Towards a Deeply Virtual Neutral Pion Production Cross Section Measurement at CLAS12

Fall 2022 DNP Meeting

R. Johnston

Massachusetts Institute of Technology
CLAS12 Collaboration

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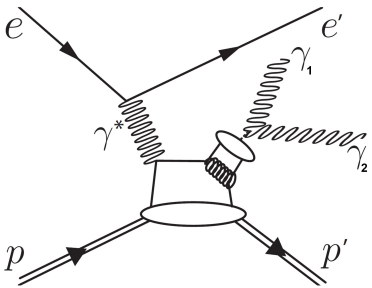
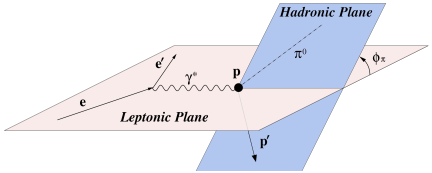
Process Background

Deeply Virtual π^0 Production (DVπ^0P)

$$e + p \rightarrow$$
$$e' + p' + \pi^0 \rightarrow$$
$$e' + p' + \gamma_1 + \gamma_2$$



- 4-fold differential cross section $\frac{d\sigma}{dQ^2 dx_B dt d\phi}$ expressed in terms of:
  - Virtual photon 4-momentum: $Q^2 \equiv -(p_e - p_{e'})^2$
  - Bjorken x: $x_B \equiv \frac{Q^2}{2p_p \cdot (p_e - p_{e'})}$
  - Momentum transfer: -t $\equiv -(p_{p'} - p_p)^2$
  - Angle between lepton & hadron planes: ϕ = $\cos^{-1}\left(\frac{(p_e \times p_{e'}) \cdot (p_{p'} \times p_{\gamma^*})}{\|p_e \times p_{e'}\| \, \|p_{p'} \times p_{\gamma^*}\|}\right)$



Images from S. Lee, A. Kim

- In DIS regime: W> 2GeV, Q^2> 1GeV^2

Physics Motivation: $DV\pi^0P$ and GPDs

The cross section for $DV\pi^0P$ has theoretically linked to Generalized Parton Distributions (GPDs), which describe the 3D structure of the nucleon:

$$\frac{d^4\sigma_{\gamma^* p\to p'\pi^0}}{dQ^2 dx_B dt d\phi_\pi} = \Gamma(Q^2, x_B, E)\frac{1}{2\pi}\left\{\left(\frac{d\sigma_T}{dt} + \epsilon\frac{d\sigma_L}{dt}\right) + \epsilon cos(2\phi)\frac{d\sigma_{TT}}{dt} + \sqrt{2\epsilon(1+\epsilon)}cos(\phi)\frac{d\sigma_{LT}}{dt}\right\} \quad | \quad \Gamma(Q^2, x_B, E) = \frac{\alpha}{8\pi}\frac{Q^2}{m_p^2 E^2}\frac{1-x_B}{x_B^2}\frac{1}{1-\epsilon}$$

The structure functions can be expressed in terms of GPDs:

$$\frac{d\sigma_L}{dt} = \frac{4\pi\alpha}{kQ^2}\left\{(1-\xi^2)\,|\langle\tilde{H}\rangle|^2 - 2\xi^2\Re\left[\langle\tilde{H}\rangle^*\langle\tilde{E}\rangle\right] - \frac{t'}{4m^2}\xi^2|\langle\tilde{E}\rangle|^2\right\}$$

$$\frac{d\sigma_T}{dt} = \frac{2\pi\alpha\mu_\pi^2}{kQ^4}\left\{(1-\xi^2)\,|\langle H_T\rangle|^2 - \frac{t'}{8m^2}|\langle\bar{E}_T\rangle|^2\right\}$$

$$\frac{d\sigma_{LT}}{dt} = \frac{4\pi\alpha\mu_\pi}{\sqrt{2}kQ^3}\xi\sqrt{1-\xi^2}\frac{\sqrt{-t'}}{2m}\Re\left\{\langle H_T\rangle^*\langle\tilde{E}\rangle\right\}$$

$$\frac{d\sigma_{TT}}{dt} = \frac{4\pi\alpha\mu_\pi^2}{kQ^4}\frac{-t'}{16m^2}\langle\bar{E}_T\rangle^2$$

GPD Classification:

