# Measurement of azimuthal decorrelation between the leading jet and the scattered lepton in deep inelastic scattering at HERA
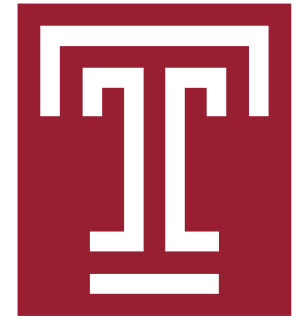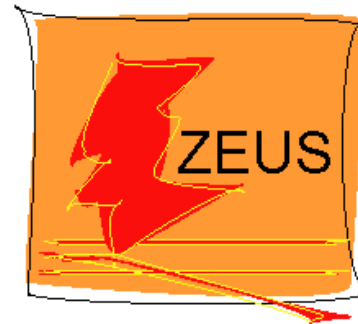
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For the ZEUS collaboration

# HERA / ZEUS







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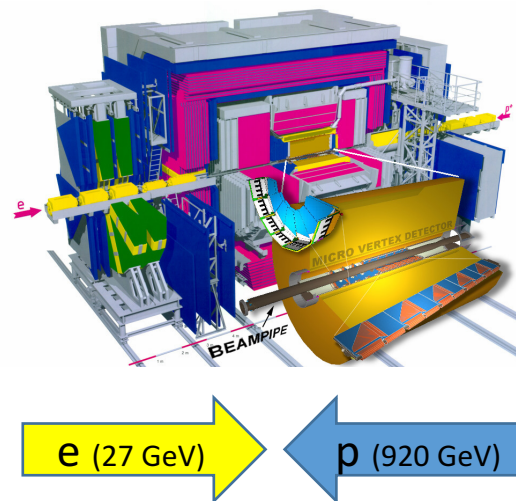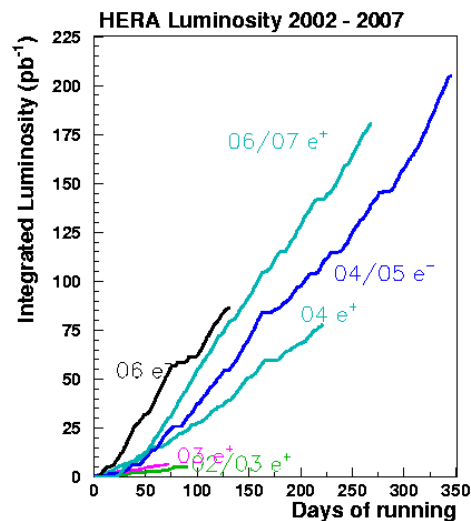
- ZEUS
  - General purpose detector
  - Jet reconstruction down to $E_T > 2.5\ GeV$ with $< 4\%$ resolution.
  - Two independent luminosity monitors, $\delta L/L \sim 2\%$.

# Previous Jet Results at HERA

:

- Inclusive jets in photoproduction
  (Nucl. Phys. B864 (2012), 1-37)

- Isolated photons accompanied by jets in DIS
  (PLB 715 (2012) 88-97)

- Isolated photons plus jets in PHP
  (PLB (2014) Volume 730, 293-301)

- More on isolated photons plus jets in PHP
  (JHEP 2014 (23))

- Diffractive di-jet production in DIS
  (EPJC 76 (2016) 16)

- Diffractive photoproduction of isolated photons at HERA
  (PRD 96 (2017) 032006)

- Further studies of isolated photon production with a jet in deep inelastic scattering at HERA
  (JHEP (2018) 2018: 32)

- Azimuthal correlation in photoproduction and deep inelastic ep scattering at HERA.
  (JHEP (2021) 102)

- Measurement and QCD analysis of inclusive jet production in deep inelastic scattering at HERA
  (Preliminary)
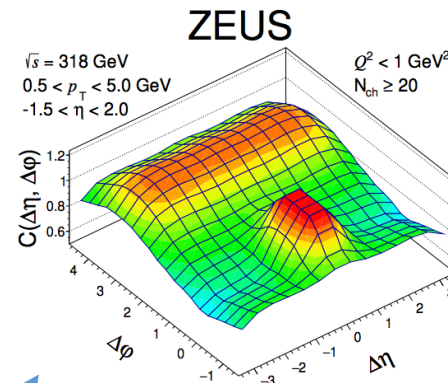


