Study of jet substructure in photoproduction events.

in ep collisions at EIC proposed energies.

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Abstract:

Study of jet substructure in the Photoproduction events in ep collisions at the EIC proposed energies.

SOFTWARES USED :

1. Pythia 8.306
2. ROOT 6.24.06
3. FastJet 3.4.0

14th December, 2022
XXV DAE-HEP Symposium
WG4 - Parallel 3

Why *ep* Collisions?

Counter rotating beams of electrons and ions collide at an interaction point (IP), where,

Lepton beams act as a clean, color-neutral probe and as a source of virtual or quasi-real photons.

Proton beams act as a *target* (which could also be light nuclei or any heavy nuclei), ie, a source of quarks and gluons.

Some of the past experiments include LEP1 and 2, HERA, and now EIC, which will pave the way for lepton colliders in the future.

LEP : 1989 - 2000

HERA 1992 - 2007

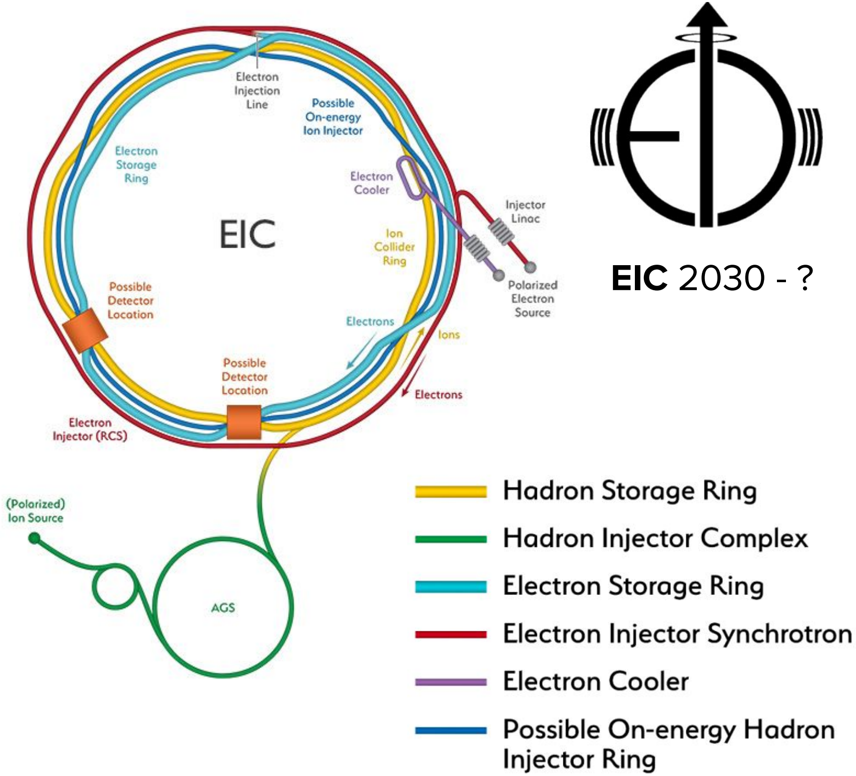
EIC 2030 - ?

Electron Ion Collider

The Electron-Ion Collider (EIC) is a powerful and versatile new accelerator facility that will be built in the U.S. and is on track to see first collisions in early **2030**’s.

EIC, with a versatile range of kinematics, beam polarizations, high luminosity and beam species, will allow for the exploration of new landscapes in QCD.

One of the main questions it aims to answer is *How do color-charged quarks and gluons, and jets, interact with a nuclear medium? How do the confined hadronic states emerge from these quarks and gluons? And many more…*



EIC 2030 - ?

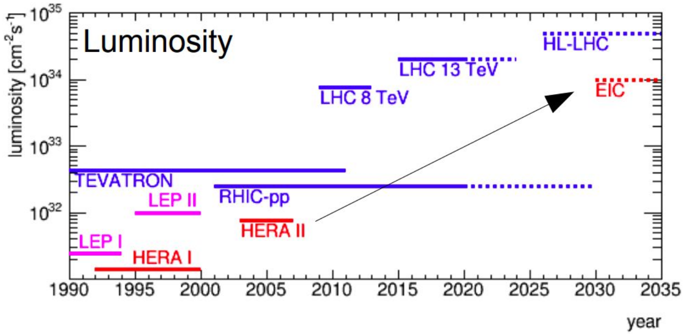
Brookhaven National Laboratory has a declared design for an EIC scheduled to be built in the 2020 decade

HERA vs EIC

Physics scopes of HERA and EIC differ but have significant overlap. EIC as compared to HERA:

- Reduced center-of-mass energy
- Higher luminosity ×100
- Better lepton polarisation
- Target polarisation
- Heavy targets
- Improved detectors

	HERA	EIC
Operation	1992-2007	>2030
Electron/Positron	27.5 GeV (polarised)	5-18 GeV (polarised)
Protons	820→920 GeV Not Available	60→280 GeV Polarised
Ions	Not Available	Up to 100 GeV/u (polarised)
E_{COM}	300→318 GeV	20→140 GeV
Luminosity	10^{32} cm^{-2}s^{-1}	10^{34} cm^{-2}s^{-1}



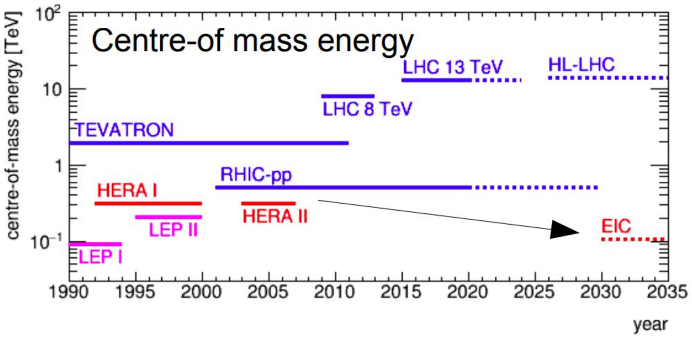


Fig: Stefan Schmitt, Workshop on EW and BSM physics at the EIC, May 2020

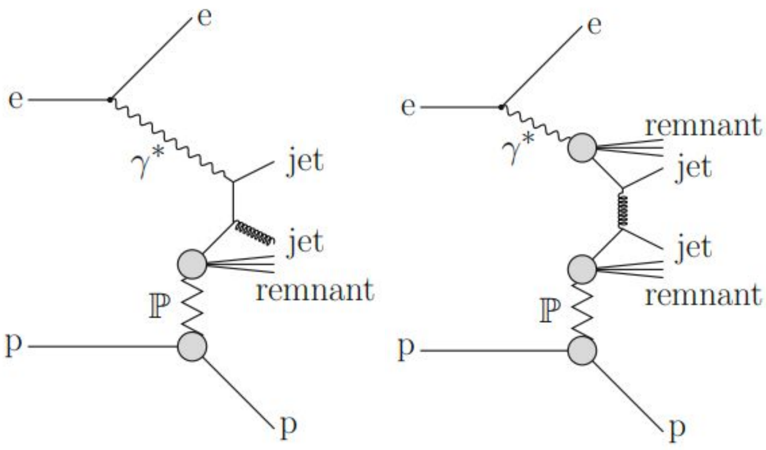
Photoproduction

High energy photon beams are generally generated by high energy electron or positron beams. Photoproduction processes are divided into two classes: **‘direct’** and **‘resolved’**:

In the **direct processes**, the photon participates as a point-like particle, interacting with a gluon (photon gluon fusion) or a quark (QCD Compton scattering) in the target proton.

