

# AN UNDERGRADUATE'S GUIDE TO NUCLEAR PHYSICS ANALYSIS: Exclusive production of $\phi$ vector meson in ZEUS detector during HERA-II

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## From HERA to the Electron Ion Collider

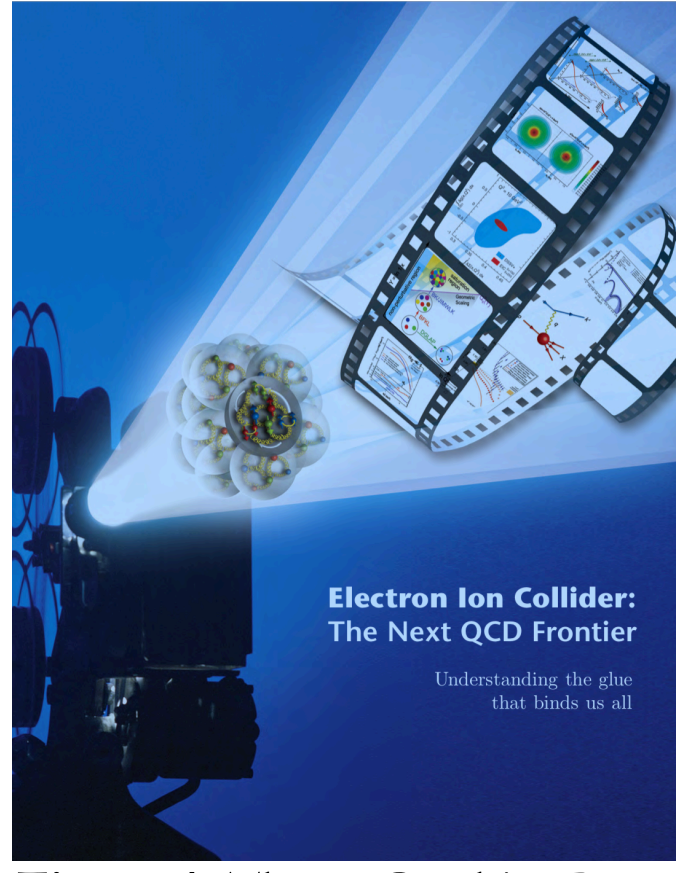


Figure 1. The EIC White Paper.

- The Nuclear Science Advisory Committee recommended the next "highest priority" facility is a high energy electron-ion collider (EIC) to probe deeper into the proton, imaging the gluons and shedding light on nucleon spin<sup>(1)</sup>
- The only other lepton-hadron collider was the Hadron Electron Ring Accelerator (HERA) at DESY, Germany
- Collided 27.5 GeV electrons/positrons with 920 GeV protons
- Data from HERA needs to be analyzed to understand detector effects and proposed physics topics for the EIC and one such process is exclusive vector meson (EVM) production**

- EVM production was studied during HERA-I in the ZEUS Detector<sup>(2)</sup> as well as in H1 detector
- The ZEUS Detector at HERA was designed with 99.7% solid angle coverage to measure deep inelastic scattering, structure of proton and physics beyond the standard model

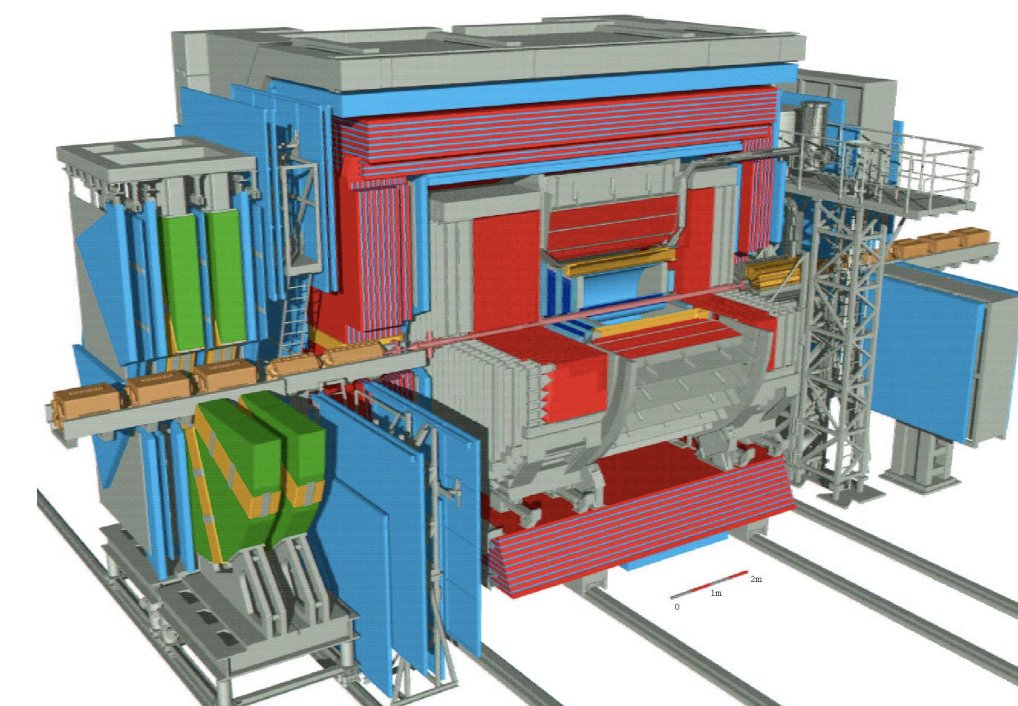


Figure 2. 3D schematic of the ZEUS detector.

