Inclusive electron scattering off the proton with CLAS12

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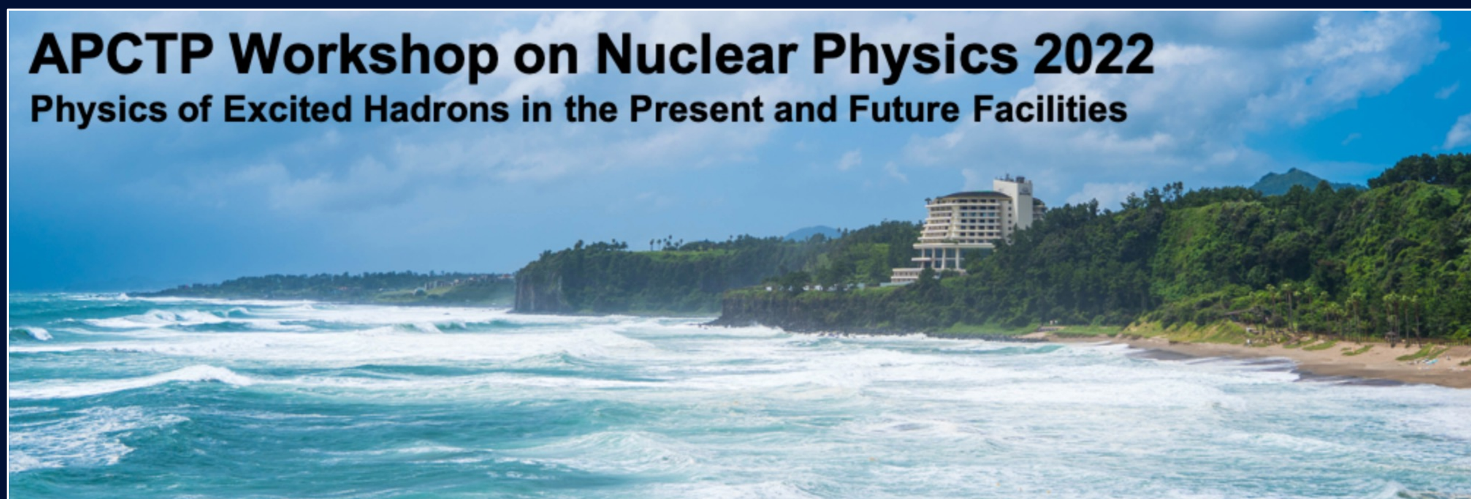

clas

July 14, 2022

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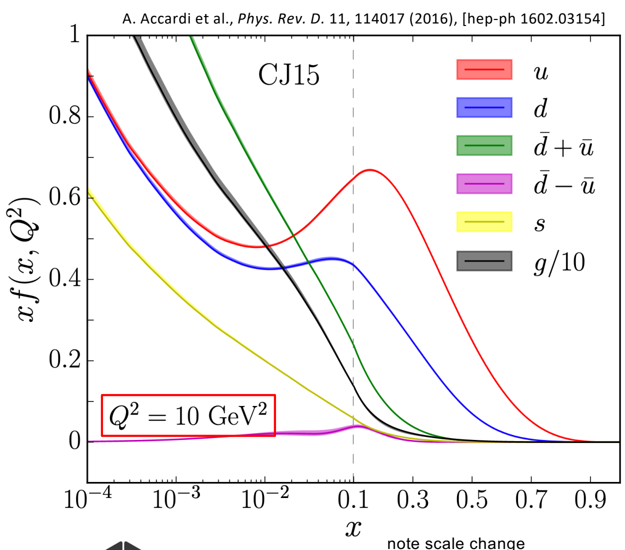
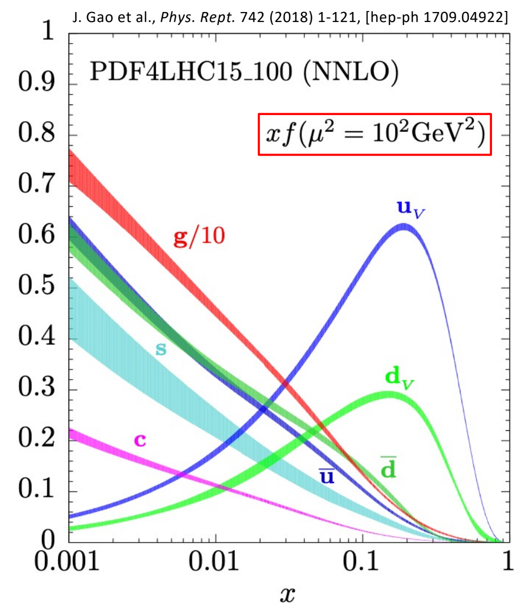
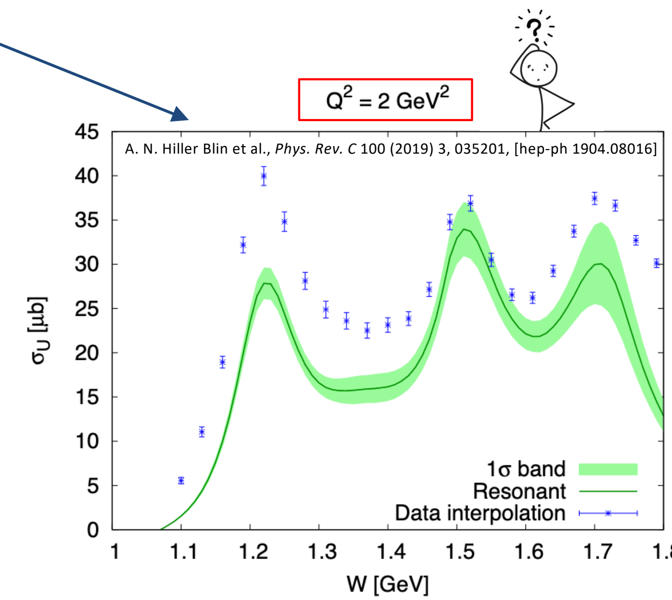
Extending Knowledge of the Nucleon PDF in the Resonance Region

- Global QCD analyses have provided detailed information on the nucleon PDFs in a wide range of fractional longitudinal momentum, x, from 10^{-4} to 0.9.
- At large x, in the nucleon resonance region W < 2.5 GeV, the PDFs are significantly less explored.
- Extractions in this region require accounting for higher twist effects, target-mass corrections and evaluation from the nucleon resonance electroexcitations.



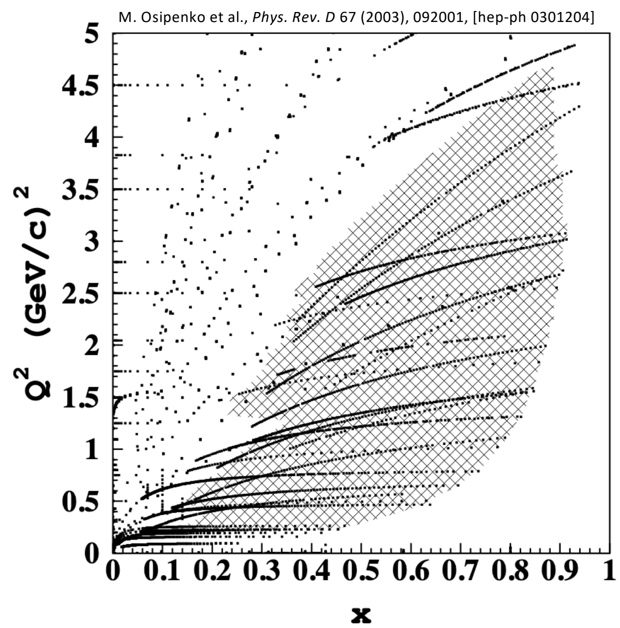


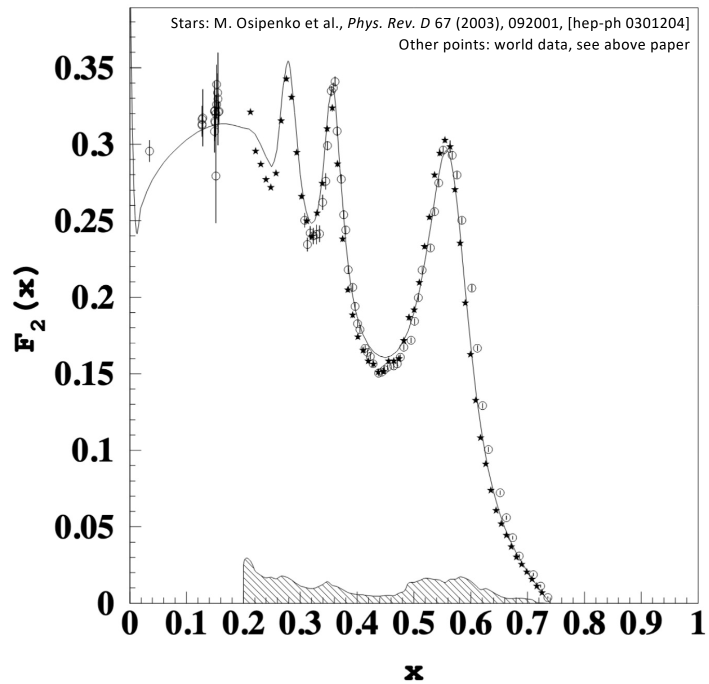


CLAS Results

- CLAS measured the inclusive cross section up to x = 0.9 (W = 2.5 GeV) and Q^2 from 0.25 to 4.5 GeV^2.
- Large acceptance of the CLAS detector allows for integration of the signal at a fixed Q^2 over a large range in x.

