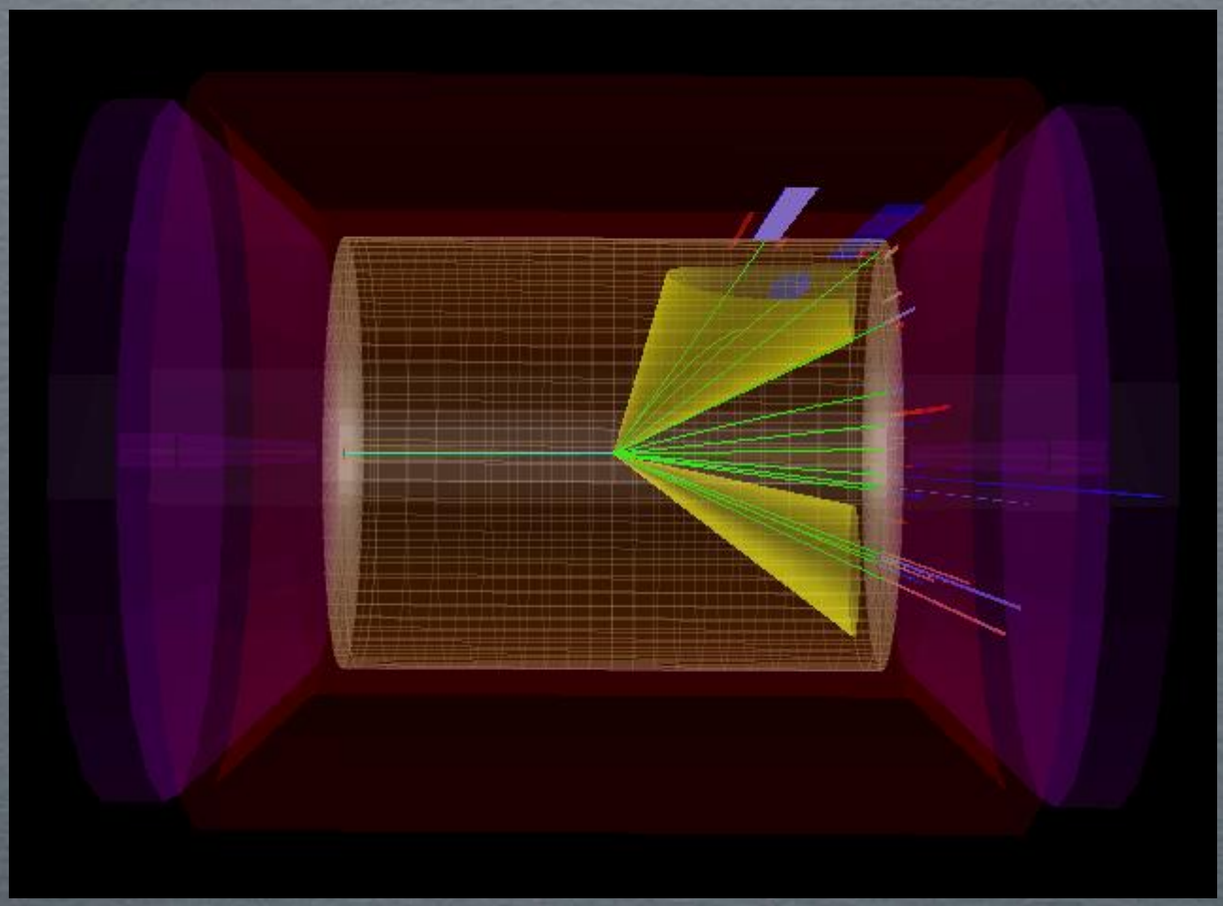
# A dedicated POWHEG generator for DIS



Andrea Banfi

MC4EIC Durham – 6 June 2024

University of Sussex

In collaboration with

S. Ferrario ravasio, B. Jäger, A. Karlberg, F. Reichenbach, G. Zanderighi

# Outline

- Motivations: renewed interest in Monte Carlo generators for DIS
  - First step to describe important DIS-like processes at the LHC (e.g. VBF) at NNLOPS
  - Provide an NLO+PS generator to the EIC community
  - High-energy cosmic neutrinos
- Dedicated POWHEG generator for DIS
  - Need to describe inclusive cross sections at pure NLO $\Rightarrow$ novel mapping for real radiation that fully preserves lepton kinematics

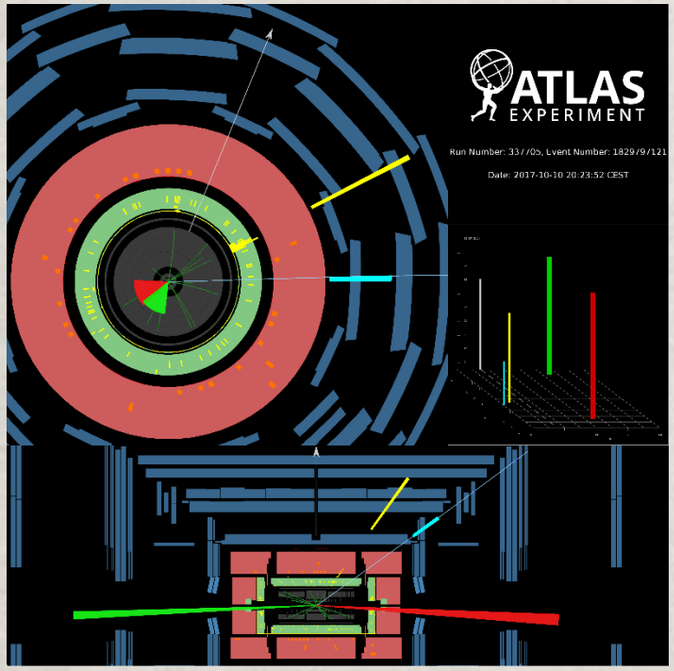
svn://powhegbox.mib.infn.it/trunk/User-Processes-RES/DIS

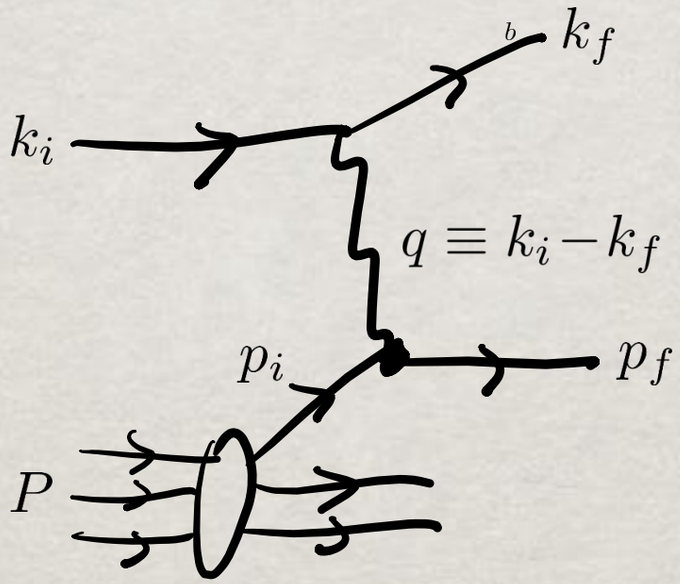
- Validation
  - inclusive cross sections, global event-shapes and VBF-like observables
  - Comparison with default POWHEG RES, which does not preserve lepton kinematics
- Phenomenology
  - Comparison with HERA data
  - New predictions for EIC

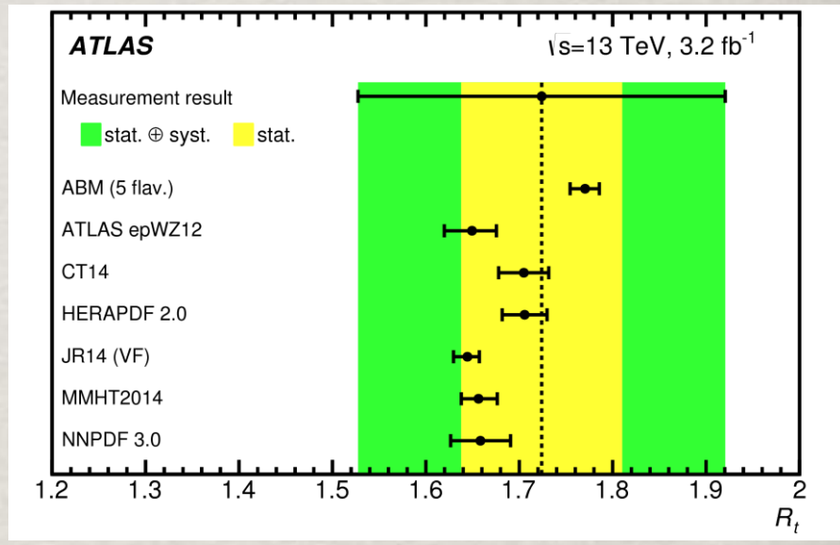
# Motivations

# DIS-LIKE PROCESSES AT THE LHC

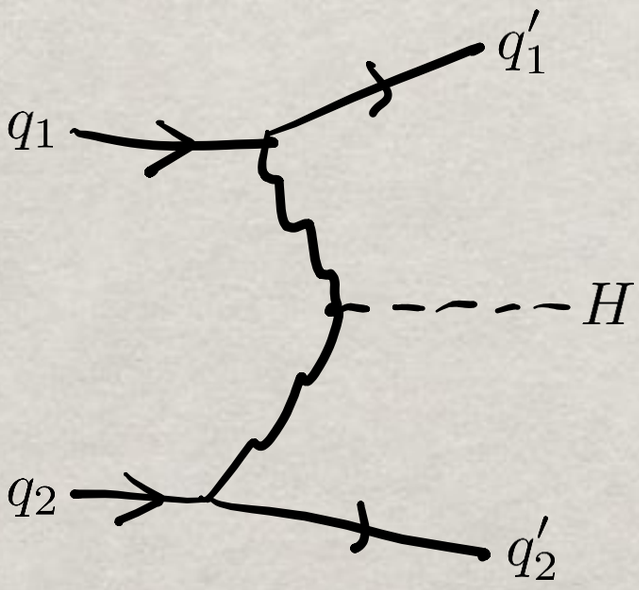
Both VBF and single-top production can be modelled using DIS kinematics

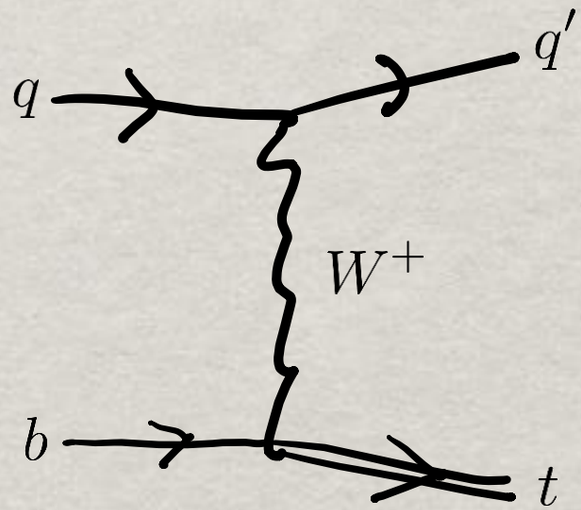


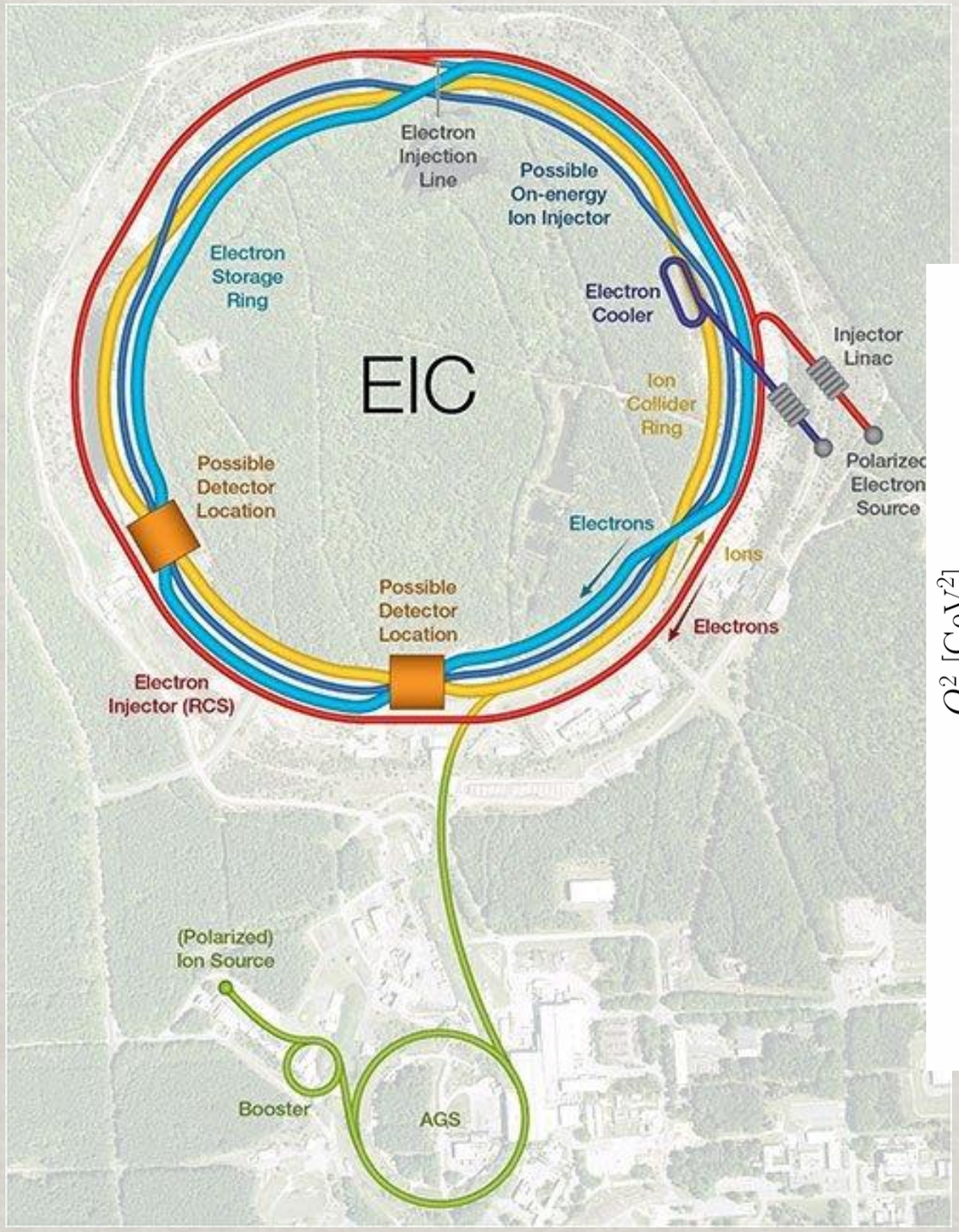

[ATLAS 1609.03920]

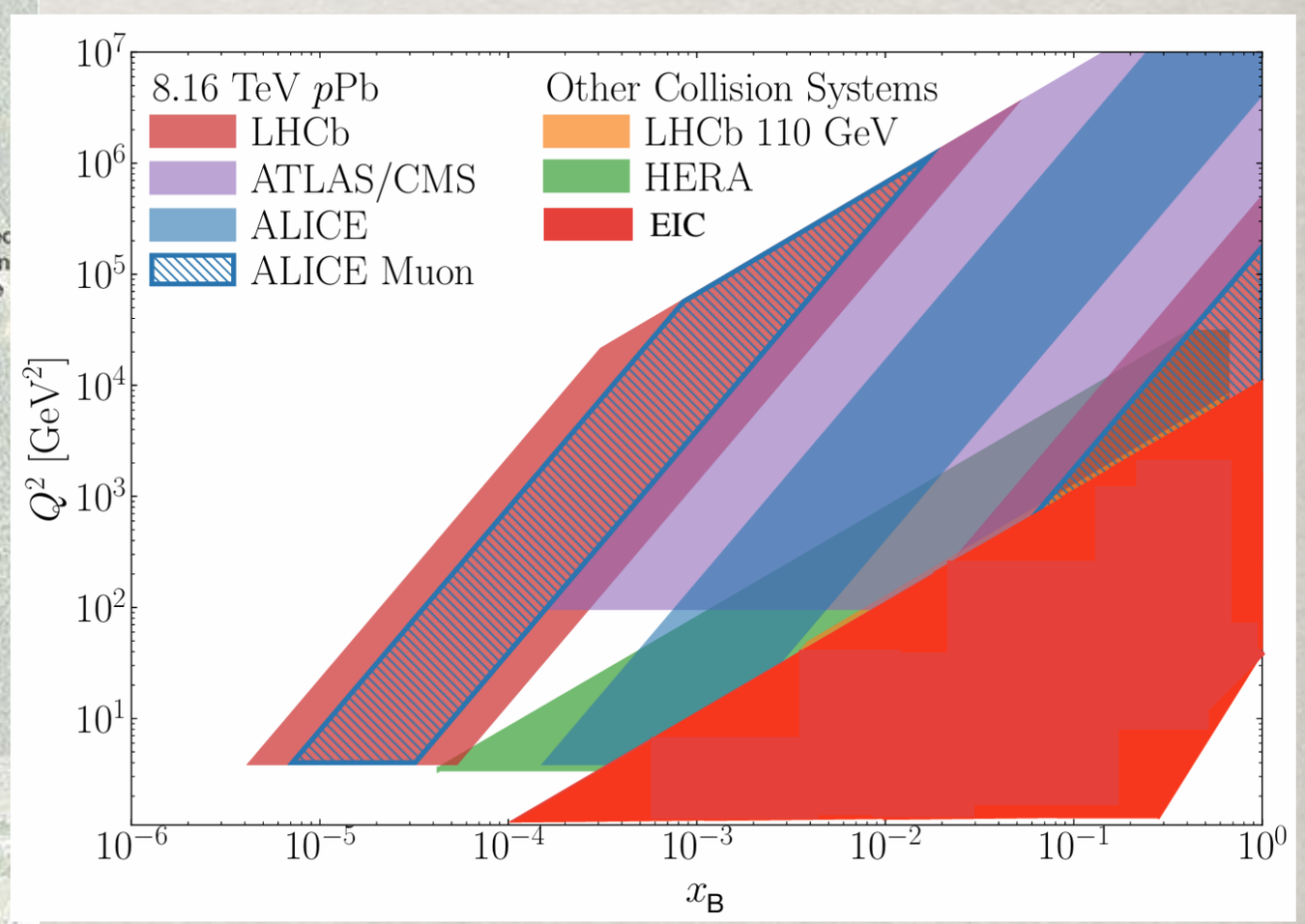


# Electron-Ion Collider

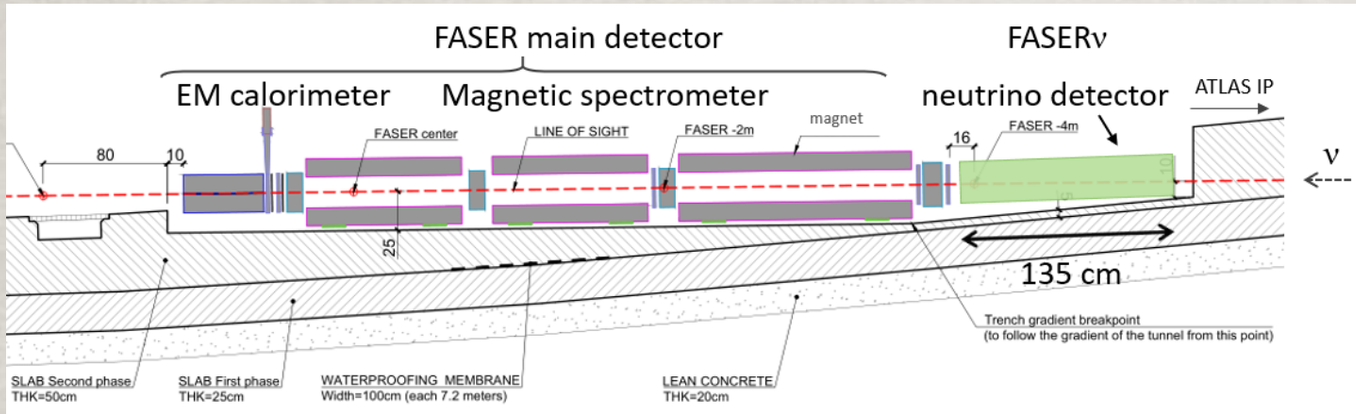
The Electron-Ion Collider will give new insight into the structure of the proton