- HERA-I ran from 1992 to 2000
- HERA-II ran from 2003 to 2007, following a luminosity upgrade
- Integrated luminosity HERA-I: 118 pb<sup>-1</sup>
- Integrated luminosity HERA-II: 457 pb<sup>-1</sup>
- Roughly 4/5 of the data collected during the HERA runs has yet to be analyzed for EVM production, which should be done before construction of the EIC**

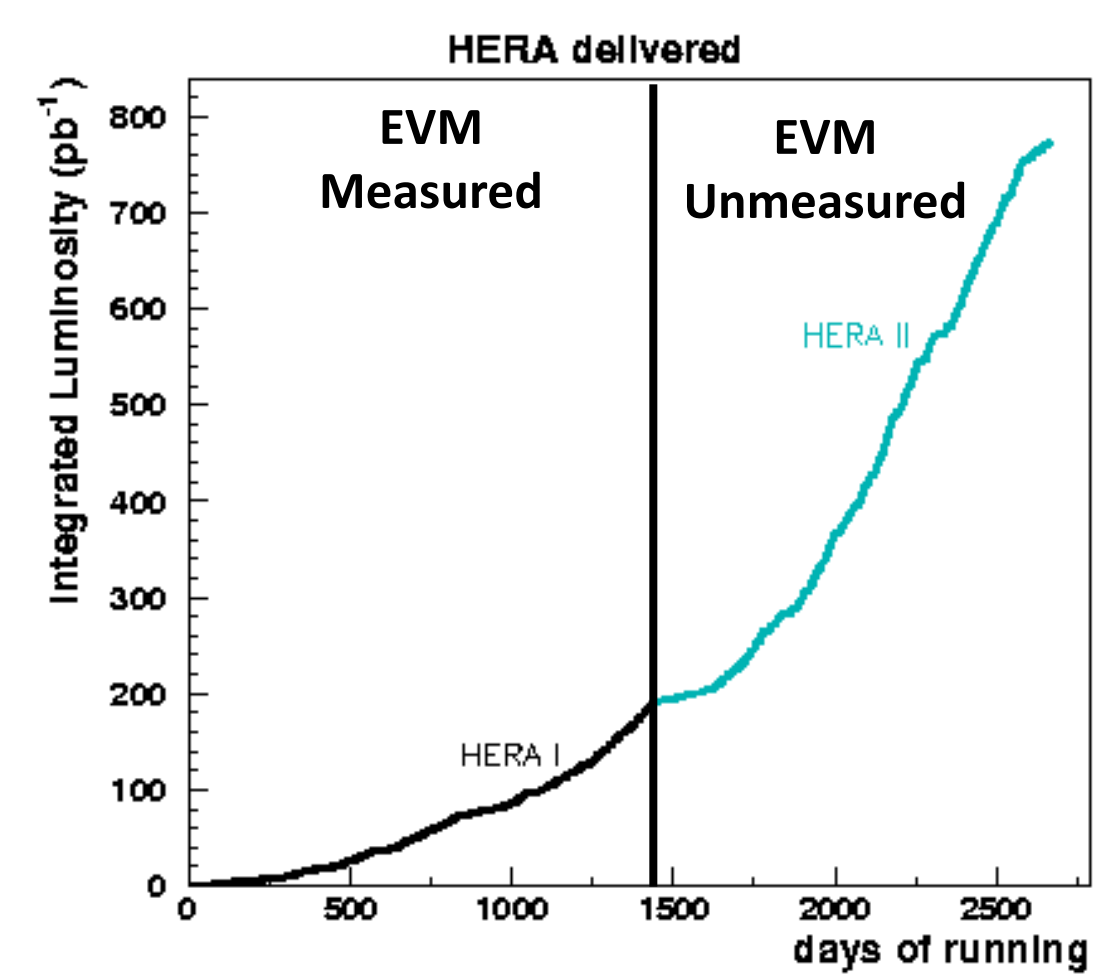


Figure 3. Total luminosity delivered to ZEUS detector. Only HERA-I has been analyzed for EVM production.