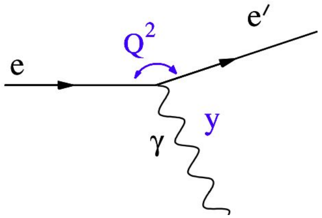
In the **resolved processes**, the photon interacts through its partonic content.

The dual identity of the photon as a fundamental gauge boson and a hadron-like object provides a number of unique opportunities for exploring QCD



(a) Direct **(b) Resolved**

Leading order Feynman diagrams for dijet production with photons in ep collisions.



$Q^2 = 1\ \text{GeV}^2$

Jets

”Truth is a place we can not go but, we can take pictures of it”

A jet can be defined as a collimated spray of stable particles arising from the fragmentation and hadronisation of a parton (quark or gluon) after a collision.

The jets provide a link between the observed colourless stable particles and the underlying physics at the partonic level.

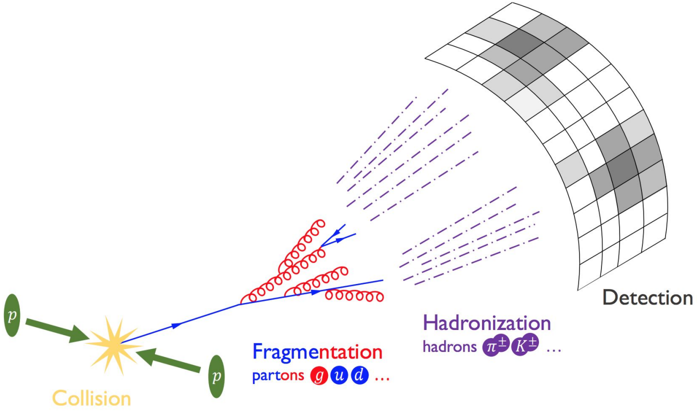


fig: https://www.ericmetodiev.com/post/jetformation/

Collision (Event Generation)

Fragmentation and Hadronization

Hadrons Produced

Jet Clustering (Formation of Jets with Jet Algorithms)

Subjets Formed (With resolution parameter)

Studying Jet Shape and Multiplicities

Jet Algorithms - *grouping particles into jets*

Jet algorithms indicate how close two particles must be for them to belong to the same jet, they help to cluster the final state hadrons as jet constituents to make up jets.

Longitudinally invariant k_t jet algorithm all input objects i, i = 1, . . . n, according to the following iterative steps:

1. For each pair of particles i, j work out the kt distance d_{ij} where p_{ti}, y_i and ϕ_i are the transverse momentum (with respect to the beam direction), rapidity and azimuth of particle i.
   R is a jet-radius parameter usually taken of order 1.
2. Calculate the beam distances, d_{iB}
3. Find the minimum d_{min} of all the d_{ij}, d_{iB}.
   If $d_{min} = d_{ij}$ merge particles i and j into a single particle, summing their four-momenta; if $d_{min} = d_{iB}$ then declare particle i to be a final jet and remove it from the list.
4. Repeat Steps 1 → 3

$$d_{ij} = \min(p_{ti}^2, p_{tj}^2)\,\Delta R_{ij}^2/R^2$$

$$\Delta R_{ij}^2 = (y_i - y_j)^2 + (\phi_i - \phi_j)^2$$

$$d_{iB} = p_{ti}^2$$

$d_{iB} < d_{ij}$: *Merge*

$d_{iB} > d_{ij}$: Jet Found

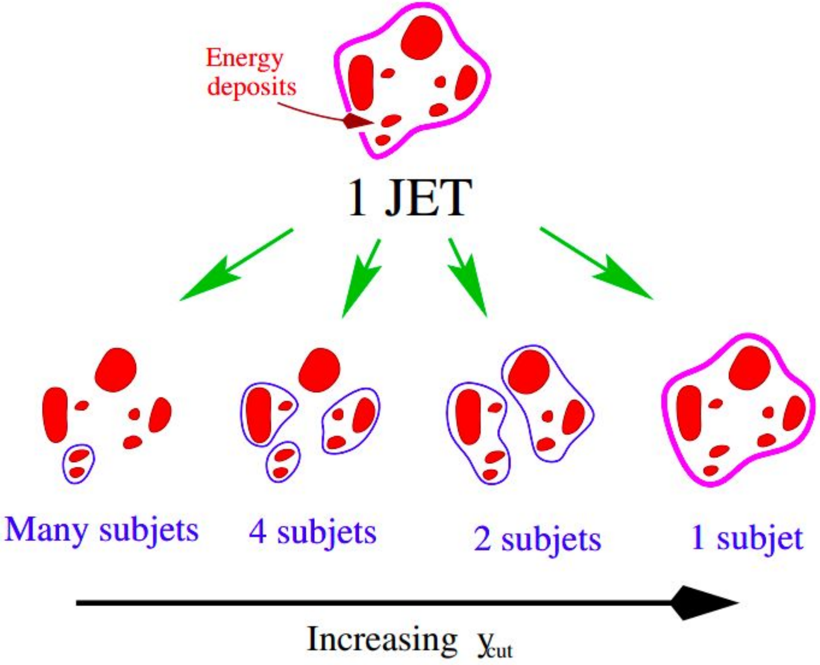
Jet Substructure

Each jet has its own substructure, ie, an internal structure of the jets within a jet. It is defined by reapplying the k_T cluster algorithm until for every pair of particles the quantity

$$d_{ij} = \min(E_{Ti}, E_{Tj})^2 \cdot [(\eta_i - \eta_j)^2 + (\varphi_i - \varphi_j)^2]$$

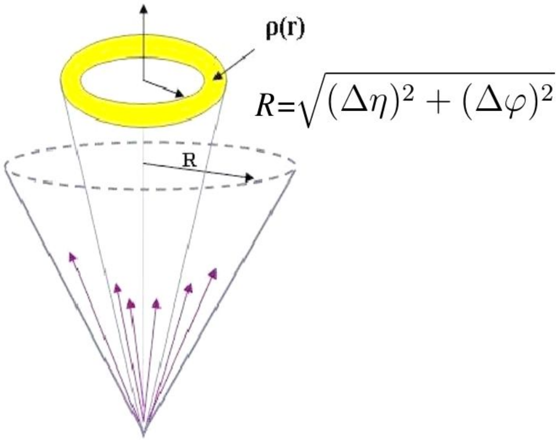
is above $y_{cut} \cdot (E_T^{jet})^2$

Where, y_{cut} is the **resolution parameter**. It decides how many subjets are formed out of one jet, the number of subjets formed are called as subjet multiplicities



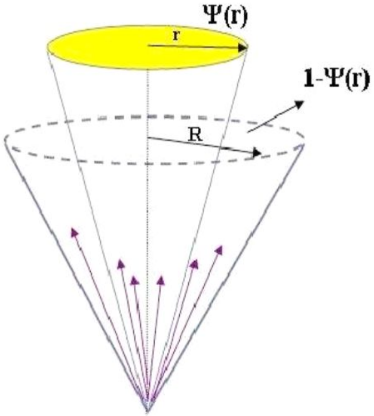
$$\langle n_{\text{sbj}}(y_{\text{cut}})\rangle = \frac{1}{N_{jet}} \sum_{jets} n_{\text{sbj}}^{jet}(y_{\text{cut}})$$

Jet Shapes



Differential Jet

$$\rho(r)=\frac{1}{N_{jets}}\cdot\frac{1}{\Delta r}\cdot\sum_{jets}\frac{E_T(r-\frac{\Delta r}{2},r+\frac{\Delta r}{2})}{E_T(0,r=1)}$$



Inclusive Jet Shape

$$\psi(r)=\frac{1}{N_{jets}}\cdot\sum_{jets}\frac{E_T(r)}{E_T(r=1)}$$

Differential jet shape (ρ)

is defined as the average fraction of the jet’s transverse energy contained inside an annulus.

