

# MEASUREMENT OF THE DV $\pi^0$ P CROSS SECTION

## AT THE THOMAS JEFFERSON NATIONAL ACCELERATOR FACILITY AT 10.6 GeV/c

R. JOHNSTON

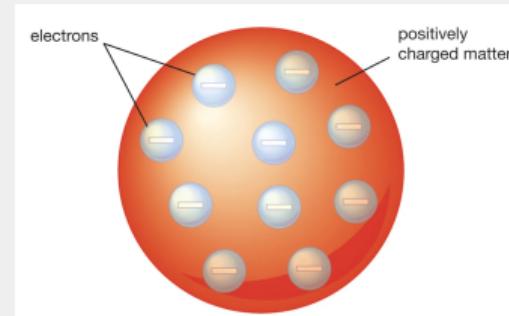
MASSACHUSETTS INSTITUTE OF TECHNOLOGY  
PH.D. ORAL DEFENSE

MONDAY, AUGUST 14, 2023



# 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 subatomic particles (originally called corpuscles, renamed to electrons) [Wikipedia:Plum Pudding Model]

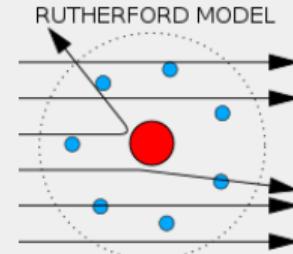


Thomson model of atom, with negatively charged electrons embedded in positively charged ball

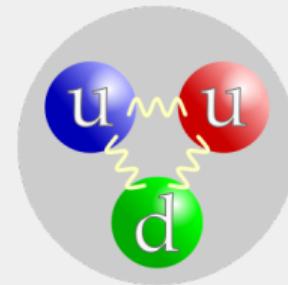
[Britannica:Thomson Atomic Model]

# BRIEF HISTORY OF THE PROTON

- ~ 1911: **Discovery of the Nucleus** - Scattering  $\alpha$  particles off gold foil yielded significant backscatter, indicating small, dense nucleus [Wikipedia:Geiger-Marsden]
- ~ 1919: **Discovery of the Proton** - Proposed by Rutherford after  $\alpha$  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]

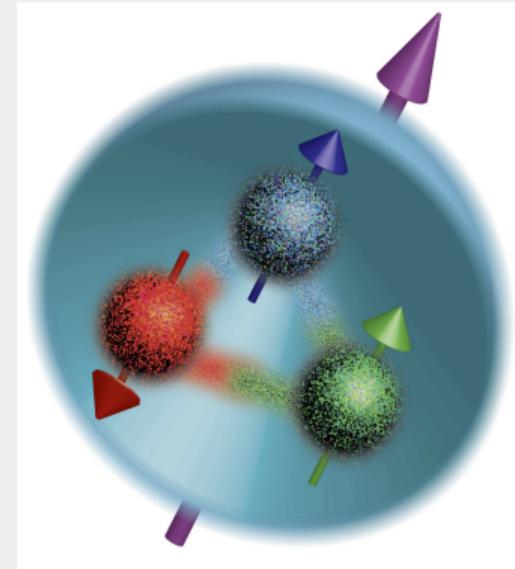
# THE PROTON IS Now WELL-UNDERSTOOD

Protons are:

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

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

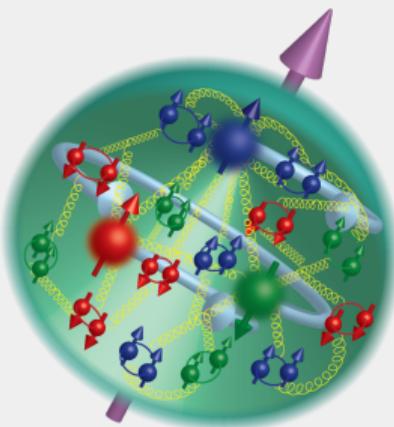
- **Small:** radius ~ 0.85 fm
  - If protons were scaled to the size of pingpong balls, atoms would be ~ 4 football fields across, humans would be ~ diameter of the inner solar system



[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  $hc = 1200 \text{ eV nm}$

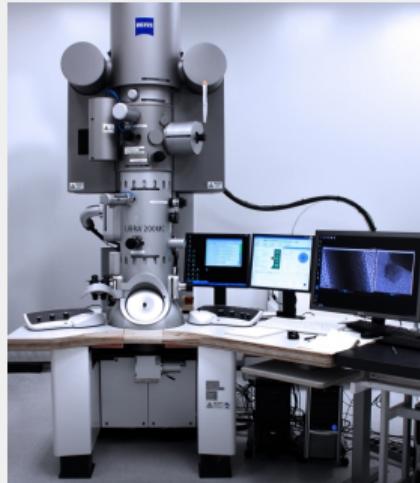
**Optical Microscope**



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

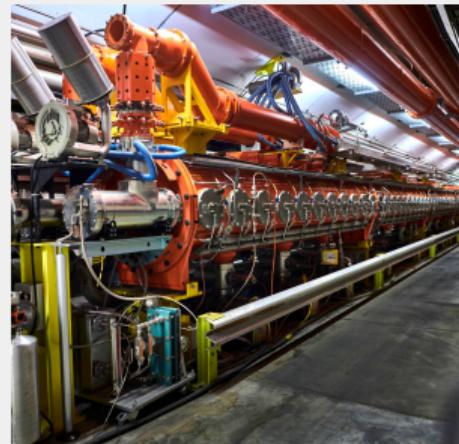
[n.b. ex. mic for bio]

**Electron Microscope**



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

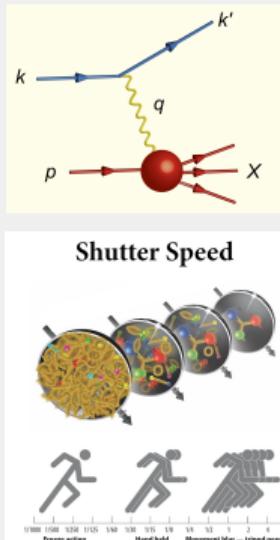
**Electron Accelerator**



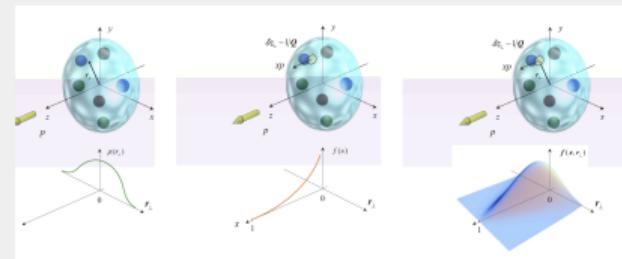
$10 \text{ GeV} \rightarrow \lambda \sim 0.1 \text{ fm}$

# 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



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



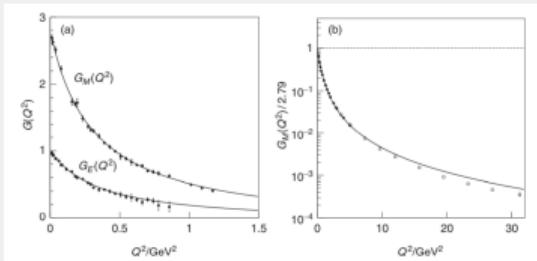
[R.G. Milner and R. Ent,

Visualizing the Proton (2022)]

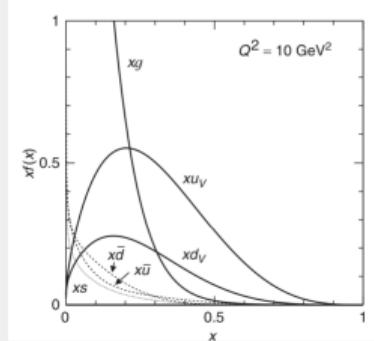
[A.V. Belitsky A.V. Radyushkin 2005]

# GPDs ENCODE PROTON 3D STRUCTURAL INFORMATION

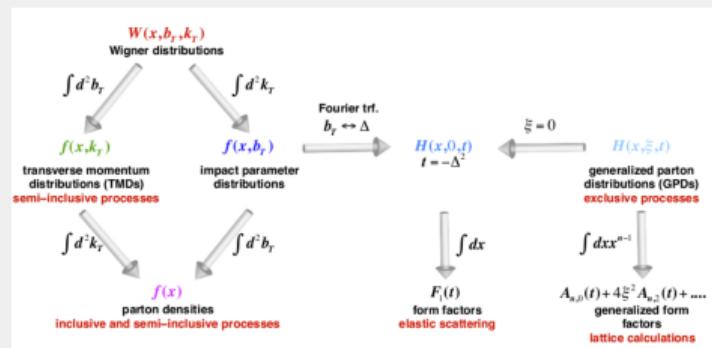
## Proton Form Factors



## 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

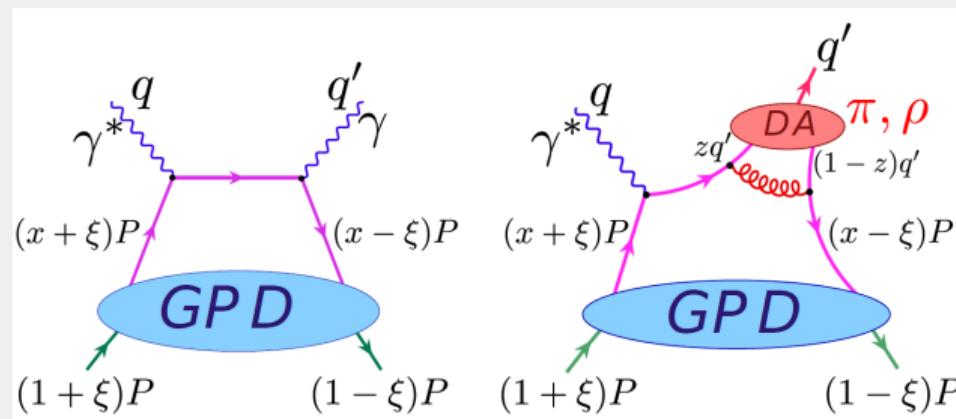


Relationships between different distribution functions

[EIC Whitepaper]

# GPDs ACCESSIBLE THROUGH DEEPLY VIRTUAL PROCESSES

- Deeply Virtual Processes (DVCS, DVMP): 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)

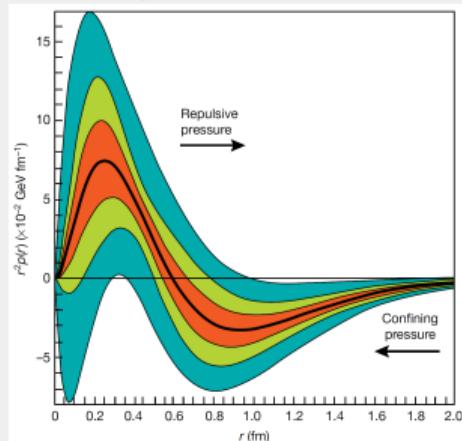


DVCS (left) and DVMP Feynman Handbag diagrams

[V. Kubarovsky Nuc Phys B 2011]

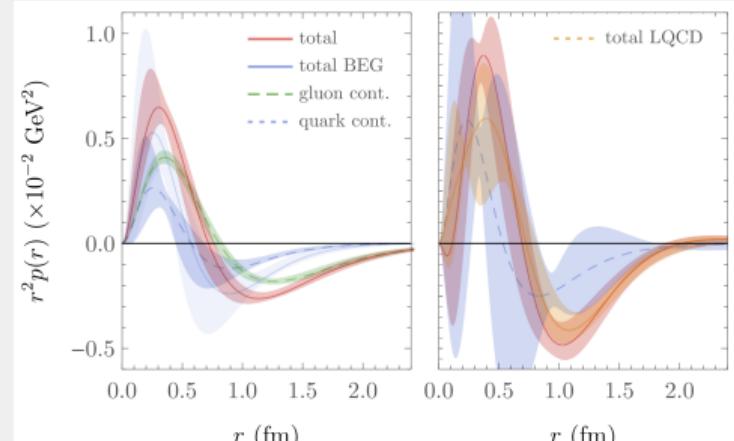
# EARLY INSIGHTS FROM DEEPLY VIRTUAL PROCESSES

- DVCS measurements enabled mapping pressure distribution inside protons
- Indicated pressures exceeding those inside of neutron stars ( $10^{30}$  atm!)



