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

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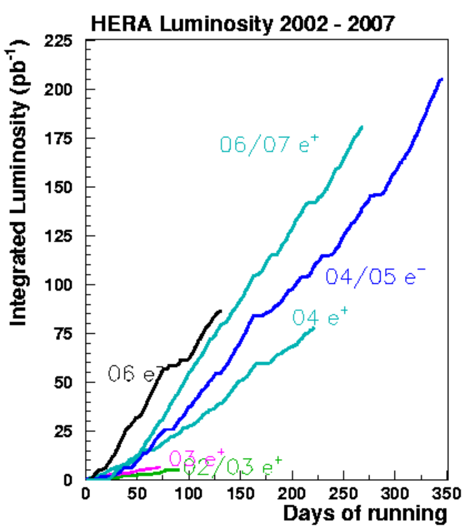
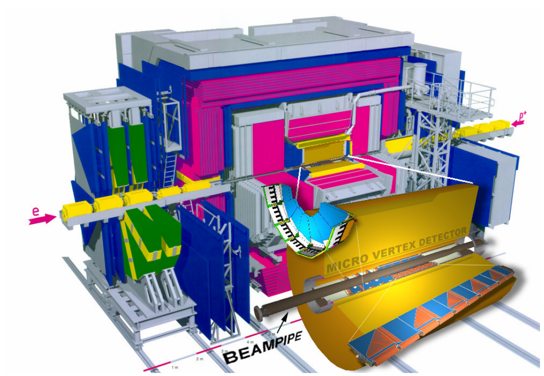
Temple Univ.

For the ZEUS collaboration

# Experiment

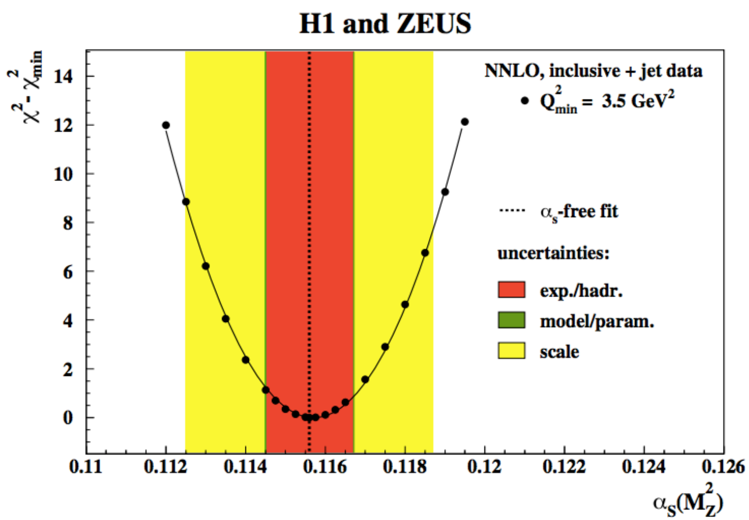



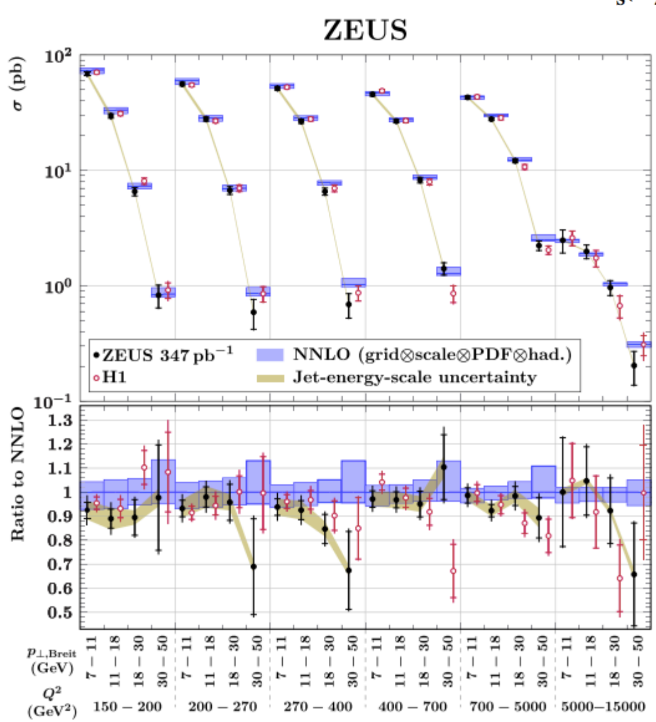

e (27 GeV) → ← p (920 GeV)

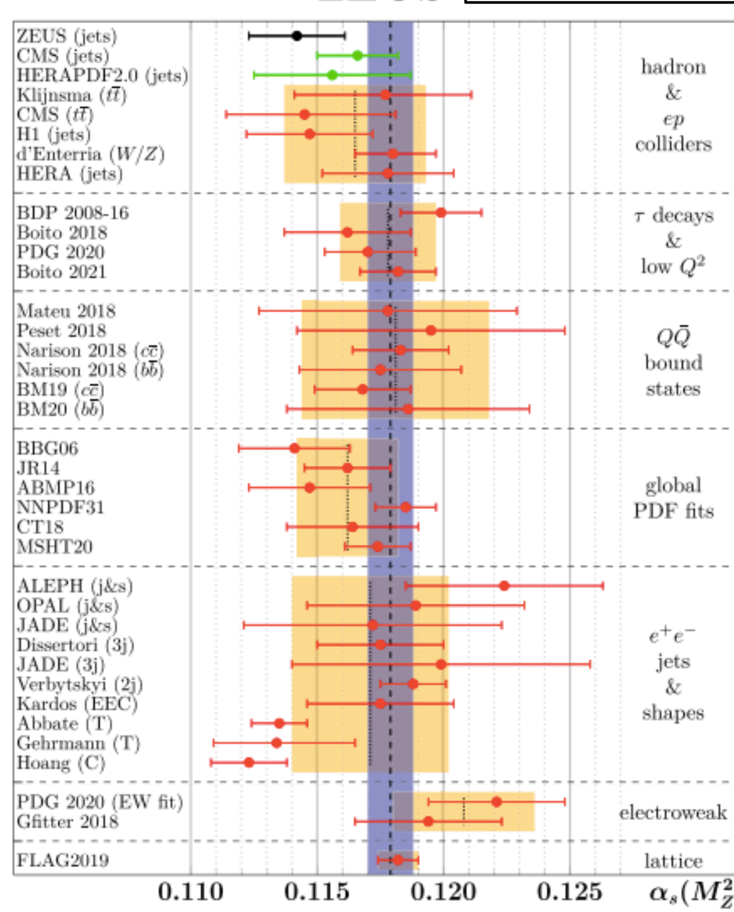
- **HERA**
  - First and only $e^{\pm}p$collider
  - $\sqrt{s} = 318\ GeV$ (HERA II)
  - $L_{int} \sim 360\ pb^{-1}$ (HERA II)
  - Access to low-$x$ ($x_{Bj} \sim 10^{-3}$) with ZEUS detector
  - Variety of existing jet studies
- **ZEUS**
  - General purpose detector
  - Jet reconstruction down to $E_T > 2.5\ GeV$ with $< 4\%$ resolution
  - Two independent luminosity monitors, $\delta L/L\ <\ 2\%$

# Recent jet measurements from HERA

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

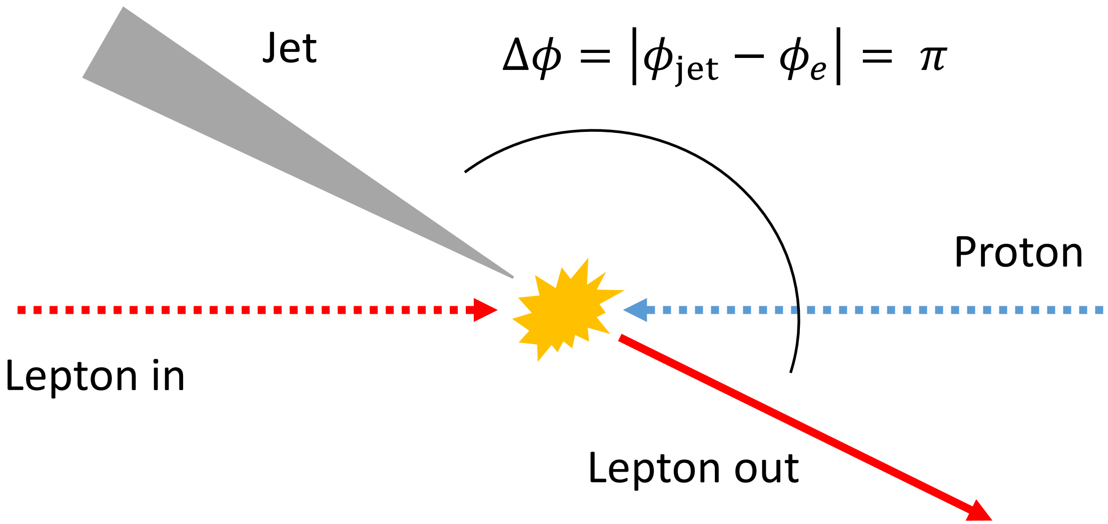



- New jet measurements continue to come from HERA data!

# Introduction




- At DIS Born limit, a jet is produced in an azimuthally back-to-back topology ($\Delta\phi = \pi$) with the outgoing lepton.