(a) Photoproduction.
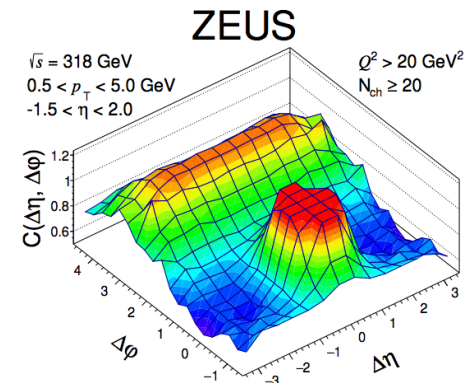
(b) NC DIS with $Q^2 > 20\,\text{GeV}^2$.
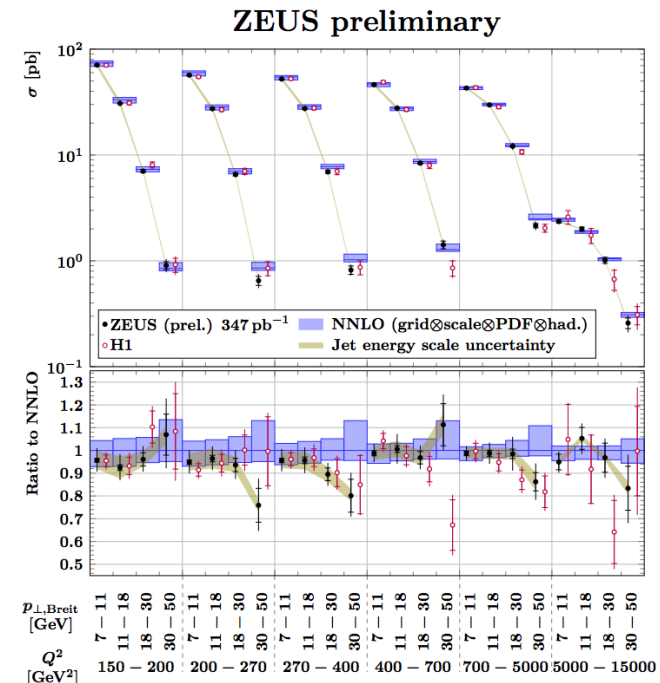
# Jet-lepton decorrelation
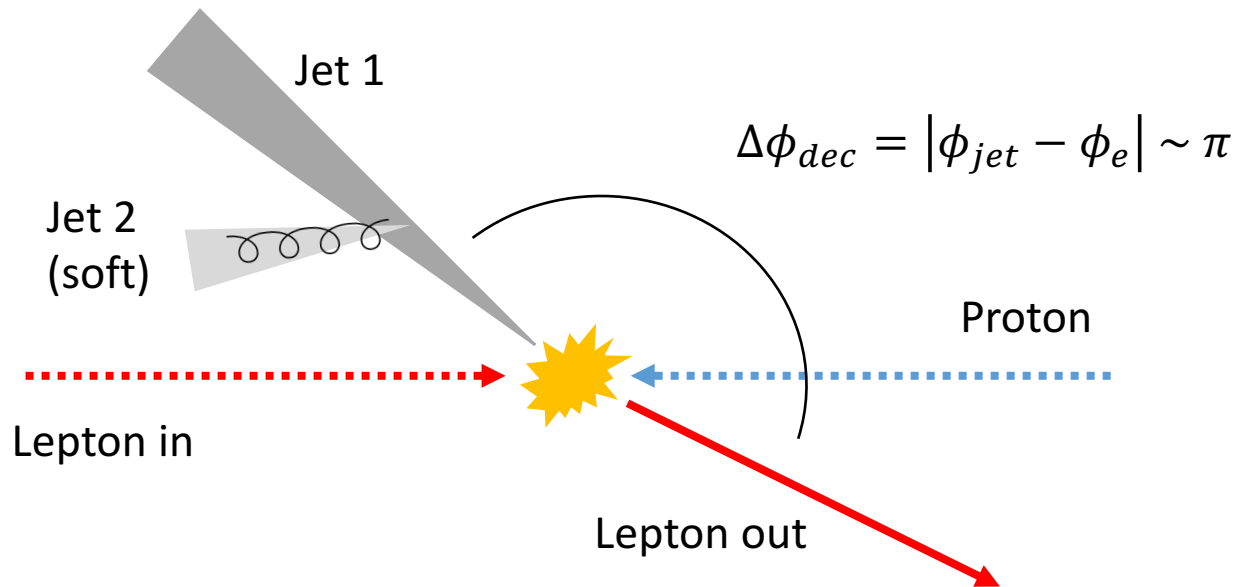


$$\Delta\phi_{dec} = \left|\phi_{jet} - \phi_e\right| \sim \pi$$

- In jet production events in DIS, the jet is produced back-to-back ($\Delta\phi_{dec} = \pi$) with respect to the outgoing lepton.

- Small deviations from $\Delta\phi_{dec} = \pi$ may arise if the struck quark carries a non-zero transverse momentum, or when the process involves soft gluon radiation.

# Jet-lepton decorrelation



$$\Delta\phi_{dec} = \left|\phi_{jet} - \phi_e\right| < \pi$$

- In jet production events in DIS, the jet is produced back-to-back ($\Delta\phi_{dec} = \pi$) with respect to the outgoing lepton.

- Large deviations from $\Delta\phi_{dec} = \pi$ may arise if extra jets are formed from hard QCD radiation.

# Jet-lepton decorrelation



Left panel:
Jet 1
Jet 2 (soft)
$\Delta\phi_{dec} = |\phi_{jet} - \phi_e| \sim \pi$
Proton
Lepton in
Lepton out