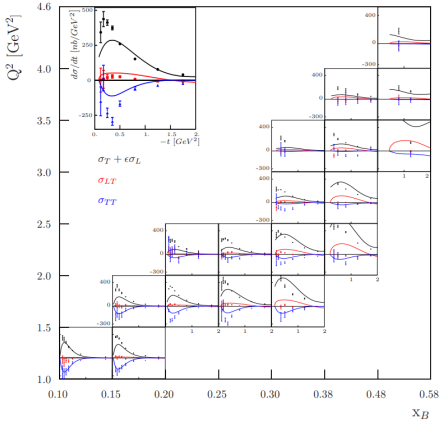
Nucleon Polarization	Quark Polarization		
	U	L	T
U	H		$\bar{E}_T$
L		$\tilde{H}$	
T	E		H_T,$\tilde{H}_T$

$\bar{E}_T = 2^*\tilde{H}_T + E_T$

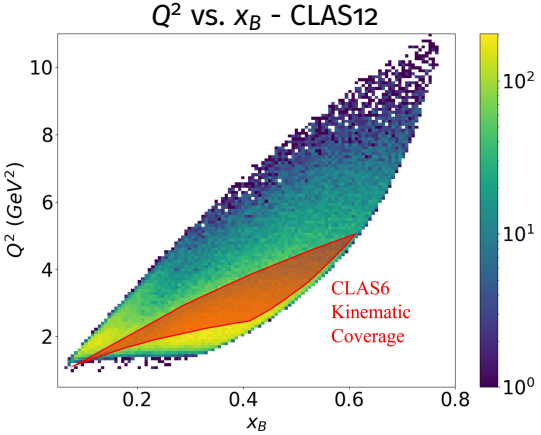
In contrast to DVCS, $DV\pi^0P$ allows access to chiral-odd GPDs, making it a distinct and valuable probe

Analysis Goal: Extract DVπ^oP Cross Section

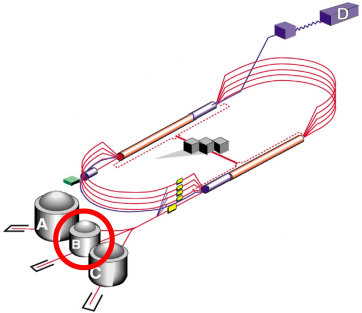
Extracting the cross section for the process will extend the CLAS6 work to a larger kinematic range with higher statistics

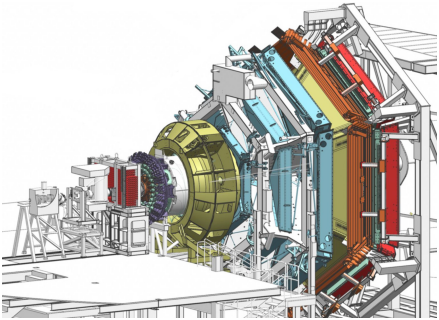


I. Bedlinskiy et al., PRC, 90, 025205 (2014)



CLAS12 Detector at Jefferson Lab Hall B





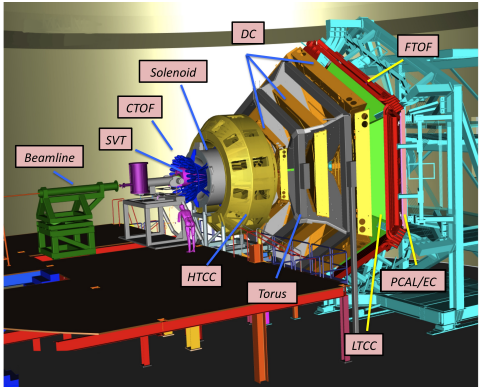
- CEBAF Large Acceptance Spectrometer in Jefferson Lab Hall B
- 10.6 GeV, $\sim$ 50 nA e^- 86% polarized beam on unpolarized LH_2 target

- Large Acceptance:
  - $\sim 2\pi$ coverage in ϕ
  - 5° - 125° coverage in θ
  - Full 4 particle final state reconstruction for this process

V. Burkert et al., NIMA, 959, 163419 (2020)

Experiment Layout And Particle Detection

- 6-fold symmetric Forward Detector ($\theta <\sim 40^\circ$) with torodial field
  - Cherenkov Counters
  - Drift Chambers
  - Time-of-Flight Detectors
  - EM Calorimeters
- Central Detector ($\sim 40 < \theta <\sim 125^\circ$) in solenoid
  - Silicon Vertex Tracker
  - Micromegas
  - ToF Detector
- Forward Tagger, Backward Angle Neutron Detector
- Faraday Cup for luminosity measurement



