# Measurement of azimuthal decorrelation angle between the leading jet and the scattered lepton in deep inelastic scattering at HERA (first preliminary addition presentation)

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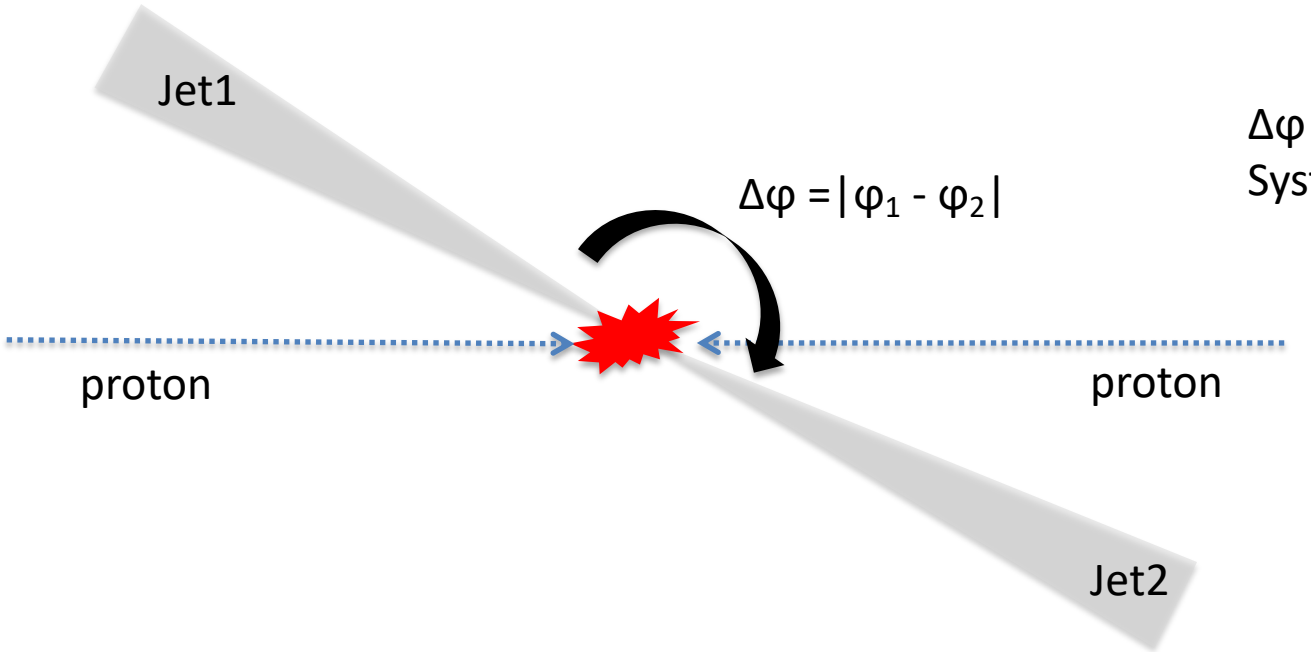
We present preliminary results of the azimuthal decorrelation angle between the leading jet and scattered lepton in deep inelastic scattering. Azimuthal angular decorrelation has been proposed to study the $Q^2$ dependence of the evolution of the transverse momentum distributions (TMDs) and understand the small x region, providing unique insight to nucleon structure with an electron-ion collider. Previous decorrelation measurements of two jets have been performed in proton collisions at very high transverse momentum; these measurements are well described by perturbative QCD at next-to-leading order. The presented measurements were obtained by the ZEUS experiment during the HERA II data-taking period. The analysis uses $e^-p$ and $e^+p$ data corresponding to integrated luminosities of 330 $pb^{-1}$. The azimuthal decorrelation angle obtained in these studies shows good agreement with predictions from QCD calculations; however, there are parts of the phase space for which deviations of up to 40% are observed. Dedicated theoretical predictions are to be tested in the future.

# Introduction

Azimuthal angular decorrelation angle ($\Delta\varphi$) of two jets, have been studies in hadron collisions [1-3].

- Study parton radiation effects.
- Test pQCD and MC generators.
- Search for new physics.



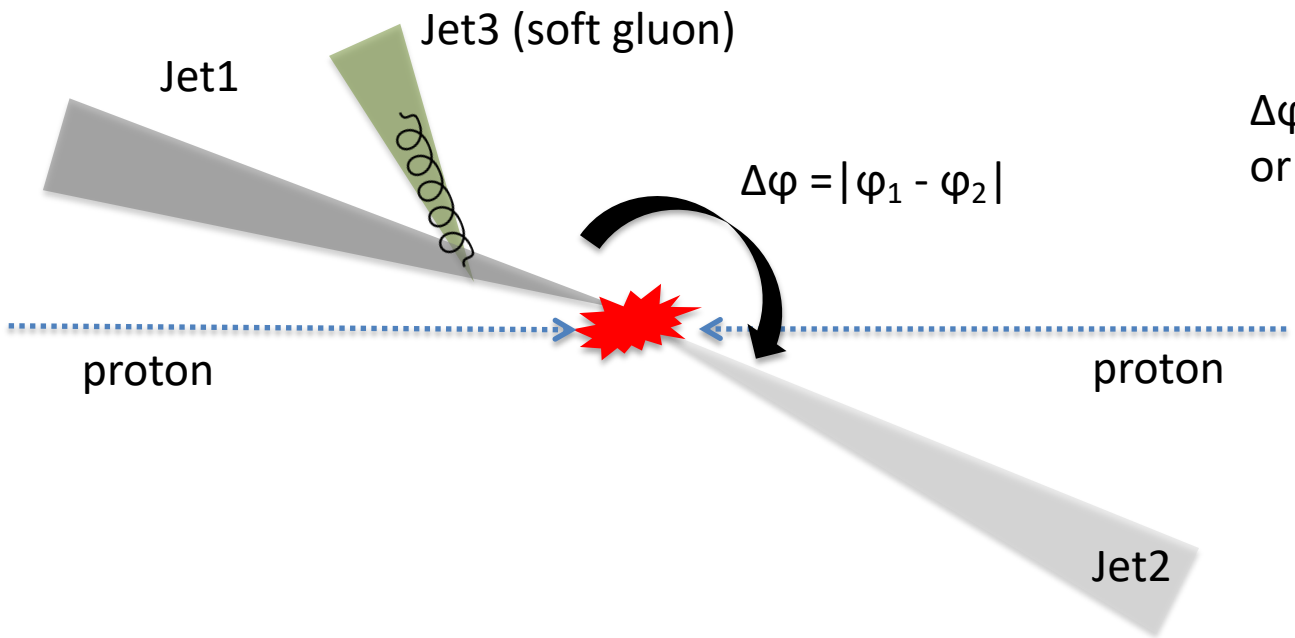

$\Delta\varphi = \pi \rightarrow p_{T1} = p_{T2}$
System is balance

Warning: LO pQCD calculations,
$\Delta\varphi = \pi$ gives a delta function

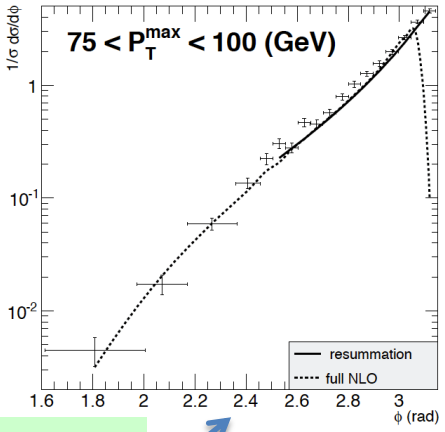
# Introduction

Azimuthal angular decorrelation angle (Δφ) of two jets, have been studies in hadron collisions [1-3].