Integrated jet shape (Ψ)

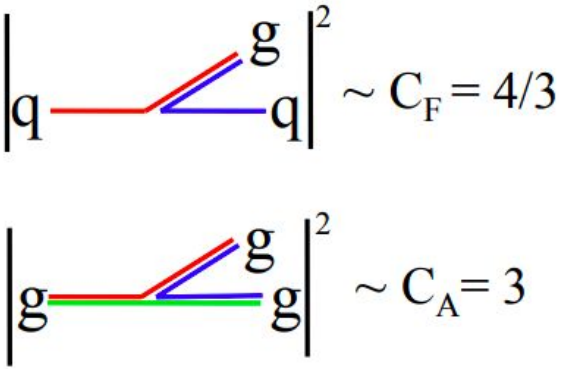
is defined as the average fraction of jet transverse momentum inside a cone of radius r concentric to the jet axis.

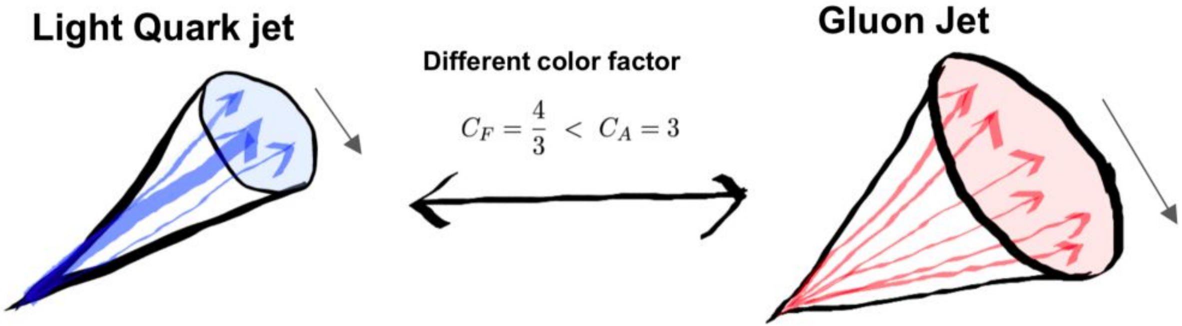
figs: Pelin Kurt, CERN-TR Weekly Meeting, 23 September 2009

Quark and Gluon Jets

Because of **different colour interaction and hadronization**, gluon jets are wider and have a higher subjet multiplicity, while quark jets are more likely to produce narrow jets with hard constituents and have lesser mean subjet multiplicity.

There is a theoretical interest in the ratio of the mean multiplicity of gluon and quark jets, $r = N_g/N_q$. As it is predicted to be equal to the ratio C_A/C_F in the limit of asymptotically large energies, where C_A and C_F are the color factors.





The ratio C_A/C_F is perhaps the most fundamental quantity in QCD besides the strong interaction coupling strength, a_S

Sample Generation

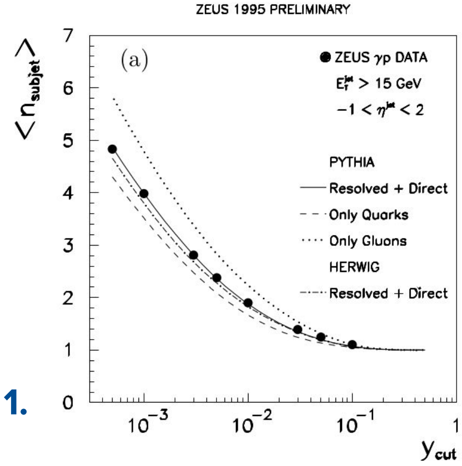
PYTHIA-8.306 + FASTJET-3.4

PYTHIA (Event Generation)
Events Generated: 10^6 - E_{COM}: 140 GeV
Lepton Beam: 18 GeV Proton Beam: 275 GeV
Flags: HardQCD:all = on, PhotonParton:all = on, Photon:Q2max = 1.0

FASTJET (Jets and Subjet reconstruction)
Longitudinally invariant k_T Algorithm
Jet Radius (R): 1 y_{cut}: 0.0005 to 0.5
Jet Shapes (Inclusive and Differential) and Subjet Multiplicity

Events are simulated by Monte Carlo Event Generator PYTHIA 8.304 for $\sqrt{s}_{EIC}$ = 140 GeV (EIC proposed) and FASTJET3.4 is used for the Jet (and subjet) reconstruction via the longitudinally invariant k_T Algorithm.

HERA results



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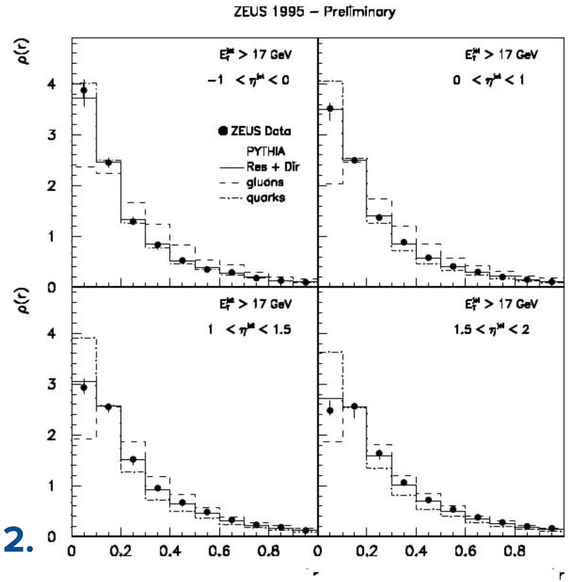

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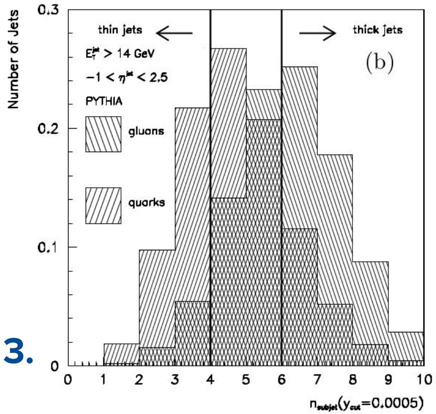

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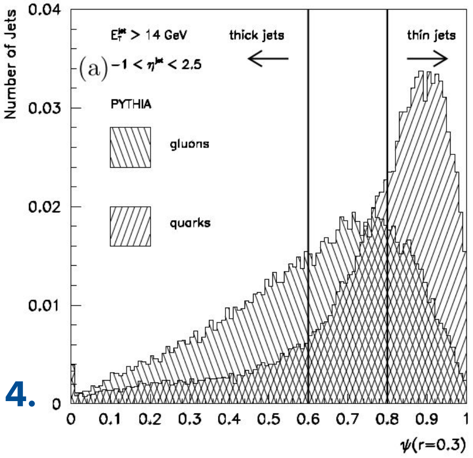


4.

Recaps from published ZEUS results:

1. Measured mean subjet multiplicity $<n_{subjet}>$ decreases as the value of y_{cut} is increased. Slopes of Combined, Quark only and Gluon only cases are studied,

2. Differential Jet shape is observed,

3&4. Quarks and Gluons are separated on the basis of thick and thin width, and their subject multiplicities are studied.

Subjet Multiplicity

Results: 18x275 √s = 140 GeV

The “thin” jet sample is dominated by quark-initiated jets in the final state and the “thick” jet sample has a high content of gluon-initiated jets coming mainly from the final-state gluon of the subprocess $q_{\gamma} g_{p} \rightarrow qg$.