- This analysis examines data taken in Fall 2018

V. Burkert et al., NIMA, 959, 163419 (2020)

Analysis Overview: Components of Cross Section

Number of DVπ⁰P Events in Bin:

- Particle ID: CLAS common analysis
- Proton Momentum corrections from S. Lee
- Fall 2018 Outbending Dataset
- Exclusivity cuts applied to all candidate events (one proton, one electron, at least two photons)

$$\frac{d^4\sigma_{\gamma^* p\to p'\pi^0}}{dQ^2 dx_B dt d\phi_\pi} = \frac{N(Q^2, x_B, t, \phi_\pi)}{\mathcal{L}_{int}\Delta Q^2 \Delta x_B \Delta t \Delta\phi} \frac{1}{\epsilon_{ACC}\delta_{RC}\delta_{Norm} Br(\pi^0 \to \gamma\gamma)}$$

Integrated Luminosity:

- Measured from Faraday Cup beam charge
- 5.5 x 10^{40} cm^{-1} from fall 2018 inbending dataset
- 4.6 x 10^{40} cm^{-1} from fall 2018 outbending dataset

Bin Widths

Correction Factors:

ε_{ACC} : acceptance correction
δ_{RC} : radiative correction
δ_{Norm} : overall normalization
$Br(\pi^0 \to \gamma\gamma)$: branching ratio of neutral pions to two photons
Others : binning corrections

Event Selection - Particle Identification and Exclusivity Cuts

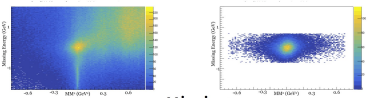
Particle Kinematics

- Electron
  - Cherenkov Counter (PID)
  - Drift Chamber (momentum)
  - Time-of-flight (PID)
  - EM Calorimeter (energy)
- Proton
  - Time-of-flights (PID)
  - Micromegas, SVT, DCs (momentum)
- Neutral Pion
  - EM Calorimeter (γ_1, γ_2)
  - $|M_{\pi^0} - M_{\gamma\gamma}| < 40$ MeV

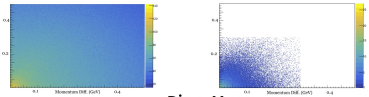
Event Cuts

- DIS Cuts
  - $Q^2 > 1$ GeV^2
  - W$^2 > 4$ GeV^2
- Exclusivity Cuts
  - $MM^2_{epX} < 0.7$ GeV^2
  - $ME_{ep\gamma\gamma} < 0.7$ GeV
  - $\theta_{X\pi} < 2^\circ$
  - $\Delta p_{x,y} < 0.3$ GeV

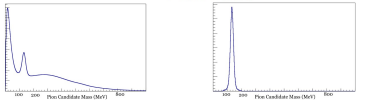
$E_{ep\gamma\gamma}$ vs. MM^2_{epX}



Missing p_T



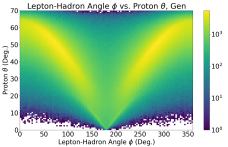
Pion Mass

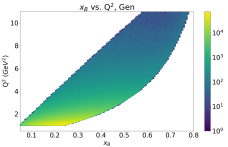


Acceptance Correction - Event Generator and Simulation

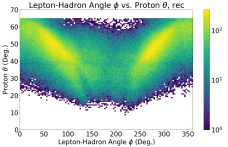
- Event Generator - aao_norad
  - Nonradiative $DV\pi^{0}P$ generator validated on CLAS6 and COMPASS data
- Simulation - GEMC
  - GEANT4 based simulation developed by CLAS collaboration
- Computing Power
  - Through OSG pipeline, CLAS has access to supercomputing clusters around the world, including dedicated nodes at MIT Tier 2, UConn, INFN, GRIDPP, and more

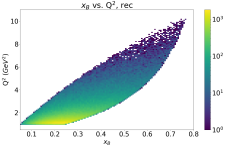
Generated





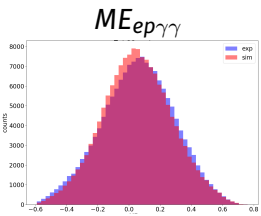
Reconstructed

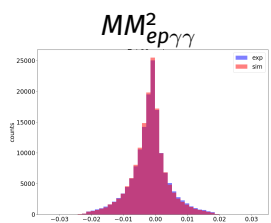


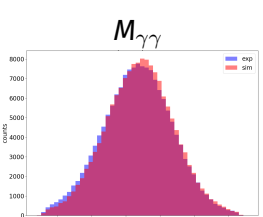


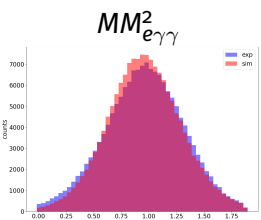
Acceptance Correction - Simulation : Experiment Matching