- Study parton radiation effects.
- Test pQCD and MC generators.
- Search for new physics.




Δφ < π: soft gluon emission or multiple jets event.




Singularity persist at Δφ = π with one or more gluon radiation

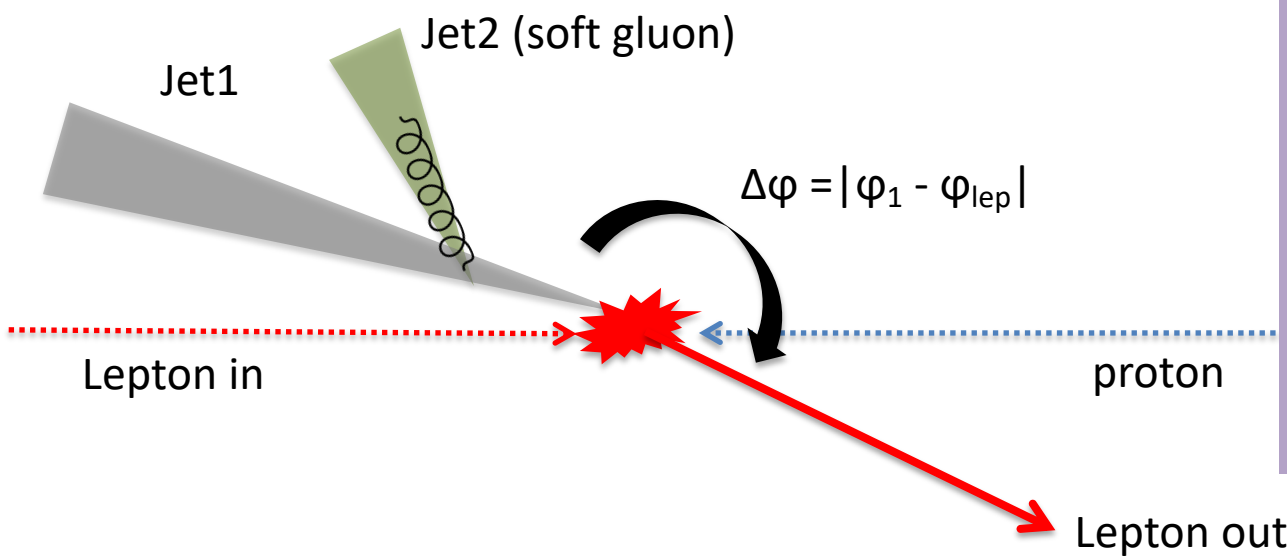
Resummation method [4], divergences cancel out.

# Motivation

Azimuthal angular decorrelation angle (Δφ) of dijet, have been studied in hadron collisions [1-3].

**Never done for ep collisions**

- Study parton radiation effects.
- Test pQCD and MC generators.
- Search for new physics.




-Start procedure for **EIC** (i.e. pt range, systematics, correction, etc.)
-Study **small-x** (HERA kinematic region).
Study **$Q^2$ dependence** on TMD evolution.
- **Low $p_T$** will probe the non-perturbative region.

Test Resummation method [4] for lepton-jet decorrelation

→

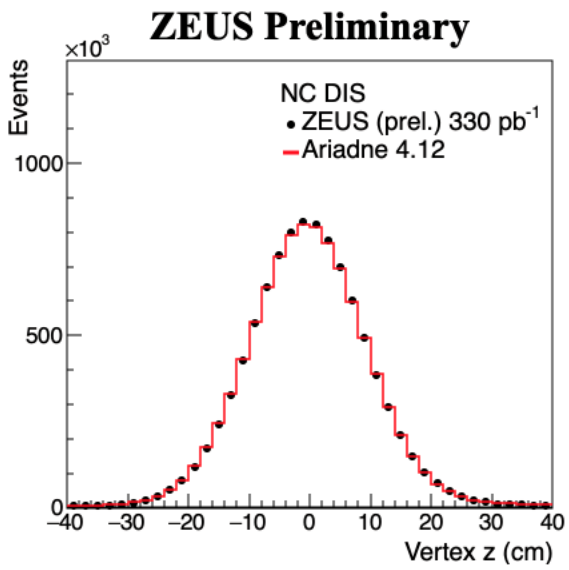
Much simpler kinematics
NEW theory paper [5]

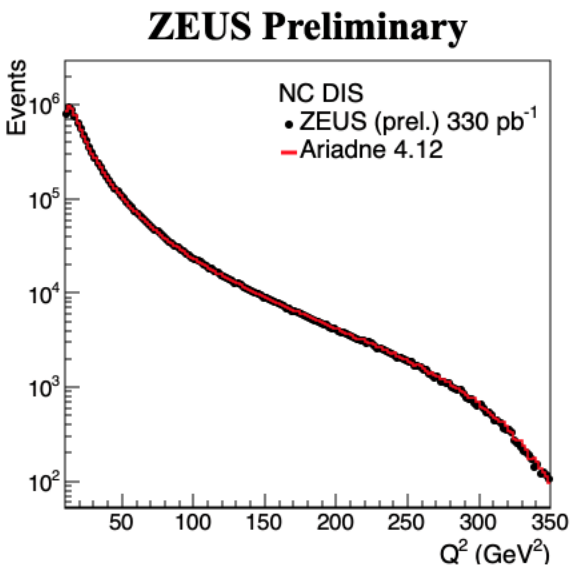
# Initial preliminary results

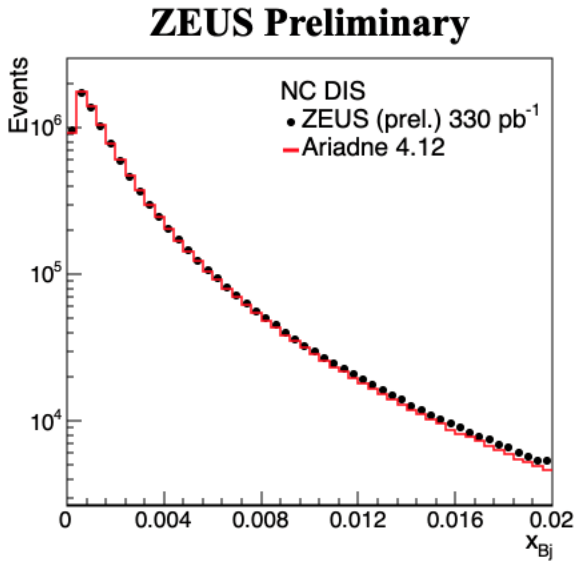
- A first set of preliminary plots were presented as poster at the EIC users meeting 2019 and talk at American Physical Society – Division of Nuclear Physics 2019.
- Only detector level measurements were approved as preliminary.
- No cross section results were presented.
- Previous approach for cross section calculation was using bin by bin unfolding to hadron level, but contamination (bin migration) was a problem.
- The previous preliminary MC sample did not include diffraction processes.