Right panel:
Jet 1
$\Delta\phi_{dec} = |\phi_{jet} - \phi_e| < \pi$
Proton
Lepton in
Jet 2 (hard)
Lepton out
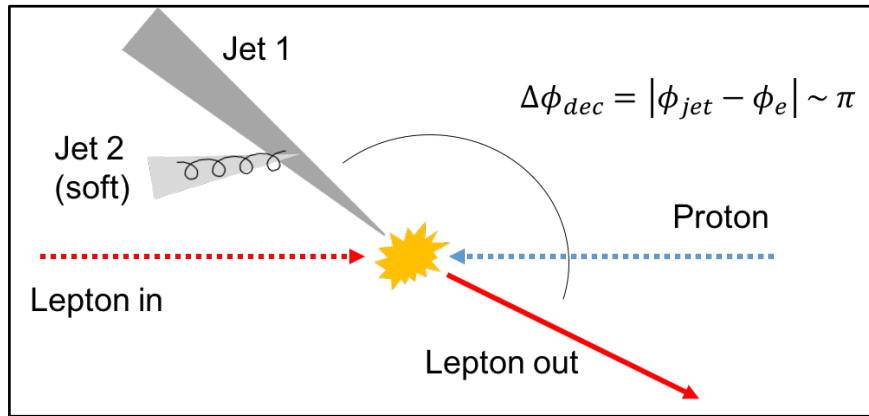
- Jet-lepton decorrelation can be used to probe soft and hard QCD radiation effects **without** explicit description of the additional jets.
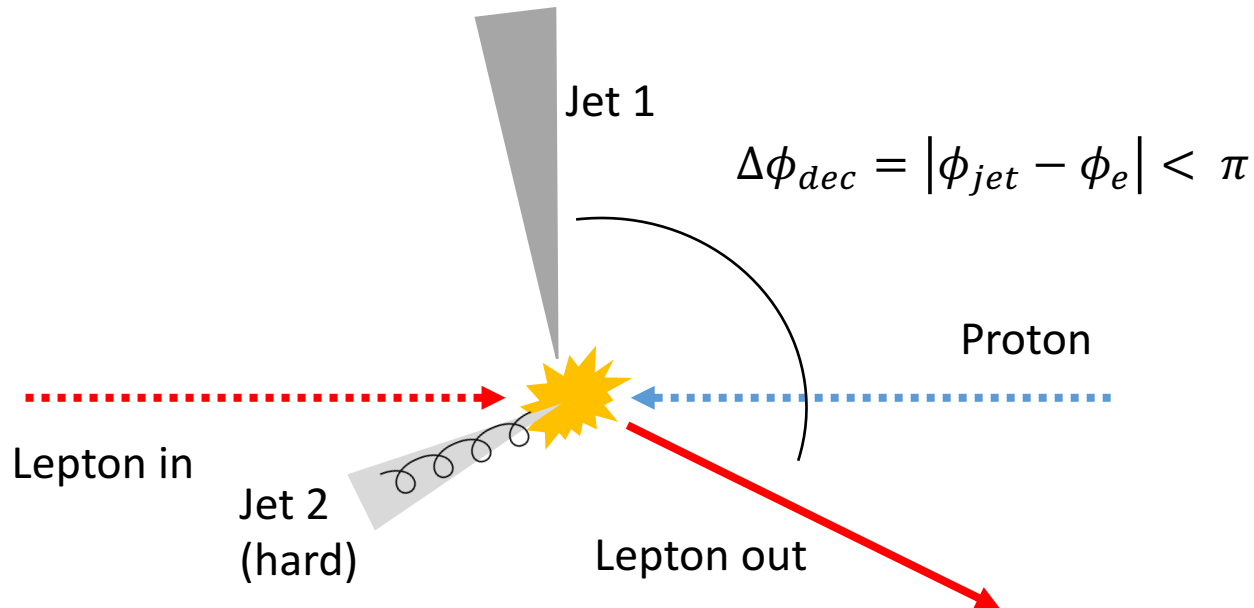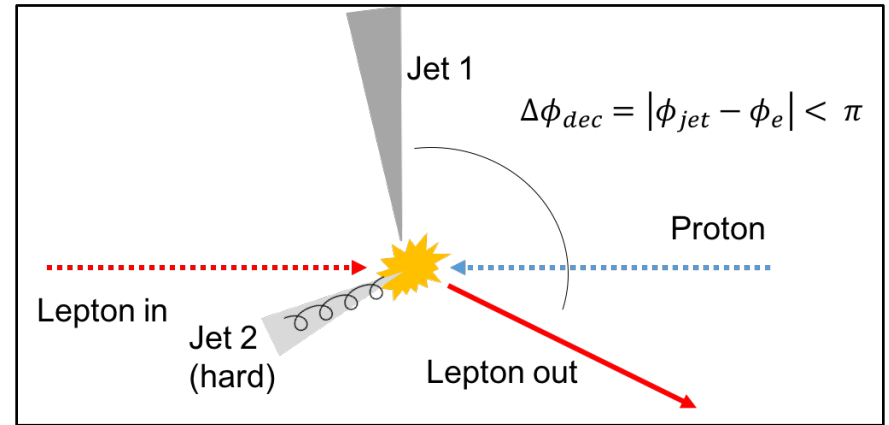
- Can access TMD distributions, complementary to SIDIS, **without** explicit description of TMD fragmentation function
  [Liu et al., PRL 122 (2019) 192003, Lui et al., PRD 102 (2020) 094022].

- Can be measured with HERA data, which already exist and are well understood.

