Symposium: Nucleon and nuclei structure from inclusive measurements

Inclusive electron scattering off the proton with CLAS12 at JLab

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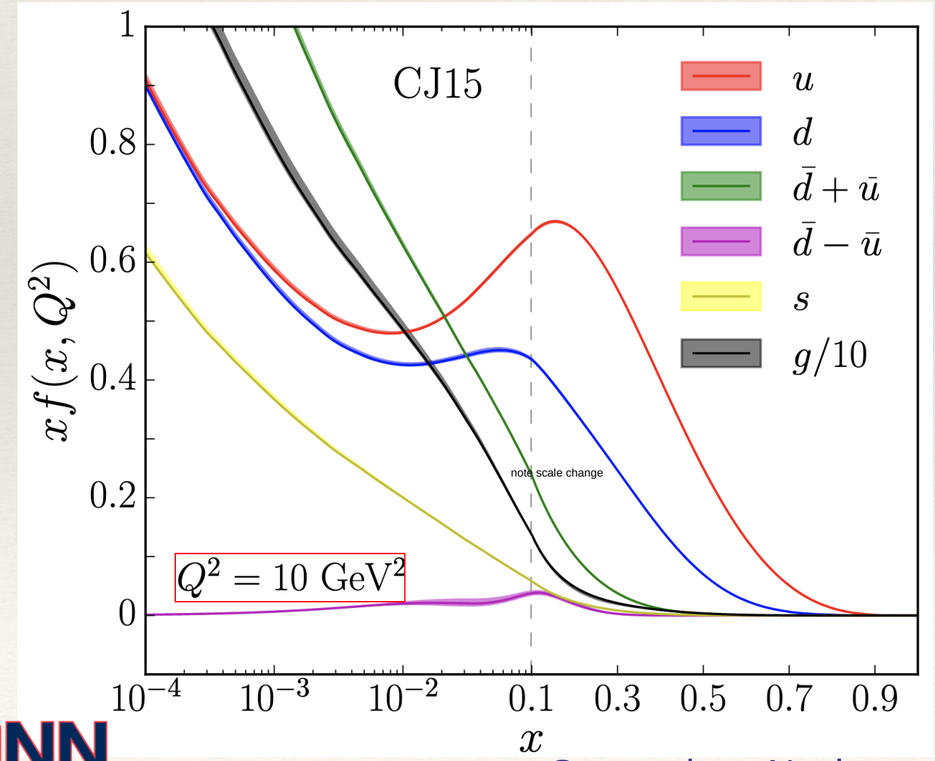
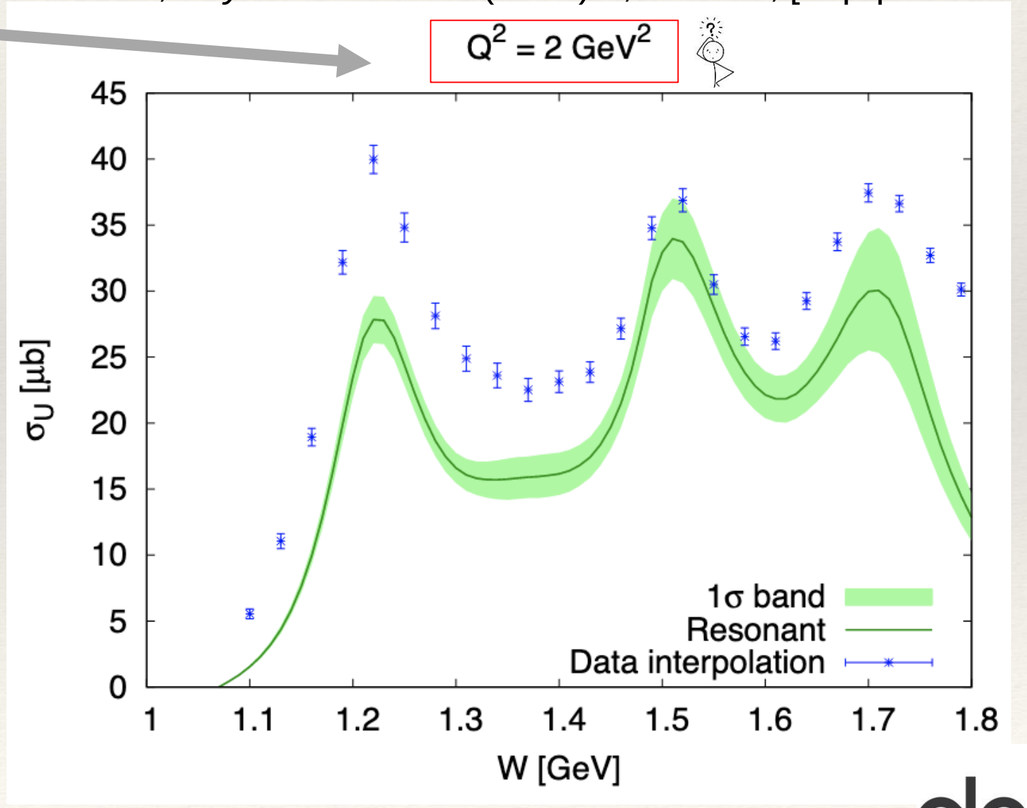
Extending Knowledge of the Nucleon PDF in the Resonance Region

- Global QCD analyses have provided detailed information on the nucleon PDFs in a wide range of parton 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.

