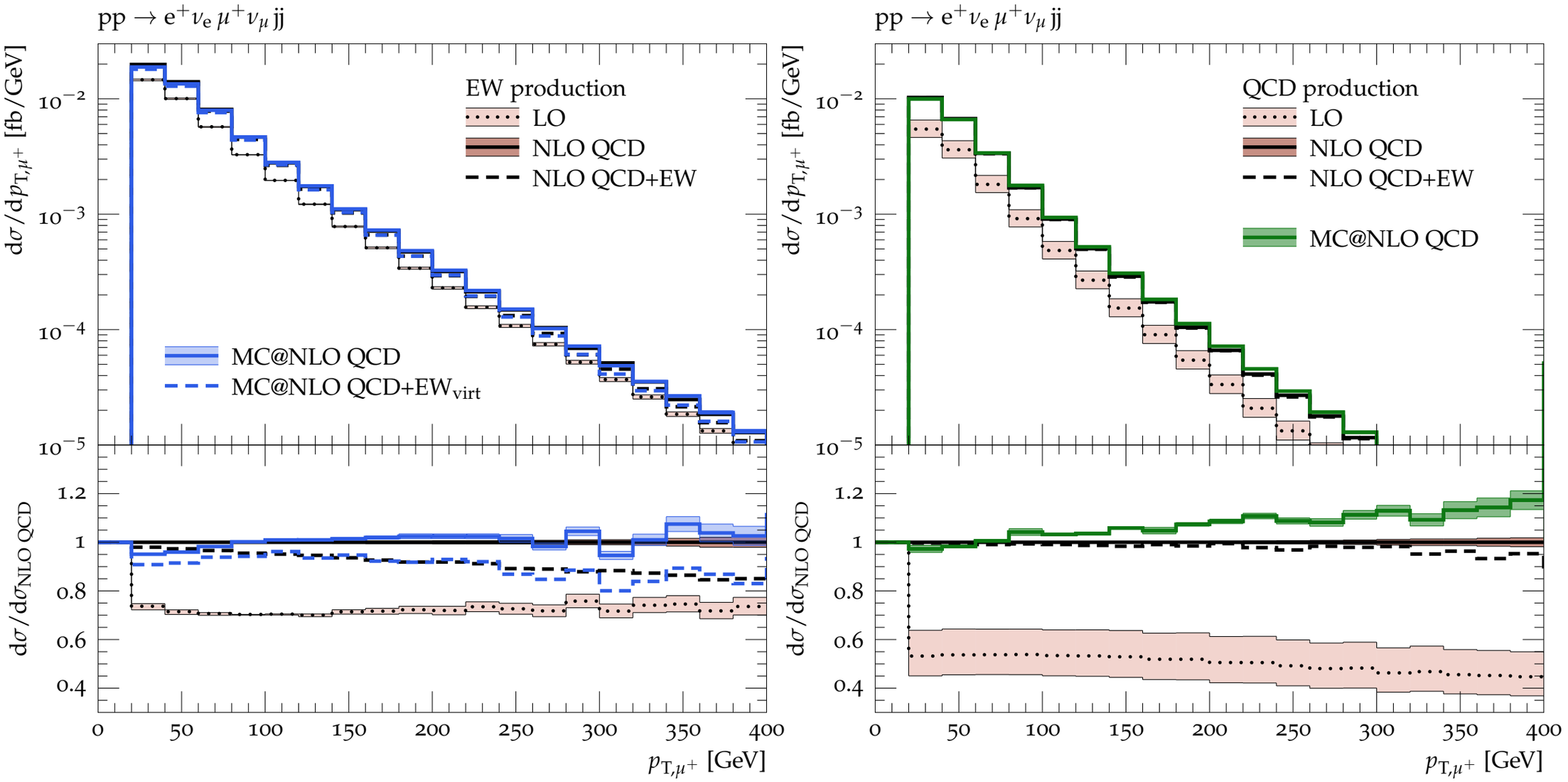
$pp \to e^+\mu^+\nu_e\nu_\mu jj$ @ full NLO



- organise into QCD and EW production, neglect LO interference
- QCD production: matching straight-forward
- EW production: rich resonance structure; NLO QCD correction contains QED div. wrt. LO interference, can be removed by separating into *s*- and *t*-channel topologies
  - QCD parton shower matched separately, added incoherently

