

The azimuthal correlation between the leading jet and the scattered lepton in deep inelastic scattering at HERA

Oleksandr Zenaiev (Hamburg University)

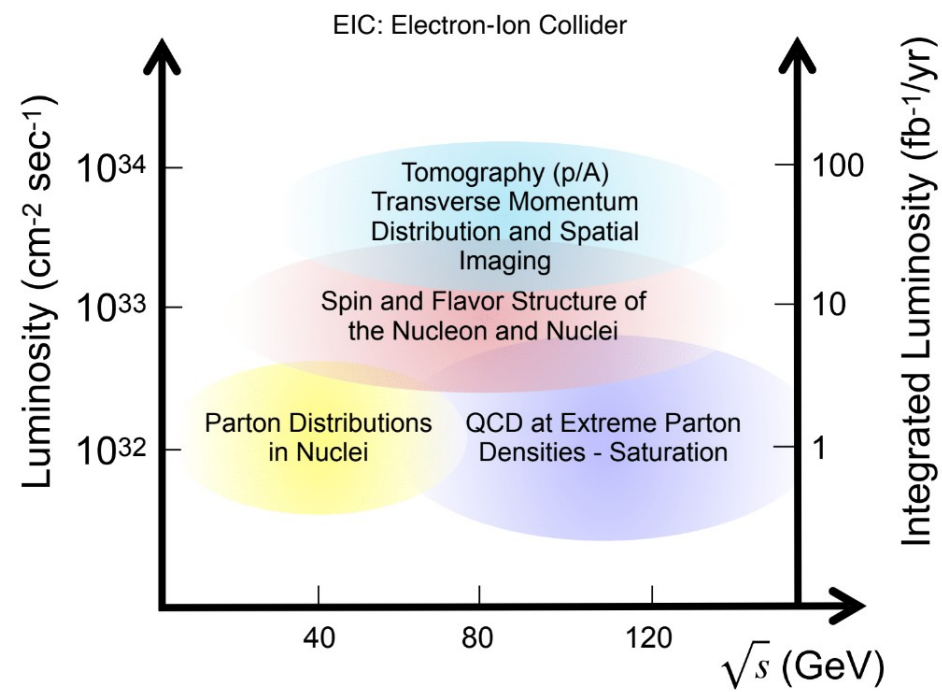
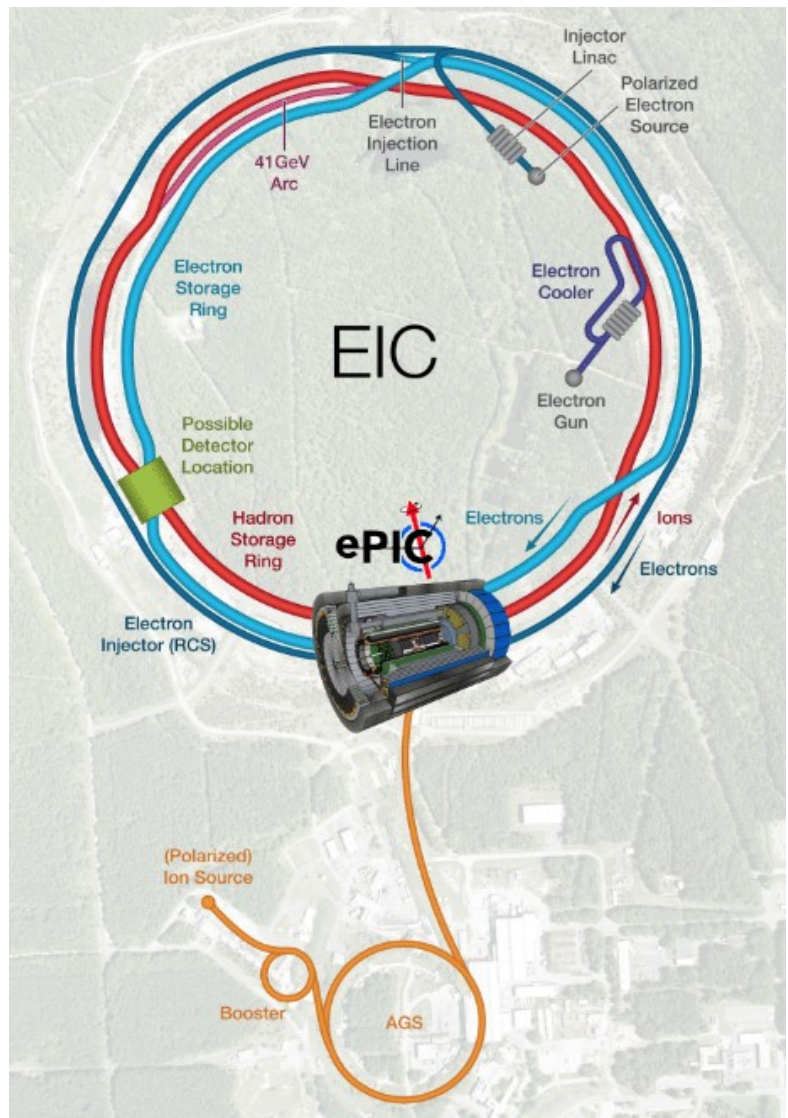
for Jae D. Nam (Temple University)

On behalf of the ZEUS collaboration

Based on: ZEUS, EPJC 84 (2024) 12, 1334

HEPdata: DOI [10.17182/hepdata.153487](https://doi.org/10.17182/hepdata.153487)

Electron Ion Collider



- Investigations into structure and dynamics of matter at **high luminosity**, **high energy** with **polarized beams** and wide range of **nuclei**
- What do we learn from **HERA**?

ZEUS Experiment at HERA

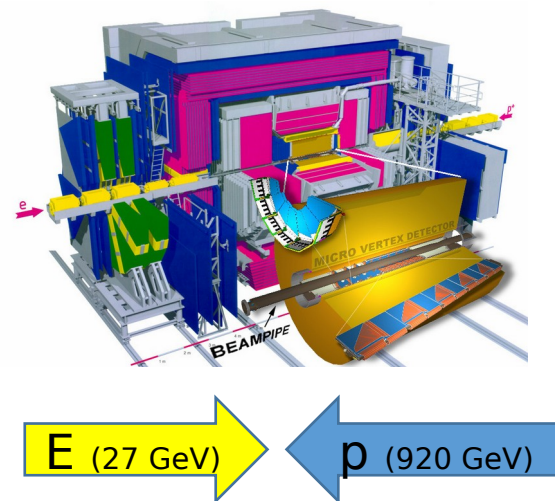
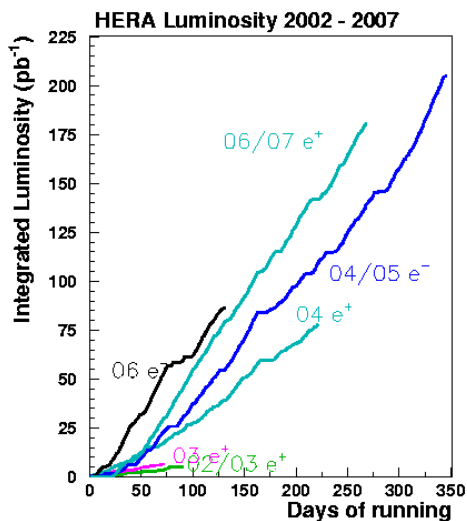


HERA

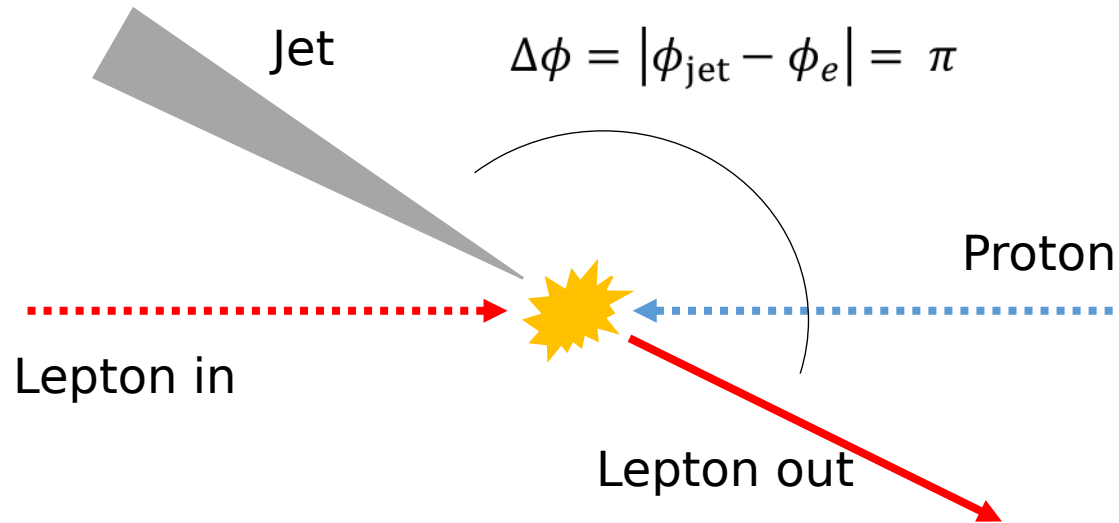
- First and only $e^\pm p$ collider
- $\sqrt{s} = 318 \text{ GeV}$ (HERA II)
- $L_{int} \sim 360 \text{ pb}^{-1}$ (HERA II)
- Access to low- x ($x_{Bj} \sim 10^{-3}$) with ZEUS detector
- Variety of existing jet studies

ZEUS

- General purpose detector
- Jet reconstruction down to $E_T > 2.5 \text{ GeV}$ with $< 4\%$ resolution
- Two independent luminosity monitors, $\delta L/L < 2\%$