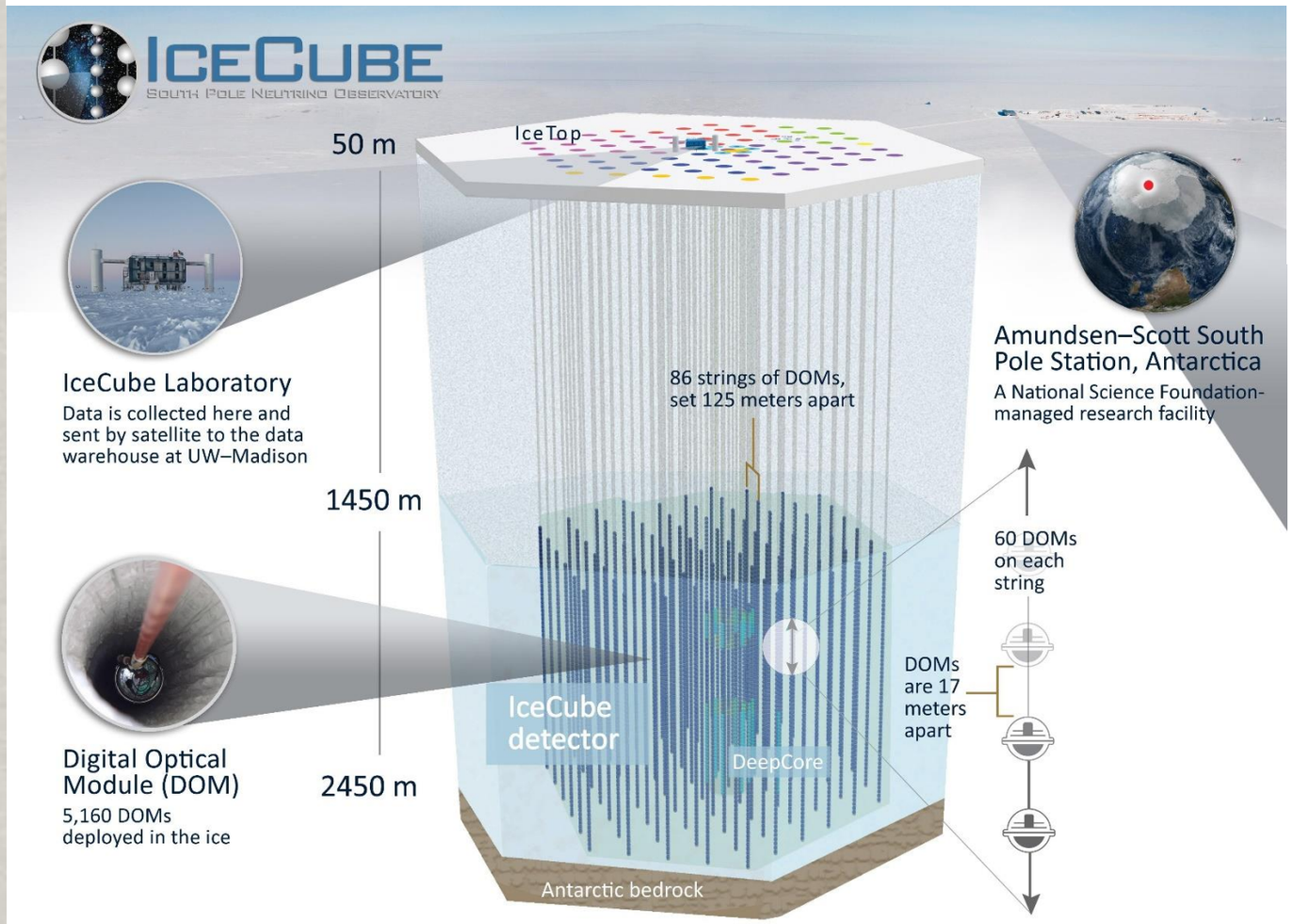


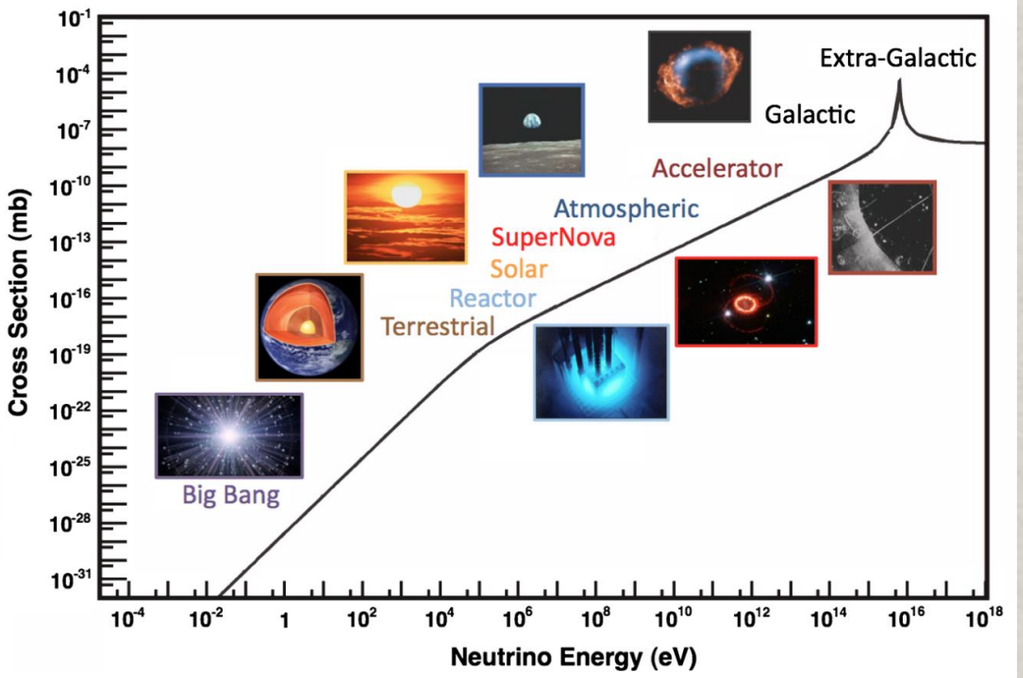



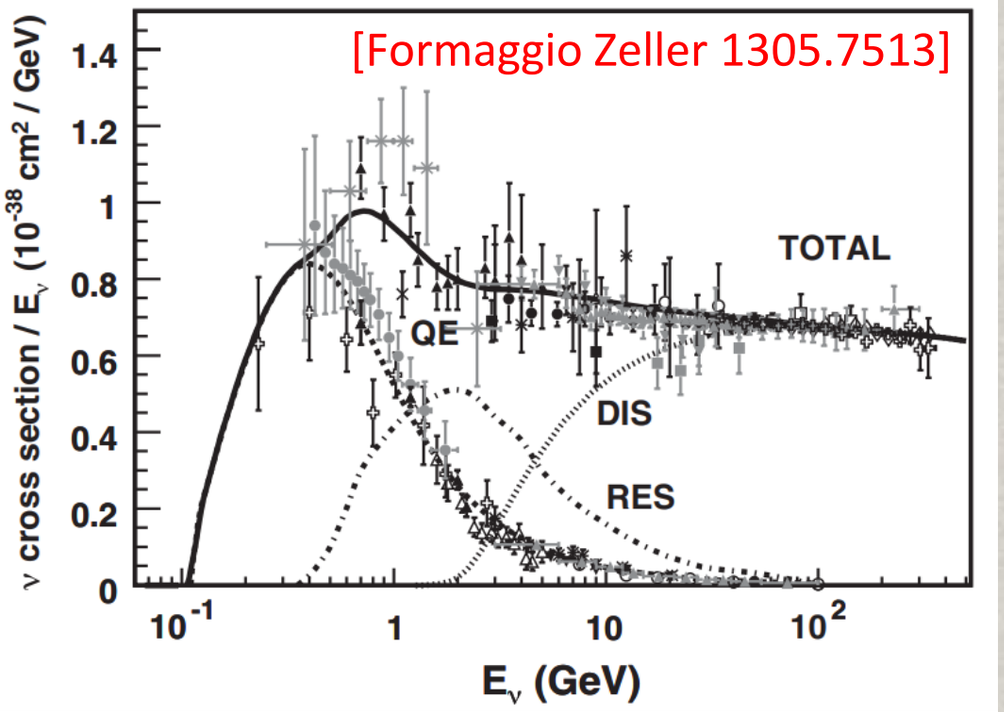
# Cosmic neutrinos

DIS is the main interaction mechanism for high-energy cosmic neutrinos



# Details of the Generator

# NLOPS Monte Carlos for DIS

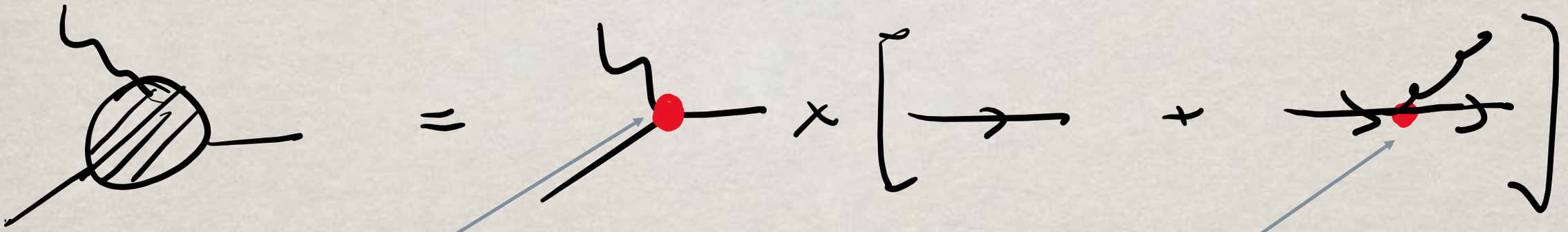
- The functionalities of Herwig and Sherpa allow for automatic matching of these Monte Carlo generators to NLO
- MadGraph5_aMC@NLO and old versions of POWHEG BOX do not support the simulation of DIS
- The default version of POWHEG BOX RES supports processes with incoming leptons, but the phase-space generation does not preserve lepton kinematics

- To reproduce inclusive fixed-order cross sections multi-differential in $x_B$, $y_{\mathrm{DIS}}$ and $Q^2$ we need a phase-space generation that preserves lepton kinematics
- The new generator is a valid starting point for the matching of parton shower and NNLO

# Basics of POHWEG

- POWHEG provides a method to interface a hard event to a parton shower so that the resulting cross section is exact at NLO
- The key feature of POWHEG is the existence of a mapping between the phase-space with additional radiation and that of the underlying Born event

$$d\Phi_{n+1} = d\bar{\Phi}_n d\Phi_{\mathrm{rad}}$$



$$d\sigma_{\mathrm{PWG}} = \bar{B}(\bar{\Phi}_n) d\bar{\Phi}_n \left[\Delta(\bar{\Phi}_n, \mu)\right.$$

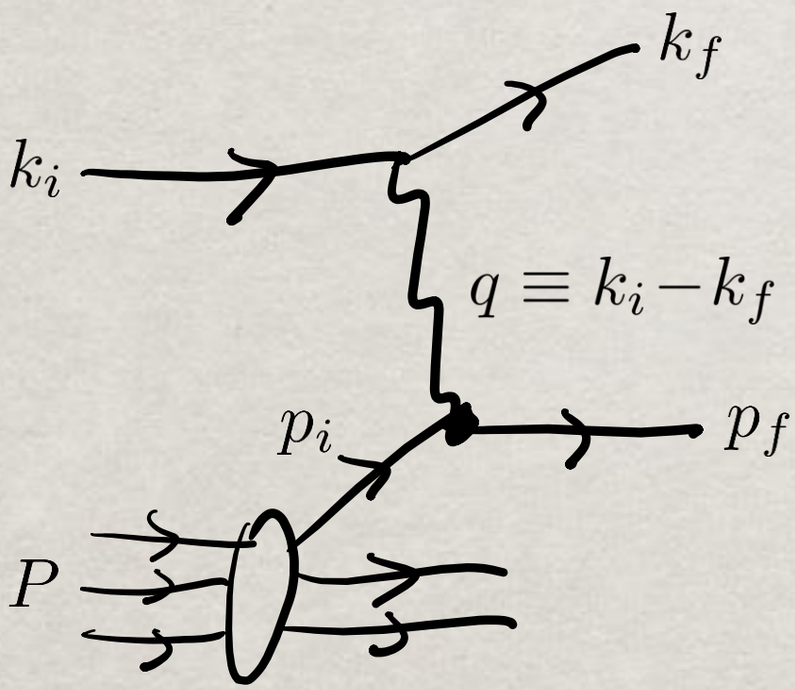
Sudakov form factor

$$\left. + d\Phi_{\mathrm{rad}} \Theta\left(\kappa_t(\Phi_{\mathrm{rad}}) - \mu\right) \frac{R(\bar{\Phi}_n, \Phi_{\mathrm{rad}})}{\bar{B}(\bar{\Phi}_n)} \Delta\left(\bar{\Phi}_n, \kappa_t(\Phi_{\mathrm{rad}})\right)\right]$$

$$\Delta(\bar{\Phi}_n, \mu) = \exp\left[-\int d\Phi_{\mathrm{rad}} \Theta\left(\kappa_t(\Phi_{\mathrm{rad}}) - \mu\right) \frac{R(\bar{\Phi}_n, \Phi_{\mathrm{rad}})}{\bar{B}(\bar{\Phi}_n)}\right]$$

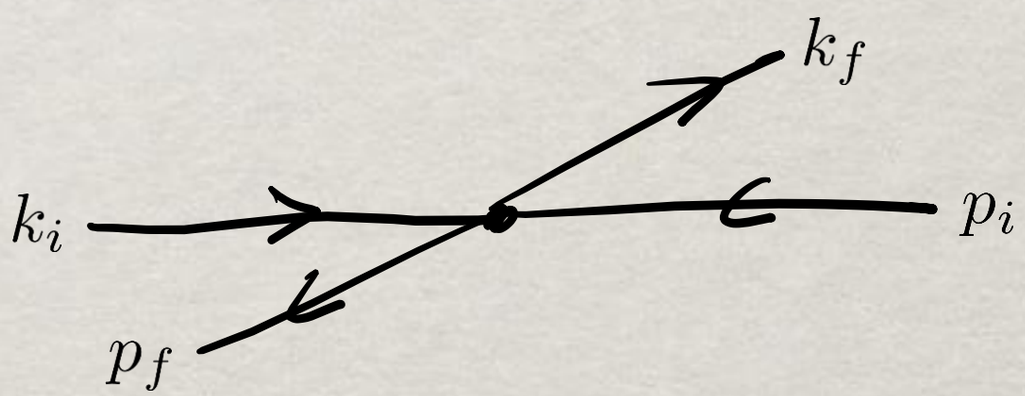
# Minimal POWHEG setup

- The default version of the POWHEG BOX is tailored to hadron collisions
- Real radiation mappings fix the partonic centre-of-mass energy




$$S \equiv 2P \cdot k_i \qquad Q^2 \equiv -q^2$$

$$x_B \equiv \frac{Q^2}{2P \cdot q} \qquad y_{\mathrm{DIS}} \equiv \frac{P \cdot q}{P \cdot k_i}$$




- We adapt the procedure to DIS by using a delta function as the lepton pdf
- We call this implementation “minimal” POWHEG setup
- This minimal setup preserves the momentum of the incoming lepton only

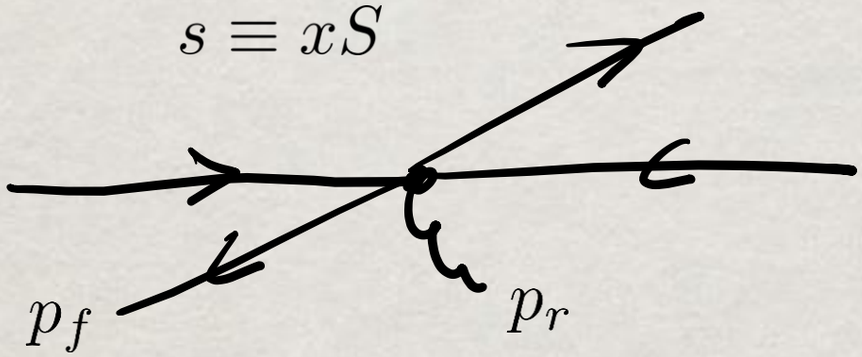
# NOVEL POWHEG SETUP

- The new version of POWHEG uses a phase-space mapping that fully preserves lepton kinematics

$$k_f = \xi_k \frac{\sqrt{s}}{2}\left(1, \sqrt{1-y_k^2}\cos\phi, \sqrt{1-y_k^2}\sin\phi, y_k\right)$$

$$s \equiv xS$$

$$k_i = \frac{\sqrt{s}}{2}(1,0,0,1) \qquad p_i = \frac{\sqrt{s}}{2}(1,0,0,-1)$$




$$\xi_k = 1 - y_{\rm DIS}(1-\lambda) \qquad \xi_k y_k = 1 - y_{\rm DIS}(1+\lambda) \qquad \lambda \equiv x_B/x$$

- The variable $\lambda$ parametrises a boost that is required to apply FKS subtraction as needed in POWHEG
- Once an event is boosted back to the original reference frame, lepton momenta depend only on the DIS variables $x_B$, $y_{\rm DIS}$ and $Q^2$

[AB Ferrario-Ravasio Jäger Karlberg Reichenbach Zanderighi 2309.02127]

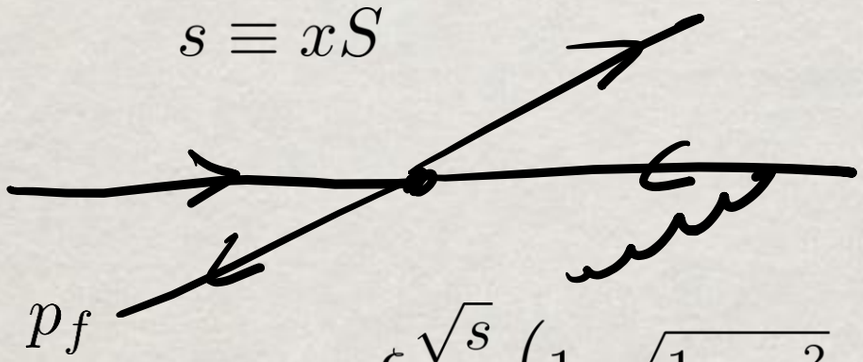
# Initial-state radiation

- Radiation kinematics depends on the FKS variables $\xi$ and $y$

$$k_f = \xi_k \frac{\sqrt{s}}{2}\left(1, \sqrt{1-y_k^2}\cos\phi, \sqrt{1-y_k^2}\sin\phi, y_k\right)$$

$$s \equiv xS$$

$$k_i = \frac{\sqrt{s}}{2}(1,0,0,1) \qquad p_i = \frac{\sqrt{s}}{2}(1,0,0,-1)$$



$$p_f$$

$$p_r = \xi \frac{\sqrt{s}}{2}\left(1, \sqrt{1-y^2}\cos\phi, \sqrt{1-y^2}\sin\phi, y\right)$$