A. Accardi et al., *Phys. Rev. D.* 11, 114017 (2016), [hep-ph 1602.03154]



A. N. Hiller Blin et al., *Phys. Rev. C* 100 (2019) 3, 035201, [hep-ph 1904.08016]

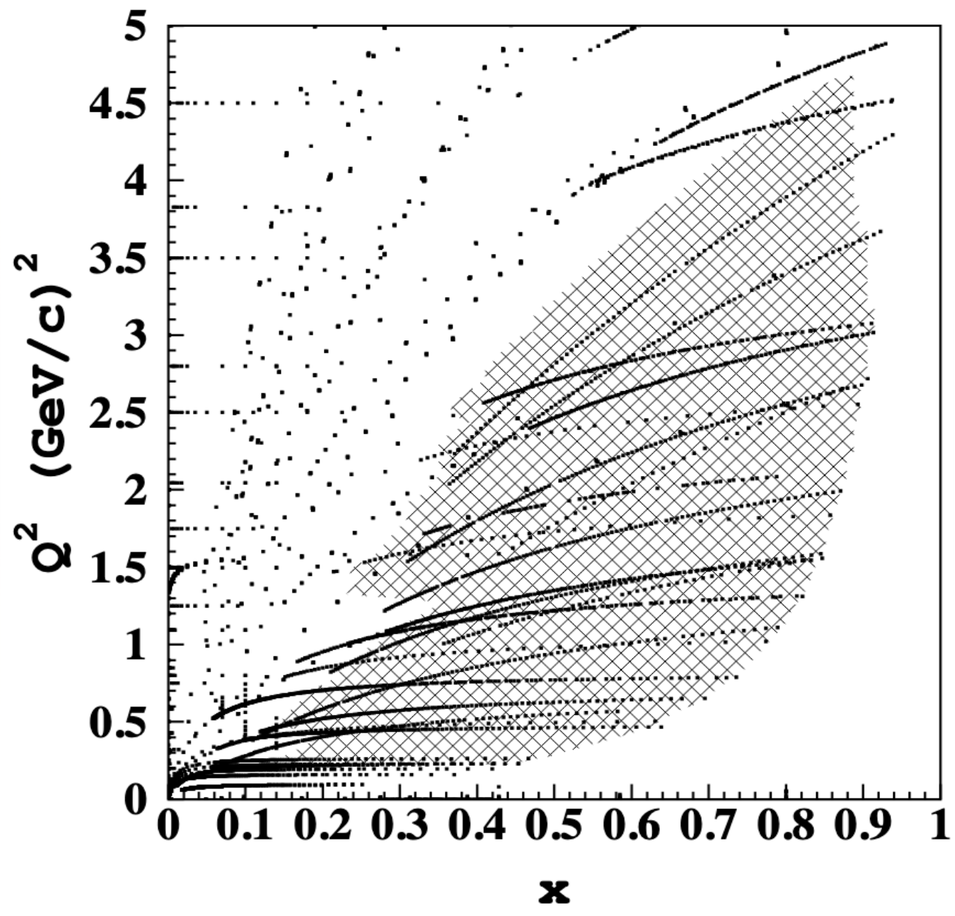


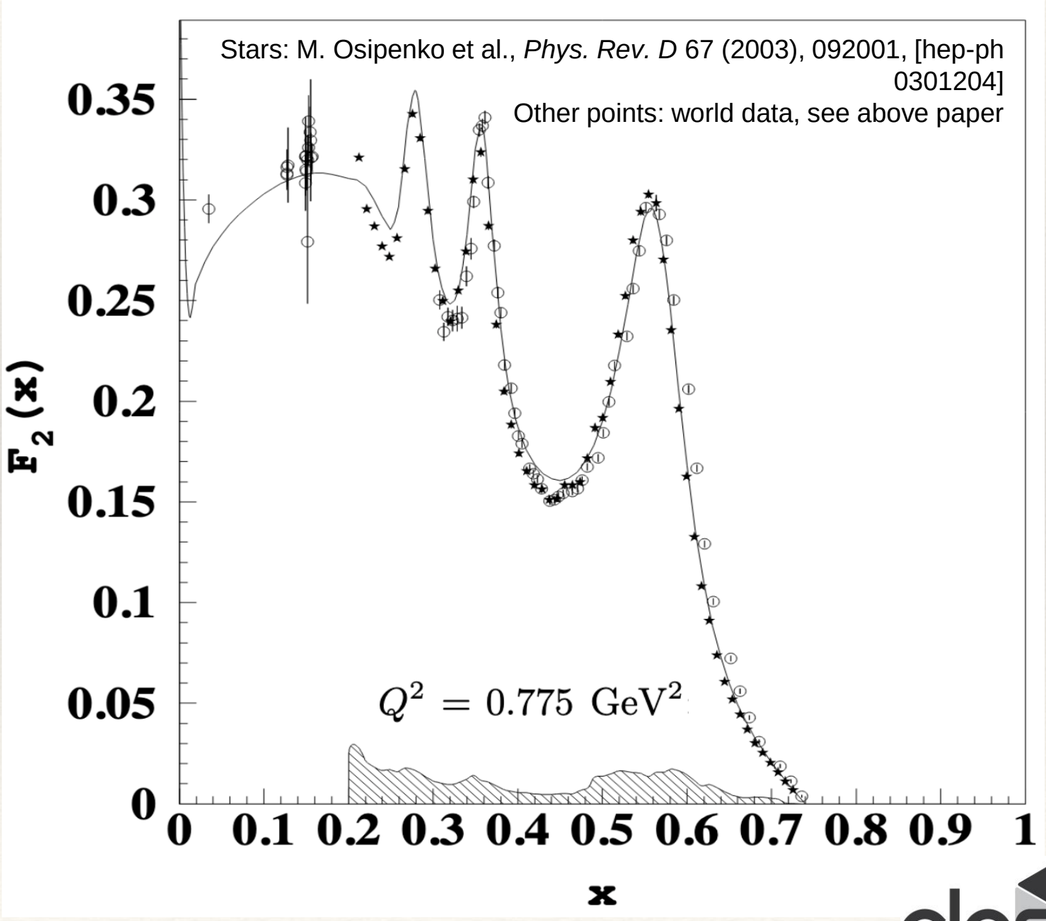
CLAS Results

- CLAS measured the inclusive cross section up to x = 0.9 and Q^2 from 0.25 to 4.5 GeV^2.
- Owing to large acceptance of CLAS, the information on inclusive structure function F_2 can be obtained within a wide range of W from pion threshold to maximal kinematically allowed W-values in any given bin of Q^2 covered in the measurements.

M. Osipenko et al., *Phys. Rev. D* 67 (2003), 092001, [hep-ph 0301204]

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





Resonant Contributions

- CLAS results on $\gamma_v pN^*$ electrocouplings for most N* in the mass range W<1.8 GeV allowed us to evaluate the resonant contributions to F_2 structure function from the experimental results on resonance electroexcitation amplitudes.
- Resonant contributions demonstrate pronounced evolution with photon virtuality Q^2 different in the first, the second and the third resonance regions.
- Information on Q^2 evolution $\gamma_v pN^*$ electrocouplings for all prominent N* is needed for realistic evaluation of the resonant contribution into inclusive electron scattering observables.

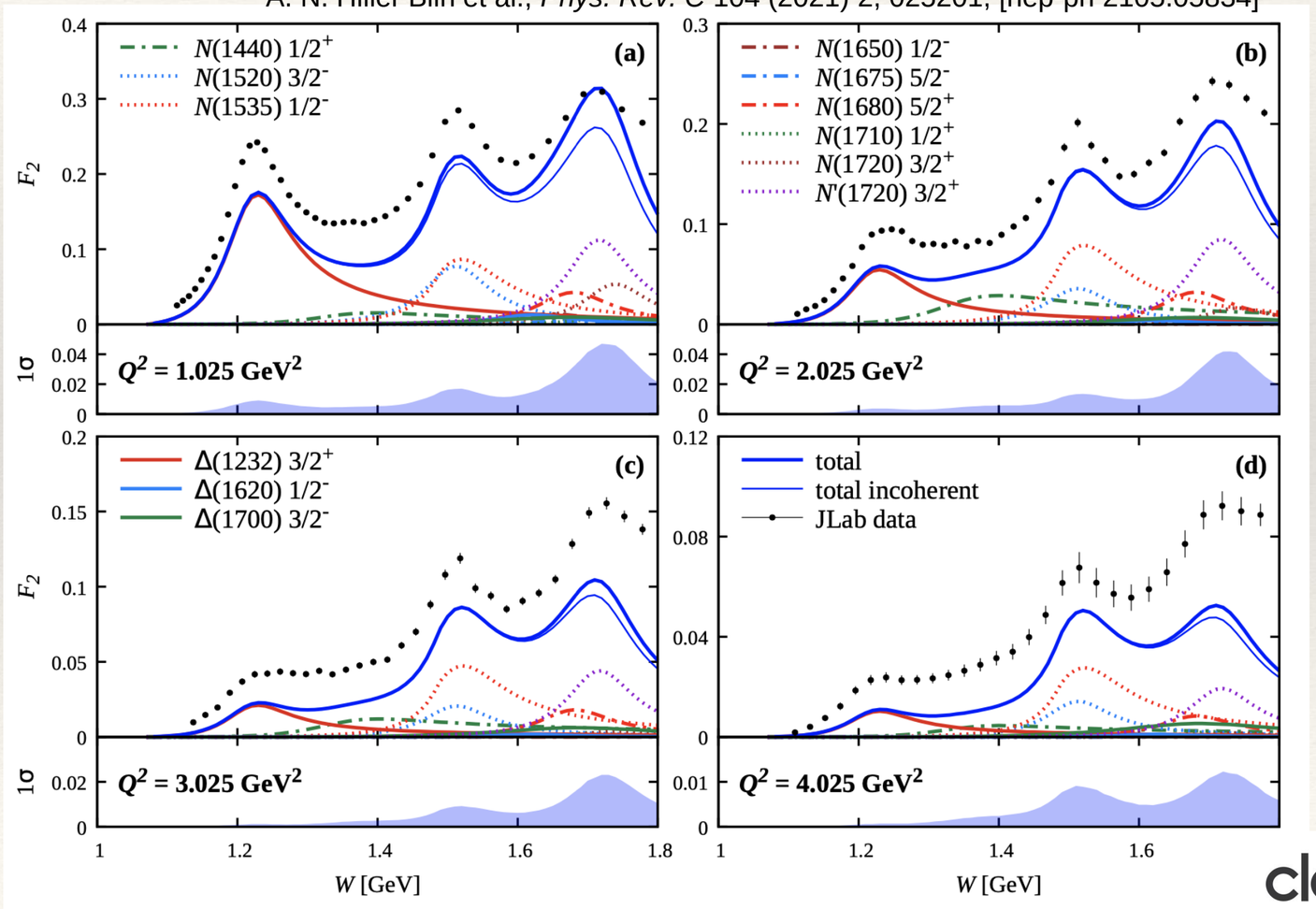
$$\sigma^R_{T,L}(W,Q^2) = \frac{\pi}{q^2_\gamma}\sum_R (2J_R+1)\frac{M_R^2\,\Gamma_R(W)\,\Gamma^{T,L}_{\gamma,R}(M_R,Q^2)}{\left(M_R^2-W^2\right)^2+\left(M_R\Gamma_R(W)\right)^2}$$

Decay widths of resonance R to $\gamma^* p$ related to electrocouplings from previous slide.