Thick Jets : **ψ(r=0.3) < 0.6** *- gluon jets*

QQ Scattering ≈ 33.01

GG Scattering ≈ 13.02

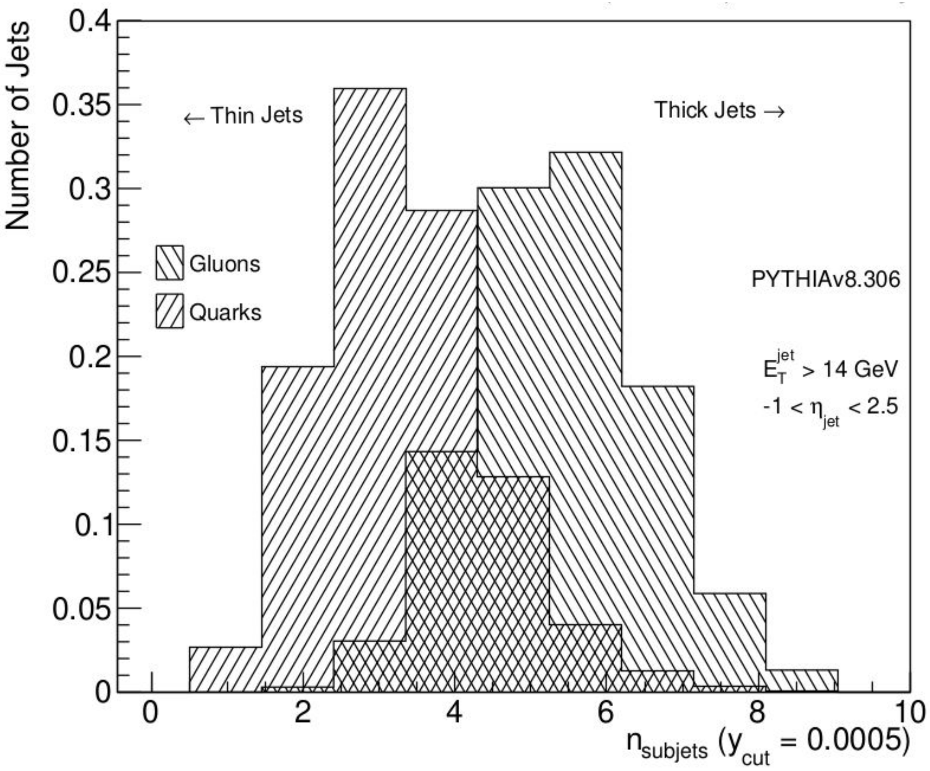
QG Scattering ≈ **53.96**

Thin Jets : **ψ(r=0.3) > 0.8** *- quark jets*

QQ Scattering ≈ **53.94**

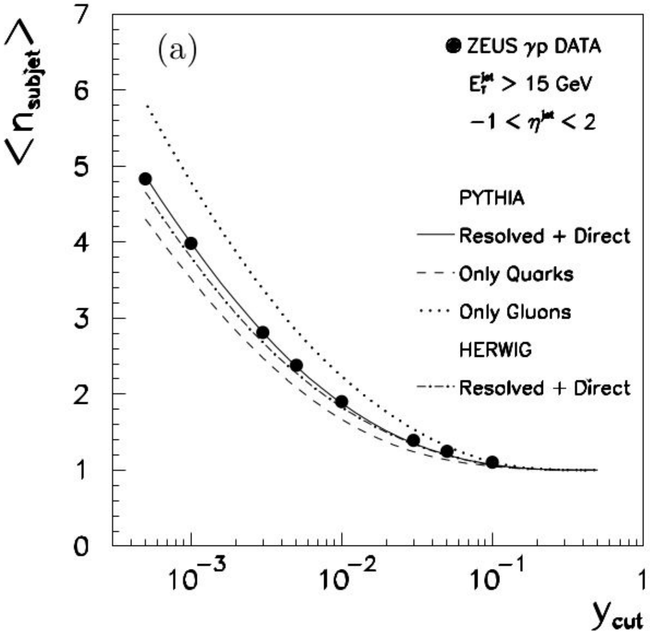
GG Scattering ≈ 1.79

QG Scattering ≈ 44.26

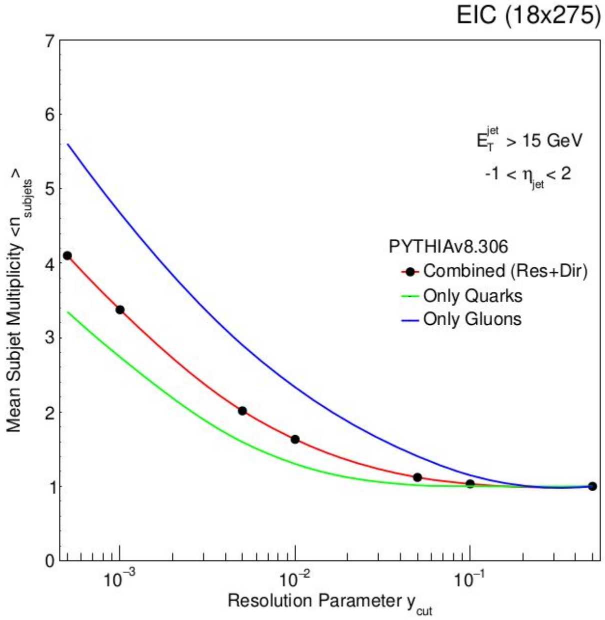


Jets separated on the basis of inclusive jet shapes

Mean Subjet Multiplicity vs Resolution parameter



HERA E_{COM}=300 GeV

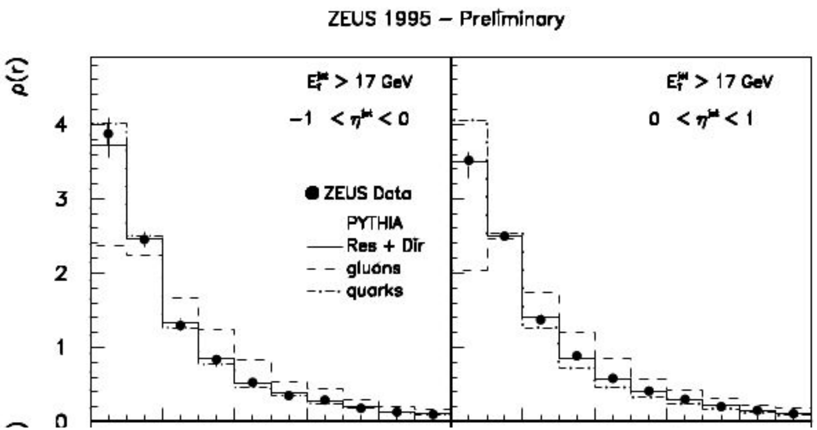


EIC E_{COM}=140 GeV

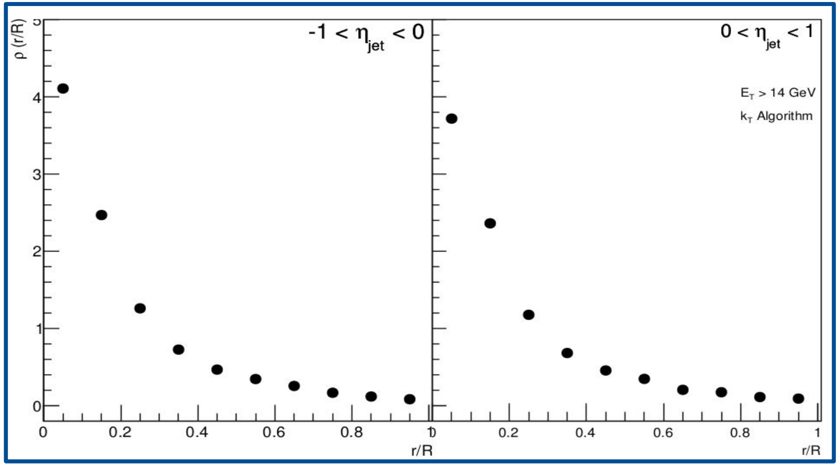
	$\langle n_{subjet} \rangle$		
y_{cut}	Res+Dir	Quarks	Gluons
0.0005	4.10	3.34	5.60
0.001	3.37	2.73	4.67
0.005	2.01	1.59	2.89
0.01	1.63	1.30	2.33
0.05	1.12	1.02	1.40
0.1	1.03	1.01	1.14