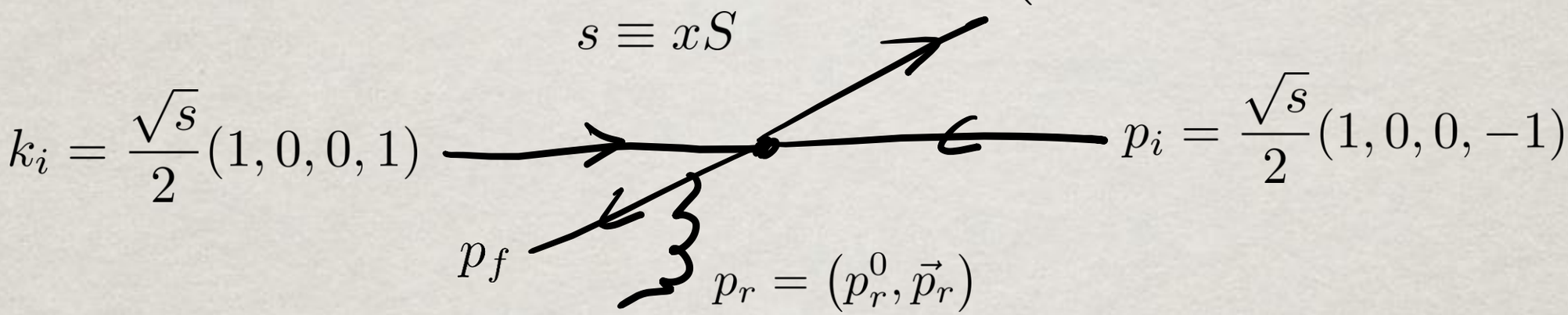
$$\xi_k = 1 - y_{\rm DIS}(1-\lambda) \qquad \xi_k y_k = 1 - y_{\rm DIS}(1+\lambda) \qquad \lambda \equiv x_B/x$$

- For initial-state radiation, energy-momentum conservation selects two values $\lambda_\pm$
- Only $\lambda_-$ is allowed in the soft and collinear limits $\Rightarrow$ interface with MC
- The solution $\lambda_+$ gives a finite contribution that can be treated at fixed order

# Final-state radiation

- Radiation kinematics depends on the FKS variables $\xi$ and $y$

$$k_f = \xi_k \frac{\sqrt{s}}{2}\left(1, \sqrt{1-y_k^2}\cos\phi, \sqrt{1-y_k^2}\sin\phi, y_k\right)$$




$$\xi_k = 1 - y_{\rm DIS}(1-\lambda) \qquad \xi_k y_k = 1 - y_{\rm DIS}(1+\lambda) \qquad \lambda \equiv x_B/x$$

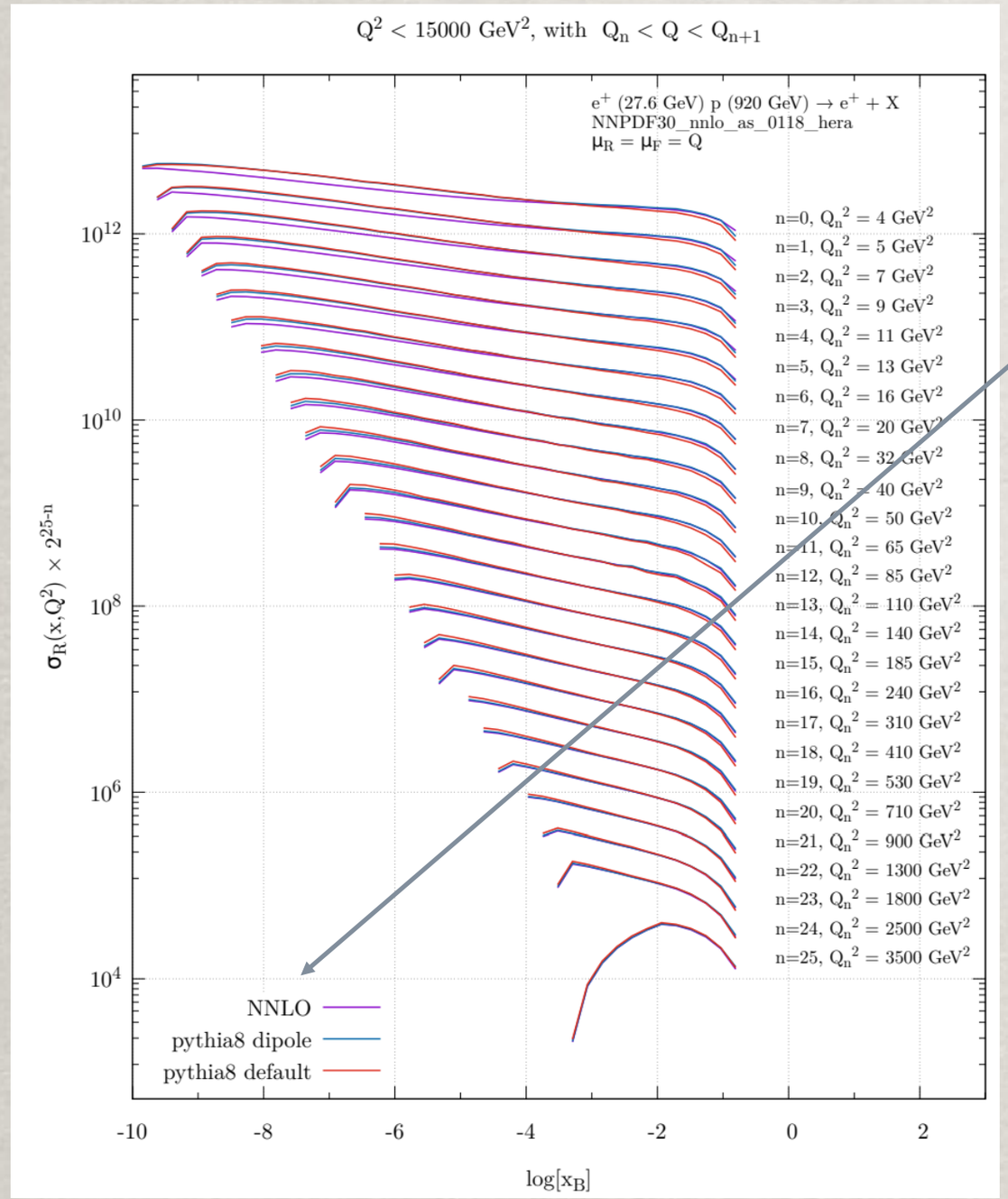
- For final-state radiation we can apply the standard POWHEG setup

$$\xi \equiv \frac{2p_r^0}{\sqrt{s}} \qquad y \equiv \frac{\vec{p}_r \cdot \vec{p}_f}{p_r^0 p_f^0}$$

- Energy-momentum conservation selects only one value of $\lambda$

# Validation

# Inclusive observables

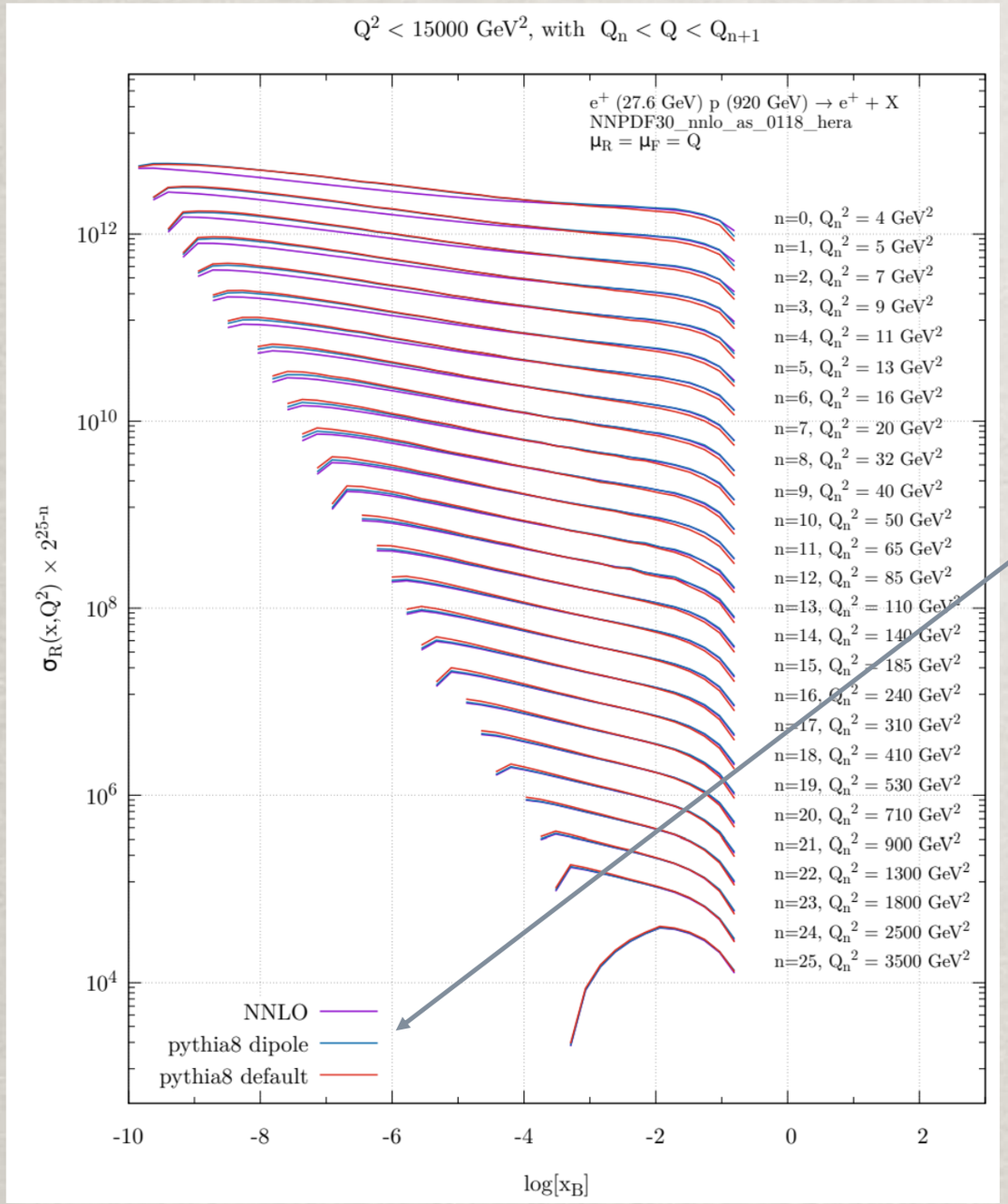



- Doubly-differential reduced cross section

$$\sigma_R(x_B, Q^2) = F_2(x_B, Q^2) + \mathcal{O}(\alpha_s)$$

- NNLO predictions obtained with DISORDER [Karlberg CERN-TH-2023-229]

# Inclusive observables

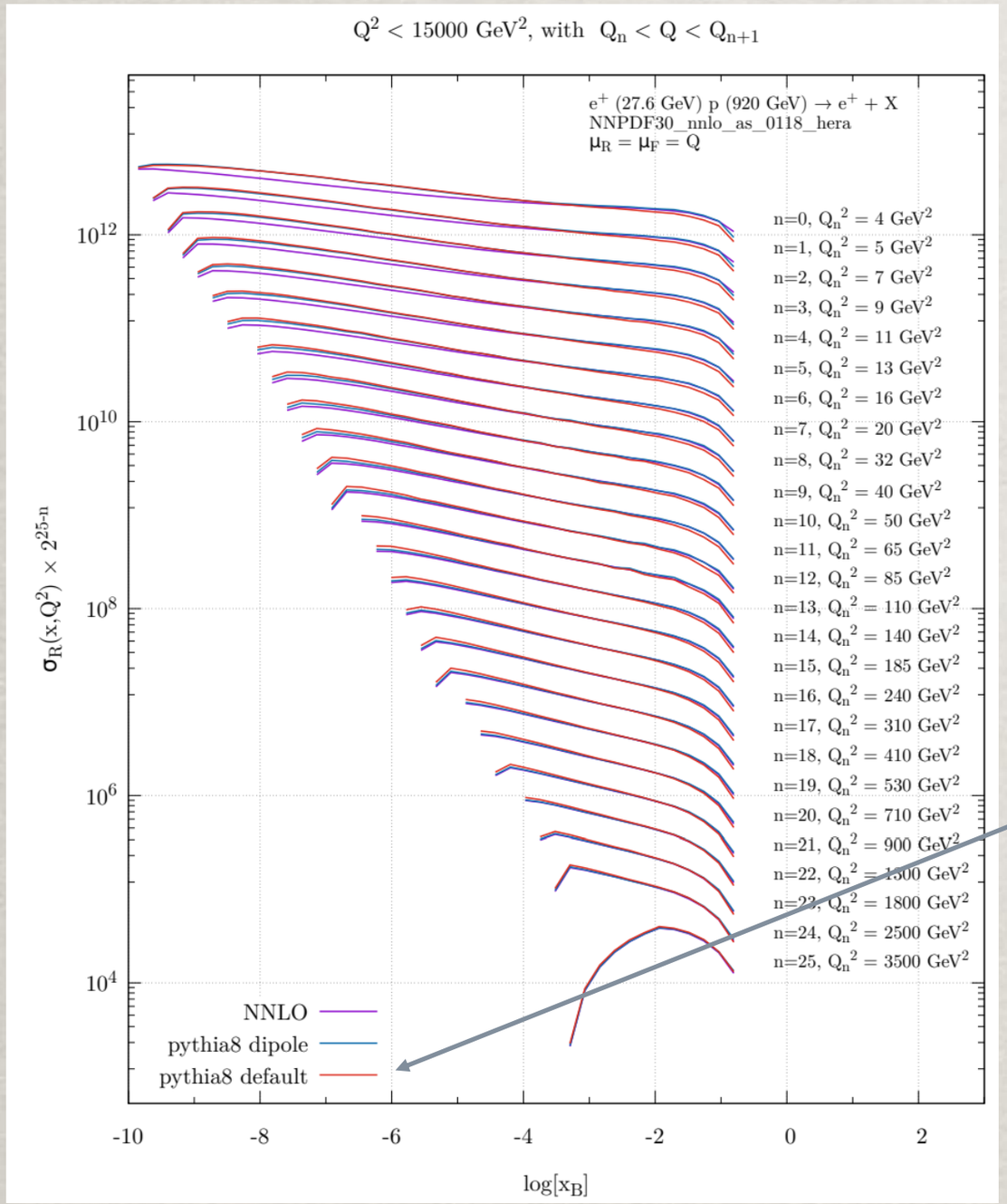



- Doubly-differential reduced cross section

$$\sigma_R(x_B, Q^2) = F_2(x_B, Q^2) + \mathcal{O}(\alpha_s)$$

- NNLO predictions obtained with DISORDER [Karlberg CERN-TH-2023-229]
- PYTHIA 8 dipole: new POWHEG mapping with dipole PYTHIA shower, which preserves lepton kinematics

# Inclusive observables

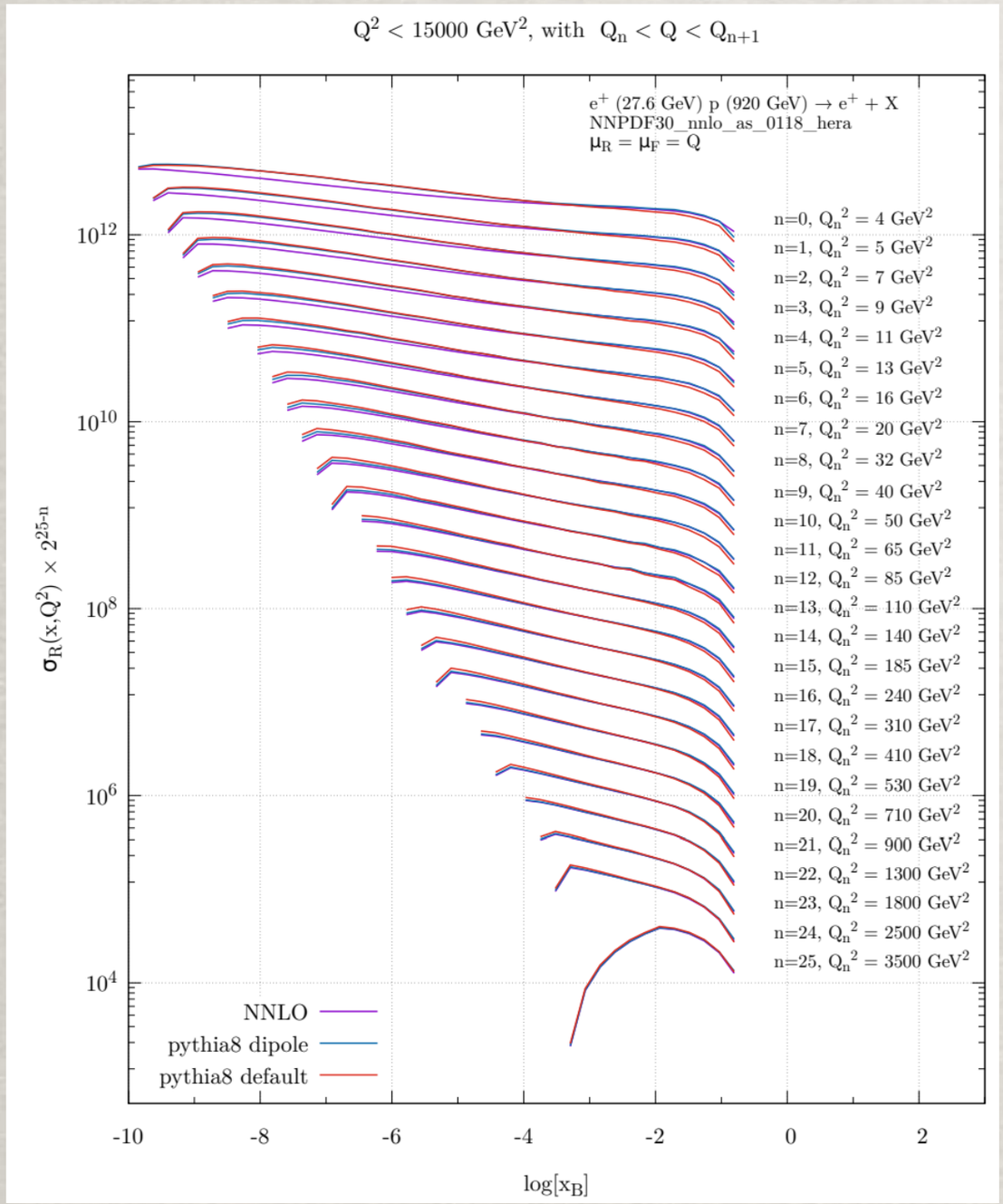



- Doubly-differential reduced cross section

$$\sigma_R(x_B, Q^2) = F_2(x_B, Q^2) + \mathcal{O}(\alpha_s)$$

- NNLO predictions obtained with DISORDER [Karlberg CERN-TH-2023-229]
- PYTHIA 8 dipole: new POWHEG mapping with dipole PYTHIA shower, which preserves lepton kinematics
- PYTHIA 8 default: new POWHEG mapping interfaced with default PYTHIA shower, which does not preserve lepton kinematics