## Exclusive Vector Meson Production

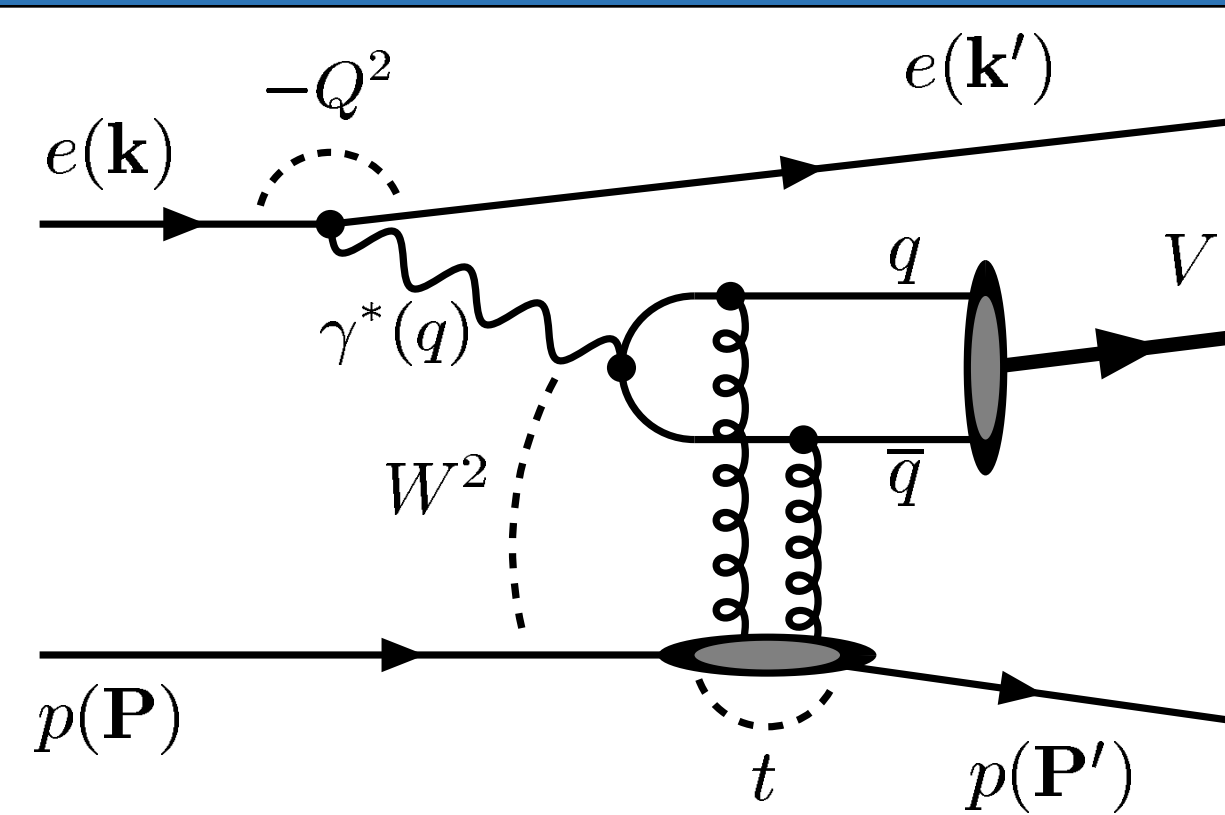


Figure 4. Exclusive vector meson production described by perturbative quantum chromodynamics (pQCD).

- $e p \rightarrow e V p$ , where  $V$  is a vector meson such as  $J/\psi$ ,  $\omega$ ,  $\phi$ , or  $\rho^0$ .
- Lowest order pQCD describes EVM production as a virtual photon, emitted by the electron, fluctuating into a  $q\bar{q}$  pair which exchanges two gluons with the proton leading to the production of a vector meson.
- EVM production is sensitive to the general parton distribution and gluon density within the proton, possibly shedding light on the transverse distribution of gluons in the proton<sup>(3)</sup>
- EVM production is an important physics channel for the proposed Electron-Ion Collider, to study nuclear shadowing, search for gluon saturation and color-glass condensate<sup>(4)</sup>

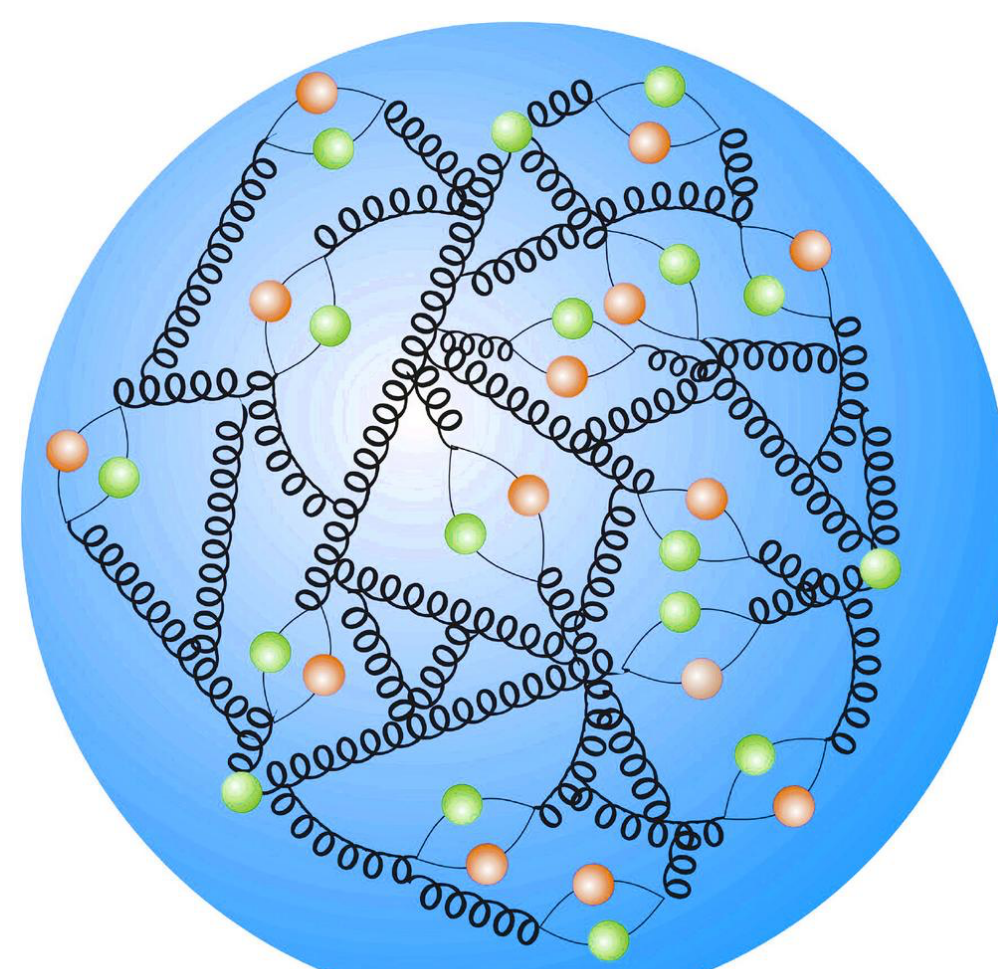
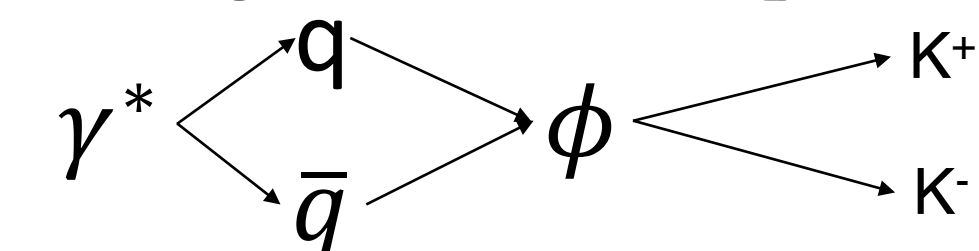


