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

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ZEUS

U.S. DEPARTMENT OF ENERGY | Office of Science
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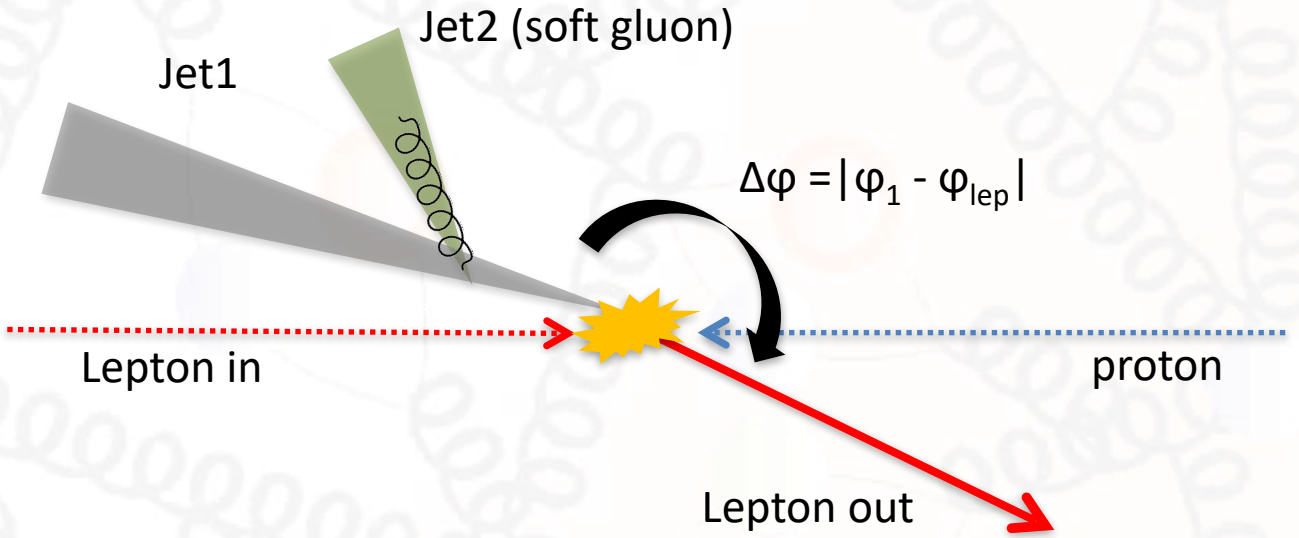
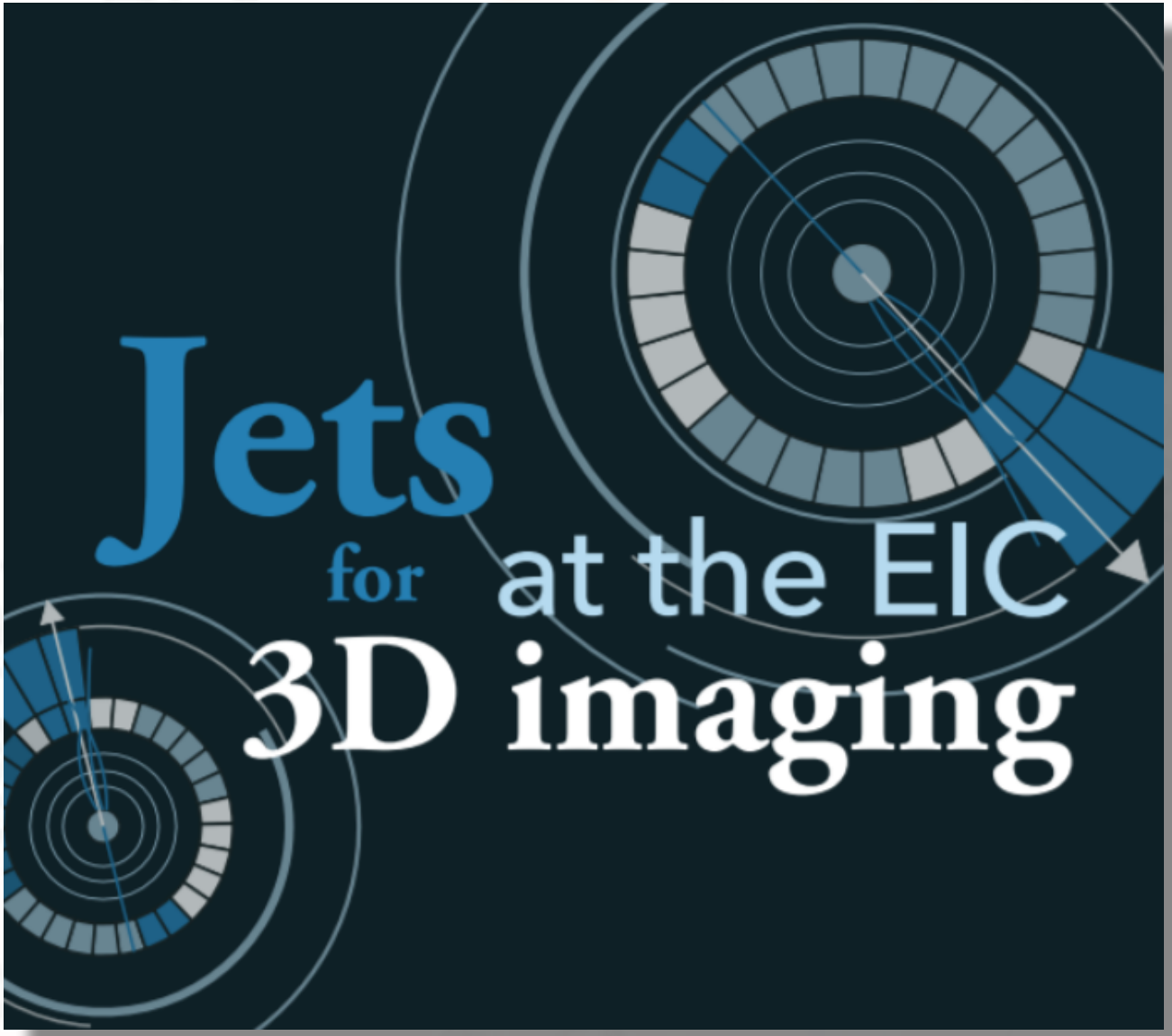
Outline

Outline


Jet2 (soft gluon)
Jet1
$\Delta\varphi = |\varphi_1 - \varphi_{lep}|$
Lepton in
proton
Lepton out

Outline



Workshop Jets at the EIC 3D imaging (https://indico.bnl.gov/event/8066/), November 23-25, 2020

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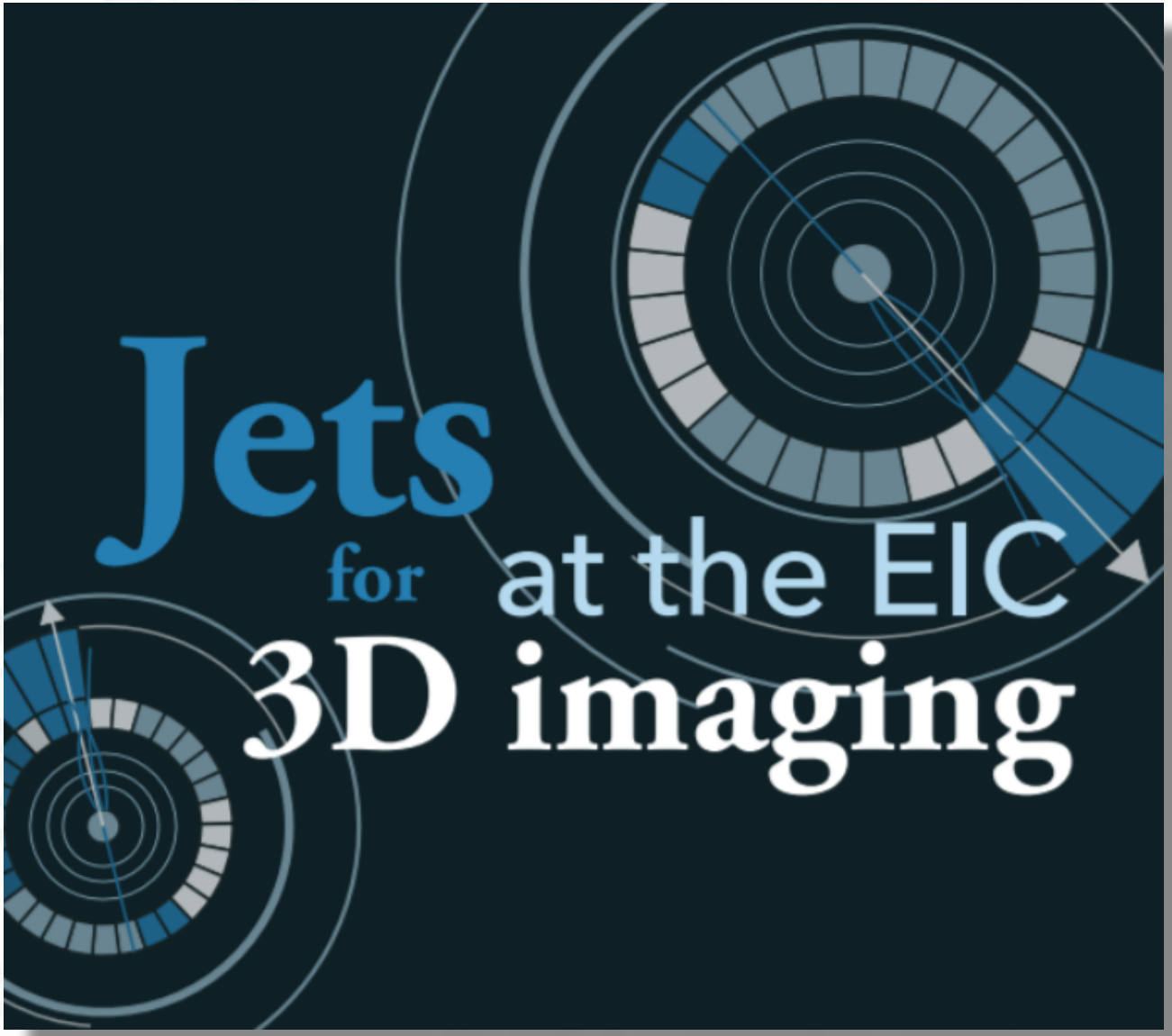

