Measurement of Azimuthal Lepton-Jet Decorrelation in Deep-Inelastic Scattering at HERA

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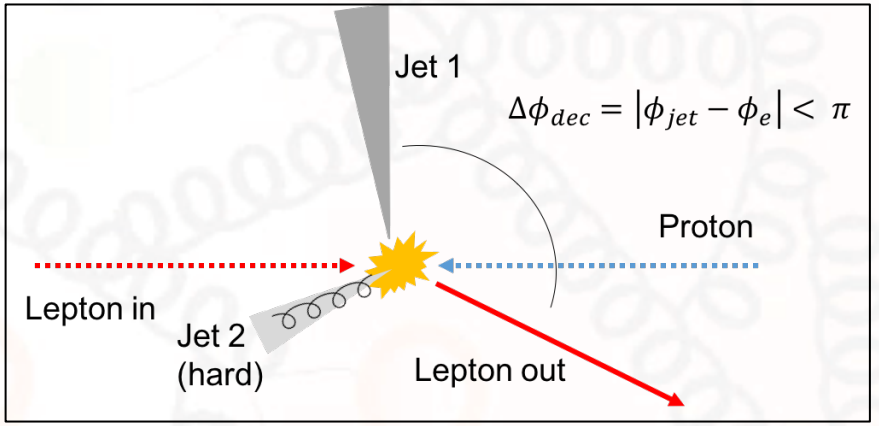
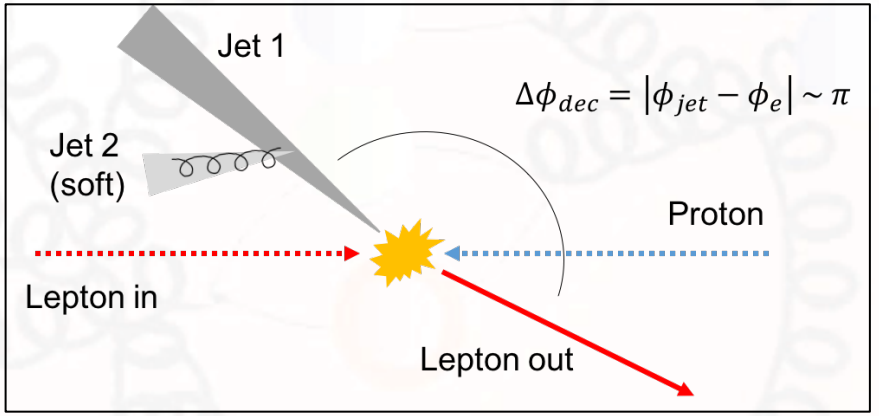
U.S. DEPARTMENT OF ENERGY | Office of Science

DOE NP contract: DE-SC0013405

Outline

- Introduction
- Analysis Details
- Results
- Summary and Outlook





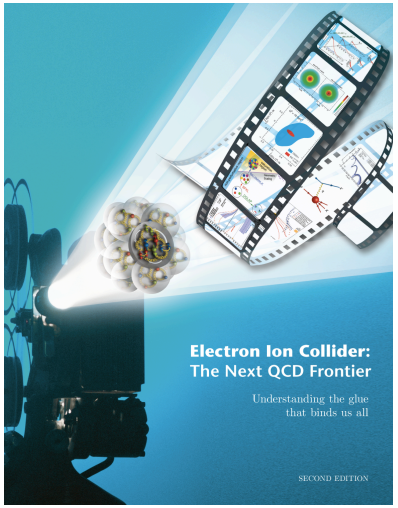
I. Abt et al. (ZEUS Collaboration), *The azimuthal correlation between the leading jet and the scattered lepton in deep inelastic scattering at HERA*, arXiv:2406.01430, Submitted to EPJC.

https://arxiv.org/abs/2406.01430

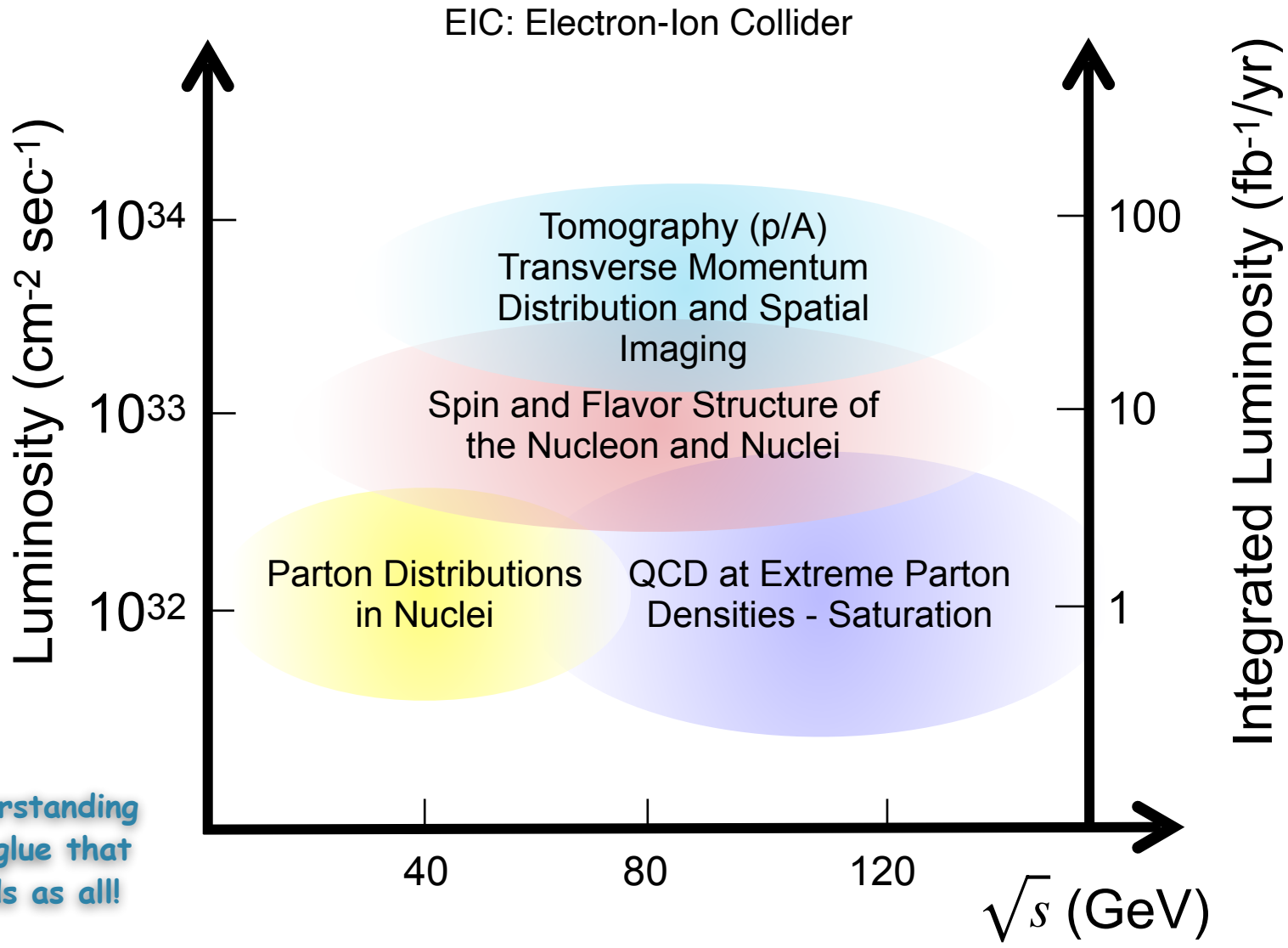
Introduction

- EIC: Study structure and dynamics of matter at high luminosity, high energy with polarized beams and wide range of nuclei
- Whitepaper:

