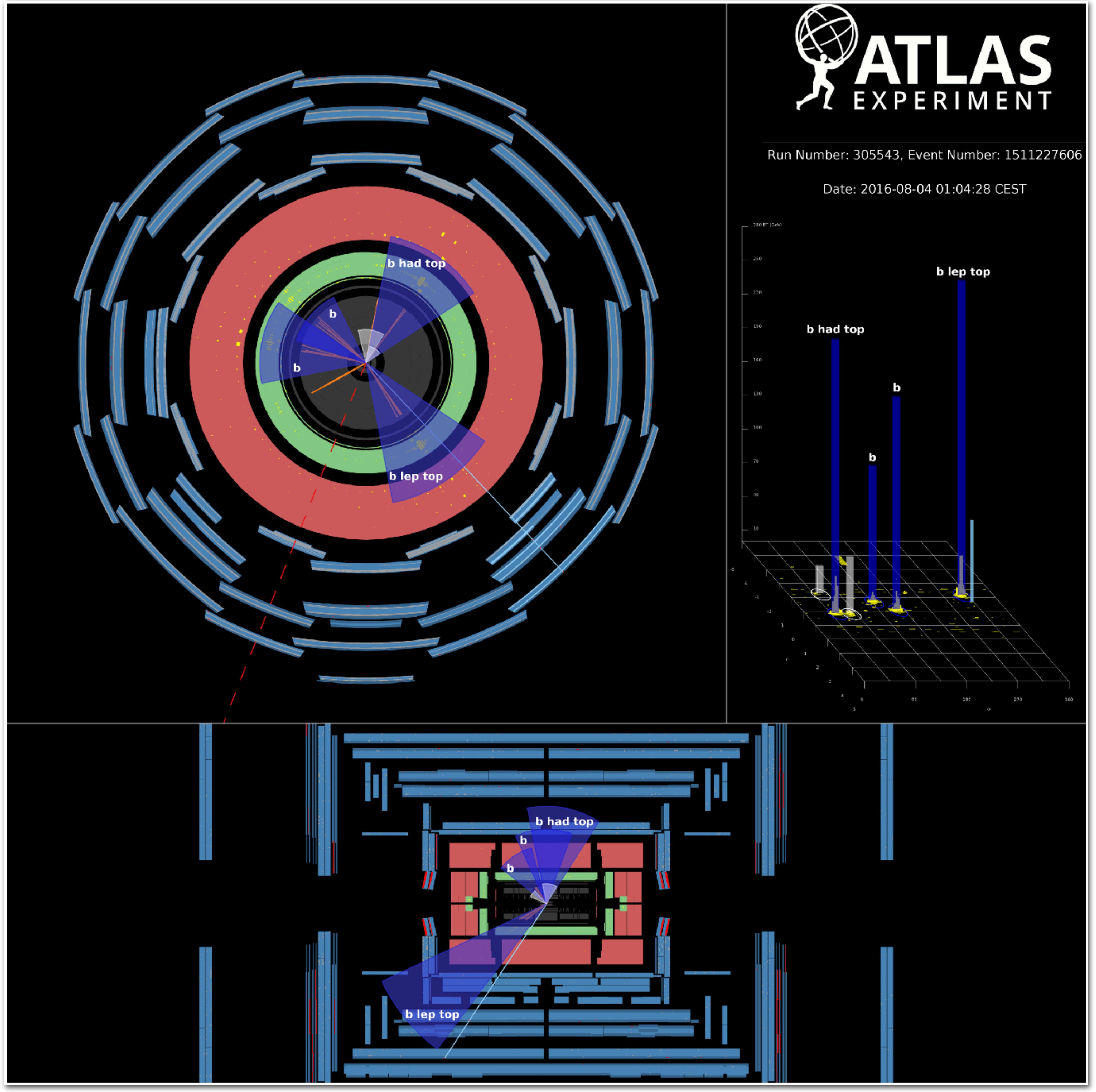
SHERPA 3 for DIS and EIC physics

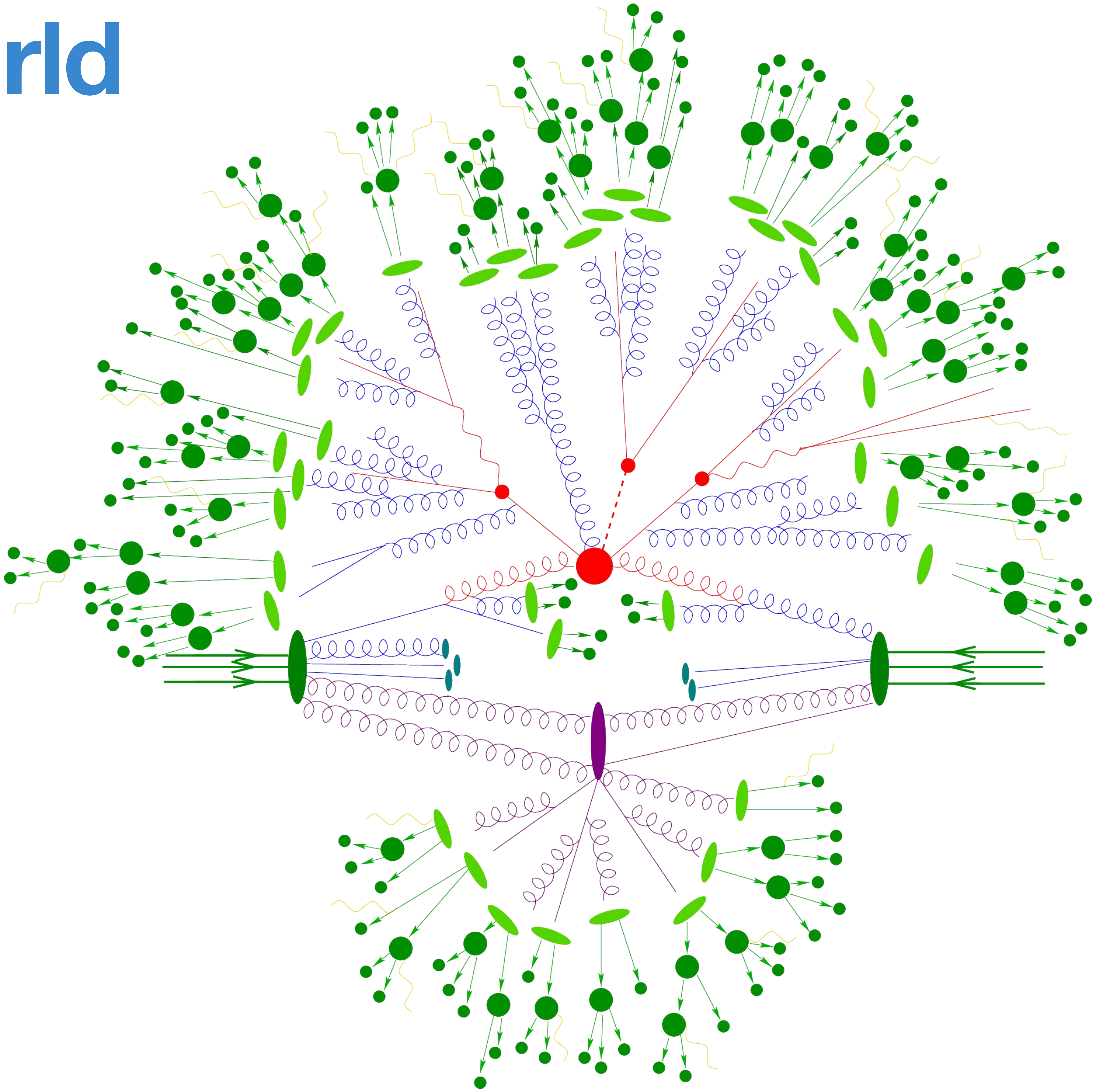
POETIC 2025

Daniel Reichelt

Funded
by the
European Union

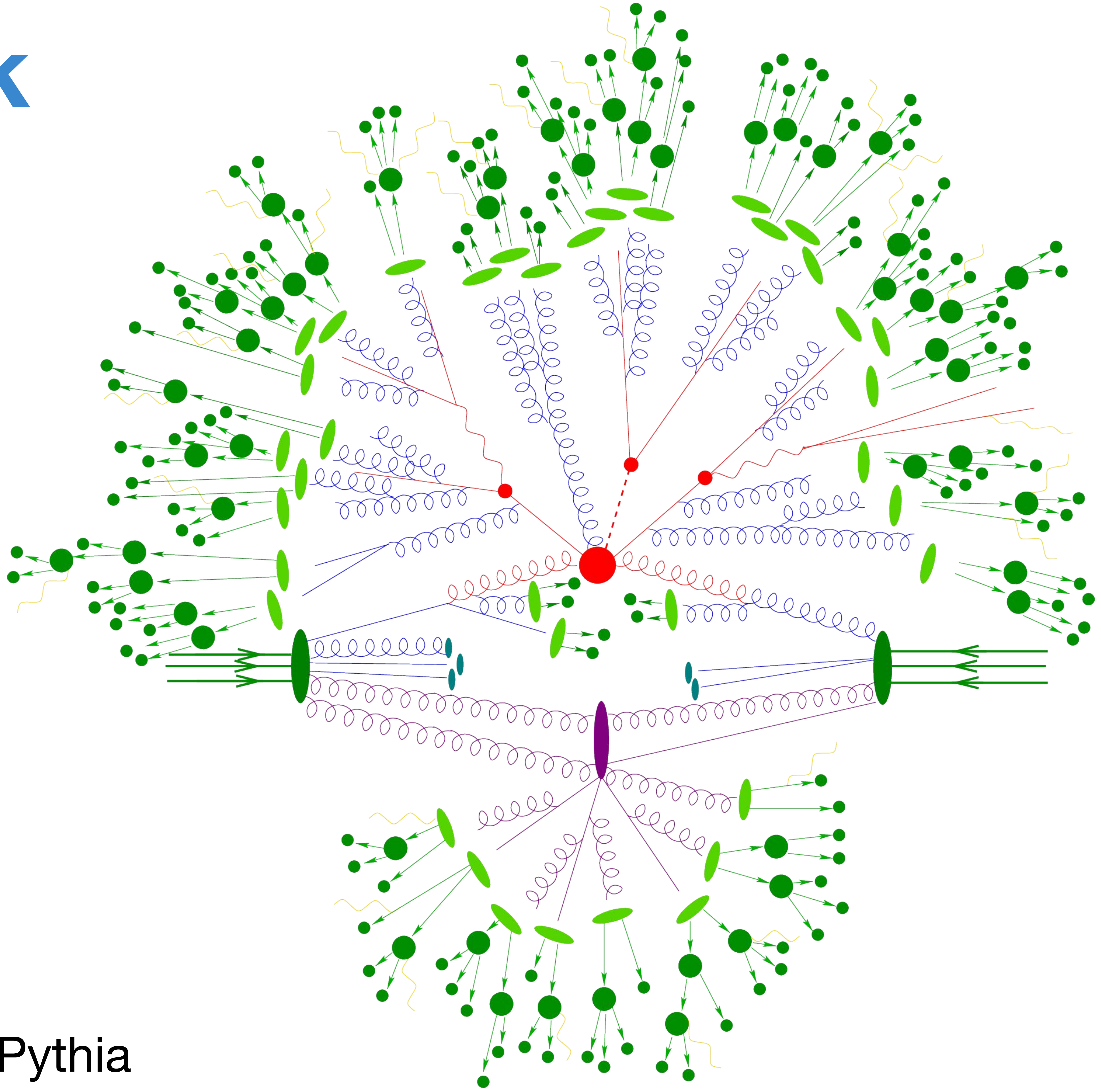
Colliders in the real world





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

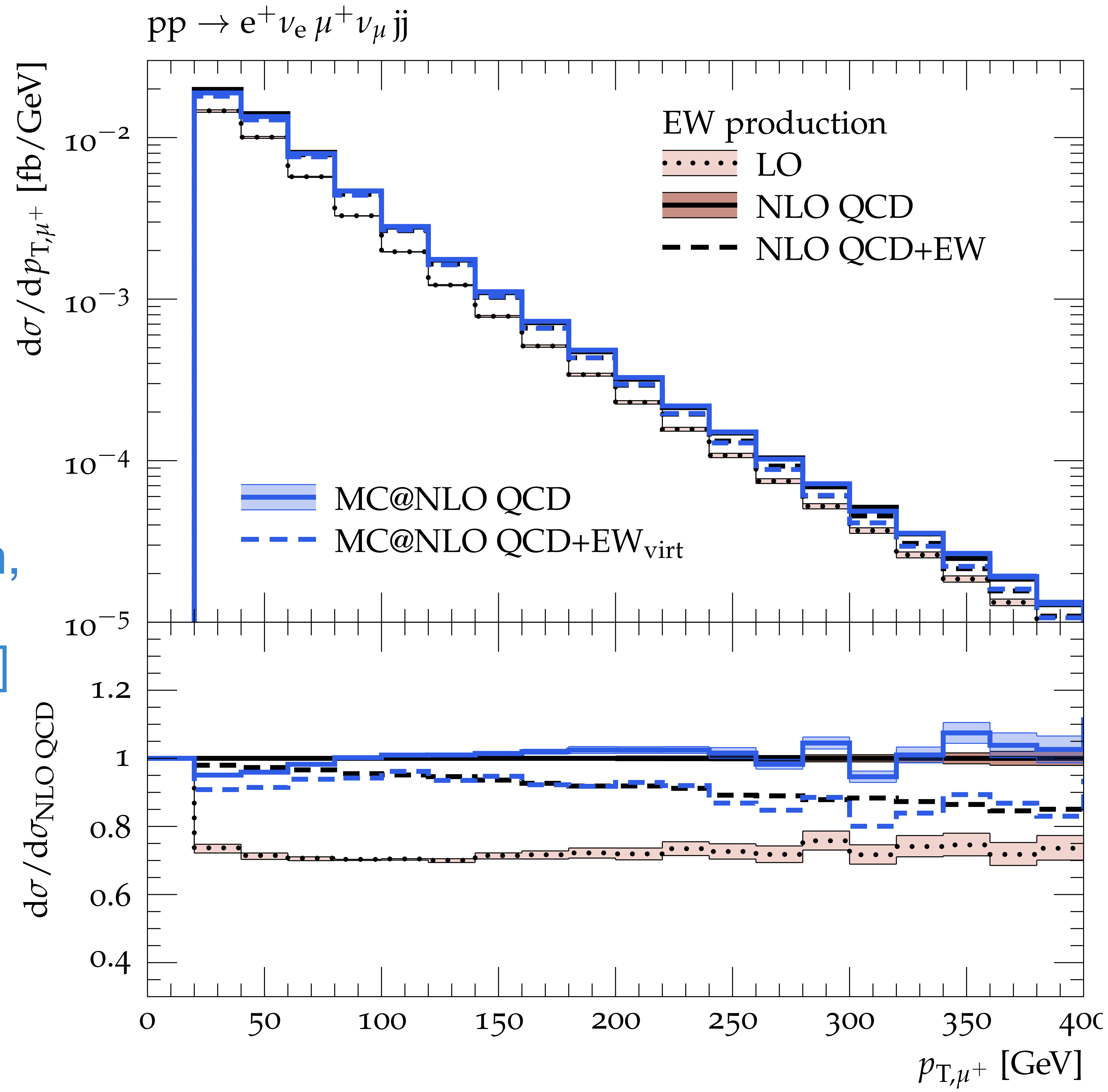
- (Selected) Features:
  - Fixed Order
    - NLO QCD+**EW**,
    - **NNLO** QCD (selected processes)
  - Automated NLO (QCD) matching in S-MC@NLO
  - **UN2LOPS** matching to NNLO QCD
  - multi-jet merging in CKKW-L
  - Approximate **EW-corrections in matching & merging** (EWvirt/EWSud)
  - **Photoproduction @ 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)

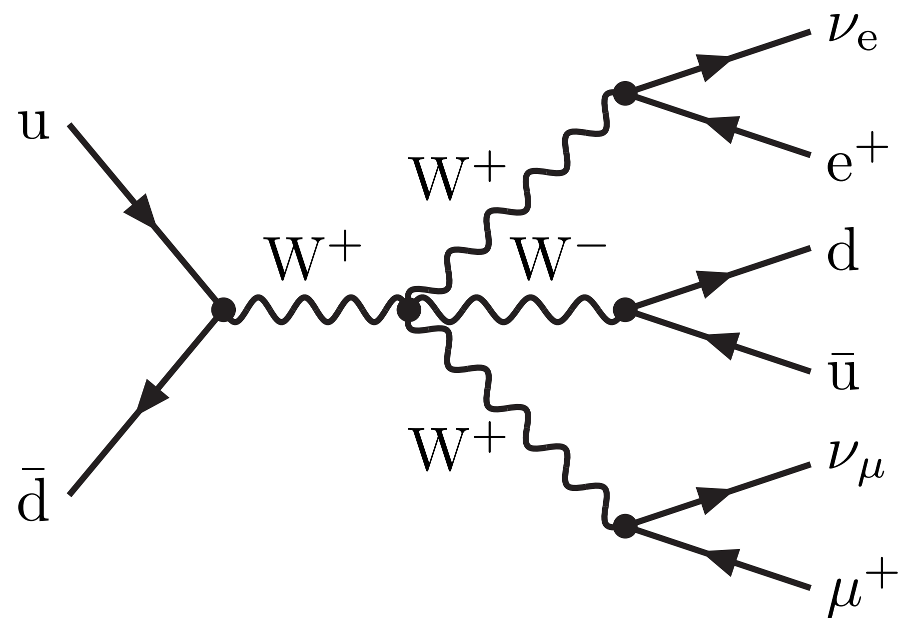
bold - added/significantly updated in Sherpa 3 development, some back-ported to Sherpa 2