World data used for moment evaluations of F_2. Shaded area corresponds to CLAS.





Hall C Results

- Extended inclusive electron data up to $Q^2 = 7.5$ GeV^2.
- Information provided on the longitudinal and transverse components of the cross section.
- Limited acceptance of the Hall C detector constrains the accessible W range for any given value of Q^2.

S. P. Malace et al., *Phys. Rev. C* 80 (2009) 035207, [nucl-ex 0905.2374]

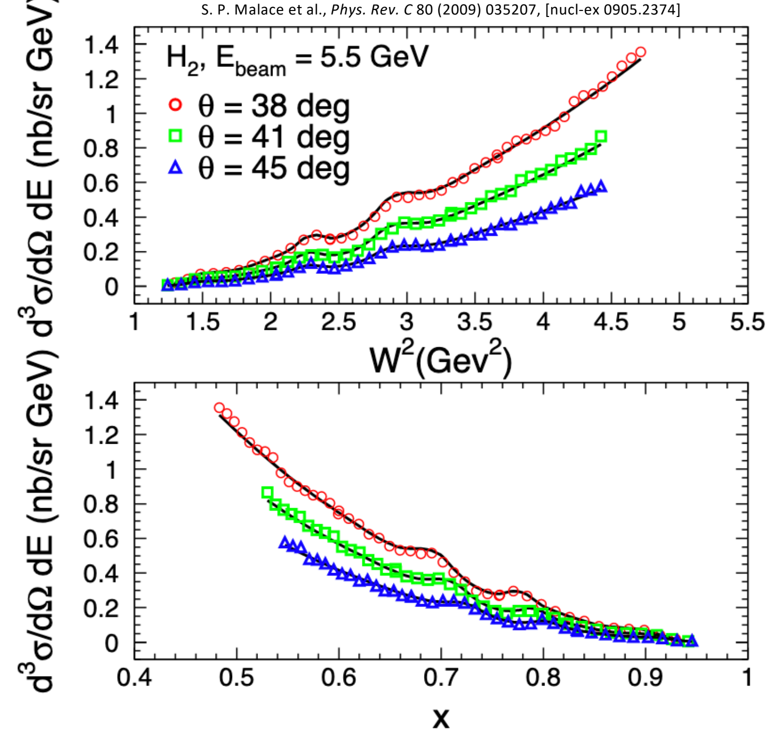


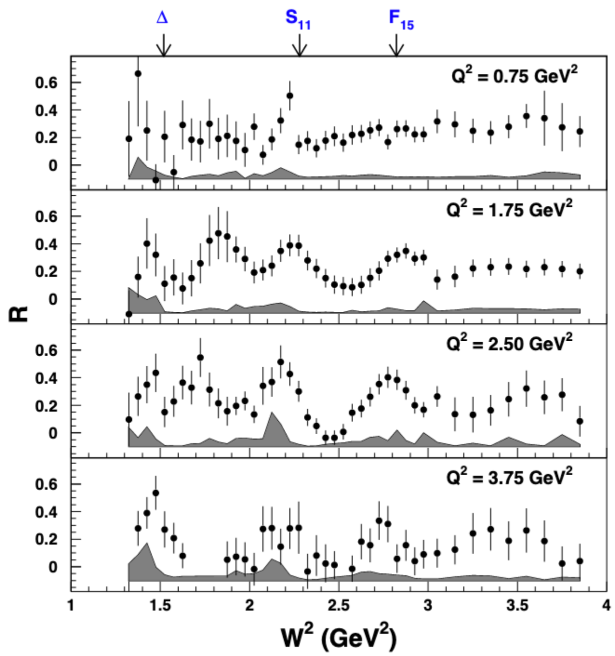
TABLE IV: An example of the x ranges covered by different resonance regions for two Q^2 values.

	x range	
W^2 region	$Q^2 = 2$ (GeV^2)	$Q^2 = 6$ (GeV^2)
1^{st}	0.66 - 0.83	0.85 - 0.93
2^{nd}	0.55 - 0.66	0.79 - 0.85
3^{rd}	0.47 - 0.55	0.73 - 0.79
4^{th}	0.40 - 0.47	0.67 - 0.73
DIS	0.35 - 0.40	0.62 - 0.67

S. P. Malace et al., *Phys. Rev. C* 80 (2009) 035207, [nucl-ex 0905.2374]

Updated R = σ_L/σ_T

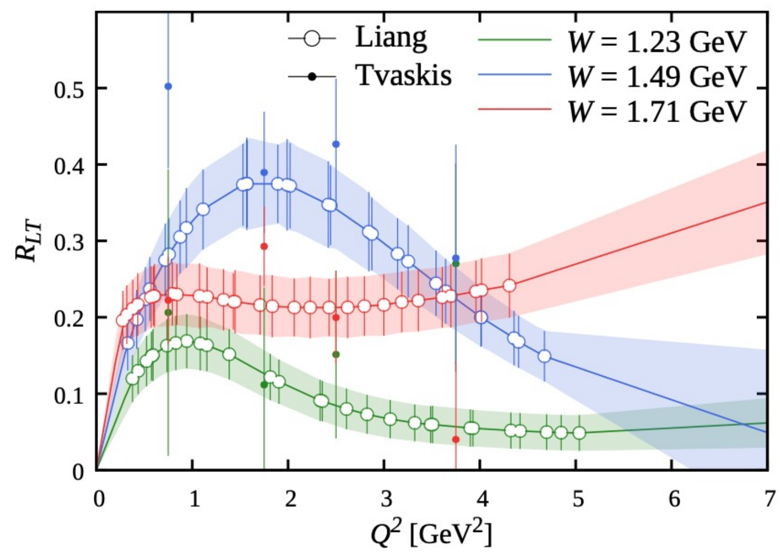
- Hall C data allows for Rosenbluth separation of 167 data points.
- First separate values of F_1 and F_L in this kinematic regime.



Y. Liang et al. (Jefferson Lab E94-110 Collaboration), [nucl-ex 0410027]

$$R \equiv \frac{\sigma_L}{\sigma_T} \equiv \frac{F_L}{2xF_1} = \frac{F_2}{2xF_1}\left(1 + \frac{4M^2x^2}{Q^2}\right) - 1$$

A. N. Hiller Blin et al., *Phys. Rev. C* 104 (2021) 2, 025201, [hep-ph 2105.05834]



Predictions at higher Q^2 performed by fitting a second-degree polynomial to the grid of the Hall-C results.

Empirical fit in the Resonance Region

- Fit by Christy & Bosted (2010).
- Constrained by L/T separated cross section measurements from Hall C.
- Fit incorporates photoproduction data at $Q^2 = 0$.
- Smooth transition from photoproduction all the way into the DIS region.