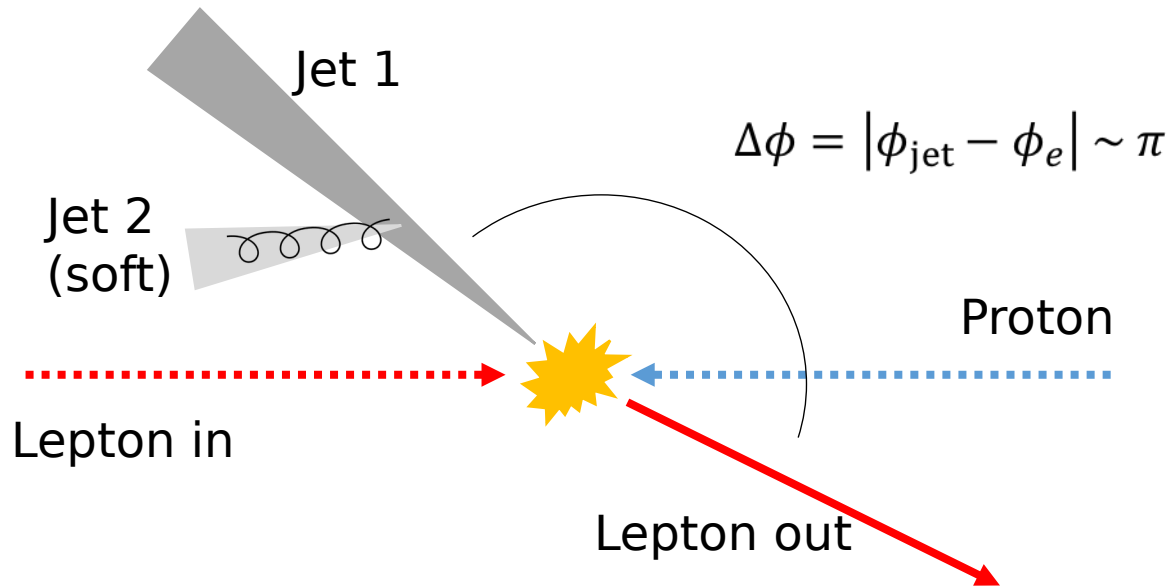


Introduction



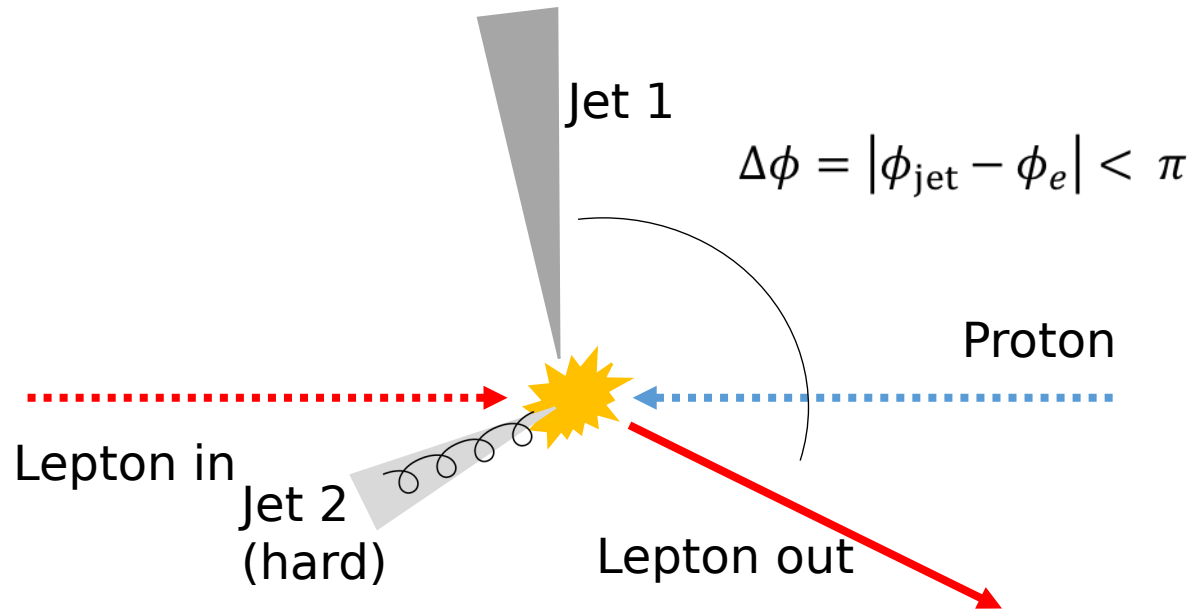
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Introduction



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- Small deviations from this back-to-back topology occur if the soft gluons are emitted, producing additional jets, and/or if the struck quark carries a non-zero transverse momentum.

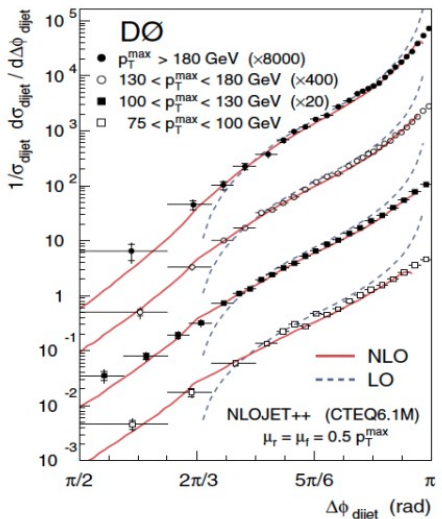
Introduction



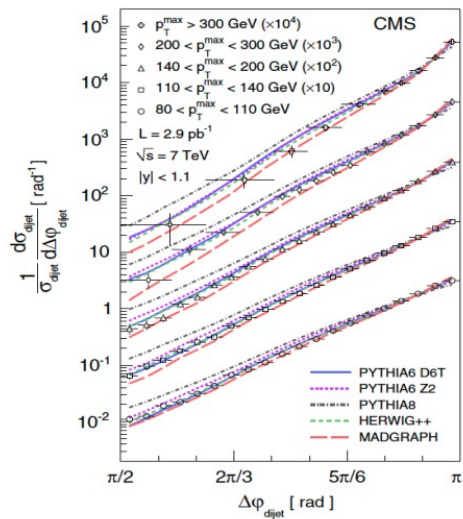
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- Small deviations from this back-to-back topology occur if the soft gluons are emitted, producing additional jets, and/or if the struck quark carries a non-zero transverse momentum.
- Large deviations arise if hard jets are produced.

Previous Studies

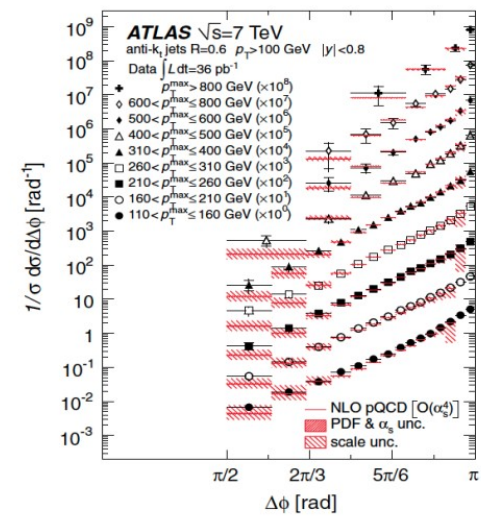
DØ, PRL 94, 221801 (2005)



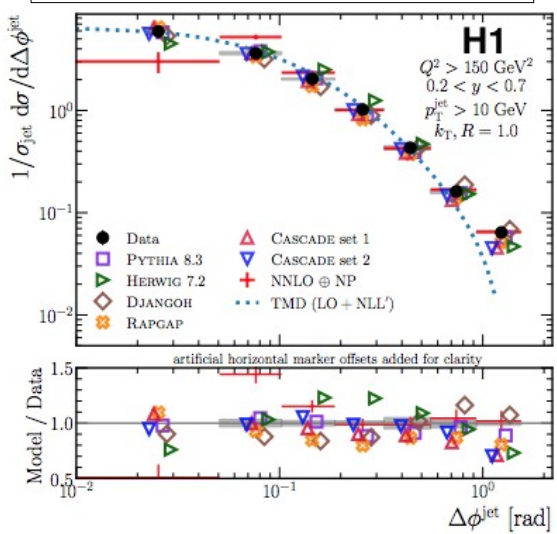
CMS, PRL 106, 122003 (2011)



ATLAS, PRL 106, 172002 (2011)

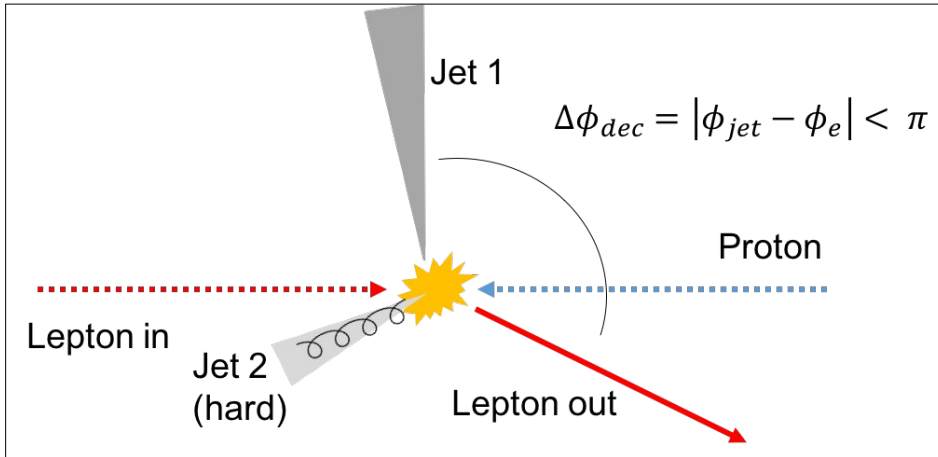
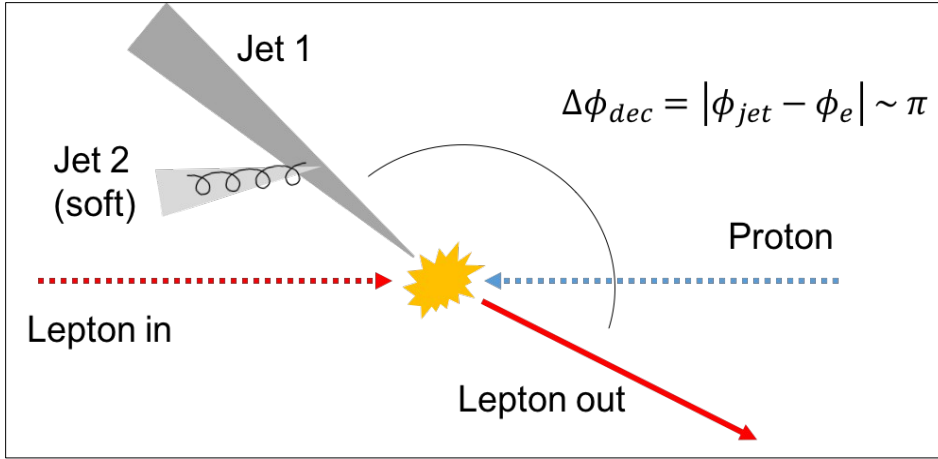


H1, PRL 128 (2022) 13, 132002



- Previous results from Tevatron and LHC
 - Improvements in data description by high order correction at high- p_T .
- Recent results from HERA (H1)
 - Improvements in data description by TMD calculation around the region $\Delta\phi \sim \pi$

Motivation



- Jet-lepton correlation probes **both** soft and hard QCD effects **without** explicit description of the additional jets.
- Tests of pQCD and LO+PS models in describing a wide range of QCD phenomena in various ranges of jet- p_T , Q^2 , and N_{jet} .
- Can be measured with already-existing HERA jet data, which have been extensively studied and understood over the years.