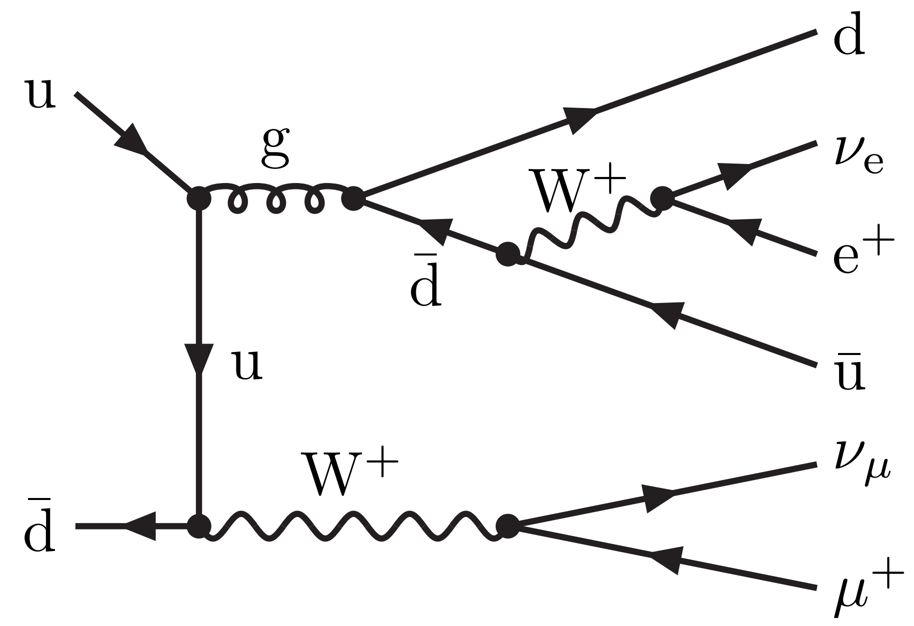
State of the art at the LHC

Some highlights from the LHC

- 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



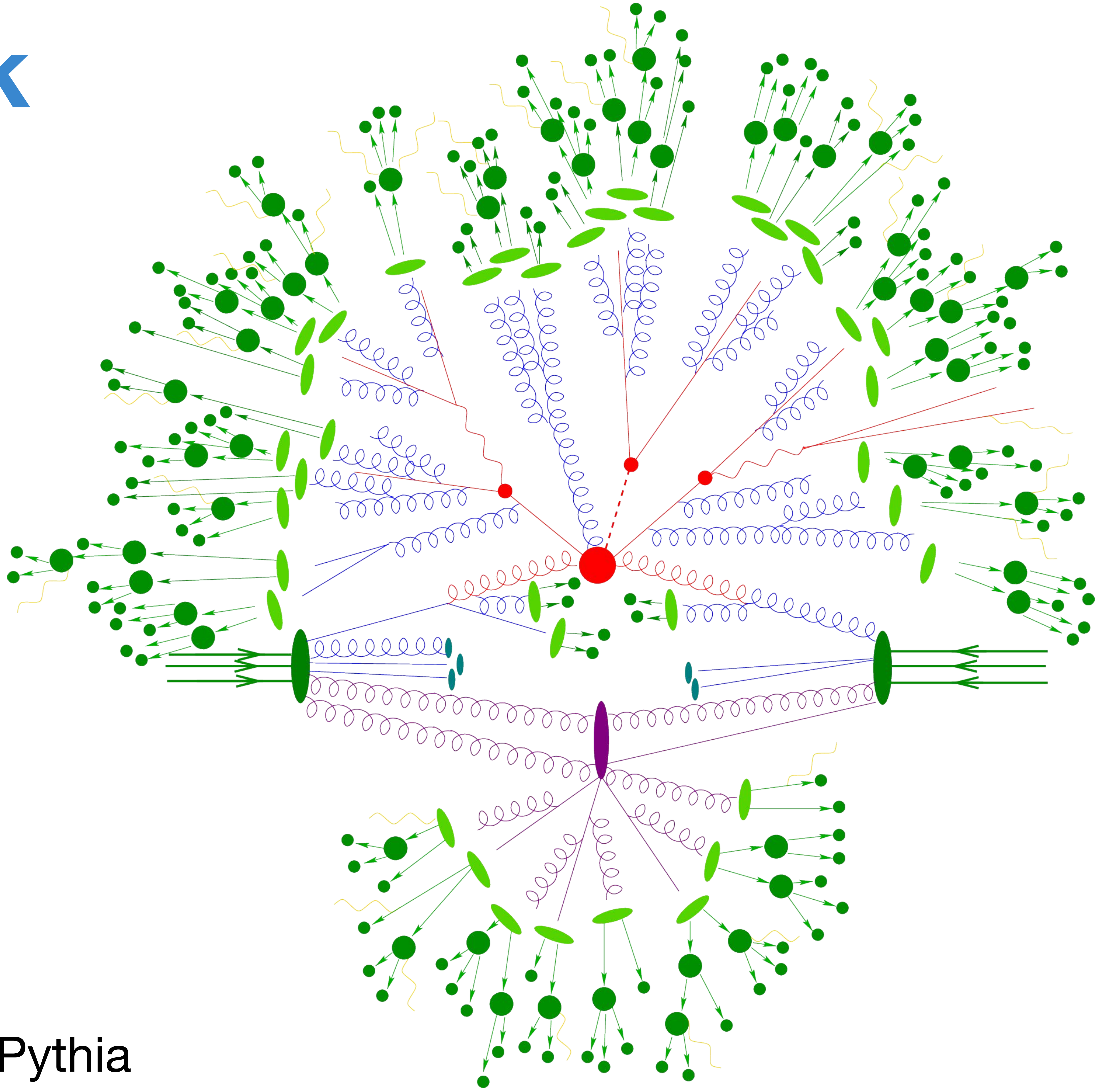




Whats in the box

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

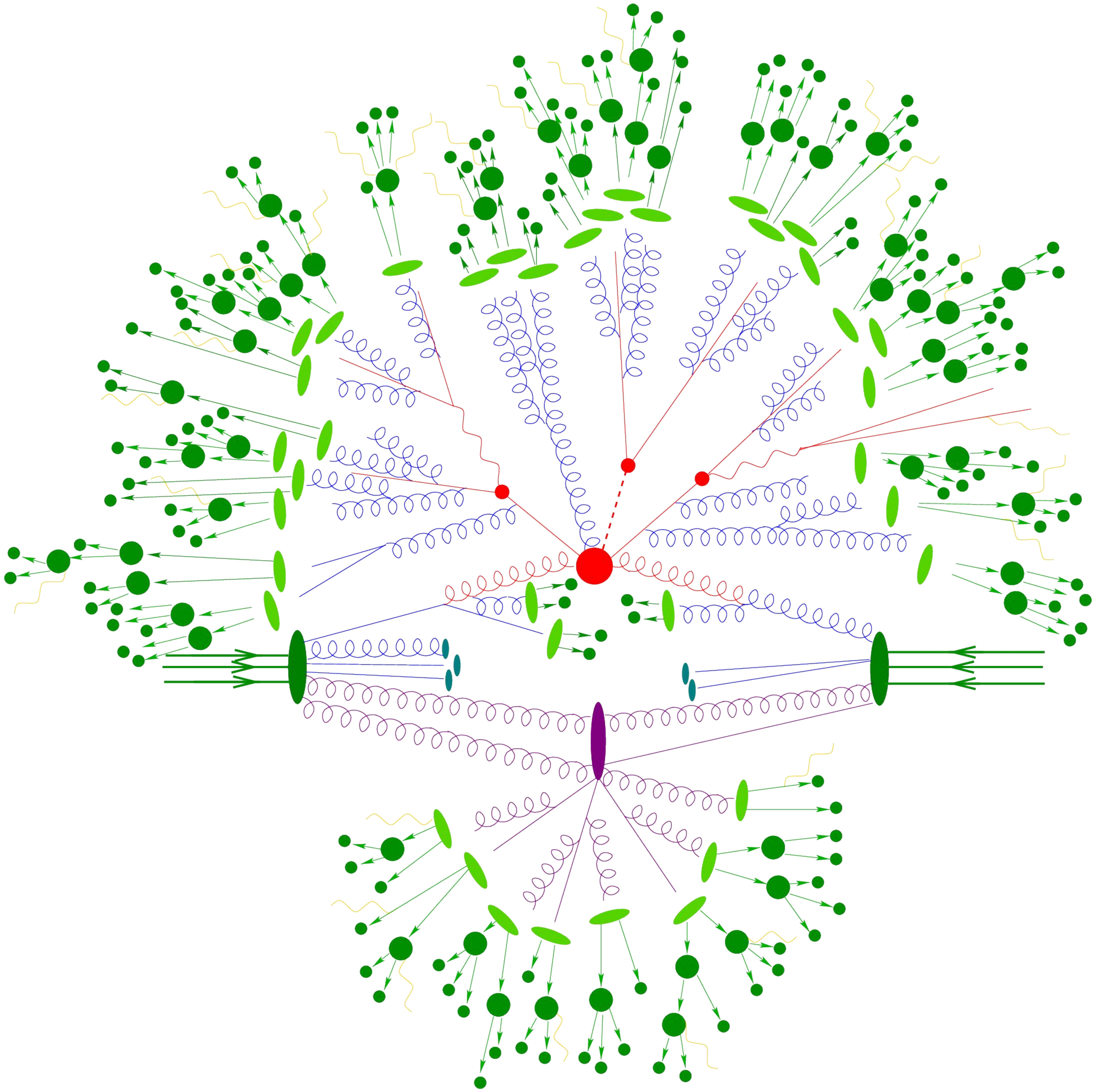


Matching

- Event simulation factorised into
  - Hard Process
  - Parton Shower

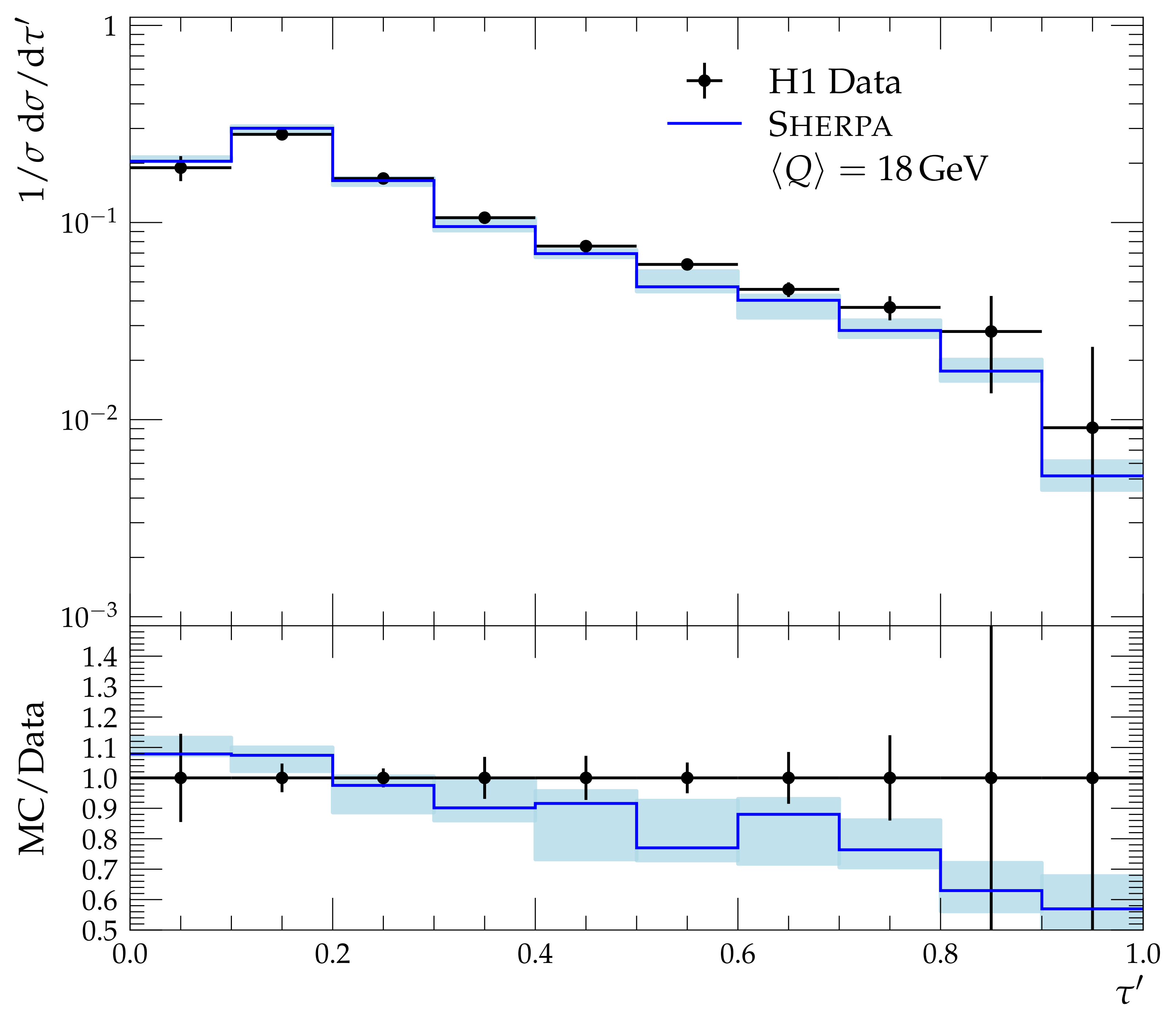
Standard for LHC SM pheno:

- matching to NLO QCD, 2 main schemes: Powheg [Nason ‘04] and MC@NLO [Frixione, Webber ‘02]