# Inclusive observables

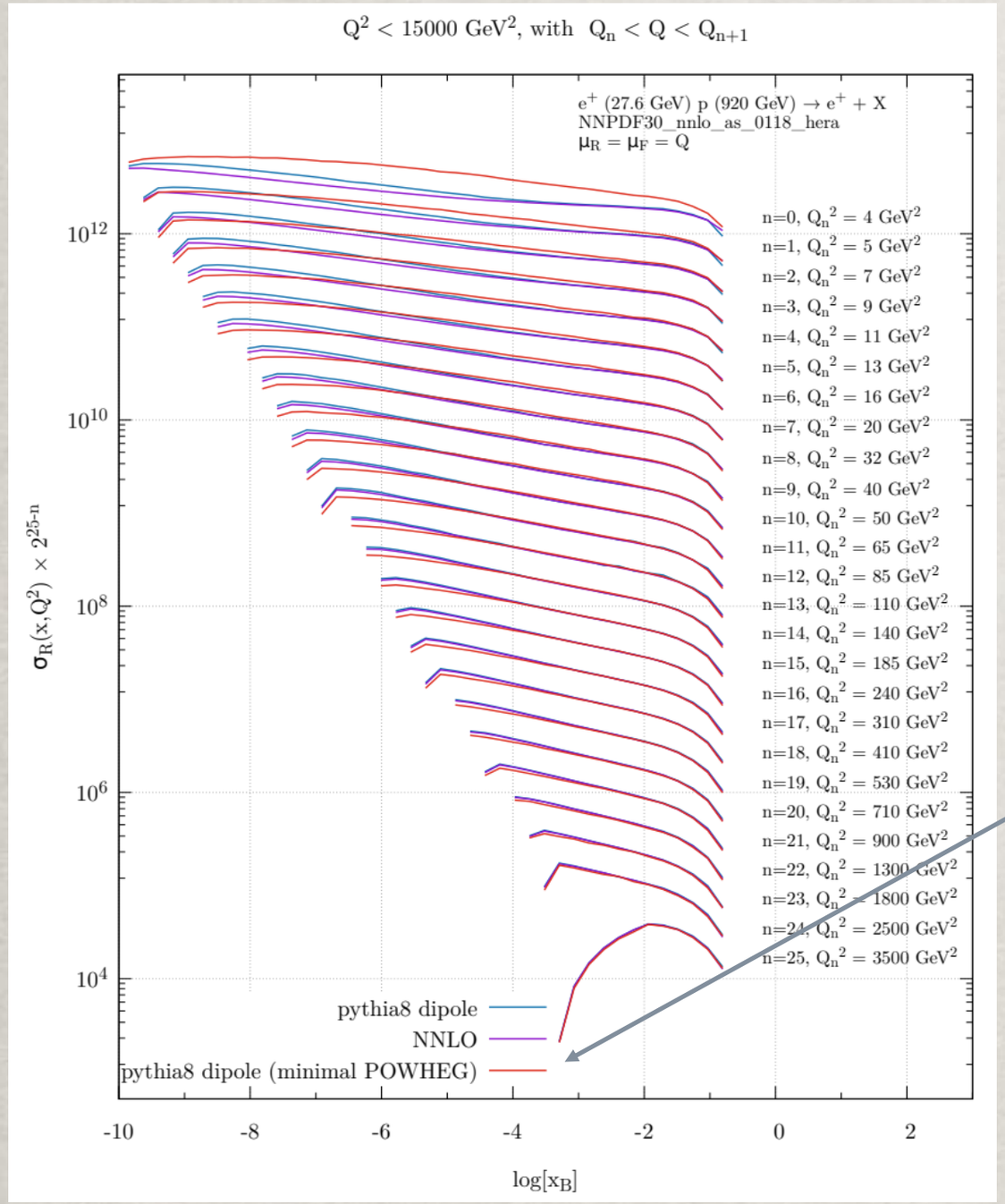



- Doubly-differential reduced cross section

$$\sigma_R(x_B, Q^2) = F_2(x_B, Q^2) + \mathcal{O}(\alpha_s)$$

- NNLO predictions obtained with DISORDER [Karlberg CERN-TH-2023-229]
- PYTHIA 8 dipole: new POWHEG mapping with dipole PYTHIA shower, which preserves lepton kinematics
- PYTHIA 8 default: new POWHEG mapping interfaced with default PYTHIA shower, which does not preserve lepton kinematics
- NLO is identical to POWHEG+PYTHIA 8 dipole, hence it's not shown

# Inclusive observables



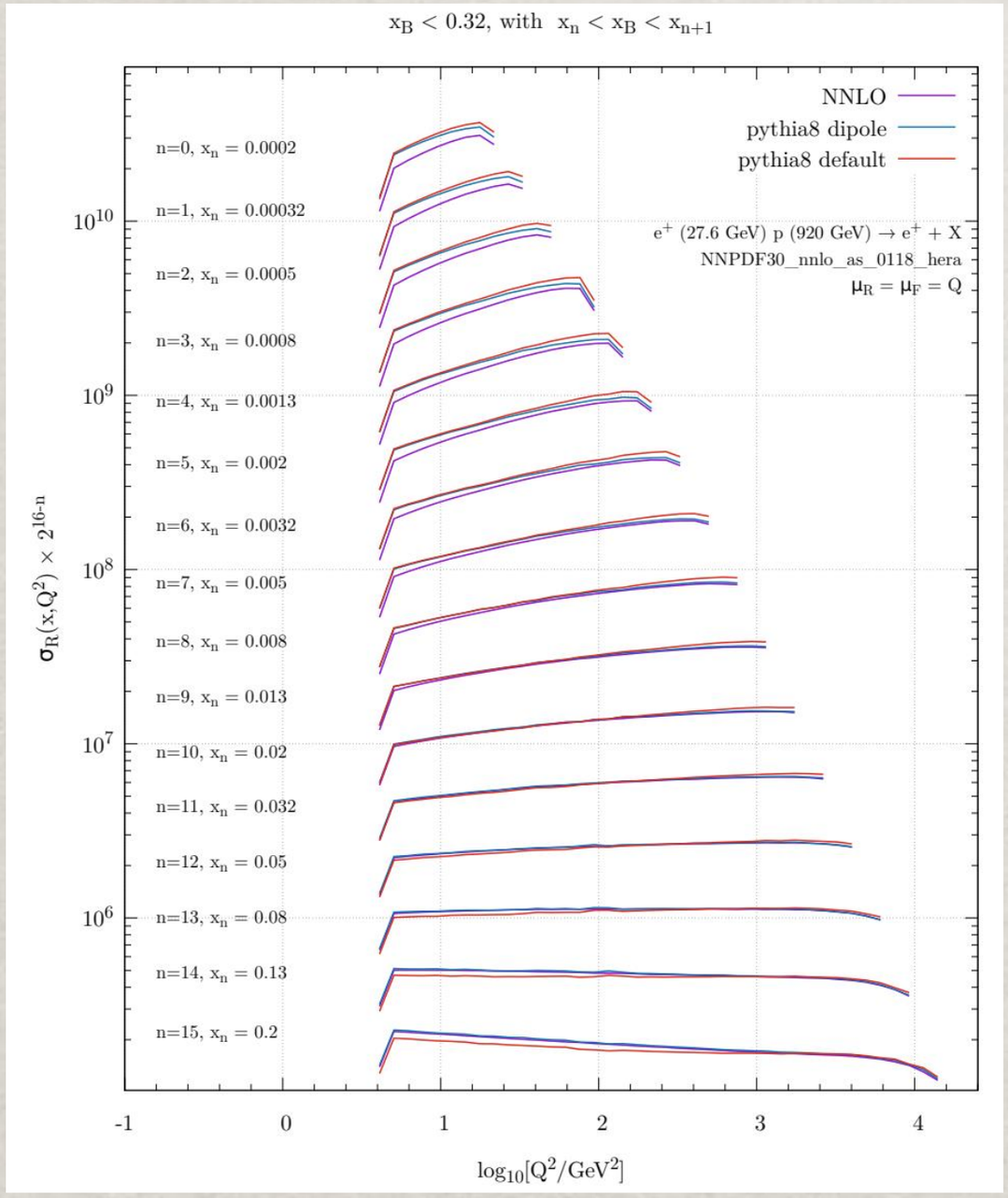

- Doubly-differential reduced cross section

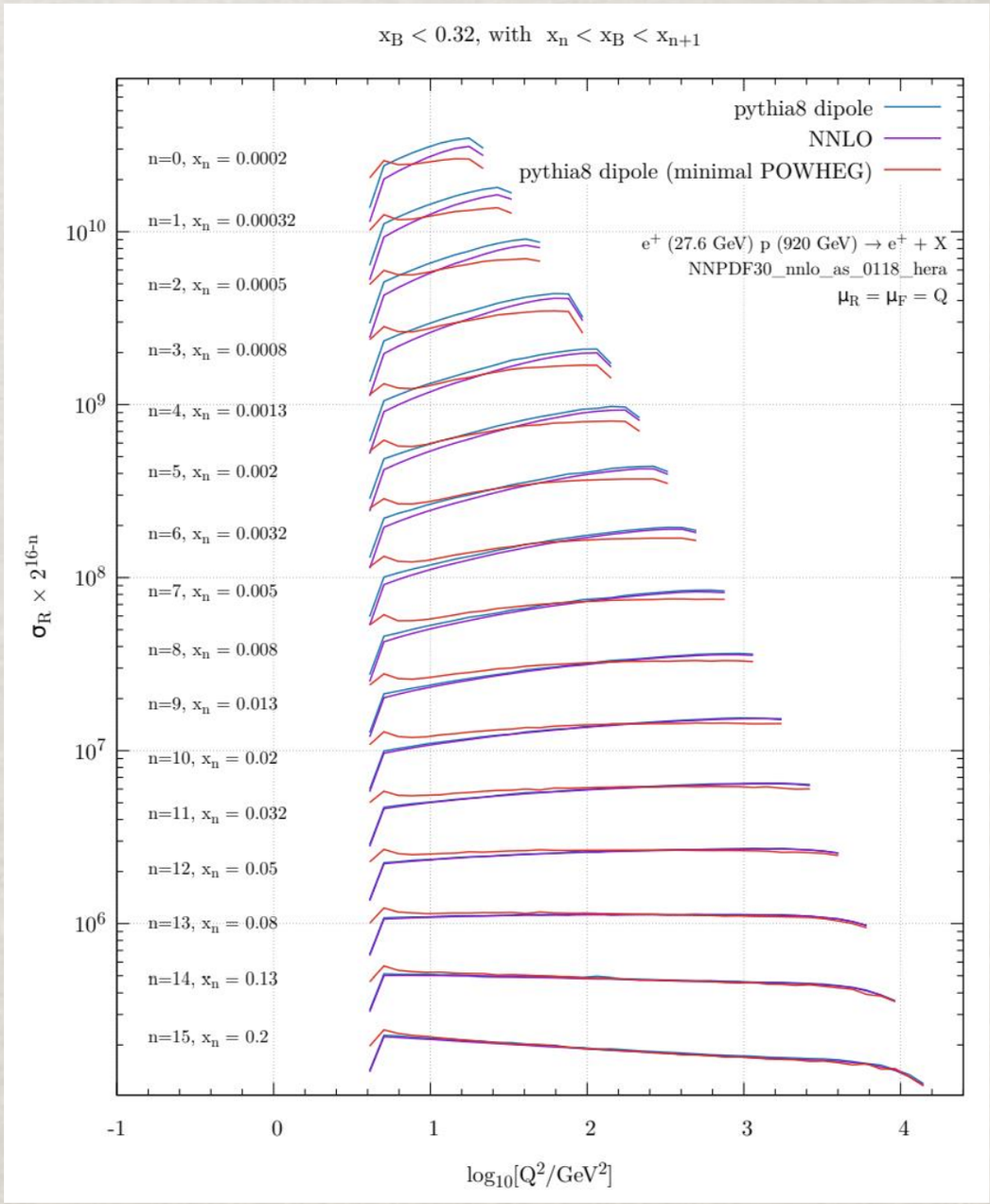
$$\sigma_R(x_B, Q^2) = F_2(x_B, Q^2) + \mathcal{O}(\alpha_s)$$

- NNLO predictions obtained with DISORDER [Karlberg CERN-TH-2023-229]
- PYTHIA 8 dipole: new POWHEG mapping with dipole PYTHIA shower, which preserves lepton kinematics
- PYTHIA 8 dipole (minimal POWHEG): POWHEG BOX RES mapping, which does not preserve lepton kinematics

# Inclusive observables

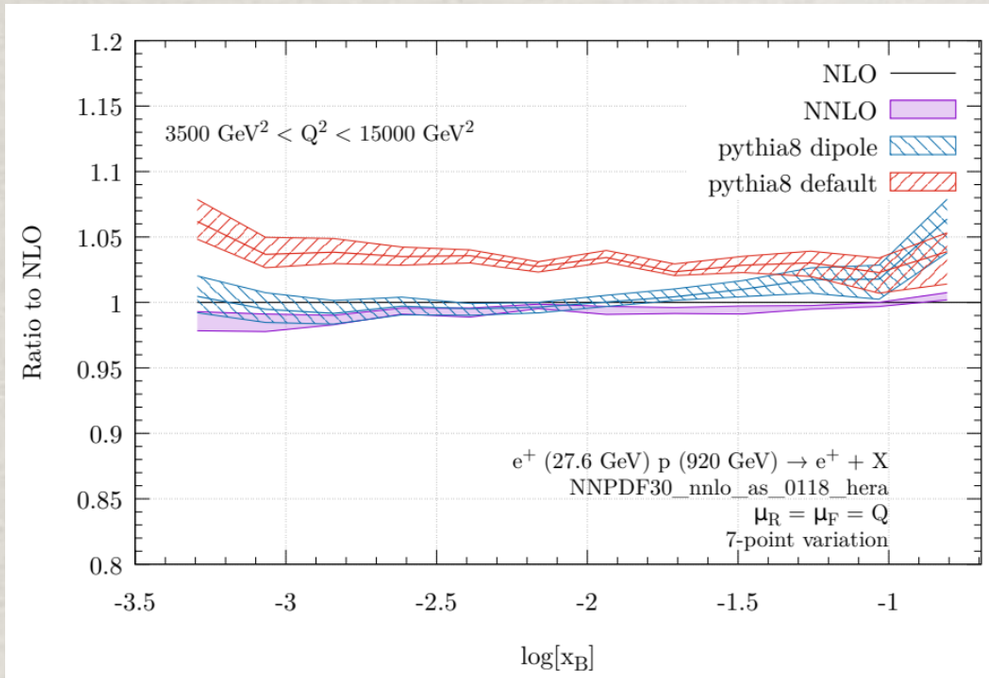
Our new mapping, interfaced to PYTHIA 8 dipole, is the only one that reproduces correctly NLO predictions

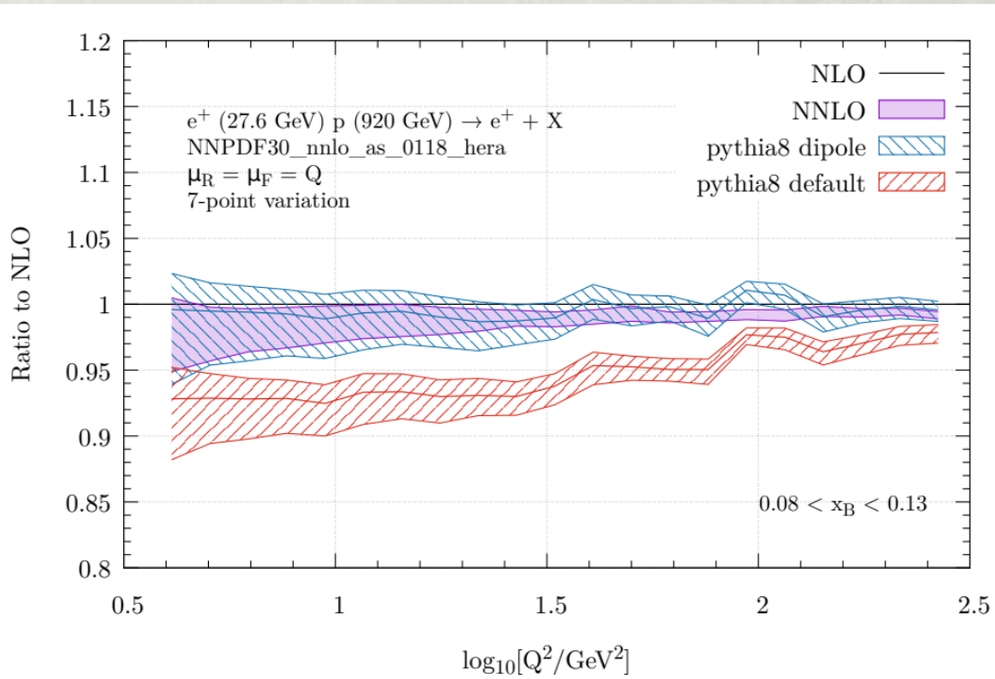


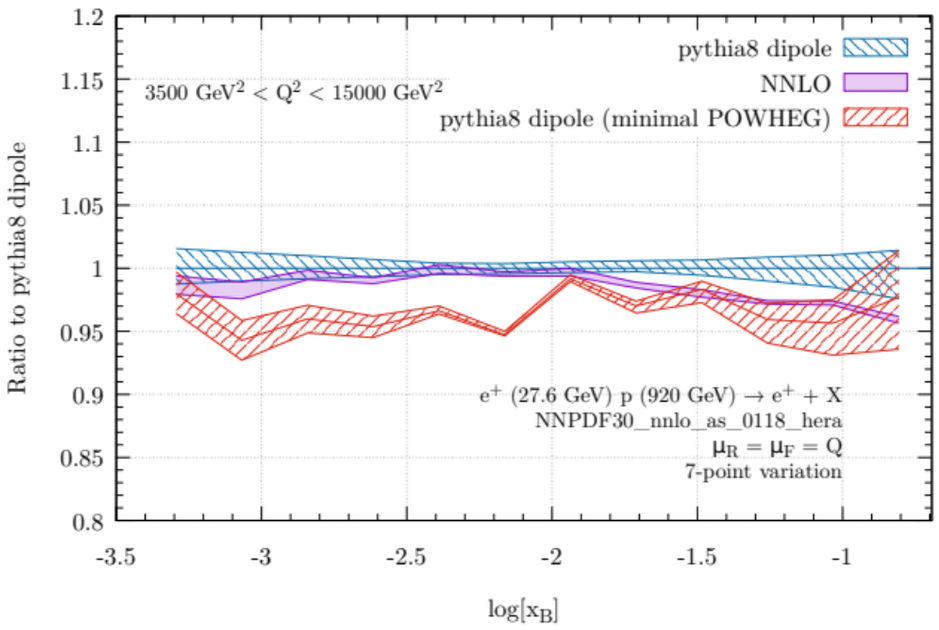



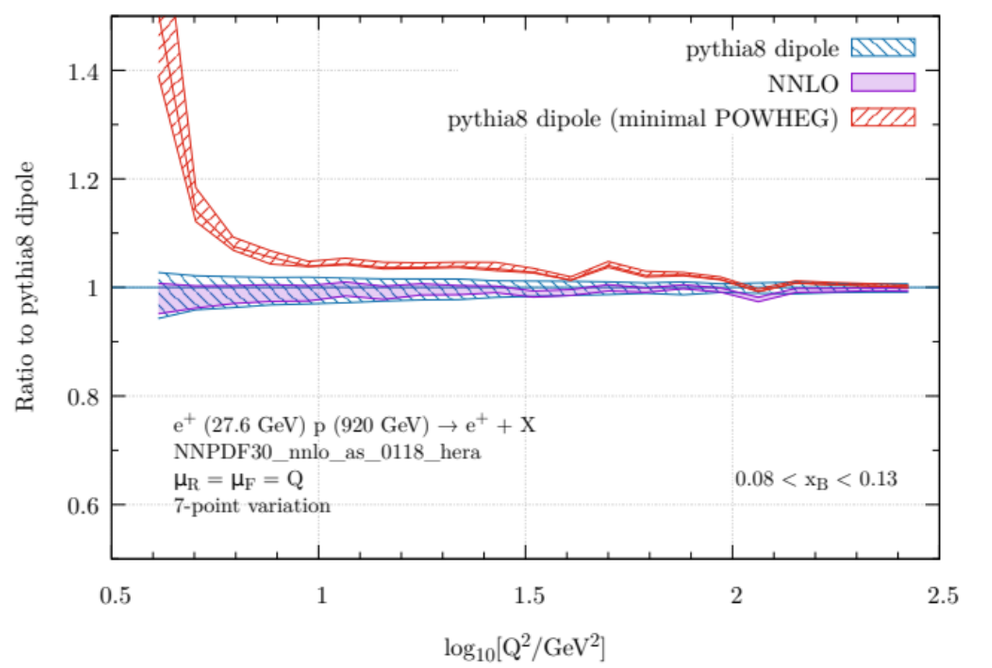
# Inclusive observables

Preserving lepton kinematics in the generation of the hard event (cf minimal POWHEG) is more important than in the shower (cf PYTHIA8 default)