Data Set	Q^2_{Min} (GeV^2)	Q^2_{Max} (GeV^2)	# Data Points
E94-110 [5]	0.18	5	1259
E00-116 [14]	3.6	7.5	256
E00-002 [15]	0.06	2.1	1346
SLAC DIS [16]	0.6	9.5	296
Photoproduction (Old) [17–19]	0	0	242
Photoproduction (DAPHNE) [20]	0	0	57

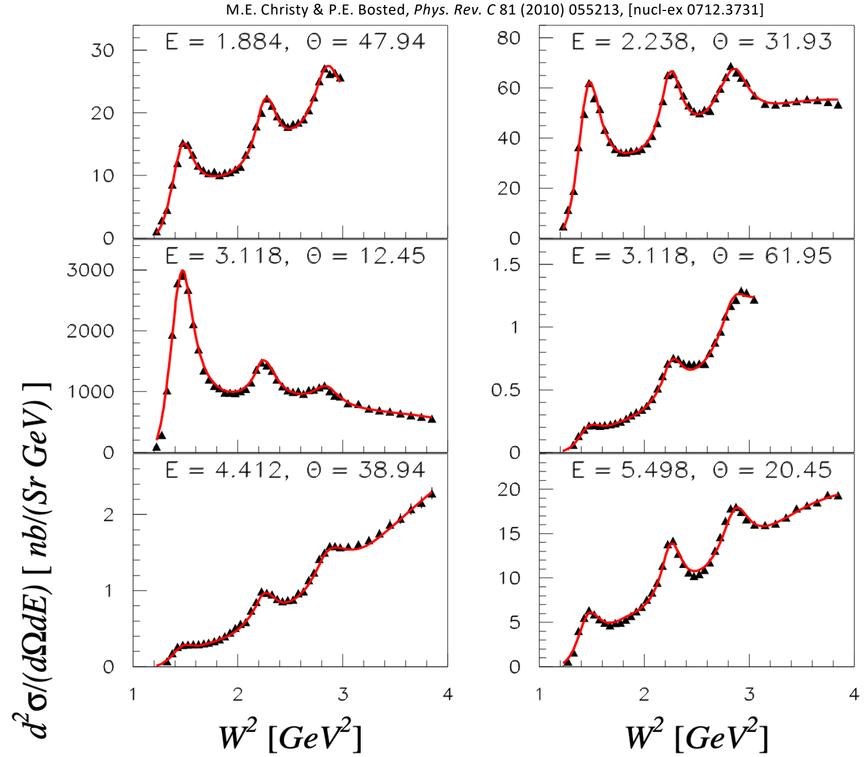
TABLE II: Summary of data sets included in the fit.

$$\sigma_{T,L}(W^2,Q^2) = \sigma^R_{T,L} + \sigma^{NR}_{T,L}$$

$$\sigma^R_{T,L}(W^2,Q^2) = W \sum_{i=1}^{7} \boxed{BW^i_{T,L}(W^2)} \cdot \boxed{[A^i_{T,L}(Q^2)]^2}$$

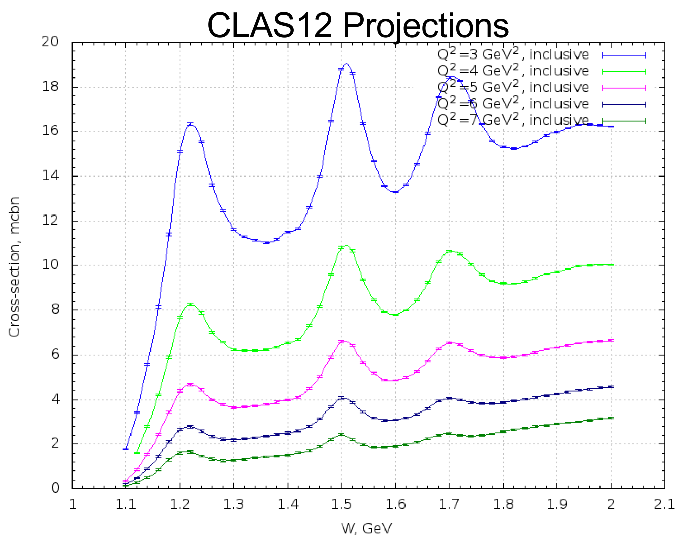
1. Cross section is the incoherent sum of contributions from resonance and non-resonance production.
2. Resonant cross section defined by threshold-dependent BW forms with Q^2 dependent amplitudes.
3. Non-resonant background varies smoothly with W.

M.E. Christy & P.E. Bosted, *Phys. Rev. C* 81 (2010) 055213, [nucl-ex 0712.3731]



Interpolative Web Feature

- 2d-interpolation over W and Q^2 of the CLAS experimental results on F_2 (W,Q^2) structure function (see CLAS Physics DB).
- $F_1(W,Q^2)$ was computed by employing M. Osipenko's parameterization for σ_T/σ_L ratio (M. Osipenko et al., *Phys. Rev. D* 67 (2003), 09200).
- CLAS results further interpolated over $Q^2 < 7.0$ GeV^2 by employing the OPE expression for the Q^2 evolution of $F_{1,2}$ accounting both for the CLAS results and world results parameterization in (P. Bosted, M.E. Christy, *Phys. Rev. C* 77, (2008) 065206).



Range of applicability (current version):

1.1 GeV < W < 2.0 GeV;   2.0 GeV² <Q²< 7.0 GeV²

- Check consistent of CLAS12 results on SF and CS with CLAS/World data.
- Validate the luminosity monitoring and efficiency evaluations for scattered electrons.

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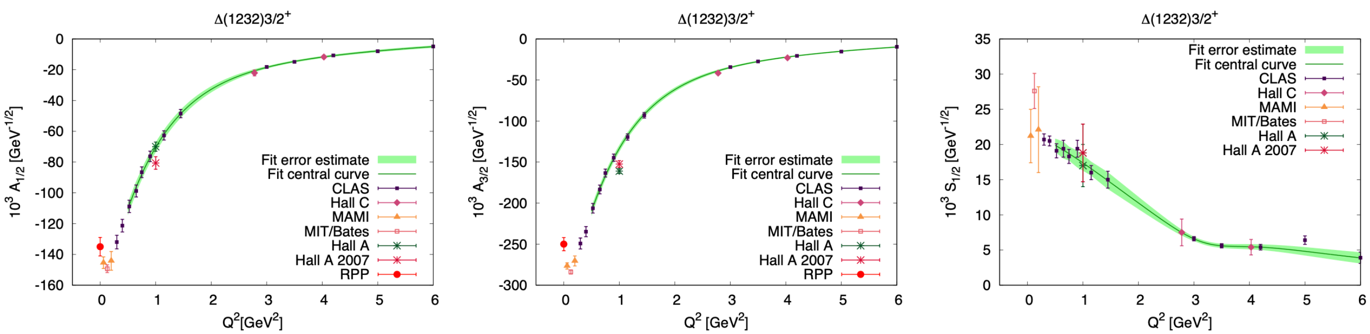
γ*pN* Electrocouplings

- γ*pN* electrocouplings derived from CLAS exclusive meson production off the proton.

$$ep \to e'\pi N \qquad ep \to e'\eta N \qquad ep \to e'\pi^+\pi^- p$$

- Estimates for contributions are therefore independent of inclusive electron scattering measurements and allow for calculations of the resonant contributions to the cross section.

N^*	M_r [MeV]	Γ_r [MeV]	L_r	$\beta_{\pi N}$	$\beta_{\eta N}$	$\beta_{r.}$	X [GeV]
$\Delta(1232)\ 3/2^+$	1232	117	1	1.00	0	0	—
$N(1440)\ 1/2^+$	1430	350	1	0.65	0	0.35	0.3
$N(1520)\ 3/2^-$	1515	115	2	0.60	0	0.40	0.1
$N(1535)\ 1/2^-$	1535	150	0	0.45	0.42	0.13	0.5
$\Delta(1620)\ 1/2^-$	1630	140	0	0.25	0	0.75	0.5
$N(1650)\ 1/2^-$	1655	140	0	0.60	0.18	0.22	0.5
$N(1675)\ 5/2^-$	1675	150	2	0.40	0	0.60	0.5
$N(1680)\ 5/2^+$	1685	130	3	0.68	0	0.32	0.2
$\Delta(1700)\ 3/2^-$	1700	293	2	0.10	0	0.90	0.22
$N(1710)\ 1/2^+$	1710	100	1	0.13	0.30	0.57	0.5
$N(1720)\ 3/2^+$	1748	114	1	0.14	0.04	0.82	0.5
$N'(1720)\ 3/2^+$	1725	120	1	0.38	0	0.62	0.5



A. N. Hiller Blin et al., *Phys. Rev. C* 100 (2019) 3, 035201, [hep-ph 1094.08016]
See text for data citations (Figs. 1-3)

Resonant Contributions

- Studies elucidate the contributions from excited nucleon states to the three resonance regions.