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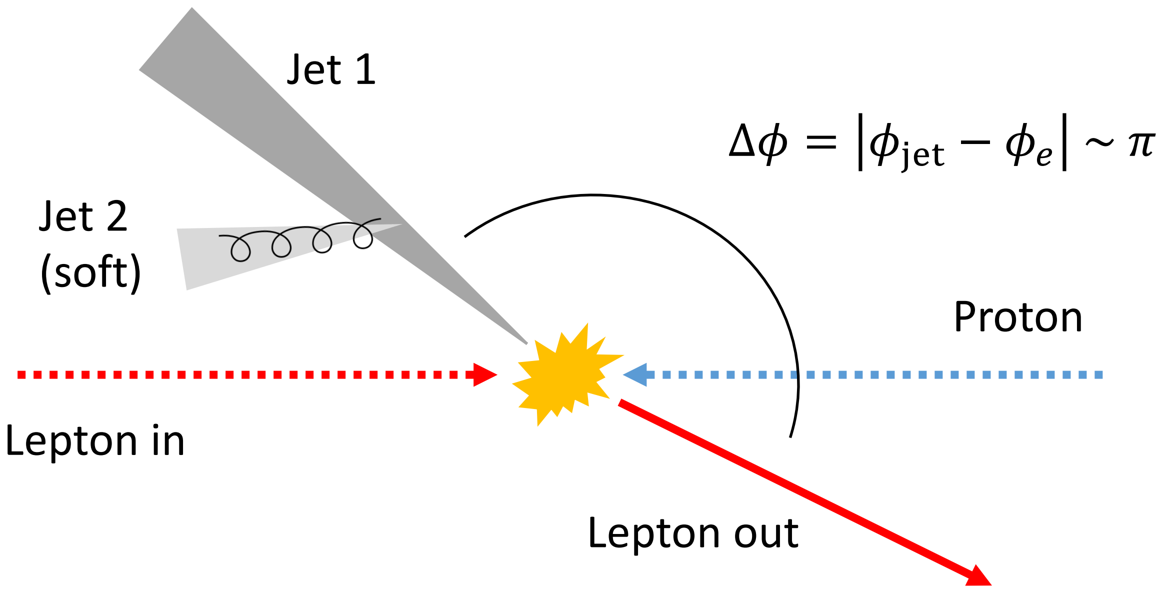


- At DIS Born limit, a jet is produced in an azimuthally back-to-back topology ($\Delta\phi = \pi$) with the outgoing lepton.
- Small deviations from this back-to-back topology occur if the soft gluons are emitted, producing additional jets, and/or if the struck quark carries a non-zero transverse momentum.

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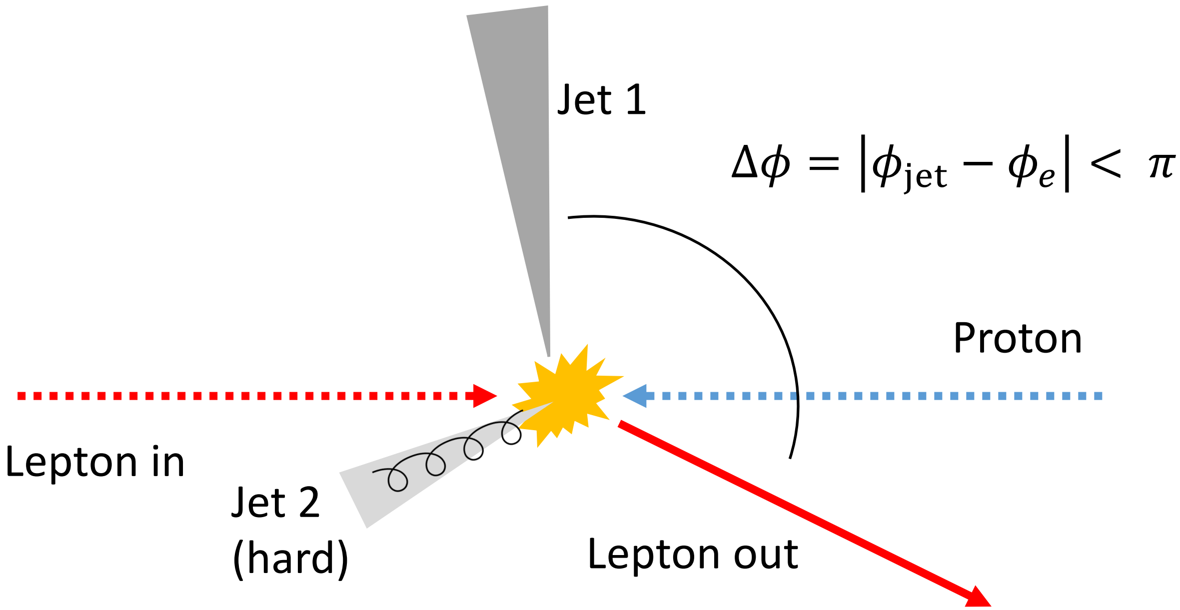


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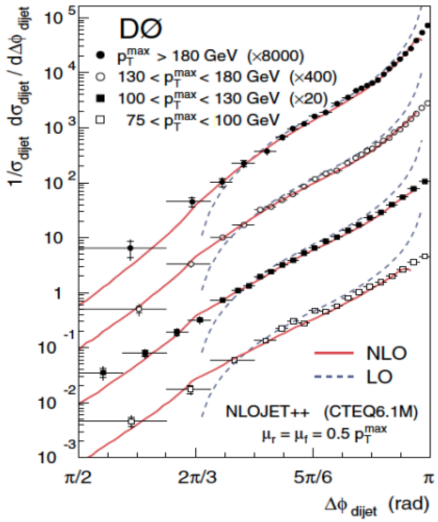
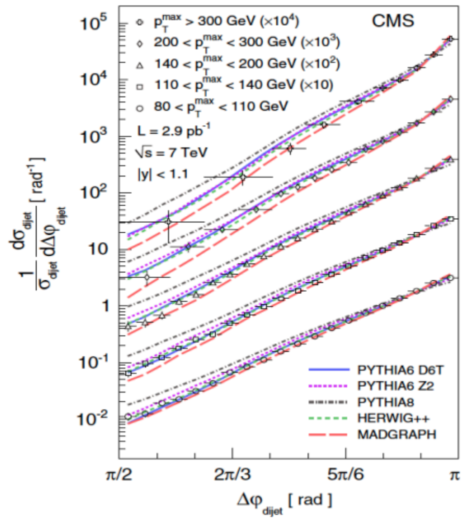
- Small deviations from this back-to-back topology occur if the soft gluons are emitted, producing additional jets, and/or if the struck quark carries a non-zero transverse momentum.
- Large deviations arise if hard jets are produced.

# Previous Studies

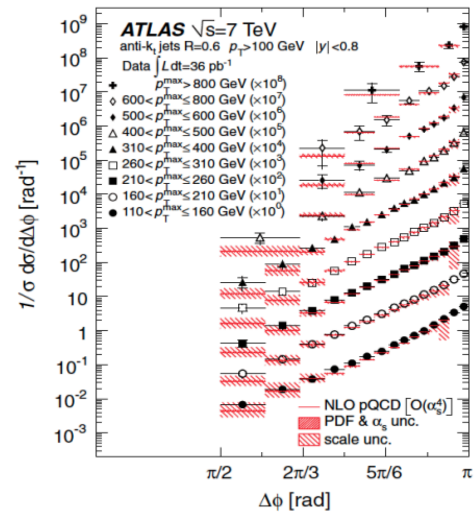
DØ, PRL 94, 221801 (2005)



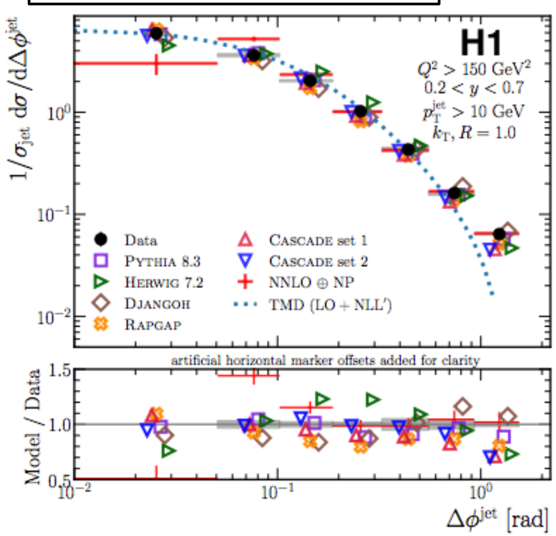

CMS, PRL 106, 122003 (2011)




ATLAS, PRL 106, 172002 (2011)