As observed, the measured mean subjet multiplicity is inversely propotional to the resolution parameter

Differential Jet Shapes



HERA E_{COM}=300 GeV



EIC E_{COM}=140 GeV

r $(r_a+r_a)/2$	**ρ(r/R)** **$-1 < \eta < 0$**	**ρ(r/R)** **$0 < \eta < -1$**
0.05	4.10	3.71
0.15	2.46	2.36
0.25	1.26	1.17
0.35	0.73	0.68
0.45	0.46	0.46
0.55	0.34	0.34
0.65	0.26	0.20
0.75	0.17	0.17
0.85	0.12	0.11
0.95	0.08	0.09

Simulated Data for the differential Jet shape at the EIC energies E_{COM} = 140 GeV, at two pseudorapidity ranges.

Summary

- PYTHIAv8.306 is used as a Monte Carlo generator and FASTJETv3.4 is used to reconstruct jets,
- Jets (algorithm, shapes and subjet multiplicities) are briefly described,
- Measurements of jet shape and subjet multiplicity have been performed for inclusive jet samples for given values of E_T^{Jet} and η^{Jet}, in the kinematic region of $Q^2 \leq 1$,
- The Monte Carlo models reproduce the measurements of the jet shape and subjet multiplicity and display the expected differences for quark- and gluon-initiated jets,
- Use of the jet shape and subjet multiplicity to select samples enriched in quark- and gluon-initiated jets to study the dynamics of the subprocesses.

EIC, with its cutting-edge detectors and enhanced luminosity, along with advanced software tools, will help us understand more about the colour factors and give a highly precise measurement, which will further lead to a better understanding of QCD.

Thank You!

References

1. High Energy Photoproduction - (https://arxiv.org/pdf/hep-ex/0509018.pdf)
2. Resolved Photon Processes - (https://arxiv.org/pdf/hep-ph/9508221.pdf)
3. Matteo Cacciari - (https://indico.mitp.uni-mainz.de/event/167/attachments/651/689/Cacciari_1.pdf)
4. FastJet user manual - (http://fastjet.fr/repo/fastjet-doc-3.3.2.pdf)
5. Colour factors - Michiel Botje - (https://www.nikhef.nl/~h24/qcdcourse/section-5.pdf)
6. Subjet Multiplicities at LHC Energies and the QCD Color Factor Ratio - M Kaur and AP Kaur - (https://www.hindawi.com/journals/ahep/2013/585809/)
7. Inclusive-jet photoproduction at HERA and determination of alphas - (https://arxiv.org/abs/1205.6153)
8. Photoproduction at HERA - (https://arxiv.org/abs/hep-ex/0311044)
9. The Electron-Ion Collider - (https://arxiv.org/pdf/2211.02785.pdf)
10. Jet substructure at HERA - (https://arxiv.org/pdf/0812.0757.pdf)

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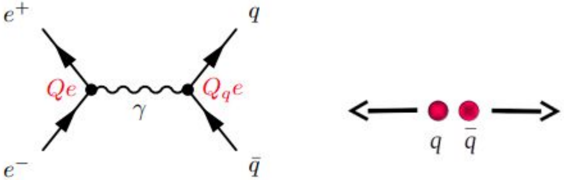
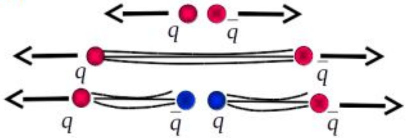
More on Jets

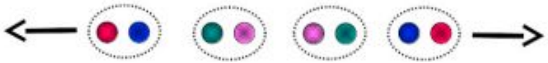
Consider the $q\bar{q}$ pair produced in $e^+e^- \to q\bar{q}$



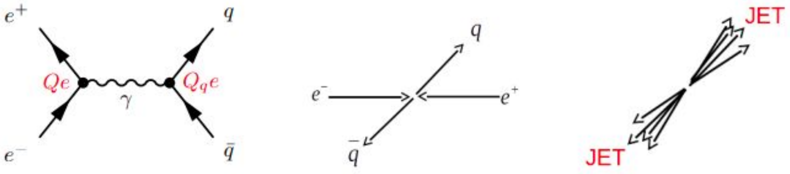
As the quarks separate, the potential energy in the colour field ("string") starts to increase linearly with separation. When the energy stored exceeds $2m_q$, new $q\bar{q}$ pairs can be created.



As energy decreases, hadrons (mainly mesons) freeze out



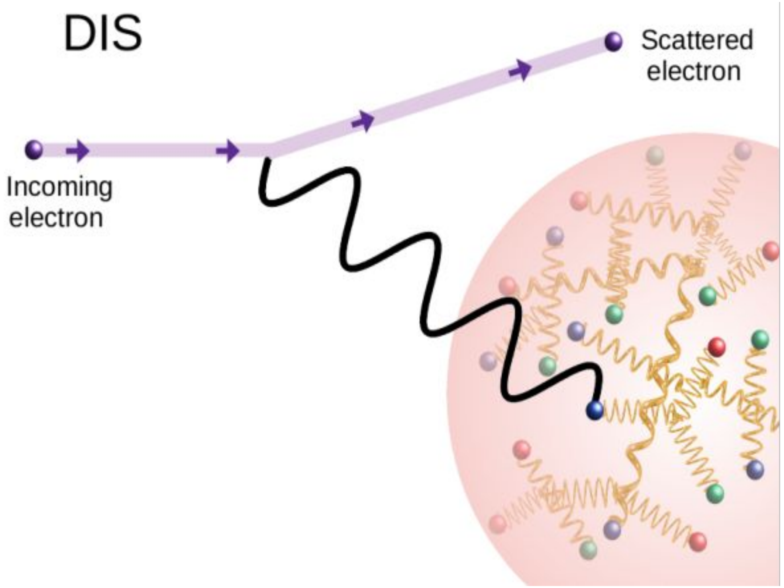
As quarks separate, more $q\bar{q}$ pairs are produced. This process is called hadronisation. Start out with quarks and end up with narrowly collimated jets of hadrons.