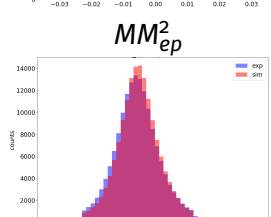
With the addition of smearing factors to simulated particle reconstruction values, the simulation matches experimental distributions well. [Collaborator S. Lee]

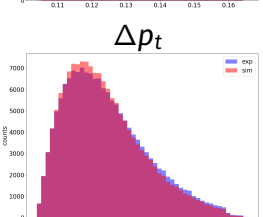






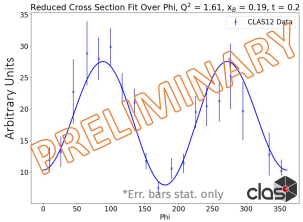


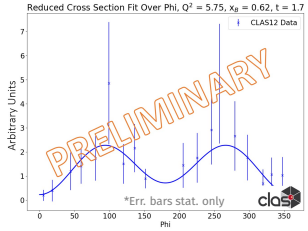


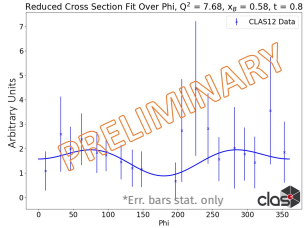


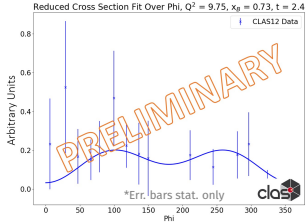
Progress on Preliminary Cross Section

- Acceptance corrected data follows functional form expected from structure function decomposition









Theory Predictions - GK Model

- Goloskokov-Kroll (GK) model predicts exclusive π electroproduction cross sections using handbag approach

  [S.V. Goloskokov & P. Kroll, EPJC, 65,137 (2010)]

- Model parameters chosen to best describe recent CLAS π^+ BSA result

  [S. Diehl et al., PRL 125 182001 (2020)]

- Software implementation from K. Tezgin / PARTONS Framework

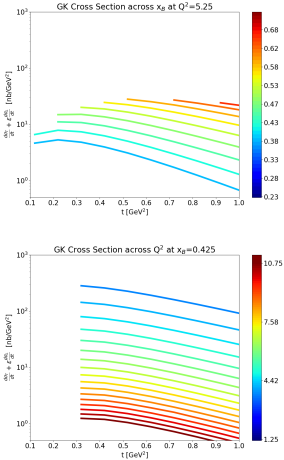
  [B. Berthou et al., EPJC, 78, 478 (2018)]

Note:

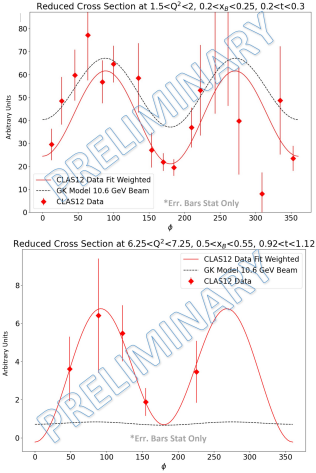
$W > 2$ GeV $\implies \frac{Q^2(1-x_B)}{x_B} > 3.12$ GeV^2

$t > t_{min} \implies t > \frac{m_p^2 x_B^2}{1-x_B}$

Model Predictions



GK and CLAS12 Data



Conclusion - Towards a Full Cross Section

Preliminary efforts on event selection, simulations, and acceptance corrections yield promising results but more work is needed to extract a complete cross section measurement:

- Determination of remaining correction factors - radiative, binning, and absolute normalization
- Study of systematic uncertainties
- Quantitative comparisons between data and theory model will be meaningful when uncertainties and binning are more complete

