Studies of DIS: from Jlab12 to JLab24

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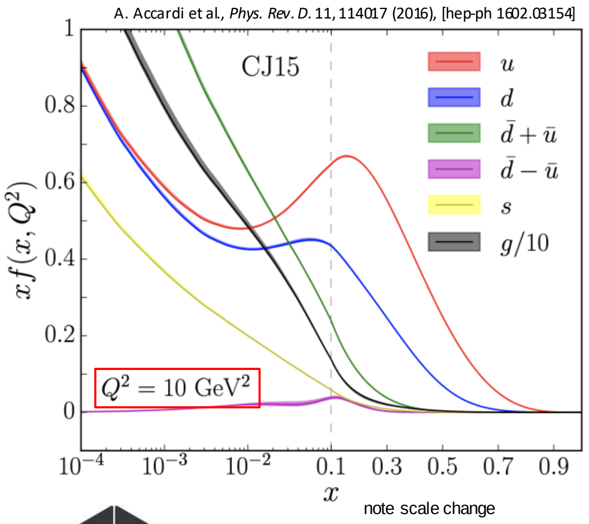
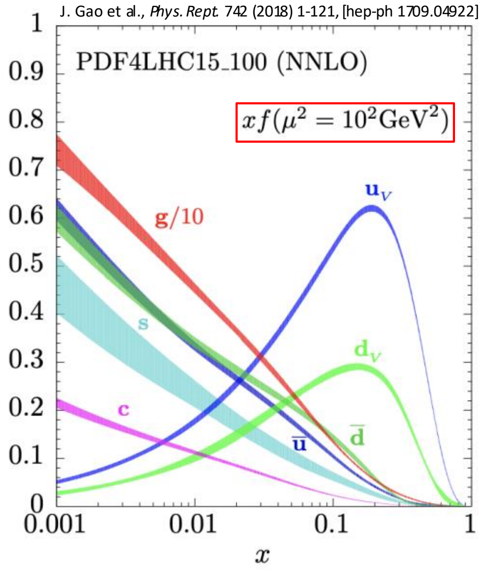
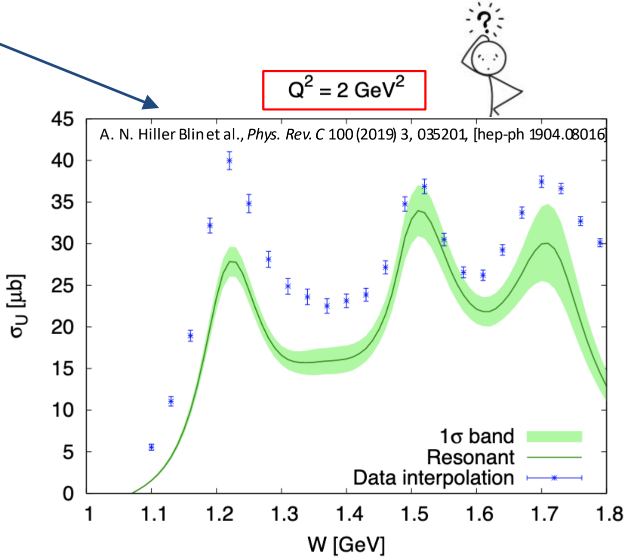
UCONN

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.





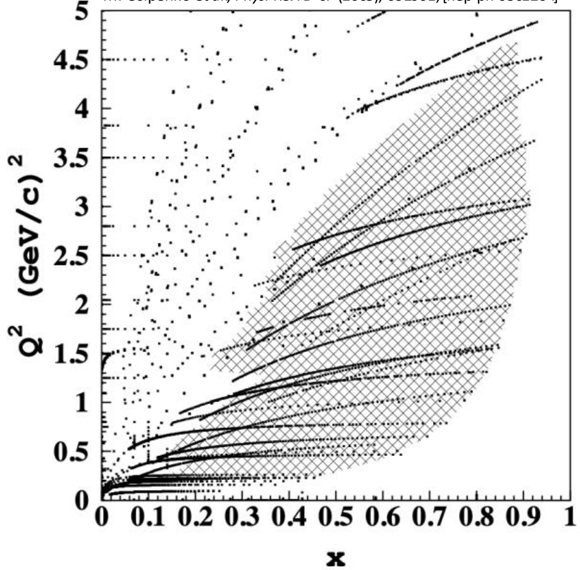


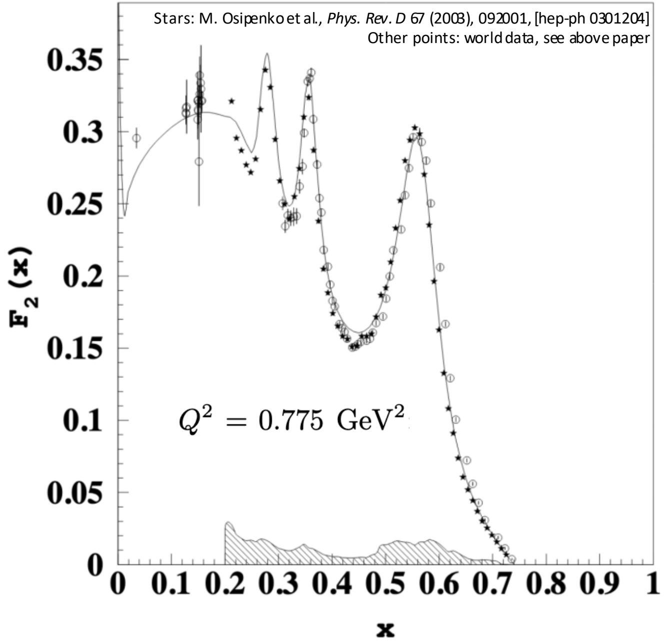
CLAS Results

- 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.

