Measurement of the DVπ^0P Cross Section

at the Thomas Jefferson National Accelerator Facility at 10.6 GeV

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Ph.D. Oral Defense

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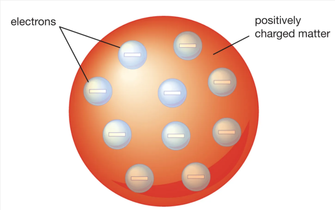
What is Matter? A Brief History

- ~ **500 BCE: *Atomism***: From Greek *átomos* [uncuttable]: philosophical belief that the universe consists of indivisible units of matters (also present in ancient Indian philosophy) [Wikipedia:Atomism,Leucippus]
- **~1800s: Law of Multiple Proportions**: John Dalton: discovered that elements react and combine in small, integer ratios [Wikipedia:Atom]
- **1897: Plum Pudding Model**: J.J. Thomson: discovered *sub*atomic particles (originally called corpuscles, renamed to electrons) [Wikipedia:Plum Pudding Model]

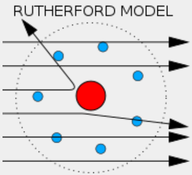


Thomson model of atom, with negatively charged electrons embedded in positively charged ball

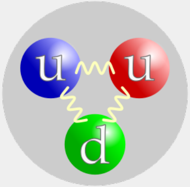
[Britannica:Thomson Atomic Model]

Brief History of the Proton

- ~ **1911: Discovery of the Nucleus** - Scattering α particles off gold foil yielded significant backscatter, indicating small, dense nucleus [Wikipedia:Geiger-Marsden]
- ~ **1919: Discovery of the Proton** - Proposed by Rutherford after α particle scattering experiments off atoms [E. Rutherford doi:10.1080/14786431003659230]
- ~**1961: Discovery of Quarks** - Electron scattering experiments provided evidence consistent with the proton being a composite object of point-like constituents



[Wikimedia:Geiger-Marsden Exp.]



[Wikimedia:Proton Quark Structure]

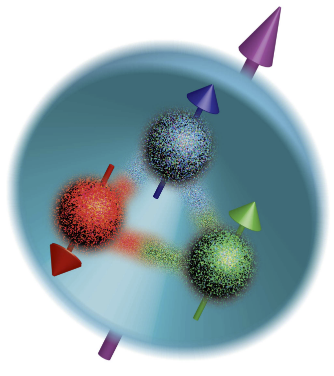
The Proton is Now Well-Understood

Protons are:

- **Spin 1/2**
- **Stable**: mean lifetime > 1E34 years
- **Lightweight**: 938.272088 MeV; lightest baryon

  [n.b. 1 eV = 1.8E-36 kg]

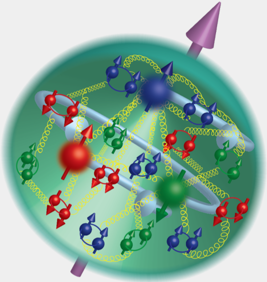
- **Small**: radius ~ 0.85 fm
  - If protons were scaled to the size of pingpong balls, atoms would be ~ 4 football fields across, humans would be ~ diameter of the inner solar system



[EIC Whitepaper]

The Proton is **NOT YET** well-understood - Testbed for Physics

Macroscopic features are well measured, but many properties remain to be understood



[Argonne National Lab]

- **Proton Spin Crisis:** Where does the proton's spin come from? 1987 measurement showed valence quarks only contribute a small percent to overall proton spin
- **Proton Decay:** Popular Beyond-Standard-Model theories predict the proton to decay, but never has been observed
- **Proton Radius Puzzle:** (possibly resolved) discrepancy in proton charge radius between experimental methods

[Proton Puzzles, Nat Rev Phys, 2021]

Probing the Proton: Accelerators as Electron Femtoscopes

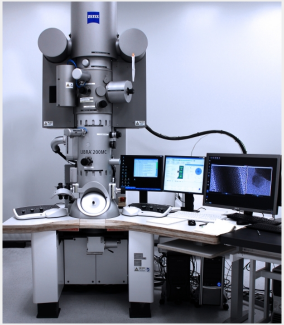
Imaging limited by diffraction ($\sim \frac{\lambda}{2}$) $\rightarrow$ scale set by $\lambda = \frac{hc}{pc}$ with hc = 1200 eV nm

Optical Microscope

$3\ \mathrm{eV} \rightarrow \lambda \sim 400\ \mathrm{nm}$

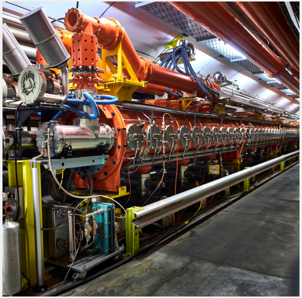
[n.b. ex. mic for bio]

Electron Microscope



$10\ \mathrm{keV} \rightarrow \lambda \sim 0.01\ \mathrm{nm}$

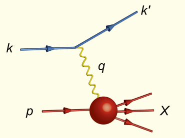
Electron Accelerator

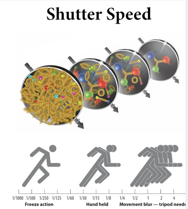


$10\ \mathrm{GeV} \rightarrow \lambda \sim 0.1\ \mathrm{fm}$

Proton Structure must be Indirectly Imaged

Unlike optical imaging, must infer structure from reaction rates (cross sections) → structure encoded in various form factors and distribution functions

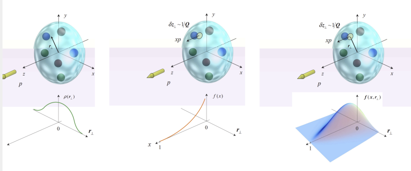




[R.G. Milner and R. Ent,

Visualzing the Proton (2022)]

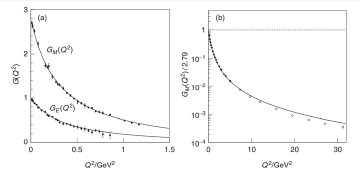
- Reactions of the form e + p → e + X
  - X = p: elastic scattering
  - X = X: inclusive scattering
  - X = p + π: DVπP (in proper kinematic regime)
- $\frac{1}{q}$ determines the spatial resolution
- $\frac{1}{x_B}$ determines the shutter speed



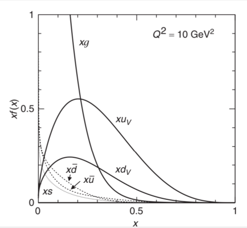
[A.V. Belitsky A.V. Radyushkin 2005]

GPDs Encode Proton 3D Structural Information

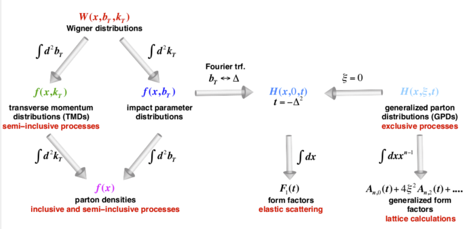
Proton Form Factors



Parton Distribution Functions



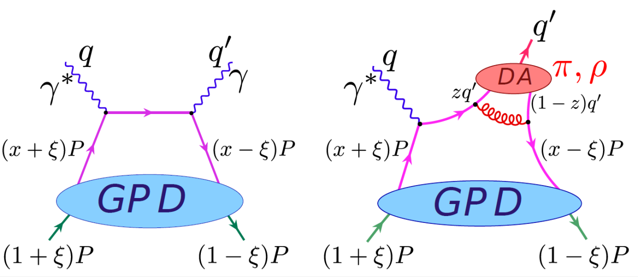
- All distribution functions related through limiting cases of Wigner distributions
- Quark and gluon Wigner distributions have no known direct physical observable
- Can experimentally access TMDs and GPDs