# Previous Azimuthal Jet Results

PRL 94, 221801 (2005)
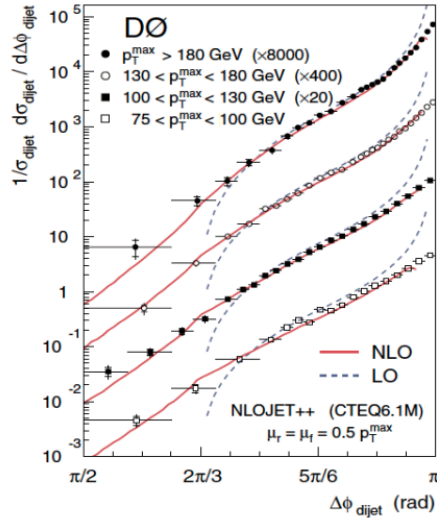


PRL 106, 122003 (2011)
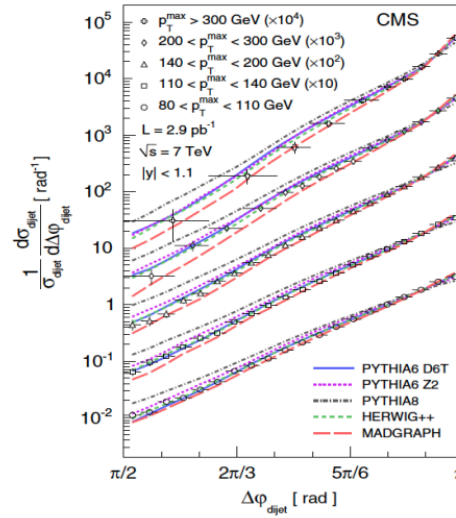


PRL 106, 172002 (2011)
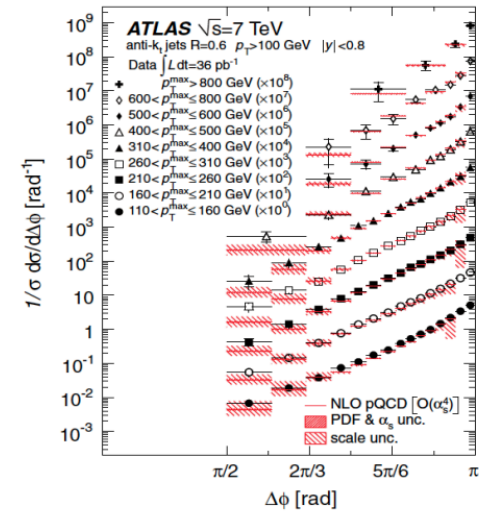


PRL 128 (2022) 13, 132002
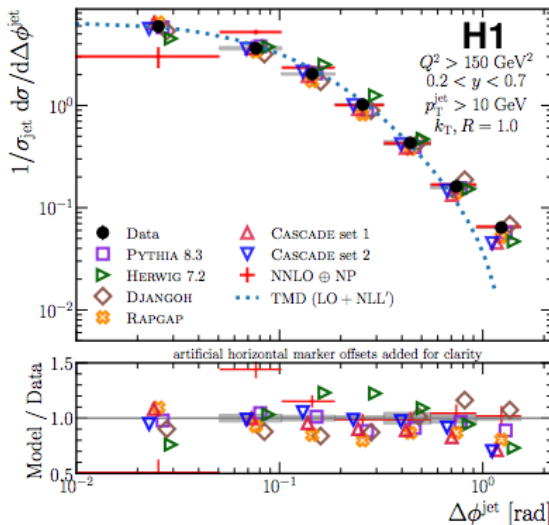


- Previous results from Tevatron (D0) and LHC (ATLAS, CMS)
  - Improvements in data description by high order correction (NLO to LO).
  - MC generators describe data well except in the region $\Delta\phi \sim \pi \Longrightarrow$ tune MC based on data.

**Tomorrow, WG4,**
**Yao Xu, Fernando Acosta**

- 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.

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# Analysis Details (Event Selection)

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

- Electron
  - $E_e > 10\ GeV$
  - $140^o < \theta_e < 180^o$
    (detector effects $\theta < 175^o$)

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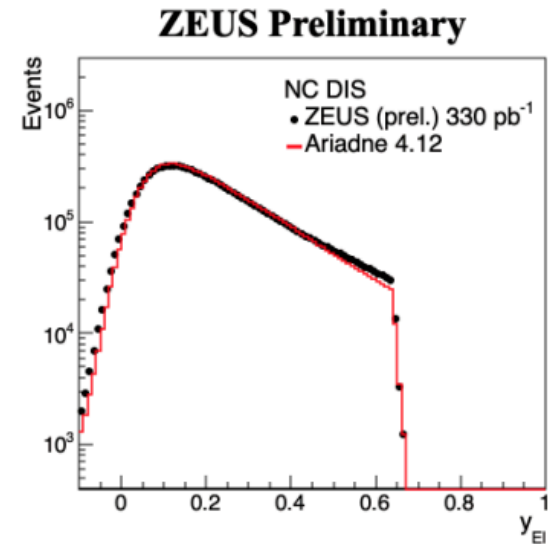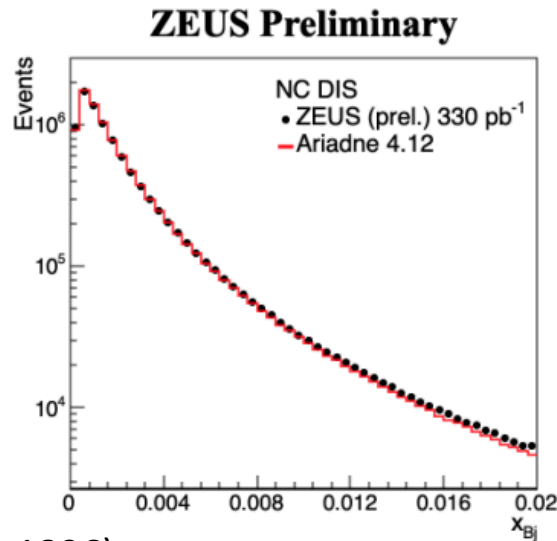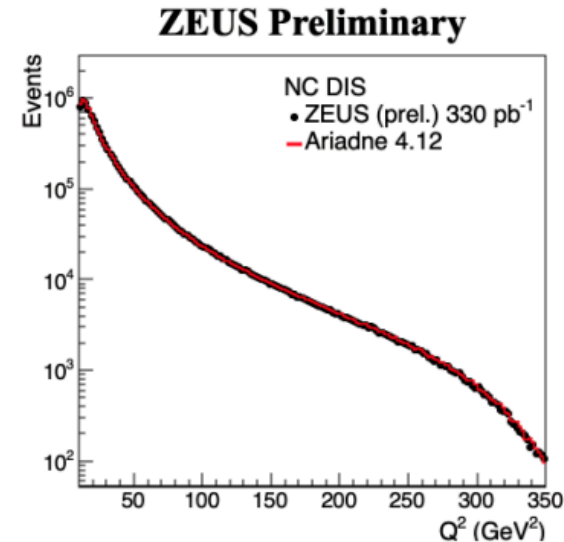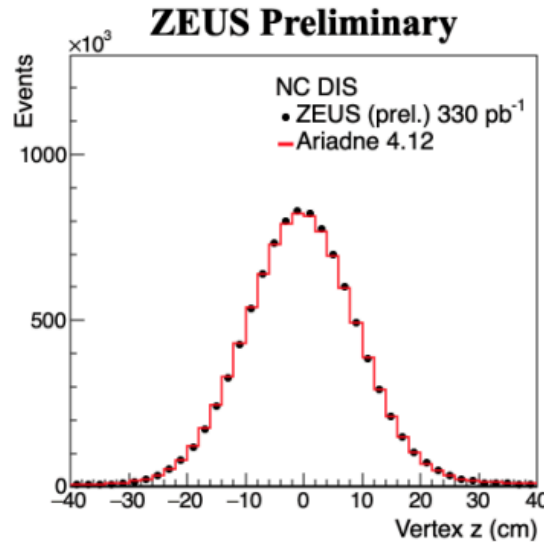