Data & MC

Data

- HERA II data collected at ZEUS
- $e^\pm p$ collisions at $\sqrt{s} = 318 \text{ GeV}$
- $L_{int} = 326 \text{ pb}^{-1}$

Simulations

- **ARIADNE** colour-dipole model
- **LEPTO** leading-log parton cascade

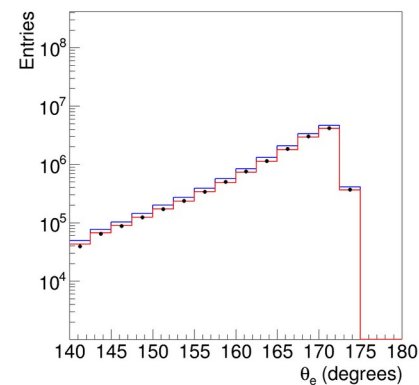
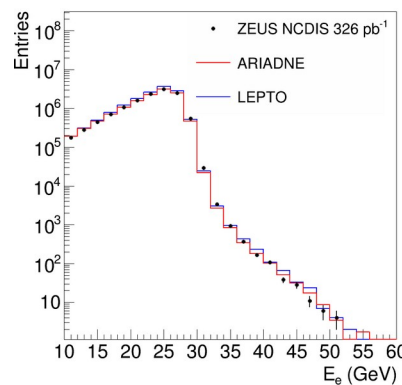
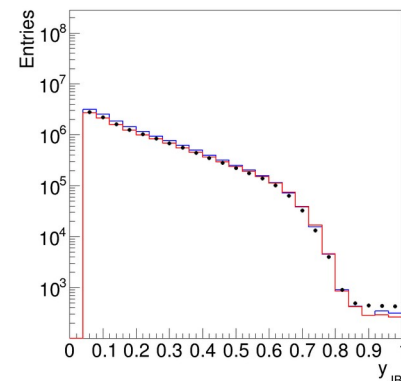
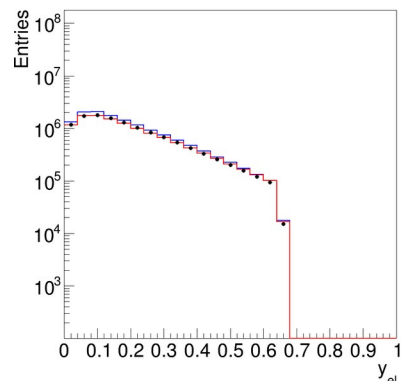
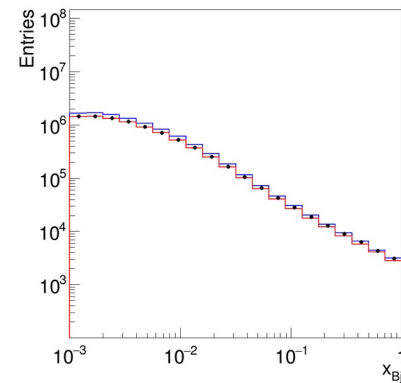
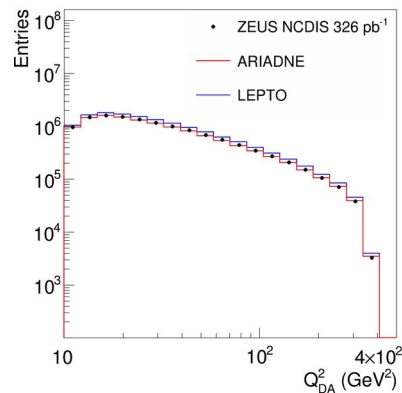
Kinematic range

- $10 \text{ GeV}^2 < Q^2 < 350 \text{ GeV}^2$
- $0.04 < y < 0.7$
- Covers a wide range in x_{Bj} ,
 $0.0002 < x_{Bj} < 0.2$

Scattered lepton

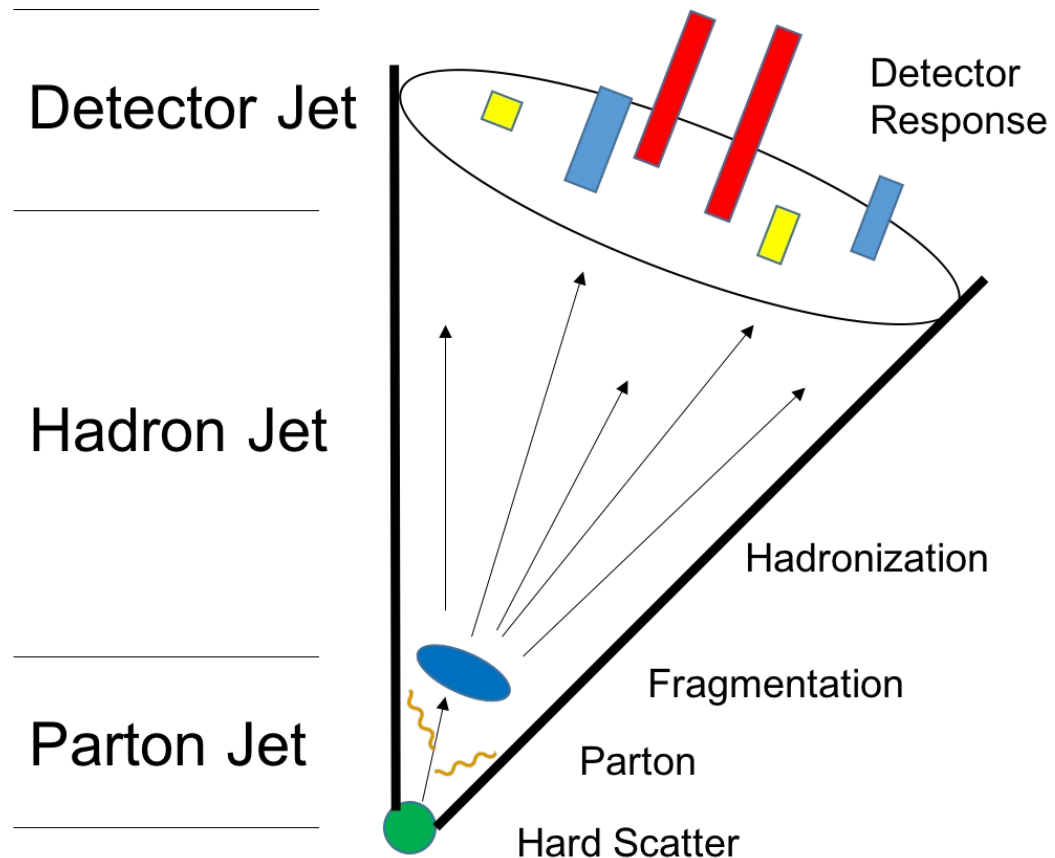
- SINISTRA algorithm
- $E_e > 10 \text{ GeV}$

ZEUS

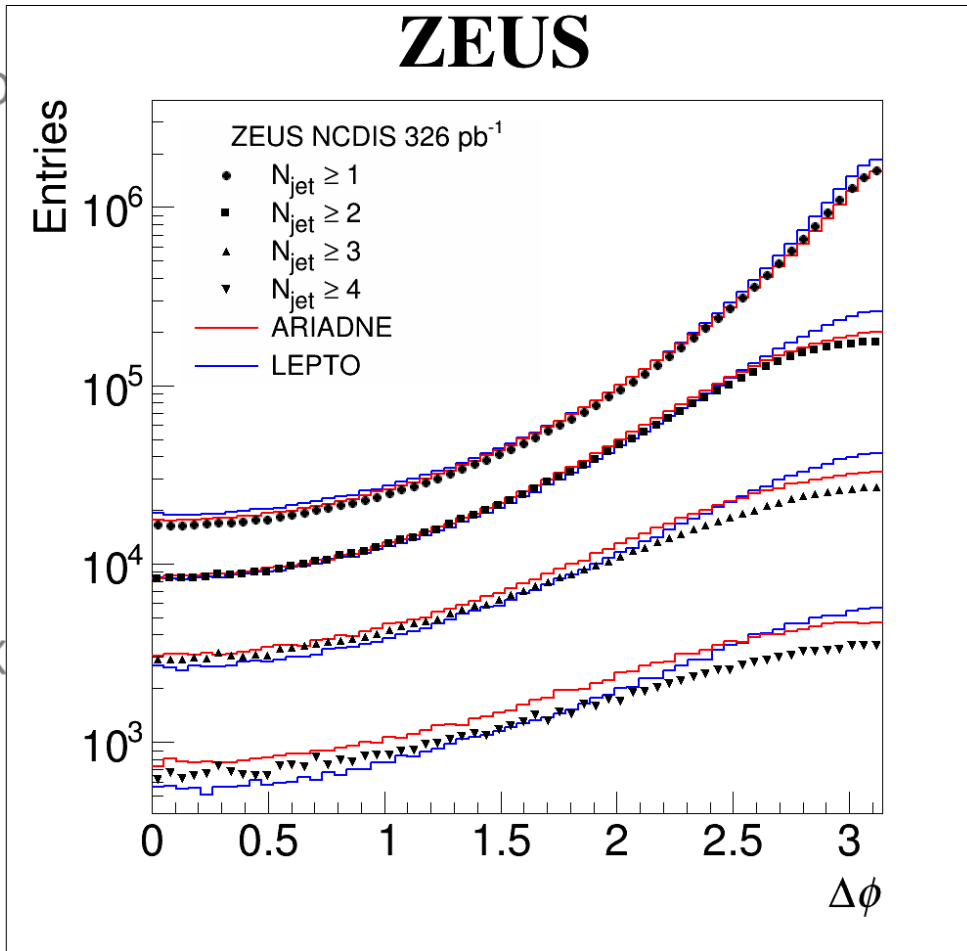


Jet reconstruction

- Detector jets:
 - All calorimeter & tracking signal (EFOs), except for scattered electron as input
 - k_T -clustering algorithm, $R = 1$
 - E -scheme, using 4-vector of input particles in the lab frame
 - Facilitated in FastJet3.4.0
[M. Cacciari et al., EPJC 72 (2012) 1896]
- Kinematic range (jet)
 - $2.5 \text{ GeV} < p_{T,jet} < 30 \text{ GeV}$
 - High-performance calorimetry allows access to low- p_T regime.



