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

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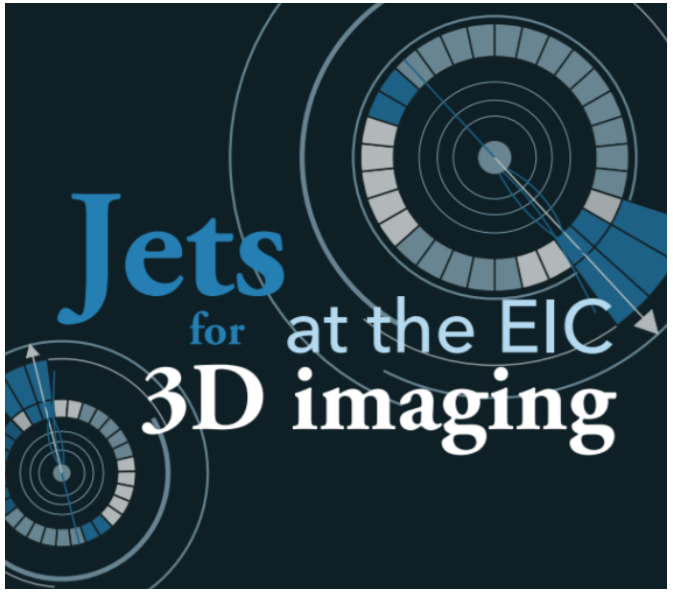
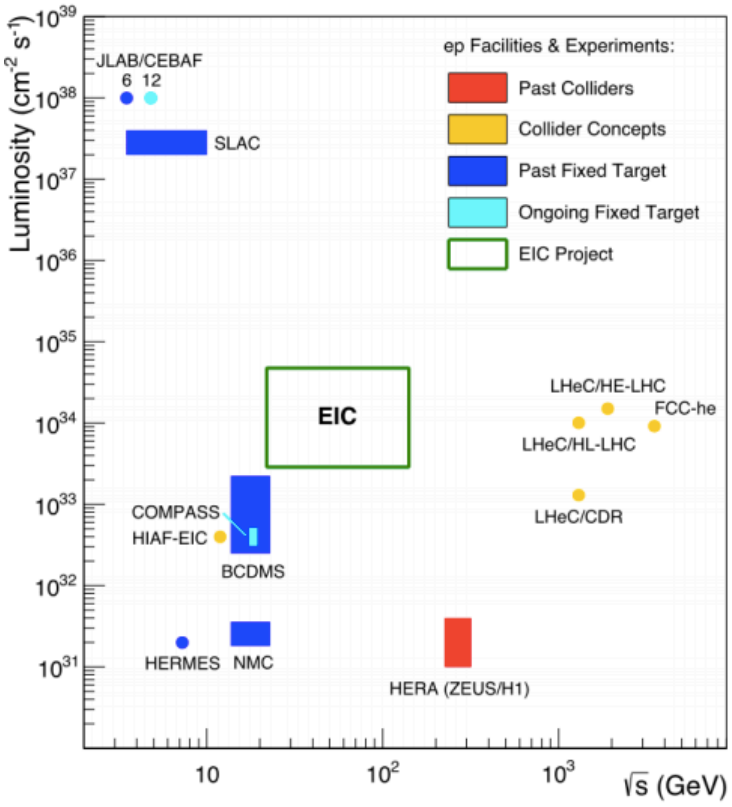


*Slide from J. Nam DNP2020

# HERA and EIC




HERA (1992 - 2007):

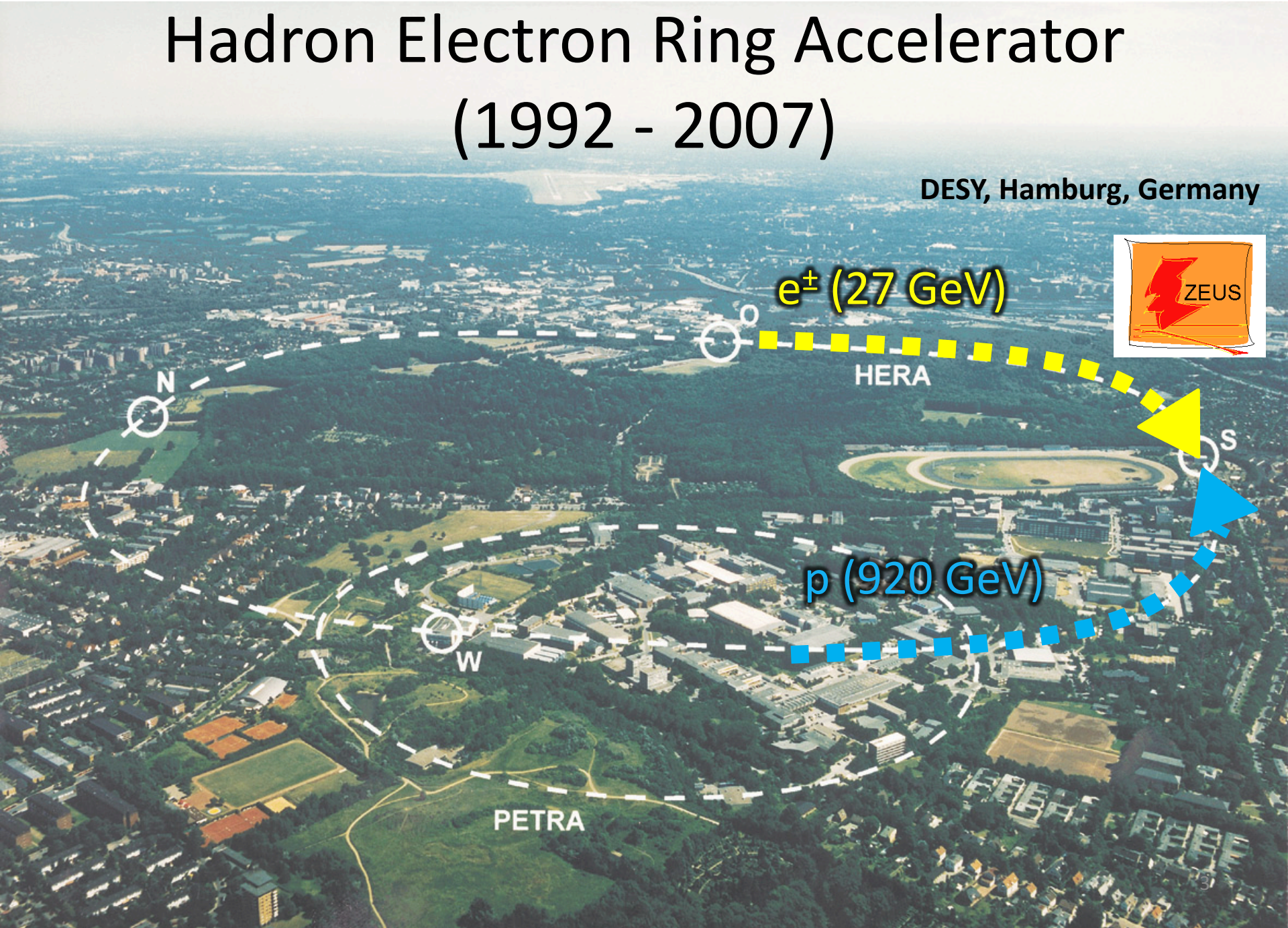
- Unpolarized $ep$ collider at $\sqrt{s}$ = 318 $GeV$.
- ZEUS measurement ~360 pb$^{-1}$(HERA II), both $e^{-}p$ (~185 $pb^{-1}$) and $e^{+}p$ (~173$pb^{-1}$).
- MC simulation: DJANGOH 1.6, ARIADNE 4.12.
- PDF: CTEQ-5D.