Relationships between different distribution functions

[EIC Whitepaper]

- Deeply Virtual Processe (DVCS, DVMP)s: target nucleon remains intact, DIS regime
- Relies on factorization between hard scattering and soft QCD vertices
- Factorization proved rigorously for DVCS in Bjorken limit, for DVMP with longitudinally polarized photons (sufficient if dominates)



DVCS (left) and DVMP Feynman Handbag diagrams

[V. Kubarovsky Nuc Phys B 2011]

Early Insights from Deeply Virtual Processes

- Deeply Virtual Processe (DVCS, DVMP)s: target nucleon remains intact, DIS regime
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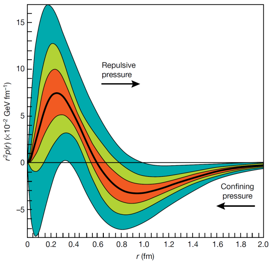
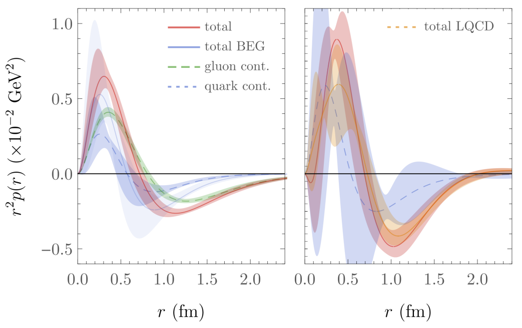


DVCS (left) and DVMP Feynman Handbag



DVCS (left) and DVMP Feynman Handbag

The cross section for DVπ^0P can be expressed in terms of structure functions, which can be expressed as convolutions of GPDs:

$$\frac{d^4\sigma_{\gamma^* p\to p'\pi^0}}{dQ^2 dx_B dt d\phi_\pi} = \Gamma(Q^2, x_B, E)\frac{1}{2\pi}\left\{\left(\frac{d\sigma_T}{dt} + \epsilon\frac{d\sigma_L}{dt}\right) + \epsilon cos(2\phi)\frac{d\sigma_{TT}}{dt} + \sqrt{2\epsilon(1+\epsilon)}cos(\phi)\frac{d\sigma_{LT}}{dt}\right\} \quad | \quad \Gamma(Q^2, x_B, E) = \frac{\alpha}{8\pi}\frac{Q^2}{m_p^2 E^2}\frac{1-x_B}{x_B^3}\frac{1}{1-\epsilon}$$

The structure functions can be expressed in terms of GPDs:

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

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

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

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

GPD Classification:

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

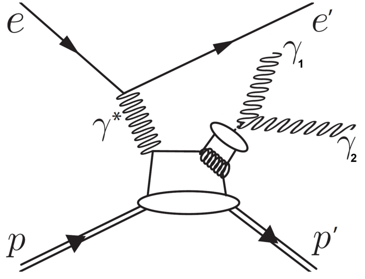
$\bar{E}_T = 2times\ \tilde{H}_T + E_T$

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

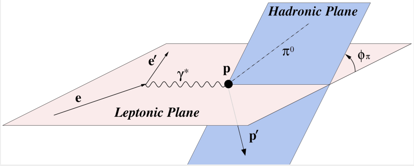
$DV\pi^0P$: 4 PARTICLE FINAL STATE, 4 DEGREES OF FREEDOM

Deeply Virtual π^0 Production
($DV\pi^oP$)

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



- 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: $\phi = \cos^{-1}\left(\frac{(p_e \times p_{e'}) \cdot (p_{p'} \times p_{\gamma^*})}{\| p_e \times p_{e'} \| \, \| p_{p'} \times p_{\gamma^*} \|}\right)$

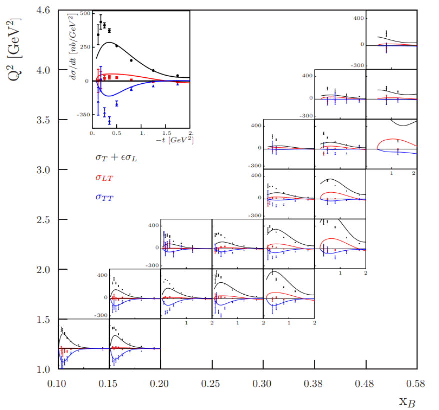


1111111 Images from S. Lee, A. Kim

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

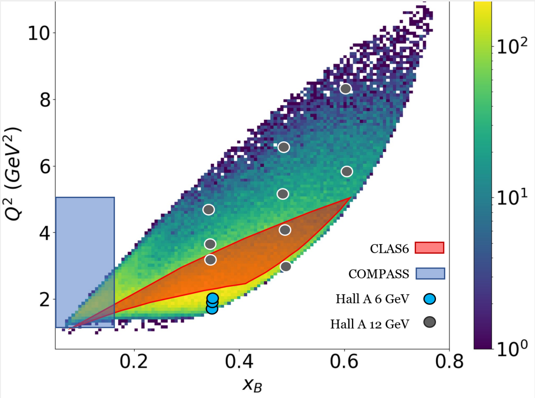
Analysis Goal: Extract DVπ^0P Cross Section

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)]

Q^2 vs. x_B - CLAS12



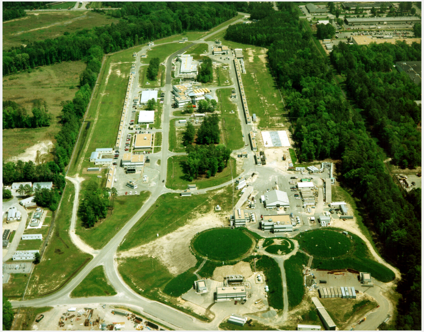
The Path to Measurement has Many Steps

- **Design and Build Detectors**: 2006-2018
- **Take Data**: 2018 start, continuing
- **Process Data**: Reconstruct particle paths from detector signals
- **Analyze Data**: Event selection to find raw process rates
- **Correct Data**: Run simulations and apply correction factors
- **Extract Physics**: Calculate structure functions, deconvolve GPDS,

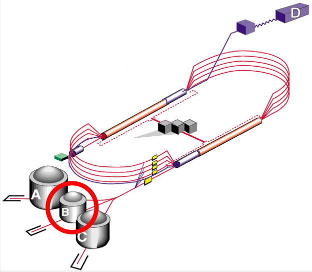
Detector construction - wire chamber stringing