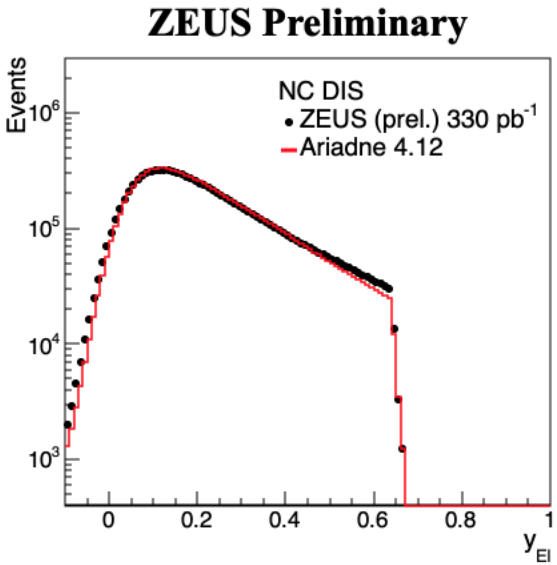
# Initial preliminary plots

Official

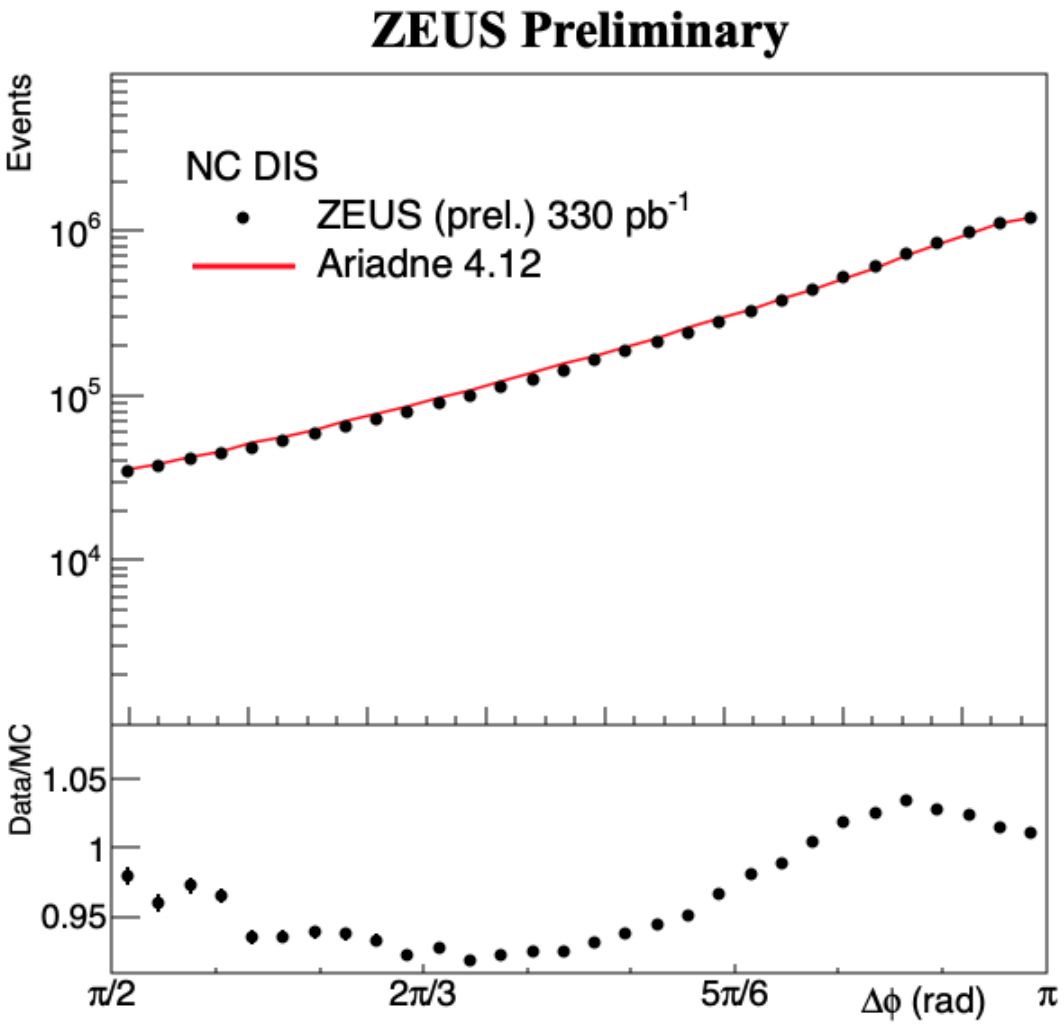


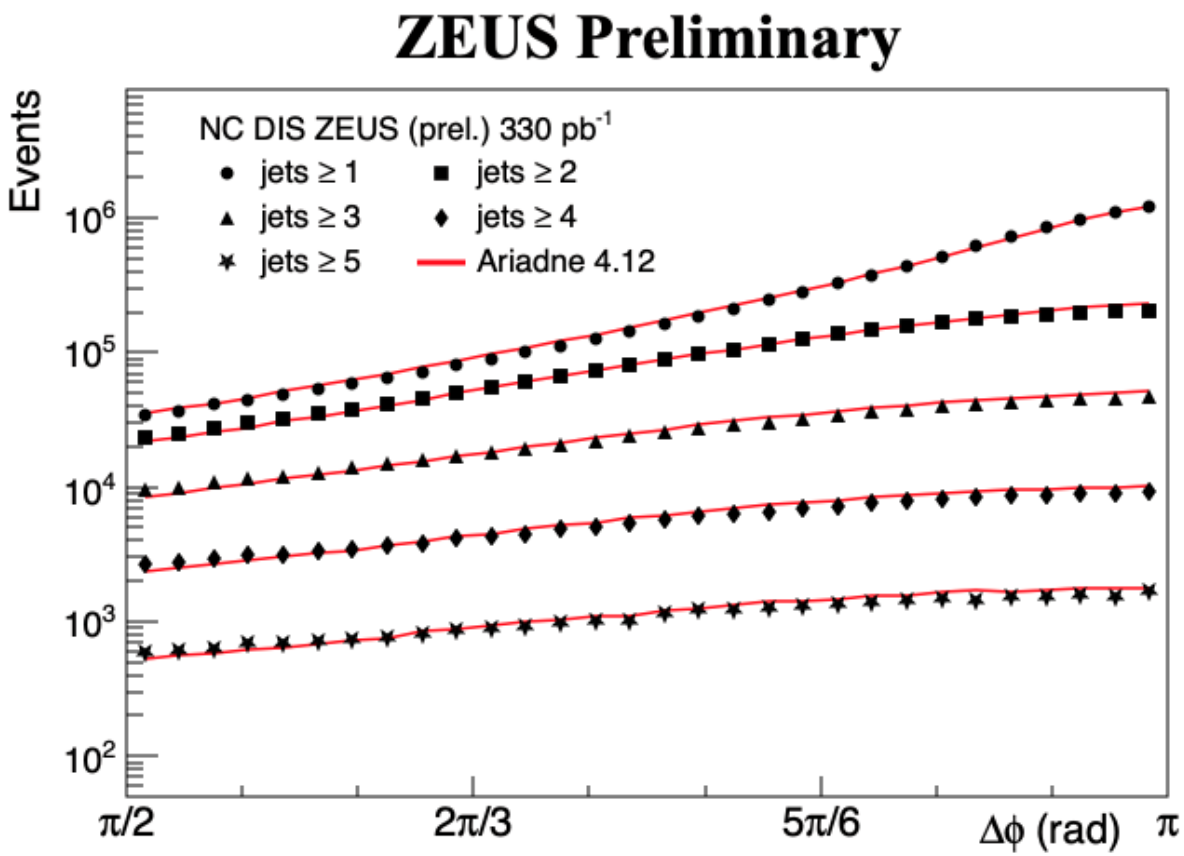



Official


ZEUS Preliminary
Events
NC DIS
ZEUS (prel.) 330 pb$^{-1}$
Ariadne 4.12
$10^6$
$10^5$
$10^4$
Data/MC
1.05
1
0.95
π/2
2π/3
5π/6
Δφ (rad)
π

Official


ZEUS Preliminary
NC DIS ZEUS (prel.) 330 pb-1
jets ≥ 1
jets ≥ 2
jets ≥ 3
jets ≥ 4
jets ≥ 5
Ariadne 4.12
Events
10^6
10^5
10^4
10^3
10^2
π/2
2π/3
5π/6
Δφ (rad)
π

# Additional preliminary results

- The goal is to present cross section measurements (new additions) at DIS 2020.
- Using TUnfold package [6] to unfold the measurements to hadron level.
- Including diffraction processes in the MC sample.
- Minor modifications to the event selection cuts: 45 GeV < E – $p_z$, before was 35 GeV.
- Using the same |eta| < 1 cuts as before.

# Event selection

**Data:**
040506e ~**189** $pb^{-1}$, 0607p ~**143** $pb^{-1}$

**MC:**
ari_incl_nc_DIS_lowQ2_040506e
ari_incl_nc_DIS_lowQ2_0607p

**Phase Space:**
$10 < Q^2 < 350\ GeV^2$
$y_{el} < 0.7$ && $y_{jb} > 0.04$

**Cleaning cuts:**
-40 < Zvtx/cm < 40
45 GeV < $E - p_z$ < 65 GeV (both Cal and Zufo)
Cal_pt / sqrt(Cal_et) < 2.5

**Electron cuts:**
10 GeV < Energy (Siecorr)
$140^o$ < Theta < $180^o$