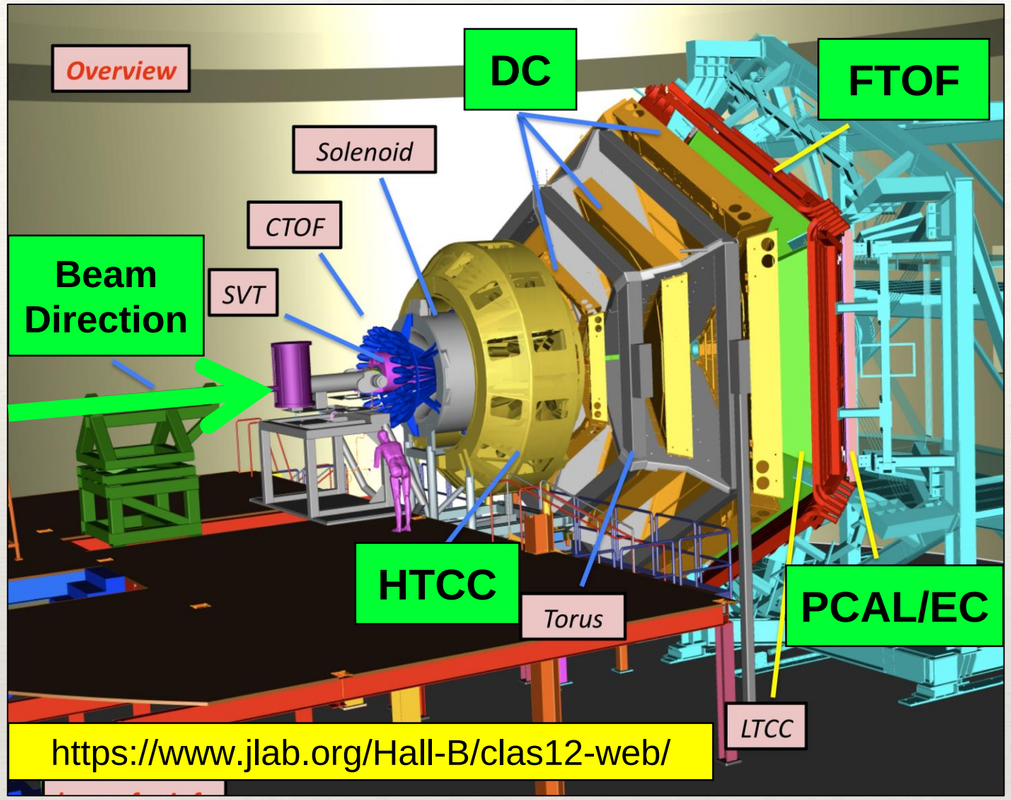
$$\Gamma^T_{\gamma,R}(W=M_R,Q^2) = \frac{q^2_{\gamma,R}(Q^2)}{\pi}\frac{2M}{(2J_R+1)M_R} \times\left(\left|A^R_{1/2}(Q^2)\right|^2+\left|A^R_{3/2}(Q^2)\right|^2\right),$$

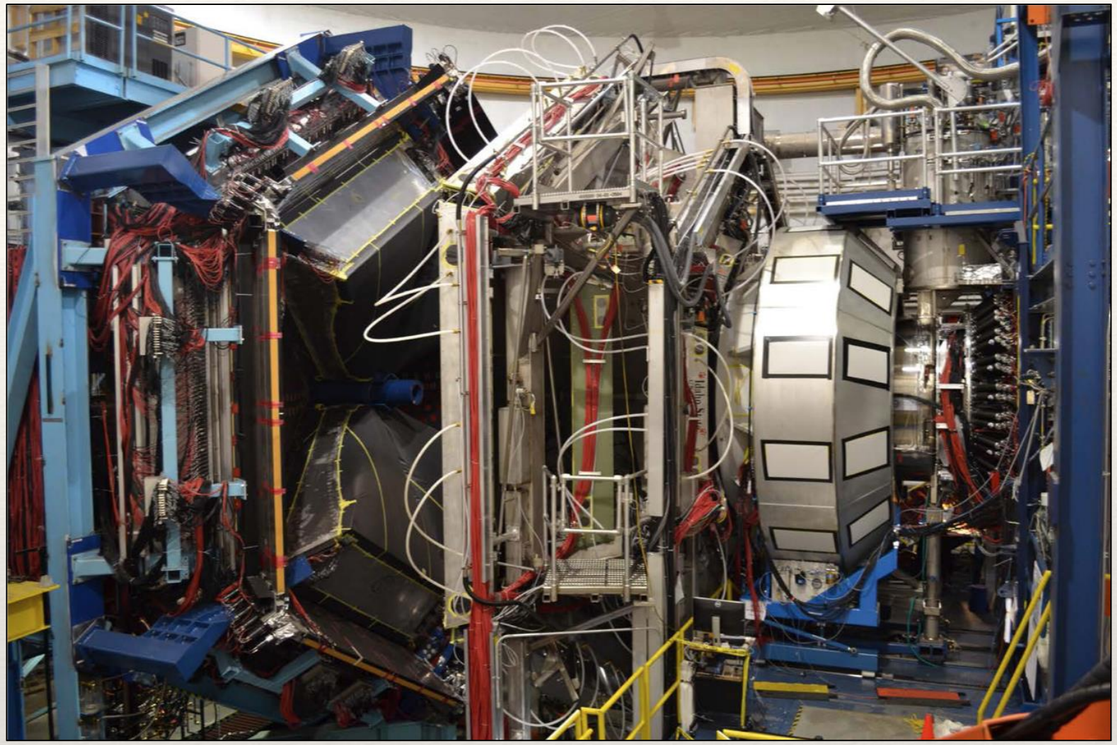
$$\Gamma^L_{\gamma,R}(W=M_R,Q^2) = \frac{2q^2_{\gamma,R}(Q^2)}{\pi}\frac{2M}{(2J_R+1)M_R} \times\left|S^R_{1/2}(Q^2)\right|^2,$$

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



Inclusive Measurement



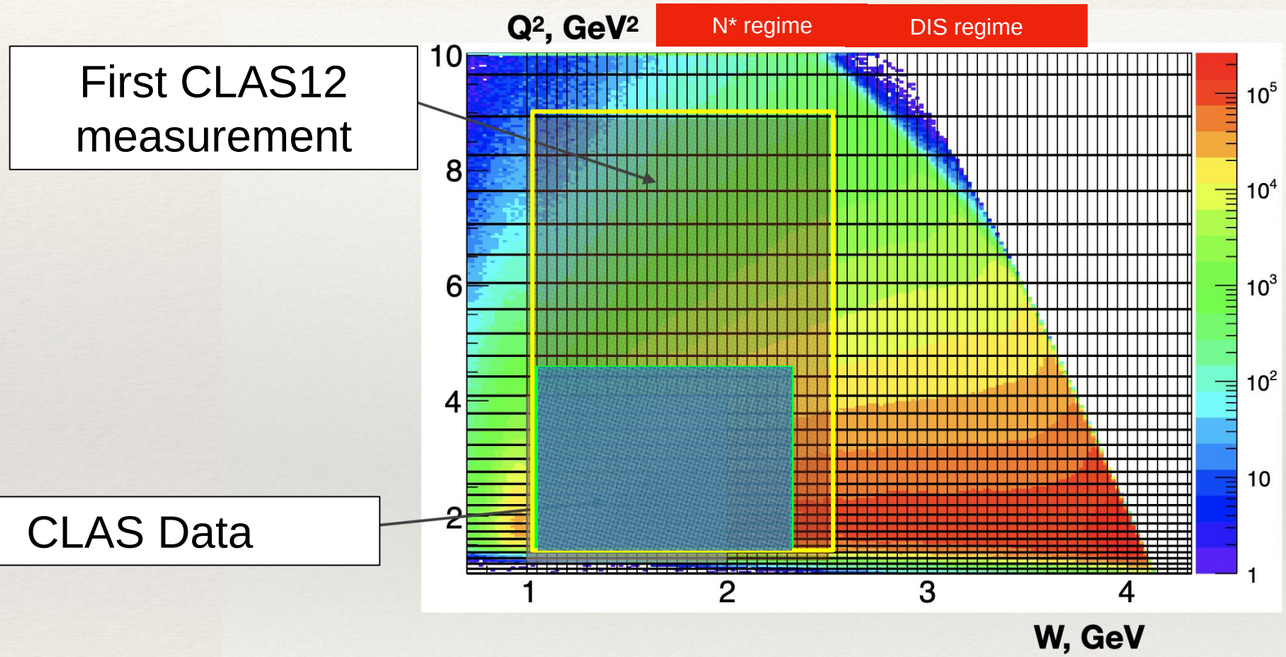


V. Burkert et al., Nucl. Instrum. Meth. A 959 (2020) 163419

- Measurements of (e,e'X) inclusive cross sections are important to understand electron detection efficiency needed for evaluation of the cross sections of semi-inclusive and exclusive processes foreseen in the exploration with the CLAS12 detector
- CLAS12: 10^{35} $cm^{-2}sec^{-1}$ luminosity, nearly 4π acceptance, 0.05 $GeV^2 < Q^2 < 10.0$ GeV^2 coverage over photon virtuality.
- 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.