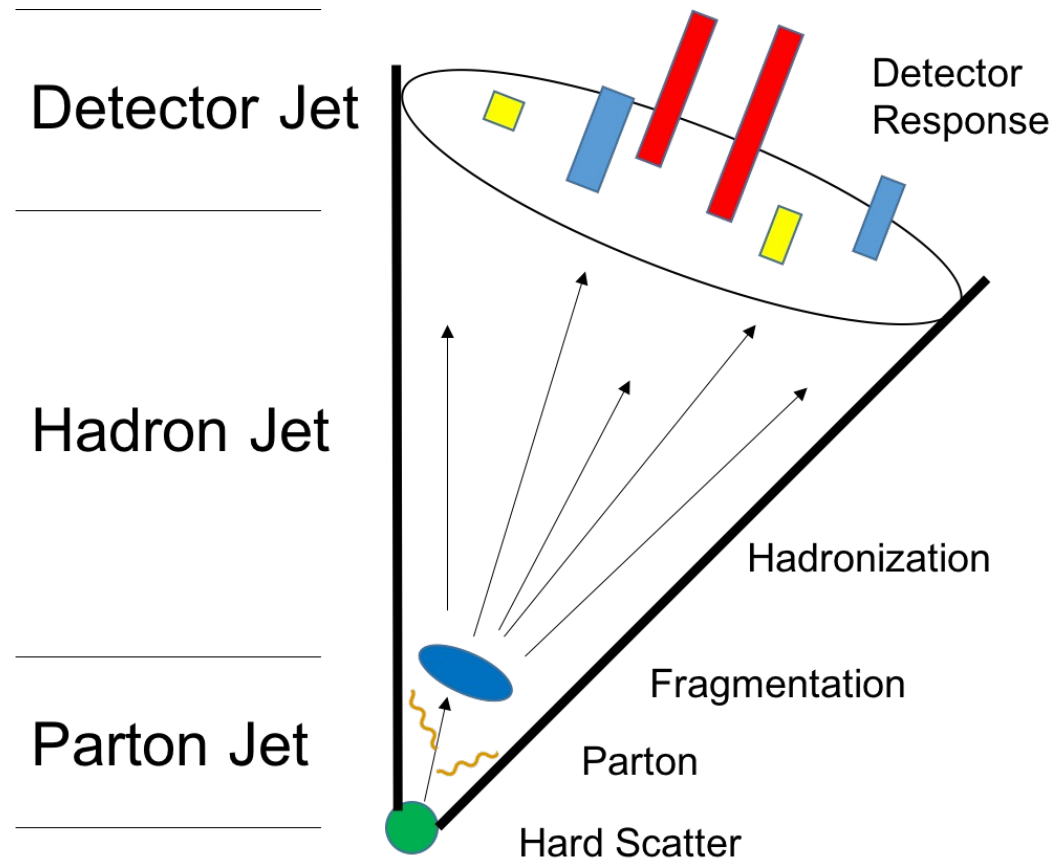
Jet reconstruction



- Detector jets with the highest p_T in the event chosen as the leading jet.
- Azimuthal correlation angle $\Delta\phi$ formed from the reconstructed electron and the leading jet.
$$\Delta\phi = |\phi_{jet} - \phi_e|$$
- Good description of data by ARIADNE

Signal extraction

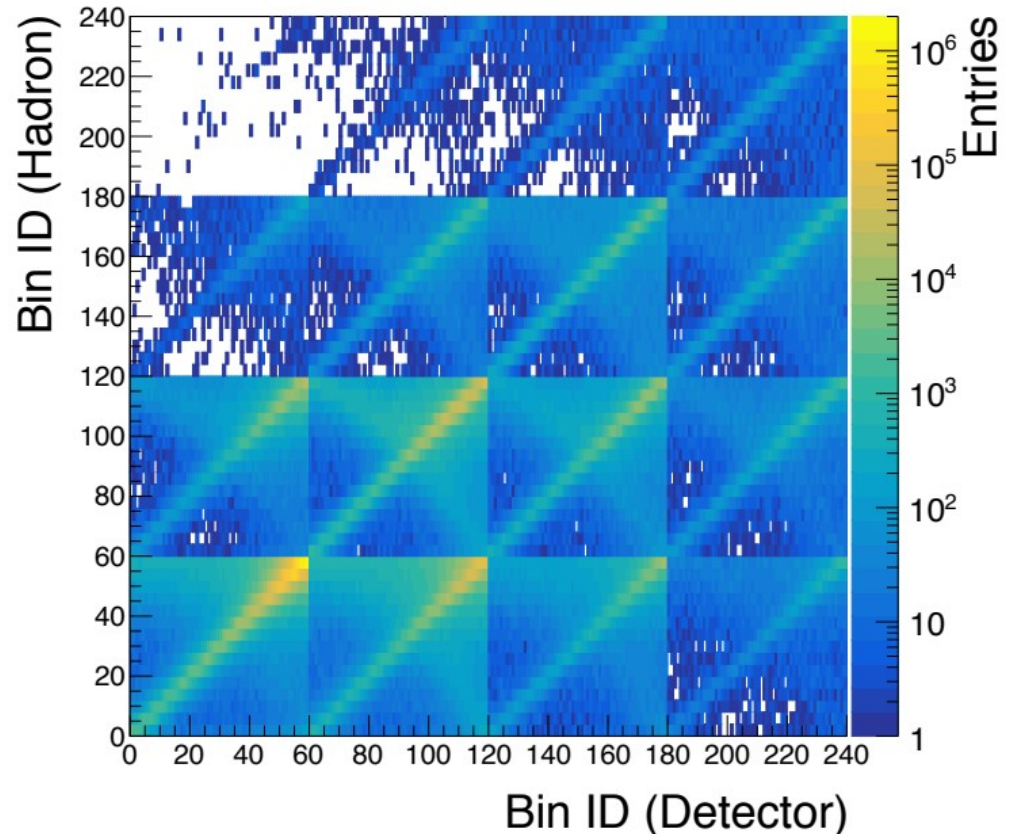
- Hadron-level $\Delta\phi$ reconstructed in ARIADNE events
 - True electron after initial and final state QED rad.
 - Hadron jets with the same jet finder algorithm & parameters, with all final-state particles ($\tau > 10 ps$), except neutrino/electron
- Hadron-level $\Delta\phi$ extracted using a regularized unfolding
 - L -scan method as implemented in TUnfold [S. Schmitt, JINST 7 (2012) T10003]
 - Migration matrix of $\Delta\phi \otimes N_{jet}$ as input



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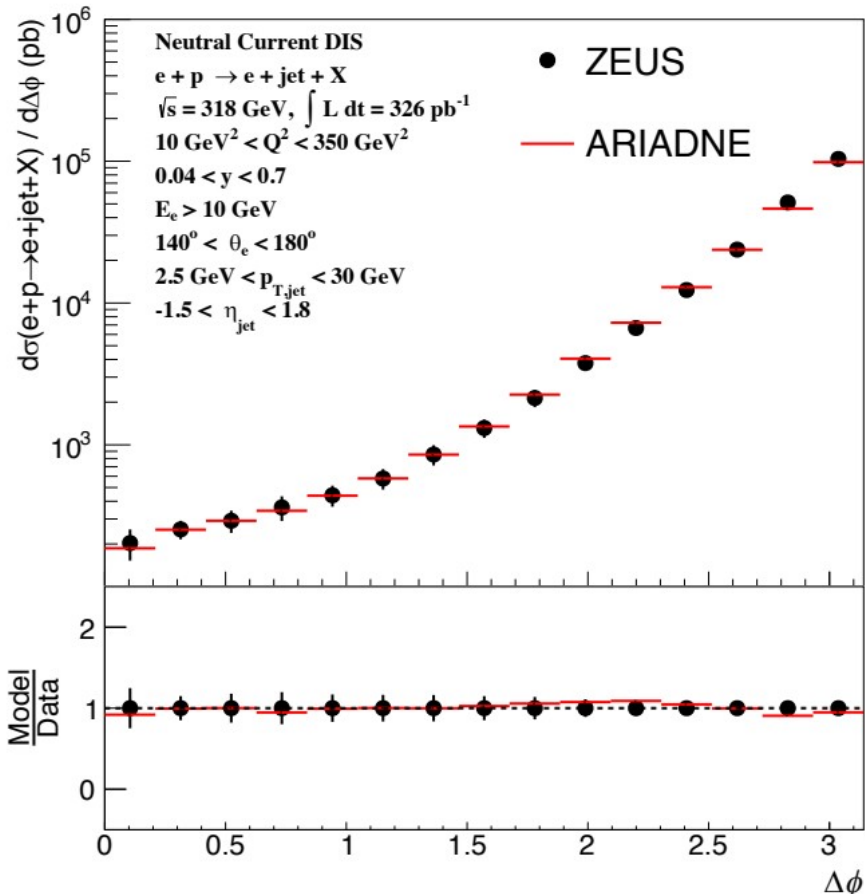
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*Bin ID = $[0-60 \text{ for } 0 < \Delta\phi < \pi] + 60 \times (N_{jet} - 1)$