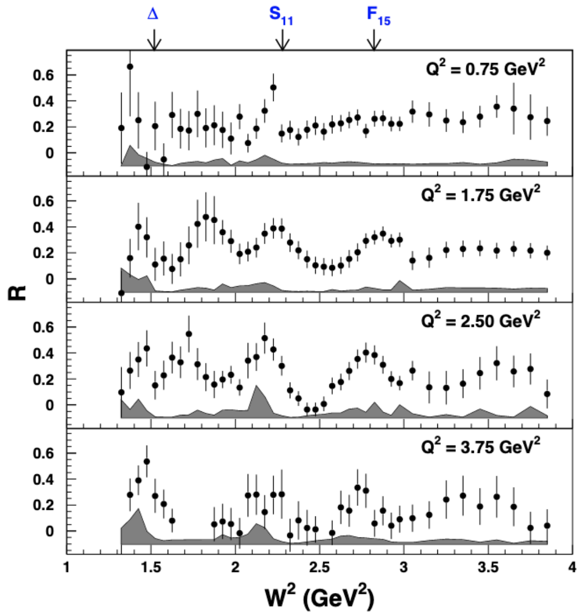
M. Osipenko et al., *Phys. Rev. D* 67 (2003), 092001, [hep-ph 0301204]





Updated $R = \sigma_L/\sigma_T$

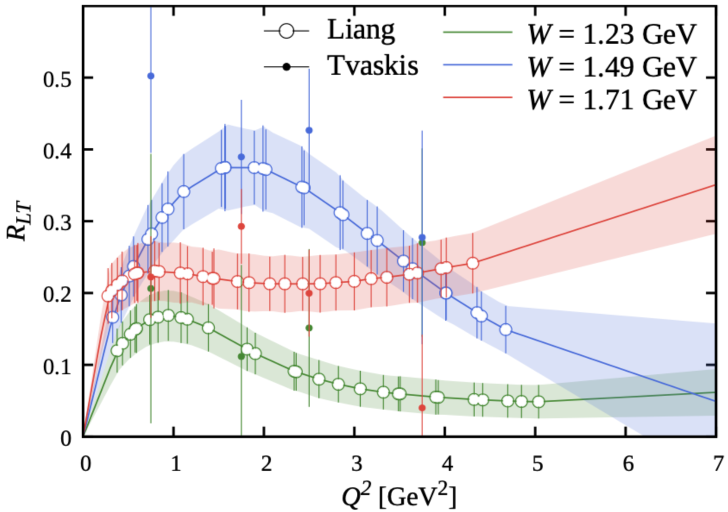
- Hall C data allows for Rosenbluth separation of 167 data points.
- First separate values of F_1 and F_L in this kinematic regime.



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.

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Resonant Contributions

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

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

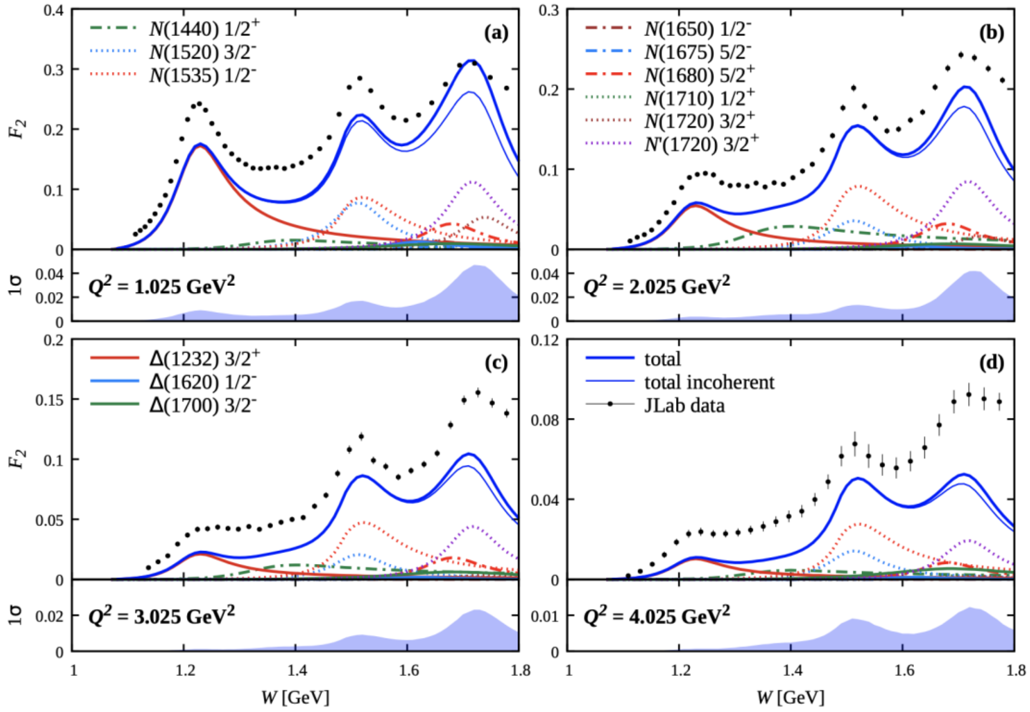
Decay widths of resonance R to $\gamma^* p$ related to electrocouplings from previous slide.

