

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

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DOE NP contract: DE-SC0013405

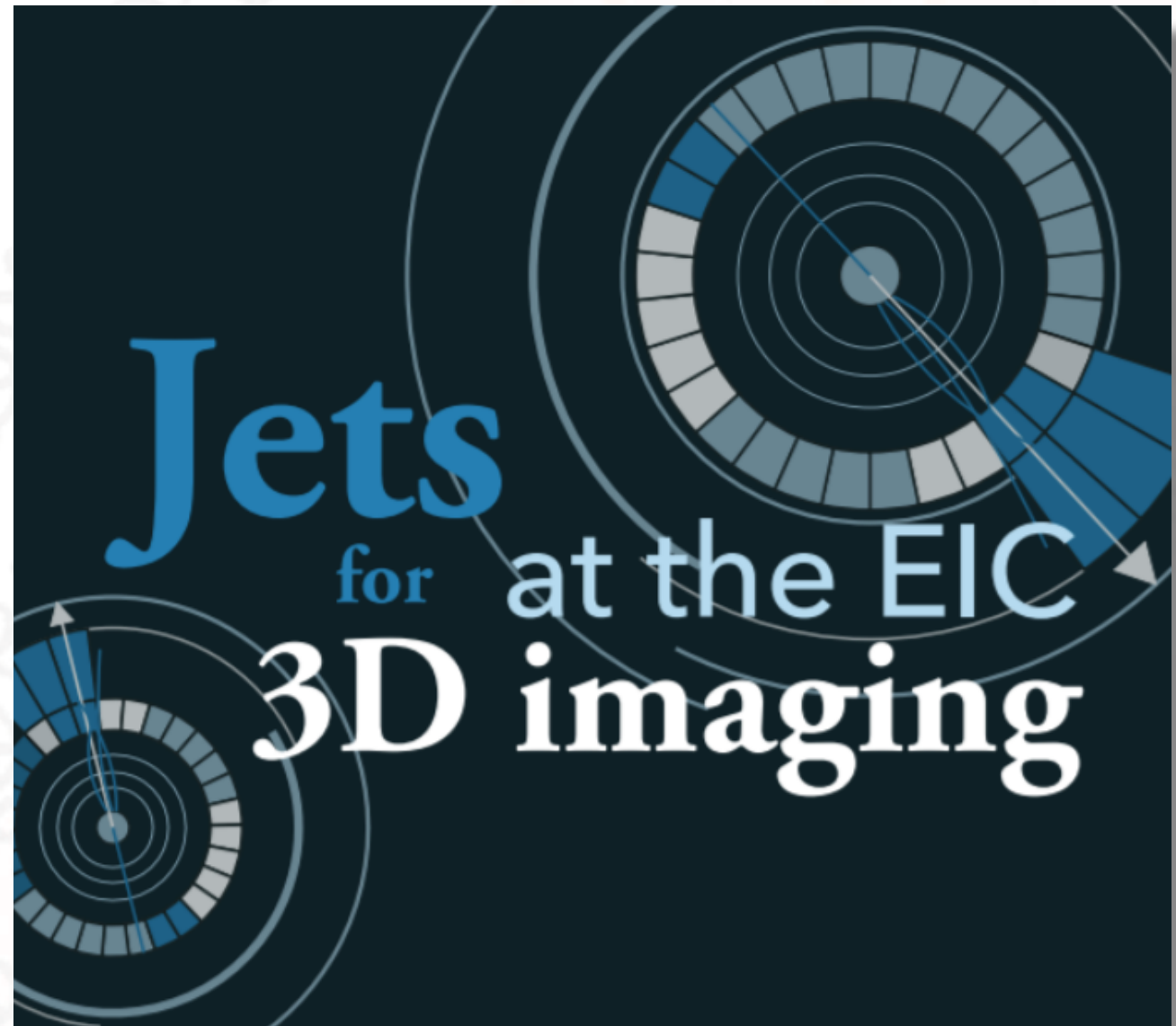
Bernd Surrów



Low-x workshop 2023
Leros, Greece, September 3-8, 2023

Outline

- Introduction
- Analysis Details
- Results
- Summary and Outlook

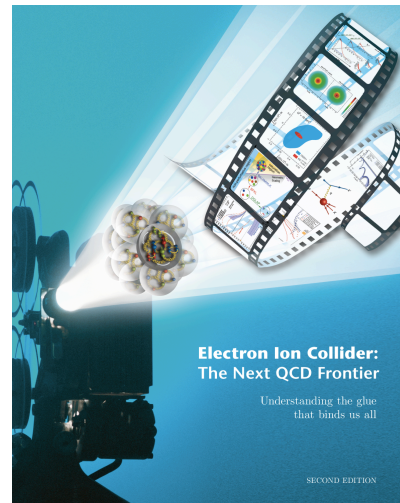


Introduction

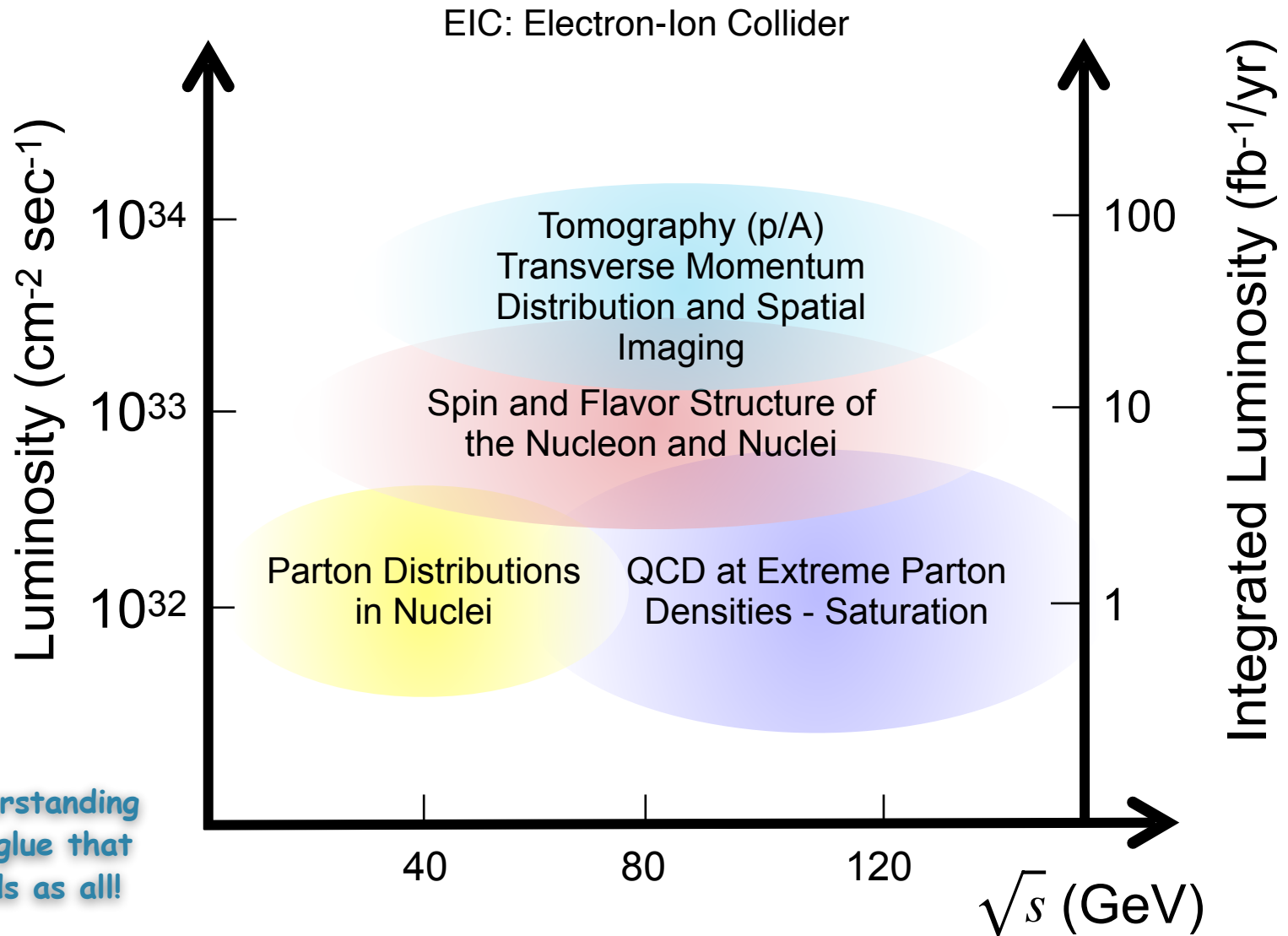
- EIC: Study structure and dynamics of matter at **high luminosity**, **high energy** with **polarized beams** and **wide range of nuclei**