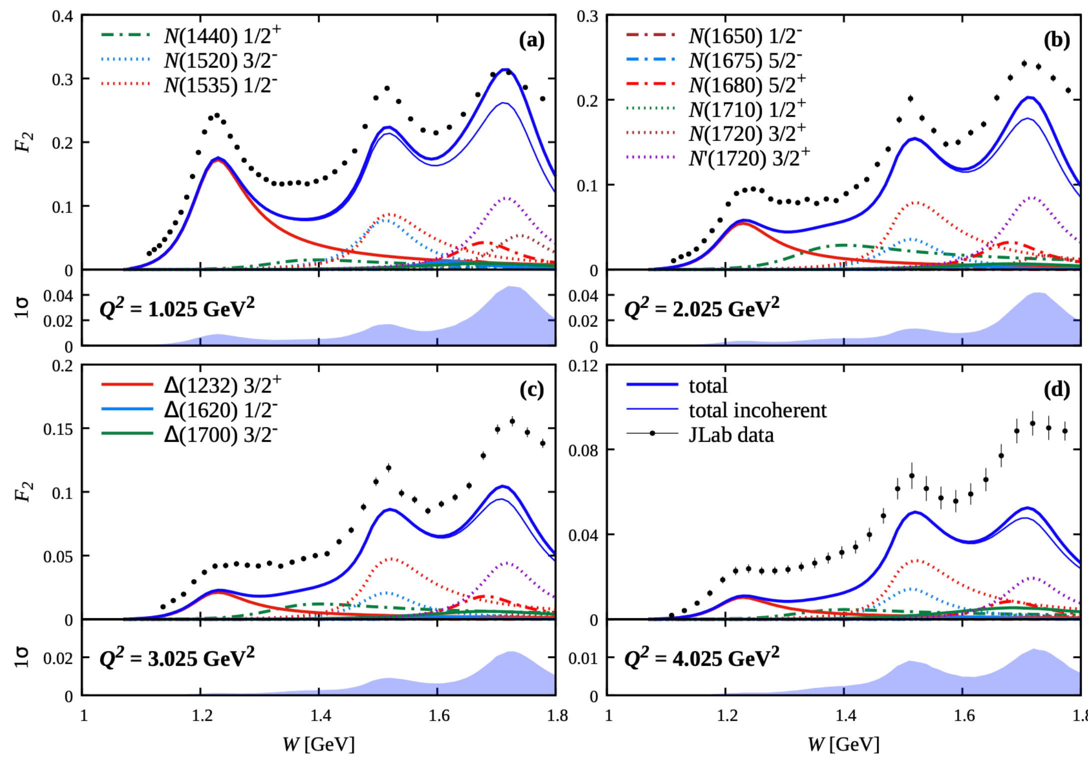
$$\sigma^R_{T,L}(W,Q^2)$$
$$= \frac{\pi}{q_\gamma^2}\sum_R (2J_R+1)\frac{M_R^2\,\Gamma_R(W)\,\Gamma^{T,L}_{\gamma,R}(M_R,Q^2)}{\left(M_R^2-W^2\right)^2+\left(M_R\Gamma_R(W)\right)^2}$$

Decay widths of resonance R to γ*p related to electrocouplings from previous slide.

$$\Gamma^T_{\gamma,R}(W=M_R,Q^2)=\frac{q^2_{\gamma,R}(Q^2)}{\pi}\frac{2M}{(2J_R+1)M_R}\times\left(\left|A^R_{1/2}(Q^2)\right|^2+\left|A^R_{3/2}(Q^2)\right|^2\right),$$
$$\Gamma^L_{\gamma,R}(W=M_R,Q^2)=\frac{2q^2_{\gamma,R}(Q^2)}{\pi}\frac{2M}{(2J_R+1)M_R}\times\left|S^R_{1/2}(Q^2)\right|^2,$$

- Extension of previous analysis to now include interference effects by adding the amplitudes coherently.

A. N. Hiller Blin et al., *Phys. Rev. C* 104 (2021) 2, 025201, [hep-ph 2105.05834]

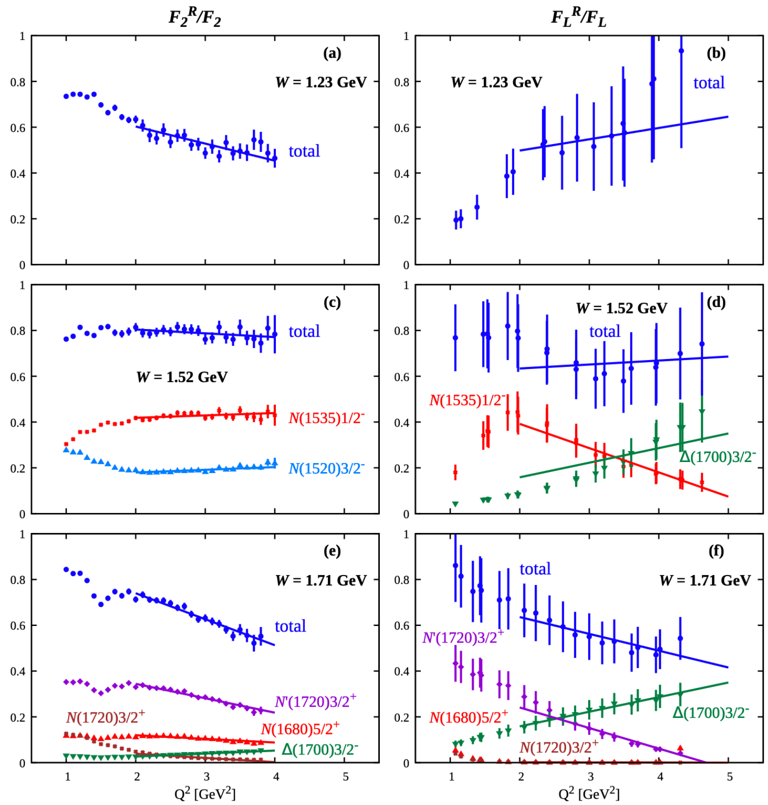


Q^2 evolution

1st resonance

2nd resonance

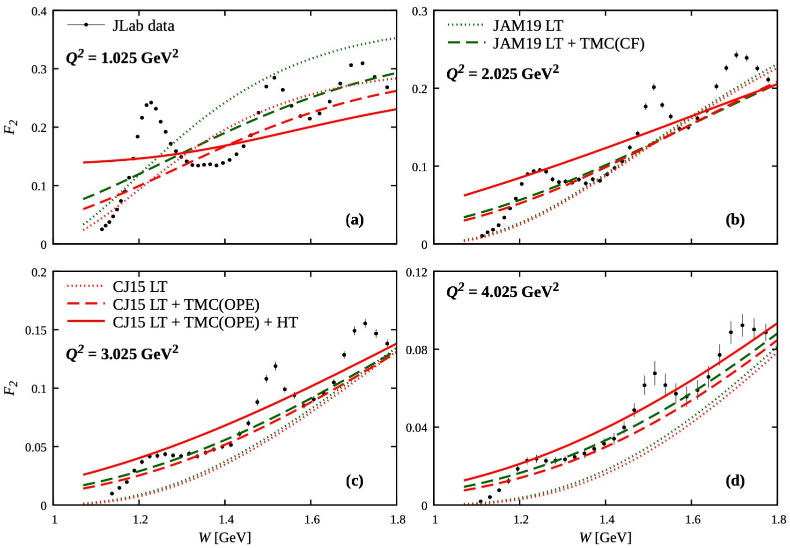
3rd resonance



A. N. Hiller Blin et al., *Phys. Rev. C* 104 (2021) 2, 025201, [hep-ph 2105.05834]

- Resonant contributions remain strong over the range of available data.
- First and third peaks decrease with Q^2 (in absolute value) when compared to the second peak which decreases more slowly.
- Further extensions to higher Q^2 become possible as CLAS12 exclusive meson production analyses continue.

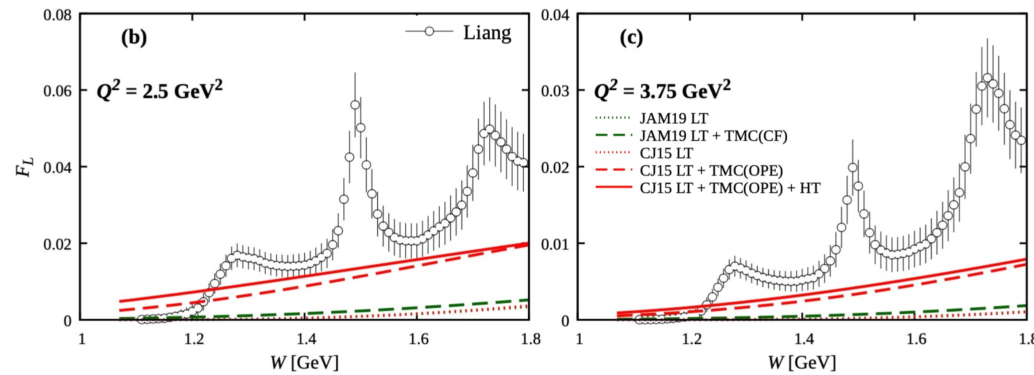
From Resonances to DIS



A. N. Hiller Blin et al., *Phys. Rev. C* 104 (2021) 2, 025201, [hep-ph 2105.05834]
See text for PDF fits.

1. LT fits (dotted lines) slightly underestimate the data.
2. Inclusion of TMC (dashed lines) increases the PDFs generally increase.
3. Inclusion of HT (solid lines) further increases the fits.