EIC:

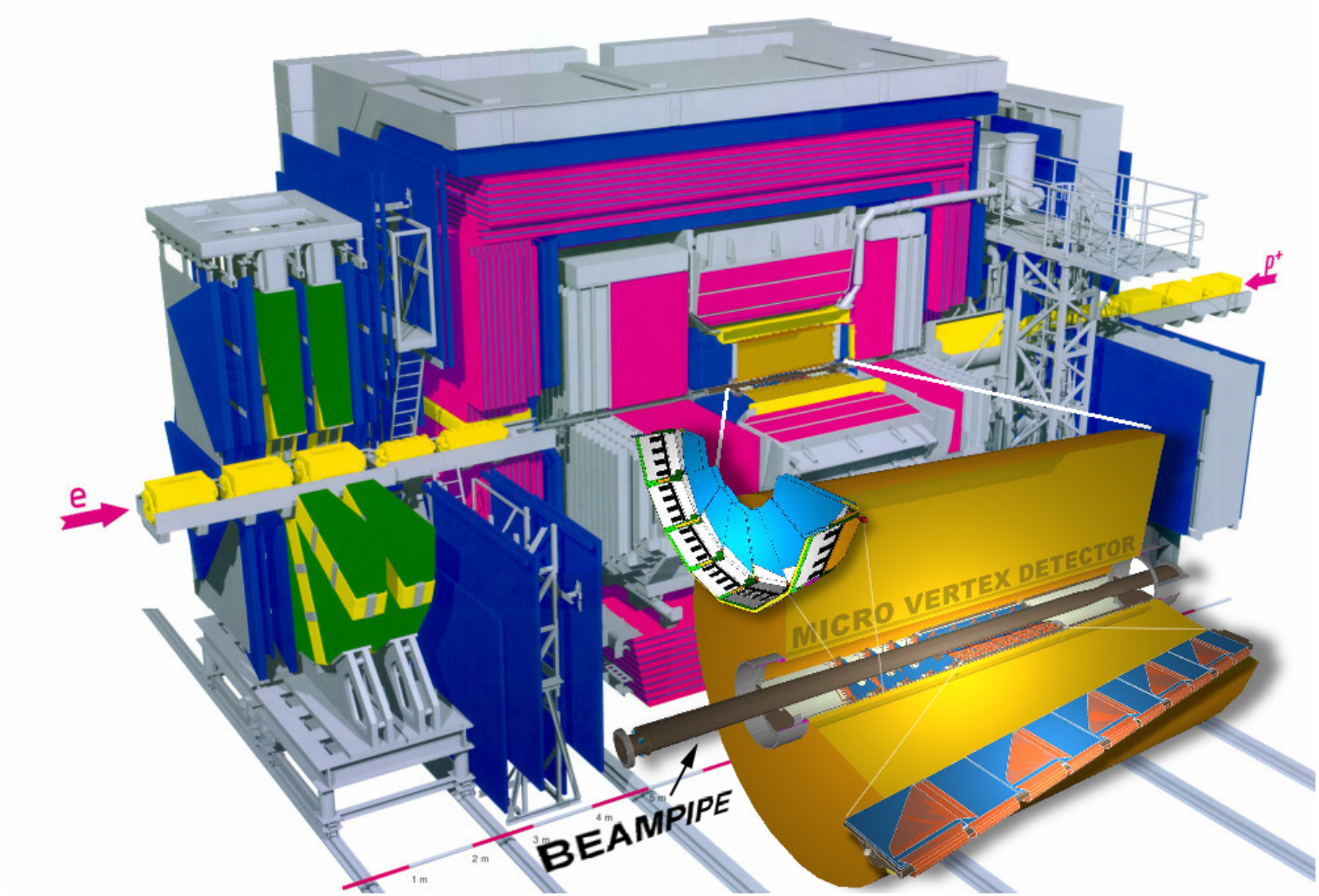
- Polarized $ep/A$ collider.
- Luminosity ~three orders of magnitude higher
- Detector design in progress.
- Updated generators and PDFs.

| Pythia samples | $\sqrt{s}$ (GeV) | Luminosity ($pb^{-1}$) |
|---|---|---|
| HERA | 318 | ~180 |
| EIC (high energy) | 141 | ~10,000 |
| EIC (nominal) | 104 | ~100,000 |

# Hadron Electron Ring Accelerator (1992 - 2007)



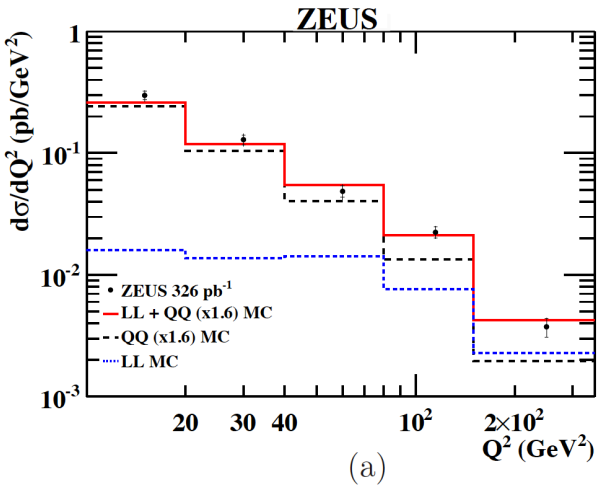
# ZEUS Experiment

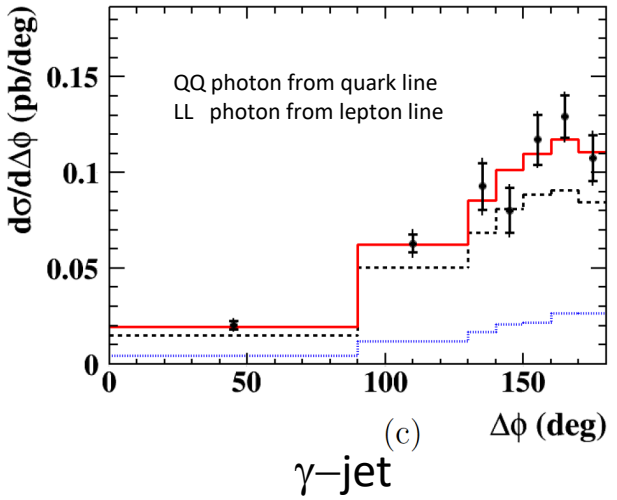



- One of the two largest multi-purpose collider experiments at HERA.
- The detector component, optimized to measure jets, was a high-resolution Uranium Calorimeter that surround a thin superconducting solenoid (1.43T) and the tracking detectors (CTD and MVD).