- Whitepaper:

arXiv:1212.1701

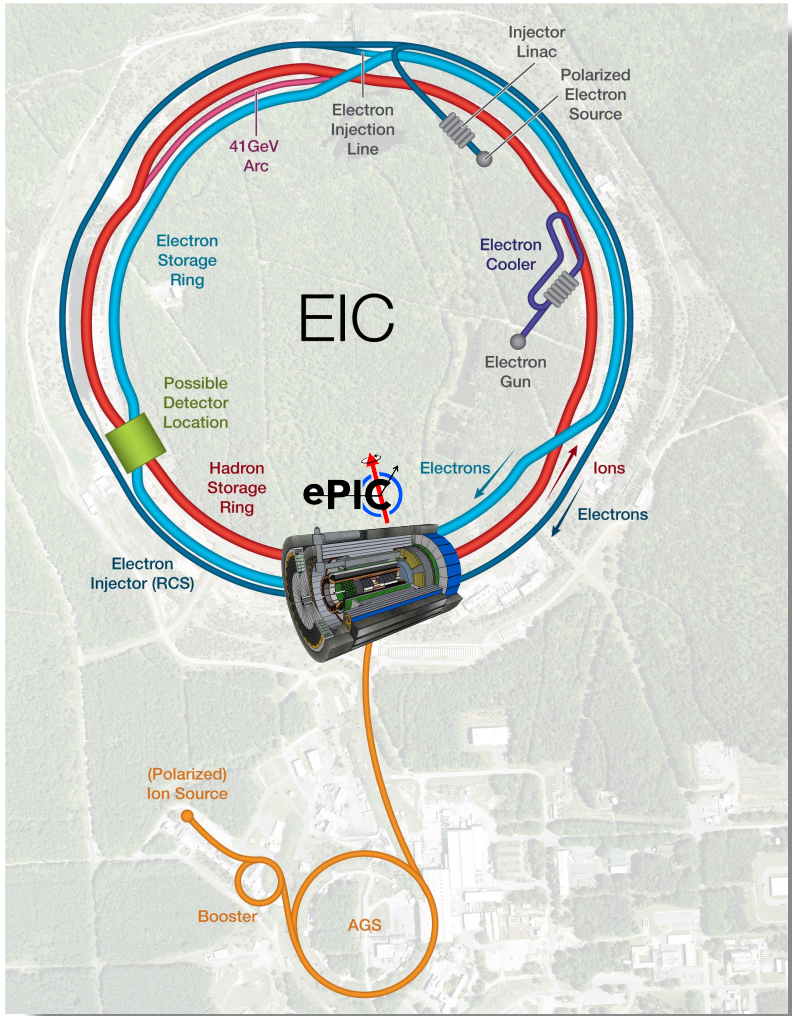


Understanding
the glue that
binds as all!



Introduction

□ EIC



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

- Award of DOE CDO*: December 2019
- Site selection at BNL: January 2020
- Award of DOE CD1*: June 2021
- Anticipated award of CD2*: ~January 2024
- Anticipated start of construction CD3*: ~April 2025
- Anticipated start of operation CD4*: ~April 2032-2034

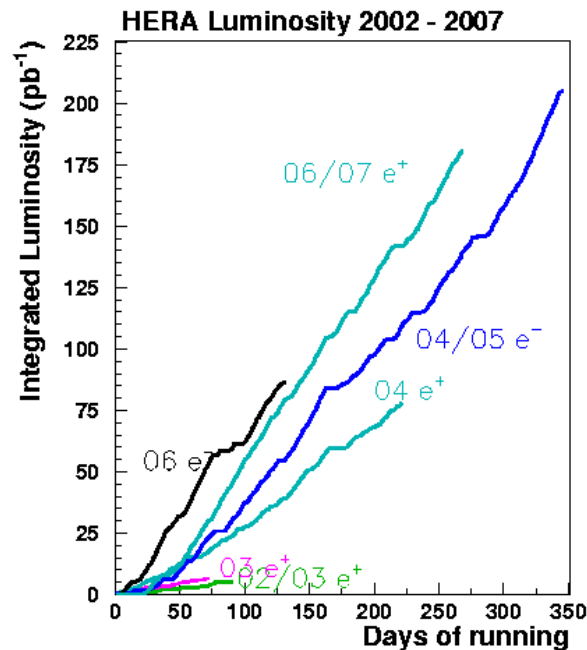
* CD: Critical Decisions - DOE Project Approval Process