arXiv:1212.1701

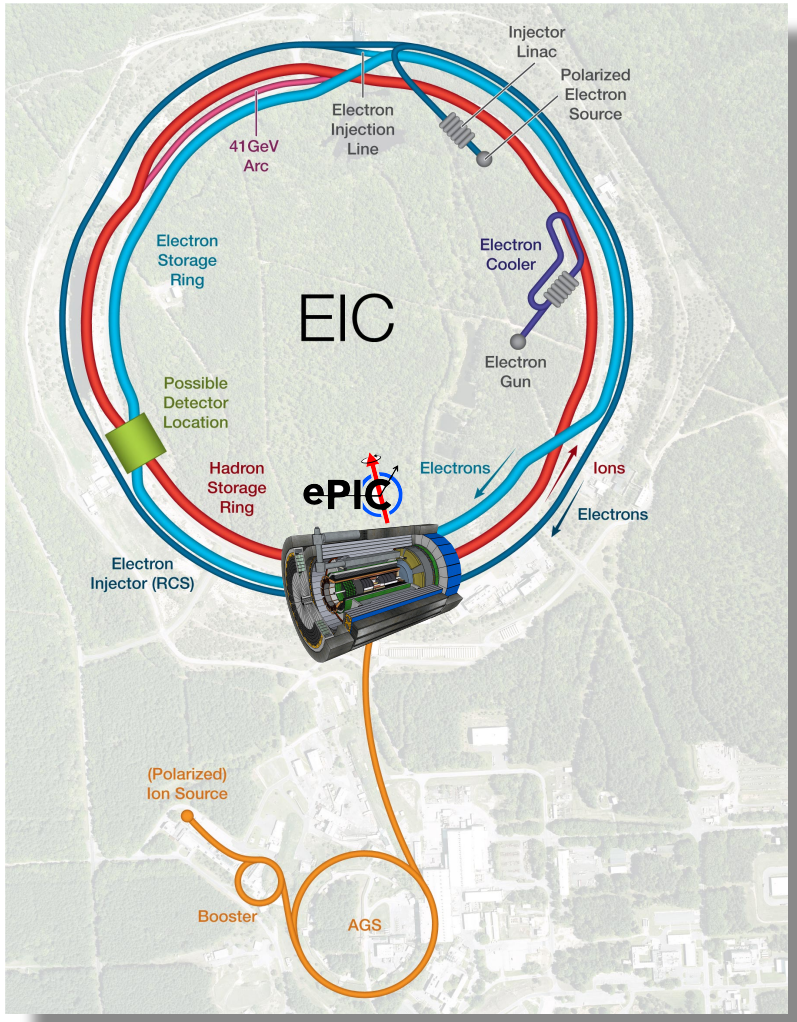


Understanding the glue that binds as all!



Introduction

- EIC



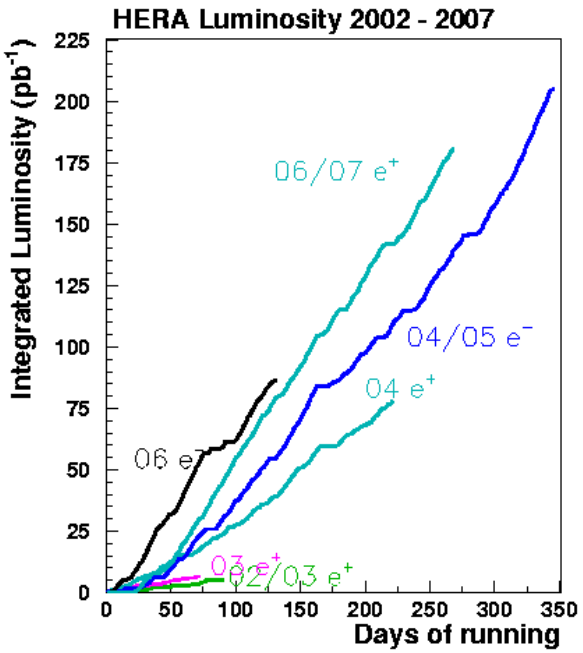
Center of Mass Energies:	29GeV - 140GeV
Luminosity:	10^{33} - 10^{34} $cm^{-2}s^{-1}$ / 10-100fb^{-1} / year
Highly Polarized Beams:	70%
Large Ion Species Range:	p to U
Number of Interaction Regions:	Up to 2!

- Award of DOE CD0*: December 2019
- Site selection at BNL: January 2020
- Award of DOE CD1*: June 2021
- Anticipated award of CD2*: ~April 2025
- Anticipated start of construction CD3*: ~April 2025
- Anticipated start of operation CD4*: ~April 2032-2034

