CFNS Summer Lecture: Introduction to the forward physics at the Electron Ion Collider
Day 1

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MISSISSIPPI STATE UNIVERSITY™

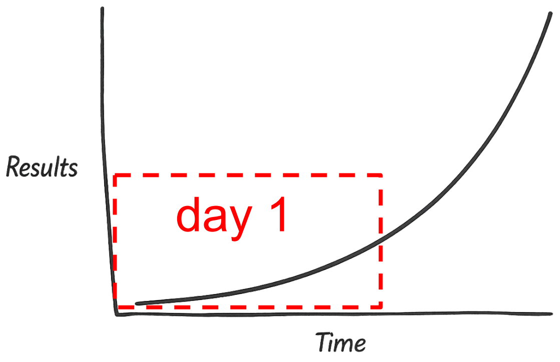
Center for Frontiers in Nuclear Science

Content for Day 1

- "Forward"? What does that mean?

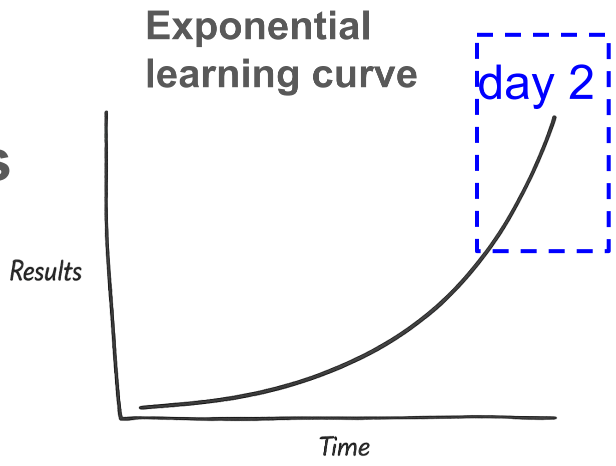
- EIC geometry

- Scattering Languages
    - "Backward neutral π electroproduction above the resonance region at Jefferson Lab Hall C"



Content for Day 2

- ePIC Physics “forward” physics goals
- ePIC Far forward instrumentations
- “Forward” Physics examples
- Construction and operating challenges
- Conclusive remarks

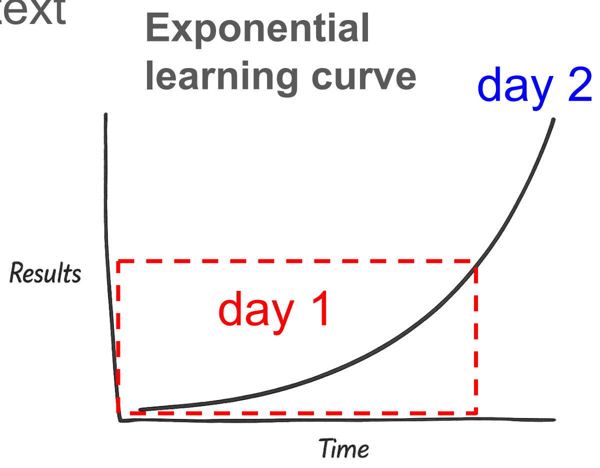


Objective for Day 1

- **Understanding the coordinate, geometry and language of the EIC**

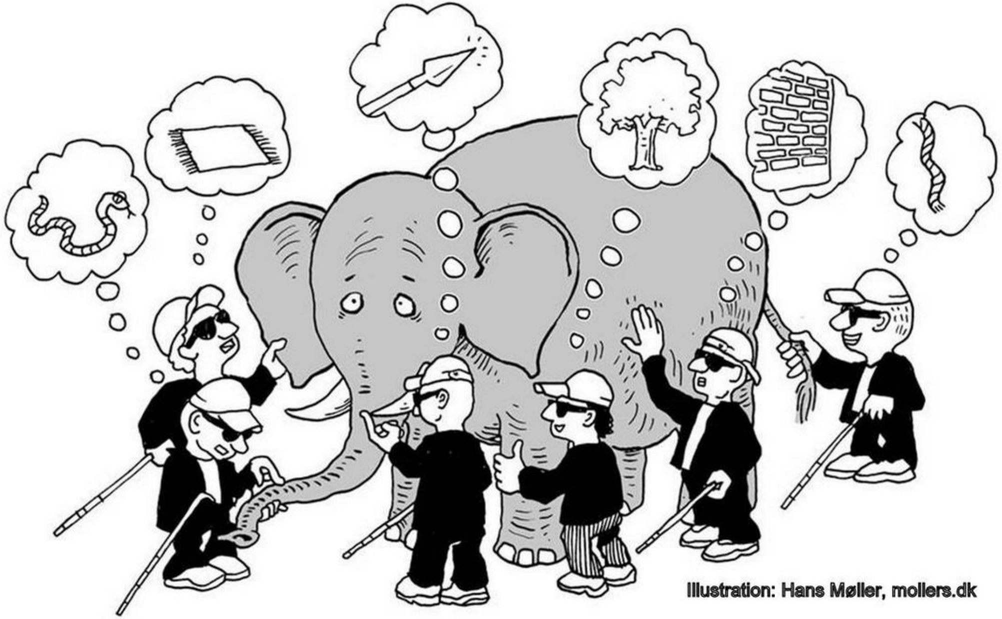
- **Be aware of the inconsistencies and points of potential confusion**

- **By the end of the lecture:**
  - Understanding what is “Forward” in the EIC context
  - A clear EIC ep scattering geometry



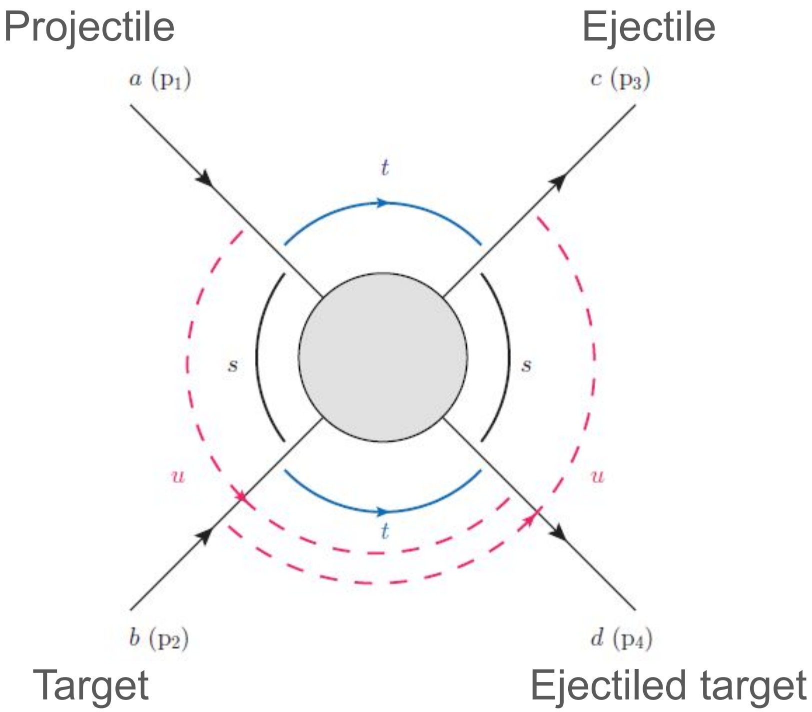
Forward? What do we mean by that?

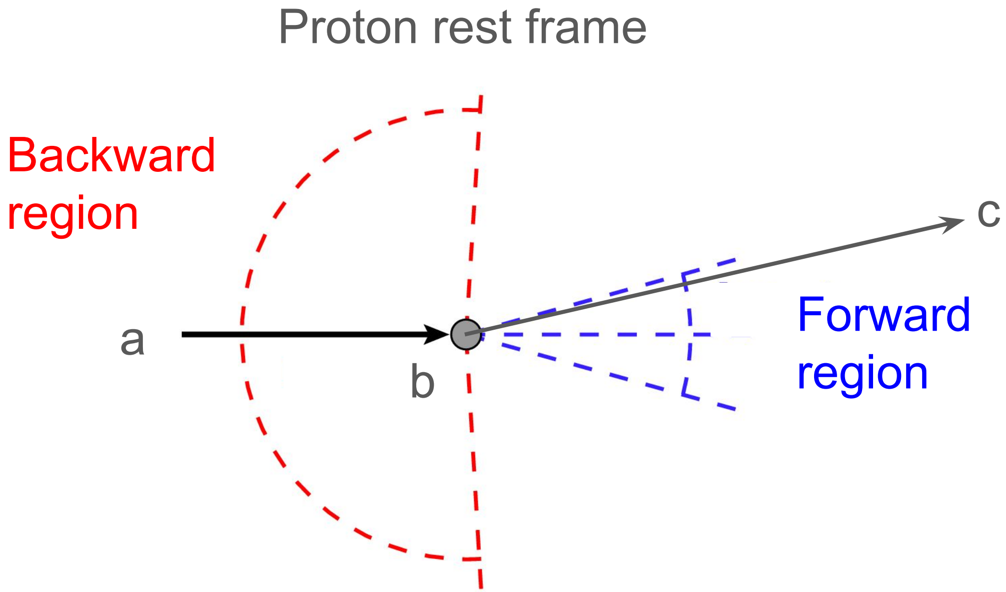
- **Forward Physics at the EIC**
  - The word "Forward" could be misleading
  - If there is "Forward", then what is "backward"?