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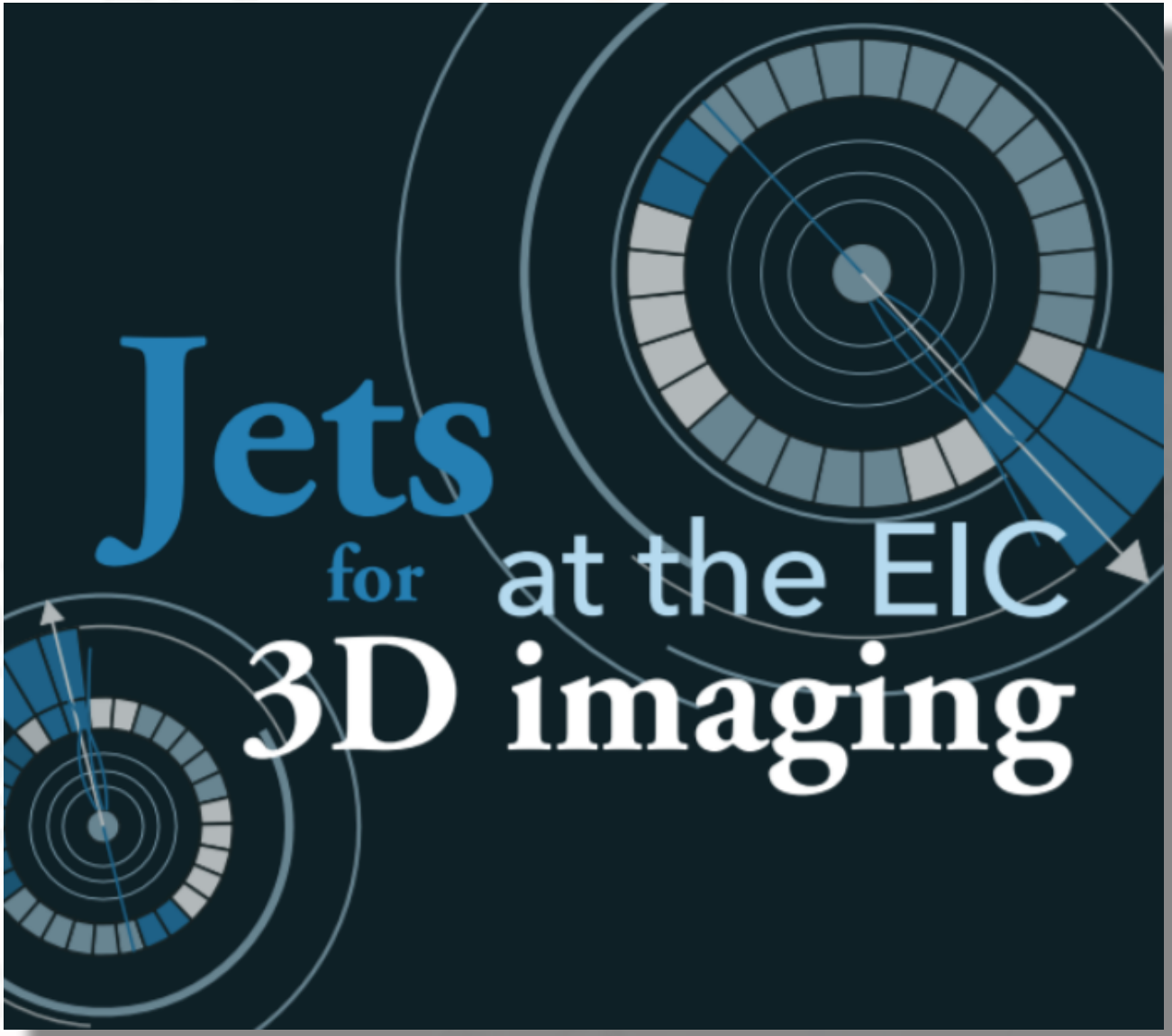

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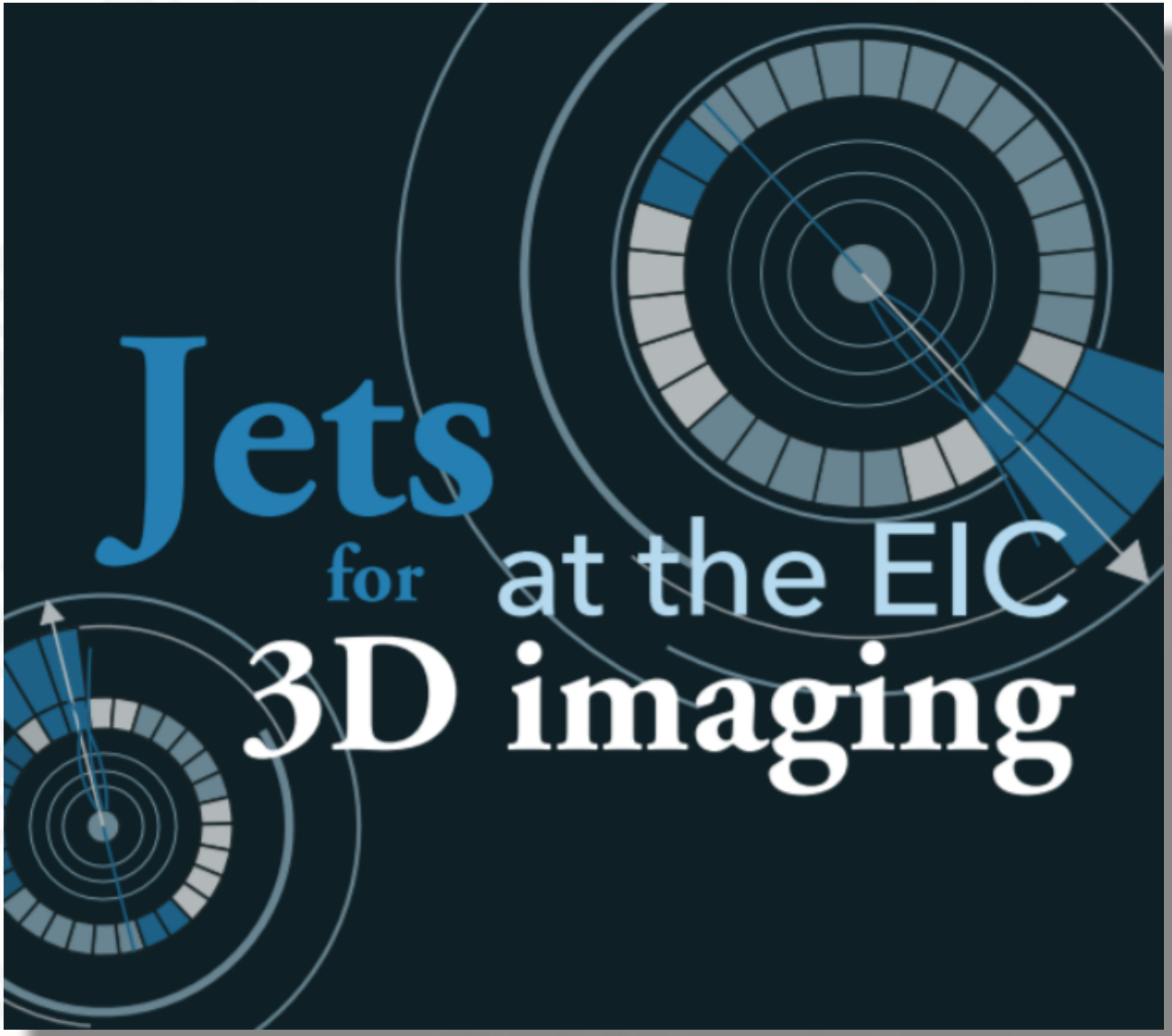