Inclusive Measurement

- RG-A Fall 2018
- Beam energy is 10.6 GeV
- Torus/Solenoid = -100%/-100% (inbending)
- Beam current 45 – 55 nA
- Faraday cup charge is 3 * 10^7 nC
- CLAS Kinematic coverage:
  - $0.225 < Q^2 < 4.5$ GeV^2
  - $1.0815 < W < 2.4$ GeV
- CLAS12 Kinematic coverage:
  - $0.5 < Q^2 < 10$ GeV^2
  - $0.1 < W < 4$ GeV



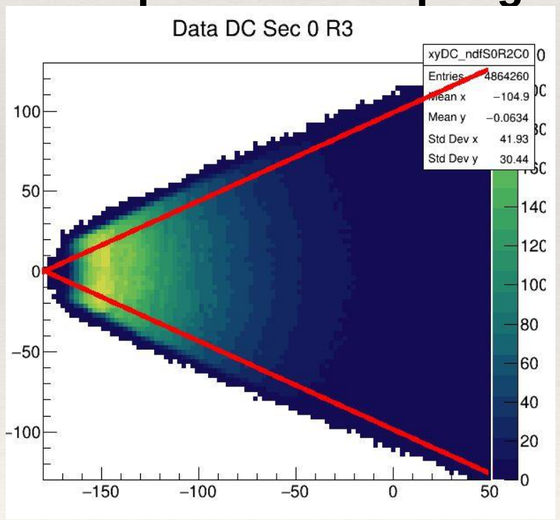
Cross Section Calculation

$$\frac{d\sigma}{dQ^2 dW} = \frac{1}{\Delta Q^2 \Delta W} \cdot \frac{N}{\eta \cdot R \cdot BC \cdot N_0} \cdot \frac{1}{N_A \rho t / A_\omega} \quad (1)$$

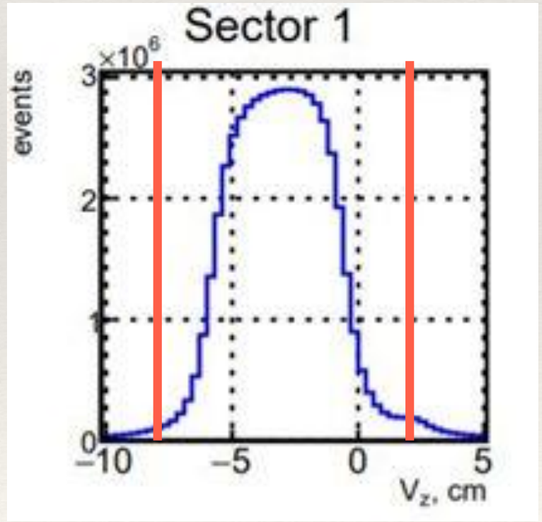
- Q^2 - four-momentum transfer squared
- W - invariant mass of the final hadron system
- RC - radiative correction factor
- BC - bin centering correction
- N - bin event yield
- η - is the product of geometrical acceptance and electron detection efficiency
- N_0 - live-time corrected incident electron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

Electron PID

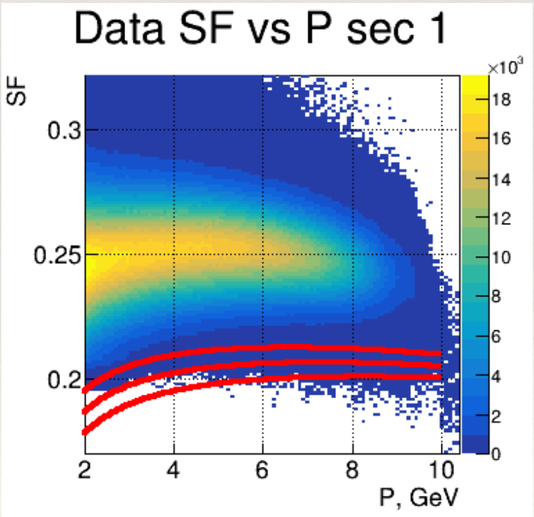
- Limited to Forward Detector (5 - 35° coverage in polar angle).
- Negative track with a hit in Time-of-Flight, Electromagnetic Calorimeters and High Threshold Cherenkov Counter (HTCC).
- >2.0 photoelectrons in HTCC.
- **DC Fiducial cuts**.
- **-8 < Vertex Z < 2 cm**
- **3.5-σ cuts on a parameterized momentum-dependent sampling fraction.**
- PCAL fiducial cut
- >70 MeV PCAL
- Electron/pion separation (triangular cut)



DC fid cut



Vz cut



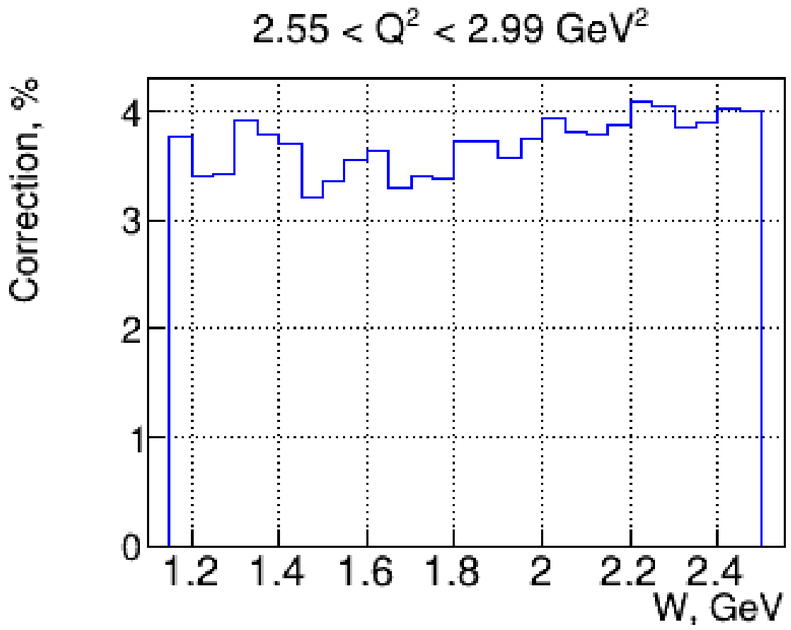
Forward Calorimeter sampling fraction for electrons: 3.5σ ± 0.5σ

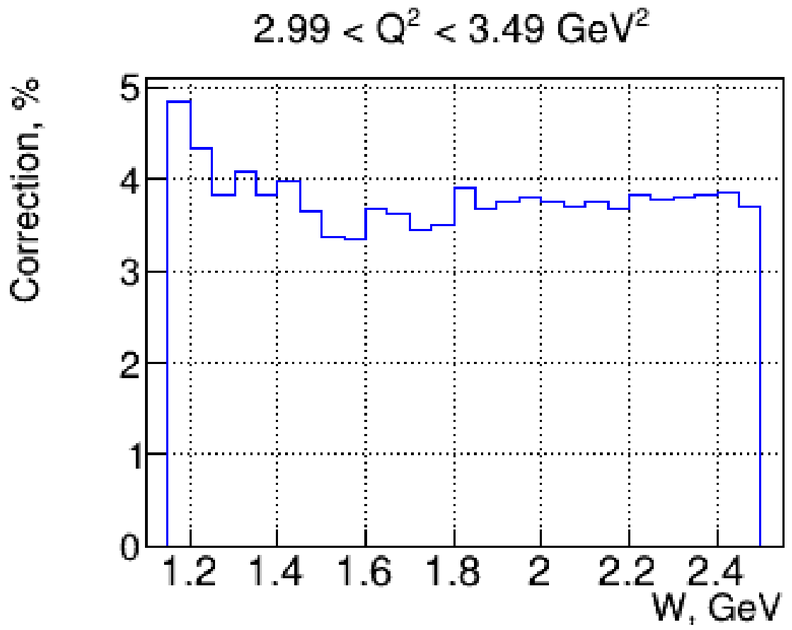
Empty Target Contribution

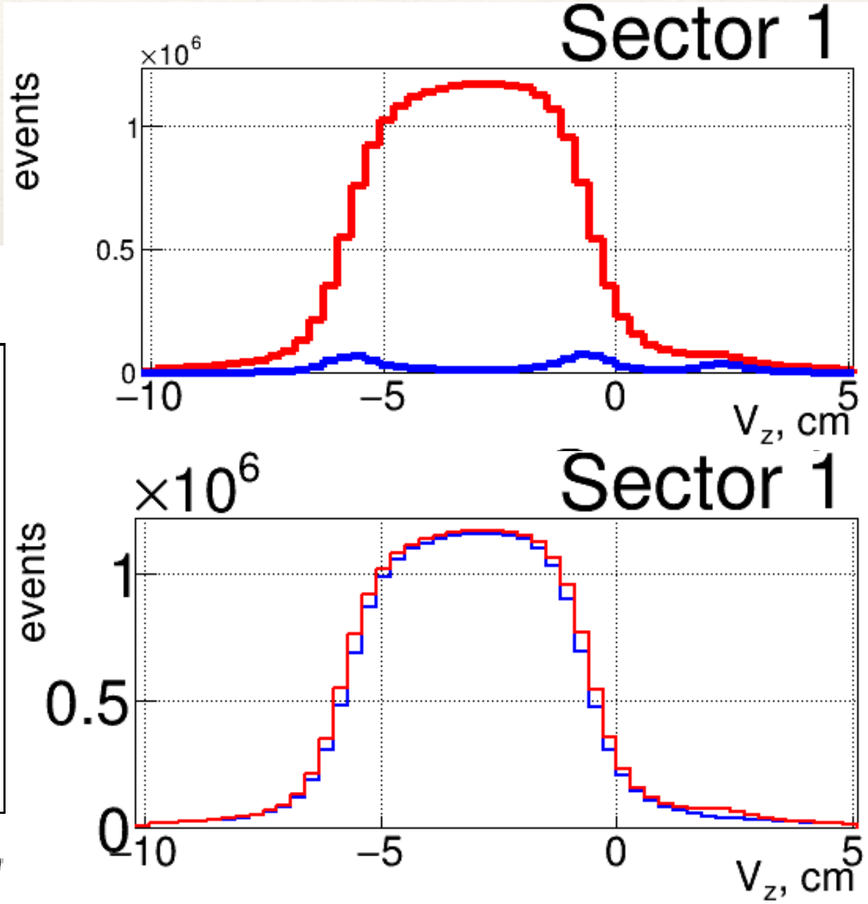
- Empty Target Contribution

$$yield_{hydrogen} = yield_{Full\ Target} - yield_{empty} * \frac{Faraday\ Cup\ Charge\ Full\ Target}{Faraday\ Cup\ Charge\ Empty}$$