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

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

- 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]

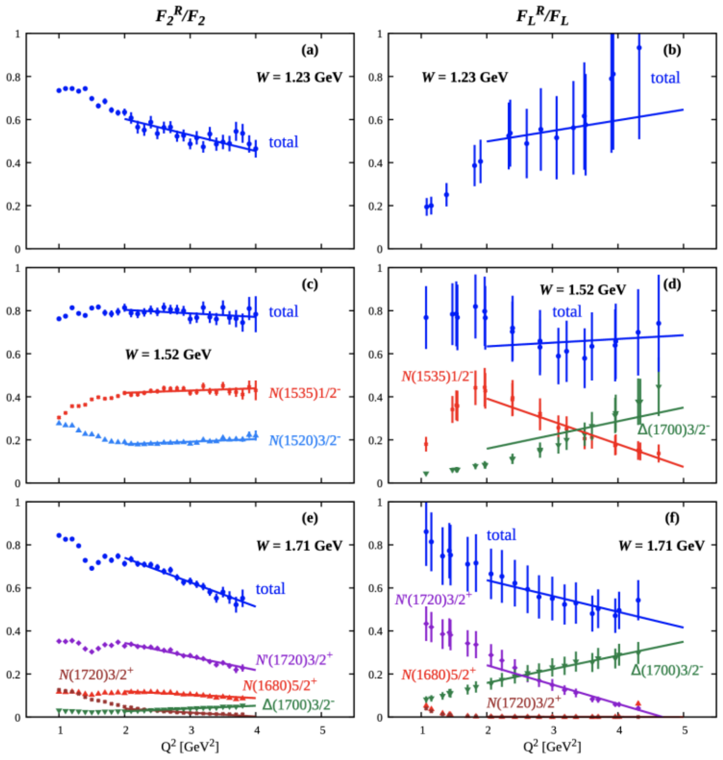


Q^2 evolution

1st resonance

2nd resonance

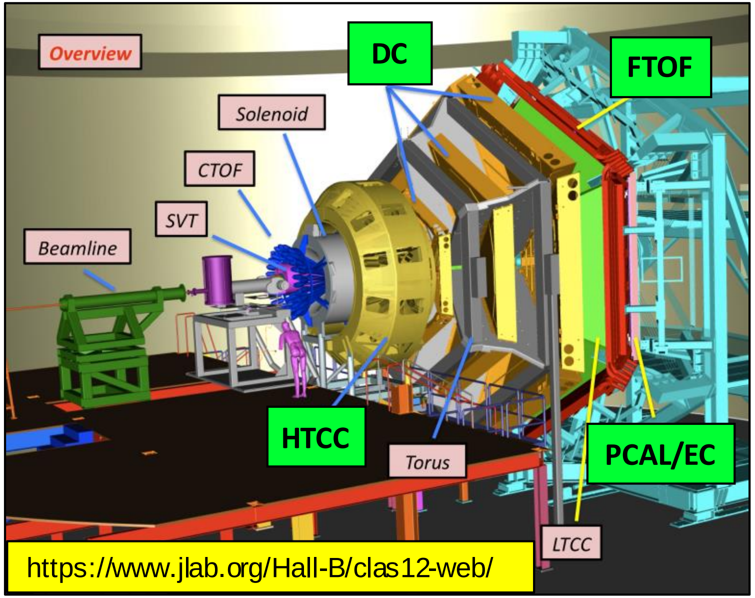
3rd resonance

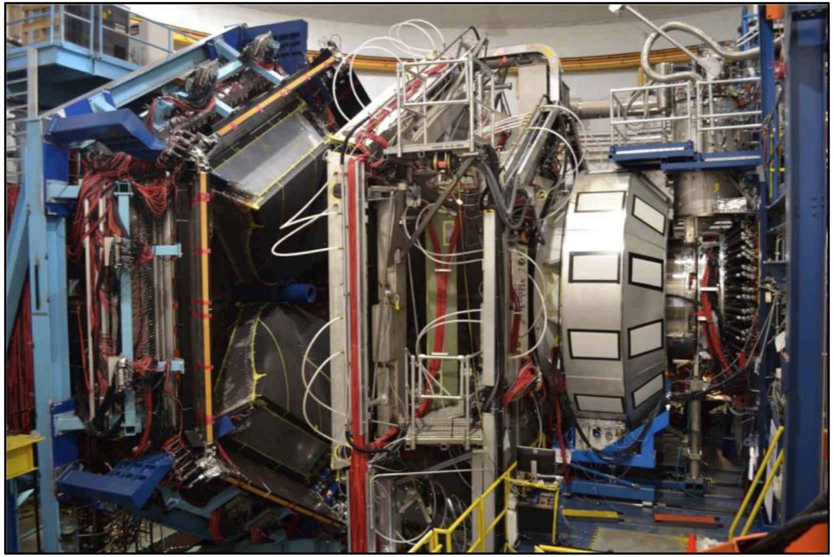


A. N. Hiller Blin et al., *Phys. Rev. C* 104 (2021) 2, 025201, [hep-ph 2105.05834]

- 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.