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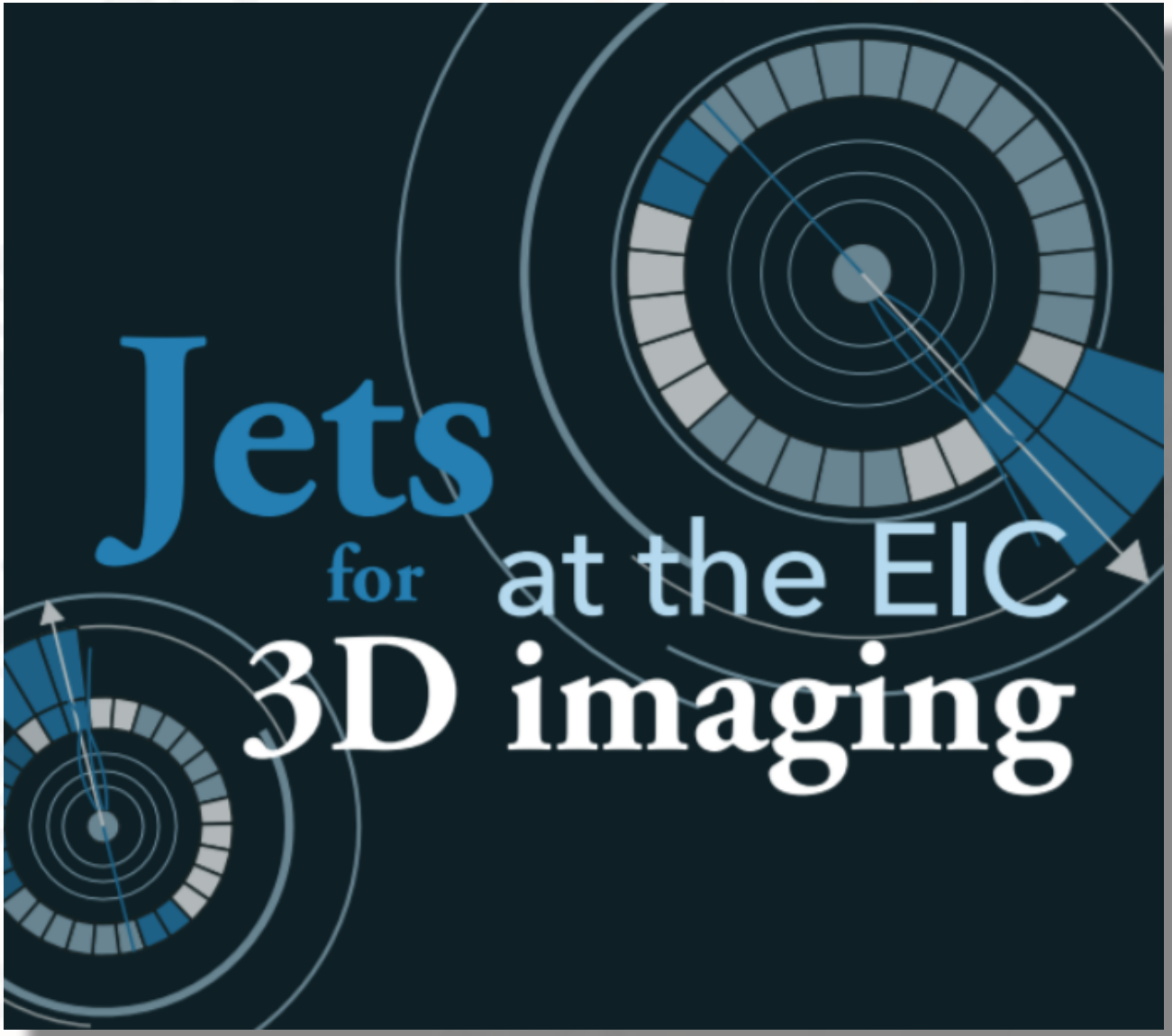
- Analysis Details
- Results
- Summary and Outlook

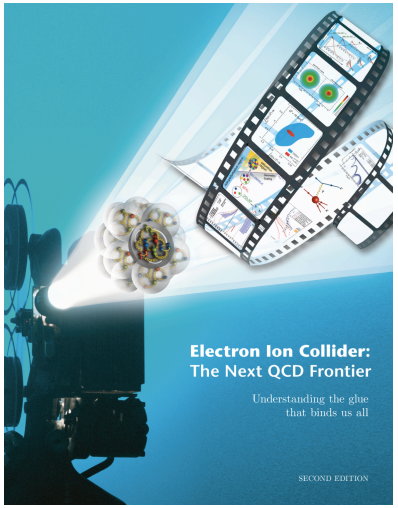


Workshop Jets at the EIC 3D imaging (https://indico.bnl.gov/event/8066/), November 23-25, 2020