- With adequate accounting for low-energy effects the resonance data agree with the scaling curve from DIS/Drell-Yan/etc (more or less known for 50 years!).
- Comparisons between interpolated F_2 from CLAS data and extrapolated F_2 from higher W shows the **intriguing possibility to provide constraints for nucleon PDFs by utilizing resonance data.**
- CLAS12 with higher Q^2 could be even more useful for bridging the gap to DIS.



A. N. Hiller Blin et al., *Phys. Rev. C* 104 (2021) 2, 025201, [hep-ph 2105.05834]
See text for PDF fits.

Motivations for (e,e’X) CLAS12

- First measurements $Q^2>5$ GeV^2 with nearly complete coverage in W (from meson threshold to 2.5 GeV) of inclusive electron scattering in the resonance region.

- Increase knowledge of the nucleon PDF in the resonance region in order to study the structure of the proton.

- Extend our understanding of the emergence of hadron mass and extend the scope of explorations of quark-hadron duality.

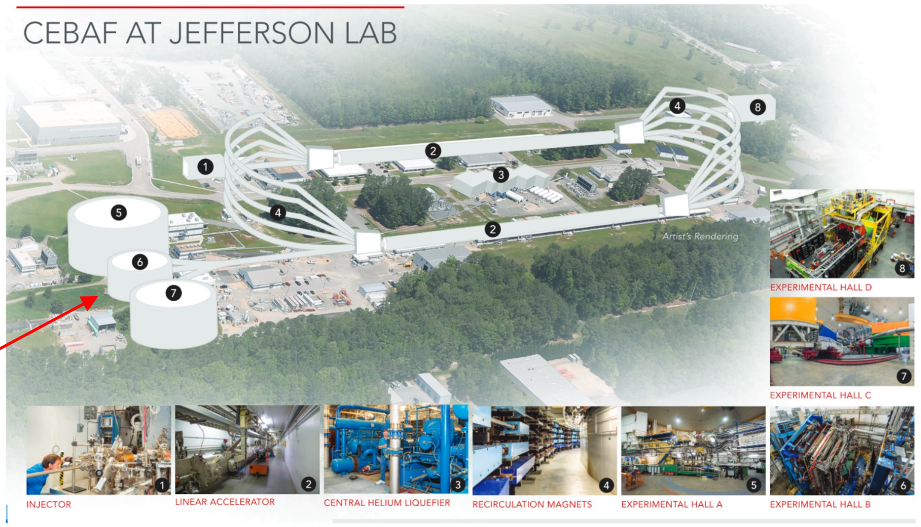
Thomas Jefferson National Accelerator Facility

- Continuous Electron Beam Accelerator Facility (CEBAF) is located in Newport News, VA.

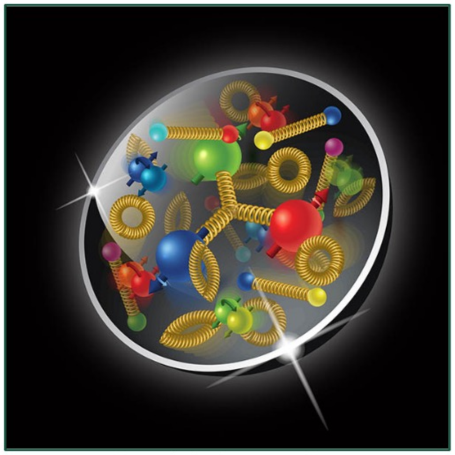
- Four experimental halls (A, B, C and D) receive a recently upgraded 12 GeV electron beam.

- Race track design with parallel north and south linear accelerators that pass the beam up to five times.

- CLAS12 located in Hall B.

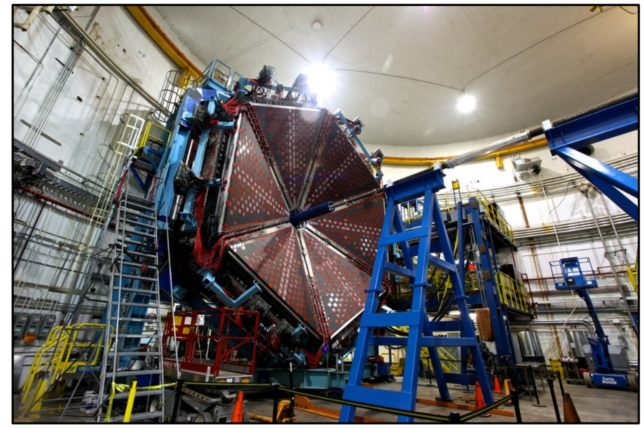


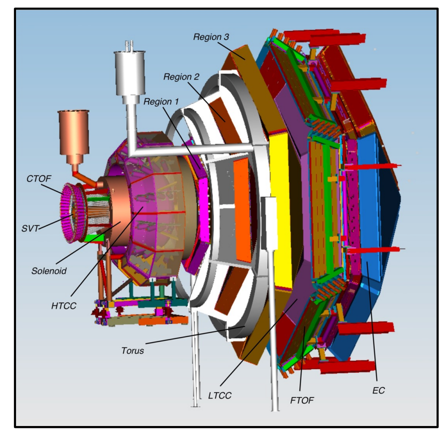
CLAS12 (Hall B) Physics Program



Stony Brook University News, August 2017

- International collaboration with more than 40 member institutions and 200 full members.
- CLAS(12) is the world's only large acceptance and high luminosity spectrometer for fixed target lepton scattering experiments.





1. Study of the nucleon resonance structure at photon virtualities from 2.0 to 12 GeV^2
2. Study of Generalized Parton Distributions (GPDs), (2 +1) D imaging of the proton and the study of its gravitational and mechanical structure.
3. Study of the Transverse Momentum Dependence (TMDs) and the of 3D structure in momentum space.
4. Study of J/ψ Photoproduction, LHCb Pentaquarks and Timelike Compton Scattering.
5. Study of meson spectroscopy in search of hybrid mesons
6. Much more!

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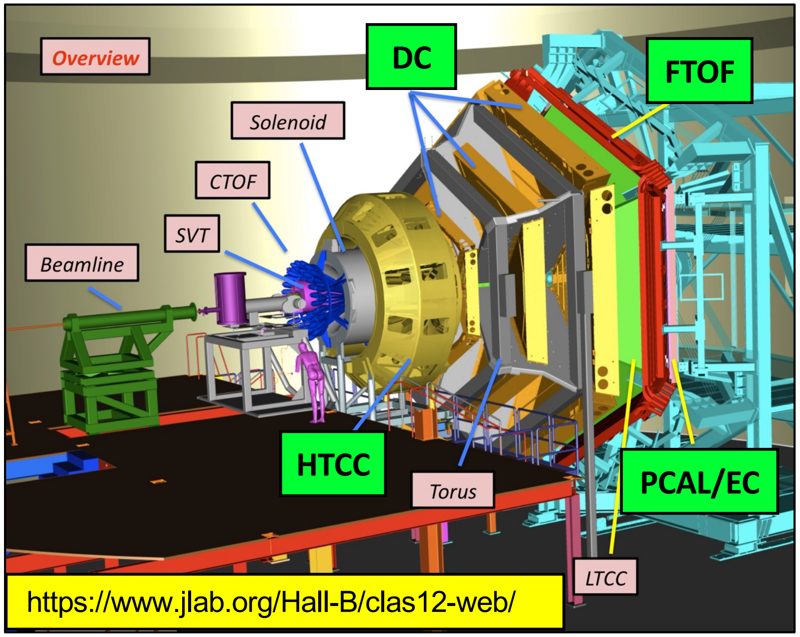
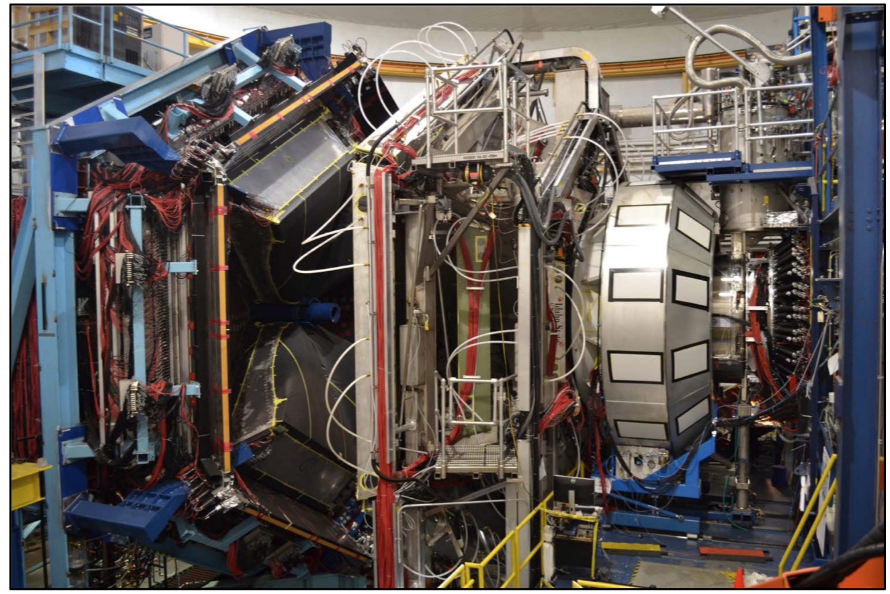
CLAS12 Spectrometer