- concepts in general not collider dependent, but some recent DIS specific studies [Banfi, Ravasio, Jäger, Karlberg, Reichenbach ’23], [Knobbe, DR, Schumann ‘23]

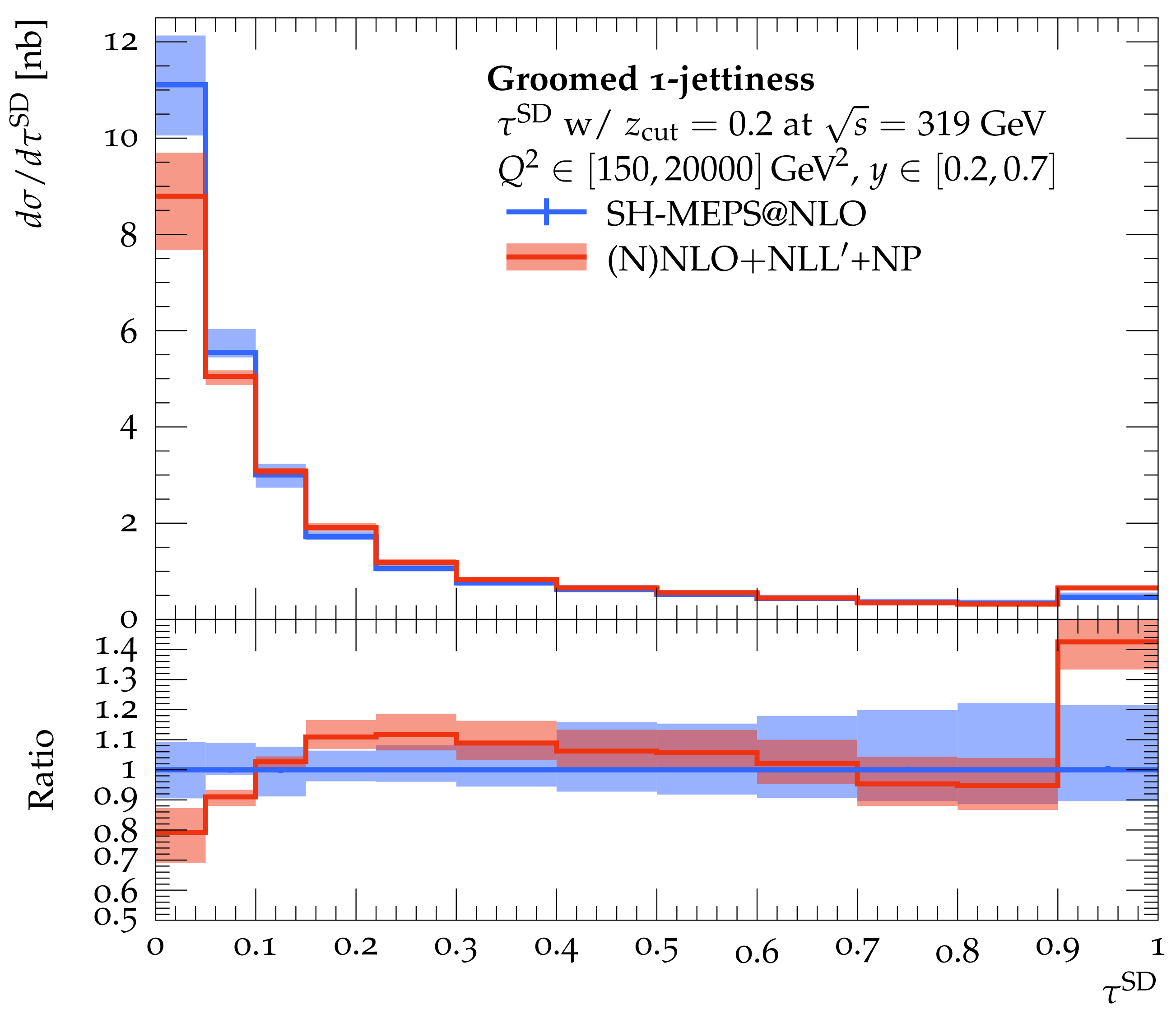


MC@NLO matching

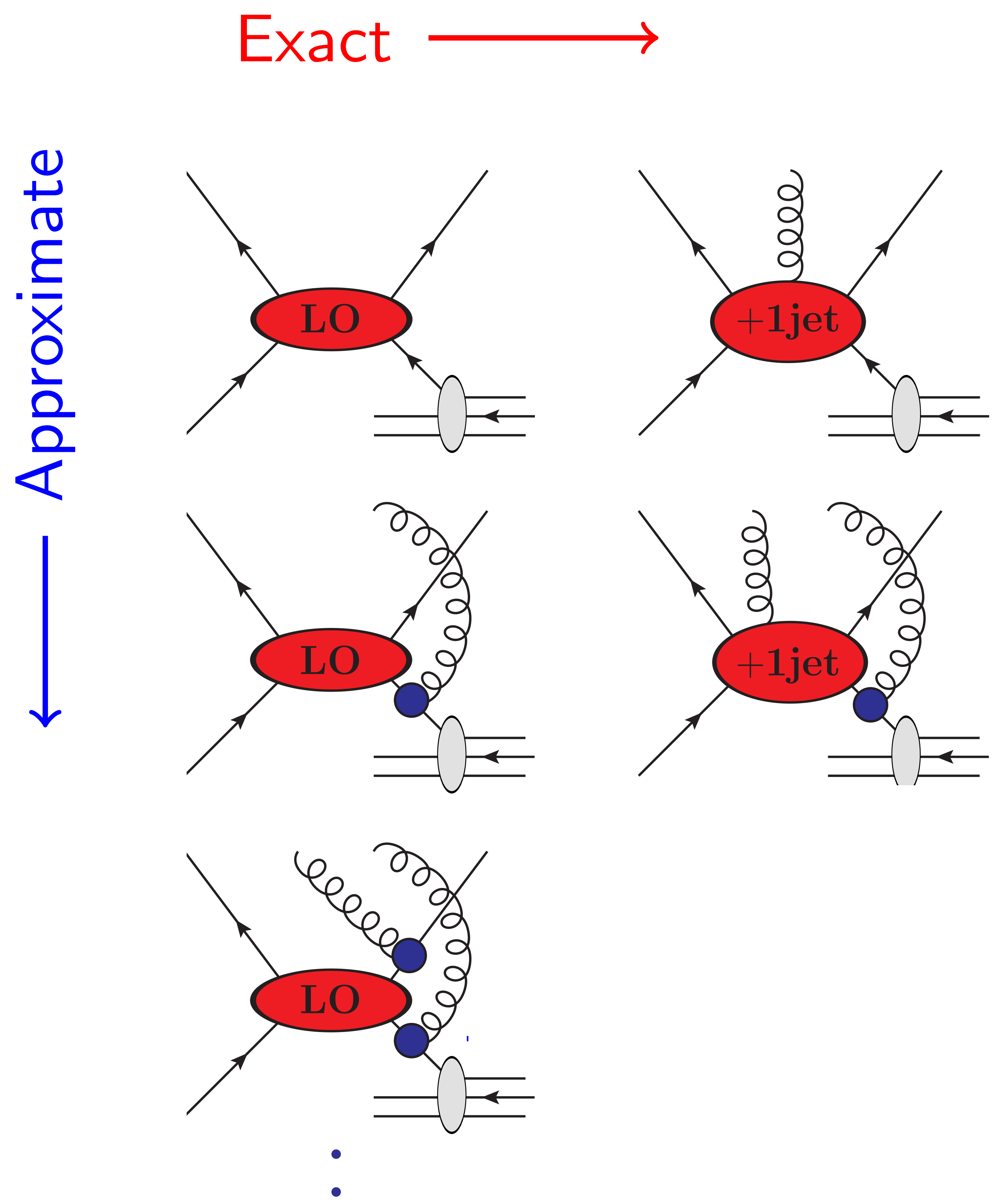
- [Frixione, Webber ‘02] :
  - splitting kernels serve as subtraction terms
  - multiply weight (at LO) with Born-local K-factor including integrated subtraction terms and virtual corrections
  - add hard remainder function, i.e. real emission and subtraction term