* CD: Critical Decisions - DOE Project Approval Process

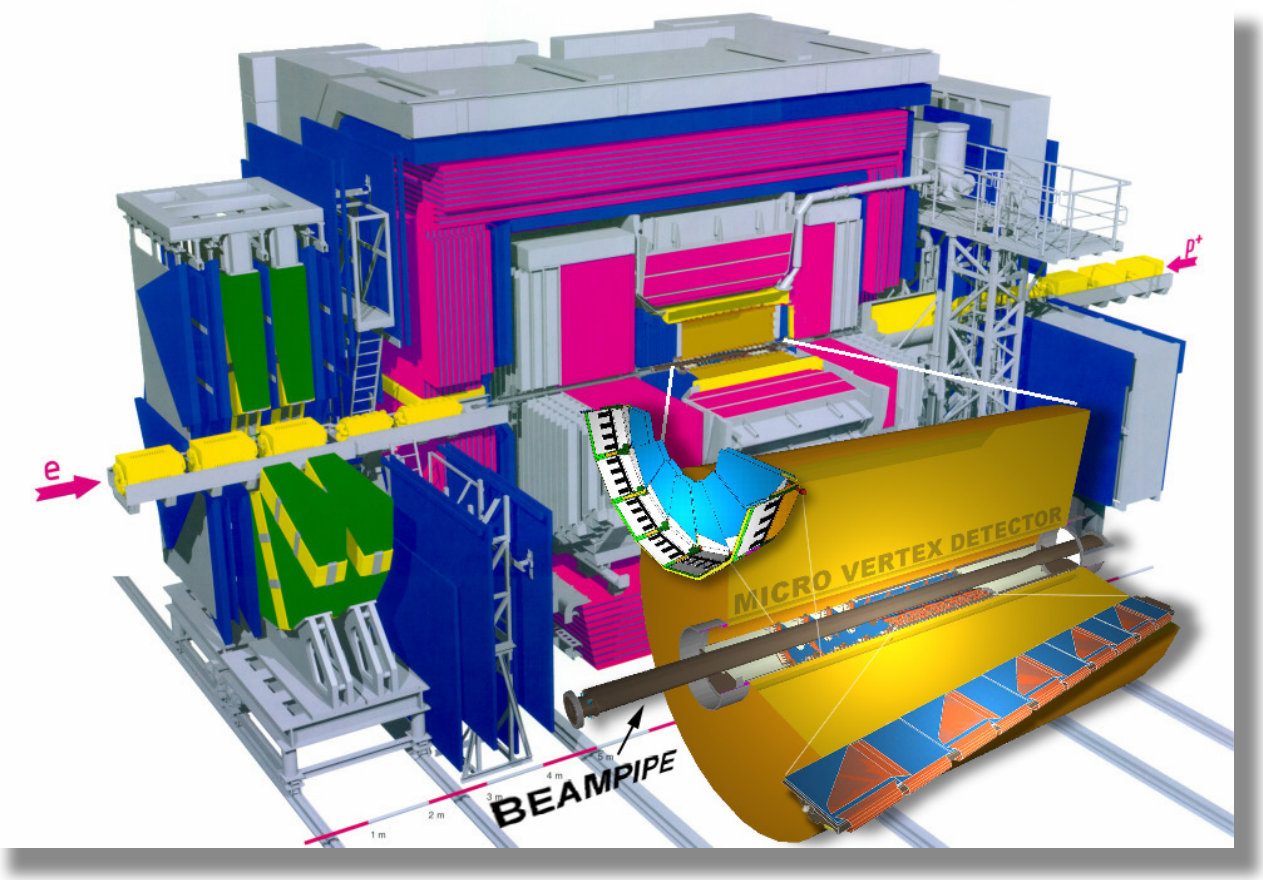
Introduction

- HERA
  - HERA: Hadron-Electron Ring Accelerator
    - First and only $e^{\pm}p$ collider so far!
    - $\sqrt{s} = 318\,GeV$ (HERA II)
    - Variety of existing jet studies
    - Analysis based on: $L \simeq 326\,pb^{-1}$



Introduction

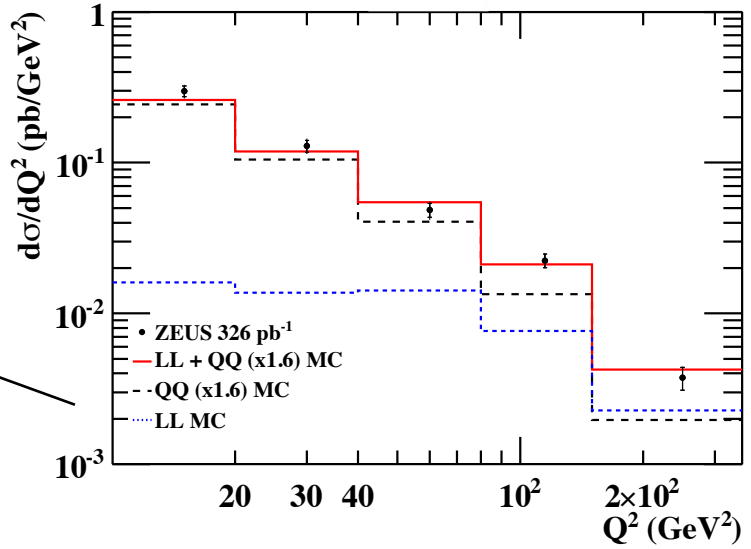
- ZEUS Experiment at HERA
  - General purpose detector
    - Jet reconstruction for $E_T > 2.5\,\mathrm{GeV}$
    - Two independent luminosity monitors (lead-scintillator calorimeter and magnetic spectrometer) using the Bethe-Heitler process, $\delta L/L \sim 2\,\%$

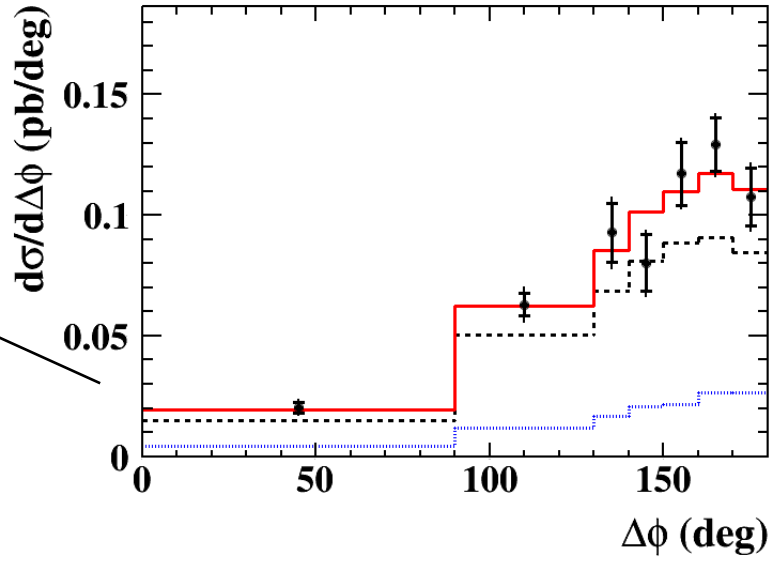


Introduction

Previous ZEUS jet results

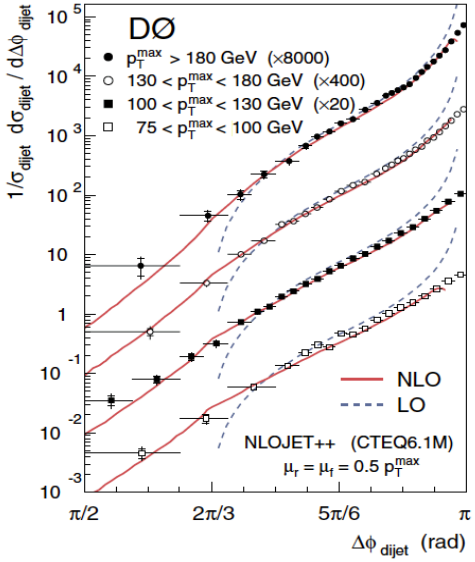
- Inclusive jets with anti-kt and SIScone algorithms (arXiv:1003.2923, Phys. Lett. B 691 (2010) 127-137)
- Inclusive jets in photoproduction (arXiv:1205.6153, Nucl. Phys. B864 (2012), 1-37)
- Isolated photons accompanied by jets in DIS (arXiv:1206.2270, Phys Lett B 715 (2012) 88-97)
- Isolated photons plus jets in PHP (arXiv:1312.1539 , Phys.Let B (2014) Volume 730, 293-301)
- More on isolated photons plus jets in PHP (arXiv:1405.7127, JHEP 2014 (23))
- Diffractive di-jet production in DIS (Eur. Phys. J. C 76 (2016) 16)
- Diffractive photoproduction of isolated photons at HERA (arXiv: 1705.10251 , Phys. Rev. D 96 (2017) 032006)
- Further studies of isolated photon production with a jet in deep inelastic scattering at HERA (arXiv: 1712.04273 , J. High Energ. Phys. (2018) 2018: 32)
- Azimuthal correlation in photoproduction and deep inelastic ep scattering at HERA (arXiv:2106.12377,) (JHEP (2021) 102)