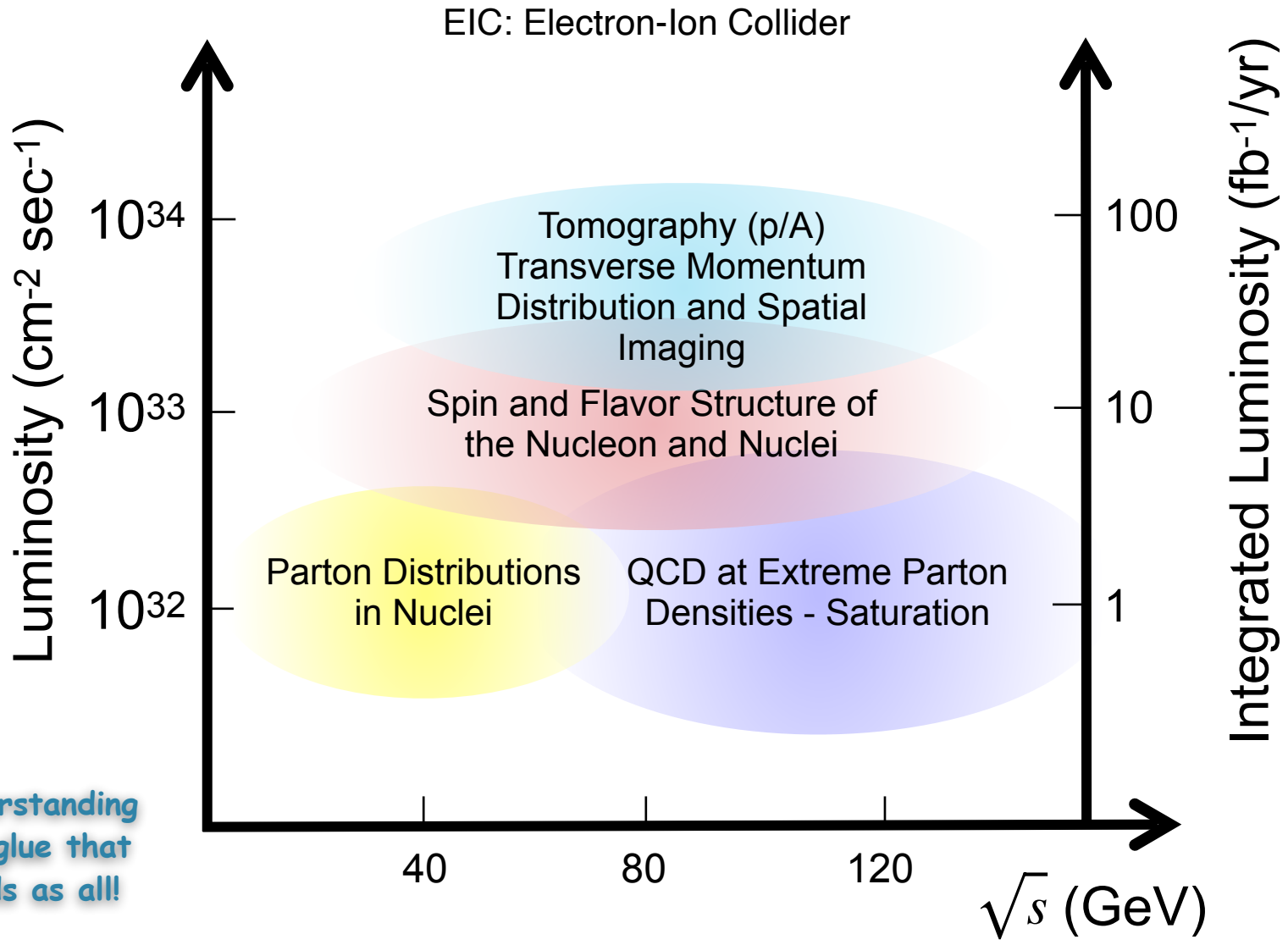
Introduction

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

arXiv:1212.1701

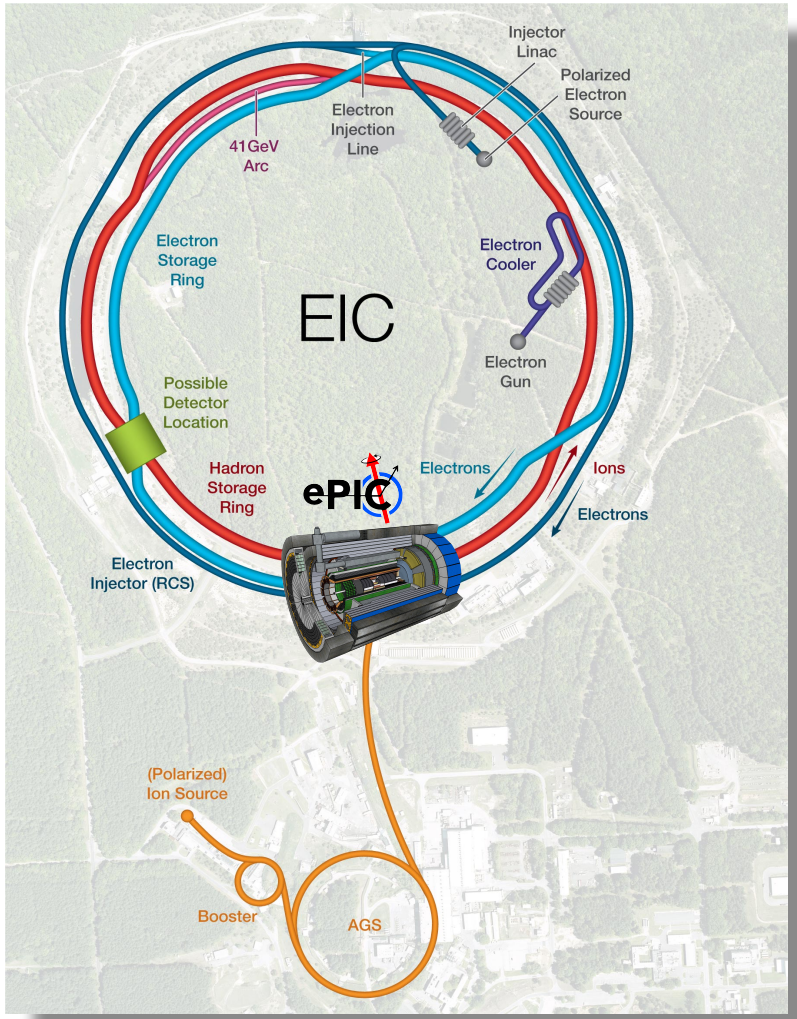


Understanding the glue that binds as all!



Introduction

- EIC



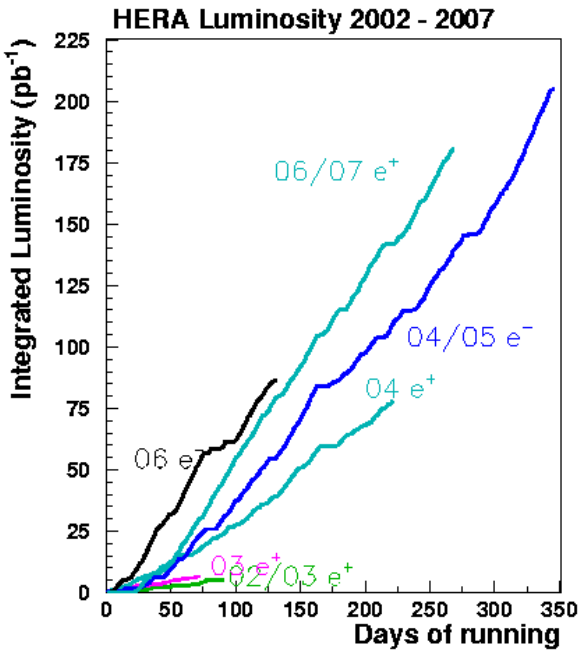
Center of Mass Energies:	29GeV - 140GeV
Luminosity:	10^{33} - 10^{34} $cm^{-2}s^{-1}$ / 10-100fb^{-1} / year
Highly Polarized Beams:	70%
Large Ion Species Range:	p to U
Number of Interaction Regions:	Up to 2!

- Award of DOE CD0*: December 2019
- Site selection at BNL: January 2020
- Award of DOE CD1*: June 2021
- Anticipated award of CD2*: ~January 2024
- Anticipated start of construction CD3*: ~April 2025
- Anticipated start of operation CD4*: ~April 2032-2034

* CD: Critical Decisions - DOE Project Approval Process

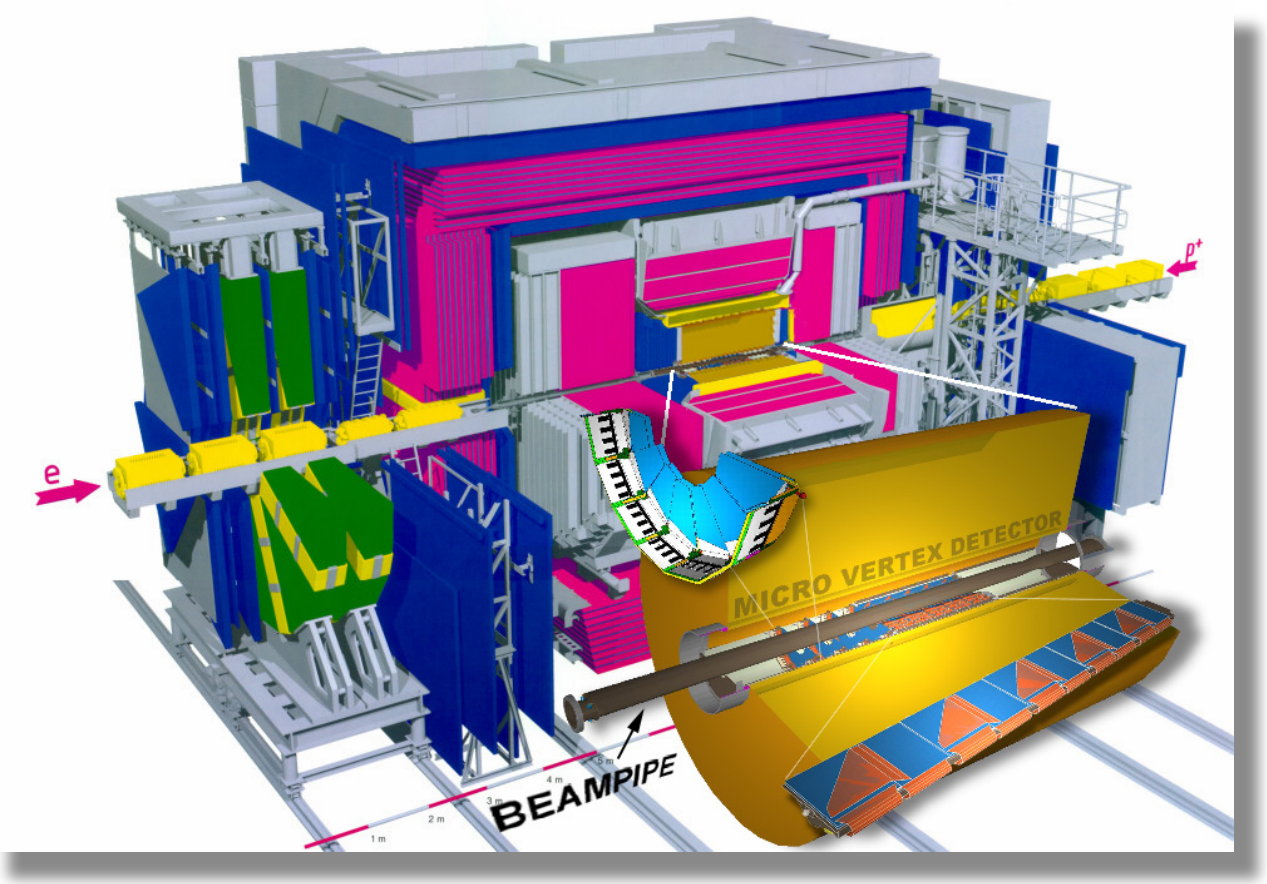
Introduction

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



Introduction

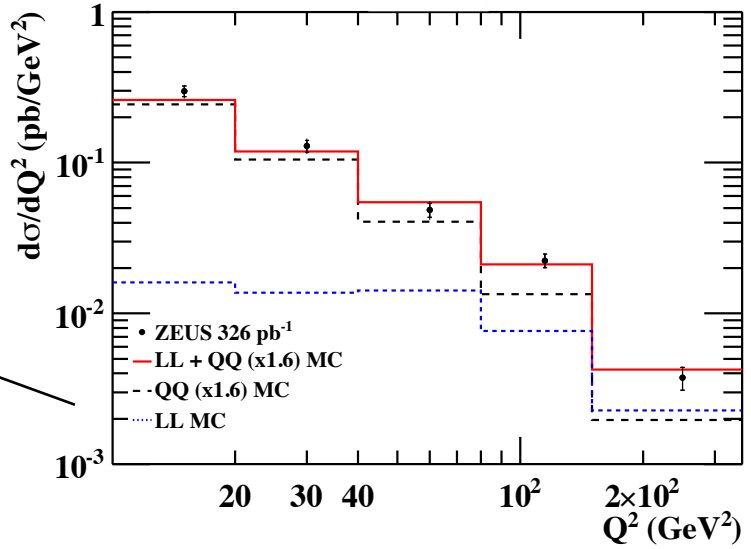
- ZEUS Experiment at HERA
  - General purpose detector
    - Jet reconstruction for $E_T > 2.5\,\mathrm{GeV}$
    - Two independent luminosity monitors (lead-scintillator calorimeter and magnetic spectrometer) using the Bethe-Heitler process, $\delta L/L \sim 2\,\%$