# Some previous ZEUS jet results

- High ET dijet photoproduction at HERA (PRD 76 (2007) 072011, arXiv:0706.3809)
- 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)




γ–jet

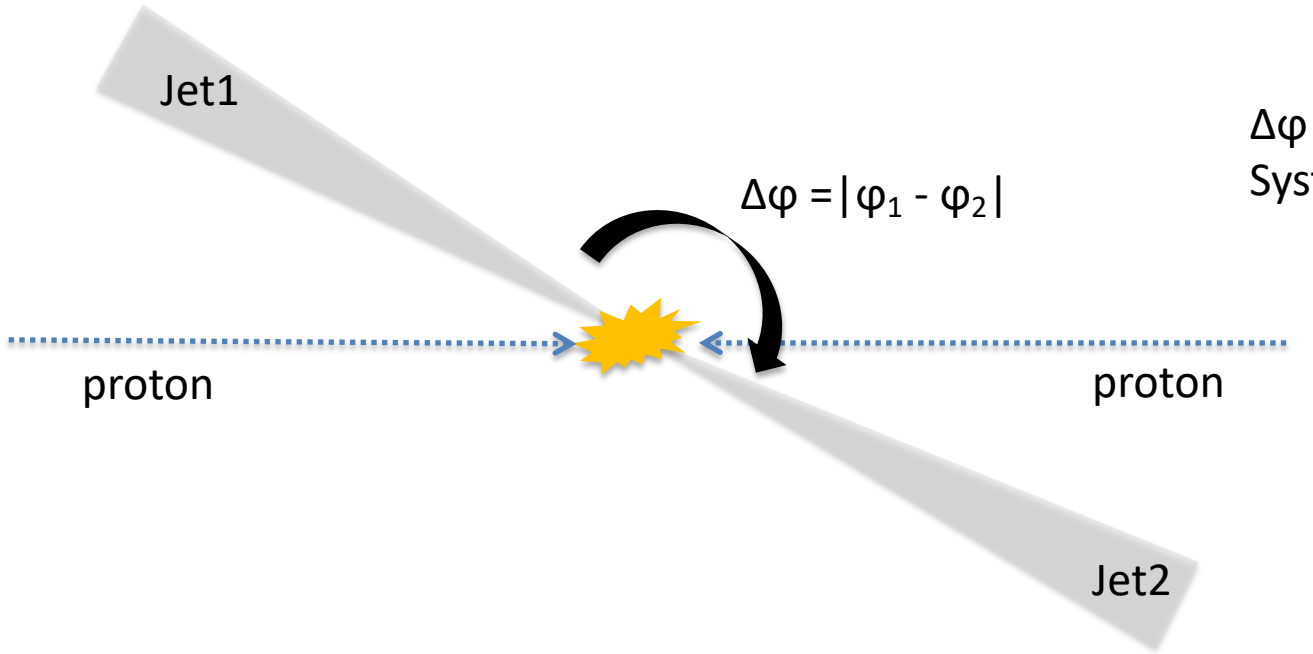
- Prompt photons are unaffected by parton hadronization.
- Direct probe of the underlying partonic process.
- Measurements motivated to test and further improve QCD calculations.

More information at https://www-zeus.desy.de

# Measurements in proton collisions

Azimuthal angular decorrelation angle ($\Delta\varphi$) was studied for dijet events in proton proton collisions [1-3].

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




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

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


[1] D0, Phys. Rev. Lett. 94, 221801 (2005).
[2] CMS, Phys. Rev. Lett. 106, 122003 (2011).
[3] ATLAS, Phys. Rev. Lett. 106, 172002 (2011).

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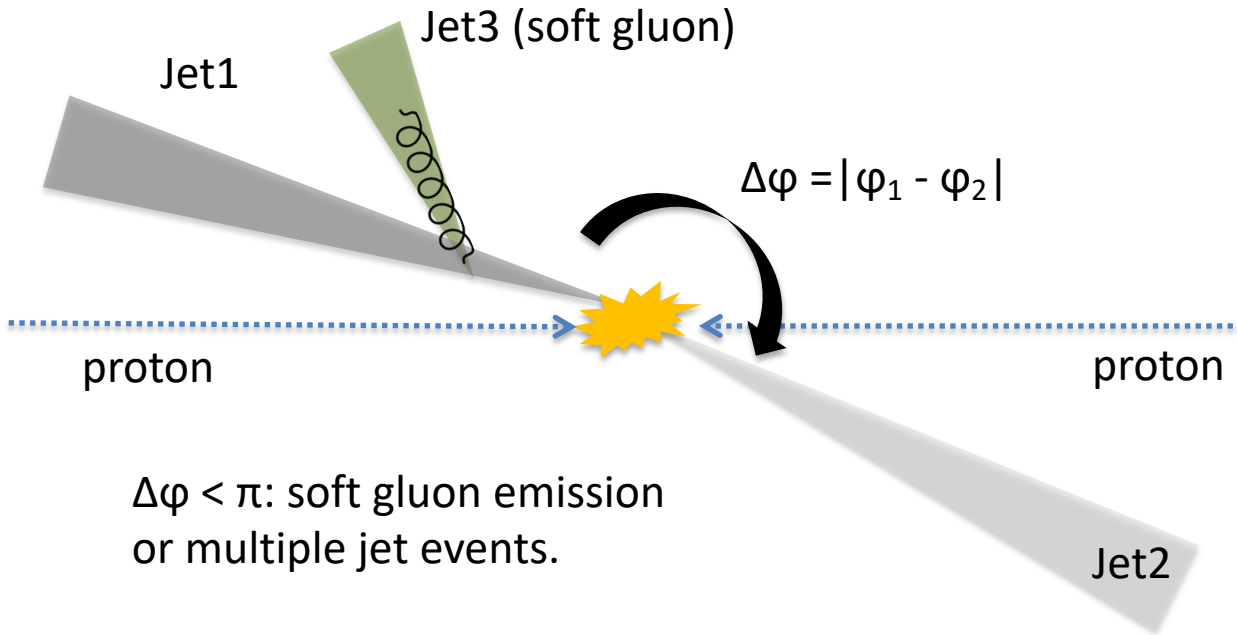
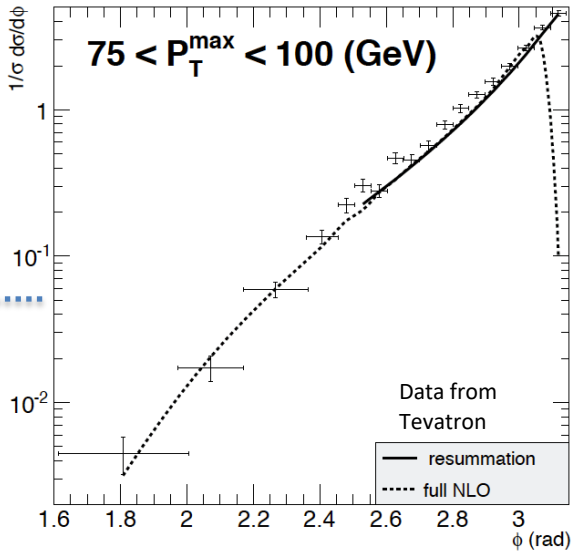



$\Delta\varphi < \pi$: soft gluon emission or multiple jet events.



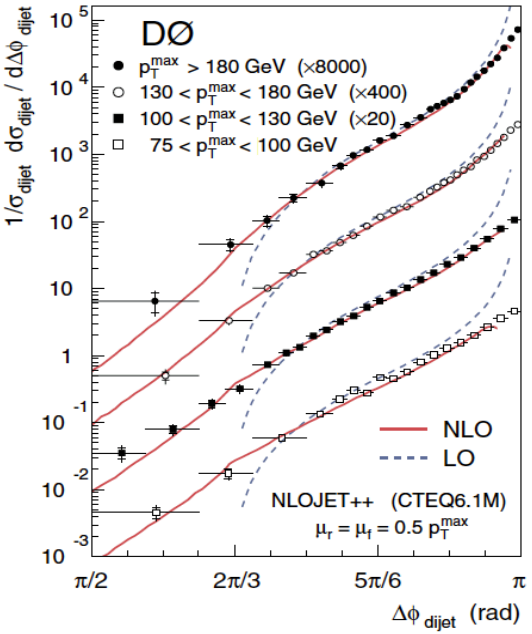

Singularity persist at $\Delta\varphi = \pi$ with one or more gluon radiation.