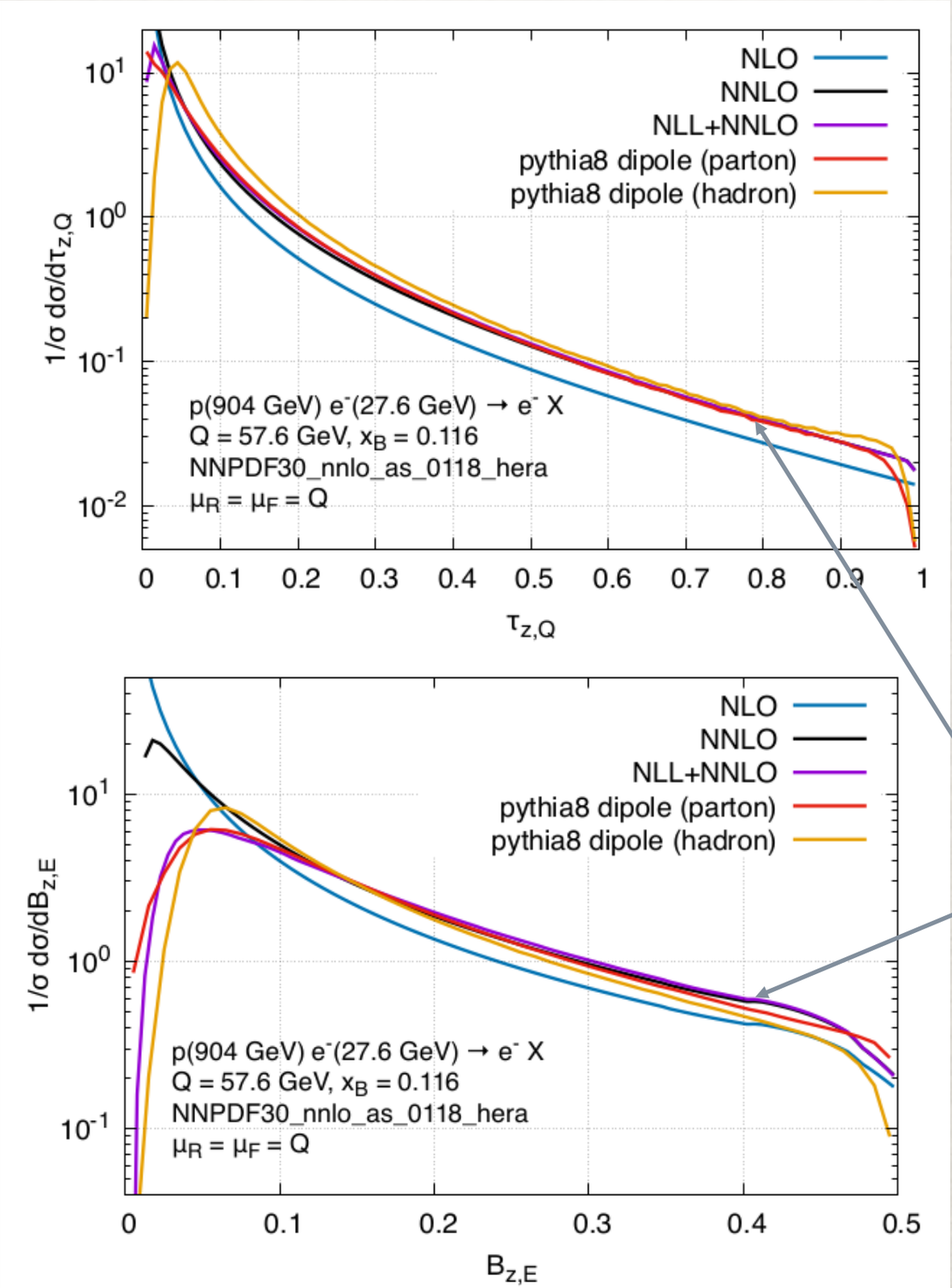


# Continuously global observables

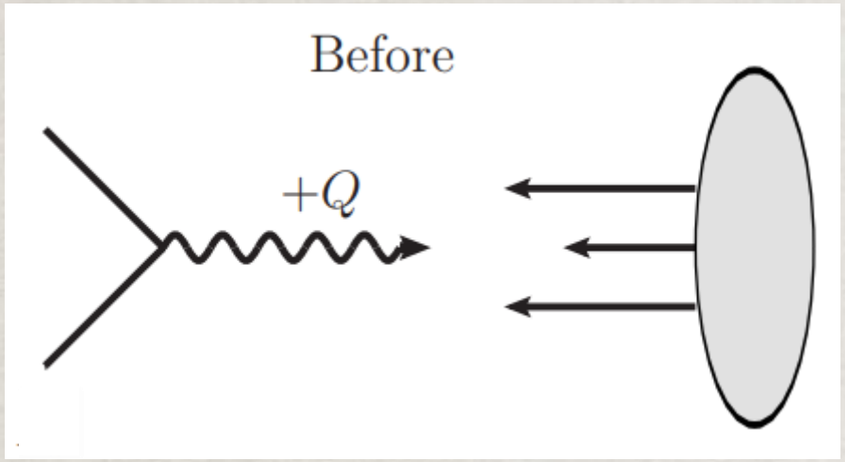


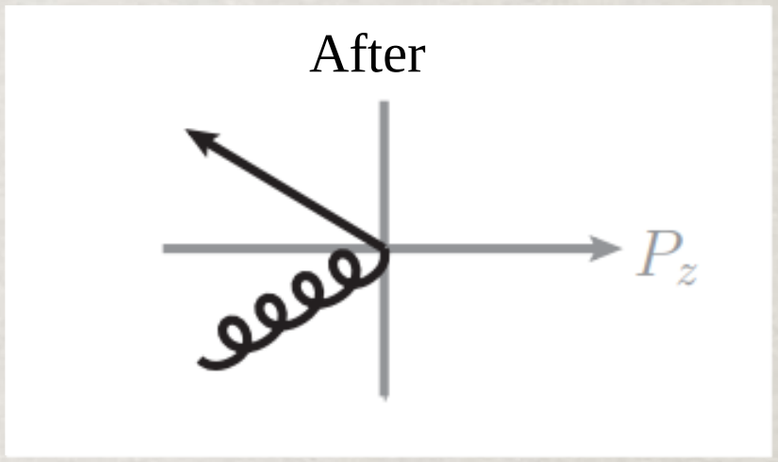

- Continuously global event shapes in DIS, such as $\tau_{z,Q}$ and $B_{z,E}$ are directly sensitive to real radiation
- Resummation at NLL+NNLO accuracy can be performed automatically using CAESAR
- Excellent agreement between POWHEG+PYTHIA at parton level and NLL+NNLO
- Although POWHEG+PYTHIA is formally NLO, it agrees quite well with NNLO in the tail of the distributions

# Phenomenology

# Empty current hemisphere

- H1 measured the fraction of events where the current hemisphere in the Breit frame is empty [H1 2403.08982]

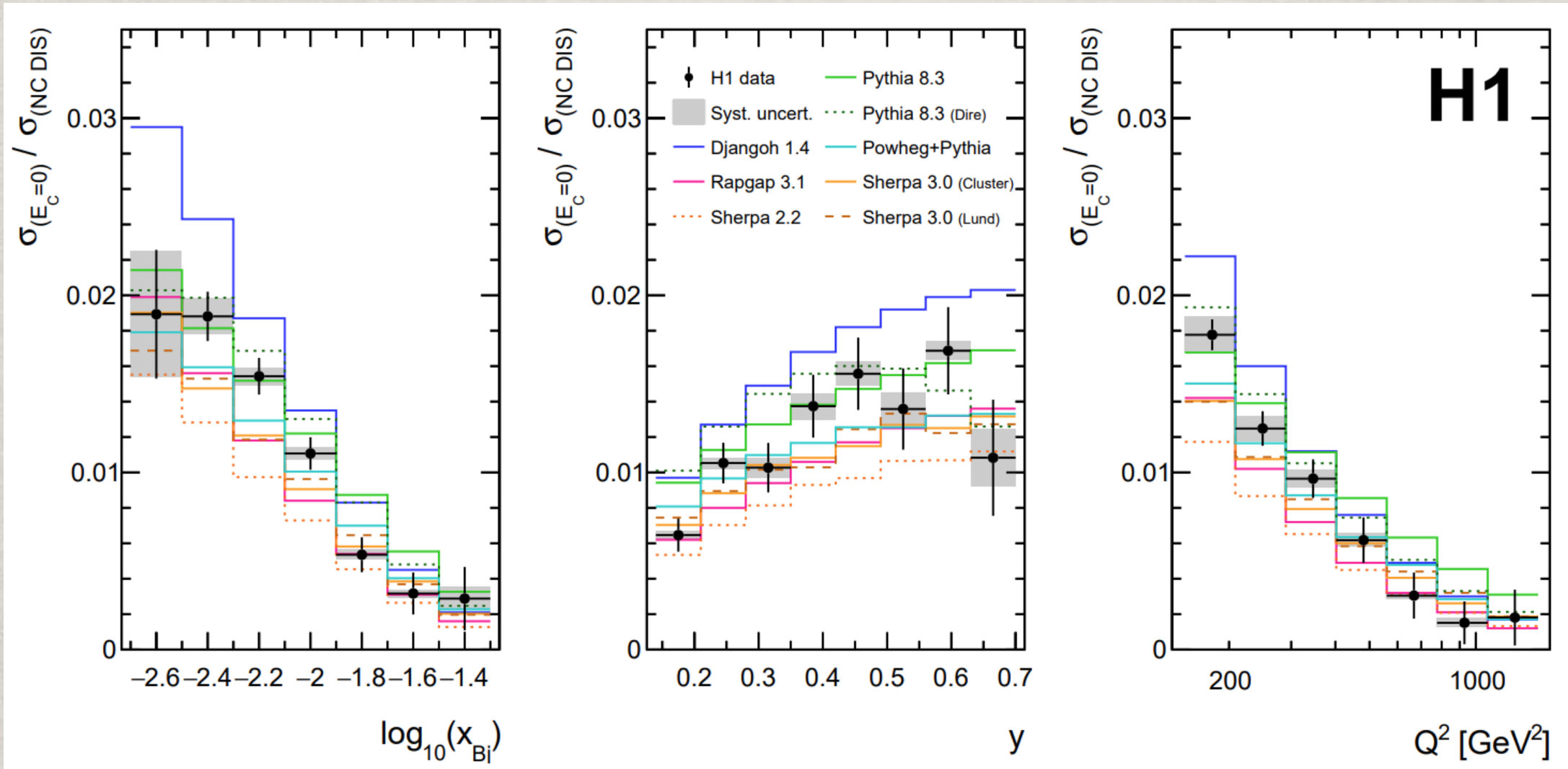



- Such events start at order $\alpha_s$ and involve the presence of an extra jet
- Excellent testing ground for parton-shower event generators

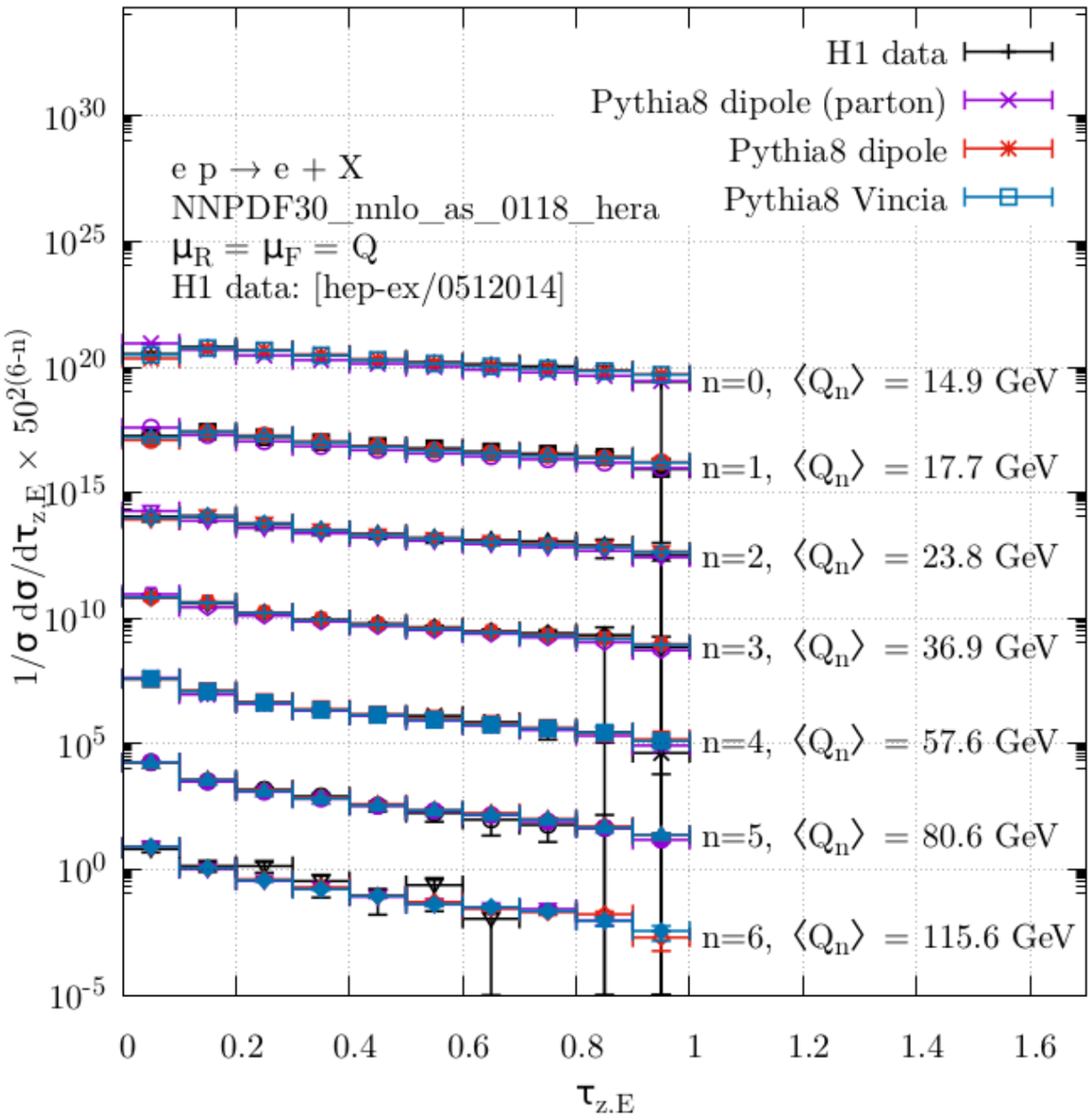
# Empty current hemisphere

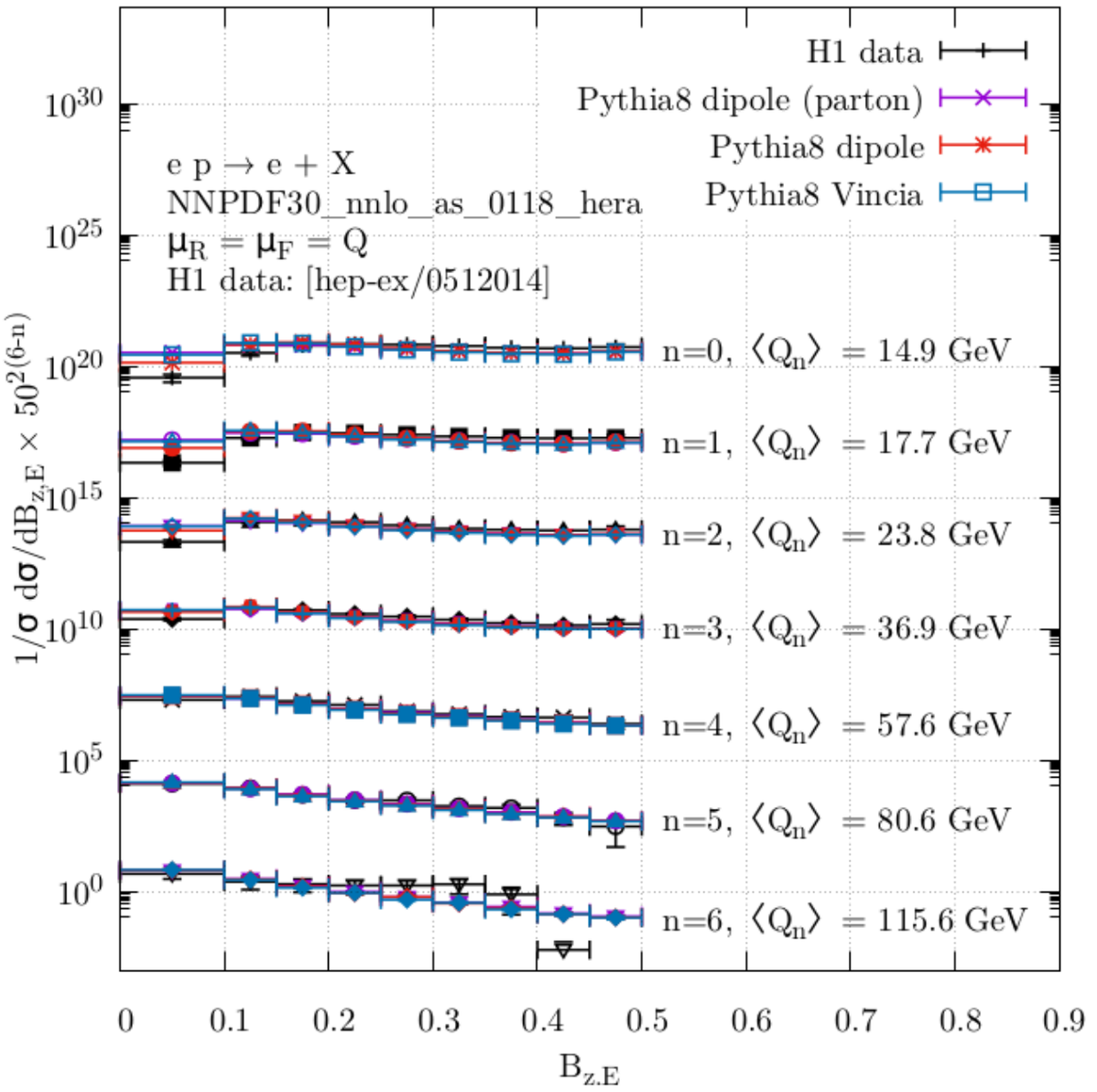
- H1 measured the fraction of events where the current hemisphere in the Breit frame is empty
- Our new POWHEG generator agrees with all distributions within experimental errors