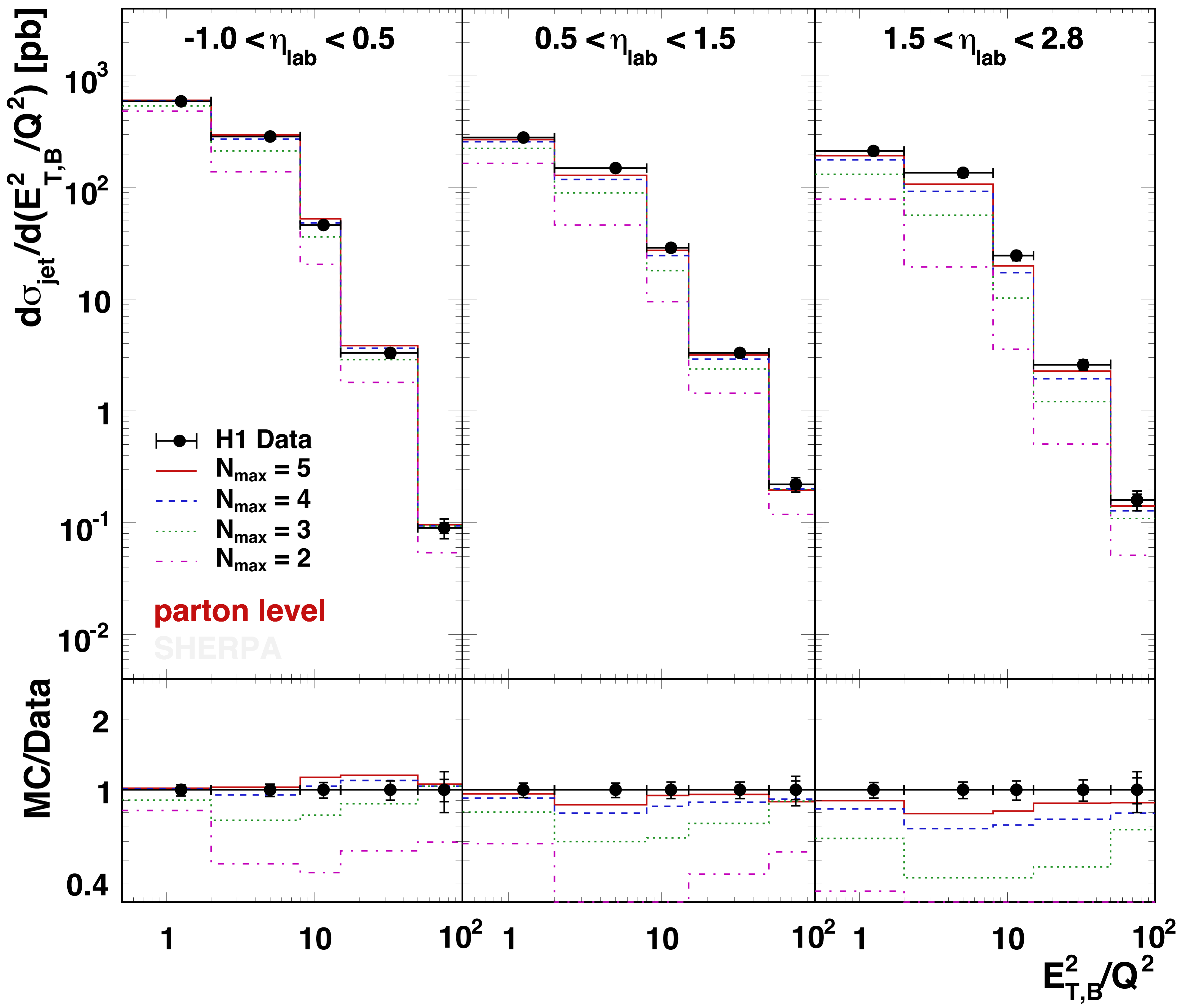
- Recent Example [Knobbe, DR, Schumann ‘23] :
  - case study, event shapes used for tuning and as predictions of upcoming H1 measurements
  - also comparison to fixed order and resummed calculation
  - including merging at LO and NLO



Matrix Element Merging



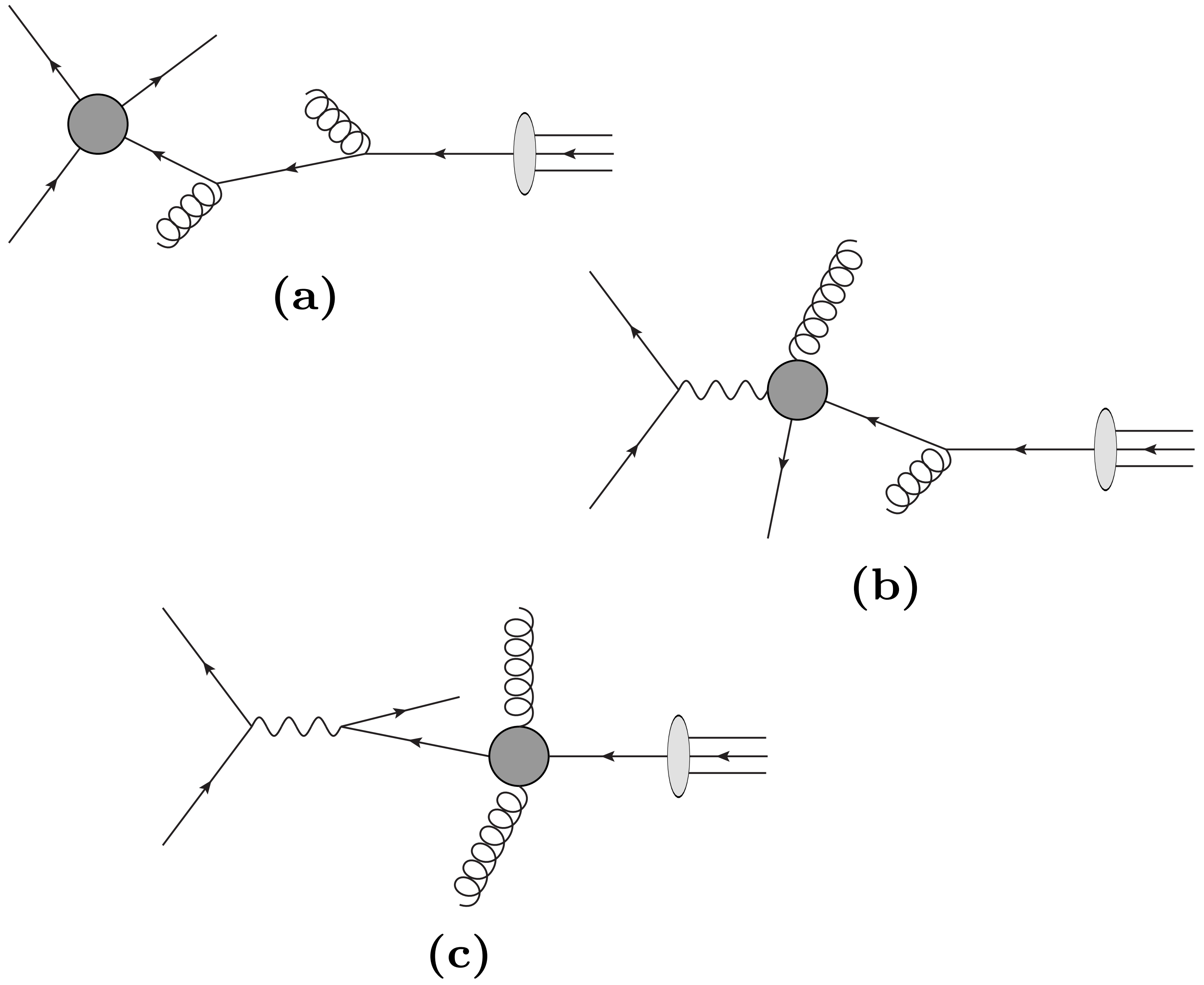
+ MEPS@NLO [Höche, Krauss, Schönherr, Siegert '13] to include NLO accurate MEs



[Carli, Gehrmann, Höche '09]

Technology fully applicable in DIS, with some care in clustering and resolution parameters:

$$Q_{\rm cut} = \bar{Q}_{\rm cut}\left[1 + \frac{\bar{Q}_{\rm cut}^2/S_{\rm DIS}^2}{Q^2}\right]^{-1/2}$$

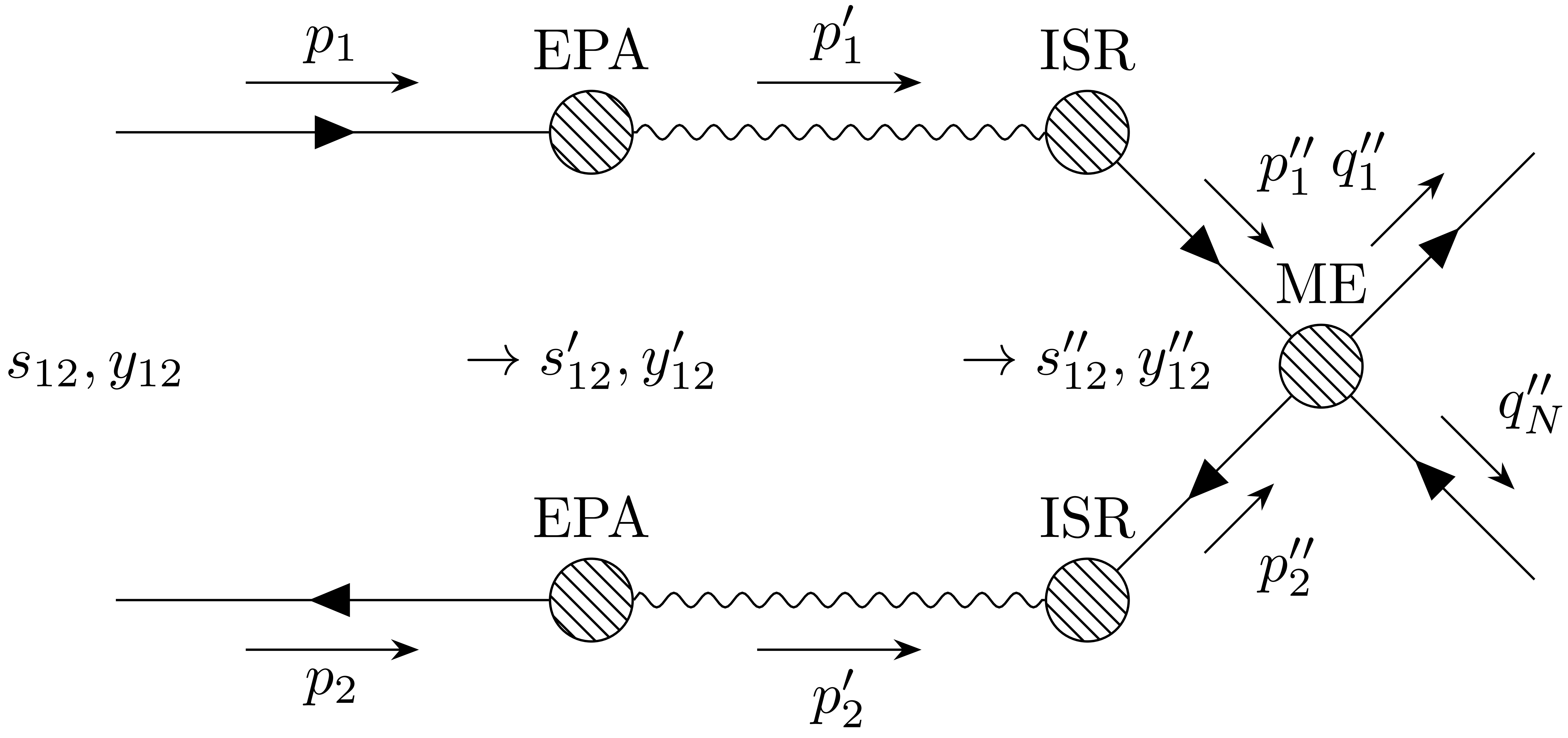


Photoproduction

- low Q^2 region will be important, real photon production at $Q^2 \to 0$
- focus on photo production of jets

- Effective Photon Approximation (EPA), based on Weizsäcker-Williams formula

$$\mathrm{d}n = \frac{\alpha_{\mathrm{em}}}{2\pi}\frac{\mathrm{d}x}{x}\left[\left(1+(1-x)^2\right)\log\left(\frac{Q^2_{\mathrm{max}}}{Q^2_{\mathrm{min}}}\right) - 2m_e^2x^2\left(\frac{1}{Q^2_{\mathrm{min}}} - \frac{1}{Q^2_{\mathrm{max}}}\right)\right]$$



[Höche, Krauss, Meinzinger '23]