Empty Target Contribution for a few Q^2 bins



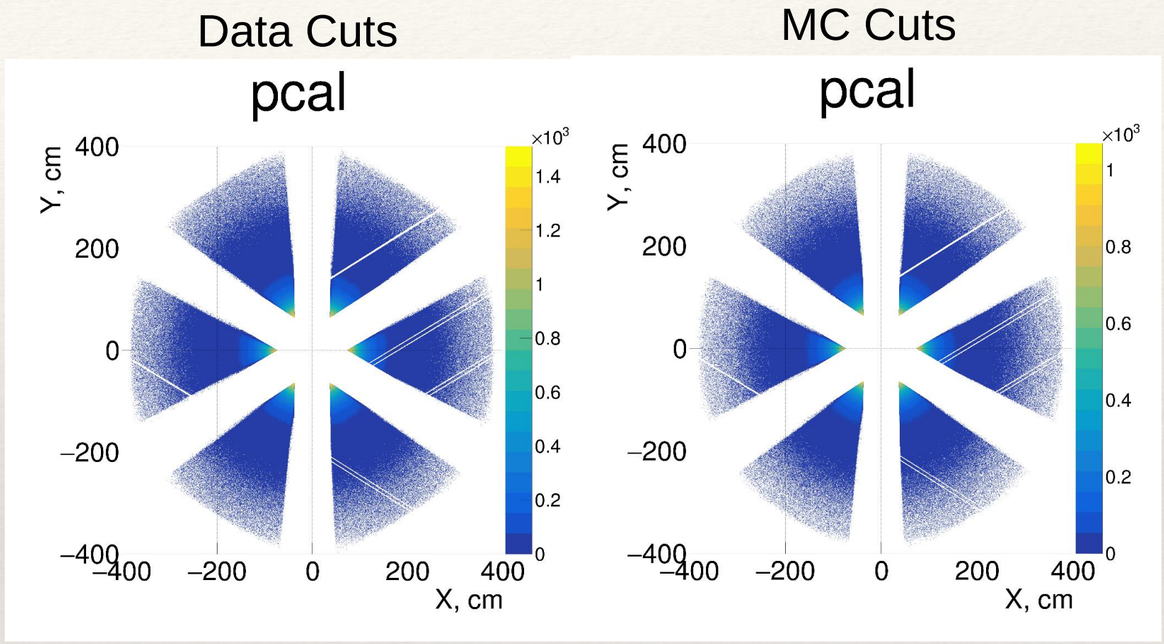




Simulation

Acceptance η in (1)

- Inclusive EG: M. Sargsyan, CLAS-NOTE 90-007 (1990).
- Elastic tail + Inelastic radiated.
- Background merging 45-55 nA
- Kinematic range:
  - Theta range 5 - 40°
  - Scattered electron momentum 1.4 – 11 GeV
  - Full Q^2 coverage.
  - Additional kinematic smearing to match the resolution of reconstructed data.



Acceptance Corrections

Acceptance η in (1)

Acceptance corrections can be done with multiple methods. One is bin-by-bin method and there are plenty of matrix methods:

- **Bin-by-bin:**

$$Acceptance = \frac{\#\ Events\ Reconstructed}{\#\ Events\ Generated}$$

It is enough in case of “realistic” EG and “good ”MC. It does not include connection between Gen. and Rec. event.

CERN RooUnfold package was used:
https://gitlab.cern.ch/RooUnfold/RooUnfold

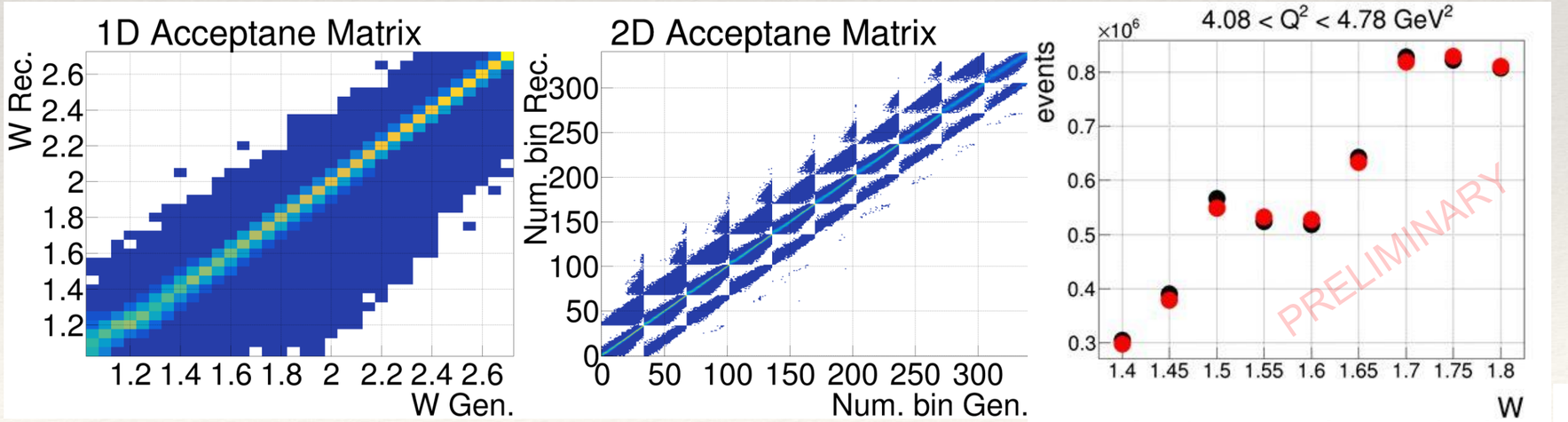
- **Acceptance Matrix:** $A_{(i,j)}$ describes both Acceptance (geometrical acceptance and detector efficiency) and Bin Migration:

$$A_{(i,j)} = \frac{\#\ Events\ Generated\ in\ bin\ j\ but\ Reconstructed\ in\ bin\ i}{Total\ number\ of\ Events\ Generated\ in\ the\ jth\ bin}$$

Acceptance unfolding: $Y_i = A_{(i,j)}X_j \Rightarrow X_j = A^{-1}_{(i,j)}Y_i$ where Y_i number of measured events in i-th bin, X_j is number of acceptance corrected events in j-th bin

We used:

1. Bin-by-bin
2. SVD
3. Bayesian Matrix 2D



Red - 2D Bayesian method
Black - Bin-by-bin method

Radiative Corrections

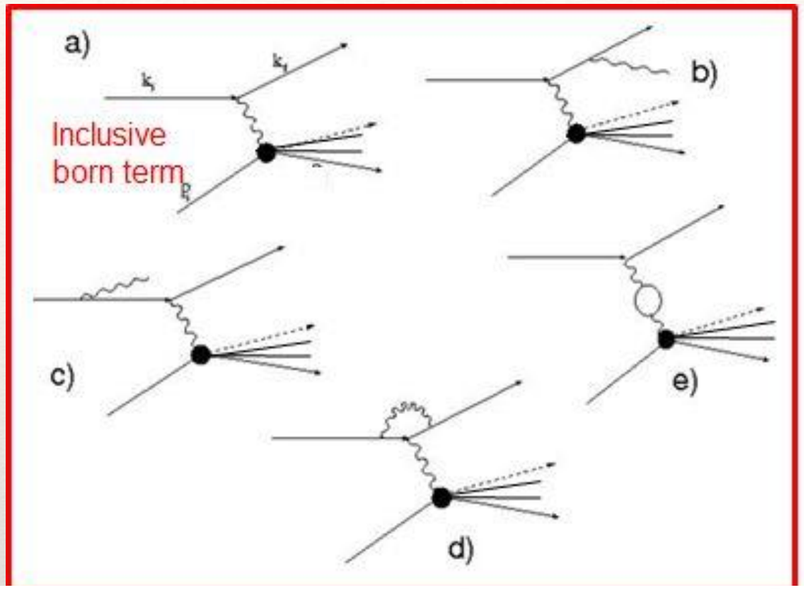
R in (1)

Each (Q^2,W) bin was divided into 21x11 sub bins. Cross Sections with rad. effects on and off were calculated in every sub bin.