Direction does matter

Scattering Experiment



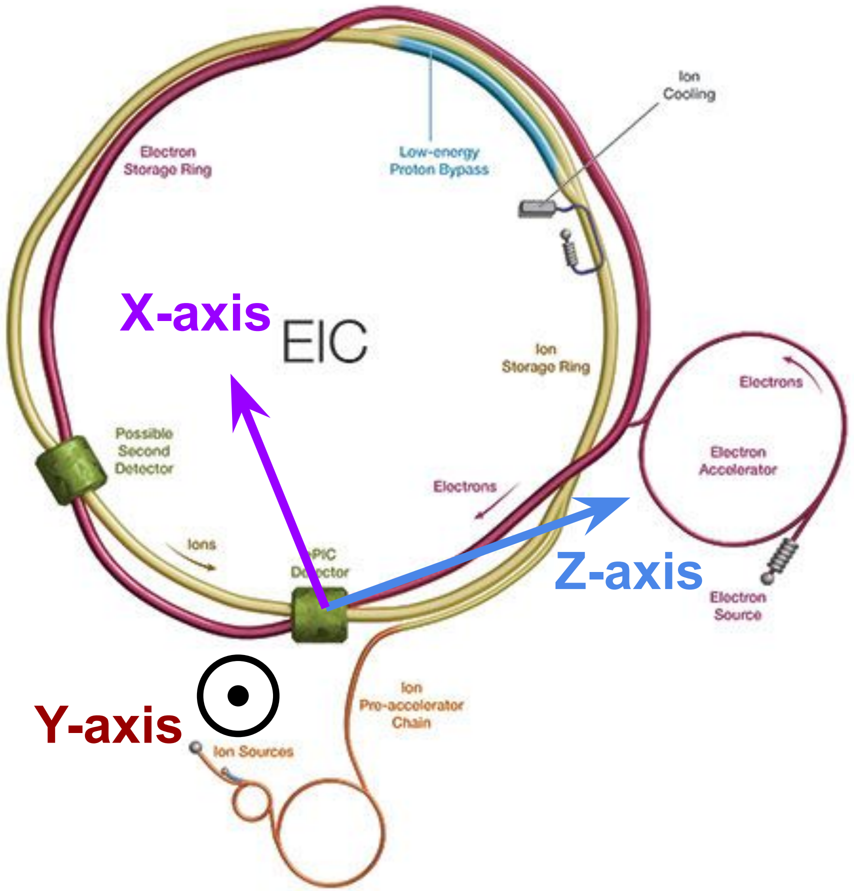


- **Scattering Reaction:**
  - a+b→c+d

Definition of "Forward"

- Dual meaning of "**Forward**"
  - **Meaning #1: In scattering physics, "forward"** usually means the phase-space region close to the direction of the incoming projectile, such as an incident hadron, photon, or virtual photon: $\alpha, \gamma, \gamma*$
    - In this sense, "forward" is defined relative to the exchanged probe or projectile direction.
  - **Meaning #2:** At the Electron-Ion Collider, **"forward"** refers to the **hadron-going direction**, where the outgoing recoil proton, neutron, or nuclear fragment is detected by the **far-forward detector system**.
  - These are not equivalent. For the EIC, case 1 is a small subset of case 2.

Experimental Coordinate (XYZ axis)



- In the EIC and ePIC, **"forward"** means +z direction
- Z-axis: -ve electron beam momentum
  - ePIC central detector is parallel to the electron beam
- X-axis: Points to the center of accelerator ring
- **Y-Axis:** Points upwards
- Quantifying "forward"-ness, we use Rapidity (y) and Pseudorapidity (η)

Rapidity and Pseudorapidity

Rapidity is defined using the particle energy ***E*** and longitudinal momentum $\boldsymbol{p_z}$

$$y = \frac{1}{2}\ln\left(\frac{E+p_z}{E-p_z}\right)$$

1. When $\boldsymbol{p_z}$ = 0 (no longitudinal momentum), particle move transversely/perpendicular to the beam then y = 0;
2. When $\boldsymbol{p_z}$ ~ ***E*** (no transverse momentum), particle move along the beam axis then y >> 0, or $y \sim \infty$;
3. When $\boldsymbol{p_z}$ ~ ***E*** (no transverse momentum), particle move against the beam axis then y < 0;
4. Under a Lorentz boost along the beam axis, rapidities shift by a constant. So differences in rapidity are boost-invariant.

Rapidity and Pseudorapidity

Pseudorapidity uses the polar angle for the emitted particle, θ, measured from the beam axis:

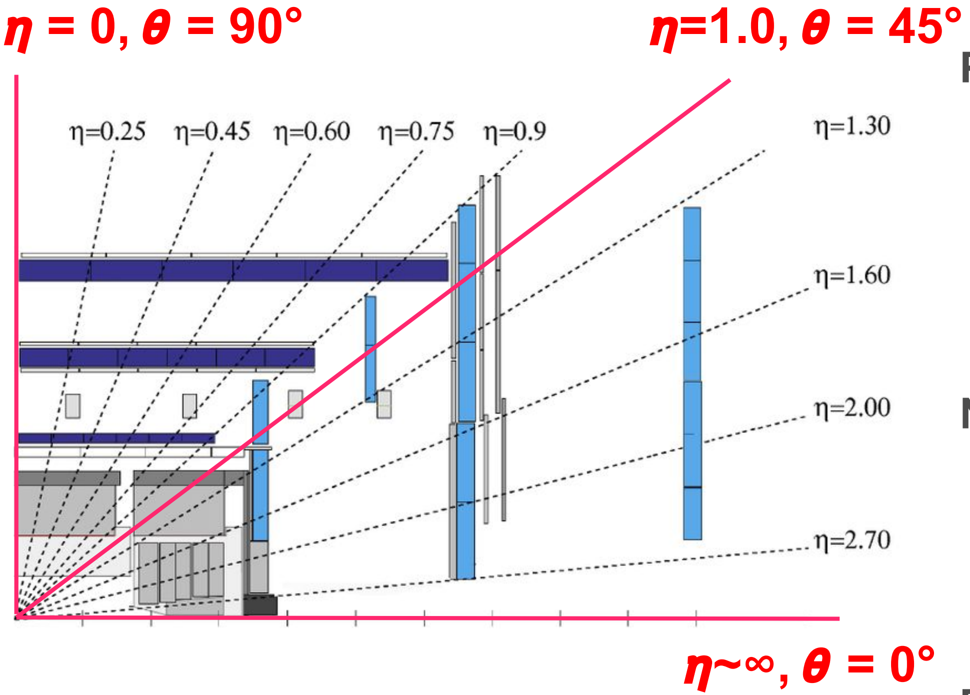
$$\eta = -\ln\left[\tan\left(\frac{\theta}{2}\right)\right]$$

“Pseudo” because η approximates true y when the particle is highly relativistic.

When $E \gg m$, Then $\eta \approx y$

Experimentalists prefers to use η: it only requires the angle information, not full energy and momentum reconstruction. Or one could use the η information to reconstruct the momentum information.

Pseudorapidity In EIC and ePIC



CMS detector schematics is used as an example

Pseudorapidity is easy at the EIC!

- Defined with respect to the proton beam
- η=0 when particle is at θ = 90°
- η=1 when particle is at θ = 45°
- η~∞ when particle is at θ = 0°
- Easy to remember!

Now read the ePIC detector coverage again:

- Central detector: $\eta \le |3.5|$
- Forward endcap: $+1.5 \le \eta \le +3.5$
- Backward endcap: $-3.5 \le \eta \le 1.5$
- Far-forward/far-backward systems: $|\eta| > 6$

Forbidden question:

- Why ePIC is not designed to use η~1 (θ = 45°) as detector system boundary.

Dilemma #1 to be aware of

1. In terms of experimental coordinate and construction for EIC
   a. XYZ coordinate is used, where -ve e-beam momentum is used.
   b. η is +ve in the proton beam direction.

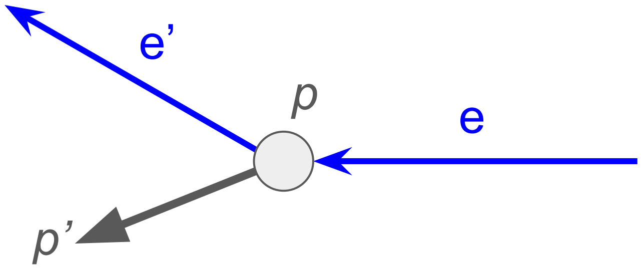
2. In terms of physics reconstruction, η often refers to proton beam direction, <u>which is not along the experimental z-axis!</u>
   a. 25 mRad crossing angle
   b. ePIC coverage as an prime example (see in day 2)

3. **Dilemma:**
   a. Definition is somewhat against the convention.
   b. Proton beam momentum define the “forward” not along the experimental axis.

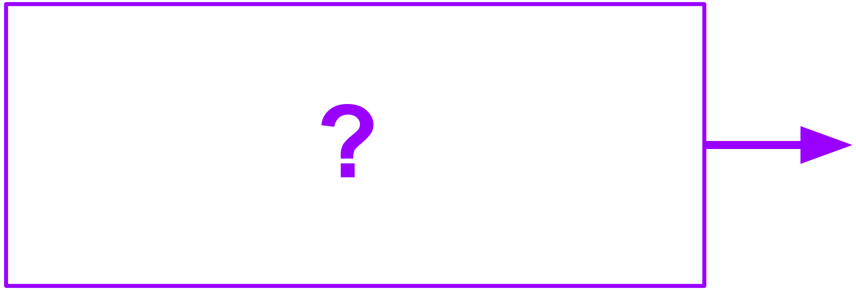
4. **Who is going to fix these inconsistencies?**
   a. First attempt, we define the definition
   b. Needs to be fixed in the future

Quiz on Special Relativity

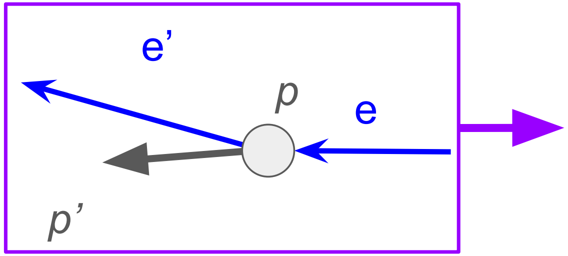
Proton rest frame



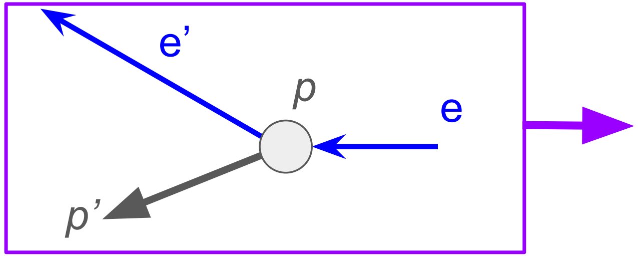
Boosted the reaction in the -p_e



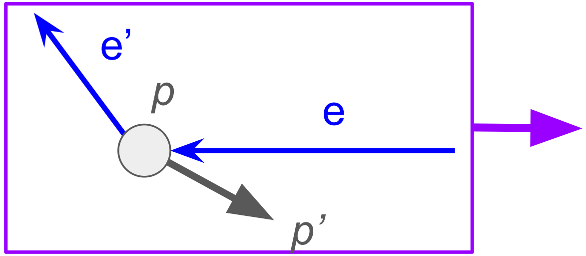
Option A:



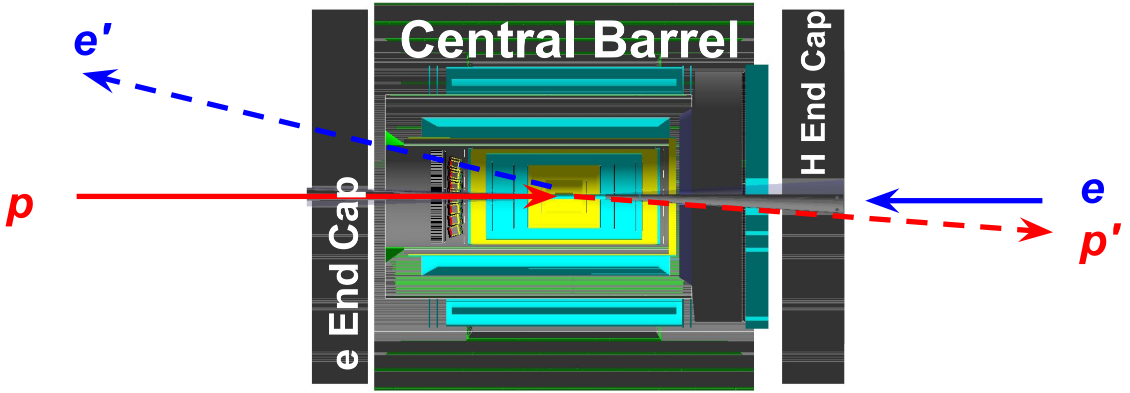
Option B: No Change

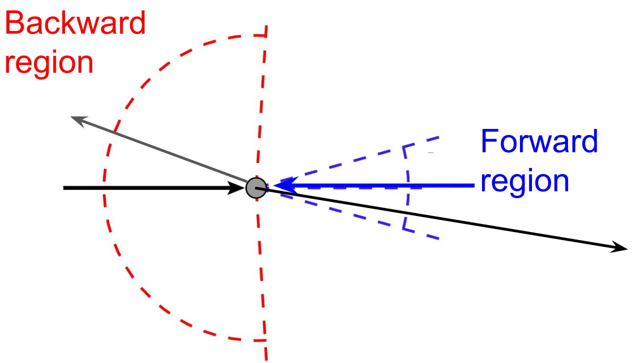


Option C:

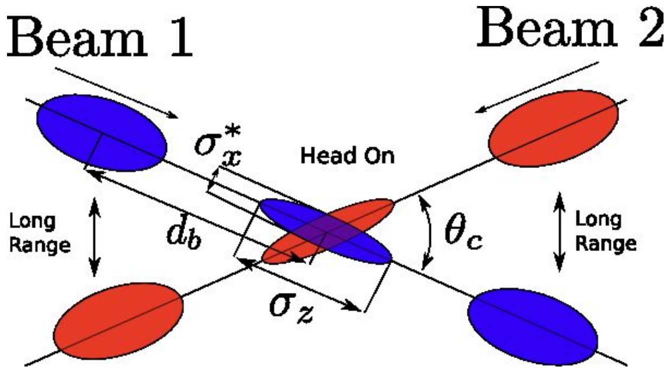


Electron Ion Collider Design if designed 30 years ago

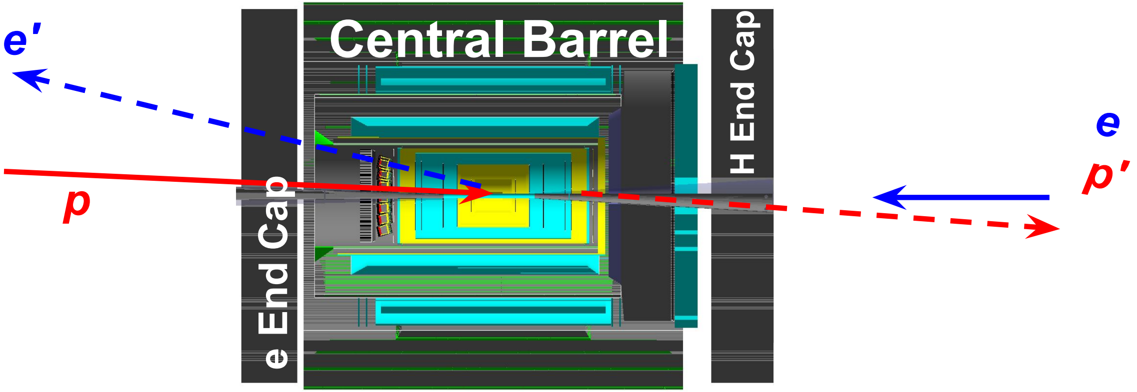


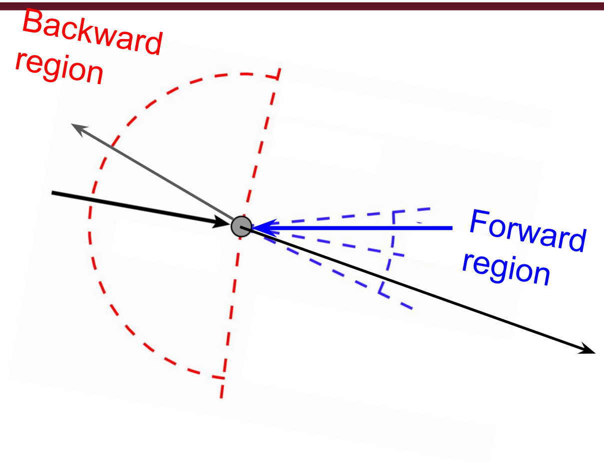


- **Head-on collision**
  - Maximizes the overlap between the electron bunch and proton bunch or luminosity
  - HERA accelerator at DESY had 5 mRad crossing angle.
  - Significant drawback: the particle remnants overlaps with the incoming electron beam?



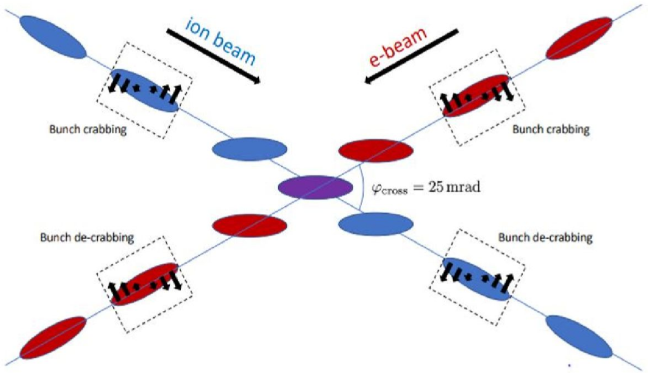
Innovative Electron Ion Collider Design



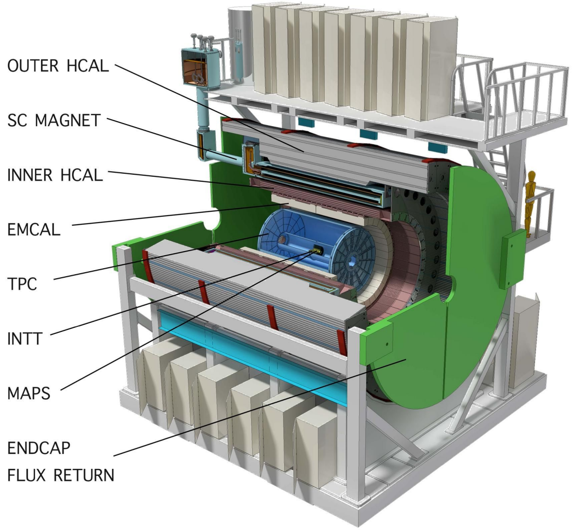


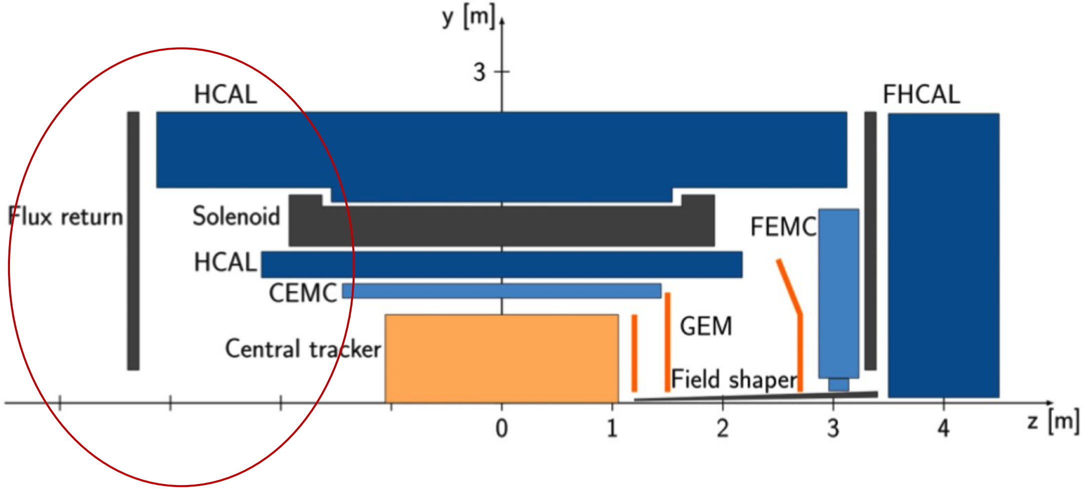
Innovative design at ePIC 25 mRad Cross angle

- More space near the interaction point
- Improves far-forward detection
- Easier for construction

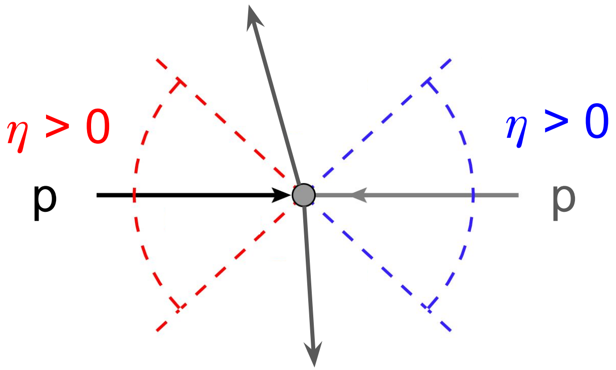


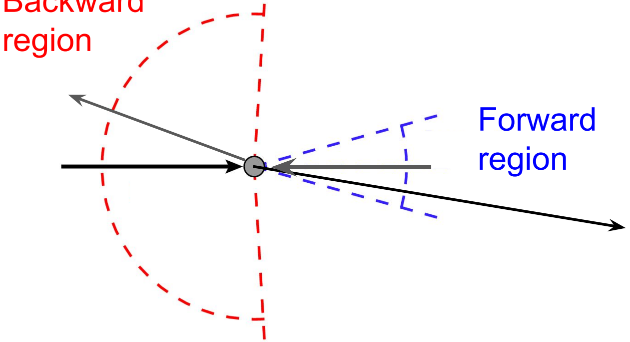
Why SPhenix or STAR detector cannot be used by EIC?