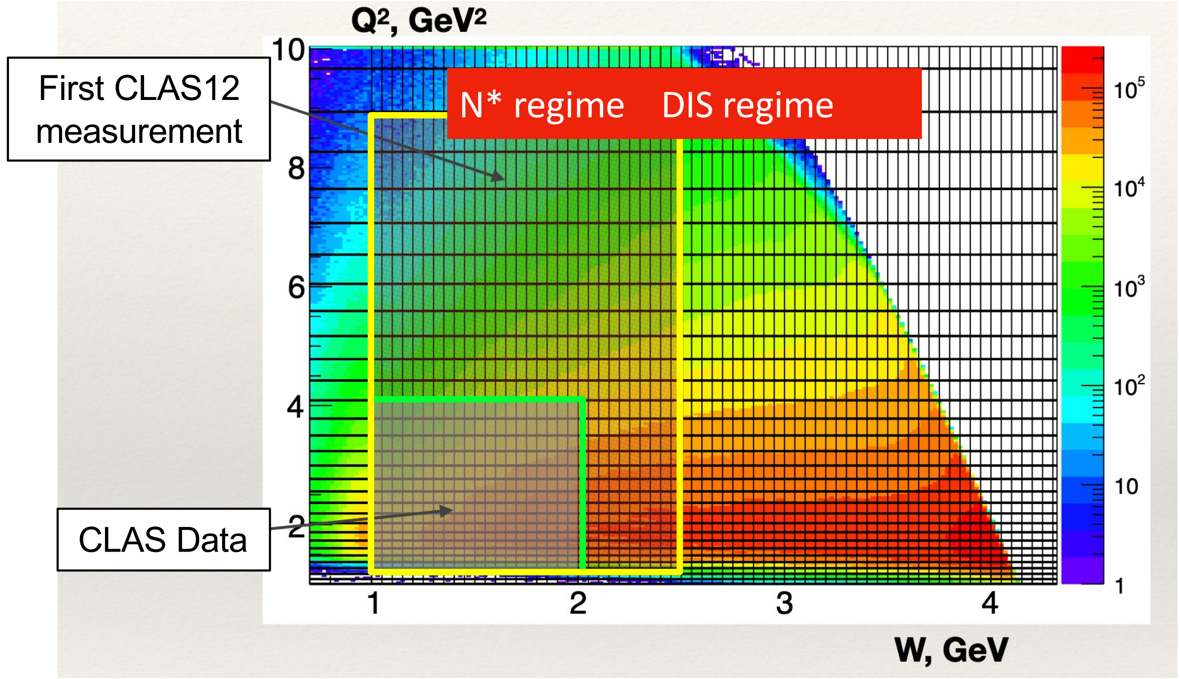


V. Burkert et al., Nucl. Instrum. Meth. A 959 (2020) 163419

- This is our first cross section measurement at 12 GeV; important to understand electron efficiency for other semi-inclusive and exclusive experiments
- CLAS12: very high luminosity, wide acceptance, low Q^2
- Began data taking in Spring 2018 – many “run periods” now available.
- Data from Fall 2018 - 10.6 GeV electron beam, longitudinally polarized beam, liquid H_2 target.

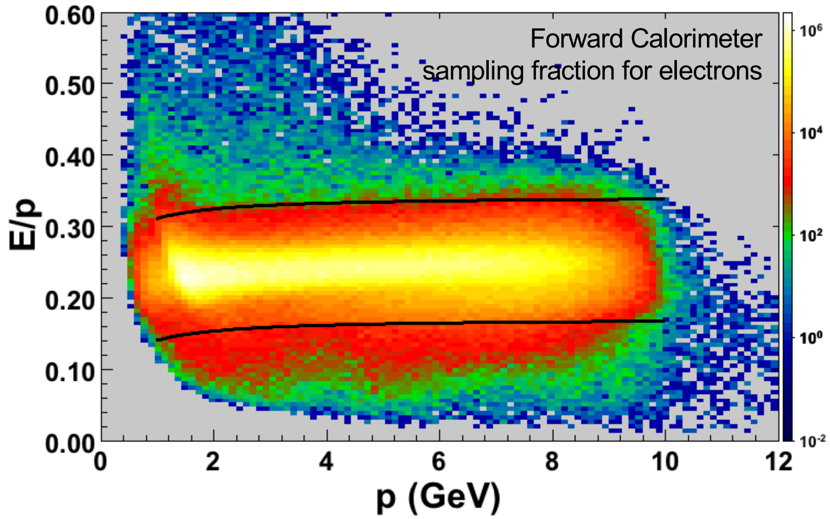
CLAS12 Kinematic Reach

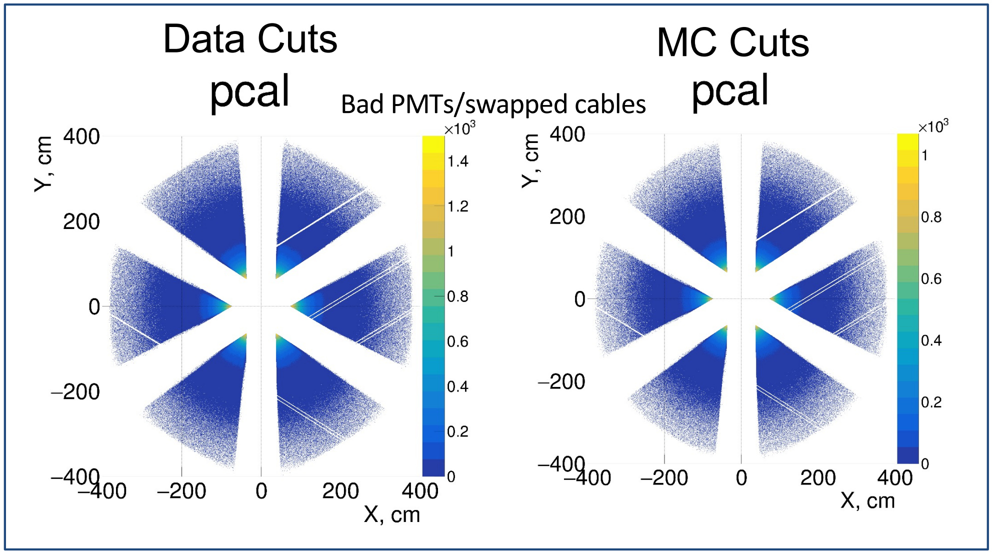
- CLAS12 inclusive data offer opportunities to explore evolution of the ground state nucleon PDF at a Q^2 range where the transition from the strong-QCD toward pQCD regimes is expected.