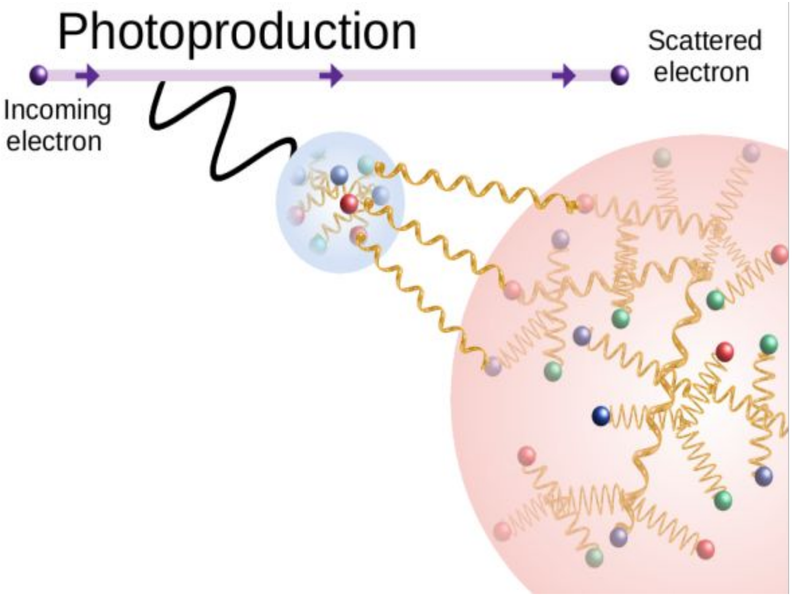


Typical $e^+e^- \to q\bar{q}$ event

The hadrons in a quark(antiquark) jet follow the direction of the original quark(antiquark). Consequently, $e^+e^- \to q\bar{q}$ is observed as a pair of back-to-back jets.

Difference between Photoproduction and DIS





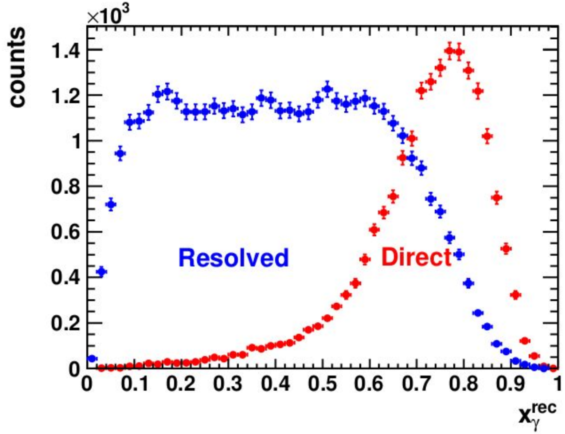
Direct vs Resolved Processes

In photoproduction events, the dominant subprocesses are $q_\gamma g_p \rightarrow qg$ in resolved and $\gamma g \rightarrow q\bar{q}$ in direct.

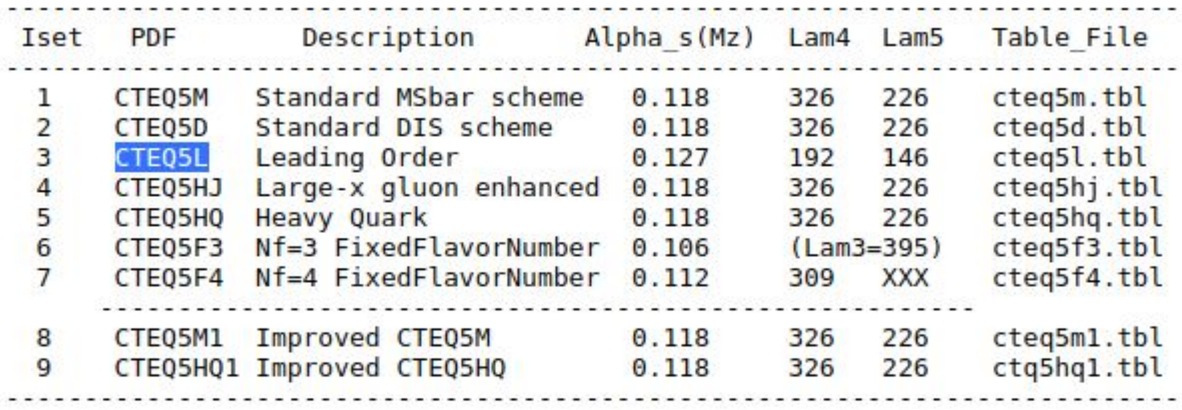
This observable measures the energy invested by the photon in producing the dijet system and can be used to separate resolved and direct processes since they populate different regions of phase space.

$$x_\gamma = \frac{1}{2E_e y}(p_{T,1}e^{-\eta_1} + p_{T,2}e^{-\eta_2})$$

On the other hand, direct processes are dominated by quark jets,



PDF used for Simulation of Photoproduction



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---------------------------------------------------------------------------
 Iset   PDF          Description        Alpha_s(Mz)  Lam4  Lam5   Table_File
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  2    CTEQ5D   Standard DIS scheme     0.118      326   226    cteq5d.tbl
  3    CTEQ5L   Leading Order           0.127      192   146    cteq5l.tbl
  4    CTEQ5HJ  Large-x gluon enhanced  0.118      326   226    cteq5hj.tbl
  5    CTEQ5HQ  Heavy Quark             0.118      326   226    cteq5hq.tbl
  6    CTEQ5F3  Nf=3 FixedFlavorNumber  0.106      (Lam3=395)   cteq5f3.tbl
  7    CTEQ5F4  Nf=4 FixedFlavorNumber  0.112      309   XXX    cteq5f4.tbl
      --------------------------------------------------------
  8    CTEQ5M1  Improved CTEQ5M         0.118      326   226    cteq5m1.tbl
  9    CTEQ5HQ1 Improved CTEQ5HQ        0.118      326   226    ctq5hq1.tbl
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```

The **CTEQ5L** (PYTHIA8+) PDF is used for the proton, because contrary to modern PDFs (i.e., CT, NNPDF, HERAPDF, MSTW) its PDF is not frozen at its input scale Q^2_0, but allows description of the partonic structure of the proton at $Q^2 \leq Q^2_0$

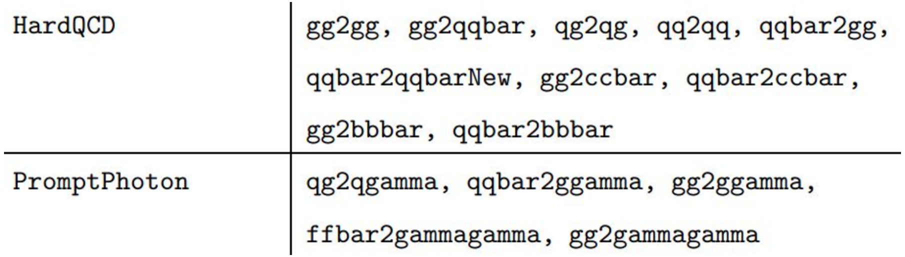
https://www.physics.smu.edu/scalise/cteq/CTEQ5Table/

Paper: DOI 10.1140/epjc/s10052-008-0598-2
PYTHIA8: https://pythia.org/latest-manual/PDFSelection.html

PYTHIA Initializations & Subprocess

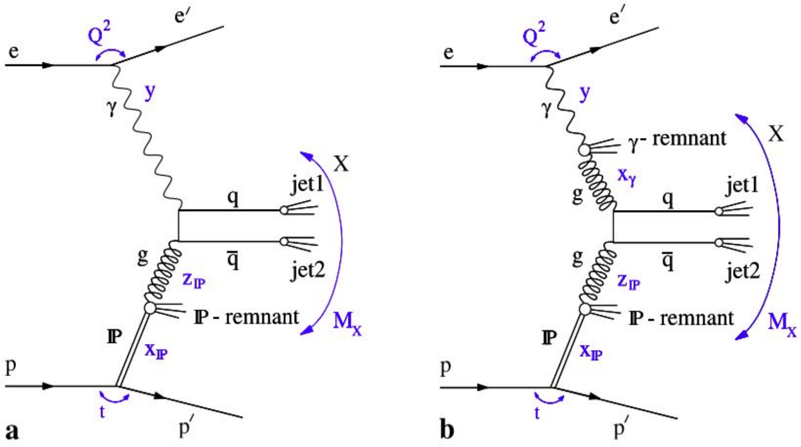
```
// Beam parameters :
pythia.readString("Beams:frameType = 2");    // Beams of unequal energies
pythia.readString("Beams:idA = -11");        // Beam A : Electrons/Positrons
pythia.readString("Beams:idB = 2212");       // Beam B : Protons
pythia.readString("Beams:eA = 18");          // electron_En : HERA=27.5GeV && EIC=18 GeV
pythia.readString("Beams:eB = 275");         // proton_En : HERA=820|920Gev && EIC=275 GeV
pythia.readString("PDF:beamA2gamma = on");   // Set PDF for beam photons


// Set Event Settings :
settings.mode("Photon:ProcessType", 0);                          // Switch on : Automatic Mix
pythia.readString("Photon:Q2max = 1.0");                         // Maximal Q2
pythia.readString("MultipartonInteractions:pT0Ref = 3");         // Use tuned pT0ref for photon-hadron
pythia.readString("PhaseSpace:pTHatMin = 10.");                  // Limit partonic pThat.
```