New Parton Showers - NLL accuracy

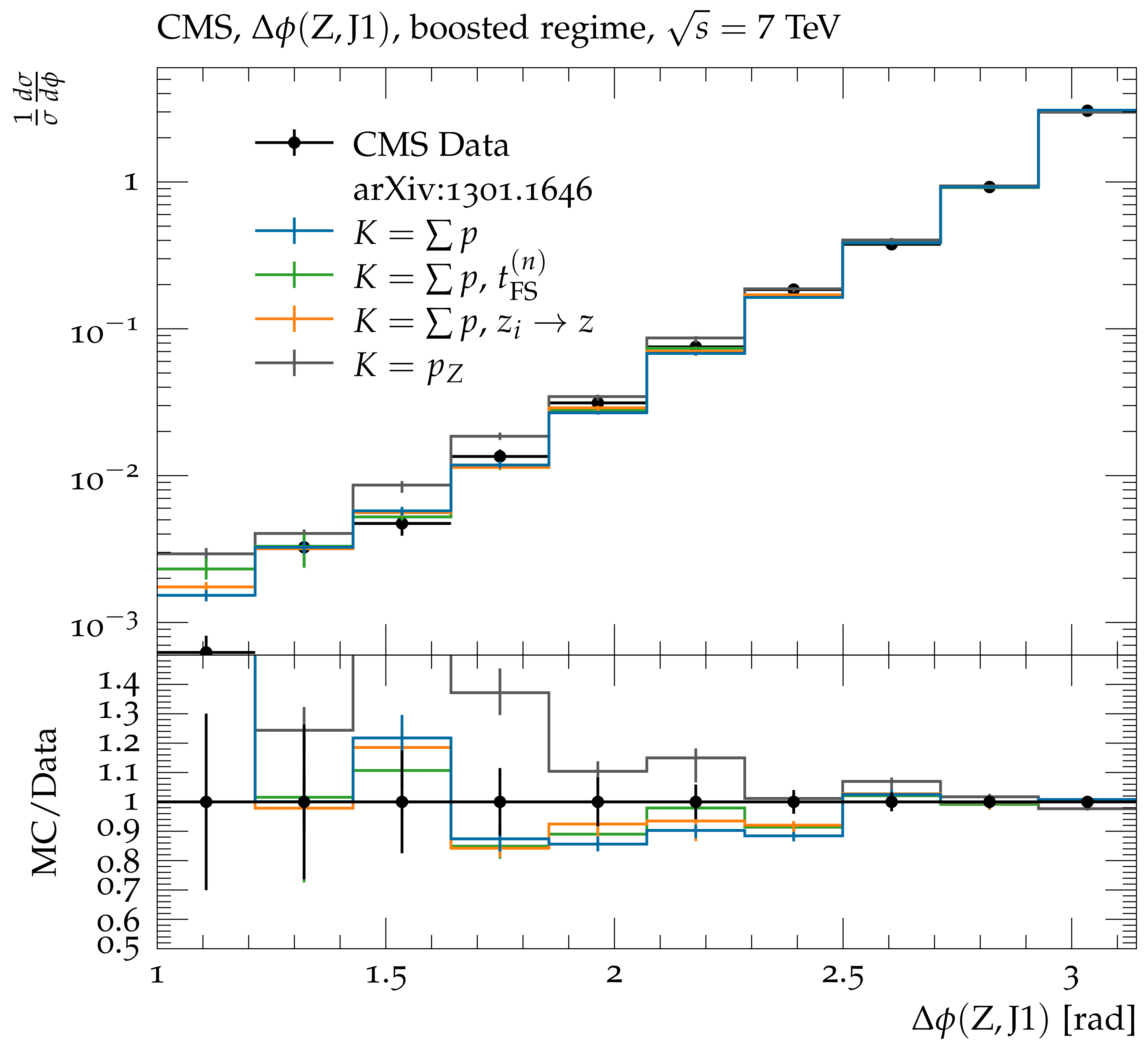
- typical claim based on accuracy of splitting functions etc.
  - parton showers ∼ NLL accurate if CMW scheme for strong coupling is used
- observation in [Dasgupta, Dreyer, Hamilton, Monni, Salam '18] (PanScales collaboration):
  - subtleties arise in distribution of recoil for subsequent emissions ⇒ phase space where accuracy is spoiled if soft gluon absorbs recoil
  - + in colour assignment
  - also: set of tests for shower accuracy [Dasgupta, Dreyer, Hamilton, Monni, Salam '20]

- Several solutions/re-evaluations of parton shower concepts:
  - [Dasgupta,Dreyer,Hamilton,Monni,Salam,Soyez '20], [vanBeekveld,Ferrario Ravasio,Hamilton,Salam,Soto-Ontoso,Soyez '22]
  - [Forshaw,Holguin,Plätzer '20]
  - [Nagy, Soper '11]
  - [Herren, Krauss, DR, Schönherr, Höche '22]

Alaric at the LHC

- Alaric [Herren et. al. '22] for LHC applications [Höche, Krauss, DR '24]
- analytical proof of NLL correctness + numerical validation for $e^+e^- \to jj$
- LO merging available
- New view of treatment of coherence and split between soft/collinear correction

  $\Rightarrow$ preparing new view on spin correlations
- Missing pieces for full release:
  - MC@NLO (subtraction terms known, need to validate and fix bugs…)
  - DIS implementation (i.e. treatment of IF/FI type dipoles)



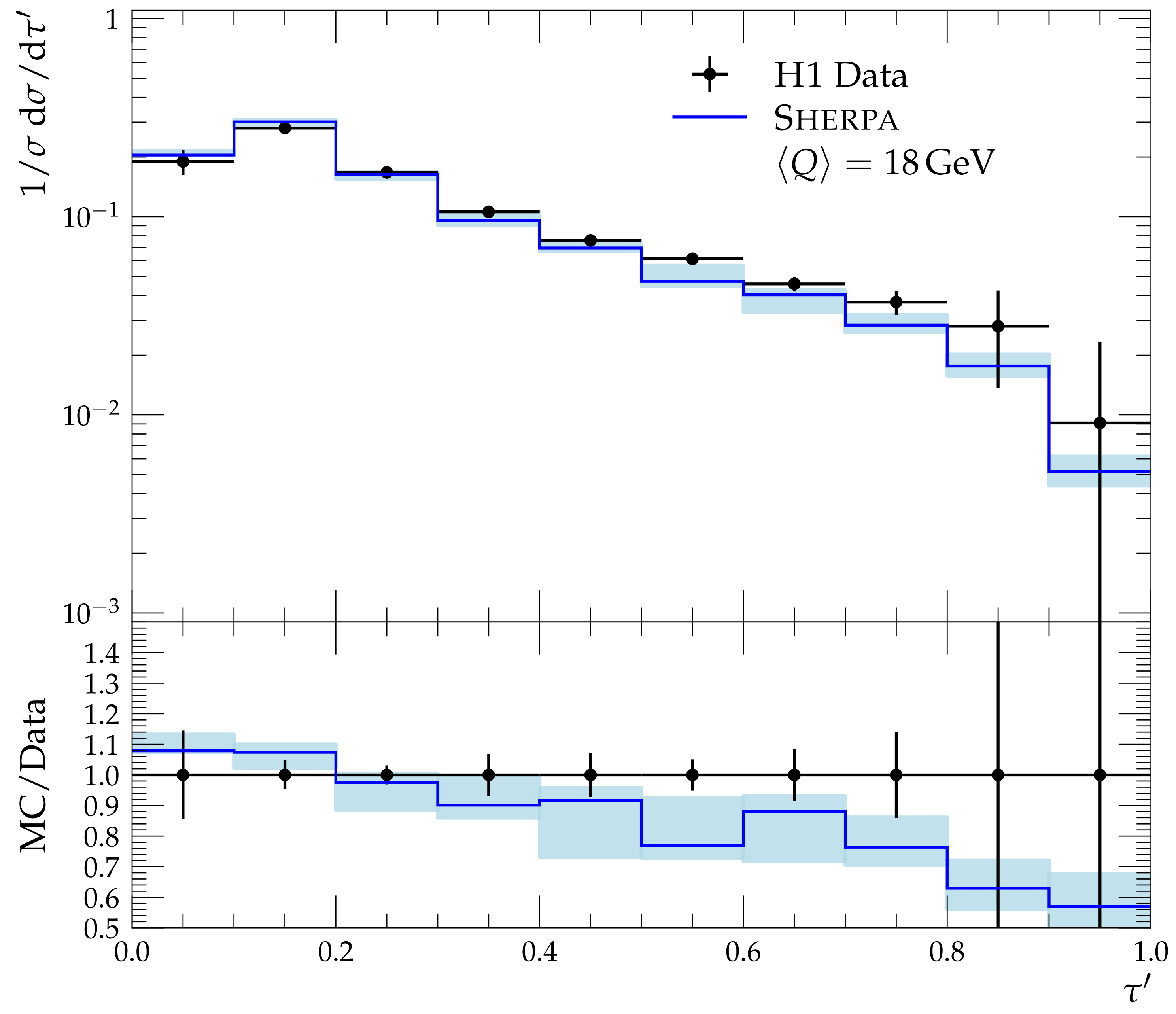
Looking back to HERA

Looking back to HERA

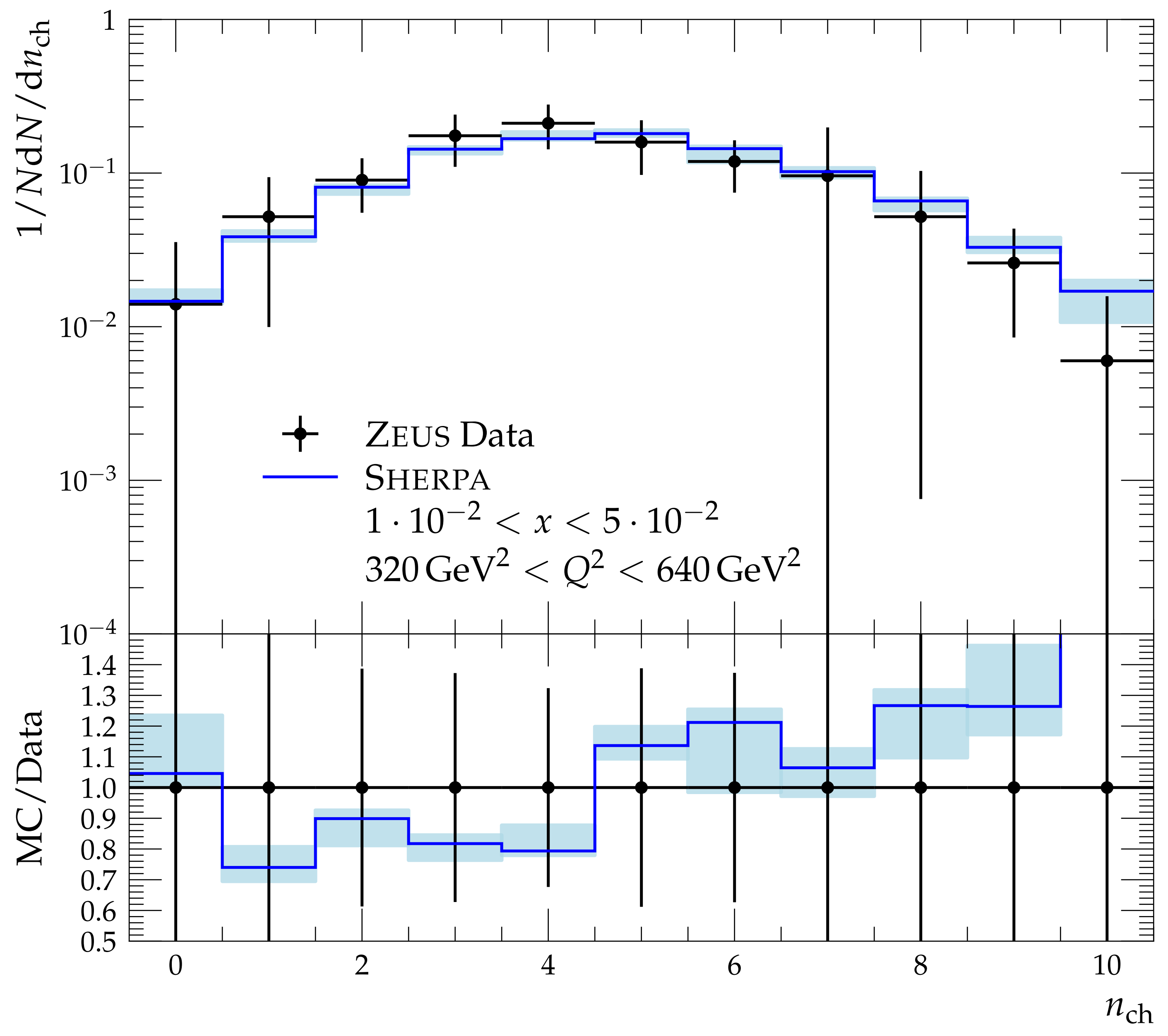
- Still (or again) active analyses of HERA data
- A lot of lessons learned since data taking
  - Experimental/Pheno side:
    - new observables, jet substructure techniques etc.
  - Theory side:
    - general NLO matching/merging available now, challenge new tools
    - interest in tuning, prepare for EIC + clean environment for beam fragmentation (without massive UE/MPI contamination)