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

Thomas Jefferson National Accelerator Facility - Newport News, VA



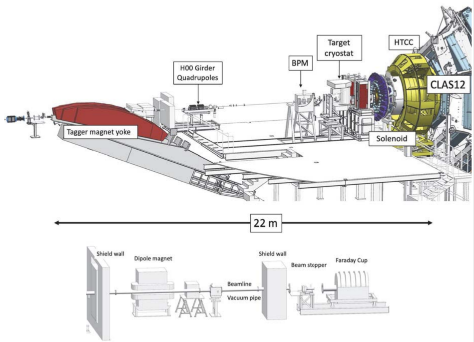
- Jefferson Lab aerial view [jlab.org]

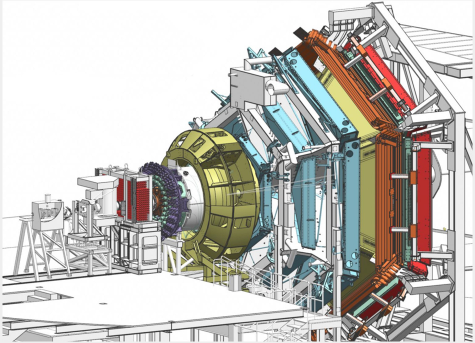


- CEBAF 1,400 m racetrack, 50 RF cryomodules
- 10.6 GeV, ~ 50 nA electron beam

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

CLAS12 Detector at Jefferson Lab Hall B

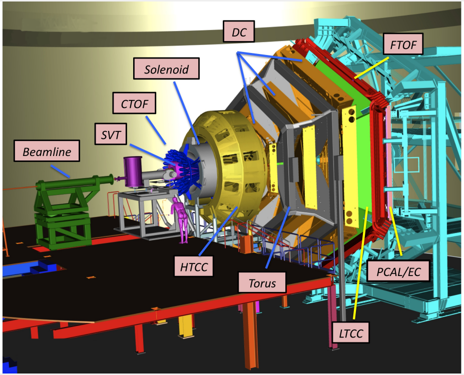




- Top: Beamline into unpolarized LH_2 target (cryostat)
- Bottom: Downstream beamline to Faraday Cup (current monitor)
- CEBAF Large Acceptance Spectrometer:
  - ~ 2π coverage in ϕ
  - 5° - 125° coverage in θ
  - Full 4 particle final state reconstruction for this process

Experiment Layout And Particle Detection

- 6-fold symmetric Forward Detector (θ <~ 40°) with torodial field
  - Cherenkov Counters
  - Drift Chambers
  - Time-of-Flight Detectors
  - EM Calorimeters
- Central Detector (~ 40° < θ <~ 125°) inside solenoid
  - Silicon Vertex Tracker
  - Micromegas
  - ToF Detector



- Forward Tagger, Backward Angle Neutron Detector
- Faraday Cup for luminosity measurement [V. Burkert et al., NIMA, 959, 163419 (2020)]

- This analysis examines data taken in Fall 2018

Components of Cross Section

Number of DVπ^oP 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
- 5.5×10^{40} cm^{-1} from fall 2018 inbending dataset
- 4.6×10^{40} cm^{-1} from fall 2018 outbending dataset

Bin Widths

Correction Factors:

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

Components of Cross Section: Luminosity

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Others : binning corrections

$$L = \frac{N_A l \rho Q_{FCUP}}{e}$$

Quantity		CLAS12 Value
Avogadro's Number	N_A	$6x10^{23}$
Electron Charge	e	$1.6x10^{-19}$
Target Length	l	5 cm
Target Density	ρ	0.07 g/cm^3 (LH2)
Charge on Faraday Cup	Q_{FCUP}	In data

Caption

Components of Cross Section

Number of DVπ⁰P Events in Bin:

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Bin Widths

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Components of Cross Section: Event Counts

Number of DVπ°P Events in Bin:

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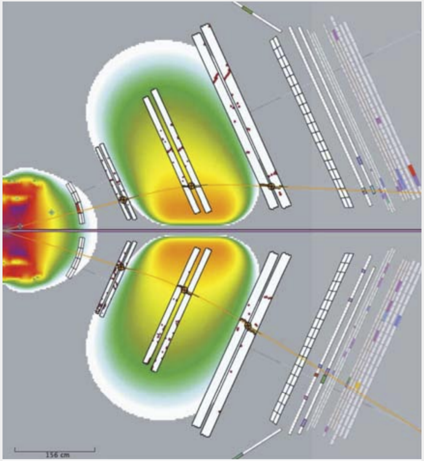
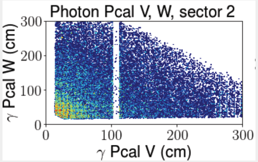
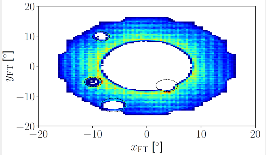
Events and Preliminary Particle Identification



Sample Recon. Event with Detector Hits

- Reconstruction conducted at collaboration level
- Provides particle features (momentum, charge, mass)
- Additional fiducial cuts, momentum corrections applied afterwards





[S. Lee]

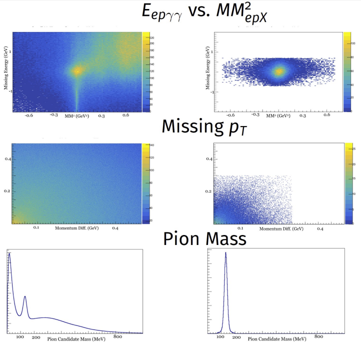
EVENT SELECTION - PARTICLE IDENTIFICATION AND EXCLUSIVITY CUTS

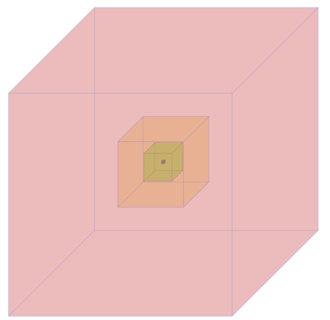
Particle Kinematics

- 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

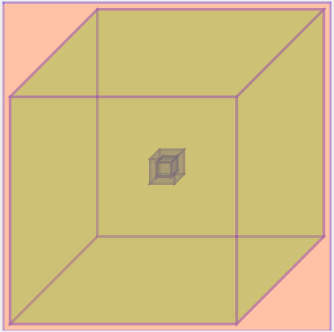
Event Cuts

- 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





Caption



Caption

Calculated Integrated Luminosity from Fall 2018 dataset: 5.512 e+40 cm^{-2} inbending, 4.652 e+40 cm^{-2} outbending

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

Components of (Binned) Cross Section: Bin Width

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)

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

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

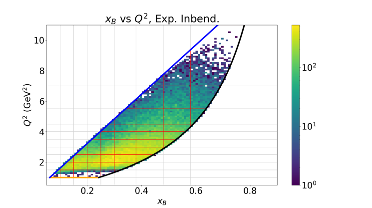
Bin Widths

Correction Factors:

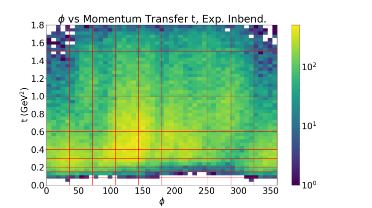
ε_{ACC} : acceptance correction
δ_{RC} : radiative correction
δ_{Norm} : overall normalization
$Br(\pi^0 \to \gamma\gamma)$: branching ratio of neutral pions to two photons
Others : binning corrections