Proton pressure distribution from DVCS data

[V.D. Burkert, L. Elouadrhiri, F.X. Girod, Nature 2018]



Proton pressure distribution from LQCD

[P.E. Shanahan and W. Detmold, Phys. Rev. Lett. 2019]

# GPD ENCODING IN DV $\pi^0 P$ CROSS SECTION IS NONTRIVIAL

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

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

## GPD Classification:

The structure functions can be expressed in terms of GPDs:

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

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

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

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

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

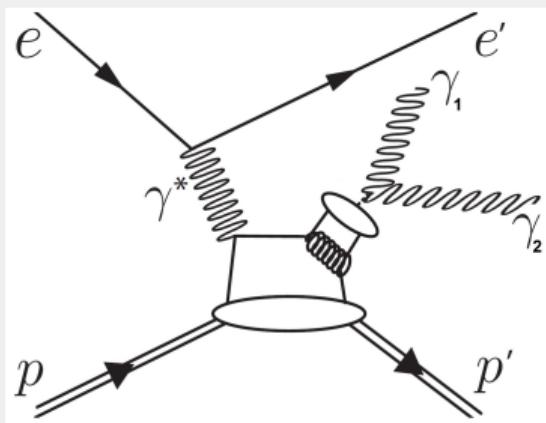
$\bar{E}_T = 2 \times \tilde{H}_T + E_T$

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

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

## Deeply Virtual $\pi^0$ Production (DV $\pi^0$ P)

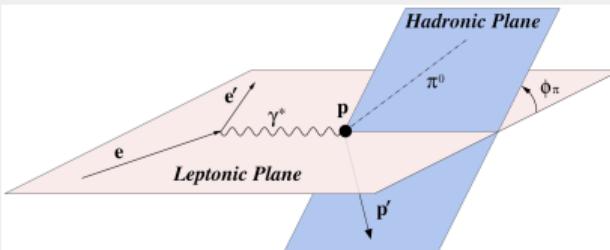
$$\begin{aligned} e + p &\rightarrow \\ e' + p' + \pi^0 &\rightarrow \\ e' + p' + \gamma_1 + \gamma_2 \end{aligned}$$



■ 4-fold differential cross section  $\frac{d\sigma}{dQ^2 dx_B dt d\phi}$

expressed in terms of:

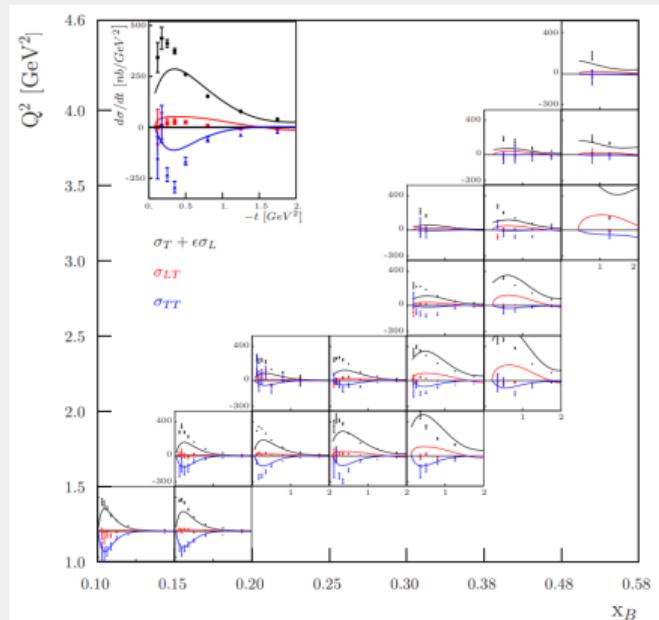
- ▶ Virtual photon 4-momentum:  $Q^2 \equiv -(p_e - p_{e'})^2$
- ▶ Bjorken x:  $x_B \equiv \frac{Q^2}{2p_p \cdot (p_e - p_{e'})}$
- ▶ Momentum transfer:  $-t \equiv -(p_{p'} - p_p)^2$
- ▶ Angle between lepton & hadron planes:  $\phi = \cos^{-1} \left( \frac{(p_e \times p_{e'}) \cdot (p_{p'} \times p_{\gamma^*})}{\|p_e \times p_{e'}\| \|p_{p'} \times p_{\gamma^*}\|} \right)$



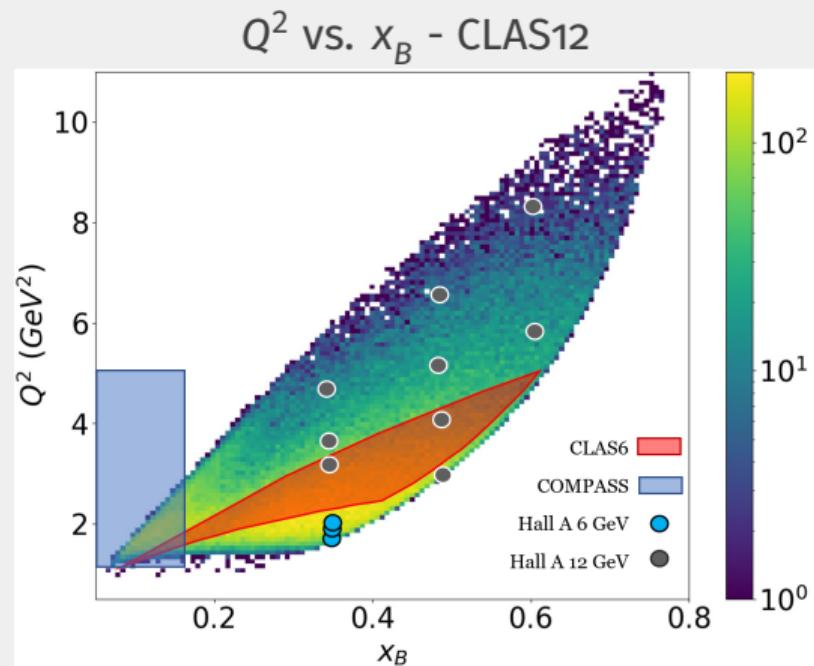
Images from S. Lee, A. Kim

# ANALYSIS GOAL: EXTRACT DV $\pi^0$ P 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)]



# 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

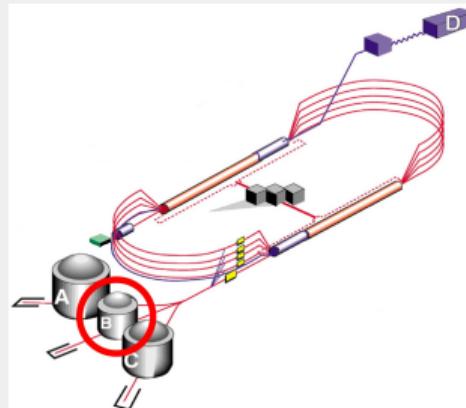
[V. Burkert et al., NIMA, 959, 163419 (2020)]

# JEFFERSON LAB 10.6 GEV CEBAF ACCELERATOR

Thomas Jefferson National Accelerator Facility - Newport News, VA

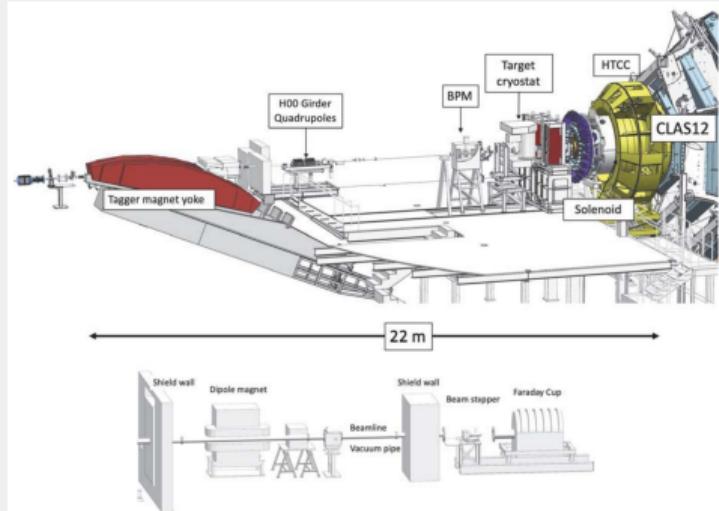


■ Jefferson Lab aerial view [\[jlab.org\]](http://jlab.org)

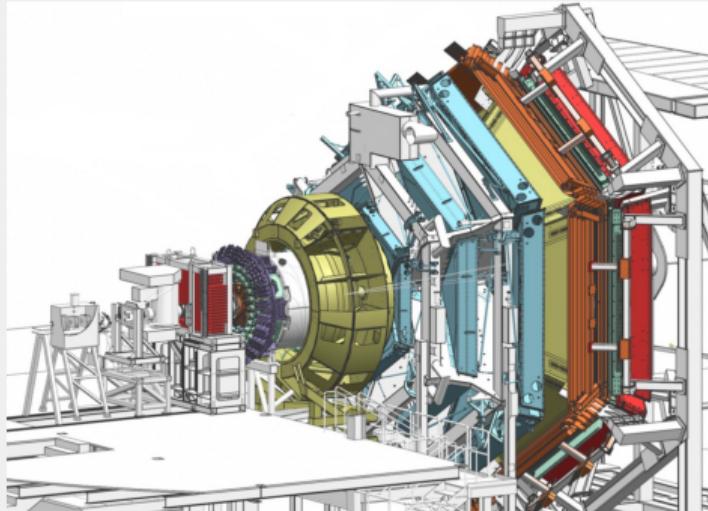


- CEBAF 1,400 m racetrack, 50 RF cryomodules
- 10.6 GeV, ~ 50 nA electron beam

# CLAS12 DETECTOR AT JEFFERSON LAB HALL B



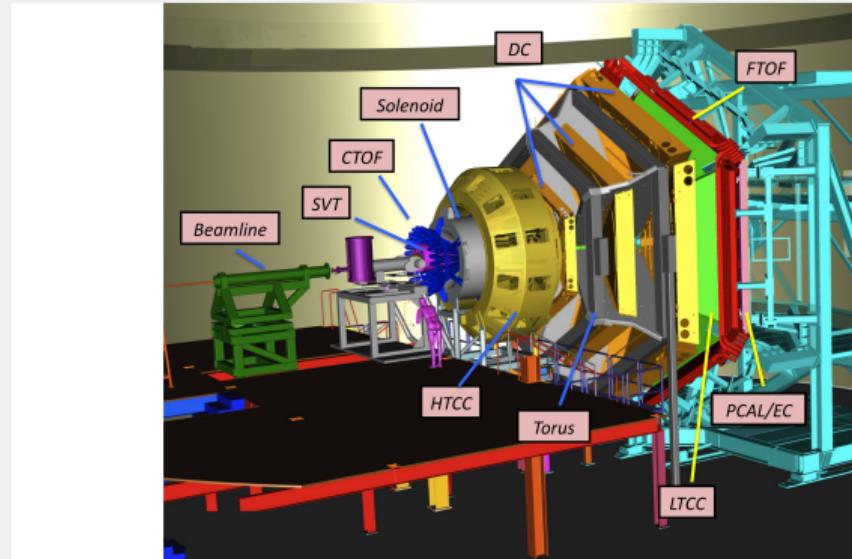
- Top: Beamlne into unpolarized LH<sub>2</sub> target (cryostat)
- Bottom: Downstream beamline to Faraday Cup (current monitor)



- CEBAF Large Acceptance Spectrometer:
  - ▶ ~  $2\pi$  coverage in  $\phi$
  - ▶ 5° - 125° coverage in  $\theta$
  - ▶ Full 4 particle final state reconstruction for this process

# EXPERIMENT LAYOUT AND PARTICLE DETECTION

- 6-fold symmetric Forward Detector ( $\theta < \sim 40^\circ$ ) with toroidal field
  - ▶ Cherenkov Counters
  - ▶ Drift Chambers
  - ▶ Time-of-Flight Detectors
  - ▶ EM Calorimeters
- Central Detector ( $\sim 40^\circ < \theta < \sim 125^\circ$ ) inside 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

# COMPONENTS OF CROSS SECTION

## Number of DV $\pi^0$ 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)

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

## Integrated Luminosity:

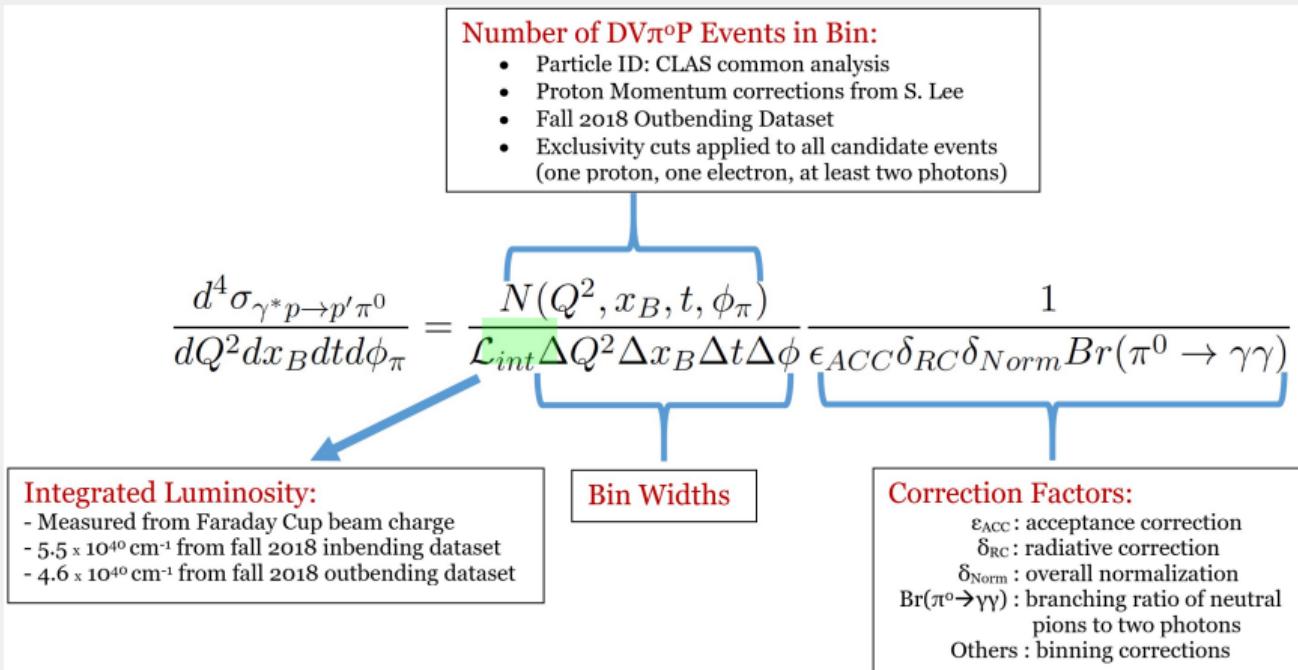
- Measured from Faraday Cup beam charge
- $5.5 \times 10^{40} \text{ cm}^{-1}$  from fall 2018 inbending dataset
- $4.6 \times 10^{40} \text{ cm}^{-1}$  from fall 2018 outbending dataset

## Bin Widths

## Correction Factors:

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

# COMPONENTS OF CROSS SECTION: LUMINOSITY



# LUMINOSITY DETERMINATION FROM FARADAY CUP

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



Hall B Faraday Cup

[P. Achenbach 2022]