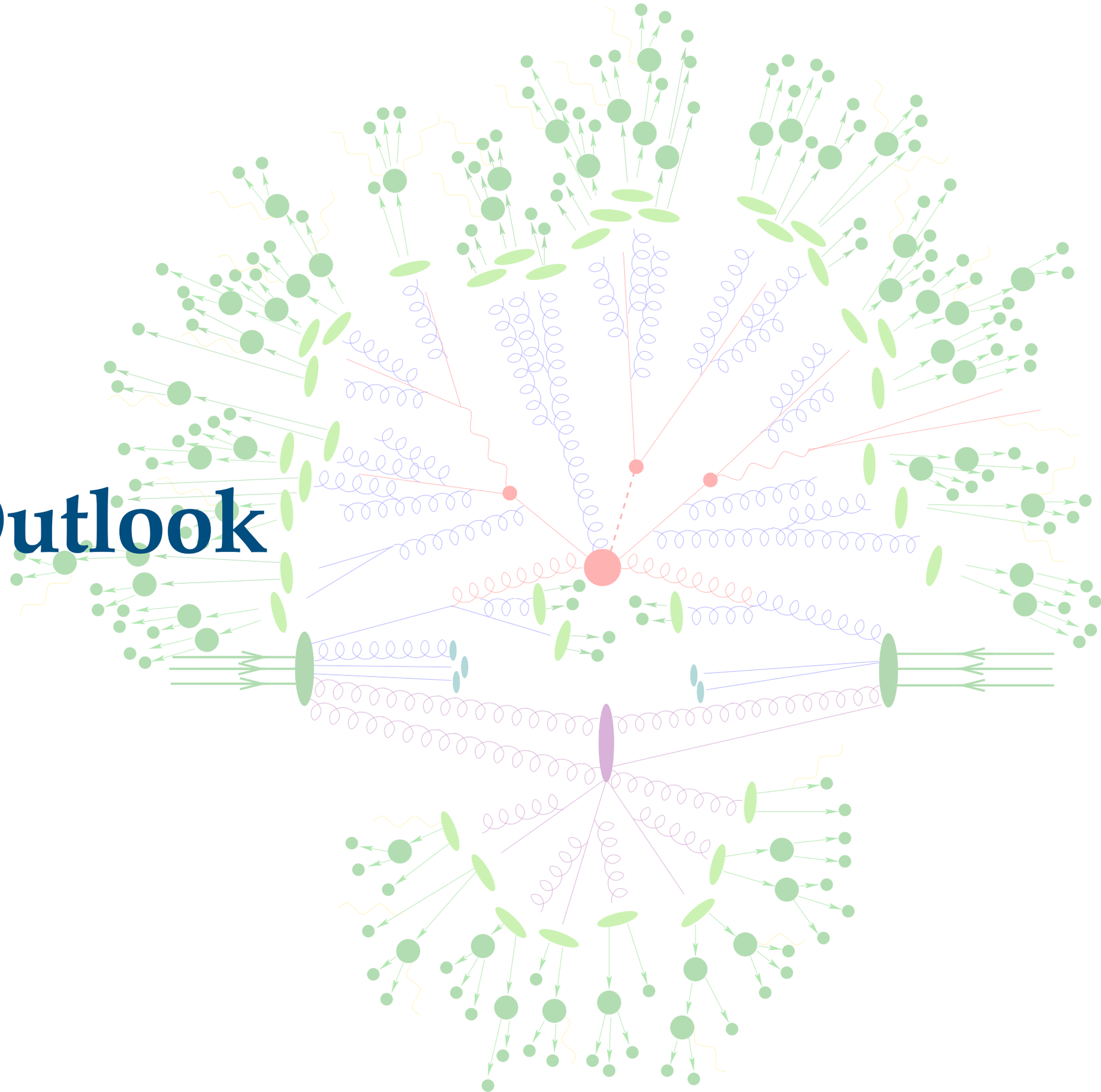
Off-shell tri-bosons @ MC@NLO

$pp \to e^+\mu^+\nu_e\nu_\mu jj$ @ full NLO



- small EW corr. to QCD production
- EW corr. to EW production well reproduced

Outlook



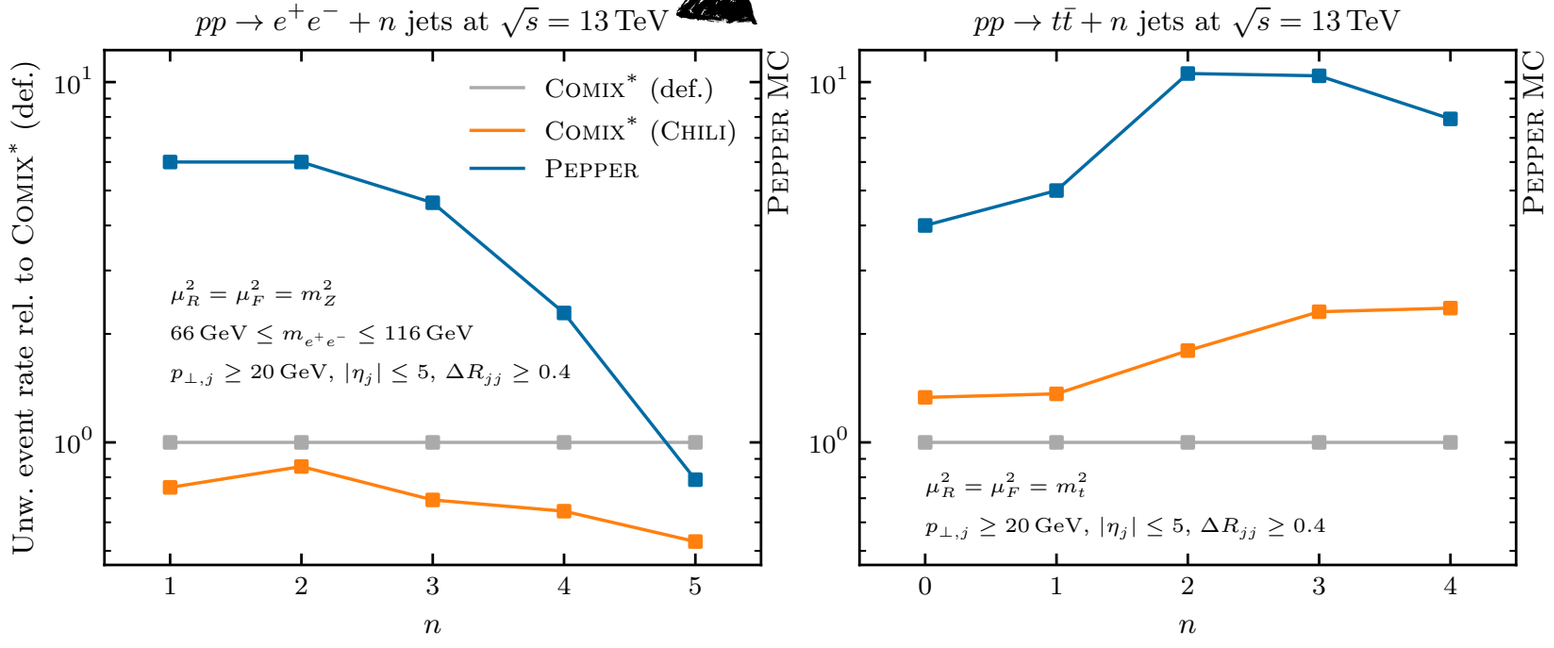
Performance studies

Identified as bottleneck for (HL-)LHC!

c.f. MCEG performance workshop @ CERN, Nov. 2023

- **Interfaces and optimization**
  - HDF5 file I/O a.k.a. LHEH5 *[arxiv:2309.13154]*
  - Pilot runs and faster PDF evaluation (published in Sherpa 2.2.12 & now Sherpa 3.0) *[arxiv:2209.00843]*
- **Neural Networks for better sampling**
  - Nested Sampling *[arxiv:2205.02030]*
  - Factorisation-aware NN *[arxiv:2301.13562]*
- **GPUs and portability**
  - Portable code for GPUs & CPUs in parton-level event generator PEPPER *[arxiv:2311.06198]*, *[arxiv:2302.10449]*, *[arxiv:2106.06507]*