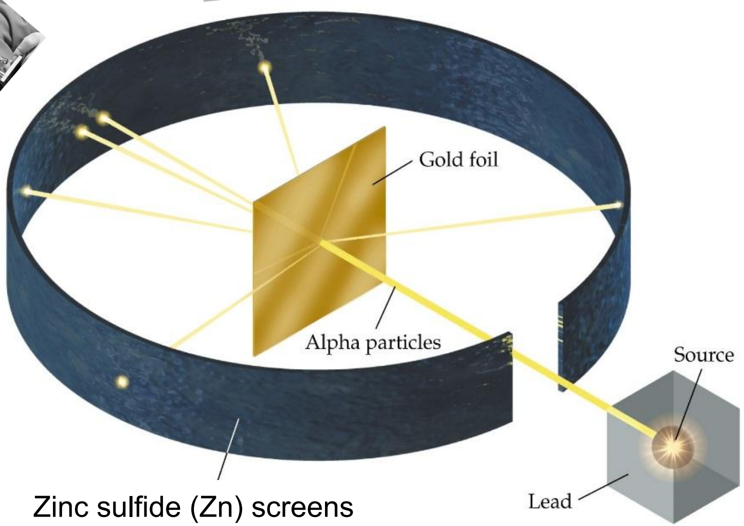
Problem here



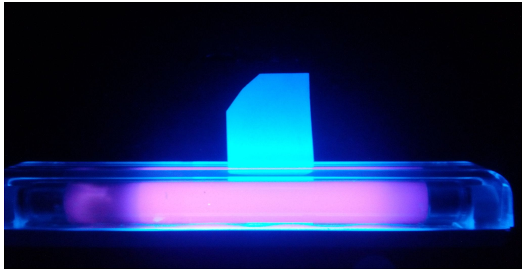


Scattering experiment: Rutherford experiment in 1909

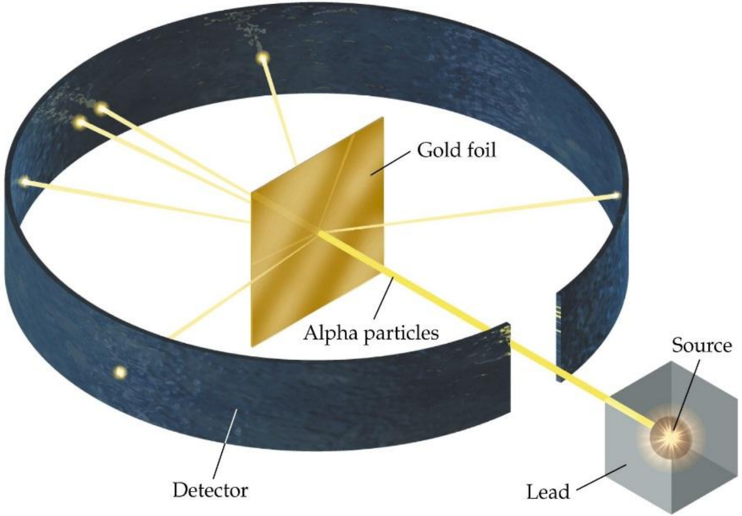
Student with a scope and a clicker counter



- Zinc sulfide (Zn) is a scintillator material
- When an alpha particle hits ZnS, it excites the atoms
- A Tiny flash of light (spark) is generated when as de-excitation occur
- One “spark” of light correspond to one detected alpha particle
- Light capture by a student with a scope at specific angle (rotatable rail)
- **The backward (angle) scattered event was discovered by accident!**
  - **By Rutherford’s graduate student: Hans Geiger and Ernest Marsden**

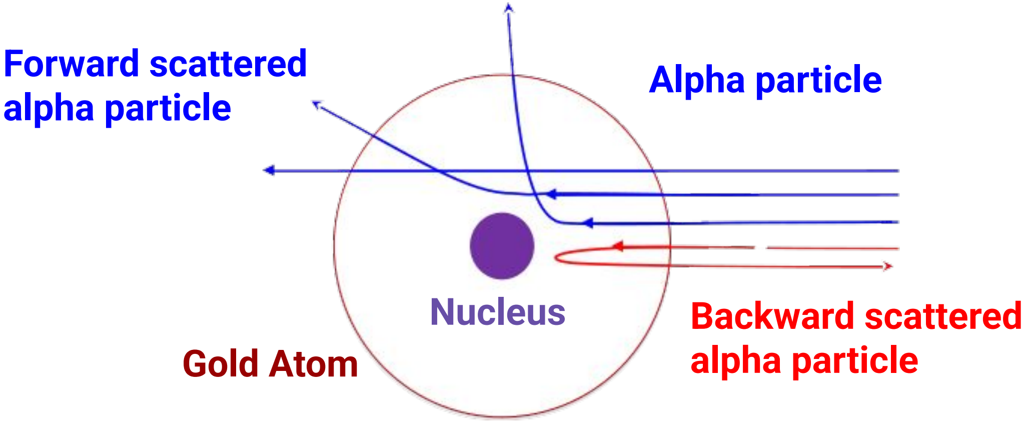


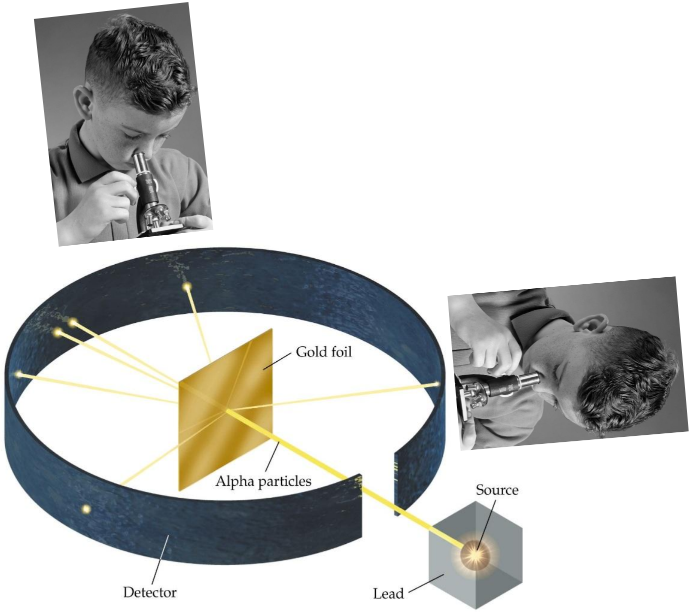
Rutherford's Student Geiger and the Geiger counter



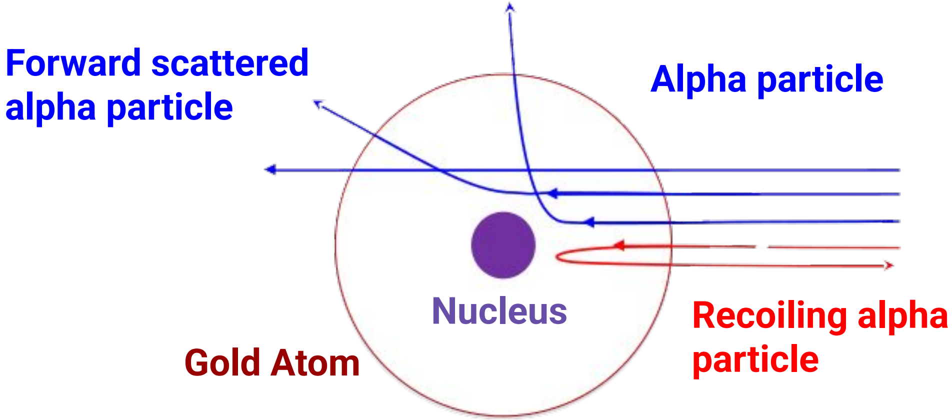
- Hans Geiger and his student invented Geiger–Müller tube in 1928.
- Geiger–Müller tube (Geiger counter) uses the principle of ionization
- Fantastic for detecting beta and gamma articles
  - Generating a sparking sound via speaker corresponds to each hit by ionizing radiation

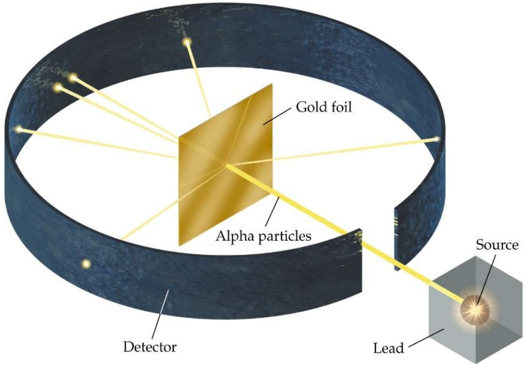
Forward Scattering and Backward Scattering