Tuning to HERA data

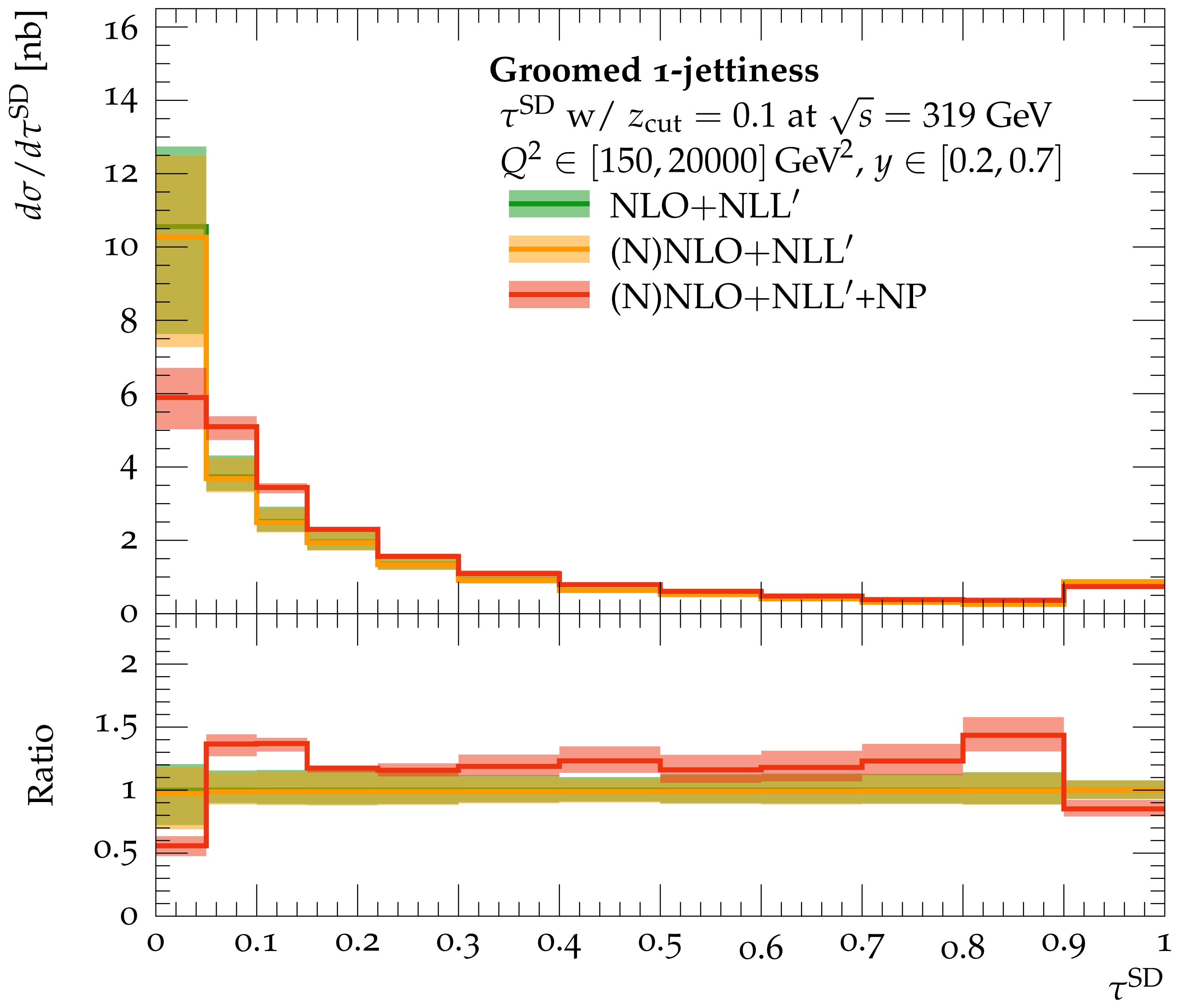
- "Traditional" approach:
  - Tune FS against LEP (mostly Z-pole) data, then UE model with Tevatron/ LHC data
- "Clean" environment in DIS:
  - No UE/MPI contamination
  - but additional complication because final state is color connected to beam remnants
  - Opportunity to fix this ambiguity "inbetween"
  - Next to valuable data on NP effects in general

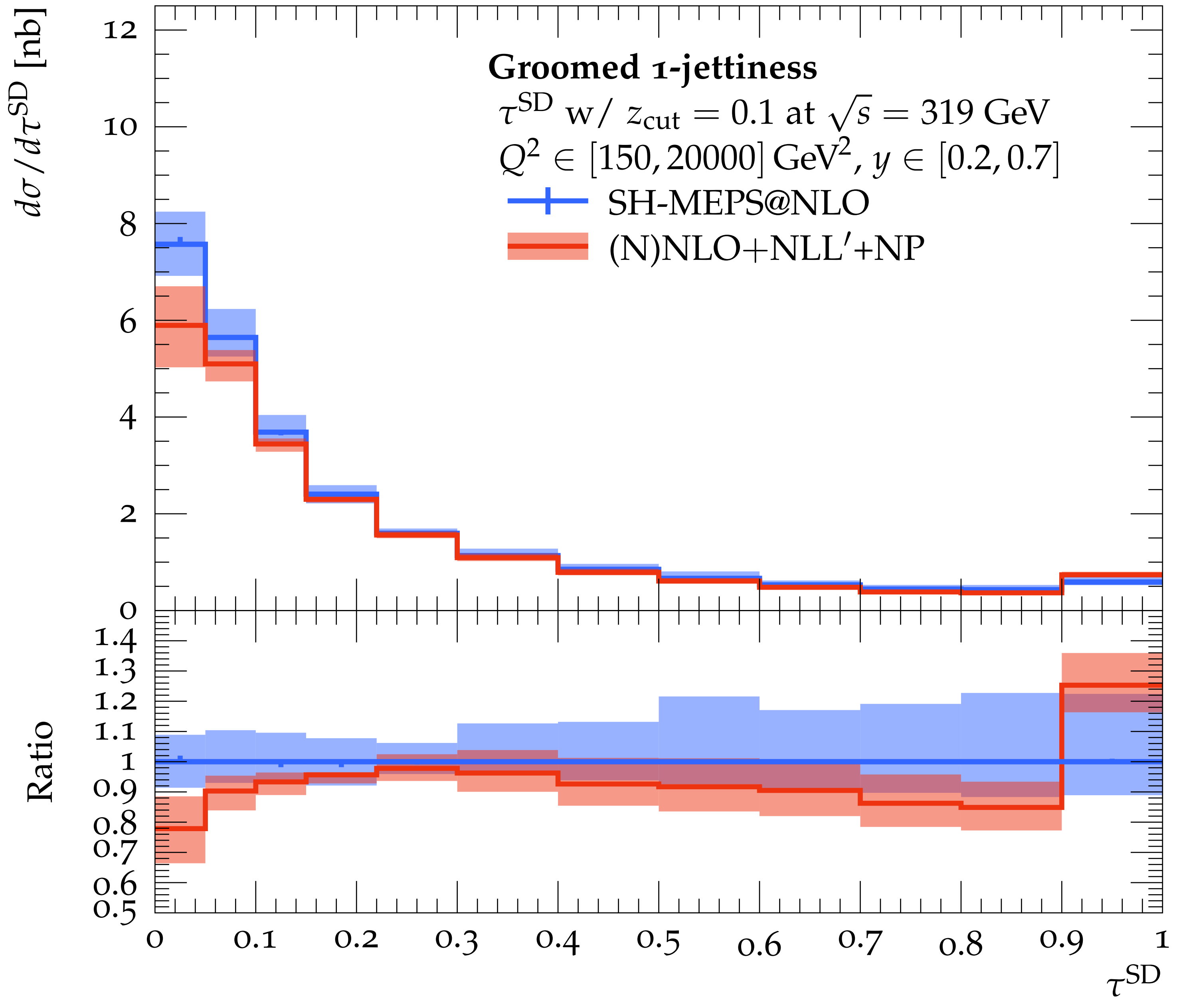


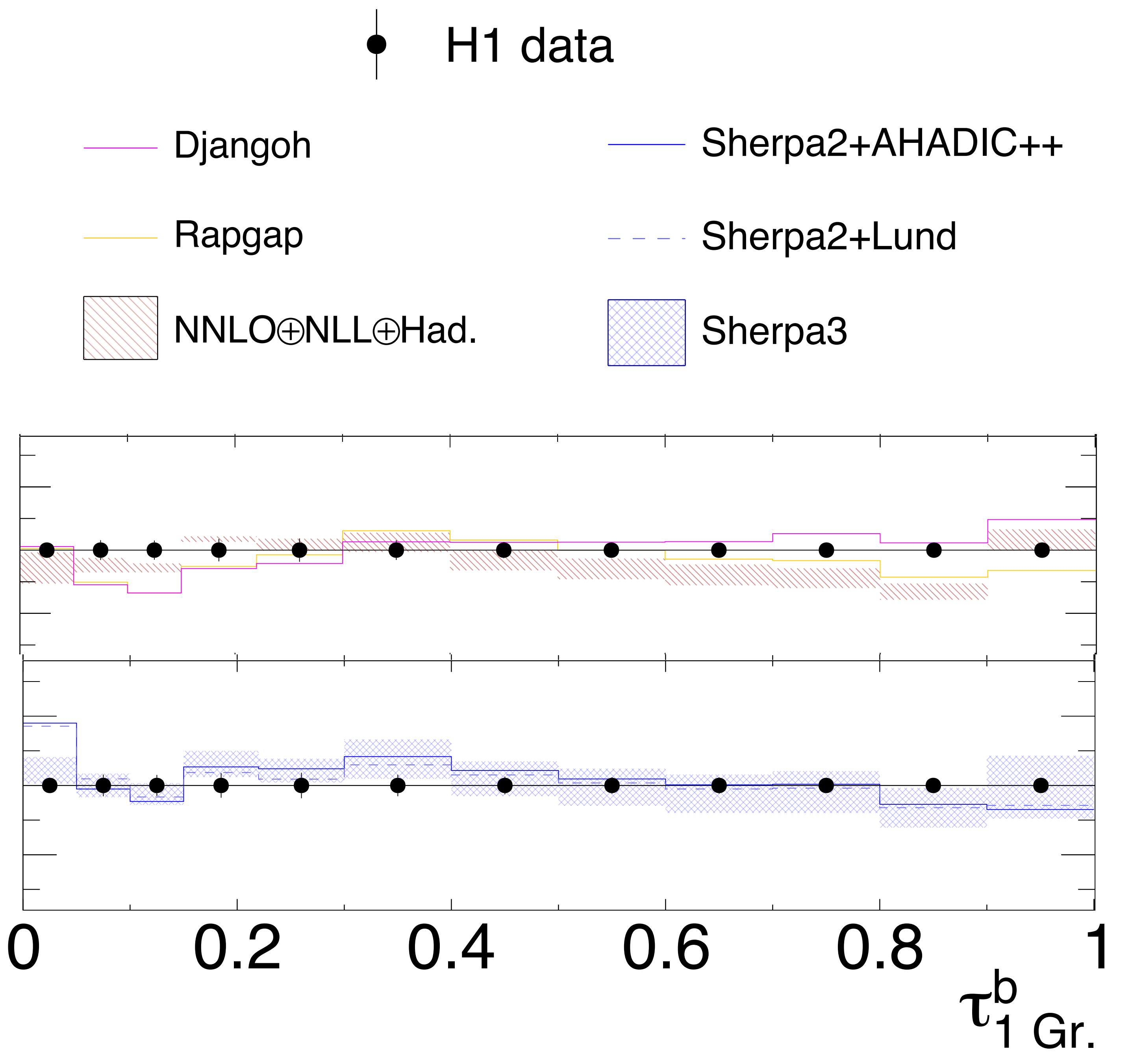
[Knobbe, DR, Schumann '23]