Introduction

□ HERA

○ HERA: Hadron-Electron Ring Accelerator

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



Introduction

□ ZEUS Experiment at HERA

○ General purpose detector

□ Jet reconstruction for

$$E_T > 2.5 \text{ GeV}$$

□ Two independent

luminosity monitors

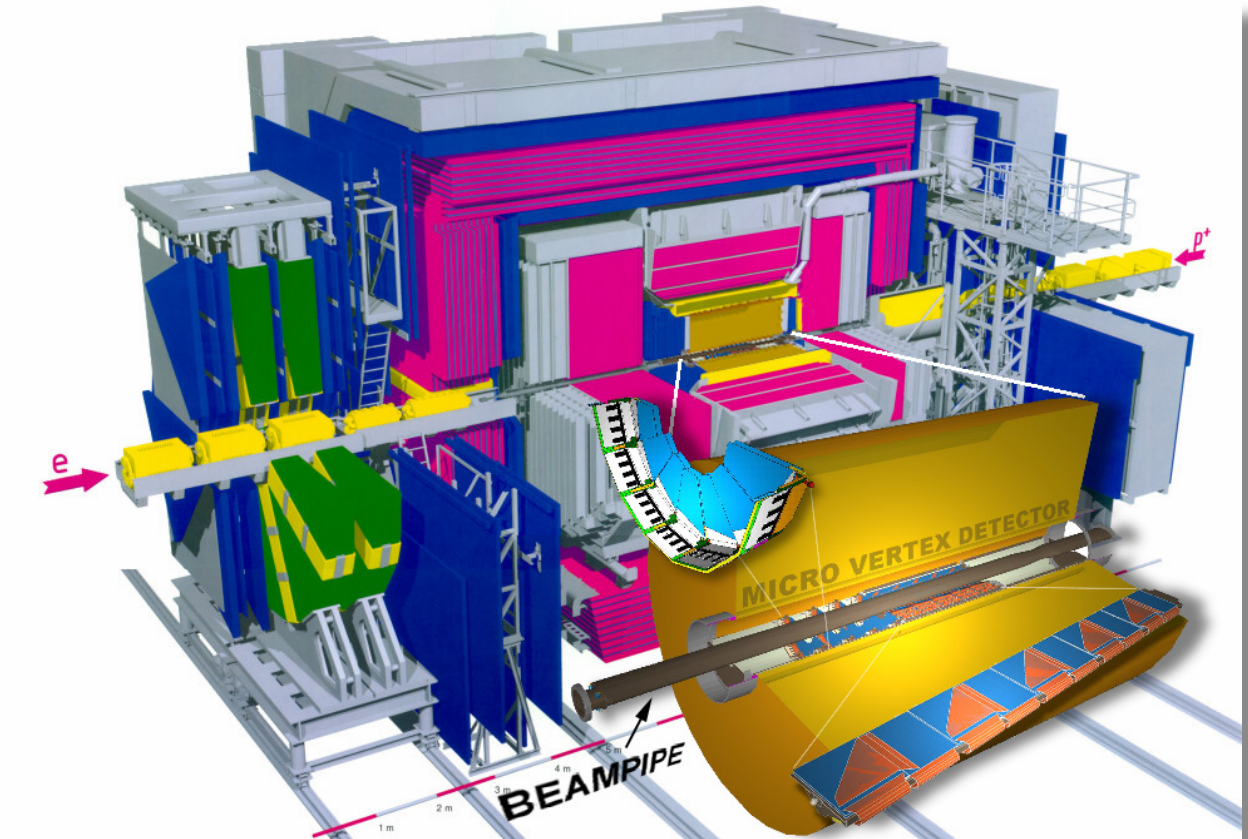
(lead-scintillator

calorimeter and

magnetic spectrometer)

using the Bethe-Heitler

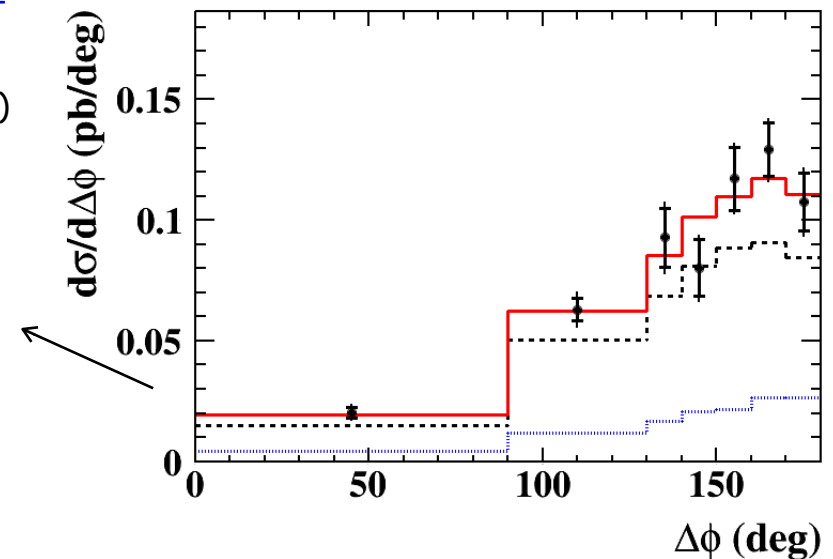
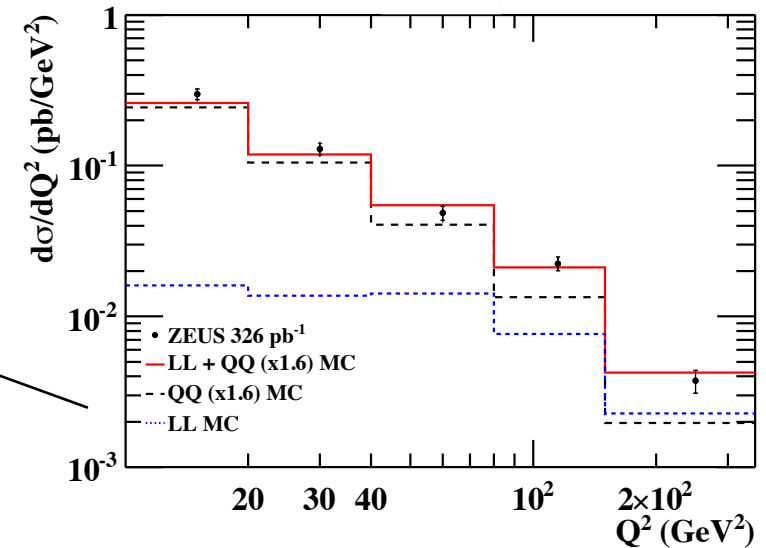
process, $\delta L/L \sim 2\%$