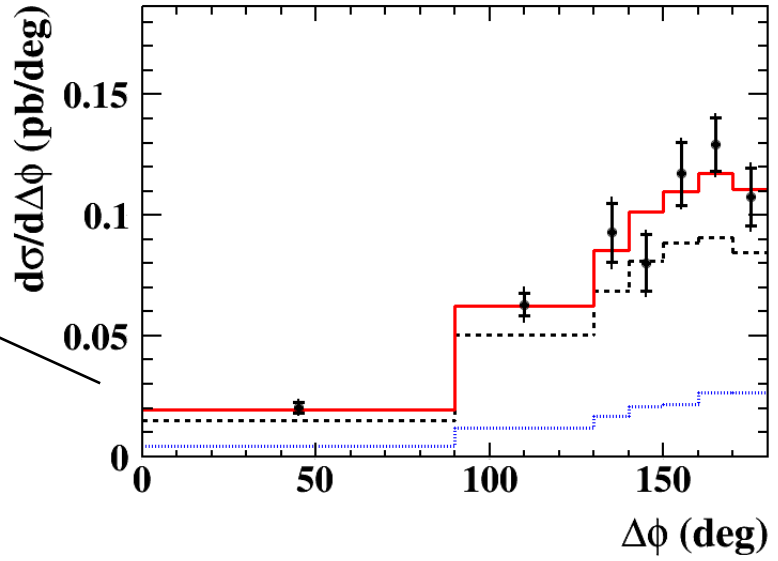


Introduction

Previous ZEUS jet results

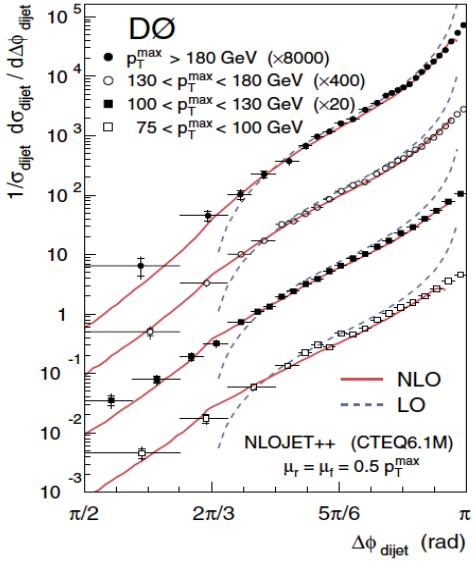
- Inclusive jets with anti-kt and SIScone algorithms (arXiv:1003.2923, Phys. Lett. B 691 (2010) 127-137)
- Inclusive jets in photoproduction (arXiv:1205.6153, Nucl. Phys. B864 (2012), 1-37)
- Isolated photons accompanied by jets in DIS (arXiv:1206.2270, Phys Lett B 715 (2012) 88-97)
- Isolated photons 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)

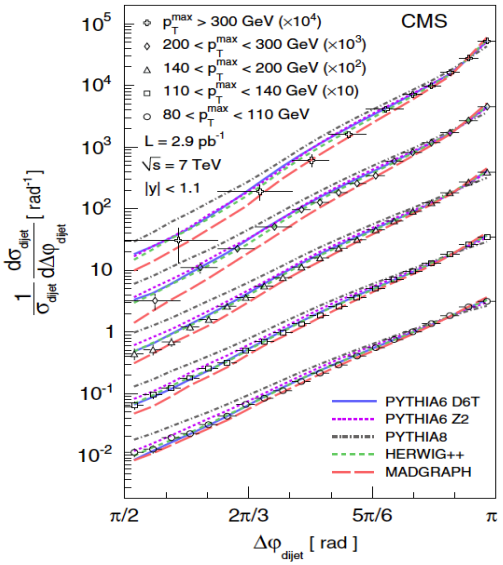


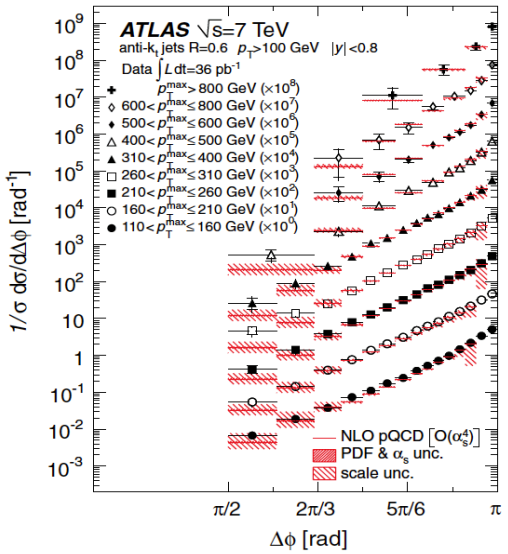


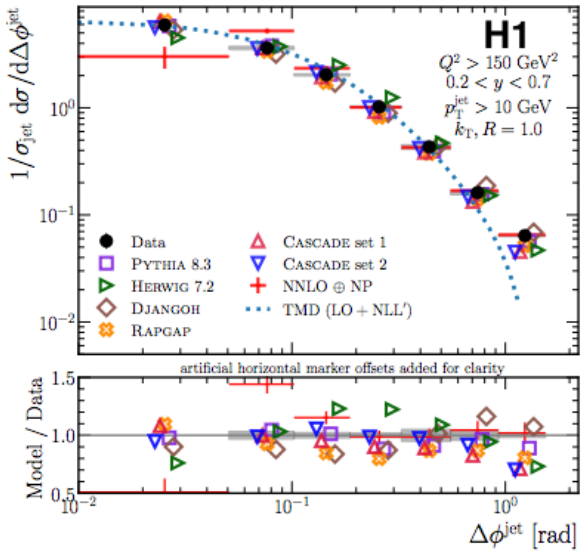
Introduction

- Previous azimuthal jet results at hadron-hadron colliders:









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

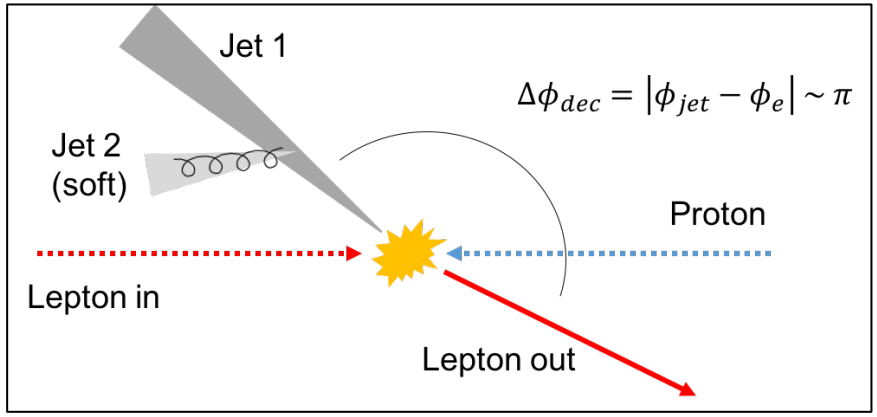
- Improvements in data description by high order correction (NLO to LO).
- MC generators describe data well except in the region $\Delta\phi \sim \pi \Longrightarrow$ tune MC based on data.