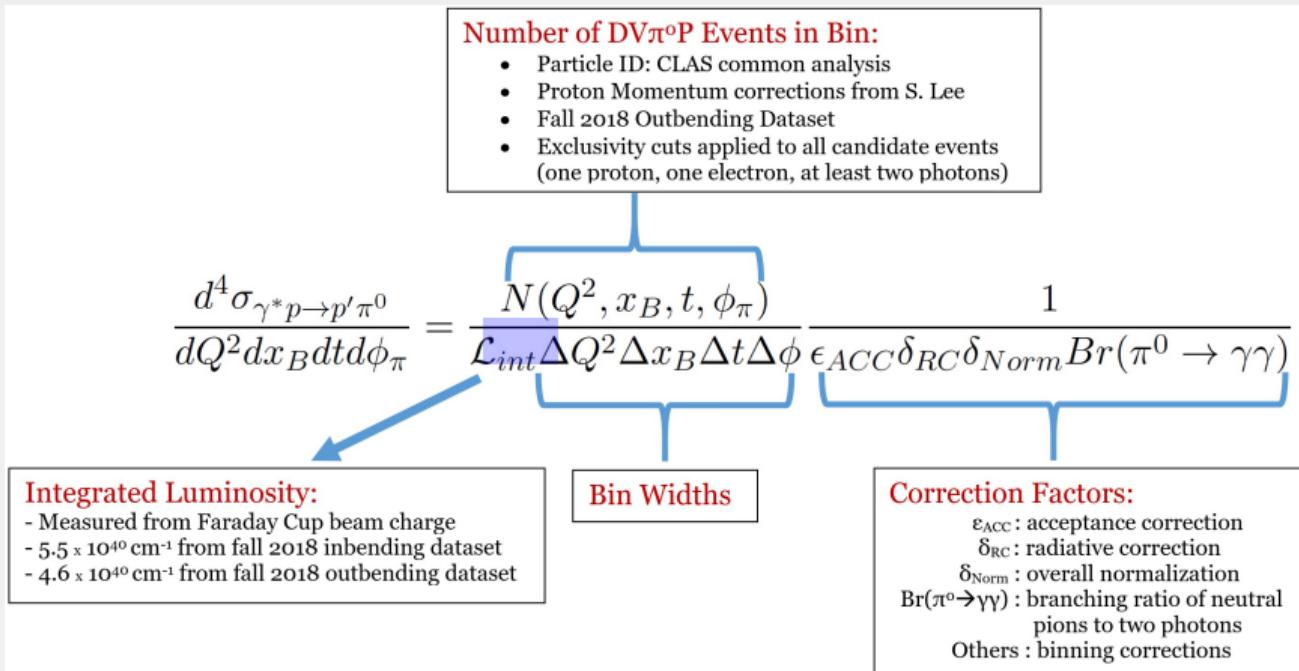
Quantity	CLAS12 Value
Avogadro's Number	$N_A$
Electron Charge	$e$
Target Length	$l$
Target Density	$\rho$
Charge on Faraday Cup	$Q_{FCUP}$

Fall 2018 Integrated Luminosity:

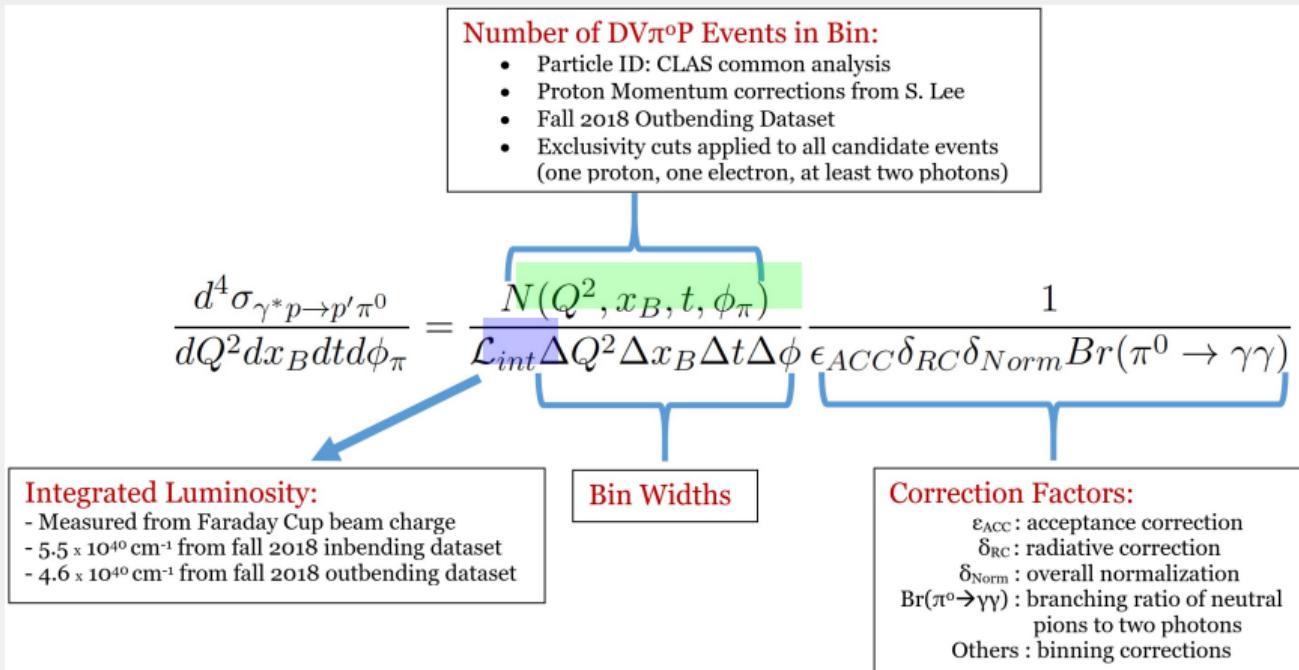
$5.512 \times 10^{40} \text{ cm}^{-2}$  inbending

$4.652 \times 10^{40} \text{ cm}^{-2}$  outbending

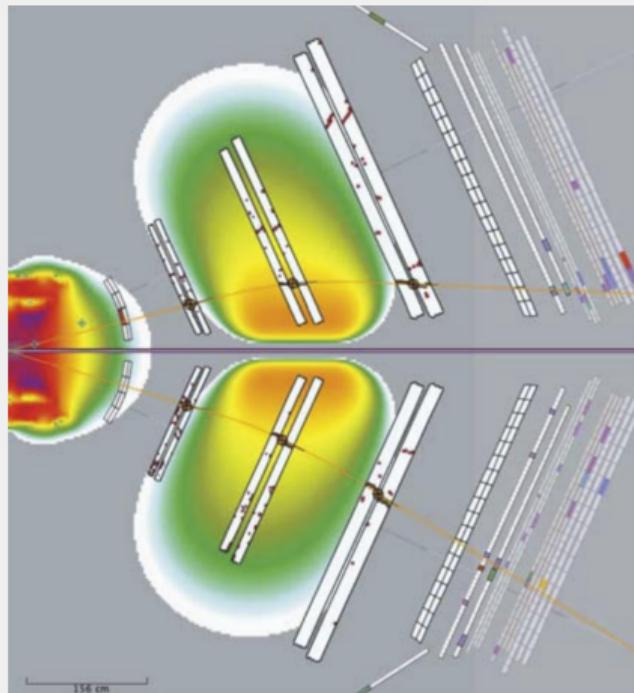
# COMPONENTS OF CROSS SECTION



# COMPONENTS OF CROSS SECTION: EVENT COUNTS

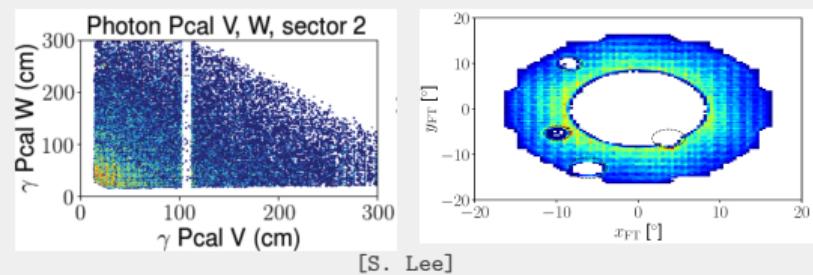


# EVENTS AND PRELIMINARY PARTICLE IDENTIFICATION



Sample Recon. Event with Detector Hits

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



# 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 ( $\gamma_1, \gamma_2$ )
- ▶  $|M_{\pi^0} - M_{\gamma\gamma}| < 40 \text{ MeV}$

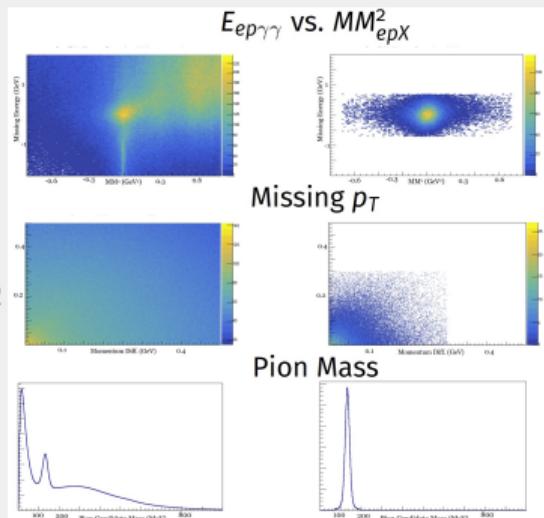
## Event Cuts

### ■ DIS Cuts

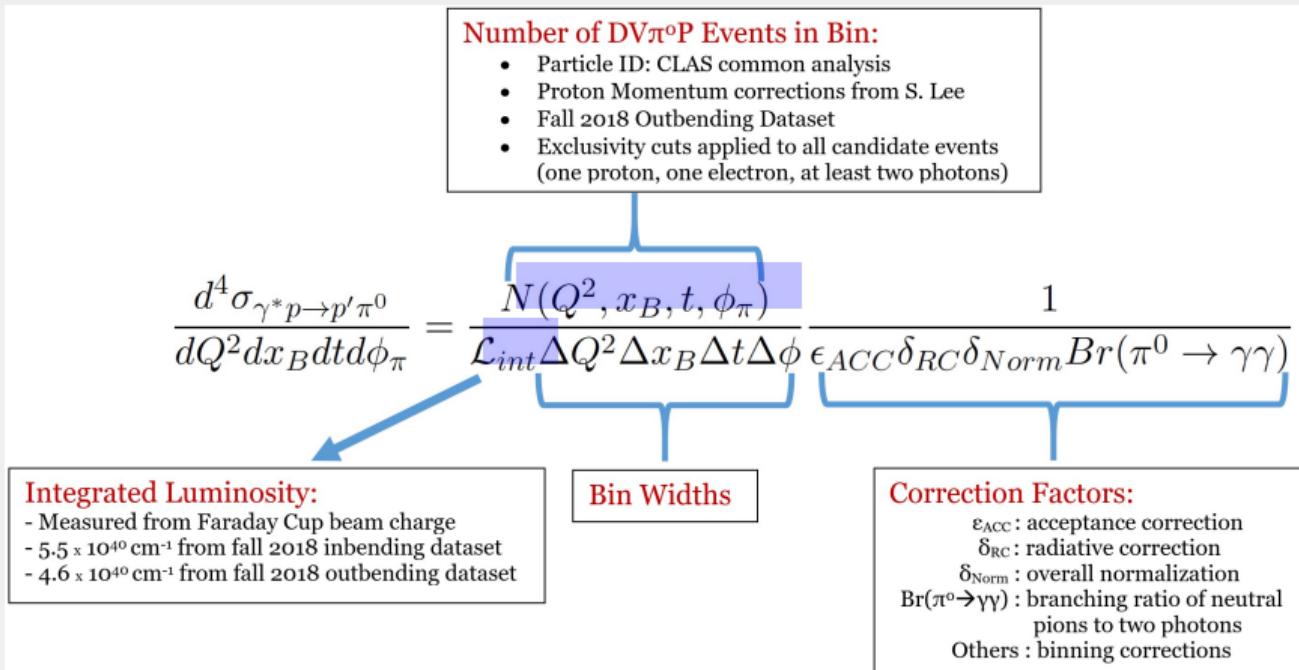
- ▶  $Q^2 > 1 \text{ GeV}^2$
- ▶  $W^2 > 4 \text{ GeV}^2$

### ■ Exclusivity Cuts

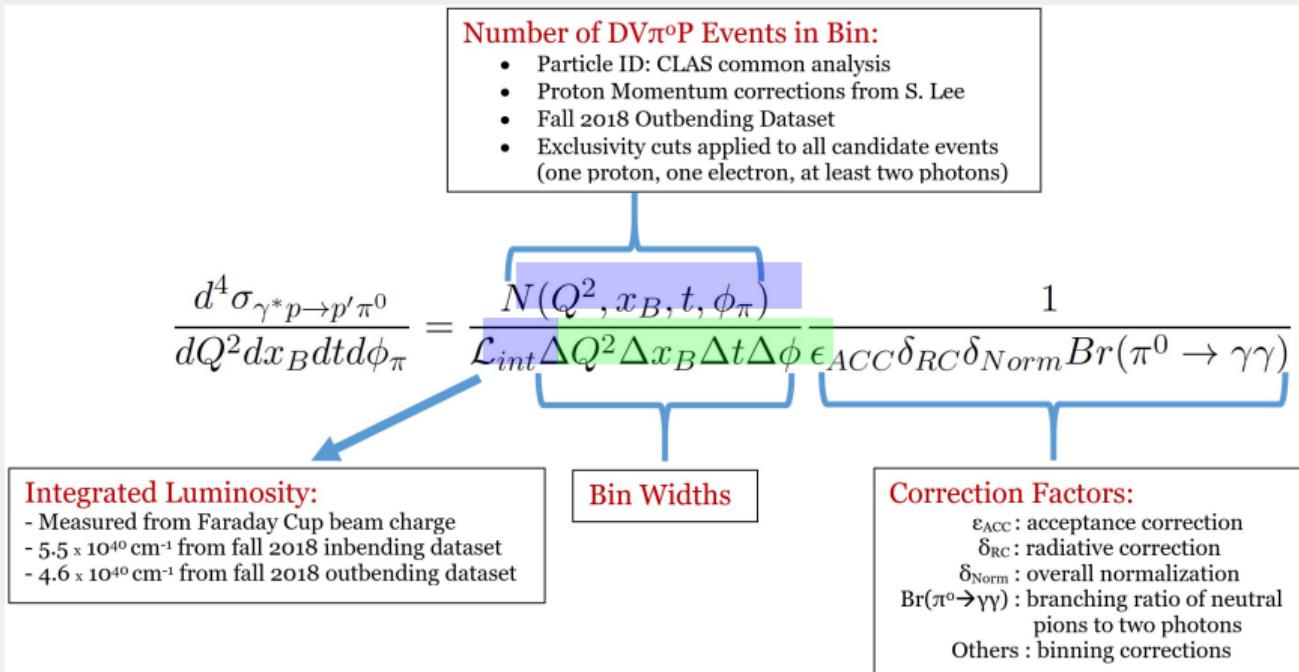
- ▶  $MM_{epX}^2 < 0.7 \text{ GeV}^2$
- ▶  $ME_{ep\gamma\gamma} < 0.7 \text{ GeV}$
- ▶  $\theta_{X\pi} < 2^\circ$
- ▶  $\Delta p_{x,y} < 0.3 \text{ GeV}$