Electron position sqrt( $x^2 + y^2$) > 20.0
Sienin[0] > 0.1*(Siein[0] +Sienin[0]) (energy in cone)
Chimney cut
Siprob[0], the lepton with highest prob (> 0.9)

**Triggers:**
SPP02 (Tltw[2] & (1 << 1)) for 0405e
SPP09 (Tltw[2] & (1 << 8)) for 06e and 0607p

**Jet selection:**
$E_T > 2.5$ GeV && $P_T < 30$
|eta| < 1.0
Using "Kt_etjet_b[0]" (massive), the leading jet only

Control plots at: https://indico.desy.de/indico/event/24851/contribution/2/material/slides/0.pdf (backup 1-6 pages)

# Event selection for true MC

**~~Data:~~**
~~040506e ~189 pb$^{-1}$, 0607p ~143 pb$^{-1}$~~

**MC:**
ari_incl_nc_DIS_lowQ2_040506e
ari_incl_nc_DIS_lowQ2_0607p

**Phase Space:**
$10 < Q^2 < 350$ GeV$^2$
~~$y_{el} < 0.95$ && $y_{jb} > 0.04$~~ $0.04 < y < 0.95$

**Cleaning cuts:**
$-40 <$ Zvtx/cm $< 40$
~~45 GeV < E – $p_z$ < 65 GeV (both Cal and Zufo)~~
~~Cal_pt / sqrt(Cal_et) < 2.5~~

**Electron cuts:**
10 GeV < ~~Siecorr~~ Mc_pfsl[3]
$140^o <$ Theta $< 180^o$
~~Electron position sqrt( $x^2 + y^2$) > 20.0~~
~~Sienin[0] > 0.1*(Siein[0] +Sienin[0]) *(energy in cone)~~
~~Chimney cut~~
~~Siprob[0], the lepton with highest prob (>0.9).~~

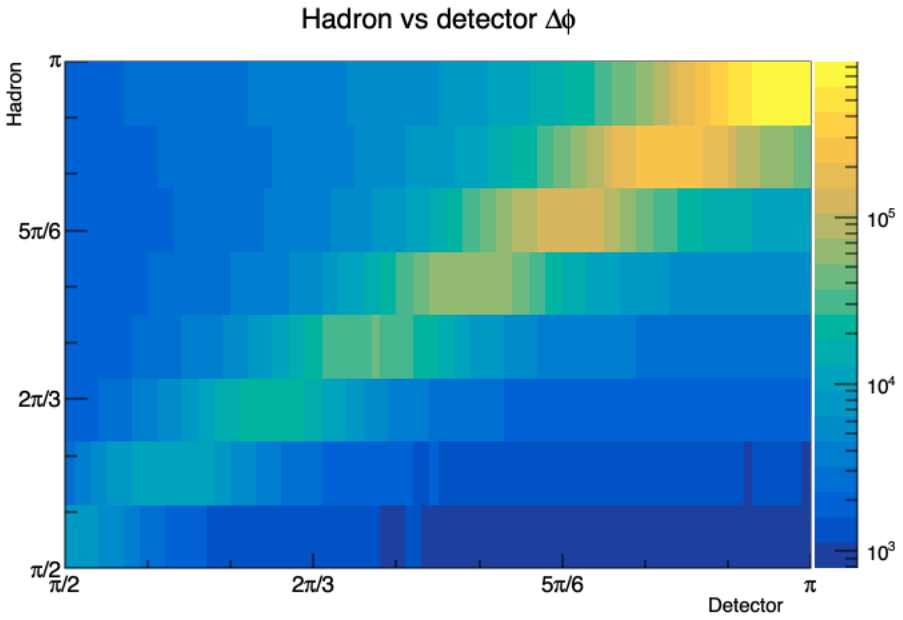
**Triggers:**
~~SPP02 (Tltw[2] & (1 << 1)) for 0405e~~
~~SPP09 (Tltw[2] & (1 << 8)) for 06e and 0607p~~