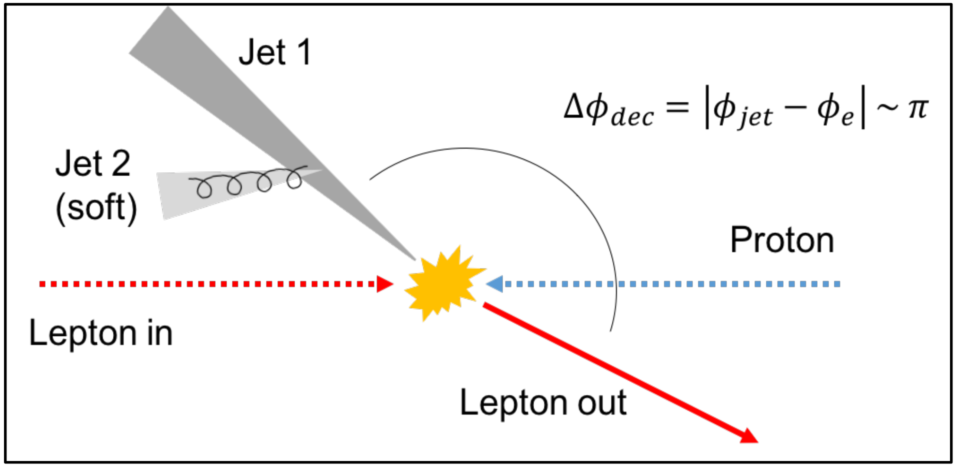


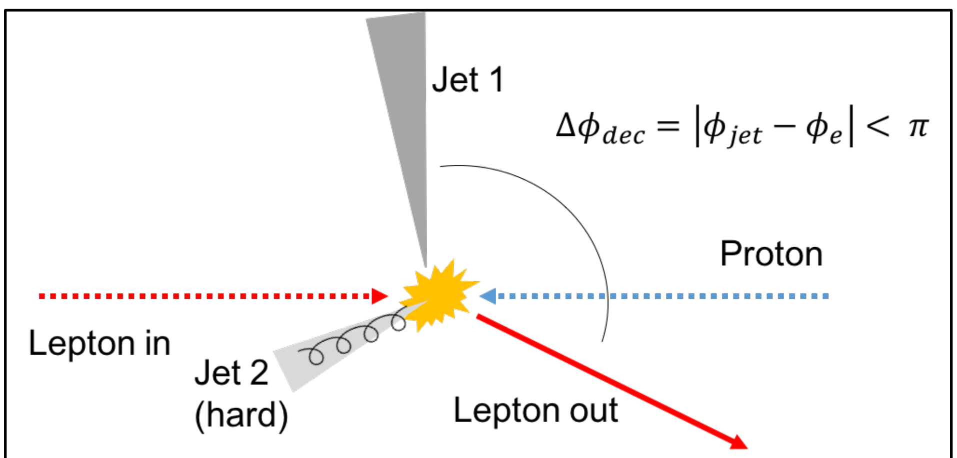

H1, PRL 128 (2022) 13, 132002




- Previous results from Tevatron (DØ) and LHC (ATLAS, CMS)
  - Improvements in data description by high order correction (LO to NLO).
- Recent results from HERA (H1)
  - Cross section unfolded using ML-based method
  - Can access TMD distributions, complementary to SIDIS, <u>**without**</u> explicit description of TMD fragmentation function
    [Liu et al., PRL 122 (2019) 192003, Lui et al., PRD 102 (2020) 094022]
  - Improvements in data description by TMD calculation around the region $\Delta\phi \sim \pi$

# Motivation

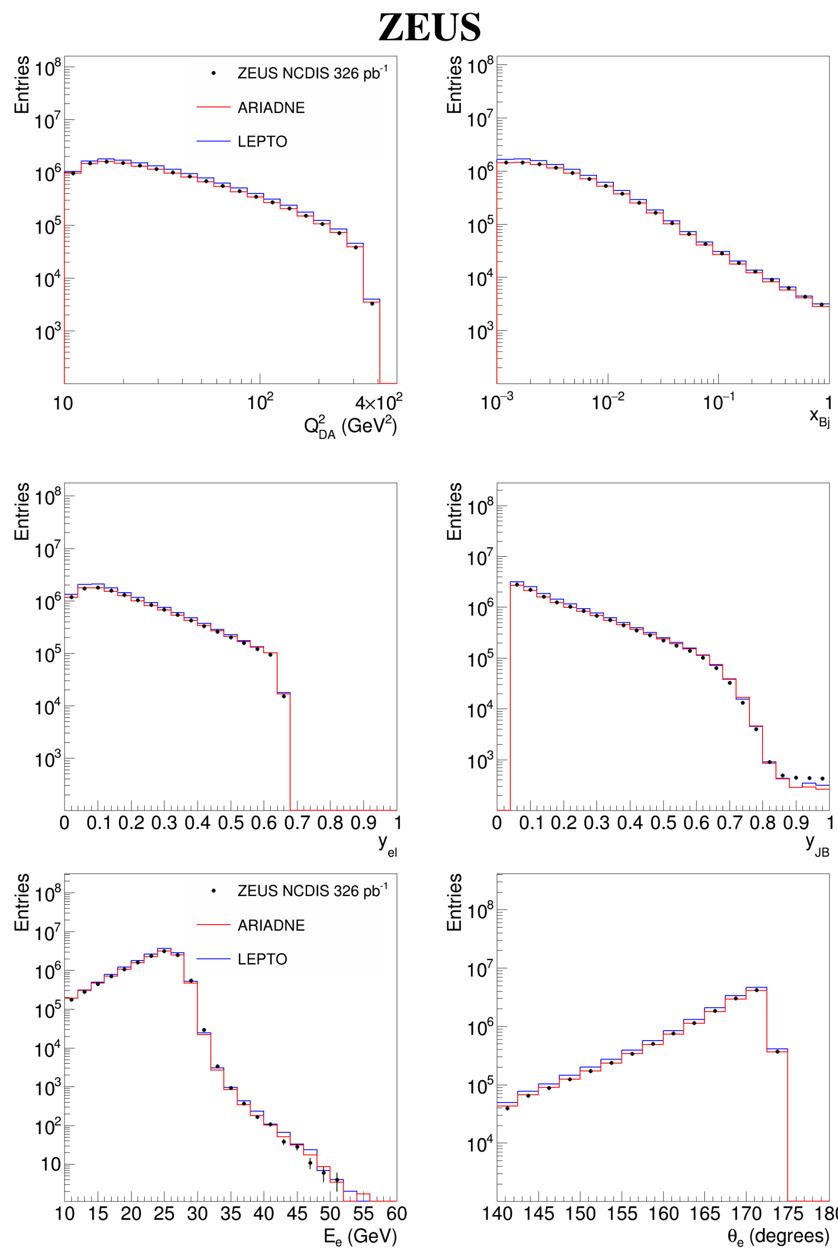



- Jet-lepton correlation probes **both** soft and hard QCD effects **without** explicit description of the additional jets.
- Tests of pQCD and LO+PS models in describing a wide range of QCD phenomena in various ranges of jet-jet-$p_T$, $Q^2$, and $N_{jet}$.
- Can be measured with already-existing HERA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

# Data & MC

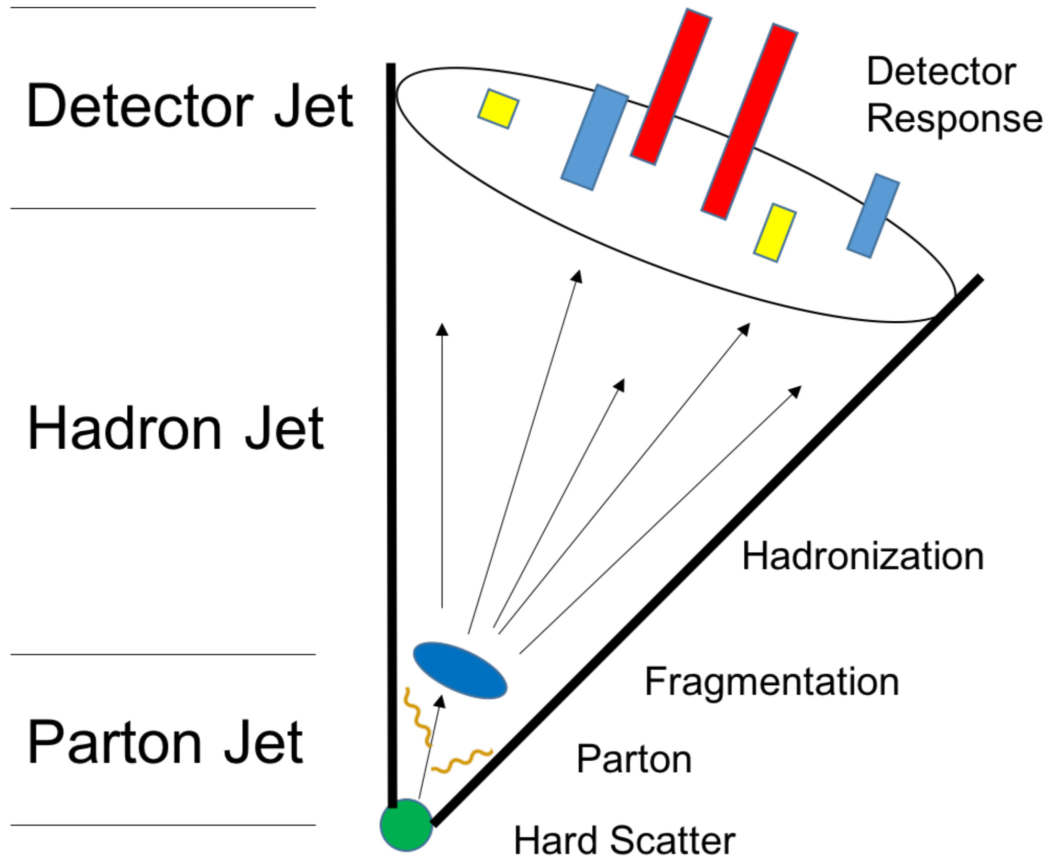
- **Data**
  - HERA II data collected at ZEUS
  - $e^{\pm}p$ collisions at $\sqrt{s} = 318\ GeV$
  - $L_{int} = 326\ pb^{-1}$
- **Simulations**
  - **ARIADNE** colour-dipole model
  - **LEPTO** leading-log parton cascade
- **Kinematic range**
  - $10\ GeV^2 < Q^2 < 350\ GeV^2$
  - $0.04 < y < 0.7$
  - Covers a wide range in $x_{Bj}$, $0.0002 < x_{Bj} < 0.2$
- **Scattered lepton**
  - SINISTRA algorithm
  - $E_e > 10\ GeV$