# COMPONENTS OF CROSS SECTION

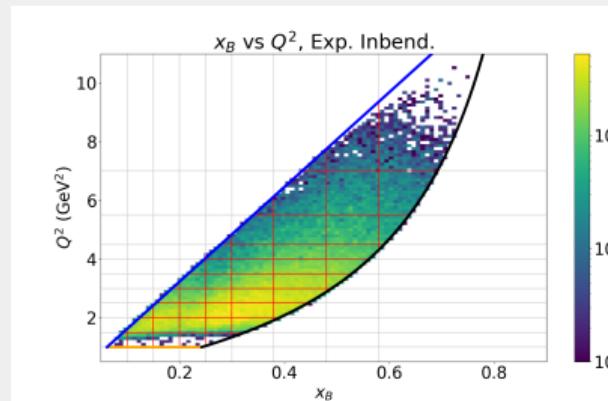


# COMPONENTS OF (BINNED) CROSS SECTION: BIN WIDTH

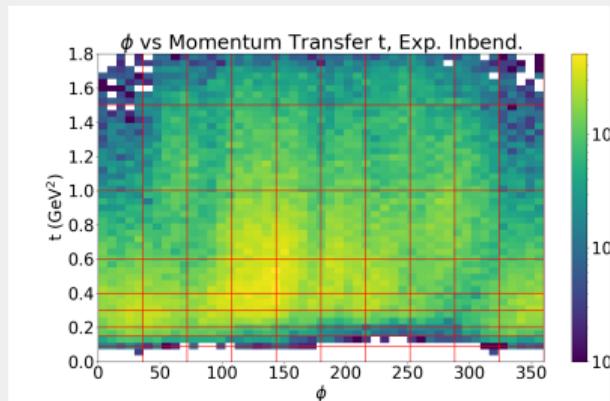


# EVENT BINNING IS HEURISTICALLY DRIVEN

- Straight bins for comparing across  $x_B, Q^2, t$
- Bounding lines:
  - ▶  $Q^2 > 1 \text{ GeV}^2$
  - ▶  $p_{e'} > 2 \text{ GeV}/c$
  - ▶  $W^2 > 4 \text{ GeV}^2$
- Edge bin volumes calculated by MC integration

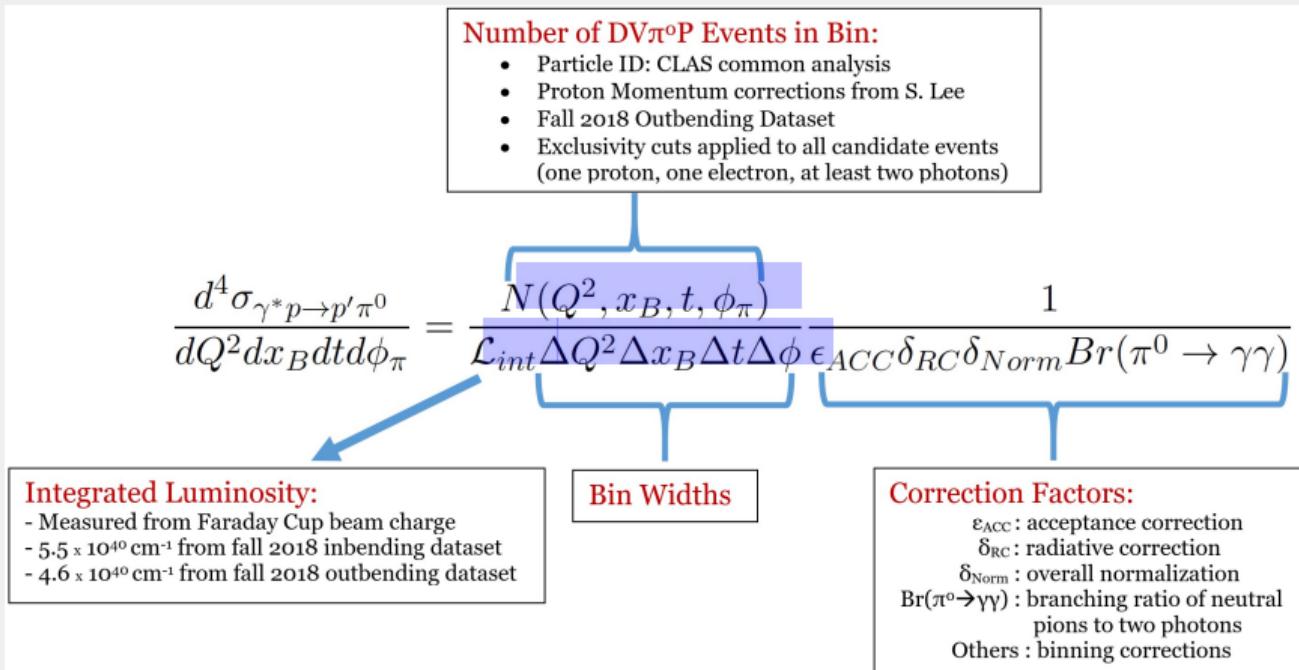


Bins across  $x_B$  and  $Q^2$



Bins across  $\phi$  and  $t$

# COMPONENTS OF CROSS SECTION



# COMPONENTS OF CROSS SECTION: CORRECTION FACTORS

## Number of DV $\pi^0$ 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)

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

## Integrated Luminosity:

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

## Bin Widths

## Correction Factors:

- $\epsilon_{ACC}$ : acceptance correction
- $\delta_{RC}$ : radiative correction
- $\delta_{Norm}$ : 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



A screenshot of the CLAS12 Monte-Carlo Job Submission Portal. At the top, there are navigation links: Home, About, OSG Stats, and Monitors. Below that is the title "CLAS12 Monte-Carlo Job Submission Portal". In the center, there is a "Summary of current jobs" table:

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

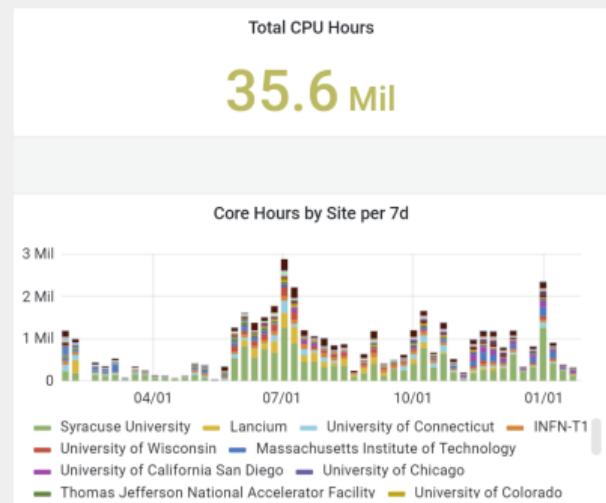
Below the table is a button "Click to submit to OSG". At the bottom, there are two sections: "Generator" and "LUND Files".

**Generator**

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

**LUND Files**

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

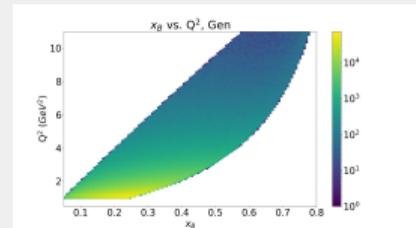
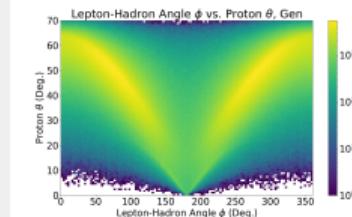


Usage facilitated in 2022

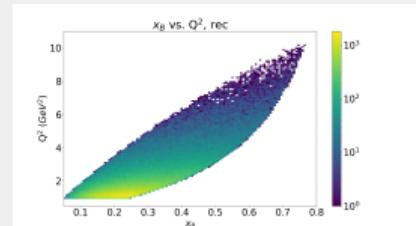
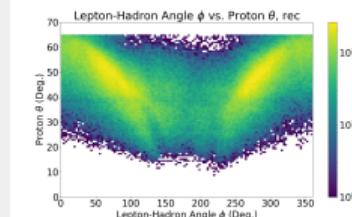
# EVENT GENERATOR AND SIMULATION DETAILS