**Jet selection:**
$E_T > 2.5$ GeV && $P_T < 30$
|eta| < 1.0
Using “MCHMJets” (massive), the leading jet only

* Use all the true MC variables and remove all the detector dependences

# Unfolding procedure

- Unfolding in 1-D was performed with default parameters of the TUnfold package.
- Previous studies by Ivan to optimize unfolding parameters did not show any improvement.
- The binning is π/16, eight bins for all the $p_T$, $Q^2$ and jet multiplicity bins.
- Unfolding is done individually for each bin combination studied.
- No reweighting of the MC was done.




Details at: https://indico.desy.de/indico/event/24498/contribution/3/material/slides/0.pdf (9-12 pages)

# Systematic studies

The systematics studied come from the procedure established for the Prompt Photon analyses [7]:

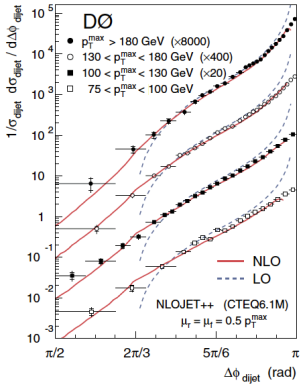
- The energy scale of the jets was varied by ±4% for jets with $E_{jet} < 10$ GeV and ±2.5% for larger energies.
- The energy scale of the scattered lepton was varied by 2%.
- The uncertainty due to the lepton selection cuts was estimated by varying the values of the cuts within the resolution of each variable (Not shown in this study*).
- Systematics related to MC generators (Not shown in this study).

The hadron-detector correlation matrix of each systematics study can be applied to the TUnfold package, and the total uncertainty is the squared sum of each systematic and the statistical error.

*Prompt photon studies suggest all other sources of systematics were found negligible.

# Results

[1]

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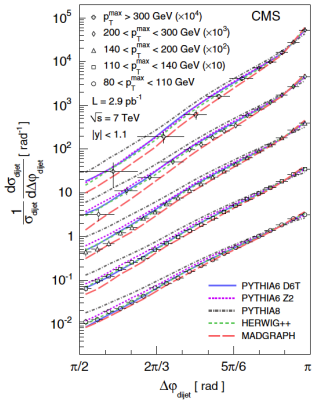
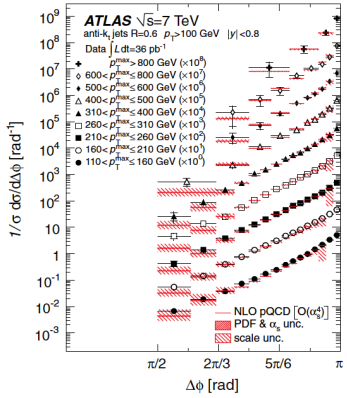
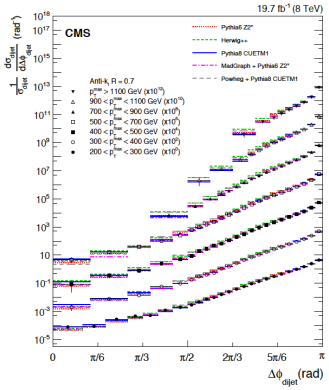


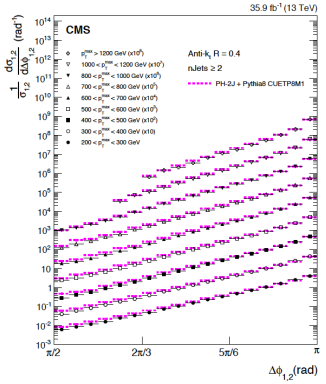

[3]

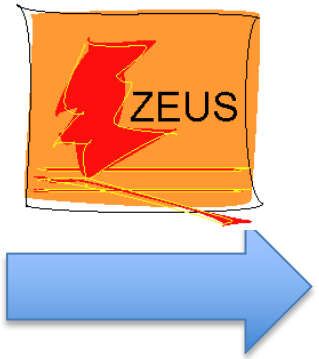



[8]