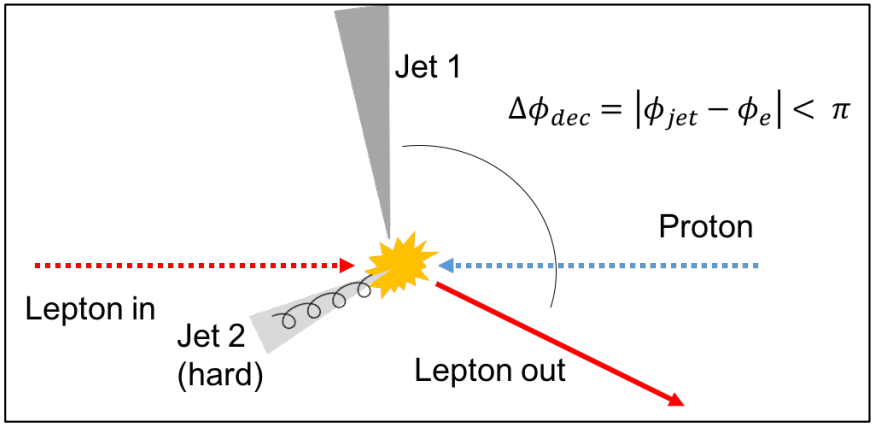
Recent results from HERA (H1):

- 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

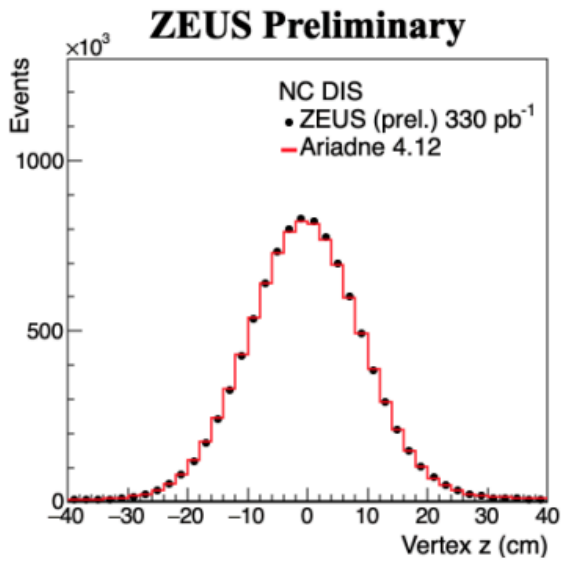


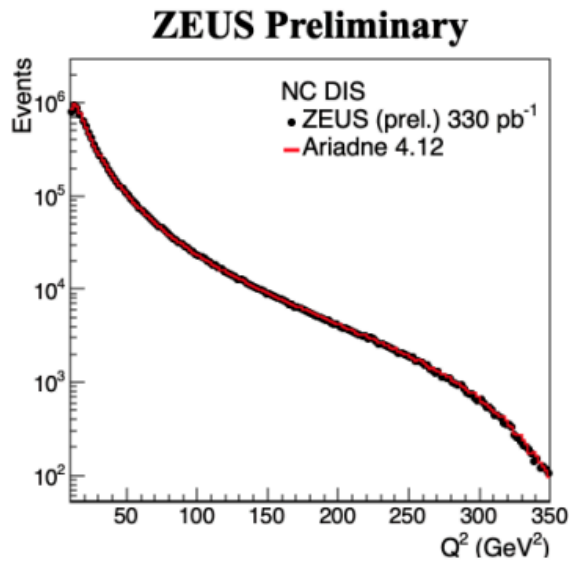


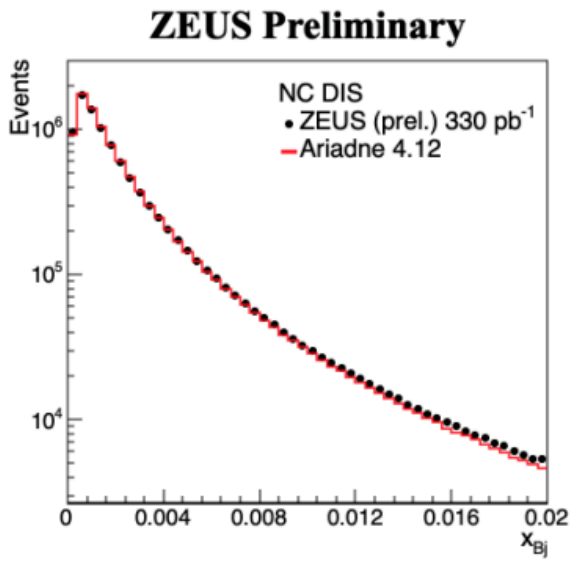
- Jet-lepton decorrelation can be used to probe soft and hard QCD radiation effects without explicit description of the additional jets.
- Can access TMD distributions, complementary to SIDIS, without an explicit description of TMD fragmentation function [Liu et al., PRL 122 (2019) 192003, Lui et al.,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

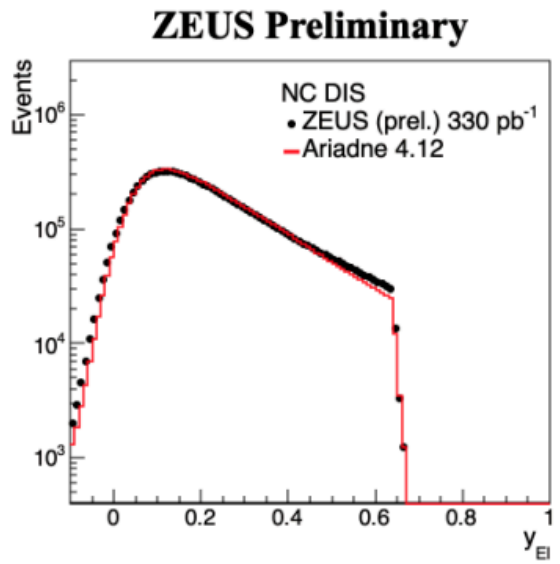
Analysis Details

- 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

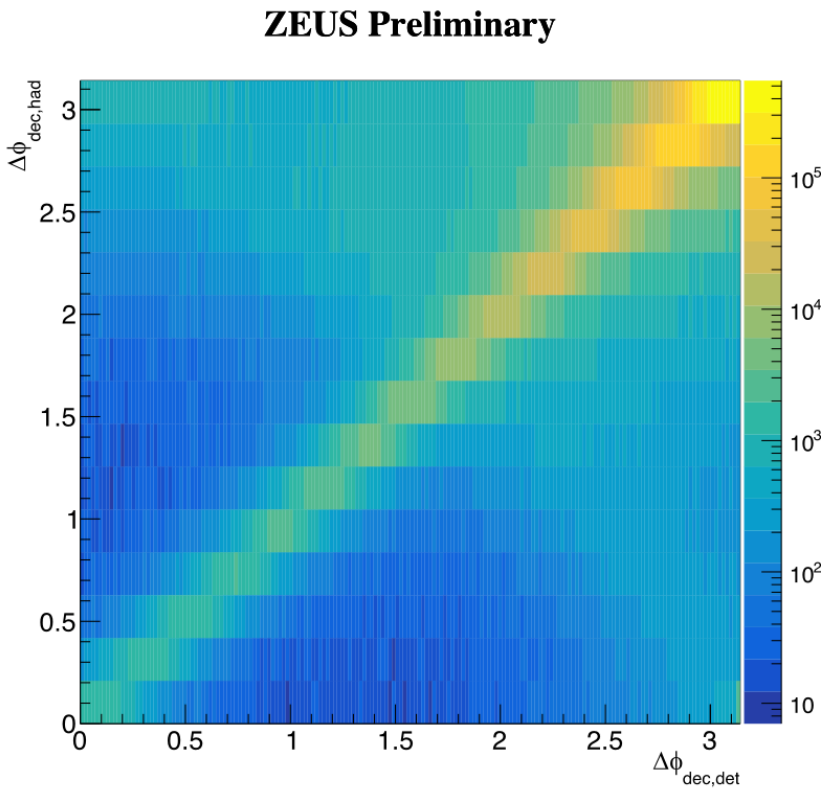
- Cross-section determination
  - Inclusive ($N_{jet} \geq 1$) measurement of differential cross section in azimuthal decorrelation $\Delta\phi_{dec}$ between the leading jet and the lepton

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

    - Leading jet = jet with the highest 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