Finite Bin Volume Corrections

Bin Average is not the same as bin center

Ditching Binning - OMNIFOLD

words

Rosenbluth Separation

Igor Paper

Classifier – box to manifold

words

Normalizing Flows

words

Simulation Based INference

Words

Extra slides

Extra Slides

Extra slides

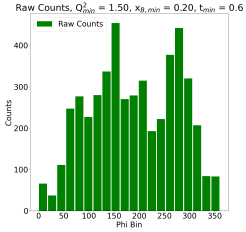
Extra Slides Find this on the web at:
https://github.com/robertej19/Thesis-Offense/blob/main/Main/presentation.tex

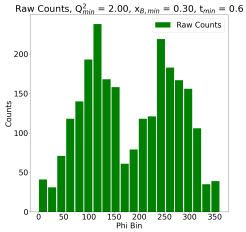
Backup slides

- QCD factorization theorem for DVMP process has only been proven for longitudinally polarized photons
- QCD factorization has been proven for DVCS

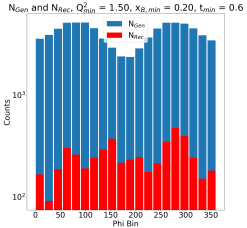
Acceptance Correction - Bin by Bin Calculation

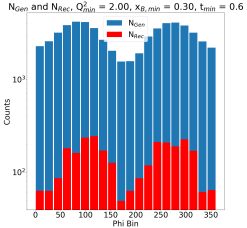
Raw Counts



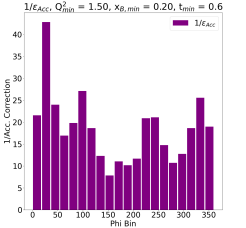


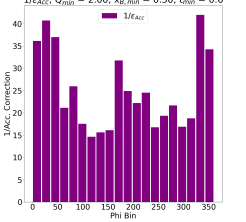
Simulated N_{Gen}, N_{Rec}



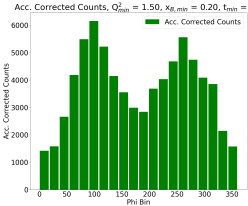


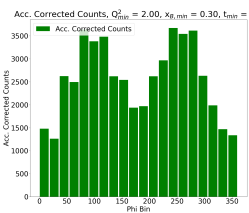
Acc. Correction



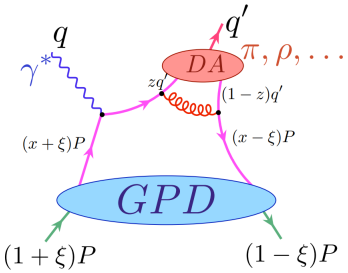


Acc. Corr. Counts





Backup slides



DVMP is sensitive to chiral odd GPDs, distinguishing it from DVCS as a GDP probe

$$\frac{d^4\sigma}{dQ^2 dx_B dt d\phi_\pi} = \Gamma(Q^2, x_B, E)\frac{1}{2\pi}\left[\left(\frac{d\sigma_T}{dt} + \epsilon\frac{d\sigma_L}{dt}\right) + \epsilon\cos 2\phi_\pi \frac{d\sigma_{TT}}{dt} + \sqrt{2\epsilon(1+\epsilon)}\cos\phi_\pi \frac{d\sigma_{LT}}{dt}\right]$$

$$\frac{d\sigma_L}{dt} = \frac{4\pi\alpha}{k'}\frac{1}{Q^6}\left\{(1-\xi^2)|\langle\tilde{H}\rangle|^2 - 2\xi^2 \mathrm{Re}[\langle\tilde{H}\rangle^*\langle\tilde{E}\rangle] - \frac{t'}{4m^2}\xi^2|\langle\tilde{E}\rangle|^2\right\},$$

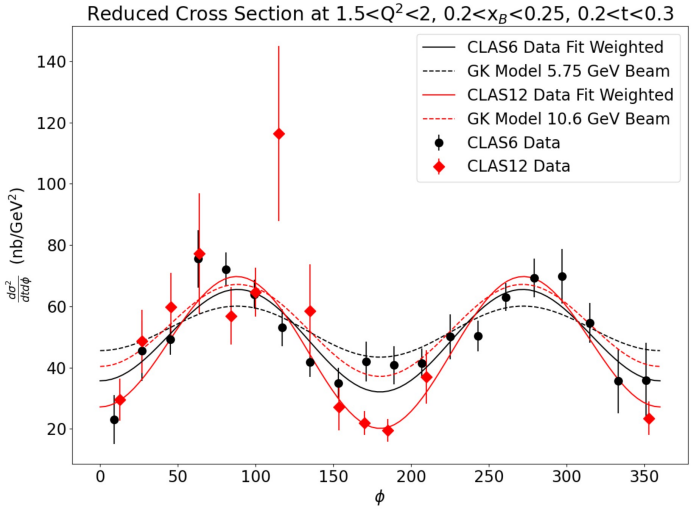
$$\frac{d\sigma_T}{dt} = \frac{4\pi\alpha}{2k'}\frac{\mu_\pi^2}{Q^8}\left[(1-\xi^2)|\langle H_T\rangle|^2 - \frac{t'}{8m^2}|\langle\tilde{E}_T\rangle|^2\right],$$