Differential cross section

ZEUS * $N_{jet} \geq 1$



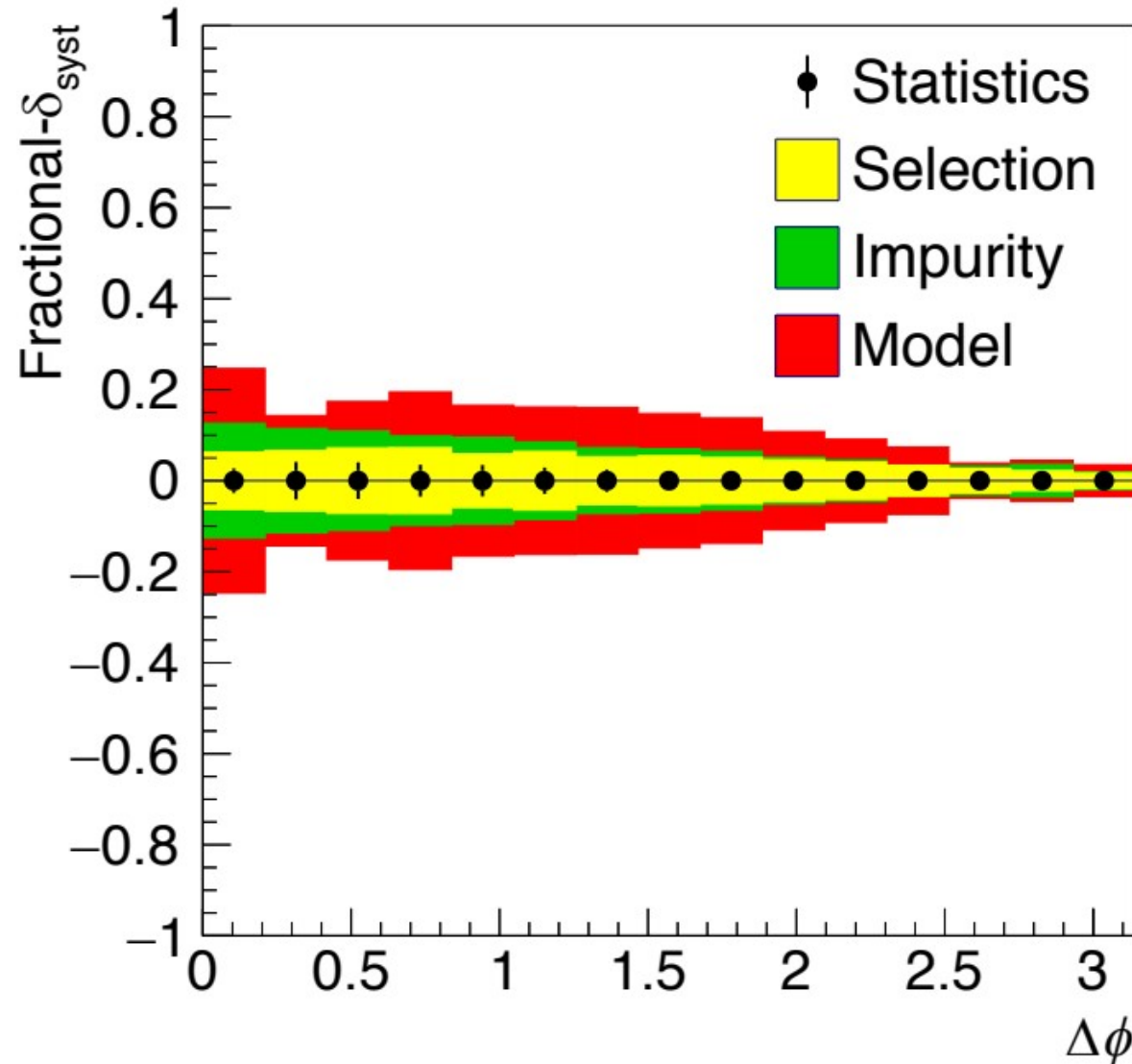
• Differential cross section of $e + p \rightarrow e + jet^{lead} + X$ defined as:

$$\frac{d\sigma}{d\Delta\phi} = \frac{1}{\mathcal{L}} \cdot c_{QED} \cdot c_L \cdot \frac{N_{had}}{\delta\Delta\phi}$$

- N_{had} : extracted hadron-level yield
- c_{QED} : QED correction factor (RAPGAP3.3)
- c_L : correction factor for leading-jet misidentification
- Additional measurements performed for different $p_{T,jet}^{lead} \otimes N_{jet}$ and $Q^2 \otimes N_{jet}$ ranges.

Systematic uncertainties

ZEUS

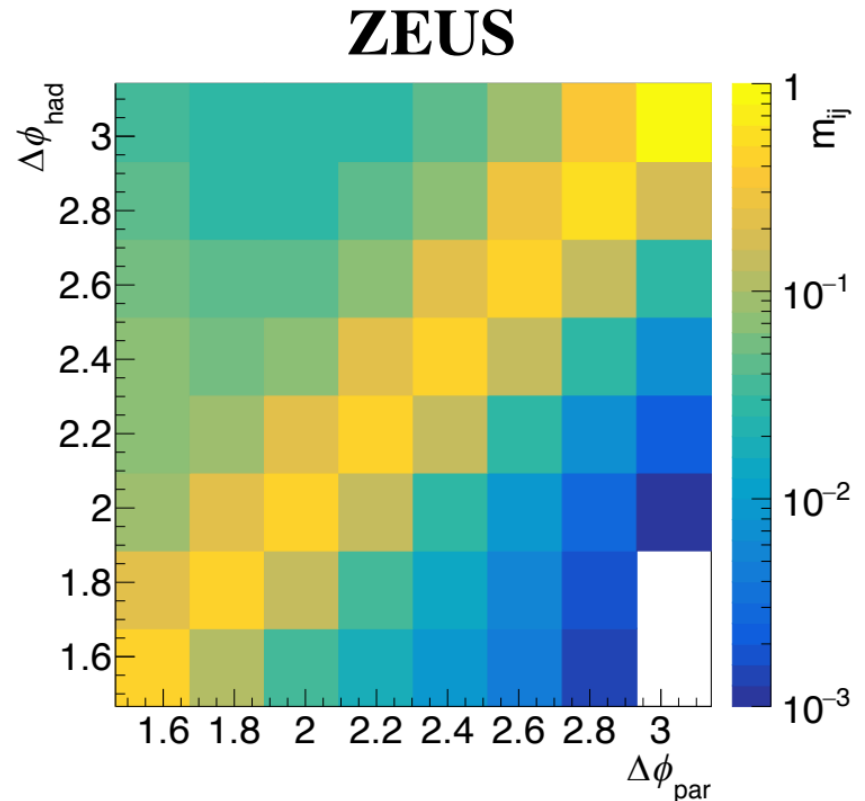


- Selection cuts and corresponding resolution
- Uncertainty associated with background estimation.
- Dependences on simulation model (ARIADNE) in unfolding/cross-section calculation.

Precision limited by event modeling

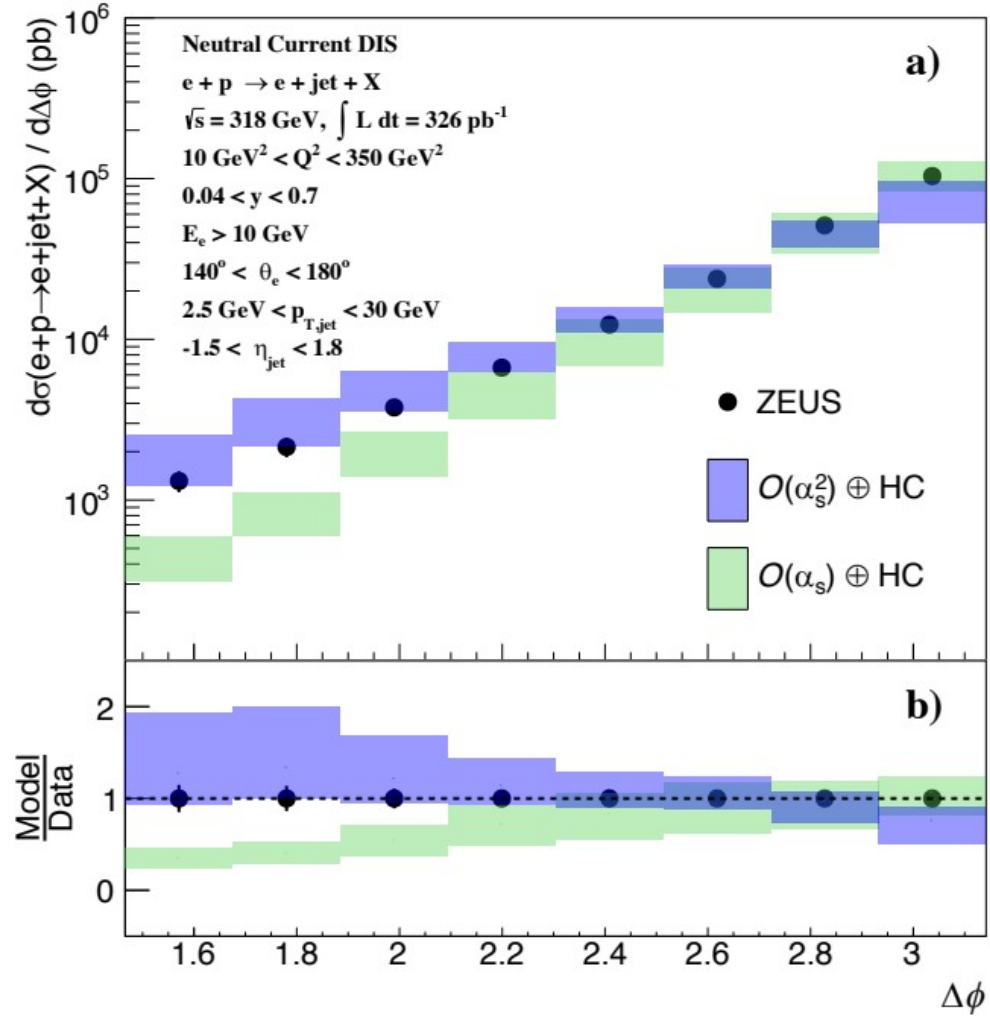
Theory prediction

- Perturbative calculations from **UNSAM (Borsa, de Florian, Pedron)**
 - Calculations for EIC adapted for HERA kinematics [Borsa et al., PRL 125 (2020) 082001]
 - Fixed order (**up to $\mathcal{O}(\alpha_s^2)$**) calculations using the projection-to-Born method
 - Calculations performed with massless parton jets
- Hadronization correction
 - Parton jets reconstructed in ARIADNE
 - Massless jets kT algo w/ $R = 1$ (FastJet 3.4.0)
 - A matrix-based correction using a probability matrix.
 - Model dependence studied with LEPTO and added to the scale uncertainty



Results (Inclusive)