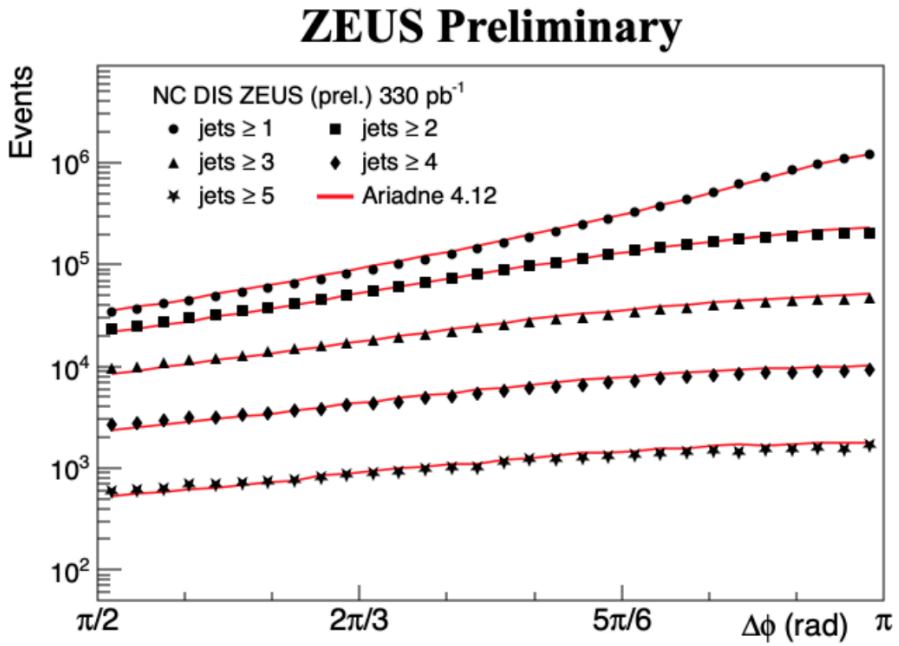


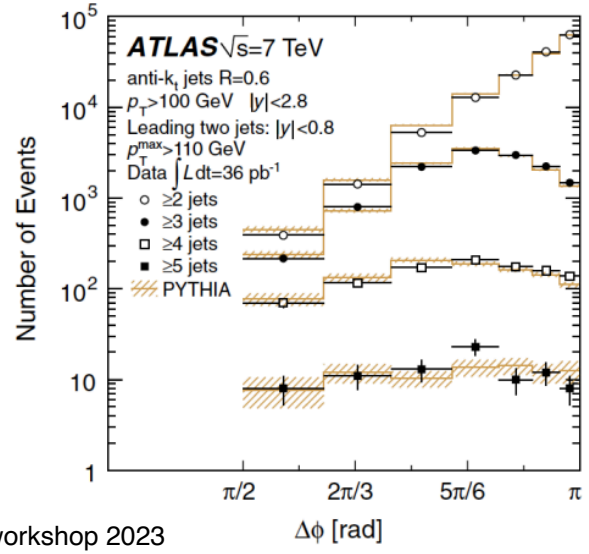
Theory

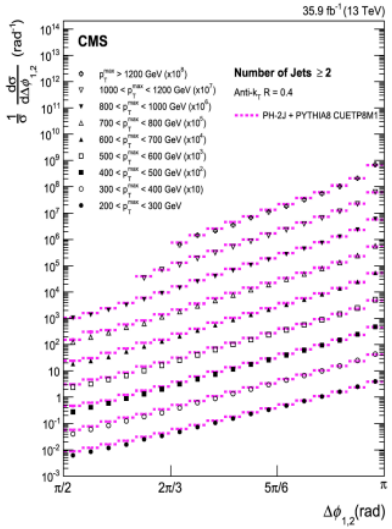
- Theoretical framework
  - Perturbative calculations from UNSAM (Borsa, de Florian, Pedron).
    - Calculations for EIC (Borsa et al., PRL 125 (2020) 082001)
      revisited for HERA kinematics
    - Fixed order (up to $O(\alpha_s^2)$) calculations using the projection-to-Born method
    - Takes a jet 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, ~5%
  - Ongoing communication with experts (Feng Yuan) for TMD calculations for ZEUS kinematics!

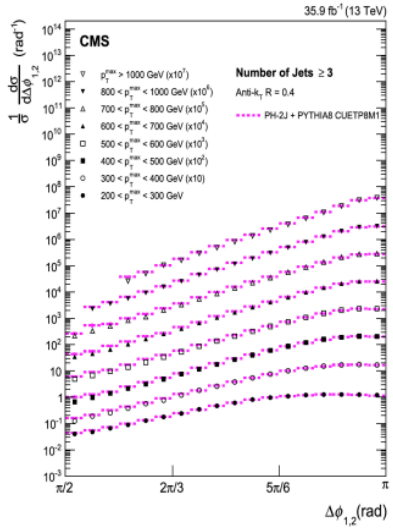
Results

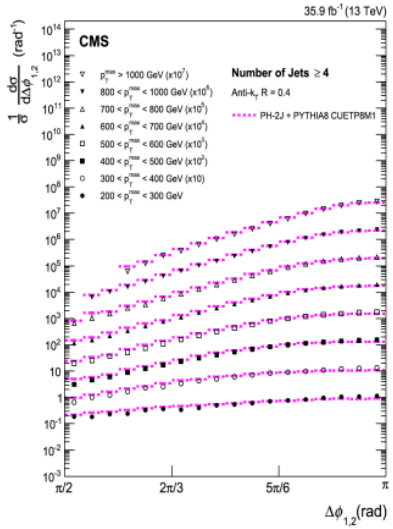
- Preliminary result
  - Previous preliminary $\Delta\phi_{dec}$ distribution compared to LHC finds a qualitative agreement
  - Soft gluon effects near $\Delta\phi \sim \pi$ in high jet multiplicity cases
  - Agreement with MC degrades at high jet multiplicity, pointing to the need for improvements in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





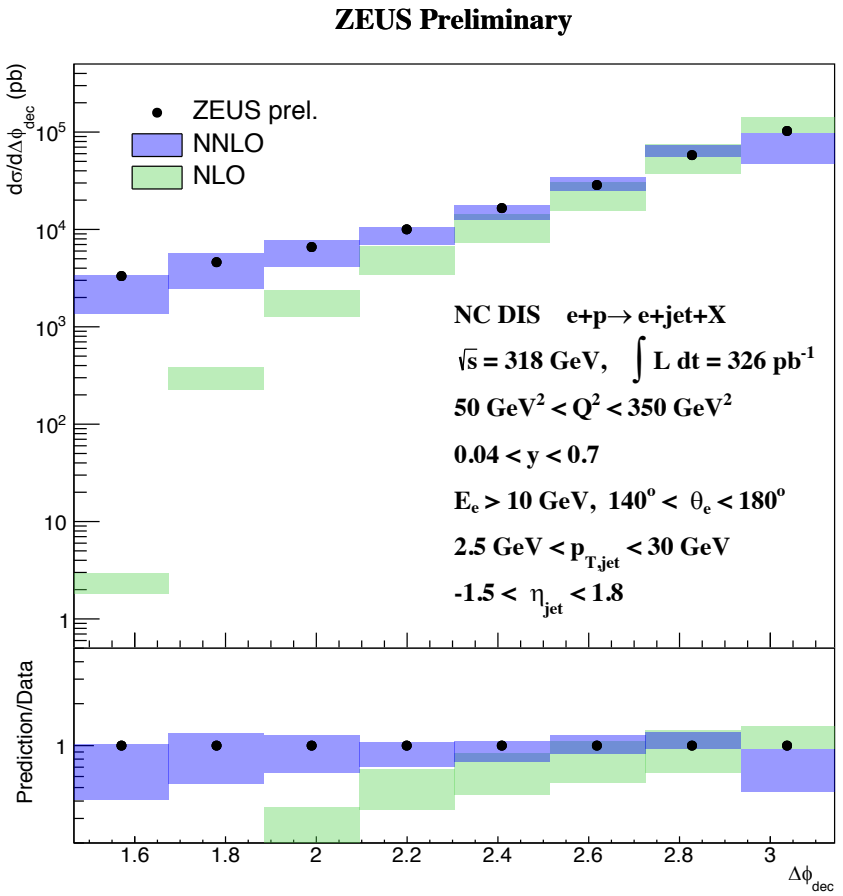






Results

- 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
    - 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