# Jet reconstruction

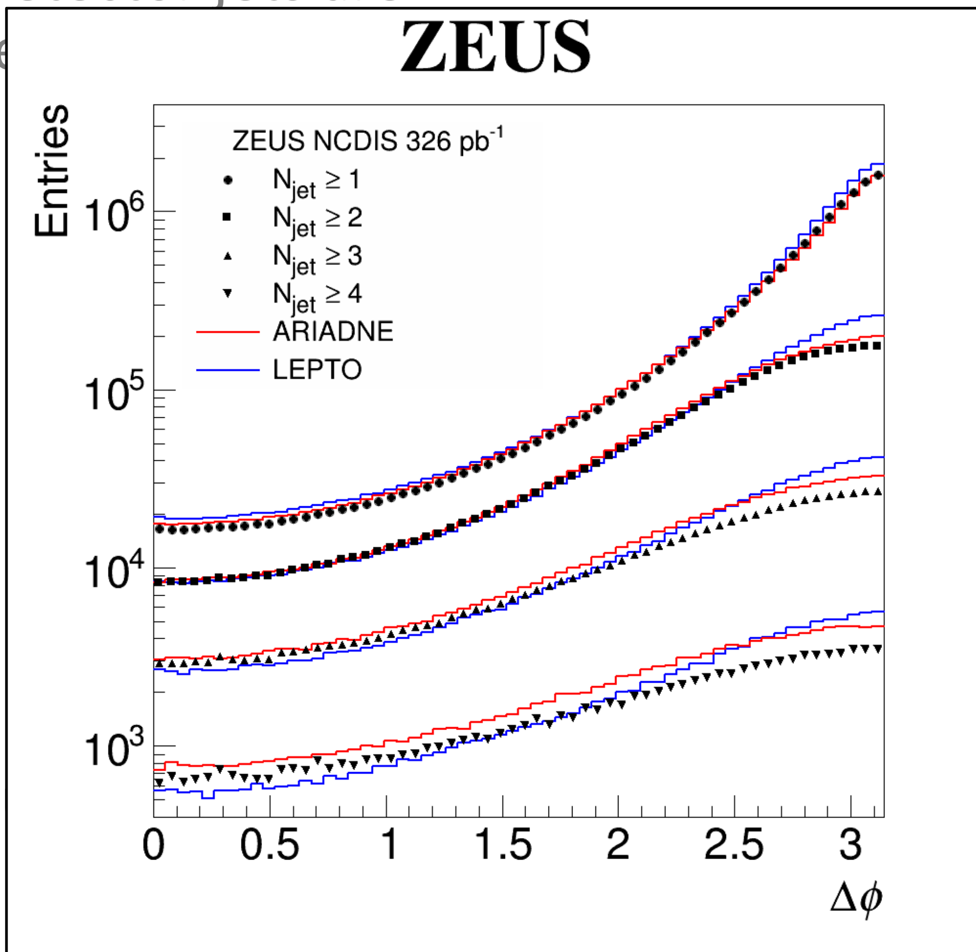
- Detector jets are reconstructed using:
  - All calorimeter & tracking signal (EFOs), except for scattered electron as input
  - $k_T$-clustering algorithm, $R = 1$
  - $E$-scheme, using 4-vector of input particles in the lab frame
  - Facilitated in FastJet3.4.0
    [M. Cacciari et al., EPJC 72 (2012) 1896]

- Kinematic range (jet)
  - $2.5\ GeV < p_{T,jet} < 30\ GeV$
  - High-performance calorimetry allows access to low-$p_T$ regime.



# Jet reconstruction

- Detector jets are re




- 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.

$$\Delta\phi = |\phi_{jet} - \phi_e|$$

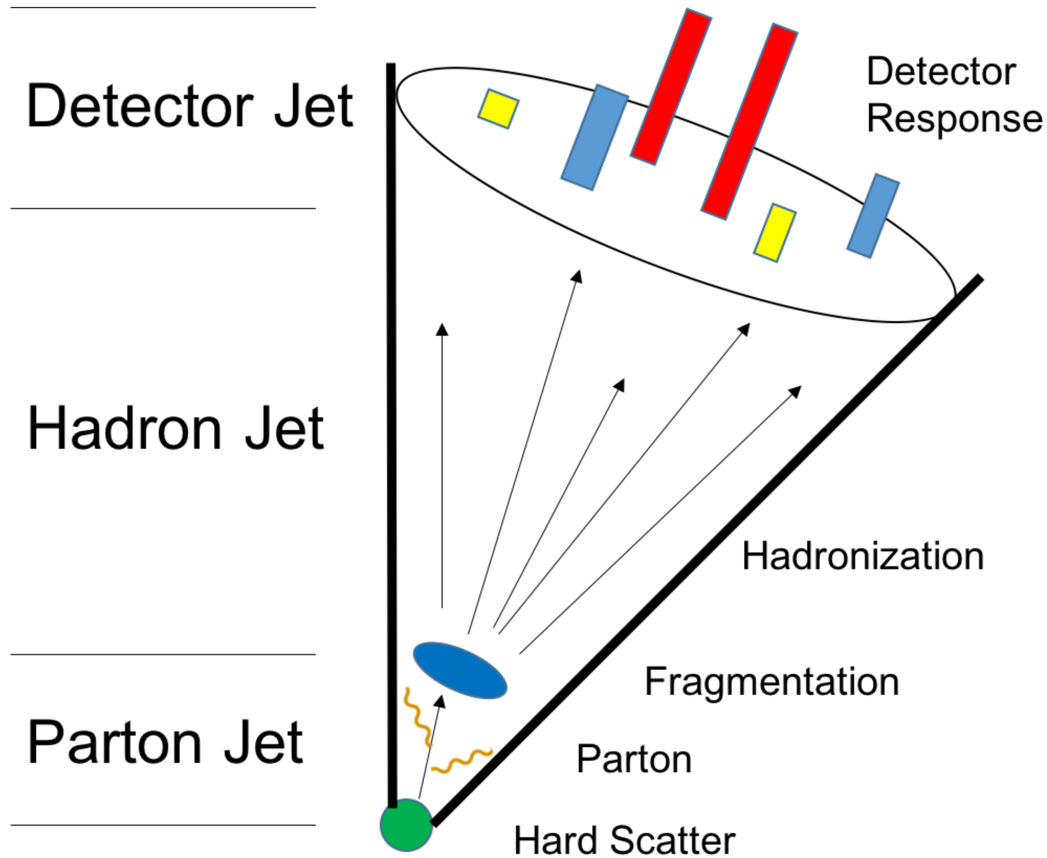
- Better description of data by ARIADNE

- F

covering low $p_T$ regime

# 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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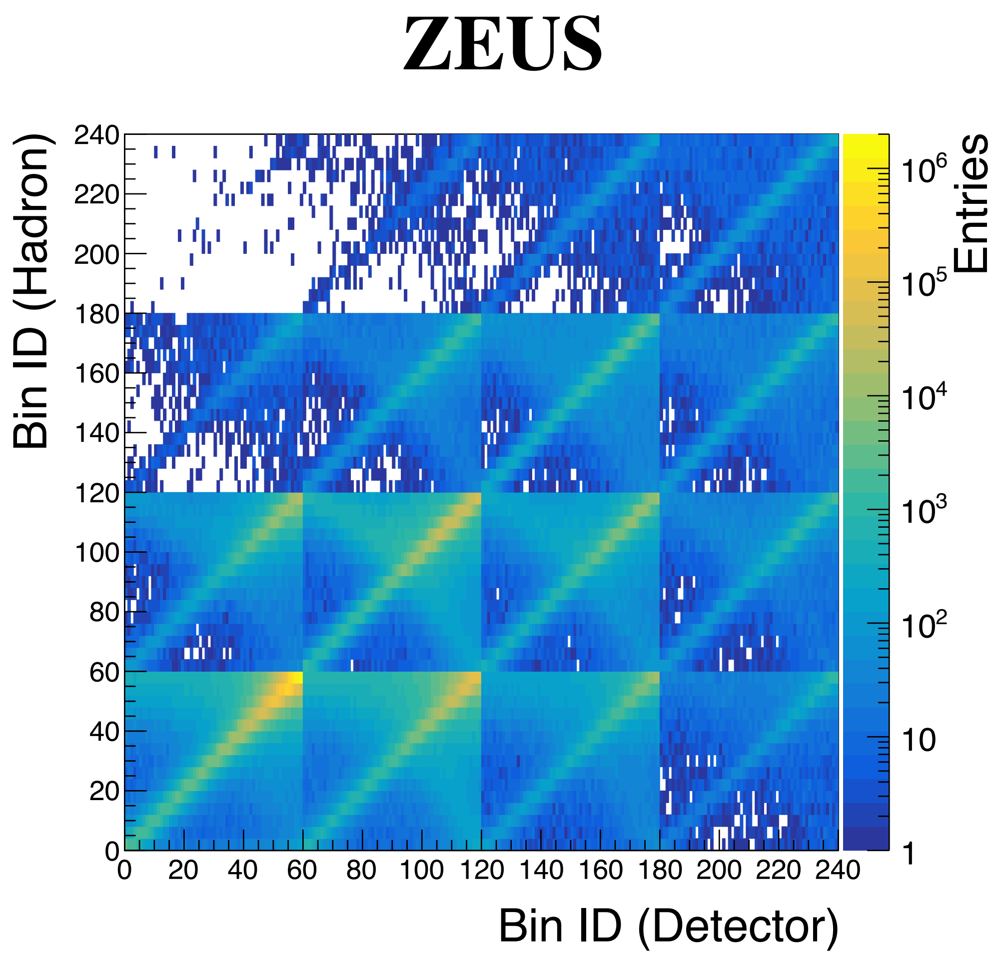
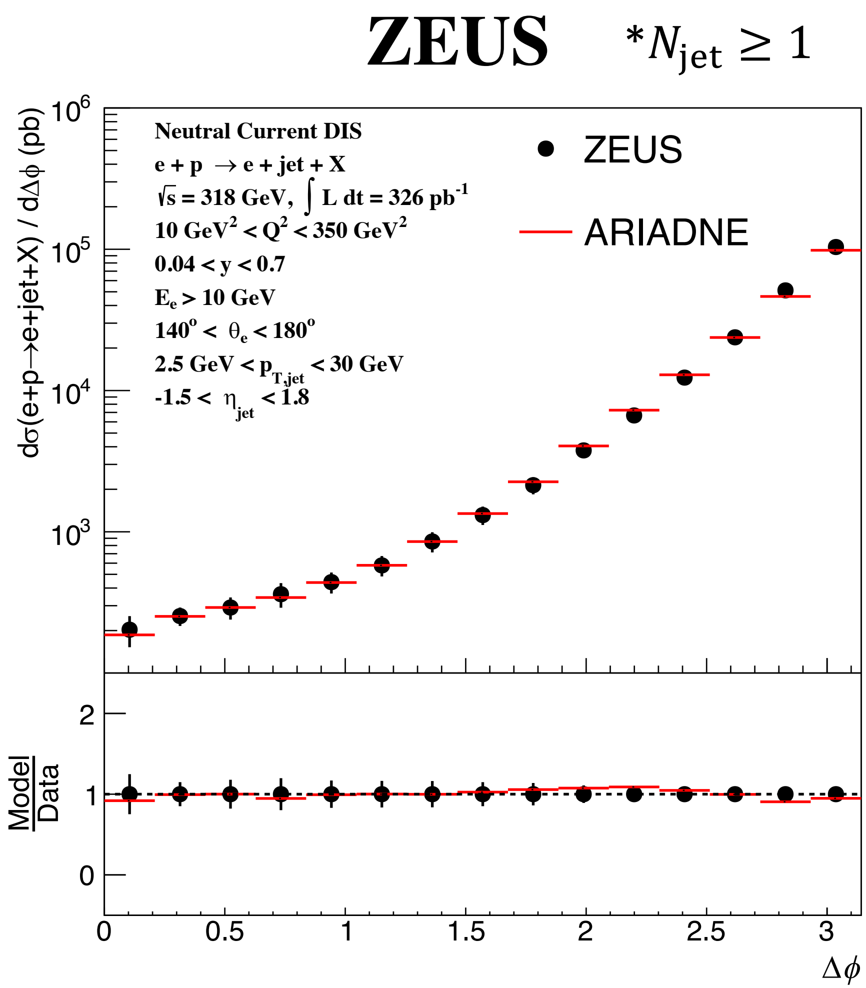