Introduction

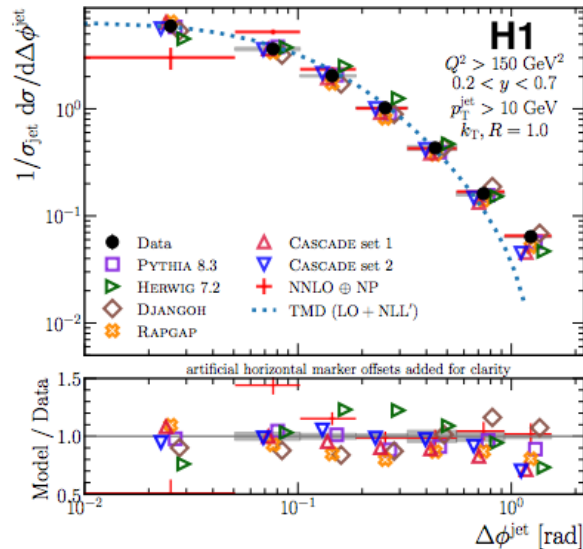
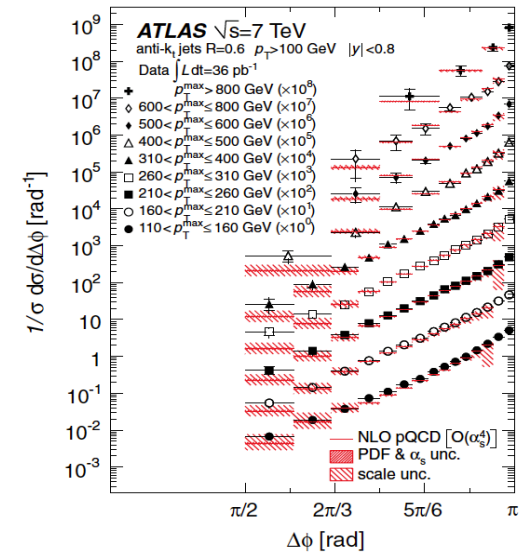
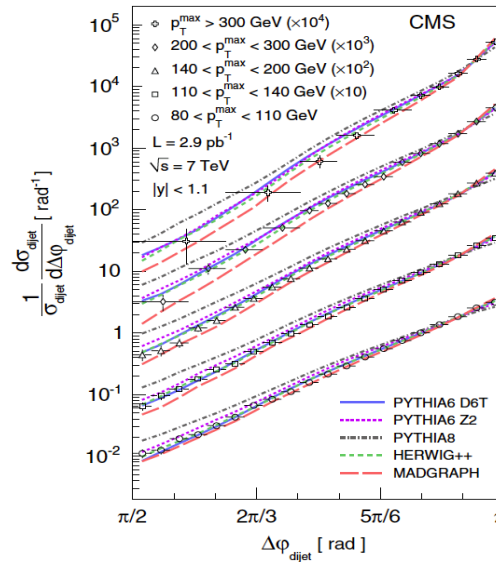
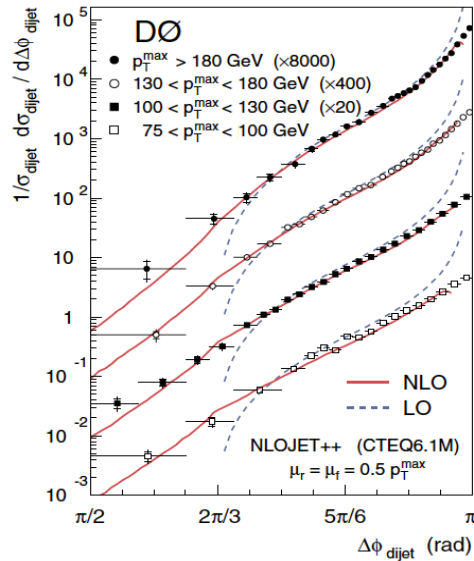
Previous ZEUS jet results

- 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.Lett 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 (DØ) and LHC (ATLAS and CMS):

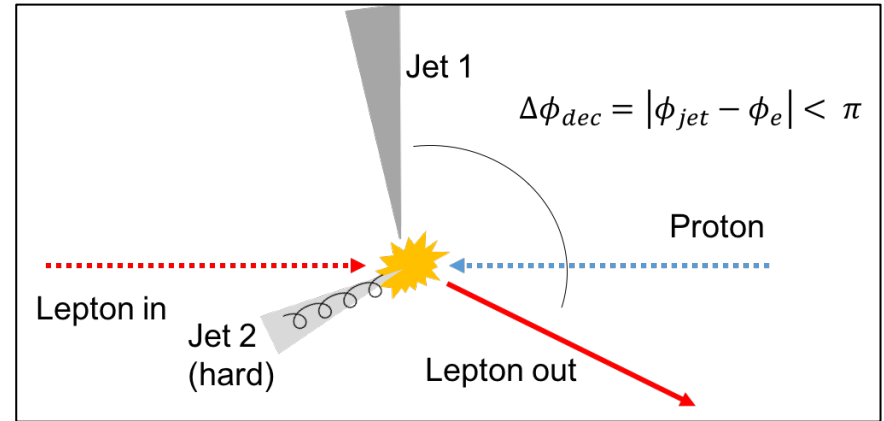
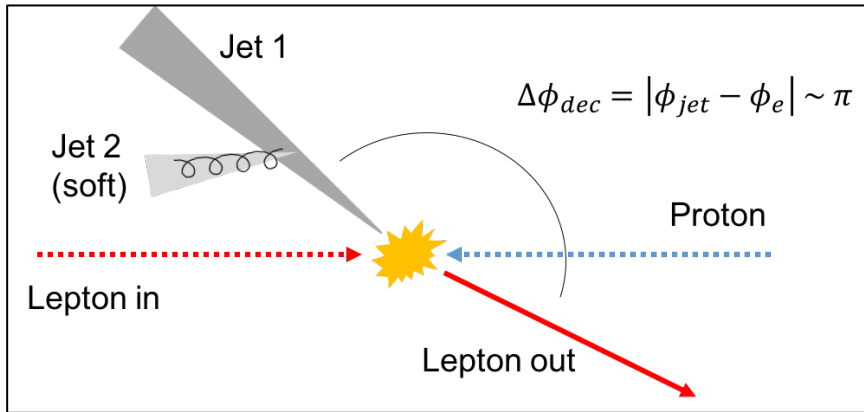
- Improvements in data description by high order correction (NLO to LO).
- MC generators describe data well except in the region $\Delta\phi \sim \pi \implies$ tune MC based on data.