CLAS12 Spectrometer



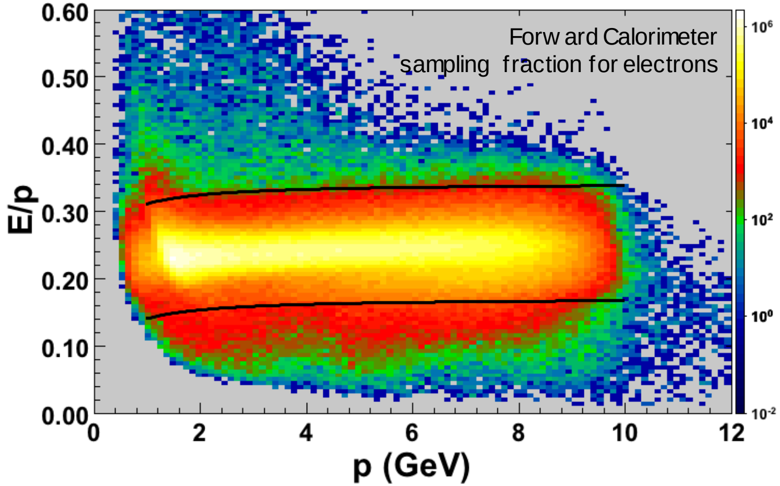


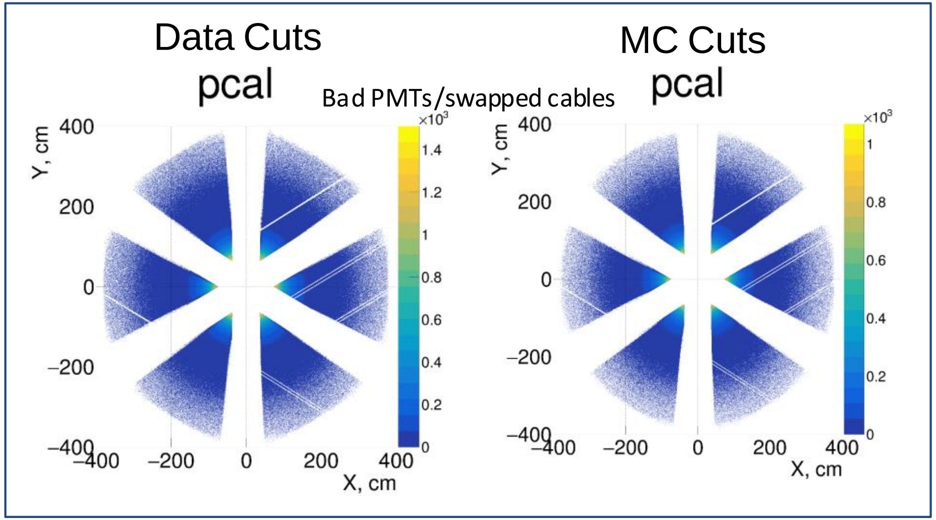
V. Burkert et al., Nucl. Instrum. Meth. A 959 (2020) 163419

- 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.