*Bin ID = [0-60 for $0 < \Delta\phi < \pi$] + 60 × $(N_{jet} - 1)$

# Differential cross section



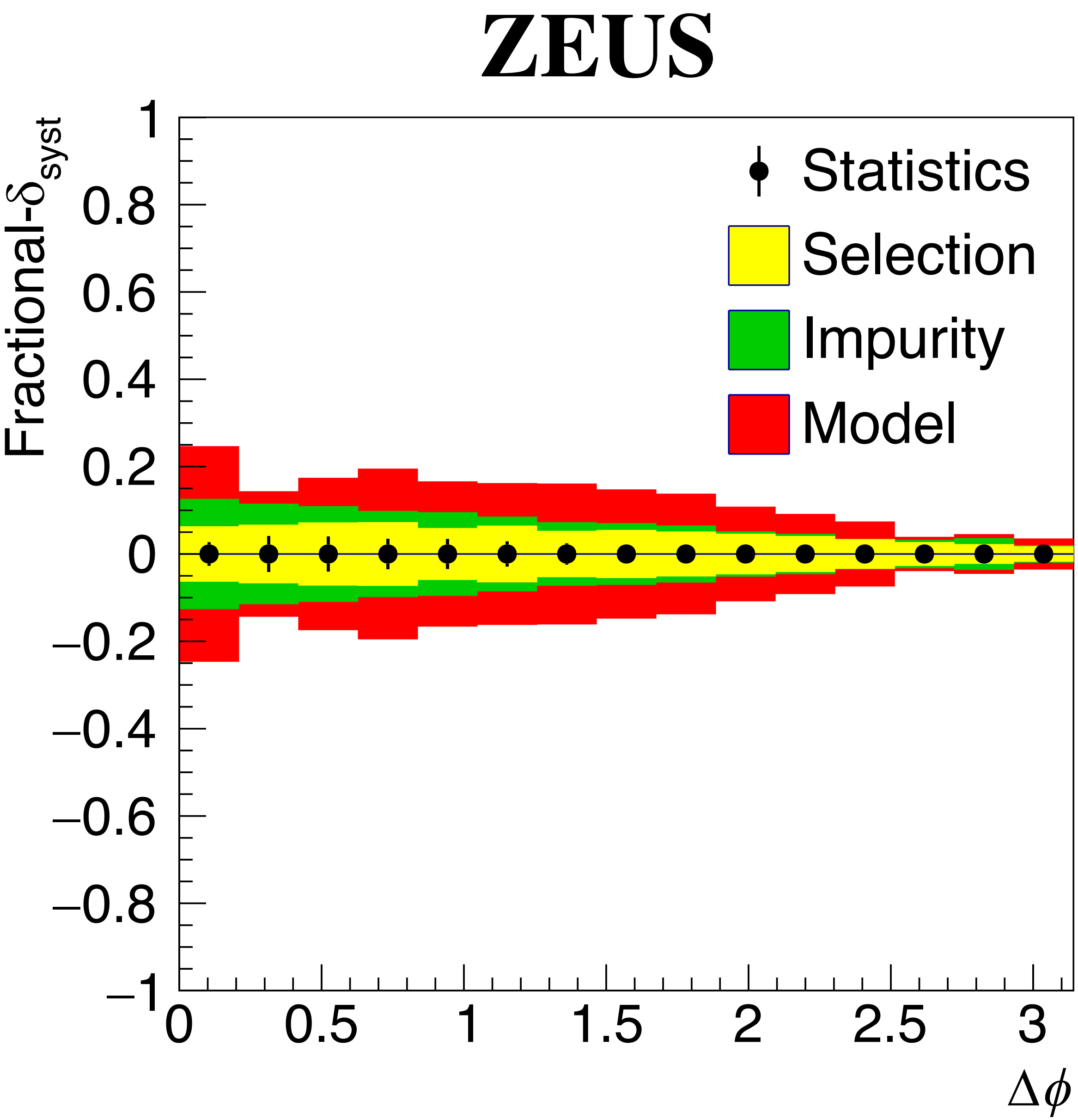

- Differential cross section of $e + p \to e + \text{jet}^{\text{lead}} + X$ defined as:

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

  - $N_{had}$: 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.

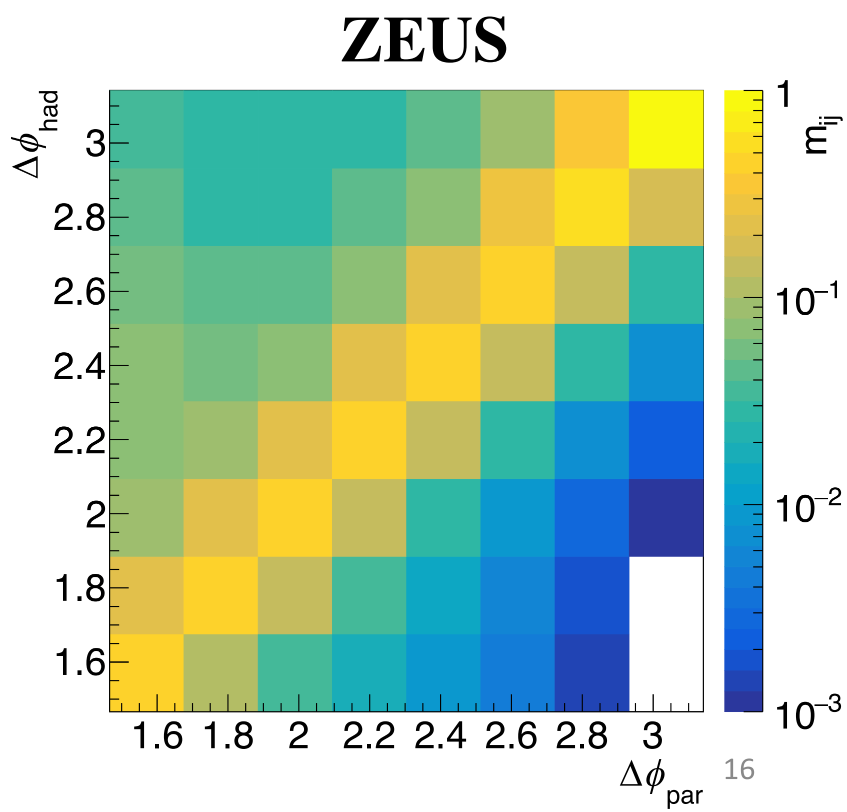
# Systematic uncertainties




- Selection cuts varied by their corresponding resolution
- Uncertainty associated with the correction procedure for event-level mismatch btw. detector-level pairs and hadron-level pairs (Impurity) estimated by comparing the results using an alternative approach.
- Dependences on simulation model (ARIADNE) used in unfolding/cross-section calculation are estimated by comparing the result obtained with LEPTO.