Forward Scattering and Backward Scattering

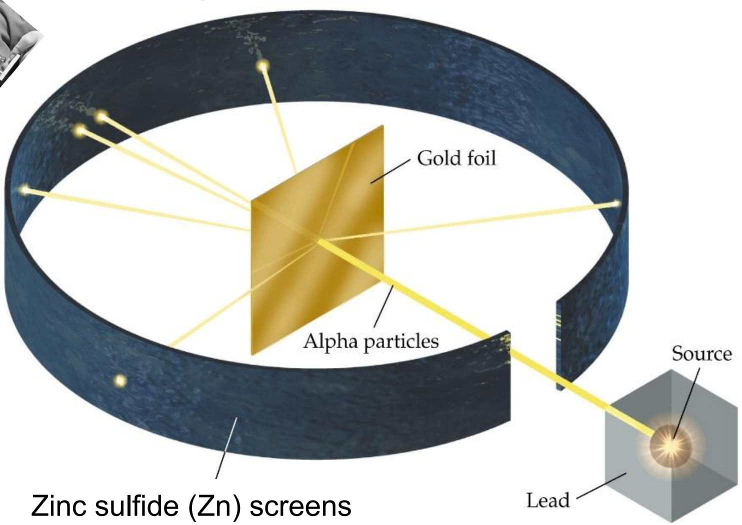




- Forward scattered alpha particle: extracting the interaction radius of the nucleus and mapping out the transverse structure of the atom (mostly empty)
- Recoiling alpha particle: stiffness of the "point-like" structure.
- Full structure = forward angle + backward angle observables.

Significance of the Rutherford experiment

Student with a scope and a clicker counter



Zinc sulfide (Zn) screens

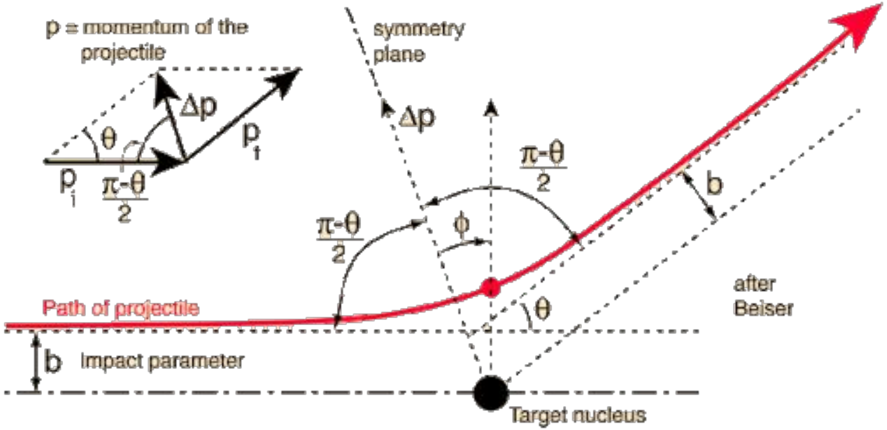
- Accurately protracted the image of the atomic structure
  - the atom is constructed out of nucleus and electrons, which are surrounded by large empty spaces

- **Experimental wise**
  - **Scintillator material and process is still used for detecting particles to this date.**
  - **Established the scattering**
  - **Differential cross section**

$$\frac{d\sigma}{d\Omega}(\Omega)d\Omega = \frac{\text{number of particles scattered into solid angle } d\Omega \text{ per unit time}}{\text{incident intensity}}$$

  - **These methodology are still used in the modern day scattering/collision style experiment**

Rutherford Experiment Formalism



$$b = \text{impact parameter}$$

$$E = \text{center-of-mass kinetic energy}$$

$$\theta = \text{scattering angle.}$$

- **Differential cross section:**

$$\frac{d\sigma}{d\Omega} = \frac{b}{\sin\theta}\left|\frac{db}{d\theta}\right|$$

- **Impact parameter to scattering angle:**

$$\tan\left(\frac{\theta}{2}\right) = \frac{1}{4\pi\epsilon_0}\frac{q_1 q_2}{2Eb}$$

$$b \text{ small} \Rightarrow \theta \text{ large}$$

$$b \text{ large} \Rightarrow \theta \text{ small.}$$

- **A head-on collision, $b=0$, minimum radius could be calculated**

$$r_{\min} = \frac{1}{4\pi\epsilon_0}\frac{q_1 q_2}{E}$$

Electron proton scattering: the probe

Before interaction

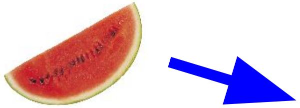
e + *H*

Bullet is not “electron”

t-channel

***n* (938 MeV)**

Remains at target position

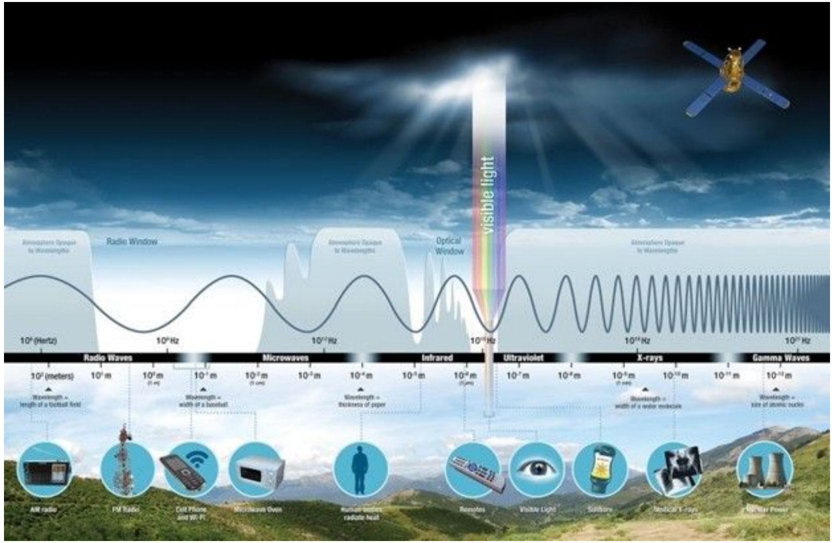


- H(*e*, *e’* π^+)*n*

Virtual Photon vs Real Photon

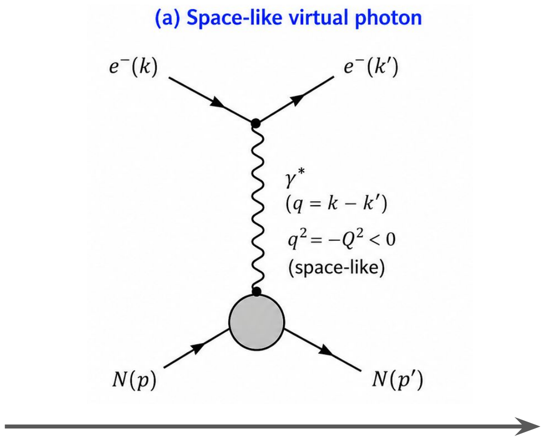
Real Photon (γ)

- On-shell condition/limit: $Q^2 = q^2 = 0$
- Directly detectable
- Could only be transversely polarized
- Interaction involves real photon: <u>photoproduction</u>



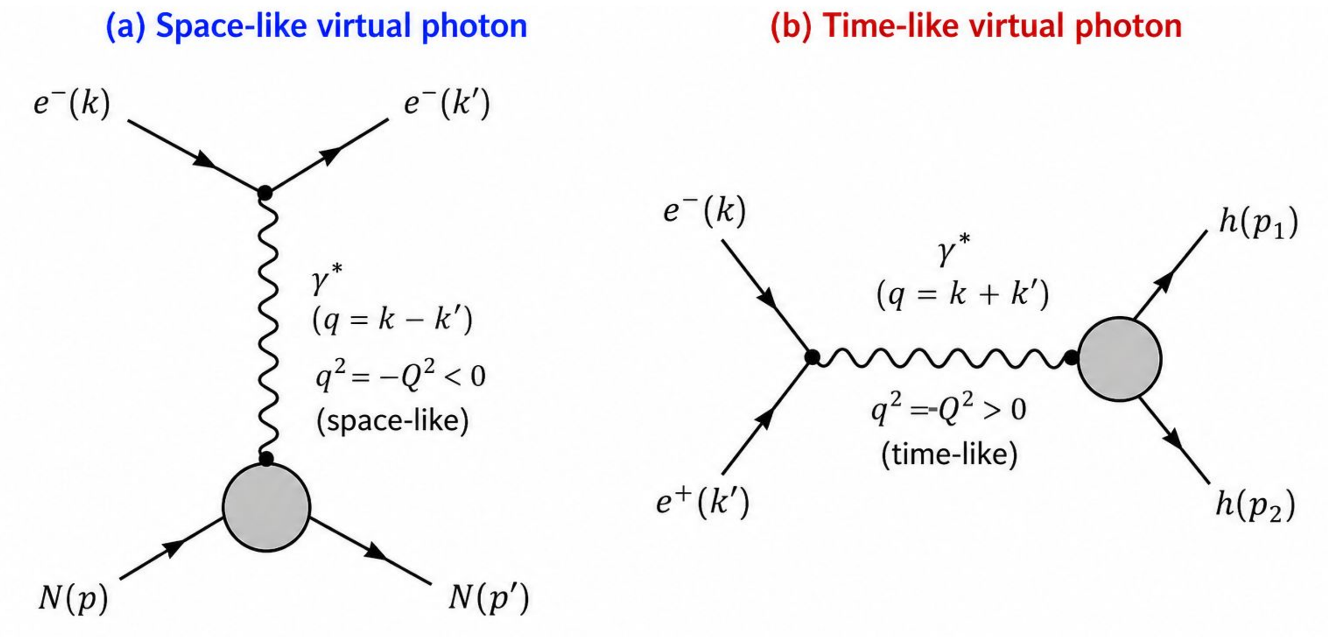
Virtual Photon (γ^*)

- On-shell condition/limit: $Q^2 = q^2 \neq 0$
- Time-like : $Q^2 = - q^2 < 0$
- Space-like: $Q^2 = - q^2 > 0$
- Transversely and longitudinally polarized
- Interaction involves virtual photon: <u>electroproduction</u>