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





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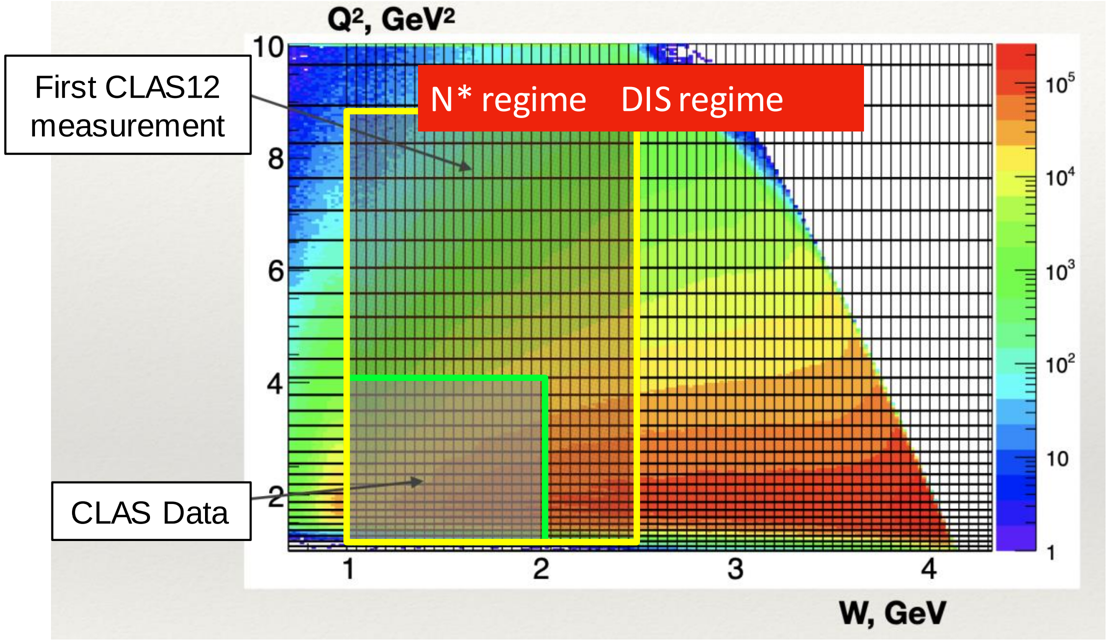
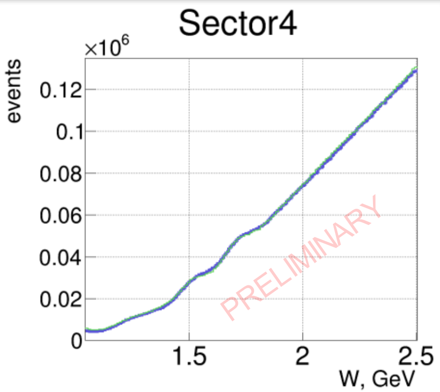
CLAS12 Kinematic Reach

- 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.

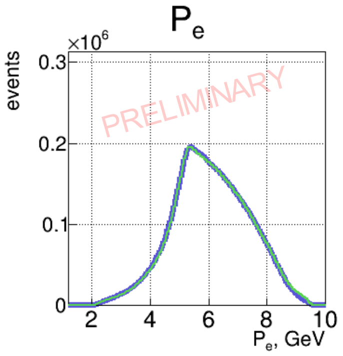


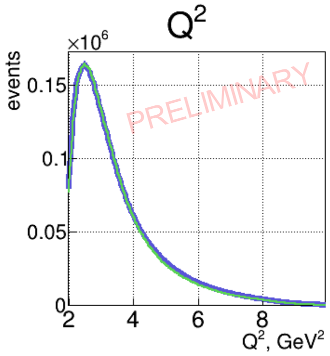
Simulation

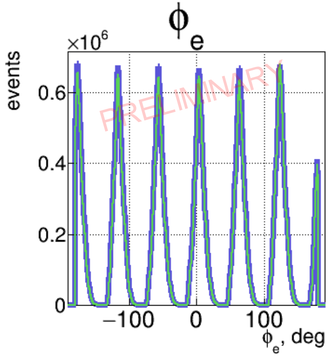
- Inclusive EG: M. Sargsyan, CLAS-NOTE 90-007 (1990)
- Elastic tail + Inelastic radiated
- Kinematic range:
  - Theta range 5 - 36°
  - Scattered electron momentum 1.9 – 10 GeV
  - Full Q^2 coverage
  - Additional kinematic smearing to match the resolution of reconstructed data.

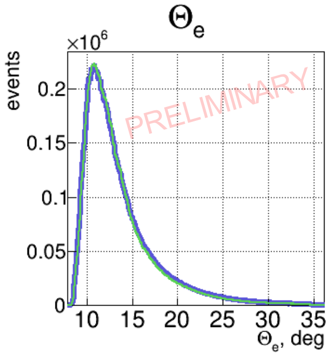


- Green – Data
- Blue – MC reconstructed









Cross Section Calculation

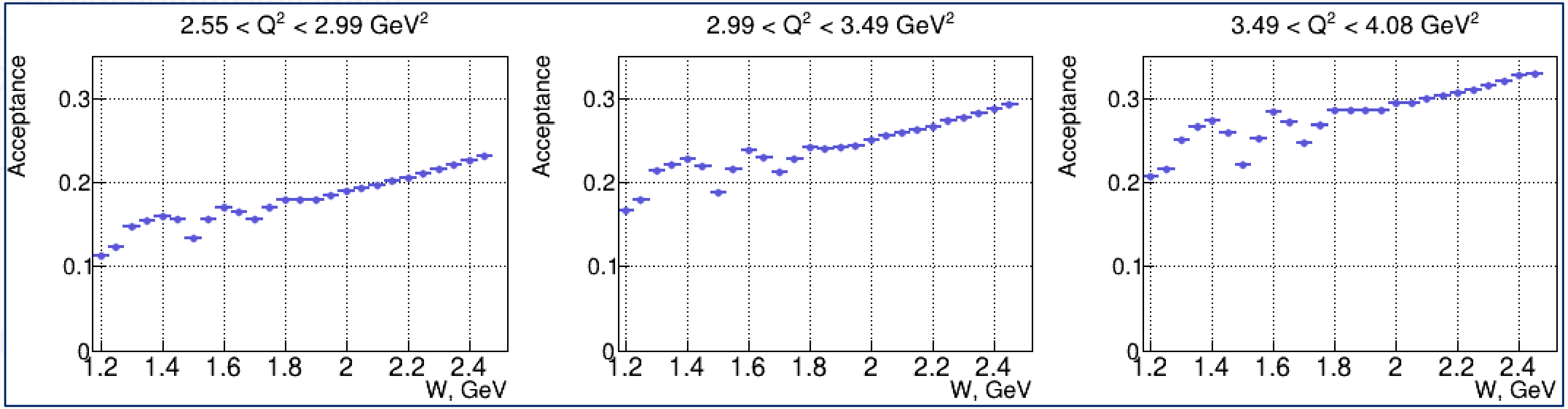
$$\frac{d\sigma}{dQ^2 dW} = \frac{1}{\Gamma_\nu} \cdot \frac{1}{\Delta Q^2 \Delta W} \cdot \frac{RC \cdot N \cdot BCC}{\eta \cdot N_0} \cdot \frac{1}{N_A \rho t / A_\omega}$$