Electron Identification

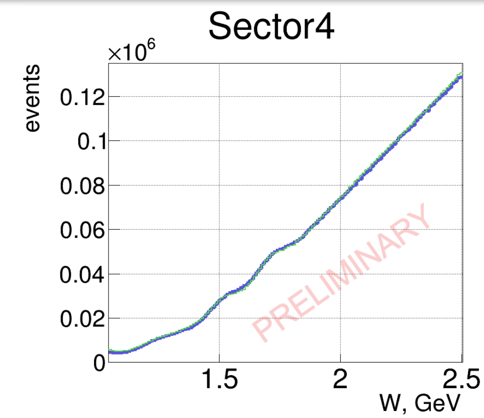
- Limited to Forward Detector (5 - 35° coverage in polar angle)
- Negative track with a hit in TOF, ECAL and HTCC
- >2.0 photoelectrons in HTCC
- 3.5-σ cuts on a parameterized momentum-dependent sampling fraction
- PCAL and DC Fiducial cuts



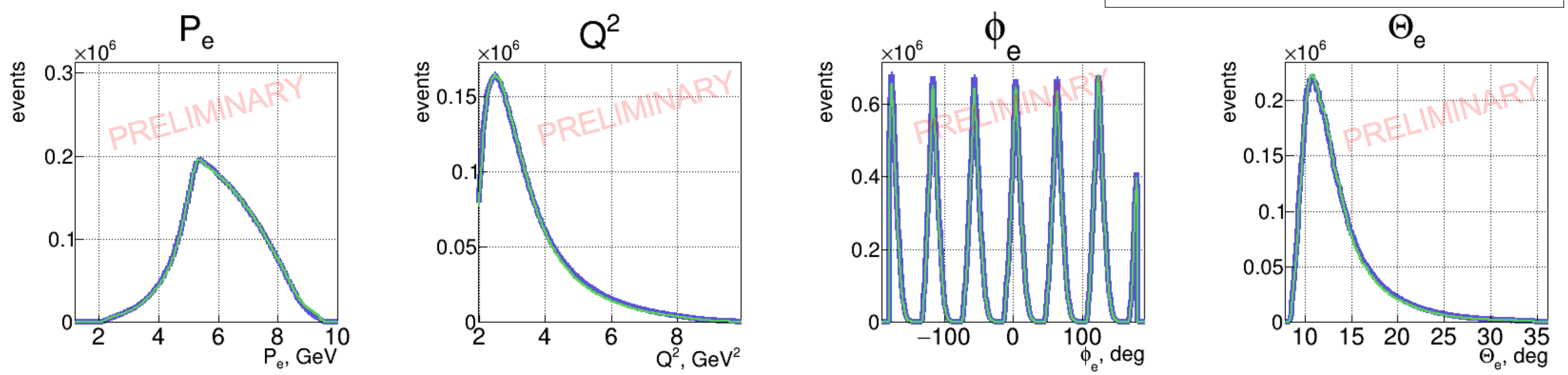


Simulation

- Inclusive EG: M. Sargsyan, CLAS-NOTE 90-007 (1990)
- Elastic tail + Inelastic radiated
- Kinematic range:
  - Theta range 5 - 36°
  - Scattered electron momentum 1.9 – 10 GeV
  - Full Q^2 coverage
  - Additional kinematic smearing to match the resolution of reconstructed data.



- Green – Data
- Blue – MC reconstructed



Cross Section Calculation

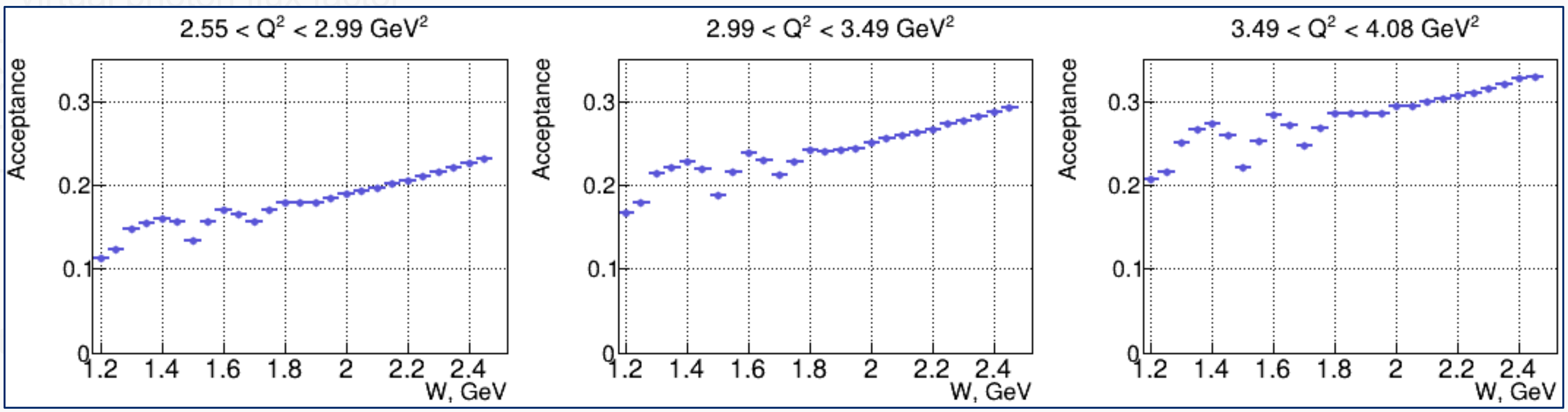
$$\frac{d\sigma}{dQ^2 dW} = \frac{1}{\Gamma_\nu} \cdot \frac{1}{\Delta Q^2 \Delta W} \cdot \frac{RC \cdot N \cdot BCC}{\eta \cdot N_0} \cdot \frac{1}{N_A \rho t / A_\omega}$$

Q^2 - four-momentum transfer squared
W - invariant mass of the final hadron system
Γ_ν - virtual photon flux factor
RC - radiative correction factor
BCC - bin centering correction
N - bin event yield
η - is the product of geometrical acceptance and electron detection efficiency
N_0 - live-time corrected incident electron flux summed over all data runs
N_A - Avogadro's number
ρ - target density
t - target length
A_ω - atomic weight of the target

Acceptance and Efficiency

$$\frac{d\sigma}{dQ^2 dW} = \frac{1}{\Gamma_\nu} \cdot \frac{1}{\Delta Q^2 \Delta W} \cdot \frac{RC \cdot N \cdot BCC}{\eta \cdot N_0} \cdot \frac{1}{N_A \rho t / A_\omega}$$

- CLAS12 detector system described in "GEMC"[1], a detailed GEANT4 simulation package.
- Same reconstruction algorithm used for simulation and data – ~10-40% acceptance depending on the bin.



1. M. Ungaro et al., "The CLAS12 Geant4 simulation," Nucl. Instrum. Meth. A, vol. 959, p. 163422, 2020.

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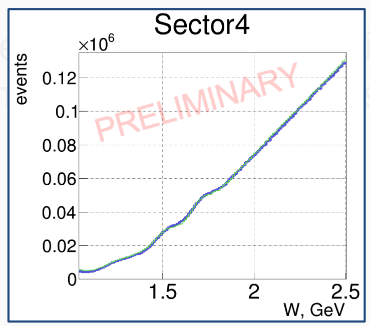
Bin Centering Corrections

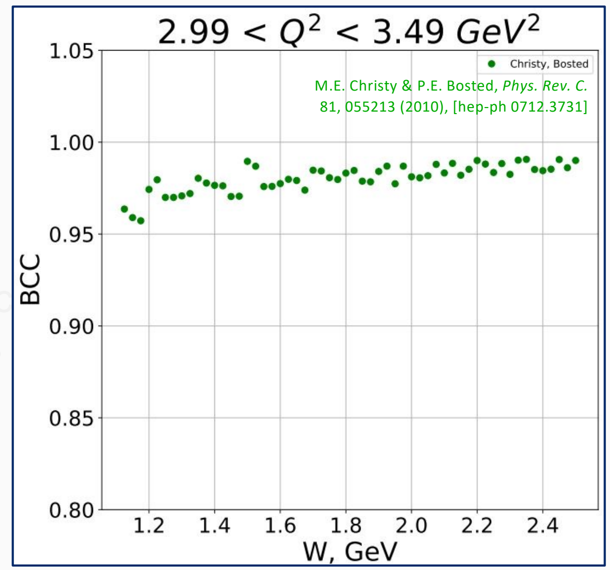
$$\frac{d\sigma}{dQ^2dW} = \frac{1}{\Gamma_\nu} \cdot \frac{1}{\Delta Q^2 \Delta W} \cdot \frac{RC \cdot N \cdot BCC}{\eta \cdot N_0} \cdot \frac{1}{N_A \rho t / A_\omega}$$

Each (Q^2,W) bin was divided into (the same) 21x11 bins

$$\text{BC Corrections (BCC)} = \frac{\textit{Cross Section (No Rad) in the central point}}{\textit{Mean Cross Section (No Rad)}}$$

Cross section generally increasing with W so BCC < 1.