ZEUS

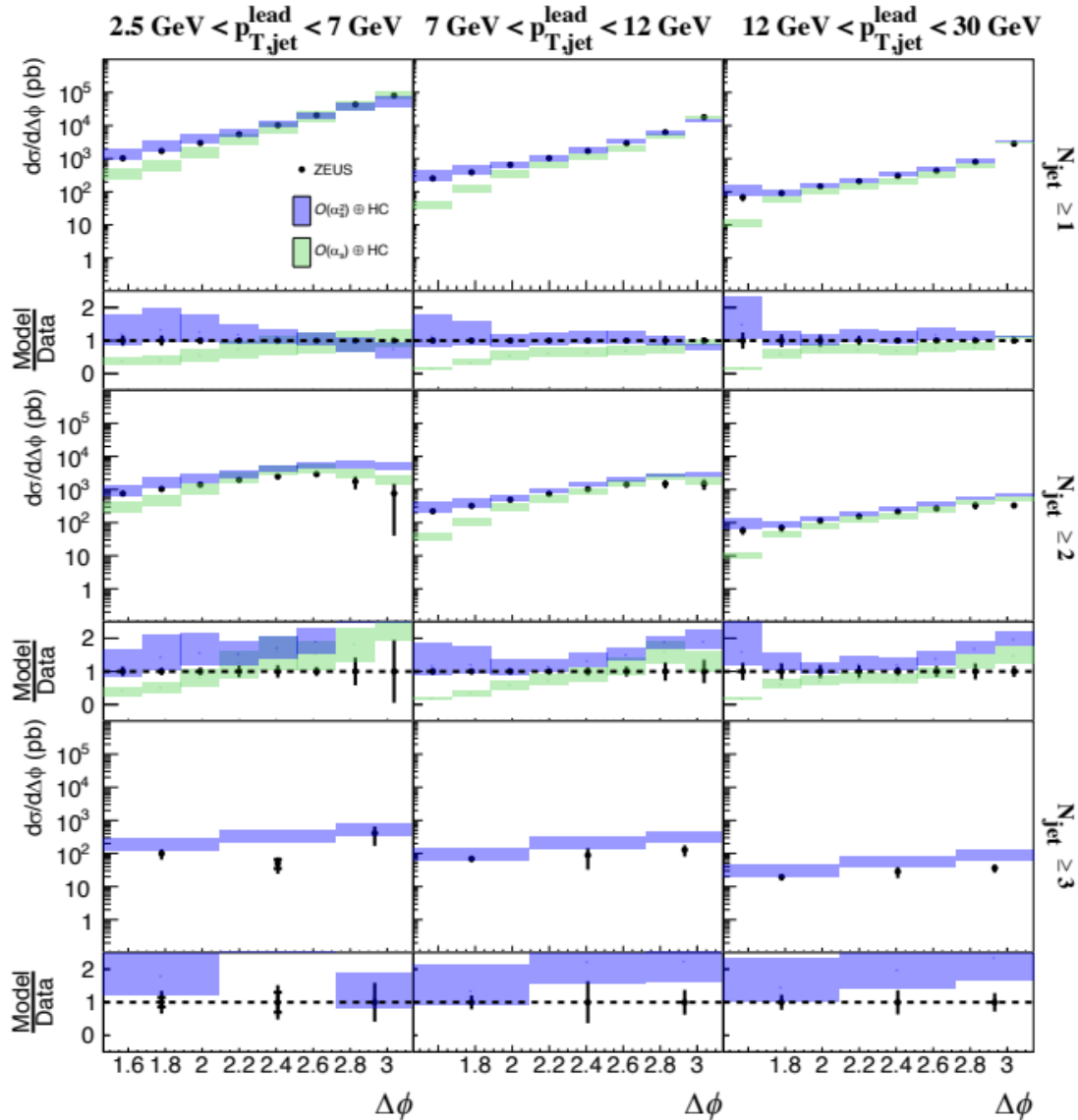


*Inclusive refers to measurements with no N_{jet} , $p_{T,\text{jet}}^{\text{lead}}$, or Q^2 requirements other than imposed by fiducial space.

- For $\Delta\phi = \pi$, $O(\alpha_s^2)$ is NNLO and $O(\alpha_s)$ is NLO. For all the other bins, $O(\alpha_s)$ is LO.
- Clear improvements in $O(\alpha_s^2)$, especially $\Delta\phi < 3\pi/4$
- No significant improvement in $\Delta\phi \rightarrow \pi$, which is characterized by soft QCD and k_T effects
- Consistent with findings of DØ, CMS, ATLAS, H1
- pQCD already describe data well in $\Delta\phi \rightarrow \pi$.

Results ($p_{T,jet}^{lead} \otimes N_{jet}$ -dependent)

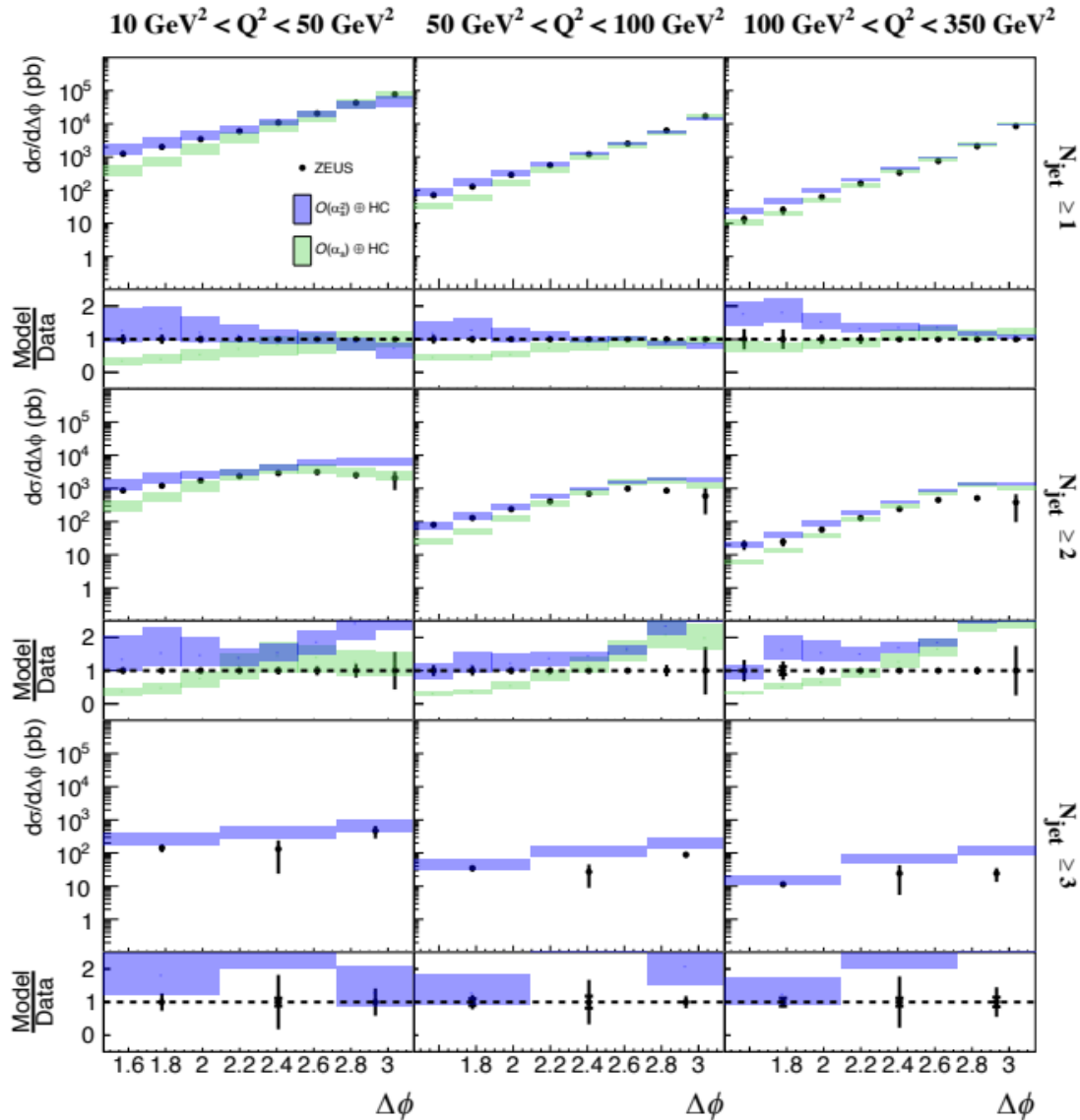
ZEUS



- 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 $p_{T,jet}^{lead} > 2.5 GeV$
- Enhanced events with reduced $\Delta\phi$ (flatter in terms of shape) with increasing N_{jet} , as also seen in hadron experiments

Results (Q^2 -dependent)

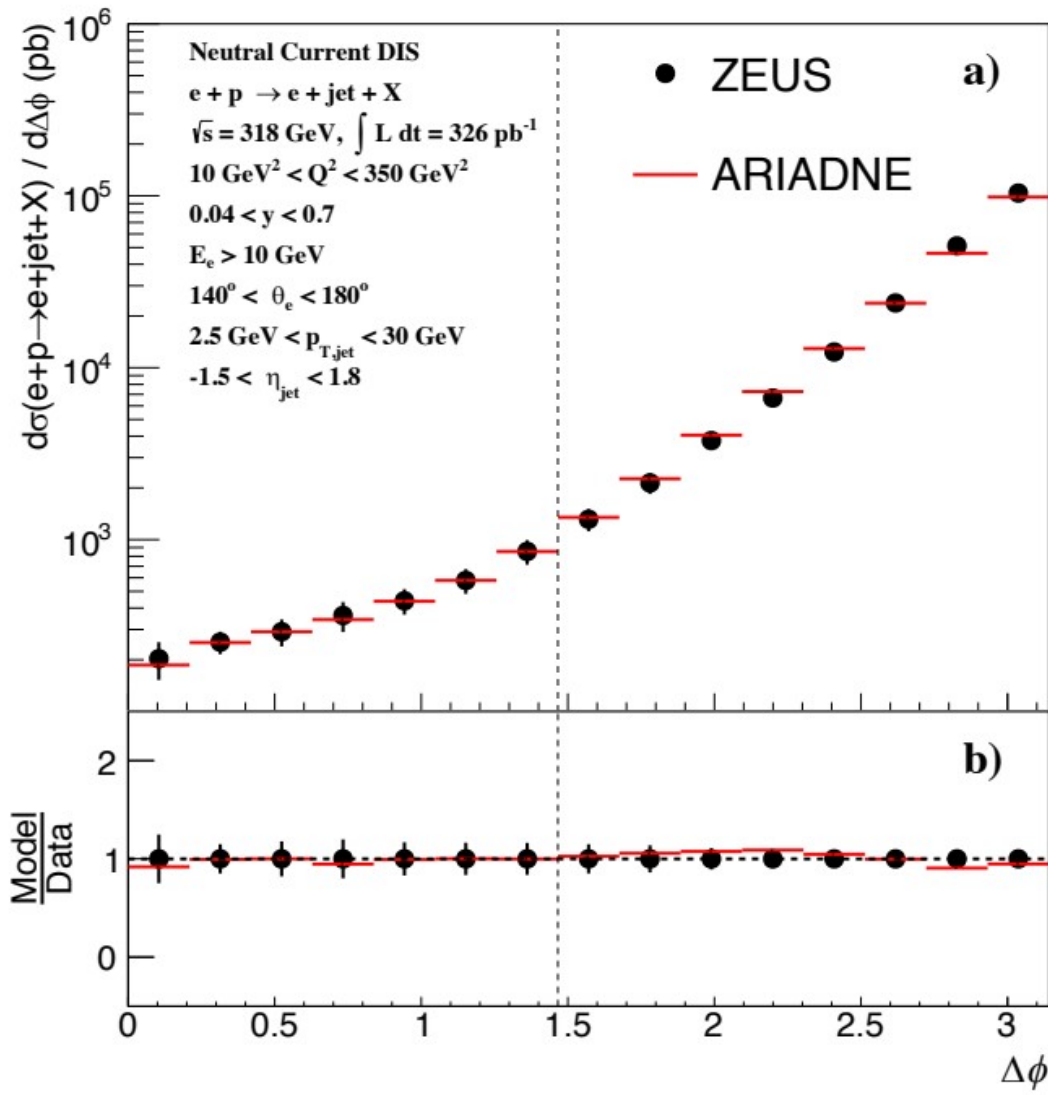
ZEUS



- 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 (ARIADNE, Inclusive)