Up to 10x better performance in first study



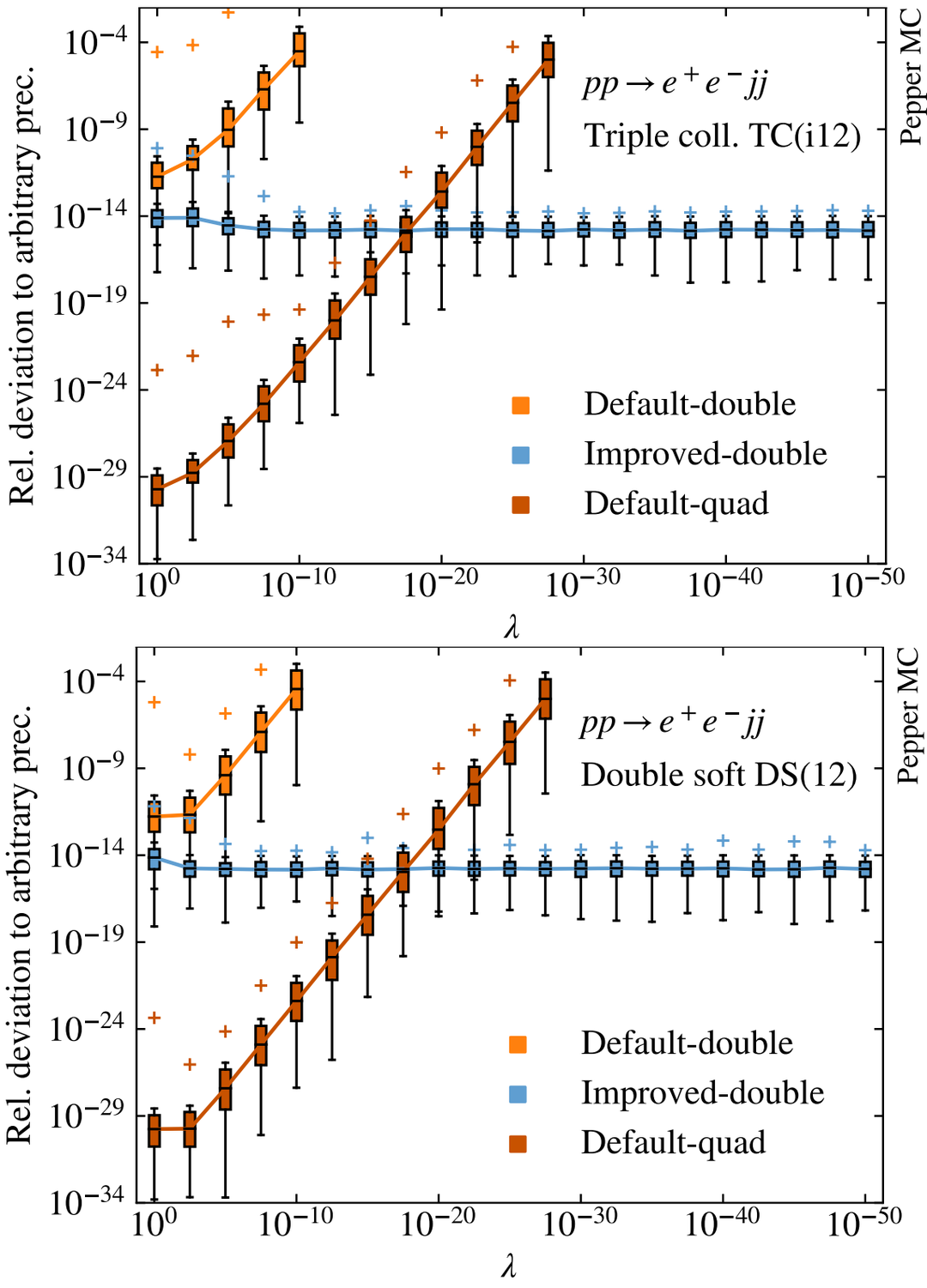
Performance studies

Numerical stability *[2406.07671]*

Numerical stability important for cancellation; usually differences between large numbers need to be computed