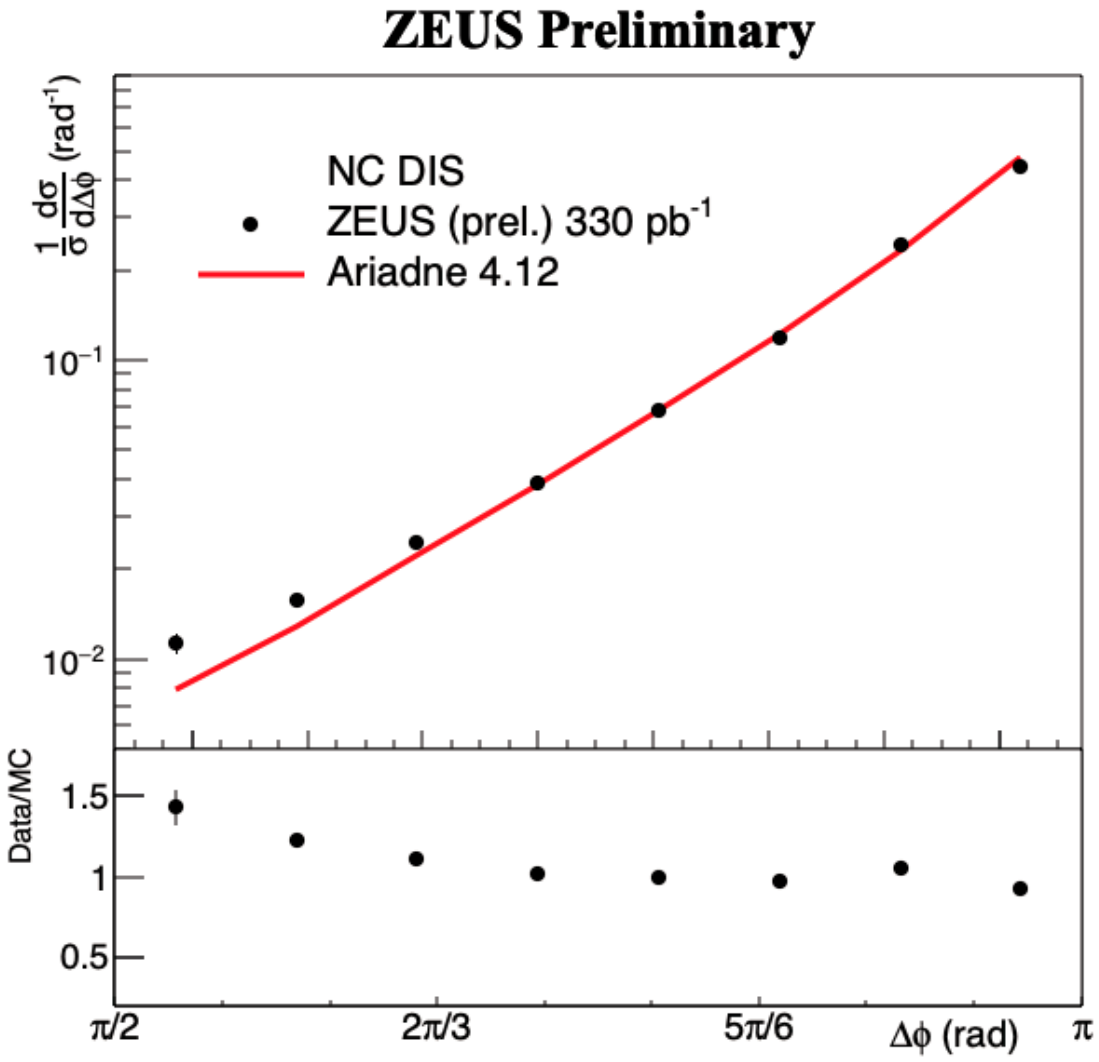



[9]



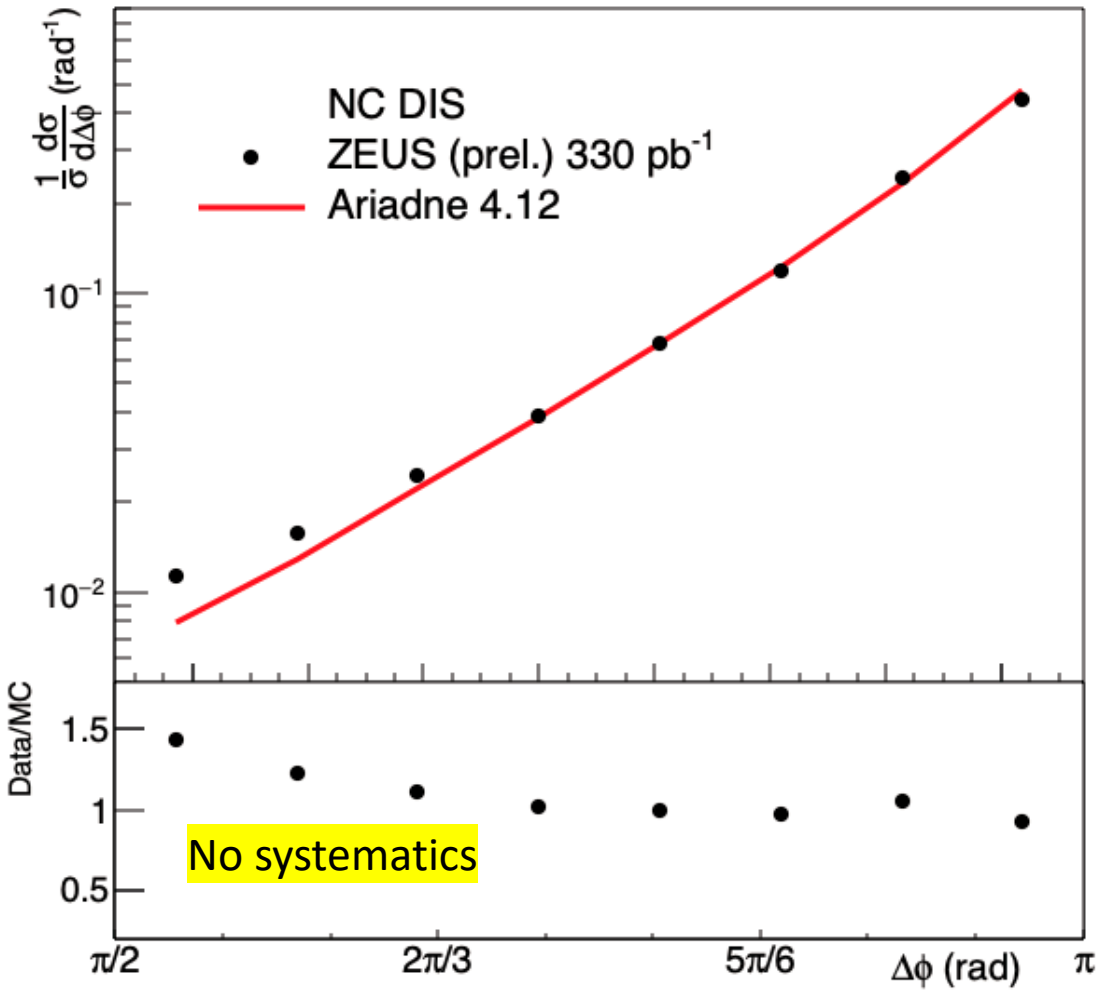




Both statistical and systematics uncertainties are very small.

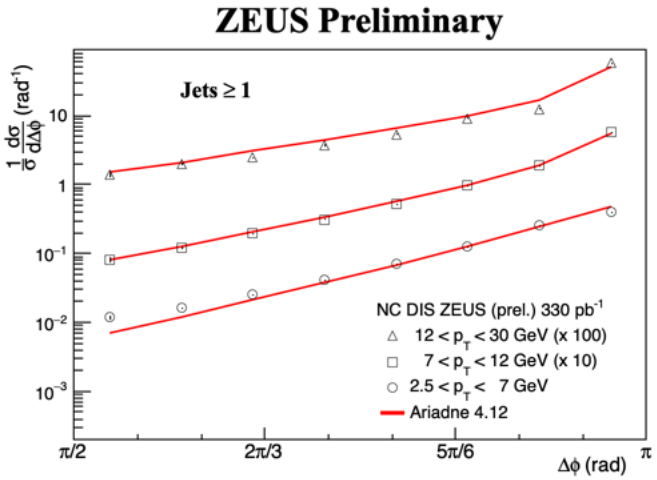

ZEUS Preliminary
NC DIS
ZEUS (prel.) 330 pb$^{-1}$
Ariadne 4.12
$\frac{1}{\sigma}\frac{d\sigma}{d\Delta\phi}$ (rad$^{-1}$)
$10^{-1}$
$10^{-2}$
Data/MC
1.5
1
0.5
π/2
2π/3
5π/6
Δϕ (rad)
π