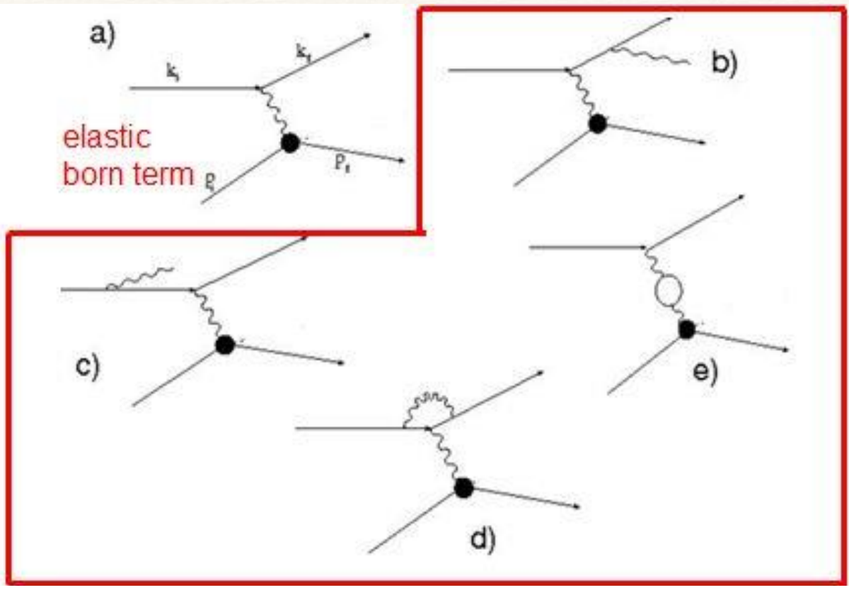
Radiative Correction factor:

$$\frac{Mean\ Cross\ Section\ (Rad)}{Mean\ Cross\ Section\ (No\ Rad)}$$

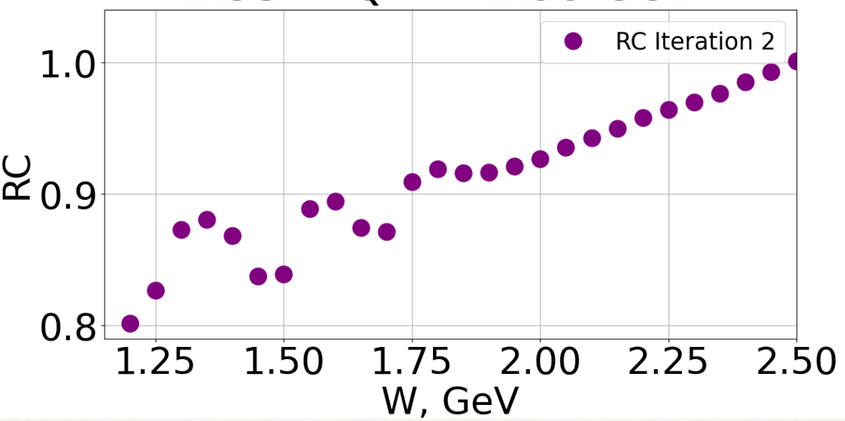
Inclusive with radiative effects



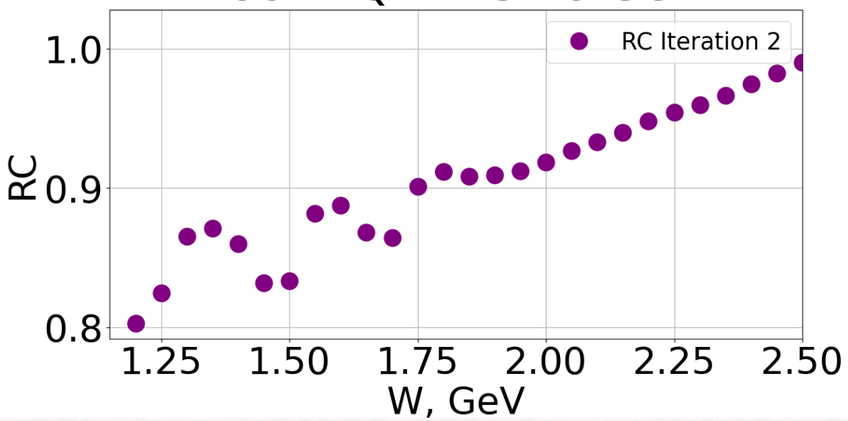
Elastic with radiative effects



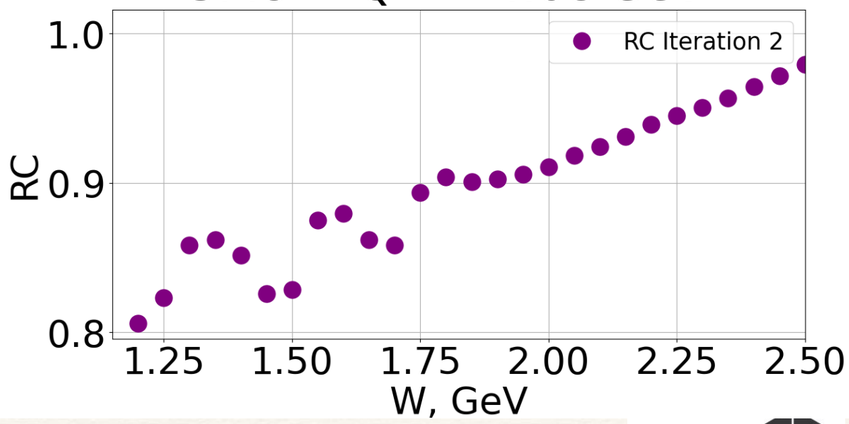
$2.55 < Q^2 < 2.99\ GeV^2$



$2.99 < Q^2 < 3.49\ GeV^2$



$3.49 < Q^2 < 4.08\ GeV^2$



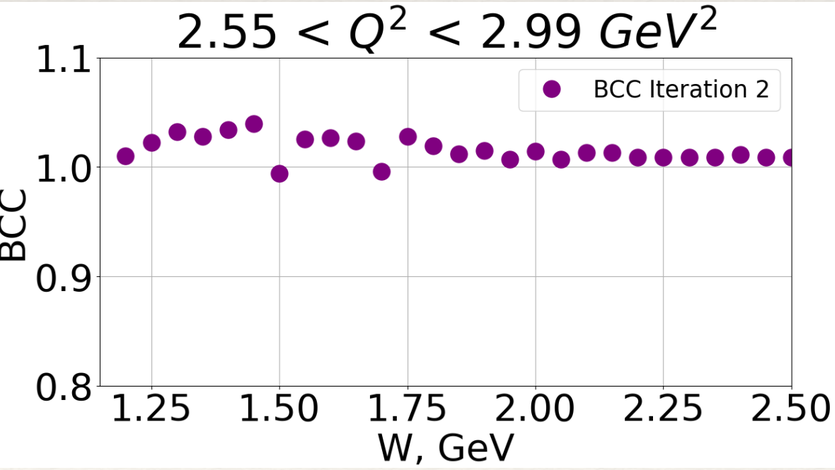
Bin Centering Corrections

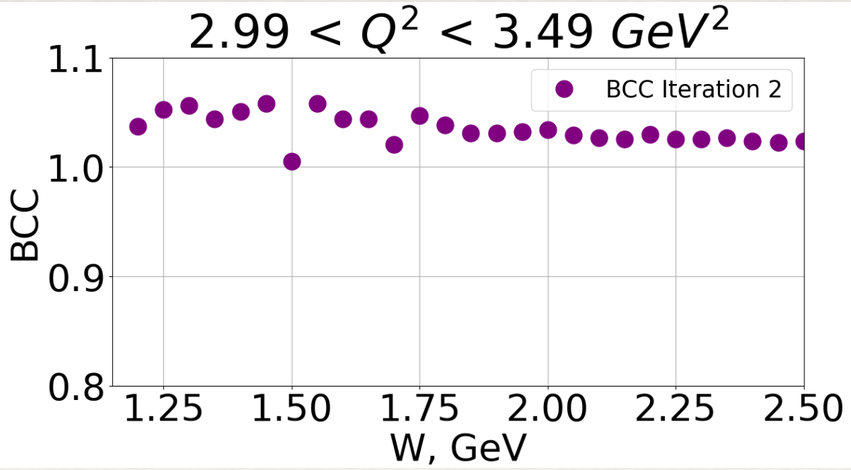
BC in (1)

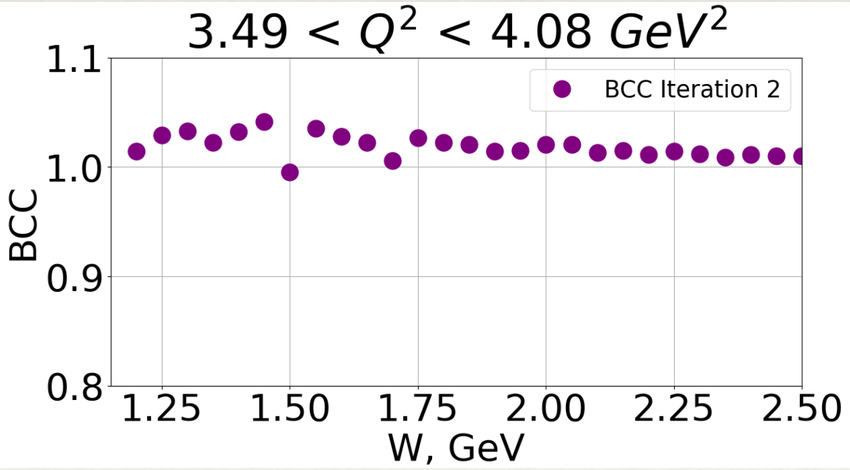
$$\frac{d\sigma}{dQ^2dW} = \frac{1}{\Delta Q^2 \Delta W} \cdot \frac{N}{\eta \cdot R \cdot \boxed{BC} \cdot N_0} \cdot \frac{1}{N_A \rho t / A_\omega}$$