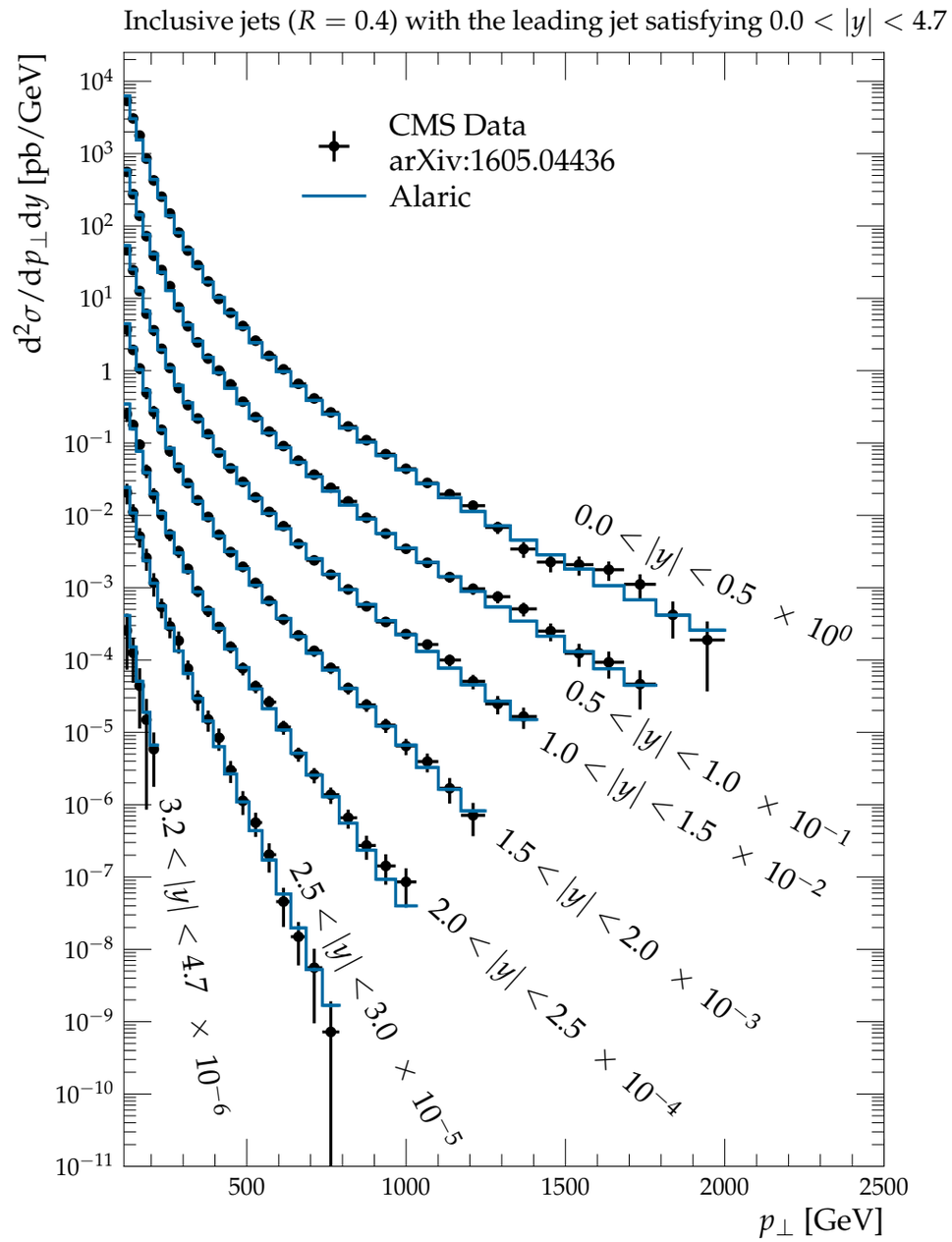
Solution:

- Represent four-momenta as five-vectors with virtuality
- Reformulate four-momenta products using the virtuality
- In infrared limit, differences are now ratios of small over large components
- In the limit, even better than naive quad-precision



Alaric for the LHC

- NLL accuracy proven analytically and numerically *[arxiv:2208.06057]*
- Extension to Initial State evolution and CKKW merging *[arxiv:2404.14360]*
- Choice of different recoil schemes possible
- Next steps:
  - implementation of MC@NLO matching and MEPS@NLO merging
  - inclusion of higher order splitting kernels as done in DIRE *[arxiv:1705.00742]*