HardQCD	gg2gg, gg2qqbar, qg2qg, qq2qq, qqbar2gg, qqbar2qqbarNew, gg2ccbar, qqbar2ccbar, gg2bbbar, qqbar2bbbar
PromptPhoton	qg2qgamma, qqbar2ggamma, gg2ggamma, ffbar2gammagamma, gg2gammagamma

Kinematics of Resolved and Direct Processes



Leading-order diagrams for **a** direct and **b** resolved processes in photoproduction of dijets
[*DOI 10.1140/epjc/s10052-008-0598-2*]

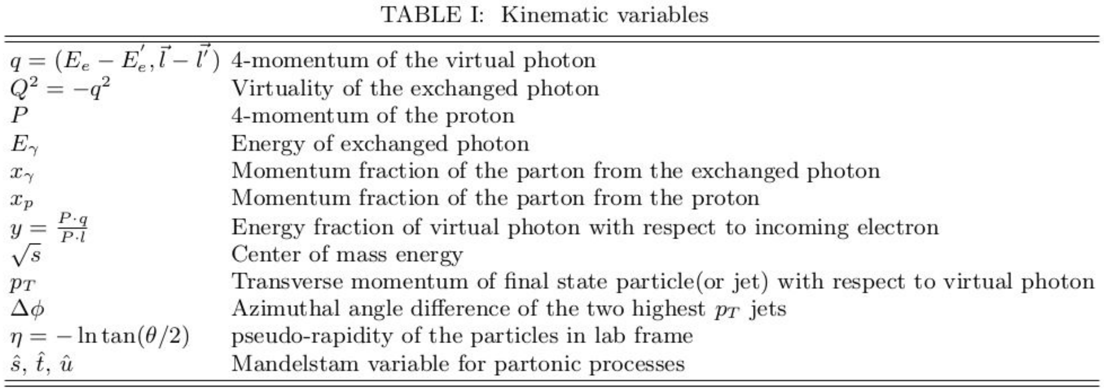
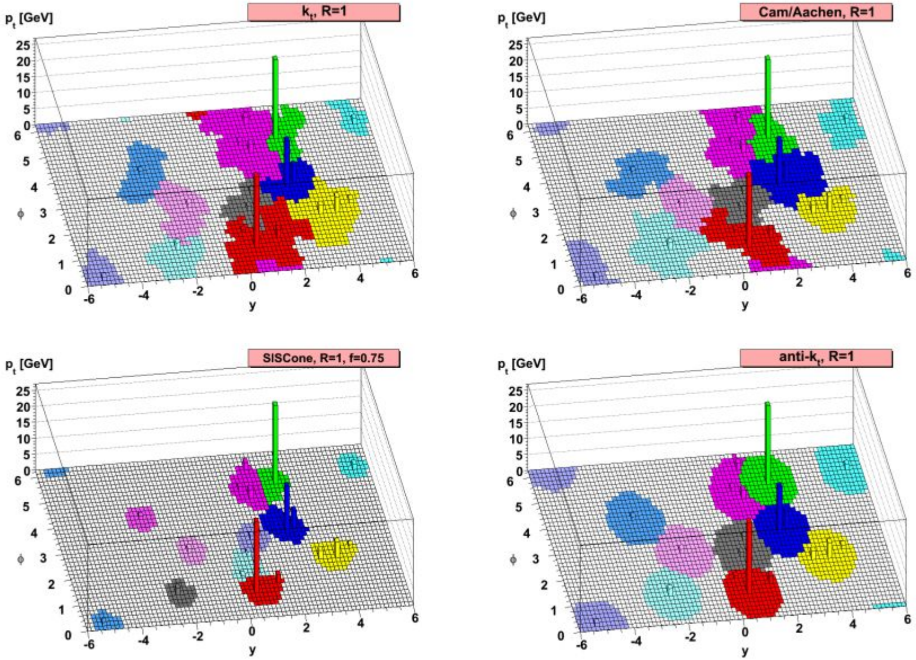


TABLE I: Kinematic variables

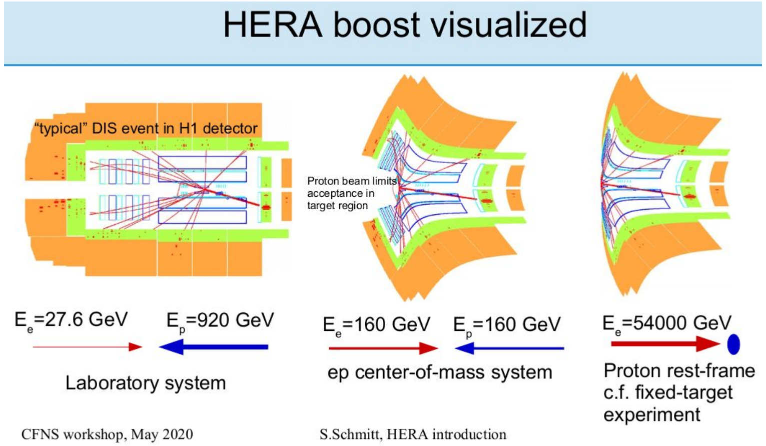
$q = (E_e - E_e^{'}, \vec{l} - \vec{l}^{'})$	4-momentum of the virtual photon
$Q^2 = -q^2$	Virtuality of the exchanged photon
P	4-momentum of the proton
E_γ	Energy of exchanged photon
x_γ	Momentum fraction of the parton from the exchanged photon
x_p	Momentum fraction of the parton from the proton
$y = \frac{P \cdot q}{P \cdot l}$	Energy fraction of virtual photon with respect to incoming electron
$\sqrt{s}$	Center of mass energy
p_T	Transverse momentum of final state particle(or jet) with respect to virtual photon
$\Delta\phi$	Azimuthal angle difference of the two highest p_T jets
$\eta = -\ln\tan(\theta/2)$	pseudo-rapidity of the particles in lab frame
$\hat{s}$, $\hat{t}$, $\hat{u}$	Mandelstam variable for partonic processes

Jet cluster visualization



Jets clustered with four different jets algorithms, illustrating the “active” catchment areas of the resulting hard jets.

fig: Matteo Cacciari and Gavin P. Salam [arXiv: 0802.1189v2]