Figure 5. Current model of the internal structure of the proton showing a complex gluon and quark distribution

## Steps of a Nuclear Physics Analysis

### Determine signatures of $\phi$ production



- $\phi$  vector meson decays into two kaons,  $K^+$  and  $K^-$ , almost immediately
- Since kaons are charged, their momentum and position are measured in the Central Tracking Detector
- If two kaons (from  $\phi$ ) were observed in an event, the invariant mass of those two kaons should be the mass of the  $\phi$ .
- Use relativistic two particle decay equations to find the invariant mass of the initial parent particle

$$M_\phi = 1.019455 \pm 0.000020 \text{ GeV}^{(5)}$$

$$M_\phi = \sqrt{(E_{K^+} + E_{K^-})^2 - |\vec{p}_{K^+} + \vec{p}_{K^-}|^2}$$

$$E_{K^{\pm}} = \sqrt{|\vec{p}_{K^{\pm}}|^2 + M_{K^{\pm}}^2}$$

### Get Data

- All of the events, detected by ZEUS, are stored on a grid by DESY
- ZEUS collected over 360 billion events with 613 million physics events, corresponding to close to 0.5 fb<sup>-1</sup> integrated luminosity<sup>(6)</sup>
- Previously ran MC data are also stored on the grid
- A HERA-I analysis saw 4000 events using only 66 pb<sup>-1</sup> of data<sup>(2)</sup>
- HERA-II had an additional 400 pb<sup>-1</sup> delivered to the ZEUS detector, which has not been analyzed for exclusive  $\phi$  production
- Data for this study looked at all events from 2005 adding up to 136 pb<sup>-1</sup>**

### Find only exclusive $\phi$ production events

- Need to define a set of properties that is associated with this process and remove events that do not have these properties
- The invariant mass signal is fit to a Relativistic Breit-Wigner Distribution:

$$N = \int \frac{m_{KK} m_\phi \Gamma_\phi(m_{KK})}{(m_{KK}^2 - m_\phi^2)^2 + m_\phi^2 \Gamma_\phi^2(m_{KK})} dm_{KK} + B(m_{KK})$$

$$\Gamma_\phi(m_{KK}) = \frac{m_\phi}{m_{KK}} \Gamma_0 \left( \frac{(m_{KK}/2)^2 - m_K^2}{(m_\phi/2)^2 - m_K^2} \right)^{3/2}$$

Where  $\Gamma_0 = 4.26 \pm 0.04 \text{ MeV}^{(5)}$ , and  $B(m_{KK})$  is the background function.

### Calculate cross sections

- Cross sections determine what the probability is of a specific process to occur. The experimental  $e p \rightarrow e \phi p$  process can be described

$$\sigma_{DATA}^{ep \rightarrow e \phi p} = \frac{N}{ABL}$$

- To put the cross section in terms of pQCD and described by the fundamental interaction  $\gamma^* p \rightarrow \phi p$ , convert to Born level cross section:

$$\sigma_{Tot}^{\gamma^* p \rightarrow \phi p}(Q^2, W, t) = \sigma_{DATA}^{ep \rightarrow e \phi p} \cdot \frac{\sigma_{MC}^{\gamma^* p \rightarrow \phi p}(Q^2, W, t)}{\sigma_{MC}^{ep \rightarrow e \phi p}}$$

- Determine the cross section as a function of different kinematic parameters ( $Q^2$ ,  $W$ ,  $|t|$ ,  $x$ )

### Answer remaining questions

- Can we extend region of kinematic space,  $Q^2 > 70 \text{ GeV}^2$  due to increased statistics?
- How does the design of the detector affects the observation of exclusive vector meson events to help with the design of electron ion collider?
- gluon structure functions in the proton?
- Transitional regime between Regge theory and pQCD?