Fusing

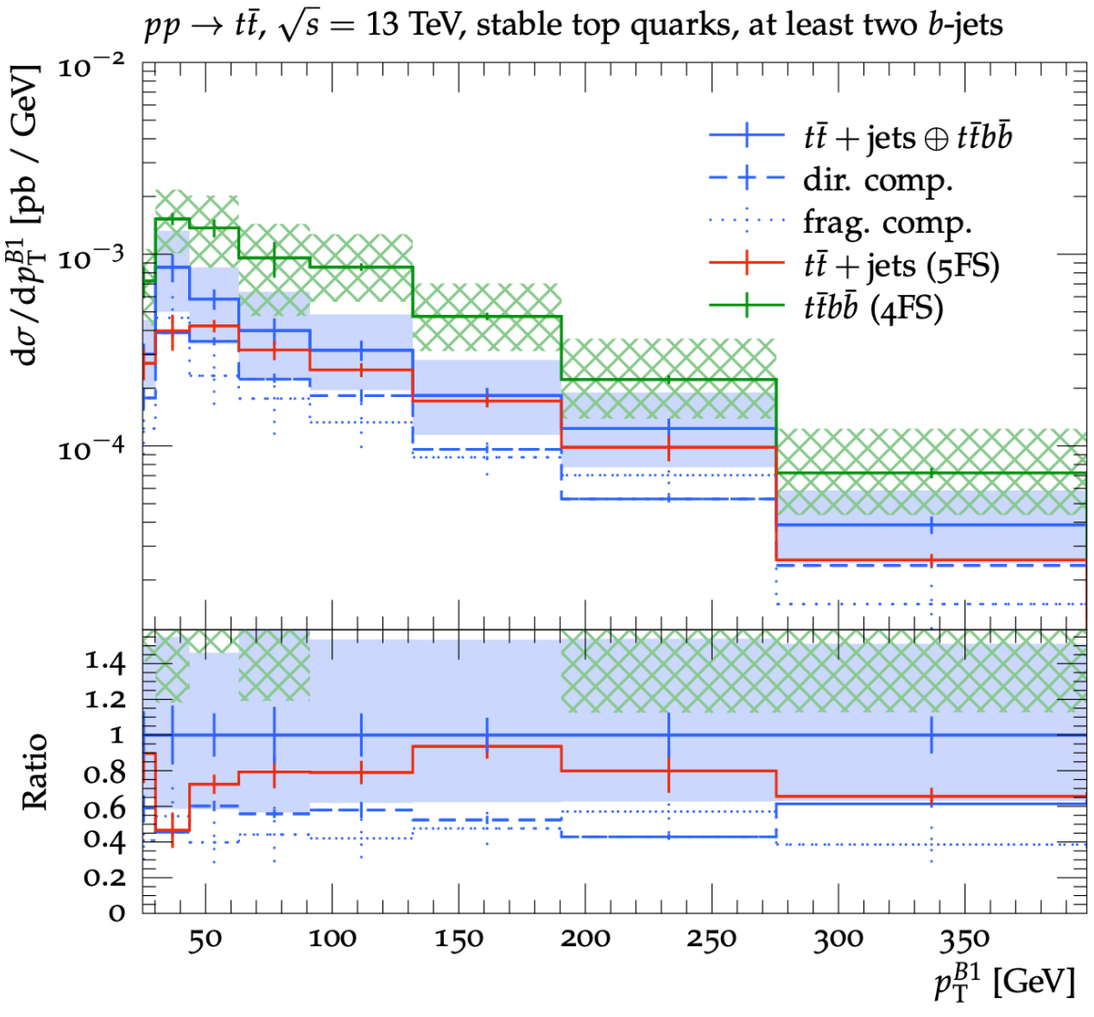
$pp \to t\bar{t}b\bar{b}$ in a variable flavour number scheme

[arxiv:2402.15497]

forms irreducible background to $pp \to t\bar{t}H$

Procedure:

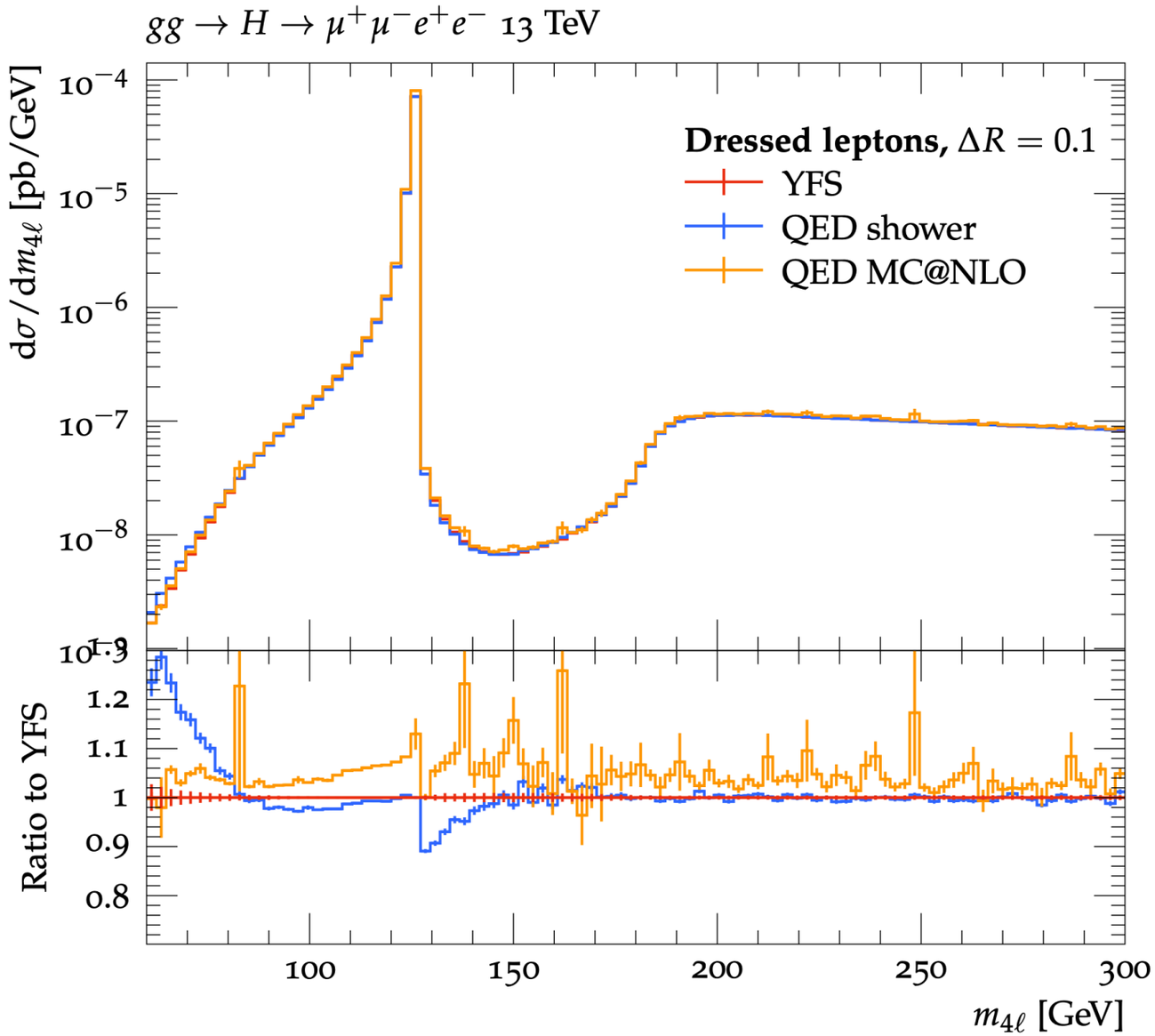
- Generate $t\bar{t}jj$ (5flav scheme) and $t\bar{t}b\bar{b}$ (4flav scheme) separately
- Process $t\bar{t}b\bar{b}$ as if part of the inclusive multi-jet merged sample, i.e. clustering, α_S reweighting, Sudakov reweighting, *"direct component"*
- Remove configurations from $t\bar{t}jj$ which according to shower history derive from $t\bar{t}b\bar{b}$ matrix element, *"fragmentation component"*
- Add the two modified samples



QED-MC@NLO

c.f. Lois Flower's talk this morning

- Interleaved QCD+QED parton shower
- Automated matching of QED NLO with QED parton shower
- Goal: QCD+QED MC@NLO



Conclusion

Sherpa 3.0 finally public

A lot of development, e.g.

- new syntax & modern build system
- new features: polarized XS for intermediate VB, photon splittings, UFO 2.0 & Rivet 4 support, EW Sudakov corrections, EIC physics, and more
- faster simulation

More to come in future feature updates SHERPA 3.x, e.g.:

- ALARIC
- Event generation on GPUs
- QED MC@NLO
- Fusing

Thank you for your attention!