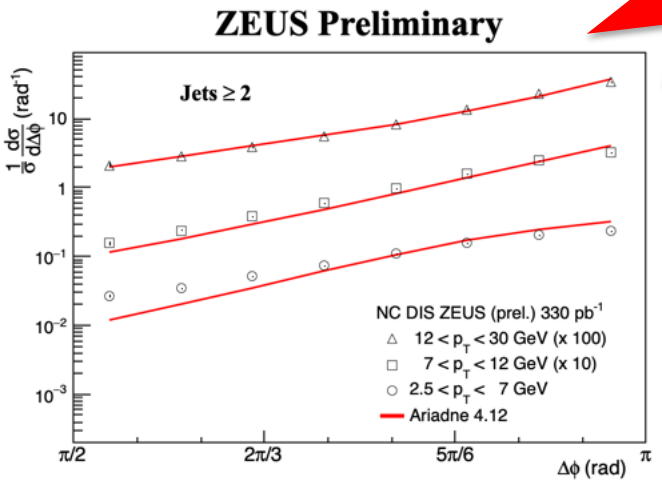
Request

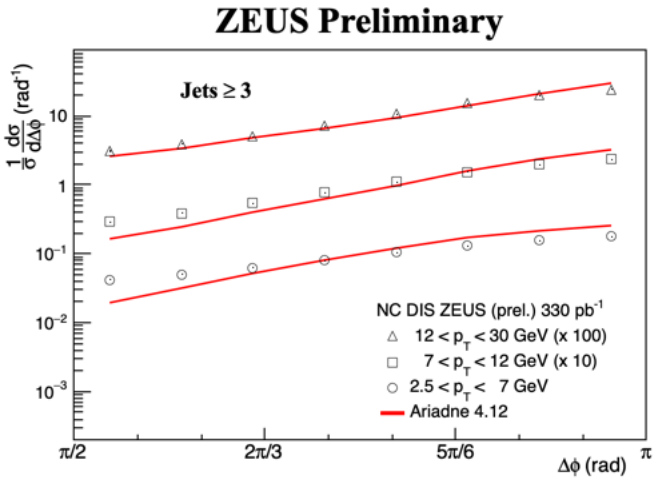
# Test

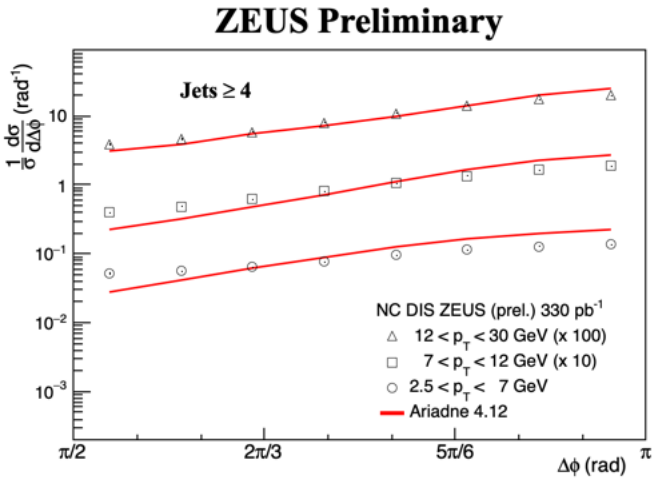

$\frac{1}{\sigma}\frac{d\sigma}{d\Delta\phi}$ (rad$^{-1}$)
NC DIS
ZEUS (prel.) 330 pb$^{-1}$
Ariadne 4.12
$10^{-1}$
$10^{-2}$
Data/MC
1.5
1
0.5
No systematics
π/2
2π/3
5π/6
Δϕ (rad)
π

Request

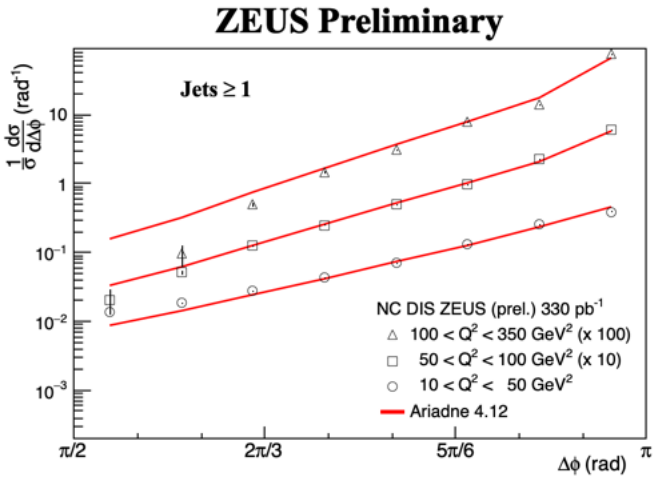

ZEUS Preliminary
Jets ≥ 1
$\frac{1}{\sigma}\frac{d\sigma}{d\Delta\phi}$ (rad$^{-1}$)
NC DIS ZEUS (prel.) 330 pb$^{-1}$
12 < $p_T$ < 30 GeV (x 100)
7 < $p_T$ < 12 GeV (x 10)
2.5 < $p_T$ < 7 GeV
Ariadne 4.12
π/2
2π/3
5π/6
π
Δφ (rad)

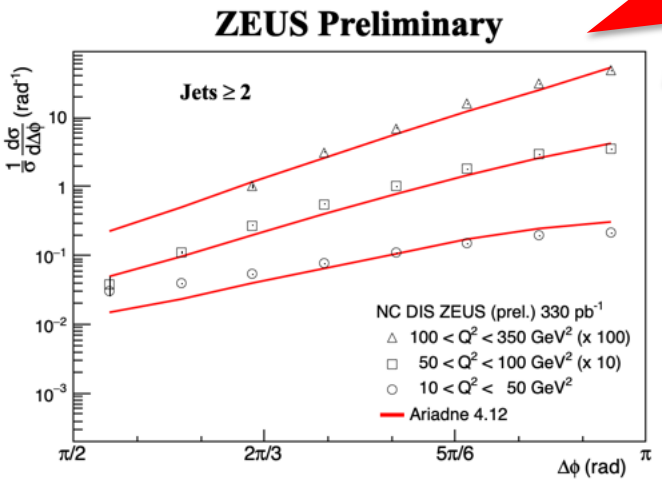

ZEUS Preliminary
Jets ≥ 2
$\frac{1}{\sigma}\frac{d\sigma}{d\Delta\phi}$ (rad$^{-1}$)
NC DIS ZEUS (prel.) 330 pb$^{-1}$
12 < $p_T$ < 30 GeV (x 100)
7 < $p_T$ < 12 GeV (x 10)
2.5 < $p_T$ < 7 GeV
Ariadne 4.12
π/2
2π/3
5π/6
π
Δφ (rad)