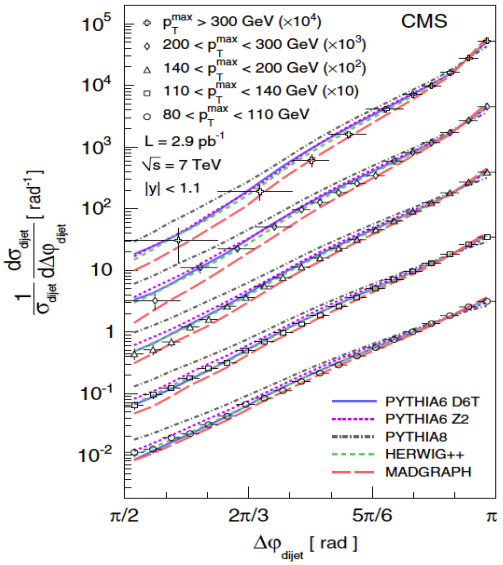


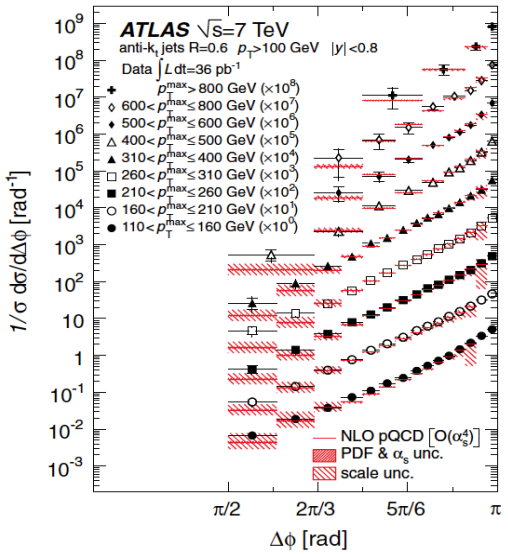


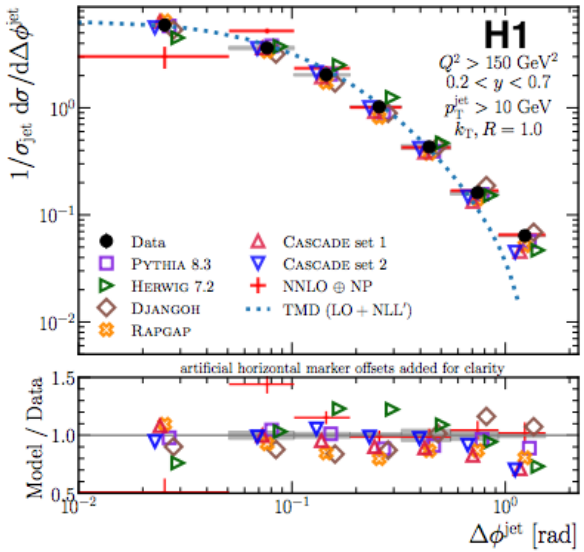
Introduction

- Previous azimuthal jet results at hadron-hadron colliders:









Conclusions for results at Tevatron (D0) and LHC (ATLAS and CMS):

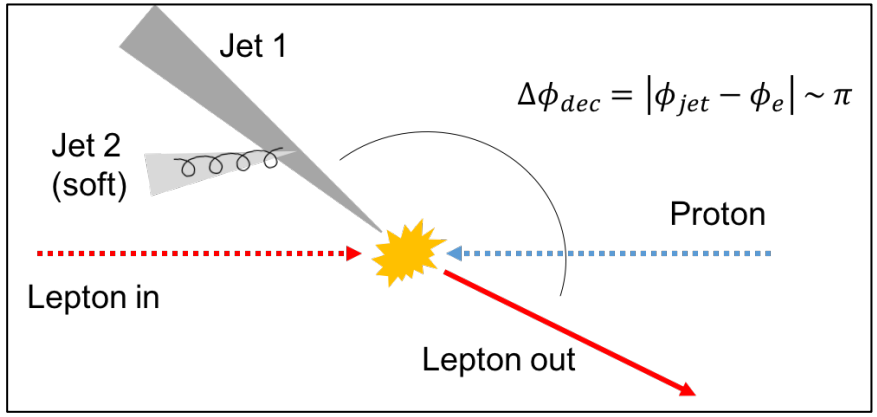
- Improvements in data description by high order correction (NLO to LO).
- MC generators describe data well except in the region $\Delta\phi \sim \pi \Longrightarrow$ tune MC based on data.

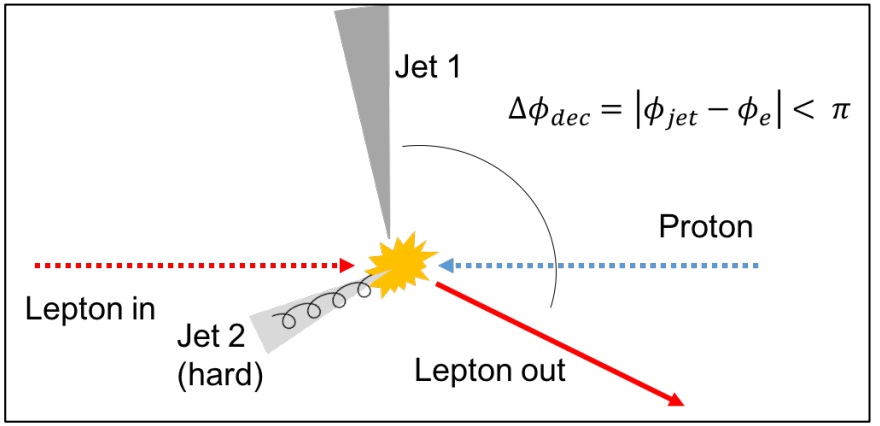
Recent results from HERA (H1):

- Improvements in data description by TMD calculation around the region $\Delta\phi \sim \pi$. / Large overlap of collinear/TMD frameworks.

Introduction

- Motivation Jet-lepton decorrelation





- Jet-lepton decorrelation can be used to probe soft and hard QCD radiation effects without explicit description of the additional jets.
- Can access TMD distributions, complementary to SIDIS, without an explicit description of TMD fragmentation function [Liu et al., PRL 122 (2019) 192003, Lui et al., PRD 102 (2020) 094022].
- HERA measurements: Probe TMDs at small x!

Analysis Details

Selection Cuts and Control Plots

Kinematic region

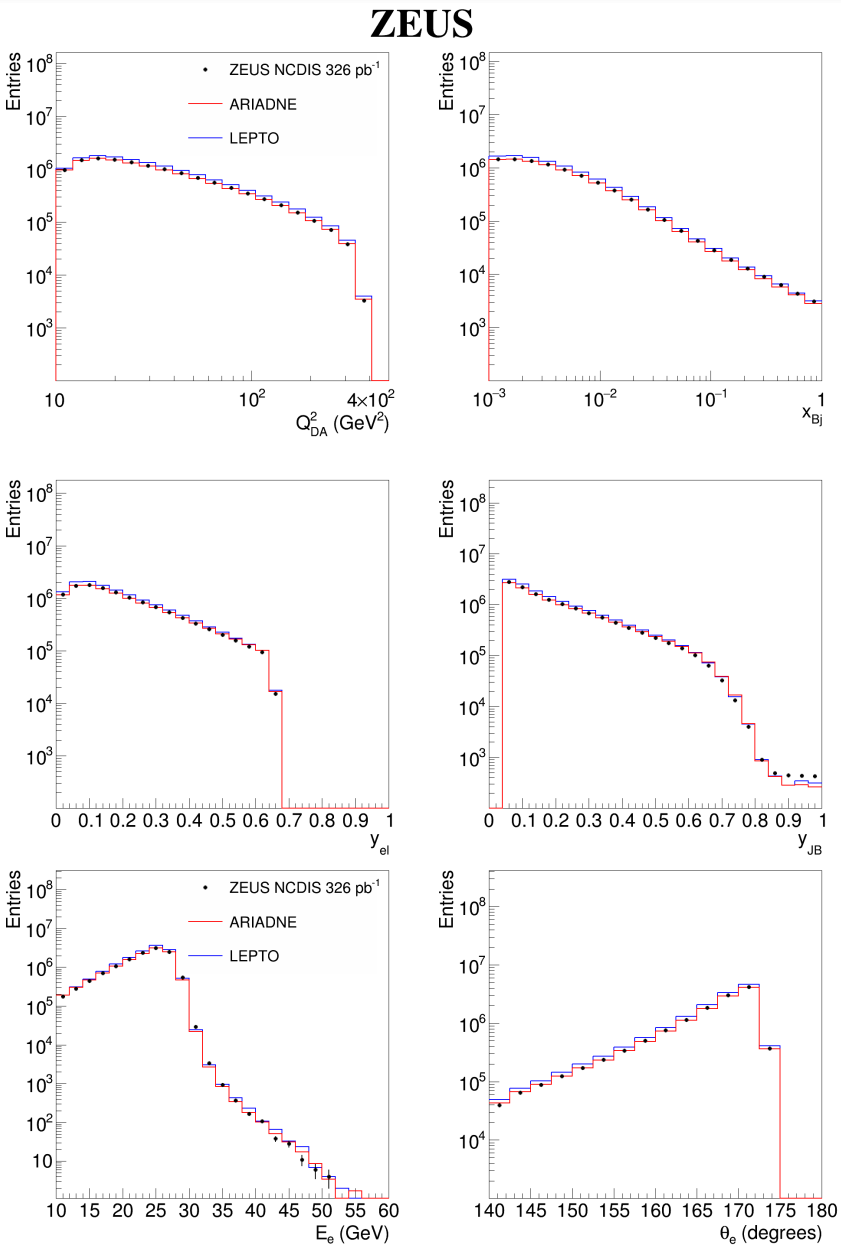
- $10\,\mathrm{GeV}^2 < Q^2 < 350\,\mathrm{GeV}^2$
  (Double-angle)
- $0.04 < y < 0.7$
  (Electron, Jacquet-Blondel)