# Event shapes at HERA

- Good agreement with H1 data for event shapes

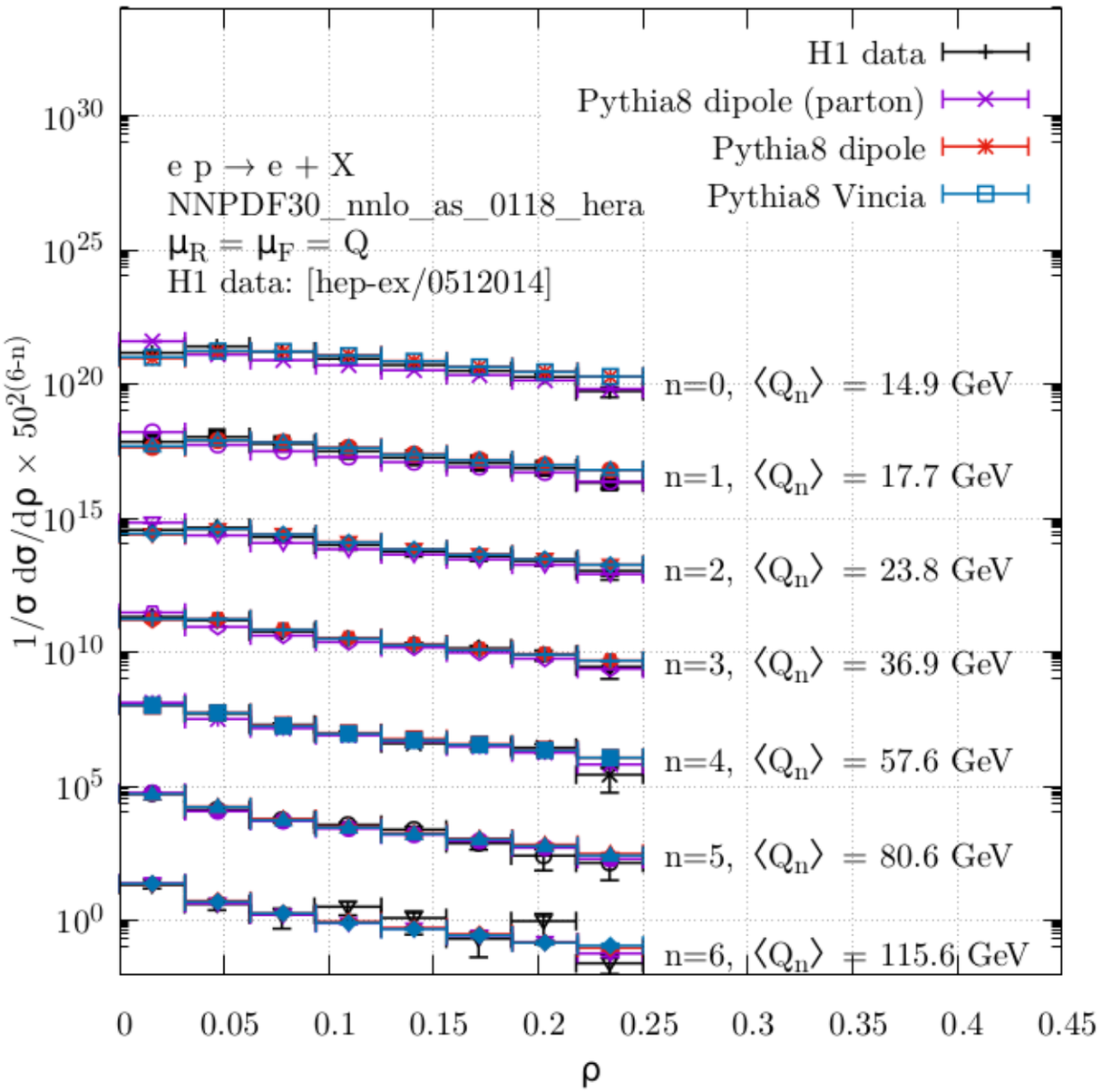


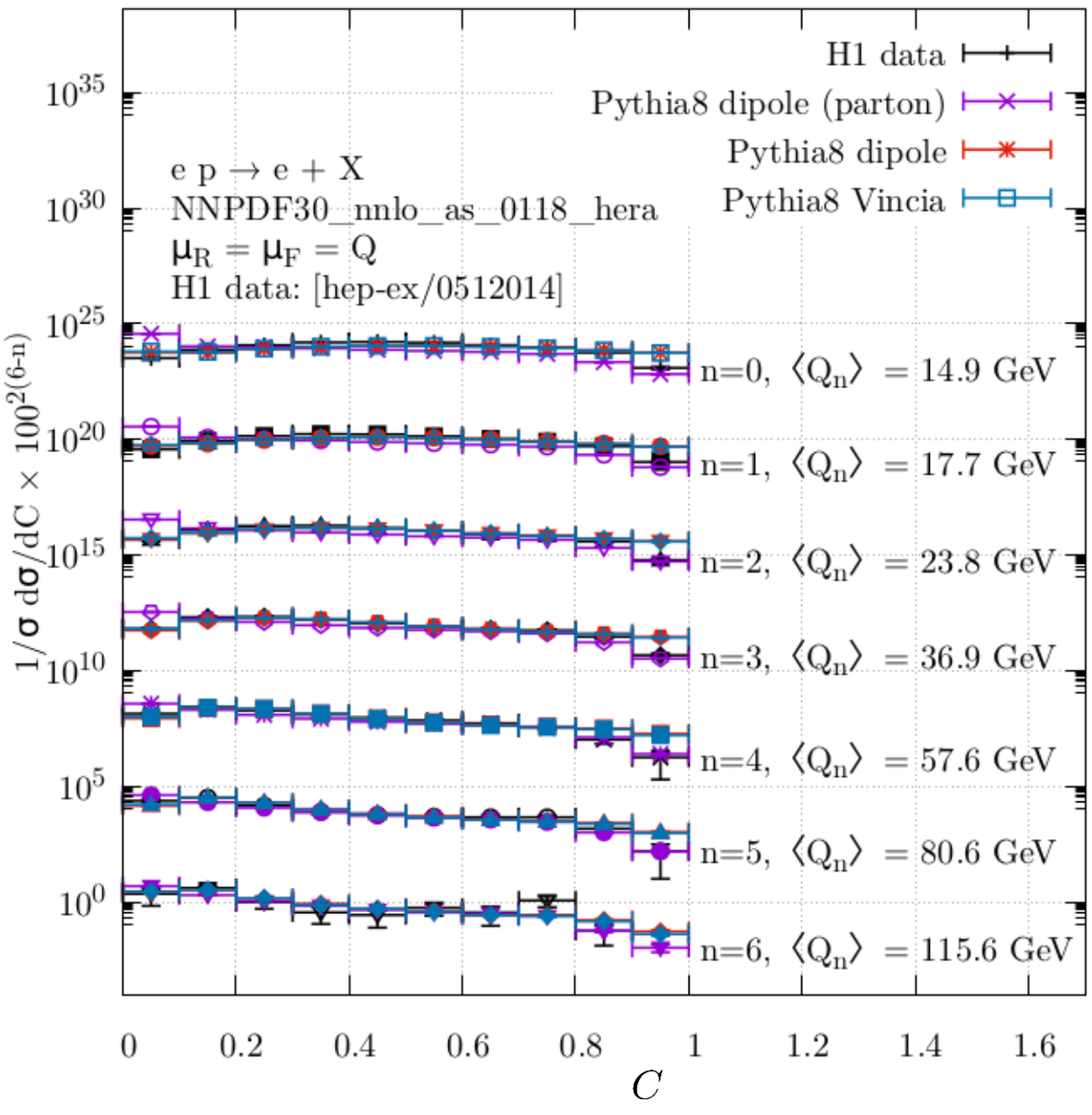




- For event-shape distributions, hadronisation is crucial to describe the data

# Event shapes at HERA

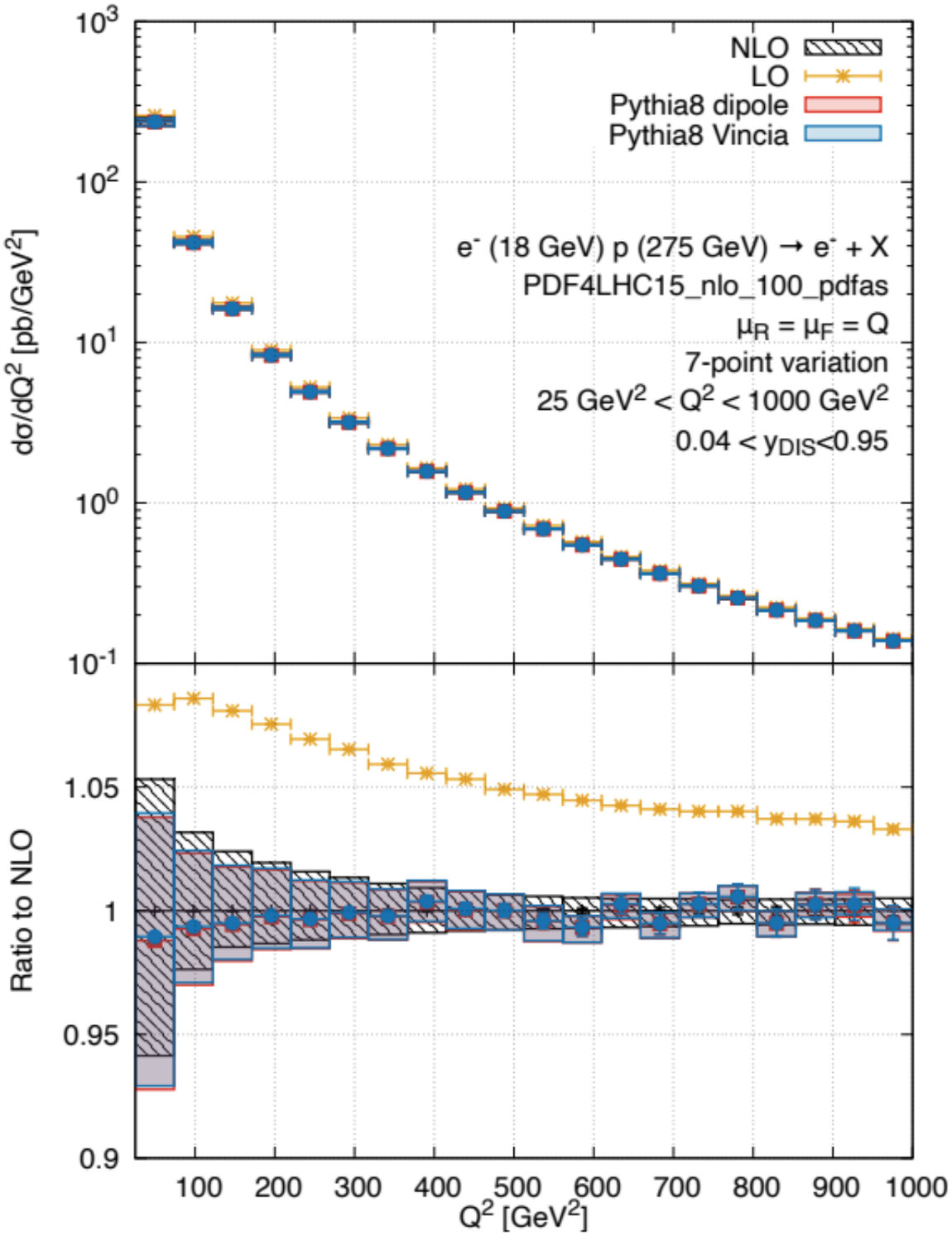
- Good agreement with H1 data for event shapes