Predictions for new H1 analyses



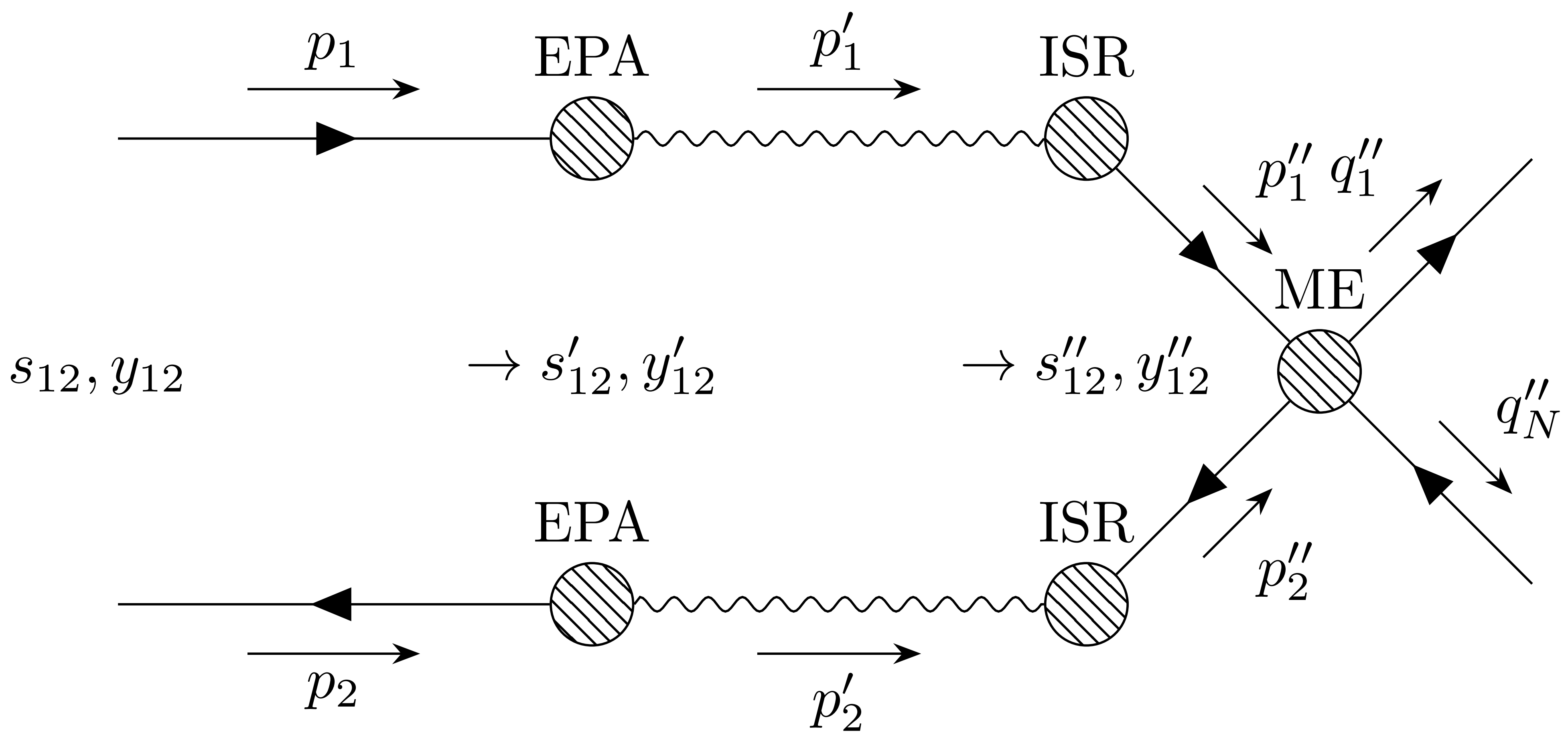


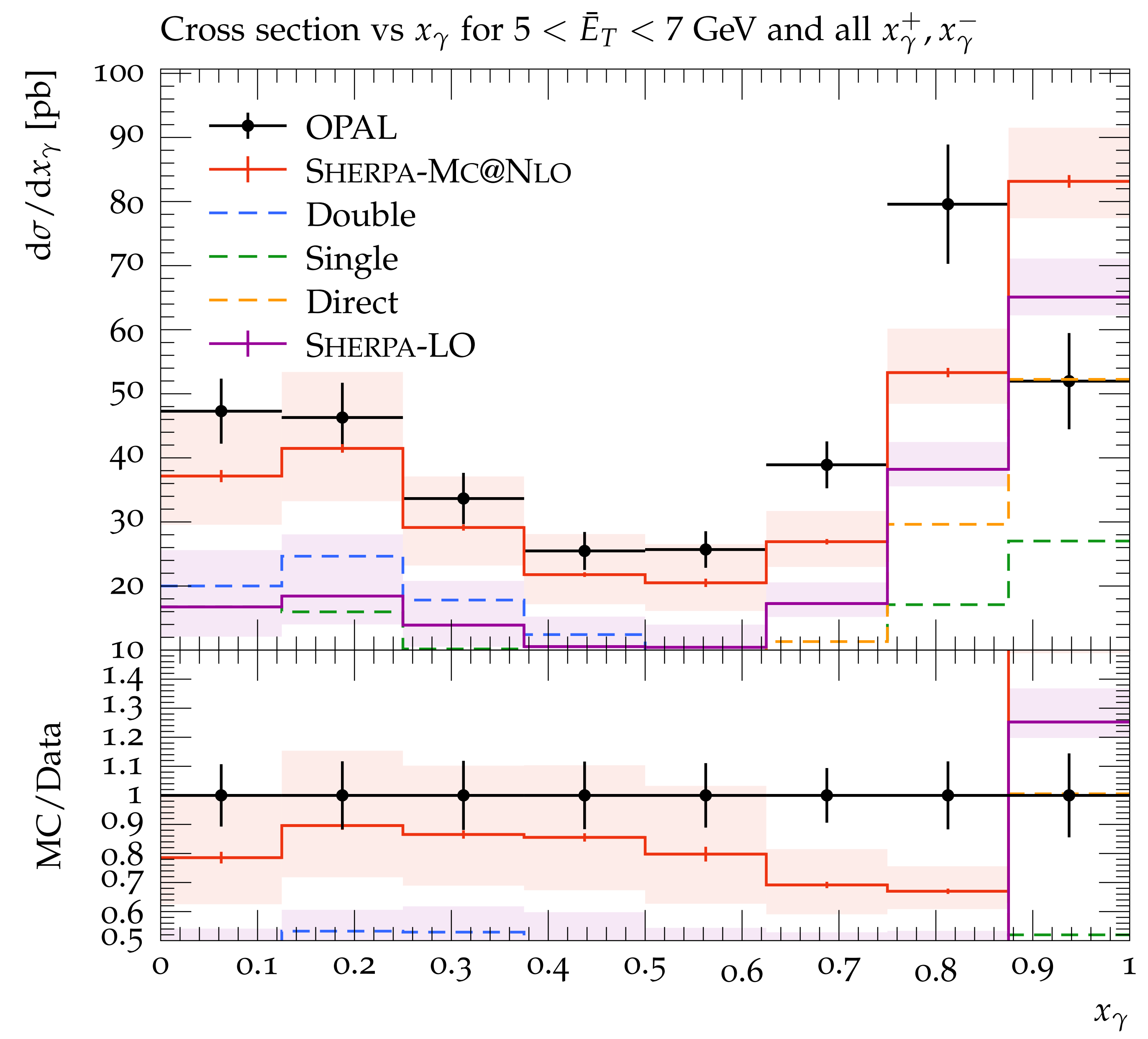


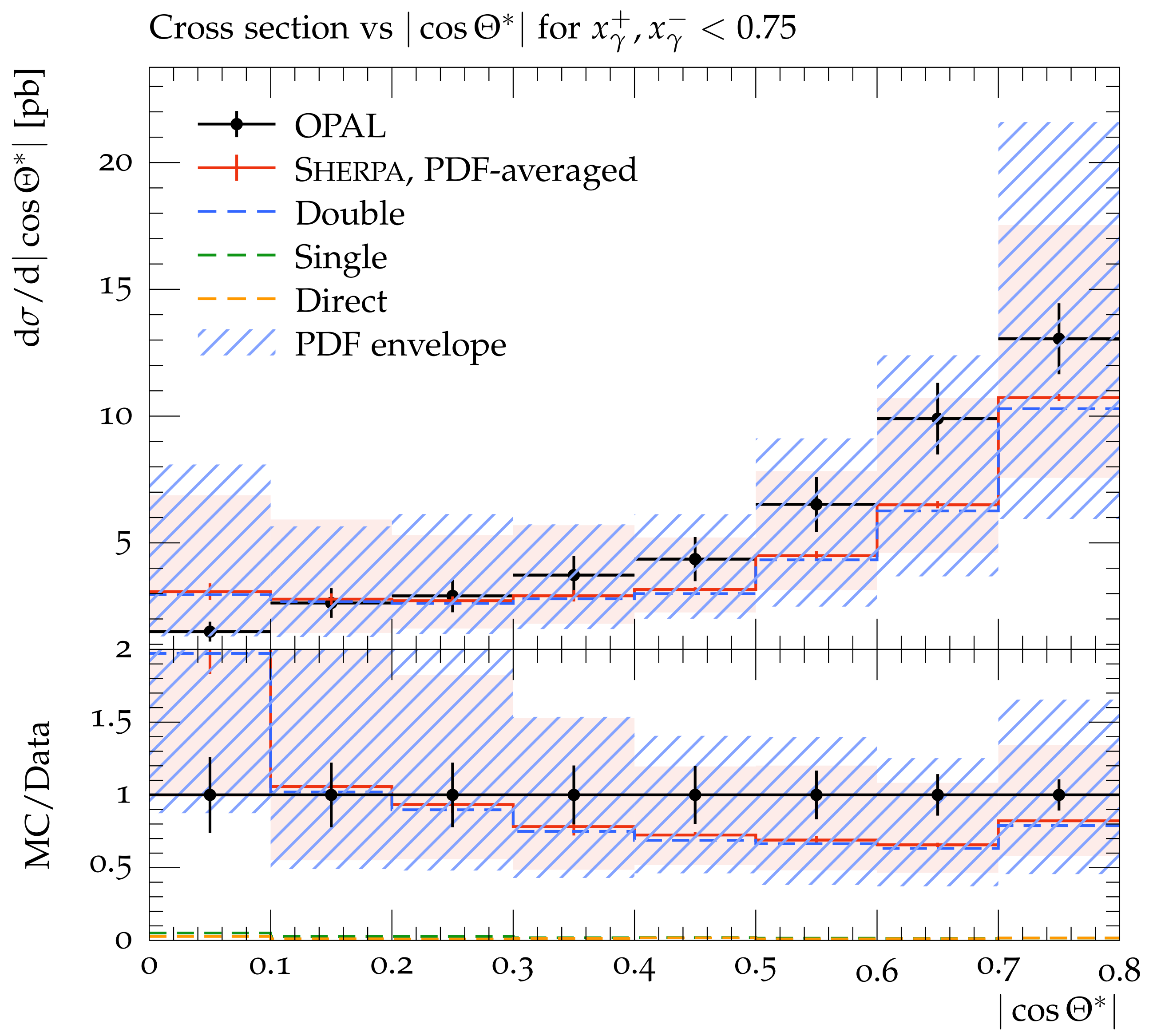
- groomed 1-jettiness, measurements from [H1 arXiv:2403.10134]
- comparison agains several MC generators, H1 standard DJANGOH & RAPGAP and current LHC defaults including Sherpa
- Including (N)NLO+NLL’ resumed predictions with automated implementation in Sherpa

Photoproduction

- **New in Sherpa 3:** 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







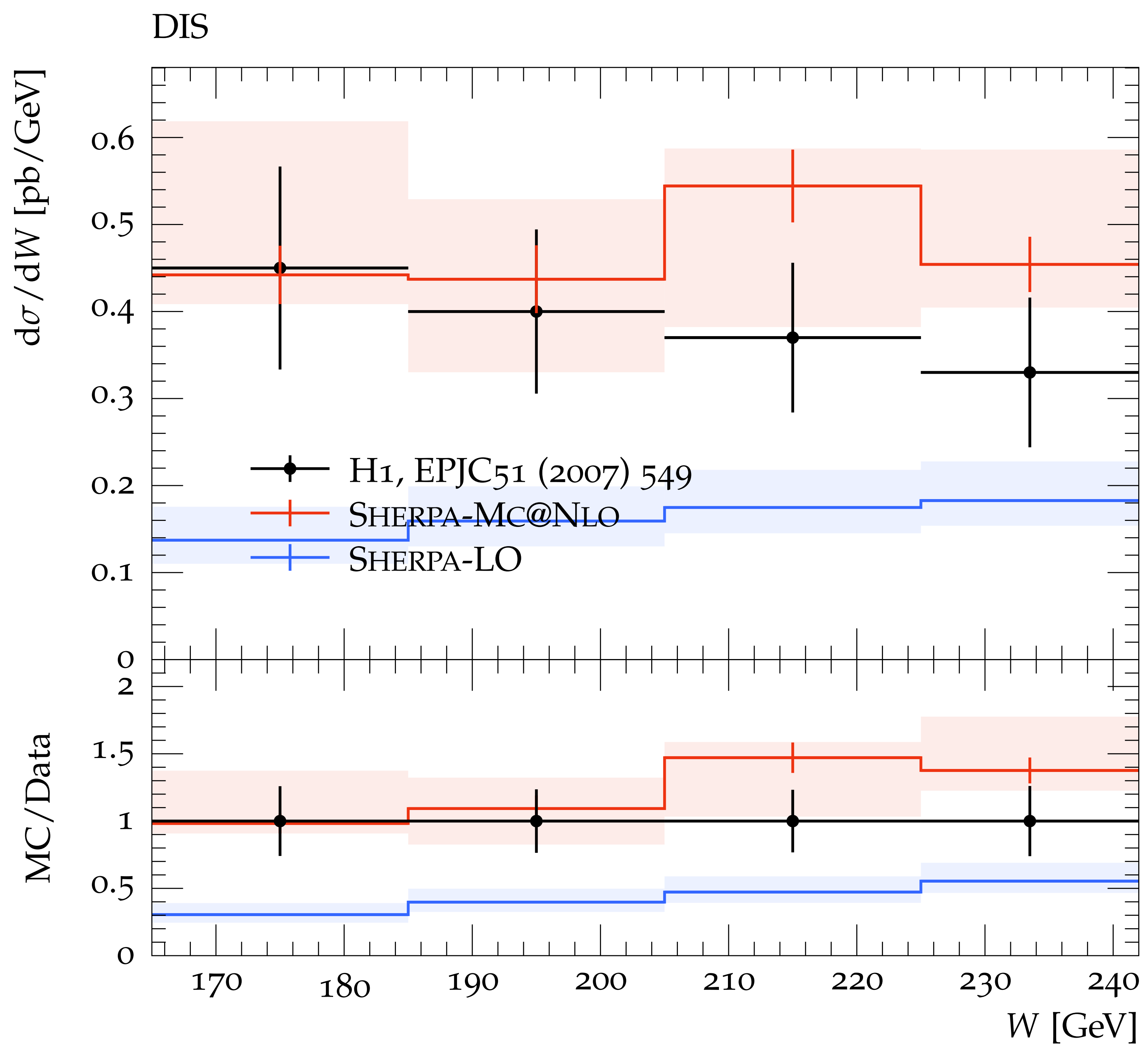
Hard Diffraction

- New Implementation based on Pomeron pdf approach [Meinzinger, Krauss ’24]

$$\sigma^{(\mathrm{DDIS})}\left(ep \to eXY\right) = \int_0^{x_{I\!P,\max}} \mathrm{d}x_{I\!P} \int_{t_{\mathrm{cut}}}^{t_{\min}} \mathrm{d}t \int_0^1 \mathrm{d}x_i f_i^D\left(x_i, \mu_F, x_{I\!P}, t\right) \hat{\sigma}\left(ei \to eXY\right)$$