Electron

- $E_e > 10\,\mathrm{GeV}$
- $140^\circ < \theta_e < 180^\circ$

Jets

- Massive jets in the lab frame,
  k_T algorithm with
  E recombination scheme
- $2.5\,\mathrm{GeV} < p_T < 30\,\mathrm{GeV}$
- $-1.5 < \eta < 1.8$
- FastJet 3.4.0
  (M. Cacciari et al., EPJC 72 (2012) 1896)



Analysis Details

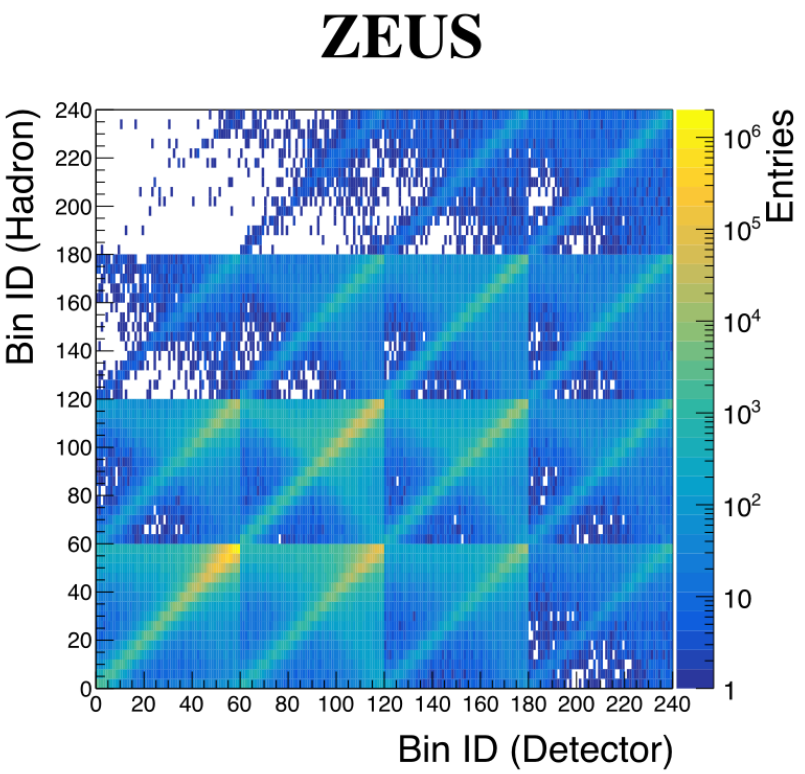
- Cross-section determination
  - Inclusive ($N_{jet} \geq 1$) measurement of differential cross section in azimuthal decorrelation $\Delta\phi_{dec}$ between the leading jet and the lepton

$$\frac{d\sigma}{d\Delta\phi_{dec}}(e + p \to e + \text{jet} + X) = \frac{1}{\mathcal{L}} \frac{N_{i,\,\text{had}}}{\delta\Delta\phi_{\text{dec},\,i}}$$

    - Leading jet = jet with the highest p_T
    - $\Delta\phi_{dec} = |\phi_{jet} - \phi_e|$
    - MC-based (ARIADNE 4.12) unfolding & efficiency correction
      - $\epsilon \sim 0.8$, no strong dependence found.
    - Measurement unfolded to the hadron level:
      - Hadron jets with FastJet 3.4.0, kT-algo with E scheme and R = 1
      - Massive jets in the lab frame
        with all final state particles, as identified by ARIADNE,
        without scattered lepton and neutrino.

Analysis Details

- Unfolding
  - Matrix-based unfolding:
    - L-scan method as interfaced in TUnfold package (S.Schmitt, JINST 7 (2012) T10003)
    - Takes the migration matrix of $\Delta\phi_{dec}$ as input
  - No additional jet matching outside the unfolding
    - Leading jet misidentification shows up as $\Delta\phi$ shift of, for the case of dijet, $\sim \pi$.
  - Model-dependence of the unfolding process estimated with MEPS-LEPTO based MC sample
    - $\sim 5\,\%$ effect at $\Delta\phi \sim \pi$.
  - For final publication, N_{jet} correlation included in the unfolding process



*Bin ID = [0-60 for $0 < \Delta\phi < \pi$] + $60 \times (N_{jet} - 1)$

Analysis Details

- Theoretical framework

  Perturbative calculations from UNSAM (Borsa, de Florian, Pedron).

  - Calculations for EIC (I. Borsa et al., PRL 125 (2020) 082001)