Good description of data by MC!

# Analysis Details (Measurement)

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

$$\frac{d\sigma\,(e + p \to e + jet + X)}{d\Delta\phi_{dec}} = \frac{1}{\epsilon} \times A^{-1} \frac{dN_{jet}(\Delta\phi_{dec})}{d\Delta\phi_{dec}}$$

efficiency      unfolding

- Leading jet = jet with the highest $E_T$
- $\Delta\phi_{dec} = \left|\phi_{jet} - \phi_e\right|$

- 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)



ZEUS Preliminary
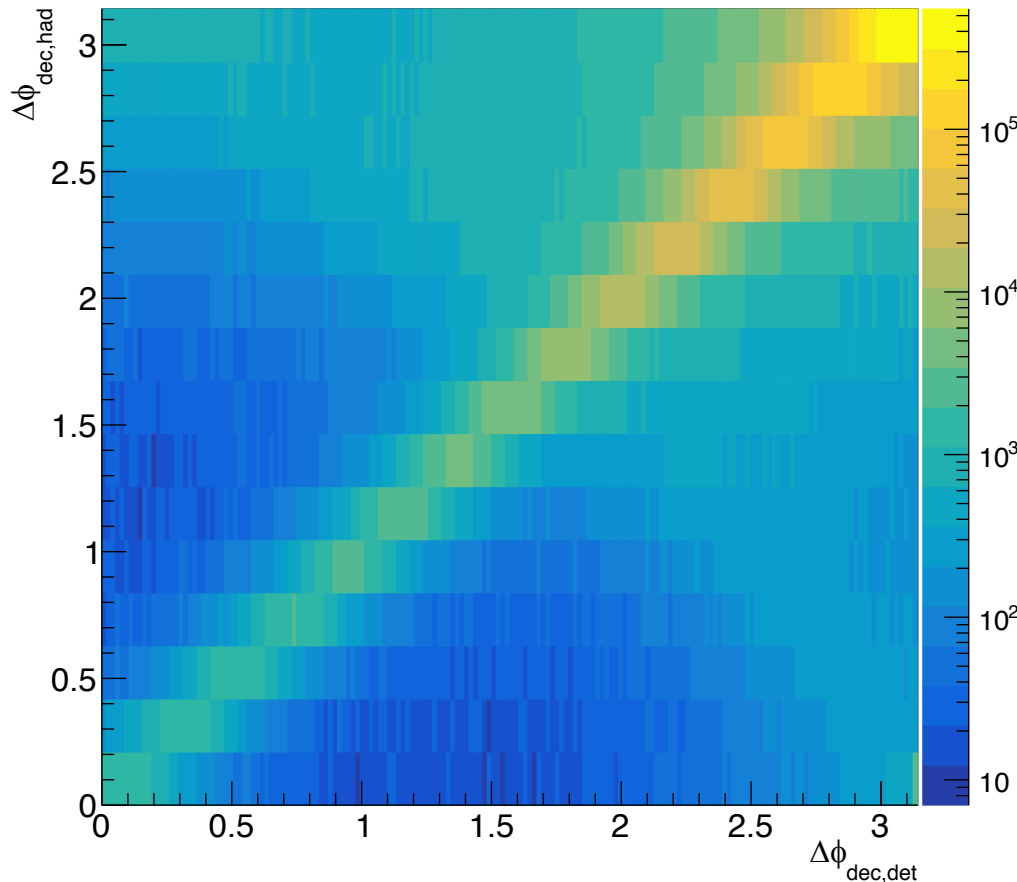
- Matrix-based unfolding
  - L-scan method as interfaced in TUnfold package (S.Schmitt, JINST 7 (2012) T10003)
  - Takes the migration matrix of $\Delta\phi_{dec}$ as input

- 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.
  - $\sim5\%$ effect at $\Delta\phi\sim\pi$.

- For final publication, $N_{jet}$ correlation will also be included in the unfolding process.