HERA boost visualized

“typical” DIS event in H1 detector

Proton beam limits acceptance in target region

E_e=27.6 GeV E_p=920 GeV

Laboratory system

E_e=160 GeV E_p=160 GeV

ep center-of-mass system

E_e=54000 GeV

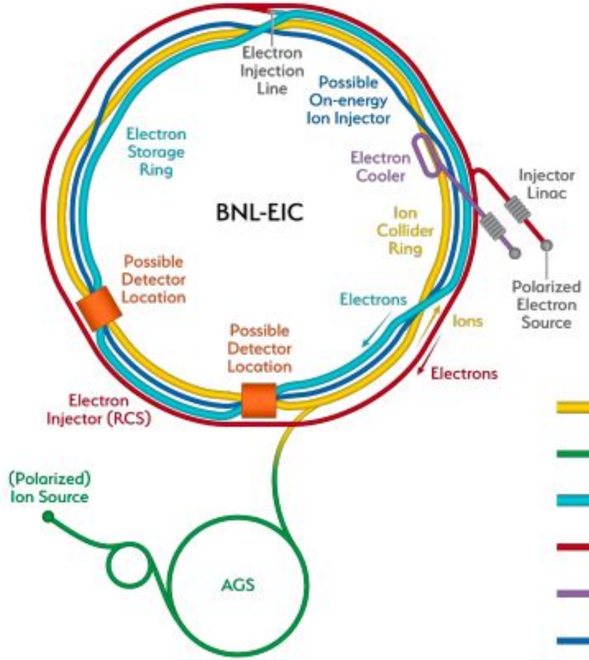
Proton rest-frame c.f. fixed-target experiment

CFNS workshop, May 2020

S.Schmitt, HERA introduction

EIC Accelerator Design

☐ EIC accelerator design



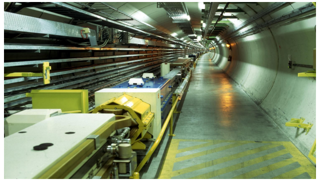
- Center of Mass Energies: 20 GeV - 141 GeV
- Maximum Luminosity: 10^{34} cm^{-2}s^{-1}
- Hadron Beam Polarization: 80%
- Electron Beam Polarization: 80%
- Ion Species Range: p to Uranium
- Number of interaction regions: Up to two

source

🟨 Hadron Storage Ring
🟩 Hadron Injector Complex
🟦 Electron Storage Ring
🟥 Electron Injector Synchrotron
🟪 Electron Cooler
🟦 Possible On-energy Hadron Injector Ring

Talk by A. Seryi

Workshop on Physics, Detector and Accelerator Opportunities at the EIC
Online / Philadelphia, PA, July 27, 2020



LEP : 1989 - 2000

HERA 1992 - 2007

EIC Features

High luminosity: The EIC will produce particle collisions at a rate of 1 × 1034 per square centimetre per second. Lots of collisions (also referred to as high luminosity) means lots of data.

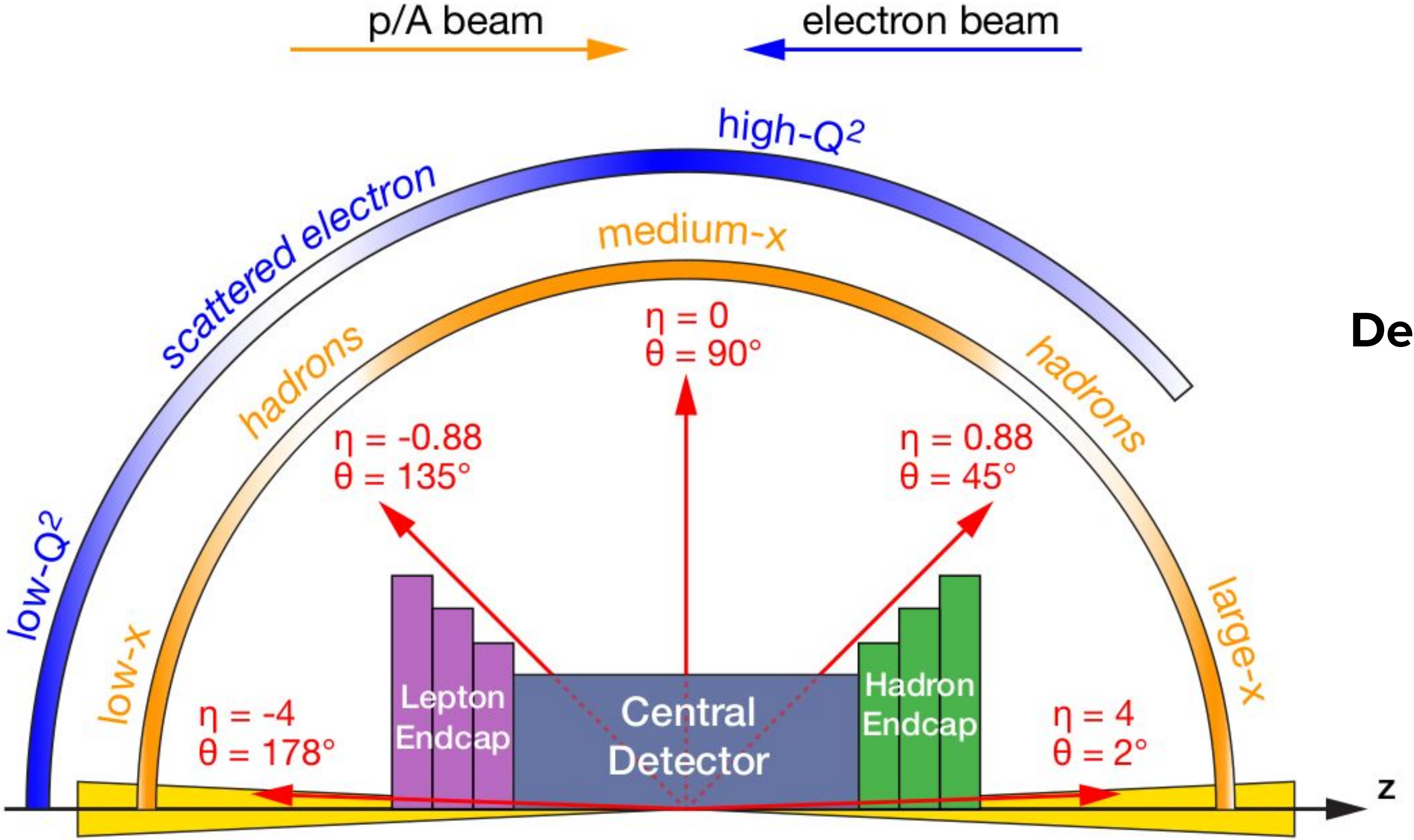
High polarization: Both the electrons and some ion beams will be polarized, making the EIC the only facility in the world with this capability. This means the particles’ spins can be aligned in a particular way. EIC physicists will collide polarized particles to study how the spins and orbital motion of their internal building blocks contribute to their overall spin.

High energy: The EIC will produce collisions at variable center-of-mass energies, from 20 billion to 140 billion electron volts (GeV). At the scale of ordinary things, that is less energy than two mosquitoes colliding. But, at the scale of an electron colliding with a proton, it is enough to produce high-resolution snapshots of the proton’s internal components.

Varied ion species: The ion sources for the EIC, already in use at the Relativistic Heavy Ion Collider (RHIC) and the adjacent NASA Space Radiation Laboratory, can provide ions of almost any element on the periodic table. Light ion beams (protons, deuterons, and helium-3) will emerge polarized from their source. EIC scientists will use a wide range of beams, from protons to heavy ions, to explore how ion size and other features of nuclei affect properties and interactions of quarks and gluons.

Detector Geometry

for ATHENA at EIC



A schematic showing how hadrons and the scattered lepton for different x–Q^2 are distributed over the detector rapidity coverage

Predicting the **Future**

Sample Generation
(Event Simulation)

Cross-Validation
(of the Simulated output to the HERA real world data)

Re-Simulation EIC
(Running Sim again with updated tunings and initializations)

Prediction for EIC