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 TMD at small x !**

Analysis Details

□ Selection Cuts and Control Plots

○ Kinematic region

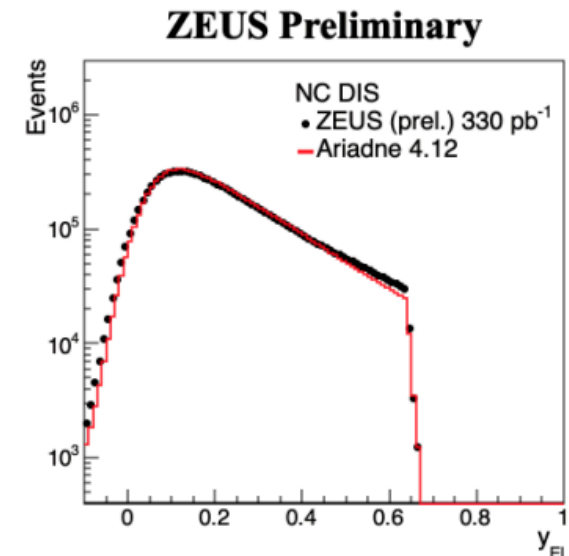
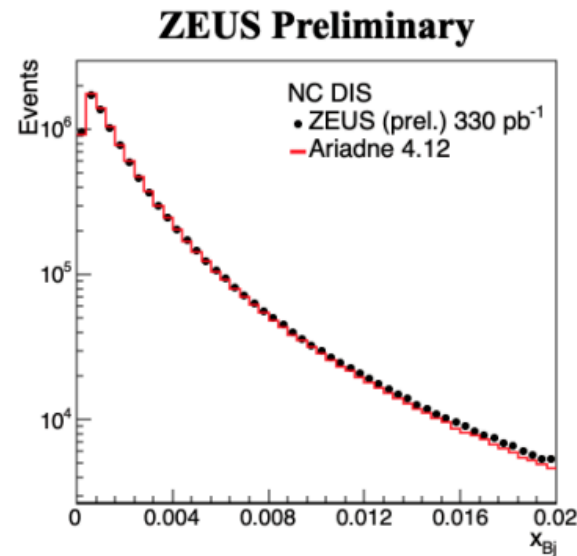
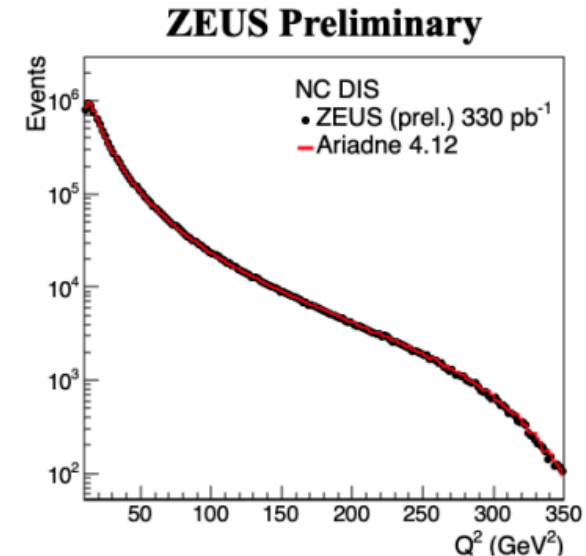
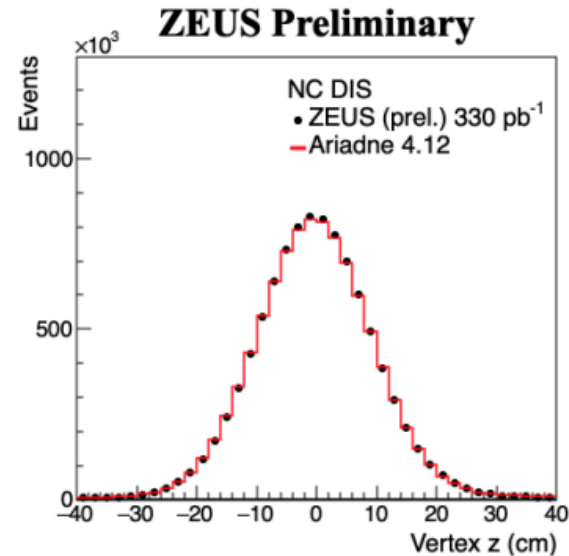
- $10 \text{ GeV}^2 < Q^2 < 350 \text{ GeV}^2$
(Double-angle)
- $0.04 < y < 0.7$
(Electron, Jacquet-Blondel)

○ Electron

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

○ Jets

- Massive jets in the lab frame,
 k_T algorithm with
E recombination scheme
- $2.5 \text{ GeV} < p_T < 30 \text{ GeV}$
- $-1.5 < \eta < 1.8$
- 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

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

- Leading jet = jet with the highest E_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

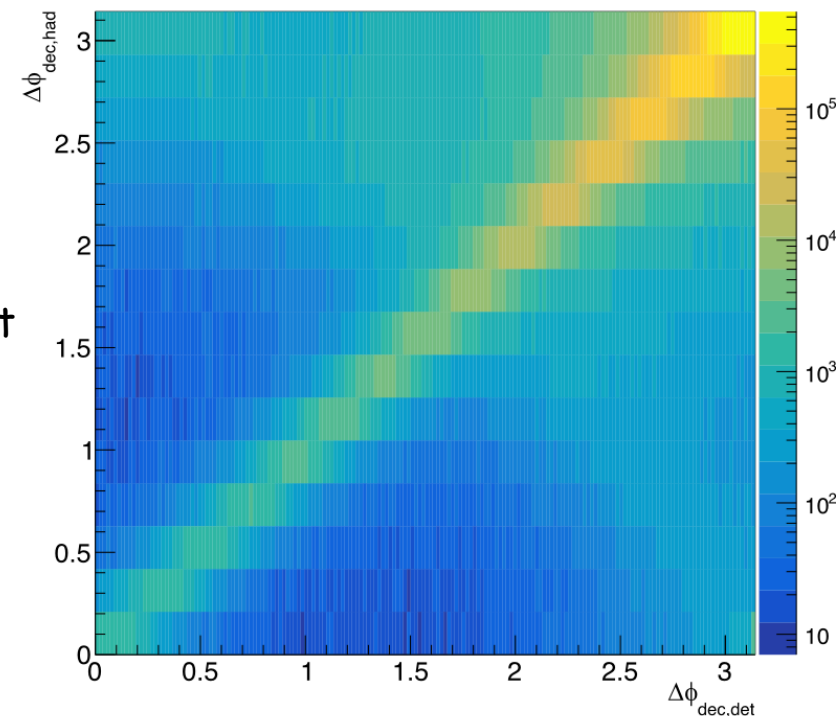
□ Leading jet misidentification shows up as $\Delta\phi$ shift
of, for the case of dijet, $\sim \pi$.