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# Theory

- 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



ZEUS Preliminary
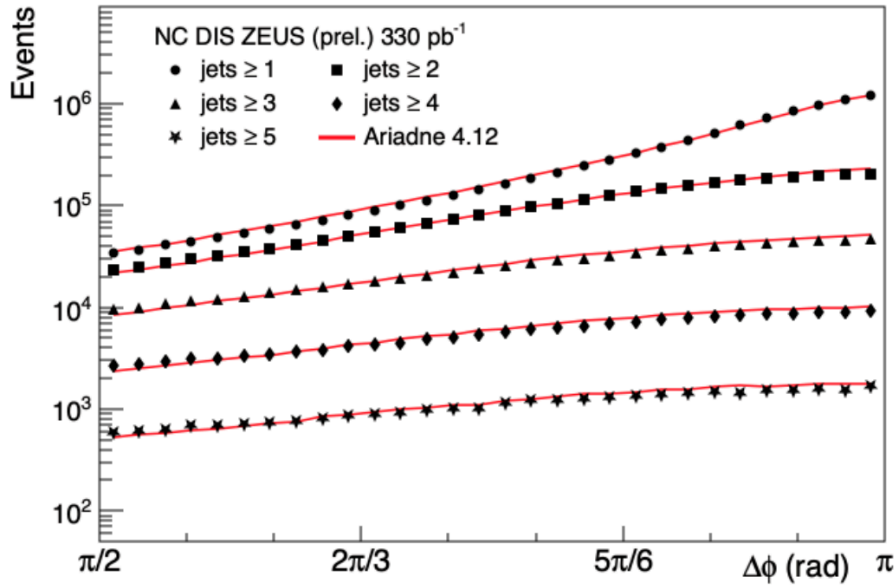
- Previous preliminary $\Delta\phi_{dec}$ distribution compared to LHC finds a qualitative agreement.

- 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.

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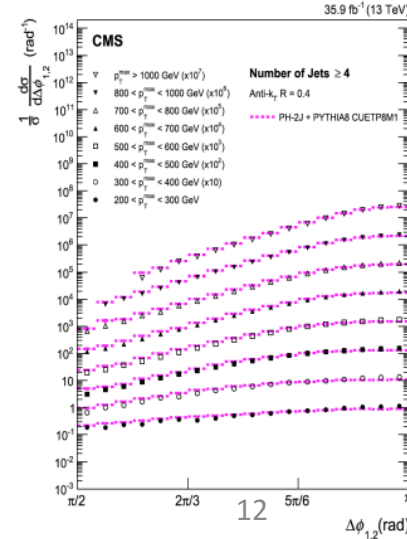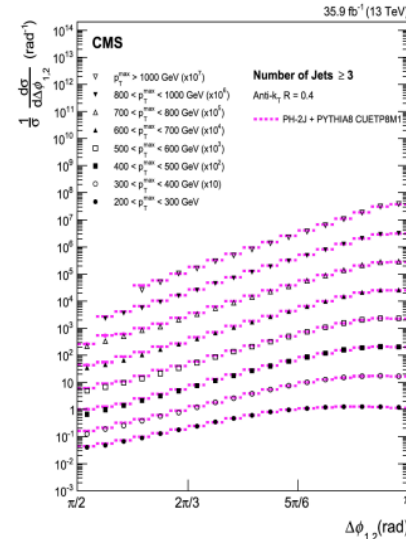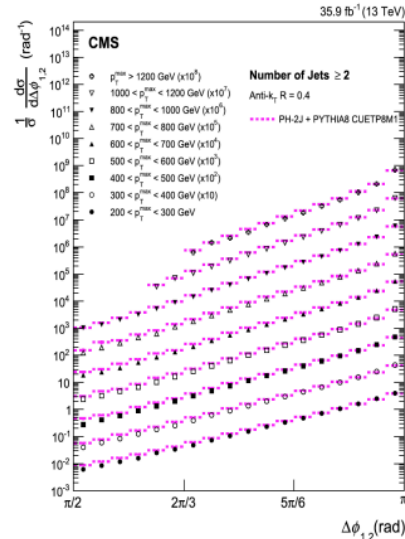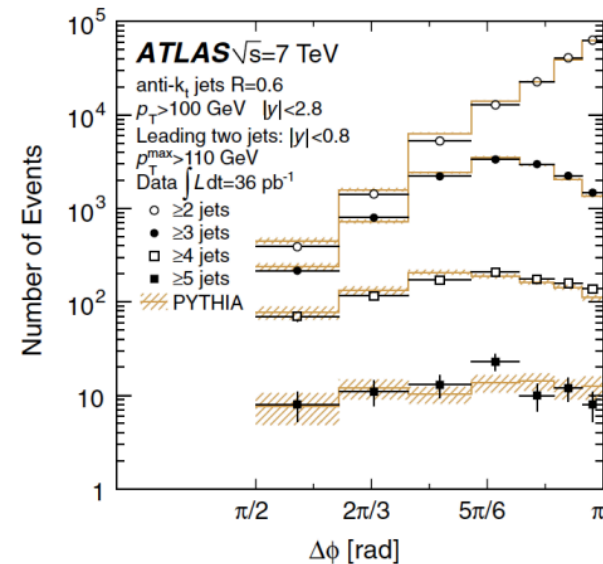
# Results (Inclusive)



ZEUS Preliminary

- 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.