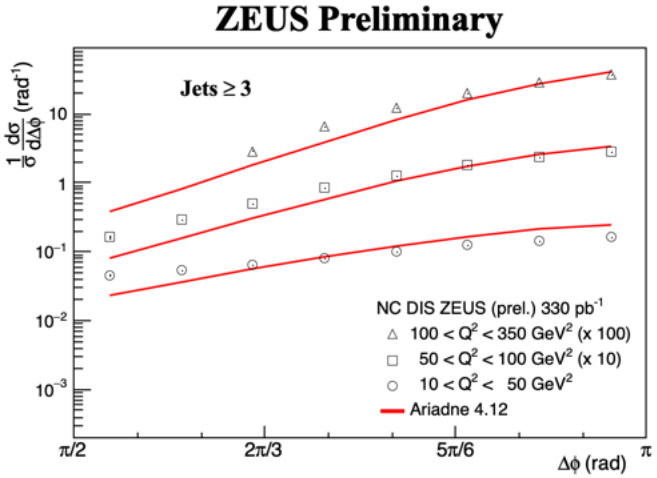

ZEUS Preliminary
Jets ≥ 3
$\frac{1}{\sigma}\frac{d\sigma}{d\Delta\phi}$ (rad$^{-1}$)
NC DIS ZEUS (prel.) 330 pb$^{-1}$
12 < $p_T$ < 30 GeV (x 100)
7 < $p_T$ < 12 GeV (x 10)
2.5 < $p_T$ < 7 GeV
Ariadne 4.12
π/2
2π/3
5π/6
π
Δφ (rad)

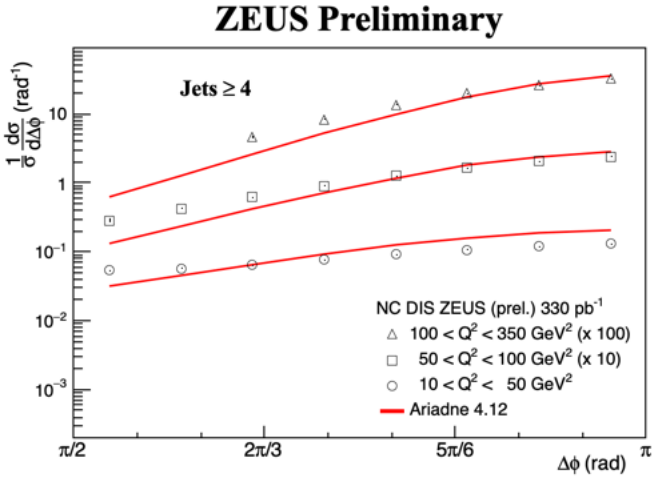

ZEUS Preliminary
Jets ≥ 4
$\frac{1}{\sigma}\frac{d\sigma}{d\Delta\phi}$ (rad$^{-1}$)
NC DIS ZEUS (prel.) 330 pb$^{-1}$
12 < $p_T$ < 30 GeV (x 100)
7 < $p_T$ < 12 GeV (x 10)
2.5 < $p_T$ < 7 GeV
Ariadne 4.12
π/2
2π/3
5π/6
π
Δφ (rad)

Request


ZEUS Preliminary
Jets ≥ 1
$\frac{1}{\sigma}\frac{d\sigma}{d\Delta\phi}$ (rad$^{-1}$)
NC DIS ZEUS (prel.) 330 pb$^{-1}$
△ 100 < Q$^2$ < 350 GeV$^2$ (x 100)
□ 50 < Q$^2$ < 100 GeV$^2$ (x 10)
○ 10 < Q$^2$ < 50 GeV$^2$
Ariadne 4.12
π/2
2π/3
5π/6
π
Δφ (rad)


ZEUS Preliminary
Jets ≥ 2
$\frac{1}{\sigma}\frac{d\sigma}{d\Delta\phi}$ (rad$^{-1}$)
NC DIS ZEUS (prel.) 330 pb$^{-1}$
△ 100 < Q$^2$ < 350 GeV$^2$ (x 100)
□ 50 < Q$^2$ < 100 GeV$^2$ (x 10)
○ 10 < Q$^2$ < 50 GeV$^2$
Ariadne 4.12
π/2
2π/3
5π/6
π
Δφ (rad)


ZEUS Preliminary
Jets ≥ 3
$\frac{1}{\sigma}\frac{d\sigma}{d\Delta\phi}$ (rad$^{-1}$)
NC DIS ZEUS (prel.) 330 pb$^{-1}$
△ 100 < Q$^2$ < 350 GeV$^2$ (x 100)
□ 50 < Q$^2$ < 100 GeV$^2$ (x 10)
○ 10 < Q$^2$ < 50 GeV$^2$
Ariadne 4.12
π/2
2π/3
5π/6
π
Δφ (rad)


ZEUS Preliminary
Jets ≥ 4
$\frac{1}{\sigma}\frac{d\sigma}{d\Delta\phi}$ (rad$^{-1}$)
NC DIS ZEUS (prel.) 330 pb$^{-1}$
△ 100 < Q$^2$ < 350 GeV$^2$ (x 100)
□ 50 < Q$^2$ < 100 GeV$^2$ (x 10)
○ 10 < Q$^2$ < 50 GeV$^2$
Ariadne 4.12
π/2
2π/3
5π/6
π
Δφ (rad)

# Summary

- Perform decorrelation measurements of DIS lepton with leading jet, similar to Tevatron, CMS and Atlas.
- Presented results for different $p_T$, $Q^2$ and jet multiplicity, showing similar behavior as proton-proton measurements.
- Fair to good matching between data and MC at hadron level for angles greater than $2\pi/3$.
- Systematic uncertainties studied are small.
- Accepted abstract for DIS 2020 in March.

# Backup

# References


[1] Phys. Rev. Lett. 94, 221801 (2005). D0

[2] Phys. Rev. Lett. 106, 122003 (2011). CMS

[3] Phys. Rev. Lett. 106, 172002 (2011). Atlas

[4] Phys. Rev. D 92, 094007 (2015). Feng Yuan

[5] Phys. Rev. Lett. 122, 192003 (2019). F. Yuan

[6] JINST 7 (2012) T10003 [arXiv:1205.6201] S. Schmitt

[7] Phys. Lett. B 715 (2012) 88 [arXiv:1206.2270] ZEUS Prompt Photons

[8] Eur. Phys. J. C 76:536 (2016). CMS

[9] Eur. Phys. J. C 78:566 (2018). CMS

# Code

- Location: /nfs/dust/zeus/group/pidhii/jets/runner

- There is a README.txt in that directory where that shows how to use it.