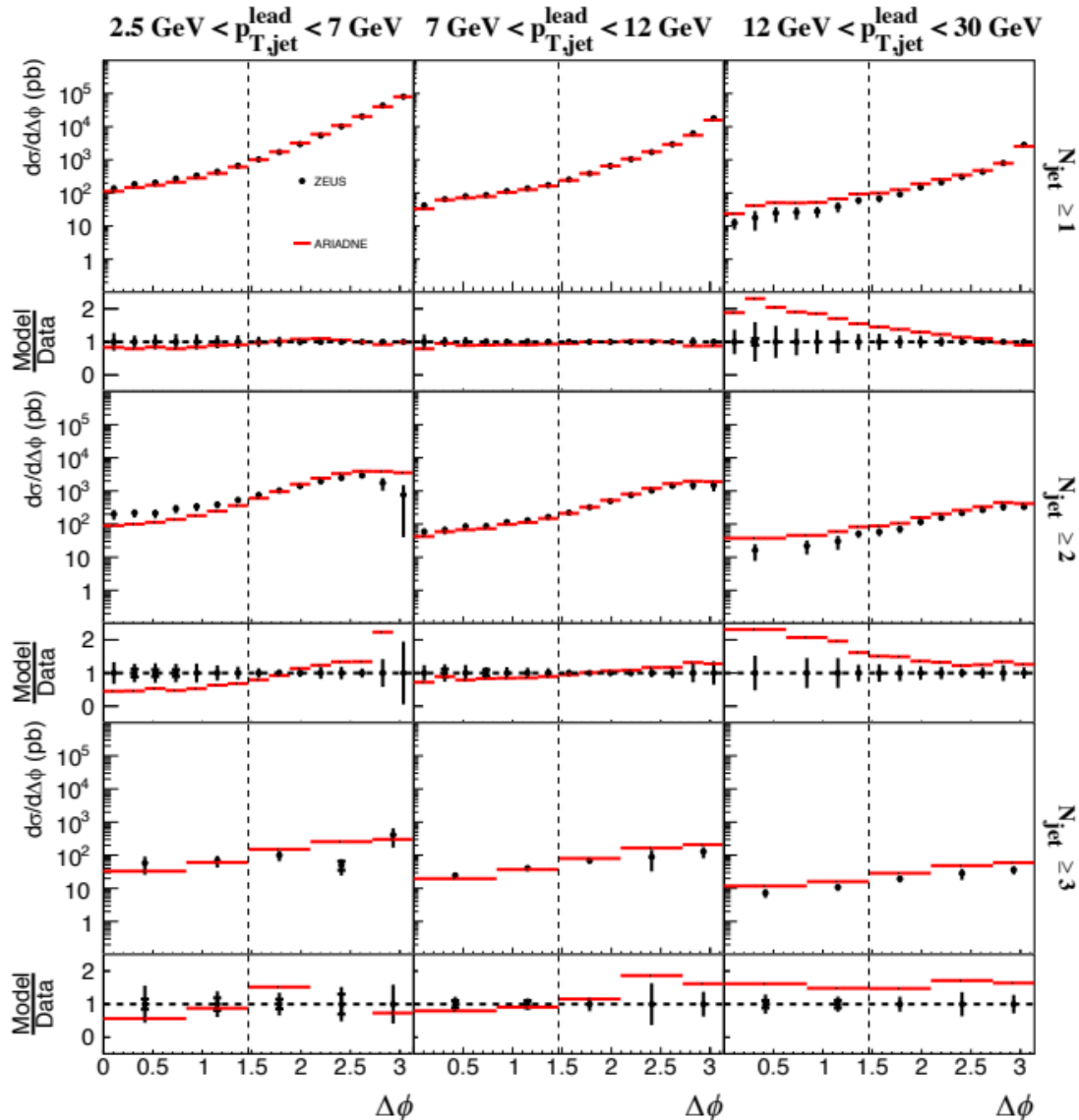
ZEUS



- Excellent description of data by ARIADNE, although **higher order** processes are **not fully represented**

Results (ARIADNE, $p_{T,jet}$ -dependent)

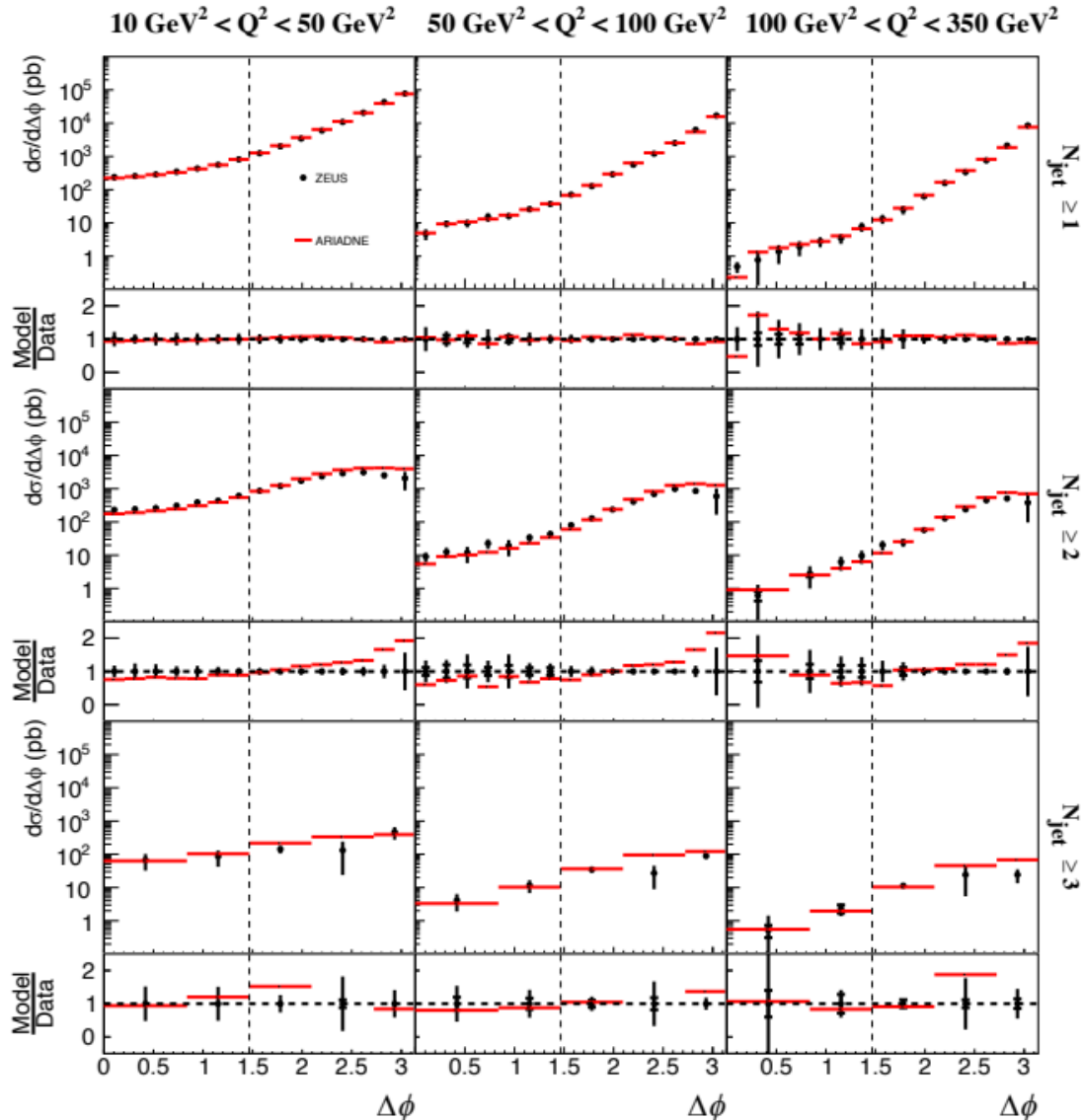
ZEUS



- Excellent description of data by ARIADNE, although **higher order processes are not fully represented**
- 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 → Improvement expected from **further tuning**

Results (ARIADNE, Q^2 -dependent)