    revisited for HERA kinematics

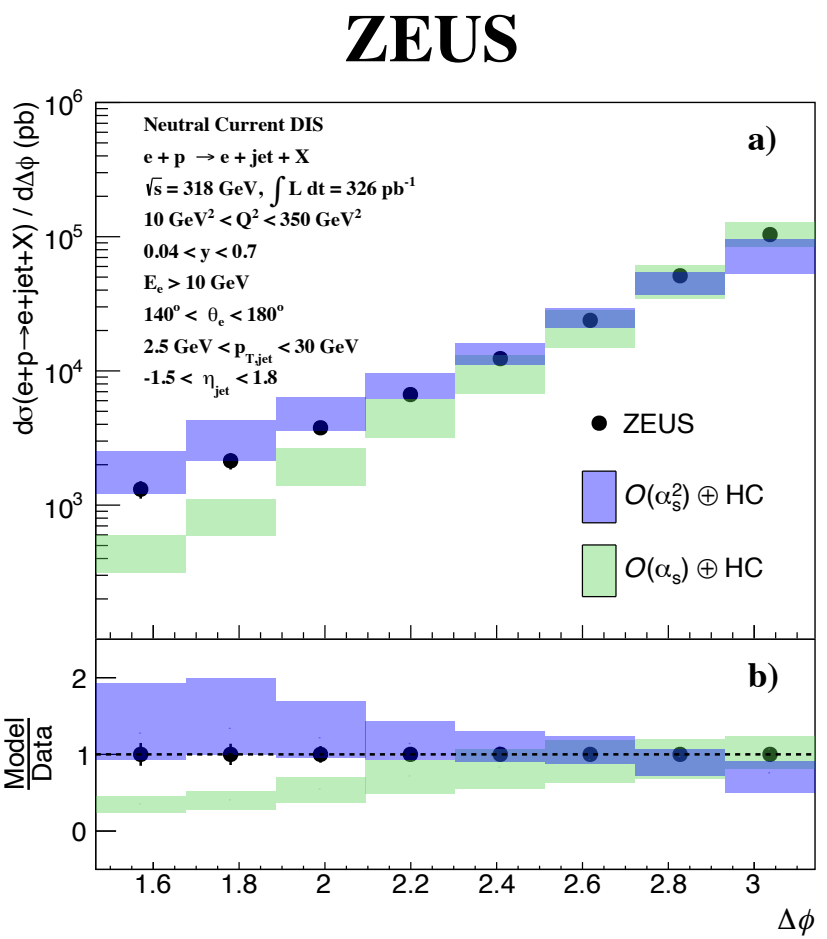
    https://journals.aps.org/prl/references/10.1103/PhysRevLett.125.082001

  - Fixed order (up to $O(\alpha_s^2)$) calculations using the projection-to-Born method
  - Takes a jet plus an extra jet at NLO and fully inclusive DIS at NNLO

    to produce single-inclusive ($N_{jet} \geq 1$) calculation at NNLO
  - PDF4LHC15 sets
  - No HQ contribution
  - Calculations are produced at the parton level
    - Hadronization correction with ARIADNE
    - Model dependence in hadronization correction evaluated with LEPTO, ~5%

Results

- Azimuthal angle jet/electron cross-section
  - Azimuthal angle jet/electron measurement for the inclusive case ($N_{jet} \geq 1$)
    - Systematics study suggests that the model dependence of the unfolding process is the dominating contribution (~5% at $\Delta\phi_{dec} \sim \pi$)
    - Efficiency correction ~20%
  - Comparison to pQCD calculations.
    - Hadronization correction with uncertainty of ~5%
    - Clear improvement seen from NNLO compared to NLO
    - High $\Delta\phi_{dec}$ behavior due to large logs from soft gluon radiation
    - Input from TMD will improve the understanding for larger x region (x > 0.1)



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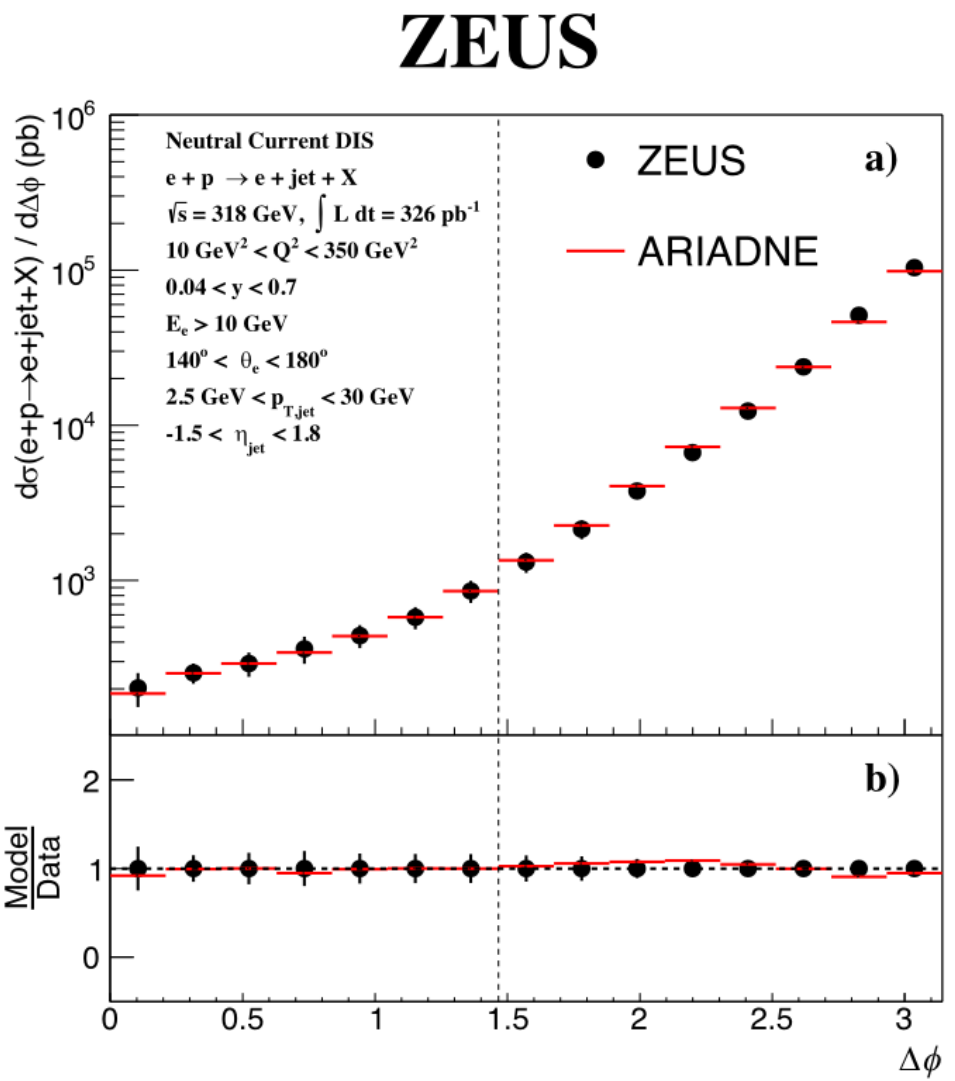
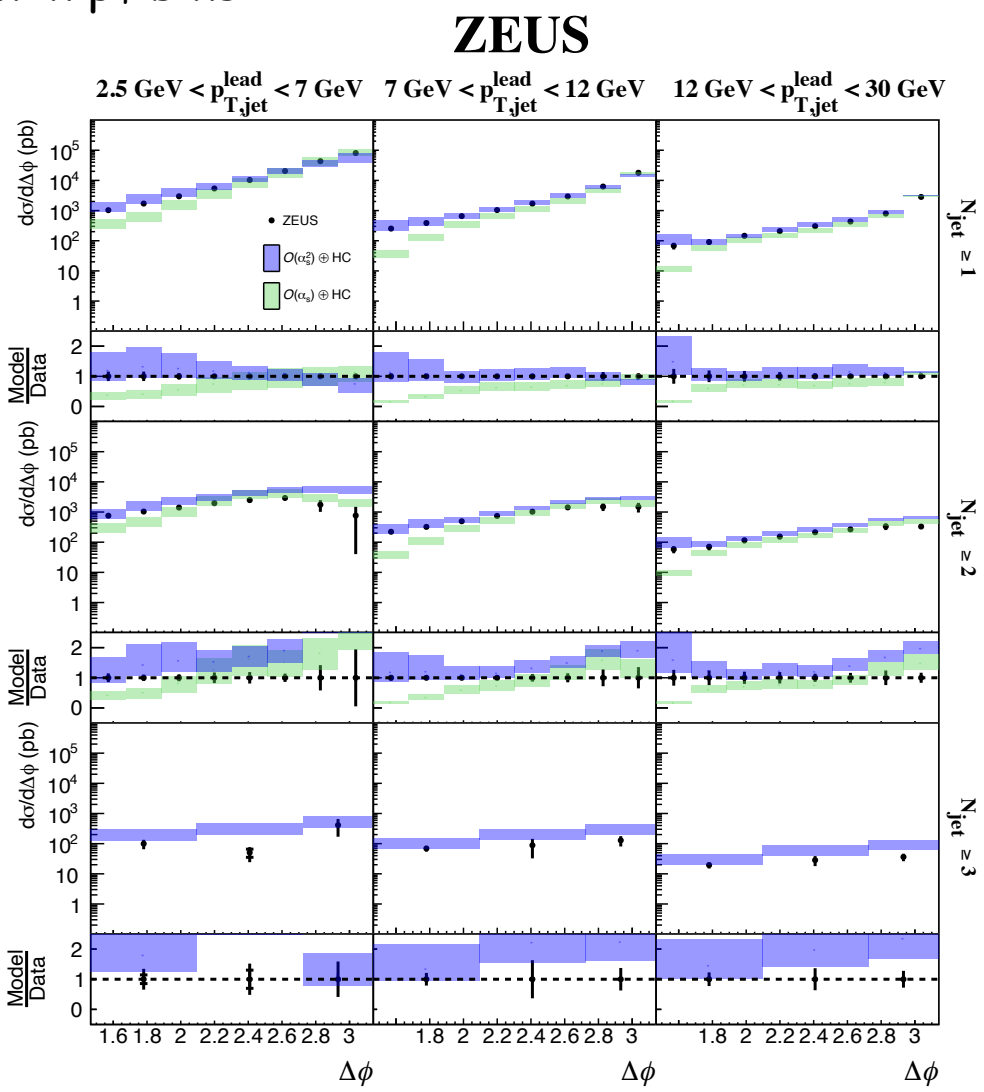
    - Efficiency correction ~20%
  - Comparison to ARIADNE MC.
    - ARIADNE is normalized to data luminosity
    - Overall reasonable agreement to data, based on LO + parton shower modeling
    - Measurement is soon to be submitted to HEPData and Rivet for comparisons with simulations based on higher order matrix elements, such as POWHEG and SHERPA