Time axis

Spacelike vs Timelike Virtual Photons

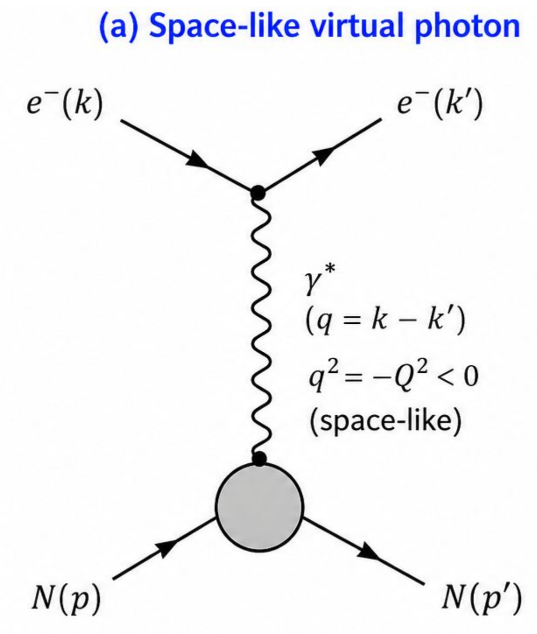


$E^2_{\gamma^*} - p^2_{\gamma^*} < 0$

$E^2_{\gamma^*} - p^2_{\gamma^*} > 0$

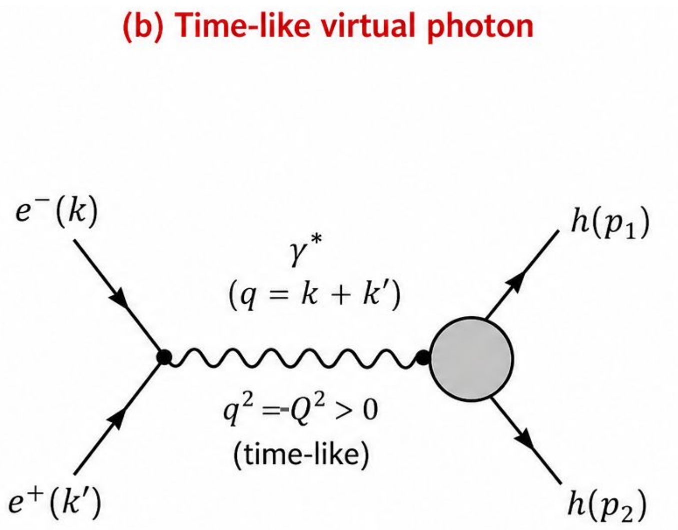
Time axis

Spacelike vs Timelike Virtual Photons



$E^2_{\gamma^*} - p^2_{\gamma^*} < 0$

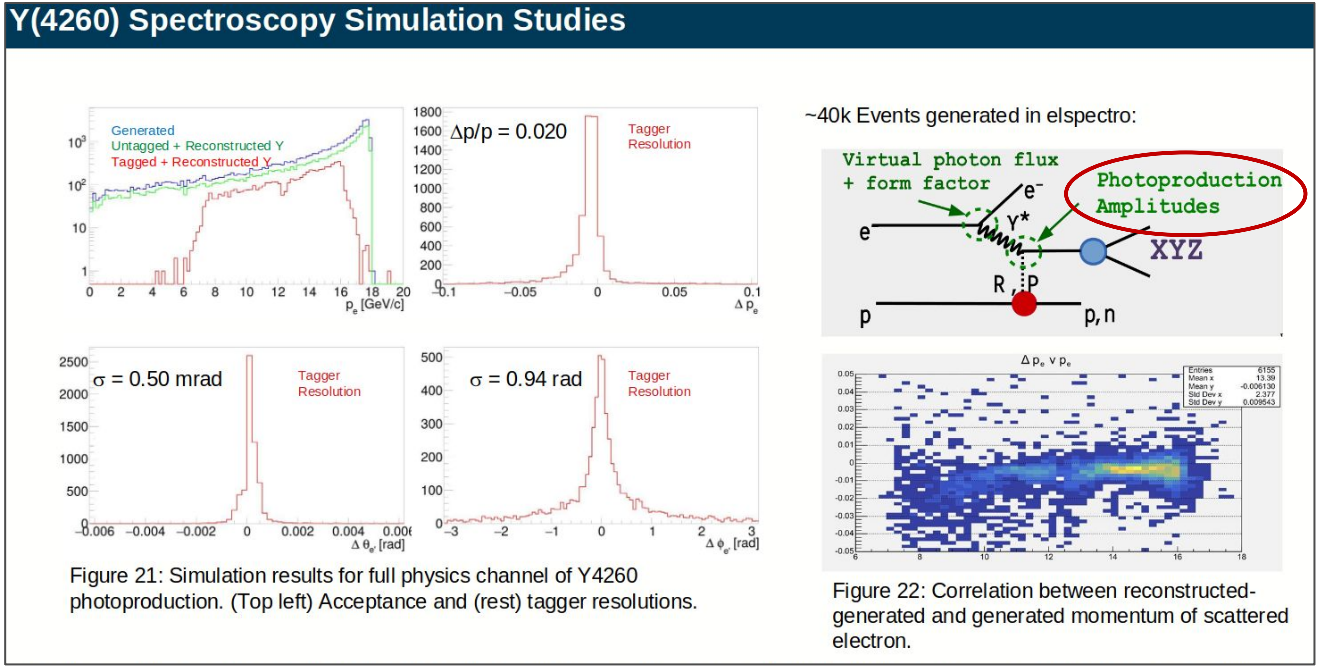
Most of the processes at JLab, EIC



$E^2_{\gamma^*} - p^2_{\gamma^*} > 0$

Collider experiments, Drell-Yan process,

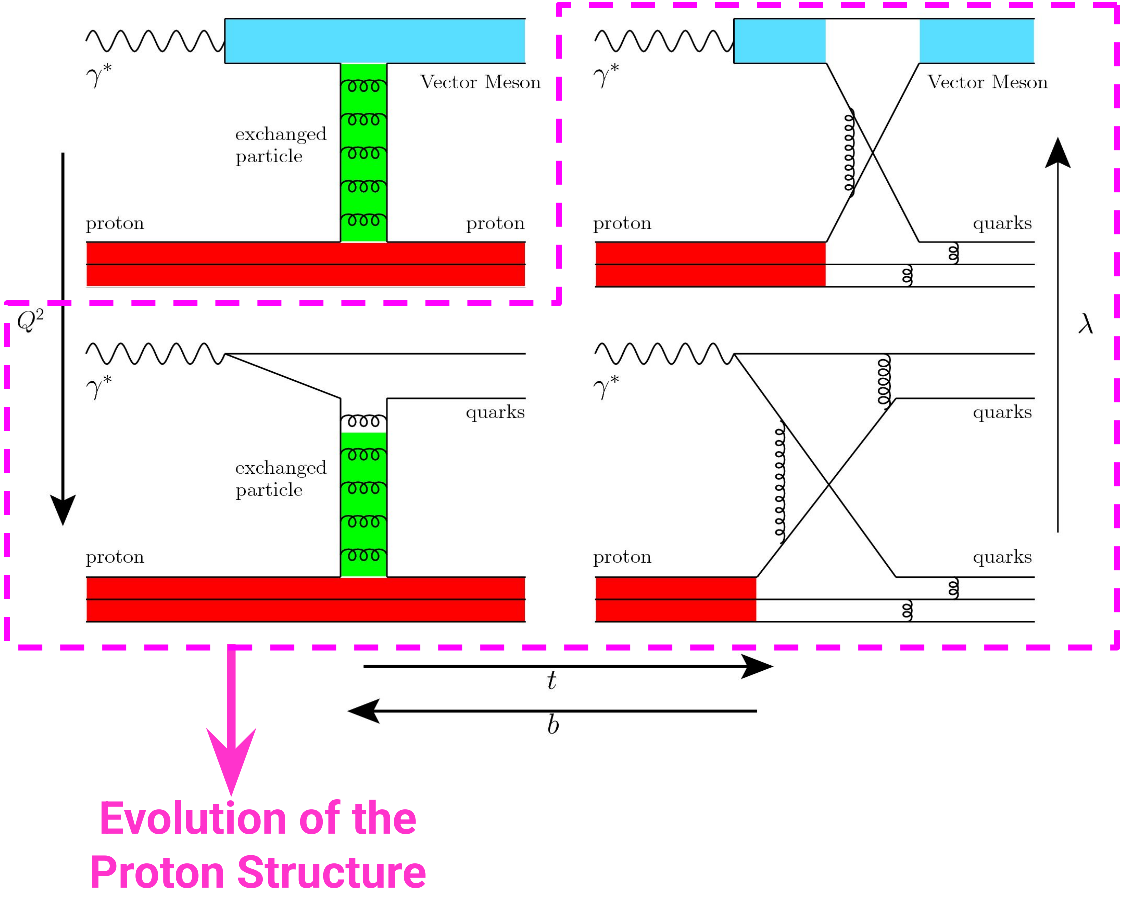
Dilemma #2 “Photoproduction” at EIC



Photoproduction?
At the EIC?
No real photon beam line at the EIC

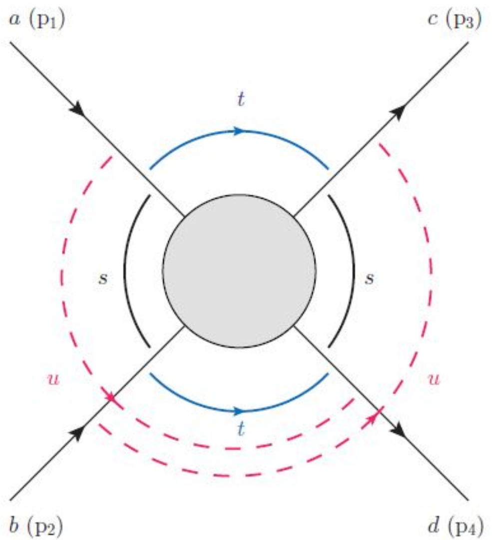
- Some studies, mis-labeled “near-photoproduction” as “photoproduction”
- **Dilemma:** small Q^2 is not the same as $Q^2 = 0$, but Q^2 limit for γ^* to behave like γ?
  - $Q^2 \sim 10^{-3}$ GeV^2 close enough? $Q^2 \sim 10^{-6}$ GeV^2? $Q^2 \sim 10^{-3}$ GeV^2 ?
  - We actually don’t know