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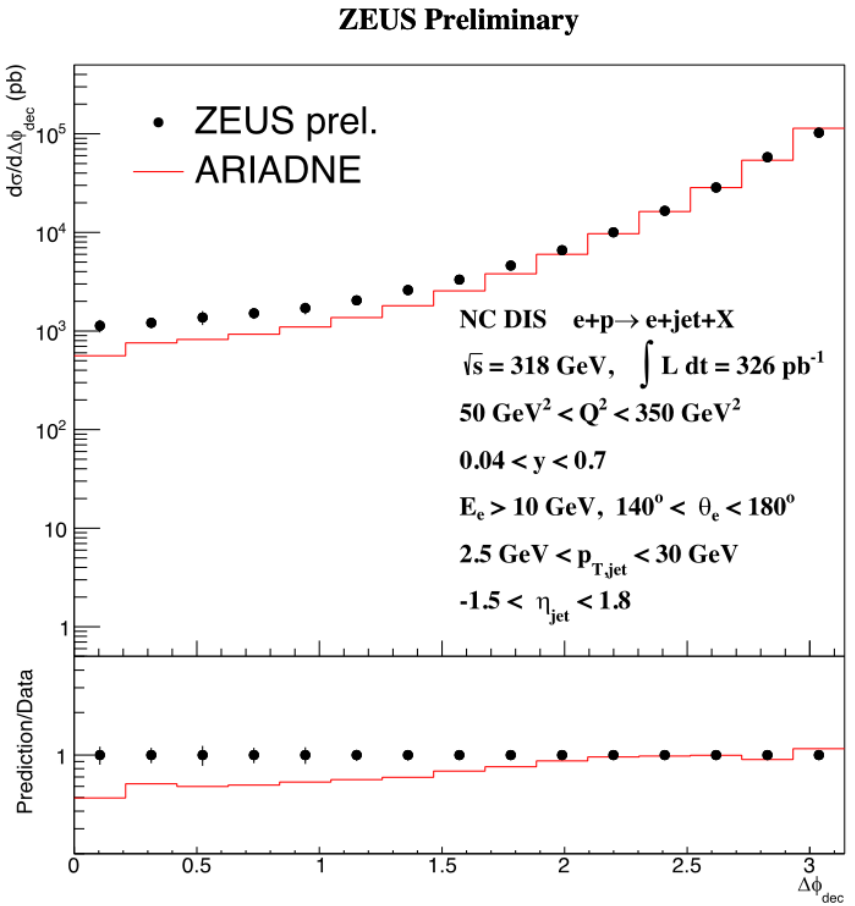
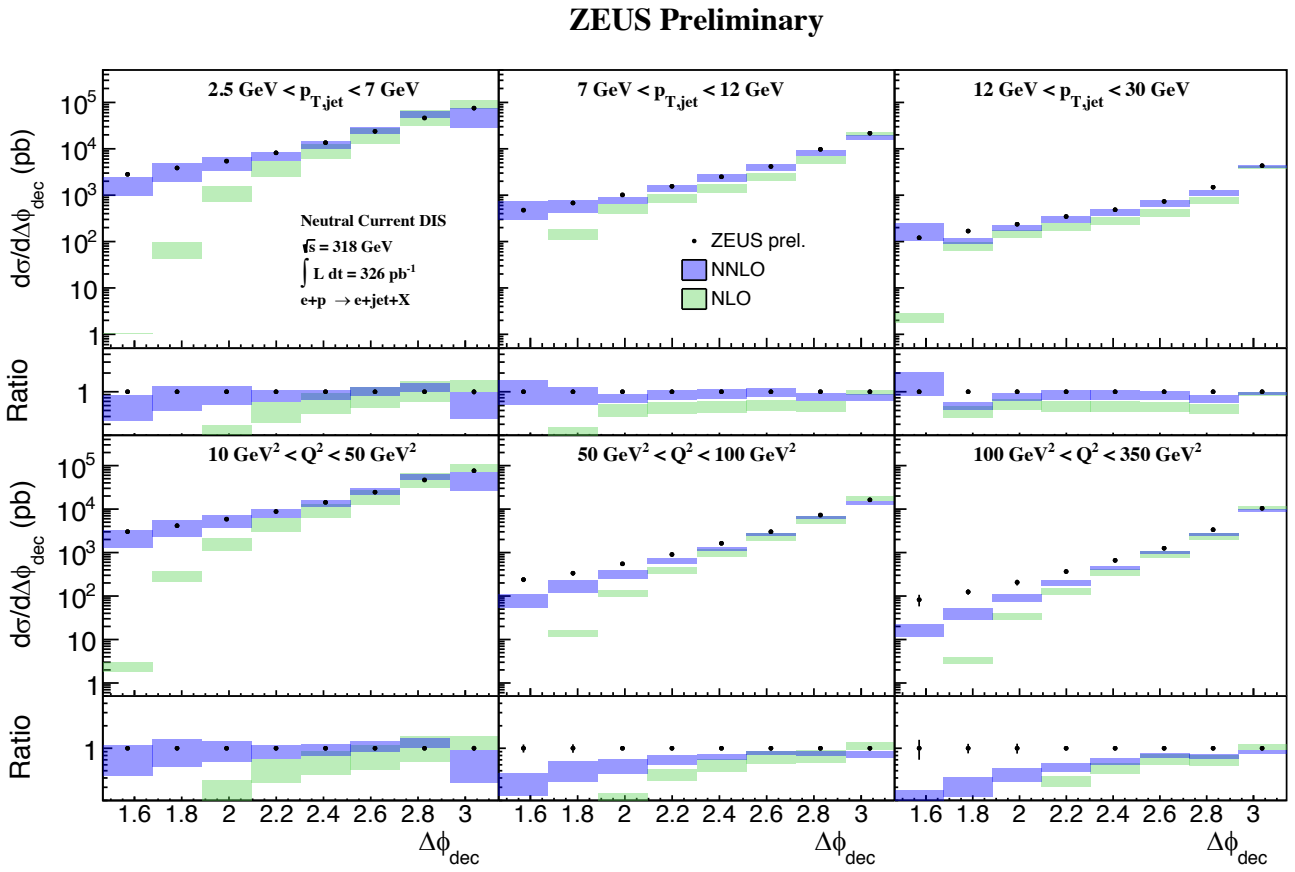
    - Systematics study suggests that the model dependence of the unfolding process is the dominating contribution (~5% at $\Delta\phi_{dec} \sim \pi$)
    - Efficiency correction ~20%
  - Comparison to ARIADNE MC.
    - ARIADNE is normalized to data luminosity
    - Overall reasonable agreement to data, 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



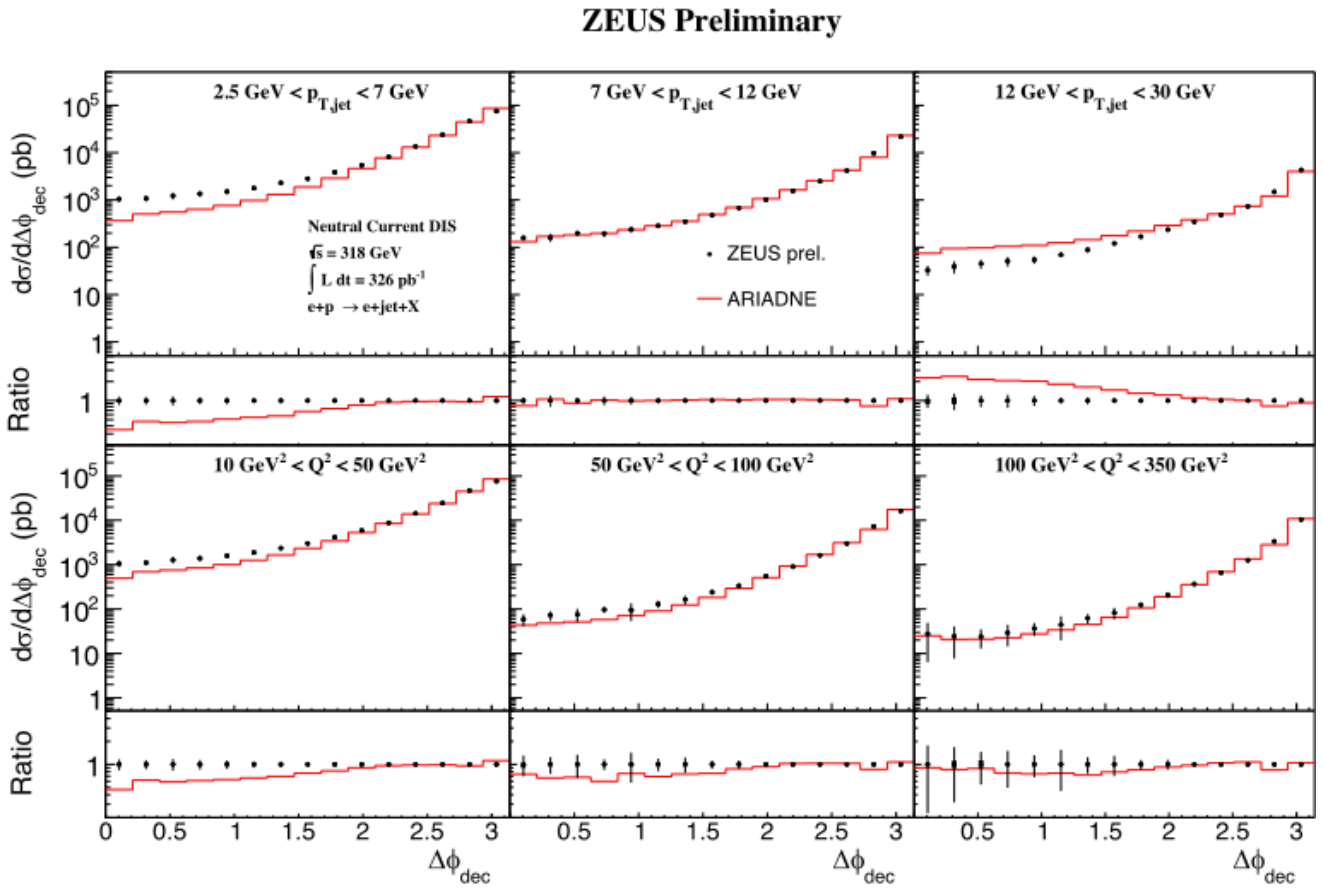
Results

- Azimuthal angle jet/electron cross-section in p_T and Q^2 bins
  - Comparison to pQCD in different ranges of $p_{T,jet}$ and Q^2.
  - Good jet reconstruction near the kinematic limit $p_{T,jet} \sim 2.5\ GeV$, 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 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!