○ 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 will also be included in the unfolding process

ZEUS Preliminary



Theory

□ Theoretical framework

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

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

revisited for HERA kinematics

□ 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

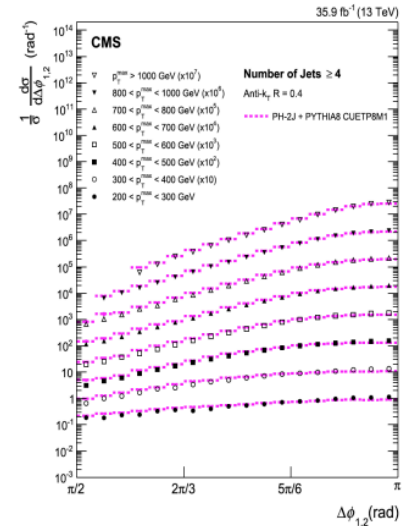
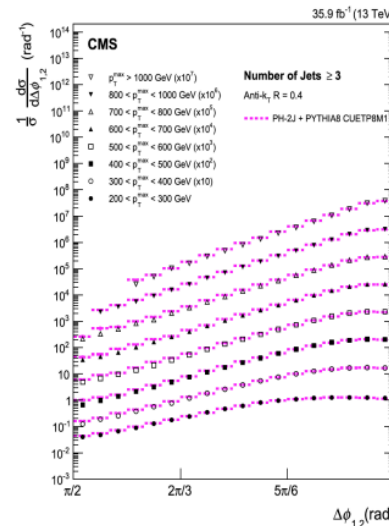
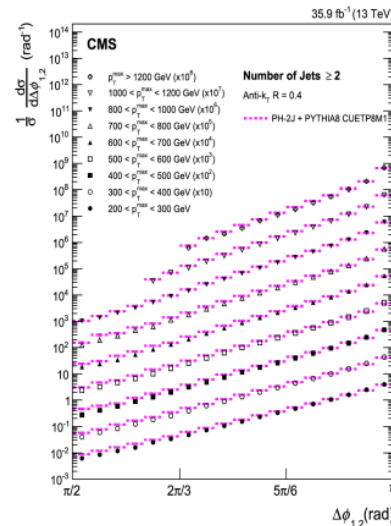
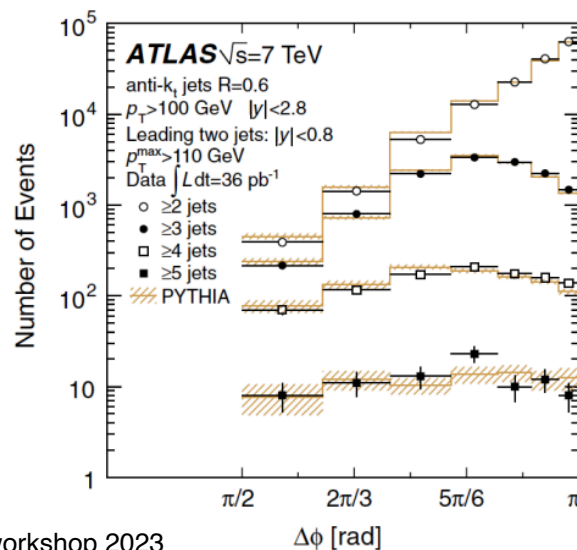
○ Model dependence in hadronization correction evaluated with LEPTO, $\sim 5\%$

○ Ongoing communication with experts (Feng Yuan) for TMD calculations for ZEUS kinematics!

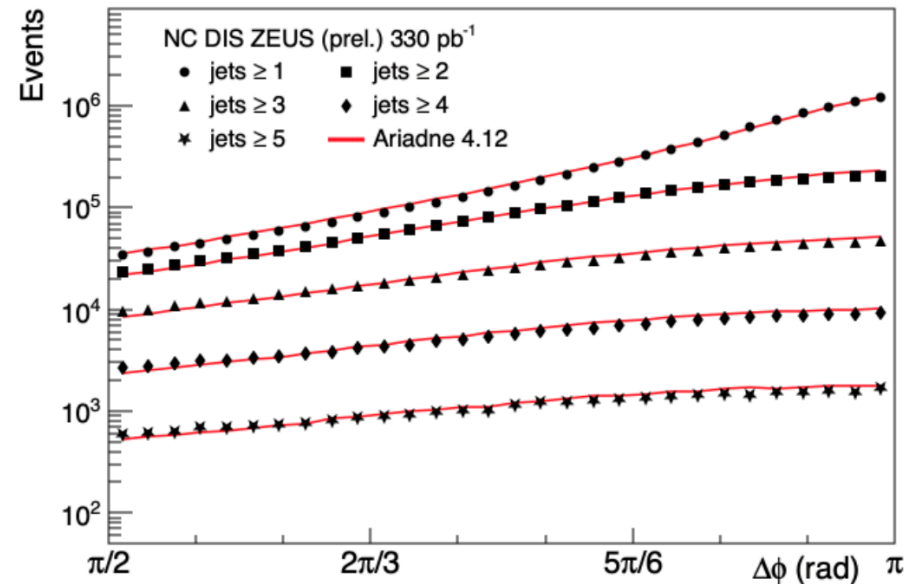
Results

□ Preliminary result

- Previous preliminary $\Delta\phi_{dec}$ distribution compared to LHC finds a qualitative agreement
- Soft gluon effects near $\Delta\phi \sim \pi$ in high jet multiplicity cases
- Agreement with MC degrades at high jet multiplicity, pointing to the need for improvements in the theoretical description