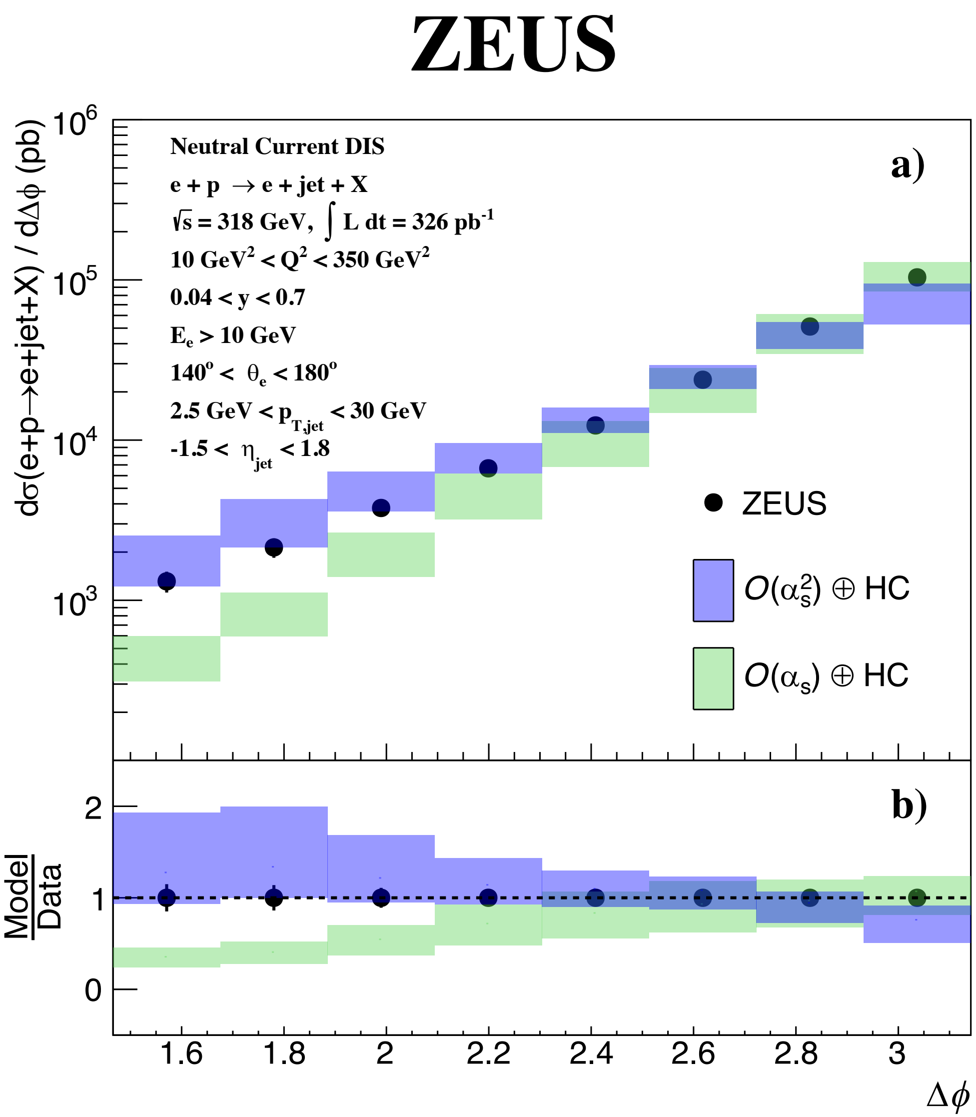
# Theory prediction

- 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 $O(\alpha_s^2)$) 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



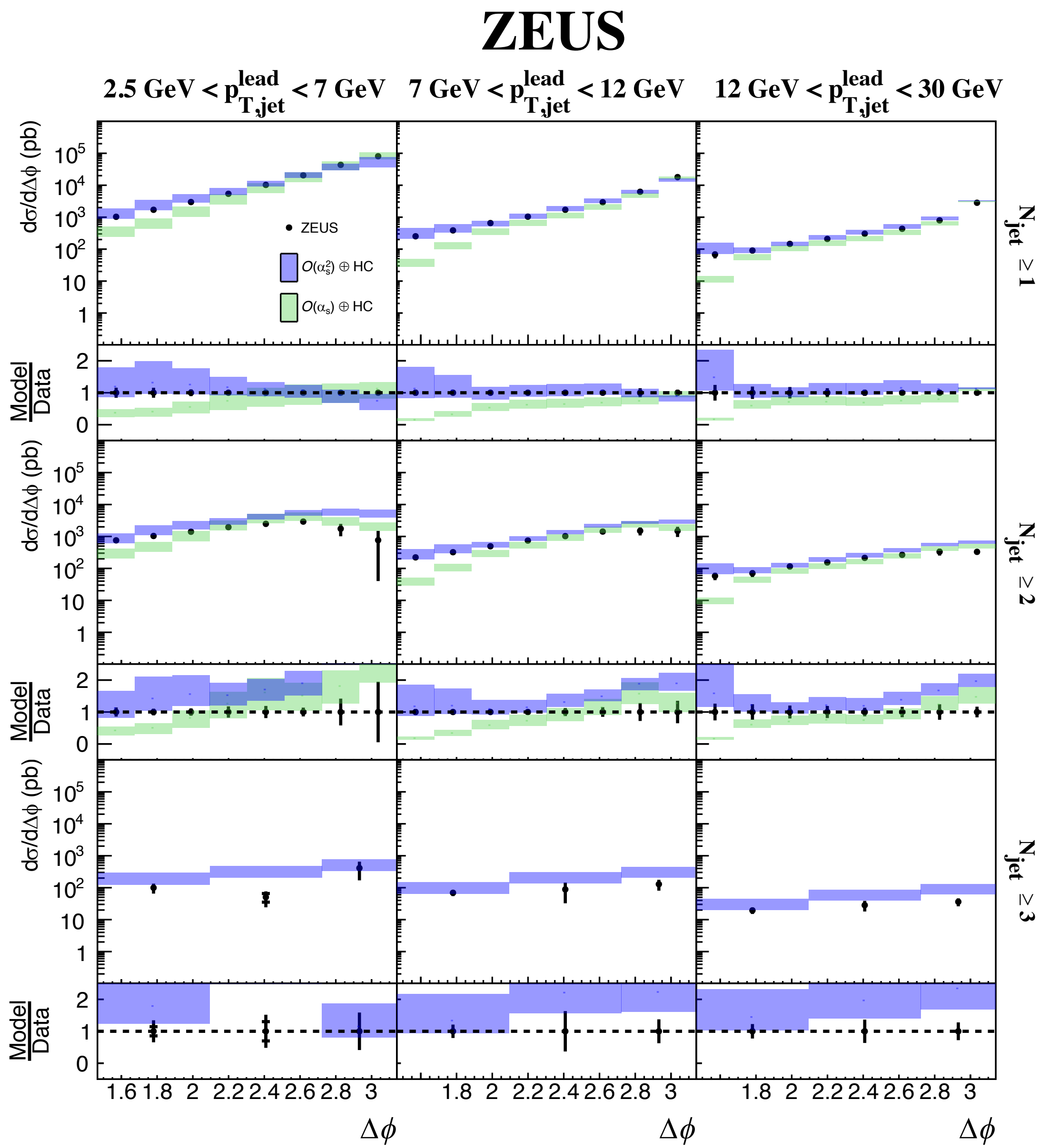
# Results (Inclusive)

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



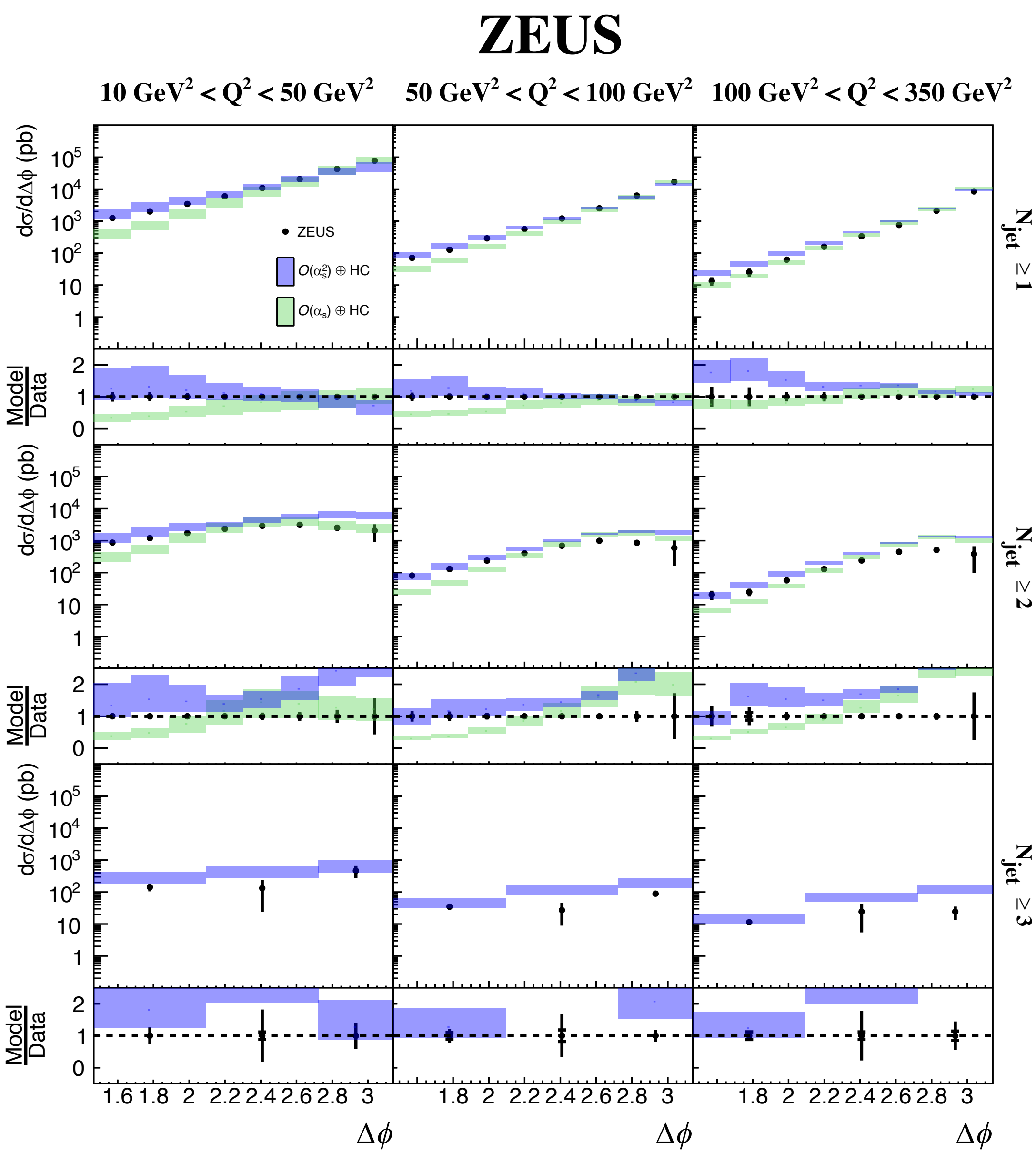

- For $\Delta\phi = \pi$, $O(\alpha_s^2)$ is NNLO and $O(\alpha_s)$ is NLO. For all the other bins, $O(\alpha_s)$ is LO.
- Clear improvements in $O(\alpha_s^2)$, especially $\Delta\phi < 3\pi/4$
- No significant improvement in $\Delta\phi \to \pi$, which is characterized by soft QCD and $k_T$ effects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