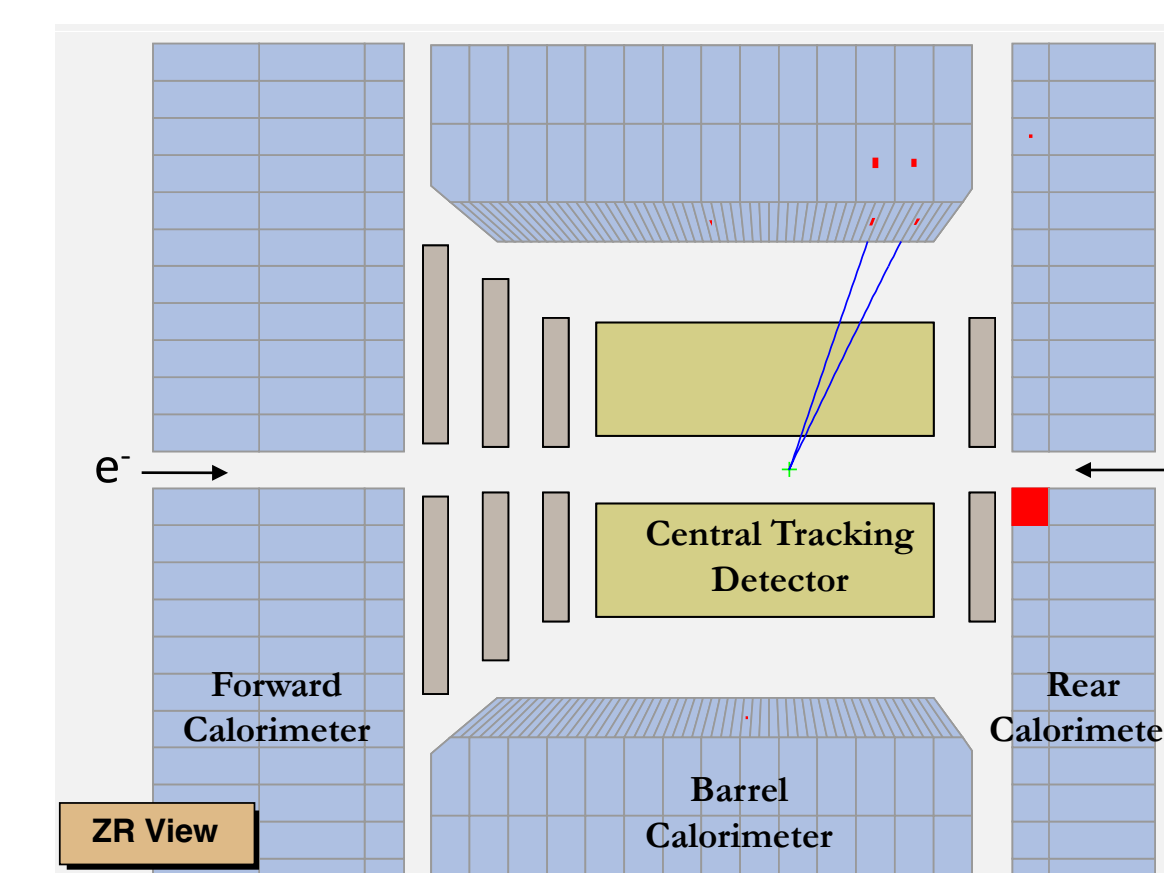


Figure 6. Example of the tracks and energy deposits for exclusive  $\phi$  production.

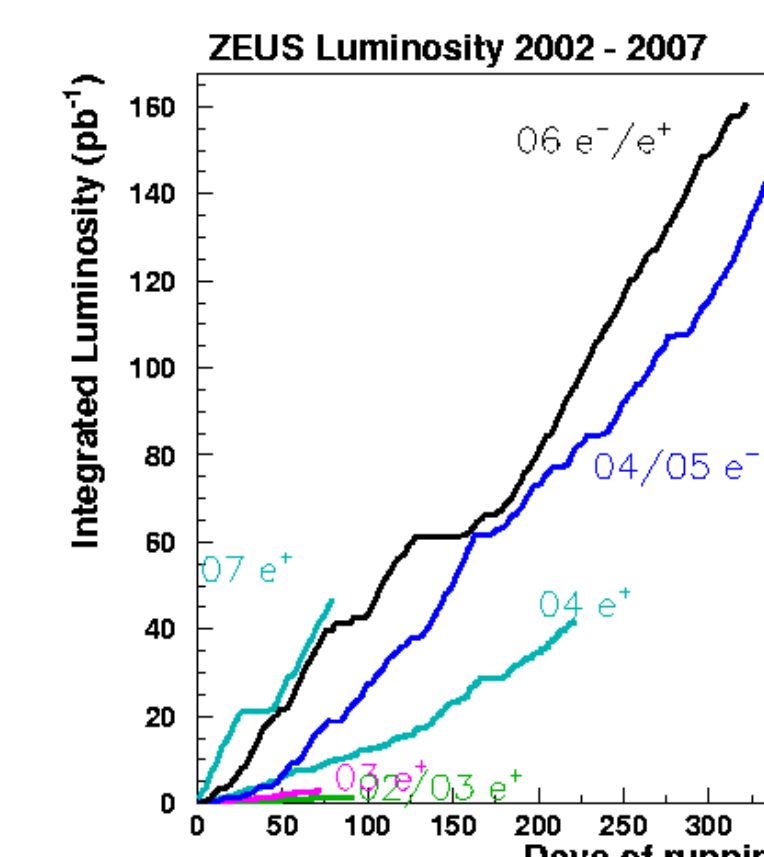


Figure 7. Yearly integrated luminosity during HERA-II.