Theoretical work [4] (including gluon radiation) describes the data very well.

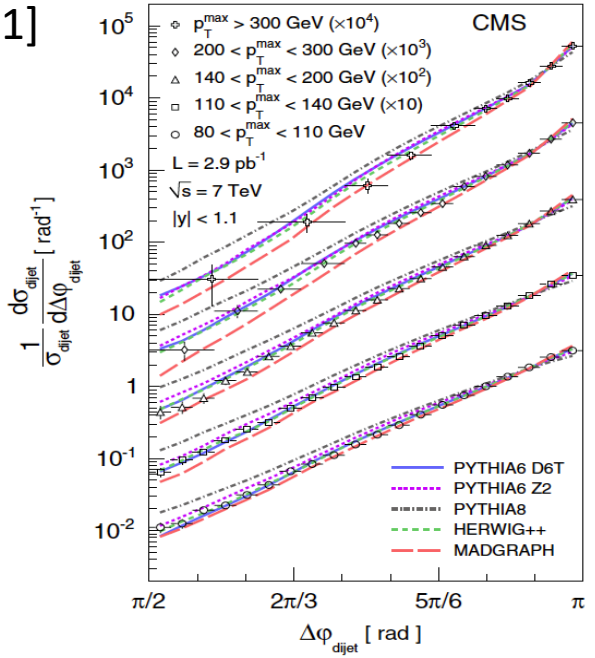


[4] Phys. Rev. D 92, 094007 (2015).

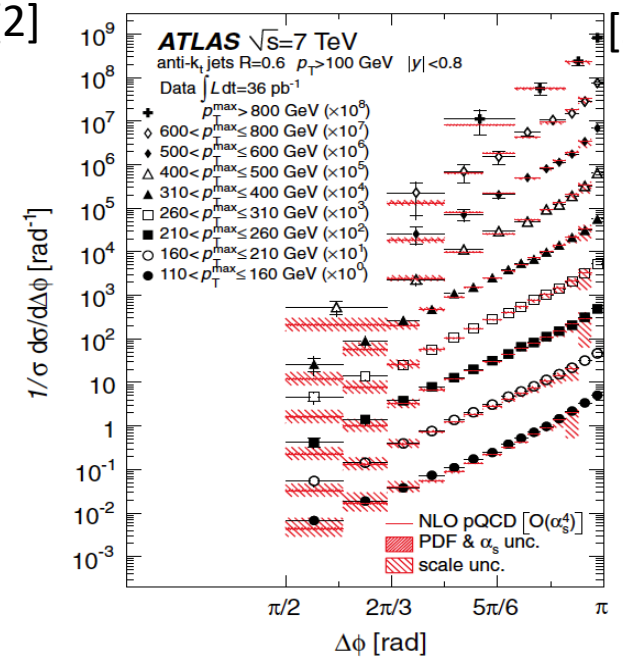
# Initial results from proton collisions




[1]




[2]




[3]

Similar conclusions in for Tevatron (ppbar at 1.96GeV), ATLAS and CMS (pp):

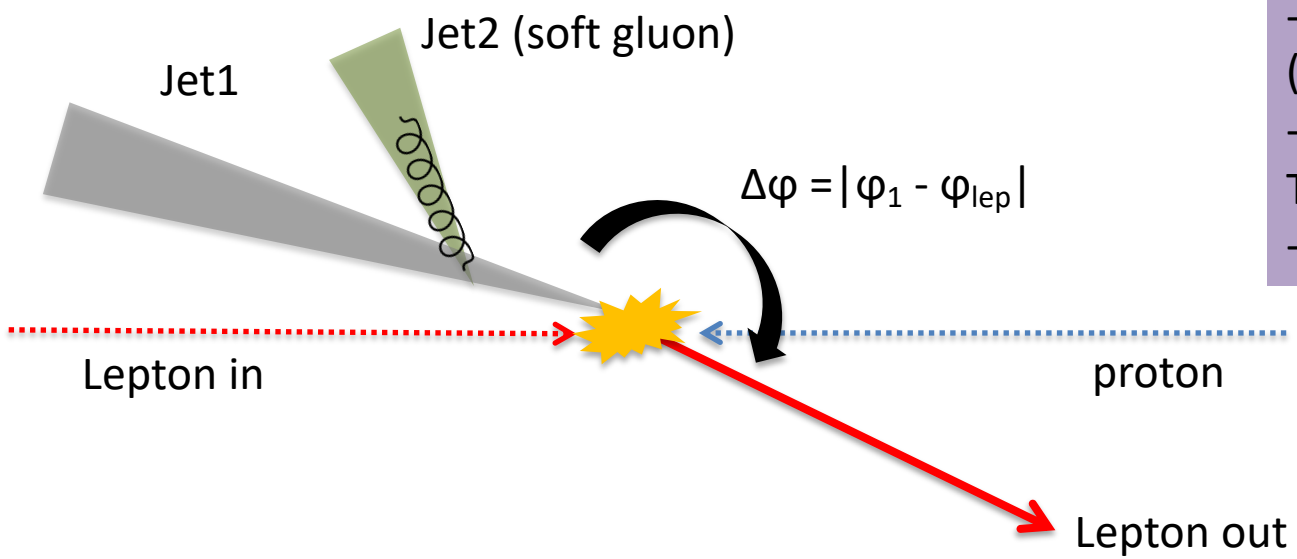
- NLO describes the data better than LO calculations (except at $\Delta\varphi \sim \pi$).
- MC generators describe the data fairly good however discrepancies at $\Delta\varphi \sim \pi$ where soft gluon radiation dominated.
- Suggest these results to tune MC generators at the time.

# Motivation

Azimuthal angular decorrelation angle ($\Delta\varphi$) was studied in dijet events in proton-proton collisions [1-3].

**Never done for lepton - jet**

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




-Access **small Bjorken-x** (HERA kinematic region).
-Study **$Q^2$ dependence** on TMD evolution.
-**Non-perturbative** effects.

Test theoretical framework [4] for lepton-jet decorrelation angle.

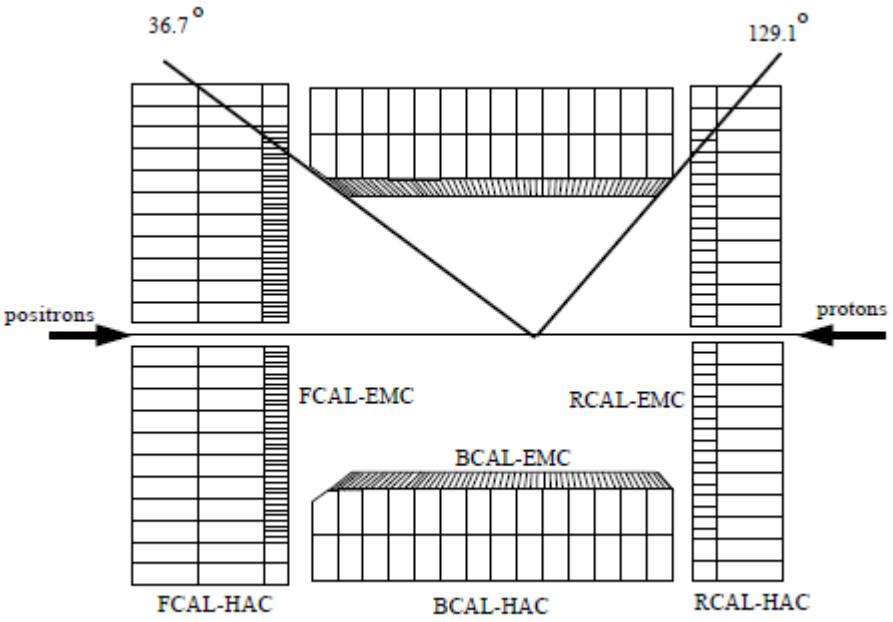
Lepton-proton collisions provide a theoretically simpler environment to test the calculations [5].