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

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

- 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.

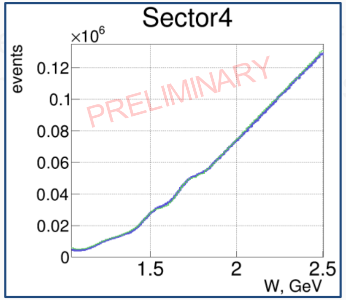
Bin Centering Corrections

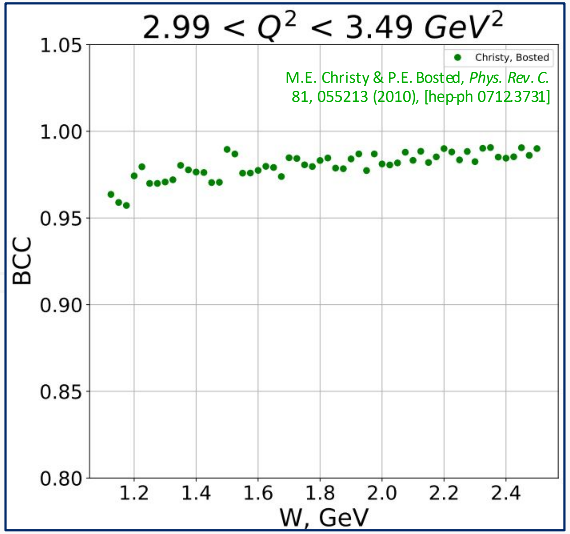
$$\frac{d\sigma}{dQ^2dW} = \frac{1}{\Gamma_\nu}\cdot\frac{1}{\Delta Q^2\Delta W}\cdot\frac{RC\cdot N\cdot \boxed{BCC}}{\eta\cdot N_0}\cdot\frac{1}{N_A\rho t/A_\omega}$$

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.



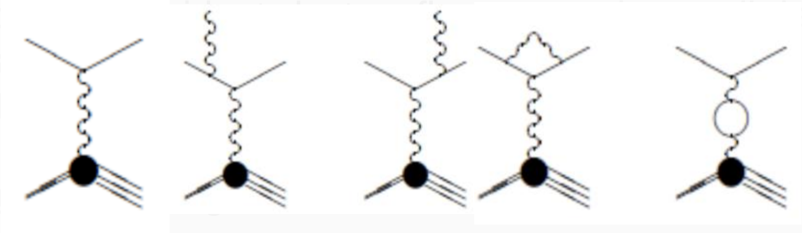


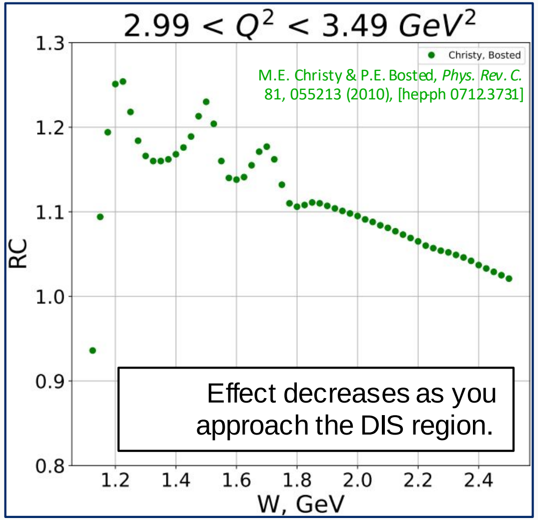
Radiative Corrections

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

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)