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# Results (Inclusive)



ZEUS Preliminary

NC DIS    $e+p \rightarrow e+jet+X$

$\sqrt{s} = 318$ GeV,  $\int$ L dt = 326 $pb^{-1}$

$50$ $GeV^2 < Q^2 < 350$ $GeV^2$

$0.04 < y < 0.7$

$E_e > 10$ GeV,  $140^o < \theta_e < 180^o$

$2.5$ GeV $< p_{T,jet} < 30$ GeV

$-1.5 < \eta_{jet} < 1.8$
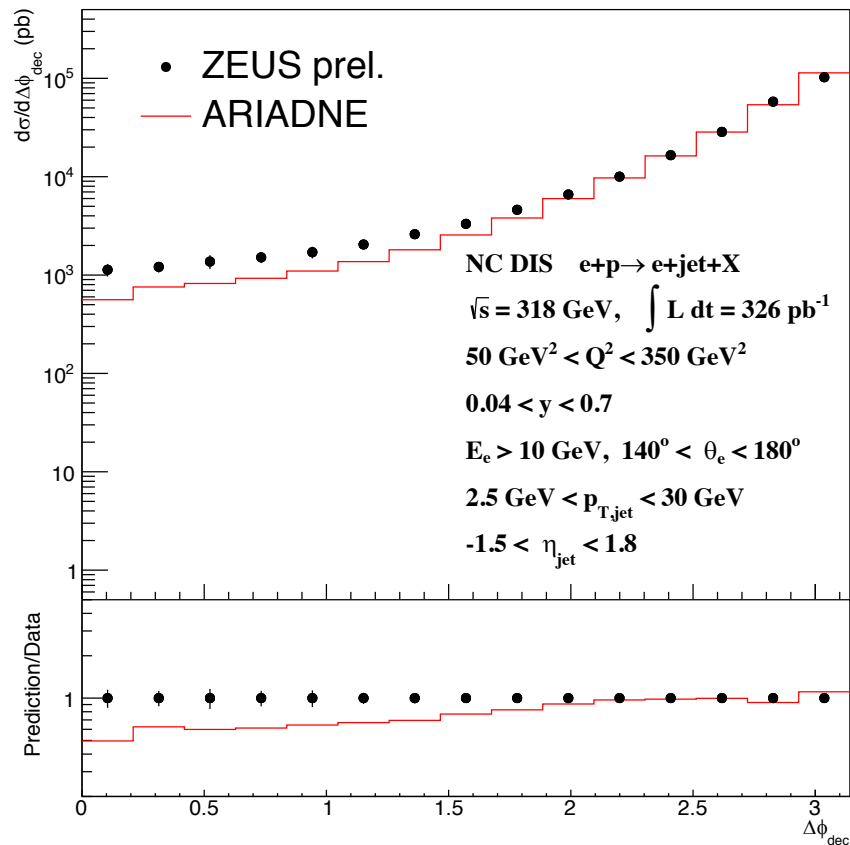
- Azimuthal angle jet/electron measurement for the inclusive case ($N_{jet} \geq 1$).
  - Systematics study suggests that the model dependence of the unfolding process is the dominating contribution ($\sim 5\%$ at $\Delta\phi_{dec} \sim \pi$)
  - Efficiency correction $\sim 20\%$.

- Comparison to ARIADNE MC.
  - ARIADNE is normalized to data, as it is only at LO + parton shower.
  - The $\Delta\phi_{dec}$ distribution is much steeper with ARIADNE, hinting that the high jet multiplicity from hard production may be underestimated.

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# Results ($p_{T,jet}$ & $Q^2$)