Hadronic Model: Transition (Evolution) of Proton Structure



- Common physical parameters:
  - x_b, *W* (or *s*), Q^2, ***t***, ***u***
  - Lorentz Invariant quantities
- $\boldsymbol{x_b}$: Parton momentum fraction:
  - 0.2< x<0.3 valence quark distribution is pronounced
- ***W***: Dictates if a process is in the resonance region
- Q^2: probe size or the resolving power
- ***t***: target momentum transfer squared
  - Inversely related to the Impact parameter b

Mandelstam variables (s,t,u-Channels)



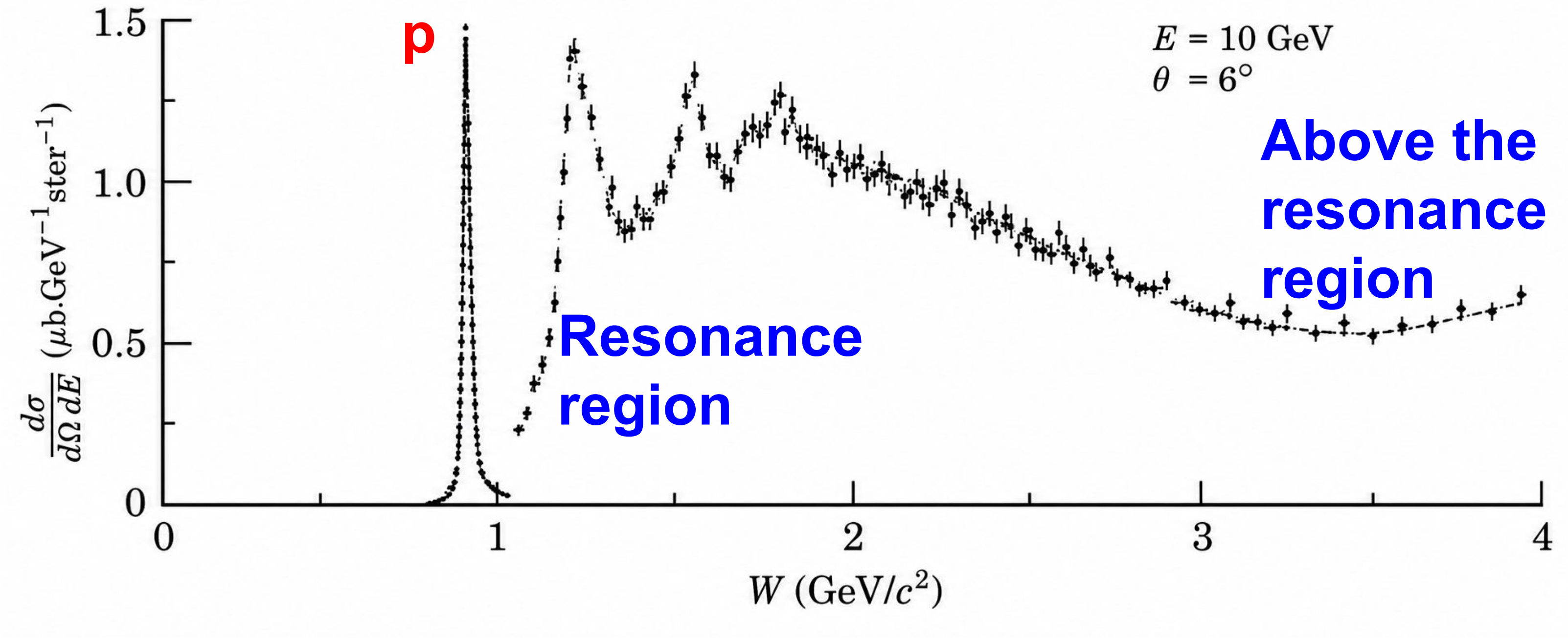
$$s = (p_1 + p_2)^2 = (p_3 + p_4)^2$$

$$t = (p_1 - p_3)^2 = (p_2 - p_4)^2$$

$$u = (p_1 - p_4)^2 = (p_2 - p_3)^2$$

- ***s***: invariant mass of the system
- ***t***: Four-momentum-transfer squared between **target before and after interaction.**
- ***u***: Four-momentum-transfer squared between **virtual photon before interaction and target after interaction**
- ***t*-channel*: -t ~ 0*, after interaction**
  - **Target: stationary,**
  - **Meson: forward**
  - **Measure of how forward could the meson go.**
- ***u*-channel: *-u~0,* after interaction**
  - **Target: forward**
  - **Meson: stationary**
  - **Measure of how backward could the meson go**

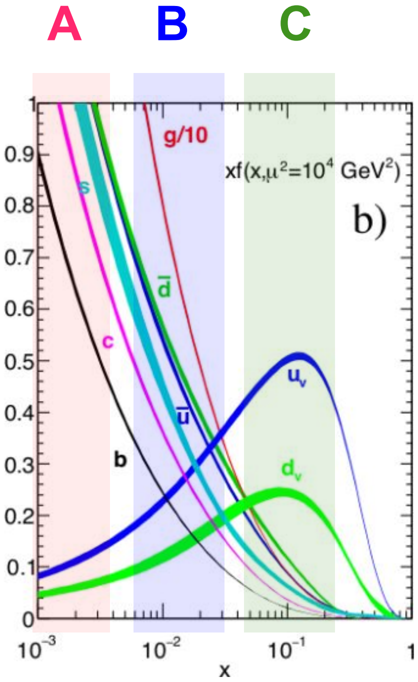
Why Kinematics Matter? Invariant mass W or √s



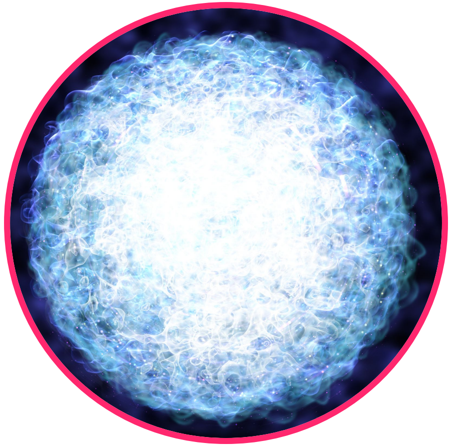
First experimental proof of quarks by Friedman, Kendall and Taylor, data ~1970, from SLAC

Why Kinematics Matter? Momentum fraction Bjerken x_j

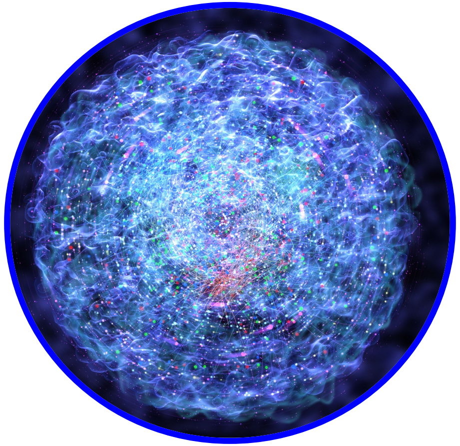
- **Parton Distribution Function**
  - **Gluon** and **quark sea**: **heavy-ion collisions** and **future EIC**
  - **Valence quark**: JLab



A: Ultra-high energy



B: High Energy



C: Medium Energy

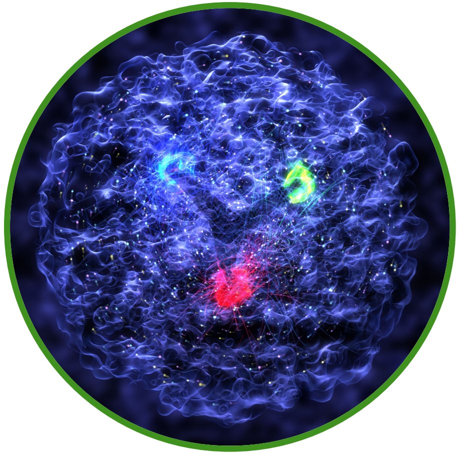
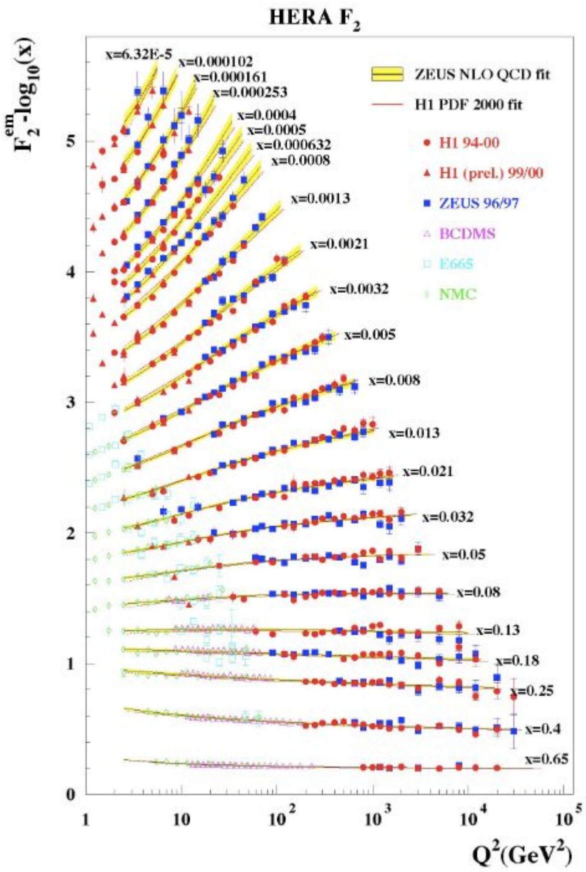
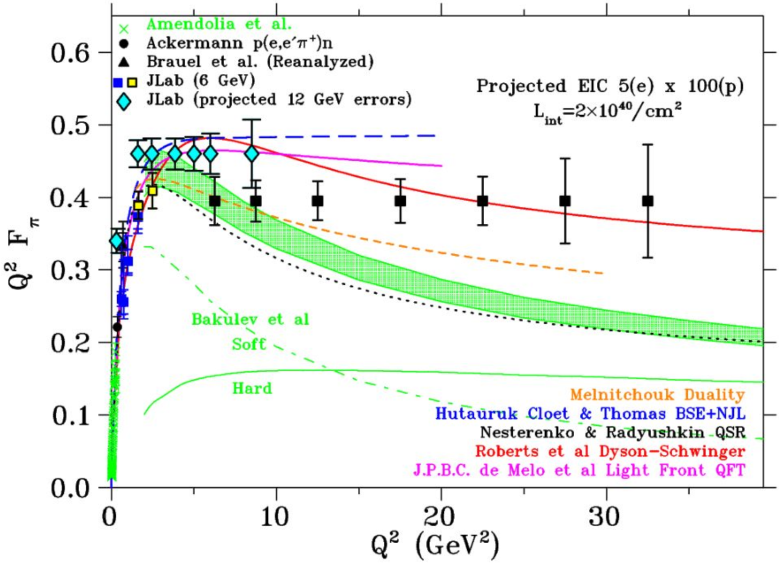