Event Binning

words about binning



Caption



Caption

Components of Cross Section

Number of DVπ^0P 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
- 5.5×10^{40} cm^{-1} from fall 2018 inbending dataset
- 4.6×10^{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

Components of Cross Section: Correction Factors

Number of DVπ°P 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)

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

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

$Br(\pi^0 \rightarrow \gamma\gamma)$: branching ratio of neutral pions to two photons

Others : binning corrections

Simulations Needed to Determine Correction Factors

- High computational demands: 5 hours to simulate 10K events
- Need $O(2B)$ events → need 1M core-hours for this analysis alone
- Built service to connect research collaboration with HTC nodes worldwide

Open Science Grid

HTCondor High Throughput Computing

Home About OSG Stats Monitors

CLAS12 Monte-Carlo Job Submission Portal

Summary of current jobs

user	submission	total	done	run	idle
lanza	1	2000	819	1181	0
jsalvg	1	10000	9998	0	0
robertej	1	10000	9996	0	0
total	3	22000	20813	1181	0

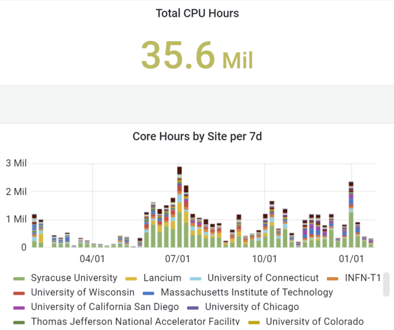
Click to submit to OSG

Generator

- clas12-mcgen or gemc internal generator
- Arbitrary number of jobs
- Arbitrary number of events for each job (max 10,000)

LUND Files

- LUND files (.txt) from a web location
- One job per LUND file
- File define number of events for each job (max 10,000)

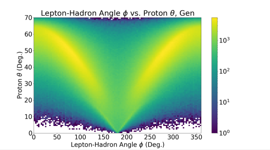


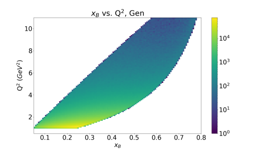
Usage facilitated in 2022

Event Generator and Simulation Details

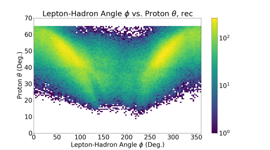
- Event Generator - aao_(no)rad
  - *DVMP* generator validated on CLAS6 and COMPASS data, origin 1990s
- Simulation - GEMC
  - GEANT4 based simulation developed by CLAS collaboration
- Computing Power
  - Through OSG pipeline, CLAS has access to supercomputing clusters around the world, including dedicated nodes at MIT Tier 2, UConn, INFN, GRIDPP, new groups still joining

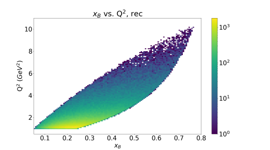
Generated





Reconstructed

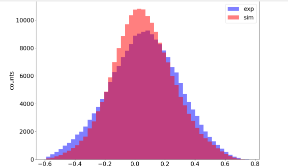




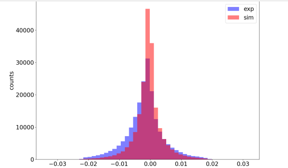
Simulation Needs to be Adjusted to Match Experimental Data

GEANT4 simulation results in reconstructed tracks that are overly optimistic - resolution is better in simulation than in real data

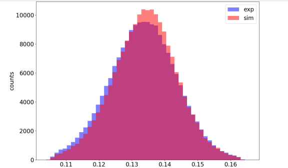
$ME_{ep\gamma\gamma}$



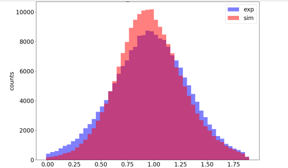
$MM^2_{ep\gamma\gamma}$



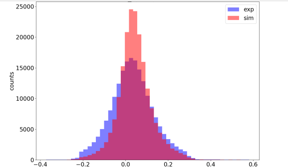
$M_{\gamma\gamma}$



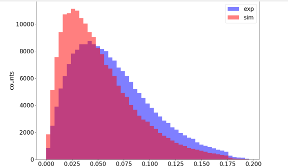
$MM^2_{e\gamma\gamma}$



MM^2_{ep}



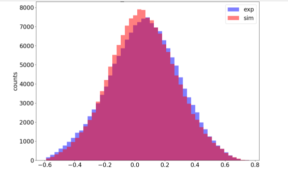
Δp_t



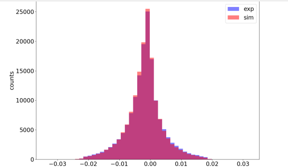
Smearing Factors makes Simulation More Realistic

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

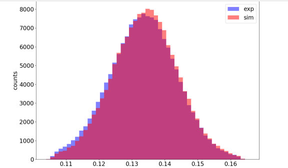
$ME_{ep\gamma\gamma}$



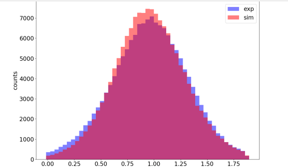
$MM^2_{ep\gamma\gamma}$



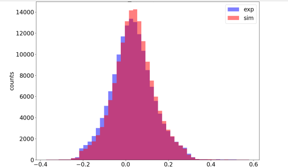
$M_{\gamma\gamma}$



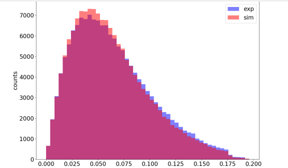
$MM^2_{e\gamma\gamma}$



MM^2_{ep}



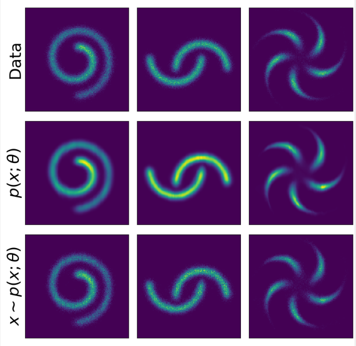
Δp_t



Decrease Computational Needs with Normalizing Flows

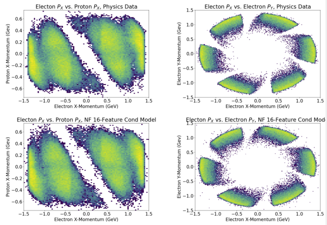
- **Normalizing Flows**: generative model, uses series of invertible transforms to map simple prior distributions into (very complex) target distributions

- **Idea**: Pass only a small percent of generated events through GEANT4 micro physics and reconstruction algorithms (~90% of comp. load), use to train a NF model to quickly generate the rest



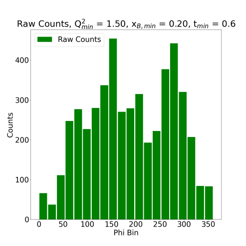
[arxiv:1908.05164]

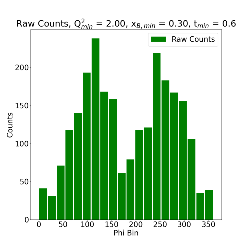
- **Result**: Worked well, but needs additional mechanism for lost particles; unused