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



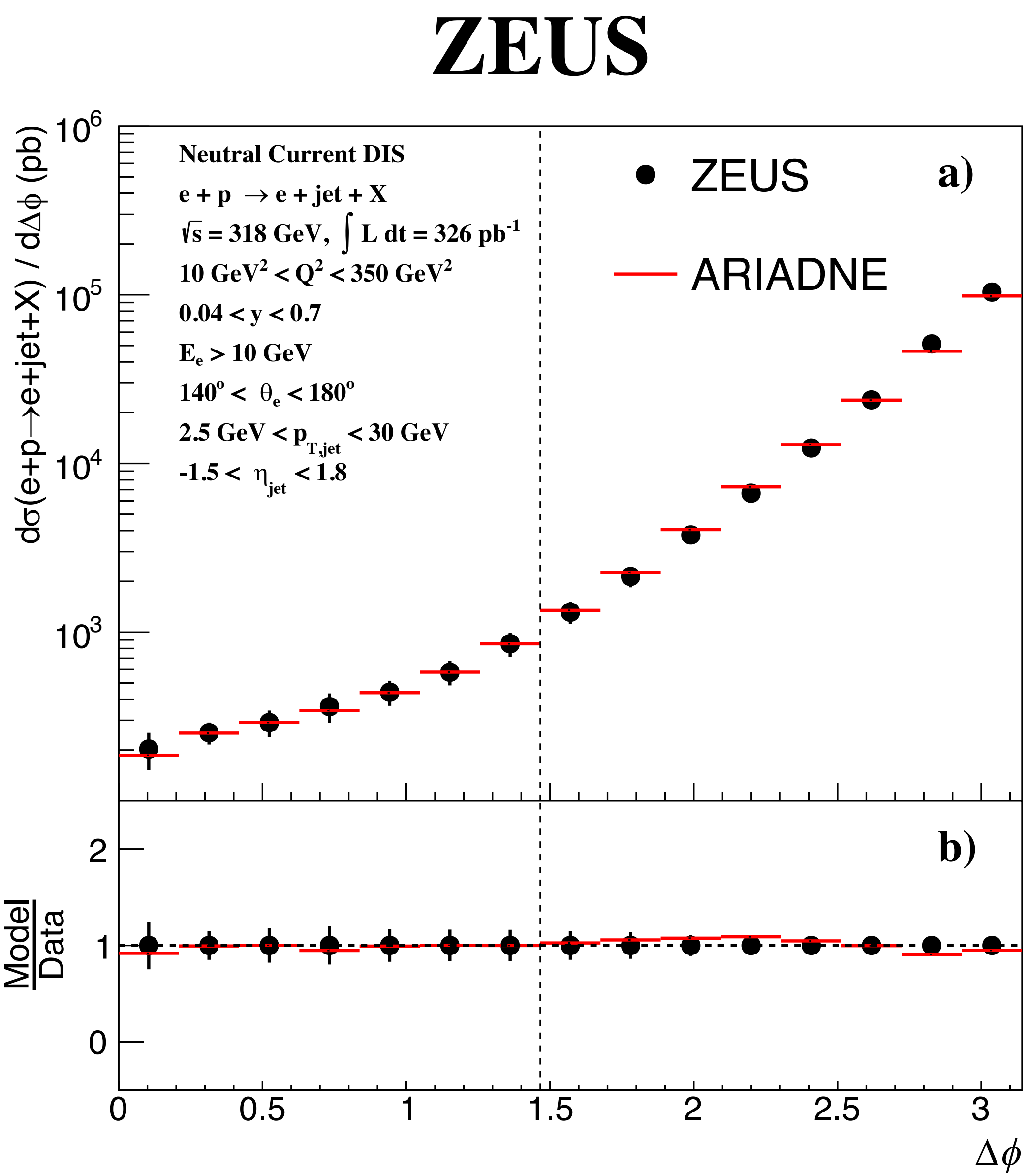

- As for inclusive measurement, $O(\alpha_s^2)$ improves over $O(\alpha_s)$
- Only $O(\alpha_s^2)$ for $N_{jet} \geq 3$ as it is LO
- Good description of data in low-$p_T$ regime down to $p_{\mathrm{T,jet}}^{\mathrm{lead}} > 2.5\ GeV$
- Enhanced events with reduced $\Delta\phi$ (flatter in terms of shape)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

# Results ($Q^2$-dependent)



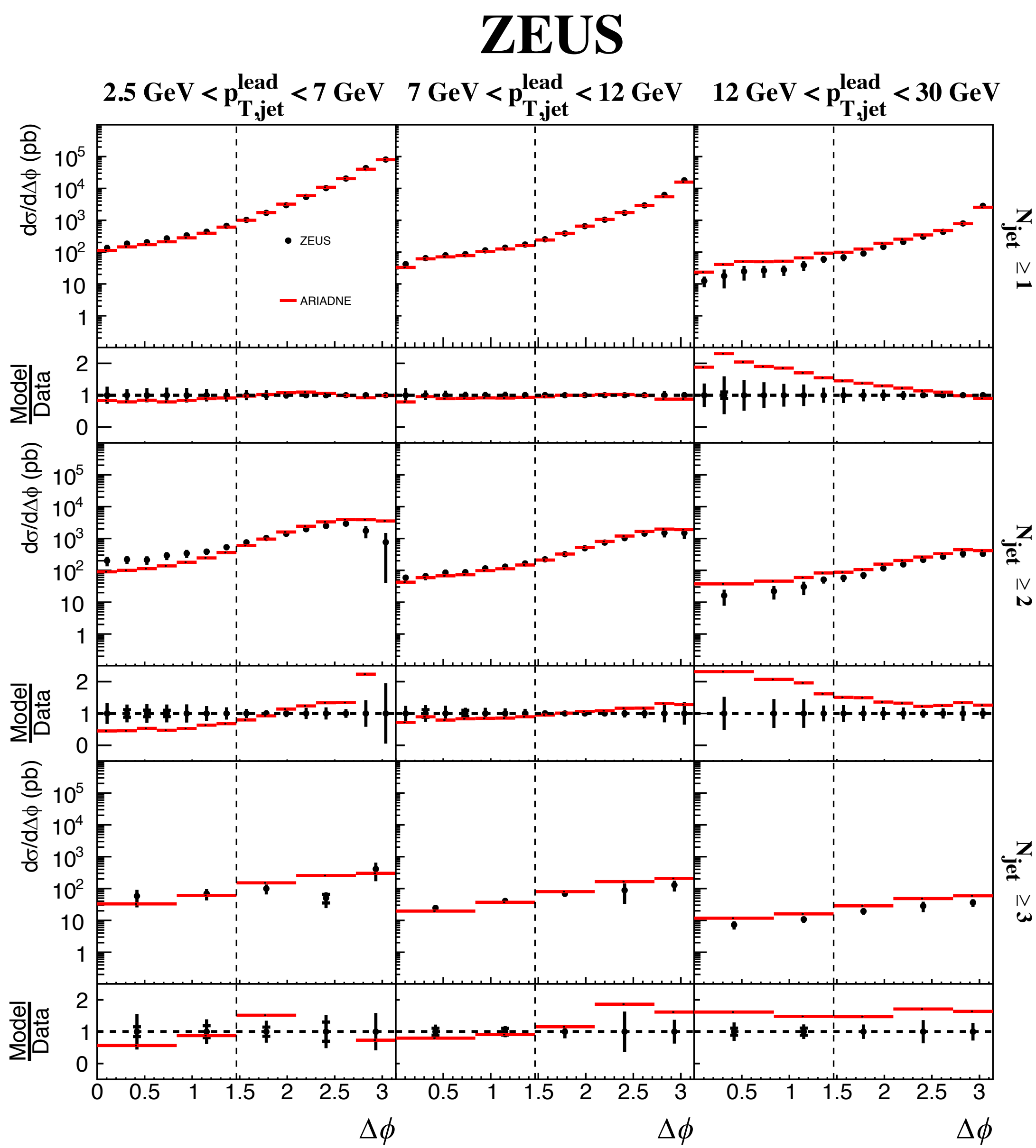

- As for inclusive measurement, $O(\alpha_s^2)$ improves over $O(\alpha_s)$
- Enhancement in slope ($\Delta\phi < 3\pi/4$) with increasing $Q^2$ as higher order contributions and the kinematic space for additional jets diminish.
- Consistent with hadron experiments where the highest momentum jet in dijet is analogous to electron in DIS (when one of the two jets carries less $p_T$ than DIS electron)