Results

- Azimuthal angle jet/electron cross-section in p_T bins
  - As for inclusive measurement, $O(\alpha_s^2)$ improves over $O(\alpha_s)$
  - Only $O(\alpha_s^2)$ for $N_{jet} \geq 3$ as it is LO
  - Good description of data in low-p_T regime down to $p_{\mathrm{T,jet}}^{\mathrm{lead}} > 2.5\ GeV$
  - Enhanced events with reduced $\Delta\phi$ (flatter in terms of shape) with increasing N_{jet}, as also seen in hadron experiments



Results

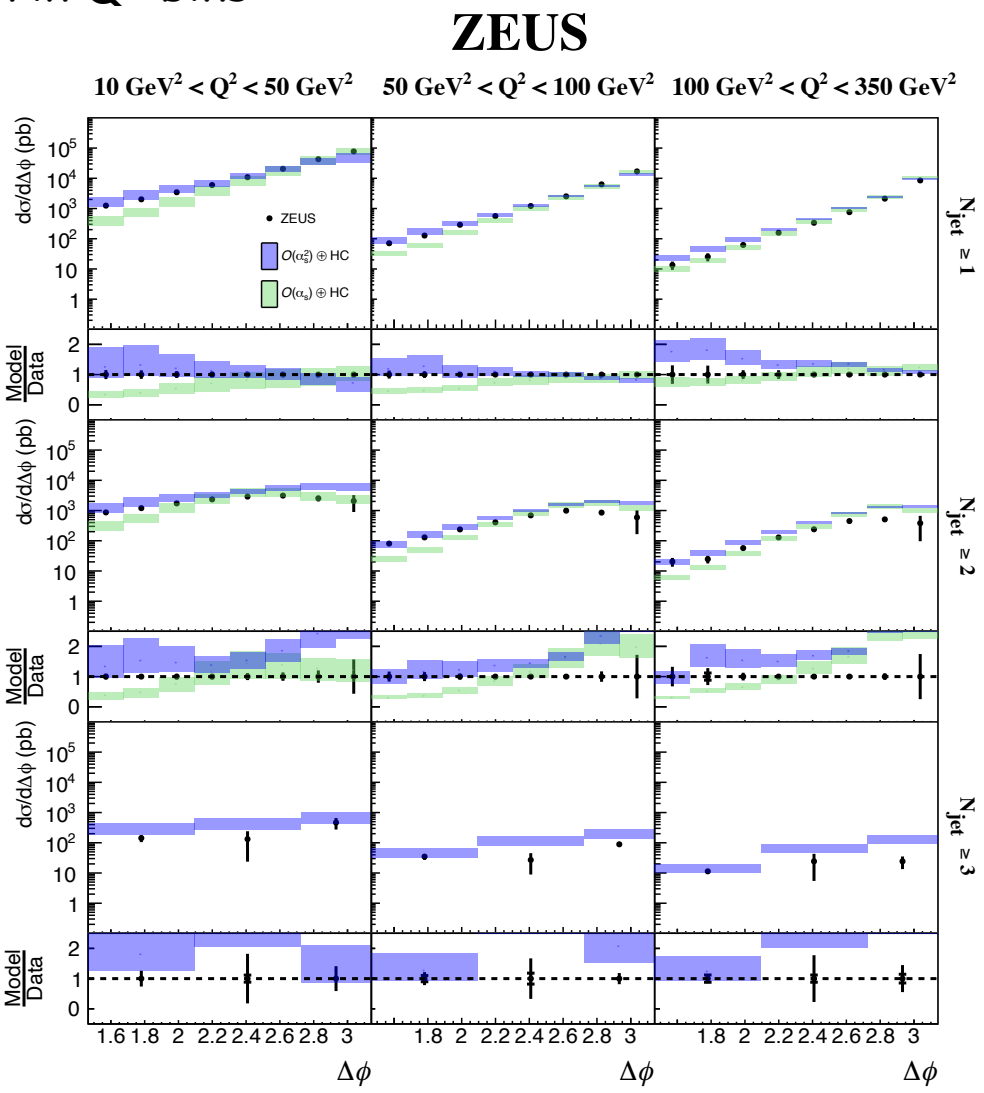
- Azimuthal angle jet/electron cross-section in Q^2 bins
  - As for inclusive measurement,