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

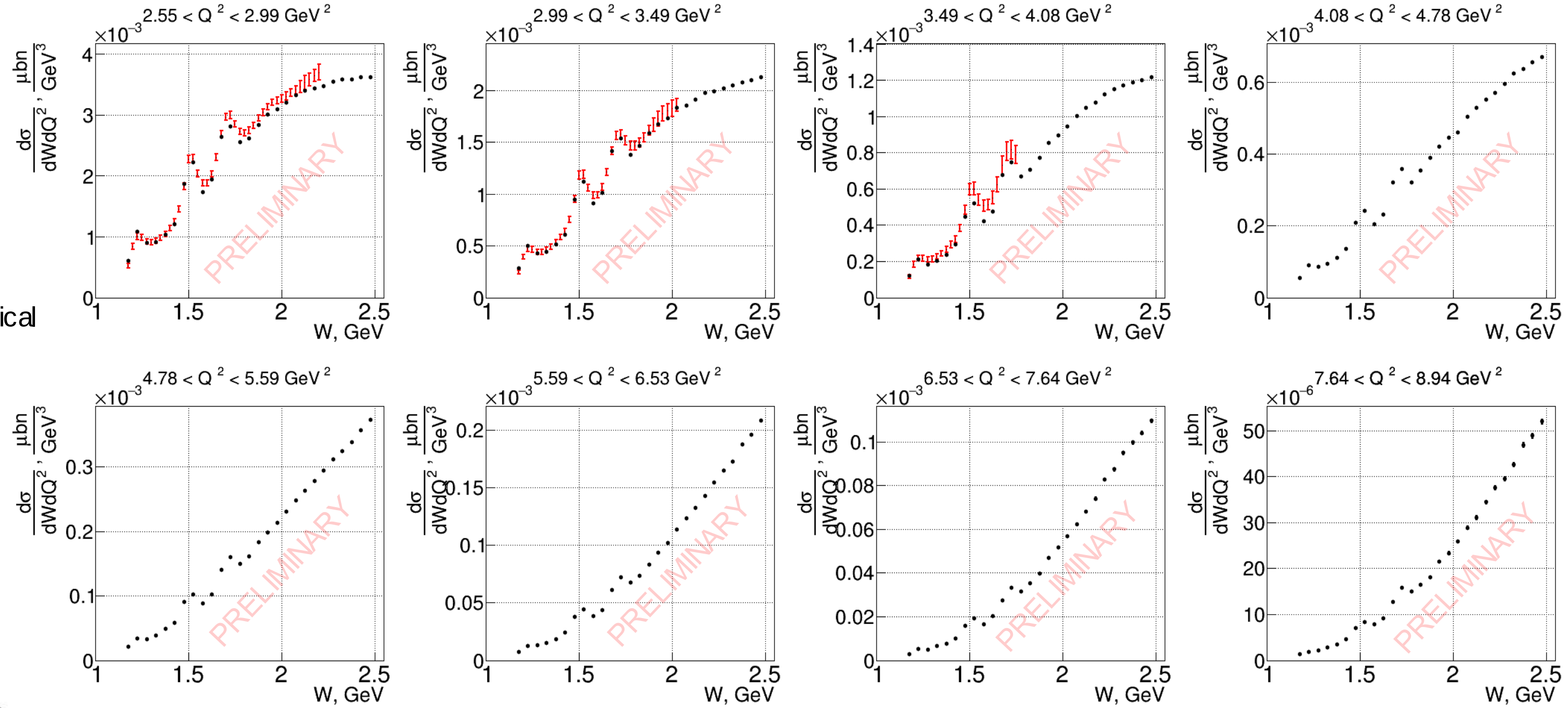




Preliminary Results

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

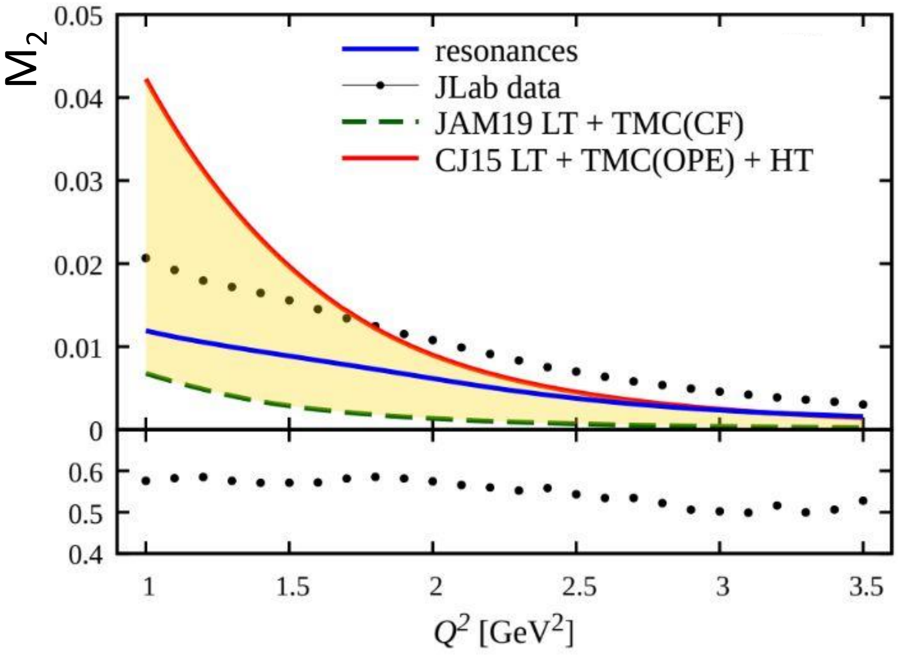
Only statistical errors.