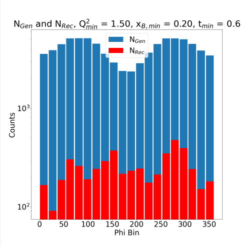
Acceptance Correction - Bin by Bin Calculation

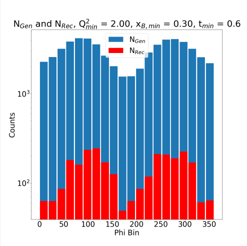
Raw Counts



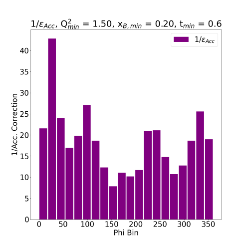


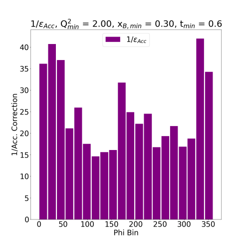
Simulated N_{Gen}, N_{Rec}



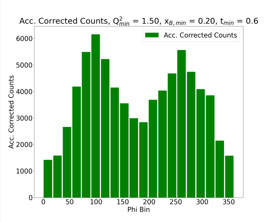


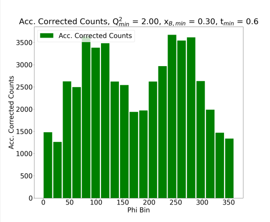
Acc. Correction





Acc. Corr. Counts

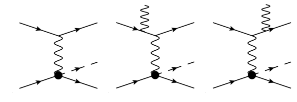




The acceptance dominates the correction factors, but others must be included for a finalized cross section.

Radiative Corrections

- Finalizing results with radiative generator, ~5% correction



Binning Corrections

- Finite bin size: average, not differential cross sections
- Bin volume effects
- Bin migration effects
- Preliminary work indicates ~ 10% correction in most bins

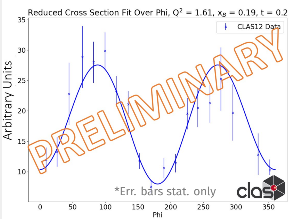
Overall Normalization

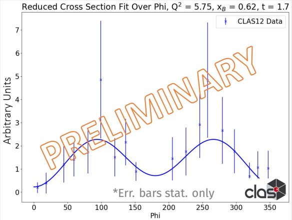
- Simulation detector efficiencies need to be corrected to true efficiencies
- Comparing with well known processes
- Similar processes report ~ 10 % effect

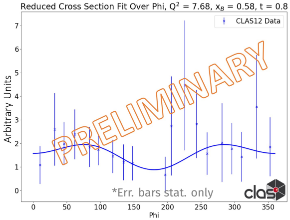
Bin-by-Bin Cross Sections

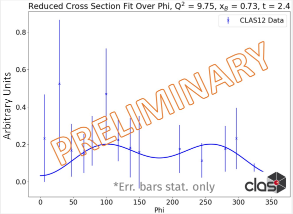
- Acceptance corrected data follows functional form expected from structure function decomposition

- Binning is currently being improved, along with larger simulation runs to decrease statistical uncertainties



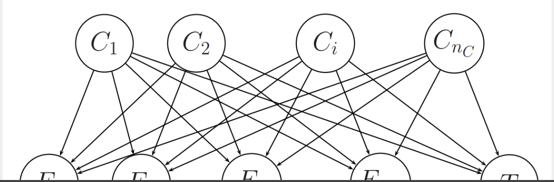






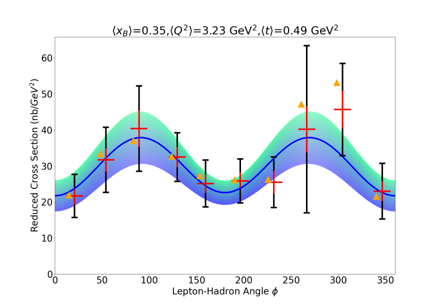
Not true

- **Goal:** Correct distortions in measured data distributions.
- Iteratively applies a Bayesian approach to adjust the measured distribution.
- Starts with an initial guess for the true distribution.
- Uses a response matrix that relates the true and measured quantities.
- **Procedure:**
  1. Use the current guess to predict the measurement.
  2. Compare the predicted measurement to the actual measurement.
  3. Adjust the guess based on Bayesian probability.
  4. Repeat until convergence.
- Often used in high-energy physics to correct for detector effects and other distortions.



Iterative Bayseian Unfolding: Method

Iterative Bayseian Unfolding: Result



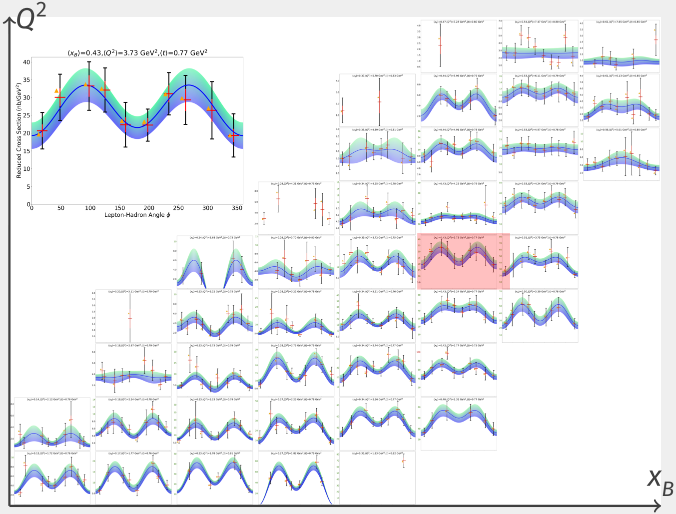
Summary of Systematic Uncertainties

Systematic Uncertainty	Median Percent Value	Bin or Overall
Fiducial Cuts / PID	12.3 %	Bin-by-bin
Reconstruction Efficiency	8.0 %	Bin-by-bin
Simulation Resolution Matching	8.6 %	Bin-by-bin
Exclusivity Cuts	12.4 %	Bin-by-bin
Acceptance Correction	9.8 %	Bin-by-bin
Radiative Correction	5.1 %	Bin-by-bin
Finite Bin Width	3.2 %	Bin-by-bin
Unfolding Methods	13.4 %	Bin-by-bin
Accumulated Beam Charge	<1 %	Overall
Physical Target Properties	<1%	Overall
Absolute Normalization	13%	Overall
Total (quadrature)	30%	Bin-by-bin

Table: Systematic uncertainties, their median percent values, and their calculation type.