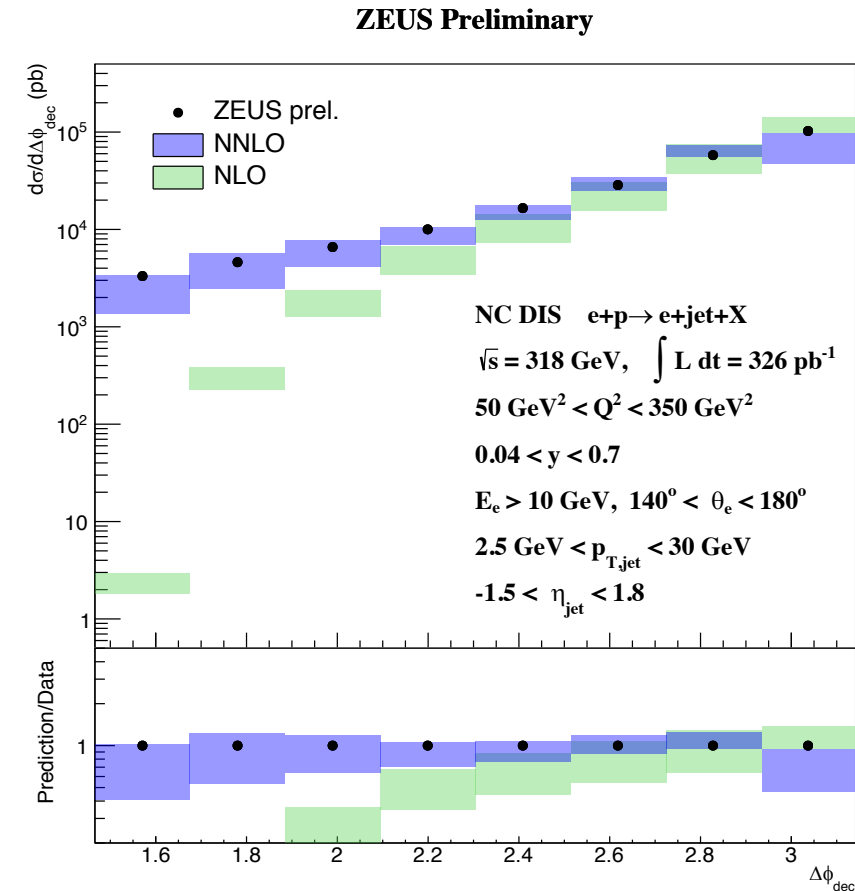


ZEUS Preliminary



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 ($\sim 5\%$ at $\Delta\phi_{dec} \sim \pi$)
 - Efficiency correction $\sim 20\%$
 - Comparison to pQCD calculations.
 - Hadronization correction with uncertainty of $\sim 5\%$
 - Clear improvement seen from NNLO compared to NLO
 - Not enough phase space available for additional jet production with NLO around $\Delta\phi_{dec} < 3/4\pi$
 - High $\Delta\phi_{dec}$ behavior due to large logs from soft gluon radiation
 - Input from TMD will improve the understanding in this region



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 ($\sim 5\%$ at $\Delta\phi_{dec} \sim \pi$)

□ Efficiency correction $\sim 20\%$

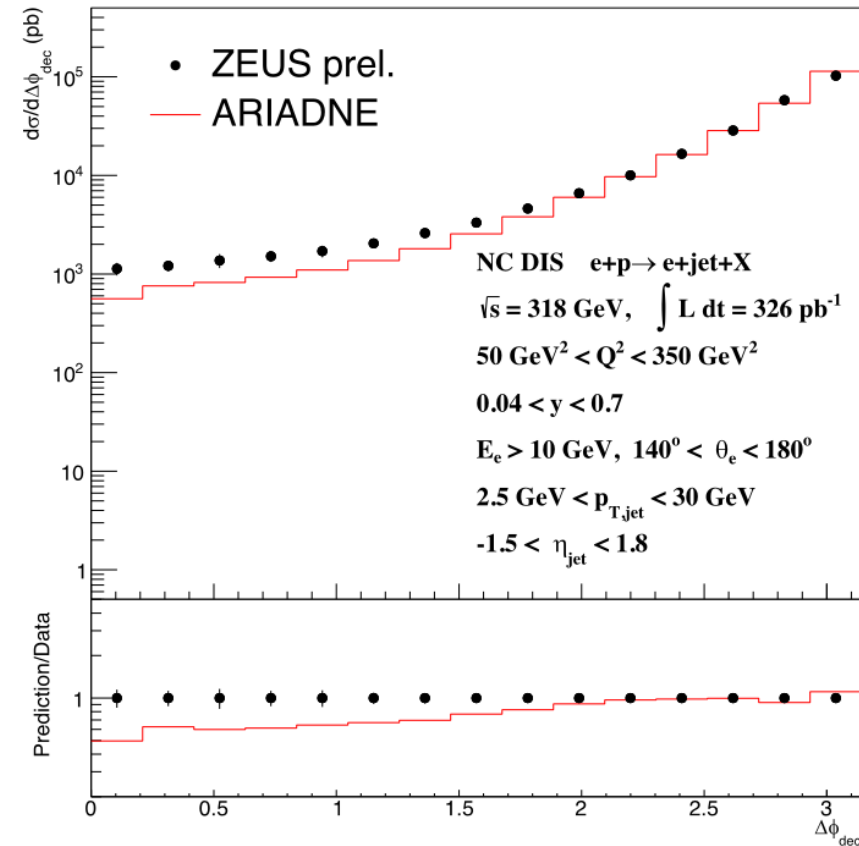
○ Comparison to ARIADNE MC.

□ ARIADNE is normalized to data luminosity

□ Overall reasonable agreement to data, based on LO + parton shower modeling

□ The $\Delta\phi_{dec}$ distribution is much steeper with ARIADNE, hinting that the high jet multiplicity from hard production may be underestimated