- Matrix element calculate at NLO and matched in MC@NLO approach

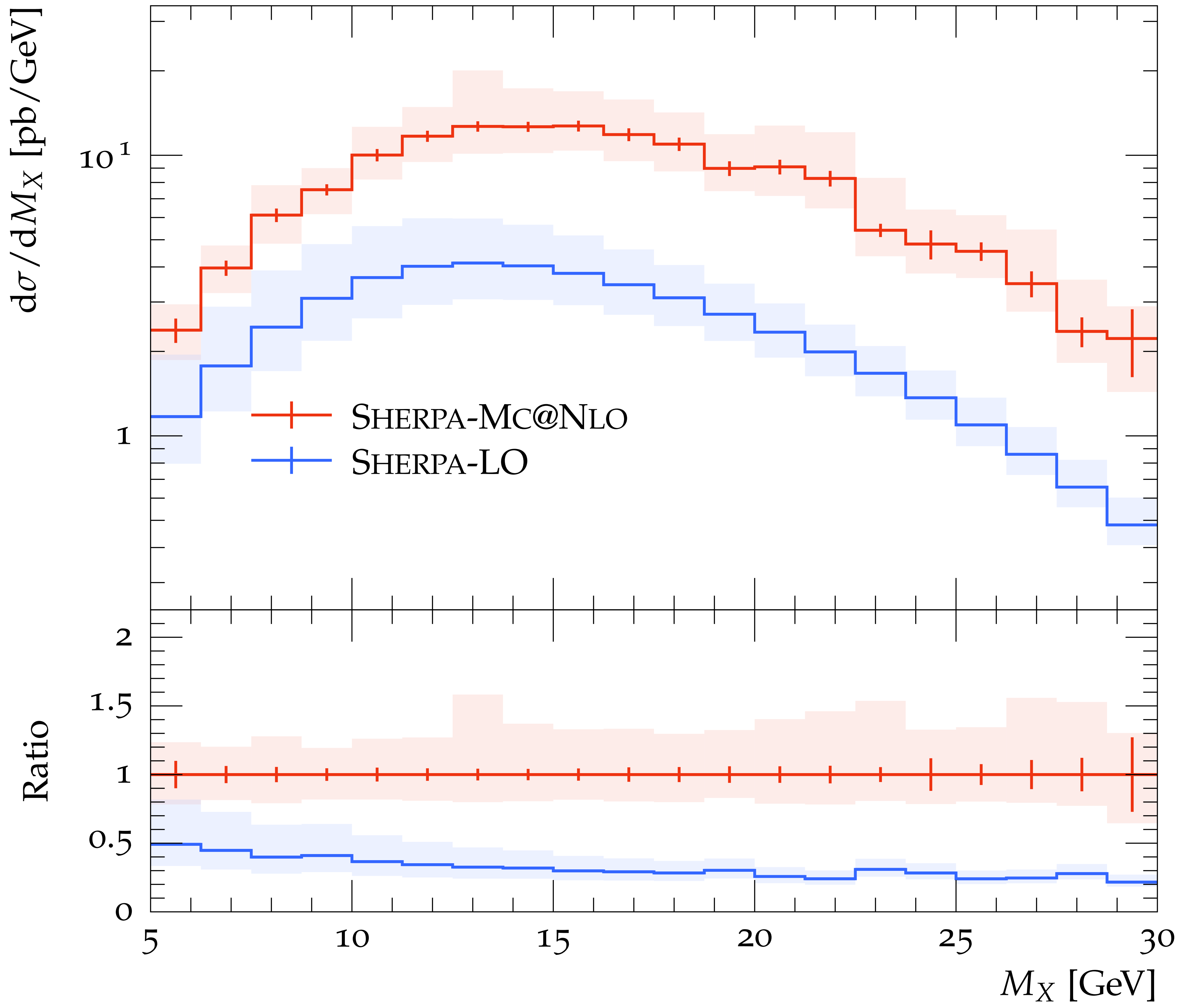
- Also: diffractive photoproduction, connected to conceptual questions about factorisation

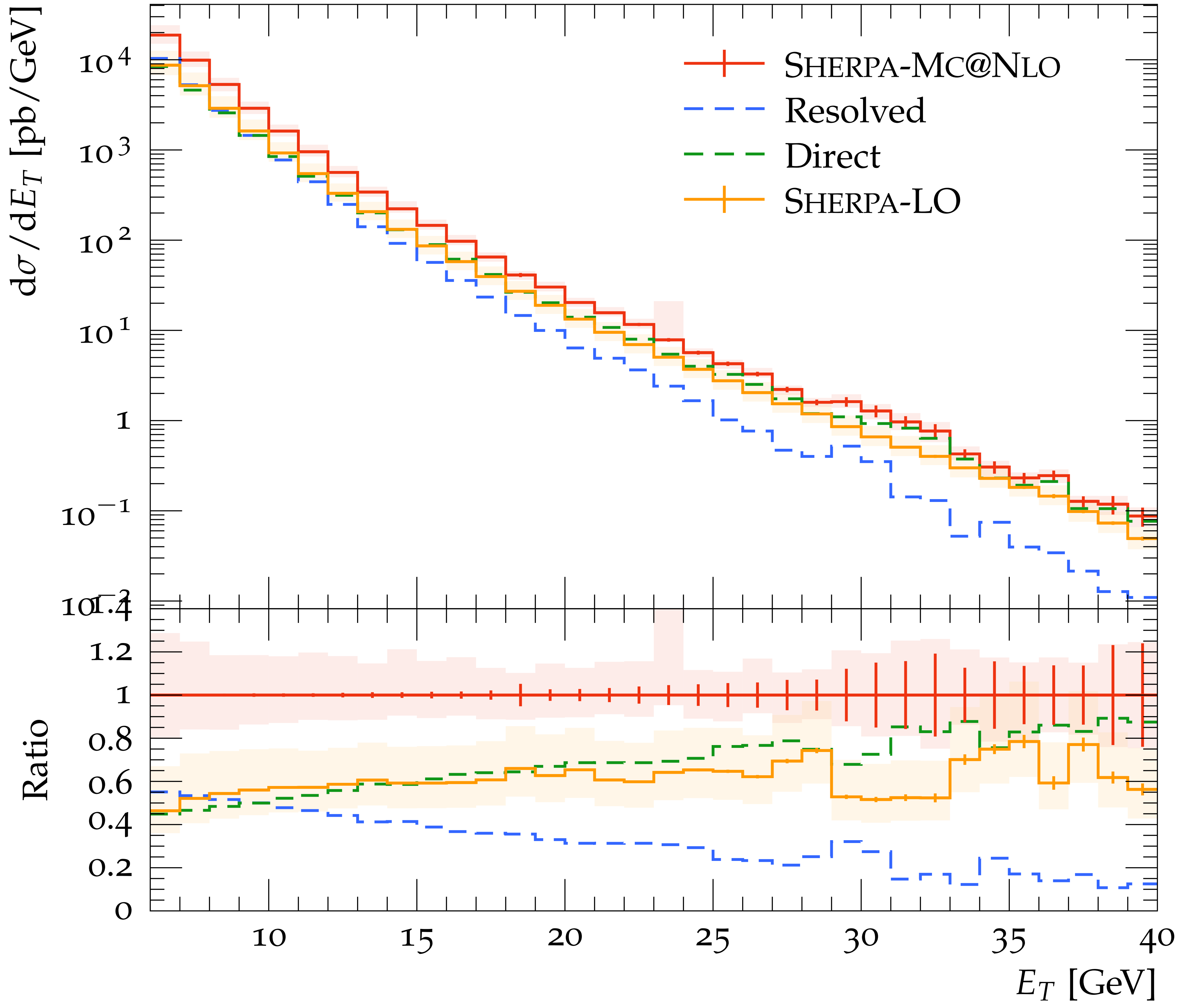


Summary & Outlook

Preparing for the EIC

Hard Diffraction and Photoproduction

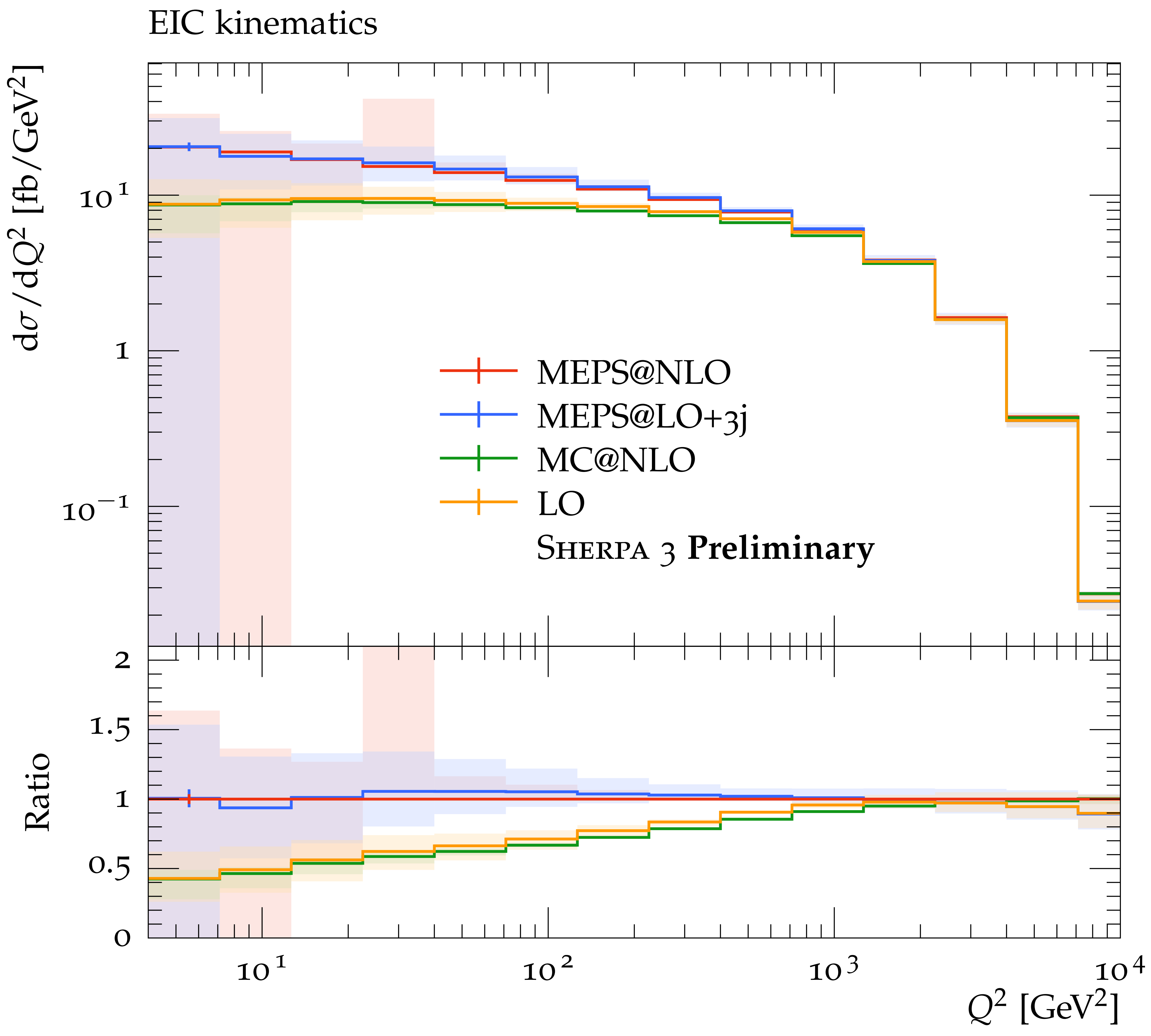




- Hard diffraction from [Meinzinger, Krauss '24] with EIC kinematics
- As well as photo production, see [Meinzinger, Krauss '24]

(NLO) Merged CC/NC predictions for the EIC

- Study with EIC kinematics
  [Meinzinger, DR, Silvetti WIP]
- Including CC with MC@NLO and MEPS@NLO
- Uncertainty budget with NP uncertainties from replicas
  [Knobbe, DR, Schumann '23]



Summary

- Sherpa 3 multi purpose event generator
  - Traditional focus on perturbative precision calculations applicable at high energy scales (e.g. Q^2) matched to parton showers
  - merging of matrix elements with many jets
    - crucial for extrapolation to small Q^2
  - Photoproduction for $Q^2 \to 0$, related ideas for hard diffractive process
  - Re-evaluating DIS simulation with HERA data and making first predictions for the EIC