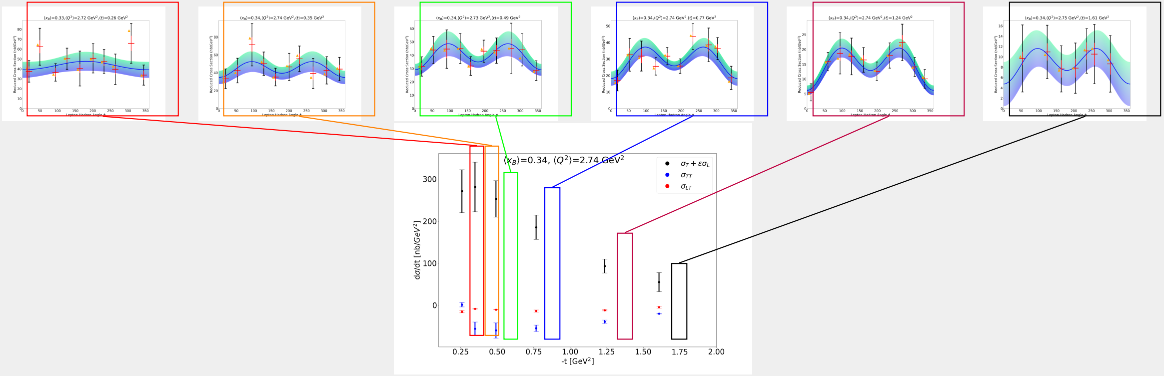
Preliminary Cross Section Results

words about it



Structure Function Extraction

Fit A+Bcos(2ph)+Ccos(phi) for each distribution



- 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)]

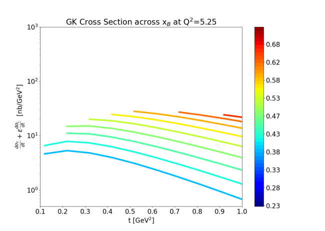
- Software implementation from K. Tezgin / PARTONS Framework
  [B. Berthou et al., EPJC, 78, 478 (2018)]

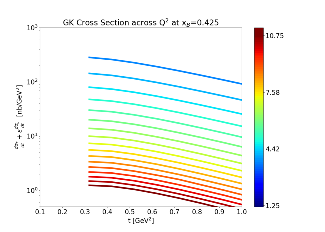
Note:

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

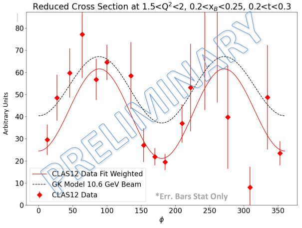
$m^2 x^2$

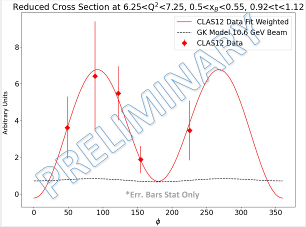
Model Predictions





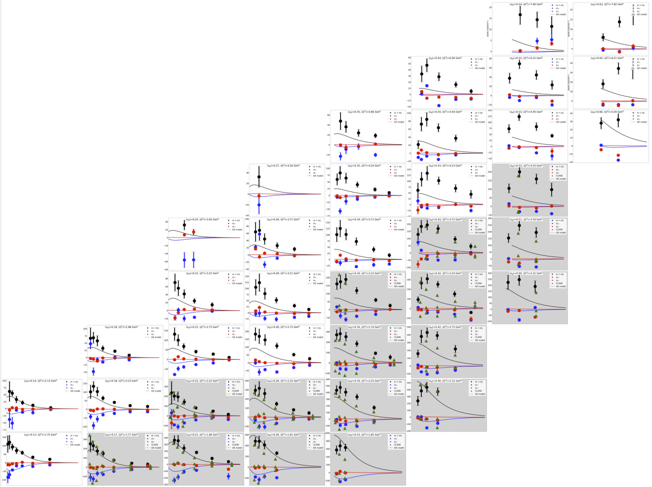
GK and CLAS12 Data





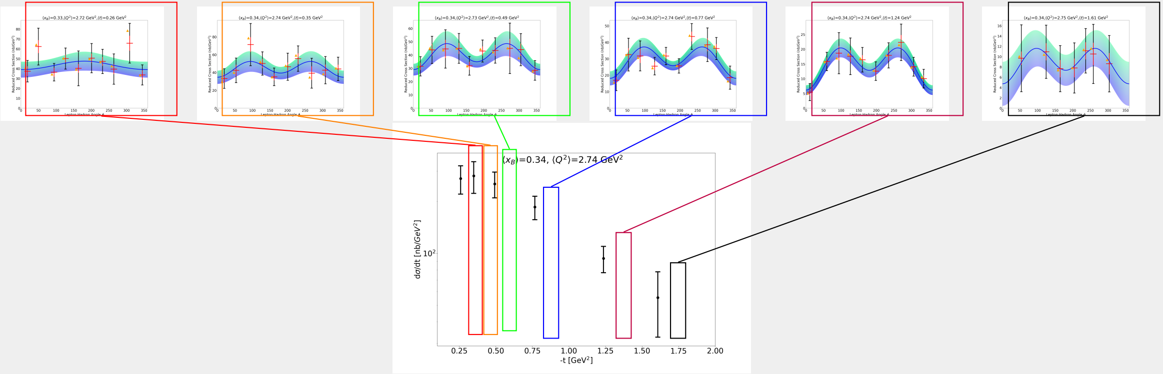
Structure Function Extraction

curves = gk model - more details -



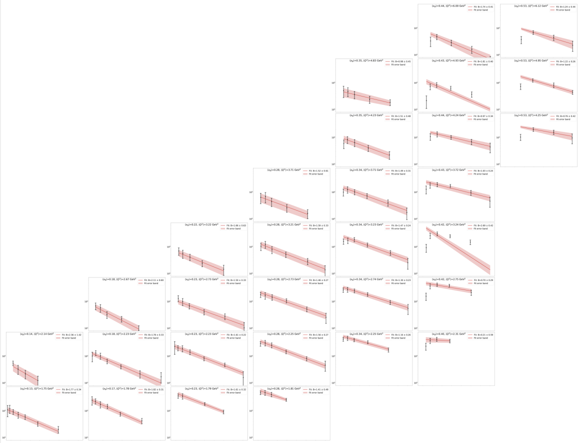
Cross Section t Dependence

Instead of fitting A+Bcos(2ph)+Ccos(phi), integrate over phi

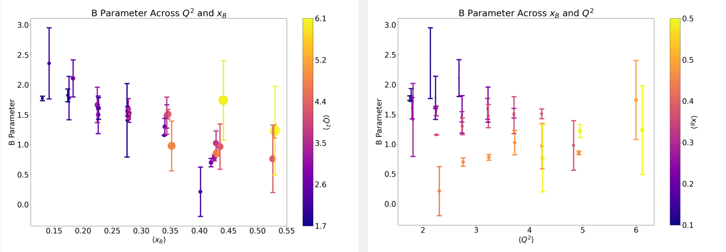


this will give straight lines over t with exponential fit it, now get b impact paramtetr

fit to exponential



Extracting Physics - B Parameter



- Cross section expected to decrease across increasing **t** as $e^{B\mathbf{t}}$
- The parameter B is related to the distance between the struck quark and the rest of

Conclusion and Path Forward

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

- Complete remaining correction factors - radiative, binning, and absolute normalization, and systematic uncertainties
- Quantitative comparisons between data and theory model will be meaningful when uncertainties and binning are more understood
- Pursue extraction of physics, and investigate Omnifold as an alternative analysis methodology
  This work will be continued while at