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

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

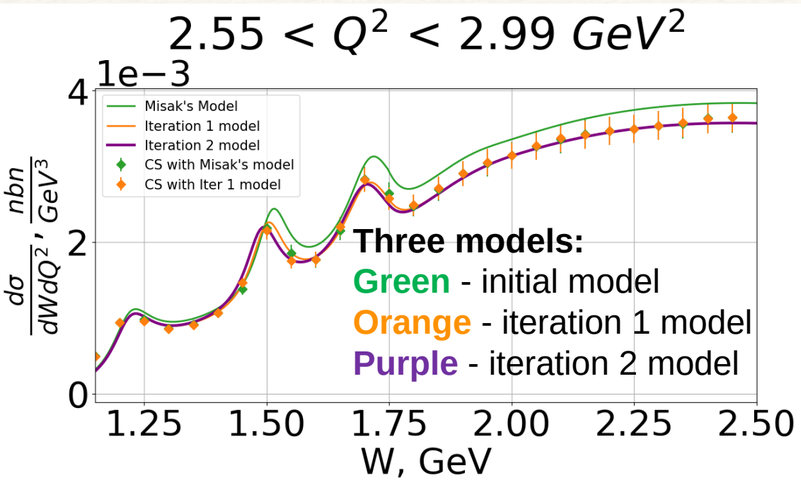


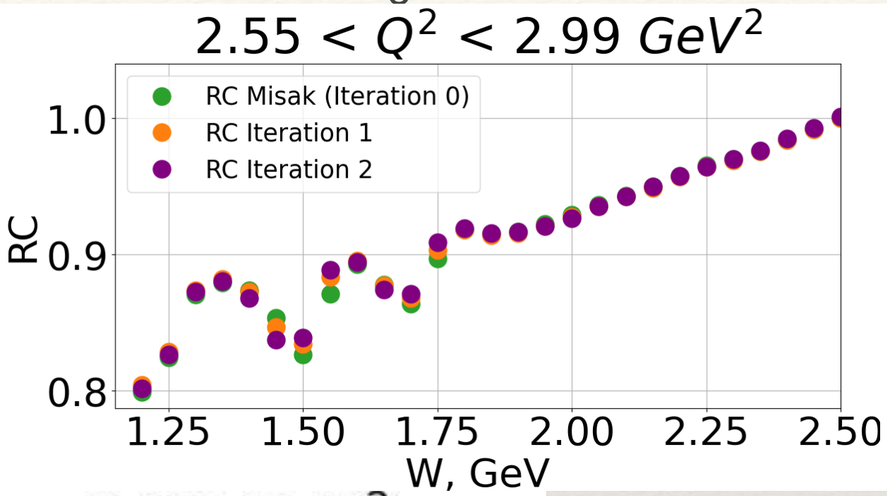


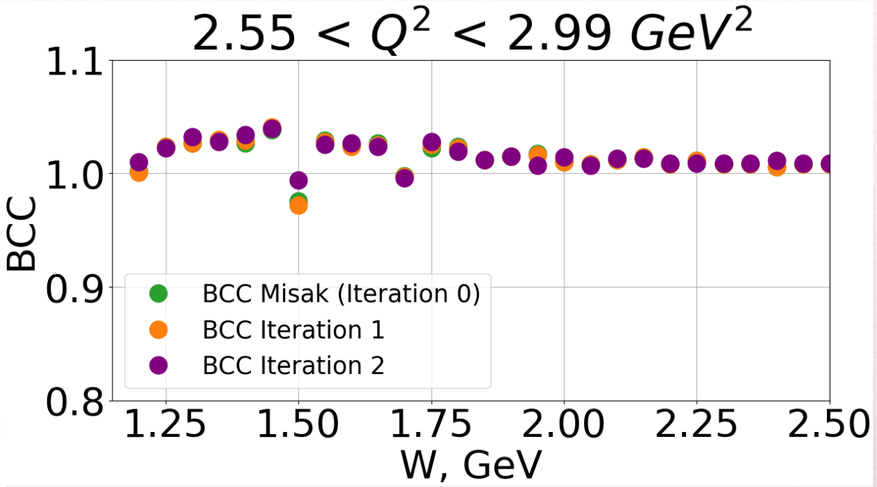


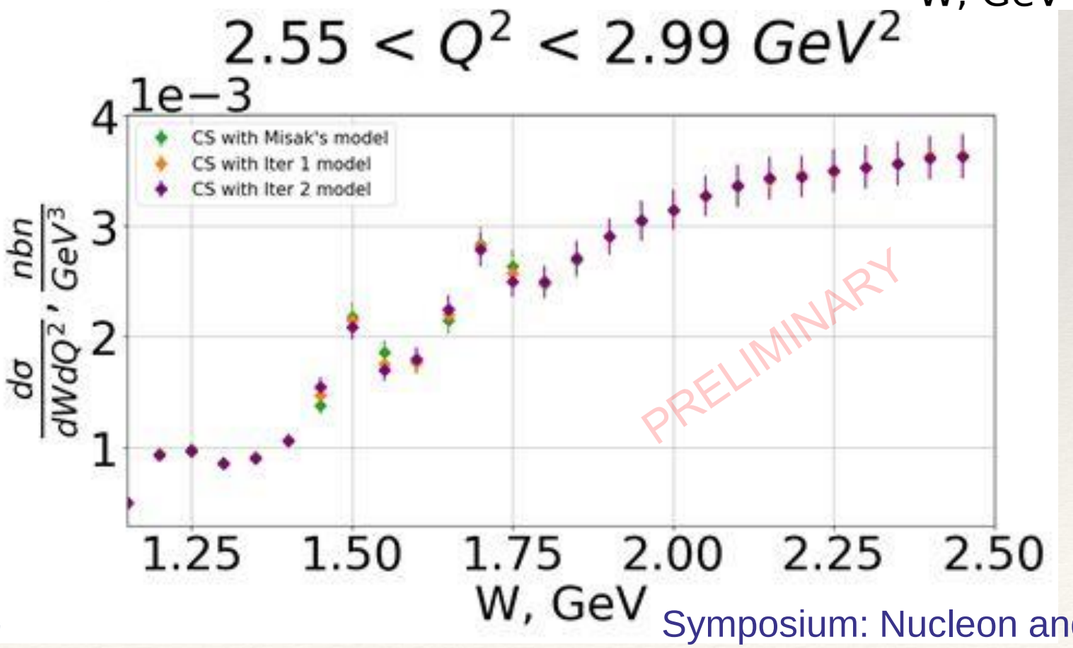
Iterations

After applying all the corrections and normalization accordingly to faraday cup charge we obtained preliminary cross section. That cross sections can be used as a base for new event generator and as a new model for RC and BC estimation.