- 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

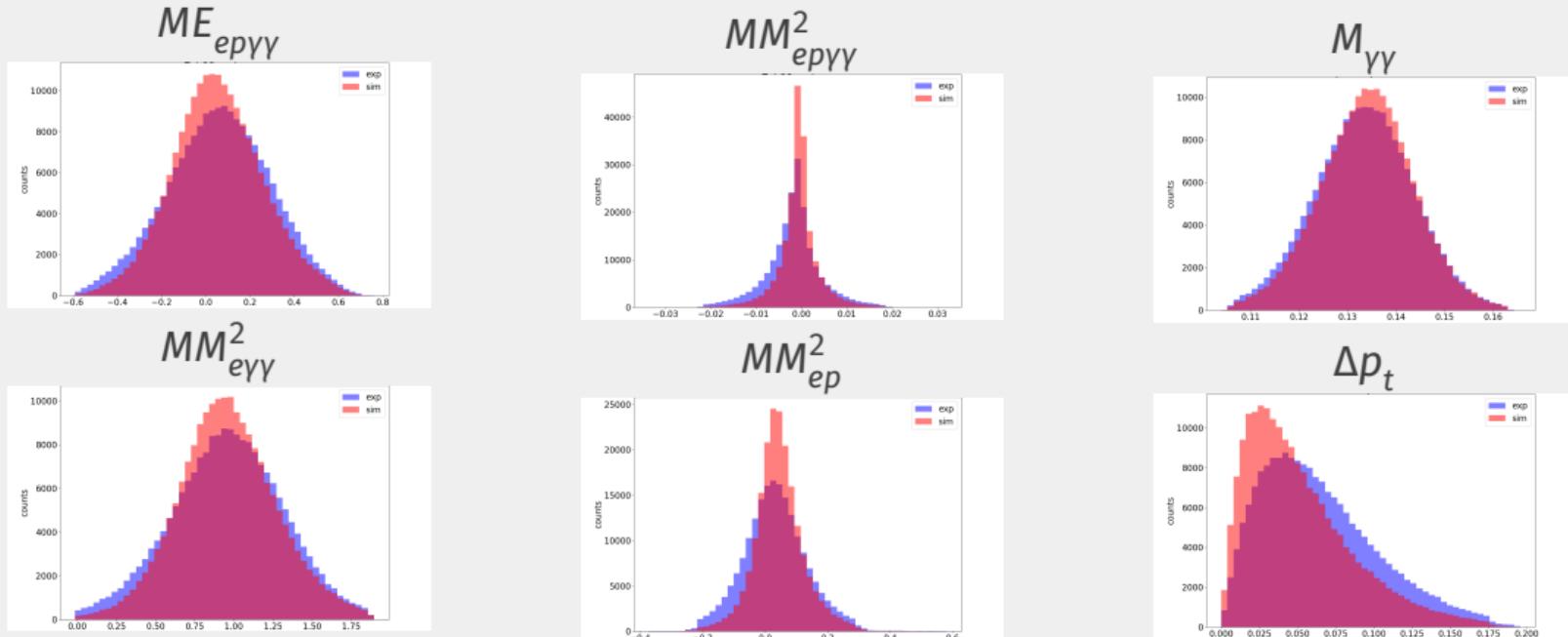


Reconstructed



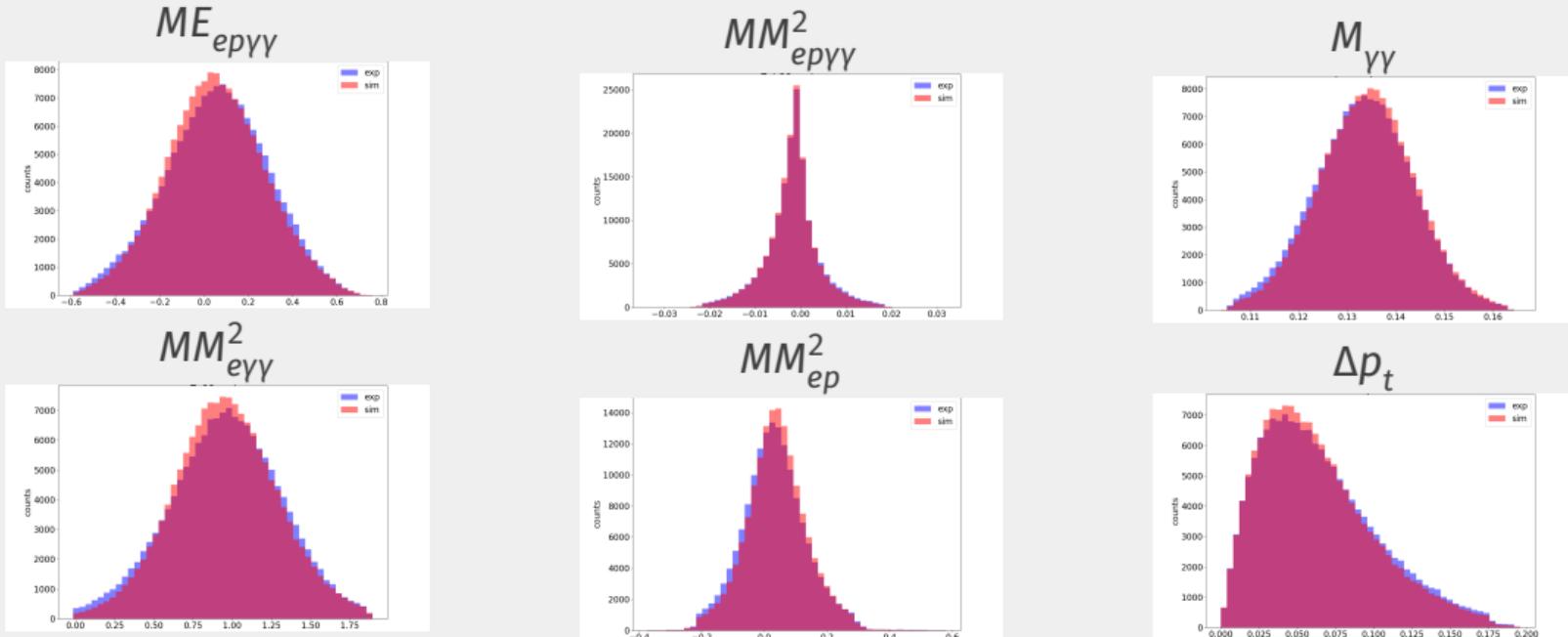
# SIMULATION NEEDS TO BE ADJUSTED TO MATCH EXPERIMENTAL DATA

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



# SMEARING FACTORS MAKES SIMULATION MORE REALISTIC

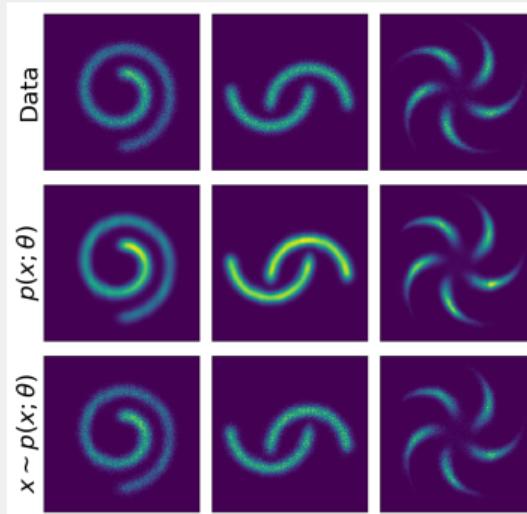
With the addition of smearing factors to simulated particle reconstruction values, the simulation matches experimental distributions well. [Collaborator S. Lee]



# DECREASE COMPUTATIONAL NEEDS WITH NORMALIZING FLOWS

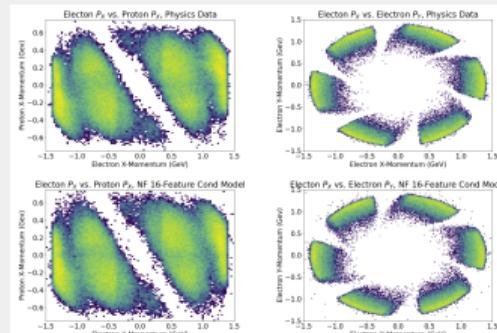
- **Normalizing Flows:** generative model, uses series of invertible transforms to map simple prior distributions into (very complex) target distributions

- **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



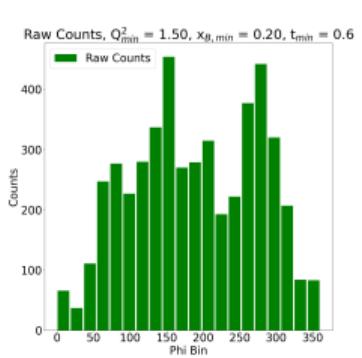
[arxiv:1908.05164]

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

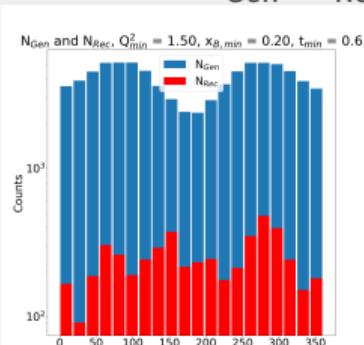


# ACCEPTANCE CORRECTION - BIN BY BIN CALCULATION

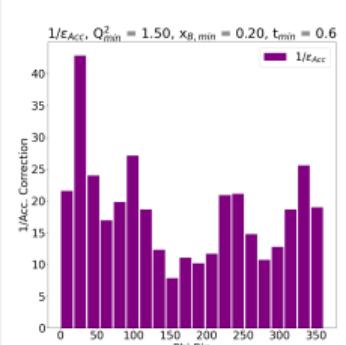
Raw Counts



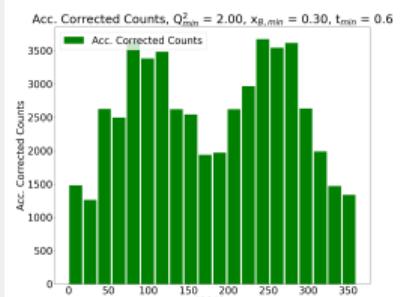
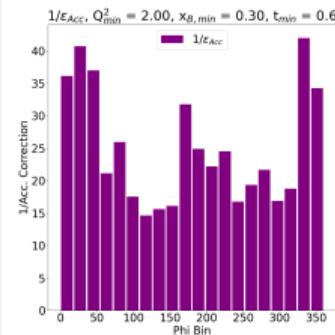
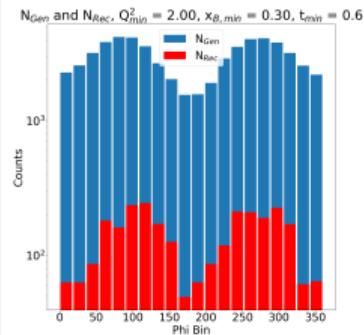
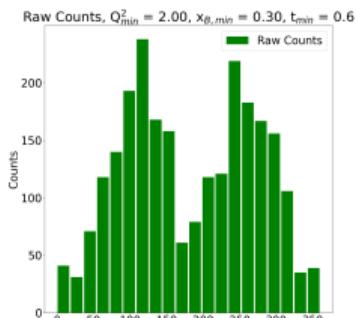
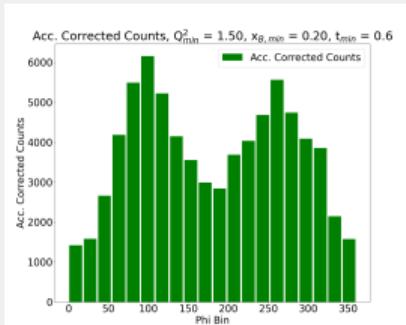
Simulated  $N_{Gen}$ ,  $N_{Rec}$



Acc. Correction



Acc. Corr. Counts

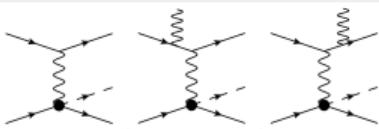


# ADDITIONAL CORRECTIONS

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

## Radiative Corrections

- Full radiative generator,  
~15% correction,  
 $\pm 1\%$  correction uncertainty



## Binning Corrections

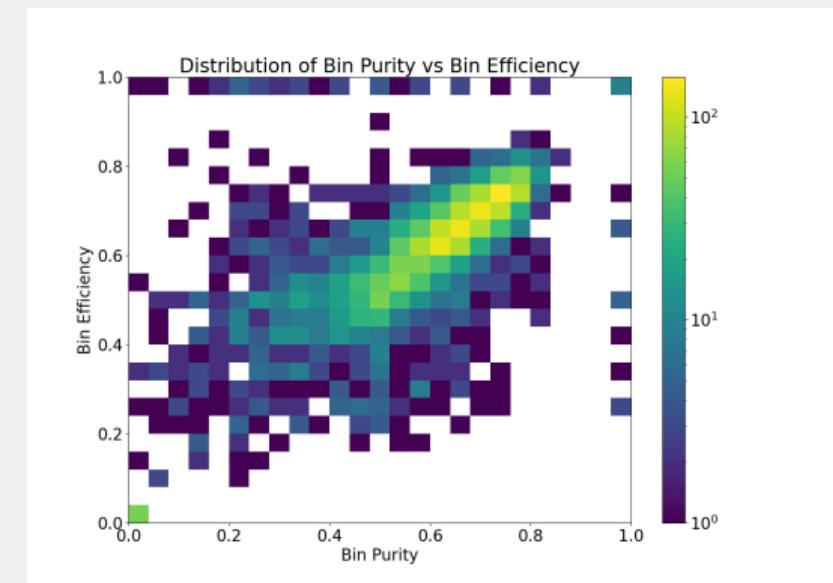
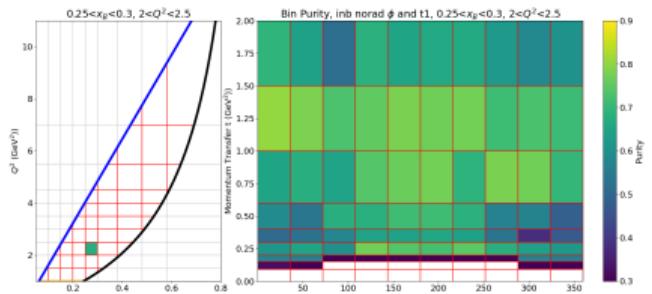
- Finite bin size:  
average, not  
differential cross  
sections
- Bin volume effects
- Bin migrations

## Overall Normalization

- Simulation detector efficiencies need match true efficiencies
- Normalizing to prior CLAS result yields 9% correction, ~10% spread
- Studies ongoing collaboration-wide

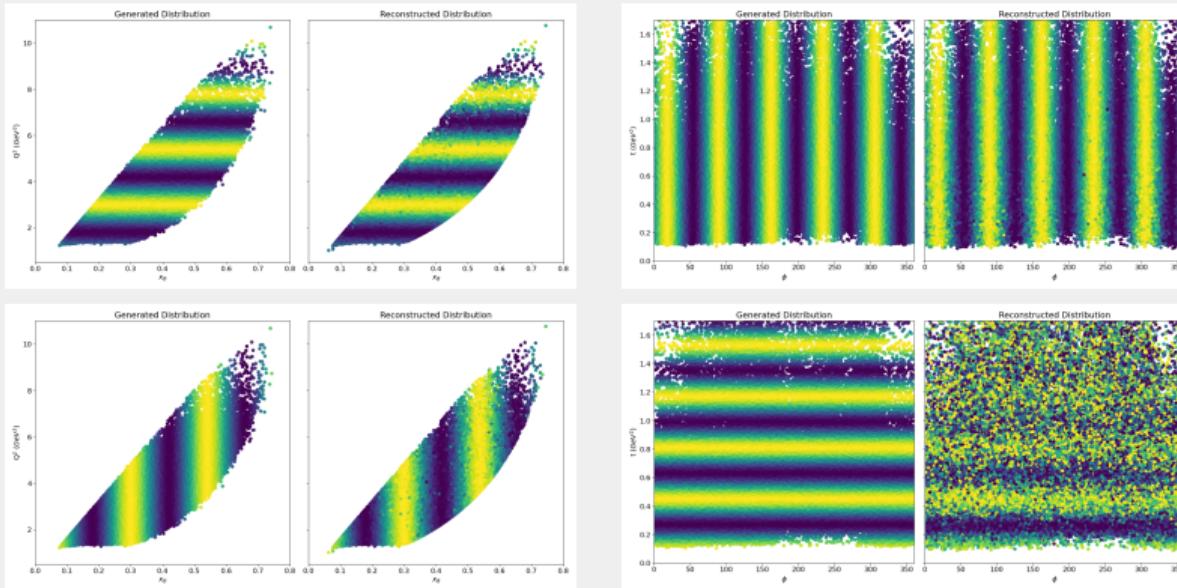
# CORRECTING BIN-BY-BIN ANALYSIS

Bin-by-bin analysis neglects cases where events are observed in a bin different from the one they were generated in



# T VARIABLE IS RESPONSIBLE FOR MAJORITY OF DRIFT

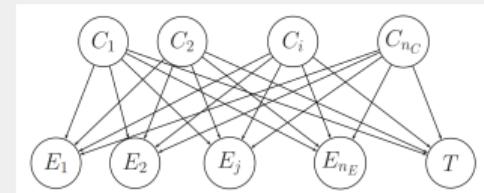
Superimposed sine-wave coloring indicates reconstruction performance