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

# Event selection and control plots

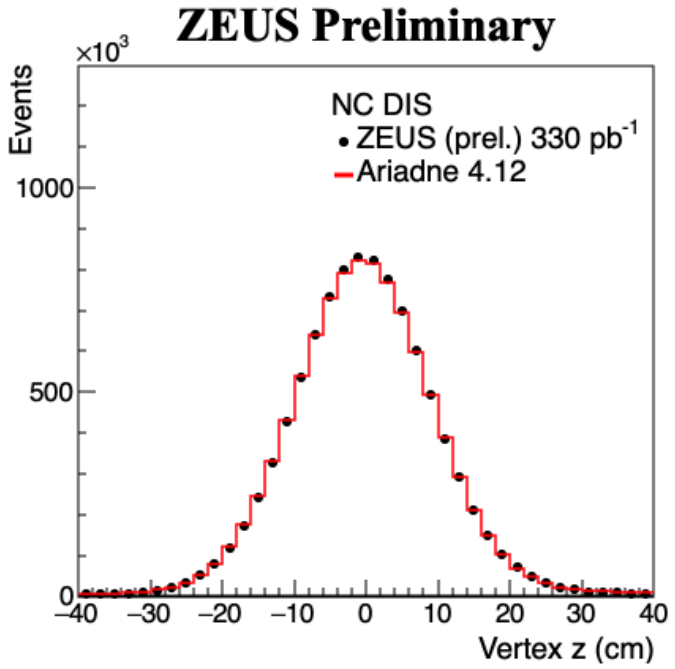
- Data from the HERA II period with $\sqrt{s}$ = 318 GeV and integrated luminosity of 330 $pb^{-1}$.
- Jets are reconstructed using the $k_T$ [6] algorithm in the laboratory frame.
- Measurements were obtained for the kinematic region (similar than previous $\gamma$–jet measurements at ZEUS).
- No significant differences in the results when separating electron and positrons.

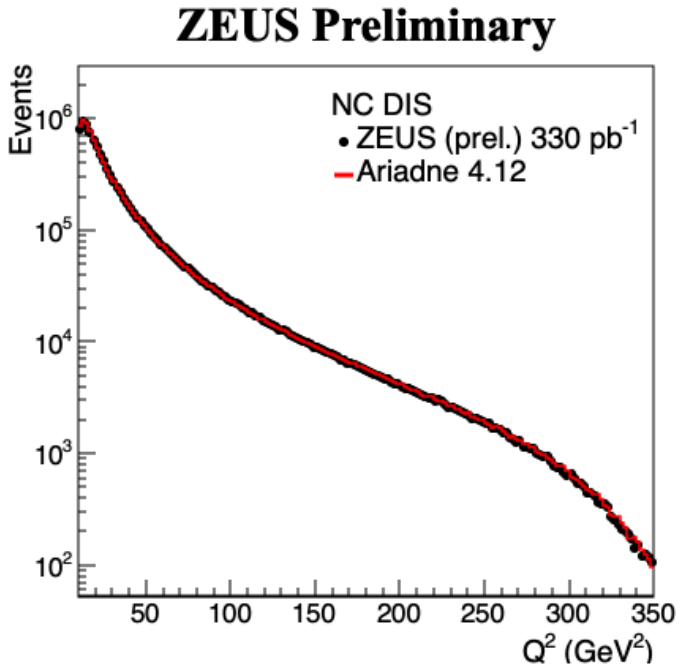
| |
|---|
| $10\ GeV^2 < Q^2 < 350\ GeV^2$ |
| $E_{lepton} > 10\ GeV$ |
| $140^o < \theta_{lepton} < 180^o$ |
| $E_T^{jet} > 2.5\ GeV$ |
| $\lvert\eta_{jet}\rvert < 1$ |

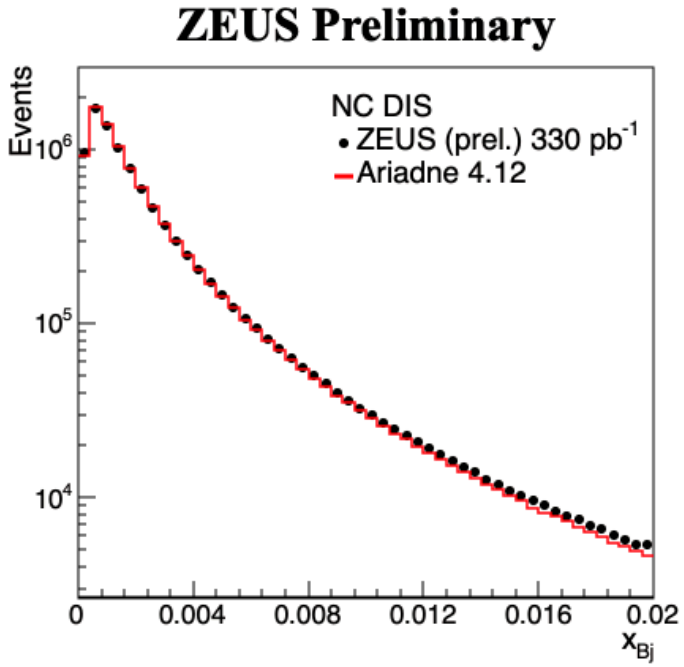


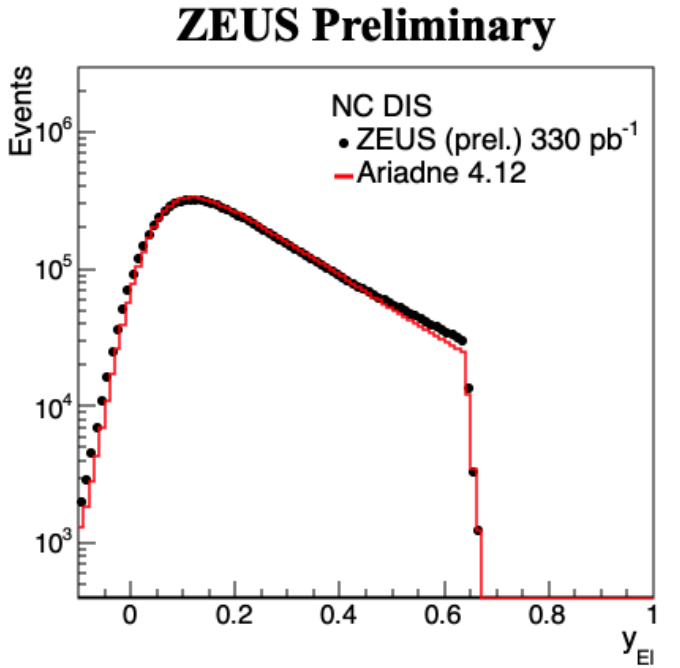



[6] Phys. Lett. B 691 (2010) 127-137)