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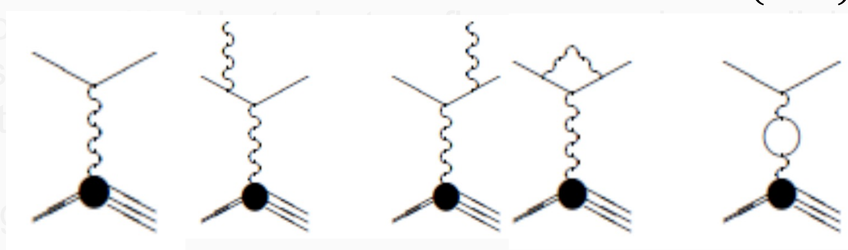
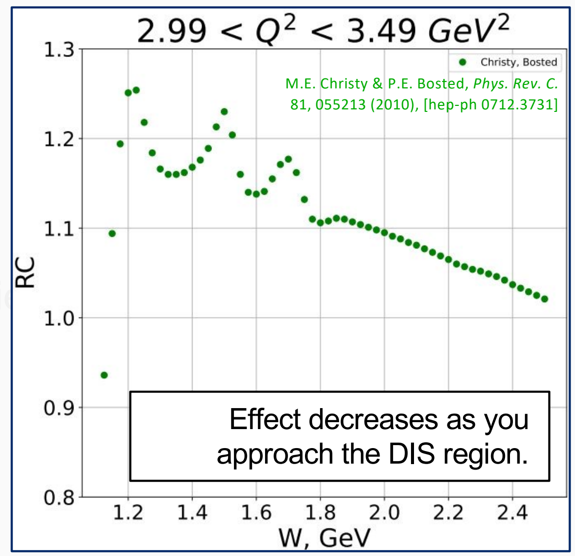
Radiative Corrections

$$\frac{d\sigma}{dQ^2dW} = \frac{1}{\Gamma_\nu}\cdot\frac{1}{\Delta Q^2\Delta W}\cdot\frac{RC\cdot N\cdot BCC}{\eta\cdot N_0}\cdot\frac{1}{N_A\rho t/A_\omega}$$

We measure the radiative cross section but want the unradiated cross section…
Christy & Bosted fit includes Hall C data with and without radiative corrections from L. W. Mo and Y. S. Tsai, Rev. Mod. Phys. 41 (1969)

$$\text{Radiative Correction (RC)} = \frac{Mean\ Cross\ Section\ (No\ Rad)}{Mean\ Cross\ Section\ (Rad)}$$

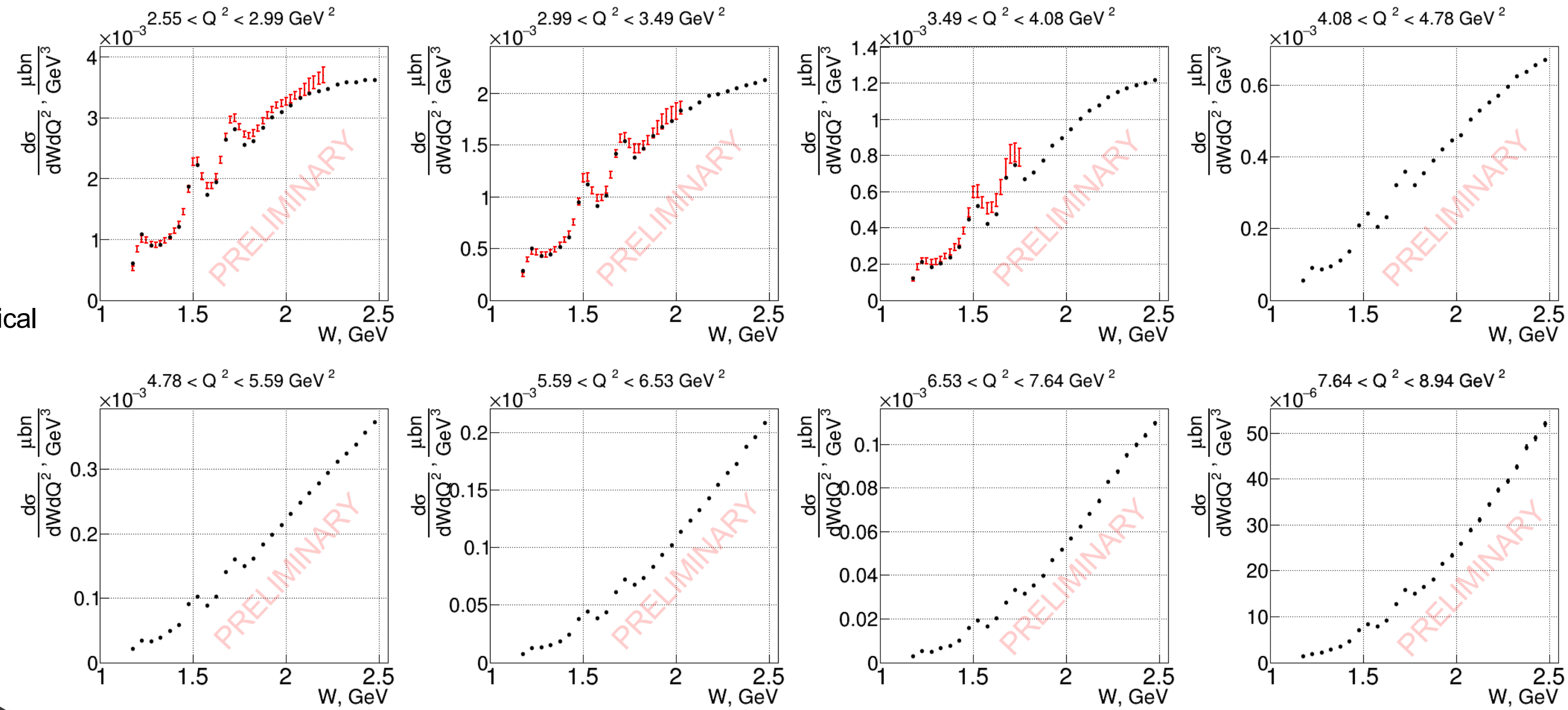




Preliminary Results

- Preliminary CLAS12 measurements
- CLAS data (after interpolation into the grid of our experiment), Phys. Rev. D67, 092001 (2003)

Only statistical errors.



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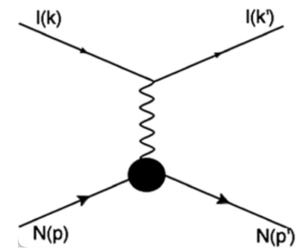
Summary

- Preliminary results on inclusive electron scattering cross sections are available from CLAS12 in the kinematic range of $1.18 < W < 2.50$ GeV and $2.6 < Q^2 < 9.0$ GeV^2 and show agreement with world data in overlapping Q^2 regions to with 20%.
- First data with broad coverage in W over the entire resonance region up to $Q^2 = 9.0$ GeV^2 where the transition from quark-gluon confinement toward pQCD is expected to take place.
- Approach for the evaluation of the resonance contributions to inclusive electron scattering by employing the CLAS results on $\gamma_v pN^*$ electrocouplings has been developed, tested with CLAS, Hall A/C data and can be extended to higher Q^2 with exclusive data from CLAS12.
- Inclusive electron scattering data from CLAS12 and the evaluated resonant/non-resonant contributions will be important in order to gain insight into the ground state nucleon PDF at large values of x in the resonance region.

Back up

Structure Functions in Inclusive Scattering

Inclusive F_1 and F_2 structure functions are related to the total virtual photon-nucleon cross sections σ_T and σ_L for transversely and longitudinally polarized photons,



$$F_1(Q^2,W) = \frac{KM}{4\pi^2\alpha}\sigma_T(Q^2,W)$$

$$F_2(Q^2,W) = \frac{KM}{4\pi^2\alpha}\frac{2x}{\rho}(\sigma_T(Q^2,W) + \sigma_L(Q^2,W))$$

F_2 can be written in terms of the unpolarized cross section (measured here).

$$F_2(Q^2,W) = \frac{KM}{4\pi^2\alpha}2x\rho^2\frac{1+R}{1+\epsilon R}\sigma_U(Q^2,W)$$

$$\sigma_U(Q^2,W) = \sigma_T(Q^2,W) + \epsilon\sigma_L(Q^2,W),$$

$$R(Q^2,W) = \frac{\sigma_L(Q^2,W)}{\sigma_T(Q^2,W)}$$

$$F_L(Q^2,W) = \frac{KM}{4\pi^2\alpha}2x\sigma_L(Q^2,W) = \rho^2 F_2(Q^2,W) - 2xF_1(Q^2,W)$$

Convenient to define the longitudinal structure function F_L in terms of the longitudinal cross section (or F_1 and F_2).

R is the ratio of longitudinal to transverse cross sections. Total inclusive cross sections have been measured extensively but the ratio R is known with much less accuracy.

c.f. A. N. Hiller Blin et al., *Phys. Rev. C* 104 (2021) 2, 025201, [hep-ph 2105.05834]

Systematics

- Pion misidentification as electrons
- Model dependence (RC, BCC, etc.)
- Momentum corrections
- Sector dependence

Empty Target

- Empty Target Contribution

$$yield = yield_{hydrogen} - yield_{empty} * \frac{Faraday\ Cup\ Charge\ Hydrogen}{Faraday\ Cup\ Charge\ Empty}$$

Empty Target Contribution for a few Q^2 bins