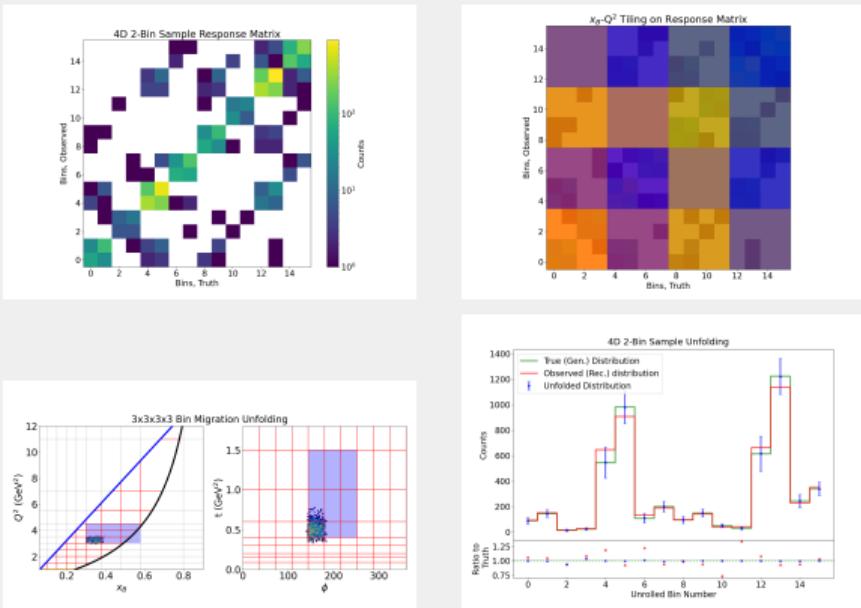
# ITERATIVE BAYESIAN UNFOLDING: THEORY

- **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:**

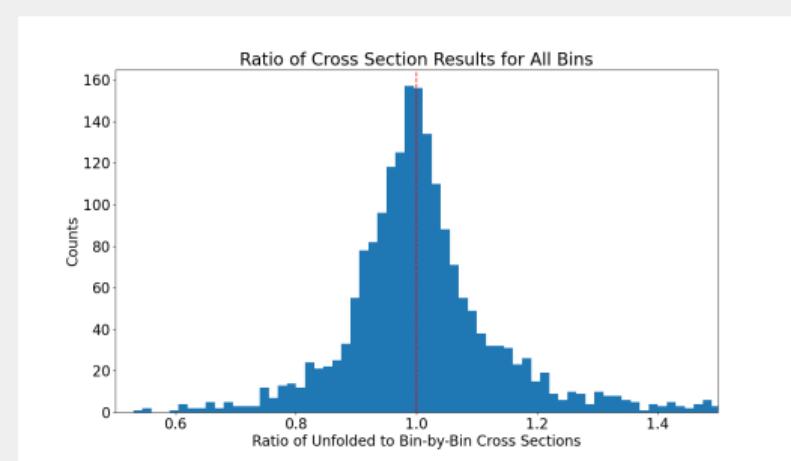
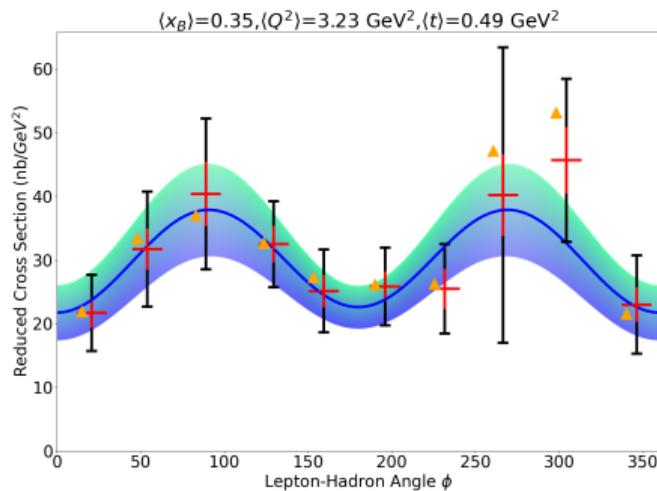
1. Use the current guess to predict the measurement.
2. Compare the predicted measurement to the actual measurement.
3. Adjust the guess based on Bayesian probability.
4. Repeat until convergence.



# ITERATIVE BAYESIAN UNFOLDING: METHOD



# ITERATIVE BAYESIAN UNFOLDING: RESULT

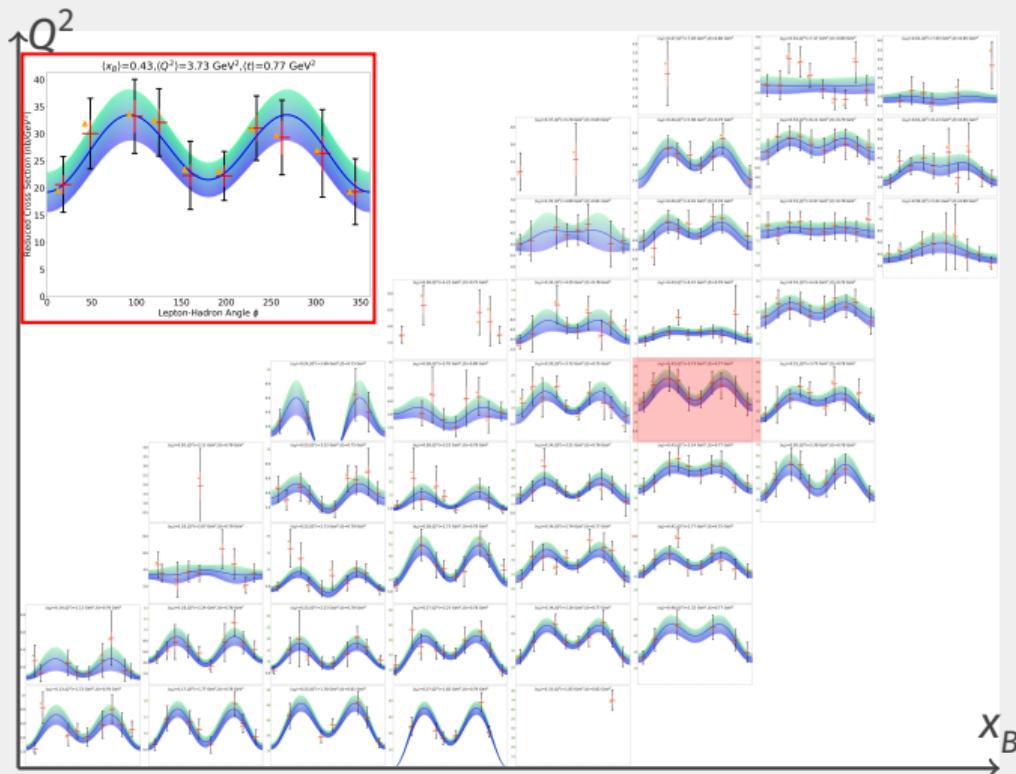


# SUMMARY OF SYSTEMATIC UNCERTAINTIES

Systematic Uncertainty	Typical Scale	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
<b>Total (quadrature)</b>	<b>30%</b>	Bin-by-bin

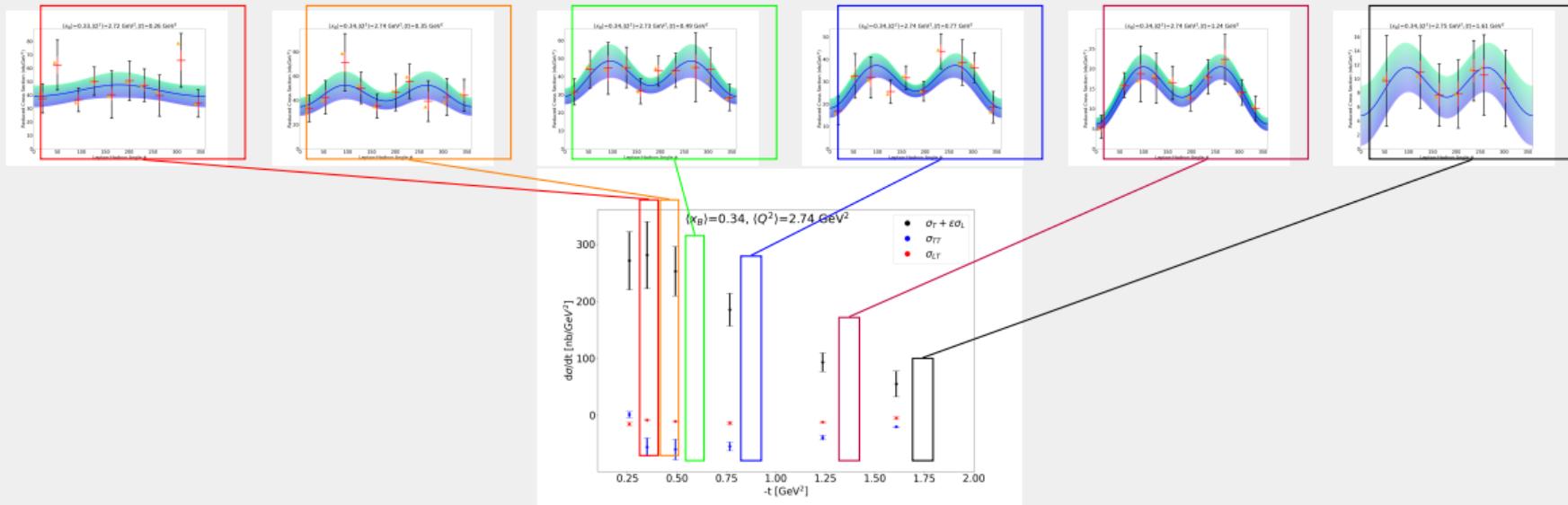
# PRELIMINARY CROSS SECTION RESULTS

- 1841 total bins passing all criteria
- 7 bins in  $t$  from  $t=0.12$  to  $t=1.7$
- Bins with enough statistics used in further analysis:
  - ▶ structure function extraction
  - ▶ dimension dependence



# STRUCTURE FUNCTION EXTRACTION

Fit  $A + B\cos(2\phi) + C\cos(\phi)$  for each distribution



# STRUCTURE FUNCTION EXTRACTION (PRELIMINARY)

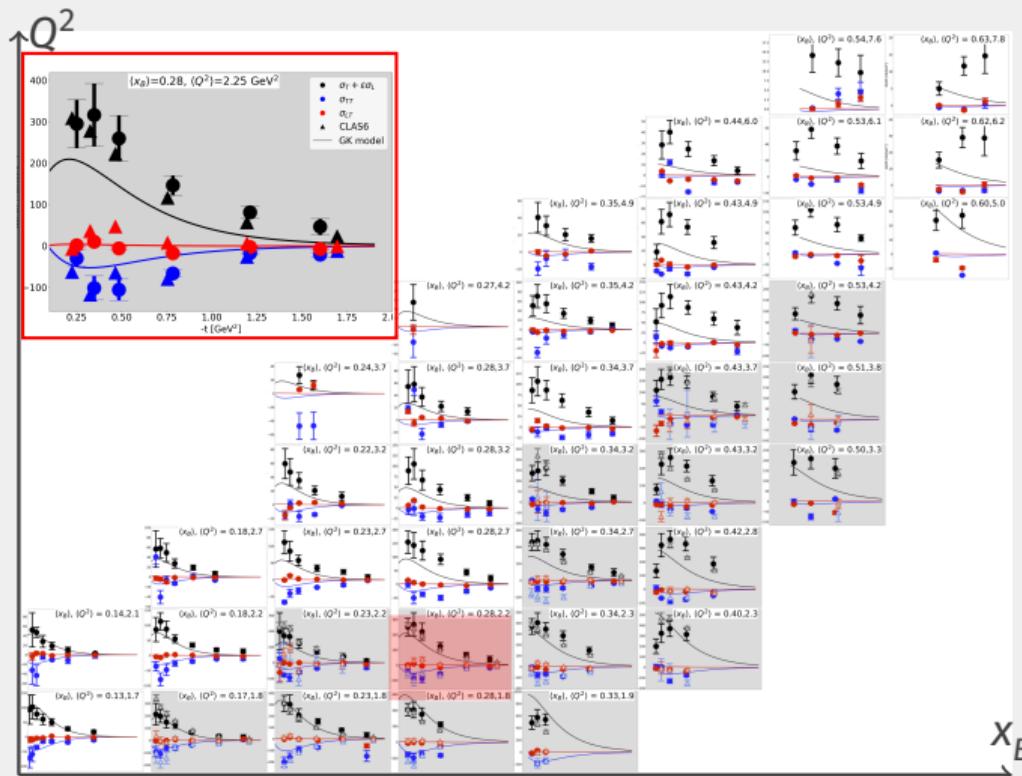
- Compare with Goloskokov-Kroll (GK) model [S.V. Goloskokov & P.