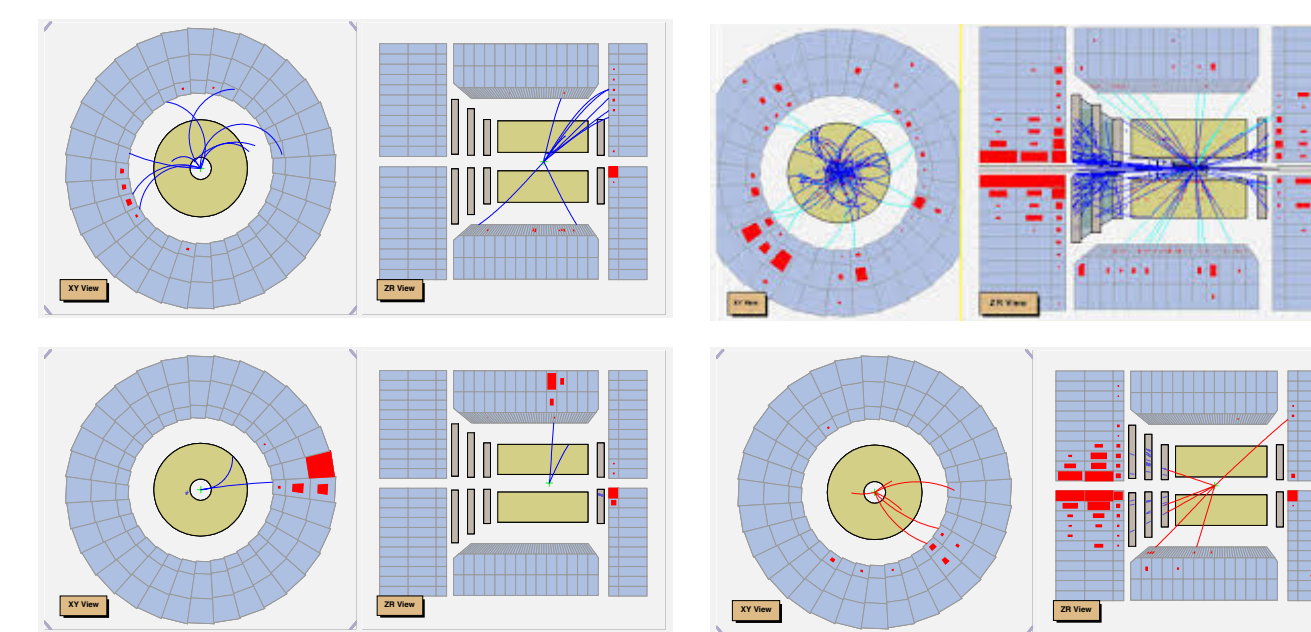


Figure 8. Examples of events that are not exclusive  $\phi$  production, that get removed during the analysis.

### Cuts used for data selection

- $2 < \#$  of tracks in CTD  $< 5$
- Tracks must have opposite charges and be associated with primary vertex
- $E'_e > 10 \text{ GeV}$  in a reliable region of detector
- Tracks must pass through  $> 3$  superlayers in the CTD
- Tracks must have trans. momentum  $> 0.15 \text{ GeV}$
- Tracks must be within  $|\eta| < 1.7$  (angle)
- $|V_{tx}| < 50 \text{ cm}$  and  $V_{tx} < 0.8 \text{ cm}$
- Energy in inner ring of forward calorimeter  $< 1 \text{ GeV}$
- No extraneous tracks with  $E > 0.3 \text{ GeV}$
- $2 < Q^2 < 70 \text{ GeV}^2$
- $45 < E_{p_2} < 65 \text{ GeV}$
- $35 < W < 200 \text{ GeV}$
- $|t| < 0.6$
- $1.01 < M_{KK} < 1.10 \text{ GeV}$

Figure 9. List of specific cuts made to remove all events from data except for exclusive  $\phi$  production.

Kinematic Variables		
$Q^2$	4-momentum of the virtual photon	$(k - k')^2$
$W^2$	Center of photon and proton mass energy	$(q + p)^2$
$x$	Fraction of protons momentum carried by the struck quark	$\frac{Q^2}{(p \cdot q)}$
$t$	Square of the momentum transfer to the proton	$(p - p')^2$

Table 2. Kinematic variables relevant to Deep Inelastic Scattering processes.