ZEUS Preliminary
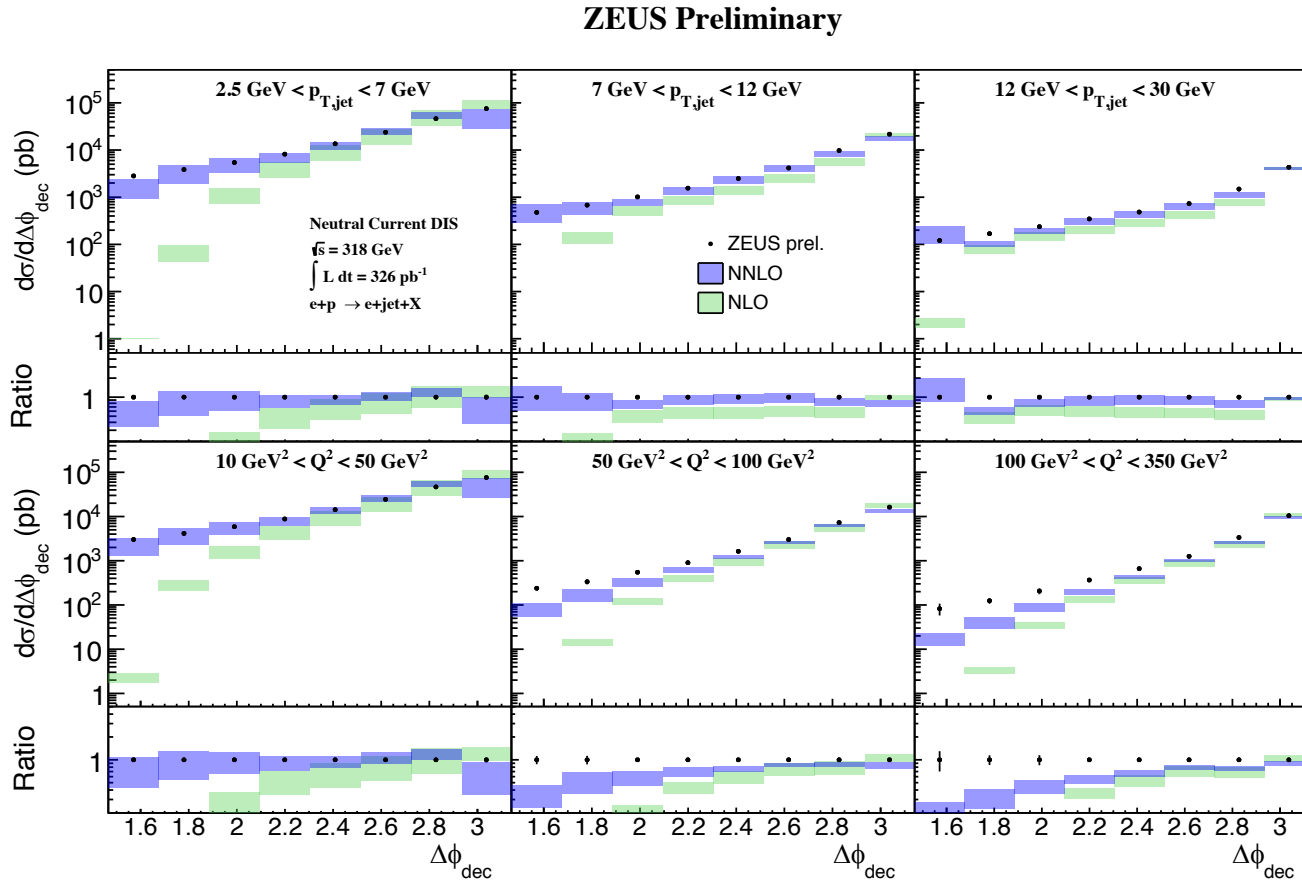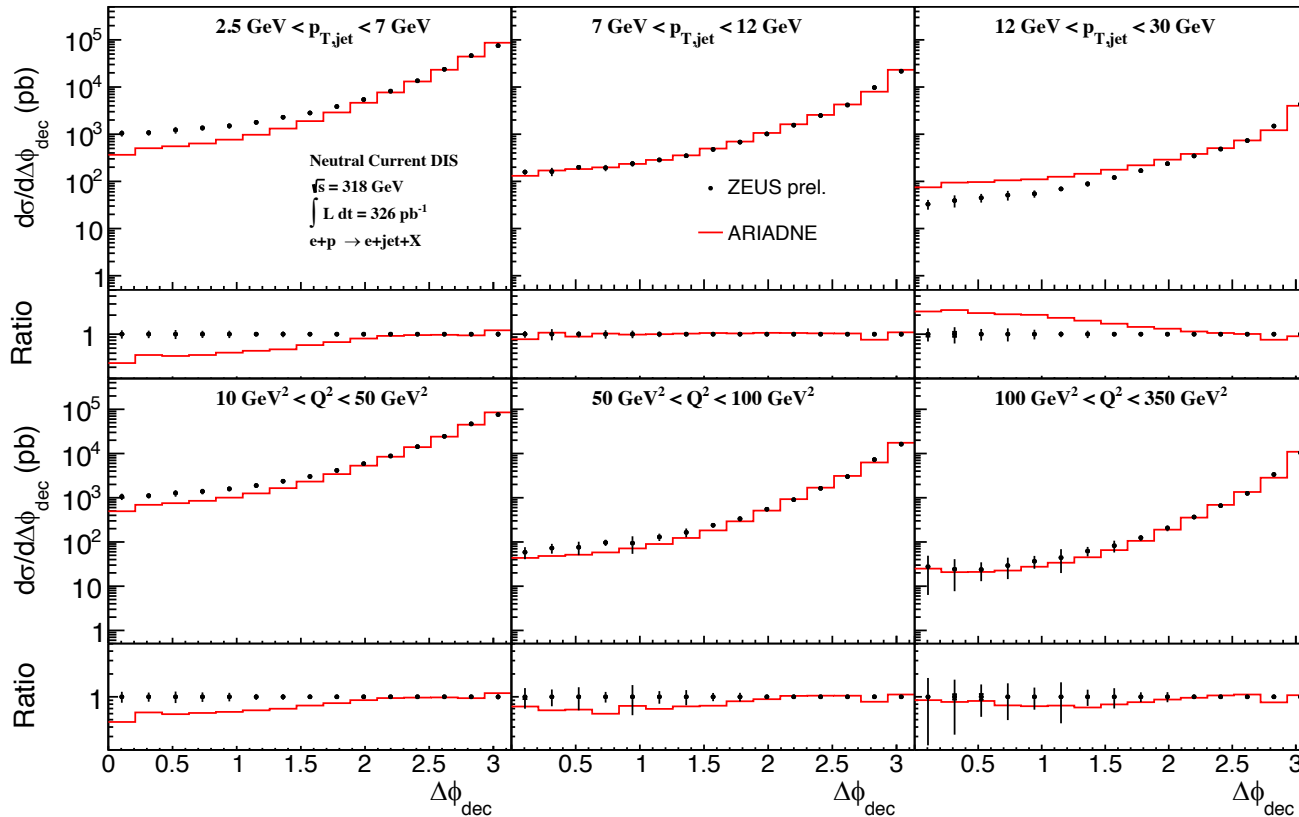
- Comparison to pQCD in different ranges of $p_{T,jet}$ and $Q^2$.

- 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 ($p_{T,jet}$ & $Q^2$ MC)



ZEUS Preliminary

- 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/Outlook

- Summary
    - Preliminary results of azimuthal decorrelaton measurements of lepton and leading jet in DIS, similar to previous ZEUS $\gamma$-jet results and other experiments in $pp$ collisions.
    - Measurement of new jet observable with the existing ZEUS data.
    - Comparisons to pQCD provide test of perturbative stability of the jet production process.
    - May serve as a complementary measurement to SIDIS measurements with added benefits of not needing TMD FF.
    - Overall, the pQCD at NNLO accuracy and ARIADNE describe main features of data well; some discrepancies are observed which will be investigated further in the final measurement.

- Outlook
    - Final measurement/publication will include measurements in various $N_{jet}$ configurations.
    - In communication with TMD experts for input.
    - Jet-lepton decorrelation measurement will provide an important probe in future colliders, such as EIC.