    $O(\alpha_s^2)$ improves over $O(\alpha_s)$
  - Enhancement in slope

    $(\Delta\phi < 3\pi/4)$

    with increasing Q^2

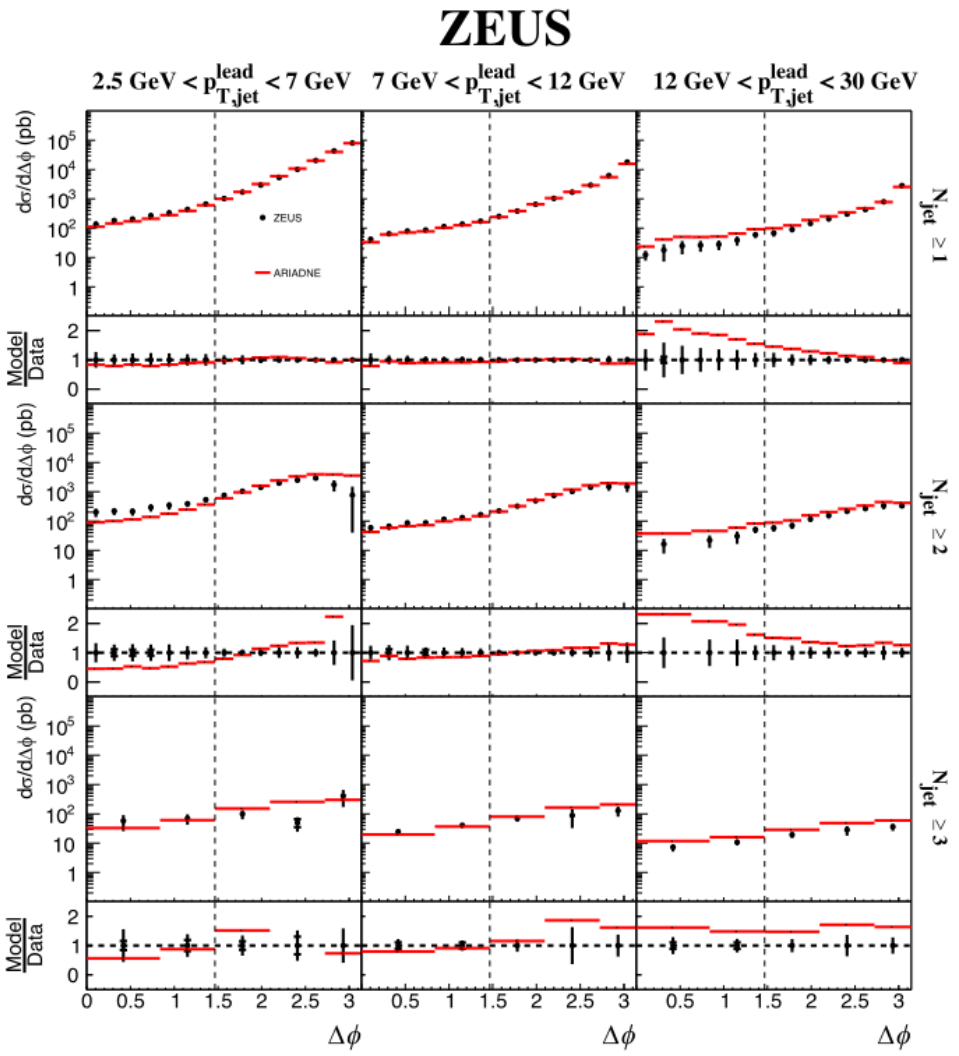
    as higher-order contributions and the kinematic space for additional jets diminish.
  - Consistent with hadron experiments where the highest momentum jet in dijet is analogous to electron in DIS (when one of the two jets carries less p_T than DIS electron)



Results

- Azimuthal angle jet/electron cross-section in p_T bins - MC comparison
  - Excellent description of data by ARIADNE, although higher order processes are not fully represented in matrix element
  - Similar degree of agreement (compared to $O(\alpha_s^2)$) is observed throughout all p_T, Q^2, and N_{jet} ranges
  - Enhancement of events with reduced $\Delta\phi$ with increasing $p_{T,jet}$ for $N_{jet} \geq 2$ for all Q^2

    → Further tuning might improve agreement



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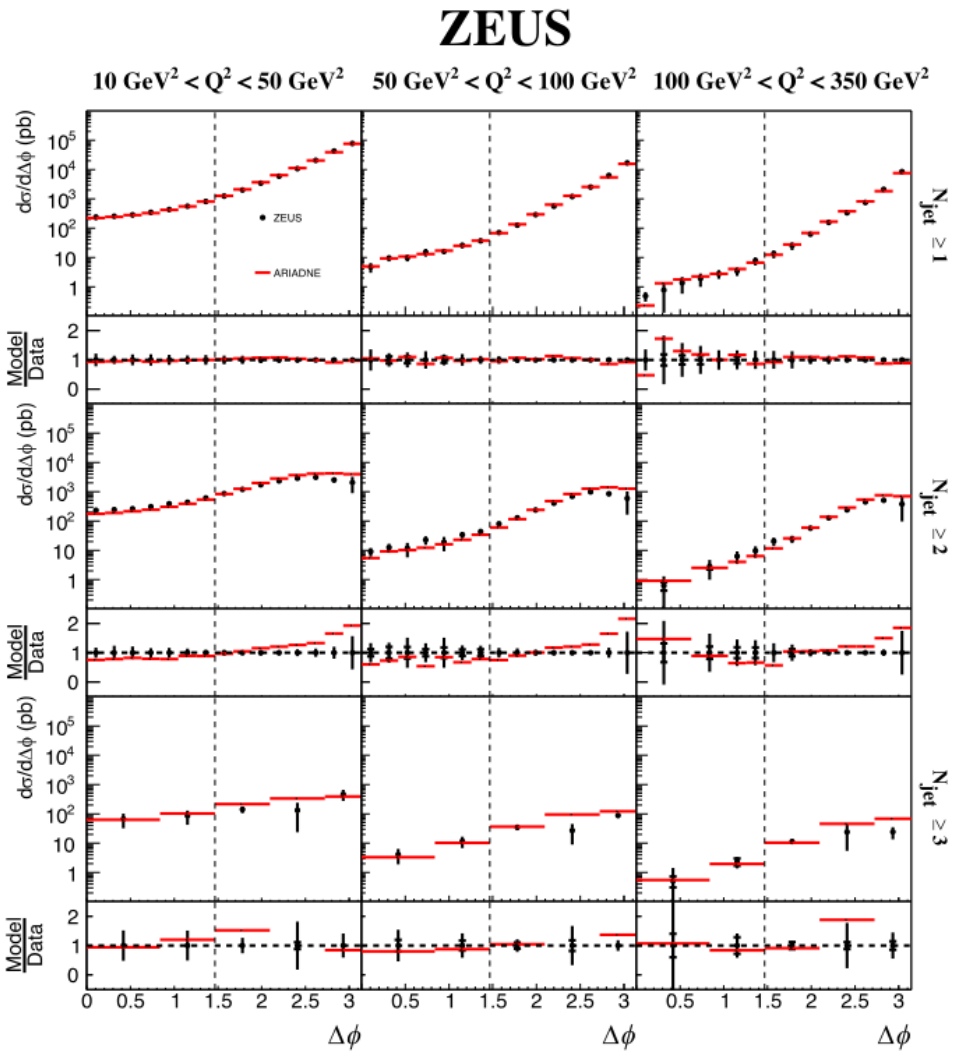

Summary and Outlook

- ZEUS results* of decorrelation measurements of lepton and leading jet in DIS, similar to previous ZEUS γ–jet results and other experiments in proton-proton collisions
- Dedicated TMD study planned focusing on high-x region using azimuthal angular correlations of final state lepton and jet measurements - Complementary to Semi-Inclusive DIS measurements with added benefit of no need for TMD fragmentation functions
- The MC predictions from ARIADNE describe the main features of data well. However, some discrepancies are observed
- Clear improvement seen from NNLO compared to NLO (at low-pT regime, pTjet > 2.5 GeV
- Measurement will be submitted to HEPData and Rivet soon
- Decorrelation measurements of lepton and leading jet in DIS will provide an important probe of TMDs at EIC

I. Abt et al. (ZEUS Collaboration), *The azimuthal correlation between the leading jet and the scattered lepton in deep inelastic scattering at HERA*, arXiv:2406.01430, Submitted to EPJC.
https://arxiv.org/abs/2406.01430