ZEUS Preliminary
Events
×10³
1000
500
0
NC DIS
• ZEUS (prel.) 330 pb⁻¹
Ariadne 4.12
−40 −30 −20 −10 0 10 20 30 40
Vertex z (cm)

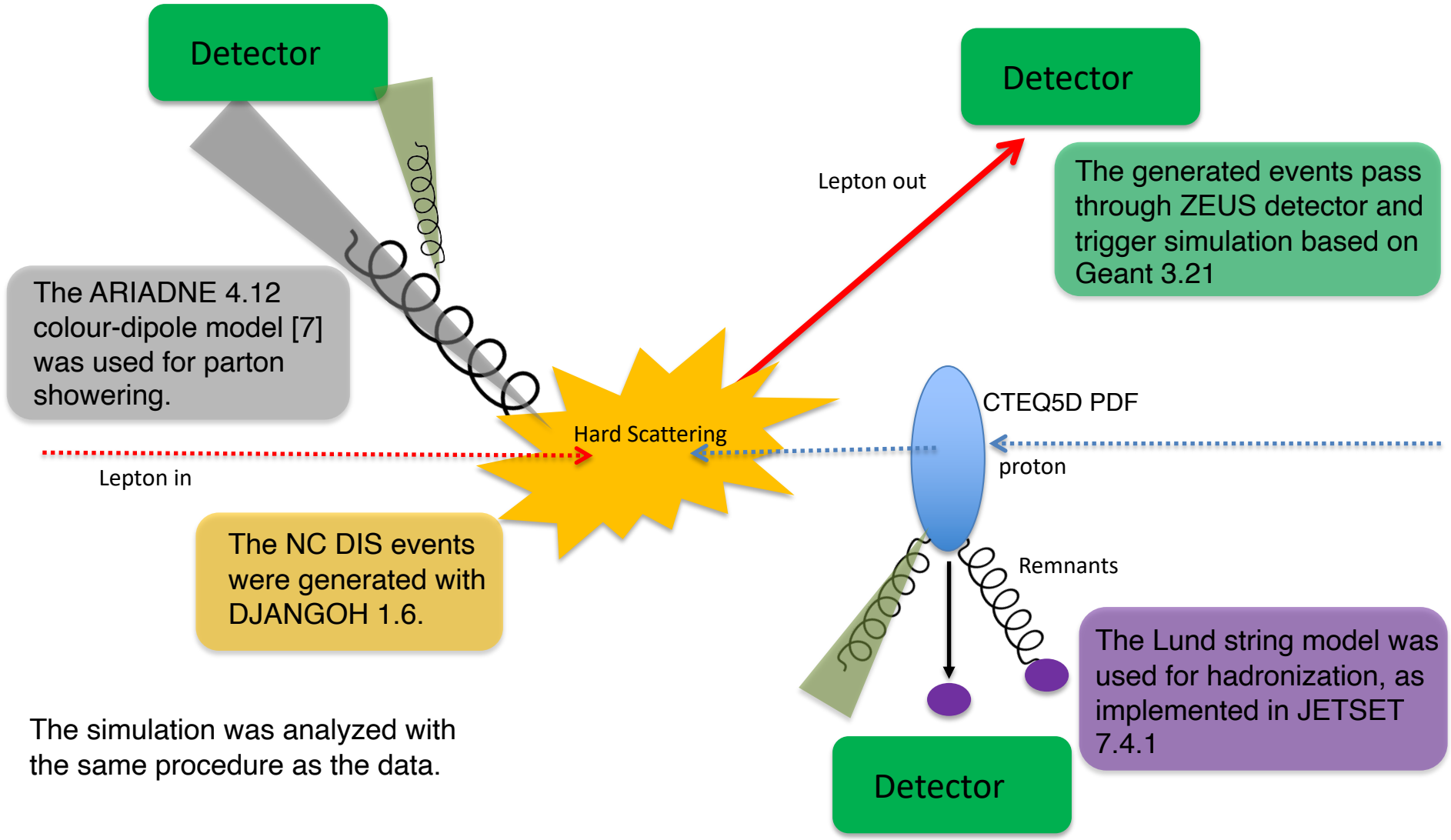

ZEUS Preliminary
Events
10⁶
10⁵
10⁴
10³
10²
NC DIS
• ZEUS (prel.) 330 pb⁻¹
Ariadne 4.12
50 100 150 200 250 300 350
Q² (GeV²)


ZEUS Preliminary
Events
10⁶
10⁵
10⁴
NC DIS
• ZEUS (prel.) 330 pb⁻¹
Ariadne 4.12
0 0.004 0.008 0.012 0.016 0.02
x_Bj


ZEUS Preliminary
Events
10⁶
10⁵
10⁴
10³
NC DIS
• ZEUS (prel.) 330 pb⁻¹
Ariadne 4.12
0 0.2 0.4 0.6 0.8 1
y_El

*Simplified representation

# Simulation




The simulation was analyzed with the same procedure as the data.



[7] ARIADNE, Comp. Phys. Comm. 71,15 (1992).