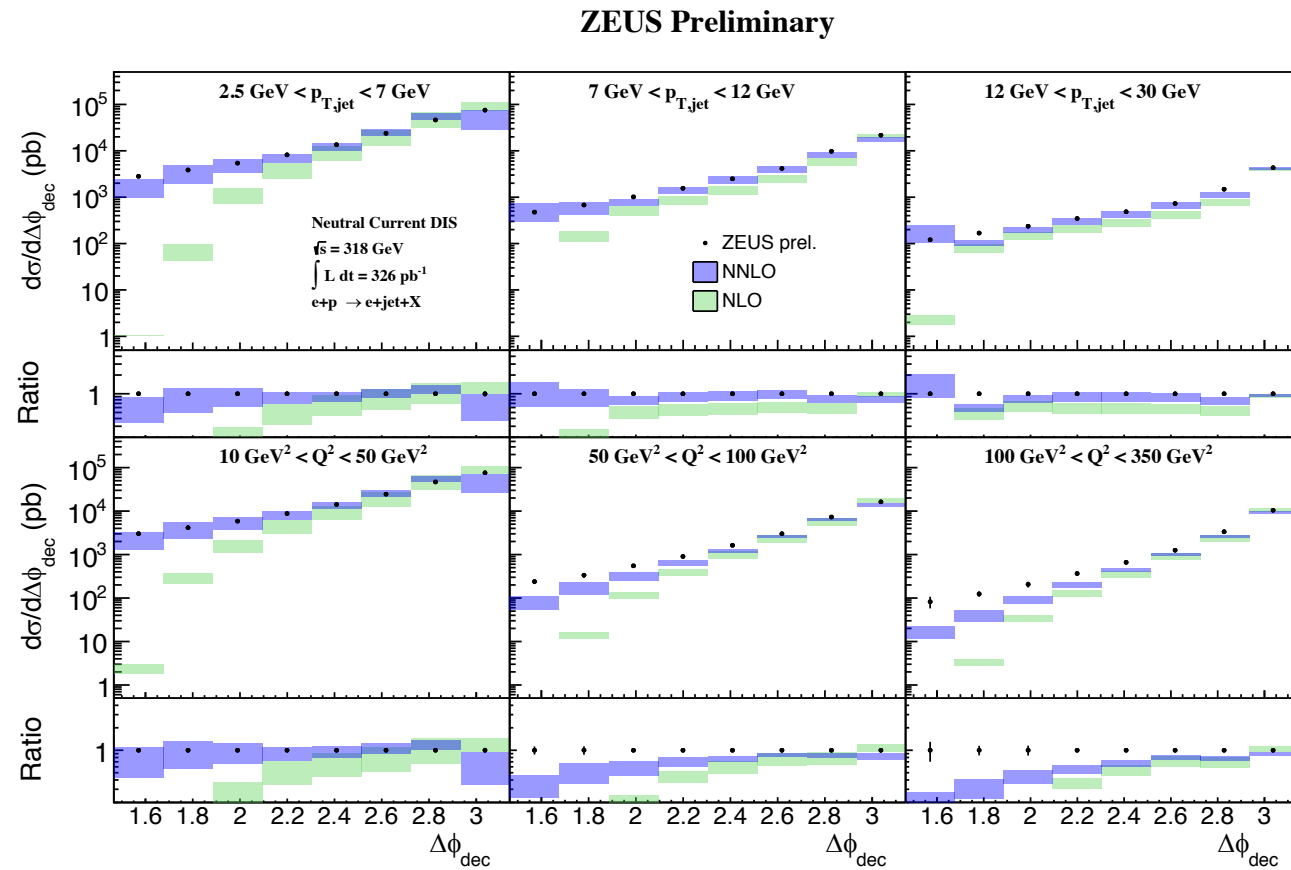
ZEUS Preliminary



Results

□ Azimuthal angle jet/electron cross-section in $p_{T,jet}$ and Q^2 bins

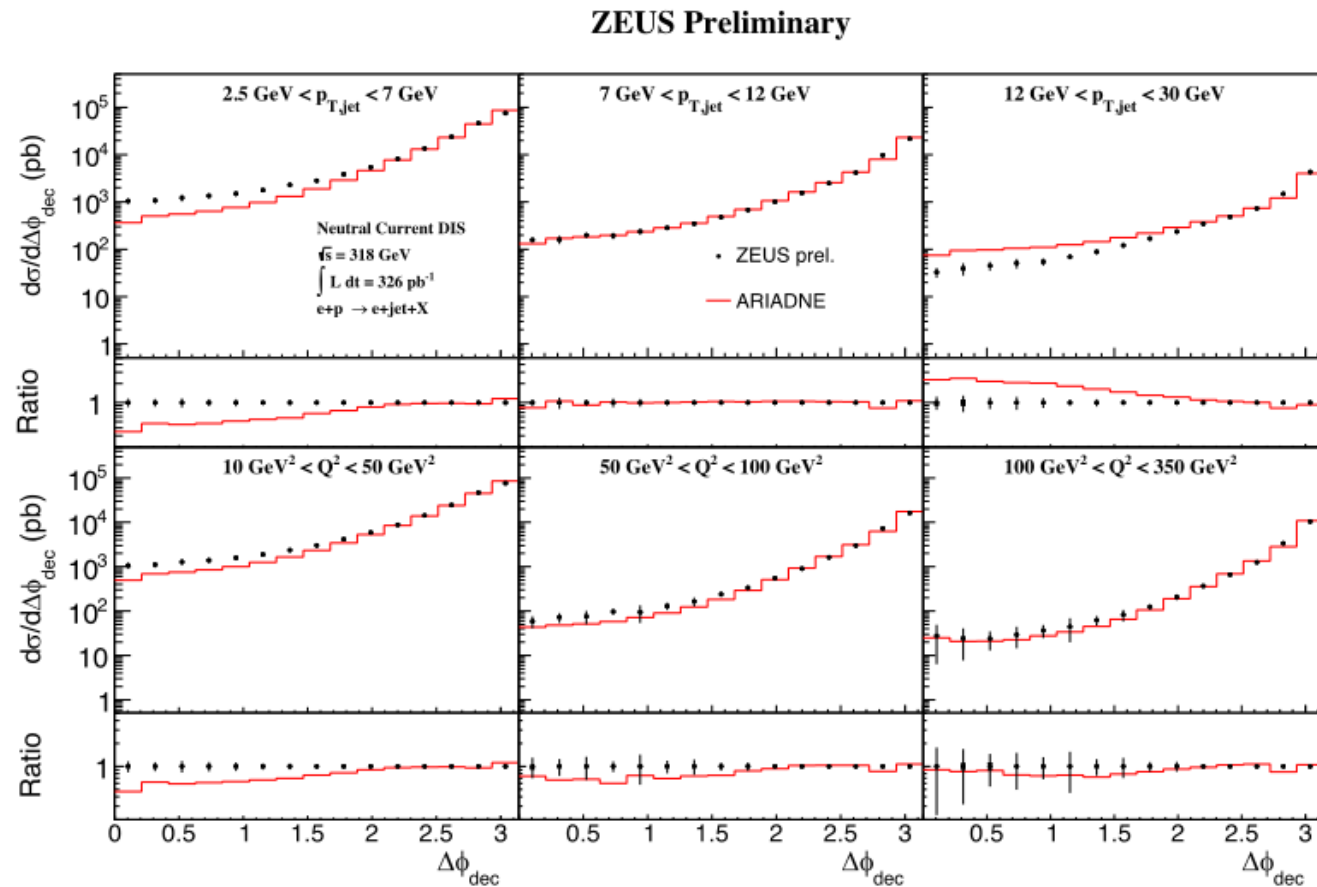
- Comparison to pQCD in different ranges of $p_{T,jet}$ and Q^2 .
- Good jet reconstruction near the kinematic limit $p_{T,jet} \sim 2.5 \text{ GeV}$, as suggested by this comparison
- Soft gluon effects near $\Delta\phi \sim \pi$ maximize in low- $p_{T,jet}$ and Q^2
- Poor description of data in high- Q^2 around $\Delta\phi < 3/4\pi$ currently under investigation.



Results

□ Azimuthal angle jet/electron cross-section in $p_{T,jet}$ and Q^2 bins - MC comparison

- Comparison to MC in different ranges of $p_{T,jet}$ and Q^2 .
- The $\Delta\phi$ distribution of MC much more sensitive to $p_{T,jet}$ than data
- Final results will also include N_{jet} measurement





Summary and Outlook

- Prelim. 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
- Probe Transverse-Momentum Distribution Functions (TMD) 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 observable!
- Clear improvement seen from NNLO compared to NLO
- Final Differential cross-section measurements/publication will be presented at different p_T , Q^2 and jet multiplicity bins.
- Decorrelation measurements of lepton and leading jet in DIS will provide an important probe of TMDs at EIC!