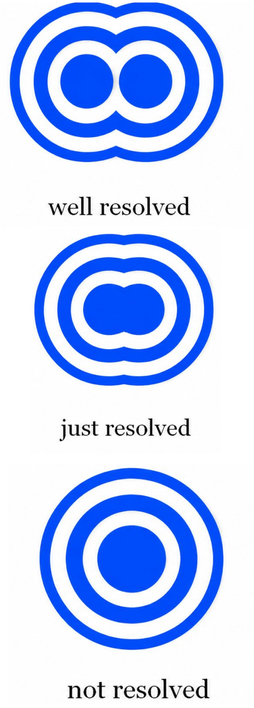
Image credit to JLab and MIT: Full video available on YouTube

Why Kinematics Matter? Resolving Power Q^2

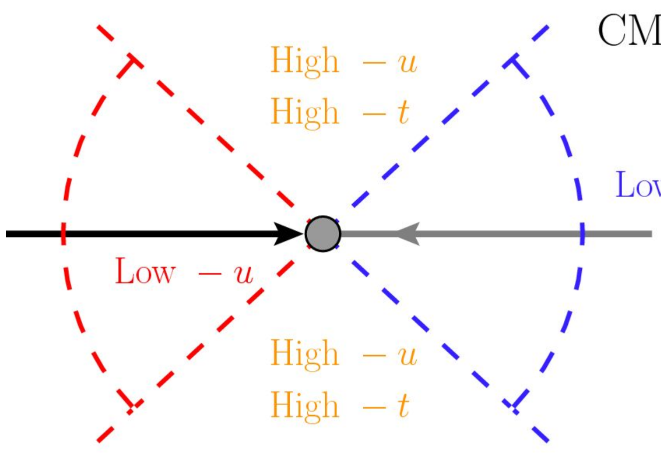


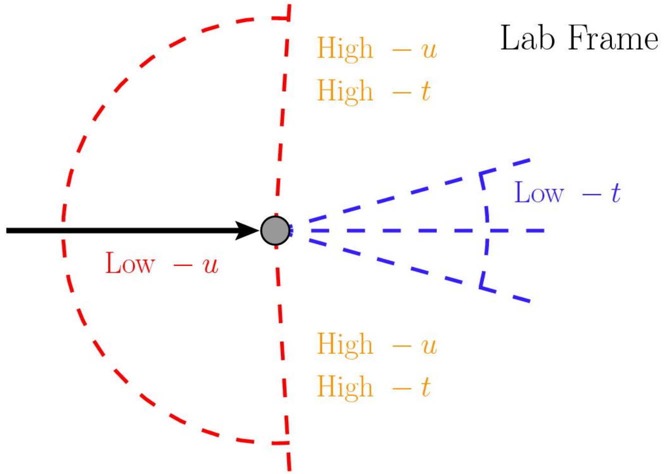
- Q^2: probe size or the resolving power
- Higher the Q^2, lower the wavelength of the virtual photon, which corresponds to higher resolving power
- If you want to resolve the proton structure, the wavelength required <10^{-15}m, corresponds 1 GeV^2 or higher





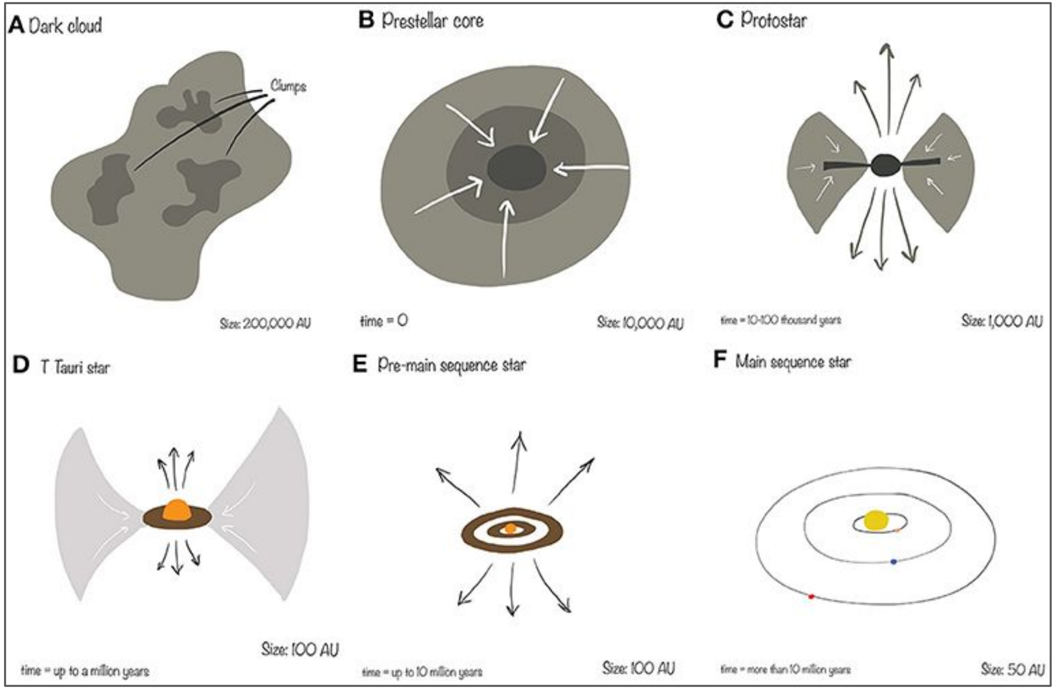
Lorentz Invariant Quantities





- x_b, W (or s), Q2, t, u are Lorentz Invariant quantities
- These are reference frame independent
- Differential cross section computed in the CM frame $\frac{d\sigma}{dt}$ is direct compared with the experimental extracted values.

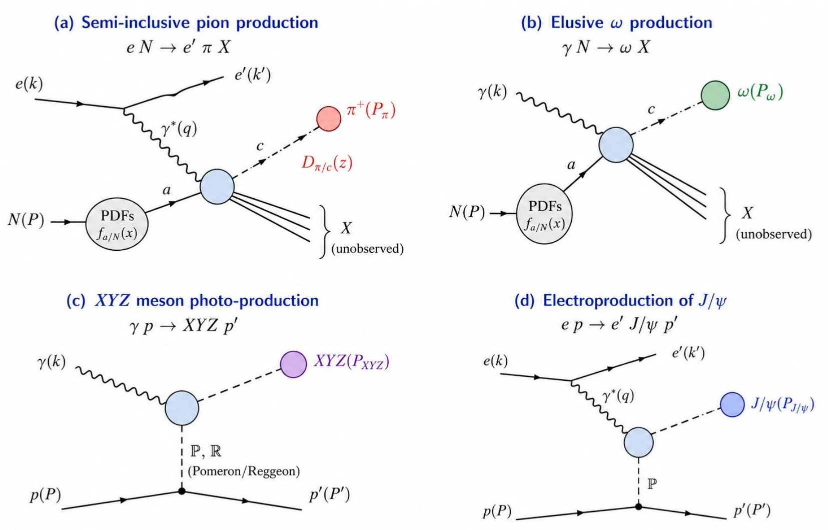
How to fool an astronomer?



Theme: you finished listening to an astronomy seminar on star formation. For whatever reason, you didn't understand it. But you are expected to ask an intelligent question, what do you do?

Try this: "<u>How would the result different if the magnetic field is twice as strong</u>?"

How to fool a particle physicist?



- **What is the kinematics of your reaction?**
  - Q^2, x, W, $-t$
  - Proton wavelength, momentum fraction, invariant mass, impact parameter
- **What is the probe?**
  - Real or Virtual Photon?
  - Timelike or space like Virtual photon?
- **Which parton are you measuring?**
  - Quark, gluon or sea-quark?
- **<u>Is it polarized?</u>**
  - What if the beam or the target is polarized?

Day 1 Summary

- **Dual definition of "forward"**
  - Now we know, the EIC orientation and coordinate, right
- **Dilemas:**
  - The ePIC forward is not along the z-axis
  - "Misuse" of the term "photoproduction"
- **Language of the EIC and scattering**
  - Kinematics variables and their physical meanings
  - Probe
  - Different reference frames
- **List that fouls particle physicists**
  - Ask for the polarization

Thesis/paper Titles (intuitive now?)

- **Zakia's thesis title "Backward-angle neutral π electroproduction above the resonance region at Jefferson Lab Hall C"**
    - **Backward-angle:** particle going to the backward angle region.
    - **Neutral pion:** particle is π^0
    - **Electropproduction:** probe is virtual photon γ*
    - **Above the resonance region:** W >2 GeV
    - **Jefferson Lab:** $0.2 < x_j < 0.4$
    - **Hall C:** fix target spectrometer experiment access Q^2 >1 GeV^2

- **My thesis titles "Exclusive Backward-Angle Omega Meson Electroproduction"**

Questions?