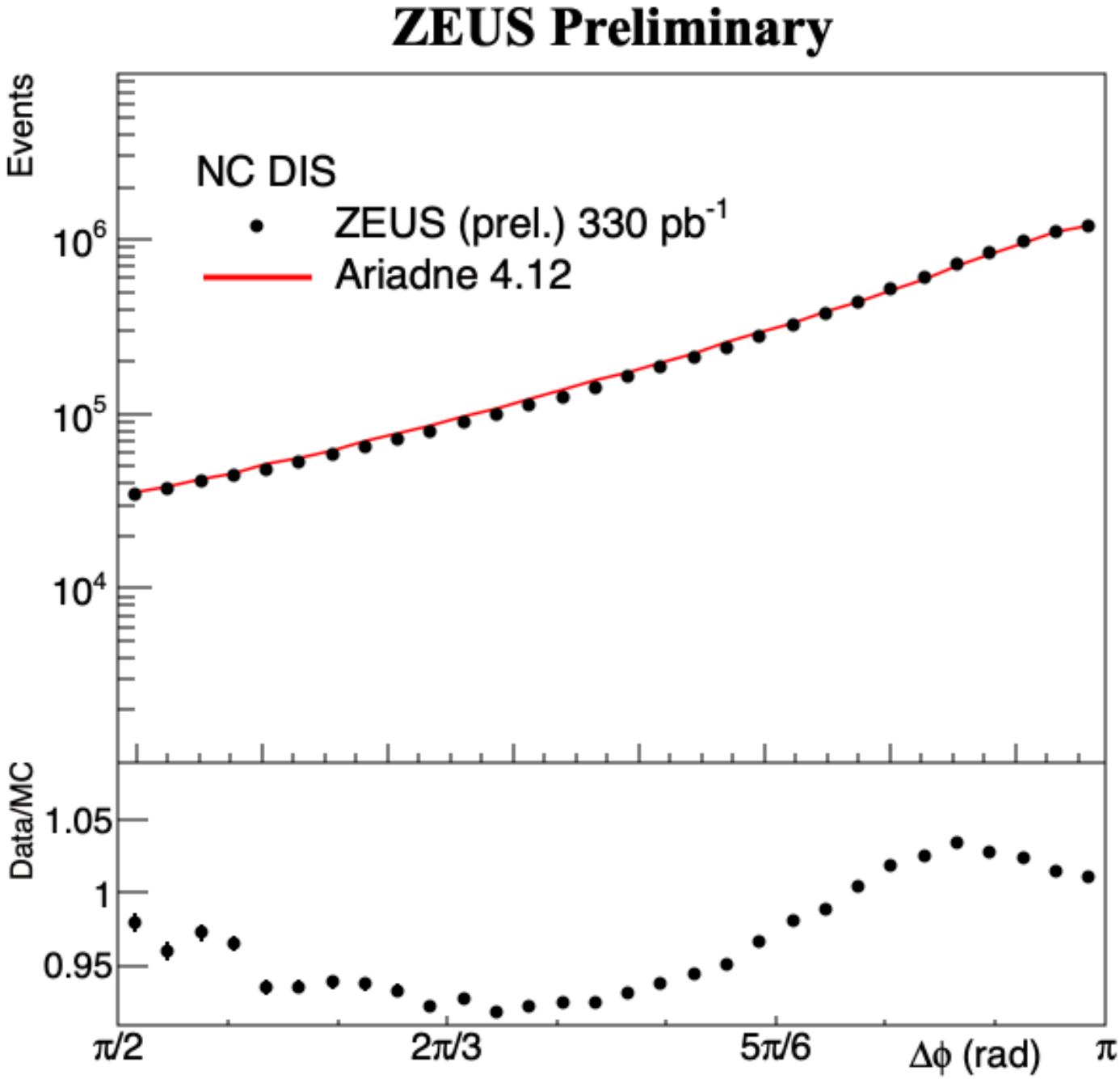
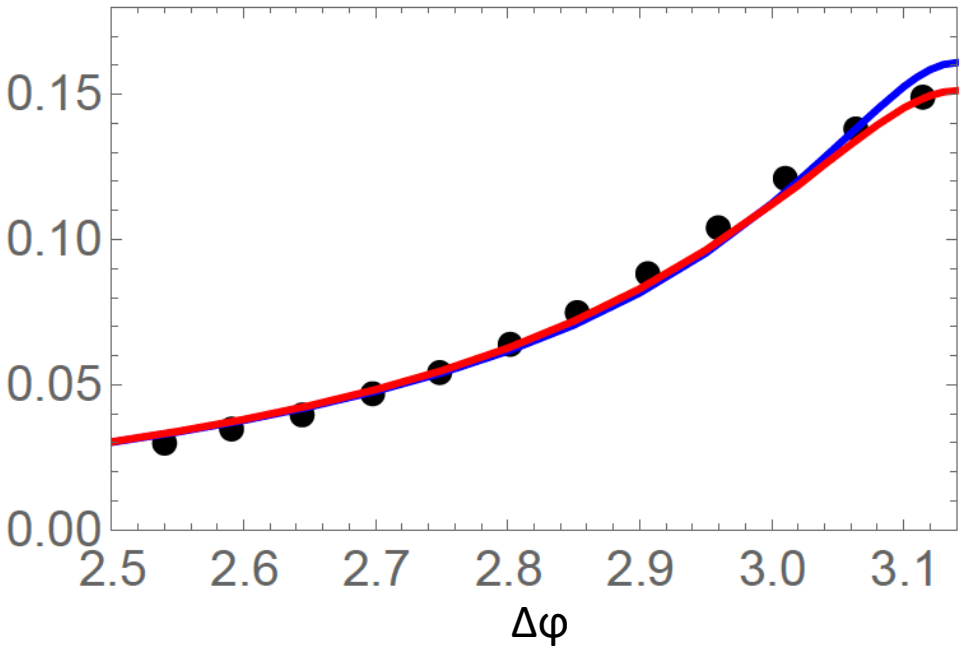

ZEUS Preliminary
Events
NC DIS
ZEUS (prel.) 330 pb-1
Ariadne 4.12
10^6
10^5
10^4
Data/MC
1.05
1
0.95
π/2
2π/3
5π/6
Δφ (rad)
π

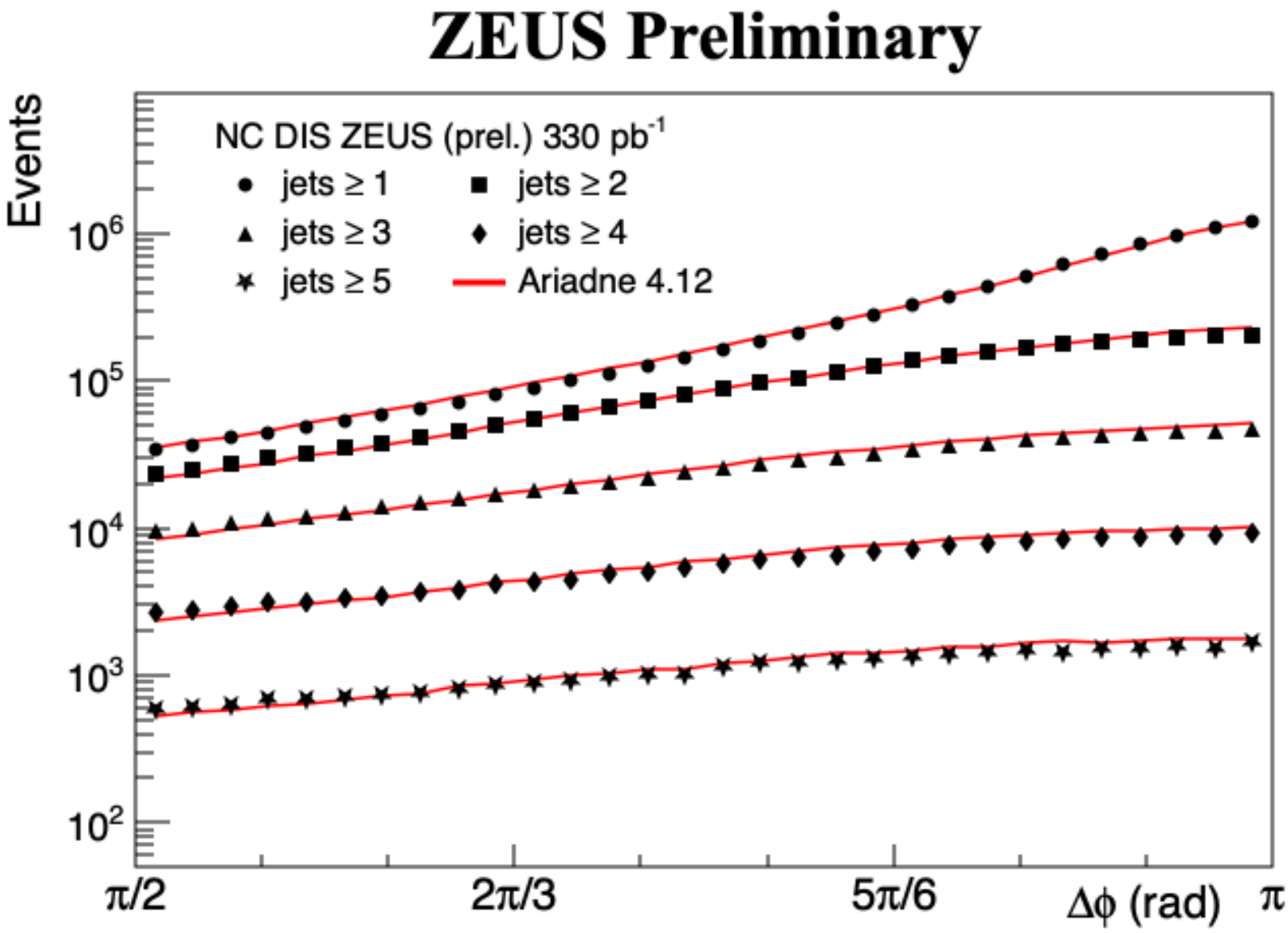
*Figure from F. Yuan (private communication)

# Theoretical comparison

- Gluon saturation will modify the TMD quark distribution [8,9].
- The azimuthal angular decorrelation, within the HERA kinematics, could be sensitive to these gluon saturation effects.
- Theoretical framework for lepton-jet decorrelation angle at HERA [10], conclude a sizable impact on the small-x contribution to the TMDs
- The black dots represent the ZEUS preliminary result at $\Delta\varphi > 5\pi/6$.
- The blue line represents the result from the default parametrization of the non-perturbative form factor [11,12]
- Red line include an additional small-x contribution.