ZEUS



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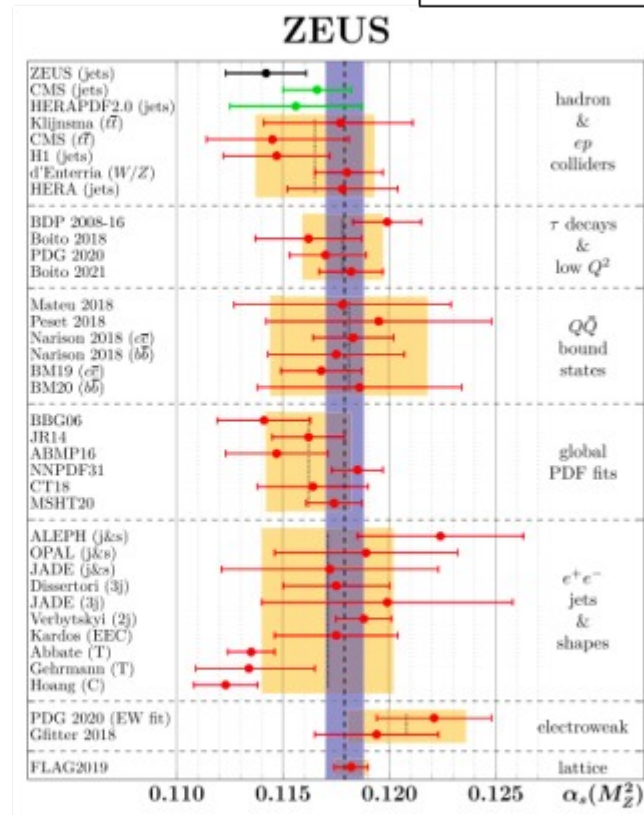
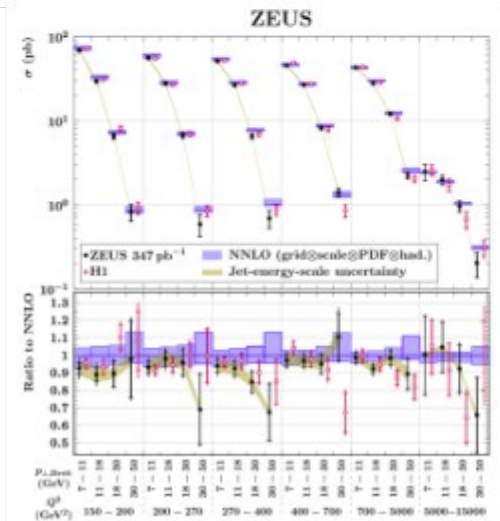
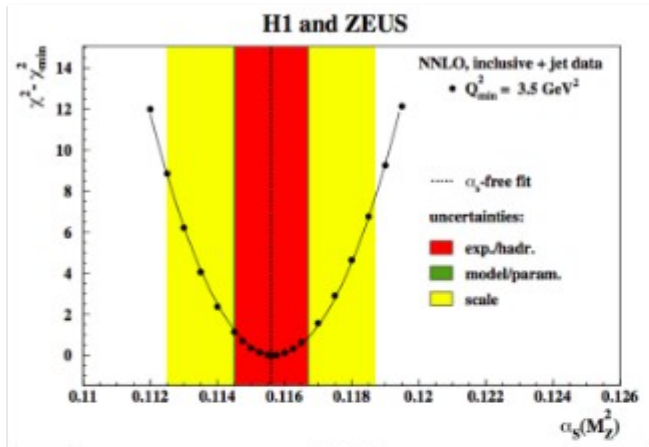
Summary & Outlook

- Differential cross sections of jet production in NCDIS has been measured as functions of $\Delta\phi$ with HERA II data
- **Uncertainty dominated by model-dependent** assumptions made during cross section extraction procedure.
- Performance of pQCD has been tested in the **low- $p_{T,jet}$ regime** ($p_{T,jet} > 2.5 \text{ GeV}$).
- Well-tuned **LO+PS** models **describe** a wide range of characteristics of the **data well**.
- Future experiments, e.g., EIC, can benefit from:
 - **Electron identification** at low E_e (at ZEUS, 10 GeV vs. initial-state energy of 27.5 GeV);
 - **Jet reconstruction** at low jet- p_T accompanied by high-performance EM and Hadron calorimetry.

Backup

Recent jet measurements from HERA

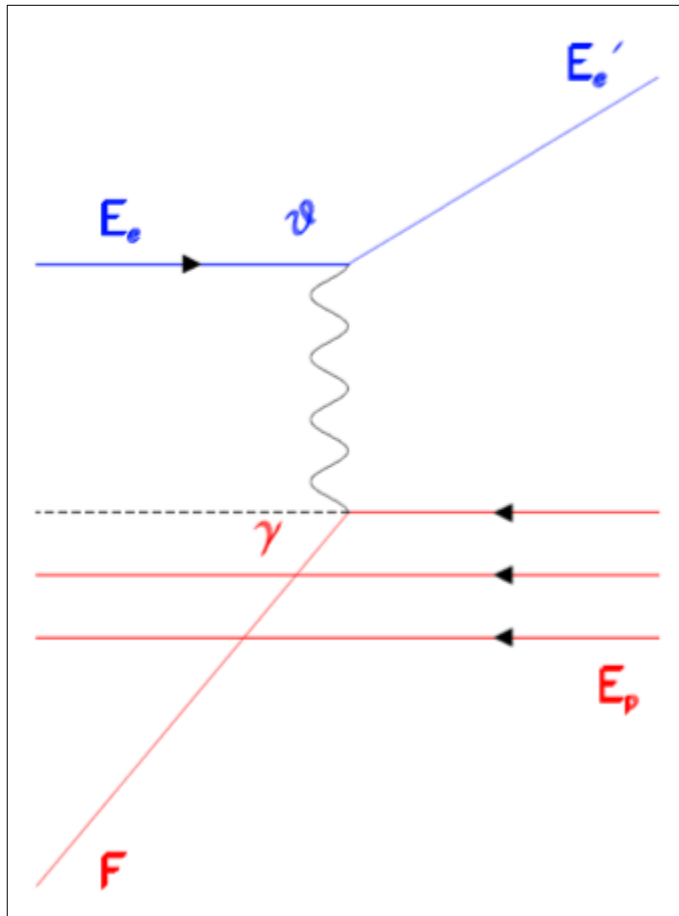
H1/ZEUS, EPJC 82 (2022) 3, 243
 ZEUS, EPJC 83 (2023) 11, 1082



- New jet measurements from HERA!

DIS event kinematics

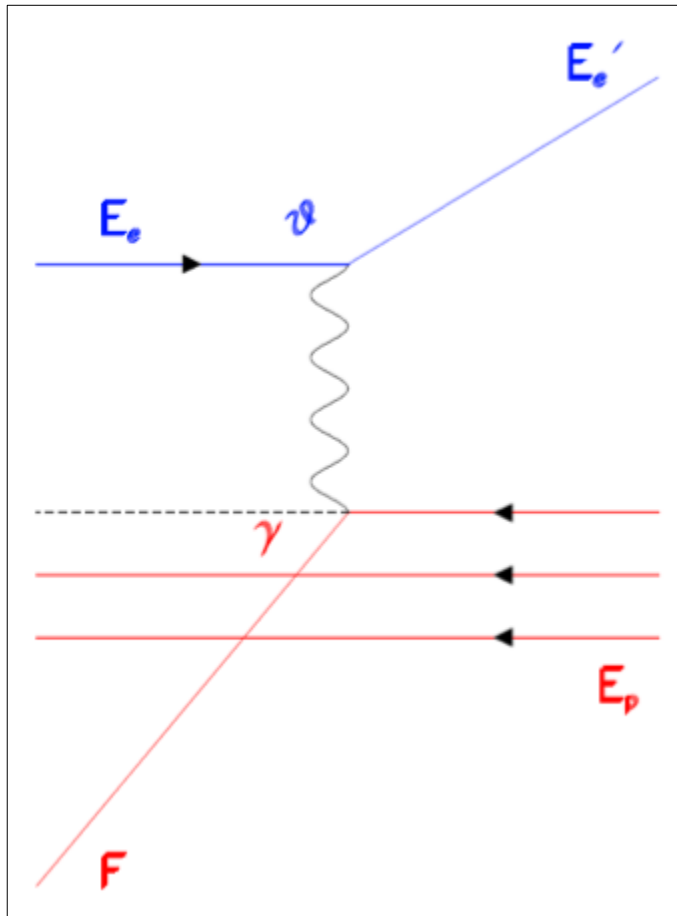
EIC wiki
(wiki.bnl.gov/eic)



- DIS events are typically described with the following kinematic quantities:
 - $Q^2 =$ Photon virtuality
 - $x_{Bj} =$ Bjorken-scaling variable x
 - $y =$ Inelasticity
 - ...
- These quantities are reconstructed experimentally based on six quantities shown on the left.
- With two (E_e, E_p) fixed, any combination of two out of the remaining four can be used to reconstruct DIS event kinematics.
 - Each provides differing reconstruction resolution in different kinematic domain with finite detector resolution.

DIS event kinematics

EIC wiki
(wiki.bnl.gov/eic)



- This measurement aims to provide a wide coverage in x_{Bj} , $0.002 < x_{Bj} < 0.2$.
- Kinematic selection
 - $10 \text{ GeV}^2 < Q_{DA}^2 < 350 \text{ GeV}^2$ (Double-Angle method)
 - $y_{JB} > 0.04$ (Jacquet–Blondel method)
 - $y_{el} < 0.7$ (Electron method)
- Selection based on the final-state electron energy to ensure clean selection of DIS electron.
 - SINISTRA neural-network algorithm
 - $E_e' > 10 \text{ GeV}$

Data/Simulation

- HERA II data collected with the ZEUS detector
 - $e^\pm p$ collisions at $\sqrt{s} = 318 \text{ GeV}$
 - $L_{int} = 326 \text{ pb}^{-1}$ (05-07)
- NCDIS selection
 - Based on previous ZEUS jet measurements
[PLB 691 (2010) 127, PLB 715 (2012) 88, JHEP 01 (2018) 032]
 - $10 \text{ GeV}^2 < Q_{DA}^2 < 350 \text{ GeV}^2$
 - $y_{JB} > 0.04, y_{el} < 0.7$
 - $E_e > 10 \text{ GeV}$
 - $140^\circ < \theta_e < 175^\circ$ * (effective)
- Jet reconstruction
 - kT algorithm with E-scheme in the lab frame, $R = 1$
 - ZUFO 4-vector as input (excl. SINISTRA electron)
 - FastJet 3.4.0
 - $2.5 \text{ GeV} < p_{T,jet} < 30 \text{ GeV}$
 - $-1.5 < \eta_{jet} < 1.8$
- MC sample
 - ZEUS standard low- Q^2 ($Q^2 > 5 \text{ GeV}^2$) sample
 - Colour dipole model with ARIADNE 4.12 /DJANGO 1.6
 - JETSET 7.4.1 for hadronisation, HERACLES 4.5 for QED radiation
 - CTEQ5D PDF sets, ALEPH $e^+e^- \rightarrow Z$ tune
 - Used to extract cross section from detector response
Used for hadronisation correction
 - Used for LO+PS predictions
- MC samples for additional studies
 - MEPS-LEPTO 6.5 for model dependences
 - Pythia 6.4 to estimate PHP contribution
 - RAPGAP 3.3 for QED radiative correction

Correlation Matrix

ZEUS