Kroll, EPJC, 65, 137 (2010)]

- Software implementation from K. Tezgin / PARTONS Framework

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

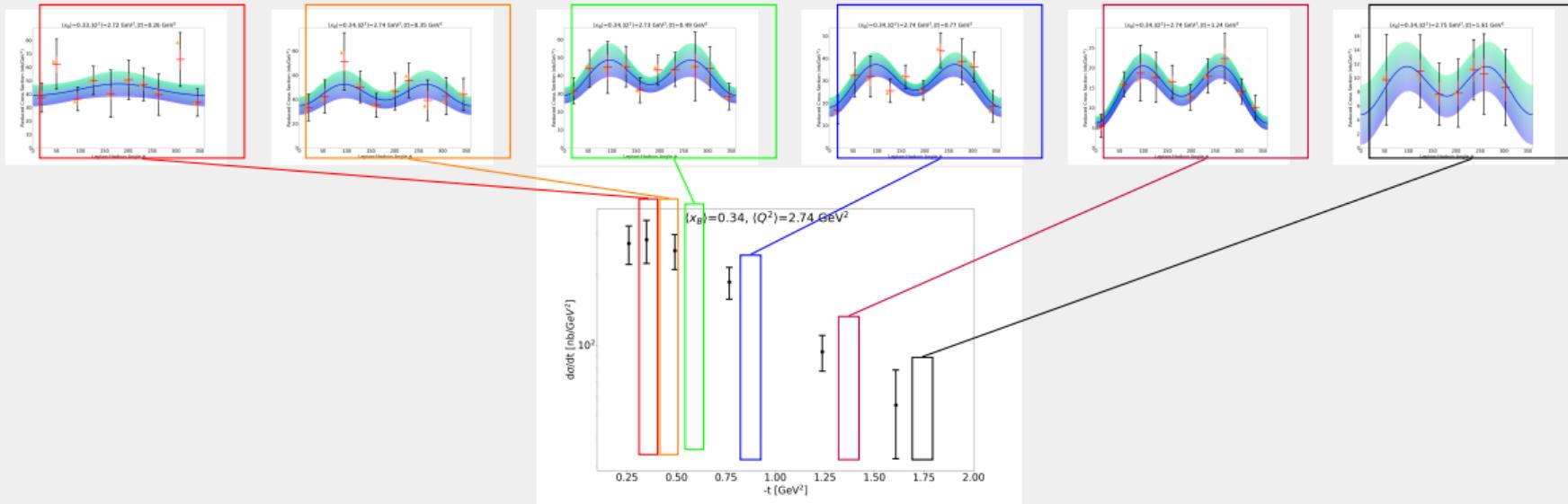
- Also compare to prior CLAS result; gray kinematic overlap bins



$x_B$

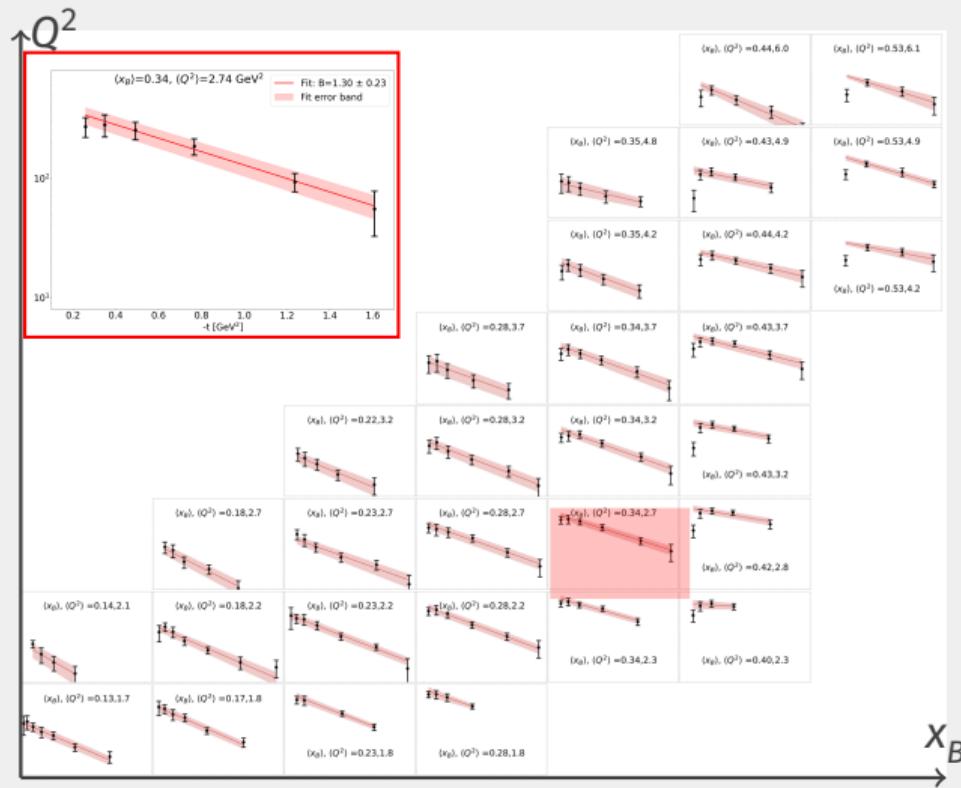
# CROSS SECTION T DEPENDENCE

Instead of fitting  $A + B\cos(2\phi) + C\cos(\phi)$ , integrate over  $\phi$

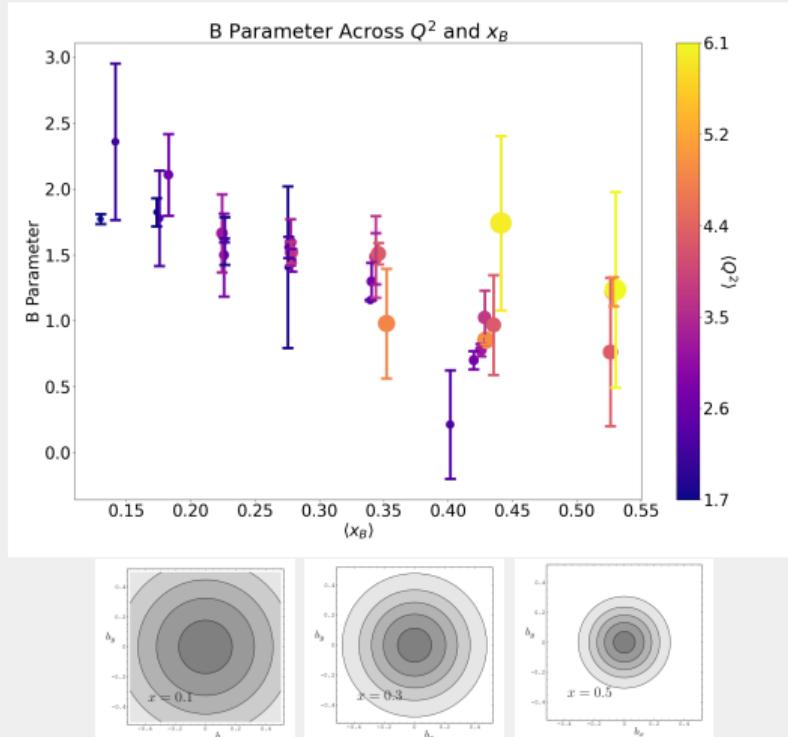


# CROSS SECTION T DEPENDENCE (PRELIMINARY)

Cross section expected to decrease across increasing  $t$  as  $e^{Bt}$



# $x_B$ DEPENDENCE OF B PARAMETER (PRELIMINARY)



- **Top:**  $B$  parameter across  $x_B$
- **Bottom:** Theory model of quark distribution in nucleon
- Dependence of  $B$  parameter decreases in agreement with Impact Parameter Space Interpretation of GPDs

[M. Burkardt arXiv 0207047]

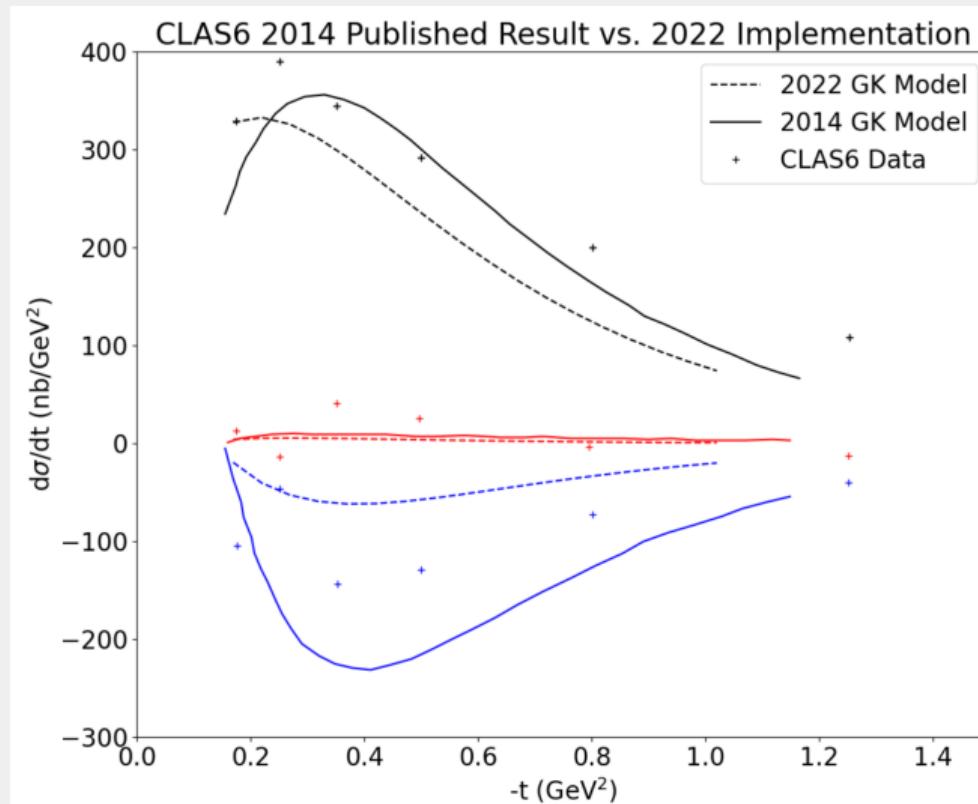
## CONCLUSION AND PATH FORWARD

- Efforts have allowed for measurement of DV $\pi^0$ P cross section over a wide range of kinematics, the first DVMP cross section measurement at CLAS12.
- Overall normalization efforts are a collaboration wide effort and ongoing; normalization independent results can already be extracted. Results are consistent with expectations from prior results.
- Path is cleared for further analysis - e.g. Rosenbluth separation of  $\sigma_L$  and  $\sigma_T$  terms, expansion to unbinned cross section results.

# BACKUP SLIDES

Backup Slides

# TRACKING GK MODEL DRIFT



# EXTRACTING PHYSICS DIRECTLY WITH OMNIFOLD

## OmniFold: A Method to Simultaneously Unfold All Observables

Anders Andreasen,<sup>1,2,3,\*</sup> Patrick T. Komiske,<sup>4,†</sup> Eric M. Metodiev,<sup>4,‡</sup> Benjamin Nachman,<sup>2,§</sup> and Jesse Thaler<sup>4,¶</sup>

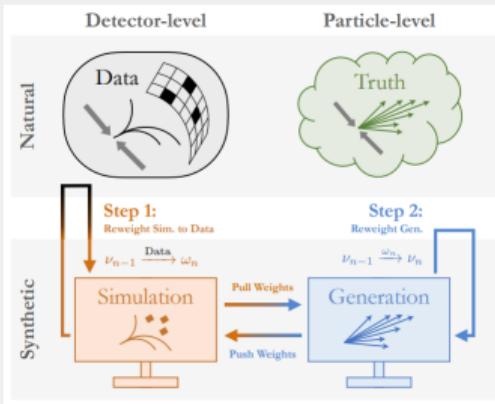
<sup>1</sup>Department of Physics, University of California, Berkeley, CA 94720, USA

<sup>2</sup>Physics Division, Lawrence Berkeley National Laboratory, Berkeley, CA 94720, USA

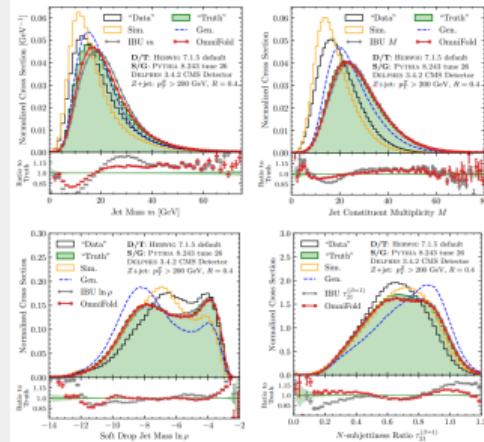
<sup>3</sup>Google, Mountain View, CA 94043, USA

<sup>4</sup>Center for Theoretical Physics, Massachusetts Institute of Technology, Cambridge, MA 02139, USA

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 OMNI FOLD, 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

Miguel Arratia,<sup>a,b</sup> Anja Butter,<sup>c</sup> Mario Campanelli,<sup>d</sup> Vincent Croft,<sup>e</sup> Dag Gillberg,<sup>f</sup> Kristin Lohwasser,<sup>g</sup> Bogdan Malaescu,<sup>h</sup> Vinicius Mikuni,<sup>i</sup> Benjamin Nachman,<sup>j,k</sup> Juan Rojo,<sup>l,m</sup> Jesse Thaler,<sup>n,o</sup> Ramon Winterhalder<sup>p</sup>

<sup>a</sup>Department of Physics and Astronomy, University of California, Riverside, CA 92521, USA

<sup>b</sup>Thomas Jefferson National Accelerator Facility, Newport News, VA 23606, USA

# UNBINNED CROSS SECTIONS

## Presenting Unbinned Differential Cross Section Results

Miguel Arratia,<sup>a,b</sup> Anja Butter,<sup>c</sup> Mario Campanelli,<sup>d</sup> Vincent Croft,<sup>e</sup> Dag Gillberg,<sup>f</sup> Aishik Ghosh,<sup>g,h</sup> Kristin Lohwasser,<sup>i</sup> Bogdan Malaescu,<sup>j</sup> Vinicius Mikuni,<sup>k</sup> Benjamin Nachman,<sup>h,l</sup> Juan Rojo,<sup>m,n</sup> Jesse Thaler,<sup>o,p</sup> Ramon Winterhalder<sup>q</sup>

<sup>a</sup>Department of Physics and Astronomy, University of California, Riverside, CA 92521, USA

<sup>b</sup>Thomas Jefferson National Accelerator Facility, Newport News, VA 23606, USA

<sup>c</sup>Institut für Theoretische Physik, Universität Heidelberg, Heidelberg, Germany

<sup>d</sup>University College London, London WC1E 6BT, UK

<sup>e</sup>Department of Physics and Astronomy, Tufts University, Boston, MA 02155, USA

<sup>f</sup>Department of Physics, Carleton University, Ottawa ON K1S 5B6, Canada

<sup>g</sup>Department of Physics and Astronomy, University of California, Irvine, CA 92697, USA

<sup>h</sup>Physics Division, Lawrence Berkeley National Laboratory, Berkeley, CA 94720, USA

<sup>i</sup>University of Sheffield, Sheffield, S10 2TN, UK

<sup>j</sup>LPNHE, Sorbonne Université, Université de Paris, CNRS/IN2P3, Paris, France

<sup>k</sup>National Energy Research Scientific Computing Center, Berkeley, CA 94720, USA

<sup>l</sup>Berkeley Institute for Data Science, University of California, Berkeley, CA 94720, USA

<sup>m</sup>Nikhef Theory Group, Science Park 105, 1098 XG Amsterdam, The Netherlands

<sup>n</sup>Department of Physics and Astronomy, Vrije Universiteit Amsterdam, NL-1081 HV Amsterdam, The Netherlands