## Results

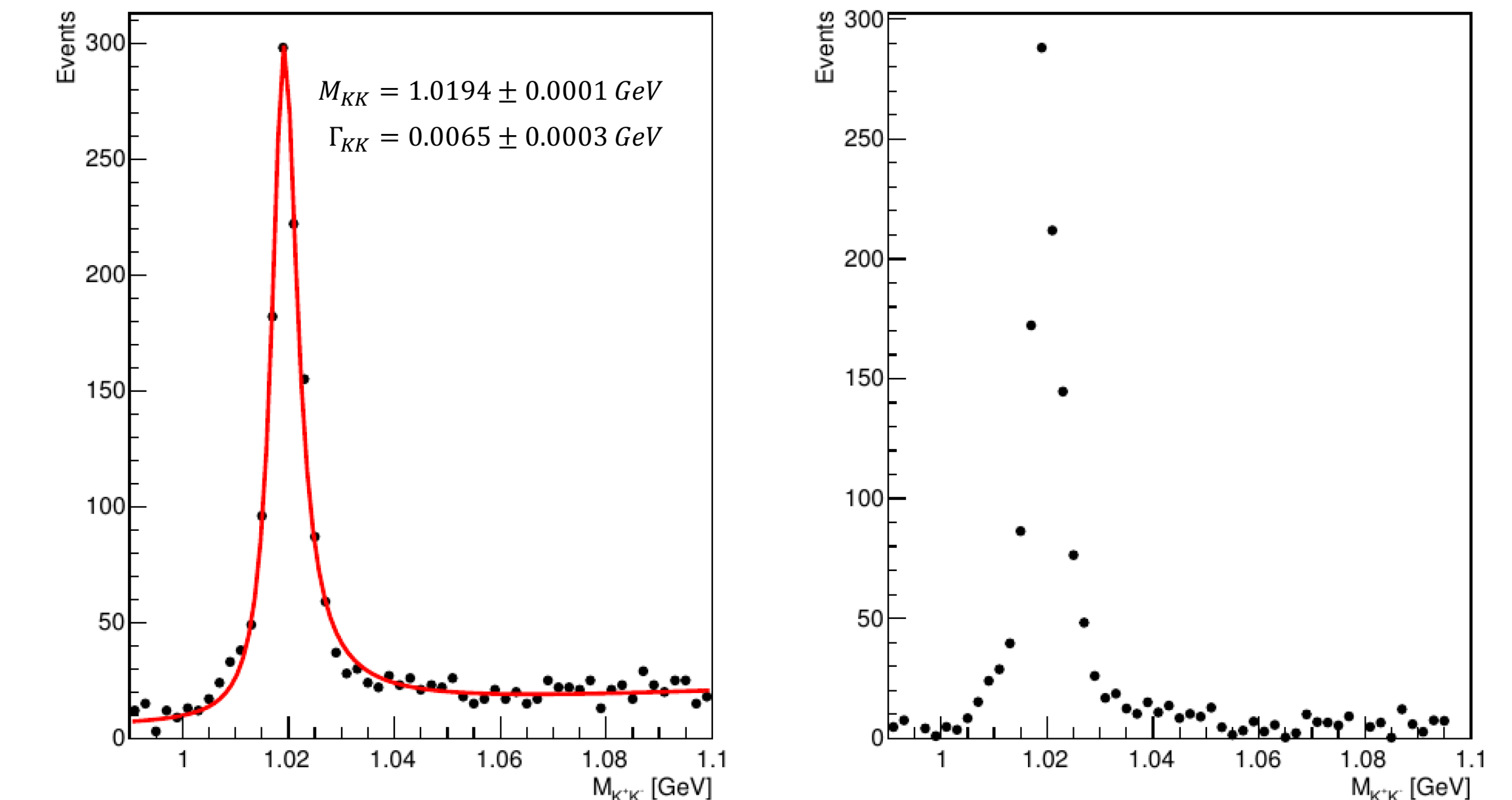


Figure 10. (Left) Invariant mass peak for  $\phi$  vector meson fit with a Relativistic Breit-Wigner distribution and an underlying second order polynomial to describe the background. (Right) 1206 events were detected, after subtraction of the background, from all data collected by the ZEUS detector in 2005 corresponding to a luminosity of 136 pb<sup>-1</sup>.