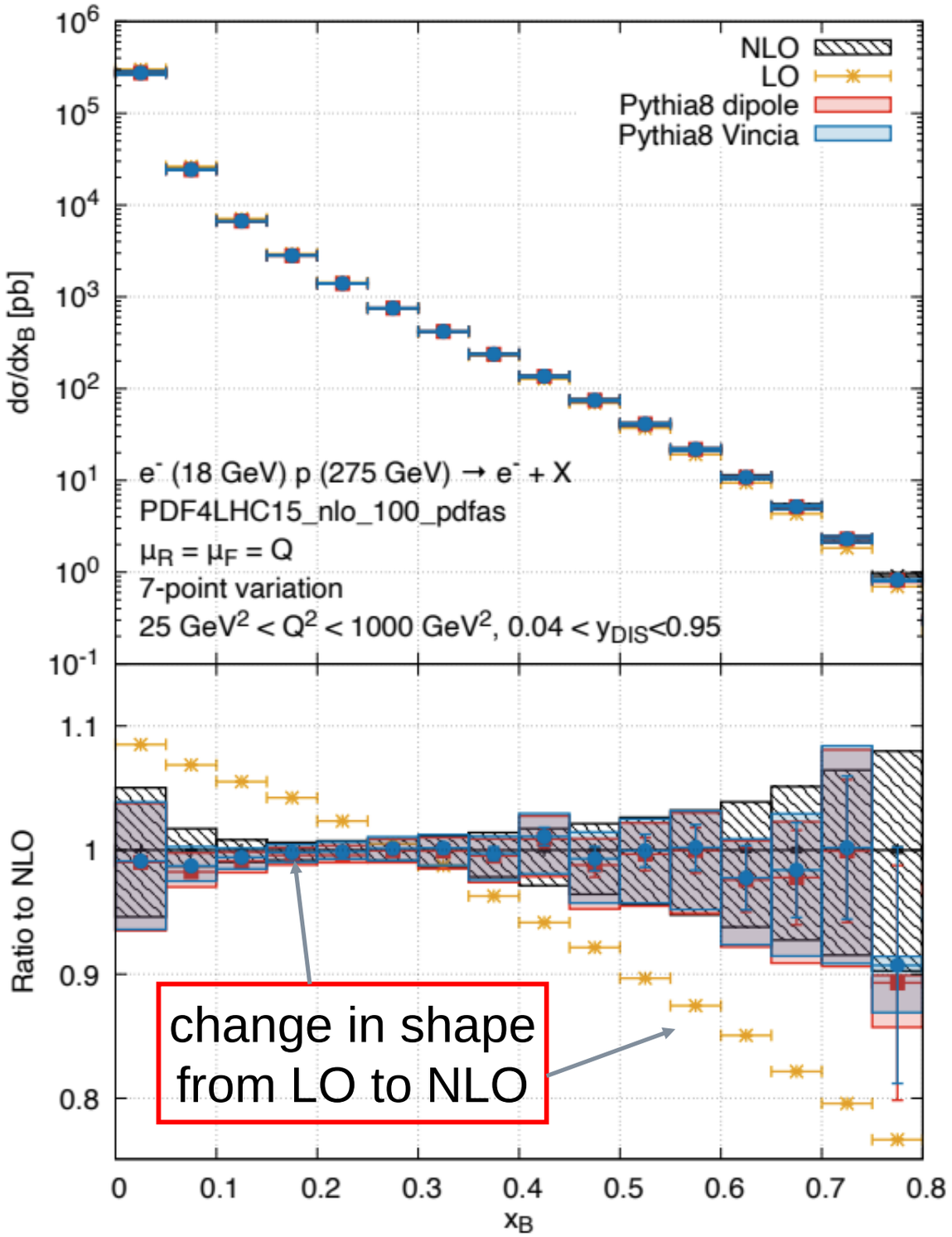


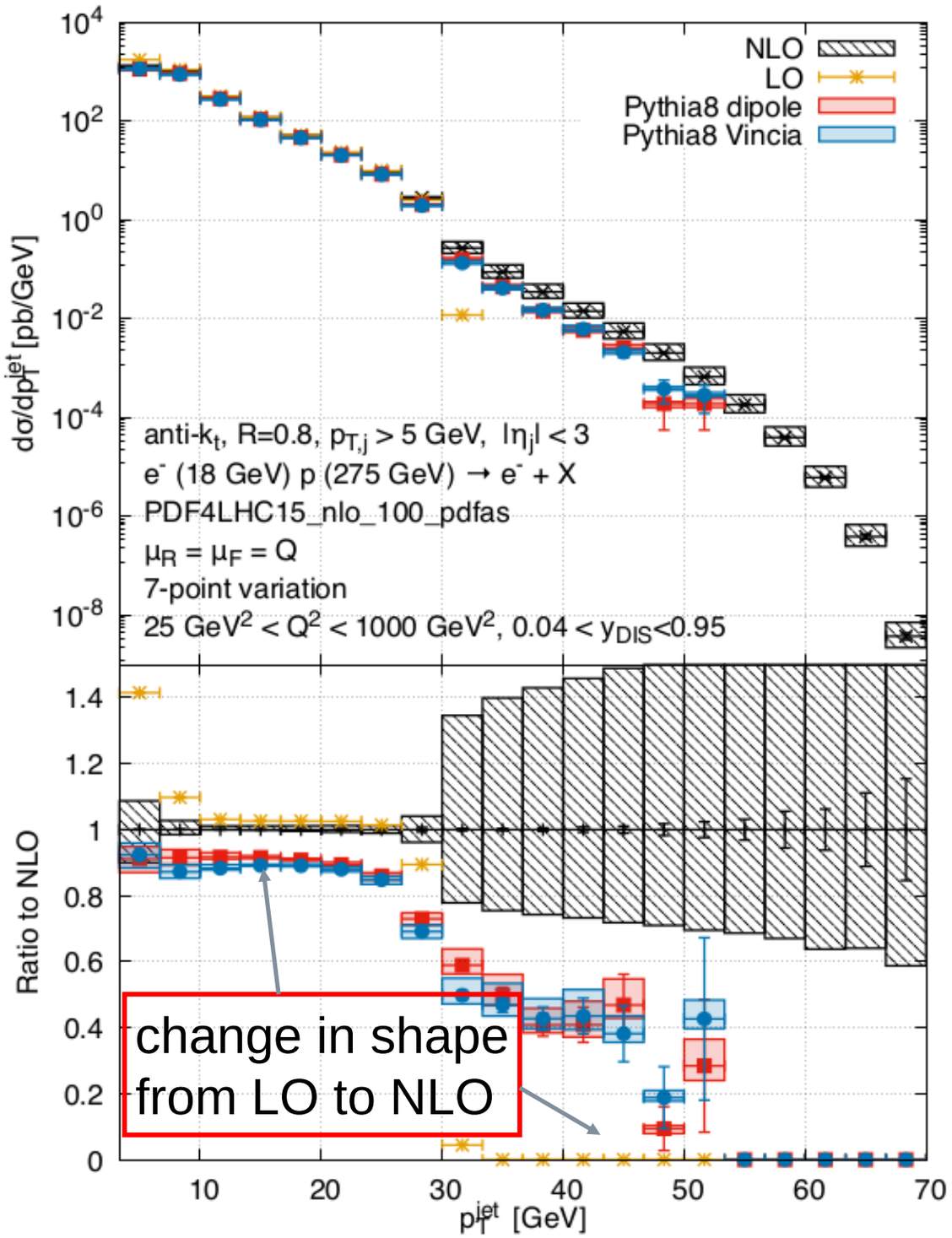

- For event-shape distributions, hadronisation is crucial to describe the data

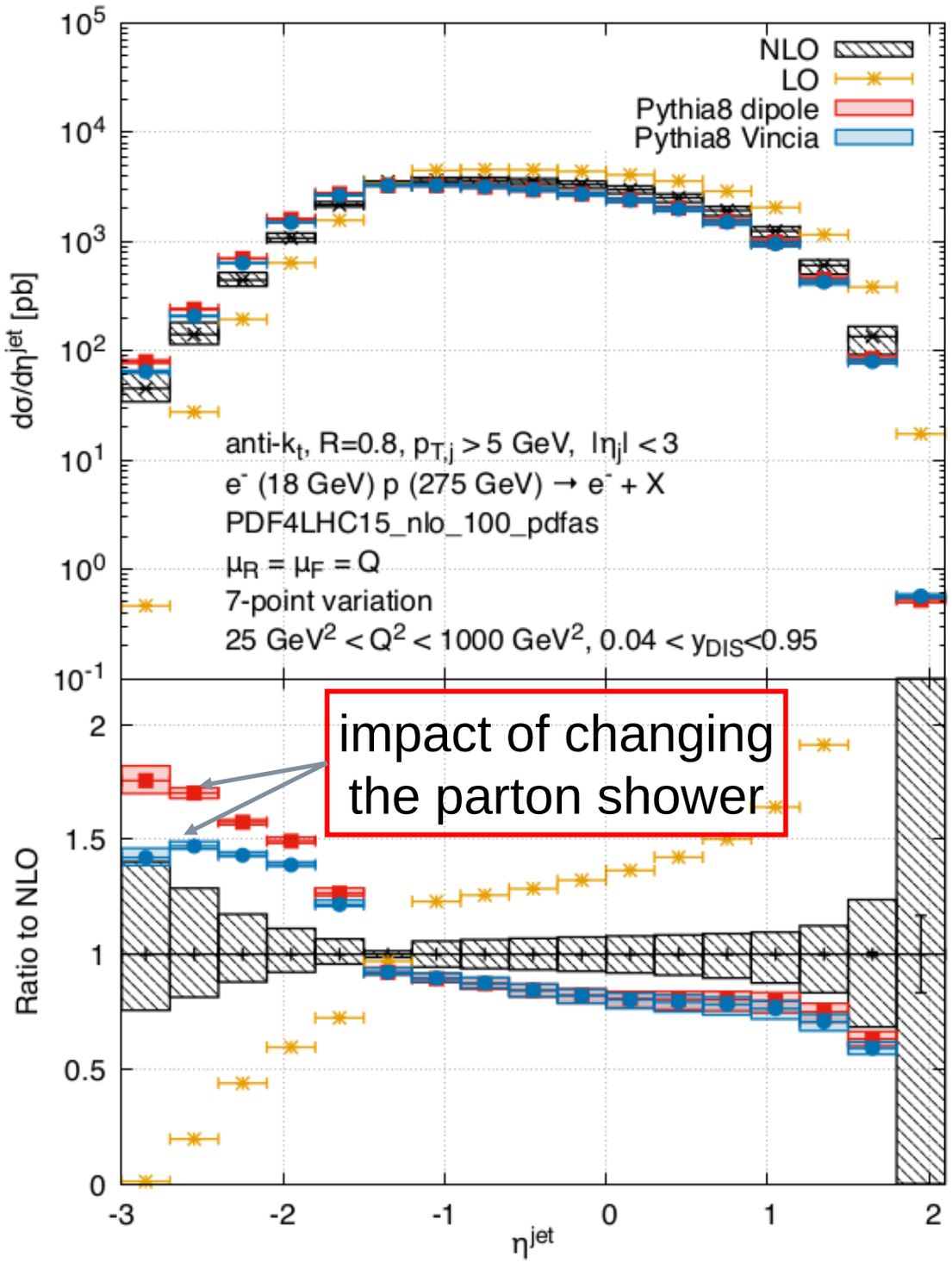
# EIC: NEUTRAL CURRENT



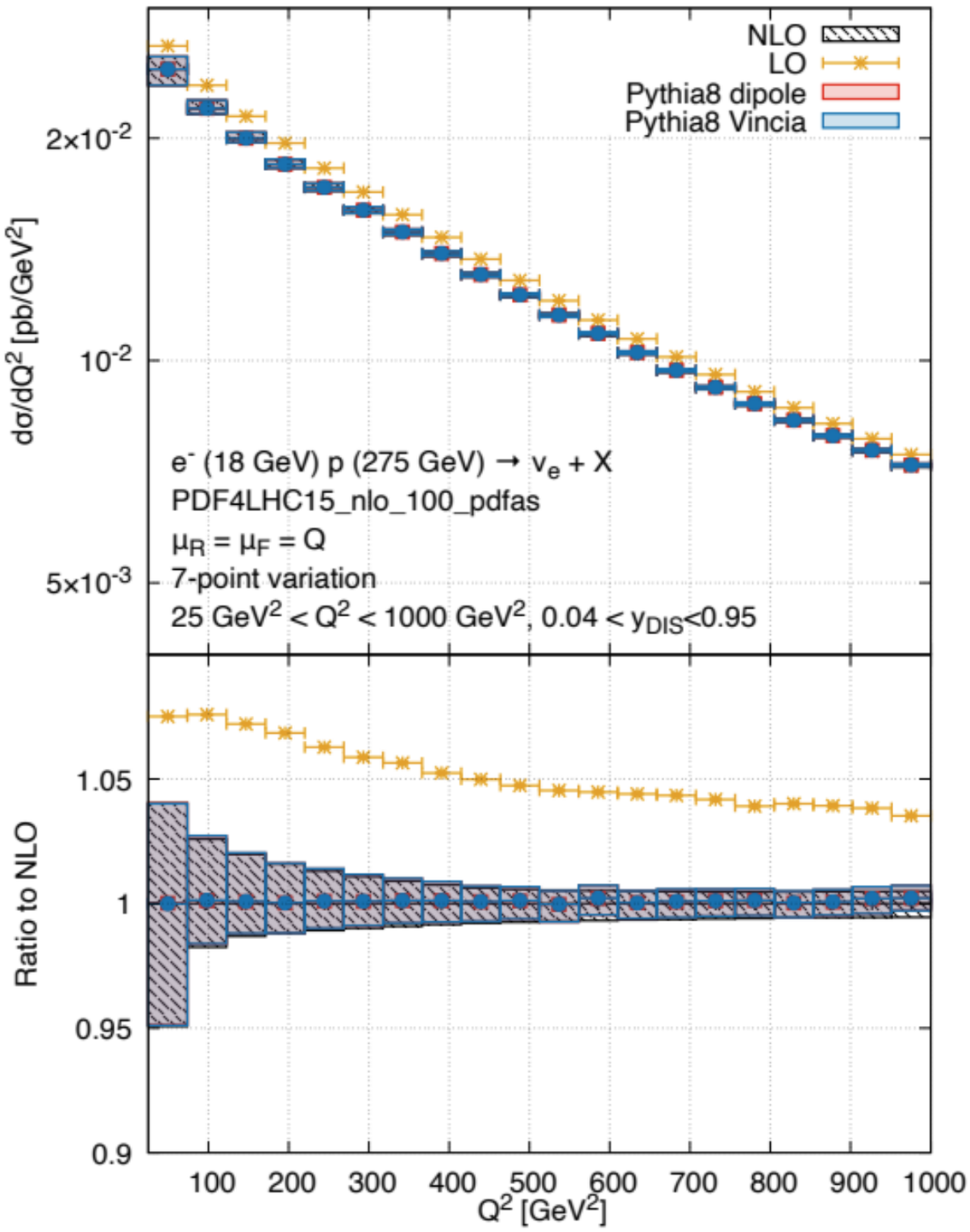



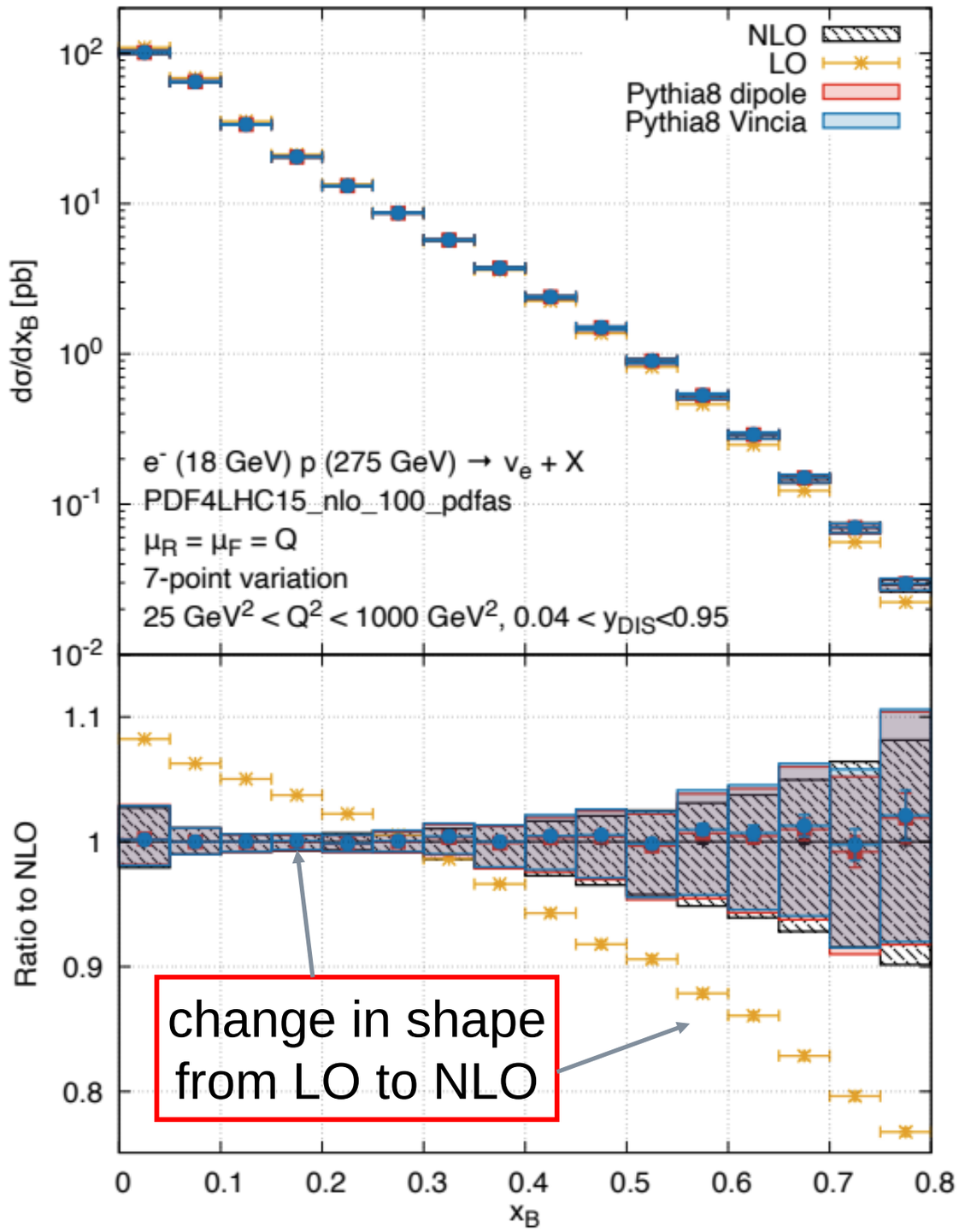
# EIC: NEUTRAL CURRENT



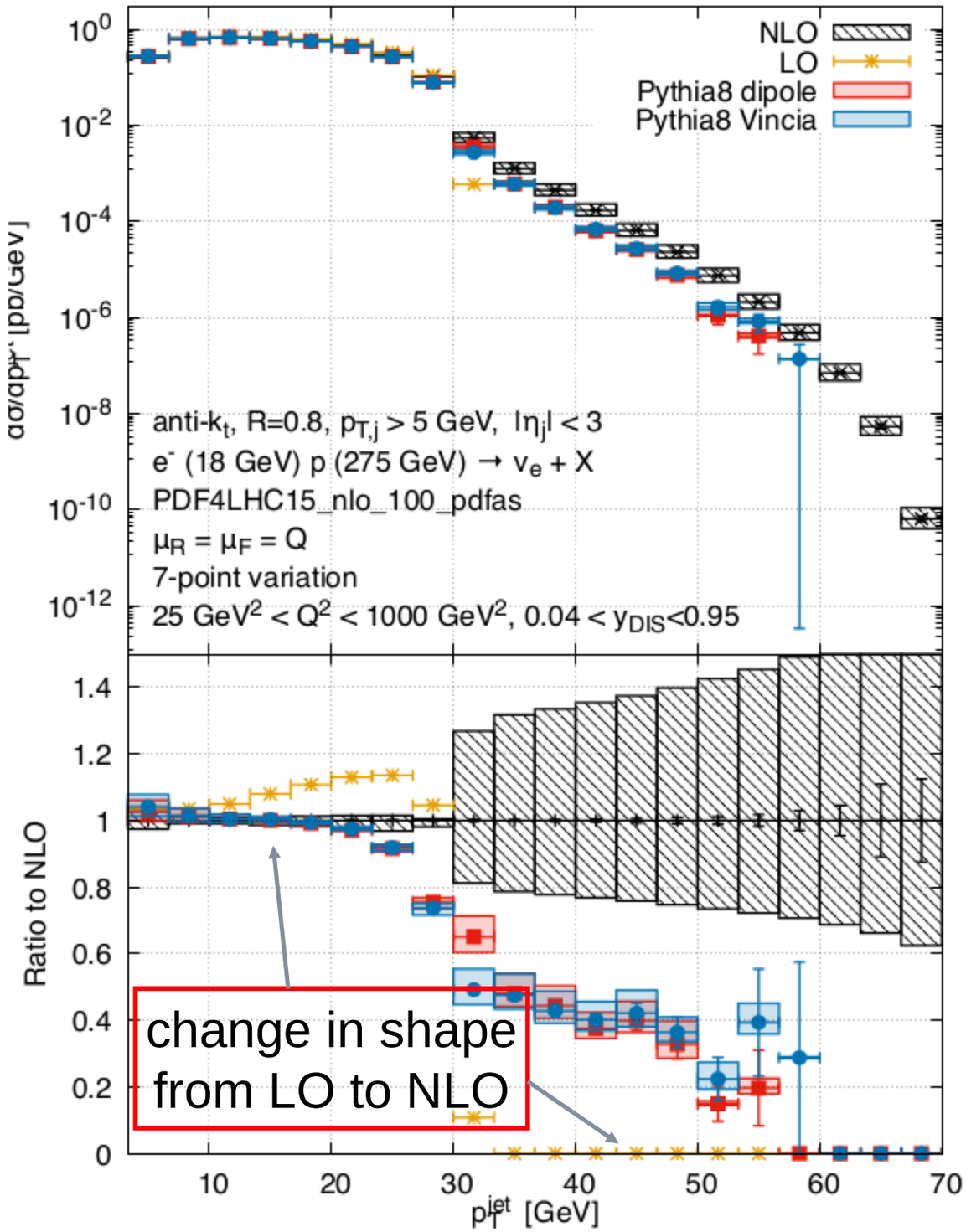



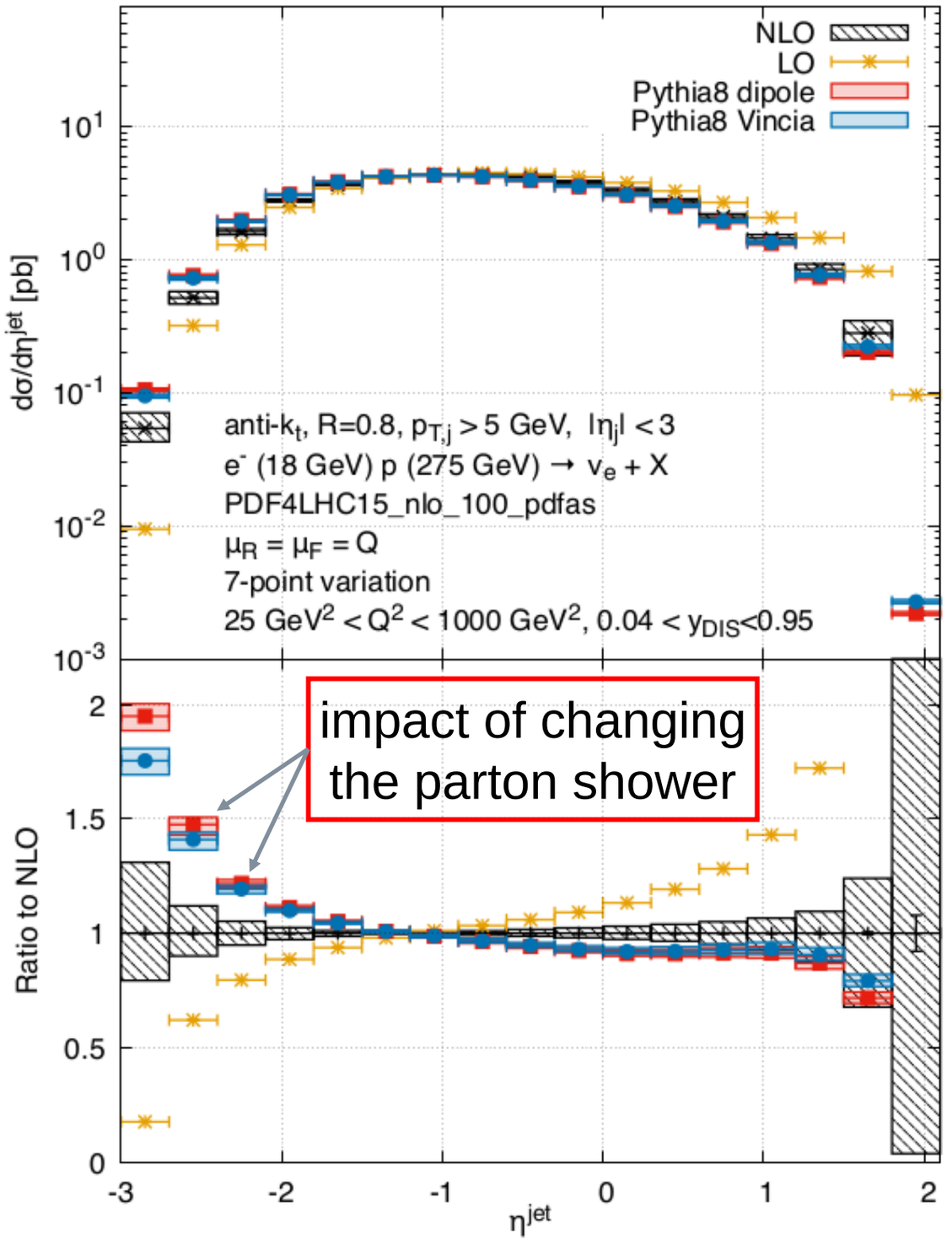
# EIC: CHARGED CURRENT



# EIC:CHARGED CURRENT



# Outlook

- We have now a POWHEG generator for DIS, available at

  svn://powhegbox.mib.infn.it/trunk/User-Processes-RES/DIS

Future plans include

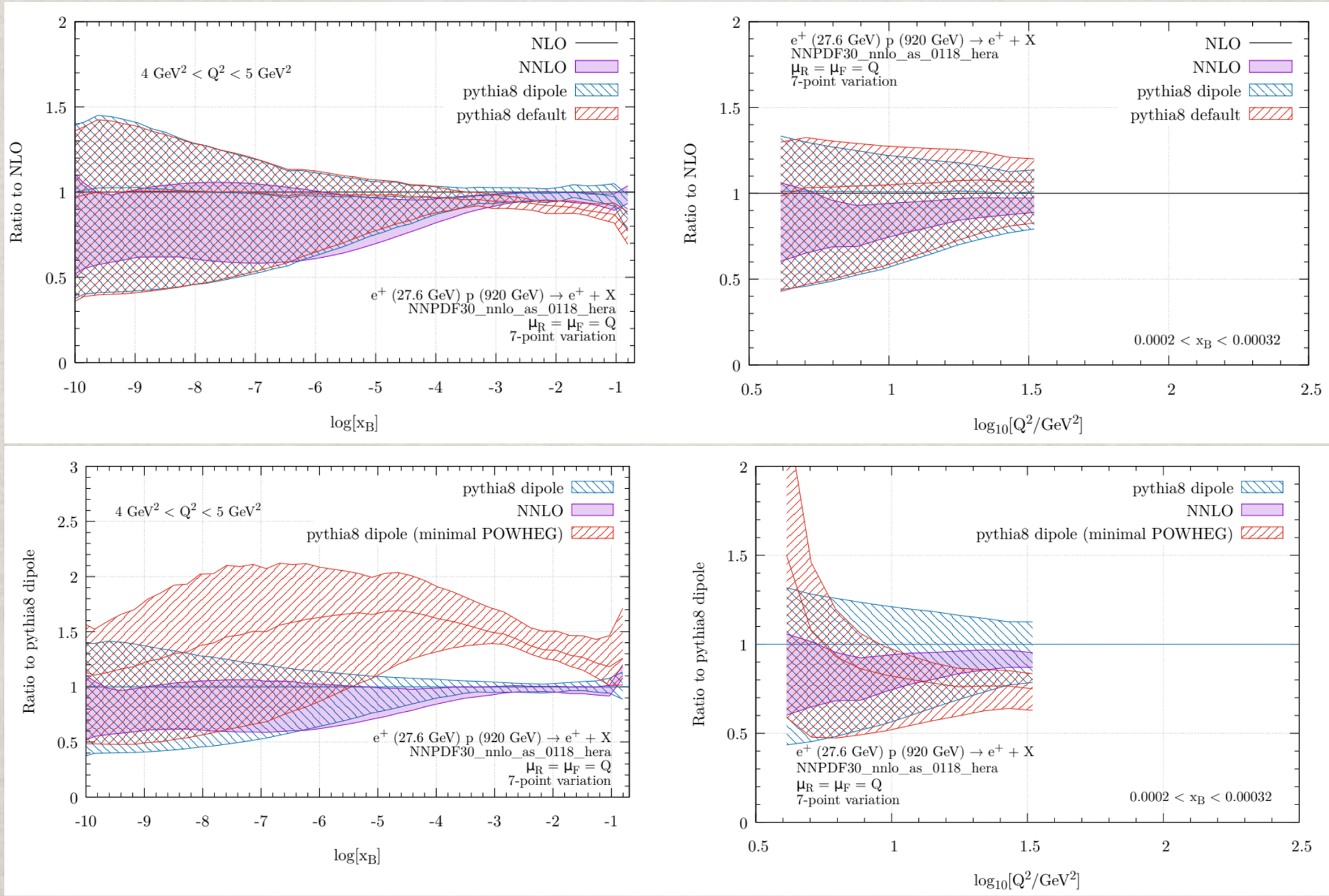
- Matching to NNLO a la MINLO needs NNLL resummation of Lund-plane declustering variables, or 1-jettiness
- Neutrino-nucleon scattering and applications to cosmic rays
- Generalisation hadron-hadron DIS-like processes (VBF, single-top)