$$\frac{d\sigma_{LT}}{dt} = \frac{4\pi\alpha}{\sqrt{2}k'}\frac{\mu_\pi}{Q^7}\xi\sqrt{1-\xi^2}\frac{\sqrt{-t'}}{2m}\,\mathrm{Re}[\langle H_T\rangle^*\langle\tilde{E}\rangle],$$

$$\frac{d\sigma_{TT}}{dt} = \frac{4\pi\alpha}{k'}\frac{\mu_\pi^2}{Q^8}\frac{t'}{16m^2}|\langle\tilde{E}_T\rangle|^2.$$

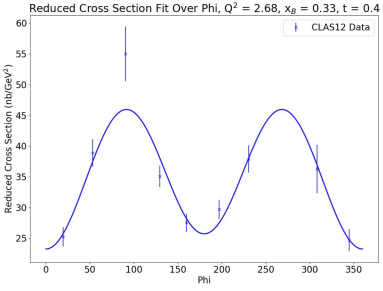
Backup slides

Comparision with CLAS6



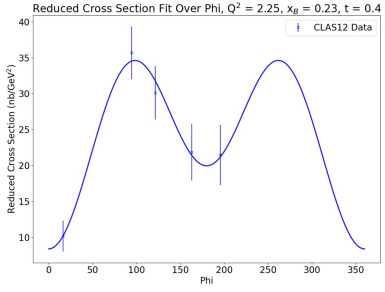
Backup slides

Low Q2

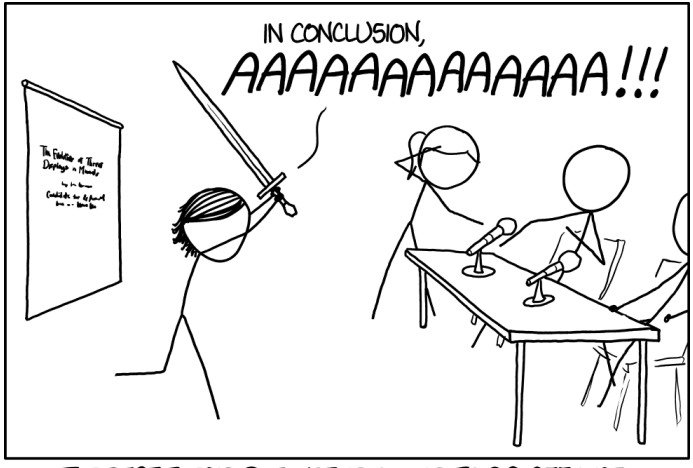


Backup slides

Inbending



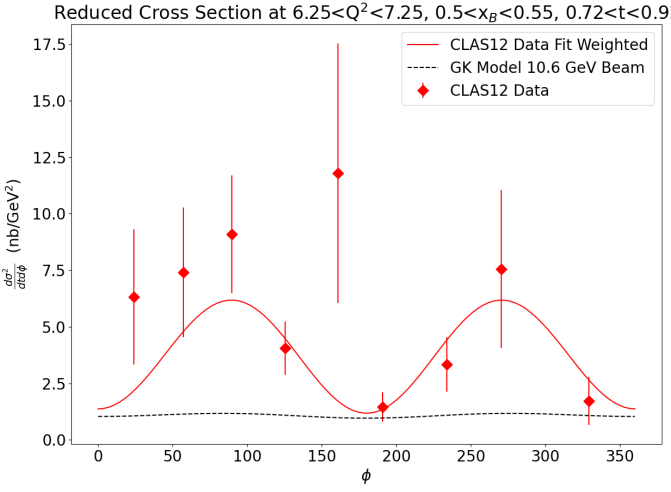
De-Fence!



https://xkcd.com/1403/

Backup slides

Other



Backup slides

Issues: Misfits