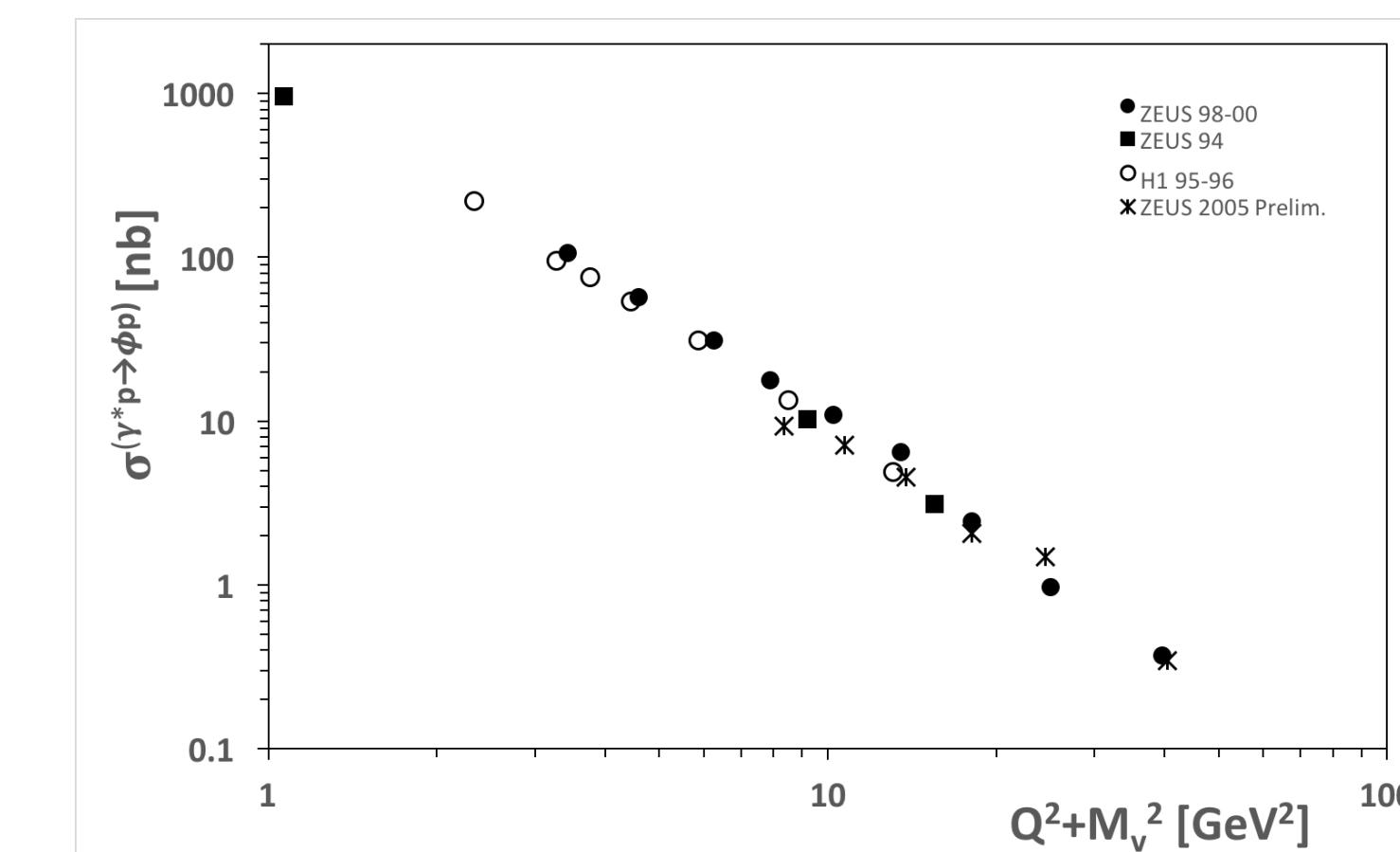


Figure 11. Comparison of the  $(\gamma^* P \rightarrow \phi P)$  Born level cross section as a function of  $Q^2 + M_\phi^2$ . The measured data is compared with previous ZEUS data as well as measurements from H1.

Q <sup>2</sup> Bin [GeV <sup>2</sup> ]	<Q <sup>2</sup> > [GeV <sup>2</sup> ]	Events	$\sigma_{Tot}^{\gamma^* P \rightarrow \phi P}$ [nb]
6-8	8.36	35	9.27
8-11	10.73	393	7.12
11-15	13.80	436	4.56
15-20	18.10	214	2.05
20-30	24.53	114	1.48
30-70	40.54	26	0.46

Table 3. The exclusive production of  $\phi$  cross section as a function of  $Q^2$ . The data was used for Figure 11.

- Measured invariant mass of the two kaons matched the invariant mass of the  $\phi$  vector meson within uncertainty
- 1206 events from 136 pb<sup>-1</sup> of data were detected
- The decreased numbers is from the change in the electron position cut for HERA-II, from the installation of a Micro Vertex Detector preventing low  $Q^2$  measurements

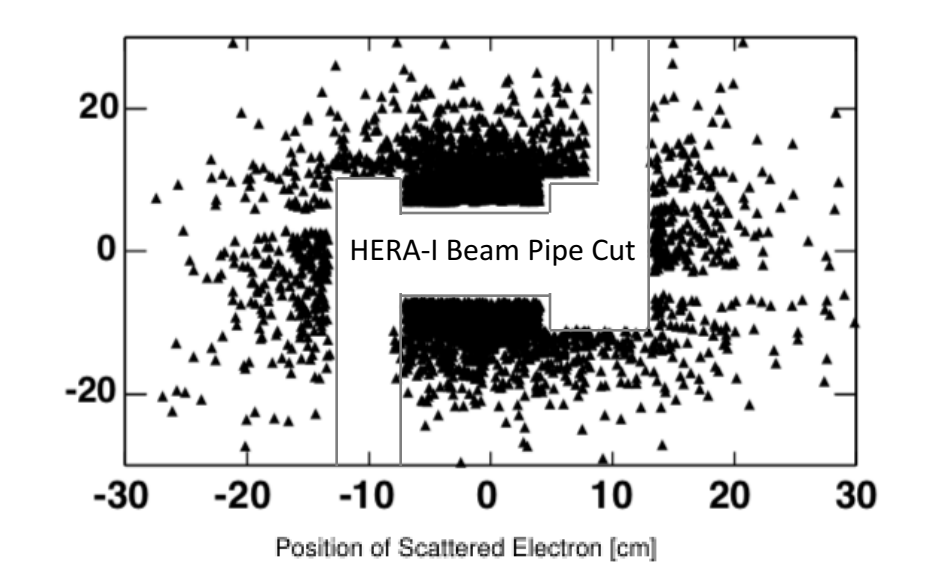


Figure 12. Electron position cuts from ZEUS detector during HERA-I (top) and HERA-II (bottom).

## Future Work

- Calculate systematic errors from different cuts
- Calculate the cross section as a function of  $Q^2$  and  $W$ ,  $Q^2$  and  $|t|$
- Combine all the data from both HERA-I and HERA-II to possibly extend the cross section to  $Q^2 > 70 \text{ GeV}^2$
- Determine how the analysis can help plan for the EIC detector design

## Acknowledgements

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## References

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