**Thanks for your attention**

# Extra

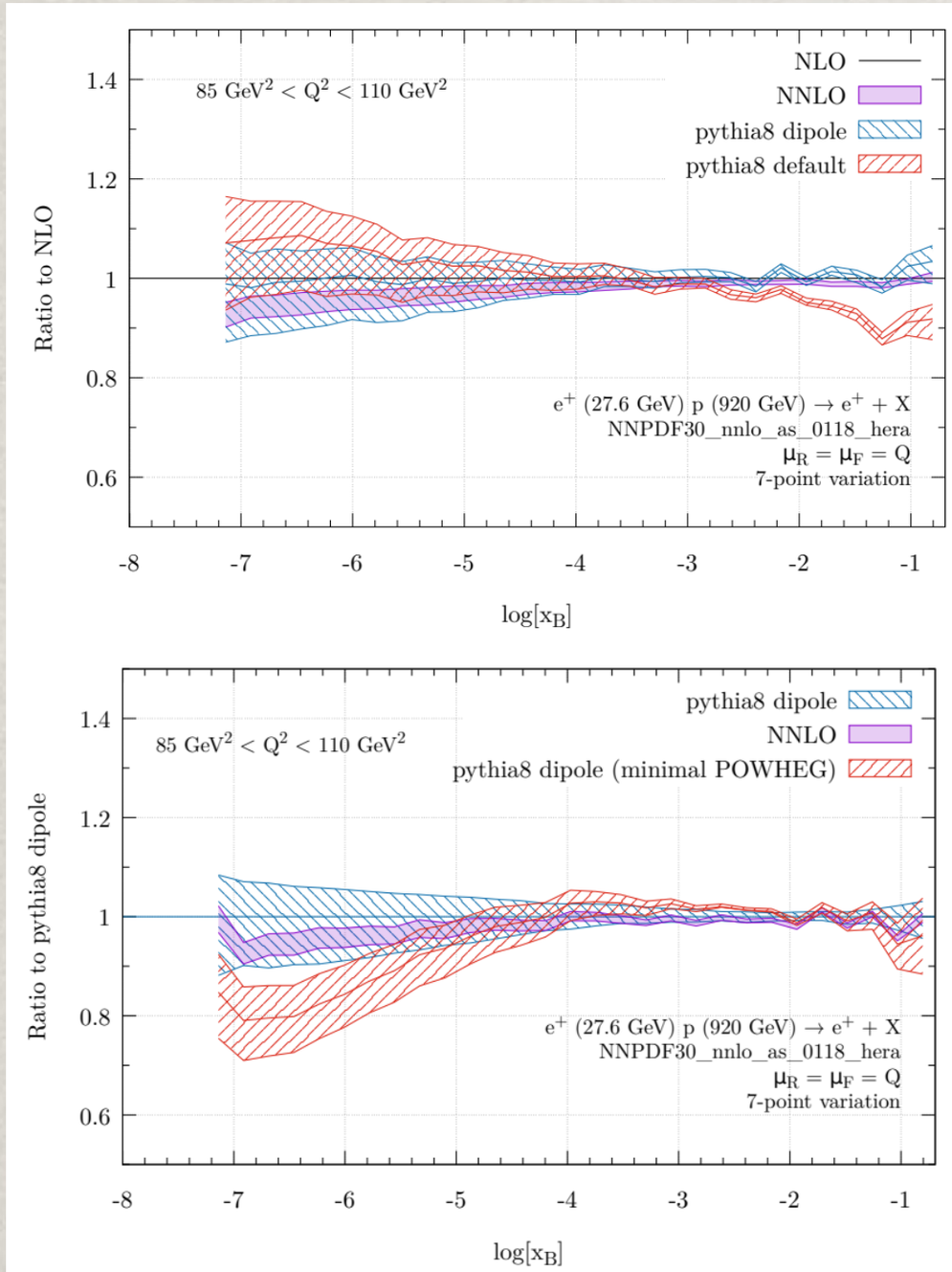
# Inclusive observables

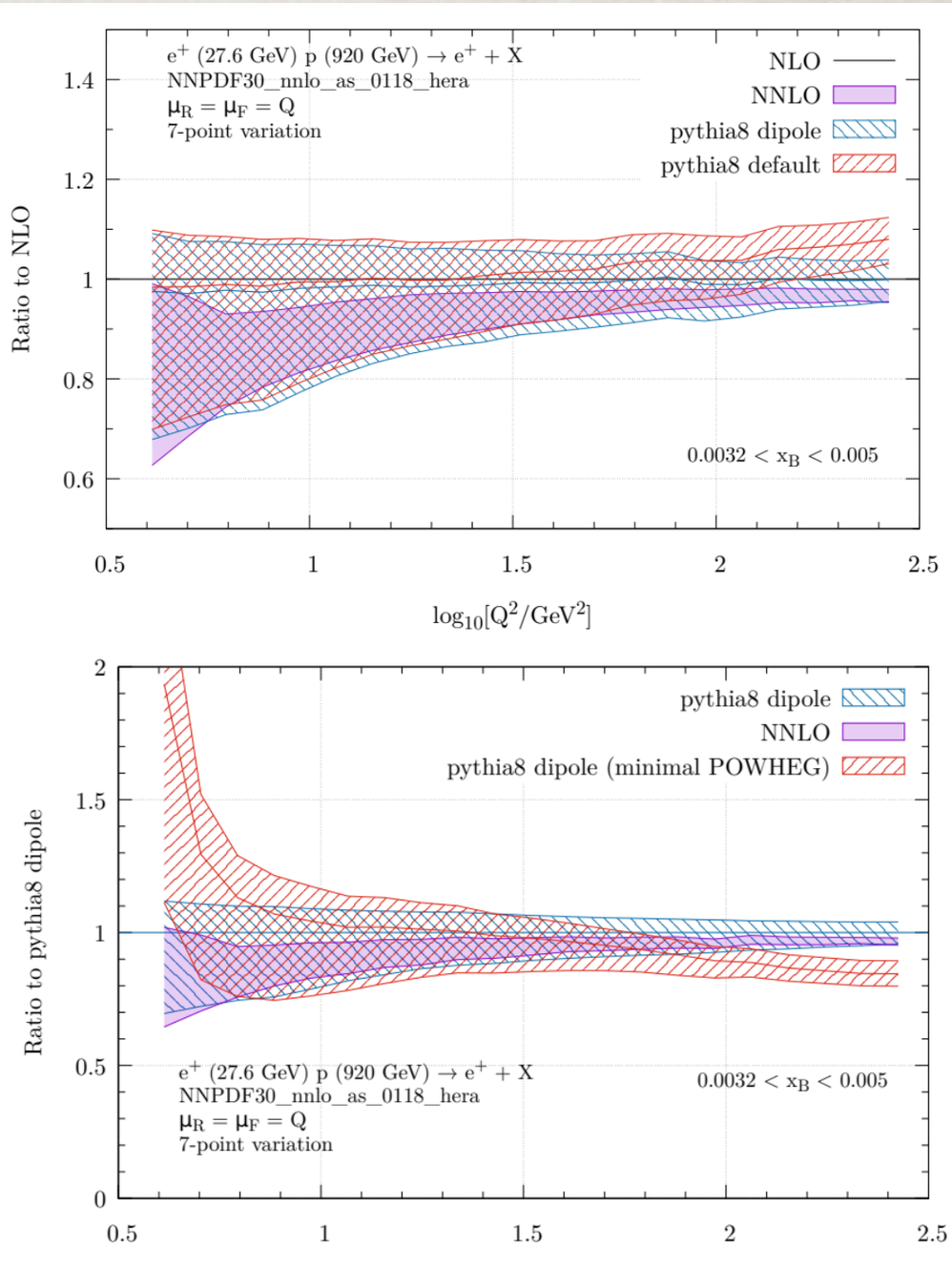
Preserving lepton kinematics in the generation of the hard event is more important than in the shower (see pythia8 default vs minimal POWHEG)



# Inclusive observables

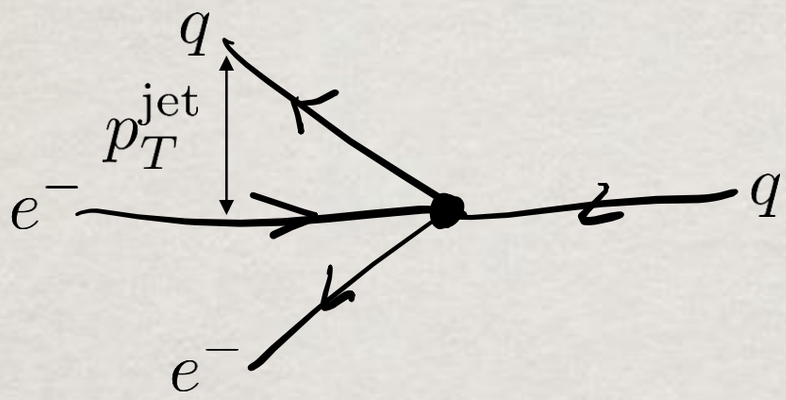
Preserving lepton kinematics in the generation of the hard event is more important than in the shower (see pythia8 default vs minimal POWHEG)

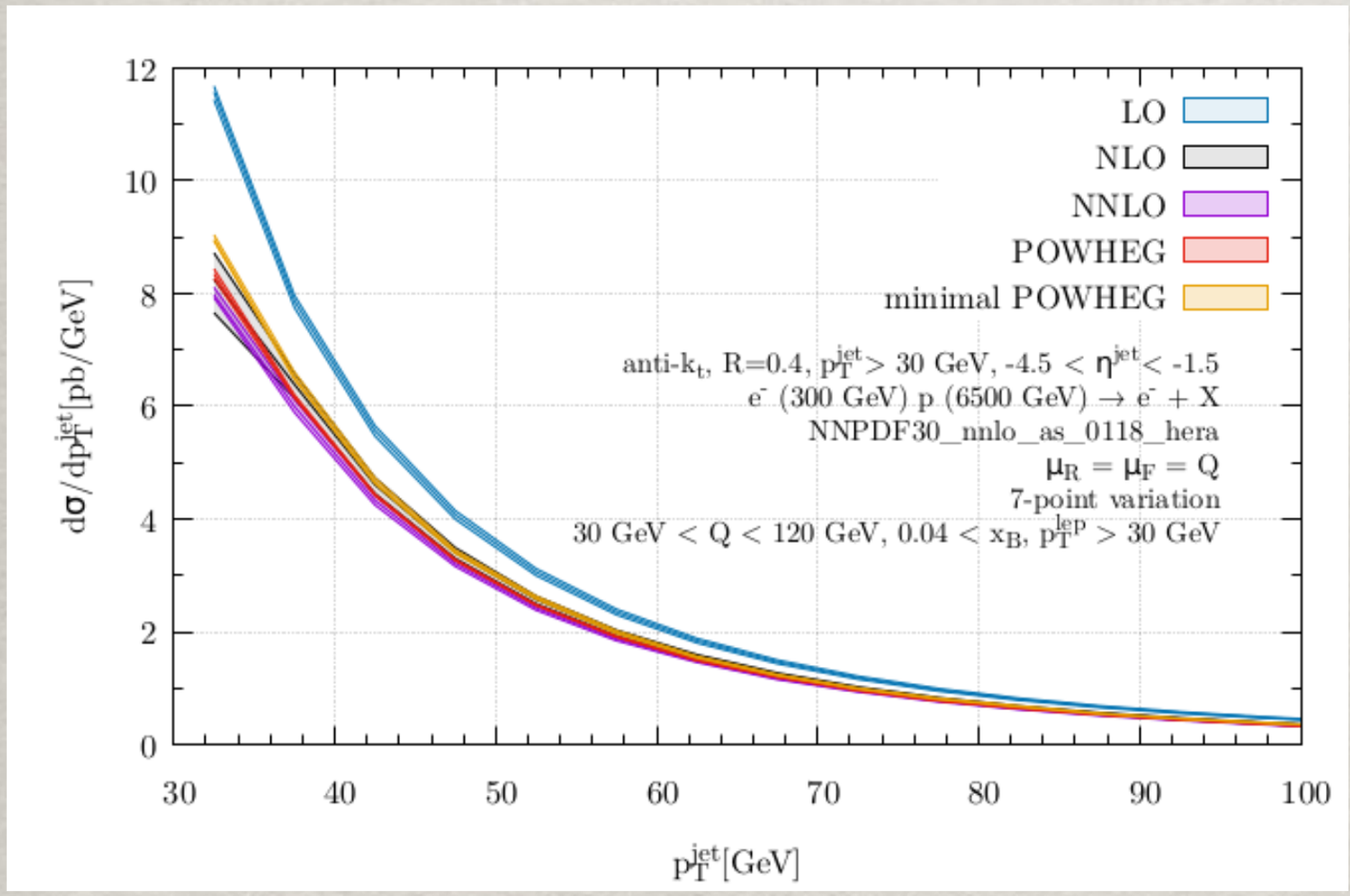


# VBF-LIKE OBSERVABLES

We consider highly asymmetric collisions that resemble VBF kinematics

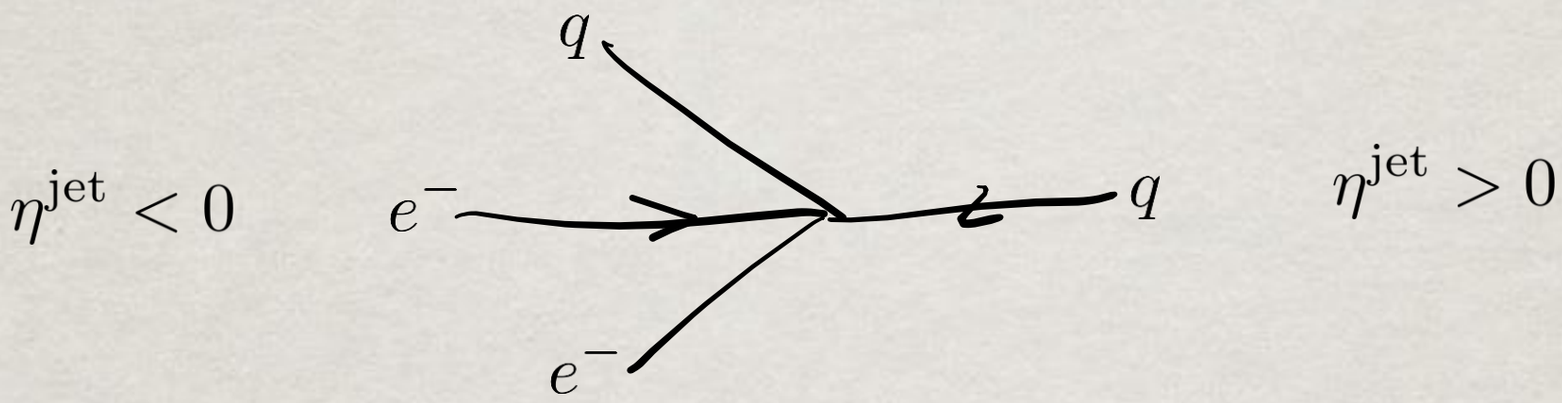


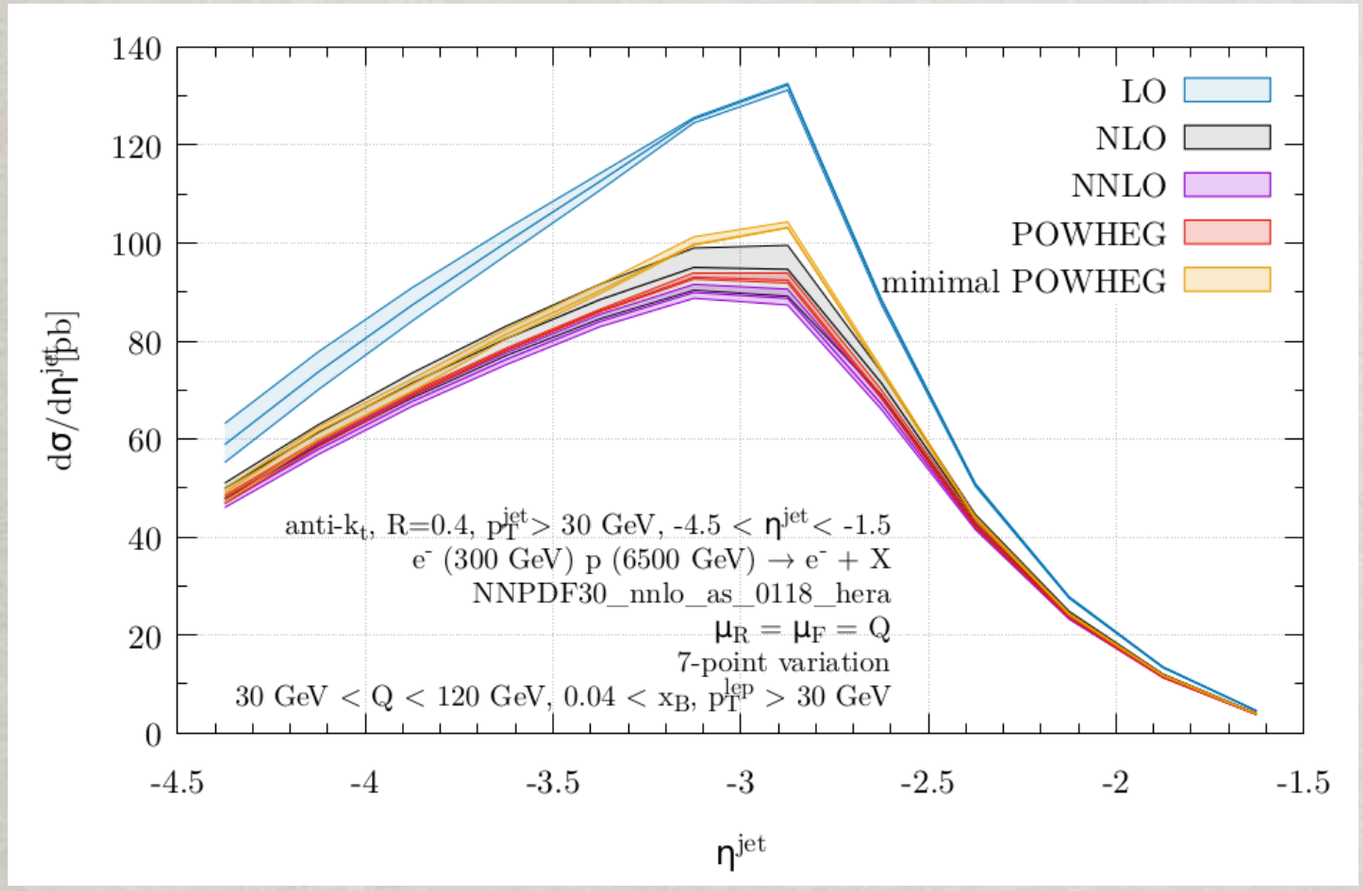




- Good agreement between all versions of POWHEG and NNLO for the jet transverse momentum distribution
- Uncertainties in POWHEG are underestimated, as changing the scales only affects the overall normalisation

# VBF-LIKE OBSERVABLES

We consider highly asymmetric collisions that resemble VBF kinematics




- For the jet rapidity distribution, the minimal POWHEG has a shape that is similar to LO, whereas the new POWHEG is closer to NNLO