Caption

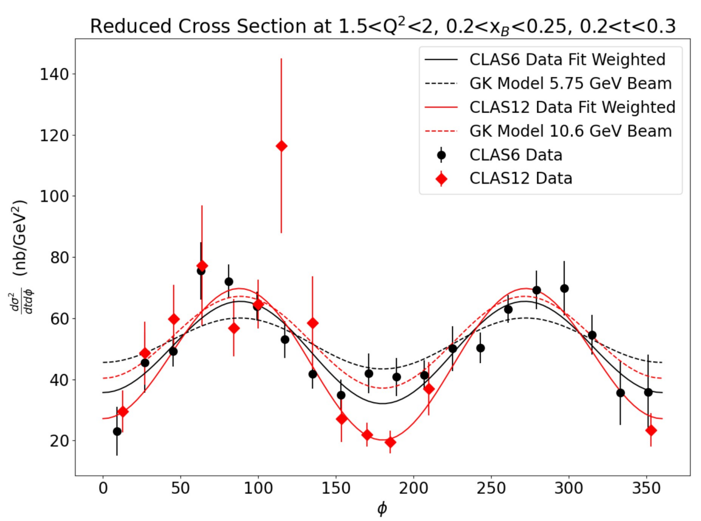
Backup slides

Backup Slides

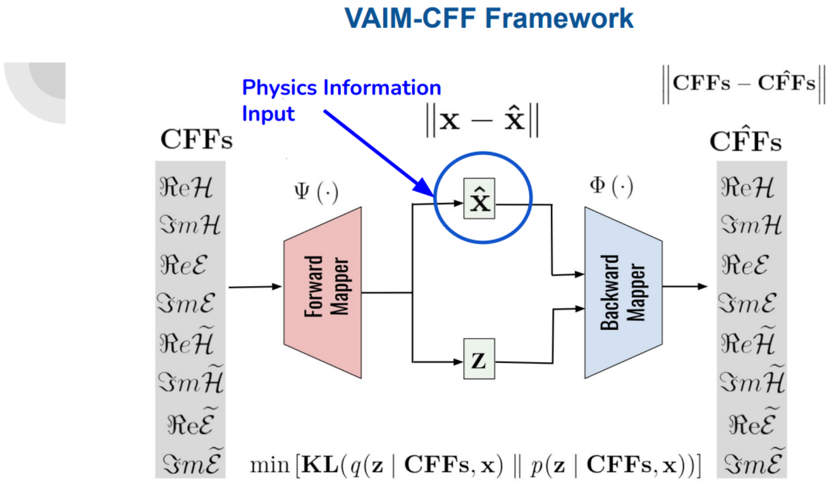
Acknowledgements

MIT Milner Hadronic Physics Research Group: Richard Milner, Doug Hasell, Sangbaek Lee, Igor Korover, Xiaqing Li, Patrick Moran
CLAS Collaboration, Bates Engineering, MIT Tier 2 Computing Group

Comparision with CLAS6



AUTOENCODER APPROACH TO GPDS



M. Almaeen, J. Hoskins, BK, Y. Li, H-W. Lin, S. Liuti (**in progress**)

Reframing the Extraction of Compton Form Factors

Standard

8 CFFs / 8 polarization configurations.

All observables have to match at the exact kinematics, with controllable uncertainties and systematics from each experiment.

Amazing statistics needed

Nobody has gotten all 8 CFFs before.

FemtoNet

Extraction of 8 CFFs from a single polarization observable treated as an "inverse problem" of extracting 8 unknowns from a single equation.

Quantification of **information that is possible to extract** from certain experiments.

Informed high impact measurements.

M. Almaeen, J. Hoskins, BK, Y. Li, H-W. Lin, S. Liuti (**in progress**)

Backup slides

All data bins
removed

Concrete Abstract

The structure of the proton has been studied extensively since its discovery a century ago. Electron scattering experiments have been utilized as a clean probe into the dynamics of the nucleon, and the past several decades of work investigating structure functions have yielded information on the proton Parton Distribution Functions, which describe the proton's physical inner workings along one dimension. Presently, in specific kinematic regimes nuclear reactions can be theoretically linked to the 3D substructure of the nucleon. This presentation will discuss work towards measuring the properties of one such reaction - Deeply Virtual Neutral Pion Production - from analyzing the data of a 10.6 GeV electron scattering experiment at the CLAS12 detector in Jefferson Lab Hall B.

Backup slides

Find this online at:
https://github.com/robertej19/Thesis-Offense/blob/main/presentation.pdf

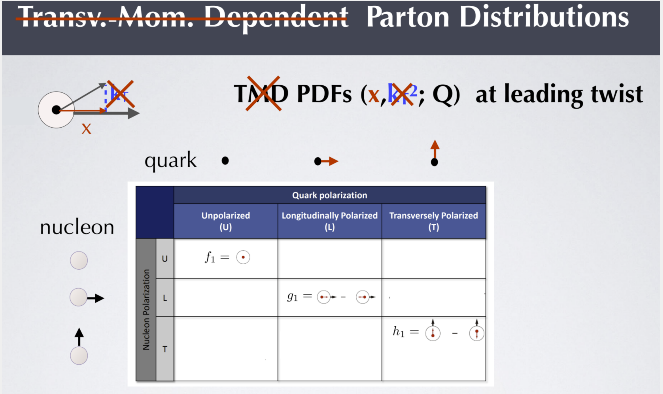
Backup slides

Include information at end of Thesis Defense of pictures from Personal Archieves including pics of me and Sangbaek and stuff at BAND

Mass of Photon

The photon is regarded in the standard model as being massless.
If, on the other hand, photons did have mass, it would mean they are catholic
- credit: possibly Axel Schmidt

BACKUP SLIDES



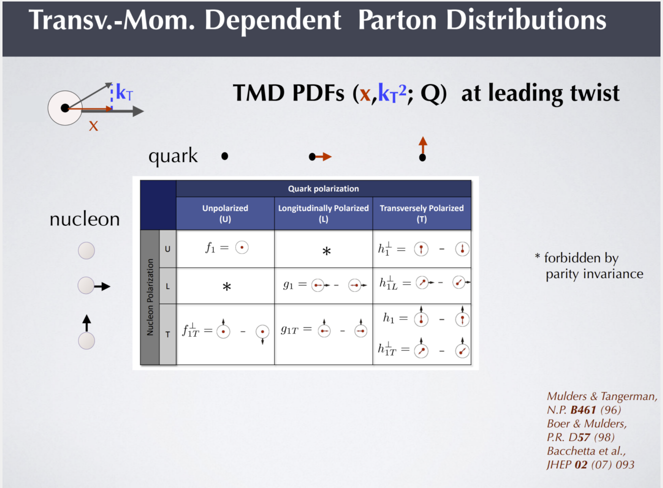
From Marco Radici

People

Slide about Lincoln Labs

Im going to Lincoln Labs but will continue this work

BACKUP SLIDES



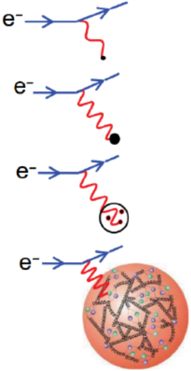
From Marco Radici

BACKUP SLIDES

Probing the structure of hadrons

Wave length $\lambda = hc/E$

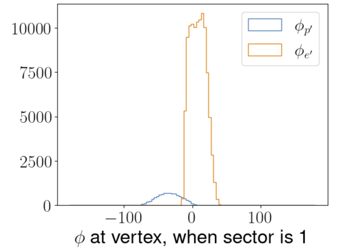
- At very Low electron beam ($\lambda >> r_p$): scattering from a **point-like spin-less** object
- Low electron beam energies ($\lambda \approx r_p$): scattering from an **extended charged** object
- High electron beam energies ($\lambda < r_p$): scattering from **constituent quarks**
- High electron beam energies ($\lambda << r_p$): proton appears as **sea of quarks and gluons**