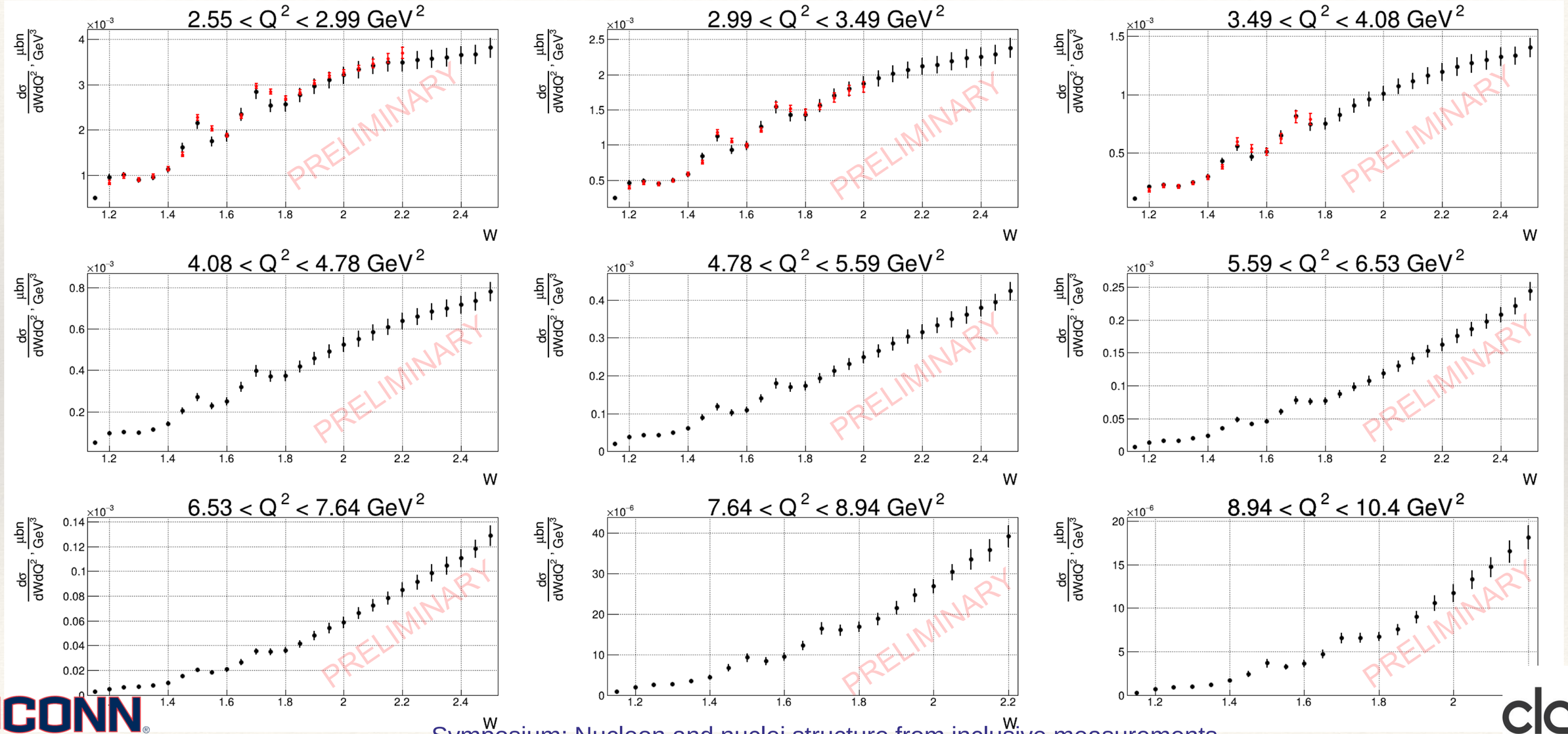


Cross Section with three models:
Green – Cross Sections with initial model
Orange - Cross Sections with iteration 1 model
Purple - Cross Sections with iteration 2 model

There is small peak shift. Peaks become narrower with iterations number.

Preliminary Cross Section

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



Systematic Uncertainty

Cuts:	**Systematic Uncertainty**
1. PCAL fiducial cuts	1. < 1%
2. DC fiducial cuts	2. ~ 2%
3. Triangular cut	3. ~ 3%
4. -8 < vertex < 2	4. ~ 2%
5. EC Sampling Fraction cut $3.5\sigma \pm \sigma$	5. ~ 2%
6. PCAL dep. Energy > 0.07 GeV	6. ~ 0%
Other:	**Systematic Uncertainty:**
1. Sector dependence	**1. 2% - 10% (< 5% for $Q^2 < 6.5$ GeV^2)**
2. RC corrections	2. < 2%
3. Momentum corrections	3. < 1.5%
4. Bin centering corrections	4. ~ 1%
5. Bad\wrong PMTs knock out	5. ~ 1.5%
6. Smearing	6. ~ 1%

Summary

- Preliminary results on inclusive electron scattering cross sections are available from CLAS12 in the kinematic range of 1.15 < W < 2.5 GeV and 2.55 < Q^2 < 9.0 GeV^2. Our new measurements show reasonable agreements with world data in overlapping Q^2 regions.

- First (e,e'X) data from CLAS12 have become available within a broad coverage over W from pion threshold ton 2.5 GeV at any given bin of Q^2 within the range of photon virtuality from 2.55 GeV^2 to 9.0 GeV^2.

- Evaluation of the resonant contributions from exclusive meson electroproduction data will pave a way to extend knowledge on PDF at large x in the resonance region.

- The (e,e'X) data from CLAS12 offer an opportunity to explore evolution of inclusive structure function F_2 within the range of distances where the transition from strongly coupled to pQCD regimes is anticipated.

Back Up

Charge Symmetrical Background

- Momentum range for the last but one Q^2 bin is 3.7 – 6.3 GeV
- Momentum range for the last bin Q^2 is 2.9 – 5.7 GeV

```
W = 2.225
prMass = 0.938272
Q2 = 10.4
Ebeam = 10.604
Ebeam - (W**2+Q2-prMass**2) / (2*prMass)
```

```
2.8928721745847668
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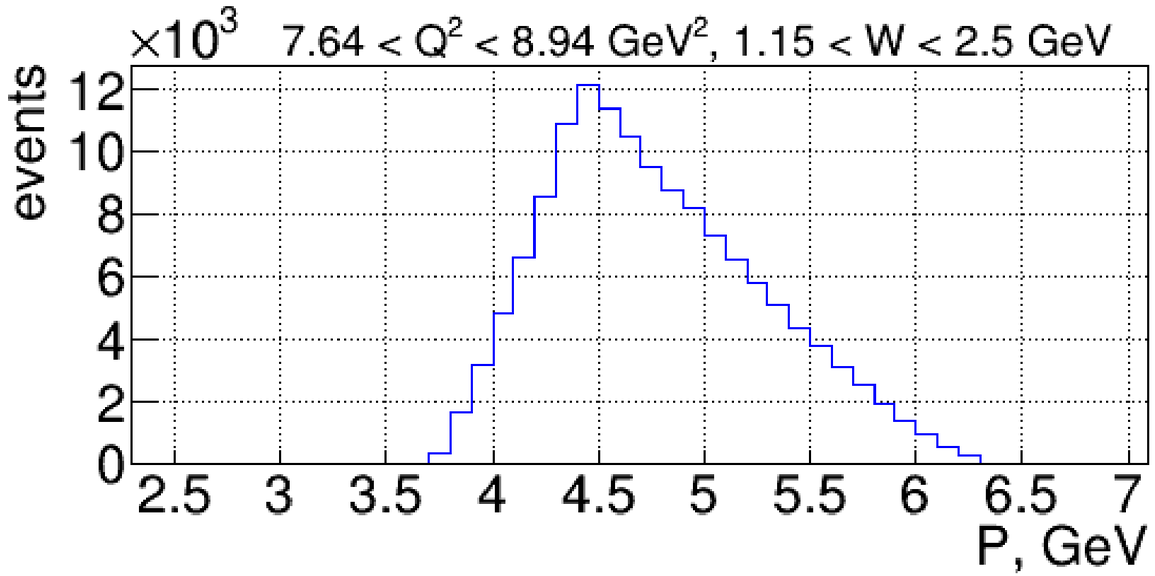
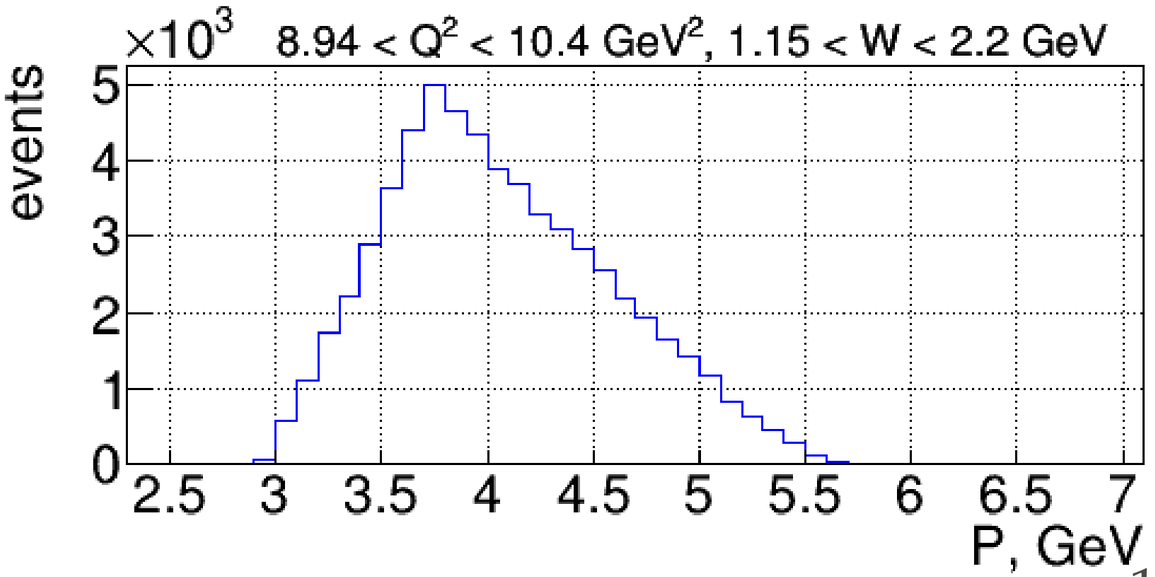
- Minimal possible momentum for our kinematics is at W = 2.225 GeV, Q^2 =10.4 GeV^2 so P_{min} = 2.893 GeV
- **Charge symmetrical background is negligible in our kinematic range**



P distribution for the last but one Q^2 bin



P distribution for the last Q^2 bin