Inclusive electron scattering with CLAS 6/12

- Data on inclusive structure functions available within entire resonance region at any given Q^2 bin from CLAS 6/12 offer precise evaluation for the F_2 truncated moments by direct integration over x.

- The results on F_2 moments at $Q^2 < 10$ GeV^2 from CLAS 6/12 will allow us to explore PDF evolution within the range of distances where QCD running coupling α_s begin to decrease but still remain comparable with unity

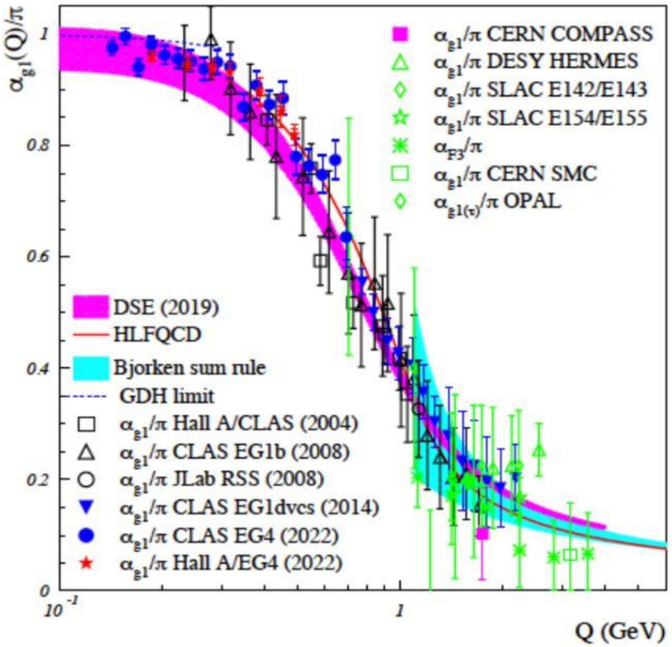


A. N. Hiller Blin et all, Phys. Rev. C **104**, 025201

CLAS 24

QCD Running Coupling α(k)
Zh-F. Cui et al., Chin. Phys. C44, 083102 (2020)
A. Deur et al., Particles 5, 171 (2022)

Increasing CEBAF energy > 20 GeV and pushing CLAS 12 detector capability to measure inclusive electron scattering at luminosities up to 2-3 10^{35} cm^{-2} * s^{-1} will provide the only foreseen opportunity to explore Q^2 evolution of F_2 moments within full range of distance where transition from sQCD to pQCD is expected elucidating emergence of the nucleon structure from QCD



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 within 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.

- 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.

- Moments of inclusive structure functions within Q^2 range up to 20 GeV^2 foreseen after CEBAF energy increase will offer the only foreseen opportunity to explore emergence of nucleon structure from QCD

Back up

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

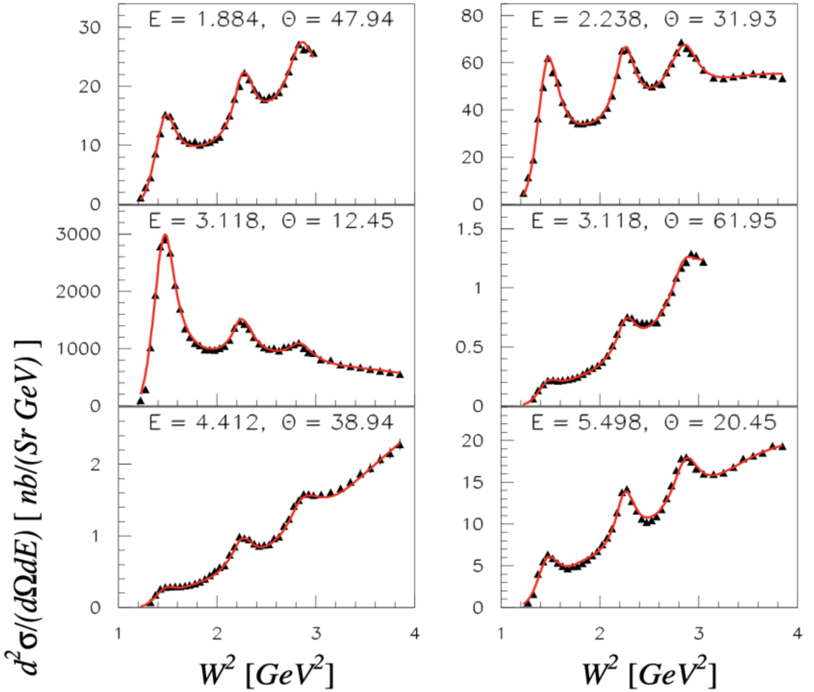
TABLE II: Summary of data sets included in the fit.

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

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

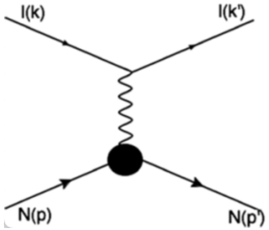
1. Cross section is the incoherent sum of contributions from resonance and non-resonance production.
2. Resonant cross section defined by threshold-dependent BW forms with Q^2 dependent amplitudes.
3. Non-resonant background varies smoothly with W.

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



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).

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

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

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

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

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]

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Systematics

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

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