# Results (ARIADNE, Inclusive)



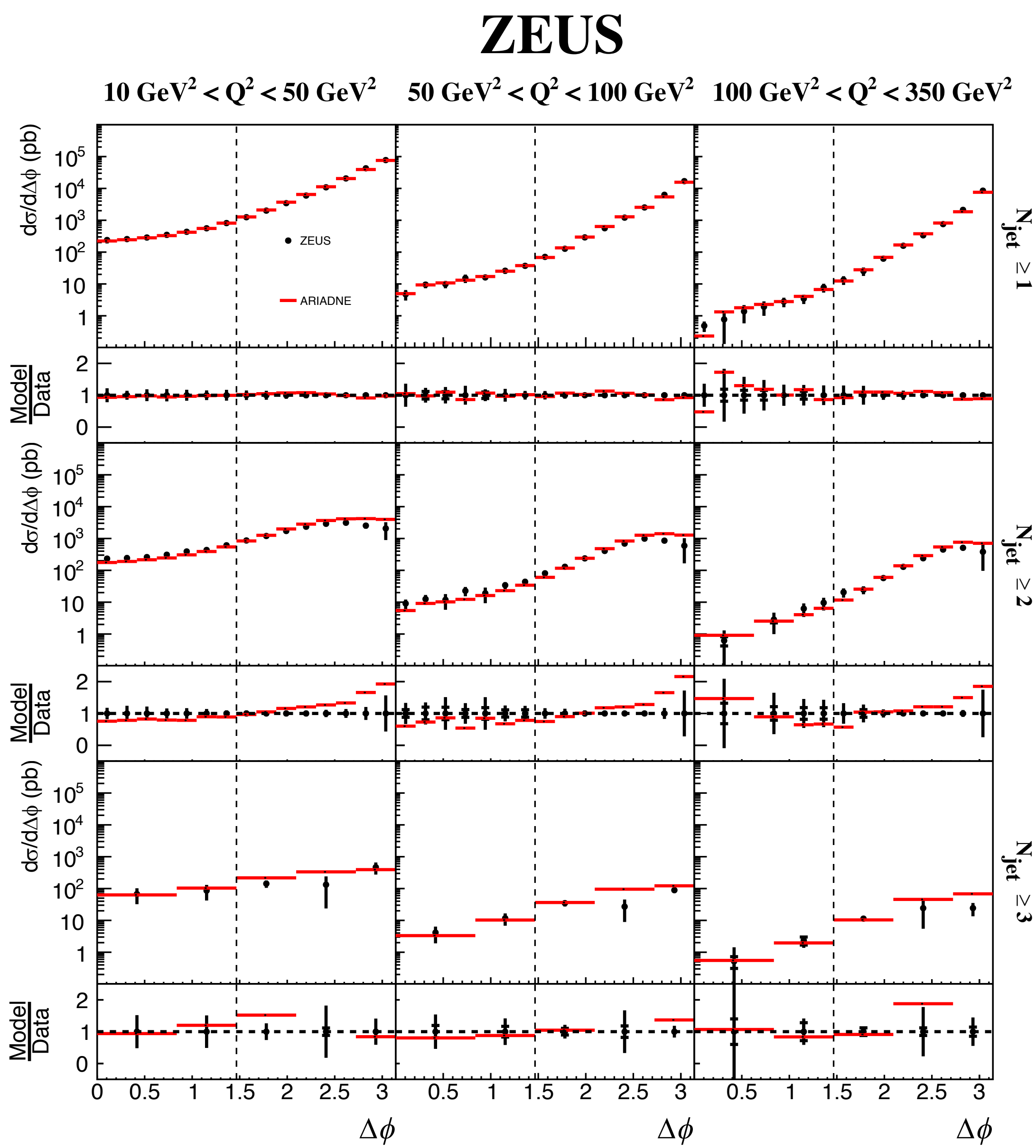

- Excellent description of data by ARIADNE, although higher order processes are not fully represented in matrix element

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




- 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

# Results (ARIADNE, $Q^2$-dependent)

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# Summary & Outlook

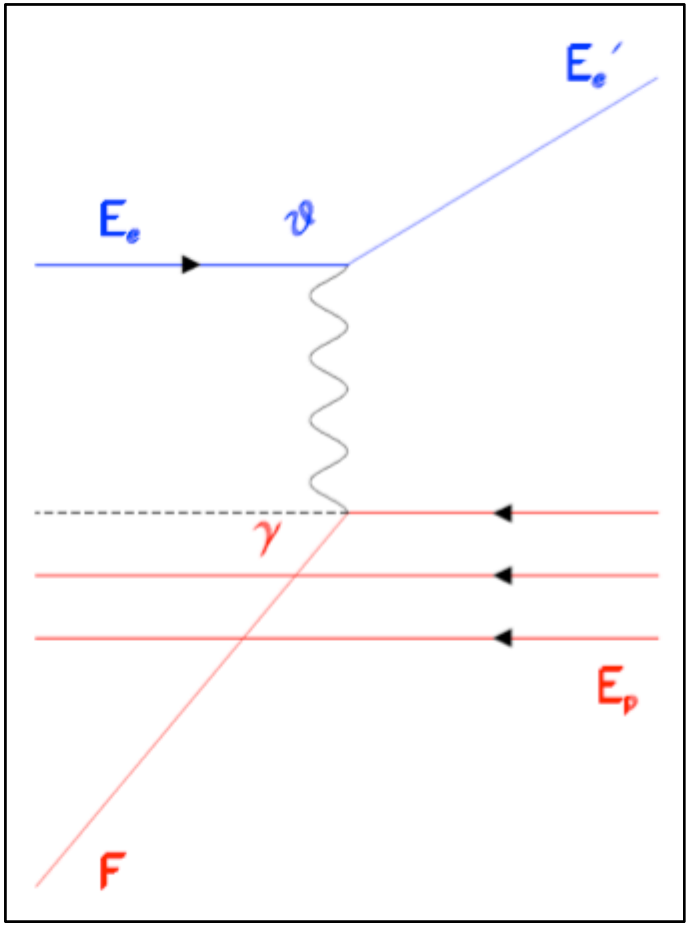
- Differential cross sections of jet production in NCDIS has been measured as functions of $\Delta\phi$ with HERA II data
  - Uncertainty dominated by model-dependent assumptions made during cross section extraction procedure.
  - Performance of pQCD has been tested in the low-$p_{T,jet}$ regime ($p_{T,jet} > 2.5\ GeV$).
  - Properly-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.

- Outlook
  - Paper submission very (very) soon!

# Backup

# DIS event kinematics

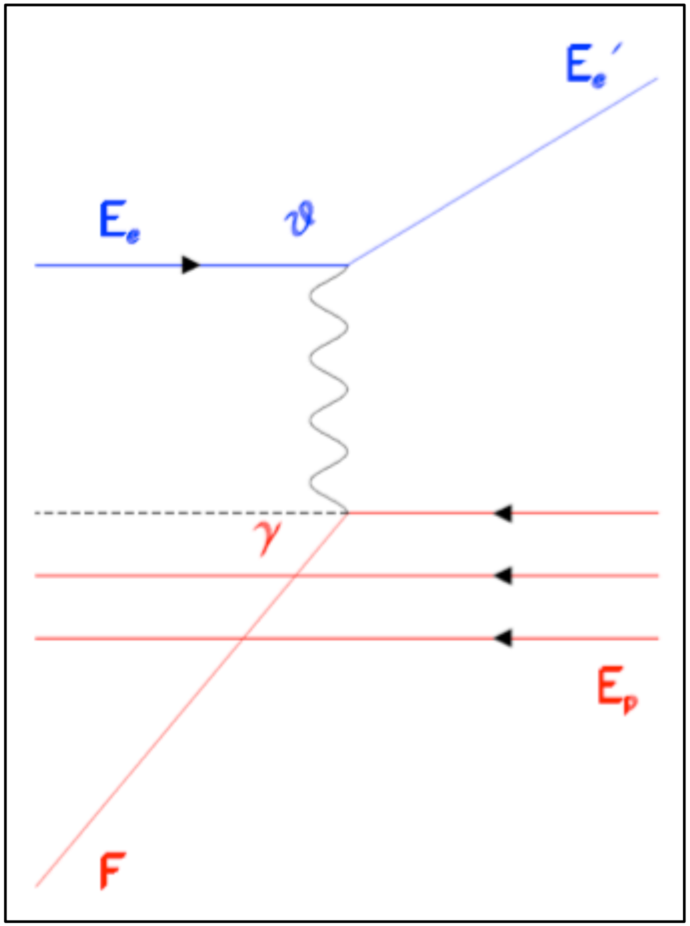
EIC wiki
(wiki.bnl.gov/eic)




- 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
  - $10\ GeV^2 < Q^2_{DA} < 350\ GeV^2$ (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
  - $E_e' > 10\ GeV$

# Data/Simulation

- HERA II data collected with the ZEUS detector
  - $e^{\pm}p$ collisions at $\sqrt{s} = 318\ GeV$
  - $L_{int} = 326\ pb^{-1}$ (05-07)
- NCDIS selection
  - Based on previous ZEUS jet measurements
    [PLB 691 (2010) 127, PLB 715 (2012) 88, JHEP 01 (2018) 032]
  - $10\ GeV^2 < Q^2_{DA} < 350\ GeV^2$
  - $y_{JB} > 0.04,\ y_{el} < 0.7$
  - $E_e > 10\ GeV$
  - $140° < \theta_e < 175°$* (effective)
- Jet reconstruction
  - kT algorithm with E-scheme in the lab frame, $R = 1$
  - ZUFO 4-vector as input (excld. SINISTRA electron)
  - FastJet 3.4.0
  - $2.5\ GeV < p_{T,jet} < 30\ GeV$
  - $-1.5 < \eta_{jet} < 1.8$
- MC sample
  - ZEUS standard low-$Q^2$ ($Q^2 > 5\ GeV^2$) sample
  - Colour dipole model with ARIADNE 4.12 /DJANGOH 1.6
    - JETSET 7.4.1 for hadronisation, HERACLES 4.5 for QED radiation
    - CTEQ5D PDF sets, ALEPH $e^+e^- \to Z$ 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