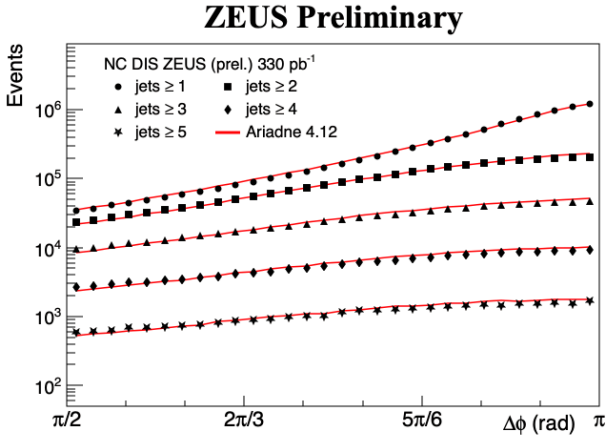


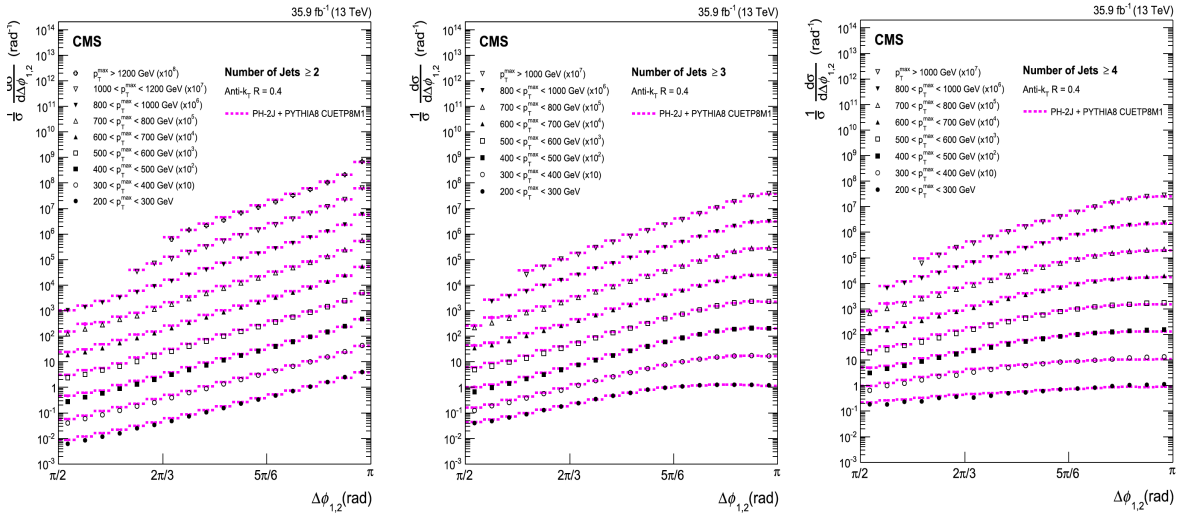

[8] Phys. Rev. D 49, 2233-2241 (1994).
[9] Phys. Rev. D 50, 2225-2233 (1994).
[10] arXiv:2007.12866 (2020).
[11] Phys. Lett. B 750, 533 (2015).
[12] Int. J. Mod. Phys. A 33, no. 11, 1841006 (2018).


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

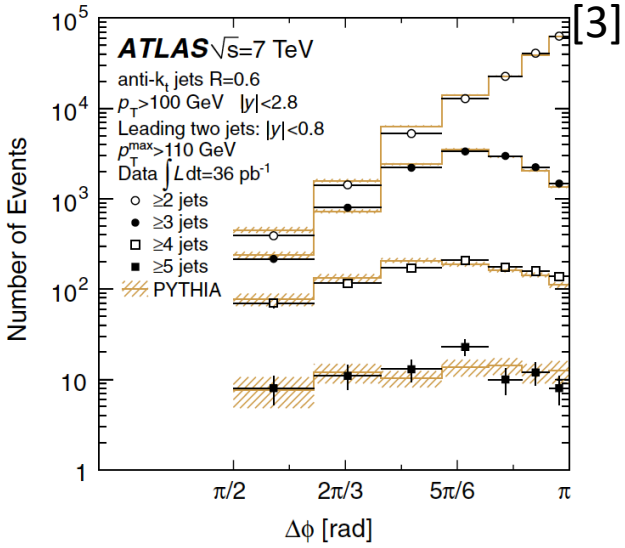
# Multi-jet events

[13]




[3]




- Decorrelation measurements in different jet multiplicities per event, exhibit the same behavior as reported in [3] and [13].
- High jet multiplicity events should be dominated by soft gluon radiation.
- The agreement with the MC model degrades.
- Similar conclusions were reported in proton collisions by the CMS collaboration [13], stating the need from improvements of theoretical models.

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

# Unfolding and Systematics

- Unfolding in 1-D will be performed with the **TUnfold** package.
- Differential cross section measurements will be presented, at different **$p_T$, $Q^2$ and jet multiplicity regions**.
- The following sources of systematic uncertainty were considered for normalized cross sections measurements, according to previous ZEUS analyses and similar from other experiments measurements in proton collisions:
  - The **energy of the scattered lepton** was varied by its known scale uncertainty of 2%.
  - The **jet energy scale** was varied 4% for values of $E^{jet}_T < 10$ GeV and 2.5% for $E^{jet}_T > 10$ GeV.
  - The uncertainty due to the **selection cuts** was estimated by varying the values of the cuts within the resolution of each variable.
  - The **differences** in the measurements obtained by using **ARIADNE and Lepto-MEPS** to correct the data for detector effects and bin migration.
  - The **decorrelation angle** was varied to account for its **resolution** effect into the measurements.
- TUnfold calculate systematics by propagating variations of bin migration matrix.

[13] TUnfold, JINST 7, T10003 (2012).

# Summary

- Perform decorrelation measurements of lepton and leading jet in DIS, similar to previous ZEUS $\gamma$–jet results and other experiments in proton collisions.
- The MC predictions from ARIADNE [7] describe the main features of the data well. However, some discrepancies are observable.
- Dedicated predictions for ep collisions from [10] are in progress.
- Differential cross section measurements will be presented, at different $p_T$, $Q^2$ and jet multiplicity bins.
- These measurements represent a prelude ($p_T$ range, systematics, etc) of future measurement at a new electron ion collider (EIC), particularly for measurements using polarized beams.

I want to thank Iris Abt, Katarzyna Wichmann, Matthew Wing and Feng Yuan.