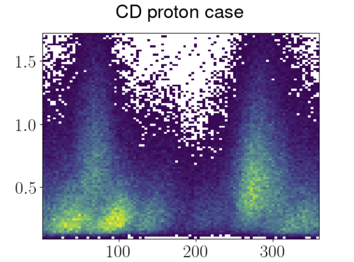


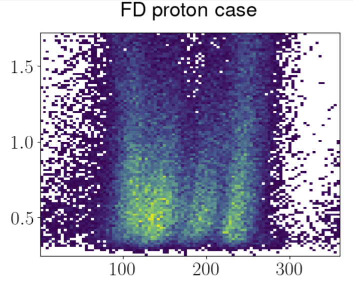
From Alaa Dbeyssi

Explaination of Phi Assymetry

So, the phi angle is roughly the azimuthal angle of proton w.r.t. electron. Let's forget about the reference plane defined by the incoming electron. I believe there's nothing wrong with this. We can reproduce this asymmetry in phi in GEMC that doesn't have no local efficiency input yet. My guess is as follows. Unlike the electron mainly moving straightforward, proton not only moves in/outward by torus, but only moves spiral by solenoid. You can draw the lab phi angle of electrons and protons, and label the each sector to see what happens. Now the protons are not symmetric w.r.t. electron because of this spiral motion, and due to the detector acceptance, we are seeing this weird shape. (edited) If you draw the t vs phi plot for each detector subsystem, the plot looks less angry. From S. Lee.







Explaination of Phi Assymetry

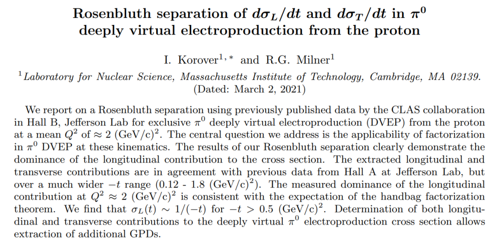
Motivation for xB relating to timing resolution in camera analogy

On xB being related to the timing resolution scale - essentially a post hoc interpretation: given you had an event at $x_B = 0.3$ you can hand-waivingly conceive of the interaction as happening over a large time scale, where only the valence quarks are relevant. If you observed an event at low x_B, you (very probably) saw a transient sea quark or gluon, which since they only ”exist” for brief moments, you can consider your time resolution aka shutter speed to be very small.

Extracting Physics - Rosenbluth Separation

- Cross section measurement does not give a separation on σ_T and σ_L terms:

$$\frac{d^4\sigma_{\gamma^* p \to p' \pi^0}}{dQ^2 dx_B dt d\phi_\pi} = \Gamma(Q^2, x_B, E)\frac{1}{2\pi}\left\{\left(\frac{d\sigma_T}{dt} + \epsilon\frac{d\sigma_L}{dt}\right) + \ldots\right\}$$



Rosenbluth separation of $d\sigma_L/dt$ and $d\sigma_T/dt$ in π^0 deeply virtual electroproduction from the proton

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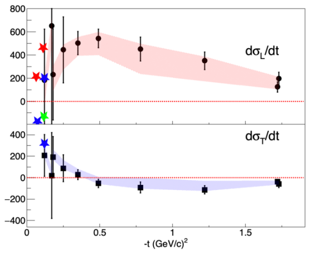
(Dated: March 2, 2021)

We report on a Rosenbluth separation using previously published data by the CLAS collaboration in Hall B, Jefferson Lab for exclusive π^0 deeply virtual electroproduction (DVEP) from the proton at a mean Q^2 of ≈ 2 (GeV/c)^2. The central question we address is the applicability of factorization in π^0 DVEP at these kinematics. The results of our Rosenbluth separation clearly demonstrate the dominance of the longitudinal contribution to the cross section. The extracted longitudinal and transverse contributions are in agreement with previous data from Hall A at Jefferson Lab, but over a much wider $-t$ range (0.12 - 1.8 (GeV/c)^2). The measured dominance of the longitudinal contribution at $Q^2 \approx 2$ (GeV/c)^2 is consistent with the expectation of the handbag factorization theorem. We find that $\sigma_L(t) \sim 1/(-t)$ for $-t > 0.5$ (GeV/c)^2. Determination of both longitudinal and transverse contributions to the deeply virtual π^0 electroproduction cross section allows extraction of additional GPDs.

- However, can leverage different beam energies between CLAS12 and CLAS6 data to perform Rosenbluth separation
- Will extend prior results and further constrain GPDs



Extracting Physics Directly with OMNIFOLD

OmniFold: A Method to Simultaneously Unfold All Observables

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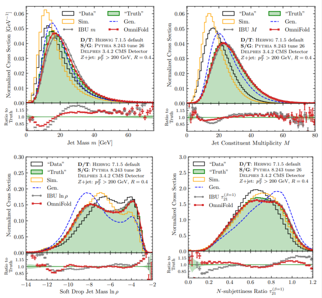
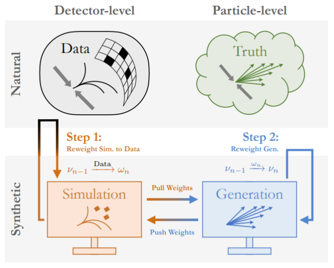
Collider data must be corrected for detector effects ("unfolded") to be compared with many theoretical calculations and measurements from other experiments. Unfolding is traditionally done for individual, binned observables without including all information relevant for characterizing the detector response. We introduce OMNIFOLD, an unfolding method that iteratively reweights a simulated dataset, using machine learning to capitalize on all available information. Our approach is unbinned, works for arbitrarily high-dimensional data, and naturally incorporates information from the full phase space. We illustrate this technique on a realistic jet substructure example from the Large Hadron Collider and compare it to standard binned unfolding methods. This new paradigm enables the simultaneous measurement of all observables, including those not yet invented at the time of the analysis.





[arxiv:1911.09107]

Presenting Unbinned Differential Cross Section Results

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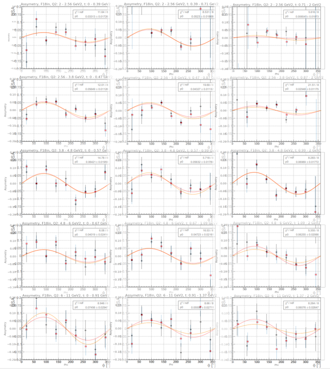
BSA



Caption

Calculated Integrated Luminosity from Fall 2018 dataset: 5.512 e+40 cm^{-2} inbending, 4.652 e+40 cm^{-2} outbending