<sup>o</sup>Center for Theoretical Physics, Massachusetts Institute of Technology, Cambridge, MA 02139, USA

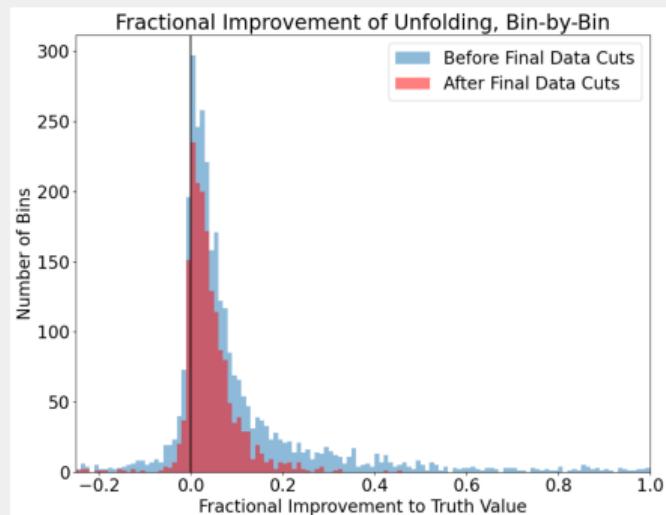
<sup>p</sup>The NSF AI Institute for Artificial Intelligence and Fundamental Interactions

<sup>q</sup>Centre for Cosmology, Particle Physics and Phenomenology (CP3), Université catholique de Louvain, 1348 Louvain-la-Neuve, Belgium

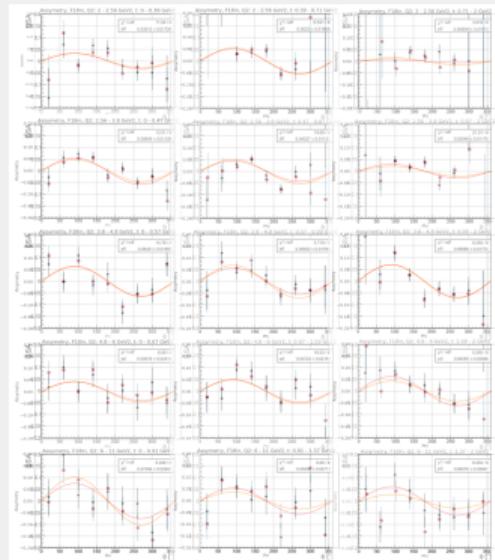
E-mail: [bpachsan@lbl.gov](mailto:bpachsan@lbl.gov)

ABSTRACT: Machine learning tools have empowered a qualitatively new way to perform differential cross section measurements whereby the data are unbinned, possibly in many dimensions. Unbinned measurements can enable, improve, or at least simplify comparisons between experiments and with theoretical predictions. Furthermore, many-dimensional measurements can be used to define observables after the measurement instead of before.

# UNFOLDING OUTLIERS



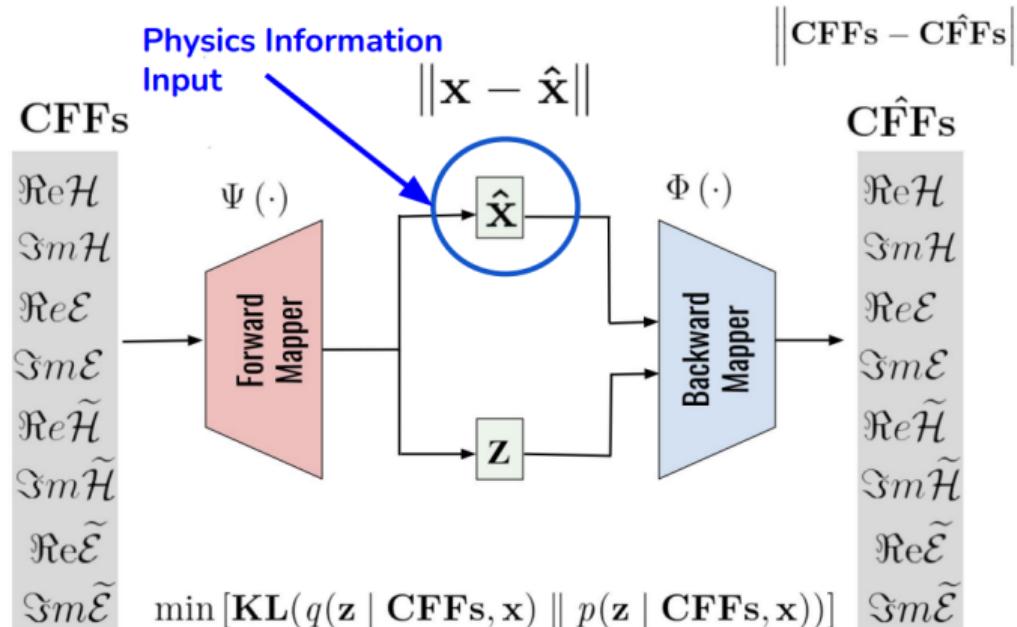
# BSA



Caption

# AUTOENCODER APPROACH TO GPDS

## VAIM-CFF Framework



# AUTOENCODER APPROACH TO GPDs

## 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

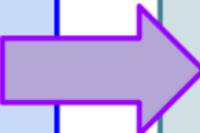
Nobody has gotten all 8 CFFs before.

### FemtoNet

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

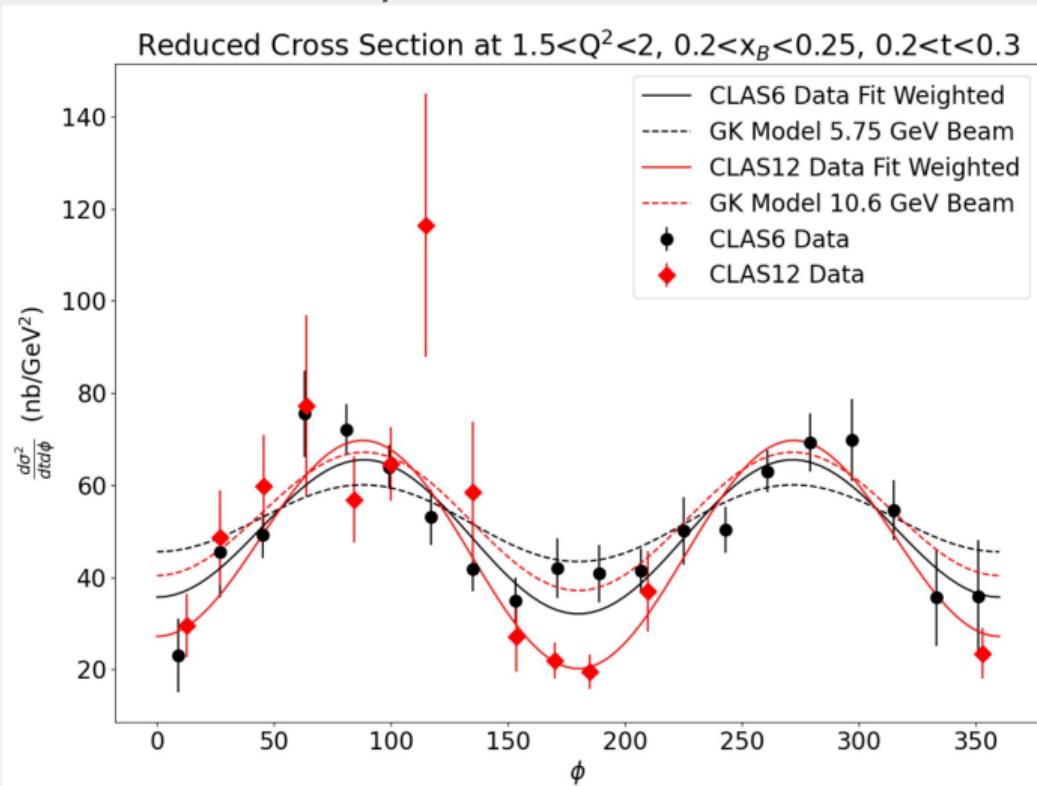
Quantification of **information that is possible to extract** from certain experiments.

Informed high impact measurements.



# BACKUP SLIDES

## Comparision with CLAS6



# 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>

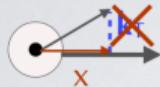
## BACKUP SLIDES

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

## ~~Transv. Mom. Dependent Parton Distributions~~



~~TMD PDFs ( $x, p^2; Q$ ) at leading twist~~

quark



nucleon



Nucleon Polarization	Quark polarization		
	Unpolarized (U)	Longitudinally Polarized (L)	Transversely Polarized (T)
U	$f_1 = \odot$		
L		$g_1 = \odot - - \odot -$	-
T			$h_1 = \uparrow \odot - \uparrow \odot$

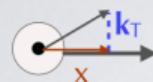
From Marco Radici

# SLIDE ABOUT LINCOLN LABS

I'm going to Lincoln Labs but will continue this work

# BACKUP SLIDES

## Transv.-Mom. Dependent Parton Distributions



TMD PDFs ( $x, k_T^2; Q$ ) at leading twist

nucleon	Quark polarization		
	Unpolarized (U)	Longitudinally Polarized (L)	Transversely Polarized (T)
U	$f_1 = \odot$	*	$h_1^\perp = \odot \downarrow - \odot \uparrow$
L	*	$g_1 = \odot \leftarrow - \odot \rightarrow$	$h_{1L}^\perp = \odot \leftarrow - \odot \rightarrow$
T	$f_{1T}^\perp = \odot \downarrow - \odot \uparrow$	$g_{1T} = \odot \downarrow - \odot \uparrow$	$h_1 = \odot \downarrow - \odot \uparrow$ $h_{1T}^\perp = \odot \downarrow - \odot \uparrow$

\* forbidden by parity invariance

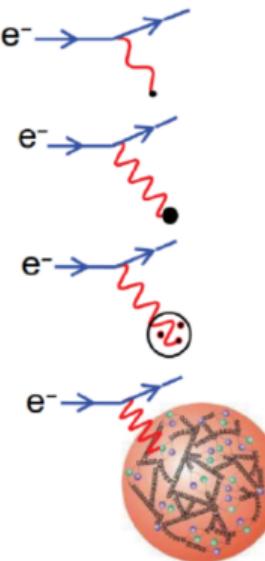
Mulders & Tangerman,  
N.P. **B461** (96)  
Boer & Mulders,  
P.R. **D57** (98)  
Bacchetta et al.,  
*JHEP* **02** (07) 093

From Marco Radici

## Probing the structure of hadrons

Wave length  $\lambda = hc/E$

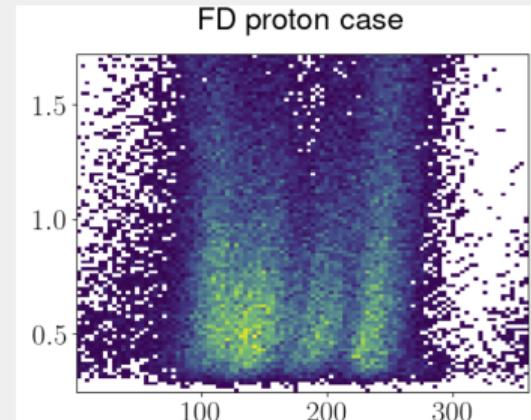
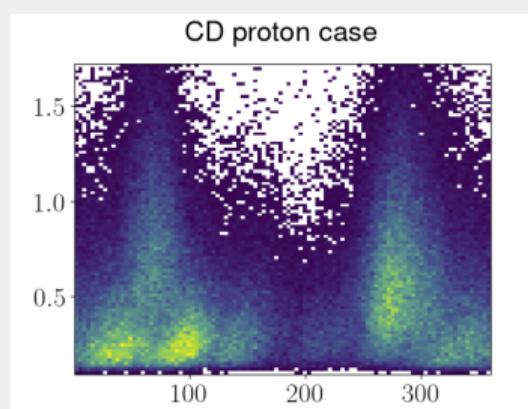
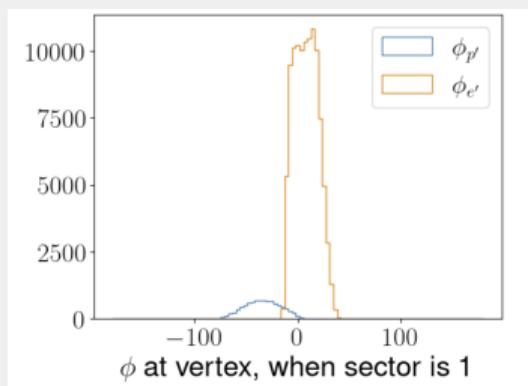
- At very Low electron beam ( $\lambda \gg r_p$ ): scattering from a **point-like spin-less** object
- Low electron beam energies ( $\lambda \approx r_p$ ): scattering from an **extended charged** object
- High electron beam energies ( $\lambda < r_p$ ): scattering from **constituent quarks**
- High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



From Alaa Dbeissi

# 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 $x_B$ relating to timing resolution in camera analogy**

On  $x_B$  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  $\sigma_T$  and  $\sigma_L$  terms:

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

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

I. Korover<sup>1,\*</sup> and R.G. Milner<sup>1</sup>

<sup>1</sup>Laboratory for Nuclear Science, Massachusetts Institute of Technology, Cambridge, MA 02139.  
(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  $\pi^0$  deeply virtual electroproduction (DVEP) from the proton at a mean  $Q^2 \approx 2$   $(\text{GeV}/c)^2$ . The central question we address is the applicability of factorization in  $\pi^0$  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  $(\text{GeV}/c)^2$ ). The measured dominance of the longitudinal contribution at  $Q^2 \approx 2$   $(\text{GeV}/c)^2$  is consistent with the expectation of the handbag factorization theorem. We find that  $\sigma_L(t) \sim 1/(-t)$  for  $-t > 0.5$   $(\text{GeV}/c)^2$ . Determination of both longitudinal and transverse contributions to the deeply virtual  $\pi^0$  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

